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New Physics in B anomalies

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collaboration with

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Flavor Physics at LHC run II
May 21 - 27

CENTRO DE CIENCIAS DE BENASQUE PEDRO PASCUAL

Anomalies in B physics

They tend to come and go after experimental and theoretical scrutiny

- [x] < 2011
- [x] 2011 same-sign dimuon asymmetry (D0) ?
- [x] 2011 B → τ τ (Belle)

- [ ] 2012 …. R_D, R_{D^*} LF non-universal, V_{cb} → $V^{(\tau)}_{cb}$?
- [ ] 2013 …. P_5'
- [ ] 2014 …. R_K
- [ ] 2017 …. R_{K^*}

} neutral current $b \to s\ell^+\ell^-$

natural habitat for NP

Have to take it seriously if the hints of a particular anomaly from experiment keep accumulating (after reassessing the Standard model prediction).

What NP models explain (i.e., can accomodate) each (or both) of these anomalies? What are model-specific side effects?

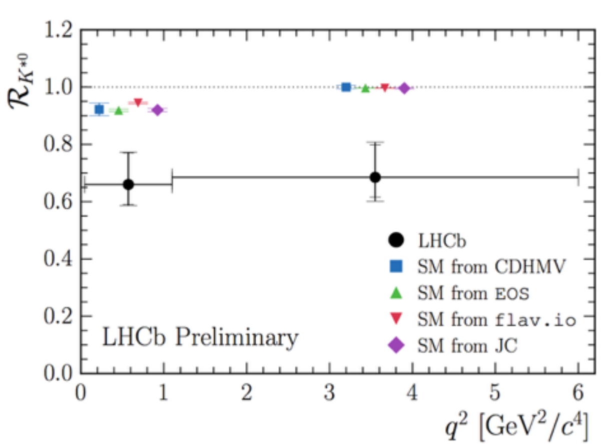
Current status of "B-anomalies"

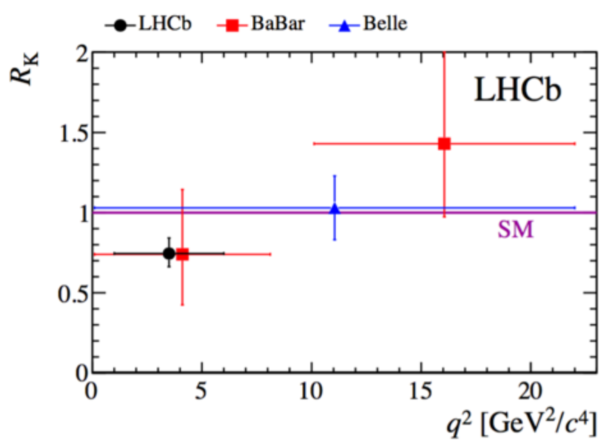
Quick overview

$b \to s \ell^+ \ell^-$

LFU

$$R_K^{\text{exp}} = 0.745 \pm^{0.090}_{0.074} \pm 0.036$$
$$R_{K^*}^{\text{exp,low}\, q^2} = 0.660^{+0.110}_{-0.070} \pm 0.024 \quad \text{(In SM = 1 ± %)}$$
$$R_{K^*}^{\text{exp,central}\, q^2} = 0.685^{+0.113}_{-0.069} \pm 0.047$$





See talk by Patrick on Friday

$S_i, P_i^{(\prime)}$ $\quad B \to K^{(*)} \mu^+ \mu^-$

angular

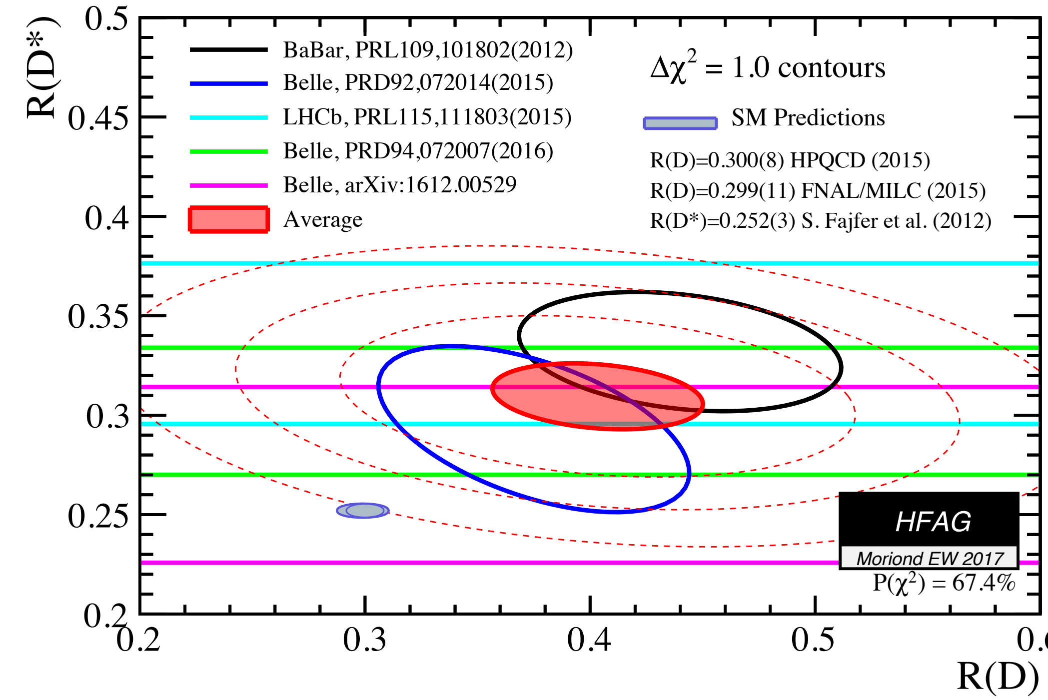
optimized observables, see talk by Bernat

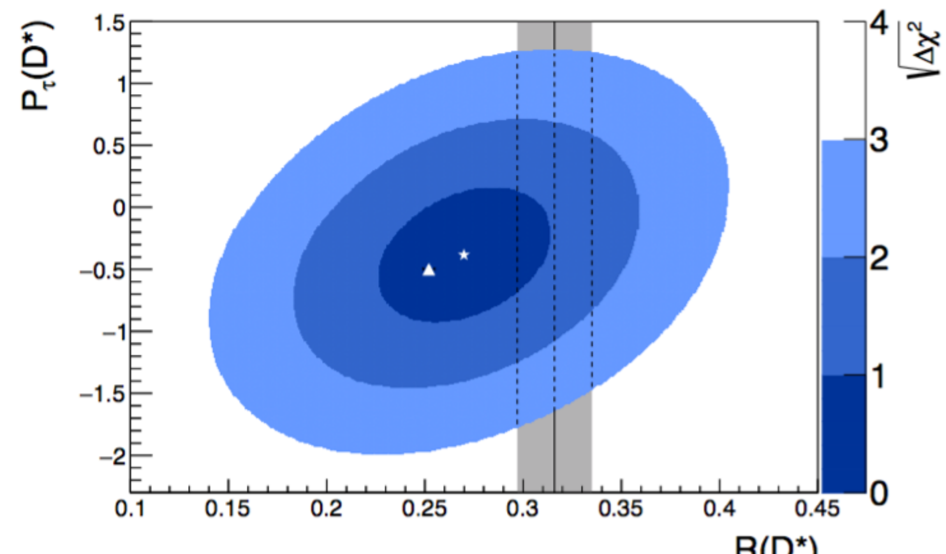
$B \to K^{(*)} \mu^+ \mu^-$ $\quad B_s \to \mu^+ \mu^-$

$B_s \to \phi \mu^+ \mu^-$ $\quad$ inclusive, …

(partial) rates

$b \to c \ell^- \nu$





[Belle 1612.00529]

NP scale sensitivity

Both effects are ~20% correction to the amplitude. Naive scale sensitivity

$b \to s \ell^+ \ell^-$	$b \to c \ell^- \nu$
e.g. $C_9 = -1 \quad \Rightarrow \quad \Lambda = 3$ TeV (1-loop NP) $\frac{V_{ts}}{(4\pi)^2 v^2}$ vs. $\frac{1}{(4\pi)^2 \Lambda^2}$ $\Lambda = 30$ TeV (tree-level NP) $\frac{V_{ts}}{(4\pi)^2 v^2}$ vs. $\frac{1}{\Lambda^2}$	$\Lambda = 3$ TeV (tree-level NP) $\frac{V_{cb}}{v^2}$ vs. $\frac{1}{\Lambda^2}$

However, dimensionless couplings of NP are arbitrary parameters, so the scales just reflect different sensitivity to NP.

Signals either: 1) different scale responsible for the two processes,
2) flavor coupling hierarchy of NP

b→s$\ell\ell$

Effective theory

Standard Model + dim-6 operators at scale Λ (SM-EFT)

$$\mathcal{L}_{\rm SM-EFT} = \frac{1}{\Lambda^2}\sum_i C_i Q_i \qquad Q_i \sim (HD_\mu H)(\bar{q}\gamma^\mu q) \quad \text{“Higgs current”}$$
$$(\bar{q}\sigma^{\mu\nu}V_{\mu\nu}q)H \quad \text{“dipoles”}$$
$$\bar{q}q\bar{\ell}\ell \quad \text{“4-fermion”}$$

RG running to the b-energy scale

$$\mathcal{L}_{\rm eff} = \frac{4G_F}{\sqrt{2}}V_{tb}V_{ts}^*\left[\sum_{i=1}^{6} C_i\mathcal{O}_i + \sum_{i=7,8,9,10,S,P}(C_i\mathcal{O}_i + C_i'\mathcal{O}_i')\right]$$

$$\mathcal{O}_7^{(\prime)} = \frac{e}{(4\pi)^2}m_b(\bar{s}\sigma_{\mu\nu}P_{R(L)}b)F^{\mu\nu}$$

$$\mathcal{O}_9^{(\prime)} = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\ell}\gamma^\mu\ell) \qquad \mathcal{O}_{10}^{(\prime)} = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\ell}\gamma^\mu\gamma_5\ell)$$

$$\mathcal{O}_S^{(\prime)} = \frac{e^2}{(4\pi)^2}(\bar{s}P_{R(L)}b)(\bar{\ell}\ell) \qquad \mathcal{O}_P^{(\prime)} = \frac{e^2}{(4\pi)^2}(\bar{s}P_{R(L)}b)(\bar{\ell}\gamma_5\ell)$$

See Federico’s talk

[Grinstein, Camalich, Alonso, 1407.7044]
[Grinstein, Camalich, Alonso, 1505.05164]
[Cata, Jung, 1505.05804]
[Feruglio, Paradisi, Pattori, 1606.00524]

1. no tensor currents
2. scalars: $C_S=-C_P$, $C_S'=C_P'$
3. $C_{9,SM}=-C_{10,SM}=4.2$
4. LFU violation from semileptonic operators

b→sℓℓ

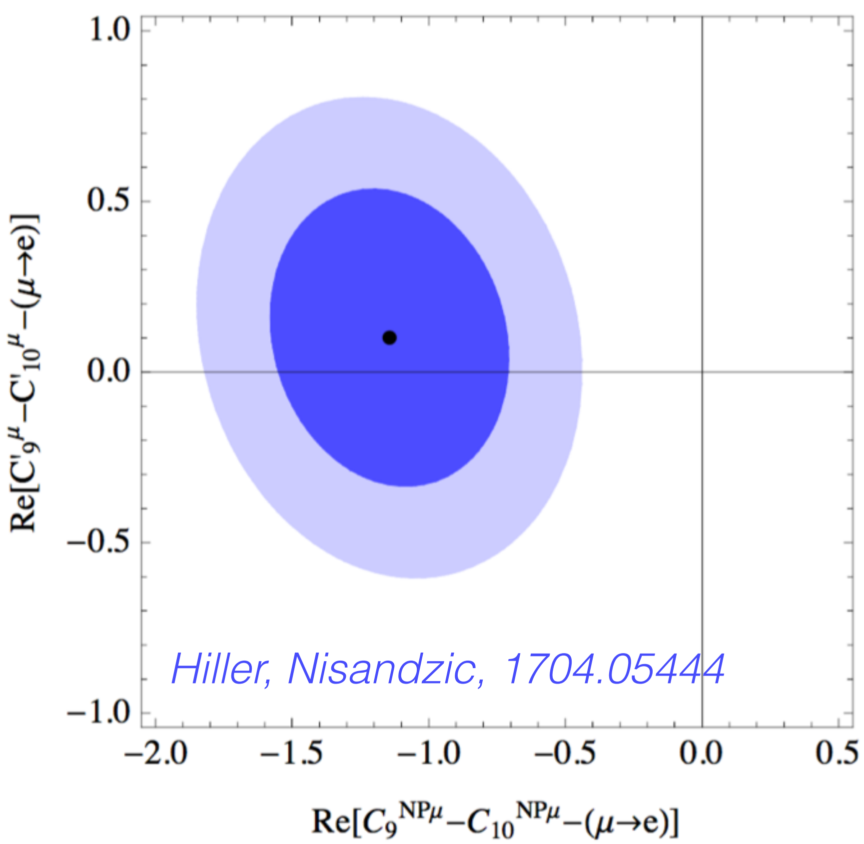
LFU observables

$$\mathcal{O}_9^\ell = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell) \qquad \mathcal{O}_{10}^\ell = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

$$\mathcal{O}_S^\ell = \frac{e^2}{(4\pi)^2}(\bar{s}P_R b)(\bar{\ell}\ell) \qquad \mathcal{O}_P^\ell = \frac{e^2}{(4\pi)^2}(\bar{s}P_R b)(\bar{\ell}\gamma_5 \ell)$$

Leading LFUV effects

- R_K and R_{K^*} impose:



[Hiller, Schmaltz, 1408.1627, 1411.4773]

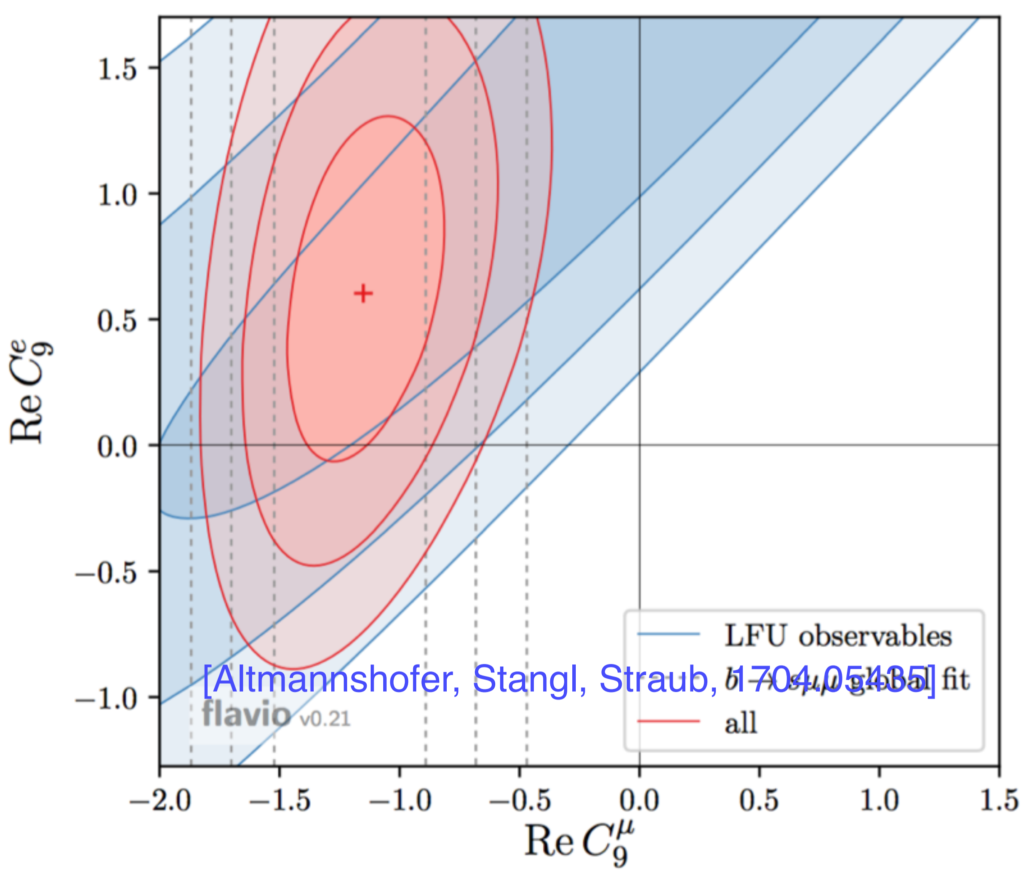
$$\mathrm{Re}[C_9^{\mathrm{NP}\mu} - C_{10}^{\mathrm{NP}\mu} - (\mu \to e)] \sim -1.1 \pm 0.3 \qquad \mathrm{Re}[C_9'^{\mu} - C_{10}'^{\mu} - (\mu \to e)] \sim 0.1 \pm 0.4$$

- Scalar operators $C_S=-C_P$, $C_S'=C_P'$: excluded by $Br(B_s \to \mu\mu)$

Global fits of b→sμμ

- Fit the whole set of observables driven by b→sμμ. [*See talk by Bernat*]

$$B \to K^{(*)}\mu^+\mu^- \qquad S_i, P_i^{(\prime)}$$
$$B_s \to \phi\mu^+\mu^-$$
$$B_s \to \mu^+\mu^-$$



[Altmannshofer, Stangl, Straub, 1704.05485]

Vector leptonic current with left quarks

C_9^μ, $C^\mu_9=-C^\mu_{10}$, (C^μ_9, C^μ_{10}), … $(C^\mu_9, *)$

$$C_9 = -C_{10} \in [-0.73, -0.48] \quad (5.2\sigma \text{ pull})$$

[Capdevila, Crivellin, Descotes-Genon, Matias, Virto, 1704.05340]

[Descotes-Genon, Hofer, Matias, Virto, 1510.04239]

[+many more…..]

