Current state of Flavour Physics

Martin Bauer

Annual theory meeting, 17.12.2018

Why Flavour is important

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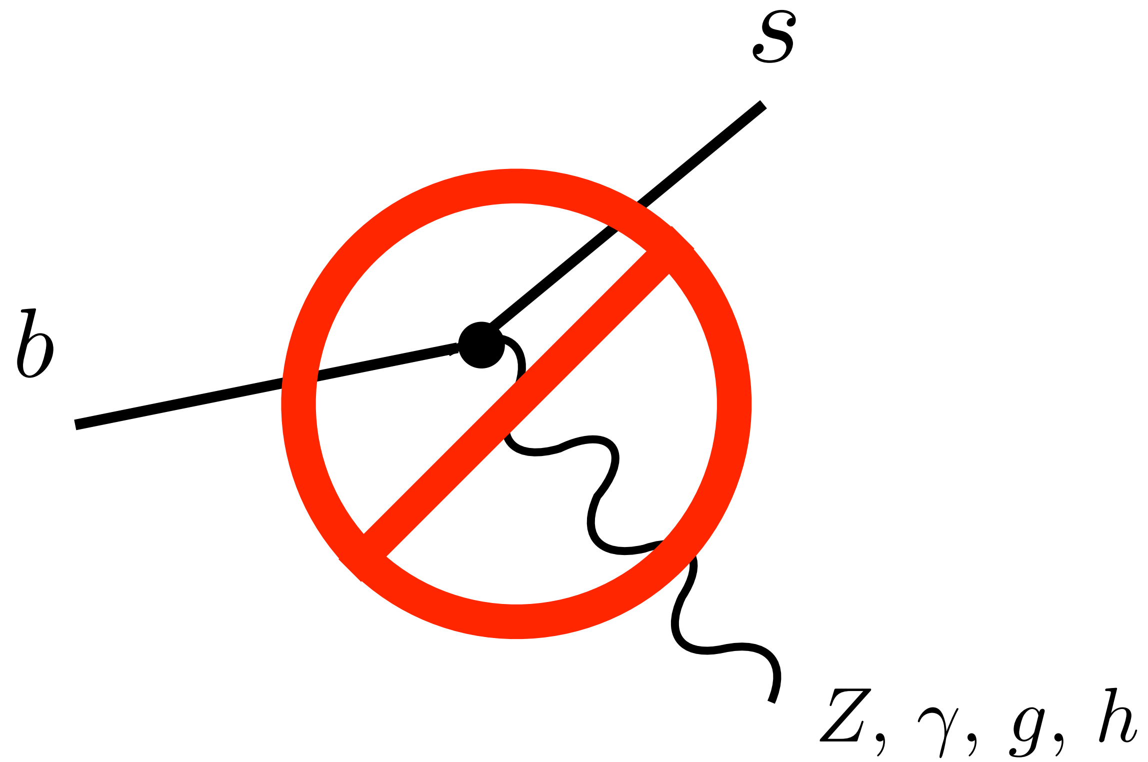
Flavour changing neutral currents probe the SM as a quantum field theory.

Classically, there are no flavour transitions with neutral currents:



Why Flavour is important

$$\mathcal{L}^{\text{SM}} \ni \bar{d}_L \, Y_d \, d_R \phi + \bar{u}_L \, Y_u \, u_R \tilde{\phi}$$

Symmetry breaking:
$\phi \to v + h$

$$d = \begin{pmatrix} d \\ s \\ b \end{pmatrix} \qquad u = \begin{pmatrix} u \\ c \\ t \end{pmatrix} \qquad Y_{u,d} = \begin{pmatrix} y_{11} & y_{12} & y_{13} \\ y_{21} & y_{22} & y_{23} \\ y_{31} & y_{32} & y_{33} \end{pmatrix}$$

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Rotate to the mass eigenbasis:

$$D_L \, Y_u \, D_R^\dagger = \frac{1}{v} \text{diag}(m_d, m_s, m_b) \qquad U_L \, Y_u \, U_R^\dagger = \frac{1}{v} \text{diag}(m_u, m_c, m_t)$$

gives

$$\mathcal{L}^{\text{SM}} \ni \bar{d}_L \, \frac{m_d}{v} \, d_R \, (v+h) + \bar{u}_L \, \frac{m_u}{v} \, u_R \, (v+h)$$

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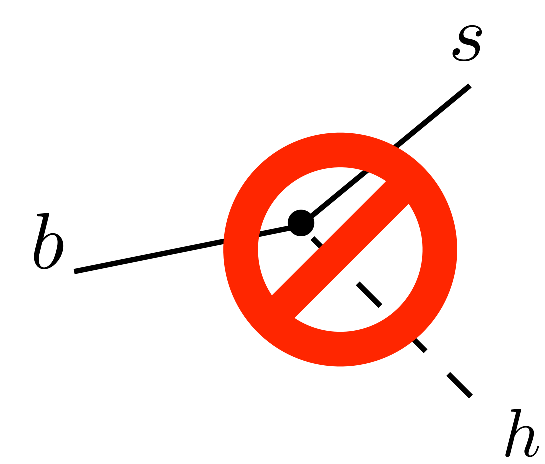

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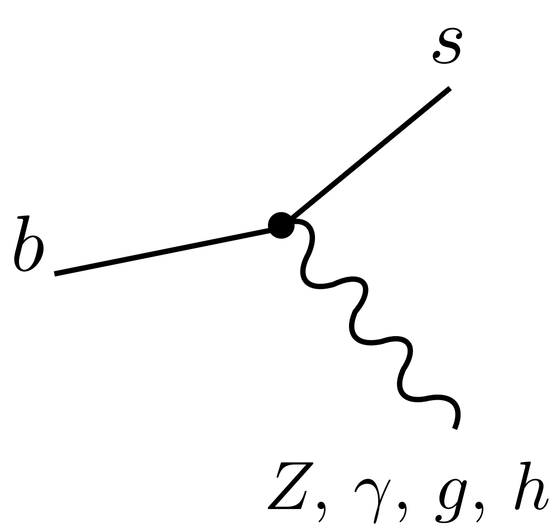

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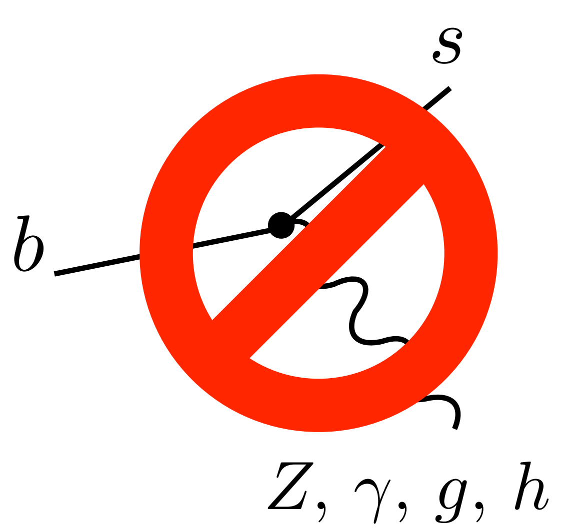

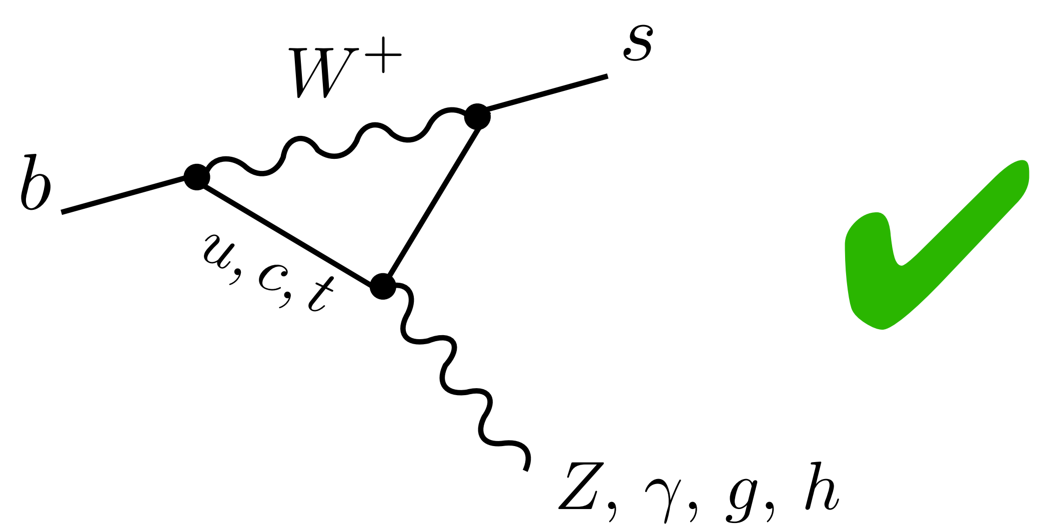

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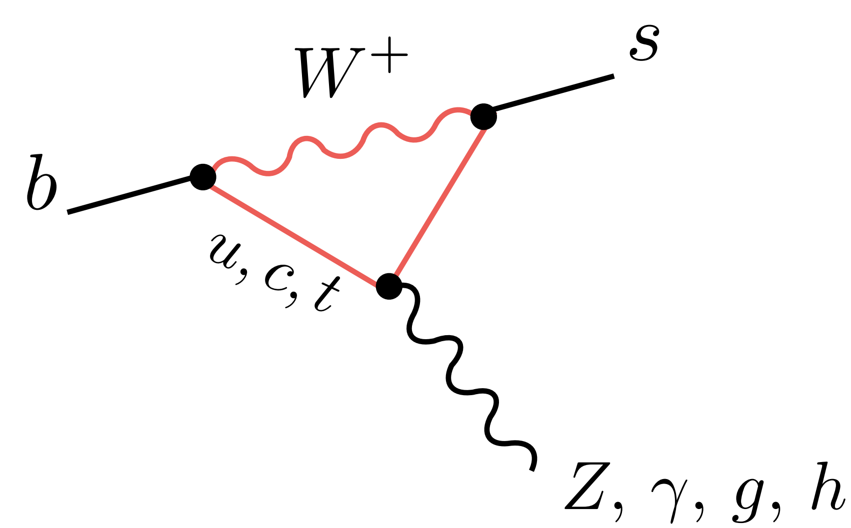
Why Flavour is important

- Loop suppressed



$$\mathcal{A} \propto V_{ub}V_{us}^{*}\, f_u + V_{cb}V_{cs}^{*}\, f_c + V_{tb}V_{ts}^{*}\, f_t$$

$$\begin{aligned}\mathcal{L}^{\mathrm{SM}} \ni\ & \bar{d}_L\, \frac{m_d}{v}\, d_R\,(v+h) + \bar{u}_L\, \frac{m_u}{v}\, u_R\,(v+h) \\ & + \bar{d}_L \underbrace{D_L\, g\, D_L^{\dagger}}_{=\, g\, D_L \mathbb{1}_{3\times 3} D_L^{\dagger} \,=\, g} \gamma_\mu\, d_L Z^{\mu} + \bar{u}_L \underbrace{U_L g\, U_L^{\dagger}}_{g} \gamma_\mu\, u_L\, Z^{\mu} + \bar{u}_L \underbrace{U_L g\, D_L^{\dagger}}_{=\, g\, U_L \mathbb{1}_{3\times 3} D_L^{\dagger} \,=\, g\, V_{\mathrm{CKM}}} \gamma_\mu\, d_L\, W_{+}^{\mu} + \ldots\end{aligned}$$

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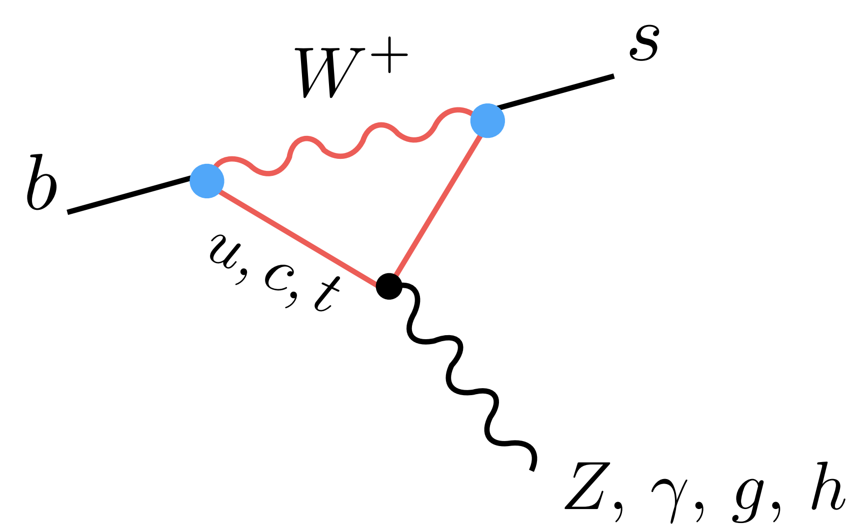

✔

$$\mathcal{A} \propto V_{ub}V_{us}^* \, f_u + V_{cb}V_{cs}^* \, f_c + V_{tb}V_{ts}^* \, f_t$$

$$= V_{tb}V_{ts}^*(f_t - c.)$$

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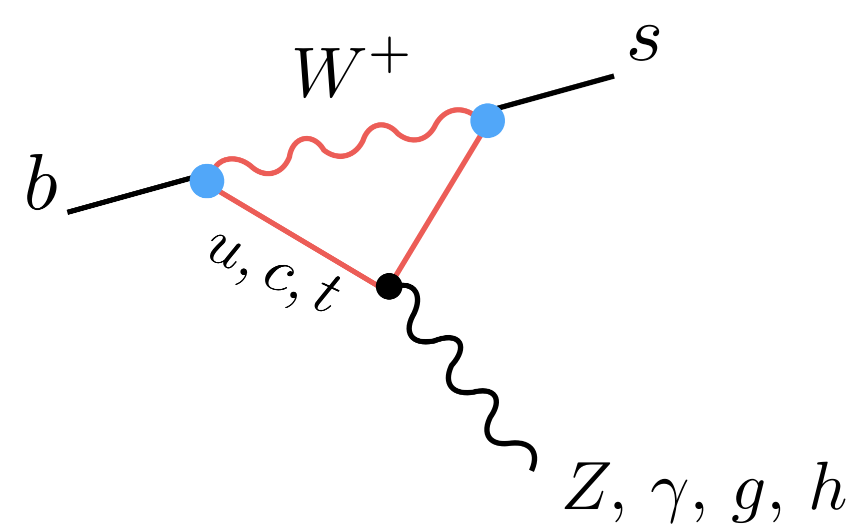

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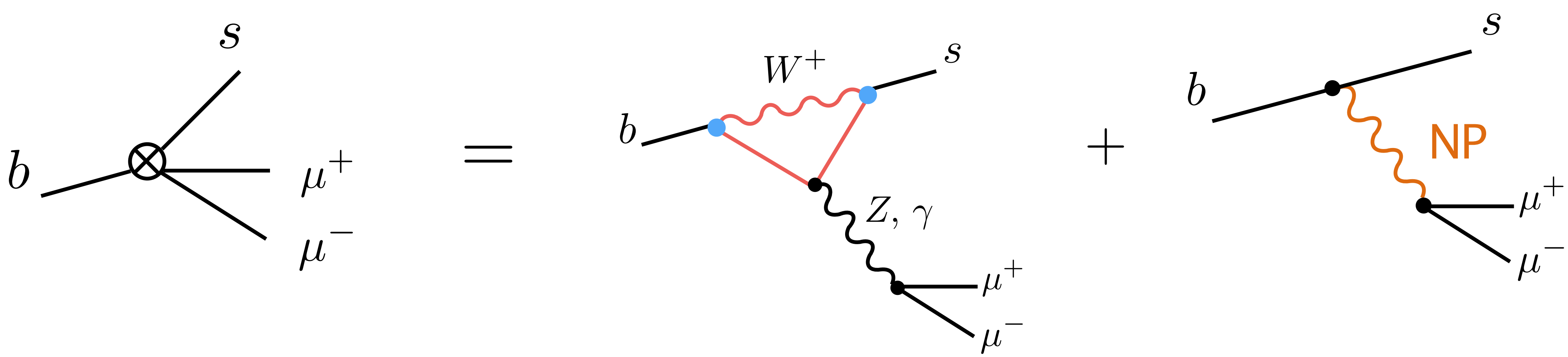
$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$ with $\lambda \approx 0.23$

[Glashow, Iliopoulos, Maiani, Phys. Rev. D**2**, 1285 (1970)]

Why Flavour is important

- Loop suppressed
- GIM suppressed

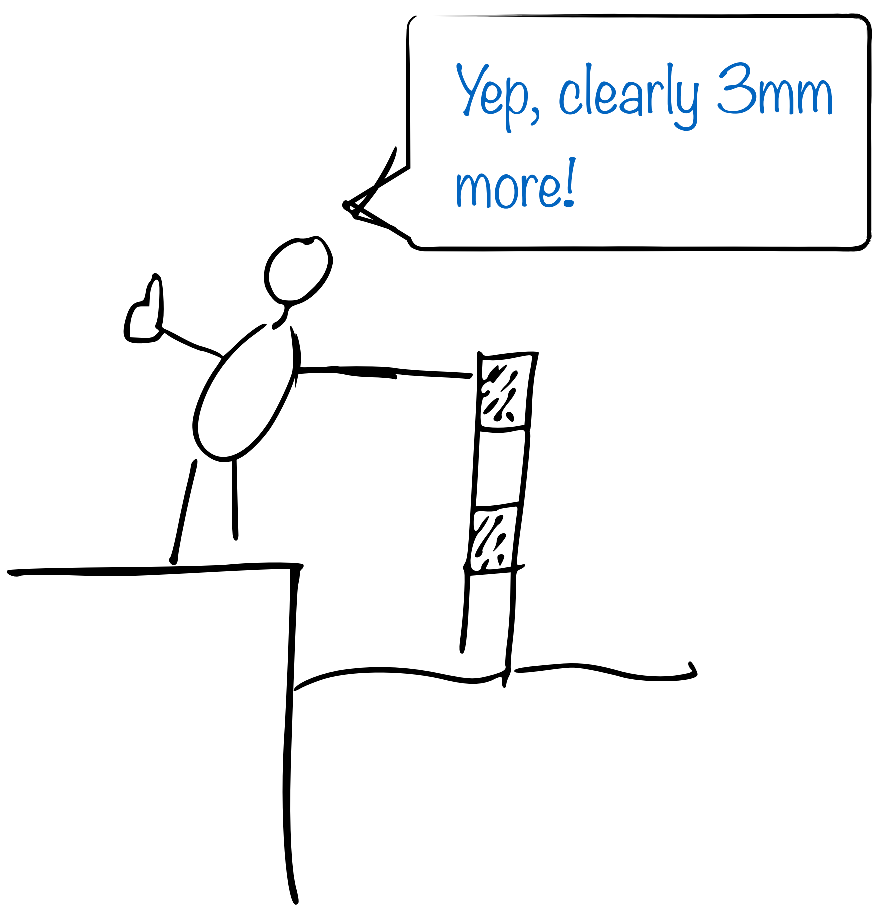


$$G \sim \frac{1}{16\pi^2}\frac{g^4}{m_W^2}\frac{m_t^2}{m_W^2} V_{tb}V_{ts}^* + \frac{g_{bs}\, g_{\mu\mu}}{M_{Z'}^2}$$

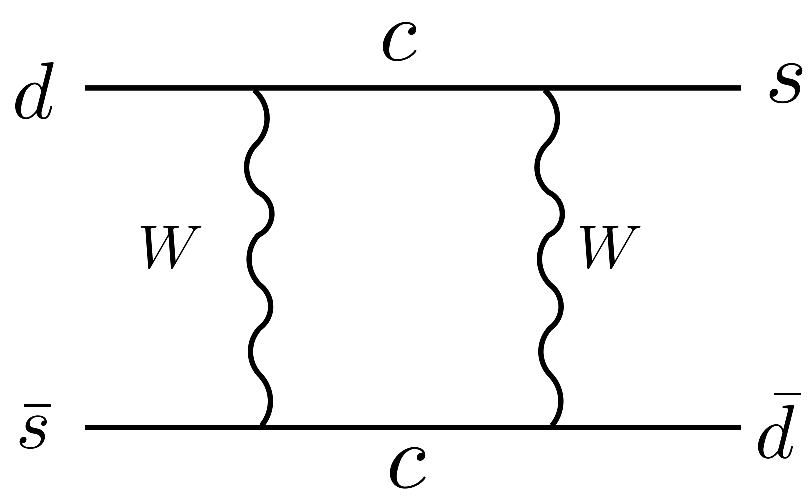
Measure — Compute — Find

Why Flavour is important

This is why we look for New Physics there. The effects might be small, but still large relative to the SM.



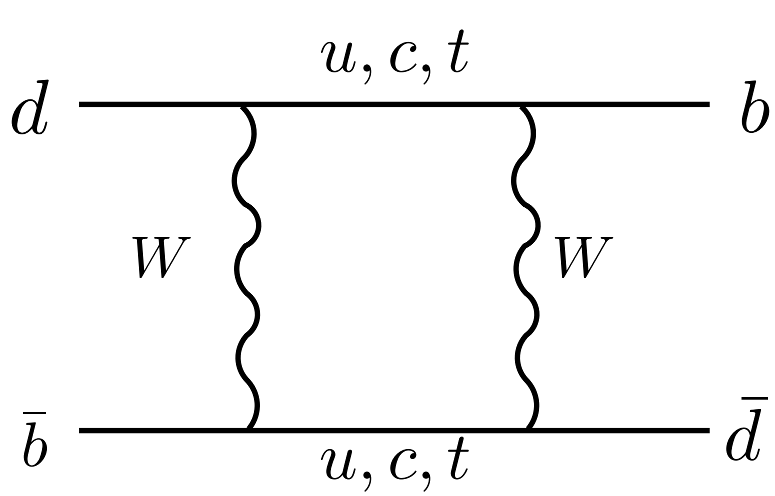
Historical Successes



$$\Rightarrow \Delta m_K \propto \frac{G_F^2}{4\pi^2}\big((M_W^2 + m_u^2) - (M_W^2 + m_c^2)\big)\cos^2\theta\,\sin^2\theta\, f_K^2 m_K$$

$$\Delta m_K^{\mathrm{exp}} \approx 10^{-12}\,\mathrm{MeV} \quad \Rightarrow \quad m_c \approx 1\mathrm{GeV}$$

[K. Gaillard and B. W. Lee, 1974]

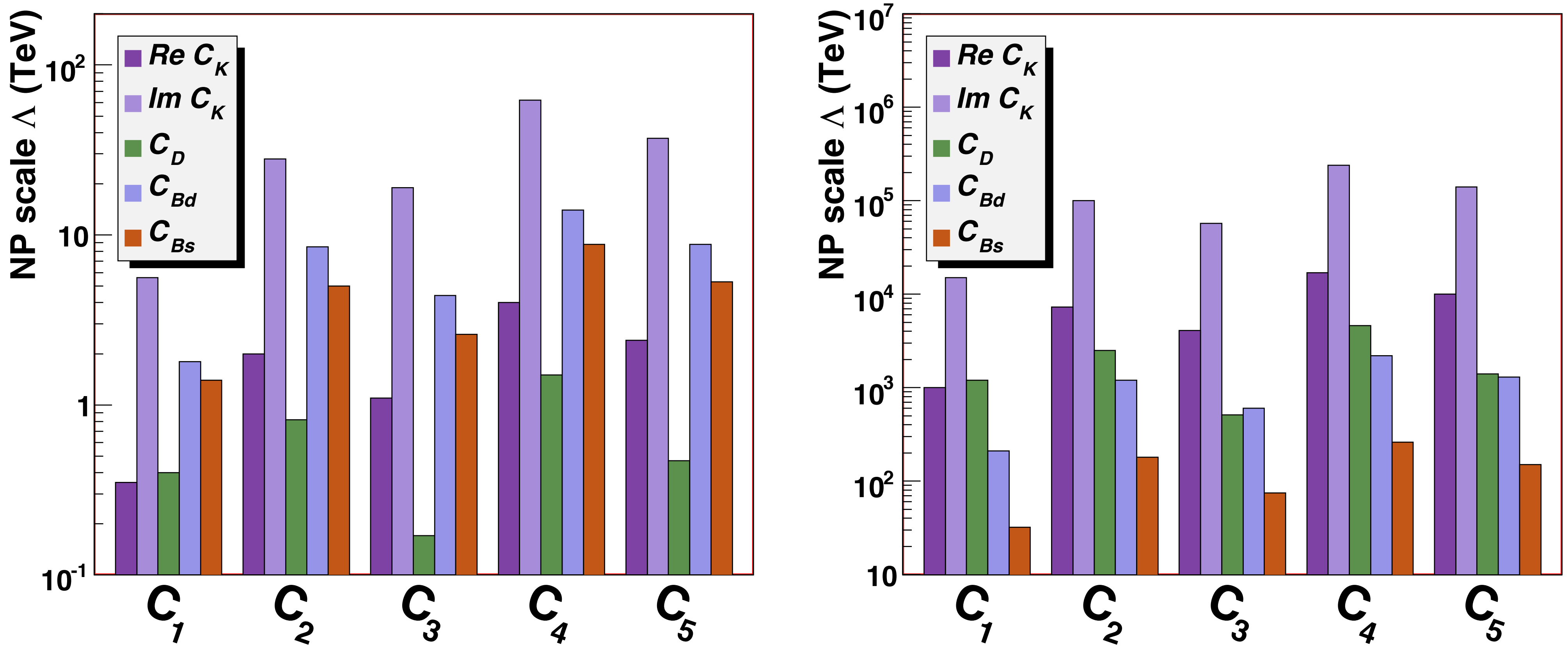


ARGUS $1987\ : m_t > 50\ \mathrm{GeV}$

Flavour observables predicted the charm and the top.

Historical Successes

Flavour also predicted no new physics at the TeV scale…



[UTfit collaboration 2007]

Future Successes ?

Several measurements of rare transitions deviate from the SM prediction … a sign of new physics?

- An intriguing pattern in $b \to s\mu^+\mu^-$ transitions $4\,\sigma$
- Lepton flavour non-universality in R_K, R_{K^*} $2.5\,\sigma$
- Lepton flavour non-universality in $R(D^{(*)})$ $4\,\sigma$
- The anomalous magnetic moment of the muon $(g-2)_\mu$ $3.6\,\sigma$
  and of the electron $(g-2)_e$ $2.5\,\sigma$

A pattern in $b \to s$ transitions

and

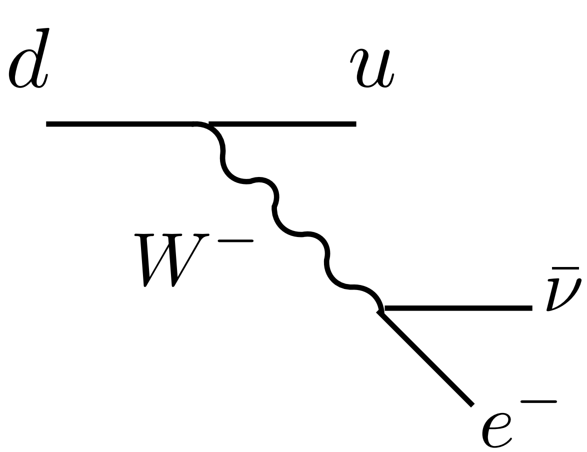
Lepton Non-Universality in $b \to s$

A pattern in b → s transitions

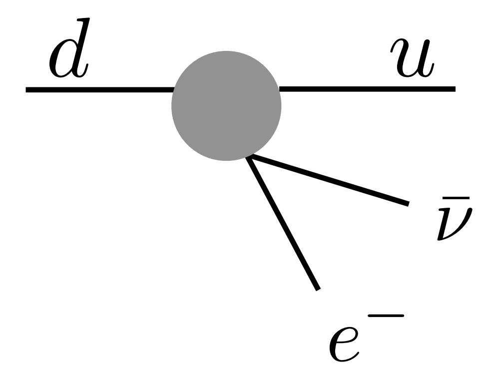
In flavour physics the momentum transfer is small

$$M_{\text{Neutron}} \approx 1\,\text{GeV} \ll M_W \approx 80\,\text{GeV}$$

Example: Beta decay in Fermi theory



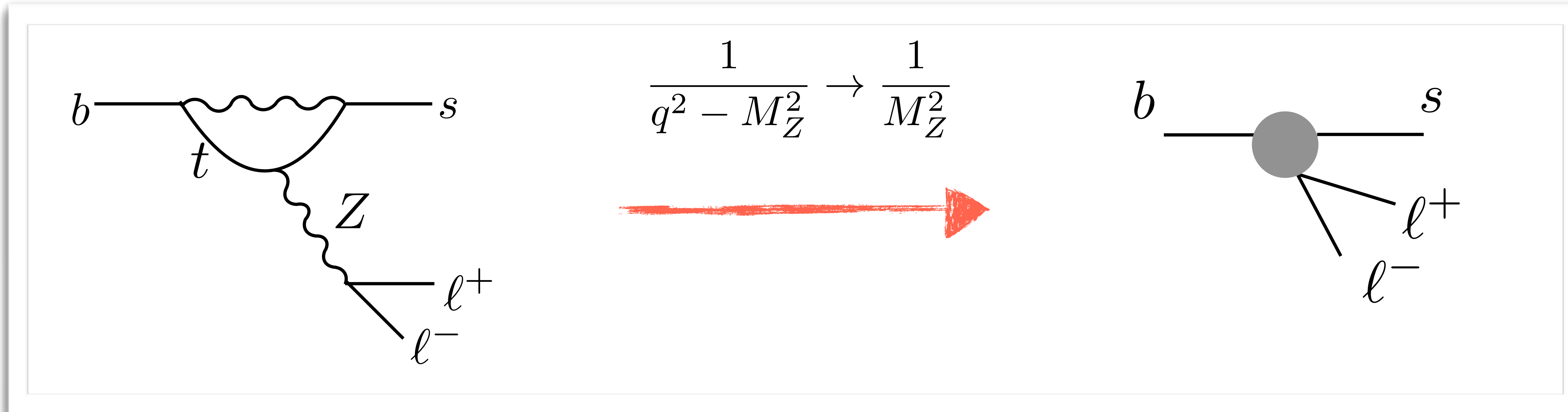
$$\frac{1}{q^2 - M_W^2} \to \frac{1}{M_W^2}$$



$$\mathcal{L} = -\frac{4G_F}{\sqrt{2}} \left(\bar{d}_L \gamma_\mu u_L\right) \left(\bar{e}_L \gamma^\mu \nu_L\right) \qquad G_F \propto \frac{1}{M_W^2}$$

A pattern in b → s transitions

Since B decays involve an on-shell B meson (~ 5 GeV), heavy SM particles can be integrated out



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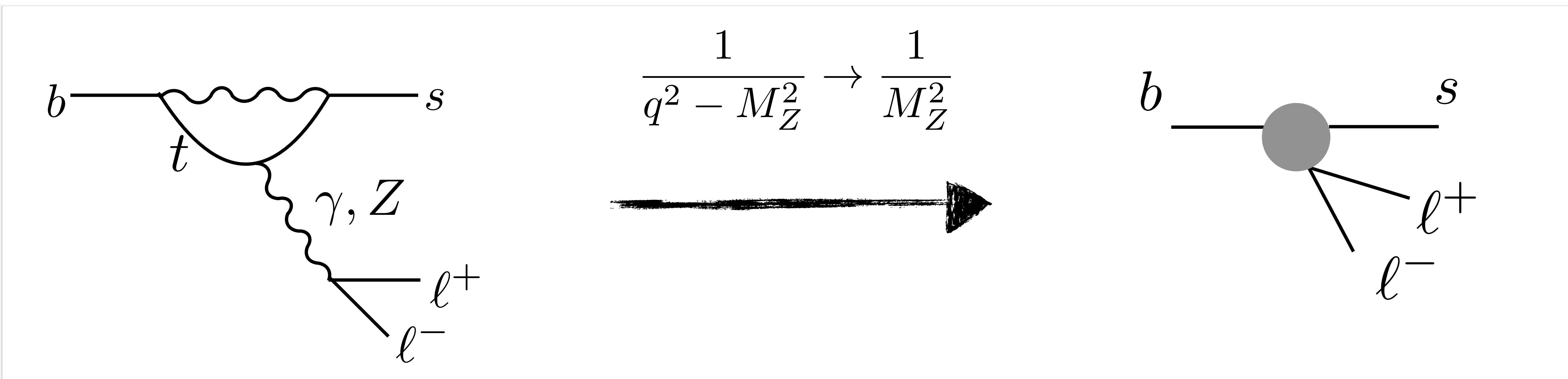
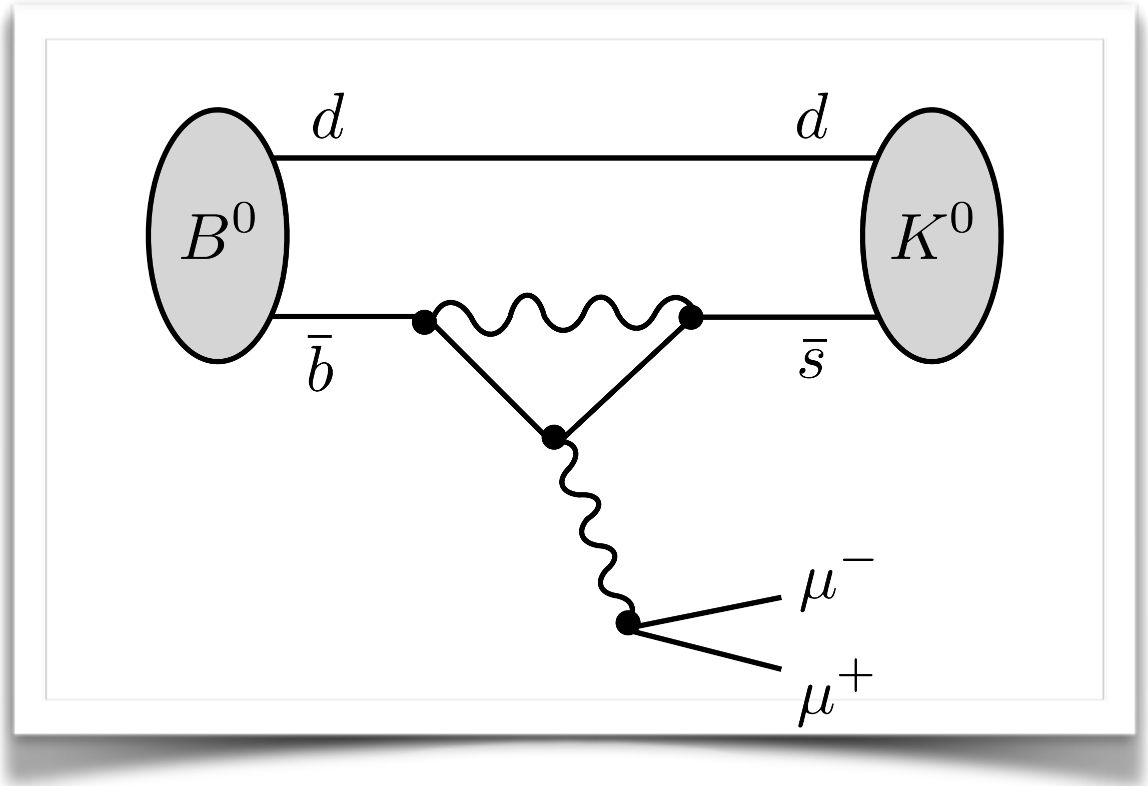


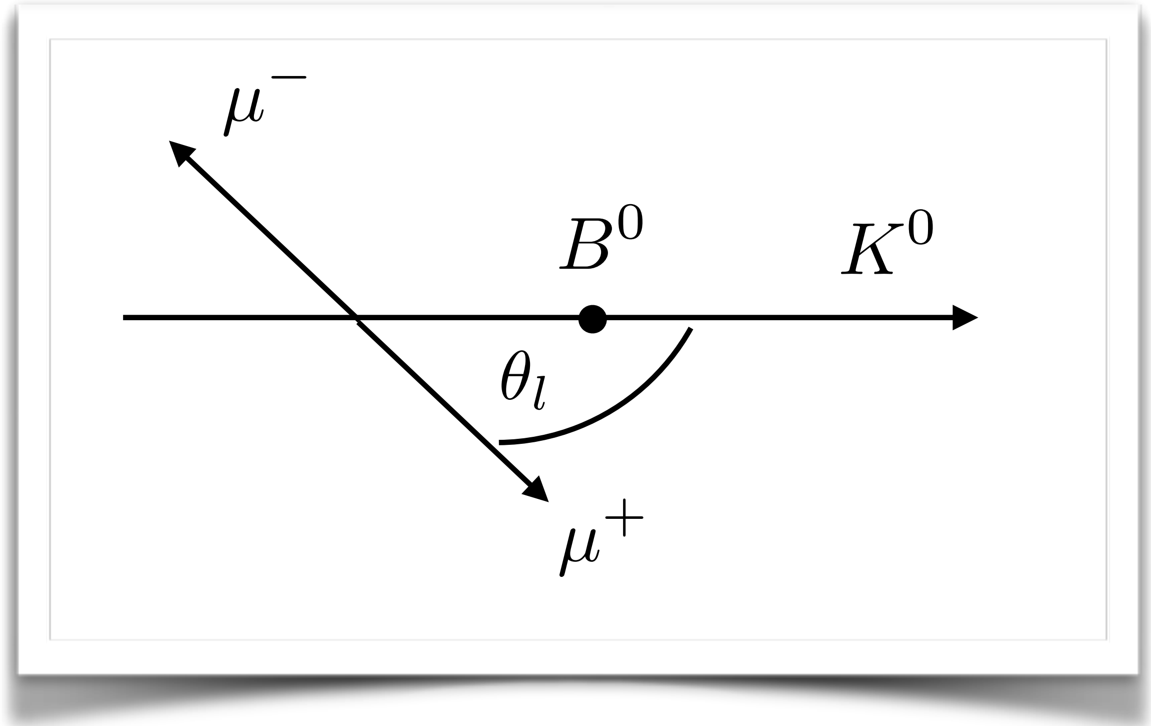
$$\mathcal{H}_{\rm eff} = -\frac{4\,G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha_e}{4\pi} \sum_i C_i(\mu) \mathcal{O}_i(\mu)\,,$$

$$\mathcal{O}_9 = [\bar{s}\gamma_\mu P_L b]\,[\bar{\ell}\gamma^\mu \ell]\,, \quad \mathcal{O}_{10} = [\bar{s}\gamma_\mu P_L b]\,[\bar{\ell}\gamma^\mu\gamma_5 \ell]\,,$$

$$\mathcal{O}_S = [\bar{s} P_R b]\,[\bar{\ell}\ell]\,, \quad \mathcal{O}_P = [\bar{s} P_R b]\,[\bar{\ell}\gamma_5 \ell]\,, \qquad \mathcal{O}_7 = \frac{e}{16\pi^2} m_b (\bar{s}\sigma_{\mu\nu} P_R b) F^{\mu\nu}$$

A pattern in b → s transitions





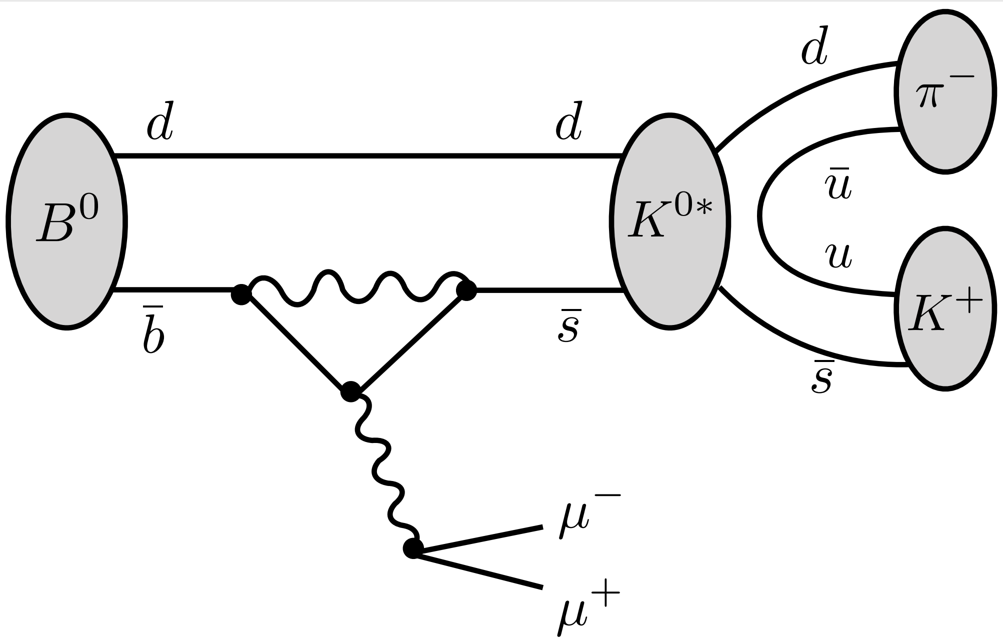
$$\frac{1}{\Gamma}\frac{d^2\Gamma}{dq^2 d\cos\theta} = \lambda^{3/2}(M_B^2, M_K^2, q^2)\frac{1}{4}(1-\cos^2\theta_l)\left[|F_A|^2 + |F_V|^2\right]$$

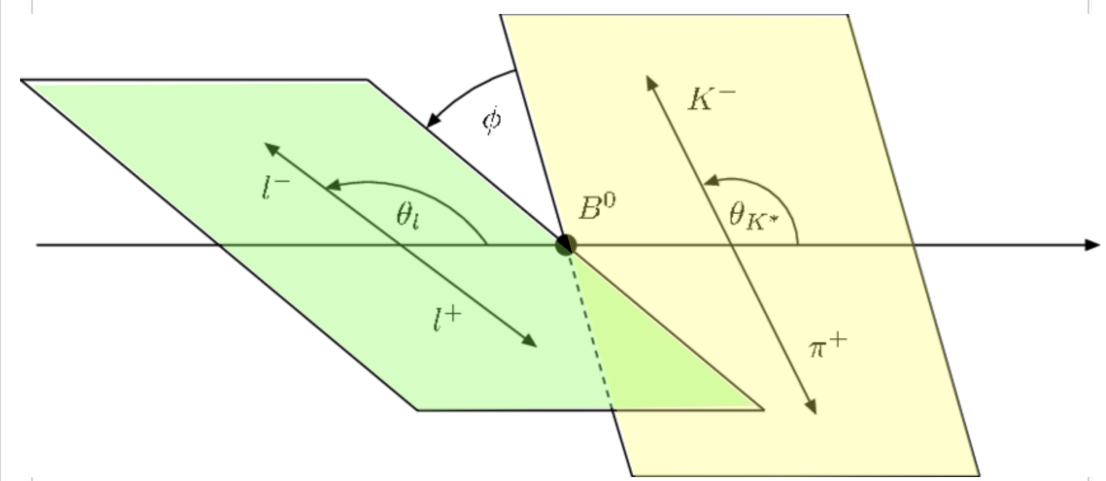
$$F_A = C_{10} f_+(q^2) \qquad F_A = C_9 f_+(q^2) + 2C_7^{\text{eff}} m_b \frac{f_T(q^2)}{M_B + M_K}$$

$$C_9^{\text{SM}} = -C_{10}^{\text{SM}} \approx -4.2 \qquad C_7^{\text{SM}} = -0.31$$

