The lepton universality anomalies in Flavor Physics

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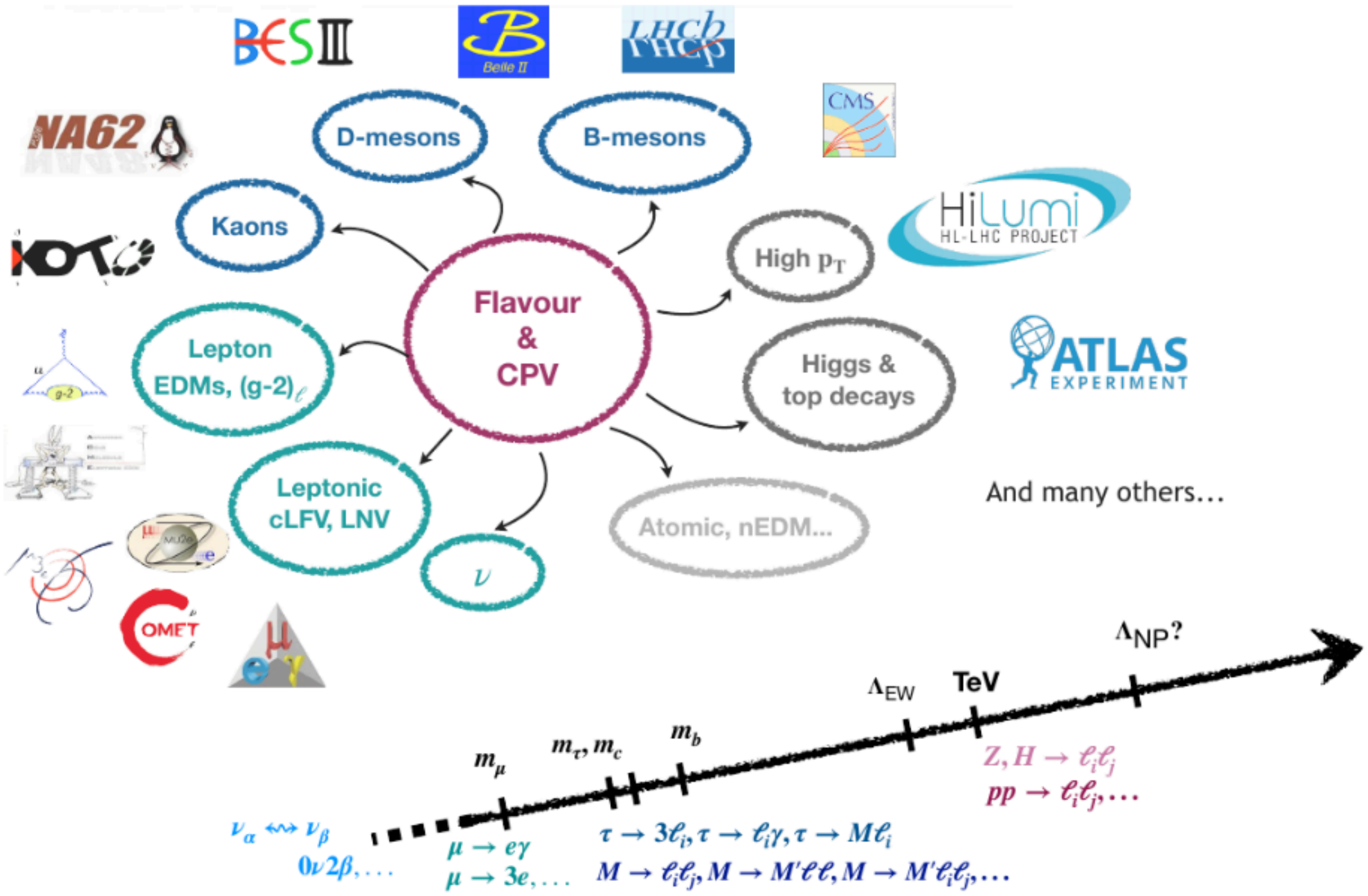
#About the origin of "penguin" nomenclature check this link

Flavor physics is leaving a golden experimental era

- Multi-scale probes of flavor interactions in (B)SM

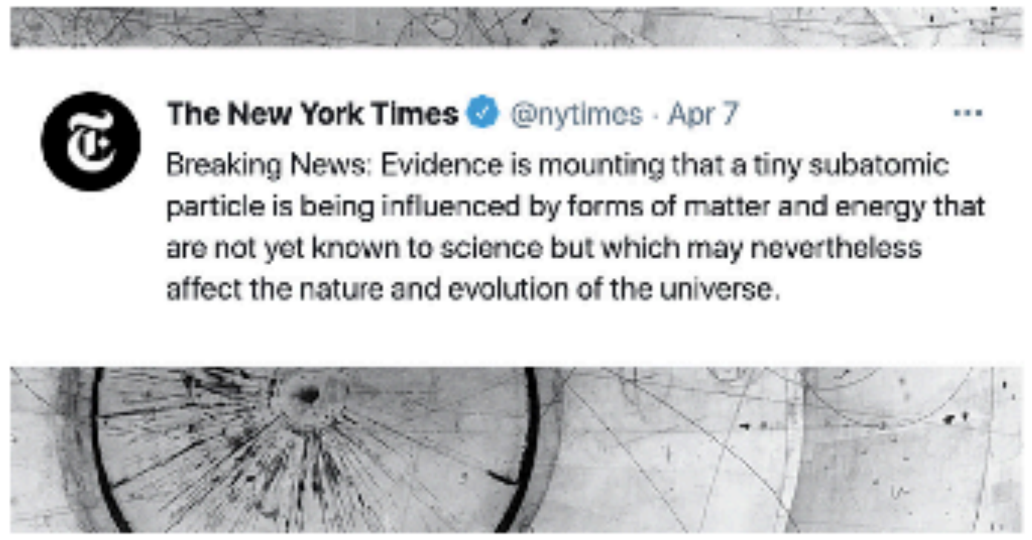


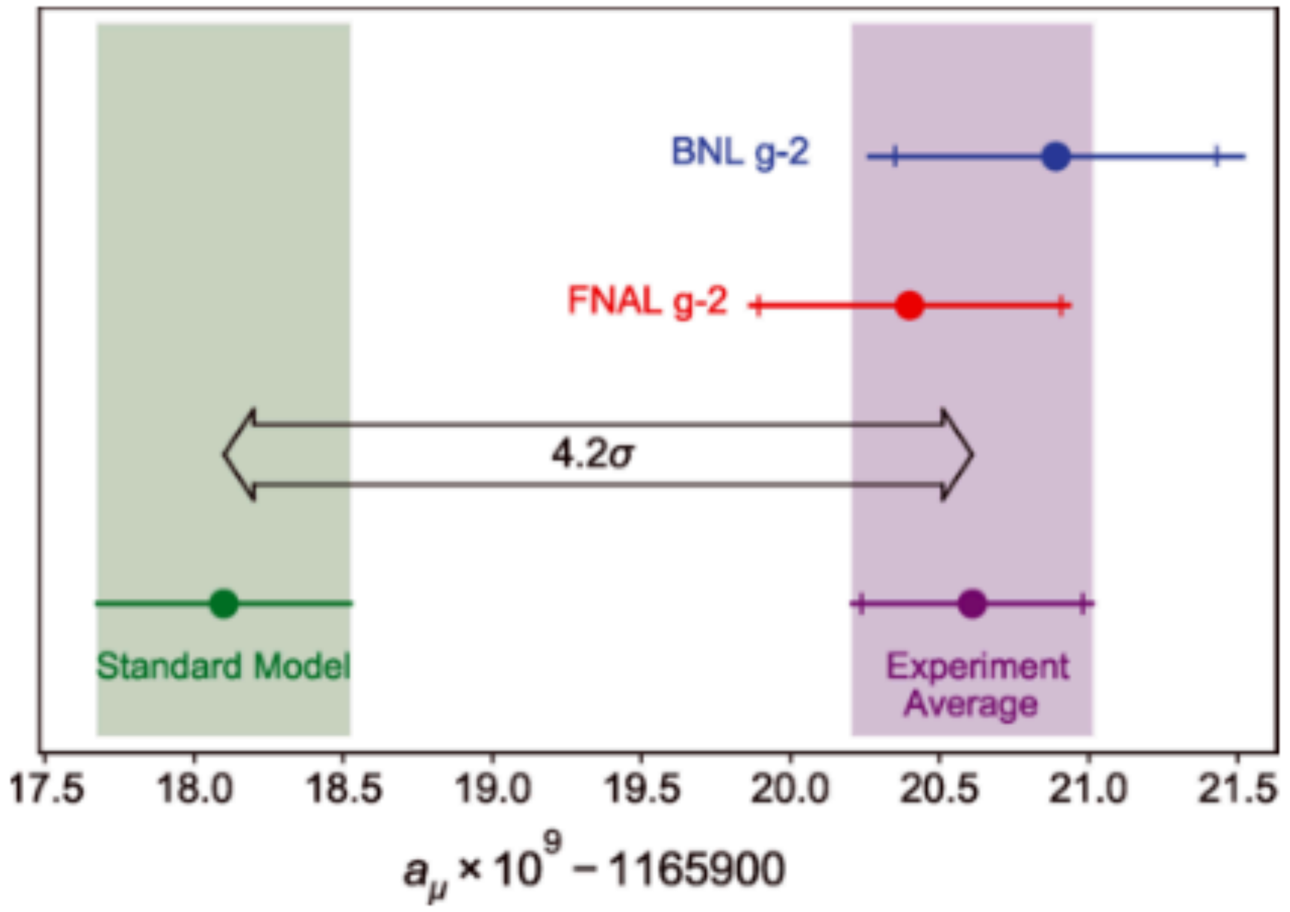
Plenary talk **Ana Teixeira** @ EPS-HEP 2021

Anomalies involving lepton flavors!

- *B*-decay anomalies

- Muon's $(g-2)_\mu$





New fundamental forces violating **lepton-flavor universality (LFU)**?