- Assume that B → Kee is SM-like. Fits well with data.

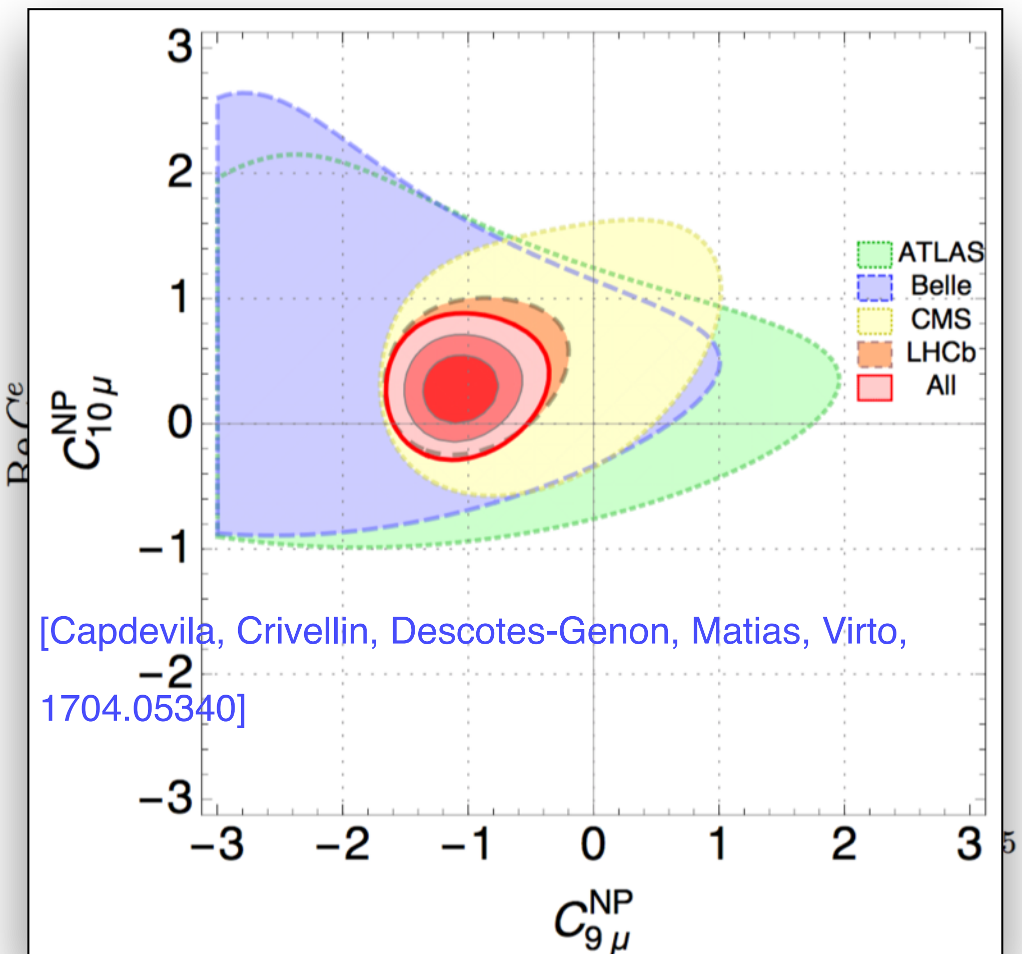
Global fits of b→sμμ

- Fit the whole set of observables driven by b→sμμ. [*See talk by Bernat*]

$$B \to K^{(*)}\mu^+\mu^- \qquad S_i, P_i^{(\prime)}$$

$$B_s \to \phi\mu^+\mu^-$$

$$B_s \to \mu^+\mu^-$$



Vector leptonic current with left quarks

C_9^μ, $C^\mu_9=-C^\mu_{10}$, (C^μ_9,C^μ_{10}), … $(C^\mu_9,*)$

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[Capdevila, Crivellin, Descotes-Genon, Matias, Virto, 1704.05340]

[Descotes-Genon, Hofer, Matias, Virto, 1510.04239]

[+many more…..]

- Assume that B → Kee is SM-like. Fits well with data.

NP models for b→sμμ

- Loop level
  - ✳ Z' + vector-like quarks
  - ✳ leptoquarks
  - ✳ 2HDM

Talk by Javier on Friday

- Tree-level mediators:
  - ✳ Charged and colored: scalar or vector leptoquarks
  - ✳ Neutral vectors: Z'

- On-shell
  - ✳Light vector resonances - lead to q^2 dependent effects

EFT analysis of R_{D^*}

Data can be best described by (a combination of) following operators

$$\mathcal{L} = -\frac{4G_F V_{cb}}{\sqrt{2}}\Big[(1+g_V)(\bar{\tau}_L\gamma^\mu\nu_L)(\bar{c}_L\gamma_\mu b_L) + g_S(\bar{\tau}_R\nu_L)(\bar{c}_R b_L) + g_T(\bar{\tau}_R\sigma^{\mu\nu}\nu_L)(\bar{c}_R\sigma_{\mu\nu}b_L)\Big]$$

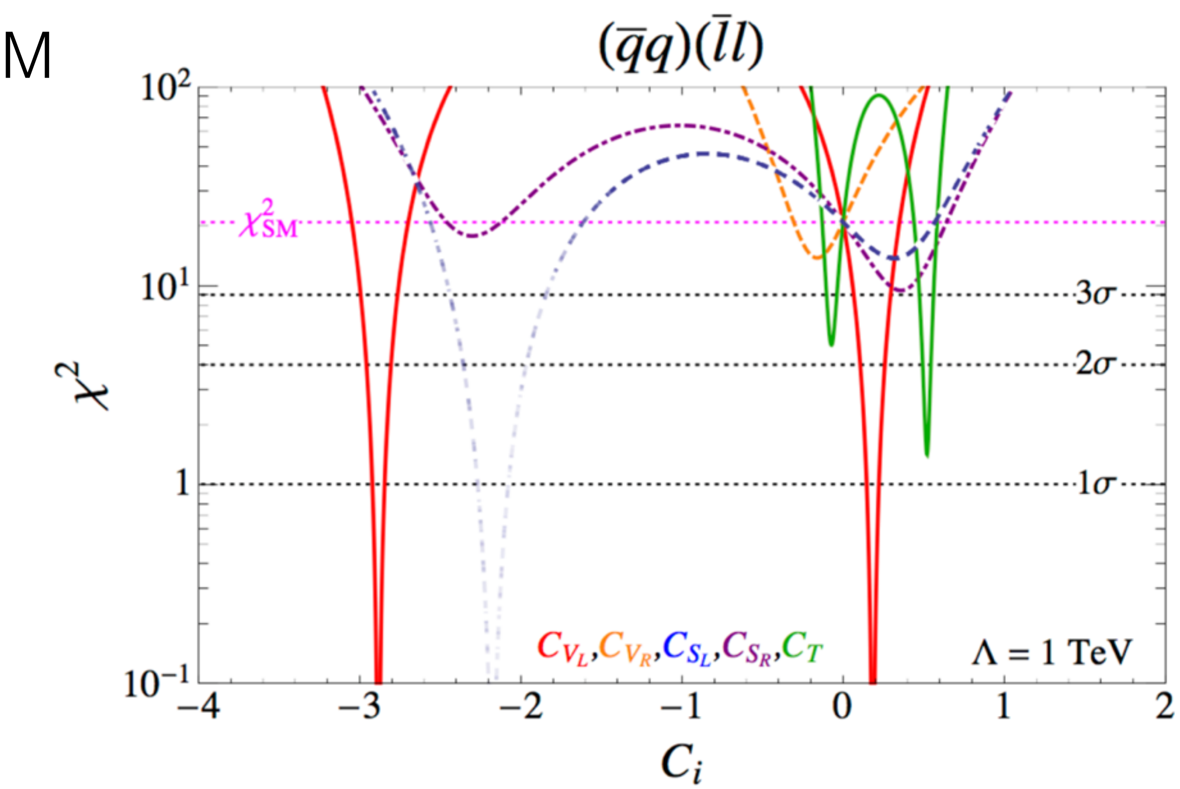
[Freytsis, Ligeti, Ruderman, 1506.08896]
[Becirevic, NK, Tayduganov,1206.4977]

	Operator
$\mathcal{O}_{V_L}$	$(\bar{c}\gamma_\mu P_L b)\,(\bar{\tau}\gamma^\mu P_L \nu)$
$\mathcal{O}_{V_R}$	$(\bar{c}\gamma_\mu P_R b)\,(\bar{\tau}\gamma^\mu P_L \nu)$
$\mathcal{O}_{S_R}$	$(\bar{c}P_R b)\,(\bar{\tau}P_L \nu)$
$\mathcal{O}_{S_L}$	$(\bar{c}P_L b)\,(\bar{\tau}P_L \nu)$
$\mathcal{O}_T$	$(\bar{c}\sigma^{\mu\nu}P_L b)\,(\bar{\tau}\sigma_{\mu\nu}P_L \nu)$
$\mathcal{O}'_{V_L}$	$(\bar{\tau}\gamma_\mu P_L b)\,(\bar{c}\gamma^\mu P_L \nu)$
$\mathcal{O}'_{V_R}$	$(\bar{\tau}\gamma_\mu P_R b)\,(\bar{c}\gamma^\mu P_L \nu)$
$\mathcal{O}'_{S_R}$	$(\bar{\tau}P_R b)\,(\bar{c}P_L \nu)$
$\mathcal{O}'_{S_L}$	$(\bar{\tau}P_L b)\,(\bar{c}P_L \nu)$
$\mathcal{O}'_T$	$(\bar{\tau}\sigma^{\mu\nu}P_L b)\,(\bar{c}\sigma_{\mu\nu}P_L \nu)$
$\mathcal{O}''_{V_L}$	$(\bar{\tau}\gamma_\mu P_L c^c)\,(\bar{b}^c\gamma^\mu P_L \nu)$
$\mathcal{O}''_{V_R}$	$(\bar{\tau}\gamma_\mu P_R c^c)\,(\bar{b}^c\gamma^\mu P_L \nu)$
$\mathcal{O}''_{S_R}$	$(\bar{\tau}P_R c^c)\,(\bar{b}^c P_L \nu)$
$\mathcal{O}''_{S_L}$	$(\bar{\tau}P_L c^c)\,(\bar{b}^c P_L \nu)$
$\mathcal{O}''_T$	$(\bar{\tau}\sigma^{\mu\nu}P_L c^c)\,(\bar{b}^c\sigma_{\mu\nu}P_L \nu)$

Only operators interfering with the SM

$$\mathcal{H} = \sum \frac{C_i}{\Lambda^2}\mathcal{O}_i$$

$$C_{V_L} = 0.18 \pm 0.04$$



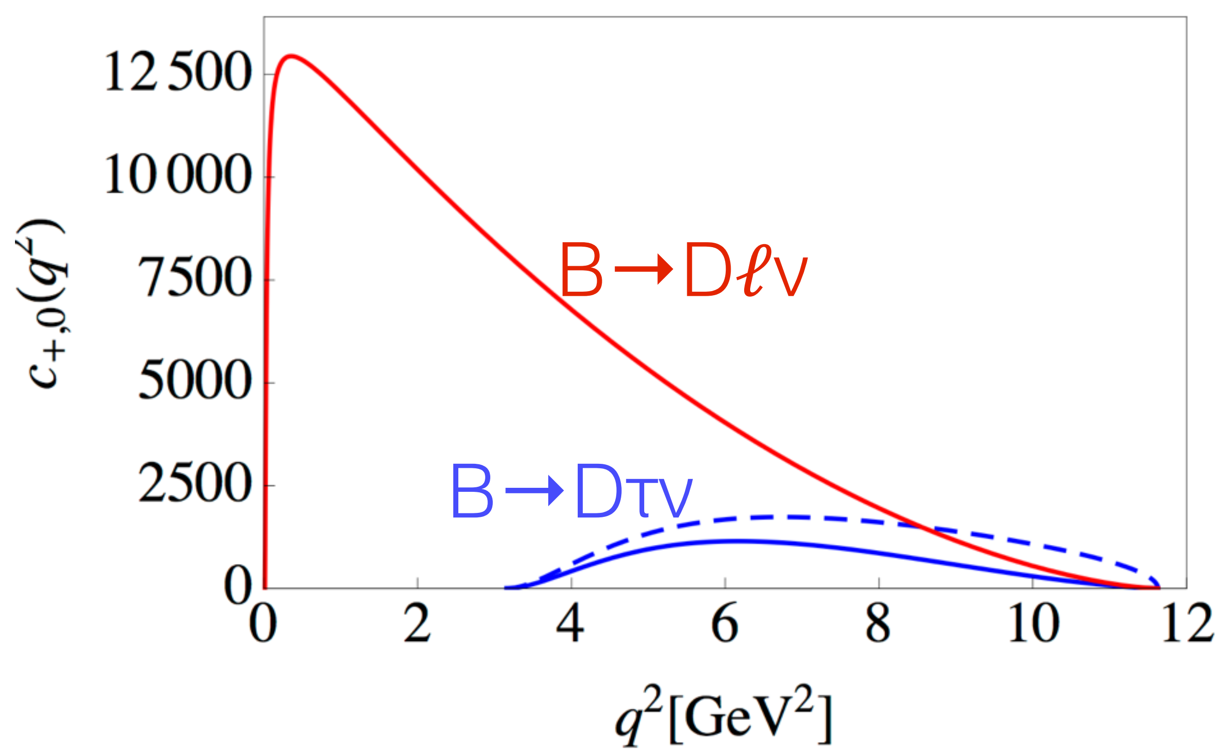
[Freytsis, Ligeti, Ruderman, 1506.08896]

Models for b→cτν

Only tree-level NP can compete with tree-level SM!

Charged scalars: extra Higgs(es)

- Non-minimal flavour structure (e.g. type III)
- Scalar form factor F_0 enhanced in B→Dτν, absent in B→Dℓν



[Crivellin, Greub, Kokulu,1206.2634]
[Celis, Jung, Li, Pich,1210.8443]
…

[Ko, Omura, Yu, 1212.4607]
[Crivellin, Heeck, Stoffer,1507.07567]

Coloured bosons - LQs

- Fierzed basis of operators: →scalar/vector/tensor

[Sakaki, Tanaka, Tayduganov, Watanabe,1309.0301]
[Bauer, Neubert, 1511.01900]
[Li, Yang, Zhang, 1605.09308]
…

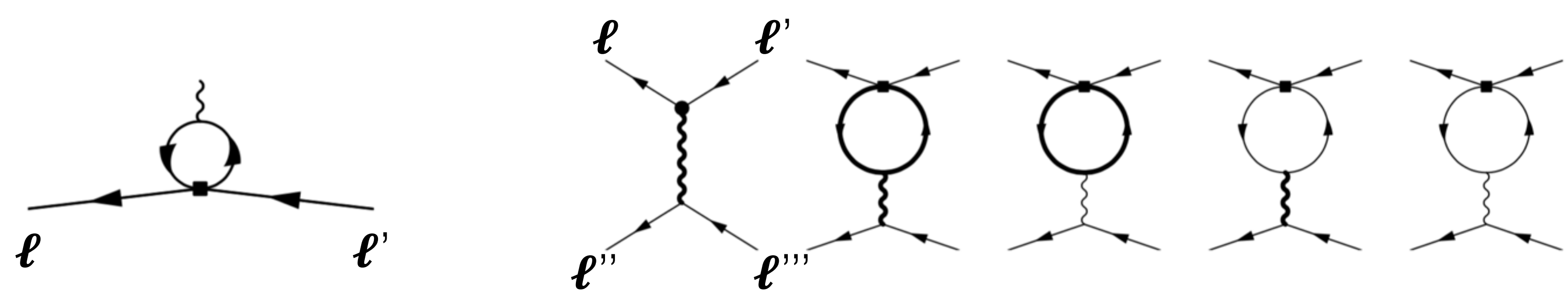
b→s$\ell\ell$ and b→c$\ell\nu$

Effective theory - mixing effects

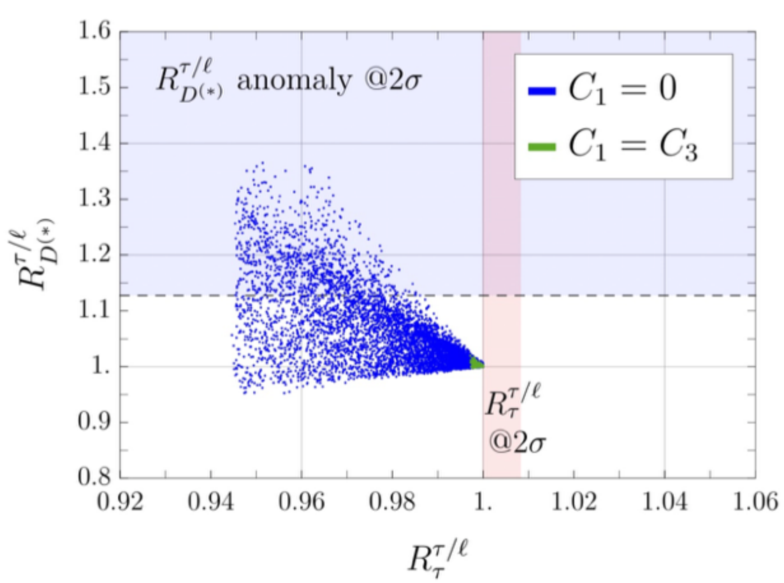
RG running of "beneficial operators" to the b-energy scale generates dangerous couplings

Feruglio, Paradisi, Pattori, 1606.00524, 1705.00929

$$\mathcal{L}^0_{NP}(\Lambda) = \frac{1}{\Lambda^2}\left(C_1\ \bar{q}'_{3L}\gamma^\mu q'_{3L}\ \bar{\ell}'_{3L}\gamma_\mu \ell'_{3L} + C_3\ \bar{q}'_{3L}\gamma^\mu\tau^a q'_{3L}\ \bar{\ell}'_{3L}\gamma_\mu\tau^a \ell'_{3L}\right)$$



Effects in $(\bar{\ell}_1\gamma_\mu\ell_2)(\bar{\ell}_3\gamma^\mu\ell_4), V\bar{f}_1\gamma^\mu f_2$ are experimentally well constrained, e.g.,



$$R^{\tau/e}_\tau = \frac{\mathcal{B}(\tau\to\mu\nu\bar{\nu})_{\rm exp}/\mathcal{B}(\tau\to\mu\nu\bar{\nu})_{\rm SM}}{\mathcal{B}(\mu\to e\nu\bar{\nu})_{\rm exp}/\mathcal{B}(\mu\to e\nu\bar{\nu})_{\rm SM}}$$

$R^{\tau/\mu}_\tau = 1.0022 \pm 0.0030$ $\qquad$ $R^{\tau/e}_\tau = 1.0060 \pm 0.0030$

Challenges EFT explanations of R_K and R_D, not directly applicable to top-down approaches that contribute to many Wilson coefficient at matching scale.