[Bobeth, Ewerth, Krüger, Urban 0104284]

A pattern in b → s transitions



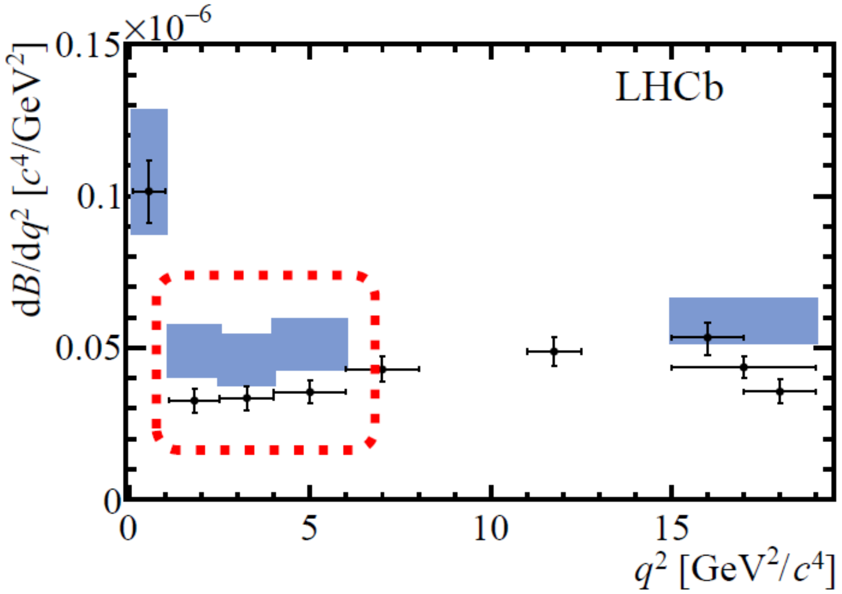


$$\frac{1}{\mathrm{d}\Gamma/dq^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell$$
$$-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

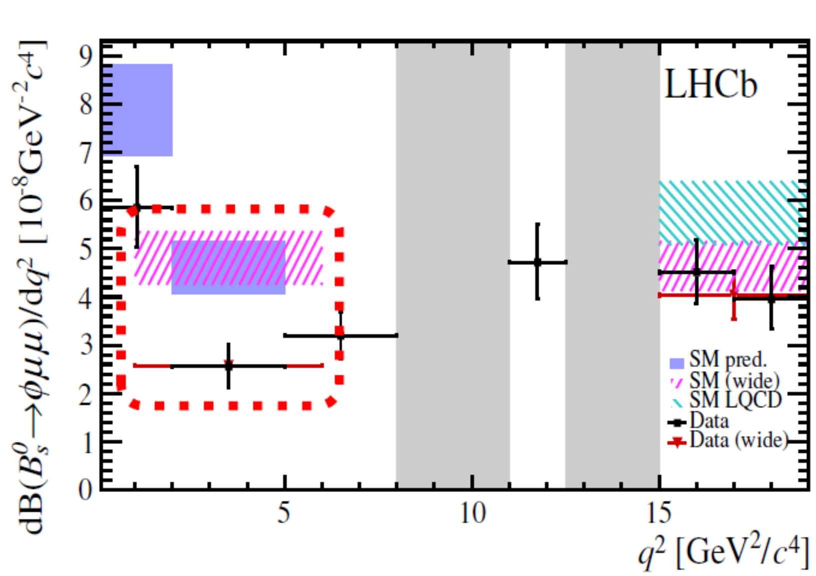
$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}}$$

A pattern in b → s transitions

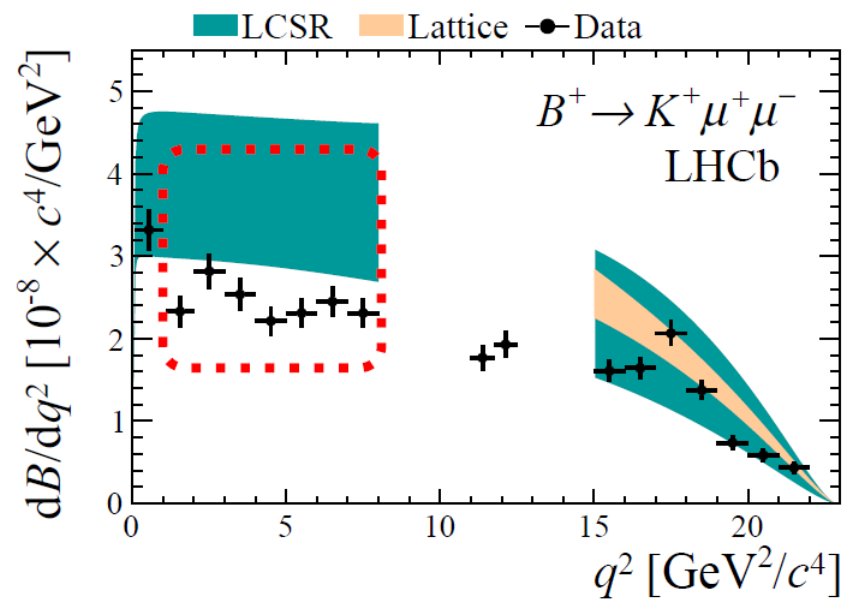
LHCb $B^0 \to K^{*0}\mu^+\mu^-$ [JHEP 11 (2016) 047]



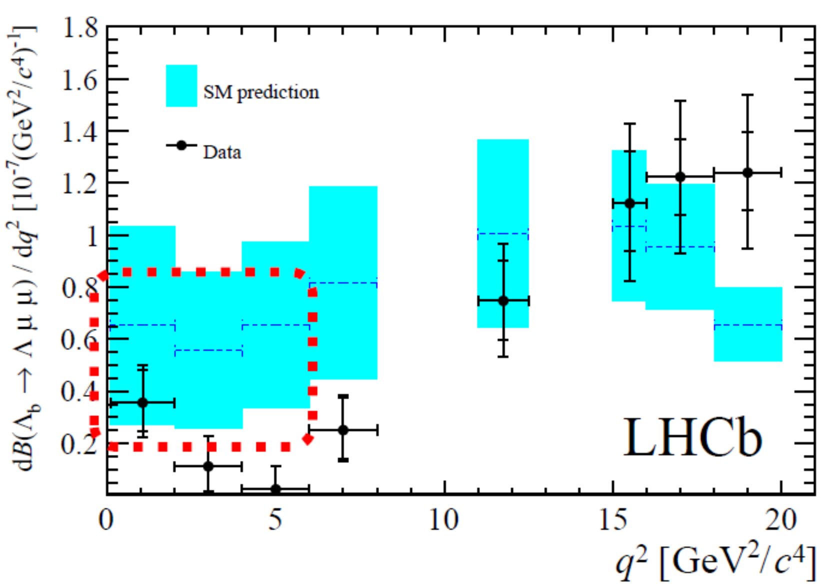
LHCb $B_s^0 \to \phi\mu^+\mu^-$ [JHEP 09 (2015) 179]



LHCb $B^+ \to K^+\mu^+\mu^-$ [JHEP 06 (2014) 133]



$\Lambda_b^0 \to \Lambda\mu^+\mu^-$ [JHEP 06 (2015) 115]



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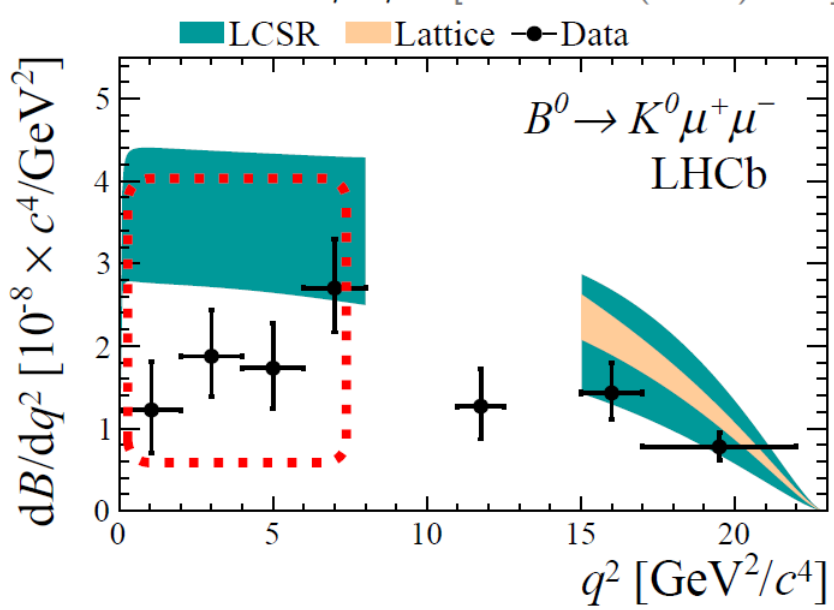
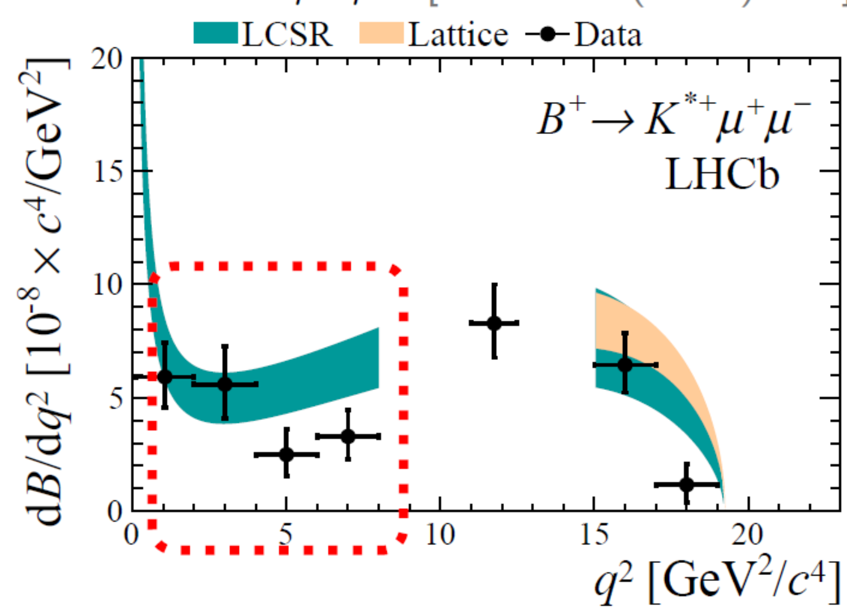
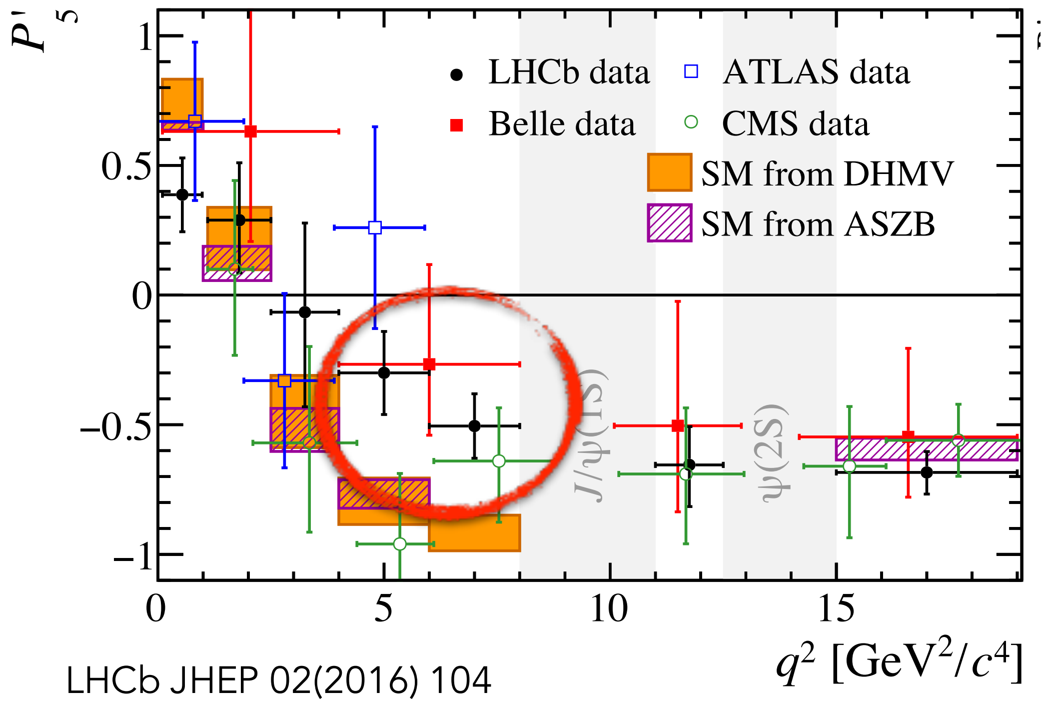


$B^+ \to K^{*+}\mu^+\mu^-$ [JHEP 06 (2014) 133]



[Langenbruch, LHCb implications ’18]

A pattern in b → s transitions



LHCb JHEP 02(2016) 104

Belle PRL118, 111801 (2017)

ATLAS, preliminary Moriond EW

CMS, preliminary Moriond EW

Marie-Hélène Schune, Moriond

Deviations in several observables

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
$B^- \to K^{*-}\mu^+\mu^-$	$10^7\ \frac{dBR}{dq^2}$	$[4, 6]$	0.54 ± 0.08	0.26 ± 0.10	LHCb	$+2.1$
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8\ \frac{dBR}{dq^2}$	$[0.1, 2]$	2.71 ± 0.50	1.26 ± 0.56	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8\ \frac{dBR}{dq^2}$	$[16, 23]$	0.93 ± 0.12	0.37 ± 0.22	CDF	$+2.2$
$B_s \to \phi\mu^+\mu^-$	$10^7\ \frac{dBR}{dq^2}$	$[1, 6]$	0.48 ± 0.06	0.23 ± 0.05	LHCb	$+3.1$

[Altmannshofer, Straub, 1503.06199]

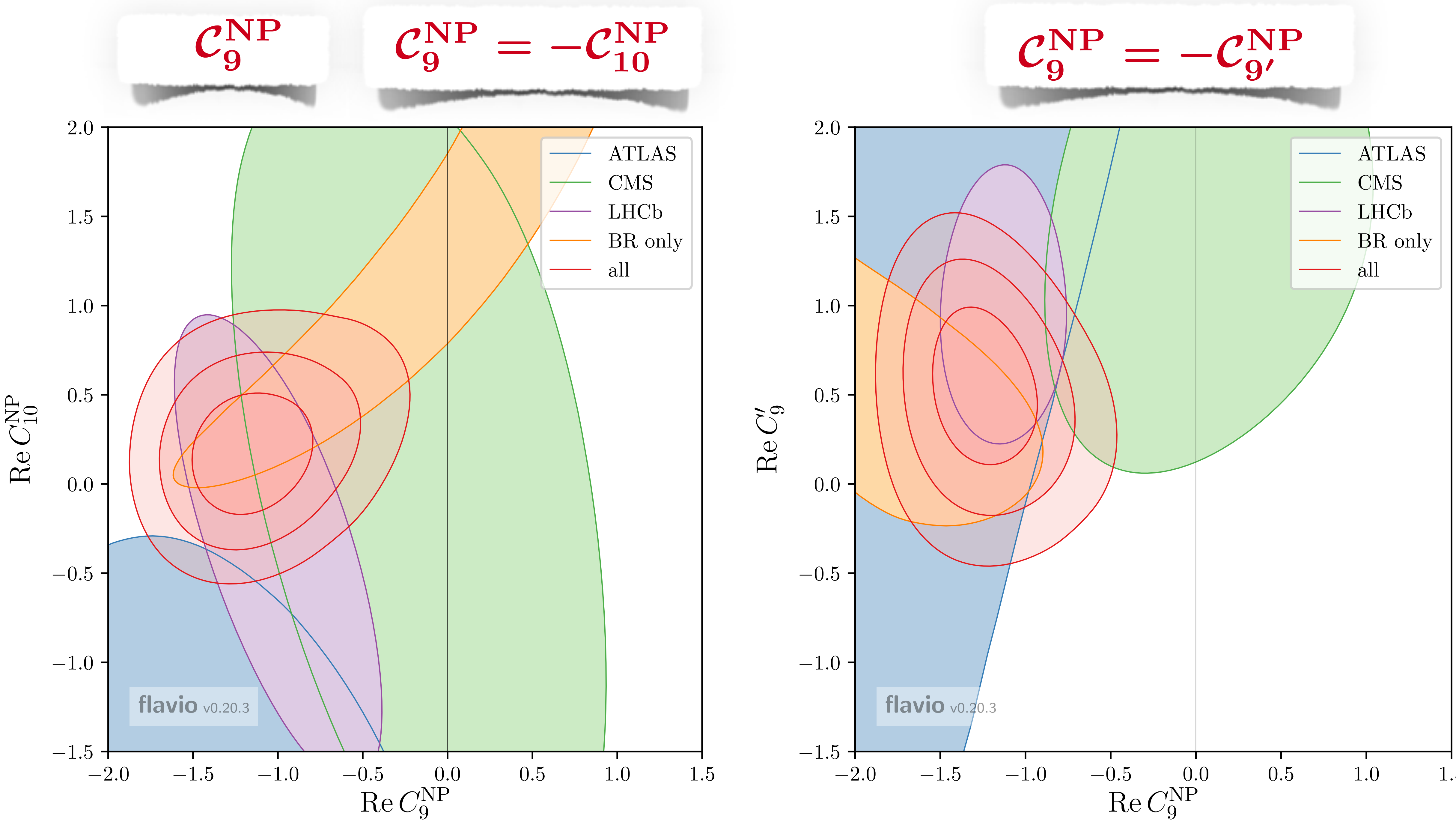
A pattern in b → s transitions

Coefficient	Best fit	1σ	3σ	Pull_{SM}
$\mathcal{C}_7^{\text{NP}}$	-0.02	$[-0.04, -0.00]$	$[-0.07, 0.04]$	1.1
$\boldsymbol{\mathcal{C}_9^{\text{NP}}}$	$\mathbf{-1.11}$	$[-1.32, -0.89]$	$[-1.71, -0.40]$	**4.5**
$\mathcal{C}_{10}^{\text{NP}}$	0.58	$[0.34, 0.84]$	$[-0.11, 1.41]$	2.5
$\mathcal{C}_{7'}^{\text{NP}}$	0.02	$[-0.01, 0.04]$	$[-0.05, 0.09]$	0.7
$\mathcal{C}_{9'}^{\text{NP}}$	0.49	$[0.21, 0.77]$	$[-0.33, 1.35]$	1.8
$\mathcal{C}_{10'}^{\text{NP}}$	-0.27	$[-0.46, -0.08]$	$[-0.84, 0.28]$	1.4
$\mathcal{C}_9^{\text{NP}} = \mathcal{C}_{10}^{\text{NP}}$	-0.21	$[-0.40, 0.00]$	$[-0.74, 0.55]$	1.0
$\boldsymbol{\mathcal{C}_9^{\text{NP}} = -\mathcal{C}_{10}^{\text{NP}}}$	$\mathbf{-0.69}$	$[-0.88, -0.51]$	$[-1.27, -0.18]$	**4.1**
$\boldsymbol{\mathcal{C}_9^{\text{NP}} = -\mathcal{C}_{9'}^{\text{NP}}}$	$\mathbf{-1.09}$	$[-1.28, -0.88]$	$[-1.62, -0.42]$	**4.8**

$$\mathcal{O}_9 = [\bar{s}\gamma_\mu P_L b]\,[\bar{\ell}\gamma^\mu \ell]\,, \quad \mathcal{O}_{10} = [\bar{s}\gamma_\mu P_L b]\,[\bar{\ell}\gamma^\mu \gamma_5 \ell]\,,$$

DHMV, 1510.04239

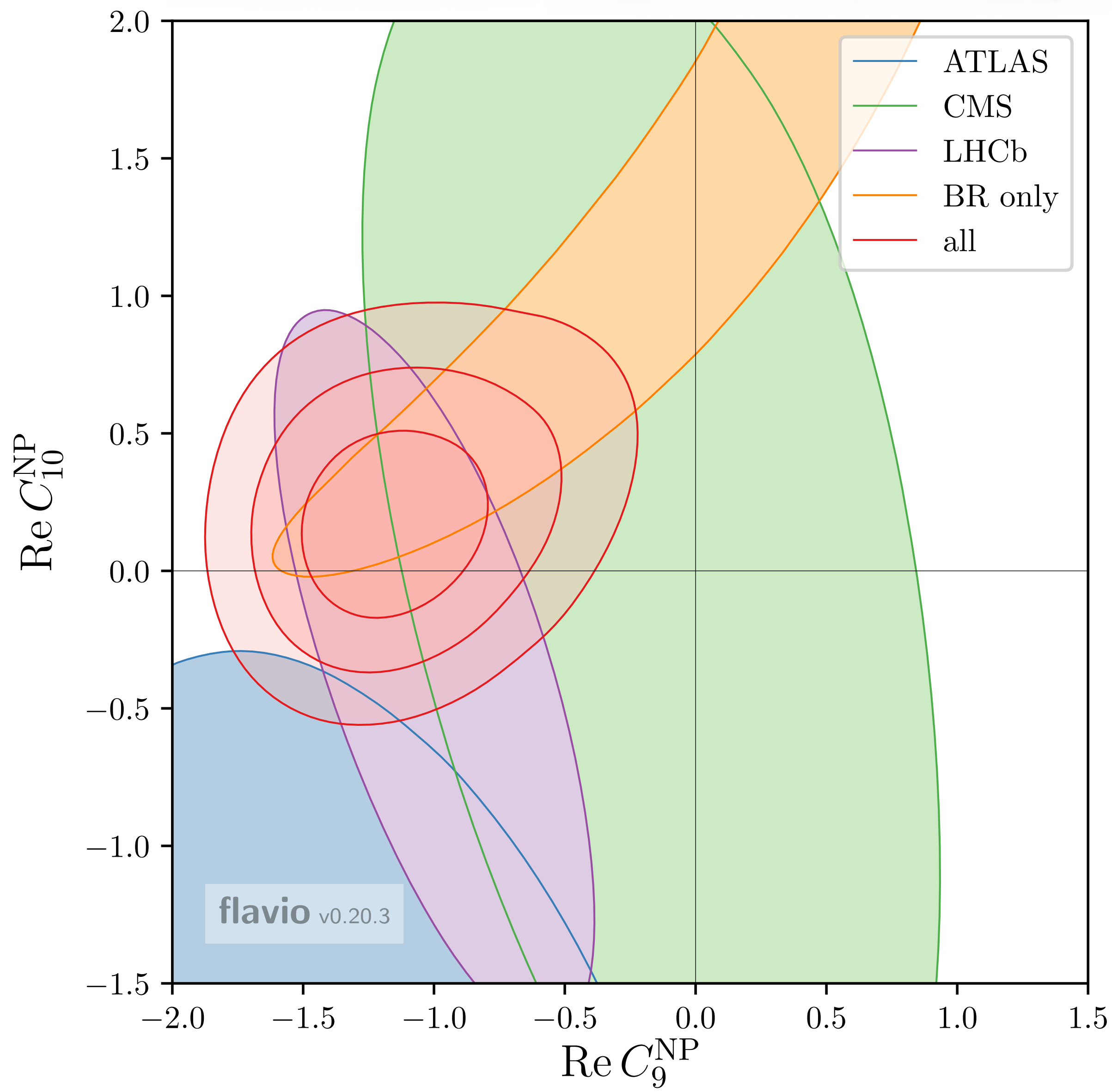
A pattern in b → s transitions



[Altmannshofer, Straub, 1703.09189]

A pattern in b → s transitions

$\mathcal{C}_9^{\mathrm{NP}}$ $\quad$ $\mathcal{C}_9^{\mathrm{NP}} = -\mathcal{C}_{10}^{\mathrm{NP}}$



Is this New Physics?

$$\sim 4 - 5\,\sigma$$

$$C_{9/10}^{\mathrm{NP}} \approx C_{10}^{\mathrm{SM}}/4$$

$$\Rightarrow \quad \frac{1}{M^2}\left(\frac{2V_{tb}V_{ts}^*}{v^2}\frac{\alpha_e}{4\pi}\right)^{-1} = \frac{1}{4}$$

$$\Rightarrow \quad M \approx 35\,\mathrm{TeV}$$

[Altmannshofer, Straub, 1703.09189]

A pattern in b → s transitions

…an enhanced SM contribution would have the right structure to explain this as well…

$$\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{10}^{\rm NP}$$

A pattern in b → s transitions

- Error budget of P_5' in [4, 6] GeV^2 bin:

$$-0.82^{+0.01}_{-0.01}{}^{+0.02}_{-0.02}{}^{+0.03}_{-0.06}{}^{+0.06}_{-0.06}{}^{+0.07}_{-0.08}$$

(medium red)	parametric
(lightest)	non-factorizable power corrections
(light)	form factors
(darker)	factorizable power corrections
(darkest)	long-distance $c\bar{c}$ effects

[Matias, talk at Moriond EW 2015]

[from Haisch 2016]

A pattern in b → s transitions

- Dominant uncertainties of theoretical origin. What to do?

$$-0.82^{+0.01}_{-0.01}{}^{+0.02}_{-0.02}{}^{+0.03}_{-0.06}{}^{+0.06}_{-0.06}{}^{+0.07}_{-0.08}$$

all errors are Gaussian

$$-0.82\,(1 \pm 13\%)$$

maybe better to add errors linearly

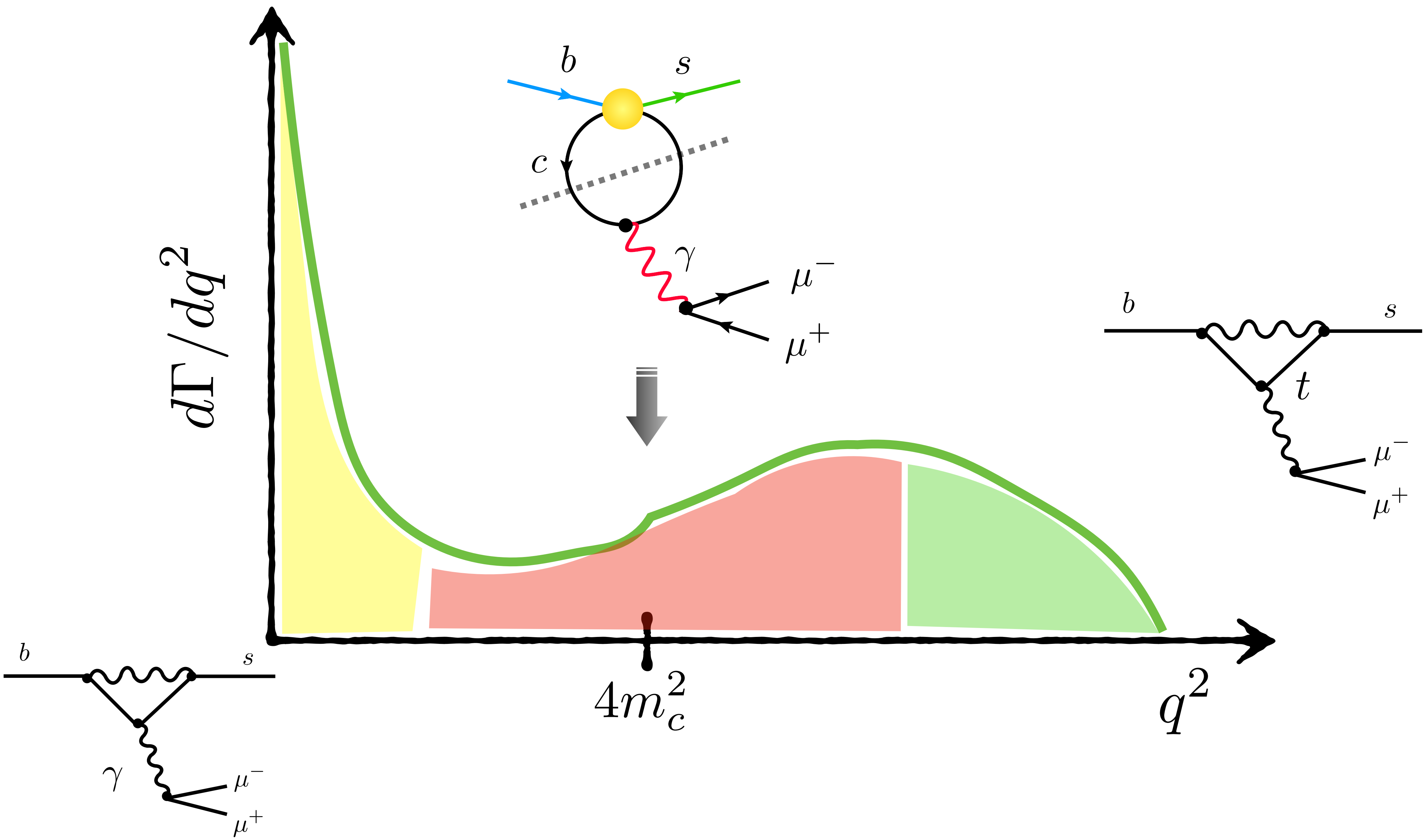
$$-0.82\,(1 \pm 26\%)$$

- Largest individual uncertainty due to long-distance $c\bar{c}$ effects. What is the problem & what does this mean for the error?

[from Haisch 2016]

A pattern in b → s transitions

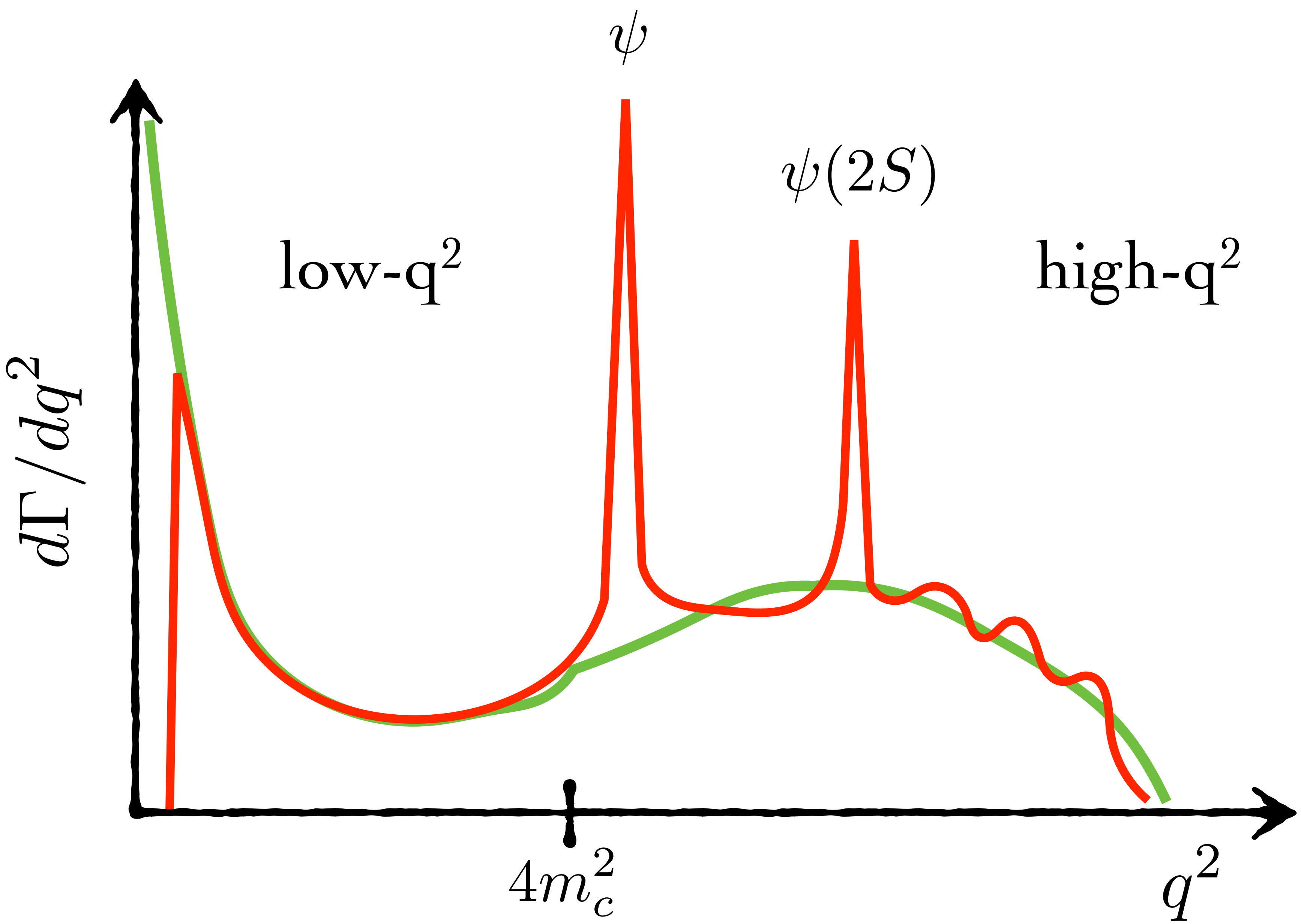
In an ideal world …



[from Haisch 2016]

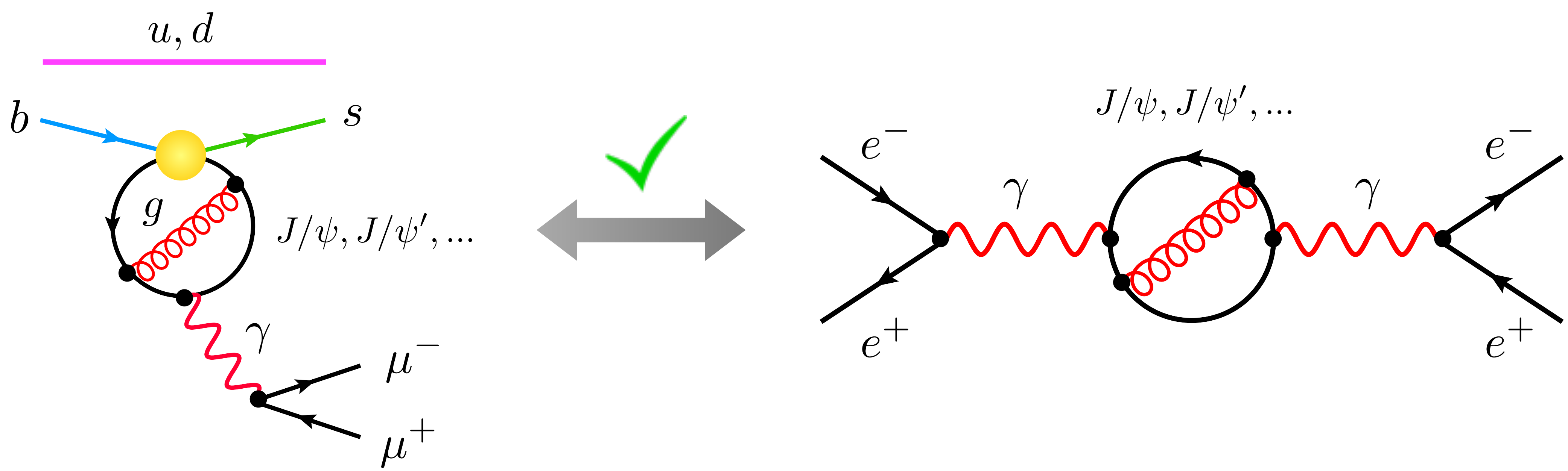
A pattern in b → s transitions

… in reality



[from Haisch 2016]

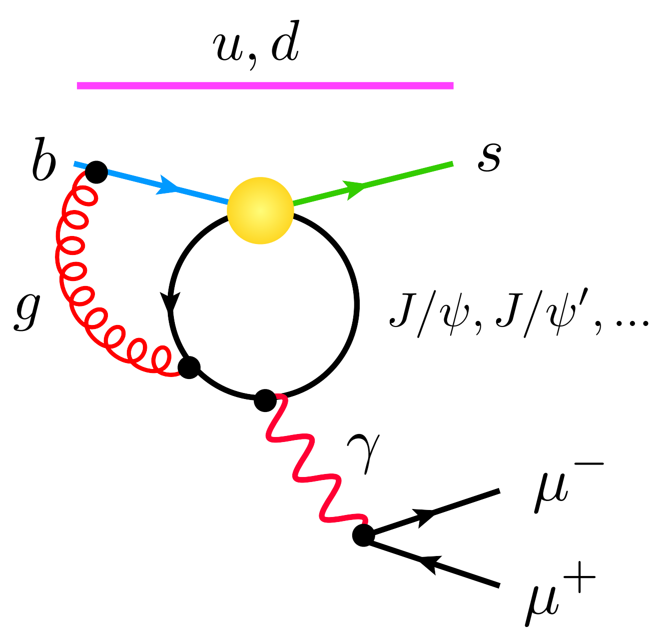
A pattern in b → s transitions

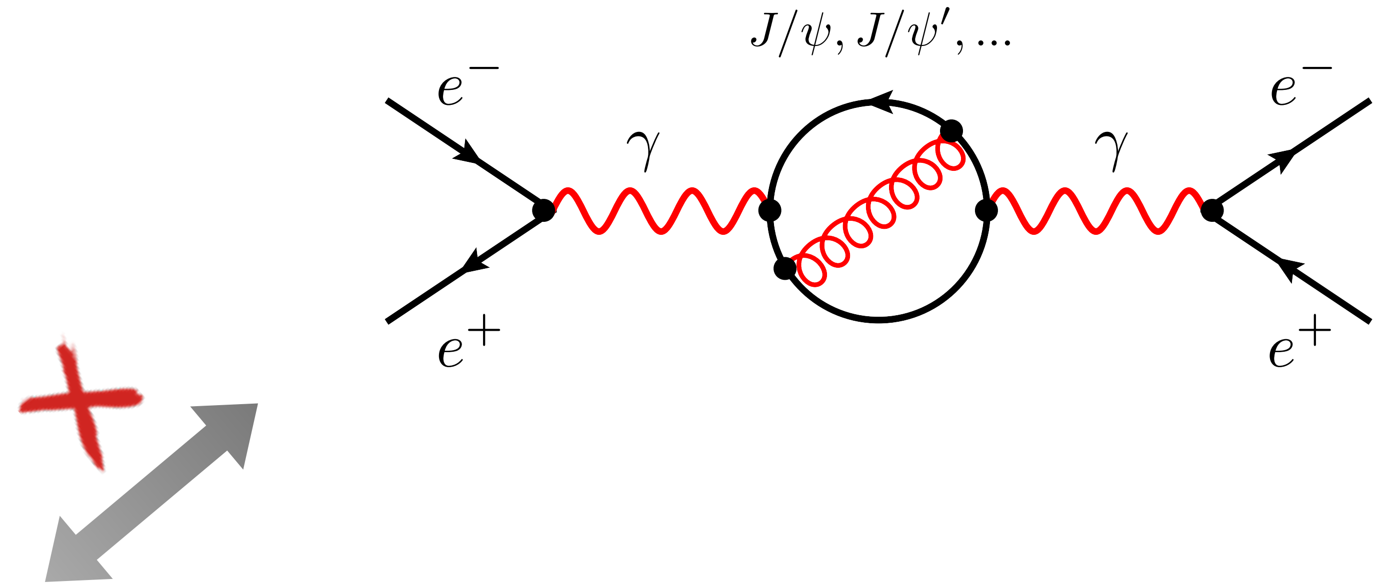


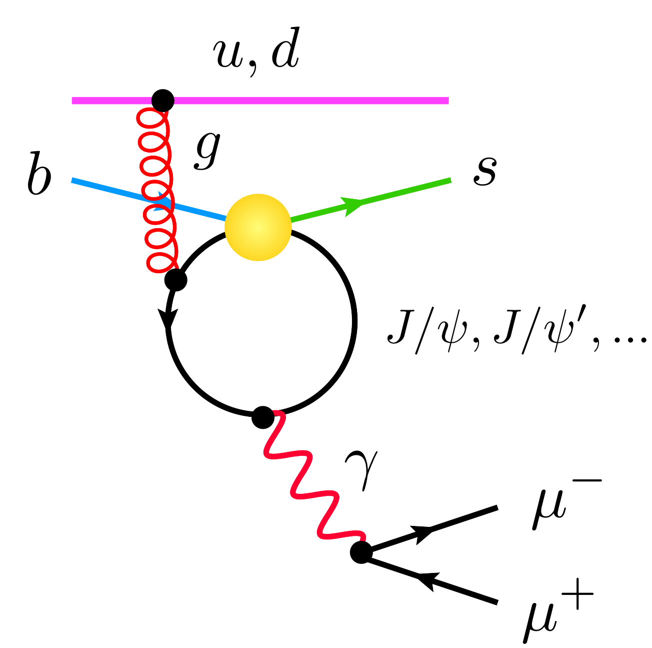
[from Haisch 2016]

A pattern in b → s transitions

Breakdown of factorization







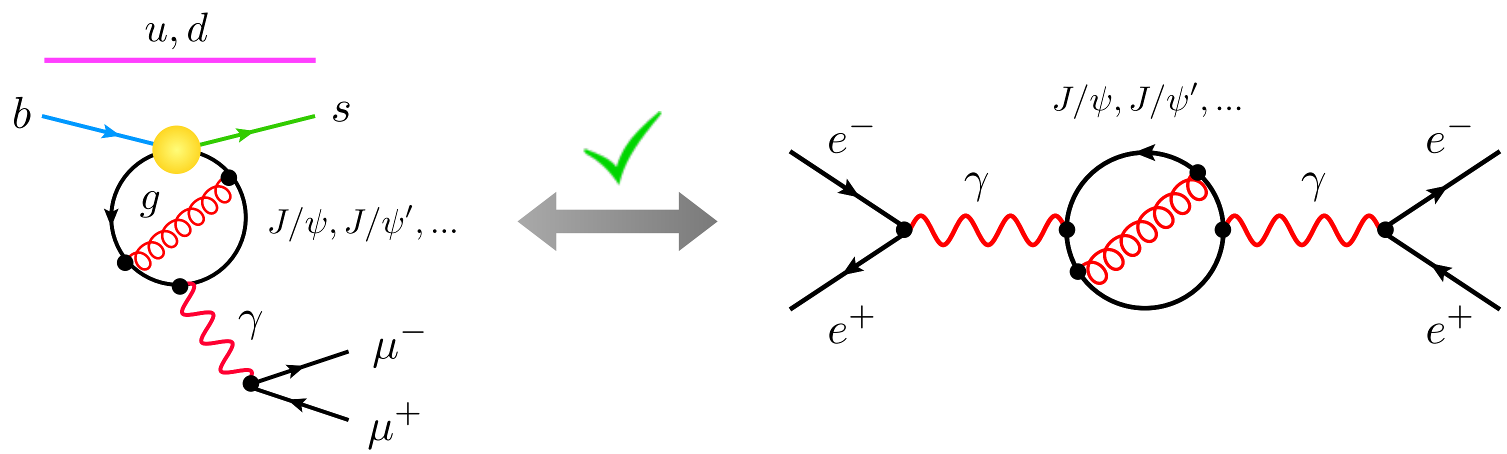
- Unfortunately, there are other contributions which cannot be related to vacuum polarization. Such effects break factorization

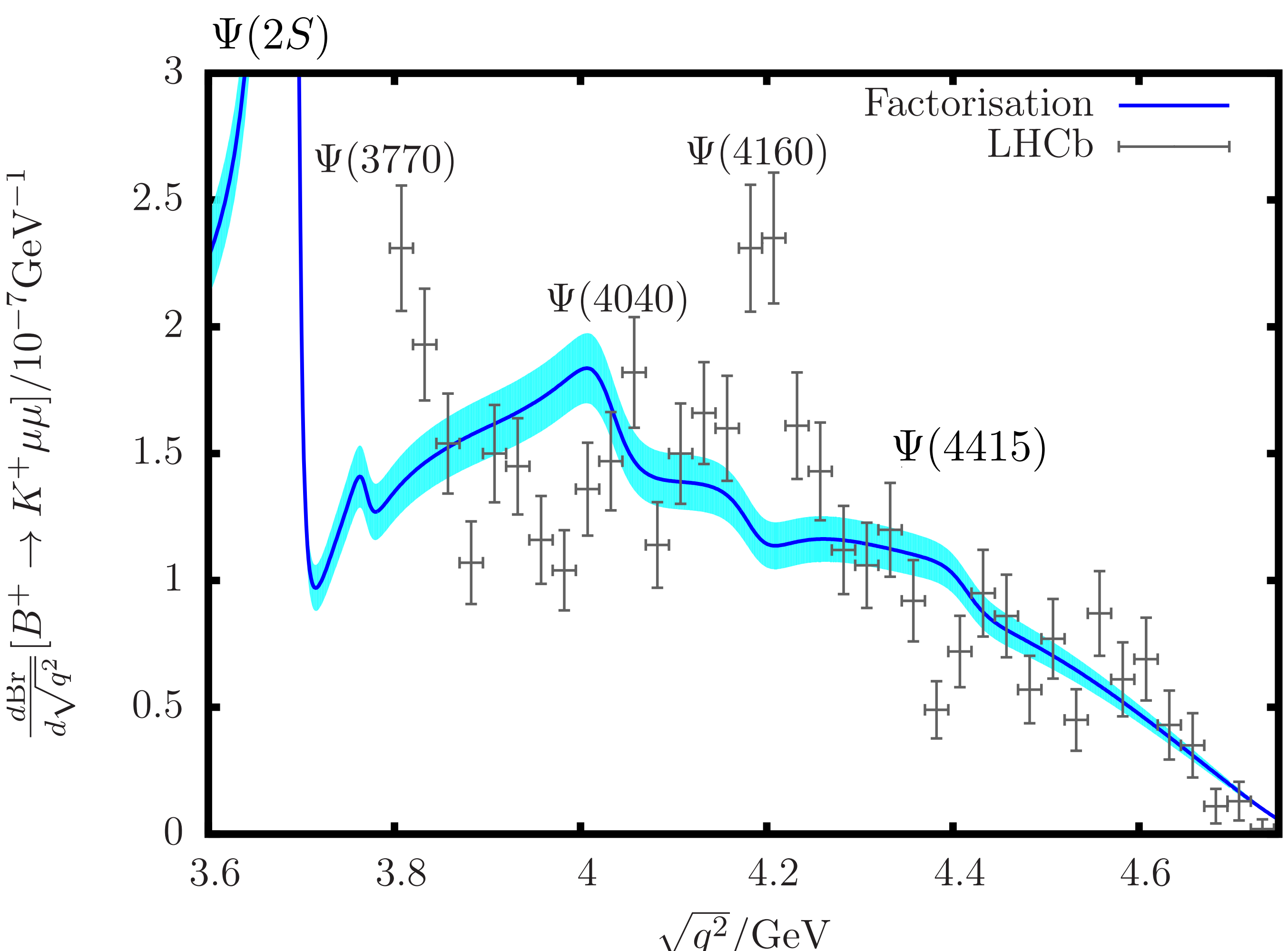
[from Haisch 2016]

A pattern in b → s transitions

How bad is it?

