Topical Lectures – Rare Decays

Discussion

N. Tuning

Discussion

Assignment:

1) History: study literature
   - Mixing
   - Cabibbo
   - GIM
   - KM
2) Combination of BR($B_s^0 \rightarrow \mu^+\mu^-$)
3) Latest status
   - W→lnu
   - g-2
   - Proton radius

Lessons:

1) Jargon: many "primes"… P_5', C_9', Z'
2) CKM vs PMNS
3) Different kaons
4) Significance global fit b→sll
5) Common misunderstandings

Assignments

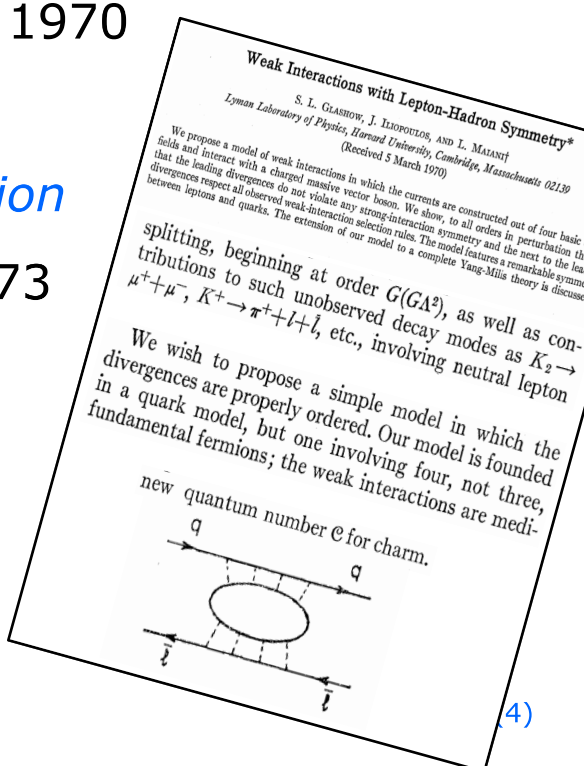
1) Study Literature

- Abraham Pais and Murray Gell-Mann, *Behavior of neutral particles under charge conjugation*, 1955

- Nicola Cabibbo, *Unitary symmetry and leptonic decays*, 1963

- Sheldon Lee Glashow, John Iliopoulos, and Luciano Maiani, *Weak interactions with lepton-hadron symmetry*, 1970

- Makoto Kobayashi, Toshihide Maskawa, *CP-violation in the renormalizable theory of weak interaction*, 1973


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 fields and interact with a charged massive vector boson. We show, to all orders in perturbation th that the leading divergences do not violate any strong-interaction symmetry and the next to the lea divergences respect all observed weak-interaction selection rules. The model features a remarkable symme between leptons and quarks. The extension of our model to a complete Yang-Mills theory is discusse

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.

2) $BR(B_s^0 \to \mu\mu)$ combination?

Exp	Year	Lumi	Sign	BR
LHCb	2011-2016	4.4 fb^{-1}	7.8σ	$3.0^{+0.7}_{-0.6}$
CMS	2011-2012	25 fb^{-1}	4.3σ	$3.0^{+1.0}_{-0.9}$
ATLAS	2011-2016	36 fb^{-1}	4.6σ	$2.8^{+0.8}_{-0.7}$

