# フレーバーアノマリーの新たな展開

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# Introduction

- Three types of approach to consider new physics:
  - **Top-down: based on symmetry with breaking, naturalness**
  - **Bottom-up: based on our world and data**
  - **More fundamental physics and apply it to this world**
- Quark and lepton flavor physics provide a ton of data, so research of flavor physics is mainly performed by the bottom-up approach
- The ultimate goal is to solve unresolved problems in the Universe, e.g., Matter-antimatter asymmetry, Strong CP problem, Neutrino mass, etc

Flavor physics in the past

Theoretical uncertainty,
Experimental uncertainty,
Lattice uncertainty…

Current flavor physics

The uncertainties are satisfactorily small to discover "something"

AI images: created by Bing

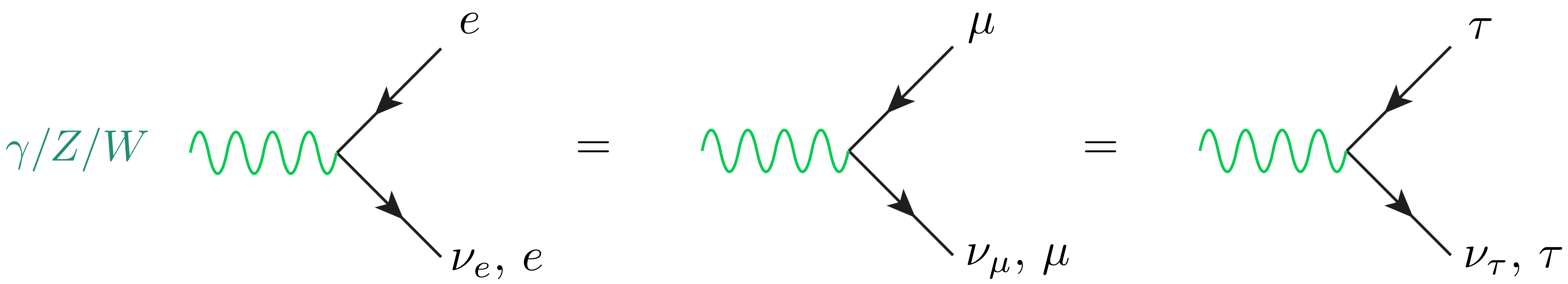
# Contents

- Topic1: $B \to D\tau\nu, D\ell\nu$ (robust)
- Topic2: $B \to K\ell\ell$ (excess?)
- Topic3: $B^0 \to DK, B_s^0 \to D_s\pi$ (excess?)
- Topic4: CKM unitarity test (robust)
- Topic5: Beryllium anomaly (excess?)

# Topic1: $B \to D\tau\nu, D\ell\nu$ (robust)

# Test of Lepton Flavor Universality (LFU)

- Gauge symmetry predicts lepton flavor universal (**LFU**) phenomena:



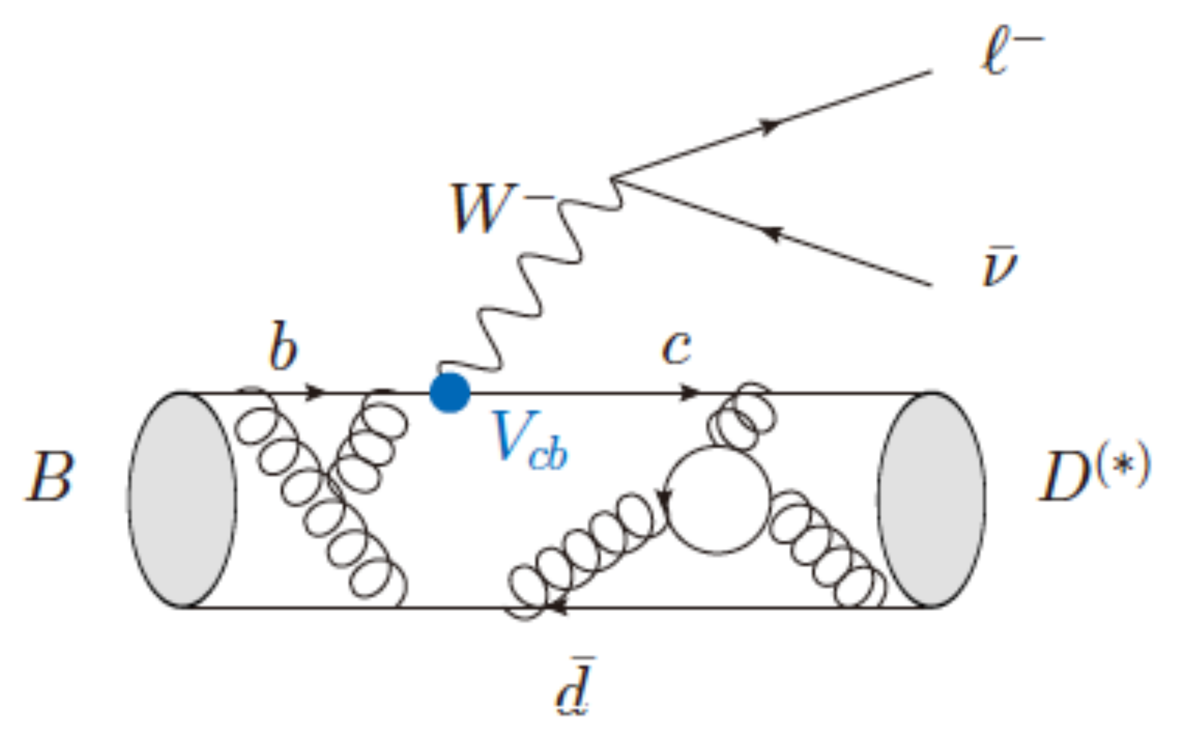

- Only **lepton mass** (+QED corrections) violates LFU within the SM (Higgs exchange is negligible)

$m_e = 0.5\,\text{MeV}$, $m_\mu = 105\,\text{MeV}$, $m_\tau = 1776\,\text{MeV}$ ⇒ Different kinematical phase space

# Lepton-flavor-universality observables: $R(D)$ and $R(D^*)$

$$R(D^{(*)}) = \frac{\mathrm{BR}(B \to D^{(*)}\bar{\tau}\nu_\tau)}{\mathrm{BR}(B \to D^{(*)}\bar{\ell}\nu_\ell)}$$

$(\ell = e\,,\mu)$



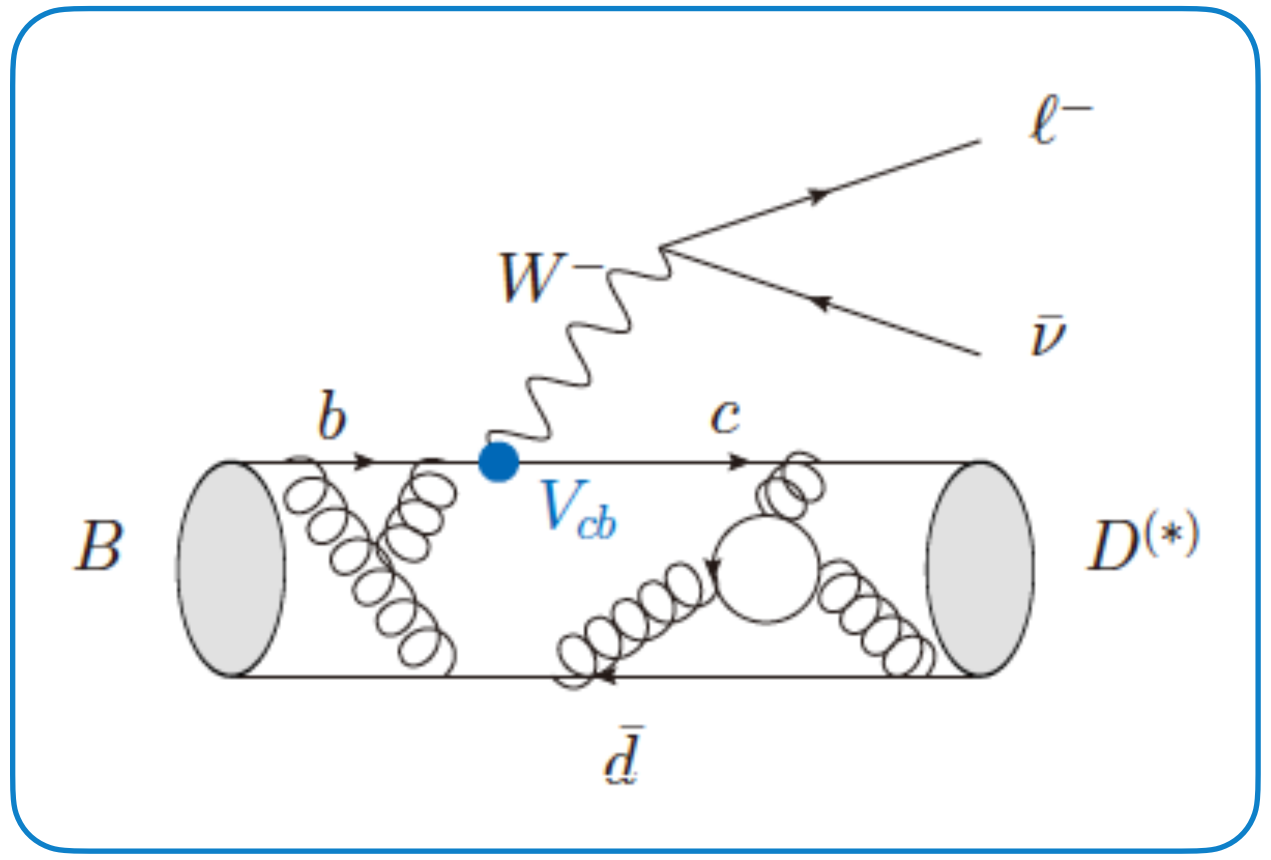

| Experiment | | $R_{D^*}$ | $R_D$ | Correlation |
|---|---|---|---|---|
| BaBar | | $0.332 \pm 0.024 \pm 0.018$ | $0.440 \pm 0.058 \pm 0.042$ | $-0.27$ |
| Belle | | $0.293 \pm 0.038 \pm 0.015$ | $0.375 \pm 0.064 \pm 0.026$ | $-0.49$ |
| Belle | | $0.270 \pm 0.035^{+0.028}_{-0.025}$ | – | – |
| Belle | | $0.283 \pm 0.018 \pm 0.014$ | $0.307 \pm 0.037 \pm 0.016$ | $-0.51$ |
| LHCb | 2022Oct | $0.281 \pm 0.018 \pm 0.024$ | $0.441 \pm 0.060 \pm 0.066$ | $-0.43$ |
| LHCb | 2023Mar | $0.257 \pm 0.012 \pm 0.018$ | – | – |
| Belle II | 2023Jul | $0.267^{+0.041}_{-0.039}{}^{+0.028}_{-0.033}$ | – | – |
| World average | | $0.284 \pm 0.009 \pm 0.008$ | $0.356 \pm 0.025 \pm 0.014$ | $-0.38$ |

*p*-value of the data= 0.33 ; implying data are consistent

# Lepton-flavor-universality observables: *R*(*D*) and *R*(*D**)

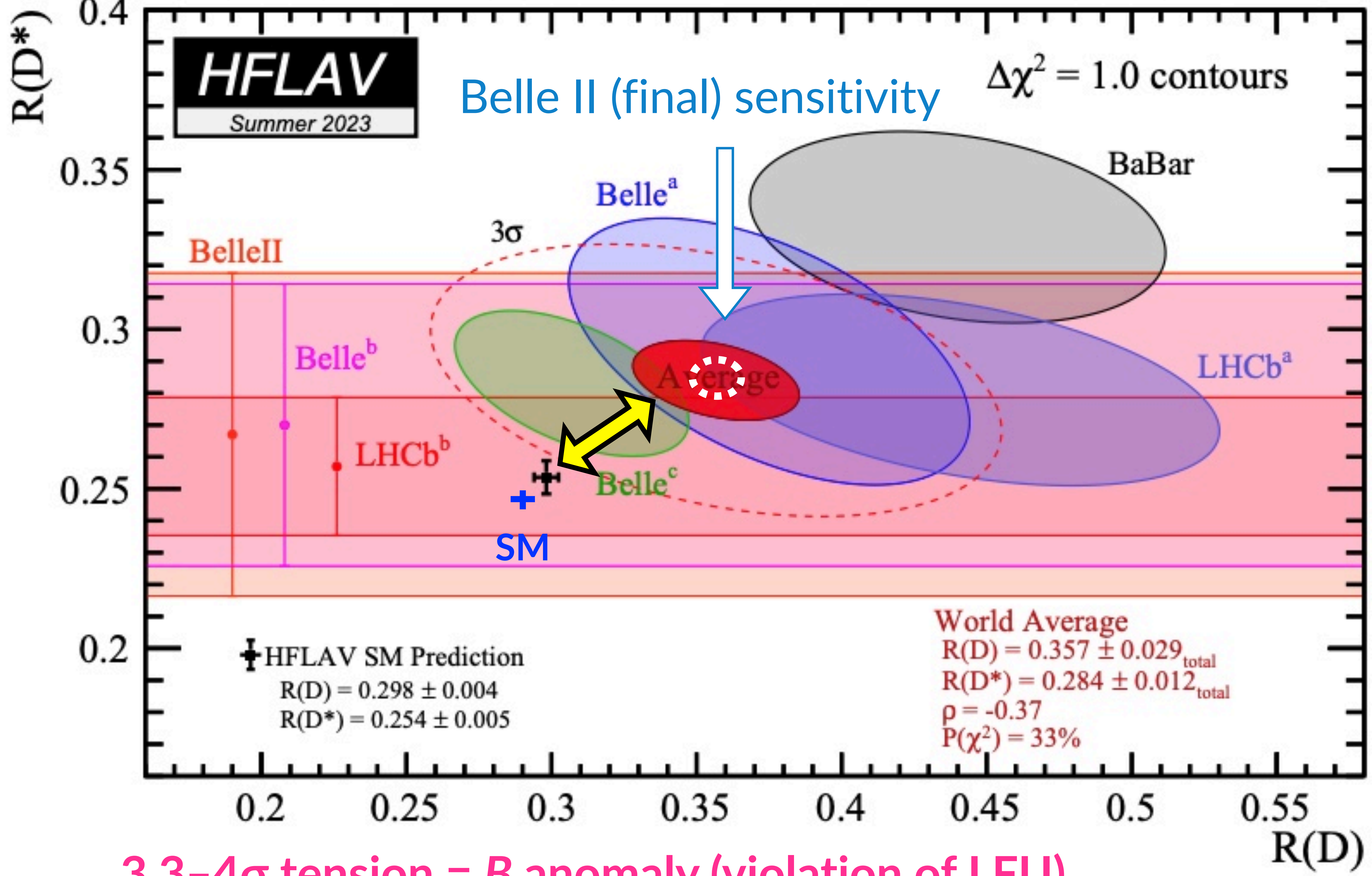
$$R(D^{(*)}) = \frac{\mathrm{BR}(B \to D^{(*)}\bar{\tau}\nu_\tau)}{\mathrm{BR}(B \to D^{(*)}\bar{\ell}\nu_\ell)}$$

$(\ell = e\,,\mu)$




$b \to c\tau\nu$ anomaly

[HFLAV summer2023 + Iguro, Watanabe, 2004.10208 for SM]




**3.3–4σ tension = *B* anomaly (violation of LFU)**

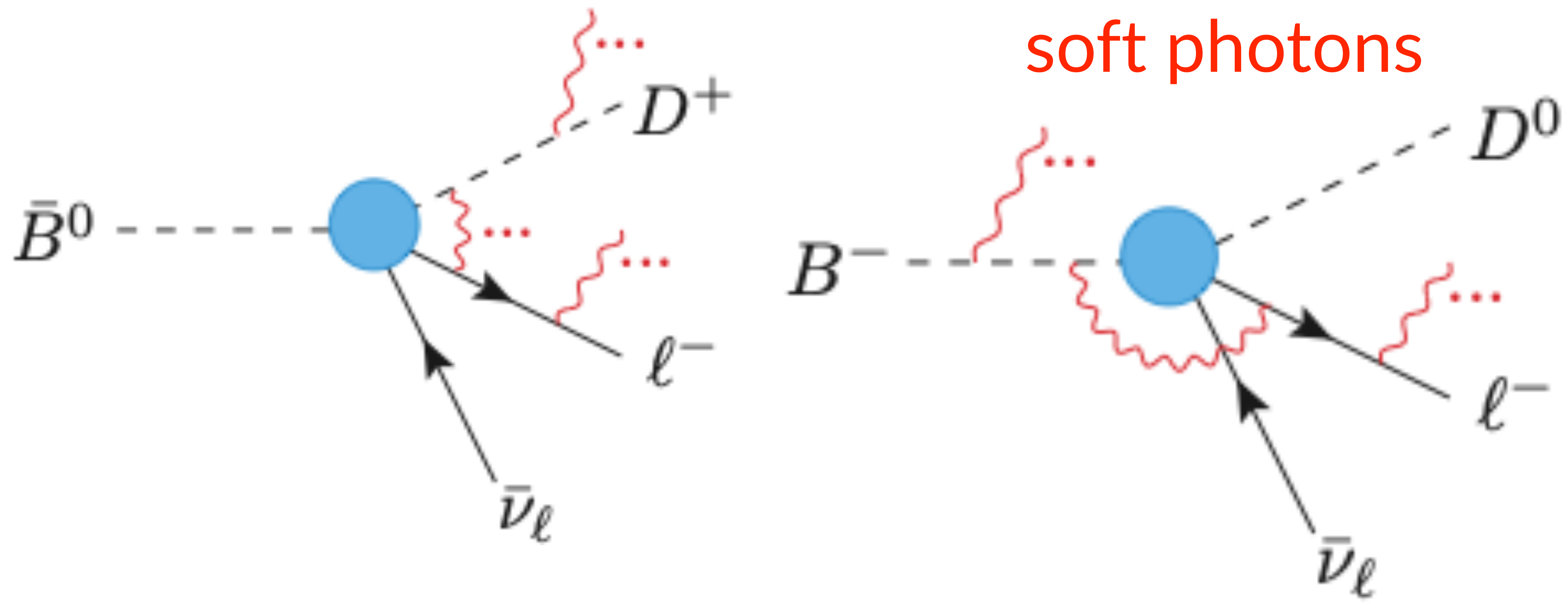
without BaBar → 2.5-3.2σ (Thanks to Syuhei!)

# QED correction within the SM

- Long-distance QED correction could violate the lepton flavor universality

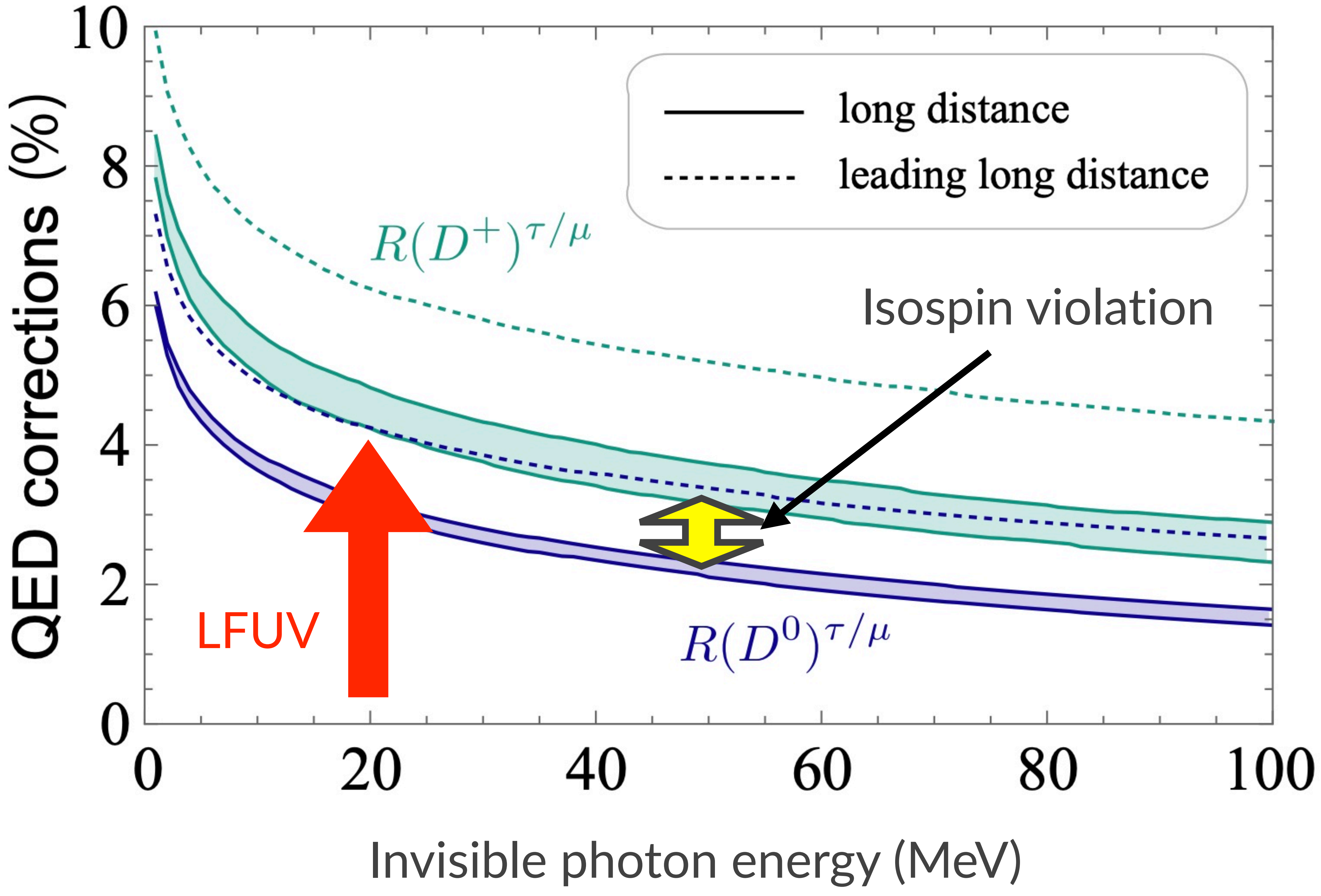
  [de Boer, TK, Nisandzic, 1803.05881; Calí, et al, 1905.02702; Isidori, Nabeebaccus, Zwicky, 2009.00929]

  Note that $B \to D\ell\nu$ measurements are not soft-photon inclusive ($q^2_{\rm miss} = 0$ is required)




The QED corrections depend on the lepton velocities; non-rela $\tau$ vs relativistic $\mu$ → ***opposite sign***

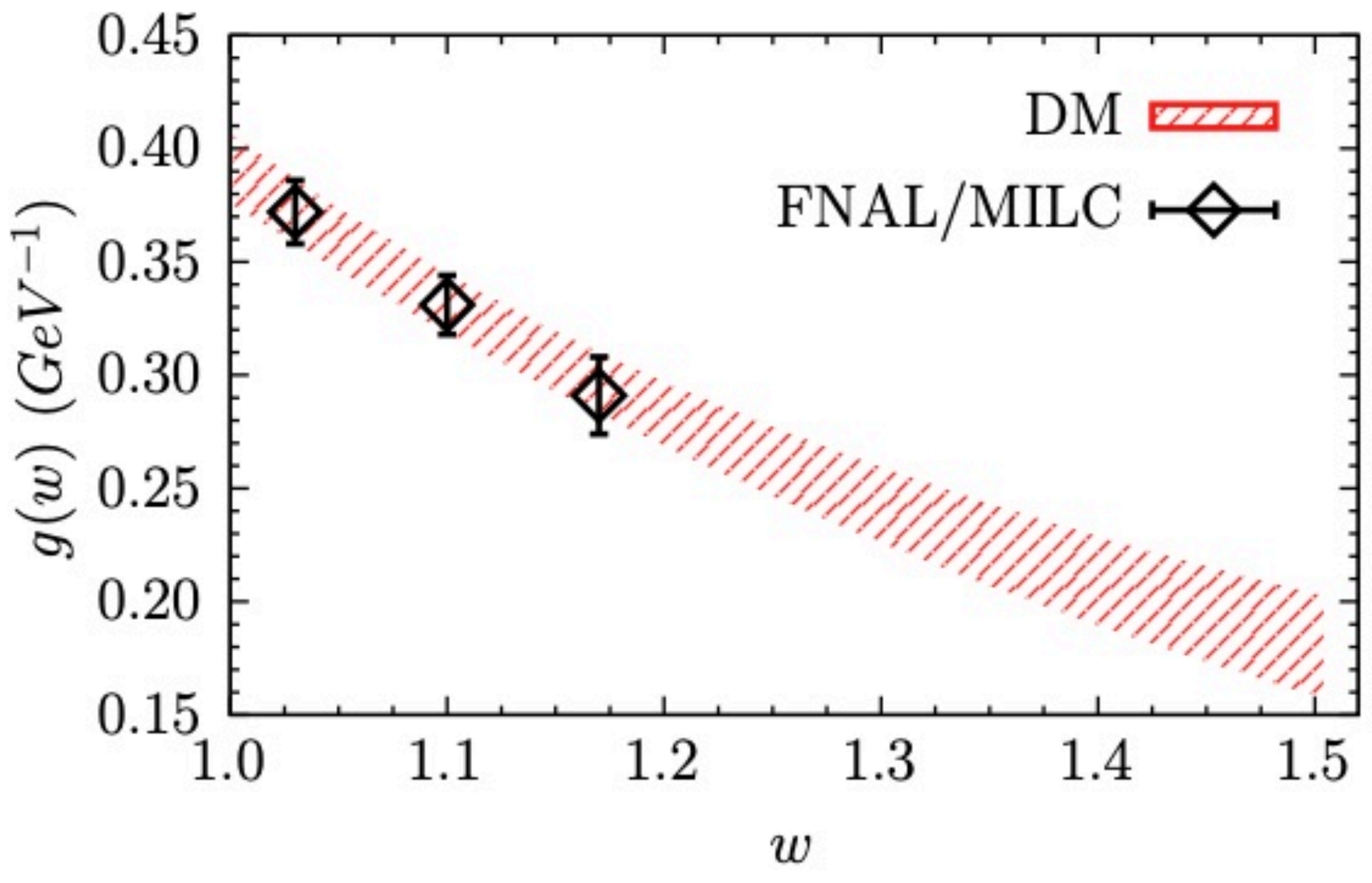
Soft-photon interference (FS-FS & IS-FS) is significant, see additional slide for the details