[Lyon, Zwicky 1406.0566]





Quark-hadron duality is broken globally!

$$\frac{d\Gamma(B \to \pi\pi)}{dq^2} \propto \left(\mathrm{Im}\,\Pi(q^2)\right)^2$$

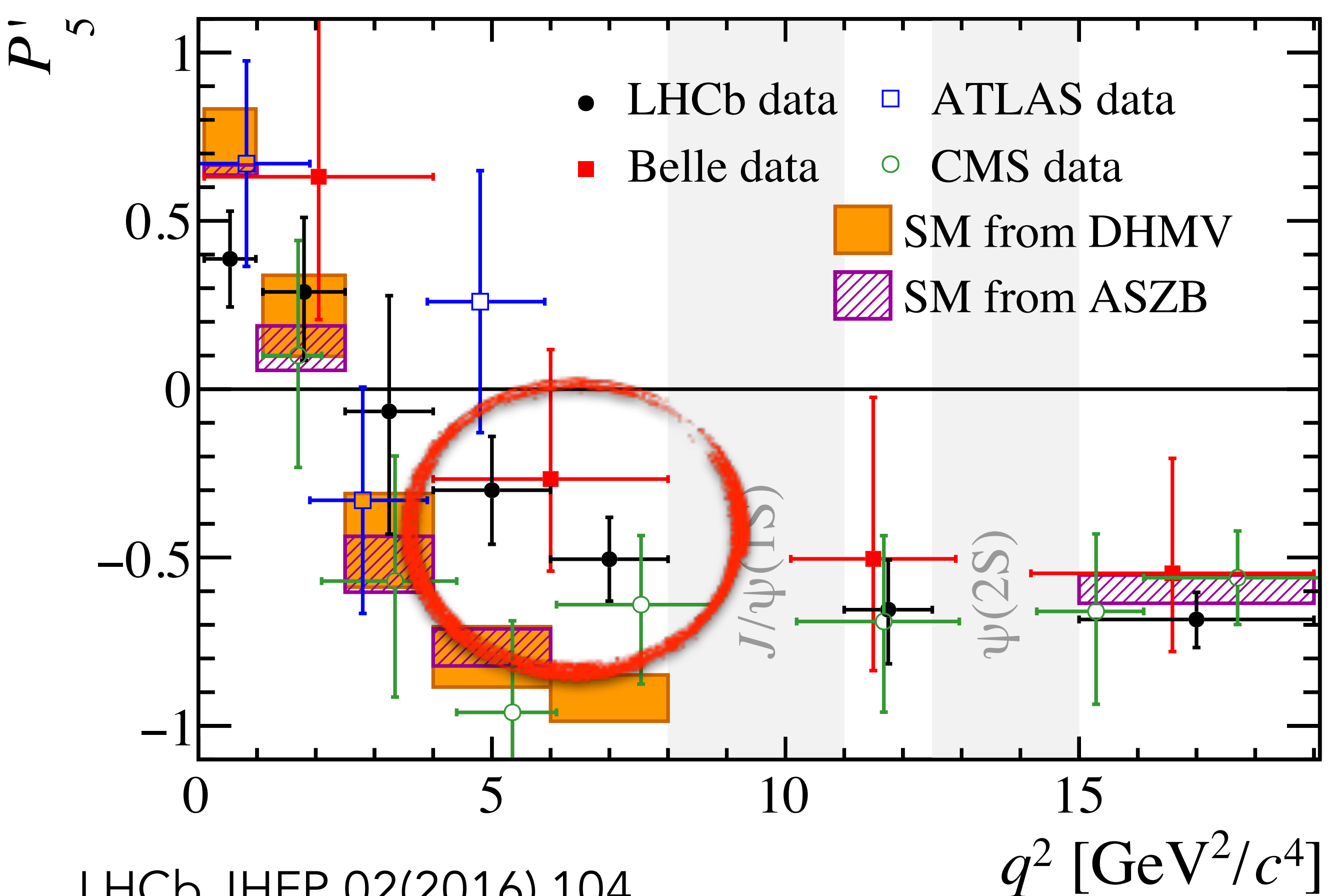
$$\frac{d\Gamma(B \to X_s \ell^+ \ell^-)}{dq^2} \propto |\Pi(q^2)|^2$$

Beautiful toy model in

[Beneke, Buchalla, Neubert, Sachrajda, 0902.4446]

A pattern in b → s transitions

Largest deviations are expected close to the J/Psi resonance, which is exactly where the anomaly sits.

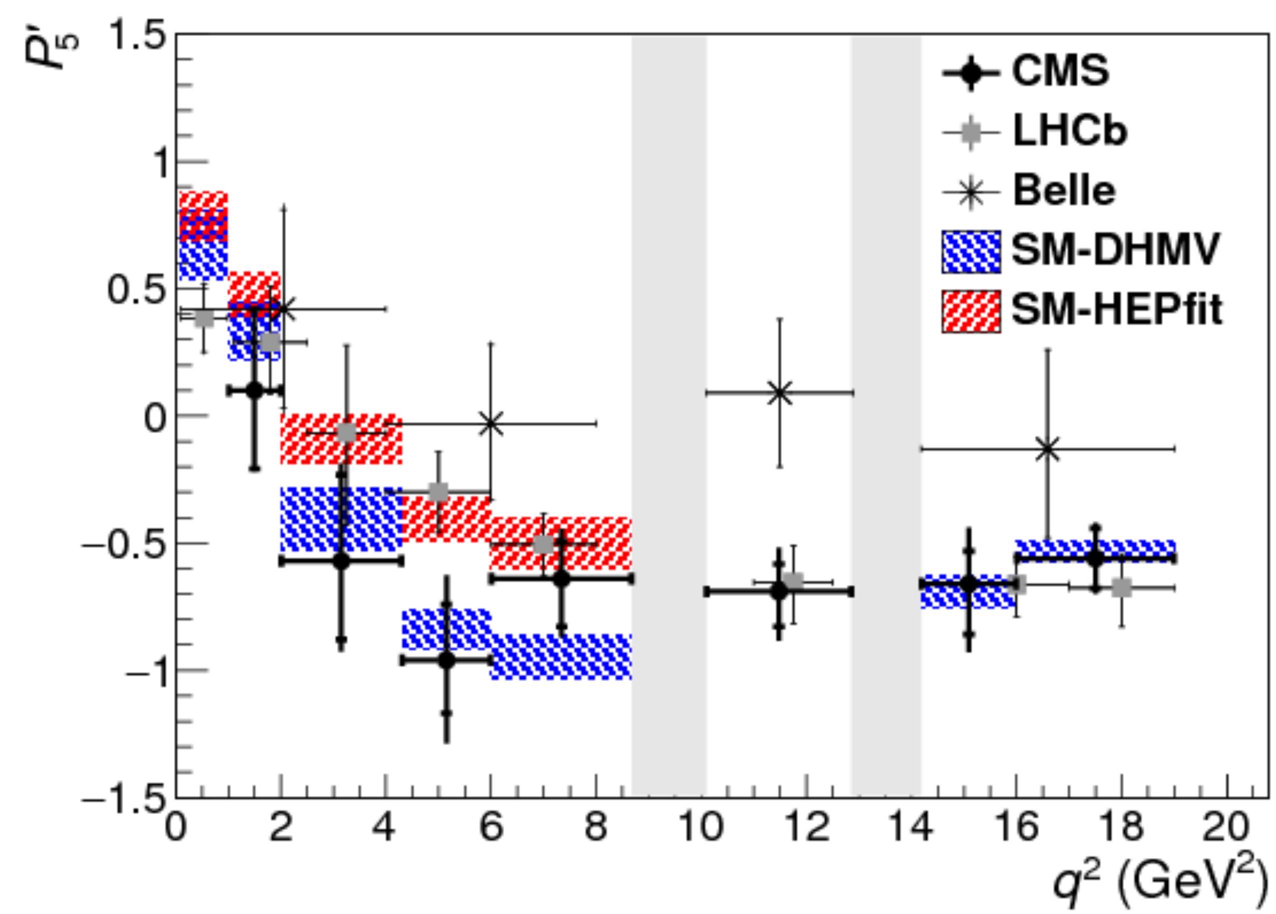


LHCb JHEP 02(2016) 104

Belle PRL118, 111801 (2017)

ATLAS, preliminary Moriond EW

CMS, preliminary Moriond EW



[Albrecht, Reicher, van Dyk, 1806.05010]

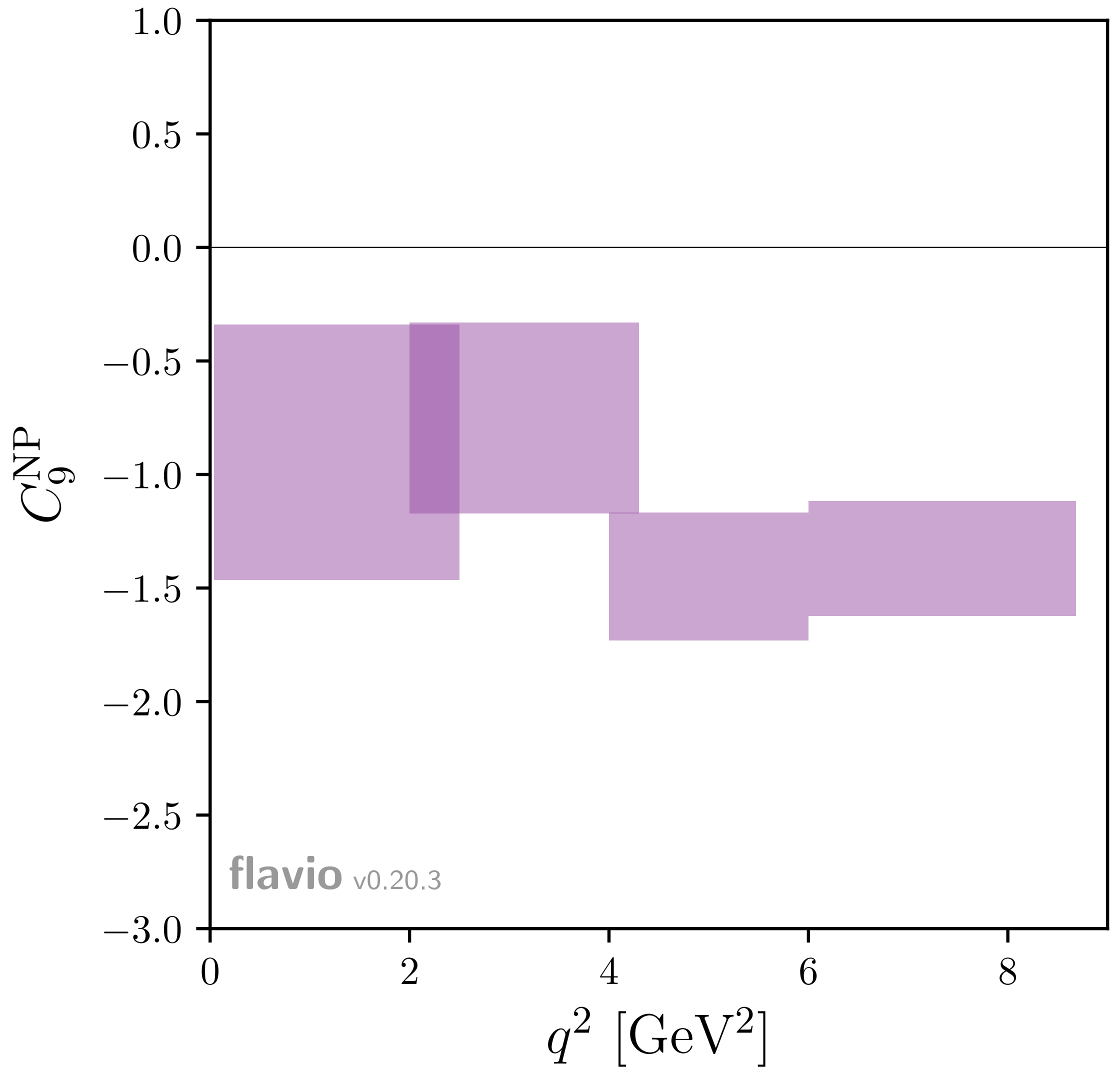
[Ciuchini et.al. 1809.03789]

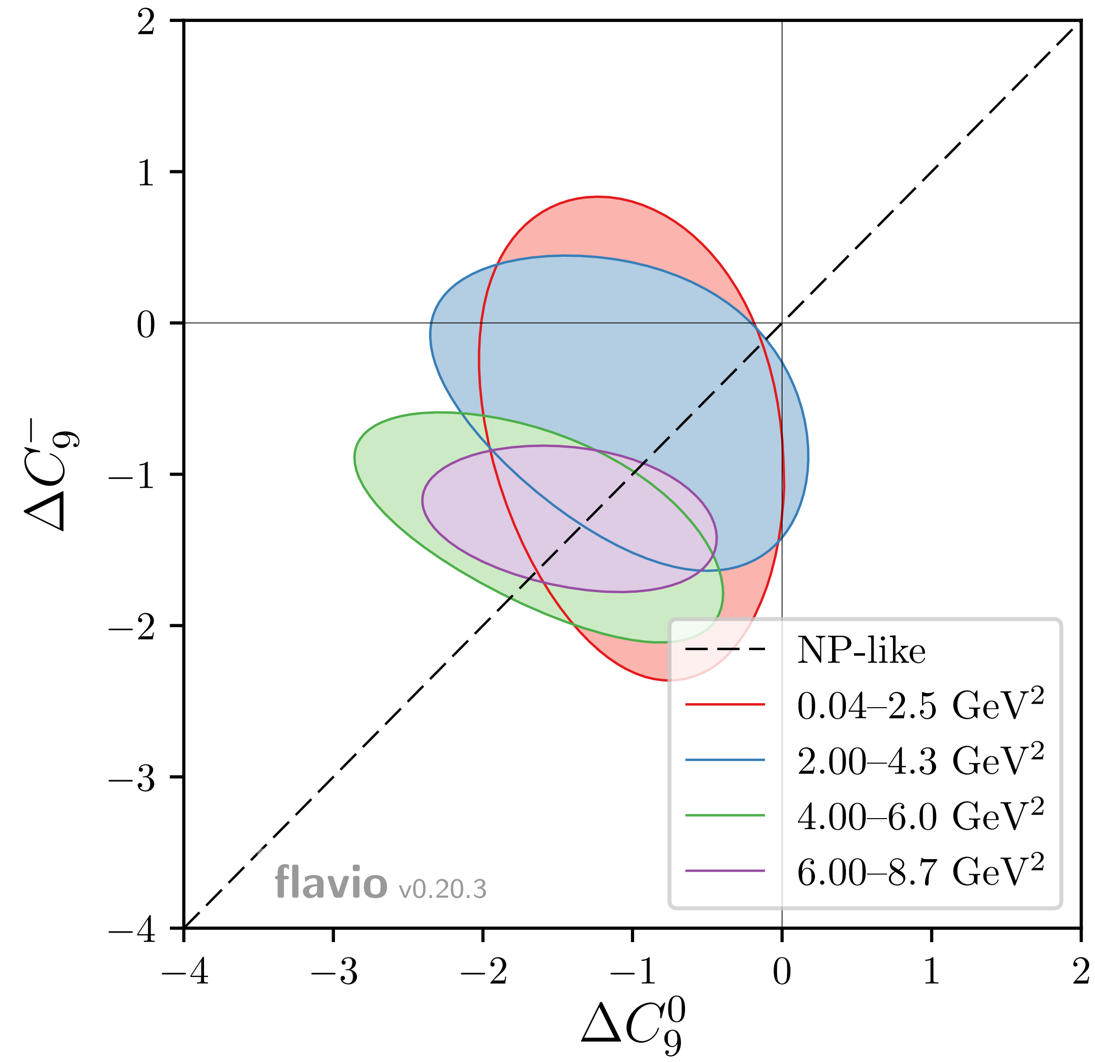
A pattern in $b \to s$ transitions

How can we know whether is is new physics?

A pattern in b → s transitions

The fit is flat in q² and prefers no helicity amplitude at 1 sigma…

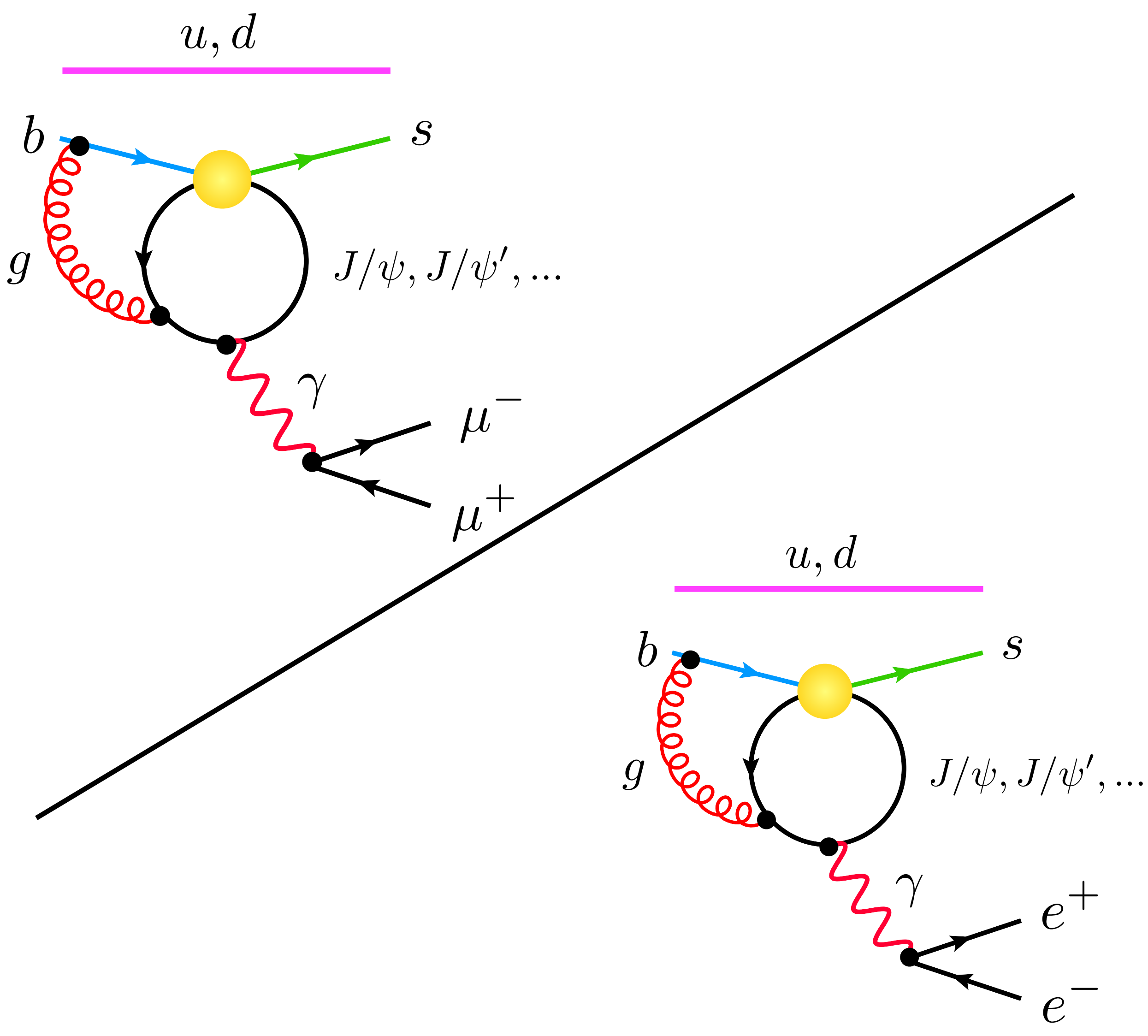




[Altmannshofer, Straub, 1703.09189]

Lepton Non-Universality in b→s

Much better: Measure ratios free from hadronic uncertainties

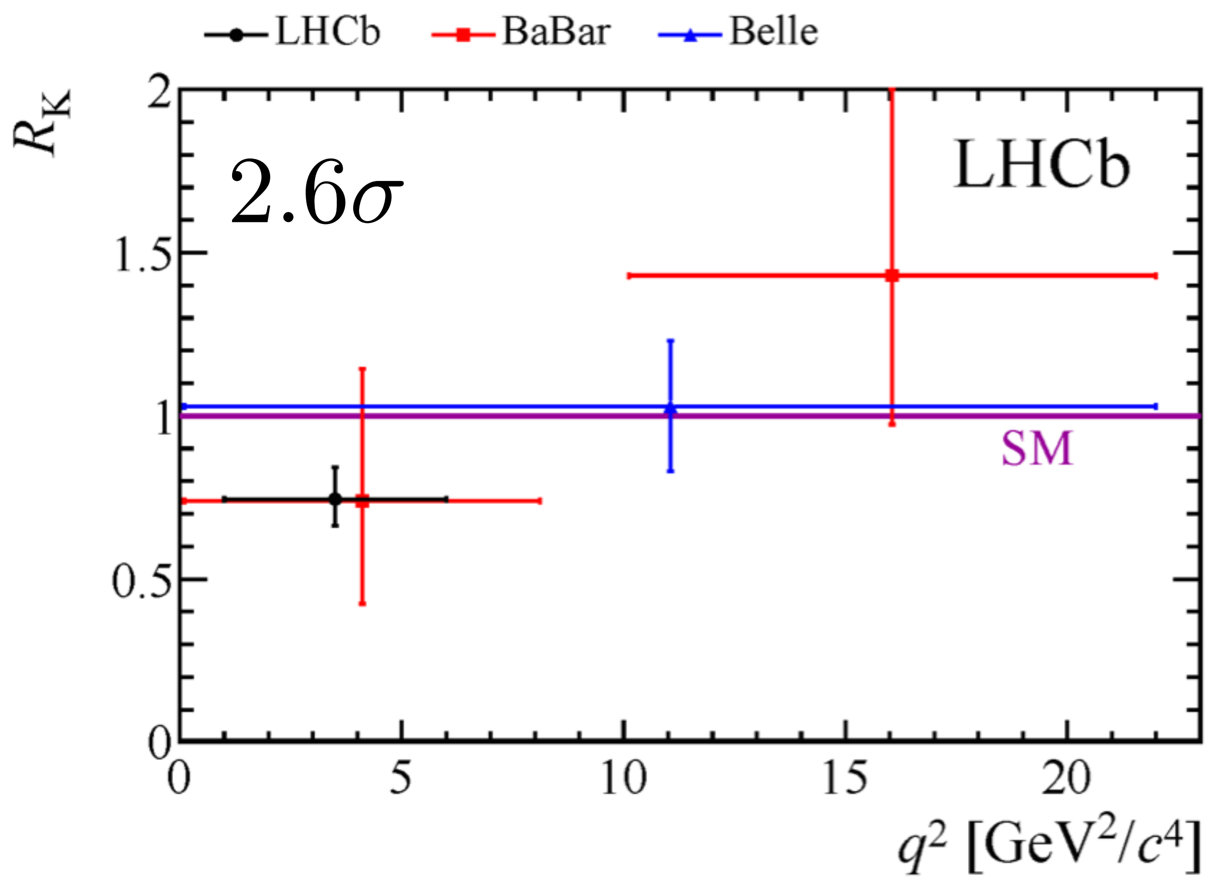


$$\frac{\Gamma(\bar{B} \to \bar{K} \mu^+ \mu^-)}{\Gamma(\bar{B} \to \bar{K} e^+ e^-)}$$

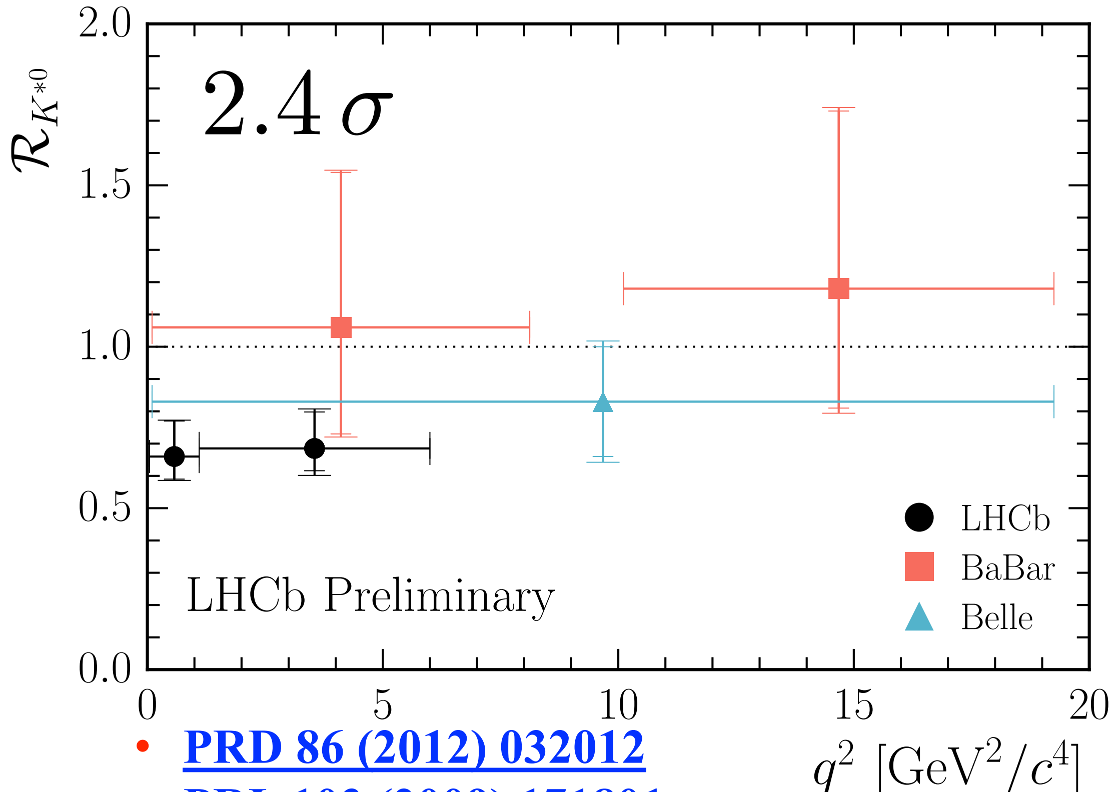
Lepton Non-Universality in b→s

$$R_K = \frac{\Gamma(\bar{B} \to \bar{K}\mu^+\mu^-)}{\Gamma(\bar{B} \to \bar{K}e^+e^-)} = 0.745\,^{+0.090}_{-0.074} \pm 0.036$$

$$R_{K^*} = \frac{\Gamma(\bar{B} \to \bar{K}^*\mu^+\mu^-)}{\Gamma(\bar{B} \to \bar{K}^*e^+e^-)} = \begin{cases} 0.660^{+0.110}_{-0.070} \pm 0.024 \\ 0.685^{+0.113}_{-0.069} \pm 0.047 \end{cases}$$



[LHCb,1406.6482]



- **PRD 86 (2012) 032012**
- **PRL 103 (2009) 171801**

[Simone Bifani CERN Seminar]
[LHCb,1705.05802]

Theoretically **very clean**, QED corrections ~ 1% [Bordone, Isidori, Pattori, 1605.07633]

Lepton Non-Universality in b→s

What about the inclusive rate?

Hard to do at the LHC, because the second B meson cannot be reconstructed.

Belle:

$$R_{X_s} = \frac{\displaystyle\int_{1\,\mathrm{GeV}^2}^{6\,\mathrm{GeV}^2} dq^2\, \frac{d\Gamma\left(B \to X_s \mu^+ \mu^-\right)}{dq^2}}{\displaystyle\int_{1\,\mathrm{GeV}^2}^{6\,\mathrm{GeV}^2} dq^2\, \frac{d\Gamma\left(B \to X_s e^+ e^-\right)}{dq^2}} = 0.34 \pm 0.16$$

$$R_{X_s}^{\mathrm{SM}} = 1 - 4.3\%$$

3.9σ

[http://belle.kek.jp/belle/theses/doctor/2009/Nakayama.pdf]

[from Haisch 2016]

Lepton Non-Universality in b→s

$$R_K = \frac{\Gamma(\bar{B} \to \bar{K}\mu^+\mu^-)}{\Gamma(\bar{B} \to \bar{K}e^+e^-)} = 0.745\,^{+0.090}_{-0.074} \pm 0.036$$

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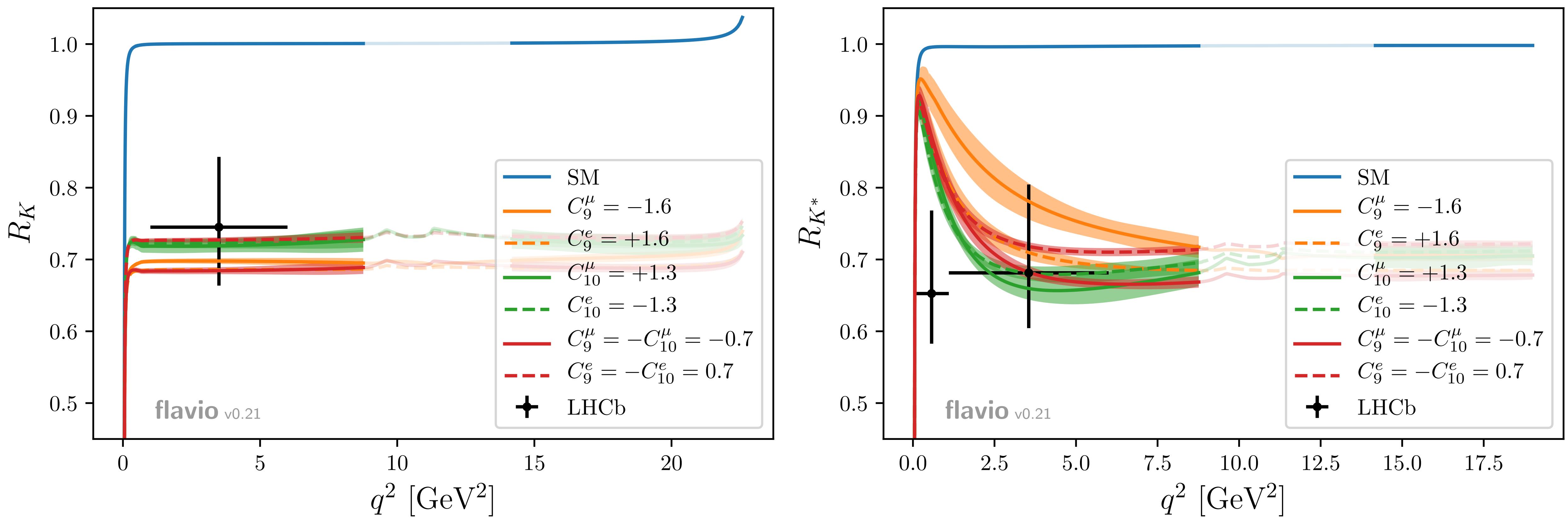

[Altmannshofer et al. 1704.05435]

Lepton Non-Universality in b→s

Lepton flavour non-universality in R_K, R_{K^*}

$$R_K = 0.745\,^{+0.090}_{-0.074} \pm 0.036 \qquad R_{K^*} = \begin{cases} 0.660^{+0.110}_{-0.070} \pm 0.024 \\ 0.685^{+0.113}_{-0.069} \pm 0.047 \end{cases} \qquad R_{X_s} = 0.34 \pm 0.16$$

$$R_K \propto 1 + \mathrm{Re}(C + C')$$
$$R_{K^*} \propto 1 + \mathrm{Re}(C + C') - 2\mathrm{Re}(C')$$
$$R_{X_s} \propto 1 + \mathrm{Re}(C)$$

$$\frac{R_{K^*}}{R_K} \approx 1 \quad \Rightarrow \quad C' = 0$$

$$C \equiv C^\mu - C^e$$

[Hiller, Schmaltz 1411.4773]

Coefficient	Best fit	1σ	3σ	Pull$_{\mathrm{SM}}$
$\mathcal{C}_7^{\mathrm{NP}}$	-0.02	$[-0.04, -0.00]$	$[-0.07, 0.04]$	1.1
$\mathcal{C}_9^{\mathrm{NP}}$	-1.11	$[-1.32, -0.89]$	$[-1.71, -0.40]$	**4.5**
$\mathcal{C}_{10}^{\mathrm{NP}}$	0.58	$[0.34, 0.84]$	$[-0.11, 1.41]$	2.5
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$\mathcal{C}_{10'}^{\mathrm{NP}}$	-0.27	$[-0.46, -0.08]$	$[-0.84, 0.28]$	1.4
$\mathcal{C}_9^{\mathrm{NP}} = \mathcal{C}_{10}^{\mathrm{NP}}$	-0.21	$[-0.40, 0.00]$	$[-0.74, 0.55]$	1.0
$\mathcal{C}_9^{\mathrm{NP}} = -\mathcal{C}_{10}^{\mathrm{NP}}$	-0.69	$[-0.88, -0.51]$	$[-1.27, -0.18]$	**4.1**
~~$\mathcal{C}_9^{\mathrm{NP}} = -\mathcal{C}_{9'}^{\mathrm{NP}}$~~	~~-1.09~~	~~$[-1.28, -0.88]$~~	~~$[-1.62, -0.42]$~~	~~**4.8**~~

killed by RK*

DHMV, 1510.04239

Lepton Non-Universality in b→s

So… New Physics either in

C_9

or

$C_9 = -C_{10}$

?