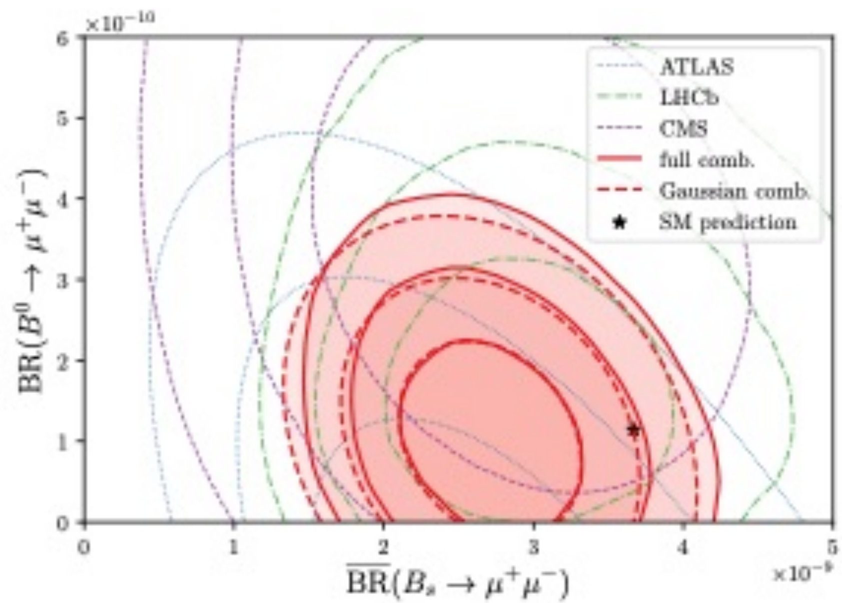
B-decay discrepancies after Moriond 2019

J.Aebischer, W. Altmannshofer, D. Guadagnoli, M.Reboud, P.Stangl, D.M. Straub

arXiv:1903.10434

?

$$\overline{\mathrm{BR}}(B_s \to \mu^+\mu^-) = (2.67^{+0.45}_{-0.35}) \times 10^{-9}$$



3) Latest status?

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

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

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:

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

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

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

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

BNL, hep-ex/0602035

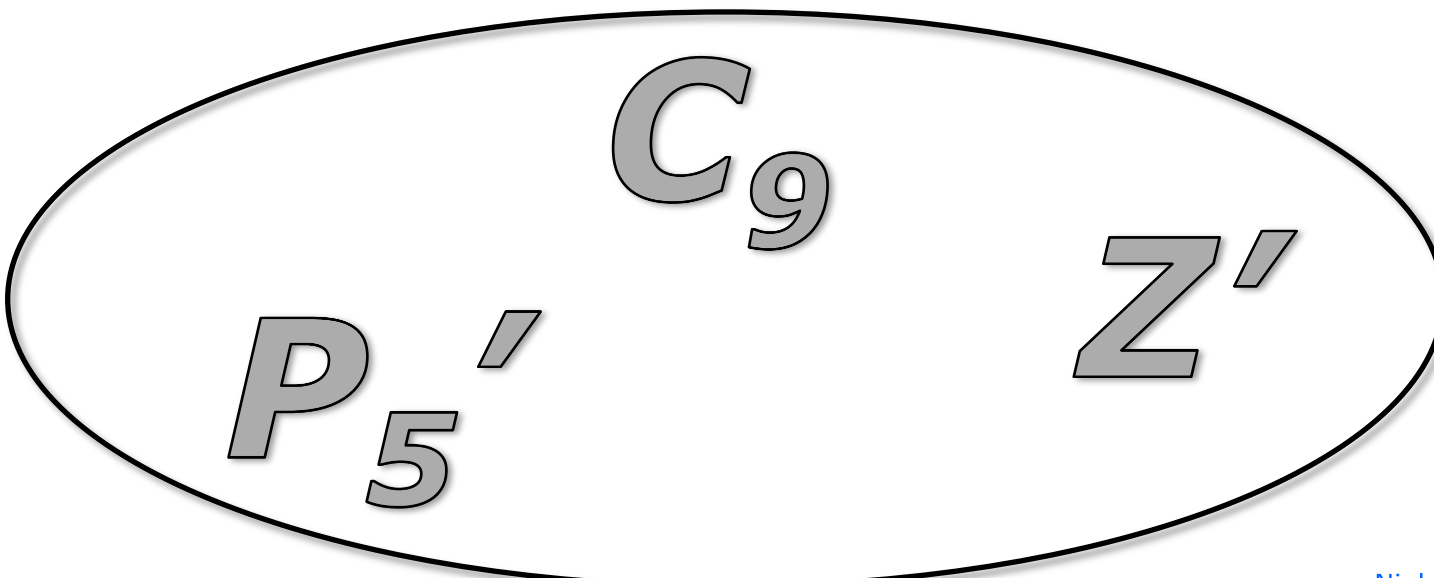
- Proton radius puzzle
  - 7 σ

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

Lessons

1) Jargon: “primes”



1) Jargon: “primes”

Theory

(What are Wilson coefficients?)

