Floccinaucinihilipilification

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Standard Model $\times\ U(1)$

Anomaly cancellation

Z' v LQ model for $b \to s\mu^+\mu^-$

During the 2000s

We wanted to be the Grand Architects

During the 2020s

Happy with **any** beyond SM roof

Gauge Rank++

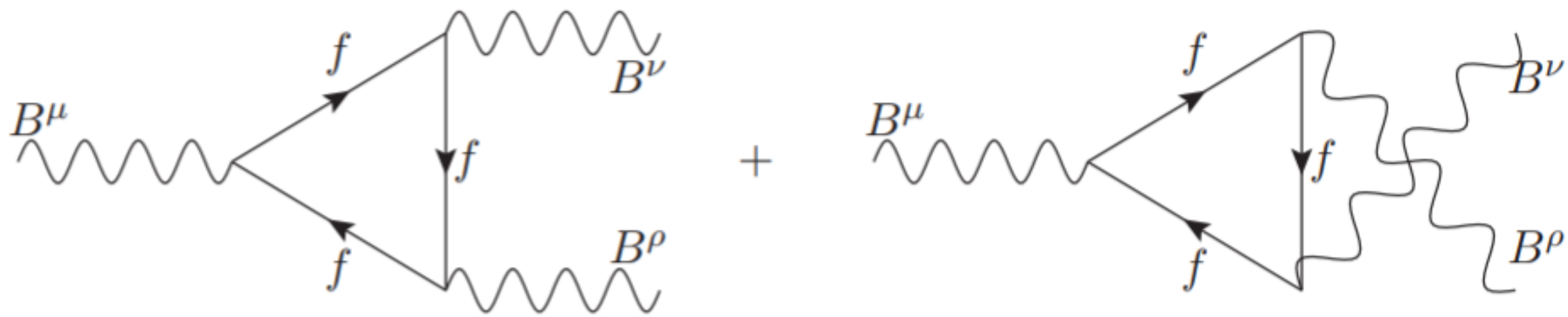
$\not{U(1)_X}$ Z' can explain $b \to s\mu^+\mu^-$ and/or fermion mass problem

Family dependent charges

Z' couplings depend on these

So they change Z' phenomenology

SM: Local Anomalies



$$A \equiv \sum_{LH\ \ f_i} Y_i^3 - \sum_{RH\ \ f_i} Y_i^3$$

$+$two RH $B \rightarrow g/G/W$.

Extra $U(1)$

3 RH ν: N_i

Field labels denote the extra $U(1)$ charge

18 Charges

Anomaly cancellations conditions

$$3^2 X: \quad 0 = \sum_{j=1}^{3} \left(2Q_j + U_j + D_j\right),$$

$$2^2 X: \quad 0 = \sum_{j=1}^{3} \left(3Q_j + L_j\right),$$

$$Y^2 X: \quad 0 = \sum_{j=1}^{3} \left(Q_j + 8U_j + 2D_j + 3L_j + 6E_j\right),$$

$$\mathsf{grav}^2 X: \quad 0 = \sum_{j=1}^{3} (6Q_j + 3U_j + 3D_j + 2L_j + E_j + N_j),$$

$$Y X^2: \quad 0 = \sum_{j=1}^{3} \left(Q_j^2 - 2U_j^2 + D_j^2 - L_j^2 + E_j^2\right),$$

$$X^3: \quad 0 = \sum_{j=1}^{3} \left(6Q_j^3 + 3U_j^3 + 3D_j^3 + 2L_j^3 + E_j^3 + N_j^3\right).$$

Diophantus

Solutions over $\mathbb{Z}^{18}$

Can absorb overall real factor in $-g\sum_\psi Q_\psi \bar{\psi} X_\mu \gamma^\mu \psi$

Charges are commensurate

For generic polynomials: number theory can solve one cubic in 3D

Anomaly-free Atlas

Charges between $-Q_{max}$ and $Q_{max} = 10$: numerical scan $(\cancel{21^{18} \sim 10^{24}})$: `BCA, Davighi, Melville, 1812.04602`.

An Anomaly-Free Atlas is available for public use:
`http://doi.org/10.5281/zenodo.1478085`

$Q_{\max}$	**Solutions**	Symmetry	Quadratics	Cubics	Time/sec
1	**38**	16	144	38	0.0
2	**358**	48	31439	2829	0.0
3	**4116**	154	1571716	69421	0.1
4	**24552**	338	34761022	932736	0.6
5	**111152**	796	442549238	7993169	6.8
6	**435305**	1218	3813718154	49541883	56
7	**1358388**	2332	24616693253	241368652	312
8	**3612734**	3514	127878976089	978792750	1559
9	**9587085**	5648	558403872034	3432486128	6584
10	**21546920**	7540	2117256832910	10687426240	24748

Inequivalent solutions with 3 RH ν

Q	Q	Q	ν	ν	ν	e	e	e	u	u	u	L	L	L	d	d	d
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	-1	0	1	-1	0	1
0	0	0	0	0	0	-1	0	1	0	0	0	-1	0	1	0	0	0
0	0	0	0	0	0	-1	0	1	-1	0	1	0	0	0	-1	0	1
-1	0	1	0	0	0	0	0	0	0	0	0	-1	0	1	0	0	0
-1	0	1	0	0	0	0	0	0	-1	0	1	0	0	0	-1	0	1
-1	0	1	0	0	0	-1	0	1	-1	0	1	0	0	0	0	0	0
-1	0	1	0	0	0	-1	0	1	-1	0	1	-1	0	1	-1	0	1

eg: $Q_{max} = 1$, $N_i = 0$. Charges within a species are listed in *increasing order*.

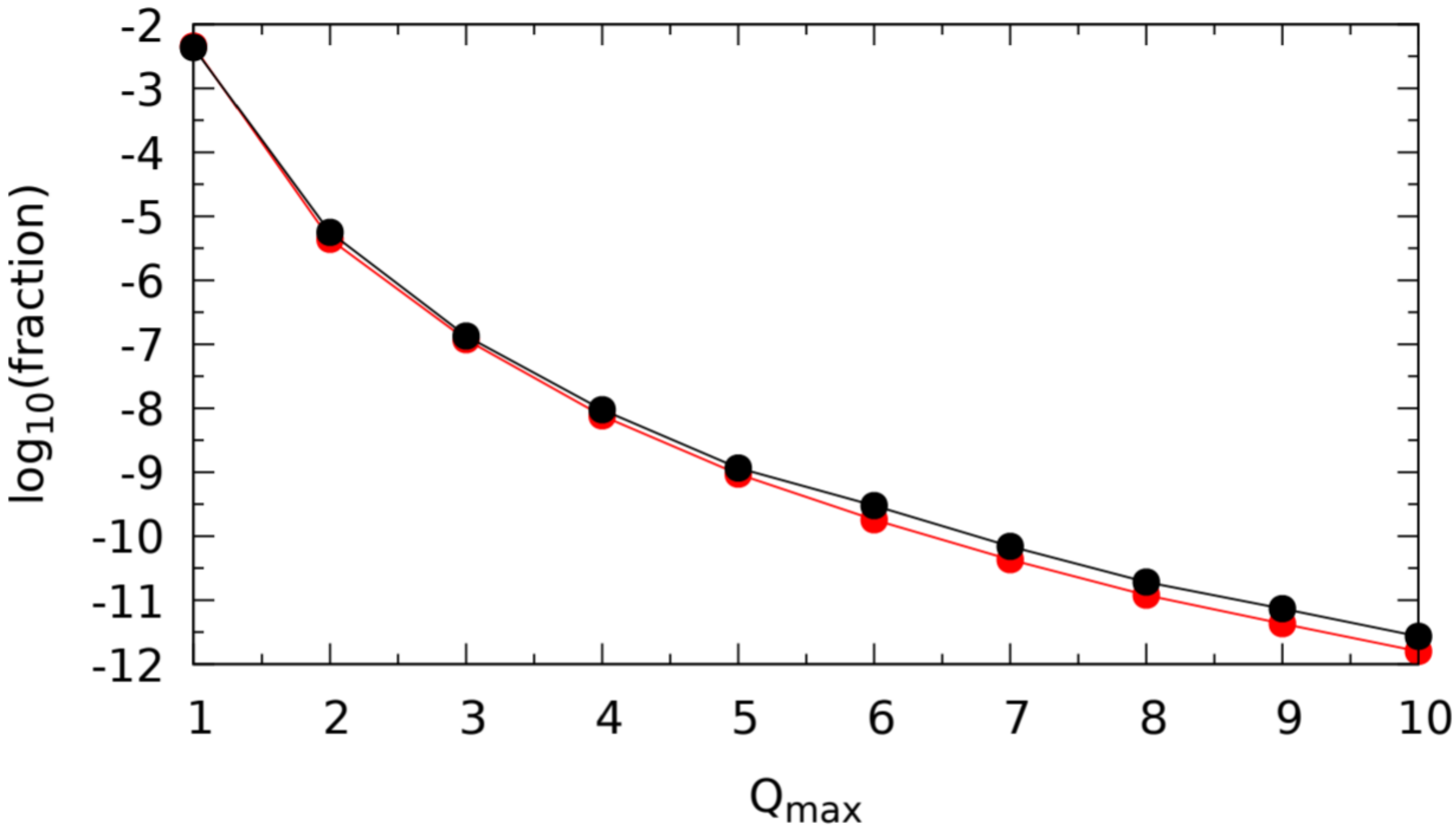
Examples of interest

	Q_1	Q_2	Q_3	U_1	U_2	U_3	D_1	D_2	D_3	L_1	L_2	L_3	E_1	E_2	E_3	N_1	N_2	N_3
A	0	0	1	0	0	-4	0	0	-2	0	0	-3	0	0	6	0	0	0
B	1	1	1	-1	-1	-1	-1	-1	-1	-3	-3	-3	3	3	3	3	3	3
C	-1	0	1	-1	0	1	-1	0	1	-1	0	1	-1	0	1	0	0	0

A is TFHM (`BCA, Davighi, arXiv:1809.01158`)

B is $B - L$

C has inter-family cancellation



18 charges and 6 ACCs: sparser away from $\mathbf{0}$. Want analytic understanding.

Analytic Solution: any Q_{max}

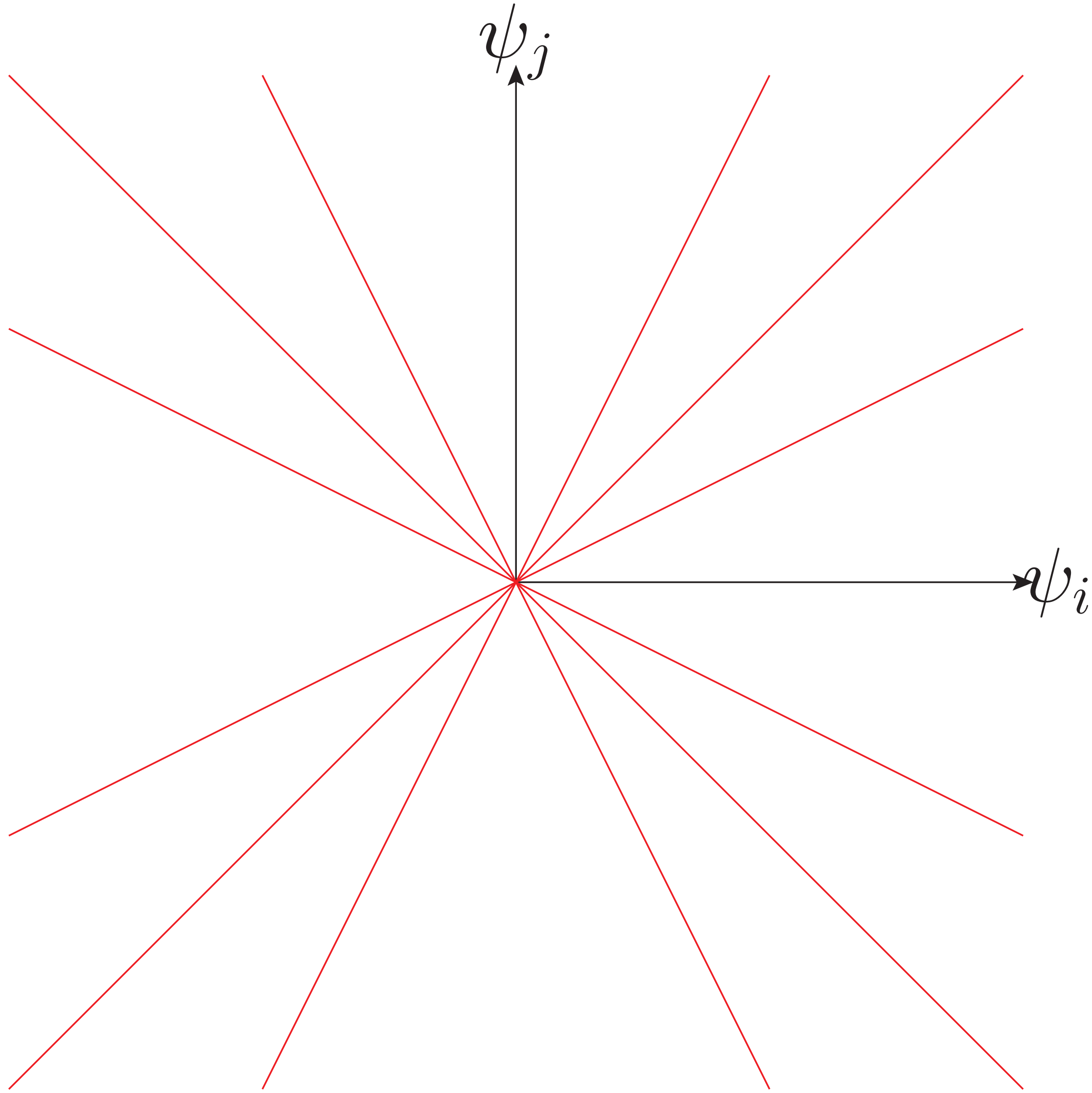
g re-scaling symmetry of charges ψ_i leads to an equivalence class

So solutions in $\mathbb{Z}^{18}$ equivalent to $\mathbb{Q}^{18}$

$\mathbb{Q}^{18}$ is a field: can define geometry on it

`BCA, Gripaios, Tooby-Smith 2104.14555`

Projective space $P\mathbb{Q}^{17}$



Preliminaries

4 linear ACCS: $P\mathbb{Q}^{17} \to P\mathbb{Q}^{13}$.

Then, find intersection of quadratic

$$0 = \sum_{j=1}^{3} \left(Q_j^2 - 2U_j^2 + D_j^2 - L_j^2 + E_j^2 \right)$$

and cubic surface

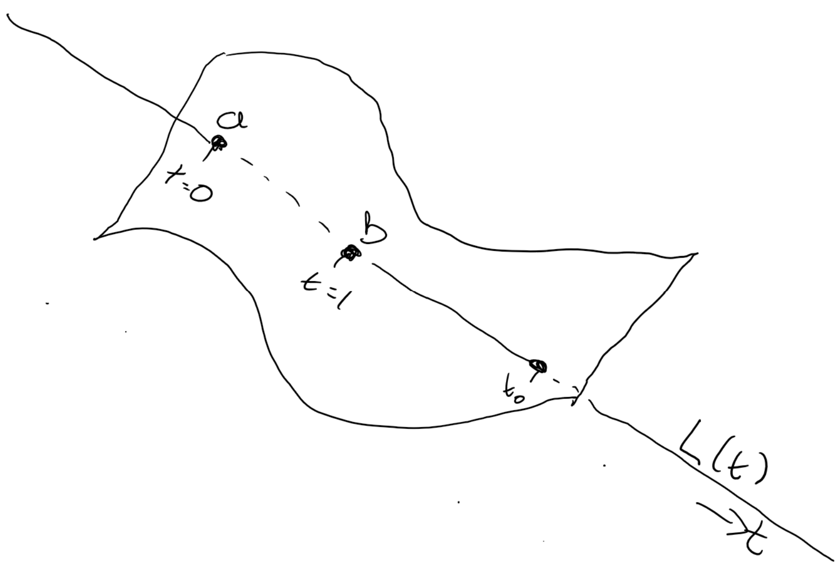
$$0 = \sum_{j=1}^{3} \left(6Q_j^3 + 3U_j^3 + 3D_j^3 + 2L_j^3 + E_j^3 + N_j^3 \right)$$

The Method of Chords[1]

Rational cubic (quadratic) $c(\psi_i) = 0$.

$L(t) = a + t(b - a)$.

$c(L(t)) = kt(t-1)(t-t_0)$; $k, t_0 \in \mathbb{Q}$



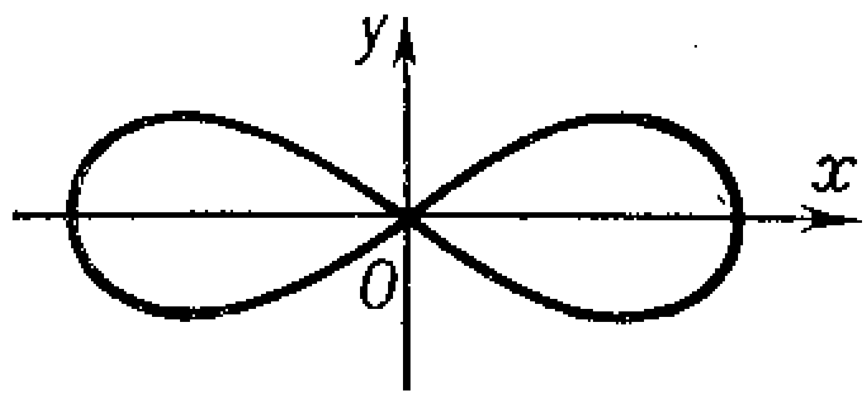
Important caveat: $c(L(t)) = 0$ irrespective of t.

[1] Newton, Fermat, C17

Double Points

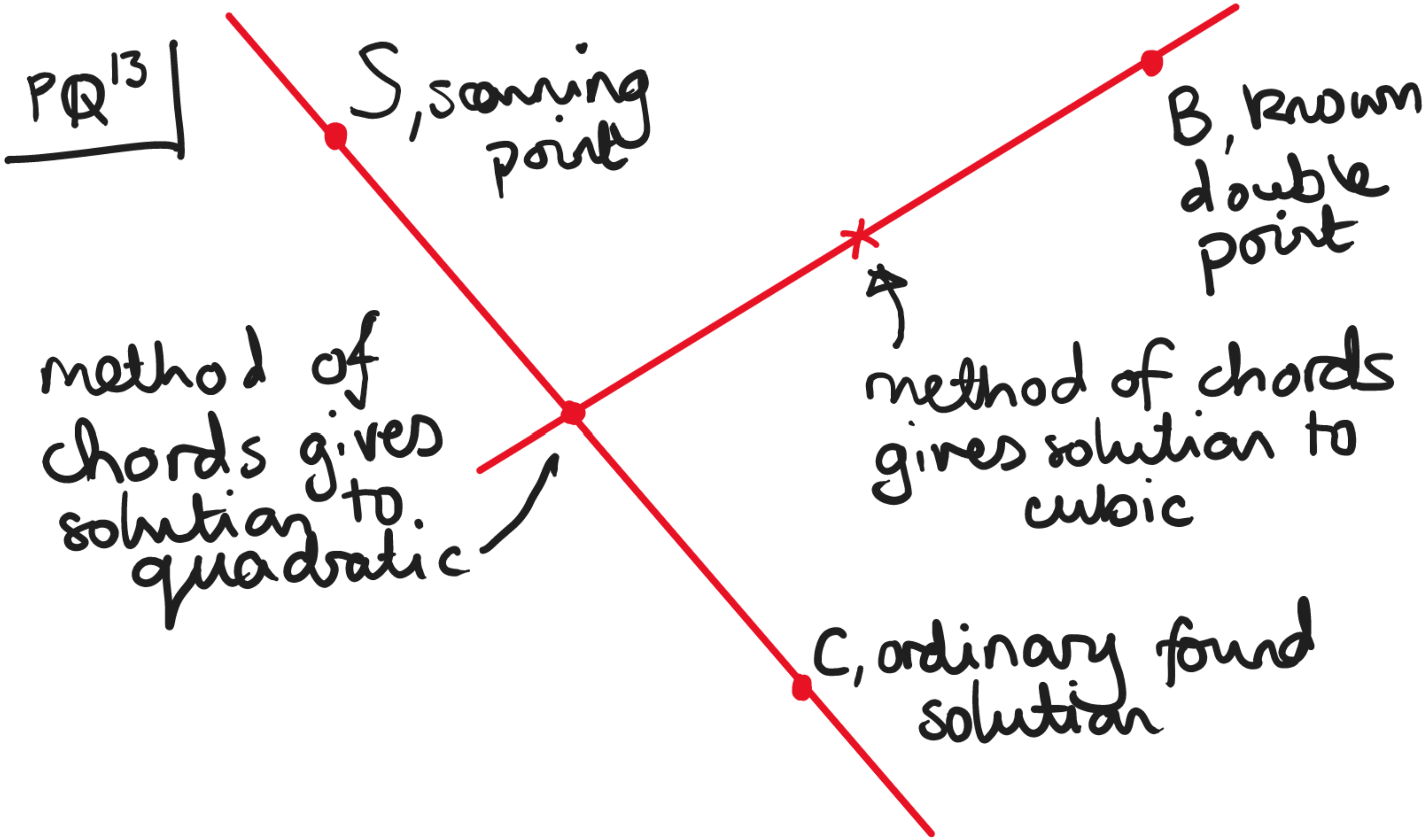
Solutions of multiplicity two. Partial derivatives vanish there, eg origin

$$(x^2 + y^2 + a^2)^2 - 4a^2x^2 - a^4 = 0$$



B is *double point* of quadratic and cubic

Method



PQ[13]
S, scanning point
B, known double point
method of chords gives solution to quadratic
method of chords gives solution to cubic
C, ordinary found solution

The Nitty-Gritty

$$Q_1 = \Gamma - \Sigma + \Lambda S_{Q_1},$$
$$Q_2 = \Gamma + \Lambda S_{Q_2},$$
$$Q_3 = \Gamma + \Sigma + \Lambda S_{Q_3},$$
$$U_1 = -\Gamma - \Sigma + \Lambda S_{U_1},$$
$$U_2 = -\Gamma + \Lambda S_{U_2},$$
$$U_3 = -\Gamma + \Sigma + \Lambda S_{U_3},$$
$$D_1 = -\Gamma - \Sigma + \Lambda S_{D_1},$$
$$D_2 = -\Gamma + \Lambda S_{D_2},$$
$$D_3 = -\Gamma + \Sigma + \Lambda S_{D_3},$$
$$L_1 = -3\Gamma - \Sigma + \Lambda S_{L_1},$$
$$L_2 = -3\Gamma + \Lambda S_{L_2},$$
$$L_3 = -3\Gamma + \Sigma + \Lambda S_{L_3},$$
$$E_1 = 3\Gamma - \Sigma + \Lambda S_{E_1},$$
$$E_2 = 3\Gamma + \Lambda S_{E_2},$$
$$E_3 = 3\Gamma + \Sigma + \Lambda S_{E_3},$$
$$N_1 = 3\Gamma + \Lambda S_{N_1},$$
$$N_2 = 3\Gamma + \Lambda S_{N_2},$$
$$N_3 = 3\Gamma + \Lambda S_{N_3},$$

$$\Gamma = c(R,R,R) + r\delta_{c(B,R,R),0}\delta_{c(R,R,R),0},$$
$$\Sigma = (-3c(B,R,R) + t\delta_{c(B,R,R),0}\delta_{c(R,R,R),0})$$
$$(q(S,S) + a\delta_{q(S,S),0}\delta_{q(C,S),0}),$$
$$\Lambda = (-3c(B,R,R) + t\delta_{c(B,R,R),0}\delta_{c(R,R,R),0})$$
$$(-2q(C,S) + b\delta_{q(S,S),0}\delta_{q(C,S),0}).$$

$$q(P,P') := \sum_{i=1} \big(Q_i Q_i' - 2U_i U_i' + D_i D_i'$$
$$-L_i L_i' + E_i E_i'\big),$$

$$c(P,P',P'') := \sum_{i=1}^{3} \big(6Q_i Q_i' Q_i'' + 3U_i U_i' U_i'' + 3D_i D_i' D_i''$$
$$+2L_i L_i' L_i'' + E_i E_i' E_i'' + N_i N_i' N_i''\big). \qquad (3)$$

$$R = q(S,S)C - 2q(C,S)S + \delta_{q(S,S),0}\delta_{q(C,S),0}(aC + bS),$$

$$S_{Q_3} = \frac{1}{2}\left[-2S_{Q_1} - 2S_{Q_2} + \sum_{i=1}^{3}(S_{D_i} + S_{N_i})\right],$$

$$S_{U_3} = -\left[S_{U_1} + S_{U_2} + \sum_{i=1}^{3}(2S_{D_i} + S_{N_i})\right],$$

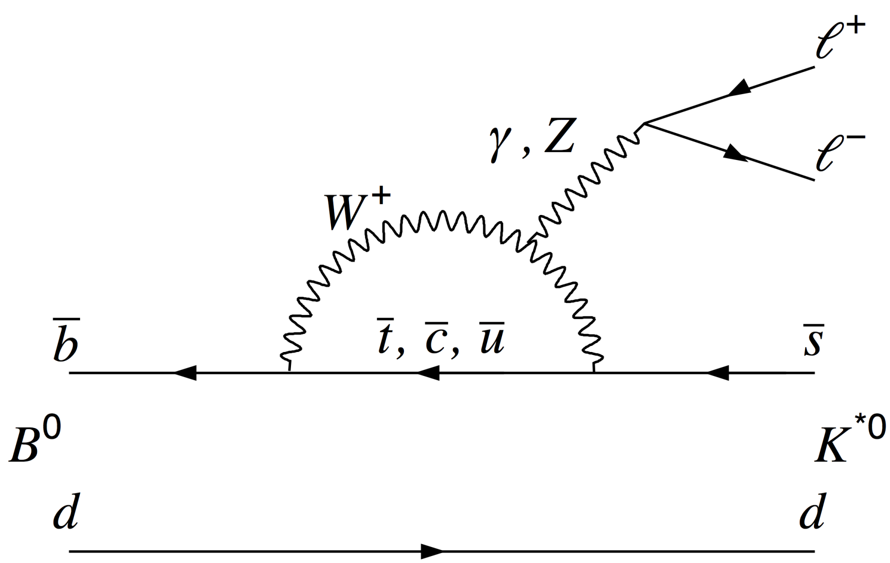
$$S_{L_3} = -\frac{1}{2}\left[2S_{L_1} + 2S_{L_2} + 3\sum_{i=1}^{3}(S_{D_i} + S_{N_i})\right],$$

$$S_{E_3} = -S_{E_1} - S_{E_2} + \sum_{i=1}^{3}(3S_{D_i} + 2S_{N_i}).$$

$b \to s l^+ l^-$ in Standard Model

$$R_K = \frac{BR(B \to K\mu^+\mu^-)}{BR(B \to Ke^+e^-)}.$$

BR$\sim \mathcal{O}(10^{-7})$: loop+EW+CKM



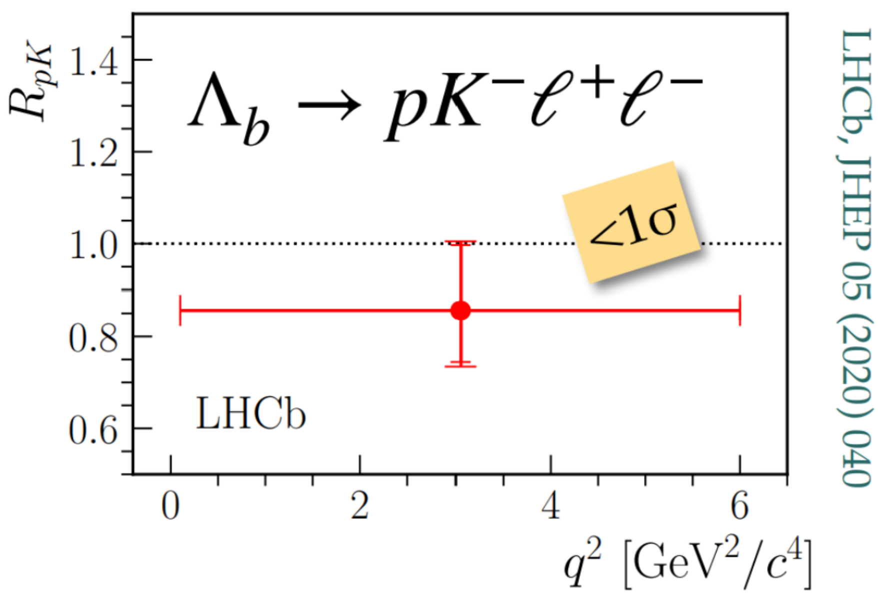
LHCb 2212.09152

$$\text{low-}q^2 \begin{cases} R_K & = 0.994 \ {}^{+0.090}_{-0.082}\,(\text{stat})\,{}^{+0.029}_{-0.027}\,(\text{syst}), \\ R_{K^*} & = 0.927 \ {}^{+0.093}_{-0.087}\,(\text{stat})\,{}^{+0.036}_{-0.035}\,(\text{syst}), \end{cases}$$

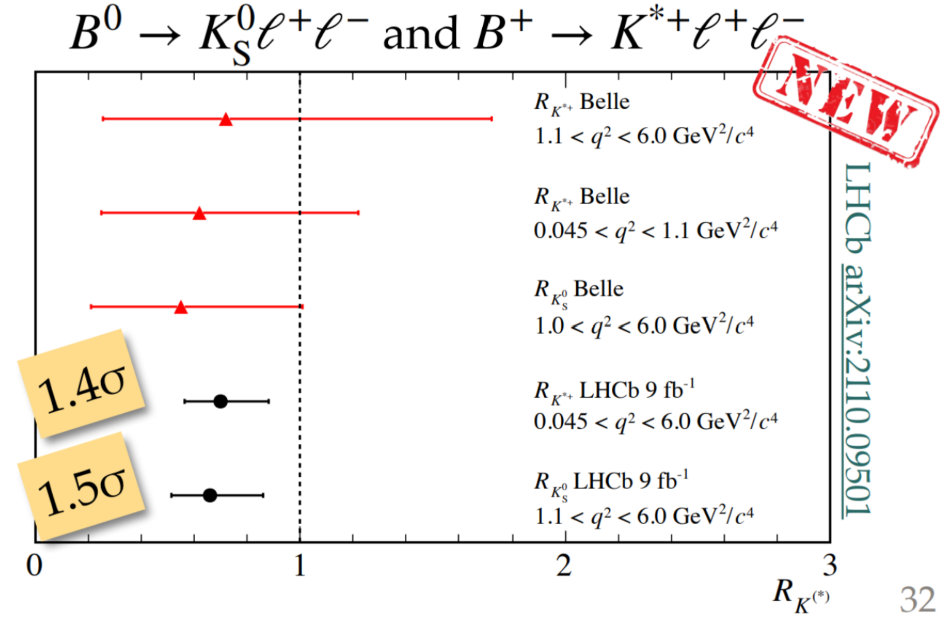
$$\text{central-}q^2 \begin{cases} R_K & = 0.949 \ {}^{+0.042}_{-0.041}\,(\text{stat})\,{}^{+0.022}_{-0.022}\,(\text{syst}), \\ R_{K^*} & = 1.027 \ {}^{+0.072}_{-0.068}\,(\text{stat})\,{}^{+0.027}_{-0.026}\,(\text{syst}). \end{cases}$$

$$R_X(q^2) = \frac{BR(B \to X\mu^+\mu^-)}{BR(B \to Xe^+e^-)}(q^2)$$

Other LFU



$\Lambda_b \to pK^-\ell^+\ell^-$
<1σ
LHCb
R_{pK}
q^2 [GeV$^2/c^4$]
LHCb, JHEP 05 (2020) 040