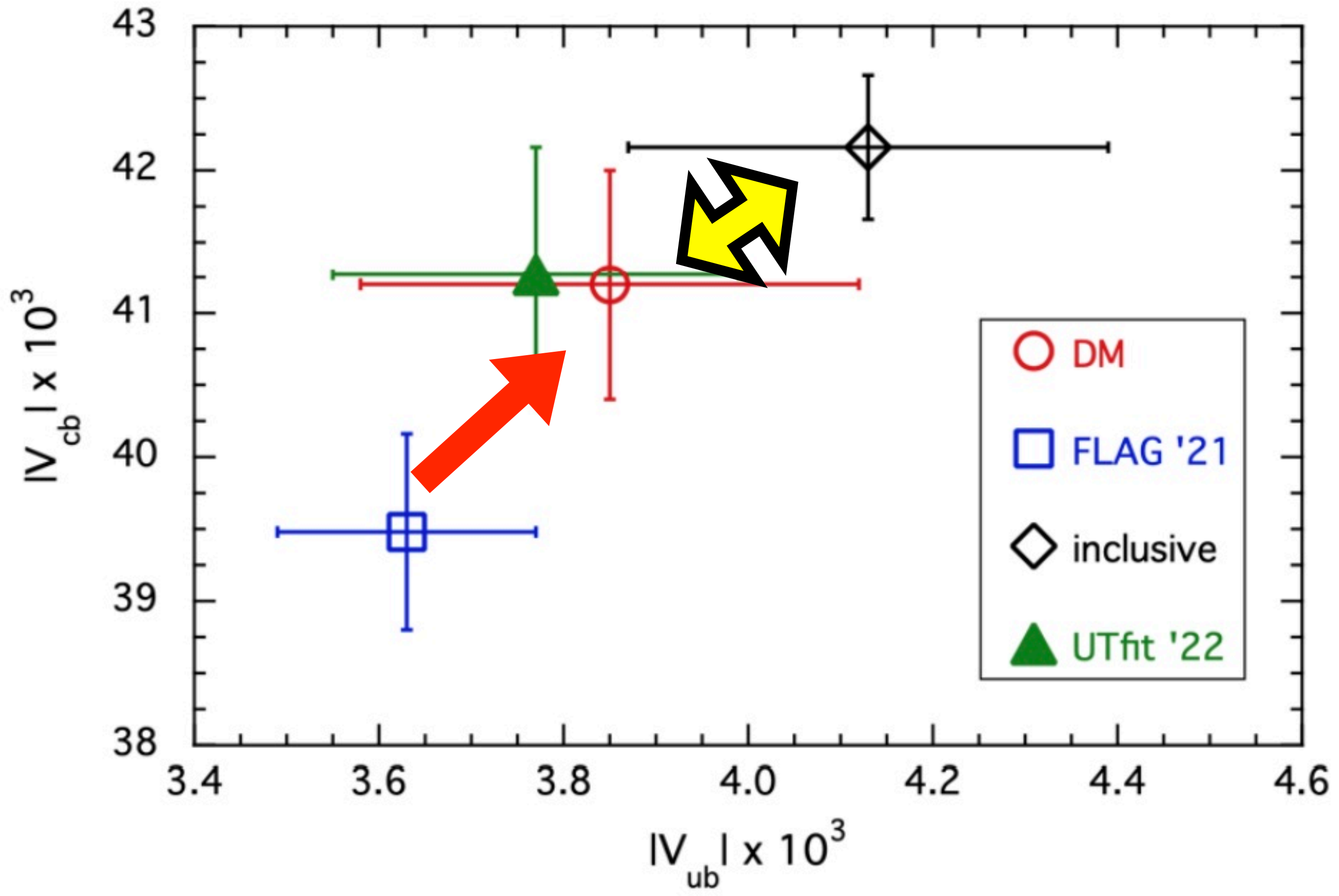


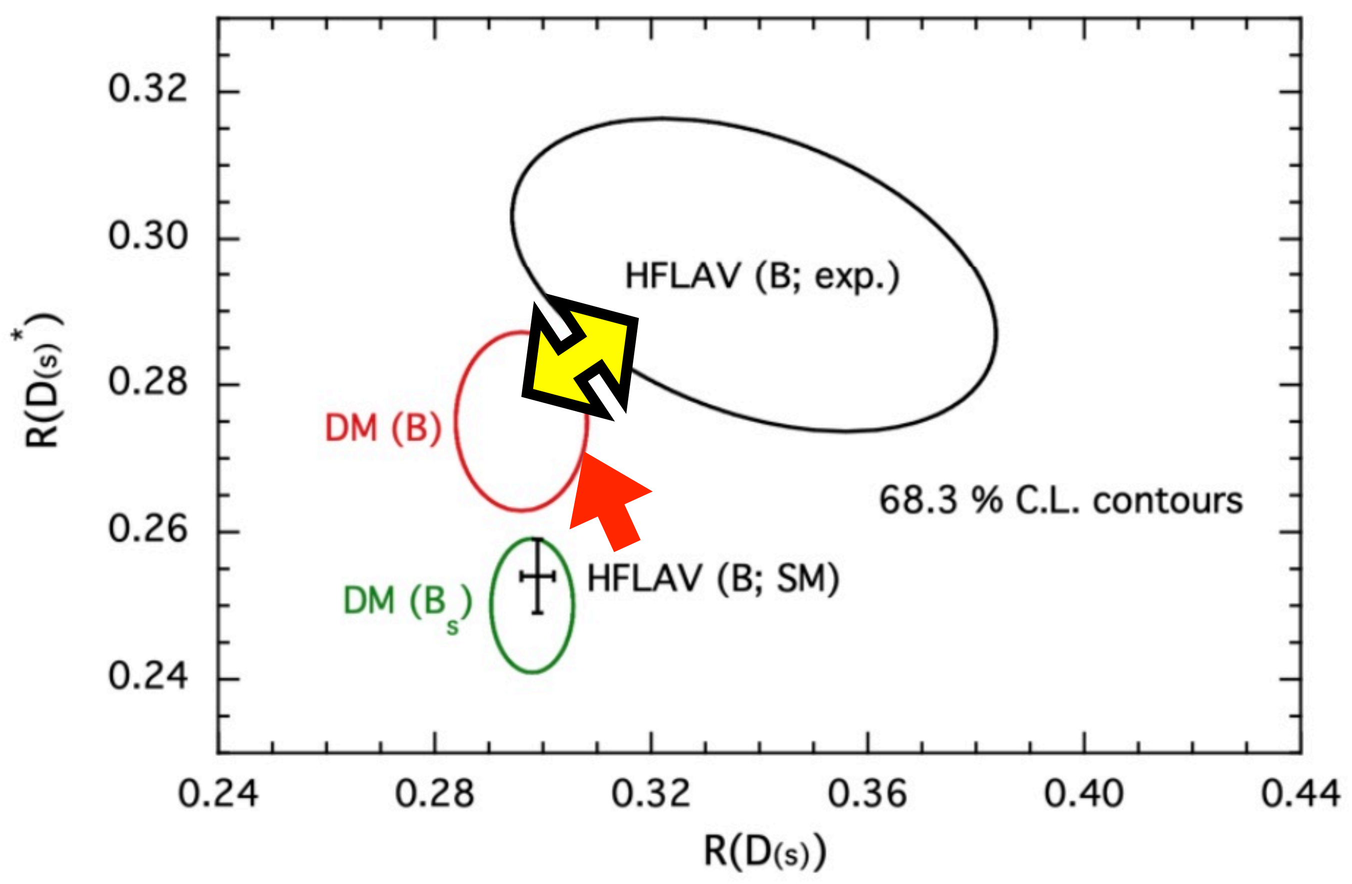
# Recent progress in SM: Dispersion matrix approach

- Dispersion matrix approach is novel form factor's description for $B \to D^{(*)}$
- Based on the **lattice QCD data only**. By applying the unitarity condition, one can extract the form factors for all $q^2$ region with non-perturbative and model-independent manner
- No experimental data are needed [Di Carlo, et al, 2105.02497; Martinelli, et al, 2105.07851]

Are tensions relaxed nicely?



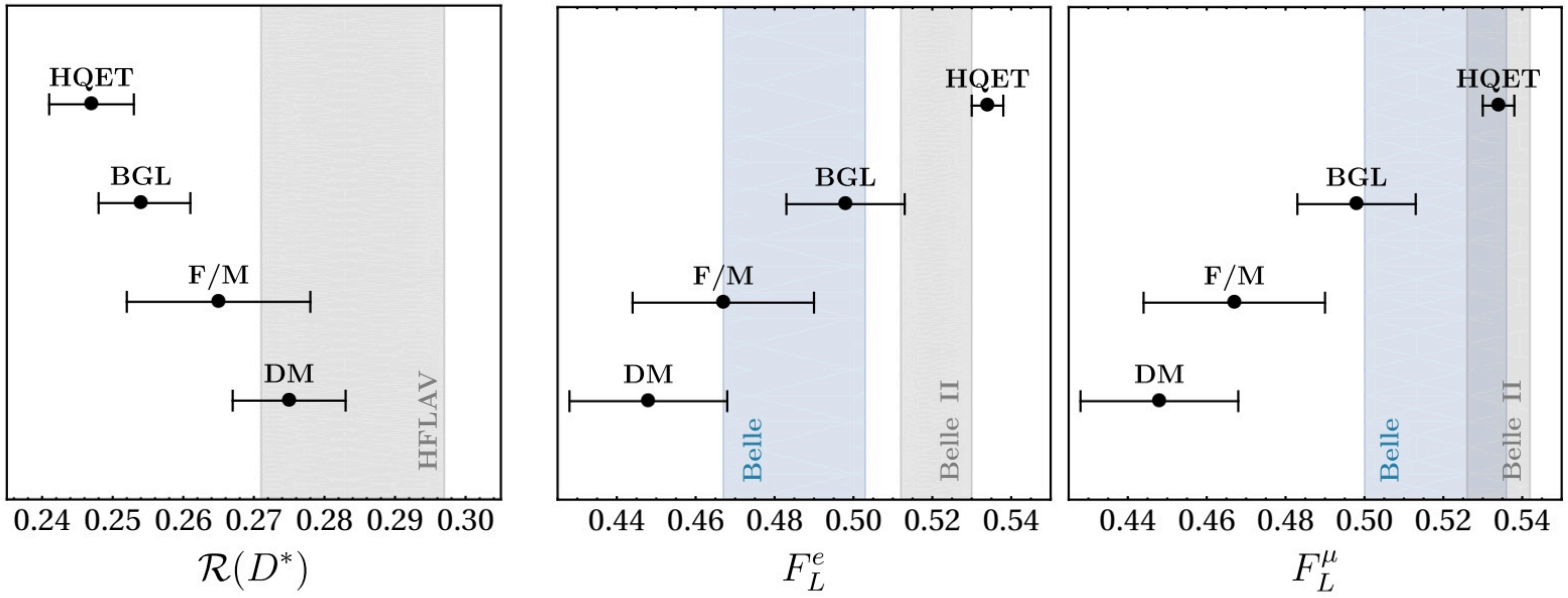



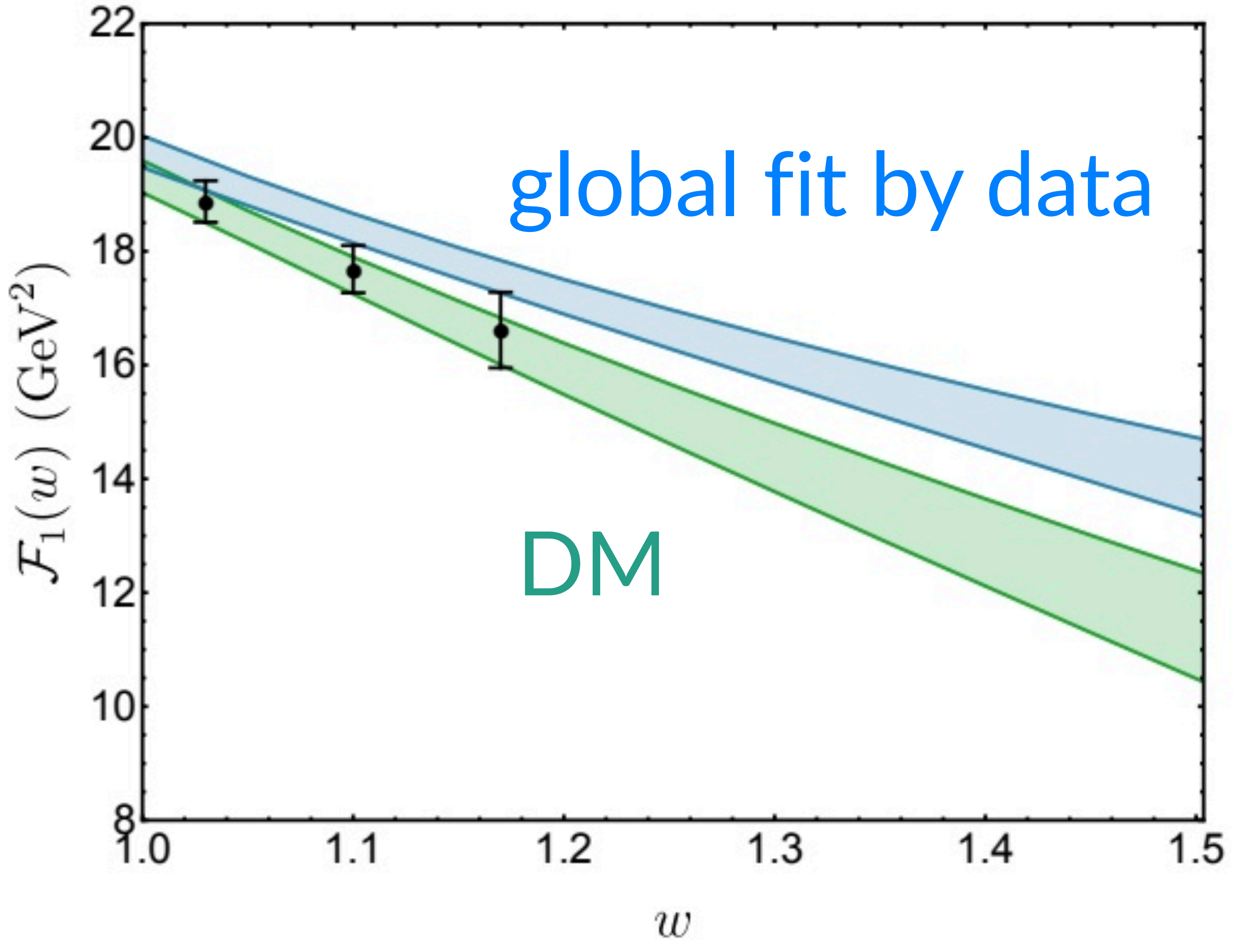



# Recent progress in SM: Dispersion matrix approach

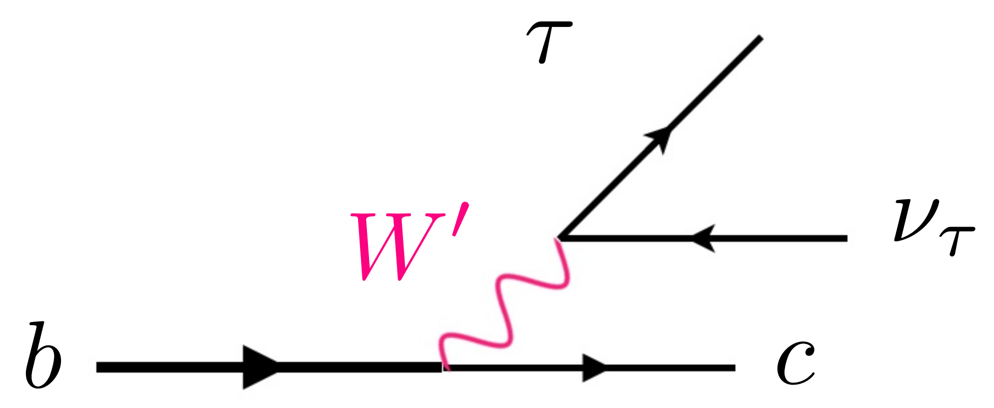
- It is pointed out that there are 3σ tension in the dispersion matrix approach with light-lepton data [Fedele, et al, 2305.15457]

$D^*$ longitudinal polarization fraction

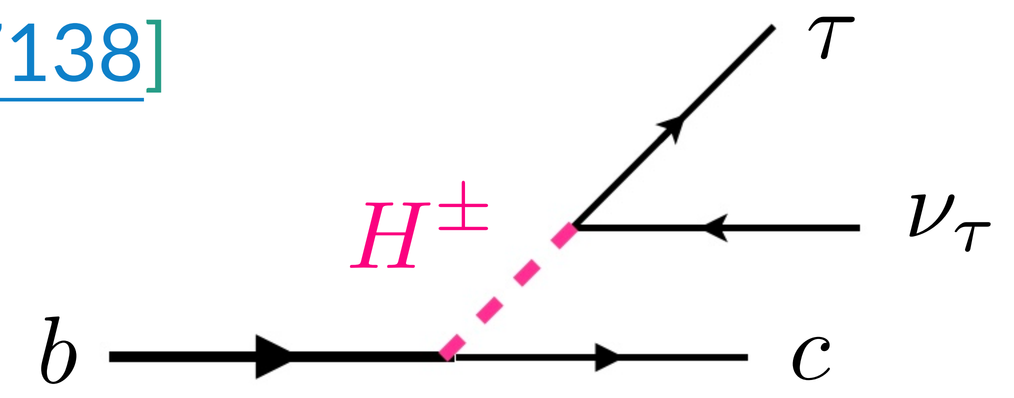


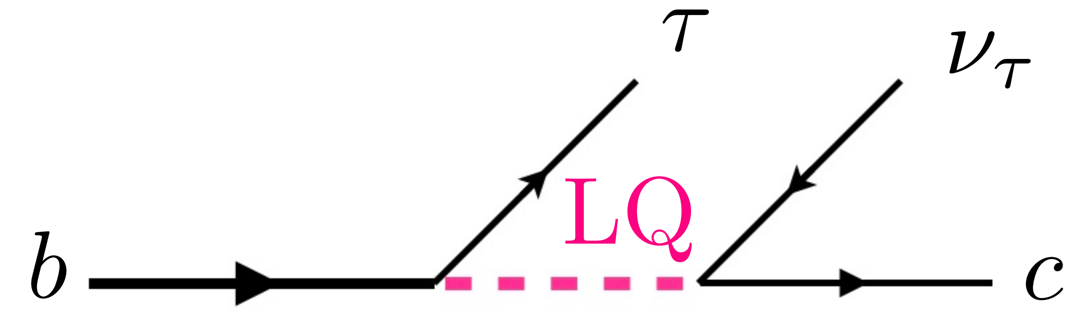
# New physics interpretations of $b \to c\tau\nu$ anomaly




- $W'$ **(additional SU(2) gauge symmetry)**
  - Severely constrained from $\Delta M_s$ ($B_s^0$-$\bar{B}_s^0$ mixing), $W' \to \tau\nu$ search [Abdullah, et al, 1805.01869] and $Z' \to \tau\tau$ search [Faroughy, Greljo, Kamenik, 1609.07138]

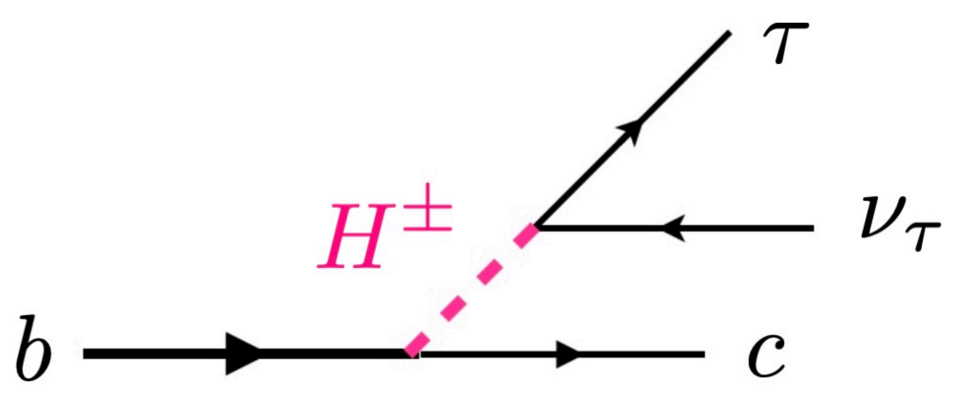



- **Charged-Higgs with generic flavor structure**
  - Constrained from BR($B_c \to \tau\nu$) and $H^\pm \to \tau\nu$ search, but still allowed [Blanke, Iguro, Zhang, 2202.10468; Iguro, 2201.06565, 2302.08935] (next slide)



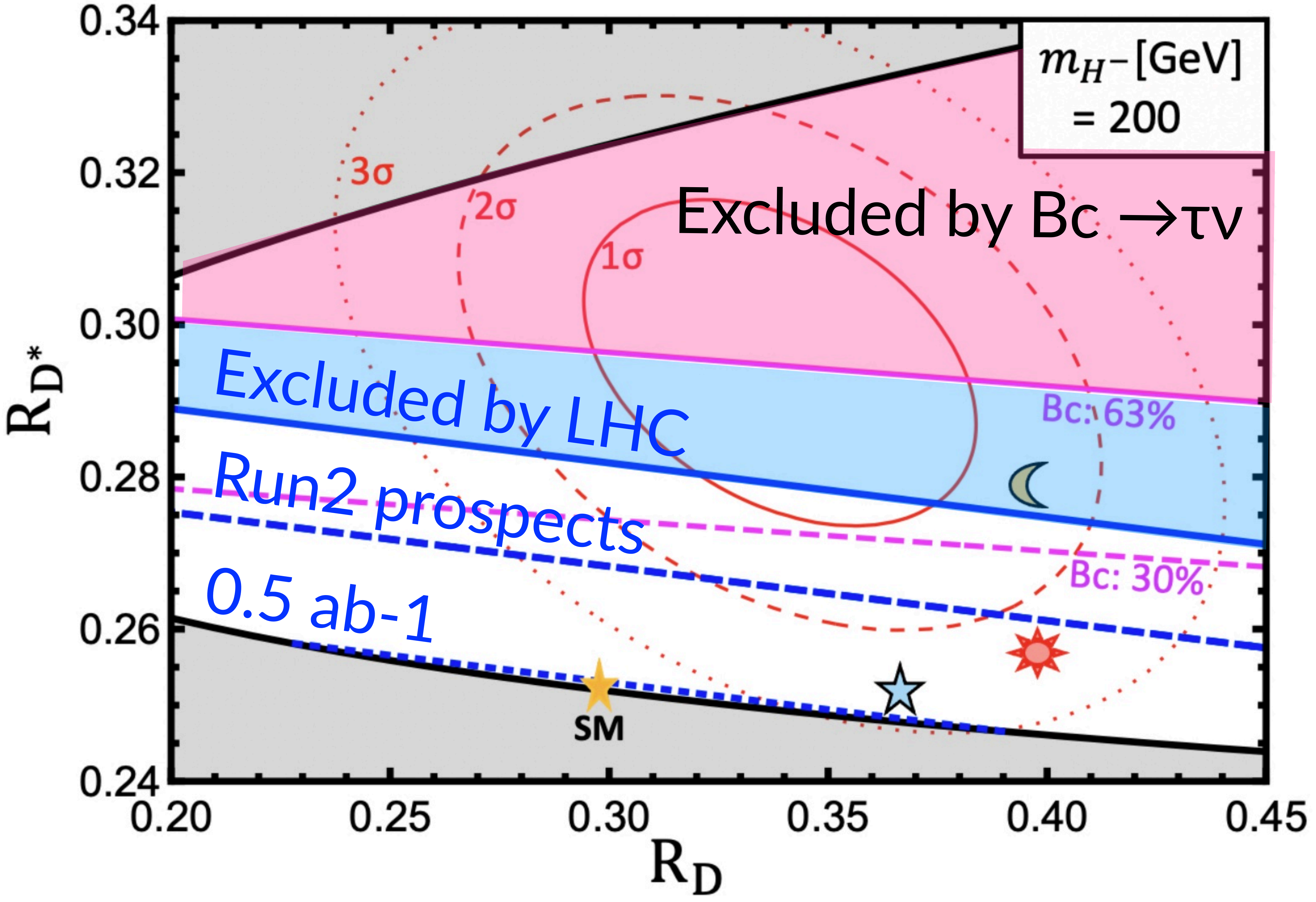

- **Leptoquark (LQ)**
  - Collider bound comes from $pp \to$ LQ LQ$^*$, and broad parameter regions are still allowed

# Charged-Higgs scenario

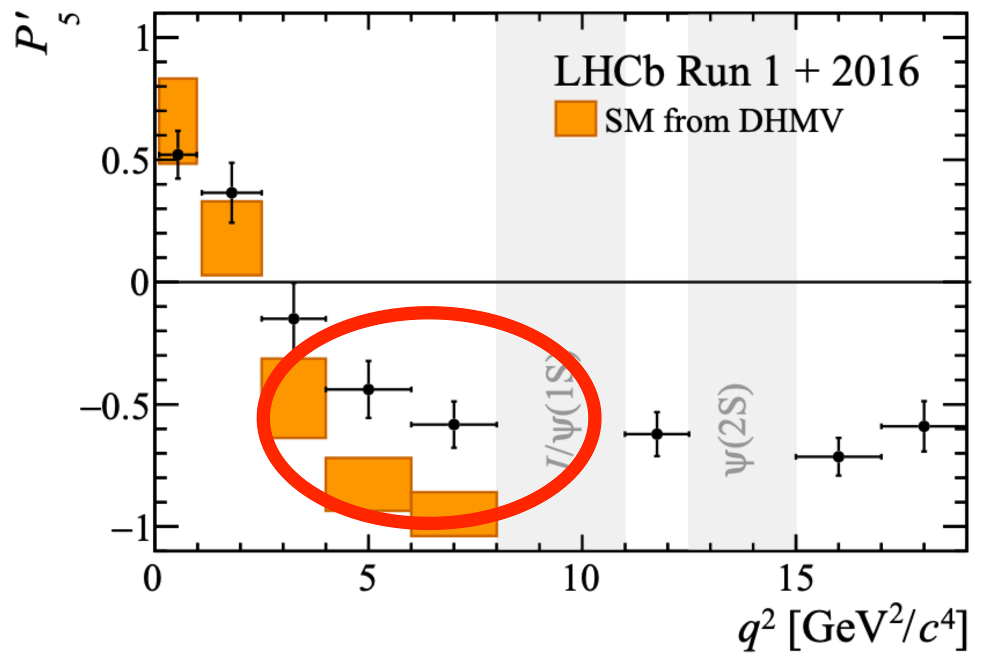



- For heavy charged Higgs, strong LHC bounds come from 2τ +MET, 2b (+γ), 2j, τ +MET (+b);

$m_{H^\pm} \leq 250$ GeV is allowed [Blanke, Iguro, Zhang, 2202.10468; Iguro,2201.06565, 2302.08935]

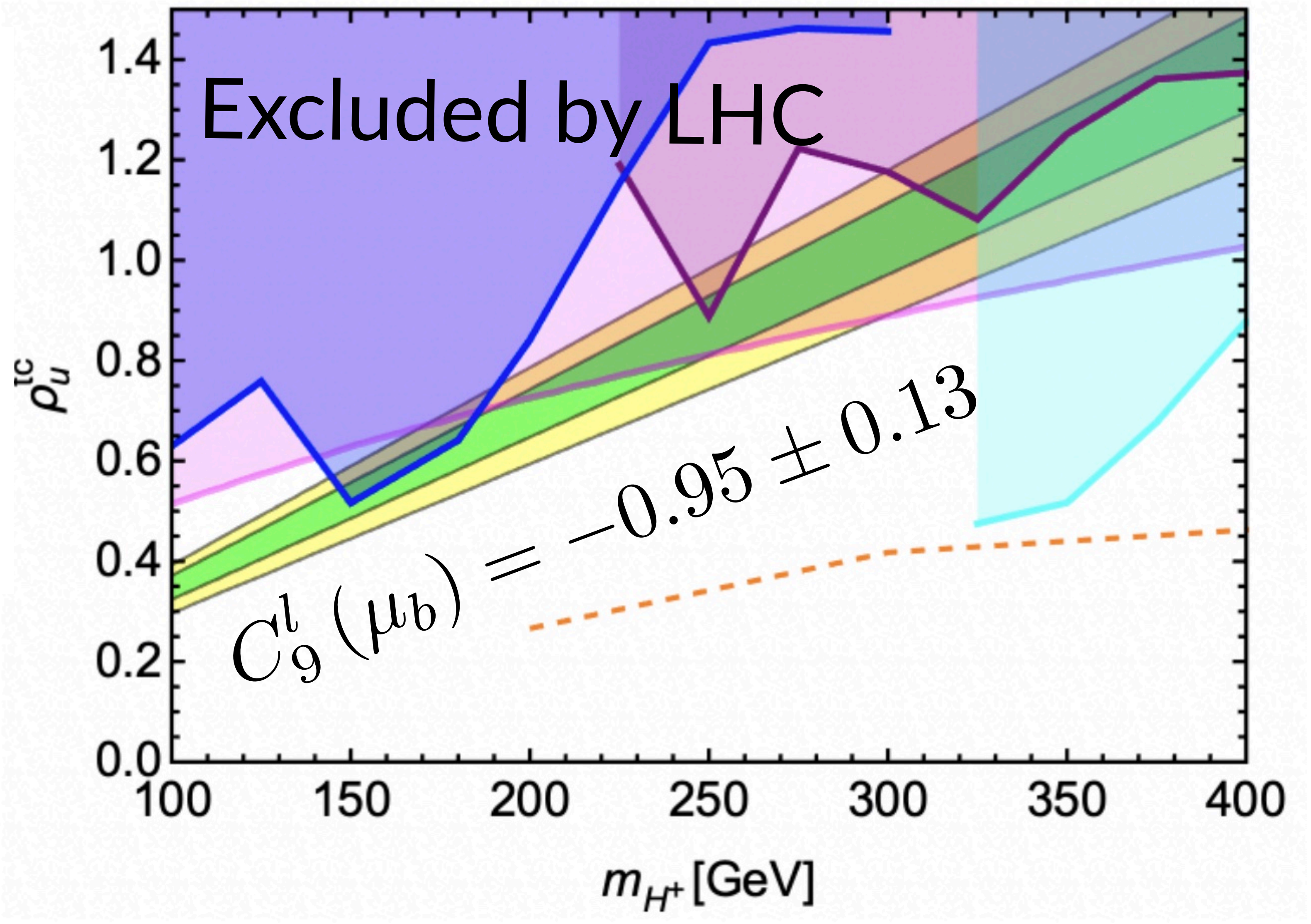



- Unique prediction $F_L(D^*) \gtrsim 0.5,\ P_\tau(D^*) \gtrsim -0.35$
- $P'_5$ anomaly can be solved simultaneously




in $B \to K^*\mu^+\mu^-$

[LHCb, 2003.04831]