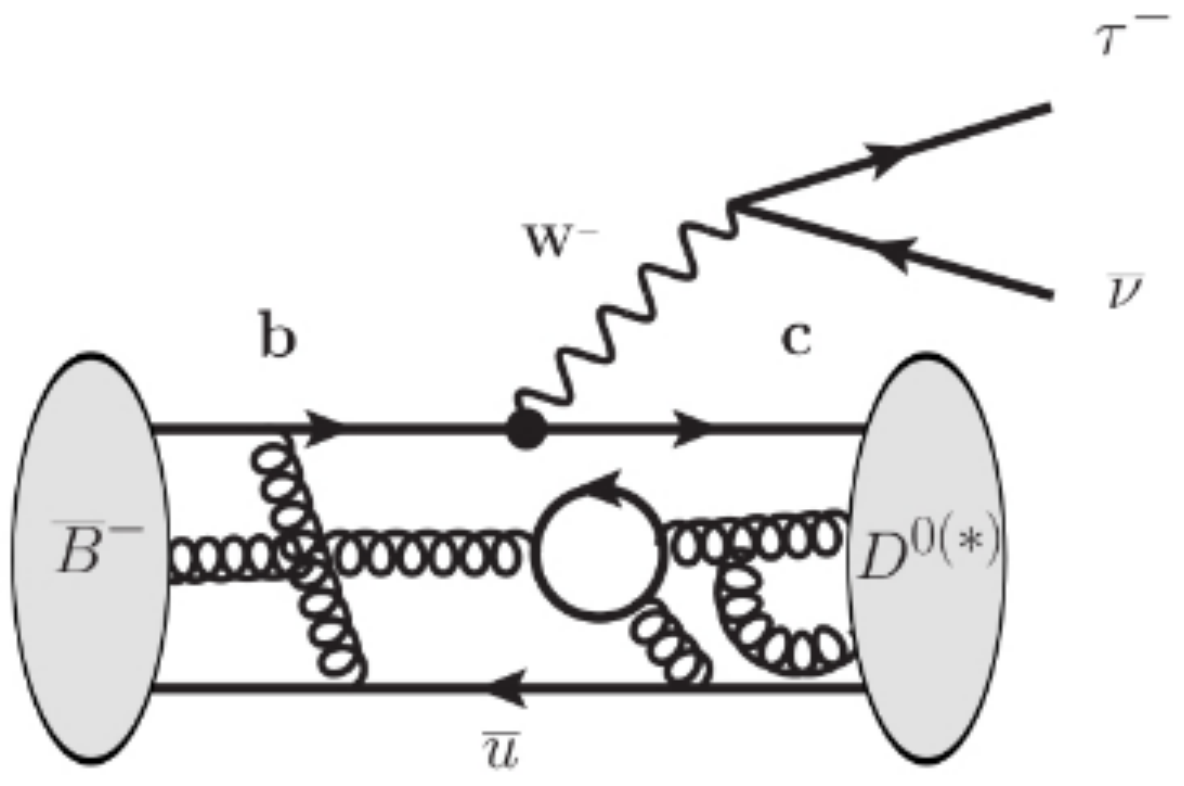
Reminder about LUF in the SM

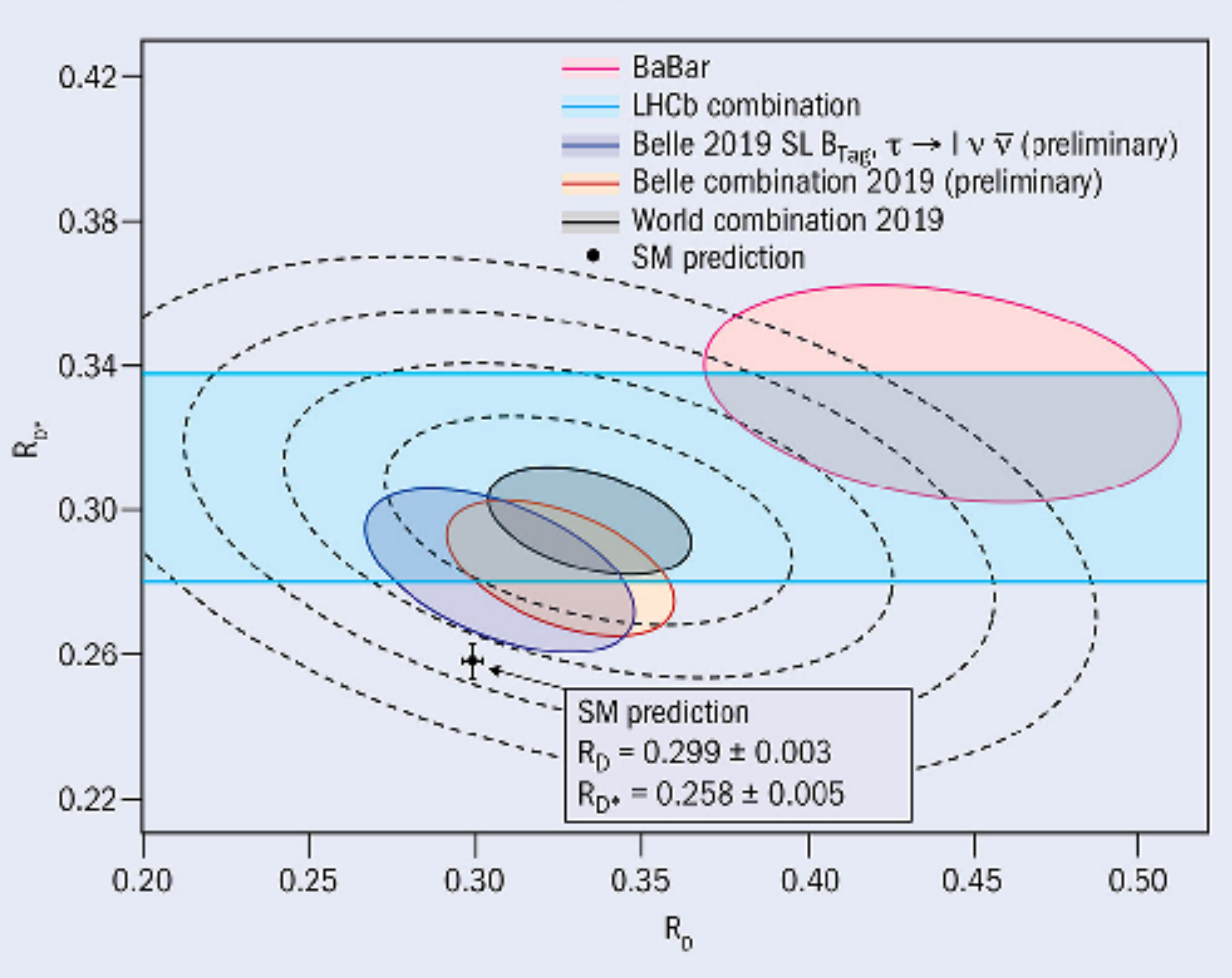
- **The interactions in the SM are *almost* LU**
  - The gauge interactions are LU
  - The yukawa interactions are LUV

LU test: The flavor transition rates must be equal up to the contributions of:

- Yukawa couplings: **Negligible**
- Masses of leptons: **Not always negligible but calculable!**

First LUV anomaly: Rates in CC $b \to c\tau\nu$





Define the LU ratios

$$R_{D^{(*)}} = \frac{\mathrm{Br}(B \to D^{(*)}\tau\nu)}{\mathrm{Br}(B \to D^{(*)}\ell\nu)}$$

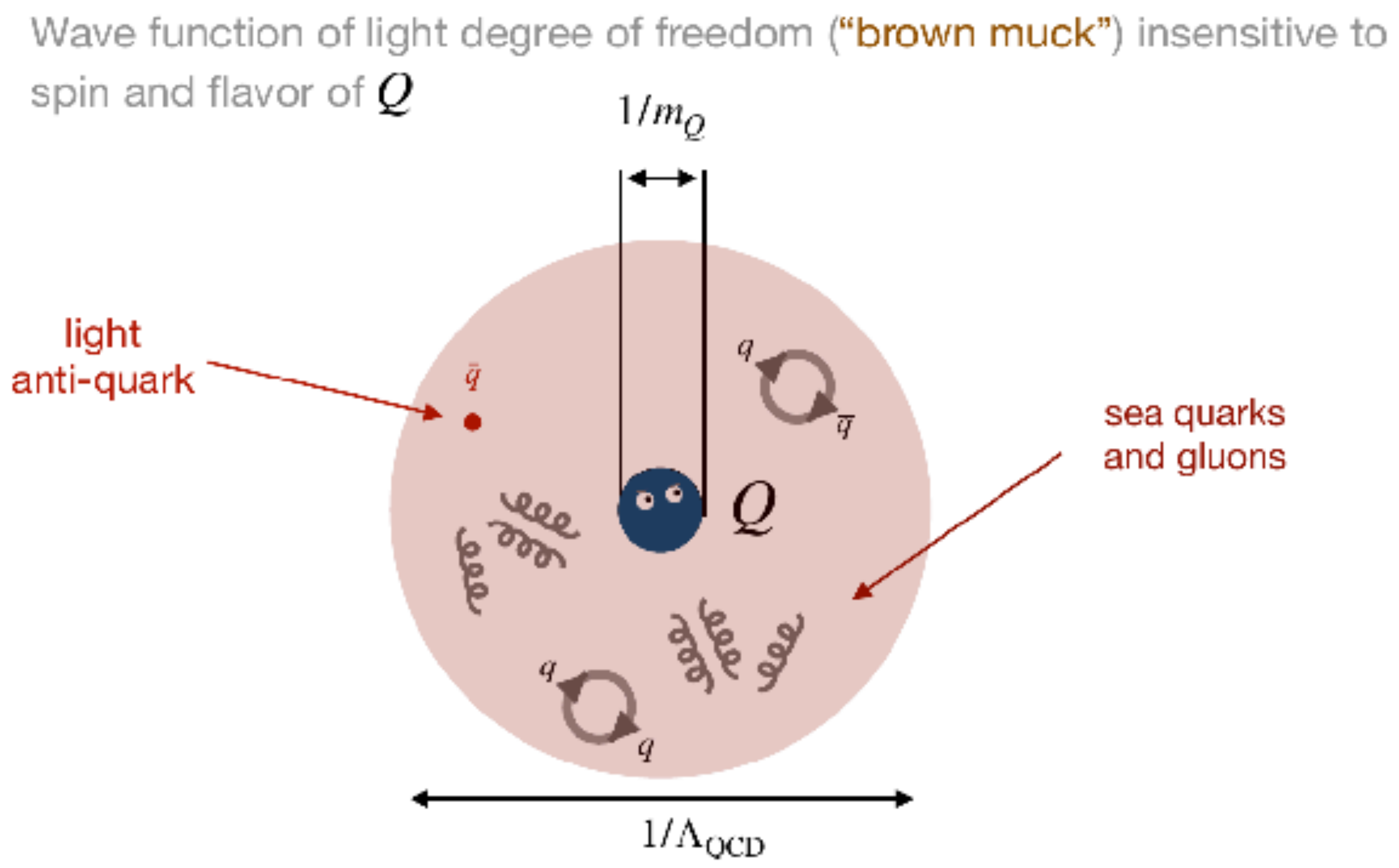
There is an **enhancement** at **3.6σ** in the CC $bc\tau\nu$ couplings!

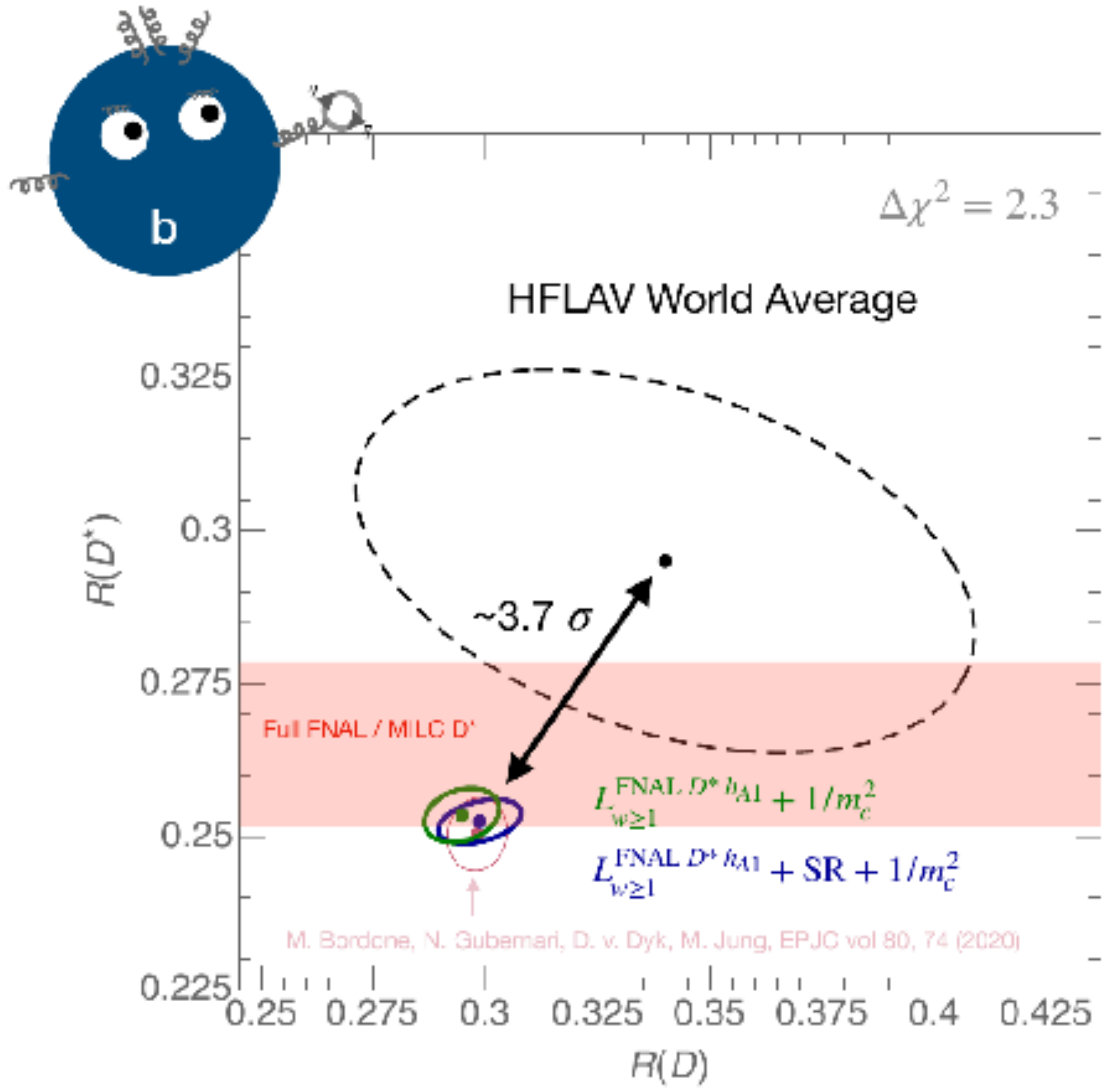
The SM prediction of the $R_{D^{(*)}}$ LU ratios

Physical case where the mass of the lepton (τ) matters!