Leptoquarks

LQ = color triplet bosons

Their origin can be traced to gauge bosons or Higgs sector of Grand Unified Theories*. Consider SU(5) GUT.

gauge bosons (24): $(8,1,0) \oplus (1,3,0) \oplus (1,1,0)$
$\oplus (3,2,-5/6) \oplus (3,2,1/6)$

fermions: $5_i = (3,1,-1/3)_i \oplus (1,2,1/2)_i$ $\quad$ $i=1,2,3$
$10_i = (3,2,1/6)_i \oplus (3^*,1,-2/3)_i \oplus (1,1,1)_i$

scalar sector: 5, 10, 15, 24, 45

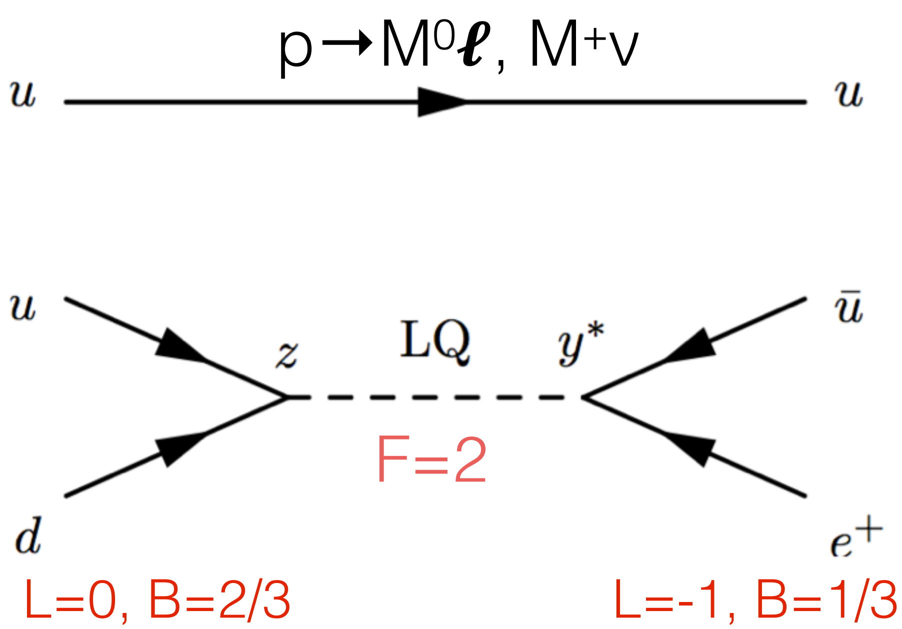
e.g. Georgi-Jarlskog mechanism uses 5- and 45-dim. scalar reps. to reproduce the fermion mass ratios

$5 = (1,2,1/2) \oplus (3,1,-1/3)$ "doublet-triplet"
$10 = (3,2,1/6) \oplus \ldots$
$15 = (1,3,1) \oplus (3,2,1/6) \oplus (6,1,-2/3)$
$24 = (8,1,0) \oplus (1,3,0) \oplus (3,2,-5/6) \oplus (\bar{3},2,5/6) \oplus (1,1,0)$
$45 = (8,2,1/2) \oplus (6^*,1,-1/3) \oplus (3,3,-1/3) \oplus (3^*,2,-7/6)$
$\oplus (3,1,-1/3) \oplus (3^*,1,4/3)$

*Composite LQ scenarios also possible

Light LQs and proton stability

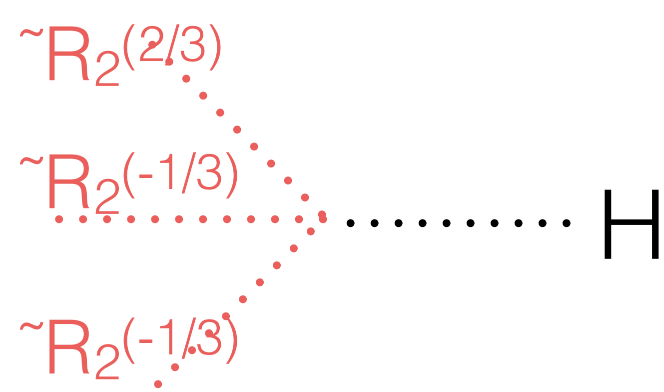
- Couplings with SM fermions
  - lepton and quark
  - diquark (F=2)



- F=0 or F=2 determined by quantum numbers

spin	SU(3)xSU(2)xU(1)	F=3B+L	B	L
vectors (gauge bosons)	$V_2(\bar{3},2,5/6)$	2	/	/
	$\tilde{V}_2(\bar{3},2,-1/6)$	2	/	/
	$U_3(3,3,2/3)$	0	**1/3**	**-1**
	$U_1(3,1,2/3)$	0	**1/3**	**-1**
scalars	$S_1(3,1,-1/3)$	2	/	/
	$S_3(3,3,-1/3)$	2	/	/
	$R_2(3,2,7/6)$	**0**	**1/3**	**-1**
	$\tilde{R}_2(3,2,1/6)$	0	/	/
	$\tilde{S}_1(\bar{3},1,4/3)$	2	/	/

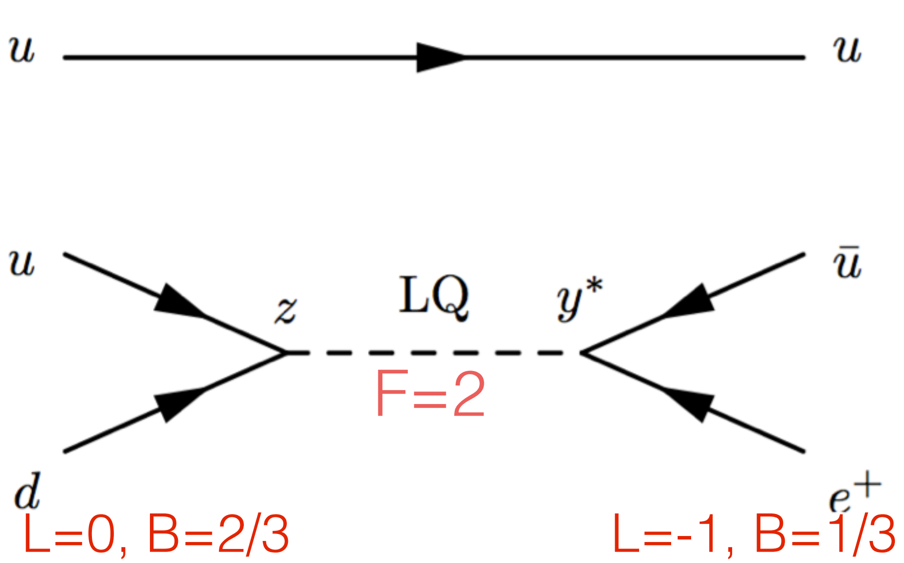
- F = 2 LQs destabilize proton (baryon number violating)
- F = 0 LQs have no diquark couplings and are potentially safe w.r.t. proton decay

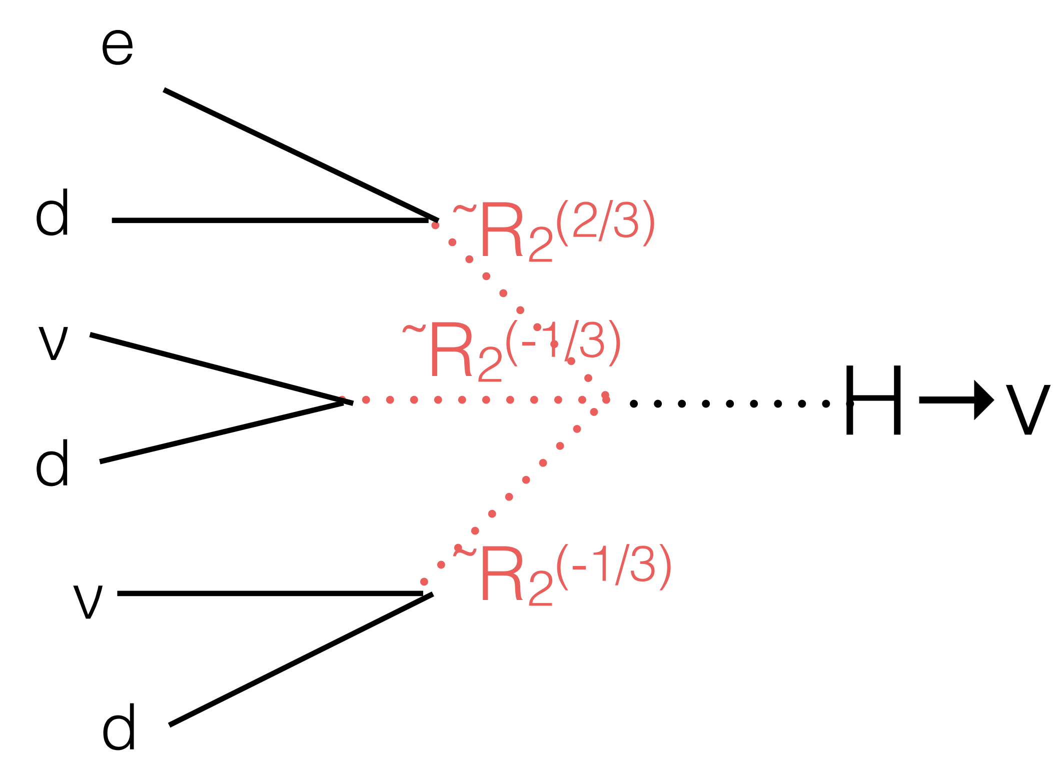


- Possible baryon num. violation in the scalar potential

$p \to M^+ M^+ \ell \nu\nu$

Light LQs and proton stability





p→M⁰ℓ⁺, M⁺ν

p→M⁺M⁺ℓνν

τ>8.2 x10^{33} yr (πe⁺) [SK]

τ>2 x 10^{29} yr (invisible modes) [SNO]

Light LQs and $b \to s\mu\mu$

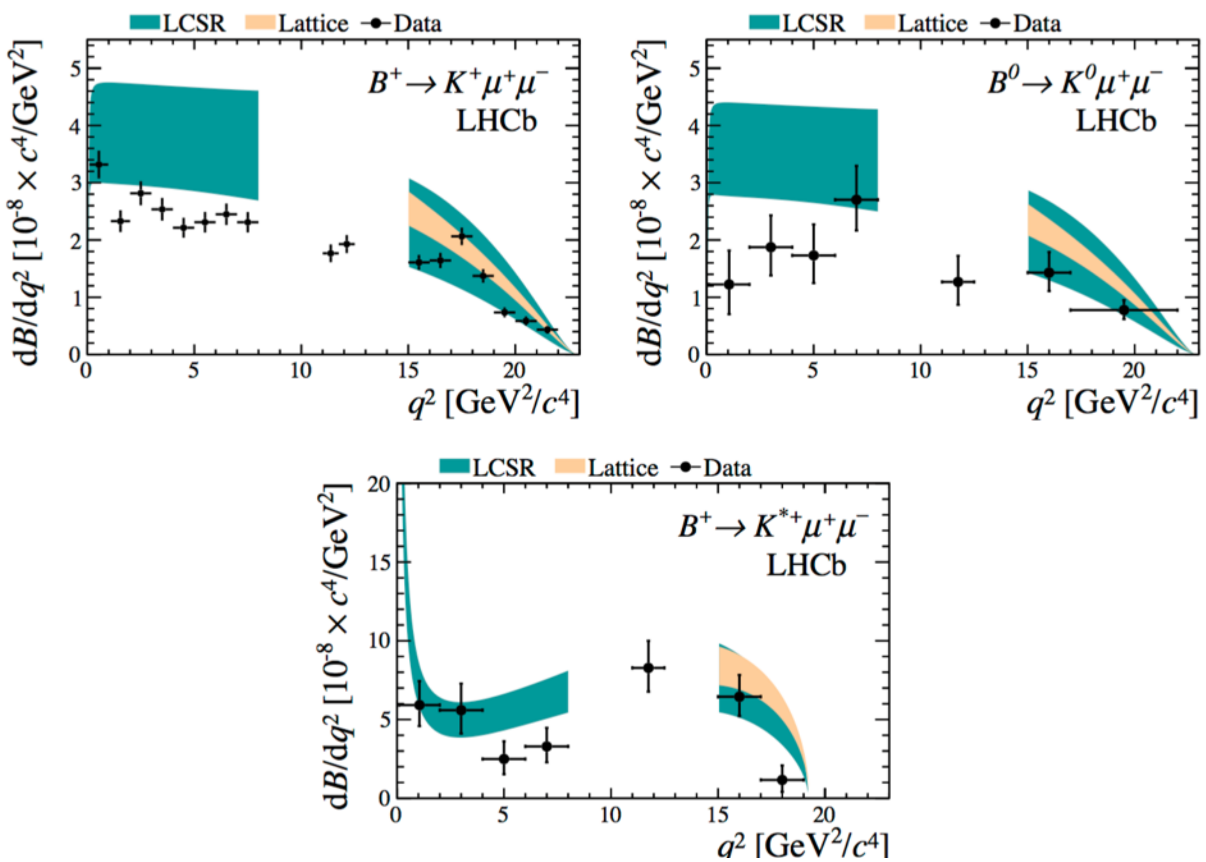
spin	SU(3)xSU(2)xU(1)	F	B	L	
vectors (gauge bosons)	$V_2(\bar{3},2,5/6)$	2	/	/	
	$\tilde{V}_2(\bar{3},2,-1/6)$	2	/	/	
	$U_3(3,3,2/3)$	**0**	**1/3**	**-1**	$C_9 = -C_{10}$
	$U_1(3,1,2/3)$	**0**	**1/3**	**-1**	$C_9 = -C_{10}$, $C_9' = C_{10}'$, $C_S^{(\prime)}$, $C_P^{(\prime)}$
scalars	**$S_1(3,1,-1/3)$**	**2**	**/**	**/**	$C_9 = \pm C_{10}$ (1-loop) [1]
	$S_3(3,3,-1/3)$	**2**	**/**	**/**	$C_9 = -C_{10}$
	$R_2(3,2,7/6)$	**0**	**1/3**	**-1**	$C_9 = +C_{10}$ (at 1-loop $C_9 = -C_{10}$) [2]
	$\tilde{R}_2(3,2,1/6)$	**0**	**/**	**/**	$C_9' = -C_{10}'$
	$\tilde{S}_1(\bar{3},1,4/3)$	2	/	/	$C_9' = +C_{10}'$

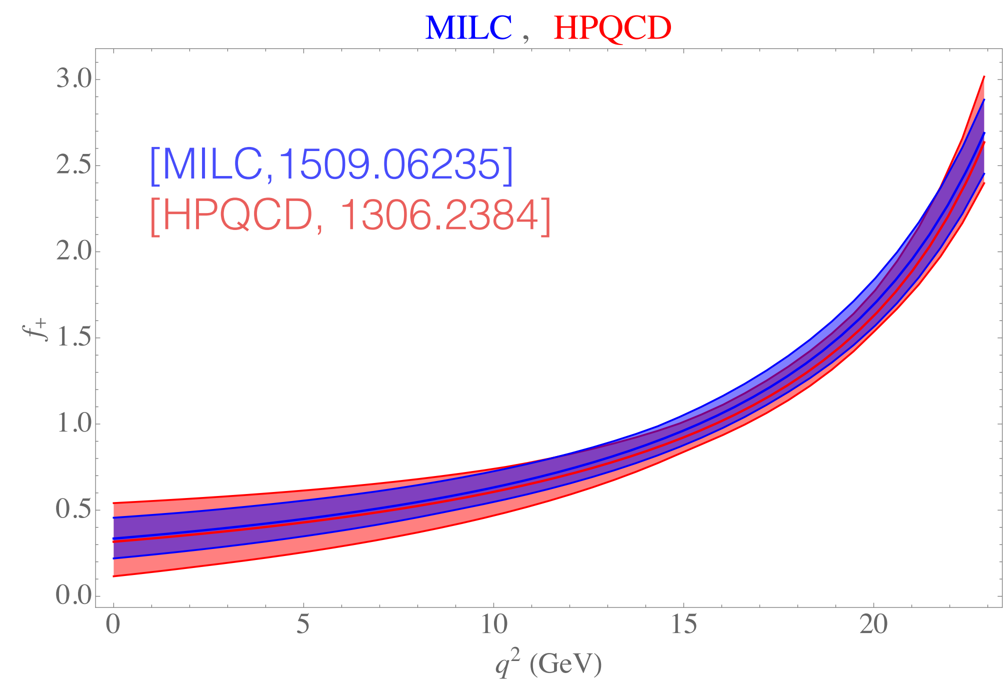
[1] Bauer, Neubert, 1511.01900
Becirevic, NK, Sumensari,Zukanovich, 1608.07583
[2] Becirevic,Sumensari, 1704.05835

