New Physics in Flavor Physics

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Ecole de GIF

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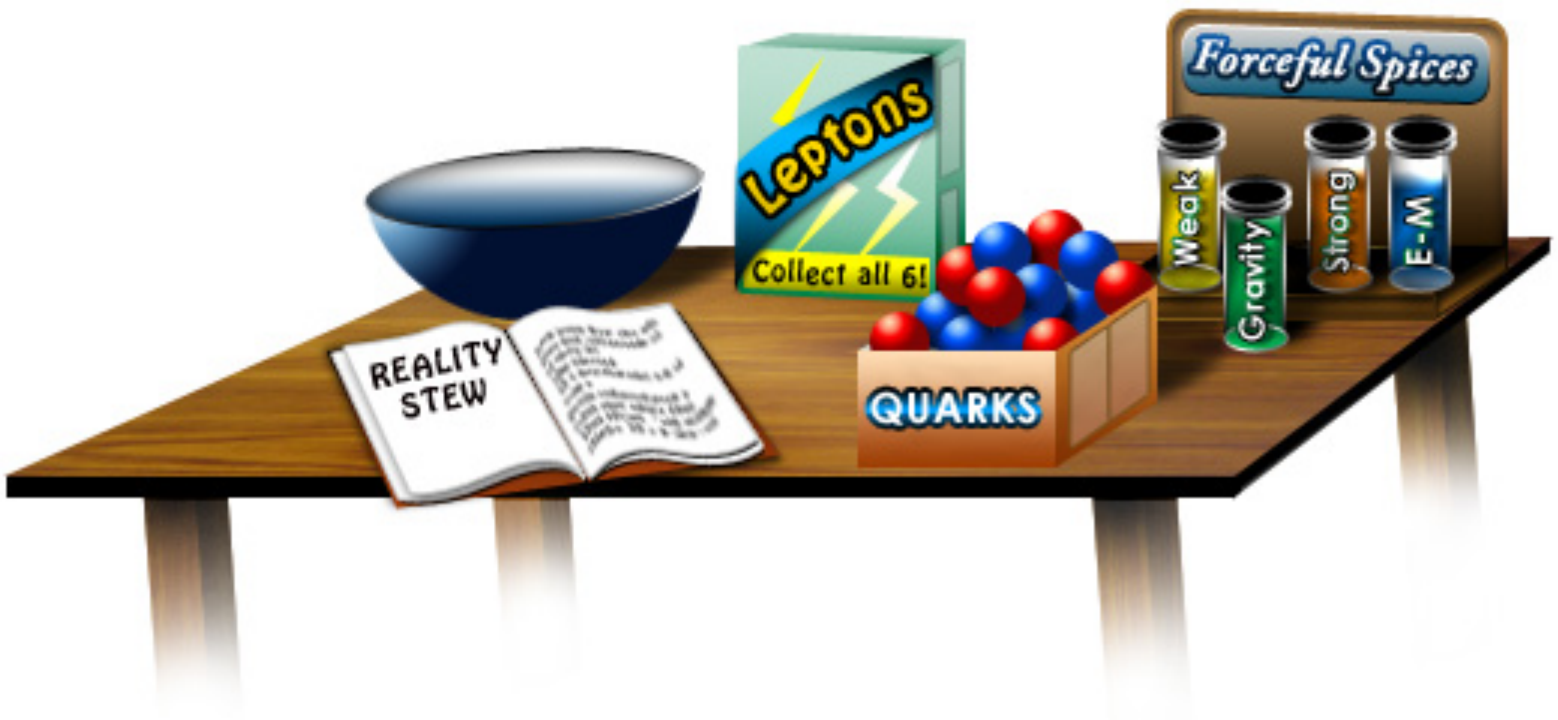

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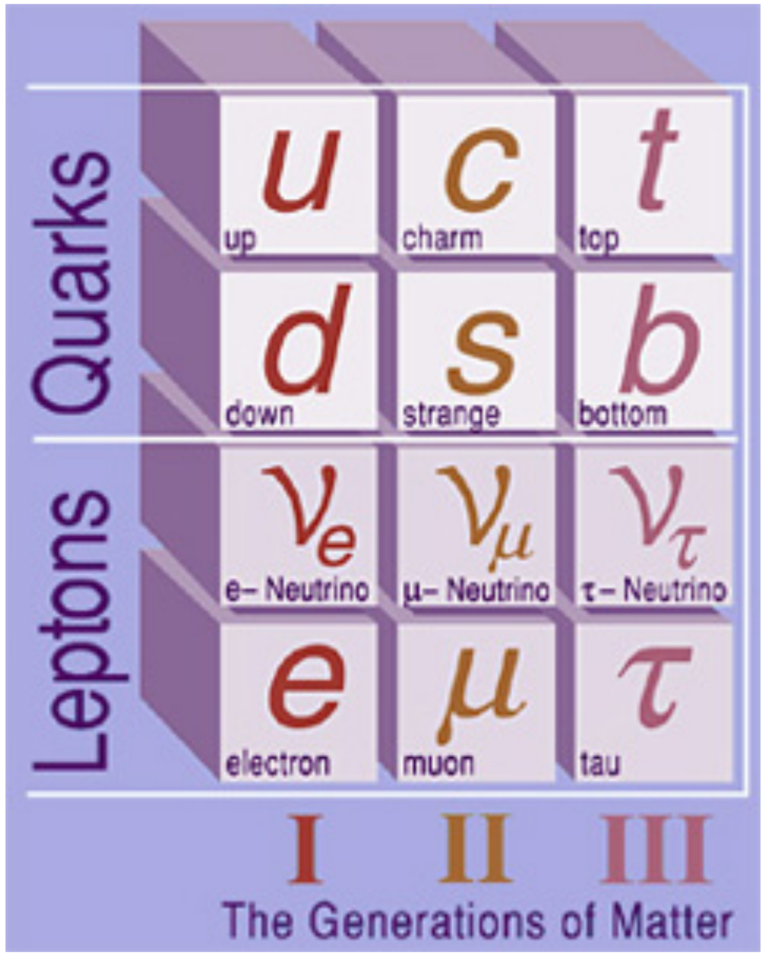
Flavor Physics



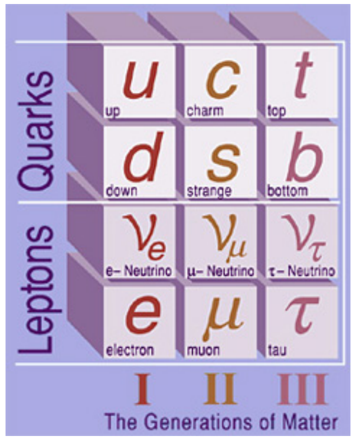
In the Standard Model

✘ Gauge sector entirely fixed by symmetry

$$i\bar{\psi}\not{D}\psi \qquad\qquad D_\mu = \partial_\mu - ig_s t_a A^a_\mu - ig\mathbf{T}\cdot\mathbf{W}_\mu - ig'\frac{Y}{2}B_\mu$$

✘ Flavor sector loose (a bunch of parameters)

13 of 19 are fermion masses and q.mixing parameters



We know

fermions come in 3 generations

$$\begin{pmatrix} \nu_e & u \\ e & d' \end{pmatrix} \qquad \begin{pmatrix} \nu_\mu & c \\ \mu & s' \end{pmatrix} \qquad \begin{pmatrix} \nu_\tau & t \\ \tau & b' \end{pmatrix}$$

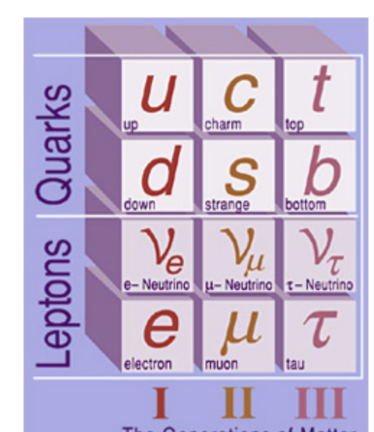
$$\left\{ \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L, \quad (\nu_e)_R, \quad e_R^- \right\}, \quad \left\{ \begin{pmatrix} u \\ d' \end{pmatrix}_L, \quad u_R, \quad d_R \right\}$$

- ✘ All generations interact equally with gauge bosons
- ✘ Neutral currents:

$$eQ_f \bar{f} \gamma_\mu f \mathcal{A}^\mu, \qquad \frac{e}{2s_W c_W} \bar{f} \gamma_\mu (v_f - a_f \gamma_5) f \; Z^\mu$$

- ✘ Charged currents:

$$\frac{g}{2\sqrt{2}} \bar{\nu}_\ell \gamma_\mu (1 - \gamma_5) \ell \; W^{\dagger\mu}, \qquad \frac{g}{2\sqrt{2}} \bar{u} \gamma_\mu (1 - \gamma_5) d \; W^{\dagger\mu}$$

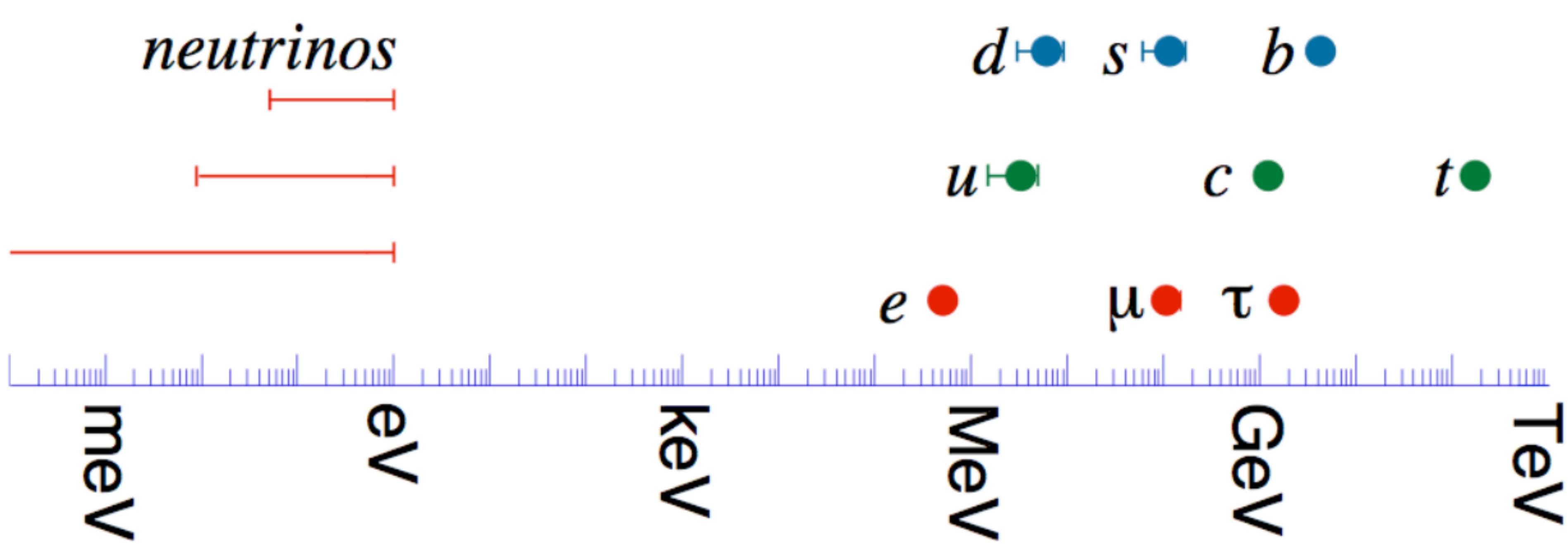


We know

- ✘ P and C broken by weak int. but CP is a symmetry (1 gen)
- ✘ Going from the gauge to mass basis

$$\mathcal{L}_Y^{\rm SM} = -Y_d^{ij}\overline{Q}_L^i \phi D_R^j - Y_u^{ij}\overline{Q}_L^i \widetilde{\phi} U_R^j + \text{h.c.}$$

$$\mathcal{L}_Y^{\rm SM} = -\left(1+\frac{h}{v}\right)\left[m_d \bar{d}d + m_u \bar{u}u + m_e \bar{e}e\right]$$



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$$\mathcal{L}_Y^{\rm SM} = -\left(1+\frac{h}{v}\right)\left[m_d \bar{d}d + m_u \bar{u}u + m_e \bar{e}e\right]$$

- ✘ With 3 gen trickier - cannot simultaneously diagonalize *u* and *d* — mixing: CKM matrix
- ✘ V_{CKM} unitary ⇒ 3 real parameters + 1 phase (CPV!)

$$\lambda \qquad A \qquad \rho \qquad \eta$$

CKM-ology

$$\lambda \qquad A \qquad \rho \qquad \eta$$

$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$$\lambda = \sin\theta_C \approx 0.224 \qquad A \simeq 0.82 \qquad \sqrt{\rho^2+\eta^2} \approx 0.45$$

- ✘ Fix CKM entries through tree level processes; over constrain by loop-induced ones
- ✘ V_{CKM} unitary ⇒ 3 real parameters + 1 phase (CPV!)

Example : Kaon physics

Tree level decays

hadronic uncertainty!

$$K \to \pi \ell \nu \quad \longleftrightarrow \quad \langle \pi | \bar{s} \gamma_\mu u | K \rangle \to f_{0,+}(q^2)$$

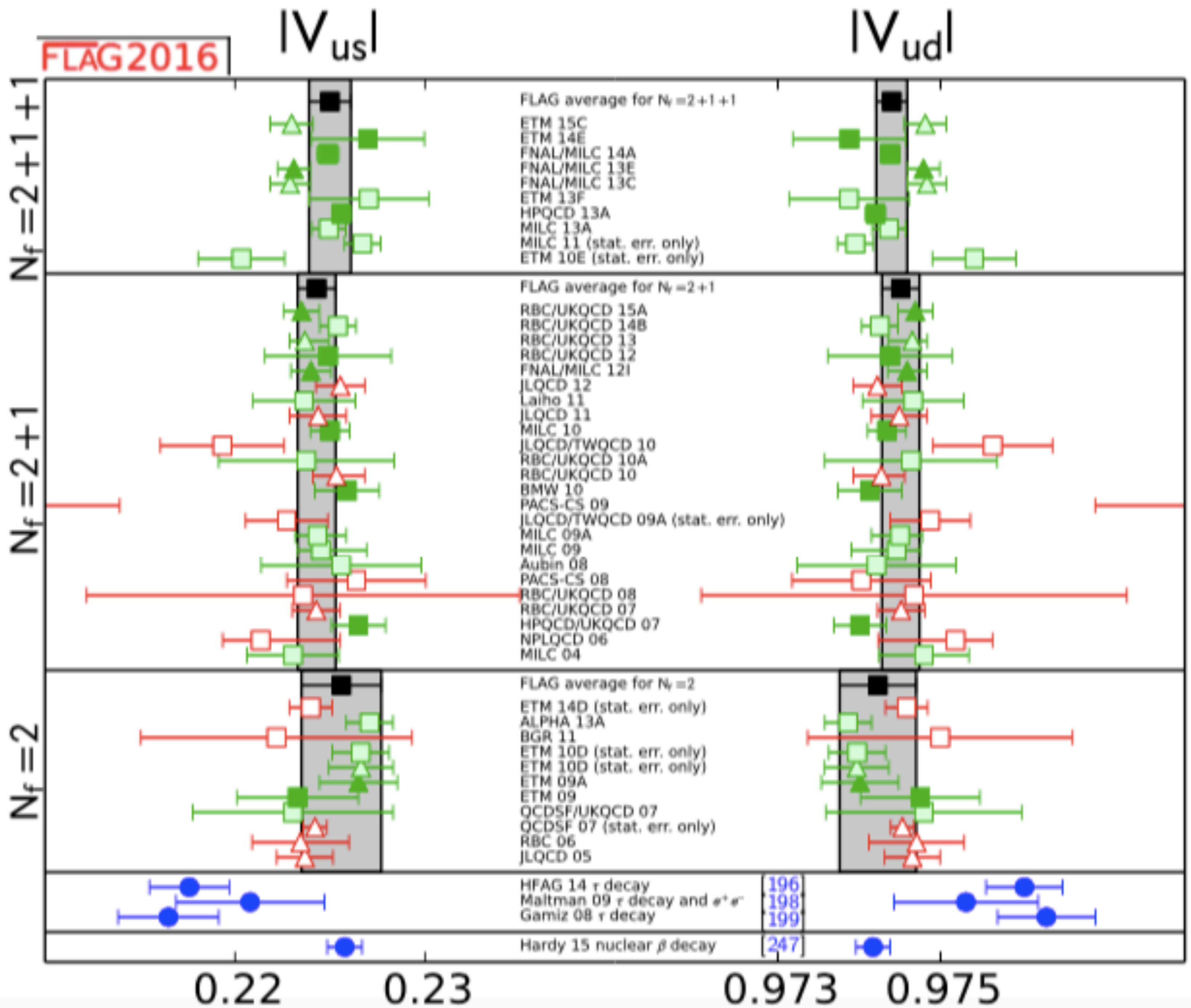
$$K \to \mu \nu \quad \longleftrightarrow \quad \langle 0 | \bar{s} \gamma_\mu \gamma_5 u | K \rangle \to f_K$$

$$f_K / f_\pi$$

Nonperturbative QCD - symmetries help (eg. Ademollo-Gatto) but ultimately needs LQCD

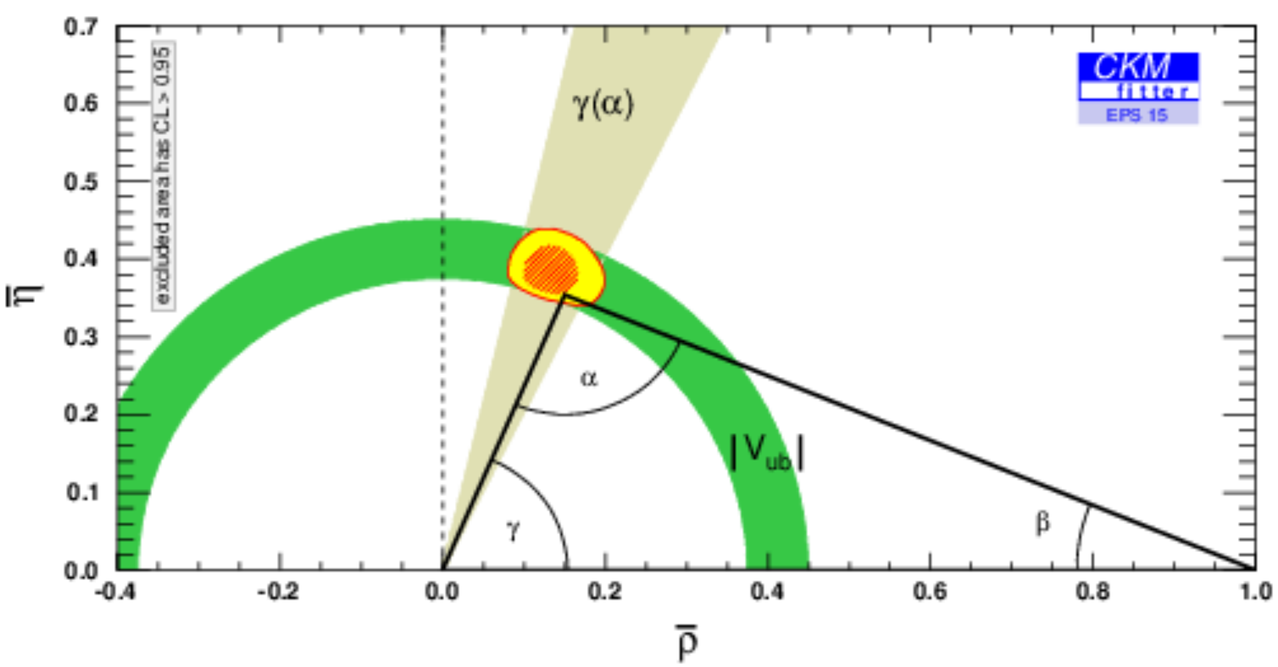
Huge coordinated effort! (cf. FLAG review - new to appear soon — towards the end of 2018)

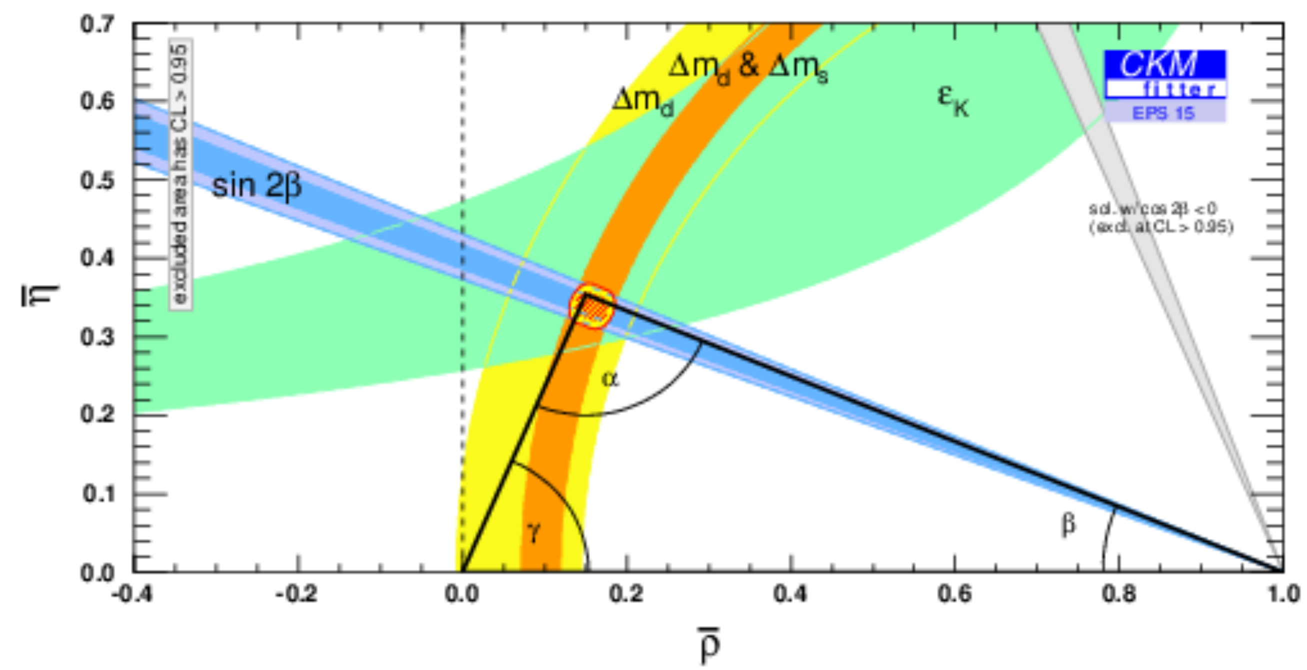
LQCD


FLAG2016
|Vus|
|Vud|
Nf=2+1+1
Nf=2+1
Nf=2
FLAG average for Nf=2+1+1
ETM 15C
ETM 14E
FNAL/MILC 14A
FNAL/MILC 13E
FNAL/MILC 13C
ETM 13F
HPQCD 13A
MILC 13A
MILC 11 (stat. err. only)
ETM 10E (stat. err. only)
FLAG average for Nf=2+1
RBC/UKQCD 15A
RBC/UKQCD 14B
RBC/UKQCD 13
RBC/UKQCD 12
FNAL/MILC 12I
JLQCD 12
Laiho 11
JLQCD 11
MILC 10
JLQCD/TWQCD 10
RBC/UKQCD 10A
RBC/UKQCD 10
BMW 10
PACS-CS 09
JLQCD/TWQCD 09A (stat. err. only)
MILC 09A
MILC 09
Aubin 08
PACS-CS 08
RBC/UKQCD 08
RBC/UKQCD 07
HPQCD/UKQCD 07
NPLQCD 06
MILC 04
FLAG average for Nf=2
ETM 14D (stat. err. only)
ALPHA 13A
BGR 11
ETM 10D (stat. err. only)
ETM 10D (stat. err. only)
ETM 09A
ETM 09
QCDSF/UKQCD 07
QCDSF 07 (stat. err. only)
RBC 06
JLQCD 05
HFAG 14 τ decay
Maltman 09 τ decay and e+e-
Gamiz 08 τ decay
Hardy 15 nuclear β decay
196
198
199
247
0.22
0.23
0.973
0.975

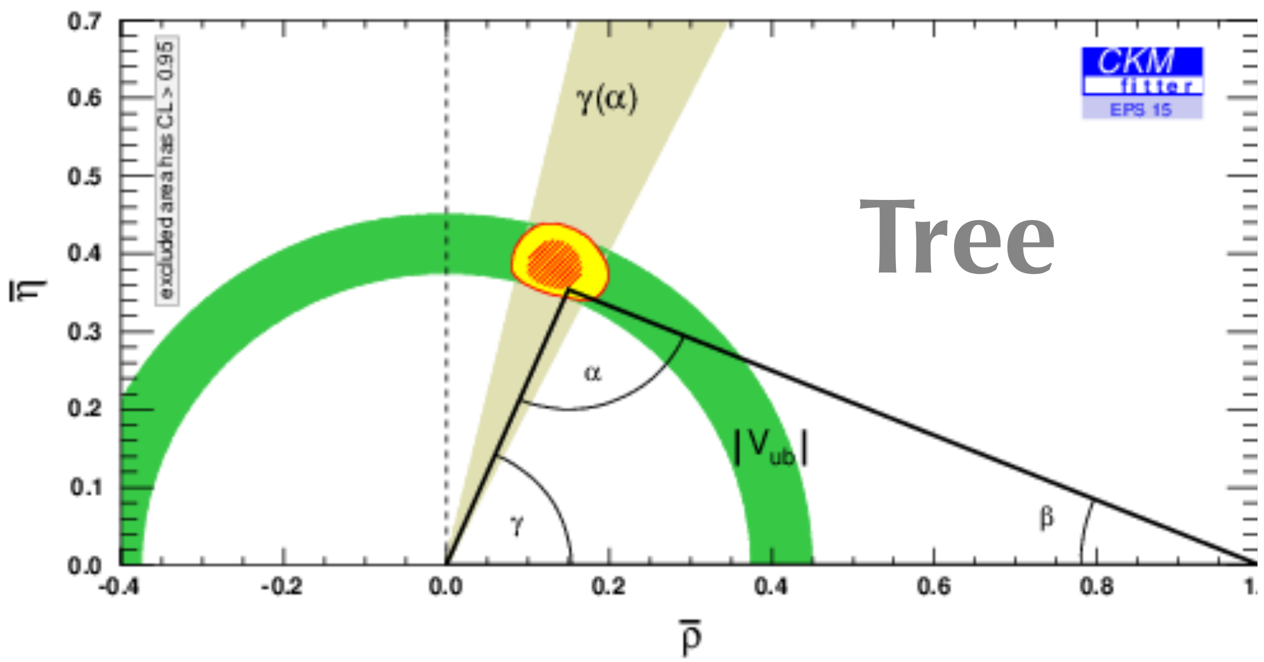
Experiments

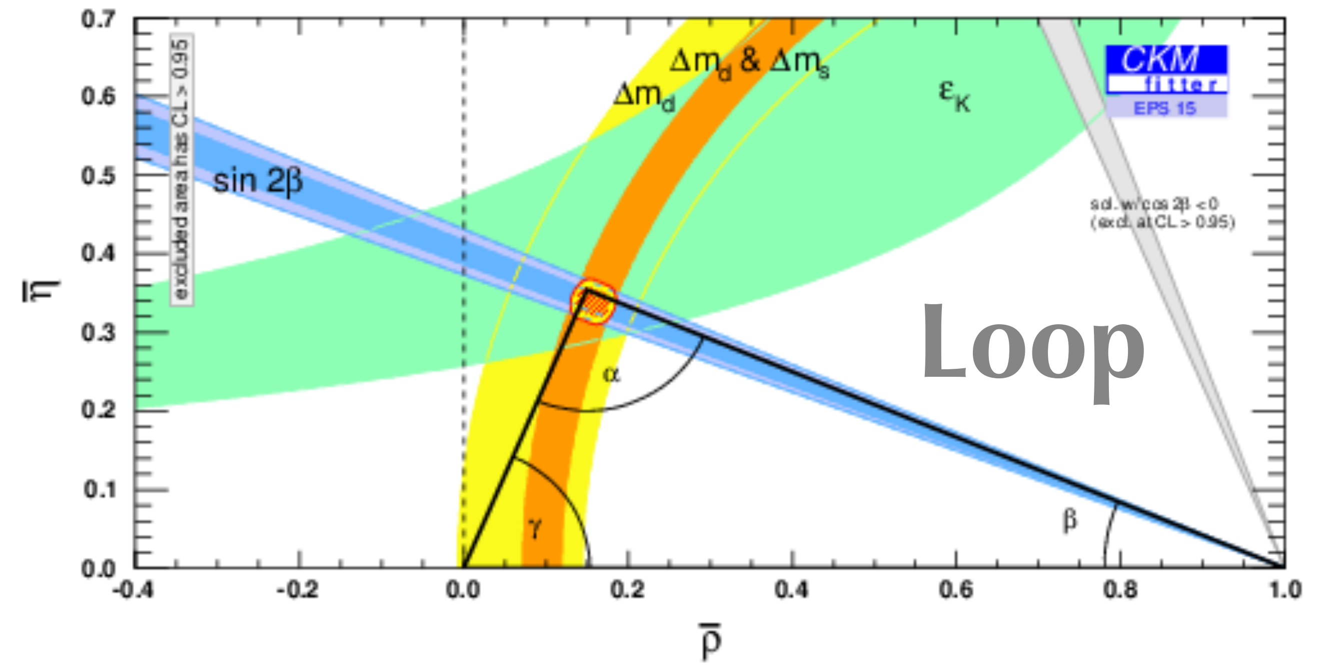
- K-factories u,d,s [NA62, KOTO]
- Tau-charm τ,c [BES III]
- B-factory b,c,τ [Belle II]
- LHC t,b,c
- LC t,…
- νF





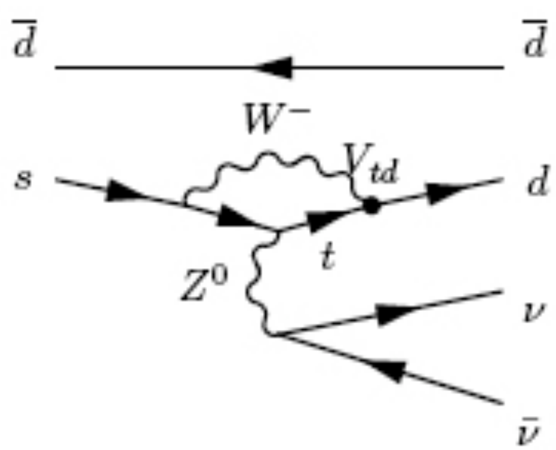
CKM

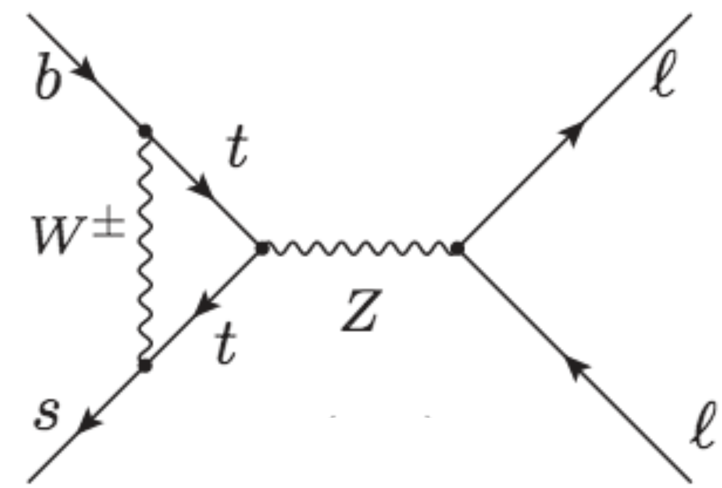




Impressively — TL UT and LP UT agree to less than 10%
[Experiment will do better! Lattices will do better too!]
Only tensions in Vub and Vcb (inclusive Vs. exclusive) but all in all, CKM is very unitary!
2008, Nobel Prize

