Hints for Flavorful New Physics

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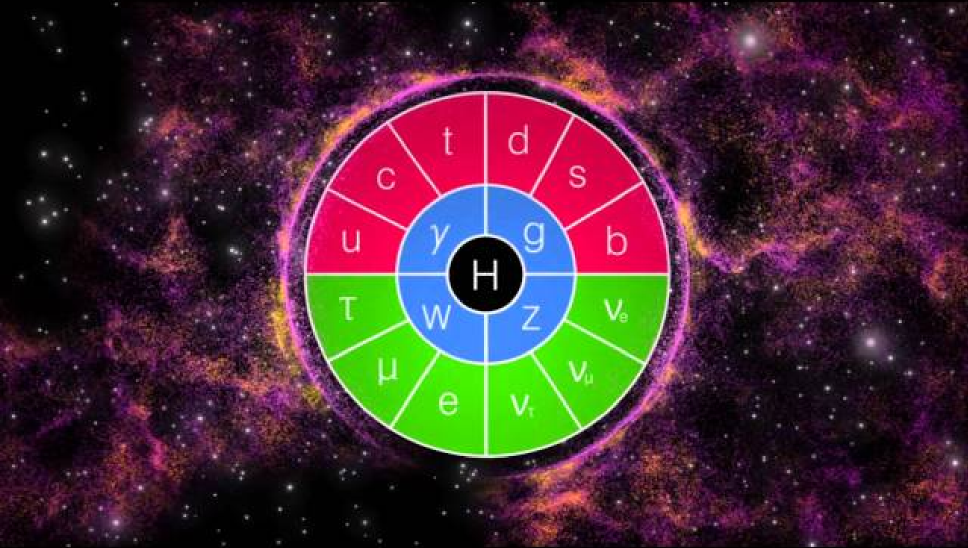
PERIMETER INSTITUTE

Colloquium
Nikhef

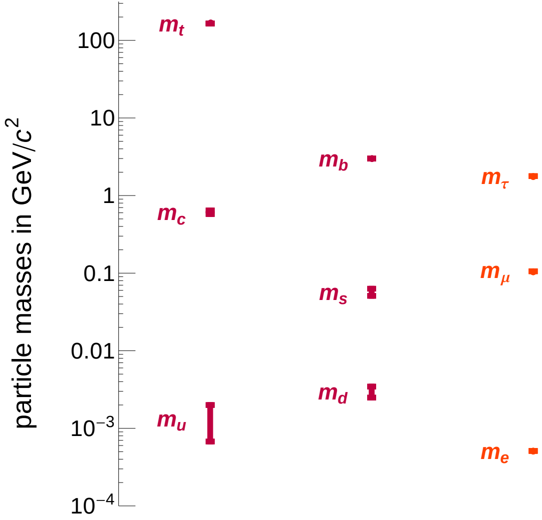
June 26, 2015

The Standard Model of Particle Physics



particlefever.com

Quark and Lepton Masses



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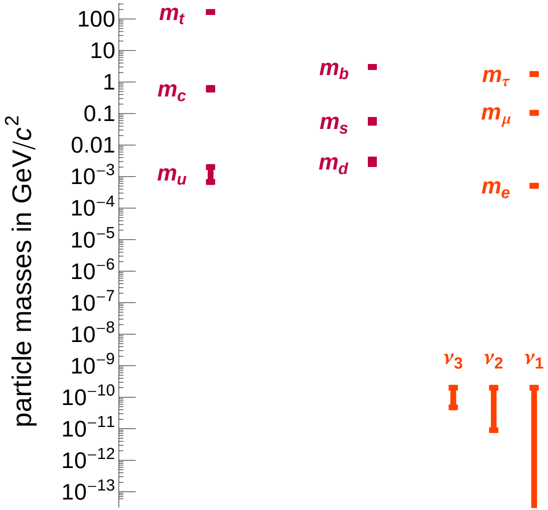
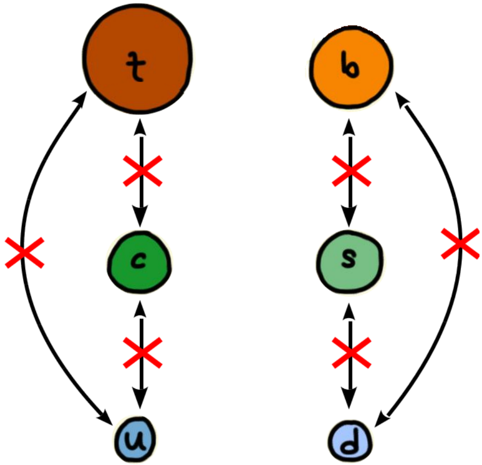


Distinct Decay Pattern of the Quarks in the SM



in the Standard Model there are
no direct transitions
within up-type or down-type quarks

→ GIM mechanism
(Glashow, Iliopoulos, Maiani)

no flavor changing neutral currents
(FCNCs) at tree level

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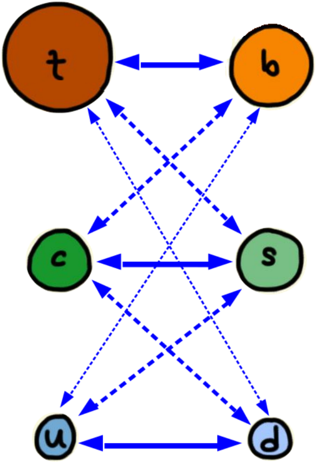

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$\rightarrow$ GIM mechanism
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no flavor changing neutral currents
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transitions among the generations
are mediated by the $W^\pm$ bosons
and their relative strength is
parametrized by the
Cabibbo-Kobayashi-Maskawa
(CKM) matrix

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Testing the CKM Picture of Flavor Violation

CKM matrix is the only source of quark flavor violation in the Standard Model

depends on only 4 parameters

λ, A, $\bar{\rho}$, $\bar{\eta}$

measuring many flavor transitions allows to over-constrain the 4 CKM parameters and to test the CKM picture of quark flavor violation

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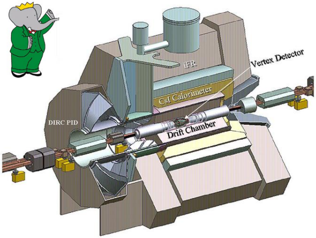
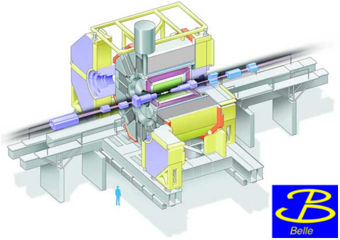
such tests were carried out at the B factories BaBar and Belle