# New physics interpretations of $b \to c\tau\nu$ anomaly

[Iguro, TK, Watanabe, 2210.10751 + Iguro, Omura, 2306.00052]

| | | Spin | Charge | Operators | $R_D$ | $R_{D^*}$ | LHC | Flavor |
|---|---|---|---|---|---|---|---|---|
| | $H^\pm$ | 0 | $(\mathbf{1}, \mathbf{2}, 1/2)$ | $O_{S_L}$ | ✓ | ✓ | $b\tau\nu$ | $B_c \to \tau\nu$, $F_L^{D^*}$, $P_\tau^{D^*}$, $M_W$ |
| LQ | $\mathrm{S}_1$ | 0 | $(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$ | $O_{V_L}$, $O_{S_L}$, $O_T$ | ✓ | ✓ | $\tau\tau$ | $\Delta M_s$, $P_\tau^D$, $B \to K^{(*)}\nu\nu$ |
| LQ | $\mathrm{R}_2^{(2/3)}$ | 0 | $(\mathbf{3}, \mathbf{2}, 7/6)$ | $O_{S_L}$, $O_T$, $(O_{V_R})$ | ✓ | ✓ | $b\tau\nu$, $\tau\tau$ | $R_{\Upsilon(nS)}$, $P_\tau^{D^*}$, $M_W$ |
| LQ | $\mathrm{U}_1$ | 1 | $(\mathbf{3}, \mathbf{1}, 2/3)$ | $O_{V_L}$, $O_{S_R}$ | ✓ | ✓ | $b\tau\nu$, $\tau\tau$ | $R_{K^{(*)}}$, $R_{\Upsilon(nS)}$, $B_s \to \tau\tau$ |
| LQ | $\mathrm{V}_2^{(1/3)}$ | 1 | $(\bar{\mathbf{3}}, \mathbf{2}, 5/6)$ | $O_{S_R}$ | ✓ | $2\sigma$ | $\tau\tau$ | $B_s \to \tau\tau$, $B_u \to \tau\nu$, $M_W$ |

Leptoquark (LQ)

They can be deviated from SM

One can distinguish each model by these observables

# Polarization obserbavles

$$P_\tau(D^{(*)}) = \frac{\Gamma\left(B \to D^{(*)}\tau^{\lambda=+1/2}\nu\right) - \Gamma\left(B \to D^{(*)}\tau^{\lambda=-1/2}\nu\right)}{\Gamma\left(B \to D^{(*)}\tau\nu\right)}$$

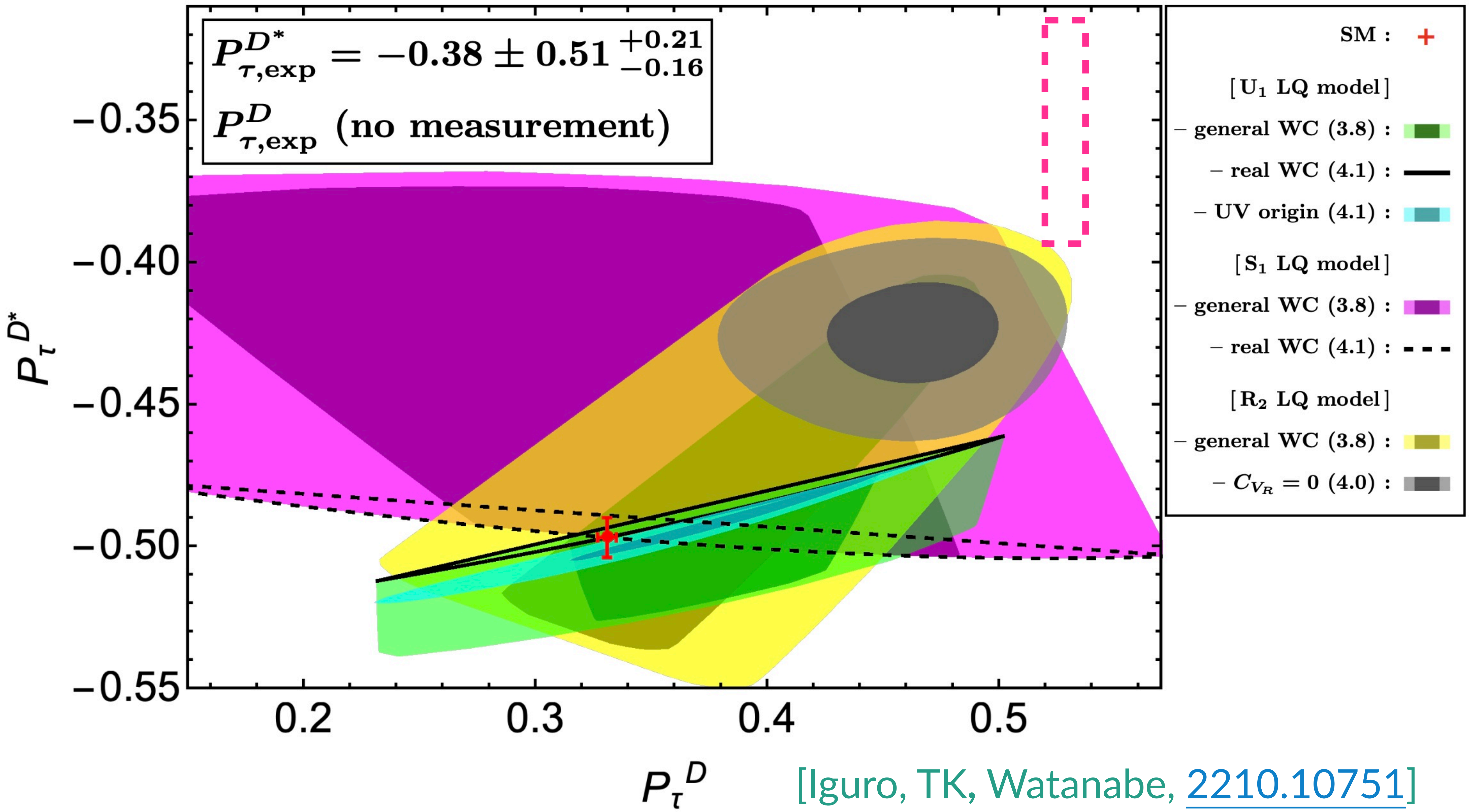
- $\tau$ polarization asymmetry along the longitudinal directions of $\tau$ [$\tau \to \pi\nu,\ \rho\nu$]

  [Tanaka, hep-ph/9411405]

  Fit of an angle dependence: between π/ρ and W*(→τν) in τ rest frame

- Belle II sensitivity is enough to distinguish NP models

Belle II (final) sensitivity




[Iguro, TK, Watanabe, 2210.10751]

# New idea: LFU violation in Upsilon decay

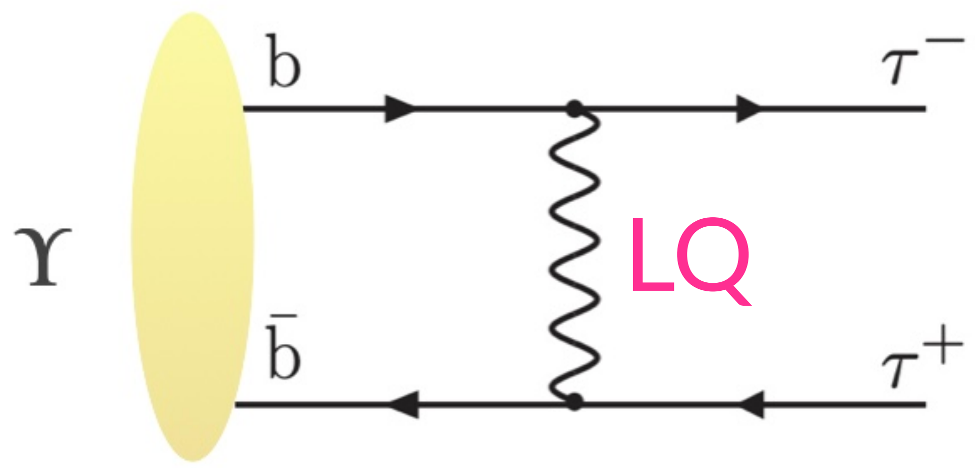
- $\Upsilon(nS)$ [n=1,2,3] leptonic decays can provide new LFU observable ($b\bar{b} \to \tau\bar{\tau}$)

$$R_{\Upsilon(nS)} = \frac{\mathcal{B}(\Upsilon(nS) \to \tau^+\tau^-)}{\mathcal{B}(\Upsilon(nS) \to \ell^+\ell^-)},$$

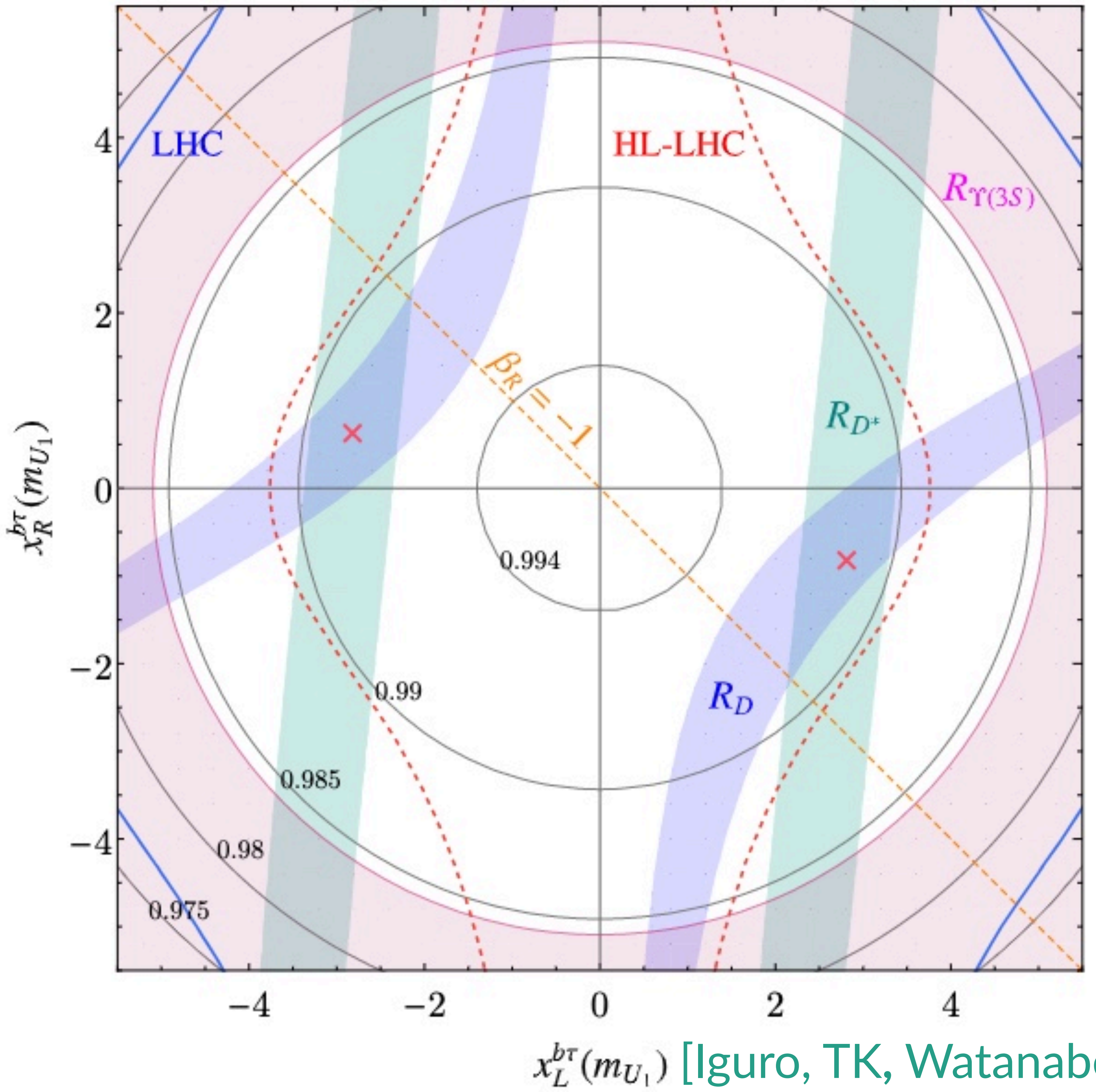
$$R^{\rm SM}_{\Upsilon(3S)} = 0.9948 \pm \mathcal{O}(10^{-5}),$$

$$R^{\rm exp}_{\Upsilon(3S)} = 0.968 \pm 0.016.$$

[CLEO+BaBar data]




Correlation in the $U_1$ LQ scenario




[Iguro, TK, Watanabe, 2210.10751]

- Belle II can measure $R_\Upsilon$ precisely
- less than 1% accuracy is needed

# New idea: sum-rule between $R(\Lambda_c)$ and $R(D^{(*)})$

- Baryonic counterpart ($b \to c\tau\nu$) : $\mathcal{R}(\Lambda_c) = \dfrac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \ell^- \bar{\nu}_\ell)}$

- There is a **model-independent sum-rule** for R(D), R(D*), and $R(\Lambda_c)$, through new physics form factor analysis (originated from heavy quark symmetry)

$$\frac{R(\Lambda_c)}{R(\Lambda_c)_{\rm SM}} \simeq 0.28 \frac{R(D)}{R(D)_{\rm SM}} + 0.72 \frac{R(D^*)}{R(D^*)_{\rm SM}}$$

[Fedele, et al, 2211.14172 ]

It can crosscheck of $R(D^{(*)})$ anomaly by coherent amplification of $R(\Lambda_c)$

R(D(*)) anomaly data →

$$R(\Lambda_c) = 0.380 \pm 0.012_{R(D^{(*)})} \pm 0.005_{\rm FF}$$

$$R(\Lambda_c)_{\rm SM} = 0.324 \pm 0.004$$

$$R(\Lambda_c)_{\rm exp} = 0.242 \pm 0.075$$

[LHCb, 2201.03497]

Currently, a slight (~2σ) inconsistency appeared

# $R(D^{(*)})$ requires CPV and EDM via LQ

[Iguro, TK, 2307.11751]

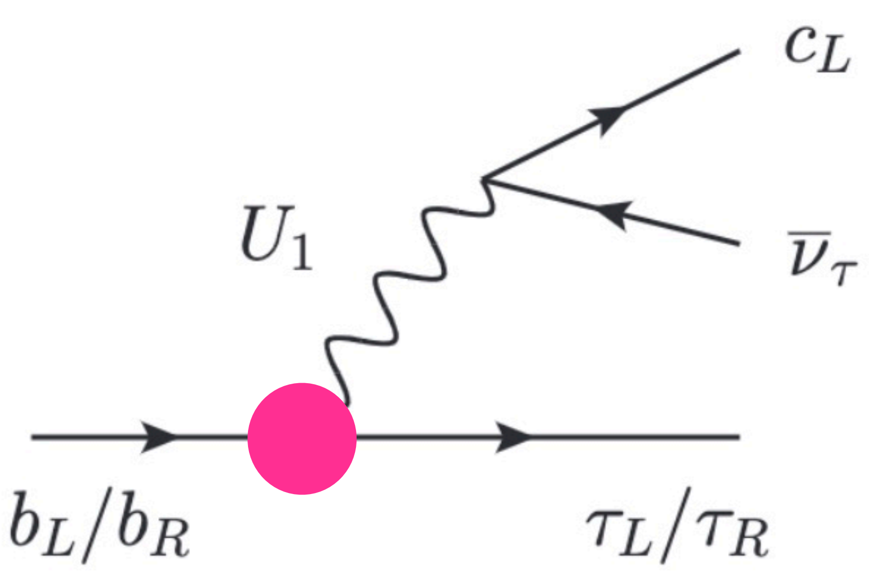
[Babu, et al, 2009.01771; Bečirević, at al, 2206.09717; Kirk, Okawa, Wu, 2307.11152]

- Generally, LQ-Yukawa contains CPV phase: $\mathcal{L} = \left( Y_L \bar{Q}_i \gamma_\mu P_L L_3 + Y_R \bar{b} \gamma_\mu P_R \tau \right) U_1^\mu$
- Interestingly, a certain LQ provides robust correlation of the CPV phase with $R(D^{(*)})$
- For $U_1$ vector LQ case, single CPV phase $\phi_R$ is predicted ( one can set $\phi_R = \mathrm{Arg}[(Y_R)_{33}]$ )

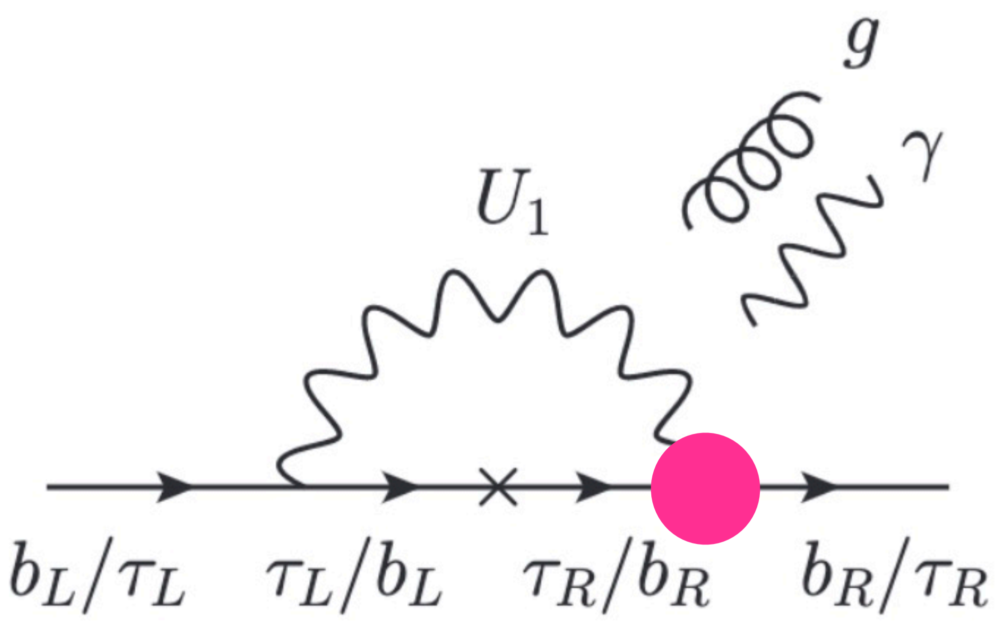
When UV model is 3rd-generation-philic gauge symmetry with universal (L=R) gauge coupling:

Tree-level matching condition: $C_{S_R}(\Lambda_{\mathrm{LQ}}) = -2 e^{i\phi_R} C_{V_L}(\Lambda_{\mathrm{LQ}})$

$$O_{V_L} = (\bar{c}\gamma^\mu P_L b)(\bar{\tau}\gamma_\mu P_L \nu_\tau),$$
$$O_{S_R} = (\bar{c} P_R b)(\bar{\tau} P_L \nu_\tau).$$




$R(D^{(*)})$




(C)EDMs

Leading contribution to neutron EDM is the Weinberg operator (comes from bottom CEDM) [Haisch, Hala, 1909.08955]

CPV in $b \to s\gamma$ would be interesting as well

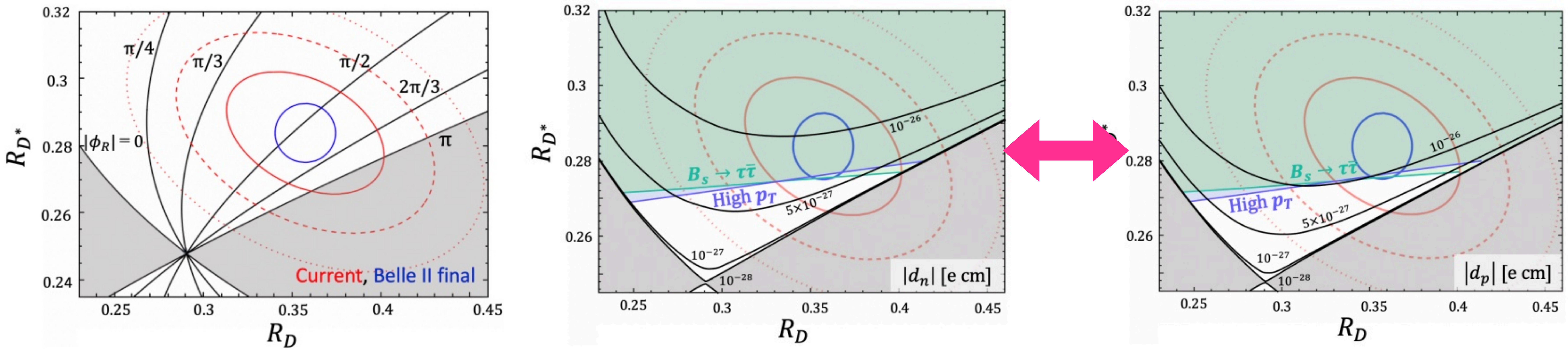
# $R(D^{(*)})$ requires CPV and EDM via LQ

[Iguro, TK, 2307.11751]

[Babu, et al, 2009.01771; Bečirević, at al, 2206.09717; Kirk, Okawa, Wu, 2307.11152]

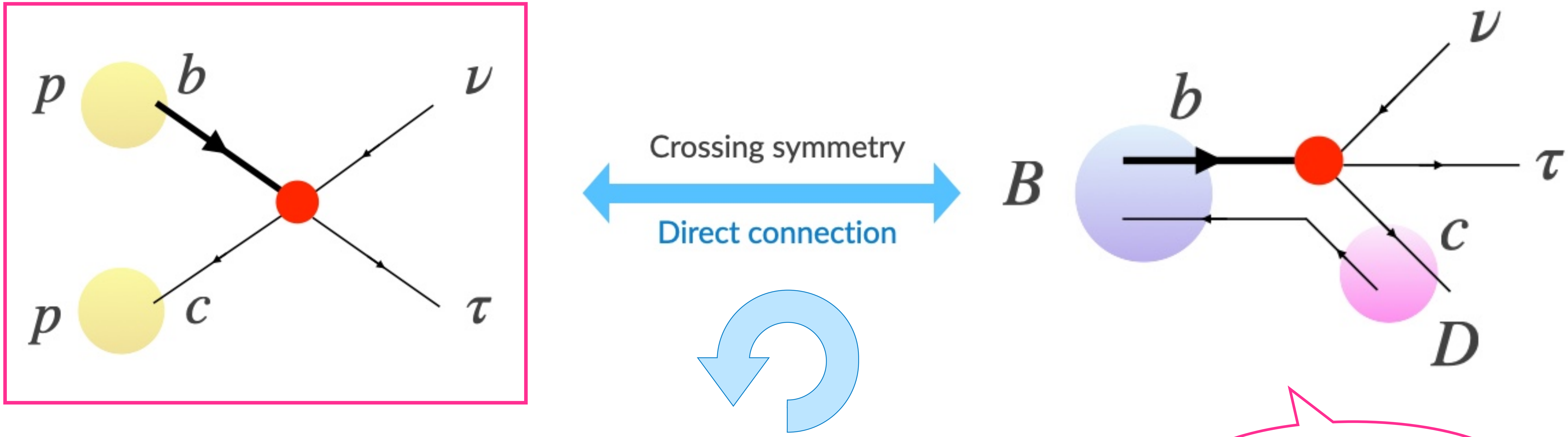
- Since $R(D^{(*)})$ is CPC observable, it depends on $\cos\phi_R$, while EDMs depend on $\sin\phi_R$
- There is a robust relation:

CPV phase dependence | neutron EDM sensitivity | proton EDM sensitivity




Opposite signs within reaches of the future prospects

- $|d_e| < 10^{-32}\ e\,$cm → null electron EDM is predicted




non-resonance search

→ **new study direction**

B anomaly!