Strategy:
fix V_{ij} by tree level processes, then look for NP in FCNC



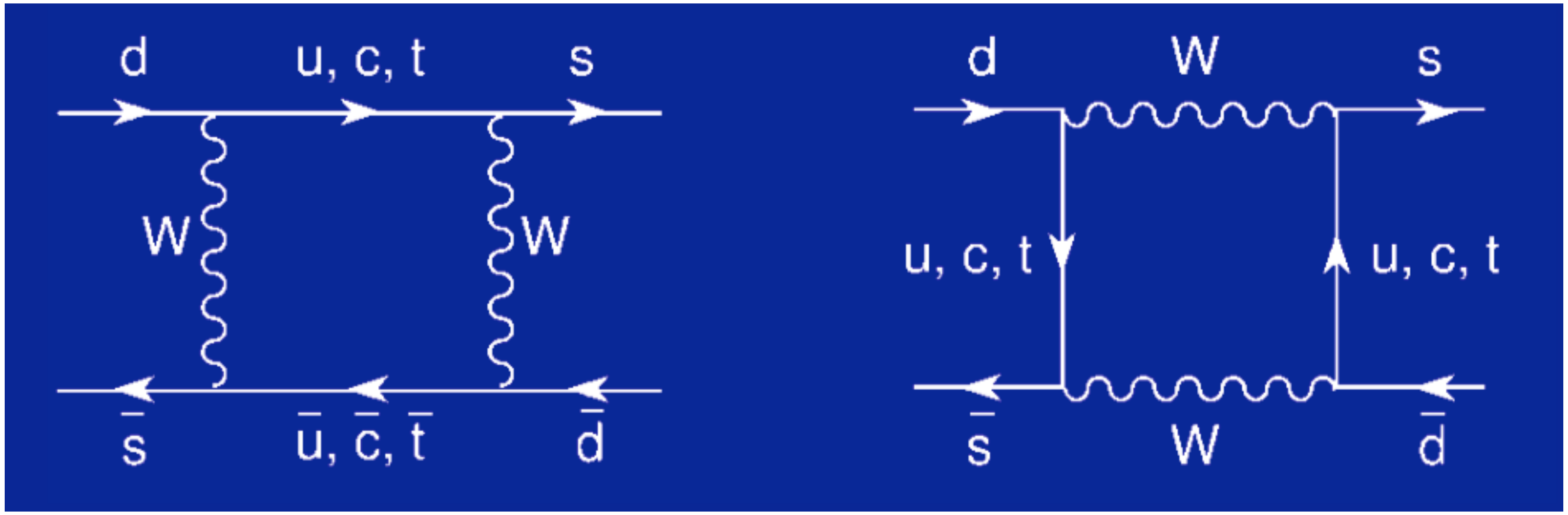


$\mathcal{B}(B_s \to \mu^+\mu^-)_{\rm theo.} = 3.34\,\left({}^{+13}_{-25}\right) \times 10^{-9}$ $\mathcal{B}(B_s \to \mu^+\mu^-)_{\rm LHCb+CMS} = 2.9(7) \times 10^{-9}$

C_{ij}	1	$V_{ti}V^*_{tj}$
$B_s \to \mu^+\mu^-$	> 10 TeV	> 2.5 TeV
$K \to \pi\nu\bar{\nu}$	> 100 TeV	> 1.8 TeV

$$O = \frac{1}{\Lambda^2} C_{ij} \bar{Q}_i \gamma^\mu Q_j H^\dagger D_\mu H$$

Strategy:
fix V_{ij} by tree level processes, then look for NP in FCNC



$$O = \frac{1}{\Lambda^2} C'_{ij} \bar{Q}_i \gamma^\mu Q_j \bar{Q}_i \gamma_\mu Q_j$$

C'_{ij}	1	$\lvert V_{ti} V^*_{tj} \rvert^2$
$K^0 - \overline{K}^0$	$> 2 \times 10^4$ TeV	> 8 TeV
$B^0 - \overline{B}^0$	$> 0.5 \times 10^4$ TeV	> 5 TeV
$B^0_s - \overline{B}^0_s$	$> 0.1 \times 10^4$ TeV	> 5 TeV

Flavor puzzle

C_{ij}	1	$V_{ti}V_{tj}^*$
$B_s \to \mu^+\mu^-$	> 10 TeV	> 2.5 TeV
$K \to \pi\nu\bar{\nu}$	> 100 TeV	> 1.8 TeV

C'_{ij}	1	$\lvert V_{ti}V_{tj}^*\rvert^2$
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$B_s^0 - \overline{B}_s^0$	$> 0.1 \times 10^4$ TeV	> 5 TeV

- **For natural C~O(1), NP scale is huge**
- **Need lots of fine tuning to reduce NP scale to O(1TeV) as needed to mend the hierarchy problem**
- **Way out: NP is (almost) aligned with the SM**
- **MFV**

MFV

To protect quark flavor mixing BSM, assume flavor symmetry is the one present in the limit of vanishing Yukawa's, U(3)^3, and that two quark Yukawa, *Yu* and *Yd*, are the only symmetry breaking and CP violating terms

$$\mathcal{L}_Y^{\mathrm{SM}} = -Y_d^{ij}\overline{Q}_L^i \phi D_R^j - Y_u^{ij}\overline{Q}_L^i \widetilde{\phi} U_R^j + \mathrm{h.c.}$$

Promote *Yu* and *Yd* to non-dynamical fields. Higher dim operators made of SM fields and *Yud*.
Eigenvalues of *Yud* small except for top, off-diagonal elements suppressed $\Longrightarrow \left[Y_u (Y_u)^\dagger\right]^n_{i\neq j} \approx y_t^{2n} V_{ti}^* V_{tj}$

Questions and progress

- ✘ Why is there a flavor? Why families? Why 3?
- ✘ Why such a strong hierarchy?
- ✘ Why quark mixing is small (and lepton mixing is large)?
- ✘ Why is there quark alignment?
- ✘ How to solve strong CP-problem? [Peccei-Quinn elegant solution, but where are axions?]
- ✘ Need CPV in quark and lepton sector for BAU
- ✘ Does the scalar sector play a non-trivial role in the questions of flavor?
- ✘ Work to figure out a symmetry which imposed on SM+2HDM provides a structure of Yukawas such that there is no FCNC at tree-level and their strength controlled by CKM (!)

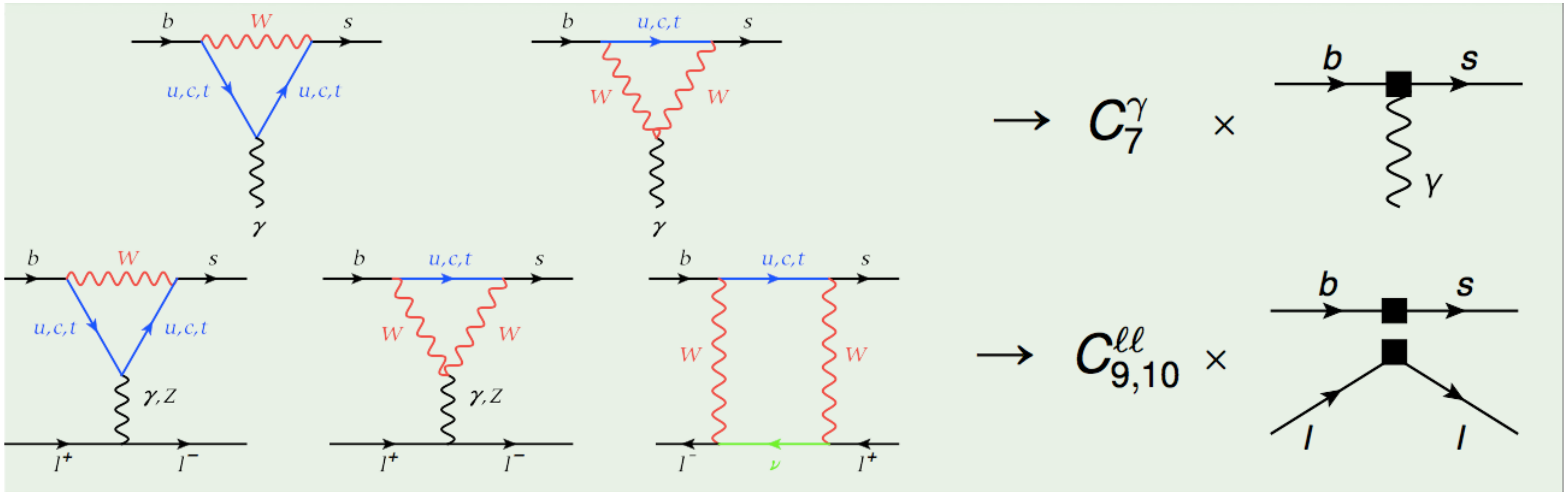
LHC era

Before LHC was switched on we expected
(a) exciting physics in direct searches with many new resonances at TeV scale
(b) boring but useful flavor physics

After the first two runs at LHC we got
(a) slightly boring direct searches with no new resonance at TeV scale
(b) exciting flavor physics

$b \longrightarrow s$ anomalies

Basics



$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left[C_1 \mathcal{O}_1 + C_2 \mathcal{O}_2 + \sum_{i=3}^{6} C_i \mathcal{O}_i + \sum_{i=7,8,9,10,P,S} (C_i \mathcal{O}_i + C_i' \mathcal{O}_i') \right]$$

$$\mathcal{O}_7 = \frac{e}{g^2} m_b (\bar{s}\sigma_{\mu\nu} P_R b) F^{\mu\nu}, \qquad \mathcal{O}_7' = \frac{e}{g^2} m_b (\bar{s}\sigma_{\mu\nu} P_L b) F^{\mu\nu},$$

$$\mathcal{O}_8 = \frac{1}{g} m_b (\bar{s}\sigma_{\mu\nu} T^a P_R b) G^{\mu\nu\, a}, \qquad \mathcal{O}_8' = \frac{1}{g} m_b (\bar{s}\sigma_{\mu\nu} T^a P_L b) G^{\mu\nu\, a},$$

$$\mathcal{O}_9 = \frac{e^2}{g^2} (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \mu), \qquad \mathcal{O}_9' = \frac{e^2}{g^2} (\bar{s}\gamma_\mu P_R b)(\bar{\mu}\gamma^\mu \mu),$$

$$\mathcal{O}_{10} = \frac{e^2}{g^2} (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \gamma_5 \mu), \qquad \mathcal{O}_{10}' = \frac{e^2}{g^2} (\bar{s}\gamma_\mu P_R b)(\bar{\mu}\gamma^\mu \gamma_5 \mu),$$

$$C_7^{\rm eff} = \frac{4\pi}{\alpha_s}C_7 - \frac{1}{3}C_3 - \frac{4}{9}C_4 - \frac{20}{3}C_5 - \frac{80}{9}C_6$$

$$C_8^{\rm eff} = \frac{4\pi}{\alpha_s}C_8 + C_3 - \frac{1}{6}C_4 + 20C_5 - \frac{10}{3}C_6$$

$$C_9^{\rm eff} = \frac{4\pi}{\alpha_s}C_9 + Y(q^2)$$

!!!

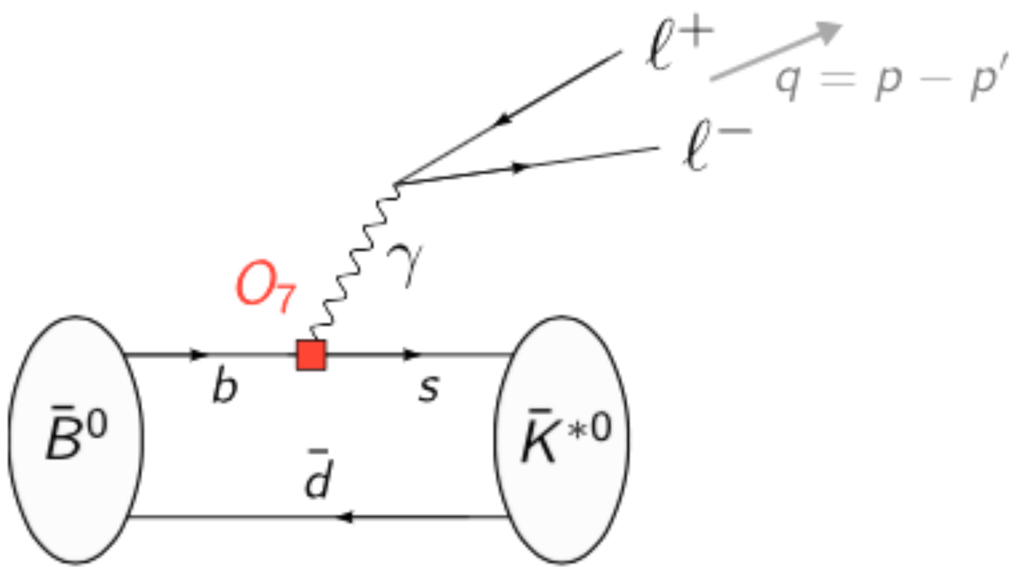
$$Y(q^2) = \frac{4}{3}C_3 + \frac{64}{9}C_5 + \frac{64}{27}C_6 - \frac{1}{2}h(q^2,0)\left(C_3 + \frac{4}{3}C_4 + 16C_5 + \frac{64}{3}C_6\right)$$
$$+ h(q^2,m_c)\left(\frac{4}{3}C_1 + C_2 + 6C_3 + 60C_5\right) - \frac{1}{2}h(q^2,m_b)\left(7C_3 + \frac{4}{3}C_4 + 76C_5 + \frac{64}{3}C_6\right)$$

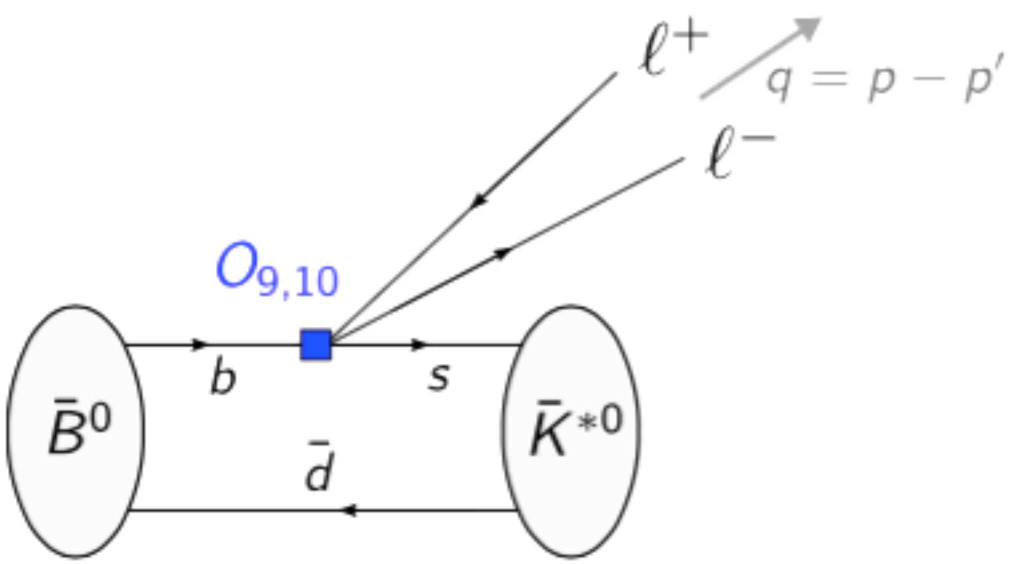
Very slowly varying functions of q^2

$$\mathcal{M} = \frac{G_F\,\alpha}{\sqrt{2}\pi} V_{tb} V_{ts}^* \Big[(\mathcal{A}_\mu + \mathcal{T}_\mu) \bar{u}_\ell \gamma^\mu v_\ell + \mathcal{B}_\mu \bar{u}_\ell \gamma^\mu \gamma_5 v_\ell \Big],$$

$$\mathcal{A}_\mu = -\frac{2m_b}{q^2} q^\nu C_7 \langle K^* | \bar{s}\, i\sigma_{\mu\nu} \tfrac{1+\gamma_5}{2} b \,| B\rangle + C_9 \langle K^* | \bar{s}\gamma_\mu \tfrac{1-\gamma_5}{2} b \,| B\rangle$$

$$\mathcal{B}_\mu = C_{10} \langle K^* | \bar{s}\gamma_\mu \tfrac{1-\gamma_5}{2} b \,| B\rangle$$

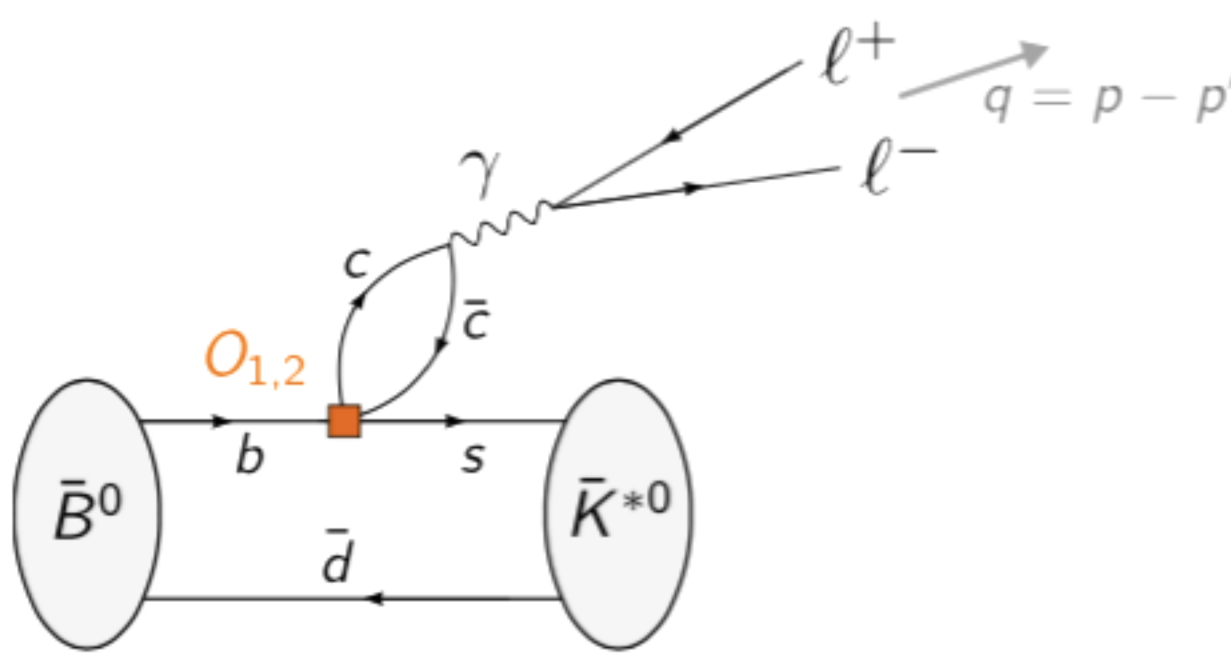




Can be and are computed on the lattice

$$\mathcal{M} = \frac{G_F\, \alpha}{\sqrt{2}\pi} V_{tb} V_{ts}^{*} \Big[(\mathcal{A}_\mu + \mathcal{T}_\mu) \bar{u}_\ell \gamma^\mu v_\ell + \mathcal{B}_\mu \bar{u}_\ell \gamma^\mu \gamma_5 v_\ell \Big],$$

$$\mathcal{T}_\mu = \frac{-16 i \pi^2}{q^2} \sum_{i=1\ldots6;8} C_i \int \mathrm{d}^4x \;\; e^{iq\cdot x} \, \langle K^* | \, \mathrm{T} \; O_i(0) \; j_\mu(x) \, | B \rangle$$

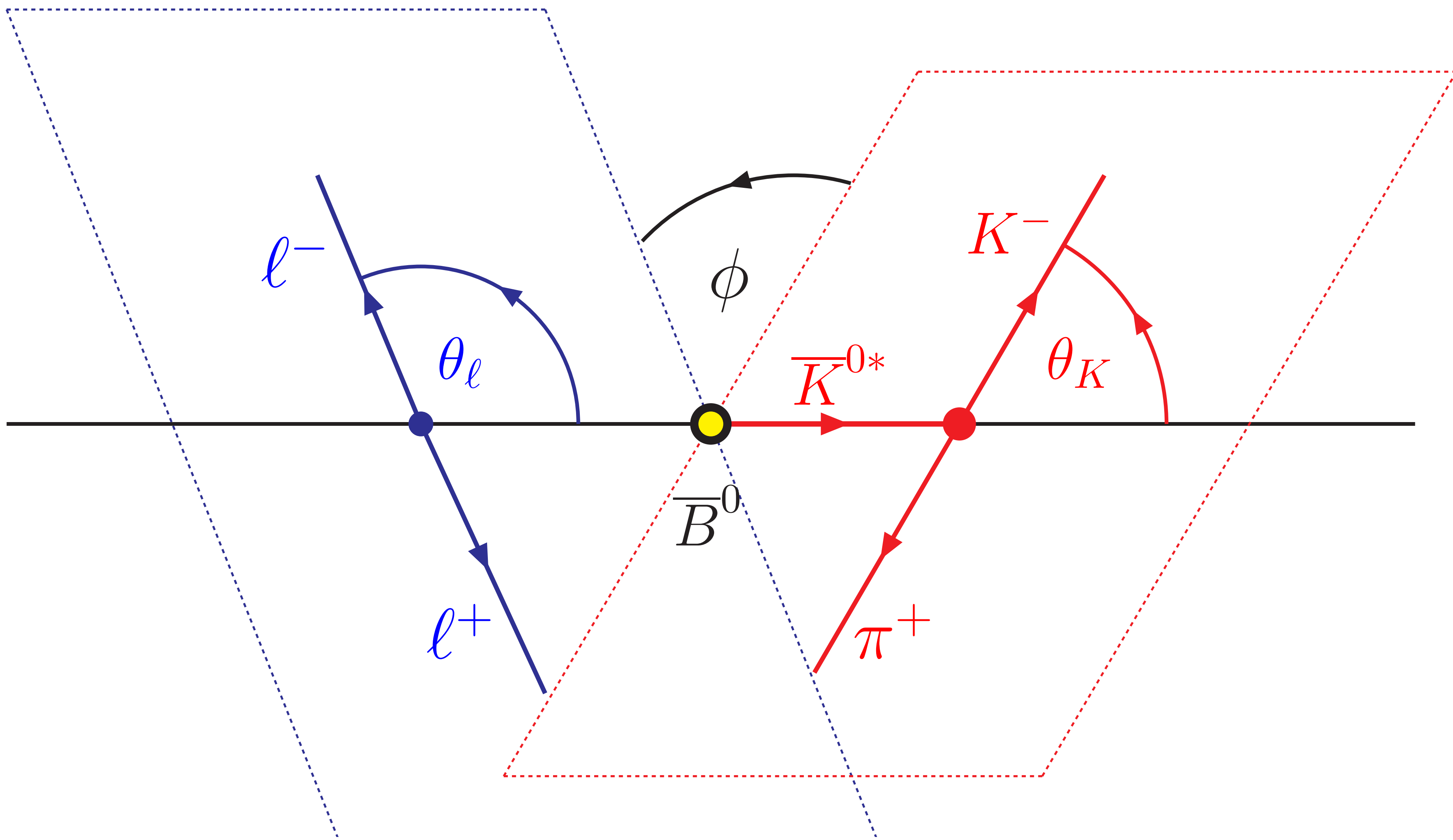


Cannot be computed on the lattice

- work either at very low or very high q^2

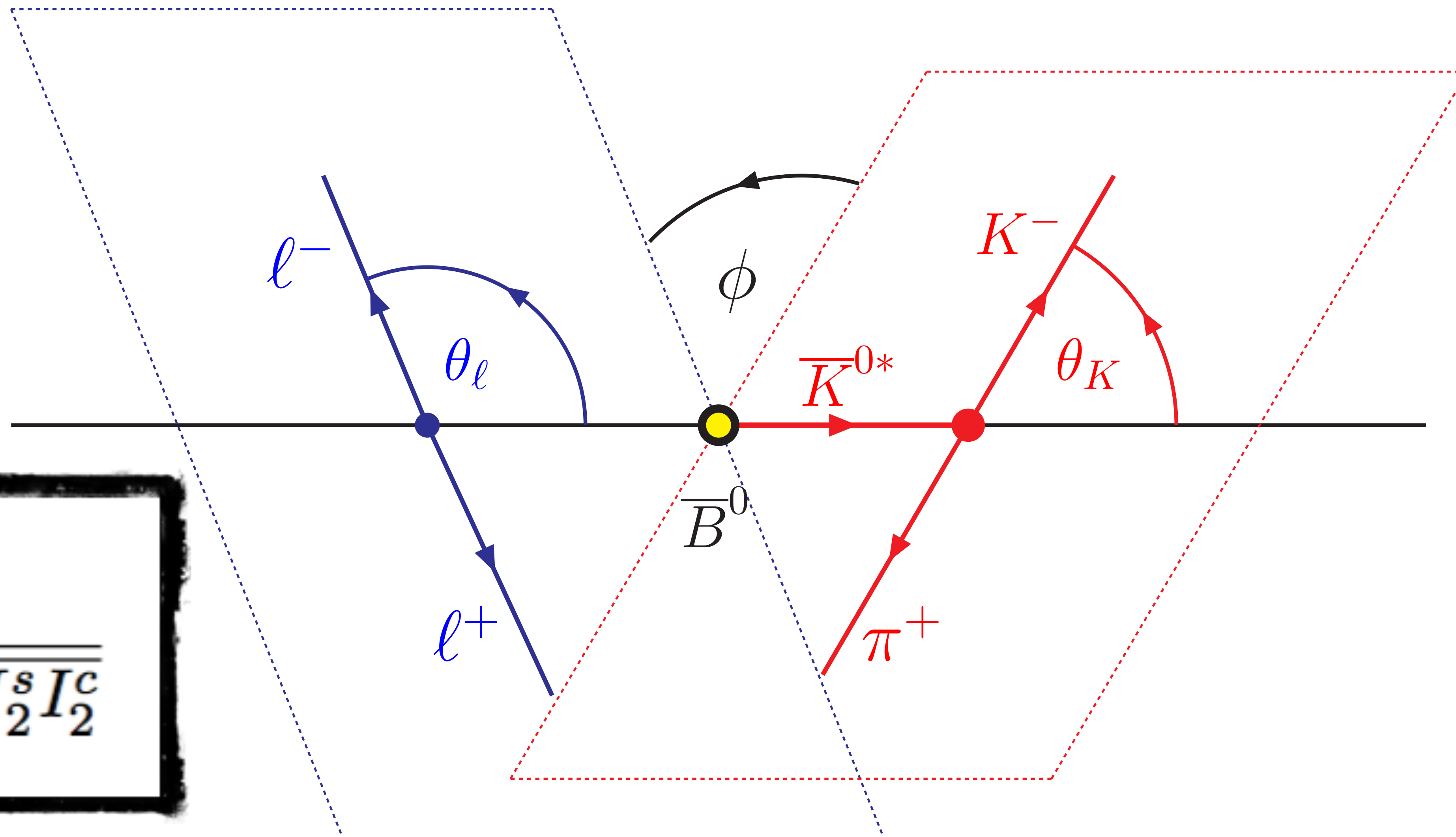
Better sensitivity to NP:

$B \to K^* \ell^+ \ell^-$



$$\frac{d^4\Gamma(\bar{B}^0 \to \bar{K}^{*0}\ell^+\ell^-)}{dq^2\ d\cos\theta_\ell\ d\cos\theta_K\ d\phi} = \frac{9}{32\pi} I(q^2, \theta_\ell, \theta_K, \phi)$$

Full decay distribution



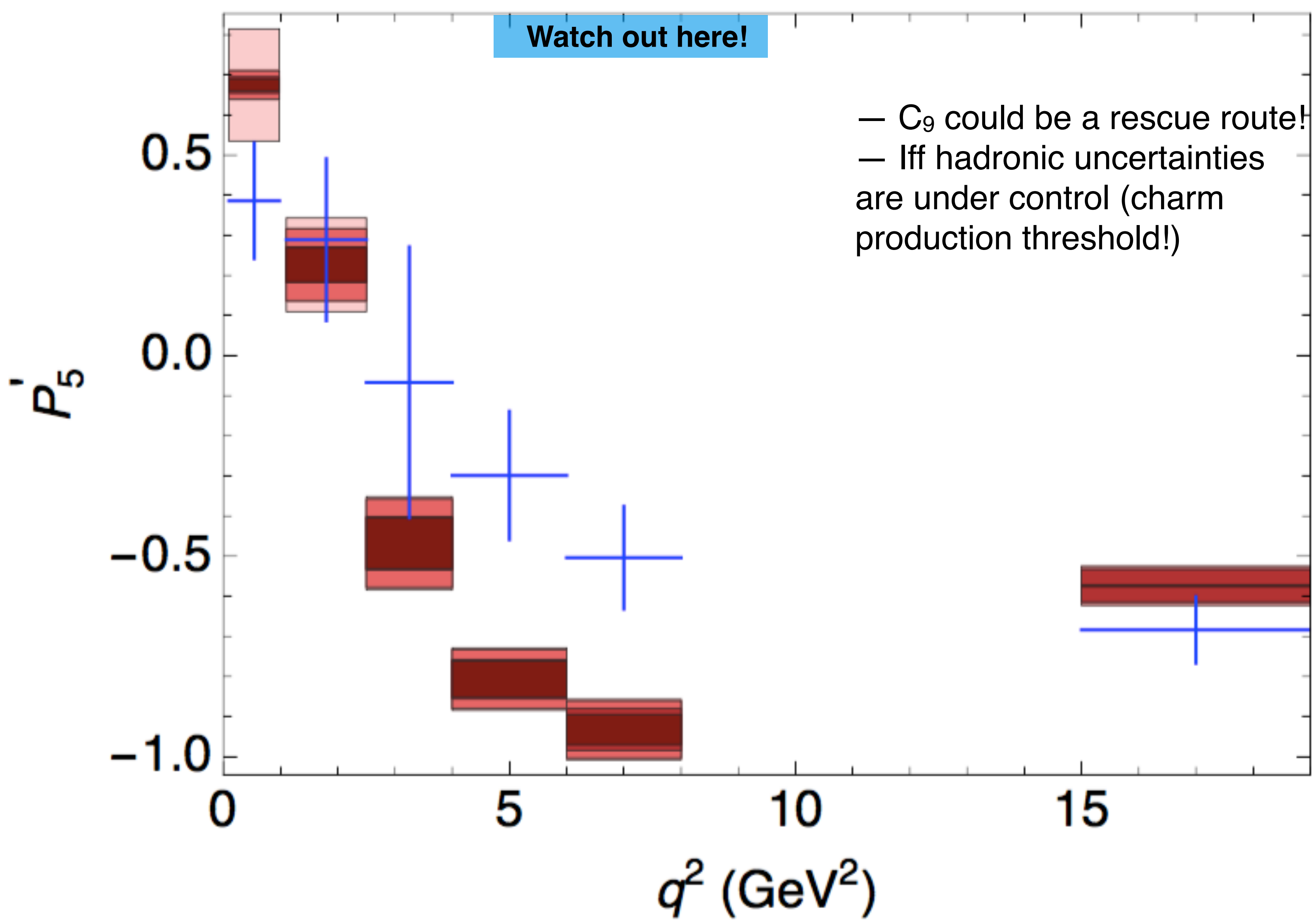
$$\boxed{P_5' = \frac{I_5}{\sqrt{-4I_2^s I_2^c}}}$$