Lepton Non-Universality in b→s

$$R_K = \frac{\Gamma(\bar{B} \to \bar{K}\mu^+\mu^-)}{\Gamma(\bar{B} \to \bar{K}e^+e^-)} = 0.745\,^{+0.090}_{-0.074} \pm 0.036$$

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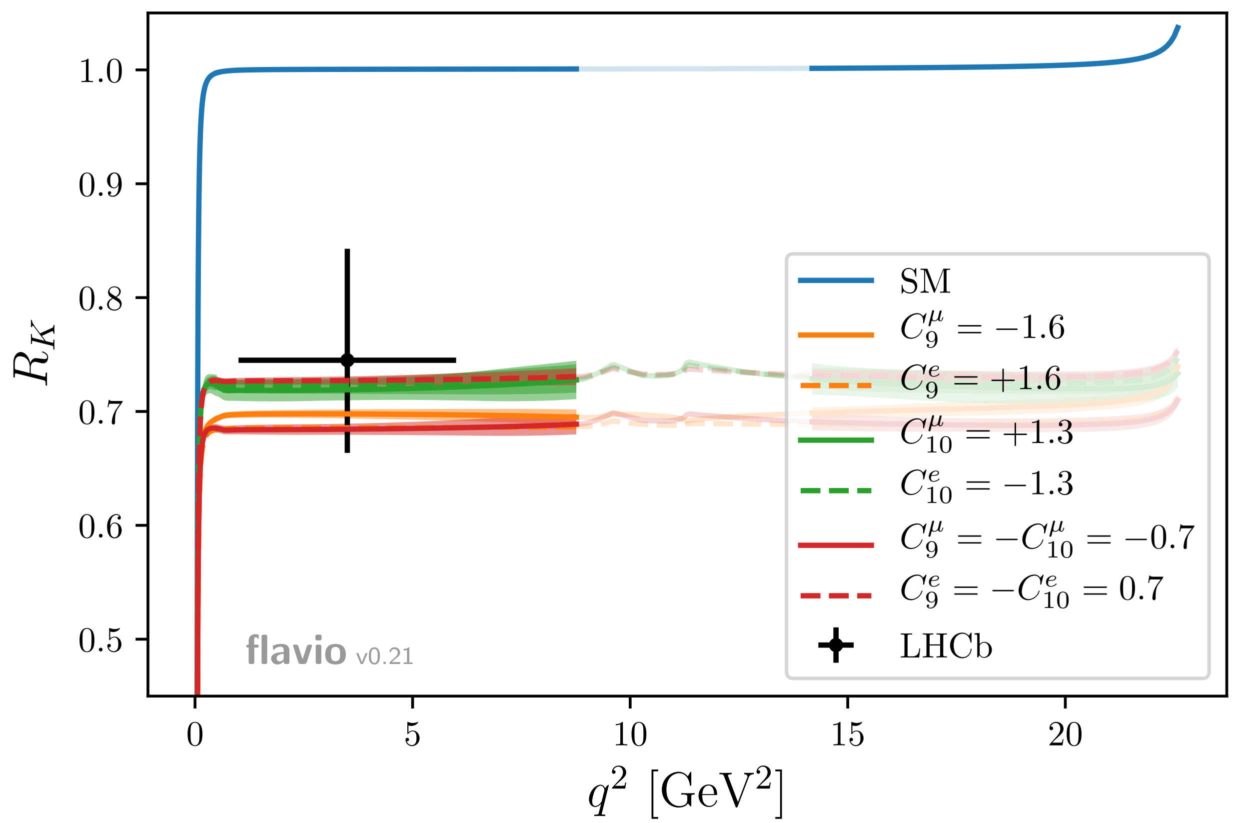
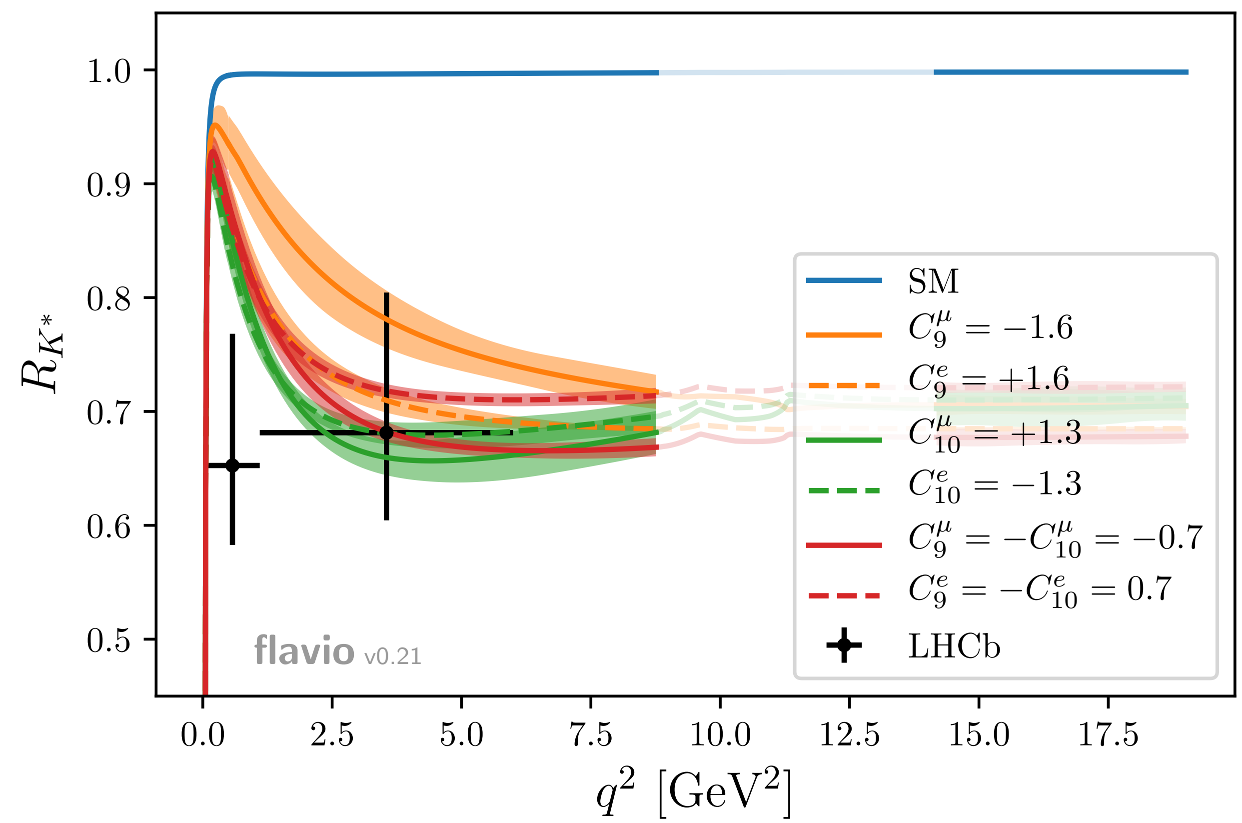
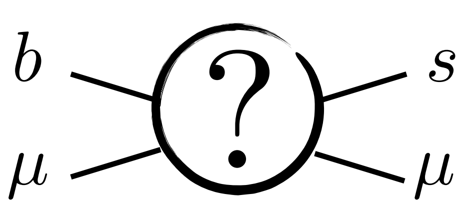
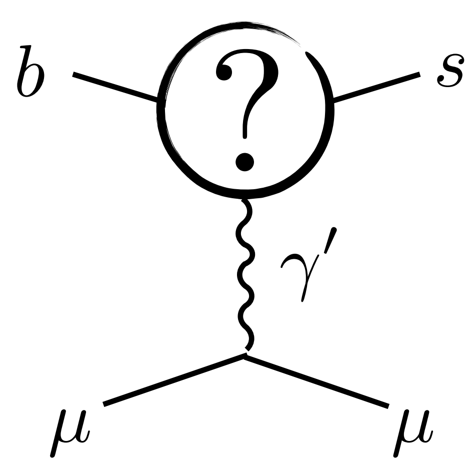






or



[Altmannshofer et al. 1704.05435]

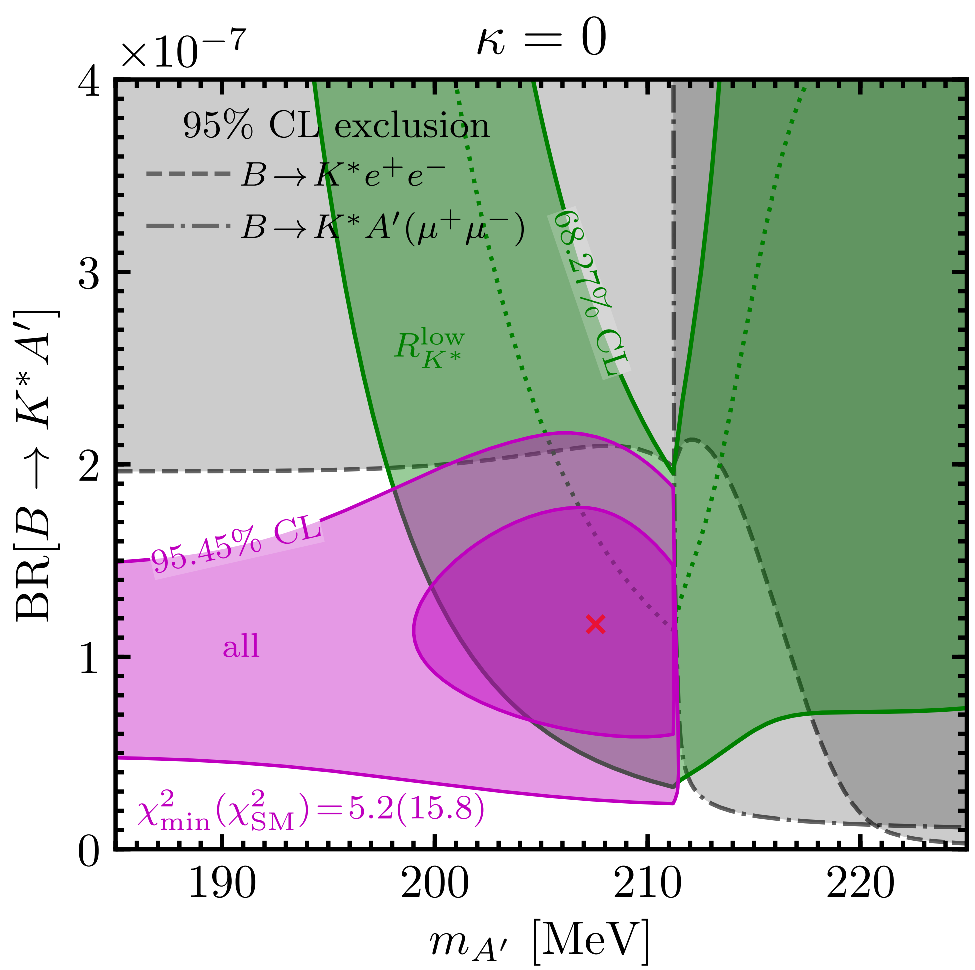
Lepton Non-Universality in b→s

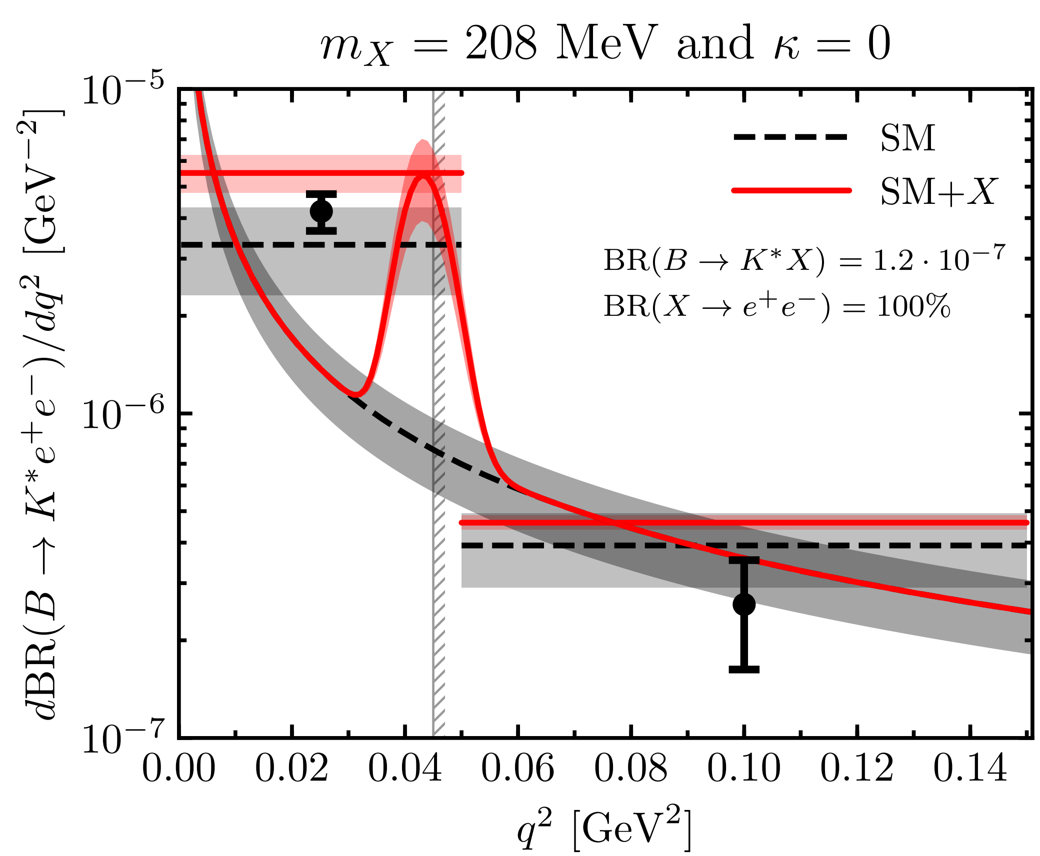
Any enhancement of the photon penguin is excluded by $B \to K^* \gamma$ and $B \to X_s \gamma$.

It cannot be an off-shell effect

$$\frac{\Gamma(B \to X_s X)}{\Gamma^{\rm SM}_{B,\rm tot}} \sim \frac{e^2}{4 g_\ell^2} (\Delta R_{K^*})^2 \times {\rm BR}(B \to X_s \gamma) \simeq 800\% \times \left(\frac{0.3 \cdot 10^{-3}}{g_\ell}\right)^2 \left(\frac{\Delta R_{K^*}}{0.3}\right)^2$$

Needs an (additional) new on-shell resonance.

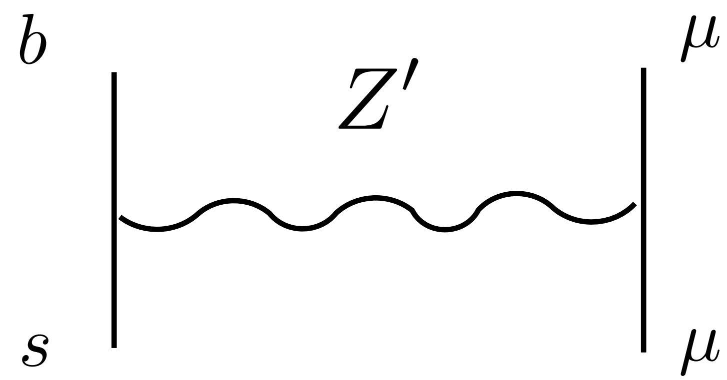


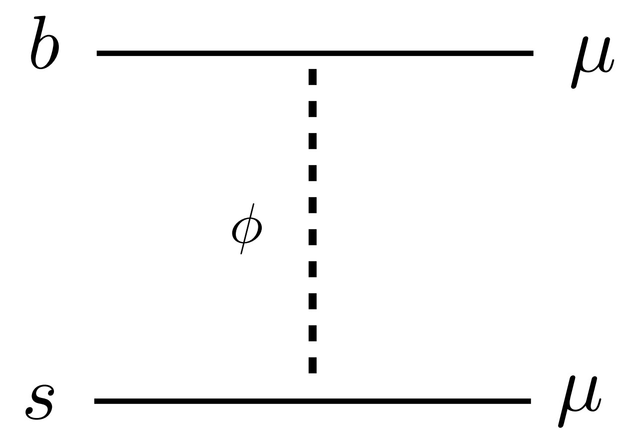


[Altmannshofer, Baker et al. 1711.07494]

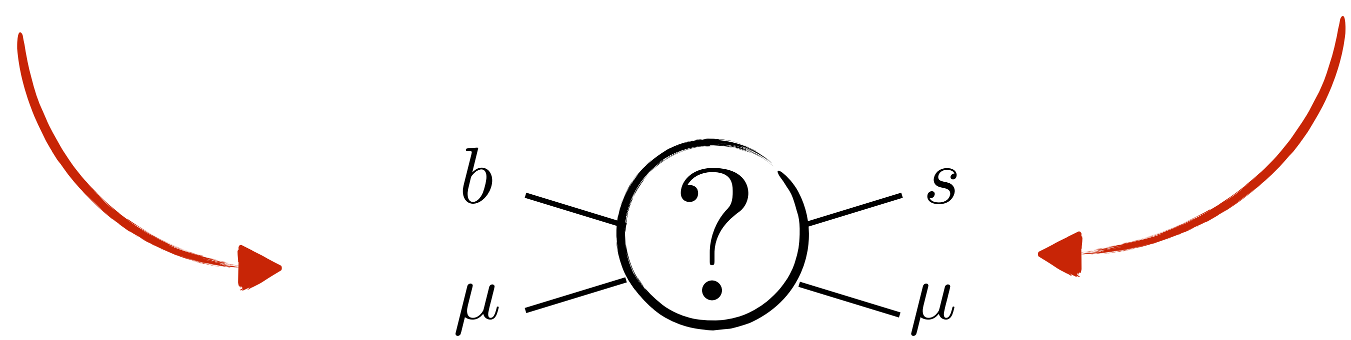
Lepton Non-Universality in b→s

What kind of new physics?





C_9



$C_9 = -C_{10}$

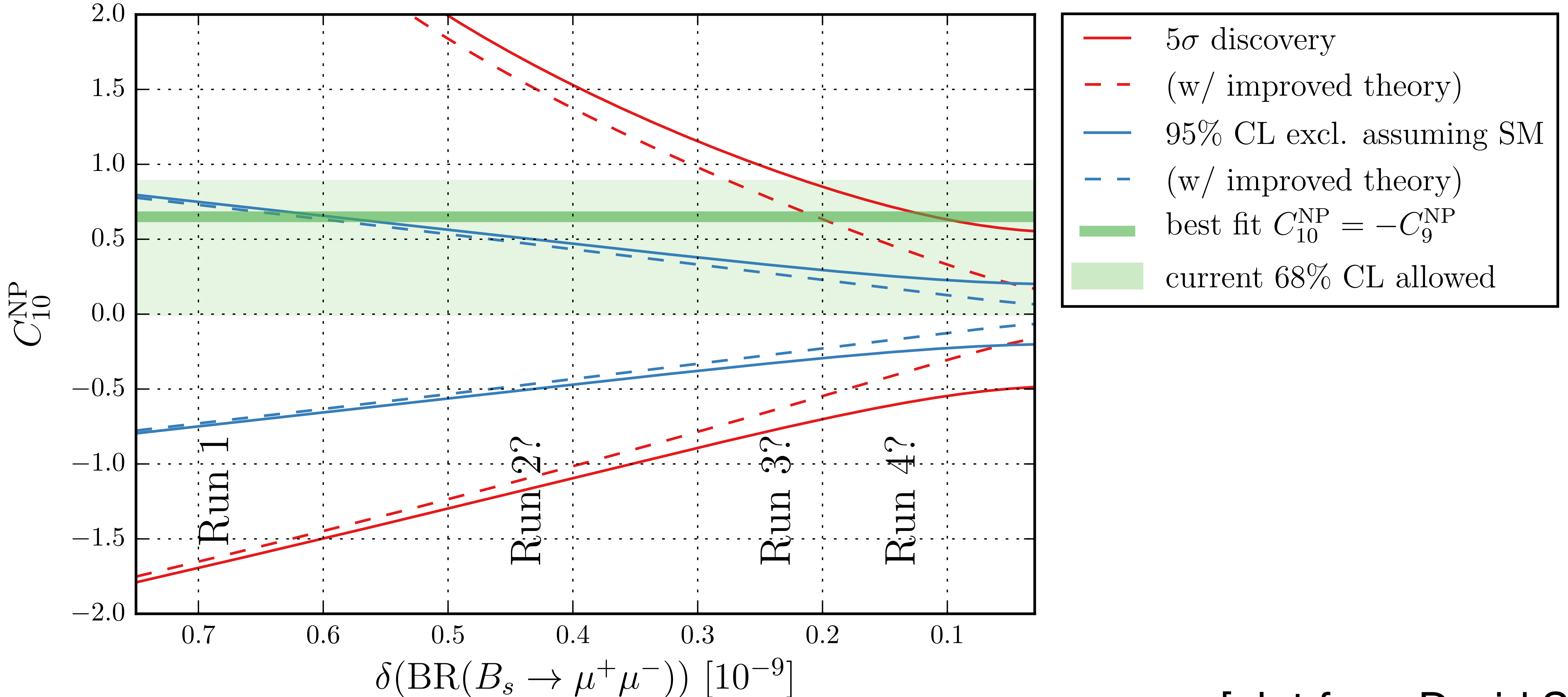
$$C_{9/10}^{\mathrm{NP}} \approx C_{10}^{\mathrm{SM}}/4 \quad \Rightarrow \quad \frac{1}{M^2}\left(\frac{2V_{tb}V_{ts}^*}{v^2}\frac{\alpha_e}{4\pi}\right)^{-1} = \frac{1}{4} \quad \Rightarrow$$

$M \approx 35\,\mathrm{TeV}$

Lepton Non-Universality in b→s

Can we differentiate between leptoquarks and new Z'
gauge bosons?

$$\frac{\mathrm{Br}(B_s \to \mu^+\mu^-)}{\mathrm{Br}(B_s \to \mu^+\mu^-)_{\mathrm{SM}}} = \frac{|C_{10}^{\mathrm{SM}} + C_{10}^{\mathrm{NP}}|^2}{|C_{10}^{\mathrm{SM}}|^2}$$



[plot from David Straub]

Lepton Non-Universality in b→s

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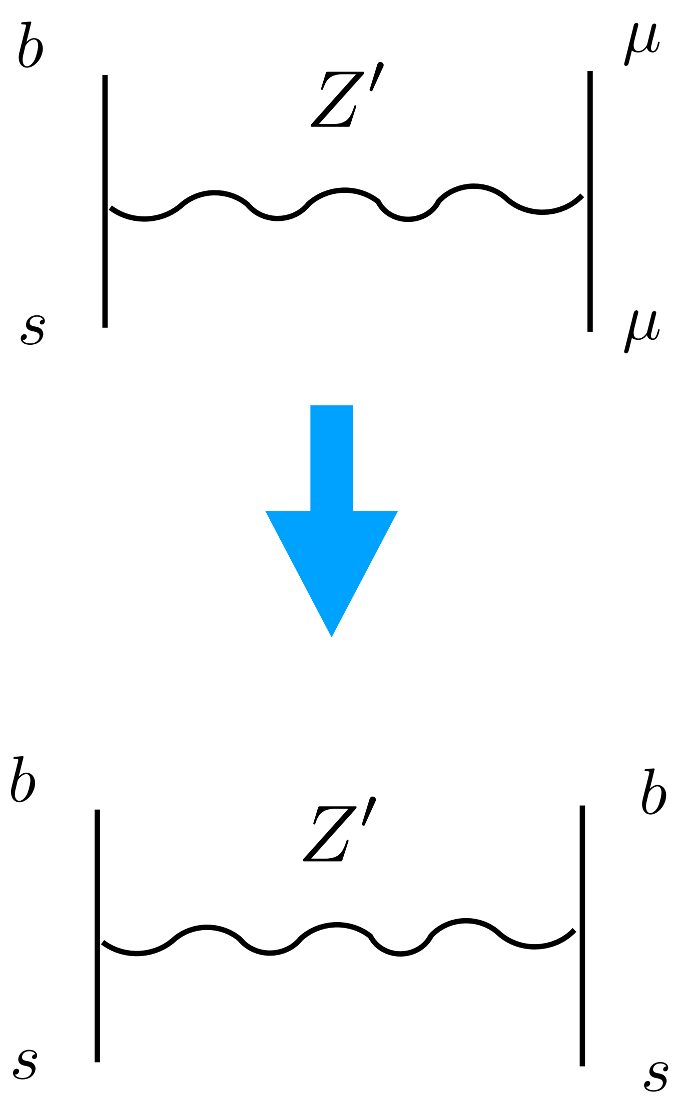
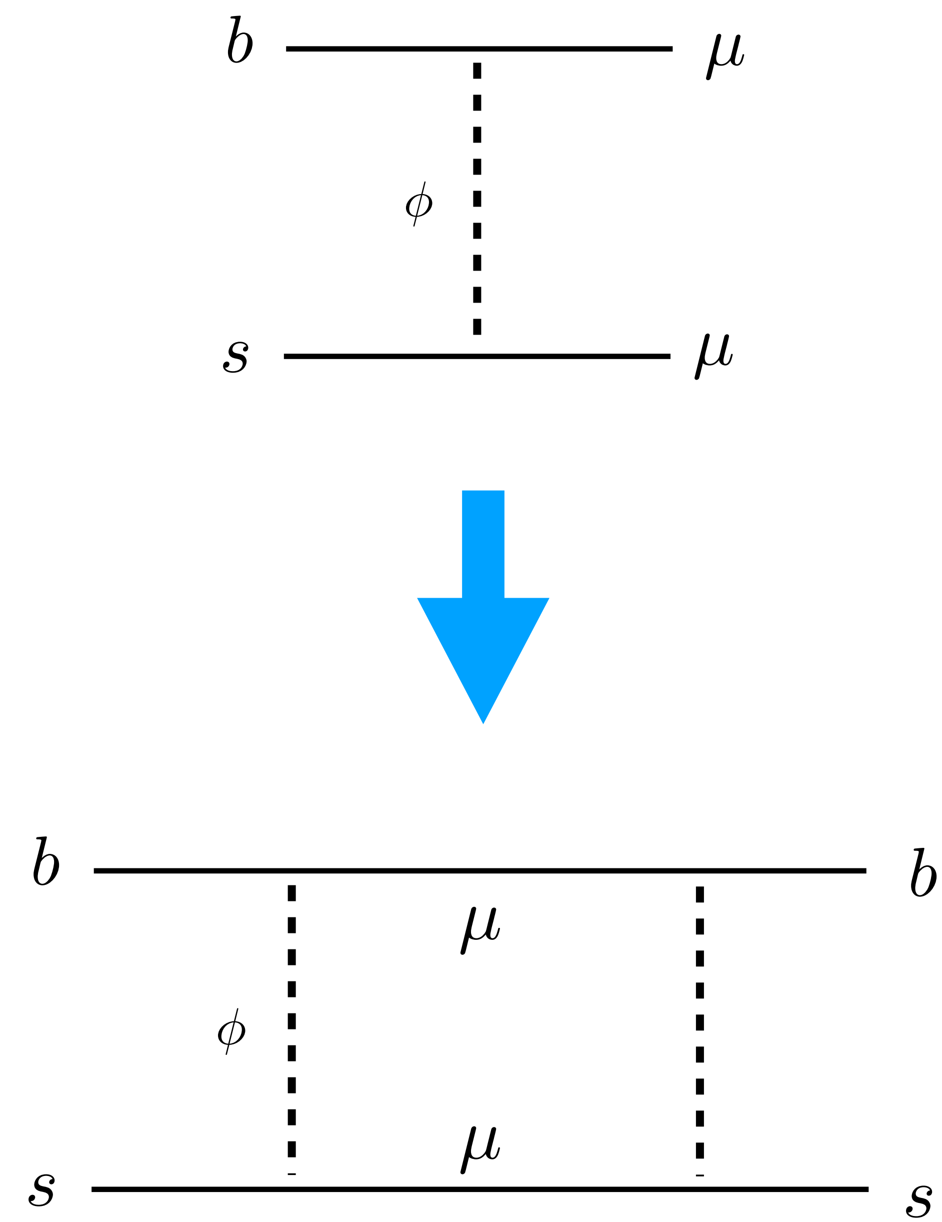


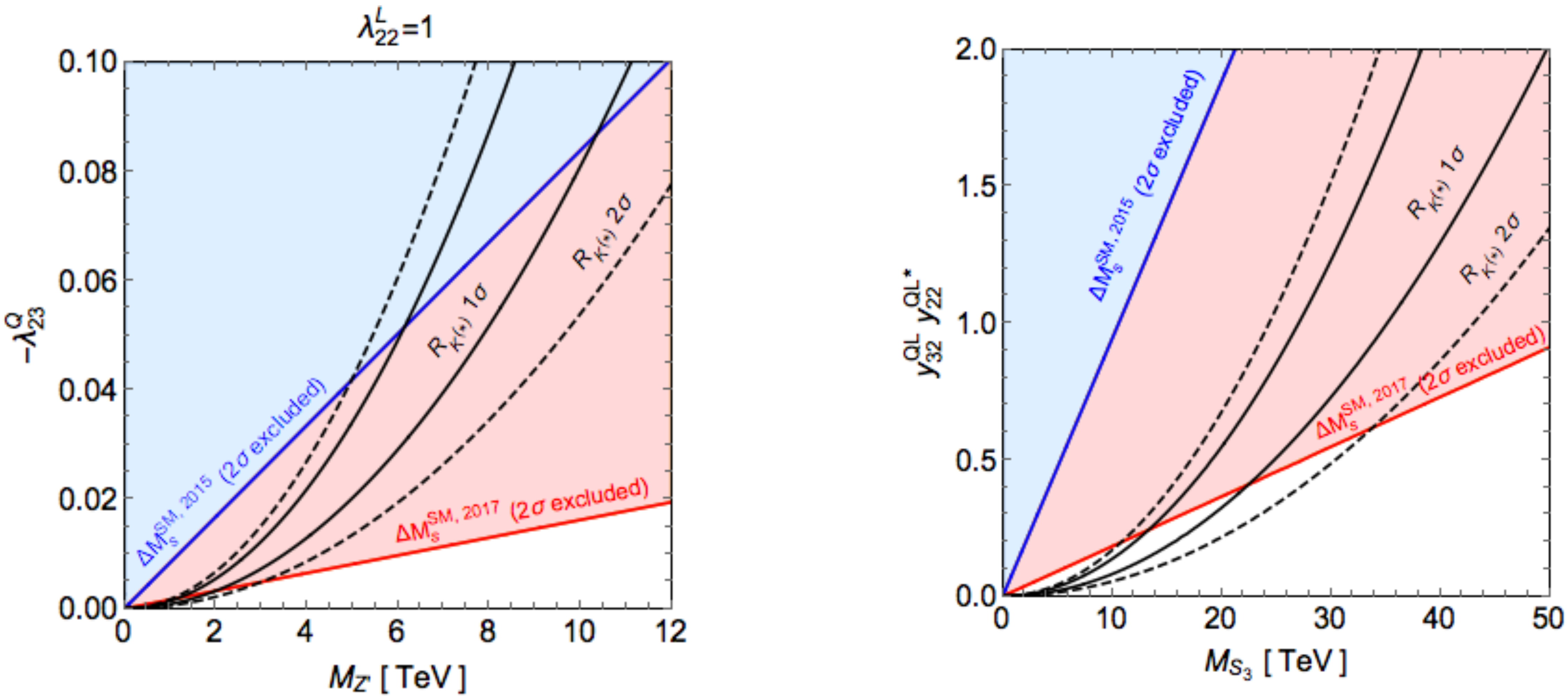


Lepton Non-Universality in b→s

Can we differentiate between leptoquarks and new Z’ gauge bosons?

$$\Delta M_s^{\mathrm{SM,\,2015}} = (18.3 \pm 2.7)\ \mathrm{ps}^{-1} \quad \longrightarrow \quad \Delta M_s^{\mathrm{SM,\,2017}} = (20.01 \pm 1.25)\ \mathrm{ps}^{-1}$$

$$\Delta M_s^{\mathrm{Exp}} = (17.757 \pm 0.021)\ \mathrm{ps}^{-1}$$



[di Luzio, Kirk, Lenz, 1712.06572]

Lepton Non-Universality in b→s

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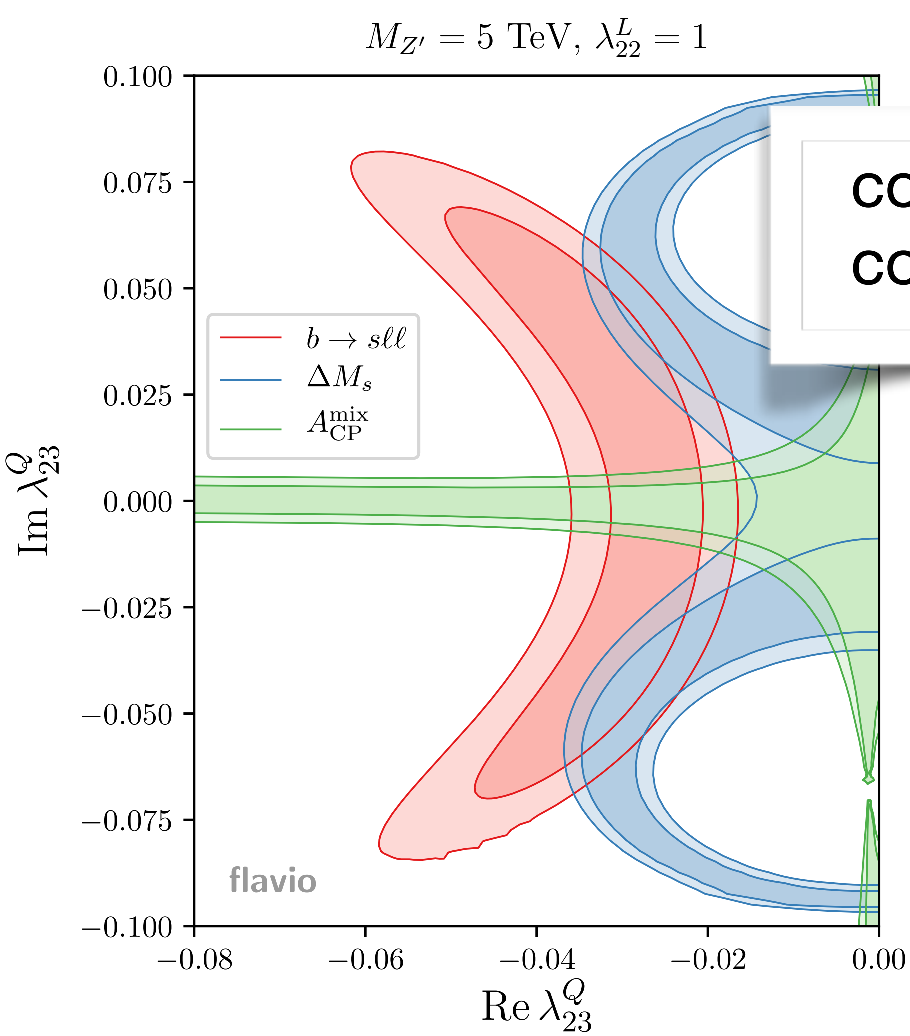
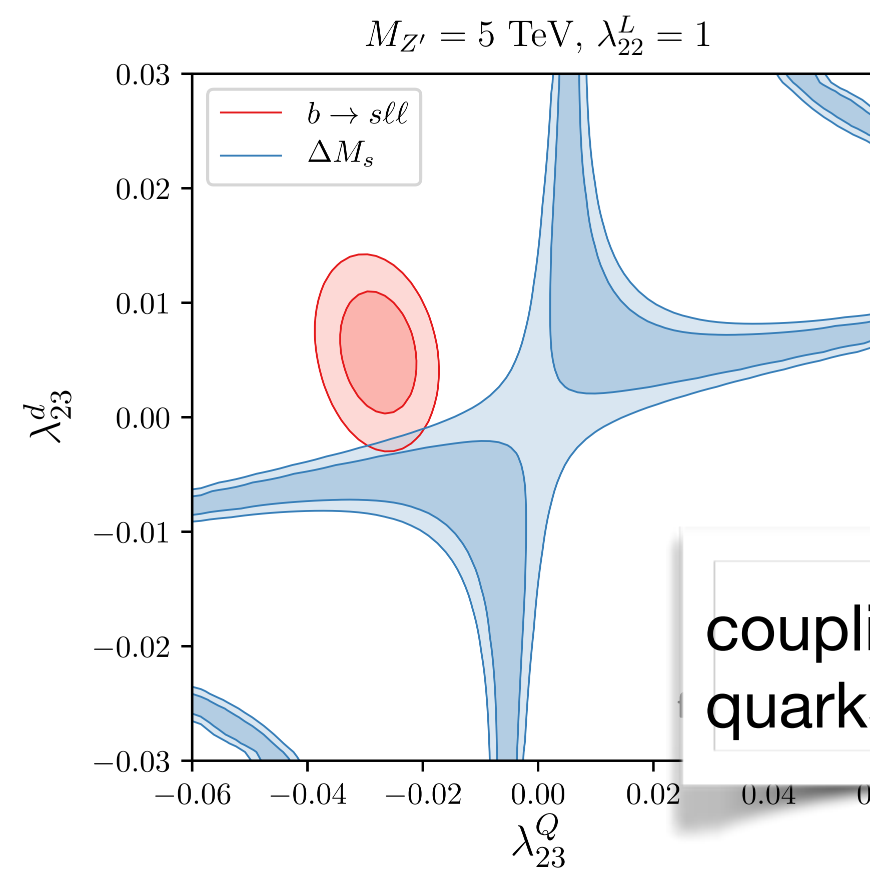
$$\Delta M_s^{\mathrm{SM,\,2015}} = (18.3 \pm 2.7)\ \mathrm{ps}^{-1} \quad \longrightarrow \quad \Delta M_s^{\mathrm{SM,\,2017}} = (20.01 \pm 1.25)\ \mathrm{ps}^{-1}$$

$$\Delta M_s^{\mathrm{Exp}} = (17.757 \pm 0.021)\ \mathrm{ps}^{-1}$$



complex couplings



couplings to RH quarks

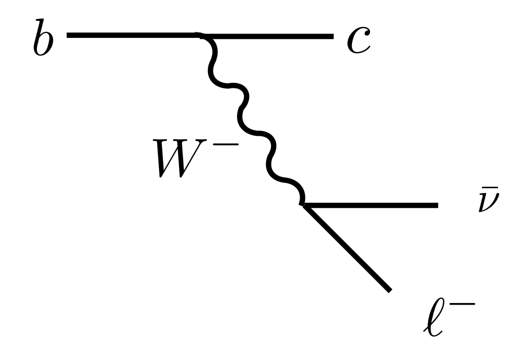
Z' needs to couple to electrons…

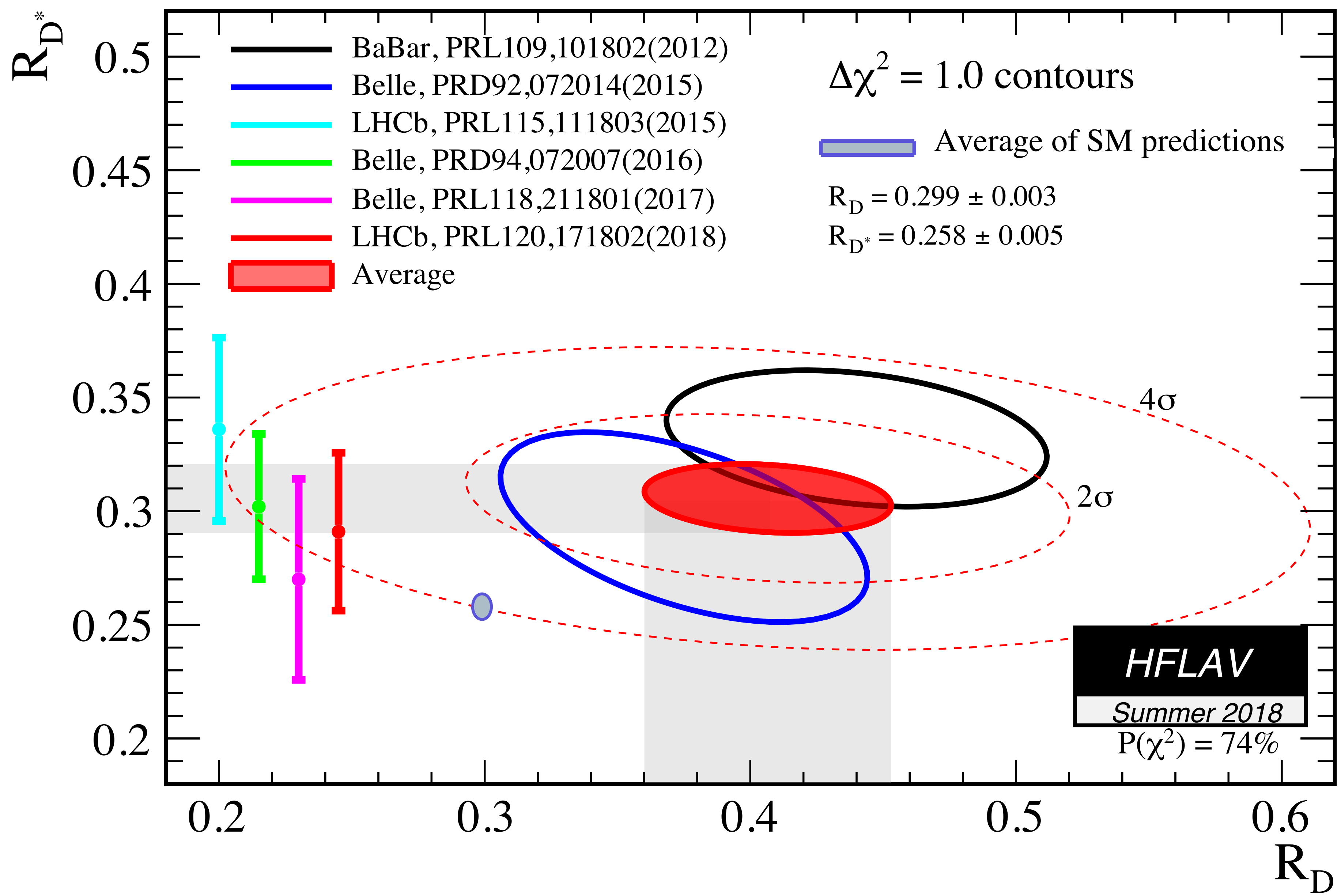
[di Luzio, Kirk, Lenz, 1811.12884]

Lepton Non-Universality in $b \to c$

Lepton Non-Universality in b→c

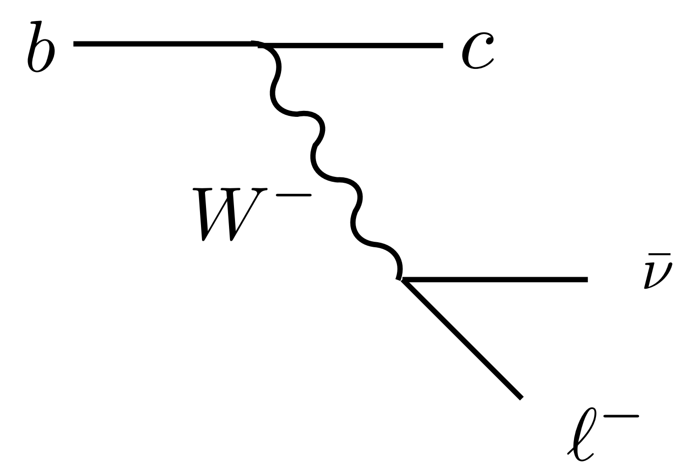
Anomaly in $R(D^{(*)}) = \dfrac{\bar{B} \to D^{(*)}\tau\bar{\nu}}{\bar{B} \to D^{(*)}\ell\bar{\nu}}$





Lepton Non-Universality in b→c

Anomaly in $$R(D^{(*)}) = \frac{\mathrm{Br}(\bar{B} \to D^{(*)}\tau\nu)}{\mathrm{Br}(\bar{B} \to D^{(*)}\ell\nu)}$$



Anomaly in $$R(J/\psi) = \frac{\mathrm{Br}(B_c^+ \to J/\psi\tau^+\nu)}{\mathrm{Br}(B_c^+ \to J/\psi\mu^+\nu)}$$

Observable	SM prediction		Measurement	
R_D	0.300 ± 0.008	[1]	0.407 ± 0.046	[3]
	0.299 ± 0.011	[2]		
	0.299 ± 0.003	[4]		
R_{D^*}	0.252 ± 0.003	[5]	0.304 ± 0.015	[3]
	0.260 ± 0.008	[6]		
$P_\tau(D^*)$	-0.47 ± 0.04	[6]	$-0.38 \pm 0.51(\mathrm{stat.})\,^{+0.21}_{-0.16}(\mathrm{syst.})$	[7,8]
$R_{J/\psi}$	0.290		0.71 ± 0.25	[9]

[LHCb, 1711.05623]

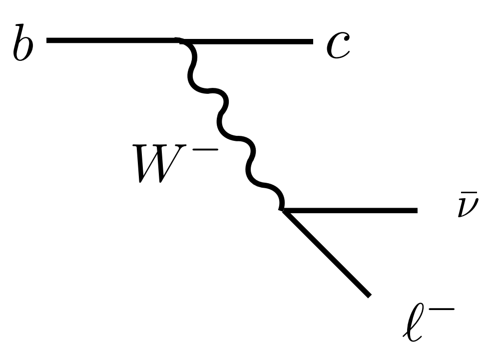
$F_L(D*) = 0.6 \pm 0.08 \pm 0.03$ D* polarization, Belle [Nishida , CKM 2018]

[Azatov et al., 1805.03209] [Aebischer et al, 1810.07698]

Lepton Non-Universality in b→c

	Measurement	**SM Prediction**
$R(D^{(*)}) = \dfrac{\bar{B} \to D^{(*)}\tau\bar{\nu}}{\bar{B} \to D^{(*)}\ell\bar{\nu}}$, D	$0.388 \pm 0.047\,, \quad D$	$0.300 \pm 0.010\,, \quad D$
D^*	$0.321 \pm 0.021\,, \quad D^*$	$0.252 \pm 0.005\,, \quad D^*$

SM contribution is tree-level…



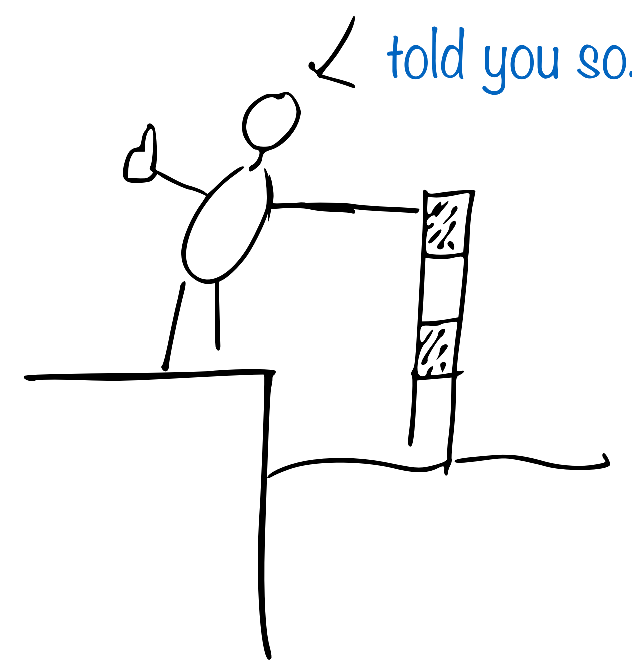
$$\propto \quad \frac{V_{cb}\, g^2}{M_W^2}$$

…and we want a 10-20% shift

Needs a large new physics contribution:

$$C_{NP} \approx C_{SM}/10 \quad \Rightarrow \quad \frac{1}{V_{cb}} \left(\frac{v}{M}\right)^2 = \frac{1}{10}$$

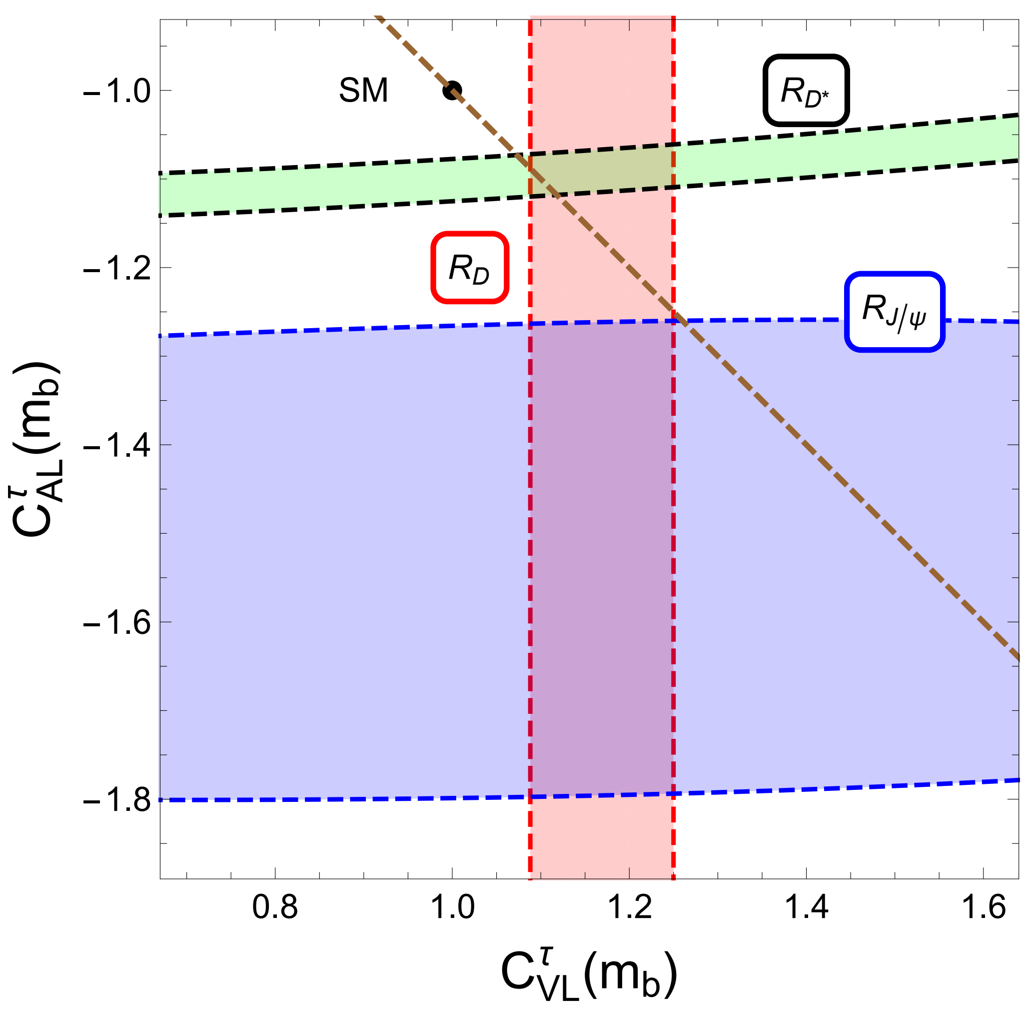
$$M = 1 - 5\,\mathrm{TeV}$$



Lepton Non-Universality in b→c

Rescaling the SM operator gives a good fit.

