New Physics in Flavor Physics

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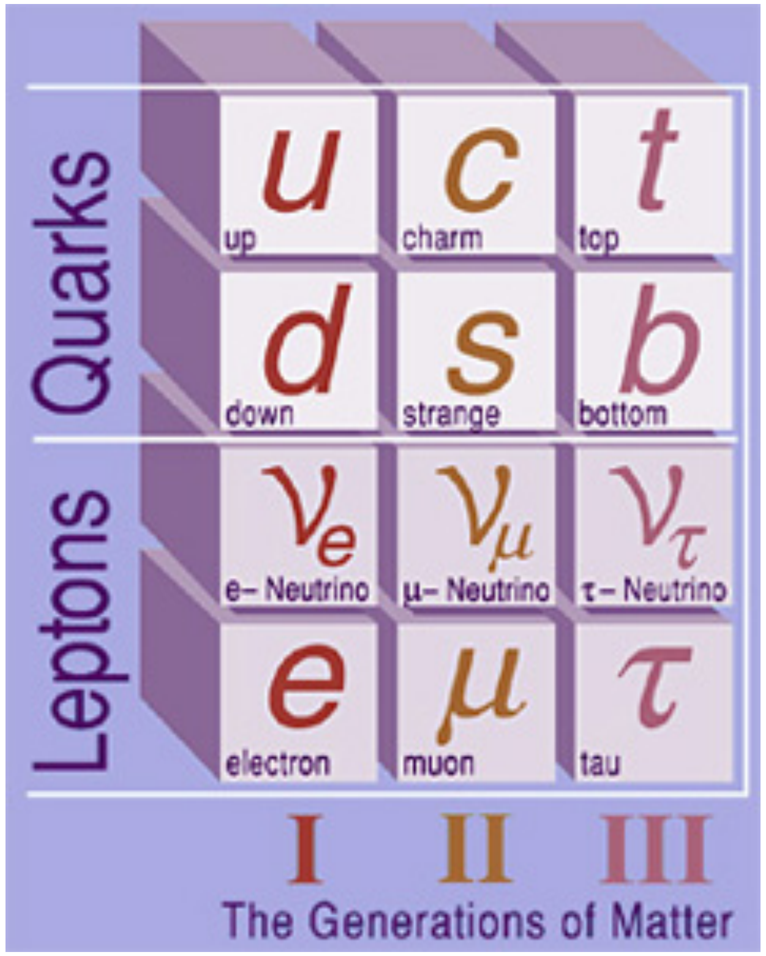
Flavor Physics



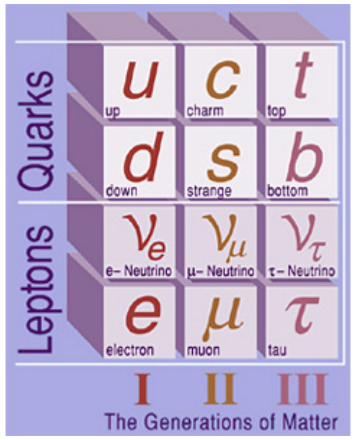
In the Standard Model

- ✗ Gauge sector entirely fixed by symmetry

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

- ✗ Flavor sector loose (a bunch of parameters)

13 of 19 are fermion masses and q.mixing parameters



We know

fermions come in 3 generations

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

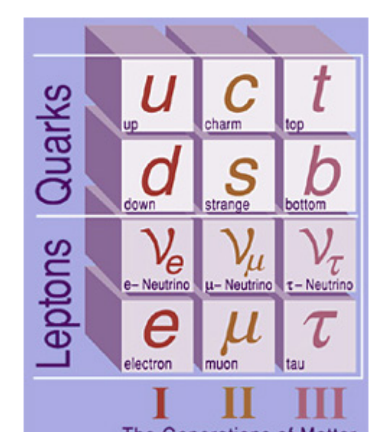
$$\left\{ \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L , \quad (\nu_e)_R , \quad e_R^- \right\} , \quad \left\{ \begin{pmatrix} u \\ d' \end{pmatrix}_L , \quad u_R , \quad d_R \right\}$$

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

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

- ✘ Charged currents:

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

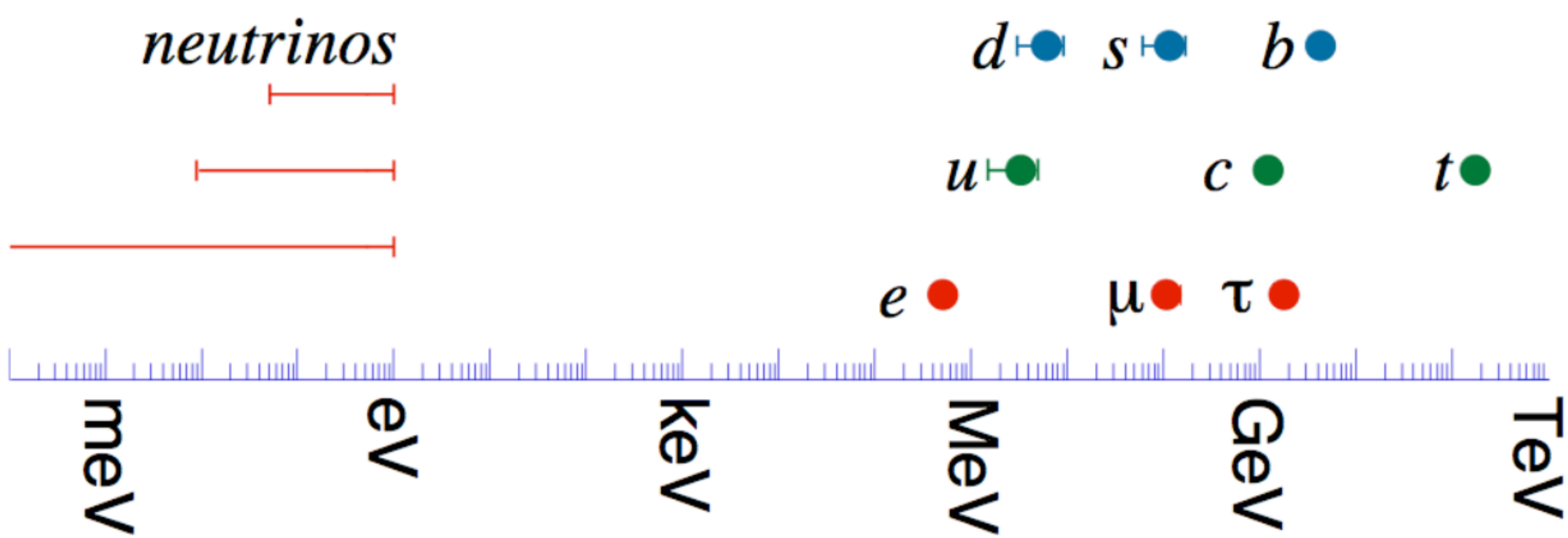


We know

- ✘ 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

$$\lambda \quad A \quad \rho \quad \eta$$

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

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

- ✘ 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!

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

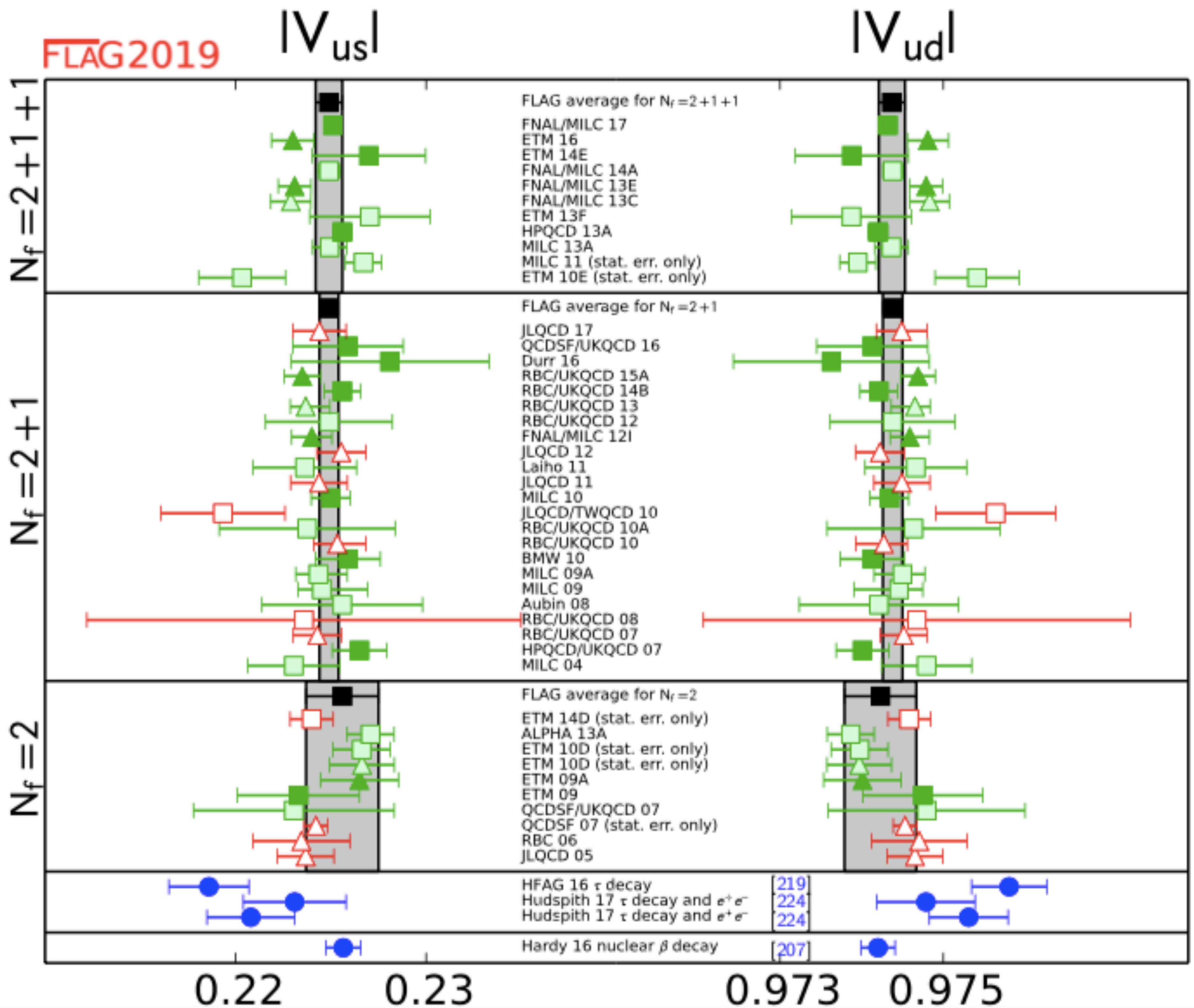
$K \to \mu \nu$ ⟷ $\langle 0 | \bar{s} \gamma_\mu \gamma_5 u | K \rangle \to f_K$

f_K / f_π

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

Huge coordinated effort! (cf. recent FLAG review - 2019)

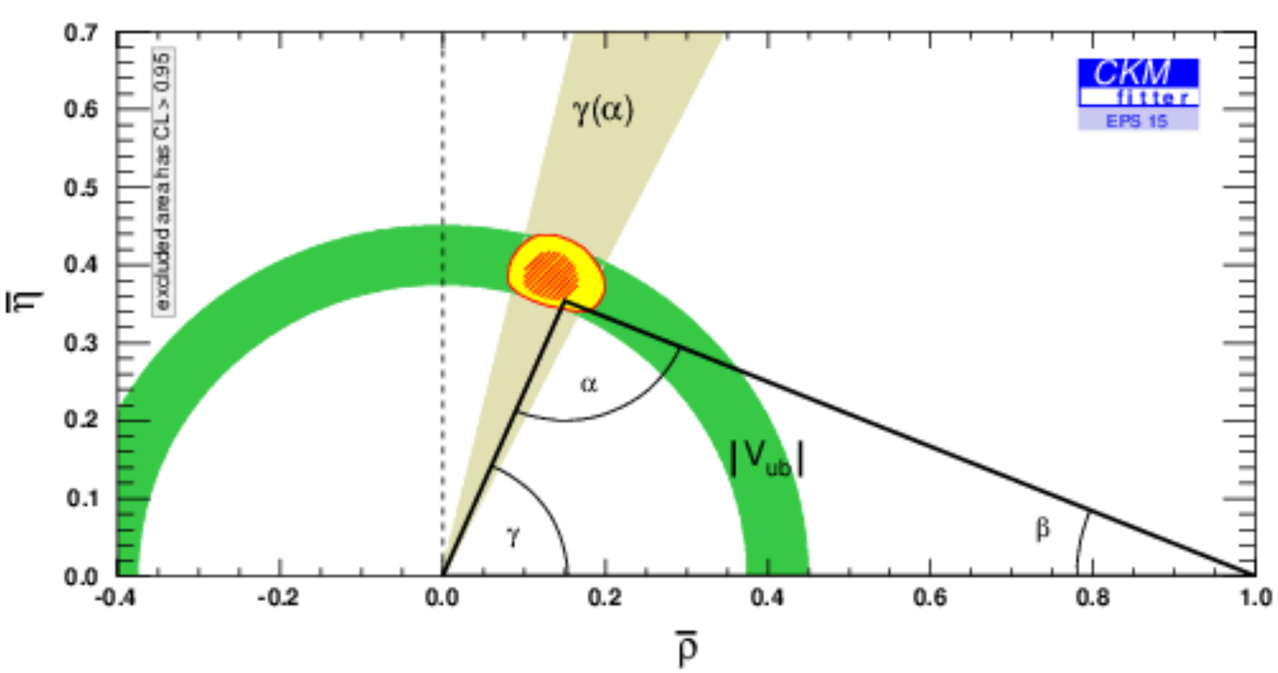
LQCD

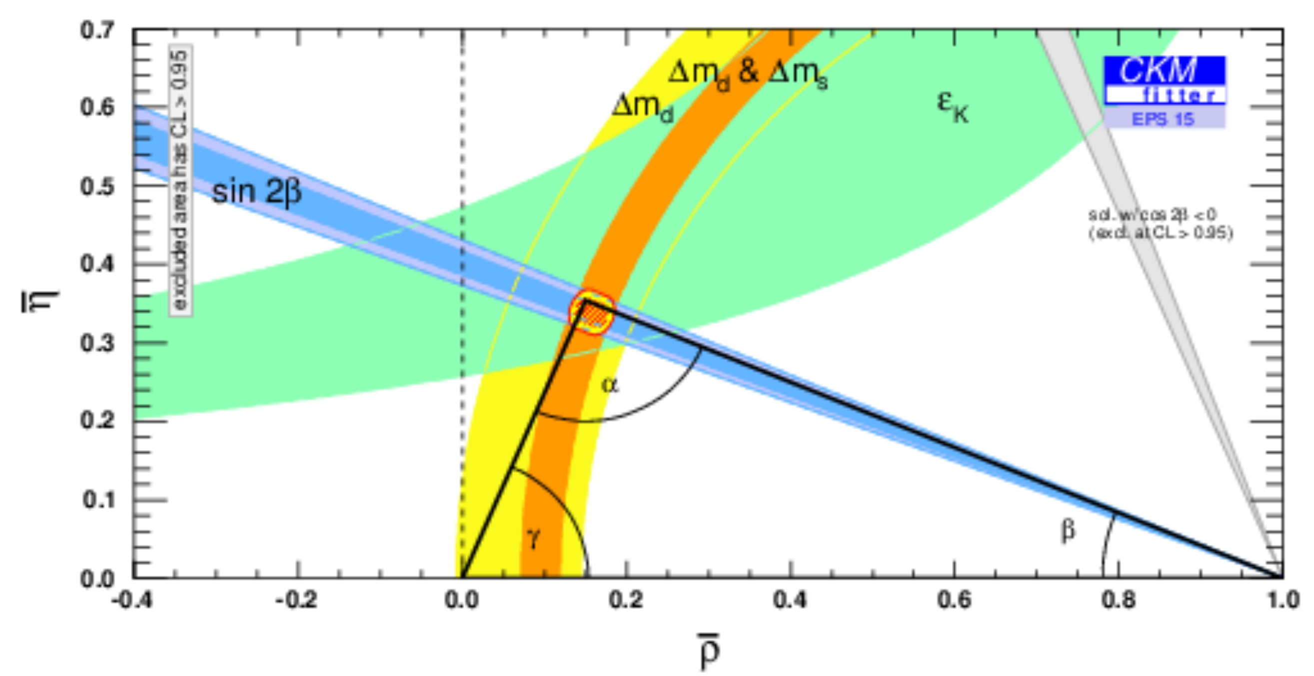


FLAG2019
|Vus|
|Vud|
Nf=2+1+1
Nf=2+1
Nf=2
FLAG average for Nf=2+1+1
FNAL/MILC 17
ETM 16
ETM 14E
FNAL/MILC 14A
FNAL/MILC 13E
FNAL/MILC 13C
ETM 13F
HPQCD 13A
MILC 13A
MILC 11 (stat. err. only)
ETM 10E (stat. err. only)
FLAG average for Nf=2+1
JLQCD 17
QCDSF/UKQCD 16
Durr 16
RBC/UKQCD 15A
RBC/UKQCD 14B
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
MILC 09A
MILC 09
Aubin 08
RBC/UKQCD 08
RBC/UKQCD 07
HPQCD/UKQCD 07
MILC 04
FLAG average for Nf=2
ETM 14D (stat. err. only)
ALPHA 13A
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 16 τ decay [219]
Hudspith 17 τ decay and e+e− [224]
Hudspith 17 τ decay and e+e− [224]
Hardy 16 nuclear β decay [207]
0.22
0.23
0.973
0.975

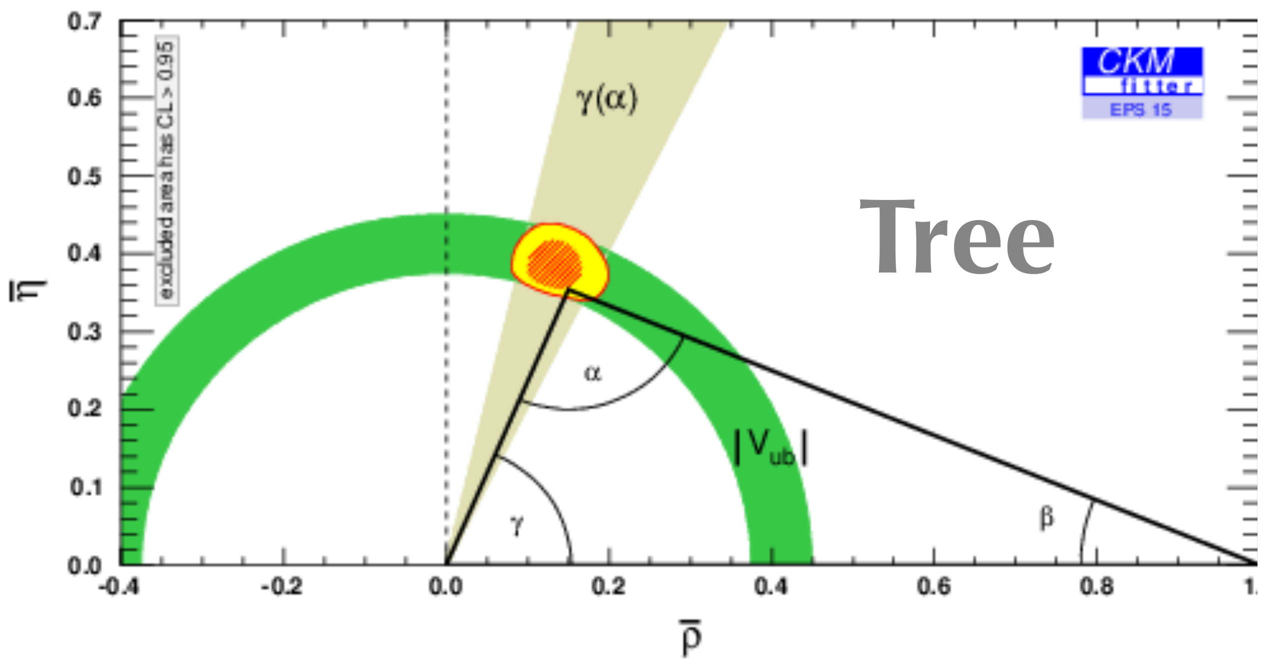
Experiments

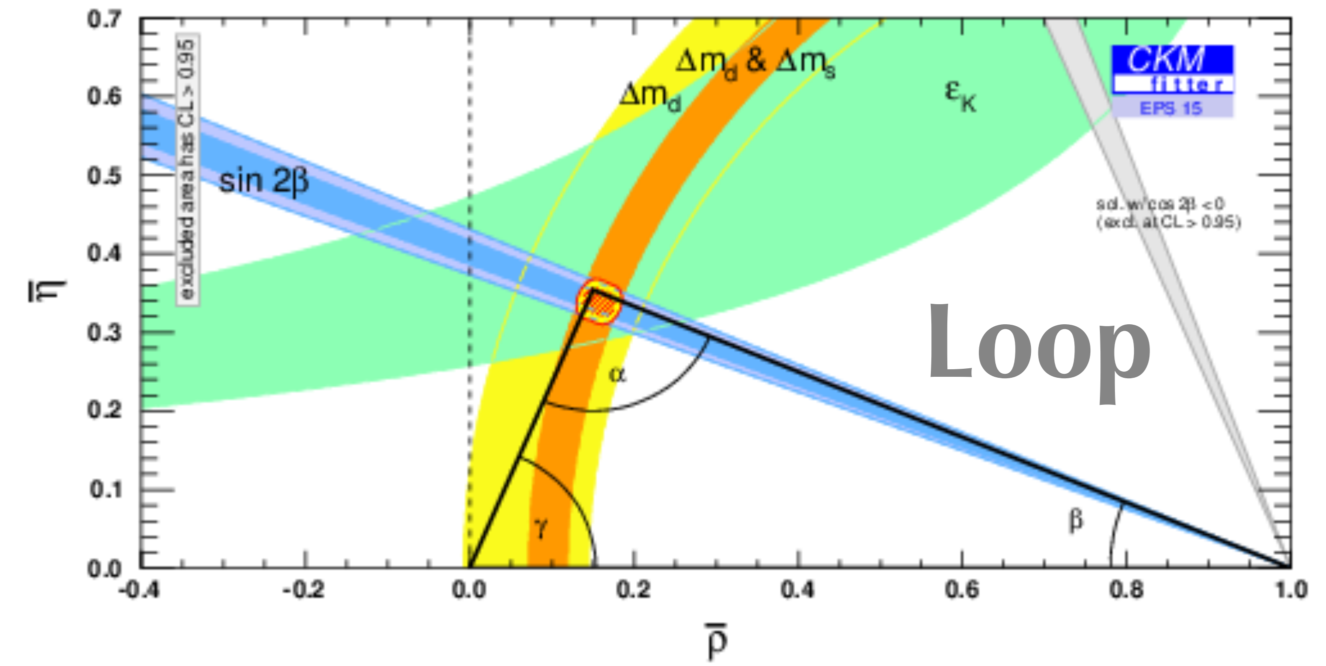
- ✘ K-factories u,d,s [NA62, KOTO]
- ✘ Tau-charm τ,c [BES III]
- ✘ B-factory b,c,τ [Belle II]
- ✘ LHC t,b,c
- ✘ FCC (Z),t,…
- ✘ νF





CKM

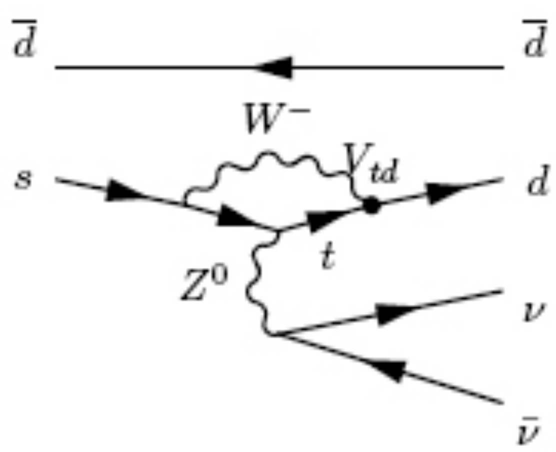


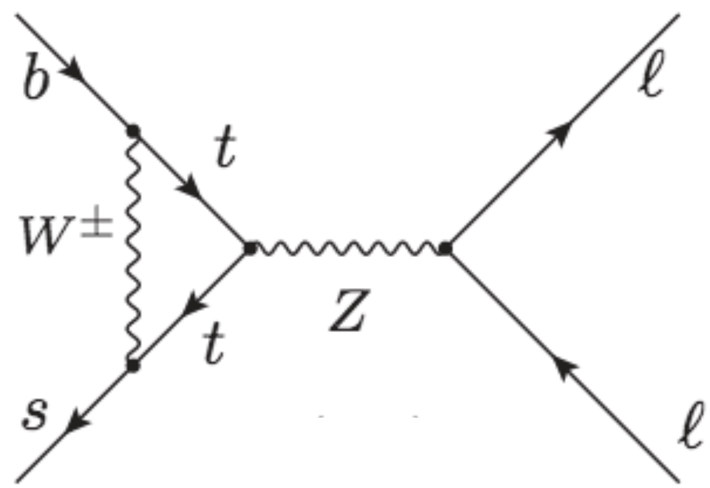


Impressively — TL UT and LP UT agree to less than 10%
[Experiment will do better! Lattices will do better too!]
Only tensions in Vub and Vcb (inclusive Vs. exclusive) but all in all, CKM is very unitary!