BaBar @ SLAC 1999 - 2008





Belle @ KEK 1999 - 2010

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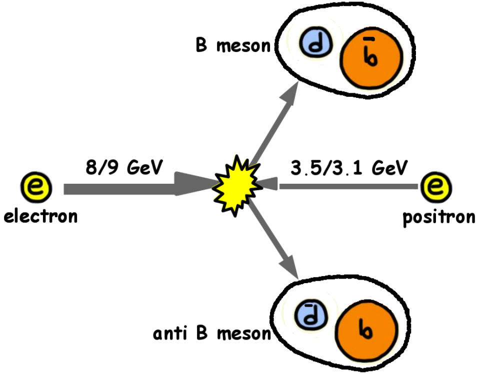
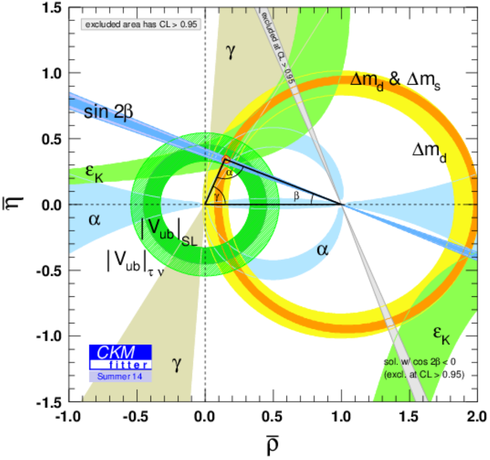


the B factories produced more than 1 billion $B\bar{B}$ pairs and studied their properties and decays

A Consistent Description of All Data

Within the experimental and theoretical uncertainties, the CKM matrix gives a consistent description of the observed flavor changing phenomena



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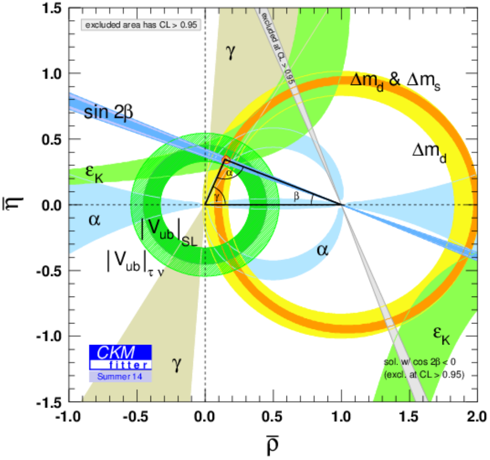
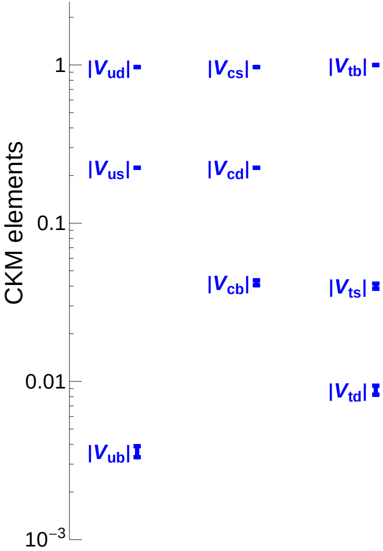
Nobel Prize 2008 for

Makoto Kobayashi

Toshihide Maskawa



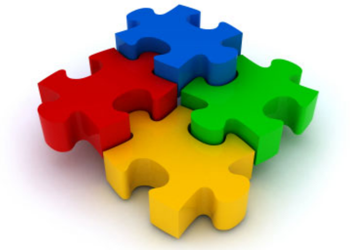
Quark Mixing Hierarchy



the measured CKM elements
show a very hierarchical pattern

$$|V| \simeq \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} , \quad \lambda \simeq 0.2$$

The Standard Model Flavor Puzzle



The Standard Model gives a reasonable description of all flavor transitions measured up to now, but it does not explain its mysteries

- Why are there three generations of quarks and leptons?
- What is the origin of the hierarchies in the fermion spectrum?
- What is the origin of the hierarchies in the quark mixing?

we are lacking a *theory of flavor*

In addition to the flavor puzzle,
the Standard Model
leaves many questions
unanswered

- Dark Matter
- Dark Energy
- Matter-Antimatter Asymmetry
- Grand Unification
- Hierarchy Problem
- ...

The Hierarchy Problem

What gives mass to the Higgs itself?

The Higgs mass parameter
is not forbidden by any
symmetry of the Standard Model

$$m^2 = m^2_{(0)} + \Delta m^2 \sim (125\text{GeV})^2$$

1) can be added by hand

2) not protected from
quantum corrections

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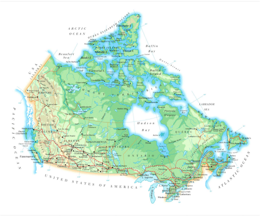
quantum corrections to
the Higgs mass are
sensitive to the largest scales

$$\Delta m^2 \sim \frac{1}{16\pi^2} M^2_{\text{Planck}} \simeq 10^{36}\text{GeV}^2$$

fine tuned cancellation between the
quantum corrections and the "bare mass" is required

The Hierarchy Problem



–

Canada		United States	
9,984,670 km^2	$-$	9,826,675 km^2	$=$ 157,995 km^2

The Hierarchy Problem

$-$

$= \quad 1\ \text{Å}^2$

Canada		United States		
9,984,670 km^2	$-$	9,826,675 km^2	$=$	157,995 km^2

tuning of the Higgs mass would correspond to
the surface area of Canada and the United States
differing by approximately the size of an atom!

In order to protect the Higgs mass
from huge quantum corrections and to avoid finetuning,
we expect New Physics at or below the TeV scale
not far above the mass of the Higgs

Direct searches for New Physics

Directly produce new particles
in high energy collisions

unique effort towards high energies

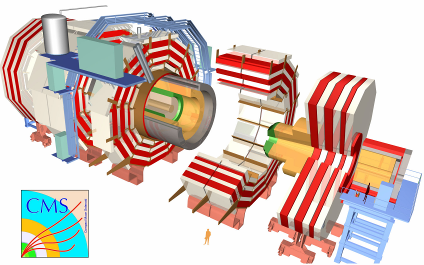
a very successful approach:

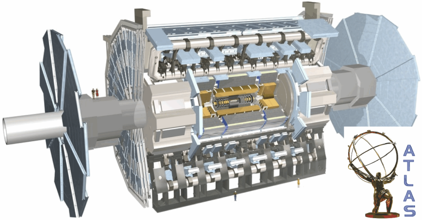
- Super Proton Synchrotron at CERN
(center of mass energy 0.54 TeV)
discovery of the W and Z bosons 1983

- Tevatron at Fermilab
(center of mass energy 1.96 TeV)
discovery of the top quark 1995

- Large Hadron Collider at CERN
(center of mass energy 8 TeV)
discovery of the Higgs boson 2012

- Run 2 of the Large Hadron Collider
(center of mass energy 13 TeV)
discovery of ??? in 2016?





