Charging a leptoquark under $L_\mu - L_\tau$

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La Sapienza, Rome

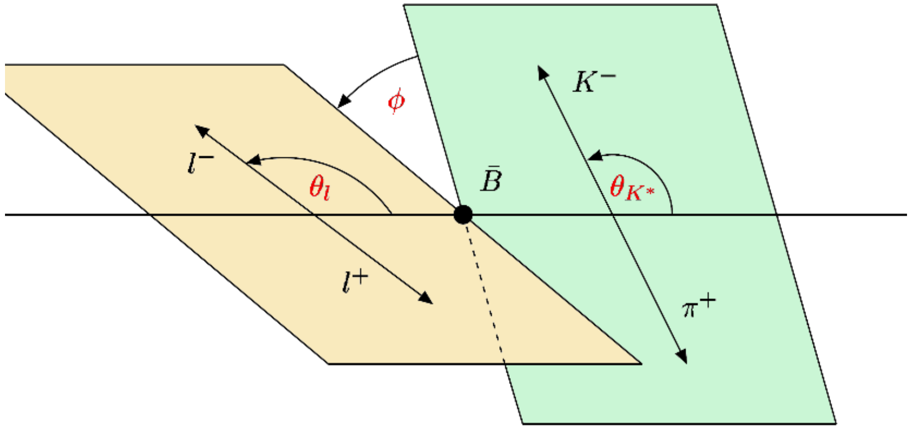
Siegen seminar – 22 June 2020

(based on 2007.xxxxx with Joe Davighi, Marco Nardecchia)

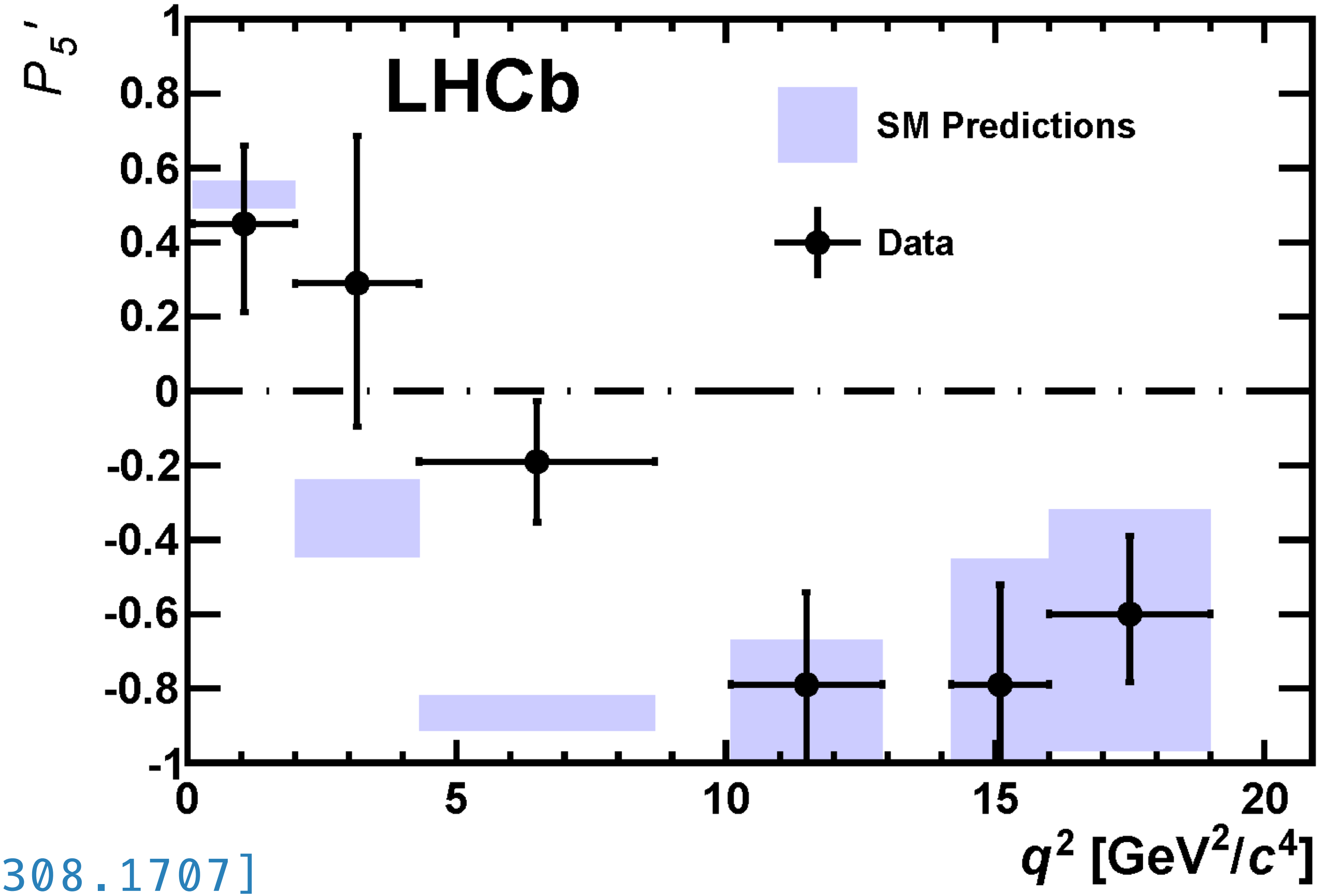
Flavour Anomalies – a history

- P_5' in 2013, $2.8\,\sigma$ deviation
- R_K in 2014, $2.6\,\sigma$ deviation
- R_{K^*} in 2017, $2.5\,\sigma$ deviation
- R_K in 2019, $2.5\,\sigma$ deviation
- R_{pK}^{-1} in 2019, $< 1\,\sigma$ deviation
- P_5' in 2020, $2.5\,\sigma$ deviation

P_5'



$$
\begin{aligned}
\frac{1}{\mathrm{d}\Gamma/dq^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[& \frac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K + \frac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_\ell \\
& - F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi \\
& + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi \\
& + S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi \\
& + S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi \Big],
\end{aligned}
$$

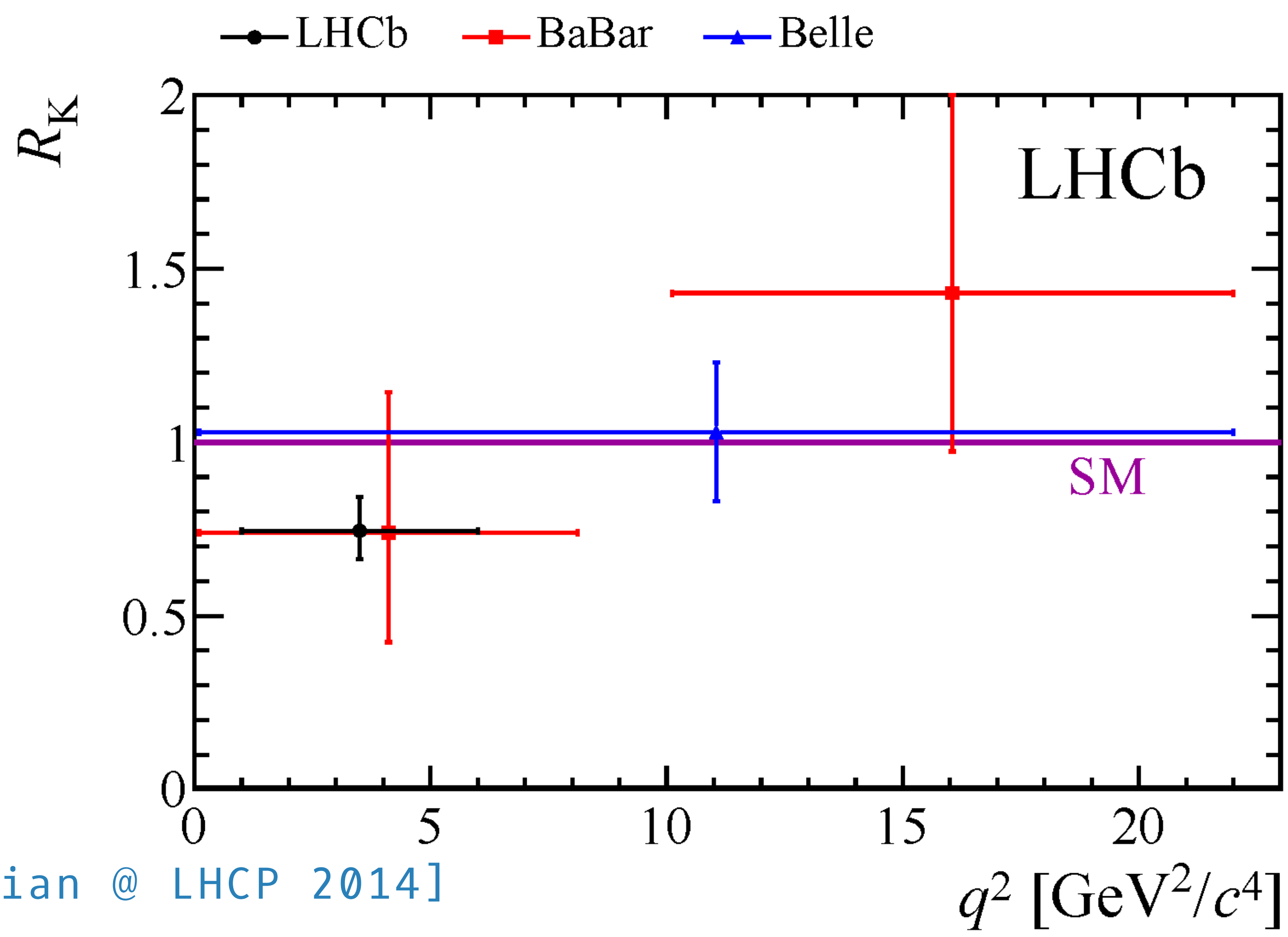


LHCb
SM Predictions
Data
P_5'
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
0
5
10
15
20
q^2 [GeV^2/c^4]