Vectors: 1) if gauge bosons must be at the GUT scale
2) if non-gauge vectors -> UV incomplete theory

~R_2 to explain R_K

Not addressing the global fit, only LFU!





$$\frac{d^2\Gamma_\ell(q^2,\cos\theta)}{dq^2 d\cos\theta} = a_\ell(q^2) + b_\ell(q^2)\cos\theta + c_\ell(q^2)\cos^2\theta$$

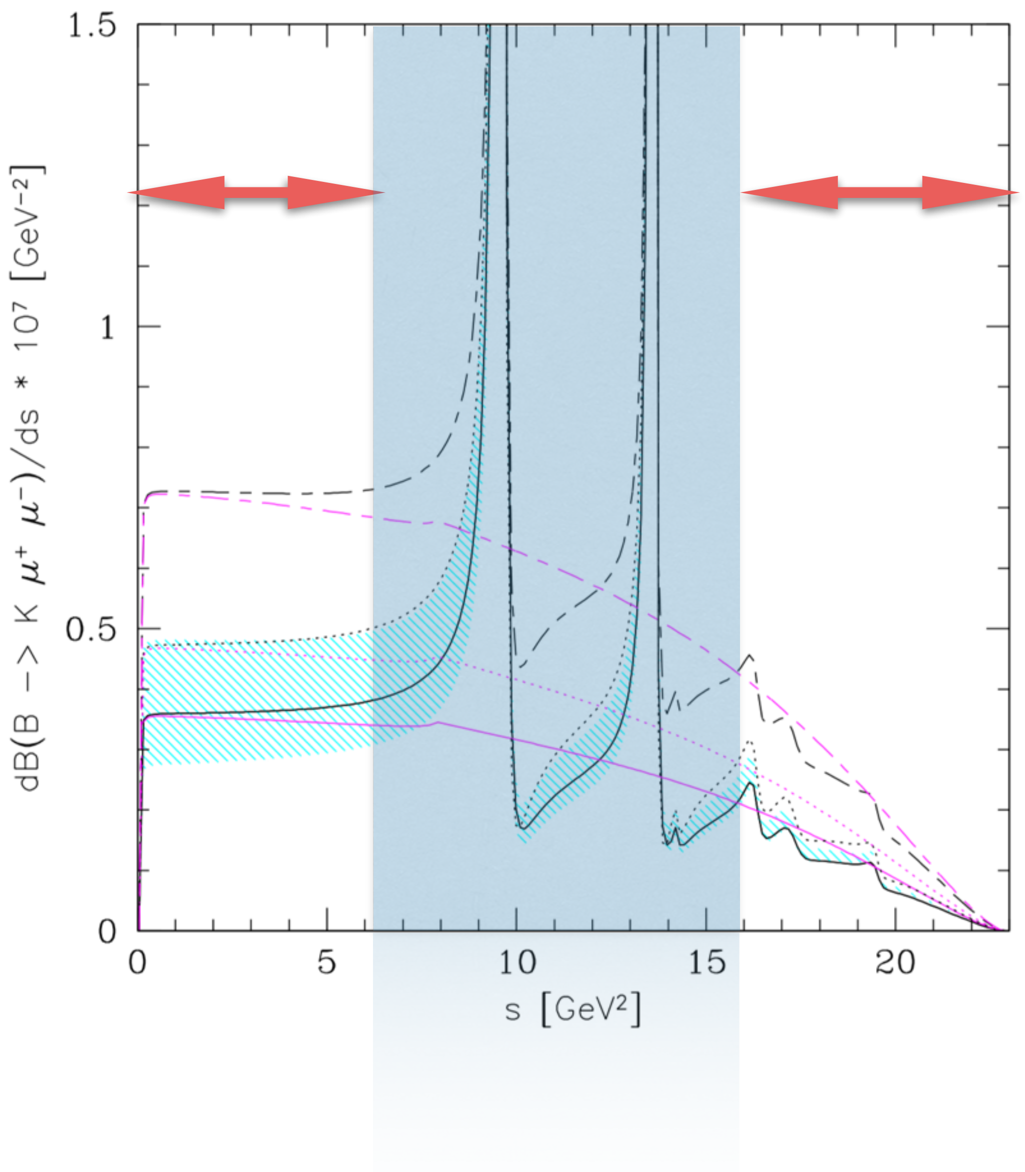
$$\frac{1}{\Gamma^\ell}\frac{d\Gamma^\ell}{d\cos\theta_\ell} = \frac{3}{4}(1-F_H^\ell)(1-\cos^2\theta_\ell) + \frac{F_H^\ell}{2} + A_{\rm FB}^\ell \cos\theta_\ell$$

} $B \to K\mu^+\mu^-$

$$\mathcal{B}(B^+ \to K^+\mu^+\mu^-)|_{q^2\in[15,22]\mathrm{GeV}^2} = (8.5 \pm 0.3 \pm 0.4) \times 10^{-8}$$ [LHCb,1403.8044]

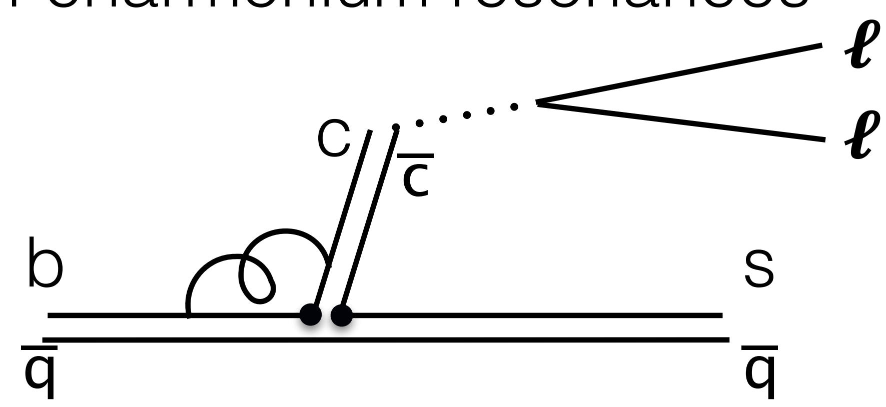
$$\mathcal{B}(B_s \to \mu^+\mu^-)^{\rm exp} = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$$ [LHCb+CMS,1411.4413]

B → K μμ at low recoil

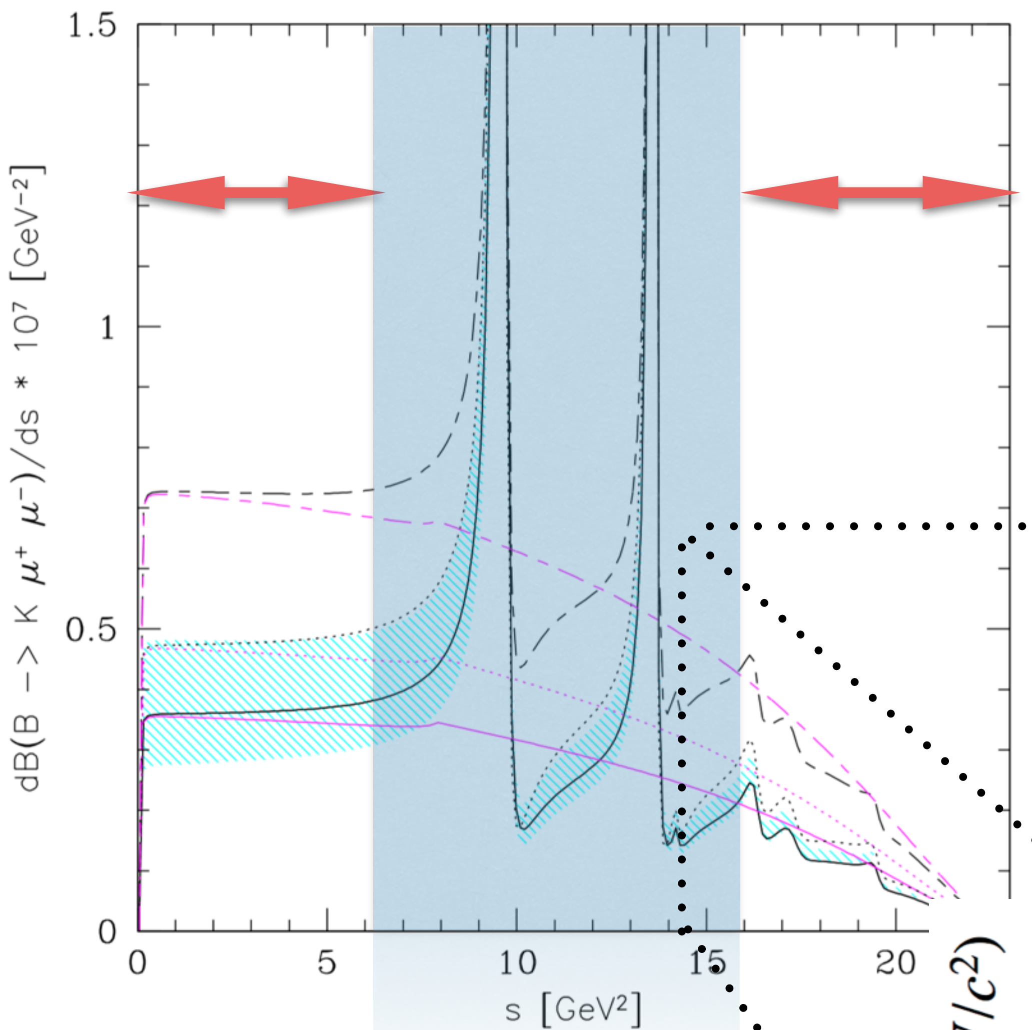


[Ali et al,hep-ph/9910221]

Factorizable and non-factorizable contributions of charmonium resonances

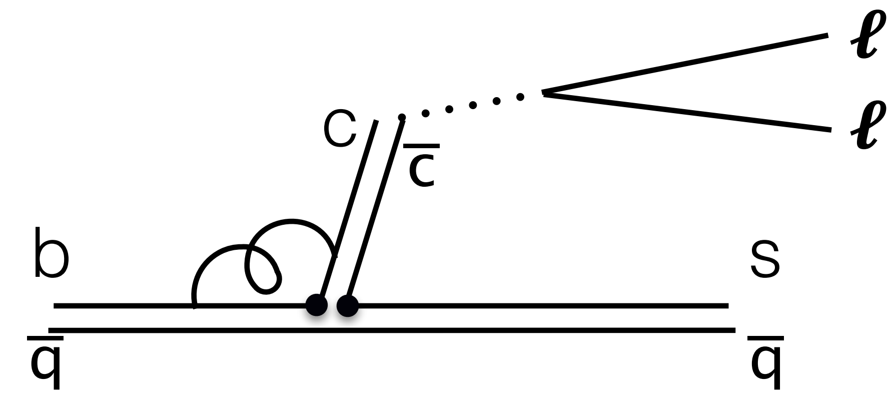


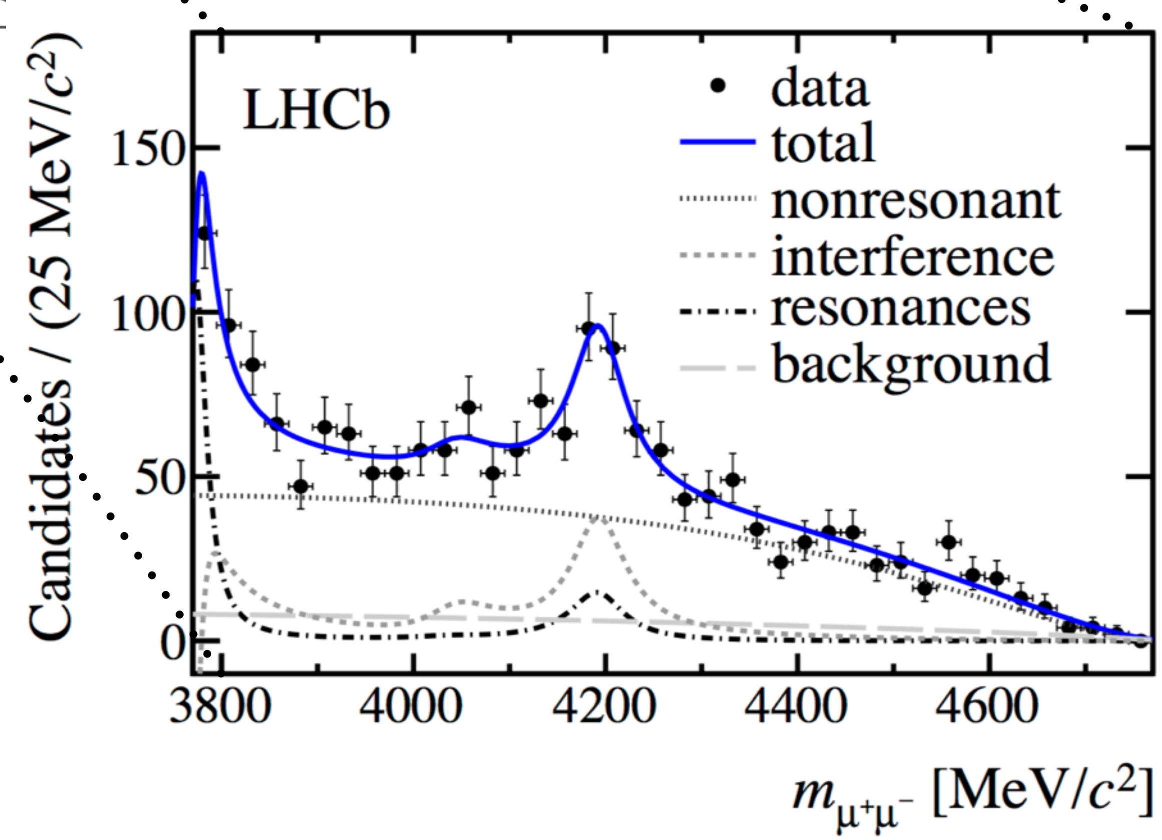
B → K μμ at low recoil



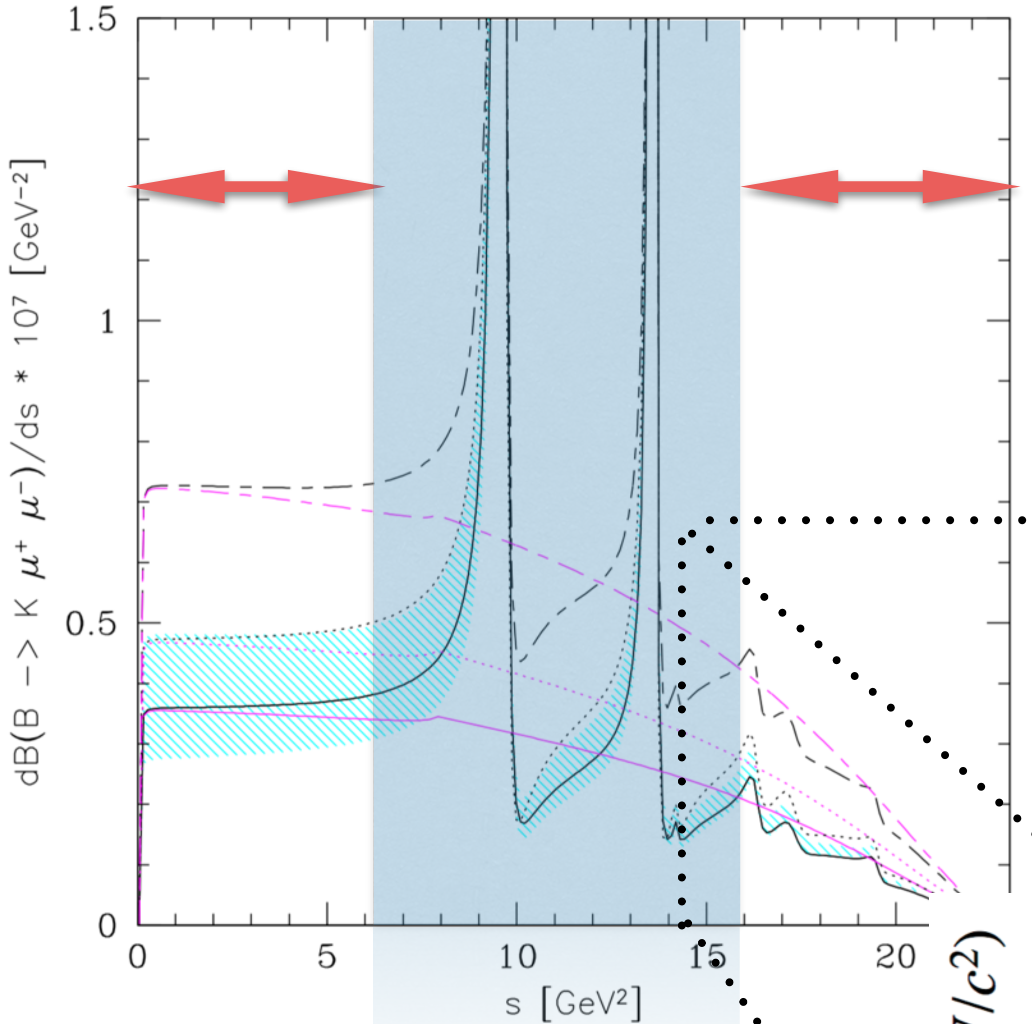
[Ali et al,hep-ph/9910221]