↓

Measurements

(sensitive to Wilson coefficients)

↓

Fit

(i.e. determine Wilson coefficients)

↓

Interpretation

(which models correspond to theses Wilson coefficients?)

P_5'

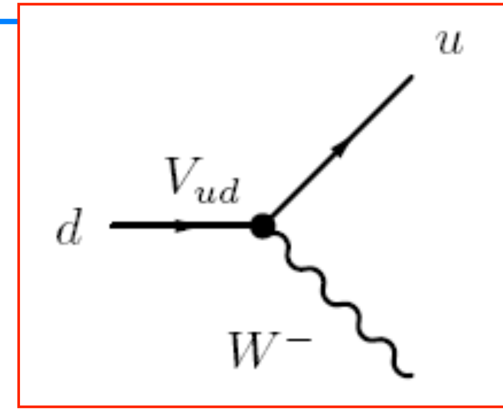
↓

C_9

↓

Z'

2) CKM vs PMNS



CKM matrix:

- Coupling strength of charged current
- Completely different hierarchy !

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

flavour mass

vs

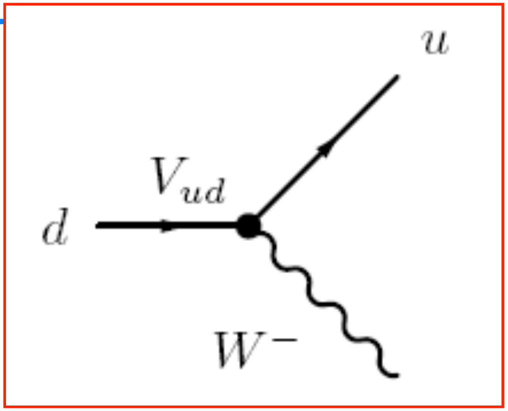
$$\begin{bmatrix} |d'\rangle \\ |s'\rangle \\ |b'\rangle \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} |d\rangle \\ |s\rangle \\ |b\rangle \end{bmatrix}.$$

flavour mass

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

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

2) CKM vs PMNS



CKM matrix:

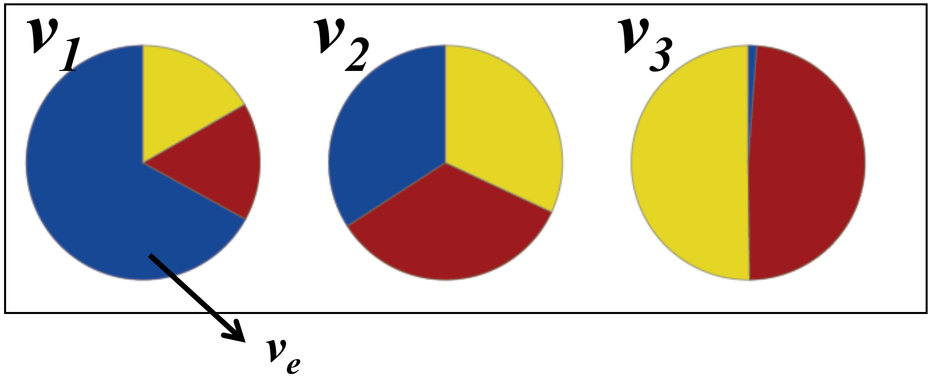
- Coupling strength of charged current
- Completely different hierarchy !