✓

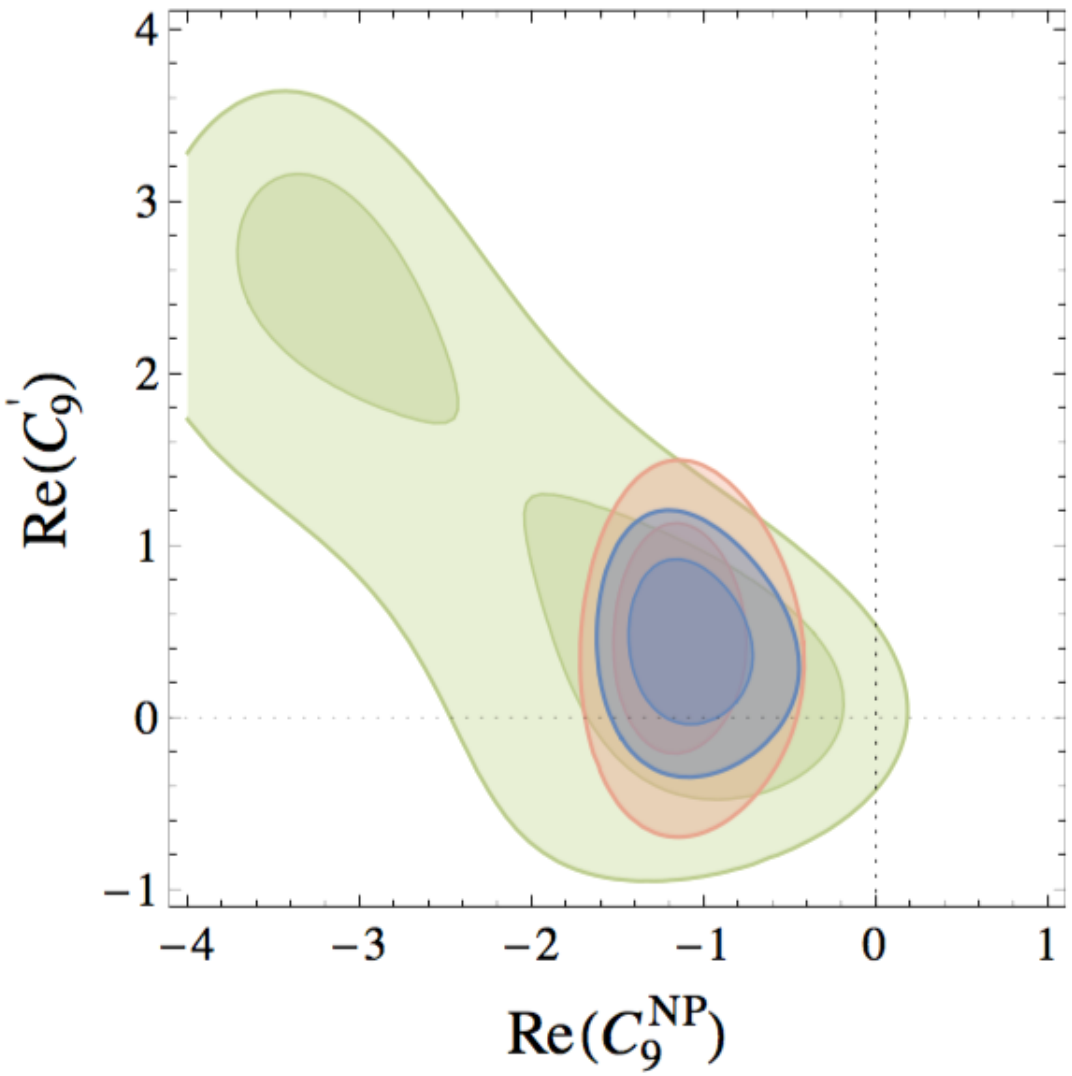
$$\begin{aligned} I(q^2,\theta_\ell,\theta_K,\phi) \;=\;& I_1^s(q^2)\sin^2\theta_K + I_1^c(q^2)\cos^2\theta_K + \left[\underline{I_2^s(q^2)}\sin^2\theta_K + \underline{I_2^c(q^2)}\cos^2\theta_K\right]\cos 2\theta_\ell \\ &+ I_3(q^2)\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + I_4(q^2)\sin 2\theta_K\sin 2\theta_\ell\cos\phi \\ &+ \underline{I_5(q^2)}\sin 2\theta_K\sin\theta_\ell\cos\phi \\ &+ \left[I_6^s(q^2)\sin^2\theta_K + I_6^c(q^2)\cos^2\theta_K\right]\cos\theta_\ell + I_7(q^2)\sin 2\theta_K\sin\theta_\ell\sin\phi \\ &+ I_8(q^2)\sin 2\theta_K\sin 2\theta_\ell\sin\phi + I_9(q^2)\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi \end{aligned}$$

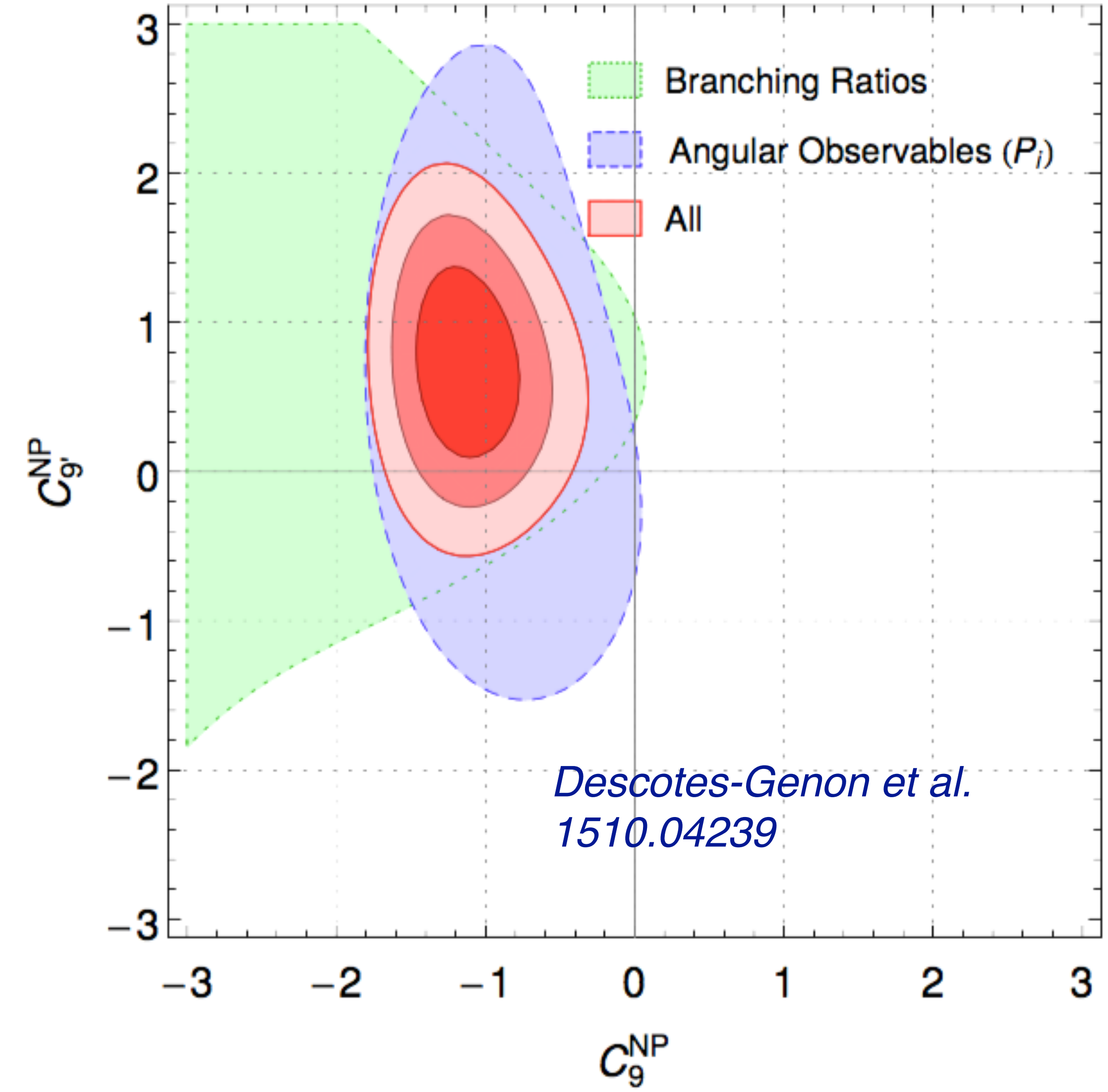
b⟶s anomalies

2-3σ deviation from SM [esp. P_5']



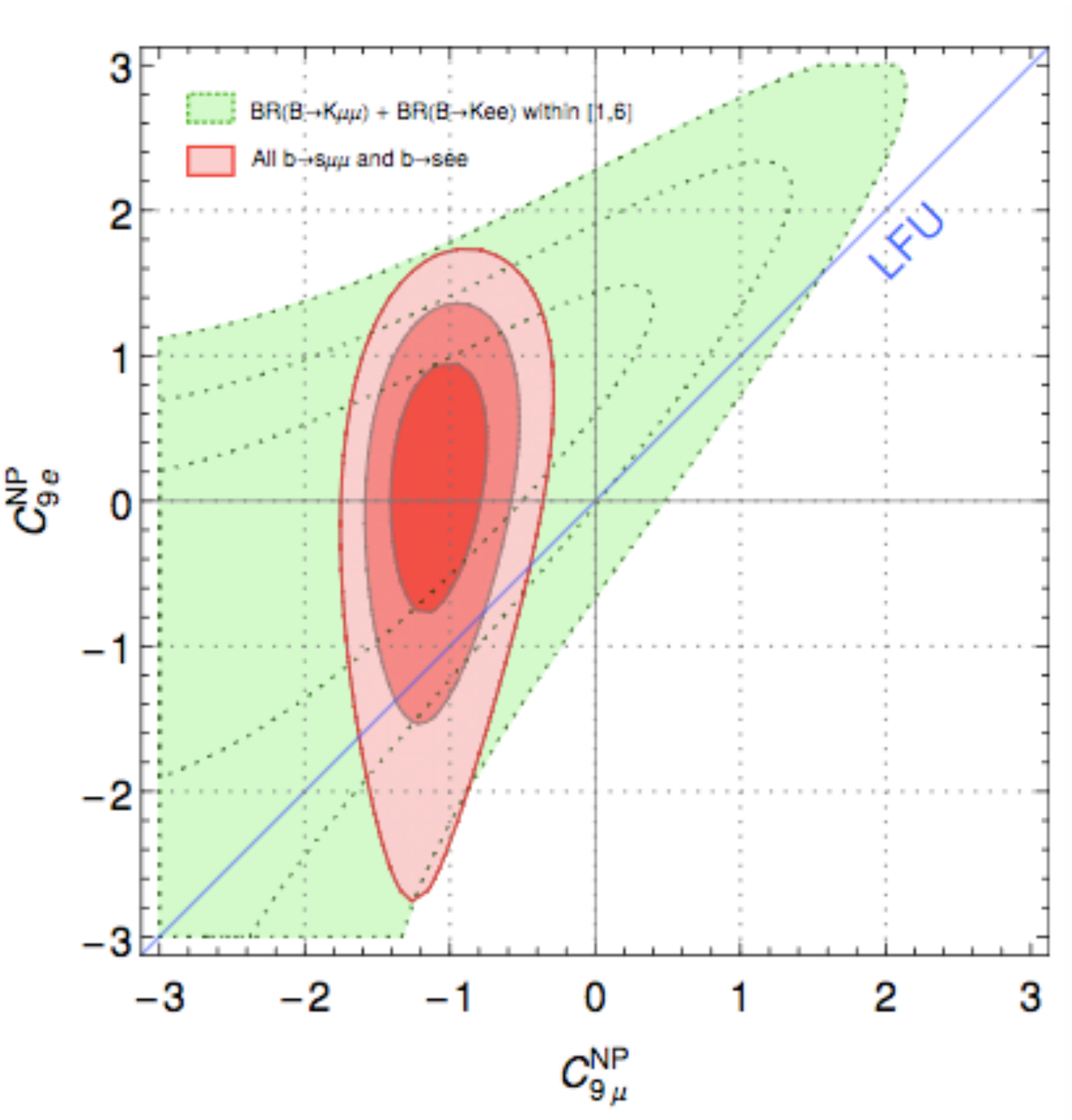
b⟶s anomalies





- Theory errors still subject to controversies.
- Some quantities are more sensitive to hadronic uncertainties than others (maybe sticking to the clean observables only?)
- Rome group claim the whole discrepancy can be absorbed into (unknown) power corrections due to charm loops.

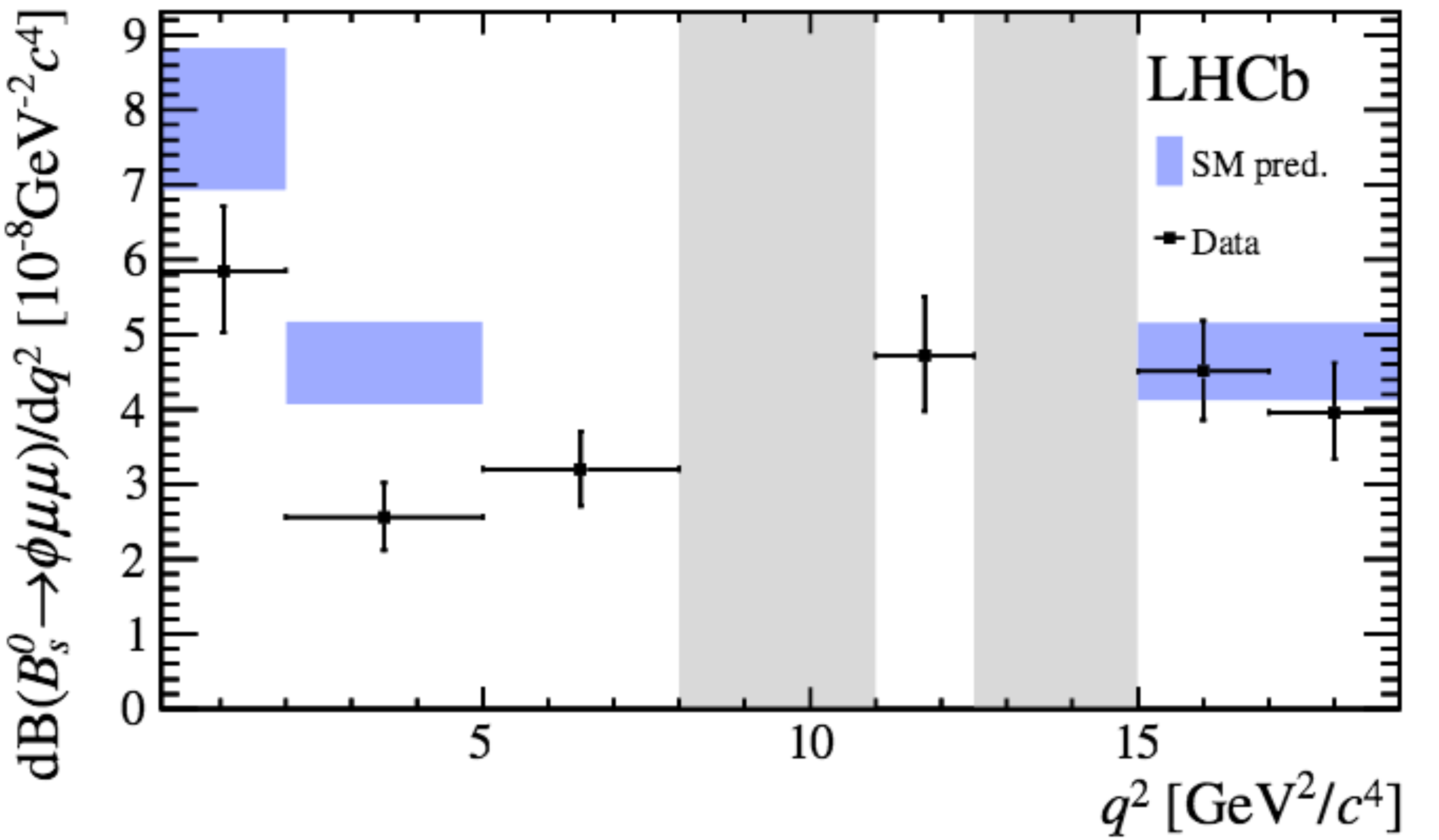
Global analyses also suggest



b⟶s anomalies

3.1σ in $Bs \to \phi\mu\mu$ bellow SM at low q^2

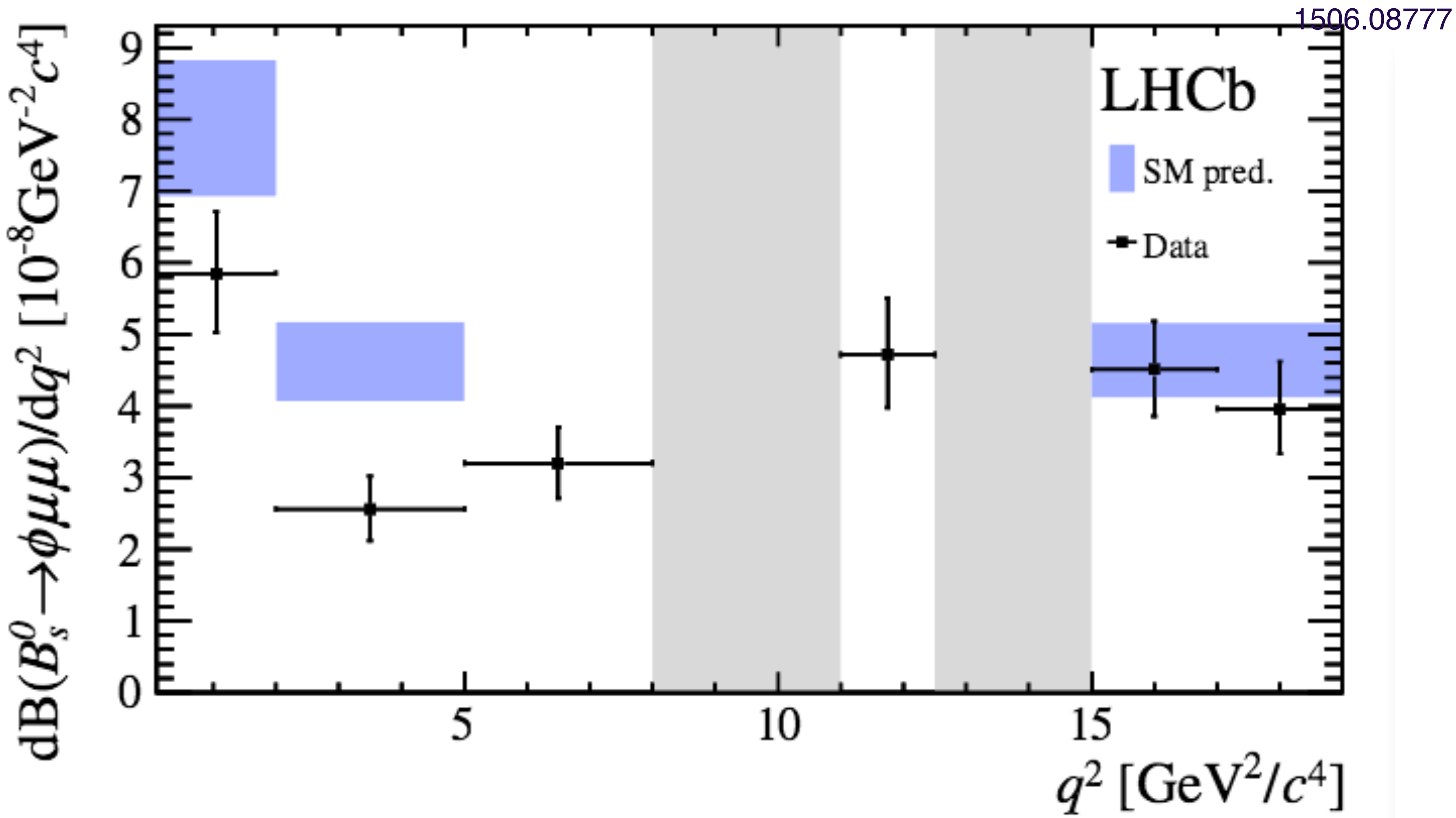
1506.08777



$$\mathcal{B}(B_s \to \phi\mu\mu)^{[1-6]} \longrightarrow 0.26(4)_{\rm LHCb} \quad < \quad 0.48(6)_{\rm SM}$$

b⟶s anomalies

3.1σ in $Bs \to \phi\mu\mu$ bellow SM at low q^2



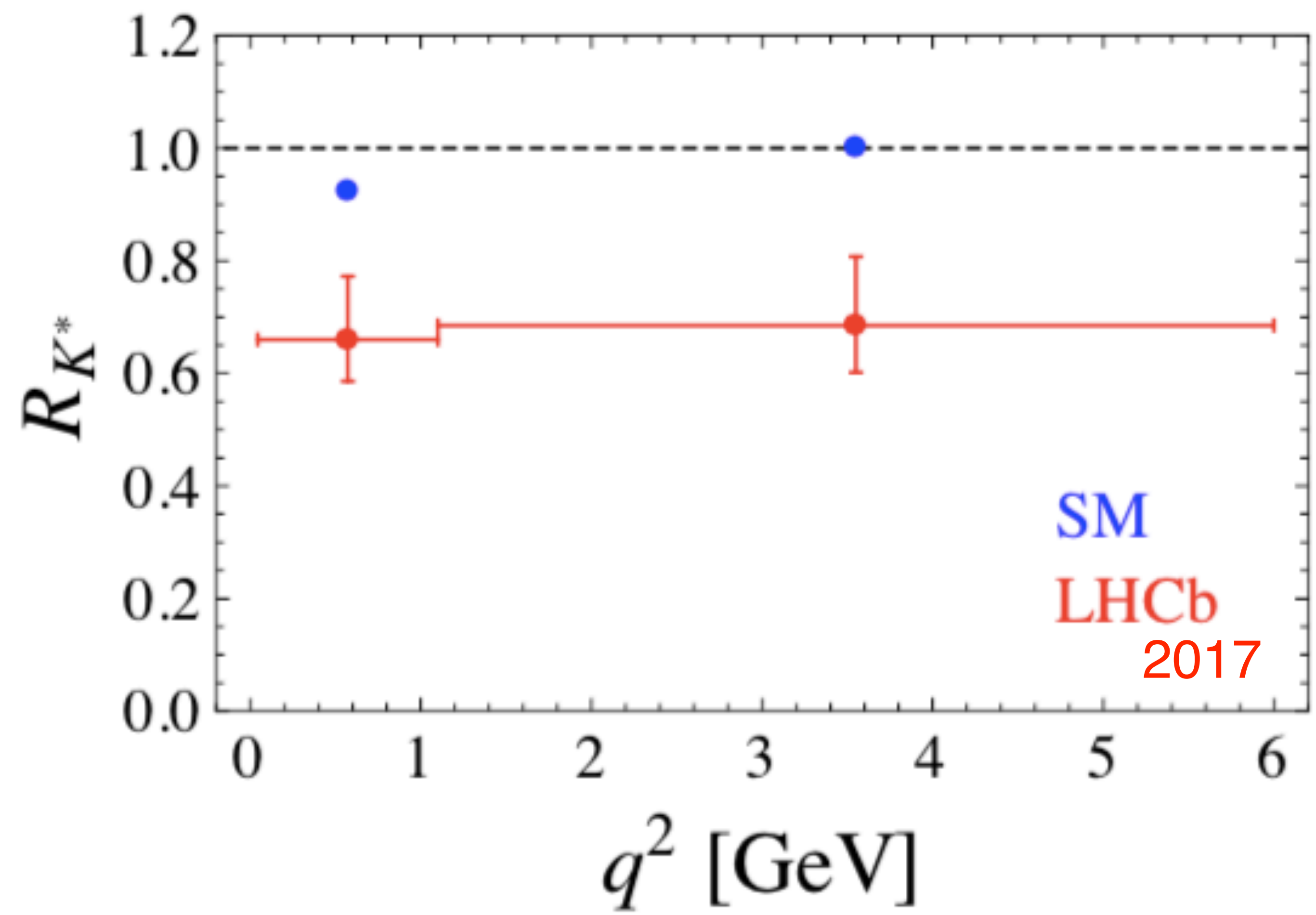
What is it? Statistical fluctuation? Hadronic uncertainties? NP? Theory error - subject to controversies... If OK, then NP in C_9 could fill the gap between experiment and SM.

R_K R_{K^*}

$$R_{K^{(*)}} \equiv \left.\frac{\mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(B \to K^{(*)}ee)}\right|_{q^2\in[1,6]\,\mathrm{GeV}^2} \stackrel{\mathrm{SM}}{=} 1.00(1)$$

$$R_K^{\mathrm{exp}} = 0.745^{+0.090}_{-0.074}(\mathrm{stat}) \pm 0.036(\mathrm{syst})$$

2014



Fitting to clean observables

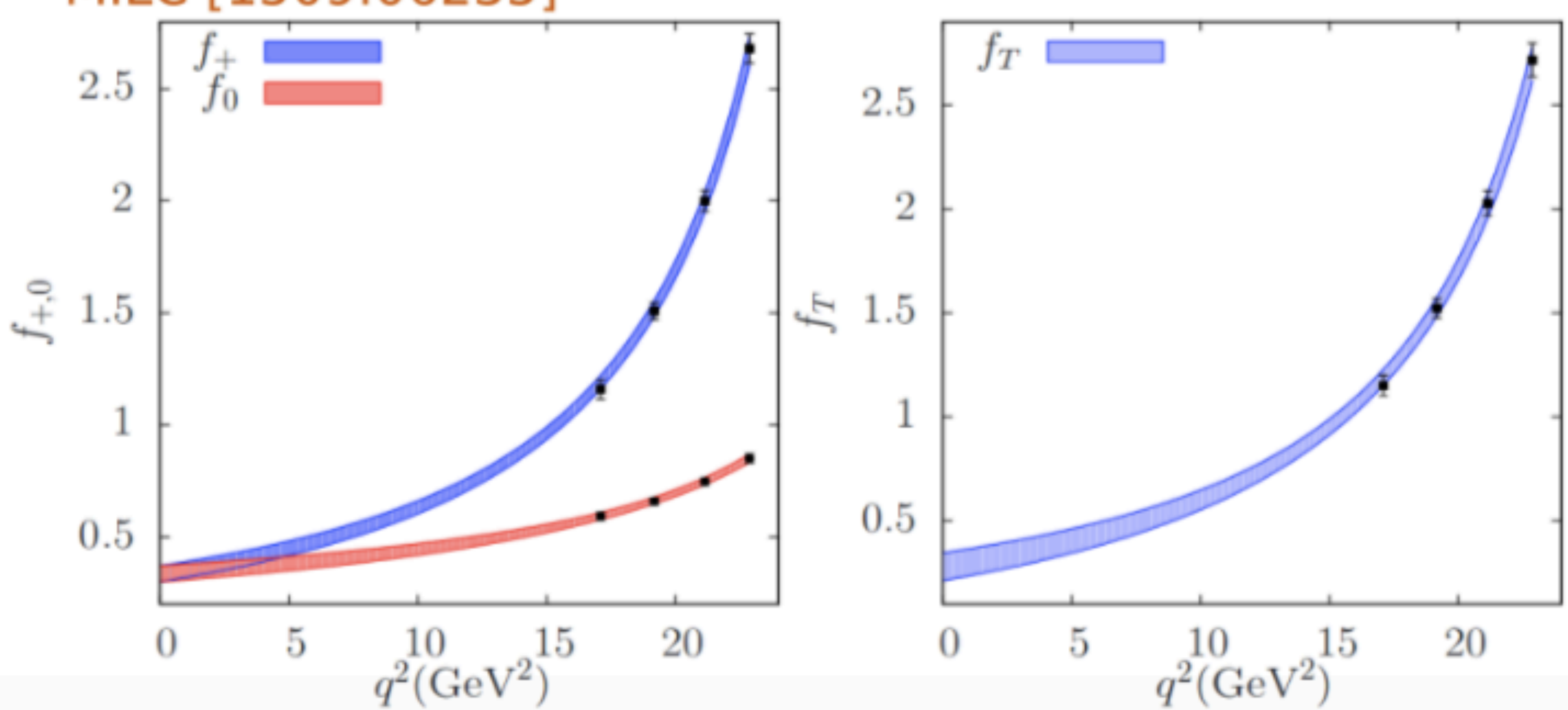
- Use $f_{B_s}^{Latt.} = 224(5)$ MeV and $\mathcal{B}(B_s \to \mu\mu) = 3.0(6)(^3_2) \times 10^{-9}$. [LHCb, 2017]

$$\mathcal{B}(B_s \to \mu^+\mu^-) = \mathcal{F}_{B_s}\left(f_{B_s}, C_{10} - C'_{10}, C_P - C'_P, C_S - C'_S\right)$$

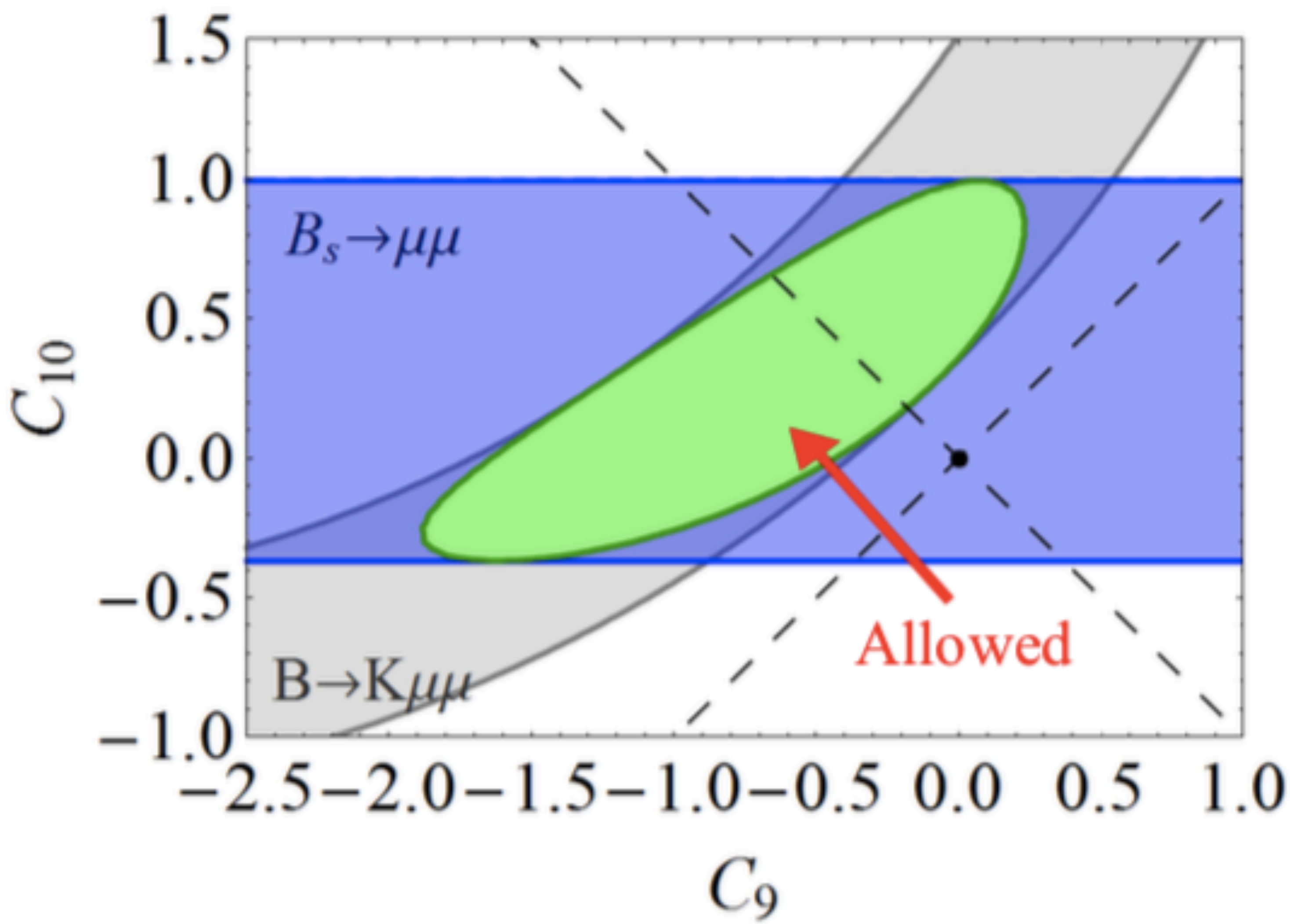
- Use $f_{+,0,T}^{B\to K}(q^2)^{Latt.}$ and $\mathcal{B}(B \to K\mu\mu)_{q^2\in[15,22]\ \mathrm{GeV}^2} = 1.95(16) \times 10^{-7}$. [LHCb, 2016]

$$\frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2}(B \to K\mu^+\mu^-) = \mathcal{F}_{BK}\left(f_{+,0,T}(q^2), C_9 + C'_9, C_{10} + C'_{10}, C_{7,S,P} + C'_{7,S,P}\right)$$

MILC [1509.06235]



Fitting to clean observables



- We find $C_9 = -C_{10} \in (-0.76, -0.04)$ at 2σ.