# Leptoquark indirect collider search

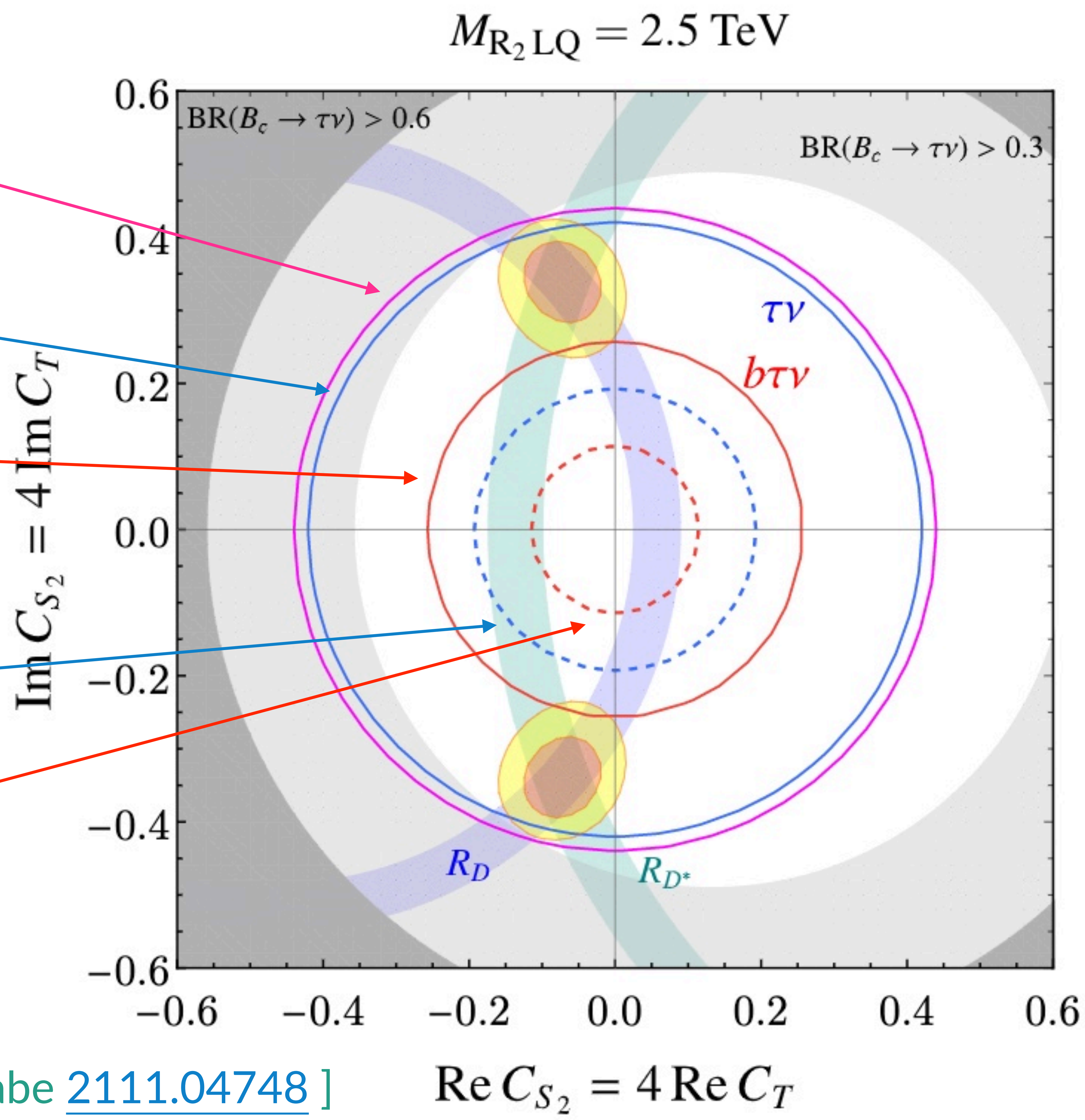
τ+MET search
36fb$^{-1}$ exclusion

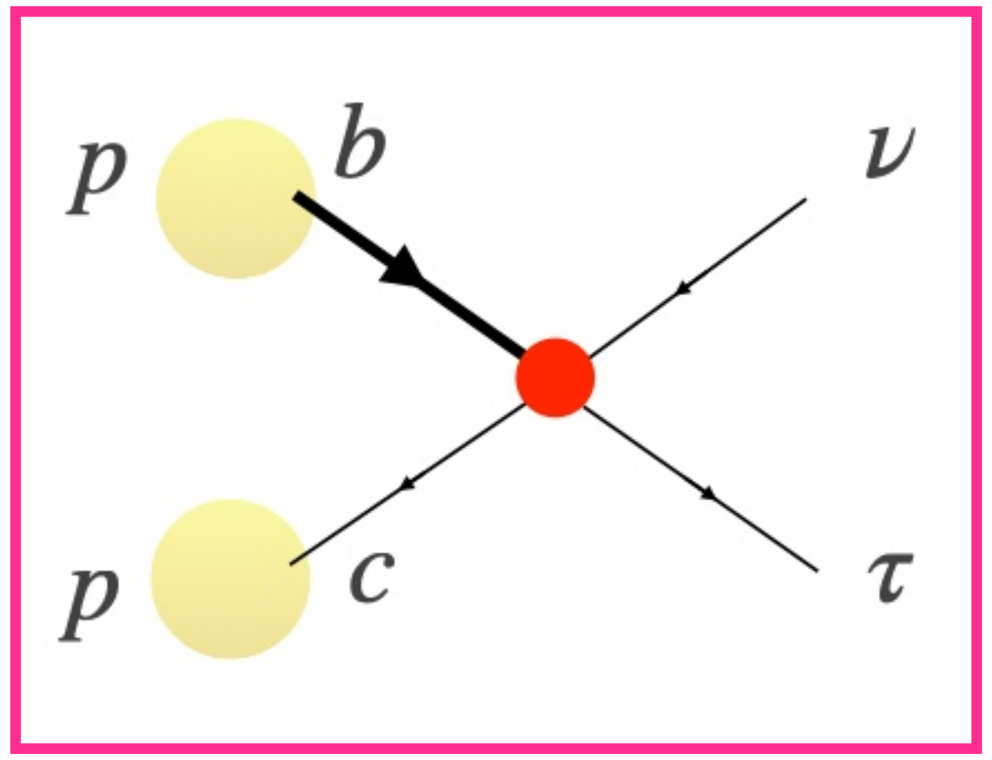
τ+MET search
139fb$^{-1}$ sensitivity

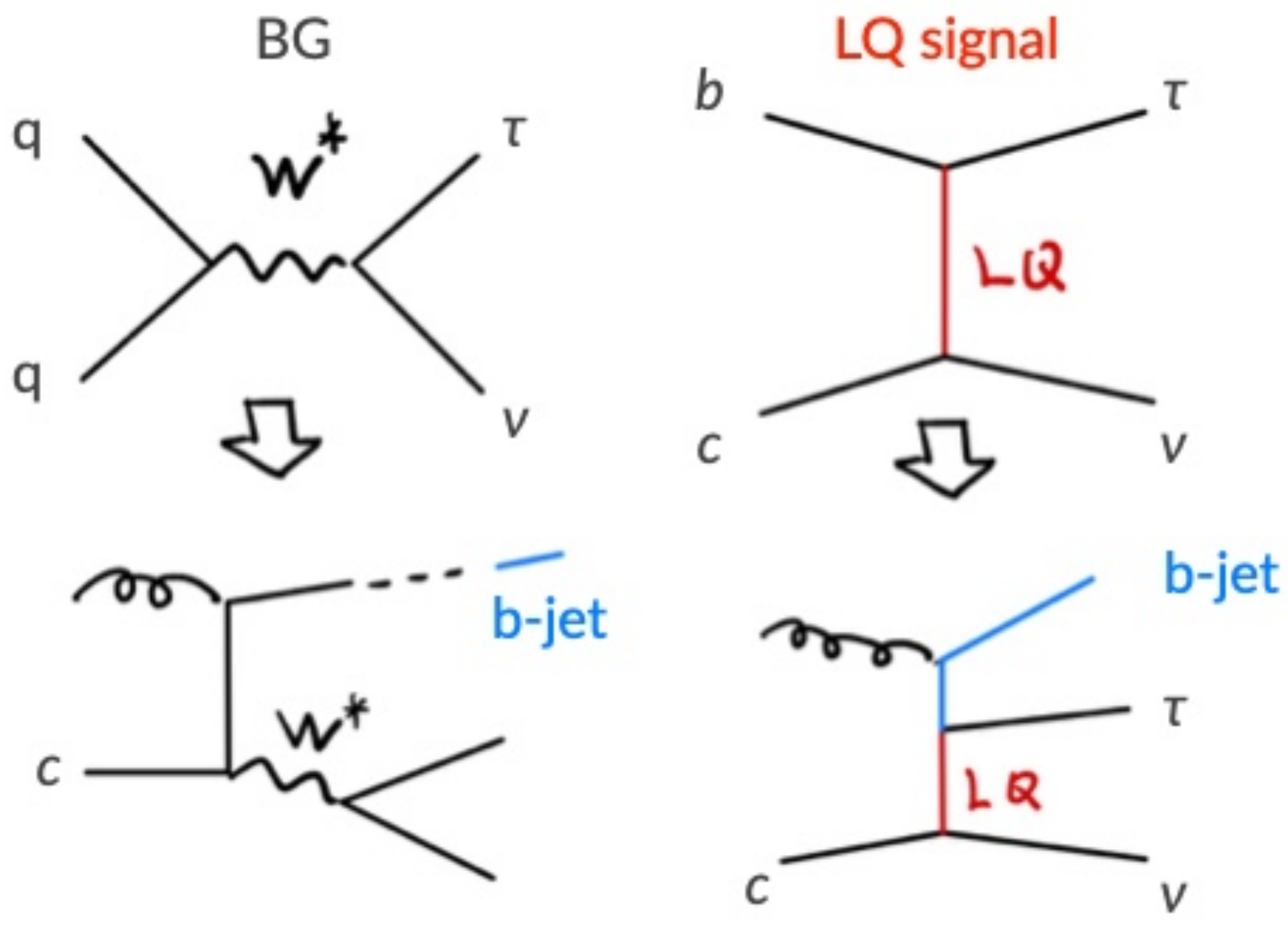
τ+MET+b search
139fb$^{-1}$ sensitivity

τ+MET search
3000fb$^{-1}$ sensitivity

τ+MET+b search
3000fb$^{-1}$ sensitivity



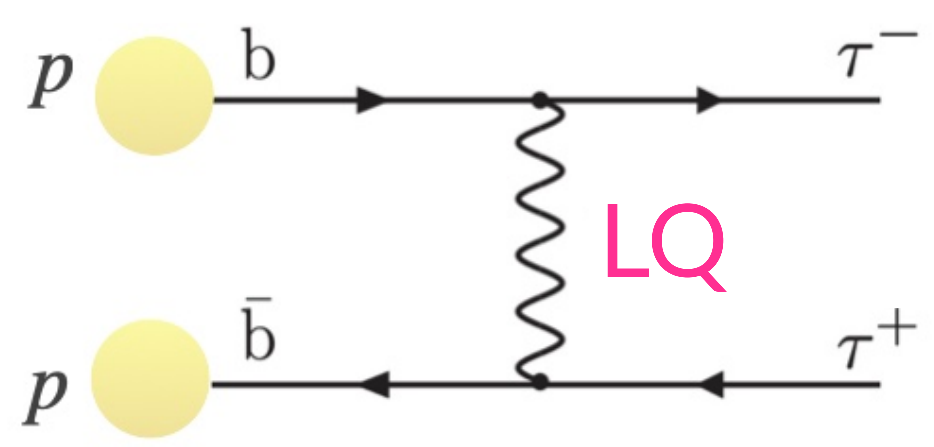




+b jet suppresses only bkg

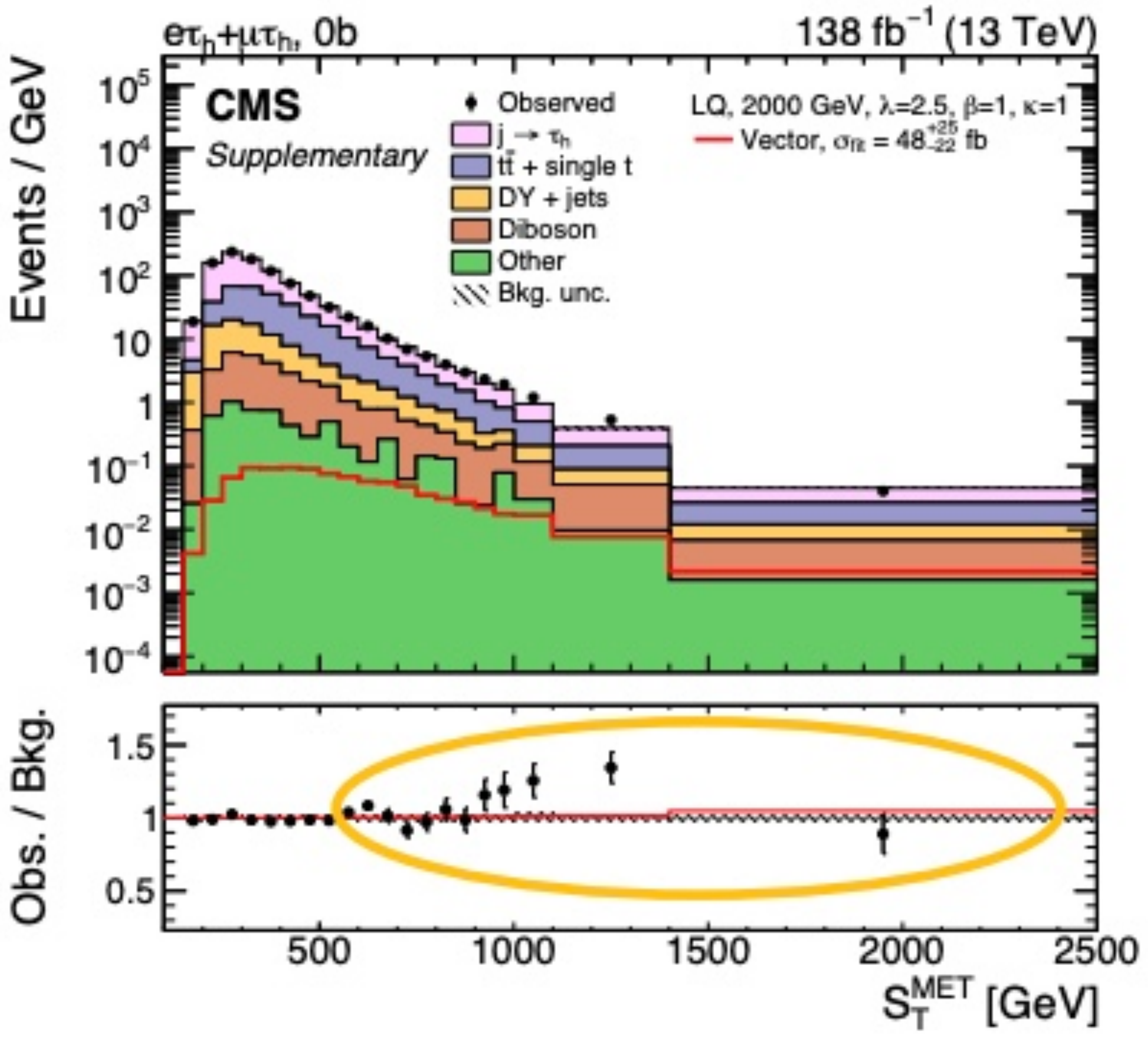
R$_2$ LQ scenario can be probed by bτ+MET search with Run 2 data

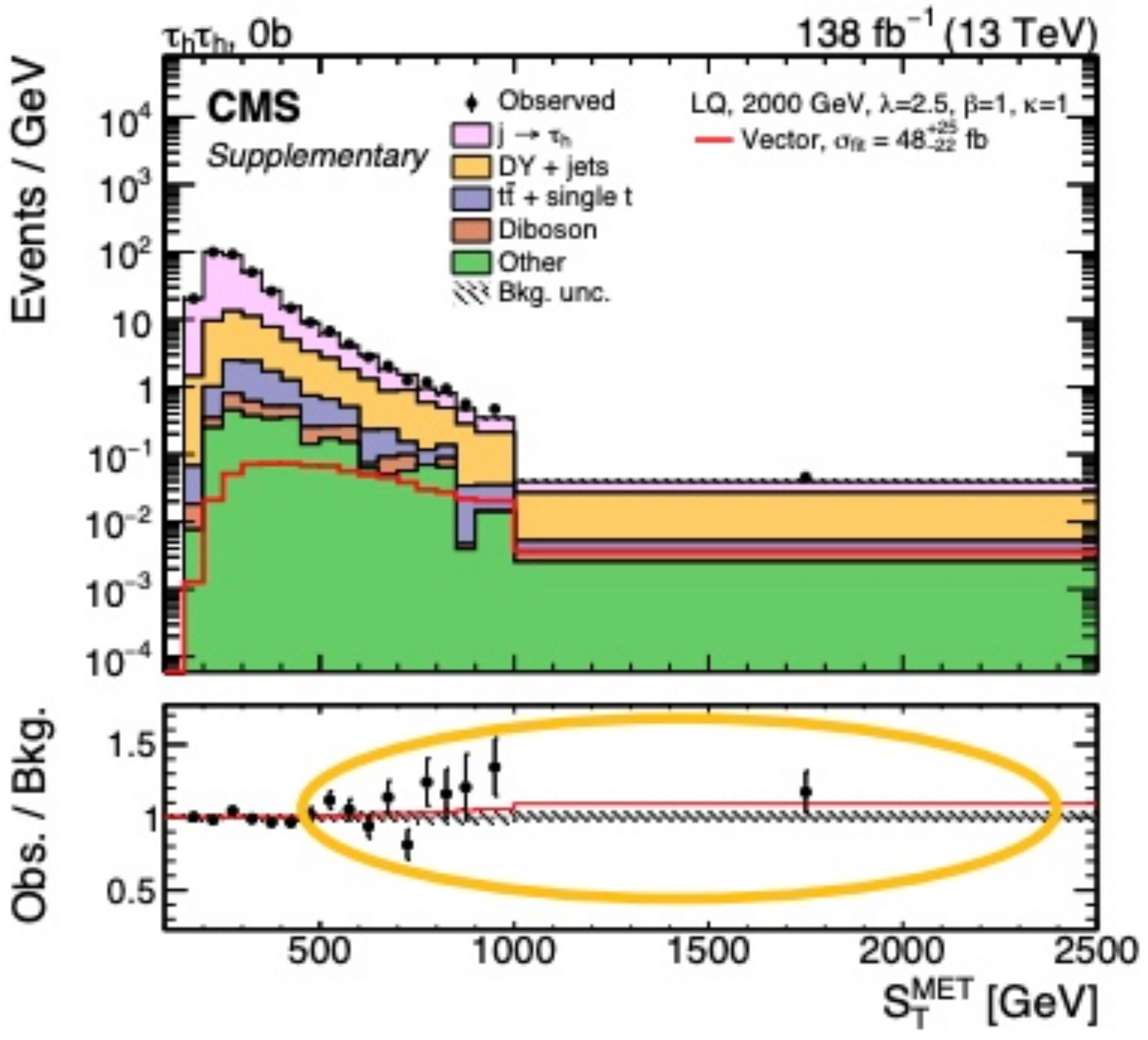
[Endo, Iguro, TK, Takeuchi, Watanabe 2111.04748 ]

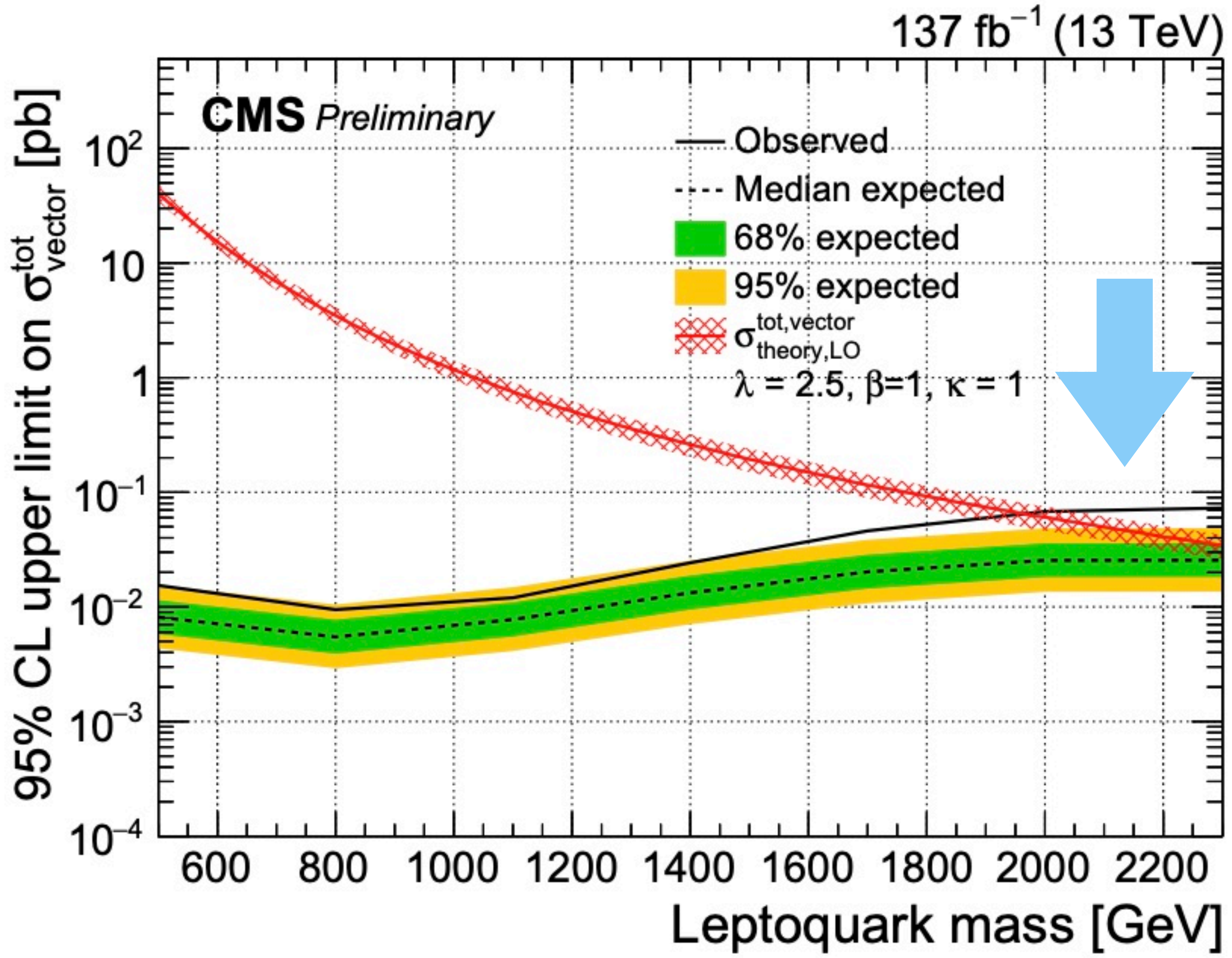
# CMS new LQ-type excess




$$pp \to \tau^+\tau^- + 1\text{jet} + 0b$$




3.4—3.7σ level excess at $M_{\rm LQ} \sim 2$ TeV @ CMS

In additional b-tag category, there is no excess [CMS, CMS-PAS-EXO-19-016 (2022); LeptonPhoton2023 update]

# Topic2: $B \to K\ell\ell$ (excess?)

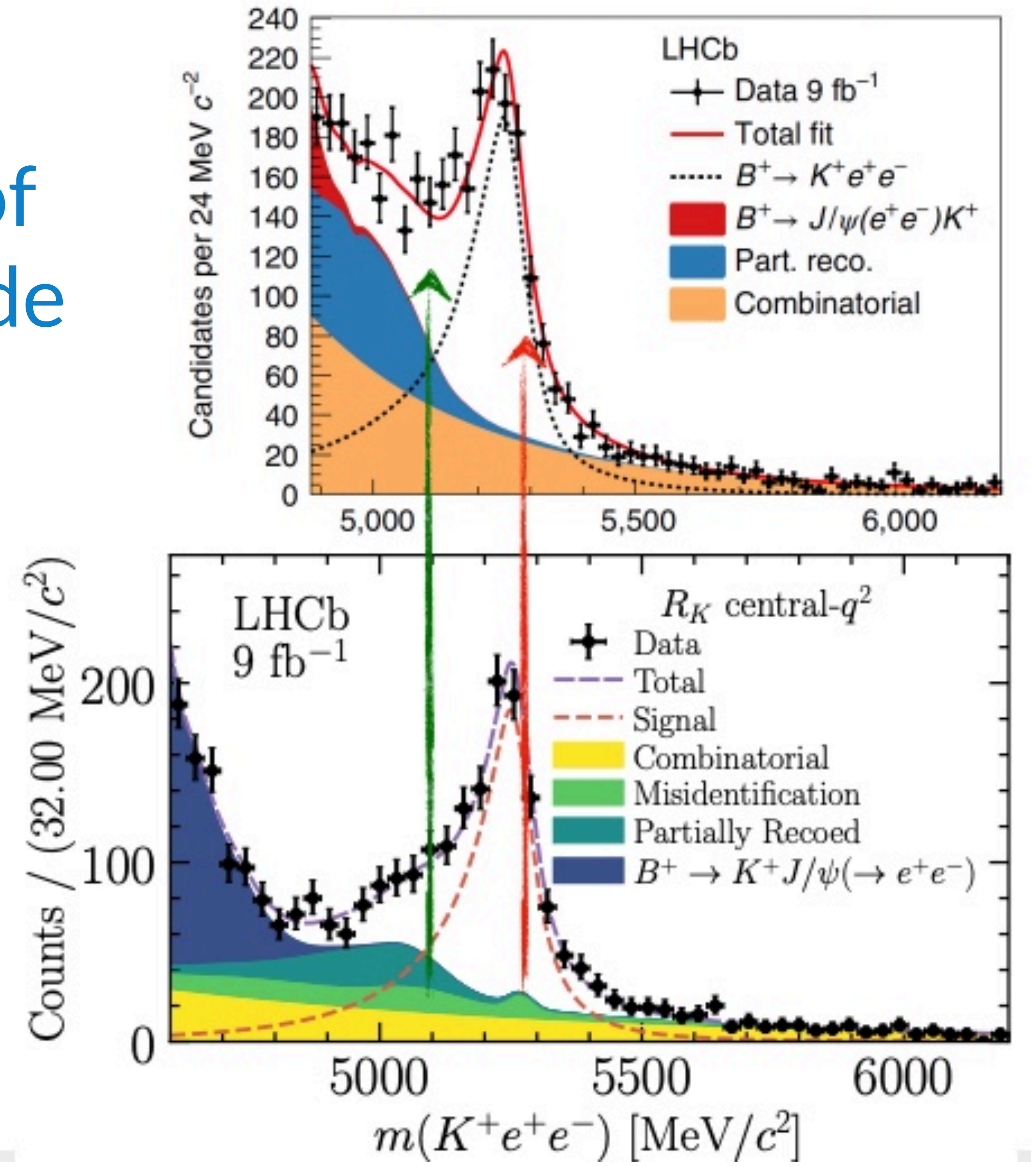
# Another LFU observables: $R(K)$ and $R(K^*)$

$$R(K^{(*)}) = \frac{\mathrm{BR}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{BR}(B \to K^{(*)}e^+e^-)}$$

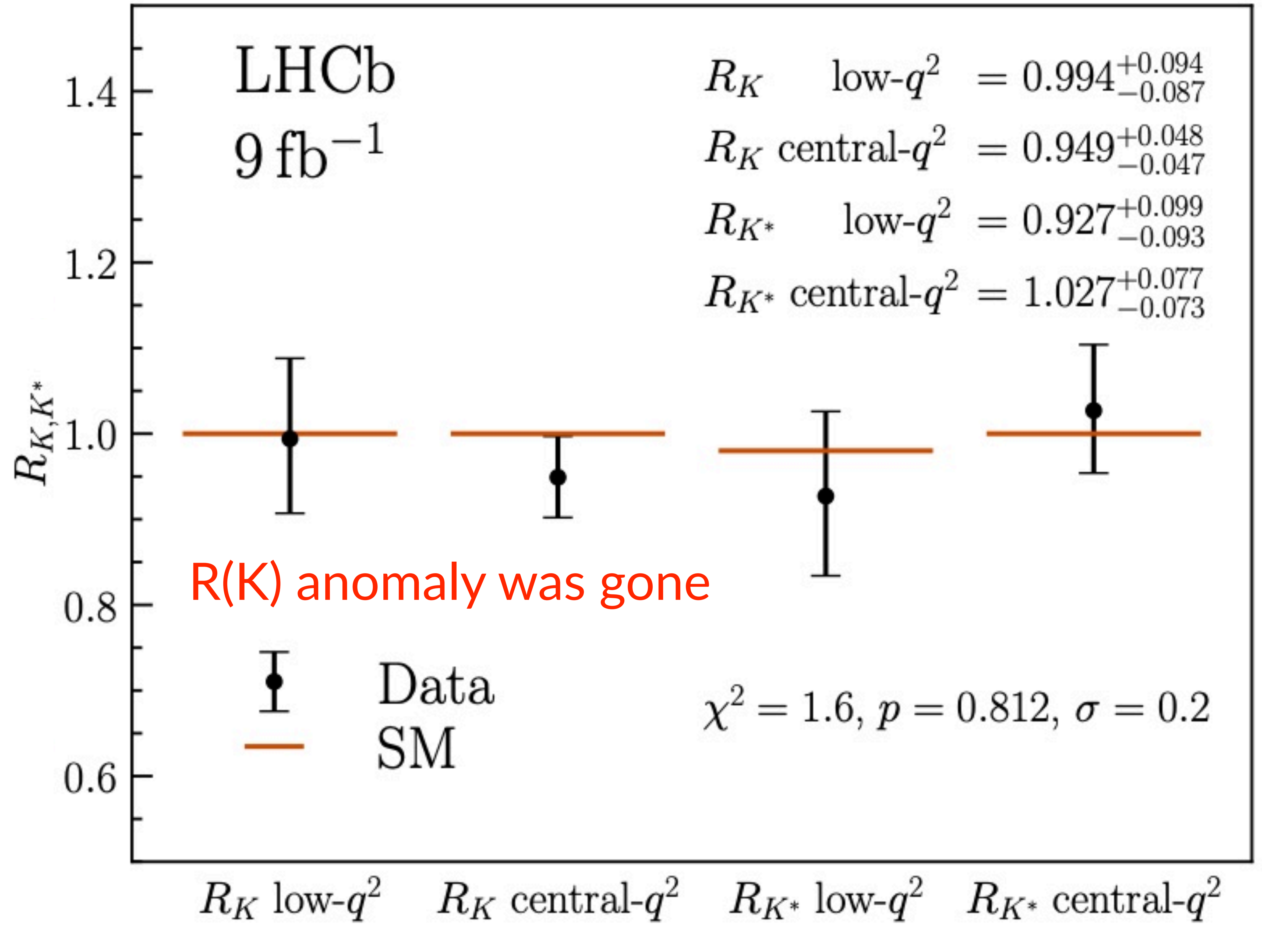
Bkg estimation of the electron mode was improved drastically

