Flavored B-L model and B anomalies

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Based on arXiv:1705.03858(PLB), with Peter Cox and Tsutomu Yanagida

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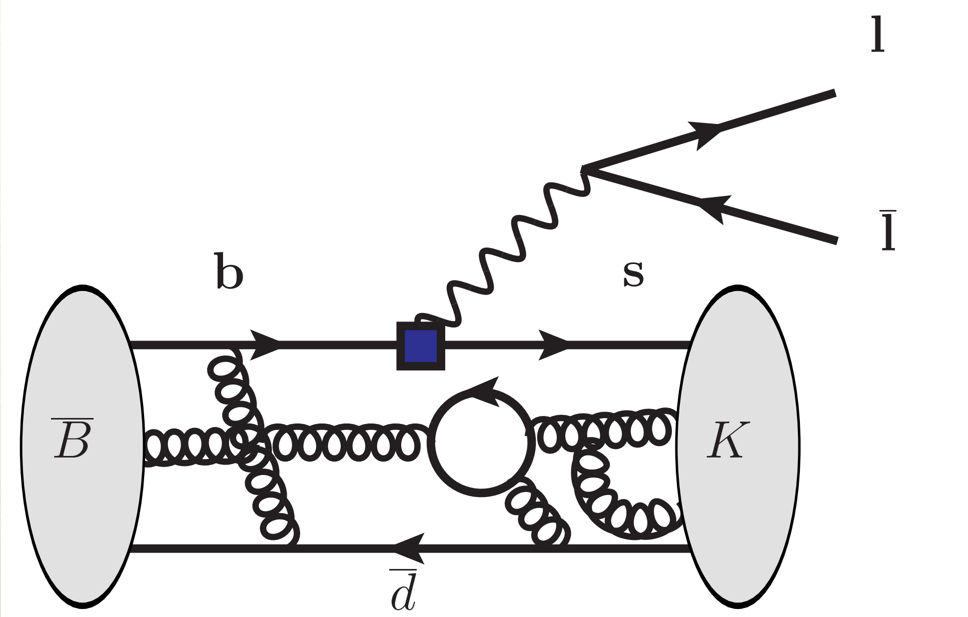
Outline

- Briefly overview the B anomaly
- The flavored B-L model and phenomenologies
- Summary and conclusions

B decay anomaly



LFU violation

LHCb arXiv:1406.6482

$$R_K = \frac{Br(B \to K\mu\mu)}{Br(B \to Kee)}_{[1,6]} = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036((\text{syst})$$

LHCb arXiv:1705.05802

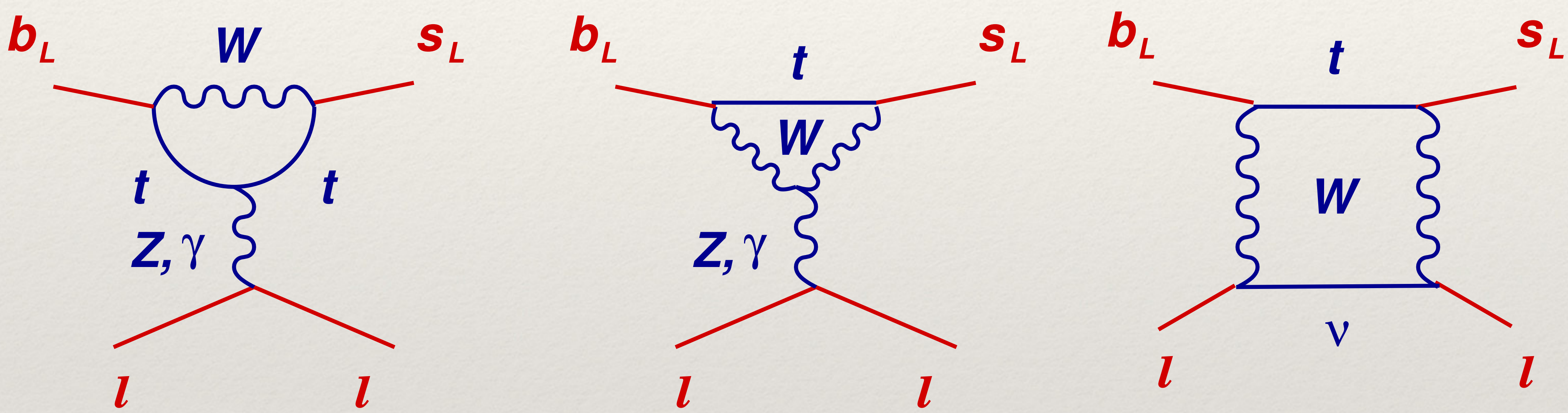
$$R_{K^*} = \frac{Br(B \to K^*\mu\mu)}{Br(B \to K^*ee)}_{[1,6]} = 0.69^{+0.11}_{-0.07}(\text{stat}) \pm 0.05((\text{syst})$$

$$_{[0.05,1]} = 0.66^{+0.11}_{-0.07}(\text{stat}) \pm 0.024(\text{syst})$$

Combined ~4sigma tension with SM(R_{SM}=1)

SM contribution

EFT $\mathcal{L}_{\rm eff} = \frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \left(C_9^l \mathcal{O}_9^l + C_{10}^l \mathcal{O}_{10}^l + C_\nu \mathcal{O}_\nu\right)$,



$$\mathcal{O}_9^l = \frac{\alpha}{4\pi}\left(\bar{s}\gamma_\mu b_L\right)\left(\bar{l}\gamma_\mu l\right) ,$$

$$C_9^{SM} \sim -C_{10}^{SM} \sim 4.1$$

$$\mathcal{O}_{10}^l = \frac{\alpha}{4\pi}\left(\bar{s}\gamma_\mu b_L\right)\left(\bar{l}\gamma_\mu \gamma^5 l\right) ,$$

$$\mathcal{O}_\nu^{ij} = \frac{\alpha}{2\pi}\left(\bar{s}\gamma_\mu b_L\right)\left(\bar{\nu}^i\gamma_\mu \nu_L^j\right) .$$

New Physics

$$\mathcal{L}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left(C_9^l \mathcal{O}_9^l + C_{10}^l \mathcal{O}_{10}^l + C_T \mathcal{O}_T + C_S \mathcal{O}_S + \ldots \right) \, ,$$