A new TeV scale vector boson? Needs



$$0.2 \approx g^2 |V_{cb}|^2 \left(\frac{\text{TeV}}{M_{W'}}\right)^2$$

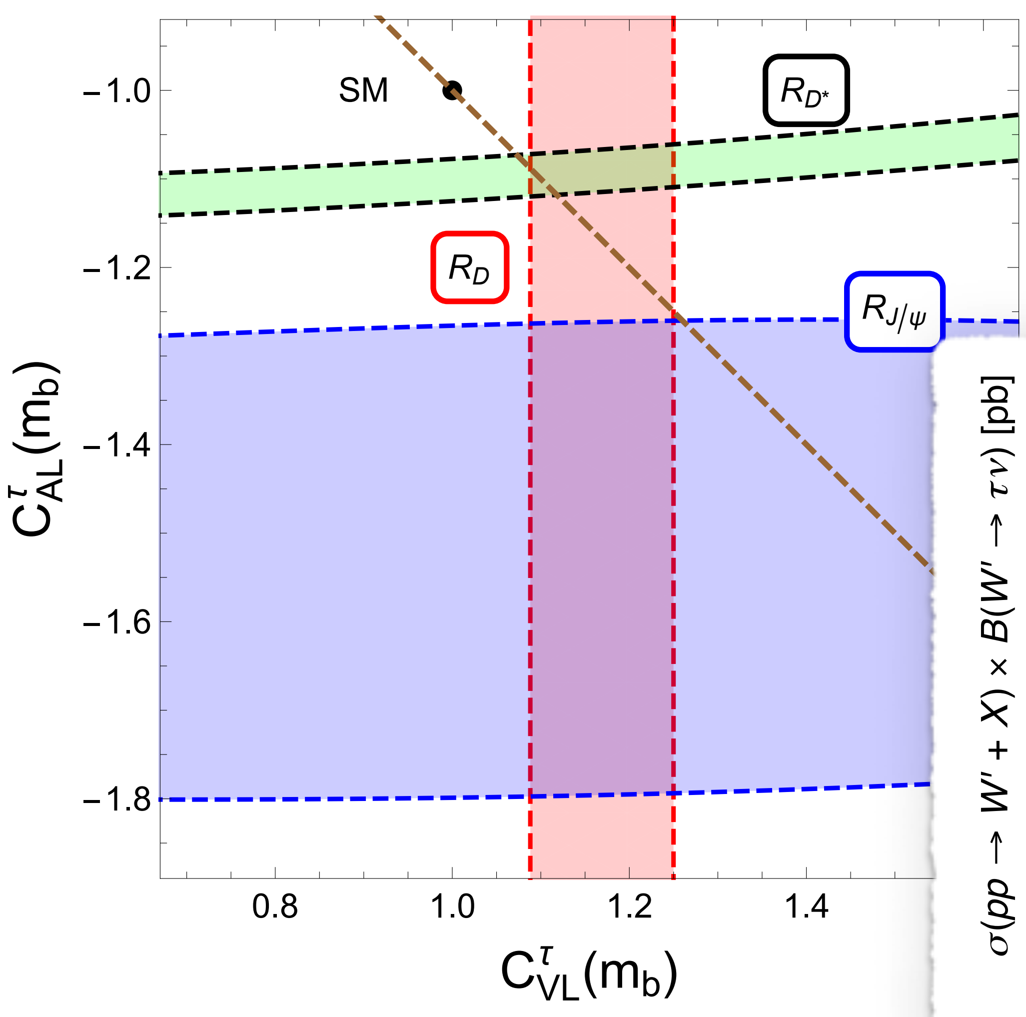
[Azatov et al. , 1805.03209]

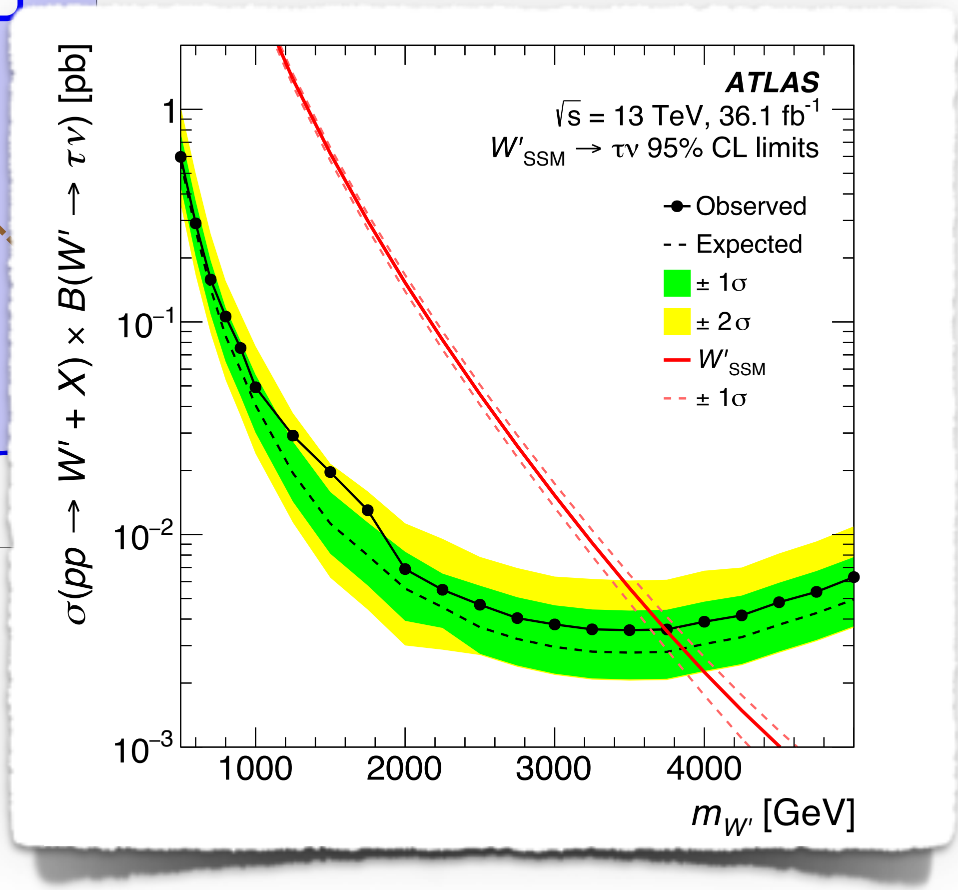
Lepton Non-Universality in b→c

Rescaling the SM operator gives a good fit.

A new TeV scale vector boson? Needs

$$0.2 \approx g^2 |V_{cb}|^2 \left(\frac{\mathrm{TeV}}{M_{W'}} \right)^2$$





Excluded by LHC searches

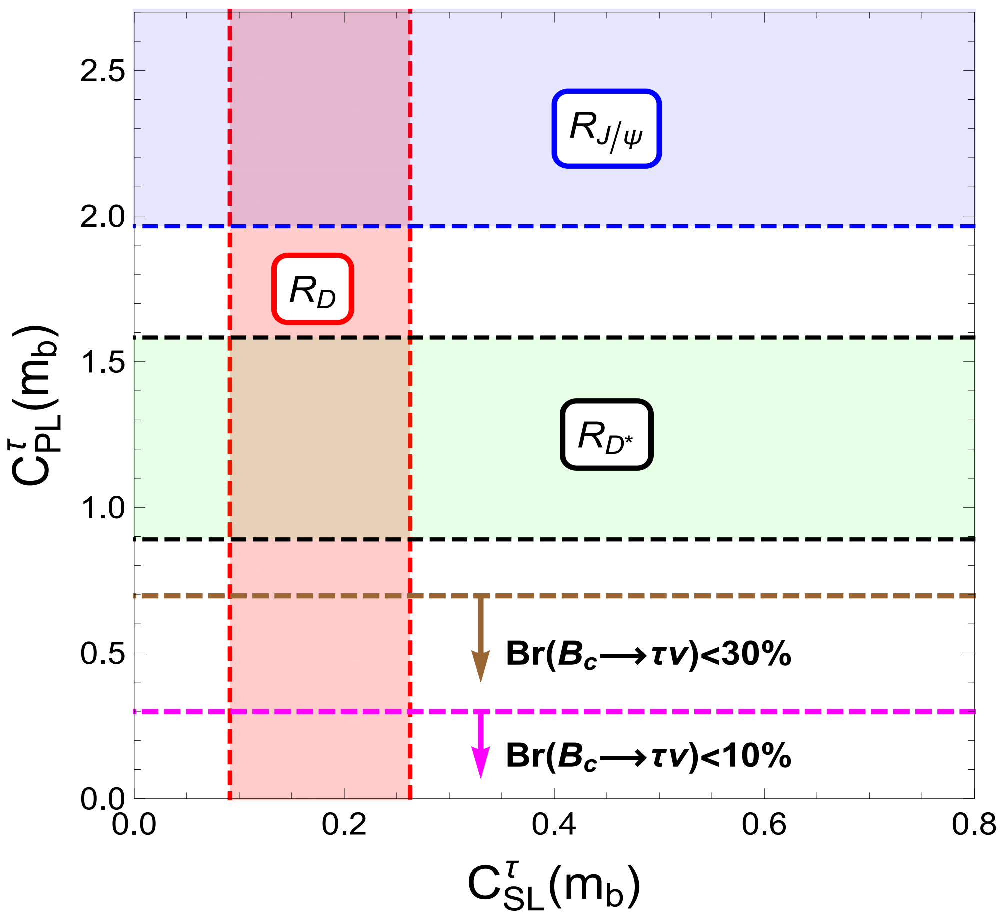
[Atlas et al. , 1801.06992]

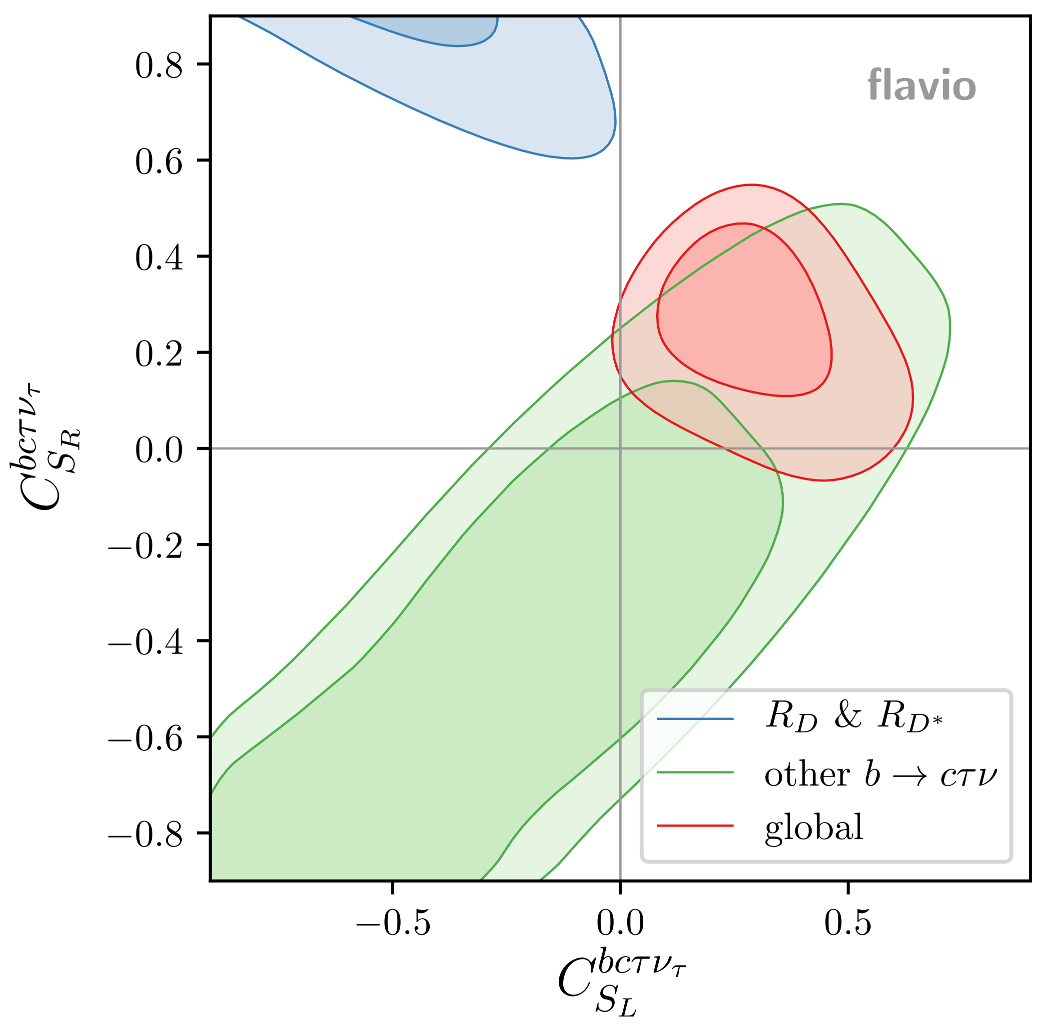
[Azatov et al. , 1805.03209]

Lepton Non-Universality in b→c

A new TeV-scale scalar?

In tension with $\mathrm{Br}(B_c \to \tau\nu)$ [Akeroyd, Chen, 1708.04072]



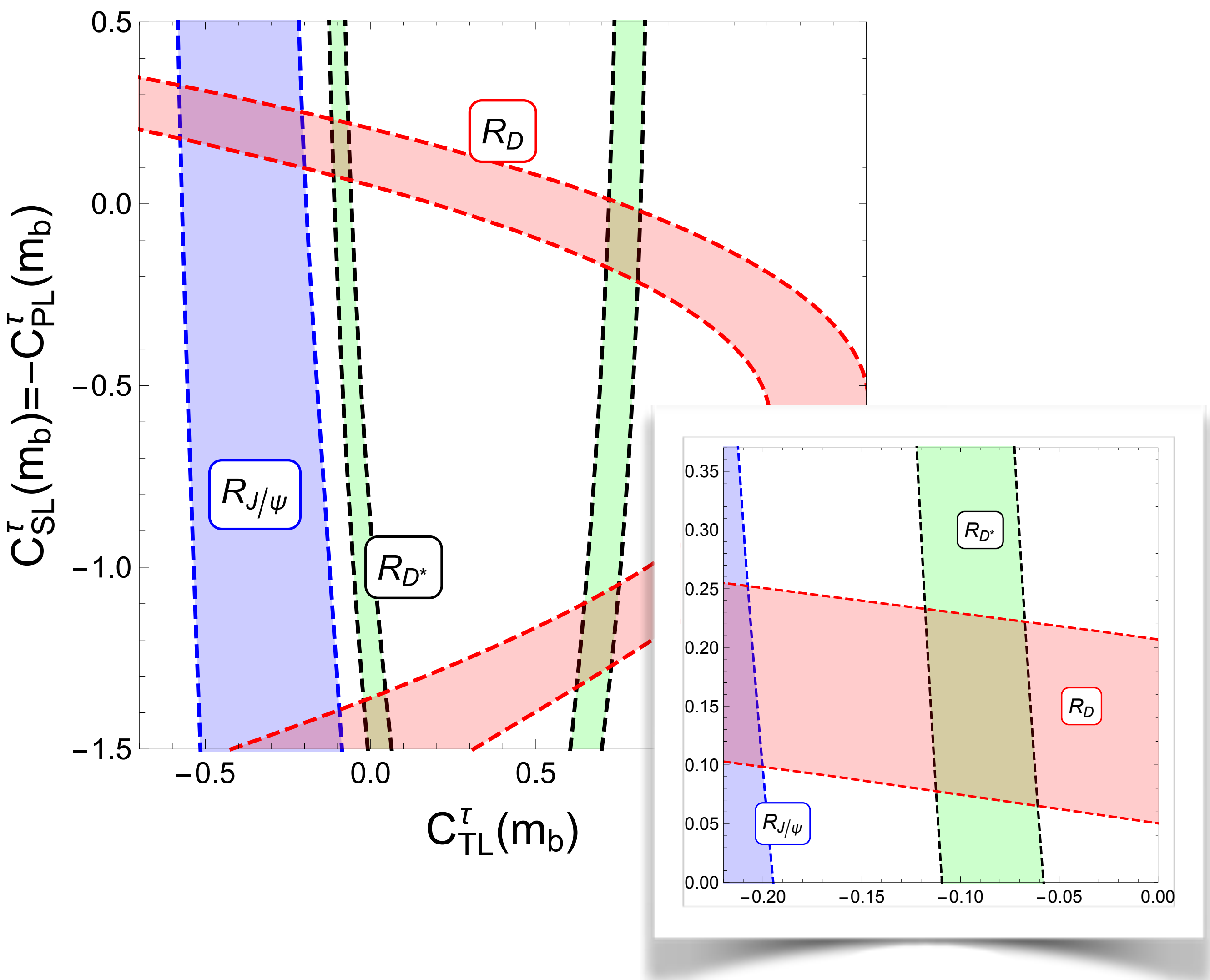


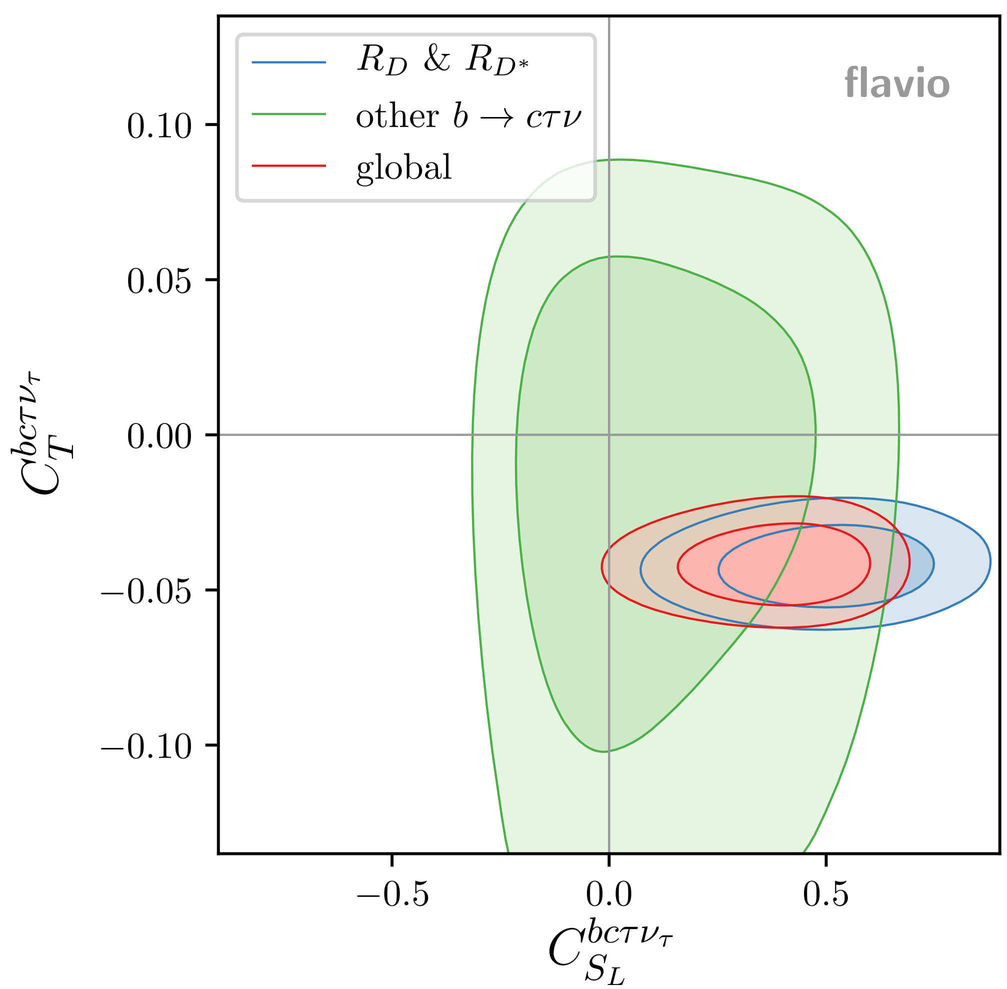
[Aebischer et al, 1810.07698] [Azatov et al. , 1805.03209]

Lepton Non-Universality in b→c

Leptoquarks?

$$(\bar{c}P_L\nu)\,(\bar{\tau}P_Lb) = -\frac{1}{8}\left[2(\mathcal{O}^{\tau}_{\rm SL} - \mathcal{O}^{\tau}_{\rm PL}) + \mathcal{O}^{\tau}_{\rm TL}\right]$$



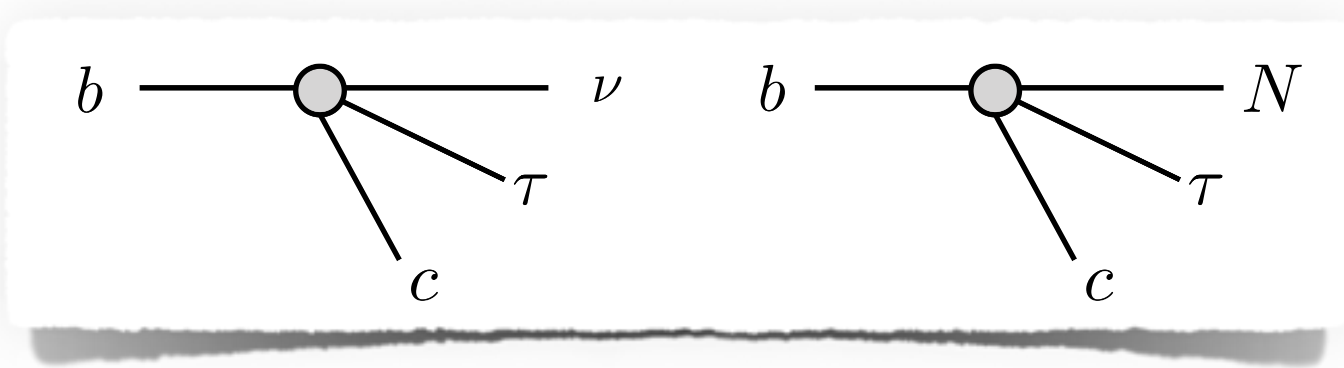


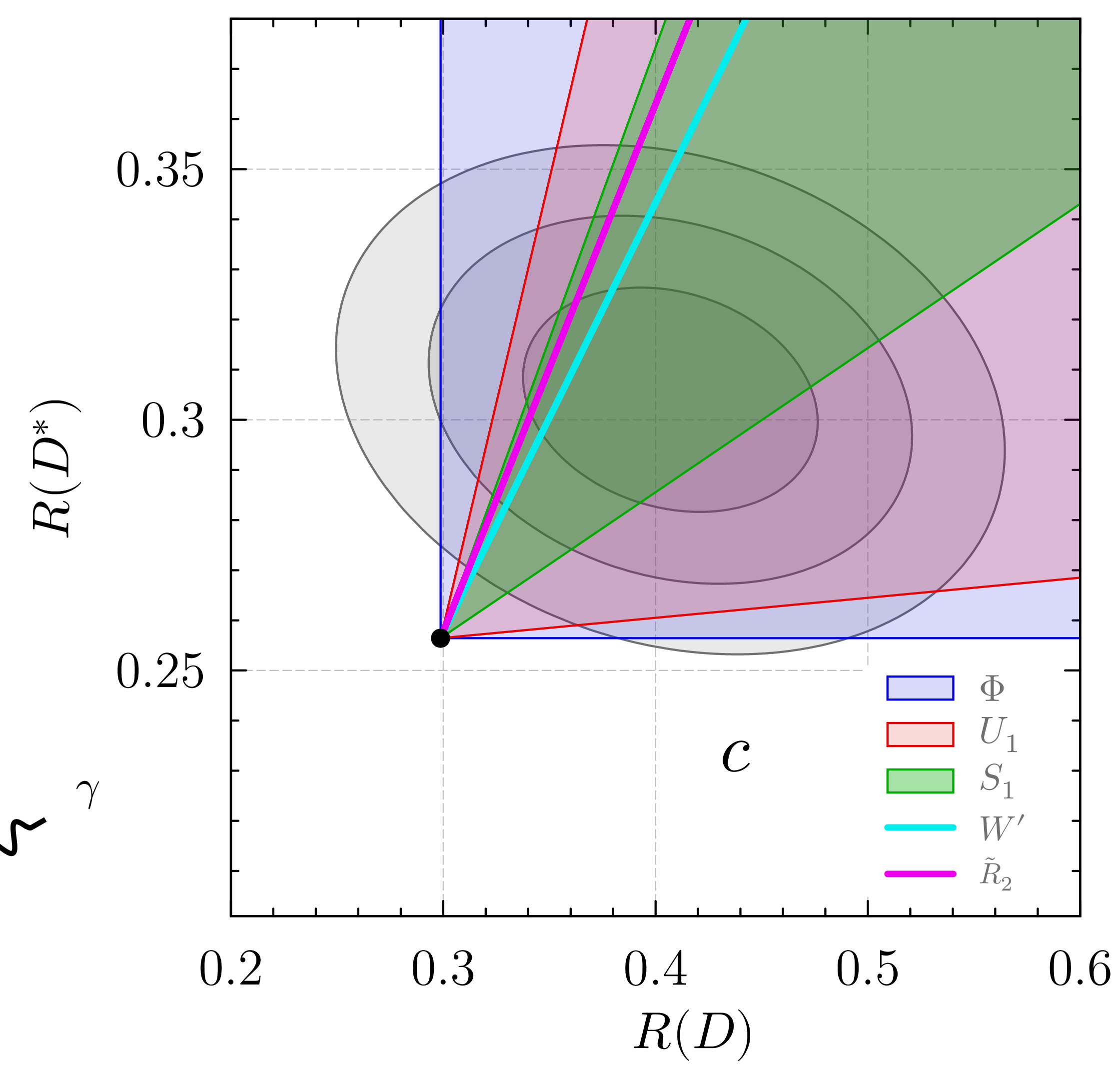
[Aebischer et al, 1810.07698] [Azatov et al. , 1805.03209]

An unconventional solution

If there are light right-handed Neutrinos,

$$m_N < m_{B_s} - m_{D^*} - m_\tau \approx 1.5\,\mathrm{GeV}$$

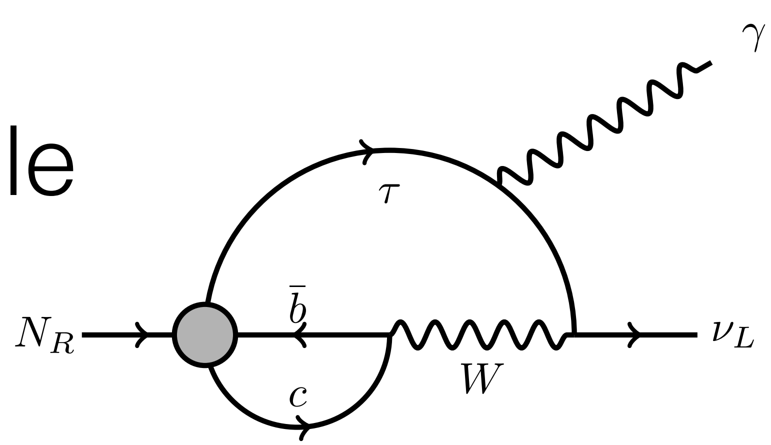




Experimentally indistinguishable

they are not stable

$$\tau_N = 1 - 10^{13}\,\mathrm{s}$$



[Becirevic et al, 1608.08501] [Cvetic et al, 1702.04335] [Robinson et al. 1807.0475]

Are we sure this time?

Are we sure this time?

The most recent calculation of the inclusive cross section…

	SM	Experiment
$\mathrm{Br}(B^+ \to D^0 \tau^+ \nu_\tau)$	$(0.75 \pm 0.13)\ \%$	$(0.91 \pm 0.11)\ \%$
$\mathrm{Br}(B^+ \to D^{*0} \tau^+ \nu_\tau)$	$(1.25 \pm 0.09)\ \%$	$(1.77 \pm 0.11)\ \%$
$\mathrm{Br}(B^+ \to X_c \tau^+ \nu_\tau)$	$(2.37 \pm 0.08)\ \%$	$(2.41 \pm 0.23)\ \%$

[Mannel, Rusov, Shahriaran, 1702.01089]

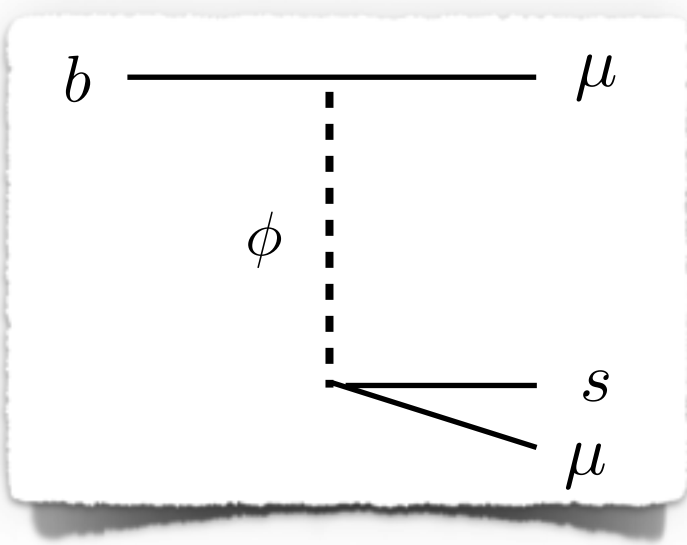
$$0.91 + 1.77 = 2.68$$

A combined explanation?

A combined explanation?

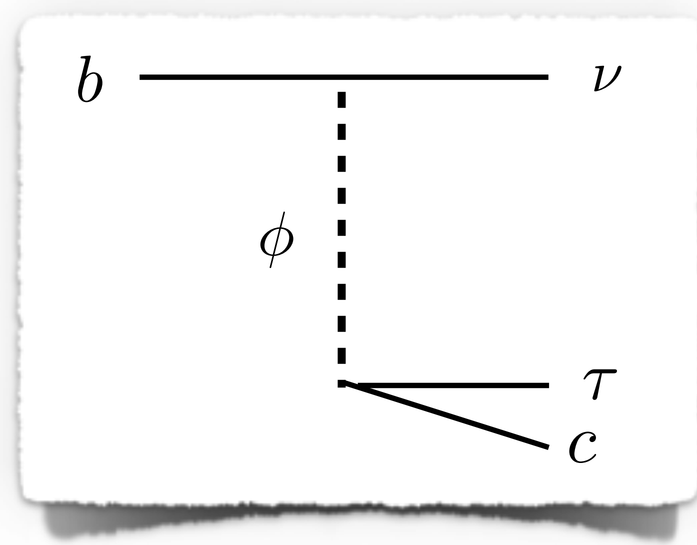
- Anomalies in neutral and charged b -> 2nd generation transition can be described by leptoquark currents
- However, one needs leptoquarks with different properties

$b \to s$



$$M_\phi = 35\,\mathrm{TeV} \times \sqrt{g_{s\mu} g_{b\mu}}$$

$b \to c$



$$M_\phi = 1\,\mathrm{TeV} \times \sqrt{g_{b\nu} g_{c\tau}}$$

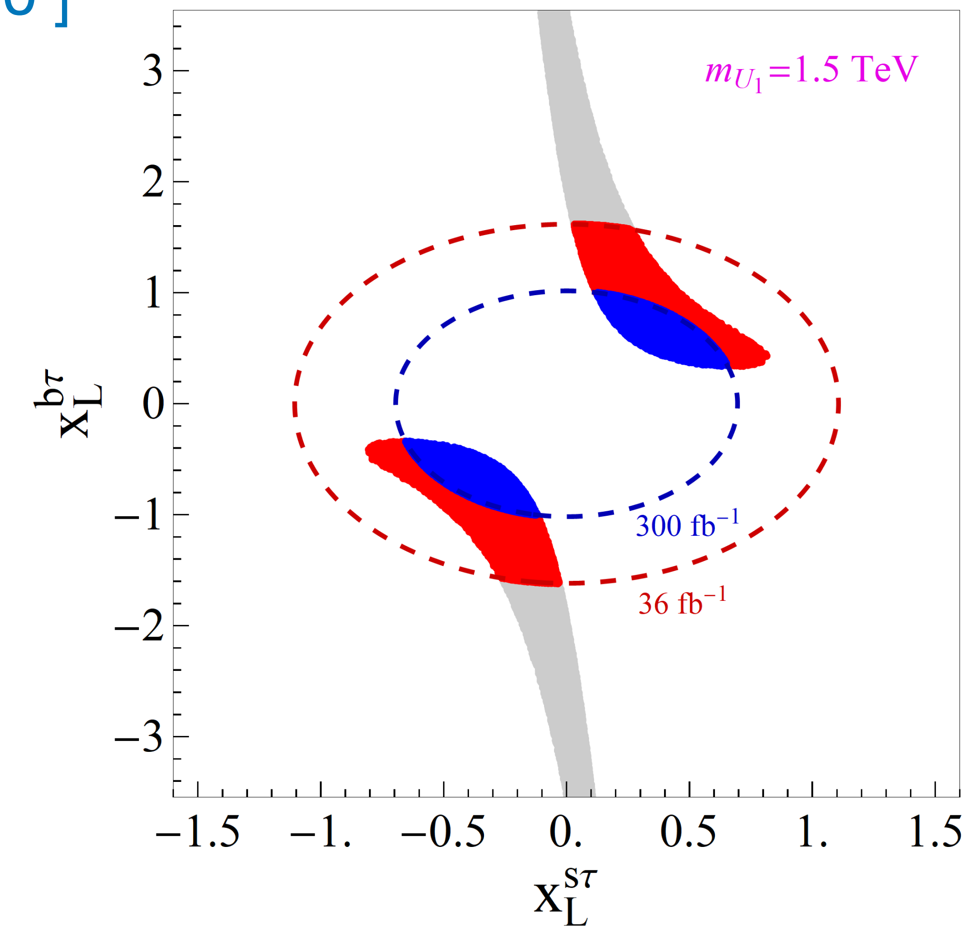
A combined explanation?

- What are the quantum numbers of a successful candidate

[MB, Neubert, 1511.01900]

Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
S_1	✗*	✓	✗*
R_2	✗*	✓	✗
$\widetilde{R}_2$	✗	✗	✗
S_3	✓	✗	✗
U_1	✓	✓	✓
U_3	✓	✗	✗

$$U_1 = (\mathbf{3}, \mathbf{1})_{2/3}$$



[Angelescu et al, 1808.08179]

- A vector LQ at the TeV scale?

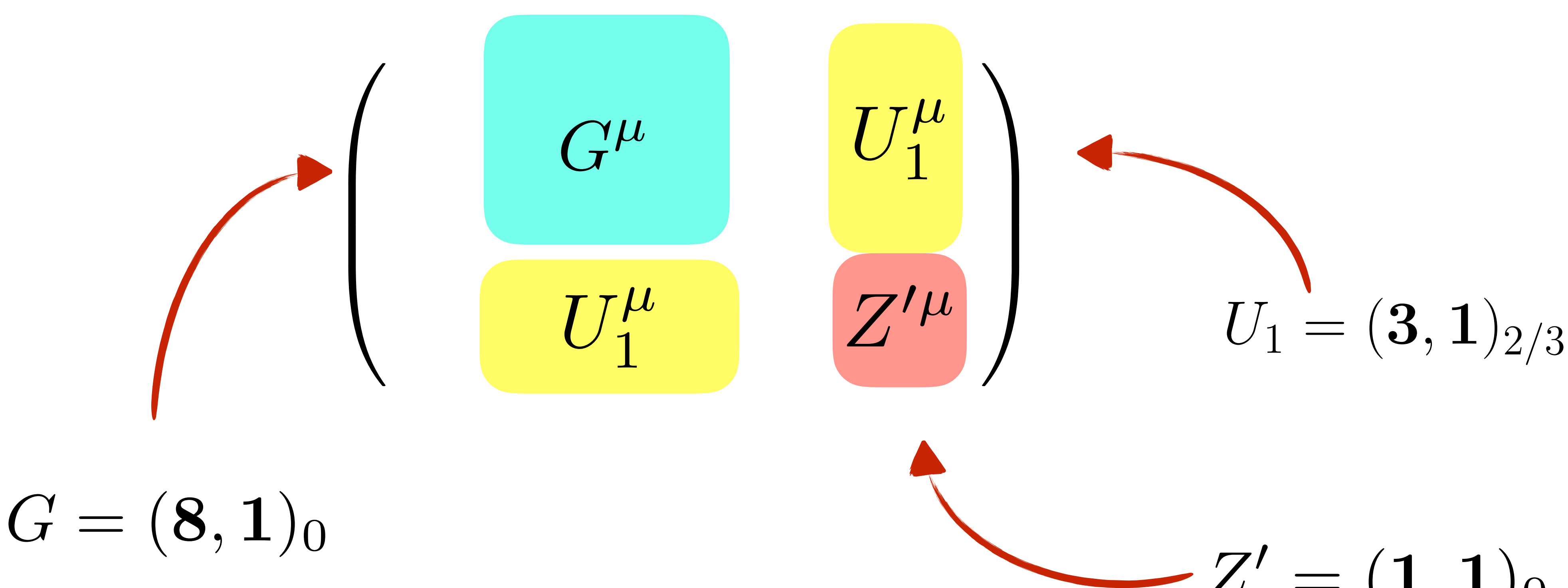
A combined explanation?

$U_1 = (\mathbf{3}, \mathbf{1})_{2/3}$ is the Pati-Salam Leptoquark ! [Pati, Salam, 1974]

Pati and Salam proposed to combine Lepton number and color in a single gauge group $SU(4)_C \times SU(2)_L \times SU(2)_R$

[Barbieri, Murphy, Senza 1611.04930]

$$\psi = \begin{pmatrix} Q_r \\ Q_b \\ Q_g \\ L \end{pmatrix}$$



Problematic because $K \to \mu e$ ➡ $M \gtrsim 100\,\text{TeV}$

A combined explanation?