$R^{\text{SM}}_{D^{(*)}} \nsim 1 \;\Rightarrow$ Need to be careful with SM calculation (**Form Factors**)

- **Exploit Heavy Quark EFT**: Calculate systematically in an expansion $(\Lambda_{\text{QCD}}/m_Q)^N$





Bernlochner talk @ EPS-HEP 2021

Hadronic effects cannot describe the data!

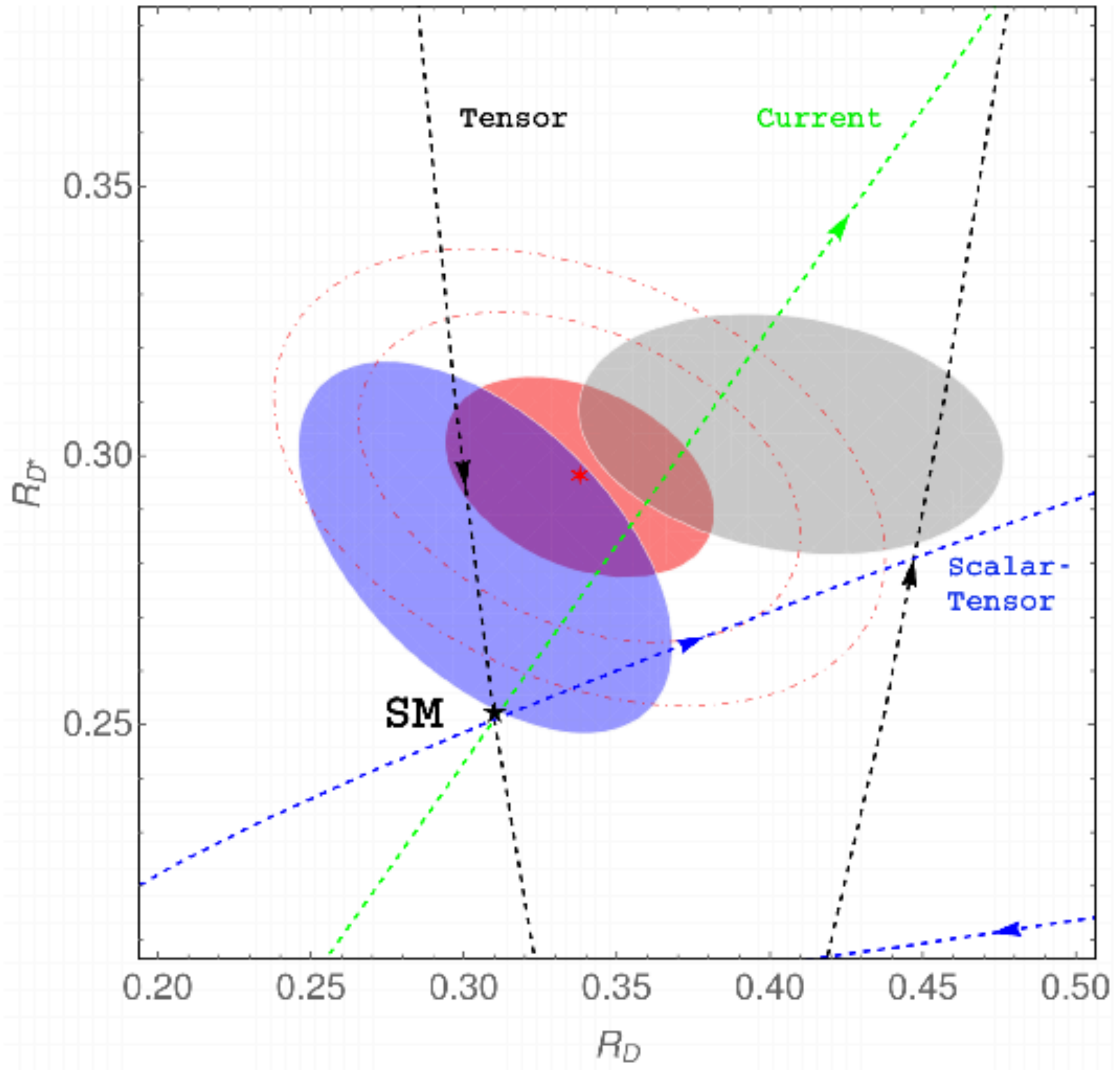
The BSM interpretation of the data in the EFT

- **Recall the general Lagrangian for CC interactions**

$$\mathcal{L}_{\mathrm{CC}} = \frac{4G_F V_{cb}}{\sqrt{2}}\Big((1+\epsilon_L^\tau)(\bar{c}\gamma^\mu P_L b)(\bar{\tau}\gamma_\mu P_L \nu) + \epsilon_R(\bar{c}\gamma^\mu P_R b)(\bar{\tau}\gamma_\mu P_L \nu) + \epsilon_{S_L}^\tau(\bar{c}P_L b)(\bar{\tau}P_L\nu) + \epsilon_{S_R}(\bar{c}P_R b)(\bar{\tau}P_L\nu) + C_T(\bar{c}\sigma^{\mu\nu}P_L b)(\bar{\tau}\sigma_{\mu\nu}P_L\nu)\Big)$$

  - ***Recall:*** ϵ_R is LU because SMEFT matching! $\Rightarrow$ **RH in quark bilinear cannot explain anomaly**

    Try introducing **light RH neutrinos** N_R: $\mathcal{L}_{\mathrm{CC}} \supset \frac{4G_F V_{cb}}{\sqrt{2}}\tilde{\epsilon}_R(\bar{c}\gamma^\mu P_R b)(\bar{\tau}\gamma_\mu P_R N_R)$



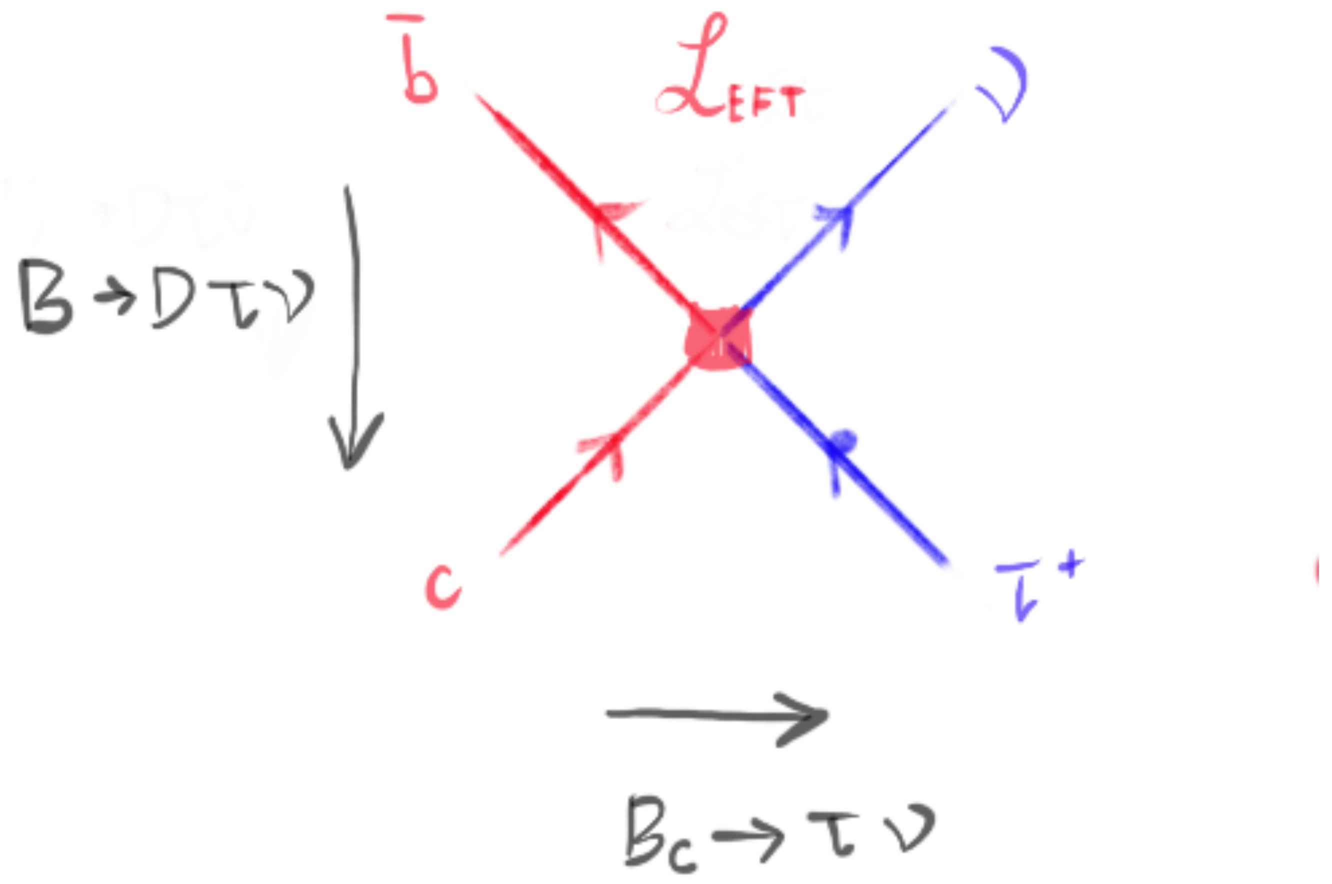
Post-Moriond 2019		
	Best fit	$\mathrm{Pull}_{\mathrm{SM}}$
ϵ_L^τ	0.07(2)	3.43
$\tilde{\epsilon}_R^\tau$	0.39(5)	3.43
ϵ_T^τ	−0.03(1)	3.30

