New physics at LHC(b)

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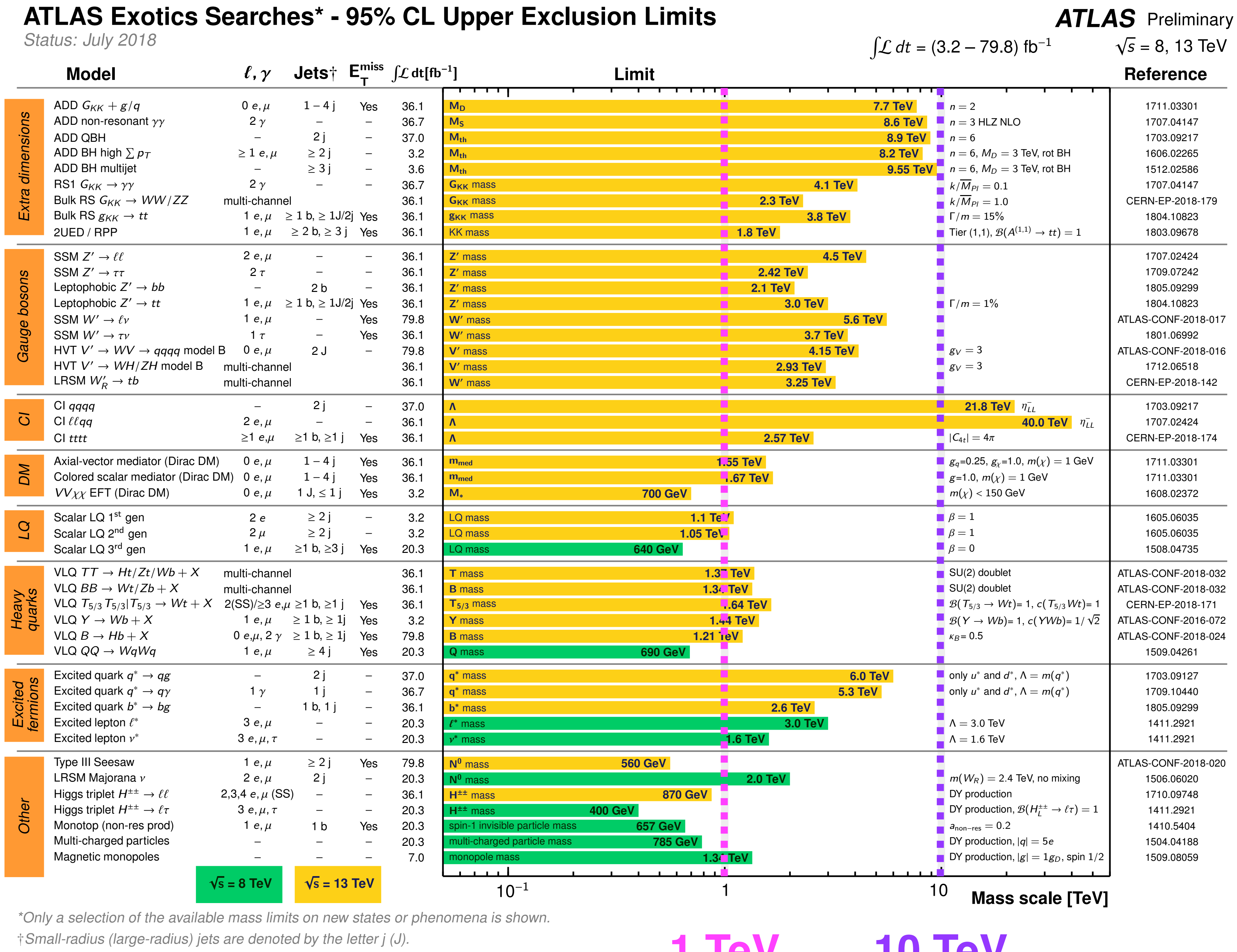
Project Review 2018, 17th of December 2018

Very loosely based on Gauld, Goertz & UH, 1308.1959; 1310.1082; Bishara, UH & Monni, 1705.03465

New physics at the LHC



ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2018

ATLAS Preliminary

$\int\mathcal{L}\,dt$ = (3.2 – 79.8) fb^{-1}

$\sqrt{s}$ = 8, 13 TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Limit			Reference
Extra dimensions	ADD $G_{KK}+g/q$	0 e, μ	1 – 4 j	Yes	36.1	🟨 M_D	7.7 TeV	$n=2$	1711.03301
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	🟨 M_S	8.6 TeV	$n=3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	🟨 M_{th}	8.9 TeV	$n=6$	1703.09217
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	3.2	🟨 M_{th}	8.2 TeV	$n=6$, $M_D=3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	🟨 M_{th}	9.55 TeV	$n=6$, $M_D=3$ TeV, rot BH	1512.02586
	RS1 $G_{KK}\to\gamma\gamma$	2 γ	–	–	36.7	🟨 G_{KK} mass	4.1 TeV	$k/\overline{M}_{Pl}=0.1$	1707.04147
	Bulk RS $G_{KK}\to WW/ZZ$	multi-channel			36.1	🟨 G_{KK} mass	2.3 TeV	$k/\overline{M}_{Pl}=1.0$	CERN-EP-2018-179
	Bulk RS $g_{KK}\to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	🟨 g_{KK} mass	3.8 TeV	$\Gamma/m=15\%$	1804.10823
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 3 j	Yes	36.1	🟨 KK mass	1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)}\to tt)=1$	1803.09678
Gauge bosons	SSM $Z'\to\ell\ell$	2 e, μ	–	–	36.1	🟨 Z' mass	4.5 TeV		1707.02424
	SSM $Z'\to\tau\tau$	2 τ	–	–	36.1	🟨 Z' mass	2.42 TeV		1709.07242
	Leptophobic $Z'\to bb$	–	2 b	–	36.1	🟨 Z' mass	2.1 TeV		1805.09299
	Leptophobic $Z'\to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	🟨 Z' mass	3.0 TeV	$\Gamma/m=1\%$	1804.10823
	SSM $W'\to\ell\nu$	1 e, μ	–	Yes	79.8	🟨 W' mass	5.6 TeV		ATLAS-CONF-2018-017
	SSM $W'\to\tau\nu$	1 τ	–	Yes	36.1	🟨 W' mass	3.7 TeV		1801.06992
	HVT $V'\to WV\to qqqq$ model B	0 e, μ	2 J	–	79.8	🟨 V' mass	4.15 TeV	$g_V=3$	ATLAS-CONF-2018-016
	HVT $V'\to WH/ZH$ model B	multi-channel			36.1	🟨 V' mass	2.93 TeV	$g_V=3$	1712.06518
	LRSM $W'_R\to tb$	multi-channel			36.1	🟨 W' mass	3.25 TeV		CERN-EP-2018-142
CI	CI $qqqq$	–	2 j	–	37.0	🟨 Λ	21.8 TeV	η_{LL}^-	1703.09217
	CI $\ell\ell qq$	2 e, μ	–	–	36.1	🟨 Λ	40.0 TeV	η_{LL}^-	1707.02424
	CI $tttt$	≥1 e,μ	≥1 b, ≥1 j	Yes	36.1	🟨 Λ	2.57 TeV	$\lvert C_{4t}\rvert=4\pi$	CERN-EP-2018-174
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	🟨 m_{med}	1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi)=1$ GeV	1711.03301
	Colored scalar mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	🟨 m_{med}	1.67 TeV	g=1.0, $m(\chi)=1$ GeV	1711.03301
	$VV\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	🟨 M_*	700 GeV	$m(\chi)<150$ GeV	1608.02372
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	3.2	🟨 LQ mass	1.1 TeV	$\beta=1$	1605.06035
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	3.2	🟨 LQ mass	1.05 TeV	$\beta=1$	1605.06035
	Scalar LQ 3rd gen	1 e, μ	≥1 b, ≥3 j	Yes	20.3	🟩 LQ mass	640 GeV	$\beta=0$	1508.04735
Heavy quarks	VLQ $TT\to Ht/Zt/Wb+X$	multi-channel			36.1	🟨 T mass	1.37 TeV	SU(2) doublet	ATLAS-CONF-2018-032
	VLQ $BB\to Wt/Zb+X$	multi-channel			36.1	🟨 B mass	1.34 TeV	SU(2) doublet	ATLAS-CONF-2018-032
	VLQ $T_{5/3}T_{5/3}\lvert T_{5/3}\to Wt+X$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	36.1	🟨 $T_{5/3}$ mass	1.64 TeV	$\mathcal{B}(T_{5/3}\to Wt)$= 1, $c(T_{5/3}Wt)$= 1	CERN-EP-2018-171
	VLQ $Y\to Wb+X$	1 e, μ	≥ 1 b, ≥ 1j	Yes	3.2	🟨 Y mass	1.44 TeV	$\mathcal{B}(Y\to Wb)$= 1, $c(YWb)$= $1/\sqrt{2}$	ATLAS-CONF-2016-072
	VLQ $B\to Hb+X$	0 e,μ, 2 γ	≥ 1 b, ≥ 1j	Yes	79.8	🟨 B mass	1.21 TeV	κ_B= 0.5	ATLAS-CONF-2018-024
	VLQ $QQ\to WqWq$	1 e, μ	≥ 4 j	Yes	20.3	🟩 Q mass	690 GeV		1509.04261
Excited fermions	Excited quark $q^*\to qg$	–	2 j	–	37.0	🟨 q^* mass	6.0 TeV	only u^* and d^*, $\Lambda=m(q^*)$	1703.09127
	Excited quark $q^*\to q\gamma$	1 γ	1 j	–	36.7	🟨 q^* mass	5.3 TeV	only u^* and d^*, $\Lambda=m(q^*)$	1709.10440
	Excited quark $b^*\to bg$	–	1 b, 1 j	–	36.1	🟨 b^* mass	2.6 TeV		1805.09299
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	🟩 ℓ^* mass	3.0 TeV	$\Lambda=3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	🟩 ν^* mass	1.6 TeV	$\Lambda=1.6$ TeV	1411.2921
Other	Type III Seesaw	1 e, μ	≥ 2 j	Yes	79.8	🟨 N^0 mass	560 GeV		ATLAS-CONF-2018-020
	LRSM Majorana ν	2 e, μ	2 j	–	20.3	🟩 N^0 mass	2.0 TeV	$m(W_R)=2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm}\to\ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	🟨 $H^{\pm\pm}$ mass	870 GeV	DY production	1710.09748
	Higgs triplet $H^{\pm\pm}\to\ell\tau$	3 e, μ, τ	–	–	20.3	🟩 $H^{\pm\pm}$ mass	400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm}\to\ell\tau)=1$	1411.2921
	Monotop (non-res prod)	1 e, μ	1 b	Yes	20.3	🟩 spin-1 invisible particle mass	657 GeV	$a_{\mathrm{non-res}}=0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	🟩 multi-charged particle mass	785 GeV	DY production, $\lvert q\rvert=5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	🟩 monopole mass	1.34 TeV	DY production, $\lvert g\rvert=1g_D$, spin 1/2	1509.08059

🟩 $\sqrt{s}$ = 8 TeV

🟨 $\sqrt{s}$ = 13 TeV

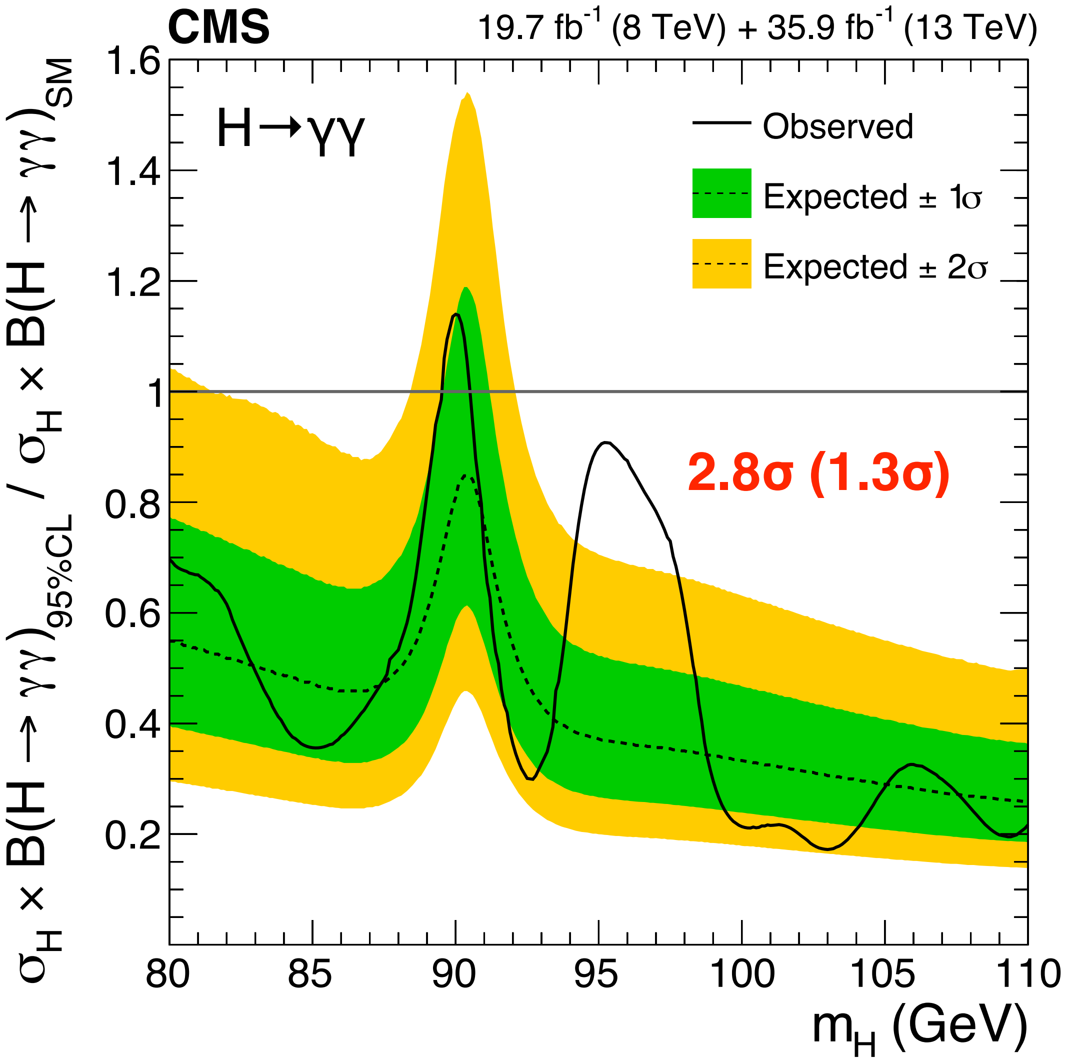
*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

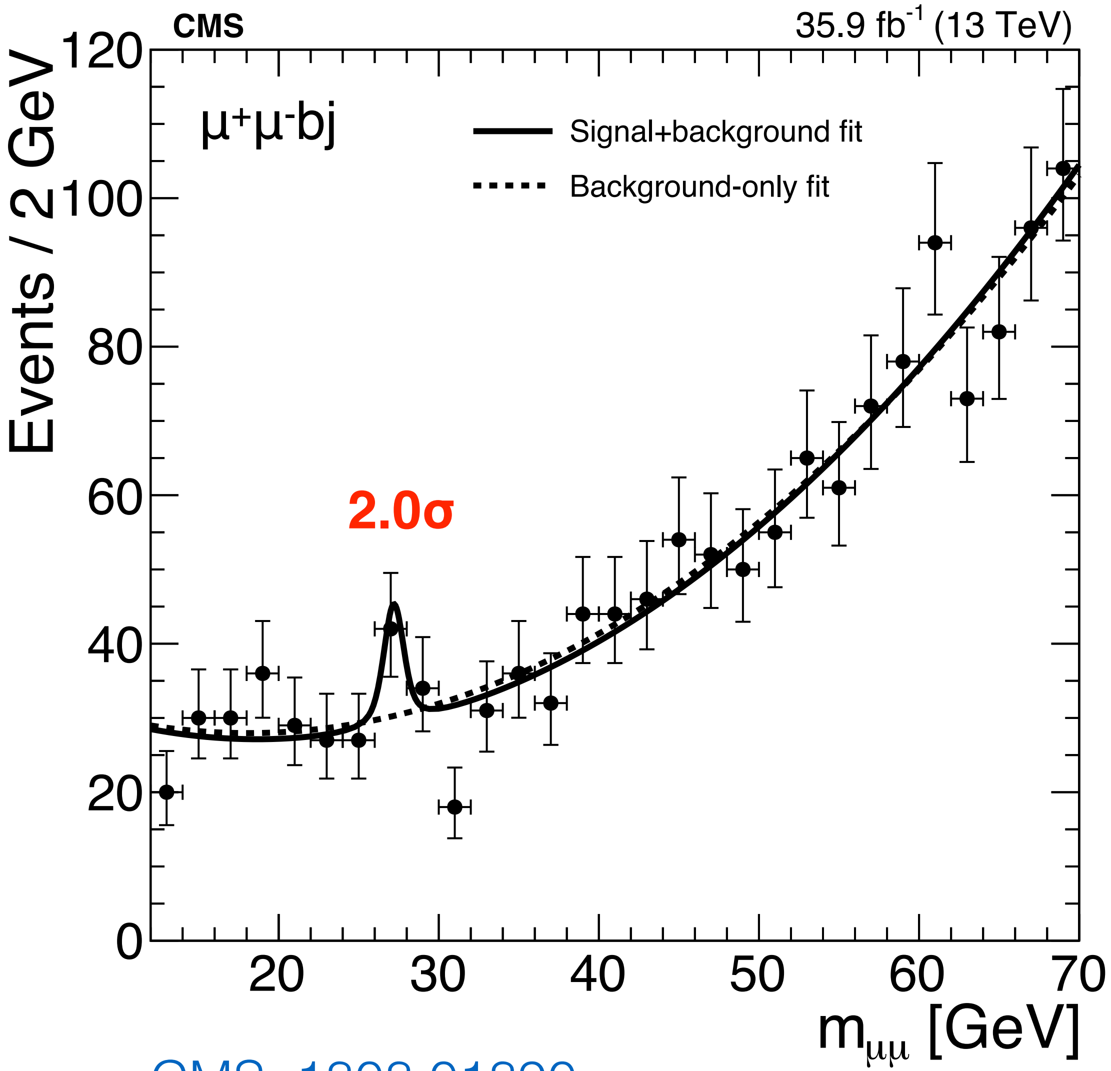
1 TeV **10 TeV**

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots

There are some glitches …



CMS, 1811.08459



CMS, 1808.01890

but (apart from Higgs boson) ATLAS & CMS has so far not found any compelling evidence for new physics

The year is 50 BC. Gaul is entirely occupied by the Romans.
Well, not entirely …

The year is 2018 AC. All LHC phenomena are well described by the Standard Model (SM). Well, maybe not all …

B anomalies in a nutshell

Measurements by BaBar, Belle & LHCb show deviations in

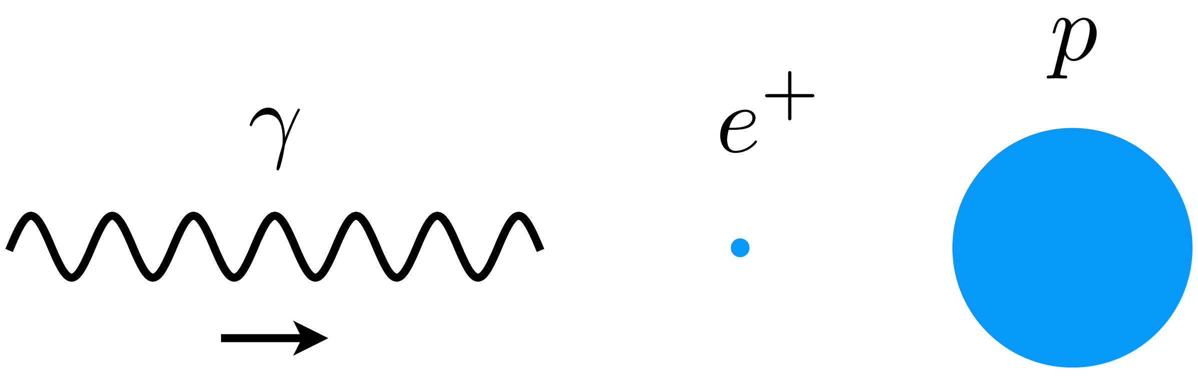
$b \to c$ charged currents, τ vs. μ, e:
R_D, R_{D^*}

$b \to s$ neutral currents, μ vs. e:
R_K, R_{K^*}, P_5', …

What is particularly interesting is that these anomalies challenge an assumption, namely lepton flavour universality (LFU), which is typically taken for granted in high-energy physics