$B \to K\pi^+\pi^-$

with $\pi \rightsquigarrow e$



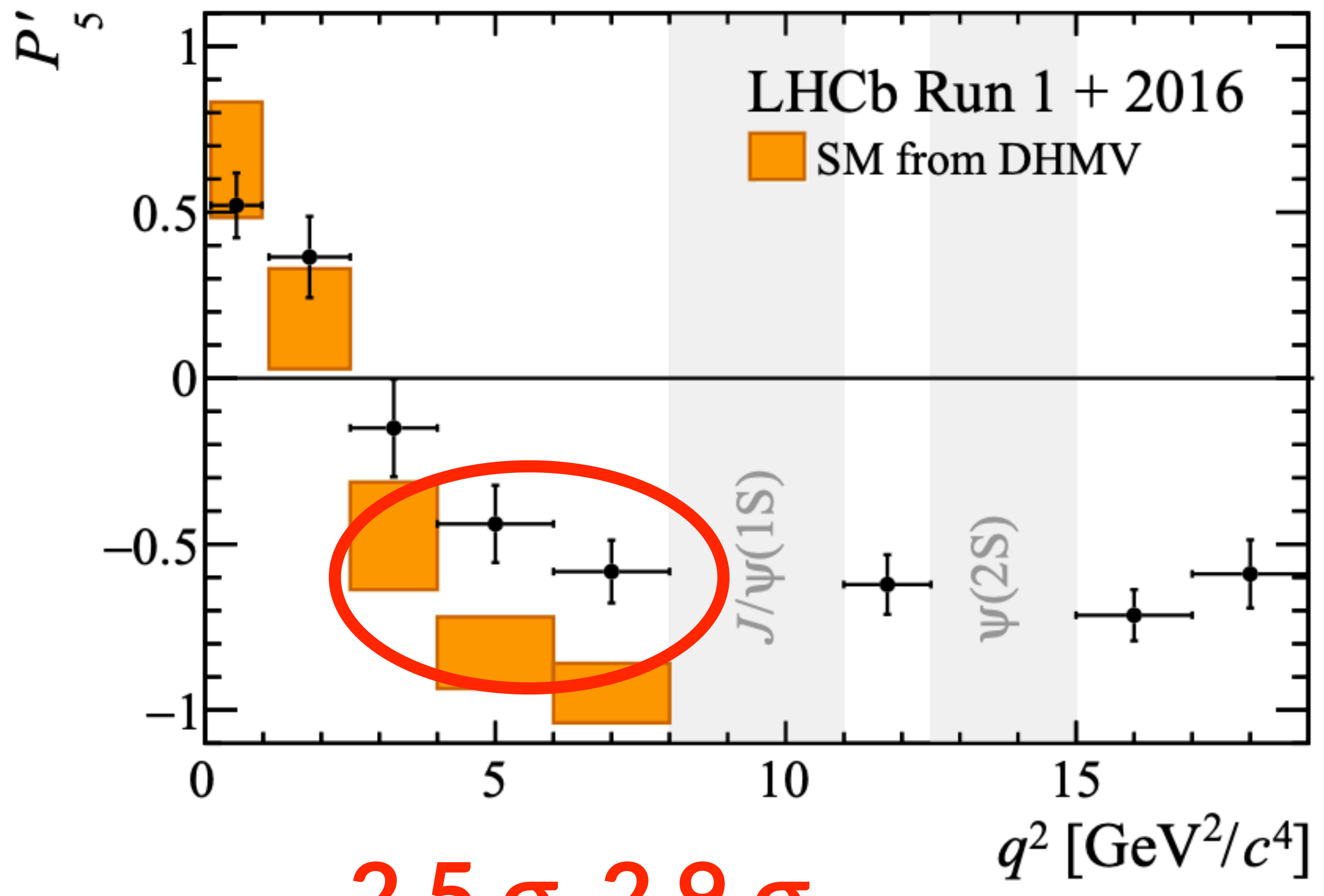

[LHCb Run1+2, 2212.09152]



# $b \to s\mu^+\mu^-$ data are still deviated

## $B \to K^*\mu^+\mu^-$

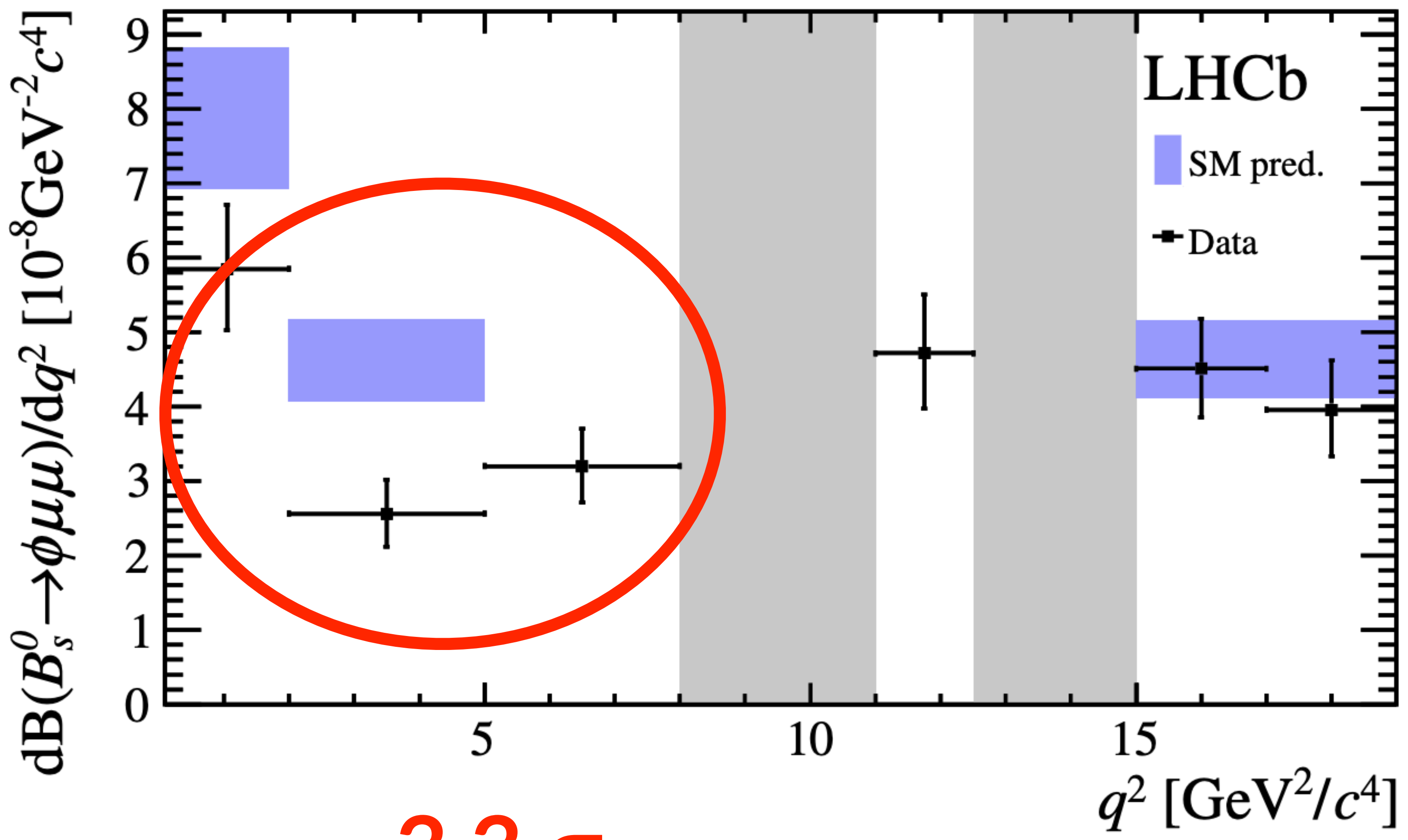
[LHCb, 2003.04831]




**2.5 σ, 2.9 σ**

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

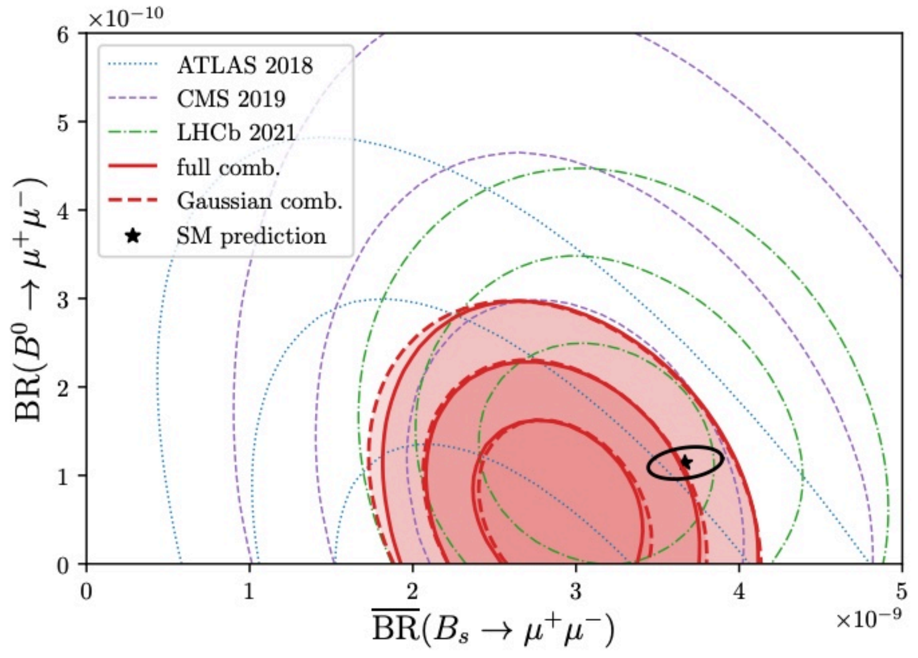
[LHCb, 1506.08777]

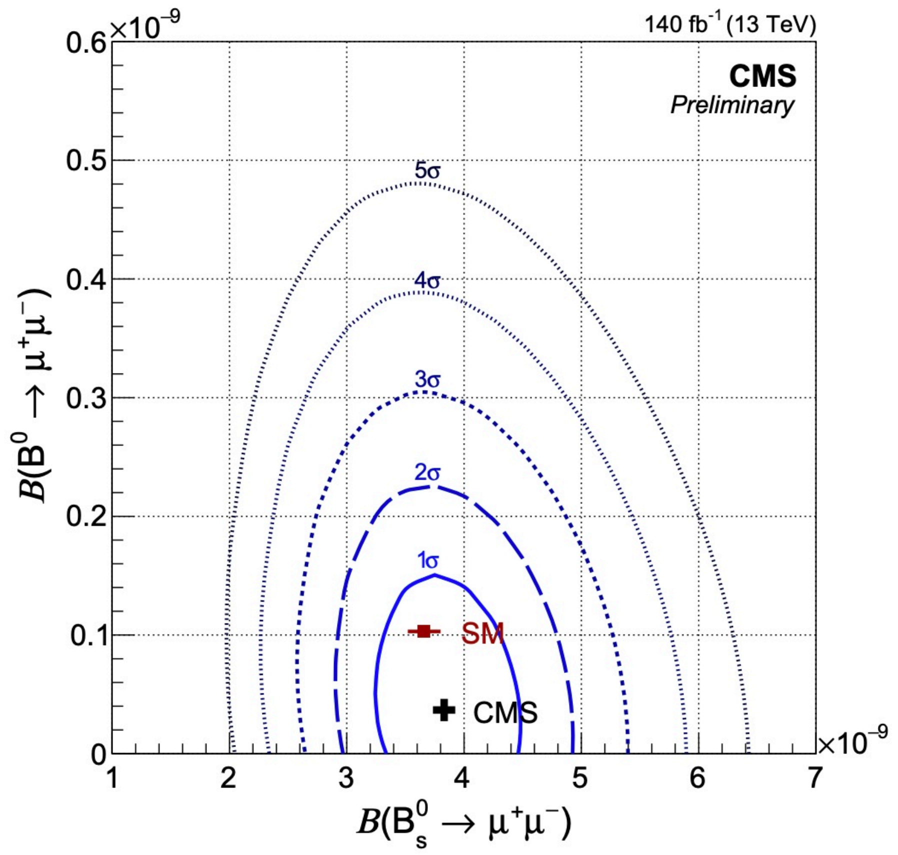



**3.3 σ**

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

[Altmannshofer, Stangl, 2103.13370]




gone

[CMS, ICHEP2022]

New HFLAV average

$$\mathrm{BR}(B_s \to \mu^+\mu^-) = (3.45 \pm 0.29) \cdot 10^{-9}$$

- Angular distribution of $\Lambda_b \to \Lambda\mu^+\mu^-$ [K6] is also deviated

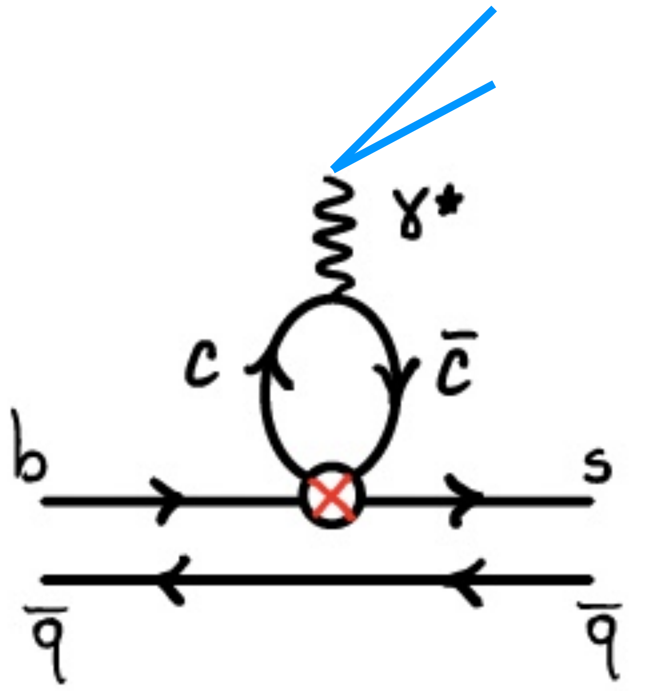
**at 2.6 σ** [LHCb, 1808.00264]

Lepton *universal* ($e = \mu$) NP is still preferred

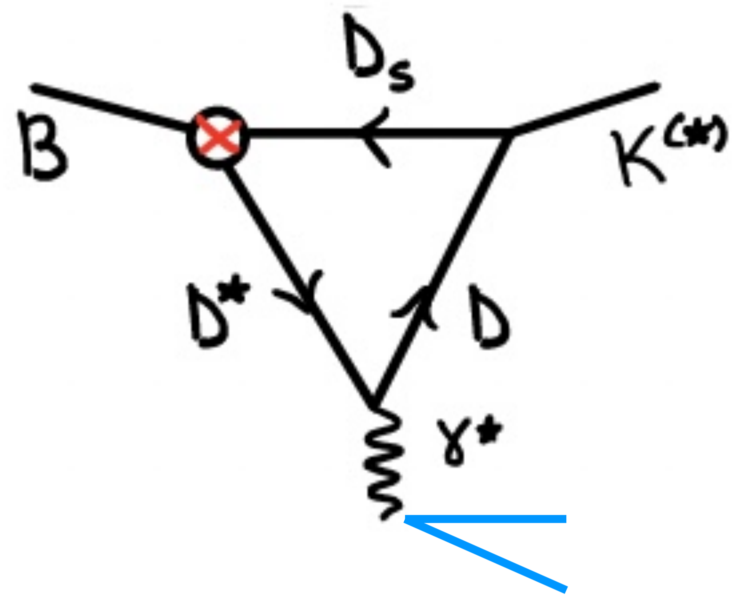
# Global fit of $b \to s\mu^+\mu^-$ data

- QCD long-distance effects are crucial

off-shell $J/\Psi$




charm-penguin

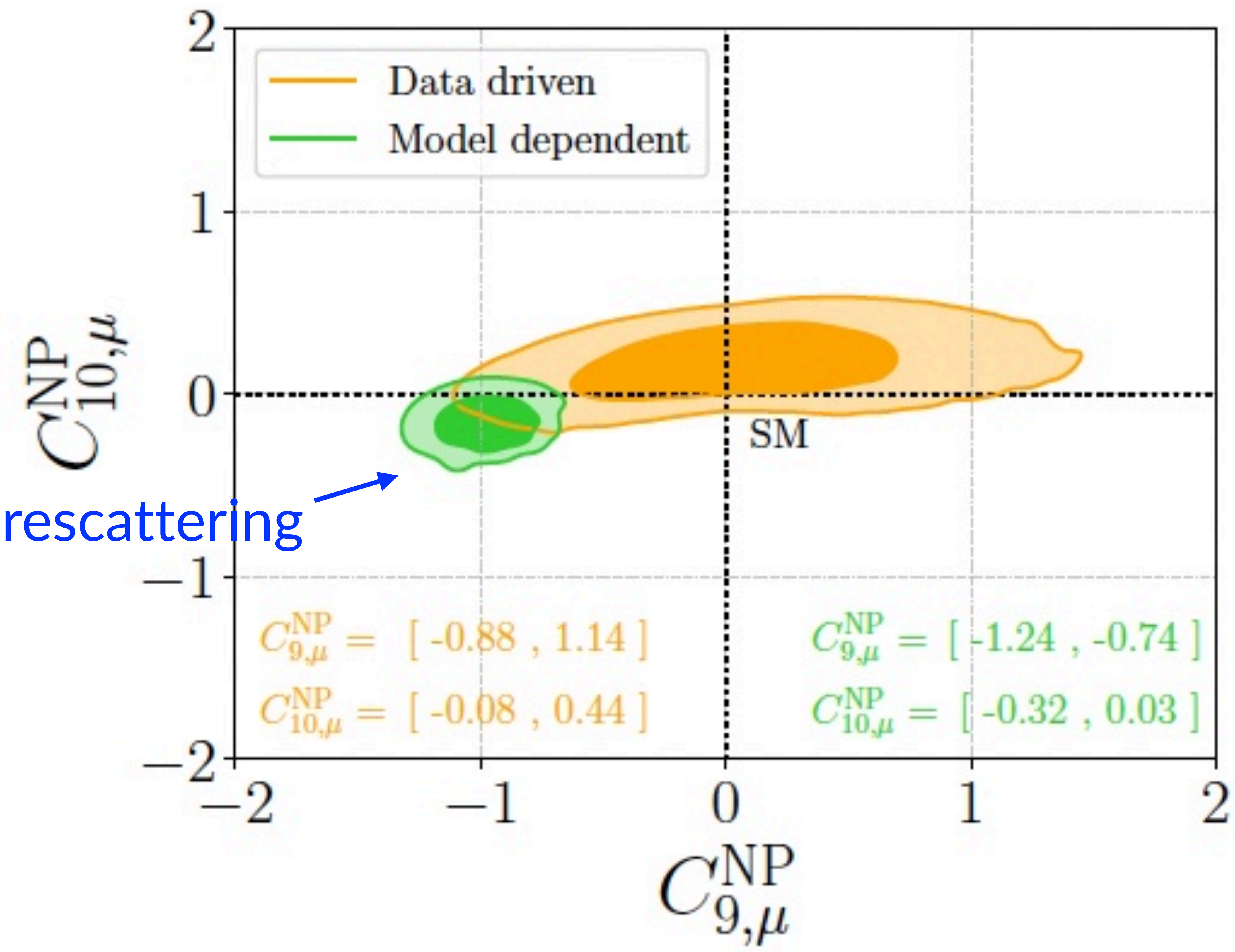



rescattering effect

- The rescattering effect can also be understood as the LFU NP contribution

rescattering effect $\simeq C^{\text{NP}}_{9,\text{universal}} = -\mathcal{O}(1)$

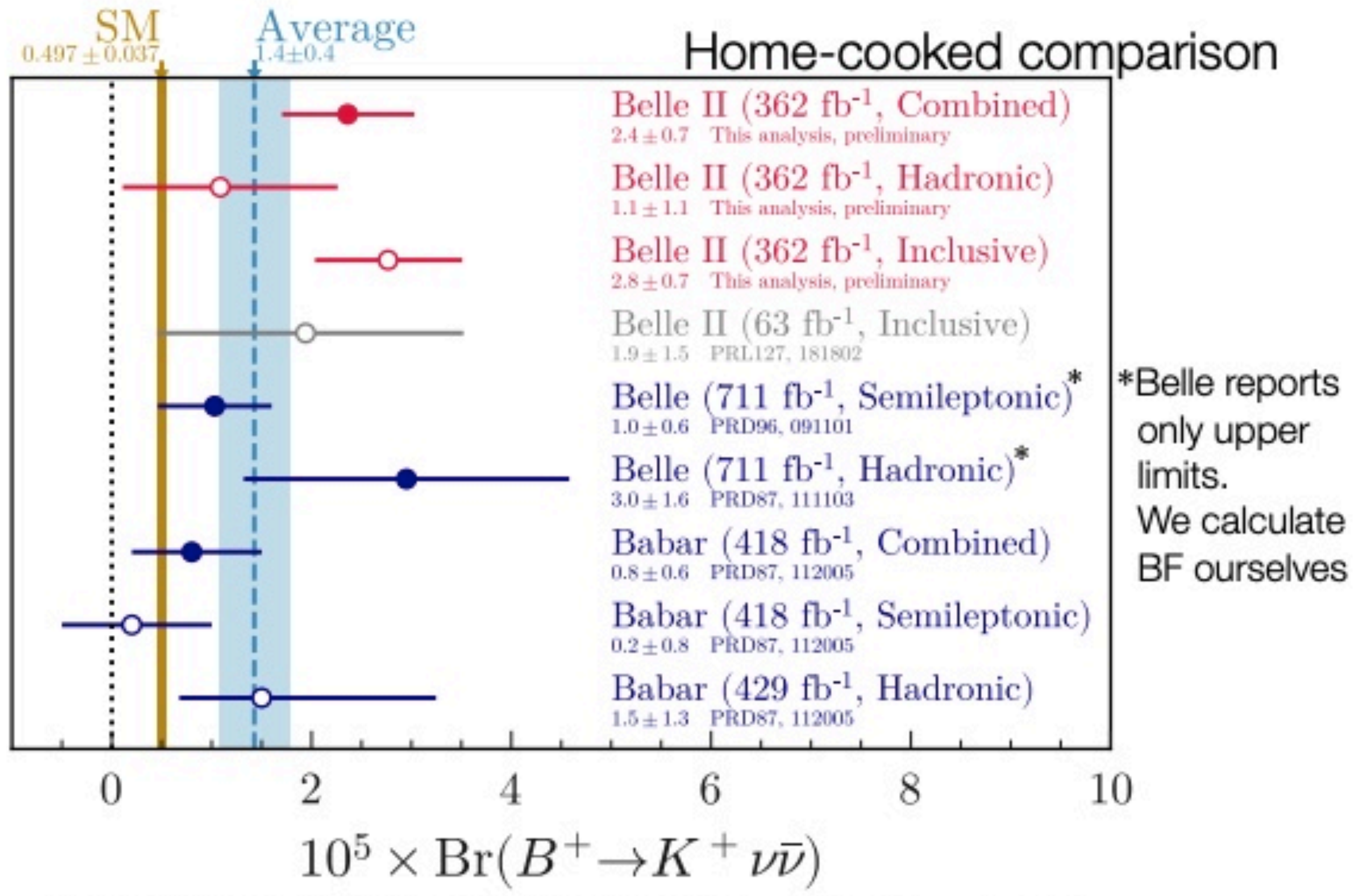
[Ciuchini, et al, 2212.10516]



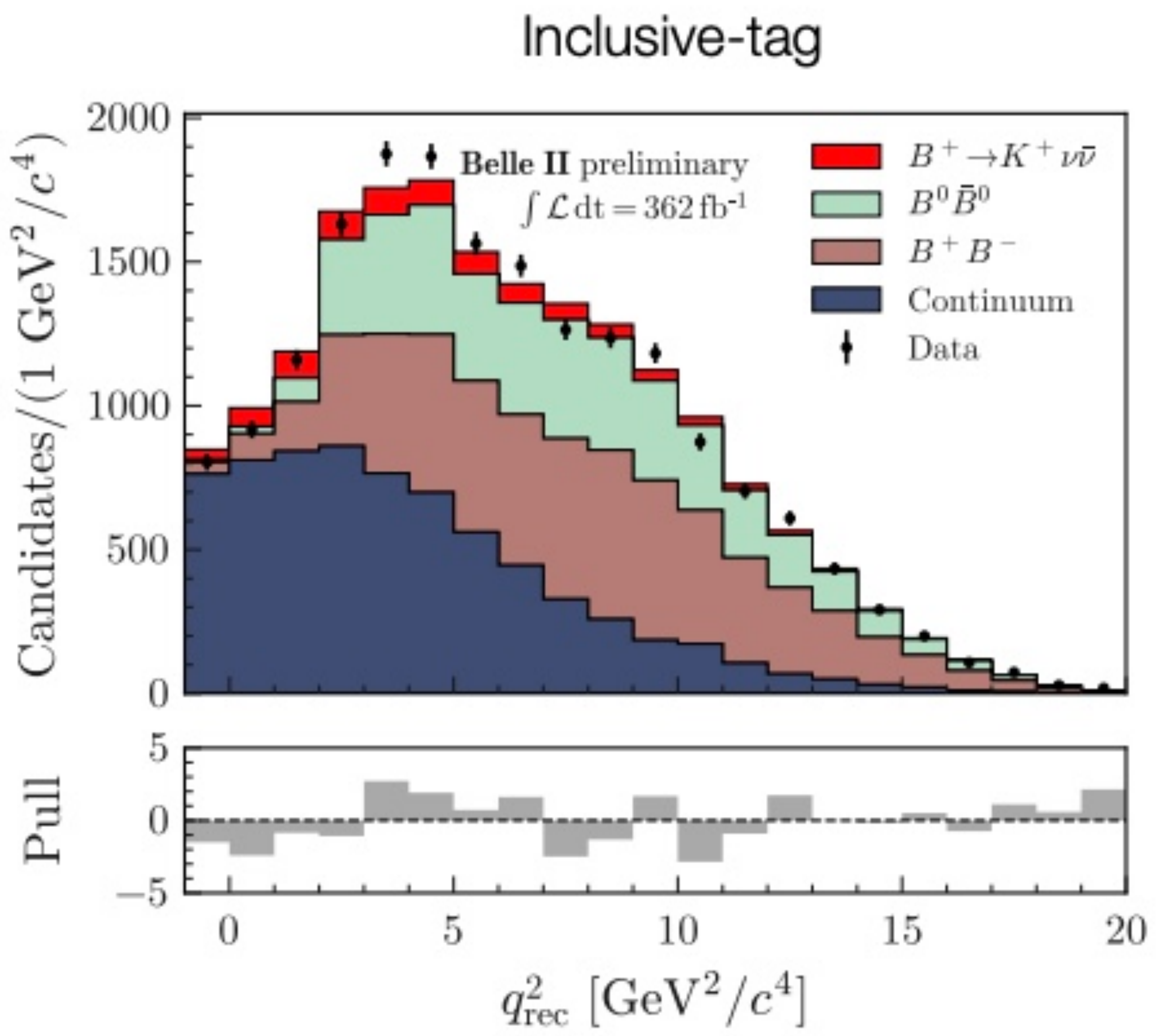

no rescattering

# New excess? in $B^+ \to K^+\nu\bar{\nu}$

- Belle II announced the result of BR$(B^+ \to K^+\nu\bar{\nu})$, which is 2.8σ above from the SM
- Then, the world average (Belle+Belle II+BaBar) gives 2.2σ above from the SM




[Belle II, EPS-HEP2023]




heavy Z' global fit:

When LF is conserved but LFU is violated

BR$(B^+ \to K^+\nu\bar{\nu}) \lesssim 1.1$ SM value

When both LF and LFU are violated $(\nu_i\bar{\nu}_j)$, Belle II data can be accommodated

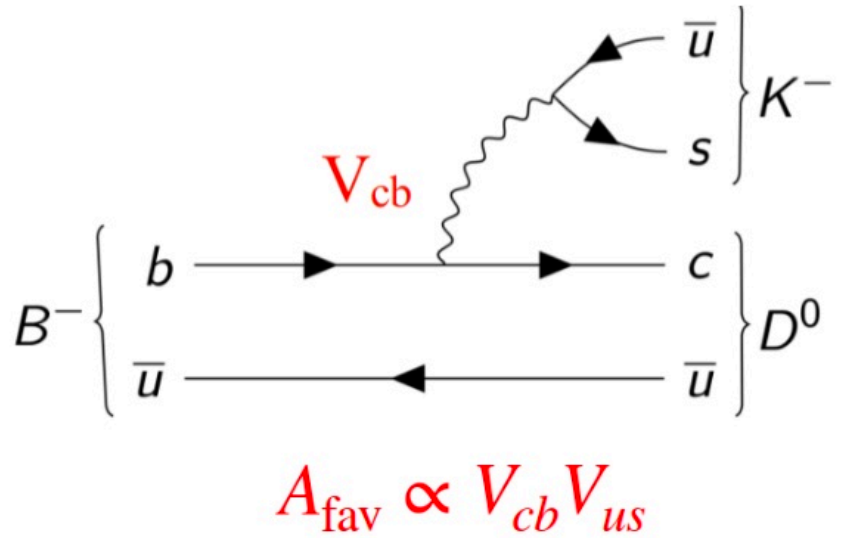
$B_s \to e\mu$ is smoking-gun

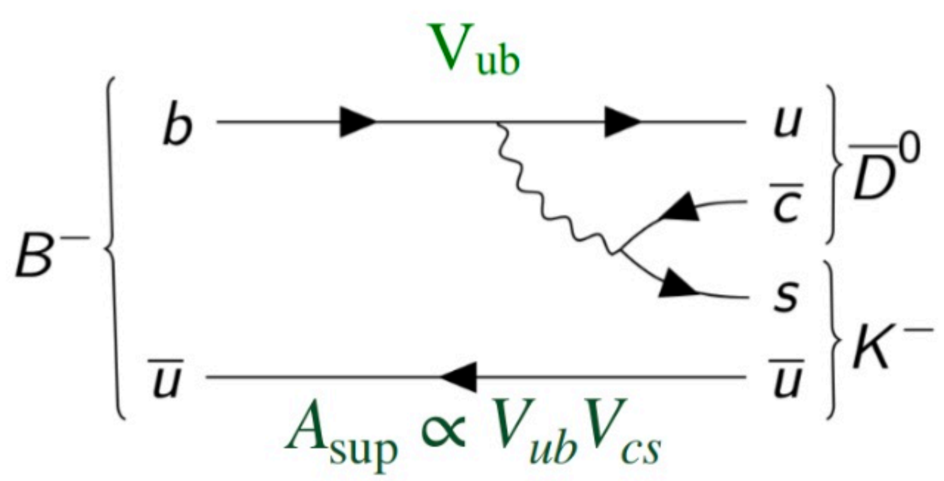
[Athron, Martinez, Sierra, 2308.13426]

# Topic3: $B^0 \to DK, B_s^0 \to D_s\pi$ (excess?)

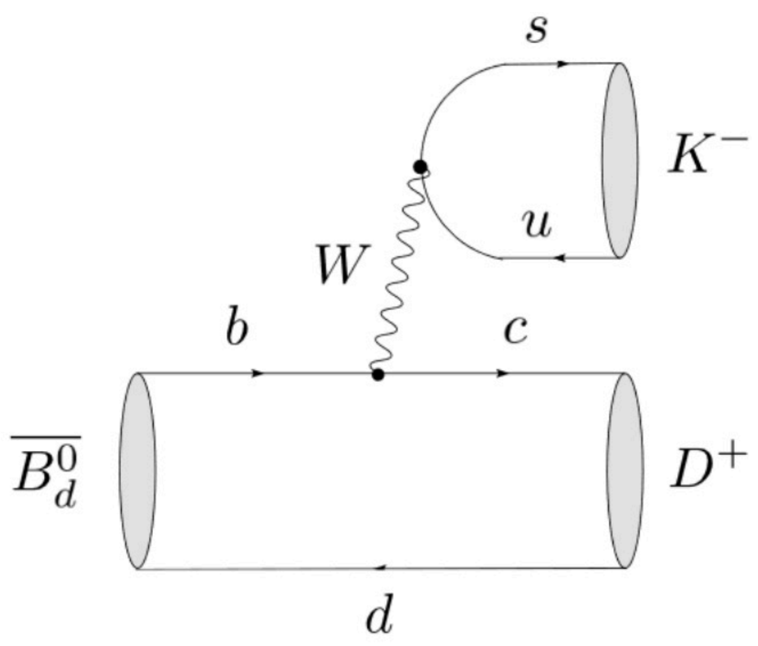
# Tree-level non-leptonic B-decays

- $B^- \to D^0 K^-, \bar{B}_s^0 \to D_s^+ K^-$ are useful colored-allowed non-leptonic tree-level decays. Their CP asymmetry can determine the CKM angle $\gamma$ ($\varphi_3$) precisely. There are tree-level interference




- On the other hand, $\bar{B}^0 \to D^{(*)+} K^-, B_s^0 \to D_s^{(*)+} \pi^-$ are unique colored-allowed tree-level decays. Only 1 topology; no annihilation and penguin. Theoretically & experimentally clean.