Indirect searches for New Physics

Look for virtual effects of new particles in low energy experiments

Discoveries from Flavor Physics

- the tiny branching ratio of the decay $K_L \to \mu^+\mu^-$ led to the prediction of the charm quark to suppress FCNCs
  (Glashow, Iliopoulos, Maiani 1970)
- the measurement of the frequency of kaon anti-kaon oscillations allowed a successful prediction of the charm quark mass
  (Gaillard, Lee 1974)

(direct discovery of the charm quark in 1974 at SLAC and BNL)

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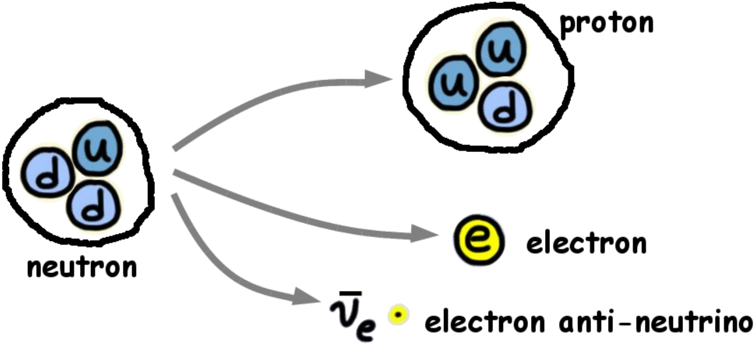
- the observation of CP violation in kaon anti-kaon oscillations
  led to the prediction of the 3rd generation of quarks
  (Kobayashi, Maskawa 1973)

- the measurement of the frequency of B - $\bar{B}$ oscillations
  allowed to predict the large top quark mass
  (various authors in the late 80's)

(direct discovery of the bottom quark in 1977 at Fermilab)
(direct discovery of the top quark in 1995 at Fermilab)

Historic Example: Beta Decay



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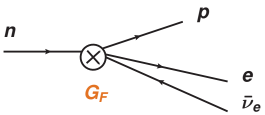

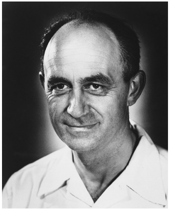

effective low energy description
of nuclear beta decay by a
4 fermion contact interaction

the interaction strength is given by
the Fermi constant

$$G_F \simeq 1.17 \times 10^{-5}\ \text{GeV}^{-2}$$

this defines an energy scale

$$\Lambda = (G_F\sqrt{2})^{-1/2} \simeq 246\ \text{GeV}$$

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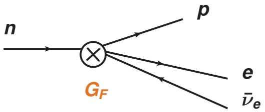

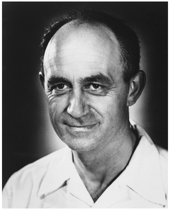

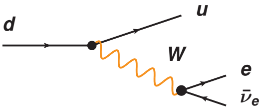

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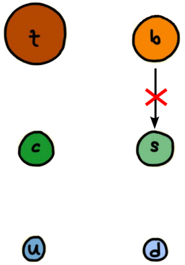
in the Standard Model
we understand beta decay
as consequence of
the exchange of virtual
weak gauge bosons

$$\frac{G_F}{\sqrt{2}} = \frac{g_2^2}{8 m_W^2}$$

$$m_W \simeq 80\ \text{GeV}$$

Flavor Changing Neutral Currents in the SM

In the SM, flavor changing neutral currents (FCNCs) are absent at the tree level



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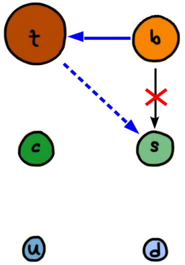
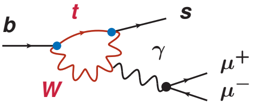
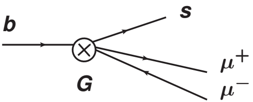


FCNCs can arise at the loop level
they are suppressed by loop factors
and small CKM elements





$$G \sim \frac{1}{16\pi^2} \frac{g^4}{m_W^2} \frac{m_t^2}{m_W^2} V_{tb} V_{ts}^*$$

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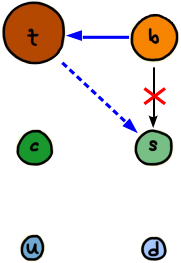
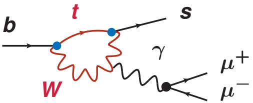
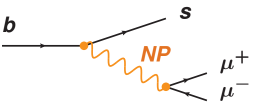
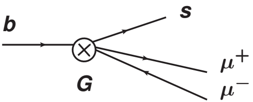




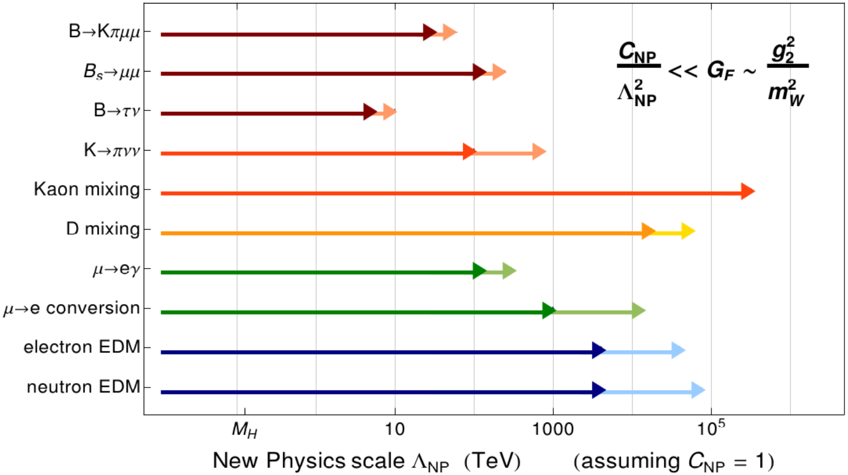




$$G \sim \frac{1}{16\pi^2} \frac{g^4}{m_W^2} \frac{m_t^2}{m_W^2} V_{tb} V_{ts}^* + \frac{C_{NP}}{\Lambda_{NP}^2}$$