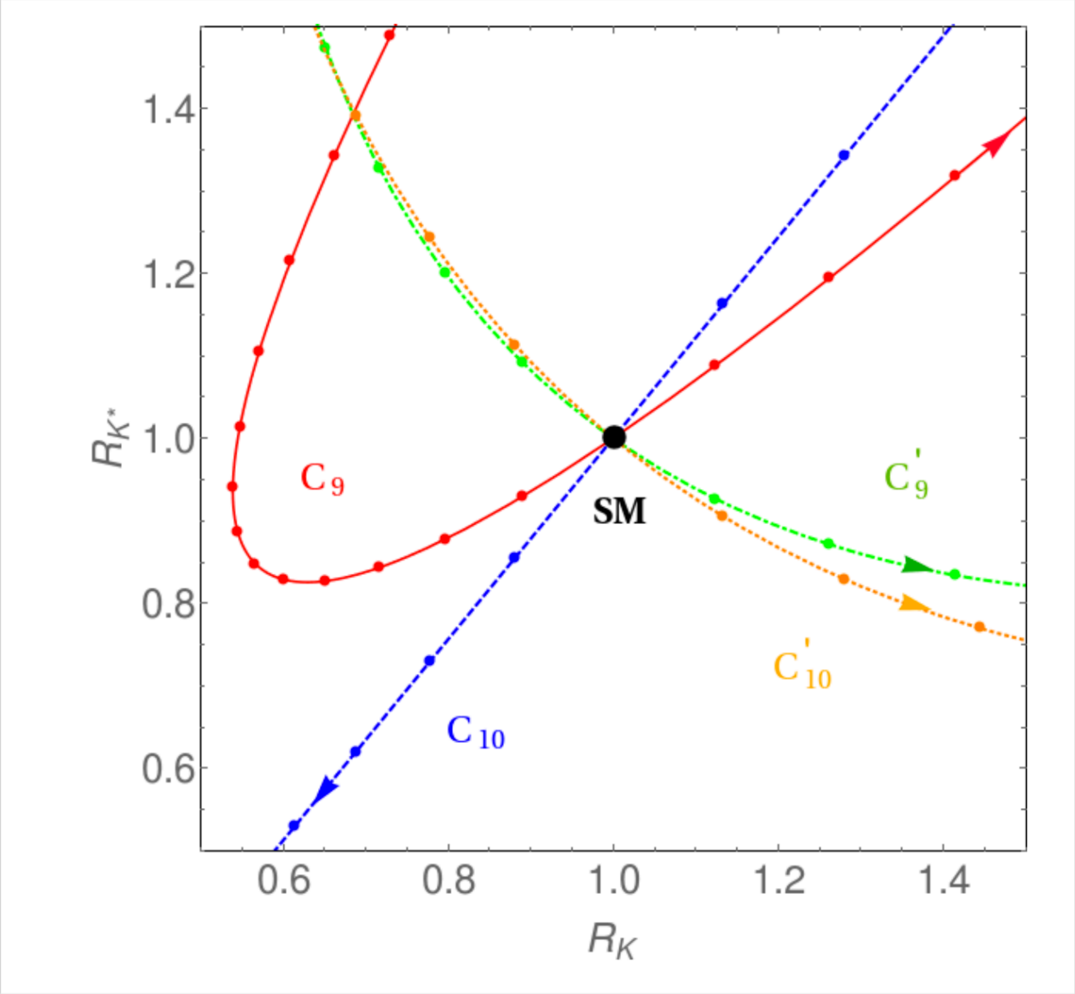
$$\mathcal{O}_9' = \frac{e^2}{(4\pi)^2} [\bar{s}\gamma_\mu P_R b][\bar{l}\gamma^\mu l], \;\; \mathcal{O}_{10}' = \frac{e^2}{(4\pi)^2} [\bar{s}\gamma_\mu P_R b][\bar{l}\gamma^\mu \gamma_5 l],$$

$$\mathcal{O}_S^{(\prime)} = \frac{e^2}{(4\pi)^2} [\bar{s} P_{R(L)} b][\bar{l} l], \;\; \mathcal{O}_P^{(\prime)} = \frac{e^2}{(4\pi)^2} [\bar{s} P_{R(L)} b][\bar{l}\gamma_5 l],$$

$$\mathcal{O}_T = \frac{e^2}{(4\pi)^2} [\bar{s}\sigma_{\mu\nu} b][\bar{l}\sigma^{\mu\nu} l], \;\; \mathcal{O}_{T5} = \frac{e^2}{(4\pi)^2} [\bar{s}\sigma_{\mu\nu} b][\bar{l}\sigma^{\mu\nu}\gamma_5 l].$$

Bobeth, Hiller, Piranishvili, ‘07

Fit results



Geng, Grinstein, Jager, Martin Camalich, Ren & Shi, 1704.05446

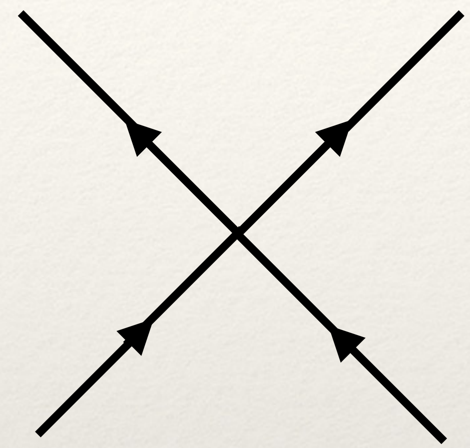
Coeff.	best fit	1σ	2σ	pull
C_9^μ	-1.59	$[-2.15, -1.13]$	$[-2.90, -0.73]$	4.2σ
C_{10}^μ	$+1.23$	$[+0.90, +1.60]$	$[+0.60, +2.04]$	4.3σ
C_9^e	$+1.58$	$[+1.17, +2.03]$	$[+0.79, +2.53]$	4.4σ
C_{10}^e	-1.30	$[-1.68, -0.95]$	$[-2.12, -0.64]$	4.4σ
$C_9^\mu = -C_{10}^\mu$	-0.64	$[-0.81, -0.48]$	$[-1.00, -0.32]$	4.2σ
$C_9^e = -C_{10}^e$	$+0.78$	$[+0.56, +1.02]$	$[+0.37, +1.31]$	4.3σ
$C_9'^\mu$	-0.00	$[-0.26, +0.25]$	$[-0.52, +0.51]$	0.0σ
$C_{10}'^\mu$	$+0.02$	$[-0.22, +0.26]$	$[-0.45, +0.49]$	0.1σ
$C_9'^e$	$+0.01$	$[-0.27, +0.31]$	$[-0.55, +0.62]$	0.0σ
$C_{10}'^e$	-0.03	$[-0.28, +0.22]$	$[-0.55, +0.46]$	0.1σ

Altmannshofer, Stangl & Straub, 1704.05435

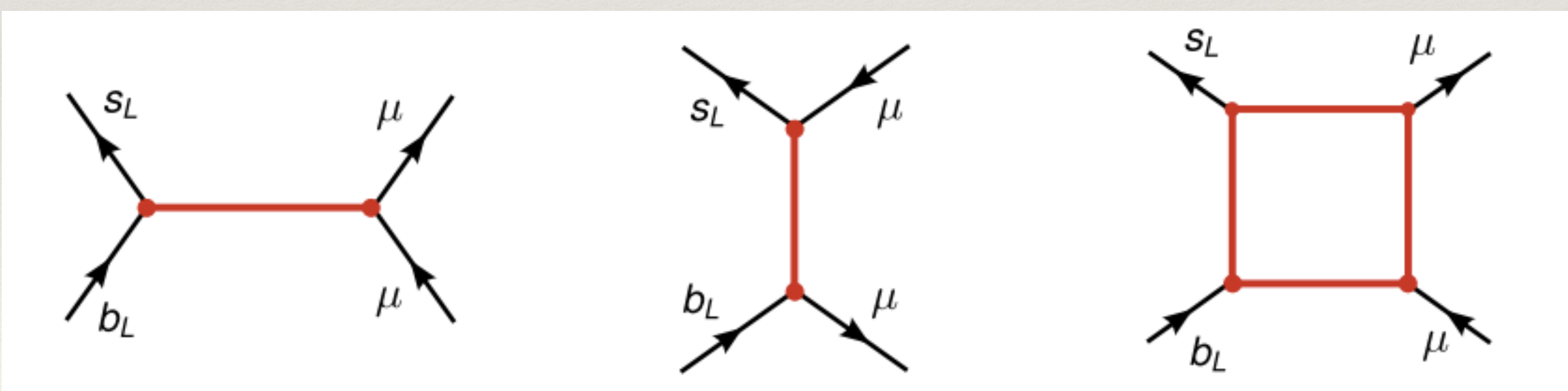
A left hand coupling in the quark sector is preferred

New Physics interpretations

$\bar{s}\gamma_\rho b_L$



$\bar{\mu}\gamma^\rho\mu$



Z' Lepto-quark Loop

Scale of new physics

W. Almannshofer, Talk at Aspen, Jan. 2016

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

Questions?

- Quark FCNC in the 2 heaviest families
- Lepton Non-Universal interaction in the lightest 2 generations
- If Z', better same coupling to first 2 families,
- Anomaly free?

Bunches of solutions

Flavored B-L

Only couple to third generation fermions

- Anomaly cancellation within one-generation
- Two Heavy right hand neutrinos still consistent with seesaw and leptogenesis
- No serious flavor changing neutral currents between first two generations
- B anomaly can be explained!