$B^0 \to K^0_S\ell^+\ell^-$ and $B^+ \to K^{*+}\ell^+\ell^-$
NEW
$R_{K^{*+}}$ Belle
$1.1 < q^2 < 6.0$ GeV$^2/c^4$
$R_{K^{*+}}$ Belle
$0.045 < q^2 < 1.1$ GeV$^2/c^4$
$R_{K^0_S}$ Belle
$1.0 < q^2 < 6.0$ GeV$^2/c^4$
1.4σ
$R_{K^{*+}}$ LHCb 9 fb^{-1}
$0.045 < q^2 < 6.0$ GeV$^2/c^4$
1.5σ
$R_{K^0_S}$ LHCb 9 fb^{-1}
$1.1 < q^2 < 6.0$ GeV$^2/c^4$
$R_{K^{(*)}}$
LHCb arXiv:2110.09501
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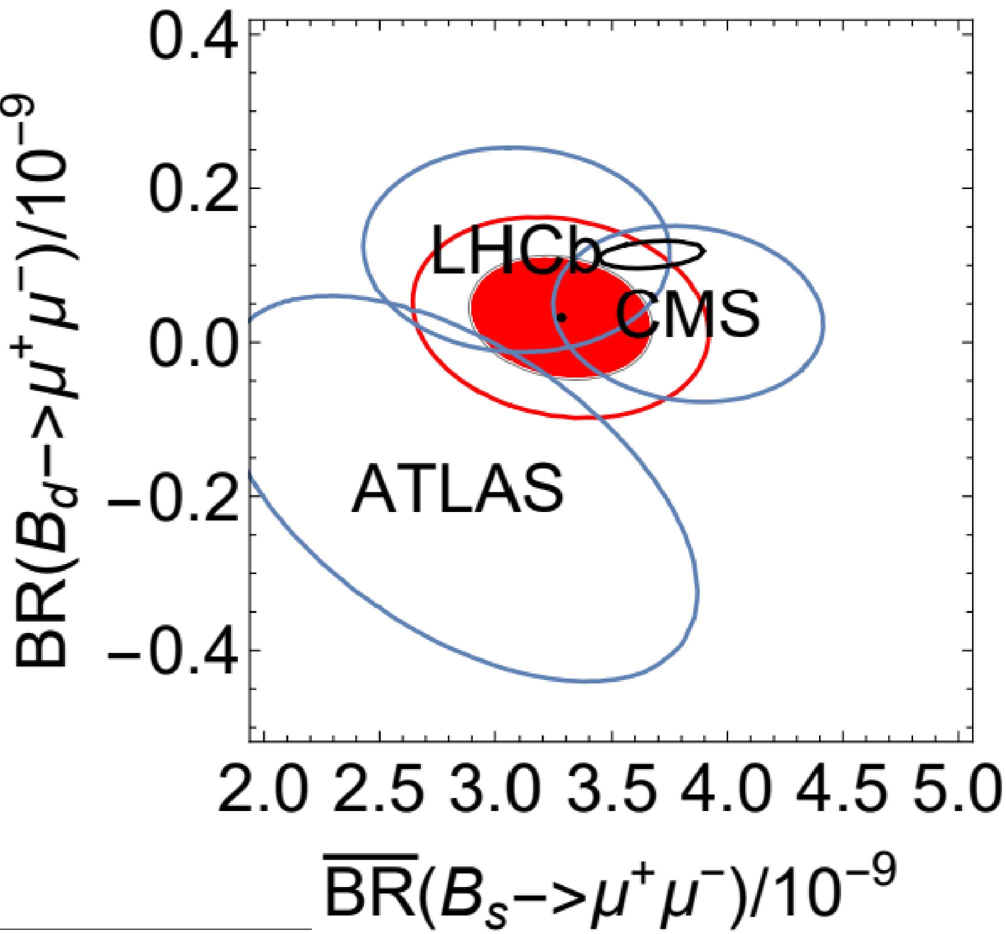
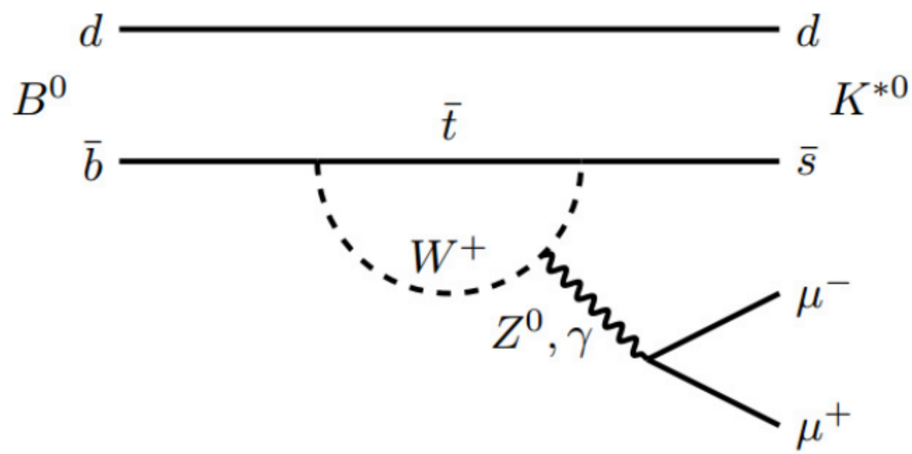
$BR(B_s \to \mu^+\mu^-)$:[2]: SM: 1.6σ

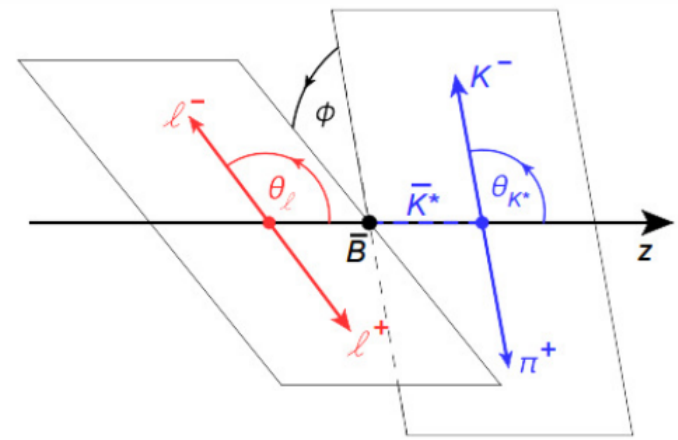
$B_s = (\bar{b}s)$, $B_d = (\bar{b}d)$



[2]SM: Feldmann, Gubernari, Huber, Seitz, 2211.04209; BCA, Davighi, 2211.11766

$B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$

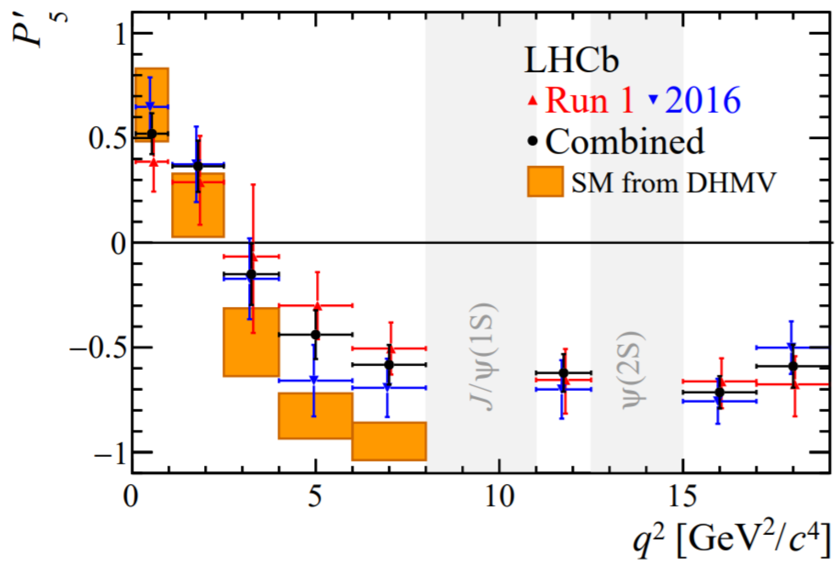


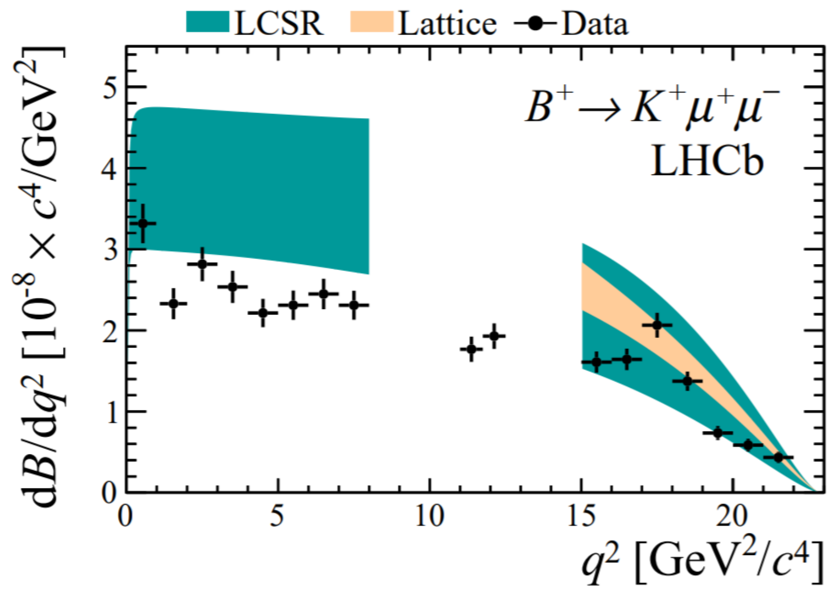


Decay fully described by three helicity angles $\vec{\Omega} = (\theta_\ell, \theta_K, \phi)$ and $q^2 = m^2_{\mu\mu}$

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

P_5'

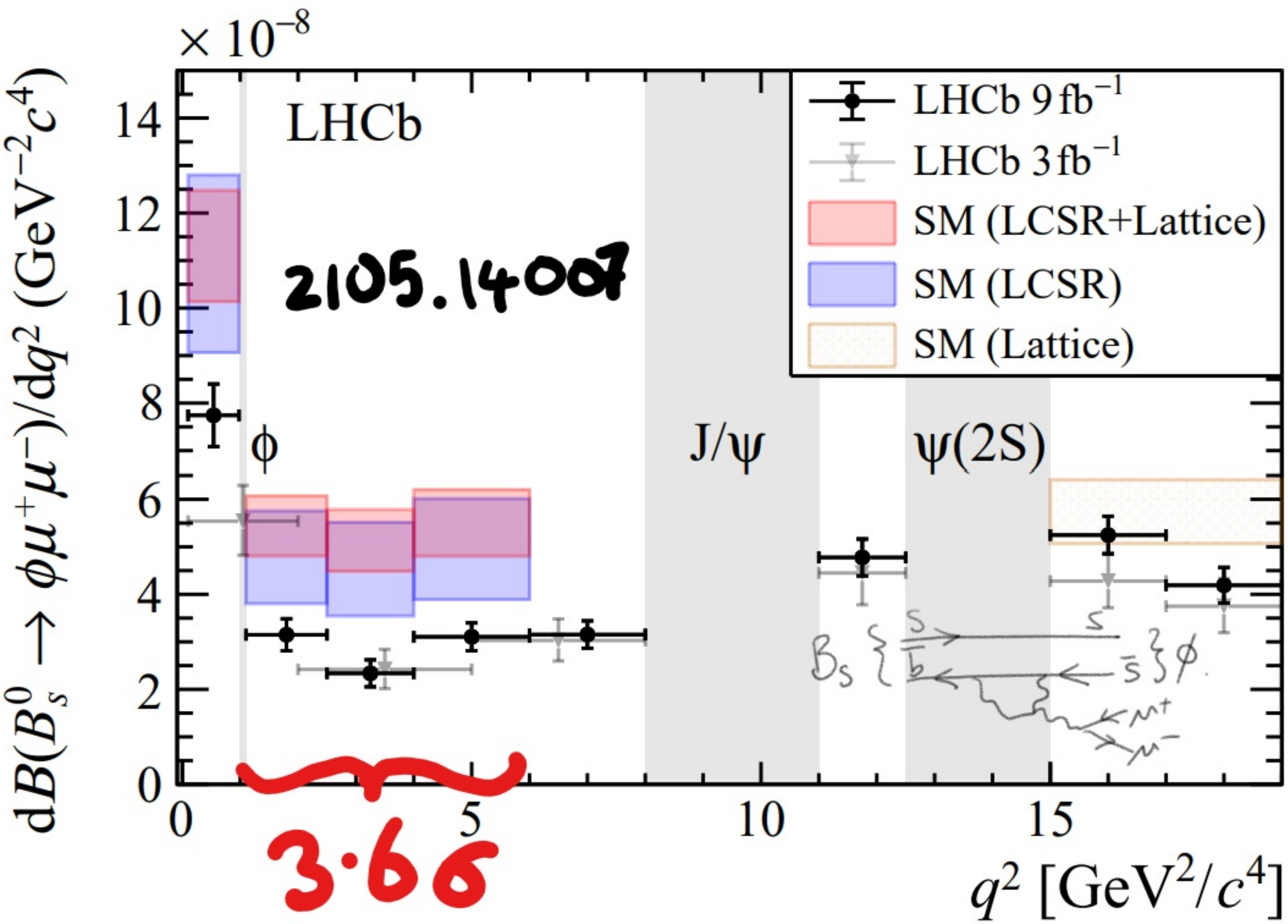




$P_5' = S_5/\sqrt{F_L(1-F_L)}$, leading form factor uncertainties cancel [3]

[3] LHCb, 2003.04831

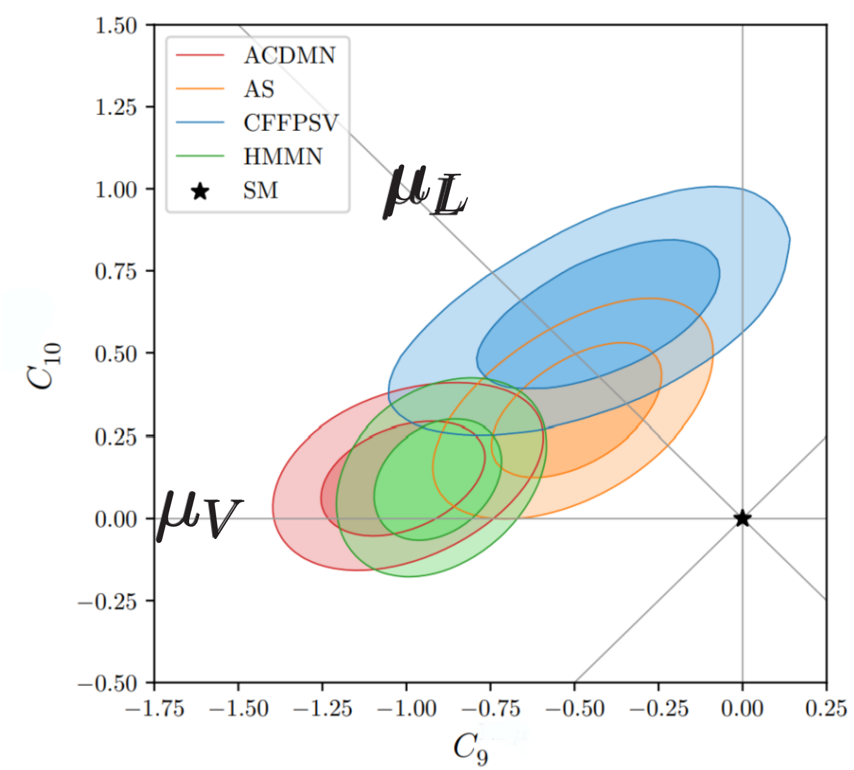
$B_s \to \phi\mu^+\mu^-$: $\phi = (s\bar{s})$



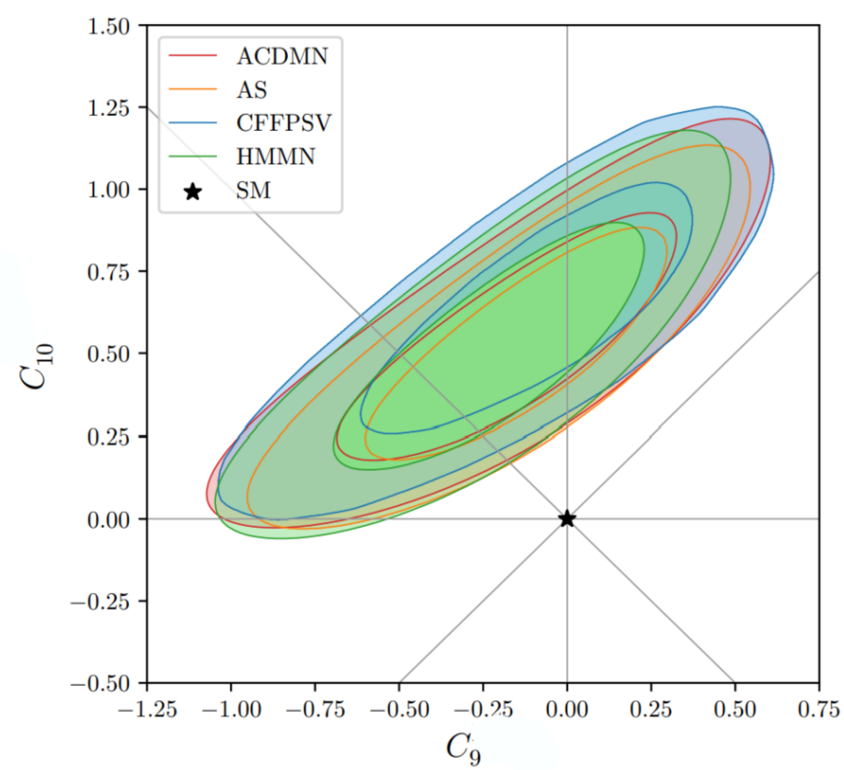
Neutral Current Fits

Alguero *et al*, 2104.08921; Altmannshofer, Stangl, flavio 2103.13370; Ciuchini *et al*, HEPfit 2011.01212; Hurth *et al*, superIso 2104.10058;

$$\mathcal{L} = N[C_9(\bar{b}_L\gamma^\mu s_L)(\bar{\mu}\gamma_\mu\mu) + C_{10}(\bar{b}_L\gamma^\mu s_L)(\bar{\mu}\gamma^5\gamma_\mu\mu)] + H.c.$$



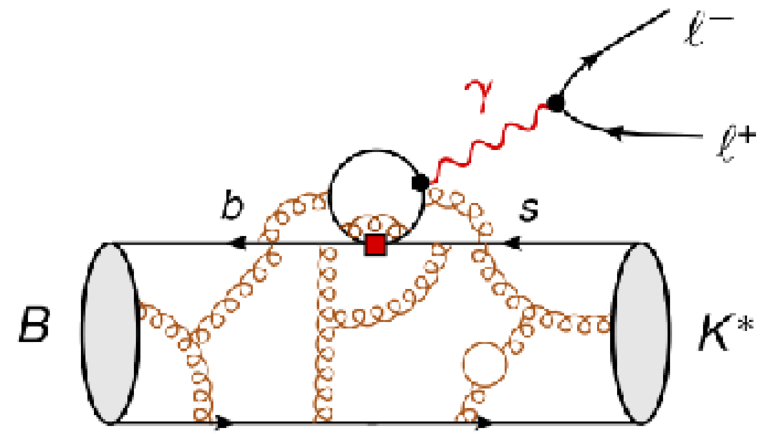
global fit



fit to LFU observables + $B_s \to \mu\mu$

Hadronic Uncertainties

- Hadronic effects like charm loop are photon-mediated ⇒ vector-like coupling to leptons just like C_9



- How to disentangle NP ↔ QCD?
  - Hadronic effect can have different q^2 dependence
  - Hadronic effect is lepton flavour universal ($\rightarrow R_K$!)

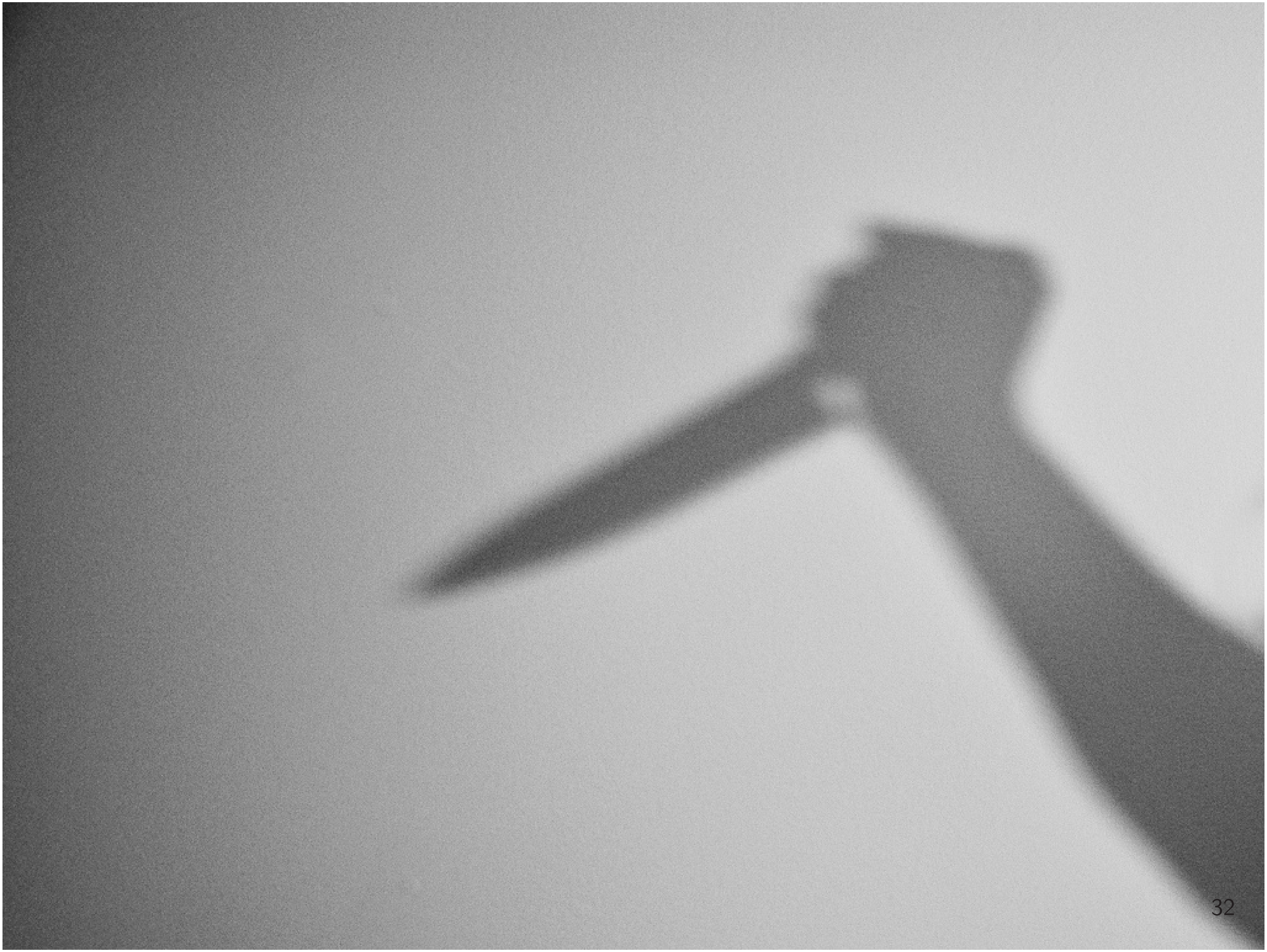
Theory: uncertainties

	parametric	form factors	non-local MEs
$BR(B \to Mll)$	yes	large	large
angular	no	small	large
$BR(B_s \to ll)$	yes	small	no
LFU	no	tiny	no

Parametric uncertainties easy

Large theory uncertainties[4] are taken into account

[4]Gubernari, Reboud, van Dyk, Virto 2206.03797



Simple $B_3 - L_2$ Z' Model

SM-singlet scalar 'flavon' $\theta_{B_3-L_2\neq 0}$

Additional $U(1)_{B_3-L_2}$ gauge symmetry broken by $\langle\theta\rangle \sim$TeV$\Rightarrow$ $M_{Z'} \sim$TeV

SM$+3\nu_R$ fermion content

Zero charges for first two generations of quark, electrons and taus

Postdicts heavy third family quarks[5]

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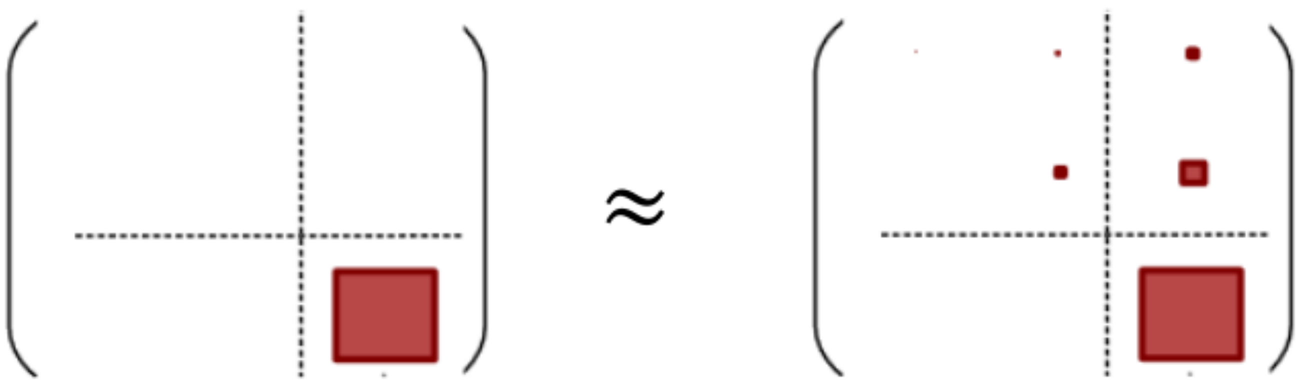
[5] Bonilla *et al*, 1705.00915; Alonso *et al* 1705.03858, BCA 2009.02197 (*simplified EFT*)

Flavour problem

$$\mathcal{L}_q = Y_t \overline{Q'_{3L}} H t'_R + Y_b \overline{Q'_{3L}} H^c b'_R + H.c.,$$



Postdicts small CKM angles

$$\mathcal{L}_{X\psi} = g_X \Big(\overline{\mathbf{u_L}}\Lambda^{(u_L)}\not{Z}'\mathbf{u_L} + \overline{\mathbf{u_R}}\Lambda^{(u_R)}\not{Z}'\mathbf{u_R}$$
$$+\overline{\mathbf{d_L}}\Lambda^{(d_L)}\not{Z}'\mathbf{d_L} + \overline{\mathbf{d_R}}\Lambda^{(d_R)}\not{Z}'\mathbf{d_R}$$
$$-3\overline{\mathbf{e_L}}\Lambda^{(e_L)}\not{Z}'\mathbf{e_L} - 3\overline{\mathbf{e_R}}\Lambda^{(e_R)}\not{Z}'\mathbf{e_R}$$
$$-3\overline{\boldsymbol{\nu}_L}\Lambda^{(\nu_L)}\not{Z}'\boldsymbol{\nu}_L - 3\overline{\boldsymbol{\nu}_R}\Lambda^{(\nu_R)}\not{Z}'\boldsymbol{\nu}_R\Big),$$

$$\Lambda^{(I)} \equiv V_I^\dagger \xi V_I, \qquad \xi = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Z' couplings, $I \in \{u_L, d_L, e_L, \nu_L, u_R, d_R, e_R\}$

A simple limiting case

$$V_{u_R} = V_{d_R} = 1$$

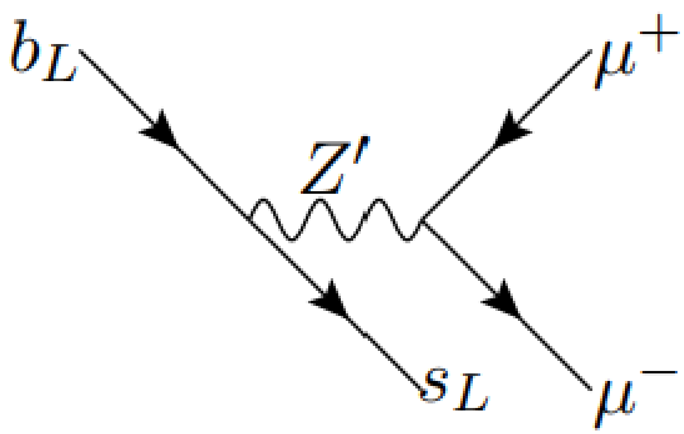
$$V_{d_L} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & -\sin\theta_{23} \\ 0 & \sin\theta_{23} & \cos\theta_{23} \end{pmatrix}, \qquad V_{e_{L,R}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix},$$

$\Rightarrow V_{u_L} = V_{d_L} V^{\dagger}_{CKM}$ and $V_{\nu_L} = V_{e_L} U^{\dagger}_{PMNS}$.

Important Z' Couplings

$$g_X \left[(\overline{d_L}\ \overline{s_L}\ \overline{b_L}) \begin{pmatrix} 0 & 0 & 0 \\ 0 & \sin^2\theta_{23} & \frac{1}{2}\sin 2\theta_{23} \\ 0 & \frac{1}{2}\sin 2\theta_{23} & \cos^2\theta_{23} \end{pmatrix} \not{Z}' \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} \right.$$

$$\left. -3(\overline{e}\ \overline{\mu}\ \overline{\tau}) \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix} \not{Z}' \begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix} \right]$$

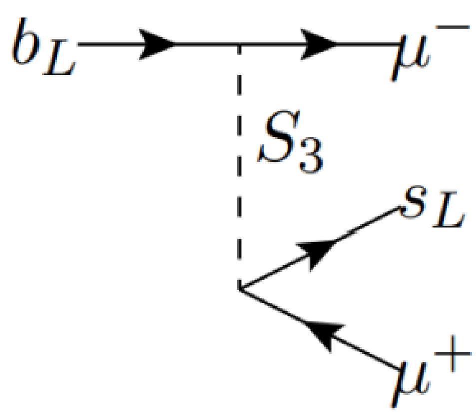


– LFU Violating, $C_9 \neq 0$

S_3 Leptoquark Model

TeV scale Scalar[6] $S_3 = (\bar{3},\ 3,\ 1/3)$:

$$\mathcal{L} = \ldots + \lambda Q_3' L_2 + \cancel{Y_{ij} Q_i Q_j S_3^\dagger} + \text{h.c.}$$
$$= \ldots + \lambda(\cos\theta_{23} Q_3 L_2 + \sin\theta_{23} Q_2 L_2) + \text{h.c.}$$

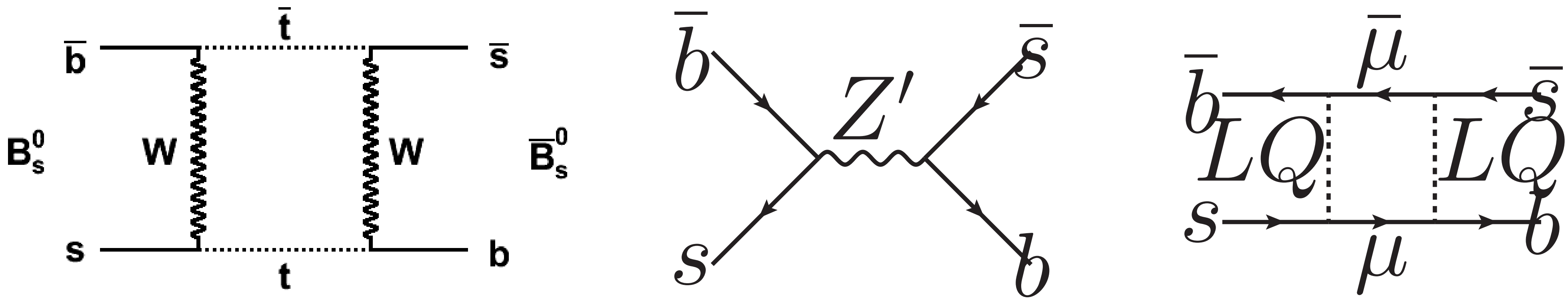


$$C_9 = -C_{10}$$

[6] Capdevila *et al* 1704.05340, Hiller and Hisandzic 1704.05444, D'Amico *et al* 1704.05438

$B_s - \bar{B}_s$ Mixing

Measurement agrees with SM.