2008, Nobel Prize

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





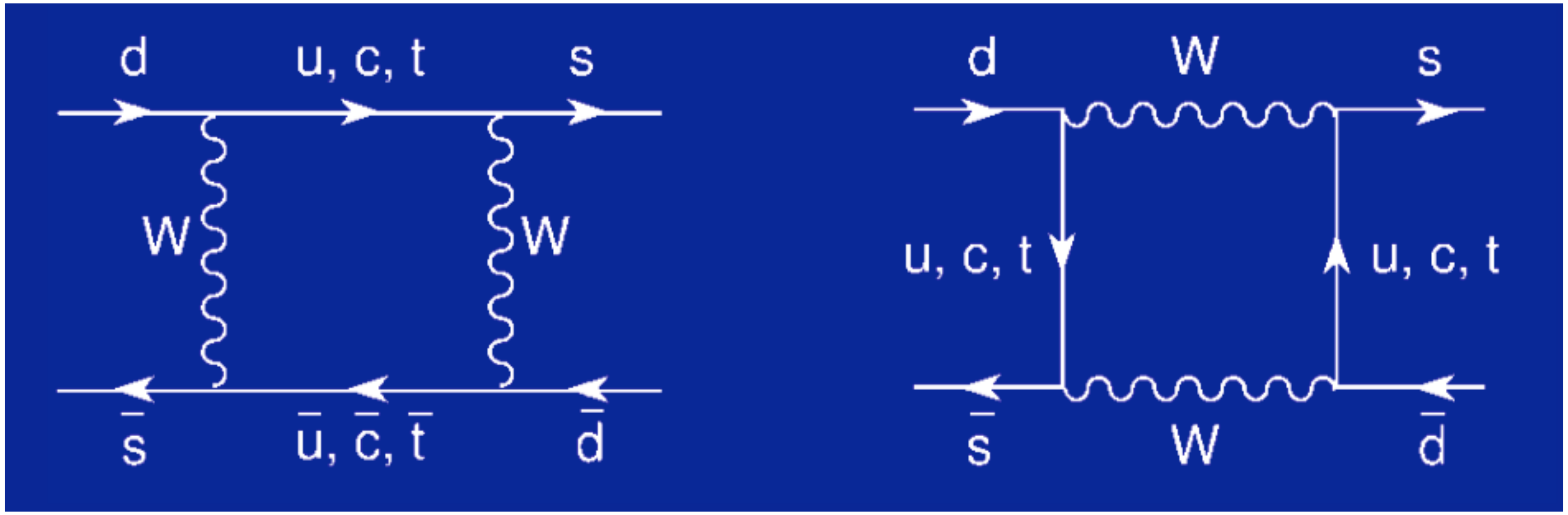
$\mathcal{B}(B_s \to \mu^+\mu^-)_{\text{theo.}} = 3.34\,\binom{+13}{-25} \times 10^{-9}$ $\mathcal{B}(B_s \to \mu^+\mu^-)_{\text{LHCb+CMS}} = 2.9(7) \times 10^{-9}$

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

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

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 $\Longrightarrow [Y_u(Y_u)^\dagger]^n_{i\neq j} \approx y_t^{2n} V_{ti}^* V_{tj}$

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 (!)

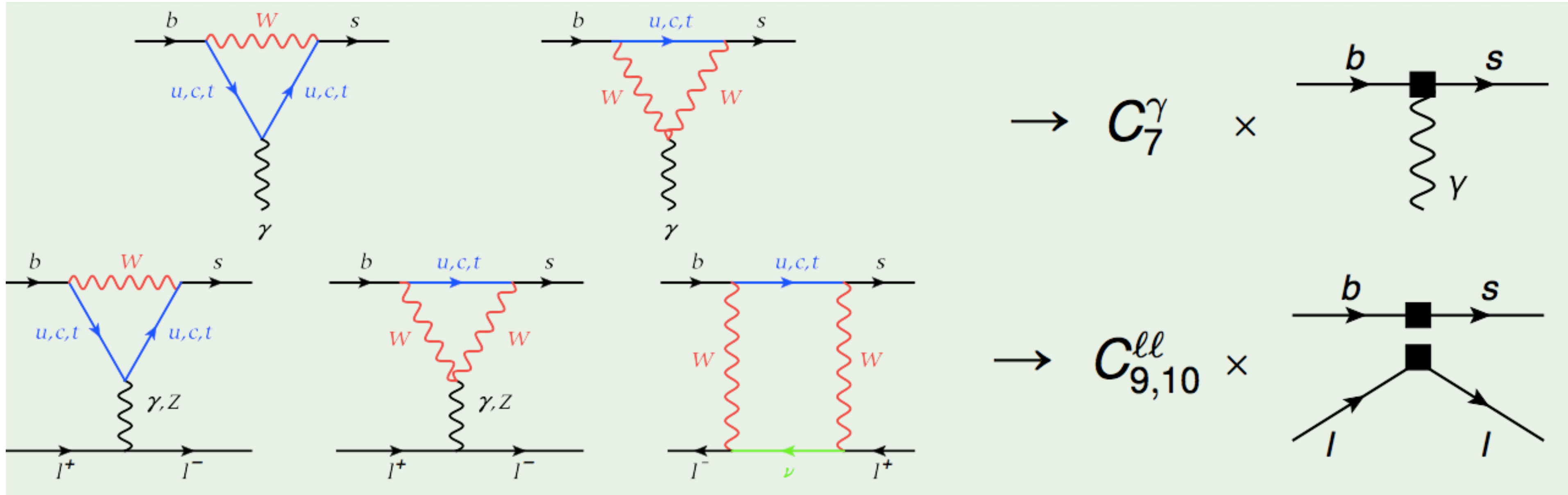
LHC era

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



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

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

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

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

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

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

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

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

!!!

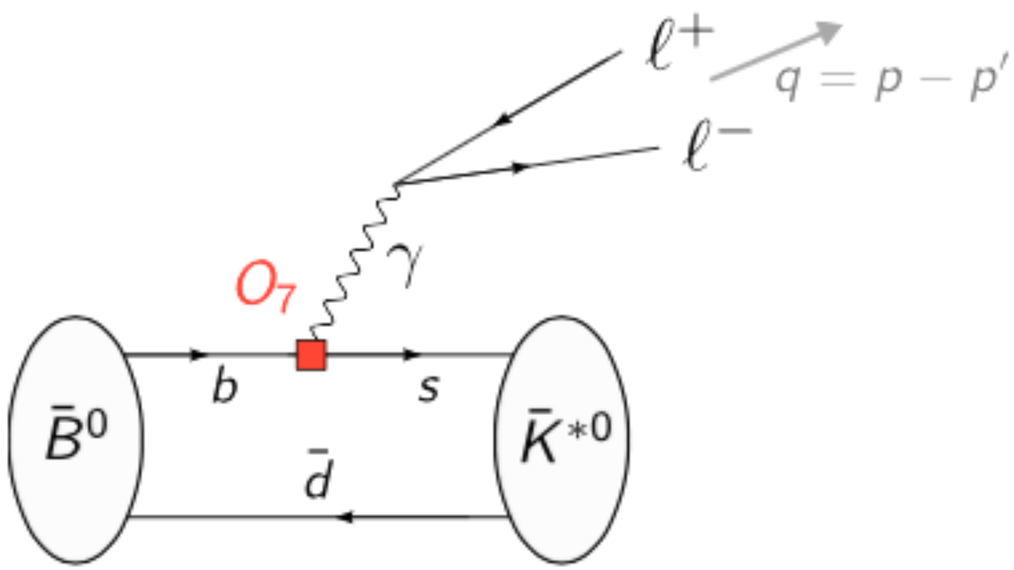
$$Y(q^2) = \frac{4}{3} C_3 + \frac{64}{9} C_5 + \frac{64}{27} C_6 - \frac{1}{2} h(q^2, 0) \left(C_3 + \frac{4}{3} C_4 + 16 C_5 + \frac{64}{3} C_6 \right)$$
$$+ h(q^2, m_c) \left(\frac{4}{3} C_1 + C_2 + 6 C_3 + 60 C_5 \right) - \frac{1}{2} h(q^2, m_b) \left(7 C_3 + \frac{4}{3} C_4 + 76 C_5 + \frac{64}{3}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

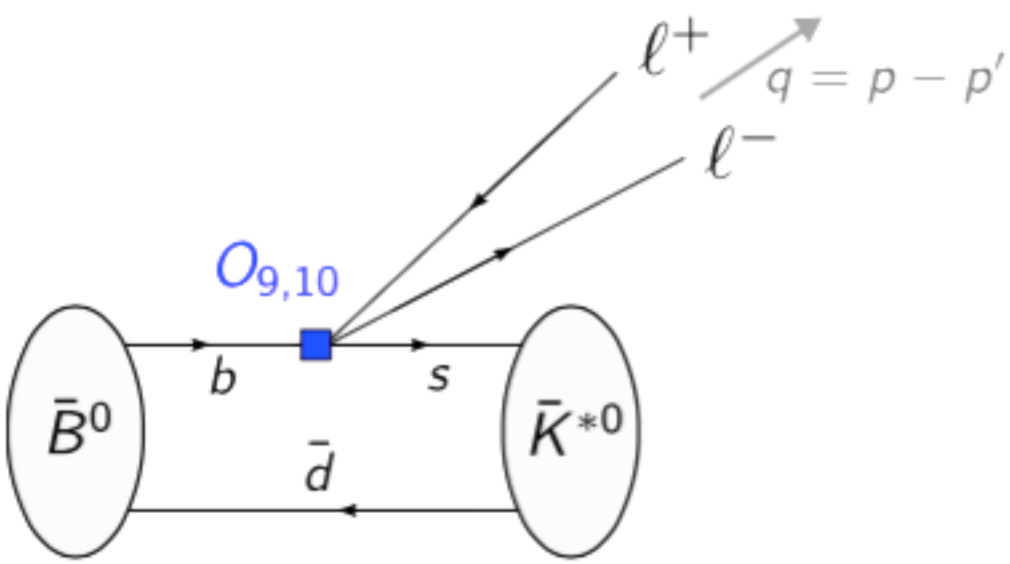
Very slowly varying functions of q^2

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

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

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

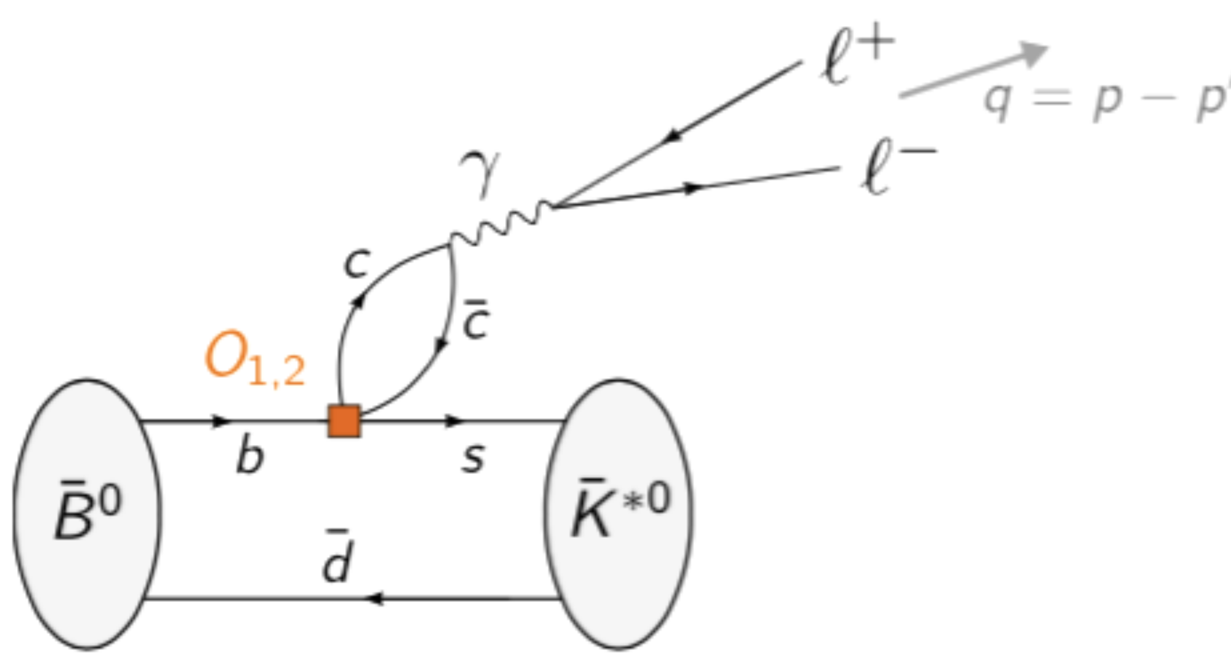




Can be and are computed on the lattice

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

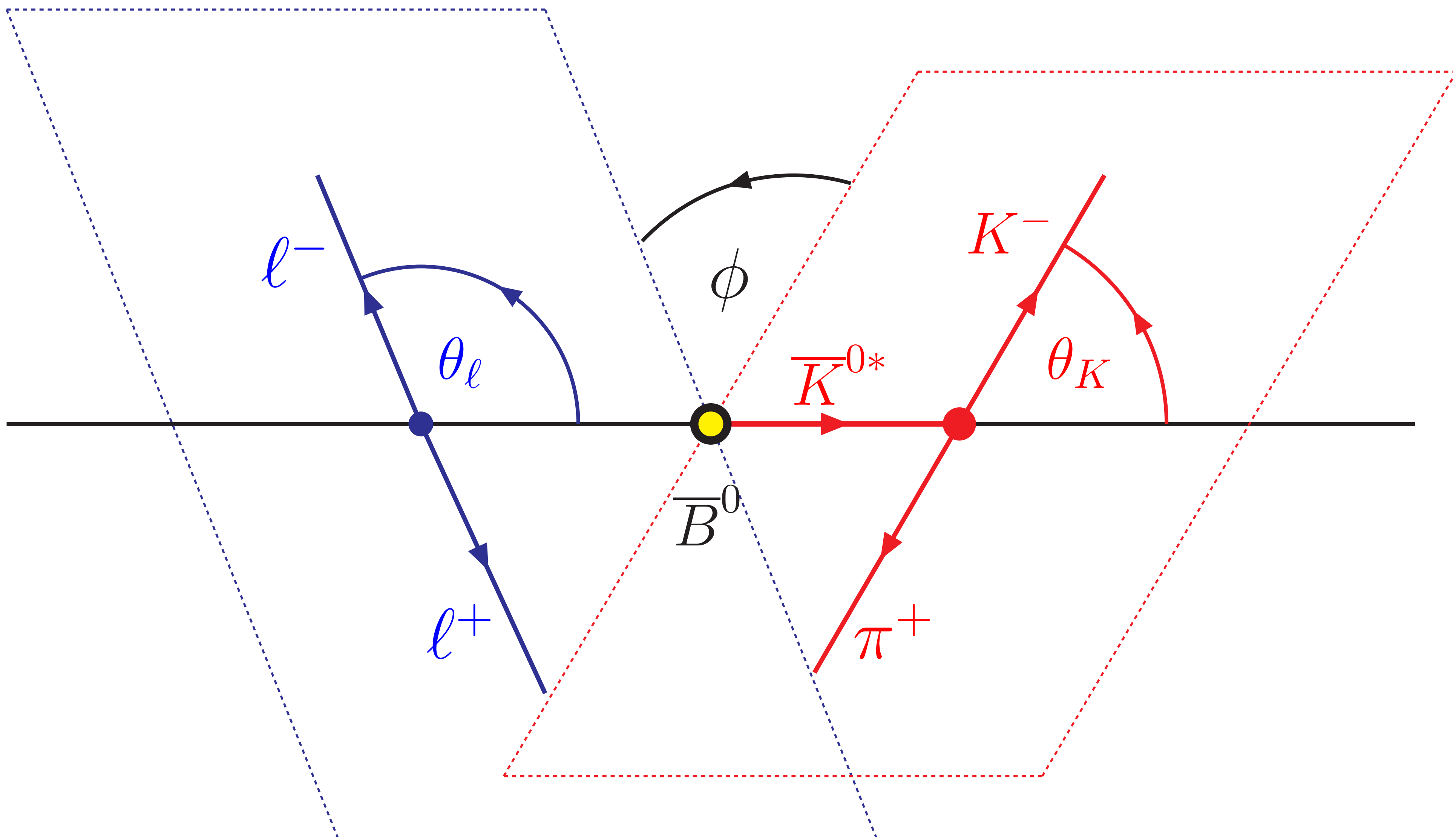
$$\mathcal{T}_\mu = \frac{-16 i \pi^2}{q^2} \sum_{i=1\ldots6;8} C_i \int \mathrm{d}^4x \;\; e^{iq\cdot x} \, \langle K^* | \, \mathrm{T} \; O_i(0) \, j_\mu(x) \, | B \rangle$$



Cannot be computed on the lattice
- work either at very low or very high q^2

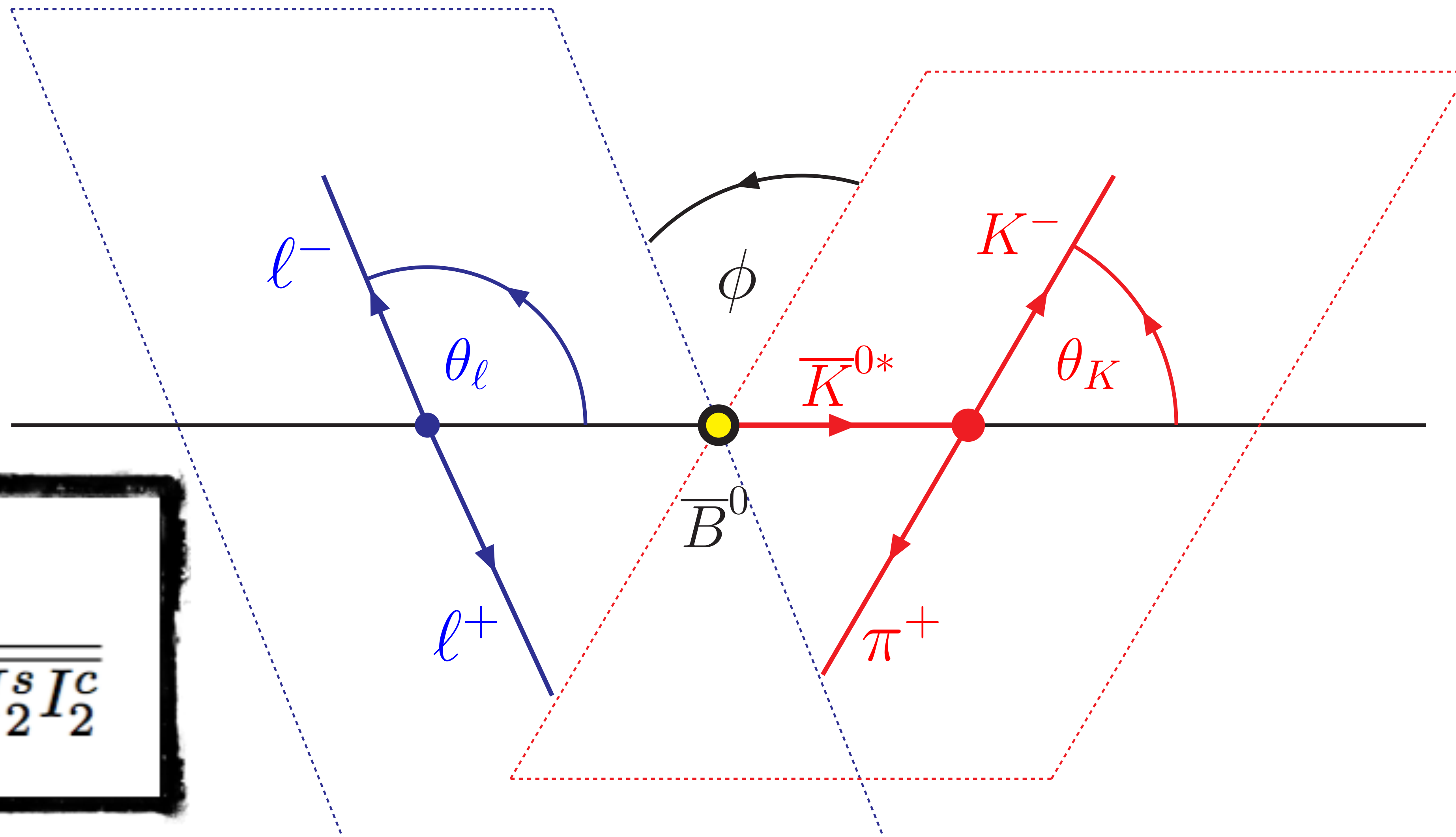
Better sensitivity to NP:

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



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

Full decay distribution



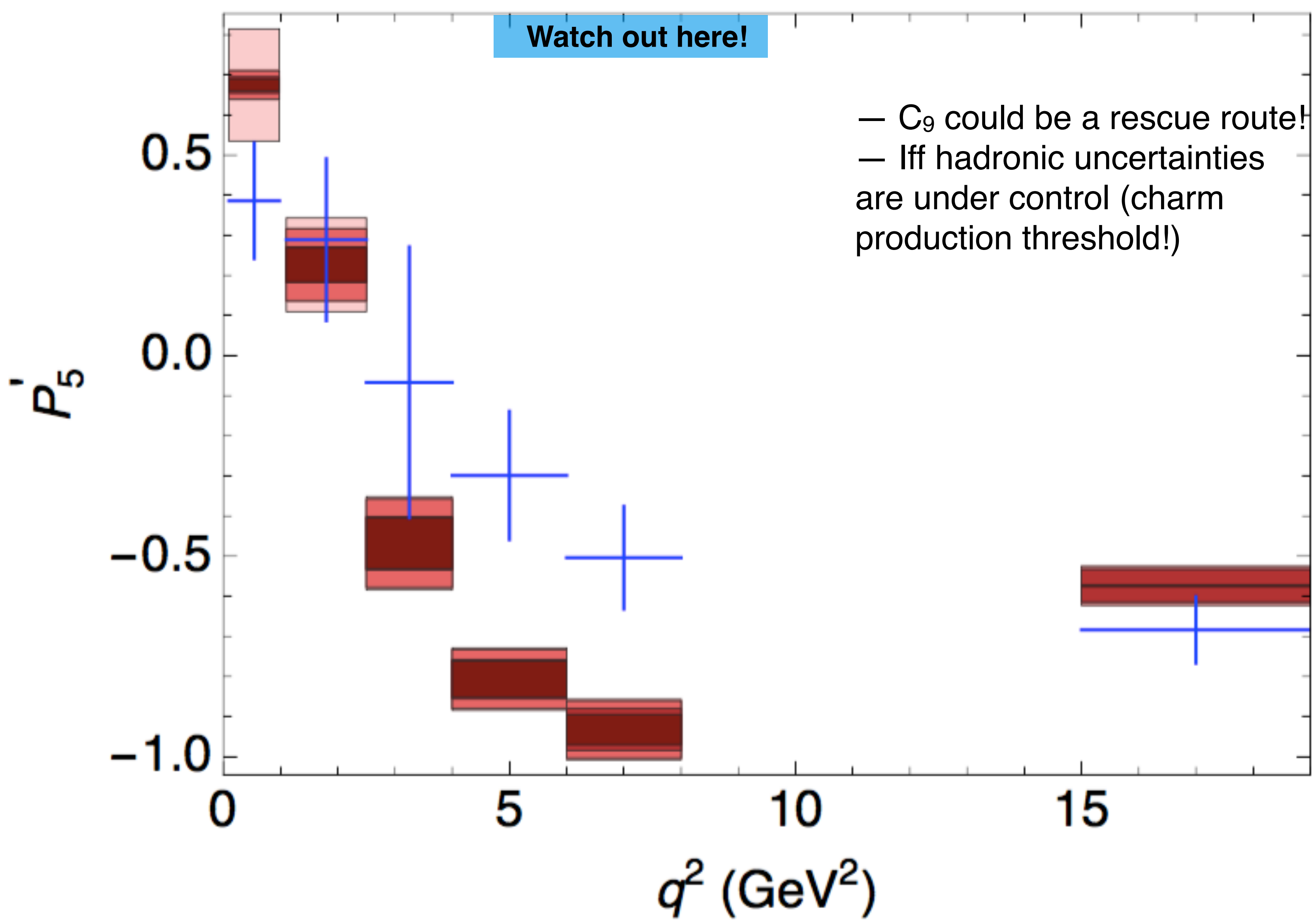
$$P_5' = \frac{I_5}{\sqrt{-4 I_2^s I_2^c}}$$

✓

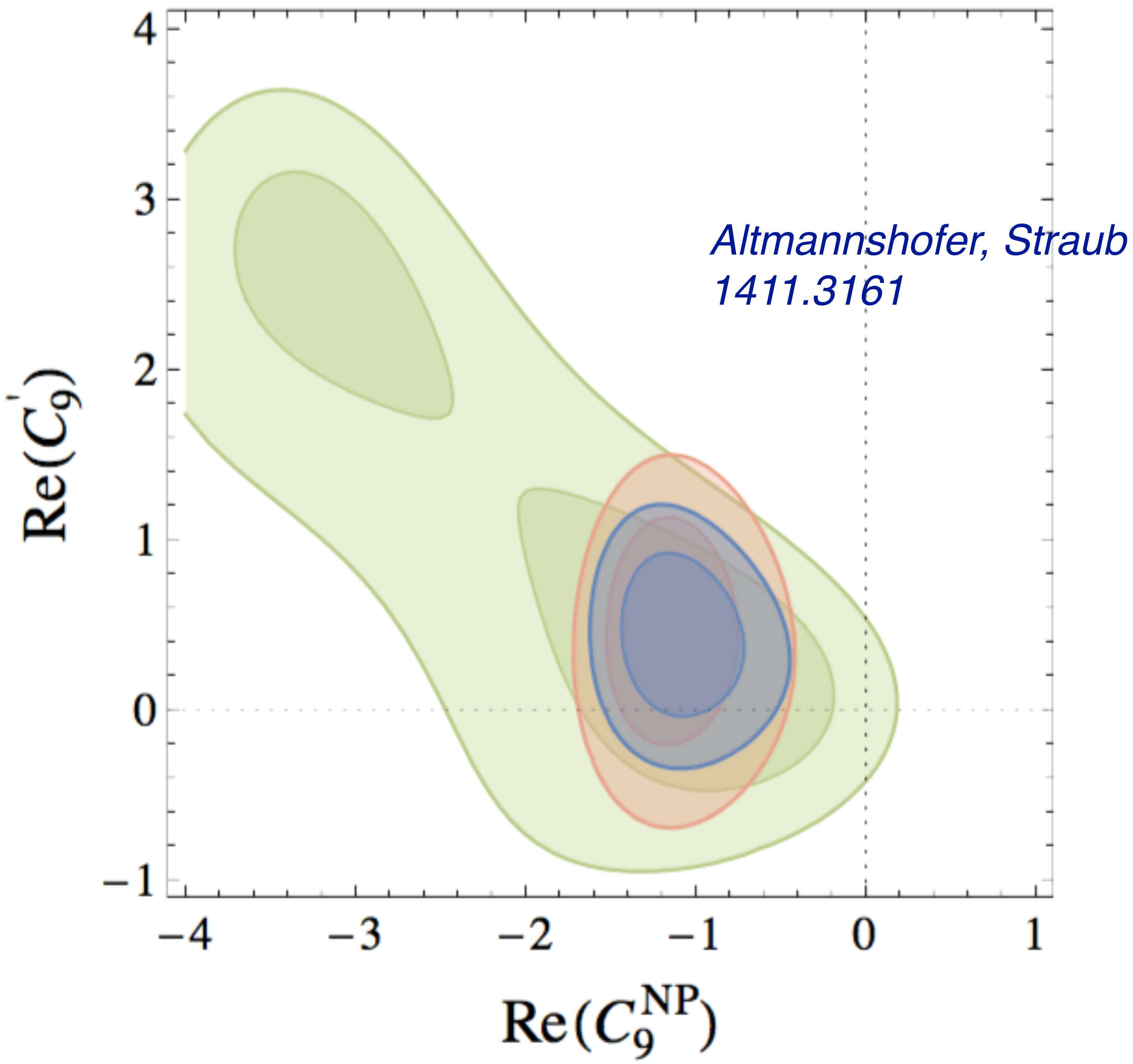
$$\begin{aligned} I(q^2,\theta_\ell,\theta_K,\phi) \;=\;& I_1^s(q^2)\sin^2\theta_K + I_1^c(q^2)\cos^2\theta_K + \left[I_2^s(q^2)\sin^2\theta_K + I_2^c(q^2)\cos^2\theta_K\right]\cos 2\theta_\ell \\ &+ I_3(q^2)\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + I_4(q^2)\sin 2\theta_K\sin 2\theta_\ell\cos\phi \\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

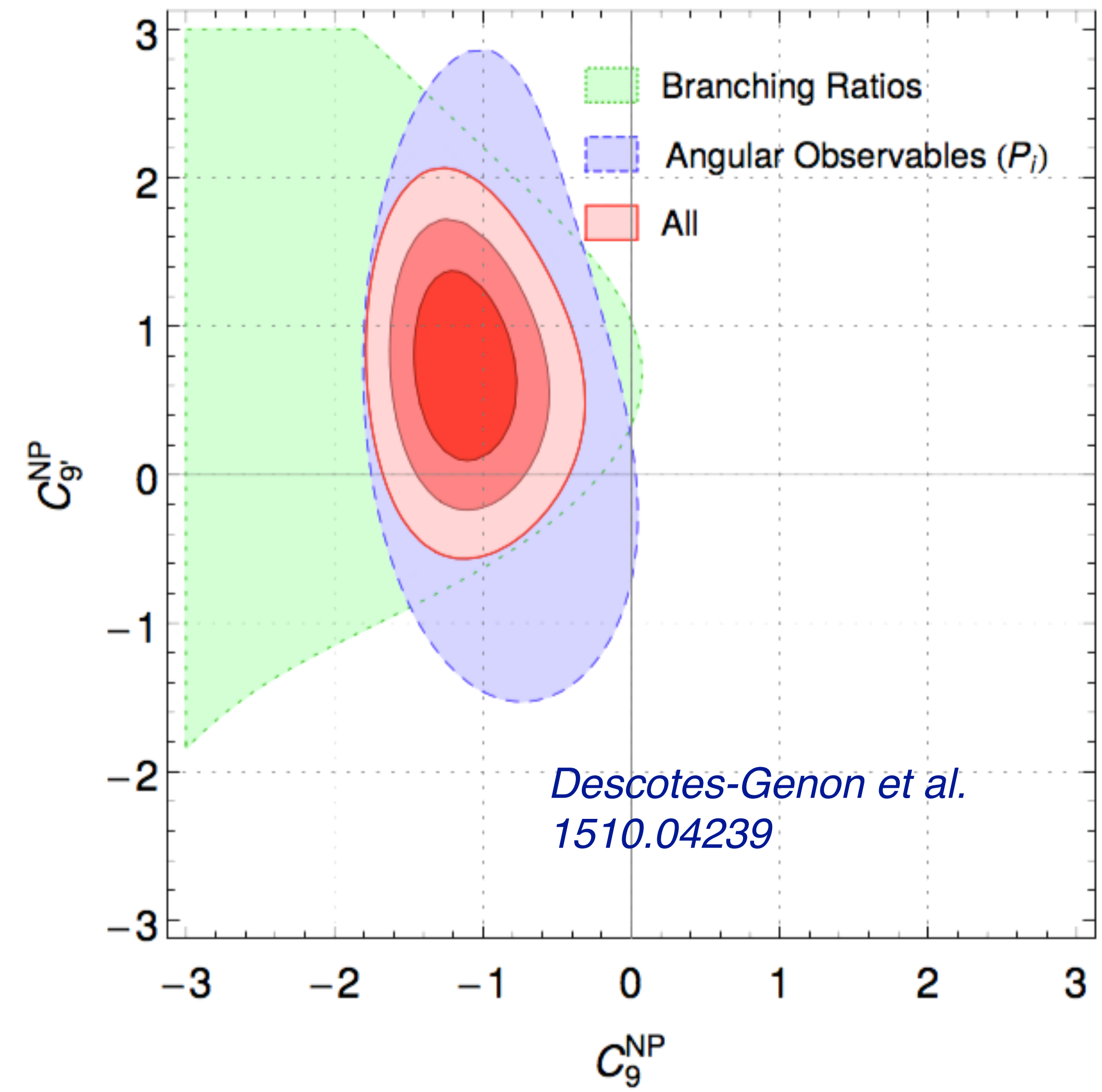
b⟶s anomalies

2-3σ deviation from SM [esp. P_5']



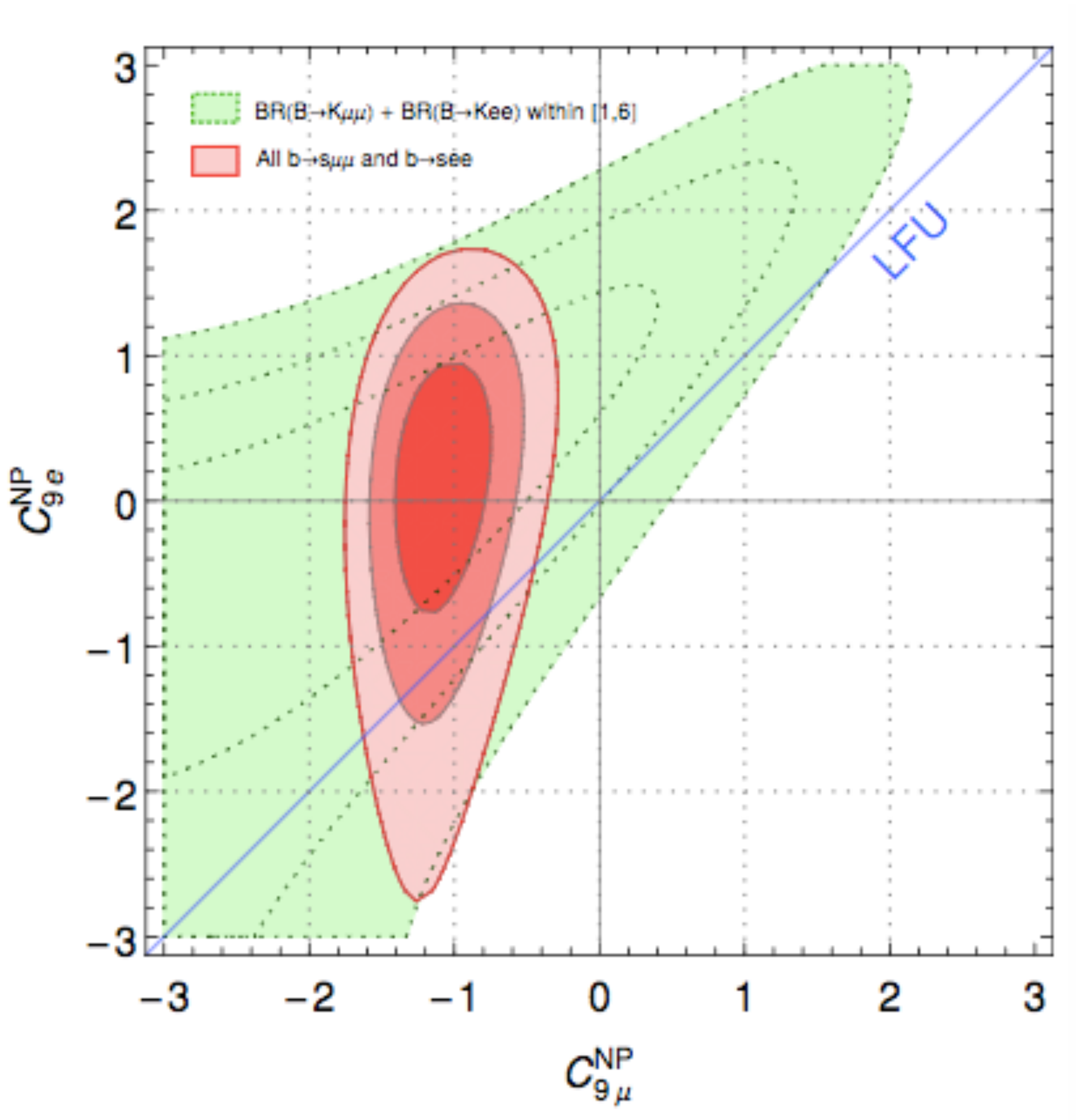
$b \longrightarrow s$ anomalies





- 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.

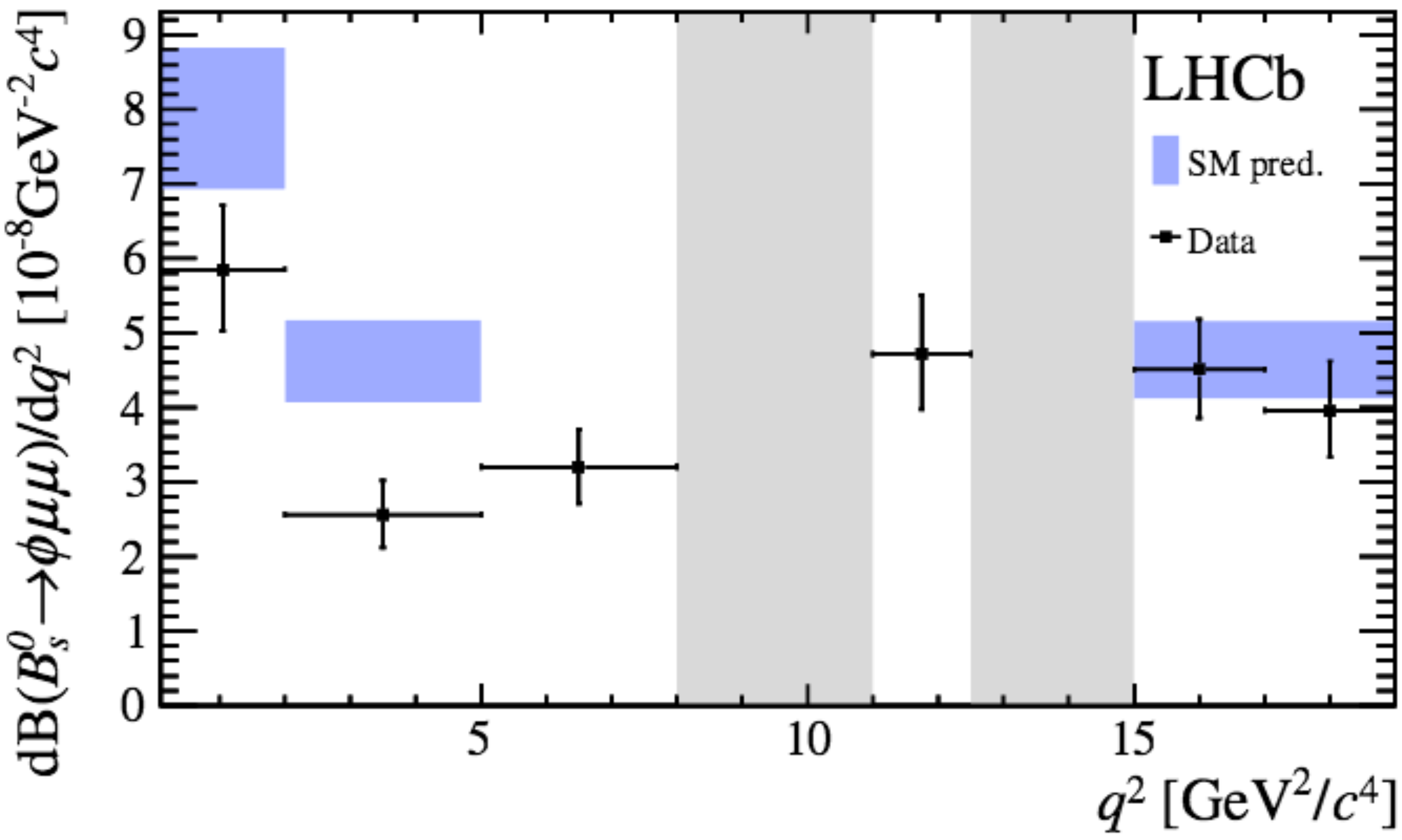
Global analyses also suggest



b⟶s anomalies

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

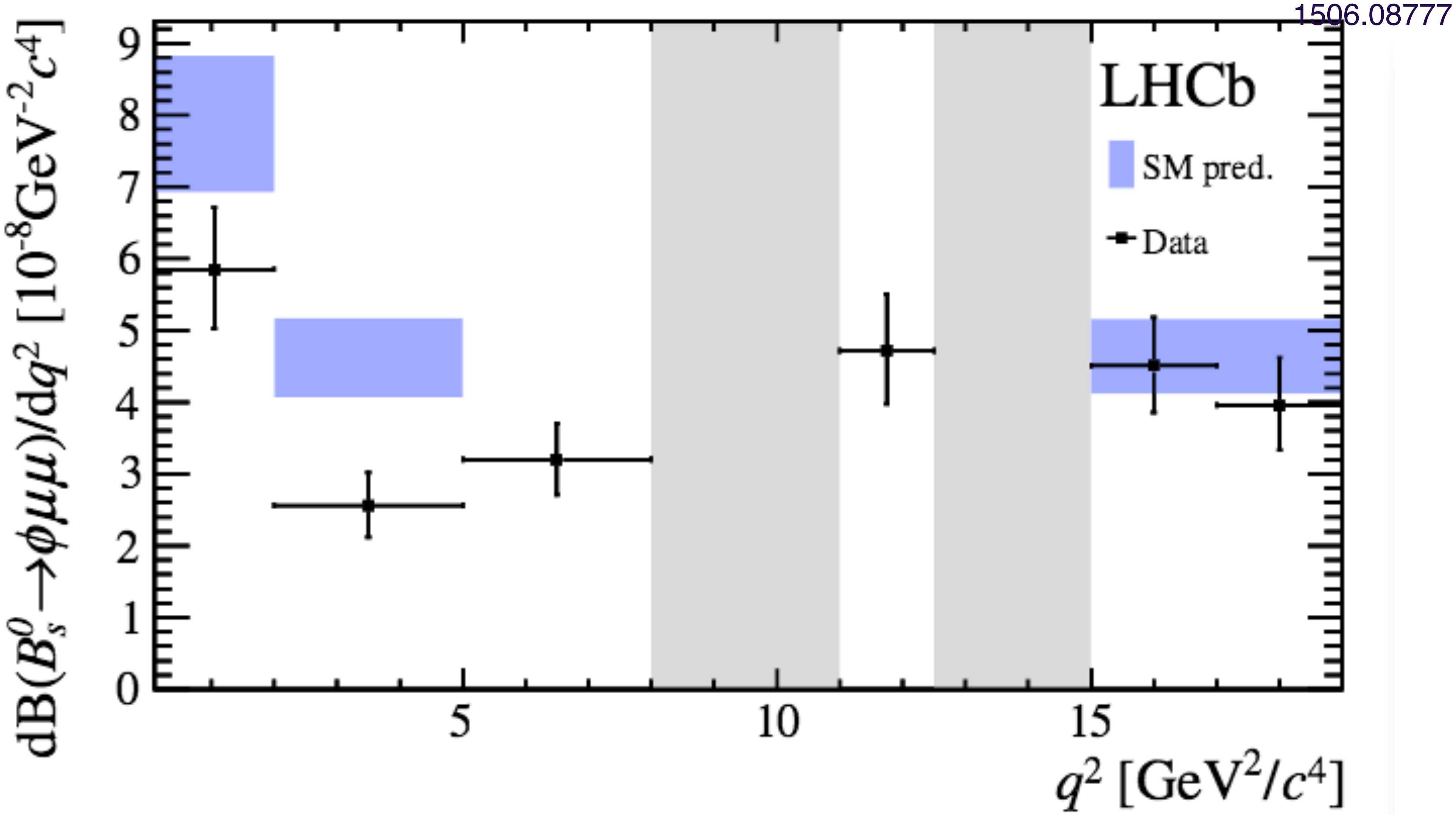
1506.08777



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

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.

