A light dimuon resonance in B decays?

based on FS Straub 1704.06188

Filippo Sala

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Why new light (vector) bosons?

Dark Matter exists   Widely believed to be a new particle

A legitimate attitude:

Our sector (SM) is very involved, why should the dark sector be so simple?

Example

New force in the dark sector   New dark gauge boson(s), that can be light

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Various **Extensions of the SM** predict new (possibly light) vector bosons

Supersymmetric "U-boson" Fayet 1976, …

Gauging $U(1)_{B-L}$, $U(1)_{L_\mu - L_\tau}$ … Langacker 1981, He+1991,…

Gauging flavour (sub)group Froggatt Nielsen 1978,…. Grinstein+ 1009.2049

Twin Higgs/mirror world Chacko+ hep-ph/0506256

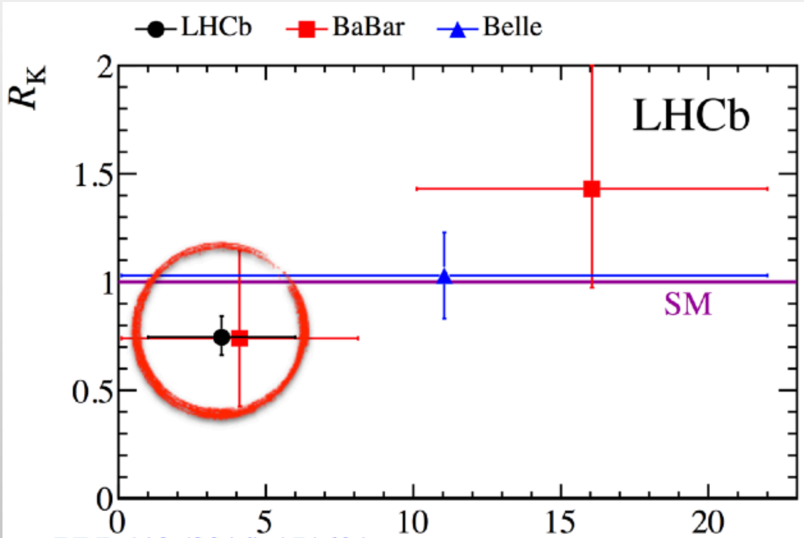
……….

Anomalies in $b \to s\mu\mu$?

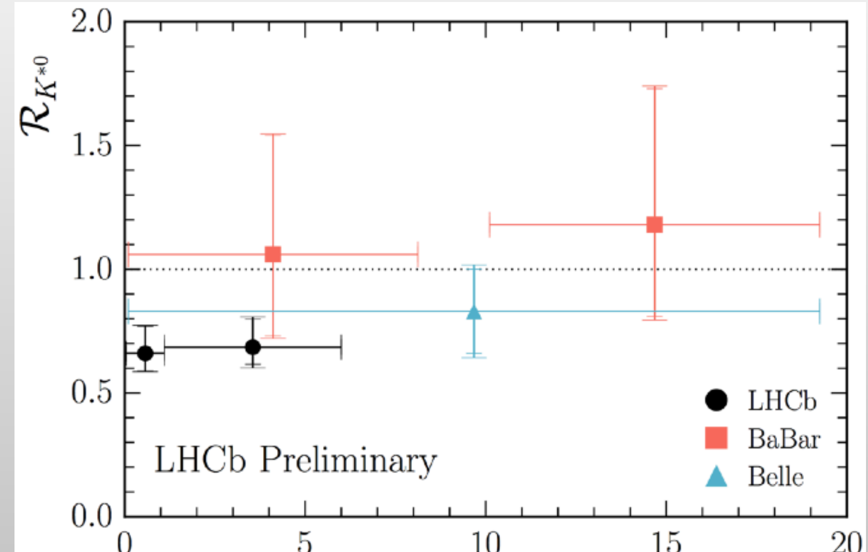
$q^2 = m^2_{\mu\mu}$

$$R_K(q^2_{\rm min}, q^2_{\rm max}) = \left.\frac{{\rm BR}(B^+ \to K^+\mu\mu)}{{\rm BR}(B^+ \to K^+ ee)}\right|_{[q^2_{\rm min}, q^2_{\rm max}]}$$

$$R_{K^*}(q^2_{\rm min}, q^2_{\rm max}) = \left.\frac{{\rm BR}(B \to K^{*0}\mu\mu)}{{\rm BR}(B \to K^{*0} ee)}\right|_{[q^2_{\rm min}, q^2_{\rm max}]}$$



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



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SM prediction

1 $q^2 \in [1, 6]{\rm GeV}^2$

~ **0.91** $[0.045, 1]$ ${\rm GeV}^2$

Bordone Isidori Pattori 1605.07633

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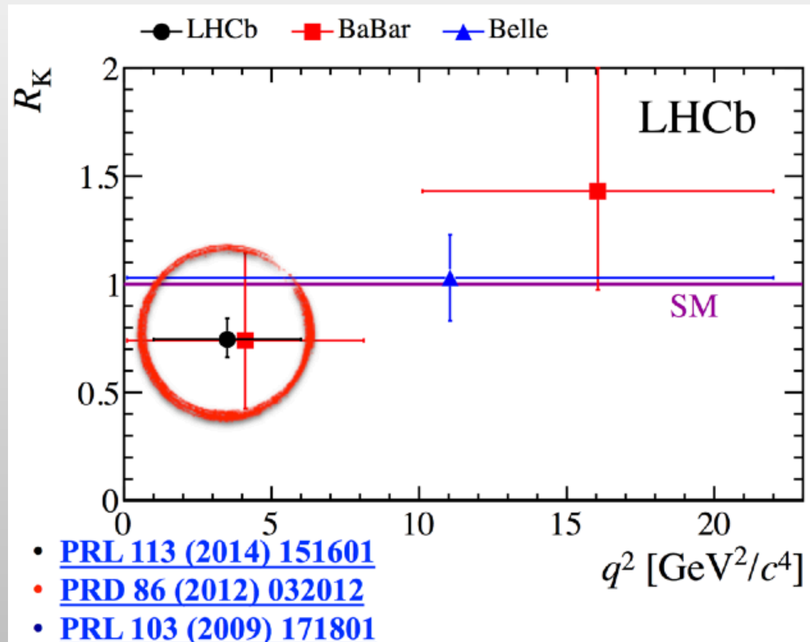