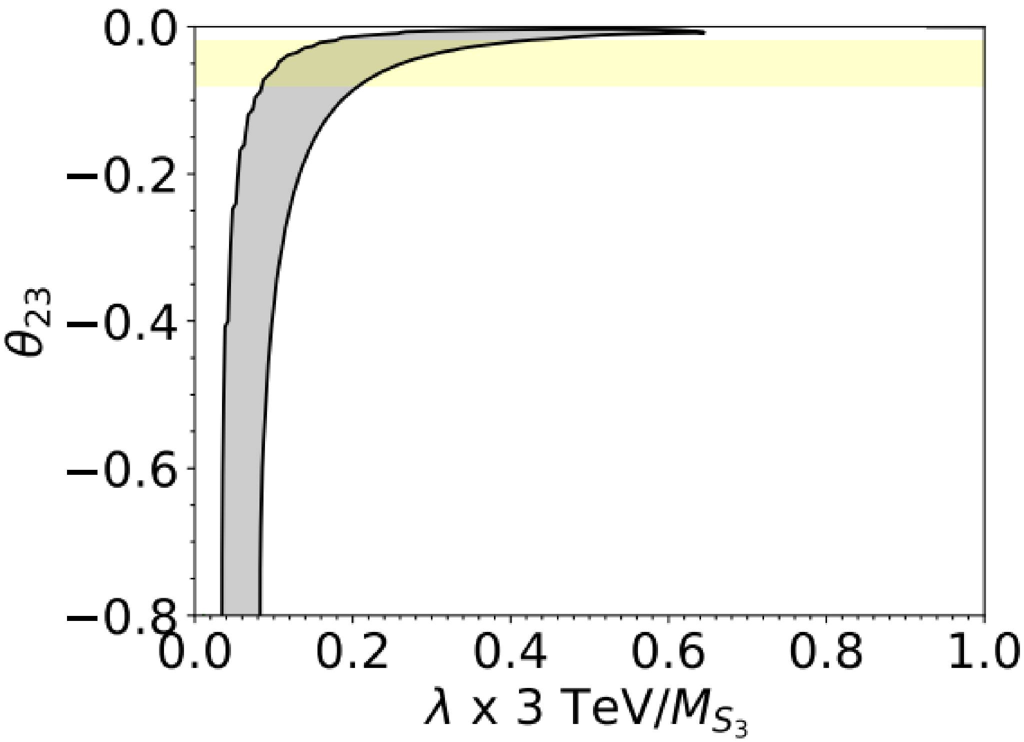
$$g_{sb} = \frac{g_X}{2} \sin 2\theta_{sb} \lesssim \frac{M_{Z'}}{194 \text{ TeV}}$$ but uncertain

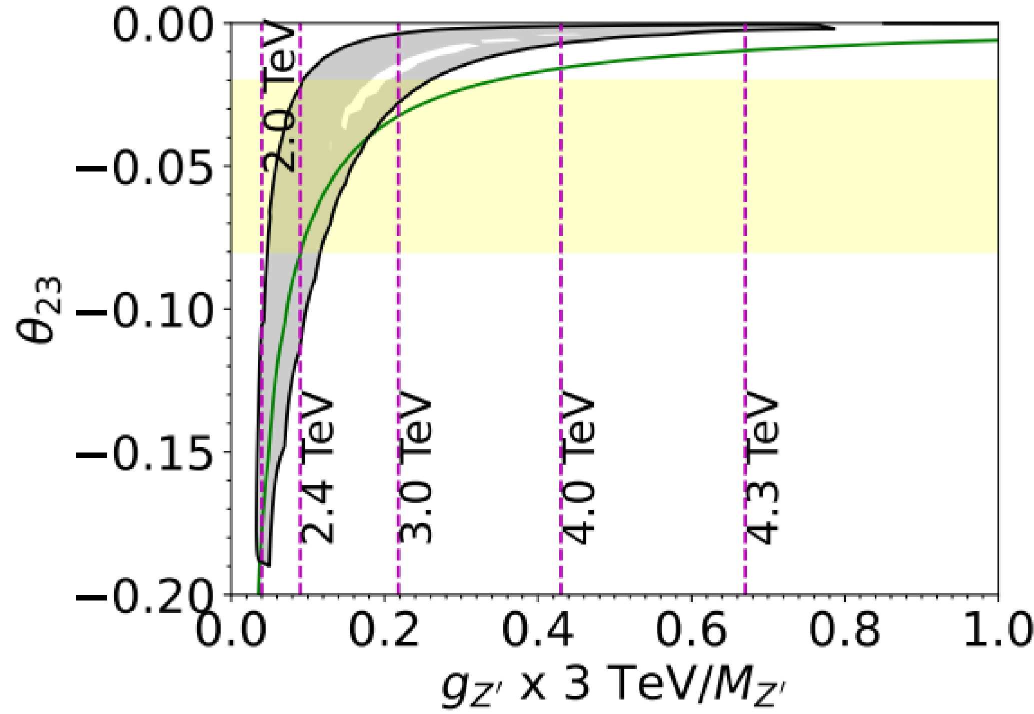
from QCD sum rules and lattice[7].

[7] King, Lenz, Rauh, arXiv:1904.00940

Parameter Space

BCA, Davighi, 2211.11766





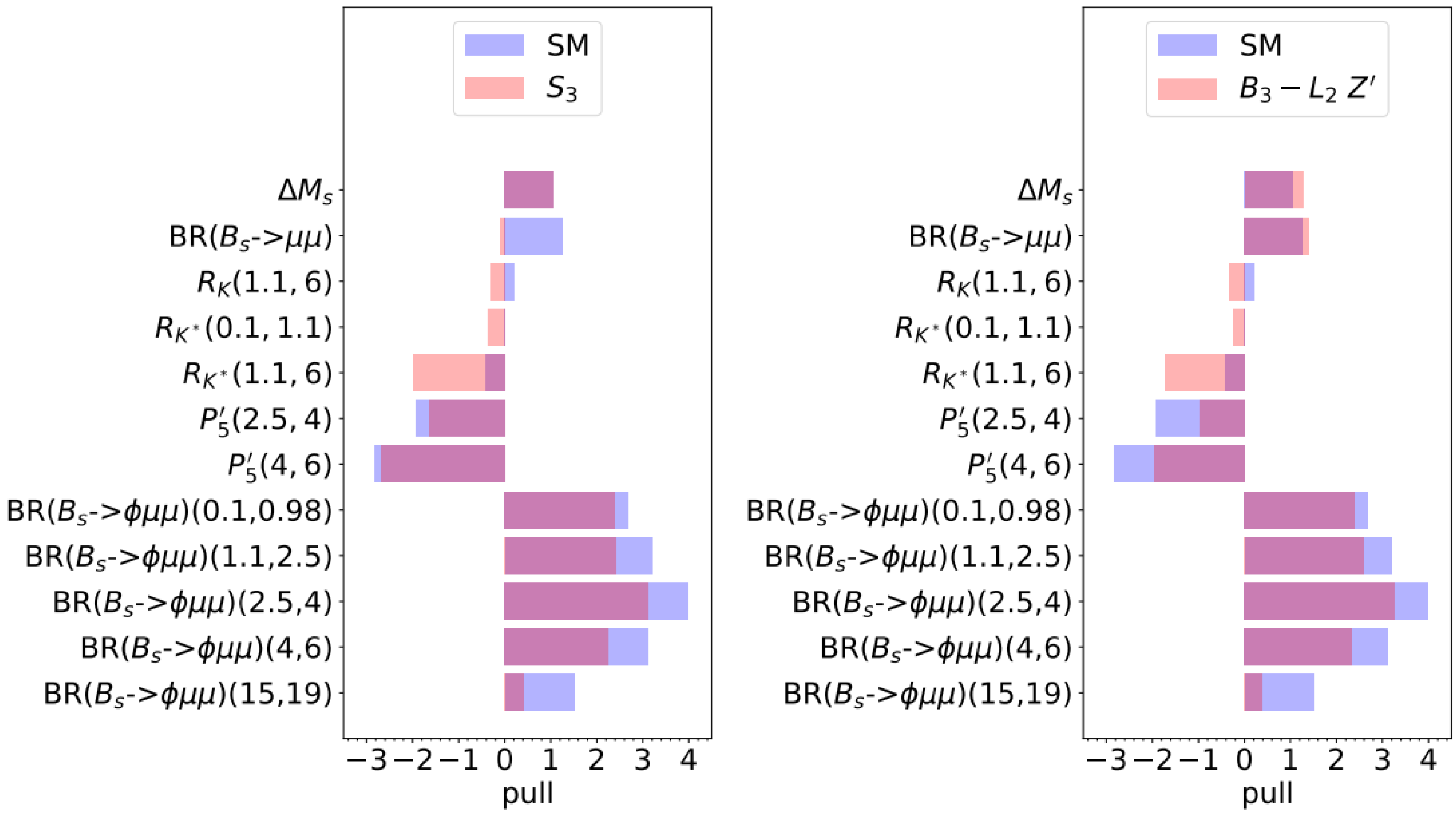
Best fits `BCA, Davighi, 2211.11766`

2-parameter fits to 247 flavour observables:

`parameters | Wilson | flavio | smelli > output`

Leptoquark/Z' $\sqrt{\chi^2_{SM} - \chi^2}$ both 3.6

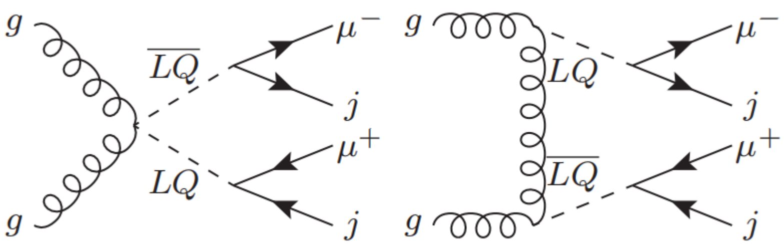
Pull=(theory-exp)/error

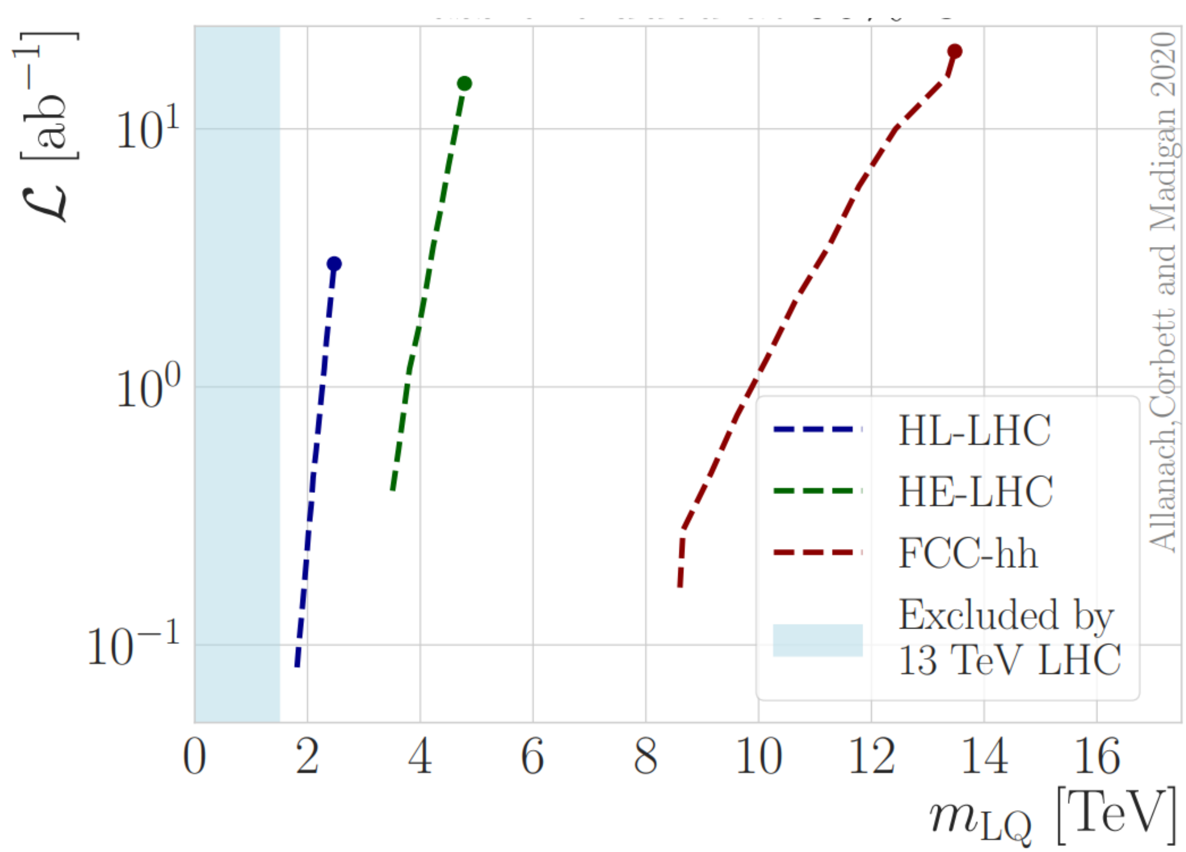


BCA, Davighi, 2211.11766

Scalar LQ[8]: eg $S_3 \sim (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$

Ban $\not{B}$ with eg $U(1)_{B_3+L_2-2L_3}$



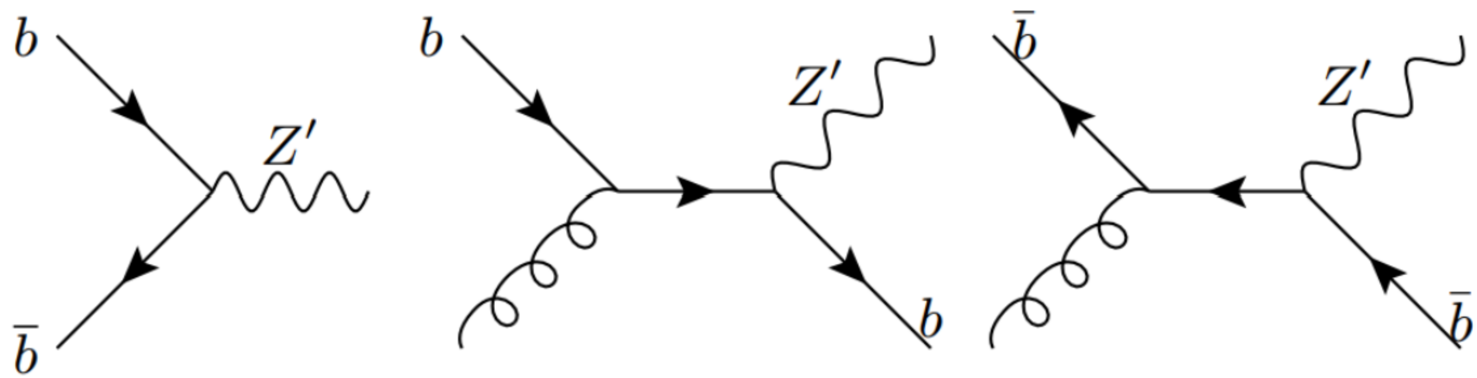


[8] BCA, Corbett, Madigan, 1911.0445

Z' Decay Modes

Mode	BR	Mode	BR	Mode	BR
$t\bar{t}$	0.15	$b\bar{b}$	0.15	$\nu\bar{\nu}'$	0.23
$\mu^+\mu^-$	0.46				

pp Z' Production:



$$\sigma_{prod} \propto g_X^2 \cos^4\theta_{sb} = g_X^2\left(1 - 2\theta_{sb}^2 + \mathcal{O}(\theta_{sb}^4)\right)$$

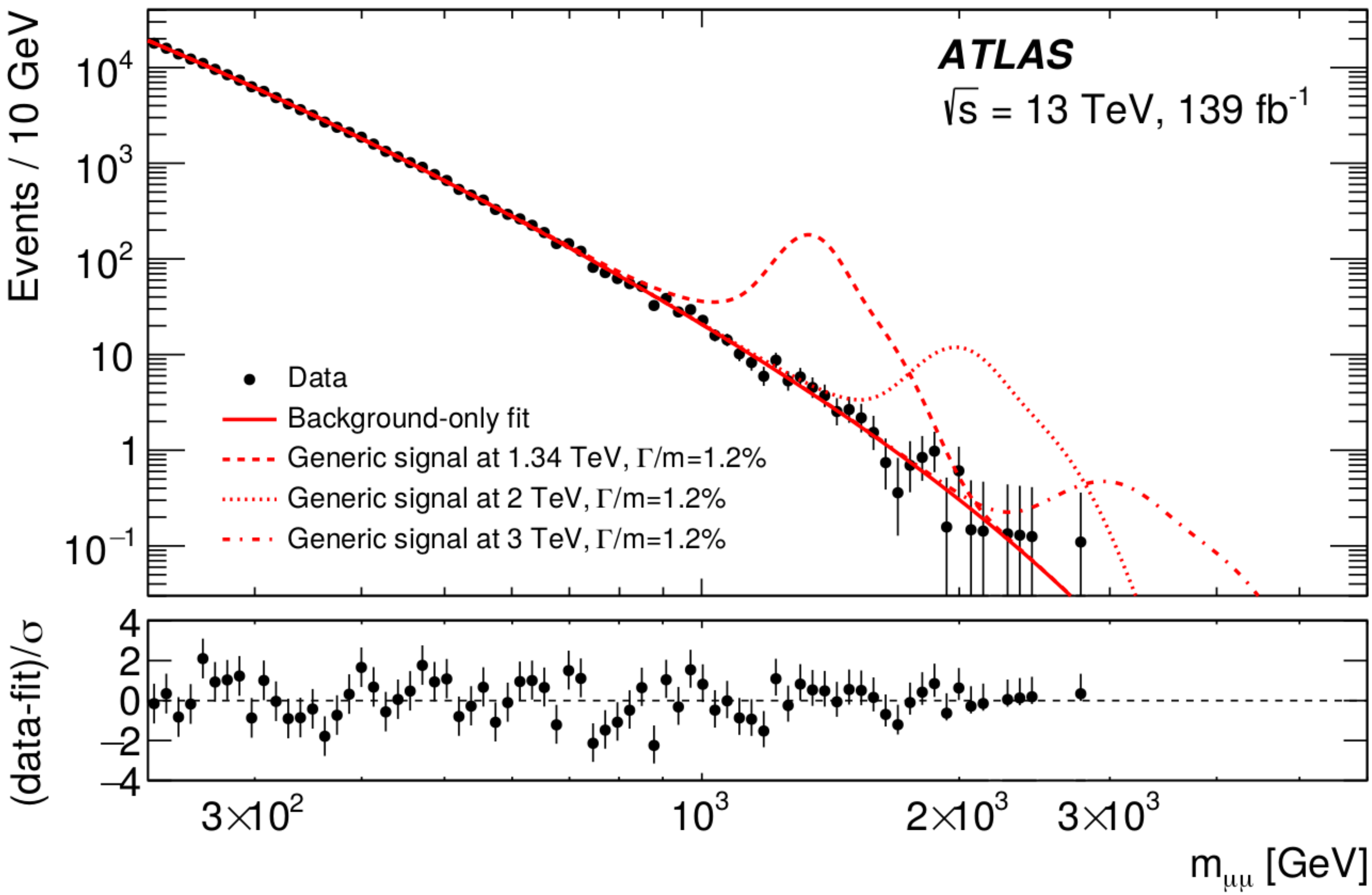
$\mu\mu$ ATLAS 13 TeV 139 fb^{-1}

2 track-based isolated μ, $p_T > 30$ GeV with reconstructed vertex.[9] Only keep pair with highest $(|p_{T_1}| + |p_{T_2}|)$.

$$m^2_{\mu_1\mu_2} = (p_1^\mu + p_2^\mu)\left(p_{1_\mu} + p_{2_\mu}\right)$$

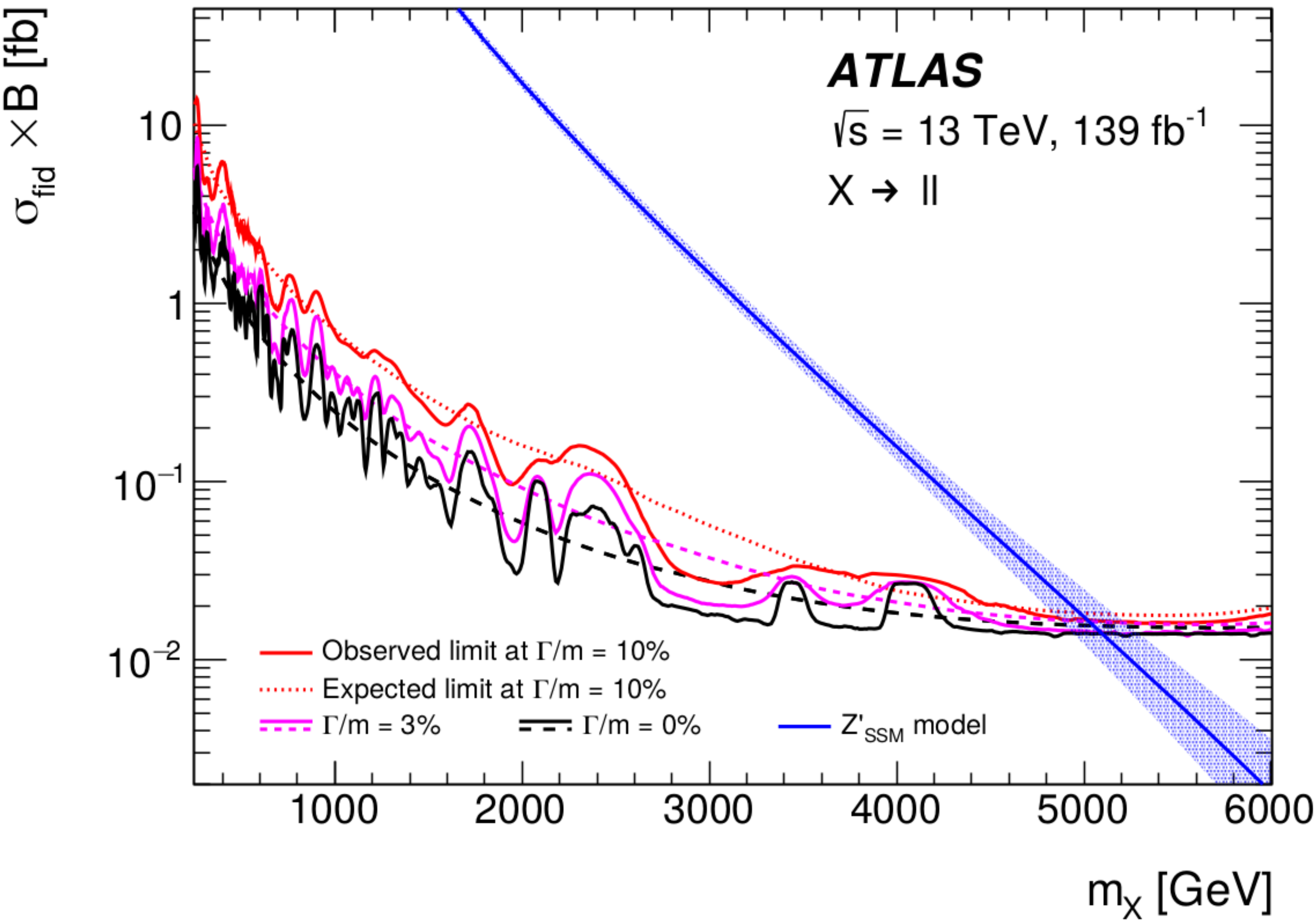
CMS also has a similar analysis[10]

[9] ATLAS, 1903.06248
[10] CMS, 2103.02708



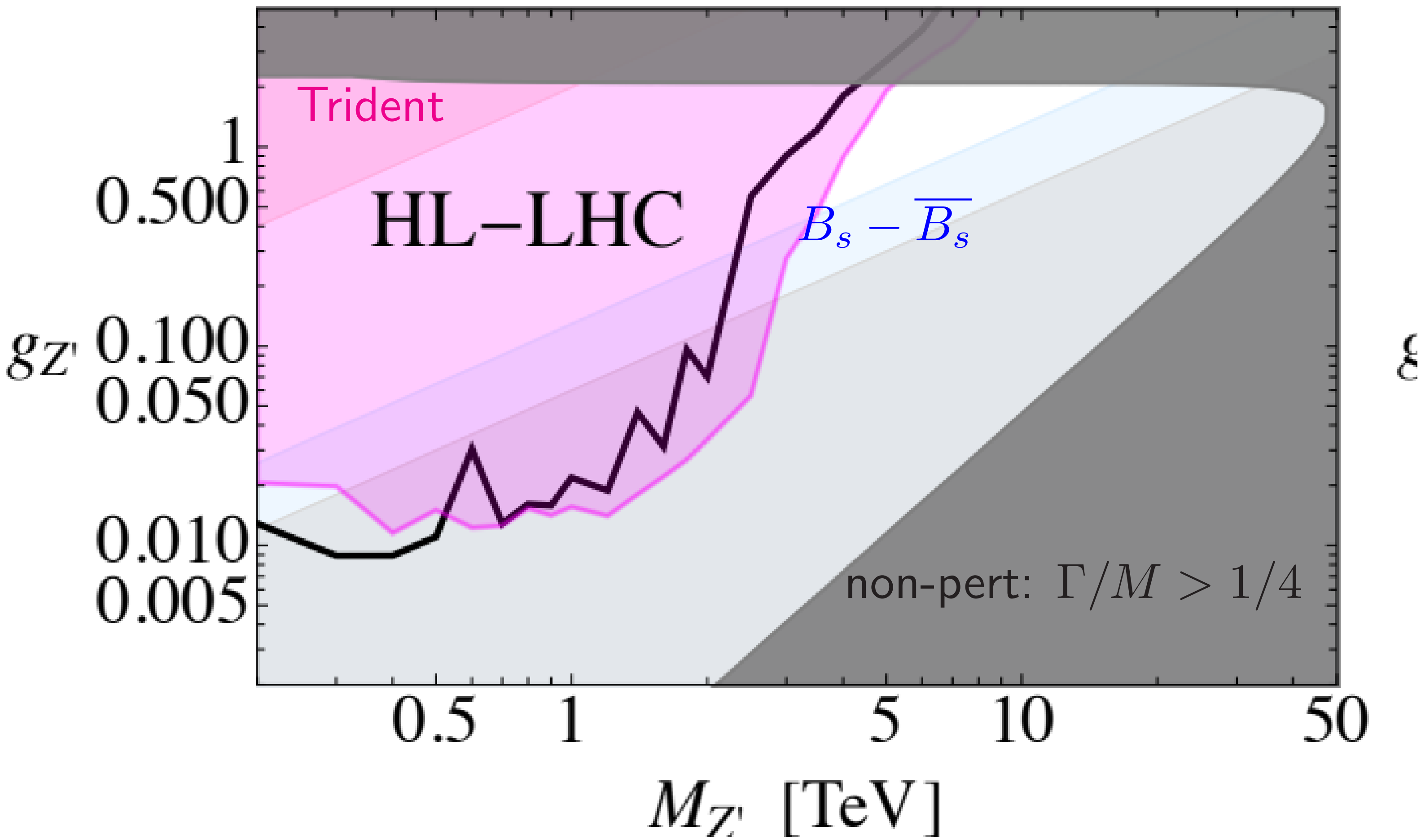
ATLAS
√s = 13 TeV, 139 fb-1
Events / 10 GeV
10^4
10^3
10^2
10
1
10^−1
Data
Background-only fit
Generic signal at 1.34 TeV, Γ/m=1.2%
Generic signal at 2 TeV, Γ/m=1.2%
Generic signal at 3 TeV, Γ/m=1.2%
(data-fit)/σ
4
2
0
−2
−4
3×10^2
10^3
2×10^3
3×10^3
m_μμ [GeV]

ATLAS l^+l^- limits



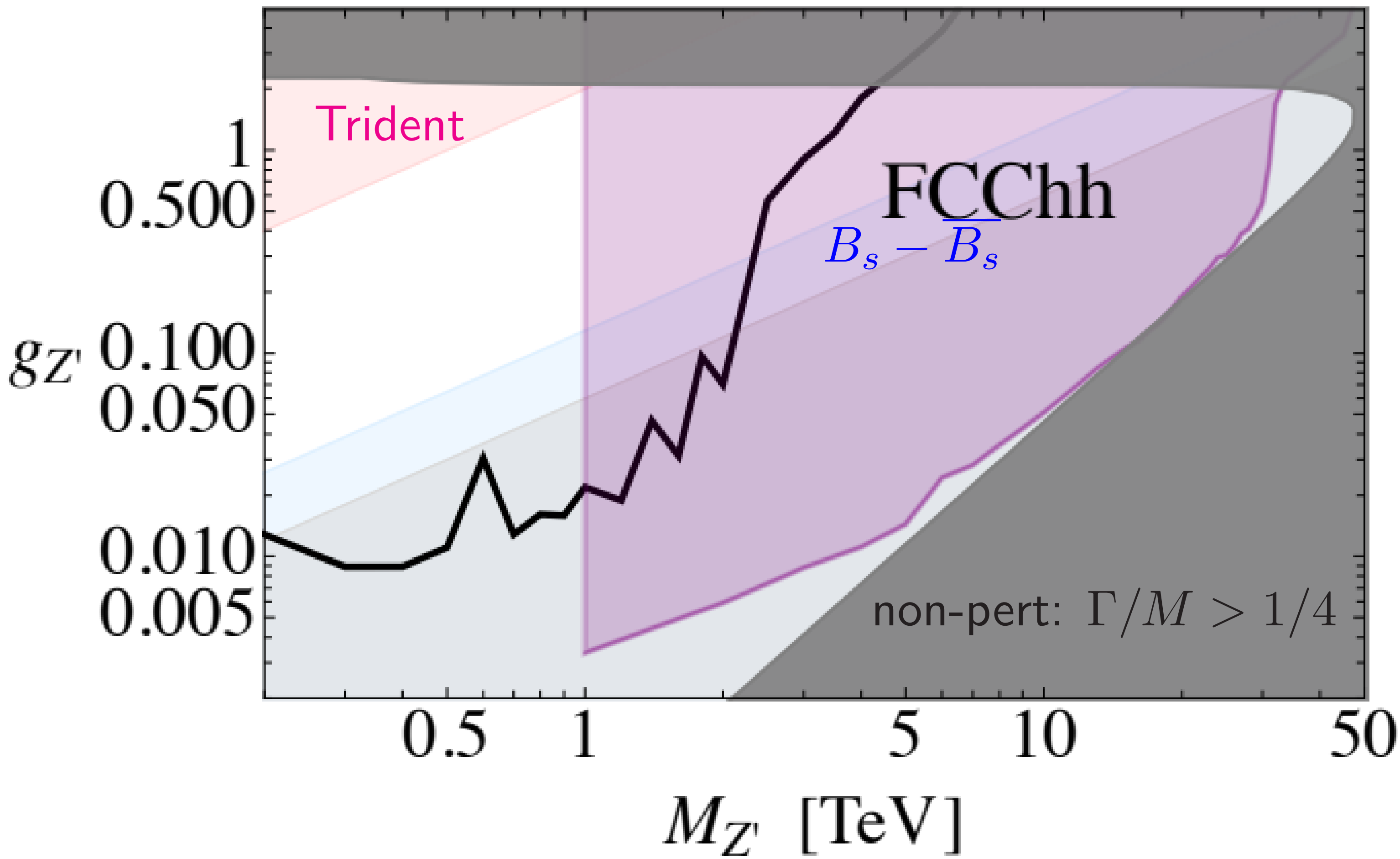
ATLAS, 1903.06248

$B_3 - L_2\ Z'$ at HL-LHC



Azatov, Garosi, Greljo, Marzocca, Salko, 2205.13552 with old $R_{K^{(*)}}$

$B_3 - L_2\ Z'$ at FCC-hh

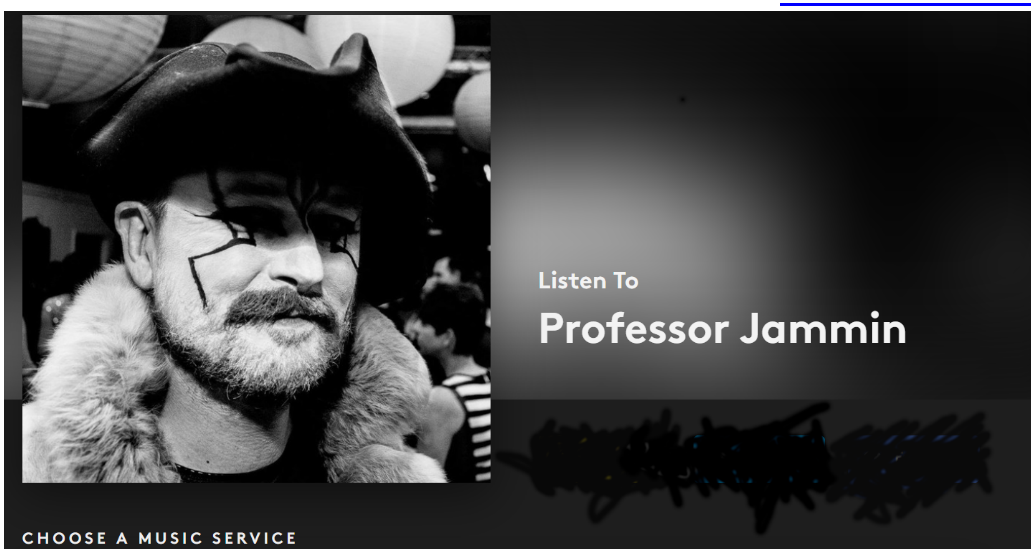


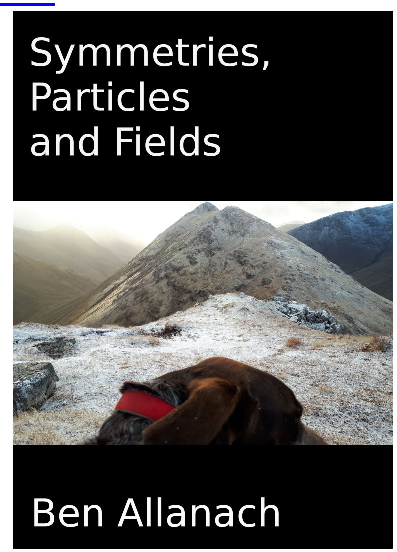
Azatov, Garosi, Greljo, Marzocca, Salko, 2205.13552 with old $R_{K^{(*)}}$

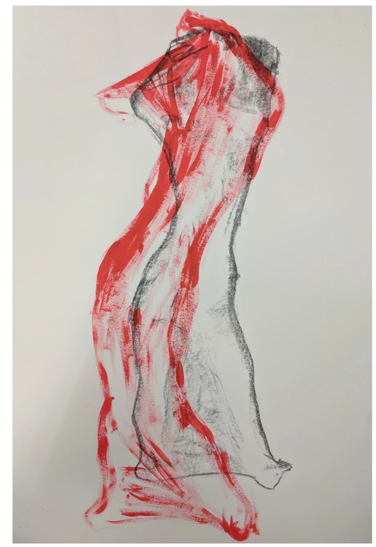
Epilogue

It's remarkable that TeV-scale flavour symmetry is still allowed

Plug for my music, book (18€) and Quantum Selves art:







Solution Space

Is a projective *variety*

Over-parameterisation in terms of 18 integers

$$S_{Q_1}, S_{Q_2}, S_{U_1}, S_{U_2}, S_{D_1}, S_{D_2}, S_{D_3}, S_{L_1}, S_{L_2}, S_{E_1}, S_{E_2}, S_{N_1}, S_{N_2}, S_{N_3}, a, b, r, t \in \mathbb{Q}$$

It is at most 11-D: $S \cdot C = S \cdot B = 0$.