Couplings

Flavor eigenstate

$$T^q = \frac{1}{3}\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad T^l = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1 \end{pmatrix}$$

Into mass eigenstate(we only assume left-hand mixing here)

$$T_{d_L} = U^\dagger_{d_L} T^q U_{d_L} = \frac{1}{3}\begin{pmatrix} 0 & 0 & 0 \\ 0 & s^2_{\theta_q} & \boxed{-s_{\theta_q} c_{\theta_q}} \\ 0 & -s_{\theta_q} c_{\theta_q} & c^2_{\theta_q} \end{pmatrix}$$

$$T_{e_L} = U^\dagger_{e_L} T^l U_{e_L} = -1\begin{pmatrix} 0 & 0 & 0 \\ 0 & \boxed{s^2_{\theta_l}} & -s_{\theta_l} c_{\theta_l} \\ 0 & -s_{\theta_l} c_{\theta_l} & c^2_{\theta_l} \end{pmatrix}$$

- To explain the B anomaly, we need opposite sign coupling with b-s and mu-mu, $\theta_q < 0$
- If assuming $U_{d_L} = V_{CKM}$, it will give wrong sign!

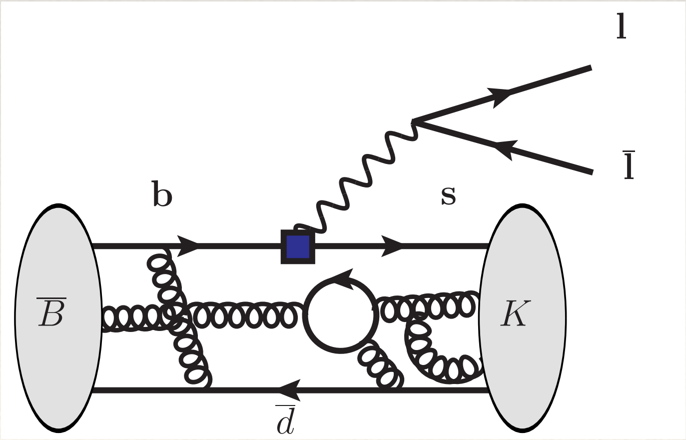
LOW ENERGY Phenomenology

$$S = \int d^4x \left\{ \frac{1}{2} Z_h^\mu \left(\partial^2 + M^2\right) Z_{h,\mu} - g_h Z_h^\mu J_\mu^h \right\}$$

$$\overset{\text{On-shell } Z_h}{=} \int d^4x \left(-\frac{1}{2} \frac{g_h^2 J_h^2}{M^2} + \mathcal{O}\left(\partial^2/M^2\right) \right)$$

LFU violation process

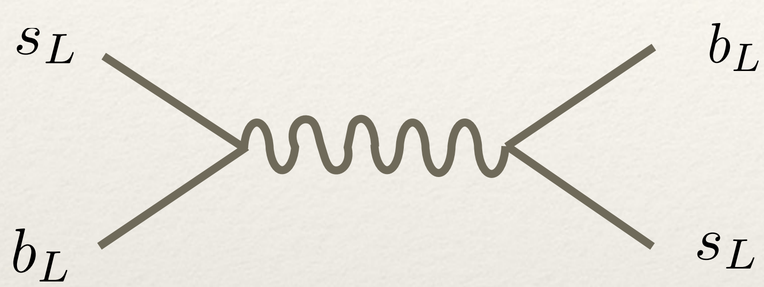
$$\mathcal{L} = -\frac{g^2 s_{\theta_q} c_{\theta_q} s_{\theta_l}^2}{3M^2} (\bar{s}\gamma^\rho b_L)(\bar{\mu}\gamma_\rho \mu_L)\,,$$



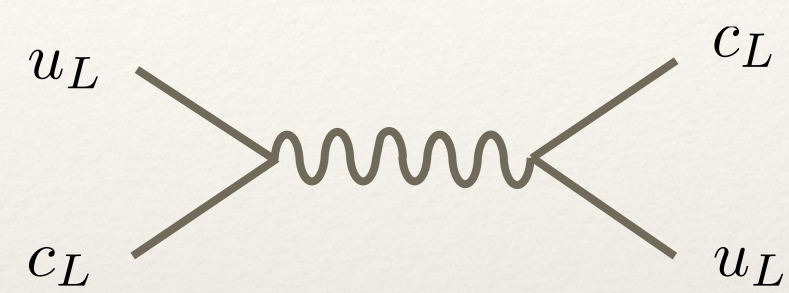
$$\delta C_9^\mu = -\delta C_{10}^\mu = -\frac{\pi}{\alpha\sqrt{2} G_F V_{tb} V_{ts}^*} \frac{g^2 s_{\theta_q} c_{\theta_q} s_{\theta_l}^2}{3M^2}$$

Constraints

$B_s - \bar{B}_s$ mixing

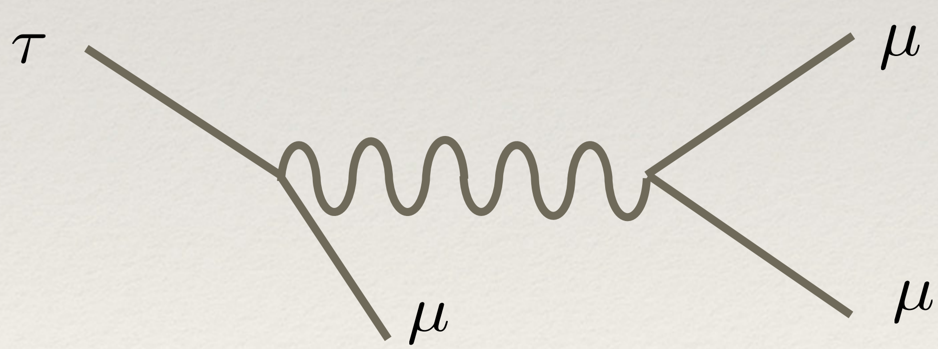


$D^0 - \bar{D}^0$ mixing



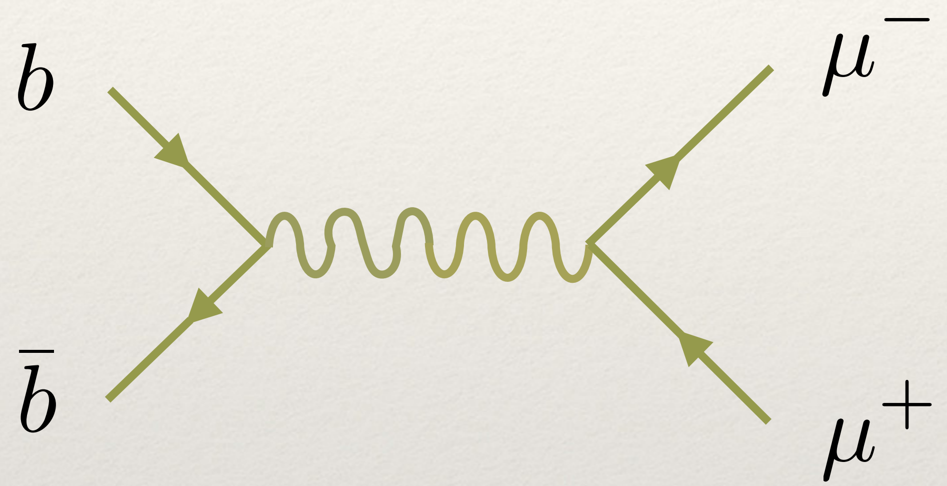
$$\mathcal{L} = -\frac{g^2 s_{\theta_q}^2 c_{\theta_q}^2}{18M^2} (\bar{s}\gamma^\mu b_L)^2 - \frac{g^2 c_D^2}{18M^2} (\bar{u}\gamma^\mu c_L)^2 \qquad c_D \equiv \left(V_{ub}\, c_{\theta_q} - V_{us}\, s_{\theta_q}\right)\left(V_{cb}^*\, c_{\theta_q} - V_{cs}^*\, s_{\theta_q}\right)$$