LFUV

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})}_{\ell\in(e,\mu)} \quad \& \quad R_{D^{(*)}}^{\mathrm{exp}} > R_{D^{(*)}}^{\mathrm{SM}}$$

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(B \to K^{(*)}ee)}\bigg|_{q^2\in[q^2_{\mathrm{min}},q^2_{\mathrm{max}}]} \quad \& \quad R_{K^{(*)}}^{\mathrm{exp}} < R_{K^{(*)}}^{\mathrm{SM}}$$

$$R_{D^{(*)}}^{\mathrm{exp}} > R_{D^{(*)}}^{\mathrm{SM}} \quad \Rightarrow \quad \Lambda_{\mathrm{NP}} \lesssim 3 \text{ TeV}$$

$$R_{K^{(*)}}^{\mathrm{exp}} < R_{K^{(*)}}^{\mathrm{SM}} \quad \Rightarrow \quad \Lambda_{\mathrm{NP}} \lesssim 30 \text{ TeV}$$

Di Luzio et al. 2017

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 - 2015

Fitting to clean observables

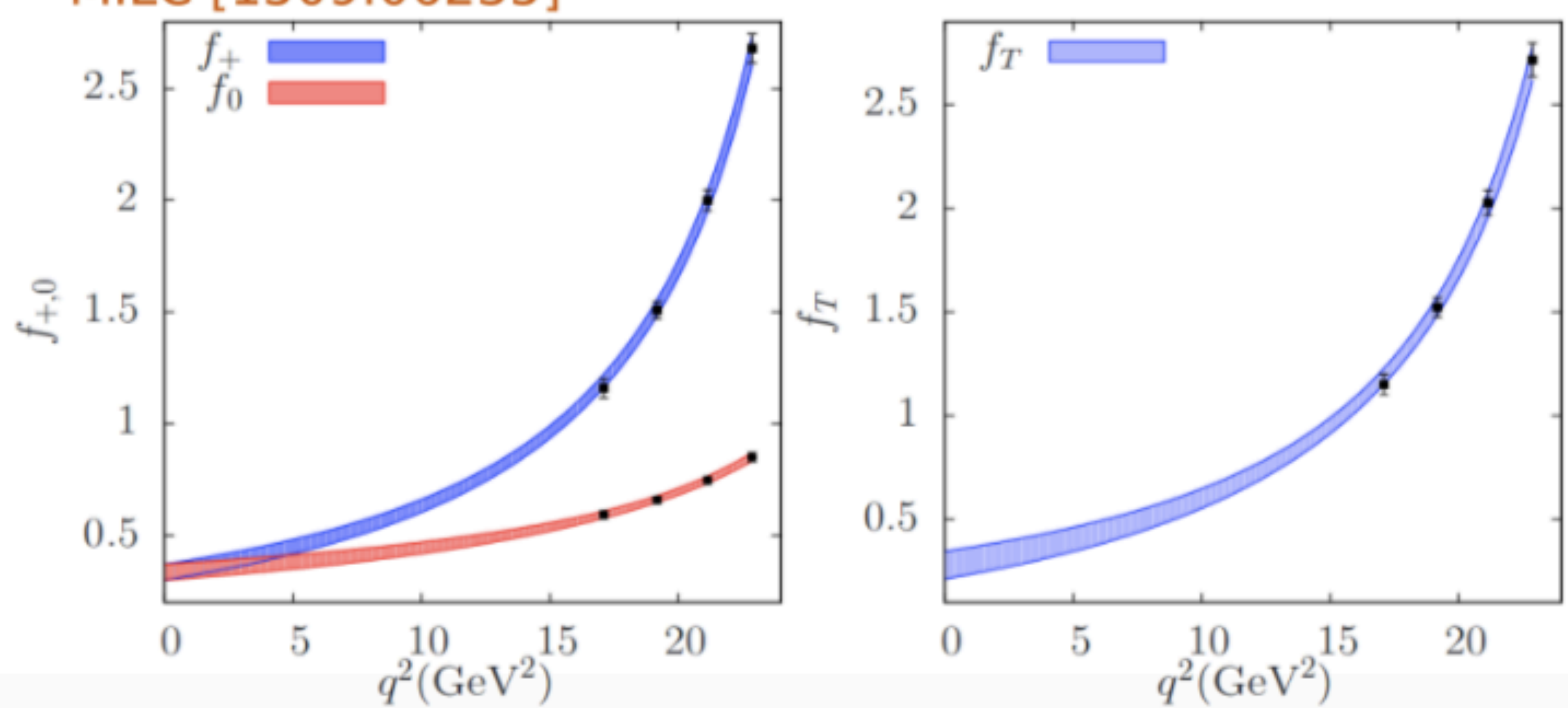
- Use $f_{B_s}^{Latt.} = 224(5)$ MeV and $\mathcal{B}(B_s \to \mu\mu) = 3.0(6)(^3_2) \times 10^{-9}$. [LHCb, 2017]

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

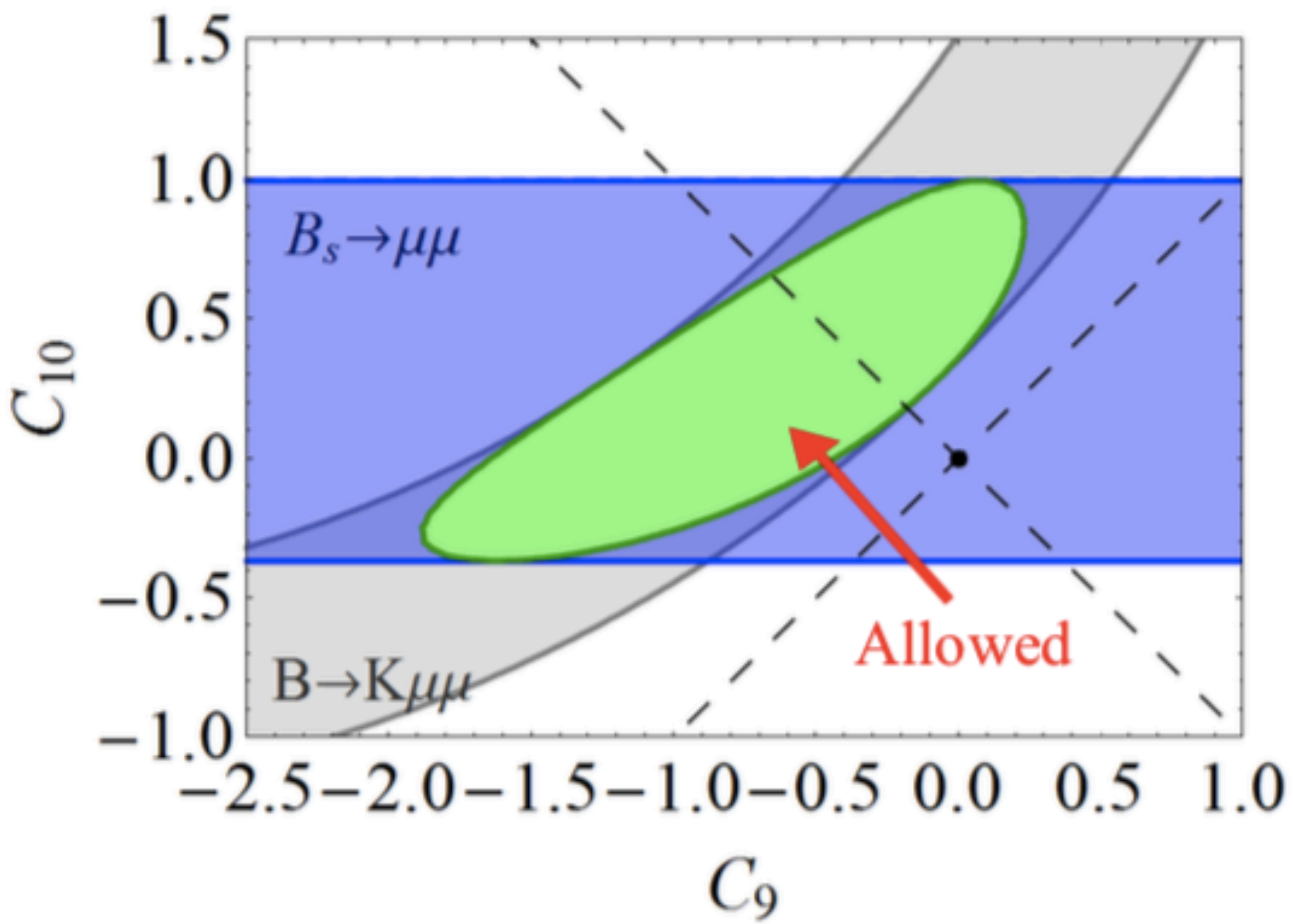
- Use $f_{+,0,T}^{B\to K}(q^2)^{Latt.}$ and $\mathcal{B}(B \to K\mu\mu)_{q^2\in[15,22]\ \mathrm{GeV}^2} = 1.95(16) \times 10^{-7}$. [LHCb, 2016]

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

MILC [1509.06235]



Fitting to clean observables



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

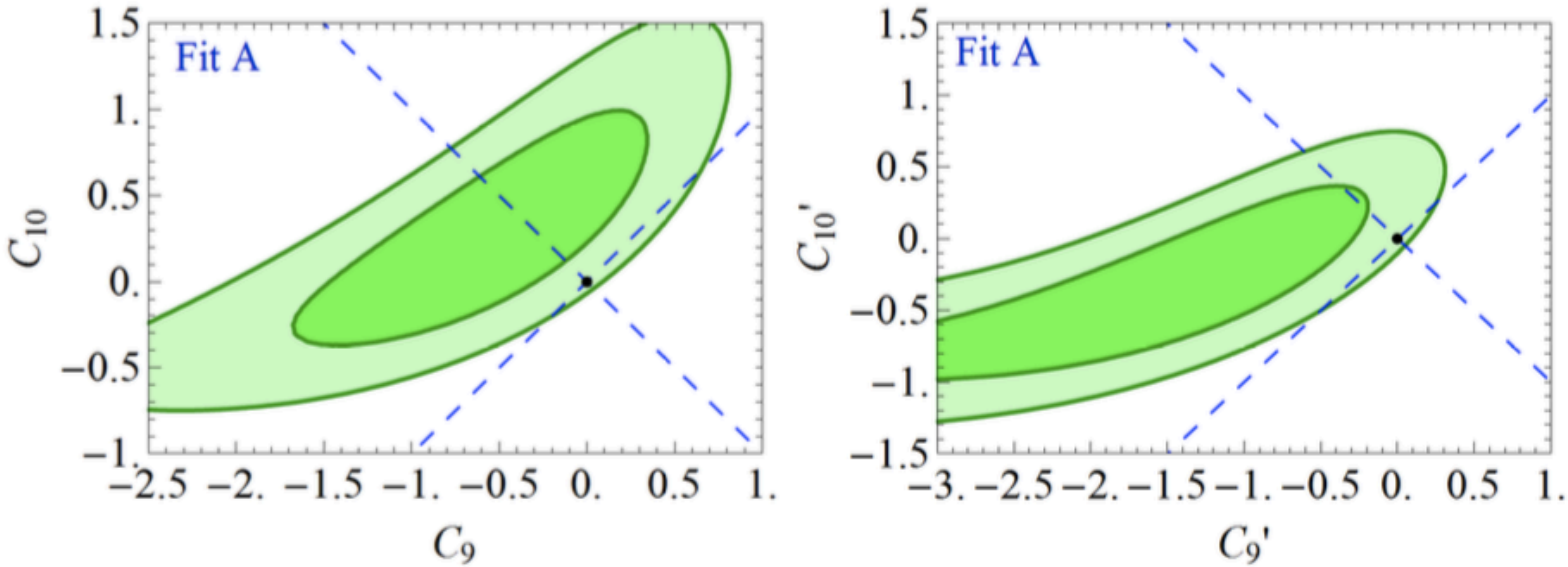
⇒ This value can be used to give **model independent** predictions for $R_{K^{(*)}}$ in the central bin:

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

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

Interestingly…

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

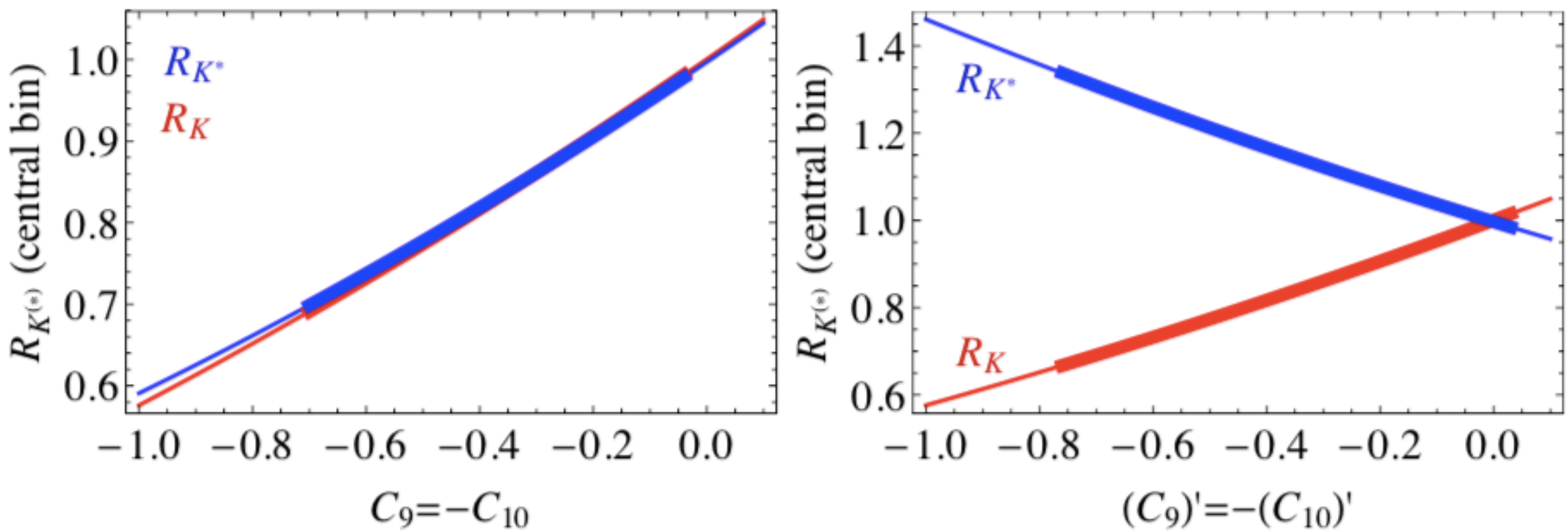


$$\mathcal{O}_9^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell), \qquad \mathcal{O}_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \gamma^5 \ell),$$

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

Interestingly...

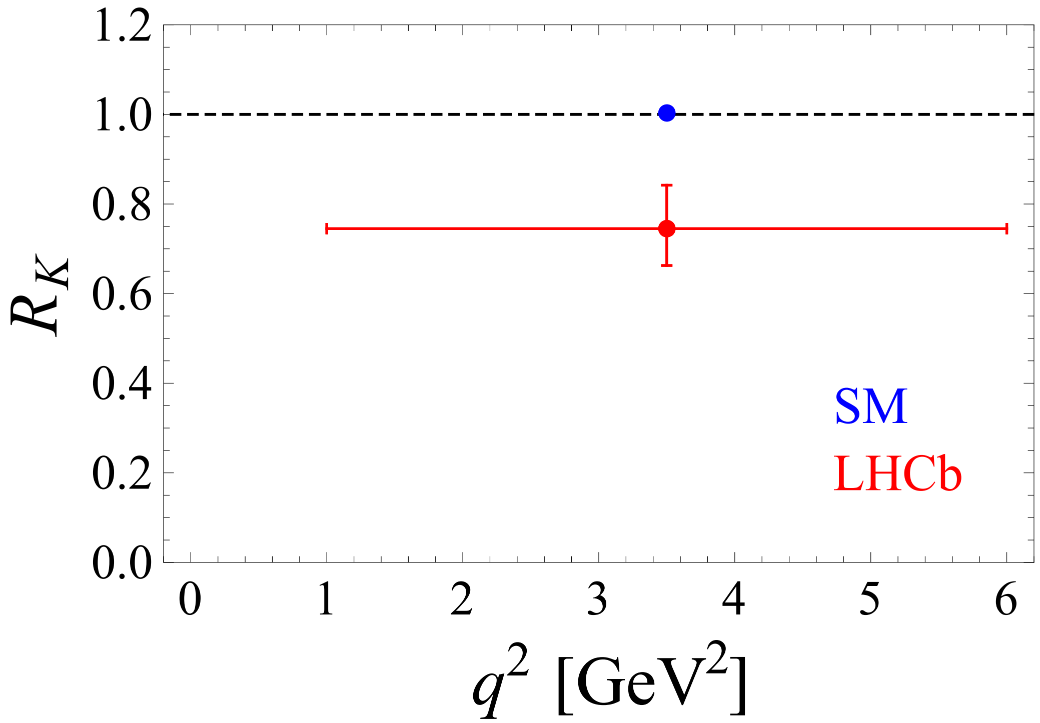
Model independent predictions for R_K and R_{K^*}:

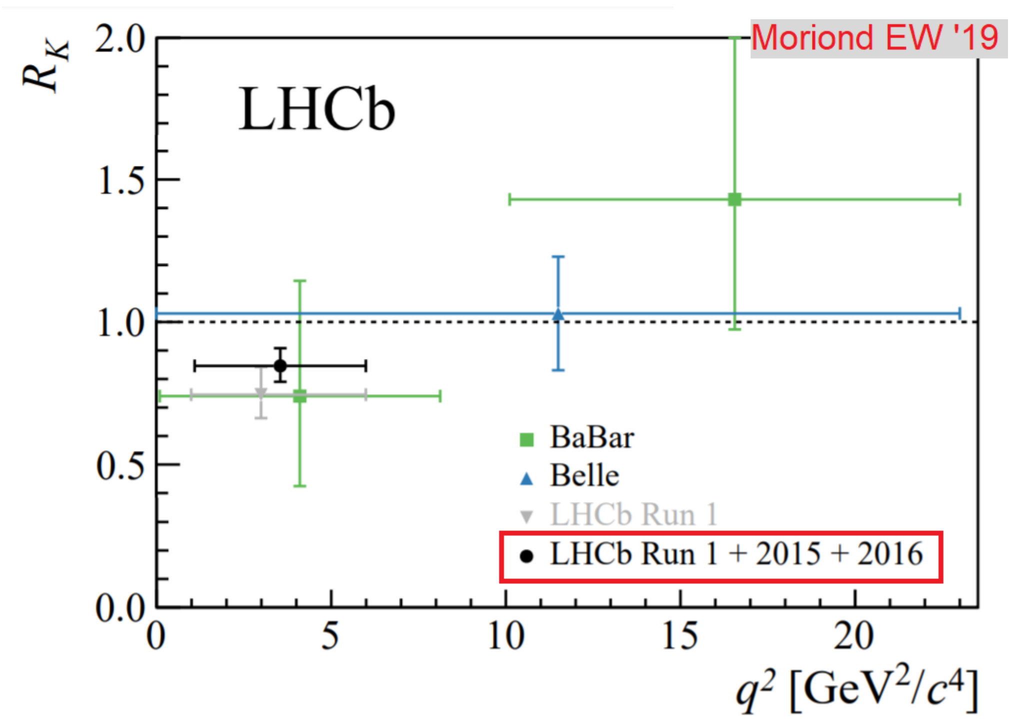


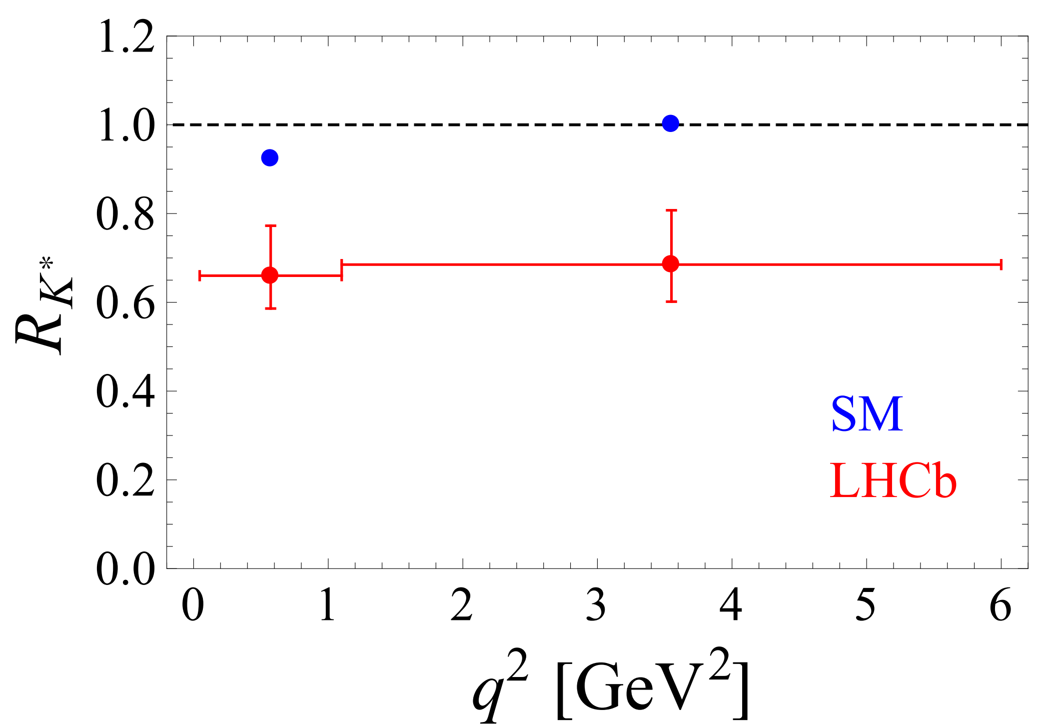
⇒ The scenario $C_9 = -C_{10}$ predicts $R_{K^{(*)}} < 1$, as observed.