→ measuring low energy flavor observables gives information on new physics flavor couplings and the new physics mass scale

High Sensitivity to Flavorful New Physics



Low energy flavor observables are sensitive to
New Physics far beyond the TeV scale

Low energy flavor observables are sensitive to
New Physics far beyond the TeV scale

solutions of the hierarchy problem require
New Physics at or below the TeV scale

The New Physics Flavor Puzzle

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in most cases good agreement
between Standard Model predictions
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The New Physics Flavor Puzzle

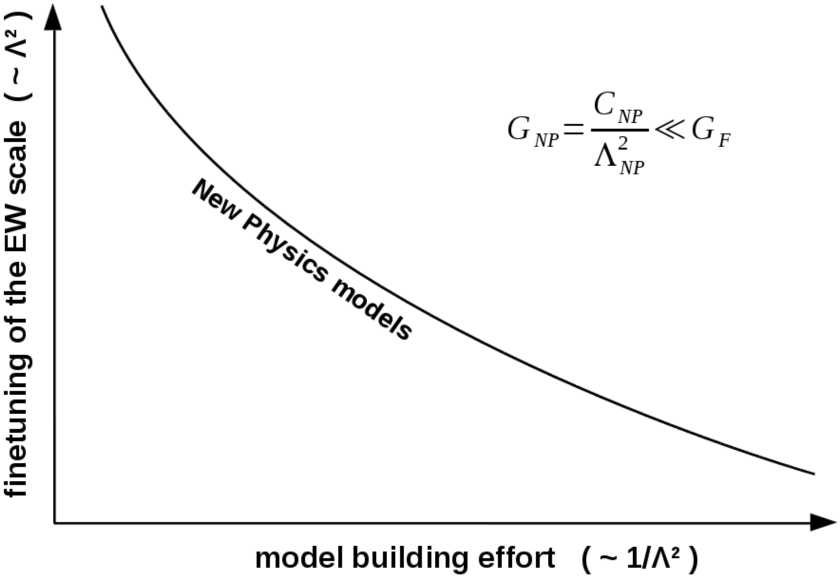
Low energy flavor observables are sensitive to New Physics far beyond the TeV scale

in most cases good agreement between Standard Model predictions and flavor experiments

If there is New Physics at or below the TeV scale, why have we not seen it yet in flavor observables?

solutions of the hierarchy problem require New Physics at or below the TeV scale

Reactions to the New Physics Flavor Puzzle



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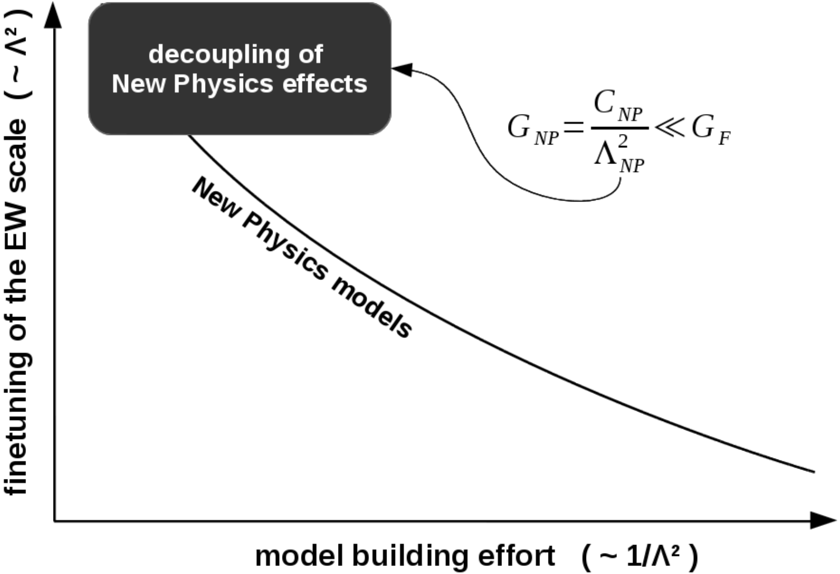

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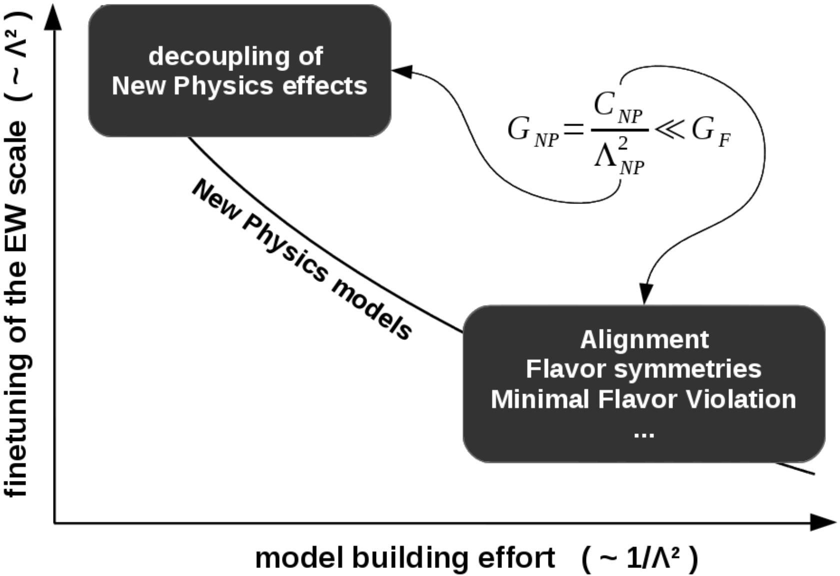
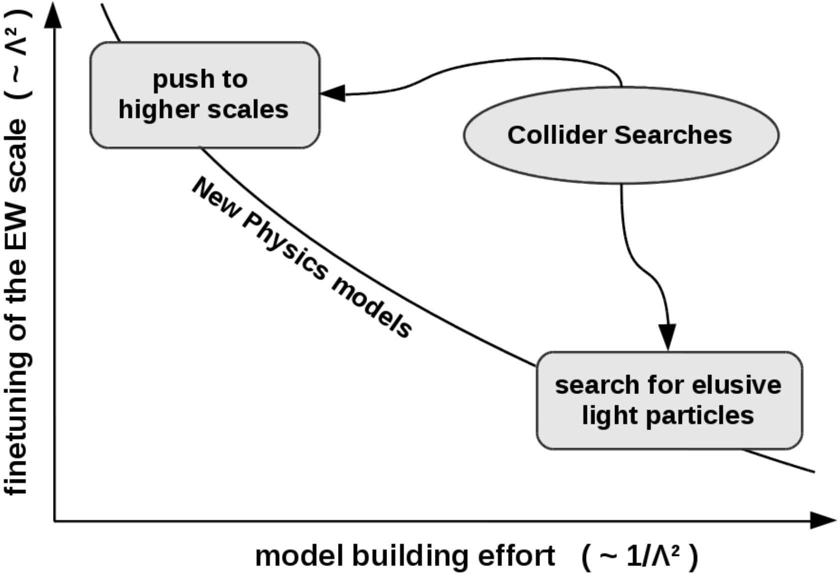
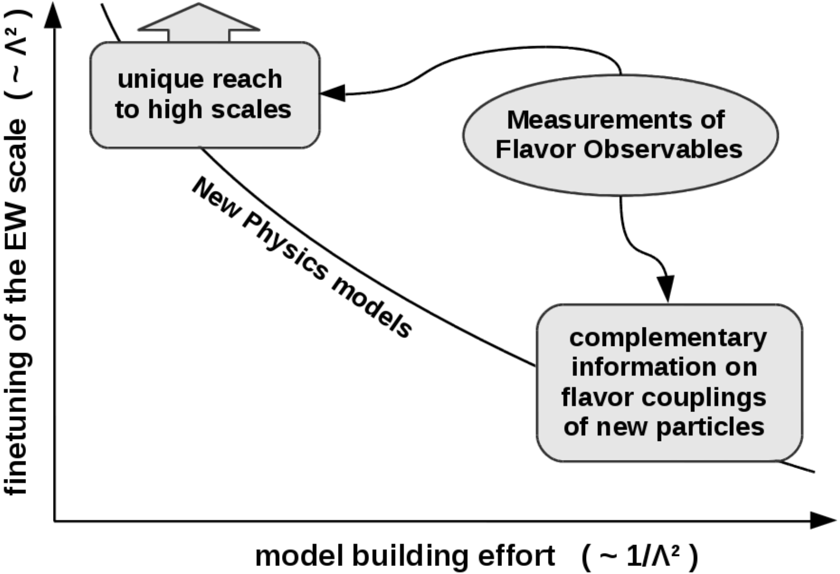