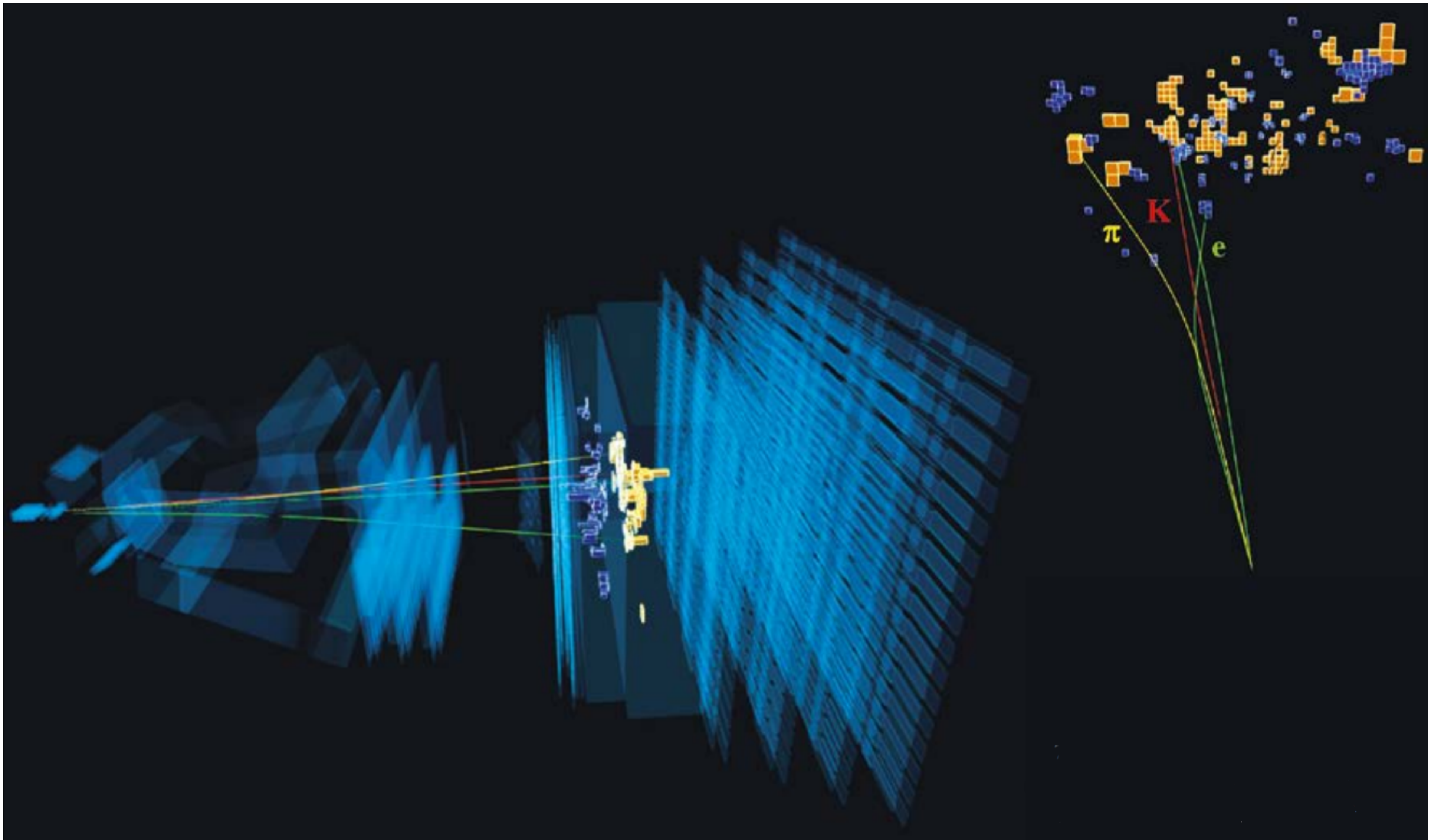
`BCA, Gripaios, Tooby-Smith 2104.14555`

Check

An inverse ($S = T, a = 0, b = 1, r = 0, t = 1$), was checked against all 21 549 920 Anomaly-free Atlas solns.

`BCA, Gripaios, Tooby-Smith 2104.14555`

LHCb $B^0 \to K^{0*}e^+e^-$ Event[11]



[11] Picture from CERN Courier April 2018

Other Constraints

Consider perturbativity:

$$\frac{d\ln g}{d\ln\mu} = \frac{g^2 \sum_{i\in\chi\cup V} z_i^2}{24\pi^2} < 1$$

$$\Leftrightarrow g < \frac{2\pi\sqrt{6}}{\sqrt{\sum_{i\in\chi\cup V} z_i^2}}.$$

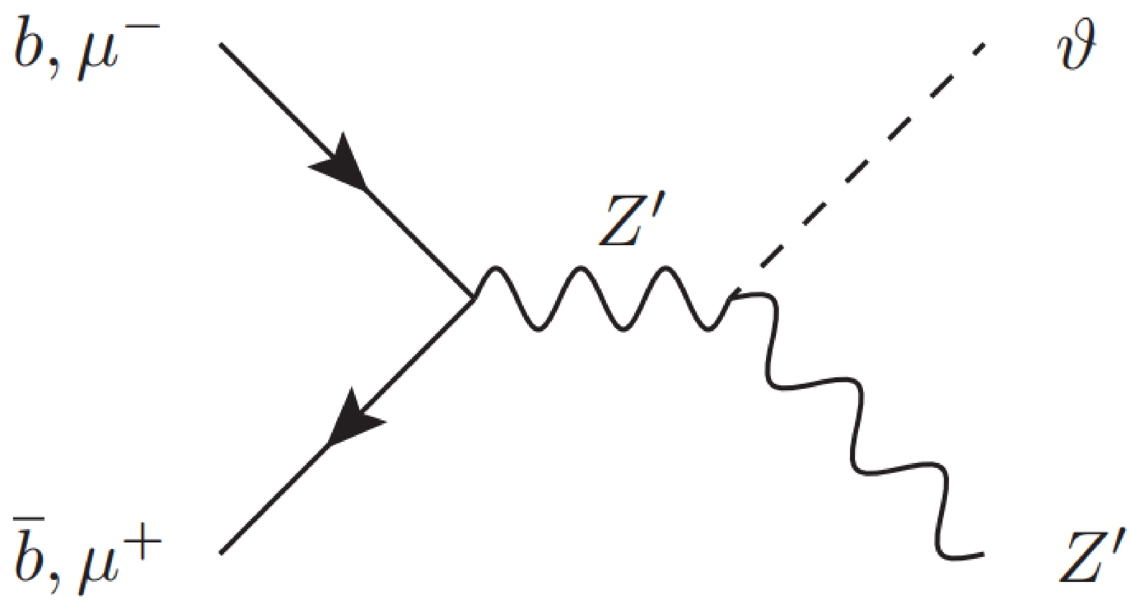
Caveat?

Anomalies can be cancelled by topological Wess-Zumino $\mathcal{L}$ term: can eg be obtained by integrating out heavy states.

Generic ones are hard to generate whilst making the relevant heavy states heavy from $U(1)$ spontaneous breakdown.

Flavonstrahlung

Models of Z' ilk possess $\mathcal{L} = \lambda H H^\dagger \theta \theta^\dagger \Rightarrow$ a *flavonstrahlung* signature:

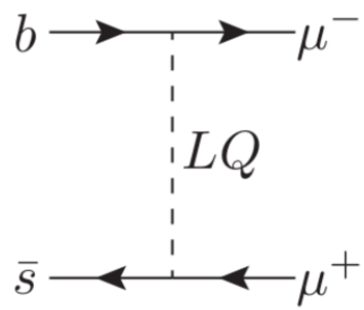


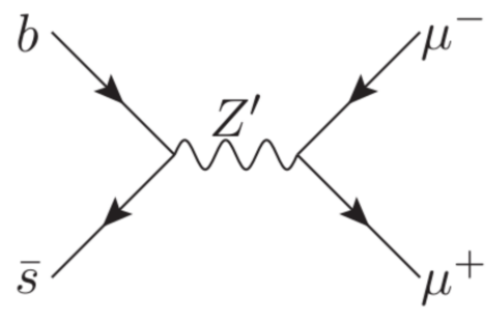
BCA, 2009.02197; BCA, Loisa, 2212.07440

Philosophy and Organisation

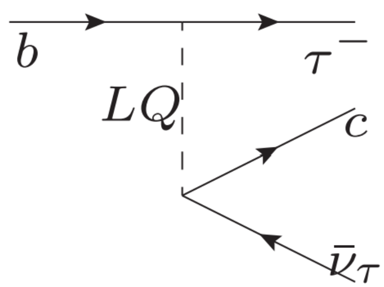
There are hundreds of specific models. Many of them reduce to the same important features at the TeV-scale, so we shall take a bottom up approach and trust LHCb data more than detailed theoretical assumptions.

Neutral current:





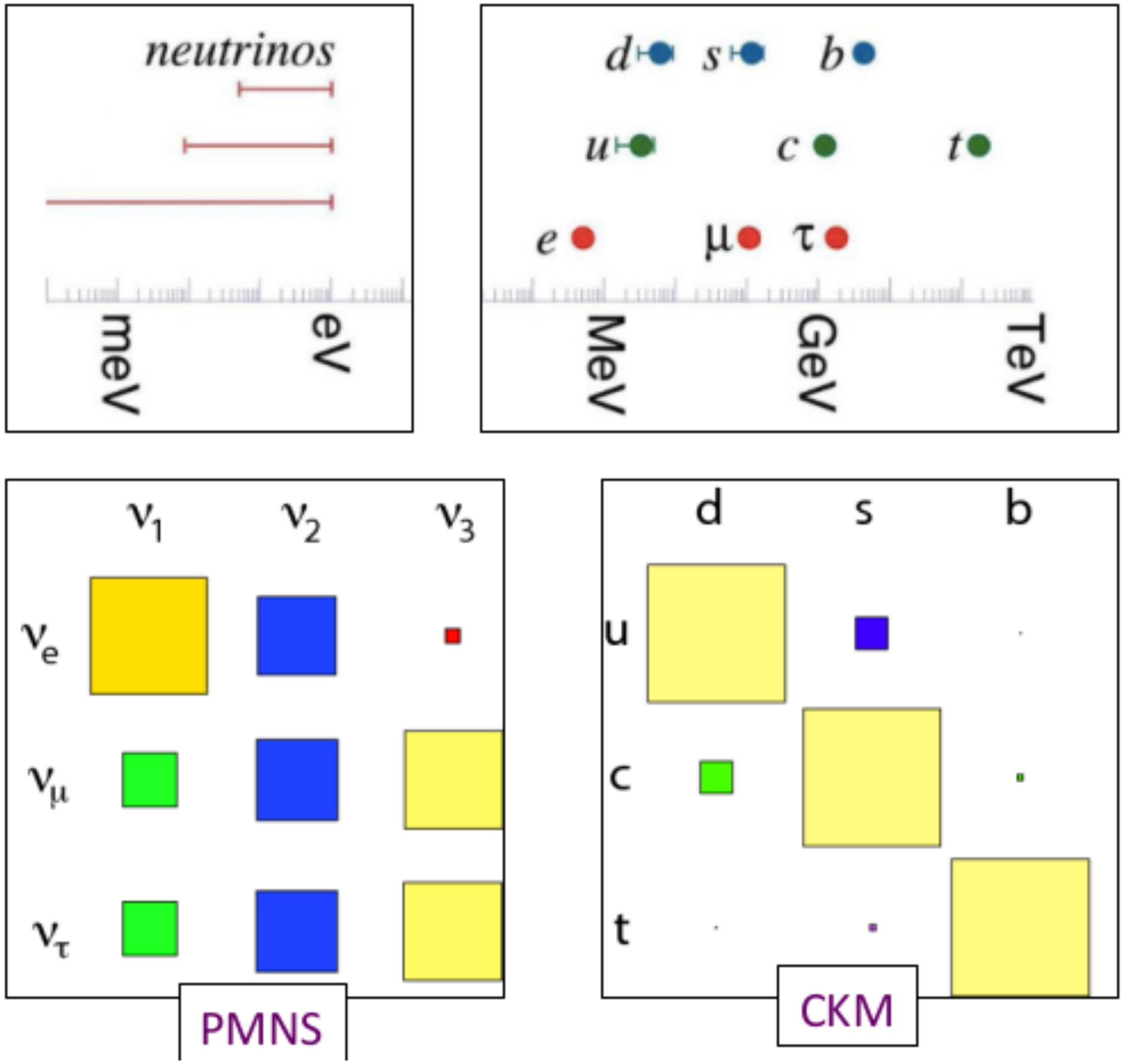
Charged current:



Vector/scalar option for leptoquark (LQ)

The Flavour Problem

The Flavour Problem



A Simple Z' Model

BCA, Davighi, 1809.01158: Add complex SM-singlet scalar 'flavon' $\theta_{X\neq 0}$ which breaks gauged $U(1)_X$:

$$SU(3) \times SU(2)_L \times U(1)_Y \times U(1)_X$$

$$\downarrow \langle\theta\rangle \sim \text{Several TeV}$$

$$SU(3) \times SU(2)_L \times U(1)_Y$$

$$\downarrow \langle H\rangle \sim 246 \text{ GeV}$$

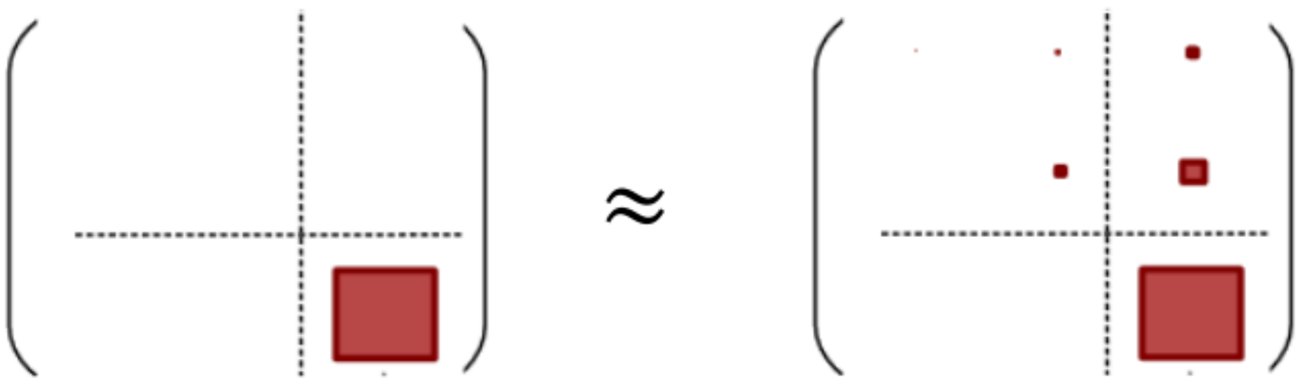
$$SU(3) \times U(1)_{em}$$

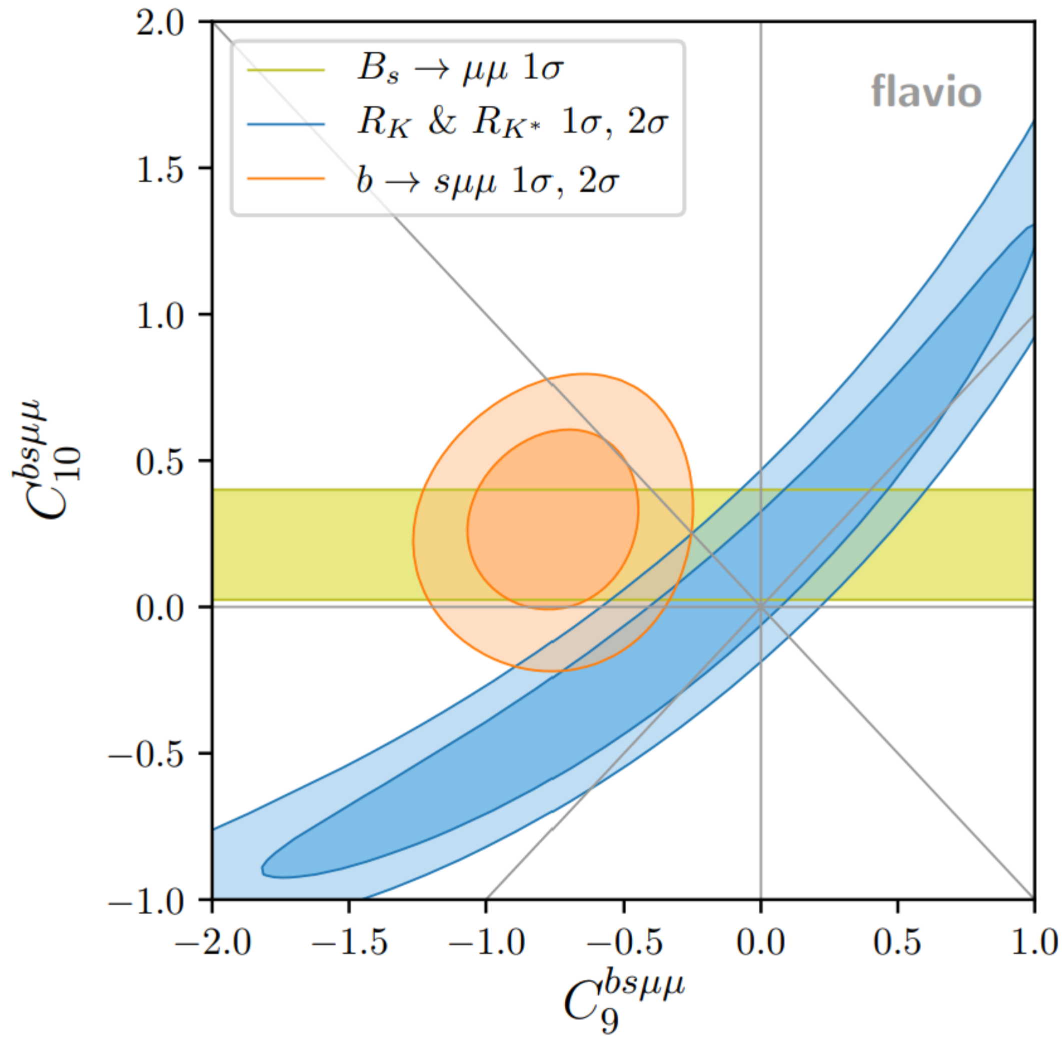
- SM fermion content
- Zero X charges for first two generations
- Solve anomaly cancellation for $U(1)_X$

Unique Solution: $X = Y_3$

$$
\boxed{\begin{array}{cccc}
X_{Q'_{1,2}} = 0 & X_{u_{R'_{1,2}}} = 0 & X_{d_{R'_{1,2}}} = 0 & X_{L'_{1,2}} = 0 \\
X_{e_{R'_{1,2}}} = 0 & X_H = -1/2 & X_{Q'_3} = 1/6 & X_{u'_{R3}} = 2/3 \\
X_{d'_{R3}} = -1/3 & X_{L'_3} = -1/2 & X_{e'_{R3}} = -1 & X_\theta \neq 0
\end{array}}
$$

$$\mathcal{L} = Y_t \overline{Q_3'}_L H t'_R + Y_b \overline{Q'_{3L}} H^c b'_R + Y_\tau \overline{L_3'}_L H^c \tau'_R + H.c.,$$





Greljo, Salko, Smolkovic, Stangl, 2212.10497

$$\mathcal{L} = N(\bar{s}\gamma^{\alpha}P_L b)\left[C_9(\bar{\mu}\gamma_{\alpha}\mu) + C_{10}(\bar{\mu}\gamma_{\alpha}\gamma_5\mu)\right]$$

A simple limiting case

$$V_{u_R} = V_{d_R} = V_{e_R}$$

for simplicity and the ease of passing bounds.

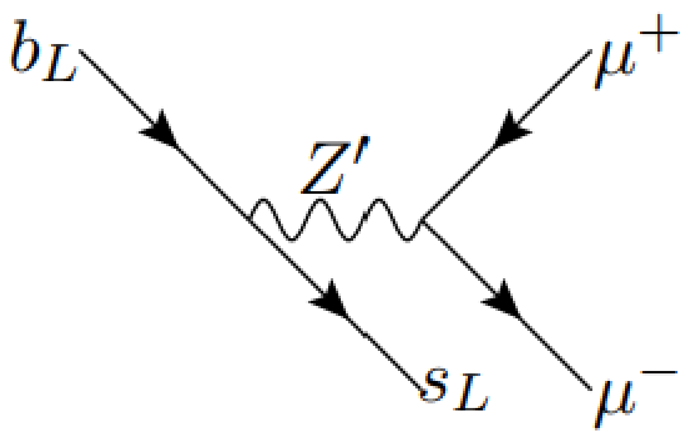
$$V_{d_L} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & -\sin\theta_{23} \\ 0 & \sin\theta_{23} & \cos\theta_{23} \end{pmatrix}, \qquad V_{e_L} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix},$$

$\Rightarrow V_{u_L} = V_{d_L} V_{CKM}^{\dagger}$ and $V_{\nu_L} = V_{e_L} U_{PMNS}^{\dagger}$.

Important Z' Couplings

$$g_X \left[(\overline{d_L}\ \overline{s_L}\ \overline{b_L}) \begin{pmatrix} 0 & 0 & 0 \\ 0 & \sin^2\theta_{23} & \frac{1}{2}\sin 2\theta_{23} \\ 0 & \frac{1}{2}\sin 2\theta_{23} & \cos^2\theta_{23} \end{pmatrix} \not{Z}' \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} \right.$$

$$\left. -3(\overline{e}\ \overline{\mu}\ \overline{\tau}) \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix} \not{Z}' \begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix} \right]$$



– LFU Violating, $C_9 \neq 0$

$Z - Z'$ mixing angle

$$\sin\alpha_z \approx \frac{g_X}{\sqrt{g^2+g'^2}}\left(\frac{M_Z}{M_Z'}\right)^2 \ll 1.$$

This gives small non-flavour universal couplings to the Z boson propotional to g_X and:

$$Z_\mu = \cos\alpha_z\left(-\sin\theta_w B_\mu + \cos\theta_w W_\mu^3\right) + \sin\alpha_z X_\mu,$$

smelli observables

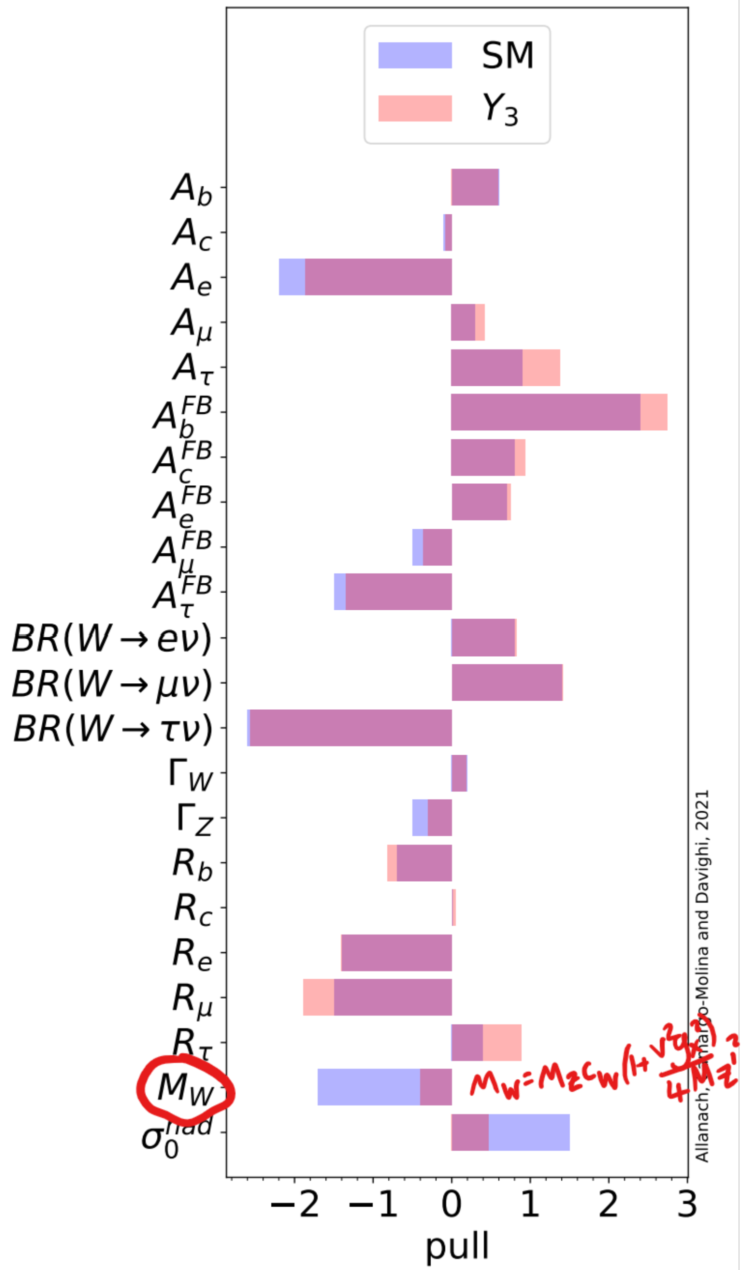
- 167 quarks: P_5', $BR(B_s \to \mu^+\mu^-)$ and others with significant theory errors
- 21 LFU FCNCs: $R_K, R_{K^\star}$, $B \to$di-tau decays
- 31 EWPOs from LEP not assuming lepton flavour universality

Theory uncertainties modelled as multi-variate Gaussians: approximated to be independent of new physics.

SM:

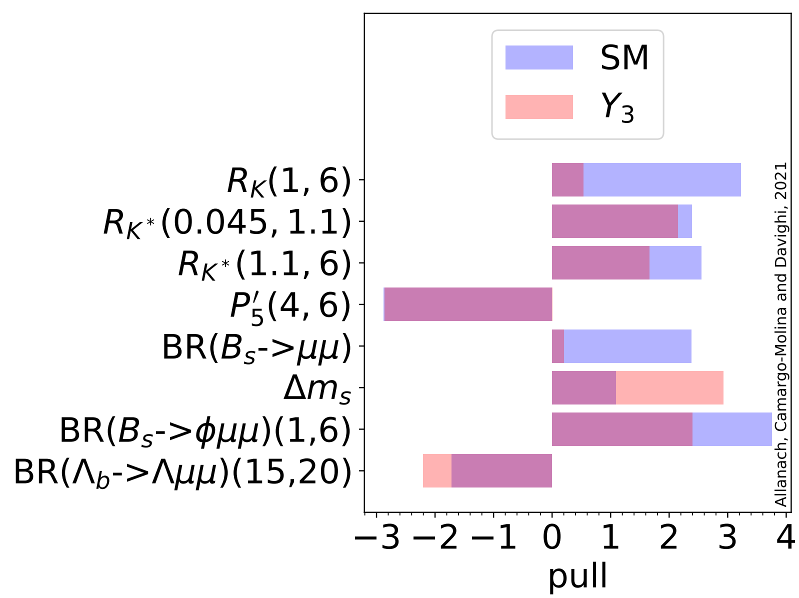
data set	χ^2	n	p−value
quarks	221.6	167	.003
LFU FCNCs	35.3	21	.026
EWPOs	35.7	31	.26
global	292.6	219	.00065

Global Fits $M_{Z'} = 3$ TeV

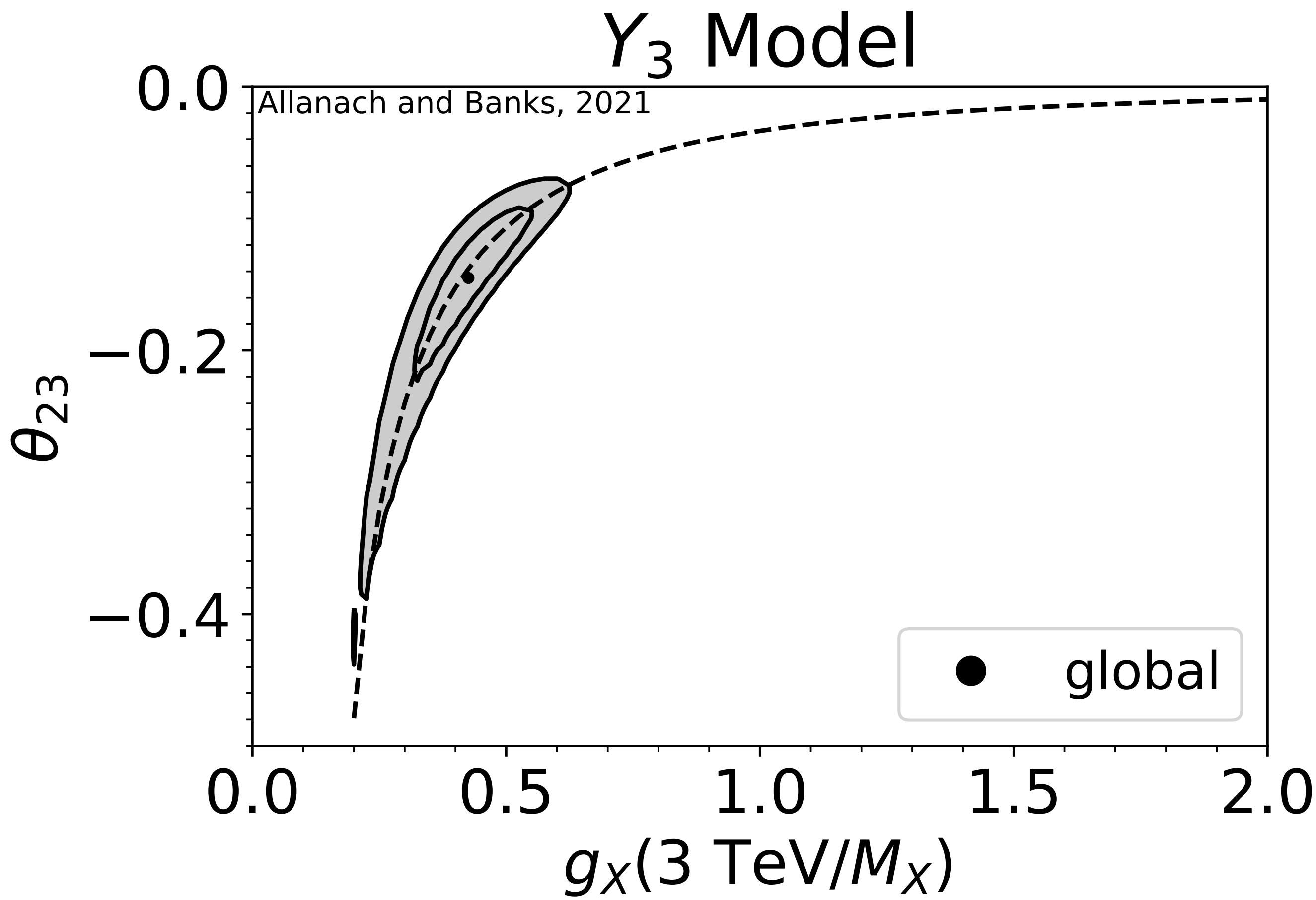


data set	χ^2	n	$p-$value
quarks	221.6	167	.003
LFU FCNCs	35.3	21	.026
EWPOs	35.7	31	.26
global	292.6	219	.00065

data set	χ^2	n	$p-$value
quarks	192.5	167	.071
LFU FCNCs	21.0	21	.34
EWPOs	36.0	31	.17
global	249.5	219	.064

