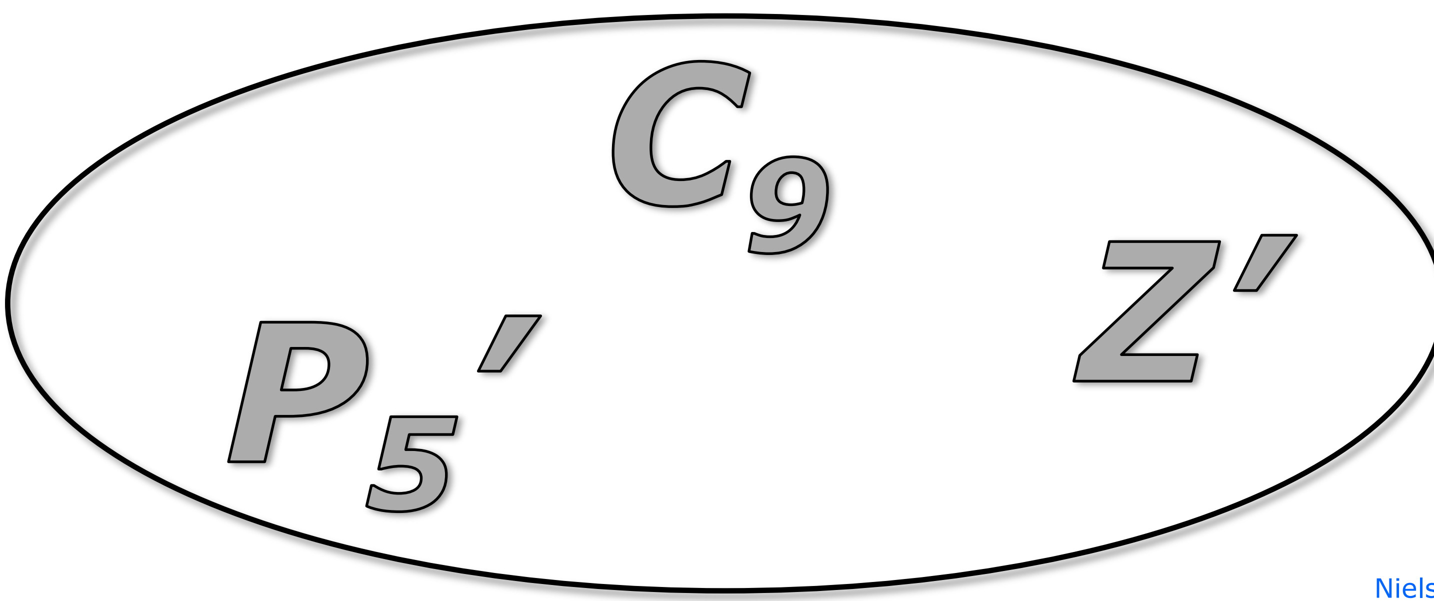
Topical Lectures – Rare Decays

N. Tuning

“Leerdoelen”

- Knowledge of historical insights
- Introduction to Wilson coefficients
- Explain the latest results / tensions



Volkskrant, 23 maart 2015

Geruchten over nieuw deeltje in Genève

De metingen waarmee in 2012 het befaamde Higgsdeeltje werd gevonden op deeltjeslab CERN in Genève hebben mogelijk een tweede onbekend deeltje opgeleverd.

Door: Martijn van Calmthout 23 maart 2015, 05:52

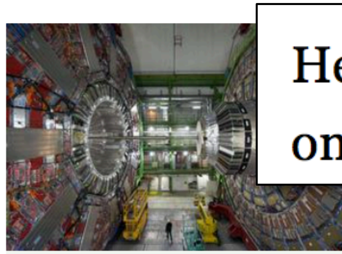
Vrijdag kondigde het LHCb-experiment op CERN afwijkingen in de metingen met de LHC-deeltjesversneller aan, die daarop zouden kunnen duiden.

> Het is te vroeg om de ontdekking te claimen, maar de speculaties over Z' zullen waarschijnlijk wel toenemen nu
>
> — Marcel Merk

Bij de deels door Nederlandse fysici gerunde LHCb-detector wordt gekeken naar het verval van zogeheten B-mesonen, die kunnen ontstaan als protonen in de versneller met hoge energie op elkaar botsen. De zogeheten B-fysica geldt als een domein waar eventuele afwijkingen van de bestaande deeltjestheorie kunnen opduiken. Daarvan is bekend dat hij niet volledig is.

Afwijking

Vrijdag maakten de onderzoekers op de jaarlijkse winterconferentie van CERN in ski-oord Moriond bekend dat het verval van de mesonen anders gaat dan de theorie zegt. Aanwijzingen daarvoor waren in 2011 voor het eerst gezien, maar nu staat de afwijking vast.



Het CMS (Compact Muon Solenoid) in CERN. © AFP

Het gevonden effect kan duiden op een onbekend deeltje, een zogeheten Z'-deeltje, dat mogelijk duizend keer zwaarder is dan een proton. Eerder in de week gingen al geruchten over de vondst van zo'n Z', dat zelfs kan duiden op een nieuwe natuurkundige kracht.

Zover is het zeker nog niet, zeggen groepsleider Marcel Merk bij LHCb en zijn

Het gevonden effect kan duiden op een onbekend deeltje, een zogeheten Z'-deeltje,

Plan

- Introduction
  - My motivation for flavour physics
  - History of indirect measurements
  - HQET: Wilson coefficients

- Rare Decays
  - $B_s^0 \rightarrow \mu\mu$
  - $B^0 \rightarrow K^*\mu\mu$
  - Present tensions in (rare) B decays

Rare Decays - Outline:

- 9h30 - 10h15 Lecture 1: Introduction
- 10h30 - 11h15 Lecture 2: Effective couplings
- 11h30 - 12h15 Lecture 3: $B_s \to \mu\mu$

Lunch

- 13h45 - 14h30 Lecture 4: $B^0 \to K^*\mu\mu$
- 15h00 - 16h30 Discussion Session

Road to discovery: Wilson coefficients

Theory

(What are Wilson coefficients?)

↓

Measurements

(sensitive to Wilson coefficients)

↓

Fit

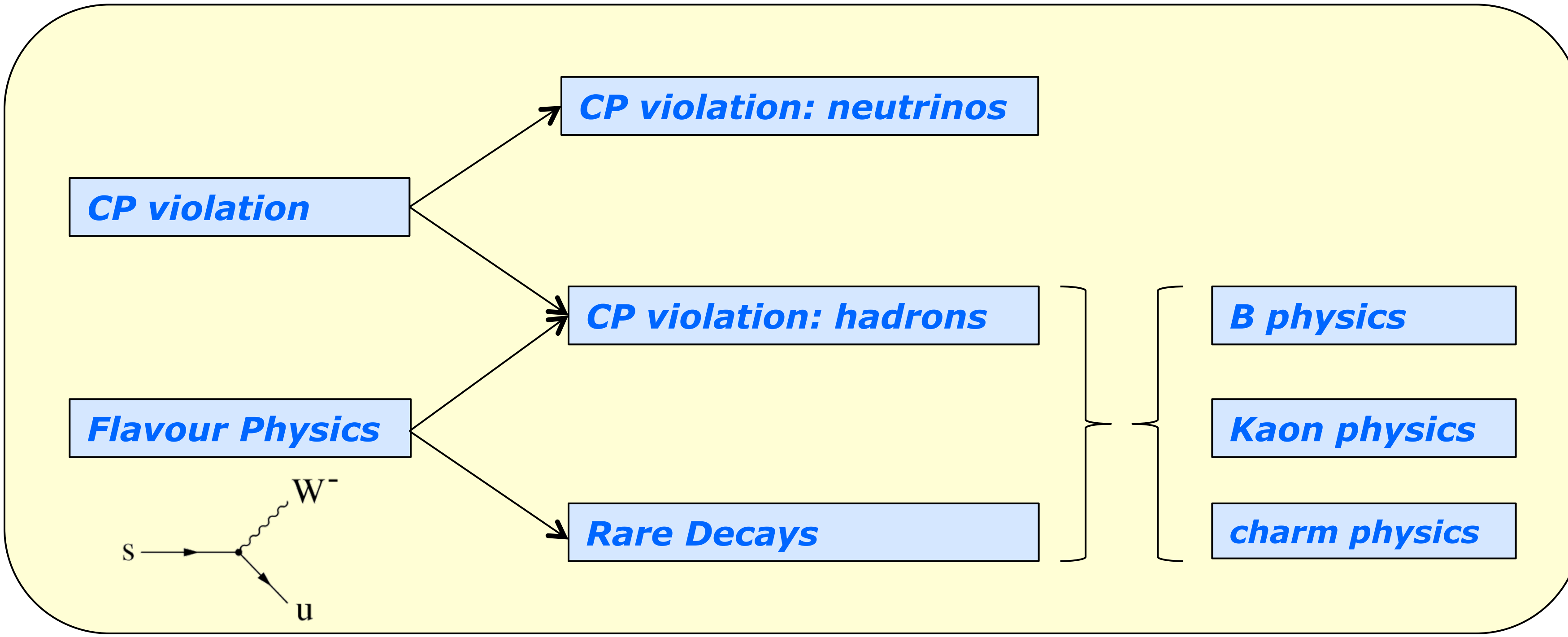
(i.e. determine Wilson coefficients)

↓

Interpretation

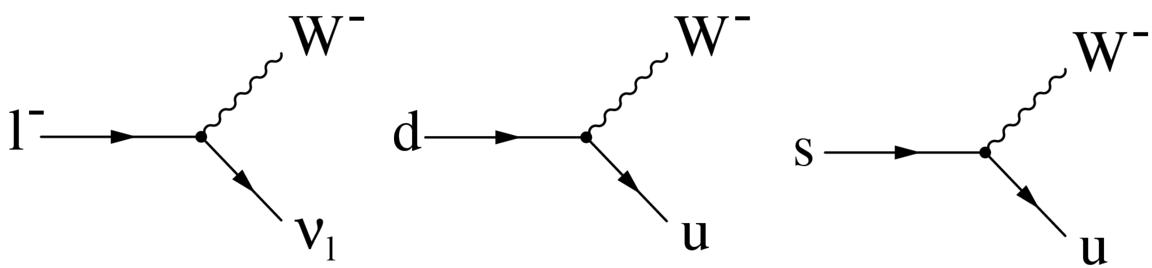
(which models correspond to theses Wilson coefficients?)

Jargon


CP violation: neutrinos
CP violation
CP violation: hadrons
B physics
Flavour Physics
Kaon physics
W⁻
s
u
Rare Decays
charm physics

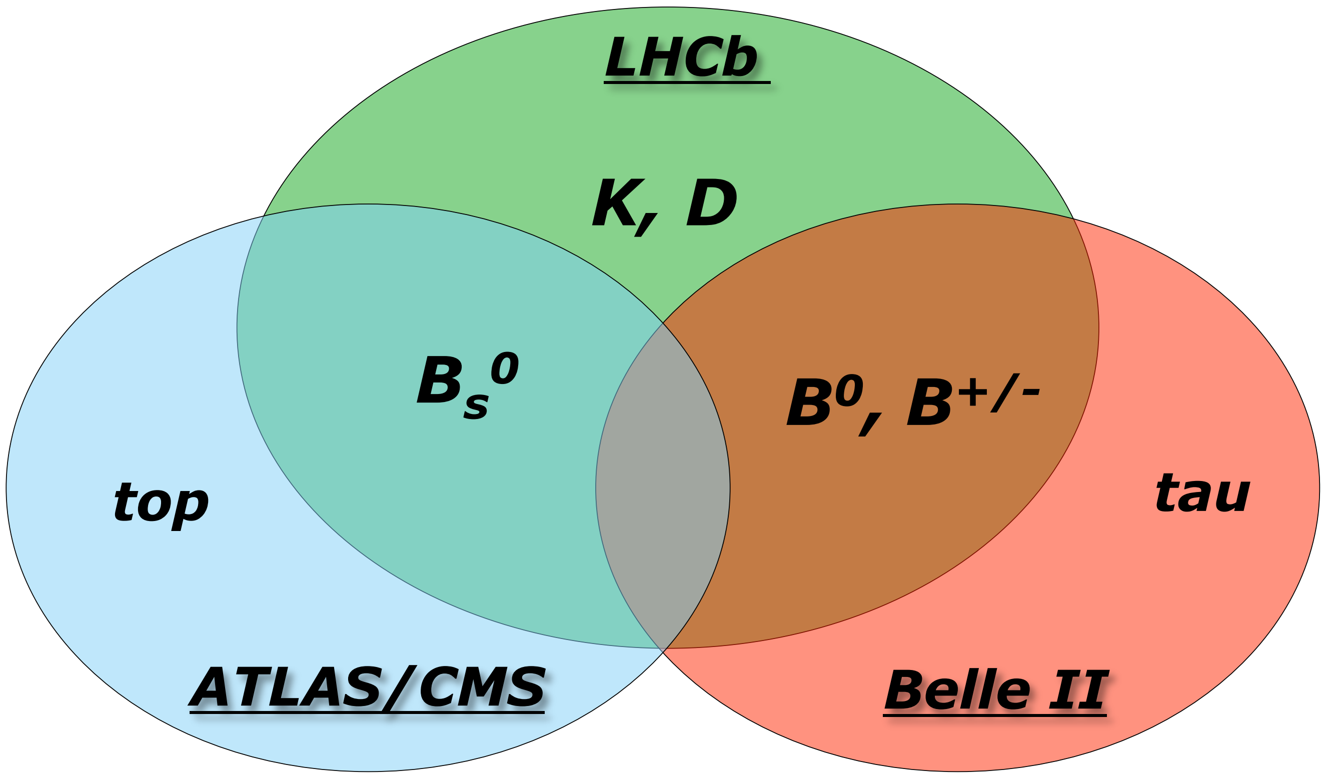
Introduction: it's all about the charged current

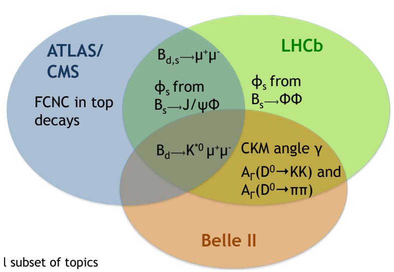
- "CP violation" is about the <u>weak interactions,</u>
- In particular, the charged current interactions:



- The interesting stuff happens in the interaction with quarks
- Therefore, people also refer to this field as "<u>flavour physics</u>"

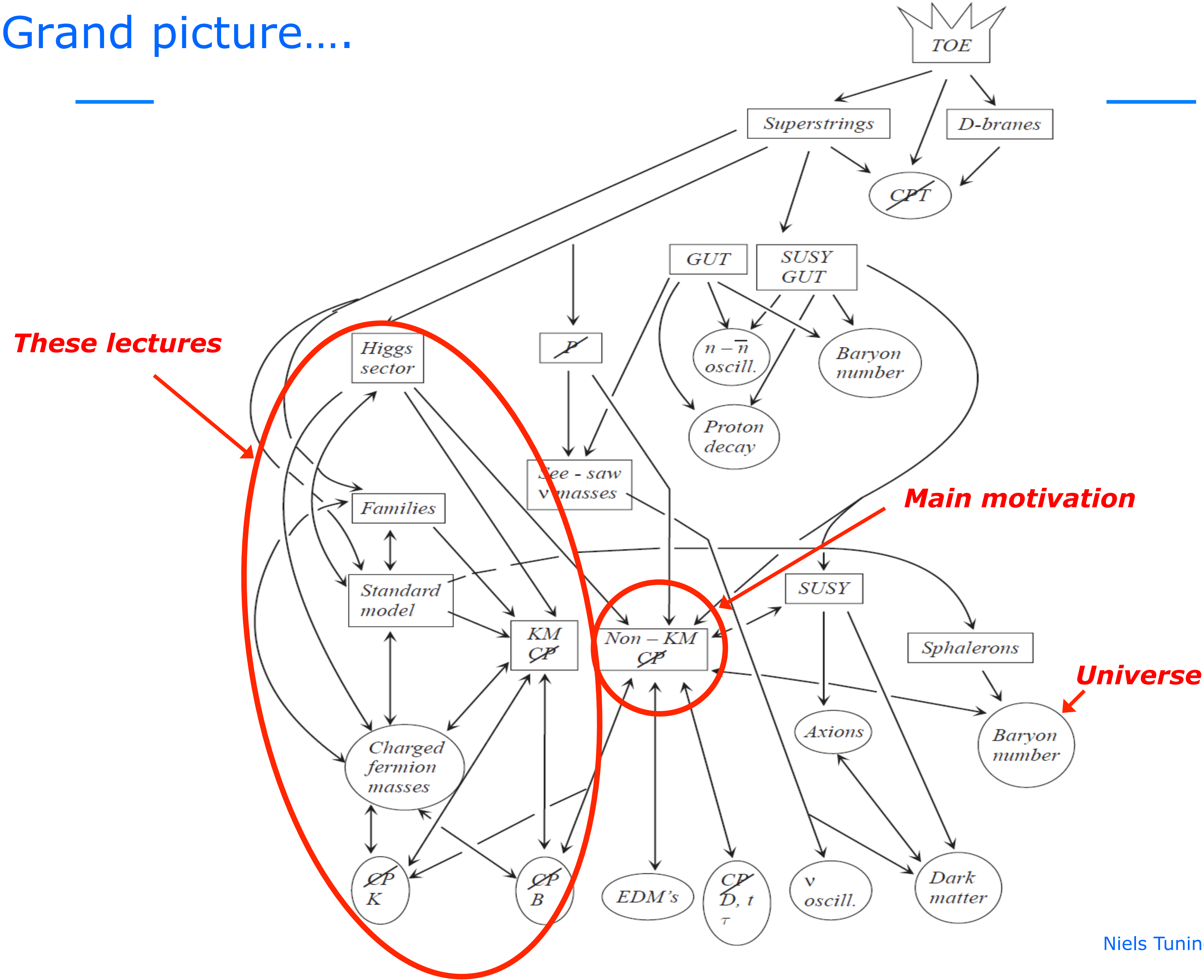
Flavour physics – Current Experiments





Sketch adopted from Marie-Hélène
Schune ECFA2013, 1 Oct 2013

Grand picture….

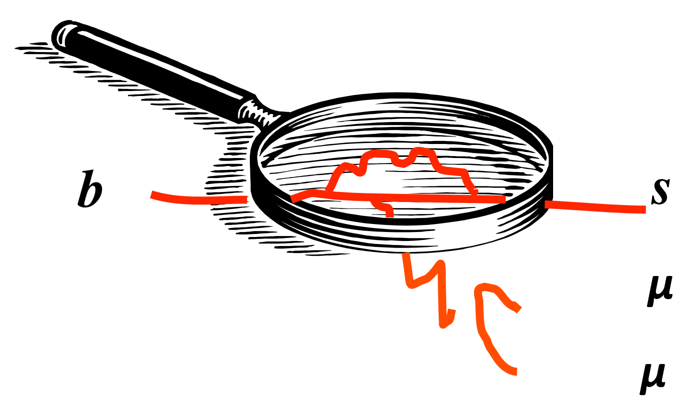


Motivation 1: New Physics in loop diagrams?

- Precision measurements
- Find deviations from the Standard Model
- Sensitive to heavy particles in loop diagrams

"Box" diagram: ΔB=2

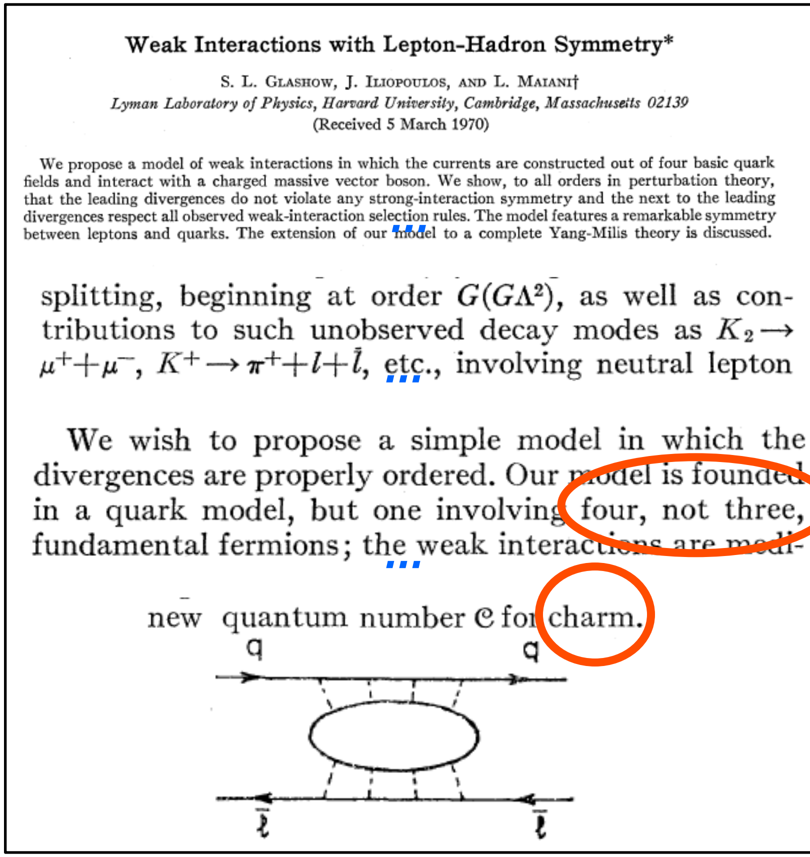
"Penguin" diagram: ΔB=1



Motivation 1: New Physics in loop diagrams?

$K^0 \rightarrow \mu\mu$ pointed to the charm quark:

GIM, Phys.Rev.D2,1285,1970



Weak Interactions with Lepton-Hadron Symmetry*

S. L. Glashow, J. Iliopoulos, and L. Maiani†
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139
(Received 5 March 1970)

We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction symmetry and the next to the leading divergences respect all observed weak-interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Milis theory is discussed.

...

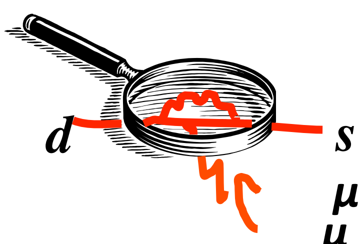
splitting, beginning at order $G(G\Lambda^2)$, as well as contributions to such unobserved decay modes as $K_2 \rightarrow \mu^+ + \mu^-$, $K^+ \rightarrow \pi^+ + l + \bar{l}$, etc., involving neutral lepton

...

We wish to propose a simple model in which the divergences are properly ordered. Our model is founded in a quark model, but one involving four, not three, fundamental fermions; the weak interactions are modi-

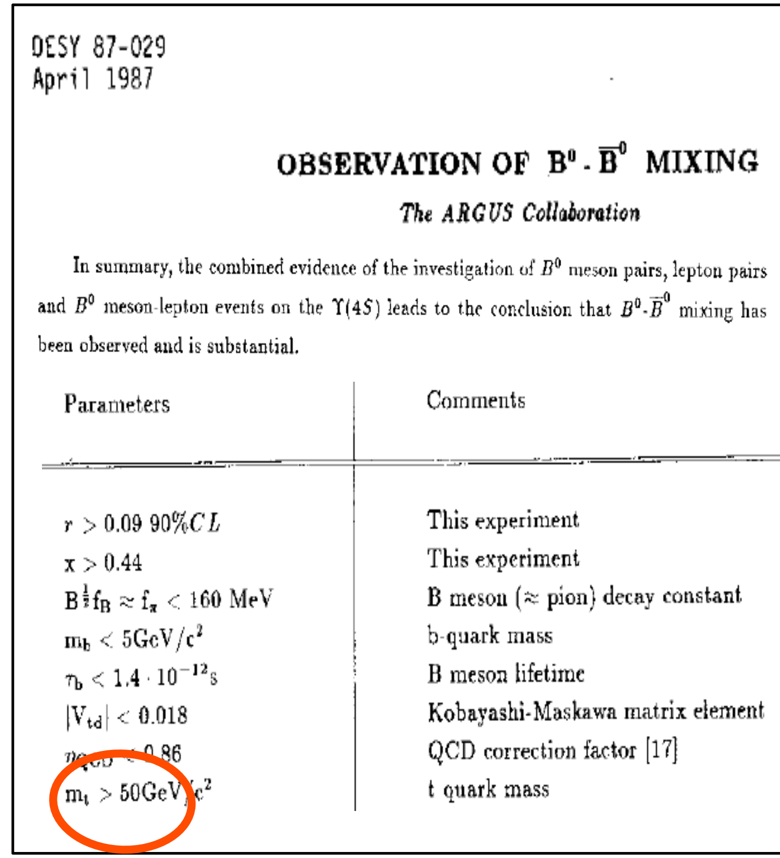
...

new quantum number $\mathcal{C}$ for charm.



B⁰ mixing pointed to heavy **top** quark:

ARGUS Coll, Phys.Lett.B192:245,1987



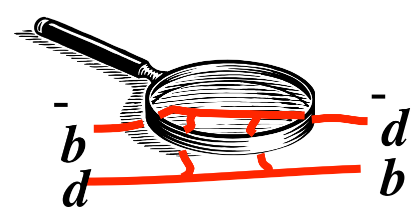
DESY 87-029
April 1987

OBSERVATION OF B^0-$\bar{B}^0$ MIXING

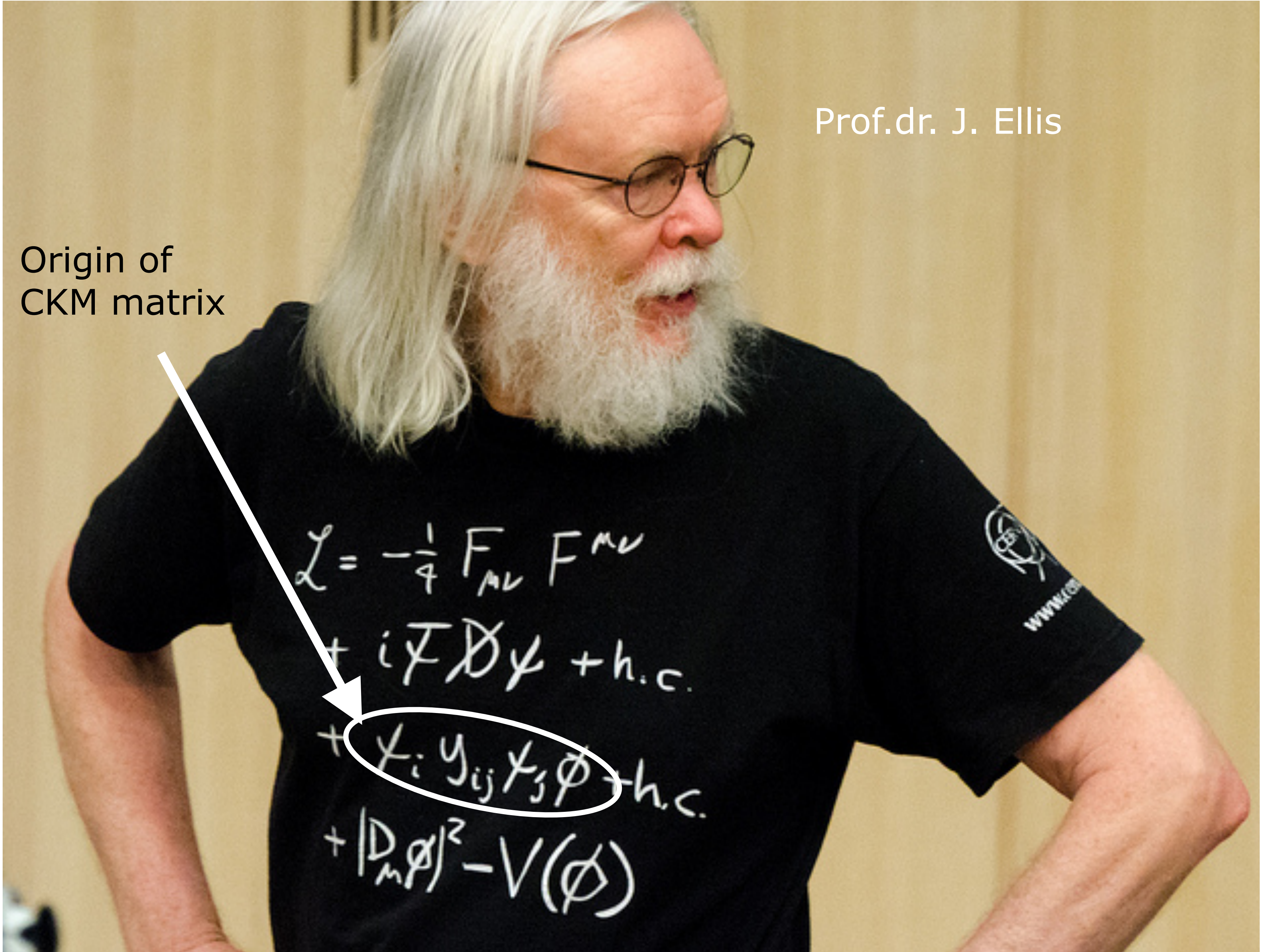
The ARGUS Collaboration

In summary, the combined evidence of the investigation of B^0 meson pairs, lepton pairs and B^0 meson-lepton events on the $\Upsilon(4S)$ leads to the conclusion that B^0-$\bar{B}^0$ mixing has been observed and is substantial.

Parameters	Comments
$r > 0.09$ 90%CL	This experiment
$x > 0.44$	This experiment
$B^{\frac{1}{2}} f_B \approx f_\pi < 160$ MeV	B meson (≈ pion) decay constant
$m_b < 5 \mathrm{GeV}/c^2$	b-quark mass
$\tau_b < 1.4 \cdot 10^{-12}$s	B meson lifetime
$\lvert V_{td} \rvert < 0.018$	Kobayashi-Maskawa matrix element
$\eta_{QCD} < 0.86$	QCD correction factor [17]
$m_t > 50 \mathrm{GeV}/c^2$	t quark mass



Motivation 2: at the heart of the SM


Prof.dr. J. Ellis
Origin of CKM matrix
$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i \bar{\psi} \not{D} \psi + h.c.$
$+ \psi_i y_{ij} \psi_j \phi + h.c.$
$+ |D_\mu \phi|^2 - V(\phi)$

Motivation 2: at the heart of the SM

$$\boxed{\mathcal{L}_{SM} = \mathcal{L}_{kinetic} + \mathcal{L}_{Higgs} + \mathcal{L}_{Yukawa}}$$

$$\boxed{i\bar{\psi}(D^\mu \gamma_\mu)\psi} \quad \boxed{(D_\mu \phi)^\dagger (D^\mu \phi) - \mu^2 \phi^\dagger \phi - \lambda(\phi^\dagger \phi)^2} \quad \boxed{Y_{ij}\overline{\psi_{Li}}\,\phi\,\psi_{Rj}}$$

Charged current:
flavour diagonal

$$\frac{g}{\sqrt{2}}\overline{u^I_{iL}}\gamma_\mu W^{-\mu} d^I_{iL}$$

Yukawa couplings:
mix between generations

$$Y^d_{ij}\overline{Q^I_{Li}}\,\phi\,d^I_{Rj} + Y^u_{ij}\overline{Q^I_{Li}}\,\tilde{\phi}\,u^I_{Rj}$$

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Diagonalize Yukawa matrix:
Off diagonal in CC Mass terms

$$\begin{aligned} u^I_i &= u_j \\ d^I_i &= V_{CKM} d_j \end{aligned}$$

$$\frac{g}{\sqrt{2}}\overline{u_{iL}}(V^u_L V^{d\dagger}_L)_{ij}\gamma_\mu W^{-\mu} d_{iL}$$

$$\overline{d_{Li}}\,(M^d_{ij})_{diag}\,d_{Rj} + \overline{u_{Li}}\,(M^u_{ij})_{diag}\,u_{Rj}$$

$$V_{CKM} = (V^u_L V^{d\dagger}_L)_{ij}$$

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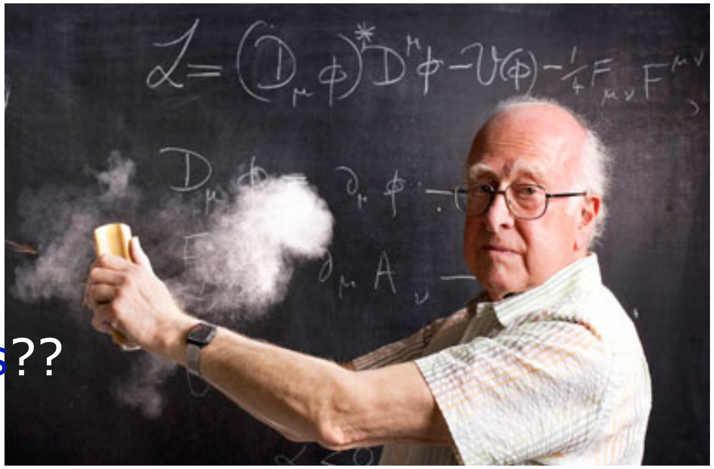
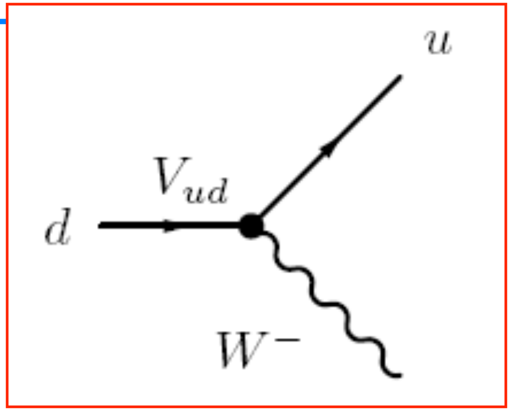
$$\frac{g}{\sqrt{2}}\overline{u_{iL}}(V_L^u V_L^{d\dagger})_{ij}\gamma_{\mu}W^{-\mu}d_{iL}$$

$$V_{CKM} = (V_L^u V_L^{d\dagger})_{ij}$$

- Flavour physics closely connected to Higgs??



Motivation 3: CKM magnitude mysterious



CKM matrix:

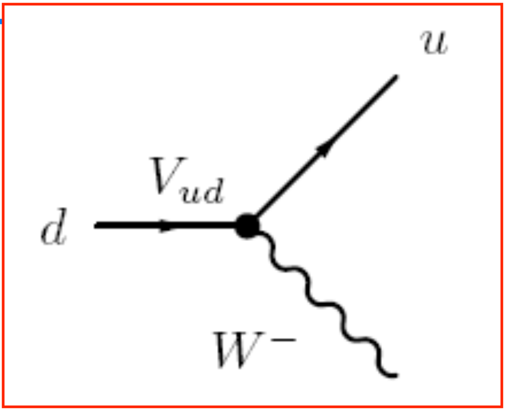
- Coupling strength of charged current
- Completely different hierarchy !

$$\underbrace{\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix}}_{\textbf{flavour}} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \underbrace{\begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}}_{\textbf{mass}} \quad \textit{vs} \quad \underbrace{\begin{bmatrix} |d'\rangle \\ |s'\rangle \\ |b'\rangle \end{bmatrix}}_{\textbf{flavour}} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \underbrace{\begin{bmatrix} |d\rangle \\ |s\rangle \\ |b\rangle \end{bmatrix}}_{\textbf{mass}} .$$

$$U_{MNSP} \approx \begin{pmatrix} 0.85 & 0.53 & 0 \\ -0.37 & 0.60 & 0.71 \\ -0.37 & 0.60 & -0.71 \end{pmatrix}$$

$$V_{CKM} = \begin{pmatrix} 0.97428 & 0.2253 & 0.00347 \\ 0.2252 & 0.97345 & 0.0410 \\ 0.00862 & 0.0403 & 0.999152 \end{pmatrix}$$

Motivation 3: CKM magnitude mysterious



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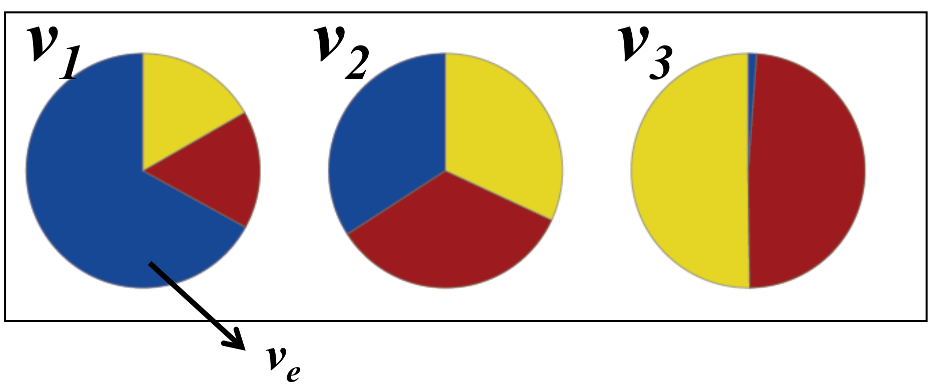
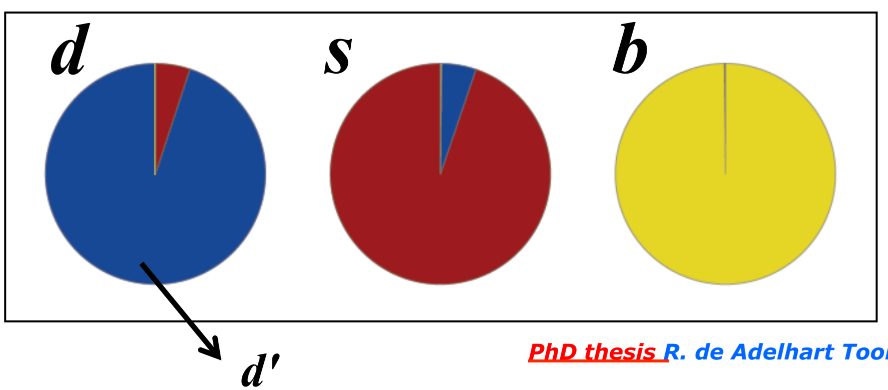
vs

$$\underbrace{\begin{bmatrix}|d'\rangle\\ |s'\rangle\\ |b'\rangle\end{bmatrix}}_{\text{flavour}} = \begin{bmatrix}V_{ud} & V_{us} & V_{ub}\\ V_{cd} & V_{cs} & V_{cb}\\ V_{td} & V_{ts} & V_{tb}\end{bmatrix} \underbrace{\begin{bmatrix}|d\rangle\\ |s\rangle\\ |b\rangle\end{bmatrix}}_{\text{mass}}.$$



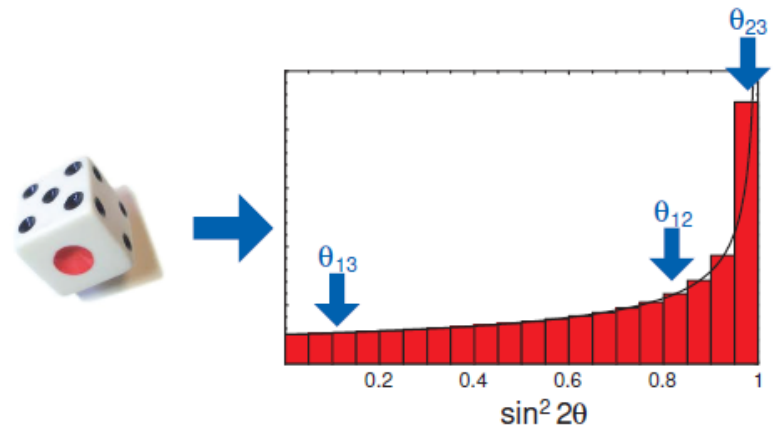


PhD thesis R. de Adelhart Toor

Intermezzo: what does the size tell us?

H.Murayama, 6 Jan 2014, arXiv:1401.0966

➢ Neutrino mixing due to ´anarchy´:



` quite typical of the ones obtained by randomly drawing a mixing matrix from an unbiased distribution of unitary 3x3 matrices´

> and found that it is 47% probable [21]! So we learned indeed that the neutrino masses and mixings do not require any deeper symmetries or new quantum numbers. On the other hand, quarks clearly do need additional input, which is yet to be understood.

Harrison, Perkins, Scott, Phys.Lett. B530 (2002) 167, hep-ph/0202074

➢Neutrino mixing due to underlying symmetry:

$$U_l = \begin{array}{c} \begin{matrix} e & \mu & \tau \end{matrix} \\ \begin{pmatrix} \frac{1}{\sqrt{3}} & \frac{\bar\omega}{\sqrt{3}} & \frac{\omega}{\sqrt{3}} \\ \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \\ \frac{1}{\sqrt{3}} & \frac{\omega}{\sqrt{3}} & \frac{\bar\omega}{\sqrt{3}} \end{pmatrix} \end{array} \qquad U_\nu = \begin{array}{c} \begin{matrix} \nu_1 & \nu_2 & \nu_3 \end{matrix} \\ \begin{pmatrix} \sqrt{\frac{1}{2}} & 0 & -\sqrt{\frac{1}{2}} \\ 0 & 1 & 0 \\ \sqrt{\frac{1}{2}} & 0 & \sqrt{\frac{1}{2}} \end{pmatrix} \end{array} \tag{4}$$

i.e. $U_l^\dagger M_l^2 U_l = \text{diag}\,(m_e^2,\ m_\mu^2,\ m_\tau^2)$ and $U_\nu^\dagger M_\nu^2 U_\nu = \text{diag}\,(m_1^2,\ m_2^2,\ m_3^2)$, so that the lepton mixing matrix (or MNS matrix) $U = U_l^\dagger U_\nu$ is given by:

$$\begin{array}{c} e \\ \mu \\ \tau \end{array} \begin{pmatrix} \frac{1}{\sqrt{3}} & \sqrt{\frac{1}{3}} & \frac{1}{\sqrt{3}} \\ \frac{\omega}{\sqrt{3}} & \sqrt{\frac{1}{3}} & \frac{\bar\omega}{\sqrt{3}} \\ \frac{\bar\omega}{\sqrt{3}} & \sqrt{\frac{1}{3}} & \frac{\omega}{\sqrt{3}} \end{pmatrix} \begin{array}{c} \begin{matrix} \nu_1 & \nu_2 & \nu_3 \end{matrix} \\ \begin{pmatrix} \sqrt{\frac{1}{2}} & 0 & -\sqrt{\frac{1}{2}} \\ 0 & 1 & 0 \\ \sqrt{\frac{1}{2}} & 0 & \sqrt{\frac{1}{2}} \end{pmatrix} \end{array} = \begin{array}{c} e \\ \mu \\ \tau \end{array} \begin{array}{c} \begin{matrix} \nu_1 & \nu_2 & \nu_3 \end{matrix} \\ \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & -\frac{i}{\sqrt{2}} \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \frac{i}{\sqrt{2}} \end{pmatrix} \end{array} \tag{5}$$

Motivation 4: EWSB / Antimatter / Cosmology

- Electro-weak symmetry breaking
  - CKM matrix is related to Yukawa couplings
  - The Yukawa couplings arose when particles acquired mass
- Antimatter – matter asymmetry
  - CP violation only known mechanism to distinguish
  - Warning: CP violation ≠ Baryon number
- Cosmology
  - Aspects above determined our faith

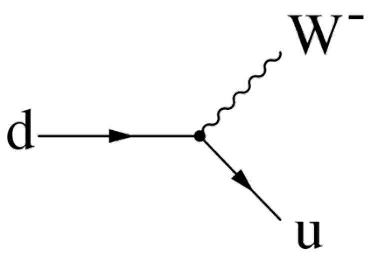
Recap:

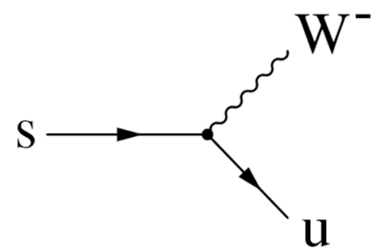
- CP-violation (or flavour physics) is about charged current interactions

- Interesting because:

  1) <u>Beyond Standard Model:</u> measurements are sensitive to new particles

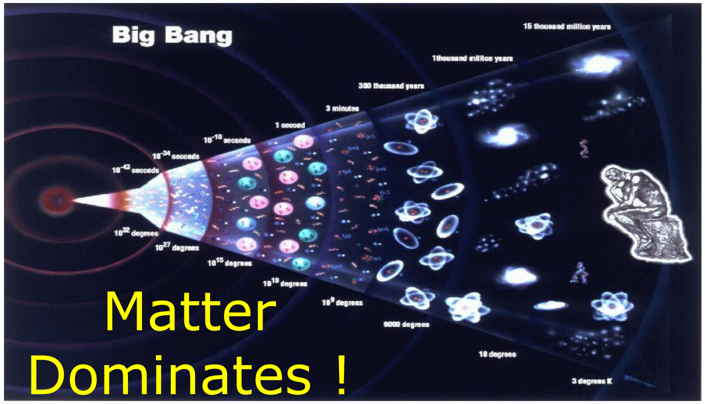
  2) <u>Standard Model:</u> in the heart of quark interactions





  3) <u>Mysterious</u>: magnitude CKM elements

  4) <u>Cosmology:</u> related to matter – anti-matter asymetry



Personal impression:

- People think it is a complicated part of the Standard Model
  Why?

1) Non-intuitive concepts?

   - *Imaginary phase* in transition amplitude, T ~ $e^{i\varphi}$
   - *Different bases* to express quark states, d' =0.97 d + 0.22 s + 0.003 b
   - *Oscillations* (mixing) of mesons: $|K^0> \leftrightarrow |\bar{K}^0>$

2) Complicated calculations?

$$\Gamma\left(B^0 \to f\right) \propto \left|A_f\right|^2 \left[\left|g_+(t)\right|^2 + \left|\lambda\right|^2 \left|g_-(t)\right|^2 + 2\Re\left(\lambda g_+^*(t) g_-(t)\right)\right]$$

$$\Gamma\left(\bar{B}^0 \to f\right) \propto \left|\bar{A}_f\right|^2 \left[\left|g_+(t)\right|^2 + \frac{1}{\left|\lambda\right|^2}\left|g_-(t)\right|^2 + \frac{2}{\left|\lambda\right|^2}\Re\left(\lambda^* g_+^*(t) g_-(t)\right)\right]$$

3) Many decay modes? *"Beetopaipaigamma…"*

   – PDG reports 347 decay modes of the B^0-meson:
      - Γ_1 $l^+ \nu_l$ *anything* (10.33 ± 0.28) × 10^{-2}
      - Γ_{347} $\nu\,\nu\,\gamma$ <4.7 × 10^{-5} CL=90%

   – And for one decay there are often more than one decay *amplitudes*…

What is a kaon?

$$|K_L\rangle = |K_2\rangle + \epsilon |K_1\rangle$$

$$|K_S\rangle = |K_1\rangle + \epsilon |K_2\rangle$$

$$|K_L\rangle = p\left|K^0\right\rangle - q\left|\overline{K^0}\right\rangle$$

$$|K_S\rangle = p\left|K^0\right\rangle + q\left|\overline{K^0}\right\rangle$$

$$\left|K_1\right\rangle = \left|K^0\right\rangle + \left|\overline{K^0}\right\rangle$$

$$\left|K_2\right\rangle = \left|K^0\right\rangle - \left|\overline{K^0}\right\rangle$$

- Different notation: confusing!