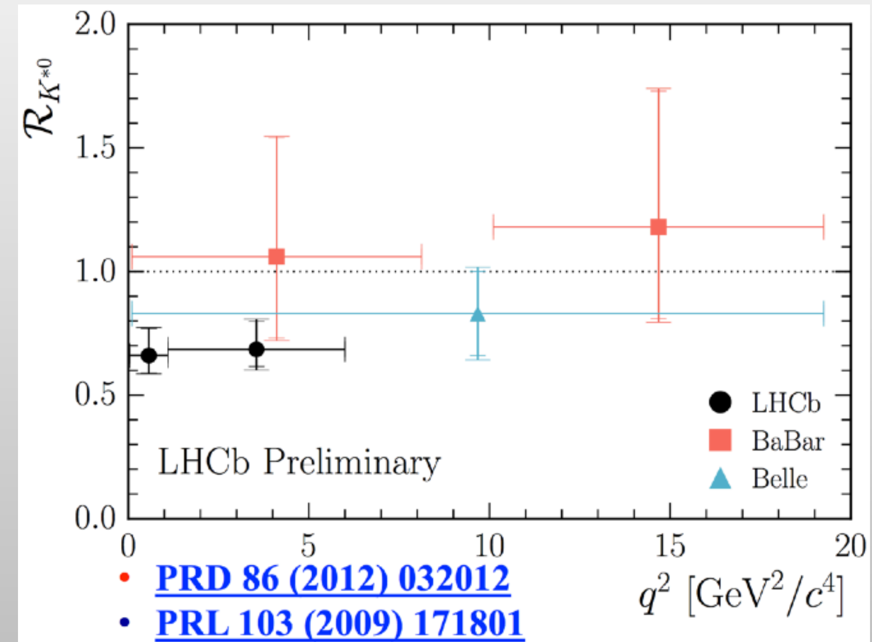

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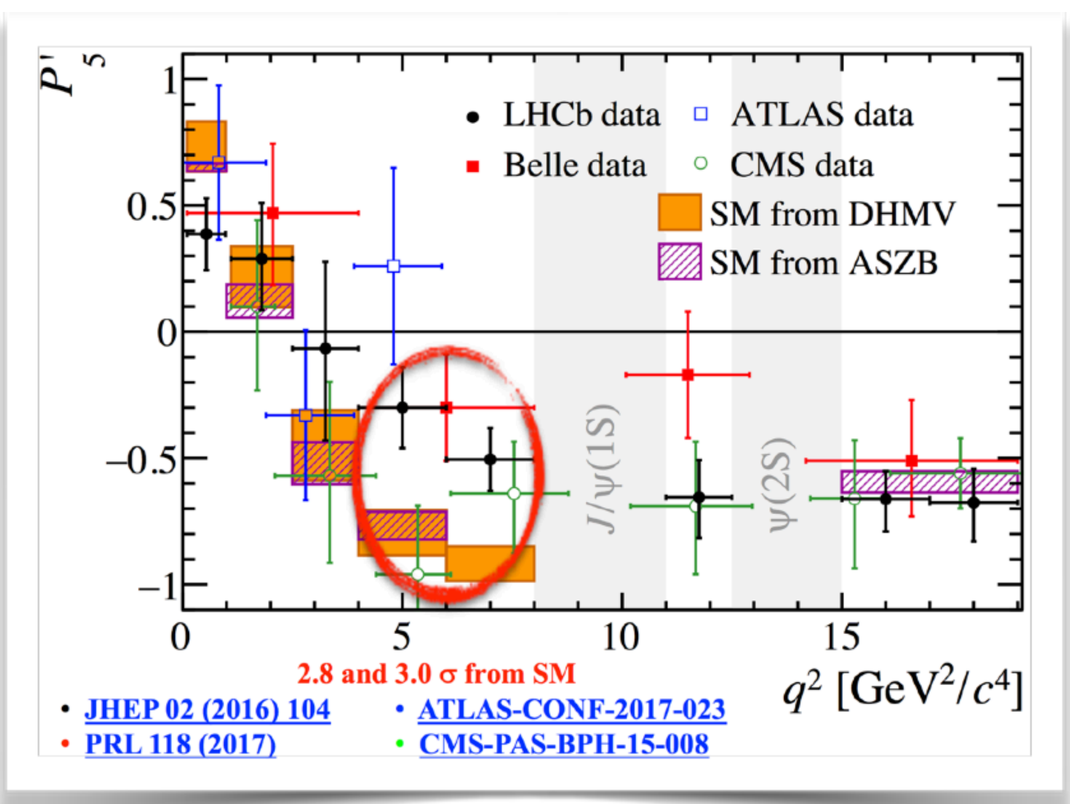
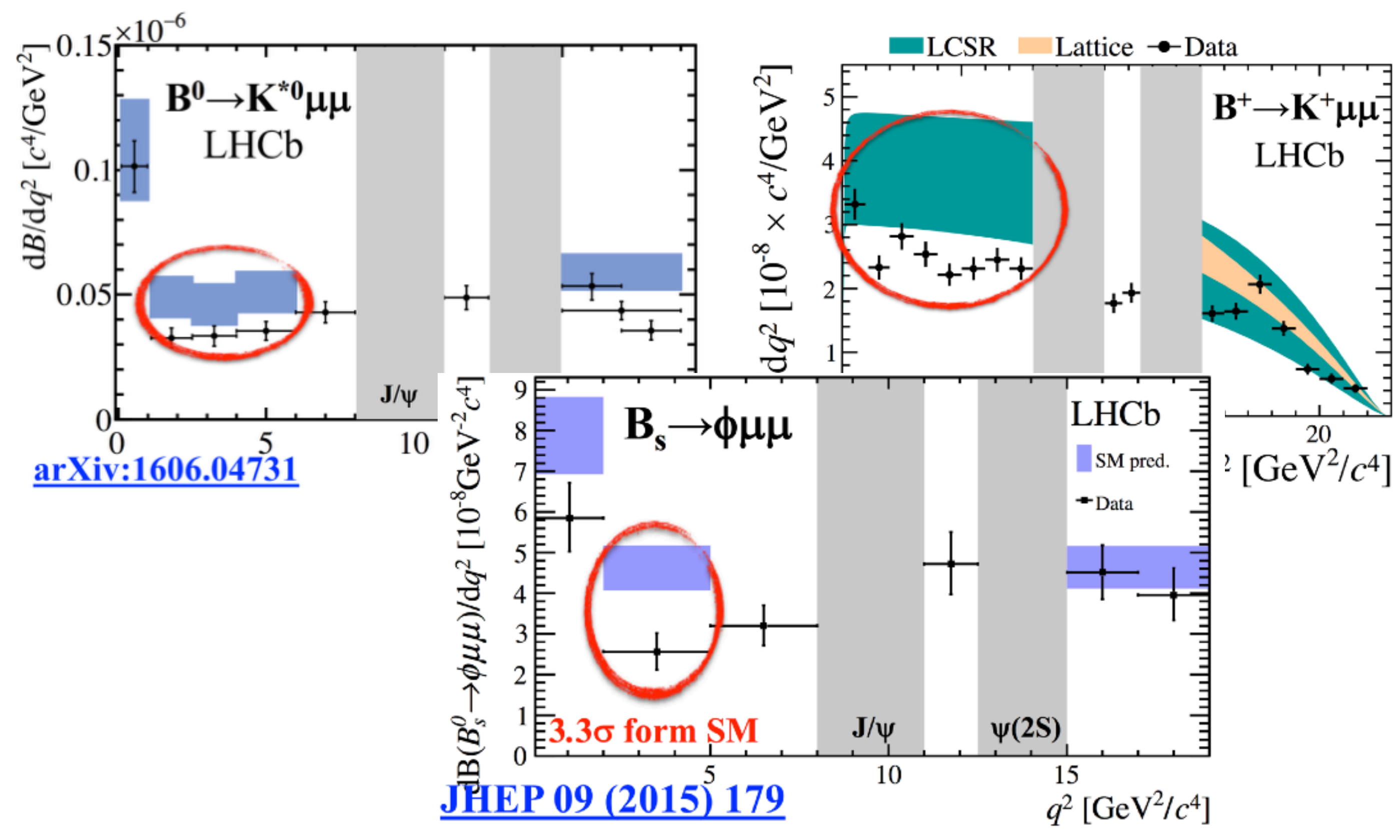




Let us assume (part of) this is New Physics

"Heavy" New Physics

$$\mathcal{H} = -N \sum_i C_i \mathcal{O}_i \qquad N = \frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha}{\pi}$$

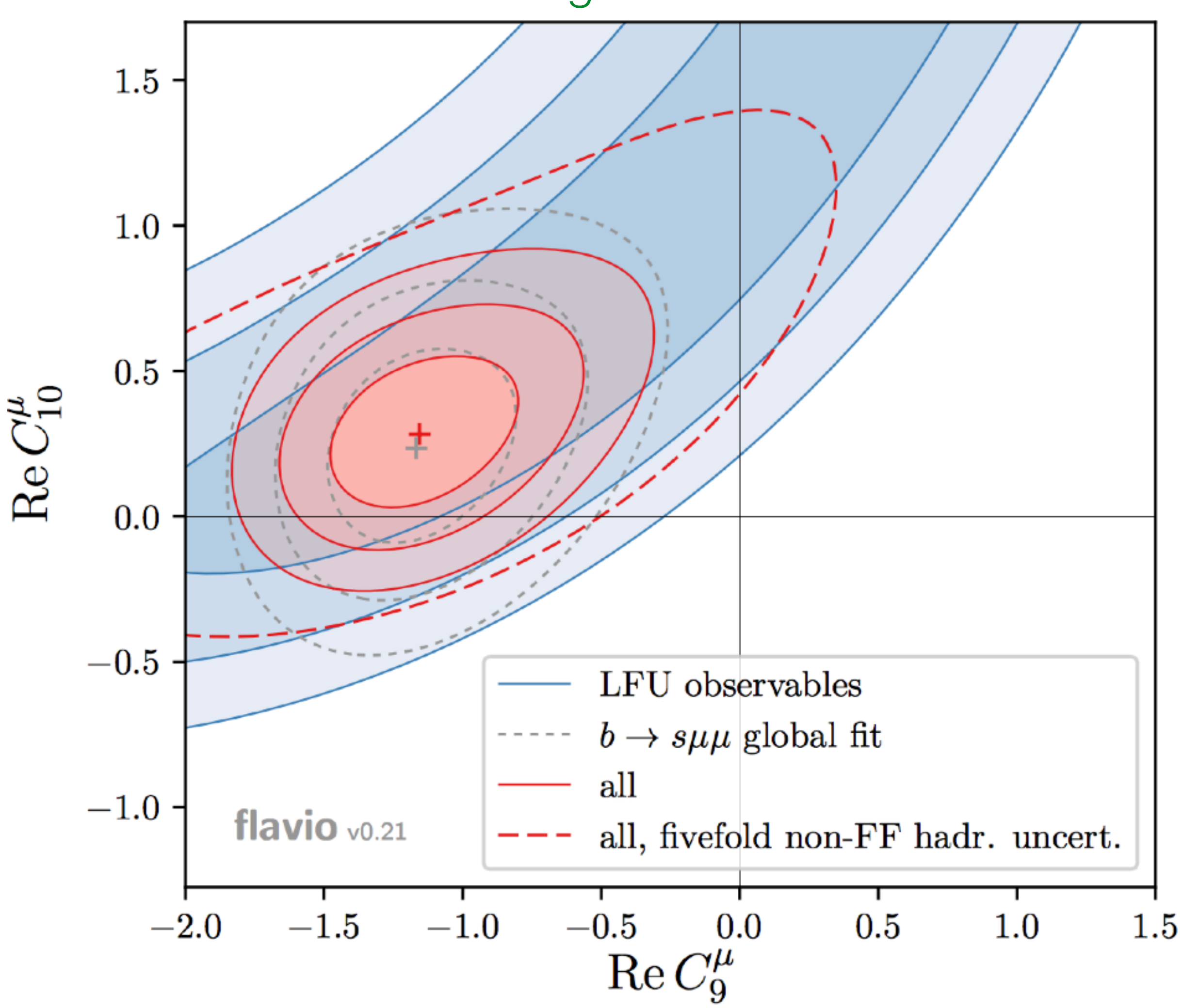
Works for $C_9^{\rm NP} \approx -1$

compatibly with all other bounds!

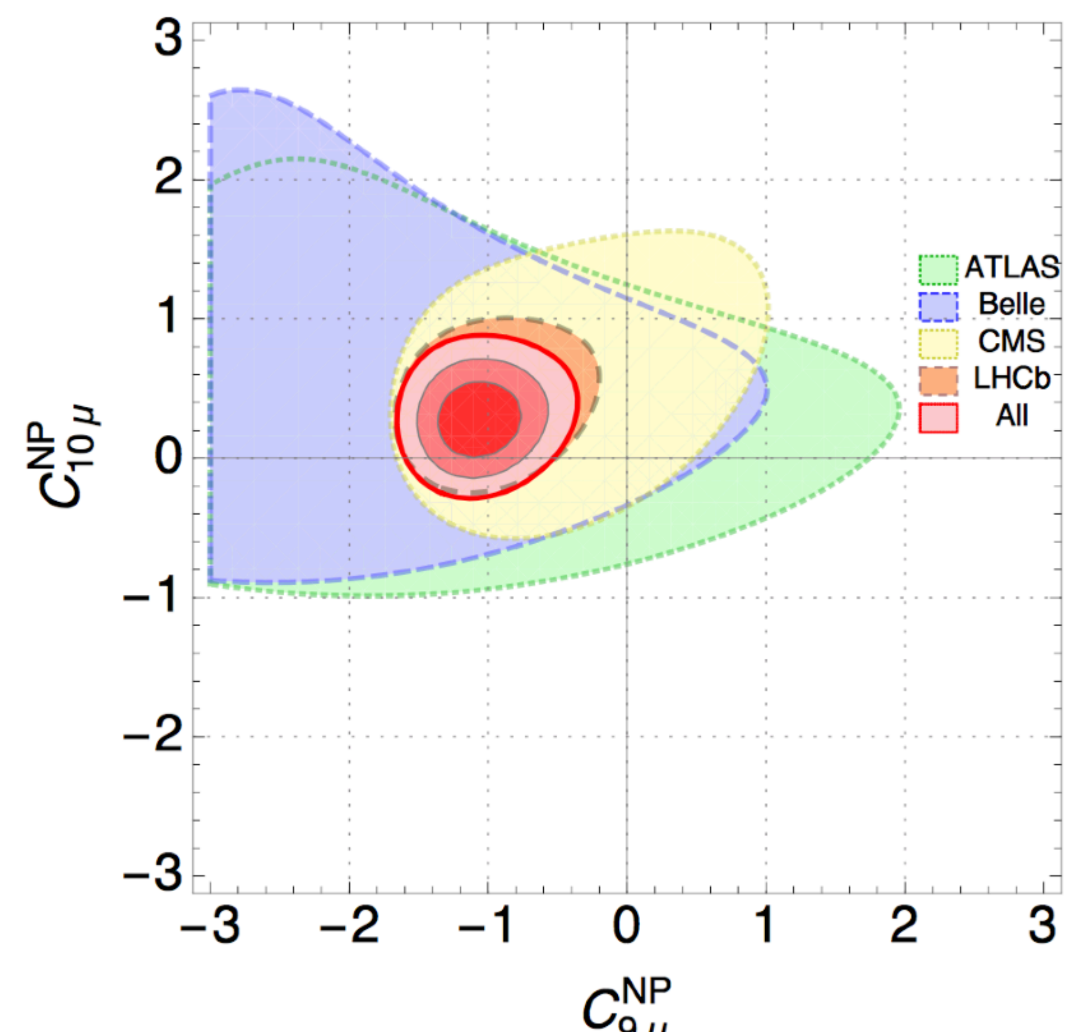
$$\mathcal{O}_9 = (\bar{s}\gamma^\nu P_L b)(\bar{\mu}\gamma_\nu \mu) \qquad C_9^{\rm SM} \simeq 4.1$$

$$\mathcal{O}_{10} = (\bar{s}\gamma^\nu P_L b)(\bar{\mu}\gamma_\nu \gamma_5 \mu) \qquad C_{10}^{\rm SM} \simeq -4.3$$

Altmannshofer Stangl Straub 1704.05435



Capdevila+ 1704.05340



Heavy NP realisations: an incomplete list

Apologies for the other papers!