push to
higher scales
Collider Searches
New Physics models
search for elusive
light particles
finetuning of the EW scale (~ Λ²)
model building effort (~ 1/Λ²)

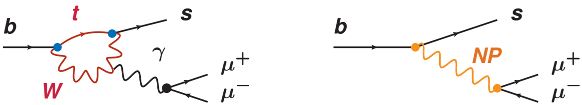
The Role of Flavor Physics



will now focus on one particular class of flavor violating processes:

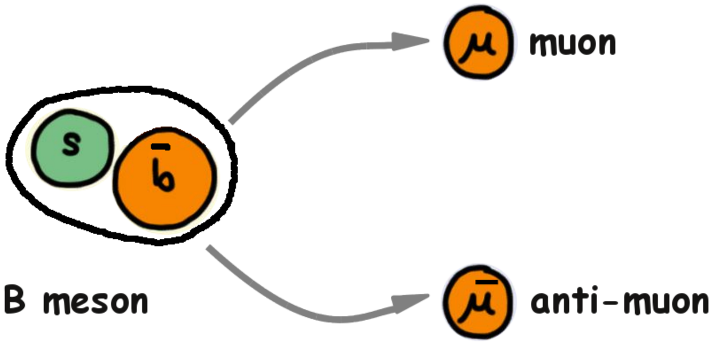
Rare B Decays

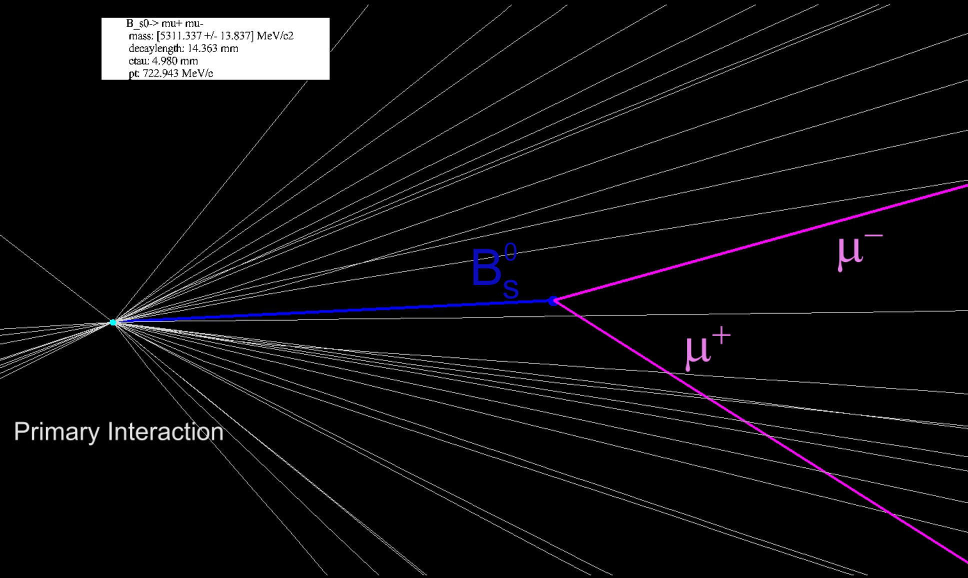
based on the $b \to s\ell\ell$ transition



$$G \sim \frac{1}{16\pi^2} \frac{g^4}{m_W^2} \frac{m_t^2}{m_W^2} V_{tb} V_{ts}^* + \frac{C_{\rm NP}}{\Lambda_{\rm NP}^2}$$

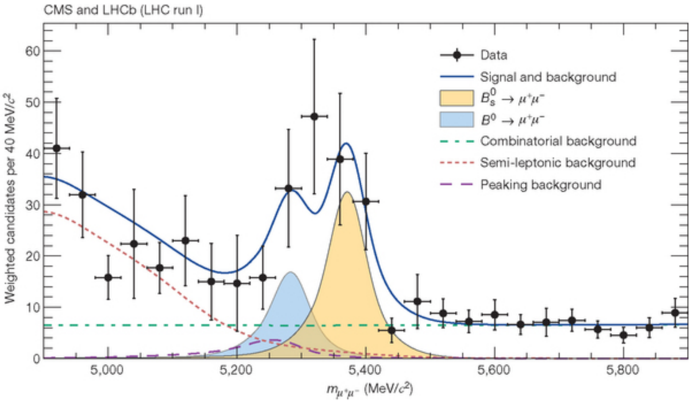
The $B_s \to \mu^+\mu^-$ Decay




B_s0-> mu+ mu-
mass: [5311.337 +/- 13.837] MeV/c2
decaylength: 14.363 mm
ctau: 4.980 mm
pt: 722.943 MeV/c
B_s^0
μ^-
μ^+
Primary Interaction