K_1, K_2, K_L, K_S, K_+, K_-, K^0

- Flavour eigenstate K^0: well-defined quarks
- Mass-, lifetime eigenstate K_S, K_L: well defined mass
- CP eigenstate K_1, K_2: well-defined CP eigenvalue

- Similar for B, but then $B_L = K_S$ and $B_H = K_L$

➢ Total confusion??

Break

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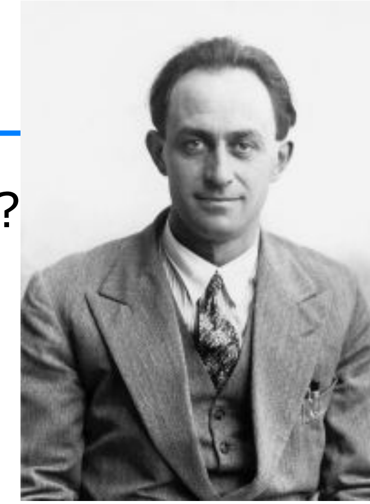
Lunch

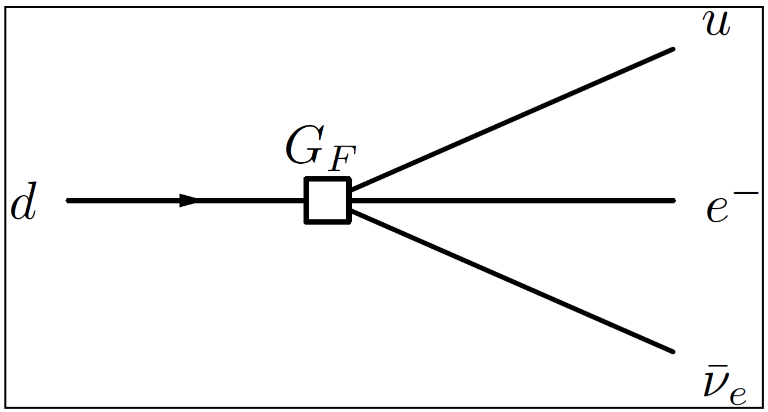
- 13h45 - 14h30 Lecture 4: $B^0 \rightarrow K^*\mu\mu$
- 15h00 - 16h30 Discussion Session

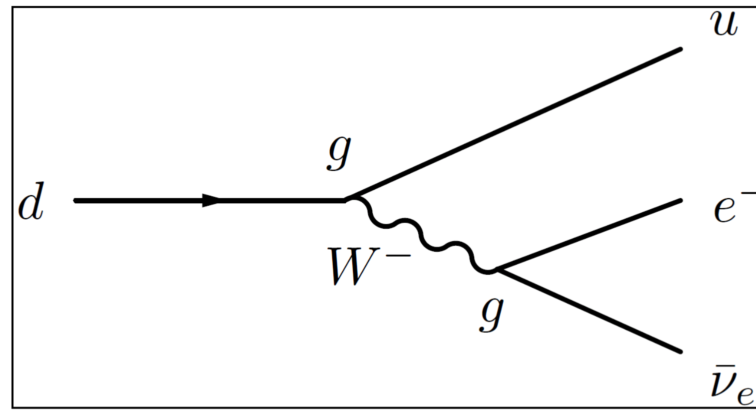
Historical perspective

Historical perspective: W

- Radioactive decay was "discovery" of weak interaction?





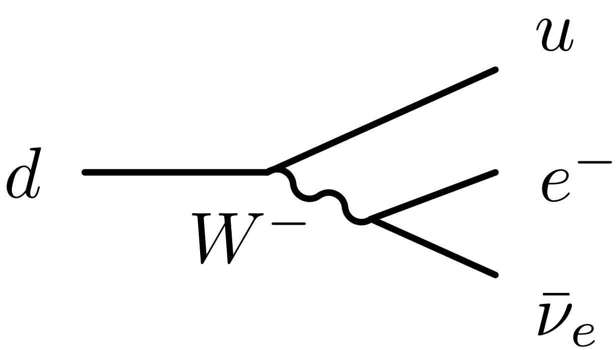


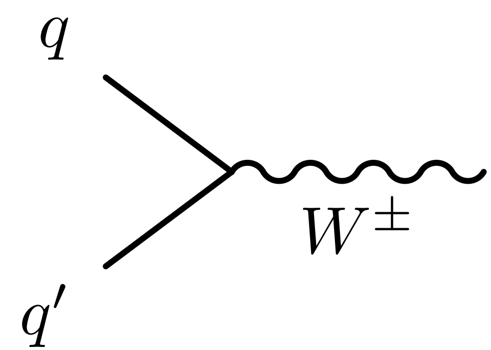
$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}$$

Historical perspective: W

- Radioactive decay was "discovery" of weak interaction?

Indirect





Direct

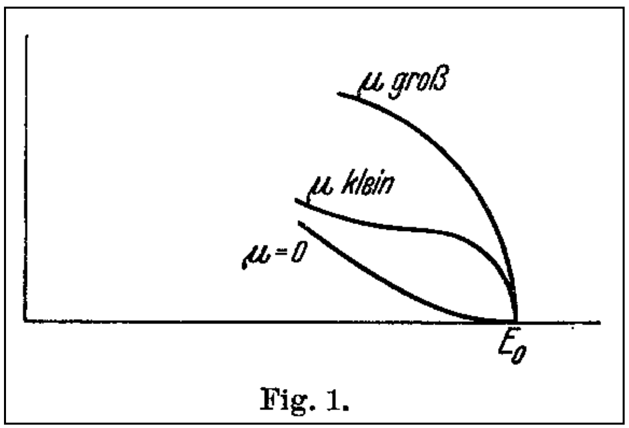
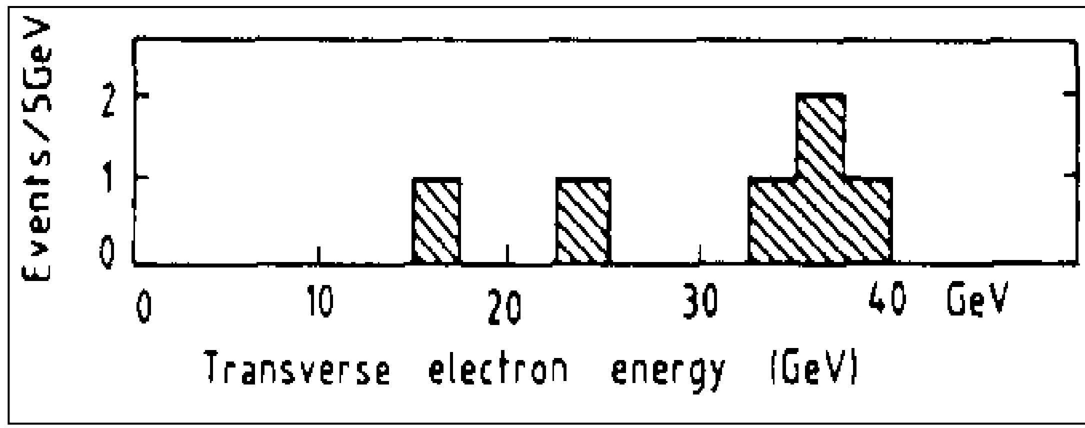


Fig. 1.



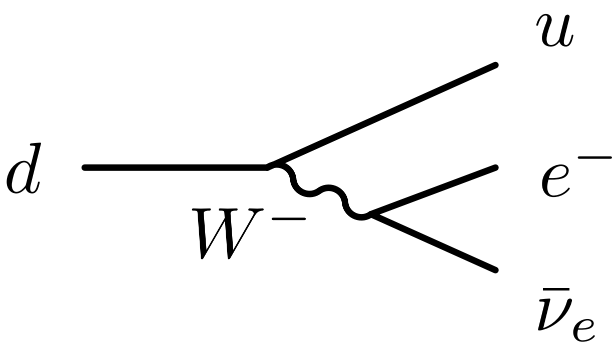
E.Fermi, Z.Phys. 88 (1934) 161

UA1 Coll., Phys.Lett. B122 (1983) 103

Historical perspective: ν

- Radioactive decay was "discovery" of neutrino?

Indirect



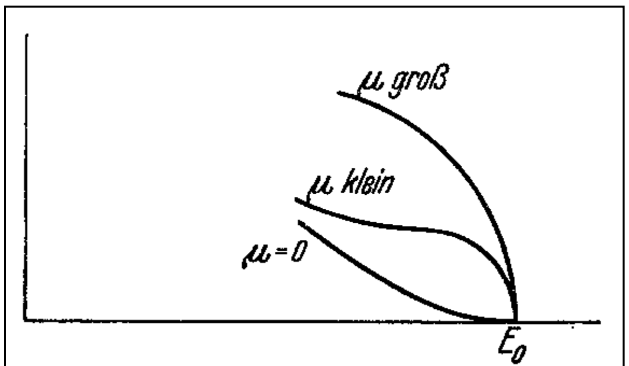
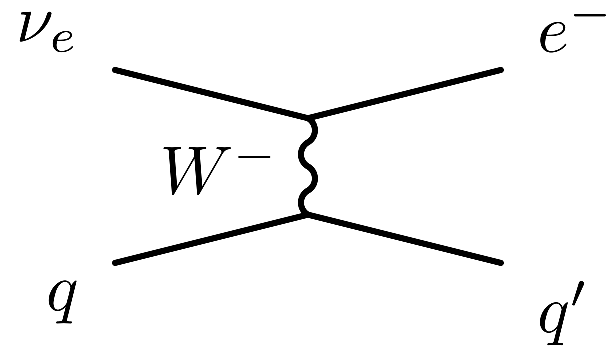
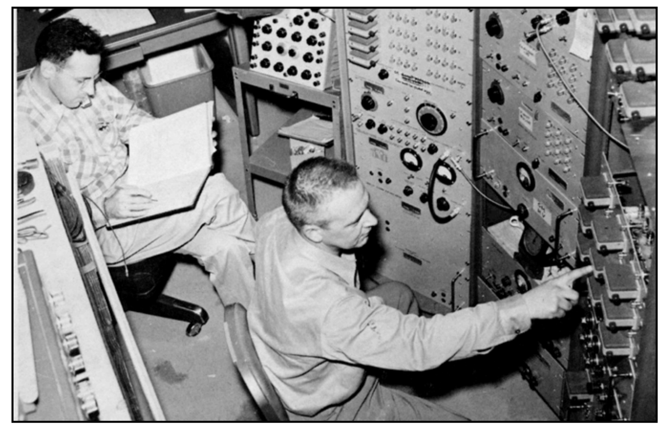


Fig. 1.

E.Fermi, Z.Phys. 88 (1934) 161

Direct



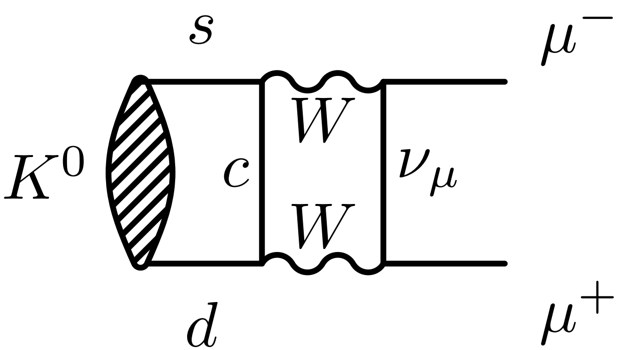


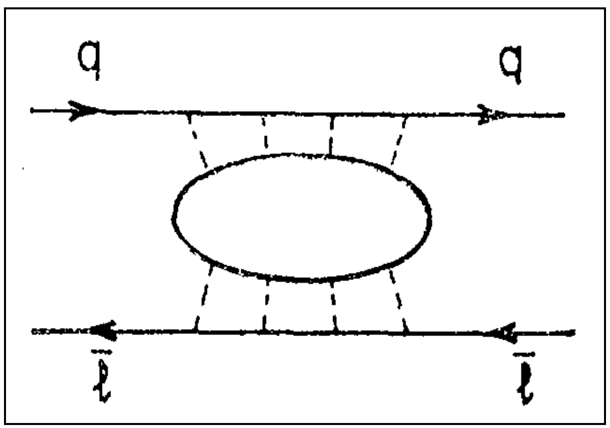
Cowan, Reines, et al., Science 124 (1956) 103-104

Historical perspective: charm

- Kaon decay was “discovery” of charm quark?

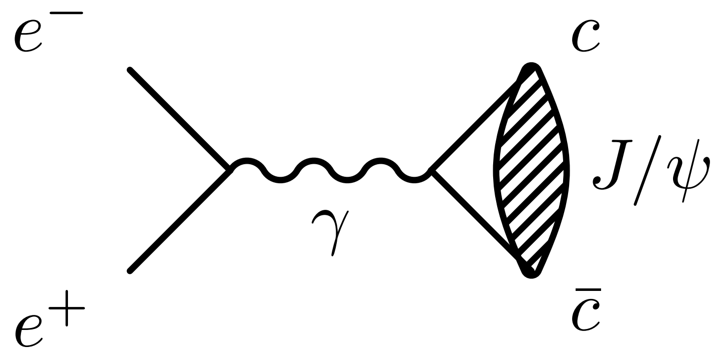
Indirect

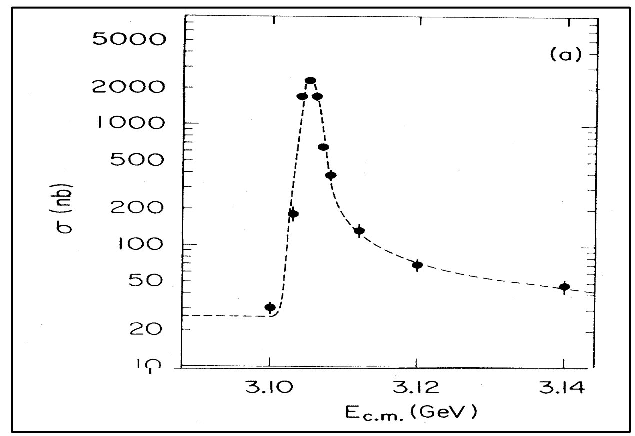




GIM, Phys.Rev. D2 (1970) 1285

Direct

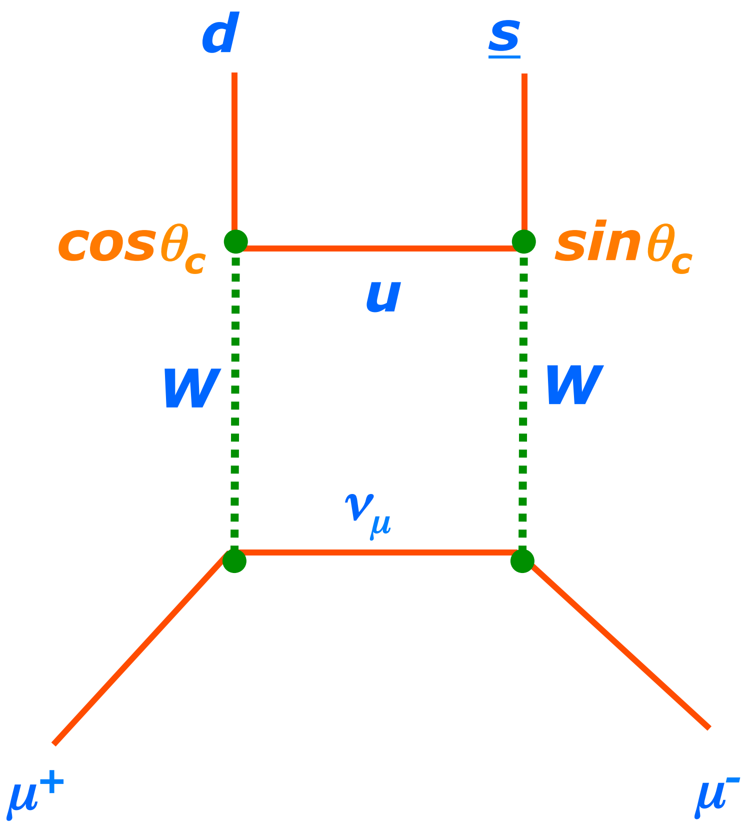




B.Richter et al, Phys.Rev.Lett. 33 (1974) 1406

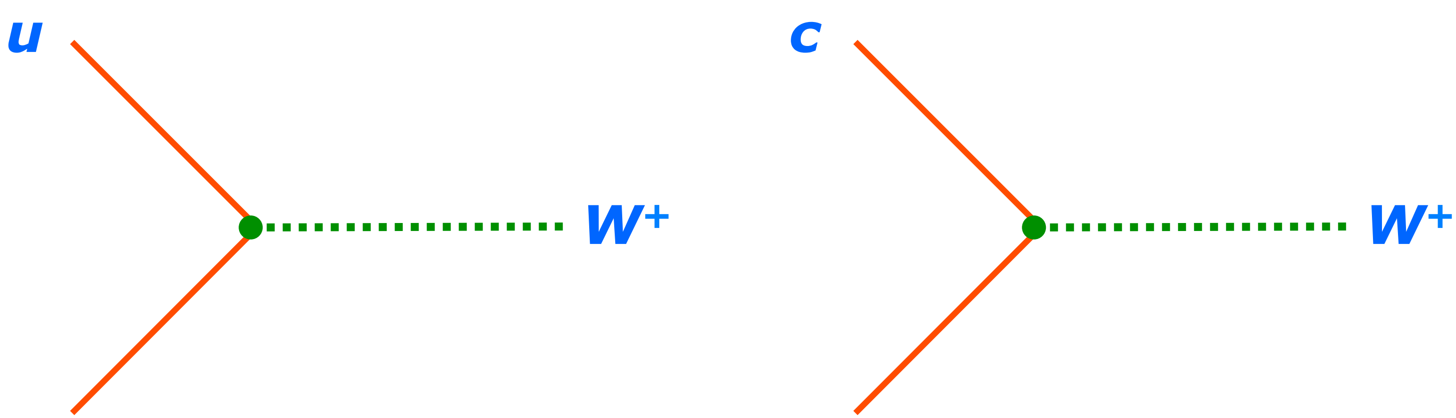
Historical perspective: charm

- There was however one major exception which Cabibbo could *not* describe: $K^0 \rightarrow \mu^+ \mu^-$
  - *Observed rate **much** lower than expected from Cabibbos rate correlations (expected rate ~ $g^8 \sin^2\theta_c \cos^2\theta_c$)*



Historical perspective: charm: GIM-mechanism

- Solution to K^0 decay problem in 1970 by Glashow, Iliopoulos and Maiani → postulate existence of 4^{th} quark
  - Two ‘up-type’ quarks decay into rotated ‘down-type’ states
  - Appealing symmetry between generations



$d' = \cos(\theta_c) d + \sin(\theta_c) s$ $\qquad$ $s' = -\sin(\theta_c) d + \cos(\theta_c) s$

$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

Historical perspective: charm: GIM-mechanism

Phys.Rev.D2,1285,1970

Weak Interactions with Lepton-Hadron Symmetry*

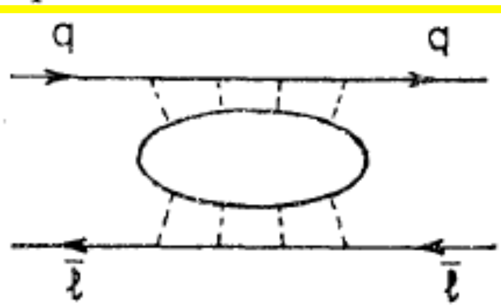
S. L. Glashow, J. Iliopoulos, and L. Maiani†
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139
(Received 5 March 1970)

We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction symmetry and the next to the leading divergences respect all observed weak-interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Milis theory is discussed.

splitting, beginning at order $G(G\Lambda^2)$, as well as contributions to such unobserved decay modes as $K_2 \to \mu^+ + \mu^-$, $K^+ \to \pi^+ + l + \bar{l}$, etc., involving neutral lepton

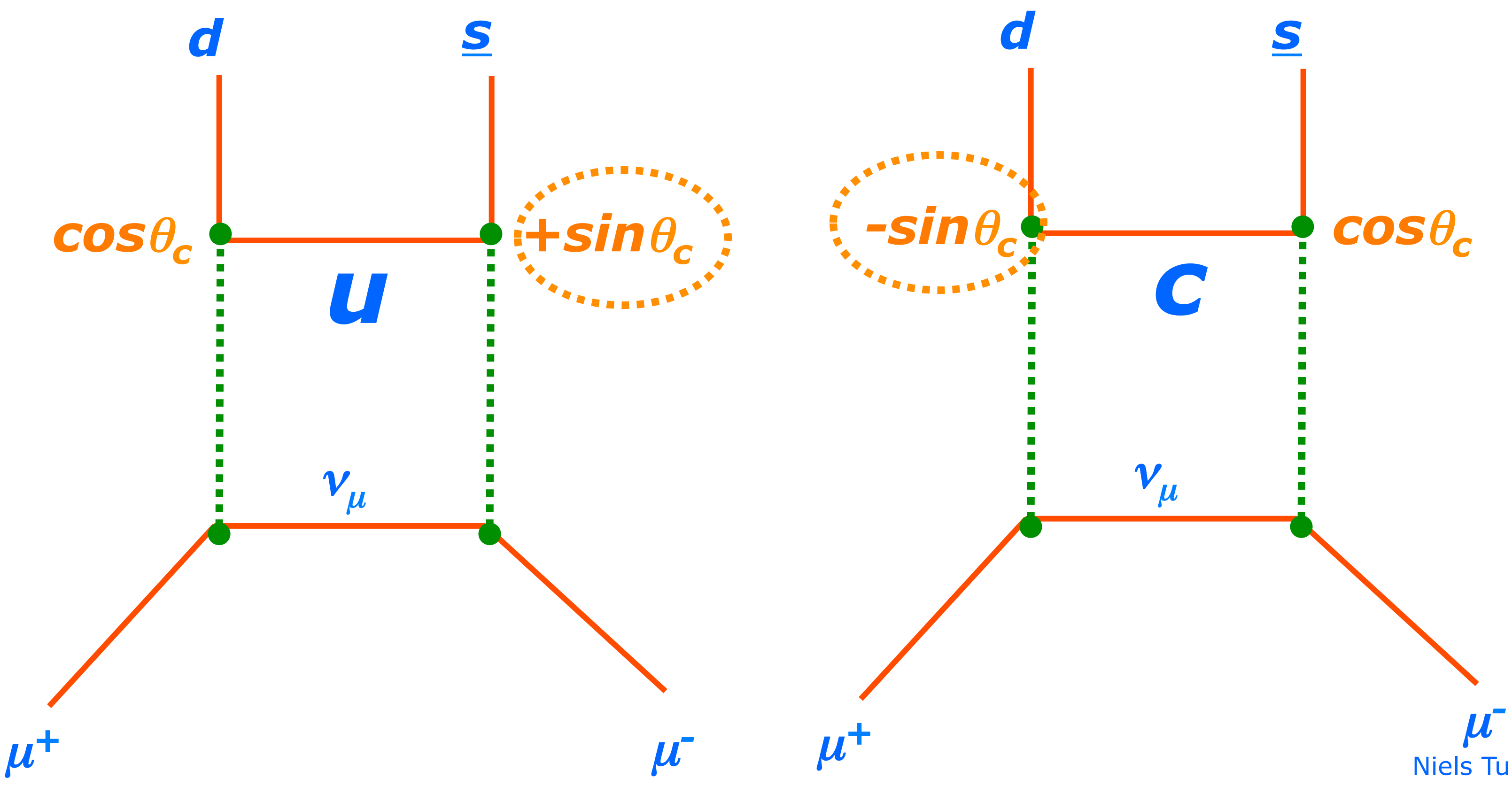
We wish to propose a simple model in which the divergences are properly ordered. Our model is founded in a quark model, but one involving four, not three, fundamental fermions; the weak interactions are medi-

new quantum number $\mathcal{C}$ for charm.



Historical perspective: charm: GIM-mechanism

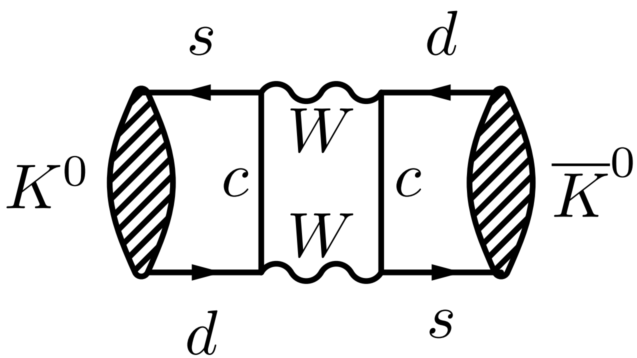
- How does it solve the $K^0 \rightarrow \mu^+\mu^-$ problem?
  - Second decay amplitude added that is almost identical to original one, *but has relative minus sign* → Almost fully destructive interference
  - Cancellation not perfect because u, c mass different

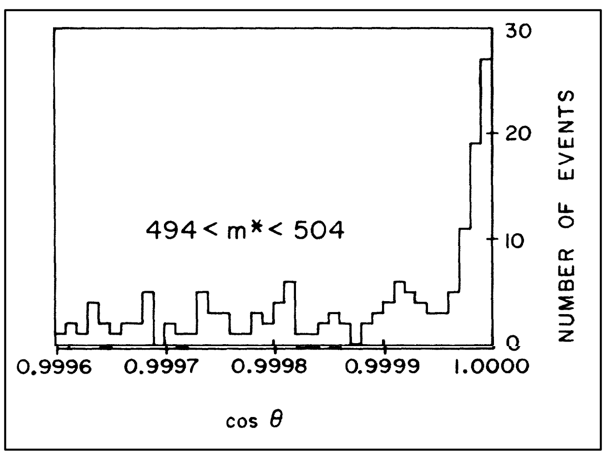


Historical perspective: bottom

- CP violation was "discovery" of 3rd generation?

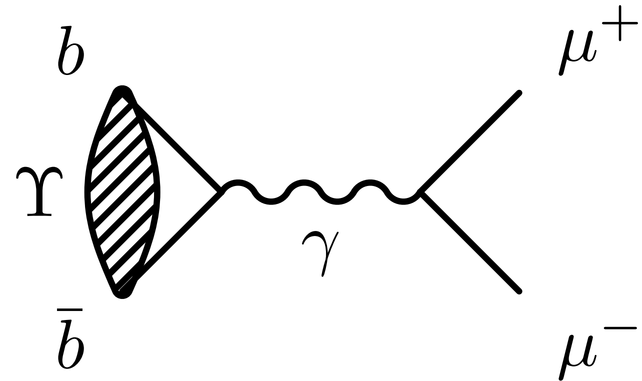
Indirect

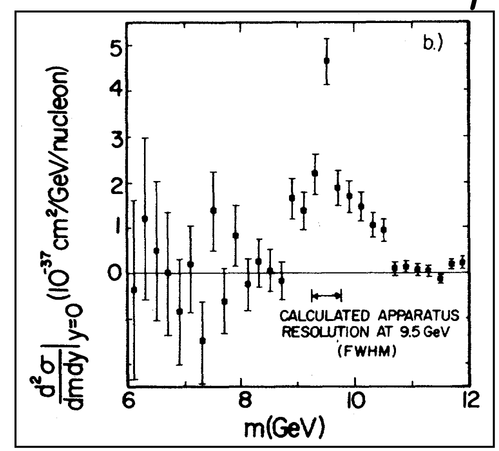




Cronin and Fitch, Phys.Rev.Lett. 13 (1964) 138

Direct



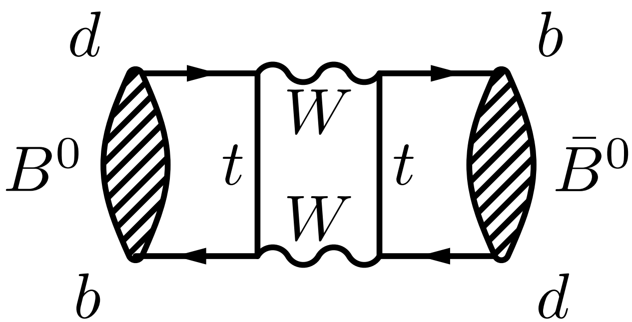


L.Lederman et al., Phys.Rev.Lett. 39 (1977) 252

Historical perspective: top

- Bottom mixing was “discovery” of top quark?

Indirect



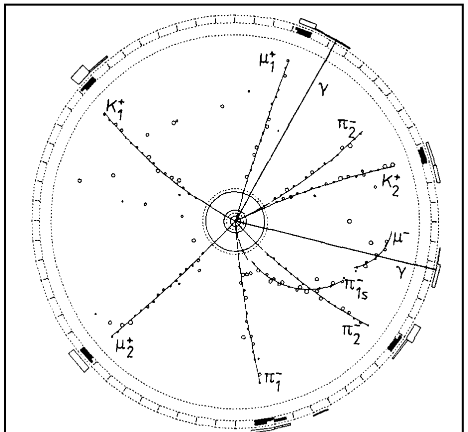
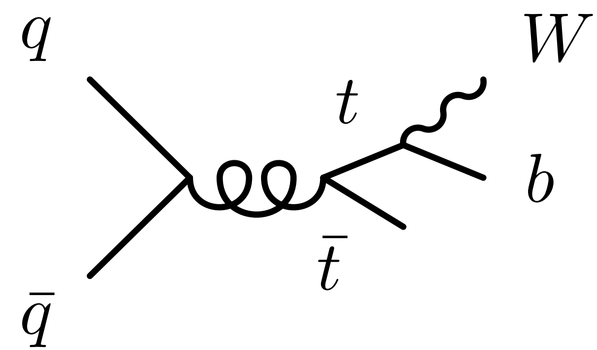
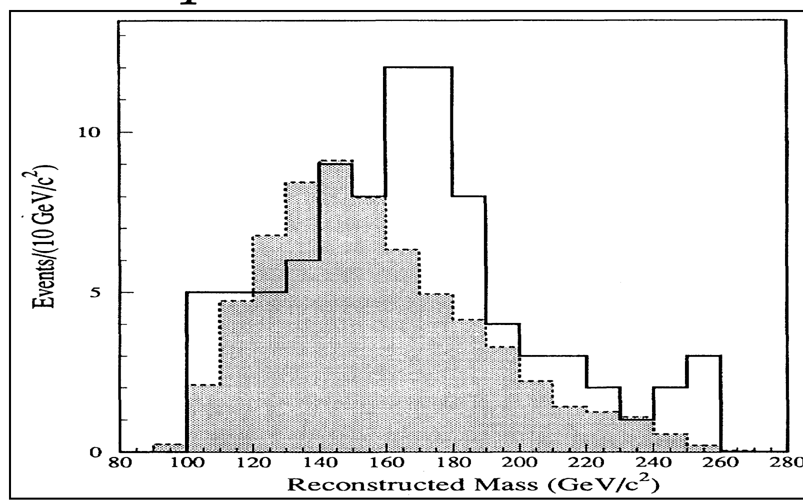


Fig. 2. Completely reconstructed event consisting of the decay $\Upsilon(4S) \to B^0B^0$.

ARGUS, Phys.Lett. B192 (1987) 245

Direct



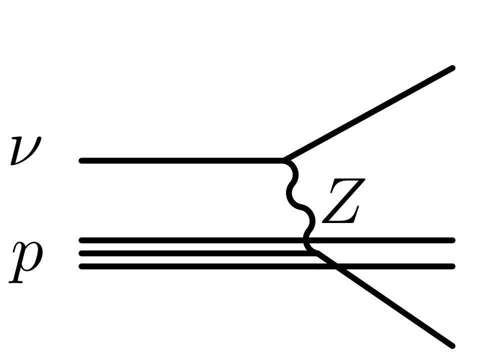


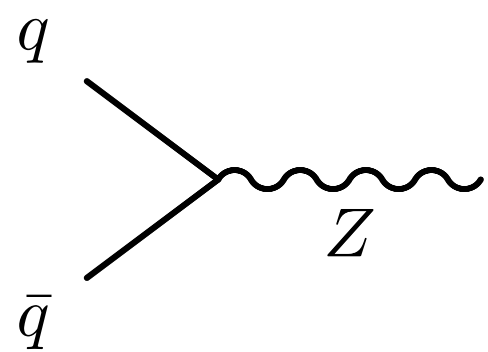
CDF Coll., Phys.Rev.Lett. 74 (1995) 2626

Historical perspective: Z

- Neutral current interaction was "discovery" of Z?

Indirect





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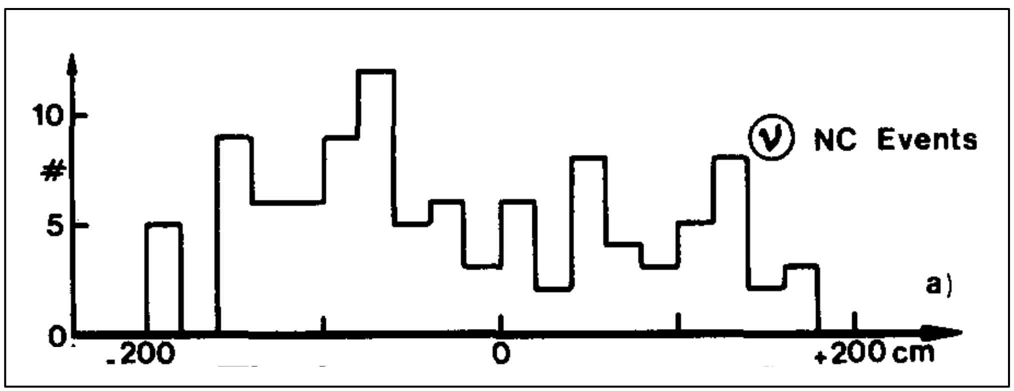
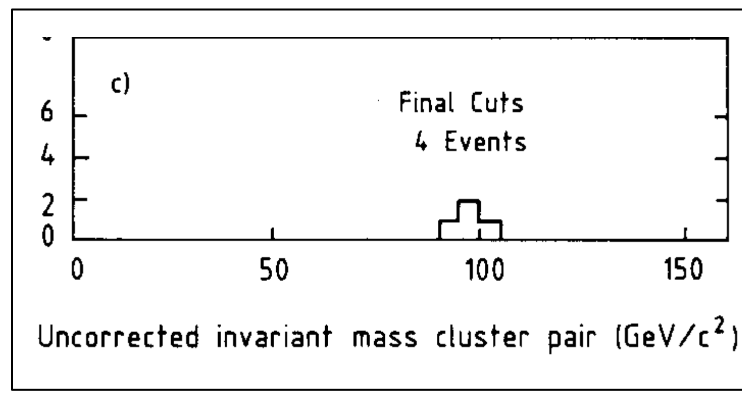


Gargamelle Coll., Phys.Lett. B46 (1973) 138

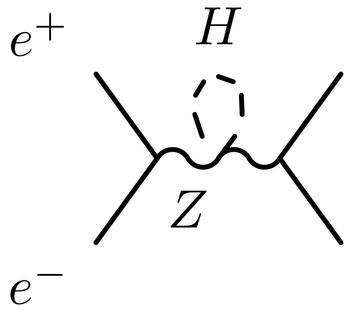


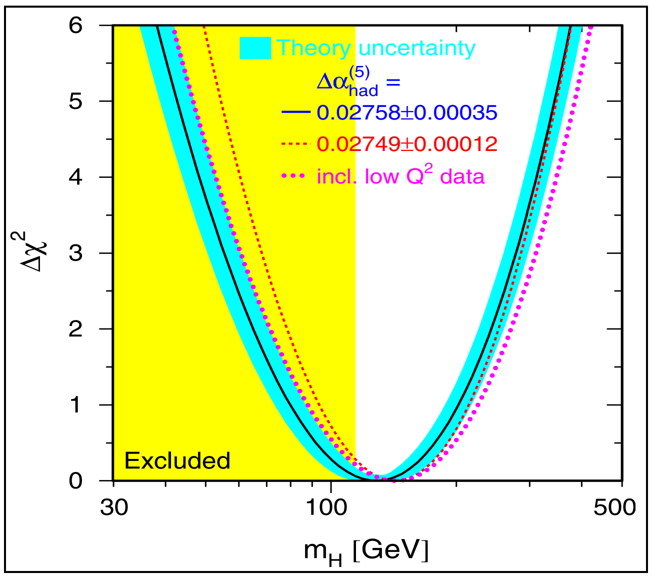
UA1 Coll., Phys.Lett. B126 (1983) 398

Historical perspective: Higgs

- Precision measurements at LEP were “discovery” of Higgs?

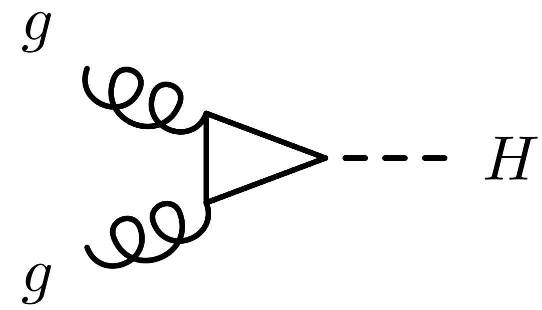
Indirect

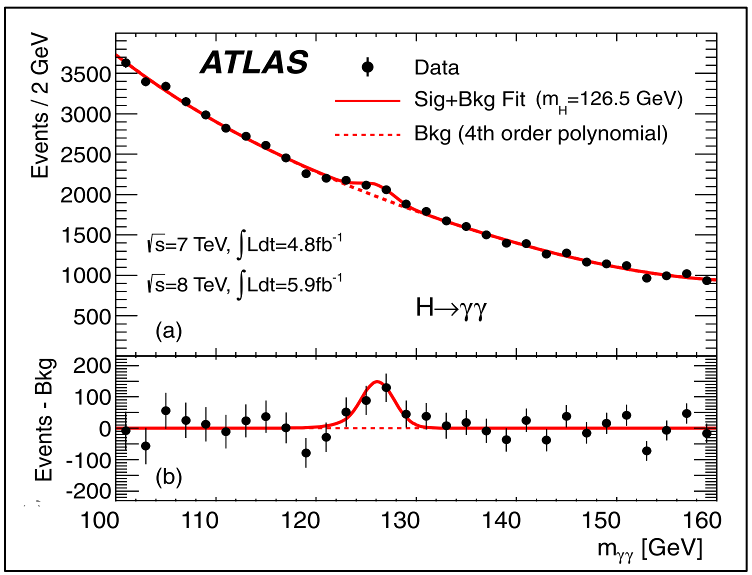




LEP, Phys.Rept. 427 (2006) 257

Direct



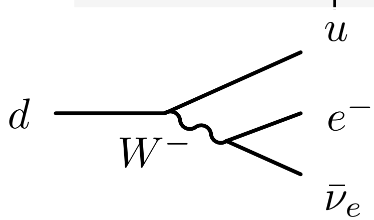


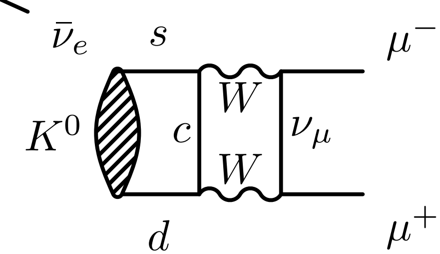
ATLAS Coll., Phys.Lett. B716 (2012) 1

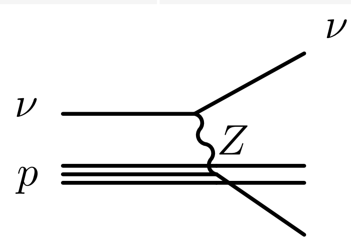
Historical perspective

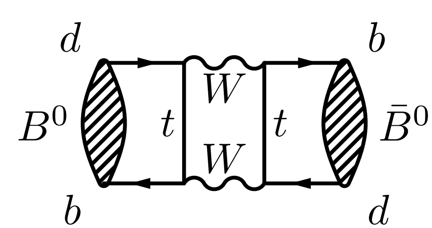
- Historical record of indirect discoveries:

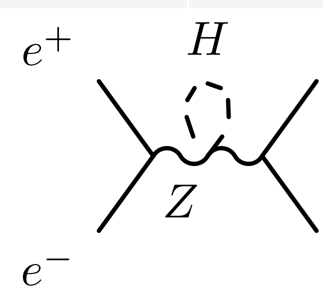
Particle	Indirect			Direct		
ν	β decay		1932	Reactor ν-CC	Cowan, Reines	1956
W	β decay		1932	$W \to e\nu$	UA1, UA2	1983
c	$K^0 \to \mu\mu$	GIM	1970	J/ψ	Richter, Ting	1974
b	CPV $K^0 \to \pi\pi$	CKM, 3rd gen	1964/72	Y	Ledermann	1977
Z	ν-NC	Gargamelle	1973	$Z \to e^+e^-$	UA1	1983
t	B mixing	ARGUS	1987	$t \to Wb$	D0, CDF	1995
H	e^+e^-	EW fit, LEP	2000	$H \to 4\mu/\gamma\gamma$	CMS, ATLAS	2012
?	**What's next ?**		?			?











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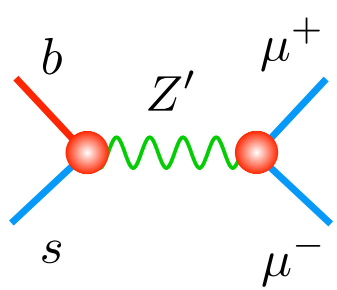
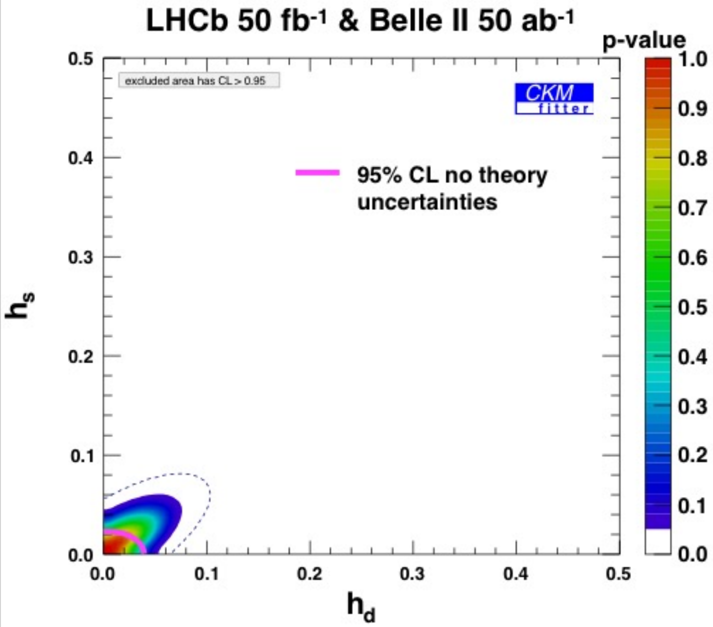
t	B mixing	ARGUS	1987	$t \rightarrow Wb$	D0, CDF	1995
H	e^+e^-	EW fit, LEP	2000	$H \rightarrow 4\mu/\gamma\gamma$	CMS, ATLAS	2012
Z′	pp→B X	LHCb	2019	pp→Z′→Y	FCC	2038



Heavy Flavour = Precision search for NP

- Depending on your model, sensitive to multi-TeV scales, eg:

[Charles et al., 1309.2293]



$$M_{12}^q = (M_{12}^q)_{\rm SM}\left(1 + h_q e^{2i\sigma_q}\right)$$

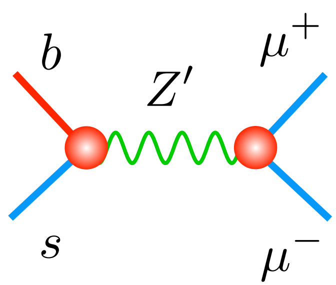
h_q parametrizes magnitude of NP in B_q mixing

$$h_d \lesssim 5\% \quad \Rightarrow \quad \Lambda \gtrsim \begin{cases} 2 \cdot 10^3\,\text{TeV}, & \text{anarchic tree} \\ 1.4\,\text{TeV}, & \text{MFV loop} \end{cases}$$

From Uli Haisch, 31 Aug 2016

Heavy Flavour = Precision search for NP

- Depending on your model, sensitive to multi-TeV scales, eg:



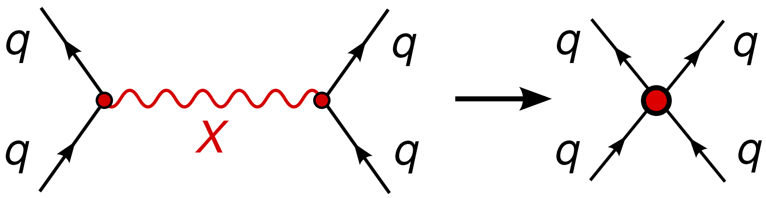
$$\mu_{B_s\to\mu^+\mu^-} \simeq 1 \pm \frac{4\pi}{g^2\,|V_{tb}^*V_{ts}|^2}\,\frac{v^2}{\Lambda^2}$$

$\mu_{B\to\mu\mu}$ is ratio BR^{exp}/BR^{SM}

$$\Lambda \gtrsim \frac{v}{\sqrt{0.2}} \times \begin{cases} \dfrac{\sqrt{4\pi}}{g\,|V_{tb}^*V_{ts}|} \\ 1 \end{cases} \simeq \begin{cases} 50\,\mathrm{TeV}\,, & \text{anarchic tree} \\ 0.6\,\mathrm{TeV}\,, & \text{MFV loop} \end{cases}$$

From Uli Haisch, 31 Aug 2016

SM as effective theory



Any new physics that is too heavy for us to produce directly (yet) can show up as a new local interaction among SM fields = a higher dimensional operator

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_{d>4} \sum_i \frac{c_i}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

- At $D = 5$: neutrino mass term $(\bar{L}_L \epsilon H)(H^T \epsilon L_L)$
  - Needed anyway to explain neutrino oscillations
- At $D = 6$: numerous operators, including flavour-changing ones such as $(\bar{Q}_L^i \gamma^\mu Q_L^j)^2$

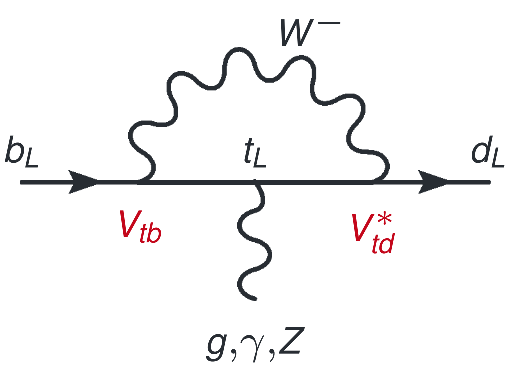
How to probe higher-dimensional operators?