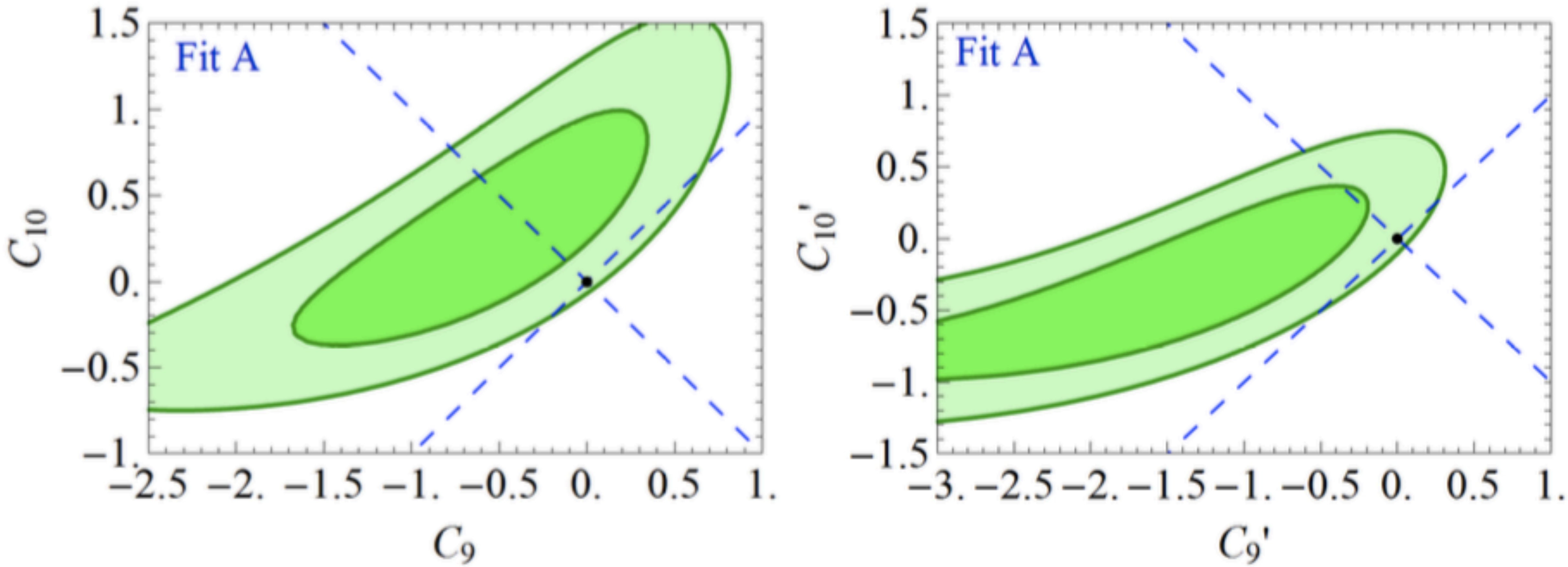
$\Rightarrow$ This value can be used to give **model independent** predictions for $R_{K^{(*)}}$ in the central bin:

$$R_K = 0.82(16) \quad \text{and} \quad R_{K^*} = 0.83(15).$$

$$C_9^{\mu\mu} = -C_{10}^{\mu\mu} \in (-0.85, -0.50)$$

Interestingly...

Different choices of Wilson Coeffs: (C_9, C_{10}) or (C_9', C_{10}')

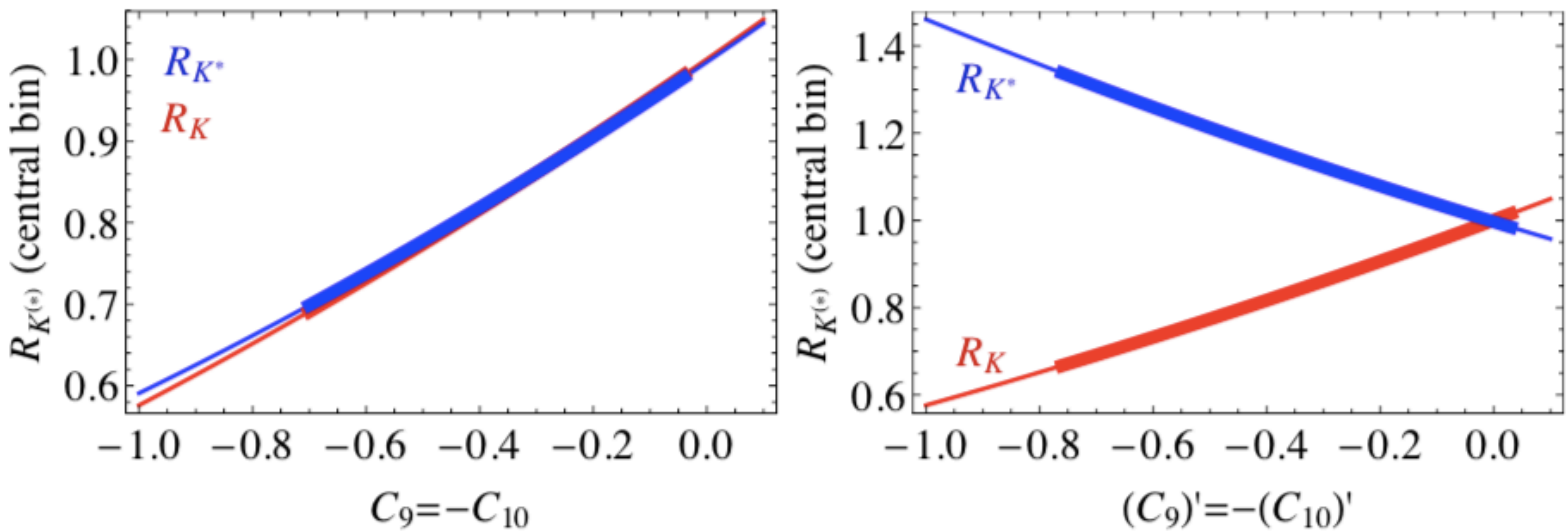


$$\mathcal{O}_9^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell), \qquad \mathcal{O}_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \gamma^5 \ell),$$

$$\boxed{C_9^{\mu\mu} = -C_{10}^{\mu\mu} \in (-0.85, -0.50)}$$

Interestingly…

Model independent predictions for R_K and R_{K^*}:



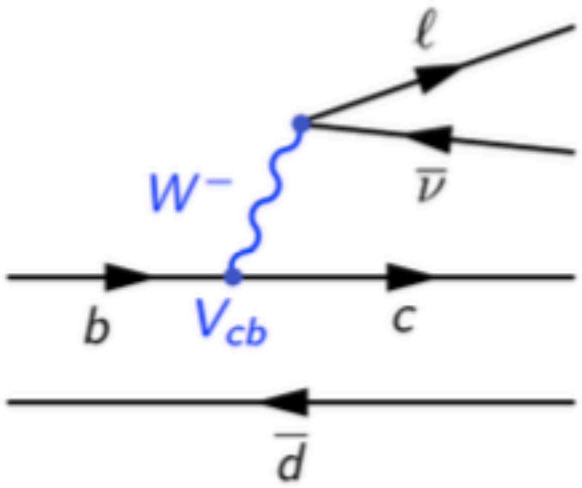
$\Rightarrow$ The scenario $C_9 = -C_{10}$ predicts $R_{K^{(*)}} < 1$, as observed.

$$\boxed{C_9^{\mu\mu} = -C_{10}^{\mu\mu} \in (-0.85, -0.50)}$$

R_D R_{D^*}

- Tree-level process in the SM:

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})}, \quad \ell = e, \mu.$$

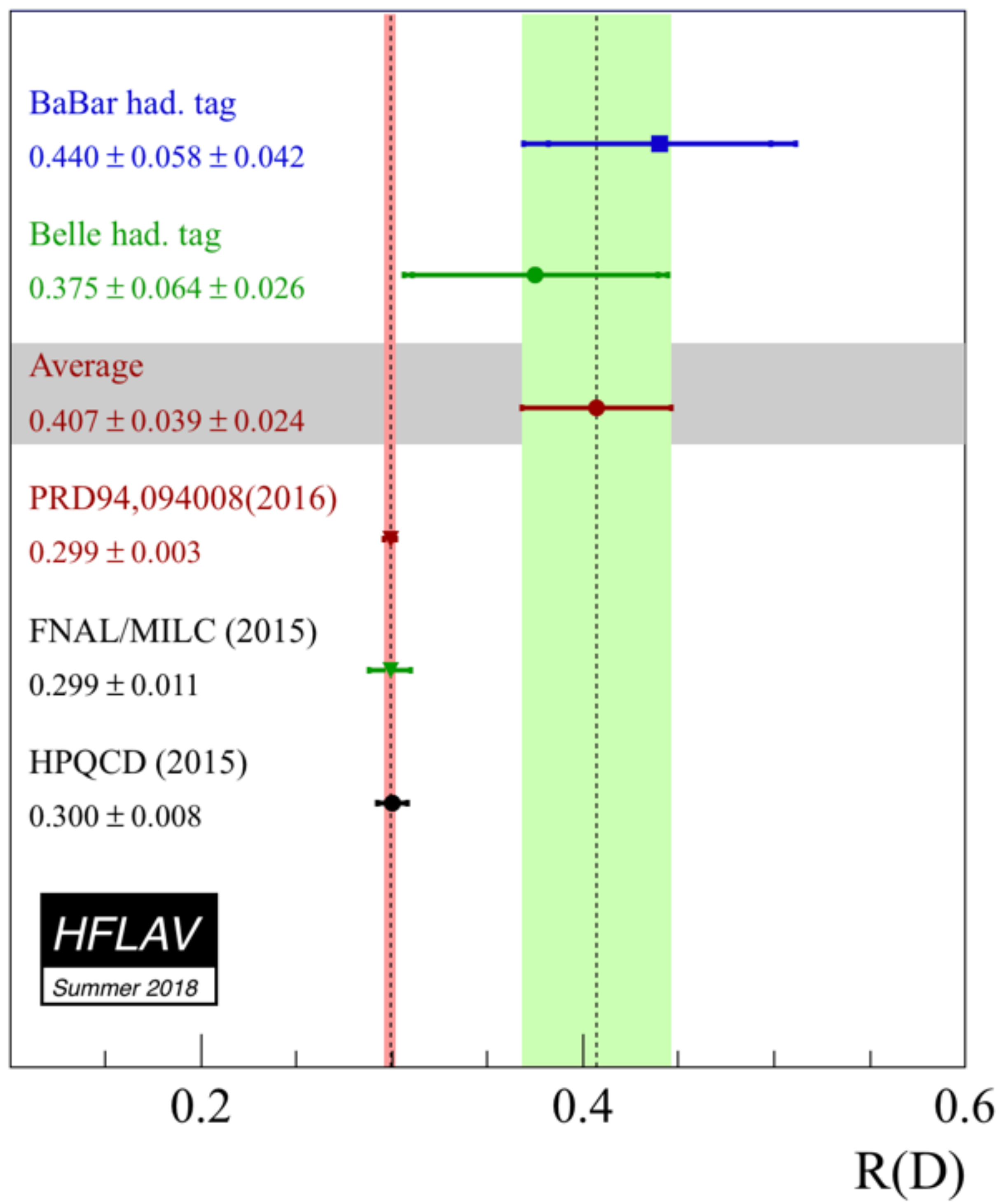


- Non-perturbative QCD $\Longleftrightarrow$ form-factors (Lattice QCD)

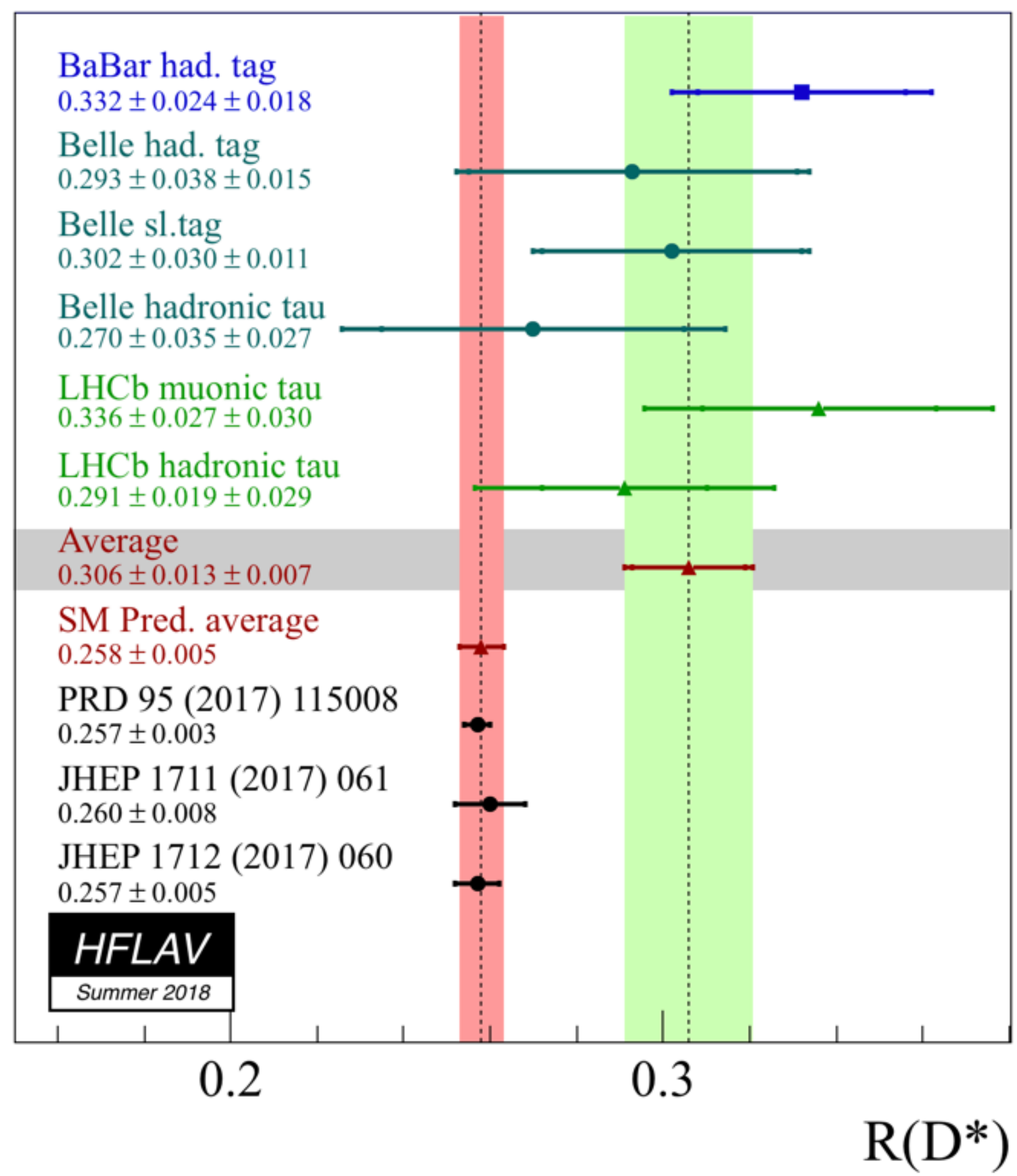
e.g. for $B \to D$, $\quad \langle D|\bar{c}\gamma_\mu b|B\rangle \propto f_{0,+}(q^2)$

- Situation less clear for $B \to D^*$ $\Rightarrow$ (more FFs, less LQCD results) [NP in τ – use angular distribution + HQET of Bernlochner et al 2017]

R_D R_{D^*}

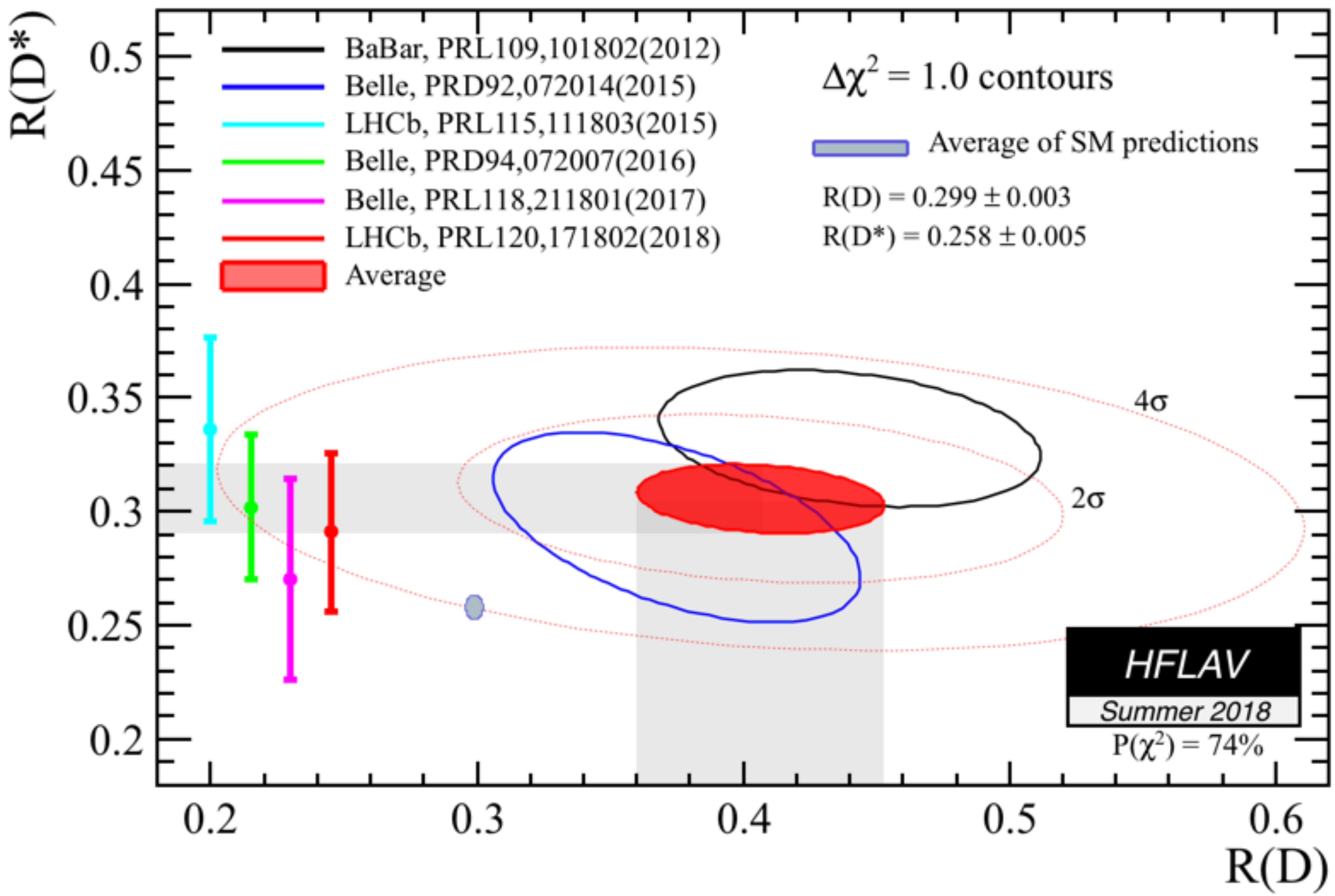


BaBar had. tag
0.440 ± 0.058 ± 0.042
Belle had. tag
0.375 ± 0.064 ± 0.026
Average
0.407 ± 0.039 ± 0.024
PRD94,094008(2016)
0.299 ± 0.003
FNAL/MILC (2015)
0.299 ± 0.011
HPQCD (2015)
0.300 ± 0.008
HFLAV
Summer 2018
0.2
0.4
0.6
R(D)



BaBar had. tag
0.332 ± 0.024 ± 0.018
Belle had. tag
0.293 ± 0.038 ± 0.015
Belle sl.tag
0.302 ± 0.030 ± 0.011
Belle hadronic tau
0.270 ± 0.035 ± 0.027
LHCb muonic tau
0.336 ± 0.027 ± 0.030
LHCb hadronic tau
0.291 ± 0.019 ± 0.029
Average
0.306 ± 0.013 ± 0.007
SM Pred. average
0.258 ± 0.005
PRD 95 (2017) 115008
0.257 ± 0.003
JHEP 1711 (2017) 061
0.260 ± 0.008
JHEP 1712 (2017) 060
0.257 ± 0.005
HFLAV
Summer 2018
0.2
0.3
R(D*)

R_D R_{D^*}



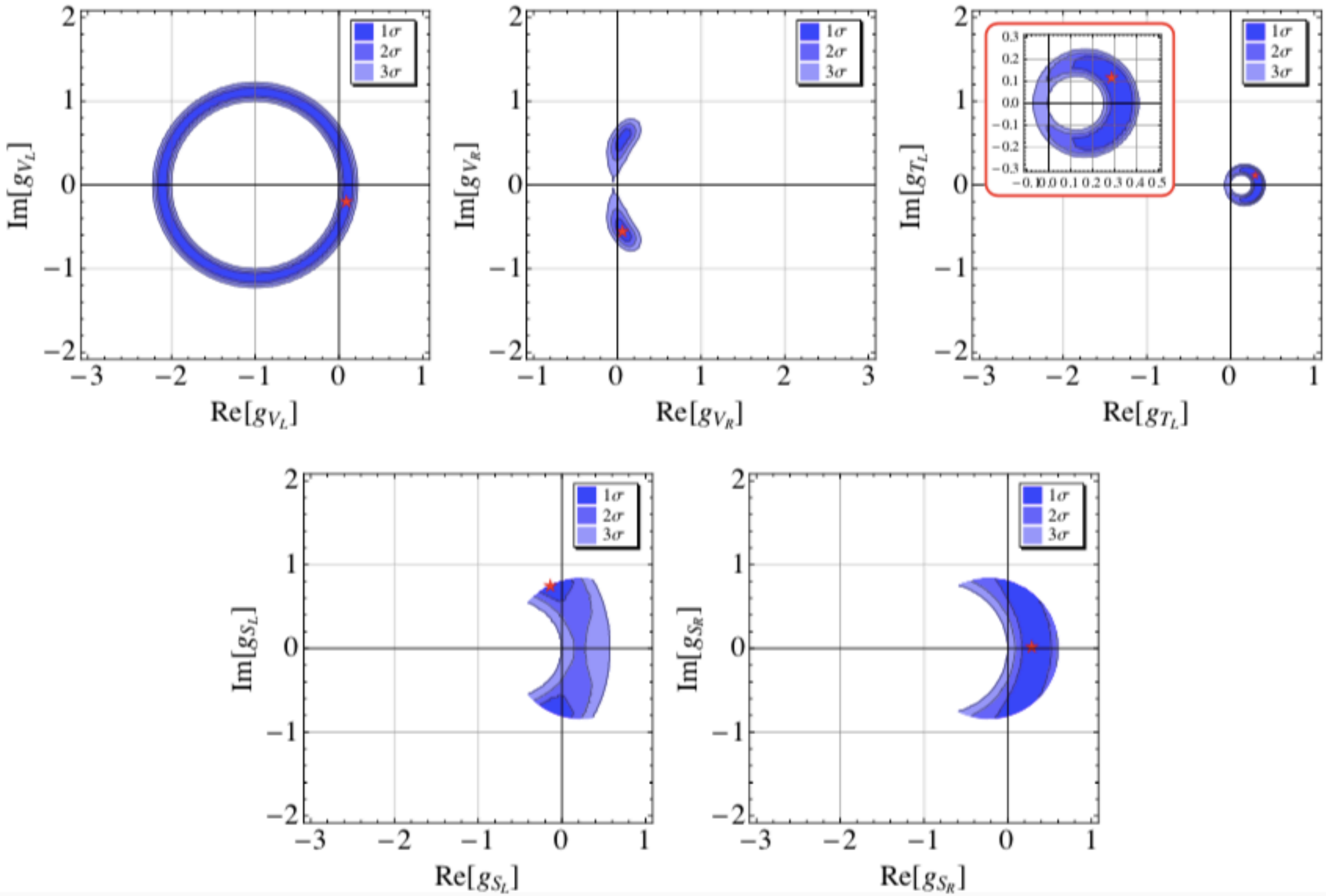
R(D*)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.2
0.3
0.4
0.5
0.6
R(D)
BaBar, PRL109,101802(2012)
Belle, PRD92,072014(2015)
LHCb, PRL115,111803(2015)
Belle, PRD94,072007(2016)
Belle, PRL118,211801(2017)
LHCb, PRL120,171802(2018)
Average
Δχ² = 1.0 contours
Average of SM predictions
R(D) = 0.299 ± 0.003
R(D*) = 0.258 ± 0.005
4σ
2σ
HFLAV
Summer 2018
P(χ²) = 74%

Effective theory

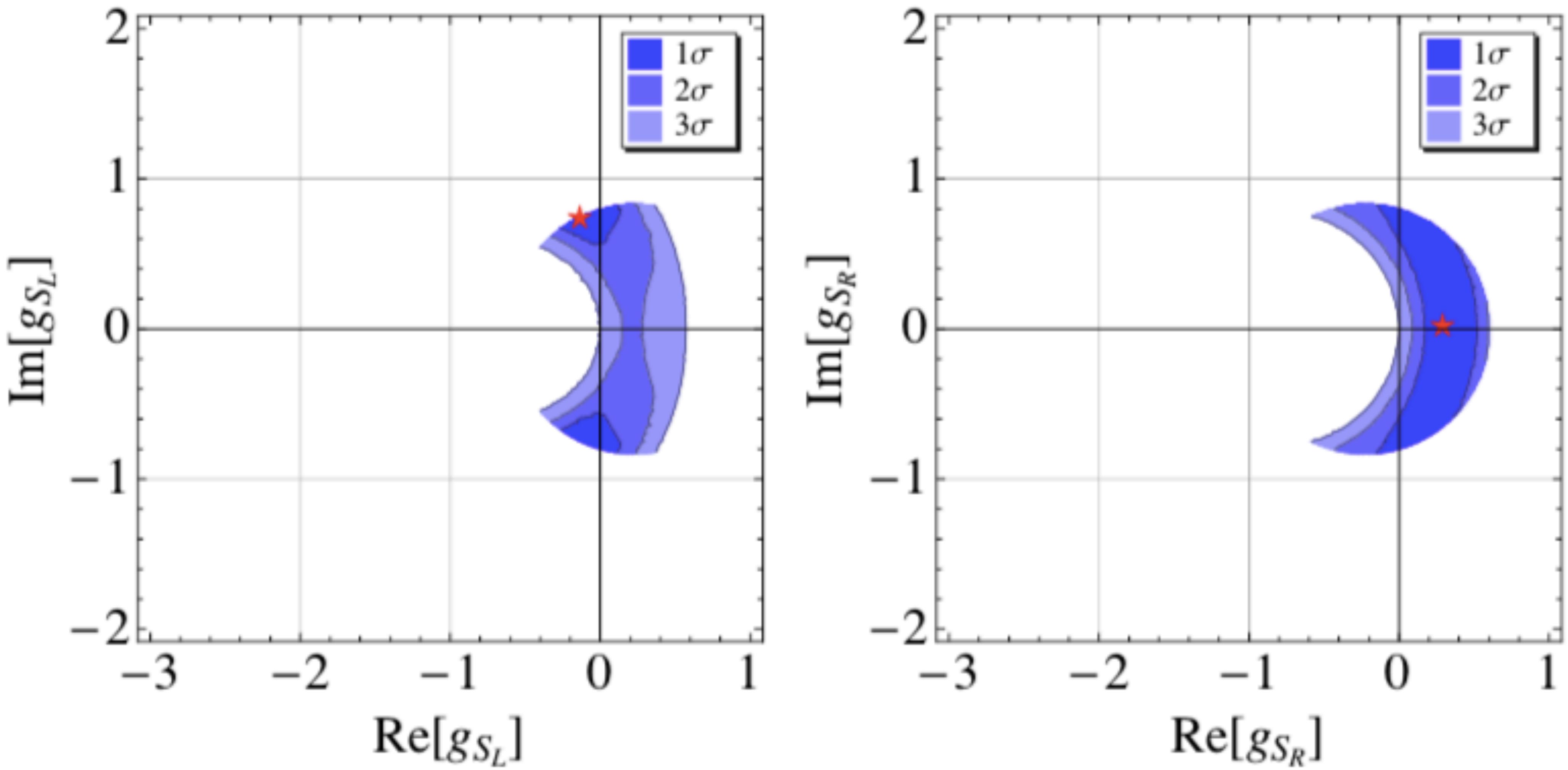
$$\mathcal{H}_{\text{eff}} = \sqrt{2} G_F V_{cb} \big[(1 + g_V)(\bar{c}\gamma_\mu b)(\bar{\ell}_L \gamma^\mu \nu_L) + (-1 + g_A)(\bar{c}\gamma_\mu\gamma_5 b)(\bar{\ell}_L\gamma^\mu \nu_L) \\ + g_S(\bar{c}b)(\bar{\ell}_R \nu_L) + g_P(\bar{c}\gamma_5 b)(\bar{\ell}_R\nu_L) \\ + g_T(\bar{c}\sigma_{\mu\nu} b)(\bar{\ell}_R\sigma^{\mu\nu}\nu_L) + g_{T5}(\bar{c}\sigma_{\mu\nu}\gamma_5 b)(\bar{\ell}_R \sigma^{\mu\nu}\nu_L)\big] + \text{h.c.}$$

$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{cb} \big[(1 + g_{V_L})(\bar{c}_L\gamma_\mu b_L)(\bar{\ell}_L \gamma^\mu \nu_L) + g_{V_R}(\bar{c}_R\gamma_\mu b_R)(\bar{\ell}_L\gamma^\mu\nu_L) \\ + g_{S_L}(\bar{c}_R b_L)(\bar{\ell}_R\nu_L) + g_{S_R}(\bar{c}_L b_R)(\bar{\ell}_R\nu_L) \\ + g_{T_L}(\bar{c}_R\sigma_{\mu\nu} b_L)(\bar{\ell}_R\sigma^{\mu\nu}\nu_L)\big] + \text{h.c.}\,,$$