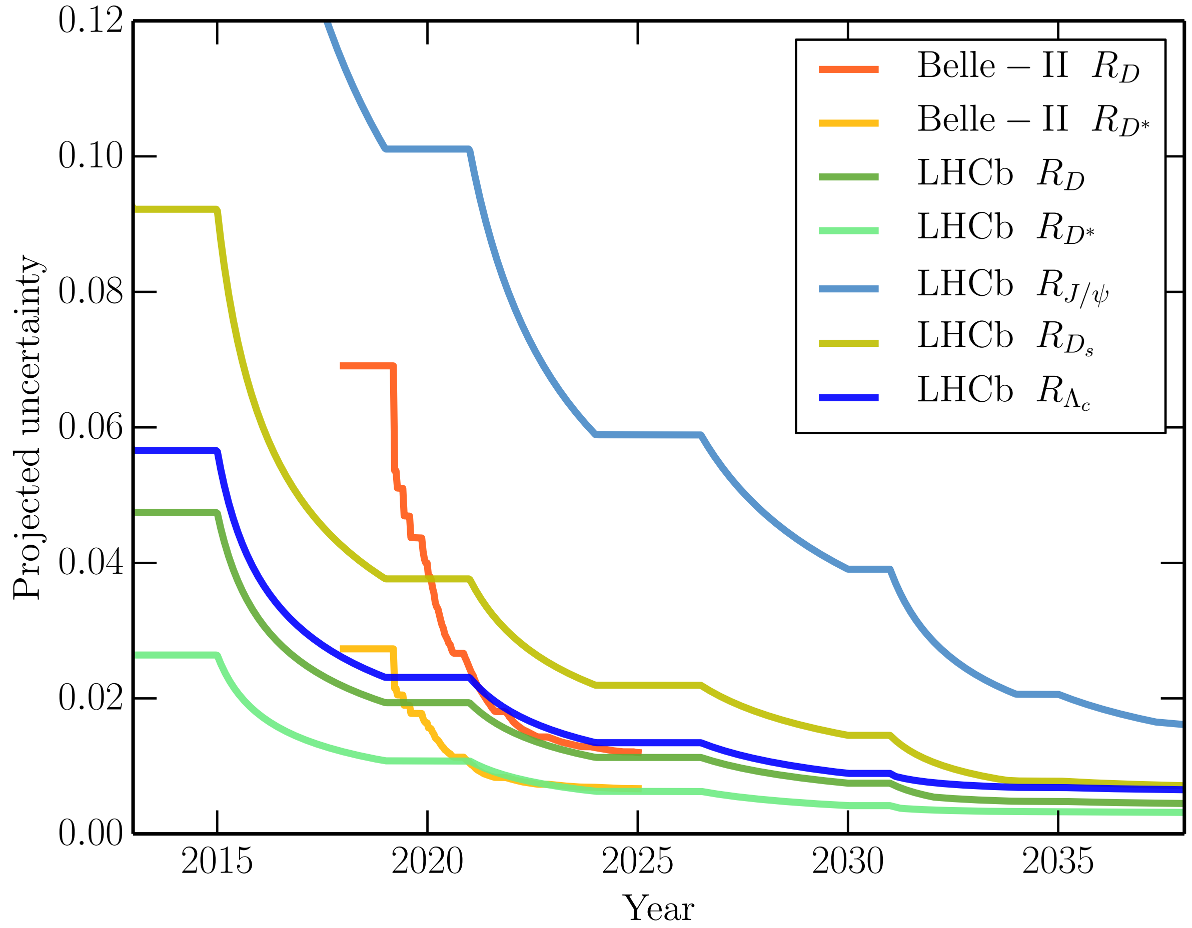
$U_1 = (\mathbf{3}, \mathbf{1})_{2/3}$ is the Pati-Salam Leptoquark ! [Pati, Salam, 1974]

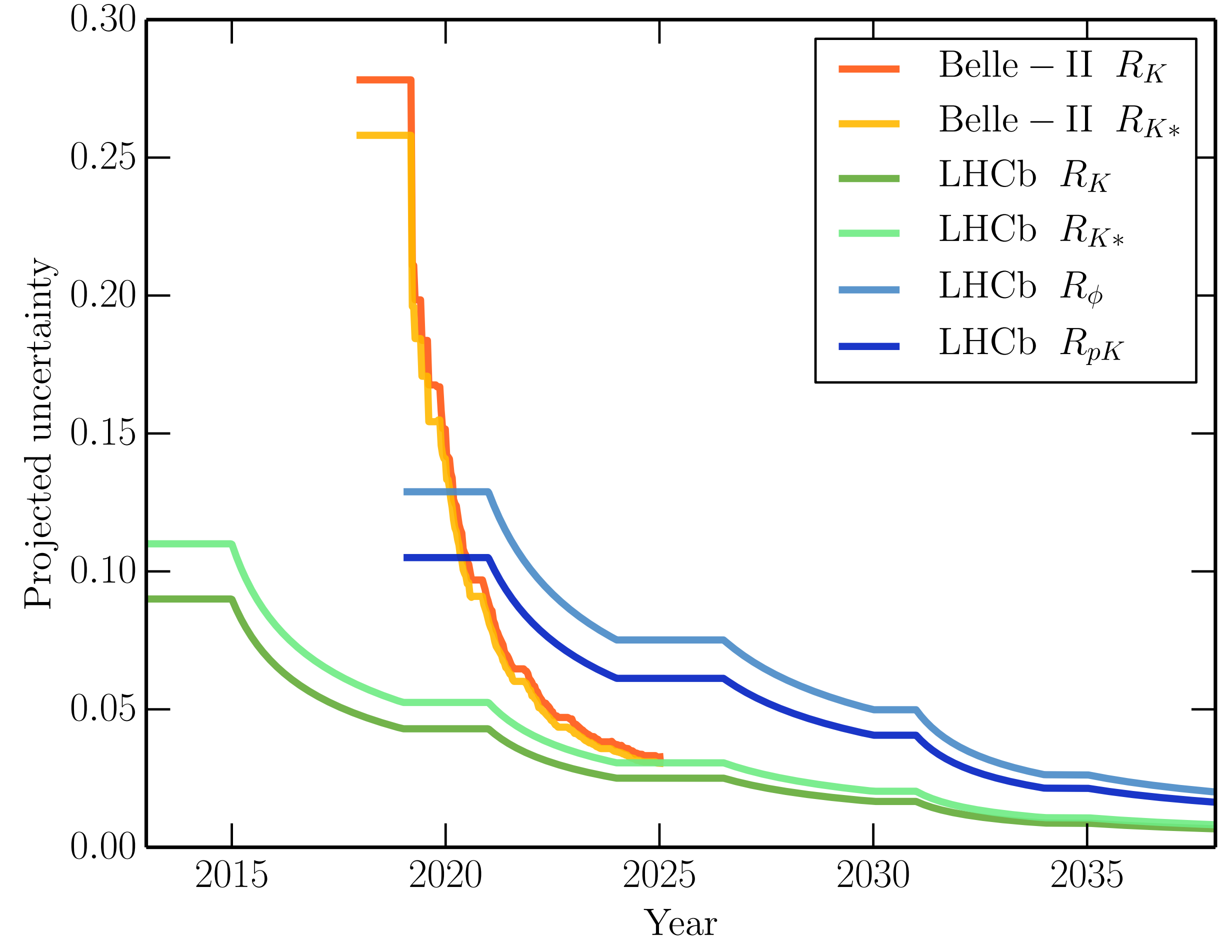
Needs more work

- $\left[SU(4)_C \times SU(2)_L \times SU(2)_R\right]^3$ [Bordone, Cornella, Fuentes-Martin, Isidori, 1712.01368]
- $SU(4)_C \times SU(3)' \times SU(2)_L \times U(1)'$ [Greljo, Stefanel 1802.04274]
- $SU(4)_C \times SU(2)_L \times SU(2)_R$ [Blanke, Crivellin 1801.07256]

  in warped extra dimension

Future Prospects

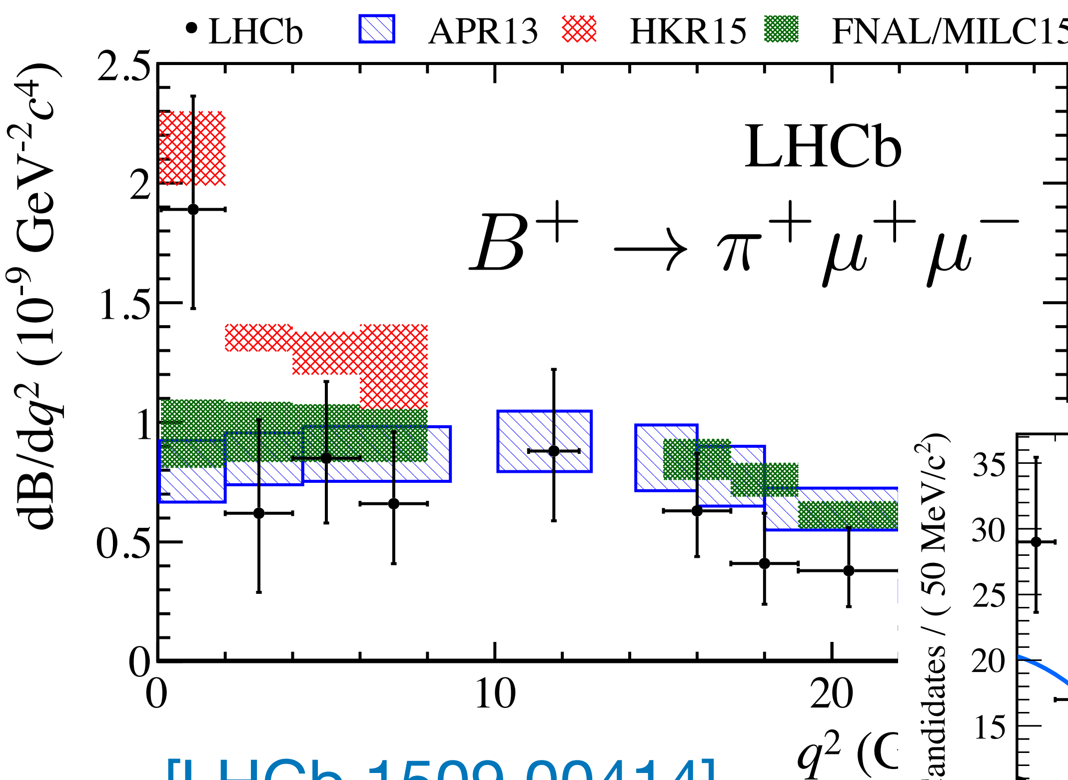




[Bifani et al, 1809.06229]

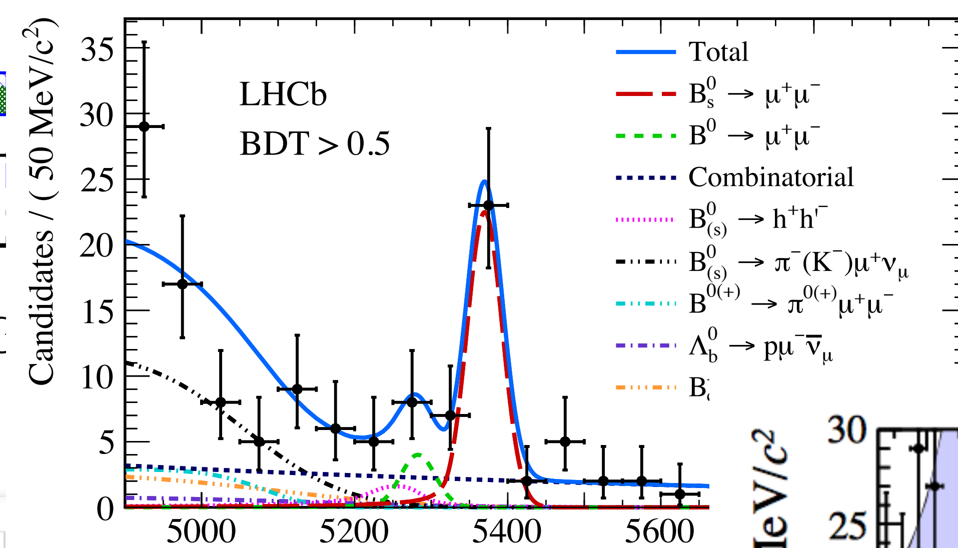
Future Prospects

Lepton Non-Universality in b→d transitions?



[LHCb,1509.00414]

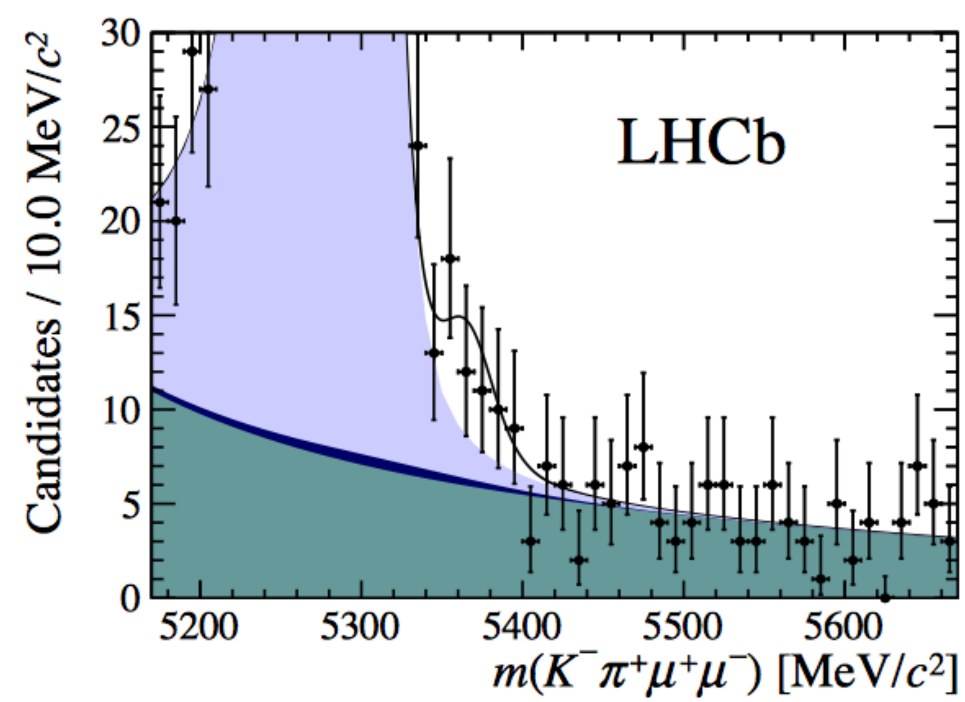
$B_d \to \mu^+\mu^-$

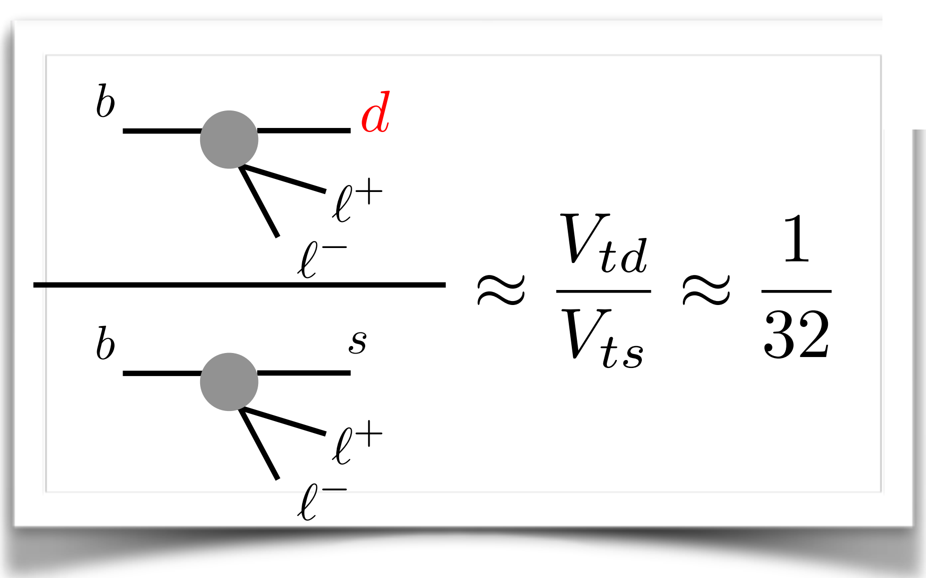


[LHCb,1703.05747]

[LHCb,1804.07167]

$\mathcal{B}(B_s^0 \to \overline{K}^{*}\mu^+\mu^-) =$



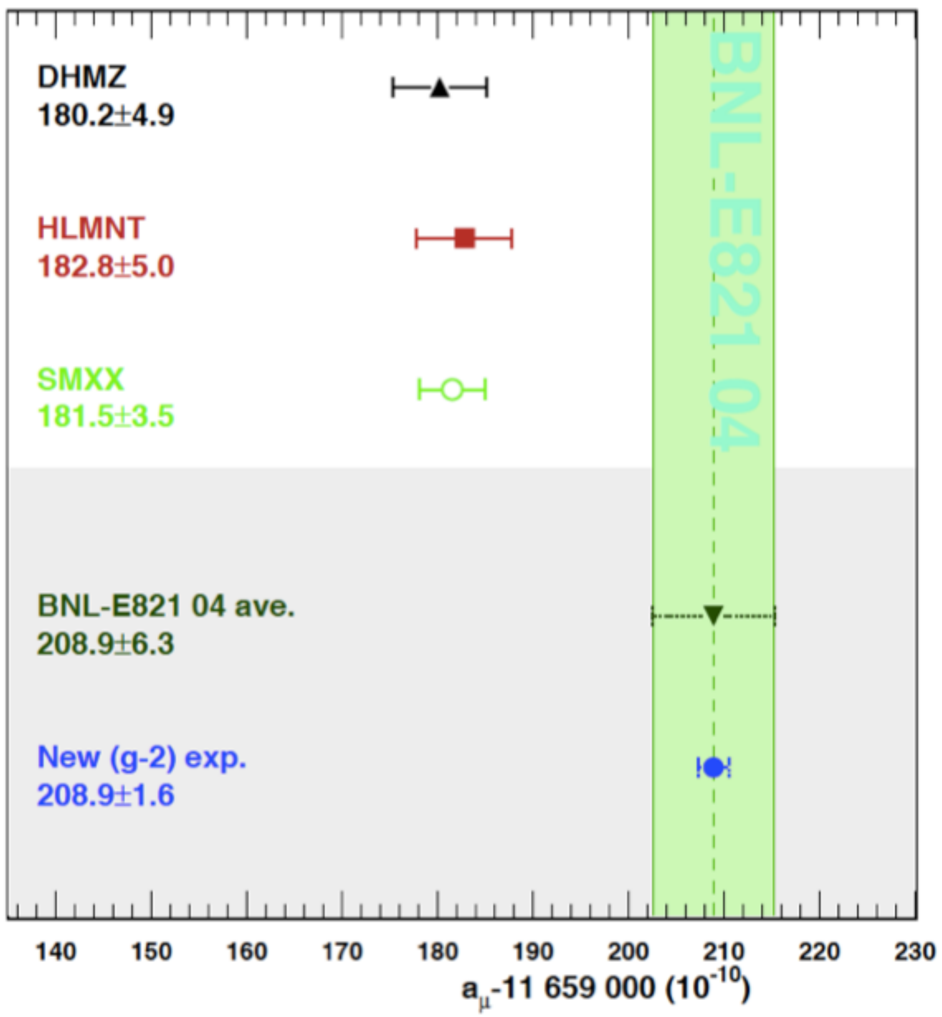


Lepton Flavour

Lepton Flavour $(g-2)_\mu$

The anomalous magnetic moment of the muon

$$a_\mu = (g-2)_\mu/2 \qquad a_\mu^{\rm exp} - a_\mu^{\rm SM} = (288 \pm 63 \pm 49) \cdot 10^{-11}$$



Currently: $3.6\,\sigma$ discrepancy

Future: $\gtrsim 5\,\sigma$?

[Gohn 1506.00608]

Lepton Flavour $(g-2)_\mu$

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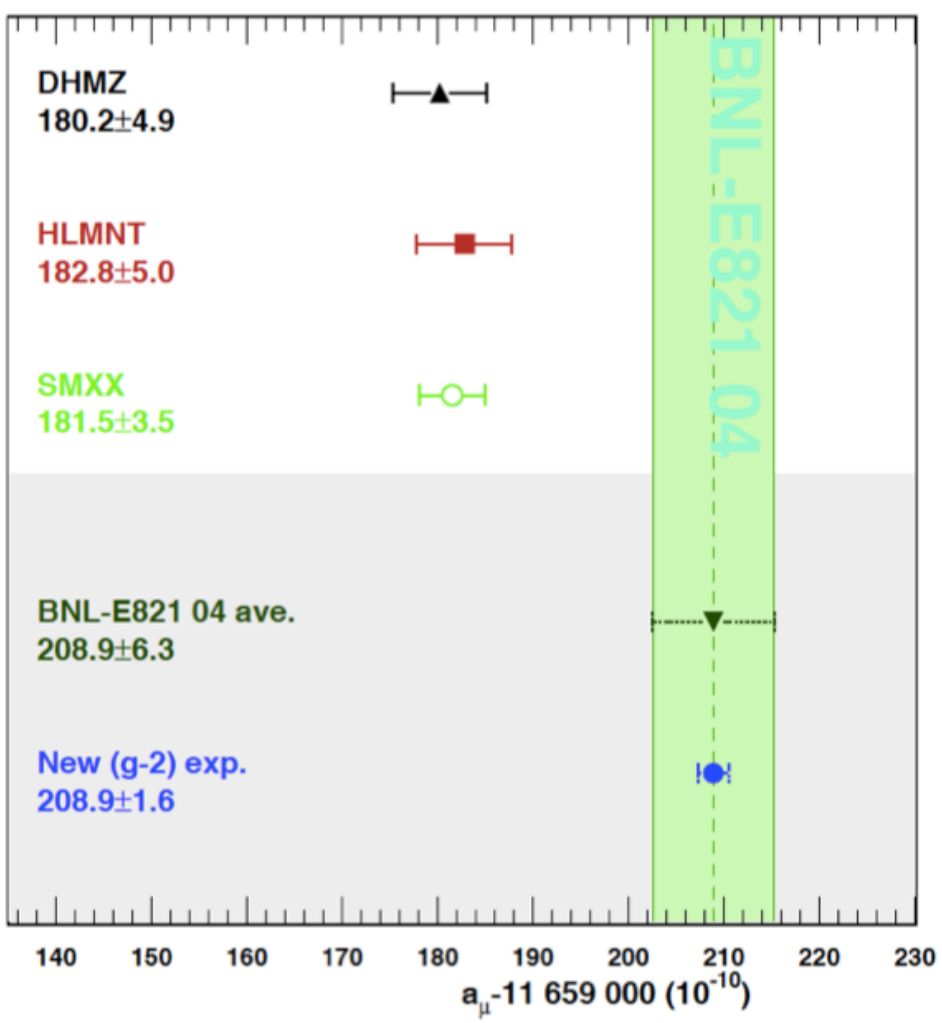


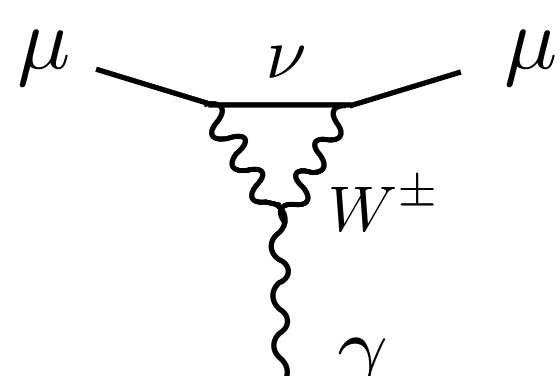
[Gohn 1506.00608]

Currently: $3.6\,\sigma$ discrepancy

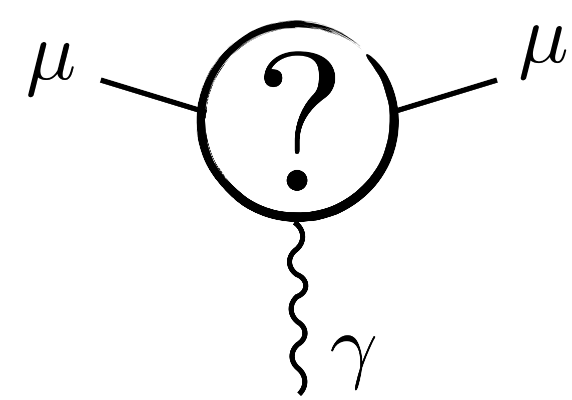
Future: $\gtrsim 5\,\sigma$?

SM

$$\delta a_\mu^W \approx \frac{g^2}{20\pi^2}\frac{m_\mu^2}{M_W^2} \approx 400 \times 10^{-11}$$



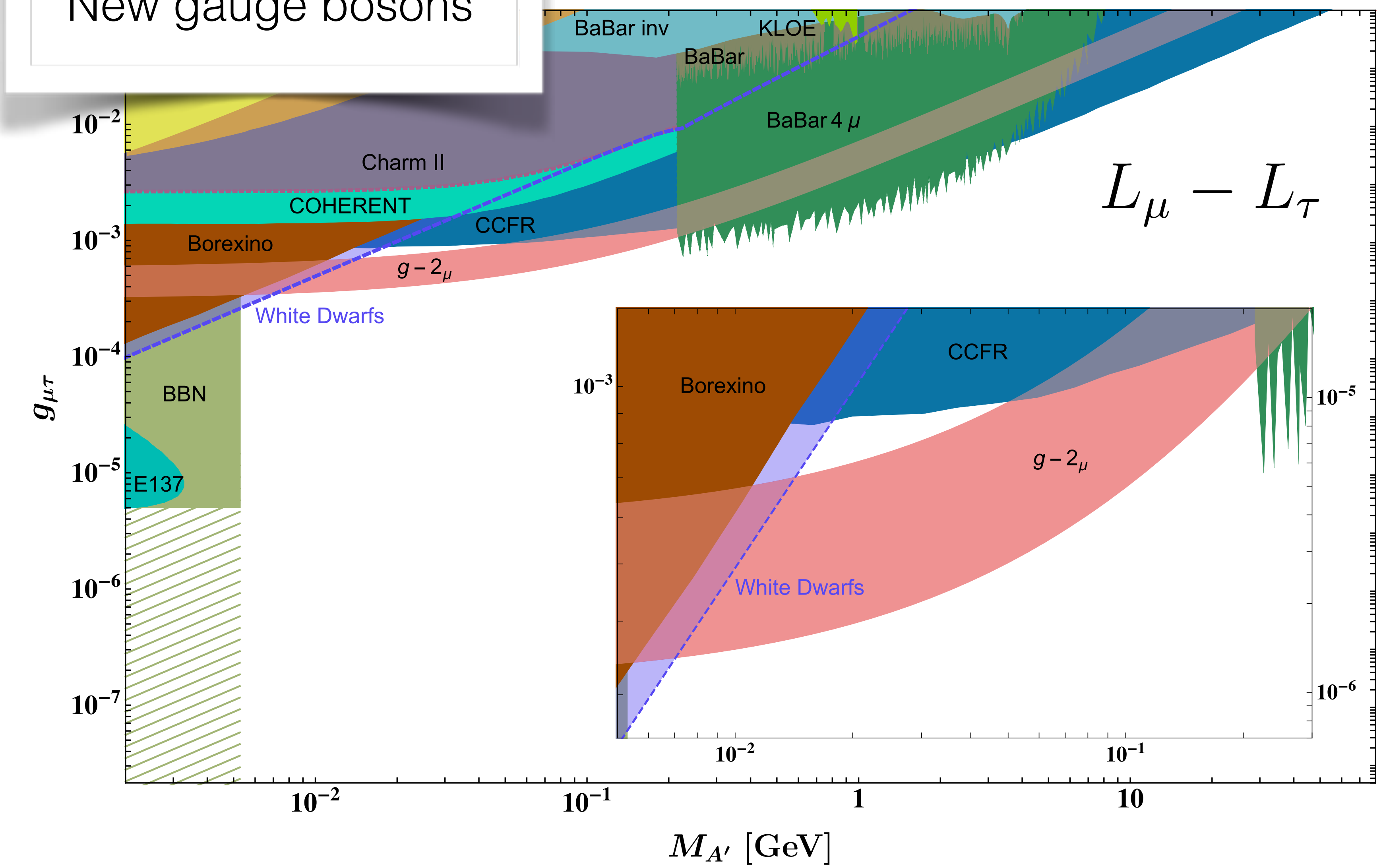
NP

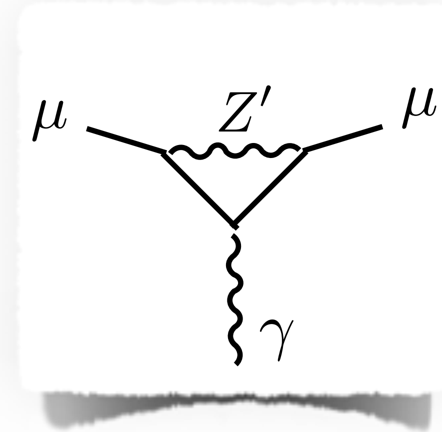


$M \approx 1 - 10\,\text{TeV}$

New Physics ?

New gauge bosons





This gauge group is special, because it is anomaly-free and predicts no FCNCs at tree-level.

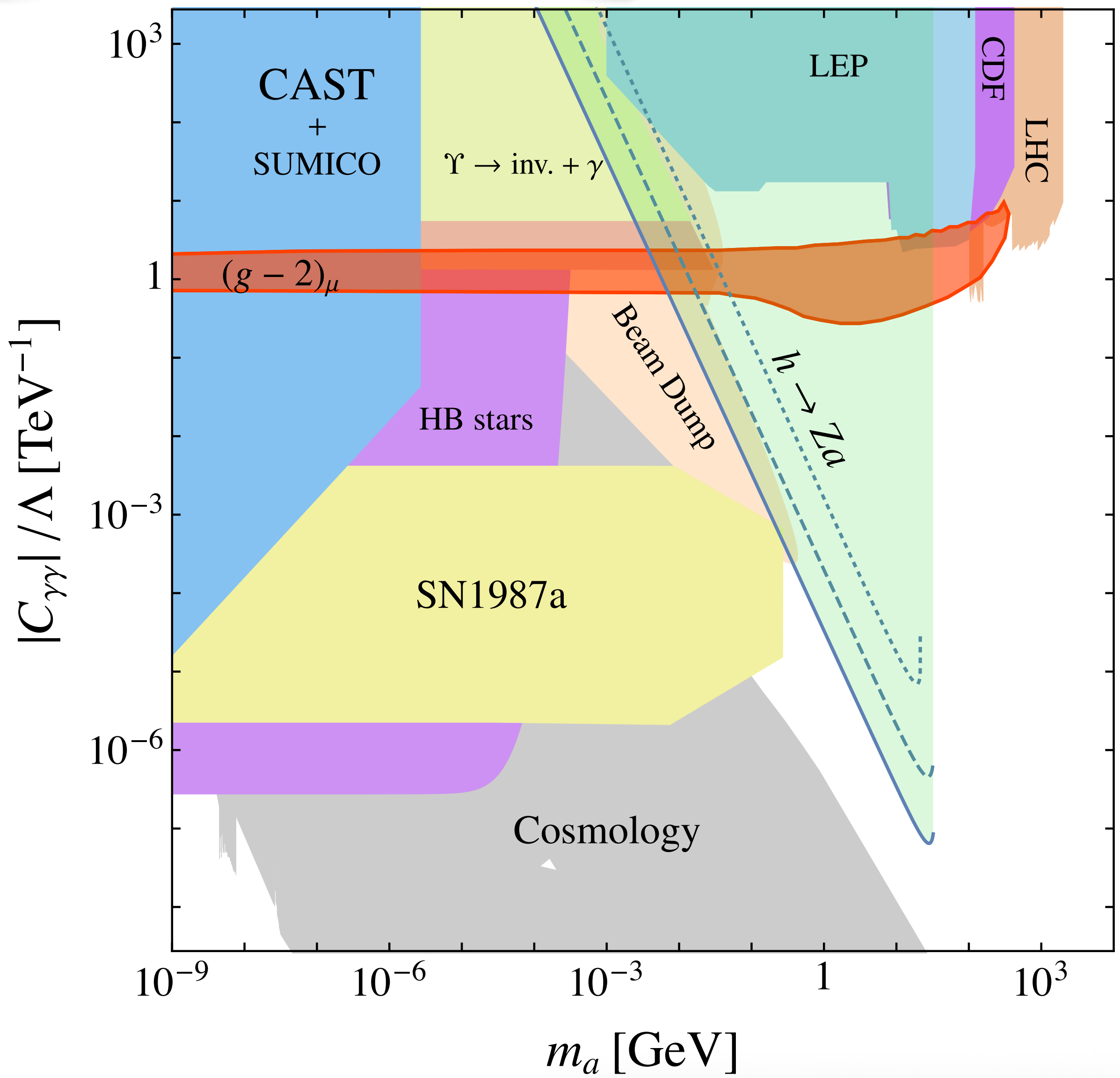
Because mass matrices are diagonal already!

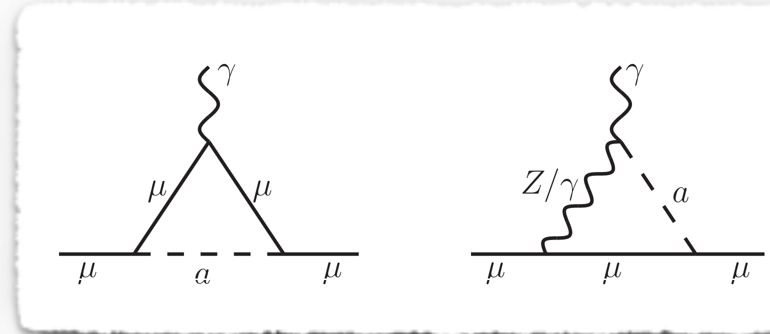
$$\mathcal{L}_{Z'} = \bar{\ell} g' \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{pmatrix} \gamma^\mu Z'_\mu \ell + \begin{pmatrix} m_e & 0 & 0 \\ 0 & m_\mu & 0 \\ 0 & 0 & m_\tau \end{pmatrix} \bar{\ell}\ell$$

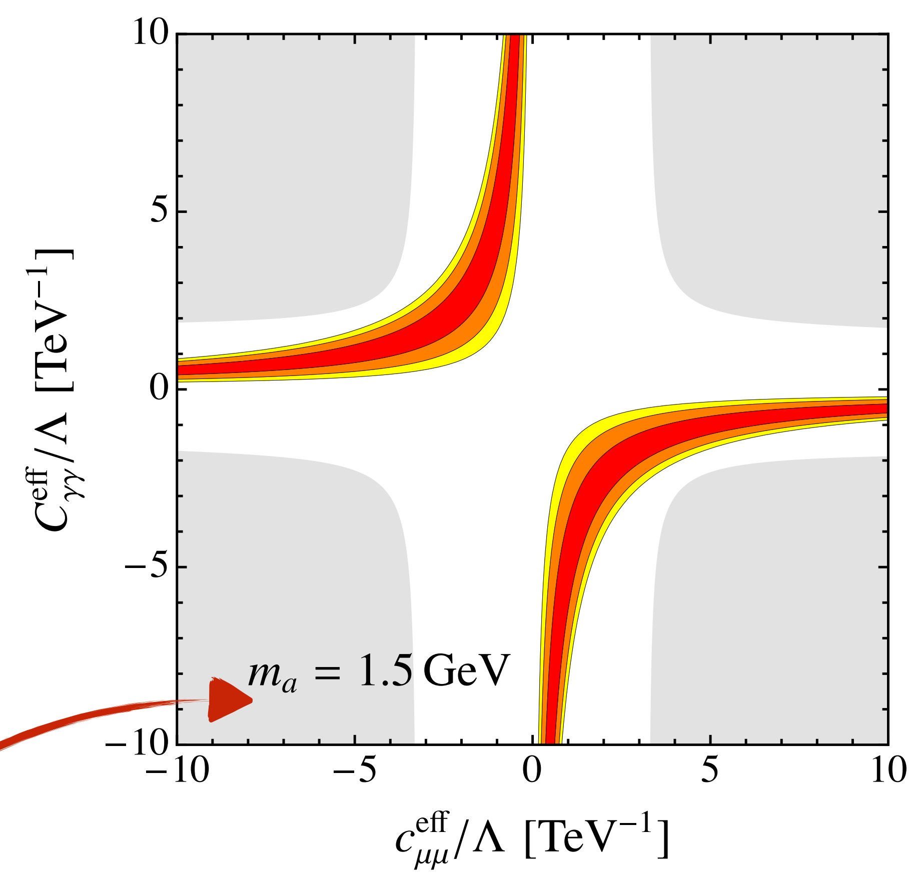
[MB, Foldenauer, Jaeckel 1803.05466]

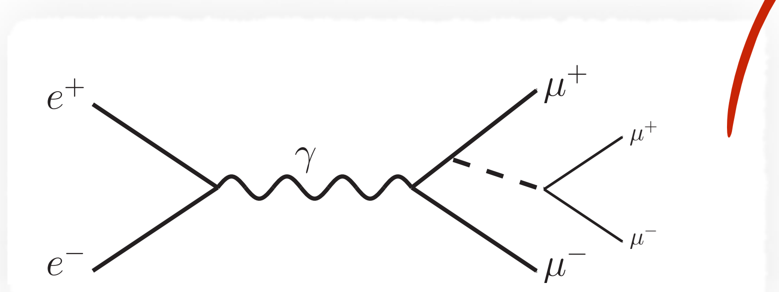
New Physics ?

An axion-like particle









[Marciano et al., PRD 94 (2016) 115033]]

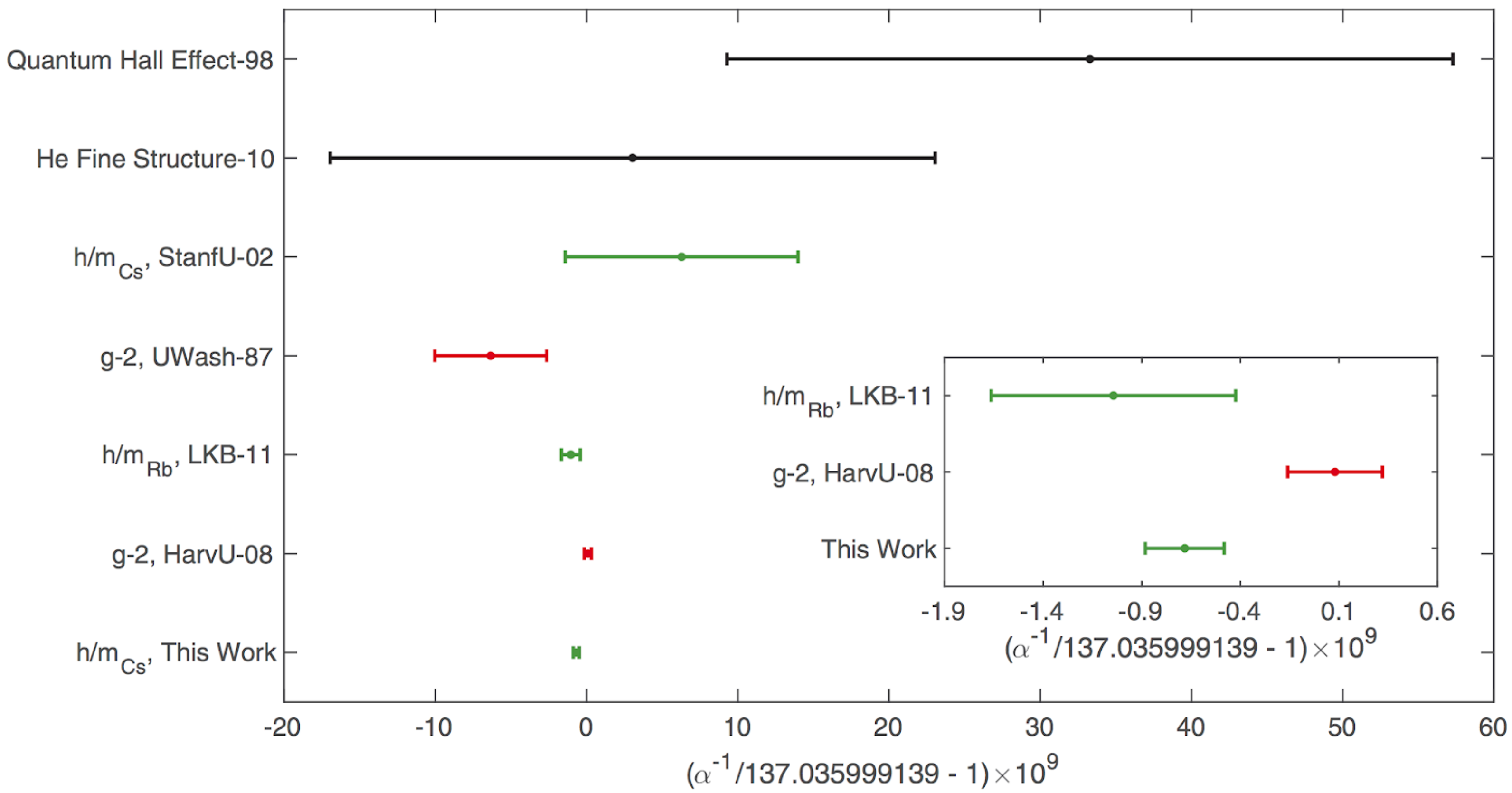
[MB, Neubert, Thamm 1704.08207]

Lepton Flavour $(g-2)_e$

The anomalous magnetic moment of the electron

$$\alpha^{-1}(\mathrm{Cs}) = 137.035999046(27) \qquad \Delta a_e = (-87 \pm 36) \times 10^{-14}$$

deviates from the SM prediction by $2.5\,\sigma$



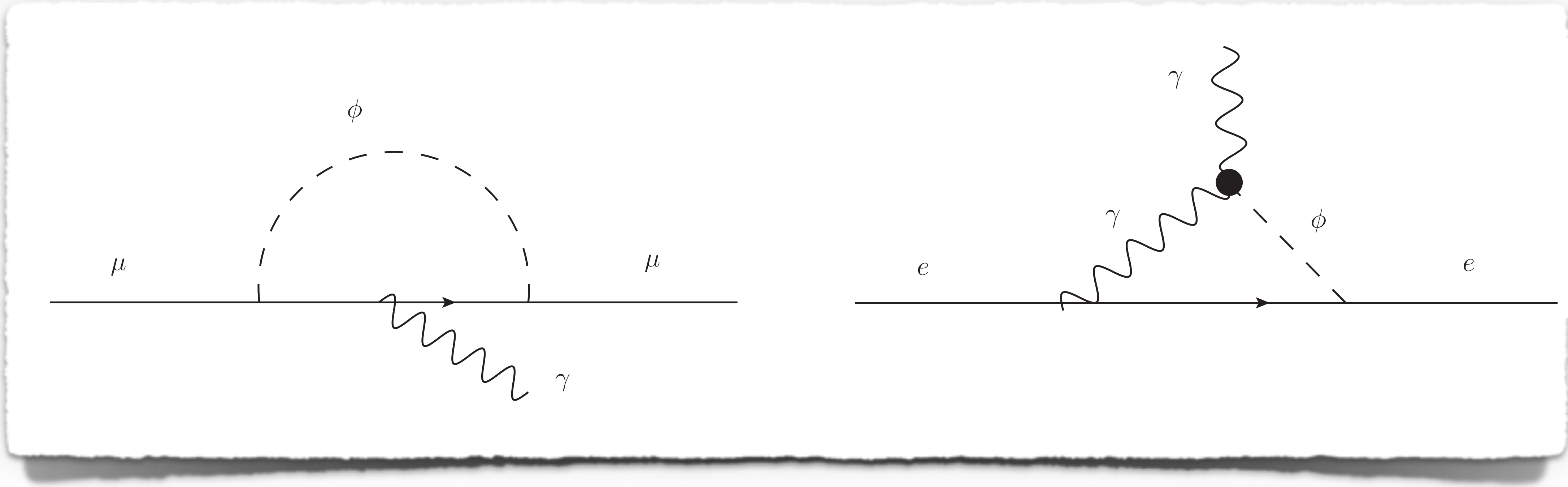
…with the opposite sign.

Taking both seriously excludes an explanation by gauge bosons.

[Parker 1812.04130]

A combined explanation?

$$\mathcal{L}_\phi = -\frac{1}{2} m_\phi^2 \phi^2 - \sum_f \lambda_f \phi \bar{f} f - \frac{\kappa_\gamma}{4} \phi F_{\mu\nu} F^{\mu\nu}$$



New scalar with ~ 100 MeV mass and couplings to muons and electrons of order 10^{-3} to 10^{-4}. Coupling to photons loop-induced.