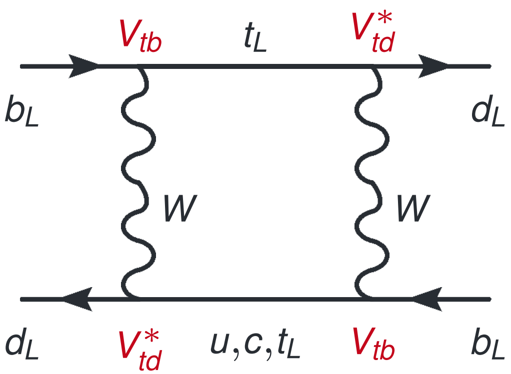
Need to look at observables that

- can be measured to an extreme precision and/or
- are suppressed in the SM but not necessarily beyond the SM

Examples

- $(g-2)_\mu$
- Electric dipole moments
- Charged lepton flavour violation
- *flavour-changing neutral currents*

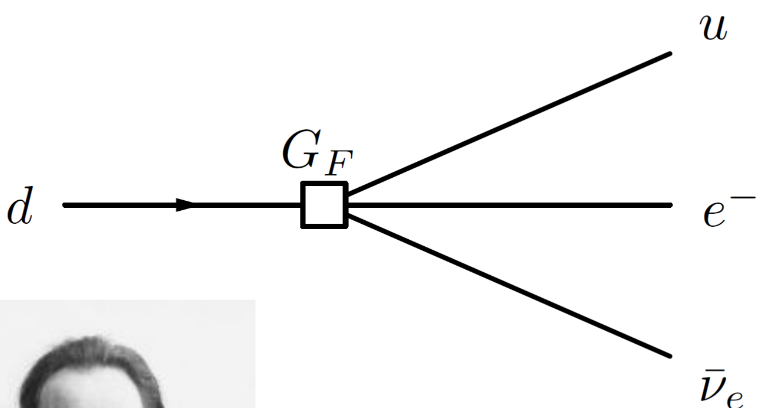


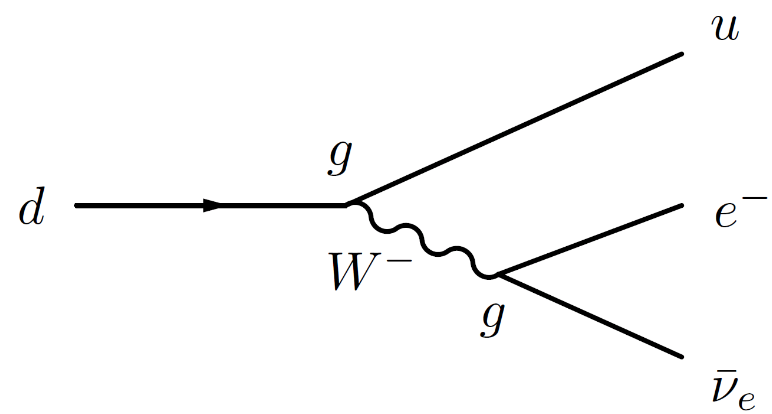


Rare Decays

Effective couplings

- Historical example:



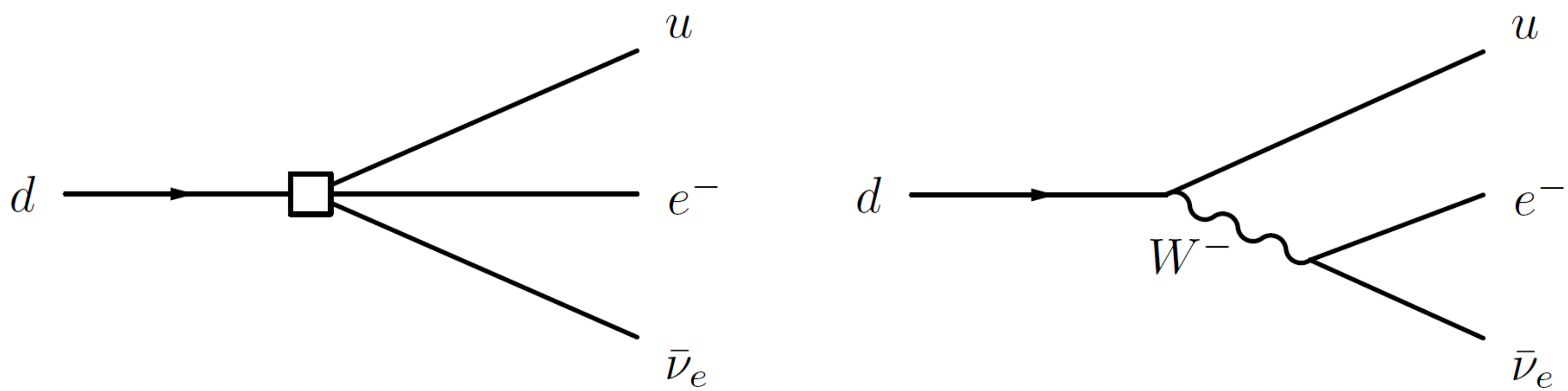


$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}$$

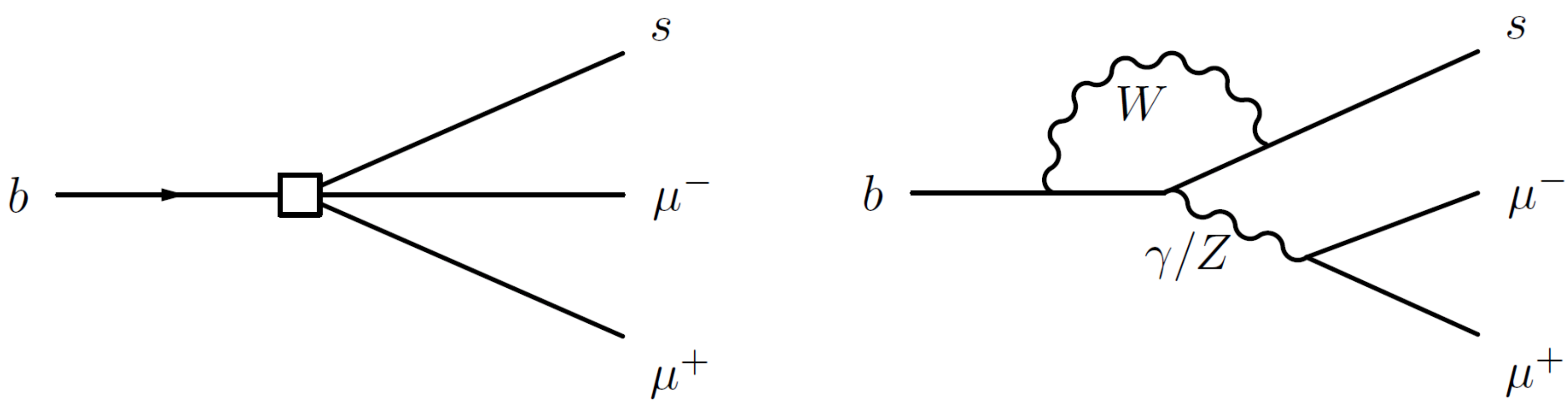
- Both are correct, depending on the energy scale you consider

Effective couplings

- Historical example



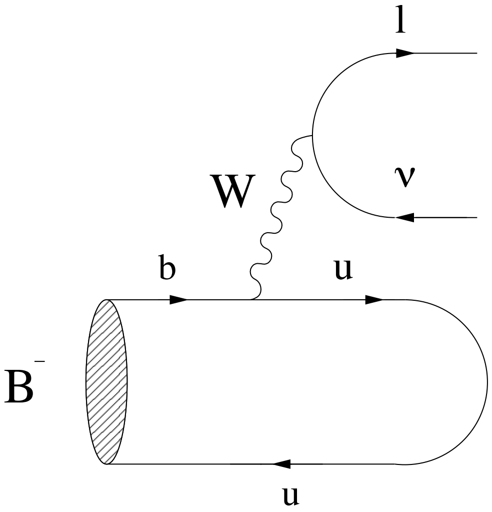
- Analog: *Flavour-changing neutral current*



Ingredients to *B*-decay calculations

Example: $B^+ \rightarrow \tau^+ \nu$

- Example: leptonic



- Factorization:

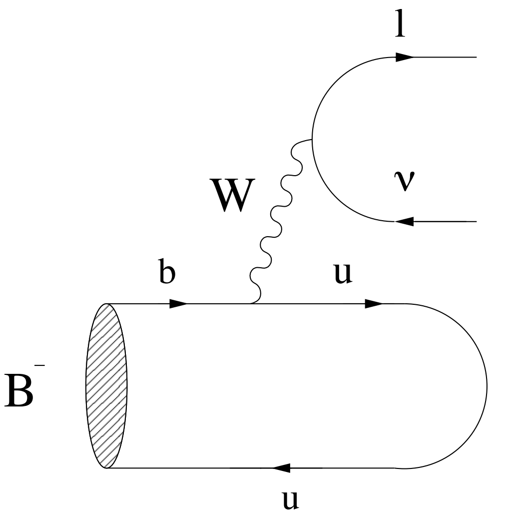
$$T_{fi} = -\frac{g_2^2}{8} V_{ub} \underbrace{[\bar{u}_\ell \gamma^\alpha (1-\gamma_5) v_\nu]}_{\text{Dirac spinors}} \left[\frac{g_{\alpha\beta}}{k^2 - M_W^2} \right] \underbrace{\langle 0 | \bar{u} \gamma^\beta (1-\gamma_5) b | B^- \rangle}_{\text{hadronic ME}}$$

Strong interaction collected in matrix element

From: Robert Fleischer, Flavour Physics and CP Violation, arXiv:0802.2882

Example: $B^+ \rightarrow \tau^+ \nu$

- Example: leptonic
- Factorization:



$$T_{fi} = -\frac{g_2^2}{8} V_{ub} \underbrace{[\bar{u}_\ell \gamma^\alpha (1-\gamma_5) v_\nu]}_{\text{Dirac spinors}} \left[\frac{g_{\alpha\beta}}{k^2 - M_W^2}\right] \underbrace{\langle 0|\bar{u}\gamma^\beta(1-\gamma_5)b|B^-\rangle}_{\text{hadronic ME}}$$

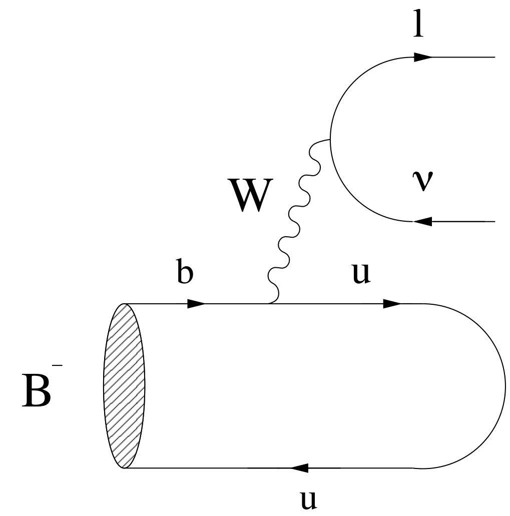
$$\boxed{\frac{g_{\alpha\beta}}{k^2 - M_W^2} \longrightarrow -\frac{g_{\alpha\beta}}{M_W^2} \equiv -\left(\frac{8G_F}{\sqrt{2}g_2^2}\right) g_{\alpha\beta}}$$

$$T_{fi} = \frac{G_F}{\sqrt{2}} V_{ub} [\bar{u}_\ell \gamma^\alpha (1-\gamma_5) v_\nu] \langle 0|\bar{u}\gamma_\alpha(1-\gamma_5)b|B^-\rangle$$

From: Robert Fleischer, Flavour Physics and CP Violation, arXiv:0802.2882

Example: $B^+ \to \tau^+ \nu$

- Example: leptonic



- Factorization:

$$T_{fi} = -\frac{g_2^2}{8} V_{ub} \underbrace{[\bar{u}_\ell \gamma^\alpha (1-\gamma_5) v_\nu]}_{\text{Dirac spinors}} \left[\frac{g_{\alpha\beta}}{k^2 - M_W^2} \right] \underbrace{\langle 0 | \bar{u} \gamma^\beta (1-\gamma_5) b | B^- \rangle}_{\text{hadronic ME}}$$

$$\boxed{\begin{aligned} \langle 0 | \overline{u} \gamma_\alpha b | B^- \rangle &= 0, \\ \langle 0 | \bar{u} \gamma_\alpha \gamma_5 b | B^-(q) \rangle &= i f_B q_\alpha \end{aligned}}$$

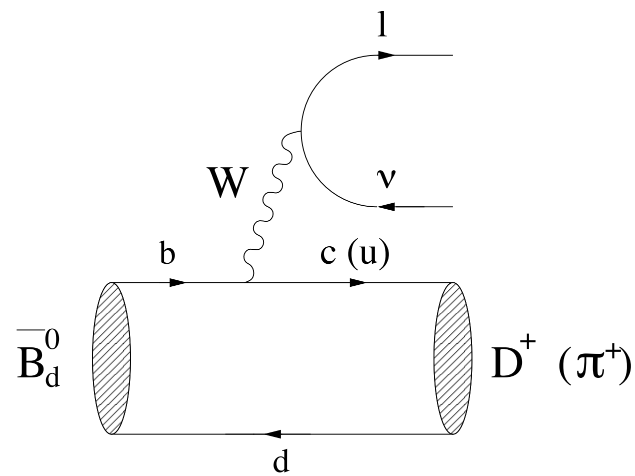
B meson is pseudo-scalar

From: Robert Fleischer, Flavour Physics and CP Violation, arXiv:0802.2882

Example: $B^0 \rightarrow D^+\mu^+\nu$

- Example: semi-leptonic

- Factorization:



$$T_{fi} = \frac{G_{\rm F}}{\sqrt{2}} V_{cb} \left[\bar{u}_\ell \gamma^\alpha (1-\gamma_5) v_\nu\right] \underbrace{\langle D^+ | \bar{c}\gamma_\alpha (1-\gamma_5) b | \bar{B}^0_d \rangle}_{\text{Strong interaction collected in matrix element}}$$

Strong interaction collected in matrix element

From: Robert Fleischer, Flavour Physics and CP Violation, arXiv:0802.2882

Example: $B^0 \rightarrow D^+ \mu^+ \nu$

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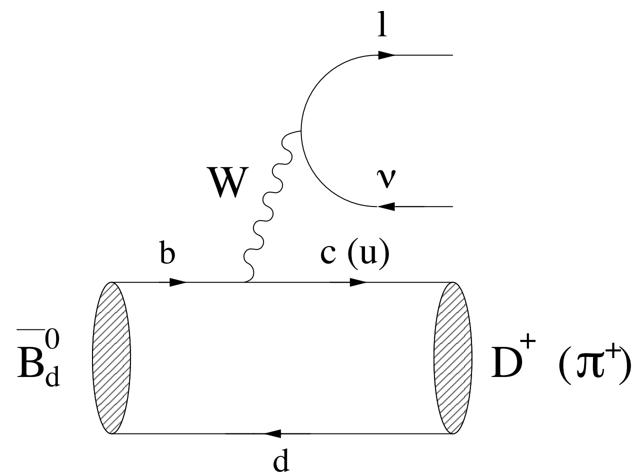


- Factorization:

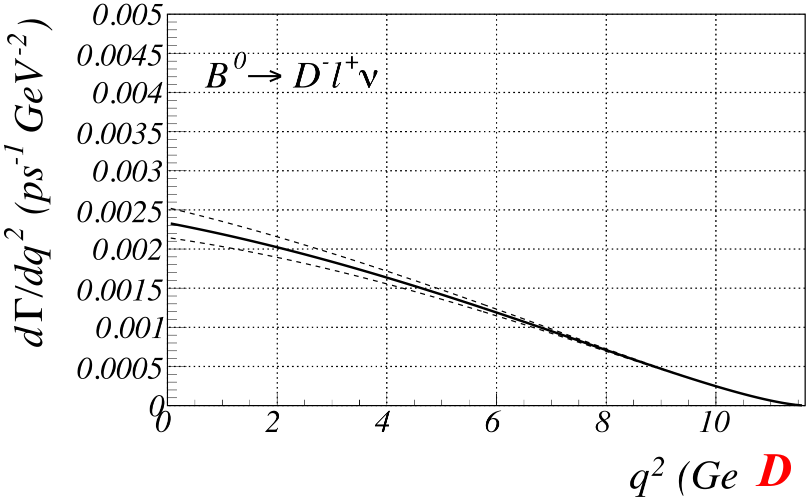
$$T_{fi} = \frac{G_{\mathrm{F}}}{\sqrt{2}} V_{cb} \left[\bar{u}_\ell \gamma^\alpha (1-\gamma_5) v_\nu\right] \langle D^+ | \bar{c}\gamma_\alpha (1-\gamma_5) b | \bar{B}^0_d \rangle$$

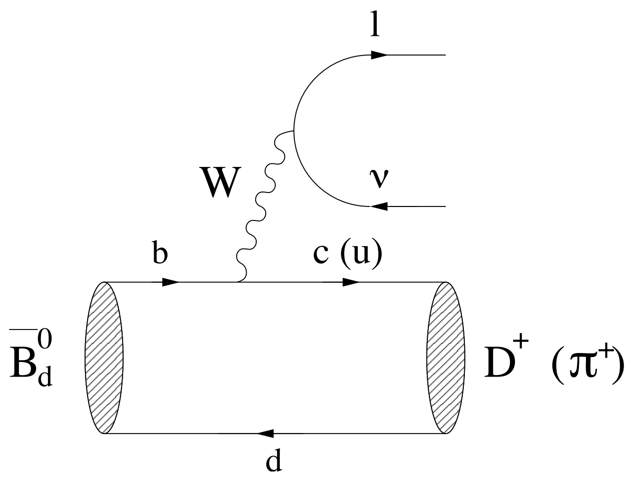
$$\langle D^+(k)|\bar{c}\gamma_\alpha b|\bar{B}^0_d(p)\rangle = F_1(q^2)\left[(p+k)_\alpha - \left(\frac{M_B^2 - M_D^2}{q^2}\right) q_\alpha\right] + F_0(q^2)\left(\frac{M_B^2 - M_D^2}{q^2}\right) q_\alpha$$

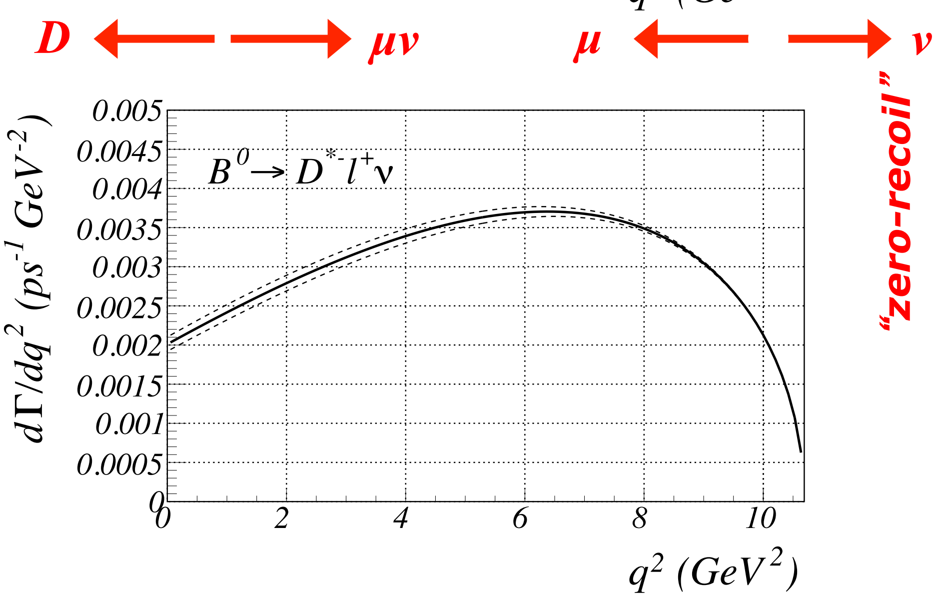
From: Robert Fleischer, Flavour Physics and CP Violation, arXiv:0802.2882

Example: $B^0 \to D^+\mu^+\nu$

- Form-factors:







$$\langle D^+(k)|\bar{c}\gamma_\alpha b|\bar{B}^0_d(p)\rangle = F_1(q^2)\left[(p+k)_\alpha - \left(\frac{M_B^2 - M_D^2}{q^2}\right) q_\alpha\right] + F_0(q^2)\left(\frac{M_B^2 - M_D^2}{q^2}\right) q_\alpha$$

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Example: $B^0 \to D^+\mu^+\nu$

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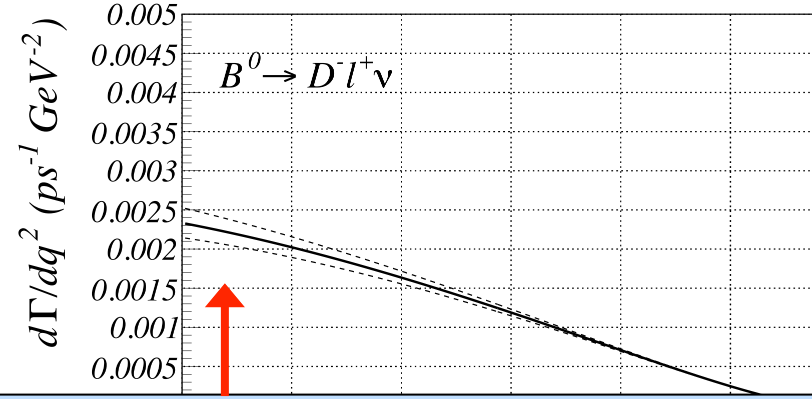
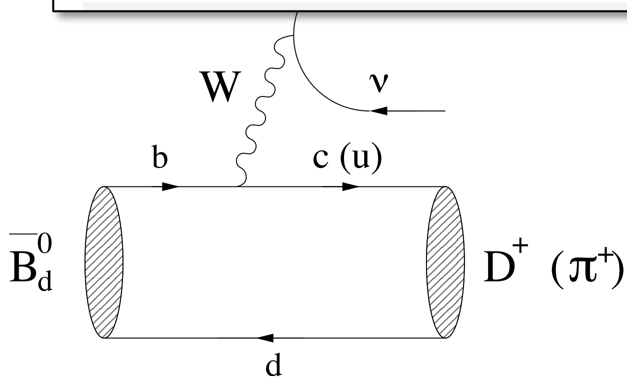
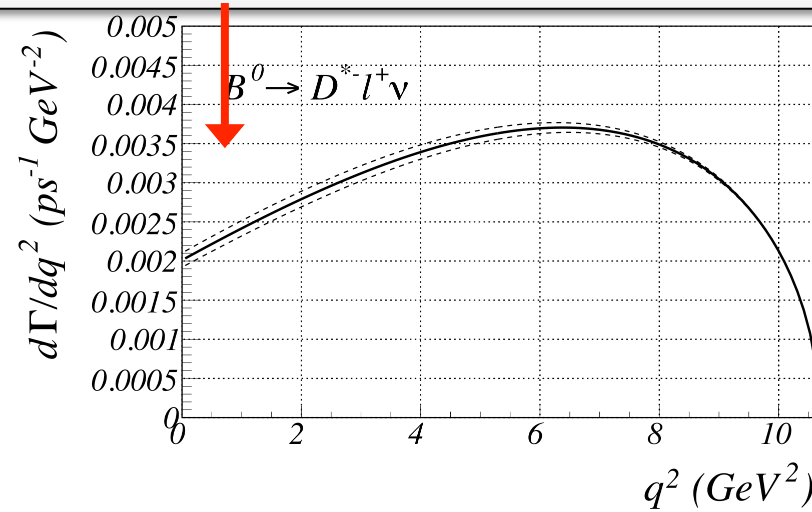


Γ_1	$D^-\pi^+$	$(2.52 \pm 0.13) \times 10^{-3}$
Γ_{11}	$D^*(2010)^-\pi^+$	$(2.74 \pm 0.13) \times 10^{-3}$





$$\langle D^+(k)|\bar{c}\gamma_\alpha b|\bar{B}^0_d(p)\rangle = F_1(q^2)\left[(p+k)_\alpha - \left(\frac{M_B^2 - M_D^2}{q^2}\right) q_\alpha\right] + F_0(q^2)\left(\frac{M_B^2 - M_D^2}{q^2}\right) q_\alpha$$

From: Robert Fleischer, Flavour Physics and CP Violation, arXiv:0802.2882

Effective Hamiltonian – Operator Product Expansion

- Hadronic decays, typically **factorization** does not hold any longer
- Separate calculable short distance effects, from non-perturbative long-distance effects

$$A(M \to F) = \langle F \mid \mathcal{H}_{\mathrm{eff}} \mid M \rangle$$

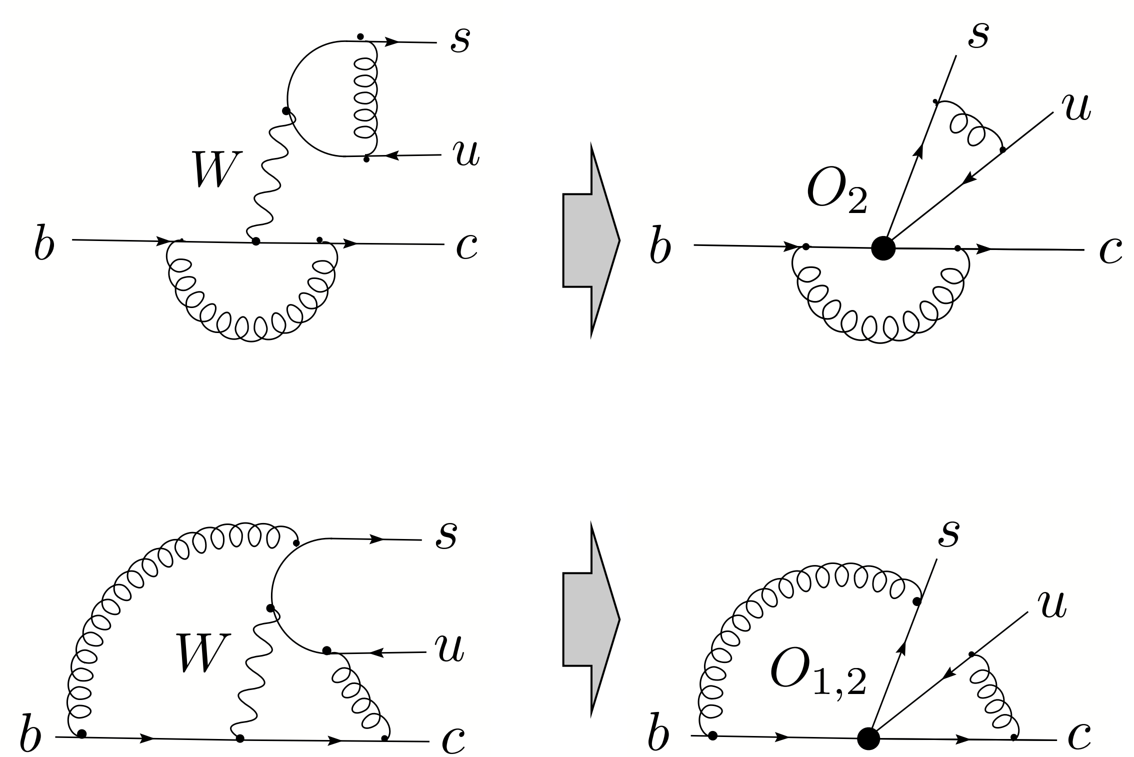
$$\boxed{\mathcal{H}_{\mathrm{eff}} = \frac{G_{\mathrm{F}}}{\sqrt{2}} V_{\mathrm{CKM}} \sum_i C_i(\mu) Q_i}$$

$$A(M \to F) = \frac{G_{\mathrm{F}}}{\sqrt{2}} V_{\mathrm{CKM}} \sum_i C_i(\mu) \langle F \mid Q_i(\mu) \mid M \rangle$$

- C_i: calculable Wilson coeffients
- To be compared to experiment

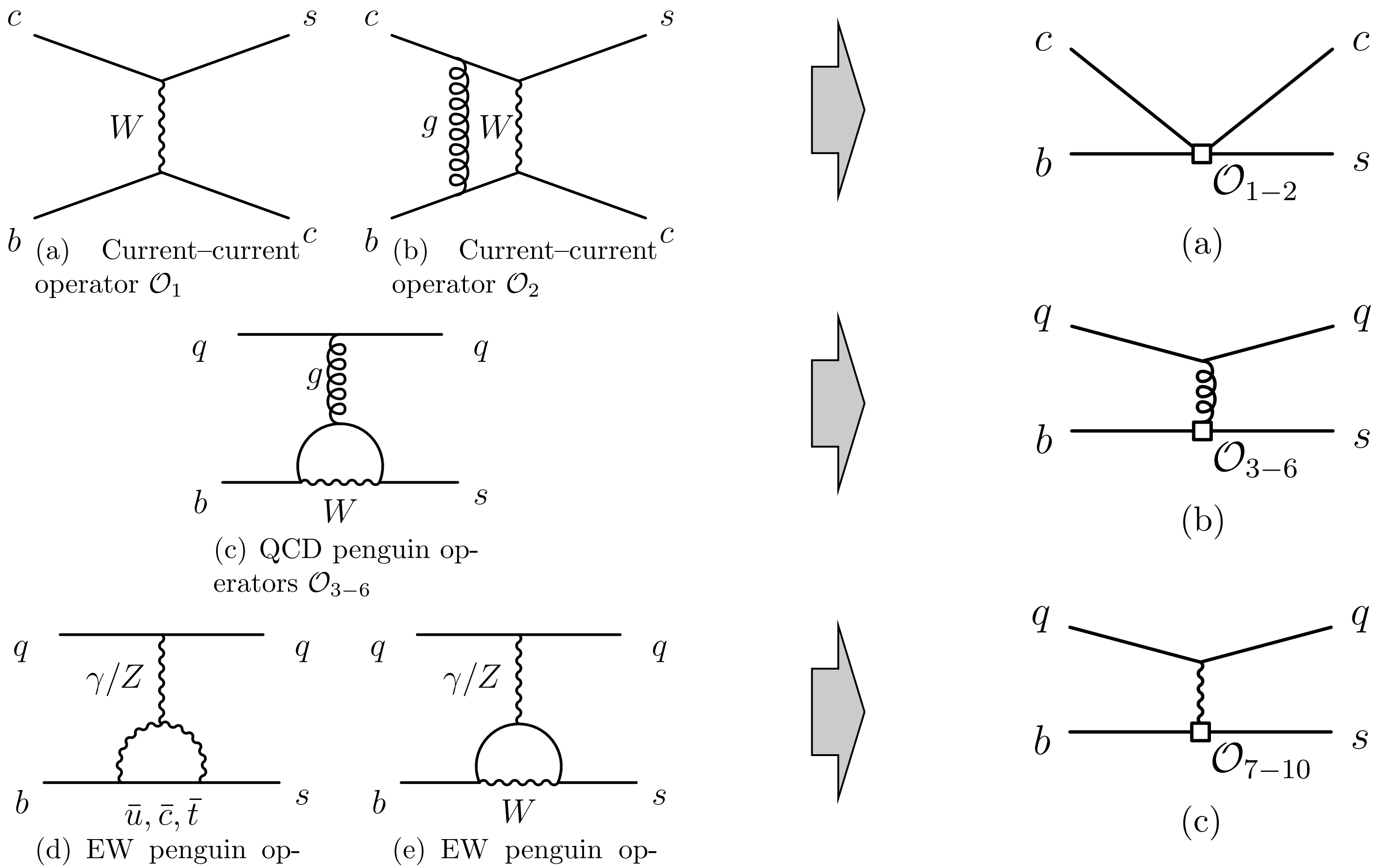
Effective couplings

- Hadronic decays, typically factorization does not hold any longer
- Separate calculable short distance effects, from non-perturbative long-distance effects



Effective couplings: b→sqq

- Hadronic decays, typically factorization does not hold any longer
- Separate calculable short distance effects, from non-perturbative long-distance effects



(a) Current–current operator $\mathcal{O}_1$

(b) Current–current operator $\mathcal{O}_2$

(c) QCD penguin operators $\mathcal{O}_{3-6}$

(d) EW penguin operators $\mathcal{O}_{7-10}$

(e) EW penguin operators $\mathcal{O}_{7-10}$

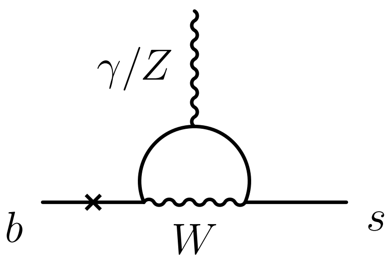
(a)

(b)

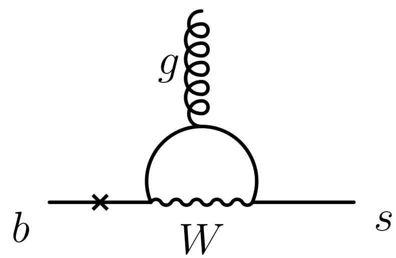
(c)

Effective couplings: b→sll

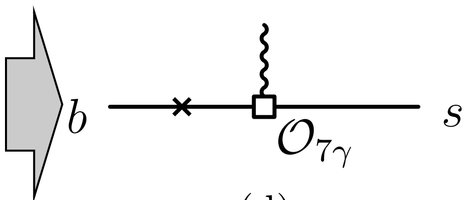
- Hadronic decays, typically factorization does not hold any longer
- Separate calculable short distance effects, from non-perturbative long-distance effects



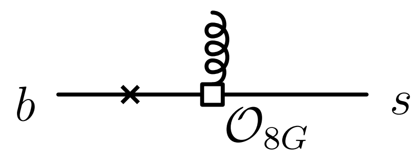
(f) Electromagnetic penguin operator $\mathcal{O}_{7\gamma}$



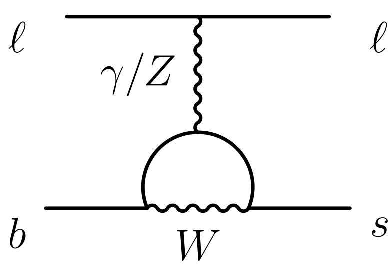
(g) Chromomagnetic penguin operator $\mathcal{O}_{8G}$



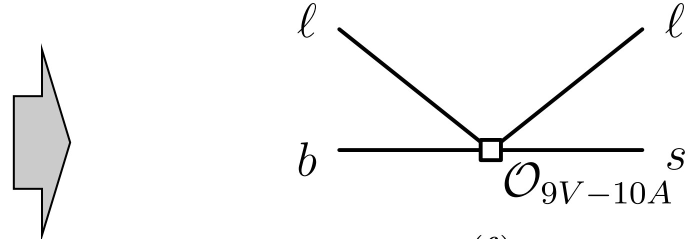
(d)



(e)



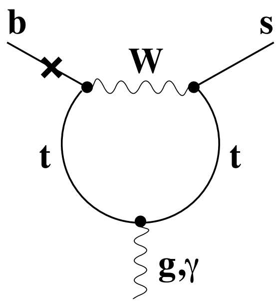
(h) Semi-leptonic operators $\mathcal{O}_{9V-10A}$



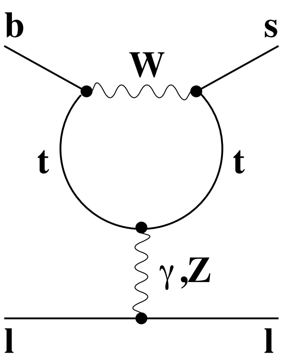
(f)

Operators for b→sll FCNC

- Remember C_7, C_9, C_{10}:



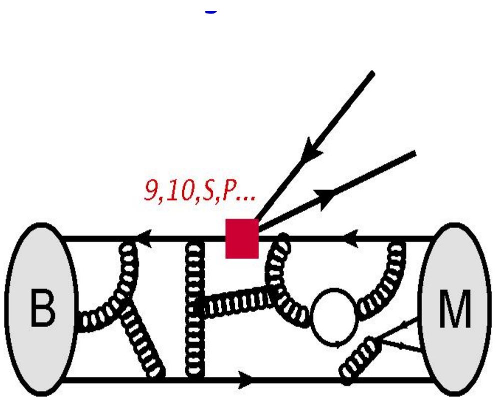
$$Q_{7\gamma} = \frac{e}{8\pi^2} m_b \bar{s}_\alpha \sigma^{\mu\nu}(1+\gamma_5) b_\alpha F_{\mu\nu}$$



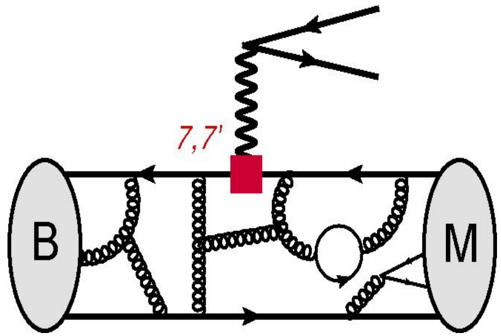
$$Q_{9V} = (\bar{s}b)_{V-A}(\bar{\mu}\mu)_V \qquad Q_{10A} = (\bar{s}b)_{V-A}(\bar{\mu}\mu)_A$$

Operators for b→sll FCNC

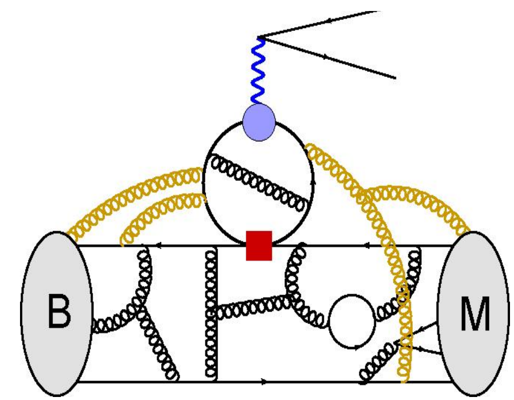
- Yet another graph:



"Genuine" b→sll



b→sγ

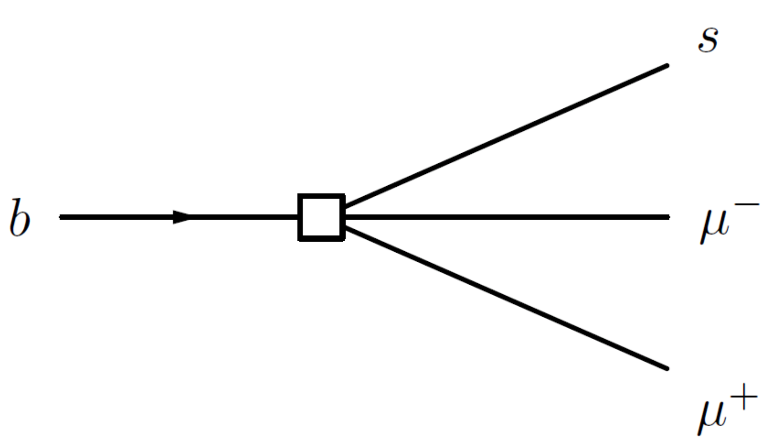


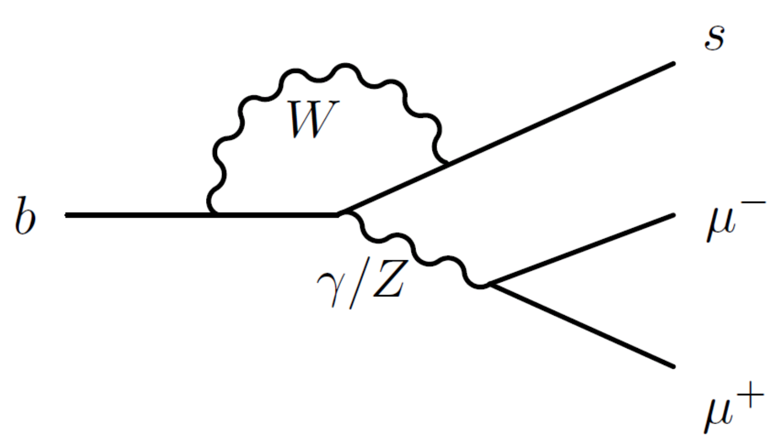
b→s cc

Effective couplings

- Effective coupling can be of various "kinds"
  - Vector coupling
  - Axial coupling
  - Left-handed coupling (V-A)
  - Right-handed (to quarks)
  - …

$$\mathcal{H}_{\mathrm{eff}} = \frac{G_{\mathrm{F}}}{\sqrt{2}} V_{\mathrm{CKM}} \sum_i C_i(\mu) Q_i$$





Effective couplings

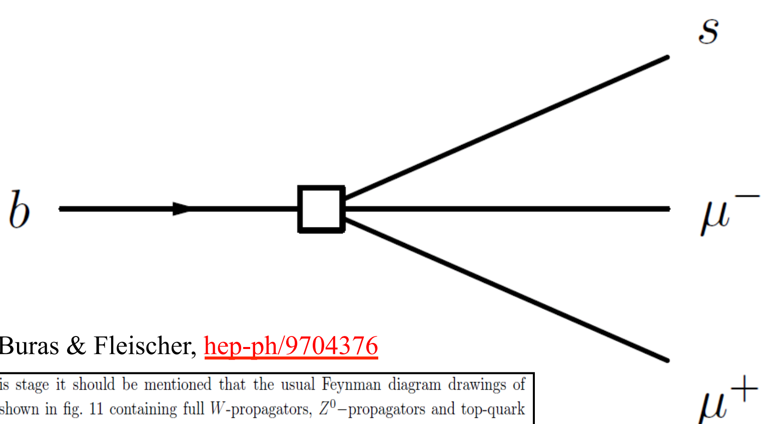
- Effective coupling can be of various "kinds"
  - Vector coupling: C_9
  - Axial coupling: C_{10}
  - Left-handed coupling (V-A): C_9-C_{10}
  - Right-handed (to quarks): C_9', C_{10}', …
  - …

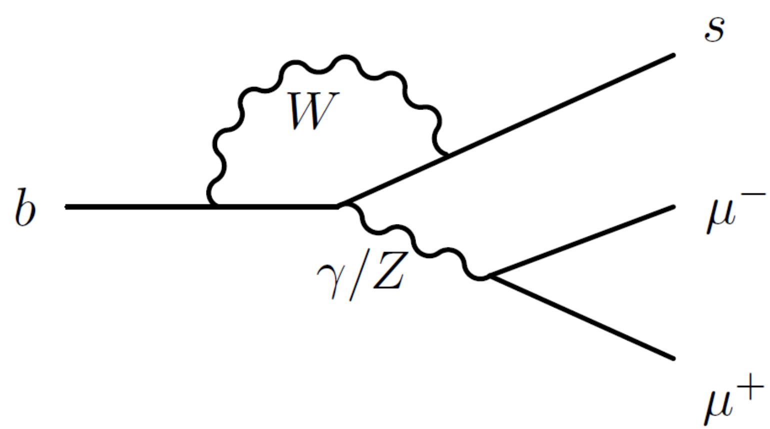
$$\mathcal{H}_{\rm eff} = \frac{G_{\rm F}}{\sqrt{2}} V_{\rm CKM} \sum_i C_i(\mu) Q_i$$

See e.g. Buras & Fleischer, hep-ph/9704376

Semi–Leptonic Operators (fig. 11f):

$$Q_{9V} = (\bar{s}b)_{V-A}(\bar{\mu}\mu)_V \qquad Q_{10A} = (\bar{s}b)_{V-A}(\bar{\mu}\mu)_A$$





From Buras & Fleischer, hep-ph/9704376

At this stage it should be mentioned that the usual Feynman diagram drawings of the type shown in fig. 11 containing full W-propagators, Z^0–propagators and top-quark propagators represent really the happening at scales $\mathcal{O}(M_{\rm W})$ whereas the true picture of a decaying hadron is more correctly described by the local operators in question. Thus, whereas at scales $\mathcal{O}(M_{\rm W})$ we have to deal with the full six-quark theory containing the photon, weak gauge bosons and gluons, at scales $\mathcal{O}(1\,{\rm GeV})$ the relevant effective theory contains only three light quarks u, d and s, gluons and the photon. At intermediate energy scales $\mu = \mathcal{O}(m_b)$ and $\mu = \mathcal{O}(m_c)$ relevant for beauty and charm decays, effective five-quark and effective four-quark theories have to be considered, respectively.

"the true picture of a decaying hadron is more correctly described by the local operators"

Measuring the Wilson coefficients

- Rare B-decays to probe Wilson coefficients:

Decay	$C_7^{(\prime)}$	$C_9^{(\prime)}$	$C_{10}^{(\prime)}$
$B \to X_s \gamma$	X		
$B \to K^* \gamma$	X		
$B \to X_s \mu^+ \mu^-$	X	X	X
$B \to K \mu^+ \mu^-$	X	X	X
$B \to K^* \mu^+ \mu^-$	X	X	X
$B_s \to \mu^+ \mu^-$			X

Measuring the Wilson coefficients

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Decay	$C_7^{(\prime)}$	$C_9^{(\prime)}$	$C_{10}^{(\prime)}$
$B \to X_s \gamma$	X		
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$B \to X_s \mu^+ \mu^-$	X	X	X
$B \to K \mu^+ \mu^-$	X	X	X
$B \to K^* \mu^+ \mu^-$	X	X	X
$B_s \to \mu^+ \mu^-$			X

$$\langle 0|\overline{u}\gamma_\alpha b|B^-\rangle = 0,$$

$$\langle 0|\bar{u}\gamma_\alpha\gamma_5 b|B^-(q)\rangle = i f_B q_\alpha$$

Road to discovery: Wilson coefficients

Theory
(What are Wilson coefficients?)

↓

Measurements
(sensitive to Wilson coefficients)

↓

Fit
(i.e. determine Wilson coefficients)

↓

Interpretation
(which models correspond to theses Wilson coefficients?)