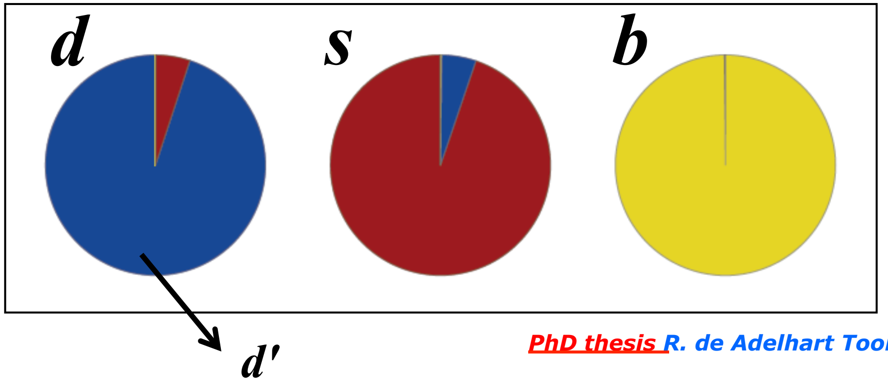
$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = \begin{bmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{bmatrix}\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}$$

vs

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

flavour **mass** **flavour** **mass**



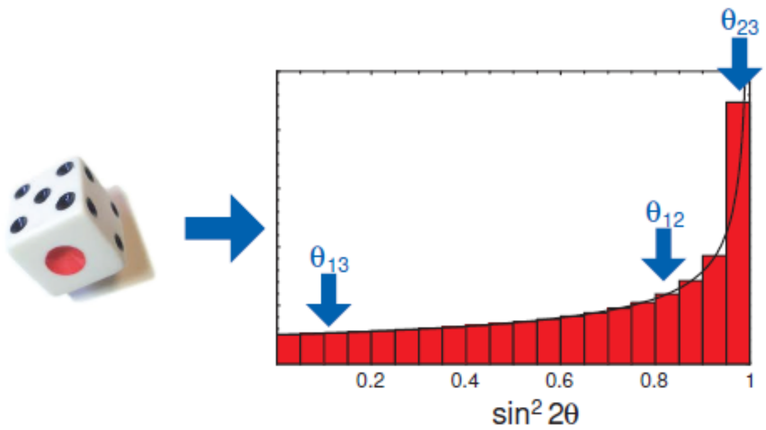


PhD thesis R. de Adelhart Toor

2) CKM vs PMNS

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:

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

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

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

3) Different kaons

- Different notation: confusing!

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

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

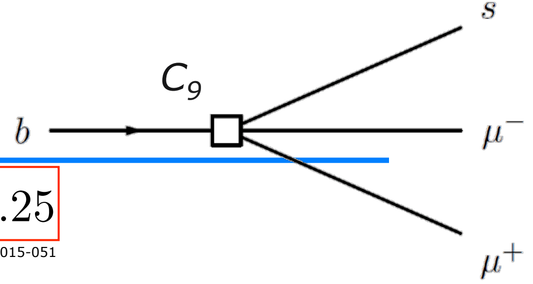
$$|K_L\rangle = p\,|K^0\rangle - q\,|\overline{K^0}\rangle$$
$$|K_S\rangle = p\,|K^0\rangle + q\,|\overline{K^0}\rangle$$

$$|K_1\rangle = |K^0\rangle + |\overline{K^0}\rangle$$
$$|K_2\rangle = |K^0\rangle - |\overline{K^0}\rangle$$

- 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??