$$\boxed{\Lambda_{\mathrm{NP}} \gtrsim 4\ \text{TeV}}$$

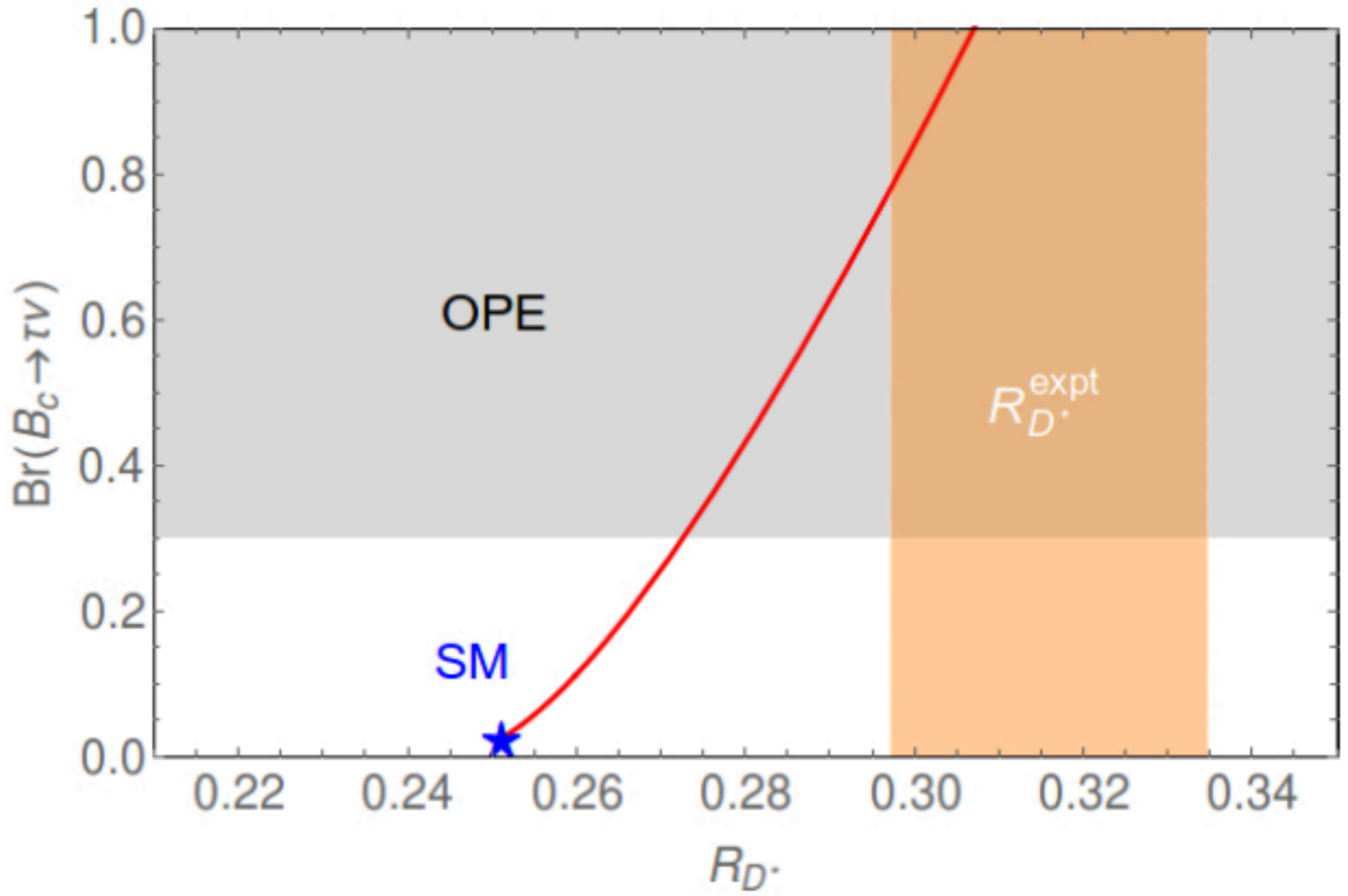
Testing the anomaly: $B_c \to \tau\nu$

- **What about pure scalar contributions?** (e.g. produced by charged higgs)

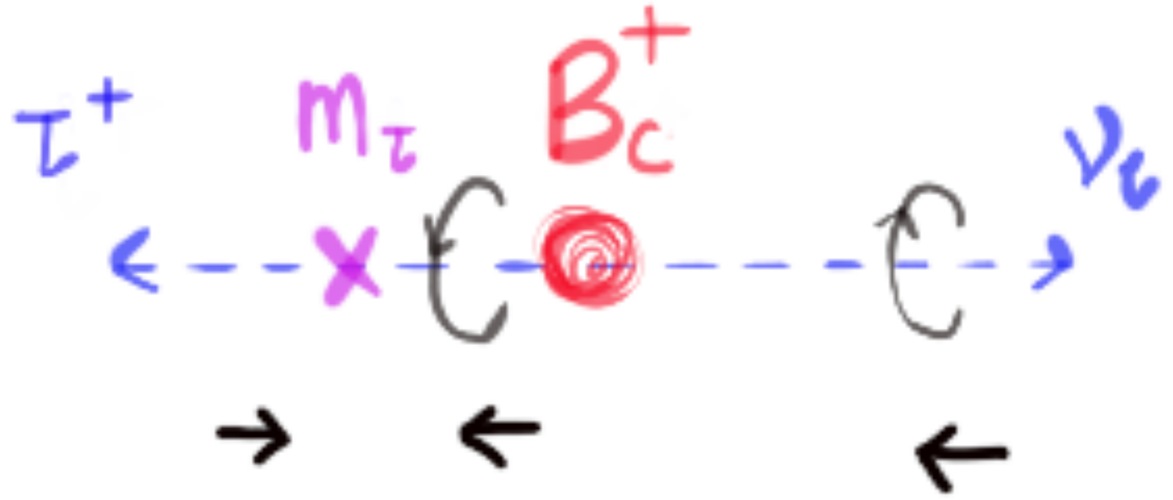
- **Connected by crossing to anomalies**