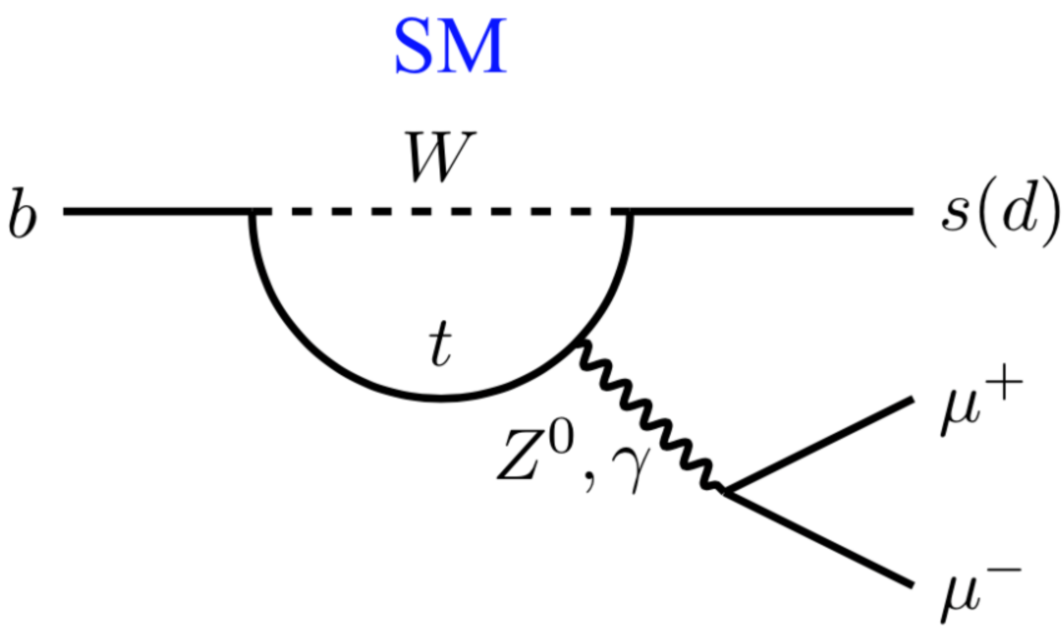
b→s μμ

- Flavour changing neutral current: **FCNC**
- In SM only at higher order:

Decay
$B \to X_s \gamma$
$B \to K^* \gamma$
$B \to X_s \mu^+ \mu^-$
$B \to K \mu^+ \mu^-$
$B \to K^* \mu^+ \mu^-$
$B_s \to \mu^+ \mu^-$

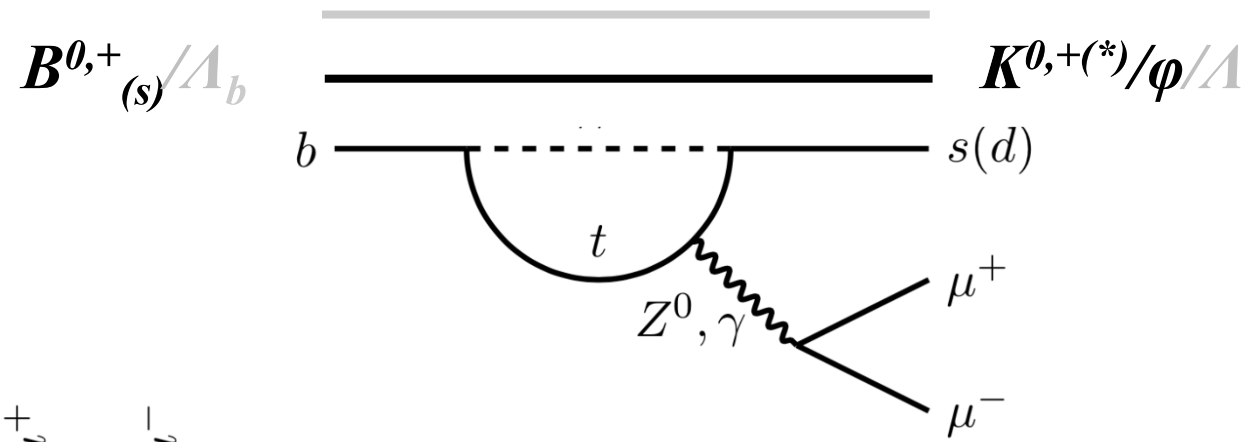
b→s μμ

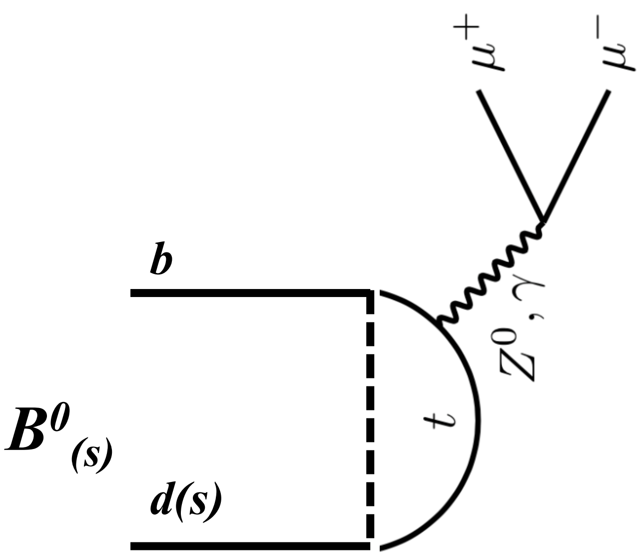
- Flavour changing neutral current: **FCNC**
- In SM only at higher order:



Decay
$B \to X_s\gamma$
$B \to K^*\gamma$
$B \to X_s\mu^+\mu^-$
$B \to K\mu^+\mu^-$
$B \to K^*\mu^+\mu^-$
$B_s \to \mu^+\mu^-$

Specific decays





- Specific decays:
  - $B \to \mu\mu$
  - $B \to K\mu\mu$

Break

Rare Decays - Outline:

- 9h30 - 10h15 Lecture 1: Introduction
- 10h30 - 11h15 Lecture 2: Effective couplings
- 11h30 - 12h15 Lecture 3: $B_s \rightarrow \mu\mu$

Lunch

- 13h45 - 14h30 Lecture 4: $B^0 \rightarrow K^*\mu\mu$
- 15h00 - 16h30 Discussion Session

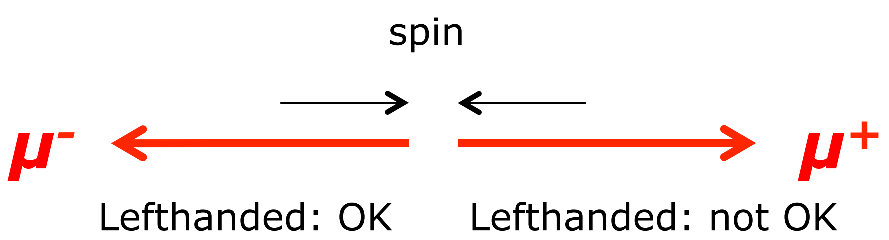
$B_s^0 \rightarrow \mu\mu$

$B_s^0 \rightarrow \mu\mu$

Small BR…

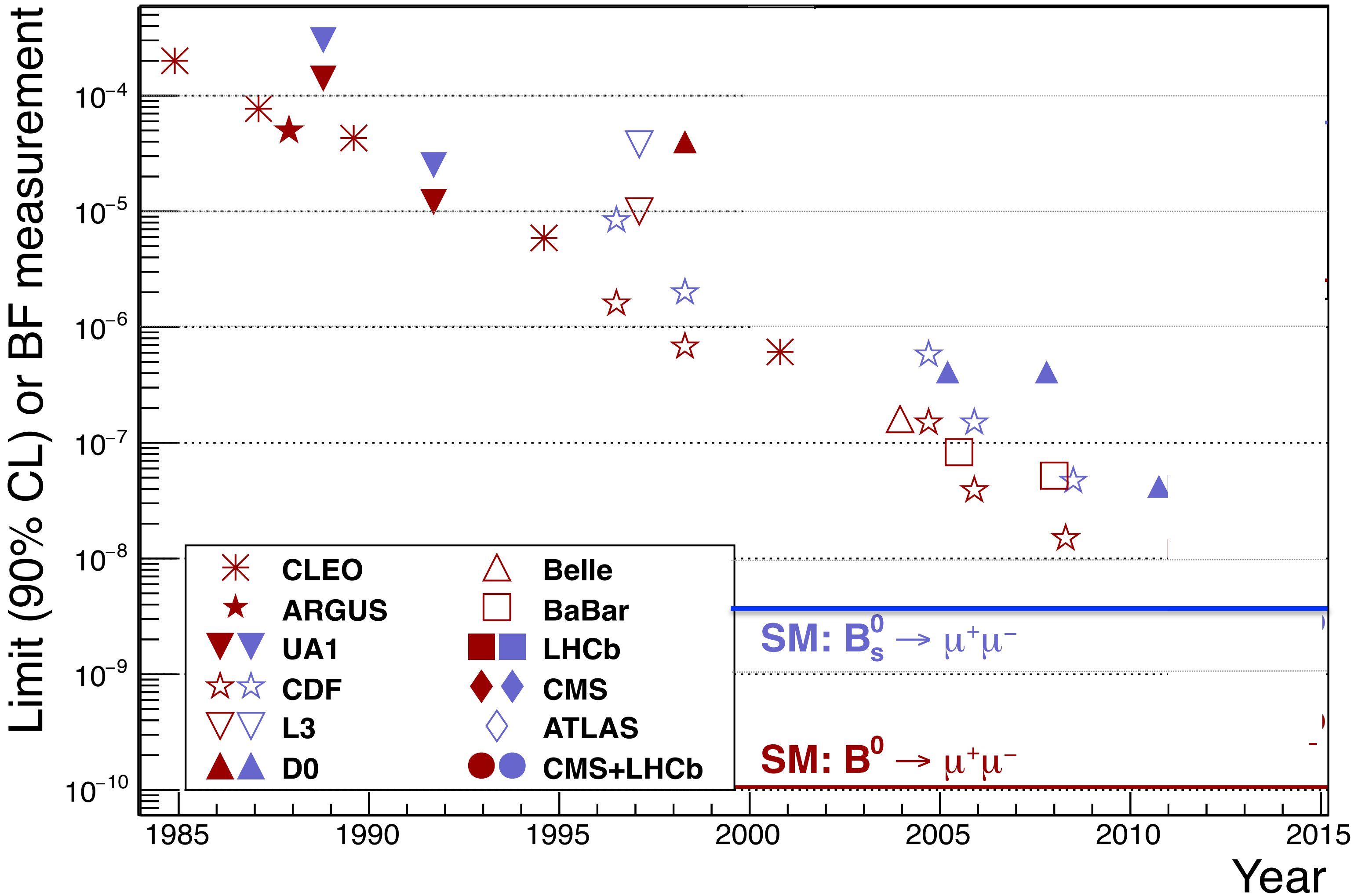
1) FCNC: b→s transition only allowed at higher order
   - GIM cancellation!

2) Weak interaction: helicity suppressed
   - Sensitive to new physics: (pseudo)scalar operators



$B_s^0 \rightarrow \mu\mu$

- Historical endeavour!



$B_s^0 \rightarrow \mu\mu$

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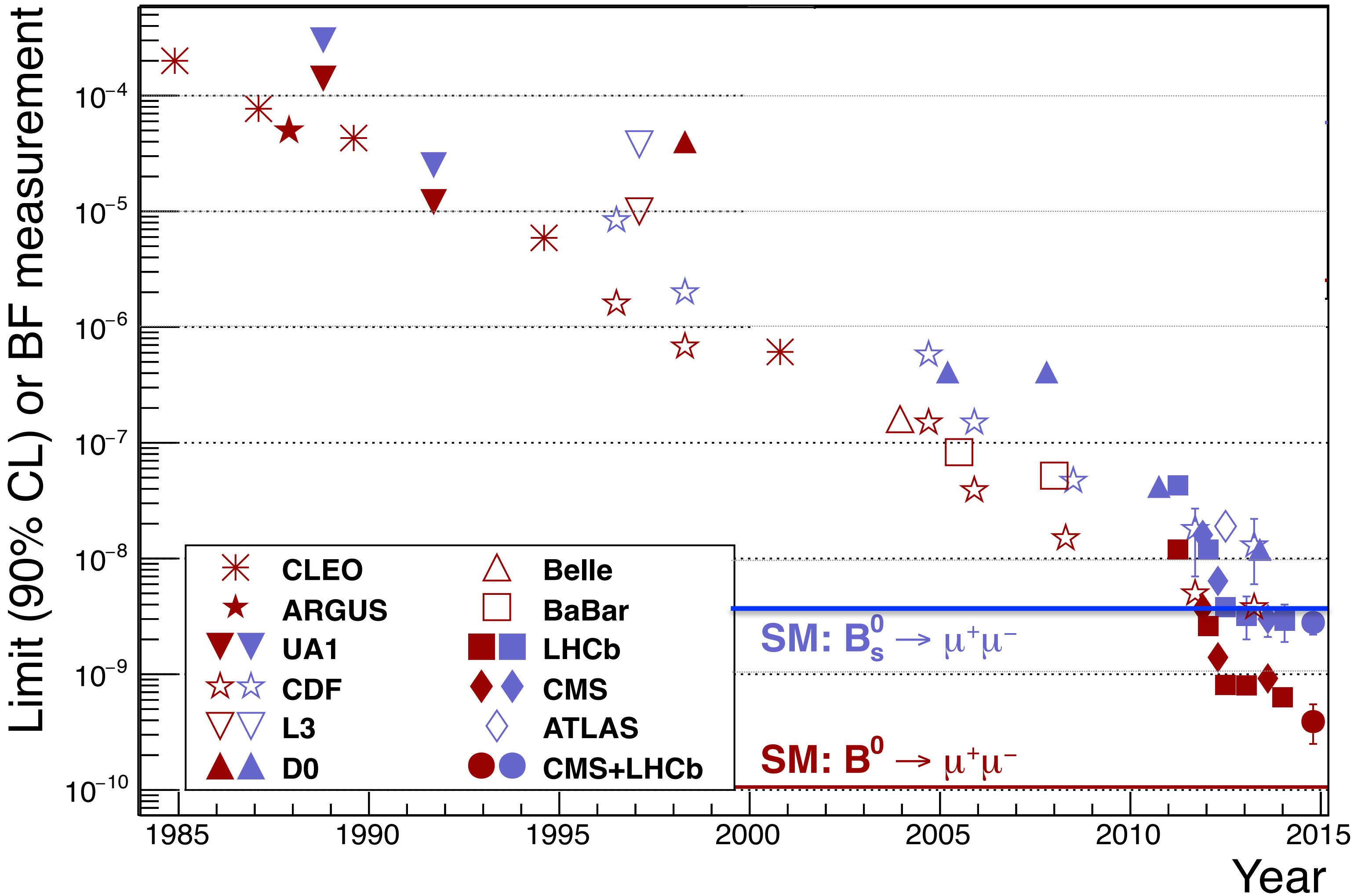
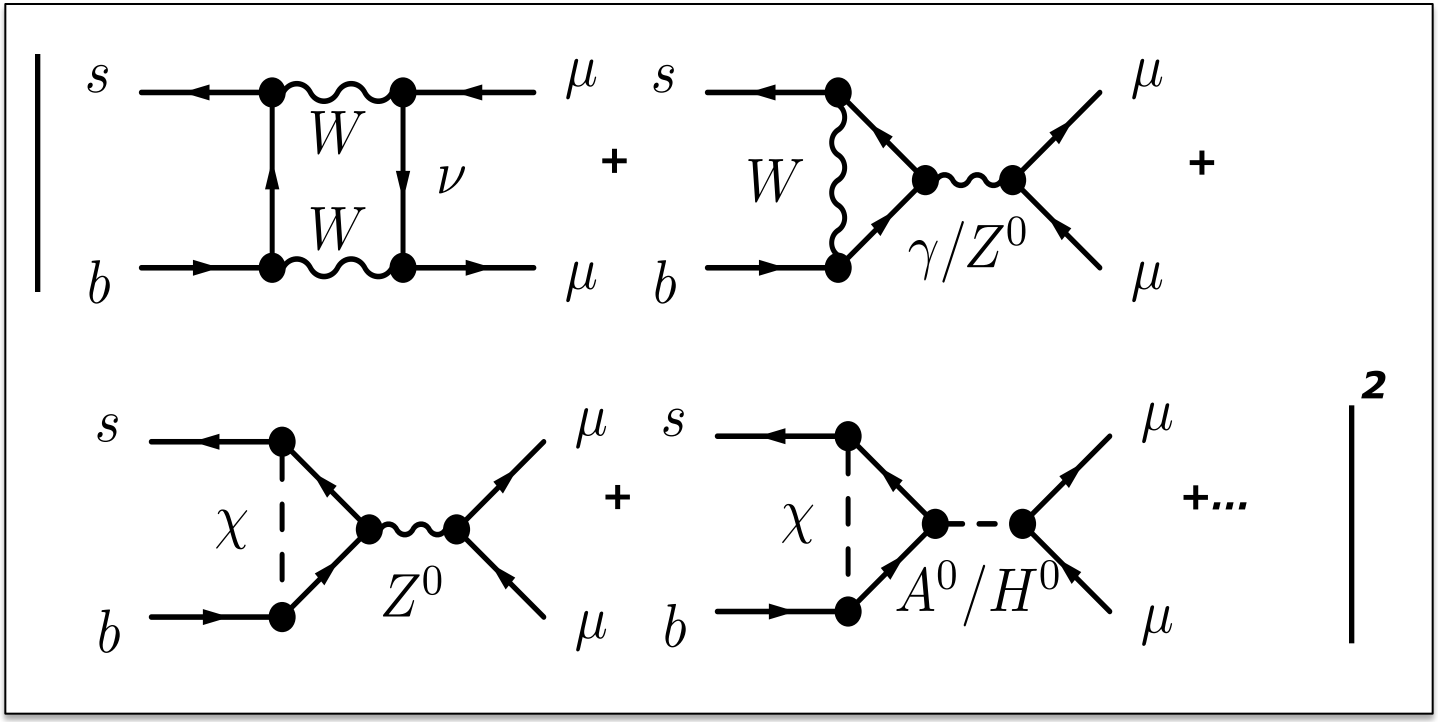


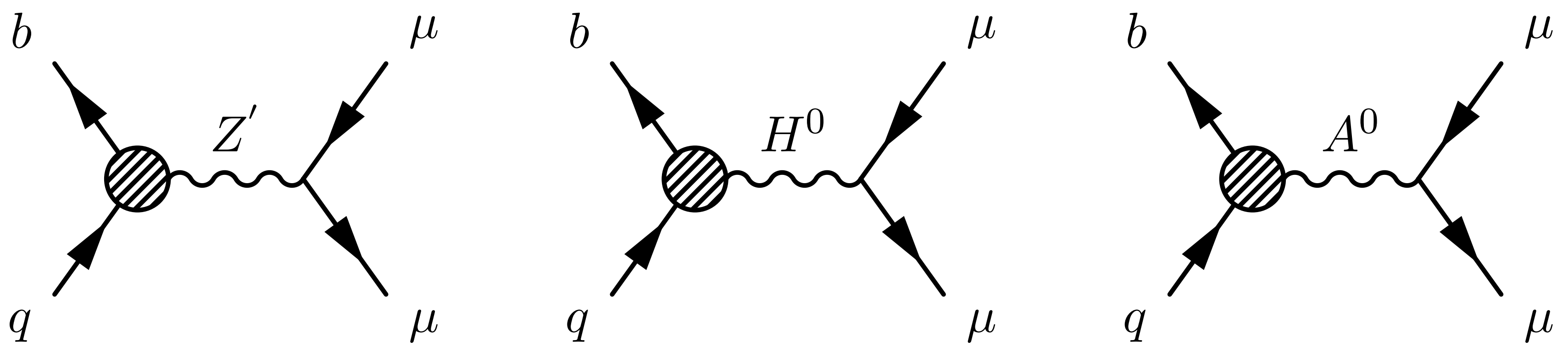
$B_s^0 \rightarrow \mu\mu$

- Historical endeavour
- Sensitive to SUSY



$B_s^0 \to \mu\mu$

- Historical endeavour
- Sensitive to SUSY
- In terms of OPE:



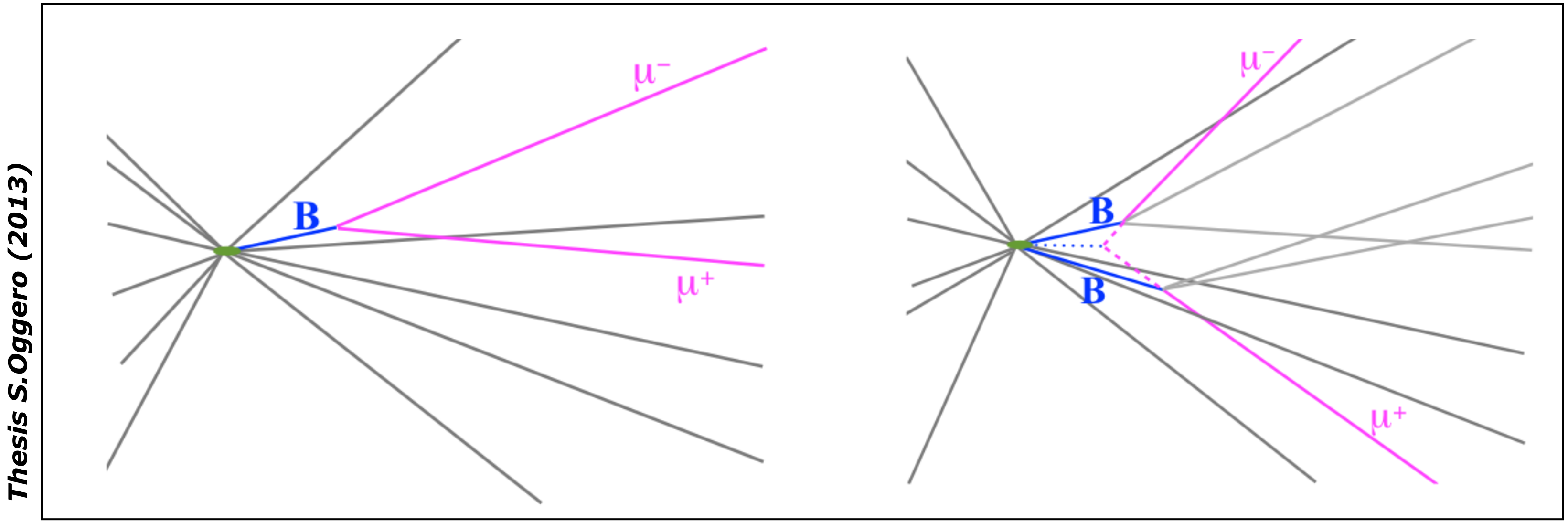
(a) V-A form (C_{10}) (b) Scalar (C_S) (c) pseudo-scalar (C_P)

From: PhD Thesis, Siim Tolk, Apr 2016

$B_s^0 \rightarrow \mu\mu$: Observation

- Challenge: huge amount of events with two muons!
  - Background: $BR(B \rightarrow X\mu^+) = 10^{-1}$
  - Signal: $BR(B_s^0 \rightarrow \mu^+\mu^-) < 10^{-8}$

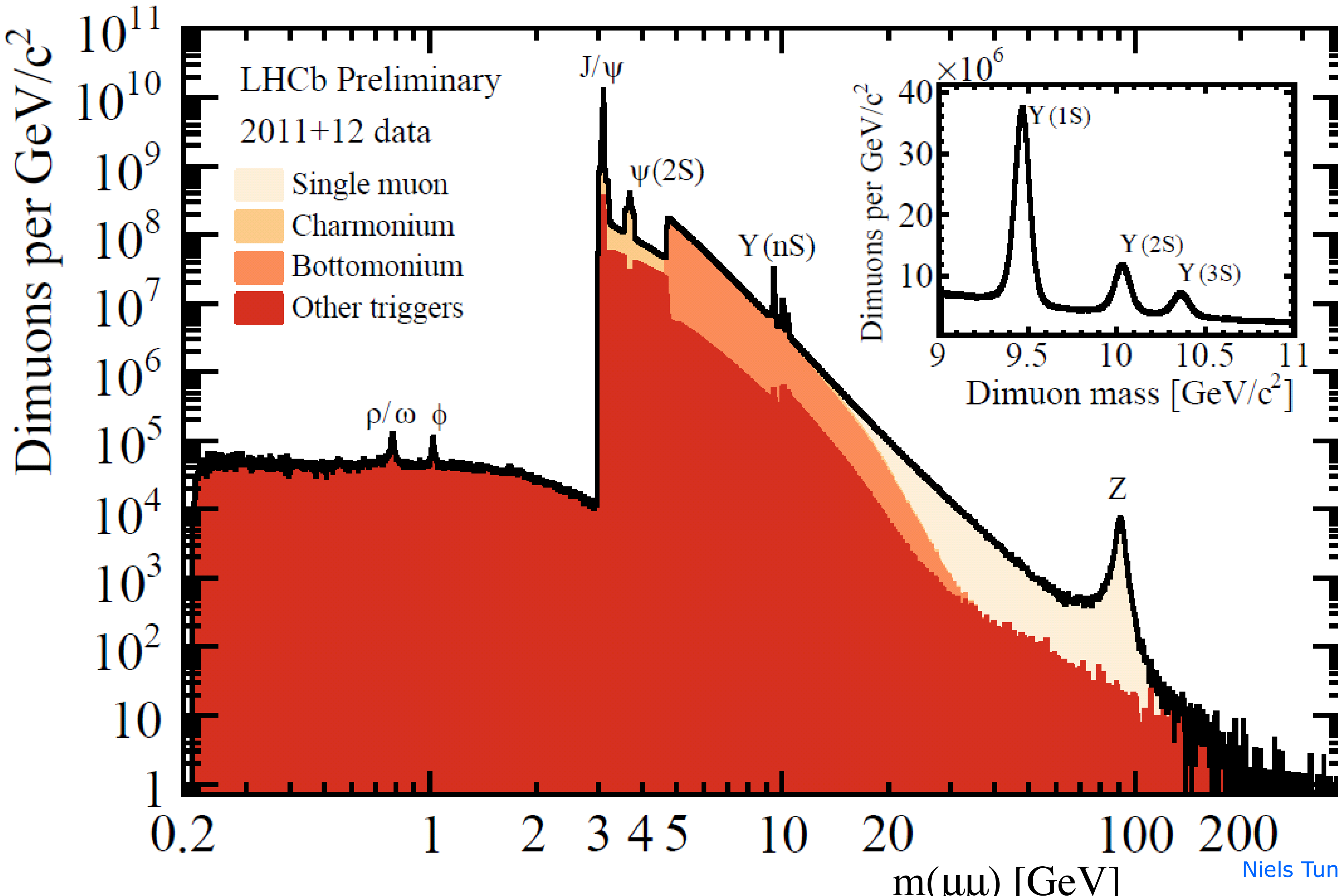
- 10^{12} B produced; probability of $\mu\mu$ decay 10^{-9}; eff ~5%
  - Expect ~50 events



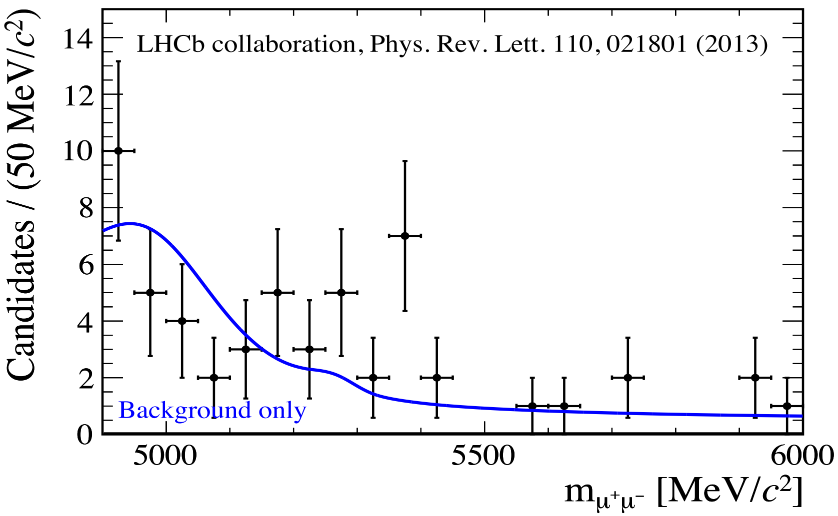
Signal 1 : 10^7 Background

$B_s^0 \rightarrow \mu\mu$: Observation

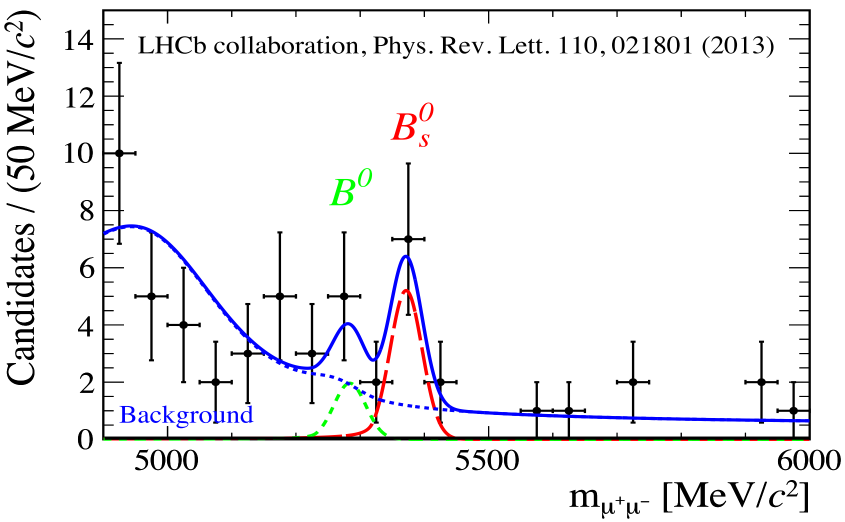
- Good luck…



$B_s^0 \rightarrow \mu\mu$: Observation



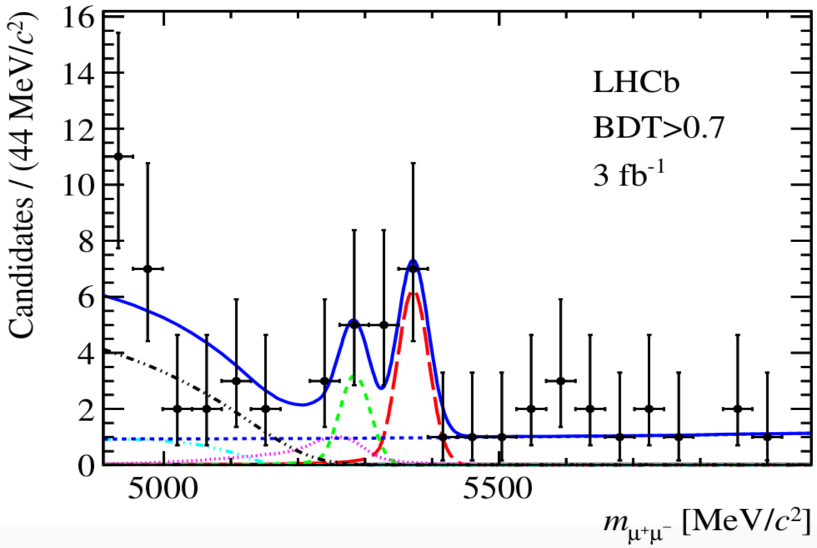
$B_s^0 \rightarrow \mu\mu$: Observation



$B_s^0 \rightarrow \mu\mu$: Observation

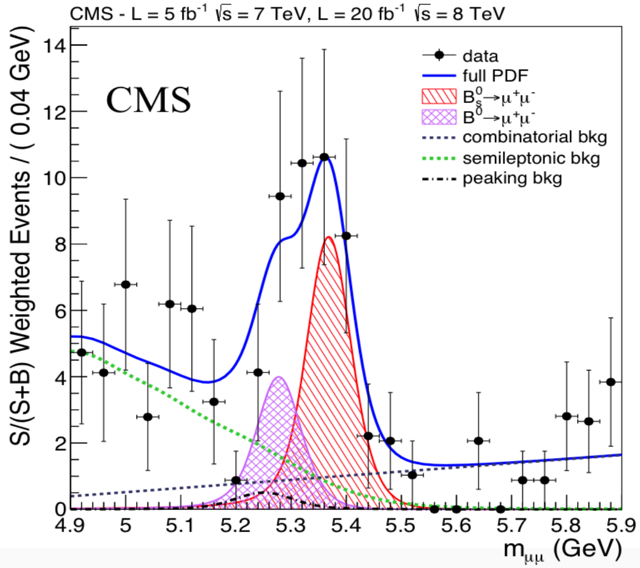
LHCb

PRL 111 (2013) 101805

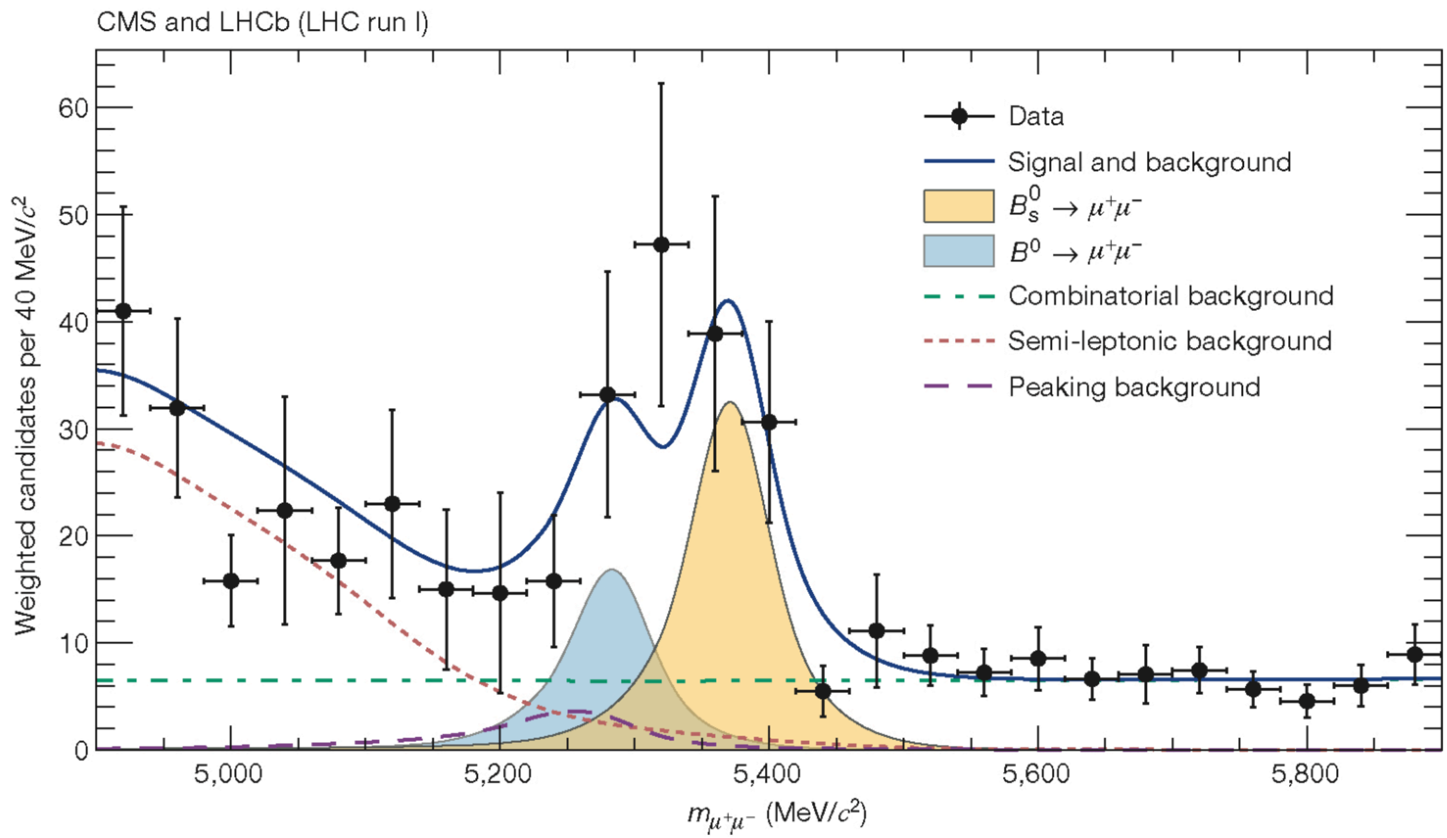


CMS

PRL 111 (2013) 101804



$B_s^0 \rightarrow \mu\mu$: Observation



Nature 522, 68–72 (04 June 2015)

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(2.8\,^{+0.7}_{-0.6}\right) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left(3.9\,^{+1.6}_{-1.4}\right) \times 10^{-10}$$

3 fb^{-1} 2.3σ

SM:

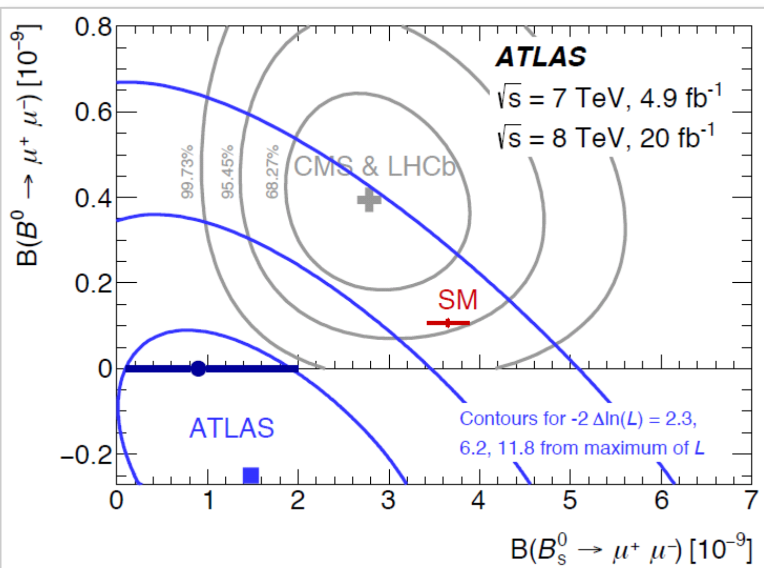
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

Bobeth et al, PRL 112 (2014) 101801

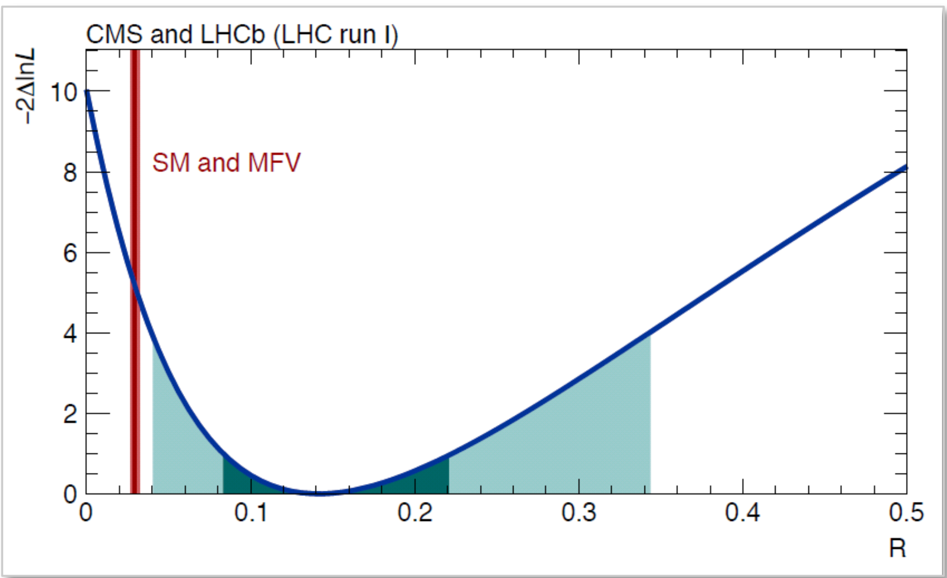
$B_s^0 \to \mu\mu$: Ratio B^0 / B_s^0

- BR($B^0 \to \mu\mu$): a little high?
  - First evidence at 3.0σ
  - 2.3σ above SM prediction:
    - $R_{SM} = 0.030 \pm 0.003$
    - $R_{exp} = 0.140\ ^{+0.080}_{-0.060}$

$$R = \frac{\mathcal{B}(B^0 \to \mu\mu)}{\mathcal{B}(B_s^0 \to \mu\mu)} = 0.14^{+0.08}_{-0.06}$$



ATLAS, EPJ C76 (2016) 513



LHCb & CMS, Nature 522, 68–72 (2015)

$B_s^0 \rightarrow \mu\mu$: 2016 ?!

- Mick unblinded last week…

- Run-I : 3 fb^{-1}, $\sqrt{s}$=7,8 TeV
- Run-II: 1.4 fb^{-1} , $\sqrt{s}$=13 TeV (Rel. stat: 13/8 * 1.4/3 = 0.75)
  - 0.6 fb-1 extra on tape...

➢ Expect 1.75x more events + analysis improvement
  - ~ x2 sensitivity
  - $5\sigma \times \sqrt{2} > 7\sigma$

$B_s^0 \rightarrow \mu\mu$: Aspects relating theory/experiment

1) Relative production rate of B_s^0

2) Correct BR for B_s^0 lifetime difference

3) Effective lifetime

1) Relative production rate

- From N($B_s^0 \to \mu\mu$) to BR($B_s^0 \to \mu\mu$)

$$\mathrm{BR}(B_s^0 \to \mu^+\mu^-) = \mathrm{BR}(B_q \to X)\frac{f_q}{f_s}\frac{\epsilon_X}{\epsilon_{\mu\mu}}\frac{N_{\mu\mu}}{N_X}$$

- But N is the product of production and decay …

$$\frac{N_{D_s\pi}}{N_{D_dK}} = \frac{f_s}{f_d}\frac{\epsilon_{D_s\pi}}{\epsilon_{D_dK}}\frac{\mathrm{BR}(\bar{B}_s^0 \to D_s^+\pi^-)}{\mathrm{BR}(\bar{B}_d^0 \to D^+K^-)},$$

1) Relative production rate

- Reverse the argument!
- From which processes do we know relative BR's ?

$$\boxed{\frac{N_{D_s\pi}}{N_{D_dK}} = \frac{f_s}{f_d}\frac{\epsilon_{D_s\pi}}{\epsilon_{D_dK}}\frac{\mathrm{BR}(\bar{B}_s^0 \to D_s^+\pi^-)}{\mathrm{BR}(\bar{B}_d^0 \to D^+K^-)},}$$

1) Relative production rate

- Dominant systematic uncertainty for BR($B_s^0 \rightarrow \mu\mu$)
- Relies on theoretical knowledge of ratio of BRs:
  - Semileptonic: $\Gamma(B_s^0 \rightarrow \mu X) = \Gamma(B \rightarrow \mu X)$

$$
\begin{aligned}
n_{\mathrm{corr}}(B \to D^0\mu) \quad = \quad & \frac{1}{\mathcal{B}(D^0 \to K^-\pi^+)\epsilon(B \to D^0)} \times \qquad\qquad (1) \\
& \left[n(D^0\mu) - n(D^0K^+\mu)\frac{\epsilon(\overline{B}{}^0_s \to D^0)}{\epsilon(\overline{B}{}^0_s \to D^0K^+)} - n(D^0p\mu)\frac{\epsilon(\Lambda_b^0 \to D^0)}{\epsilon(\Lambda_b^0 \to D^0p)}\right],
\end{aligned}
$$

$$
\begin{aligned}
n_{\mathrm{corr}}(\overline{B}{}^0_s \to D_s^+\mu) \quad = \quad & \frac{1}{\epsilon(\overline{B}{}^0_s \to D_s^+)}\left[\frac{n(D_s^+\mu)}{\mathcal{B}(D_s^+ \to K^+K^-\pi^+)} - \right. \\
& \left. N(\overline{B}{}^0 + B^-)\mathcal{B}(B \to D_s^+K\mu)\epsilon(\bar{B} \to D_s^+K\mu)\right]
\end{aligned}
$$

- Mind the cross feeds….

1) Relative production rate

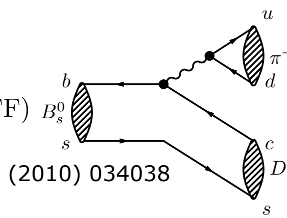
- Dominant systematic uncertainty for BR($B_s^0 \rightarrow \mu\mu$)
- Relies on theoretical knowledge of ratio of BRs:

$$\left[\frac{F_0^{(s)}(m_\pi^2)}{F_0^{(d)}(m_K^2)}\right] = 1.046 \pm 0.044(\mathrm{stat}) \pm 0.015(\mathrm{sys})$$

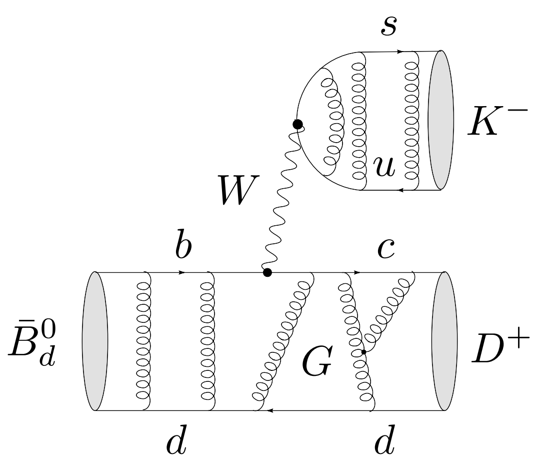
Bailey et al, PRD.85(2012)114502

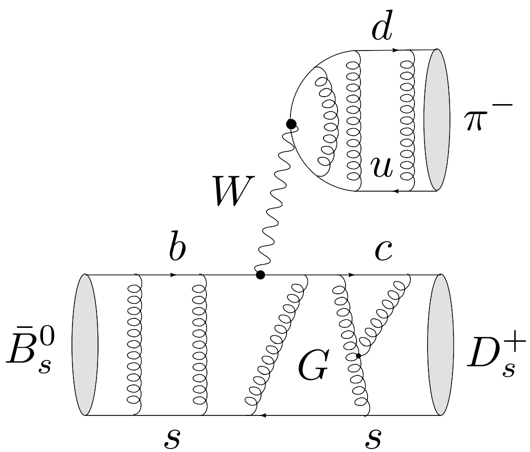
  - Semileptonic: $\Gamma(B_s^0 \rightarrow \mu X) = \Gamma(B \rightarrow \mu X)$
  - Hadronic:

$$\frac{\mathrm{BR}(\bar{B}_s^0 \to D_s^+\pi^-)}{\mathrm{BR}(\bar{B}_d^0 \to D^+K^-)} = \frac{\Phi(D_s\pi)}{\Phi(DK)}\frac{\tau_{B_s}}{\tau_{B_d}}\left|\frac{V_{ud}}{V_{us}}\right|^2\left(\frac{f_\pi}{f_K}\right)^2\left[\frac{F_0^{(s)}(m_\pi^2)}{F_0^{(d)}(m_K^2)}\right]^2\left|\frac{a_1(D_s\pi)}{a_1(D_dK)}\right|^2 = 14.2 \pm 1.3(\mathrm{FF})$$



Fleischer, Serra, NT, PRD82 (2010) 034038





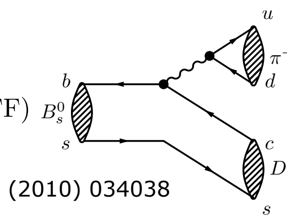
- Mind the form factor ratio….