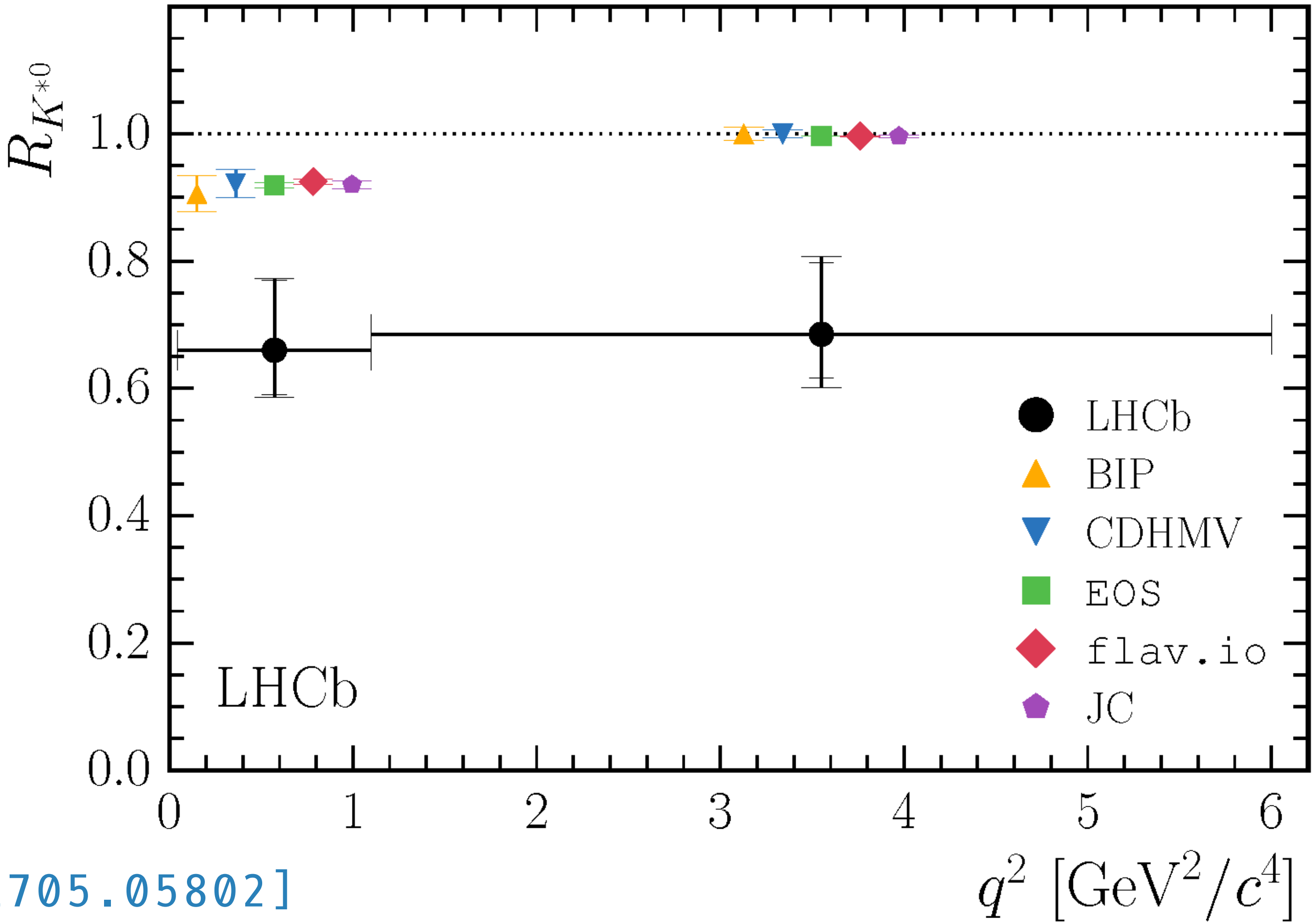
[1308.1707]

$R_{K^{(*)}}$

$$R_{K^{(*)}} = \frac{\mathcal{B}\left(B \to K^{(*)}\mu^+\mu^-\right)}{\mathcal{B}\left(B \to K^{(*)}e^+e^-\right)}$$

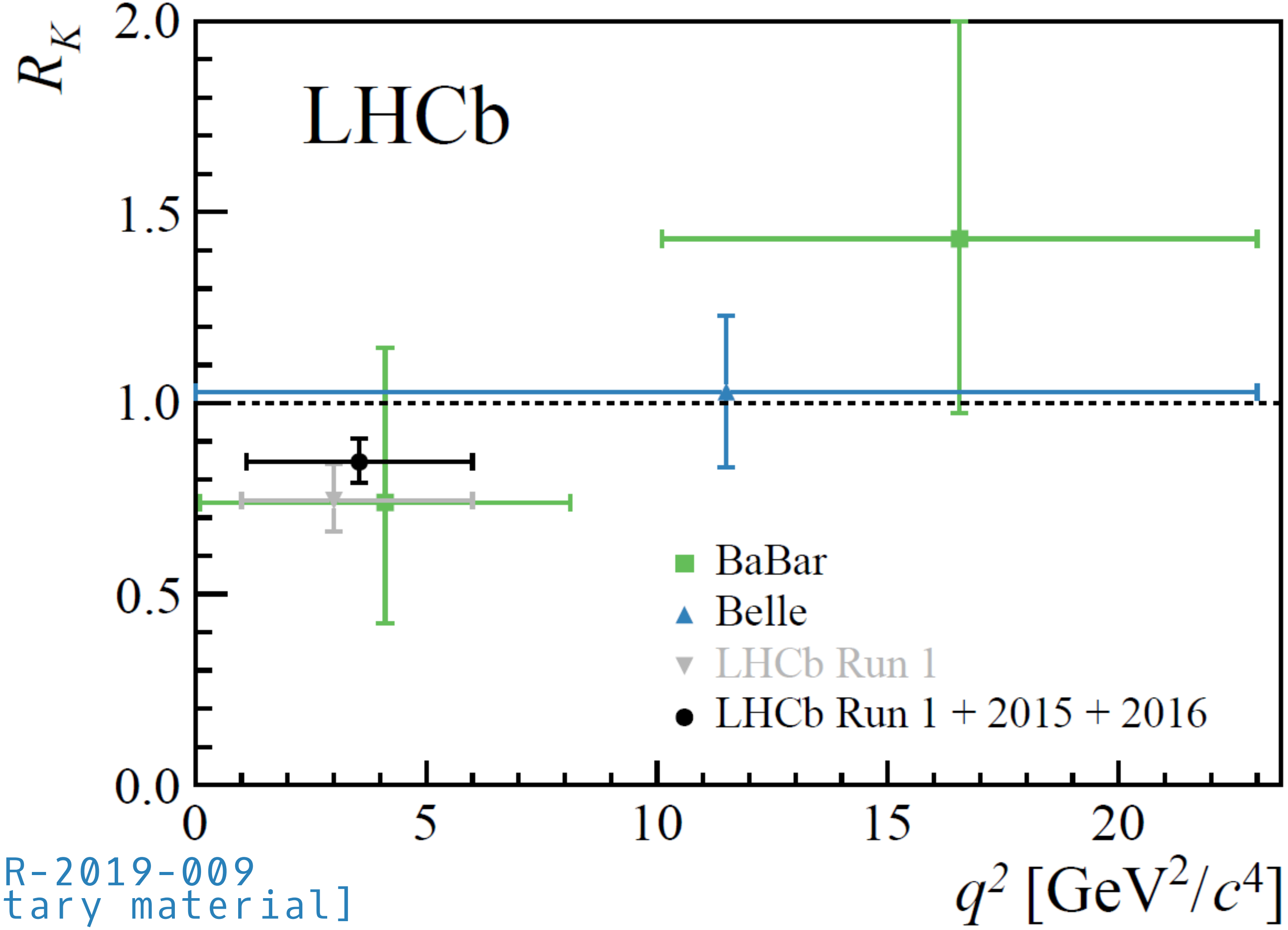


[De Cian @ LHCP 2014]