Altmannshoffer+ 1403.1269	Z' from gauging $U(1)_{L_\mu - L_\tau}$
Gripaios+ 1412.1791	Loop of a Composite Leptoquark
Bauer Neubert 1511.01900	Loop of a Leptoquark that also explains R(D)
Falkowski+ 1509.01249 Alonso+ 1704.08158	Z' from gauging a flavour symmetry
Delaunay+ 1507.06660 Allanach+ 1511.07447 Di Chiara+ 1704.06200	Z' that also explains muon g-2
Kamenik+ 1704.06005	Z' with flavour-conserving couplings
D'Amico+ 1704.05438	More complex composite dynamics

Could it be a new light $\mu\mu$ resonance?

FS Straub 1704.06188

[Spirit: let us address a logical possibility]

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$$2m_\mu < m_V \lesssim m_B$$

$$\mathcal{L} = \left[(g_{bs}\,\bar{s}_L\gamma_\nu b_L + \text{h.c.}) + g_{\mu V}\,\bar{\mu}\gamma_\nu\mu + g_{\mu A}\,\bar{\mu}\gamma_\nu\gamma_5\mu + g_\chi\,\bar{\chi}\gamma_\nu\chi\right]V^\nu$$

Resonance interferes with SM prediction

Choose signs to have dip and then peak in $q^2 = m_{\mu\mu}^2$

$$m_V^2 \gtrsim 6\ \text{GeV}^2$$

Where to hide the resonance?

If broad enough, it can be hidden in charmonium region, where SM poorly known

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$$\mathcal{H} = -N\sum_i C_i\mathcal{O}_i \qquad N = G_F V_{tb}V_{ts}^*\alpha/\sqrt{2}\pi \simeq -7.7\times 10^{-10}\ \text{GeV}^{-2}$$

$$\mathcal{O}_9 = (\bar{s}\gamma^\nu P_L b)(\bar{\mu}\gamma_\nu\mu)$$

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$$C_{9,10}^V = \frac{g_{bs}g_{\mu V,A}/N}{q^2 - m_V^2 + im_V\Gamma_V}$$

OK, but where can this Lagrangian come from? Let us first see if it works at all…

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FS Straub 1704.06188

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For even lighter resonances see

Fuyuto+ 1512.09026
Datta+ 1702.01099
Gosh 1704.06240
Alltmannshofer+ 1711.07494

Resonance interfere…

Choose signs t… $q^2 = m^2_{\mu\mu}$

$m \ldots \text{GeV}^2$

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More quantitatively

$$\mathcal{L} = \left[(g_{bs}\,\bar{s}_L\gamma_\nu b_L + \text{h.c.}) + g_{\mu V}\,\bar{\mu}\gamma_\nu\mu + g_{\mu A}\,\bar{\mu}\gamma_\nu\gamma_5\mu + g_\chi\,\bar{\chi}\gamma_\nu\chi\right]V^\nu$$

$$m_V = 2.5 \text{ GeV}$$

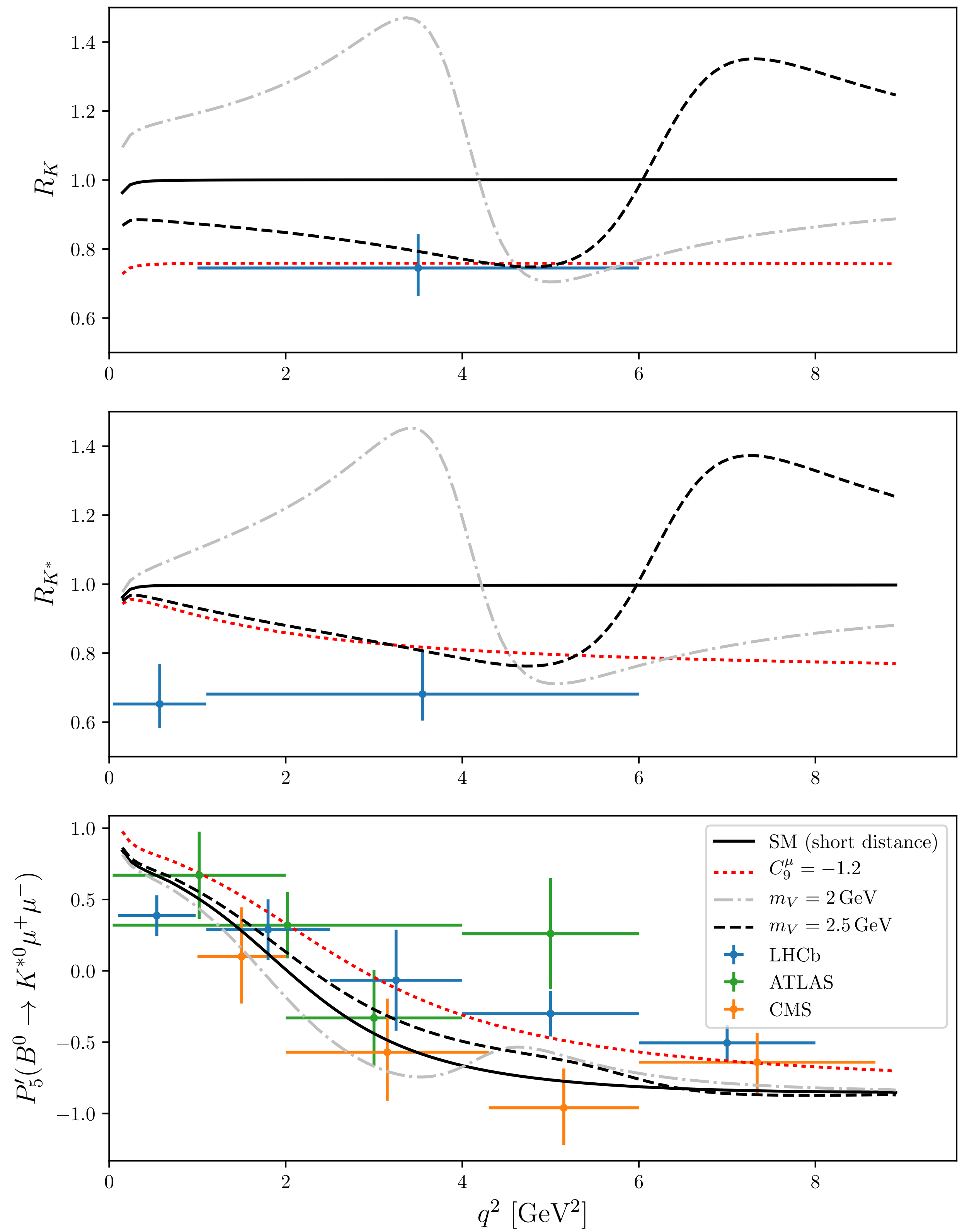
$$\Gamma_V/m_V = 20\%$$

$$g_\chi \gtrsim 2 \qquad \left(\Gamma_V \simeq \frac{m_V}{12\pi}g_\chi^2\right)$$

$$10^{-9} \lesssim |g_{bs}\,g_{\mu V}| \lesssim 3\times 10^{-9}$$

improve SM by > 2 σ

$$g_{\mu V} = 0.1 \; (= -g_{\mu A}/0.44)$$
$$g_{bs} = 1.5\times 10^{-8}$$



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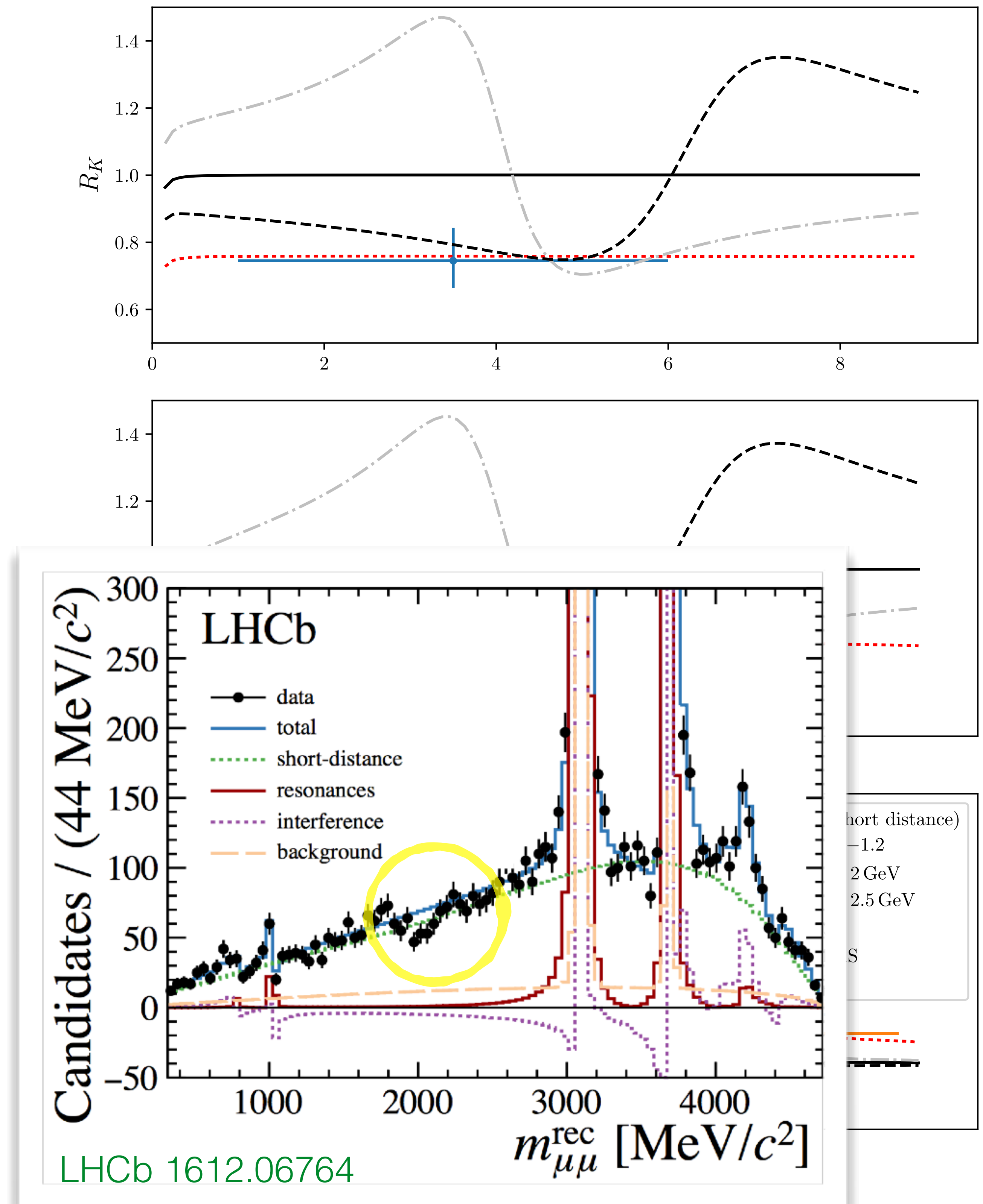