1) Relative production rate

- Dominant systematic uncertainty for BR($B_s^0 \rightarrow \mu\mu$)
- Relies on theoretical knowledge of ratio of BRs:
  - Semileptonic: $\Gamma(B_s^0 \rightarrow \mu X) = \Gamma(B \rightarrow \mu X)$
  - Hadronic: $$\frac{\mathrm{BR}(\bar{B}_s^0 \to D_s^+ \pi^-)}{\mathrm{BR}(\bar{B}_d^0 \to D^+ K^-)} = \frac{\Phi(D_s\pi)}{\Phi(DK)} \frac{\tau_{B_s}}{\tau_{B_d}} \left|\frac{V_{ud}}{V_{us}}\right|^2 \left(\frac{f_\pi}{f_K}\right)^2 \left[\frac{F_0^{(s)}(m_\pi^2)}{F_0^{(d)}(m_K^2)}\right]^2 \left|\frac{a_1(D_s\pi)}{a_1(D_d K)}\right|^2 = 14.2 \pm 1.3(\mathrm{FF})$$
  - B→J/ψX: $$R_{s/d}^{\mathrm{th.}} \equiv \frac{\mathrm{BR}(B_s \to J/\psi \phi)}{\mathrm{BR}(B_d \to J/\psi K^{*0})} \approx 0.83^{+0.03}_{-0.02}(\omega_B)^{+0.01}_{-0.00}(f_M)^{+0.01}_{-0.02}(a_i)^{+0.01}_{-0.02}(m_c)[0.83^{+0.03}_{-0.03}]$$

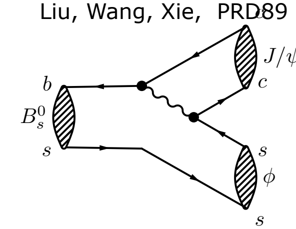
$$\left[\frac{F_0^{(s)}(m_\pi^2)}{F_0^{(d)}(m_K^2)}\right] = 1.046 \pm 0.044(\mathrm{stat}) \pm 0.015(\mathrm{sys})$$

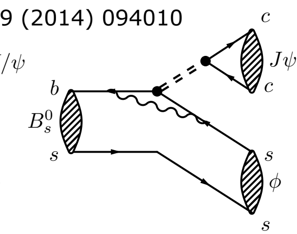
Bailey et al, PRD.85(2012)114502



Fleischer, Serra, NT, PRD82 (2010) 034038

Liu, Wang, Xie, PRD89 (2014) 094010





- Mind factorisation and penguins?!

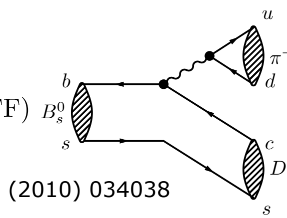
1) Relative production rate

- Dominant systematic uncertainty for BR($B_s^0 \to \mu\mu$)
- Relies on theoretical knowledge of ratio of BRs:
  - Semileptonic: $\Gamma(B_s^0 \to \mu X) = \Gamma(B \to \mu X)$
  - Hadronic:

$$\left[\frac{F_0^{(s)}(m_\pi^2)}{F_0^{(d)}(m_K^2)}\right] = 1.046 \pm 0.044(\mathrm{stat}) \pm 0.015(\mathrm{sys})$$

Bailey et al, PRD.85(2012)114502

$$\frac{\mathrm{BR}(\bar{B}_s^0 \to D_s^+\pi^-)}{\mathrm{BR}(\bar{B}_d^0 \to D^+K^-)} = \frac{\Phi(D_s\pi)}{\Phi(DK)}\frac{\tau_{B_s}}{\tau_{B_d}}\left|\frac{V_{ud}}{V_{us}}\right|^2 \left(\frac{f_\pi}{f_K}\right)^2 \left[\frac{F_0^{(s)}(m_\pi^2)}{F_0^{(d)}(m_K^2)}\right]^2 \left|\frac{a_1(D_s\pi)}{a_1(D_dK)}\right|^2 = 14.2 \pm 1.3(\mathrm{FF})$$

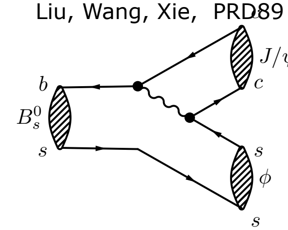


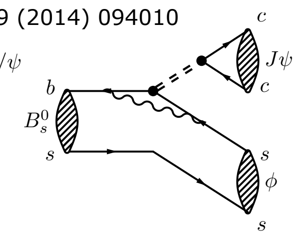
Fleischer, Serra, NT, PRD82 (2010) 034038

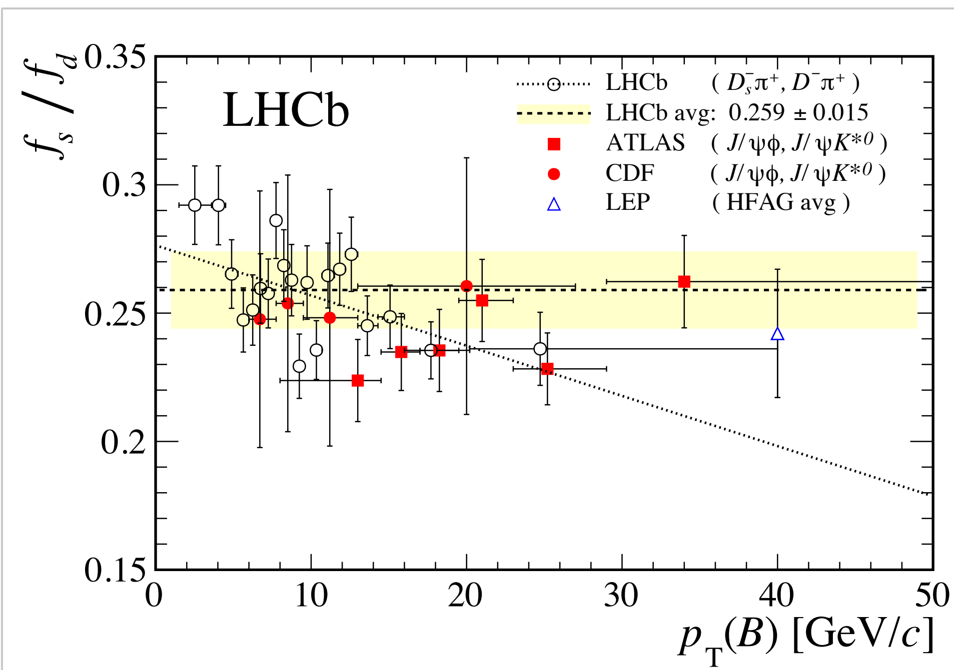
  - B→J/ψX:

$$R^{\mathrm{th.}\prime}_{s/d} \equiv \frac{\mathrm{BR}(B_s \to J/\psi\phi)}{\mathrm{BR}(B_d \to J/\psi K^{*0})} \approx 0.83^{+0.03}_{-0.02}(\omega_B)^{+0.01}_{-0.00}(f_M)^{+0.01}_{-0.02}(a_i)^{+0.01}_{-0.02}(m_c)[0.83^{+0.03}_{-0.03}]$$

Liu, Wang, Xie, PRD89 (2014) 094010



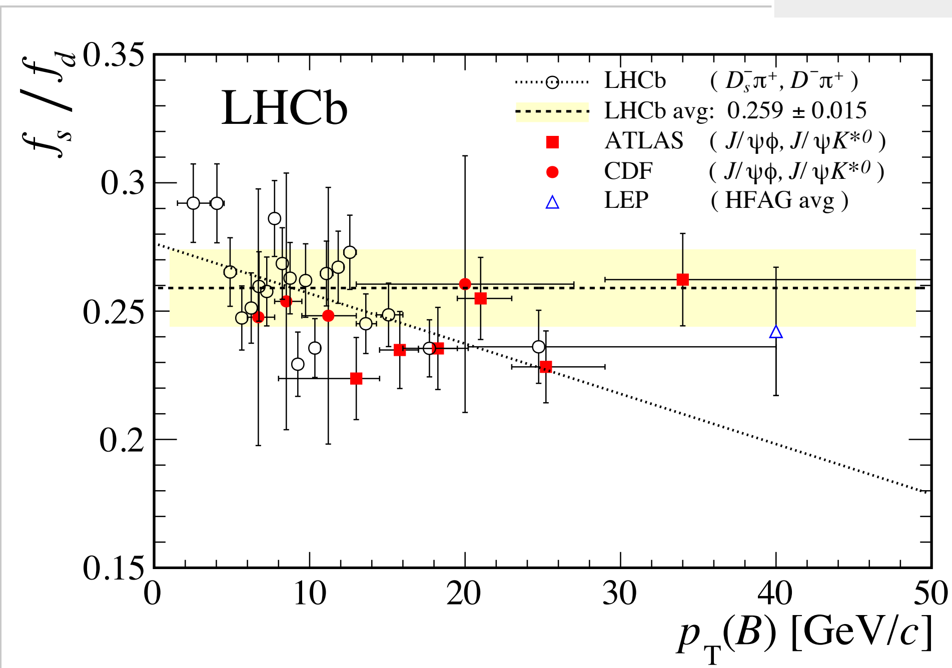




1) Relative production rate

- Dominant systematic uncertainty for BR($B_s^0 \rightarrow \mu\mu$)
- Measurements

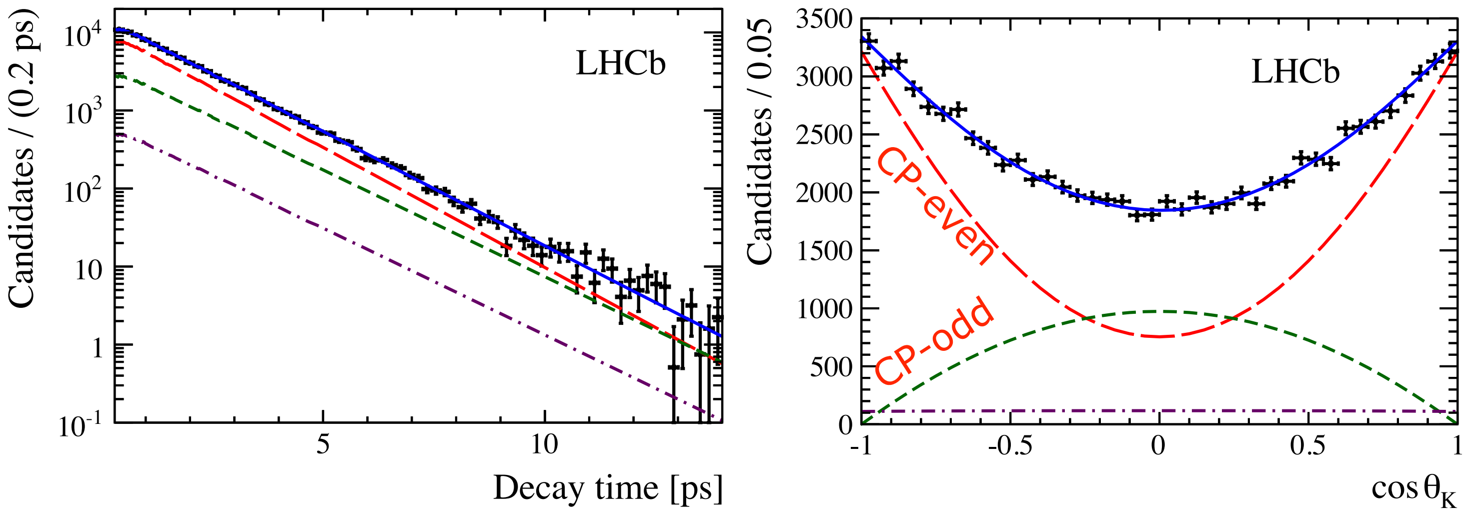
	Normalization	Dependence
LHCb	Semileptonic Phys. Rev. D 85 (2012) 032008 $B \rightarrow Dh$ Phys. Rev. Lett. 107 (2011) 211801 LHCb-CONF-2013-011	$B \rightarrow Dh$ JHEP 04 (2013) 001
CDF	Semileptonic Phys. Rev. D 77, 072003 (2008).	$B \rightarrow J/\psi X$ Public Note 10795
ATLAS	$B \rightarrow J/\psi X$	$B \rightarrow J/\psi X$ Phys.Rev.Lett. 115 (2015) 262001



- Mind kinematic dependence…

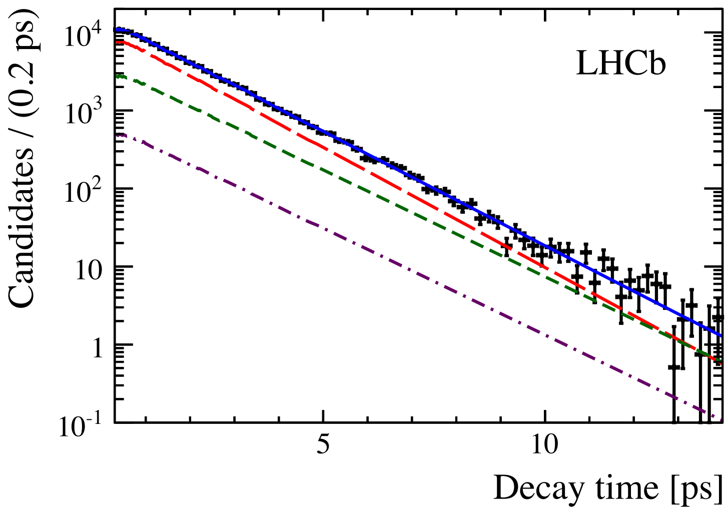
2) Correct for lifetime difference

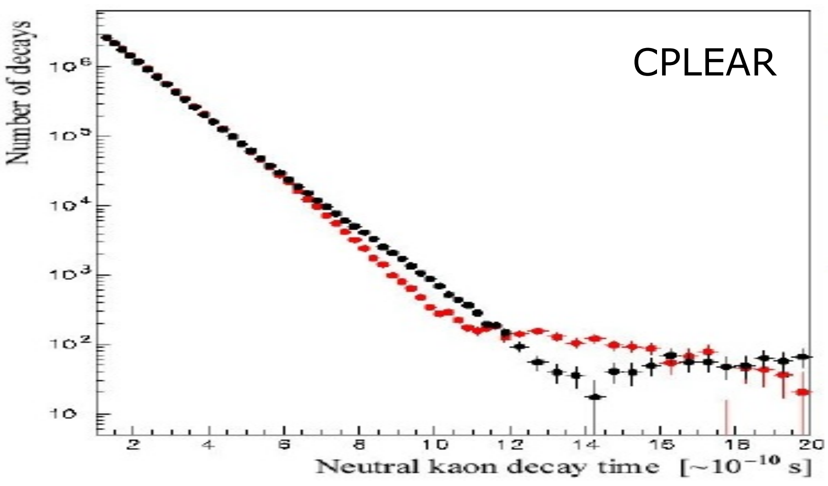
- Branching fraction at t=0 different from all (time-integrated) decays



- $B_{s,H}$: CP-odd: long-living
- $B_{s,L}$: CP-even: short-living

2) Correct for lifetime difference





- $B_{s,H}$: CP-odd: long-living
- $B_{s,L}$: CP-even: short-living

$$B_s^0 \to D_s^+ D_s^-$$

- K_L: CP-odd: long-living
- K_S: CP-even: short-living

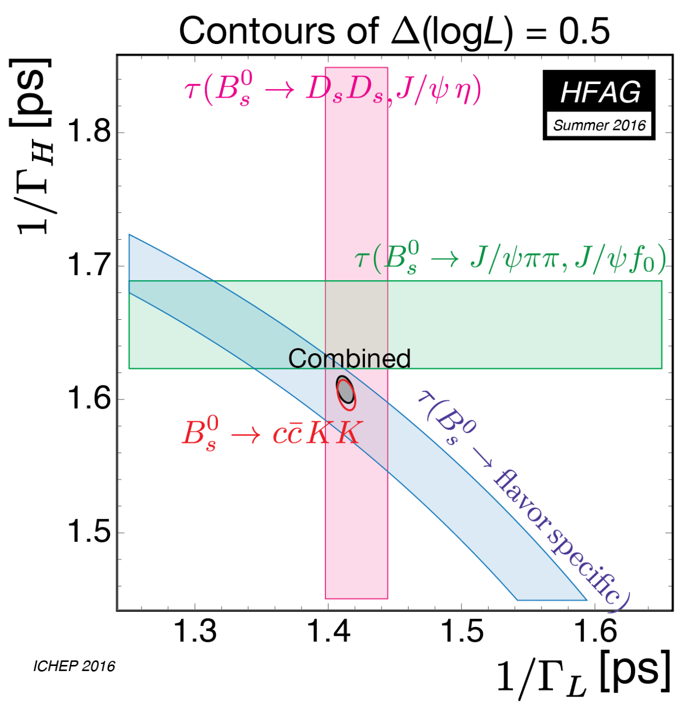
$$K_s^0 \to \pi^+ \pi^-$$

2) Correct for lifetime difference

- Branching fraction at t=0 different from all (time-integrated) decays

De Bruyn, Fleischer, NT, et al. Phys.Rev. D86 (2012) 014027

$B_s \to f$	$\mathrm{BR}(B_s \to f)_{\mathrm{exp}}$ (measured)	$\mathcal{A}^f_{\Delta\Gamma}(\mathrm{SM})$	$\mathrm{BR}(B_s \to f)_{\mathrm{theo}}/\mathrm{BR}(B_s \to f)_{\mathrm{exp}}$ From Eq. (8)	From Eq. (10)
$J/\psi f_0(980)$	$(1.29^{+0.40}_{-0.28}) \times 10^{-4}$ [18]	0.9984 ± 0.0021 [14]	0.912 ± 0.014	0.890 ± 0.082 [6]
$J/\psi K_S$	$(3.5 \pm 0.8) \times 10^{-5}$ [7]	0.84 ± 0.17 [15]	0.924 ± 0.018	N/A
$D_s^- \pi^+$	$(3.01 \pm 0.34) \times 10^{-3}$ [9]	0 (exact)	0.992 ± 0.003	N/A
K^+K^-	$(3.5 \pm 0.7) \times 10^{-5}$ [18]	-0.972 ± 0.012 [13]	1.085 ± 0.014	1.042 ± 0.033 [19]
$D_s^+ D_s^-$	$(1.04^{+0.29}_{-0.26}) \times 10^{-2}$ [18]	-0.995 ± 0.013 [16]	1.088 ± 0.014	N/A



2) Correct for lifetime difference

- *$B_s^0 \to \mu\mu$: P(seudo)* and *S(calar)* amplitude
- SM: P-amplitude dominates, selecting CP-odd (= $B_{s\,H}^0$)

$$A(\bar{B}_s^0 \to \mu_\lambda^+ \mu_\lambda^-) = \langle \mu_\lambda^- \mu_\lambda^+ | \mathcal{H}_{\rm eff} | \bar{B}_s^0 \rangle = -\frac{G_{\rm F}}{\sqrt{2}\pi} V_{ts}^* V_{tb} \alpha$$
$$\times f_{B_s} M_{B_s} m_\mu C_{10}^{\rm SM} e^{i\phi_{\rm CP}(\mu\mu)(1-\eta_\lambda)/2} \left[\eta_\lambda P + S\right], \quad (5)$$

where M_{B_s} is the B_s mass, $\eta_{\rm L} = +1$ and $\eta_{\rm R} = -1$, and

$$P \equiv \frac{C_{10} - C_{10}'}{C_{10}^{\rm SM}} + \frac{M_{B_s}^2}{2m_\mu}\left(\frac{m_b}{m_b + m_s}\right)\left(\frac{C_P - C_P'}{C_{10}^{\rm SM}}\right) \quad (6)$$

$$S \equiv \sqrt{1 - 4\frac{m_\mu^2}{M_{B_s}^2}} \frac{M_{B_s}^2}{2m_\mu}\left(\frac{m_b}{m_b + m_s}\right)\left(\frac{C_S - C_S'}{C_{10}^{\rm SM}}\right). \quad (7)$$

$$\mathrm{BR}(B_s \to \mu^+\mu^-) = \left[\frac{1 - y_s^2}{1 + \mathcal{A}_{\Delta\Gamma}\, y_s}\right] \mathrm{BR}(B_s \to \mu^+\mu^-)_{\rm exp},$$

$$\mathrm{BR}(B_s \to \mu^+\mu^-)_{\rm SM}|_{y_s} = (3.5 \pm 0.2) \times 10^{-9}$$

De Bruyn, Fleischer, NT, et al. Phys. Rev. Lett. 109, 041801 (2012)

$BR(B_s^0 \rightarrow \mu\mu)$

- BR(t=0)

$$\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{SM}} = 3.25 \times 10^{-9} \times \left[\frac{M_t}{173.2\,\mathrm{GeV}}\right]^{3.07} \left[\frac{F_{B_s}}{225\,\mathrm{MeV}}\right]^{2} \left[\frac{\tau_{B_s}}{1.500\mathrm{ps}}\right] \left|\frac{V_{tb}^* V_{ts}}{0.0405}\right|^{2}$$

[Buras, Girrbach, Guadagnoli & Isidori (2012); address also soft photon corrections]

- <u>Time integrated:</u>

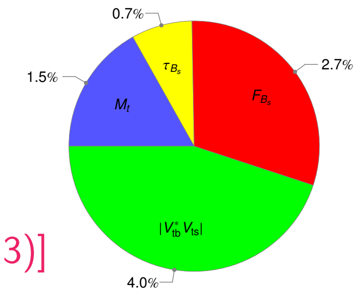
	BR x 10^9			
Fleischer (Nikhef)	3.5	0.2	PRL 109 (2012) 041801	arXiv:1204.1737
Buras, Fleischer, Knegjens	3.56	0.18	JHEP 1307 (2013) 77	arXiv:1303.3820
Bobeth, Gorbahn et al	3.65	0.23	PRL 112 (2014) 101801	arXiv:1311.0903

$BR(B_s^0 \to \mu\mu)$

- Most relevant recent changes:
  - Lattice QCD progress [FLAG]: $F_{B_s} = (227.7 \pm 4.5)$ MeV
  - Experiment [HFAG]: $\tau_{B_s} = (1.516 \pm 0.011)$ ps
  - Theory: [Bobeth *et al.*, arXiv:1311.0903]

    NLO electroweak effects [Bobeth *et al.*, arXiv:1311.1348] and NNLO QCD matching corrections [Herman *et al.*, arXiv:1311.1347]:

$$\Rightarrow \boxed{\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{SM}} = (3.38 \pm 0.22) \times 10^{-9}}$$



[supersedes prediction by Buras, R.F., Girrbach & Knegjens (2013)]

- Time integrated:

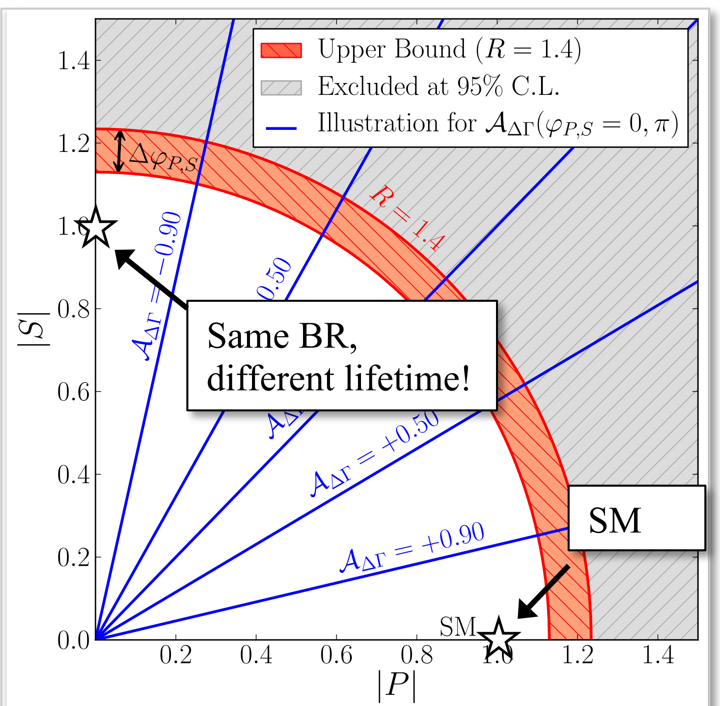
	BR x 10^9			
Fleischer (Nikhef)	3.5	0.2	PRL 109 (2012) 041801	arXiv:1204.1737
Buras, Fleischer, Knegjens	3.56	0.18	JHEP 1307 (2013) 77	arXiv:1303.3820
Bobeth, Gorbahn et al	3.65	0.23	PRL 112 (2014) 101801	arXiv:1311.0903

3) "effective lifetime"

- Effective lifetime: ~"single exponential fit to double exponential decay time"
- Different CP admixture affects effective lifetime
  - possibly not affecting the BR, when |S| and $A_{\Delta\Gamma}$ compensate…

➢ Could be due to scalar amplitude |S| from NP

$$R \equiv \frac{\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{exp}}}{\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{SM}}} = \left[\frac{1+\mathcal{A}_{\Delta\Gamma} y_s}{1-y_s^2}\right]\left(|P|^2+|S|^2\right)$$



De Bruyn, Fleischer, NT, et al. Phys. Rev. Lett. 109, 041801 (2012)

Break

Rare Decays - Outline:

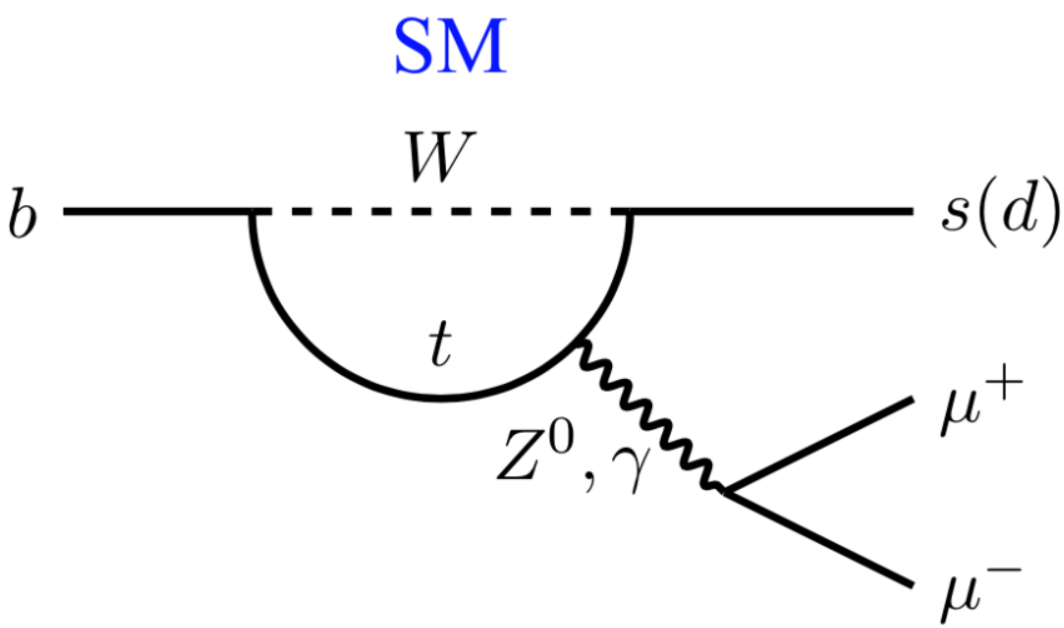
- 9h30 - 10h15 Lecture 1: Introduction
- 10h30 - 11h15 Lecture 2: Effective couplings
- 11h30 - 12h15 Lecture 3: $B_s \rightarrow \mu\mu$

Lunch

- 13h45 - 14h30 Lecture 4: $B^0 \rightarrow K^*\mu\mu$
- 15h00 - 16h30 Discussion Session

b→s μμ

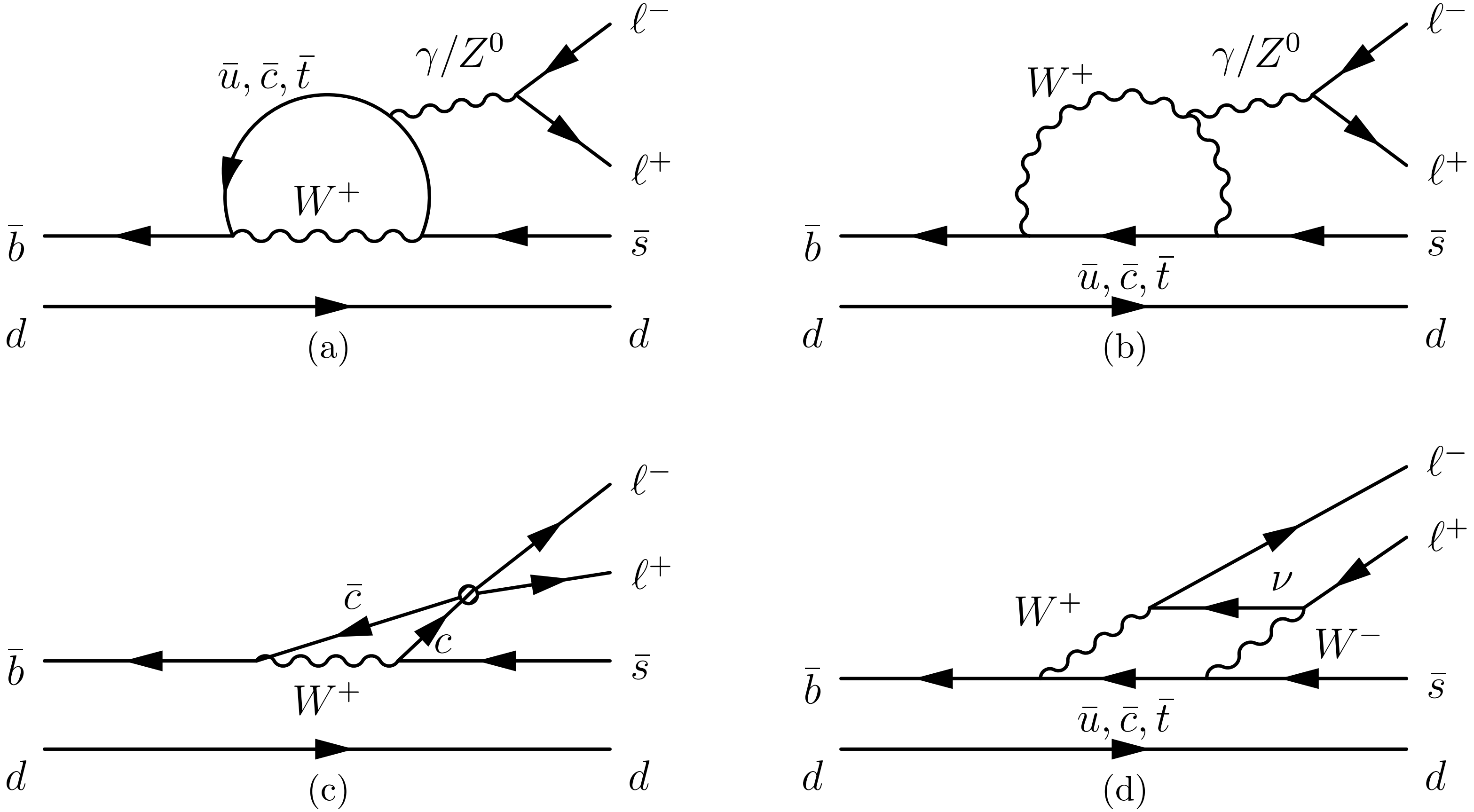
- Flavour changing neutral current: **FCNC**
- In SM only at higher order:



Decay
$B \to X_s \gamma$
$B \to K^* \gamma$
$B \to X_s \mu^+ \mu^-$
$B \to K \mu^+ \mu^-$
$B \to K^* \mu^+ \mu^-$
$B_s \to \mu^+ \mu^-$

$B^0 \rightarrow K^*\mu\mu$

- Diagrams:



$B^0 \rightarrow K^*\mu\mu$

- Decay rate

- Observables

- Wilson coefficients

$B^0 \to K^*\mu\mu$

- Decay rate

$$\frac{1}{\Gamma}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$

$$- F_L\cos^2\theta_K\cos 2\theta_\ell +$$

$$S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi +$$

$$S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6^s\sin^2\theta_K\cos\theta_\ell +$$

$$S_7\sin 2\theta_K\sin\theta_\ell\sin\phi +$$

$$S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\ \Big]$$

$B^0 \to K^*\mu\mu$

- Decay rate

- Observables

$$F_L = \frac{A_0^2}{A_\parallel^2 + A_\perp^2 + A_0^2}$$

$$S_3 = \frac{A_\perp^{L2} - A_\parallel^{L2}}{A_\perp^{L2} + A_\parallel^{L2} + A_0^{L2}} + L \to R$$

$$S_4 = \frac{\Re(A_0^{L*} A_\parallel^L)}{|A_0^L|^2 |A_\parallel^L|^2 + |A_0^L|^2} + L \to R$$

$$S_5 = \frac{\Re(A_0^{L*} A_\perp^L)}{|A_0^L|^2 + A_\perp^L|^2 + |A_0^L|^2} - L \to R$$

$$S_6 = \frac{\Re(A_\perp^{L*} A_\parallel^L)}{|A_\perp^L|^2 + |A_\parallel^L|^2 + |A_0^L|^2} - L \to R = \frac{4}{3} A_{FB}$$

$$S_7 = \frac{\Im(A_0^{L*} A_\parallel^L)}{|A_0^L|^2 + |A_\parallel^L|^2 + |A_0^L|^2} + L \to R$$

$$S_8 = \frac{\Im(A_0^{L*} A_\perp^L)}{|A_0^L|^2 + |A_\parallel^L|^2 + |A_0^L|^2} + L \to R$$

$$S_9 = \frac{\Im(A_\perp^{L*} A_\parallel^L)}{|A_\perp^L|^2 + |A_\parallel^L|^2 + |A_0^L|^2} - L \to R$$

- Wilson coefficients

$B^0 \rightarrow K^*\mu\mu$

$$A_\perp^{L,R} \propto [(C_9^{eff} + C_9^{eff\prime}) \mp (C_{10}^{eff} + C_{10}^{eff\prime}) \frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2}(C_7^{eff} + C_7^{eff\prime}) T_1(q^2)]$$

$$A_\parallel^{L,R} \propto [(C_9^{eff} - C_9^{eff\prime}) \mp (C_{10}^{eff} - C_{10}^{eff\prime}) \frac{A_1(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2}(C_7^{eff} - C_7^{eff\prime}) T_2(q^2)]$$

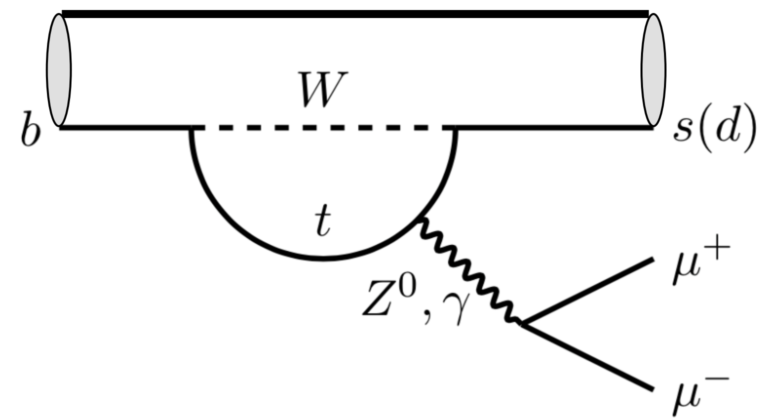
$$A_0^{L,R} \propto [(C_9^{eff} - C_9^{eff\prime}) \mp (C_{10}^{eff} - C_{10}^{eff\prime})] \times [(m_B^2 - m_{K^*}^2 - q^2)(m_B + m_{K^*} A_1(q^2) - \lambda \frac{A_2(q^2)}{m_B + m_{K^*}})] +$$

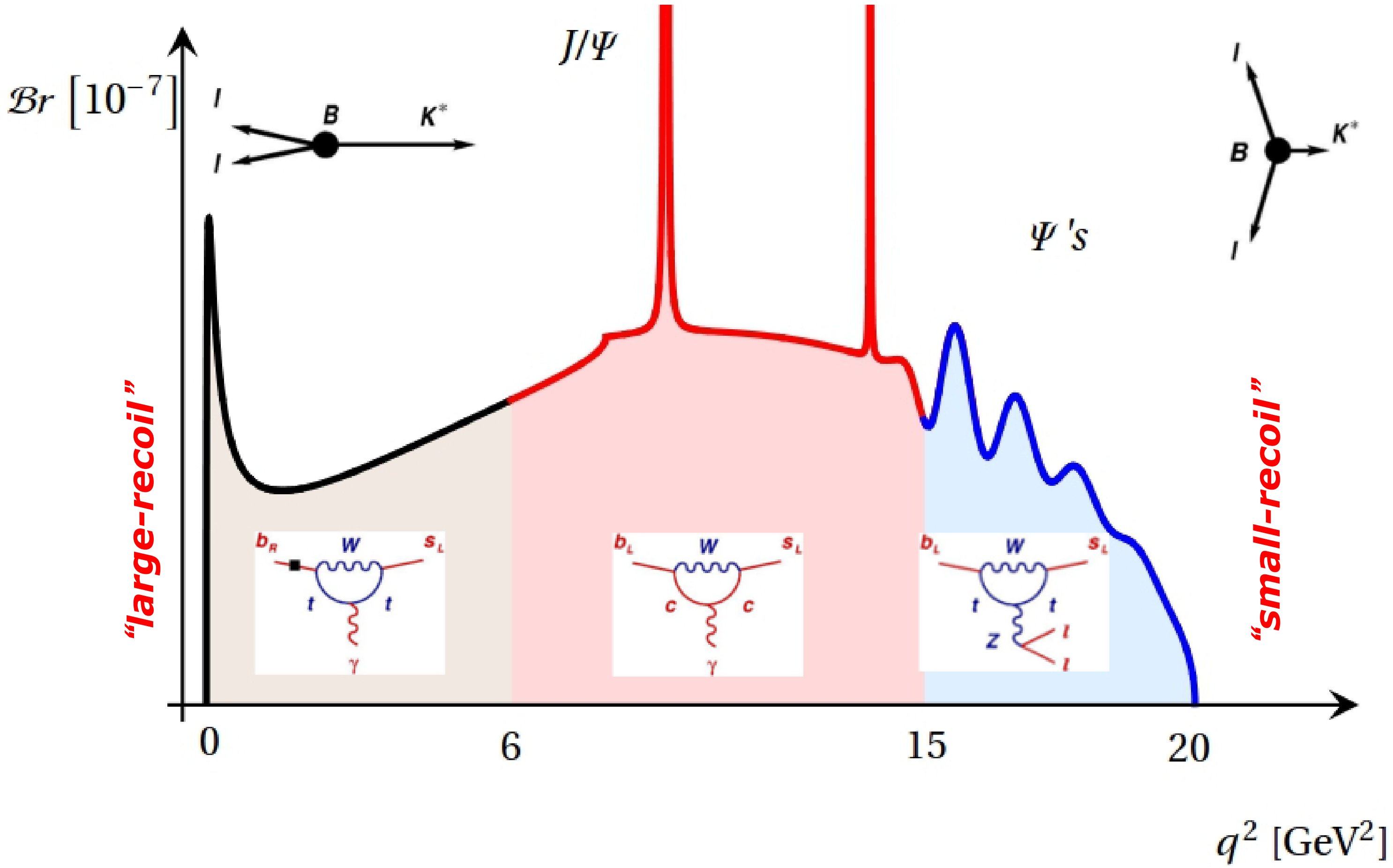
$$2m_b(C_7^{eff} + C_7^{eff\prime})[(m_B^2 + 3m_{K^*}^2 - q^2) T_2(q^2) - \frac{\lambda}{m_B^2 - m_{K^*}^2 T_3(q^2)}]$$

- Wilson coefficients

$b \to s\ \mu\mu$

- $B \to K\mu\mu$ spectrum

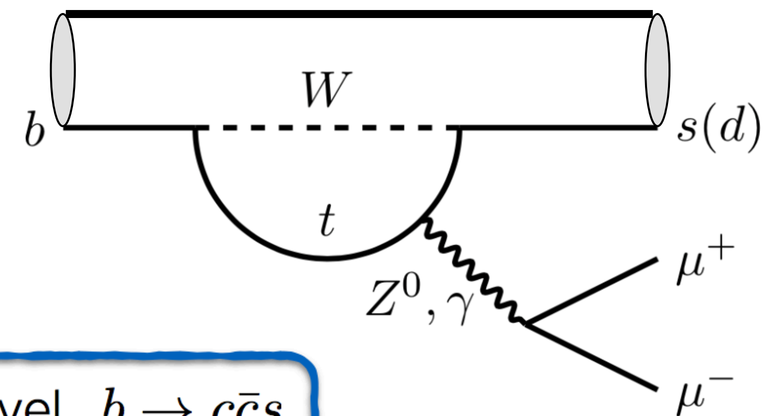


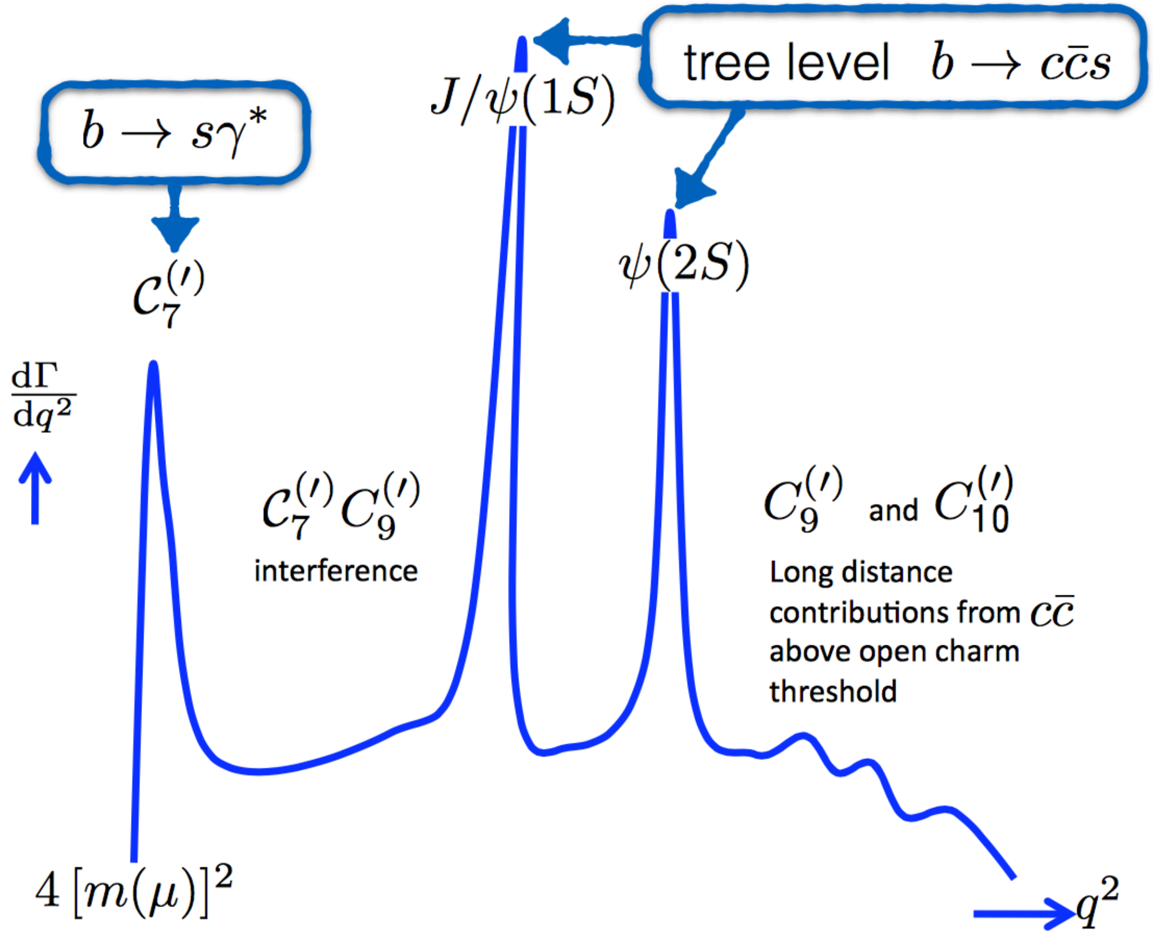


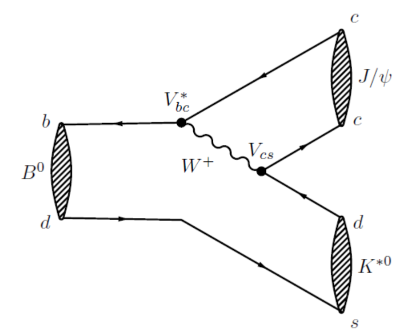
Stolen from J. Martin Camalich

$b \rightarrow s\ \mu\mu$

- $B \rightarrow K\mu\mu$ or $B \rightarrow K(J/\Psi \rightarrow)\mu\mu$?
  - If m(μμ)=3.1 GeV, we hit the J/Ψ …