Factorizable and non-factorizable contributions of charmonium resonances



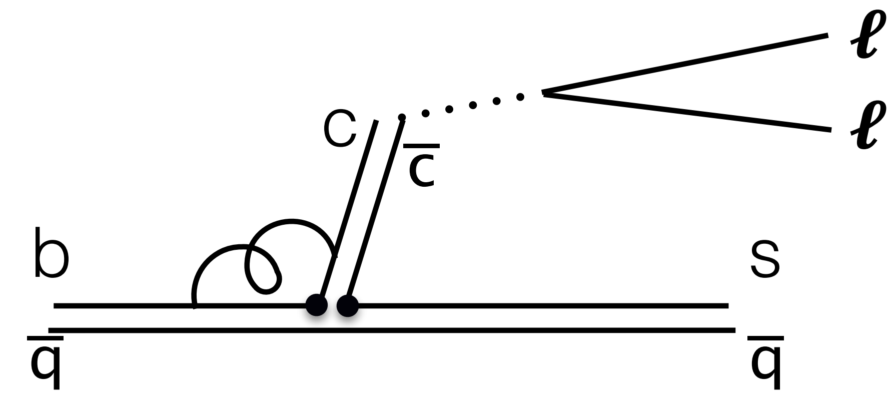


B → K μμ at low recoil



[Ali et al,hep-ph/9910221]

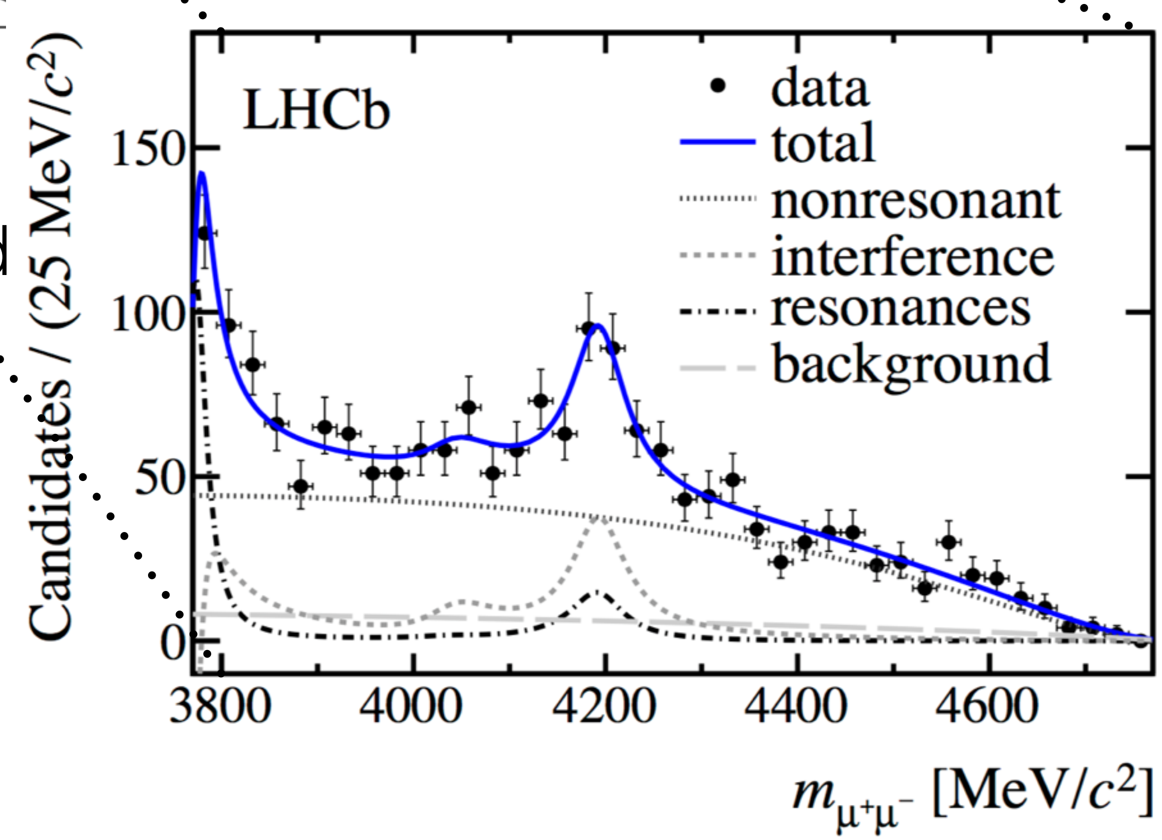
Factorizable and non-factorizable contributions of charmonium resonances



Quark-hadron duality expected to work reasonably in large enough bins (~3 % accuracy)

See e.g. [Brass, Hiller, Nisandzic '16]

[Beylich, Buchalla, Feldmann]



~R$_2$, also known as $\Delta^{(1/6)}(3,2,1/6)$

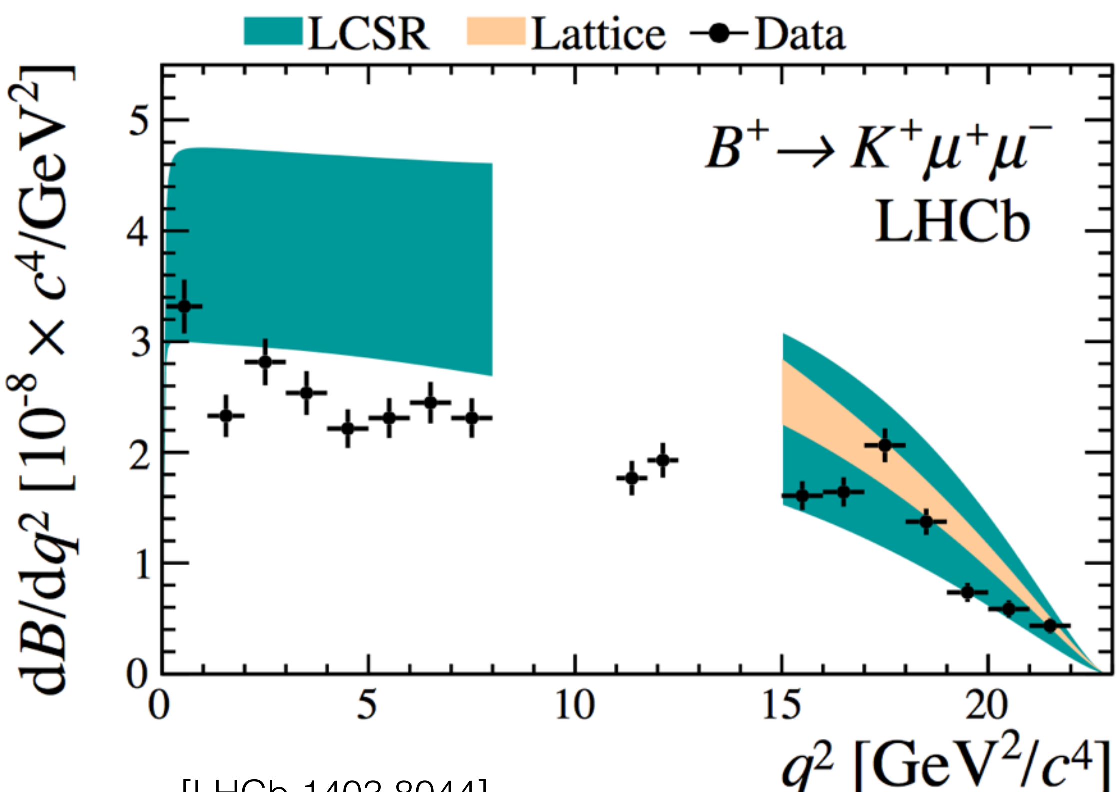
$$\mathcal{L}_{\Delta^{(1/6)}} = (g_L)_{ij}\bar{d}_{Ri}\widetilde{\mathbf{\Delta}}^{(1/6)\dagger}L_j$$
$$= (g_L)_{ij}\bar{d}_i P_L \nu_j\,\Delta^{(-1/3)} - (g_L)_{ij}\bar{d}_i P_L \ell_j\,\Delta^{(2/3)}$$

$V_{PMNS} = 1$

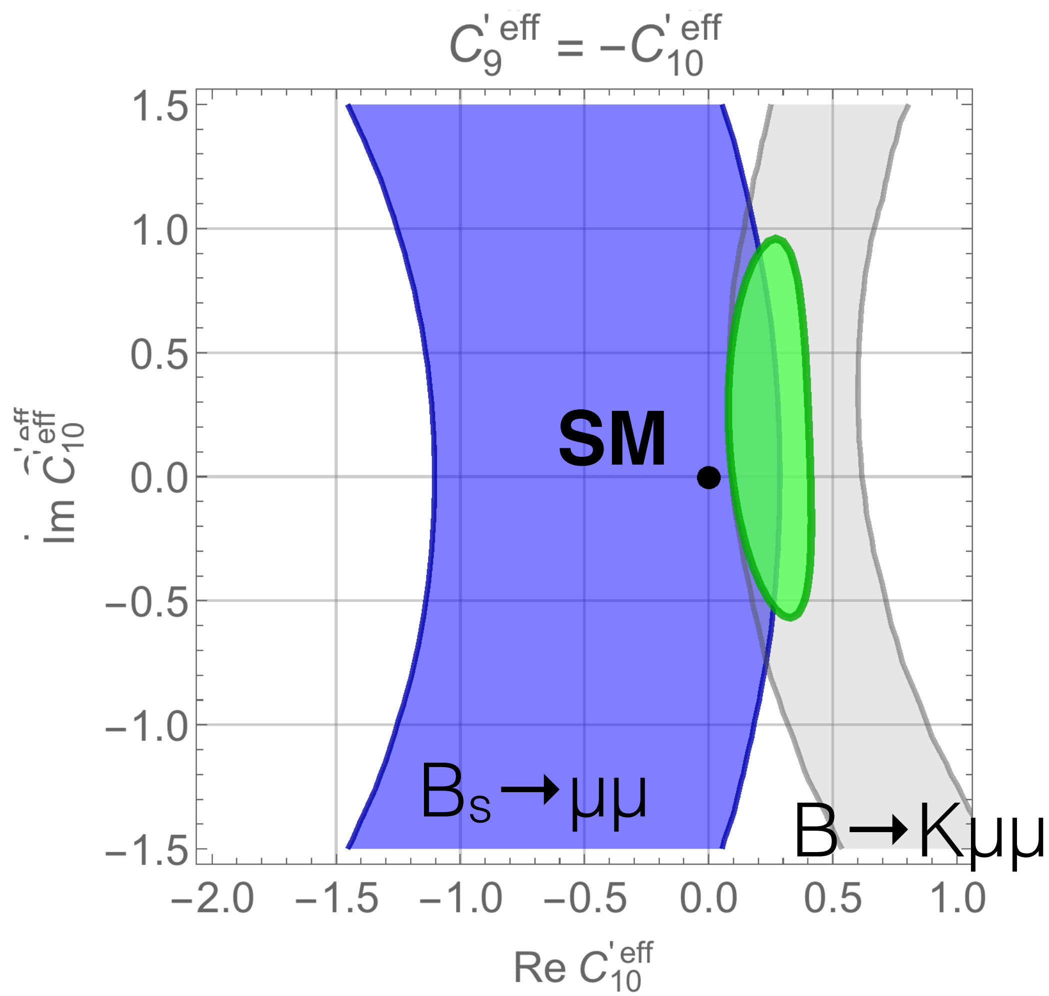
$$\left(C_9^{\ell_1\ell_2}\right)' = -\left(C_{10}^{\ell_1\ell_2}\right)' = -\frac{\pi v^2}{2V_{tb}V_{ts}^*\alpha_{\rm em}}\frac{(g_L)_{s\ell_1}(g_L)_{b\ell_2}^*}{m_\Delta^2},$$

$$g_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & (g_L)_{s\mu} & (g_L)_{s\tau} \\ 0 & (g_L)_{b\mu} & (g_L)_{b\tau} \end{pmatrix}$$

LQ features - $\Delta^{(1/6)}(3, 2, 1/6)$



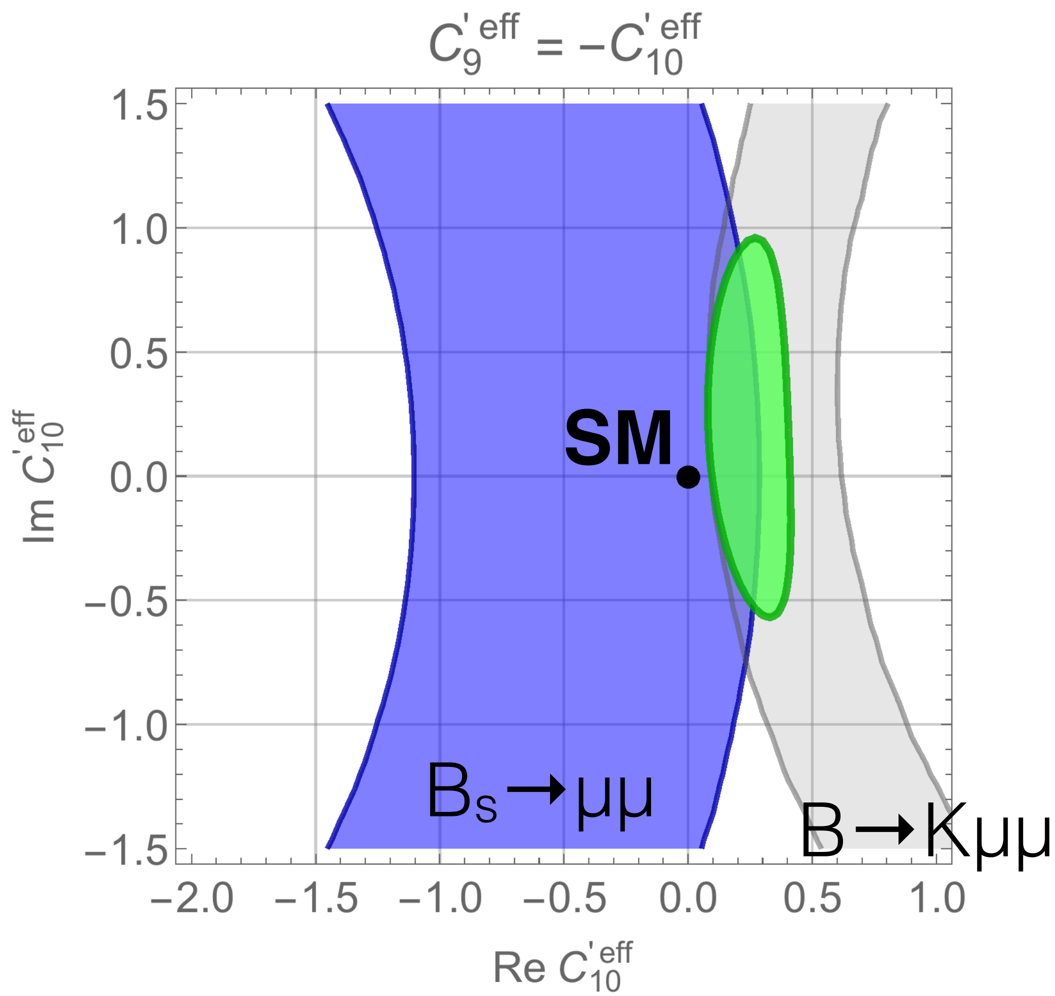
[LHCb,1403.8044]

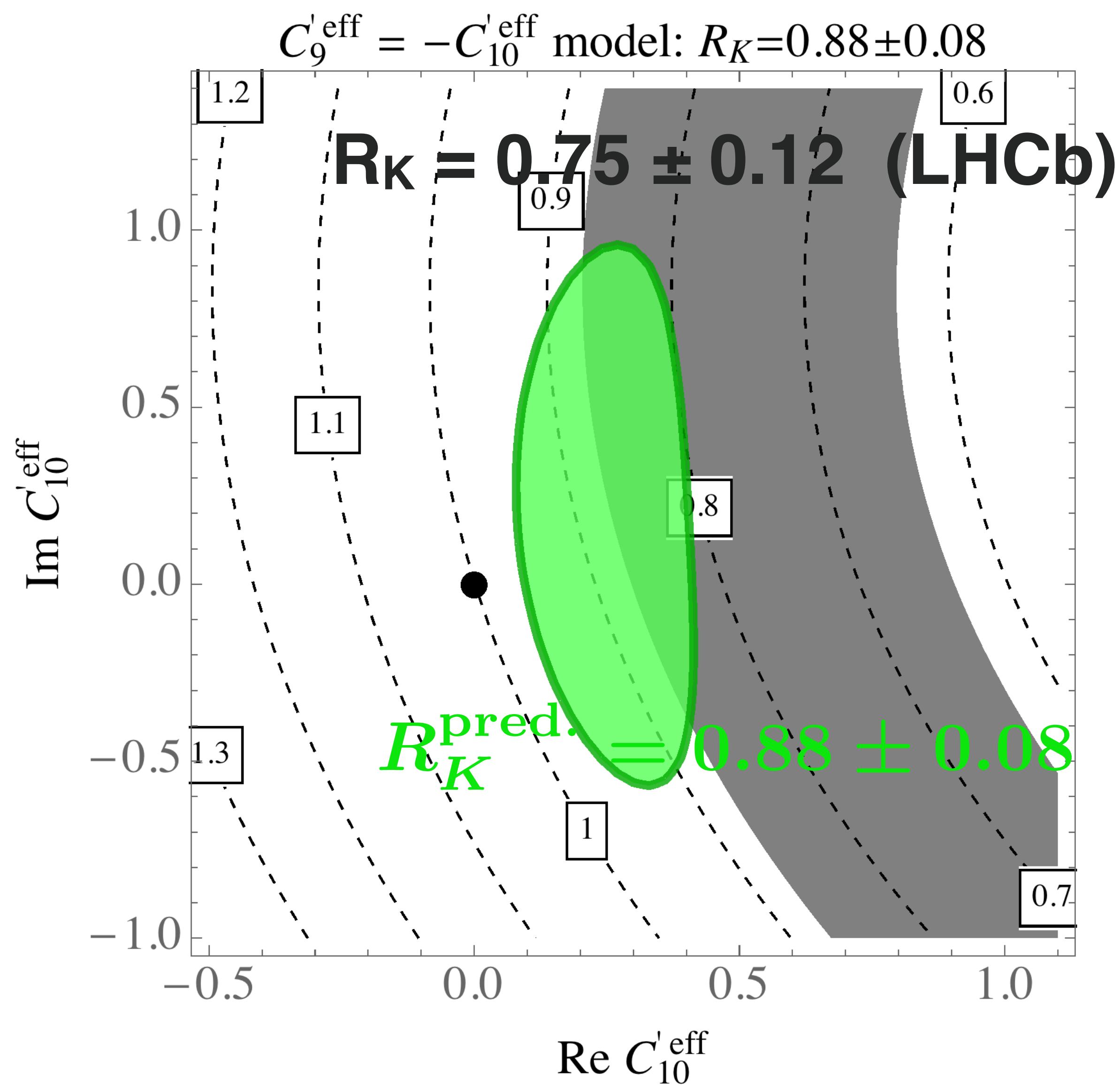


[LHCb+CMS,1411.4413]