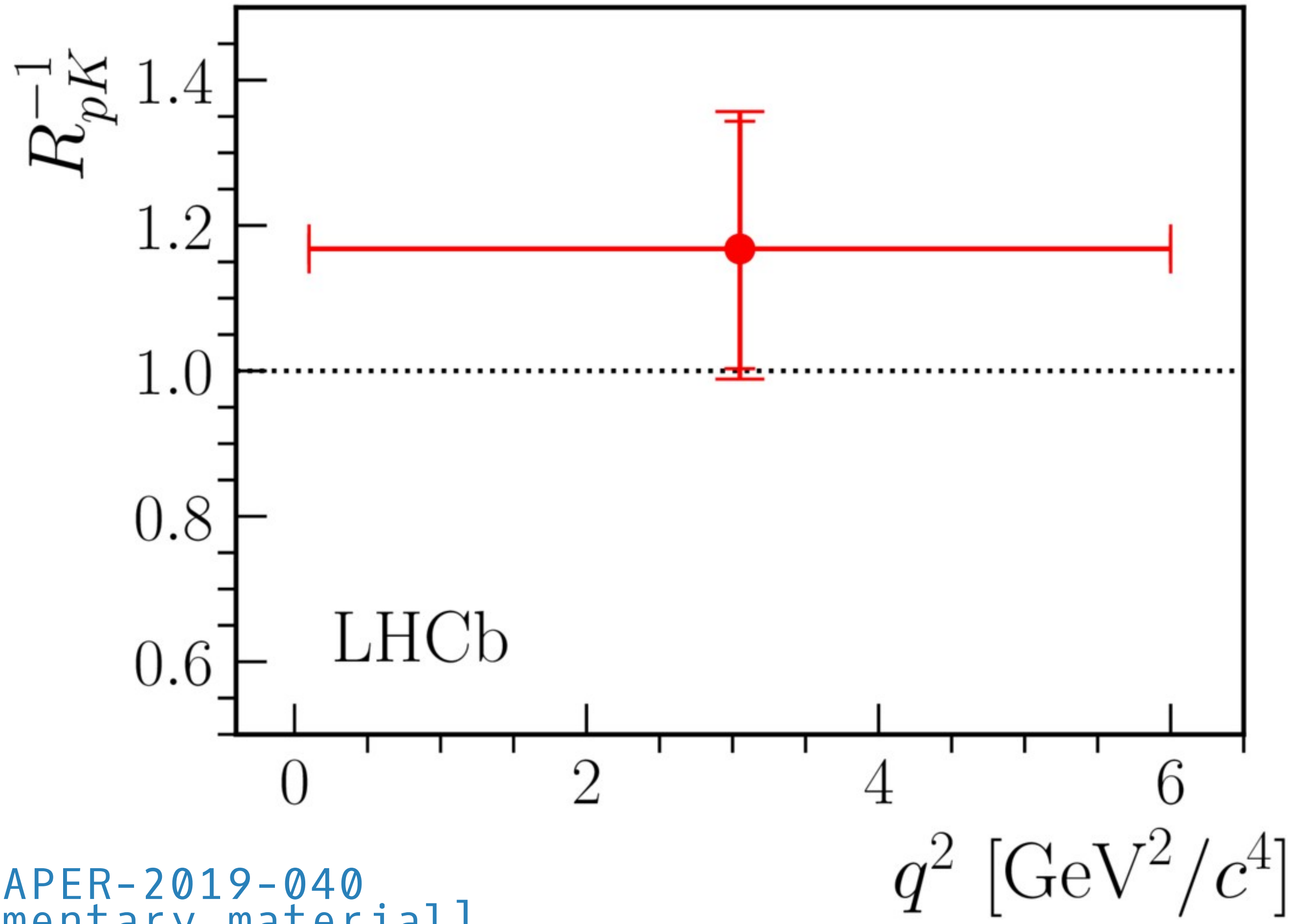


$R_{K^{*0}}$
1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
5
6
q^2 [GeV^2/c^4]
LHCb
BIP
CDHMV
EOS
flav.io
JC
LHCb

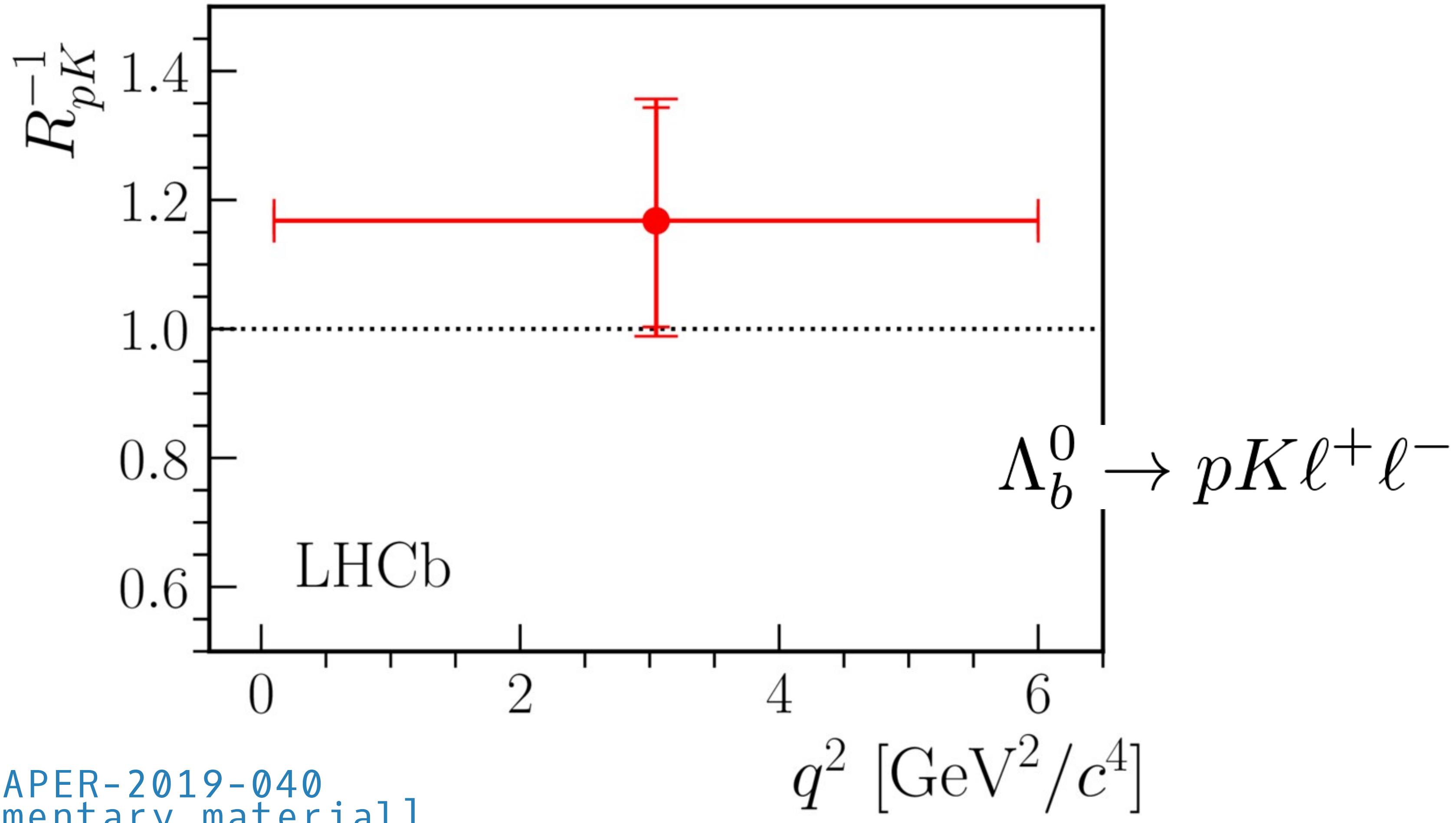
[1705.05802]



[LHCb-PAPER-2019-009 supplementary material]



[LHCb-PAPER-2019-040 supplementary material]



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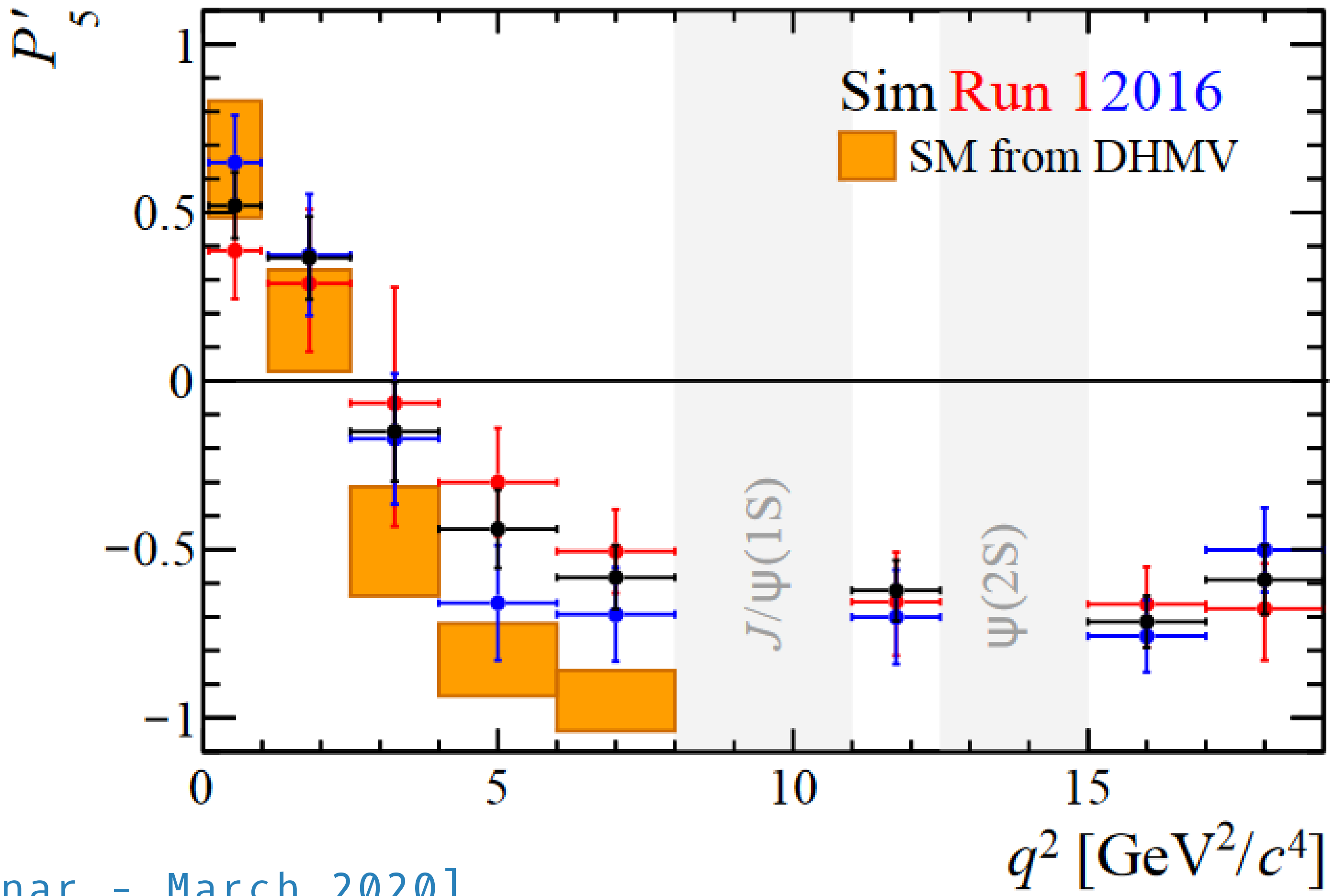