- **Needed NP leads to wrong B_c lifetime**



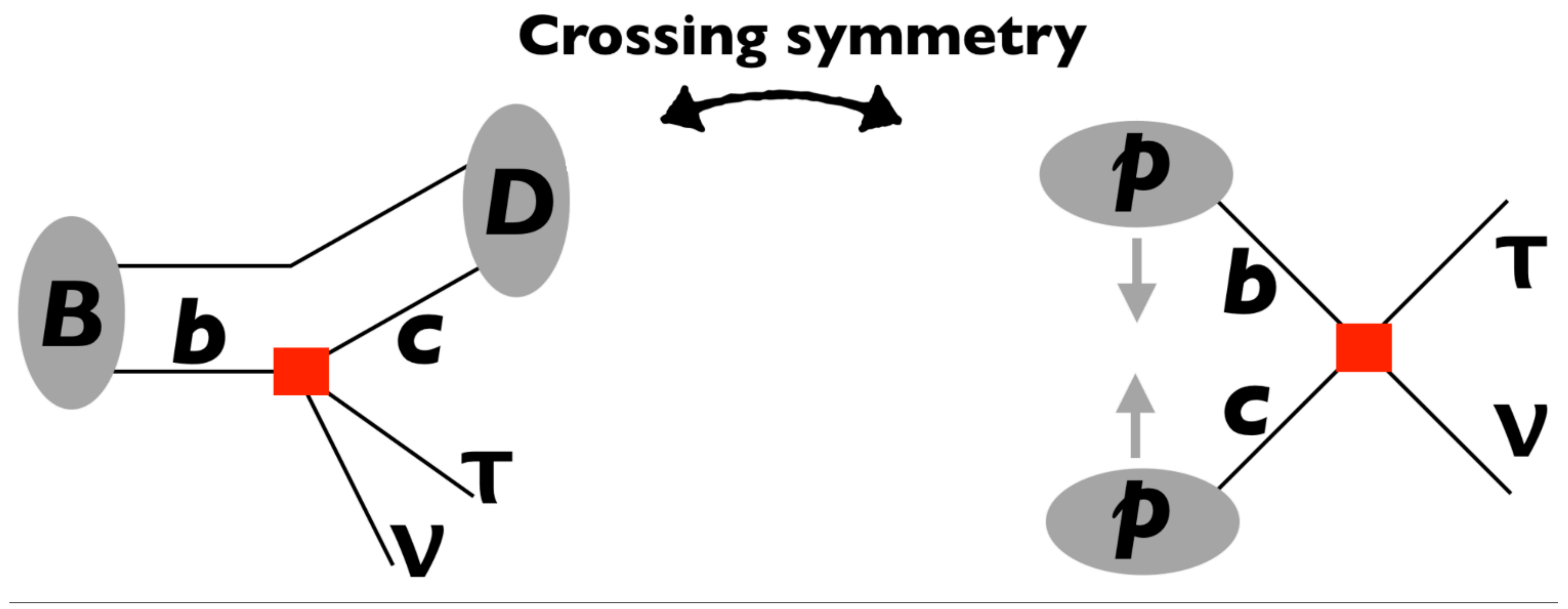
- **Chirally suppressed in the SM**

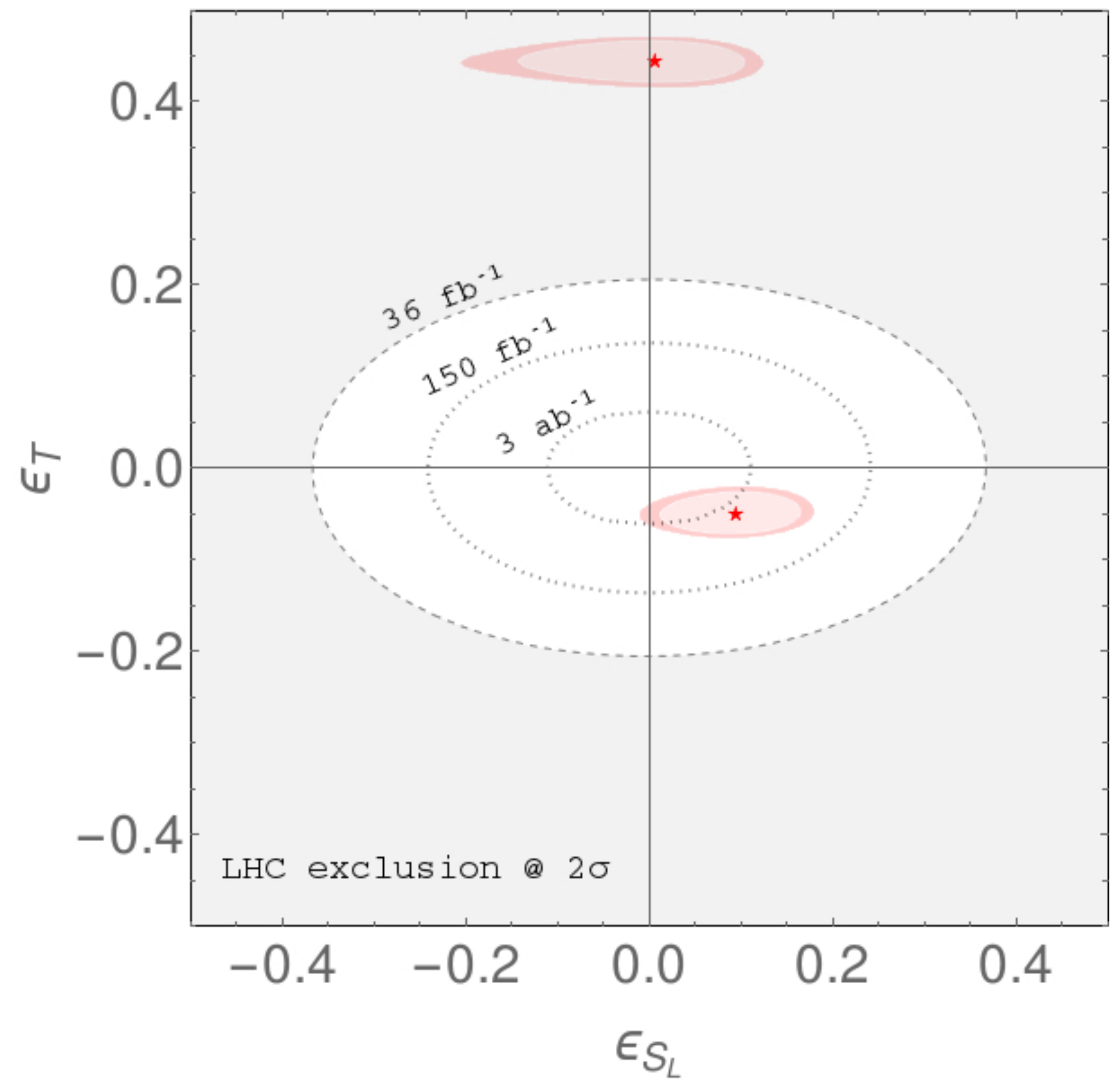


One of major flavor-physics cases for FCC-ee

Flavor physics in the LHC

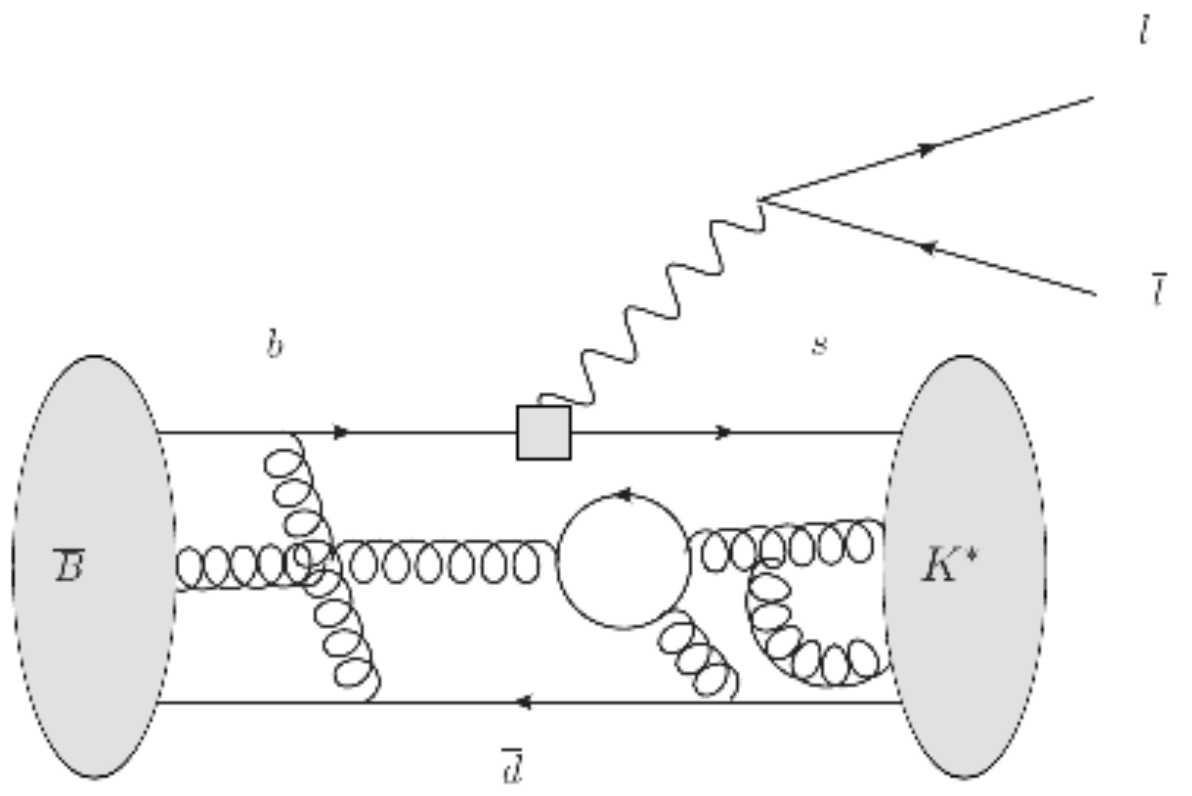
- Crossing symmetry again
  - The **scale of NP is at TeV!** Can be probed at the LHC
  - There are *virtual* b and c quarks in the proton!
  - **Same EFT can be used for collider pheno**





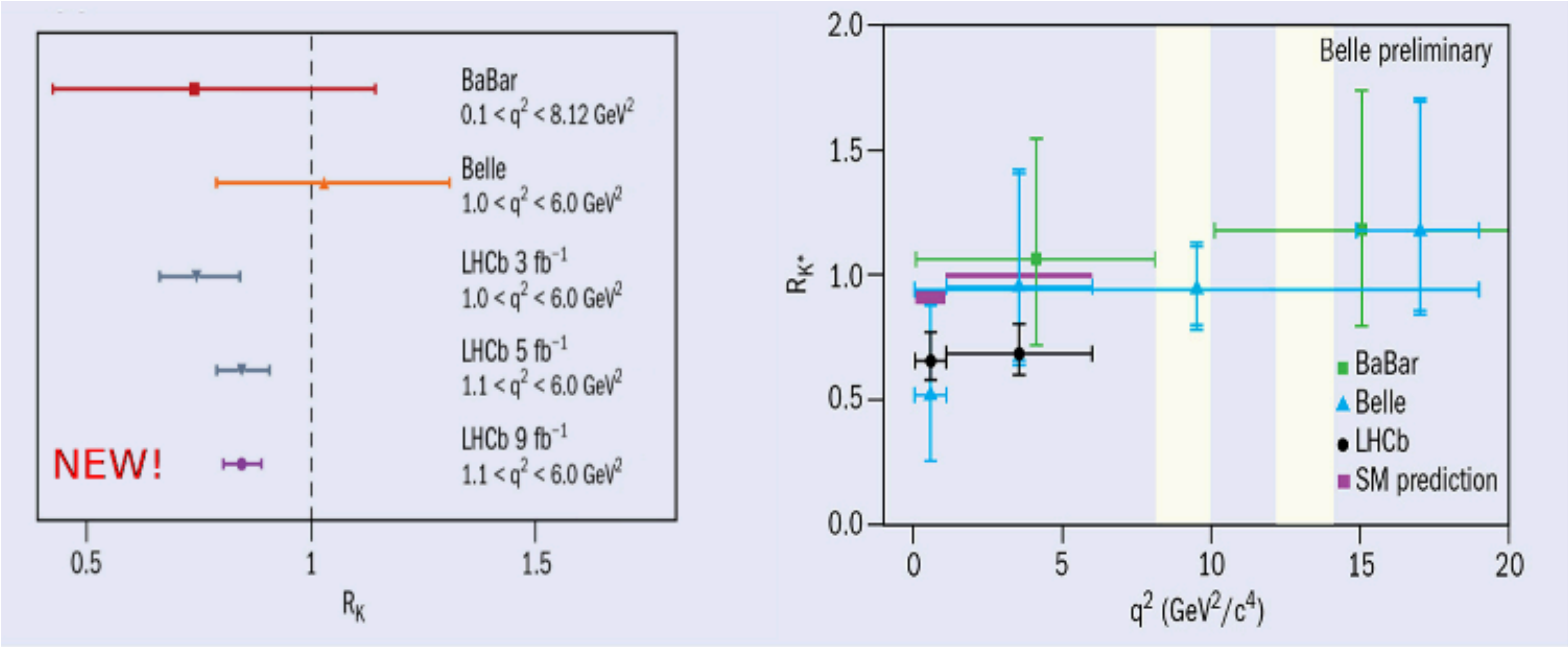
- No-loose theorem for discovery of NP at LHC
  - Almost all NP scenarios can be accessed at HL-LHC
  - **<u>If confirmed</u>, we could discover NP within next 10 yrs!**

Second LUV anomaly: Rates in FCNC $b \to s\mu\mu$



Define the LU ratios

$$R_{K^{(*)}} = \frac{\text{Br}(B \to K^{(*)}\mu^+\mu^+)}{\text{Br}(B \to K^{(*)}e^+e^-)}$$

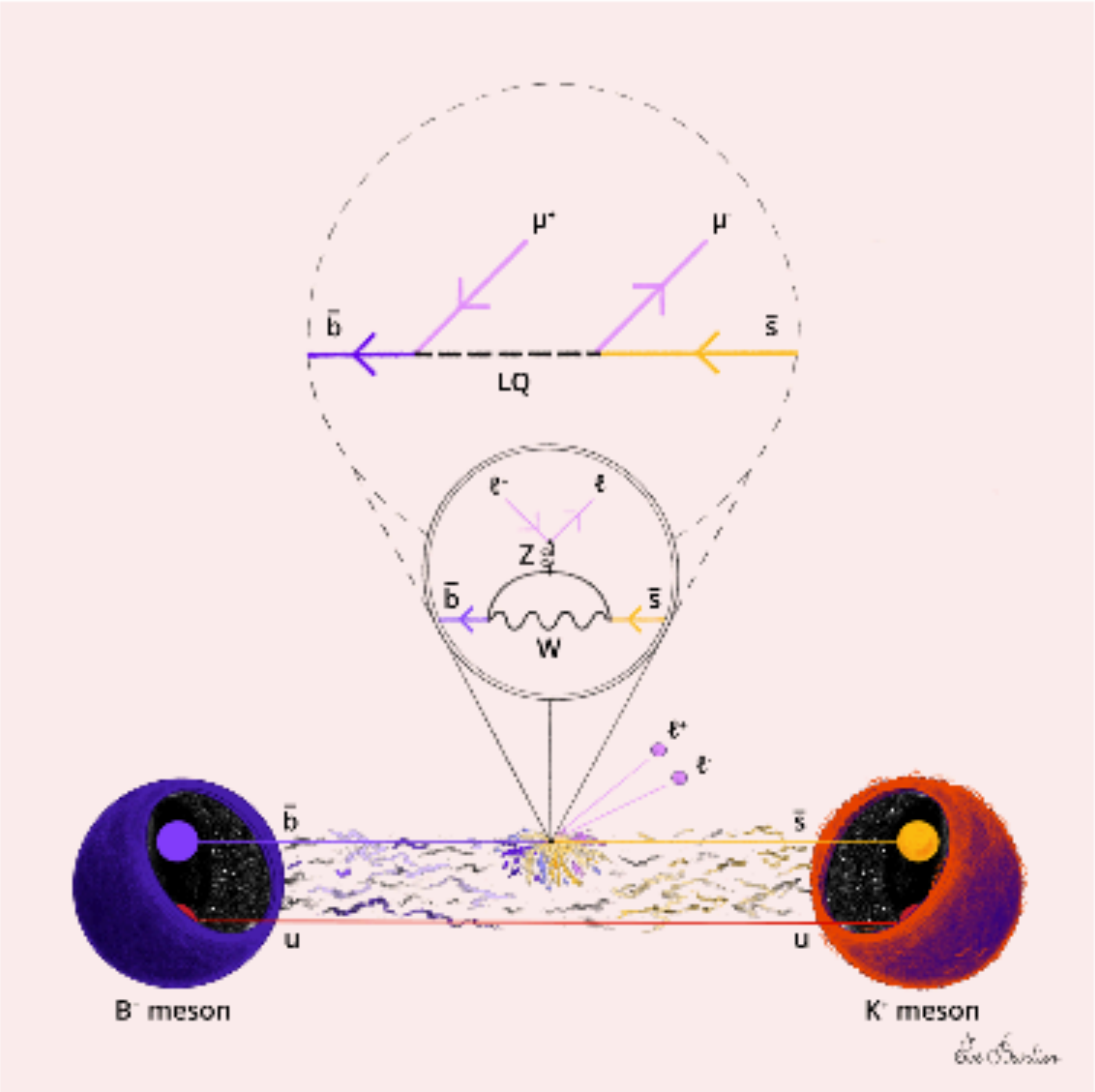


There is an **deficit** at ~5σ in the FCNC $bs\mu\mu$ couplings!