Fit: $(C_9^{\mu\mu})' \in (-0.48, -0.08)$

$\Delta^{(1/6)}(3,2,1/6)$, verdict on LFU





Further signatures:

$R_{K^*} = 1.11(8)$

$$R_{\rm fb} = \frac{A^{\mu}_{{\rm fb}[4,6]}}{A^{e}_{{\rm fb}[4,6]}} = 0.84(12)$$

[Becirevic, Fajfer, NK, ‘15]

SU(5) GUT with light scalar LQs

$S_3(3,3,-1/3)$
F=2

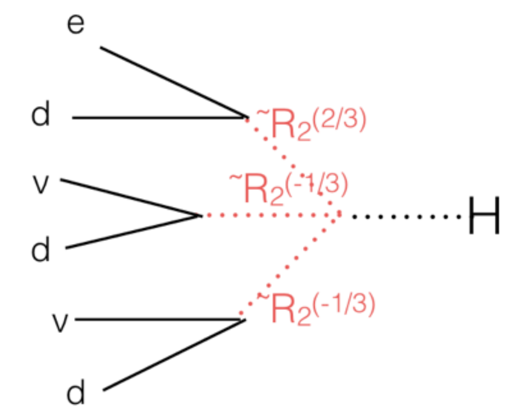
$\tilde{R}_2(3,2,1/6)$
F=0

$$\mathcal{L} = y_{ij}\bar{Q}_i^C i\tau_2 \boldsymbol{\tau}\cdot \boldsymbol{S}_3 L_j + z_{ij}\bar{Q}_i^C i\tau_2(\boldsymbol{\tau}\cdot \boldsymbol{S}_3)^\dagger Q_j$$

$$\tilde{\mathcal{L}} = -\tilde{y}_{ij}\, \bar{d}_{Ri}\tilde{R}_2\, i\tau_2 L_j$$

Put both masses close to the 1 TeV scale.

In such bottom-up approach proton would decay if $z_{ij}y_{kl}$ is not very close to 0. Also $\tilde{R}_2$ can destabilize the proton via $\tilde{R}_2\tilde{R}_2\tilde{R}_2 H$



Starting from GUT with special scalar representations:

5 = (1,2,1/2) ⊕ (3,1,-1/3) "doublet-triplet"
15 = (1,3,1) ⊕ **(3,2,1/6)** ⊕ (6,1,-2/3)
24 = (8,1,0) ⊕(1,3,0) ⊕(3,2,-5/6) ⊕($\overline{3}$,2,5/6) ⊕(1,1,0)
45 = (8,2,1/2) ⊕ (6*,1,-1/3) ⊕ **(3,3,-1/3)** ⊕ (3*,2,-7/6)⊕(3,1,-1/3) ⊕(3*,1,4/3)

SU(5) GUT with light scalar LQs

- Require S_3 and $\tilde{R}_2$ to be light, and impose unification of couplings at 1-loop

$$\frac{B_{23}}{B_{12}} = \frac{5}{8}\frac{\sin^2\theta_W - \alpha/\alpha_S}{3/8 - \sin^2\theta_W} = 0.721 \pm 0.004$$

$$B_{ij} = \sum_J (b_i^J - b_j^J) r_J$$

$$r_J = \frac{\log(m_{\rm GUT}/m_J)}{\log(m_{\rm GUT}/m_Z)}$$

$$\left.\frac{B_{23}}{B_{12}}\right|_{SM} = 0.53$$

- Both fields have positive $\mathbf{b^J_2 - b^J_3}$ and negative $\mathbf{b^J_1 - b^J_2}$, they tend to aid unification

- Furthermore, the GUT scale is raised

$$\ln\frac{m_{\rm GUT}}{m_Z} = \frac{16\pi}{5\alpha}\frac{3/8 - \sin^2\theta_W}{B_{12}} = \frac{184.8 \pm 0.1}{B_{12}}$$

- Yukawas of S_3 do not contain diquark couplings, due to GUT symmetry. Baryon number is conserved

$$y_{ij}^{45}\mathbf{10}_i\overline{\mathbf{5}}_j\overline{\mathbf{45}} \;\longrightarrow\; \mathcal{L} = y_{ij}\bar{Q}_i^C i\tau_2 \boldsymbol{\tau}\cdot\boldsymbol{S}_3 L_j + z_{ij}\bar{Q}_i^C i\tau_2(\boldsymbol{\tau}\cdot\boldsymbol{S}_3)^\dagger Q_j$$

$$y_{ij}^{15}\overline{\mathbf{5}}_i\overline{\mathbf{5}}_j\mathbf{15} \;\longrightarrow\; \tilde{\mathcal{L}} = -\tilde{y}_{ij}\,\bar{d}_{Ri}\tilde{R}_2\, i\tau_2 L_j$$

SU(5) GUT LQs: b→sμμ

$$\mathcal{L} = y_{ij}\bar{Q}_i^C i\tau_2 \boldsymbol{\tau}\cdot \boldsymbol{S}_3 L_j$$

$$\tilde{\mathcal{L}} = -\tilde{y}_{ij}\,\bar{d}_{Ri}\tilde{R}_2\, i\tau_2 L_j$$

- Mass basis of fermions, charge eigenstates of LQs

$$\mathcal{L} = -\,y_{ij}\bar{d}_L^{C\,i}\nu_L^j S_3^{1/3} - \sqrt{2}y_{ij}\bar{d}_L^{C\,i}e_L^j S_3^{4/3} + \\ +\sqrt{2}(V^* y)_{ij}\bar{u}_L^{C\,i}\nu_L^j S_3^{-2/3} - (V^* y)_{ij}\bar{u}_L^{C\,i}e_L^j S_3^{1/3}$$

$$\tilde{\mathcal{L}} = -\,\tilde{y}_{ij}\bar{d}_R^i e_L^j \tilde{R}_2^{2/3} + \tilde{y}_{ij}\bar{d}_R^i \nu_L^j \tilde{R}_2^{-1/3}$$

$$C_9 = -C_{10} = \frac{\pi}{V_{tb}V_{ts}^*\alpha}\, y_{b\mu}y_{s\mu}^* \frac{v^2}{m_{S_3}^2} \in [-0.81, -0.50]$$

$$y_{b\mu}y_{s\mu}^* \in [0.7, 1.3]\times 10^{-3}\ (m_{S_3}/\mathrm{TeV})^2$$

$$C_9' = -C_{10}'$$

Unwanted contribution from the global fit point of view.

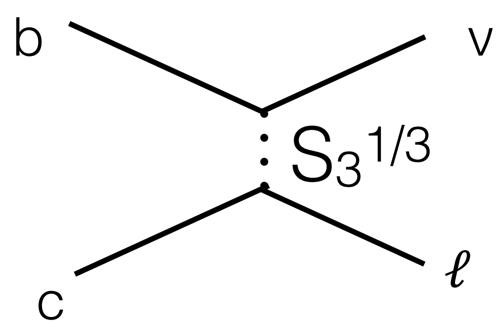
$$y = \begin{pmatrix} * & * & * \\ * & y_{s\mu} & * \\ * & y_{b\mu} & * \end{pmatrix}$$

$$\tilde{y} = \begin{pmatrix} * & * & * \\ * & * & * \\ * & * & * \end{pmatrix}$$

SU(5) GUT LQs: R_{D^*}

- Effective semileptonic Lagrangian - lepton non-universal rescaling of V_{CKM}

$$\mathcal{L}_{\bar{c}b\bar{\ell}\nu_k} = -\frac{4G_F}{\sqrt{2}}\left[(V_{cb}\delta_{\ell k} + g^L_{cb;\ell k})(\bar{c}_L\gamma^\mu b_L)(\bar{\ell}_L\gamma_\mu\nu^k_L)\right].$$



$$g^L_{cb;\ell\ell} = -\frac{v^2}{4m^2_{S_3}}(Vy^*)_{c\ell}\,y_{b\ell}$$

$$\tilde{\mathcal{L}} = -\tilde{y}_{ij}\bar{d}^i_R e^j_L \tilde{R}_2^{2/3} + \tilde{y}_{ij}\bar{d}^i_R\nu^j_L\tilde{R}_2^{-1/3}$$

No contribution at tree-level!
Possible with addition of RH-neutrino.

[Becirevic, Fajfer, NK, Sumensari]

$$\mathrm{Re}\left[V_{cb}\left(|y_{b\tau}|^2 - |y_{b\mu}|^2\right) + V_{cs}\left(y_{b\tau}y^*_{s\tau} - y_{b\mu}y^*_{s\mu}\right)\right] = -2C_{V_L}\,(m_{S_3}/\mathrm{TeV})^2\,, \qquad C_{V_L} = 0.18 \pm 0.04\,.$$

$$y_{b\tau}y^*_{s\tau} \approx -0.4(m_{S_3}/\mathrm{TeV})^2$$

$$y = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_{s\mu} & y_{s\tau} \\ 0 & y_{b\mu} & y_{b\tau} \end{pmatrix} \qquad \tilde{y} = \begin{pmatrix} * & * & * \\ * & * & * \\ * & * & * \end{pmatrix}$$

y matrix texture avoids first generation couplings of d-quarks and charged leptons

Semileptonic constraints

- B→ντ is then modified towards the measured value by ~30-40 %

$$\mathrm{Br}(B \to \tau\nu)^{\mathrm{SM}} = (7.8 \pm 0.7) \times 10^{-5}$$
$$\mathrm{Br}(B \to \tau\nu)^{\mathrm{exp}} = (10.9 \pm 2.4) \times 10^{-5}$$

$$|V_{ub}|^2 \to |V_{ub}|^2 \left(1 - \frac{v^2}{2m_{S_3}^2} \mathrm{Re}[(V_{us}/V_{ub}) y_{s\tau}^* y_{b\tau}]\right)$$

- Lepton universality in e/μ in B → D decays

$$R_{D^*}^{e/\mu} = 1.04(5)(1) \qquad R_D^{\mu/e} = 0.995(22)(39)$$

[Belle, 1510.03657, 1702.01521]

$$-\frac{v^2}{2m_{S_3}^2} \mathrm{Re}\left[\left(\frac{V_{cs}}{V_{cb}} y_{s\mu}^* + y_{b\mu}^*\right) y_{b\mu}\right] = R_{D^{(*)}}^{\mu/e} - 1 = -0.023 \pm 0.043$$

- Universality of Kaon semileptonic processes

$$R_{e/\mu}^K = \frac{\Gamma(K^- \to e^-\bar\nu)}{\Gamma(K^- \to \mu^-\bar\nu)}, \qquad R_{\tau/\mu}^K = \frac{\Gamma(\tau^- \to K^-\nu)}{\Gamma(K^- \to \mu^-\bar\nu)}$$

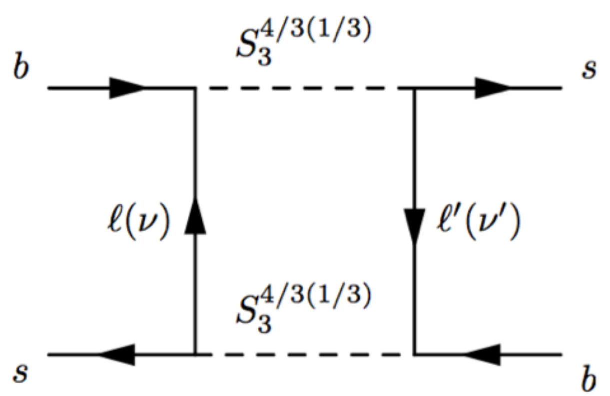
$$R_{\mathrm{e}/\mu}^{K(\mathrm{exp})} = (2.488 \pm 0.010) \times 10^{-5}, \qquad R_{\mathrm{e}/\mu}^{K(\mathrm{SM})} = (2.477 \pm 0.001) \times 10^{-5}$$

$$R_{\tau/\mu}^{K(\mathrm{exp})} = (1.101 \pm 0.016) \times 10^{-2} \qquad R_{\tau/\mu}^{K(\mathrm{SM})} = \frac{\tau_\tau}{\tau_K} \frac{m_K^3 (m_\tau^2 - m_K^2)^2}{2m_\tau m_\mu^2 (m_K^2 - m_\mu^2)^2} = (1.1162 \pm 0.00026) \times 10^{-2},$$

$$R_{\mathrm{e}/\mu}^{K(\mathrm{exp})} / R_{\mathrm{e}/\mu}^{K(\mathrm{SM})} - 1 = \frac{v^2}{2m_{S_3}^2} \mathrm{Re}\left[|y_{s\mu}|^2 + (V_{ub}/V_{us}) y_{b\mu}^* y_{s\mu}\right] = (4.4 \pm 4.0) \times 10^{-3}$$

- Small effects in D decays!

Neutral currents (1)



$$\mathcal{H}_{\Delta m_s} = (C_1^{\rm SM} + C_1^{S_3})\,(\bar{s}_L\gamma^\nu b_L)^2$$

$$C_1^{S_3}(\Lambda) = \frac{3(yy^\dagger)^2_{bs}}{128\pi^2 m^2_{S_3}} \approx \frac{3(y_{b\tau}y^*_{s\tau})^2}{128 m^2_{S_3}}$$

Proportional to $R_{D^{(*)}}$ effect!

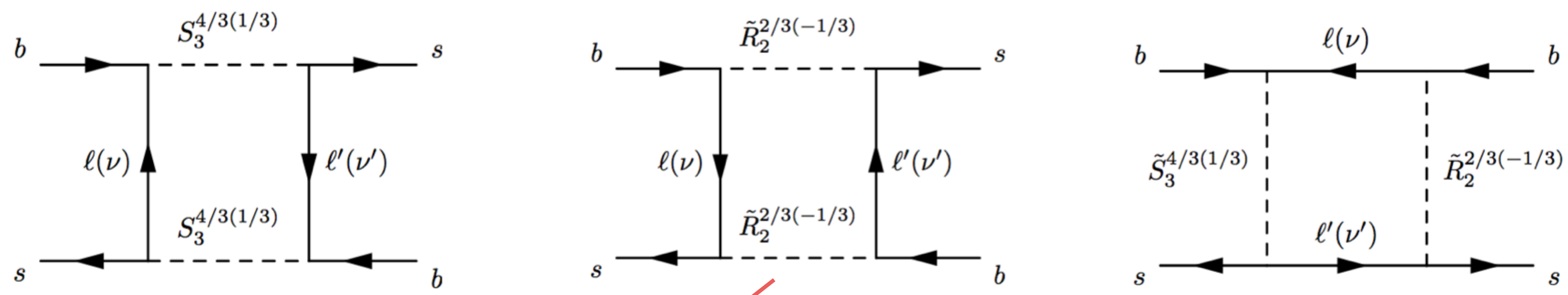
[Fermilab lattice, MILC, 1602.03560]

$$f^2_{B_s}\hat{B}^{(1)}_{B_s} = 0.0754(46)(15)\ {\rm GeV}^2$$

$$\Delta m_s^{\rm SM} = (19.6 \pm 1.6)\ {\rm ps}^{-1}$$

$$\Delta m_s^{\rm exp} = (17.757 \pm 0.021)\ {\rm ps}^{-1}$$

Neutral currents (1)



$$\tilde{y} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \tilde{y}_{s\tau} \\ 0 & 0 & \tilde{y}_{b\tau} \end{pmatrix}$$

$$\mathcal{H}_{\Delta m_s} = (C_1^{\rm SM} + C_1^{S_3})\,(\bar{s}_L \gamma^\nu b_L)^2 + \tilde{C}_1^{\tilde{R}_2}\,(\bar{s}_R \gamma^\nu b_R)^2 + C_4^{S_3\tilde{R}_2}\,(\bar{s}_R b_L)(\bar{s}_L b_R) + C_5^{S_3\tilde{R}_2}\,(\bar{s}_R^\alpha b_L^\beta)(\bar{s}_L^\beta b_R^\alpha)$$

$$C_1^{S_3}(\Lambda) = \frac{3(yy^\dagger)^2_{bs}}{128\pi^2 m^2_{S_3}} \approx \frac{3(y_{b\tau} y^*_{s\tau})^2}{128 m^2_{S_3}}$$

$$\tilde{C}_1^{\tilde{R}_2}(\Lambda) = \frac{(\tilde{y}\tilde{y}^\dagger)^2_{sb}}{64\pi^2 m^2_{R_2}},$$

$$C_4^{S_3\tilde{R}_2}(\Lambda) = 0,$$

$$C_5^{S_3\tilde{R}_2}(\Lambda) = \frac{(y\tilde{y}^\dagger)_{bb}(\tilde{y}y^\dagger)_{ss}}{16\pi^2}\,\frac{\log m^2_{S_3}/m^2_{R_2}}{m^2_{S_3} - m^2_{R_2}}$$