$\tau - \mu$ cLFV

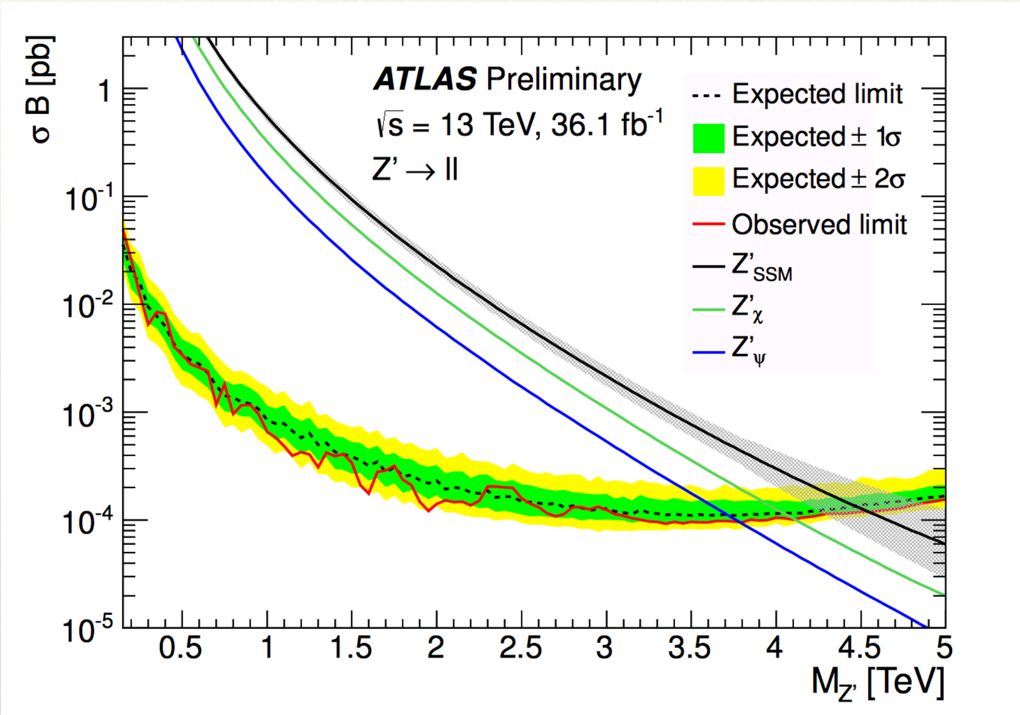


$$\mathcal{L}_{\rm LFV} = \frac{g^2}{M^2} s_{\theta_l}^3 c_{\theta_l}\, \bar{\tau}\gamma^\rho \mu_L\, \bar{\mu}\gamma_\rho \mu_L$$

LHC dimuon resonance search



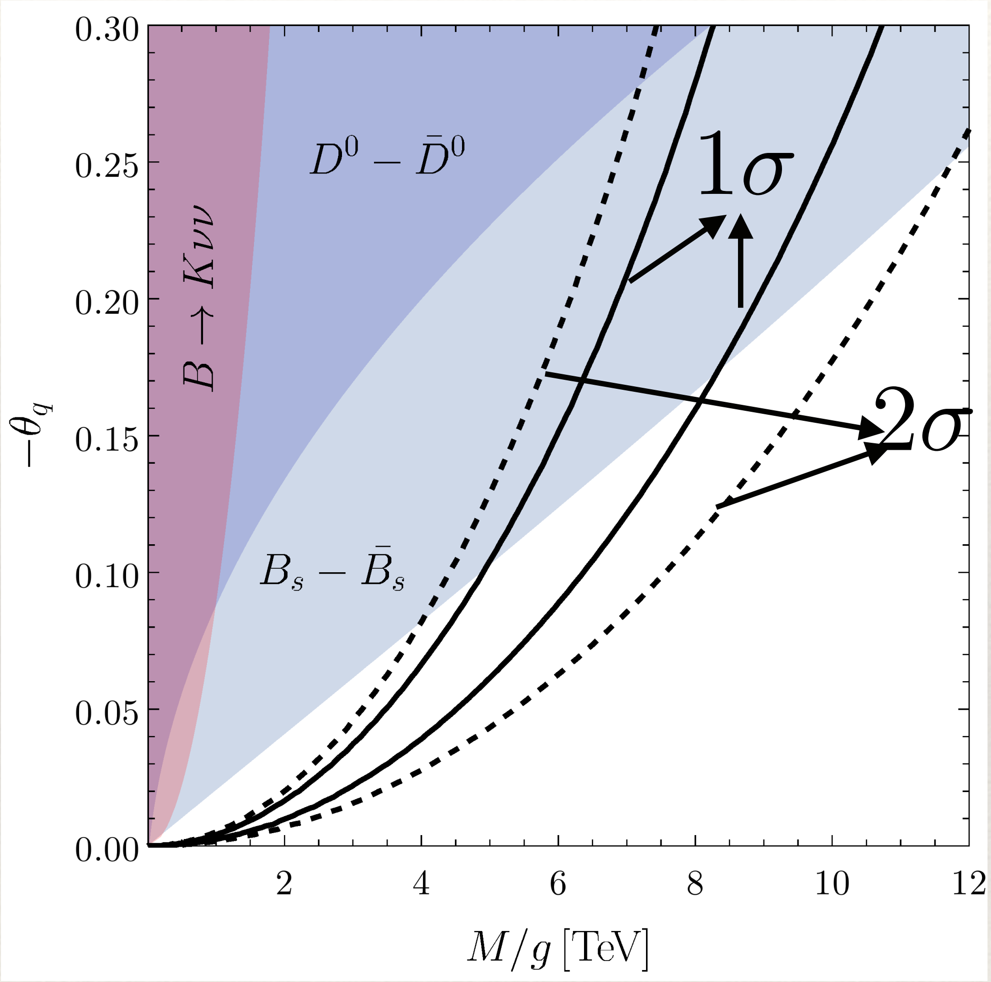
ATLAS-CONF-2017-027

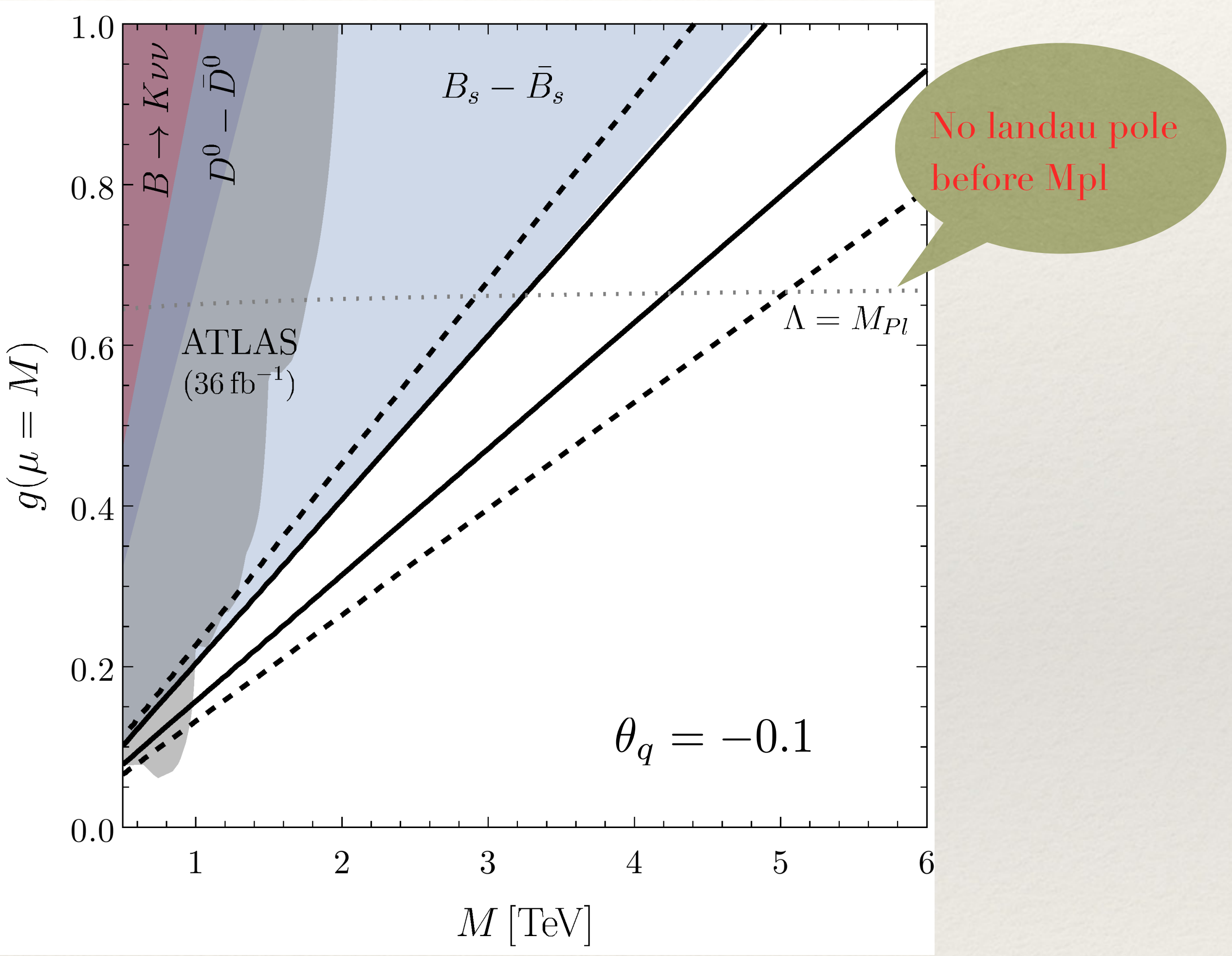


No light quark(u,d) coupling, limit could be much weaker

Favored parameter space

$\theta_l = \frac{\pi}{2}$ is assumed





- Z prime mass around few TeV
- LHC limit less than 2 TeV, could extend in the future to probe the z prime