A digression on LFU

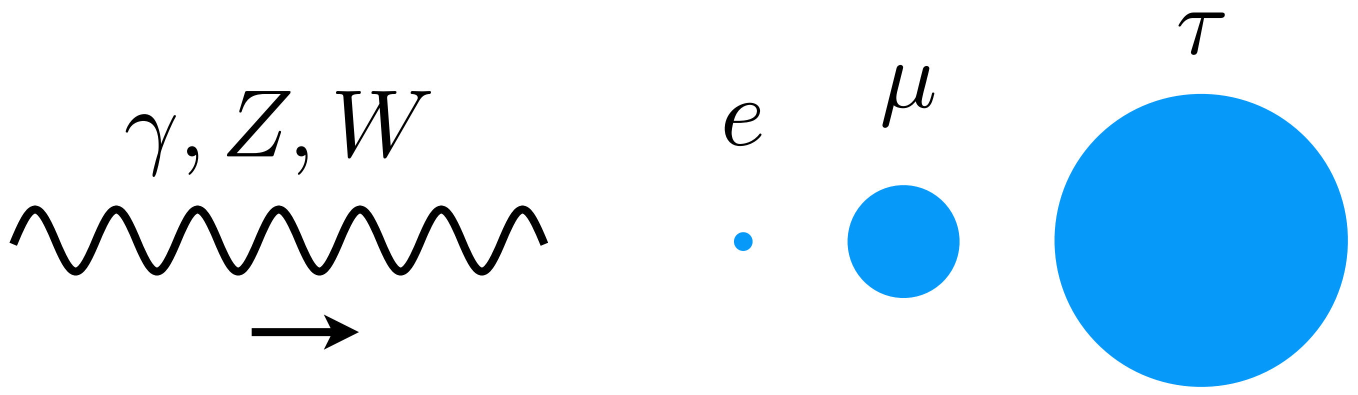
Suppose we can test matter only with long wavelength photons:



Apart from different masses, positron & proton look like identical particles in this Gedankenexperiment, since low-energy photons cannot resolve substructure of proton

A digression on LFU

We use a very similar argument to infer LFU:



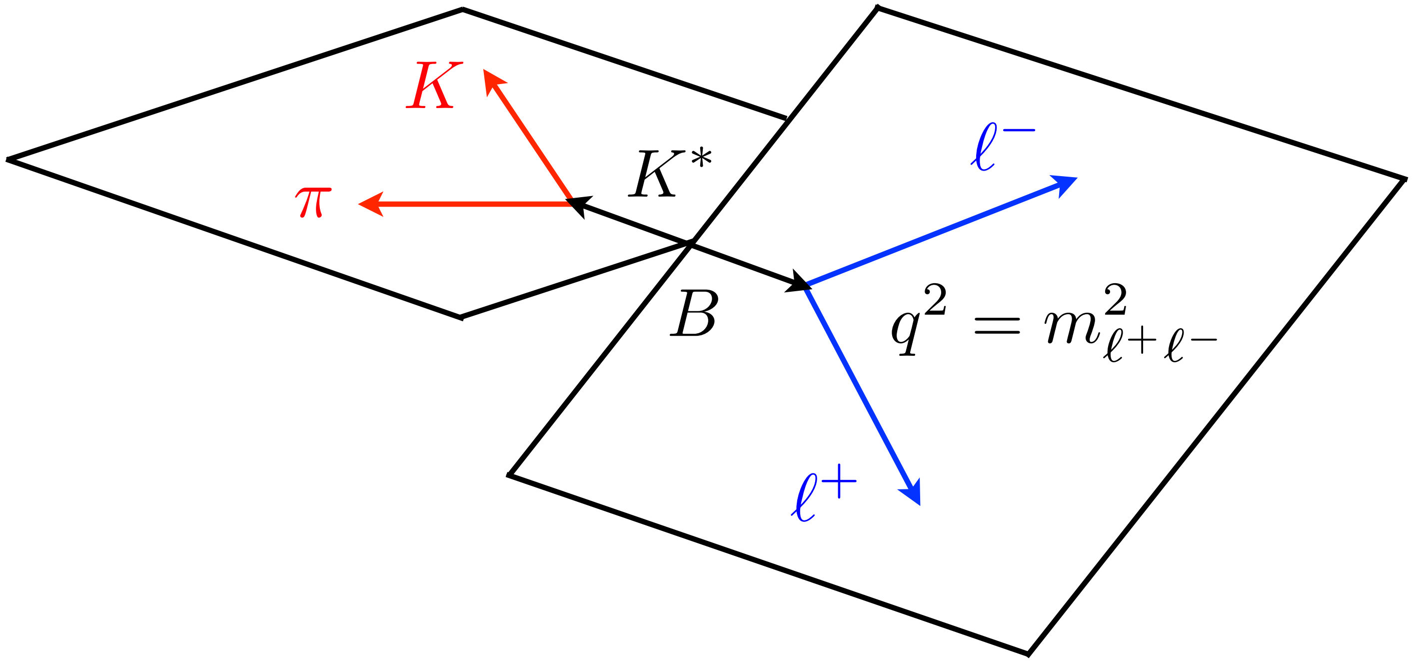
However, SM quantum numbers of three families could be an accidental low-energy property. e, μ & τ may behave differently at high energies, as signalled by their different masses. Only experiment can tell whether LFU is exact symmetry in nature

Summary of LFU tests

Decay	Precision	Channels	Deviation
Z	0.3%	e, μ & τ	—
W	0.8%	e & μ	—
W	3%	τ	2.3σ
μ & τ	0.15%	e, μ & τ	—
π	0.3%	e & μ	—
K	0.4%	e & μ	—
J/ψ	0.65%	e & μ	—
D_s	6%	μ & τ	—

Before 2012, stringent test of LFU in B decays did not exist

What is $R_{K^{(*)}}$?



$$R_{K^{(*)}}(q_0^2, q_1^2) = \frac{\displaystyle\int_{q_0^2}^{q_1^2} dq^2 \, \frac{d\Gamma(B \to K^{(*)}\mu^+\mu^-)}{dq^2}}{\displaystyle\int_{q_0^2}^{q_1^2} dq^2 \, \frac{d\Gamma(B \to K^{(*)}e^+e^-)}{dq^2}}$$

SM prediction for $R_{K^{(*)}}$

$$R_{K^{(*)}} = 1 + \mathcal{O}\left(\frac{m_\mu^2}{q^2}\right)\left(1 + \mathcal{O}\left(\frac{\Lambda}{m_b}\right) + \mathcal{O}(\alpha_s)\right) + \mathcal{O}\left(\frac{\alpha}{\pi}\ln^2\left(\frac{m_e^2}{m_\mu^2}\right)\right)$$

phase space

hadronic effects

QED corrections

SM prediction for $\mathrm{R}_{\mathrm{K}^{(*)}}$

$$R_{K^{(*)}} = 1 + \mathcal{O}\left(\frac{m_\mu^2}{q^2}\right)\left(1 + \mathcal{O}\left(\frac{\Lambda}{m_b}\right) + \mathcal{O}(\alpha_s)\right) + \mathcal{O}\left(\frac{\alpha}{\pi}\ln^2\left(\frac{m_e^2}{m_\mu^2}\right)\right)$$

phase space hadronic effects QED corrections

$$R_{K^*}(0.045\,\mathrm{GeV}^2, 1.1\,\mathrm{GeV}^2) = 0.91 \pm 0.03\,,$$

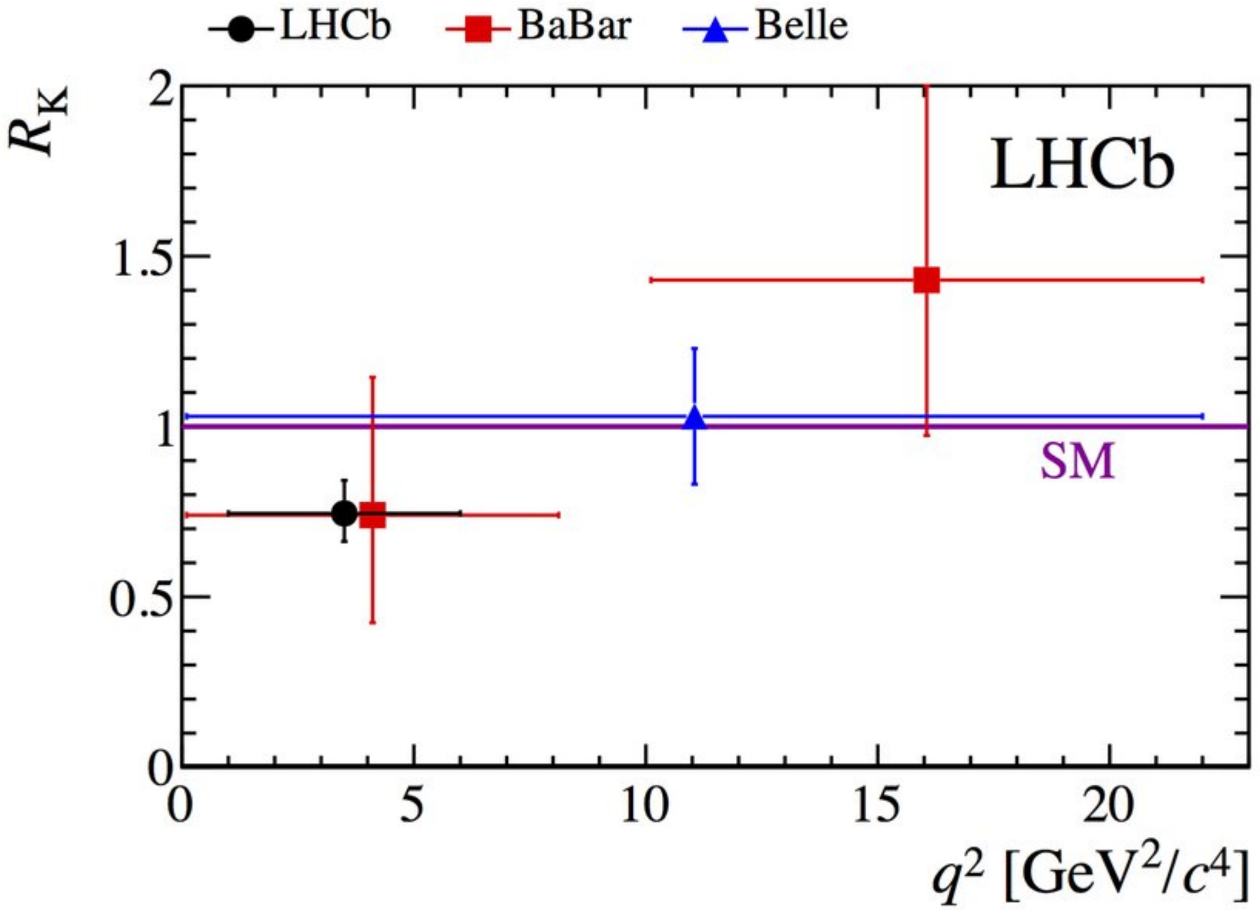
$$R_{K^{(*)}}(1.1\,\mathrm{GeV}^2, 6\,\mathrm{GeV}^2) = 1.00 \pm 0.01$$

LFU ratios can be calculated with percent precision in SM.

QED corrections well described by Monte Carlo (PHOTOS)

Bordone, Isidori & Pattori, 1605.07633

Measurements of R_K



$$R_K(1\,\mathrm{GeV}^2, 6\,\mathrm{GeV}^2) = 0.745\,{}^{+0.090}_{-0.074}{}_{\mathrm{stat}} \pm 0.036_{\mathrm{syst}}$$

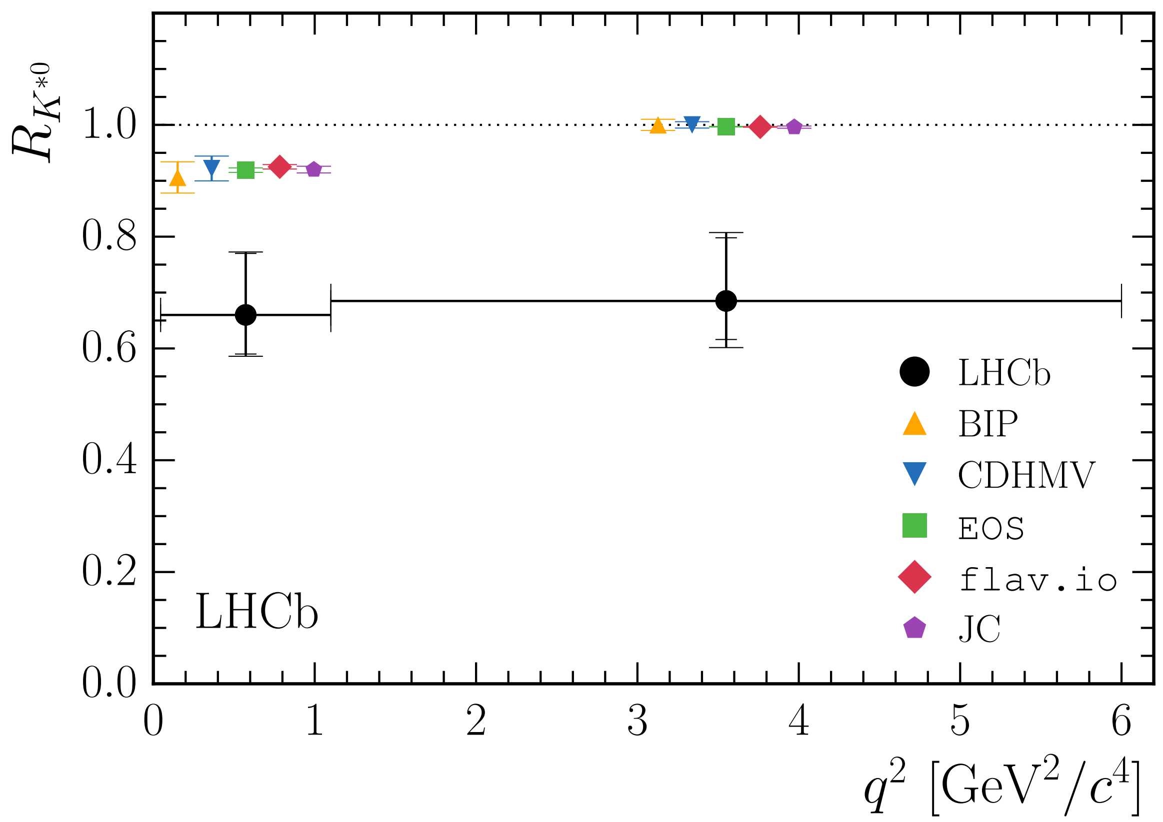
LHCb observes a 2.6σ deviation from SM prediction for R_K.

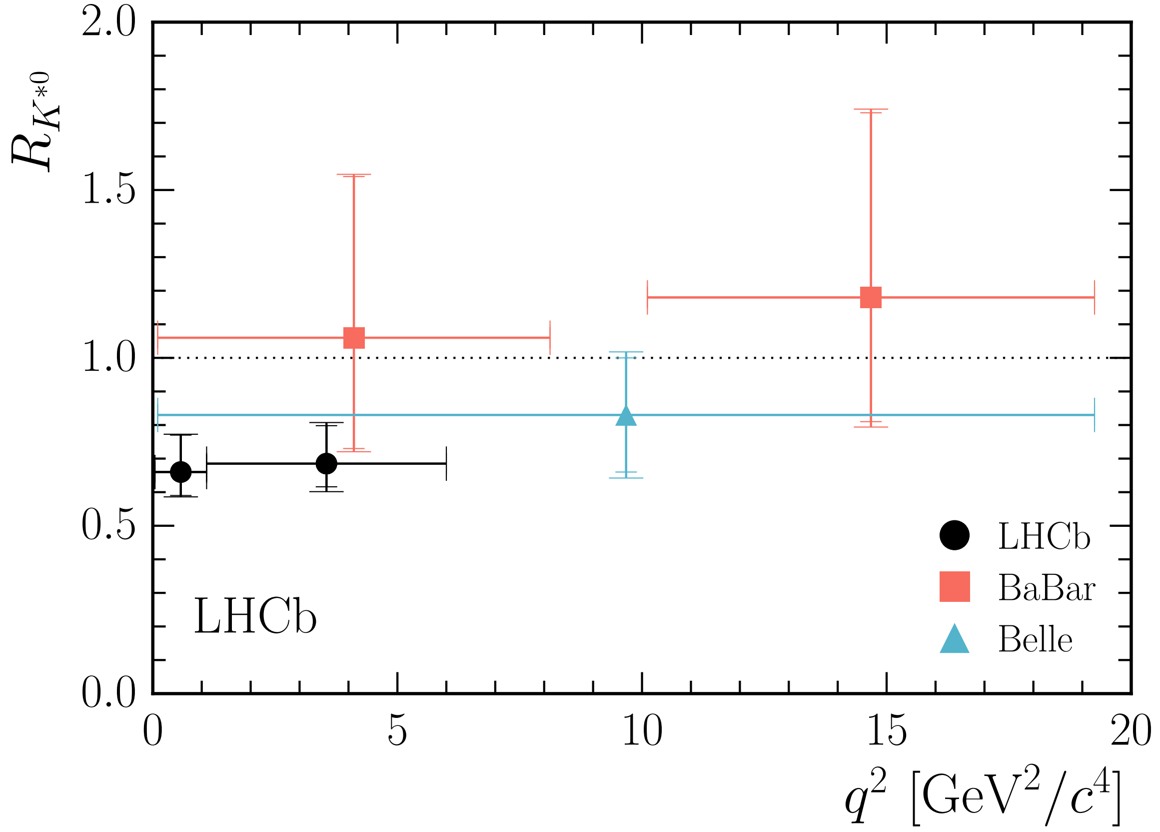
Measurement statistically limited with 3 fb^{-1} of 7 TeV & 8 TeV data

LHCb,1406.6482

Measurements of R_{K^*}

LHCb, 1705.05802



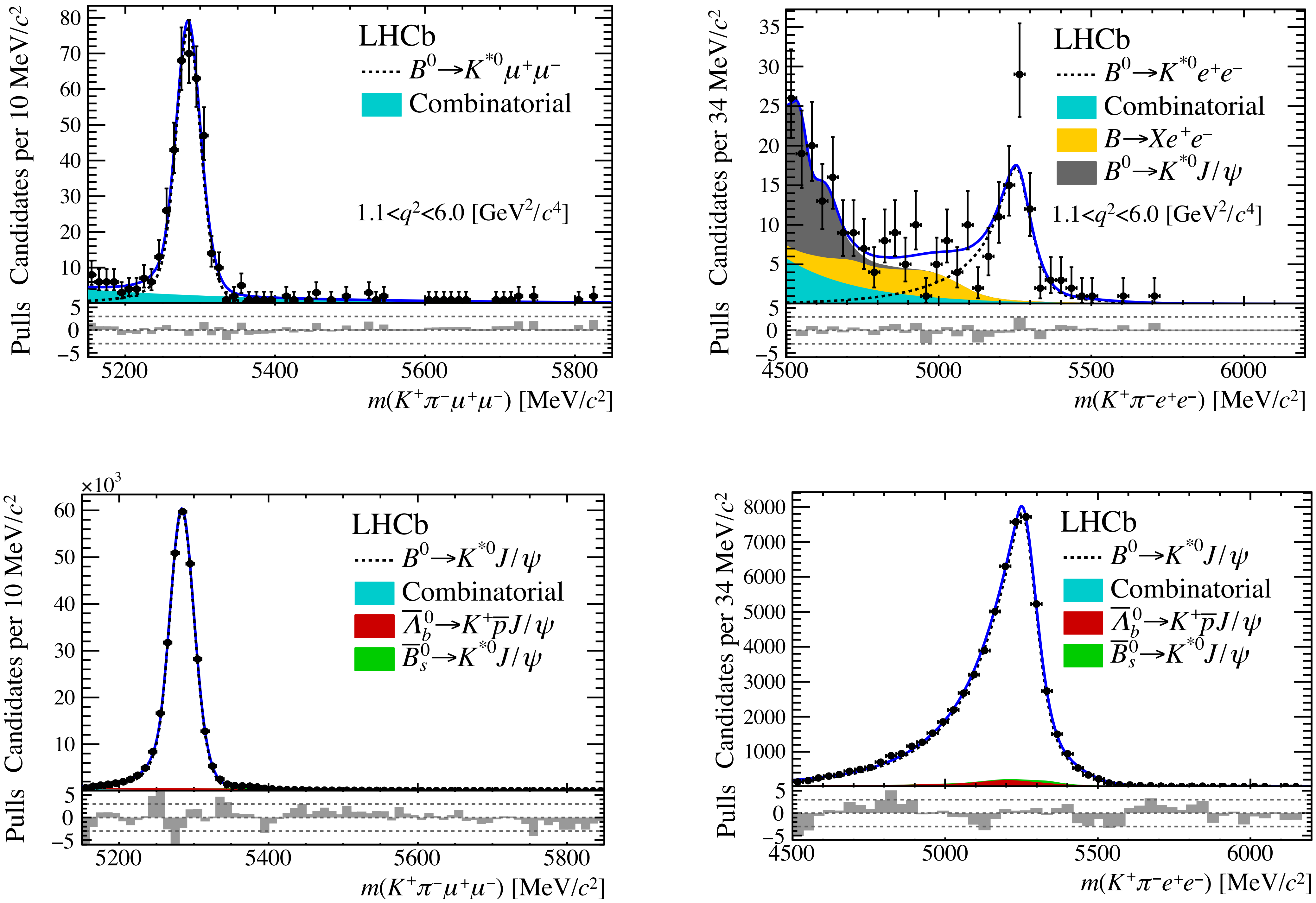


$$R_{K^*}(0.045\,\mathrm{GeV}^2, 1.1\,\mathrm{GeV}^2) = 0.66\,{}^{+0.11}_{-0.07}{}_{\mathrm{stat}} \pm 0.03_{\mathrm{syst}}\ ,$$

$$R_{K^*}(1.1\,\mathrm{GeV}^2, 6\,\mathrm{GeV}^2) = 0.69\,{}^{+0.11}_{-0.07}{}_{\mathrm{stat}} \pm 0.05_{\mathrm{syst}}$$

LHCb sees 2.1σ (2.4σ) deviation in low-q^2 (central-q^2) bin from SM

How is $R_{K^{(*)}}$ actually measured?