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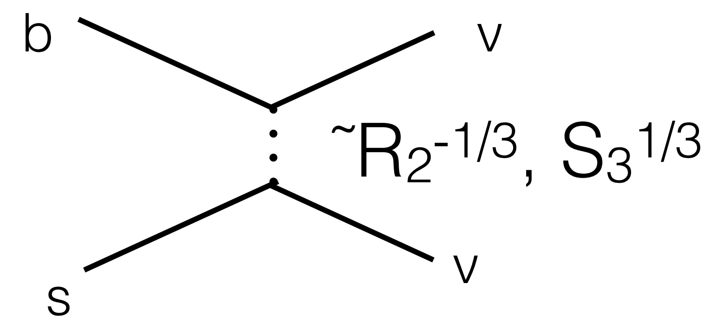
$$\Delta m_s^{\rm exp} = (17.757 \pm 0.021)\ \text{ps}^{-1}$$

Note: ˜R2 plays a role only in processes with d and (ℓ,ν)

Neutral currents and LFV (2)

- B→Kνν̄

$$\mathcal{L}_{\rm eff}^{b\to s\bar\nu\nu} = \frac{G_F\alpha}{\pi\sqrt{2}} V_{tb}V_{ts}^* \left(\bar s\gamma_\mu[C_L^{ij}P_L + C_R^{ij}P_R]b\right)\left(\bar\nu_i\gamma^\mu(1-\gamma_5)\nu_j\right)$$



$$C_L^{S_3,ij} = \frac{\pi v^2}{2\alpha V_{tb}V_{ts}^* m_{S_3}^2} y_{bj}y_{si}^* \qquad C_R^{\tilde R_2,ij} = -\frac{\pi v^2}{2\alpha V_{tb}V_{ts}^* m_{\tilde R_2}^2}\tilde y_{sj}\tilde y_{bi}^*$$

$$R_{\nu\nu} - 1 = \frac{\pi v^2}{3\alpha V_{tb}V_{ts}^* C_L^{\rm SM}}{\rm Re}\left[\frac{(yy^\dagger)_{bs}}{m_{S_3}^2} - \frac{(\tilde y\tilde y^\dagger)_{sb}}{m_{\tilde R_2}^2}\right] + \frac{(\pi v^2)^2}{12(\alpha V_{tb}V_{ts}^*|C_L^{\rm SM}|)^2}\left[\frac{(yy^\dagger)_{bb}(yy^\dagger)_{ss}}{m_{S_3}^4} + \frac{(\tilde y\tilde y^\dagger)_{bb}(\tilde y\tilde y^\dagger)_{ss}}{m_{\tilde R_2}^4} - \frac{2{\rm Re}[(y\tilde y^\dagger)_{bs}(\tilde y y^\dagger)_{bs}]}{m_{S_3}^2 m_{\tilde R_2}^2}\right].$$

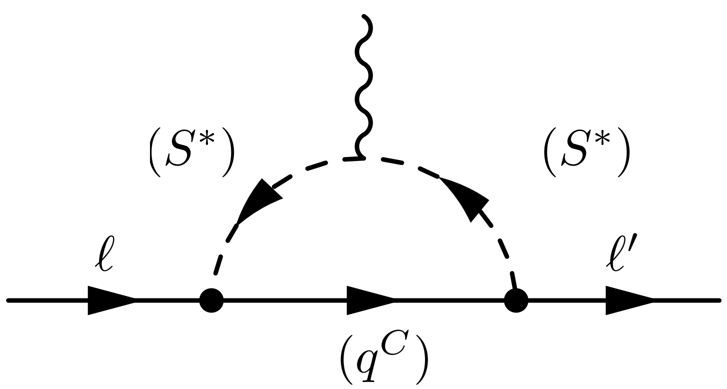
Sensitive to many distinct combinations, including $(yy^+)_{bs}$

[Belle, 1702.03224]

$$R_{\nu\nu} = \frac{{\rm Br}(B\to K\nu\bar\nu)}{{\rm Br}(B\to K\nu\bar\nu)^{\rm SM}} < 2.7 \qquad \text{from} \qquad \mathcal{B}(B\to K^*\nu\bar\nu) < 2.7\times 10^{-5}$$

- τ→μγ

$$\frac{e}{2}\sigma_L^{\tau\mu}\,\bar\mu(i\sigma^{\mu\nu}P_L)\tau\,F_{\mu\nu} \qquad \sigma_L^{\tau\mu} = \frac{3m_\tau}{64\pi^2 m_{S_3}^2}\left[5y_{s\mu}y_{s\tau}^* + y_{b\mu}y_{b\tau}^*\right]$$



Couplings and predictions

- $m_{S3} = m_{\tilde{R}2}$ = 1.5 TeV, fit the (real) couplings [preliminary, 1706.?????]

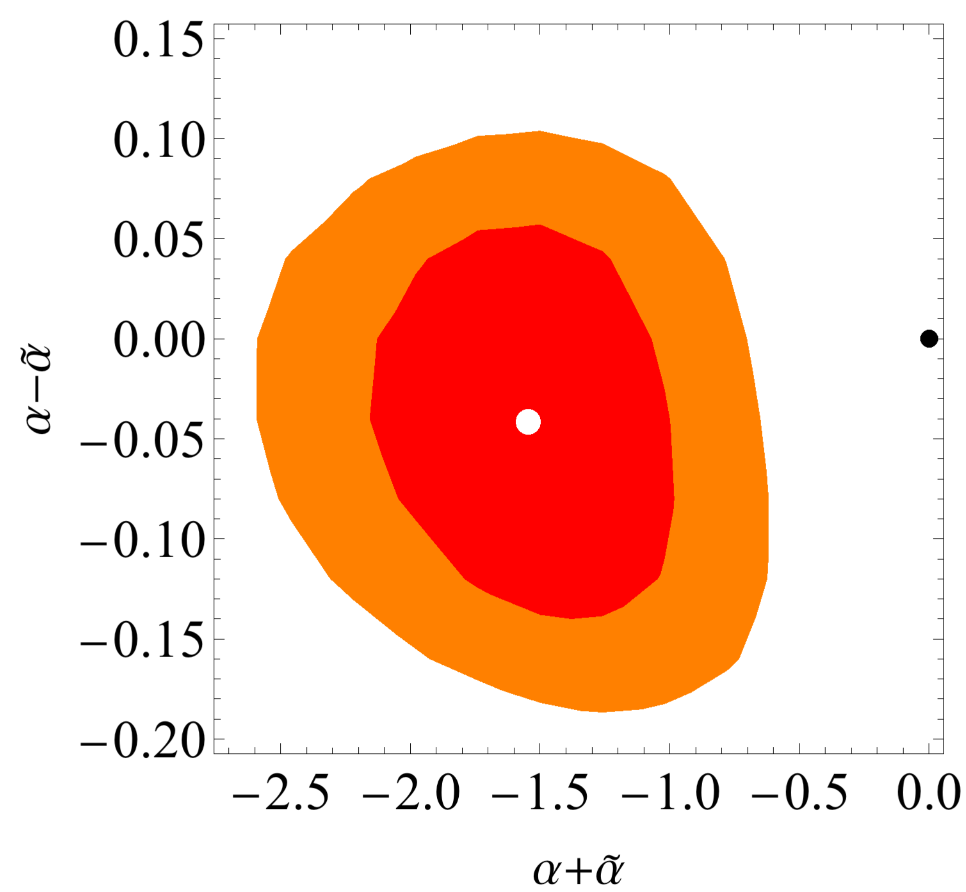
$$y = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_{s\mu} & y_{s\tau} \\ 0 & y_{b\mu} & y_{b\tau} \end{pmatrix}$$

$$\alpha = y_{s\tau} y_{b\tau} \qquad \tilde{\alpha} = \tilde{y}_{s\tau} \tilde{y}_{b\tau}$$

α and $\tilde{\alpha}$

play an important role in R_{D^*} and B_s mixing

$$y = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0.007 - 0.05 & 0.3 - 1.6 \\ 0 & 0.03 - 0.3 & 0.2 - 3 \end{pmatrix}$$



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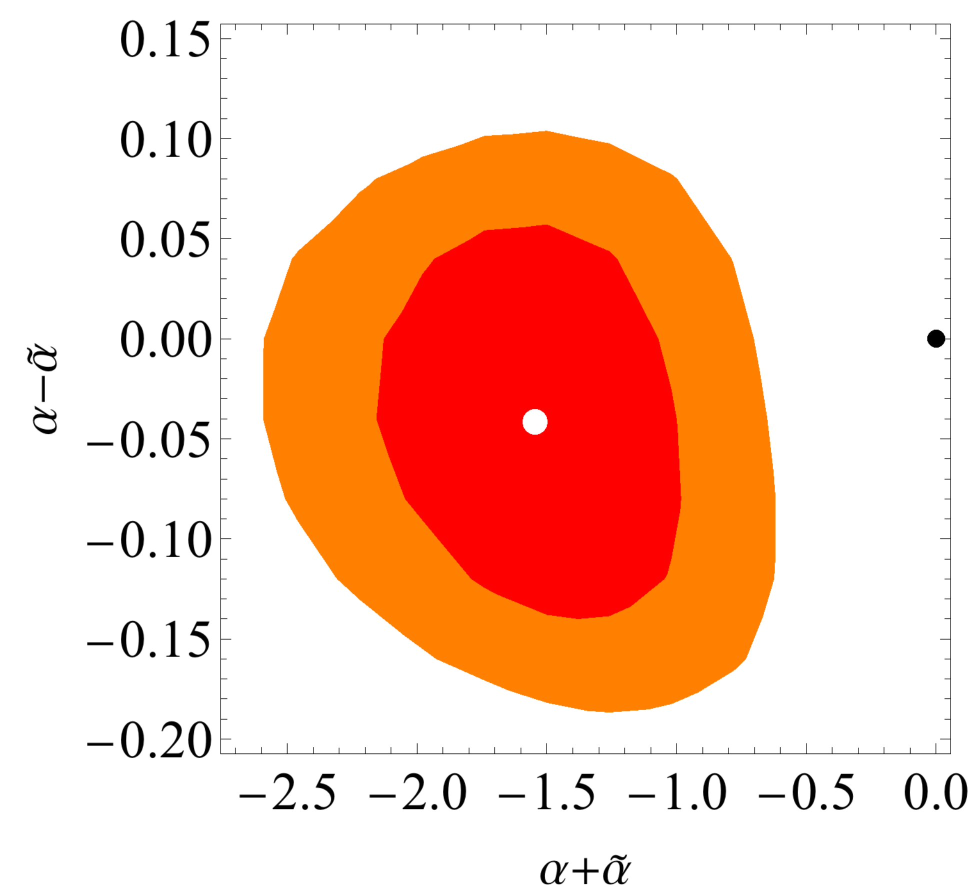
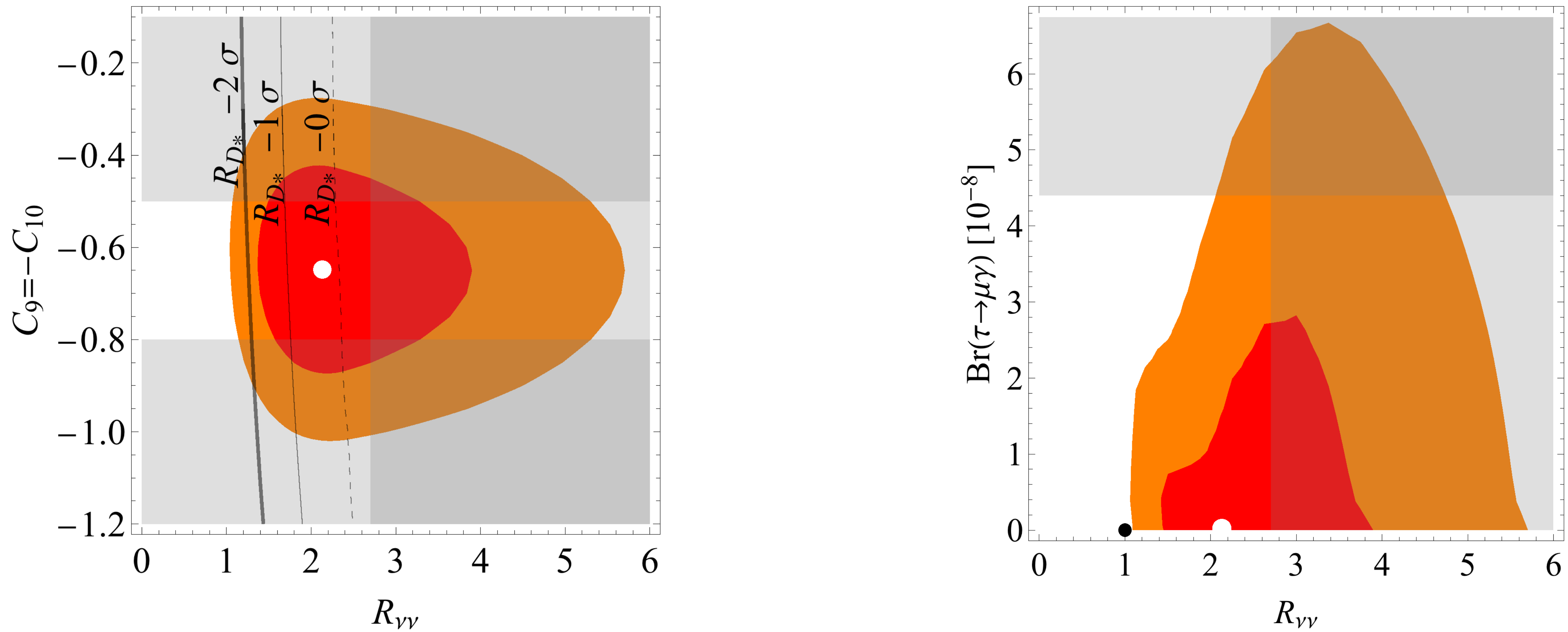


Couplings and predictions (2)

[preliminary, 1706.?????]



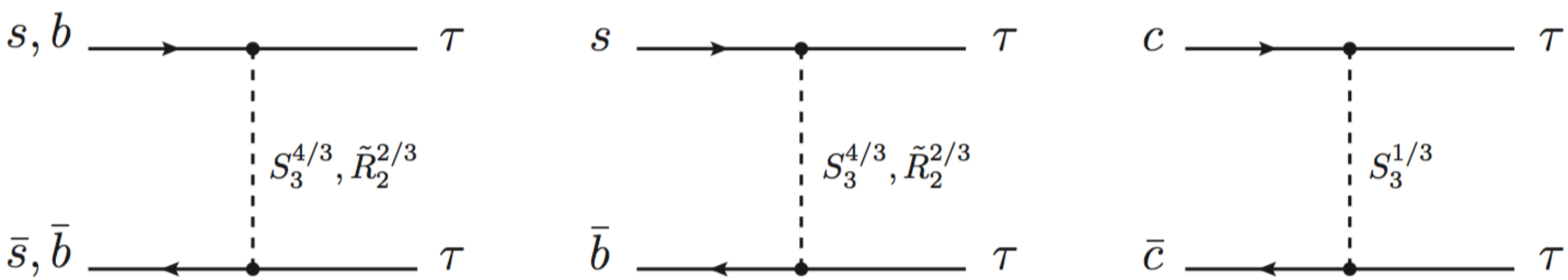
Competition between large contribution to R_{D^*} and constraint on $R_{\nu\nu}$

If $R_{\nu\nu}$ approaches 1, and R_{D^*} persists at its current large value, the model is excluded.

LHC constraints ($pp \to \tau\tau$)

$pp \to \tau^+\tau^-$ can probe parameter space of models explaining R_{D^*}

[Faroughy, Greljo, Kamenik 1609.07138]



In terms of LQ models, large couplings to b and τ are in tension with $pp \to \tau\tau$ resonance searches.