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

Before and after Moriond EW 2019







- NEW [LHCb]:

$$[R_K^{\rm new}]_{\rm avg} = 0.85(6)$$

- Discrepancy between Run 1 and Run 2 [$\approx 2\sigma$]:

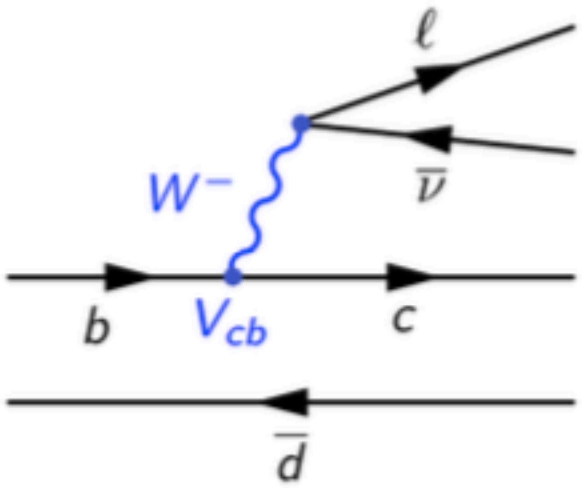
$$[R_K^{\rm new}]_{\rm run\ 1} = 0.71(8)$$

$$[R_K^{\rm new}]_{\rm run\ 2} = 0.92(8)$$

R_D R_{D^*}

- Tree-level process in the SM:

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

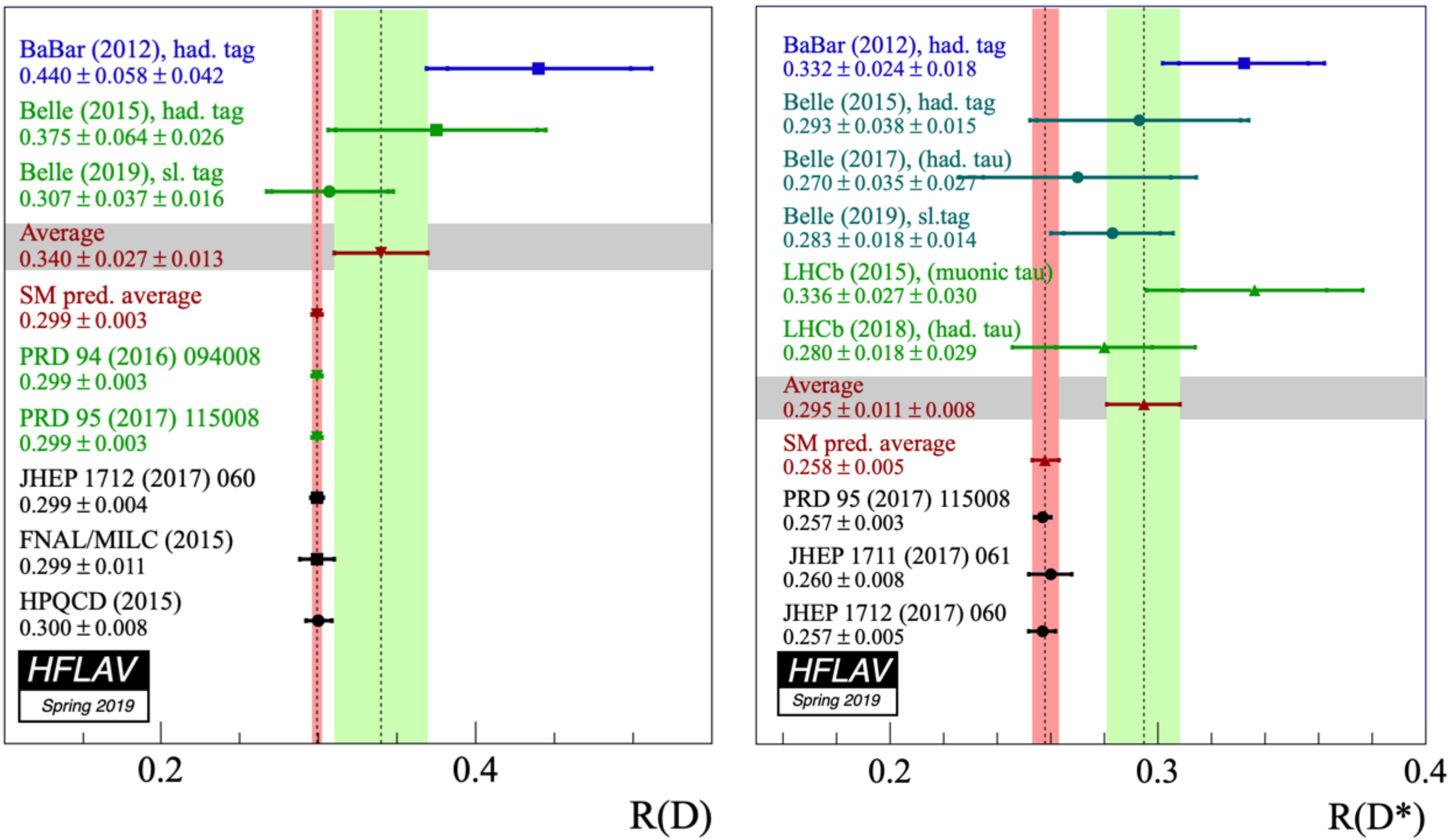


- Non-perturbative QCD $\Longleftrightarrow$ form-factors (Lattice QCD)

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

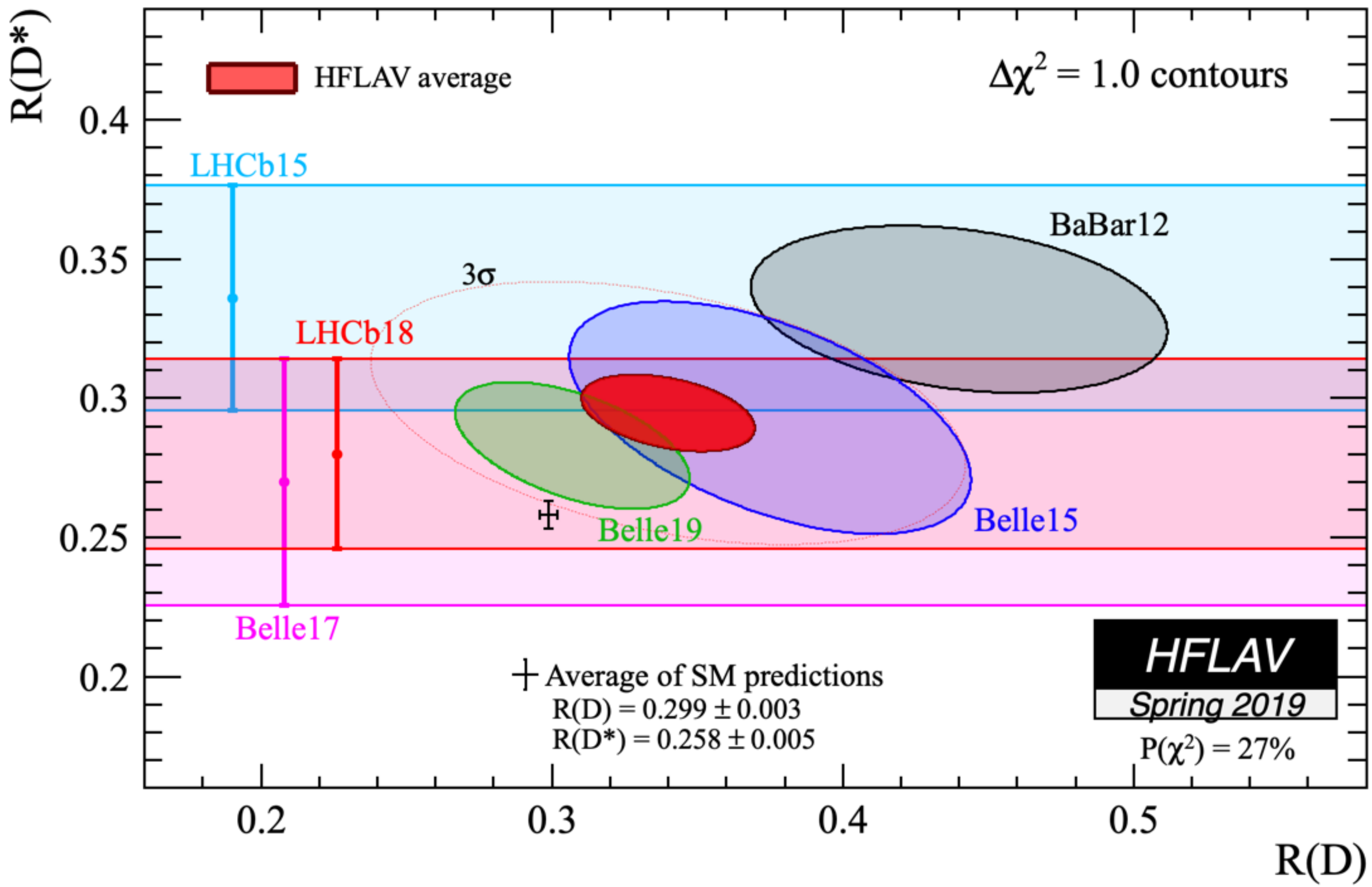
- Situation less clear for $B \to D^* \Rightarrow$ (more FFs, less LQCD results) [NP in τ – use angular distribution + HQET of Bernlochner et al 2017]

R_D R_{D^*}



BaBar (2012), had. tag
0.440 ± 0.058 ± 0.042
Belle (2015), had. tag
0.375 ± 0.064 ± 0.026
Belle (2019), sl. tag
0.307 ± 0.037 ± 0.016
Average
0.340 ± 0.027 ± 0.013
SM pred. average
0.299 ± 0.003
PRD 94 (2016) 094008
0.299 ± 0.003
PRD 95 (2017) 115008
0.299 ± 0.003
JHEP 1712 (2017) 060
0.299 ± 0.004
FNAL/MILC (2015)
0.299 ± 0.011
HPQCD (2015)
0.300 ± 0.008
HFLAV
Spring 2019
0.2
0.4
R(D)
BaBar (2012), had. tag
0.332 ± 0.024 ± 0.018
Belle (2015), had. tag
0.293 ± 0.038 ± 0.015
Belle (2017), (had. tau)
0.270 ± 0.035 ± 0.027
Belle (2019), sl.tag
0.283 ± 0.018 ± 0.014
LHCb (2015), (muonic tau)
0.336 ± 0.027 ± 0.030
LHCb (2018), (had. tau)
0.280 ± 0.018 ± 0.029
Average
0.295 ± 0.011 ± 0.008
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
Spring 2019
0.2
0.3
0.4
R(D*)

R_D R_{D^*}



R(D*)
HFLAV average
$\Delta\chi^2 = 1.0$ contours
0.4
LHCb15
0.35
BaBar12
3σ
LHCb18
0.3
0.25
Belle19
Belle15
Belle17
0.2
Average of SM predictions
R(D) = 0.299 ± 0.003
R(D*) = 0.258 ± 0.005
HFLAV
Spring 2019
$P(\chi^2) = 27\%$
0.2
0.3
0.4
0.5
R(D)

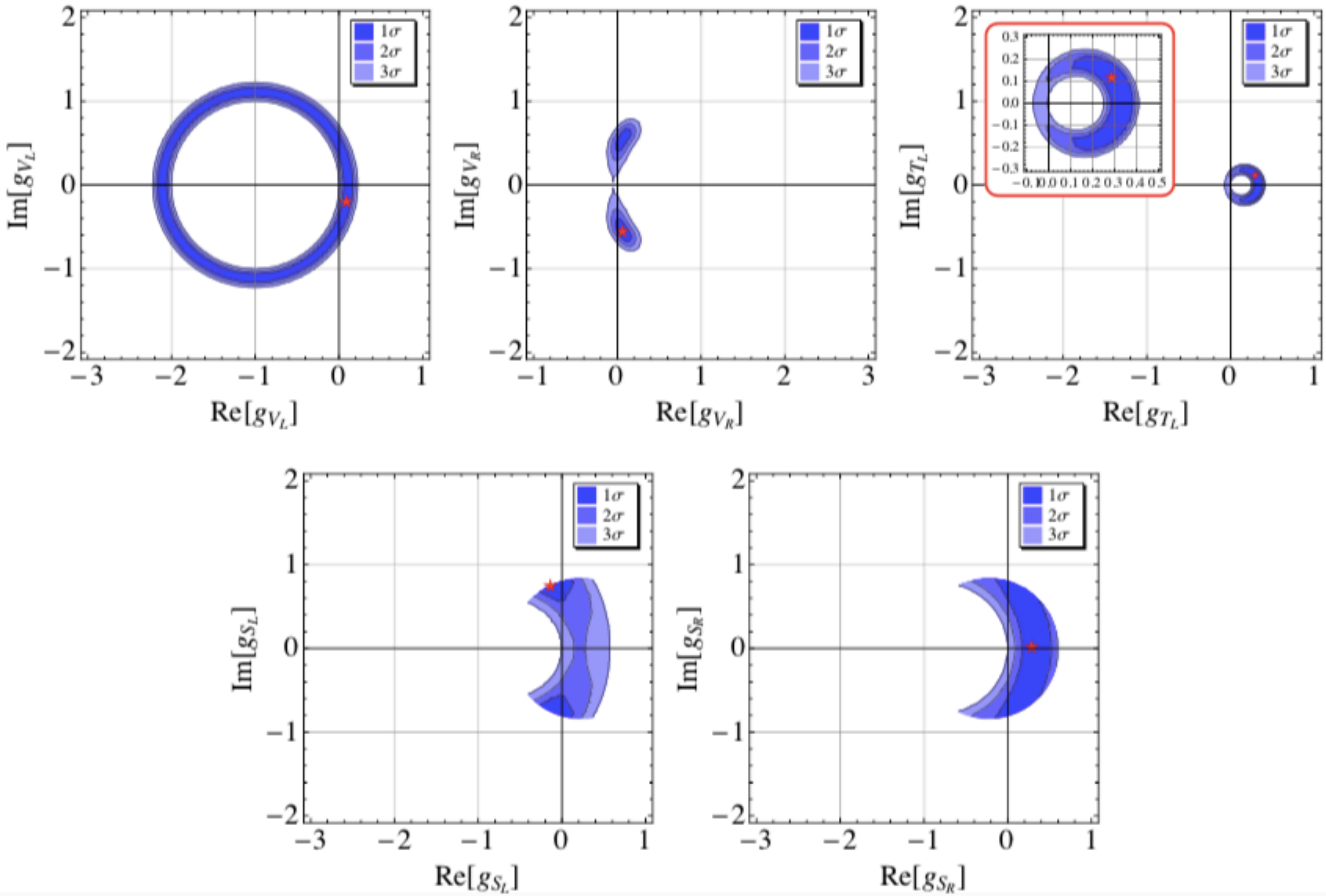
Effective theory

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

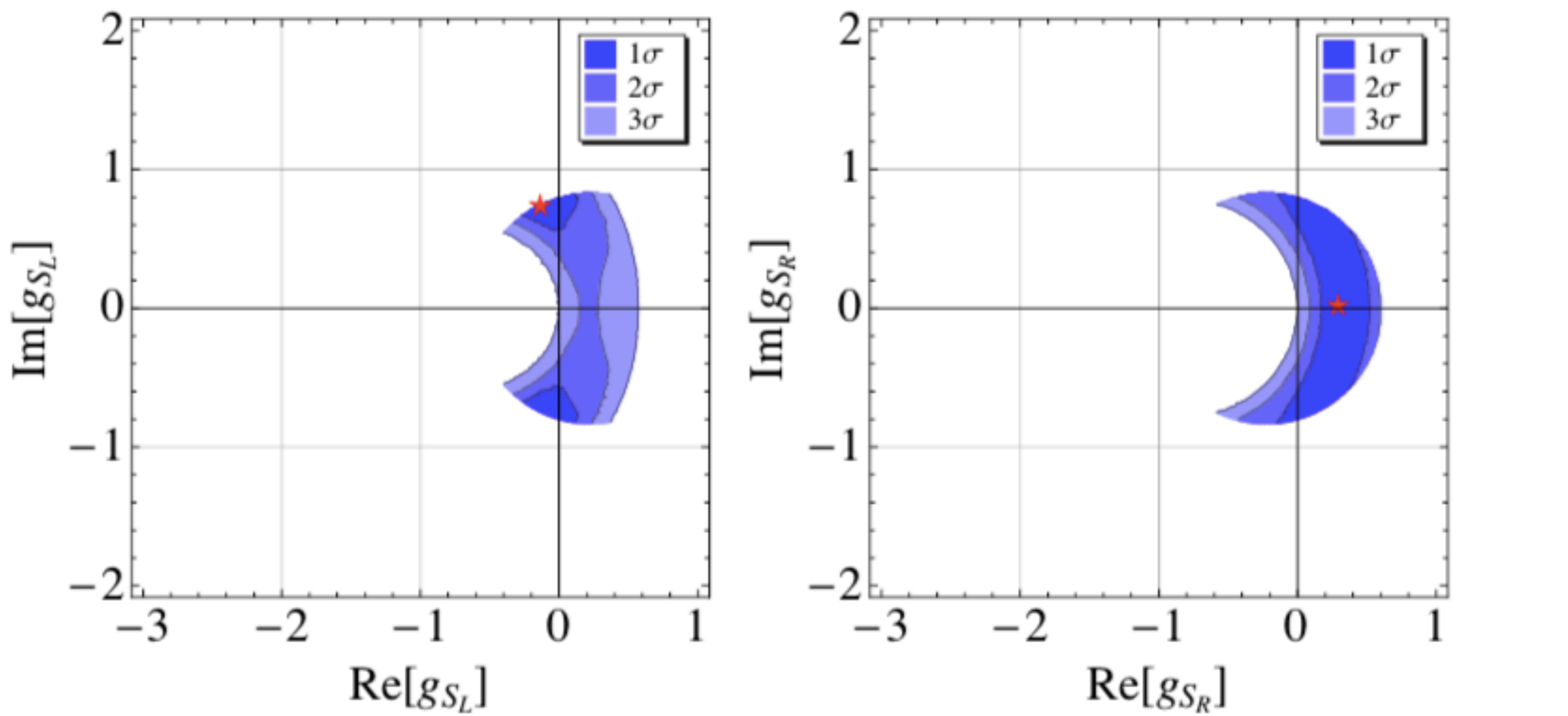
$$\mathcal{H}_{\rm eff} = \frac{4G_F}{\sqrt{2}} V_{cb} \big[(1 + g_{V_L})(\bar{c}_L \gamma_\mu b_L)(\bar{\ell}_L \gamma^\mu \nu_L) + g_{V_R}(\bar{c}_R \gamma_\mu b_R)(\bar{\ell}_L \gamma^\mu \nu_L) + g_{S_L}(\bar{c}_R b_L)(\bar{\ell}_R \nu_L) + g_{S_R}(\bar{c}_L b_R)(\bar{\ell}_R \nu_L) + g_{T_L}(\bar{c}_R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

$$\frac{G_F}{\sqrt{2}} = \frac{1}{(1.7\ \text{TeV})^2}$$

Effective theory at work



Effective theory at work



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

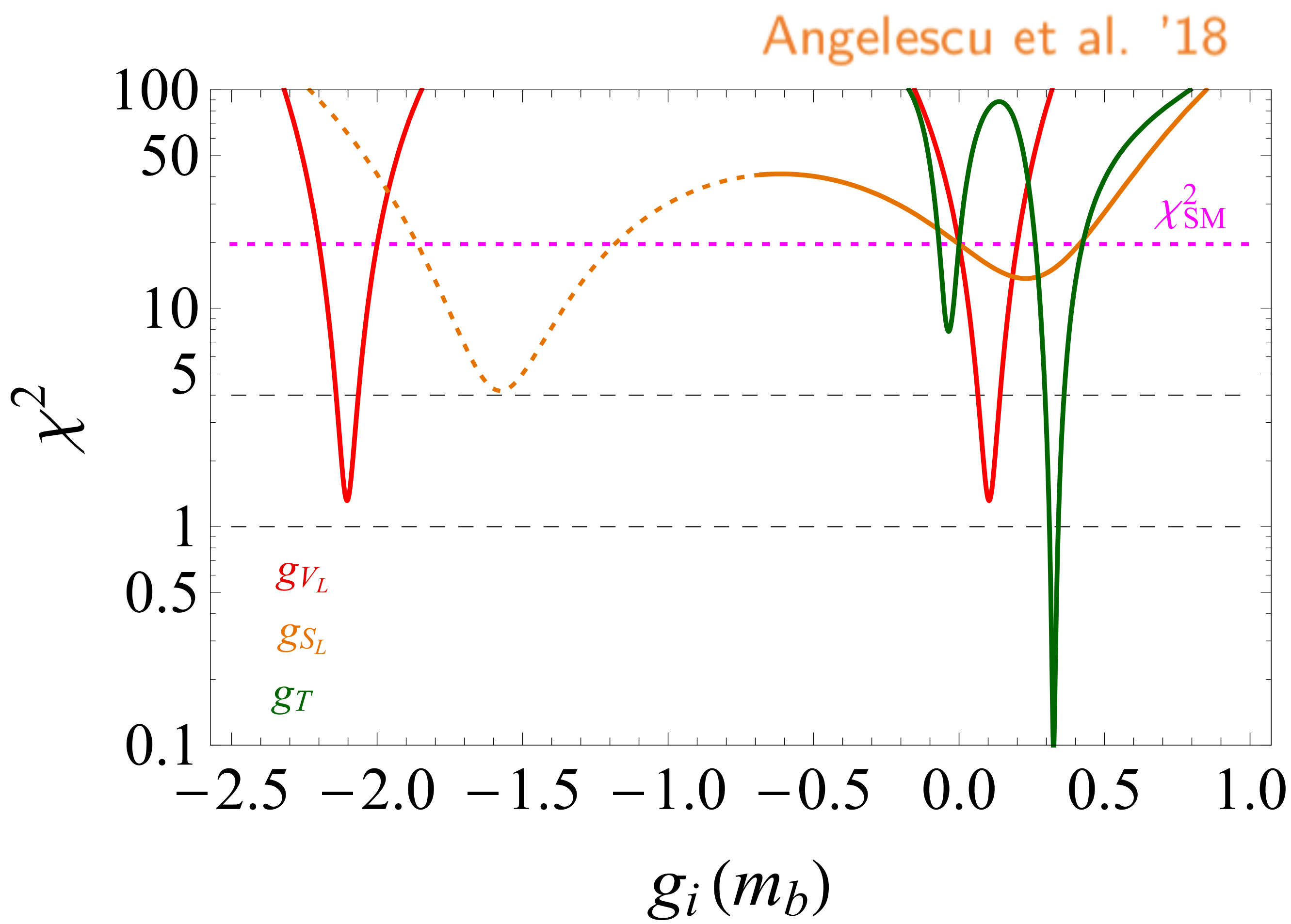
Must be less than 30%-ish in order not to upset τ_{B_c}

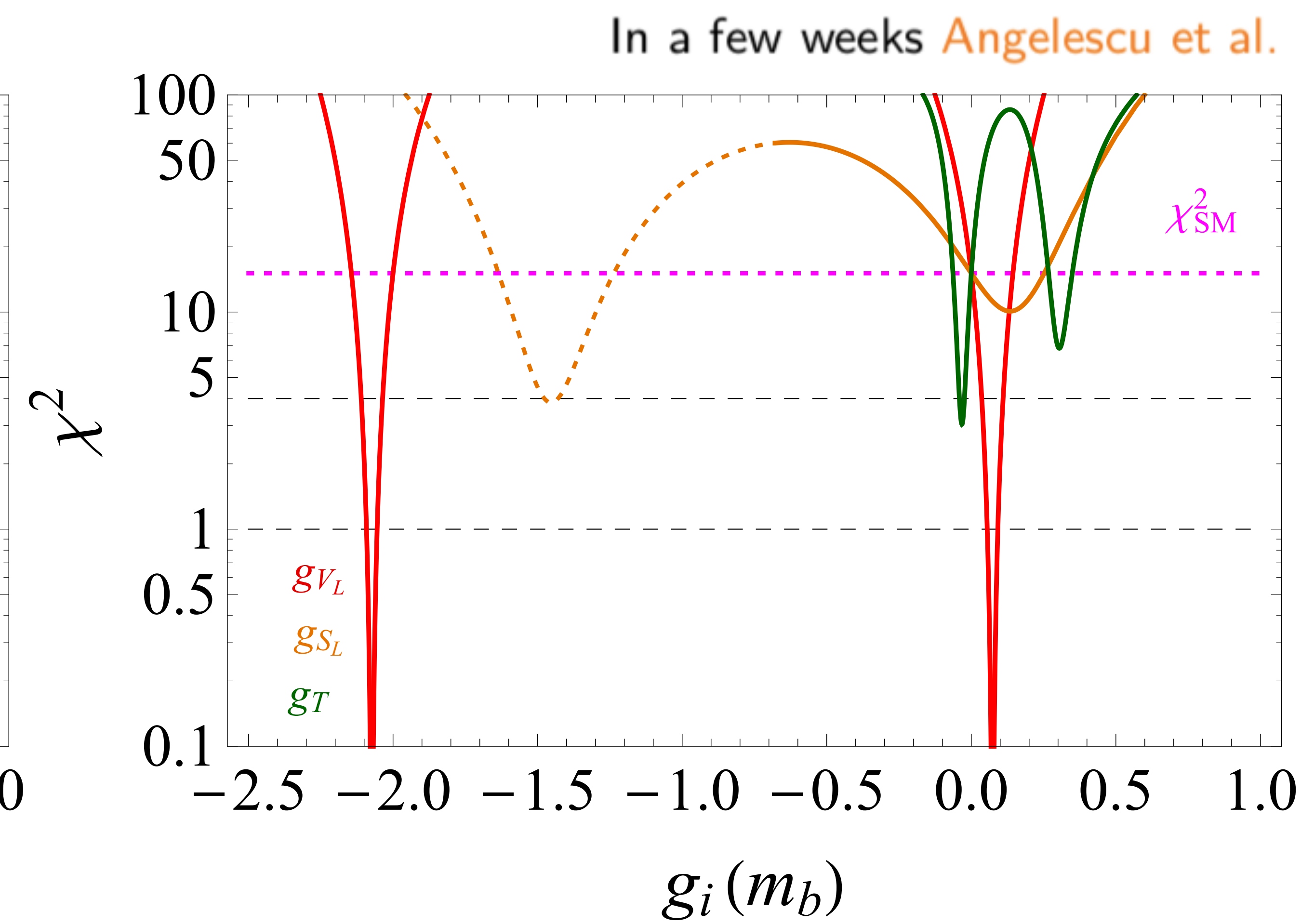
EFT - exclusive $b \to c\ell\nu$

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

- $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge invariance:
  $\Rightarrow$ g_{V_R} is LFU at dimension 6 ($W \bar{c}_R b_R$ vertex).
  $\Rightarrow$ Four coefficients left: g_{V_L}, g_{S_L}, g_{S_R} and g_T.
- Several viable solutions to $R_{D^{(*)}}$: [Freytsis et al. 2015]
  - e.g. $g_{V_L} \in (0.04, 0.11)$, but not only!