The EFT for $b \to s\ell\ell$

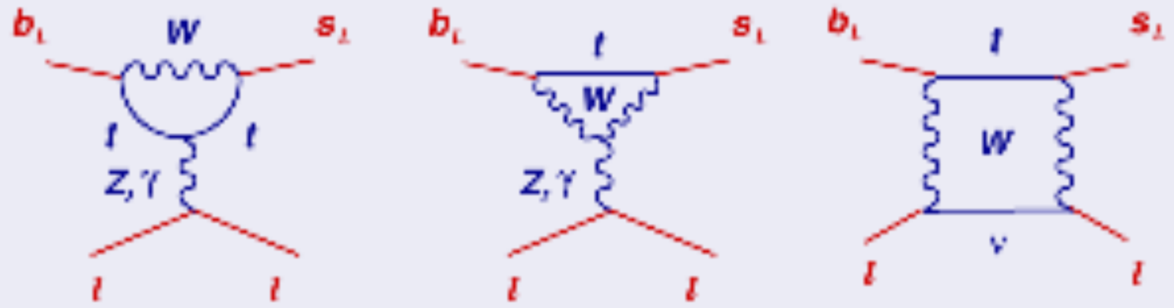
$$\mathcal{L}_{\rm eff} = \frac{4G_F}{\sqrt{2}} V_{3j} V_{3i}^* \Big[\sum_{\substack{k=7,9,\\10,S,P}} \Big(C_k(\mu)\,\mathcal{O}_k(\mu) + C_k'(\mu)\,\mathcal{O}_k'(\mu) \Big) + C_T(\mu)\,\mathcal{O}_T(\mu) + C_{T_5}(\mu)\,\mathcal{O}_{T_5}(\mu) \Big]$$

★ *B decays from $b \to s\ell\ell$*



The $b \to s\ell\ell$ transition in the SM

★ **Semileptonic operators**: $\mathcal{O}_9$ ($L + V$), $\mathcal{O}_{10}$ ($L + A$)

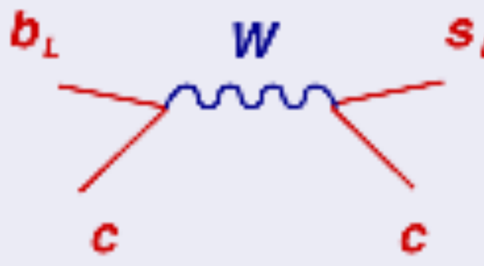


$$\frac{\alpha}{4\pi}\, C_{9(10)}\ \bar{s}_L \gamma^\mu b_L\ \bar{\ell}\gamma_\mu(\gamma_5)\ell$$

★ **Electromagnetic penguin**: $\mathcal{O}_7$

$$\frac{e}{4\pi^2}\, m_b\, C_7\ \bar{s}_L \sigma_{\mu\nu} b_R\, F^{\mu\nu}$$

★ **CC @ 1 loop**

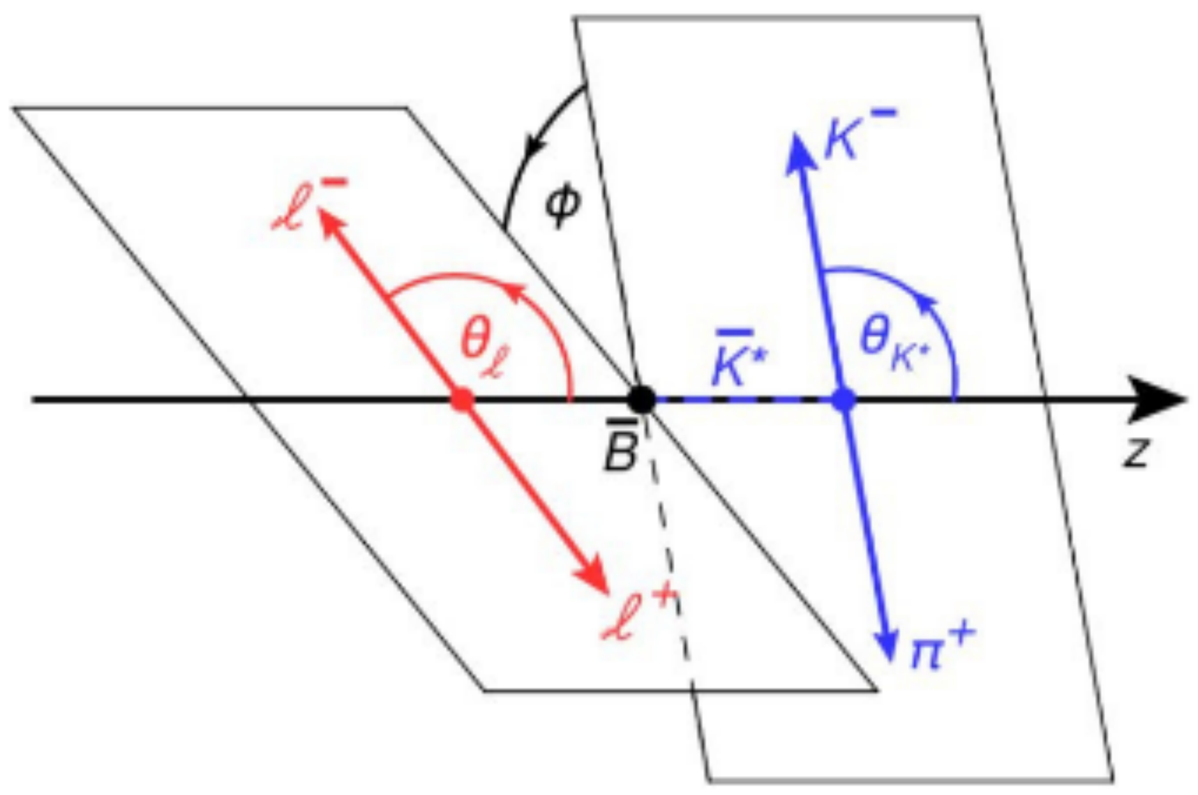


$$C_2\ \bar{c}_L \gamma^\mu b_L\ \bar{s}_L \gamma_\mu c_L$$

- **New-Physics:** in C_i or e.g. $\mathcal{O}_i'$ obtained $P_L \to P_R$ in $\bar{s}_L b$

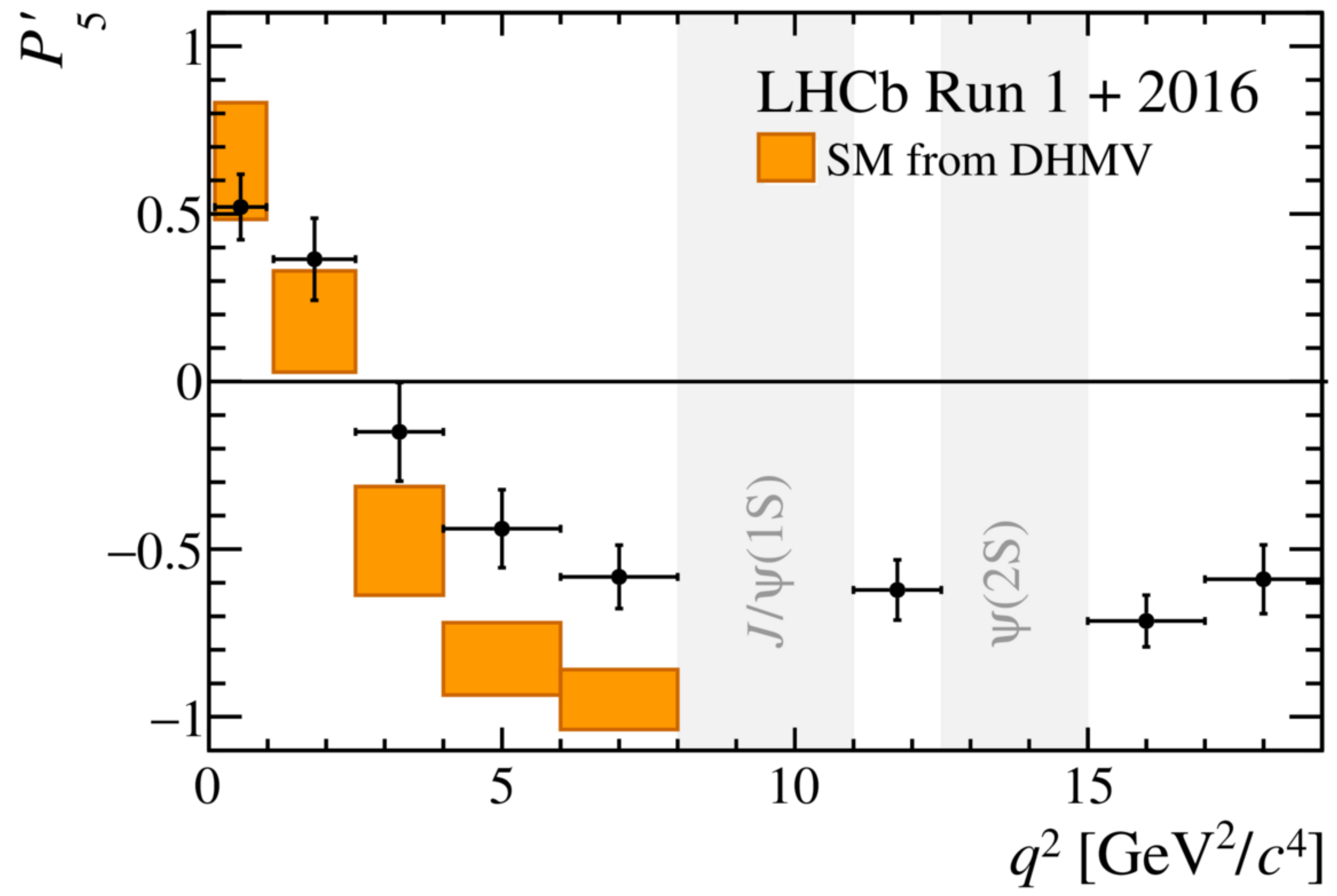
The $B \to K^*(\to K\pi)\mu^+\mu^-$ decay: Observables

- 4-body decay $\Rightarrow$ Very rich phenomenology



- 12 q^2-dependent angular observables

$$\frac{d^{(4)}\Gamma}{dq^2\, d(\cos\theta_l) d(\cos\theta_k) d\phi} = \frac{9}{32\pi}\Big(I_1^s \sin^2\theta_k + I_1^c \cos^2\theta_k$$
$$+ \quad (I_2^s \sin^2\theta_k + I_2^c \cos^2\theta_k)\cos 2\theta_l + I_3 \sin^2\theta_k \sin^2\theta_l \cos 2\phi$$
$$+ \quad I_4 \sin 2\theta_k \sin 2\theta_l \cos\phi + \mathbf{I_5} \sin 2\theta_k \sin\theta_l \cos\phi + I_6 \sin^2\theta_k \cos\theta_l$$
$$+ \quad I_7 \sin 2\theta_k \sin\theta_l \sin\phi + I_8 \sin 2\theta_k \sin 2\theta_l \sin\phi + I_9 \sin^2\theta_k \sin^2\theta_l \sin 2\phi\Big)$$