Summary

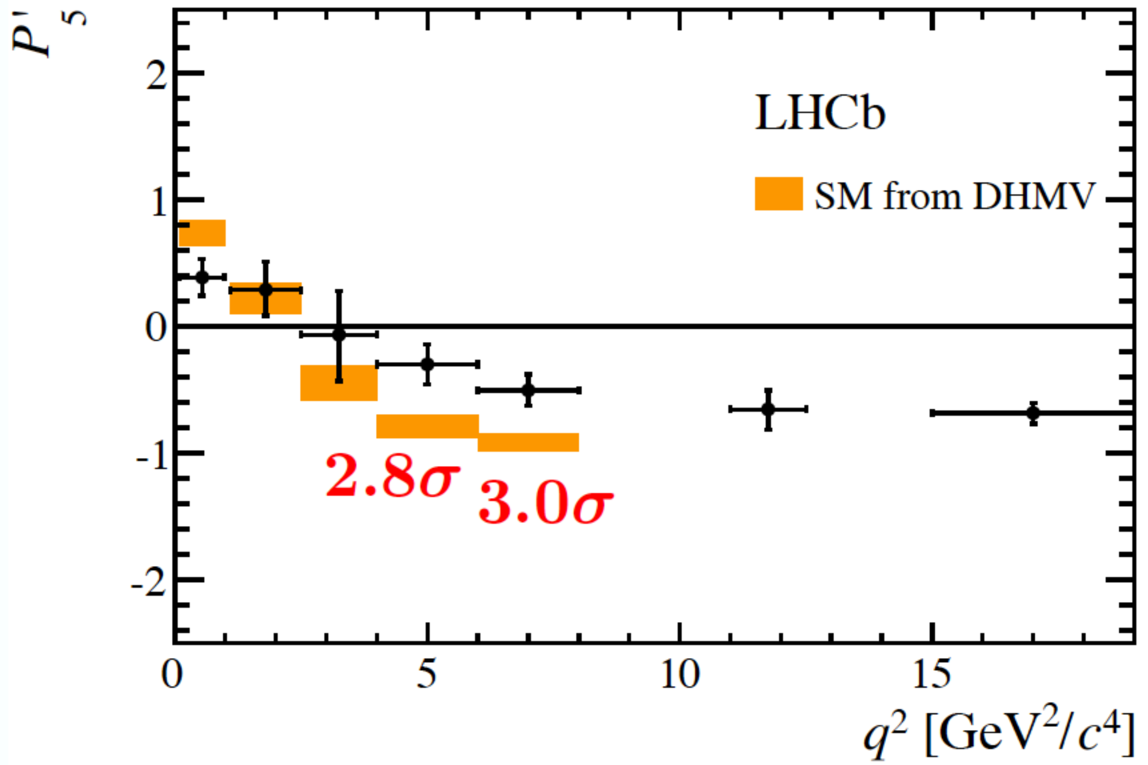
- B anomaly may indicate a new gauge sector beyond SM
- This new gauge boson may also play the role of mediator of dark matter(see Peter Cox's talk)
- Let us wait and see!

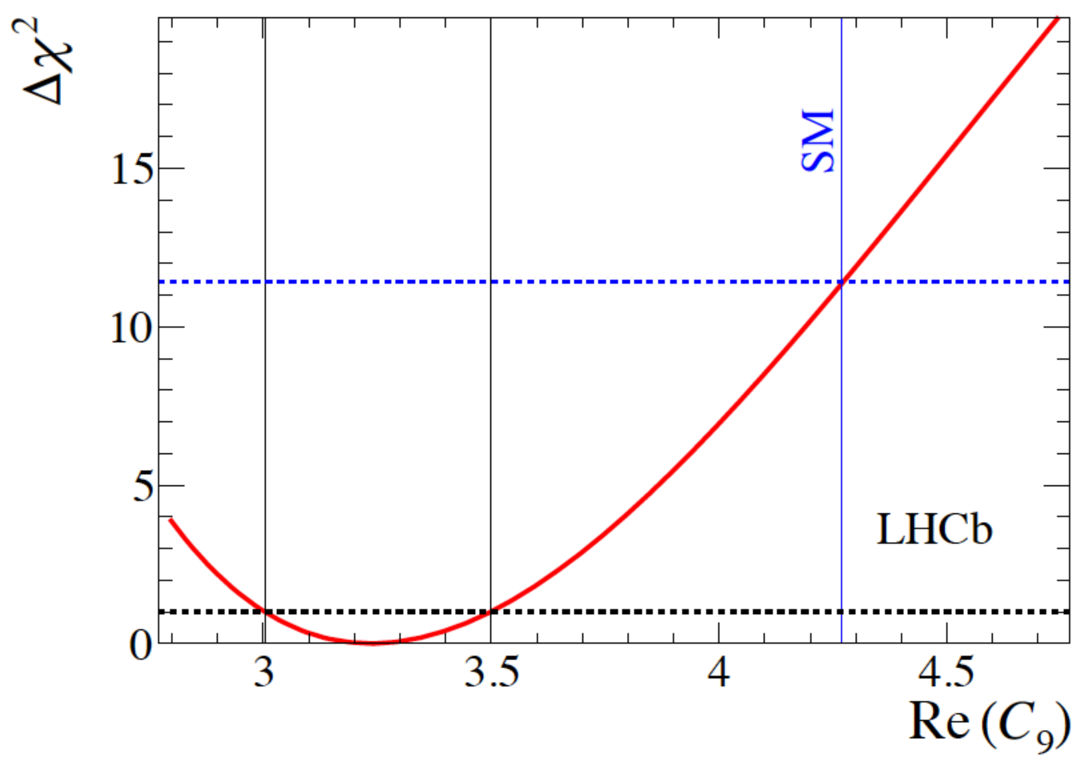
Back up

- In 2013, LHCb [1 fb-1] observed a 3.7 sigma discrepancy between the data and the SM in one bin for P5'.
- In 2015, LHCb [3 fb-1] confirmed it with a 3 sigma deviation in each of two bins.
- LHCb also observed a systematic deficit with respect to the SM predictions for the BRs of several decays, such as $B_s \to \phi\mu\mu$.
- In 2016, Belle confirmed the P5' anomaly.
- Recent ATLAS and CMS data show a good overall agreement with the LHCb results.

Anomaly?