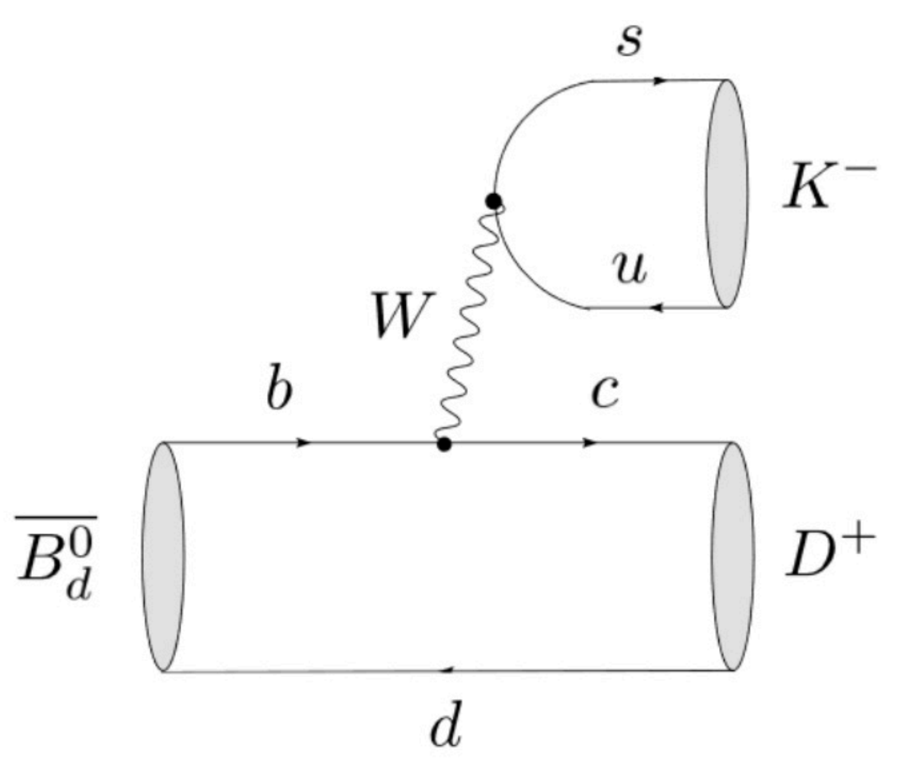

Hadronic matrix element can be precisely calculated via the QCD factorization (QCDf) [Beneke, et al, 9905312]

$$\langle D^+ K^- | \mathcal{O}_i | \bar{B}^0 \rangle \simeq \langle K^- | j_a | 0 \rangle \langle D^+ | j_b | \bar{B}^0 \rangle$$

QCD corrections are calculable

# Tree-level non-leptonic B-decays

- SM predictions by the QCDf at NNLO QCD + NLO power in $\Lambda_{QCD}/m_b$ [Bordone, et al, 2007.10338], with improved analysis [Endo, Iguro, Mishima, 2109.10811] → New calculation [Piscopo, Rusov, 2307.07594]




$\text{BR}_{\text{exp}}$ < $\text{BR}_{\text{SM}}$ $\approx 4\sigma$

SM amplitudes are *uniformly* larger by $\mathcal{O}(15\%)$

| $\times 10^4(B), \times 10^3(B_s)$ | Exp | QCDf | QCDf improved | Deviation |
|---|---|---|---|---|
| $\bar{B}^0 \to D^+ K^-$ | 1.86(20) | 3.26(15) | 3.03(15) | 5.6—4.7σ |
| $\bar{B}^0 \to D^{*+} K^-$ | 2.12(15) | $3.27^{+0.39}_{-0.34}$ | 3.27(16) | 3.1—5.3σ |
| $\bar{B}^0_s \to D^+_s \pi^-$ | 3.00(23) | 4.42(21) | 4.09(21) | 4.6—3.5σ |
| $\bar{B}^0_s \to D^{*+}_s \pi^-$ | 2.0(5) | $4.3^{+0.9}_{-0.8}$ | 4.46(22) | 2.4—4.5σ |

final-state rescattering effects are irrelevant [Endo, Iguro, Mishima, 2109.10811]
QED corrections are also irrelevant [Beneke, et al, 2107.03819]

# New physics interpretation

- Effective Lagrangian

Factorized by SM CKM factor (to provide the uniform corrections)

$$\mathcal{L} = -\frac{4G_F}{\sqrt{2}} \sum_q V_{cb} V_{uq}^* \sum_{i=1,2} C_i^q(\mu) Q_i^q(\mu) \,, \qquad \begin{aligned} Q_1^q &= (\bar{c}_L \gamma^\mu T^a b_L)(\bar{q}_L \gamma_\mu T^a u_L)\,, \\ Q_2^q &= (\bar{c}_L \gamma^\mu b_L)(\bar{q}_L \gamma_\mu u_L)\,, \end{aligned}$$

- Best fit point

$$\frac{C_2^{\rm NP}(m_b)}{C_2^{\rm SM}(m_b)} = -0.17 \pm 0.03 \,.$$

Compatible with lifetime measurements [Bordone, et al, 2007.10338]

- NP interpretation (partial explanation) is possible by TeV-scale $W'$ [Iguro, TK, 2008.01086; Bordone, Greljo, Marzocca, 2103.10332]. But one has to tune up flavor texture to avoid $\Delta M_{d,s}$

# Topic4: CKM unitarity test (robust)

# Unitarity of CKM matrix

- Each component of the CKM matrix can be measured without assuming the unitarity

  ➡ One can test the CKM unitarity conditions from data

β decays — K meson decays — B meson decays

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

D meson decays

K and B mesons mixing,
K and B mesons FCNC

$$VV^\dagger = \mathbb{I}_3 \text{ or } \neq \mathbb{I}_3?$$

SM — NP?

# CKM unitarity triangle

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

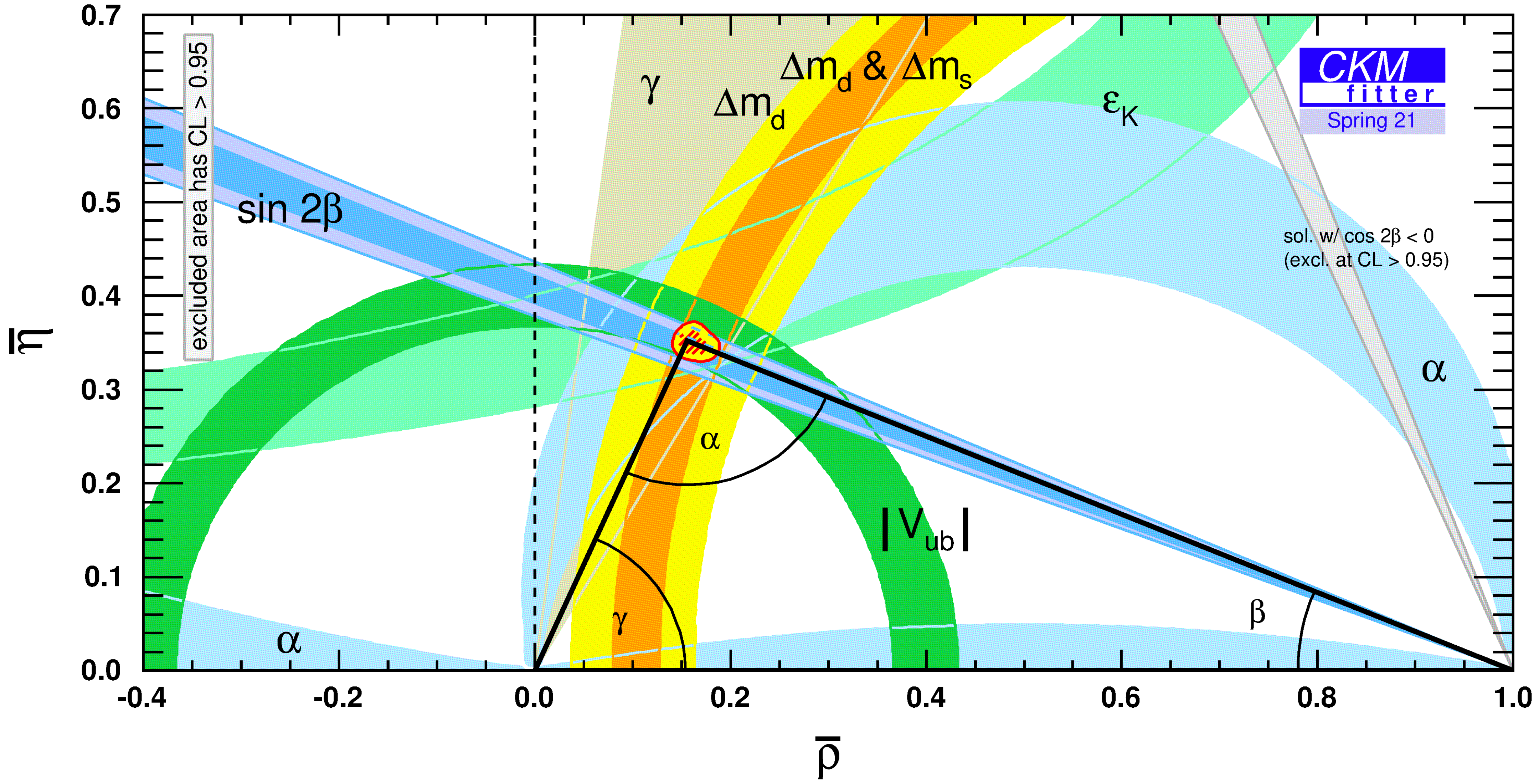
Unitarity condition

$$V^\dagger V = \mathbb{I}_3$$

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

A triangle can be drawn on a complex plane

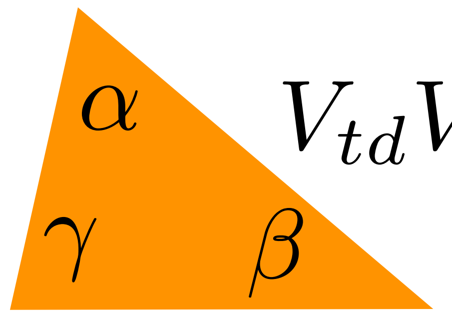
[CKM fitter 2021]




CPV

*B* triangle

$V_{ud}V_{ub}^* \sim \lambda^3$




$V_{td}V_{tb}^* \sim \lambda^3$

$V_{cd}V_{cb}^* \sim \lambda^3$

Many data are available! Currently, they are consistent with the triangle

# 1st-row Unitarity test in CKM matrix

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Unitarity condition

$$VV^\dagger = \mathbb{I}_3$$

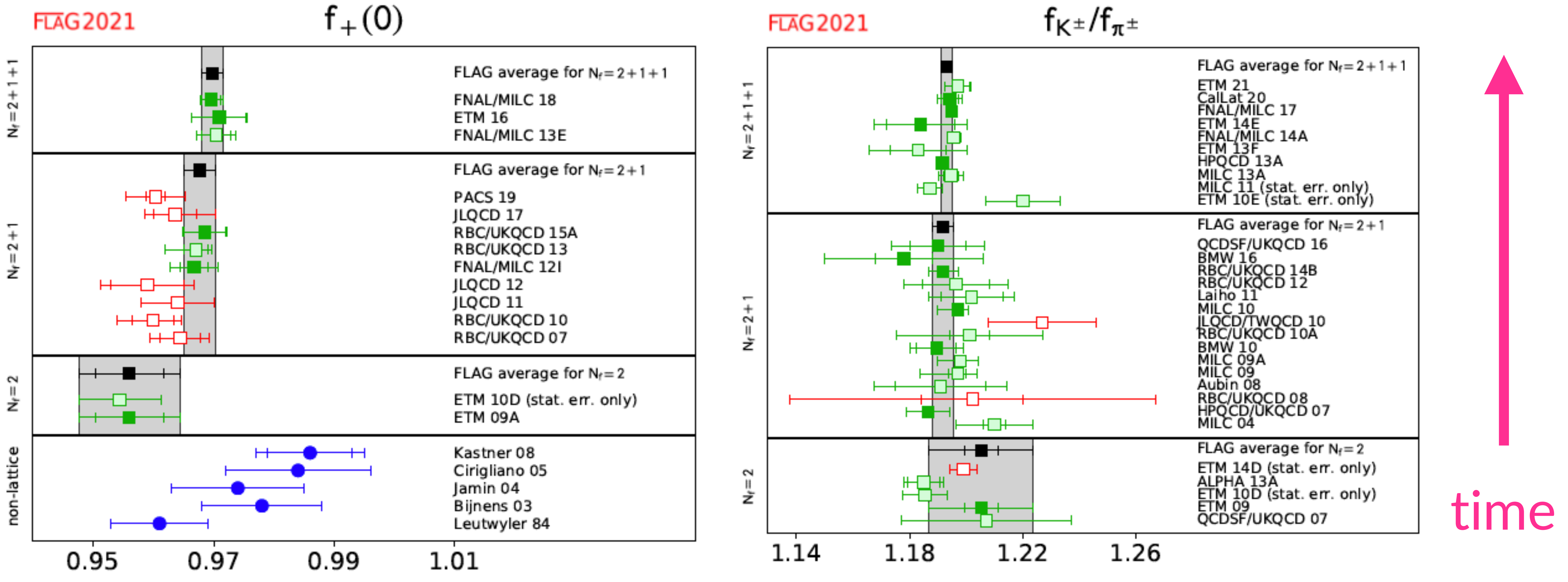
1st-row unitarity condition

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

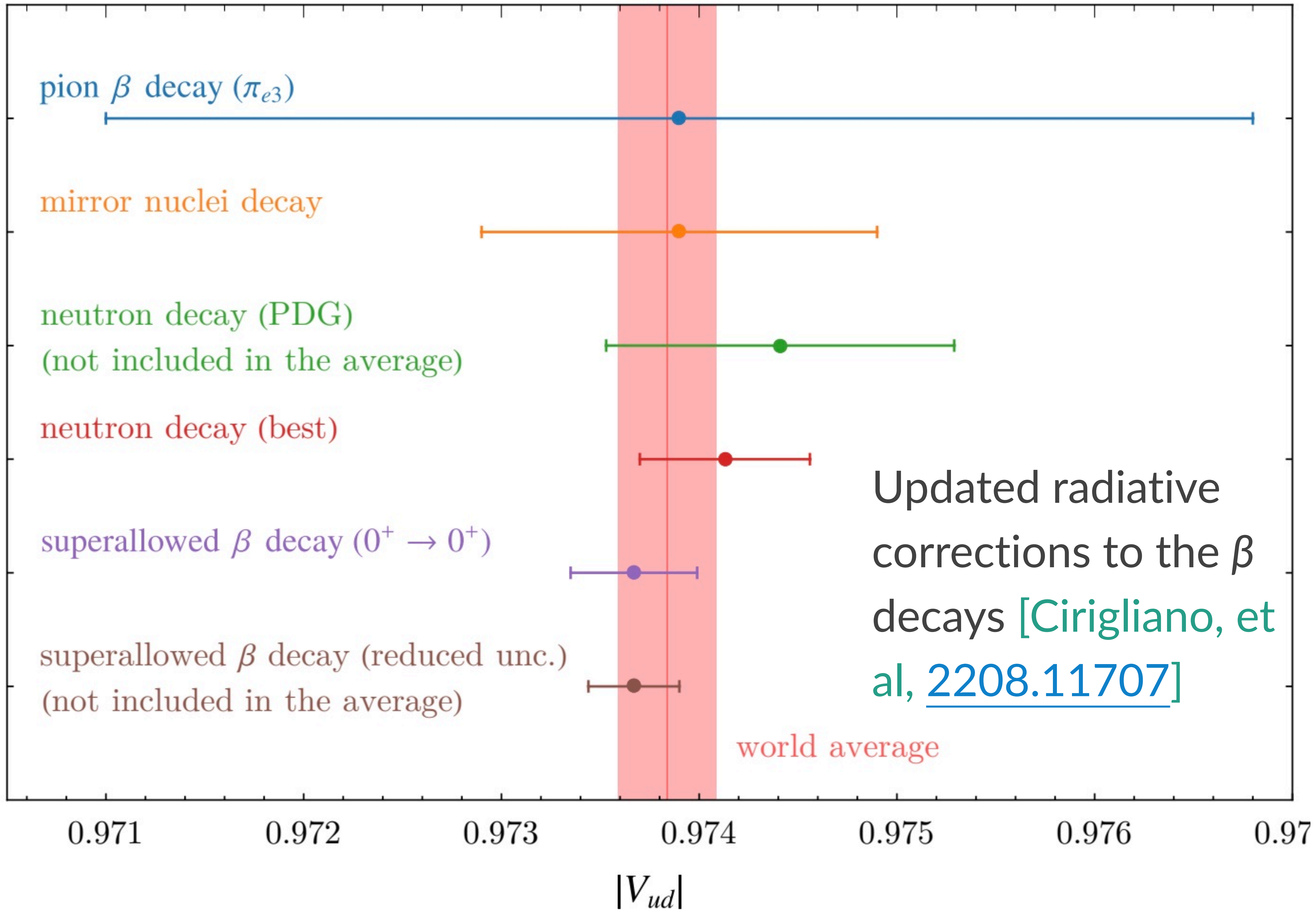
Sum of the absolute values must become **exact 1**

- Why these components?
- Leading uncertainties from kaon form factors have been improved significantly

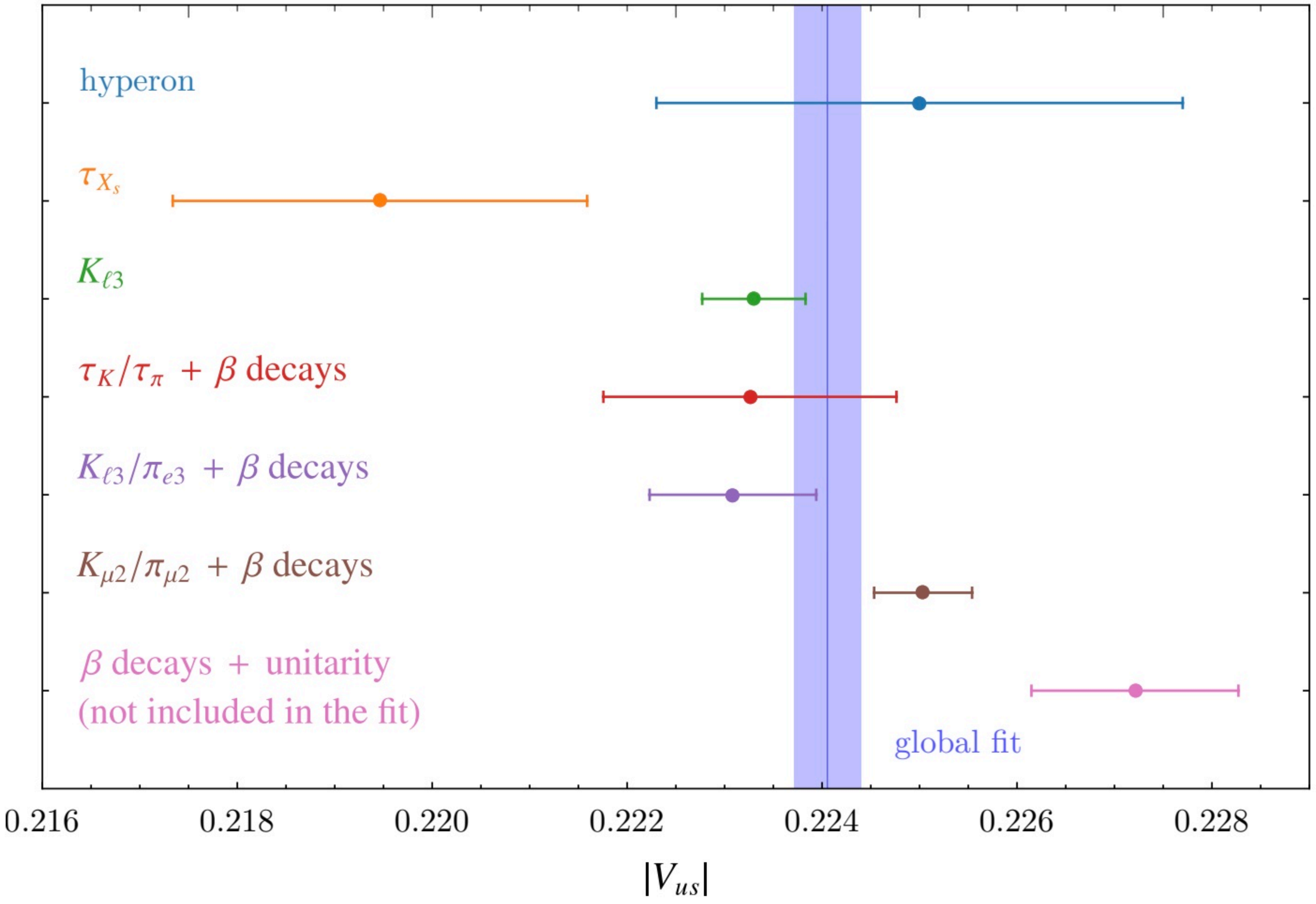
[FLAG2021, 2111.09849]



# $|V_{ud}|$ and $|V_{us}|$ determinations [Crivellin, Kirk, TK, Mescia, 2212.06862]




Updated radiative corrections to the $\beta$ decays [Cirigliano, et al, 2208.11707]




All data are consistent

One can see several tensions in $|V_{us}|$ determinations

# Global fit of $|V_{ud}|$ and $|V_{us}|$ [Crivellin, Kirk, TK, Mescia, 2212.06862]

$K_{\ell 3}$

$K^0_{L,S} \to \pi^+ \ell \bar{\nu}$

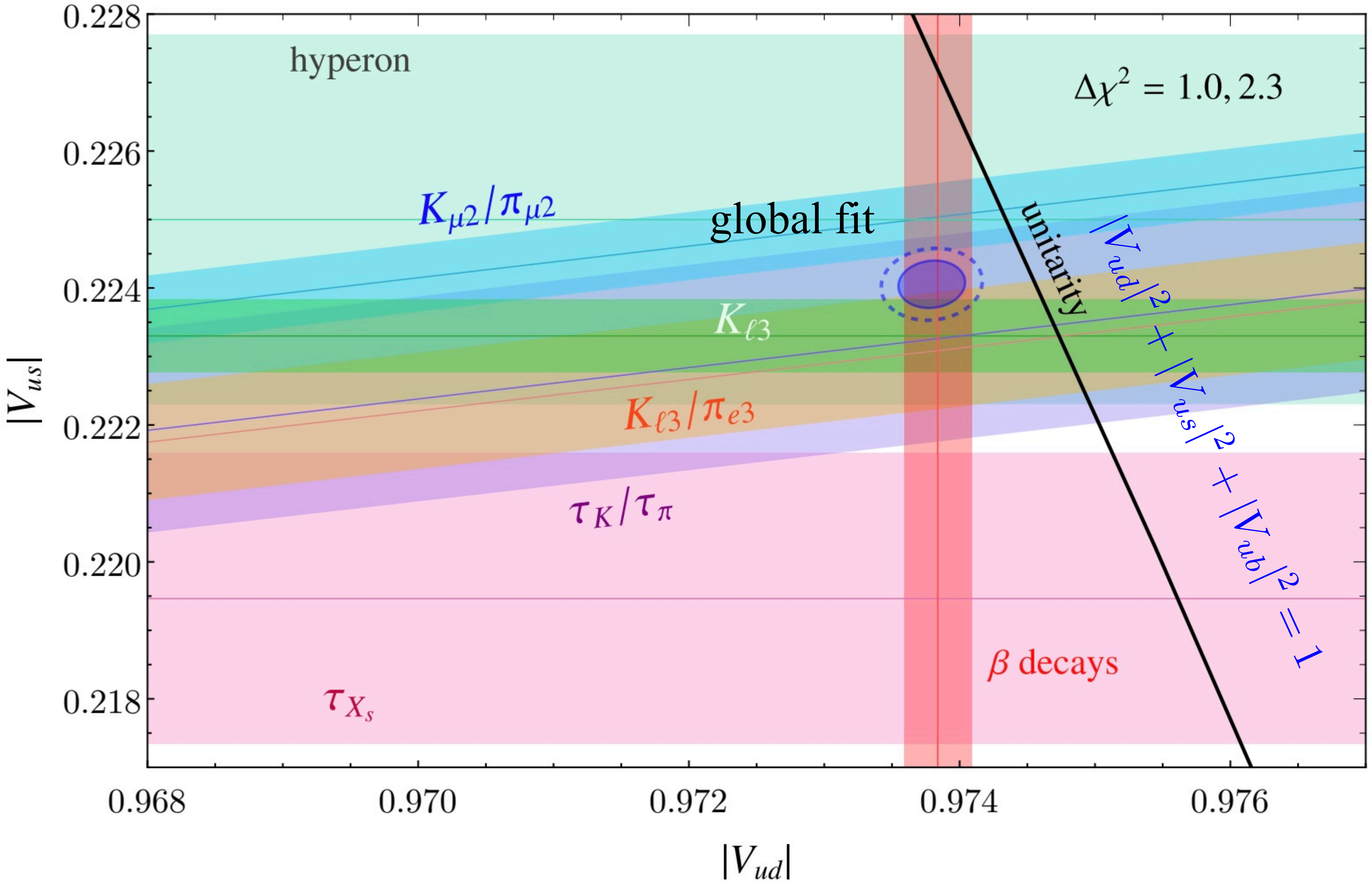
$K^- \to \pi^0 \ell \bar{\nu}$

$(\ell = e,\ \mu)$

Error budgets:

LO: data, FFs

NLO: Isospin breaking correction




$K_{\mu 2}/\pi_{\mu 2}$

$$\frac{K^- \to \mu \bar{\nu}}{\pi^- \to \mu \bar{\nu}}$$

Error budgets:

LO: FFs

NLO: data, radiative correction

Uncertainty from $|V_{ub}|$ is negligible

# Significance of Cabibbo-Angle Anomaly (CAA)

- Global fit (including with correlations) [Crivellin, Kirk, TK, Mescia, 2212.06862]

$$|V_{ud}|_{\rm global} = 0.973\,79(25)\,,\qquad \rho(V_{ud}, V_{us}) = 0.09$$

$$|V_{us}|_{\rm global} = 0.224\,05(35)\,,$$

test of unitarity

neutron-lifetime data dependence (bottle vs beam)

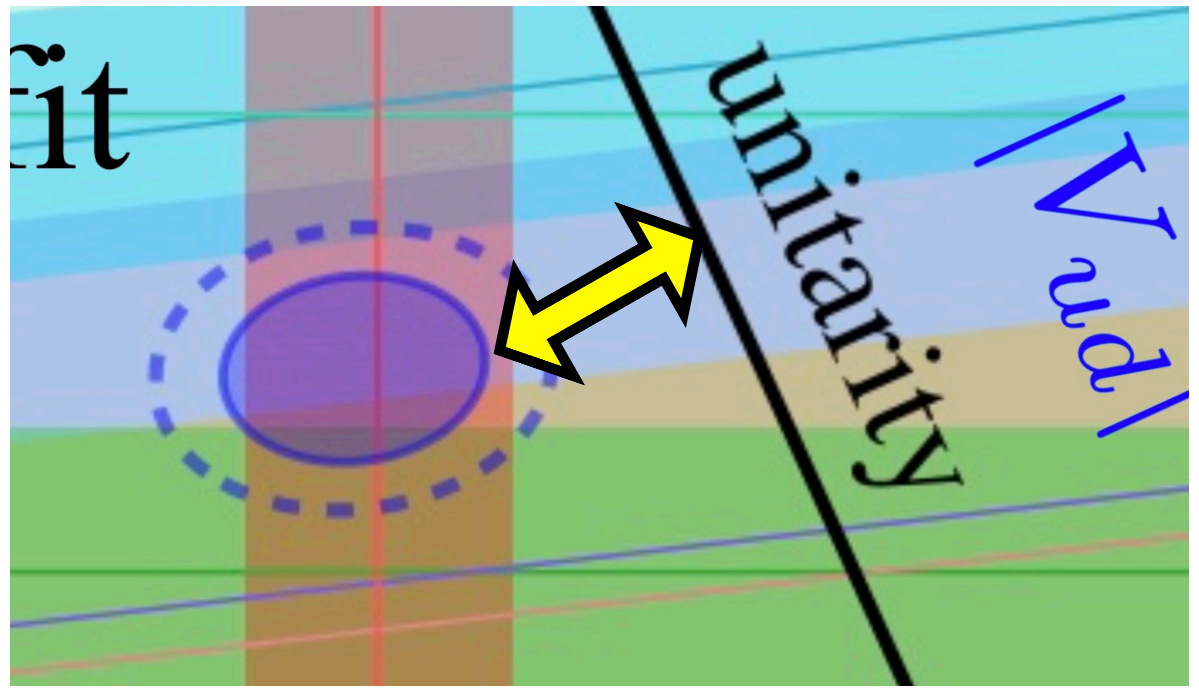
$$\Delta_{\rm CKM}^{\rm global} \equiv |V_{ud}|^2_{\rm global} + |V_{us}|^2_{\rm global} + |V_{ub}|^2 - 1 = \begin{cases} -1.51(53)\times 10^{-3} & (\text{w/ bottle UCN best})\,, \\ -2.34(62)\times 10^{-3} & (\text{w/ in-beam best})\,, \end{cases}$$

**2.8σ (3.8σ) level** deviation from the unitarity condition

the single most precise data

$$\tau_n^{\rm bottle} = 877.75(36)\,{\rm sec} \qquad |V_{ud}|_n = 0.974\,13(43)$$

$$\tau_n^{\rm beam} = 887.7(2.2)\,{\rm sec} \qquad |V_{ud}|_n = 0.968\,66(131)$$



# Significance of Cabibbo-Angle Anomaly (CAA)

- Other precise combination of the unitarity test (1st-column unitarity)

$$\Delta_{\rm CKM}^{1^{\rm st}\,{\rm column}} \equiv |V_{ud}|^2_{\rm global} + |V_{cd}|^2 + |V_{td}|^2 - 1 = -0.0028(18)\,,$$

Uncertainty is predominated by data of $D \to \mu\nu$, being probed precisely by Belle II and BES III

- Interesting new result from CMS [CMS, 2201.07861]
  - Inclusive hadronic decay of W can measure $\Sigma_{i=u,c}\Sigma_{j=d,s,b}|V_{ij}|^2$ (=2 in the SM)

| $\alpha_S(m_W{}^2)$ | $\lvert V_{cs}\rvert$ | $\sum_{ij}\lvert V_{ij}\rvert^2$ |
|---|---|---|
| $0.095 \pm 0.033$ | $0.967 \pm 0.011$ | $1.984 \pm 0.021$ |

Consistent with the unitarity

But, the $|V_{cs}|$ is deviated from the world average: $|V_{cs}| = 0.987(11)$

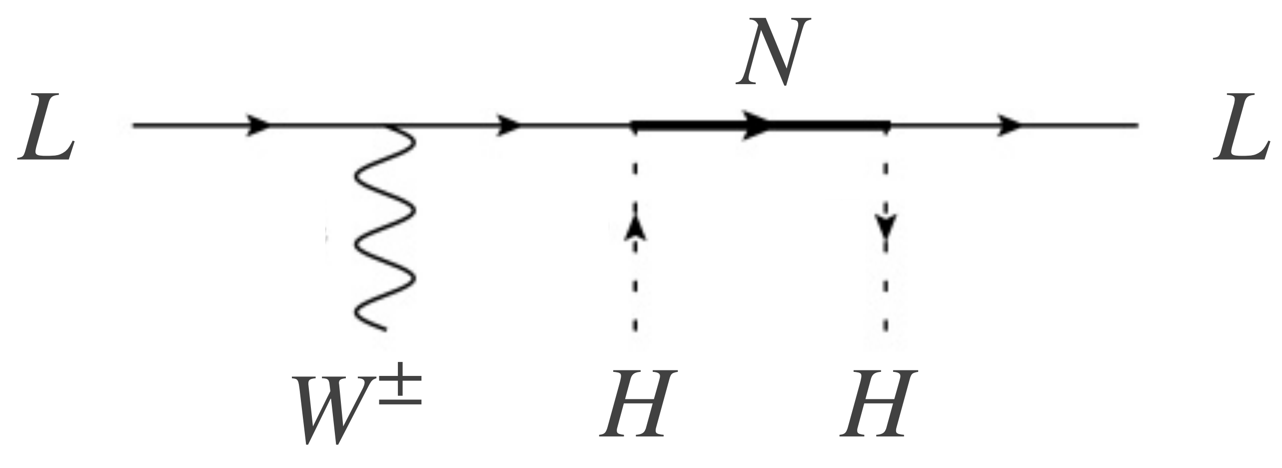
# New physics interpretations of CAA

Heavy New Physics

- EFT fittings: $(H^\dagger i D_\mu^I H)(\bar{L}\gamma^\mu \tau^I L)$ fit [Coutinho, et al, 1912.08823]; **right-handed current fit** [Grossman, et al, 1911.07821, Cirigliano, et al, 2112.02087]; $W$-$\ell$-$\nu$ fit [Crivellin, et al, 2002.07184]; $G_F$ fit [Crivellin, et al, 2102.02825]
  Best pull
- Heavy SU(2)$_L$ vector boson (~10 TeV) [Capdevila, et al, 2005.13542]
- Leptoquark (~5TeV) [Marzocca, Trifinopoulos, 2104.05730]
- **Vector-like Quark (1-5 TeV)** [Belfatto, et al, 1906.02714, 2103.05549; Cheung, et al, 2001.02853; Branco, et al, 2103.13409]
  Best pull
- Vector-like Lepton (1-2 TeV) [Endo, Mishima, 2005.03933; Crivellin, et al, 2008.01113; Kirk, 2008.03261

Vector-like quark can explain CAA with EWPO, FCNC, collider bounds [Crivellin, Kirk, TK, Mescia, 2212.06862]

- **Heavy right-handed neutrino** (type I seesaw) **can not explain** the tension [the unphysical region |mixing|$^2$ <0 is favored]




$W$-$\ell$-$\nu$ coupling

Light NP

- MeV sterile neutrino [TK, Tobioka, 2308.13003]

# EFT fitting of CAA [Crivellin, Kirk, TK, Mescia, 2212.06862]

- EFT global fitting implies that right-handed W-u-d and W-u-s new physics are preferred

[unit of $10^{-3}v^{-2}$ ]

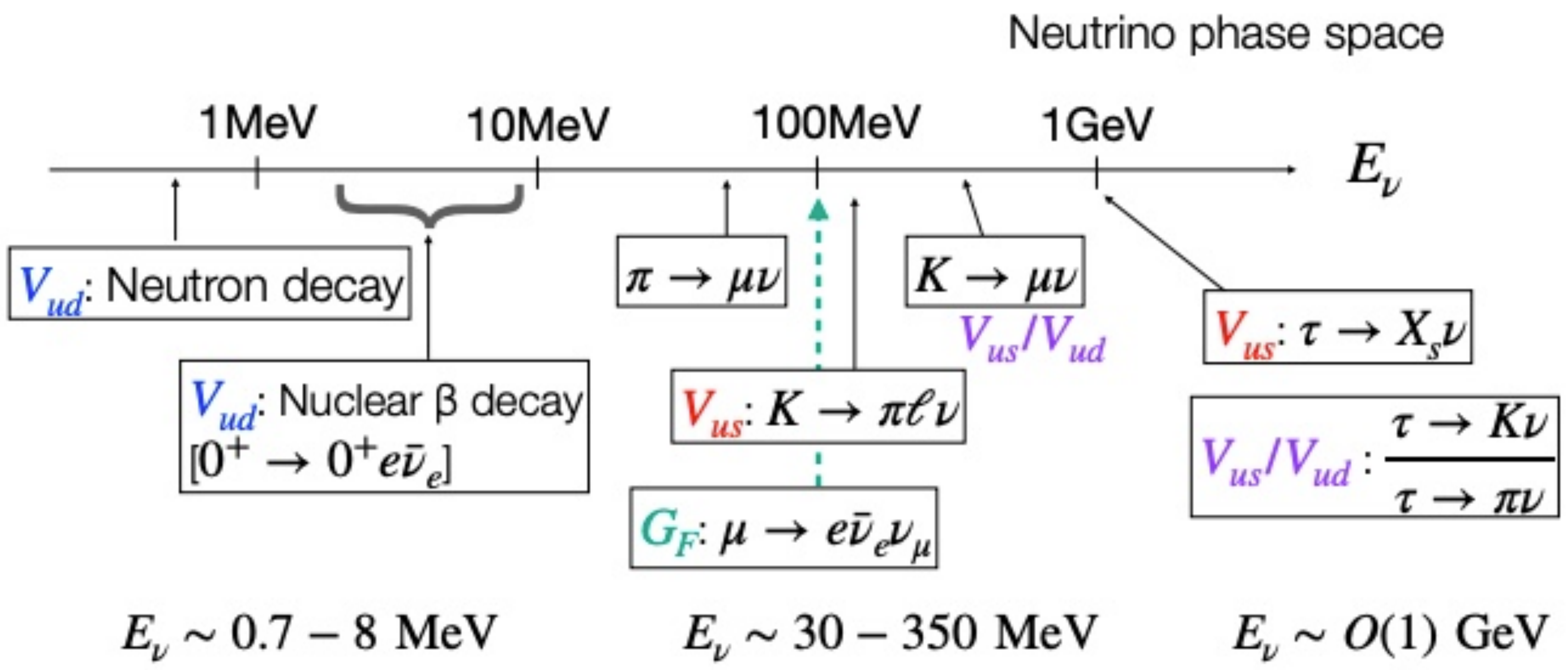
| EFT Scenario | Best fit point | $-\Delta\chi^2$ | Pull |
|---|---|---|---|
| $\left[C_{Hq}^{(3)}\right]_{11}$ | $-0.50$ | 3.3 | $1.8\,\sigma$ |
| $\left[C_{Hq}^{(3)}\right]_{11} = \left[C_{Hq}^{(3)}\right]_{22}$ | $-0.27$ | 1.1 | $1.1\,\sigma$ |
| $\left[C_{Hq}^{(3)}\right]_{11} = \left[C_{Hq}^{(1)}\right]_{11}$ | $-0.55$ | 3.7 | $1.9\,\sigma$ |
| $[C_{Hud}]_{11}$ | $-1.0$ | 3.1 | $1.8\,\sigma$ |
| $[C_{Hud}]_{12}$ | $-2.0$ | 7.4 | $2.7\,\sigma$ |
| $([C_{Hud}]_{11}, [C_{Hud}]_{12})$ | $(-1.4, -2.1)$ | 13 | $3.2\,\sigma$ |
| $\left(\left[C_{Hq}^{(3)}\right]_{11}, [C_{Hud}]_{12}\right)$ | $(-0.43, -2.0)$ | 11 | $2.8\,\sigma$ |
| $\left(\left[C_{Hq}^{(3)}\right]_{11}, [C_{Hud}]_{11}, [C_{Hud}]_{12}\right)$ | $(0.27, -1.9, -2.4)$ | 16 | $2.9\,\sigma$ |
| $\left(\left[C_{Hq}^{(3)}\right]_{11}, \left[C_{Hq}^{(3)}\right]_{22}, [C_{Hud}]_{11}, [C_{Hud}]_{12}\right)$ | $(0.59, 0.76, -2.6, -2.5)$ | 17 | $2.9\,\sigma$ |
| $\left(\left[C_{Hq}^{(3)}\right]_{11}, \left[C_{Hq}^{(1)}\right]_{11}, [C_{Hud}]_{11}, [C_{Hud}]_{12}\right)$ | $(0.29, 0.11, -2.0, -2.4)$ | 13 | $2.6\,\sigma$ |

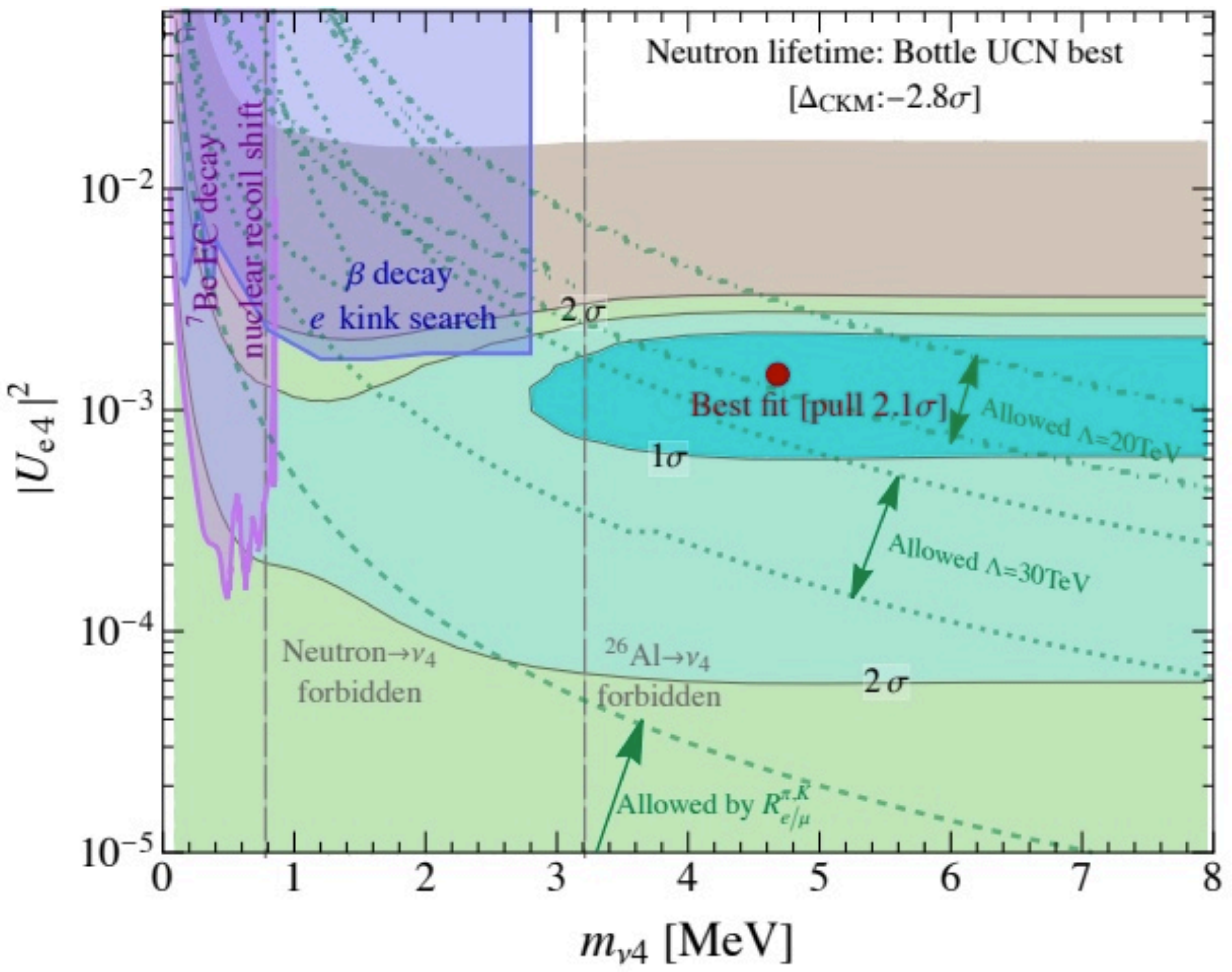
Best pull

# Sterile neutrino solution for CAA

[TK, Tobioka, 2308.13003]

- MeV sterile neutrino provides good effects on $|V_{ud}|$ determinations from superallowed β decays and neutron decay, and no effects on the others




1. active-sterile mixing
2. kinematical suppression

no effects when $E_\nu \gg m_{\nu 4}$

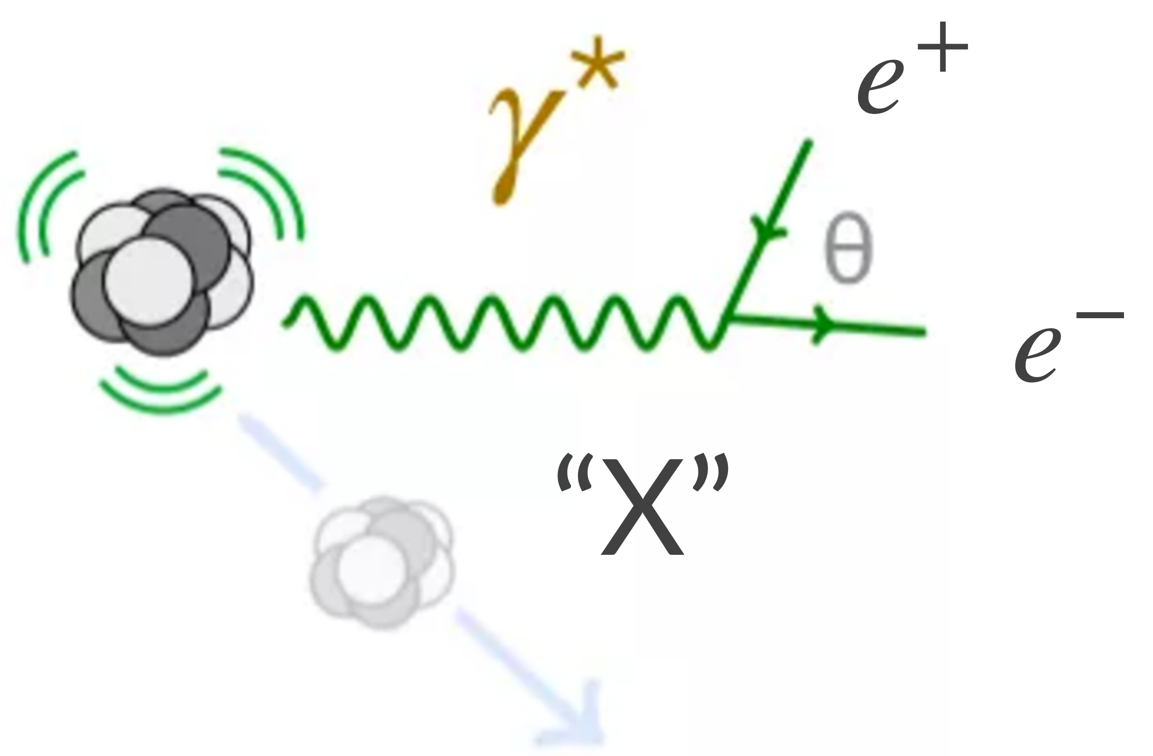
$$1 + \Delta_{\rm CKM} \approx |V_{ud}|^2 \cos^2 U_{e4} + |V_{us}|^2 \quad \Rightarrow \quad |U_{e4}|^2 \approx 10^{-3}$$

The details of constraints, see 2308.13003

# Topic5: Beryllium anomaly (excess?)

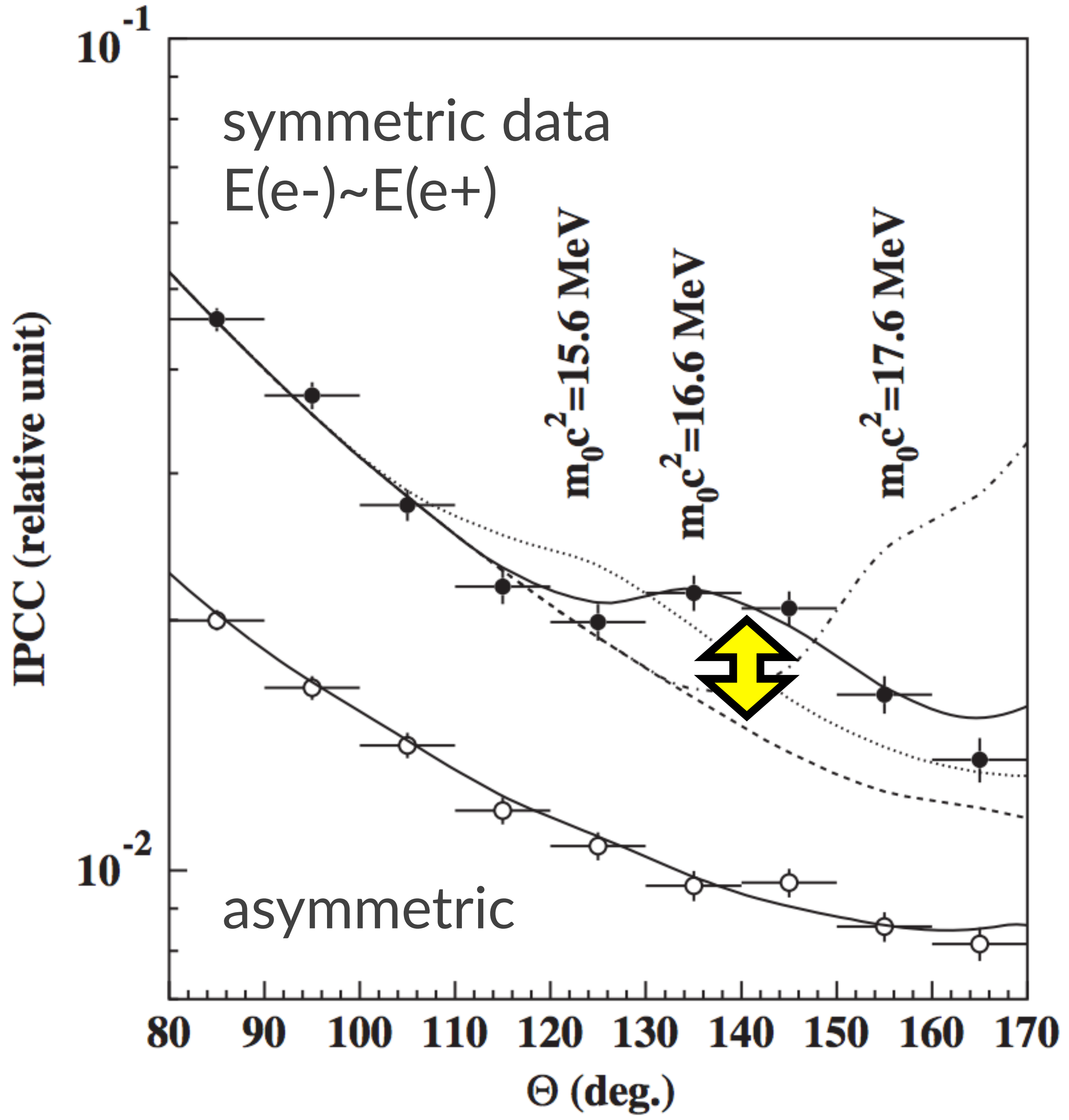
# Beryllium anomaly (X17)

figure from
www.particlebites.com



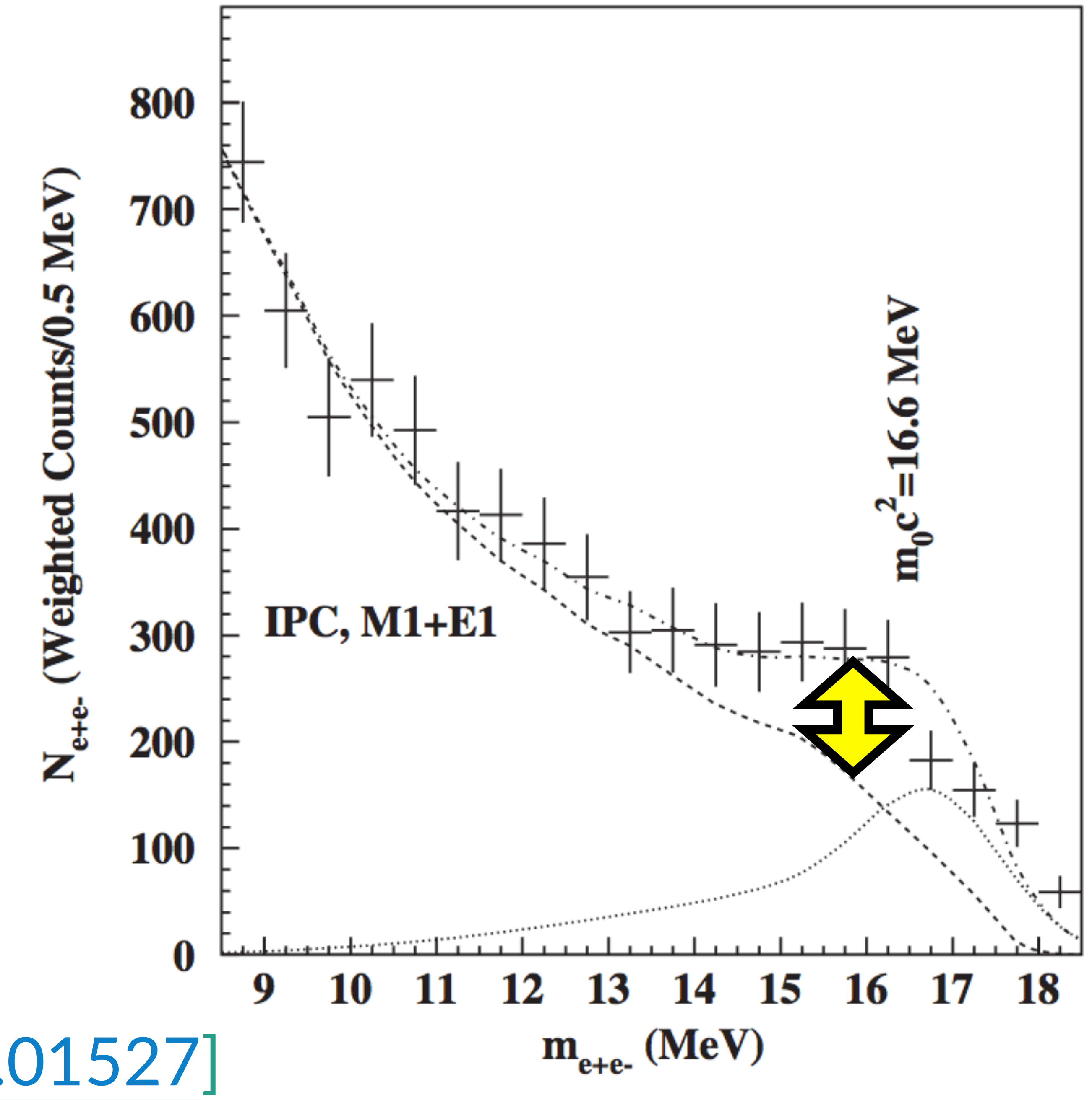

- ATOMKI experiment is searching an internal pair creation of electrons in the several nuclear transitions: $\mathrm{BR}({}^8\mathrm{Be}^* \to {}^8\mathrm{Be} + \gamma) = \mathcal{O}(10^{-5})$
  $\mathrm{BR}({}^8\mathrm{Be}^* \to {}^8\mathrm{Be} + e^+e^-) = \mathcal{O}(10^{-8})$
  target