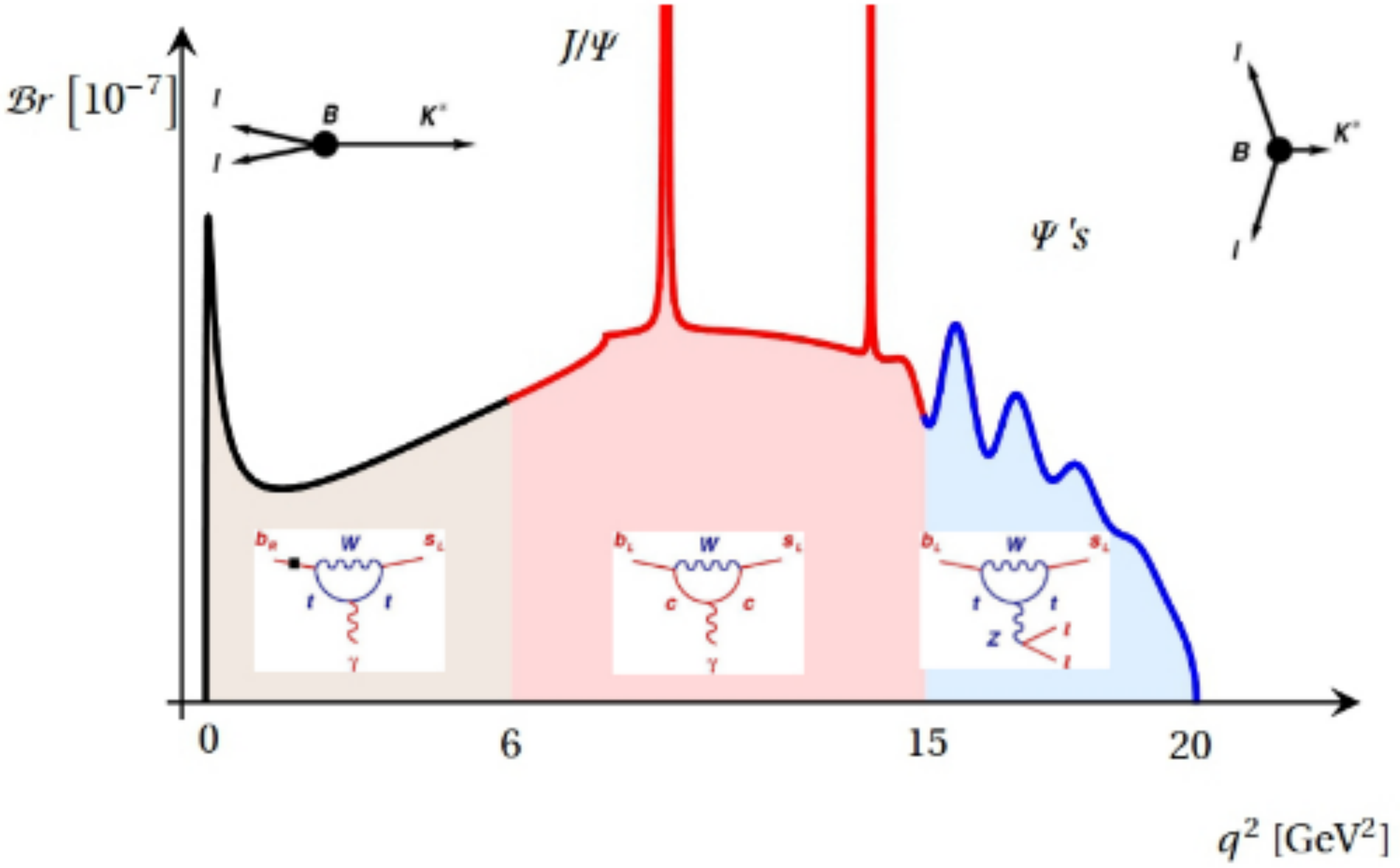
- Anomalies with SM found in P'_5 $(\sim I_5)$

The "C_9 scenario": $C_9^{\rm exp} \approx 3/4\ C_9^{\rm SM}$

But, do we control all the hadronic uncertainties?

The $B \to K^*(\to K\pi)\mu^+\mu^-$ decay: Hadronic uncertainties

- Complicated interplay of short- and long-distance physics



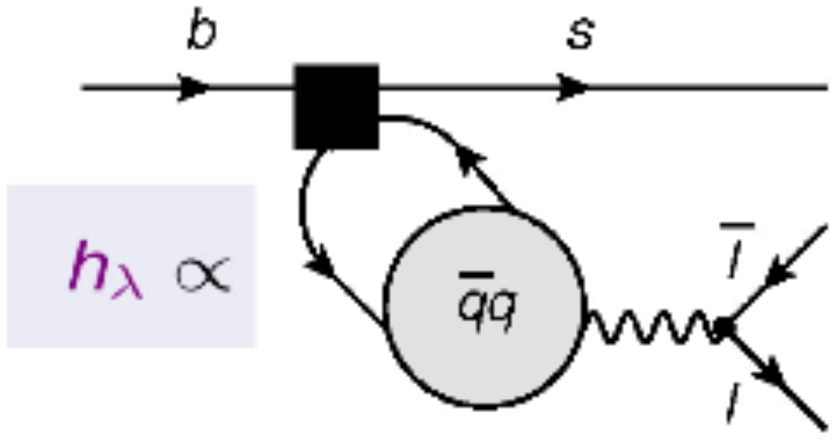
- **7 form factors**

$$H_V(\lambda) = -iN\Big\{\overbrace{\Big[C_9\tilde{V}_{L\lambda} + \frac{m_B^2}{q^2}h_\lambda\Big]}^{C_9^{\rm eff}} - \frac{\hat{m}_b m_B}{q^2}C_7\tilde{T}_{L\lambda}\Big\}$$

$$H_A(\lambda) = -iNC_{10}\tilde{V}_{L\lambda}$$

- **Very difficult in LQCD**

- **"Charm" contribution**



- **Only $C_9^{\rm eff}$ is observable!**

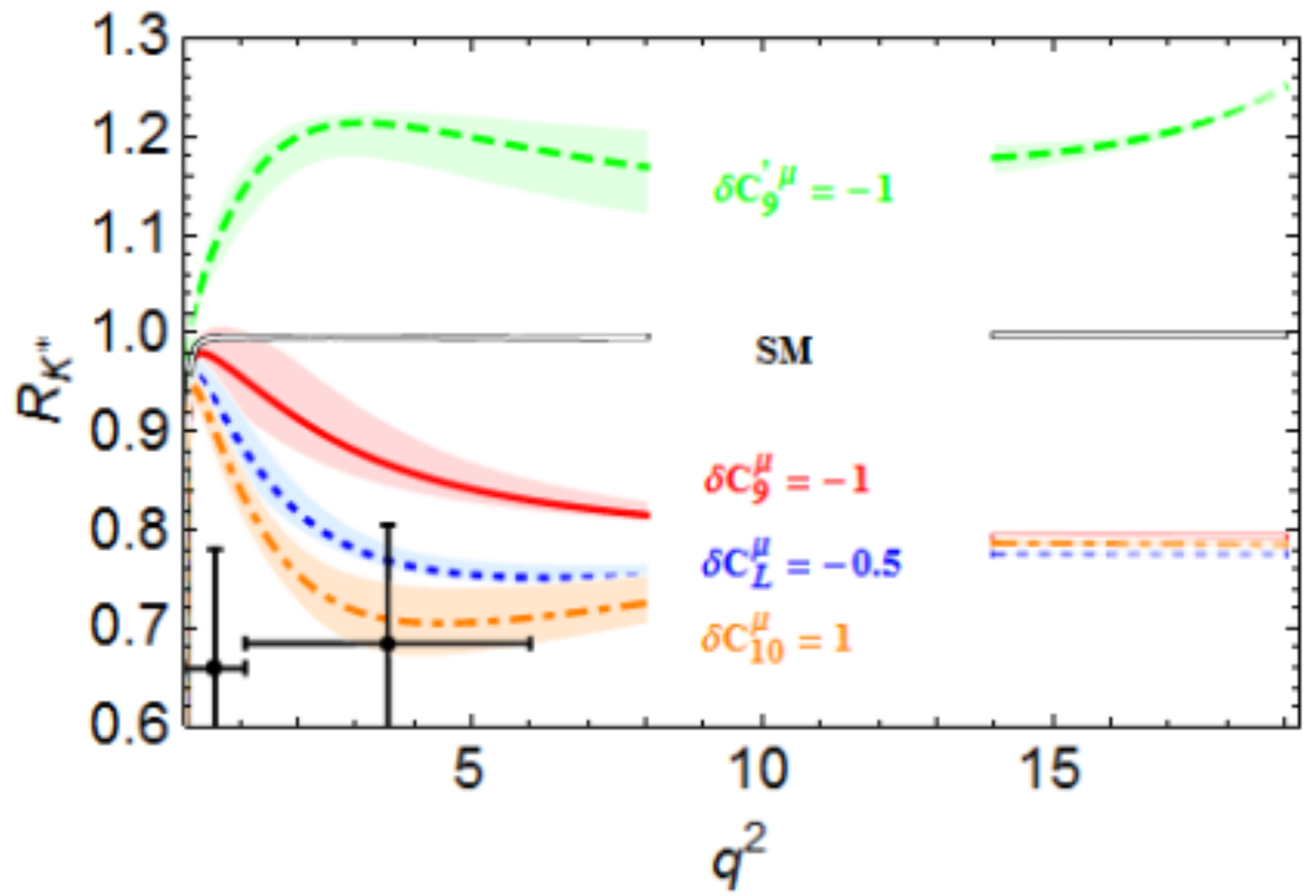
The LU ratios

- Leptons do not feel strong force
- Kinematics wide enough to suppress masses ($m_\mu^2/q^2 \ll 1$)

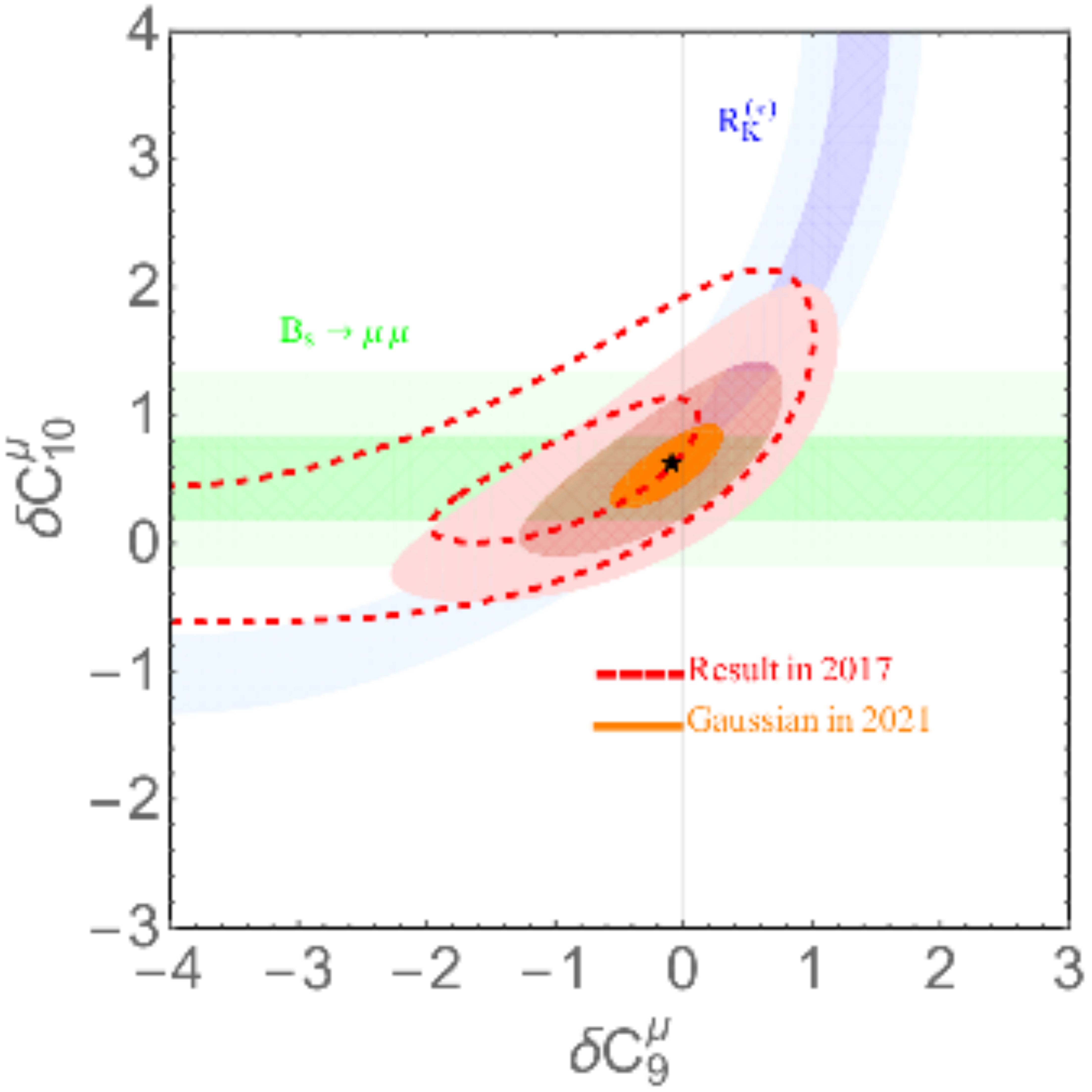
Prediction in the SM

$$R_{K^{(*)}} = \left.\frac{\mathrm{Br}(B \to K^{(*)}\mu^+\mu^+)}{\mathrm{Br}(B \to K^{(*)}e^+e^-)}\right|_{\mathrm{SM}} = 1$$

- Observables very robust against hadronic uncertainties



Fit to theoretically clean observables



Main results

- p-value (SM) = **7.6 × 10^{-5}**
  (4σ tension of SM with data)
- p-value (BSM) = **0.27**
  BSM better than SM by $\sim 4.9\sigma$**!**

Impossible to understand within the SM

- Really New Physics?! ...
- Or statistical fluke?! (4σ)
- Or an experimental problem?!