Before and after Moriond EW 2019



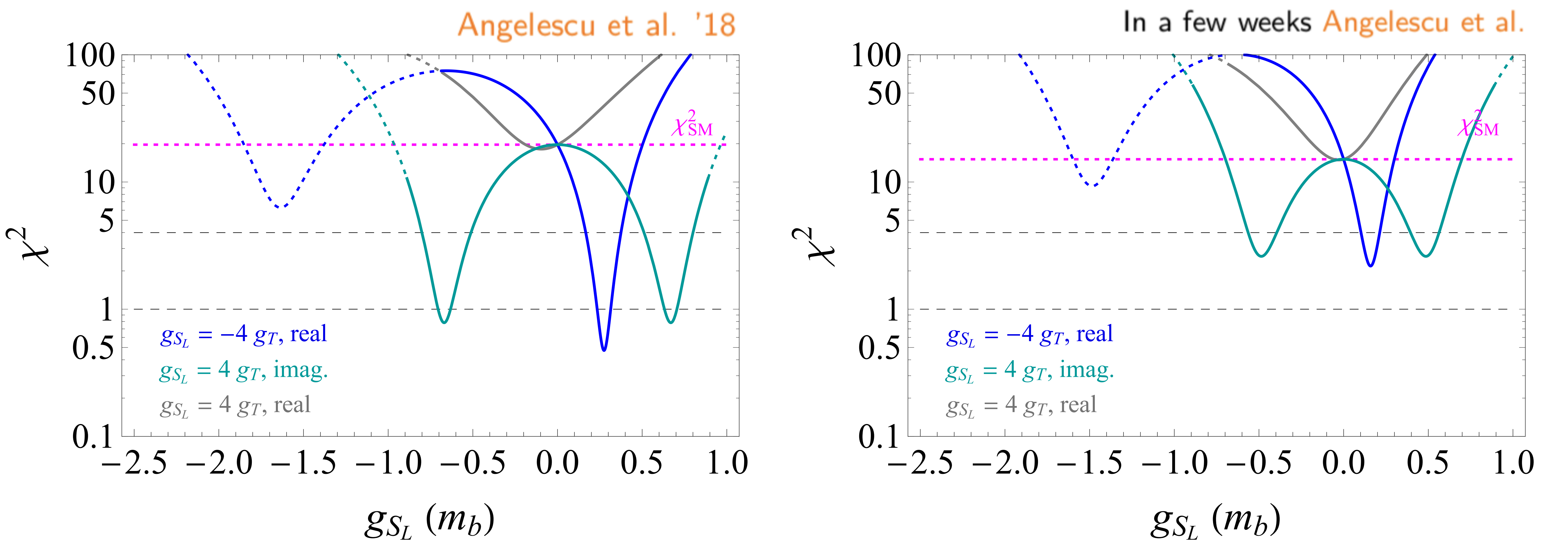


Updates of Freytsis et al. '15

Which Lorentz structure to pick?

Observables from angular distribution of $B \to D^*(D\pi)\ell\nu$ can help

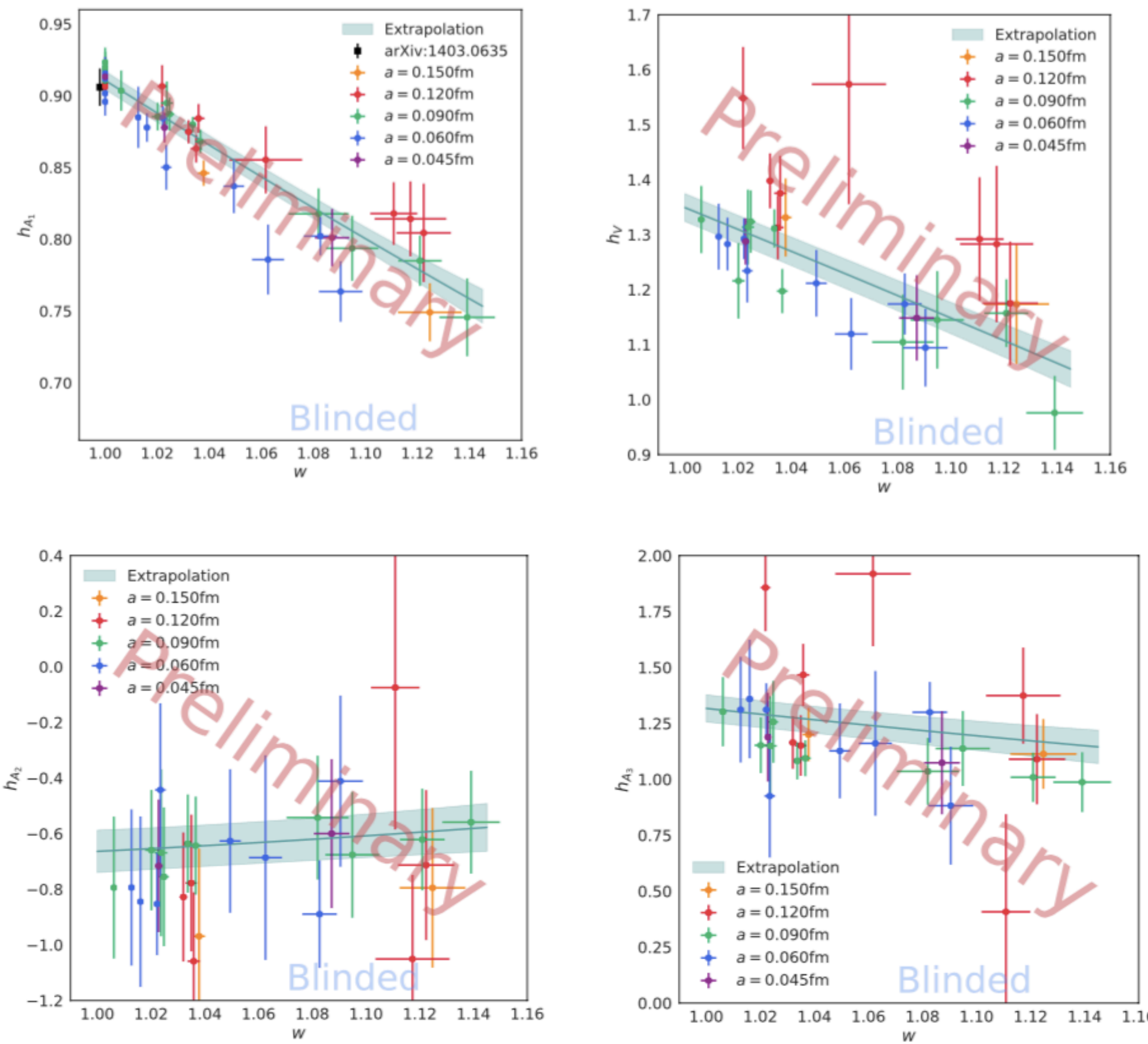
Before and after Moriond EW 2019



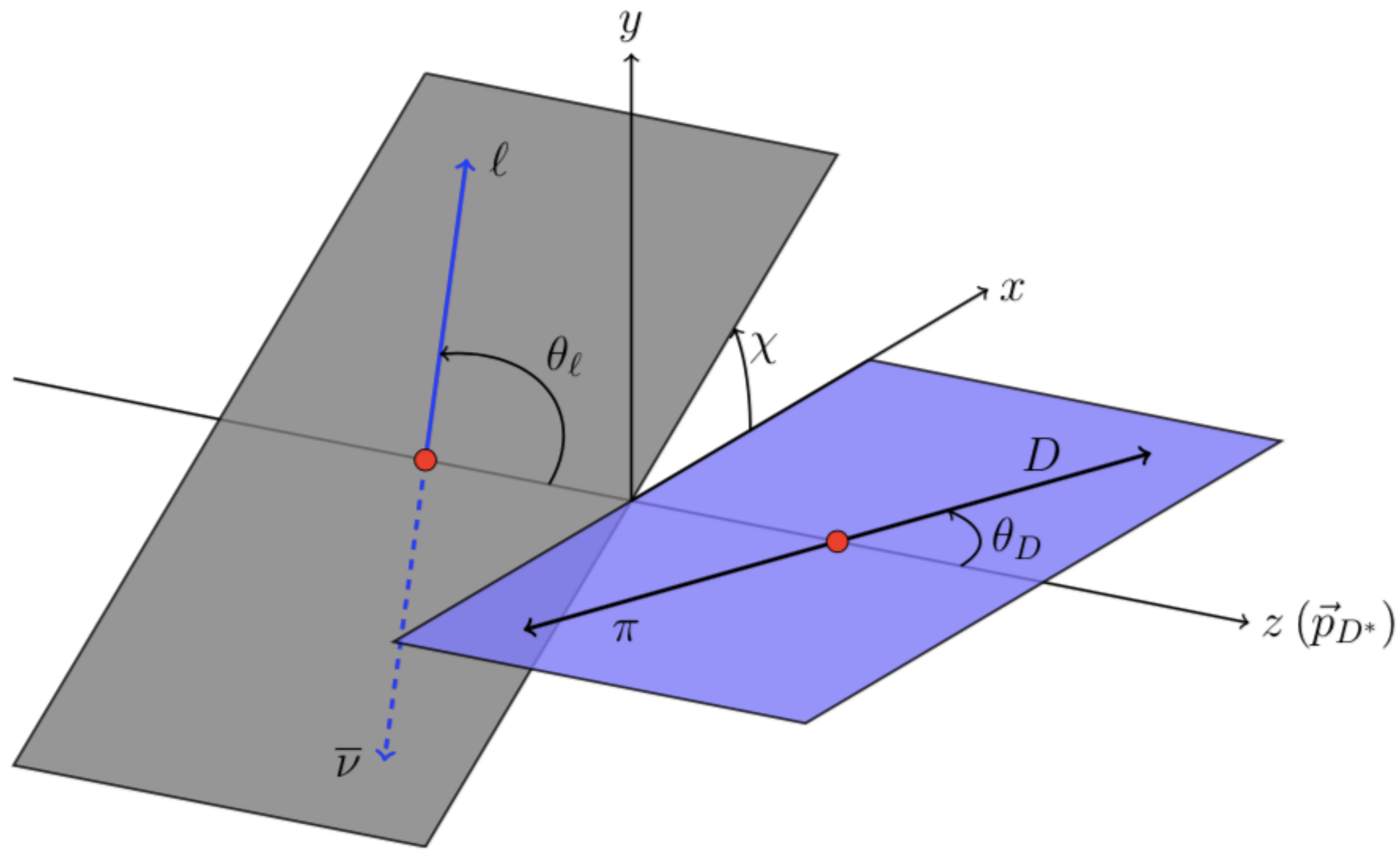
Main worry remain the hadronic uncertainties in the D* case:

No lattice QCD study regarding the shapes of FFs

Keep also in mind the SD part of the soft photon problem


Extrapolation
arXiv:1403.0635
$a = 0.150$fm
$a = 0.120$fm
$a = 0.090$fm
$a = 0.060$fm
$a = 0.045$fm
Preliminary
Blinded
h_{A_1}
w
h_V
h_{A_2}
h_{A_3}

Angular analysis (Belle II - 202x)



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

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^*}

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

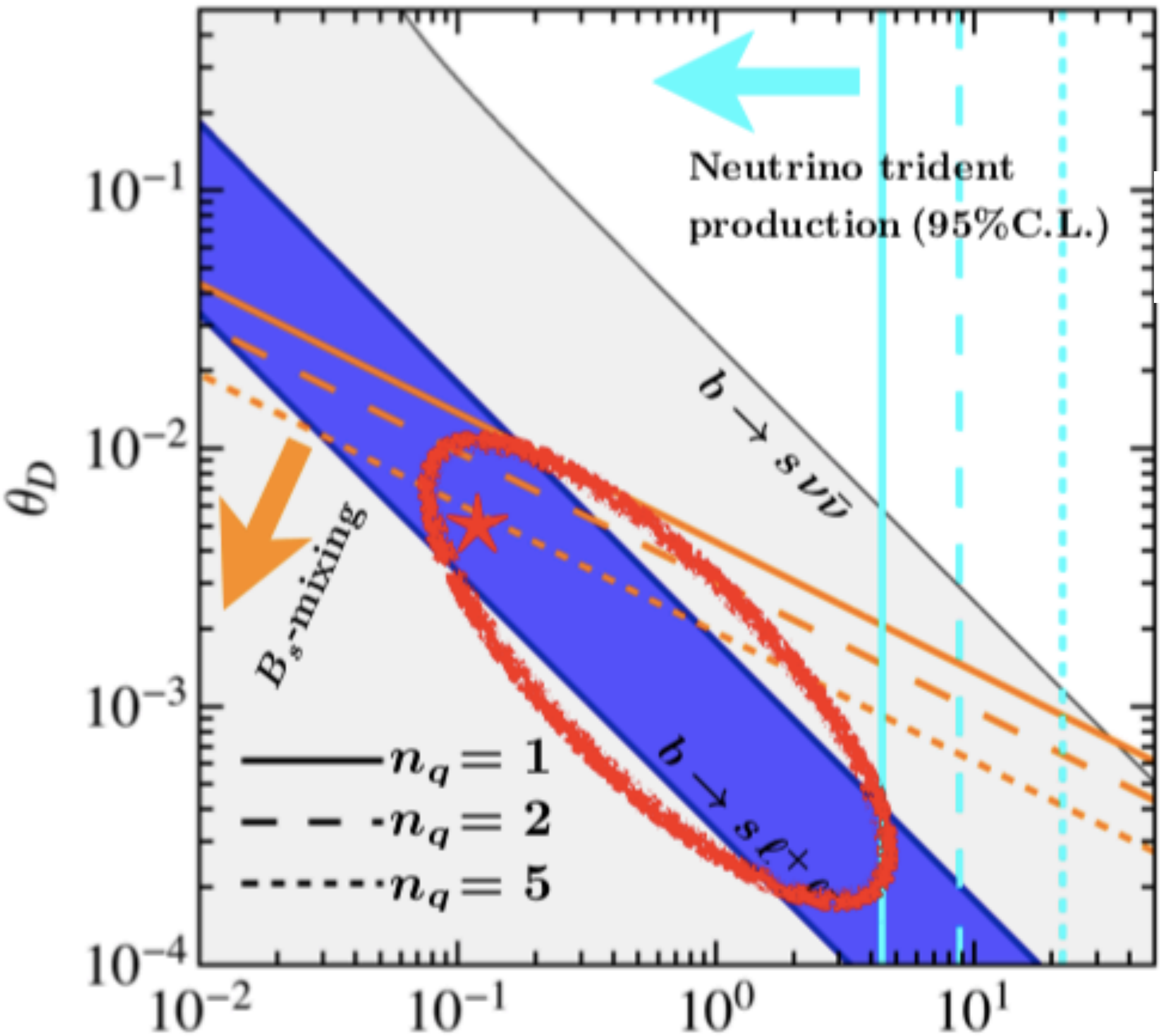
$$q_L^{(3)} = \begin{pmatrix} t_L \\ b_L \end{pmatrix} \qquad \ell_L^{(2)} = \begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix} \qquad g_f = Q_f\, g'$$

bs coupling arises through mixing in the mass eigenbasis

$$q_L^{(3)} = \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix}_{\text{gauge}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix}_{\text{mass}}$$

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

A simple model for R_K R_{K^*}

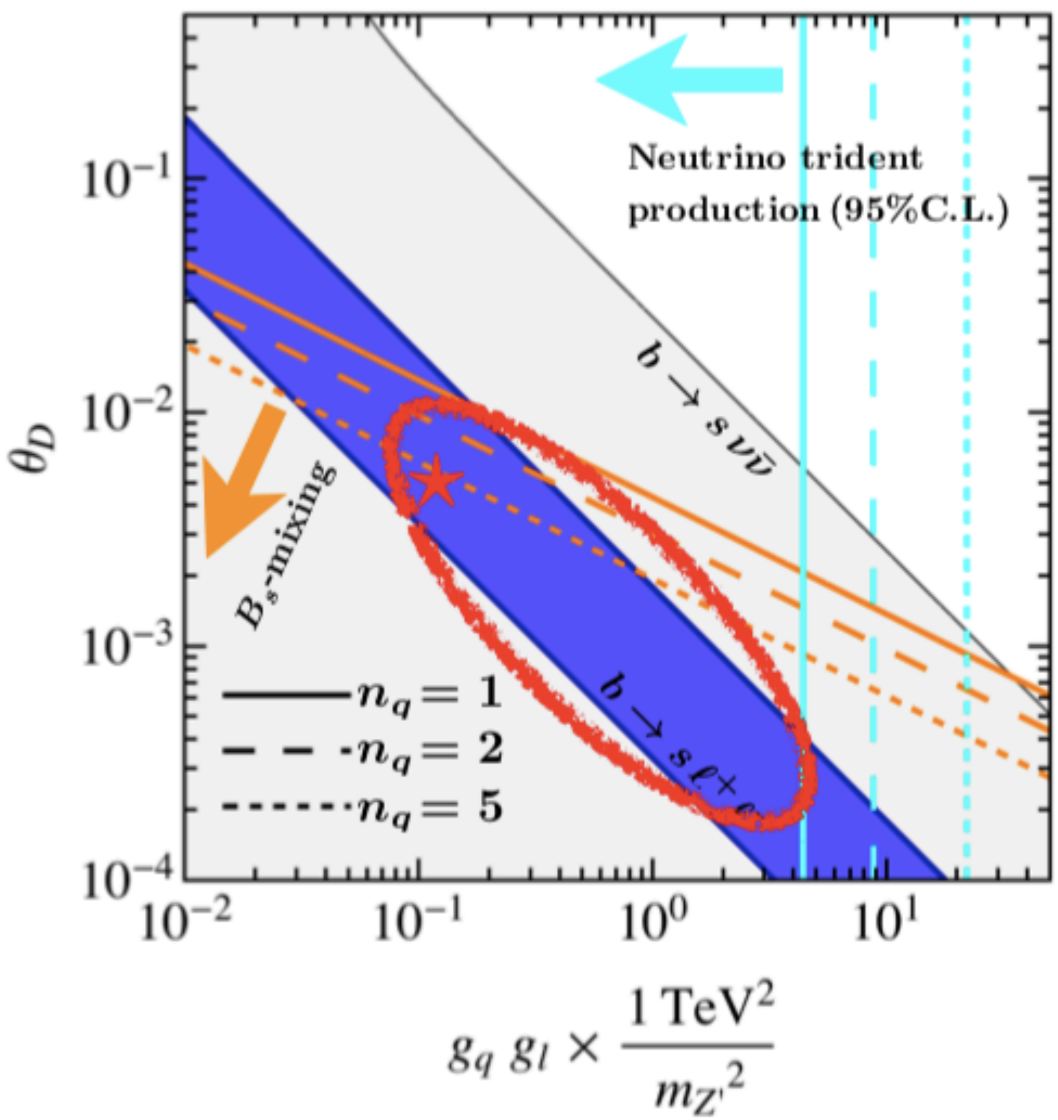


$$n_q = g_q / g_\ell$$

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

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

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

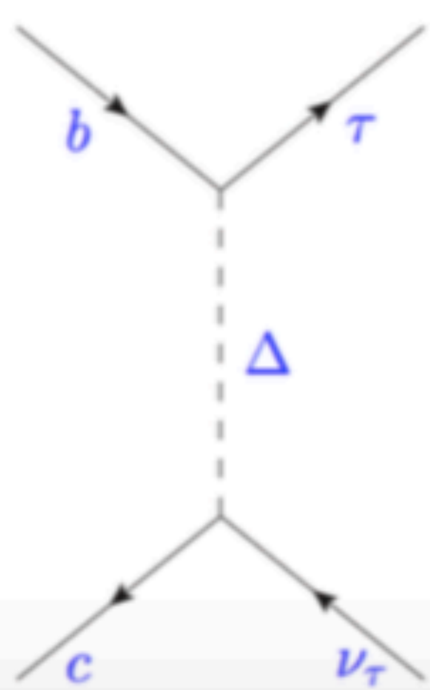
- Bosons which couple both to leptons and quarks
- Arise in GUT scenarios as gauge boson of $\mathcal{G}_{\mathrm{GUT}}$
  e.g. $\mathcal{G}_{\mathrm{GUT}} : SU(5), SO(10), SU(4) \otimes SU(2)_L \otimes SU(2)_R$
- 6 scalar and 6 vector LQ's
- Generally very heavy, but some can be light, $m_{\mathrm{LQ}}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

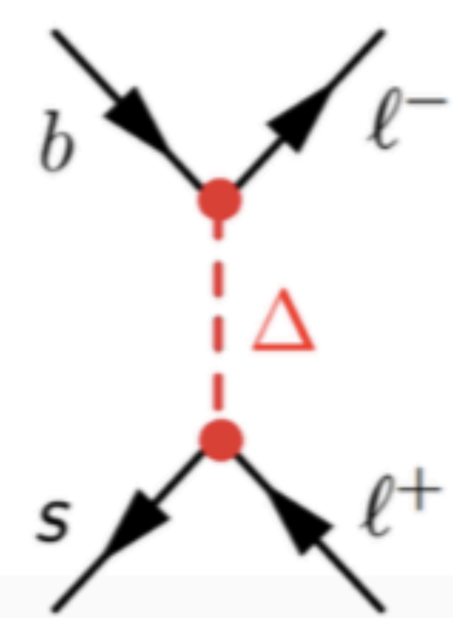
Symbol	Spin	$(SU(3)_c, SU(2)_L)_{U(1)_Y}$
S_1	0	$(\bar{3},1)_{1/3}$
S_3	0	$(\bar{3},3)_{1/3}$
R_2	0	$(\bar{3},2)_{7/6}$
$\widetilde{R}_2$	0	$(\bar{3},2)_{1/6}$
U_1	1	$(\bar{3},1)_{2/3}$
U_3	1	$(\bar{3},3)_{2/3}$

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

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

Indeed

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

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

SIC!