$m_V = 2$ GeV line just because LHCb writes that a new 2 GeV resonance improves fit of $\frac{d\Gamma}{dq^2}(B^+ \to K^+ \mu\mu)$

Can it work? Constraints

$$\mathcal{L} = \big[(g_{bs}\,\bar{s}_L\gamma_\nu b_L + \text{h.c.}) + g_{\mu V}\,\bar{\mu}\gamma_\nu\mu + g_{\mu A}\,\bar{\mu}\gamma_\nu\gamma_5\mu + g_\chi\,\bar{\chi}\gamma_\nu\chi\big]V^\nu$$

	bs	$\mu\mu$	$\chi\chi$
bs	$B_s - \bar{B}_s$	$B_s \to \mu\mu$	$B \to K\chi\chi$
$\mu\mu$		$(g-2)_\mu$ $Z \to \mu\mu, 4\mu$	$Z \to \mu\mu\chi\chi$
$\chi\chi$			

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$\chi\chi$			

Can it work? Strongest Constraints

$$a_\mu^{\rm exp} - a_\mu^{\rm SM} = (287 \pm 80) \times 10^{-11}$$ see e.g. Davier+ 1010.4180

$$\delta a_\mu \simeq \frac{g_{\mu V}^2 - 5 g_{\mu A}^2}{12\pi^2} \frac{m_\mu^2}{m_V^2}$$

$$|g_{\mu A}| \simeq 0.44\, |g_{\mu V}|$$ To have small positive contribution

(Exp error ~ Theory error Theory future?
Fermilab should improve by factor of 4, ~ 2020)

$$\mathrm{BR}(B \to K\nu\nu)_{\rm SM} \simeq 0.5 \times 10^{-5}$$ see e.g. Buras+ 1409.4557

$$\mathrm{BR}(B \to K\nu\nu)_{\rm exp} \lesssim 1.5 \times 10^{-5}$$ "combination" of Belle 1702.03224, 1303.3719, Babar 1303.7465, 1009.1529

$$g_{bs} \lesssim \frac{m_V}{\rm GeV} \times 0.7 \times 10^{-8}$$

$$\mathrm{BR}(B \to K\chi\chi) \simeq \tau_B \frac{m_B^3}{64\pi m_V^2} \lambda^{3/2} \left[f_+(m_V^2)\right]^2 g_{bs}^2$$

form factor from Lattice Bailey+ 1509.062357

(Belle 2 expected to deliver ~ 40 times of luminosity
SM uncertainty ~ 10% level)

Can it work? Yes

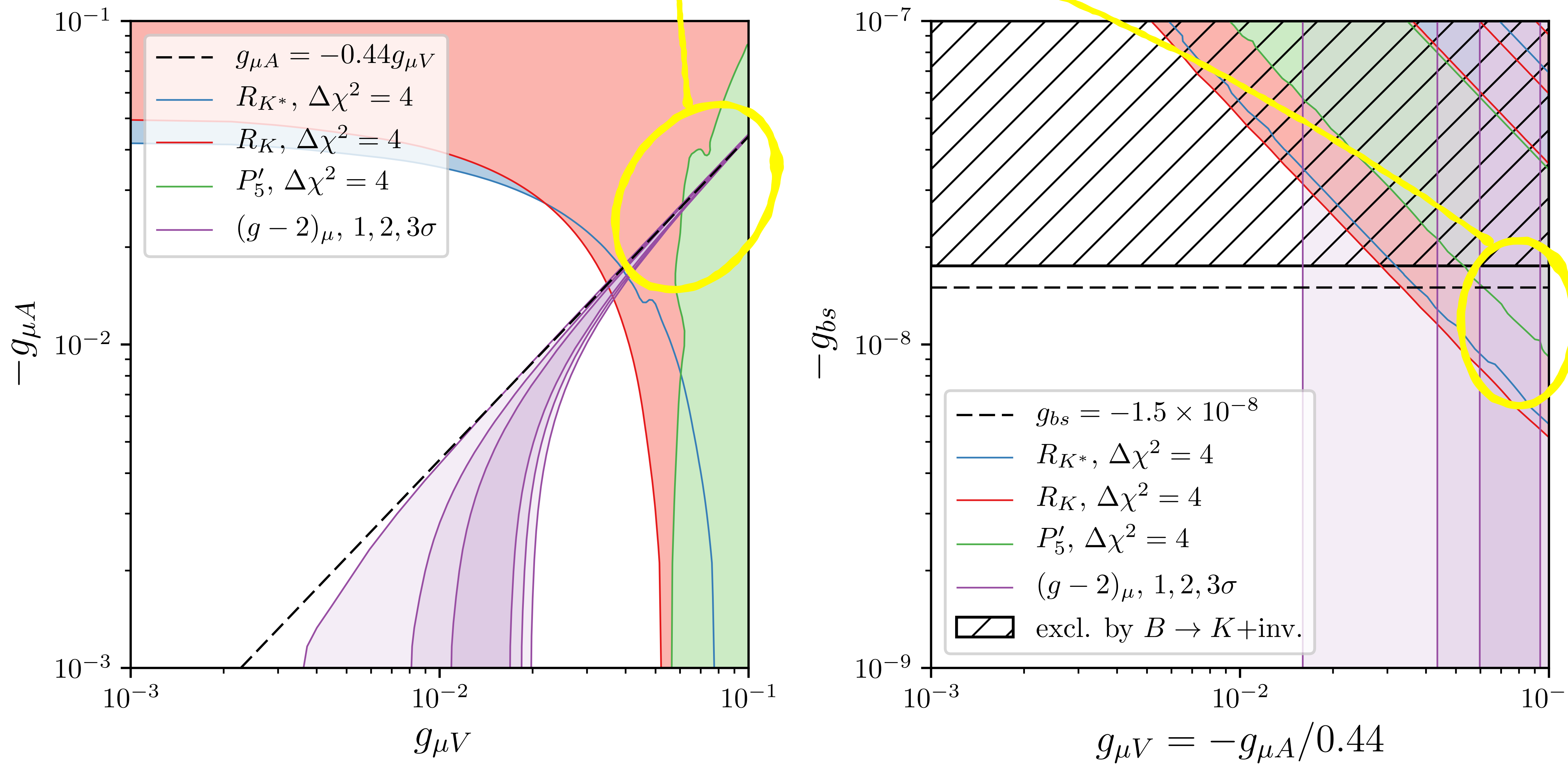
Coloured regions: good :)