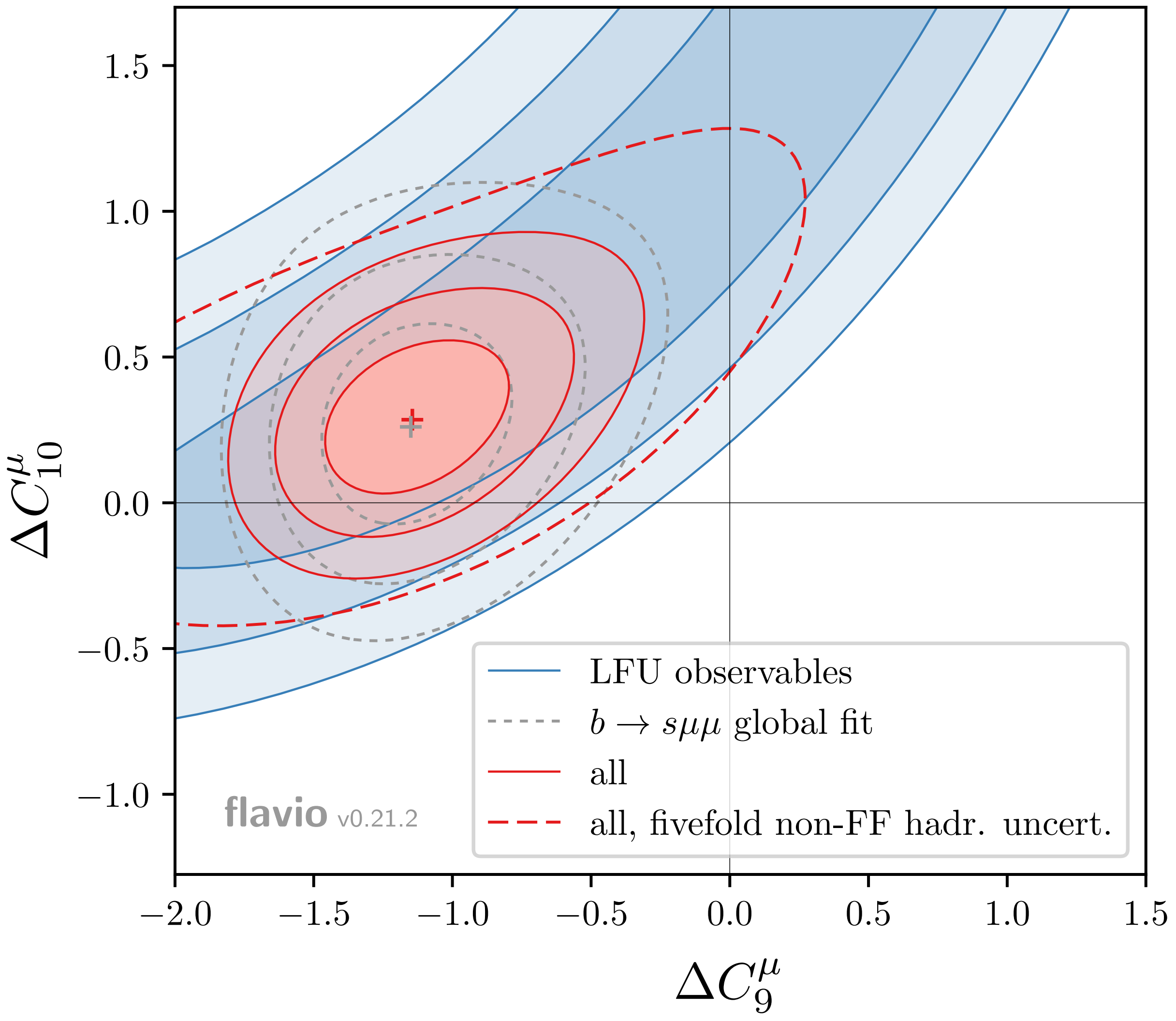

LHCb,1705.05802

How is $R_{K^{(*)}}$ actually measured?

Since LHCb performance in detecting electrons is by a factor of around 5 weaker than detection efficiency for muons, $R_{K^{(*)}}$ is in practice measured relative to LFU ratio in $B \to K^{(*)} J/\psi\ (\to l^+l^-)$. As a result LHCb measurements involve a significant amount of Monte Carlo extrapolations between signals in different phase-space regions

LHCb updates eagerly awaited & are expected to shed further light on hints of LFU violation in $b \to sl^+l^-$ modes. Future Belle-II test of LFU are also crucial. To which extent can ATLAS & CMS contribute?

Model-independent interpretations



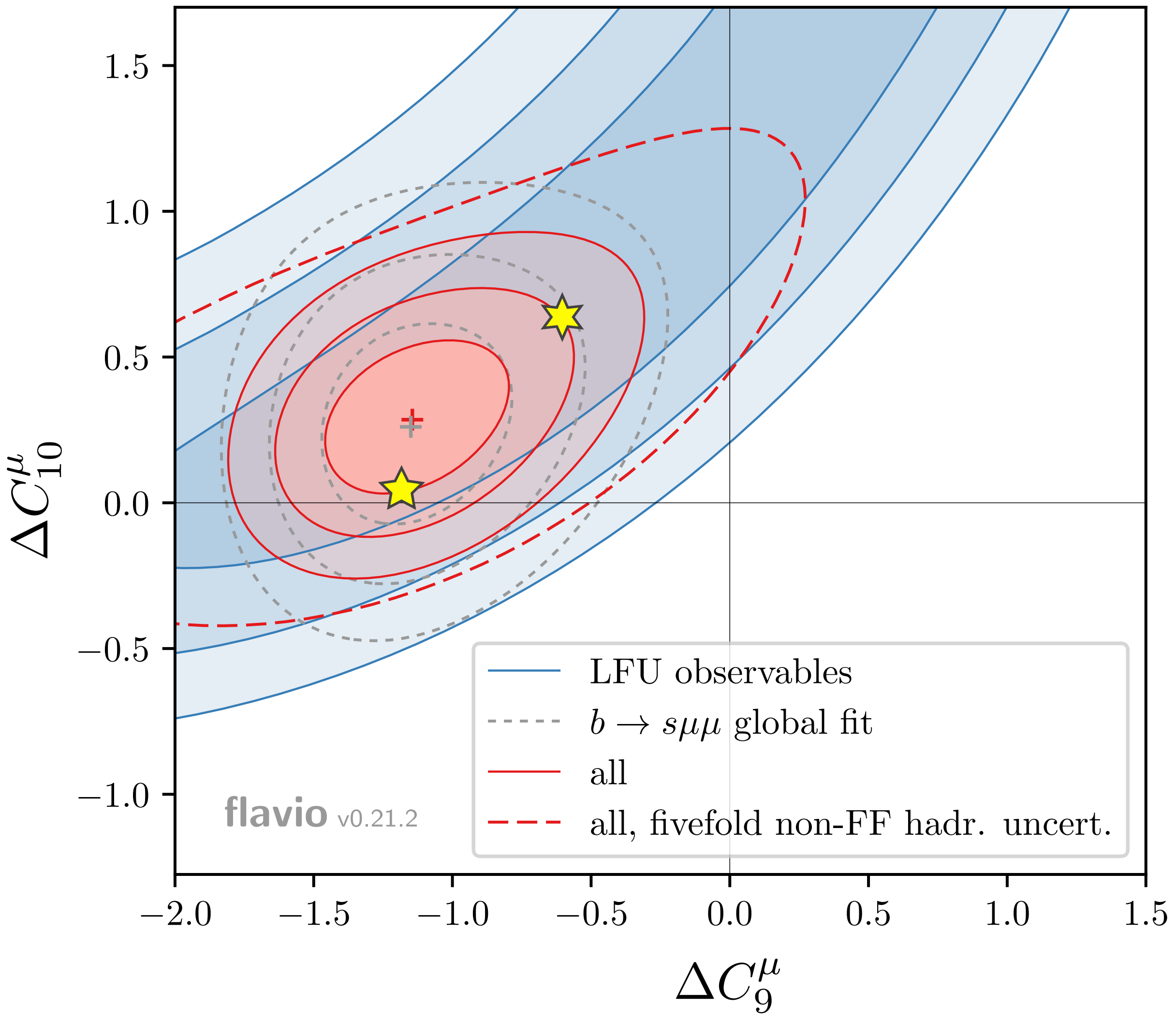
$$\Delta C_9^{\mu}\,(\bar{s}_L\gamma_\alpha b_L)(\bar{\mu}\gamma^\alpha\mu)\,,$$

$$\Delta C_{10}^{\mu}\,(\bar{s}_L\gamma_\alpha b_L)(\bar{\mu}\gamma^\alpha\gamma_5\mu)$$

Intriguingly, LHCb values of $R_{K^{(*)}}$ are fully compatible with new-physics interpretations of various other anomalies (P_5',…) in b → sl^+l^- transitions

Altmannshofer, Stangl & Straub, 1704.05435 & similar results by many others

Model-independent interpretations



$$\Delta C_9^{\mu}\,(\bar{s}_L\gamma_\alpha b_L)(\bar{\mu}\gamma^\alpha\mu)\,,$$

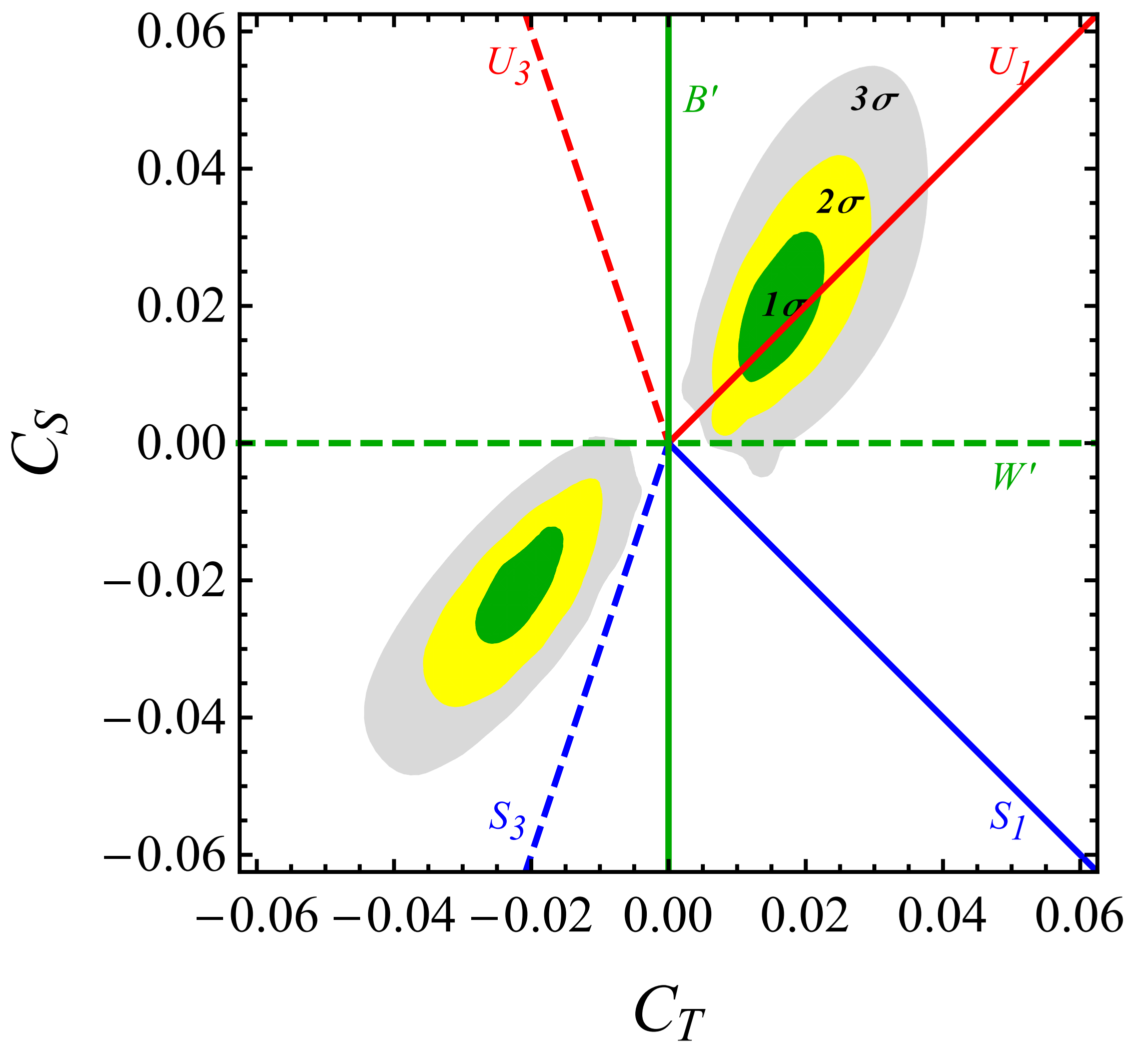
$$\Delta C_{10}^{\mu}\,(\bar{s}_L\gamma_\alpha b_L)(\bar{\mu}\gamma^\alpha\gamma_5\mu)$$

Two simple explanations that are particularly interesting for model-building are provided by $\Delta C_9^{\mu} \simeq -1.2$ & $\Delta C_9^{\mu} = -\Delta C_{10}^{\mu} \simeq -0.6$

Altmannshofer, Stangl & Straub, 1704.05435 & similar results by many others

Simplified models for B anomalies

$$\lambda^q_{ij}\lambda^l_{\alpha\beta}\left(C_T\,(\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L)+C_S\,(\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)\right)$$



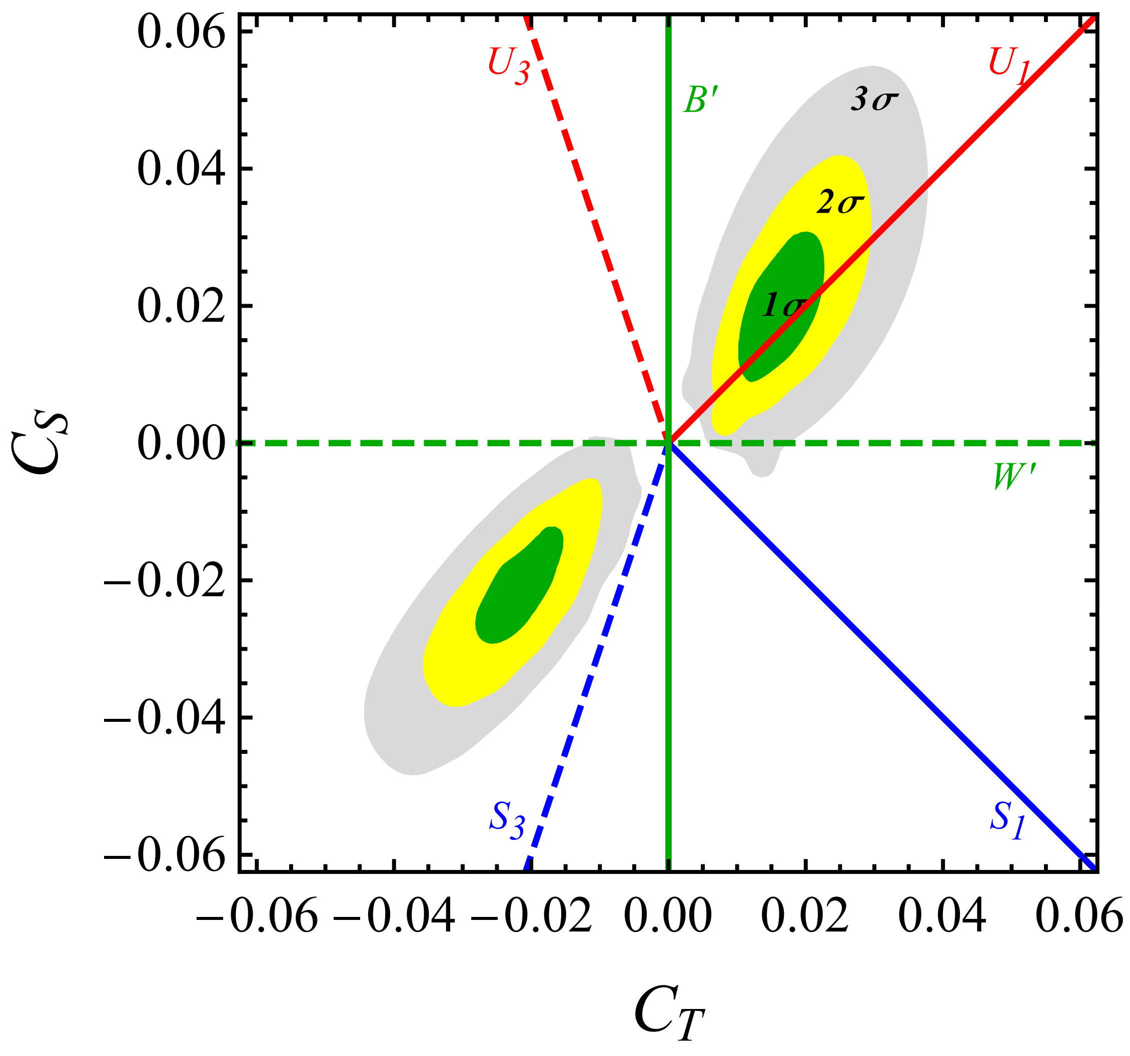
Model	Mediator	$b \to s$	$b \to c$
Colorless vectors	$B' = (1,1,0)$	✓	✗
	$W' = (1,3,0)$	✗	✓
Scalar leptoquarks	$S_1 = (\bar{3},1,1/3)$	✗	✓
	$S_3 = (\bar{3},3,1/3)$	✓	✗
Vector leptoquarks	$U_1 = (3,1,2/3)$	✓	✓
	$U_3 = (3,3,2/3)$	✓	✗

Vector leptoquark (LQ) U_1 only single-mediator model that can explain both sets anomalies

See for instance Buttazzo et al., 1706.07808

Simplified models for B anomalies

$$\lambda^q_{ij}\lambda^l_{\alpha\beta}\left(C_T\,(\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L)+C_S\,(\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)\right)$$



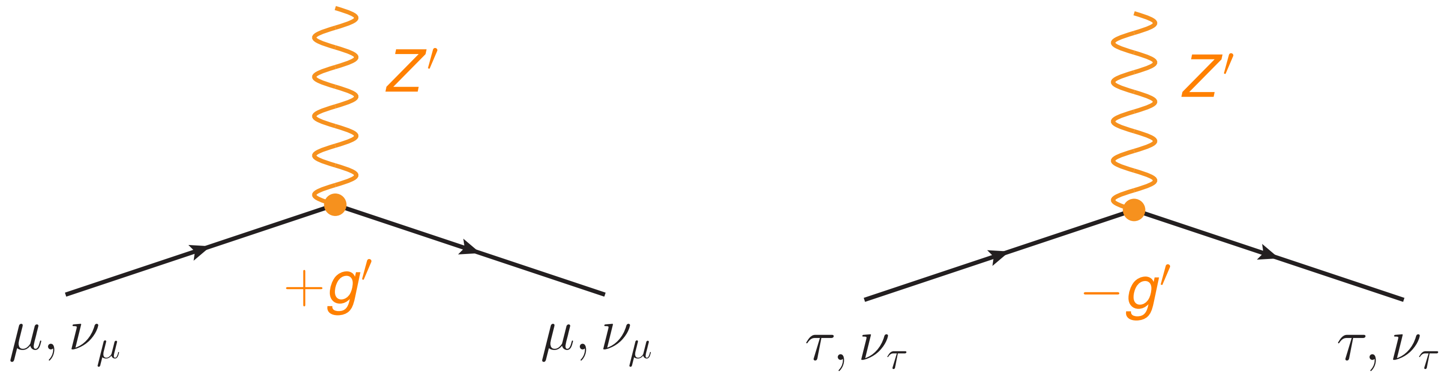
Model	Mediator	$b \to s$	$b \to c$
Colorless vectors	$B' = (1,1,0)$	✓	✗
	$W' = (1,3,0)$	✗	✓
Scalar leptoquarks	$S_1 = (\bar{3},1,1/3)$	✗	✓
	$S_3 = (\bar{3},3,1/3)$	✓	✗
Vector leptoquarks	$U_1 = (3,1,2/3)$	✓	✓
	$U_3 = (3,3,2/3)$	✓	✗

b → s (b → c) anomalies alone can be explained by several simple single-mediator models

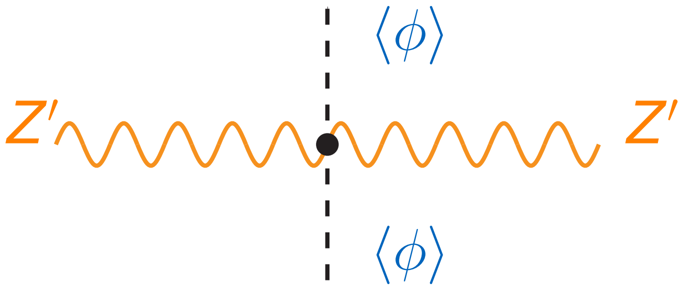
See for instance Buttazzo et al., 1706.07808

Minimal L_μ - L_τ model

L_μ - L_τ anomaly free with SM matter content. Gauging L_μ - L_τ gives Z′ with vectorial couplings to μ, τ & corresponding ν:



Z′ mass from a scalar ϕ that spontaneously breaks L_μ - L_τ:

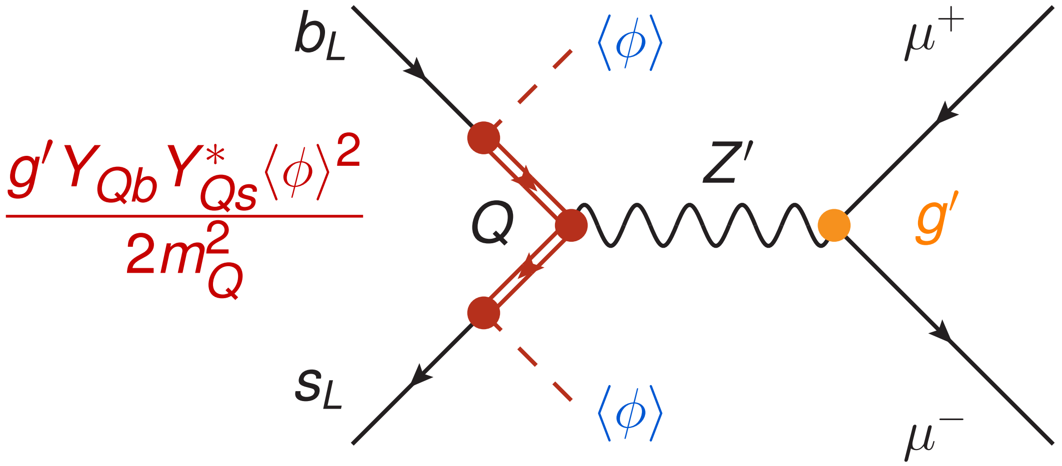


$$m_{Z'} = g'\langle\phi\rangle$$

He et al. Phys. Rev. D43 (1991) 22

Extended L_μ - L_τ model

Add vector-like quarks with masses of O(few TeV) to model to generate flavour-violating interactions:

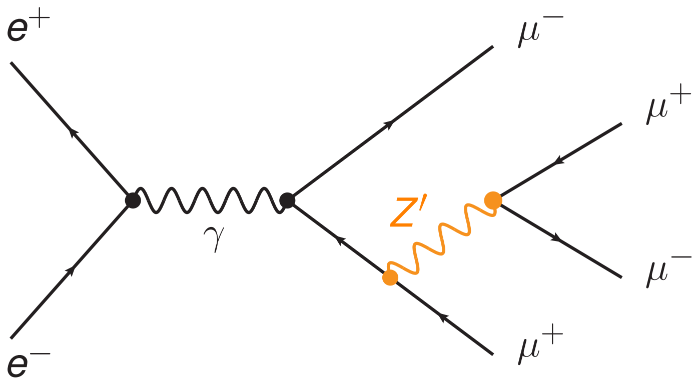


$$\Delta C_9^\mu = \frac{Y_{Qb} Y^*_{Qs}}{2m_Q^2}$$

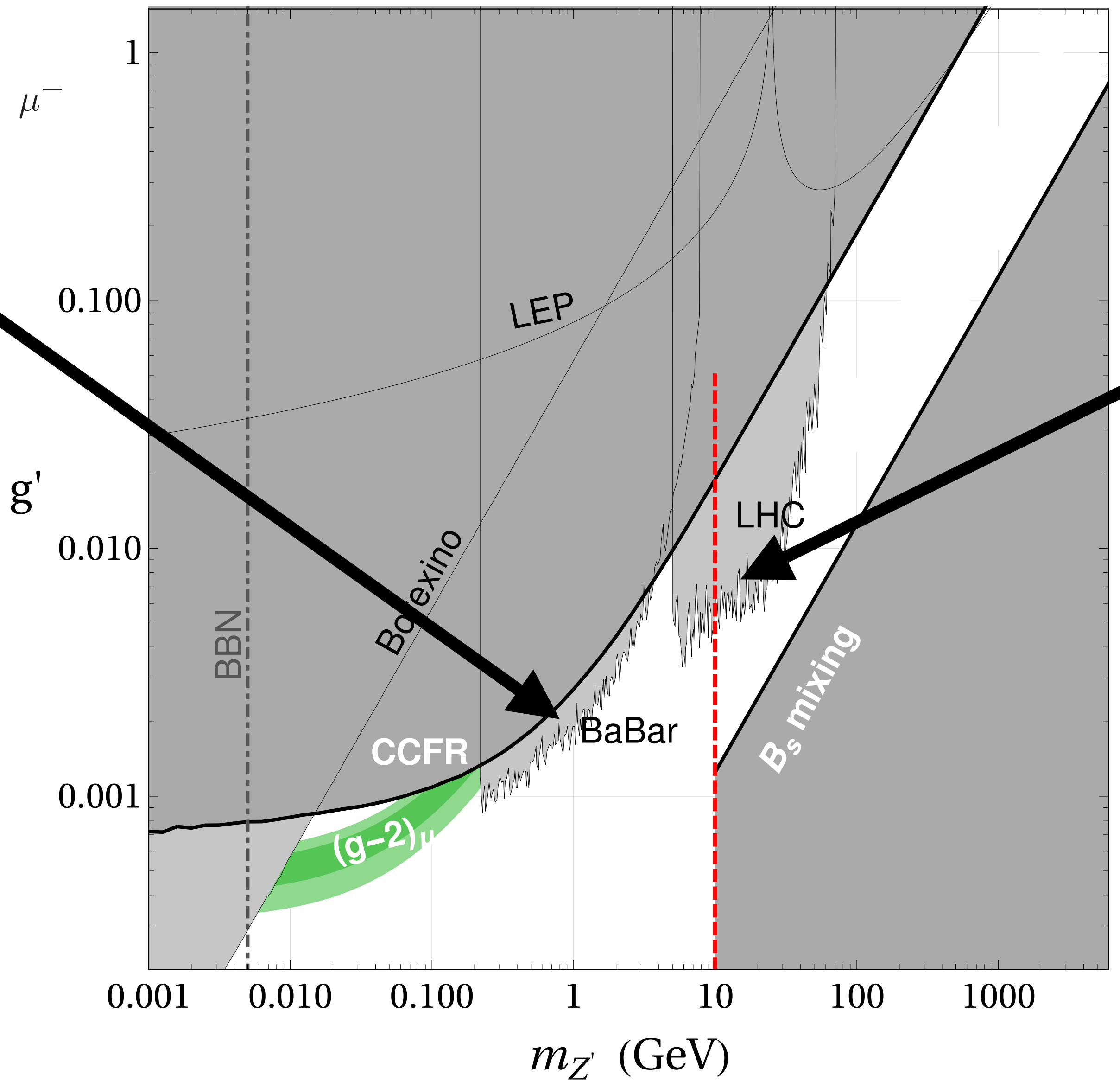
Couplings (Y_{Qq}) of light SM quarks q & vector-like quarks Q assumed to be small to suppress pp → Z′ → $\mu^+\mu^-$ rates

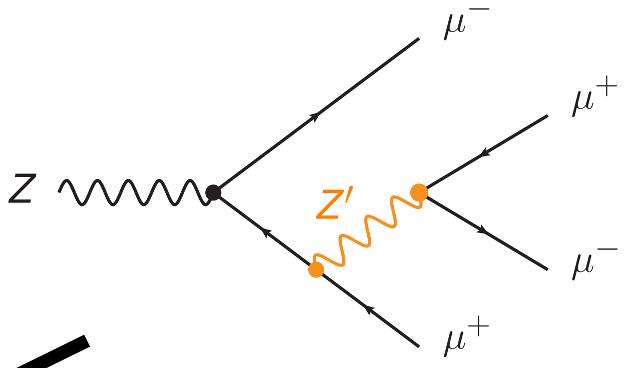
Altmannshofer et al., 1403.1269

Phenomenology of L_μ - L_τ model



excluded by BaBar searches for 4μ

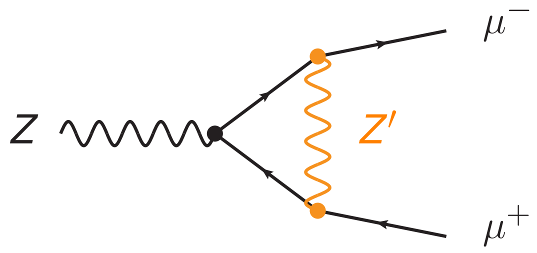




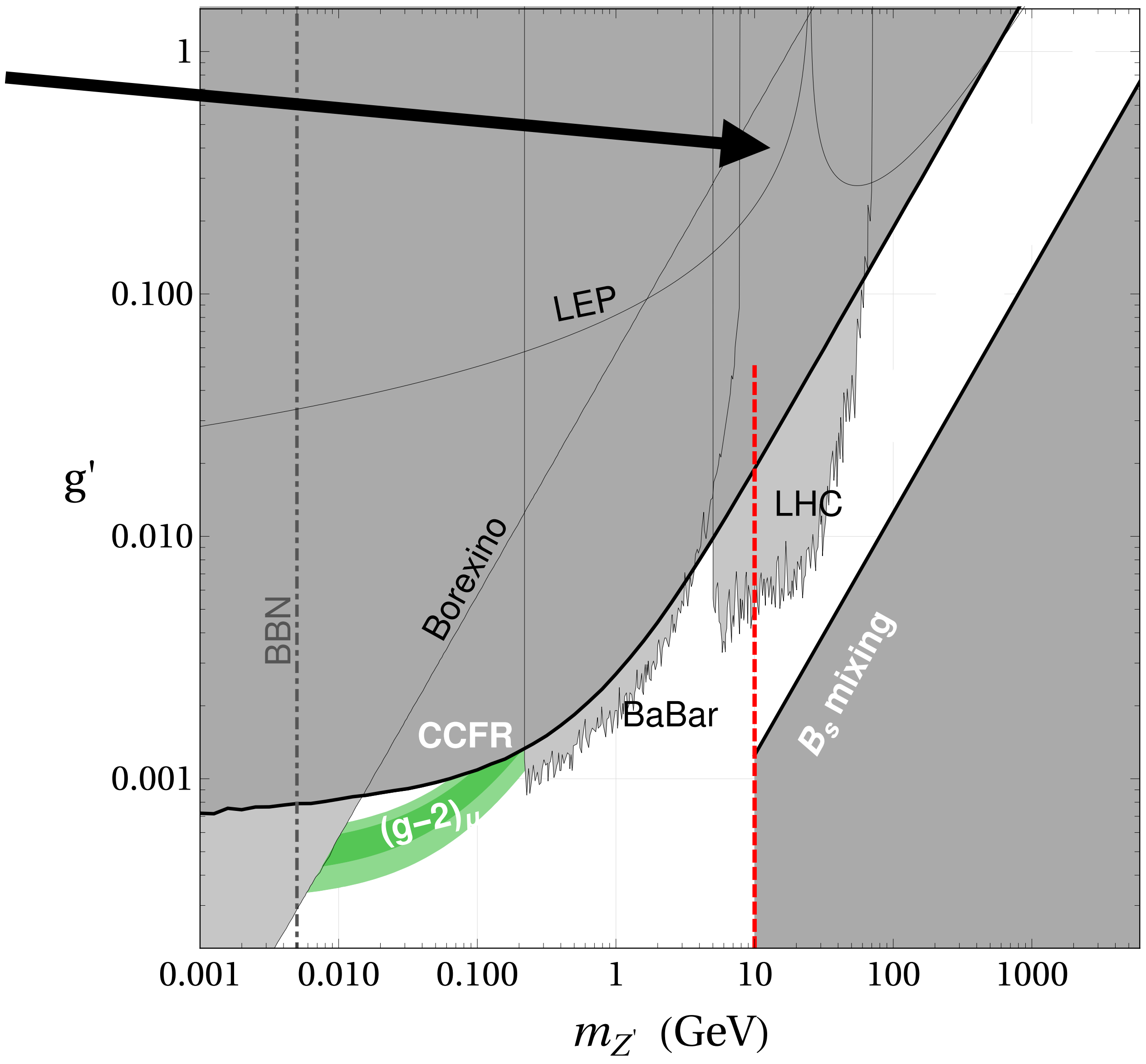
excluded by LHC searches for 4μ

Altmannshofer et al., 1403.1269; Altmannshofer & Yavin, 1508.07009

Phenomenology of $L_\mu - L_\tau$ model

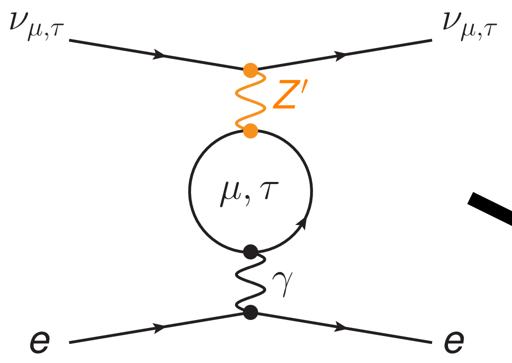


excluded by LEP
Z-pole measurements

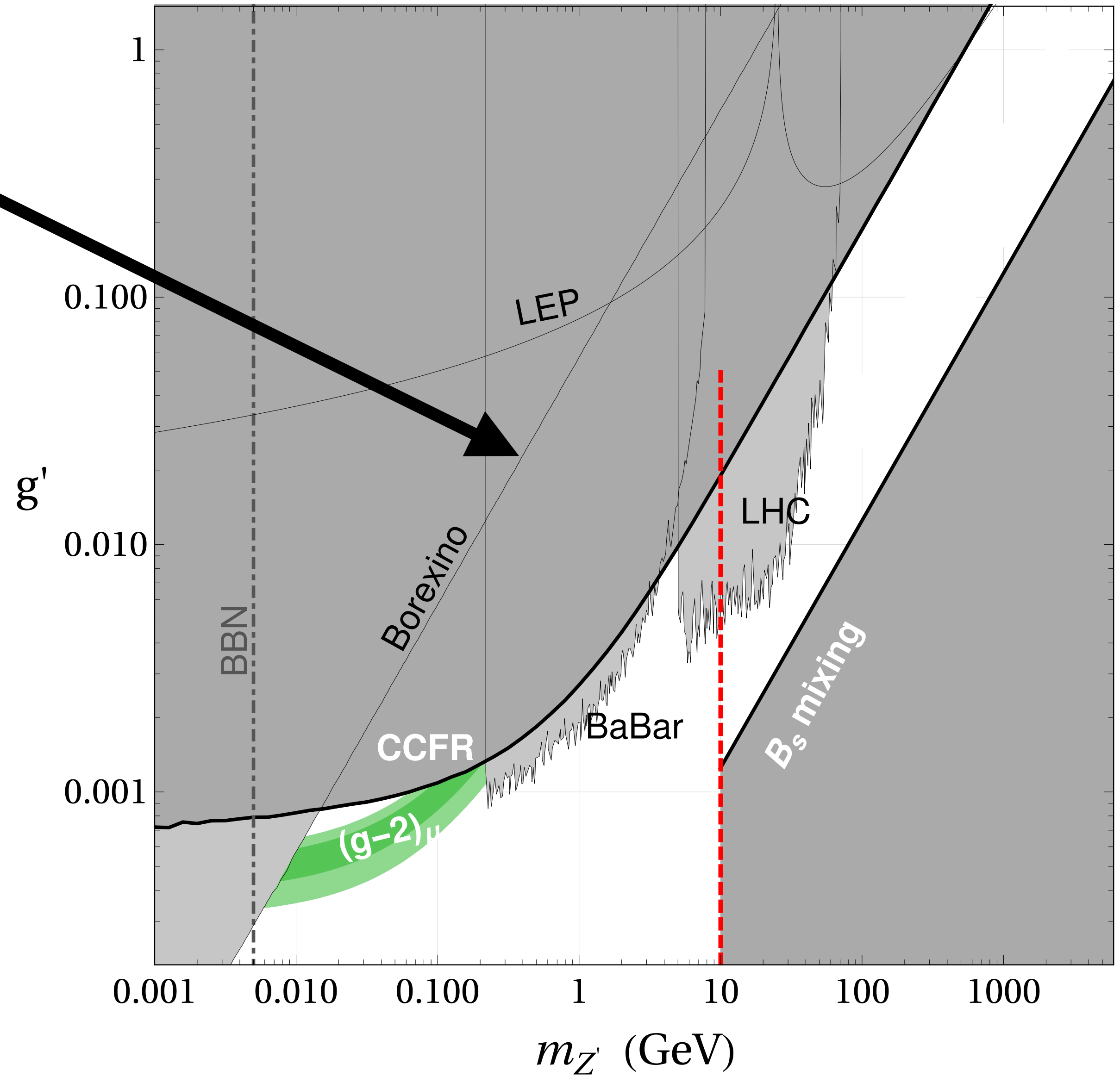


Altmannshofer et al., 1403.1269; Altmannshofer & Yavin, 1508.07009

Phenomenology of L_μ - L_τ model

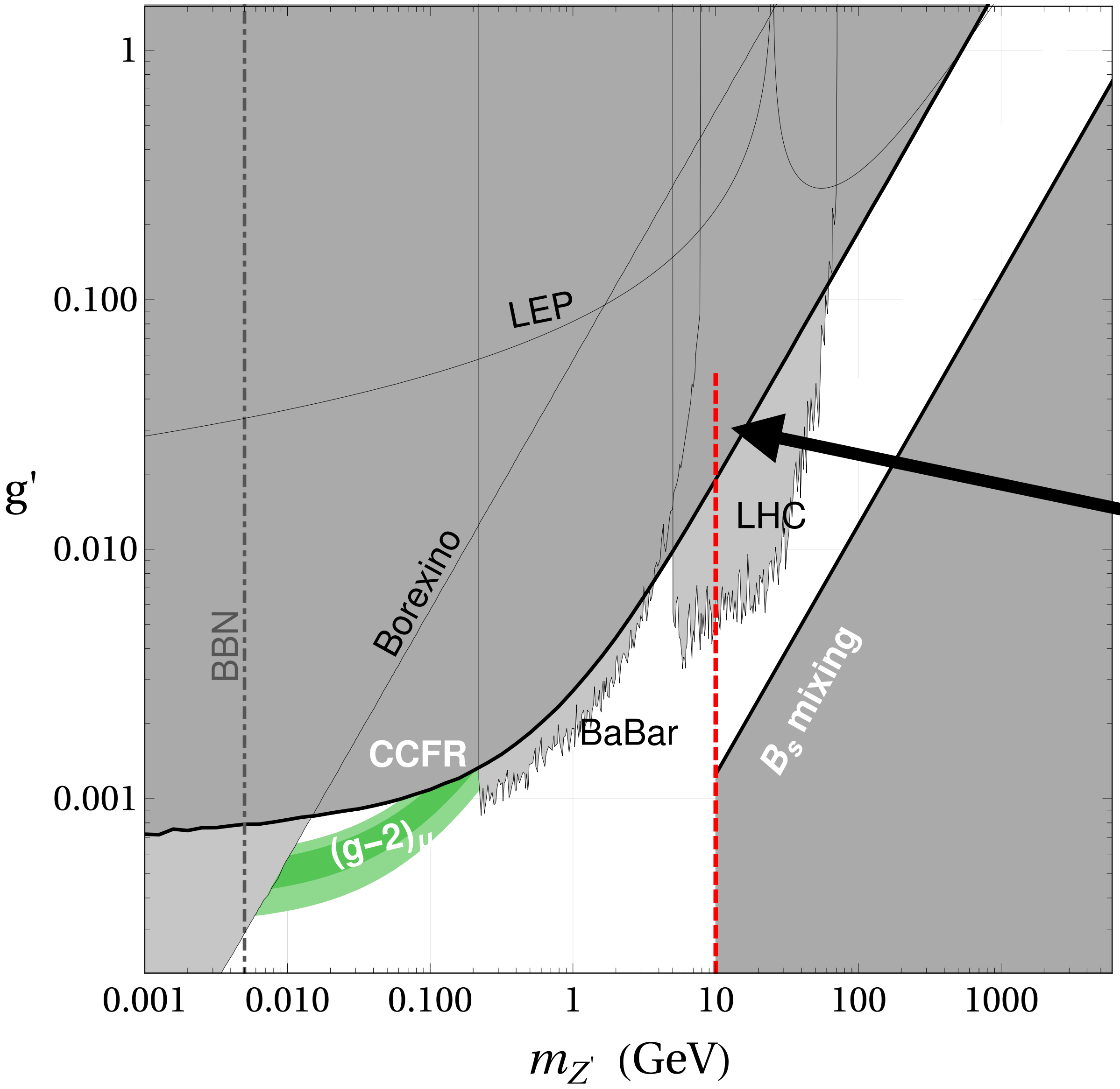


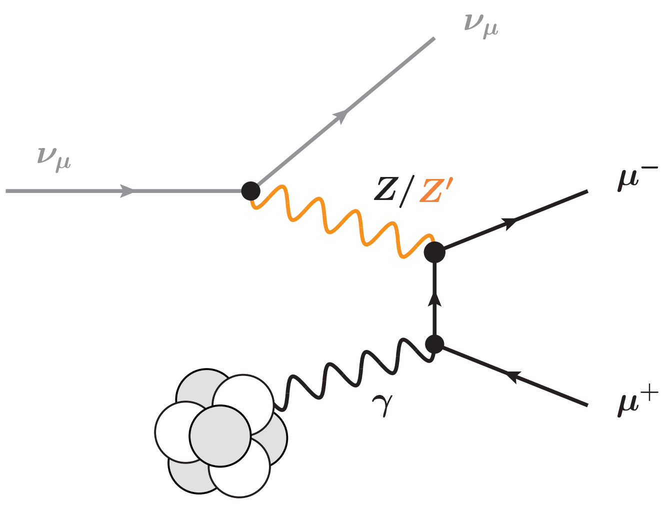
excluded by Borexino measurements of v-e scattering