Effective theory at work



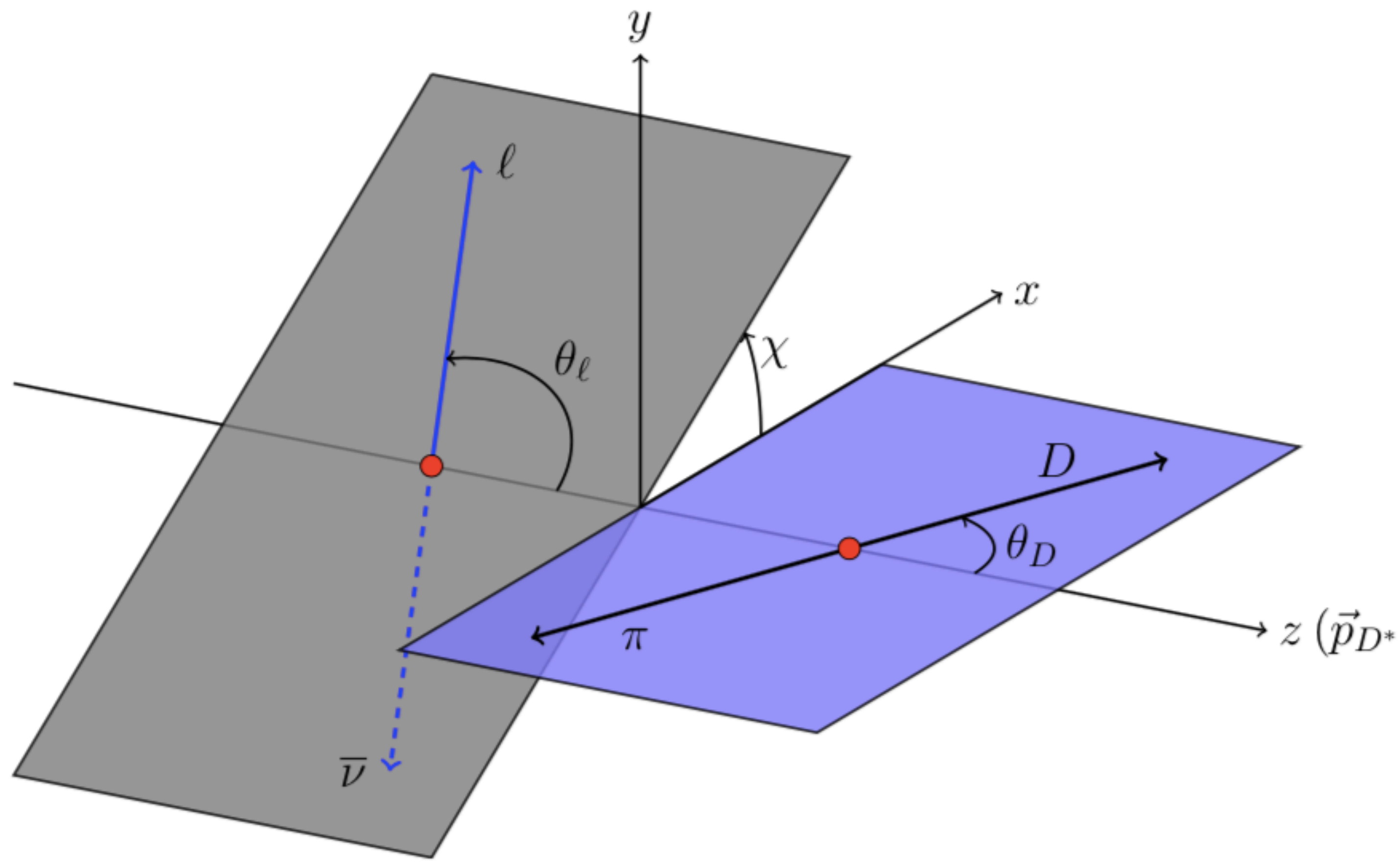
Effective theory at work



$$\mathcal{B}(B_c \to \tau\bar{\nu}) = \tau_{B_c}\frac{m_{B_c} f_{B_c}^2 G_F^2 |V_{cb}|^2}{8\pi} m_\tau^2 \left(1 - \frac{m_\tau^2}{m_{B_c}^2}\right)^2 \left| 1 + g_{V_L} + \frac{(g_{S_R} - g_{S_L})\, m_{B_c}^2}{m_\tau (m_b + m_c)} \right|^2$$

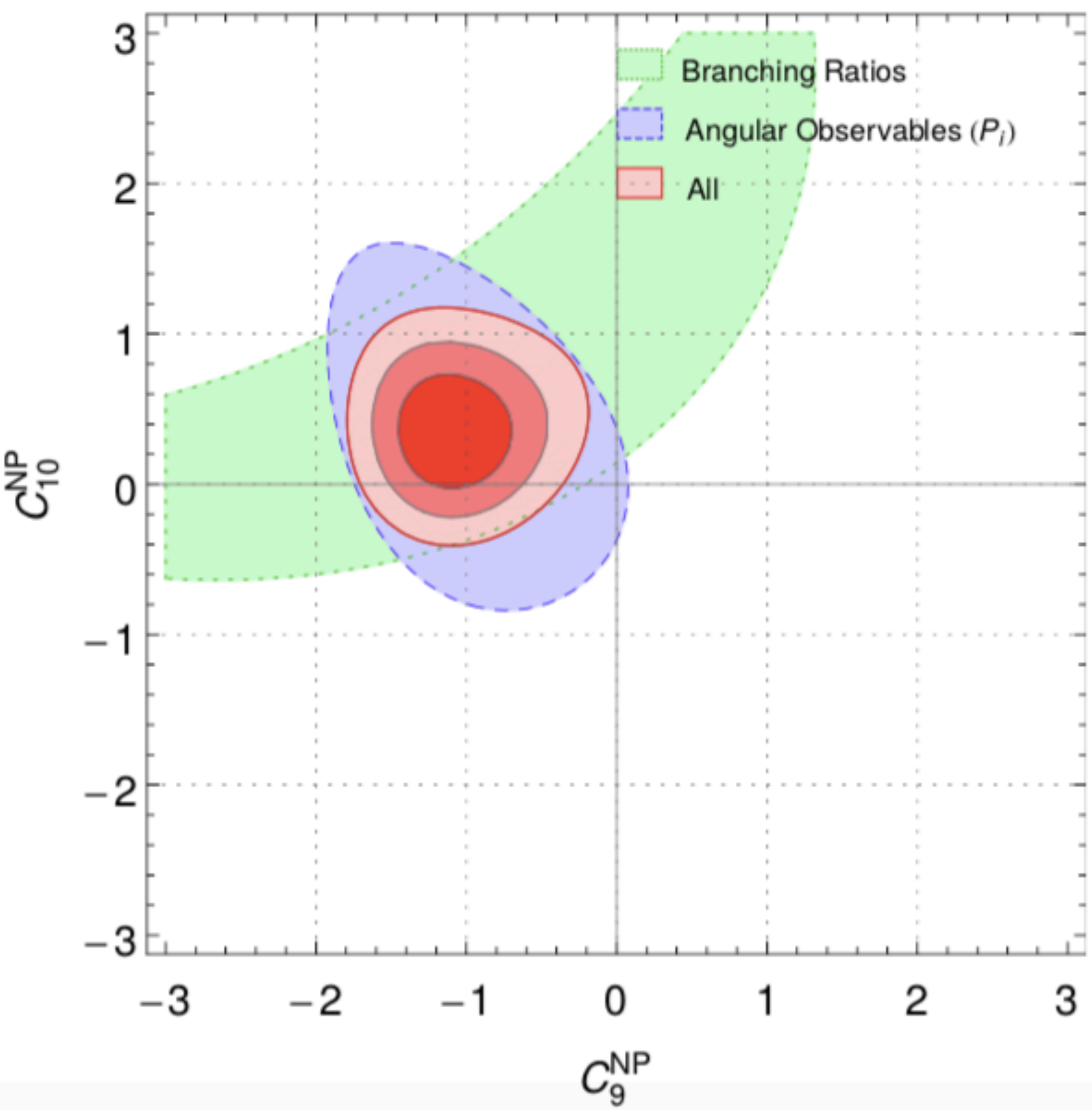
Must be less than 30%-ish in order not to upset τ_{B_c}

Angular analysis (Belle II - 202x)

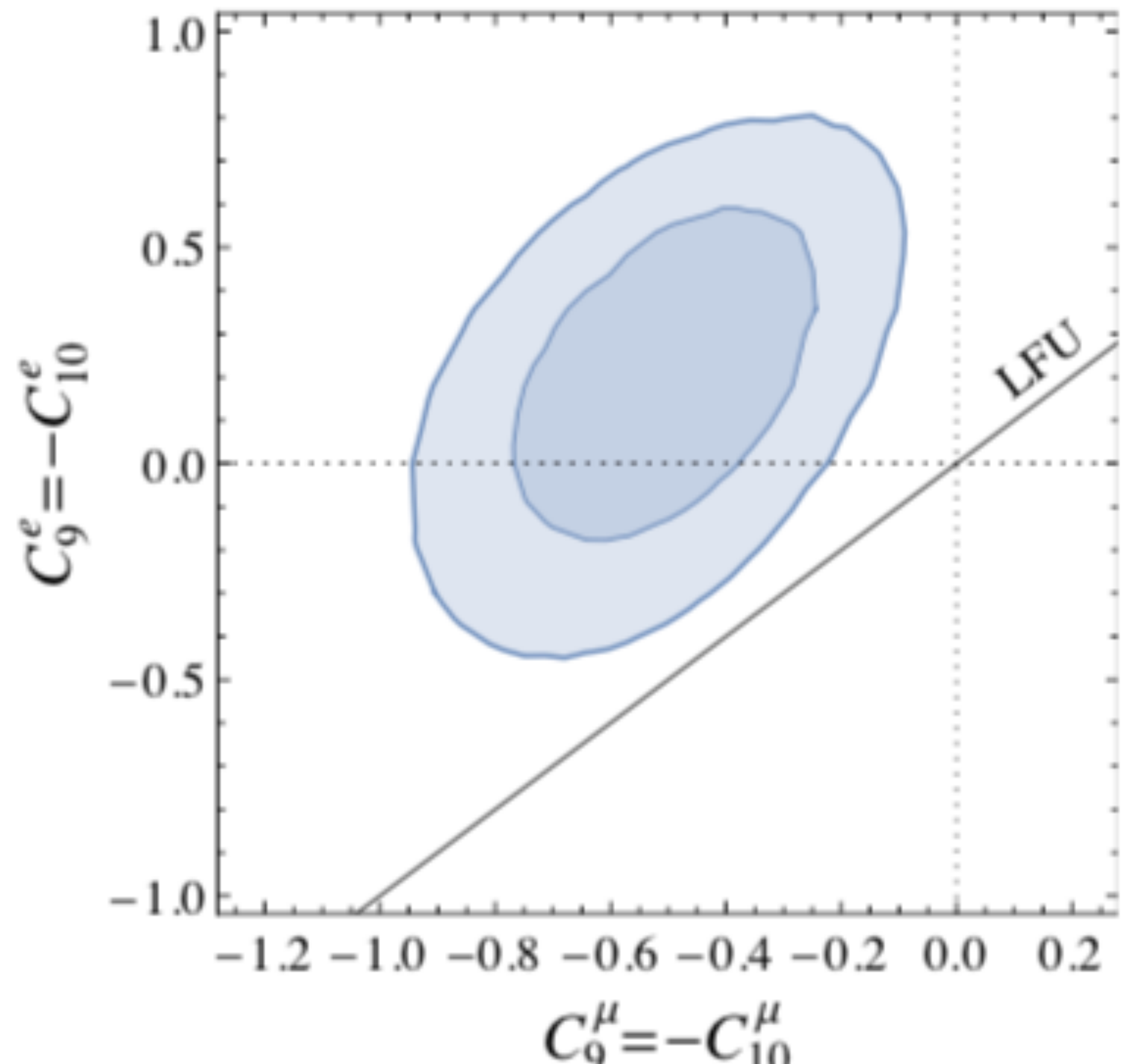


$$\frac{d^4\Gamma}{dq^2 d\cos\theta_D d\cos\theta_\ell d\chi} = \frac{9}{32\pi}\Big\{ I_{1c}\cos^2\theta_D + I_{1s}\sin^2\theta_D$$
$$+ \left[I_{2c}\cos^2\theta_D + I_{2s}\sin^2\theta_D\right]\cos 2\theta_\ell$$
$$+ \left[I_{6c}\cos^2\theta_D + I_{6s}\sin^2\theta_D\right]\cos\theta_\ell$$
$$+ \left[I_3\cos 2\chi + I_9\sin 2\chi\right]\sin^2\theta_\ell\sin^2\theta_D$$
$$+ \left[I_4\cos\chi + I_8\sin\chi\right]\sin 2\theta_\ell\sin 2\theta_D$$
$$+ \left[I_5\cos\chi + I_7\sin\chi\right]\sin\theta_\ell\sin 2\theta_D \Big\}.$$

C_9=-C_{10} for muonic channels

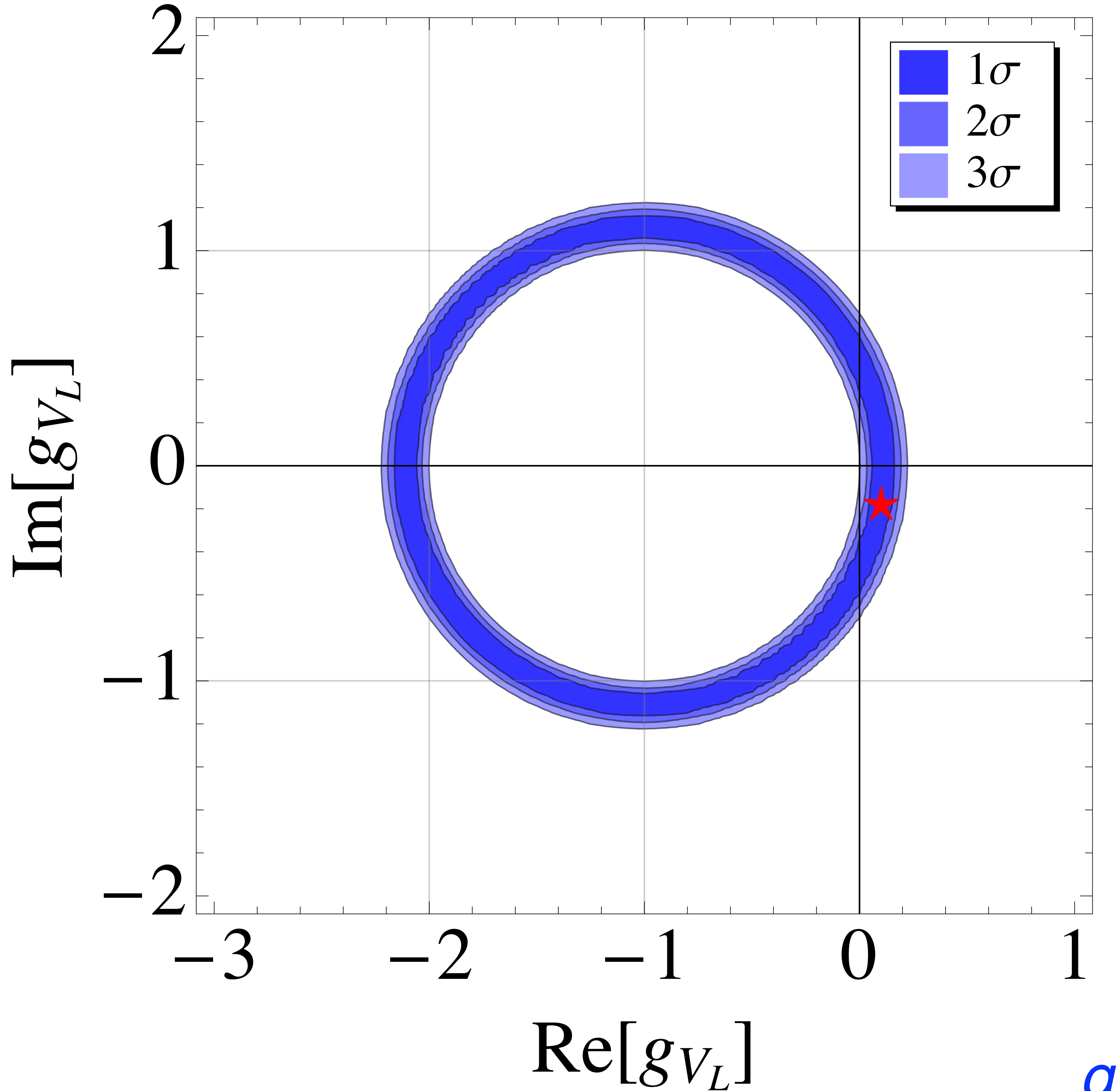


C_9=-C_{10} for muonic channels



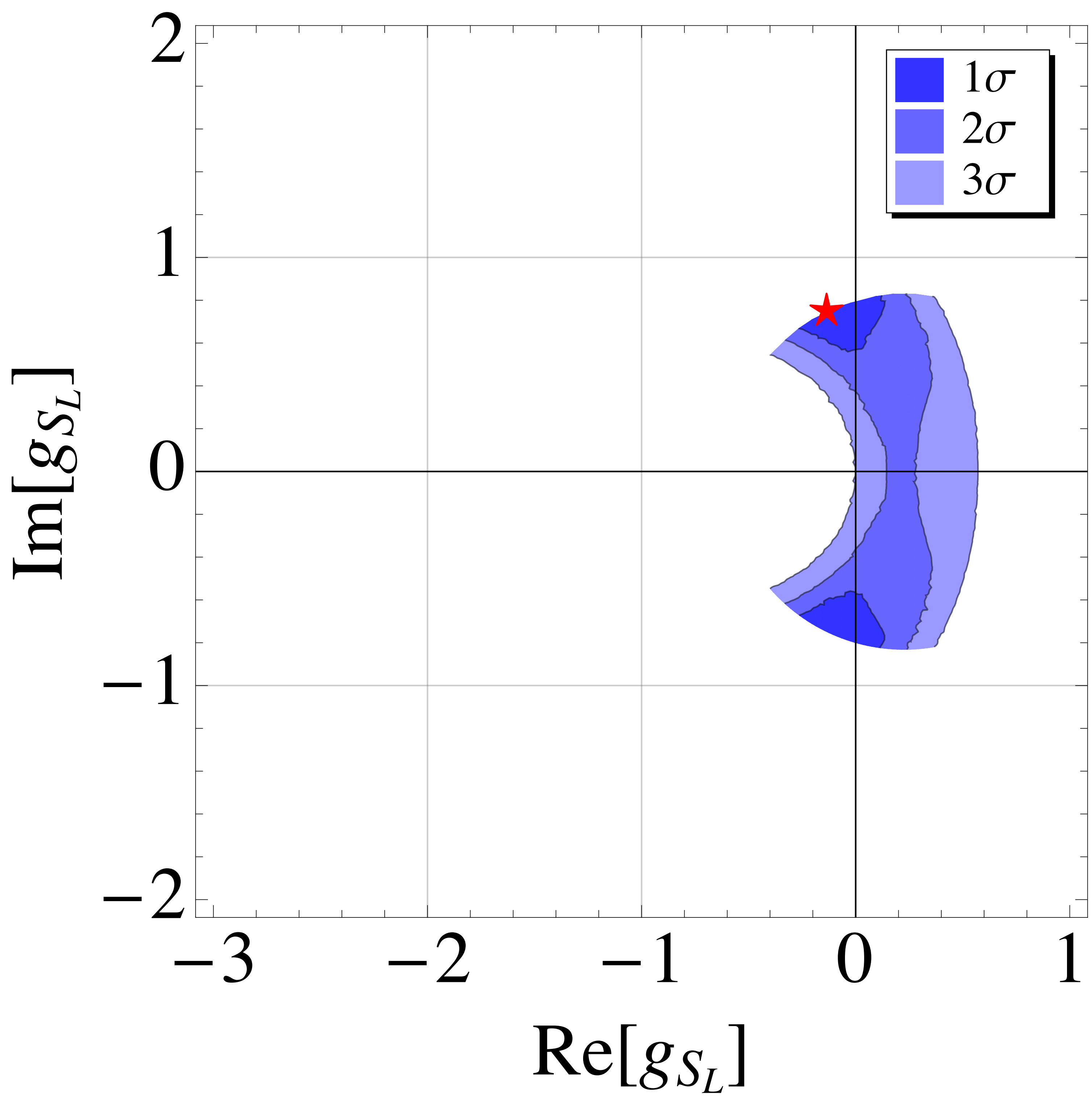
C_9 = (-0.85,-0.50)

g_{V_L} or/and g_{S_L} in tau modes

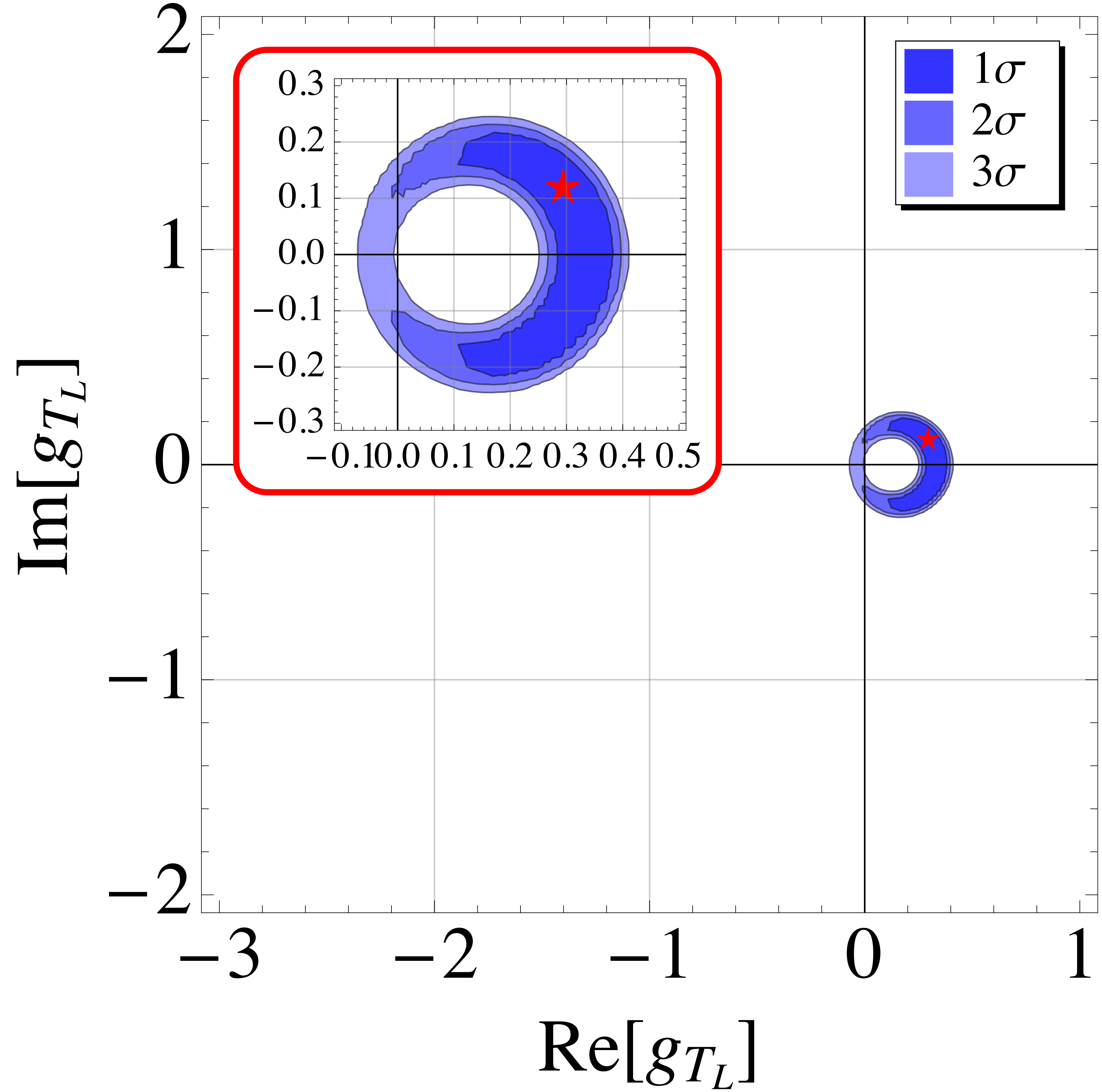


g_{V_L} = (0.09,0.13)

g_{V_L} or g_{S_L} or g_{T_L} in tau modes



g_{V_L} or g_{S_L} or g_{T_L} in tau modes



Common lore - Zurich Guide

NP to CC processes

$$\mathcal{L}_{\rm BSM} = \frac{2c}{\Lambda^2}(\bar{c}_L\gamma_\mu b_L)(\bar{\tau}_L\gamma^\mu\nu_\tau) + h.c.$$

$c_i = 1 \quad \to \quad \Lambda \sim 3.7$ TeV

$c_i = \mathrm{V_{cb}} \quad \to \quad \Lambda \sim 0.7$ TeV

$c_i = \mathrm{V_{cb}}/4\pi \quad \to \quad \Lambda \sim 0.2$ TeV

$$C_T\ (\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L)$$

$$Q^i_L = \begin{pmatrix} V^*_{ji}u^j_L \\ d^i_L \end{pmatrix}$$

NP in FCNC

$$\mathcal{L} \supset \frac{c_i}{\Lambda^2}(\bar{s}_L\gamma^\alpha b_L)(\bar{\mu}_L\gamma_\alpha\mu_L) + h.c.$$

$c_i = 1 \quad \to \quad \Lambda \sim 31$ TeV

$c_i = \mathrm{V_{ts}} \quad \to \quad \Lambda \sim 6$ TeV

$c_i = \mathrm{V_{ts}}/4\pi \quad \to \quad \Lambda \sim 0.5$ TeV

$$C_T\ (\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L) + C_S\ (\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)$$

Zurich Guide (Models V-A)

Effective theory

$$\boxed{\frac{1}{v^2}\lambda^q_{ij}\lambda^\ell_{\alpha\beta}\left[C_T\ (\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L)+C_S\ (\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)\right]}$$

CC and NC NC

- Dominant effect in 3rd generation
- Small effects with lighter fermions
- Mixing CKMish

$$\lambda^\ell = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \lambda_{\mu\mu} & \lambda_{\tau\mu} \\ 0 & \lambda_{\tau\mu} & 1 \end{pmatrix} \qquad \lambda^q = \begin{pmatrix} 0 & 0 & \lambda_{bs}\frac{V_{ub}}{V_{cb}} \\ 0 & \lambda_{ss} & \lambda_{bs} \\ \lambda_{bs}\frac{V_{ub}}{V_{cb}} & \lambda_{bs} & 1 \end{pmatrix}$$

$$\text{Parameters}: \quad C_S \quad C_T \quad \lambda_{bs} = \mathcal{O}(V_{ts}) \quad \lambda_{ss} = \mathcal{O}(\lambda^2_{bs}) \quad \lambda_{\mu\mu} = \mathcal{O}(\lambda^2_{\mu\tau})$$

Zurich Guide (Models V-A)

Tricky part

$$\frac{R_{D^{(*)}}}{R_{D^{(*)}}^{\rm SM}} \simeq 1 + 2C_T\left(1 - \lambda^q_{sb}\frac{V_{tb}}{V_{ts}}\right) \approx 1.24(5)$$

$$33 - \text{term}: -\frac{C_T}{v^2}(\overline{Q}^3_L\gamma_\mu\sigma^a Q^3_L)(\overline{L}^3_L\gamma_\mu\sigma^a L^3_L)$$

$$32 - \text{term}: -\frac{C_T}{v^2}\lambda^q_{bs}(\overline{Q}^3_L\gamma_\mu\sigma^a Q^2_L)(\overline{L}^3_L\gamma_\mu\sigma^a L^3_L)$$

$$Q^3_L = \begin{pmatrix} V^*_{tb}t_L + V^*_{cb}c_L + V^*_{ub}u_L \\ b_L \end{pmatrix}$$

Zurich Guide (Models V-A)

Tricky part

$$\frac{R_{D^{(*)}}}{R^{\mathrm{SM}}_{D^{(*)}}} \simeq 1 + 2C_T\left(1 - \lambda^q_{sb}\frac{V_{tb}}{V_{ts}}\right) \approx 1.24(5)$$

$$33 - \mathrm{term}: -\frac{C_T}{v^2}(\overline{Q}^3_L\gamma_\mu\sigma^a Q^3_L)(\overline{L}^3_L\gamma_\mu\sigma^a L^3_L)$$

$$32 - \mathrm{term}: -\frac{C_T}{v^2}\lambda^q_{bs}(\overline{Q}^3_L\gamma_\mu\sigma^a Q^2_L)(\overline{L}^3_L\gamma_\mu\sigma^a L^3_L)$$

Tiny

$$Q^3_L = \begin{pmatrix} V^*_{tb}t_L + V^*_{cb}c_L + V^*_{ub}u_L \\ b_L \end{pmatrix}$$

Needs 0.1

too large NP at 700 GeV - Sic! (direct searches)

Zurich Guide (Models V-A)

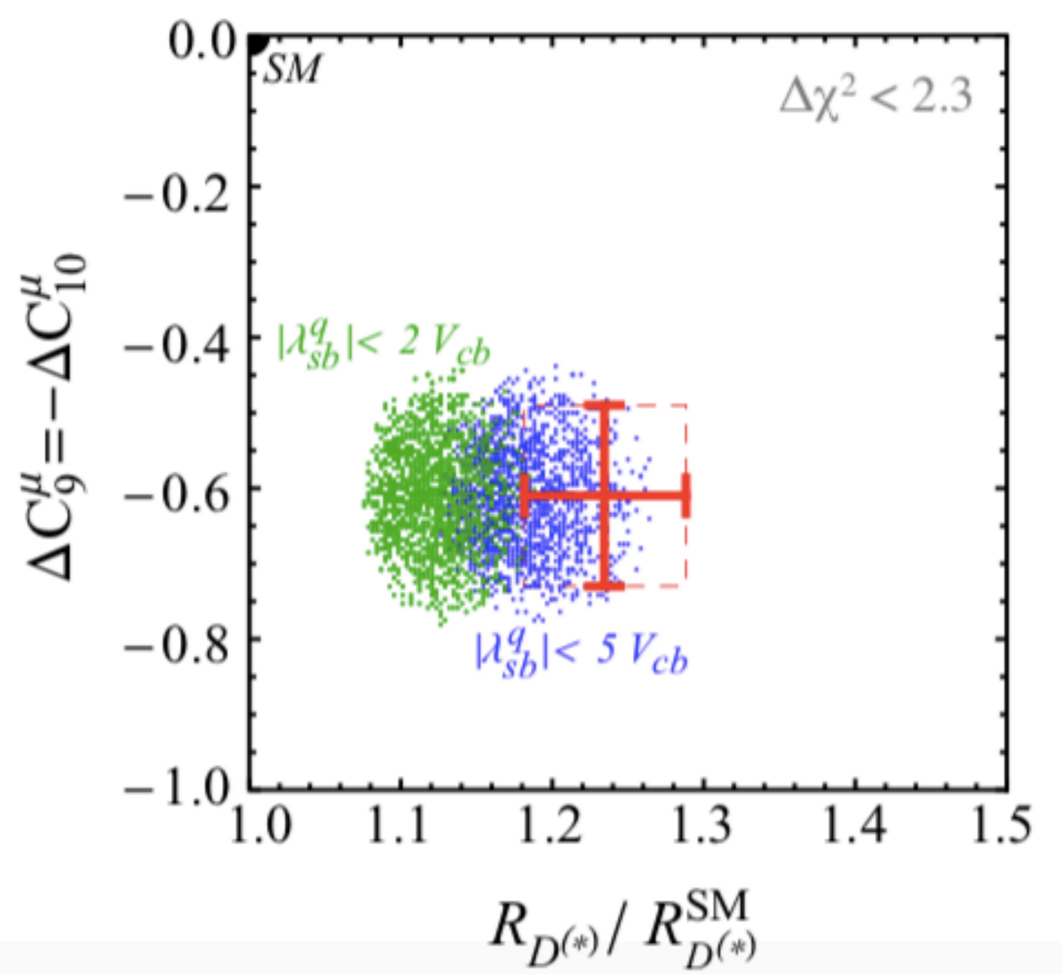
Tricky part

$$\frac{R_{D^{(*)}}}{R_{D^{(*)}}^{\mathrm{SM}}} \simeq 1 + 2C_T\left(1 - \lambda^q_{sb}\frac{V_{tb}}{V_{ts}}\right) \approx 1.24(5)$$

$$33-\text{term}: -\frac{C_T}{v^2}(\overline{Q}^3_L\gamma_\mu\sigma^a Q^3_L)(\overline{L}^3_L\gamma_\mu\sigma^a L^3_L)$$

$$32-\text{term}: -\frac{C_T}{v^2}\lambda^q_{bs}(\overline{Q}^3_L\gamma_\mu\sigma^a Q^2_L)(\overline{L}^3_L\gamma_\mu\sigma^a L^3_L)$$

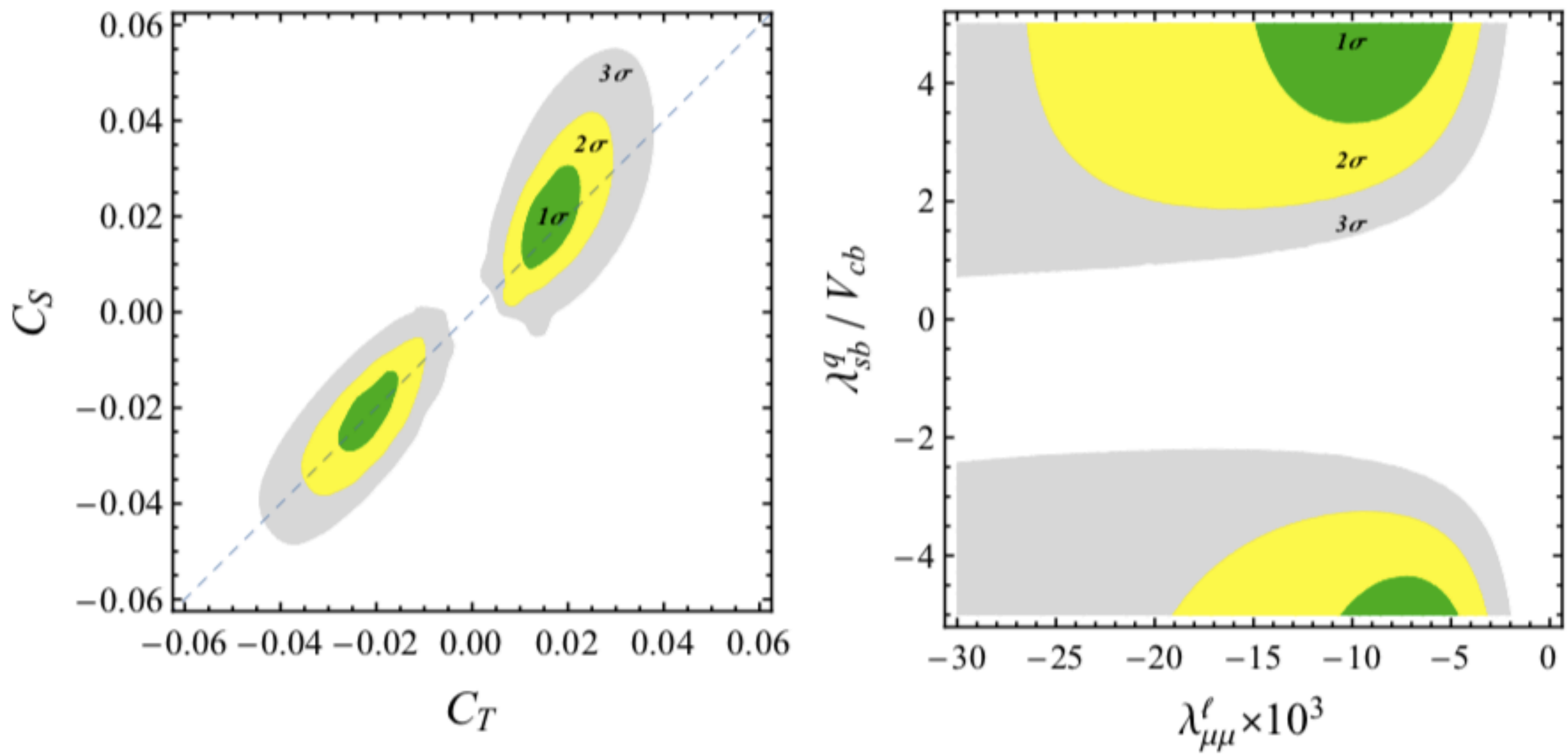
Large = few V_{cb}



Beware of $B \to K^{(*)}\nu\nu$!

$$(C_T - C_S)\lambda_{bs}(\bar{b}_L\gamma_\mu s_L)(\bar{\nu}_\tau\gamma^\mu\nu_\tau)$$

Zurich Guide (Models V-A)



A simple model for R_K R_{K^*}

$$\mathcal{L}_{Z'} = g_{bs}(\bar{s}\gamma^\mu P_L b)Z'_\mu + g_{\mu\mu}(\bar{\mu}\gamma^\mu P_L \mu)Z'_\mu$$

A simple model for R_K R_{K^*}

$$\mathcal{L}_{Z'} = g_{bs}(\bar{s}\gamma^\mu P_L b)Z'_\mu + g_{\mu\mu}(\bar{\mu}\gamma^\mu P_L \mu)Z'_\mu$$

What model can have this right?