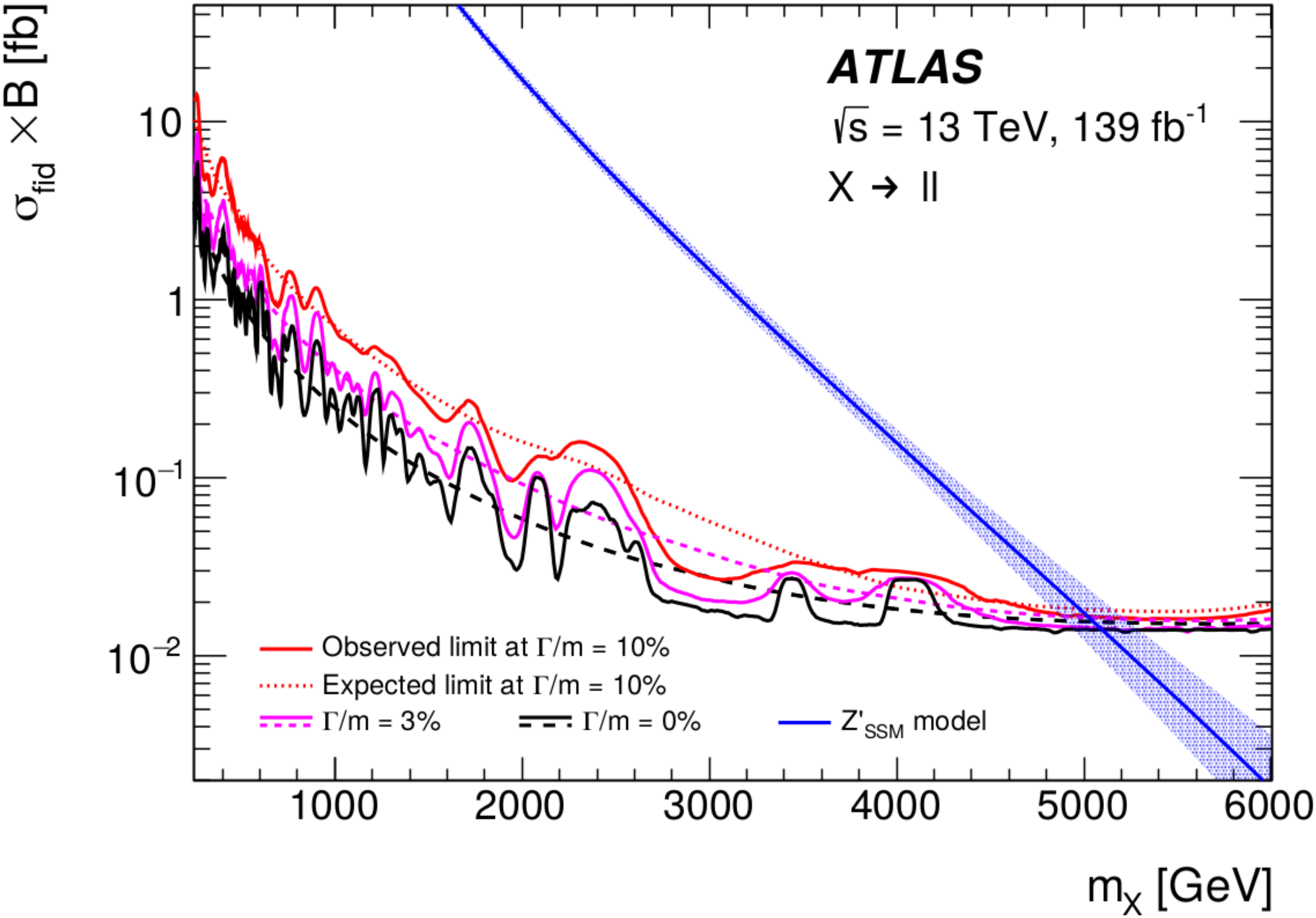


TFHM Fit, 95% CL



Relies on: `smelli-2.2.0` (Aebischer, Kumar, Stangl, Straub, `1810.07698`), `flavio-2.2.0` (Straub, `1810.08132`), `Wilson` (Aebischer *et al*, `1712.05298`)

ATLAS l^+l^- limits

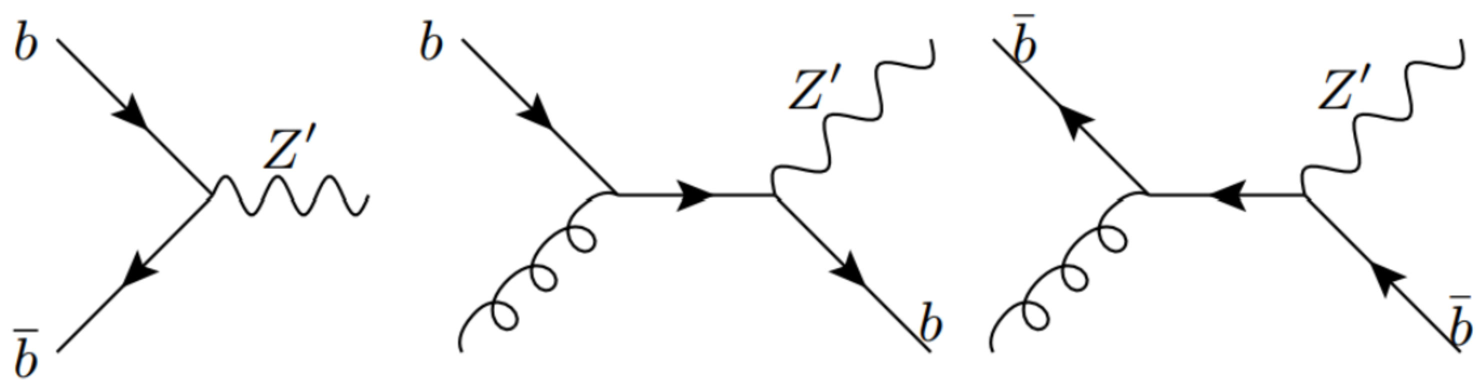


ATLAS, 1903.06248

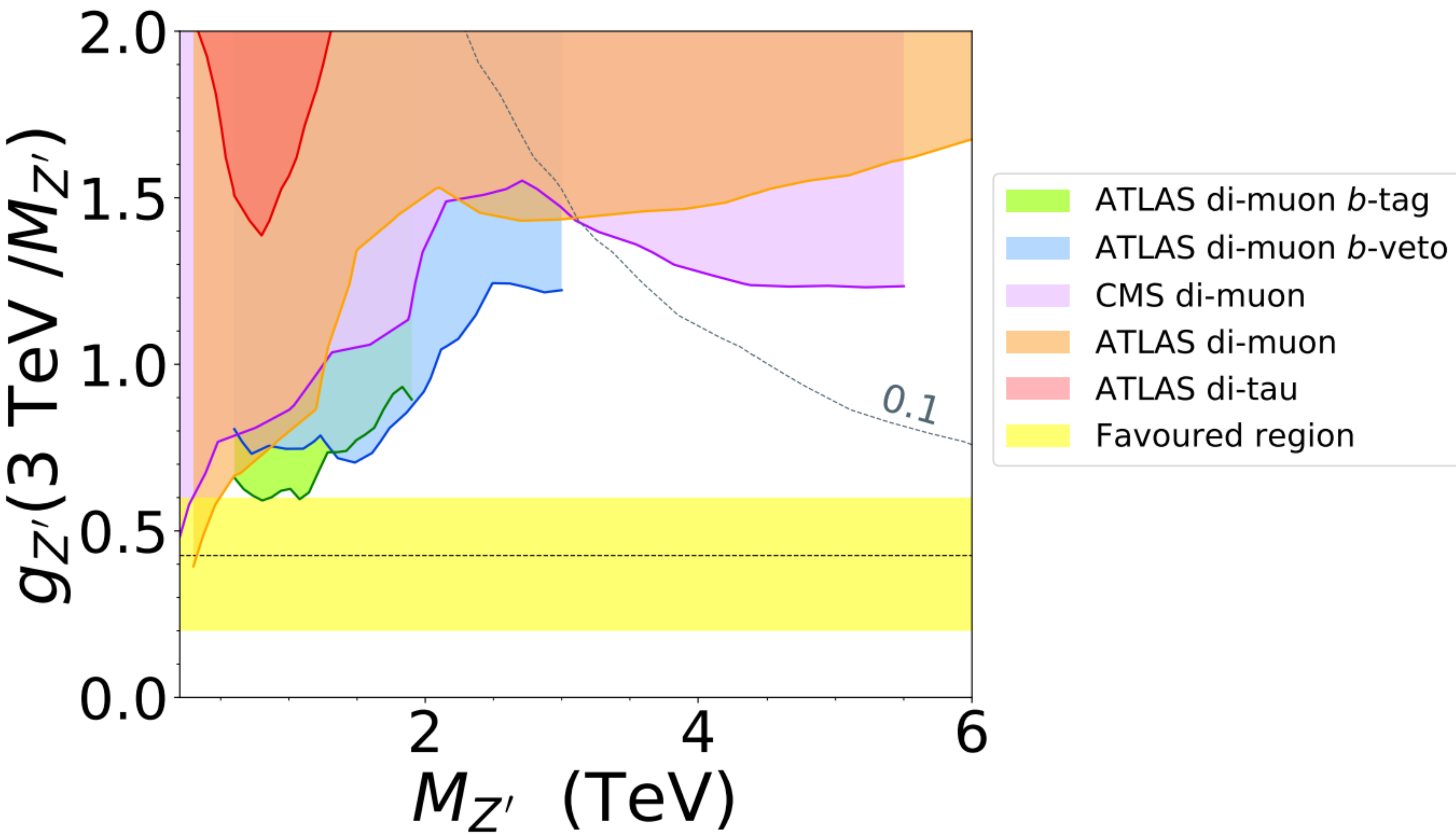
Z' Decay Modes

Mode	BR	Mode	BR	Mode	BR
$t\bar{t}$	0.42	$b\bar{b}$	0.12	$\nu\bar{\nu}'$	0.08
$\mu^+\mu^-$	0.08	$\tau^+\tau^-$	0.30	other $f_i f_j$	$\sim \mathcal{O}(10^{-4})$

LHC Z' Production:

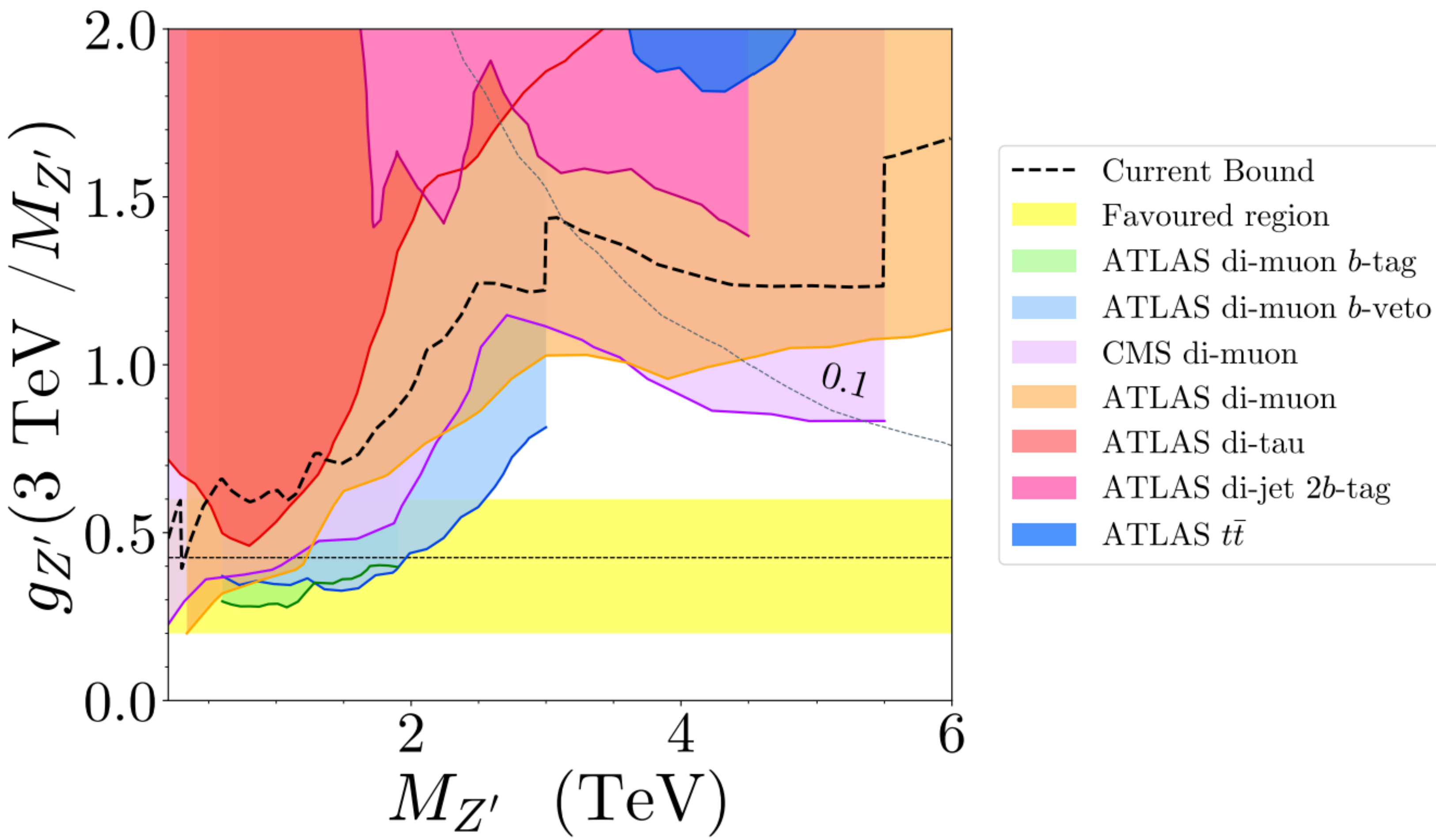


Z' Searches[12]



[12] BCA, Banks, 2111.06691

HL-LHC sensitivity[13]



[13] BCA, Banks, 2111.06691

Why $\bar{b}s\mu^+\mu^-$?

If we take these $B-$anomalies seriously, we may ask: why are we seeing the first BSM flavour changing effects particularly in the $b \to s\mu^+\mu^-$ transition, not another one?

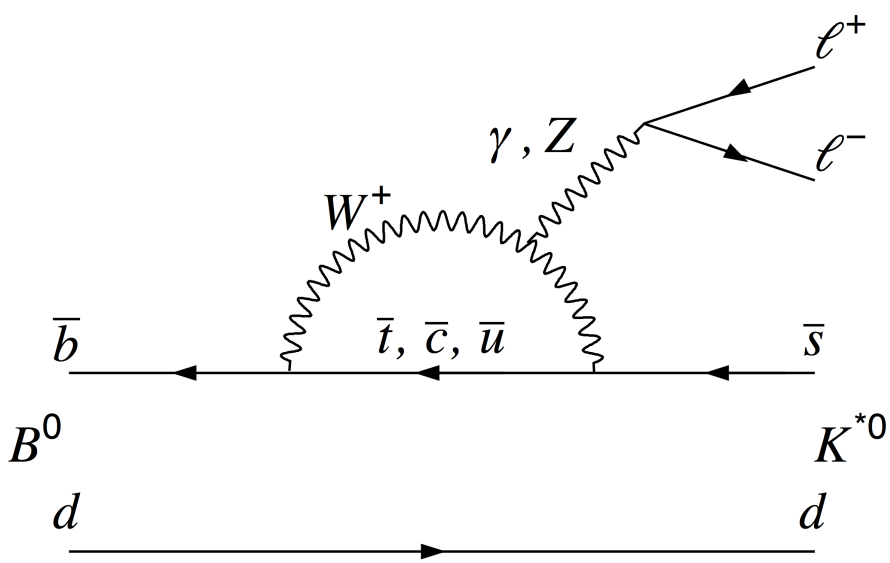
Perhaps it's because, in hindsight:

- The largest BSM flavour effects are in heavier generations
- We have many more bs than ts, particularly in LHCb
- Leptons in final states are good experimentally but not (yet) τs: they are too difficult!

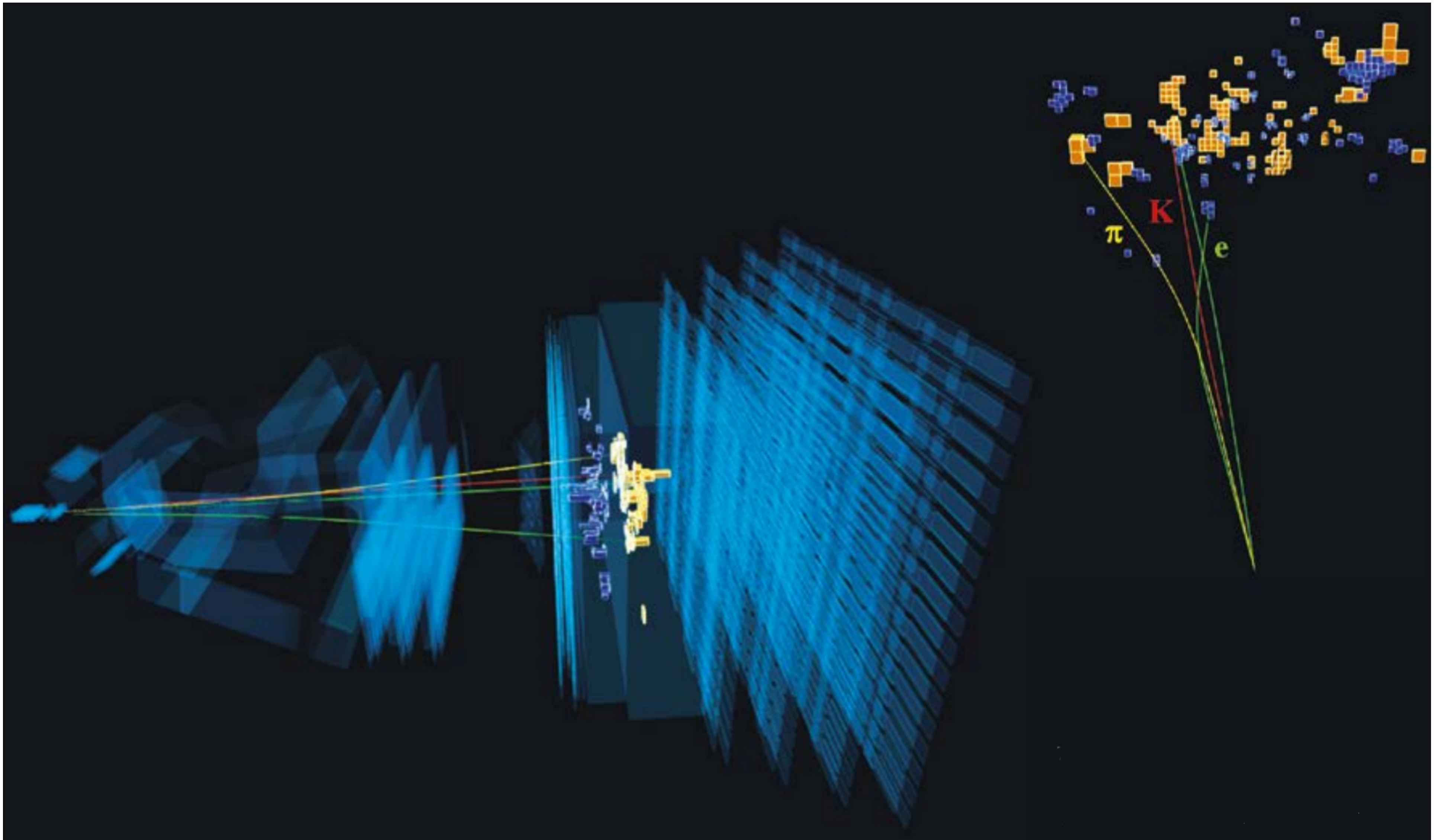
$b \to s l^+ l^-$ in Standard Model

$$R_K = \frac{BR(B \to K\mu^+\mu^-)}{BR(B \to K e^+ e^-)}.$$

BR$\sim \mathcal{O}(10^{-7})$: loop+EW+CKM

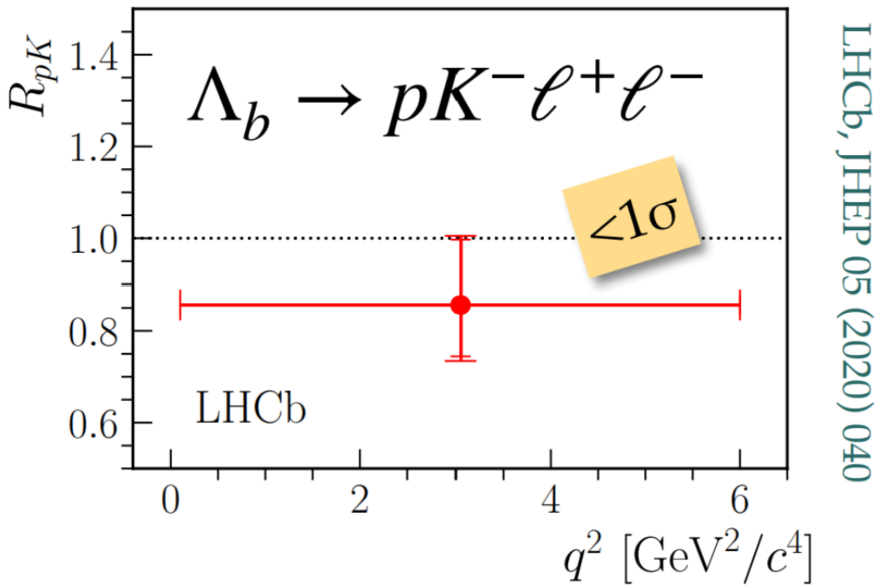


LHCb $B^0 \to K^{0*}e^+e^-$ Event[14]

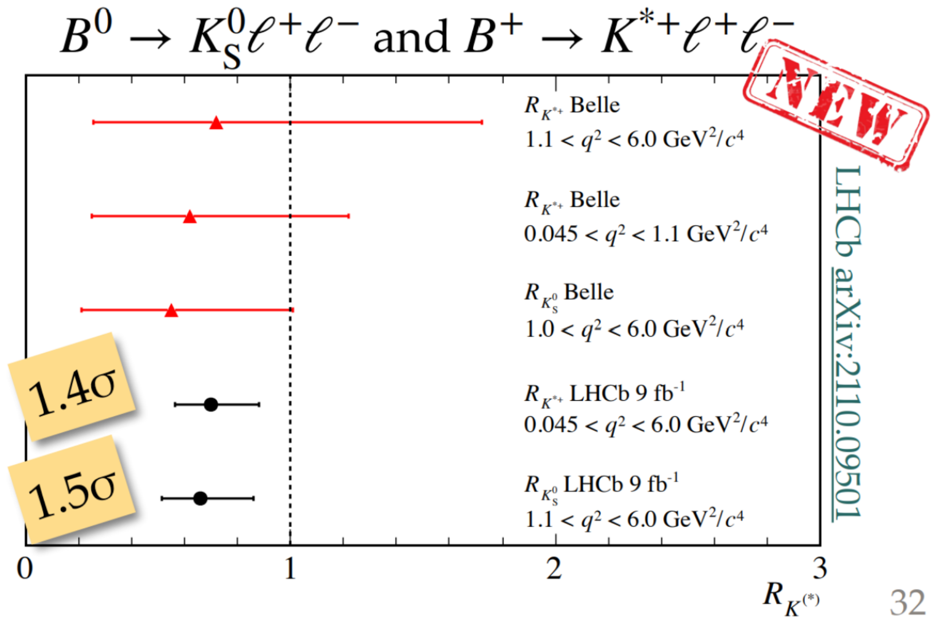


[14] Picture from CERN Courier April 2018

Other LFU



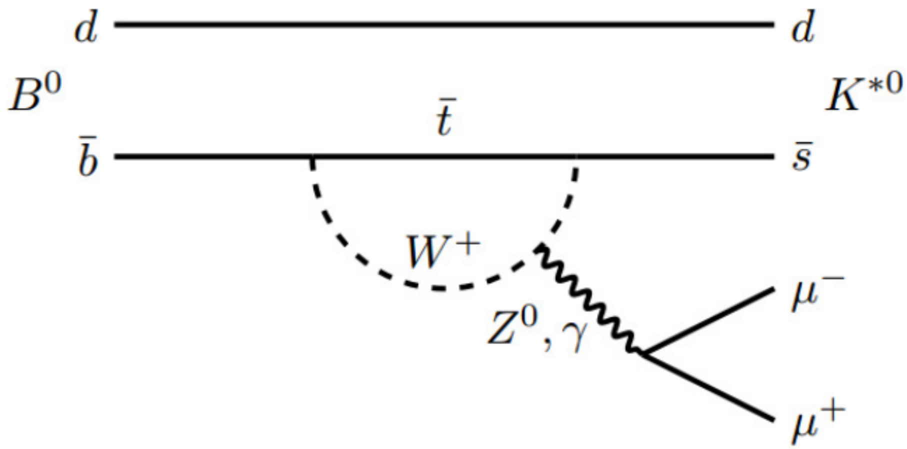
R_{pK}
1.4
1.2
1.0
0.8
0.6
$\Lambda_b \to pK^-\ell^+\ell^-$
<1σ
LHCb
0
2
4
6
q^2 [GeV$^2/c^4$]
LHCb, JHEP 05 (2020) 040

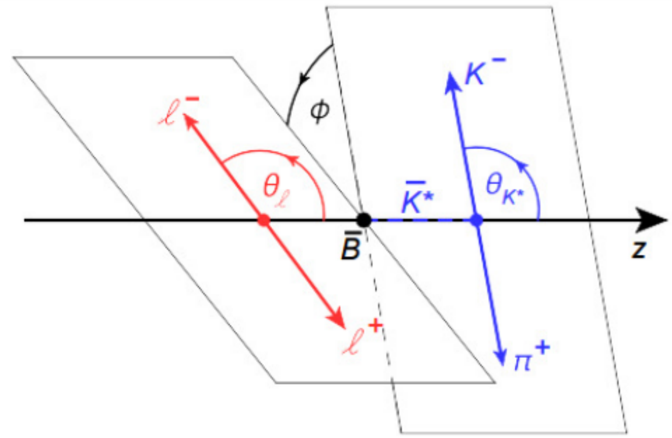


$B^0 \to K^0_S\ell^+\ell^-$ and $B^+ \to K^{*+}\ell^+\ell^-$
NEW
$R_{K^{*+}}$ Belle
$1.1 < q^2 < 6.0$ GeV$^2/c^4$
$R_{K^{*+}}$ Belle
$0.045 < q^2 < 1.1$ GeV$^2/c^4$
$R_{K^0_S}$ Belle
$1.0 < q^2 < 6.0$ GeV$^2/c^4$
1.4σ
$R_{K^{*+}}$ LHCb 9 fb^{-1}
$0.045 < q^2 < 6.0$ GeV$^2/c^4$
1.5σ
$R_{K^0_S}$ LHCb 9 fb^{-1}
$1.1 < q^2 < 6.0$ GeV$^2/c^4$
0
1
2
3
$R_{K^{(*)}}$
LHCb arXiv:2110.09501

32

$B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$

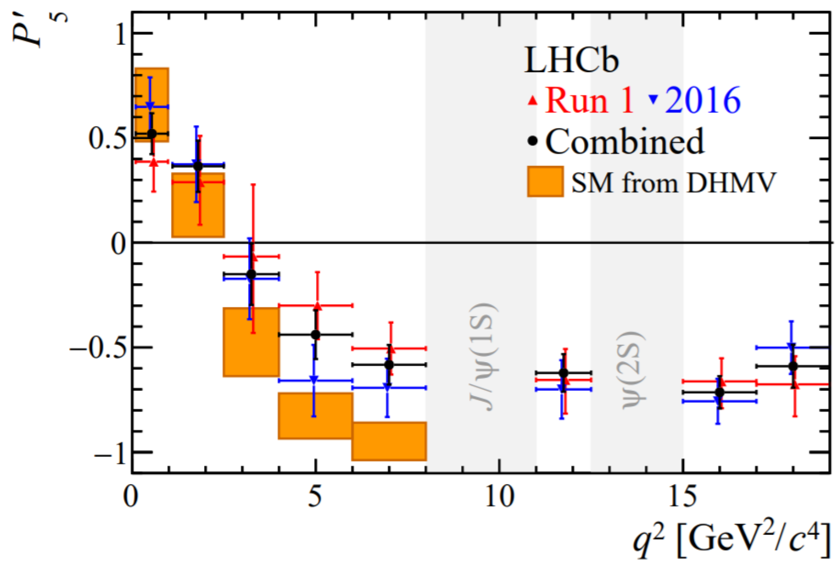


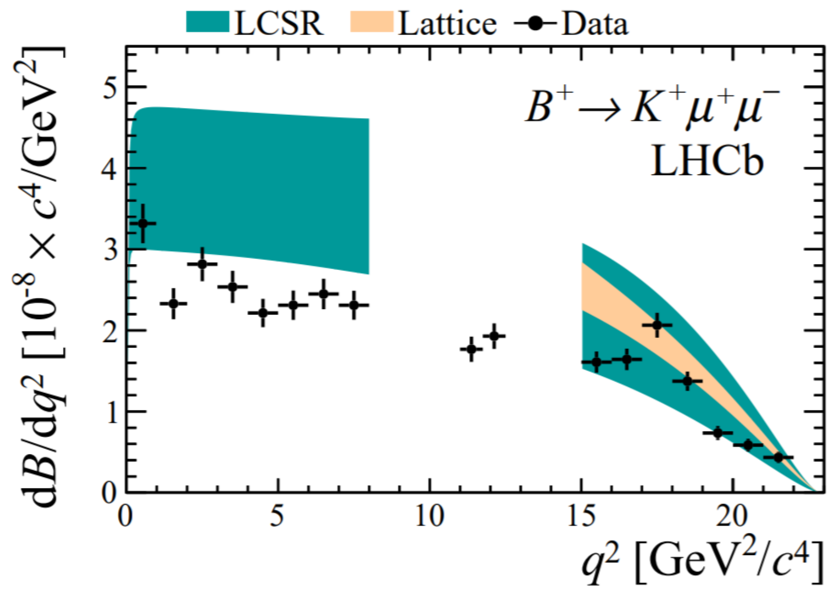


Decay fully described by three helicity angles $\vec{\Omega} = (\theta_\ell, \theta_K, \phi)$ and $q^2 = m^2_{\mu\mu}$

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

P_5'





$P_5' = S_5/\sqrt{F_L(1-F_L)}$, leading form factor uncertainties cancel [15]

[15] LHCb, 2003.04831

Wilson Coefficients c_{ij}^l

In SM, can form an EFT since $m_B \ll M_W$:

$$\mathcal{L}_{\text{eff}} = \frac{1}{(36\ \text{TeV})^2} c_{ij}^l (\bar{s}\gamma^\mu P_i b)(\bar{l}\gamma_\mu P_j l) \tag{1}$$

One loop weak interactions give $c_{ij}^l \sim \pm\mathcal{O}(1)$ in SM. $(1/36\ \text{TeV})^2 = V_{tb}V_{ts}^*\alpha/(4\pi v^2)$.

From now on, c_{ij}^l refer to *beyond* SM contribution.

Which Ones Work?

Options *for a single BSM operator*:

- c^{e}_{ij} operators fine for $R_{K^{(*)}}$ but are disfavoured by global fits including other observables.
- c^{μ}_{LR} disfavoured: predicts *enhancement* in both R_K and R_{K^*}
- c^{μ}_{RR}, c^{μ}_{RL} disfavoured: they pull R_K and R_{K^*} in *opposite directions*.
- $c^{\mu}_{LL} = -1.06$ fits well globally[16].

[16] D'Amico et al, 1704.05438; Aebischer et al 1903.10434.

Statistics[17]

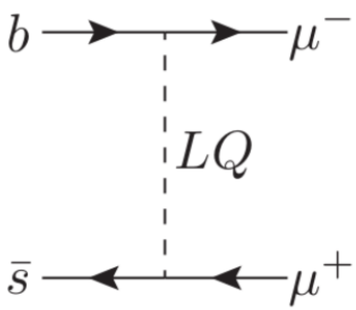
	$\bar{c}^{\mu}_{LL}$	$\sqrt{\chi^2_{SM} - \chi^2_{best}}$
clean	-1.33 ± 0.34	4.1
dirty	-1.33 ± 0.32	4.6
all	-1.06 ± 0.16	6.5
	$C^{\mu}_9 = (\bar{c}^{\mu}_{LL} + \bar{c}^{\mu}_{LR})/2$	$\sqrt{\chi^2_{SM} - \chi^2_{best}}$
clean	-1.51 ± 0.46	3.9
dirty	-1.15 ± 0.17	5.5
all	-0.95 ± 0.15	5.8

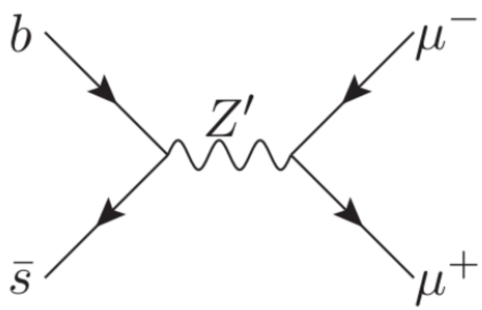
[17] 'clean' (R_K, R_{K^*}, $B_s \to \mu\mu$) and 'dirty' (P_5', $B \to \phi\mu\mu$+100 others). D'Amico, Nardecchia, Panci, Sannino, Strumia, Torre, Urbano 1704.05438; Aebischer, Altmanshoffer, Guadagnoli, Reboud, Stangl, Straub, 1903.10434. SM $p-$value around 3σ for NCBAs.