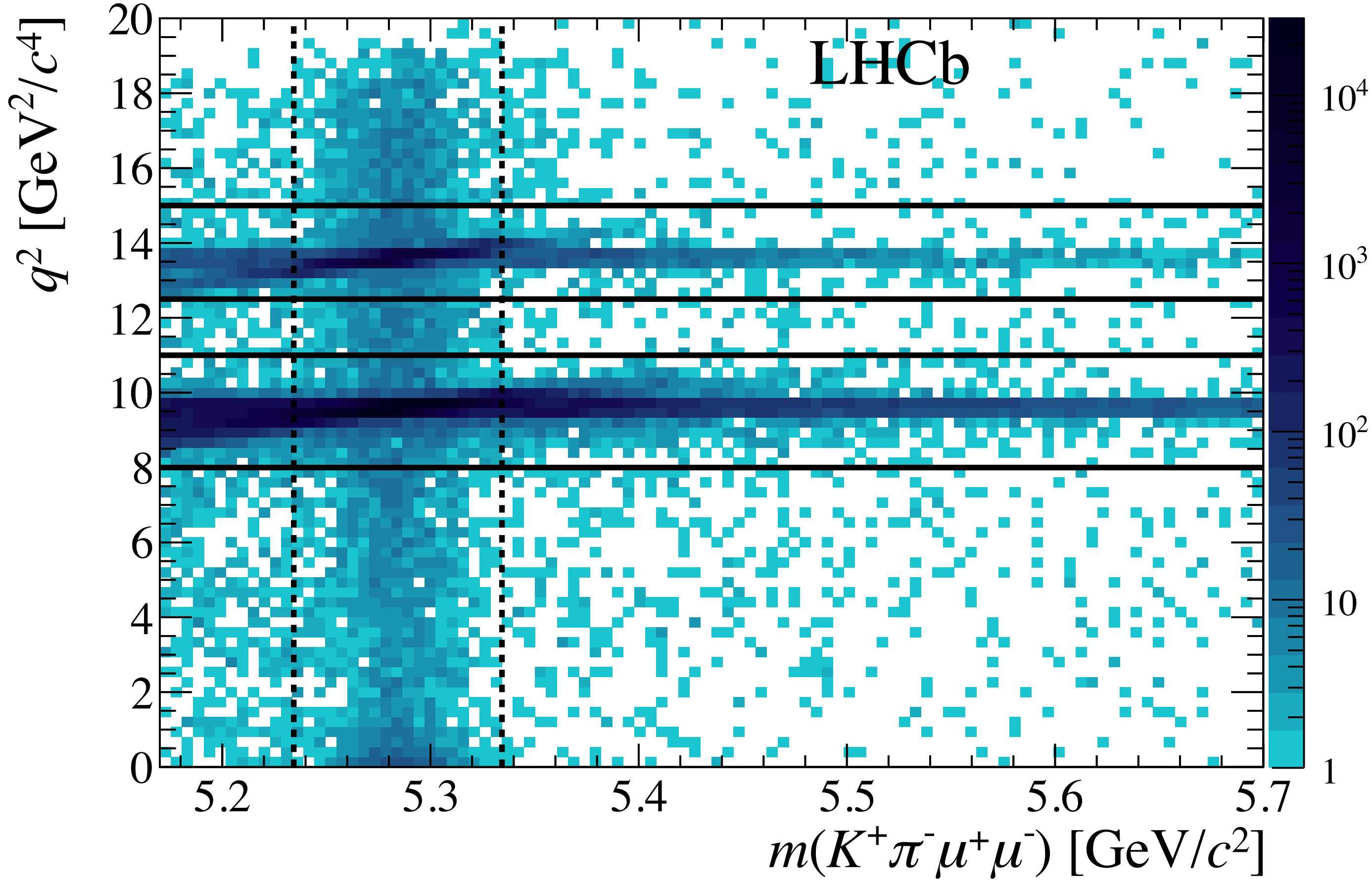




Sketch from Christian Linn

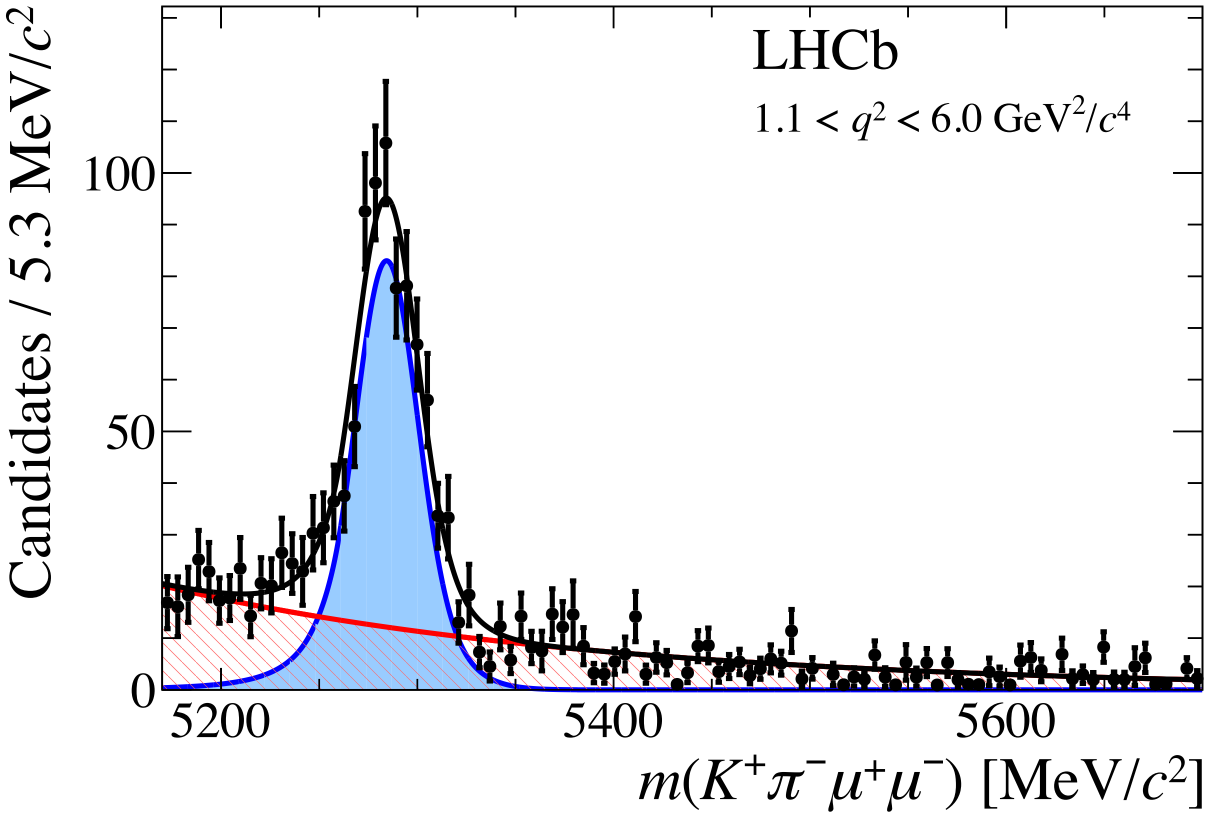
$B^0 \rightarrow K^*\mu\mu$

- Event selection:

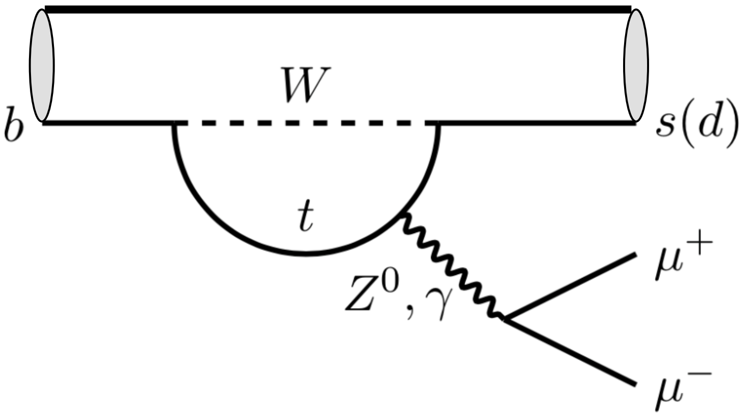


$B^0 \rightarrow K^*\mu\mu$

- Event selection:



b→s μμ



- Observables:

1) Decay rates

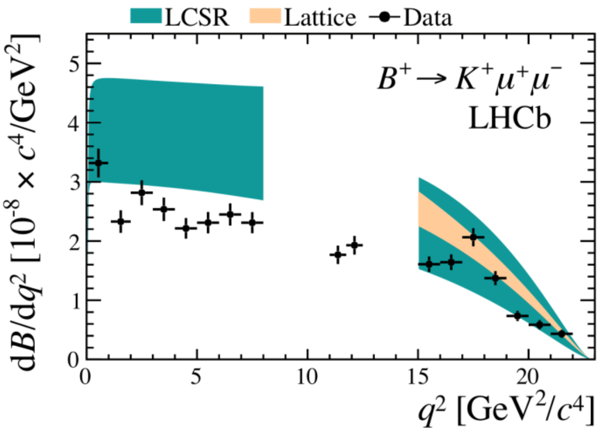
2) Angular distributions

3) Ratio of branching fractions

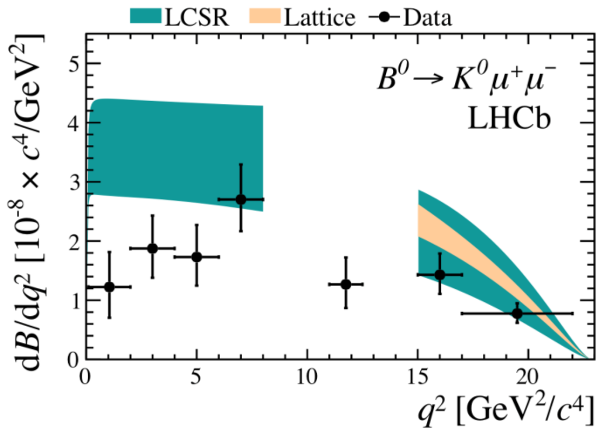
1) *b→s μμ:* Decay rates

3 fb^{-1}, arXiv:1403.8044

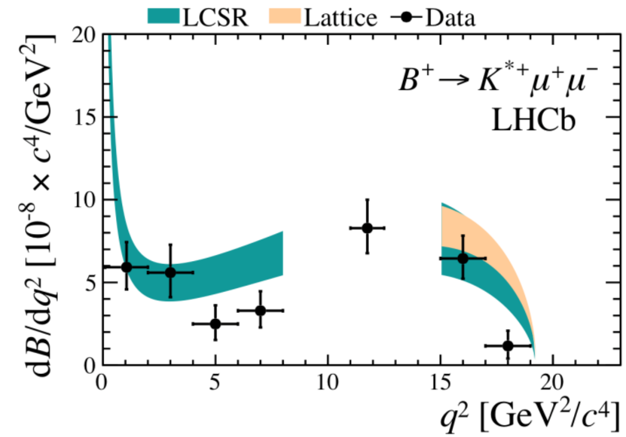
$B^+ \to K^+ \mu\mu$



$B^0 \to K^0 \mu\mu$

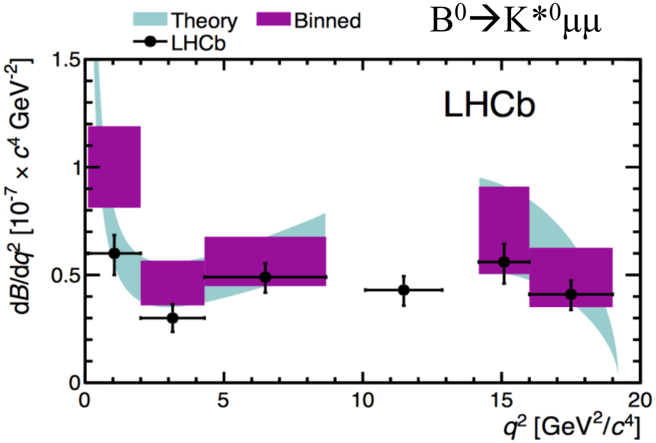


$B^0 \to K^{*+} \mu\mu$



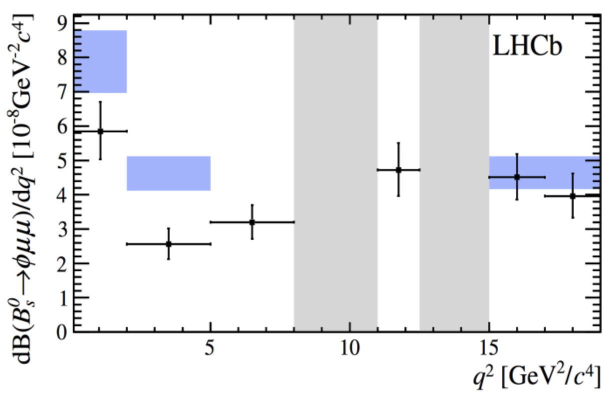
1 fb^{-1}, arXiv:1304.6325

$B^0 \to K^{*0} \mu\mu$



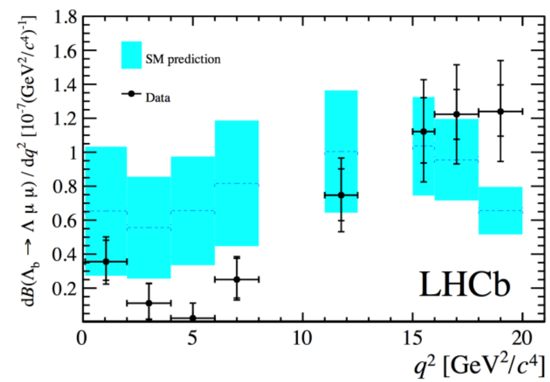
3 fb^{-1}, LHCB-2015-023

$B_s^0 \to \phi\mu\mu$



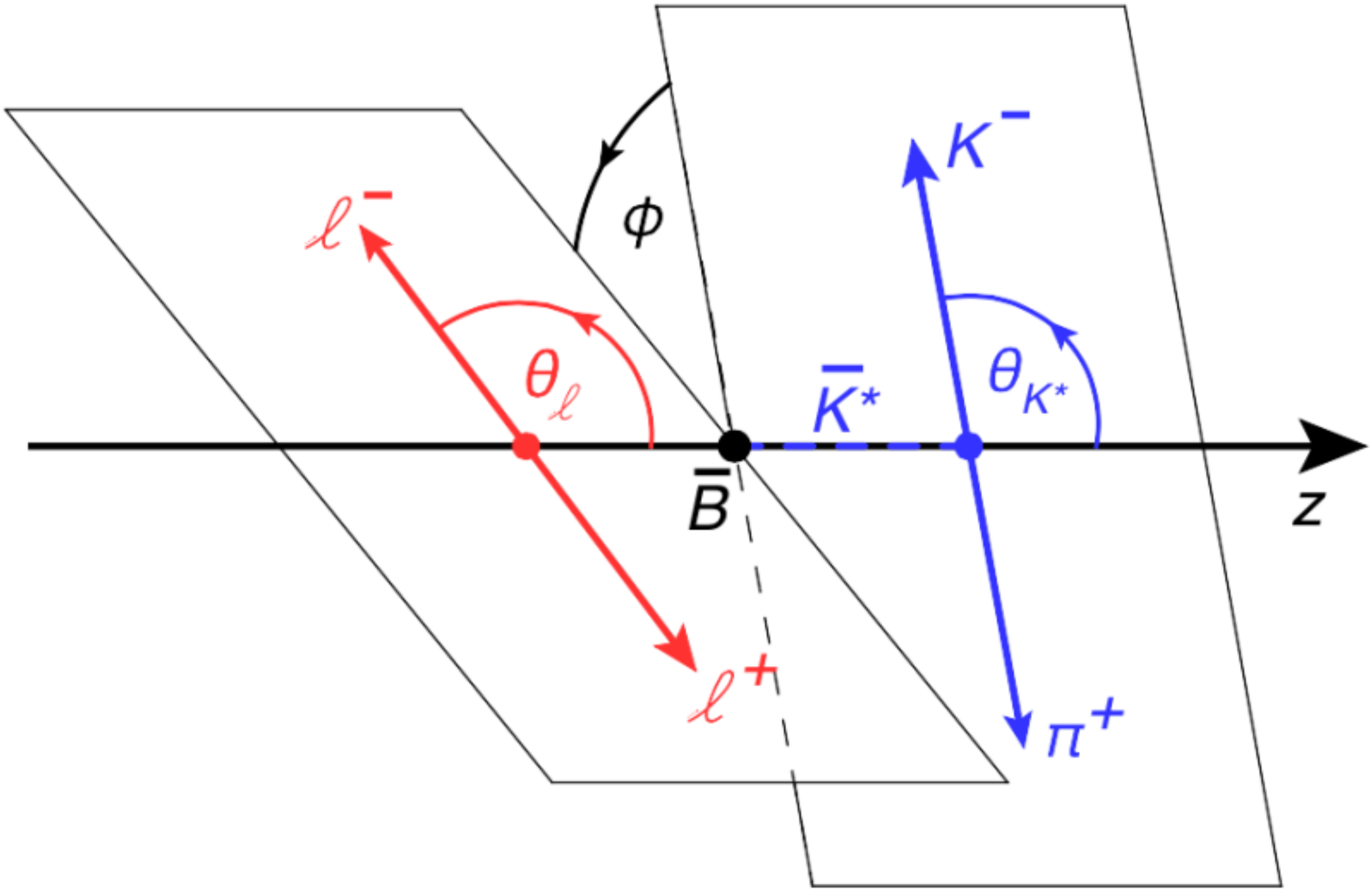
3 fb^{-1}, arXiv:1503.07138

$\Lambda_b^0 \to \Lambda\mu\mu$

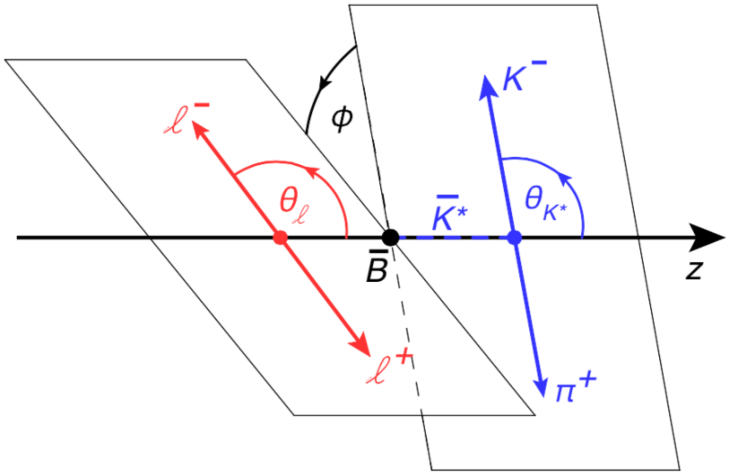


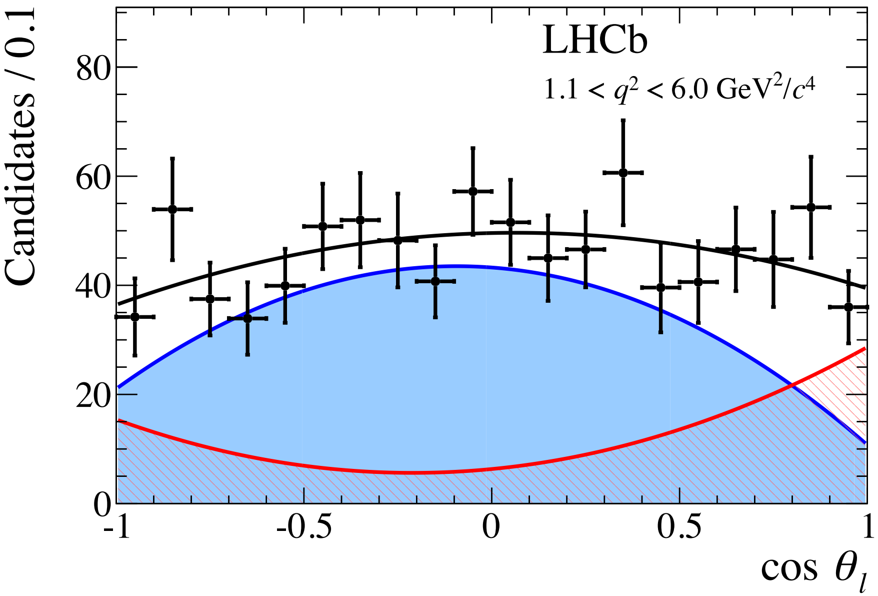
➢ Lower BRs consistent with modified C_9, it seems

2) Angular analysis $B^0 \rightarrow K^*\mu\mu$

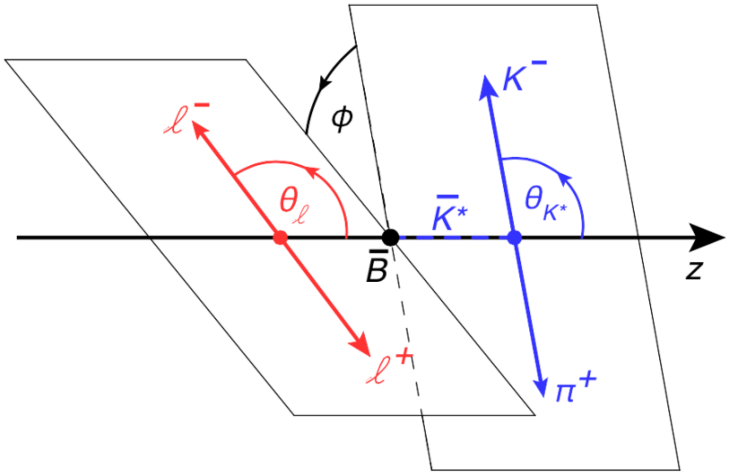


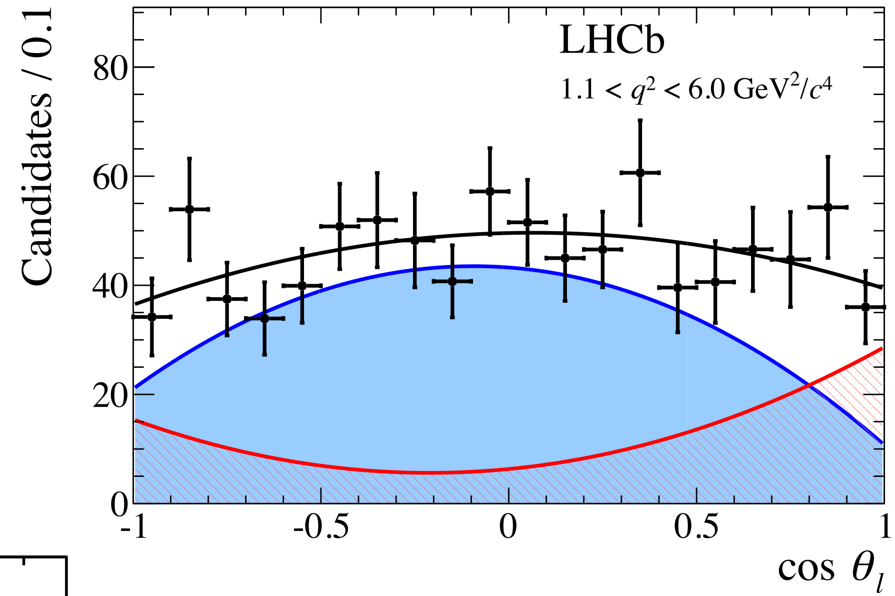
2) Angular analysis $B^0 \to K^*\mu\mu$

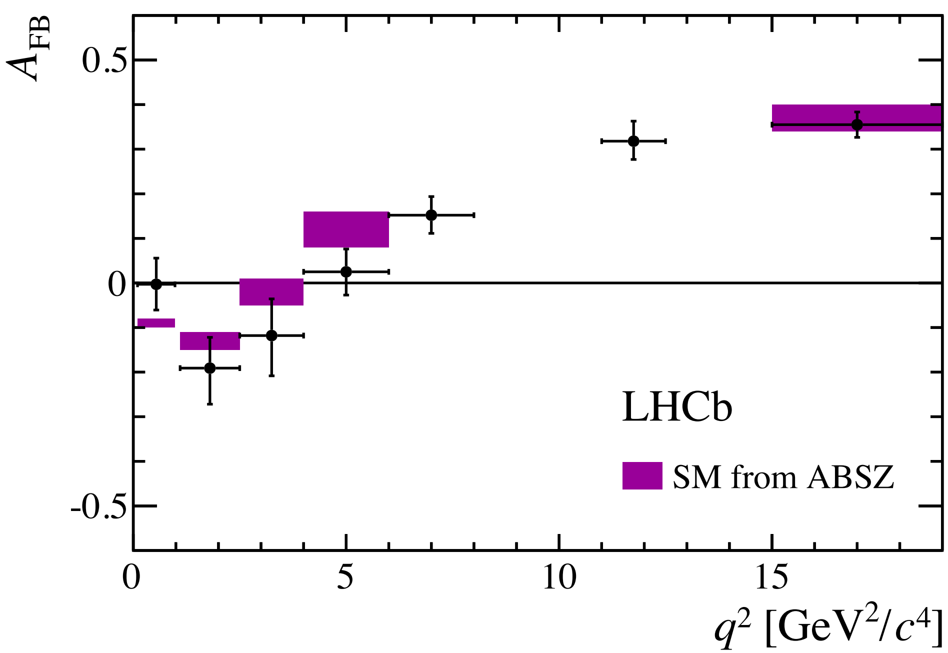




2) Angular analysis $B^0 \to K^*\mu\mu$

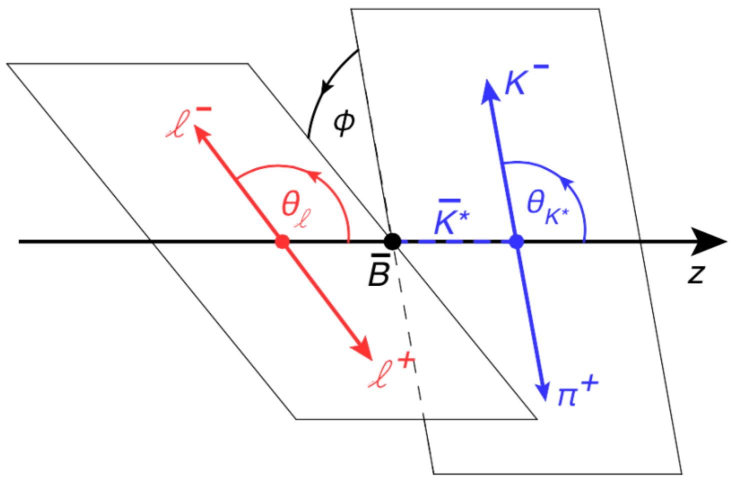


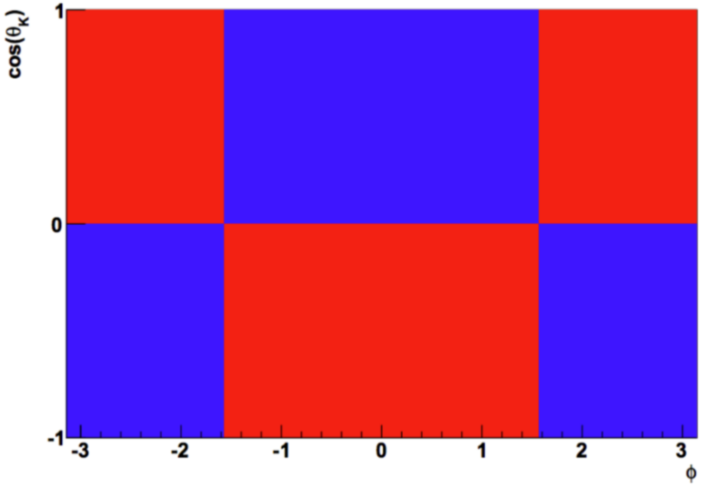




fb^{-1}, LHCb arXiv:1512.04442

2) Angular analysis $B^0 \to K^*\mu\mu$

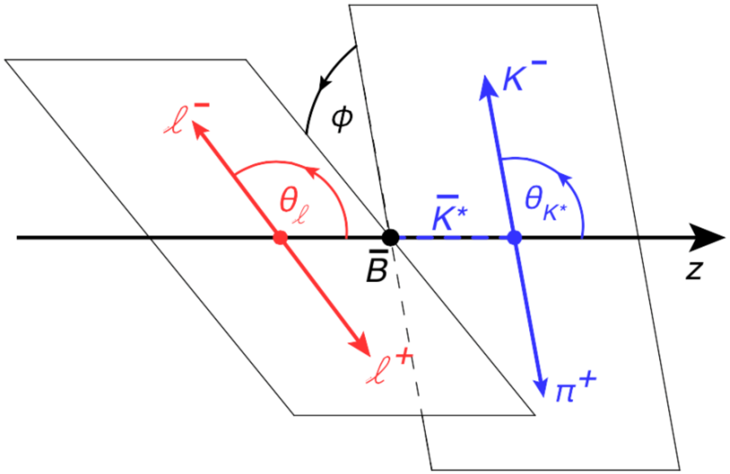


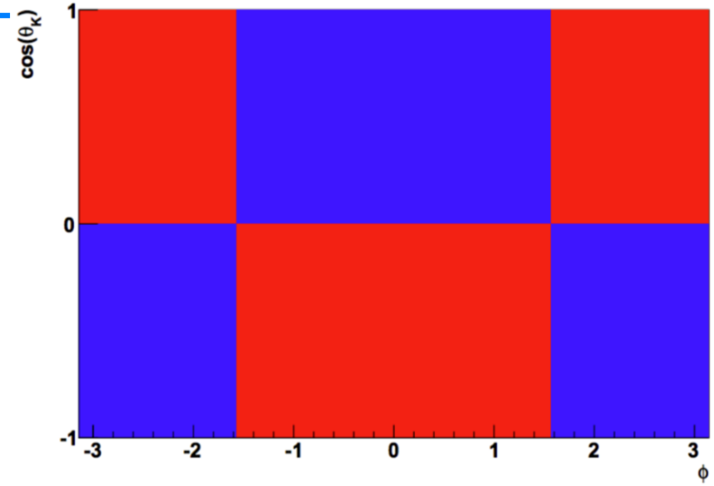


Counting S_5: blue minus red

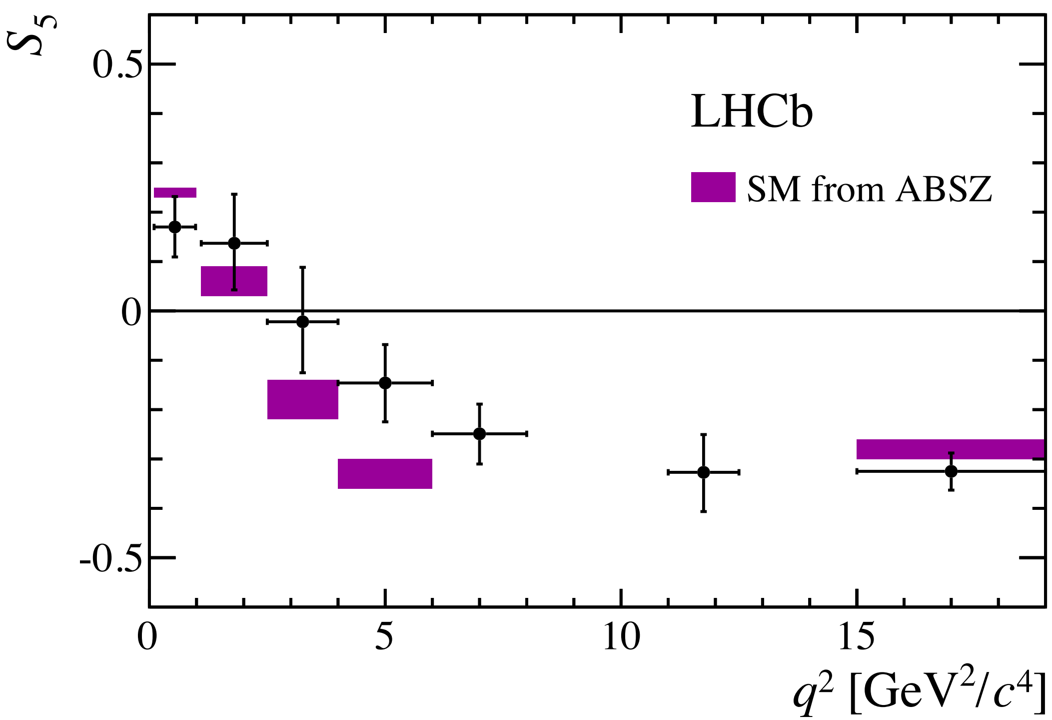
Such a mix of events can hardly cause an artificial experimental asymmetry…

2) Angular analysis $B^0 \to K^*\mu\mu$



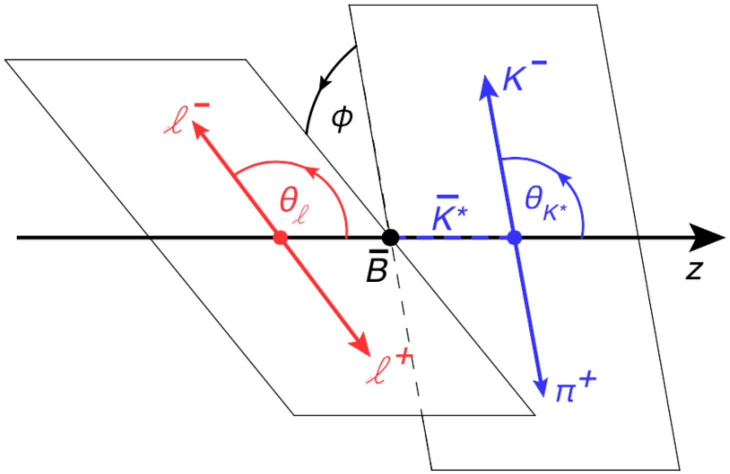


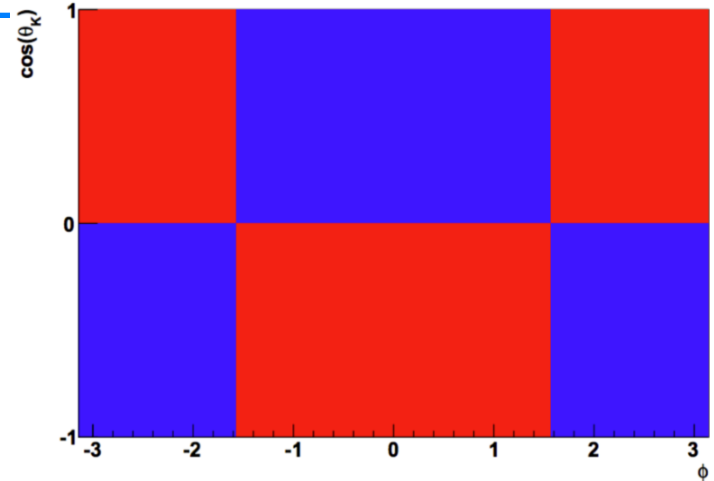
Counting S_5: blue minus red



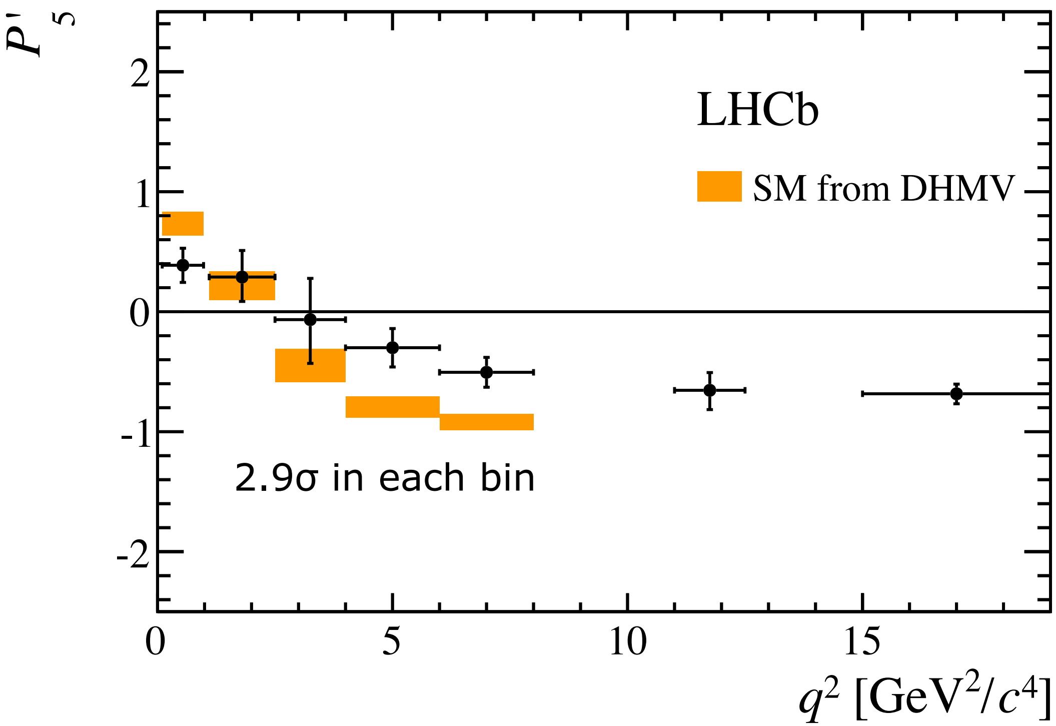
Such a mix of events can hardly cause an artificial experimental asymmetry…

2) Angular analysis $B^0 \to K^*\mu\mu$





Counting S_5: blue minus red

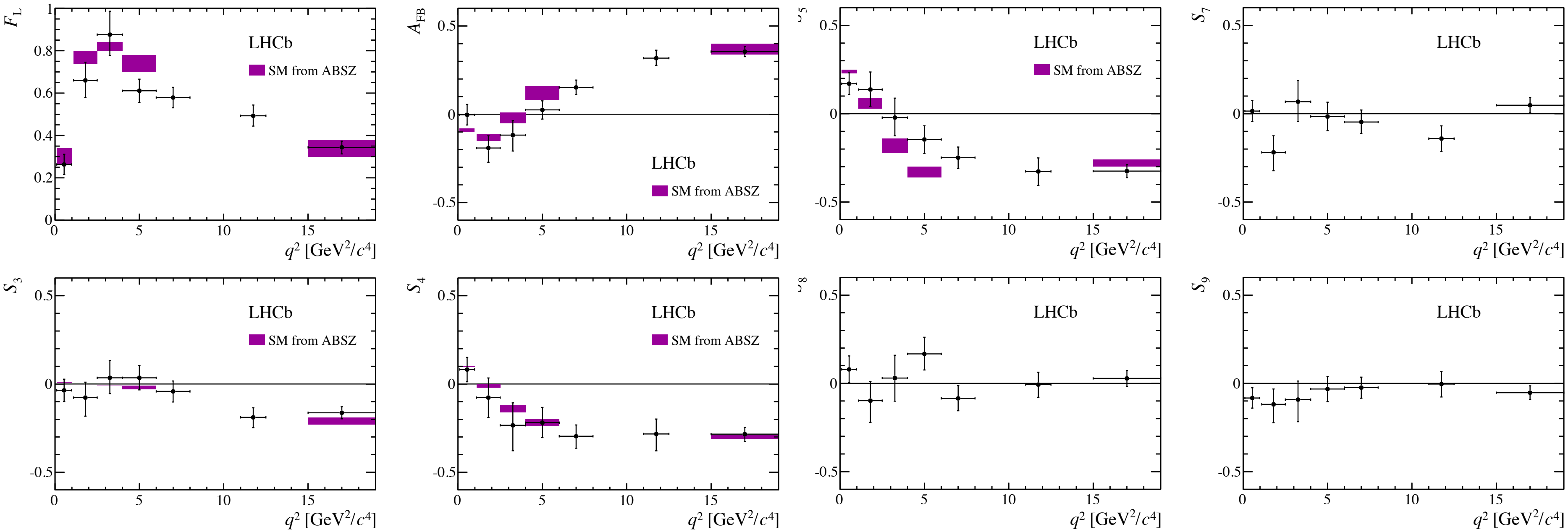


Such a mix of events can hardly cause an artificial experimental asymmetry…

$$P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_L(1-F_L)}}$$

$B^0 \rightarrow K^*\mu\mu$

- Many observable, many measurements…



$B^0 \rightarrow K^*\mu\mu$

- Many observable, many measurements
- ➢ No wonder there is some deviation somewhere?!

Fit

Road to discovery: Wilson coefficients

Theory

(What are Wilson coefficients?)

↓

Measurements

(of Wilson coefficients)

↓

Fit

(i.e. determine Wilson coefficients)

↓

Interpretation

(which models correspond to theses Wilson coefficients?)

Fit to b→sμμ

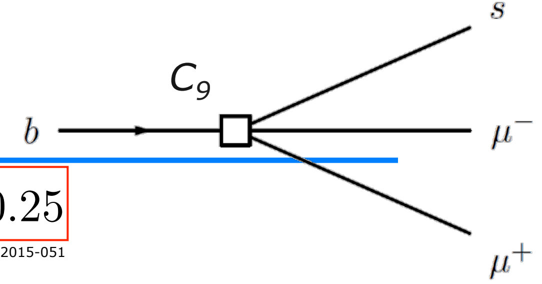
- Agreement of various measurements:

Decay	obs.	q^2 bin	SM pred.	measurement		pull
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[2, 4.3]$	0.81 ± 0.02	0.26 ± 0.19	ATLAS	$+2.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[4, 6]$	0.74 ± 0.04	0.61 ± 0.06	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	S_5	$[4, 6]$	-0.33 ± 0.03	-0.15 ± 0.08	LHCb	-2.2
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	P_5'	$[1.1, 6]$	-0.44 ± 0.08	-0.05 ± 0.11	LHCb	-2.9
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	P_5'	$[4, 6]$	-0.77 ± 0.06	-0.30 ± 0.16	LHCb	-2.8
$B^- \to K^{*-}\mu^+\mu^-$	$10^7\ \frac{d\text{BR}}{dq^2}$	$[4, 6]$	0.54 ± 0.08	0.26 ± 0.10	LHCb	$+2.1$
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8\ \frac{d\text{BR}}{dq^2}$	$[0.1, 2]$	2.71 ± 0.50	1.26 ± 0.56	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8\ \frac{d\text{BR}}{dq^2}$	$[16, 23]$	0.93 ± 0.12	0.37 ± 0.22	CDF	$+2.2$
$B_s \to \phi\mu^+\mu^-$	$10^7\ \frac{d\text{BR}}{dq^2}$	$[1, 6]$	0.48 ± 0.06	0.23 ± 0.05	LHCb	$+3.1$

Table 1: Observables where a single measurement deviates from the SM by 1.9σ or more (cf. [15] for the $B \to K^*\mu^+\mu^-$ predictions at low q^2).

Altmannshofer & Straub, arXiv:1503.06199

Fit to b→sμμ

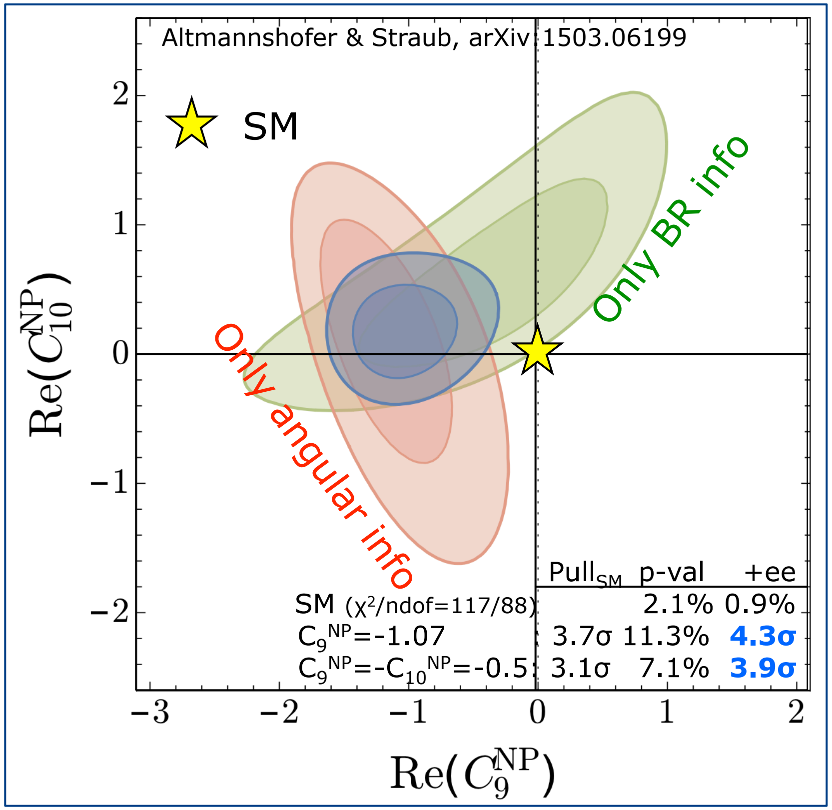


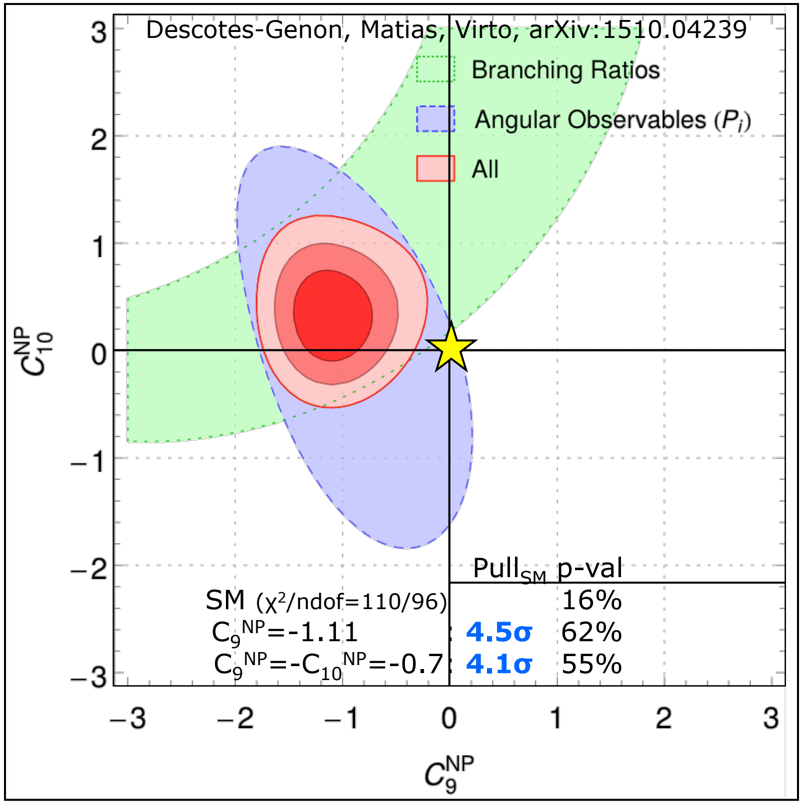
- C_9^{NP} deviates from 0 by >4σ

$$\Delta\mathrm{Re}(\mathcal{C}_9) = -1.04 \pm 0.25$$

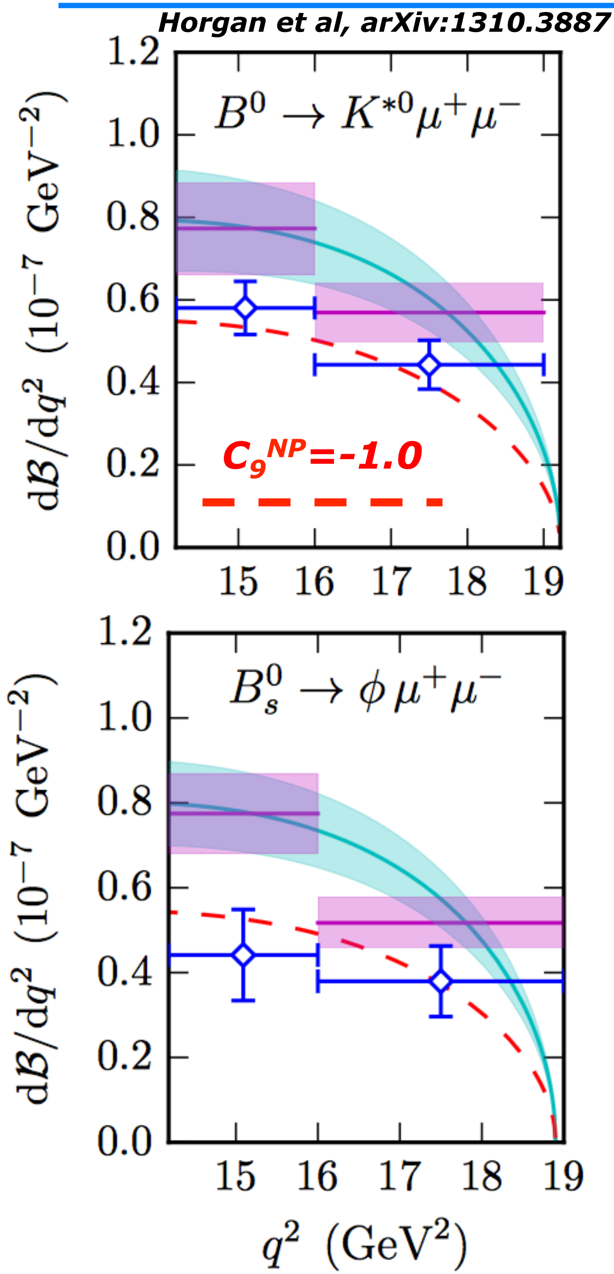
LHCb-PAPER-2015-051

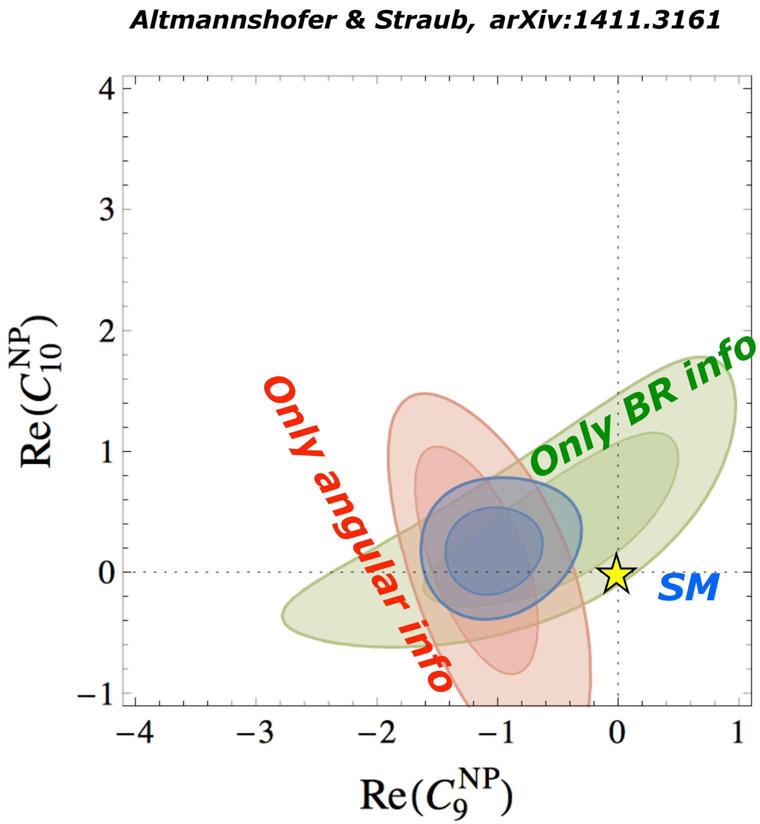
- Caveat: debate on non-pertirbative charm-loop effects





BR($b \rightarrow s\mu\mu$) vs P5′ in $B^0 \rightarrow K^*\mu\mu$





- Low BR points in same direction as angular observables

Fit to b→sμμ

- Fit could be better if SM is not imposed…:

	Coeff.	best fit	1σ	2σ	$\sqrt{\chi^2_{\text{b.f.}} - \chi^2_{\text{SM}}}$	p [%]
	C_7^{NP}	-0.04	$[-0.07, -0.01]$	$[-0.10, 0.02]$	1.42	2.4
	C_7'	0.01	$[-0.04, 0.07]$	$[-0.10, 0.12]$	0.24	1.8
V:	C_9^{NP}	-1.07	$[-1.32, -0.81]$	$[-1.54, -0.53]$	3.70	11.3
	C_9'	0.21	$[-0.04, 0.46]$	$[-0.29, 0.70]$	0.84	2.0
	C_{10}^{NP}	0.50	$[0.24, 0.78]$	$[-0.01, 1.08]$	1.97	3.2
	C_{10}'	-0.16	$[-0.34, 0.02]$	$[-0.52, 0.21]$	0.87	2.0
V+A:	$C_9^{\text{NP}} = C_{10}^{\text{NP}}$	-0.22	$[-0.44, 0.03]$	$[-0.64, 0.33]$	0.89	2.0
V-A:	$C_9^{\text{NP}} = -C_{10}^{\text{NP}}$	-0.53	$[-0.71, -0.35]$	$[-0.91, -0.18]$	3.13	7.1
	$C_9' = C_{10}'$	-0.10	$[-0.36, 0.17]$	$[-0.64, 0.43]$	0.36	1.8
	$C_9' = -C_{10}'$	0.11	$[-0.01, 0.22]$	$[-0.12, 0.33]$	0.93	2.0

Table 2: Constraints on individual Wilson coefficients, assuming them to be real, in the global fit to 88 $b \to s\mu^+\mu^-$ measurements. The p values in the last column should be compared to the p value of the SM, 2.1%.