Altmannshofer et al., 1403.1269; Altmannshofer & Yavin, 1508.07009

Phenomenology of $L_\mu - L_\tau$ model

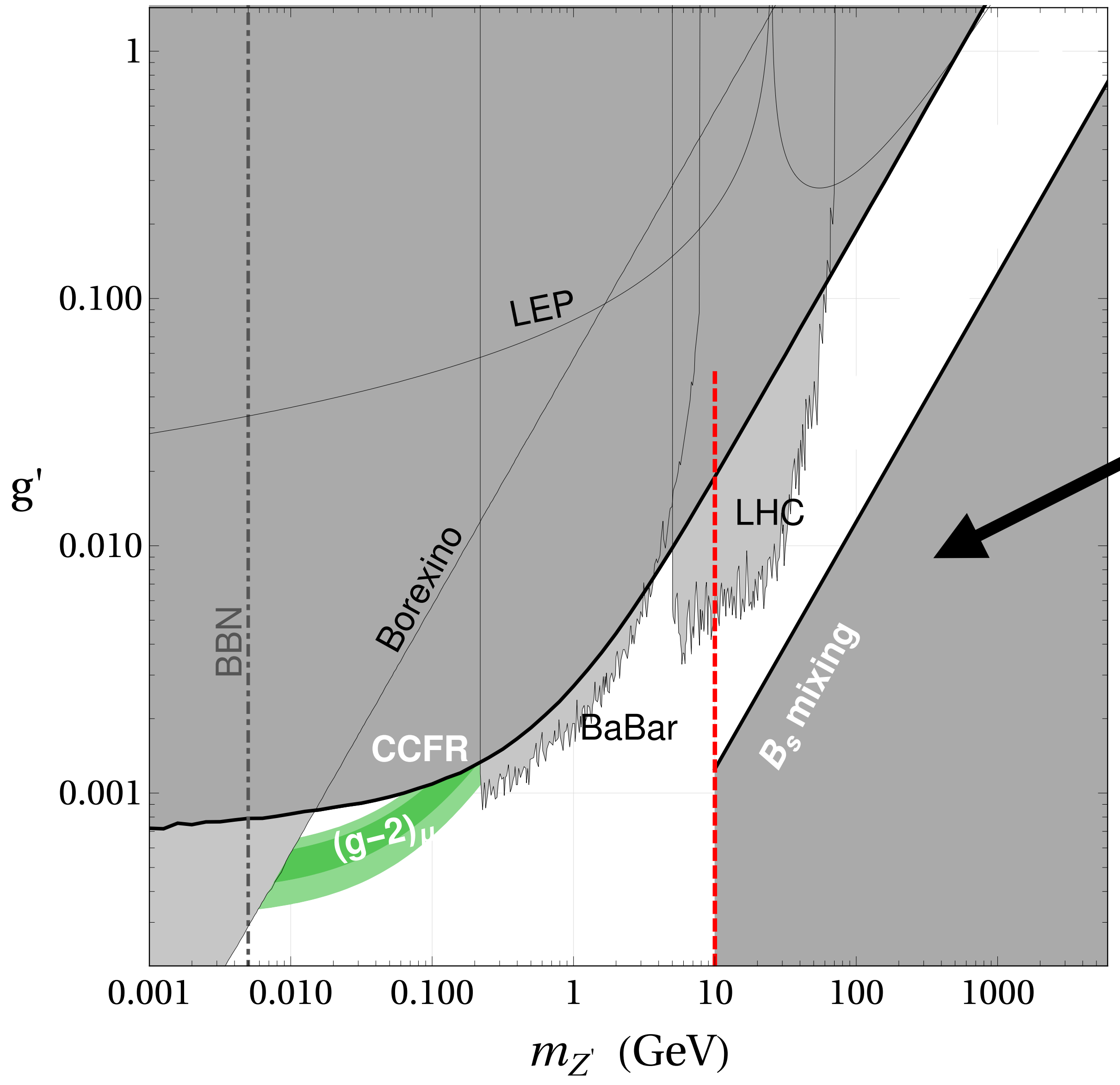


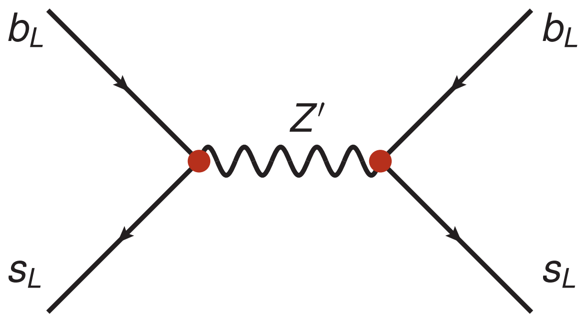


excluded by CCFR measurements of ν trident production

Altmannshofer et al., 1403.1269; Altmannshofer & Yavin, 1508.07009

Phenomenology of $L_\mu - L_\tau$ model

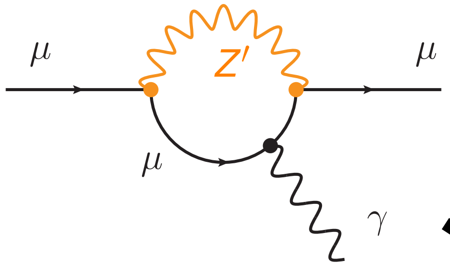




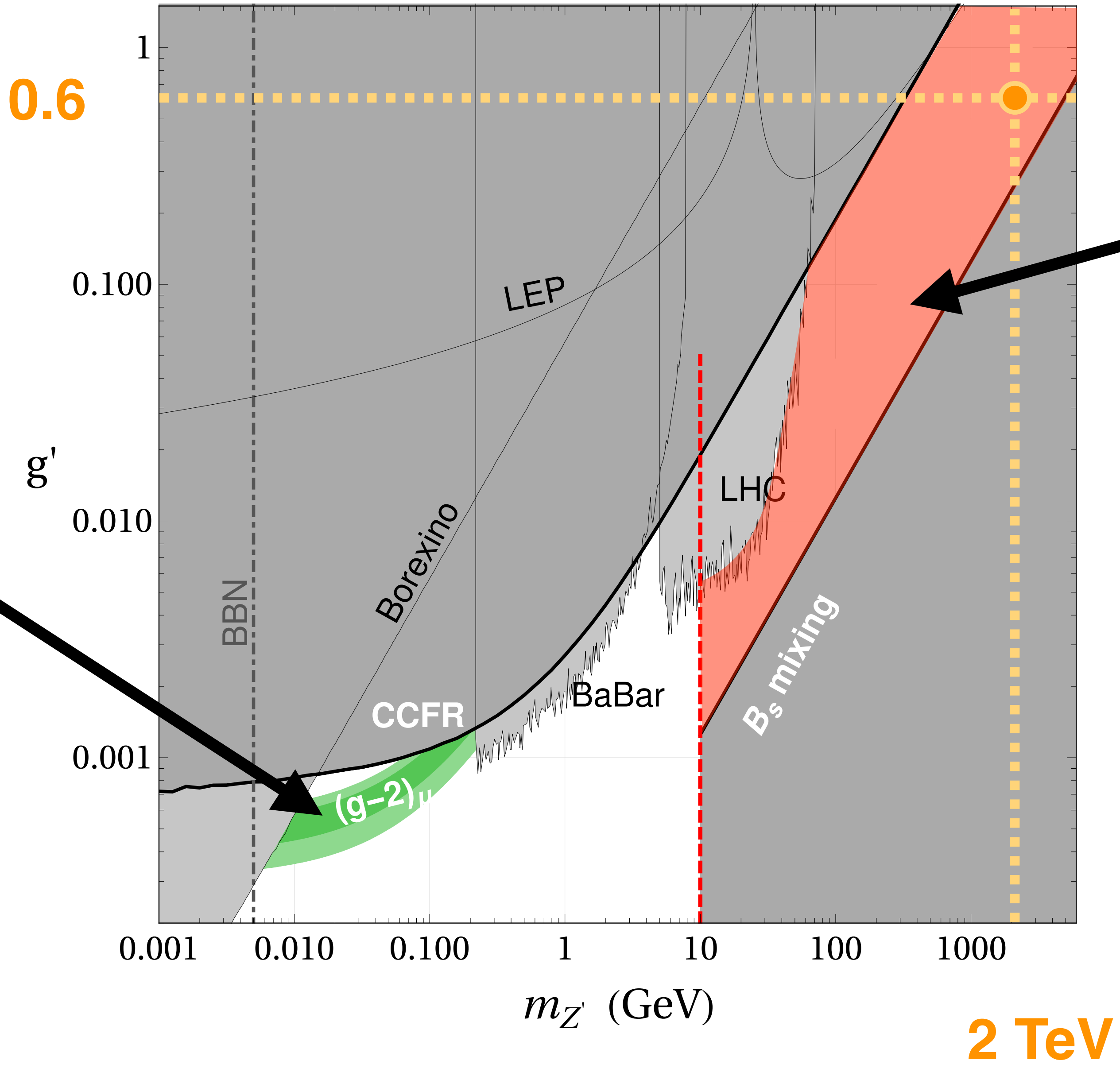
excluded by
constraints from
B_s mixing

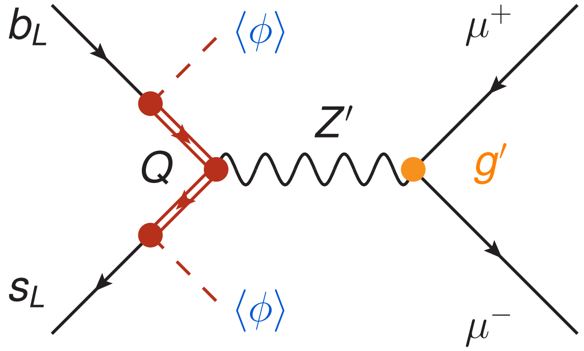
Altmannshofer et al., 1403.1269; Altmannshofer & Yavin, 1508.07009

Phenomenology of $L_\mu - L_\tau$ model



(g-2)$_\mu$ anomaly explained



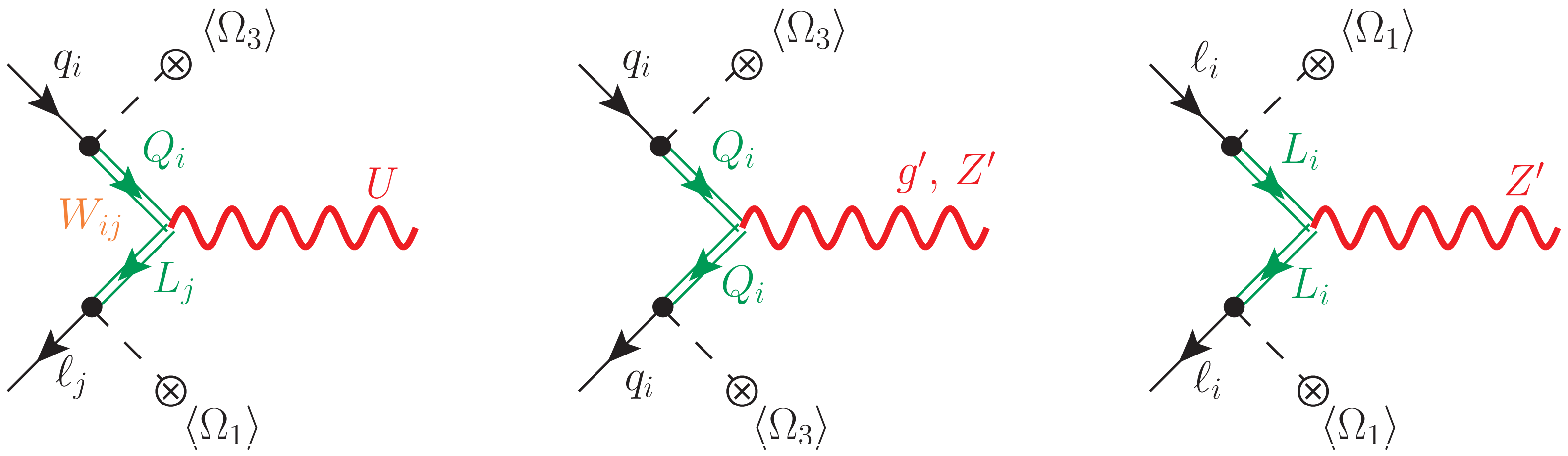


LHCb b → sl$^+$l$^-$ anomalies explained

Altmannshofer et al., 1403.1269; Altmannshofer & Yavin, 1508.07009

Ultraviolet (UV) complete U_1 models

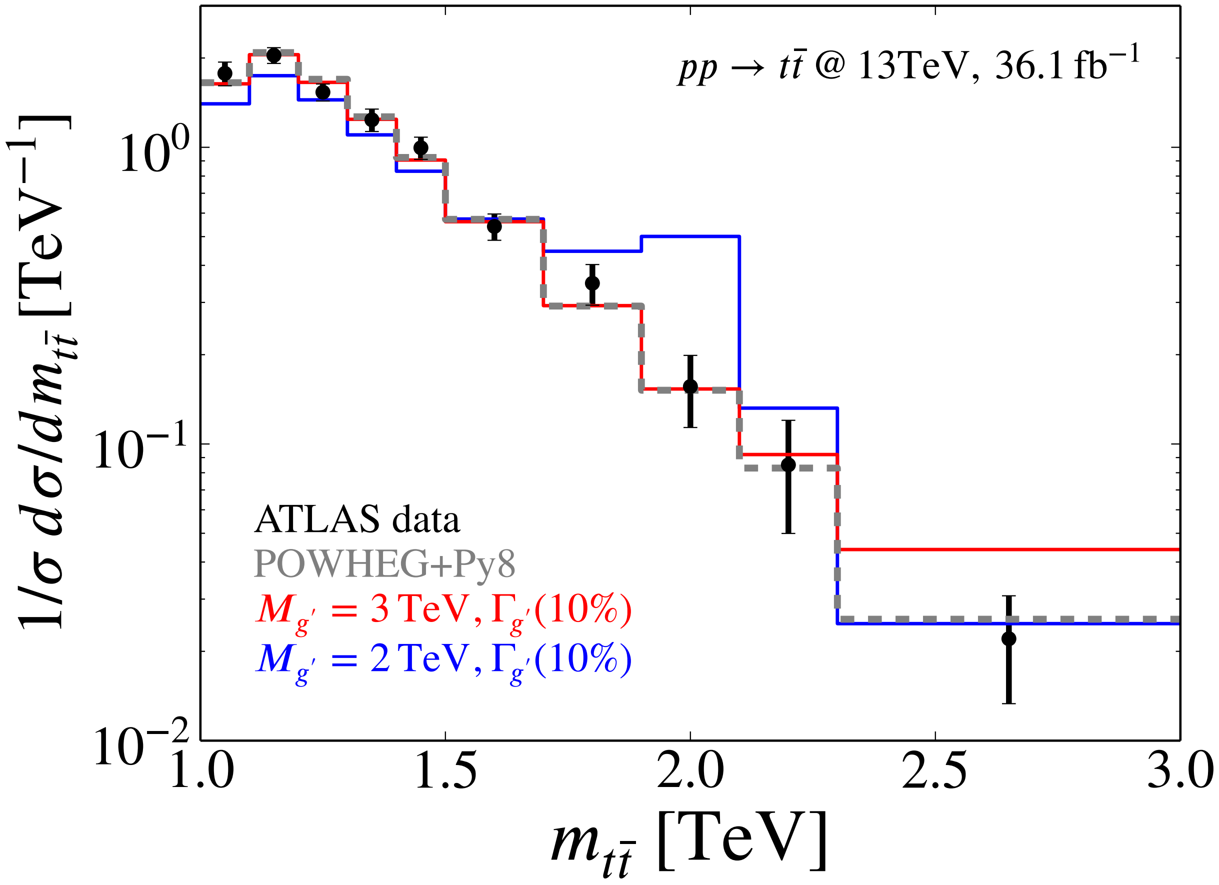
UV-complete realisations of U_1 model generically contain not only vector LQ, but also a heavy (un)coloured vector g′ (Z′), vector-like fermions Q, L & additional scalar states Ω:

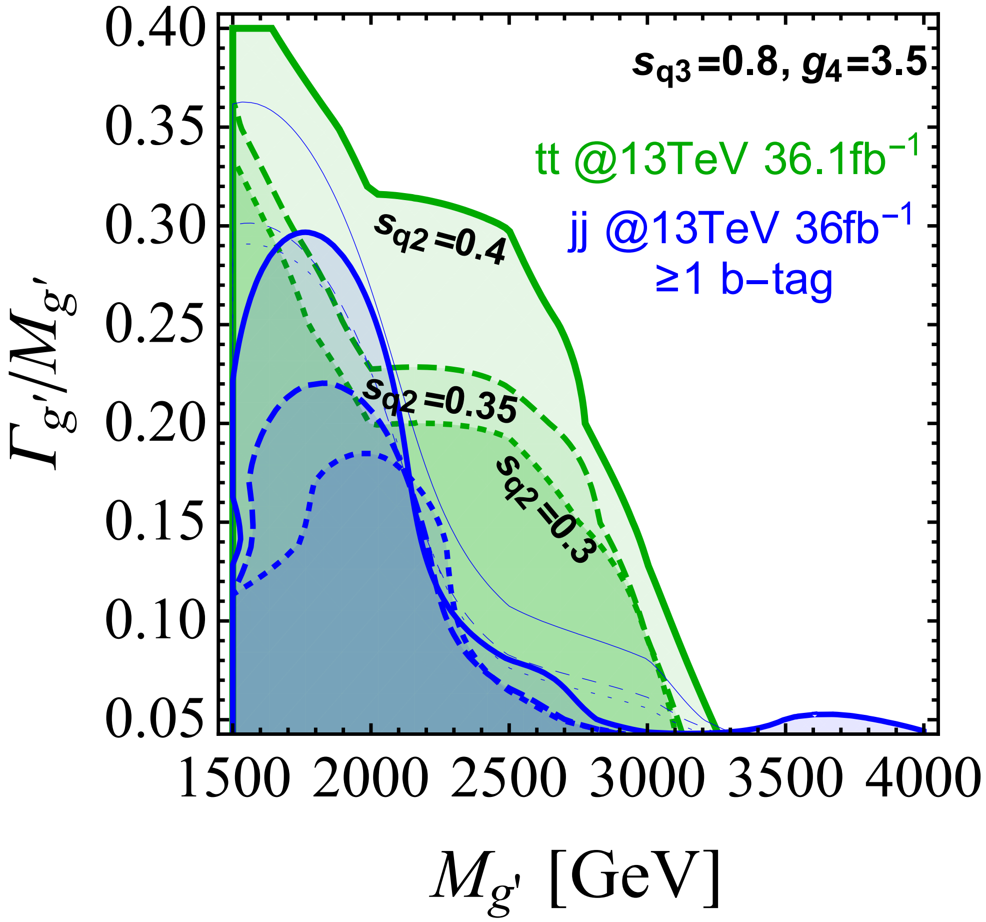


As a result, models predict a vast number of high-p_T signals such as LQ production, pp → g′ → $t\bar{t}$/jj, pp → Z′ → $\tau^+\tau^-$ & a distinct Q, L phenomenology

See for example Di Luzio et al., 1808.0094 & references therein

High-p_T highlights





$t\bar{t}$ searches push models into a regime of large couplings & heavy g′, U_1 & Z′ with masses around 3 TeV, 2.5 TeV & 2 TeV. Models would look more healthy, if deviations in $R_{D^{(*)}}$ would be reduced