LHCb, 1512.04442





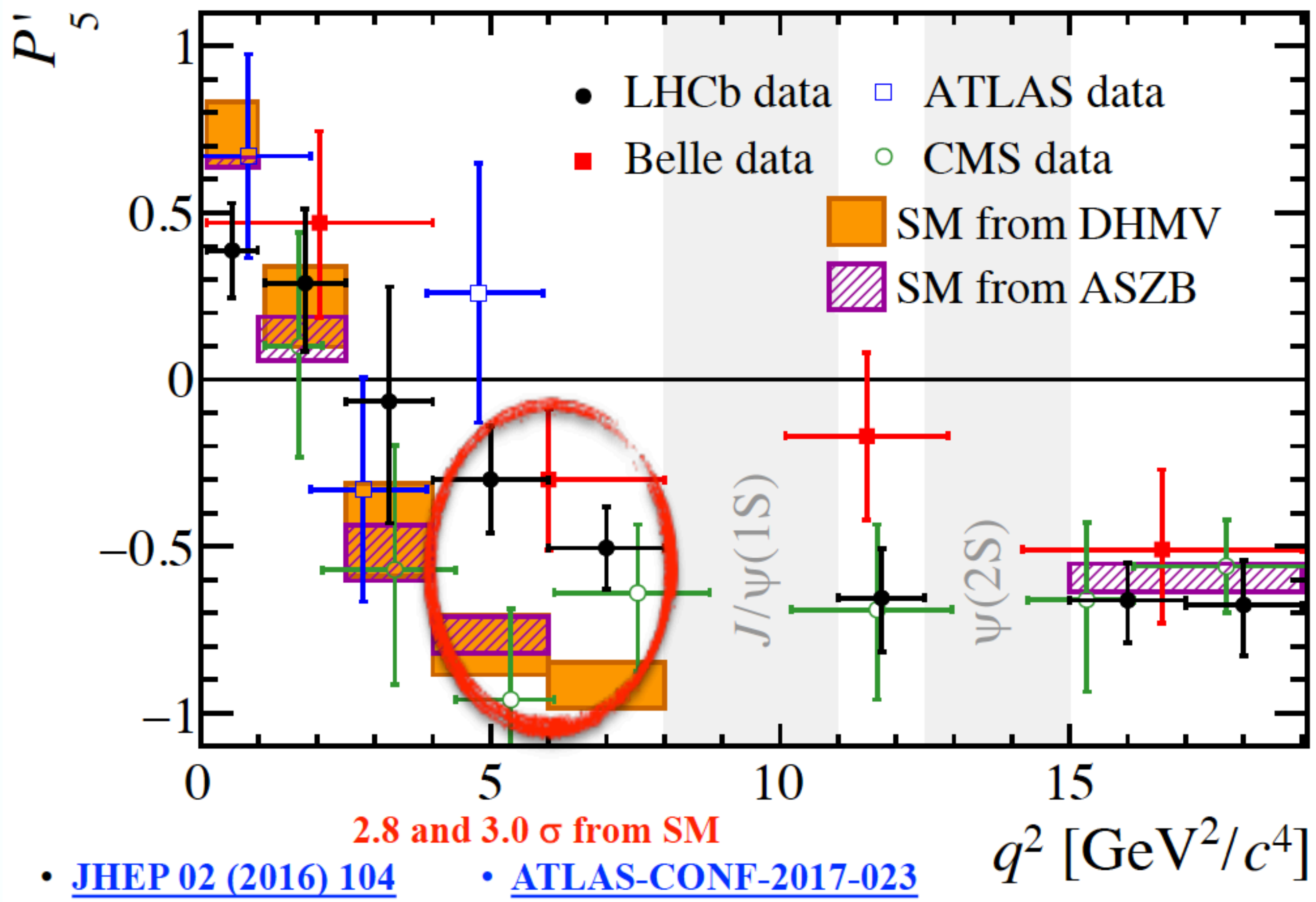
DHMV = Descotes-Genon, Hofer, Matias & Virto (2014)

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

$$C_9^{\rm NP} < 0$$

$$|C_9^{\rm NP}/C_9^{\rm SM}| \sim 25\,\%$$

P5' anomaly in $B \to K^* \mu^+ \mu^-$



2.8 and 3.0 σ from SM

- JHEP 02 (2016) 104
- PRL 118 (2017)
- ATLAS-CONF-2017-023
- CMS-PAS-BPH-15-008

Patterns of NP in $R_{K^{(*)}}$

- $B \to K\ell\ell$

$$\frac{d\Gamma_K}{dq^2} = \mathcal{N}_K |\vec{k}|^3 f_+(q^2)^2 \left(\left|C_{10}^\ell + C_{10}'^\ell\right|^2 + \left|C_9^\ell + C_9'^\ell + 2\frac{m_b}{m_B + m_K} C_7 \frac{f_T(q^2)}{f_+(q^2)} - 8\pi^2 h_K\right|^2 \right)$$

$$+ \mathcal{O}\left(\frac{m_\ell^4}{q^4}\right) + \frac{m_\ell^2}{m_B^2} \times O\left(\alpha_s, \frac{q^2}{m_B^2} \times \frac{\Lambda}{m_b}\right),$$

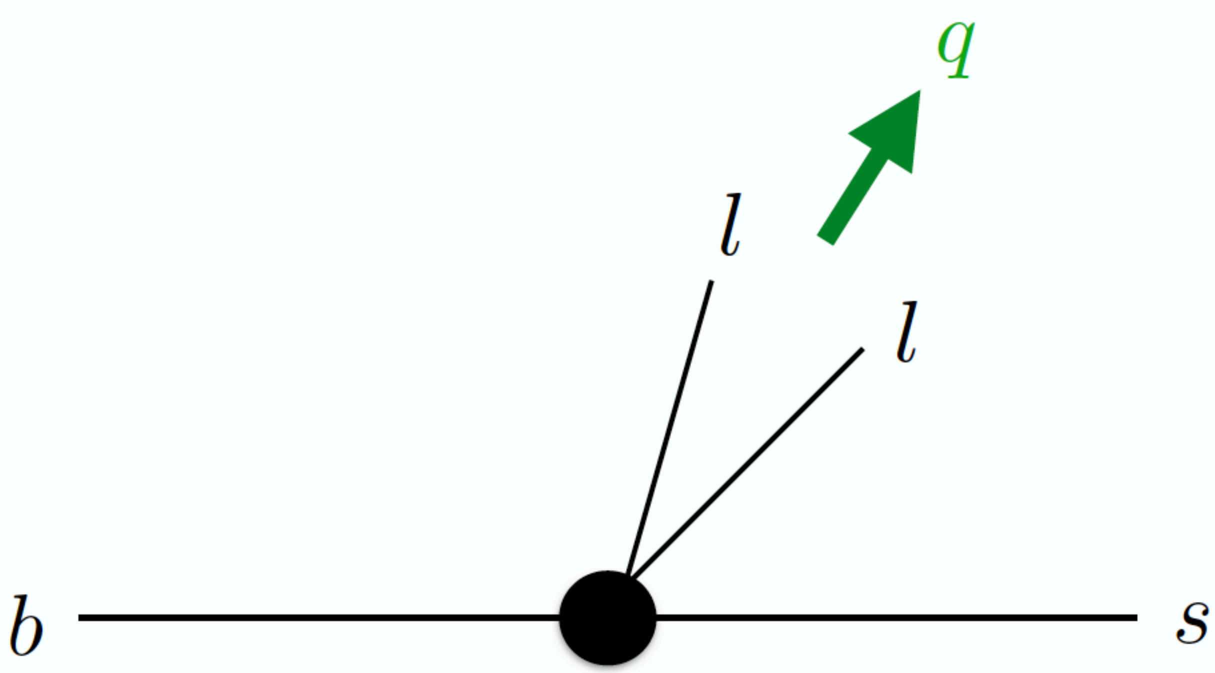
f_i, V_i, T_i : form factors
h_i : hadronic contributions