[Davoudiasl, Marciano 1806.10252]

The future of Lepton flavour is golden

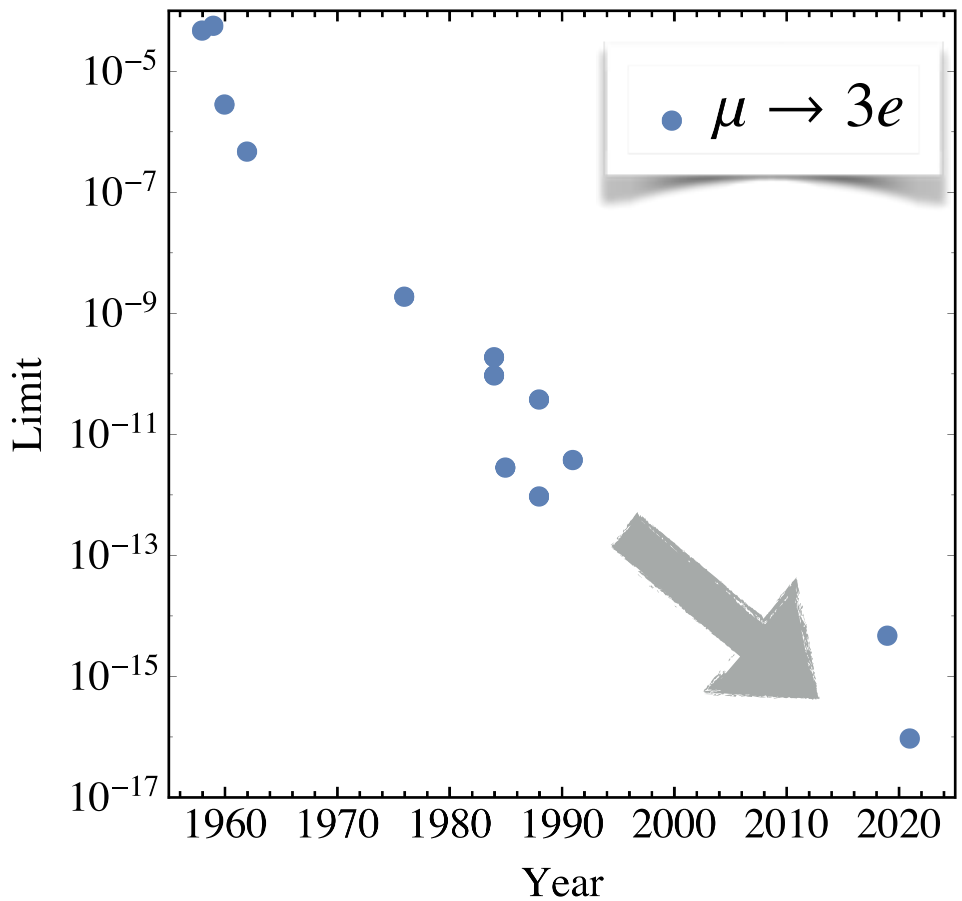
In the next years we will enter a new golden age for high precision lepton experiments

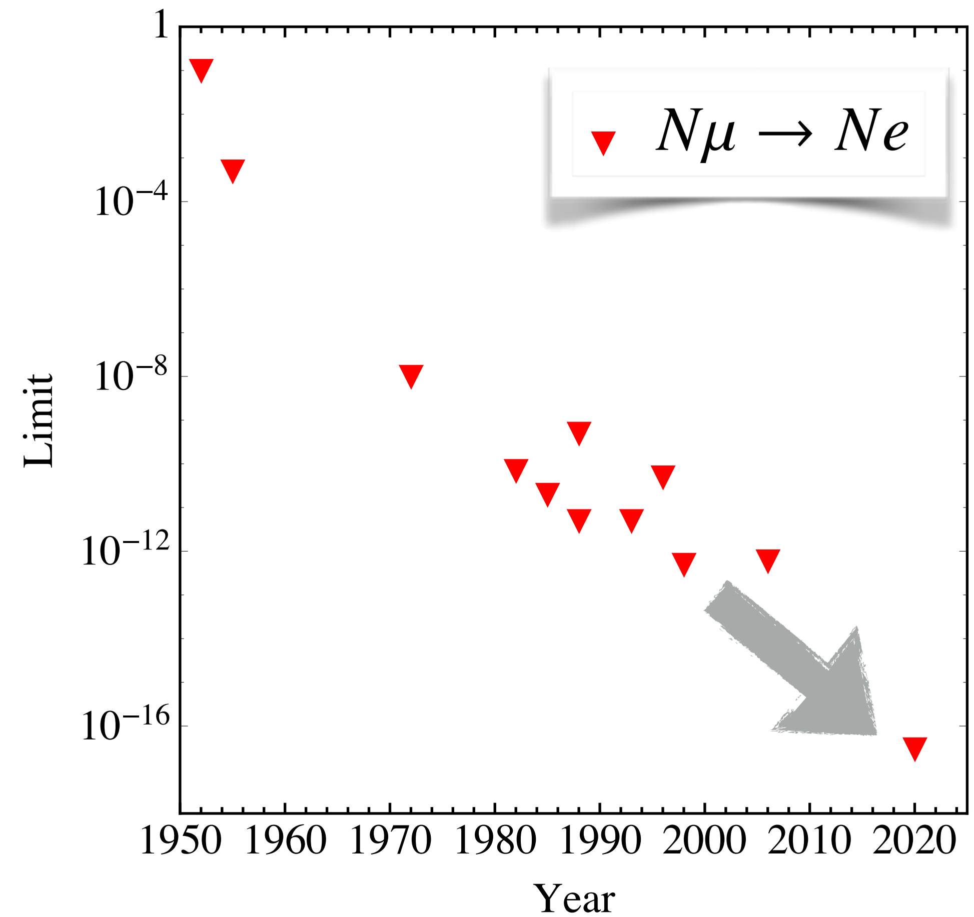
- Electron EDM $d_e \lesssim 10^{-27}\,\mathrm{e\,cm}$ ⟶ $d_e \lesssim 10^{-29}$–$10^{-31}\,\mathrm{e\,cm}$
- Muon g-2 $\delta a_\mu = 7.2 \times 10^{-9}$ ⟶ $\delta a_\mu = 1.4 \times 10^{-9}$
- $\mu \to e\gamma$ $BR(\mu \to e\gamma) < 4.2 \times 10^{-13}$ ⟶ $BR(\mu \to e\gamma) < 5 \times 10^{-14}$
- $N\mu \to Ne$ $BR(N\mu \to Ne) < 6 \times 10^{-13}$ ⟶ $BR(N\mu \to Ne) < 3 \times 10^{-17}$
- $\mu \to eee$ $BR(\mu \to eee) < 4 \times 10^{-12}$ ⟶ $BR(\mu \to eee) < 1 \times 10^{-16}$

and plans for more…

The future of Lepton flavour is golden

This is an improvement hardly found in modern physics…

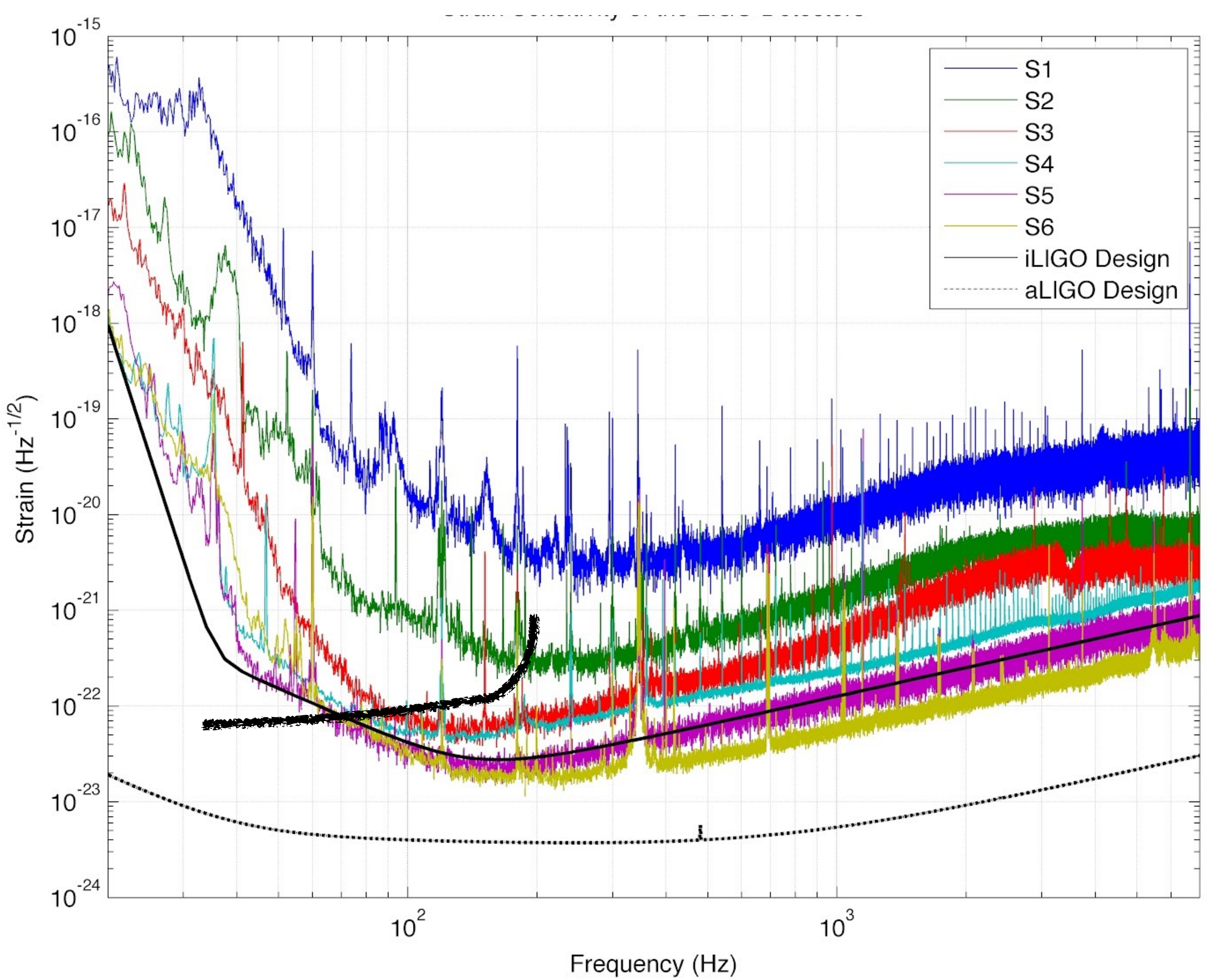




…these experiments will allow us to look at the muon with a resolution ~10 000 times better than ever before.

[Bernstein, P. S. Cooper Phys.Rept. 532 (2013)]

The future of Lepton flavour is golden



Conclusions

Several anomalies in flavour physics continue to question the validity of the SM.

Some point to scales expected from generic flavour structures! Some point to surprisingly low scales.

But future data will improve uncertainties by ~1 order of magnitude and increase sensitivity in lepton observables by up to 4 orders of magnitude.

We are designing the first probes of the multi-PeV scale.

Executive summary

b→s transitions: Clean LFV observables agree with dirty angular observables. The low-mass bin in R_{K^*} does not look like NP. NP: leptoquark (30 TeV)

b→c transitions: Large deviation in a charged current process. In question by LEP(?). NP: leptoquark (1 TeV)

Combined explanations need gauge-unification at the TeV scale.

g-2: Both muon and electron in tension with the SM, but opposite direction.
NP: axion (< GeV) or hidden photon (for the muon).

Backup

A pattern in b → s transitions

Simple example: A single resonance

$$\Pi(q^2) = \frac{f^2}{q^2 - M^2 + iM\Gamma}$$

$$\mathrm{Im}\,\Pi(q^2) = \frac{f^2 M\Gamma}{(q^2 - M^2)^2 + M^2\Gamma^2}$$

$$\Gamma \to 0$$

$$\approx \pi f^2 \delta(q^2 - M^2)$$

$$\int_0^{m^2} dq^2 \mathrm{Im}\,\Pi(q^2) \approx \pi f^2 \ll m^2$$

small compared to the non-res contribution. Duality holds!

$$|\Pi(q^2)|^2 = \frac{f^4}{(q^2 - M^2)^2 + M^2\Gamma^2}$$

$$= \frac{f^2}{M\Gamma}\mathrm{Im}\,\Pi(q^2)$$

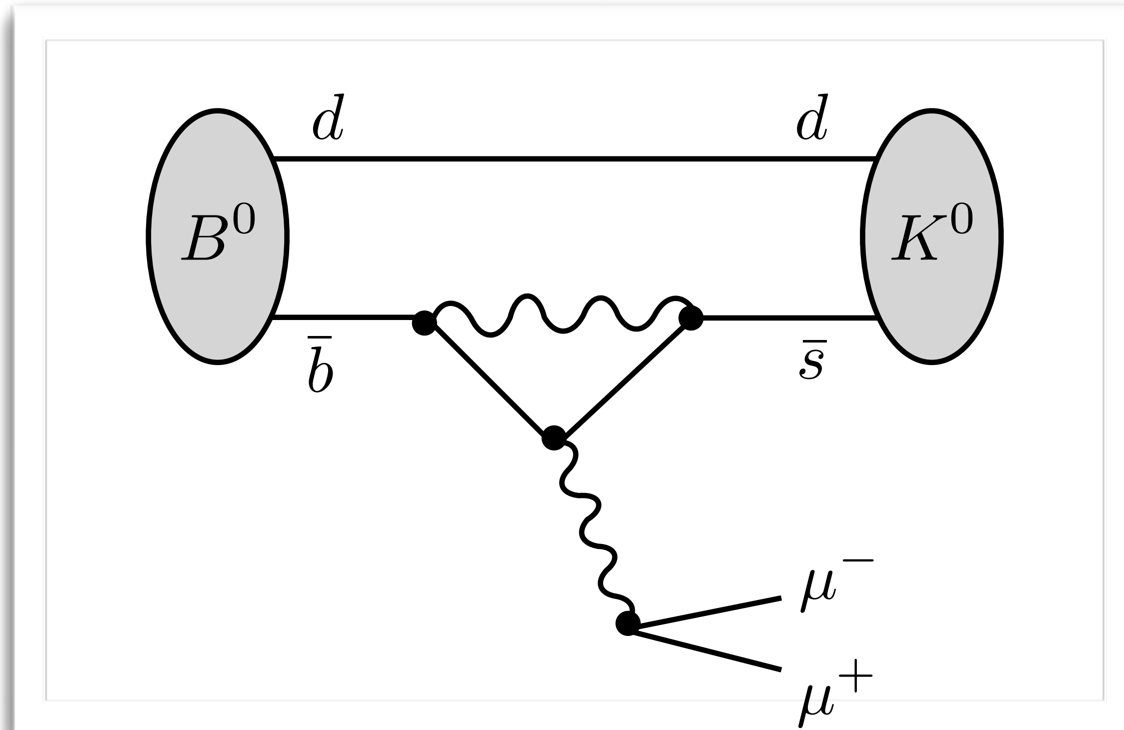
$$\approx \frac{\pi f^4}{M\Gamma}\delta(q^2 - M^2)$$

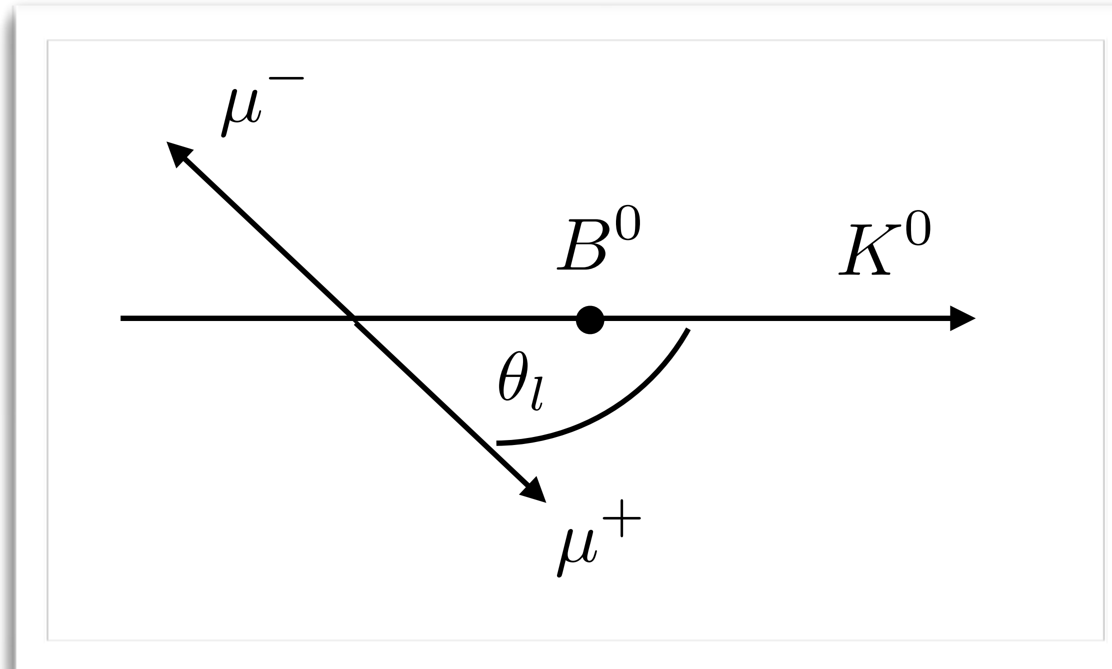
$$\int_0^{m^2} dq^2 |\Pi(q^2)|^2 \approx \frac{\pi f^4}{M\Gamma}$$

singular!

[Beneke, Buchalla, Neubert, Sachrajda, 0902.4446]

A pattern in b → s transitions





$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_l} = \frac{3}{4}(1 - F_H)(1 - \cos^2\theta_l) + \frac{1}{2}F_H + A_{\text{FB}}\cos\theta_l$$

$$\frac{d\Gamma^{\text{SM}}}{d\cos\theta_l} \propto \sin^2\theta_l + \mathcal{O}(m_l^2)$$

Helicity suppressed

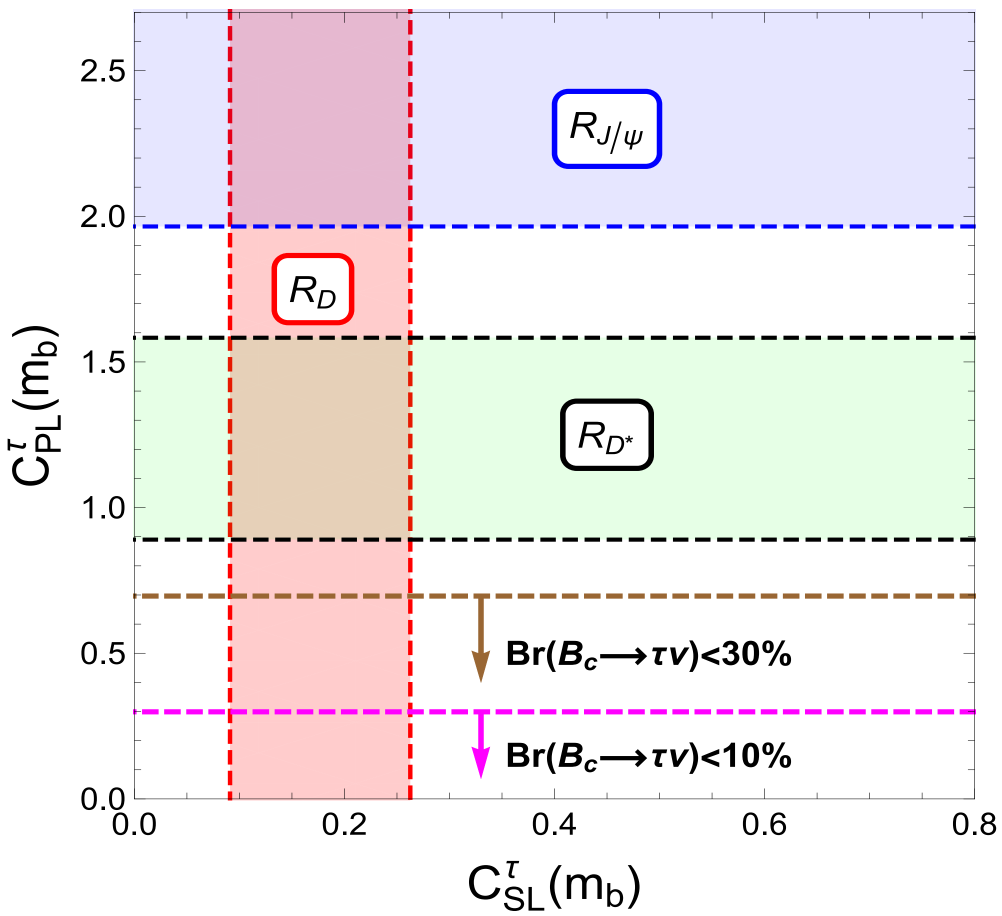
$\propto m_l^2$

[Bobeth, Hiller, Piranishvili 0709.4174]

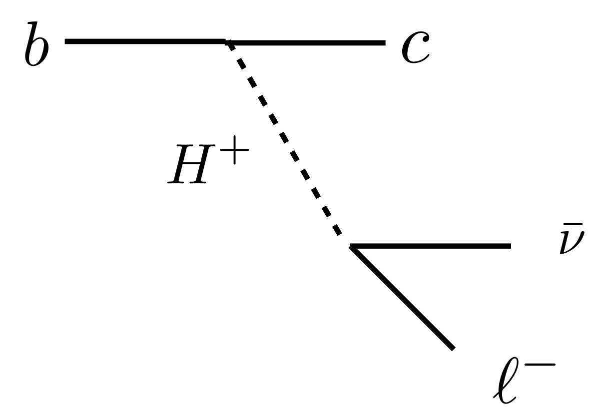
Lepton Non-Universality in b→c

A new TeV-scale scalar?

In tension with $\mathrm{Br}(B_c \to \tau\nu)$ [Akeroyd, Chen, 1708.04072]



Hard to get two sizable coefficients



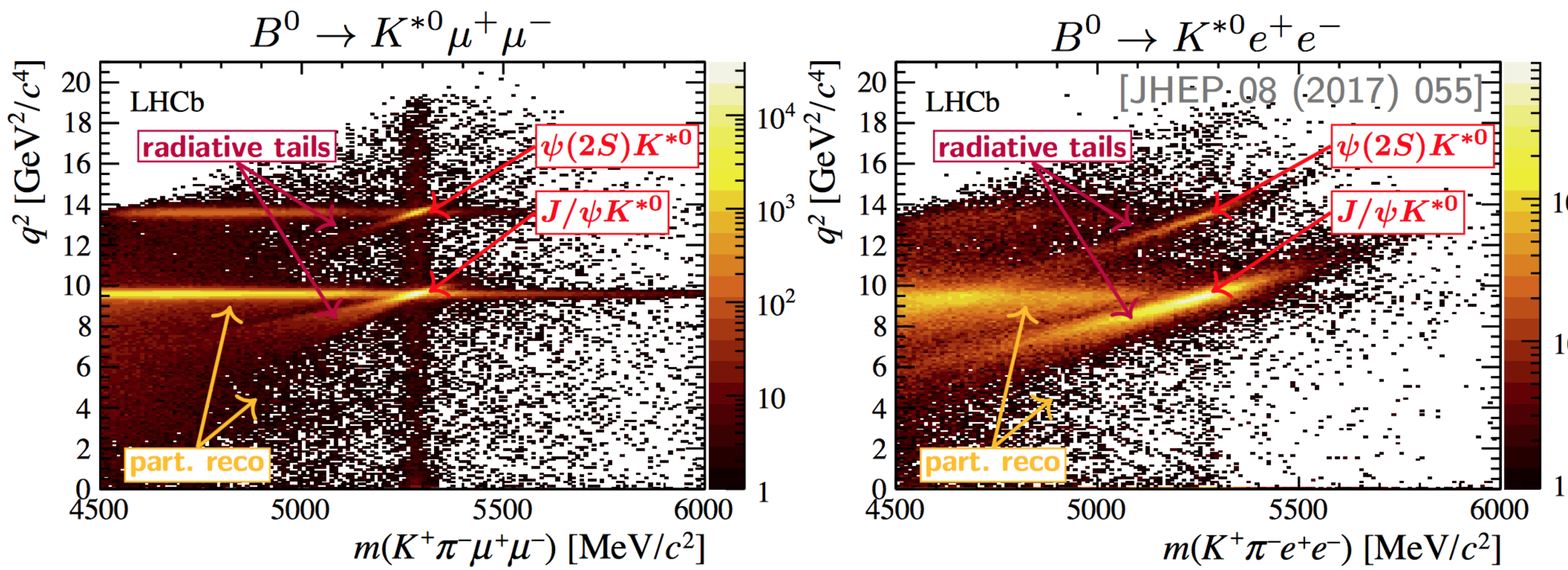
$$C_{S_R} = \frac{-2\sqrt{2}G_F}{M_{H^+}^2} V_{cb} m_b m_\tau \tan\beta^2$$

$$C_{S_L} = \frac{-2\sqrt{2}G_F}{M_{H^+}^2} V_{cb} m_c m_\tau \frac{1}{\tan\beta^2}$$

[Freytsis et al, 1506.08896] [Azatov et al. , 1805.03209]

Experimental challenge

[LHCb, JHEP 08 (2017) 055]

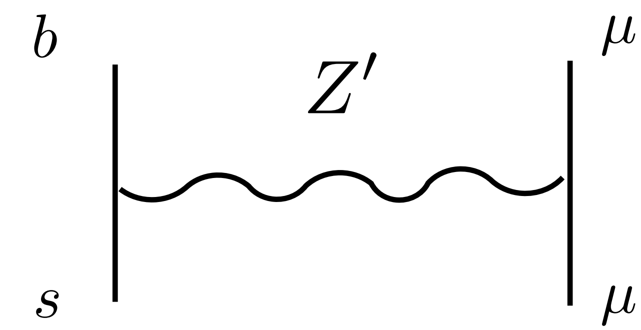


Models for bs transitions

$\mu \neq e$

C_9 : Vector Currents

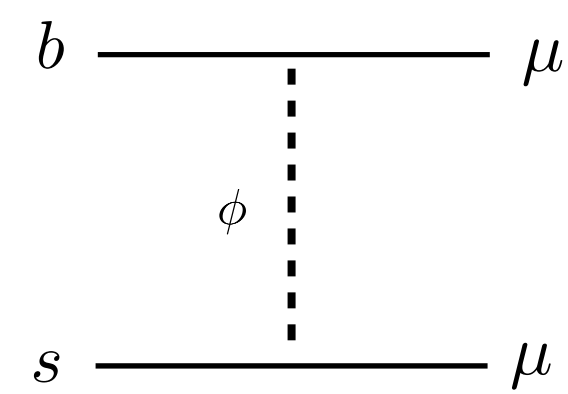
Gauld, Goetz, Haisch, 1310.1082
Altmannshofer, Gori, Pospelov, Yavin, 1403.1269
Crivellin, D'Ambrosio, Heeck 1501.00993 many more!



$C_9 = -C_{10}$: Leptoquarks

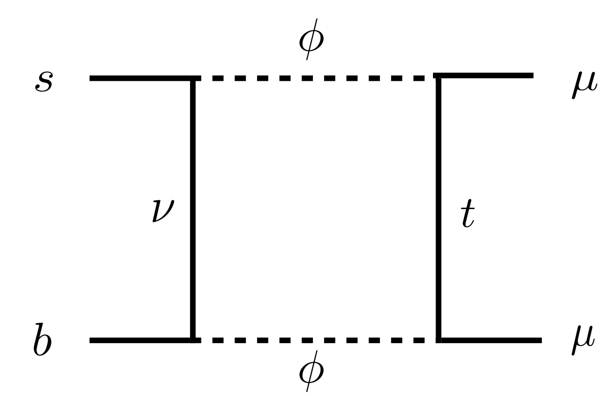
$(3,3)_{-1/3}$ $(3,2)_{1/6}$ Hiller, Schmaltz 1408.1627
Becirevic et al. 1608.08501

$(3,3)_{2/3}$ Fajfer, Kosnik 1511.06024



C_9, $C_9 = -C_{10}$: Loop Induced

Gripaois, Nardecchia, Renner 1509.05020
Arnan, Crivellin et al. 1608.07832
MB, Neubert 1511.01900

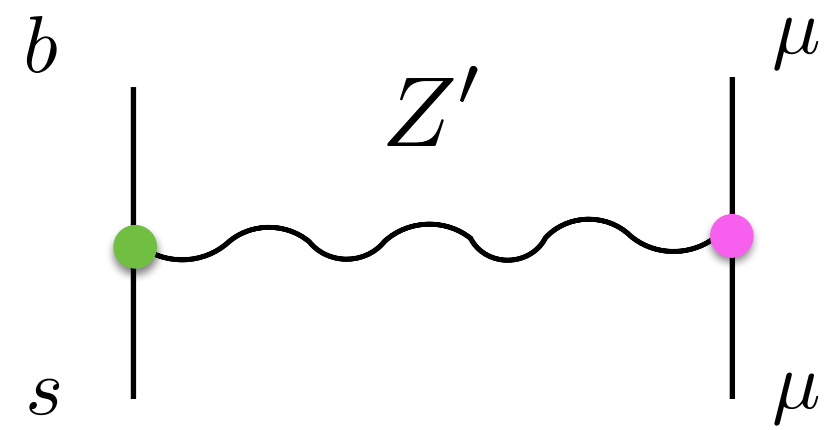


Models for bs transitions

$\mu \neq e$

C_9 : Vector Currents

Altmannshofer, Gori, Pospelov, Yavin, 1403.1269



- LFV diagonal couplings

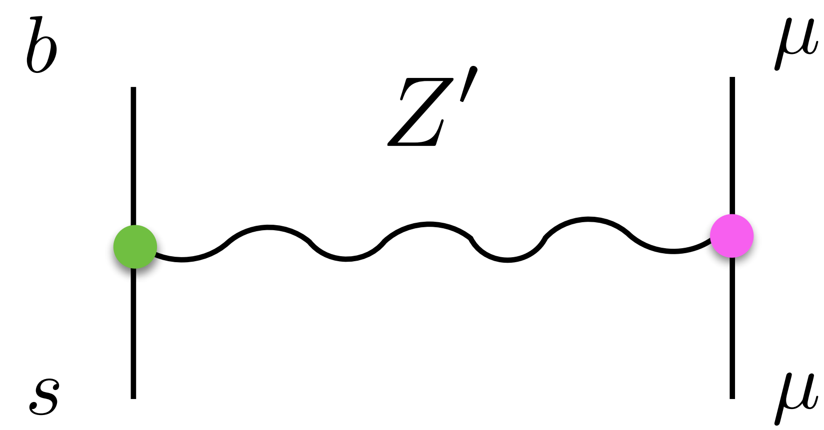
- QFV off-diagonal couplings

Models for bs transitions

$\mu \neq e$

C_9 : Vector Currents

Altmannshofer, Gori, Pospelov, Yavin, 1403.1269



- LFV diagonal couplings

Beautiful solution: gauged $L_\mu - L_\tau$ symmetry!

Anomaly free gauge group. No need for new fermions :)

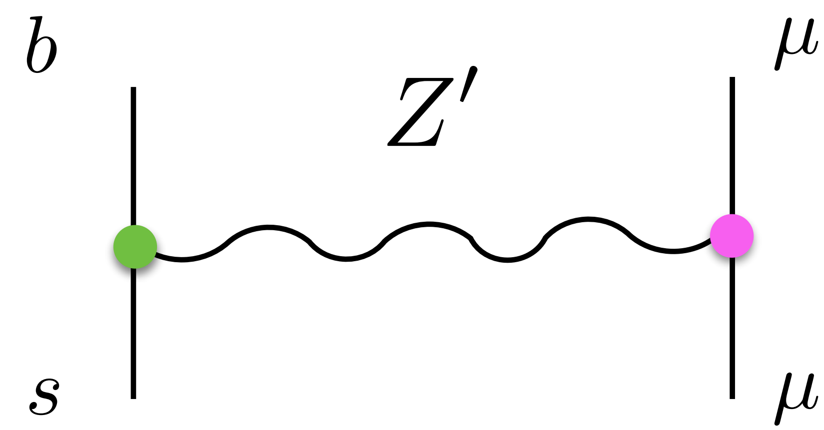
- QFV off-diagonal couplings

Models for bs transitions

$\mu \neq e$

C_9 : Vector Currents

Altmannshofer, Gori, Pospelov, Yavin, 1403.1269



- LFV diagonal couplings

Beautiful solution: gauged $L_\mu - L_\tau$ symmetry!

Anomaly free gauge group. No need for new fermions :)

- QFV off-diagonal couplings

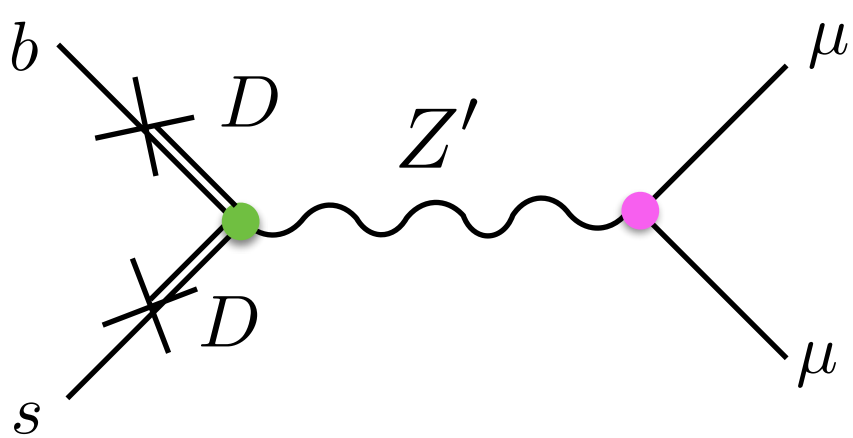
Charging b and s -> anomalies. Needs new fermions :/

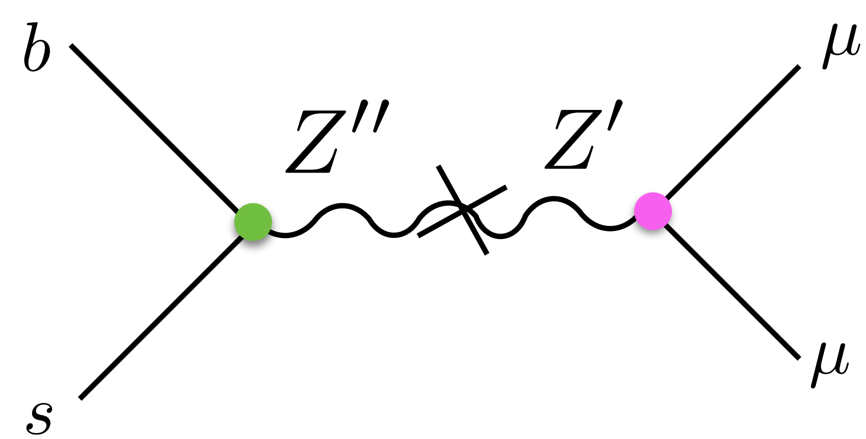
Models for bs transitions

$\mu \neq e$

C_9 : Vector Currents

Altmannshofer, Gori, Pospelov, Yavin, 1403.1269





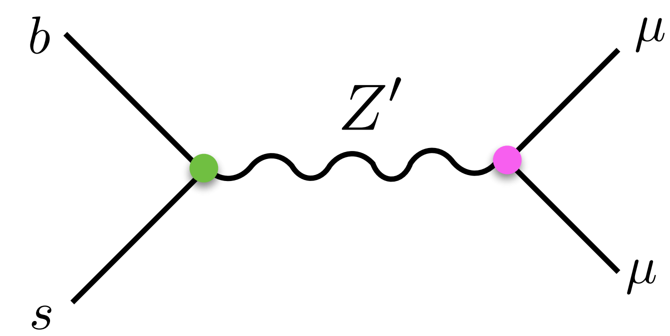
Horizontal Charges

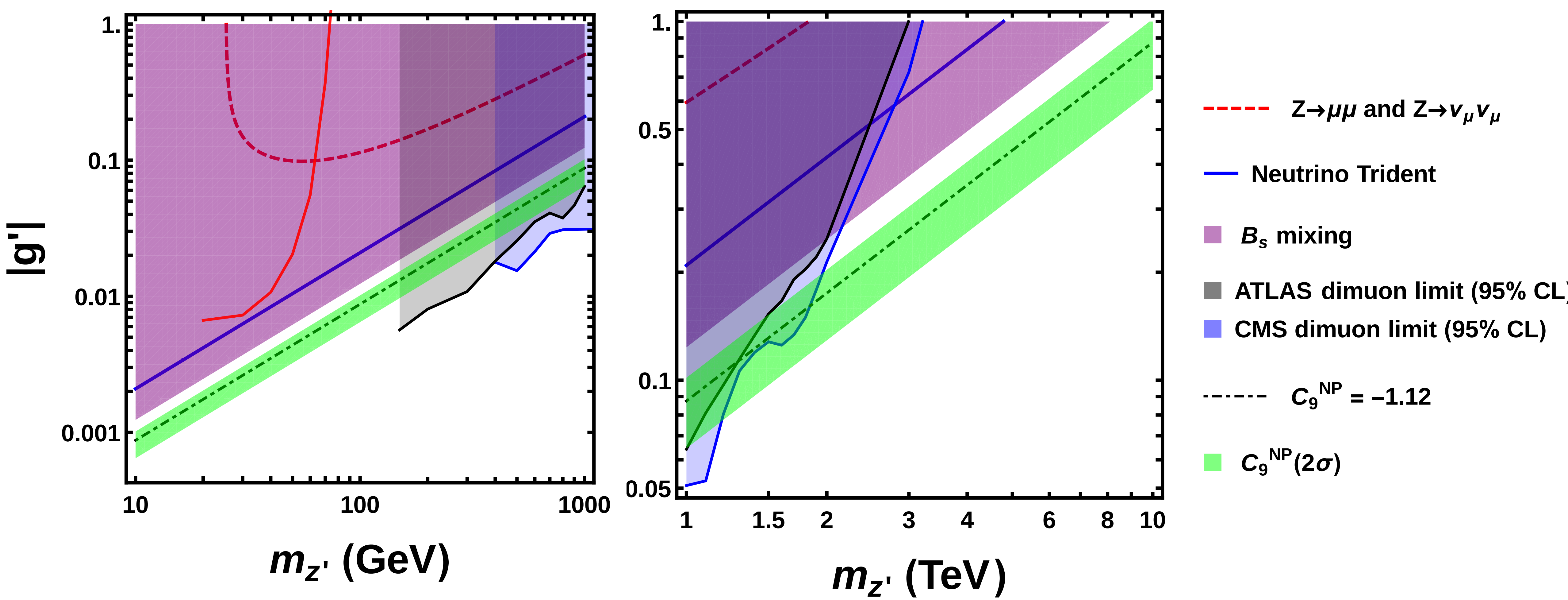
Crivellin, D'Ambrosio, Heeck 1503.03477
Bonilla et al. 1705.00915

Models for bs transitions

$\mu \neq e$

Anomaly free group: $U(1)_{B_3-3L_3}$





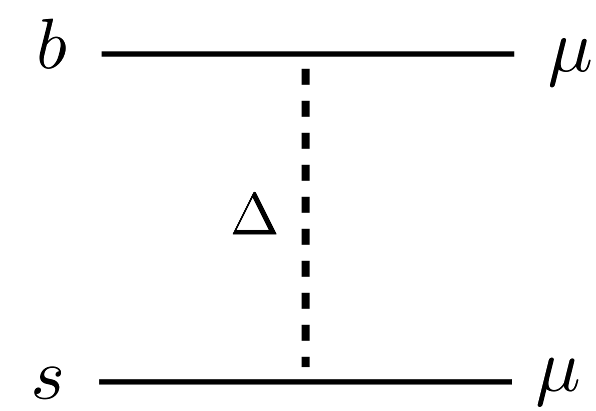
Bonilla et al. 1705.00915

Models for bs transitions

$\mu \neq e$

$C_9 = -C_{10}:$ Leptoquarks

Hiller, Schmaltz 1408.1627 Becirevic et al. 1608.08501



$$\Delta = \begin{pmatrix} \Delta^{2/3} \\ \Delta^{-1/3} \end{pmatrix} \sim (3,2)_{1/6}$$

$$\mathcal{L}_\Delta \; = \; \overline{d}'_R Y_L (\widetilde{\Delta})^\dagger L' = \overline{d}_R \left(Y_L U_{\rm PMNS} \right) \nu_L \Delta^{(-1/3)} - \overline{d}_R Y_L \ell_L \Delta^{(2/3)}$$

Contribution to b-> s transitions

$$\mathcal{L}_{\rm eff}^{d_k \to d_i \ell\ell} = \frac{1}{m_\Delta^2} Y_L^{ij} Y_L^{*kl} \; \overline{d}_i P_L \ell_j \; \overline{\ell}_l P_R d_k = -\frac{Y_L^{ij} Y_L^{*kl}}{2 m_\Delta^2} \; \overline{d}_i \gamma_\mu P_R d_k \; \overline{\ell}_l \gamma^\mu P_L \ell_j \, .$$

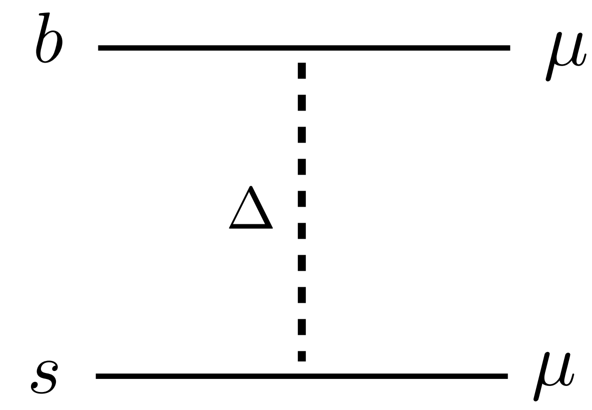
works for $$C_9 = -C_{10} = \frac{Y_L^{12} Y_L^{*\,32}}{2 m_\Delta^2} (24 \mathrm{TeV})^2$$

Models for bs transitions

$\mu \neq e$

$C_9 = -C_{10}:$ Leptoquarks

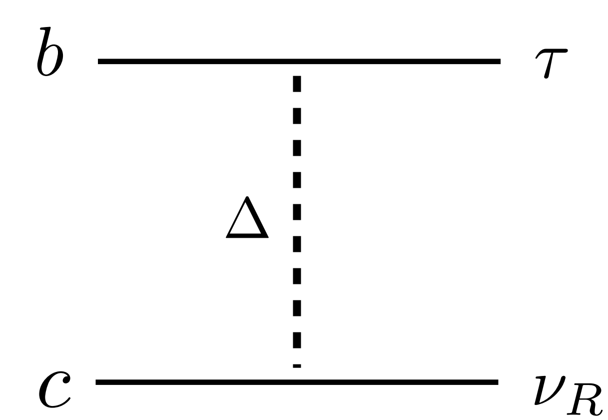
Becirevic et al. 1608.08501



$$\Delta = \begin{pmatrix} \Delta^{2/3} \\ \Delta^{-1/3} \end{pmatrix} \sim (3,2)_{1/6}$$

$$\begin{aligned} \mathcal{L}_\Delta &= \overline{d}'_R Y_L (\widetilde{\Delta})^\dagger L' + \overline{Q}' Y_R \Delta \nu'_R \\ &= \overline{d}_R \left(Y_L U_{\mathrm{PMNS}}\right) \nu_L \Delta^{(-1/3)} - \overline{d}_R Y_L \ell_L \Delta^{(2/3)} \\ &\quad + \overline{u}_L \left(V_{\mathrm{CKM}} Y_R\right) \nu_R \Delta^{(2/3)} + \overline{d}_L Y_R \nu_R \Delta^{(-1/3)} . \end{aligned}$$

$\tau \neq \mu, e$



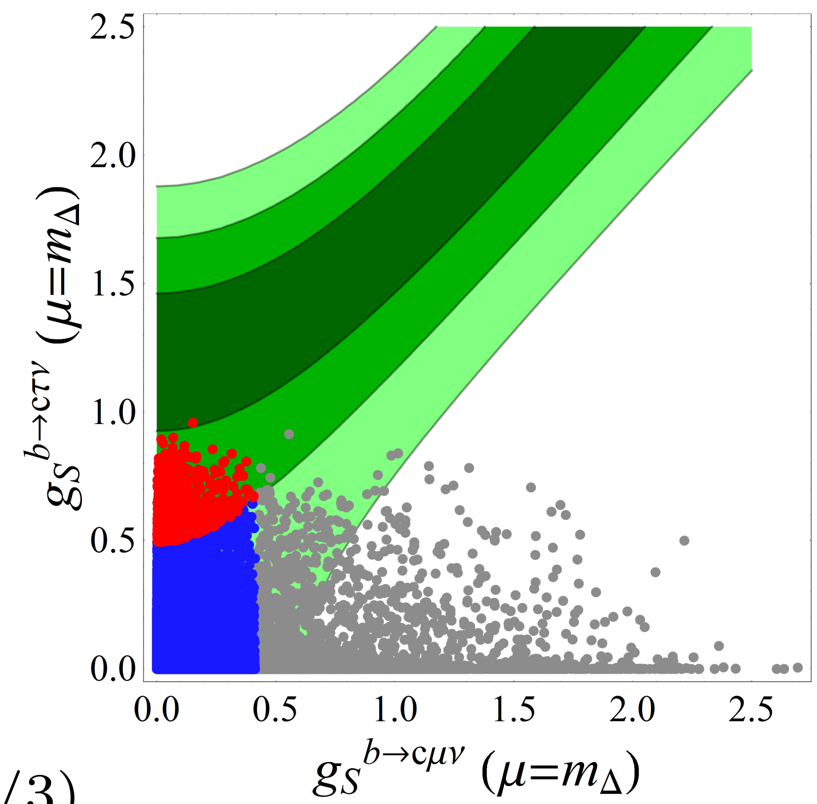
induces b -> c transitions!