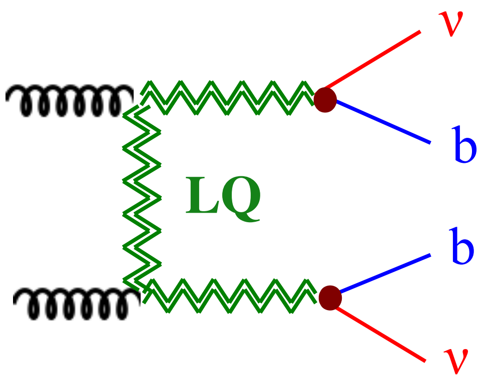
Di Luzio et al., 1808.0094

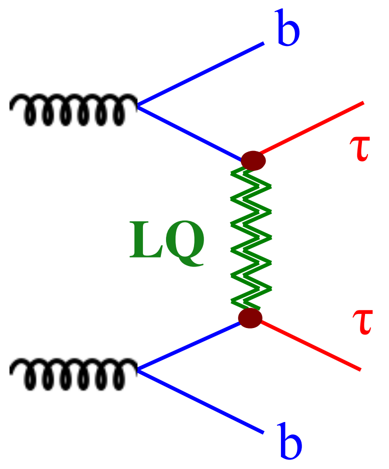
Conclusions

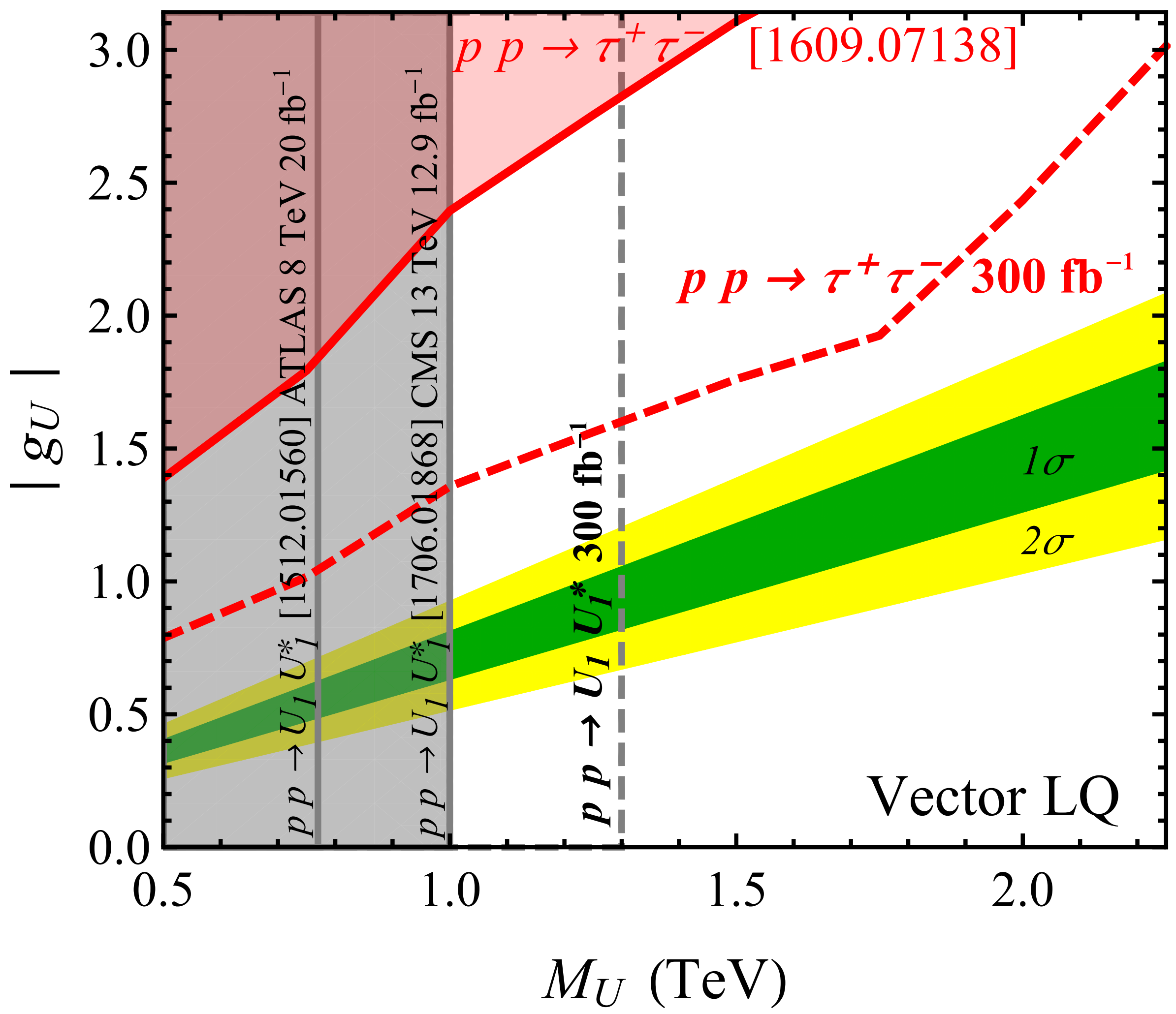
- If hints of LFU violation in B sector were confirmed, it would be a fantastic discovery with far-reaching implications
- In simplified new-physics models, explanations of $b \to s$ and/or $b \to c$ anomalies are possible that are consistent with all other existing low- & high-energy data
- UV-complete models that explain both sets of anomalies are already stress tested by existing high-p_T searches & could lead to striking signatures in upcoming LHC runs
- Only experiment can tell whether B anomalies are real or just a fluke. More low- & high-p_T measurements desperately needed

Backup

Other high-p_T constraints



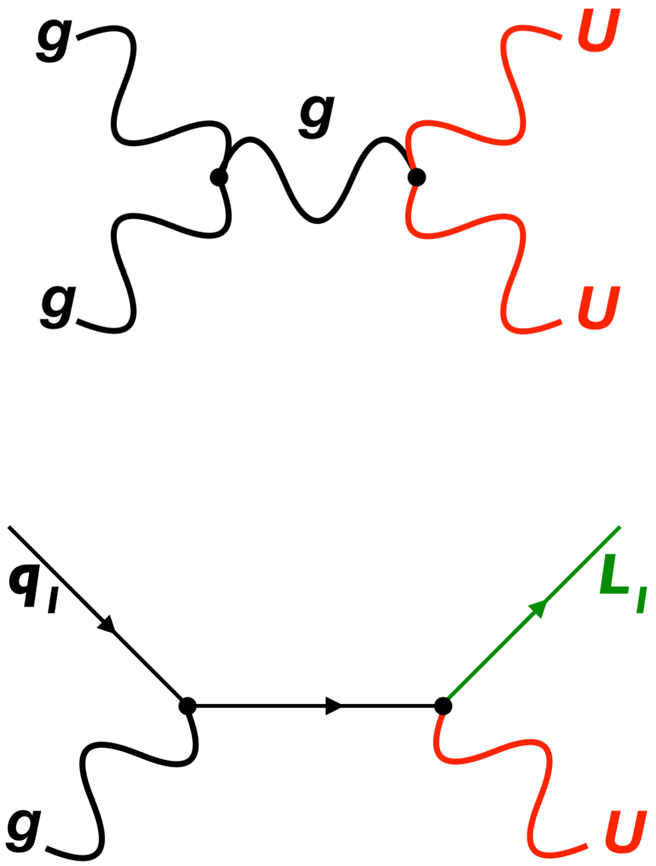


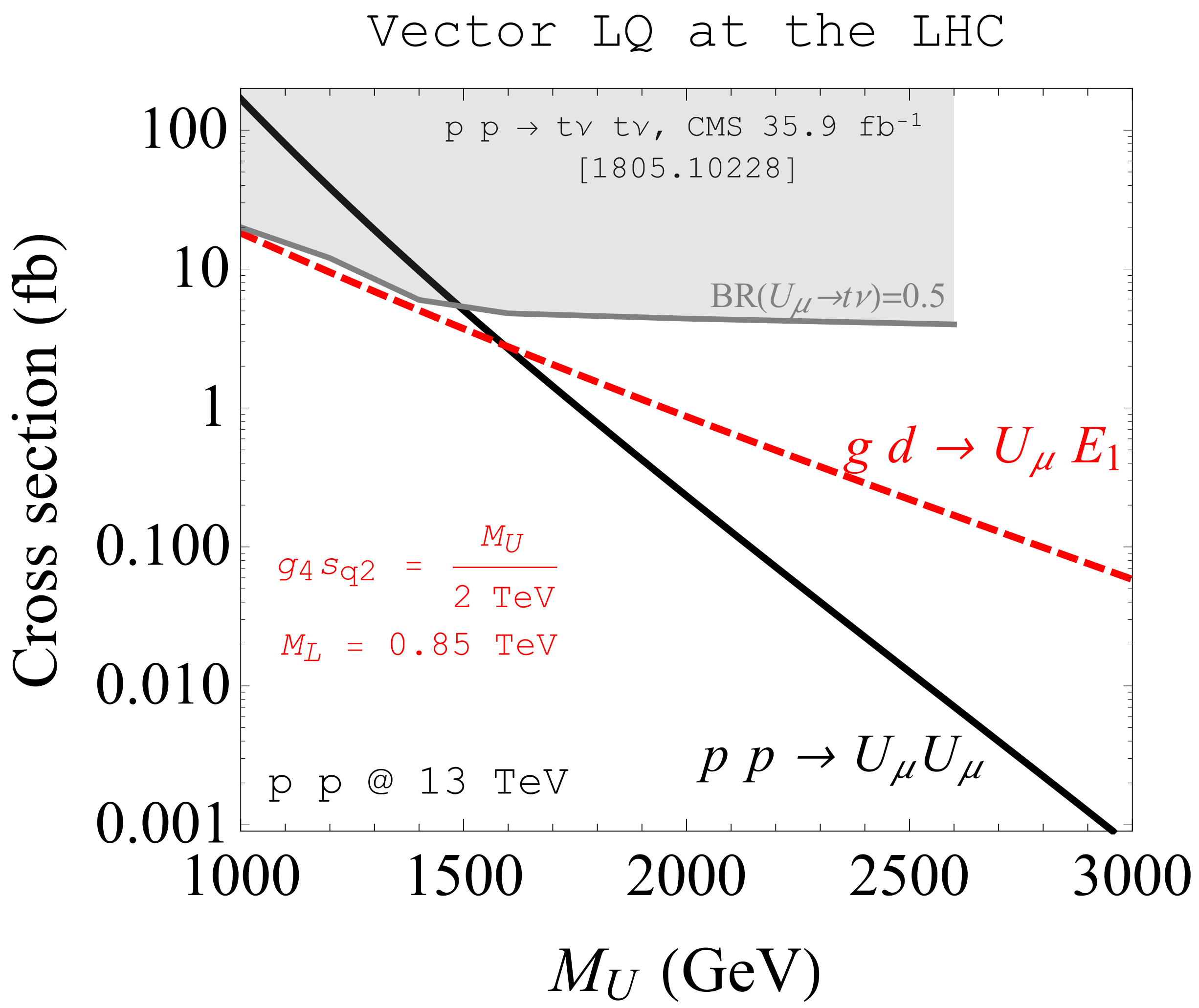


At present, vector LQ models are in good shape when it comes to LHC searches for production of LQ pairs & $\tau^+\tau^-$ final states

Buttazzo et al., 1706.07808

Other high-p_T constraints

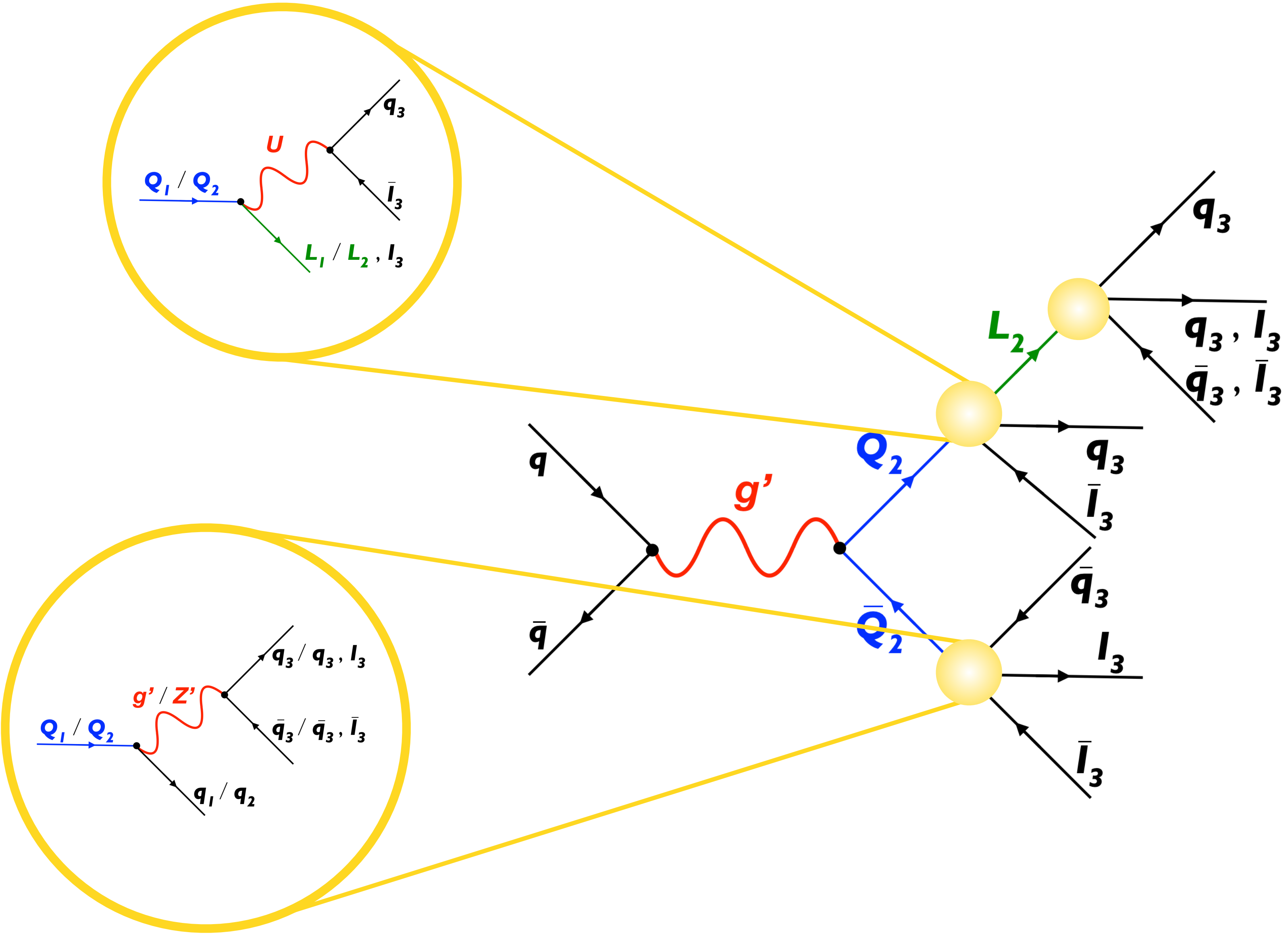




Depending on mass spectrum either pair or associated production can be largest LQ production mode. So far no dedicated LHC searches for single-production of LQ

Buttazzo et al., 1706.07808; Di Luzio et al., 1808.0094

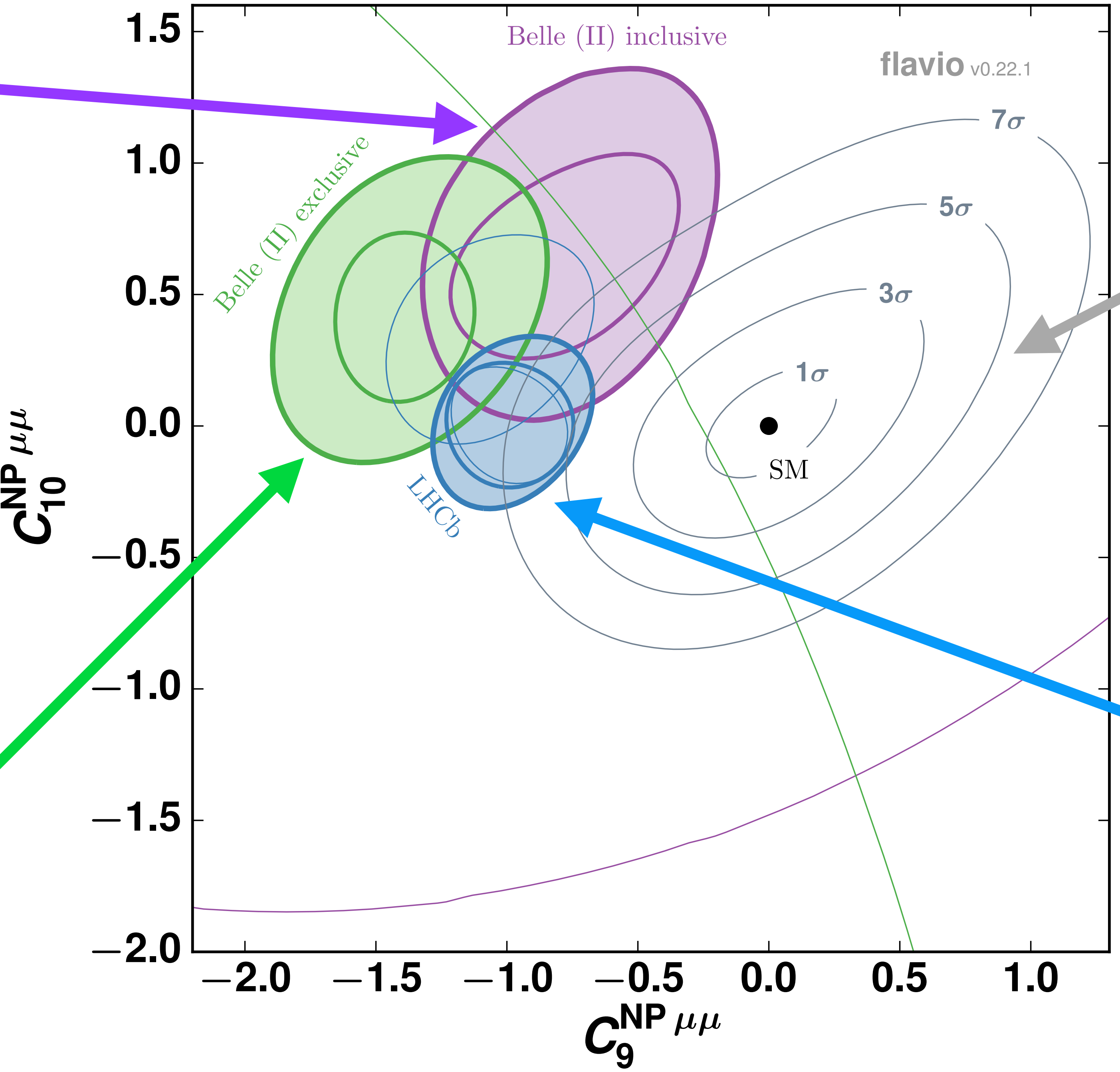
Other high-p_T constraints



Since dominant decays of vector-like fermions are 1 → 3, UV-complete U_1 models can lead to exotic multi-lepton and/or multi-jet signatures

Di Luzio et al., 1808.0094

LHCb vs. Belle-II prospects



inclusive Belle-II
measurements at
5 ab^{-1} & 50 ab^{-1}

combination of
50 fb^{-1} of LHCb
& 50 ab^{-1} of
Belle-II data

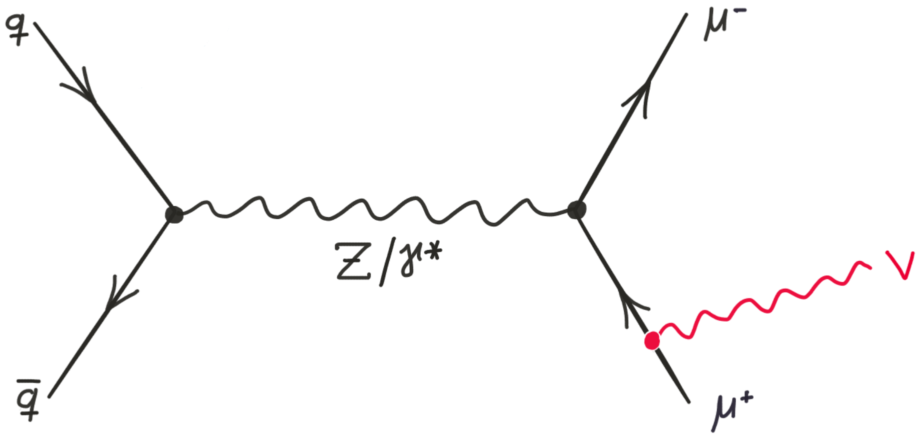
exclusive Belle-II
measurements at
5 ab^{-1} & 50 ab^{-1}

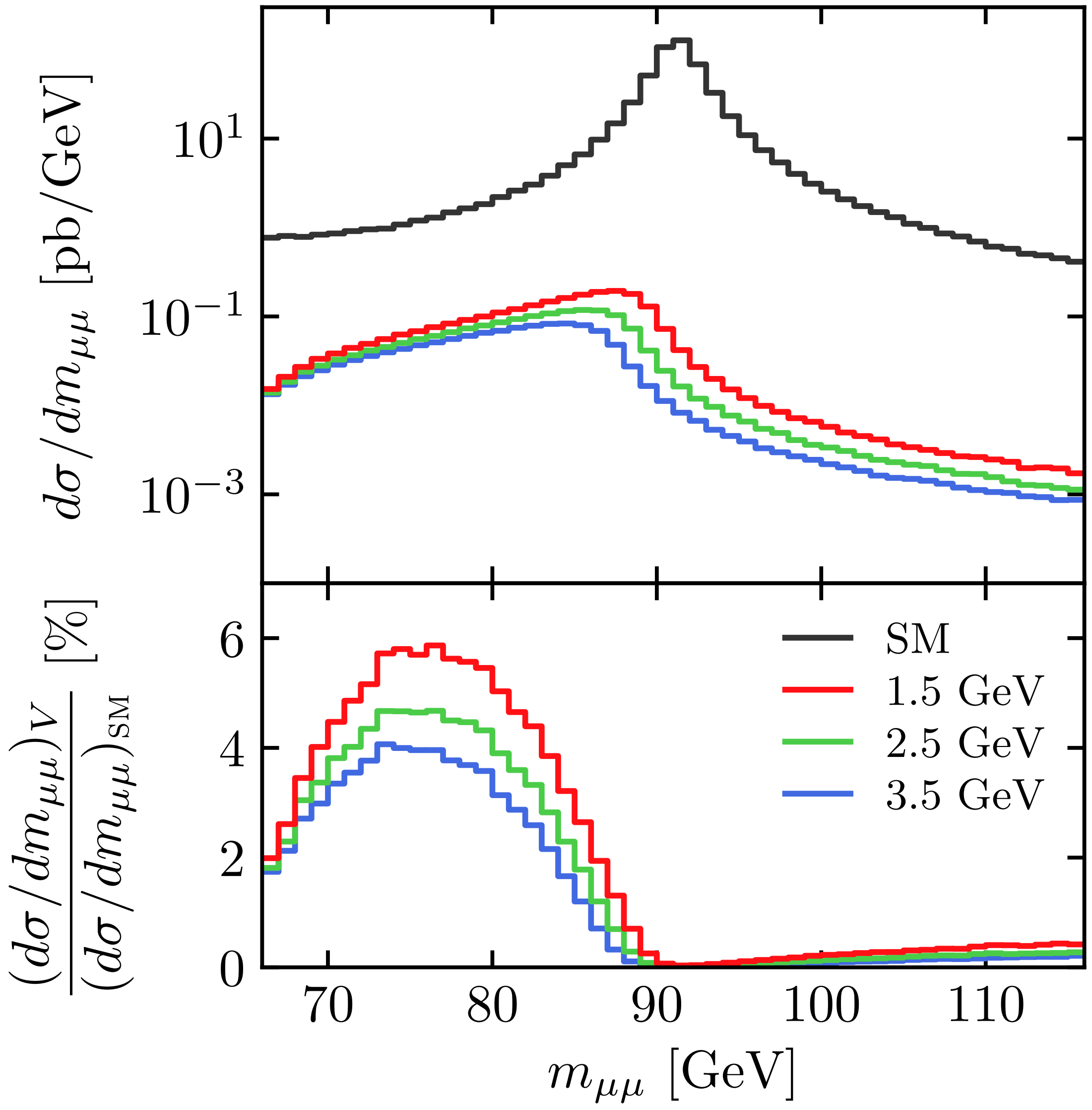
LHCb sensitivity
with 8 fb^{-1}, 22 fb^{-1}
& 50 fb^{-1} of data