Experimental Result for the Branching Ratio

Nature **522**, 68-72

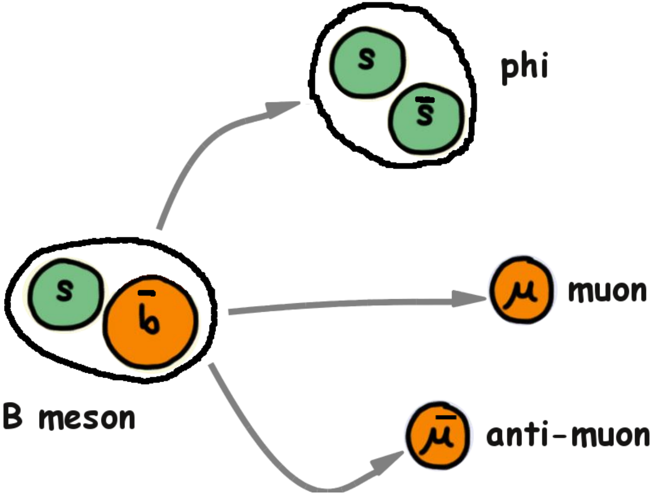


$$\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{exp}} = (2.8^{+0.7}_{-0.6})\times 10^{-9} \;, \quad \mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{SM}} = (3.65\pm 0.23)\times 10^{-9}$$

De Bruyn et al. 1204.1737

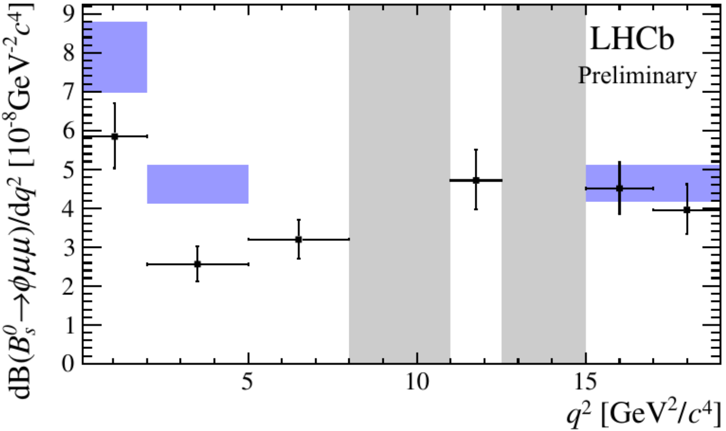
Bobeth et al. 1311.0903

The $B_s \to \phi\mu^+\mu^-$ Decay



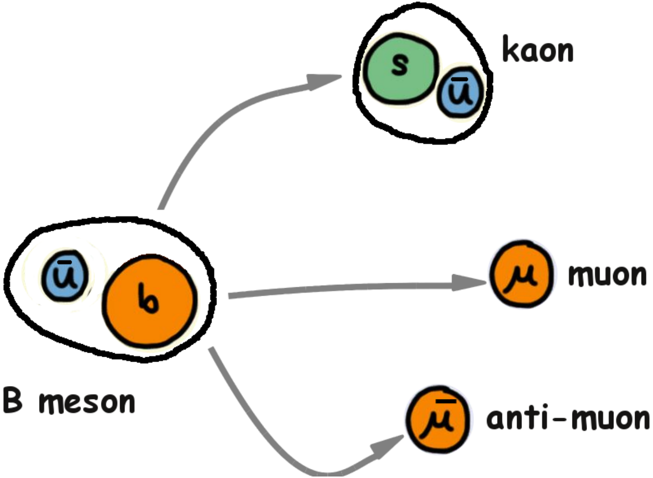
Branching Ratio Measurement

talk by Christian Linn @ FPCP 2015

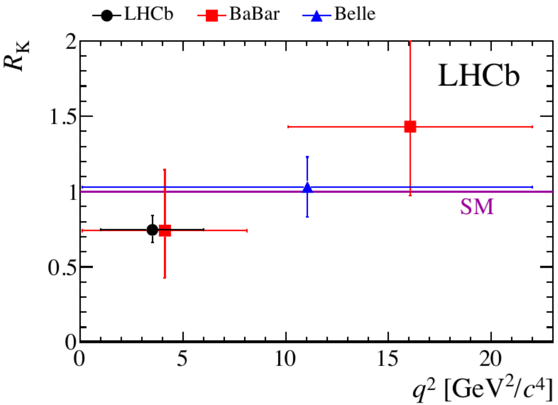


$\sim 3\sigma$ discrepancy between SM prediction (Bharucha, Straub, Zwicky '15)
and experimetal data (LHCb-Paper-2015-023)