In the model with S3 and R2 couplings to b and τ are smaller, but we introduce coupling to s and τ

$$\sigma^{\text{fid}}_{pp\to\tau\tau}(y_{s\tau}, \tilde{y}_{s\tau}, \alpha, \tilde{\alpha}) \;=\; \sigma^{(1)}(y_{s\tau}^2, \tilde{y}_{s\tau}^2) \;+\; \sigma^{(2)}(\alpha, \tilde{\alpha}) \;+\; \sigma^{(3)}\left(\frac{\alpha^2}{y_{s\tau}^2}, \frac{\tilde{\alpha}^2}{\tilde{y}_{s\tau}^2}\right)$$

$m_{\tau\tau} > 300$ GeV

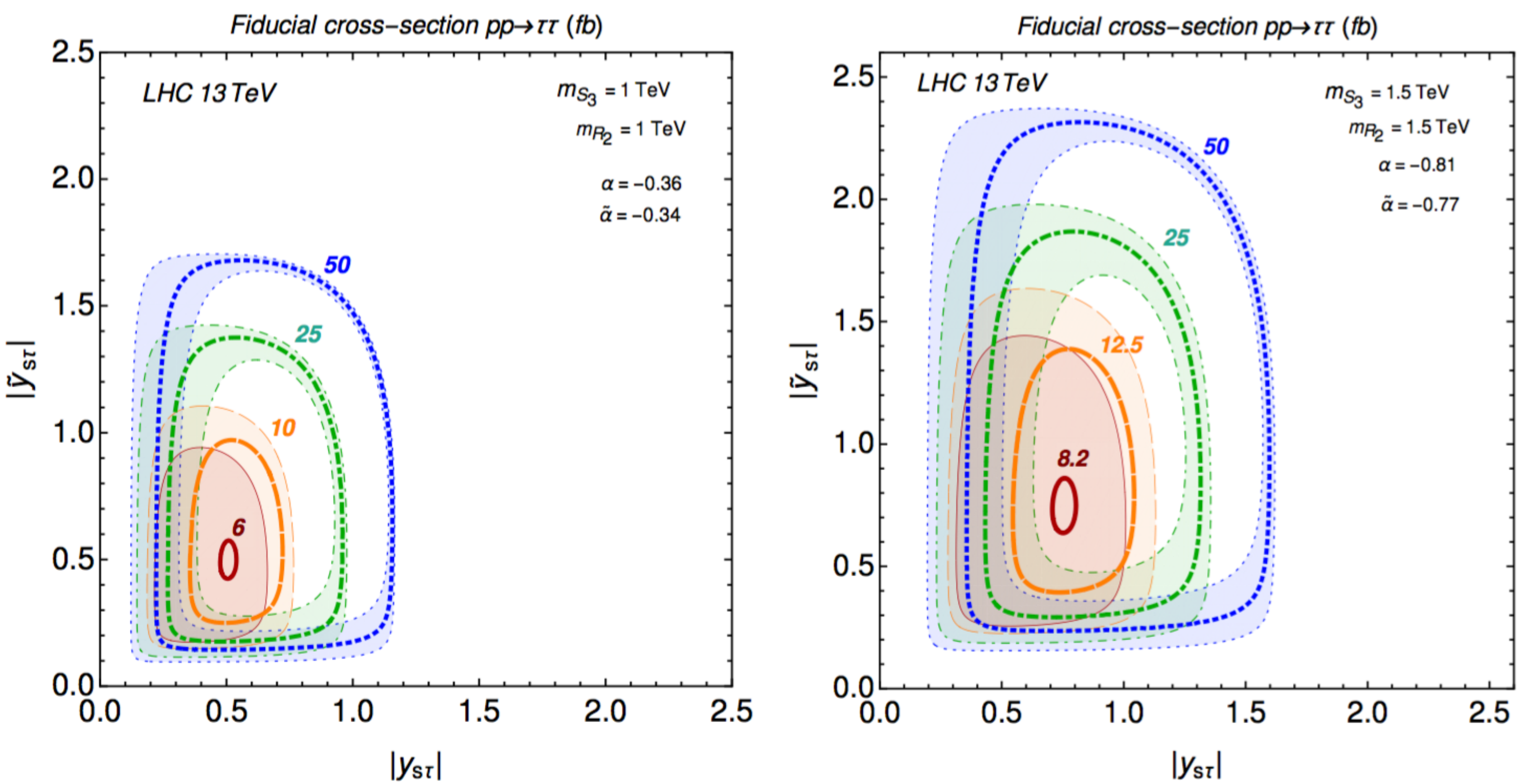
$p_T(\tau) > 150$ GeV (50 GeV)

pp→ττ

$$\sigma^{(1)}(y_{s\tau}^2, \tilde{y}_{s\tau}^2) = y_{s\tau}^4\, A_1^{(1)} + \tilde{y}_{s\tau}^4\, A_2^{(1)} + y_{s\tau}^2 \tilde{y}_{s\tau}^2\, A_3^{(1)}$$

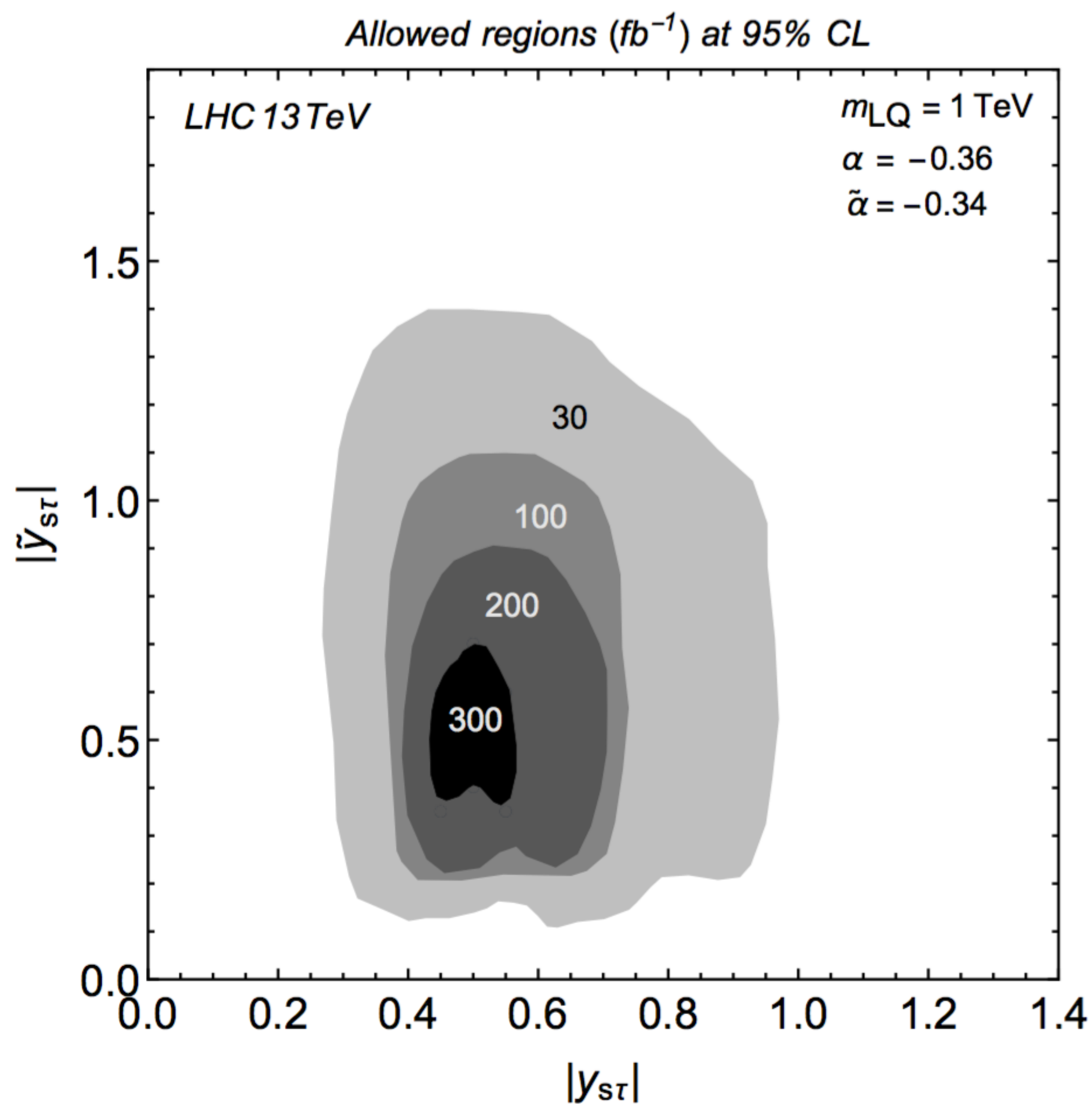
$$\sigma^{(2)}(\alpha, \tilde{\alpha}) = \alpha^2\, A_1^{(2)} + \tilde{\alpha}^2\, A_2^{(2)} + \alpha\tilde{\alpha}\, A_3^{(2)}$$

$$\sigma^{(3)}\left(\frac{\alpha^2}{y_{s\tau}^2}, \frac{\tilde{\alpha}^2}{\tilde{y}_{s\tau}^2}\right) = \frac{\alpha^4}{y_{s\tau}^4} A_1^{(3)} + \frac{\tilde{\alpha}^4}{\tilde{y}_{s\tau}^4} A_2^{(3)} + \frac{\alpha^2\tilde{\alpha}^2}{y_{s\tau}^2 \tilde{y}_{s\tau}^2} A_3^{(3)}$$



$pp \rightarrow \tau\tau$

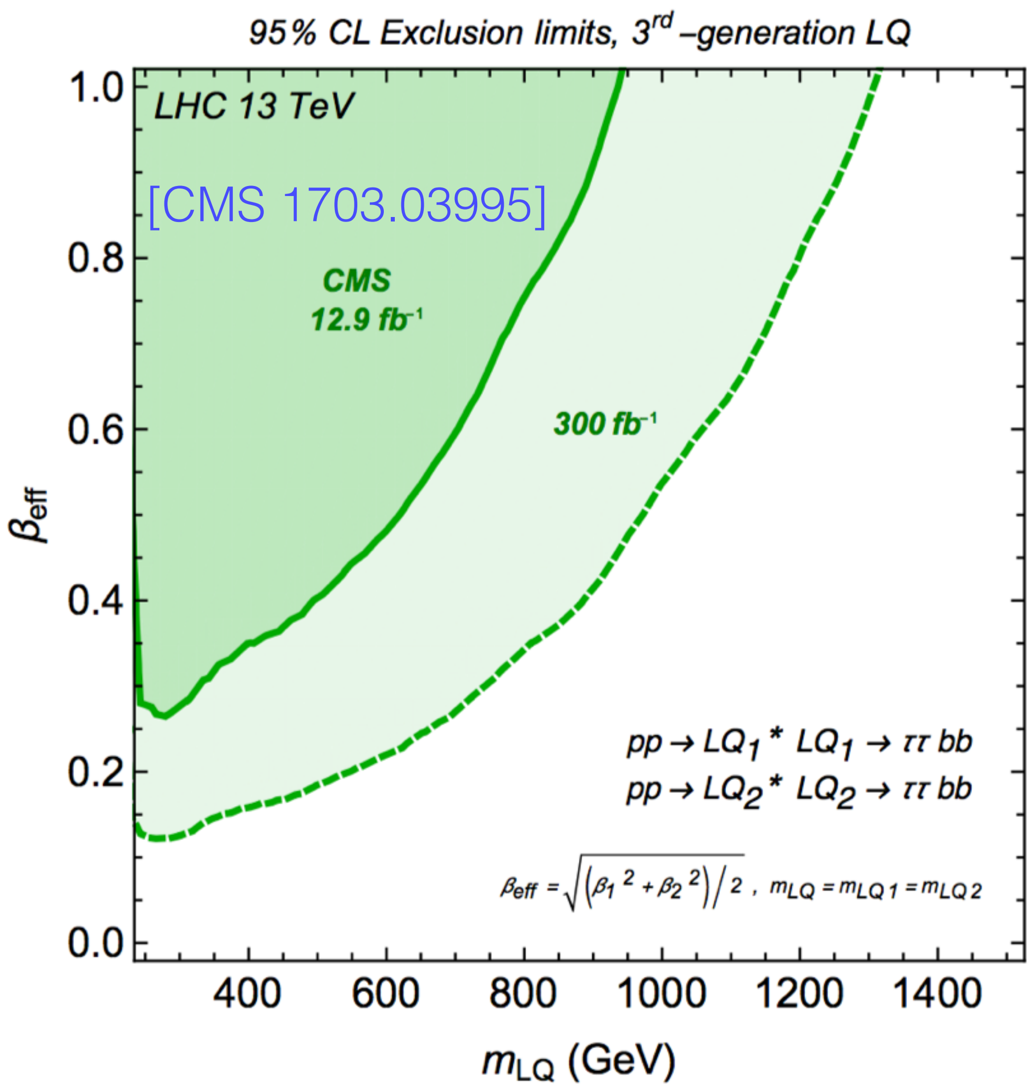
Recast of search for heavy resonances decaying to $\tau\,\tau$ [ATLAS '16]

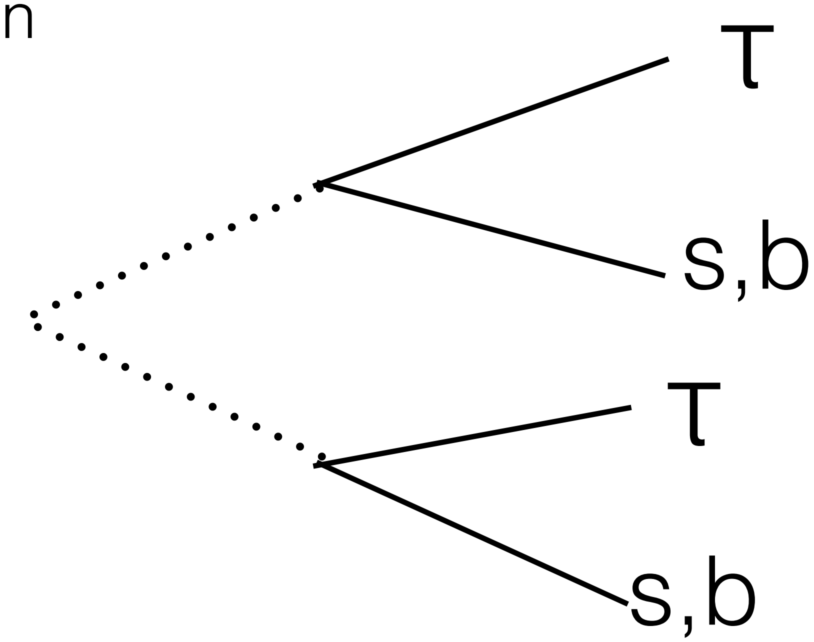


LHC Run-III can cover this scenario completely

pp→ LQ LQ* →ττjj

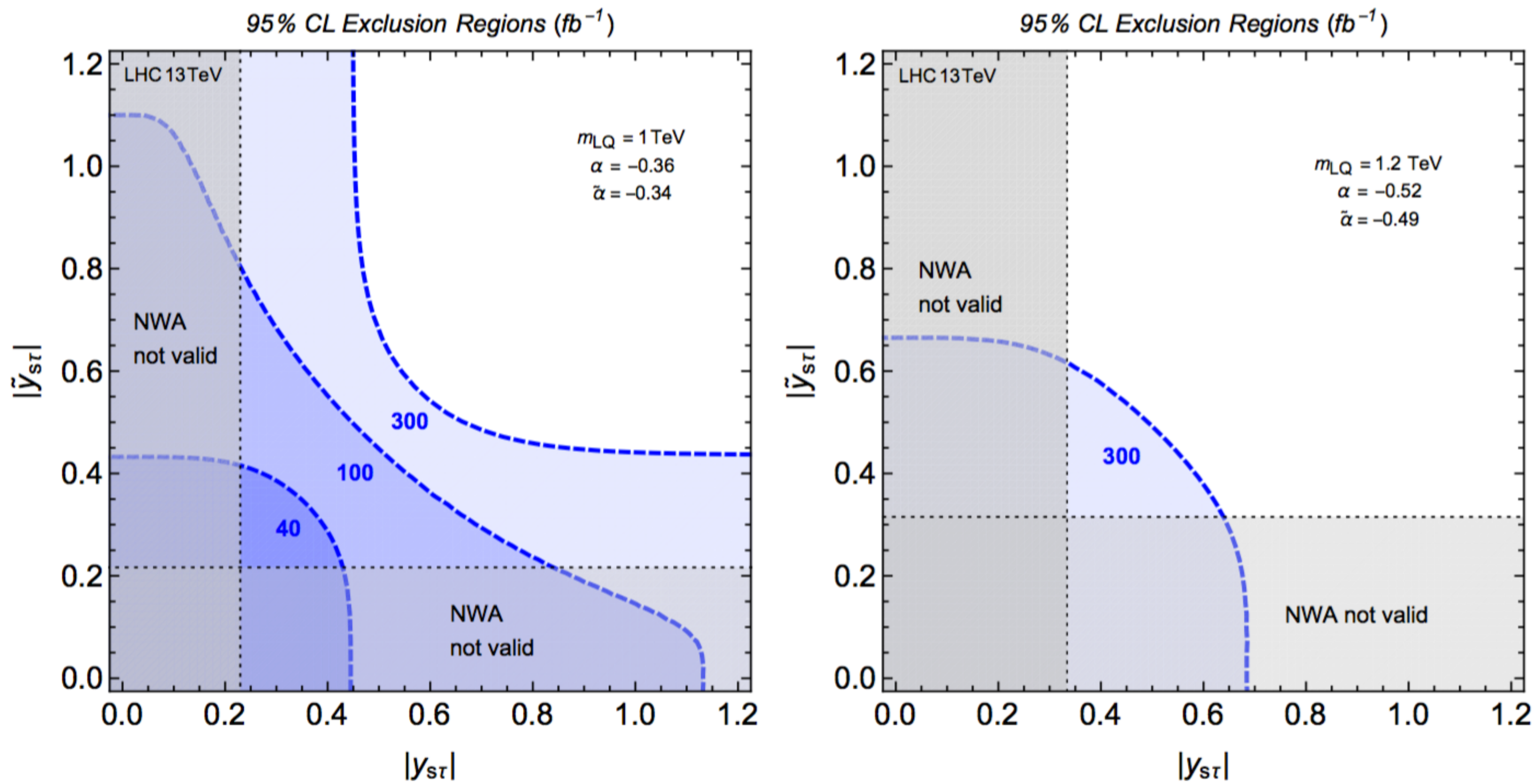
Search for pair produced LQs decaying to τ lepton





- Degenerate LQs
- Interference effects are negligible since $\tilde{R}_2 \to b_R\, \tau_L$, $S3 \to b_L\, \tau_L$

$pp \to LQ\, LQ^* \to \tau\tau jj$



Pair production very sensitive to low-mass regime.

Conclusion

* LFU ratios offer very precise validation of the Standard Model. Anomalous patterns have emerged.

* R_K is an interesting and expected place for NP.

* $R_{D^{(*)}}$ = charged current LFU violation. Large tree-level new physics needed.

* A pair of GUT motivated LQs accomodates both puzzles, stabilizes the proton.

* Complementarity between $b \to s\ell\ell$, $b \to c\tau\nu$ and $b \to s\nu\nu$.

* Proposed model can be confirmed or excluded in few years by direct searches for LQs and $\tau\tau$ final state searches.

* Squeeze flavor NP scenarios in 3rd generation from all sides, precision and LHC direct searches.

Thank you for your attention!

$\tau_{\rm had}\tau_{\rm had}$ inclusive category

- $p_T > 110$ GeV (55 GeV) for the leading (sub-leading) $\tau_{\rm had}$.
- Events with isolated electrons (muons) are vetoed if $p_T > 10$ GeV ($p_T > 15$ GeV).
- Opposite sign $\tau_{\rm had}\tau_{\rm had}$ with back-to-back topology in the transverse plane, $\Delta\phi(\tau_{\rm had}\tau_{\rm had}) > 2.7$.
- Total transverse mass cut of $m_T^{\rm tot} > 350$ GeV.