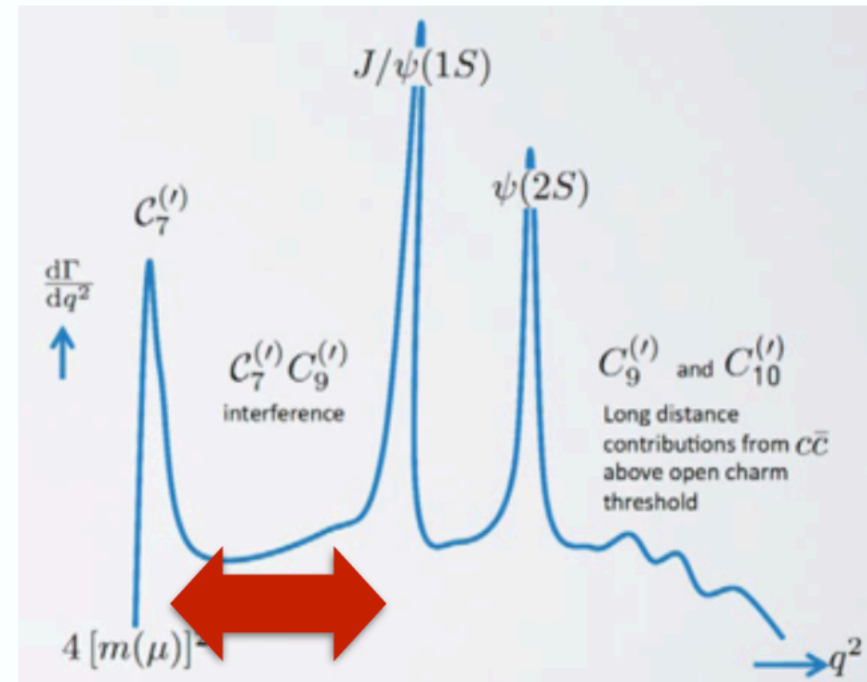
- $B \to K^*\ell\ell$ $\quad \frac{d\Gamma_{\bar{K}^*}}{dq^2} = \frac{d\Gamma_\perp}{dq^2} + \frac{d\Gamma_0}{dq^2}$

$$\frac{d\Gamma_0}{dq^2} = \mathcal{N}_{K^*0} |\vec{k}|^3 V_0(q^2)^2 \left(\left|C_{10}^\ell - C_{10}'^\ell\right|^2 + \left|C_9^\ell - C_9'^\ell + \frac{2m_b}{m_B} C_7 \frac{T_0(q^2)}{V_0(q^2)} - 8\pi^2 h_{K^*0}\right|^2 \right) + \mathcal{O}\left(\frac{m_\ell^2}{q^2}\right),$$

$$\frac{d\Gamma_\perp}{dq^2} = \mathcal{N}_{K^*\perp} |\vec{k}| q^2 V_-(q^2)^2 \left(\left|C_{10}^\ell\right|^2 + \left|C_9'^\ell\right|^2 + \left|C_{10}'^\ell\right|^2 + \left|C_9^\ell + \frac{2m_b m_B}{q^2} C_7 \frac{T_-(q^2)}{V_-(q^2)} - 8\pi^2 h_{K^*\perp}\right|^2 \right) + \mathcal{O}\left(\frac{m_\ell^2}{q^2}\right) + \mathcal{O}\left(\frac{\Lambda}{m_b}\right)$$

Recently many papers on the *b to s ll* processes appear on arXiv.





Lepton universality in $B^+ \to K^+ l^+ l^- \ (l = e,\ \mu)$ *(1406.6482)*

Angular analysis of $B_0 \to K_0^* \mu^+ \mu^-$ *(1308.1707; 1512.04442)*

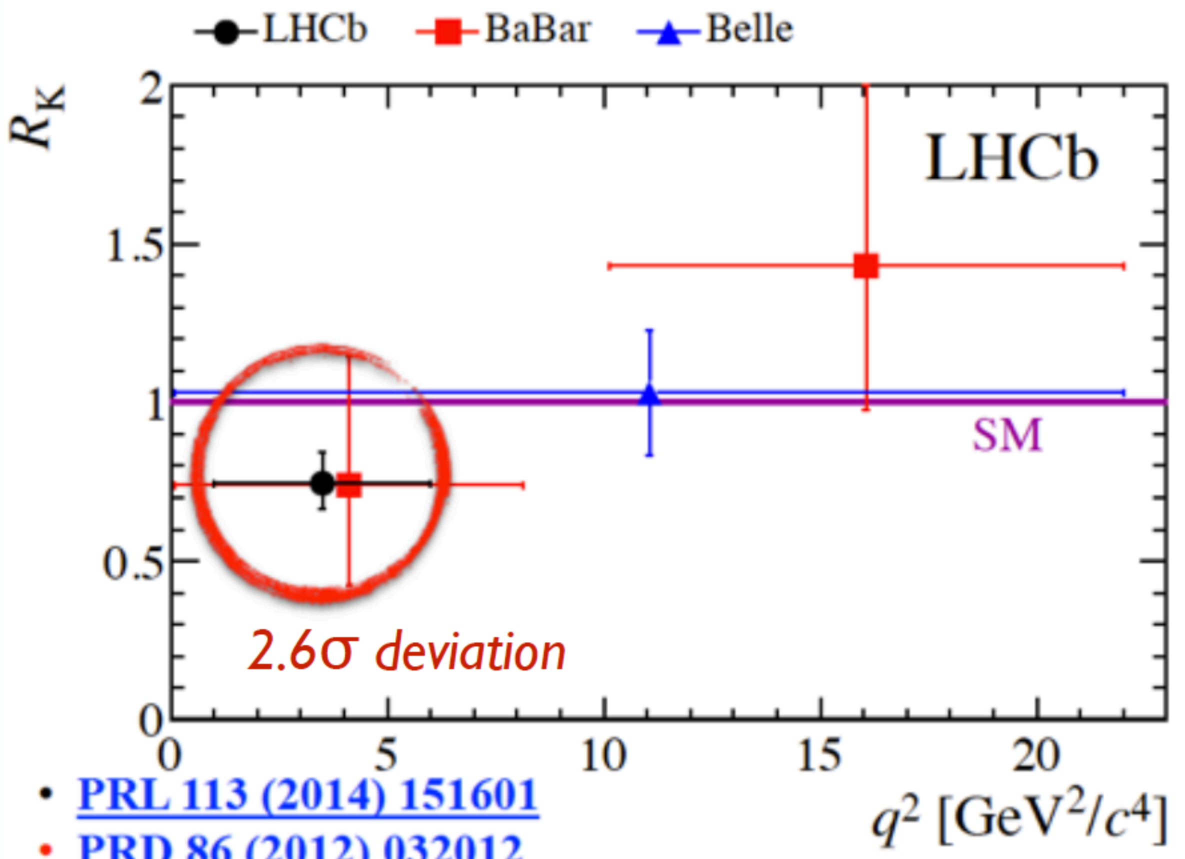
Lepton universality in $B_0 \to K_0^* l^+ l^- \ (l = e,\ \mu)$

(Talk by Bifani@CERN, 2017.4.18)

Lepton universality in $B^+ \to K^+ l^+ l^- \;(l = e,\, \mu)$ (1406.6482)

observable

$$R_K = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma[B^+ \to K^+\mu^+\mu^-]}{dq^2} dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma[B^+ \to K^+e^+e^-]}{dq^2} dq^2}$$



- PRL 113 (2014) 151601
- PRD 86 (2012) 032012
- PRL 103 (2009) 171801

- B→K ee looks consistent (Hiller, Schmaltz 1408.1627; LHCb, 1406.6482)

$$\mathcal{B}(\bar{B} \to \bar{K}ee)^{LHCb} = (1.56^{+0.19+0.06}_{-0.15-0.04}) \cdot 10^{-7},$$