The $B \to K\mu^+\mu^-$ Decay

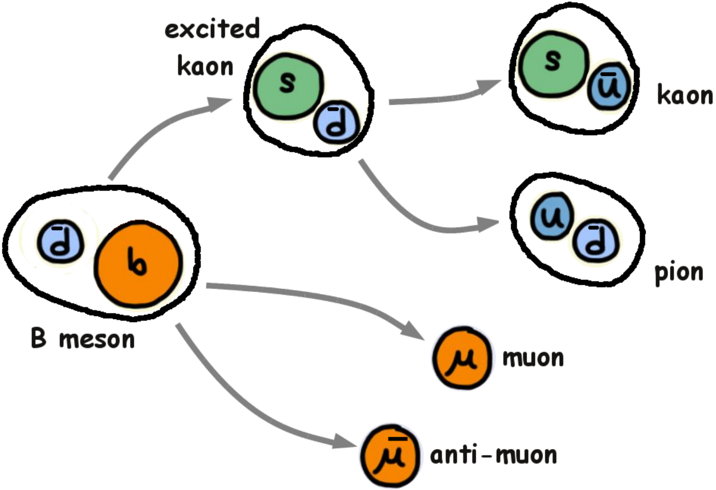


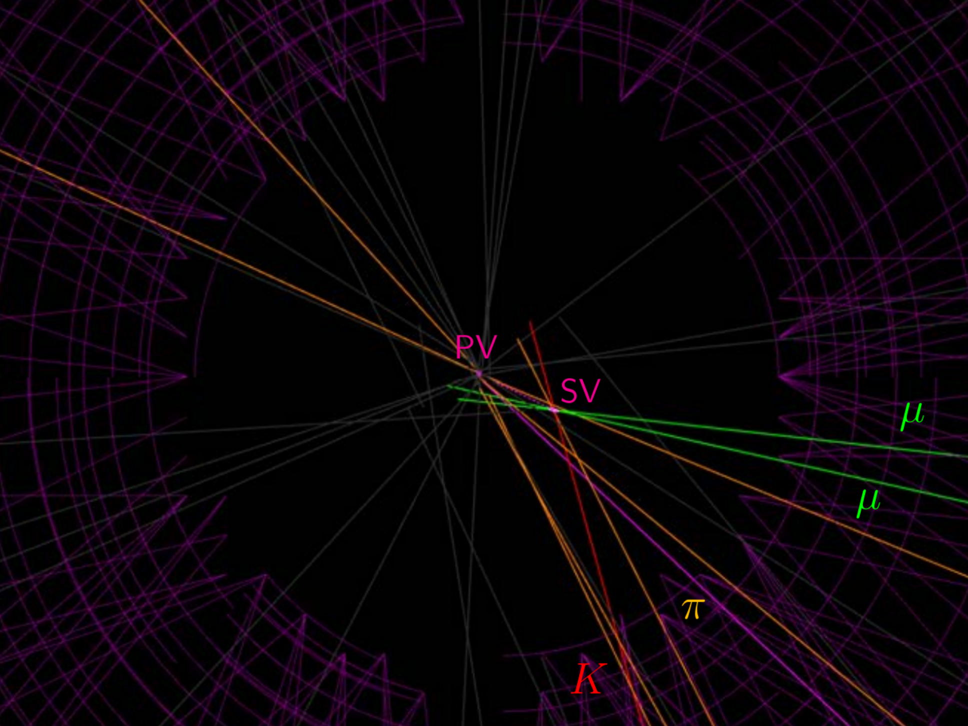
Violation of Lepton Flavor Universality?



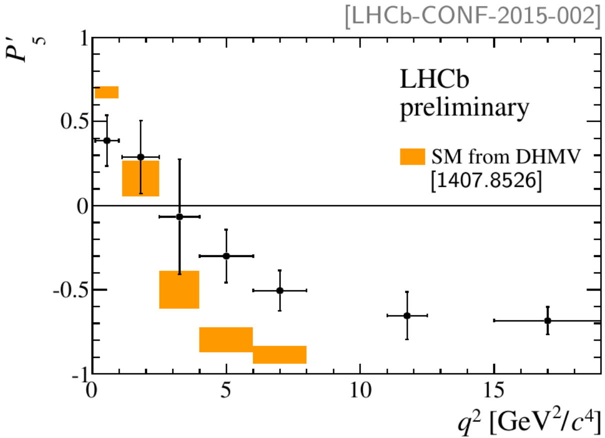
$$R_K = \frac{BR(B \to K\mu^+\mu^-)_{[1,6]}}{BR(B \to Ke^+e^-)_{[1,6]}} = 0.745^{+0.090}_{-0.074} \pm 0.036 \,, \qquad R_K^{SM} \simeq 1.00$$

The $B \to K^*(\to K\pi)\mu^+\mu^-$ Decay




PV
SV
μ
μ
π
K

“The $B \to K^* \mu^+ \mu^-$ Anomaly”



2.9σ in [4,6] GeV^2 bin   ($+2.9\sigma$ in [6,8] GeV^2 bin)

What Could It Be?

	branching ratios	angular observables	LFU ratios

What Could It Be?

	branching ratios	angular observables	LFU ratios
statistical fluctuations?	√	√	√

What Could It Be?

	branching ratios	angular observables	LFU ratios
statistical fluctuations?	✓	✓	✓
parametric uncertainties?	✓	✗	✗

What Could It Be?

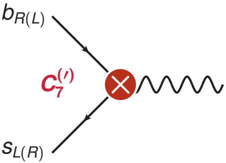
	branching ratios	angular observables	LFU ratios
statistical fluctuations?	✓	✓	✓
parametric uncertainties?	✓	✗	✗
underestimated hadronic effects?	✓	✓	✗

What Could It Be?

	branching ratios	angular observables	LFU ratios
statistical fluctuations?	✓	✓	✓
parametric uncertainties?	✓	✗	✗
underestimated hadronic effects?	✓	✓	✗
New Physics?	✓	✓	✓

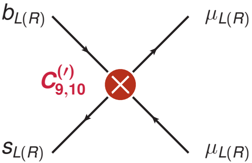
$$\mathcal{H}_{\text{eff}}^{b\to s} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i \left(C_i \mathcal{O}_i + C_i' \mathcal{O}_i' \right)$$

magnetic dipole operators



$\propto 1/q^2$

semileptonic operators



$\propto 1$

	C_7, C_7'	C_9, C_9'	C_{10}, C_{10}'
$B \to (X_s, K^*)\,\gamma$	★		
$B \to (X_s, K, K^*)\,\mu^+\mu^-$	★	★	★
$B_s \to \phi\,\mu^+\mu^-$	★	★	★
$B_s \to \mu^+\mu^-$			★

neglecting tensor operators (secretly dimension 8)

neglecting scalar operators (strongly constrained by $B_s \to \mu^+\mu^-$)

(in linear EFT)

many processes and many observables
are modified simultaneously

$\Rightarrow$ global fits are required

WA, Straub, Paradisi '11; Bobeth, Hiller, van Dyk, Wacker '11; WA, Straub '12, '13, '14;

Beaujean, Bobeth, van Dyk, Wacker; '12; Descotes-Genon, Matias, Virto '13, '14;

Beaujean, Bobeth, van Dyk '13; Hurth, Mahmoudi '13; Ghosh, Nardecchia, Renner '14;

Hurth, Mahmoudi, Neshatpour '14; Jäger, Martin Camalich '14; ...