[LHCb seminar - March 2020]

Flavour Anomalies – a history

- Plus many more non "headline" observables
- All in $b \to s\ell\ell$ decay modes
- We often talk about a coherent set of anomalies
  - i.e. all the data points the same way
- Think about this in terms of a global fit

$b \to s\ell\ell$ operators

- What operators can affect the $b \to s\ell\ell$ decay?
- $C_9, C_{10}, C_9', C_{10}'$

$$\mathcal{O}_{9\ell} = \frac{e}{16\pi^2} m_b (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell), \qquad \mathcal{O}_{9'\ell} = \frac{e}{16\pi^2} m_b (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell),$$

$$\mathcal{O}_{10\ell} = \frac{e}{16\pi^2} m_b (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell), \qquad \mathcal{O}_{10'\ell} = \frac{e}{16\pi^2} m_b (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell).$$

$b \to s\ell\ell$ operators

- What operators can affect the $b \to s\ell\ell$ decay?
- $C_9, C_{10}, C_9', C_{10}'$
- (+$C_7, C_7', C_S, C_P, C_T, C_{T5}$)
  - $C_{T,T5} = 0$ from SMEFT
  - $C_7^{(\prime)} \approx 0$ from $B \to X_s\gamma$
  - $C_{S,P} \approx 0$ from $B_s \to \mu\mu$

(see backup for more)

Global fit

	All				LFUV			
1D Hyp.	Best fit	$1\ \sigma/2\ \sigma$	Pull_{SM}	p-value	Best fit	$1\ \sigma/\ 2\ \sigma$	Pull_{SM}	p-value
$\mathcal{C}_{9\mu}^{\text{NP}}$	-1.03	$[-1.19, -0.88]$ $[-1.33, -0.72]$	6.3	37.5 %	-0.91	$[-1.25, -0.61]$ $[-1.63, -0.34]$	3.3	60.7 %
$\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{10\mu}^{\text{NP}}$	-0.50	$[-0.59, -0.41]$ $[-0.69, -0.32]$	5.8	25.3 %	-0.39	$[-0.50, -0.28]$ $[-0.62, -0.17]$	3.7	75.3 %
$\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{9'\mu}$	-1.02	$[-1.17, -0.87]$ $[-1.31, -0.70]$	6.2	34.0 %	-1.67	$[-2.15, -1.05]$ $[-2.54, -0.48]$	3.1	53.1 %
$\mathcal{C}_{9\mu}^{\text{NP}} = -3\mathcal{C}_{9e}^{\text{NP}}$	-0.93	$[-1.08, -0.78]$ $[-1.23, -0.63]$	6.2	33.6 %	-0.68	$[-0.92, -0.46]$ $[-1.19, -0.25]$	3.3	60.8 %

TABLE VII. Most prominent 1D patterns of NP in $b \to s\mu^+\mu^-$ transitions (state-of-the-art fits as of March 2020). Here, Pull_{SM} is quoted in units of standard deviation and the p-value of the SM hypothesis is 1.4% for the fit "All" and 12.6% for the fit LFUV.

[1903.09578 (Apr 2020 addendum)]

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- P_5' in 2020, 2.5s local deviation

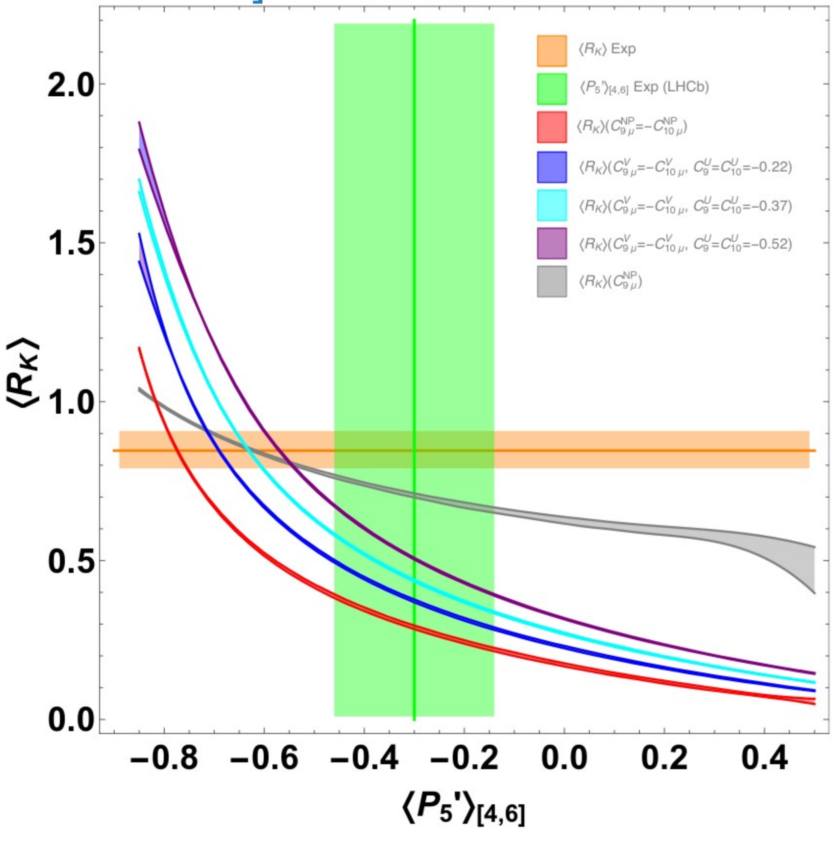
Isn’t this a bad sign?

New P_5'

- P_5' became (a little) less significant
- However, this actually improved the overall fit

New P'_5

[1902.04900]



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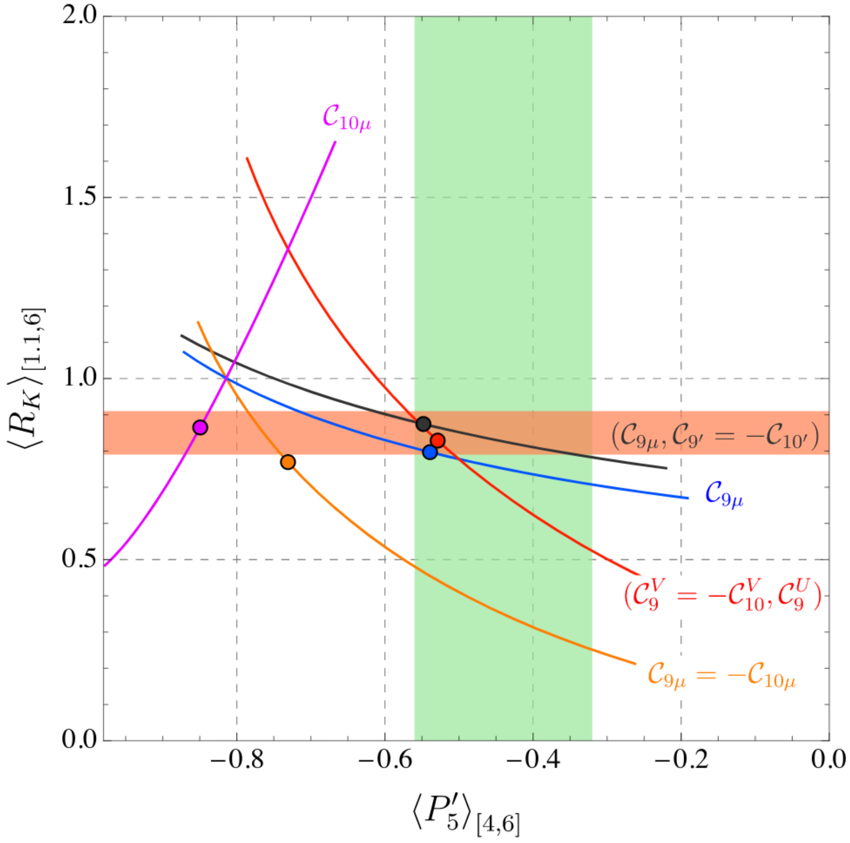

NP scenarios

	All				LFUV			
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TABLE VII. Most prominent 1D patterns of NP in $b \to s\mu^+\mu^-$ transitions (state-of-the-art fits as of March 2020). Here, Pull_{SM} is quoted in units of standard deviation and the p-value of the SM hypothesis is 1.4% for the fit "All" and 12.6% for the fit LFUV.