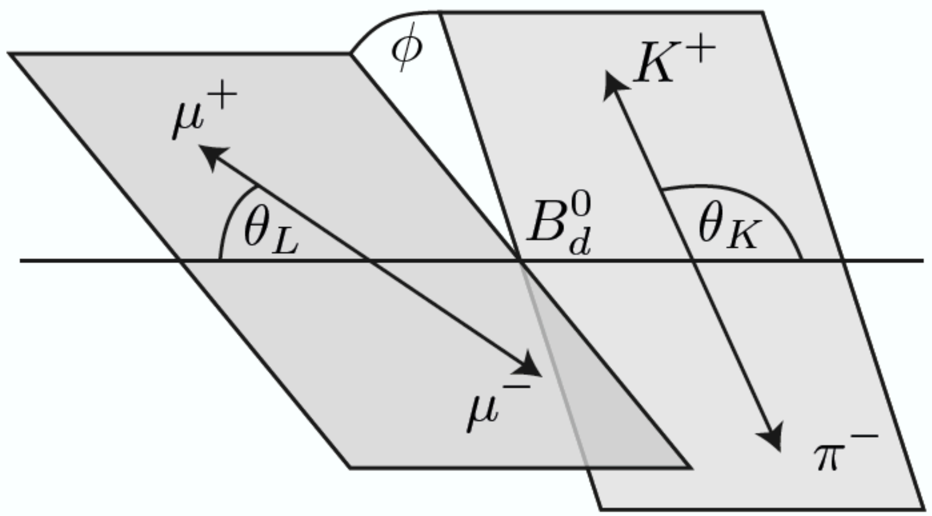
$$\mathcal{B}(\bar{B} \to \bar{K}ee)^{\rm SM} = (1.75^{+0.60}_{-0.29}) \cdot 10^{-7},$$

$$\frac{\mathcal{B}(\bar{B} \to \bar{K}ee)^{LHCb}}{\mathcal{B}(\bar{B} \to \bar{K}ee)^{\rm SM}} = 0.83 \pm 0.21\,.$$

with $1\,\mathrm{GeV}^2 \le q^2 < 6\,\mathrm{GeV}^2$

Angular analysis of $B_0 \to K_0^* \mu^+ \mu^-$

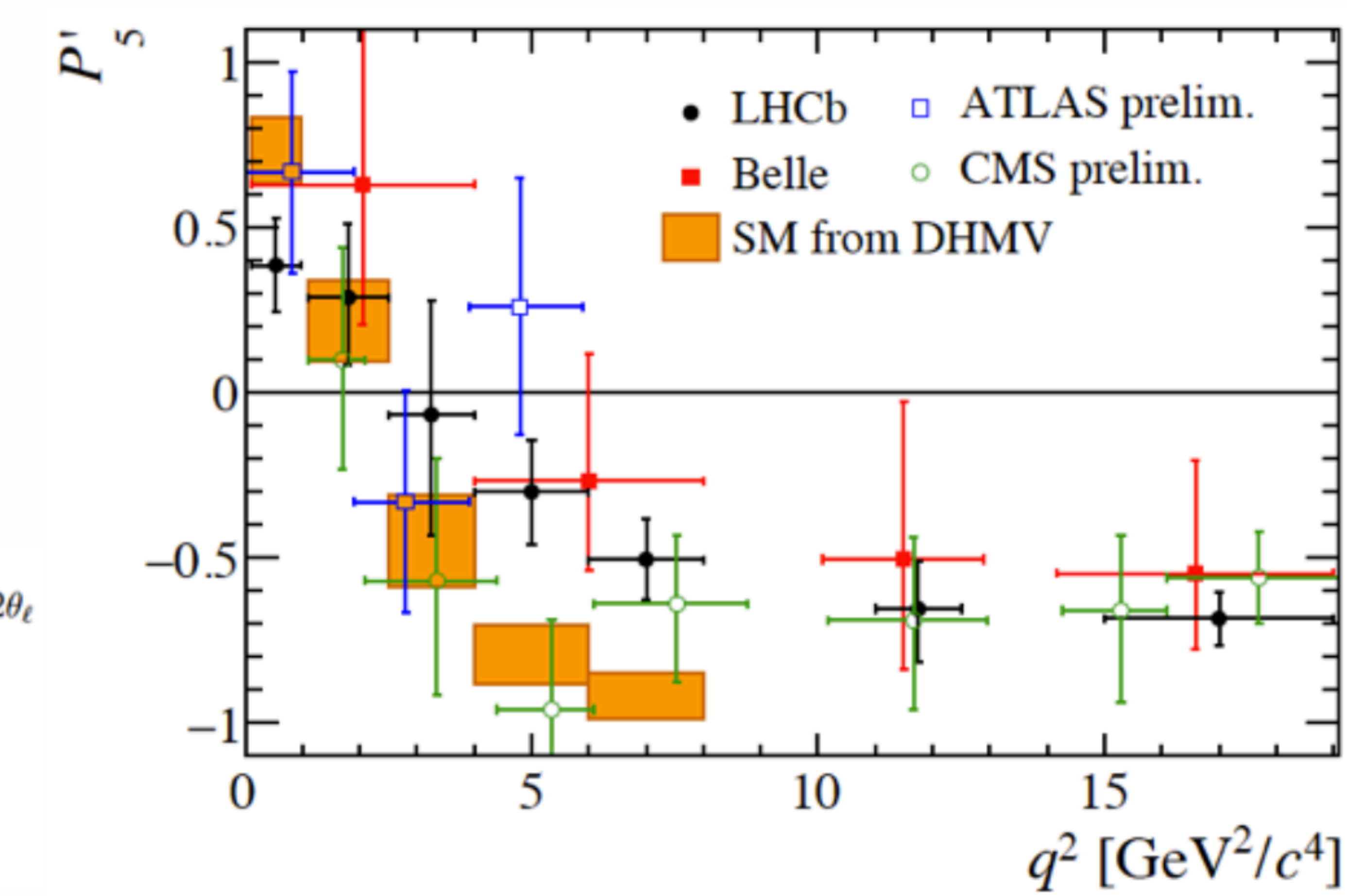
(1308.1707; 1512.04442 ;ATLAS-CONF-2017-023;CMS-PAS-BPH-15-008)



$$\frac{1}{\mathrm{d}\Gamma/dq^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2}$$

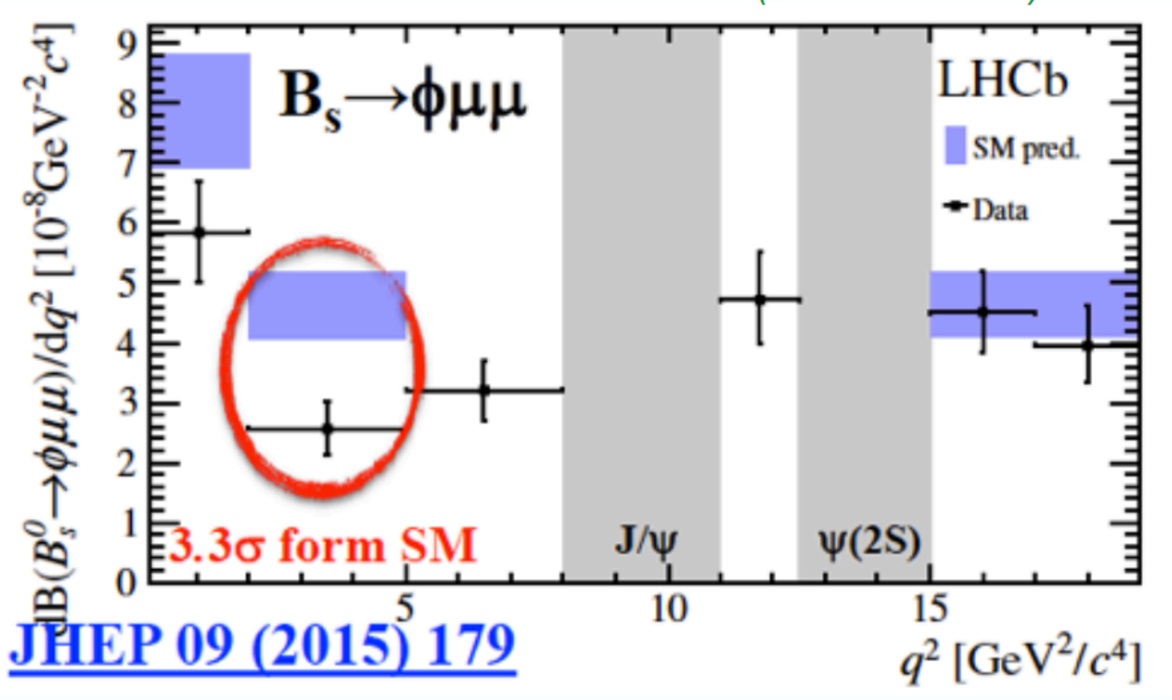
$$\begin{aligned}=\frac{9}{32\pi}\Big[&\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K+F_\mathrm{L}\cos^2\theta_K+\frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell\\&-F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell+S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi\\&+S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi+S_5\sin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

(Blake,Gersabeck, et al., 1703.10005)



Branching ratio of $B_s \to \phi\mu^+\mu^-$

(1506.08777)



Branching ratio of $\Lambda_b^0 \to \Lambda\mu^+\mu^-$

(1503.07138)