- Eg. Add an extra gauge symmetry group $U(1)'$

$$\mathcal{L}_{U(1)'} = g' Q_q(\bar{q}_L\gamma^\mu q_L)Z'_\mu + g' Q_\ell(\bar{\ell}_L\gamma^\mu \ell_L)Z'_\mu$$

$$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \qquad \ell_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$$

- Impose 3^{rd}-gen of quarks and 2^{nd}-gen of leptons to be charged under $U(1)'$

A simple model for R_K R_{K^*}

$$\mathcal{L}_{U(1)'} = g_q(\bar{q}_L^{(3)}\gamma^\mu q_L^{(3)}) Z'_\mu + g_\ell(\bar{\ell}_L^{(2)}\gamma^\mu \ell_L^{(2)}) Z'_\mu$$

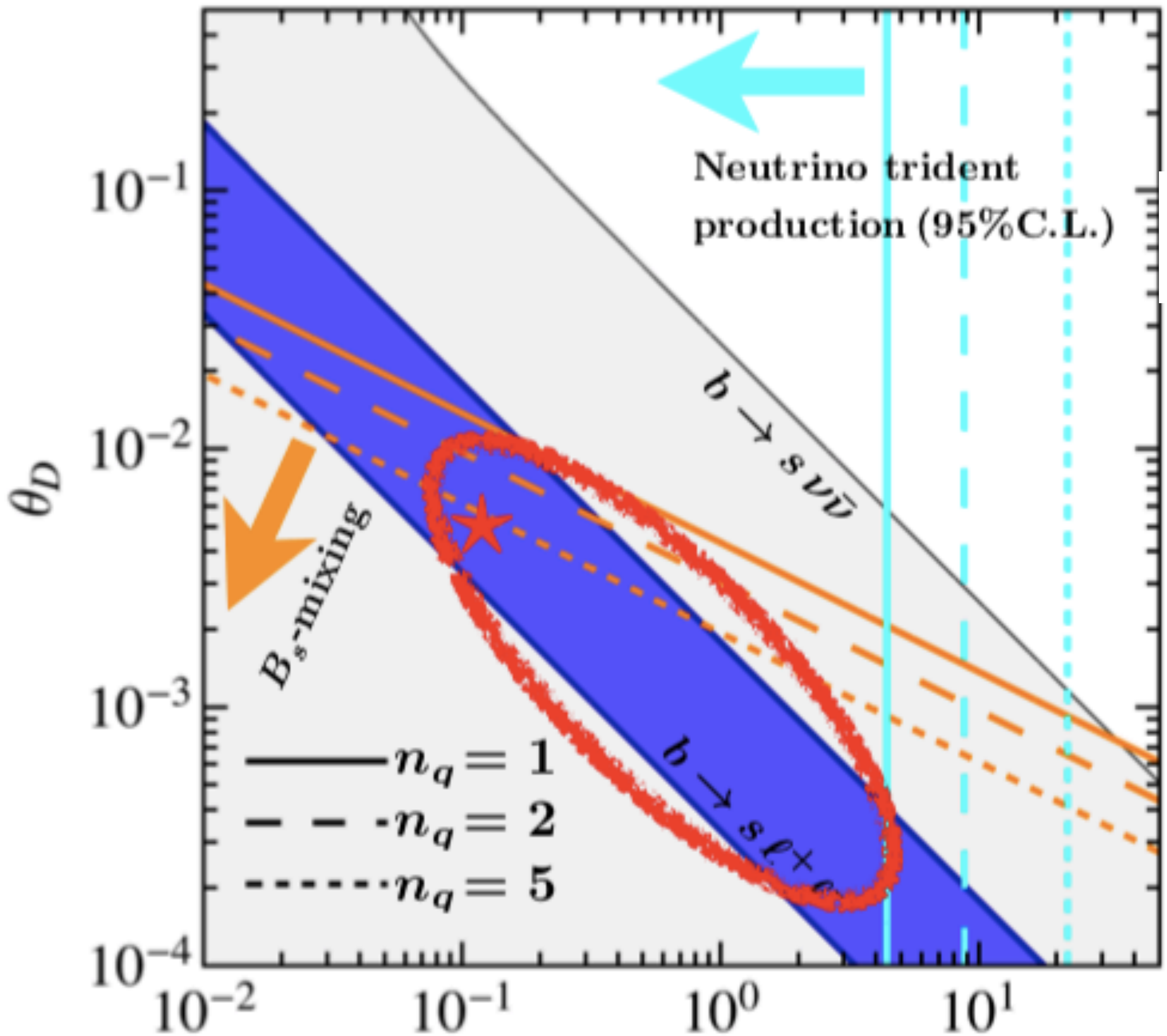
$$q_L^{(3)} = \begin{pmatrix} t_L \\ b_L \end{pmatrix} \qquad \ell_L^{(2)} = \begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix} \qquad g_f = Q_f\, g'$$

bs coupling arises through mixing in the mass eigenbasis

$$\begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix}_{\mathrm{gauge}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix}_{\mathrm{mass}}$$

Other fields don't feel $U(1)'$

A simple model for R_K R_{K^*}

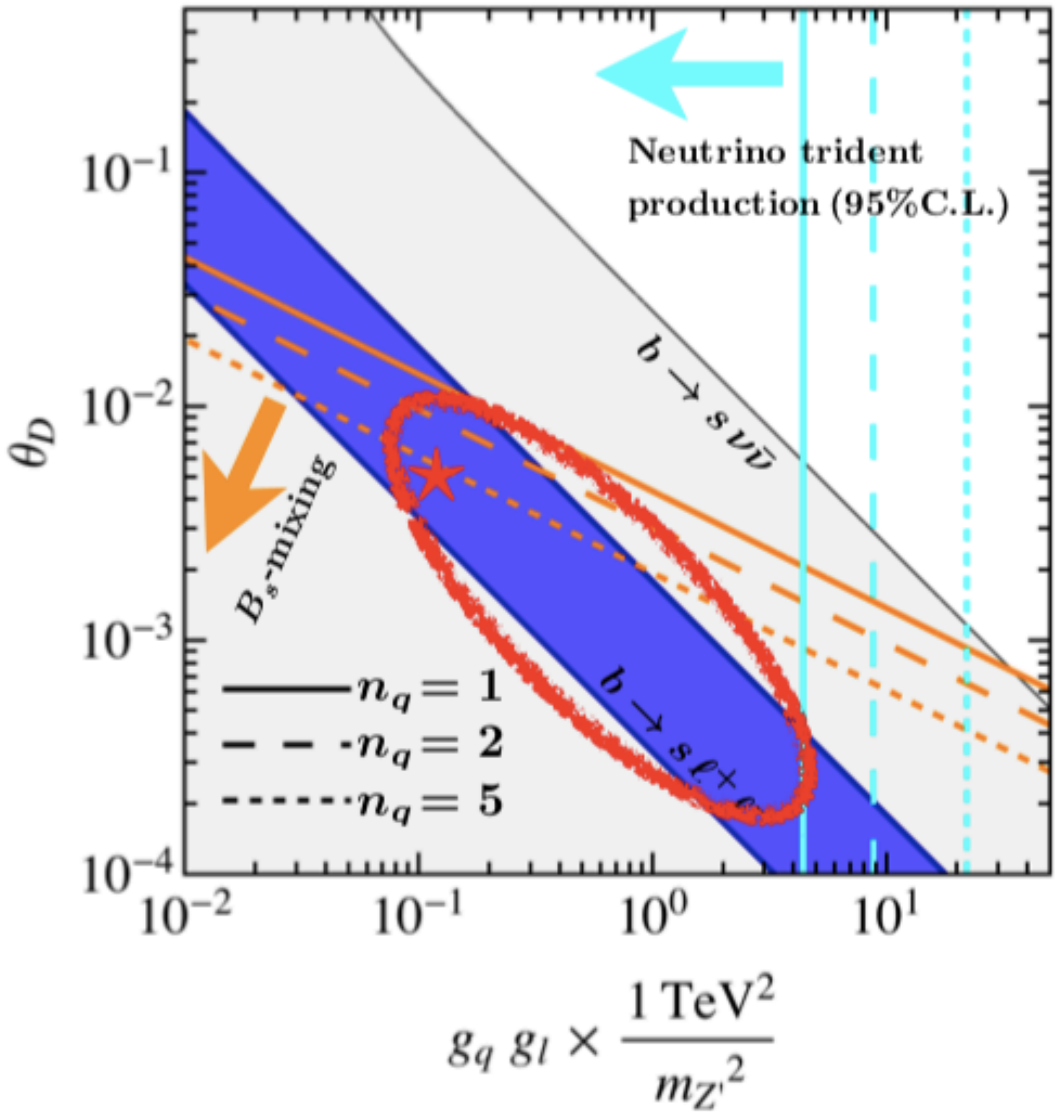


$n_q = g_q / g_\ell$

$$g_q\, g_l \times \frac{1\,\mathrm{TeV}^2}{m_{Z'}{}^2}$$

$$\frac{g_q g_\ell}{m_{Z'}^2} = 0.12/\mathrm{TeV}^2 \qquad \theta = 0.005$$

A simple model for R_K R_{K^*}



$$\mathcal{L}_{U(1)'} = g_q\,(\bar{q}_L^3\gamma^\mu q_L^3)\,Z'_\mu + g_\ell\,(\bar{\ell}_L^2\gamma^\mu \ell_L^2)\,Z'_\mu + g_\chi\,(\bar{\chi}\gamma^\mu\chi)\,Z'_\mu$$

Leptoquarks

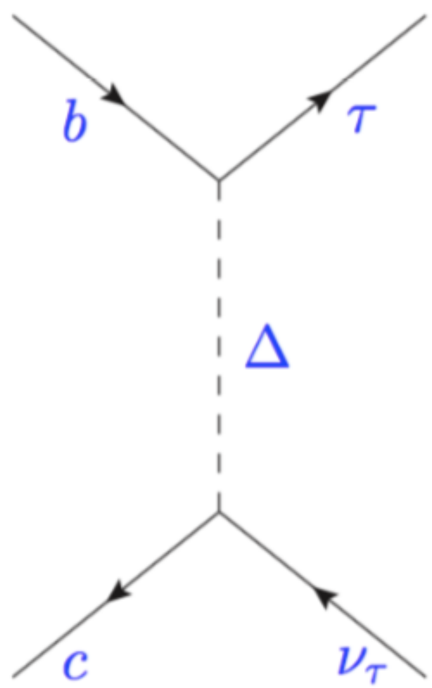
- Bosons which couple both to leptons and quarks
- Arise in GUT scenarios as gauge boson of $\mathcal{G}_{\rm GUT}$
  e.g. $\mathcal{G}_{\rm GUT}$: $SU(5), SO(10), SU(4) \otimes SU(2)_L \otimes SU(2)_R$
- 6 scalar and 6 vector LQ's
- Generally very heavy, but some can be light, $m_{\rm LQ} \simeq \mathcal{O}(1\,)$

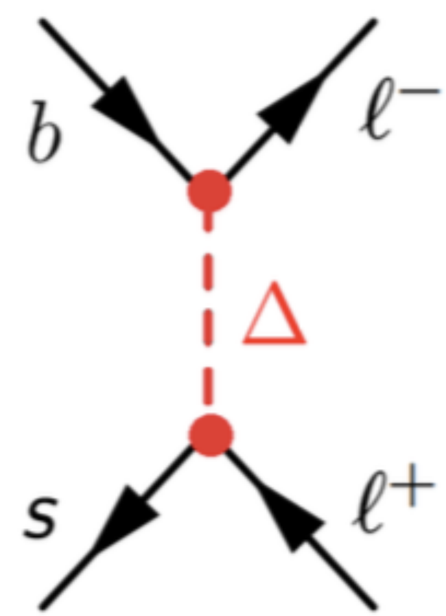
Symbol	Spin	$(SU(3)_c, SU(2)_L)_{U(1)_Y}$
S_1	0	$(\bar{3}, 1)_{1/3}$
S_3	0	$(\bar{3}, 3)_{1/3}$
R_2	0	$(\bar{3}, 2)_{7/6}$
$\widetilde{R}_2$	0	$(\bar{3}, 2)_{1/6}$
U_1	1	$(\bar{3}, 1)_{2/3}$
U_3	1	$(\bar{3}, 3)_{2/3}$

S_3 $(3,3)_{1/3}$

$$\mathcal{L}_{S_3} = y_L^{ij}\,\overline{Q_i^C} i\tau_2(\tau_k S_3^k) L_j + \text{h.c.}$$

$$\mathcal{L}_{S_3} = -\,y_L^{ij}\,\overline{d_{L\,i}^C}\nu_{L\,j}\,S_3^{(1/3)} - \sqrt{2}\,y_L^{ij}\,\overline{d_{L\,i}^C}\ell_{L\,j}\,S_3^{(4/3)}$$
$$+\sqrt{2}\,(V^* y_L)_{ij}\,\overline{u_{L\,i}^C}\nu_{L\,j}\,S_3^{(-2/3)} - (V^* y_L)_{ij}\,\overline{u_{L\,i}^C}\ell_{L\,j}\,S_3^{(1/3)} + \text{h.c.}$$





$S_3 \qquad (3,3)_{1/3}$

$$\mathcal{L}_{S_3} = y_L^{ij}\, \overline{Q_i^C} i\tau_2(\tau_k S_3^k) L_j + \text{h.c.}$$

Indeed

$$C_9^{kl} = -C_{10}^{kl} = \frac{\pi v^2}{V_{tb}V_{ts}^* \alpha_{\rm em}} \frac{y_L^{bk}\left(y_L^{sl}\right)^*}{m_{S_3}^2} \qquad \checkmark$$

$$g_{V_L} = -\frac{v^2\, y_L^{b\ell'}\,(V y_L^*)_{c\ell}}{4V_{cb}\, m_{S_3}^2} = -\frac{v^2}{4m_{S_3}^2} y_L^{b\ell'}\left[(y_L^{b\ell})^* + \frac{V_{cs}}{V_{cb}}(y_L^{s\ell})^* + \frac{V_{cd}}{V_{cb}}(y_L^{d\ell})^*\right] \qquad ✗$$

SIC!

R_2 $\quad (3,2)_{7/6}$

$$\mathcal{L}_{R_2} = y_R^{ij}\,\overline{Q}_i \ell_{R\,j}\, R_2 - y_L^{ij}\,\overline{u}_{R\,i} R_2 i\tau_2 L_j + \text{h.c.}$$

$$\mathcal{L}_{R_2} = (V y_R)_{ij}\,\overline{u}_{L\,i} \ell_{R\,j}\, R_2^{(5/3)} + (y_R)_{ij}\,\overline{d}_{L\,i} \ell_{R\,j}\, R_2^{(2/3)}$$
$$+ (y_L)_{ij} \overline{u}_{R\,i} \nu_{L\,j}\, R_2^{(2/3)} - (y_L)_{ij} \overline{u}_{R\,i} \ell_{L\,j}\, R_2^{(5/3)} + \text{h.c.}$$

R_2 $(3,2)_{7/6}$

$$\mathcal{L}_{R_2} = y_R^{ij}\,\overline{Q}_i \ell_{R\,j}\, R_2 - y_L^{ij}\,\overline{u}_{R\,i} R_2 i\tau_2 L_j + \text{h.c.}$$

$$C_9^{kl} = C_{10}^{kl} \stackrel{\text{tree}}{=} -\frac{\pi v^2}{2V_{tb}V_{ts}^*\alpha_{\text{em}}}\frac{y_R^{sl}\left(y_R^{bk}\right)^*}{m_{R_2}^2}\,; \qquad ✗$$

$$g_{S_L} = 4\,g_T = \frac{v^2}{4V_{cb}}\frac{y_L^{c\ell'}\left(y_R^{b\ell}\right)^*}{m_{R_2}^2}\,, \qquad ✓$$

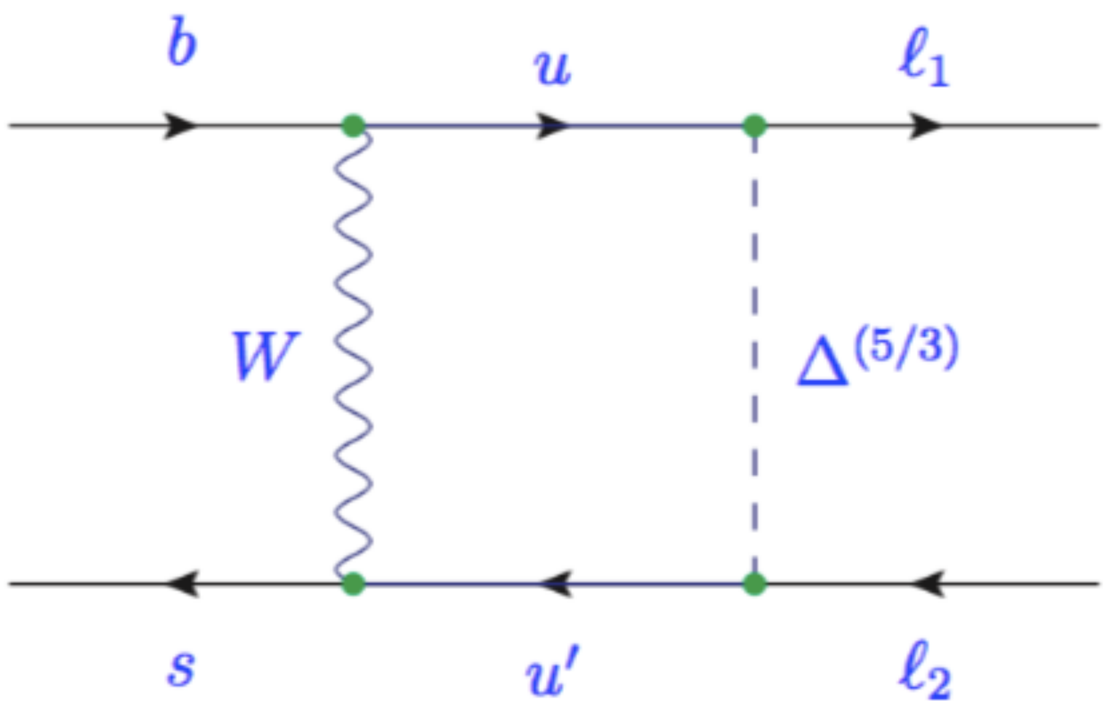
Not following the Zurich (V-A) guide!

NB: $g_{SL} = 4\,g_T$ @ $\mu = m_{R2}$ $\Rightarrow$ $g_{SL} \approx 8.14\,g_T$ @ $\mu = m_b$

R_2 $(3,2)_{7/6}$

$$\mathcal{L}_{R_2} = y_R^{ij}\,\overline{Q}_i \ell_{Rj}\,R_2 - y_L^{ij}\,\overline{u}_{Ri} R_2 i\tau_2 L_j + \text{h.c.}$$

If $y_R=0$, except $y_R^{b\tau}$



$$C_9^{kl} = -C_{10}^{kl} \overset{\text{loop}}{=} \sum_{u,u'\in\{u,c,t\}} \frac{V_{ub}V_{u's}^*}{V_{tb}V_{ts}^*} y_L^{u'k}\left(y_L^{ul}\right)^* \mathcal{F}(x_u, x_{u'})$$ ✓

charm important

< 0

$\widetilde{R}_2$ $(3,2)_{1/6}$

$$\mathcal{L}_{\widetilde{R}_2} = -y_L^{ij}\,\overline{d_{Ri}}\widetilde{R}_2 i\tau_2 L_j + \text{h.c.}\,,$$
$$= -y_L^{ij}\,\overline{d_{Ri}}\ell_{Lj}\,\widetilde{R}_2^{(2/3)} + y_L^{ij}\,\overline{d_{Ri}}\nu_{Lj}\,\widetilde{R}_2^{(-1/3)} + \text{h.c.}$$

$$C_9'^{\,kl} = -C_{10}'^{\,kl} = -\frac{\pi v^2}{2V_{tb}V_{ts}^*\alpha_{\text{em}}}\frac{y_L^{sk}\left(y_L^{bl}\right)^*}{m_{\widetilde{R}_2}^2}$$

✗

$\widetilde{R}_2$ *(3,2)1/6*

$$\mathcal{L}_{\widetilde{R}_2} = -y_L^{ij}\,\overline{d_{Ri}}\widetilde{R}_2 i\tau_2 L_j + \text{h.c.}\,,$$

$$= -y_L^{ij}\,\overline{d_{Ri}}\ell_{Lj}\,\widetilde{R}_2^{(2/3)} + y_L^{ij}\,\overline{d_{Ri}}\nu_{Lj}\,\widetilde{R}_2^{(-1/3)} + \text{h.c.}$$

- Possible to add a gauge invariant $\overline{Q}\widetilde{R}_2\nu_R$ term
- No interference with SM amplitude
  $\rightarrow$ needs too large couplings to get $R_{D^{(*)}}/R_{D^{(*)}}^{\text{SM}}$ right!
- Idea of light ν_R explored in other models.

✗

$S_1 \qquad (3,1)_{1/3}$

$$\mathcal{L}_{S_1} = y_L^{ij}\, \overline{Q^C} i\tau_2 L_j\, S_1 + y_R^{ij}\, \overline{u^C_{R\,i}} e_{R\,j}\, S_1 + \text{h.c.}$$

$$= S_1 \Big[\left(V^* y_L\right)_{ij} \overline{u^C_{L\,i}} \ell_{L\,j} - y_L^{ij}\, \overline{d^C_{L\,i}} \nu_{L\,j} + y_R^{ij}\, \overline{u^C_{R\,i}} \ell_{R\,j} \Big] + \text{h.c.}$$

$$C_9^{kl} + C_{10}^{kl} = \frac{m_t^2}{8\pi\alpha_{\rm em} m_{S_1}^2} \left(V^* y_L\right)_{tk} \left(V^* y_L\right)_{tl}^* - \frac{v^2}{32\pi\alpha_{\rm em} m_{S_1}^2} \frac{\left(y_L \cdot y_L^\dagger\right)_{bs}}{V_{tb}V_{ts}^*} \left(y_L^\dagger \cdot y_L\right)_{kl} ,$$

✗

$$C_9^{kl} - C_{10}^{kl} = \frac{m_t^2}{8\pi\alpha_{\rm em} m_{S_1}^2} \left(y_R\right)_{tk} \left(y_R\right)_{tl}^* \left[\log \frac{m_{S_1}^2}{m_t^2} - f(x_t) \right] - \frac{v^2}{32\pi\alpha_{\rm em} m_{S_1}^2} \frac{\left(y_L \cdot y_L^\dagger\right)_{bs}}{V_{tb}V_{ts}^*} \left(y_L^\dagger \cdot y_L\right)_{kl} ,$$

✓

> 0

$S_1 \quad (3,1)_{1/3}$

$$
\begin{aligned}
\mathcal{L}_{S_1} &= y_L^{ij}\, \overline{Q^C} i\tau_2 L_j\, S_1 + y_R^{ij}\, \overline{u^C_{R\,i}} e_{R\,j}\, S_1 + \text{h.c.} \\
&= S_1 \Big[\big(V^* y_L\big)_{ij}\, \overline{u^C_{L\,i}} \ell_{L\,j} - y_L^{ij}\, \overline{d^C_{L\,i}} \nu_{L\,j} + y_R^{ij}\, \overline{u^C_{R\,i}} \ell_{R\,j} \Big] + \text{h.c.}
\end{aligned}
$$

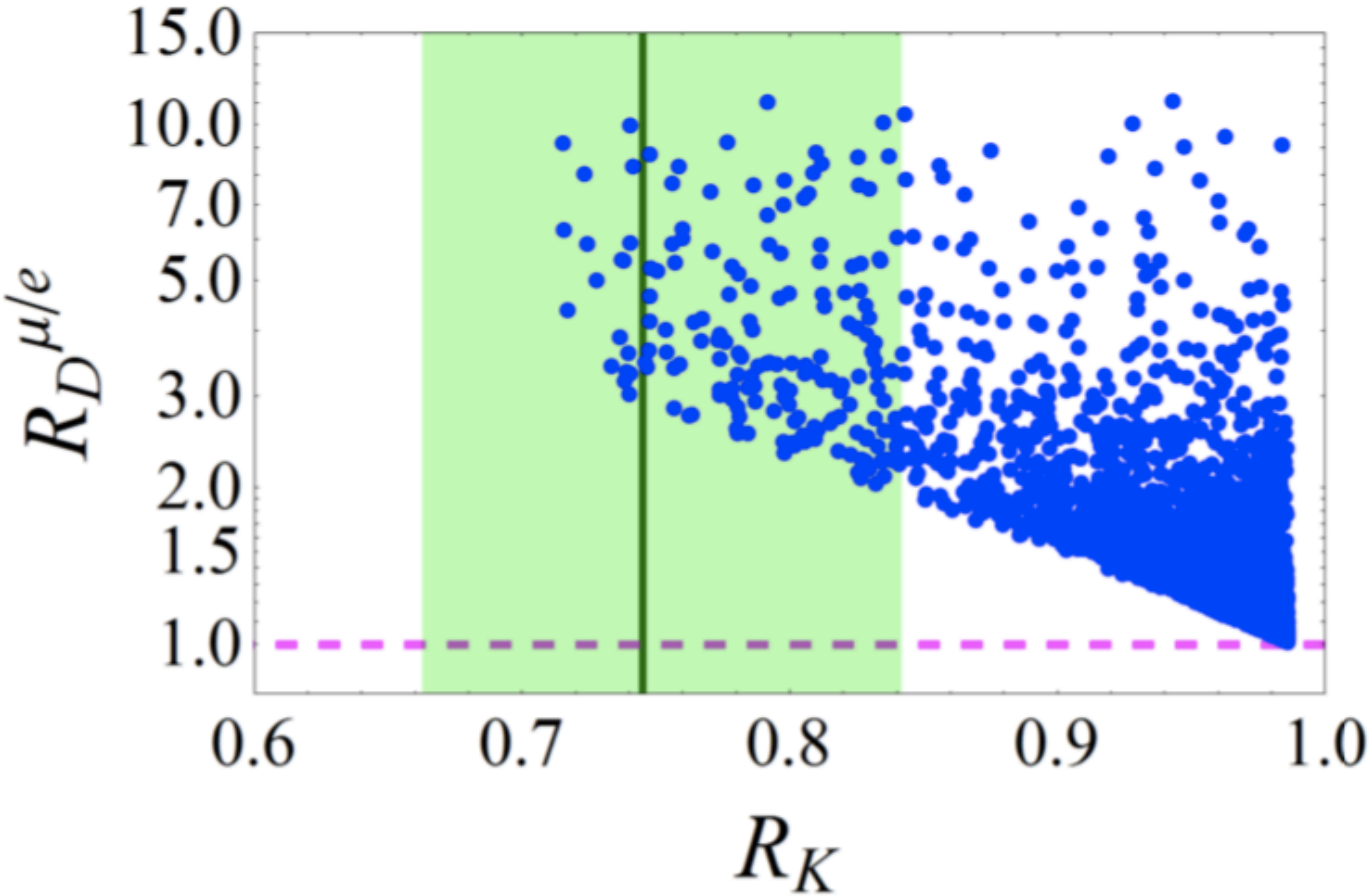
$$
g_{V_L} = \frac{v^2}{4V_{cb}} \frac{y_L^{b\ell'} \left(V y_L^*\right)_{c\ell}}{m_{S_1}^2}\,,
$$

✓

$$
g_{S_L} = -4\, g_T = -\frac{v^2}{4V_{cb}} \frac{y_L^{b\ell'} \left(y_R^{c\ell}\right)^*}{m_{S_1}^2}
$$