[1903.09578 (Apr 2020 addendum)]

NP scenarios

- $C_9^\mu = -C_{10}^\mu$ is quite appealing as this corresponds to an operator with LH quarks and LH muons
- Just what you might expect from some NP above the EW scale that is $SU(2)_L$ invariant

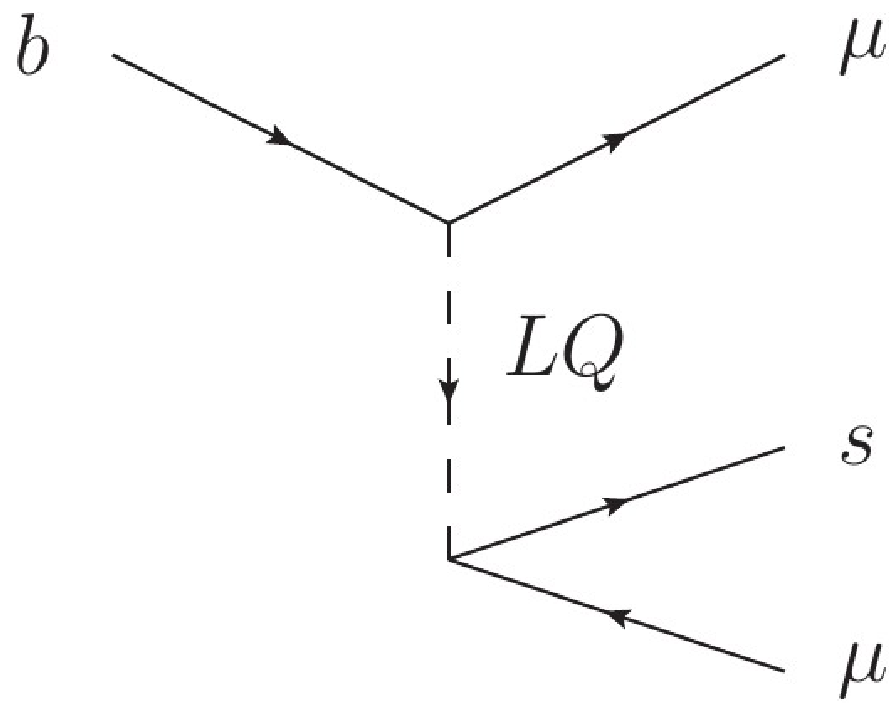
Leptoquarks

- New particle carrying baryon and lepton number
- Interactions of the form $\mathrm{LQ}\, q\, \ell$
- Can be either vectors or scalars
- Naturally arise in unified theories

Leptoquarks for $b \to s\ell\ell$

- Tree level contribution to the flavour anomalies
- Best fit indicates

$$\frac{M_{\mathrm{LQ}}}{\sqrt{\lambda_{b\mu}\lambda_{s\mu}}} \approx 35\,\mathrm{TeV}$$



Scalar or vector?

- Massive vector states need to be embeded in a UV complete theory in order to be able to make predictions at loop level
- Adding a new massive scalar is "simpler"
  - (see later for discussion of perturbative stability of scalar masses)

Scalar leptoquarks

- Only one scalar leptoquark that gives $b \to s\ell\ell$
- $S_3 \sim (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$
  - Colour anti-triplet
  - $SU(2)_L$ triplet
  - Hypercharge = 1/3

S_3 scalar leptoquark

- $S_3 \sim (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$
- The lagrangian term relevant for flavour anomalies looks like $\lambda^{QL}_{ij} \overline{Q^c_i} L_j S_3$
- In particular, we need $\lambda^{QL}_{32,22} \neq 0$
- But ...

Problems with S_3

- With non-zero coupling to electrons, we induce LFV (e.g. $\mu \to e\gamma$), which are very tightly constrained
- Similar for tau couplings (e.g. $B \to K\mu\tau$)

Problems with S_3

- There is also generically a diquark coupling that looks like $\lambda_{ij}^{QQ}\overline{Q_i^c}Q_jS_3$
- This induces proton decay

Problems with S_3

- How to get the pattern of couplings:
  - $\lambda^{QL}_{32,22} \neq 0$
  - $\lambda^{QL}_{i1,i3} \approx 0$
  - $\lambda^{QQ}_{11} \approx 0$

S_3 charged under $L_\mu - L_\tau$

- Extend the gauge symmetry
- $G_{\rm SM} = SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$
  $\to SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_{L_\mu - L_\tau}$
- $S_3 \sim (\bar{\mathbf{3}}, \mathbf{3}, 1/3) \to (\bar{\mathbf{3}}, \mathbf{3}, 1/3, -1)$

S_3 charged under $L_\mu - L_\tau$

- $S_3 \sim (\bar{\mathbf{3}}, \mathbf{3}, 1/3) \to (\bar{\mathbf{3}}, \mathbf{3}, 1/3, -1)$
- Forces
  - $\lambda_{ij}^{QL} = \alpha_i \delta_{j2}$
  - $\lambda_{ij}^{QQ} = 0$
- Also: $L_\mu - L_\tau$ is anomaly free
  - No extra fermions needed

S_3 charged under $L_\mu - L_\tau$

- Other benefits:
- $L_\mu - L_\tau$ is anomaly free
  - No extra fermions needed
- Enforces lepton flavour conservation
  - All LFV constraints automatically satisfied

Can we “see” this extra U(1)?

- Are there measurements we can make that can tell we have an extra gauge symmetry?
- A plain new U(1) => new massless gauge boson
  - Ruled out by fifth force searches
- Break the U(1) using Higgs mechanism

Can we "see" this extra U(1)?

- Can we just make our new Higgs-like scalar (Φ) and the new gauge boson (X_μ) very heavy?
- These new bosons don't contribute to the "interesting" phenomenology, so maybe?
- Is a hierarchy like $M_h \ll M_{S_3} \ll M_\Phi, M_X$ plausible?

Scalar mass stability

- In the SM, there is the hierarchy "problem"

Hierarchy problem

- Calculate the loop corrections to the Higgs mass with cutoff regularization
  - $\delta M_h^2 \sim \Lambda^2$
- If you think SM is valid up to Plank scale
- $\Lambda \approx M_{\rm Pl} \sim 10^{19}\,{\rm GeV} \Rightarrow$ enormous corrections

Hierarchy problem

- But in the SM alone, there is no higher scale
- Higgs mass corrections are calcuable in dim-reg
- $\delta M_h^2 = M_h^2 \left(0.133 + \gamma_m \ln \frac{\mu^2}{m_t^2} \right)$
- At the scale $\mu = m_t$ (which is the largest scale in the SM), the mass corrections are ~ 13%

Finite naturalness

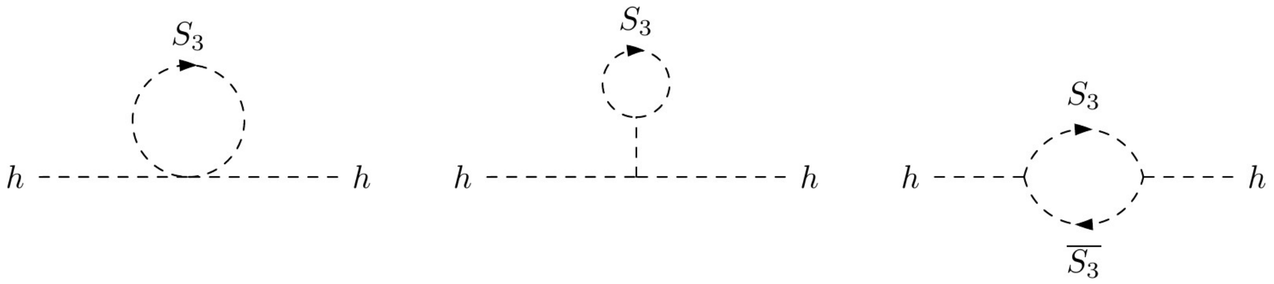
- This idea was introduced in 1303.7244 [Farina, Pappadopulo, Strumia]
- Called finite naturalness
- Define $\Delta = \delta M_h^2 / M_h^2$ as the measure of naturalness
- $\Delta \lesssim 1$ is "natural" – SM has $\Delta \approx 0.13$

Finite naturalness

- For a NP model, you can "bound" some of the parameters of your model by what size of Δ you think is acceptable.

Finite naturalness for Higgs

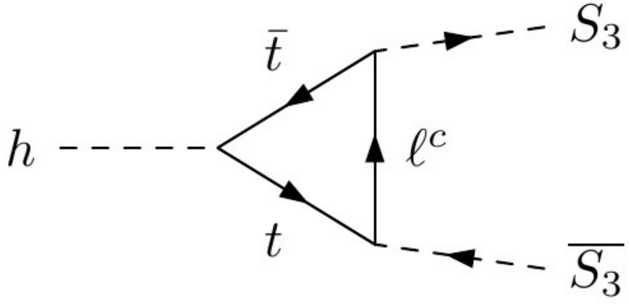
- Get Higgs mass corrections from S_3 in the loop

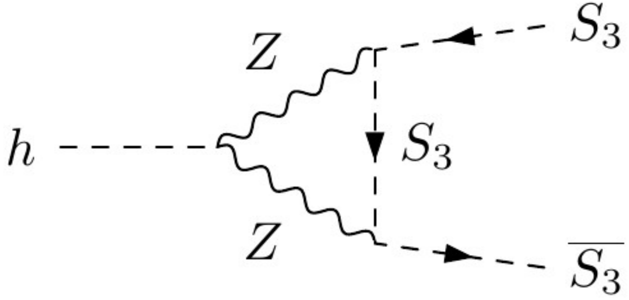


- $\delta M_h^2 = -\frac{9 M_{S_3}^2}{16\pi^2} \lambda_{HS} \left(1 + \ln \frac{\mu^2}{M_{S_3}^2} \right)$ => $M_{S_3} \lesssim \frac{520\,\mathrm{GeV}}{\sqrt{\lambda_{HS}}} \sqrt{\Delta}$
- How big is λ_{HS} ?