Altmannshofer & Straub, arXiv:1503.06199

Fit to b→sμμ

- Fit could be better if SM is not imposed...:

	Coefficient	Best fit	3σ	Pull_{SM}	p-value (%)
	SM	–	–	–	16.0
	$\mathcal{C}_7^{\text{NP}}$	-0.02	$[-0.07, 0.03]$	1.2	17.0
V:	$\mathcal{C}_9^{\text{NP}}$	-1.09	$[-1.67, -0.39]$	**4.5**	63.0
	$\mathcal{C}_{10}^{\text{NP}}$	0.56	$[-0.12, 1.36]$	2.5	25.0
	$\mathcal{C}_{7'}^{\text{NP}}$	0.02	$[-0.06, 0.09]$	0.6	15.0
	$\mathcal{C}_{9'}^{\text{NP}}$	0.46	$[-0.36, 1.31]$	1.7	19.0
	$\mathcal{C}_{10'}^{\text{NP}}$	-0.25	$[-0.82, 0.31]$	1.3	17.0
V+A:	$\mathcal{C}_9^{\text{NP}} = \mathcal{C}_{10}^{\text{NP}}$	-0.22	$[-0.74, 0.50]$	1.1	16.0
V-A:	$\mathcal{C}_9^{\text{NP}} = -\mathcal{C}_{10}^{\text{NP}}$	-0.68	$[-1.22, -0.18]$	**4.2**	56.0
	$\mathcal{C}_{9'}^{\text{NP}} = \mathcal{C}_{10'}^{\text{NP}}$	-0.07	$[-0.86, 0.68]$	0.3	14.0
	$\mathcal{C}_{9'}^{\text{NP}} = -\mathcal{C}_{10'}^{\text{NP}}$	0.19	$[-0.17, 0.55]$	1.6	18.0
	$\mathcal{C}_9^{\text{NP}} = -\mathcal{C}_{9'}^{\text{NP}}$	-1.06	$[-1.60, -0.40]$	**4.8**	72.0

Descotes, Virto, Matias, arXiv:1510.04239

Fit to b→sμμ

- Fit could be better if SM is not imposed…:
- Leave 2 coefficients free in fit:

Coefficient	Best Fit Point	$\mathrm{Pull}_{\mathrm{SM}}$	p-value (%)
SM	–	–	16.0
$(\mathcal{C}_7^{\mathrm{NP}}, \mathcal{C}_9^{\mathrm{NP}})$	$(-0.00, -1.07)$	4.1	61.0
$(\mathcal{C}_9^{\mathrm{NP}}, \mathcal{C}_{10}^{\mathrm{NP}})$	$(-1.08, 0.33)$	4.3	67.0
$(\mathcal{C}_9^{\mathrm{NP}}, \mathcal{C}_{7'}^{\mathrm{NP}})$	$(-1.09, 0.02)$	4.2	63.0
$(\mathcal{C}_9^{\mathrm{NP}}, \mathcal{C}_{9'}^{\mathrm{NP}})$	$(-1.12, 0.77)$	**4.5**	72.0
$(\mathcal{C}_9^{\mathrm{NP}}, \mathcal{C}_{10'}^{\mathrm{NP}})$	$(-1.17, -0.35)$	**4.5**	71.0
$(\mathcal{C}_9^{\mathrm{NP}} = -\mathcal{C}_{9'}^{\mathrm{NP}}, \mathcal{C}_{10}^{\mathrm{NP}} = \mathcal{C}_{10'}^{\mathrm{NP}})$	$(-1.15, 0.34)$	**4.7**	75.0
$(\mathcal{C}_9^{\mathrm{NP}} = -\mathcal{C}_{9'}^{\mathrm{NP}}, \mathcal{C}_{10}^{\mathrm{NP}} = -\mathcal{C}_{10'}^{\mathrm{NP}})$	$(-1.06, 0.06)$	4.4	70.0

Descotes, Virto, Matias, arXiv:1510.04239

Fit to b→sμμ

- Fit could be better if SM is not imposed…:
- Leave 6 coefficients free in fit:

Coefficient	1σ	2σ	3σ
$\mathcal{C}_7^{\rm NP}$	$[-0.02, 0.03]$	$[-0.04, 0.04]$	$[-0.05, 0.08]$
$\mathcal{C}_9^{\rm NP}$	$[-1.4, -1.0]$	$[-1.7, -0.7]$	$[-2.2, -0.4]$
$\mathcal{C}_{10}^{\rm NP}$	$[-0.0, 0.9]$	$[-0.3, 1.3]$	$[-0.5, 2.0]$
$\mathcal{C}_{7'}^{\rm NP}$	$[-0.02, 0.03]$	$[-0.04, 0.06]$	$[-0.06, 0.07]$
$\mathcal{C}_{9'}^{\rm NP}$	$[0.3, 1.8]$	$[-0.5, 2.7]$	$[-1.3, 3.7]$
$\mathcal{C}_{10'}^{\rm NP}$	$[-0.3, 0.9]$	$[-0.7, 1.3]$	$[-1.0, 1.6]$

▷ $\mathcal{C}_9$ consistent with SM only above $3\,\sigma$.

Descotes, Virto, Matias, arXiv:1510.04239

Fit to b→sμμ

- Fit could be better if SM is not imposed…:

		R_K	$\langle P_5' \rangle_{[4,6],[6,8]}$	$BR(B_s \to \phi\mu\mu)$	low recoil BR
$\mathcal{C}_9^{\rm NP}$	$+$				
	$-$	✓	✓	✓	✓
$\mathcal{C}_{10}^{\rm NP}$	$+$	✓		✓	✓
	$-$		✓		
$\mathcal{C}_{9'}^{\rm NP}$	$+$			✓	✓
	$-$	✓	✓		
$\mathcal{C}_{10'}^{\rm NP}$	$+$	✓	✓		
	$-$			✓	✓

$\triangleright$ $\mathcal{C}_9 < 0$ consistent with all the anomalies

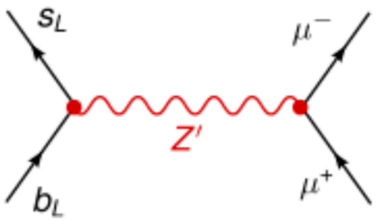
Virto, CKM2016

Interpretation?

(Both affect the vector coupling, C_9 ...)

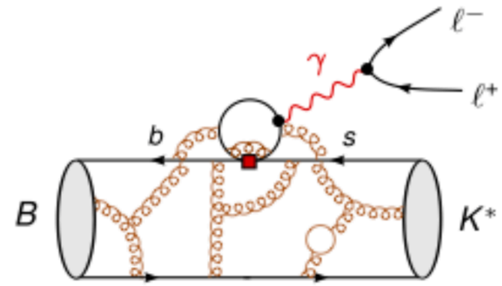
If the problem is charm, the effect should get larger closer the J/ψ.

Optimist's view point



Vector-like contribution could come from new tree level contribution from a Z' with a mass of a few TeV (the Z' will also contribute to mixing, a challenge for model builders)

Pessimist's view point

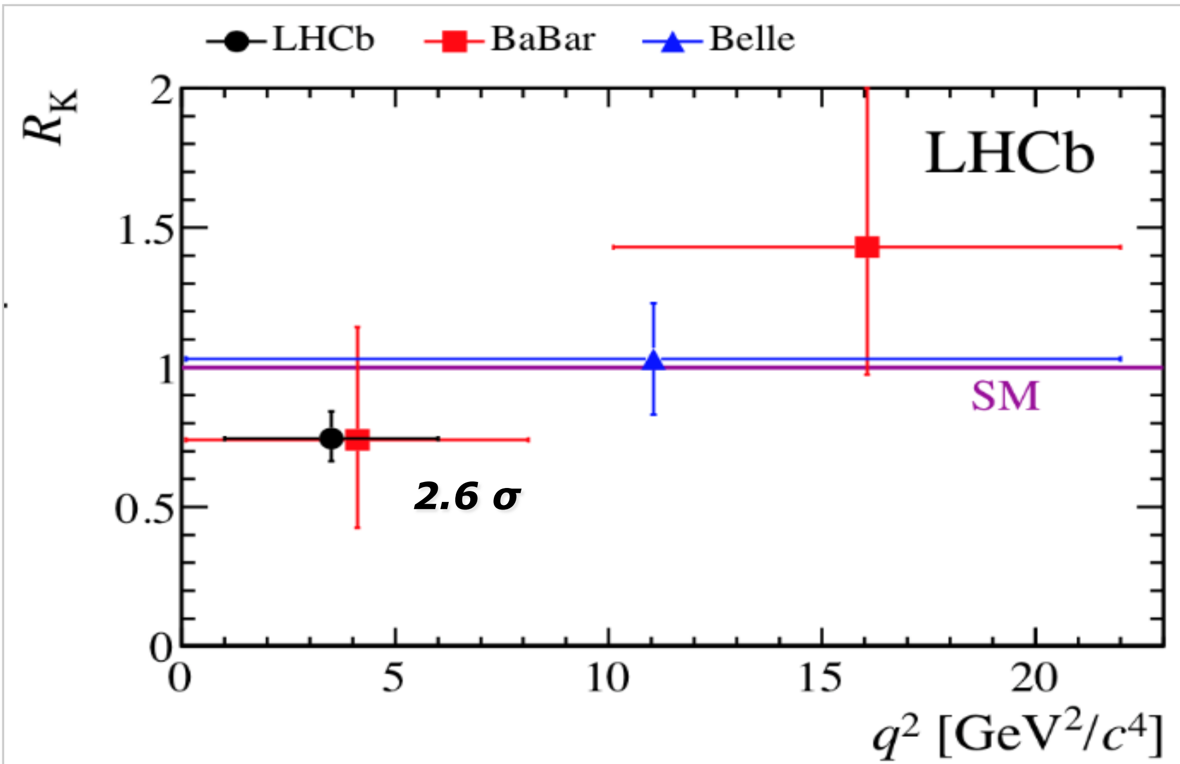


Vector-like contribution could point to a problem with our understanding of QCD, e.g. are we correctly estimating the contribution for charm loops that produce dimuon pairs via a virtual photon.

More work needed from experiment/theory to disentangle the two

3) $b \rightarrow sll$: Ratio of branching fractions

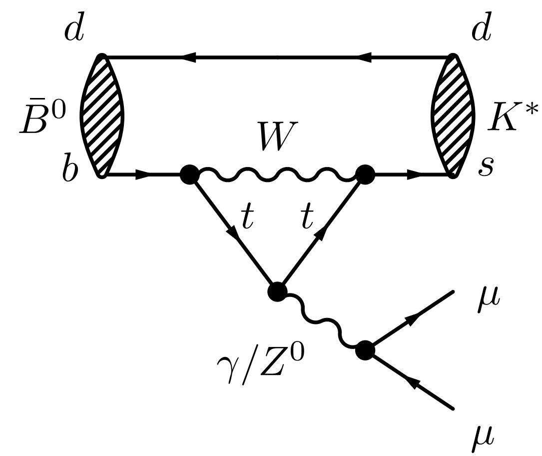
- FCNC: EW penguin

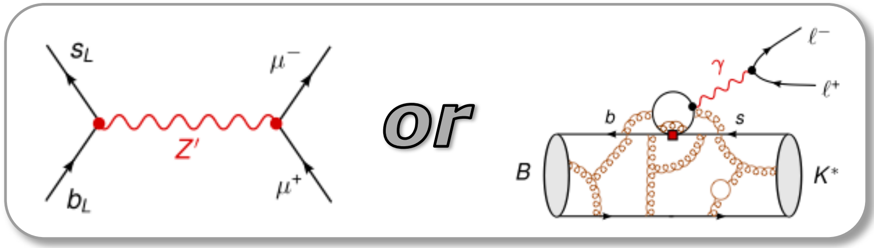


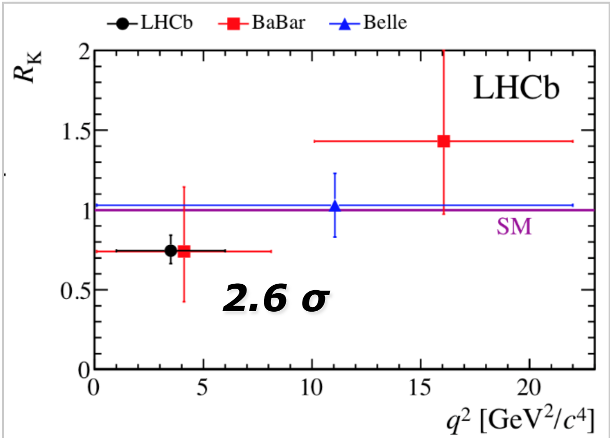
LHCb, PRL113 (2014) 151601

$b \to sll$: FCNC anomalies!?

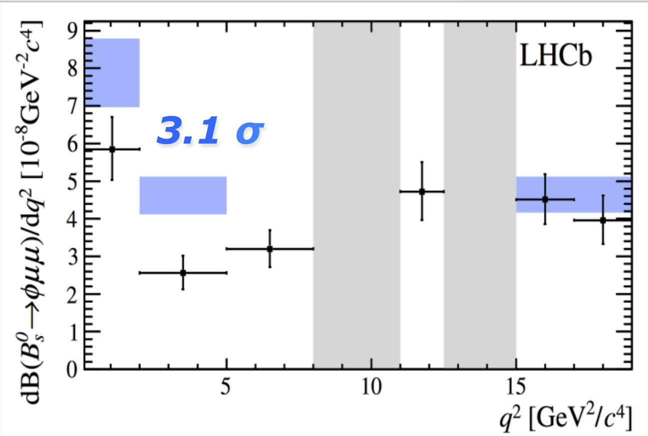
- FCNC: EW penguin
- Curious tensions:
  - Lepton flavour universality
  - Decay rates
  - Angular distributions, P_5'



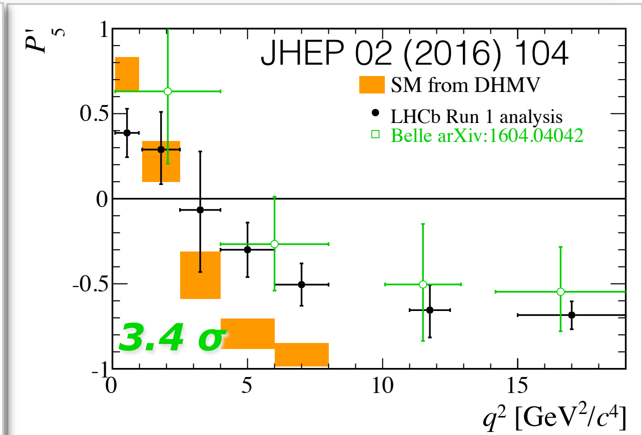




LHCb, PRL113 (2014) 151601



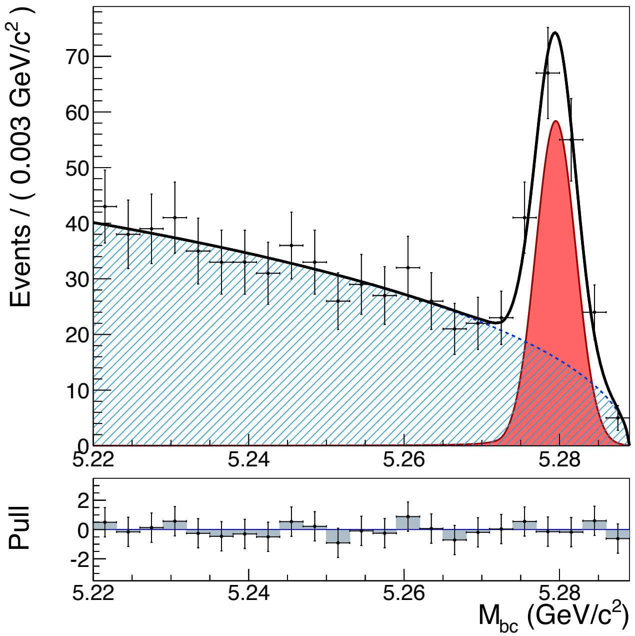
LHCb, JHEP 1509 (2015) 179



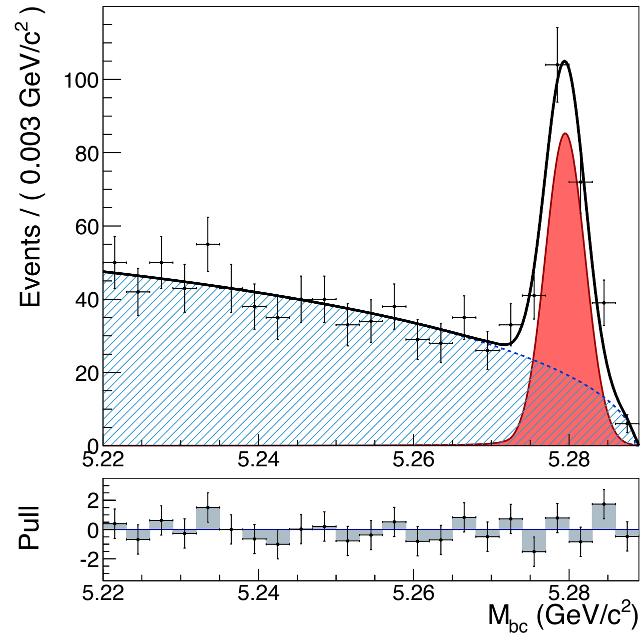
LHCb, JHEP 1602 (2016) 104

b→ sll : P5' and LFNU ?

➢ Belle: CKM workshop 2 weeks ago



$B^0 \to K^*(892)^0 e^+ e^-$
$B^+ \to K^*(892)^+ e^+ e^-$
127 ± 15 signal candidates



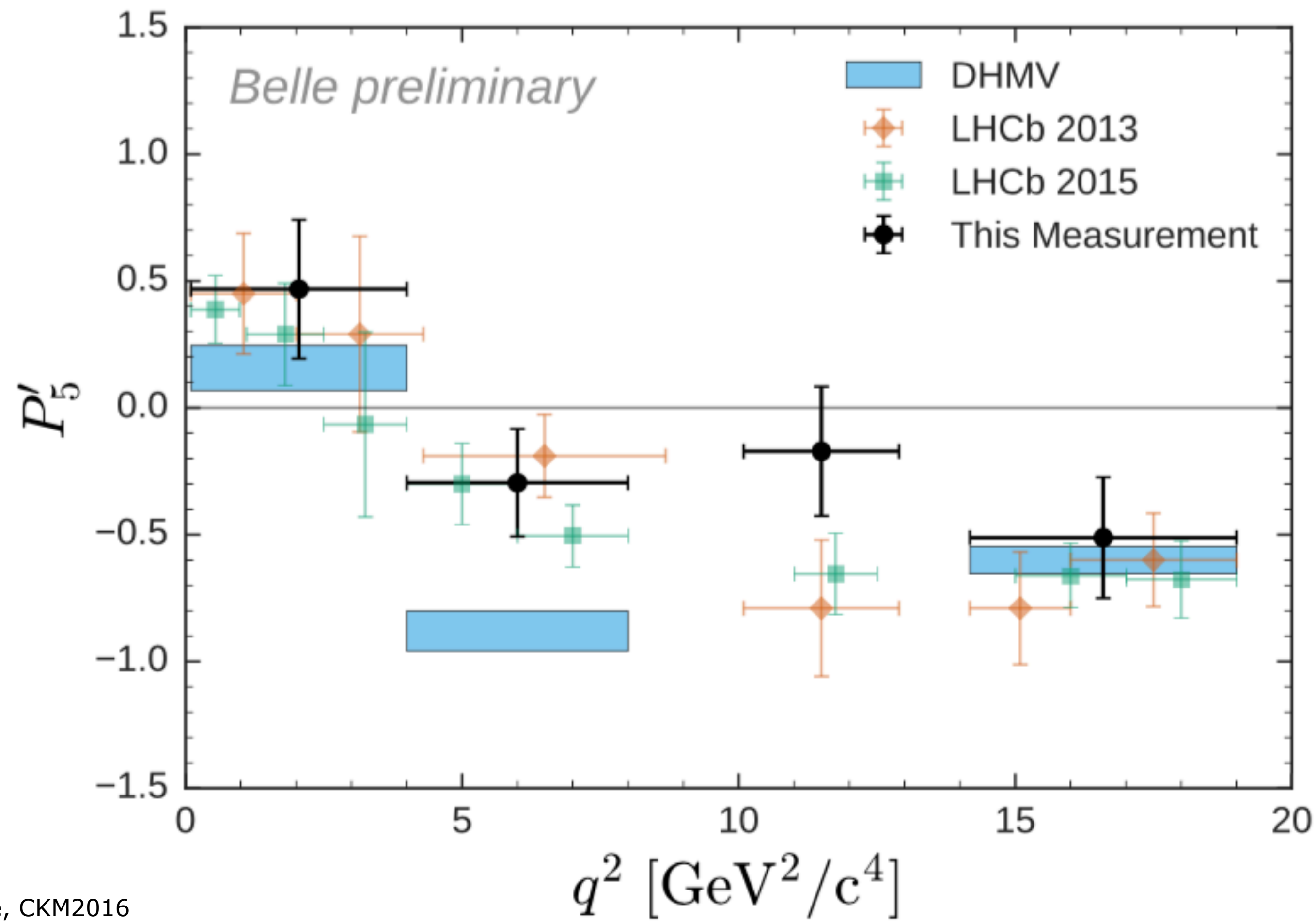
$B^0 \to K^*(892)^0 \mu^+ \mu^-$
$B^+ \to K^*(892)^+ \mu^+ \mu^-$
185 ± 17 signal candidates

Simon Wehle (Deutsches Elektronen-Synchrotron)

Wehle, CKM2016

b→ sll : P5′ and LFNU ?

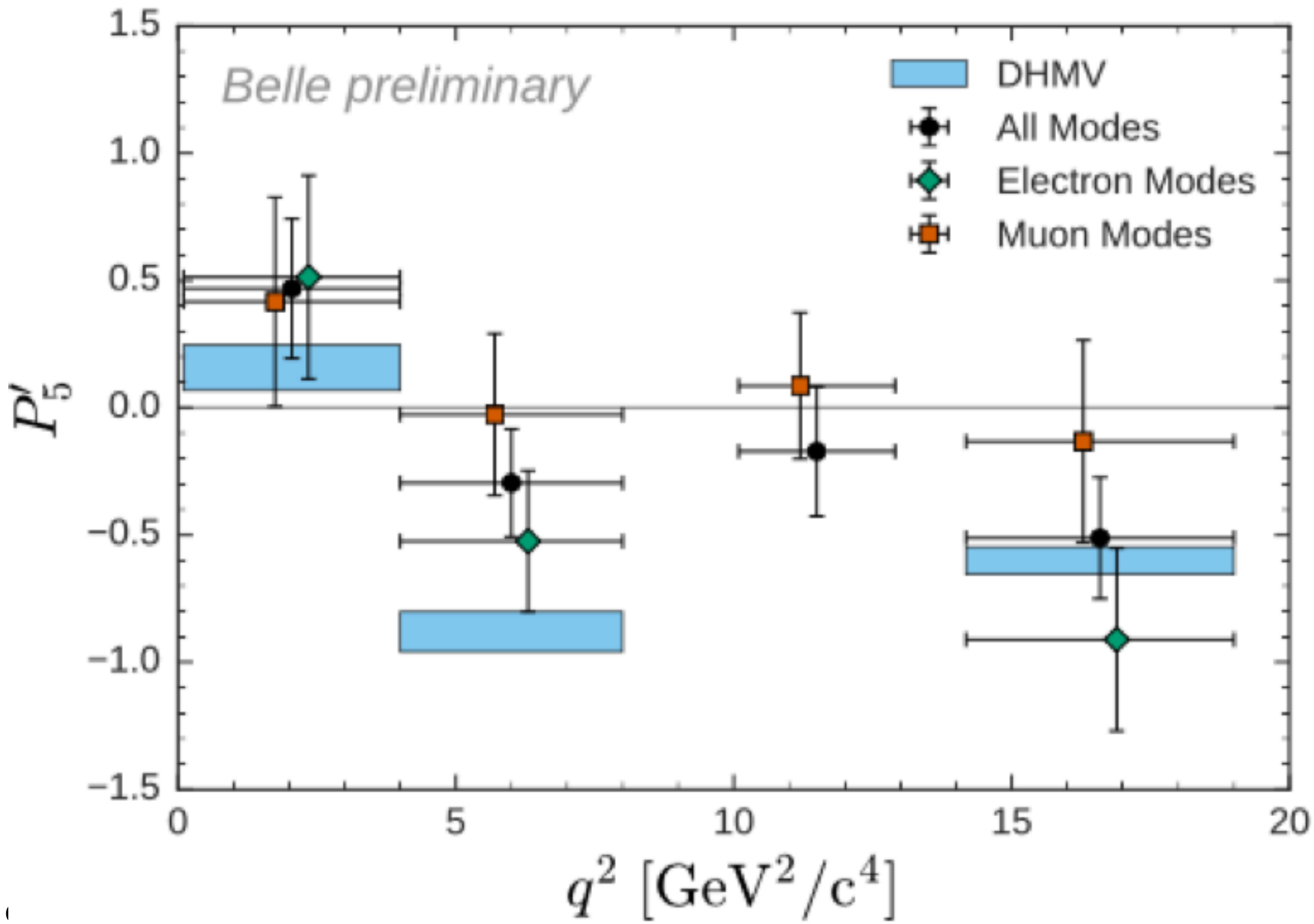
- Belle: CKM workshop 2 weeks ago
- Agreement with LHCb



Wehle, CKM2016

b→ sll : P5′ and LFNU ?

- Belle: CKM workshop 2 weeks ago
- e – μ difference …?!



Wehle, (

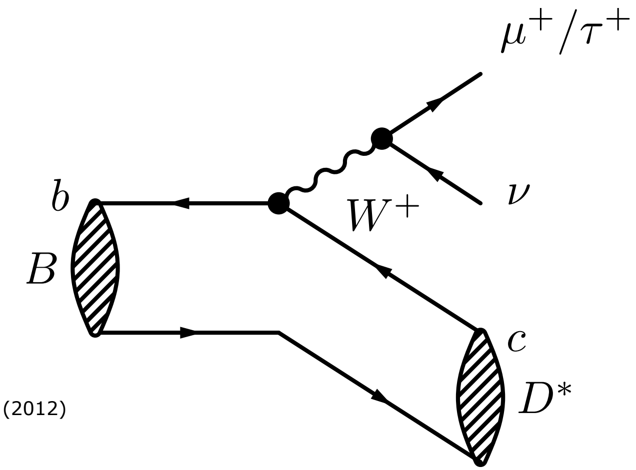
Lepton Flavour Non-Universality

- More?

Lepton-Flavour Non-Universality ?

- Surprises possible in tree-level decays?

- *B→ D*lν*
  - Measure ratio τ/μ :
  - SM: R(D*)=0.252±0.003 Fajfer, Kamenik, Nisandzic PRD 85, 094025 (2012)

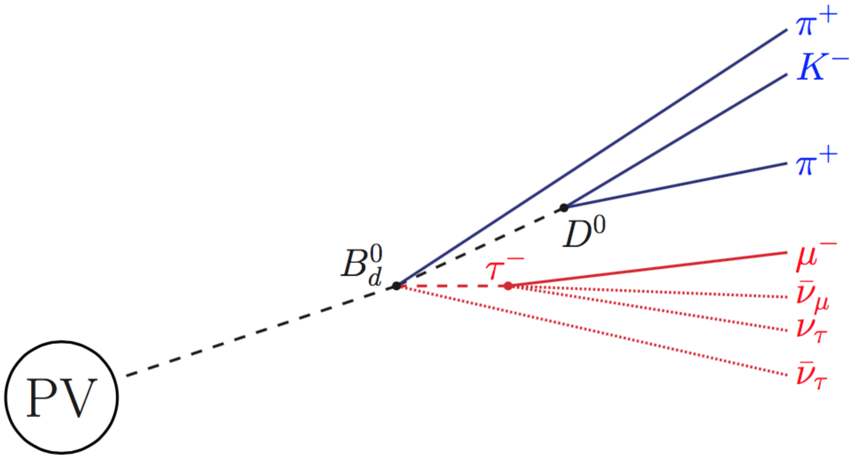


$$\boxed{\mathcal{R}(D^*) \equiv \mathcal{B}(\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau)/\mathcal{B}(\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu)}$$

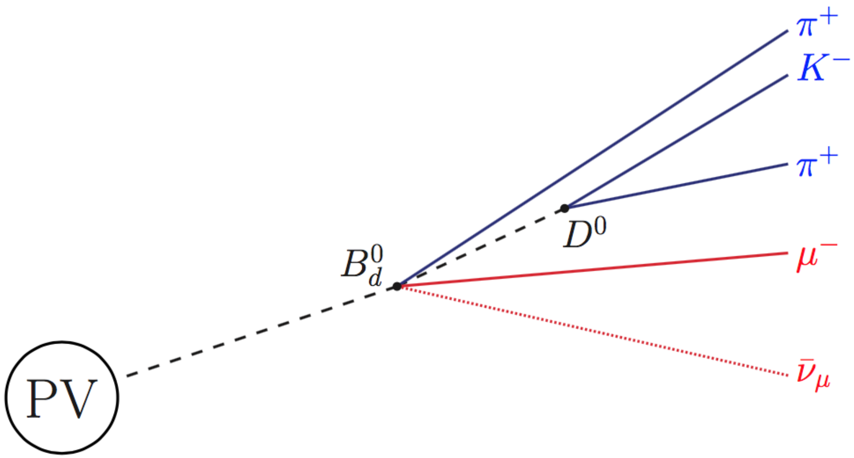
Lepton-Flavour Non-Universality ?

- Spot the differences …

$\overline{B}^0 \rightarrow D^{*+}\tau^-\overline{\nu}_\tau$



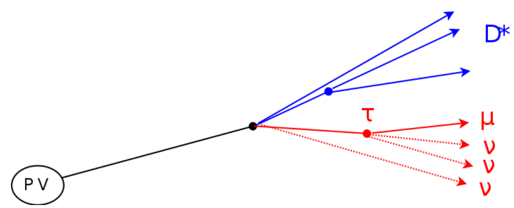
$\overline{B}^0 \rightarrow D^{*+}\mu^-\overline{\nu}_\mu$



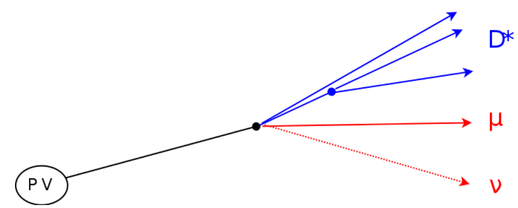
Lepton-Flavour Non-Universality ?

- Missing mass
- E_μ
- Result:

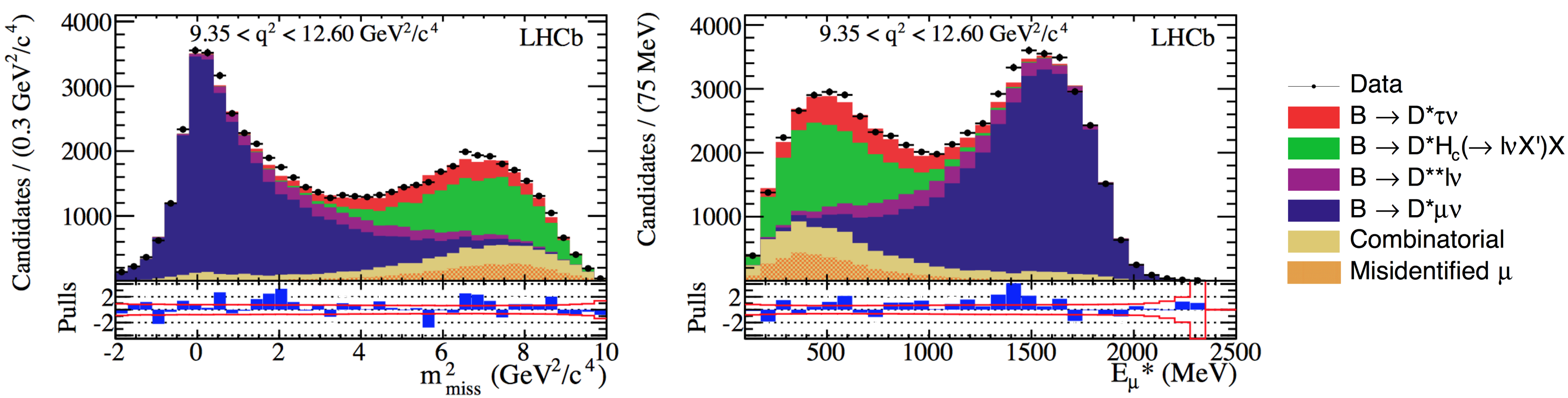
$B \to D^* \tau \nu$



$B \to D^* \mu \nu$



$$R(D^*) = 0.336 \pm 0.027 \pm 0.030$$



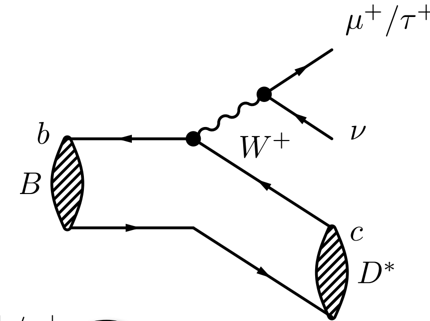
$$m^2_{\rm miss} = (p^\mu_B - p^\mu_D - p^\mu_\mu)^2$$

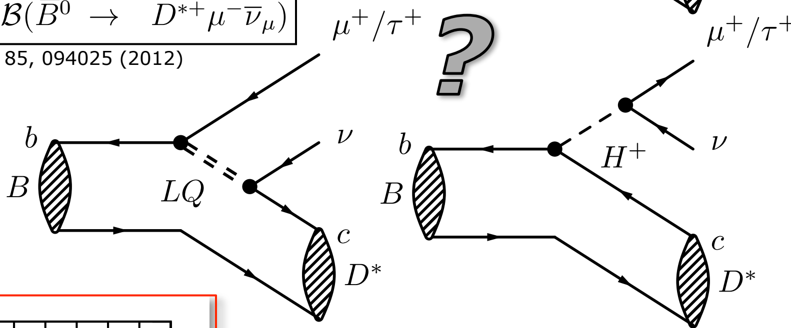
Energy of muon in B rest frame

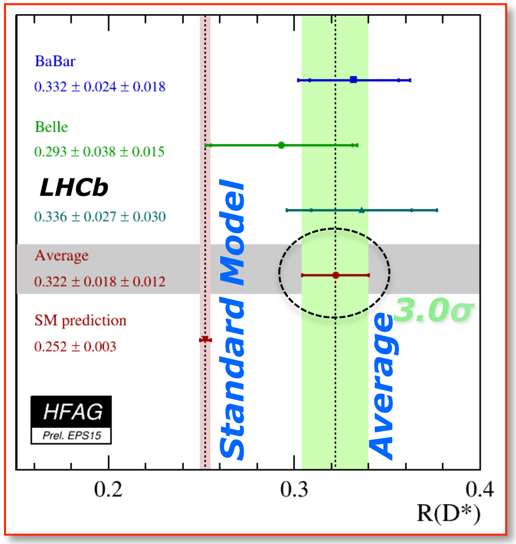
Lepton-Flavour Non-Universality

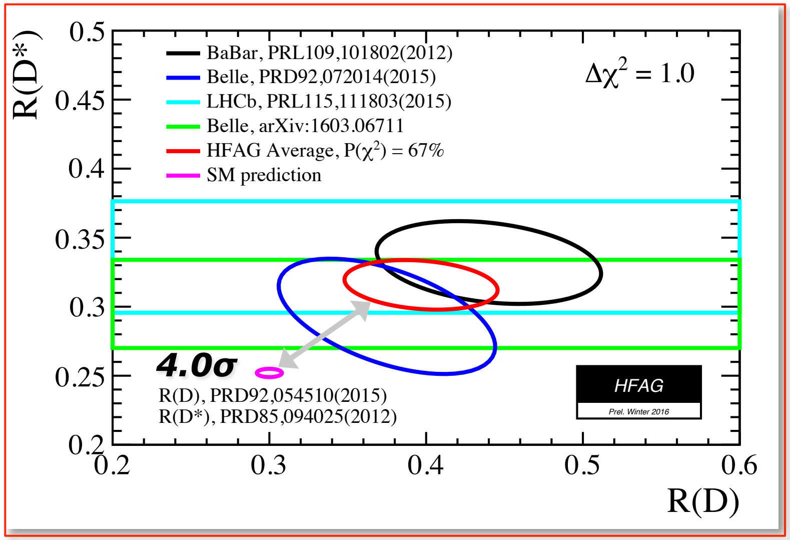
- Surprises possible in tree-level decays?
- There is more than "roadmap" channels with loops
- *B→ D*lν*
  - Measure ratio τ/μ : $\boxed{\mathcal{R}(D^*) \equiv \mathcal{B}(\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau)/\mathcal{B}(\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu)}$

    Fajfer, Kamenik, Nisandzic PRD 85, 094025 (2012)
  - SM: R(D*)=0.252±0.003
  - R(D) and R(D*) combined: 4.0σ









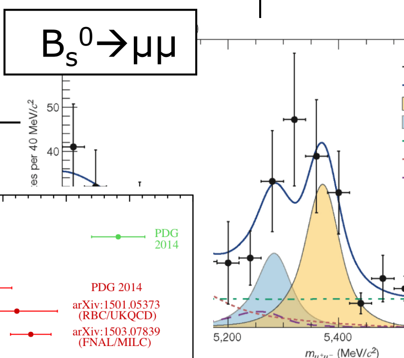
More Measurements

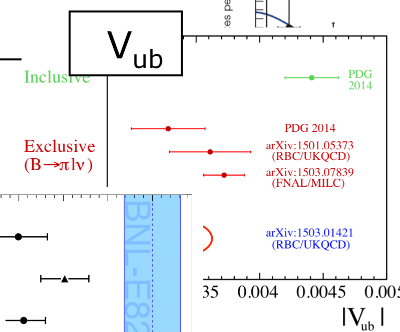
"Interesting" recent measurements at LHCb:

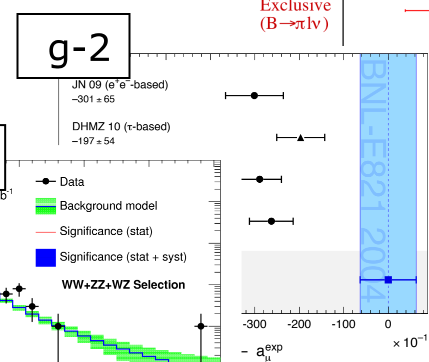
- ✓*R(D*) and R(D):* *Lepton universality $B \to D^{(*)}\tau\upsilon$ / $B \to D^{(*)}\mu\upsilon$*
- ✓R_K: *Lepton universality $B \to Kee$ / $B \to K\mu\mu$*
- ✓P_5': *Angular observable $B^0 \to K^*\mu\mu$*
- ✓$\Gamma(b \to s\,\mu\mu)$ *Decay rates of $B_{(s)} \to K(\varphi)\mu\mu$*

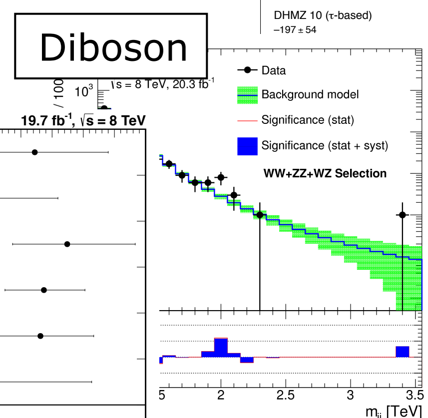
Other interesting measurements and constraints:

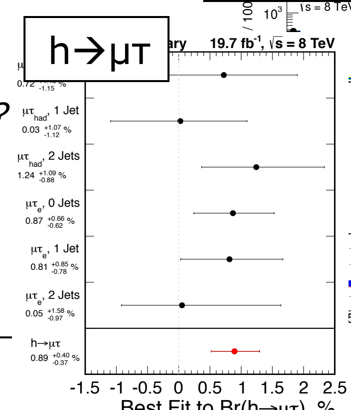
- ✓ $BR(B^0 \to \mu\mu)$: *high?*
- ✓V_{ub}: *incl vs excl:* *different?*
- ✓*g-2* *high?*
- ~~✓*Diboson resonance*~~ Diphoton *high?*
- ✓ $H \to \tau\mu$ *high?*
- ✓ ε'/ε *x10 high?*
- ❑ *B-mixing*
- ❑ $\tau \to \mu\mu\mu$
- ❑ $\mu \to e\gamma$











LHCb/CMS	Nature 522, 68 (2015)
LHCb	arXiv:1504.01568
BNL E821	PDG
ATLAS	arXiv:1506.00962
CMS	PAS-HIG-14-005

Other puzzles involving LFNU ?

- $W \to \tau\upsilon / W \to \mu\nu$:
  - 2.6 σ

$$\mathcal{B}(\mathrm{W} \to \mu\overline{\nu}_\mu) \,/\, \mathcal{B}(\mathrm{W} \to \mathrm{e}\overline{\nu}_\mathrm{e}) = 0.993 \pm 0.019\,, \tag{5.2}$$
$$\mathcal{B}(\mathrm{W} \to \tau\overline{\nu}_\tau) \,/\, \mathcal{B}(\mathrm{W} \to \mathrm{e}\overline{\nu}_\mathrm{e}) = 1.063 \pm 0.027\,, \tag{5.3}$$
$$\mathcal{B}(\mathrm{W} \to \tau\overline{\nu}_\tau) \,/\, \mathcal{B}(\mathrm{W} \to \mu\overline{\nu}_\mu) = 1.070 \pm 0.026\,. \tag{5.4}$$

The branching fraction of W into taus with respect to that into electrons and muons differs by more than two standard deviations, where the correlations have been taken into account. The branching fractions of W into electrons and into muons agree well. Assuming only partial lepton universality the ratio between the tau fractions and the average of electrons and muons can also be computed:

$$2\mathcal{B}(\mathrm{W} \to \tau\overline{\nu}_\tau) \,/\, (\mathcal{B}(\mathrm{W} \to \mathrm{e}\overline{\nu}_\mathrm{e}) + \mathcal{B}(\mathrm{W} \to \mu\overline{\nu}_\mu)) = 1.066 \pm 0.025 \tag{5.5}$$

resulting in an agreement at the level of 2.6 standard deviations only, with all correlations included.