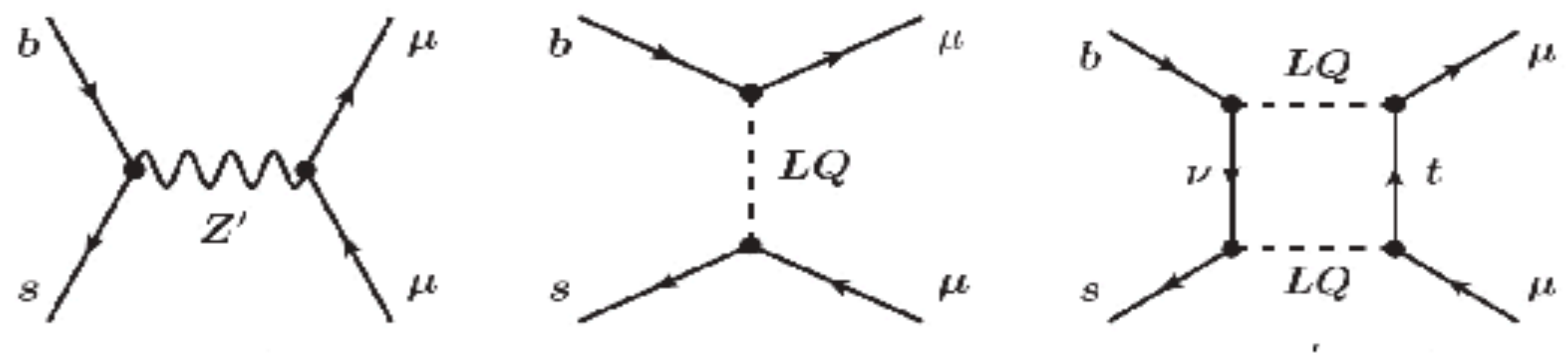
Simplified models for the $b \to s\mu\mu$ anomaly

Current-current interpretation!

$$\mathcal{L}_{eff} \supset \frac{C_{9(10)}}{\Lambda^2_{\mathrm{New-Physics}}} (\bar{s}\gamma^\mu P_L b)(\bar{\mu}\gamma_\mu(\gamma_5)\mu)$$

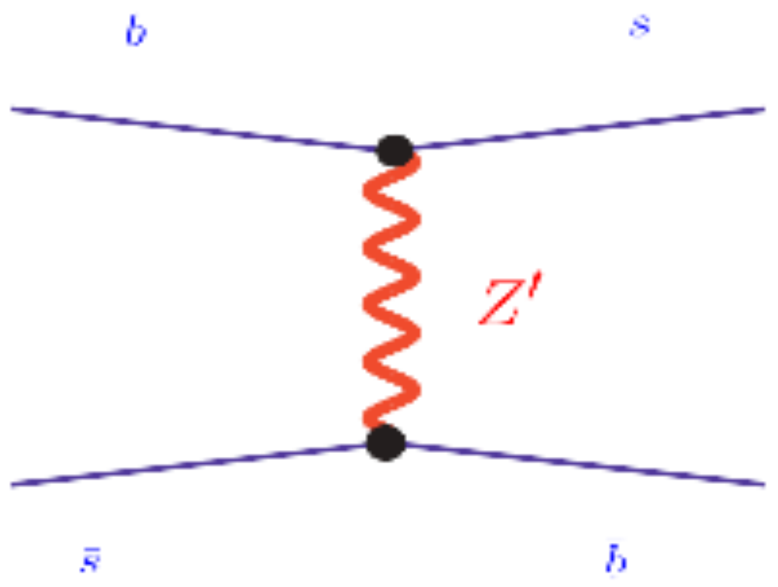
$$\Lambda_{\mathrm{New-Physics}} \sim 30 \text{ TeV!!!}$$

- UV completions: Z''s and **leptoquarks**



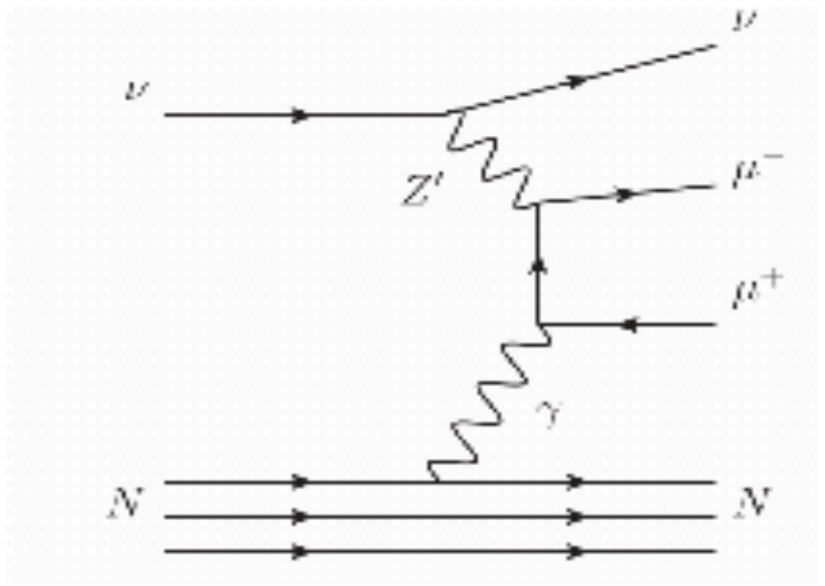
- **Extra bounds from low energy** e.g. Z'

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



  - Requires small $Z'bs$ coupling! (e.g **MFV**)

  - Neutrino trident production



  - Controls $Z'\mu\mu$ coupling!

Combined NP explanations of both LU anomalies

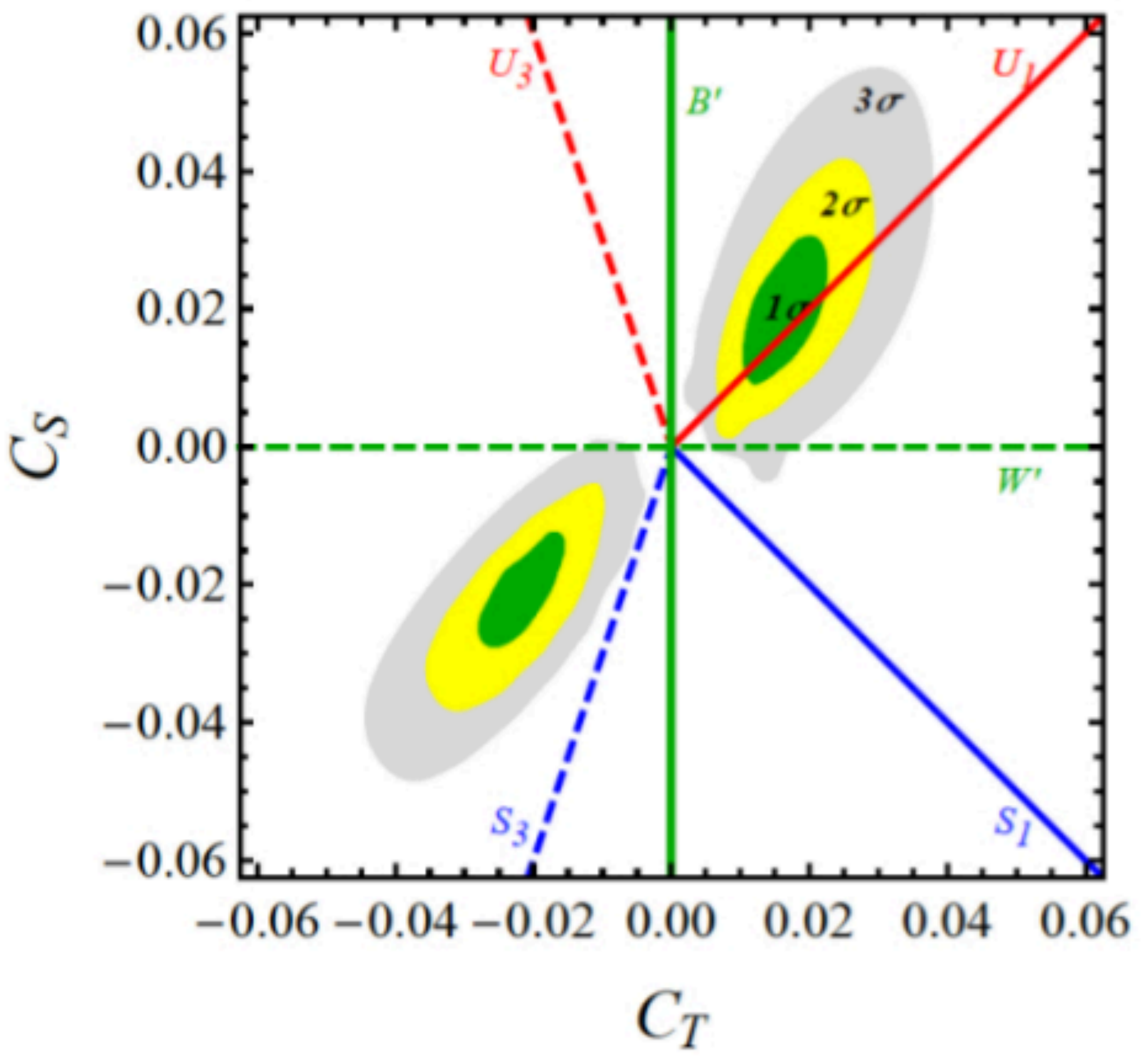
- **Important observation:** Both anomalies ...
  1. Involve the CC and FCNC semileptonic transitions of the b quark
  2. Involve violation of LU hierarchically ($\Lambda_\tau \ll \Lambda_\mu \ll \Lambda_e$): MFV-like flavor violation?

SMEFT operators: $Q^{(1)}_{\ell q(ijkl)} = \frac{1}{\Lambda^2}(\bar{Q}_L{}^i \gamma^\mu Q_L{}^j)(\bar{L}_L{}^k \gamma_\mu L_L{}^l)$, $\quad Q^{(3)}_{\ell q(ijkl)} = \frac{1}{\Lambda^2}(\bar{Q}_L{}^i \gamma^\mu \vec{\tau} Q_L{}^j)\cdot(\bar{L}_L{}^k \gamma_\mu \vec{\tau} L_L{}^l)$

- **Almost only one posibility: The vector leptoquark**

Three main options
(*for the combined explanation*):

	$SU(2)_L$ singlet	$SU(2)_L$ triplet
Vector LQ:	U_1	U_3
Scalar LQ:	S_1	S_3
Colorless vector:	B'	W'



Conclusions about anomalies

“Extraordinary claims require Extraordinary evidence”

– C. Sagan

- **Approaching that level at LHCb in “R_K”**
- Wait to Belle II ... ($\sim$ 2027)