Finite naturalness for Higgs

- λ_{HS} is generated by top and gauge boson loops
- Give opposite sign contributions





Finite naturalness for Higgs

- $M_{S_3} \lesssim \frac{4.7\,\mathrm{TeV}}{\sqrt{|0.64 - |\alpha_3 + V_{ts}\alpha_2|^2|}}\sqrt{\Delta}$
- So for certain parameter values, the Higgs mass correction is “natural”

Finite naturalness for S_3

- $\delta M_{S_3}^2 \propto g_X^2 M_X^2$
- So if we take g_X to be very small (and fix M_X, which is equivalent to large v_Φ) these corrections are also under control

What does this all mean?

- We can propose our model with the following hierarchy: $M_h \ll M_{S_3} \ll M_\Phi, M_X$
- And make an argument that it is "natural"

What does this all mean?

- Which gives us a LQ that:
  - Couples only to muons
  - Doesn’t induce proton decay term
- But the particles associated with the gauge symmetry can be hidden away at much higher mass scales

Gauge decoupled

- The new gauge sector is decoupled from the SM+leptoquark
- We are left with a reduced parameter space:
  - $M_{S_3}, \alpha_1, \alpha_2, \alpha_3$
    - $\mathcal{L} \supset \alpha_i \overline{Q_i^c} L_2 S_3$

Flavour structure

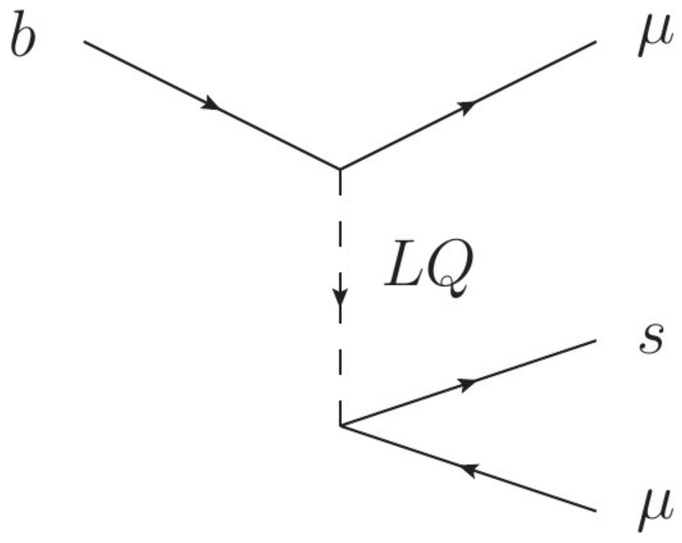
- Our Lagrangian ($\mathcal{L} \supset \alpha_i \overline{Q_i^c} L_2 S_3$) couples to a simple linear combination of quark flavours
- This an example of linear flavour violation (1509.05020 [Gripaios, Nardecchia, Renner]) and rank-one flavour violation (1903.10954 [Gherardi,Marzocca,Nardecchia,Romanino])

Flavour structure

- A plausible choice for the alignment of this vector in flavour space is the 3rd generation CKM matrix elements
- $(\alpha_1, \alpha_2, \alpha_3) \propto (V_{ub}, V_{cb}, V_{tb})$
- Come naturally out of partial compositeness framework, or a U(2) flavour symmetry for NP

Phenomenology

- What do measurements say about our quark couplings?
- Observables:
  - $b \to s\ell\ell$ anomalies
  - B_s mixing
  - Direct searches at LHC



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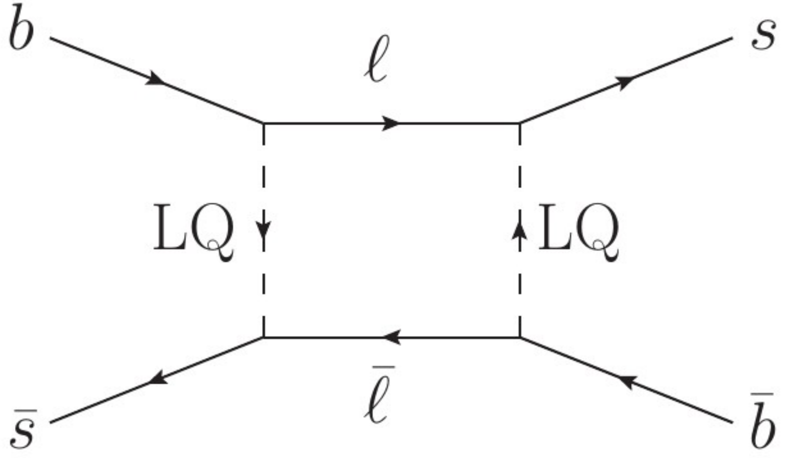

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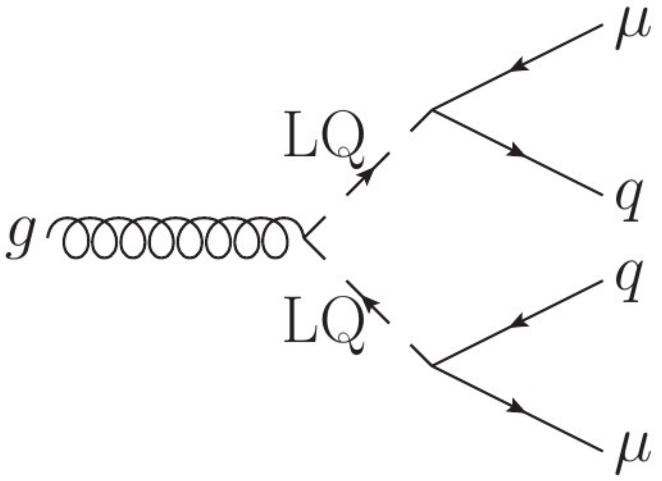