What LQ scenario for R_K and R_{K^*} ?

Model	$R_{D^{(*)}}$	$R_{K^{(*)}}$	$R_{D^{(*)}}$ & $R_{K^{(*)}}$
$S_1 = (\bar{3}, 1, 1/3)$	✓	✗	✗
$R_2 = (3, 2, 7/6)$	✓	✓*	✗
$S_3 = (\bar{3}, 3, 1/3)$	✗	✓	✗
$U_1 = (3, 1, 2/3)$	✓	✓	✓
$U_3 = (3, 3, 2/3)$	✗	✓	✗

N.B. U_1 is the only one to accommodate both!

Observable
$b \to s\mu\mu$
$b \to c\tau\nu$
$\mathcal{B}(\tau \to \mu\phi)$
$\mathcal{B}(B \to \tau\nu)$
$\mathcal{B}(D_s \to \mu\nu)$
$\mathcal{B}(D_s \to \tau\nu)$
$r_K^{e/\mu}$
$r_K^{\tau/\mu}$
$R_D^{\mu/e}$

U_1

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

Assumptions:

$$x_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & x_L^{s\mu} & x_L^{s\tau} \\ 0 & x_L^{b\mu} & x_L^{b\tau} \end{pmatrix}, \qquad x_R \approx 0\,.$$

- $b \to c\tau\bar{\nu}$:

$$g_{V_L} = \frac{v^2}{2m_{U_1}^2}\left(x_L^{b\tau}\right)^* \left(x_L^{b\tau} + \frac{V_{cs}}{V_{cb}} x_L^{s\tau}\right) \neq 0$$

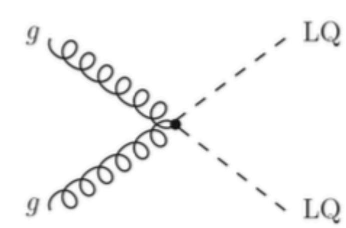
$$x_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & x_L^{s\mu} & x_L^{s\tau} \\ 0 & x_L^{b\mu} & x_L^{b\tau} \end{pmatrix}$$

- $b \to s\mu\mu$:

$$C_9^{\mu\mu} = -C_{10}^{\mu\mu} \propto -\frac{\pi v^2}{m_{U_1}^2}\left(x_L^{b\mu}\right)^* x_L^{s\mu} \neq 0$$

- Other observables: $\tau \to \mu\phi$, $B \to \tau\bar{\nu}$, $D_{(s)} \to \mu\bar{\nu}$, $D_s \to \tau\bar{\nu}$, $K \to \mu\bar{\nu}/K \to e\bar{\nu}$, $\tau \to K\bar{\nu}$ and $B \to D^{(*)}\mu\bar{\nu}/B \to D^{(*)}e\bar{\nu}$.

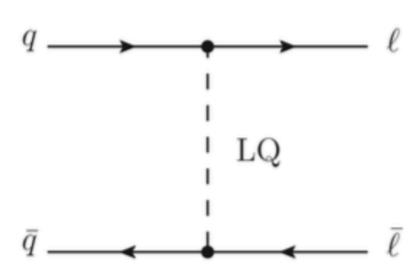
- LQ pair-production via QCD: [CMS-PAS-EXO-17-003]

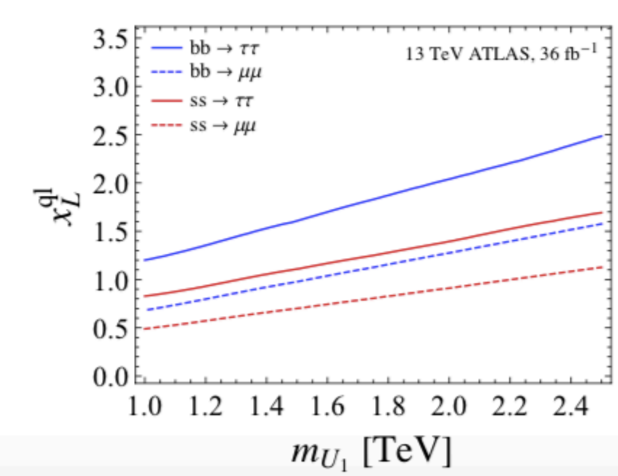


$m_{U_1} \gtrsim 1.5$ TeV

[assuming $\mathcal{B}(U_1 \to b\tau) \approx 0.5$]

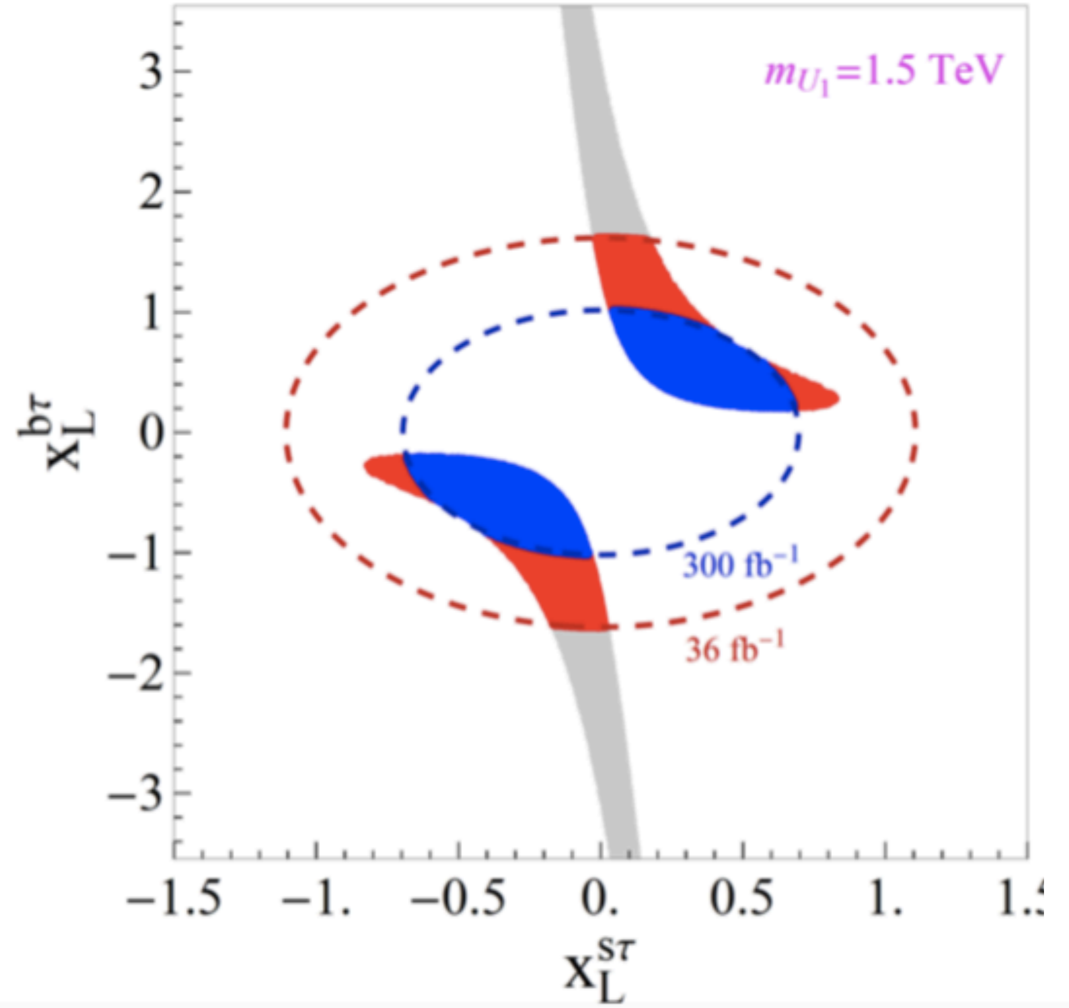
- Di-lepton tails at high-pT: [ATLAS. 1707.02424,1709.07242]

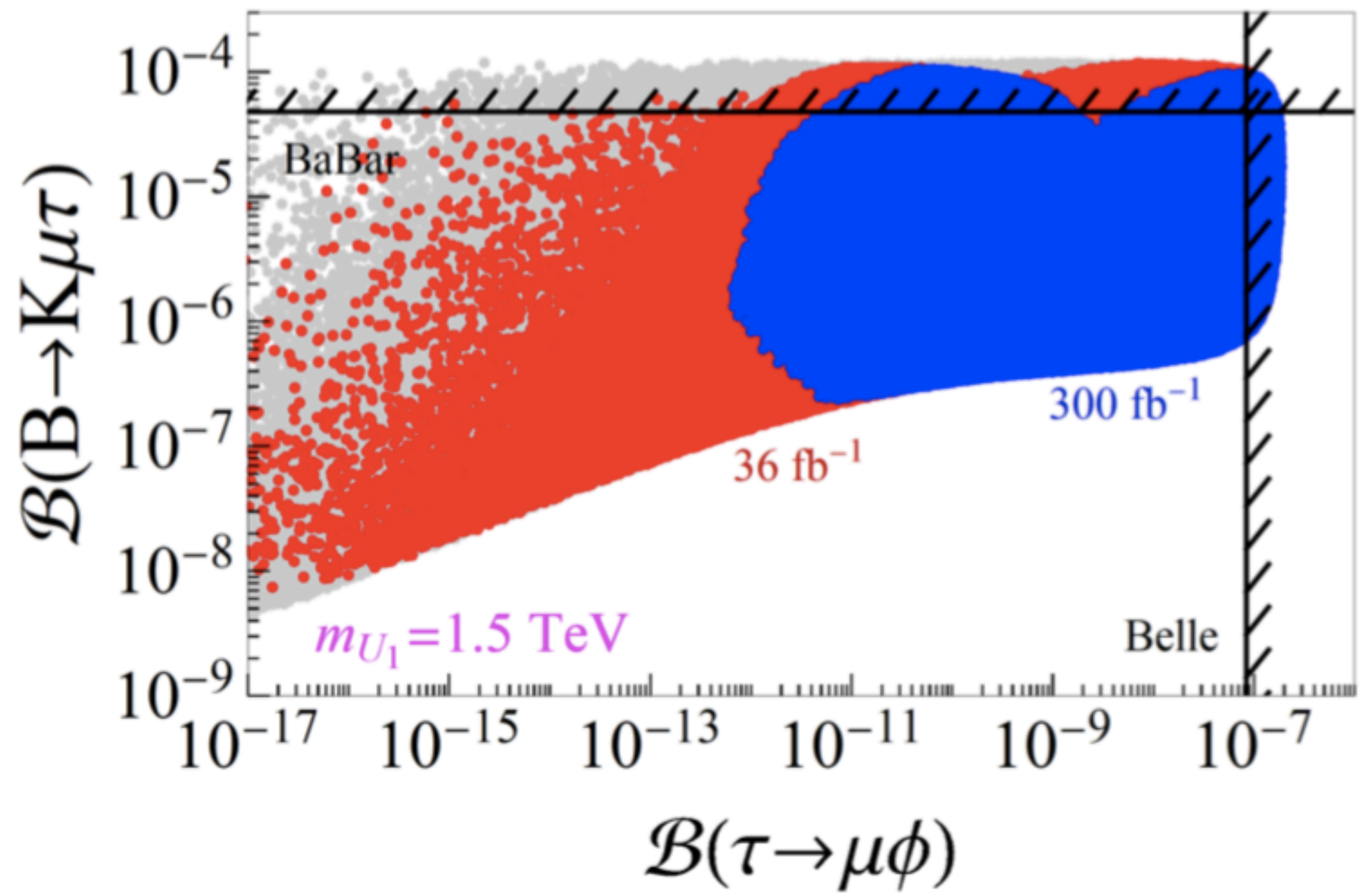




Angelescu et al '18, Faroughy et al '15

U_1





$\mathcal{B}(B \to K\mu\tau) \gtrsim \text{few} \times 10^{-7}$

UV completion:

- Pati-Salam group, $\mathcal{G}_{\rm PS} = SU(4) \times SU(2)_L \times SU(2)_R$, contains $U_1 = (3, 1, 2/3)$.
- Viable extensions of $\mathcal{G}_{\rm PS}$ at the TeV scale have been proposed: $\Rightarrow U_1 + Z' + g'$ [+new fermions]. Di Luzio et al '17, Bordone et al. '17, Cornella et al '19

Back to SLQ's

Model	$R_{D^{(*)}}$	$R_{K^{(*)}}$	$R_{D^{(*)}}$ & $R_{K^{(*)}}$
$S_1 = (\bar{3}, 1, 1/3)$	✓	✗	✗
$R_2 = (3, 2, 7/6)$	✓	✓*	✗
$S_3 = (\bar{3}, 3, 1/3)$	✗	✓	✗
$U_1 = (3, 1, 2/3)$	✓	✓	✓
$U_3 = (3, 3, 2/3)$	✗	✓	✗

Observable
$b \to s\mu\mu$
$b \to c\tau\nu$
$\mathcal{B}(\tau \to \mu\phi)$
$\mathcal{B}(B \to \tau\nu)$
$\mathcal{B}(D_s \to \mu\nu)$
$\mathcal{B}(D_s \to \tau\nu)$
$r_K^{e/\mu}$
$r_K^{\tau/\mu}$
$R_D^{\mu/e}$

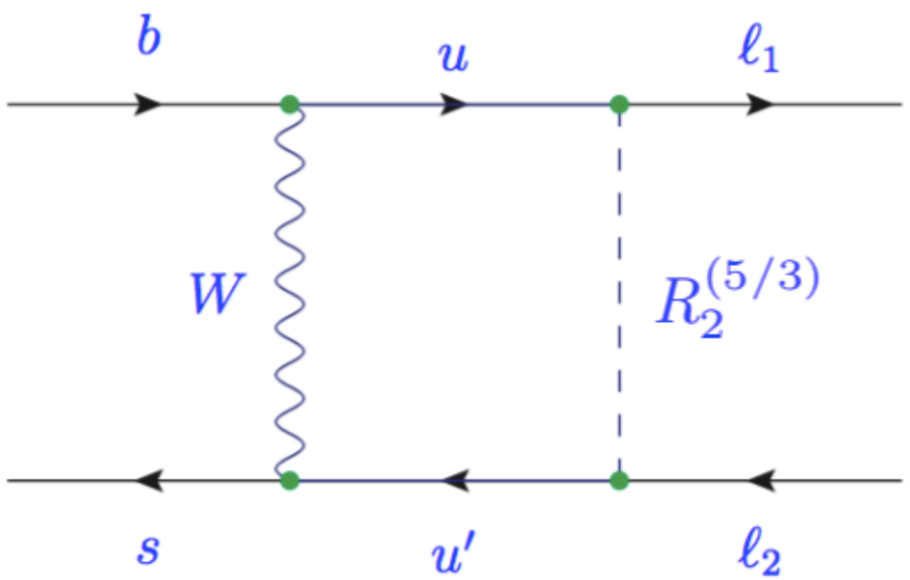
R_2

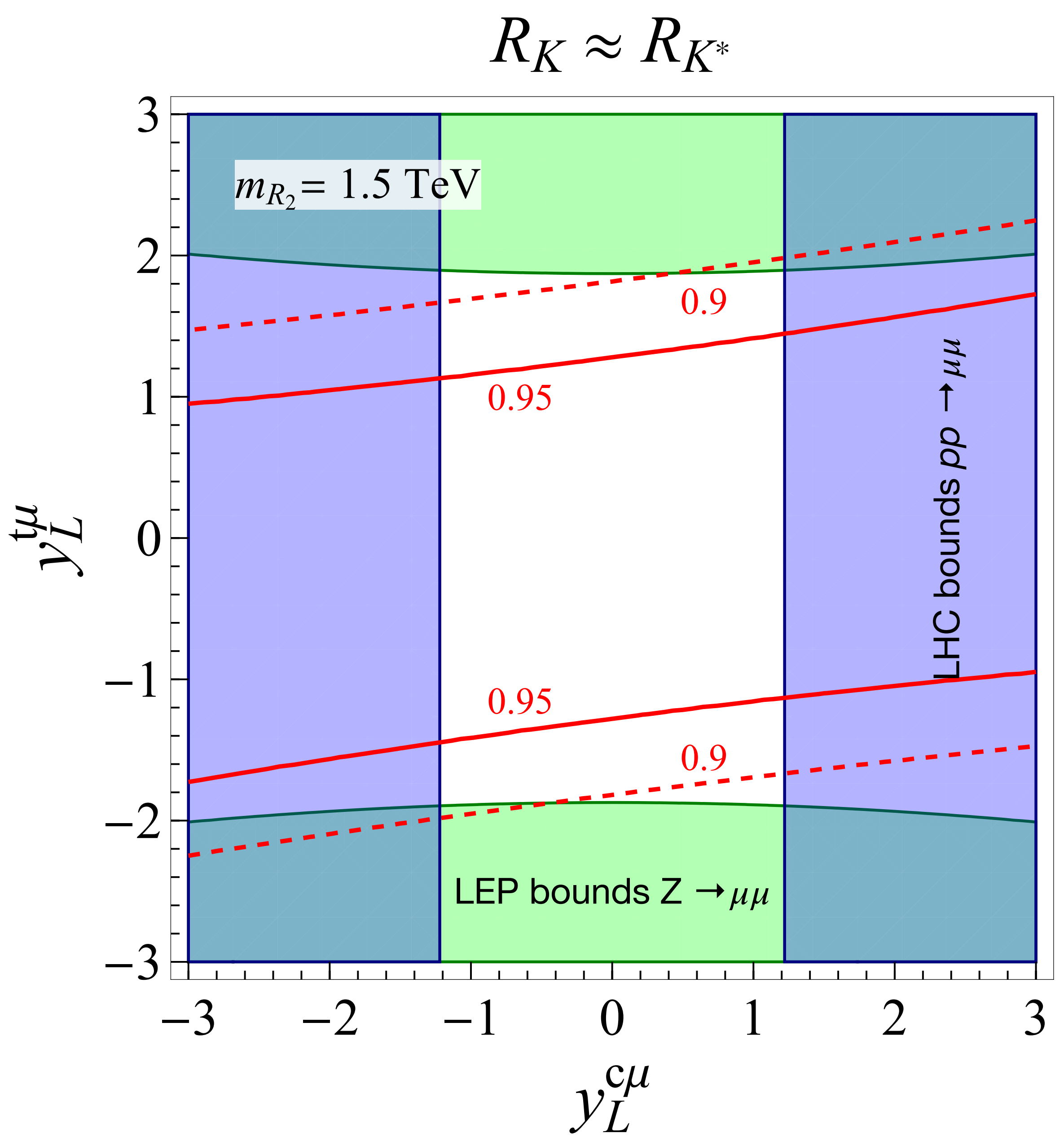
$$\mathcal{L}_{R_2} = y_R^{ij}\,\overline{Q}_i \ell_{Rj}\, R_2 - y_L^{ij}\,\overline{u}_{Ri} R_2 i\tau_2 L_j + \text{h.c.}$$

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

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

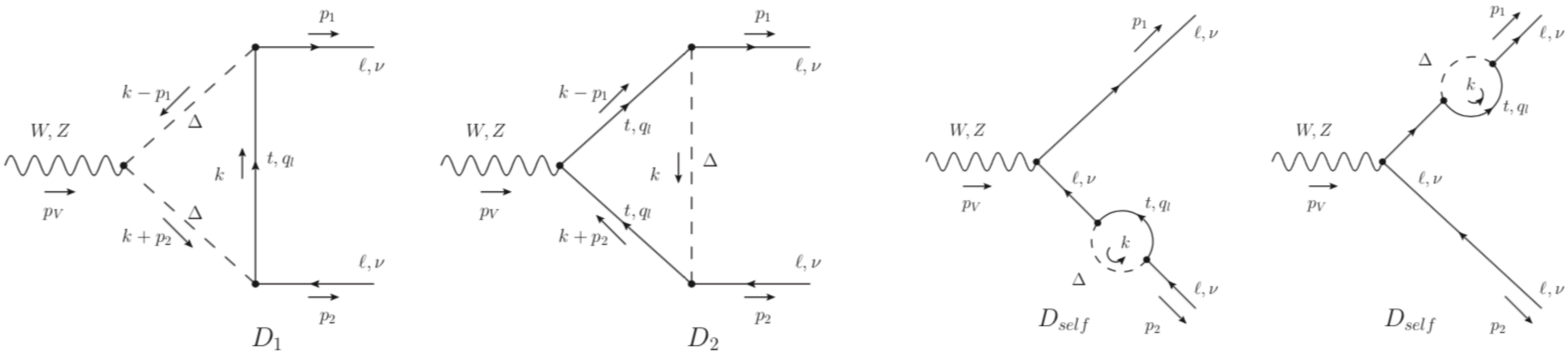
$$y_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_L^{c\mu} & 0 \\ 0 & y_L^{t\mu} & 0 \end{pmatrix}, \qquad y_R = 0$$