S_1

First attempt to explain R_D via tree LQ, and R_K vith LQ in loops required large $y^{c\mu}$



$U_1 \qquad (3,1)_{2/3}$

$$\mathcal{L}_{U_1} = x_L^{ij}\,\bar{Q}_i\gamma_\mu U_1^\mu L_j + x_R^{ij}\,\bar{d}_{R\,i}\gamma_\mu U_1^\mu \ell_{R\,j} + \text{h.c.},$$

Minimal: $x_R=0$

$$C_9^{kl} = -C_{10}^{kl} = -\frac{\pi v^2}{V_{tb}V_{ts}^*\alpha_{\rm em}}\frac{x_L^{sl}\left(x_L^{bk}\right)^*}{m_{U_1}^2}$$ ✓

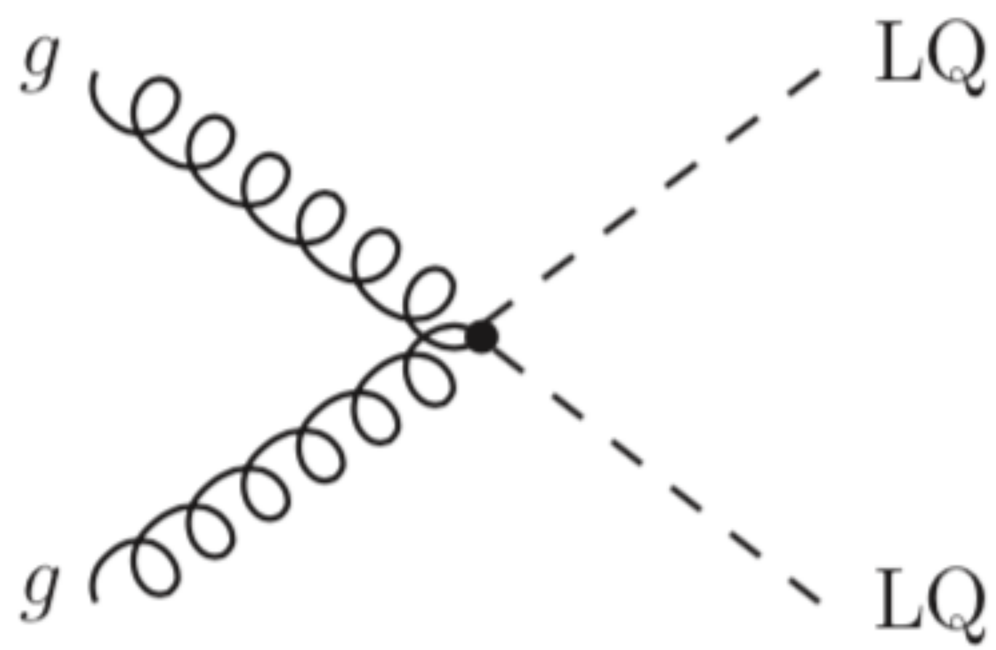
$$g_{V_L} = \frac{v^2\ (V x_L)_{c\ell'}\left(x_L^{b\ell}\right)^*}{2V_{cb}\,m_{U_1}^2}$$

$$= \frac{v^2}{2m_{U_1}^2}\left(x_L^{b\ell}\right)^*\left[x_L^{b\ell'} + \frac{V_{cs}}{V_{cb}}x_L^{s\ell'} + \frac{V_{cd}}{V_{cb}}x_L^{d\ell'}\right]$$ ✓

Cannot compute loops unless specifying UV completion (bunch of new parameters)

Direct Searches

- LQ pair production



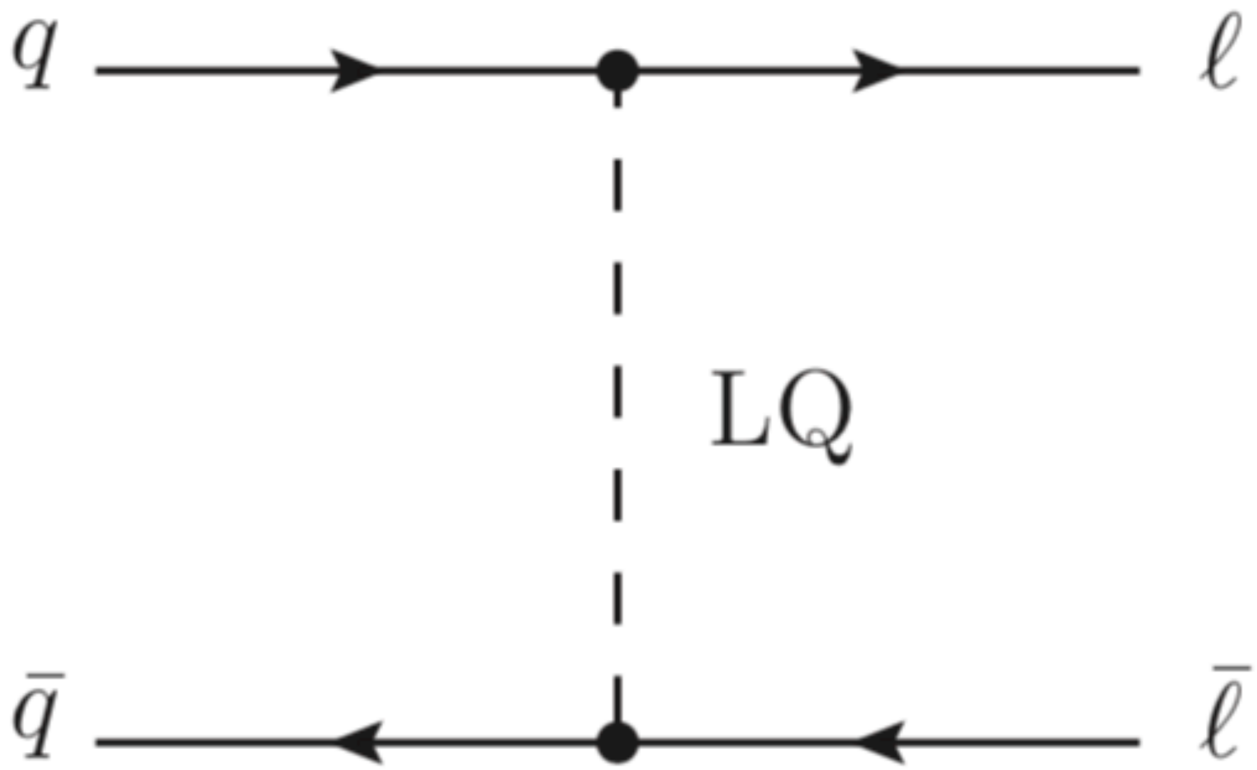
Direct Searches

- LQ pair production

Decays	LQs	Scalar LQ limits	Vector LQ limits
$jj\,\tau\bar{\tau}$	S_1, R_2, S_3, U_1, U_3	–	–
$b\bar{b}\,\tau\bar{\tau}$	R_2, S_3, U_1, U_3	850 (550) GeV	1550 (1290) GeV
$t\bar{t}\,\tau\bar{\tau}$	S_1, R_2, S_3, U_3	900 (560) GeV	1440 (1220) GeV
$jj\,\mu\bar{\mu}$	S_1, R_2, S_3, U_1, U_3	1530 (1275) GeV	2110 (1860) GeV
$b\bar{b}\,\mu\bar{\mu}$	R_2, U_1, U_3	1400 (–) GeV	1900 (1700) GeV
$t\bar{t}\,\mu\bar{\mu}$	S_1, R_2, S_3, U_3	1420 (950) GeV	1780 (1560) GeV
$jj\,\nu\bar{\nu}$	R_2, S_3, U_1, U_3	980 (640) GeV	1790 (1500) GeV
$b\bar{b}\,\nu\bar{\nu}$	S_1, R_2, S_3, U_3	1100 (800) GeV	1810 (1540) GeV
$t\bar{t}\,\nu\bar{\nu}$	R_2, S_3, U_1, U_3	1020 (820) GeV	1780 (1530) GeV

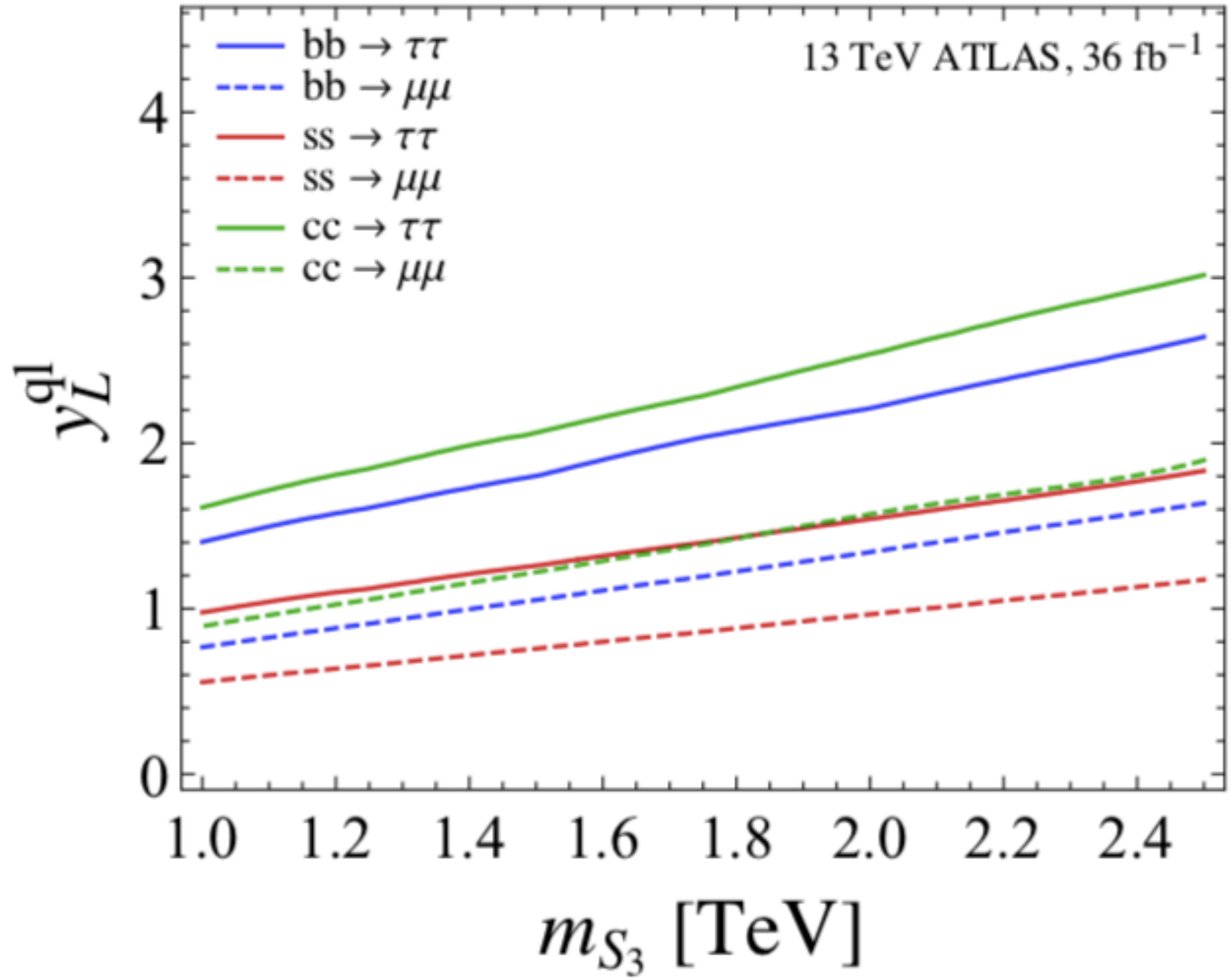
Direct Searches

- Monitor large p_T tails of $pp \to \ell\ell$



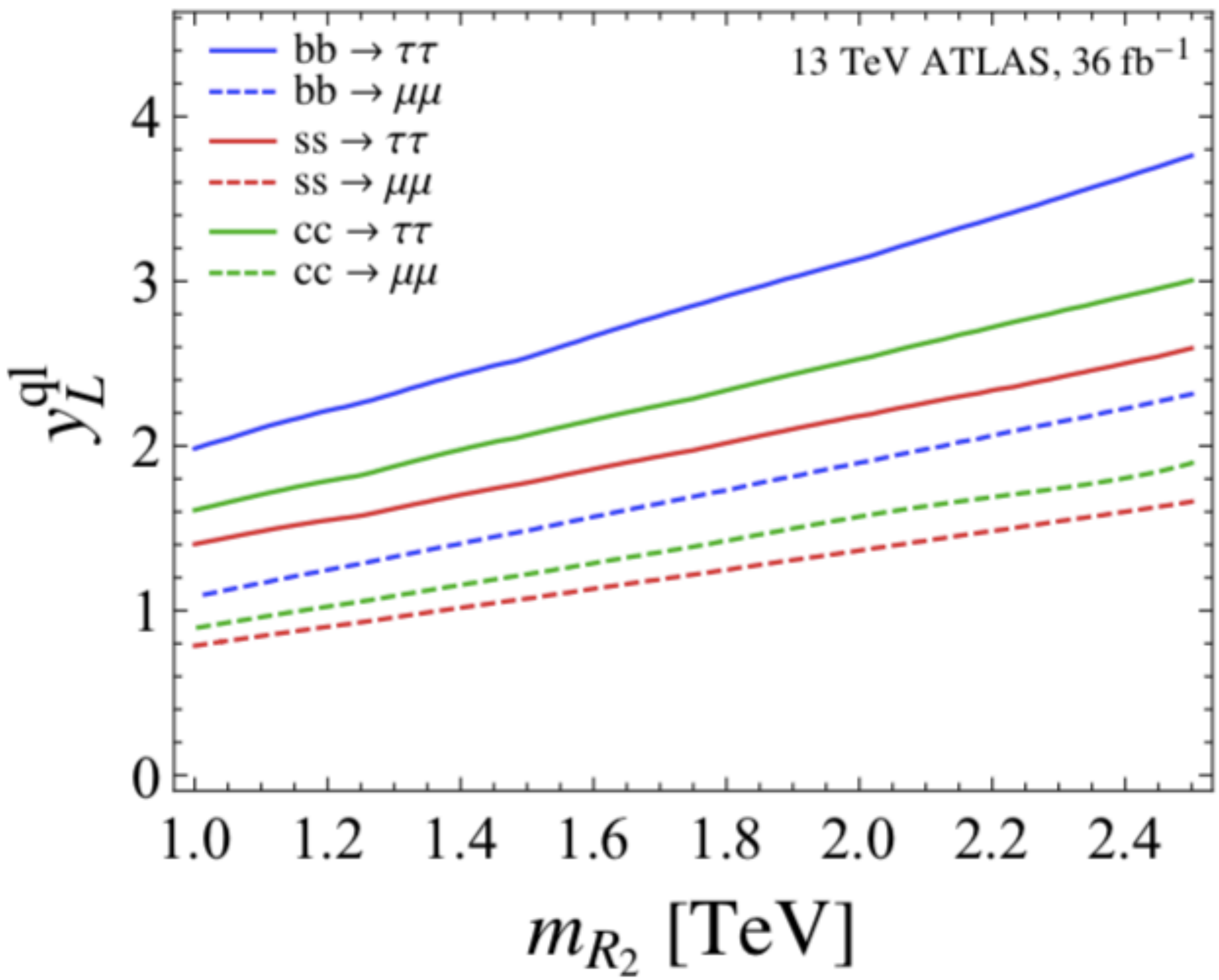
Direct Searches

- Monitor large p_T tails of $pp \to \ell\ell$



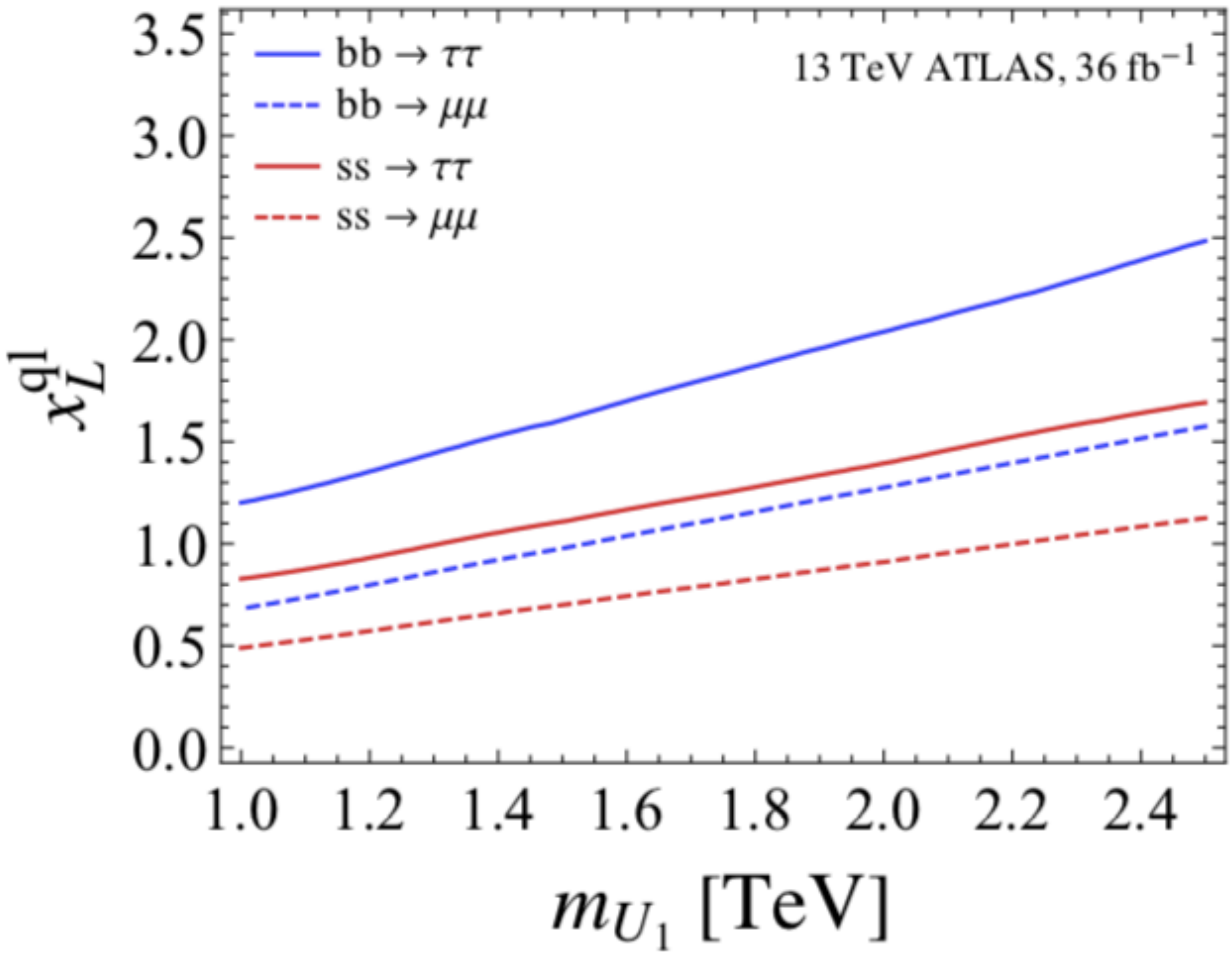
Direct Searches

- Monitor large p_T tails of $pp \to \ell\ell$



Direct Searches

- Monitor large p_T tails of $pp \to \ell\ell$



Revist R_2

$$\mathcal{L}_{R_2} = y_R^{ij}\, \overline{Q}_i \ell_{R\,j}\, R_2 - y_L^{ij}\, \overline{u}_{R\,i} R_2 i\tau_2 L_j + \text{h.c.}$$

If y_R=0 and

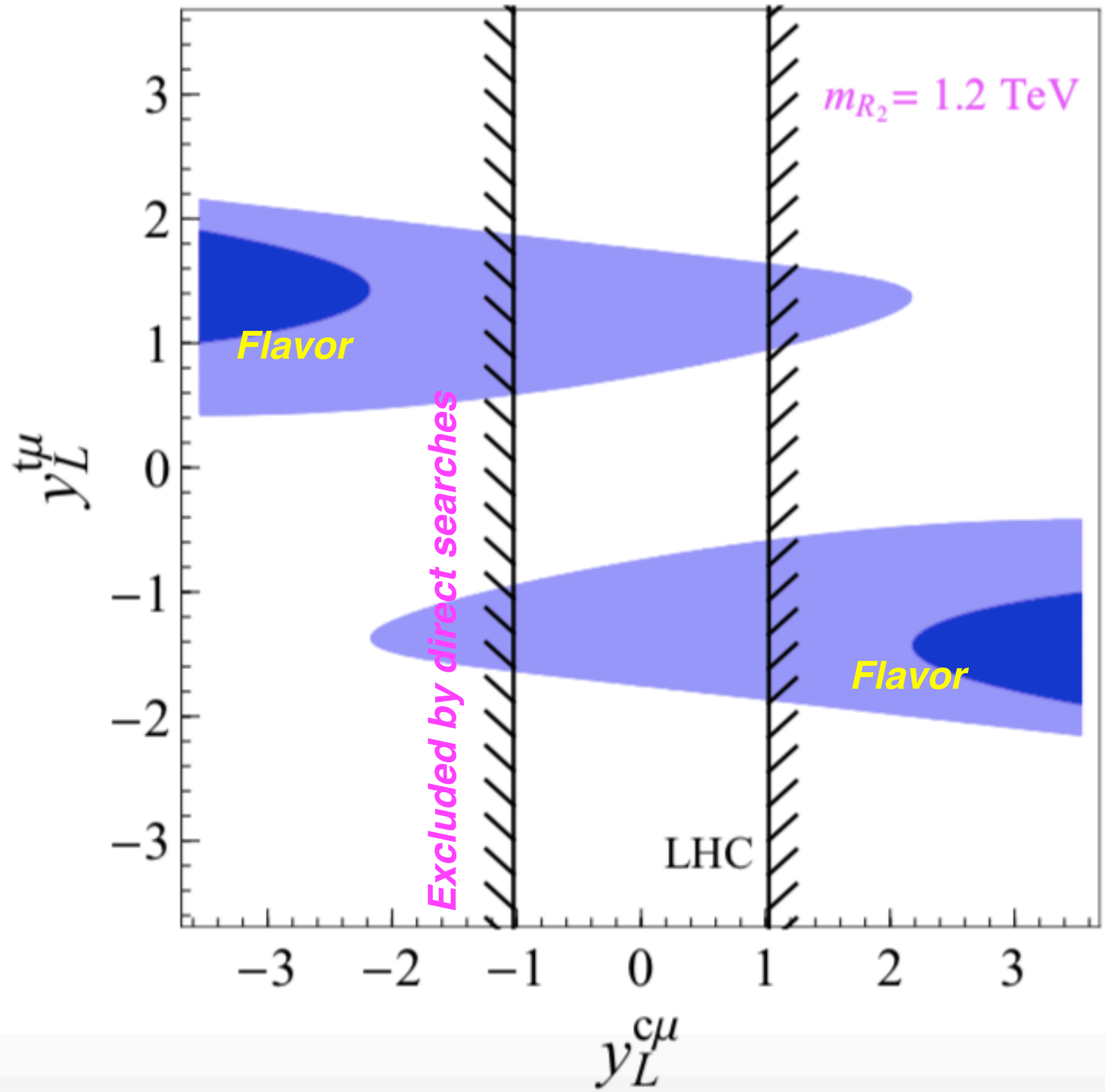
$$y_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_L^{c\mu} & 0 \\ 0 & y_L^{t\mu} & 0 \end{pmatrix}$$

$$C_9^{kl} = -C_{10}^{kl} \overset{\text{loop}}{=} \sum_{u,u' \in \{u,c,t\}} \frac{V_{ub} V_{u's}^*}{V_{tb} V_{ts}^*} y_L^{u'k} \left(y_L^{ul}\right)^* \mathcal{F}(x_u, x_{u'}) \quad ✓$$

charm important

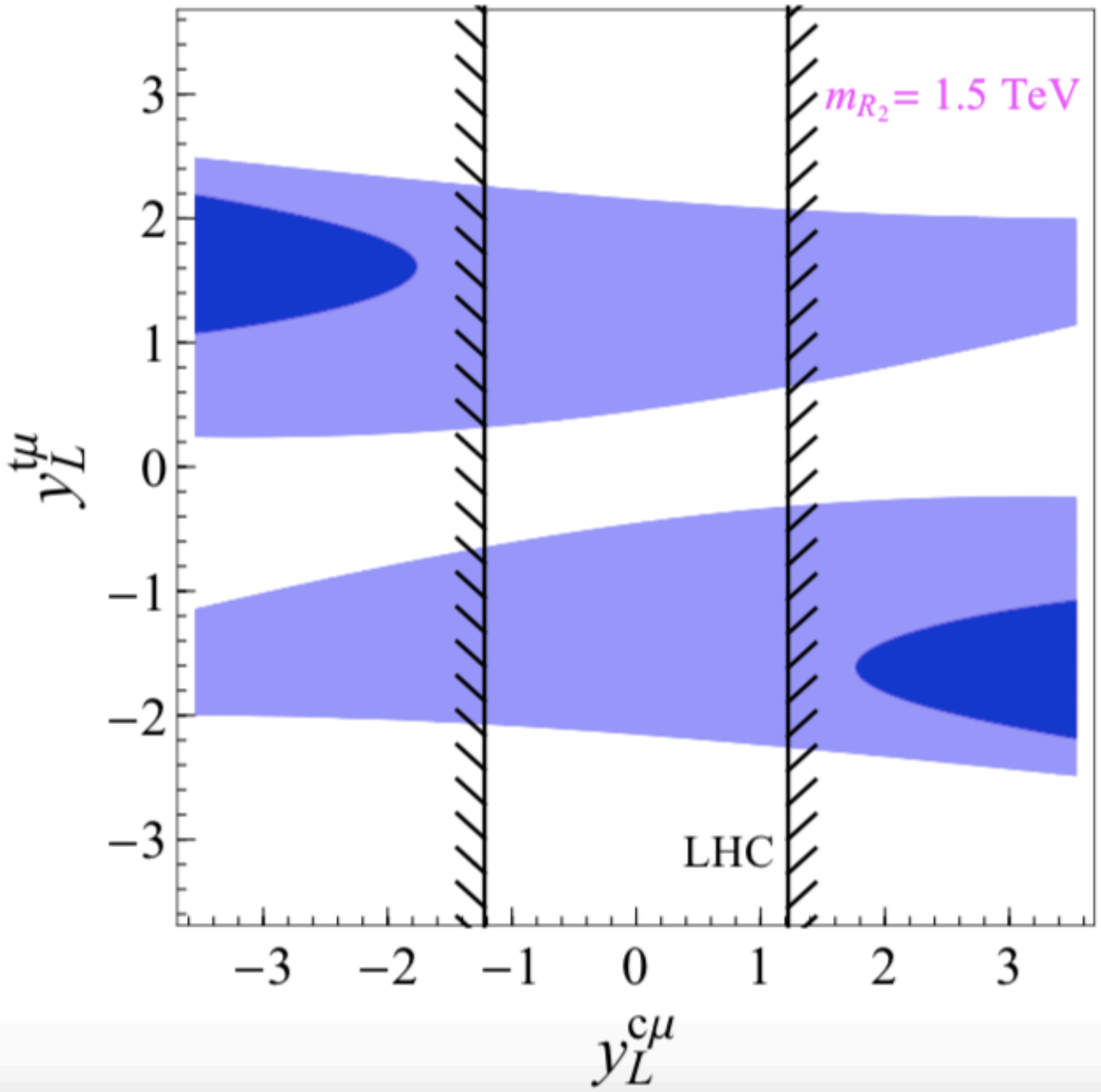
< 0

Revist R_2

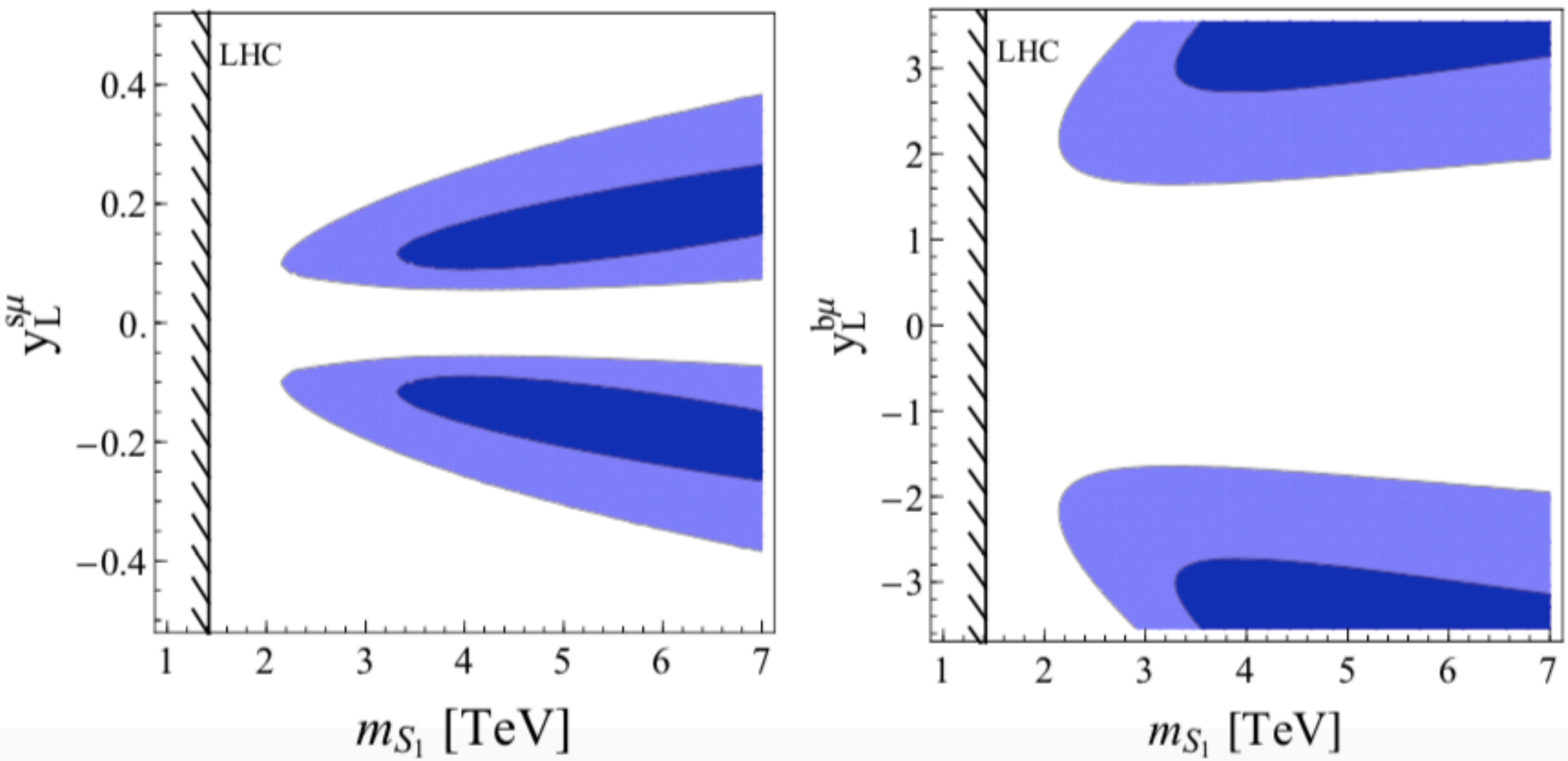


m_{R_2}= 1.2 TeV
Flavor
Flavor
Excluded by direct searches
LHC
$y_L^{t\mu}$
$y_L^{c\mu}$
3
2
1
0
−1
−2
−3

Revist R_2



In S_1


LHC
0.4
0.2
0.
−0.2
−0.4
$y_L^{s\mu}$
1 2 3 4 5 6 7
m_{S_1} [TeV]
LHC
3
2
1
0
−1
−2
−3
$y_L^{b\mu}$
1 2 3 4 5 6 7
m_{S_1} [TeV]