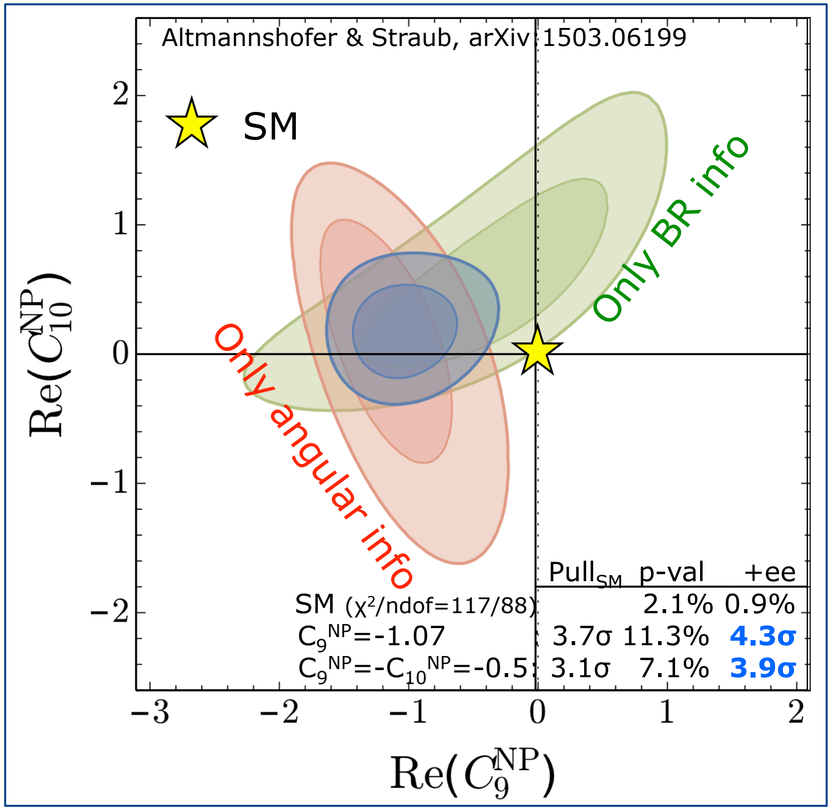
4) Significance Fit

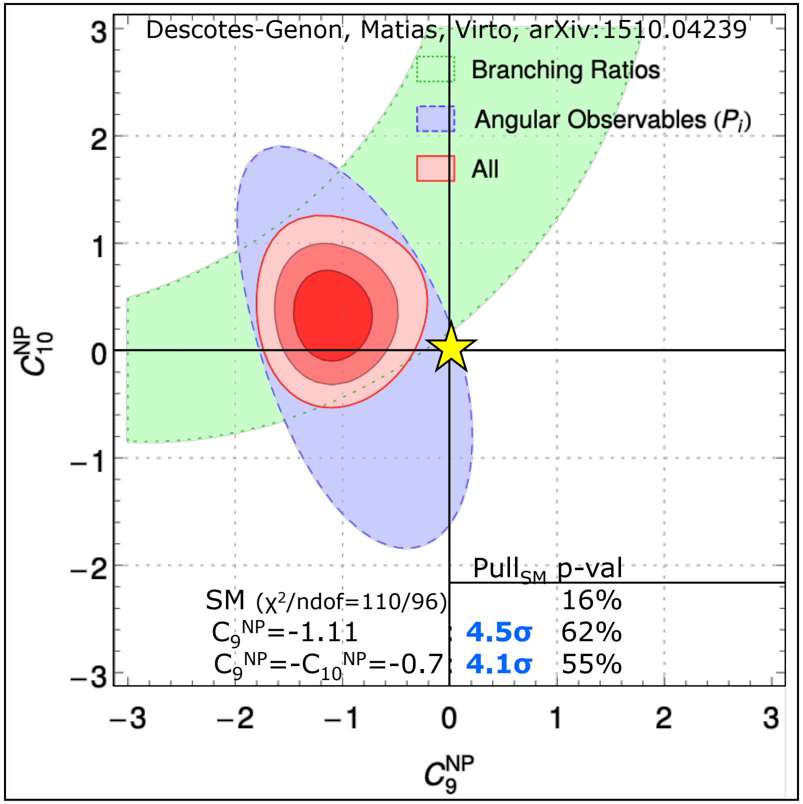


$$\boxed{\Delta\mathrm{Re}(\mathcal{C}_9) = -1.04 \pm 0.25}$$

LHCb-PAPER-2015-051

- C_9^{NP} deviates from 0 by >4σ
- Caveat: debate on non-pertirbative charm-loop effects





4) Significance Fit

- 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

4) Significance Fit

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

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

Descotes, Virto, Matias, arXiv:1510.04239

4) Significance Fit

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

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

Descotes, Virto, Matias, arXiv:1510.04239

4) Significance Fit

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

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

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

Descotes, Virto, Matias, arXiv:1510.04239

5) 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 $K_L \rightarrow \pi\ \pi$
5) K_S^0 ≠ CP eigenstate