Blue Red Green improve SM by > 2 σ Violet improves fit with muon g-2

Regions with lines: bad :(Excluded by $B \to K\chi\chi$

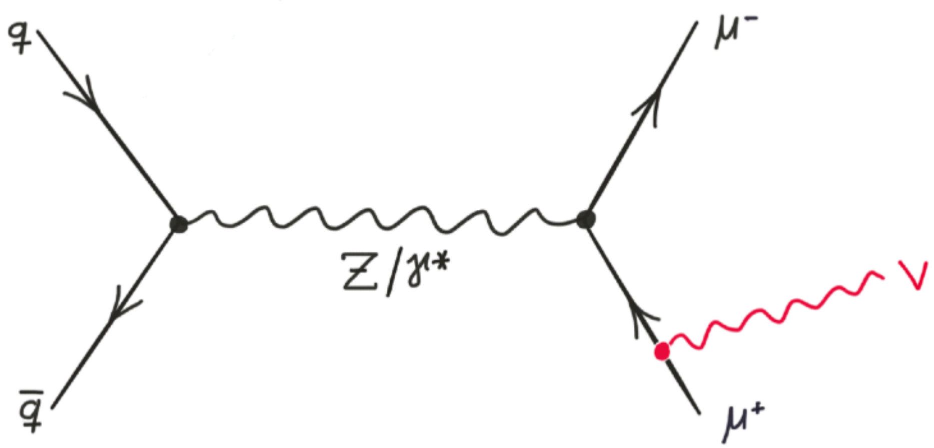
$m_V = 2.5$ GeV

Region allowed, although narrow



Dimuon shape at the LHC

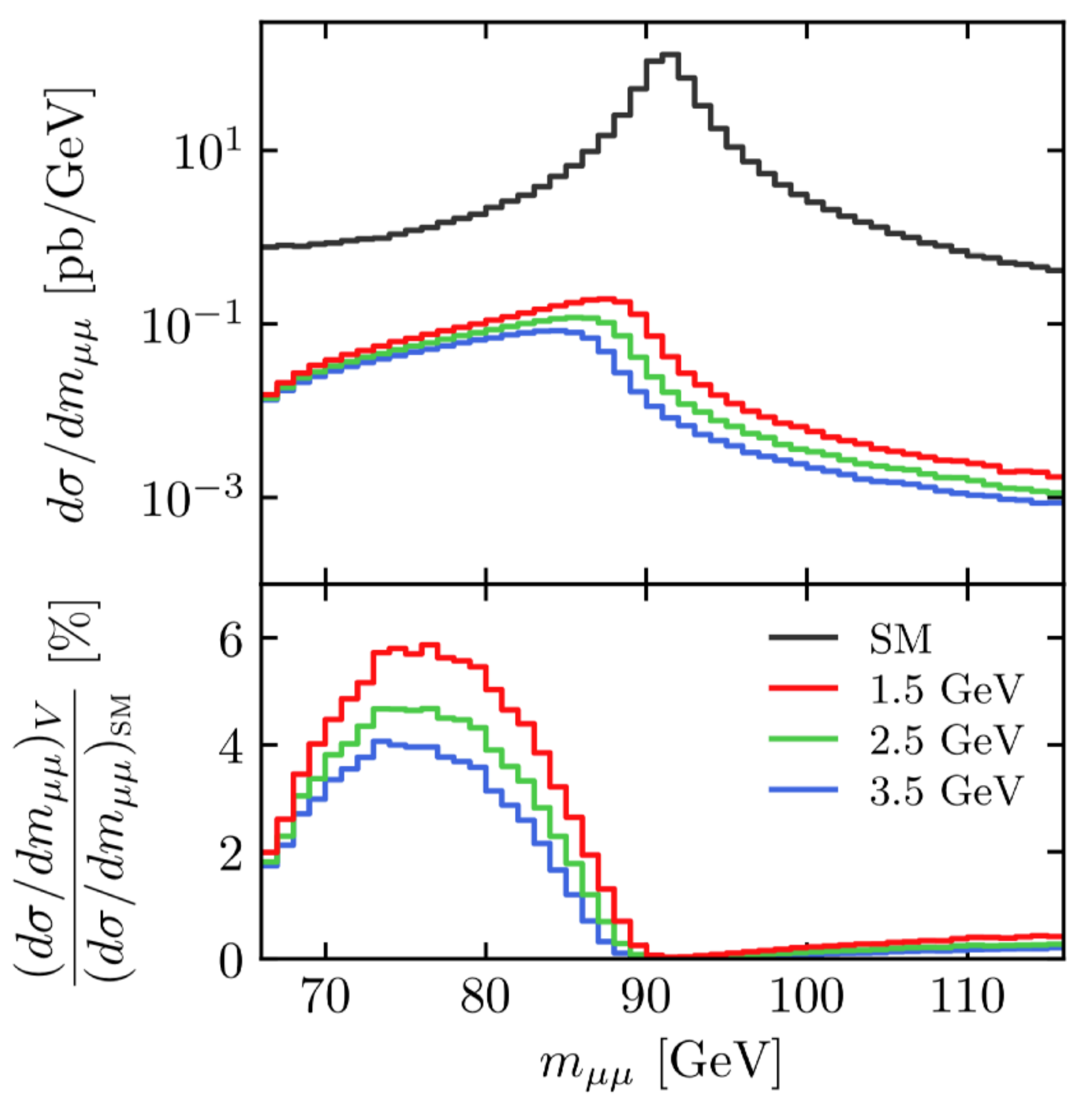
Bishara Haisch Monni 1705.03465

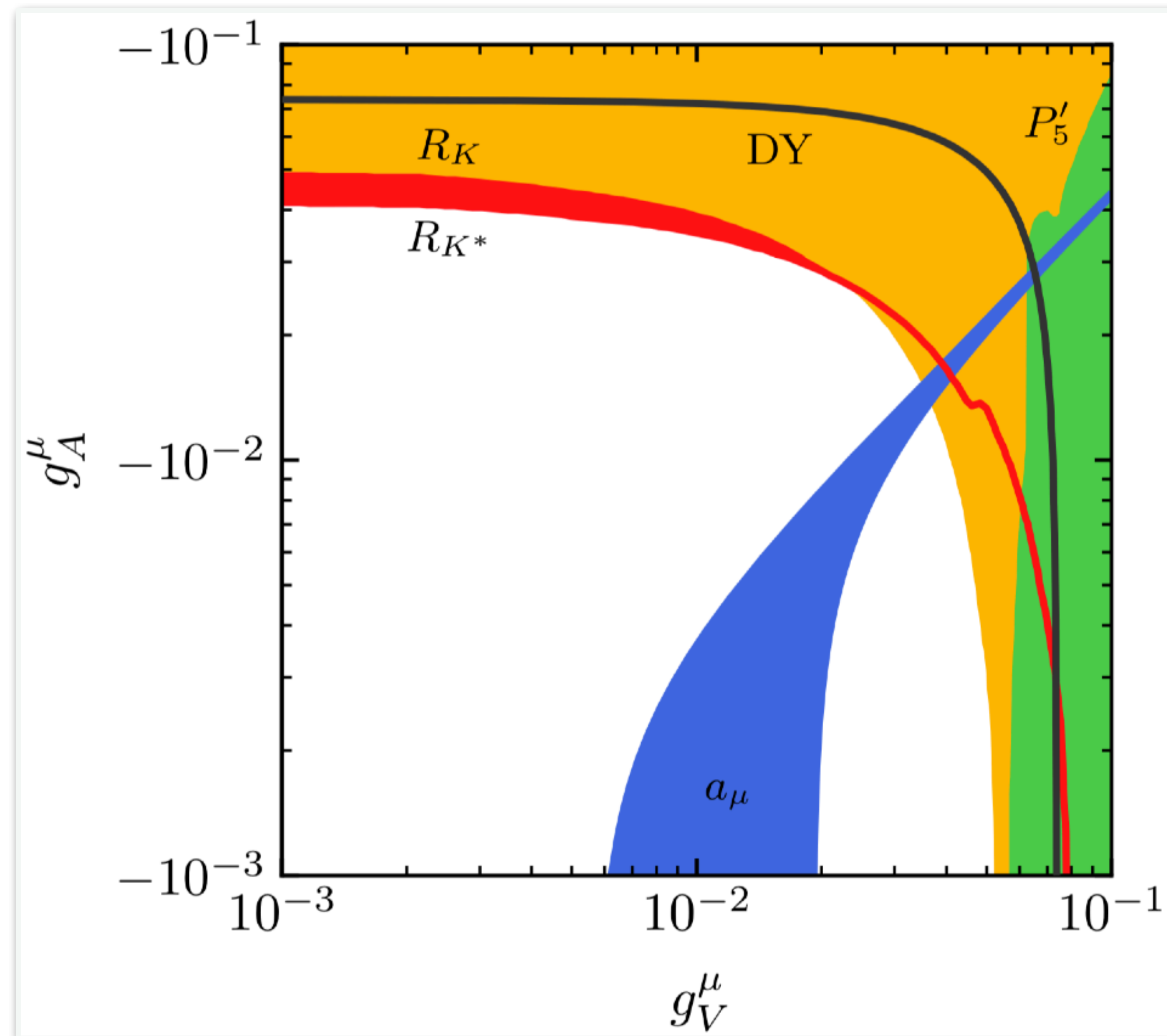


Our explanation of P_5'

is challenged by dimuon shape at the LHC

Our explanation of R_K, R_{K^*} not affected!



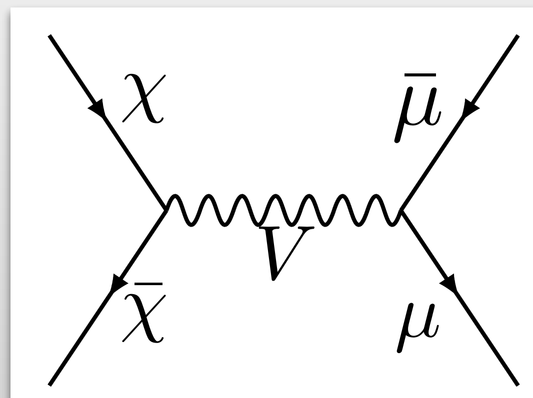


Connection with Dark Matter

$m_\chi < m_V/2 \approx \text{GeV}$

If the invisible decay is into Dark Matter → framework is predictive for DM pheno!

$m_\chi > m_\mu$



$$\langle \sigma v \rangle_{\chi\chi\to\mu\mu} \approx 3 \times 10^{-21} \frac{\text{cm}^3}{\text{sec}} \left(\frac{g_\chi}{3}\right)^2 \frac{g_{\mu V}^2 + g_{\mu A}^2}{10^{-2}}$$

$m_\chi \simeq 500 \text{ MeV}$

If scalar ϕ instead of fermion χ : annihilation is p-wave $\propto v_{\text{DM}}^2$ still

$$\langle \sigma v \rangle^{\text{f.o.}}_{\phi\phi\to\mu\mu} \approx 10^{-23} \frac{\text{cm}^3}{\text{sec}}$$

Both too large for thermal freeze-out

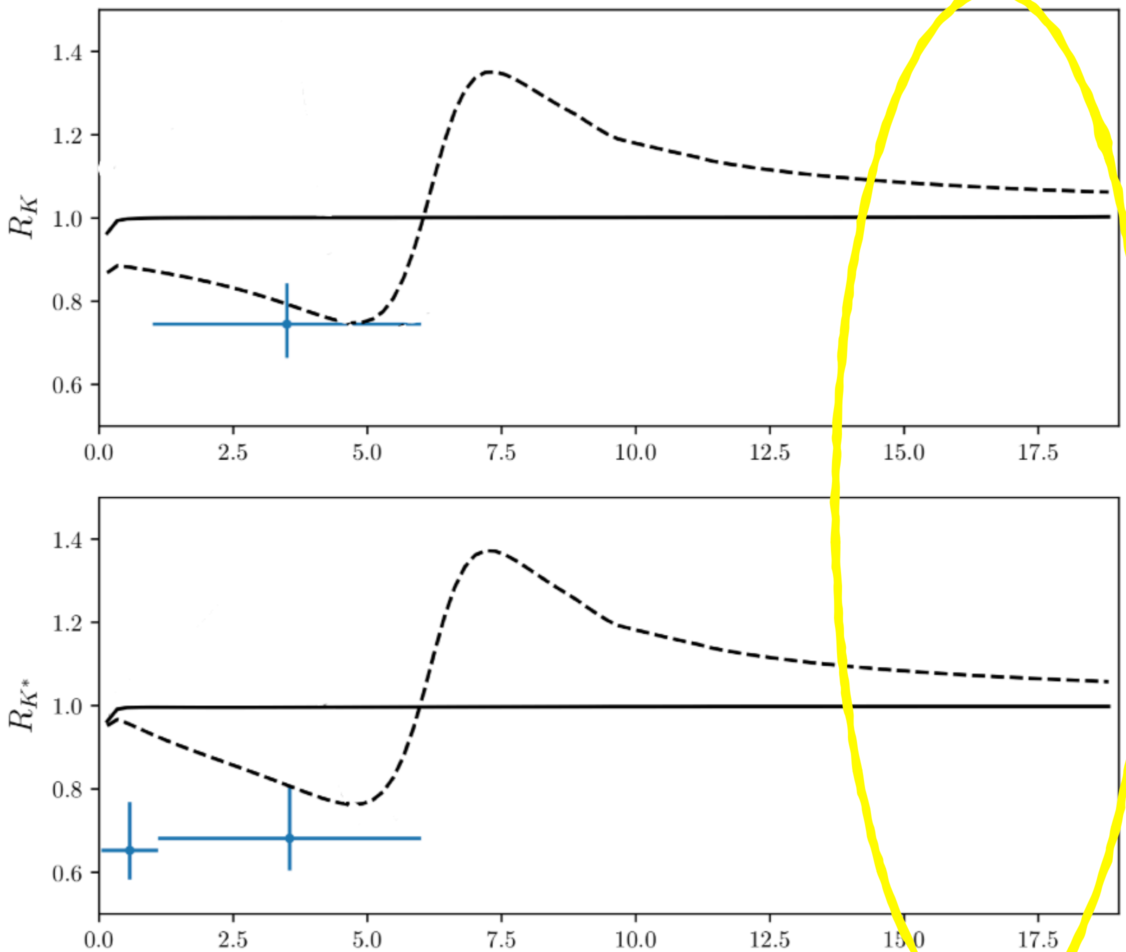
Couplings that explain flavour anomalies could suit **Asymmetric Dark Matter**