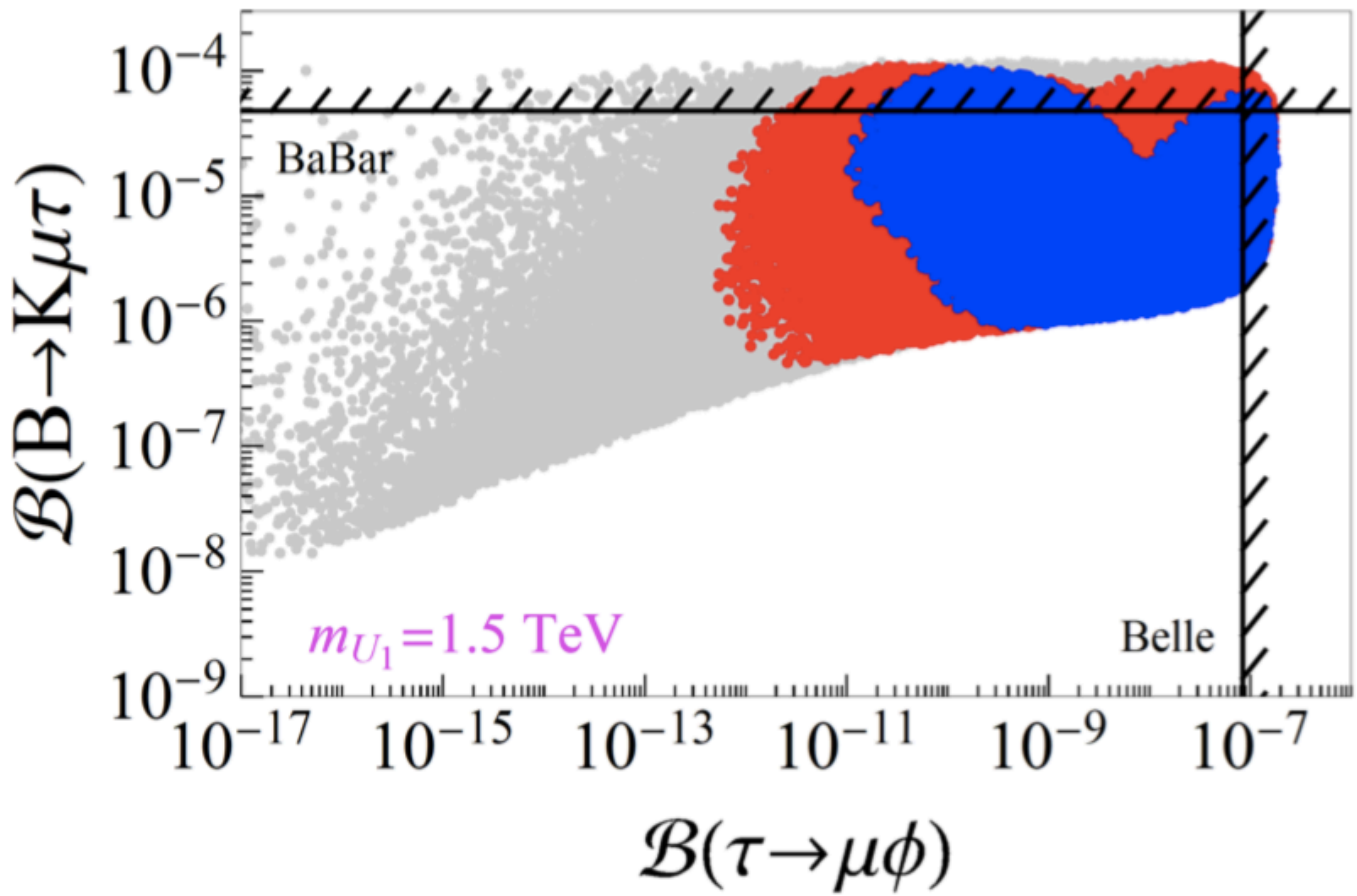
Summarizing

Single LQ solution to both kinds of anomalies

Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
S_1	✗*	✓	✗*
R_2	✗*	✓	✗
$\widetilde{R}_2$	✗	✗	✗
S_3	✓	✗	✗
U_1	✓	✓	✓
U_3	✓	✗	✗

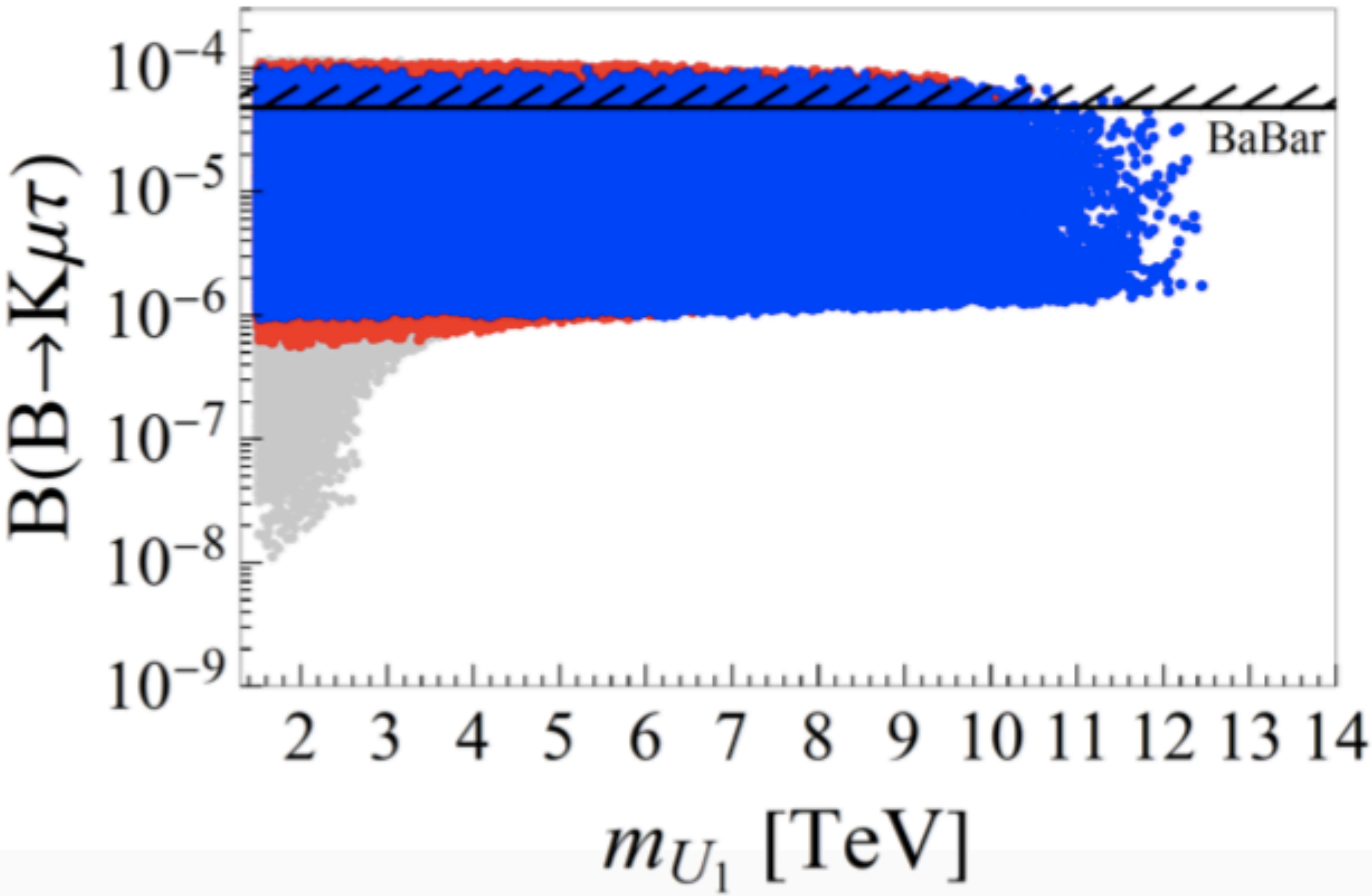
need UV completion

More on U_1



$\mathcal{B}(B \to K\mu\tau)$
$\mathcal{B}(\tau \to \mu\phi)$
BaBar
Belle
m_{U_1}=1.5 TeV
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-17}
10^{-15}
10^{-13}
10^{-11}
10^{-9}
10^{-7}

More on U_1



10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
BaBar
$\mathcal{B}(B \to K\mu\tau)$
2 3 4 5 6 7 8 9 10 11 12 13 14
m_{U_1} [TeV]

Plausible Model to accommodate all

Combine 2 SLQ

Model to accommodate both anomalies

In flavor basis

$$\mathcal{L} \supset y_R^{ij}\,\bar{Q}_i \ell_{Rj} R_2 + y_L^{ij}\,\bar{u}_{Ri} L_j \widetilde{R}_2^\dagger + y^{ij}\,\bar{Q}_i^C i\tau_2(\tau_k S_3^k) L_j + \text{h.c.}$$

$$R_2 = (3, 2, 7/6),\ S_3 = (\bar{3}, 3, 1/3)$$

In mass eigenstates basis

$$\begin{aligned}
\mathcal{L} \supset\ & (V_{\rm CKM}\, y_R\, E_R^\dagger)^{ij}\, \bar{u}'_{Li} \ell'_{Rj} R_2^{(5/3)} + (y_R\, E_R^\dagger)^{ij}\, \bar{d}'_{Li} \ell'_{Rj} R_2^{(2/3)} \\
& + (U_R\, y_L\, U_{\rm PMNS})^{ij}\, \bar{u}'_{Ri} \nu'_{Lj} R_2^{(2/3)} - (U_R\, y_L)^{ij}\, \bar{u}'_{Ri} \ell'_{Lj} R_2^{(5/3)} \\
& - (y\, U_{\rm PMNS})^{ij}\, \bar{d}'^C_{Li} \nu'_{Lj} S_3^{(1/3)} - \sqrt{2}\, y^{ij}\, \bar{d}'^C_{Li} \ell'_{Lj} S_3^{(4/3)} \\
& + \sqrt{2}(V^*_{\rm CKM}\, y\, U_{\rm PMNS})_{ij}\, \bar{u}'^C_{Li} \nu'_{Lj} S_3^{(-2/3)} - (V^*_{\rm CKM}\, y)_{ij}\, \bar{u}'^C_{Li} \ell'_{Lj} S_3^{(1/3)} + \text{h.c.}
\end{aligned}$$

Model to accommodate both anomalies

$R_2 = (3, 2, 7/6)$, $S_3 = (\bar{3}, 3, 1/3)$

$$
\begin{aligned}
\mathcal{L} \supset\ & (V_{\rm CKM}\, y_R\, E_R^\dagger)^{ij}\, \bar{u}'_{Li} \ell'_{Rj}\, R_2^{(5/3)} + (y_R\, E_R^\dagger)^{ij}\, \bar{d}'_{Li} \ell'_{Rj}\, R_2^{(2/3)} \\
& + (U_R\, y_L\, U_{\rm PMNS})^{ij}\, \bar{u}'_{Ri} \nu'_{Lj}\, R_2^{(2/3)} - (U_R\, y_L)^{ij}\, \bar{u}'_{Ri} \ell'_{Lj}\, R_2^{(5/3)} \\
& - (y\, U_{\rm PMNS})^{ij}\, \bar{d}'^{C}_{Li}\, \nu'_{Lj}\, S_3^{(1/3)} - \sqrt{2}\, y^{ij}\, \bar{d}'^{C}_{Li}\, \ell'_{Lj}\, S_3^{(4/3)} \\
& + \sqrt{2} (V^*_{\rm CKM}\, y\, U_{\rm PMNS})_{ij}\, \bar{u}'^{C}_{Li}\, \nu'_{Lj}\, S_3^{(-2/3)} - (V^*_{\rm CKM}\, y)_{ij}\, \bar{u}'^{C}_{Li}\, \ell'_{Lj}\, S_3^{(1/3)} + \text{h.c.}
\end{aligned}
$$

and assume

$$
\underline{y_R = y_R^T \qquad y = -y_L}
$$

$$
y_R\, E_R^\dagger = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_R^{b\tau} \end{pmatrix}, \quad U_R\, y_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_L^{c\mu} & y_L^{c\tau} \\ 0 & 0 & 0 \end{pmatrix}, \quad U_R = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{pmatrix}
$$

Parameters: m_{R_2}, m_{S_3}, $y_R^{b\tau}$, $y_L^{c\mu}$, $y_L^{c\tau}$ and θ

Phenomenology suggests $\theta \approx \pi/2$ and $y_R^{b\tau}$ complex

Model to accommodate both anomalies

$$\mathcal{L}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}} V_{cb} \big[(1 + g_V)(\bar{u}_L \gamma_\mu d_L)(\bar{\ell}_L \gamma^\mu \nu_L) + g_S(\mu)\,(\bar{u}_R d_L)(\bar{\ell}_R \nu_L) + g_T(\mu)\,(\bar{u}_R \sigma_{\mu\nu} d_L)(\bar{\ell}_R \sigma^{\mu\nu} \nu_L) \big] + \text{h.c.}$$

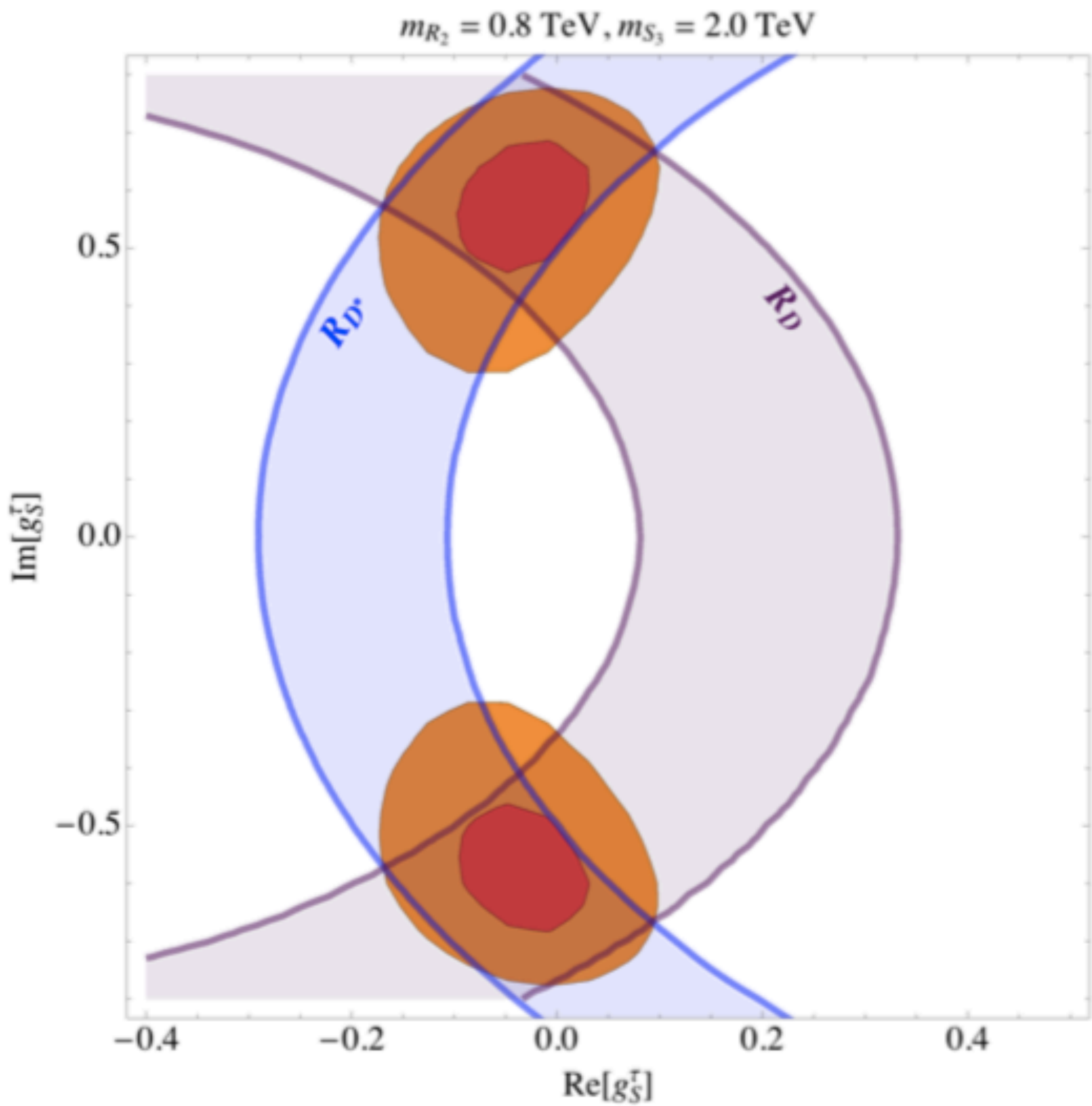
- Coefficients g_i in terms of y-couplings (up-type and down-type quarks):

$$g_S = 4\,g_T = \left. \frac{y_L^{u\ell'}\,\left(y_R^{d\ell}\right)^*}{4\sqrt{2}\,m_{R_2}^2\,G_F\,V_{ud}} \right|_{\mu = m_{R_2}} \qquad g_V = -\frac{y_{d\ell'}\,(V y^*)_{u\ell}}{4\sqrt{2}\,m_{S_3}^2\,G_F\,V_{ud}}$$

$u \in \{u, c\},\ d \in \{s, b\},\ \ell^{(\prime)} \in \{\mu, \tau\}.$

NB g_V is tiny!

Model to accommodate both anomalies



Model to accommodate both anomalies

- $R_{e/\mu}^{K\ \mathrm{exp}} = 2.488(10) \times 10^{-5}$ [PDG], $R_{e/\mu}^{K\ \mathrm{SM}} = 2.477(1) \times 10^{-5}$ [Cirigliano 2007]

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

- $R_{\mu/e}^{D\ \mathrm{exp}} = 0.995(45)$ [Belle 2017], $R_{\mu/e}^{D^*\ \mathrm{exp}} = 1.04(5)$ [Belle 2016]

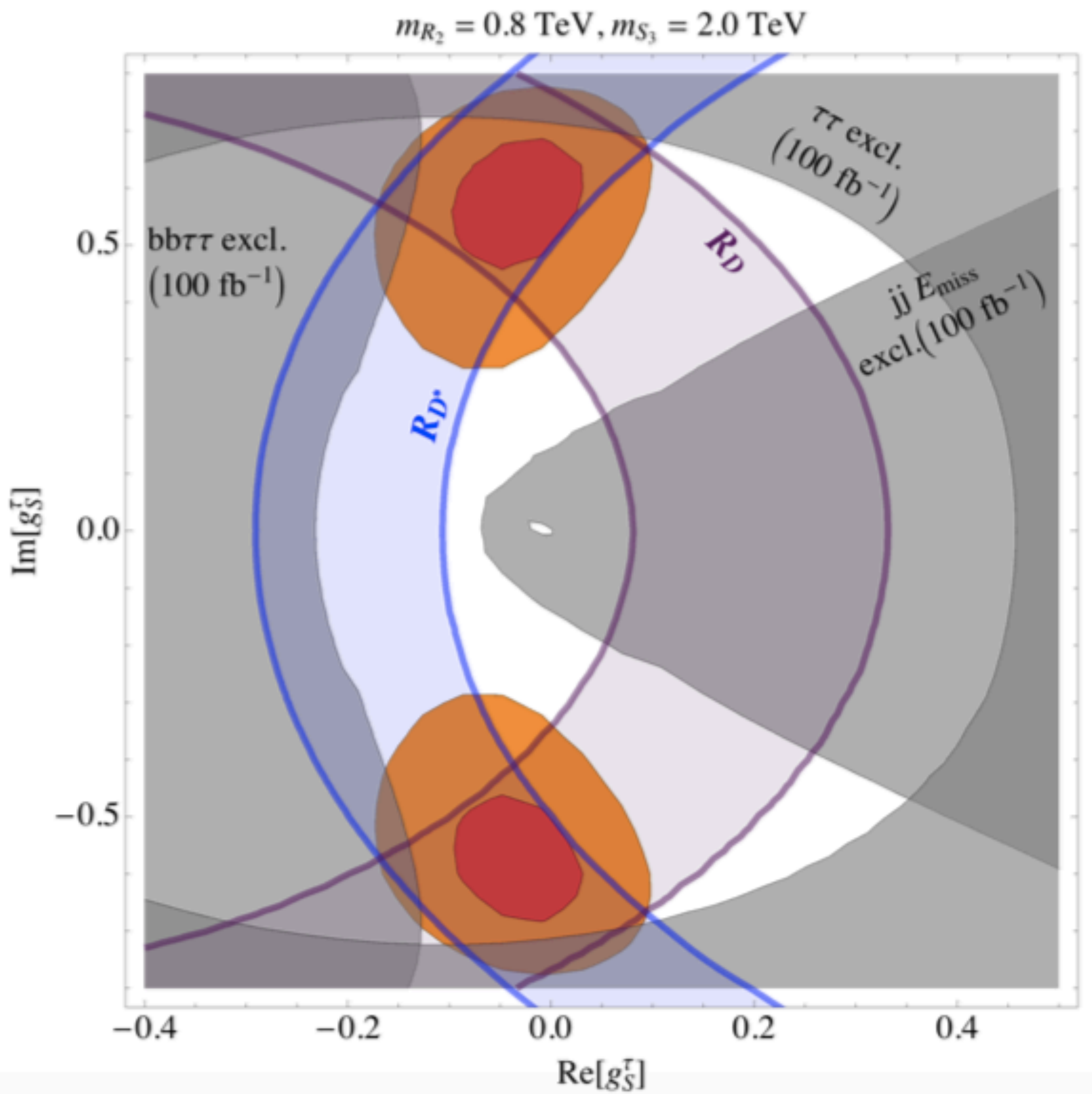
$$R_{\mu/e}^{D^{(*)}} = \frac{\Gamma(B \to D^{(*)} \mu \bar{\nu})}{\Gamma(B \to D^{(*)} e \bar{\nu})}$$

- $\mathcal{B}(\tau \to \mu\phi) < 8.4 \times 10^{-8}$ [PDG]
- Loops: $\Delta m_{B_s}^{\mathrm{exp}} = 17.7(2)\ \mathrm{ps}^{-1}$ [PDG], $\Delta m_{B_s}^{\mathrm{exp}} = (19.0 \pm 2.4)\ \mathrm{ps}^{-1}$ [FLAG 2016]
- Loops: $Z \to \mu\mu$, $Z \to \tau\tau$, $Z \to \nu\nu$ [PDG]

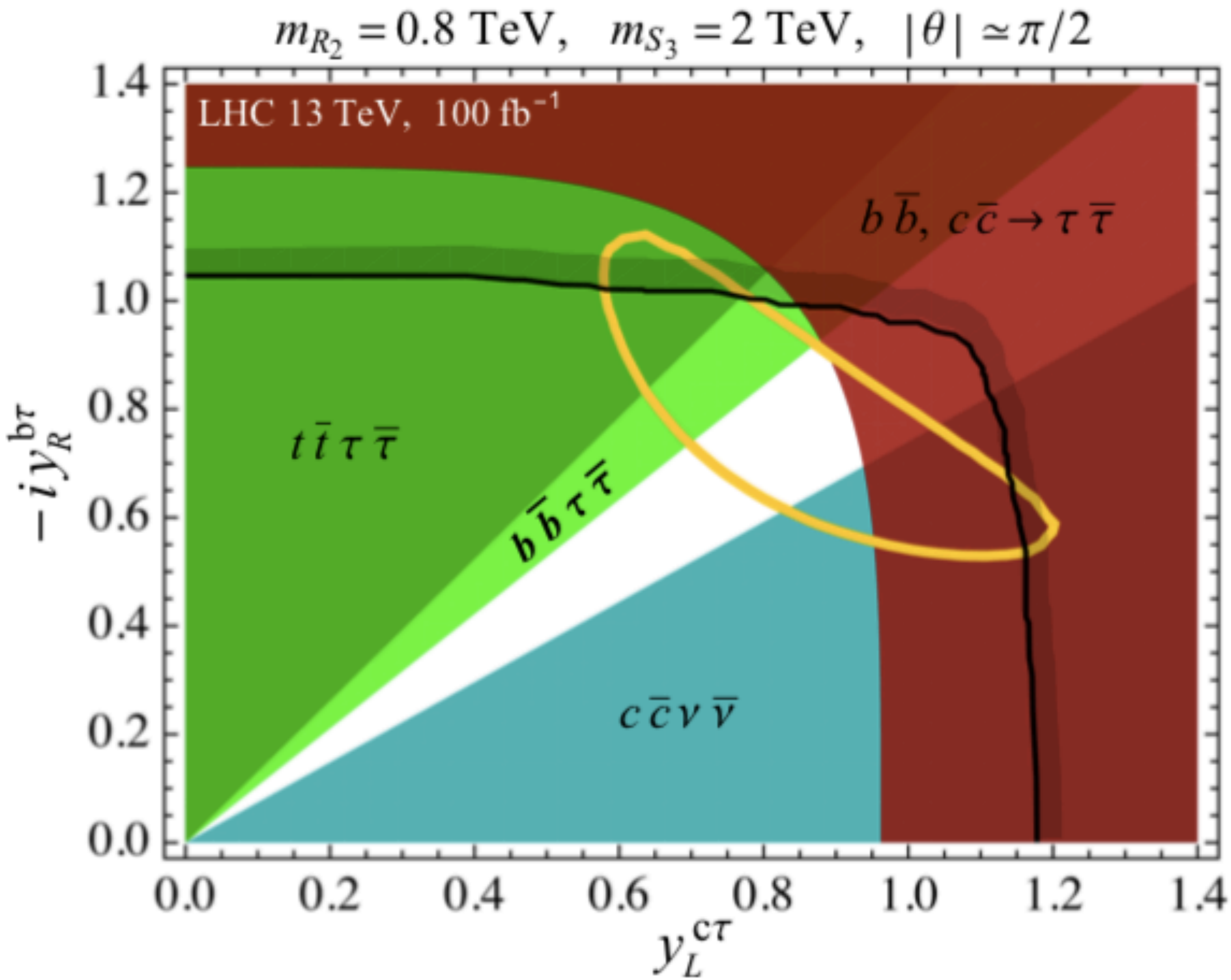
$$\frac{g_V^\tau}{g_V^e} = 0.959(29)\,, \quad \frac{g_A^\tau}{g_A^e} = 1.0019(15) \qquad \frac{g_V^\mu}{g_V^e} = 0.961(61)\,, \quad \frac{g_A^\mu}{g_A^e} = 1.0001(13)$$

$$N_\nu^{\mathrm{exp}} = 2.9840(82)$$

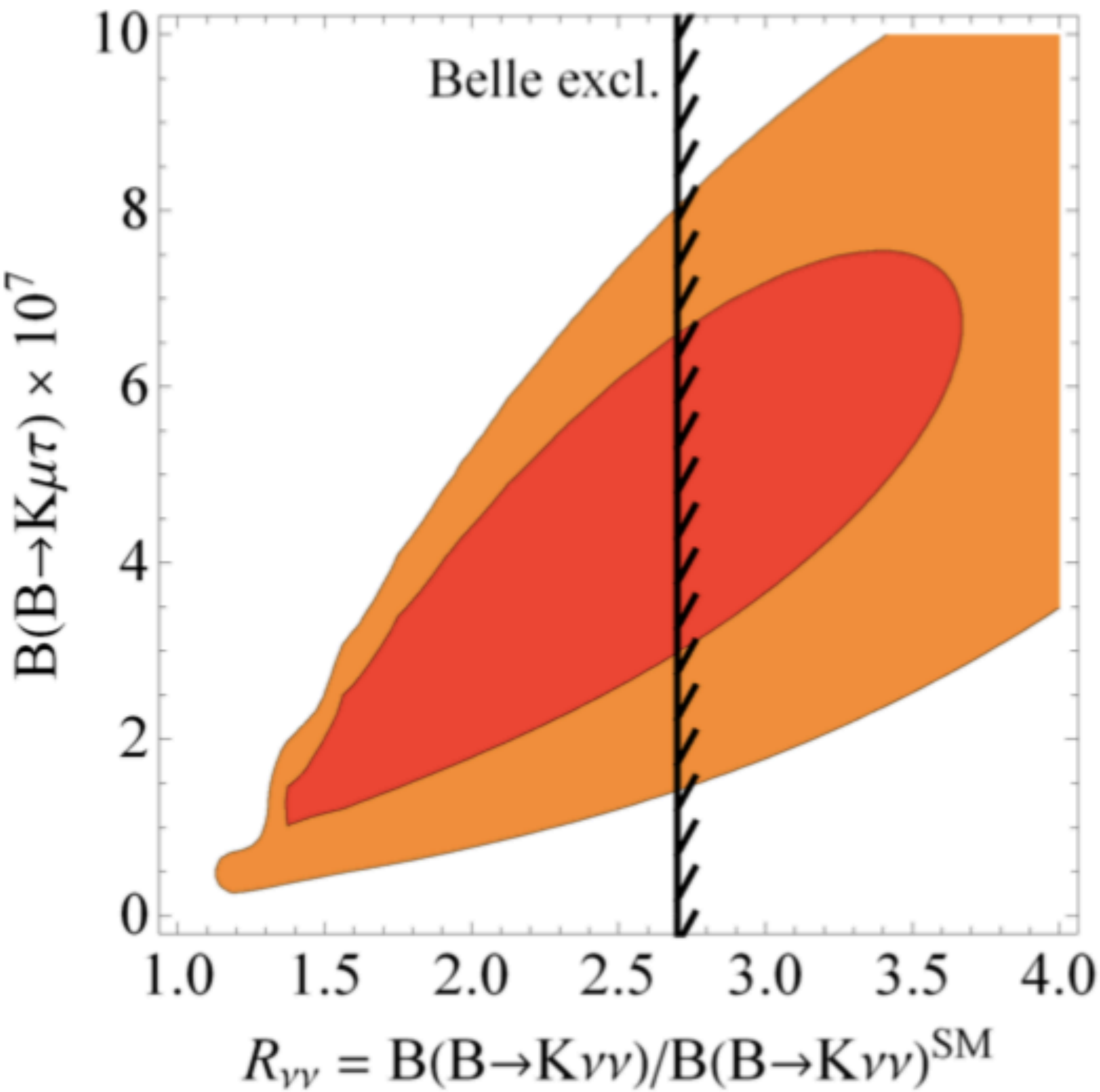
Model to accommodate both anomalies



Model to accommodate both anomalies



Interestingly…



Gravy: viable SU(5) GUT

- Our choice of Yukawas biased by $SU(5)$ GUT aspirations

- Scalars: $R_2 \in \underline{\mathbf{45}}, \underline{\mathbf{50}}$, $S_3 \in \underline{\mathbf{45}}$. SM matter fields in $\mathbf{5}_i$ and $\mathbf{10}_i$

- Operators $\mathbf{10}_i \mathbf{10}_j \underline{\mathbf{45}}$ forbidden to prevent proton decay

- Available operators

$$\begin{aligned} \mathbf{10}_i \mathbf{5}_j \underline{\mathbf{45}}: &\quad y^{RL}_{2\,ij} \overline{u}^i_R R^a_2 \varepsilon^{ab} L^{j,b}_L, \quad y^{LL}_{3ij} \overline{Q^c}^{i,a}_L \varepsilon^{ab} (\tau^k S^k_3)^{bc} L^{j,c}_L \\ \mathbf{10}_i \mathbf{10}_j \underline{\mathbf{50}}: &\quad y^{LR}_{2\,ij} \overline{e}^i_R R^{a\,*}_2 Q^{j,a}_L \end{aligned}$$

- While breaking $SU(5)$ down to SM the two R_2's mix – one can be light and the other (very) heavy. Thus our initial Lagrangian!

- Yukawas determined from flavor physics (low energies) remain perturbative ($\lesssim \sqrt{4\pi}$) up to $\Lambda_{\mathrm{GUT}} = 5 \times 10^{15}$ GeV, if we use 1-loop running