A Hint for Flavorful New Physics

favored new physics
parameter space

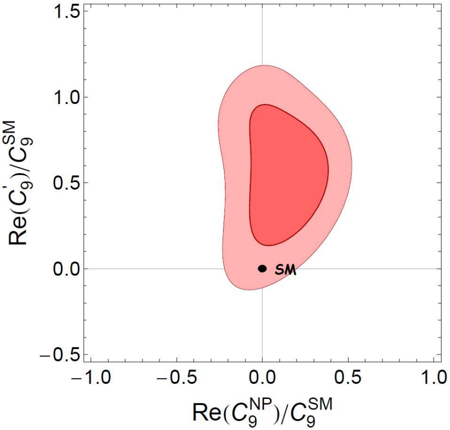
$O_9 \propto (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \mu)$

$O_9' \propto (\bar{s}\gamma_\mu P_R b)(\bar{\mu}\gamma^\mu \mu)$

muonic vector current

(WA, Straub '11 - '15)

2011



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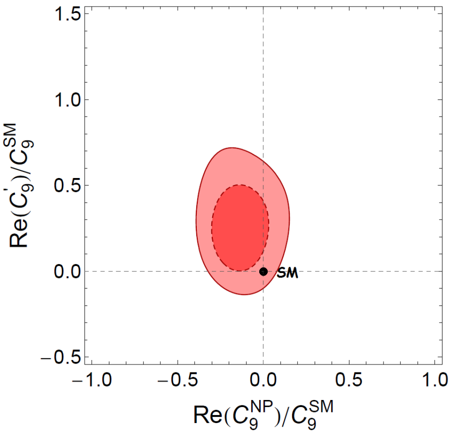
2012



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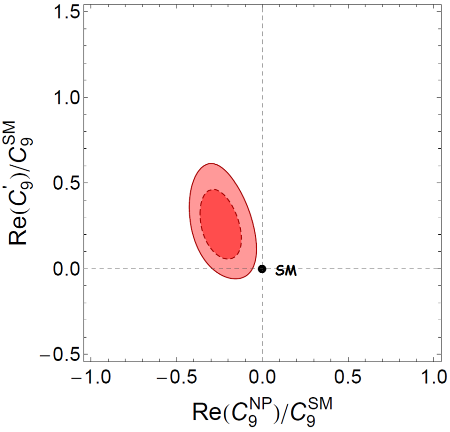
(WA, Straub '11 - '15)

2013



A Hint for Flavorful New Physics

favored new physics parameter space

$O_9 \propto (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \mu)$

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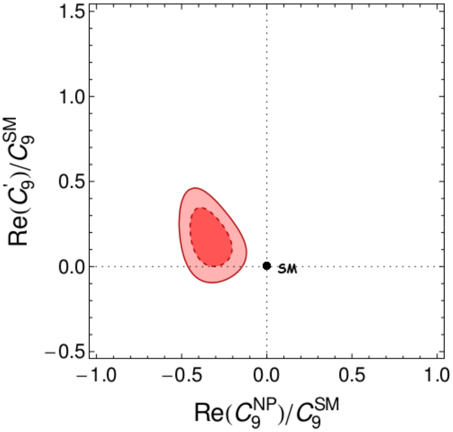
muonic vector current

(WA, Straub '11 - '15)

2014



favored new physics
parameter space

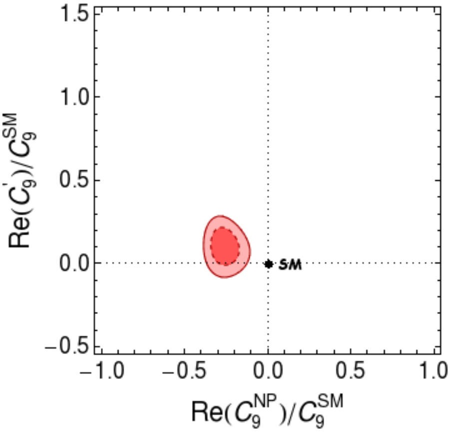
$$O_9 \propto (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \mu)$$

$$O_9' \propto (\bar{s}\gamma_\mu P_R b)(\bar{\mu}\gamma^\mu \mu)$$

muonic vector current

(WA, Straub '11 - '15)

2015



Distinguishing New Physics from Hadronic Effects

	LFU violation
hadronic effects?	✗
New Physics?	✓

Distinguishing New Physics from Hadronic Effects

	LFU violation	CP violation
hadronic effects?	✗	✗
New Physics?	✓	✓

Distinguishing New Physics from Hadronic Effects

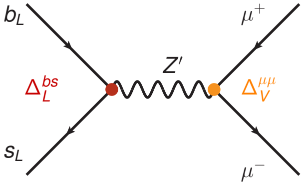
	LFU violation	CP violation	non-trivial q^2 dependence
hadronic effects?	✗	✗	✓
New Physics?	✓	✓	✗

Implications for the New Physics Scale

generic tree	$\frac{1}{\Lambda_{\rm NP}^2}(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 35~\text{TeV} \times (C_9^{\rm NP})^{-1/2}$
MFV tree	$\frac{1}{\Lambda_{\rm NP}^2}\, V_{tb}V_{ts}^*\,(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 7~\text{TeV} \times (C_9^{\rm NP})^{-1/2}$
generic loop	$\frac{1}{\Lambda_{\rm NP}^2}\frac{1}{16\pi^2}(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 3~\text{TeV} \times (C_9^{\rm NP})^{-1/2}$
MFV loop	$\frac{1}{\Lambda_{\rm NP}^2}\frac{1}{16\pi^2}\, V_{tb}V_{ts}^*\,(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 0.6~\text{TeV} \times (C_9^{\rm NP})^{-1/2}$

(assumes New Physics has O(1) coupling to muons)

Models with Flavor Changing Z' Bosons



many Z' models in the literature:

(WA, Straub '13/'14; Gauld, Goertz, Haisch '13;

Buras et al. '13/'14; WA, Gori, Pospelov, Yavin '14;

Glashow, Guadagnoli, Lane '14; Crivellin, D'Ambrosio,

Heeck '14/'15; Niehoff, Stangl, Straub '15; Aristizabal

Sierra, Staub, Vicente '15; Boucenna, Valle, Vicente '15;

Celis et al. '15; Crivellin et al. '15; ...)

alternatives:

(Datta, Duraisamy, Ghosh '13; Hiller, Schmaltz '14;

Biswas et al. '14; Gripaios, Nardecchia, Renner '14;

Buras et al. '14; Bhattacharya et al. '14;

Becirevic, Fajfer, Kosnik '15;

Alonso, Grinstein, Martin Camalich '15; ...)

$$C_9^{\rm NP} = \frac{\Delta_L^{bs}\Delta_V^{\mu\mu}}{V_{tb}V_{ts}^*}\,\frac{v^2}{M_{Z'}^2}\,\frac{4\pi^2}{e^2} \simeq \frac{\Delta_L^{bs}\Delta_V^{\mu\mu}}{V_{tb}V_{ts}^*}\,\frac{(5~{\rm TeV})^2}{M_{Z'}^2}$$

Summary

- the origin of the hierarchical flavor structure of the SM fermions remains mysterious
- in the absence of any direct sign of New Physics at the LHC, indirect probes are more important than ever
- various experimental results in rare B decays show tensions with the Standard Model predictions
- statistical fluctuations? hadronic effects? New Physics?
- looking forward to an exciting future with new data from LHC(b) and Belle II