$m_\chi < m_\mu$ Annihilation to $\mu\bar{e}\nu\bar{\nu}$, $\nu\bar{\nu}$ Extra suppression $\sim \frac{m_\chi^4}{m_W^4} \times \frac{\alpha_2^2}{16\,\pi^2}$ **Too much DM**

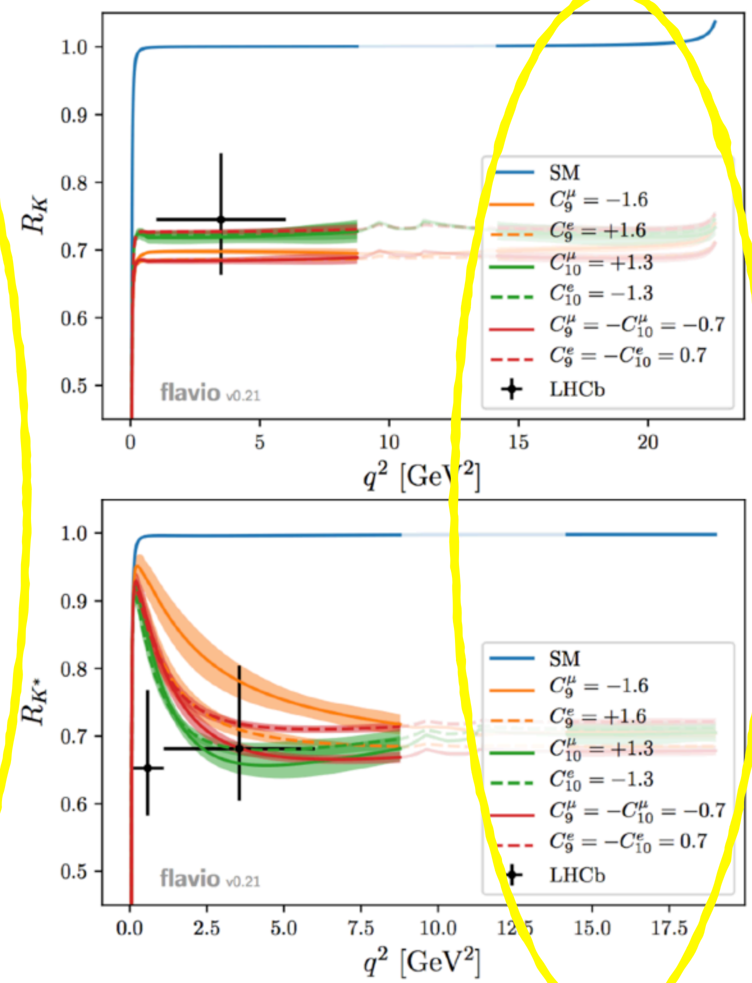
[DM self-interactions due to largish g_χ are too small to give signals in structures]

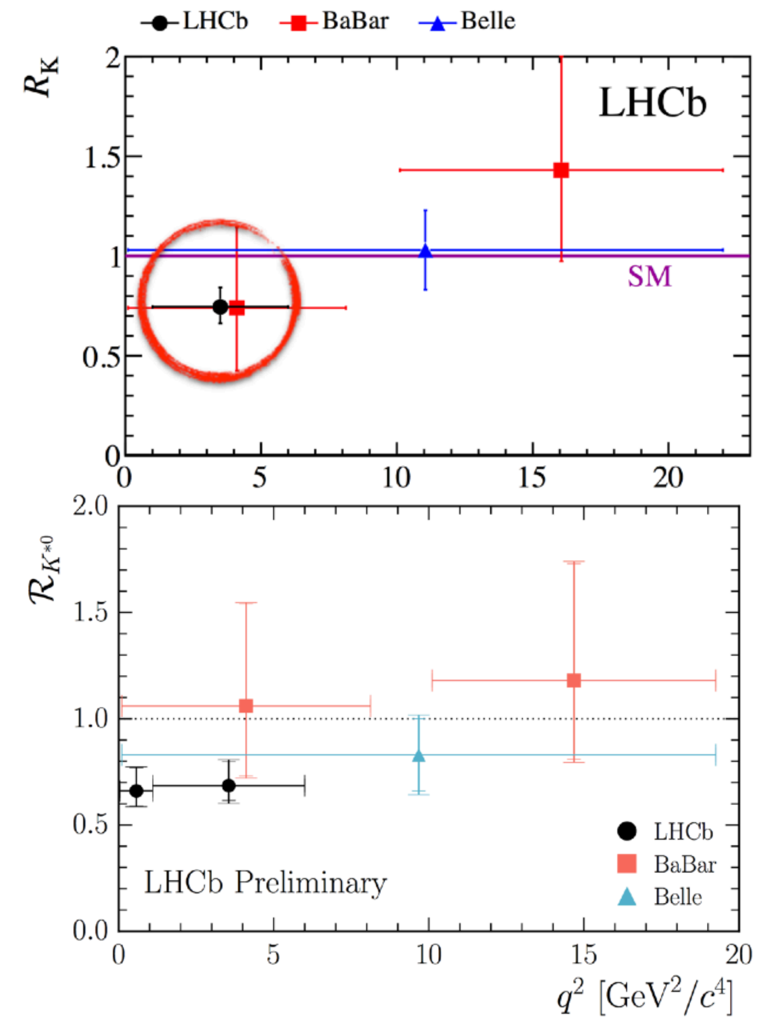
Future

FS Straub 1704.06188



Altmannshofer+ 1704.05435





Testable vs any explanation with heavy New Physics!

LHCb expected to measure R_K & R_{K^*} in $16 \lesssim q^2 \lesssim 20$ GeV^2

On top of that, **Belle2** could test $B \to K\chi\chi$

UV challenges

$$\mathcal{L} = \left[\left(g_{bs}\, \bar{s}_L \gamma_\nu b_L + \text{h.c.} \right) + g_{\mu V}\, \bar{\mu}\gamma_\nu \mu + g_{\mu A}\, \bar{\mu}\gamma_\nu\gamma_5 \mu + g_\chi\, \bar{\chi}\gamma_\nu \chi \right] V^\nu$$

V gauge boson of new $U(1)'$ under which χ is charged and SM is neutral

$g_{bs} = 1.5 \times 10^{-8}$ No big problem, e.g. couple V to top and close the loop with W

see Kamenik Soreq Zupan 1704.06005

or mix b and s with heavier fermions charged under $U(1)'$

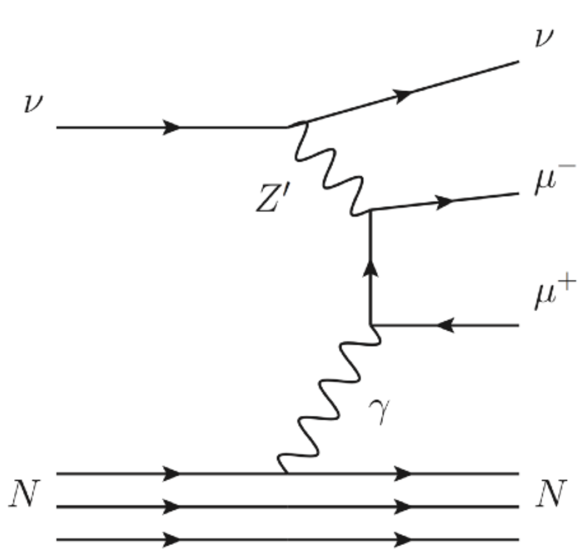
see e.g. Altmannshofer+ 1403.1269

$g_{\mu L} \simeq 0.1, \qquad g_{\mu R} \simeq 0.04$

If V couples to neutrinos like $g_{\mu L}$

Model killed by neutrino trident production!

Altmannshofer+ 1406.2332



Birth & Death of a UV completion

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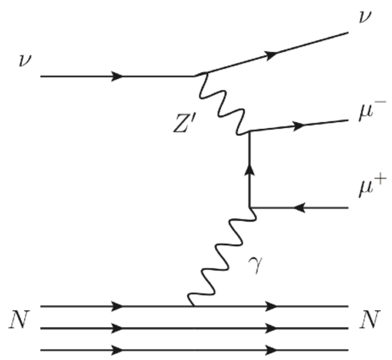

1. either find some ad-hoc NP that cancels this contribution

2. or V somehow feels EW symmetry breaking & avoid $\bar{\nu}\gamma_\mu\nu\,V^\mu$

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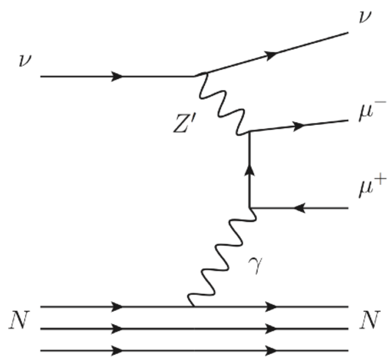

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2. Two-step mixing

add two heavy vector-like fermions, so that only one can mix with SM lepton

	$E_R^\dagger$	E_L	L_L	$L_R^\dagger$
$U(1)_Y$	1	-1	-1	1
$U(1)'$	0	0	$-q$	q

$$\begin{aligned}\mathcal{L}_{\text{NP}} &= y_H \ell_2 E_R^\dagger H^\dagger \\ &+ M_{\mu_R} E_L \mu_R^\dagger + y_{\phi\mu_R} L_L \mu_R^\dagger \phi \\ &+ y_\phi L_L E_R^\dagger \phi + \tilde{y}_\phi E_L L_R^\dagger \phi^*\end{aligned}$$