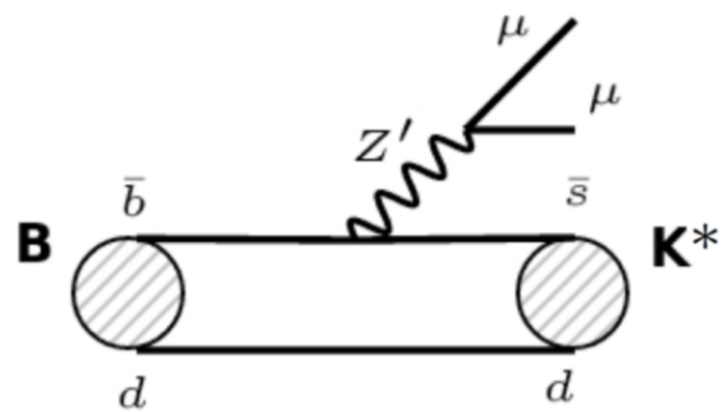
$b \to s\mu\mu$ Simplified Models

Focussing on discrepant observables[18]: 4.3σ

Tree-level:



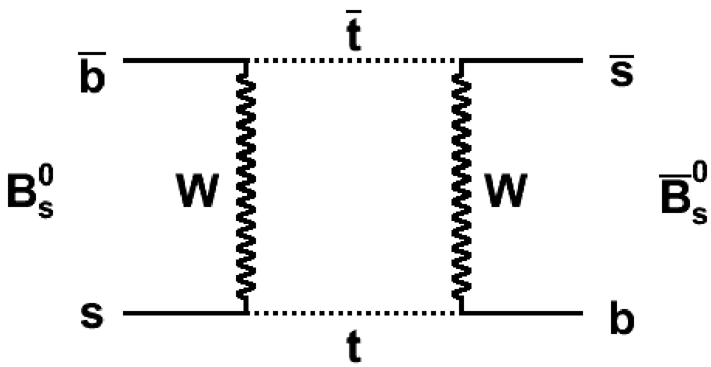


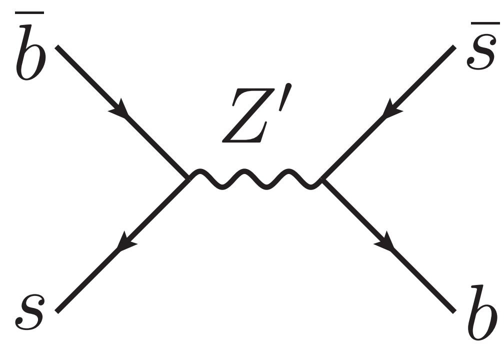


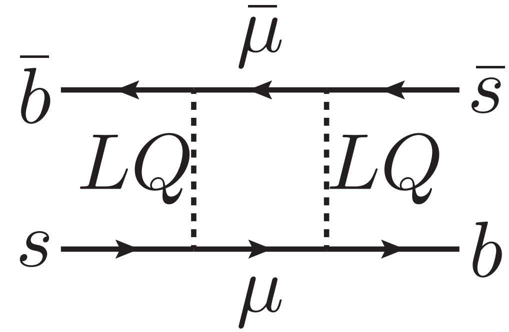
[18] Isidori, Lancierini, Owen and Serra, arXiv:2104.05631

$B_s - \bar{B}_s$ Mixing

Measurement pretty much agrees with SM calculations.







$$g_{sb} \lesssim \frac{M_{Z'}}{194 \text{ TeV}}$$ but uncertain

from QCD sum rules and lattice[19]. Weaker on LQs.

$$M_{Z'} \approx 31 \text{ TeV} \times \sqrt{g_{sb} g_{\mu\mu}}, \qquad M_{LQ} \approx 31 \text{ TeV} \times \sqrt{g_{s\mu} g_{b\mu}}$$

[19] King, Lenz, Rauh, arXiv:1904.00940

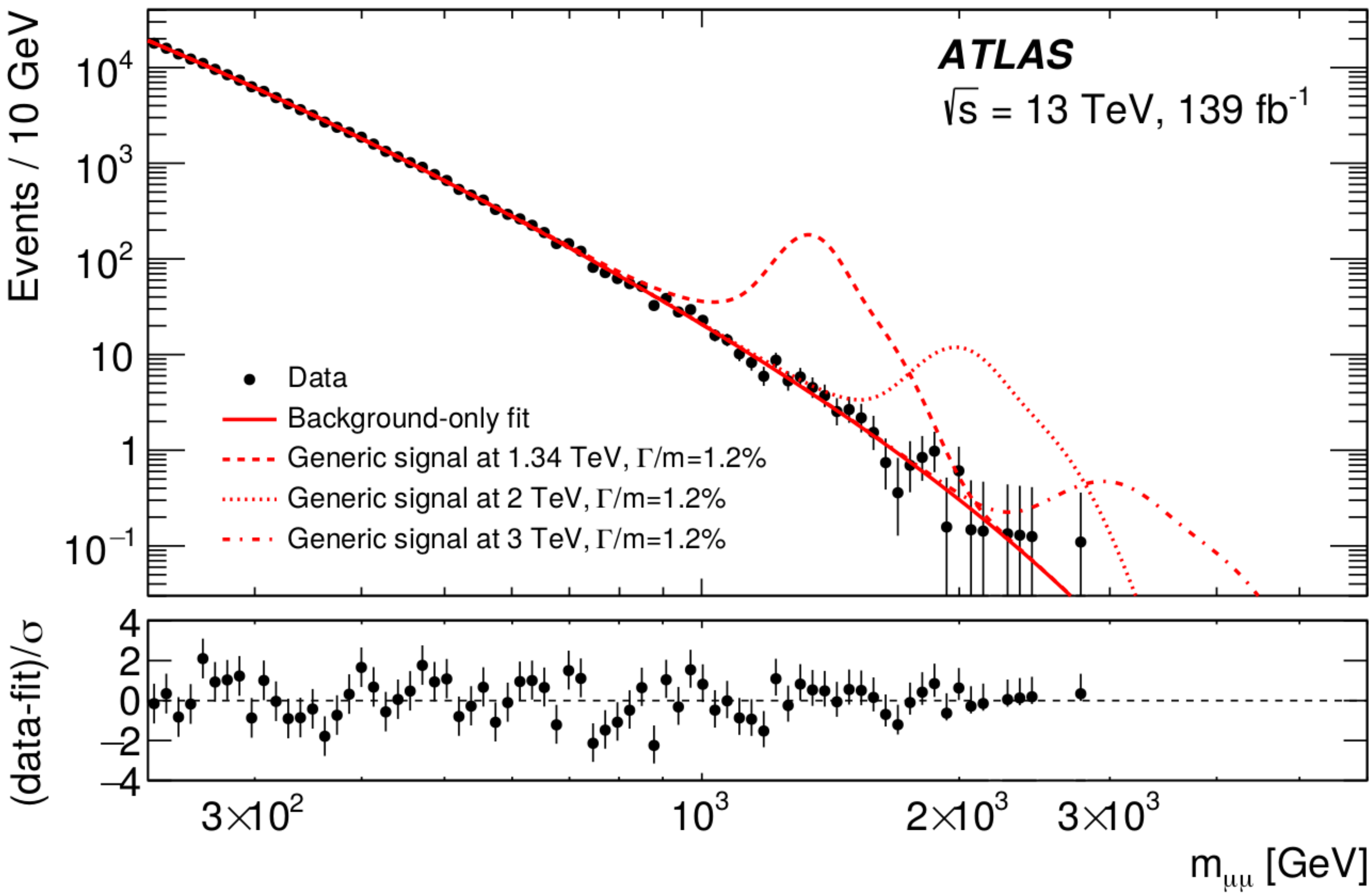
$\mu\mu$ ATLAS 13 TeV 139 fb^{-1}

2 track-based isolated μ, $p_T > 30$ GeV with reconstructed vertex.[20] Only keep pair with highest $(|p_{T_1}| + |p_{T_2}|)$.

$$m^2_{\mu_1\mu_2} = (p_1^\mu + p_2^\mu)\left(p_{1_\mu} + p_{2_\mu}\right)$$

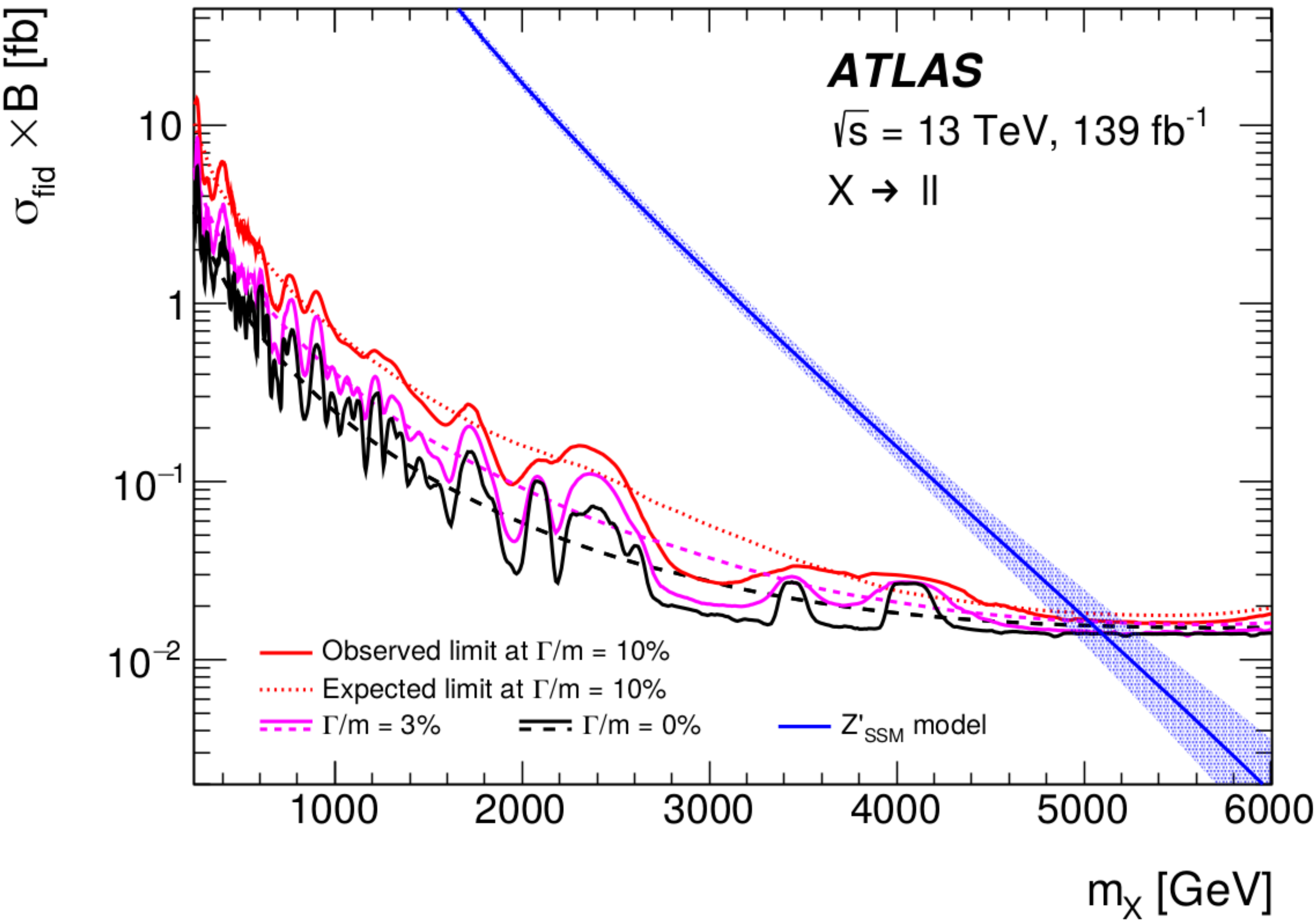
CMS also has a similar analysis[21]

[20] ATLAS, 1903.06248
[21] CMS, 2103.02708



ATLAS
√s = 13 TeV, 139 fb-1
Events / 10 GeV
Data
Background-only fit
Generic signal at 1.34 TeV, Γ/m=1.2%
Generic signal at 2 TeV, Γ/m=1.2%
Generic signal at 3 TeV, Γ/m=1.2%
(data-fit)/σ
m_μμ [GeV]

ATLAS l^+l^- limits



ATLAS, 1903.06248

A Model

BCA, Davighi, arXiv:1809.01158: Add complex SM singlet scalar θ and gauged $U(1)_F$:

$$SU(3) \times SU(2)_L \times U(1)_Y \times U(1)_F$$

$$\downarrow \langle \theta \rangle \sim \text{Several TeV}$$

$$SU(3) \times SU(2)_L \times U(1)_Y$$

$$\downarrow \langle H \rangle \sim 246 \text{ GeV}$$

$$SU(3) \times U(1)_{em}$$

- SM fermion content
- anomaly cancellation
- 0 F charges for first two generations

The Flavour Problem

A Warm Up: $U(1)$

Pioneering solution to ACCs: Costa, Dobrescu, Fox, arxiv:1905.13729. n chiral fermions with charges z_i:

$$\begin{aligned} z_1^3 + \ldots + z_n^3 &= 0, \\ z_1 + \ldots + z_n &= 0. \end{aligned} \tag{2}$$

Given 2 solutions $\underline{x}$, $\underline{y}$, construct a third by "merger"

$$\{\underline{x}\} \oplus \{\underline{y}\} := \left(\sum_{i=1}^{n} x_i y_i^2 \right) \{\underline{x}\} - \left(\sum_{i=1}^{n} x_i^2 y_i \right) \{\underline{y}\}.$$

Want to find suitably general solutions $\underline{x}$, $\underline{y}$.

Example: even n

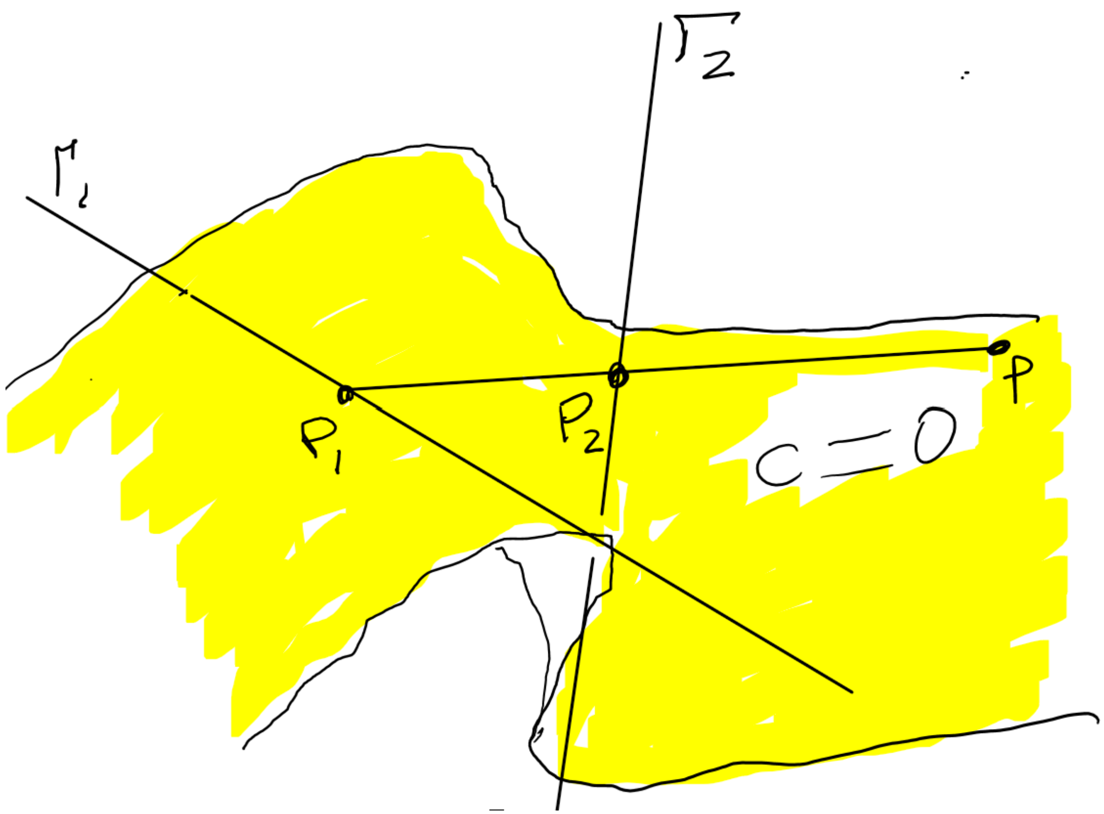
$$\{\underline{x}\} = \{l_1, k_1, \ldots, k_m, -l_1, -k_1, \ldots, -k_m\}$$
$$\{\underline{y}\} = \{0, 0, l_1, \ldots, l_m, -l_1, \ldots, -l_m\},$$
$$m = n/2 - 1 \geq 2, \qquad 1 \leq i \leq m$$

$\{\underline{x}\}$ and $\{\underline{y}\}$ are each vector-like solutions but it turns out that $\{\underline{x}\} \oplus \{\underline{y}\}$ is a new chiral solution.

$\{\underline{x}\} \oplus \{\underline{y}\}$ parameterises all solutions up to permutations. There is a *similar story* for odd n.

Mordell's Theorem[22]

Skew Γ_1, Γ_2 in $c = 0$ $\Rightarrow$all rational points on c can be found this way.



[22]Mordell (1969) *Diophantine Equations*

Geometric Understanding

In BCA, Gripaios, Tooby-Smith, arXiv:1912.04804, we provide a geometric understanding of this. First, note that each solution in $\mathbb{Q}$ is equivalent to one in $\mathbb{Z}$ by clearing denominators. Using gravitational anomaly cancellation, eliminate z_n to obtain the homogeneous cubic

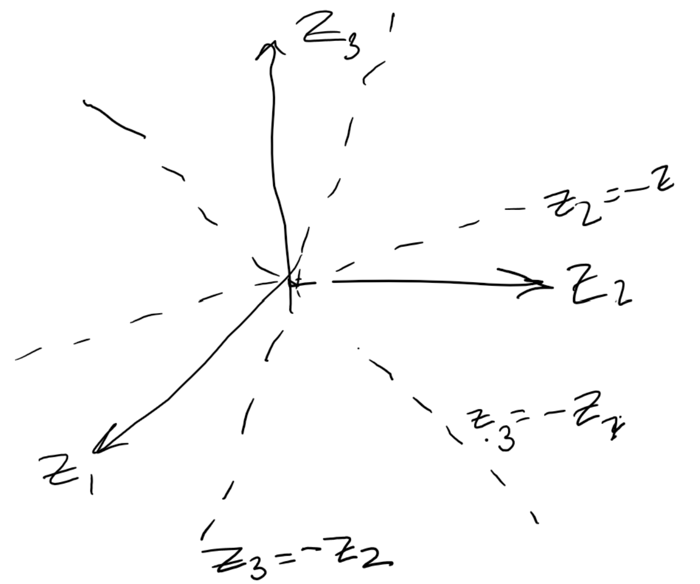
$$\sum_{i=1}^{n-1} z_i^3 - \left(\sum_{i=1}^{n-1} z_i\right)^3 = 0$$

defining a cubic hypersurface in $\mathbb{Q}^{n-1}$.

Special Surface

In fact, our cubic hypersurface is rather special: no purely cubic terms in any one variable: (add perms)

$n = 3$: $\underline{z} = [-a : 0 : a]$, ie three lines $z_3 = -z_1$, $z_2 = 0$



$n = 4$: $\underline{z} = [-x : -y : x : y]$, $x, y \in \mathbb{Q}$ ie three planes

Strategy

1. Find solutions for SM fermions charges from first 4
2. Apply $GL(3,\mathbb{Z})$ transformation to species F:
   $F_+ := F_1 + F_2 + F_3,\ F_\alpha := F_1 - F_2,\ F_\beta := F_2 + F_3$.
3. Linear equations become
   $D_+ = -2Q_+ - U_+,\ \ L_+ = -3Q_+,\ \ E_+ = 2Q_+ - U_+$.
4. Quadratic is a solveable homogeneous diophantine equation of degree 2 in the 12-tuple

$$X := (Q_+, U_+, Q_\alpha, Q_\beta, U_\alpha, U_\beta, D_\alpha, D_\beta, L_\alpha, L_\beta, E_\alpha, E_\beta).$$

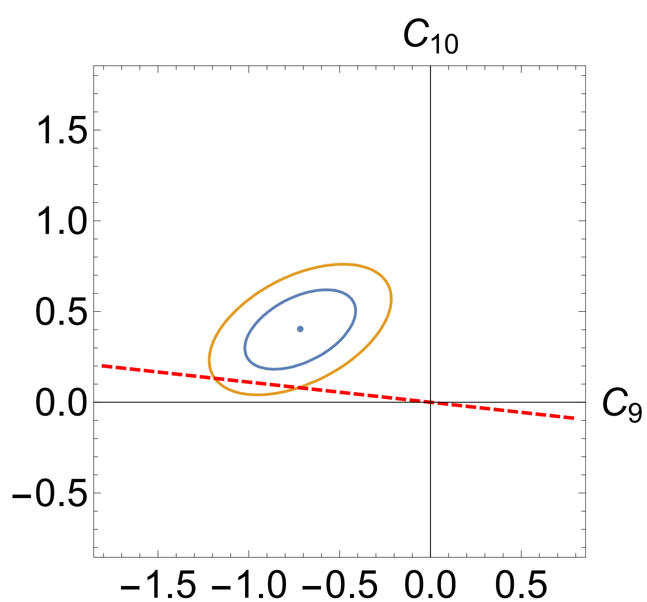
$X^T H X = 0$ defines hypersurface $\Gamma \in P\mathbb{Q}^{11}$.

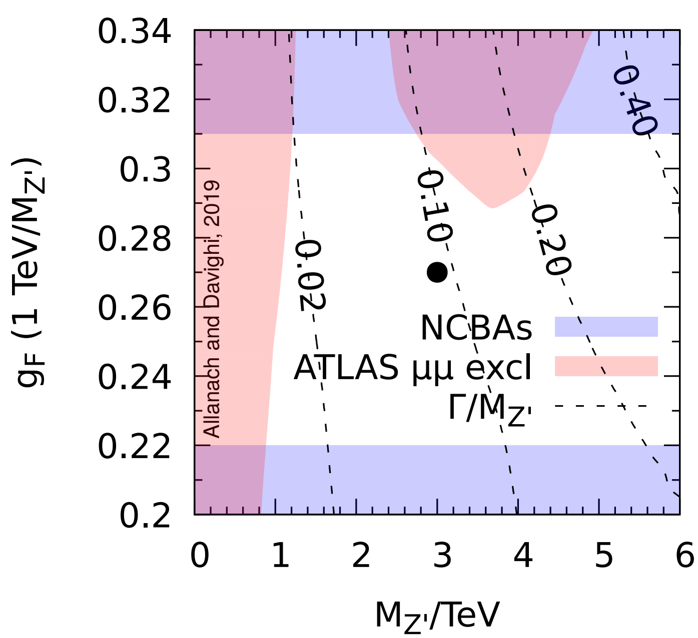
$$H = \begin{pmatrix} 0 & 0 & -2 & -4 & 0 & 0 & 4 & 8 & -6 & 0 & -4 & -8 \\ & 0 & 0 & 0 & 4 & 8 & 2 & 4 & 0 & 0 & 2 & 4 \\ & & 2 & 3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ & & & 6 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ & & & & -4 & 6 & 0 & 0 & 0 & 0 & 0 & 0 \\ & & & & & -12 & 0 & 0 & 0 & 0 & 0 & 0 \\ & & & & & & 2 & 3 & 0 & 0 & 0 & 0 \\ & & & & & & & 6 & 0 & 0 & 0 & 0 \\ & & & & & & & & -2 & 3 & 0 & 0 \\ & & & & & & & & & 6 & 0 & 0 \\ & & & & & & & & & & 2 & 3 \\ & & & & & & & & & & & 6 \end{pmatrix}.$$

Deformed TFHM

$F_{Q_i'} = 0$	$F_{u_{Ri}'} = 0$	$F_{d_{Ri}'} = 0$	$F_H = -1/2$
$F_{e_{R1}'} = 0$	$F_{e_{R2}'} = 2/3$	$F_{e_{R3}'} = -5/3$	
$F_{L_1'} = 0$	$F_{L_2'} = 5/6$	$F_{L_3'} = -4/3$	
$F_{Q_3'} = 1/6$	$F_{u'_{R3}} = 2/3$	$F_{d'_{R3}} = -1/3$	$F_\theta \neq 0$

$$\mathcal{L} = Y_t \overline{Q_{3L}'} H t_R' + Y_b \overline{Q_{3L}'} H^c b_R' + H.c.,$$





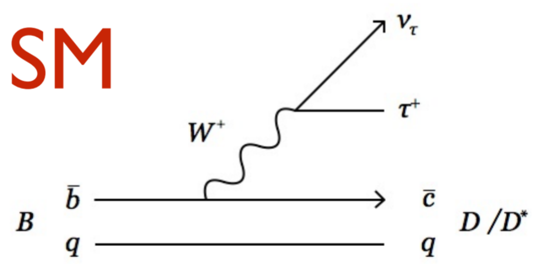
Invisible Width of Z Boson

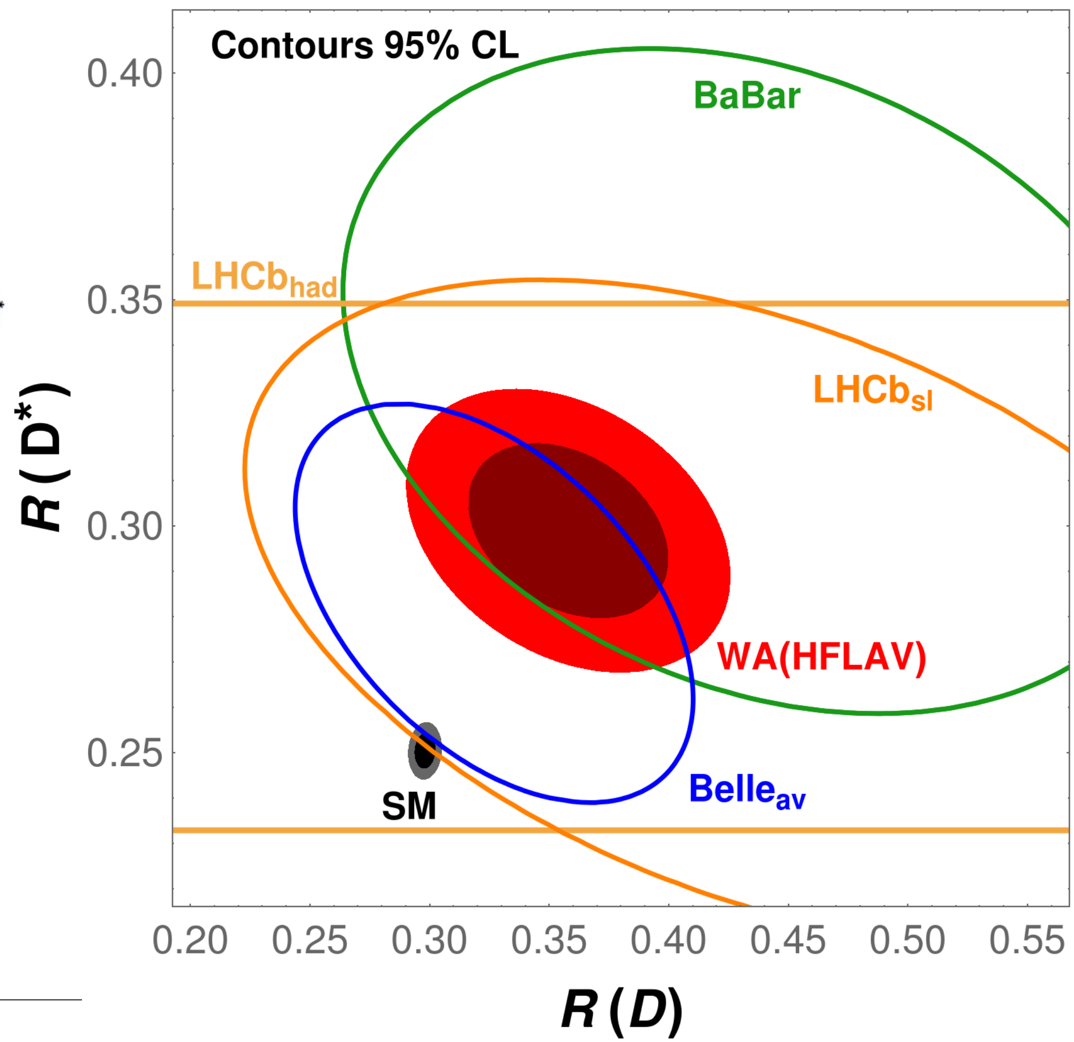
$\Gamma_{\text{inv}}^{(\text{exp})} = 499.0 \pm 1.5$ MeV, whereas $\Gamma_{\text{inv}}^{(\text{SM})} = 501.44$ MeV.

$\Rightarrow \Delta\Gamma^{(\text{exp})} = \Gamma_{\text{inv}}^{(\text{exp})} - \Gamma_{\text{inv}}^{(\text{SM})} = -2.5 \pm 1.5$ MeV.

$$\begin{aligned}
\mathcal{L}_{\bar{\nu}\nu Z} &= -\frac{g}{2\cos\theta_w}\overline{\nu'_{Le}}\not{Z} P_L \nu'_{Le} \\
&\quad -\overline{\nu'_{L\mu}}\left(\frac{g}{2\cos\theta_w} + \frac{5}{6} g_F \sin\alpha_z\right)\not{Z}\nu'_{L\mu} \\
&\quad -\overline{\nu'_{L\tau}}\left(\frac{g}{2\cos\theta_w} - \frac{8}{6} g_F \sin\alpha_z\right)\not{Z}\nu'_{L\tau}.
\end{aligned}$$

$$R_{D^{(*)}} = BR(B^- \to D^{(*)}\tau\nu)/BR(B^- \to D^{(*)}\mu\nu)^{23}$$

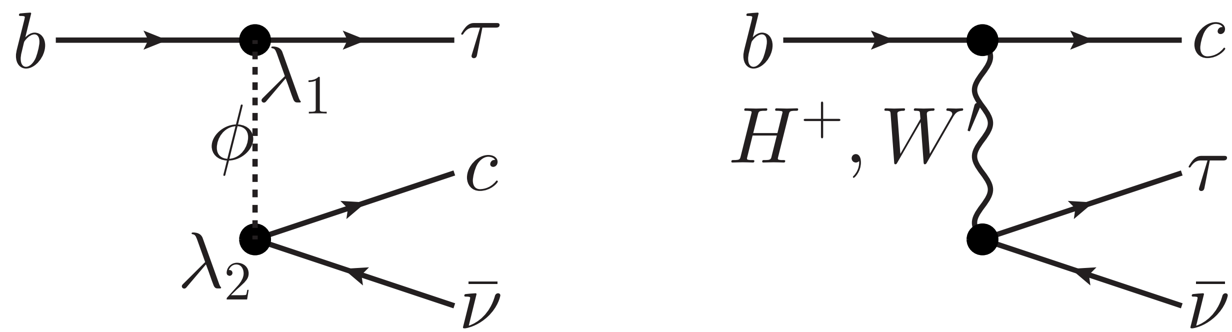




SM: 3.1σ

[23] Kind courtesy of M Jung

$R_{D^{(*)}}$: BSM Explanations

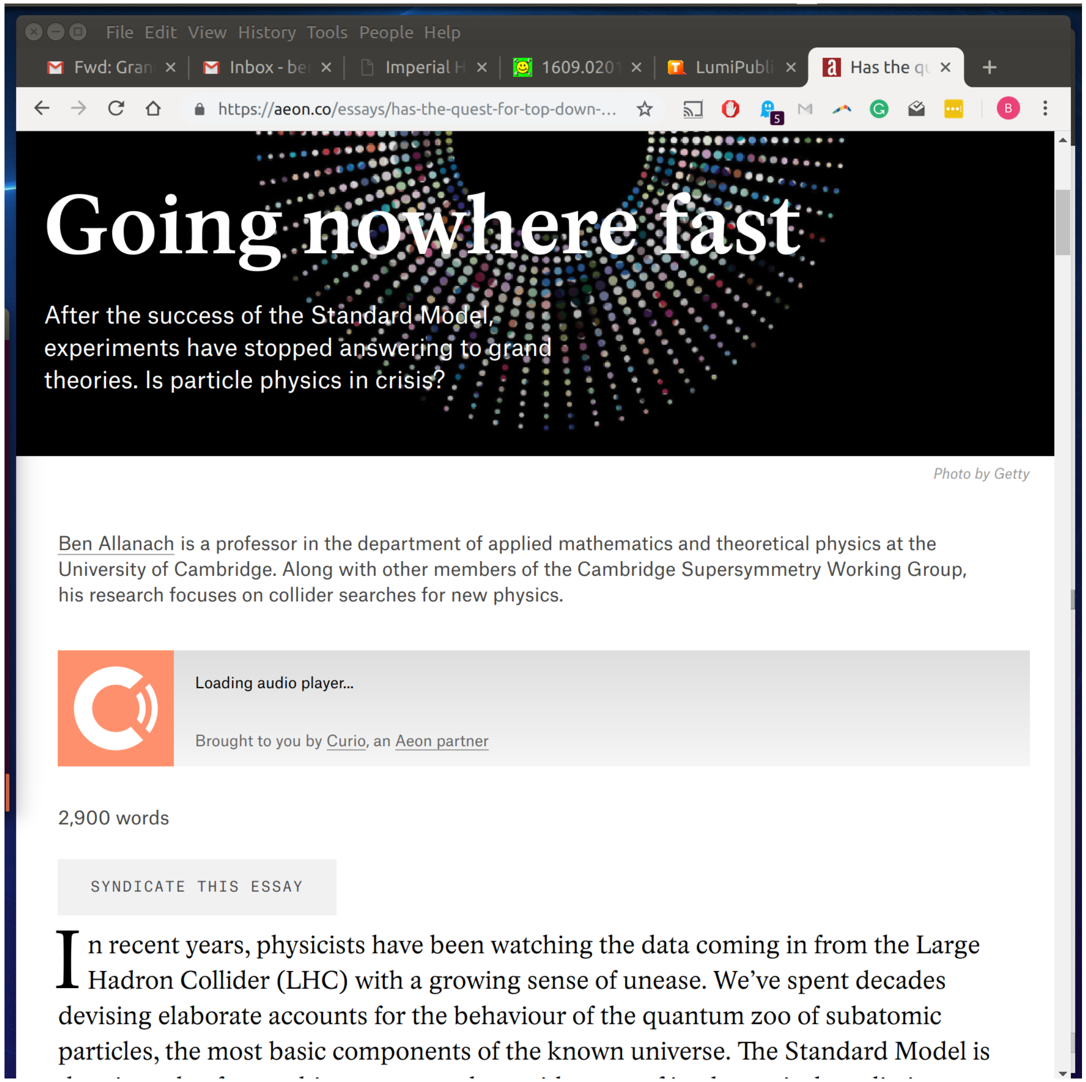


Make an effective theory with heavy BSM particle:

$$\mathcal{L}_{WET} = -\frac{2\lambda_1\lambda_2}{M^2}\left(\bar{c}\gamma^\mu P_L \nu\right)\left(\bar{\tau}\gamma_\mu P_L b\right) + H.c.$$

Fit to data tells us

$$M = 3.4 \text{ TeV} \times \sqrt{\lambda_1\lambda_2}$$



Going nowhere fast

After the success of the Standard Model, experiments have stopped answering to grand theories. Is particle physics in crisis?