Belle-II physics handbook, 1808.10567

Light resonances in b → s$\mu^+\mu^-$

$$\mathcal{L} \supset \left(g_L^{sb}\,\bar{s}_L \not{V} b_L + \text{h.c.}\right) + \bar{\mu}\left(g_V^{\mu} - g_A^{\mu}\gamma_5\right)\not{V}\mu + g_V^{\chi}\,\bar{\chi}\not{V}\chi$$

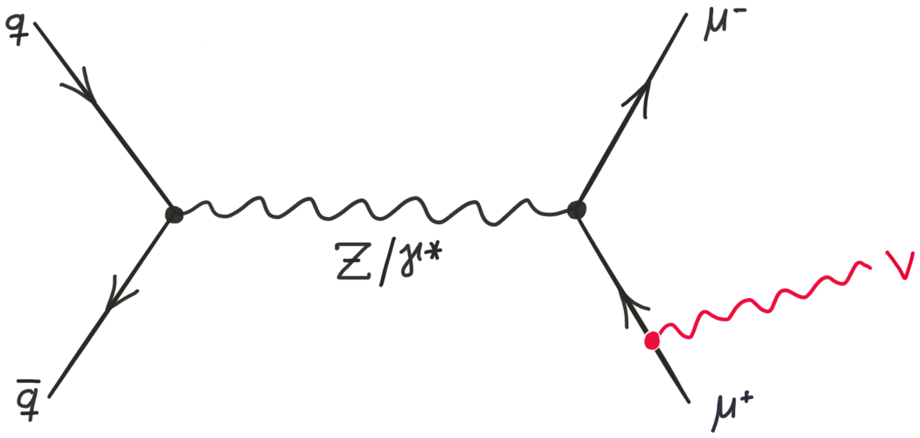


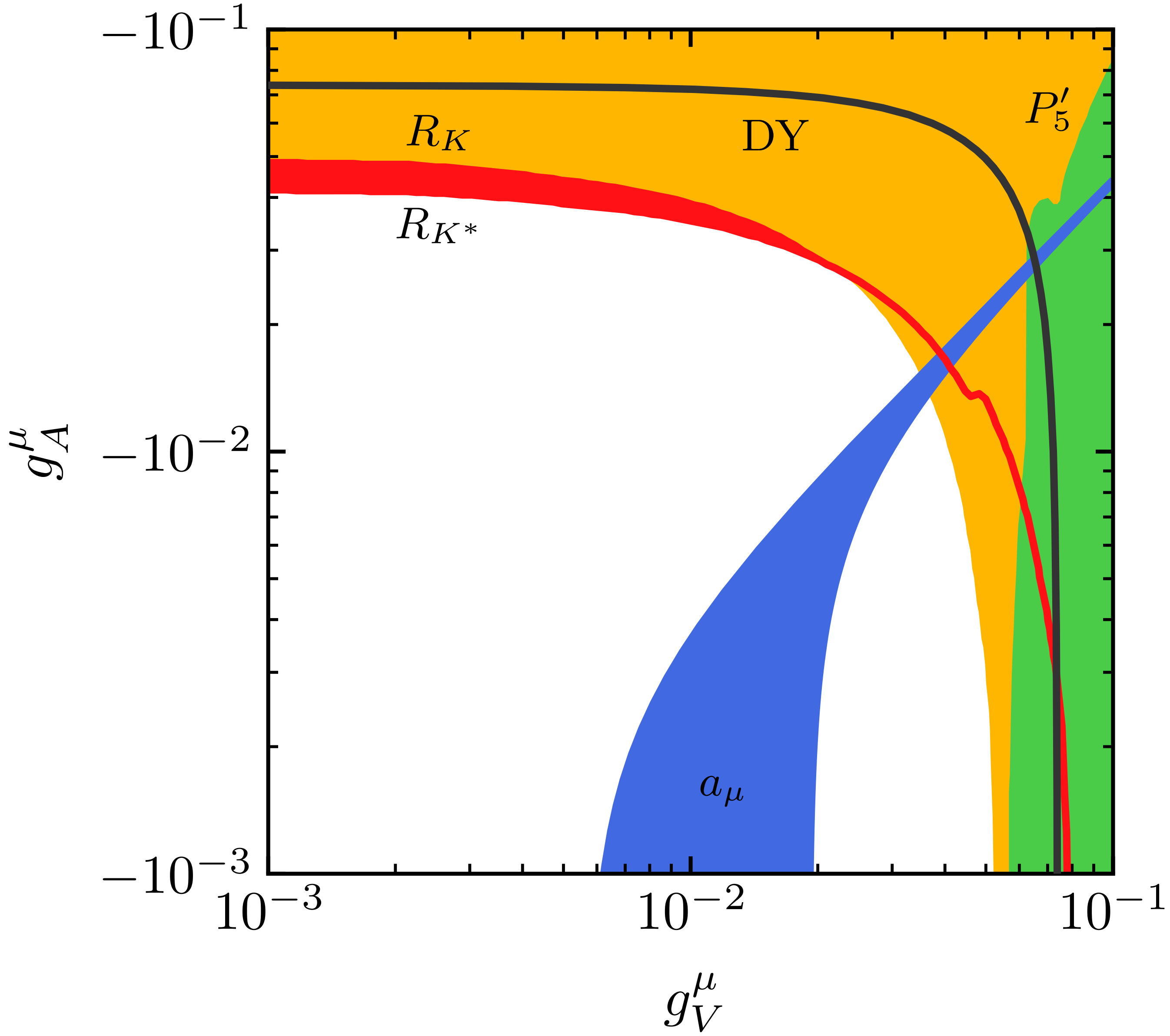


Bishara, UH & Monni, 1705.03465

Light resonances in b → s$\mu^+\mu^-$

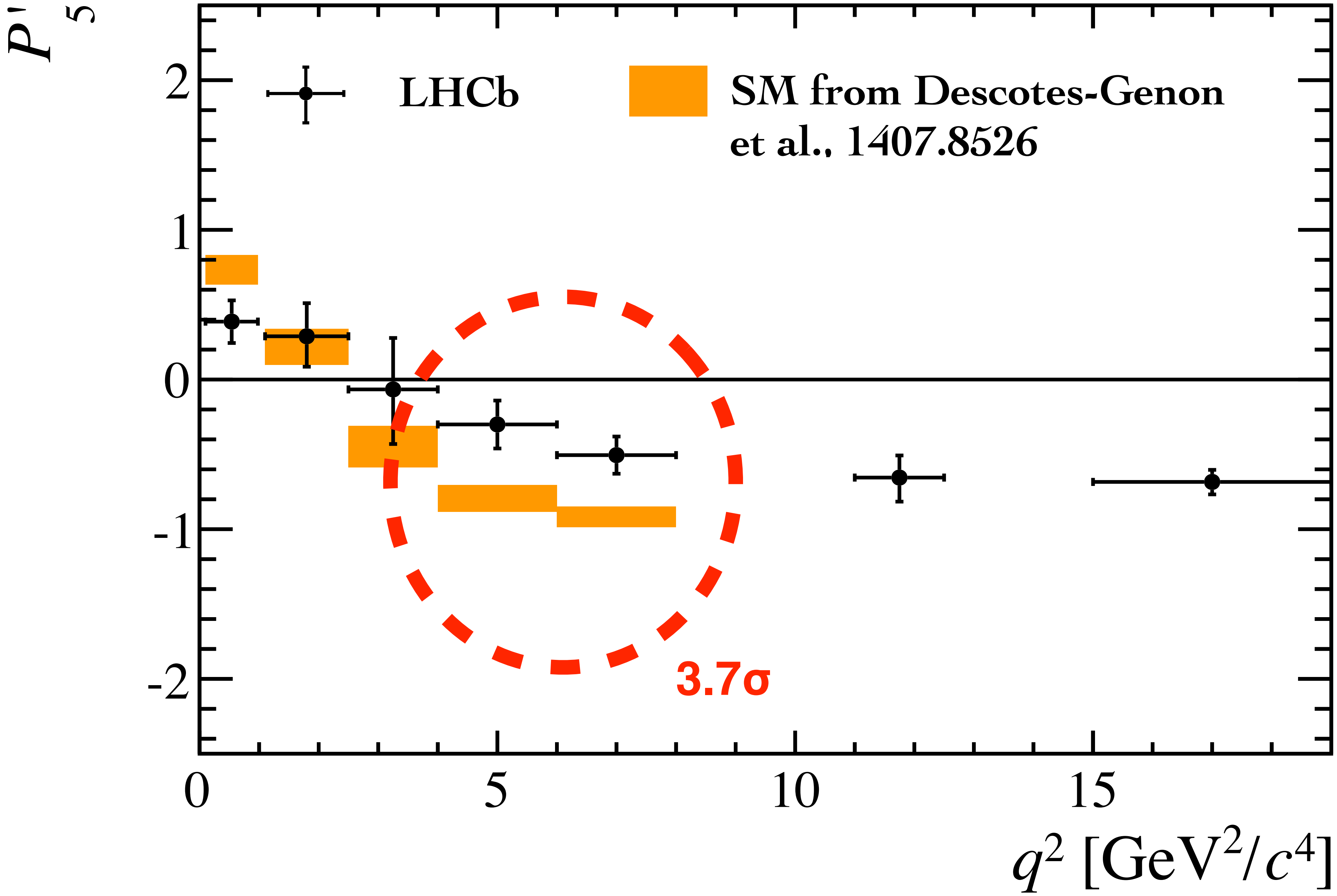
$$\mathcal{L} \supset \left(g_L^{sb}\,\bar{s}_L \not{V} b_L + \text{h.c.}\right) + \bar{\mu}\left(g_V^{\mu} - g_A^{\mu}\gamma_5\right)\not{V}\mu + g_V^{\chi}\,\bar{\chi}\not{V}\chi$$





Bishara, UH & Monni, 1705.03465

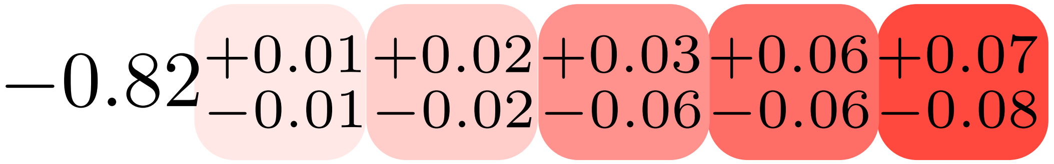
P_5' anomaly



LHCb, 1512.04442

SM prediction of P_5'

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



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

🟥 parametric

🟥 non-factorisable power corrections

🟥 form factors

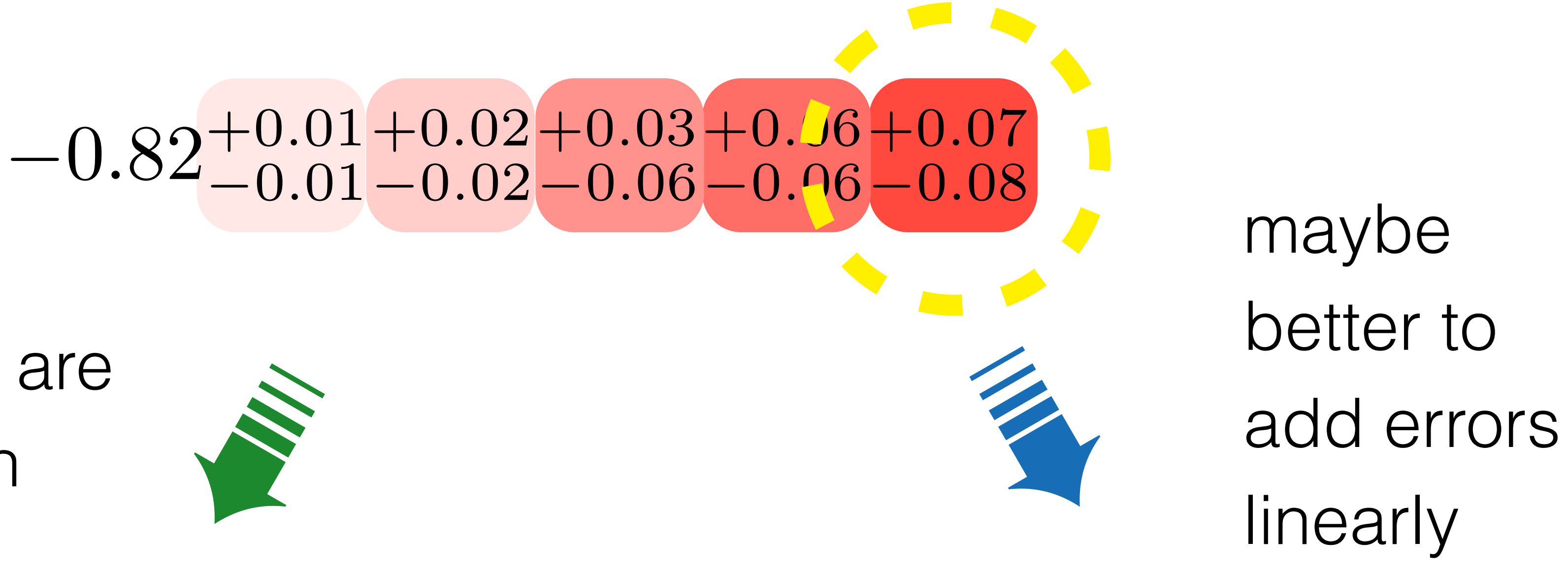
🟥 factorisable power corrections

🟥 long-distance (LD) charmonium effects

Descotes-Genon et al., 1407.8526

SM prediction of P_5'

Dominant uncertainties of theoretical origin. What to do?



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

all errors are Gaussian

maybe better to add errors linearly

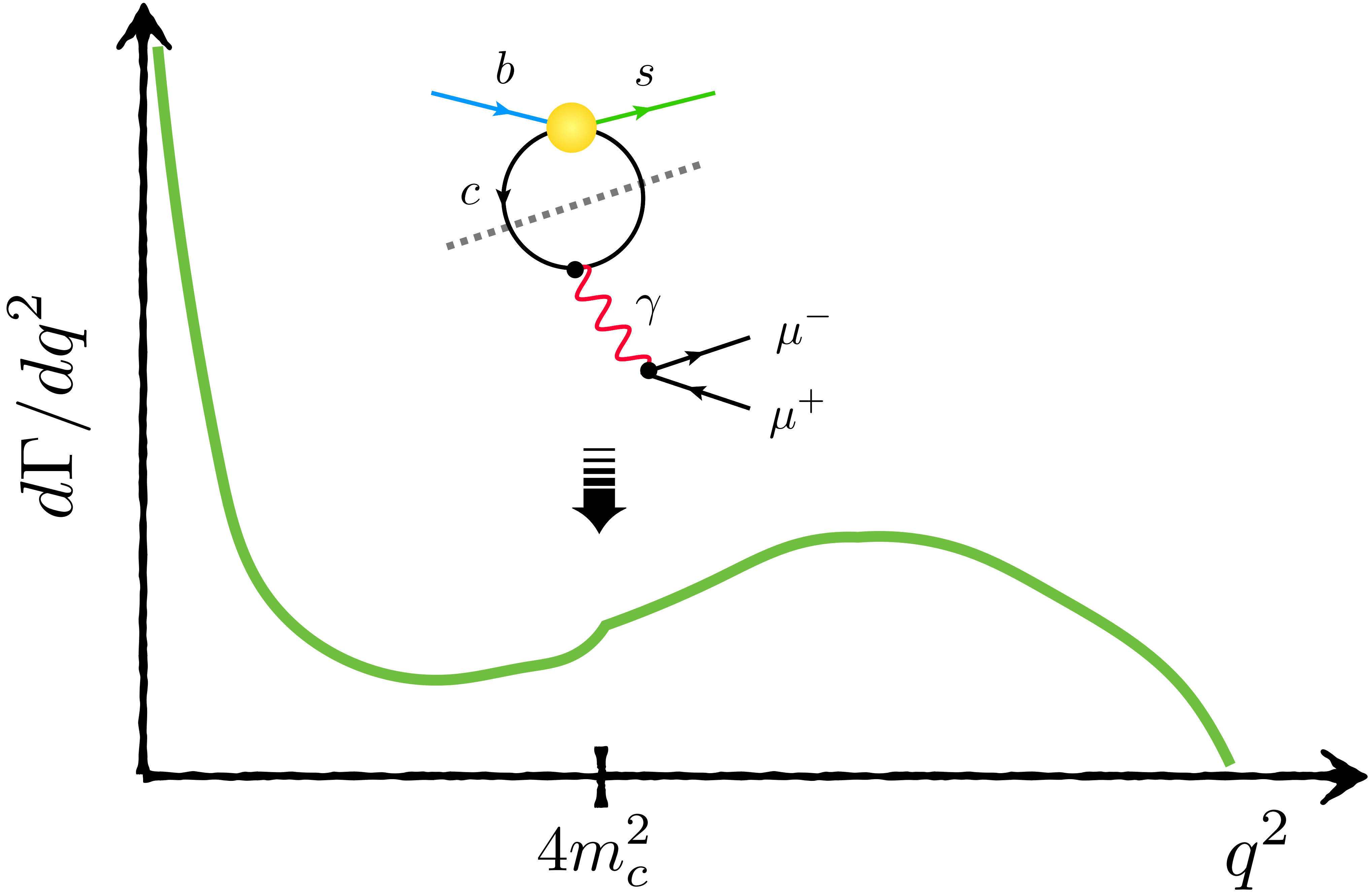
$-0.82\,(1 \pm 13\%)$

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

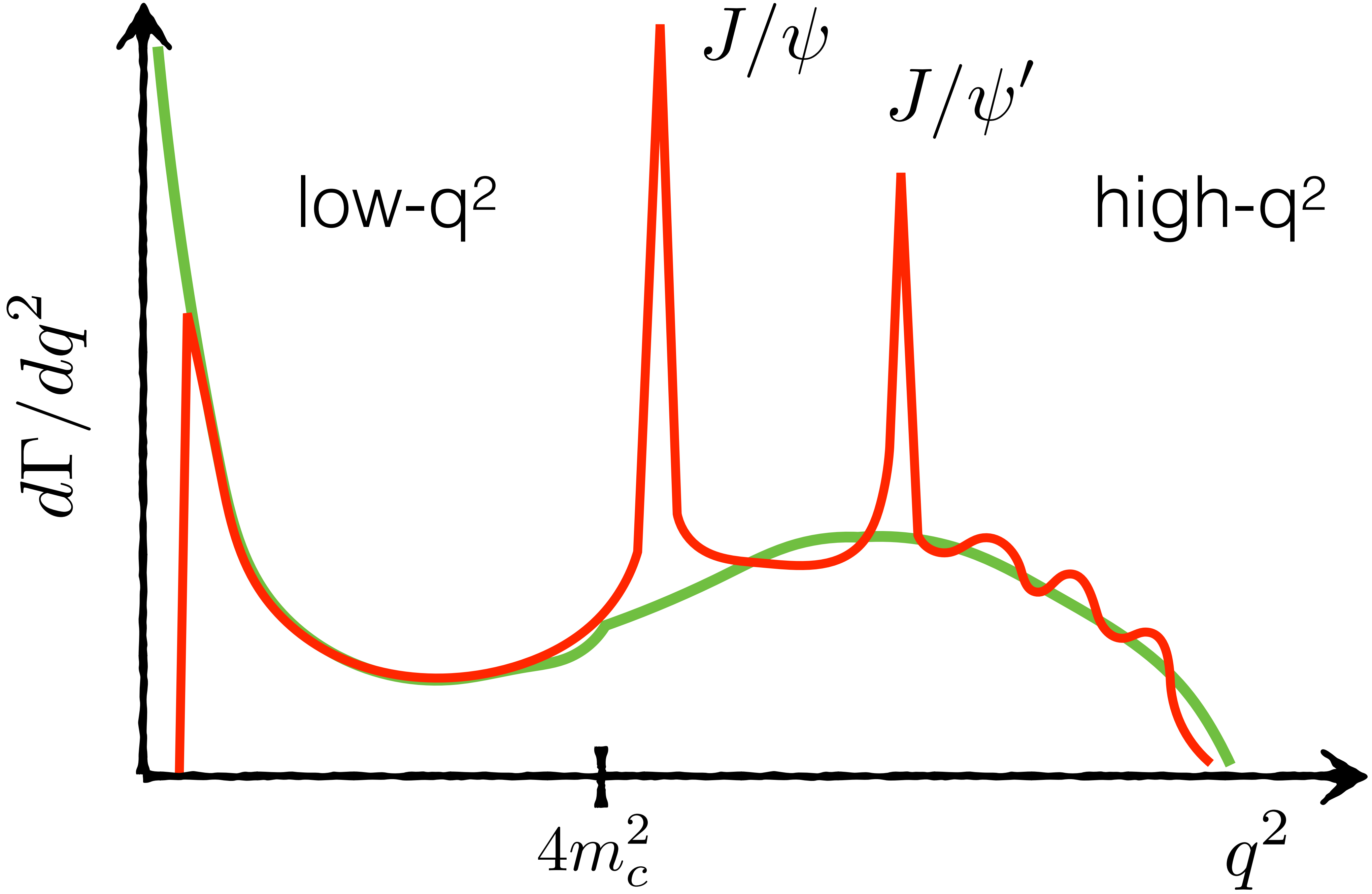
Largest individual uncertainty due to LD charmonium effects.