E inherits coupling to V from L

and transmits it to muons when the Higgs takes vev

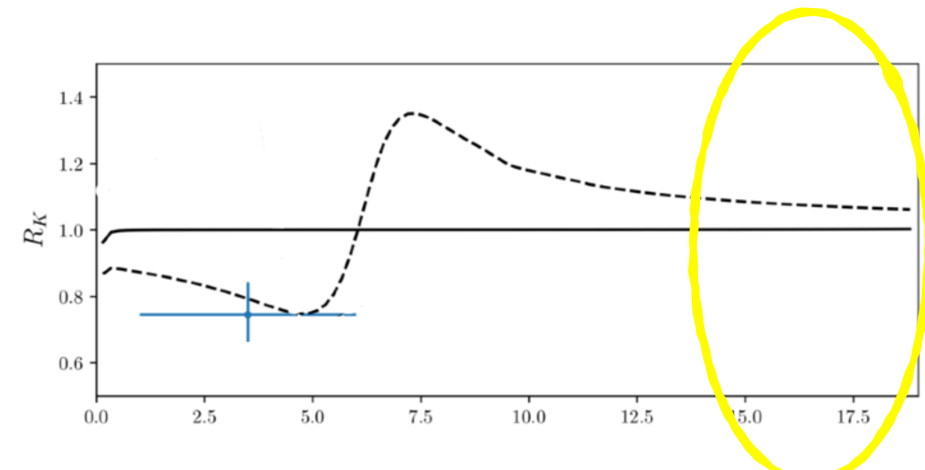
Excluded by measurements of Z couplings to left muons at LEP

Conclusions & Outlook

Observed "anomalies" in $b \to s\mu\mu$

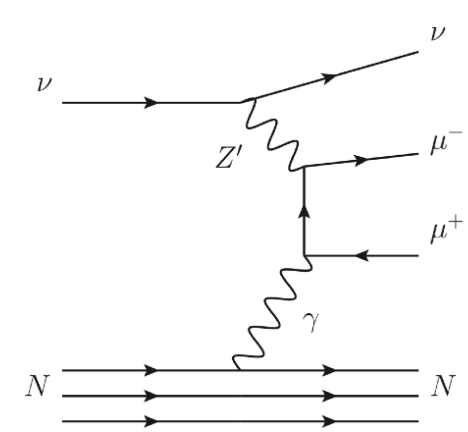
could be due to B decays to a new light dimuon resonance (that also explains muon g-2)

EXP LHCb (&Belle2) can test this



TH which UV completions?

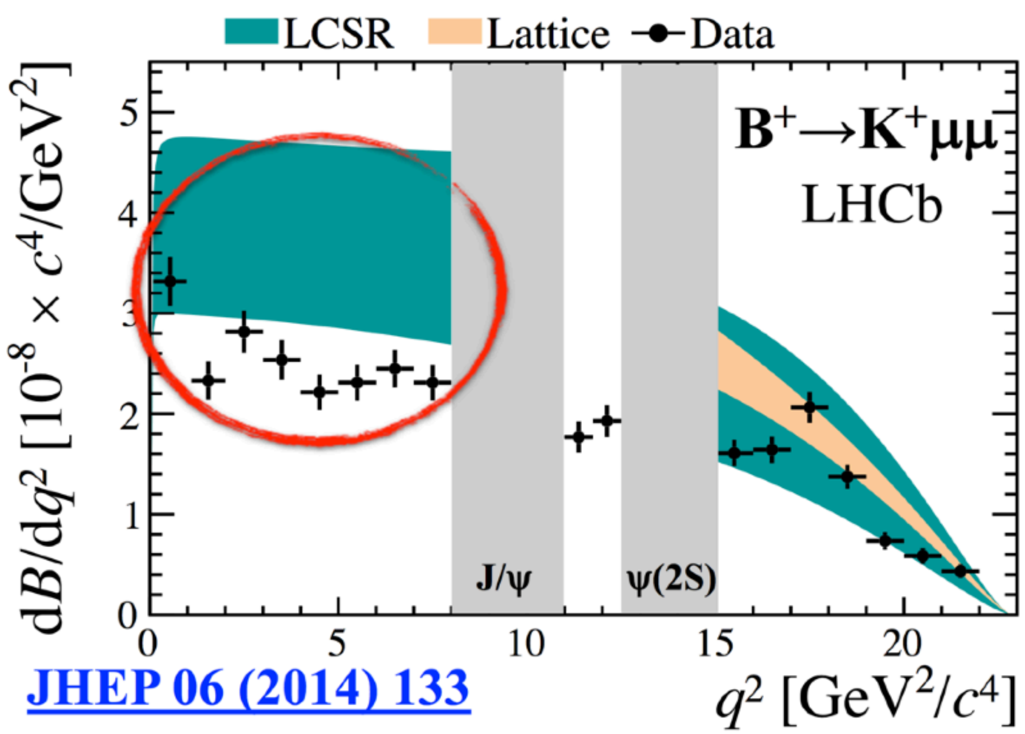
ν trident is the challenge



Back-up slides

Anomalies in $b \to s\mu\mu$?

Deviations in differential $b \to s\mu\mu$ branching ratios, all in the same direction **Exp < SM**



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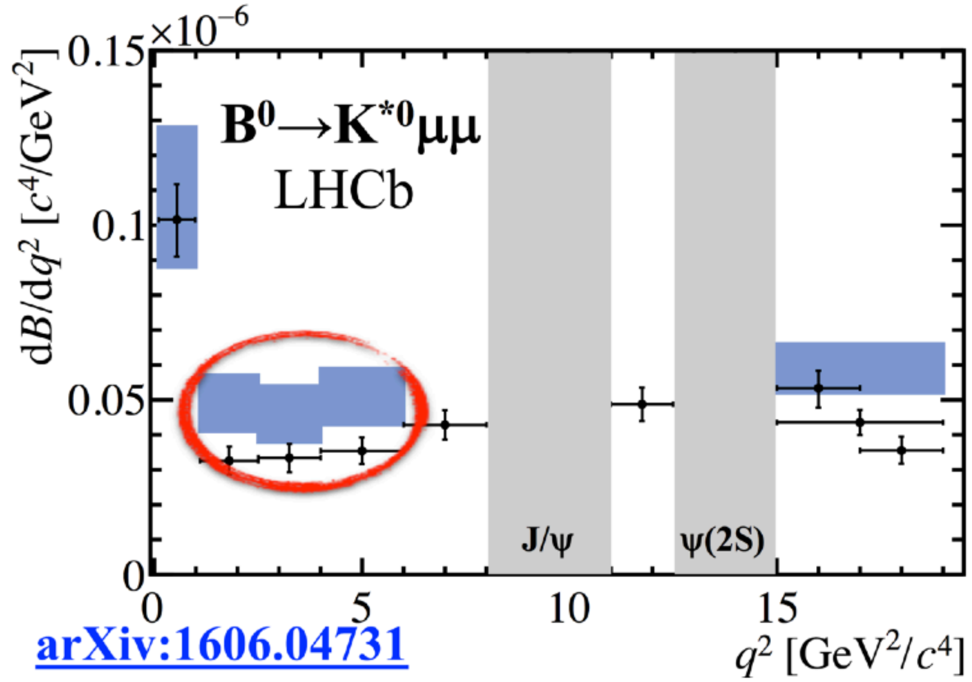
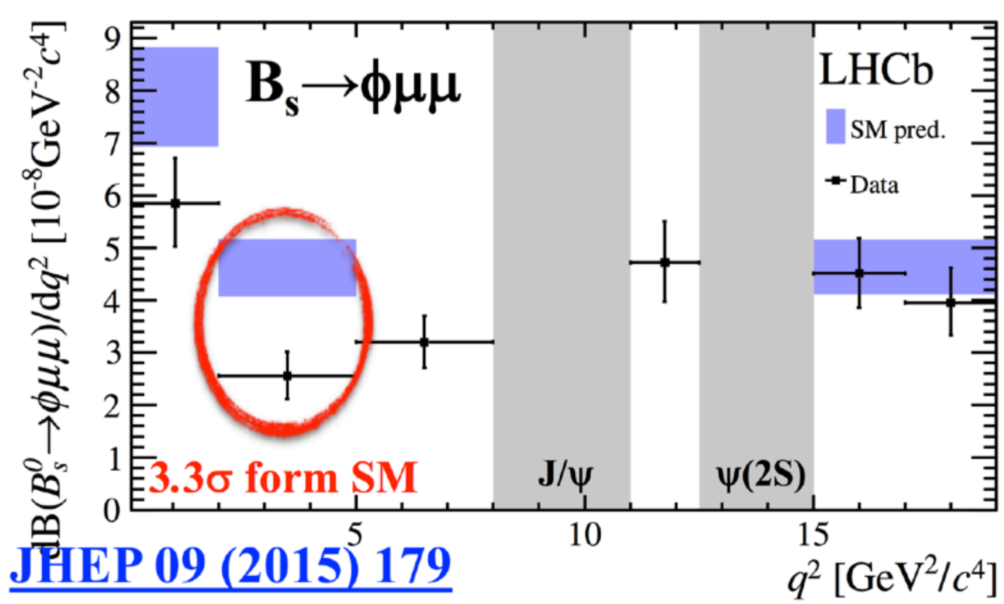