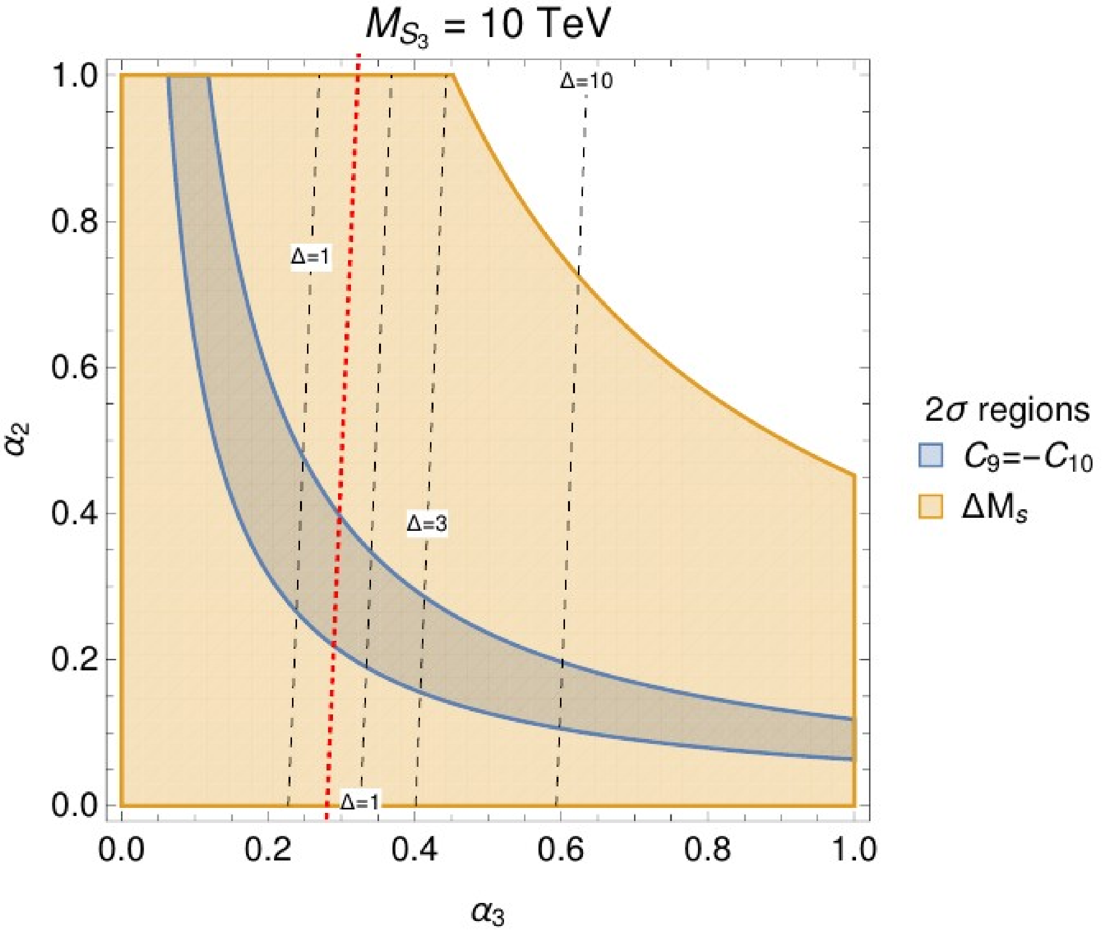
Phenomenology

- $b \to s\ell\ell$ anomalies: $2\,\sigma$ range fixes

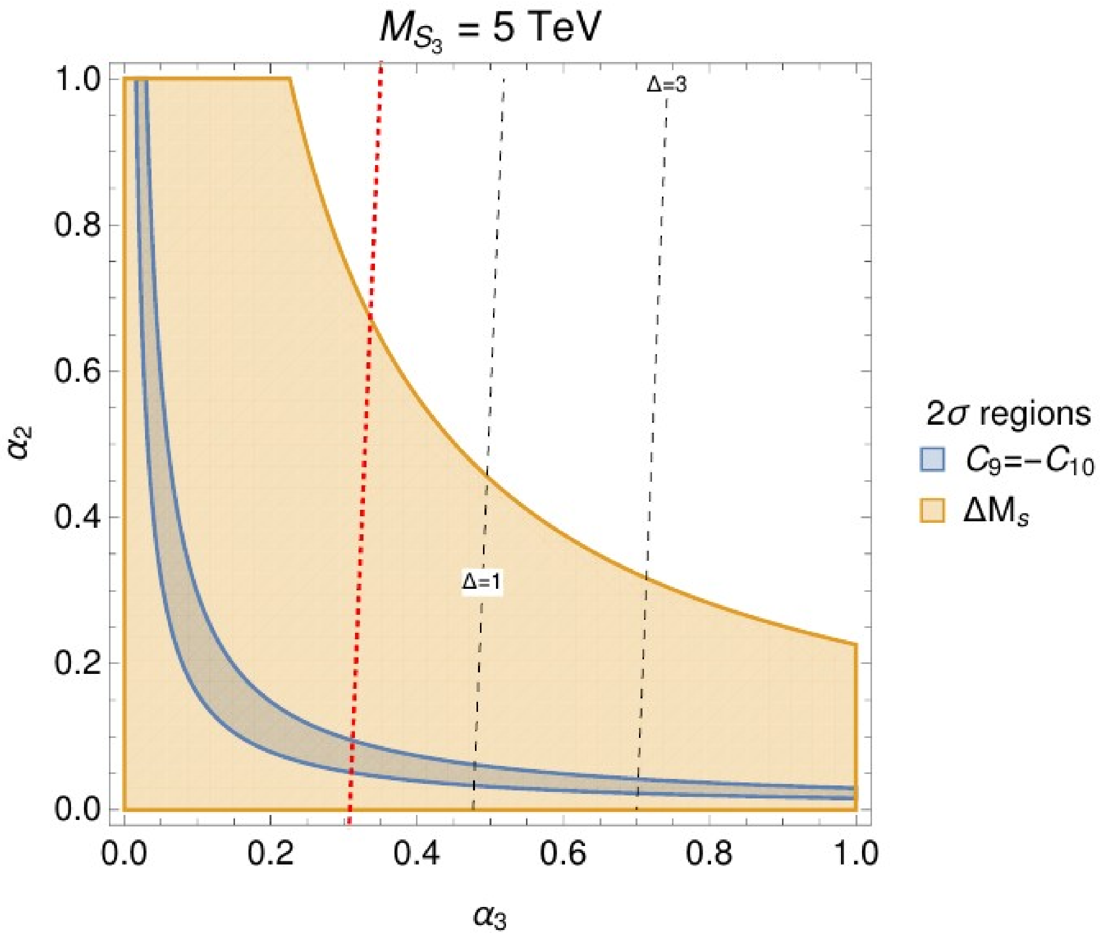
$$30\,\mathrm{TeV} \leq \frac{M_{S_3}}{\sqrt{\alpha_3\alpha_2}} \leq 45\,\mathrm{TeV}$$

- B_s mixing: $\dfrac{M_{S_3}}{\alpha_3\alpha_2} \gtrsim 22\,\mathrm{TeV}$

- Direct searches: $M_{S_3} \gtrsim 1.5\,\mathrm{TeV}$



M_{S_3} = 10 TeV
1.0
0.8
0.6
0.4
0.2
0.0
α_2
0.0
0.2
0.4
0.6
0.8
1.0
α_3
Δ=10
Δ=1
Δ=3
Δ=1
2σ regions
C_9=−C_{10}
ΔM$_s$

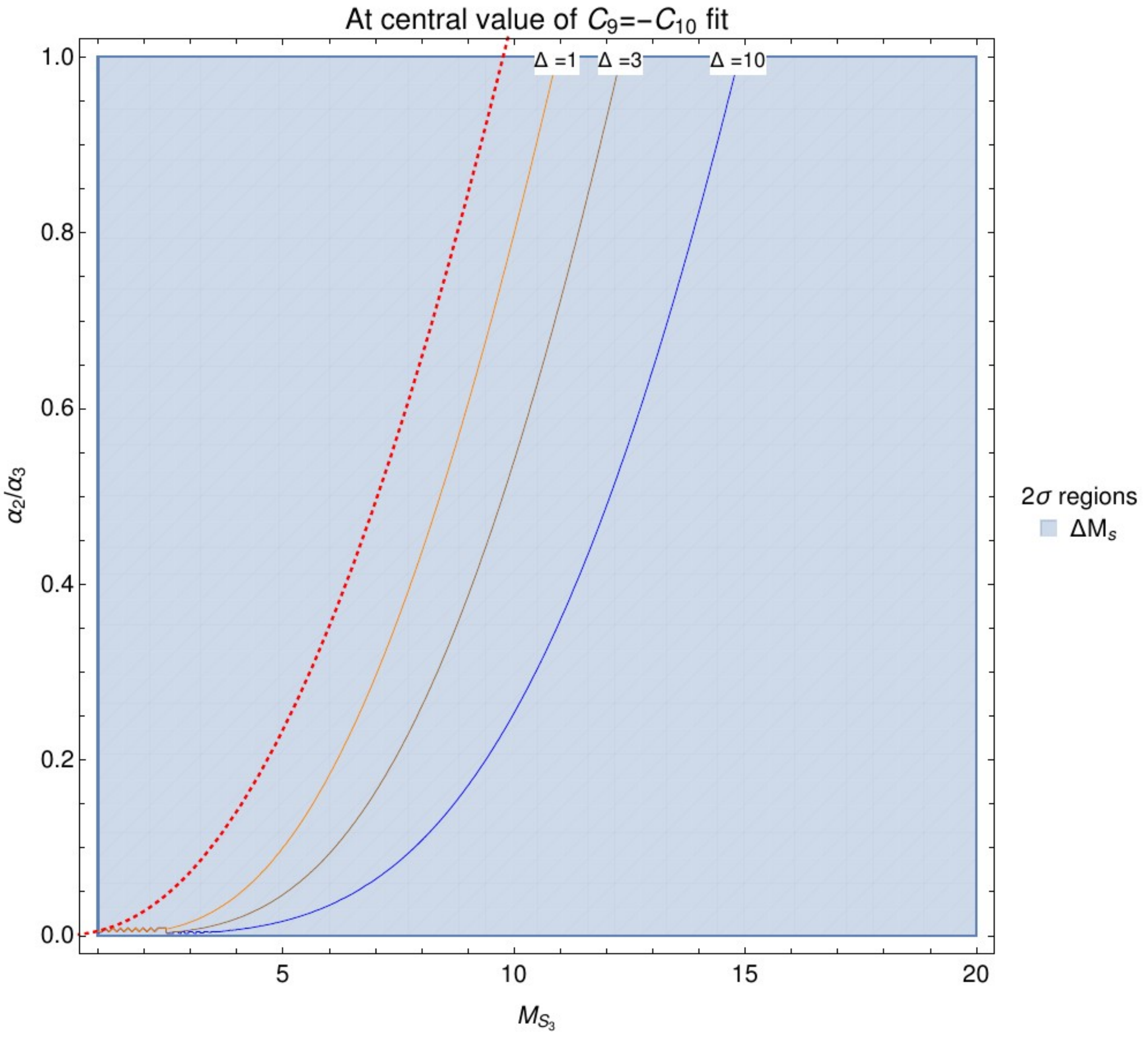


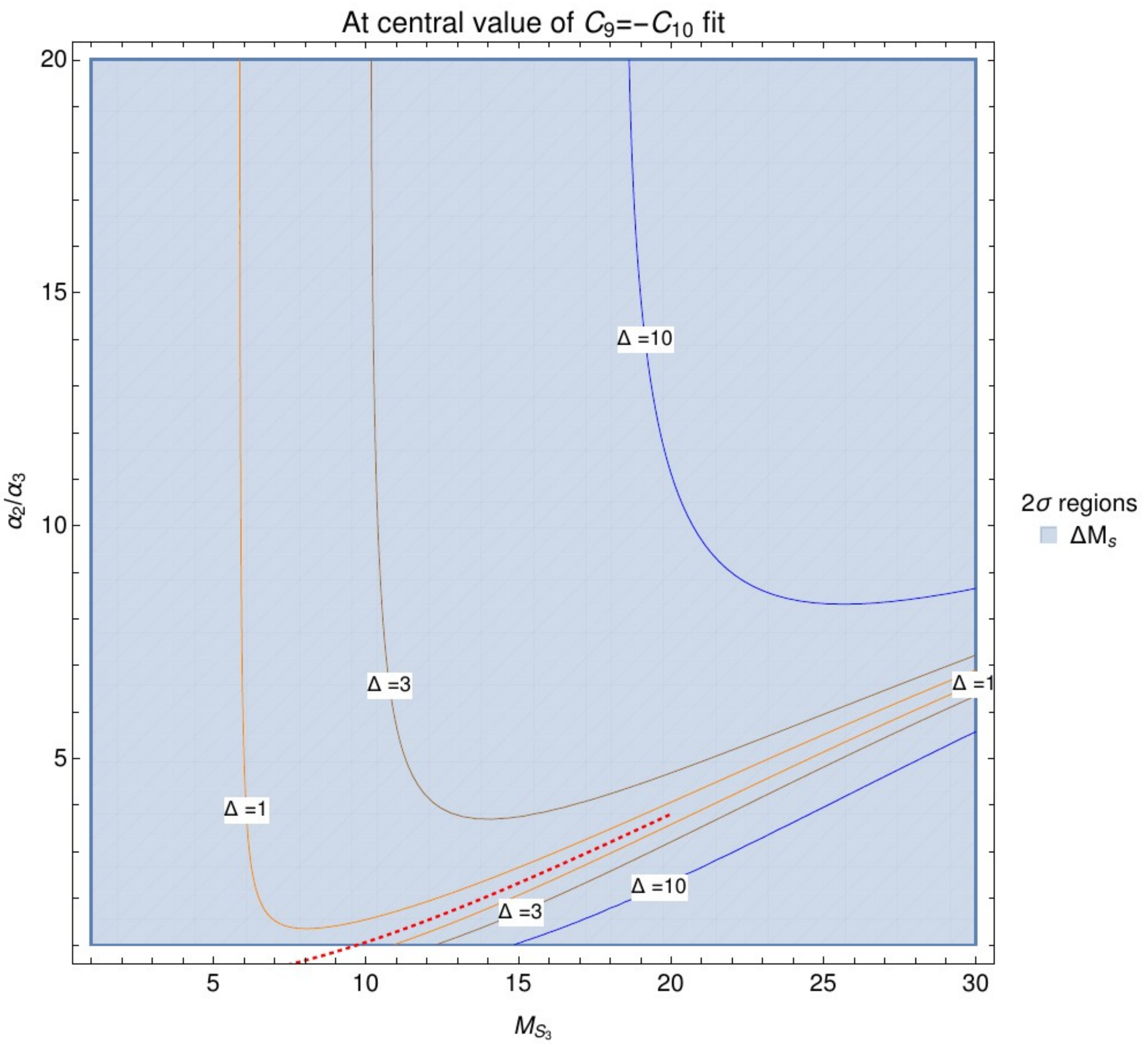
M_{S_3} = 5 TeV
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
α_2
α_3
Δ=1
Δ=3
2σ regions
C_9=−C_{10}
ΔM_s