Photo by Getty

Ben Allanach is a professor in the department of applied mathematics and theoretical physics at the University of Cambridge. Along with other members of the Cambridge Supersymmetry Working Group, his research focuses on collider searches for new physics.

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2,900 words

SYNDICATE THIS ESSAY

In recent years, physicists have been watching the data coming in from the Large Hadron Collider (LHC) with a growing sense of unease. We've spent decades devising elaborate accounts for the behaviour of the quantum zoo of subatomic particles, the most basic components of the known universe. The Standard Model is

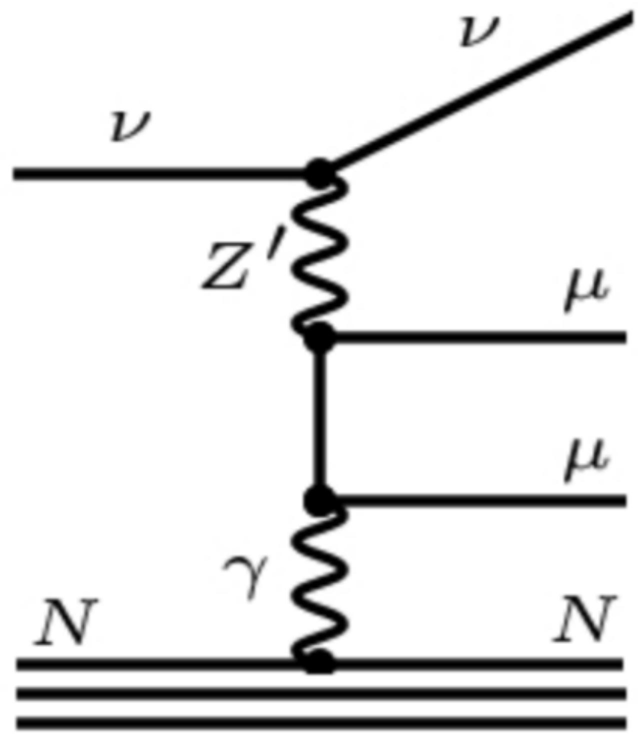
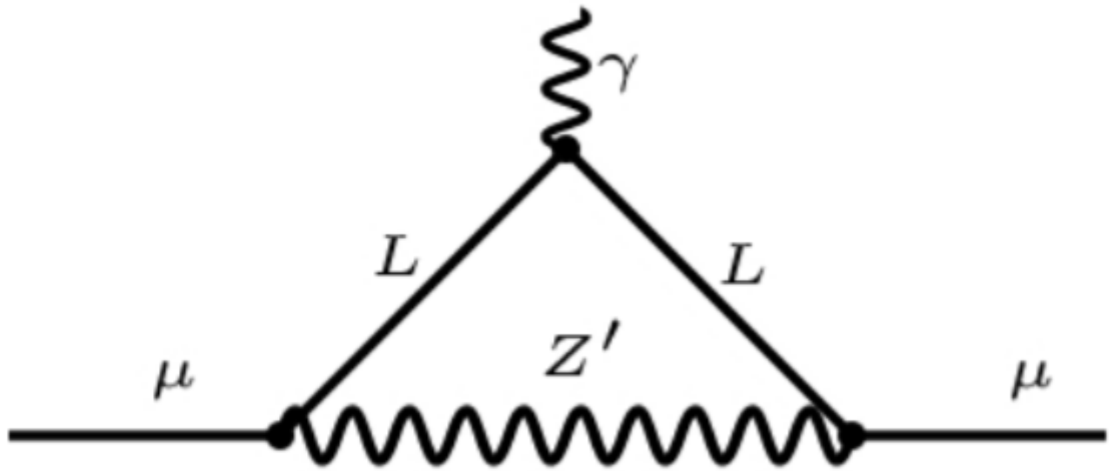
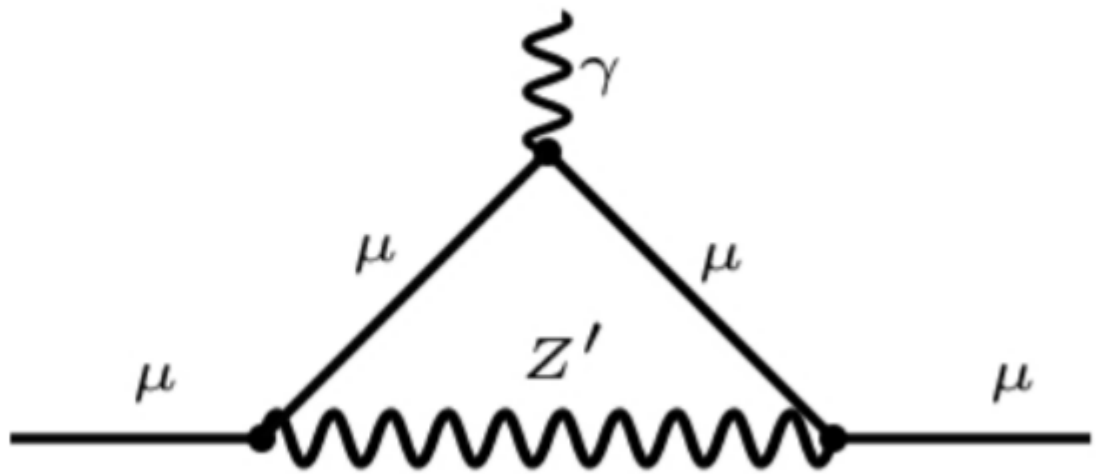


FIG. 10. Neutrino trident process that leads to constraints on the Z^{μ} coupling strength to neutrinos-muons, namely $M_{Z'}/g_{v\mu} \gtrsim 750$ GeV.

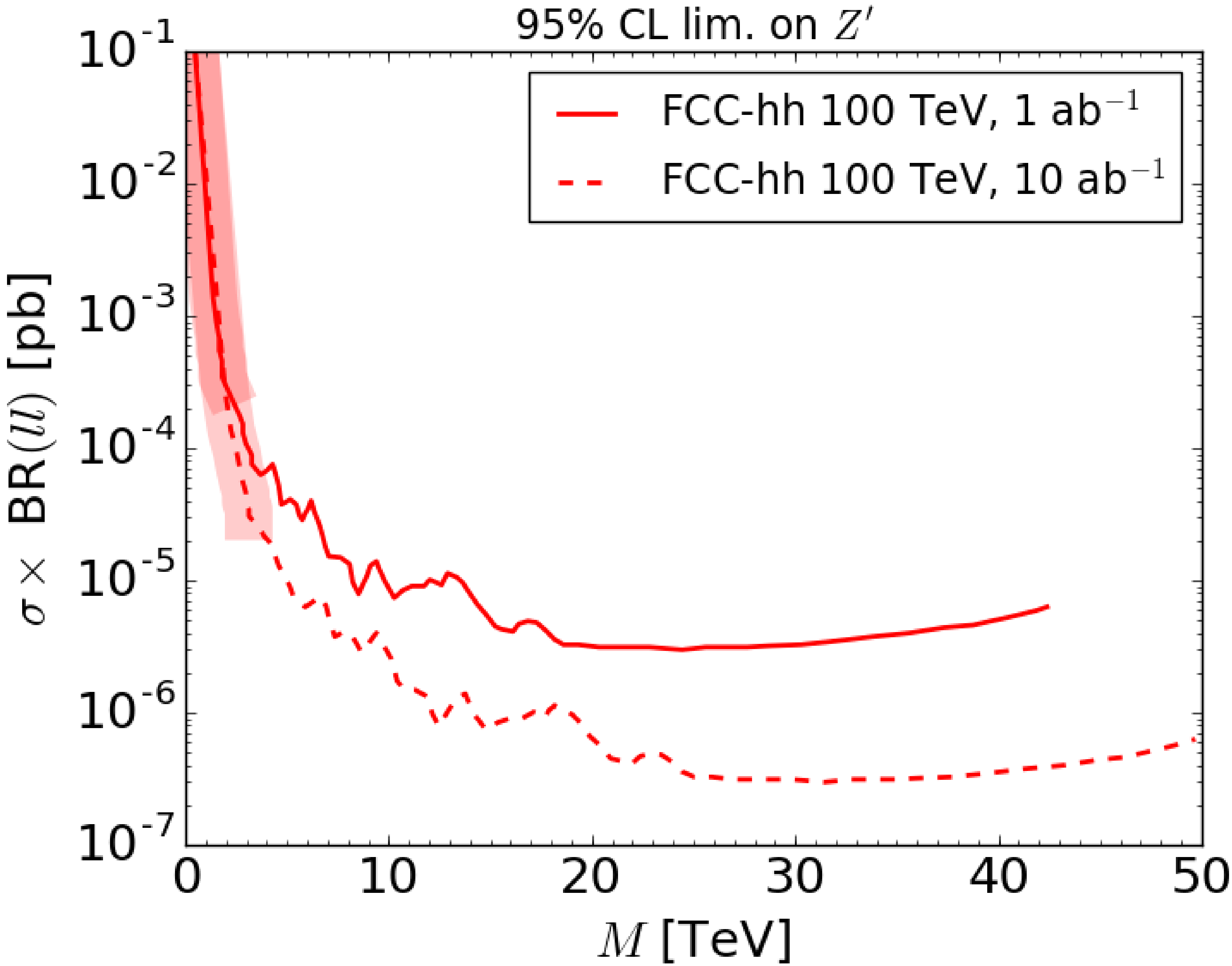

γ
L
L
Z'
μ
μ


γ
μ
μ
Z'
μ
μ

$Q_{\max}$	**Solutions**	Symmetry	Quadratics	Cubics	Time/sec
1	**38**	16	144	38	0.0
2	**358**	48	31439	2829	0.0
3	**4116**	154	1571716	69421	0.1
4	**24552**	338	34761022	932736	0.6
5	**111152**	796	442549238	7993169	6.8
6	**435305**	1218	3813718154	49541883	56

SM + 3 ν_R: number of solutions etc

13 TeV ATLAS 3.2 fb^{-1} $\mu\mu$



Neutrino Masses

At dimension 5:

$$\mathcal{L}_{SS} = \frac{1}{2M} ({L'_3}^T H^c)(L'_3 H^c),$$

but if we add RH neutrinos, then integrate them out

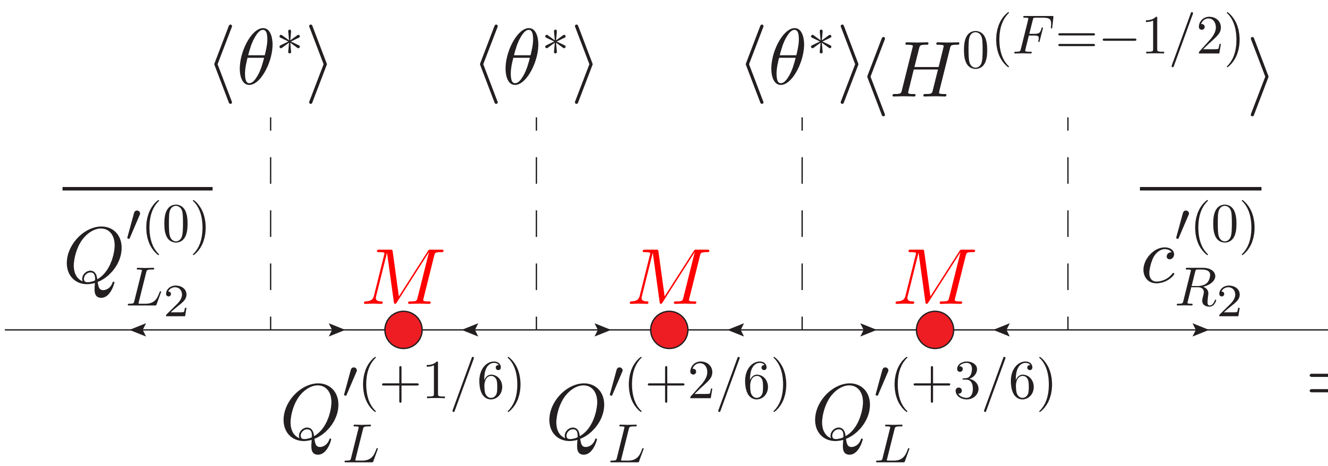
$$\mathcal{L}_{SS} = 1/2 \sum_{ij} (L'_i H^c)(M^{-1})_{ij}(L'_j H^c),$$

where now $(M^{-1})_{ij}$ may well have a non-trivial structure. If $(M^{-1})_{ij}$ are of same order, large PMNS mixing results.

Froggatt Neilsen Mechanism[24]

A means of generating the non-renormalisable Yukawa terms, e.g. $F_\theta = 1/6$:

$$Y_c \overline{Q'_{L2}}^{(F=0)} H^{(F=-1/2)} {c'_R}^{(F=0)} \sim \mathcal{O}\left[\left(\frac{\langle\theta\rangle}{M}\right)^3 \overline{Q'_{L2}} H c'_R\right]$$



eg $\left(\frac{\langle\theta\rangle}{M}\right) \sim 0.2$

$\Rightarrow Y_c/Y_t \sim 1/100$

[24] C Froggatt and H Neilsen, NPB**147** (1979) 277

LQ Models

Scalar[25] $S_3 = (\bar{3},\ 3,\ 1/3)$ of $SU(2) \times SU(2)_L \times U(1)_Y$:

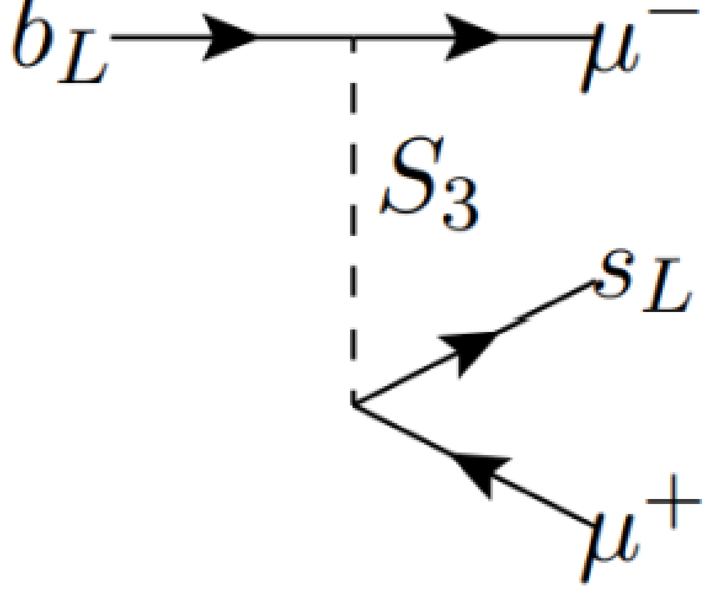
$$\mathcal{L} = \ldots + y_{3b\mu} Q_3 L_2 S_3 + y_{3s\mu} Q_2 L_2 S_3 + y_q QQS_3^\dagger + \text{h.c.}$$

Vector $V_1 = (\bar{3}, 1, 2/3)$ or $V_3 = (3, 3, 2/3)$

$$\mathcal{L} = \ldots + y_3' V_3^\mu \bar{Q} \gamma_\mu L + y_1 V_1^\mu \bar{Q} \gamma_\mu L + y_1' V_1^\mu \bar{d} \gamma_\mu l + \text{h.c.}$$

$$\Rightarrow \bar{c}_{LL}^\mu = \kappa \frac{4\pi v^2}{\alpha_{\text{EM}} V_{tb} V_{ts}^*} \frac{y_{3b\mu}^* y_{3s\mu}}{M^2}.$$

[25] Capdevila *et al* 1704.05340, Hiller and Hisandzic 1704.05444, D'Amico *et al* 1704.05438.

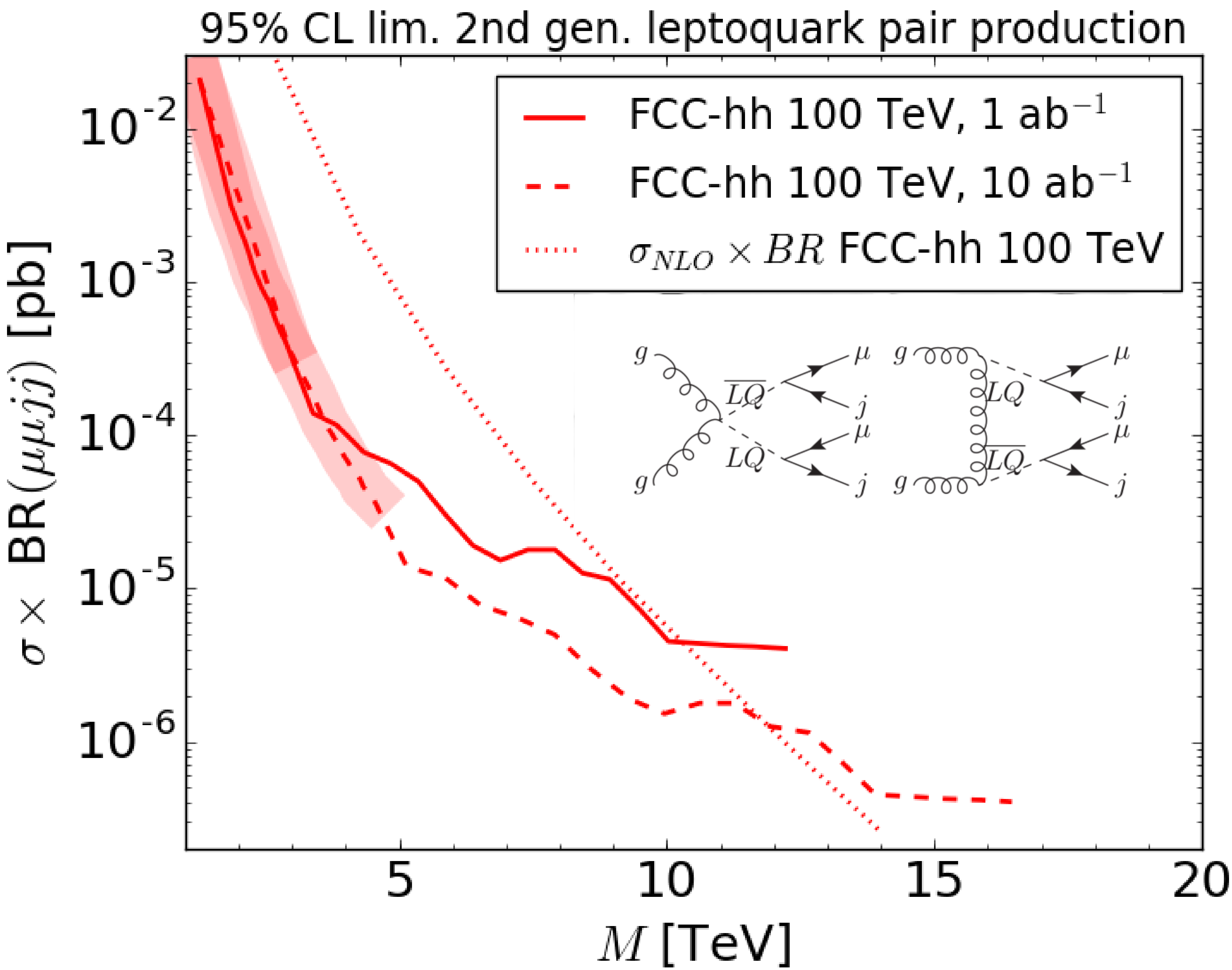
$\kappa \;=\;$ 

y_3, y_1, y'_3 for S_3, V_1, V_3.

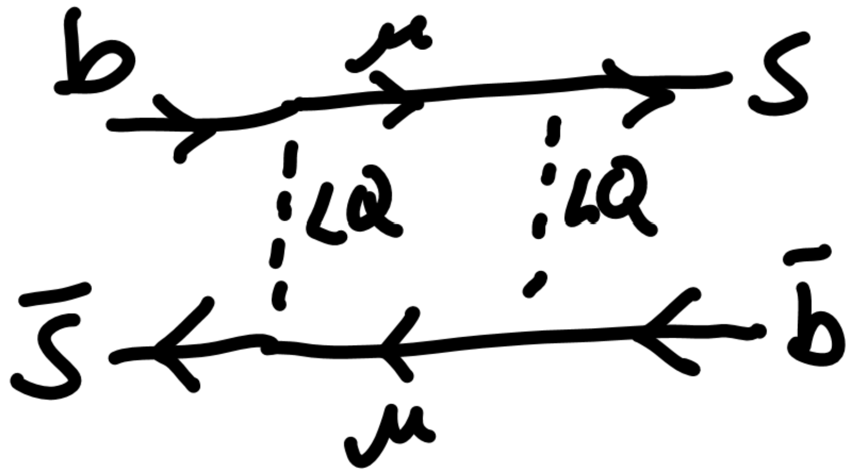
– LFU Violating

CMS 8 TeV 20fb^{-1} 2nd gen

CMS-PAS-EXO-12-042: $M > 1.07$ TeV.

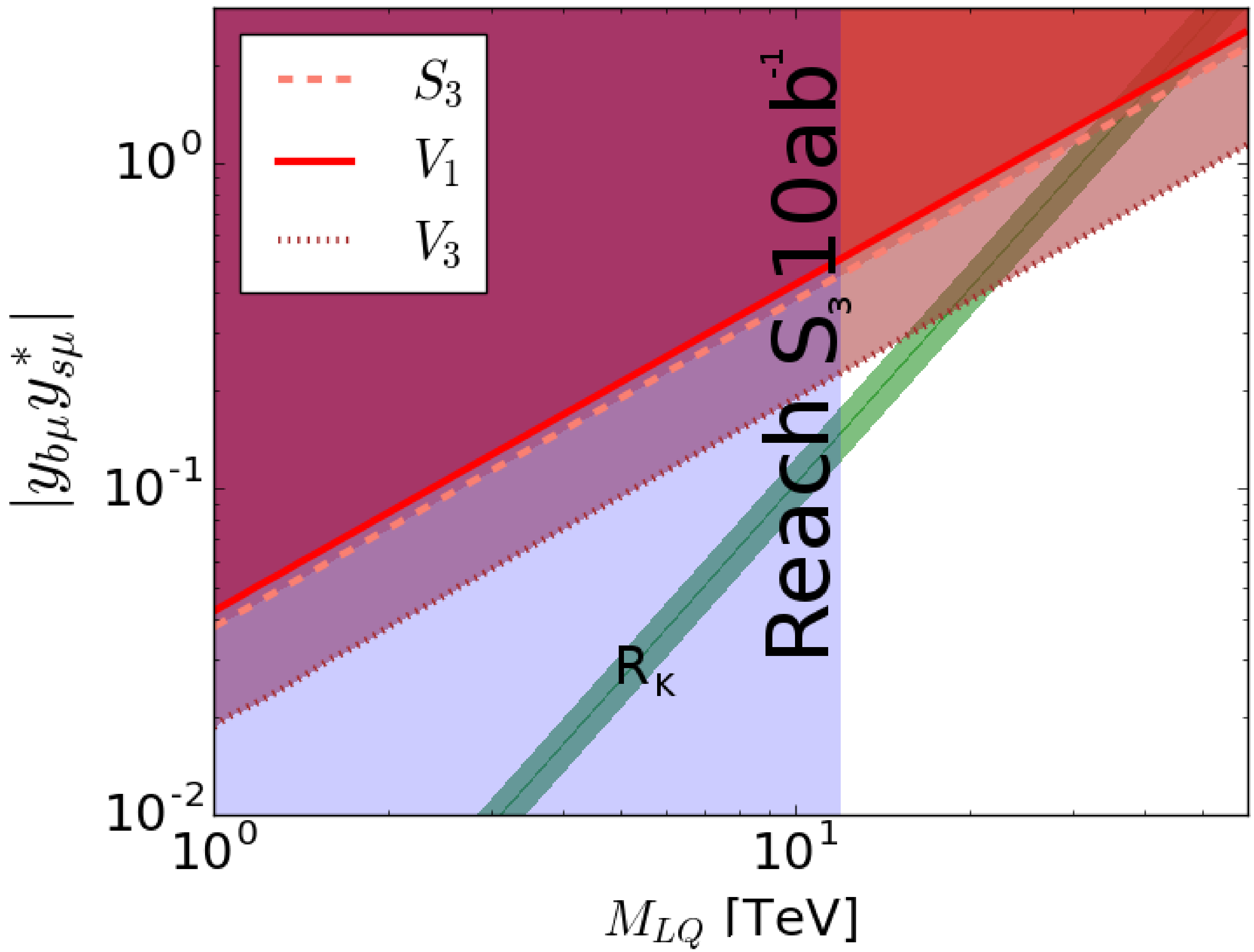


LQ $B_s - \bar{B}_s$ mixing



$$\mathcal{L}_{\bar{b}s\bar{b}s} = k\frac{|y_{b\mu}y^*_{s\mu}|^2}{32\pi^2 M^2_{LQ}}\left(\bar{b}\gamma_\mu P_L s\right)\left(\bar{s}\gamma^\mu P_L b\right) + \text{h.c.}$$

$y = y_3, y_1, y'_3$ and $k = 5, 4, 20$ for S_3, V_1, V_3.
Data $\Rightarrow c^{bsbs}_{LL} < 1/(210\text{TeV})^2$.



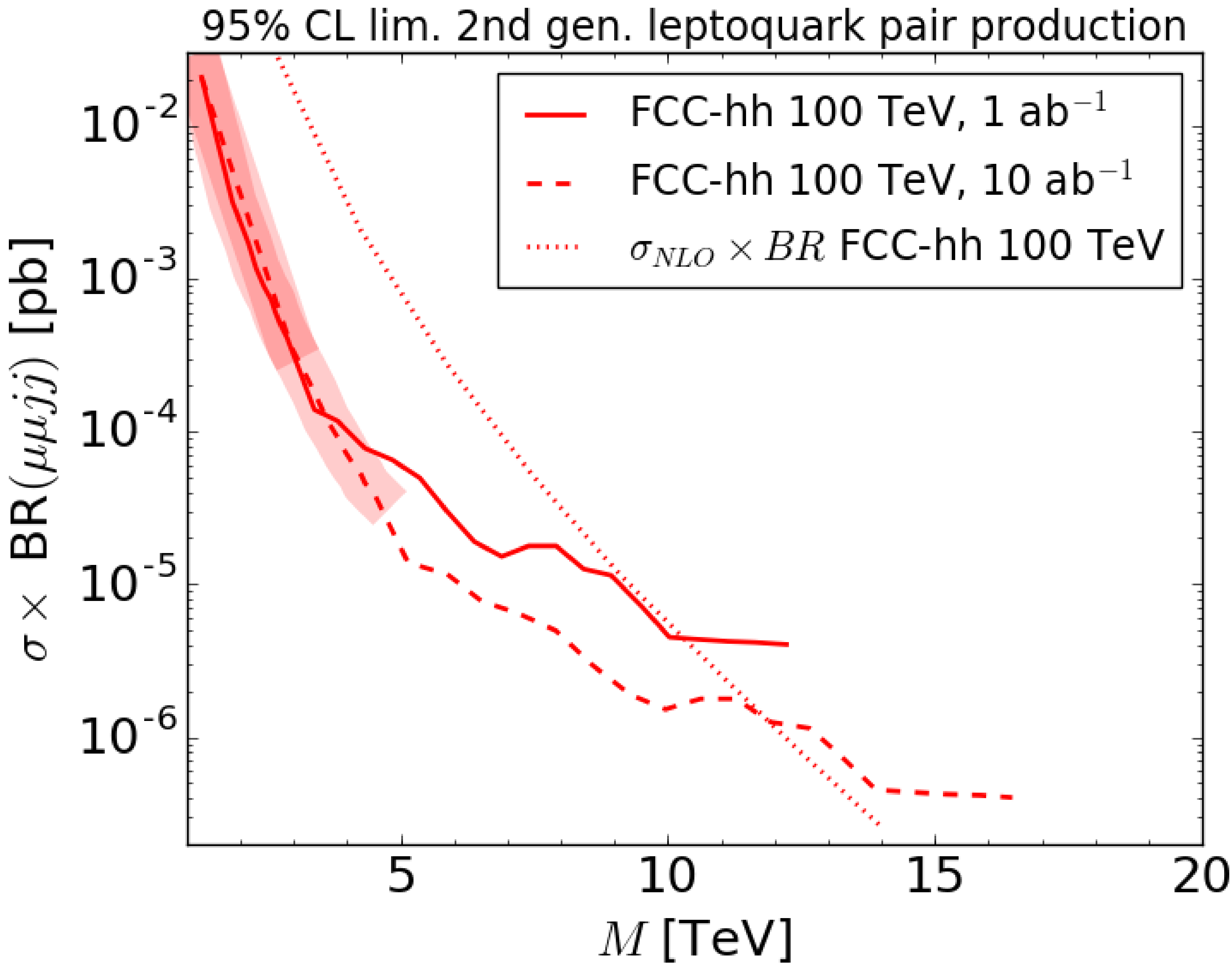
$M_{LQ} < 41$ TeV. BCA, Gripaios, You, 1710.06363

LQ Upper Mass Limits

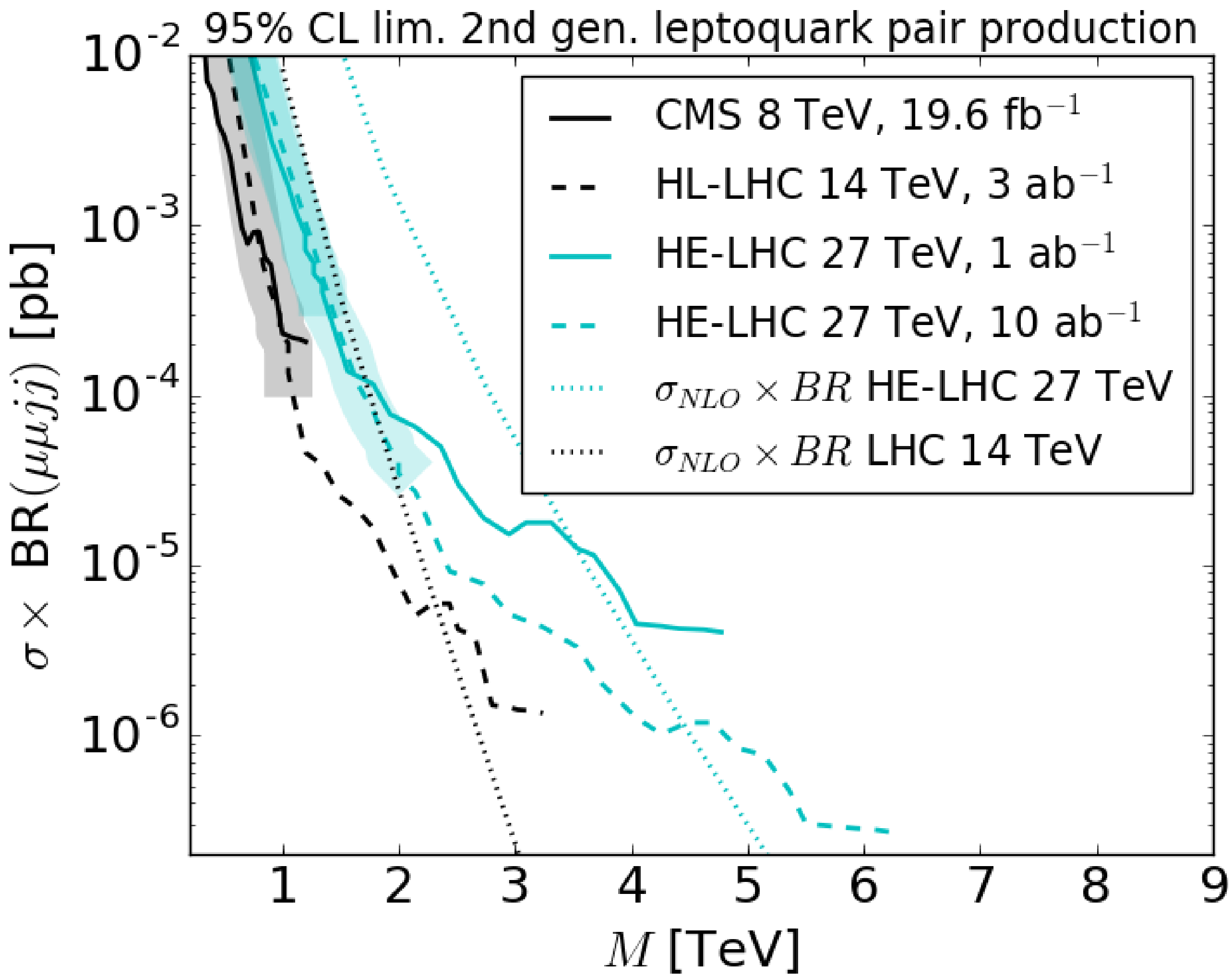
S_3	41 TeV
V_1	41 TeV
V_3	18 TeV

From $B_s - \bar{B}_s$ mixing and fitting $b-$anomalies.