LEP EW WG, arXiv:1302.3415

- g-2
  - 2.2 – 2.7 σ

$$a_\mu(\mathrm{Expt}) = 11\,659\,208.0(6.3) \times 10^{-10} \quad (0.54\,\mathrm{ppm}).$$

The difference

$$\Delta a_\mu(\mathrm{Expt} - \mathrm{SM}) = (22.4 \pm 10 \text{ to } 26.1 \pm 9.4) \times 10^{-10}, \tag{64}$$

has a significance of 2.2 to 2.7 standard deviations. Use of the τ-data gives a smaller discrepancy.

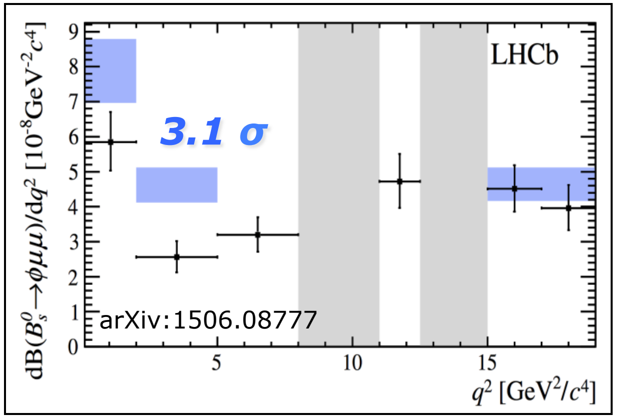
BNL, hep-ex/0602035

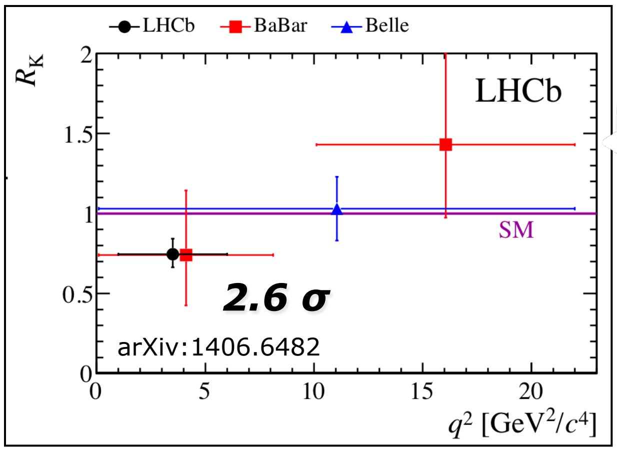
- Proton radius puzzle
  - 7 σ

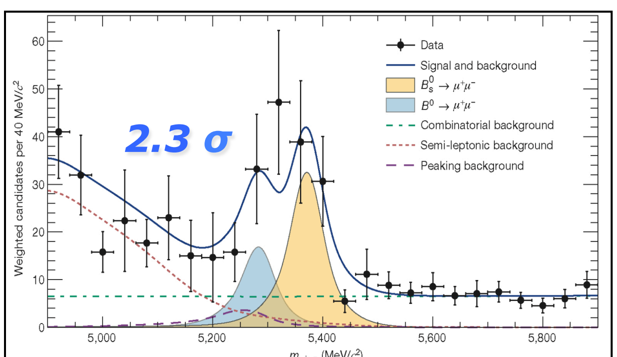
obtained value of 0.84087(39) fm differs by about 4% or 7 standard deviations from the CODATA [3] value of 0.8775(51) fm. The latter is composed from the

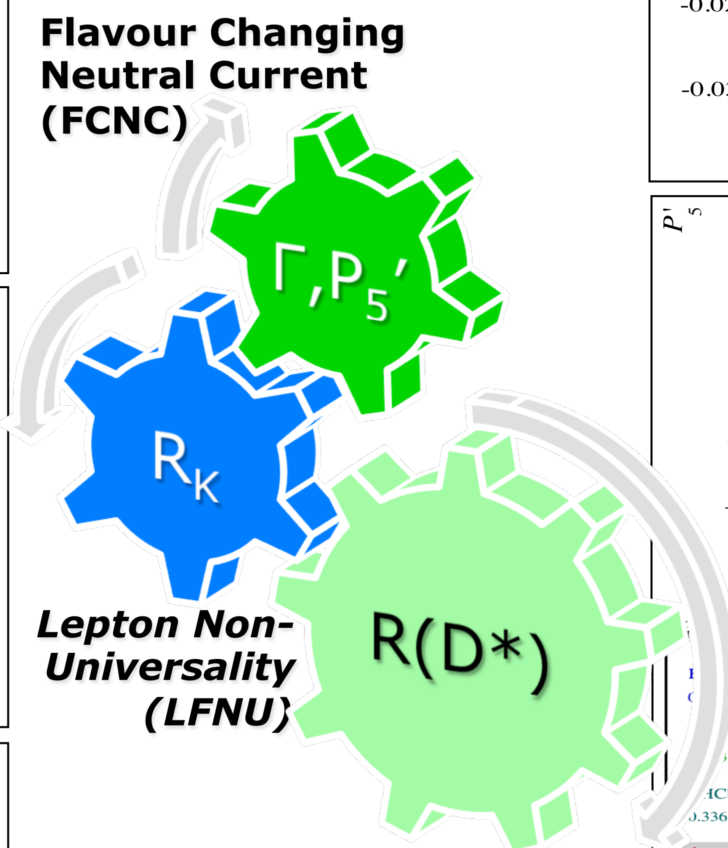
Pohl et al, arXiv:1301.0905

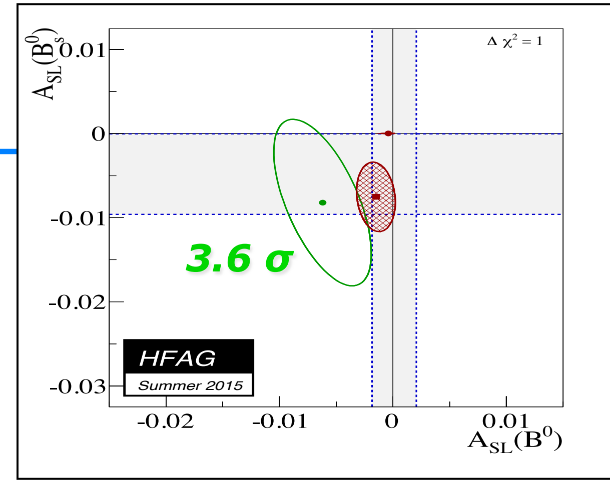
Tensions…?

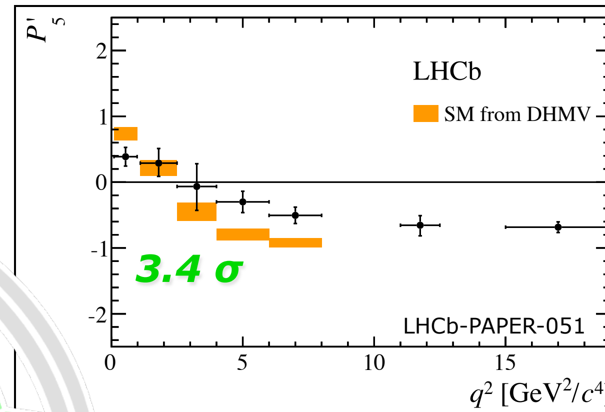

LHCb
3.1 σ
arXiv:1506.08777
$dB(B_s^0 \to \phi\mu\mu)/dq^2$ [10^{-8}GeV$^{-2}c^4$]
q^2 [GeV^2/c^4]

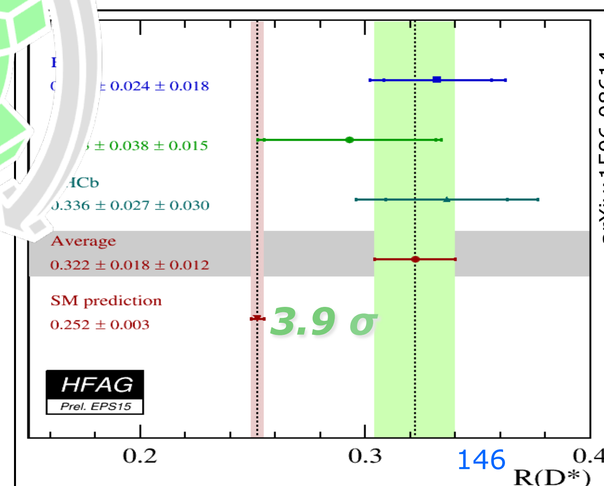

LHCb
BaBar
Belle
R_K
LHCb
SM
2.6 σ
arXiv:1406.6482
q^2 [GeV^2/c^4]


Data
Signal and background
$B_s^0 \to \mu^+\mu^-$
$B^0 \to \mu^+\mu^-$
Combinatorial background
Semi-leptonic background
Peaking background
2.3 σ
Weighted candidates per 40 MeV/c^2
$m_{\mu^+\mu^-}$ (MeV/c^2)


Flavour Changing Neutral Current (FCNC)
Γ,P5′
RK
R(D*)
Lepton Non-Universality (LFNU)


$\Delta\chi^2 = 1$
$A_{SL}(B_s^0)$
3.6 σ
HFAG
Summer 2015
$A_{SL}(B^0)$


P'_5
LHCb
SM from DHMV
3.4 σ
LHCb-PAPER-051
q^2 [GeV^2/c^4]


± 0.024 ± 0.018
± 0.038 ± 0.015
0.336 ± 0.027 ± 0.030
Average
0.322 ± 0.018 ± 0.012
SM prediction
0.252 ± 0.003
3.9 σ
HFAG
Prel. EPS15
R(D*)
arXiv:1506.08614

End

Thank you

http://www.foksuk.nl/

Road to discovery: Wilson coefficients

Theory

(What are Wilson coefficients?)

↓

Measurements

(of Wilson coefficients)

↓

Fit

(i.e. determine Wilson coefficients)

↓

Interpretation

(which models correspond to theses Wilson coefficients?)

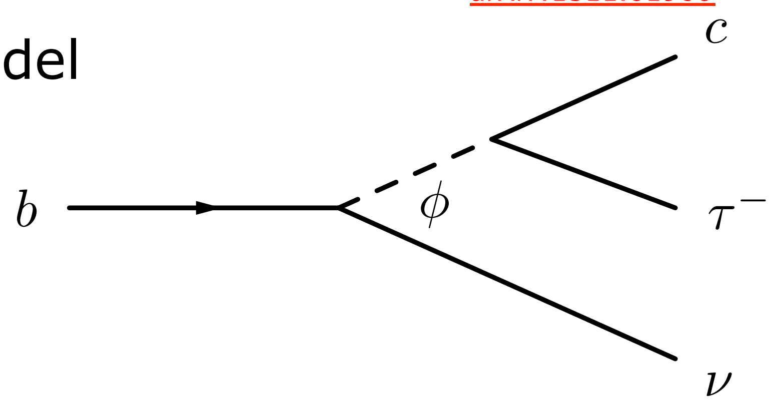
Theory: 1) Leptoquarks

One Leptoquark to Rule Them All:
A Minimal Explanation for $R_{D^{(*)}}$, R_K and $(g-2)_\mu$

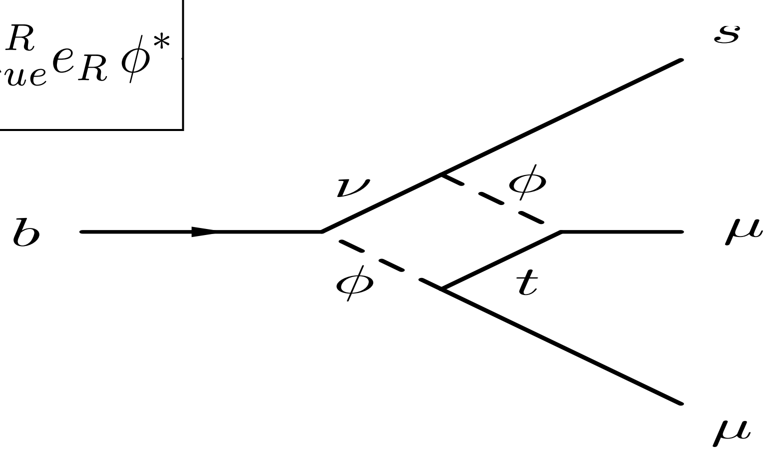
Martin Bauer[a] and Matthias Neubert[b,c]

arXiv:1511.01900

- Example: "Bauer/Neubert" model
  - Leptoquark m_Δ ~ 1 TeV
  - g-2
  - R(D*)
  - R_K
  - b→c : tree level, b→s : loop level



$$\boxed{\mathcal{L}_\phi \ni \bar{u}_L^c \boldsymbol{\lambda}_{ue}^L e_L\, \phi^* - \bar{d}_L^c \boldsymbol{\lambda}_{d\nu}^L \nu_L \phi^* + \bar{u}_R^c\, \boldsymbol{\lambda}_{ue}^R e_R\, \phi^*}$$



- Predictions:
  - 1σ effects on BR(Z→*μμ)*
  - B-mixing affected
  - (BR(*h*→*τμ)*~10^{-7})

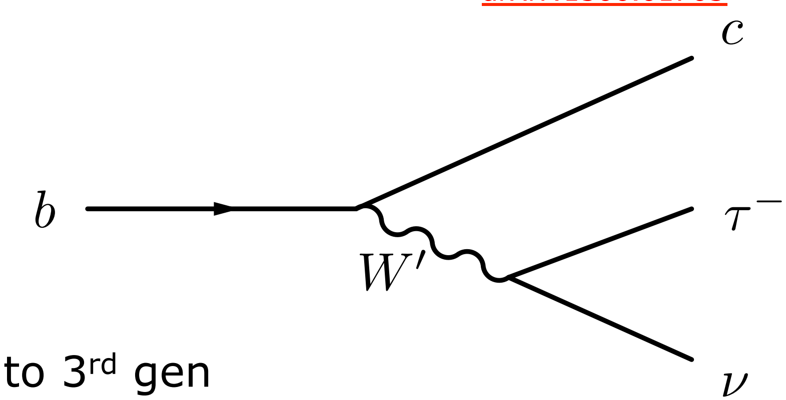
Theory: 2) heavy Z’

On the breaking of Lepton Flavor Universality in B decays

Admir Greljo[a,b], Gino Isidori[a,c], David Marzocca[a]

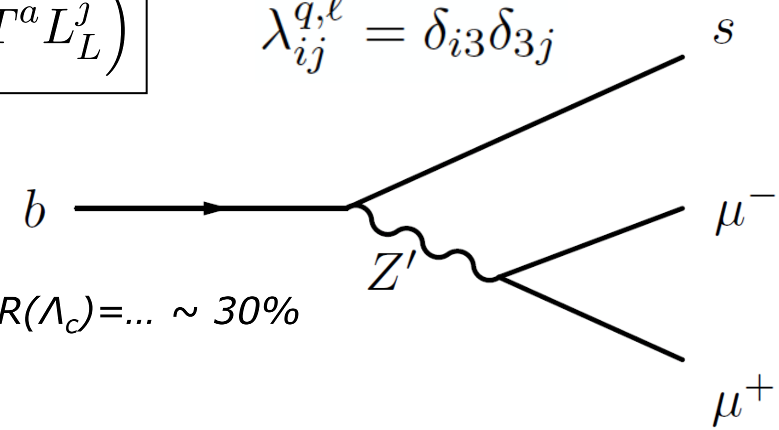
arXiv:1506.01705

- Example: “Isidori” model
  - New Z’ boson
  - Relatively simple model
  - Describes all (most?) data
  - Extra $SU(2)_L$ symmetry, coupling to 3rd gen

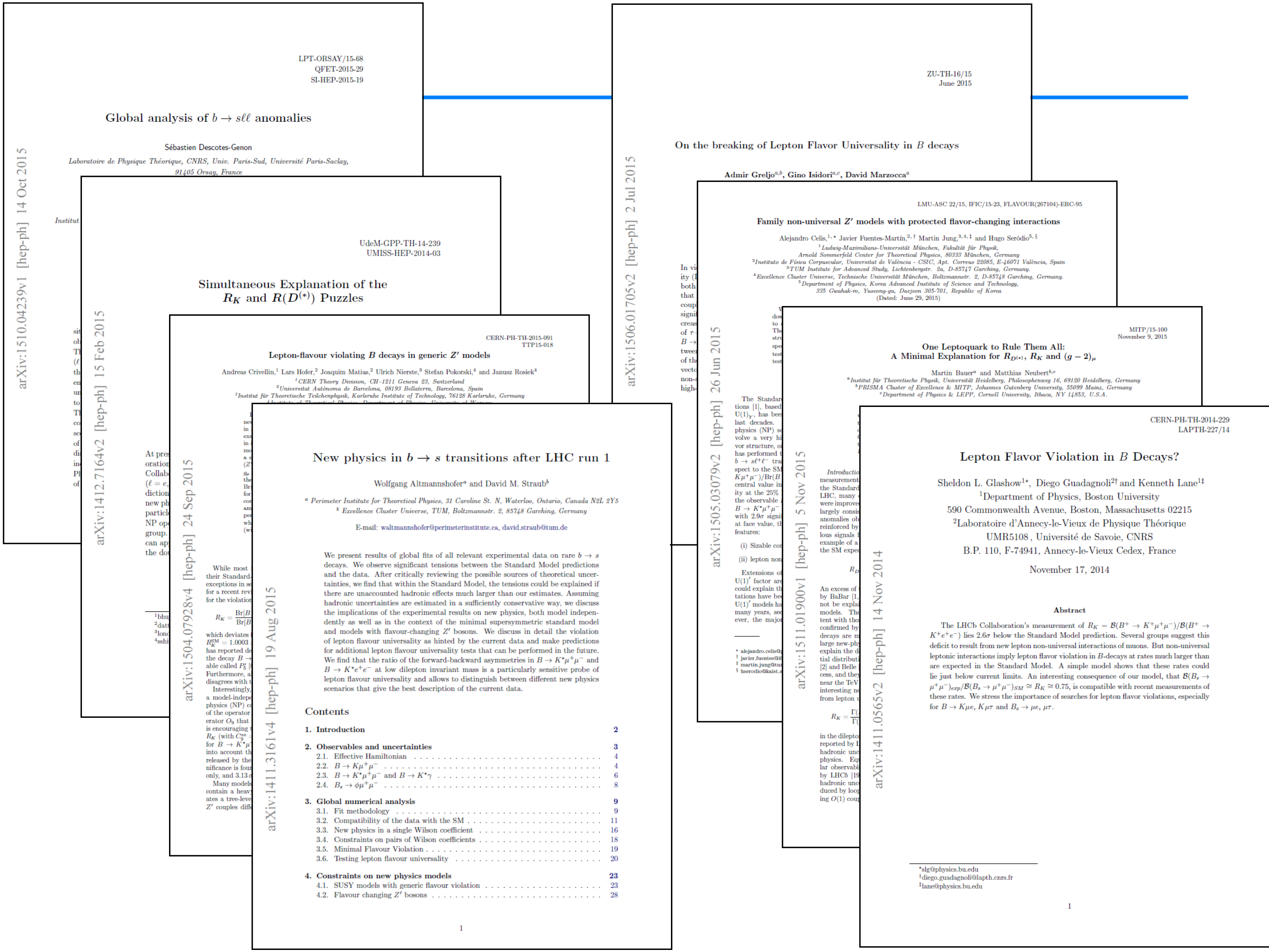


$$J^a_\mu = g_q \lambda^q_{ij} \left(\bar{Q}^i_L \gamma_\mu T^a Q^j_L \right) + g_\ell \lambda^\ell_{ij} \left(\bar{L}^i_L \gamma_\mu T^a L^j_L \right)$$

$$\lambda^{q,\ell}_{ij} = \delta_{i3}\delta_{3j}$$



- Predictions:
  - $C^{NP}_{10} = -C^{NP}_9$
  - τ,μ difference universal: *R(D)=R(D*)=R(Λ$_c$)=… ~ 30%*
  - e, μ difference: ~1-2%
  - B-mixing: 10% deviations from SM
  - τ→μμμ not far from present bound
  - No coupling to bosons, so cannot explain diboson excess…
  - Z’→tt,bb,ττ not very easy in ATLAS, most stringent constraint from m(Z’→ττ)>300 GeV, ruling out most minimal version of this model!



LPT-ORSAY/15-68
QFET-2015-29
SI-HEP-2015-19
Global analysis of $b \to s\ell\ell$ anomalies
Sébastien Descotes-Genon
Laboratoire de Physique Théorique, CNRS, Univ. Paris-Sud, Université Paris-Saclay, 91405 Orsay, France
arXiv:1510.04239v1 [hep-ph] 14 Oct 2015
UdeM-GPP-TH-14-239
UMISS-HEP-2014-03
Simultaneous Explanation of the R_K and $R(D^{(*)})$ Puzzles
arXiv:1412.7164v2 [hep-ph] 15 Feb 2015
CERN-PH-TH-2015-091
TTP15-018
Lepton-flavour violating B decays in generic Z' models
Andreas Crivellin,[1] Lars Hofer,[2] Joaquim Matias,[2] Ulrich Nierste,[3] Stefan Pokorski,[4] and Janusz Rosiek[4]
[1] CERN Theory Division, CH-1211 Geneva 23, Switzerland
[2] Universitat Autònoma de Barcelona, 08193 Bellaterra, Barcelona, Spain
[3] Institut für Theoretische Teilchenphysik, Karlsruhe Institute of Technology, 76128 Karlsruhe, Germany
arXiv:1504.07928v4 [hep-ph] 24 Sep 2015
New physics in $b \to s$ transitions after LHC run 1
Wolfgang Altmannshofer[a] and David M. Straub[b]
[a] Perimeter Institute for Theoretical Physics, 31 Caroline St. N, Waterloo, Ontario, Canada N2L 2Y5
[b] Excellence Cluster Universe, TUM, Boltzmannstr. 2, 85748 Garching, Germany
E-mail: waltmannshofer@perimeterinstitute.ca, david.straub@tum.de
We present results of global fits of all relevant experimental data on rare $b \to s$ decays. We observe significant tensions between the Standard Model predictions and the data. After critically reviewing the possible sources of theoretical uncertainties, we find that within the Standard Model, the tensions could be explained if there are unaccounted hadronic effects much larger than our estimates. Assuming hadronic uncertainties are estimated in a sufficiently conservative way, we discuss the implications of the experimental results on new physics, both model independently as well as in the context of the minimal supersymmetric standard model and models with flavour-changing Z' bosons. We discuss in detail the violation of lepton flavour universality as hinted by the current data and make predictions for additional lepton flavour universality tests that can be performed in the future. We find that the ratio of the forward-backward asymmetries in $B \to K^*\mu^+\mu^-$ and $B \to K^*e^+e^-$ at low dilepton invariant mass is a particularly sensitive probe of lepton flavour universality and allows to distinguish between different new physics scenarios that give the best description of the current data.
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3.2. Compatibility of the data with the SM 11
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3.4. Constraints on pairs of Wilson coefficients 18
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3.6. Testing lepton flavour universality 20
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4.2. Flavour changing Z' bosons 28
1
arXiv:1411.3161v4 [hep-ph] 19 Aug 2015
ZU-TH-16/15
June 2015
On the breaking of Lepton Flavor Universality in B decays
Admir Greljo[a,b], Gino Isidori[a,c], David Marzocca[a]
arXiv:1506.01705v2 [hep-ph] 2 Jul 2015
LMU-ASC 22/15, IFIC/15-23, FLAVOUR(267104)-ERC-95
Family non-universal Z' models with protected flavor-changing interactions
Alejandro Celis,[1,*] Javier Fuentes-Martín,[2,†] Martin Jung,[3,4,‡] and Hugo Serôdio[5,§]
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arXiv:1505.03079v2 [hep-ph] 26 Jun 2015
MITP/15-100
November 9, 2015
One Leptoquark to Rule Them All: A Minimal Explanation for $R_{D^{(*)}}$, R_K and $(g-2)_\mu$
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arXiv:1511.01900v1 [hep-ph] 5 Nov 2015
CERN-PH-TH-2014-229
LAPTH-227/14
Lepton Flavor Violation in B Decays?
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November 17, 2014
Abstract
The LHCb Collaboration's measurement of $R_K = \mathcal{B}(B^+ \to K^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+e^+e^-)$ lies 2.6σ below the Standard Model prediction. Several groups suggest this deficit to result from new non-universal interactions of muons. But non-universal leptonic interactions imply lepton flavor violation in B-decays at rates much larger than are expected in the Standard Model. A simple model shows that these rates could lie just below current limits. An interesting consequence of our model, that $\mathcal{B}(B_s \to \mu^+\mu^-)_{exp}/\mathcal{B}(B_s \to \mu^+\mu^-)_{SM} \cong R_K \cong 0.75$, is compatible with recent measurements of these rates. We stress the importance of searches for lepton flavor violations, especially for $B \to K\mu e$, $K\mu\tau$ and $B_s \to \mu e$, $\mu\tau$.
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arXiv:1411.0565v2 [hep-ph] 14 Nov 2014

Interpretations

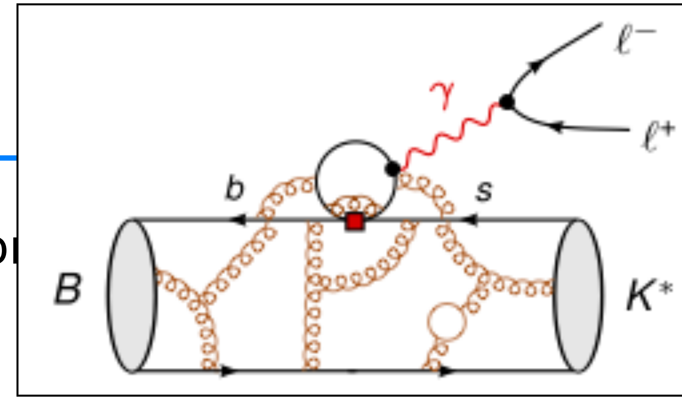
Shown	Authors	Model	Input	Predictions/ Result	arXiv
☑	Descotes-Genon, Matias, Virto	Model independent	*b→ sll, b→ sγ*	• C_9^{NP}=-1 • $C^{NP}{}_{10}$=-$C^{NP}{}_9$	1307.5683 1510.04239
☑	Altmannshofer, Straub	Model independent	*b→ sll, b→ sγ*	• C_9^{NP}=-1 • $C^{NP}{}_{10}$=-$C^{NP}{}_9$	1411.3161 1503.06199
☐	Glashow, Guadagnoli, Lane	Z'	*B^0→K*μμ, R_K, B_s^0→μμ*	LFNU → LFV	1411.0565 1507.01412
☐	Bhattacharya, Datta, London, Shivashankara	Z’ , W’	*R_K, R(D*)*	R(D)=R(D*)	1412.7164
☐	Crivellin, Hofer, Matias, Nierste, Pokorski, Rosiek	Z’	*B→K*μμ, R_K (τ→3μ, μ→eγ, g-2, B-mix)*	1) $C^{NP}{}_{10}$=0 2) $C^{NP}{}_{10}$=-$C^{NP}{}_9$ Limits on *B→(K)μe*. (h→μν 1503.03477)	1504.07928
☐	Celis, Fuentes-Martin, Jung, Serodio	Z ‘	*B^0→K*μμ, R_K*	R_K=R_{K*}	1505.03079
☑	Greljo, Isidori, Marzocca	Z’ ,W’	*B^0→K*μμ, R_K, R(D*), τ→3μ, B-mix, B→Xν*	*R(D)=R(D*), Dμν/Deν* ~ 1-2%	1506.01705
☐	Buras, Butazzo, Knegjens De Fazio	Z’ $SU(3)_L$	*ε′/ε, K_L→μμ, B_s^0→μμ*	*K→πνν, B^0→K*μμ $m_{Z'}$~3 TeV*	1507.08672 1512.02869
☐	Hiller, Schmaltz	Leptoquark	*R_K, b→ sμμ*		1408.1627
☐	Bečirević, Fajfer, Košnik	Leptoquark (scalar, or vector)	*BR(B→Kμμ), B_s^0→μμ*	C_9’ =-C_{10}’ , R_K=0.88	1503.09024 1511.06024
☐	Freytsis, Ligeti, Ruderman	Leptoquark (scalar/vector)	*R(D*),B^+→τυ*	*B^+/B^- CPV, D→πνν~10^{-5}*	1506.08896
☑	Bauer, Neubert	Leptoquark (scalar)	*R_K, R(D*), g-2 (B-mix, τ→μγ, D→μμ)*	BR(Z→μμ), *B-mix*	1511.01900

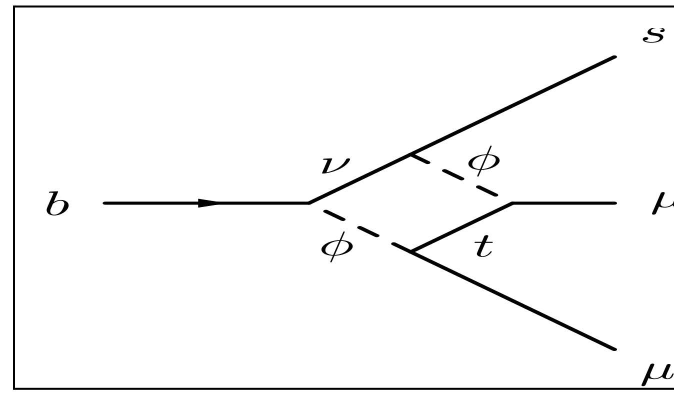
New physics?

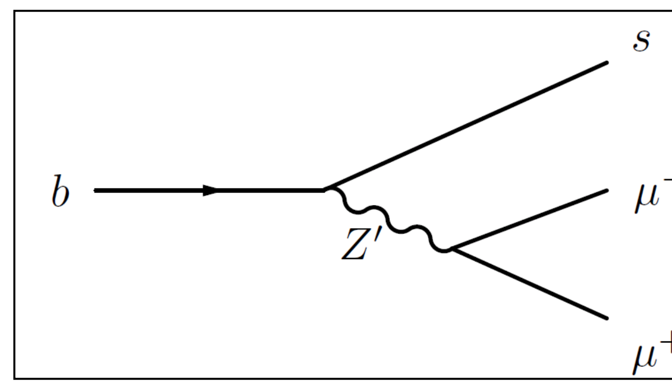
- More involved Standard Model calculatio

- Statistical fluctuations?

- Or first hints for new particles??
  - ➢ <u>Leptoquark ?</u>
    - – Couples to quark ánd leptons
    - – Explaining many open questions
      - g-2, *B→Kμμ*, *B→D**μν*, diphoton
  - ➢ <u>Z' ?</u>
    - – New symmetry, new boson (force)
    - – Explaining many open questions
      - *B→Kμμ*, *B→D**μν*







The need for more precision

Imagine if Fitch and Cronin had stopped at the 1% level, how much physics would have been missed”

– A.Soni

- “A special search at Dubna was carried out by Okonov and his group. They did not find a single $K_L^0 \to \pi^+\pi^-$ event among 600 decays into charged particles (Anikira et al., JETP 1962). At that stage the search was terminated by the administration of the lab. The group was unlucky.”

– L.Okun

(remember: $B(K_L^0 \to \pi^+\pi^-) \sim 2\ 10^{-3}$)

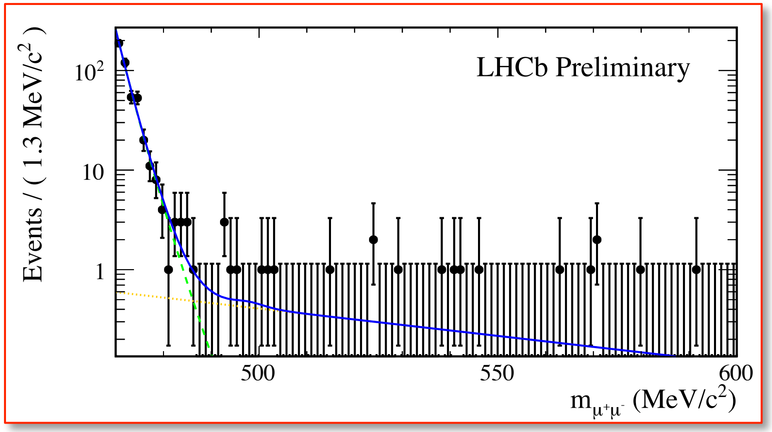
Backups

“Extraordinary claims require Extraordinary evidence”

– C. Sagan

Strange

- New field within LHCb
- Dedicated triggers
- Rich program:
  - *$K_S^0 \rightarrow \mu\mu$*
    - *BR < 5.8 x 10^{-9} @ 90% CL*
    - *Software trigger, 23 fb^{-1}: 2 x 10^{-10}*
  - *$K_S^0 \rightarrow \pi^0\mu\mu$*
    - *Hardware trigger bottleneck → upgrade!*
  - *$K_S^0 \rightarrow \mu\mu\mu\mu$*
    - *No experimental constraint to date*
  - *$K_S^0 \rightarrow \pi^+\pi^- ee$*
    - *5σ observation possible in Run-II*
  - *$K^+ \rightarrow \pi^+\pi^-\pi^+$*
    - *10^6 events observed in Run-I*
    - *software trigger in upgrade: 2x 10^{10} /fb^{-1}*
  - *$\Sigma^+ \rightarrow p\mu\mu$*
    - *Check HyperCP (E871) events*



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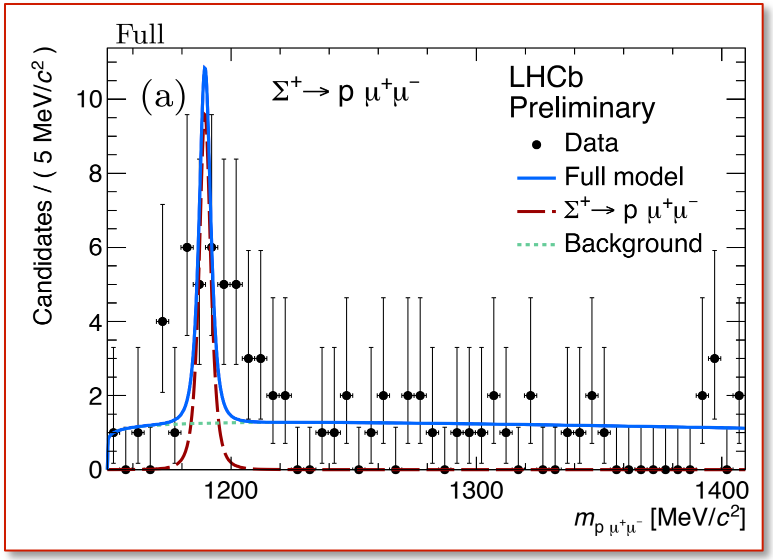


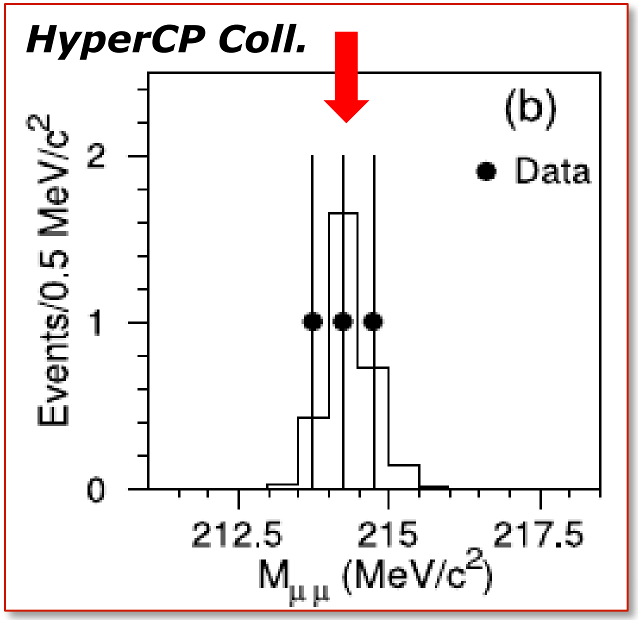
LHCb-CONF-2016-013

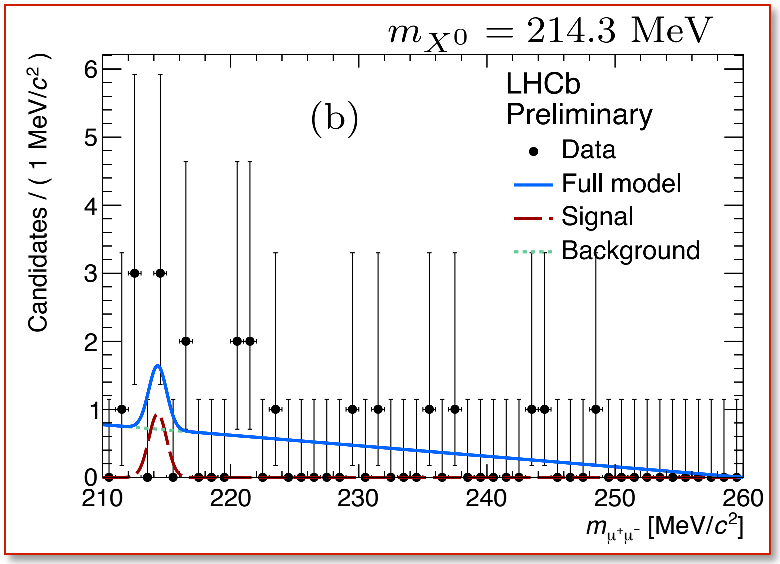
Strange

- New field within LHCb
- Dedicated triggers
- Rich program:
  - $K_S^0 \rightarrow \mu\mu$
    - *BR < 5.8 x 10^{-9} @ 90% CL*
    - *Software trigger, 23 fb^{-1}: 2 x 10^{-10}*
  - $K_S^0 \rightarrow \pi^0\mu\mu$
    - *Hardware trigger bottleneck → upgrade!*
  - $K_S^0 \rightarrow \mu\mu\mu\mu$
    - *No experimental constraint to date*
  - $K_S^0 \rightarrow \pi^+\pi^- ee$
    - *5σ observation possible in Run-II*
  - $K^+ \rightarrow \pi^+\pi^-\pi^+$
    - *10^6 events observed in Run-I*
    - *software trigger in upgrade: 2x 10^{10} /fb^{-1}*
  - $\Sigma^+ \rightarrow p\mu\mu$
    - Check HyperCP (E871) events
    - LHCb:
      - Fit at m=214.3 MeV: 1.6±1.9 evts

$$\Sigma^+ \rightarrow pX^0(\rightarrow \mu^+\mu^-)$$

HyperCP, PRL 94 (2005) 021801

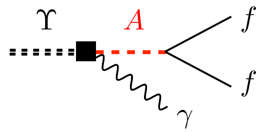


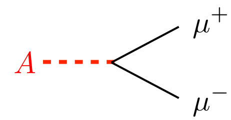


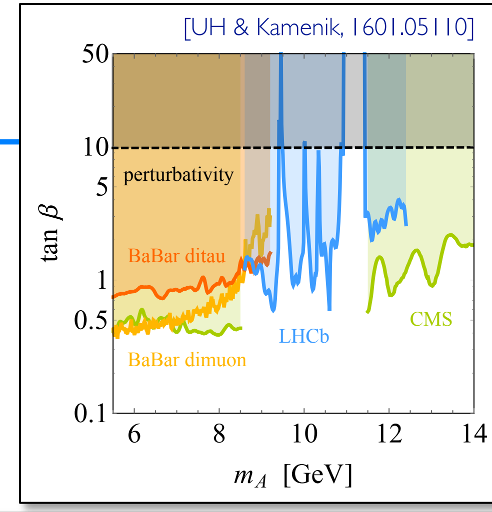
LHCb-CONF-2016-013

Searches
Dark photons, Majorana, light scalars

- Light scalars
  - A→μμ

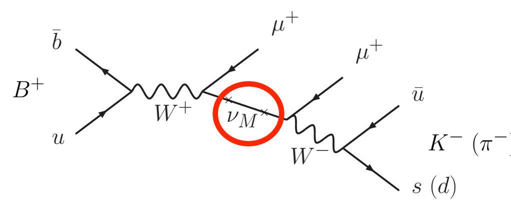


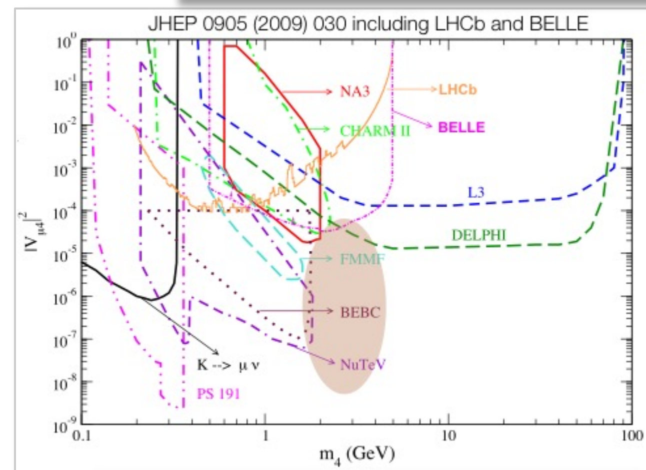




Haisch et al., PRD93 (2016) 055047

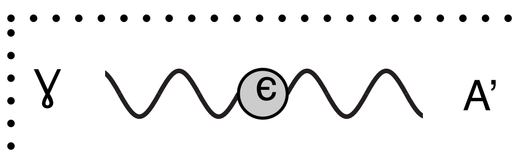
- Majorana neutrino's
  - $B^+ \to \pi^- \mu^+ \mu^+$

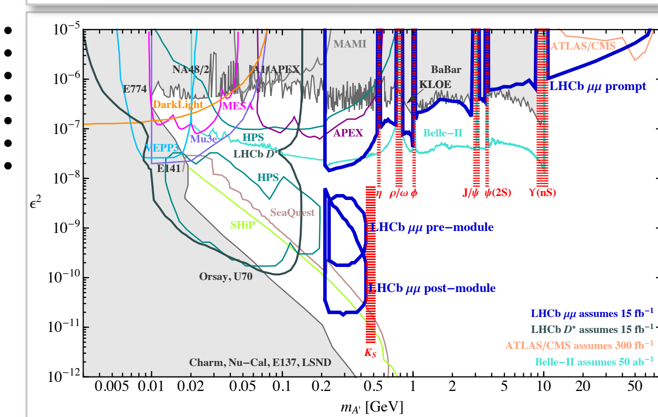




Atre et al., JHEP 0905 (2009) 030

- Dark photons
  - $D^{*0} \to D^0 \gamma$, $A \to \mu\mu$





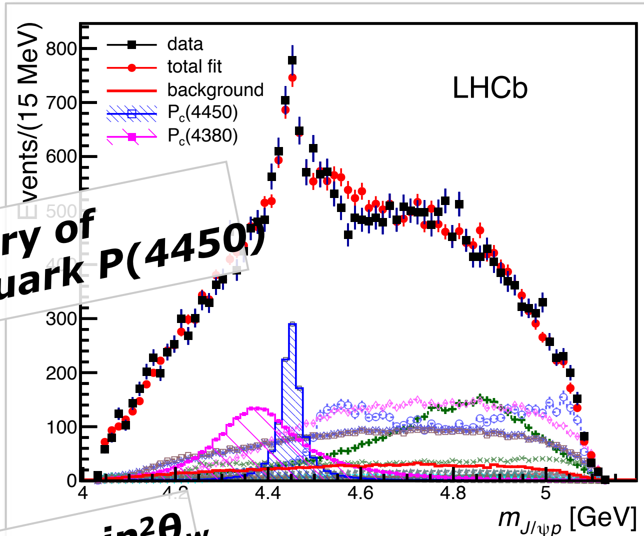
Ph.Ilten et al PRL 116 (2016) 251803

Common misunderstandings

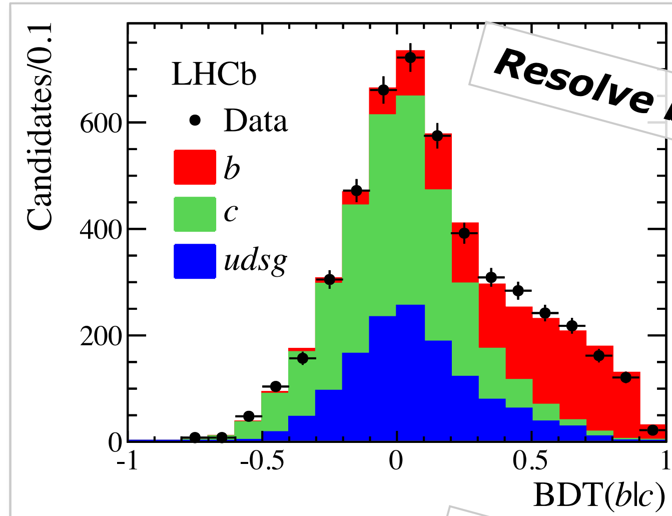
1) CP violation ≠ Baryon number violation
2) Meson mixing ≠ CP violation
3) Mixing phase φ_s ≠ Mixing phase φ_s
4) CP violation in Kaon system ≠ CPV in decay $K_L \to \pi\pi$
5) K_S^0 ≠ CP eigenstate

LHCb = more than heavy flavour

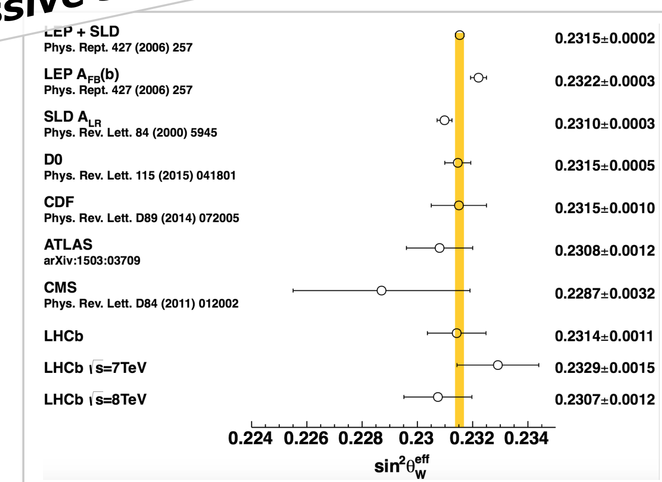
Discovery of pentaquark P(4450)



Resolve b and c jets



Impressive $\sin^2\theta_W$



Improve proton pdf's