Summary

- S_3 is a well known solution of the flavour anomaly problem
- Charging it under $U(1)_{L_\mu - L_\tau}$ solves some conceptual problems
- It is possible to “hide” the new $U(1)$ at a high scale, in a natural way

Backup


At central value of $C_9=-C_{10}$ fit
Δ =1
Δ =3
Δ =10
1.0
0.8
0.6
0.4
0.2
0.0
5
10
15
20
α_2/α_3
M_{S_3}
2σ regions
ΔM_s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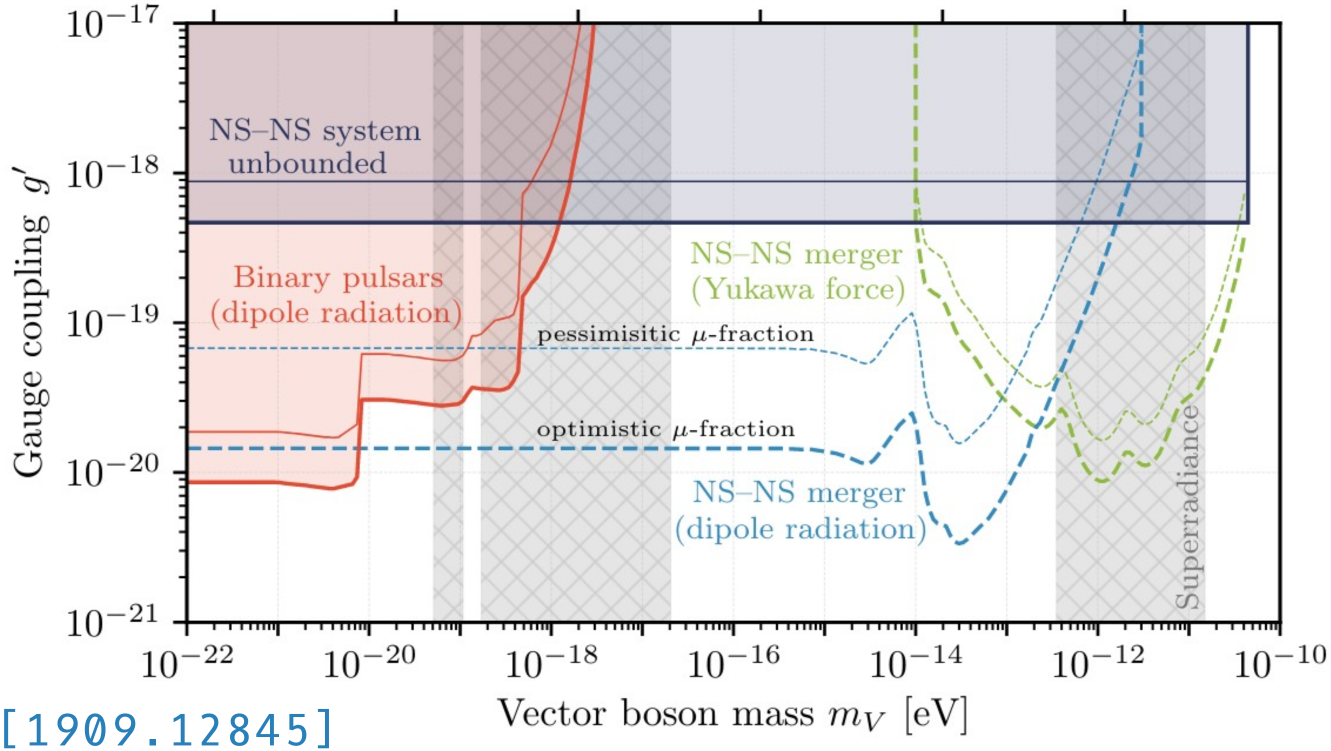
Δ =3
Δ =10
Δ =3
Δ =10
Δ =1
α_2/α_3
M_{S_3}
5
10
15
20
25
30
2σ regions
ΔM_s



[1909.12845]

[1908.09732]

Compact binary system	g(fifth force)	g(orbital period decay)
PSR B1913+16	$\leq 4.99 \times 10^{-17}$	$\leq 2.21 \times 10^{-18}$
PSR J0737-3039	$\leq 4.58 \times 10^{-17}$	$\leq 2.17 \times 10^{-19}$
PSR J0348+0432	–	$\leq 9.02 \times 10^{-20}$
PSR J1738+0333	–	$\leq 4.24 \times 10^{-20}$

[Grummer @ LHCP 2020]

Branching Fractions

- The branching fraction measurements for $B_s^0 \to \mu^+\mu^-$ and the upper limits on the $B^0 \to \mu^+\mu^-$ at 95% CL are:

ATLAS

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(2.8^{+0.8}_{-0.7}\right) \times 10^{-9}$$

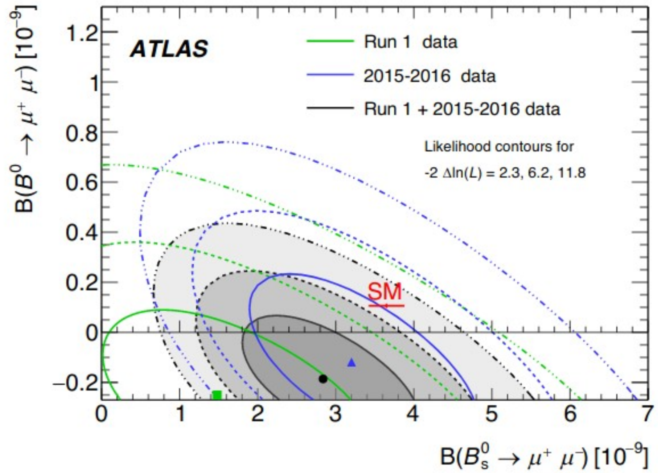
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.1 \times 10^{-10}$$

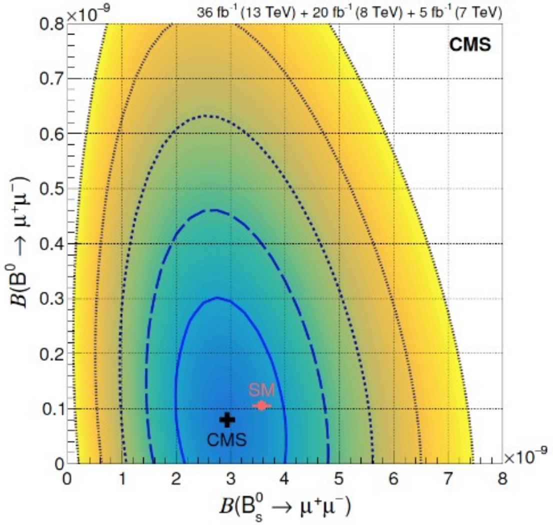
CMS

$$\mathcal{B}(\mathrm{B}_s^0 \to \mu^+\mu^-) = [2.9 \pm 0.7\,(\mathrm{exp}) \pm 0.2\,(\mathrm{frag})] \times 10^{-9}$$

$$\mathcal{B}(\mathrm{B}^0 \to \mu^+\mu^-) < 3.6 \times 10^{-10}$$

- The likelihood contours for the branching fractions are shown in the figures (the Neyman construction is used for ATLAS results)





$$\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{prompt}} = \frac{G_F^2\alpha^2}{16\pi^3} |V_{ts}V_{tb}^*|^2 f_{B_s}^2 \tau_{B_s} m_{B_s} m_\mu^2 \sqrt{1 - 4\frac{m_\mu^2}{m_{B_s}^2}} |C_{10}^{\mathrm{SM}}|^2 \left(|P|^2 + |S|^2\right), \quad (19)$$

where the Wilson coefficients appear through the combinations

$$P = \frac{C_{10} - C'_{10}}{C_{10}^{\mathrm{SM}}} + \frac{M_{B_s}^2}{2m_\mu} \frac{m_b}{m_b + m_s} \left(\frac{C_P - C'_P}{C_{10}^{\mathrm{SM}}}\right), \quad S = \sqrt{1 - 4\frac{m_\mu^2}{M_{B_s}^2}} \frac{M_{B_s}^2}{2m_\mu} \frac{m_b}{m_b + m_s} \left(\frac{C_S - C'_S}{C_{10}^{\mathrm{SM}}}\right), \quad (21)$$

[1702.05498]