$Z \to \ell\ell$ and $Z \to \nu\nu$

Arnan, D.B., Mescia, Sumensari '19 [arXiv:1901.06315]



$$\delta\mathcal{L}_{\rm eff}^{Z} = \frac{g}{\cos\theta_W} \sum_{f,i,j} \bar{f}_i \gamma^\mu \left[g_{f_L}^{ij}\, P_L + g_{f_R}^{ij}\, P_R \right] f_j\, Z_\mu$$

$$g_{f_{L(R)}}^{ij} = \delta_{ij}\, g_{f_{L(R)}}^{\rm SM} + \delta g_{f_{L(R)}}^{ij}$$

$$g_{f_L}^{\rm SM} = I_3^f - Q^f \sin^2\theta_W$$

$$g_{f_R}^{\rm SM} = -Q^f \sin^2\theta_W$$

$$g_V^{e,\,\rm exp} = -0.03817(47) \qquad g_A^{e,\,\rm exp} = -\,0.50111(35)$$

$$g_V^{\mu,\,\rm exp} = -0.0367(23) \qquad g_A^{\mu,\,\rm exp} = -\,0.50120(54)$$

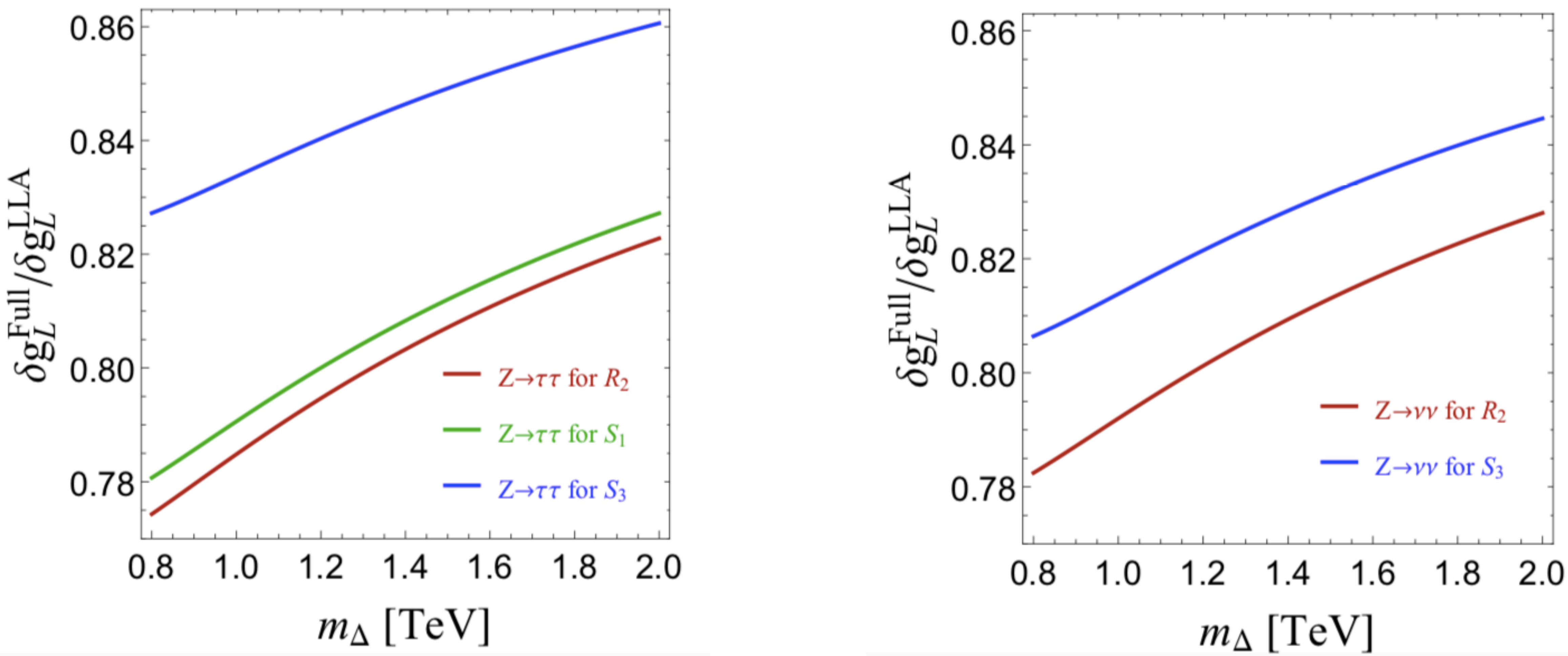
$$g_V^{\tau,\,\rm exp} = -0.0366(10) \qquad g_A^{\tau,\,\rm exp} = -\,0.50204(64)$$

$$\delta\mathcal{L}_{\text{eff}}^{Z} = \frac{g}{\cos\theta_W} \sum_{f,i,j} \bar{f}_i \gamma^\mu \left[g_{f_L}^{ij}\, P_L + g_{f_R}^{ij}\, P_R \right] f_j\, Z_\mu$$

$$g_{f_{L(R)}}^{ij} = \delta_{ij}\, g_{f_{L(R)}}^{\text{SM}} + \delta g_{f_{L(R)}}^{ij}$$

$$g_{f_L}^{\text{SM}} = I_3^f - Q^f \sin^2\theta_W$$

$$g_{f_R}^{\text{SM}} = -Q^f \sin^2\theta_W$$



LLA: $\mathcal{O}(x_t \log x_t)$, $\mathcal{O}(x_Z \log x_Z)$ $x_j = m_j^2/m_\Delta^2$ Feruglio et al. '17 and '18

Full: most significant $\mathcal{O}(x_Z \log x_t)$

S_3 & R_2 Model

D.B., Dorsner, Fajfer, Faroughy, Kosnik, Sumensari '18 [arXiv:1806.05689]

- 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

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

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

Effective Lagrangian at $\mu \approx m_{\rm LQ}$:

- $b \to c\tau\bar{\nu}$: **NB**. $\Lambda_{\rm NP}/g_{\rm NP} \approx 1$ TeV

$$\propto \frac{y_L^{c\tau}\, y_R^{b\tau\,*}}{m_{R_2}^2}\left[(\bar{c}_R b_L)(\bar{\tau}_R \nu_L) + \frac{1}{4}(\bar{c}_R \sigma_{\mu\nu} b_L)(\bar{\tau}_R \sigma^{\mu\nu} \nu_L)\right] + \ldots$$

- $b \to s\mu\mu$: **NB**. $\Lambda_{\rm NP}/g_{\rm NP} \approx 30$ TeV

$$\propto \sin 2\theta\, \frac{|y_L^{c\mu}|^2}{m_{S_3}^2}\, (\bar{s}_L \gamma^\mu b_L)(\bar{\mu}_L \gamma_\mu \mu_L)$$

- Δm_{B_s}:

$$\propto \sin^2 2\theta\, \frac{\left[\left(y_L^{c\mu}\right)^2 + \left(y_L^{c\tau}\right)^2\right]^2}{m_{S_3}^2} (\bar{s}_L \gamma^\mu b_L)^2$$

$\Rightarrow$ Suppression mechanism of $b \to s\mu\mu$ wrt $b \to c\tau\bar{\nu}$ for small $\sin 2\theta$.

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

Other notable constraints...

- $r_{e/\mu}^{K\ \mathrm{exp}} = 2.488(10) \times 10^{-5}$ [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]

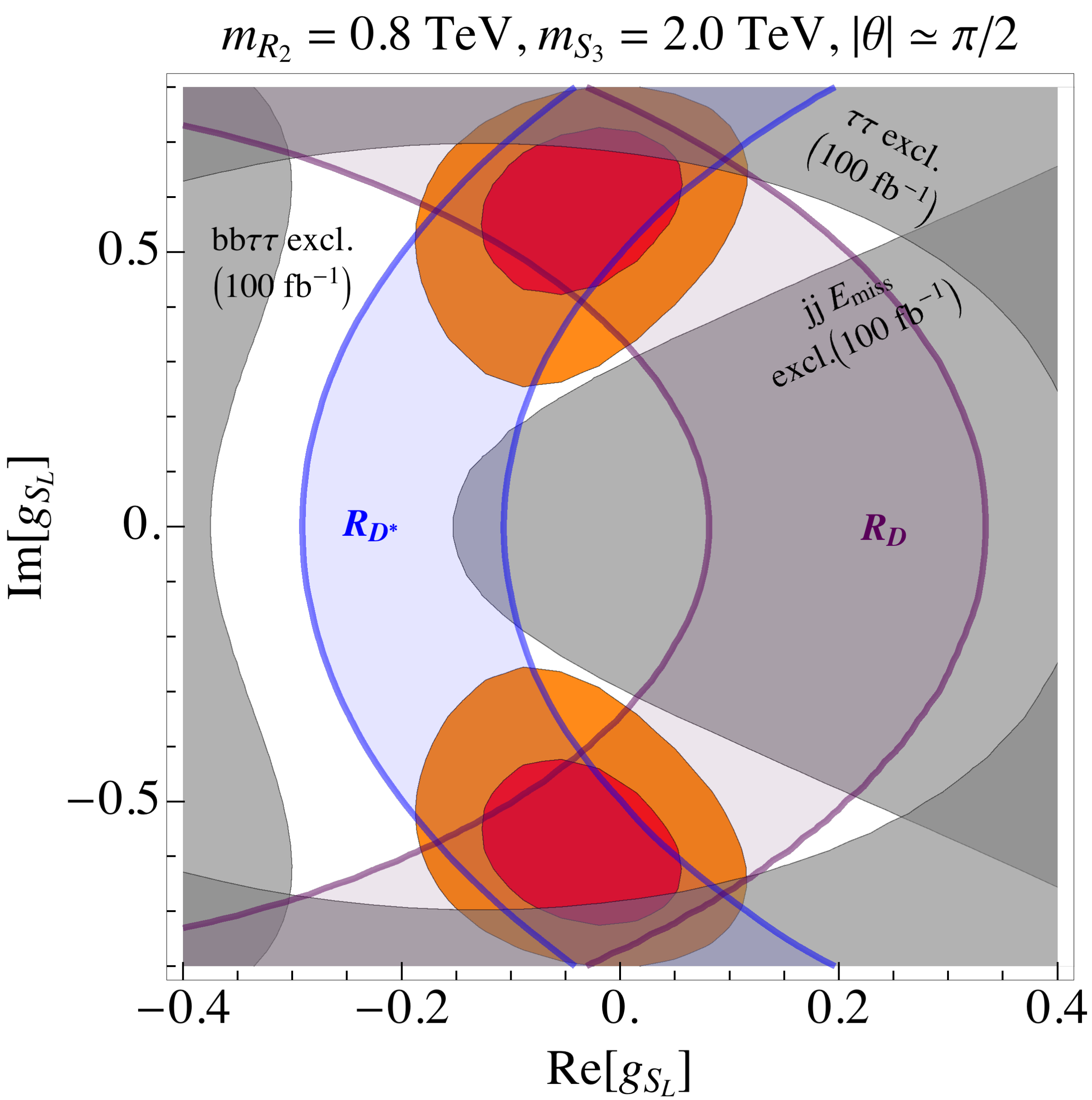
$$R_{\mu/e}^{D^{(*)}} = \frac{\Gamma(B \to D^{(*)} \mu \bar{\nu})}{\Gamma(B \to D^{(*)} e \bar{\nu})}$$

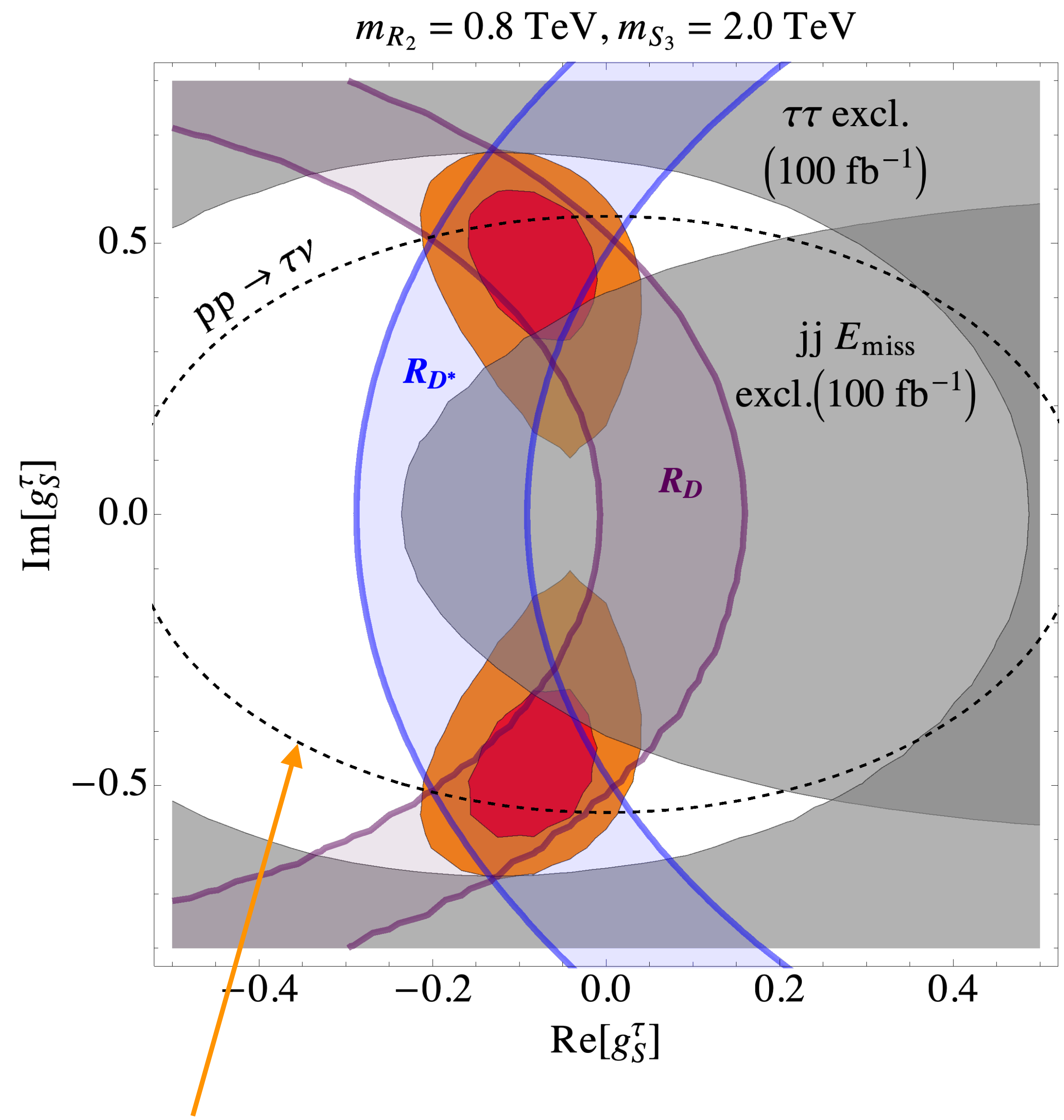
- $\mathcal{B}(\tau \to \mu\phi) < 8.4 \times 10^{-8}$ [PDG]
- Loops: $\Delta m_{B_s}^{\mathrm{exp}} = 17.7(2)\ \mathrm{ps}^{-1}$ [PDG], $\Delta m_{B_s}^{\mathrm{SM}} = (19.0 \pm 2.4)\ \mathrm{ps}^{-1}$ [FLAG 2016]
- Loops: $Z \to \mu\mu$, $Z \to \tau\tau$, $Z \to \nu\nu$ [PDG]

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

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

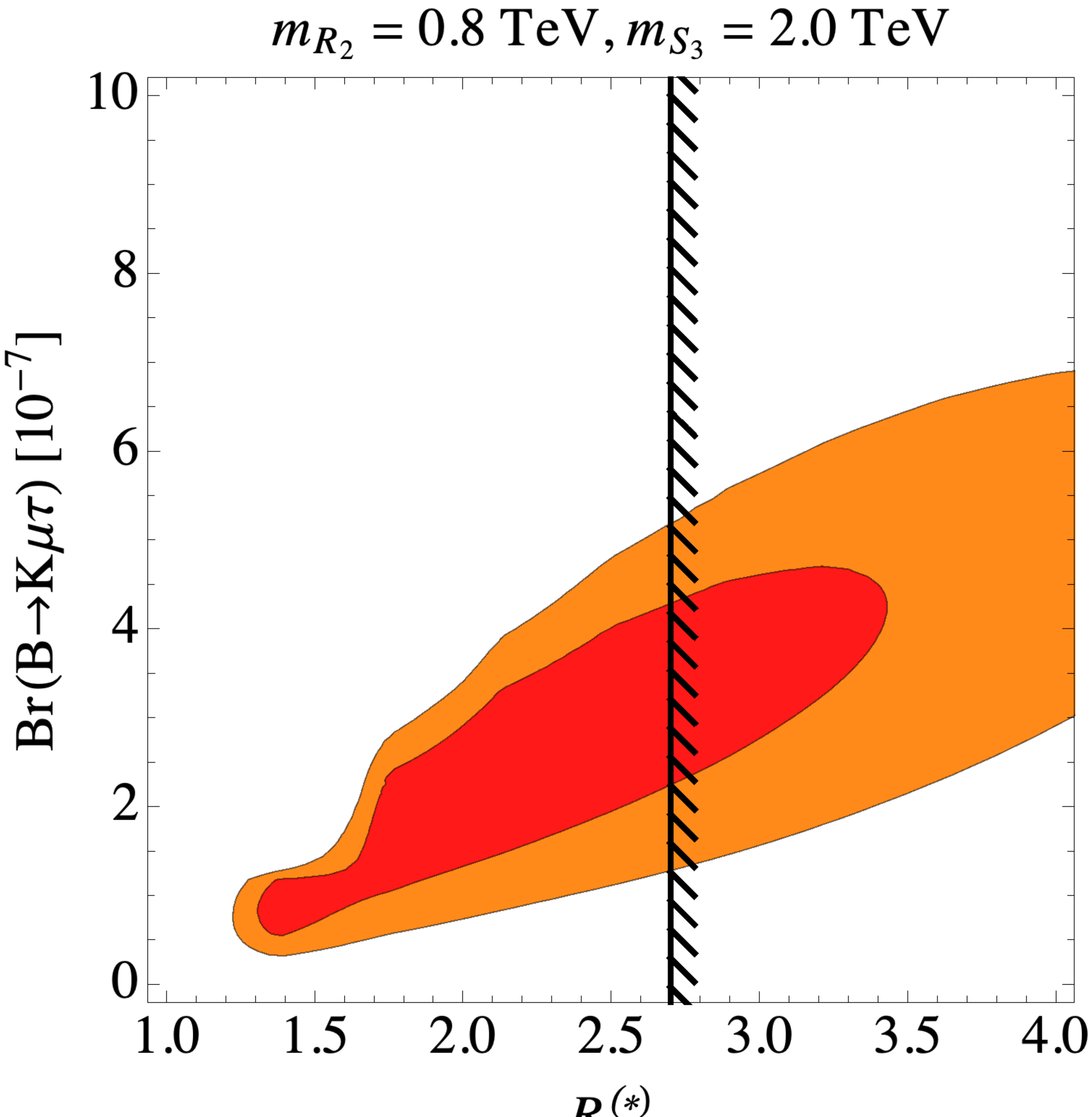
Before and after Moriond EW 2019





Greljo et al. '18

Bounds should be less stringent when considering propagating LQ!



$m_{R_2} = 0.8$ TeV, $m_{S_3} = 2.0$ TeV
10
8
6
4
2
0
Br(B→Kμτ) [10^{-7}]
1.0
1.5
2.0
2.5
3.0
3.5
4.0
$R^{(*)}_{\nu\nu}$

Common lore - Zurich Guide

NP to CC processes

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

$c_i = 1 \rightarrow \Lambda \sim 3.7$ TeV

$c_i = V_{cb} \rightarrow \Lambda \sim 0.7$ TeV

$c_i = V_{cb}/4\pi \rightarrow \Lambda \sim 0.2$ 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

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

$c_i = 1 \rightarrow \Lambda \sim 31$ TeV

$c_i = V_{ts} \rightarrow \Lambda \sim 6$ TeV

$c_i = V_{ts}/4\pi \rightarrow \Lambda \sim 0.5$ 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

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

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

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

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

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

Tiny

Needs 0.1

$$Q_L^3 = \begin{pmatrix} V_{tb}^* t_L + V_{cb}^* c_L + V_{ub}^* u_L \\ b_L \end{pmatrix}$$

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

Zurich Guide (Models V-A)

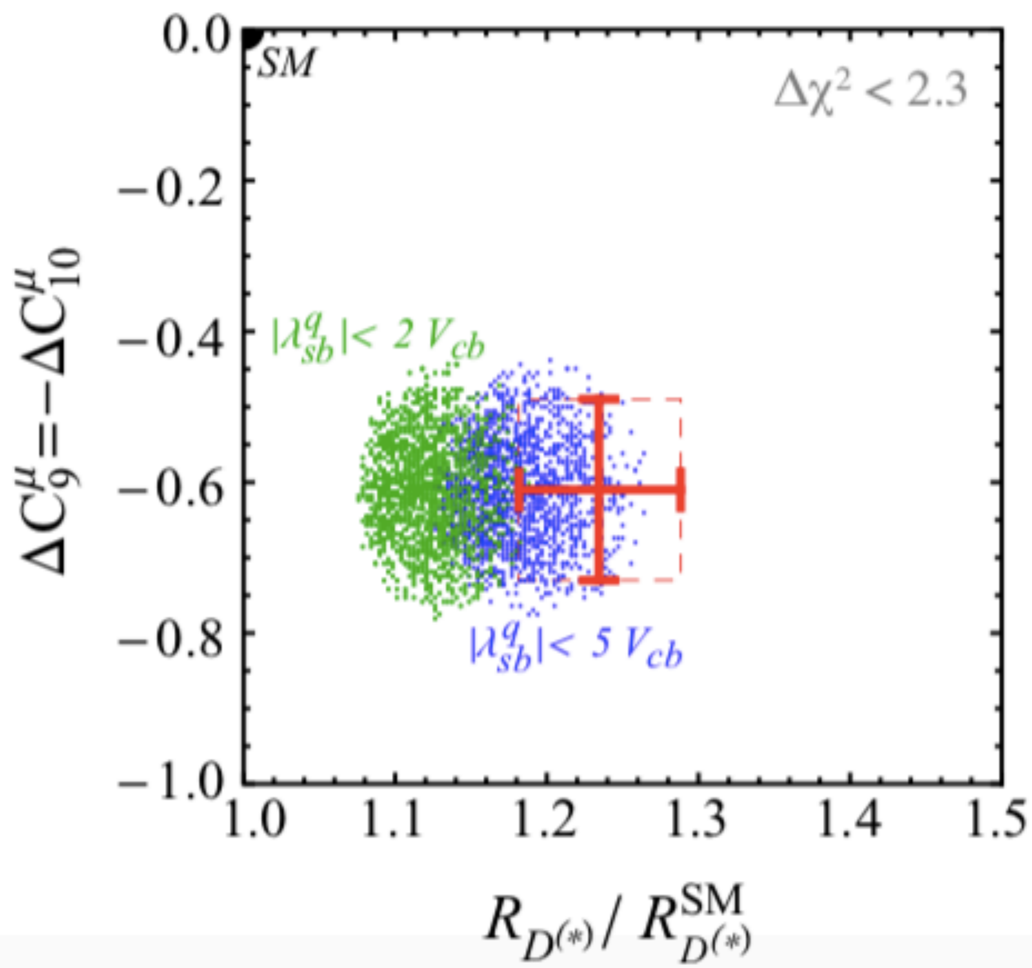
Tricky part

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

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

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

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)