Models for bs transitions

$\mu \neq e$

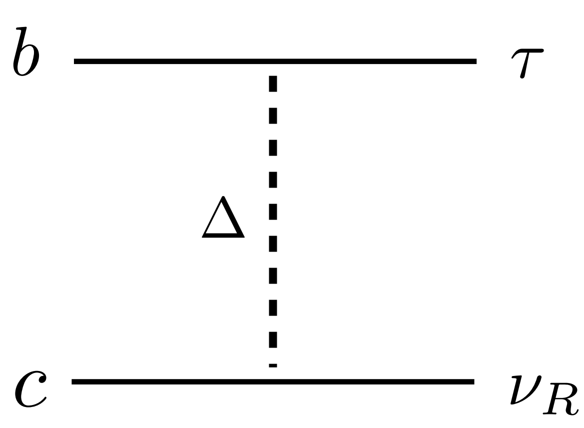
$C_9 = -C_{10}$: Leptoquarks

Becirevic et al. 1608.08501



$$\Delta = \begin{pmatrix} \Delta^{2/3} \\ \Delta^{-1/3} \end{pmatrix} \sim (3,2)_{1/6}$$

$$\begin{aligned} \mathcal{L}_\Delta &= \overline{d}'_R Y_L (\widetilde{\Delta})^\dagger L' + \overline{Q}' Y_R \Delta \nu'_R \\ &= \overline{d}_R \left(Y_L U_{\text{PMNS}}\right) \nu_L \Delta^{(-1/3)} - \overline{d}_R Y_L \ell_L \Delta^{(2/3)} \\ &\quad + \overline{u}_L \left(V_{\text{CKM}} Y_R\right) \nu_R \Delta^{(2/3)} + \overline{d}_L Y_R \nu_R \Delta^{(-1/3)} \end{aligned}$$



induces b -> c transitions!

$$M = 0.7 - 1\,\text{TeV}$$

One LQ to rule them all

Idea: Explain $R(D^{(*)})$ at tree-level and R_K, R_{K^*} at loop-level

MB, Neubert 1511.01900

Add a single leptoquark $\phi \sim (\mathbf{3}, \mathbf{1})_{-1/3}$

$$\mathcal{L}_\phi = (D_\mu \phi)^\dagger D_\mu \phi - M_\phi^2 \, |\phi|^2 - g_{h\phi} \, |\Phi|^2 |\phi|^2$$

$$+ \bar{Q}^c \boldsymbol{\lambda}^L i\tau_2 L \, \phi^* + \bar{u}_R^c \, \boldsymbol{\lambda}^R e_R \, \phi^* + \text{h.c.}$$

Rotation to mass eigenstates

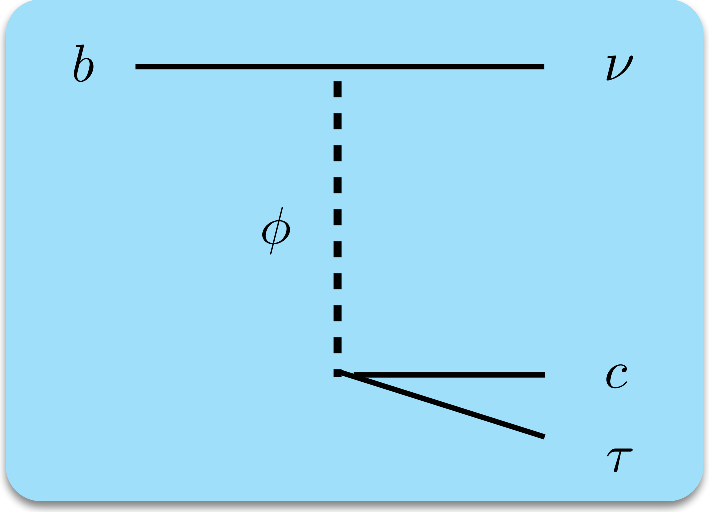
$$\mathcal{L}_\phi \ni \bar{u}_L^c \, \boldsymbol{\lambda}_{ue}^L e_L \, \phi^* - \bar{d}_L^c \, \boldsymbol{\lambda}_{d\nu}^L \nu_L \phi^* + \bar{u}_R^c \, \boldsymbol{\lambda}_{ue}^R e_R \, \phi^* + \text{h.c.}$$

One LQ to rule them all

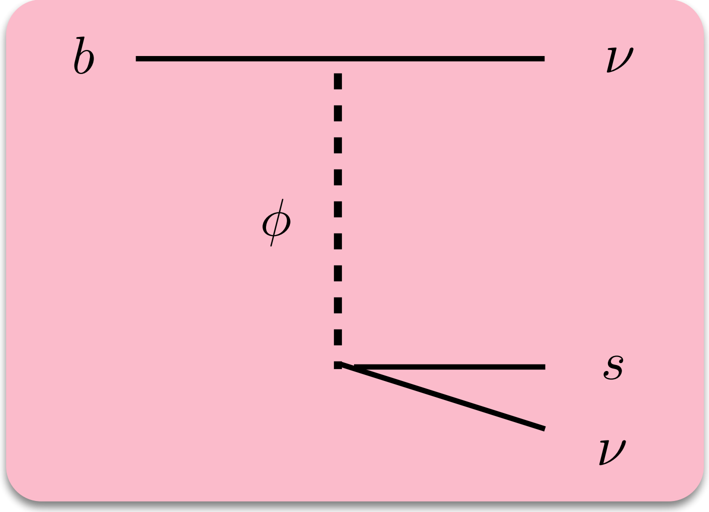
$$\mathcal{L}_\phi \ni \bar{u}^c_L\, \boldsymbol{\lambda}^L_{ue} e_L\, \phi^* - \bar{d}^c_L\, \boldsymbol{\lambda}^L_{d\nu} \nu_L \phi^* + \bar{u}^c_R\, \boldsymbol{\lambda}^R_{ue} e_R\, \phi^* + \text{h.c.}$$

at tree level gives rise to

up-quark - charged lepton couplings



down-quark - neutrino couplings

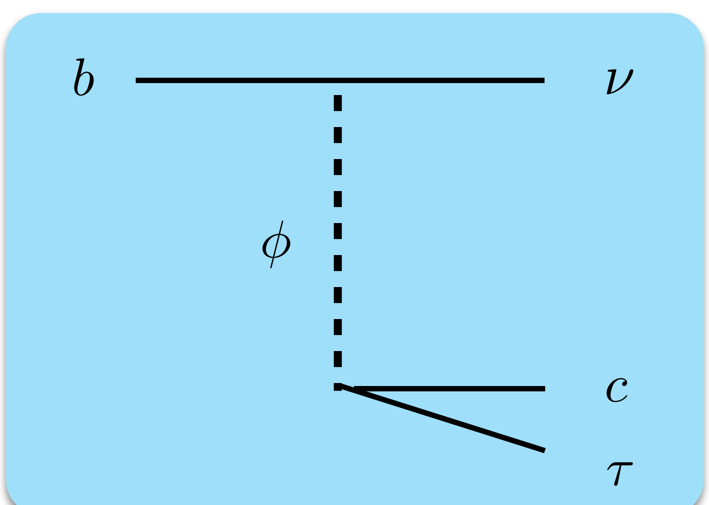


One LQ to rule them all

$$\mathcal{L}_\phi \ni \bar{u}_L^c\, \boldsymbol{\lambda}^L_{ue} e_L\, \phi^* - \bar{d}_L^c\, \boldsymbol{\lambda}^L_{d\nu} \nu_L \phi^* + \bar{u}_R^c\, \boldsymbol{\lambda}^R_{ue} e_R\, \phi^* + \text{h.c.}$$

at tree level gives rise to

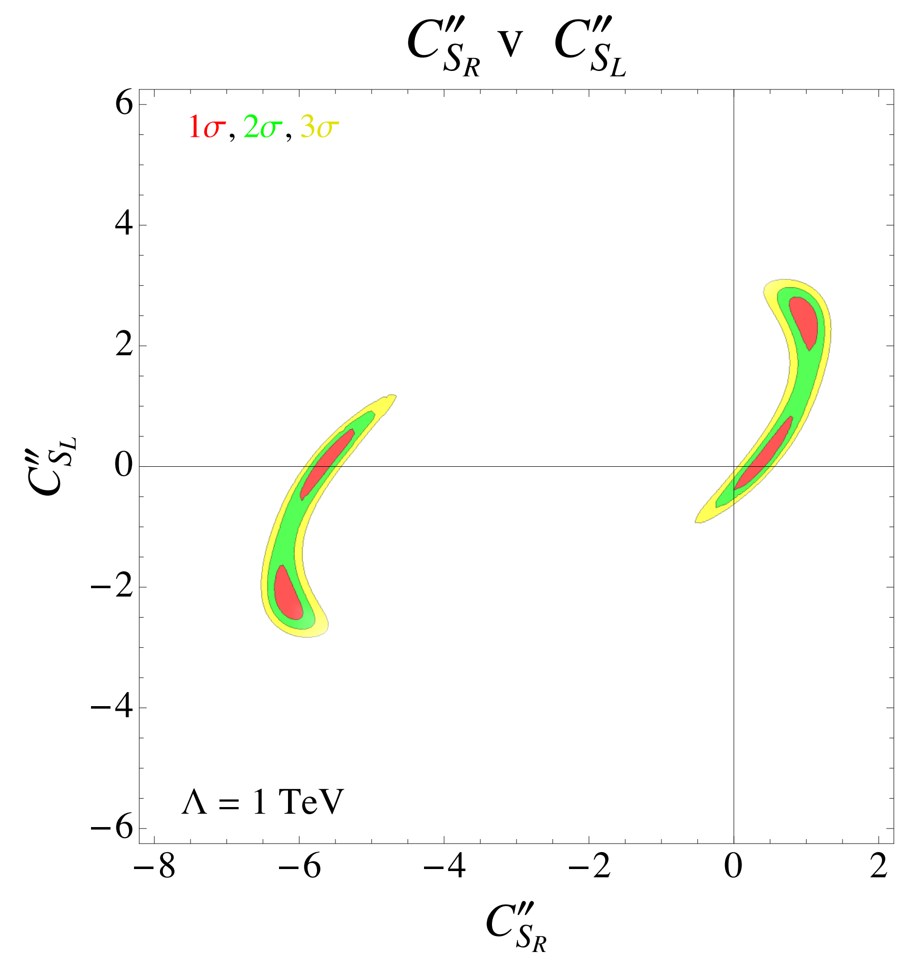
up-quark - charged lepton couplings



$R(D^{(*)})$ needs

$$\frac{\lambda^{L*}_{c\tau}\,\lambda^{L}_{b\nu_\tau}}{M_\phi^2} \approx \frac{0.35}{\text{TeV}^2}\,,$$

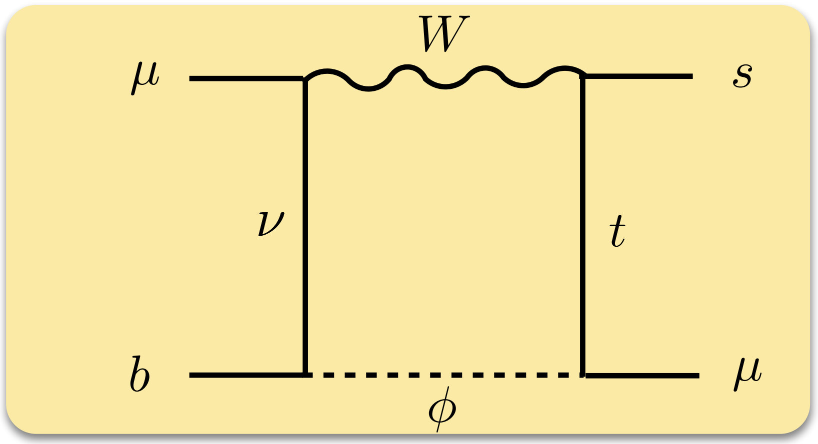
$$\frac{\lambda^{R*}_{c\tau}\,\lambda^{L}_{b\nu_\tau}}{M_\phi^2} \approx -\frac{0.03}{\text{TeV}^2}$$

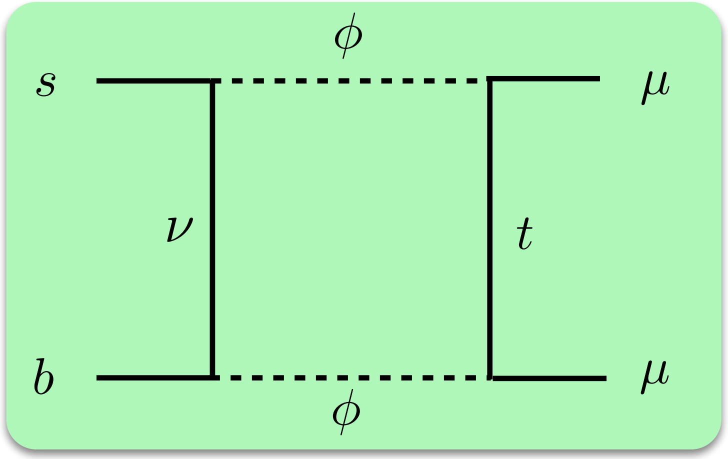


One LQ to rule them all

$$\mathcal{L}_\phi \ni \bar{u}^c_L \,\boldsymbol{\lambda}^L_{ue} e_L \,\phi^* - \bar{d}^c_L \,\boldsymbol{\lambda}^L_{d\nu} \nu_L \phi^* + \bar{u}^c_R \,\boldsymbol{\lambda}^R_{ue} e_R \,\phi^* + \mathrm{h.c.}$$

at loop level gives rise to

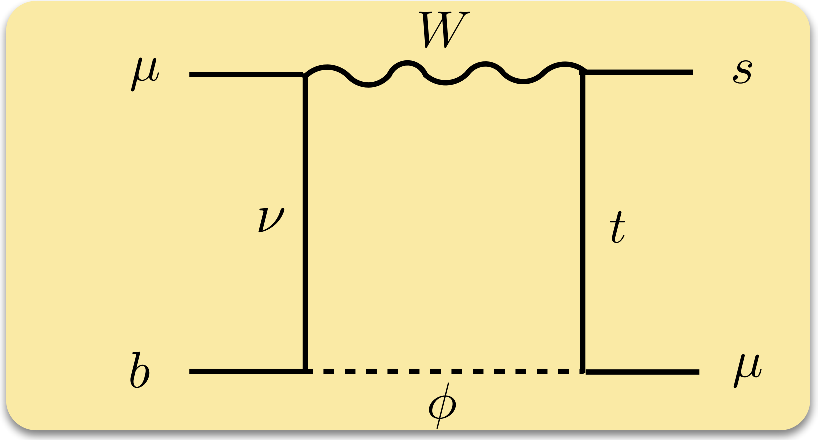


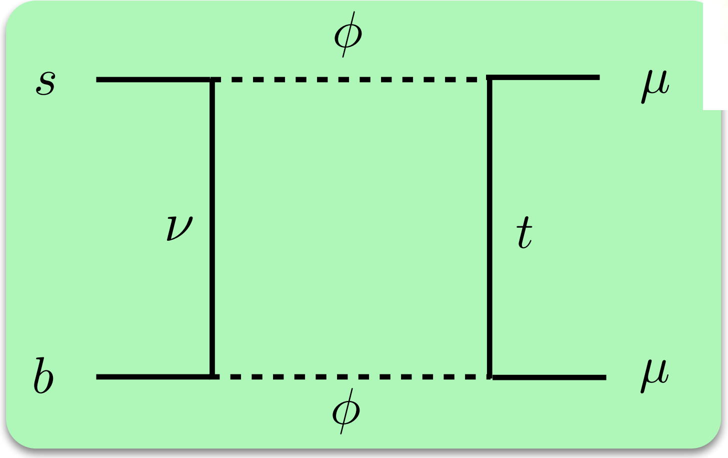


can this explain RK with a M= few TeV leptoquark?

One LQ to rule them all

We have





$$C_{LL}^{\mu(\phi)} = \frac{m_t^2}{8\pi\alpha M_\phi^2}\left|\lambda_{t\mu}^L\right|^2 - \frac{1}{64\pi\alpha}\frac{\sqrt{2}}{G_F M_\phi^2}\frac{\left(\lambda^L\lambda^{L\dagger}\right)_{bs}}{V_{tb}V_{ts}^*}\left(\lambda^{L\dagger}\lambda^L\right)_{\mu\mu},$$

$$C_{LR}^{\mu(\phi)} = \frac{m_t^2}{16\pi\alpha M_\phi^2}\left|\lambda_{t\mu}^R\right|^2\left[\ln\frac{M_\phi^2}{m_t^2} - f(x_t)\right] - \frac{1}{64\pi\alpha}\frac{\sqrt{2}}{G_F M_\phi^2}\frac{\left(\lambda^L\lambda^{L\dagger}\right)_{bs}}{V_{tb}V_{ts}^*}\left(\lambda^{R\dagger}\lambda^R\right)_{\mu\mu},$$

The $W-\phi$ box contributions have the wrong sign, but they are chirally suppressed and inherit a partial GIM-suppression. Penguins cancel!

$$C_{LL} = C_9^{\mu\mu} - C_{10}^{\mu\mu}$$

One LQ to rule them all

$$C_{LL}^{\mu(\phi)} = \frac{m_t^2}{8\pi\alpha M_\phi^2}\left|\lambda^L_{t\mu}\right|^2 - \frac{1}{64\pi\alpha}\,\frac{\sqrt{2}}{G_F M_\phi^2}\,\frac{(\lambda^L\lambda^{L\dagger})_{bs}}{V_{tb}V_{ts}^*}\,(\lambda^{L\dagger}\lambda^L)_{\mu\mu}\,,$$

$$C_{LR}^{\mu(\phi)} = \frac{m_t^2}{16\pi\alpha M_\phi^2}\left|\lambda^R_{t\mu}\right|^2\left[\ln\frac{M_\phi^2}{m_t^2} - f(x_t)\right] - \frac{1}{64\pi\alpha}\,\frac{\sqrt{2}}{G_F M_\phi^2}\,\frac{(\lambda^L\lambda^{L\dagger})_{bs}}{V_{tb}V_{ts}^*}\,(\lambda^{R\dagger}\lambda^R)_{\mu\mu}\,,$$

For the Benchmark $C^\mu_{LL} \simeq -1\,, \quad C^\mu_{ij} = 0 \text{ otherwise}$, we need

$$\sum_i \left|\lambda^L_{u_i\mu}\right|^2 \mathrm{Re}\,\frac{(\lambda^L\lambda^{L\dagger})_{bs}}{V_{tb}V_{ts}^*} - 1.74\left|\lambda^L_{t\mu}\right|^2 \approx 12.5\,\frac{M_\phi^2}{\mathrm{TeV}^2}$$

Constrained to be < 2.3 by $R_{\nu\nu}$

$$\Rightarrow \quad \sqrt{\left|\lambda^L_{u\mu}\right|^2 + \left|\lambda^L_{c\mu}\right|^2 + \left(1 - \frac{0.77}{\hat{M}_\phi^2}\right)\left|\lambda^L_{t\mu}\right|^2} > 2.36$$

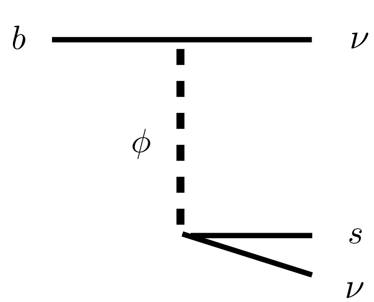
One LQ to rule them all

For the Benchmark $C^{\mu}_{LL} \simeq -1\,,\quad C^{\mu}_{ij} = 0$ otherwise, we need

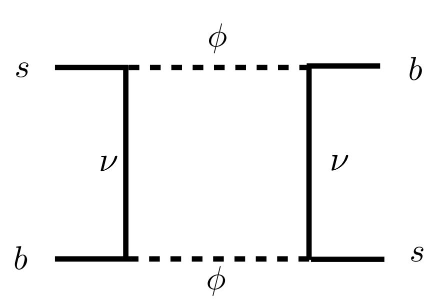
$$\underbrace{\sum_i \left|\lambda^L_{u_i\mu}\right|^2 \mathrm{Re}\,\frac{(\lambda^L\lambda^{L\dagger})_{bs}}{V_{tb}V^*_{ts}}}_{R^L_{bs}} - 1.74\left|\lambda^L_{t\mu}\right|^2 \approx 12.5\,\frac{M^2_\phi}{\mathrm{TeV}^2}$$

Constraints:

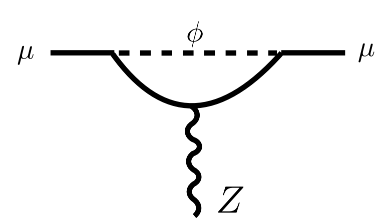
$\bar{B} \to K^{(*)}\nu\bar{\nu}$

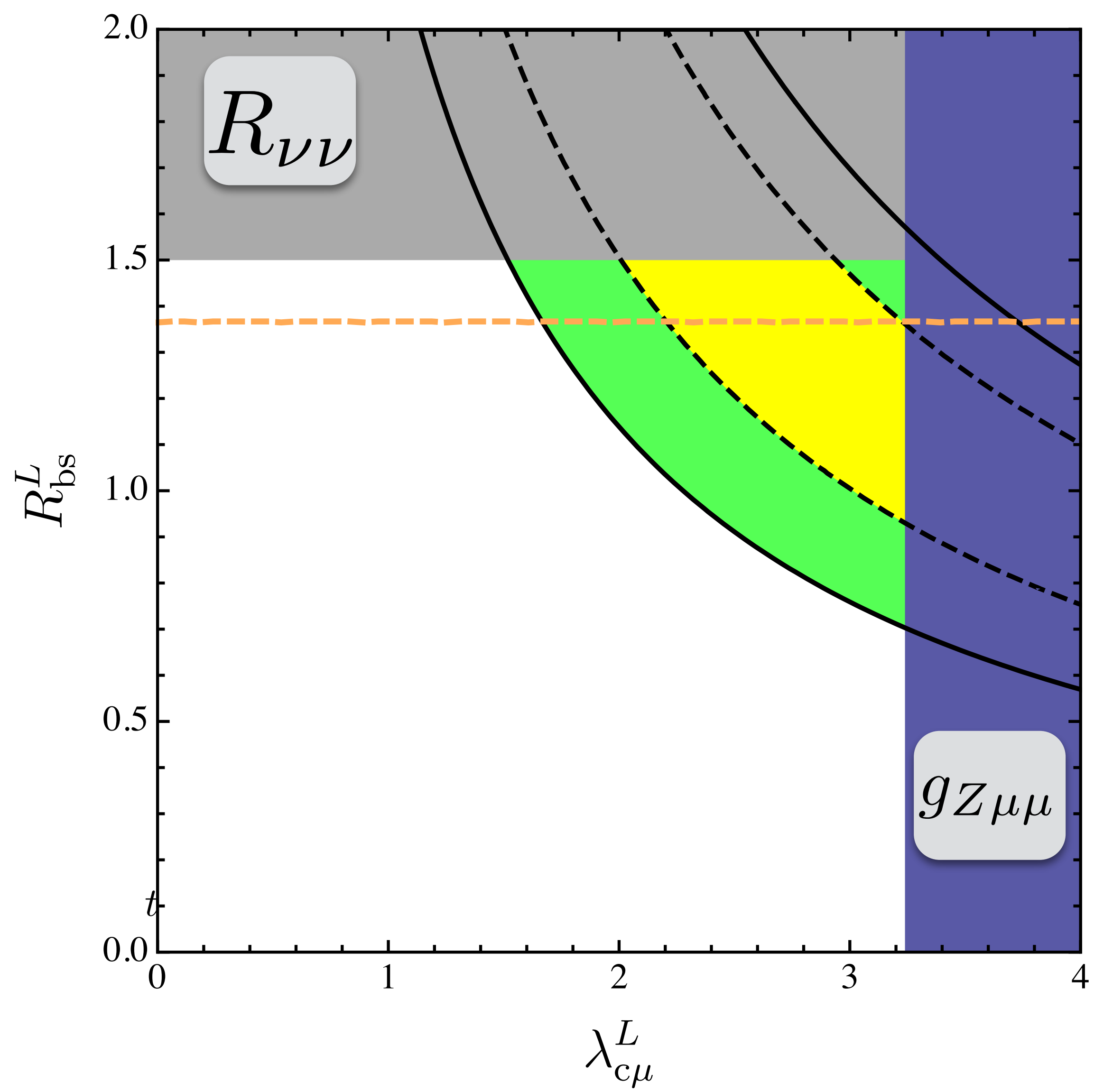


$\bar{B}_s - B_s$



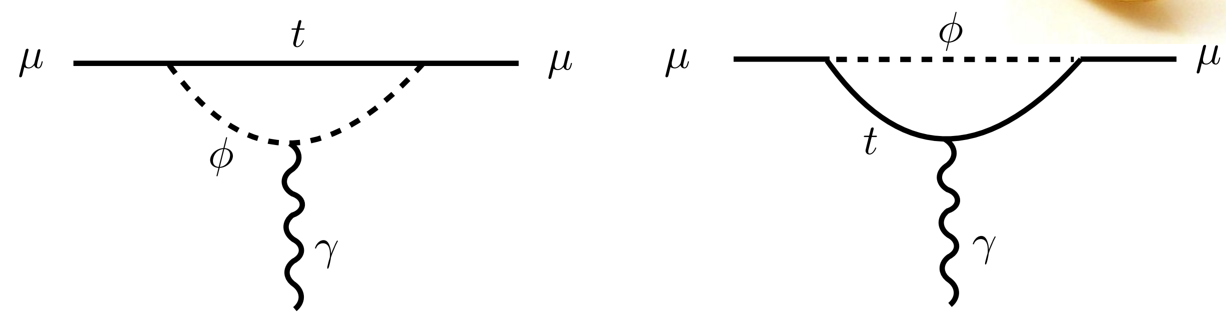
$g_{Z\mu\mu}$





One LQ to rule them all

- One-loop Contribution to g-2



$$a_\mu^{(\phi)} = \sum_{q=t,c} \frac{m_\mu m_q}{4\pi^2 M_\phi^2} \left(\ln \frac{M_\phi^2}{m_q^2} - \frac{7}{4} \right) \mathrm{Re}(\lambda_{q\mu}^R \lambda_{q\mu}^{L*}) - \frac{m_\mu^2}{32\pi^2 M_\phi^2} \left[(\lambda^{L\dagger}\lambda^L)_{\mu\mu} + (\lambda^{R\dagger}\lambda^R)_{\mu\mu} \right]$$

$$-37 \times 10^{-11}$$

$$a_\mu^{\exp} = 287 \pm 80 \times 10^{-11}$$

$$\left(1 + 0.17 \ln \frac{M_\phi}{\mathrm{TeV}}\right) \mathrm{Re}(\lambda_{c\mu}^R \lambda_{c\mu}^{L*}) + 20.7 \left(1 + 1.06 \ln \frac{M_\phi}{\mathrm{TeV}}\right) \mathrm{Re}(\lambda_{t\mu}^R \lambda_{t\mu}^{L*}) \approx 0.08 \frac{M_\phi^2}{\mathrm{TeV}^2}$$

For $|\lambda_{c\mu}^L| \sim 2.4$, we need $|\lambda_{c\mu}^R| \sim 0.03$.

One LQ to rule them all

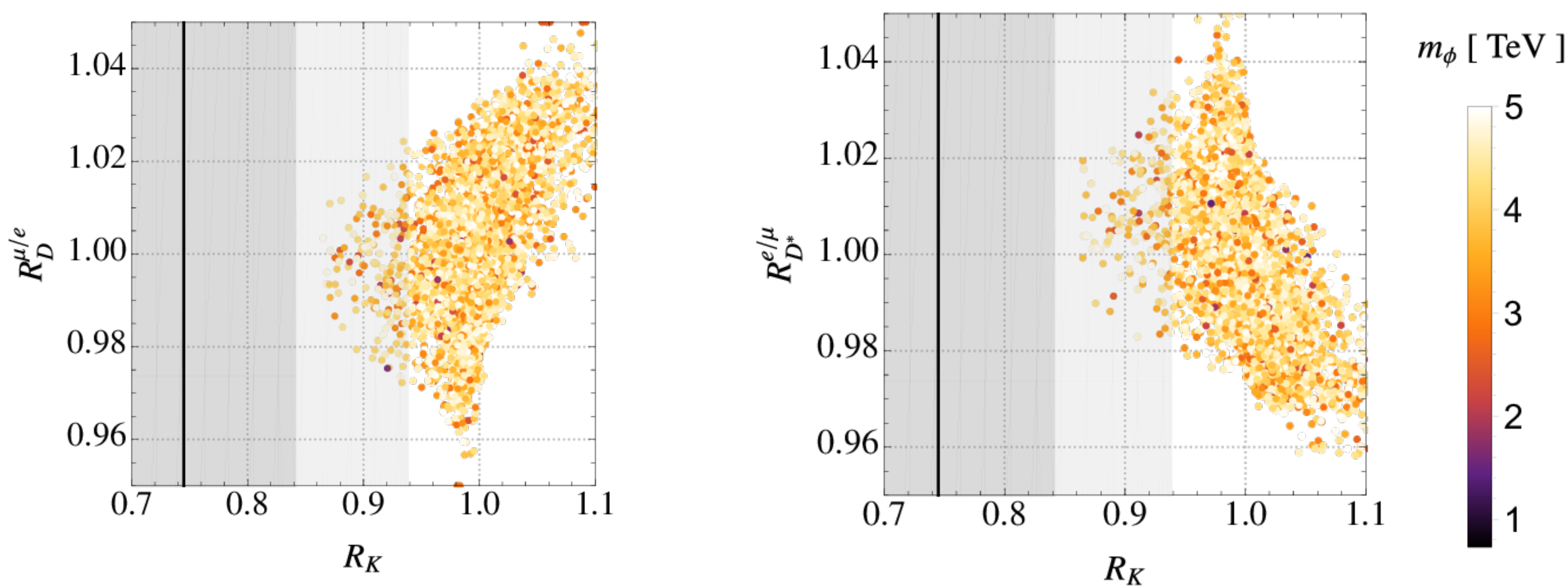
Loop-induced non-universality in mu and e comes at a prize

Becirevic et al. 1608.08501   Cai et. al. 1704.05849

$$R_{D^{(*)}}^{\mu/e} = \frac{\Gamma(\bar{B} \to D^{(*)}\mu\bar{\nu})}{\Gamma(\bar{B} \to D^{(*)}e\bar{\nu})},$$

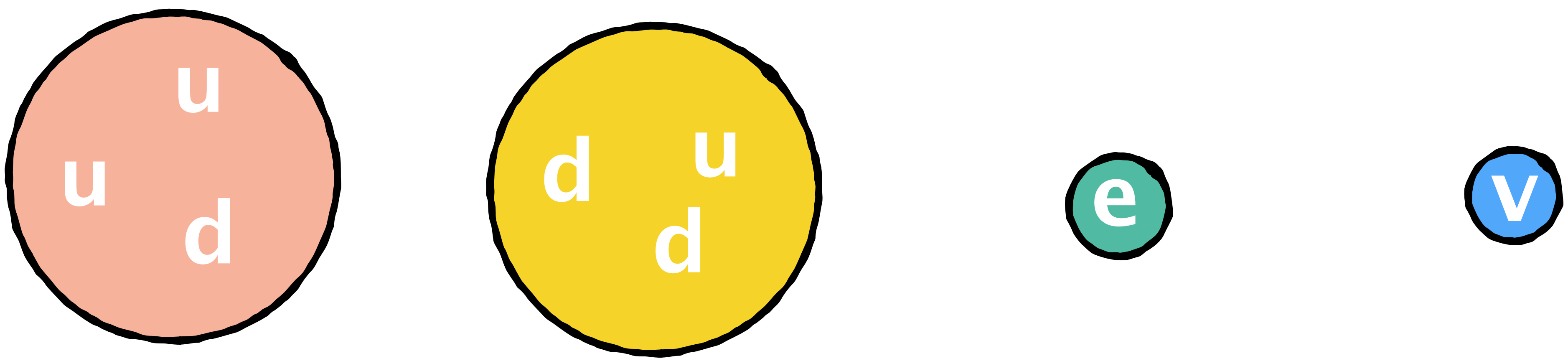
$$R_D^{\mu/e} = 0.995 \pm 0.022 \pm 0.039$$

$$R_{D^*}^{e/\mu} = 1.04 \pm 0.05 \pm 0.01$$



The Standard Model in the 30s

The known particles were the



This was a very successful model, as it greatly simplified the previous best candidate for a fundamental theory of elementary particles, the periodic table of elements.

Periodic Table of the Elements

1 IA 1A	2 IIA 2A	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 VIII 8	9 VIII 8	10 VIII 8	11 IB 1B	12 IIB 2B	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
1 **H** Hydrogen 1.008																	2 **He** Helium 4.003
3 **Li** Lithium 6.941	4 **Be** Beryllium 9.012											5 **B** Boron 10.811	6 **C** Carbon 12.011	7 **N** Nitrogen 14.007	8 **O** Oxygen 15.999	9 **F** Fluorine 18.998	10 **Ne** Neon 20.180
11 **Na** Sodium 22.990	12 **Mg** Magnesium 24.305											13 **Al** Aluminum 26.982	14 **Si** Silicon 28.086	15 **P** Phosphorus 30.974	16 **S** Sulfur 32.066	17 **Cl** Chlorine 35.453	18 **Ar** Argon 39.948
19 **K** Potassium 39.098	20 **Ca** Calcium 40.078	21 **Sc** Scandium 44.956	22 **Ti** Titanium 47.867	23 **V** Vanadium 50.942	24 **Cr** Chromium 51.996	25 **Mn** Manganese 54.938	26 **Fe** Iron 55.845	27 **Co** Cobalt 58.933	28 **Ni** Nickel 58.693	29 **Cu** Copper 63.546	30 **Zn** Zinc 65.38	31 **Ga** Gallium 69.723	32 **Ge** Germanium 72.631	33 **As** Arsenic 74.922	34 **Se** Selenium 78.971	35 **Br** Bromine 79.904	36 **Kr** Krypton 84.798
37 **Rb** Rubidium 84.468	38 **Sr** Strontium 87.62	39 **Y** Yttrium 88.906	40 **Zr** Zirconium 91.224	41 **Nb** Niobium 92.906	42 **Mo** Molybdenum 95.95	43 **Tc** Technetium 98.907	44 **Ru** Ruthenium 101.07	45 **Rh** Rhodium 102.906	46 **Pd** Palladium 106.42	47 **Ag** Silver 107.868	48 **Cd** Cadmium 112.411	49 **In** Indium 114.818	50 **Sn** Tin 118.711	51 **Sb** Antimony 121.760	52 **Te** Tellurium 127.6	53 **I** Iodine 126.904	54 **Xe** Xenon 131.294
55 **Cs** Cesium 132.905	56 **Ba** Barium 137.328	57-71	72 **Hf** Hafnium 178.49	73 **Ta** Tantalum 180.948	74 **W** Tungsten 183.84	75 **Re** Rhenium 186.207	76 **Os** Osmium 190.23	77 **Ir** Iridium 192.217	78 **Pt** Platinum 195.085	79 **Au** Gold 196.967	80 **Hg** Mercury 200.592	81 **Tl** Thallium 204.383	82 **Pb** Lead 207.2	83 **Bi** Bismuth 208.980	84 **Po** Polonium [208.982]	85 **At** Astatine 209.987	86 **Rn** Radon 222.018
87 **Fr** Francium 223.020	88 **Ra** Radium 226.025	89-103	104 **Rf** Rutherfordium [261]	105 **Db** Dubnium [262]	106 **Sg** Seaborgium [266]	107 **Bh** Bohrium [264]	108 **Hs** Hassium [269]	109 **Mt** Meitnerium [268]	110 **Ds** Darmstadtium [269]	111 **Rg** Roentgenium [272]	112 **Cn** Copernicium [277]	113 **Uut** Ununtrium unknown	114 **Fl** Flerovium [289]	115 **Uup** Ununpentium unknown	116 **Lv** Livermorium [298]	117 **Uus** Ununseptium unknown	118 **Uuo** Ununoctium unknown

Atomic Number **Symbol** Name Atomic Mass

Lanthanide Series	57 **La** Lanthanum 138.905	58 **Ce** Cerium 140.116	59 **Pr** Praseodymium 140.908	60 **Nd** Neodymium 144.243	61 **Pm** Promethium 144.913	62 **Sm** Samarium 150.36	63 **Eu** Europium 151.964	64 **Gd** Gadolinium 157.25	65 **Tb** Terbium 158.925	66 **Dy** Dysprosium 162.500	67 **Ho** Holmium 164.930	68 **Er** Erbium 167.259	69 **Tm** Thulium 168.934	70 **Yb** Ytterbium 173.055	71 **Lu** Lutetium 174.967
Actinide Series	89 **Ac** Actinium 227.028	90 **Th** Thorium 232.038	91 **Pa** Protactinium 231.036	92 **U** Uranium 238.029	93 **Np** Neptunium 237.048	94 **Pu** Plutonium 244.064	95 **Am** Americium 243.061	96 **Cm** Curium 247.070	97 **Bk** Berkelium 247.070	98 **Cf** Californium 251.080	99 **Es** Einsteinium [254]	100 **Fm** Fermium 257.095	101 **Md** Mendelevium 258.1	102 **No** Nobelium 259.101	103 **Lr** Lawrencium [262]

Alkali Metal	Alkaline Earth	Transition Metal	Basic Metal	Semimetal	Nonmetal	Halogen	Noble Gas	Lanthanide	Actinide

The Standard Model in the 30s

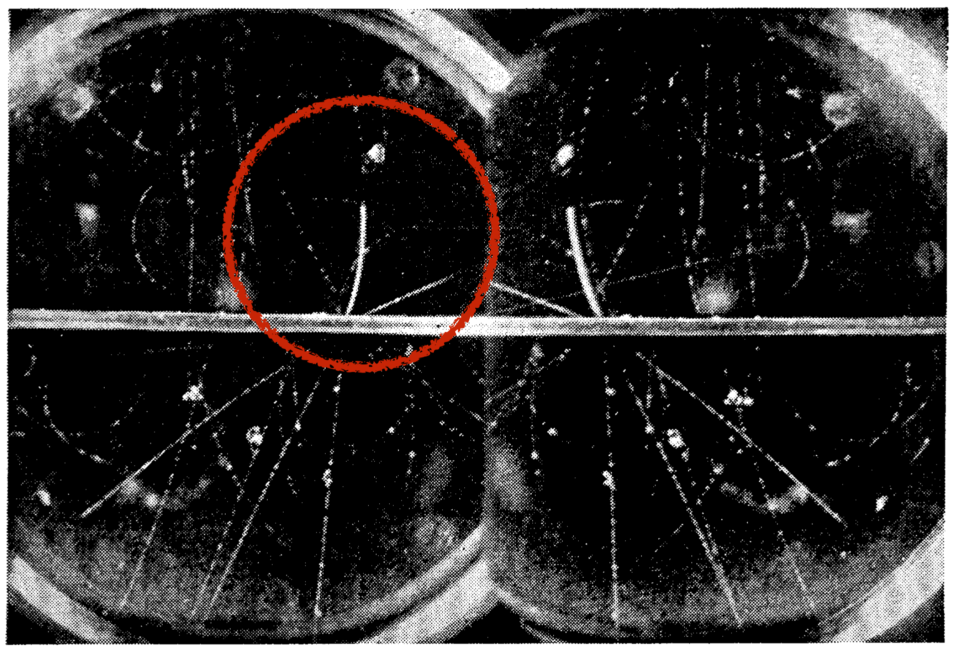
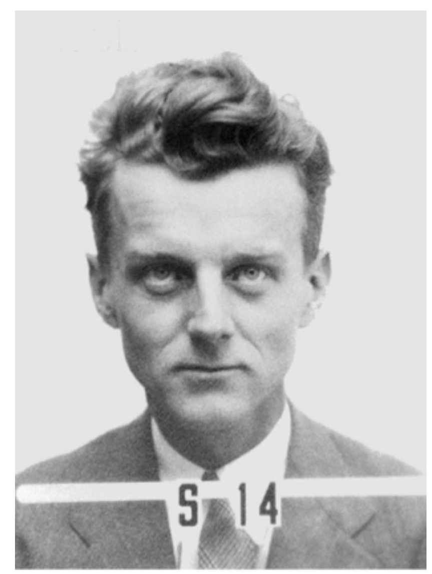


FIG. 12. Pike's Peak, 7900 gauss. A disintegration produced by a nonionizing ray occurs at a point in the 0.35 cm lead plate, from which six particles are ejected. One of the particles (strongly ionizing) ejected nearly vertically upward has the range of a 1.5 MEV proton. Its energy (given by its range) corresponds to an $H\rho = 1.7 \times 10^5$, or a radius of 20 cm, which is three times the observed value. If the observed curvature were produced entirely by magnetic deflection it would be necessary to conclude that this track represents a massive particle with an e/m much greater than that of a proton or any other known nucleus. As there are no experimental data available on the multiple scattering of low energy protons in argon it is difficult to estimate to what extent scattering may have modified the curvature in this case. The particle is therefore tentatively interpreted as a proton. The other particle ejected upward

Neddermeyer and Anderson discover a new fermion with

$$m = 106\,\mathrm{MeV}$$



Neddermeyer

Anderson

Who ordered that?

-Rabi