The pair production cross-section is insensitive to the representation of $SU(2)$ in this case.


95% CL lim. 2nd gen. leptoquark pair production
FCC-hh 100 TeV, 1 ab^{-1}
FCC-hh 100 TeV, 10 ab^{-1}
$\sigma_{NLO} \times BR$ FCC-hh 100 TeV
$\sigma \times$ BR$(\mu\mu jj)$ [pb]
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
5
10
15
20
M [TeV]

HL-LHC/HE-LHC LQs



Other Flavour Models

Realising[26] the vector LQ solution based on $PS = [SU(4) \times SU(2)_L \times SU(2)_R]^3$. SM-like Higgs lies in third generation PS group, explaining large Yukawas (others come from VEV hierarchies). Get $U(2)_Q \times U(2)_L$ approximate global flavour symmetry.

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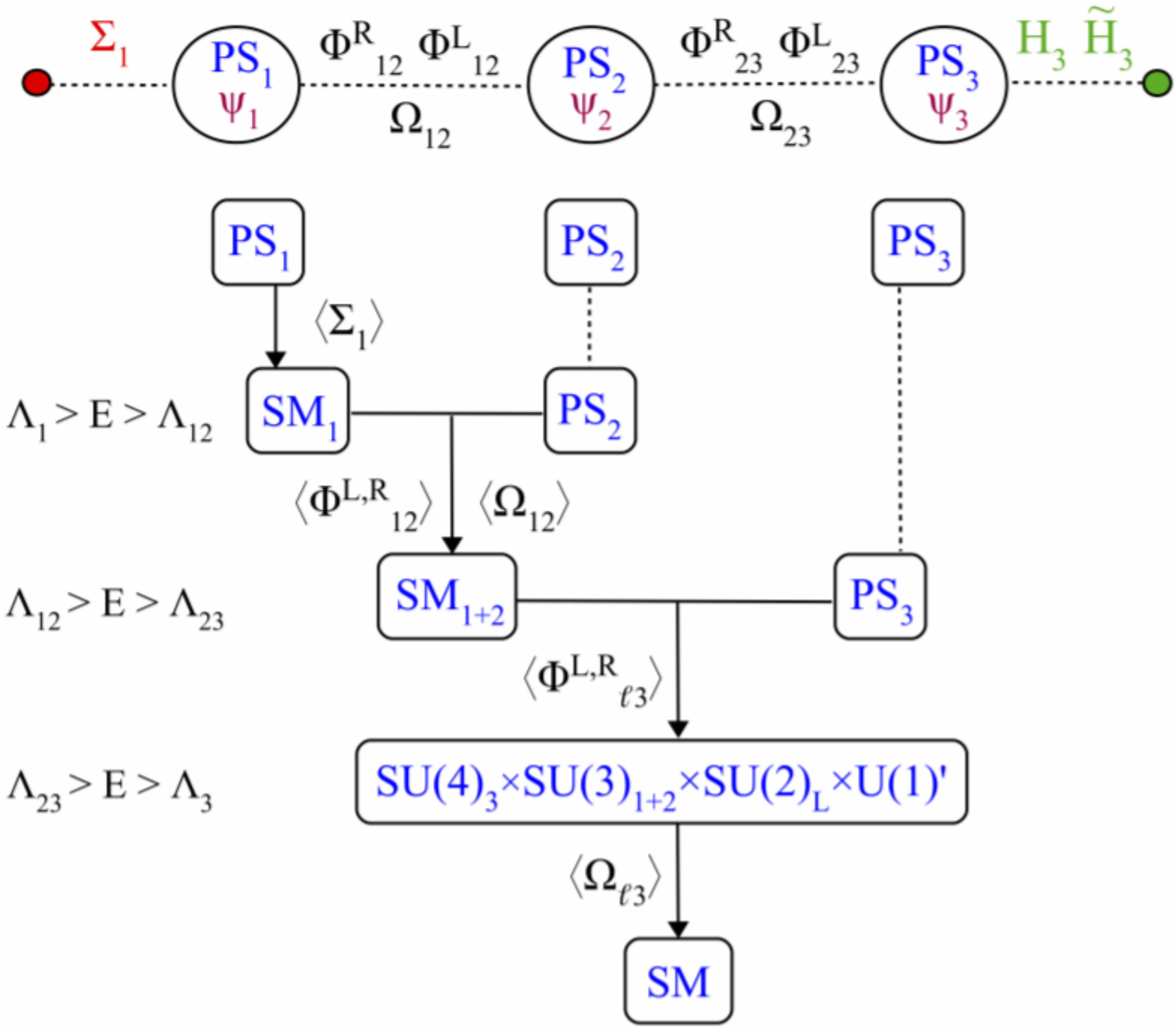
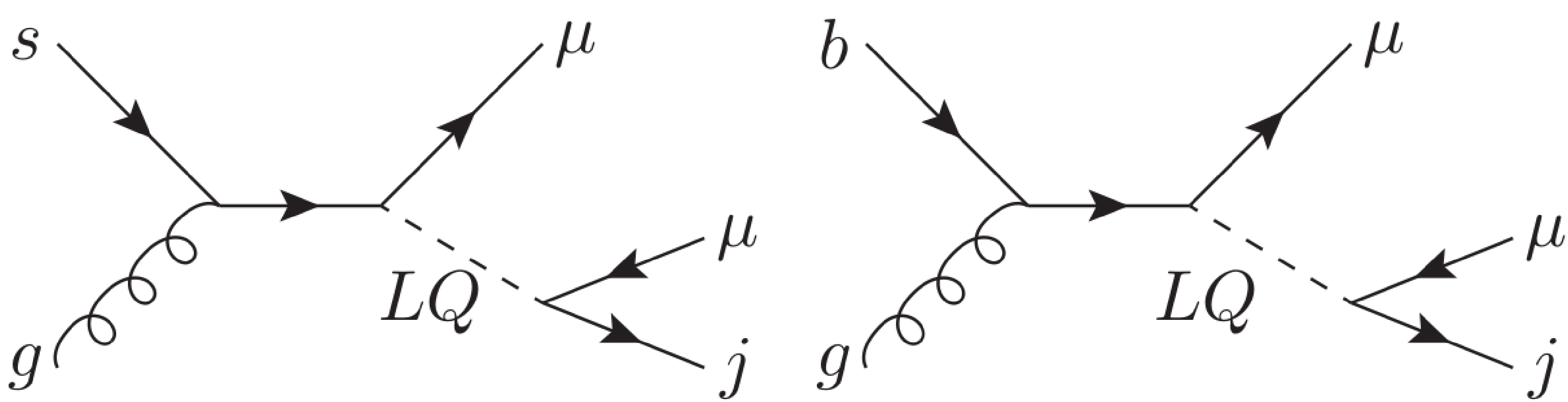
[26] Di Luzio Greljo, Nardecchia arXiv:1708.08450, Bordone, Cornella, Fuentes-Martin, Isidori, arXiv:1712.01368


Σ1
PS1 ψ1
ΦR12 ΦL12
Ω12
PS2 ψ2
ΦR23 ΦL23
Ω23
PS3 ψ3
H3 H̃3
PS1
PS2
PS3
⟨Σ1⟩
Λ1 > E > Λ12
SM1
PS2
⟨ΦL,R12⟩ ⟨Ω12⟩
Λ12 > E > Λ23
SM1+2
PS3
⟨ΦL,Rℓ3⟩
Λ23 > E > Λ3
SU(4)3×SU(3)1+2×SU(2)L×U(1)'
⟨Ωℓ3⟩
SM

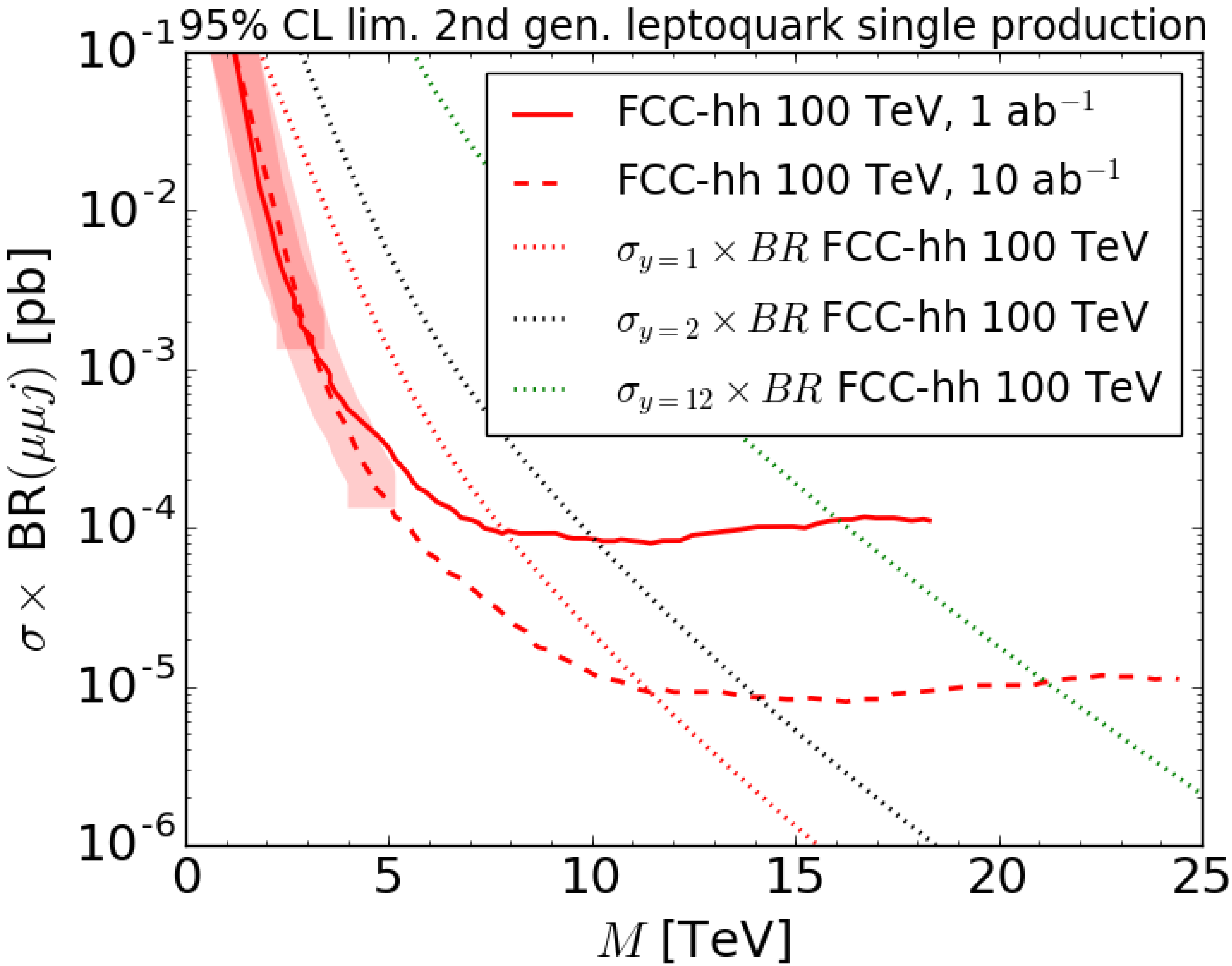
Single Production of LQ

Depends upon LQ coupling as well as LQ mass



Current bound by CMS[27] from 8 TeV 20 fb^{-1}: $M_{LQ} > 660$ GeV for $s\mu$ coupling of 1.

[27]CMS, 1509.03750



σs for S_3 with $y_{s\mu} = y_{b\mu} = y$.

Single LQ Production σ

$$\hat{\sigma}(qg \to \phi l) = \frac{y^2 \alpha_S}{96 \hat{s}} \left(1 + 6r - 7r^2 + 4r(r+1)\ln r\right) \ ,$$

where[28] $r = M_{LQ}^2/\hat{s}$ and we set $y_{s\mu} = y_{b\mu} = y$.

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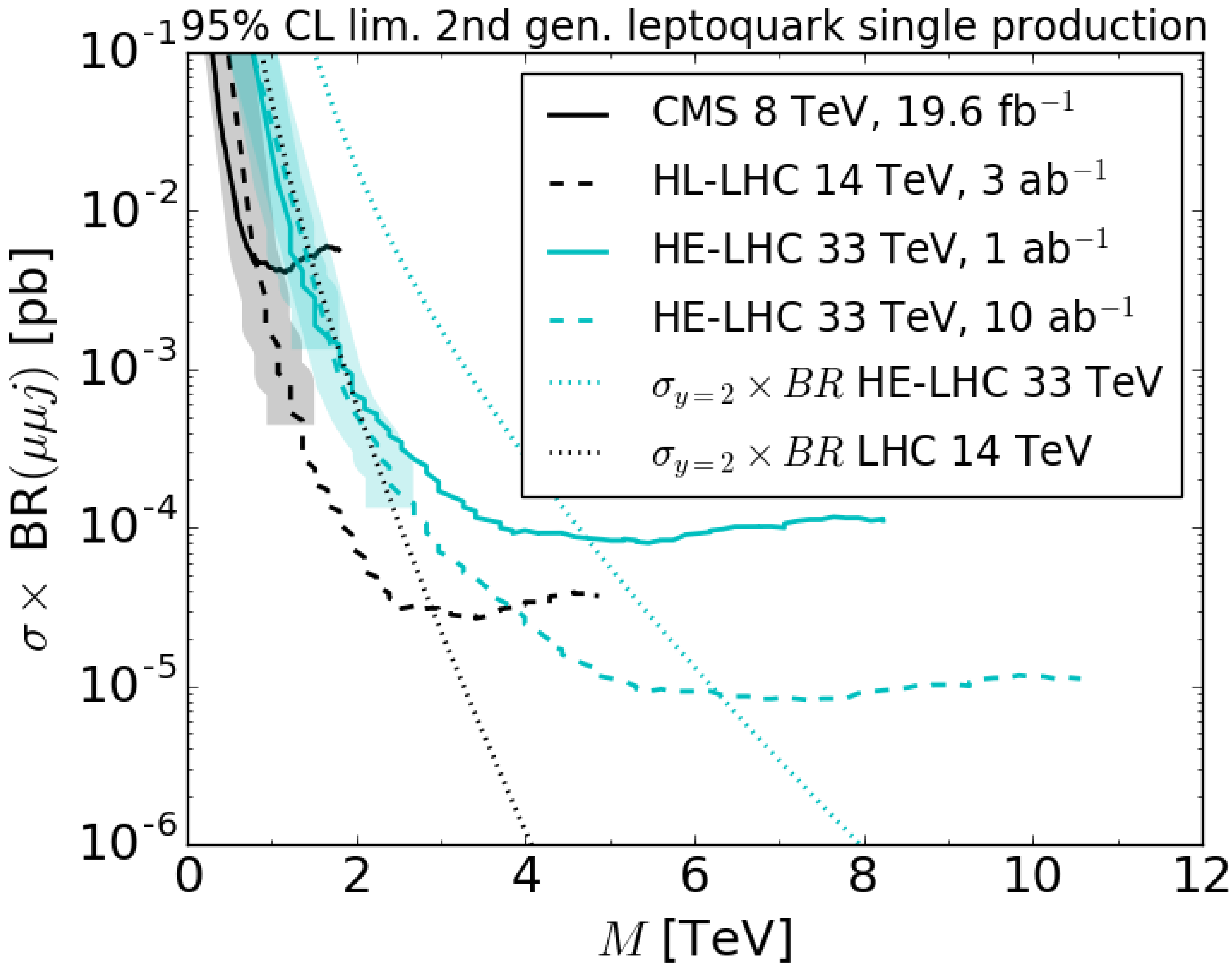
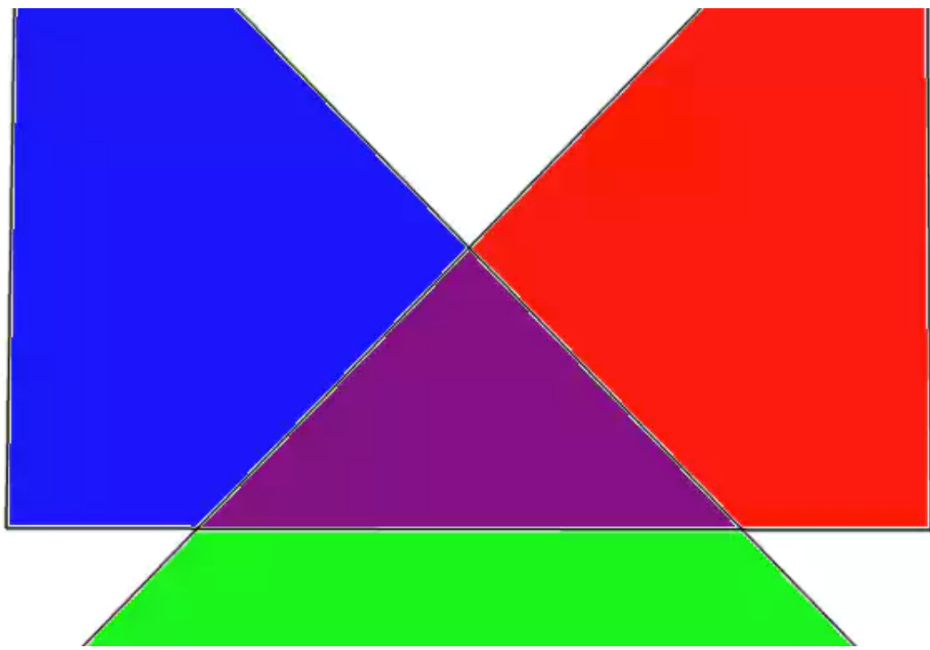
[28] Hewett and Pakvasa, PRD **57** (1988) 3165.


95% CL lim. 2nd gen. leptoquark single production
CMS 8 TeV, 19.6 fb^{-1}
HL-LHC 14 TeV, 3 ab^{-1}
HE-LHC 33 TeV, 1 ab^{-1}
HE-LHC 33 TeV, 10 ab^{-1}
$\sigma_{y=2} \times BR$ HE-LHC 33 TeV
$\sigma_{y=2} \times BR$ LHC 14 TeV
$\sigma \times$ BR$(\mu\mu j)$ [pb]
M [TeV]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0
2
4
6
8
10
12

Science Life and Physics

Modelling the fourth colour: dispatch from de Moriond

At the particle physics conference, it's clear inconclusive LHCb data are stimulating strange new ideas

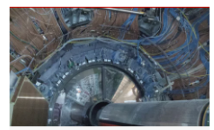


▲ Four colours (or colors?) Photograph: Ben Allanach

Ben Allanach
Sat 17 Mar 2018 10.15 GMT

In the middle of the Rencontres de Moriond particle physics conference in Italy, the scientific talks stopped to allow a standing ovation dedicated to the memory and achievements of my inspirational colleague Stephen Hawking, who we heard had died earlier that day.

The talks quickly resumed, which I think Stephen would have approved of. The most striking thing about the scientific content of the conference this year was that a whole day was dedicated to the weirdness in bottom particles that Tevong You and I wrote about last November. As Marco Nardecchia reviewed in his talk (PDF), bottom particles produced in the LHCb detector in proton collisions are decaying too often in certain particular ways, compared to predictions from the Standard Model of particle physics. Their decay products are coming out with the wrong angles too often compared with predictions, too.



Anomalous bottoms at Cern and the case for a new collider
Read more

We were hoping for an update on the data at the conference: the amount of data has roughly doubled since they were last released, and we need to see the new data to be convinced that something really new is happening in the collisions. I strongly suspect that if the effect is seen in the new data, the theoretical physics community will "go nuts" and we will quickly see the resulting avalanche of papers. If the new data look ordinary, the effect will be forgotten and everyone will move on. Taking such measurements correctly takes care and time, however, and the LHCb experiment didn't release them. We shall have to wait until other conferences later this year for the LHCb to present its analyses of the new data.

There were interesting theory talks on how new forces could explain the strange properties of the bottom particle decays. The full mathematical models look quite baroque: they need a lot of "bells and whistles" in order to pass other experimental tests. But these models prove that it can be done, and they are quite different to what has been proposed before.

One of them even unifies different classes of particle (leptons and quarks), describing the lepton as the "fourth colour" of a quark. We are used to the idea that quarks come in three (otherwise identical) copies: physicists label them red, green and blue to distinguish them. As Javier Fuentes-Martin describe (PDF), once you design the mathematics to make leptons the fourth colour, the existence of a new force-carrying particle with just the correct properties to break up the

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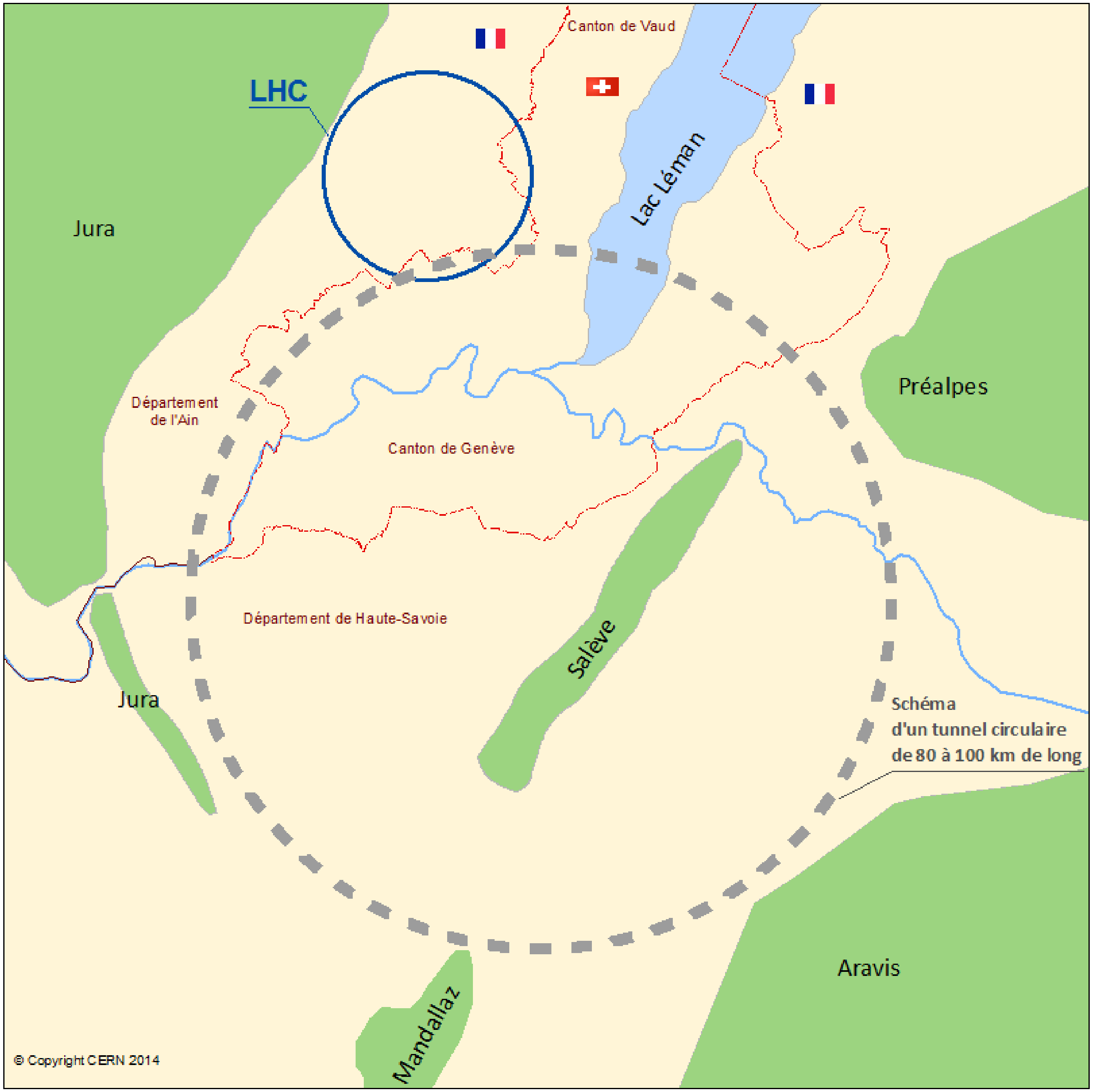
Cern

Cern draws up plans for collider four times the size of Large Hadron

The Future Circular Collider would smash particles together in a tunnel 100km long


LHC
Canton de Vaud
Lac Léman
Jura
Département
de l'Ain
Canton de Genève
Préalpes
Département de Haute-Savoie
Salève
Jura
Schéma
d'un tunnel circulaire
de 80 à 100 km de long
Aravis
Mandallaz
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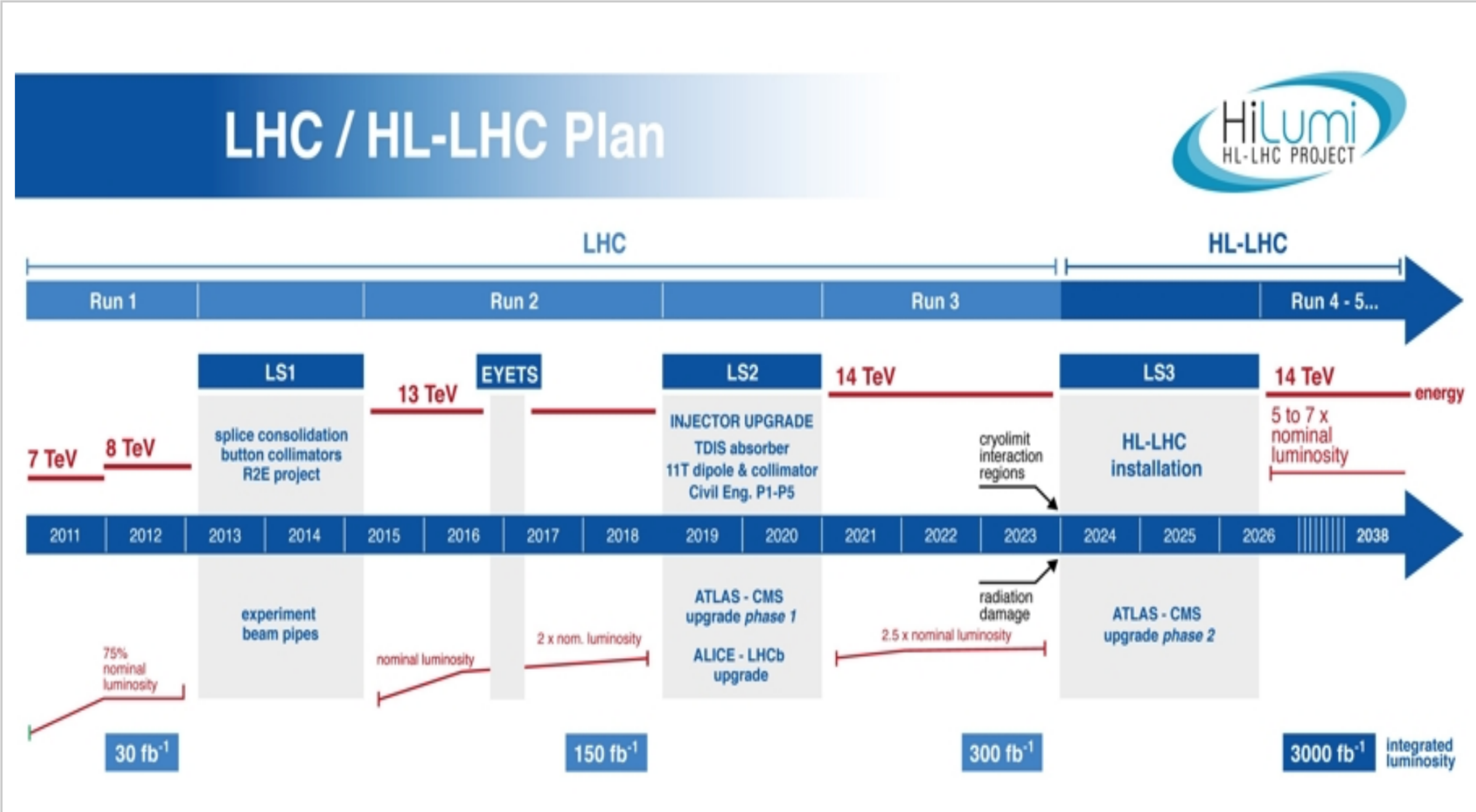
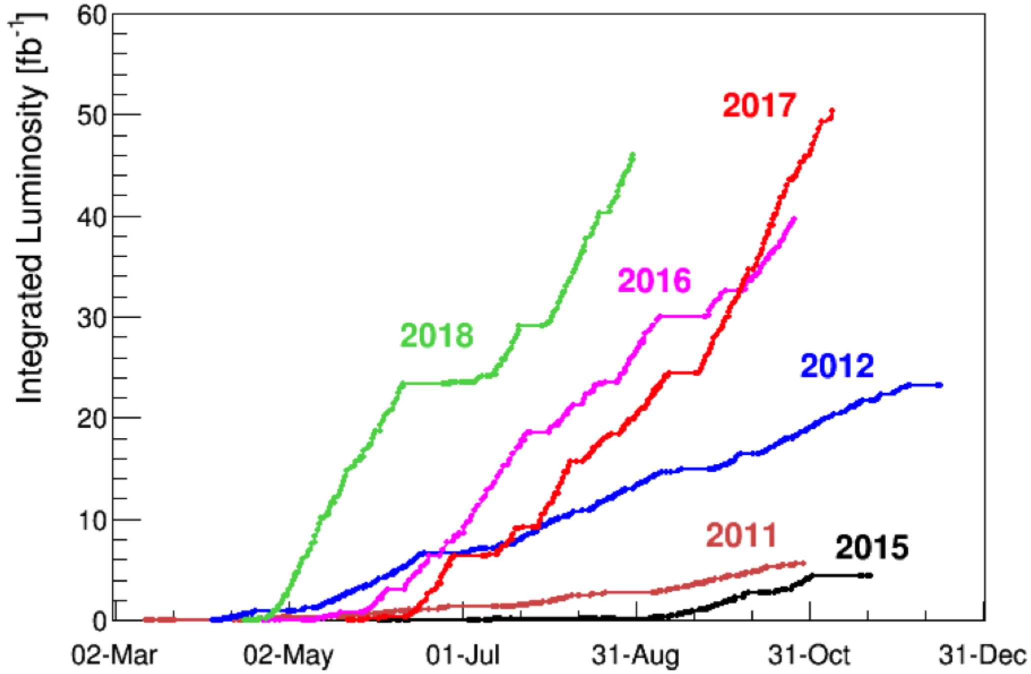

LHC / HL-LHC Plan
HiLumi
HL-LHC PROJECT
LHC
HL-LHC
Run 1
Run 2
Run 3
Run 4 - 5...
LS1
EYETS
LS2
LS3
7 TeV
8 TeV
13 TeV
14 TeV
14 TeV
energy
splice consolidation
button collimators
R2E project
INJECTOR UPGRADE
TDIS absorber
11T dipole & collimator
Civil Eng. P1-P5
cryolimit
interaction
regions
HL-LHC
installation
5 to 7 x
nominal
luminosity
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2038
experiment
beam pipes
ATLAS - CMS
upgrade phase 1
ALICE - LHCb
upgrade
radiation
damage
ATLAS - CMS
upgrade phase 2
75%
nominal
luminosity
nominal luminosity
2 x nom. luminosity
2.5 x nominal luminosity
30 fb-1
150 fb-1
300 fb-1
3000 fb-1
integrated
luminosity

LHC Upgrades



High Luminosity (HL) LHC: go to 3000 fb^{-1} (3 ab^{-1}).
High Energy (HE) LHC: Put FCC magnets (16 Tesla rather than 8.33 Tesla) into LHC ring: roughly *twice* collision energy: 27 TeV.

SM ACCs

$$Y^3 : \qquad 0 = \sum_{j=1}^{3} \left(6Y_{Q_j}^3 + 3Y_{U_j}^3 + 3Y_{D_j}^3 + 2Y_{L_j}^3 + Y_{E_j}^3 \right) ,$$

$$3^2Y : \qquad 0 = \sum_{j=1}^{3} \left(2Y_{Q_j} + Y_{U_j} + Y_{D_j} \right) ,$$

$$2^2Y : \qquad 0 = \sum_{j=1}^{3} \left(3Y_{Q_j} + Y_{L_j} \right) ,$$

$$\text{grav}^2Y : \qquad 0 = \sum_{j=1}^{3} \left(6Y_{Q_j} + 3Y_{U_j} + 3Y_{D_j} + 2Y_{L_j} + Y_{E_j} \right) .$$