arXiv:1606.04731

$$q^2 = m_{\mu\mu}^2$$



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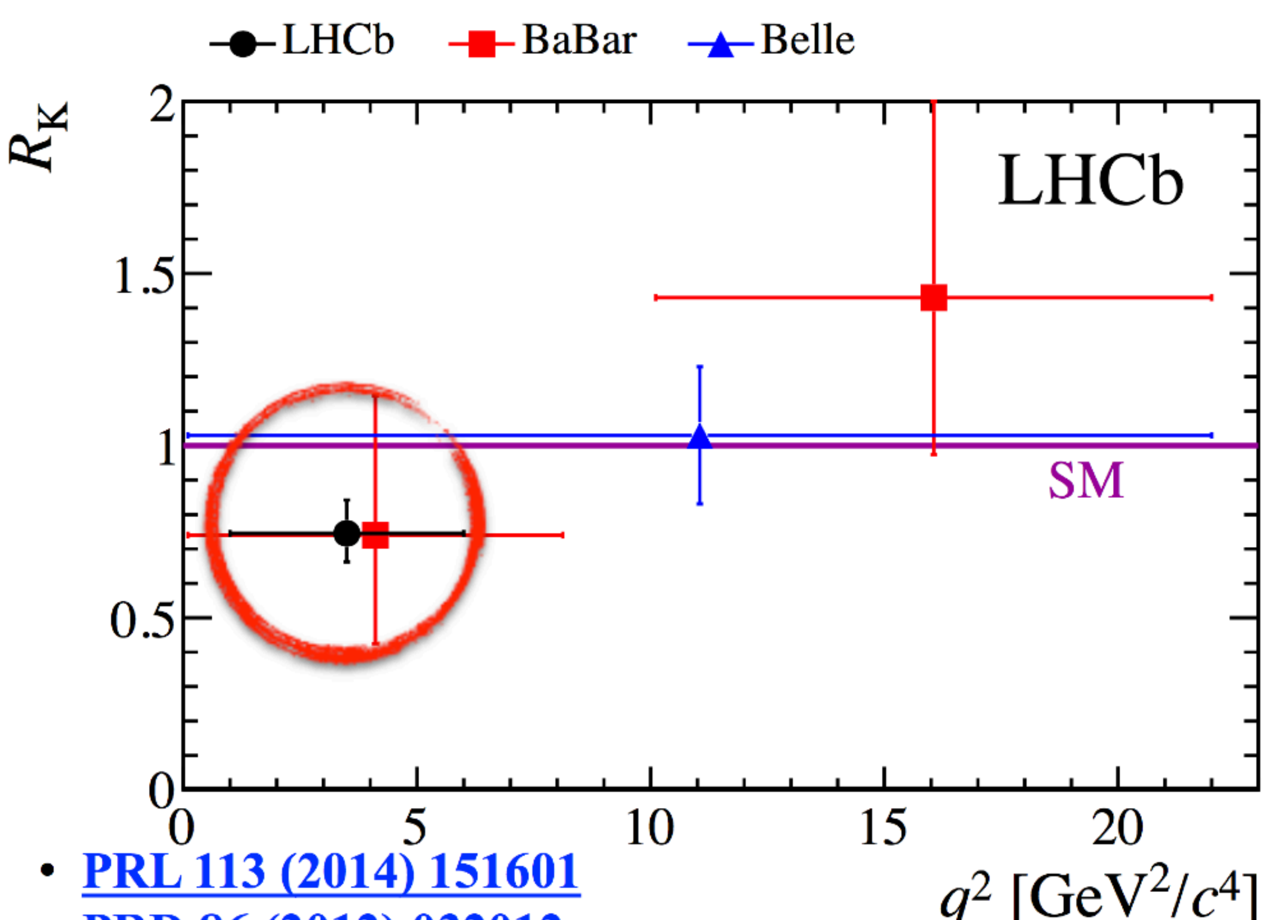
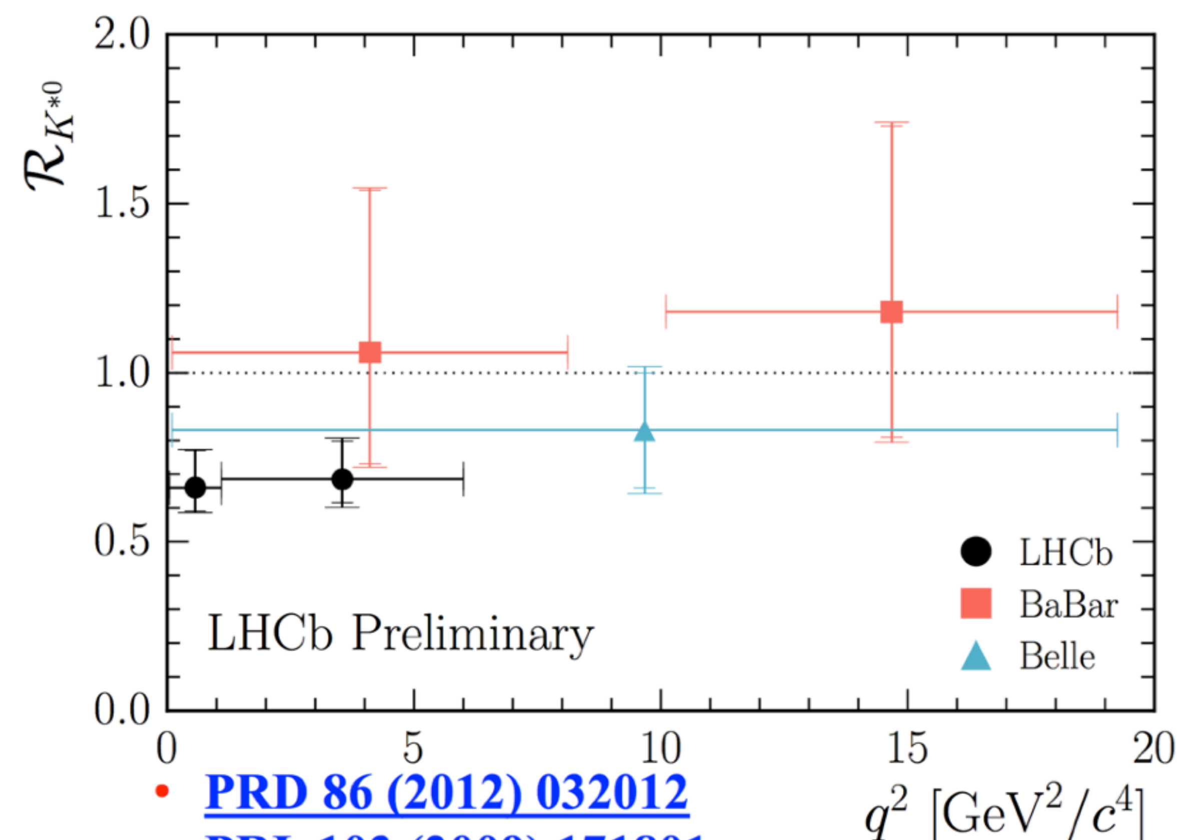
Intriguing, but large uncertainties from form factors…

Anomalies in clean ratios?

$$R_K(q^2_{\rm min}, q^2_{\rm max}) = \left.\frac{\mathrm{BR}(B^+ \to K^+\mu\mu)}{\mathrm{BR}(B^+ \to K^+ee)}\right|_{[q^2_{\rm min}, q^2_{\rm max}]} \qquad R_{K^*}(q^2_{\rm min}, q^2_{\rm max}) = \left.\frac{\mathrm{BR}(B \to K^{*0}\mu\mu)}{\mathrm{BR}(B \to K^{*0}ee)}\right|_{[q^2_{\rm min}, q^2_{\rm max}]}$$



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



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

SM prediction is **1** $\quad q^2 \in [1,6]\mathrm{GeV}^2$

~ **0.91** $\quad [0,1]\mathrm{GeV}^2$

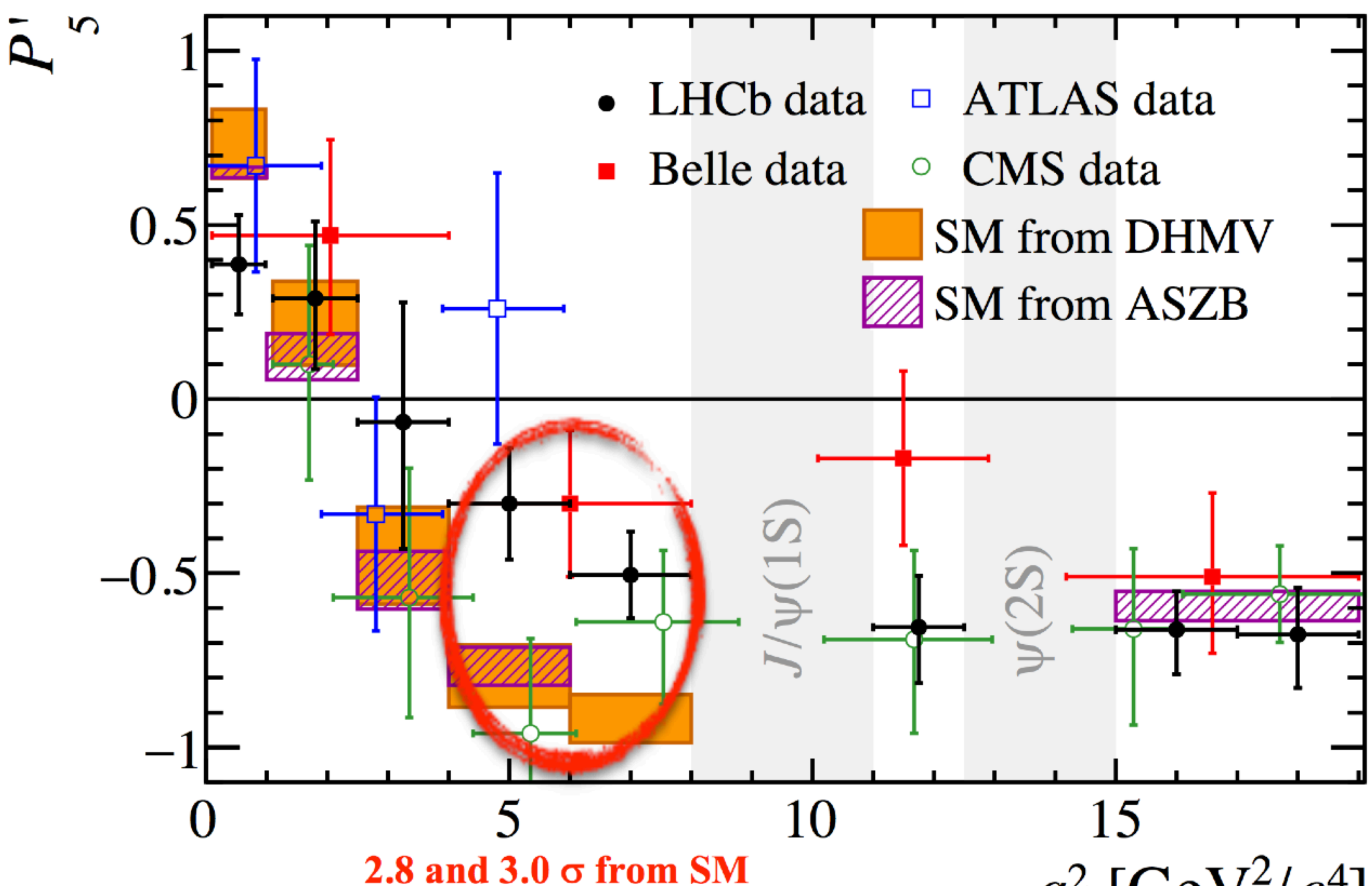
and is solid see e.g. Bordone Isidori Pattori 1605.07633

Problems w/ electrons?

Anomalies in clean(?) angular observables?

Discrepancy in one coefficient, P_5' , of the angular expansion $\frac{d^4\Gamma(B \to K^*(K\pi)\ell\ell)}{dq^2\, dc_{\theta_K}\, dc_{\theta_\ell}\, d\phi}$

Part of set of coefficients with limited sensitivity to form factors
see e.g. Descotes-Genon+ 1303.5794



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

More precisely:

Very well under control for $m_b \to \infty$

Finite m_b corrections?

Depend on who you ask

Joaquim Matias $\sim 4\sigma$

Jorge Martin Camalich $\sim 2\sigma$