What is the problem & what does this mean for the error?

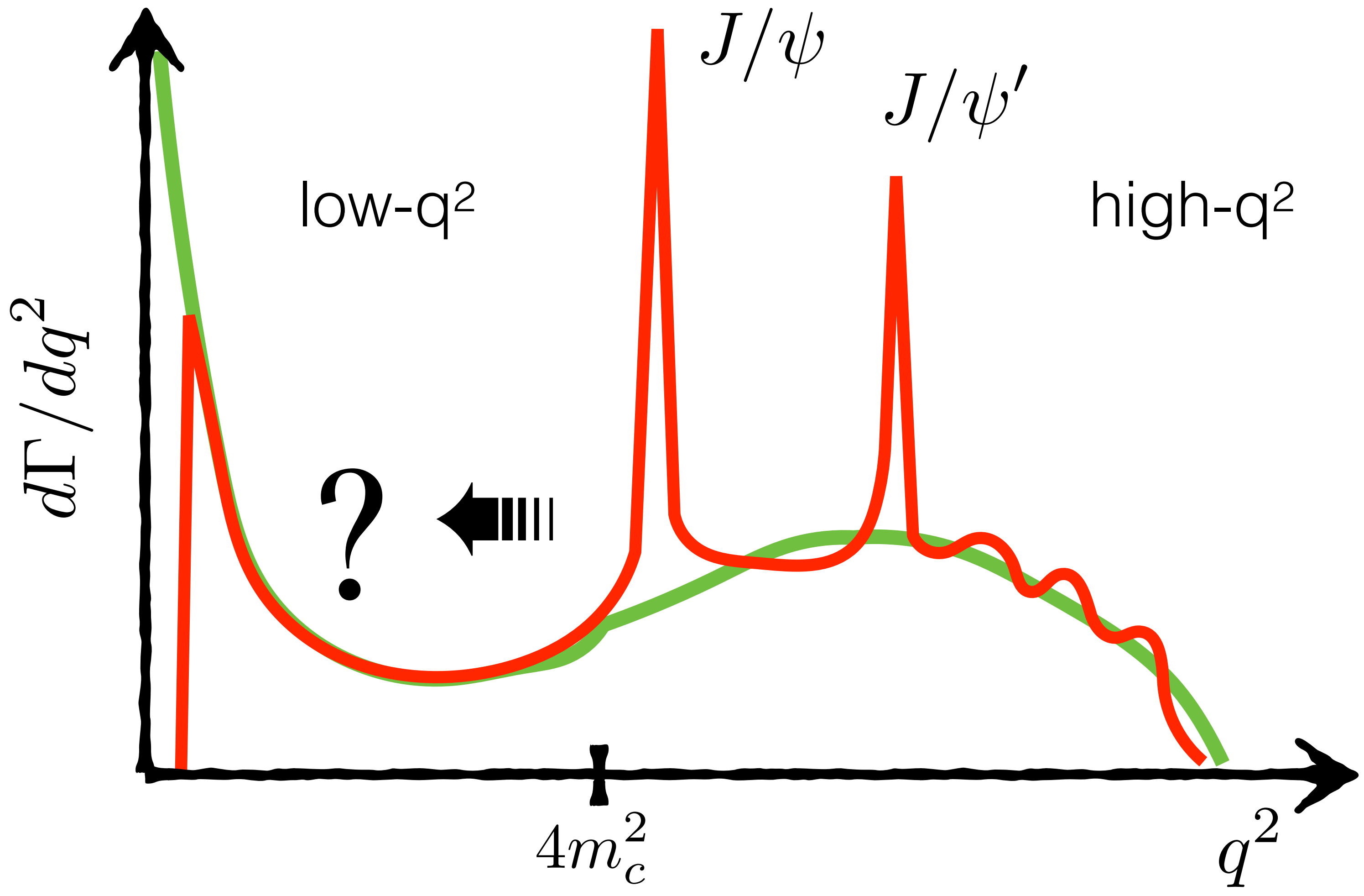
In an ideal world …



… in reality

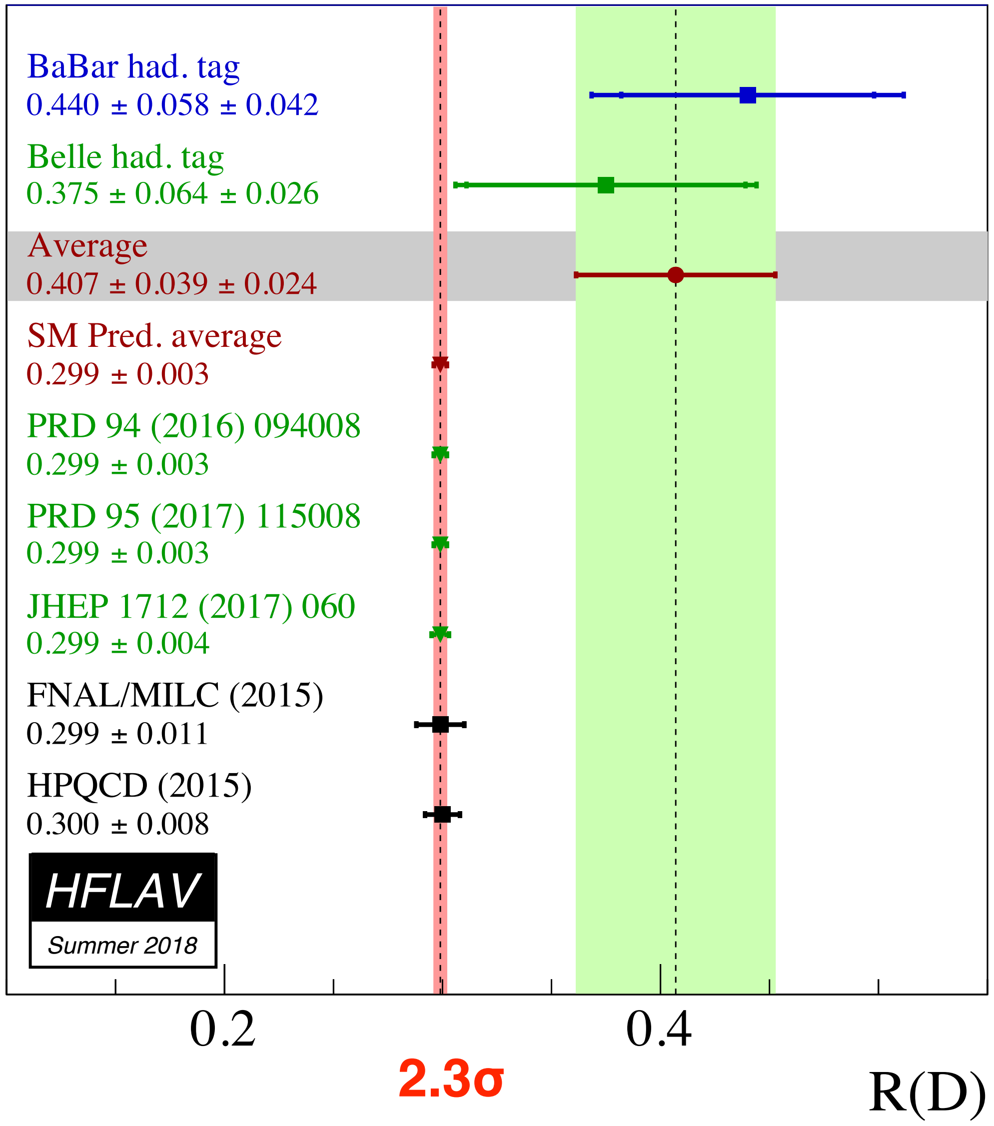


This raises the question

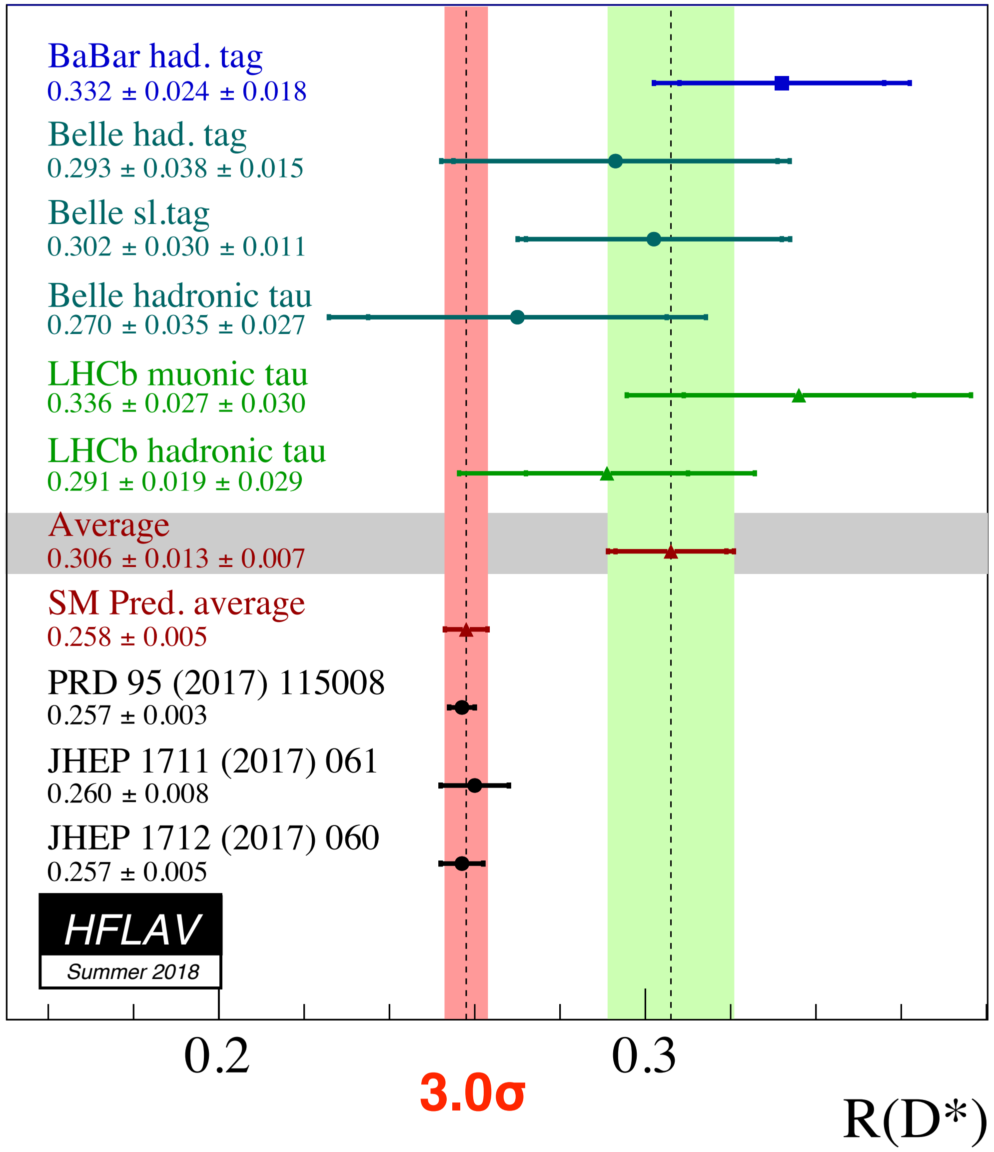


To which extent does breakdown of factorisation in charmonium region affect low-q^2 SM predictions? Lacking a solid estimate of LD effects, meaning of observed 3.7σ deviation not clear to me

$R_{D^{(*)}}$ anomalies



2.3σ

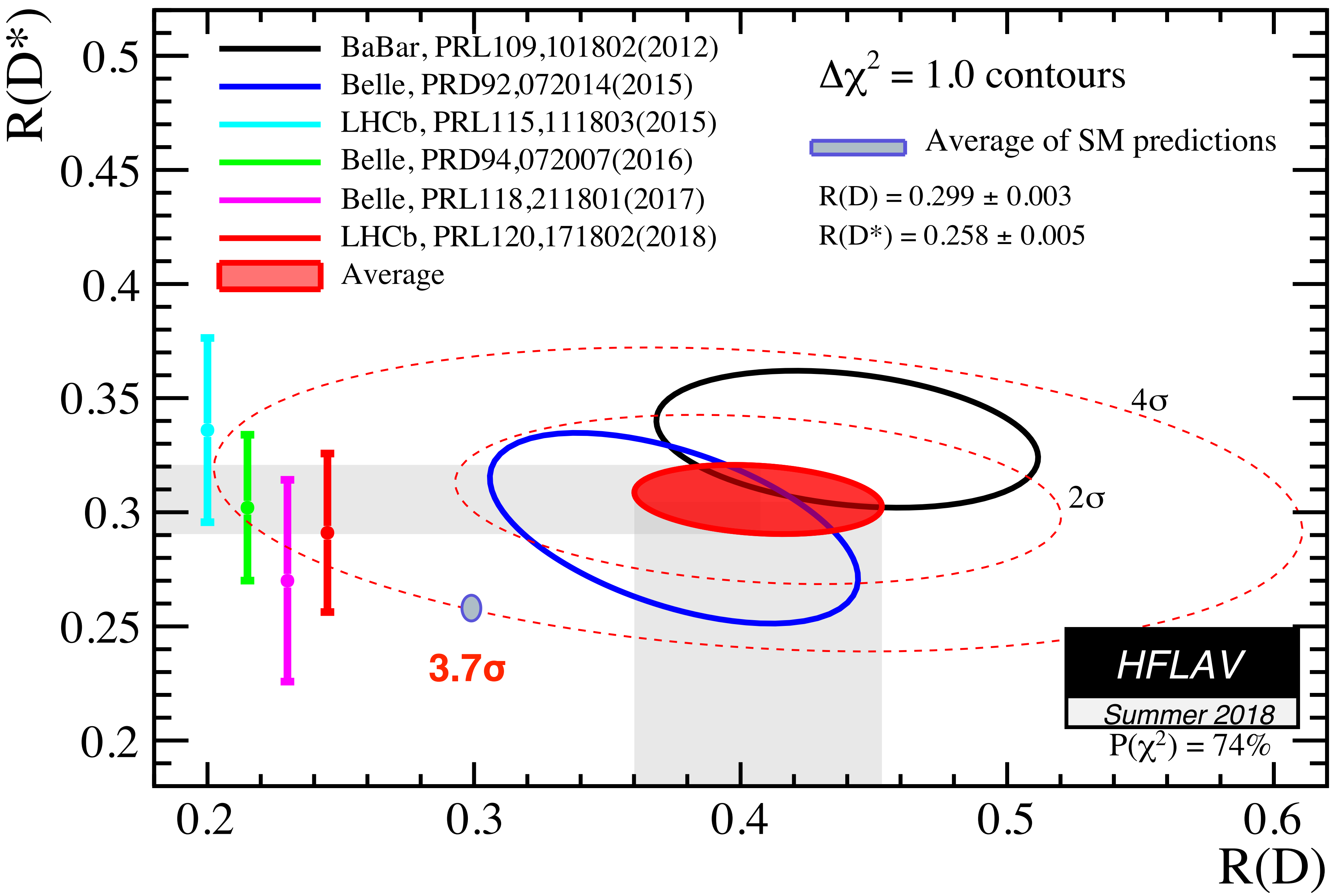


3.0σ

$$R_{D^{(*)}} = \frac{\mathrm{BR}\left(B \to D^{(*)}\tau\nu_\tau\right)}{\mathrm{BR}\left(B \to D^{(*)}l\nu_l\right)}$$

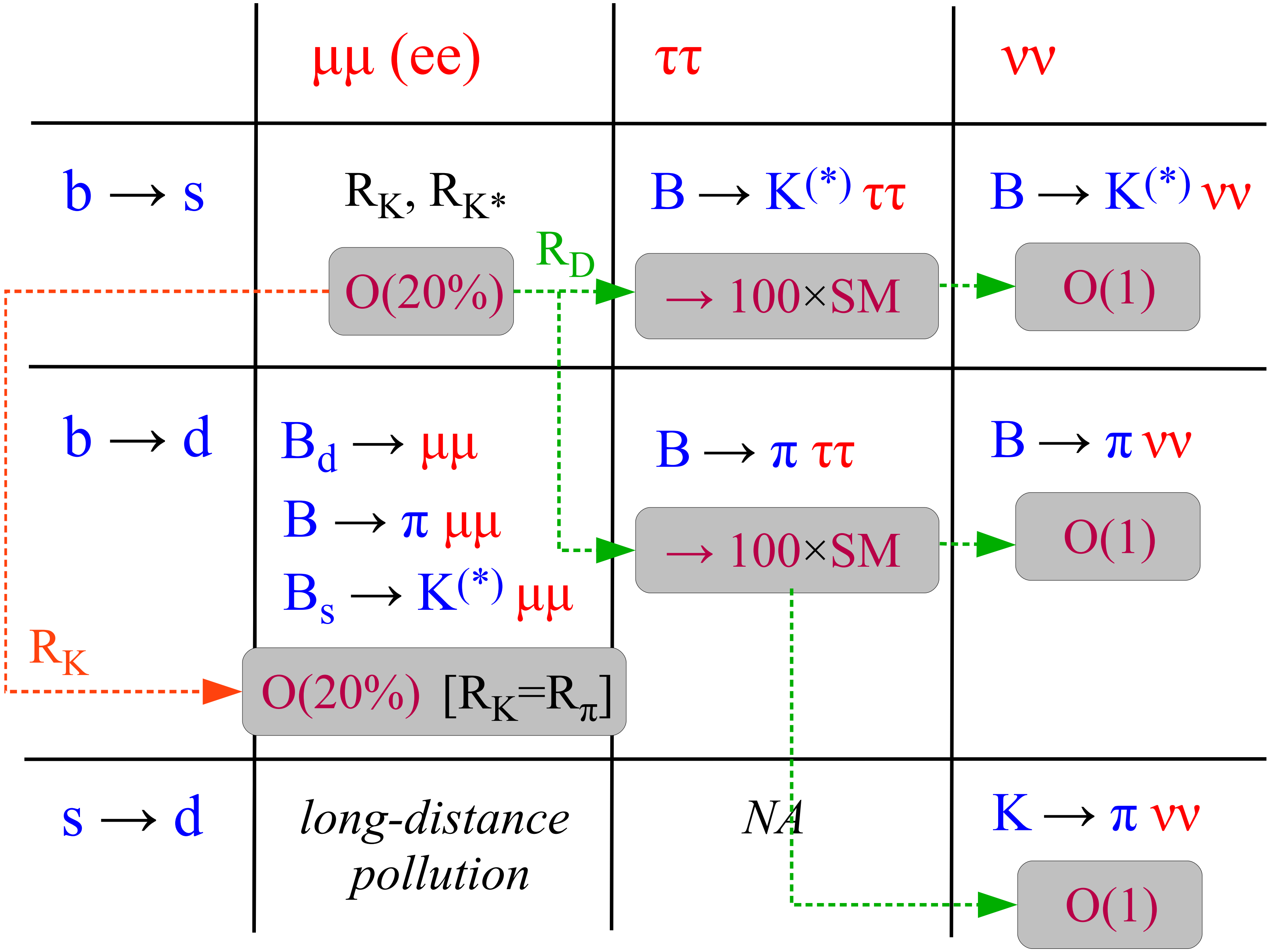
HFLAV averages for Summer 2018

$R_{D^{(*)}}$ anomalies



HFLAV averages for Summer 2018

Low-energy implications of $R_{K^{(*)},D^{(*)}}$



	$\mu\mu$ (ee)	$\tau\tau$	$\nu\nu$
$b \to s$	R_K, R_{K^*} O(20%)	$B \to K^{(*)} \tau\tau$ $\to$ 100×SM	$B \to K^{(*)} \nu\nu$ O(1)
$b \to d$	$B_d \to \mu\mu$ $B \to \pi\, \mu\mu$ $B_s \to K^{(*)} \mu\mu$ O(20%) $[R_K = R_\pi]$	$B \to \pi\, \tau\tau$ $\to$ 100×SM	$B \to \pi\, \nu\nu$ O(1)
$s \to d$	*long-distance pollution*	*NA*	$K \to \pi\, \nu\nu$ O(1)

Talk by Isidori at "Implications of LHCb measurements and future prospects", 2017

Low-energy implications of $R_{K^{(*)},D^{(*)}}$

	$\mu\mu$ (ee)	$\tau\tau$	$\nu\nu$	$\tau\mu$	μe
$b \to s$	R_K, R_{K*} O(20%)	$B \to K^{(*)} \tau\tau$ $\to 100\times$SM	$B \to K^{(*)} \nu\nu$ O(1)	$B \to K \tau\mu$ $\to \sim 10^{-6}$	$B \to K \mu e$???
$b \to d$	$B_d \to \mu\mu$ $B \to \pi \mu\mu$ $B_s \to K^{(*)} \mu\mu$ O(20%) [$R_K=R_\pi$]	$B \to \pi \tau\tau$ $\to 100\times$SM	$B \to \pi \nu\nu$ O(1)	$B \to \pi \tau\mu$ $\to \sim 10^{-7}$	$B \to \pi \mu e$???
$s \to d$	*long-distance pollution*	*NA*	$K \to \pi \nu\nu$ O(1)	*NA*	$K \to \mu e$???

Talk by Isidori at “Implications of LHCb measurements and future prospects”, 2017