- ATOMKI results
- ${}^8$Be, $m_X = 16.70(61)$ MeV
  [ATOMKI, 8Be, 1504.01527, 2308.06473]
- ${}^4$He, $m_X = 16.94(24)$ MeV
  [ATOMKI, 4He, 1910.10459, 2104.10075]
- ${}^{12}$C, $m_X = 17.03(23)$
  [ATOMKI, 12C, 2209.10795]




Large bump in large opening angle

non-relativistic on-shell decay

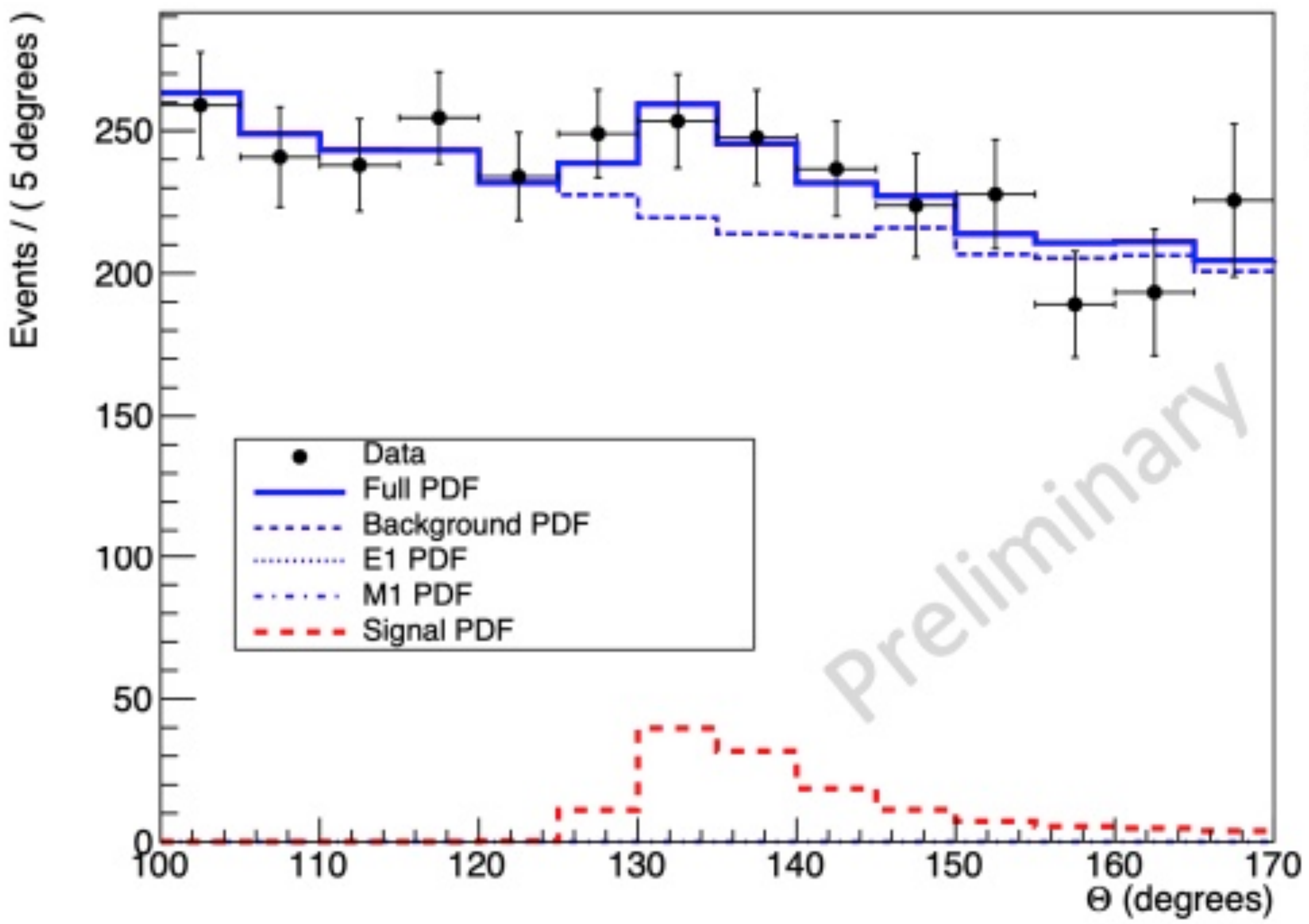


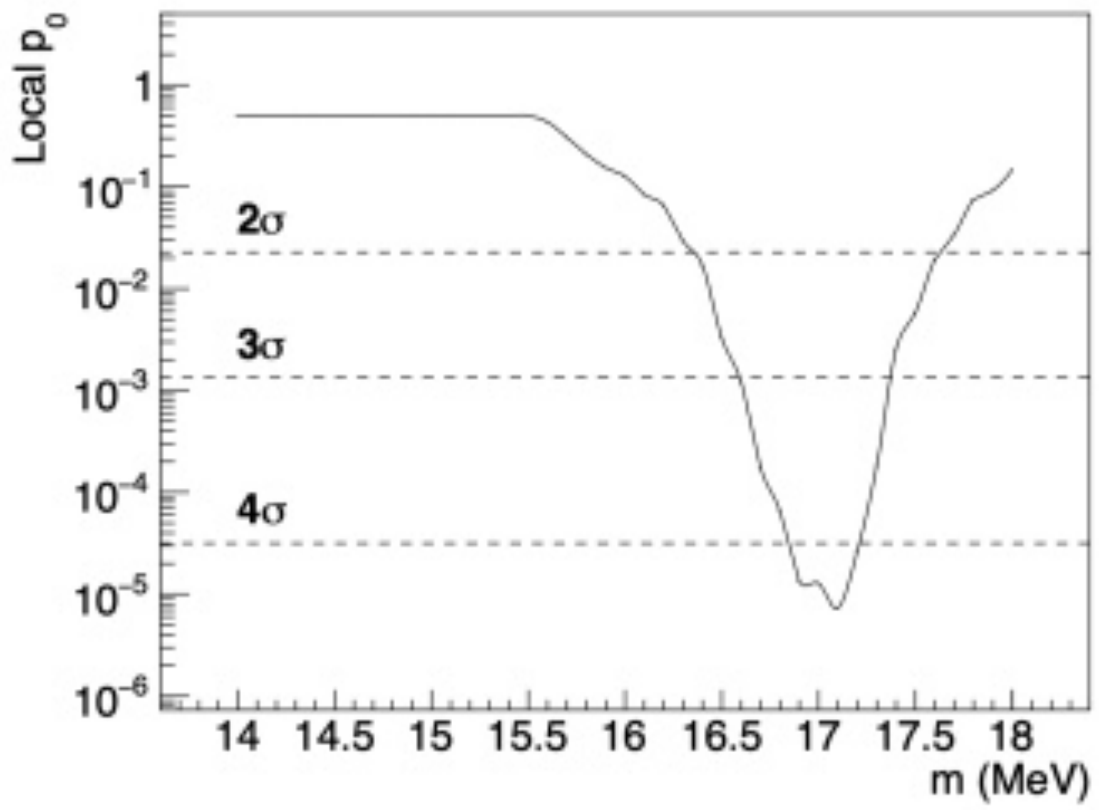

[ATOMKI, 8Be, 1504.01527]

# HUS experiment

- HUS experiment, Hanoi, Vietnam, is searching for $^{8}$Be and $^{12}$C transitions to check ATOMKI
- The preliminary result of HUS for $^{8}$Be [HUS experiment, ISMD2023]

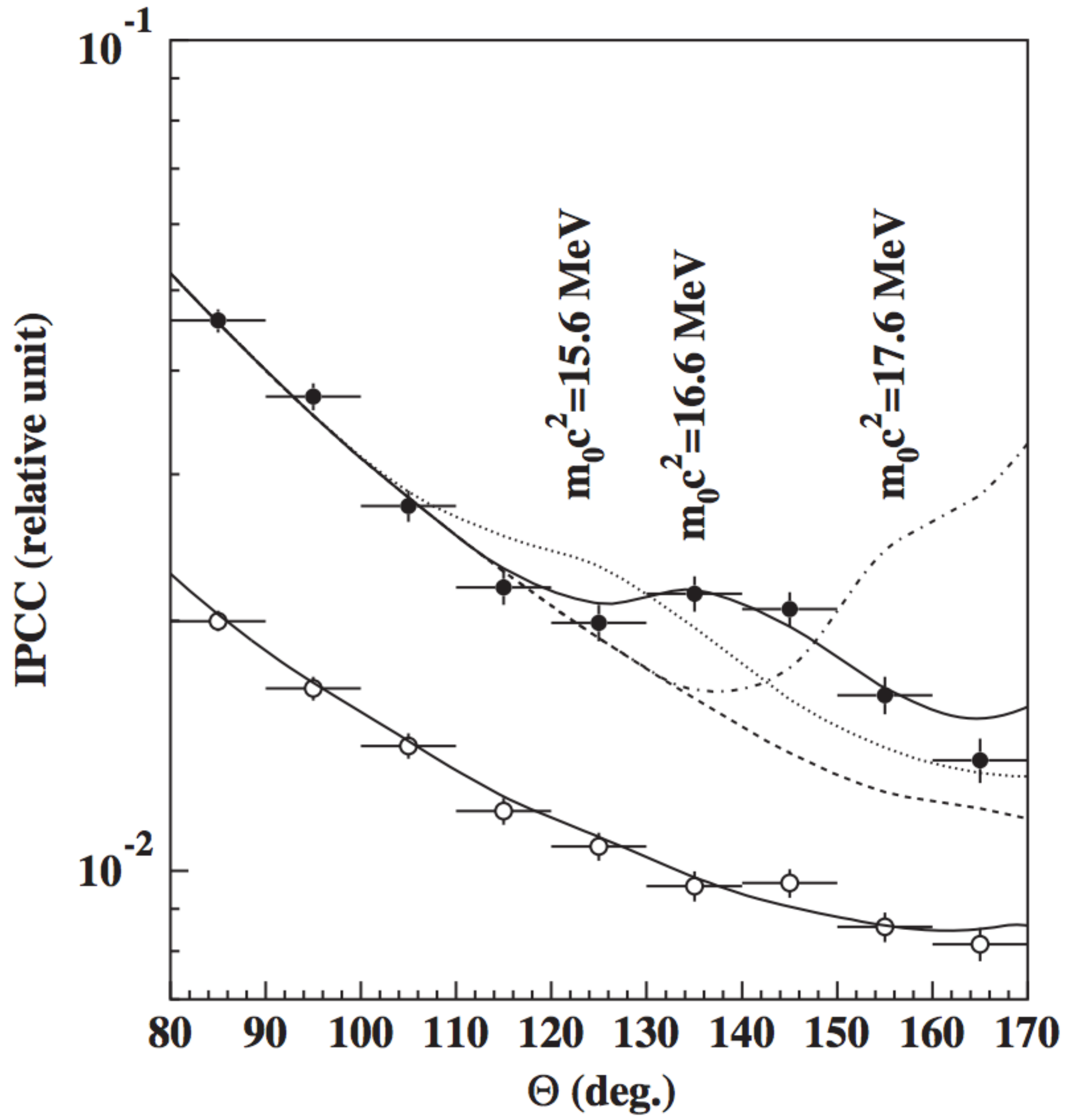
[ATOMKI, 8Be, 1504.01527]




$m_{\rm boson} = 16.7 \pm 0.5$ MeV

significance: 4–5σ



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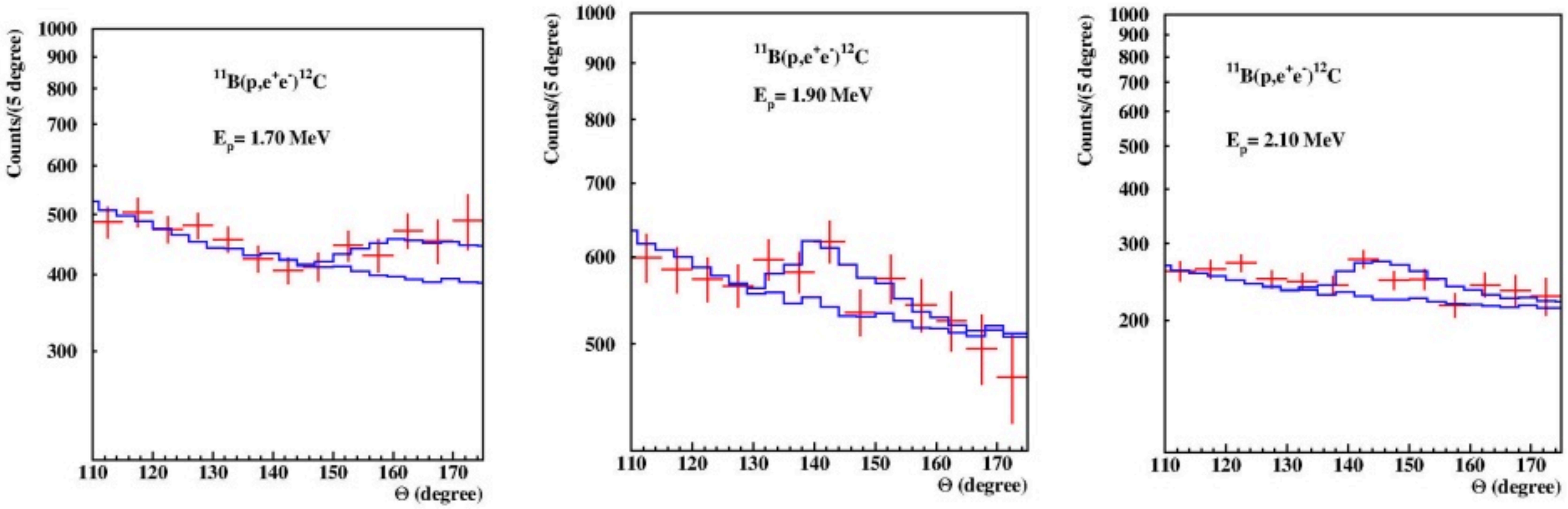
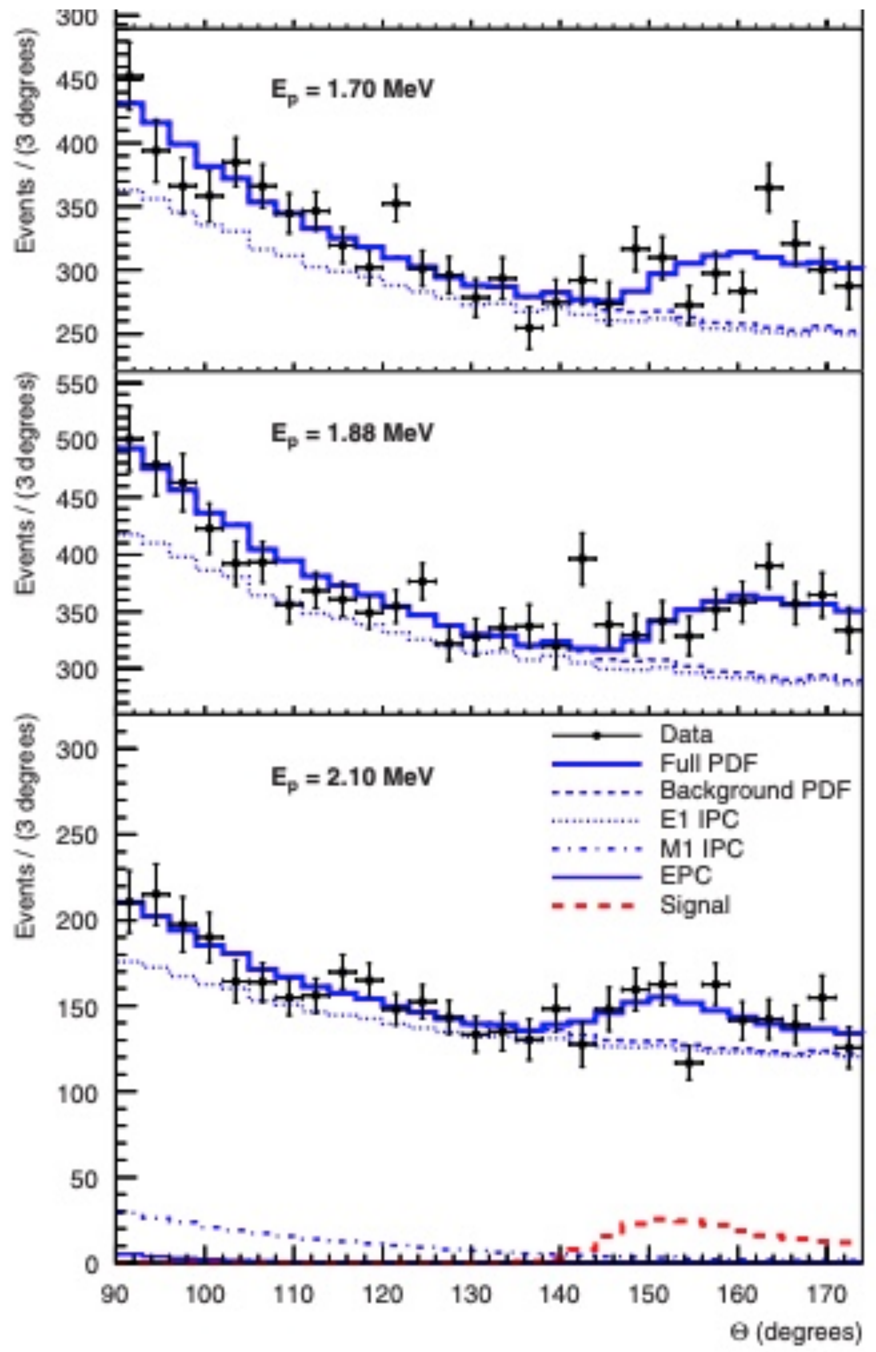



[ATOMKI, 12C, 2209.10795]




Other on-going: MEG II, PADME, Montreal Tandem, Van-de-Graaff lab

# X17 implications

$$\mathcal{A} \propto Q_u g_u - Q_d g_d = \frac{2}{3}e\left(g_u + \frac{1}{2}g_d\right) \to 0$$

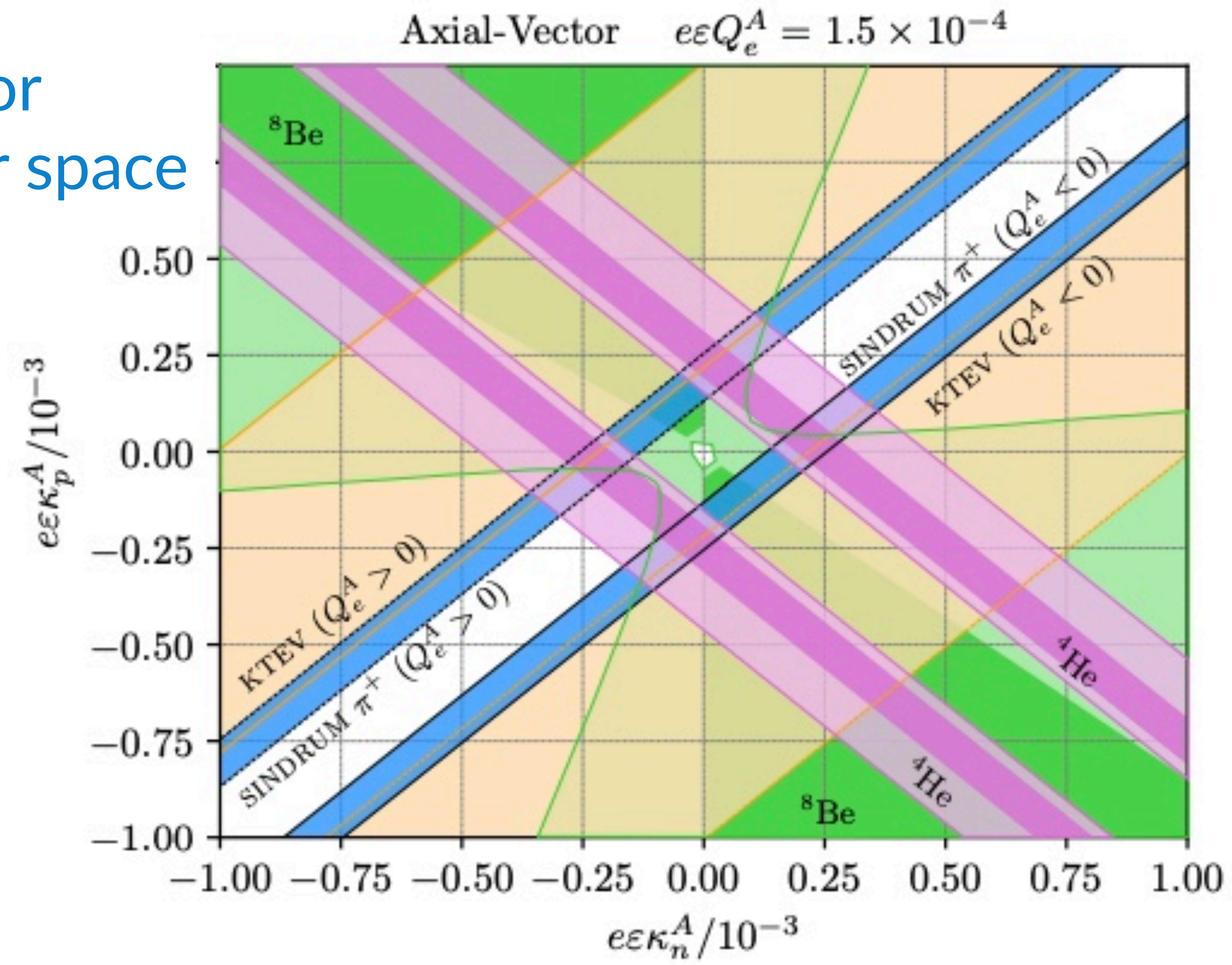
- Severe bound from $\pi^0 \to \gamma X,\ X \to e^+e^-$ (NA48/2) ➡ Protophobic nature [Feng, et al, 1608.03591]

- Additional severe bound from $\pi^+ \to e^+\nu_e X, X \to e^+e^-, \nu\bar{\nu}$ [Hostert, Pospelov, 2306.15077]

  avoid $m_e^2$ suppression ➡ Protophobic vector was excluded

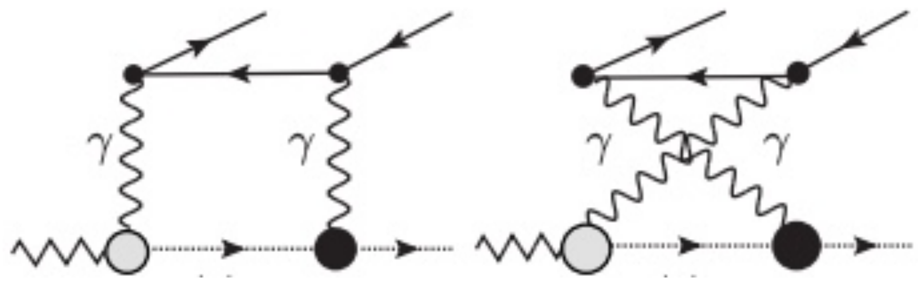
- Recent new physic studies conclude:
  promising candidate is axial vector
  [Barducci, Toni, 2212.06453; Denton, Gehrlein, 2304.09877]

axial vector parameter space




- SM explanations

  QED corrections?
  [Aleksejevs, et al, 2102.01127] (unpublished)

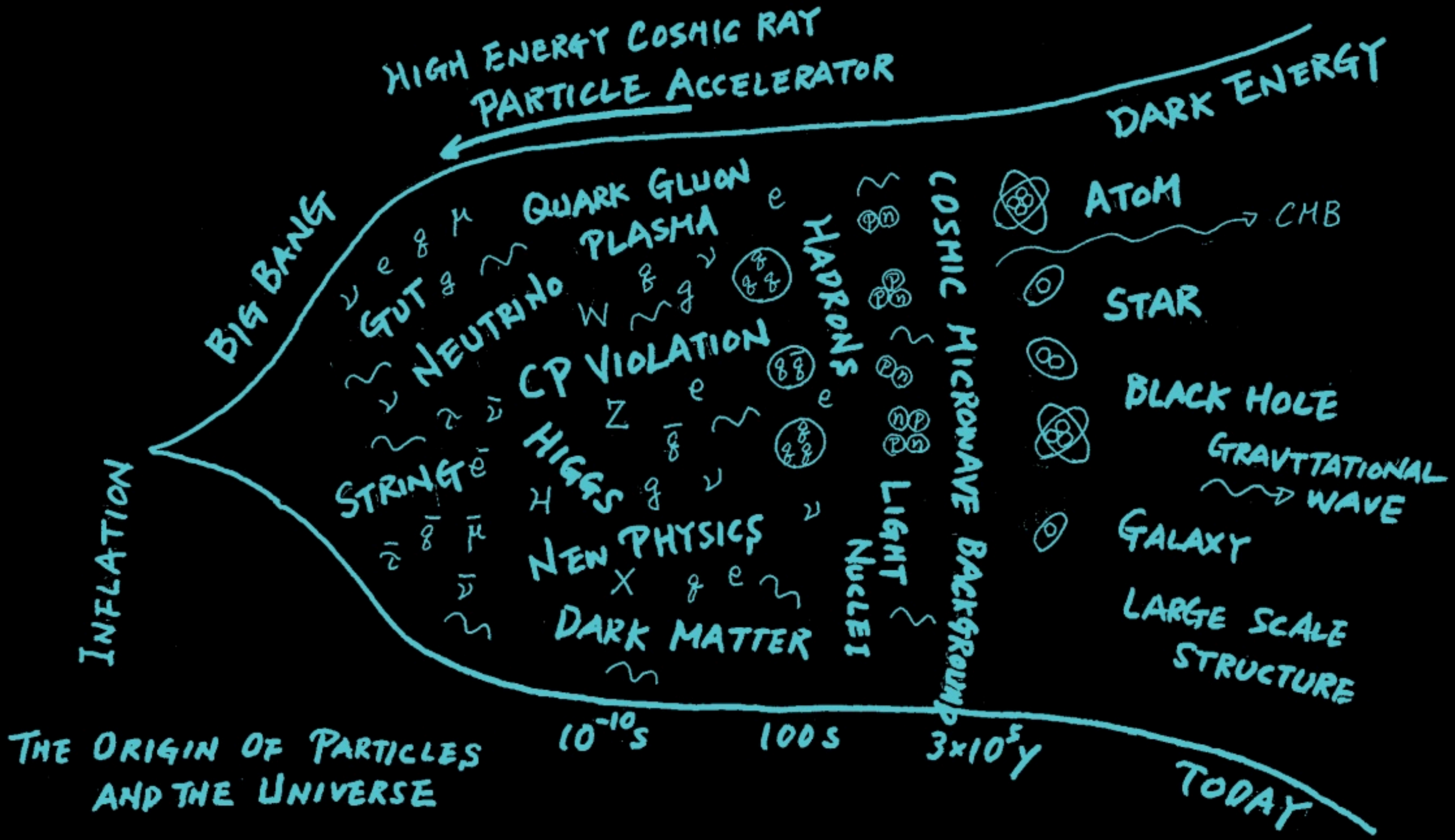



  Exotic QCD?
  [Kubarovsky, et al, 2206.14441] (unpublished)

# Conclusions

- Topic1: $B \to D\tau\nu, D\ell\nu$ (robust)
  - ~3—4σ tension. Very rich new physics phenomenology is discussed
- Topic2: $B \to K\ell\ell$ (excess?)
  - LFU new physics or charm-long-distance contribution? New excess in $B^+ \to K^+\nu\bar{\nu}$
- Topic3: $B^0 \to DK, B_s^0 \to D_s\pi$ (excess?)
  - Problem of SM calculation? New physics interpretation is not easy
- Topic4: CKM unitarity test (robust)
  - ~3σ tension. Exp data and lattice seem robust.
- Topic5: Beryllium anomaly (excess?)
  - ATOMKI data was confirmed by HUS. New physics interpretation is not easy

# Backup slides



# Leptoquark catalogue

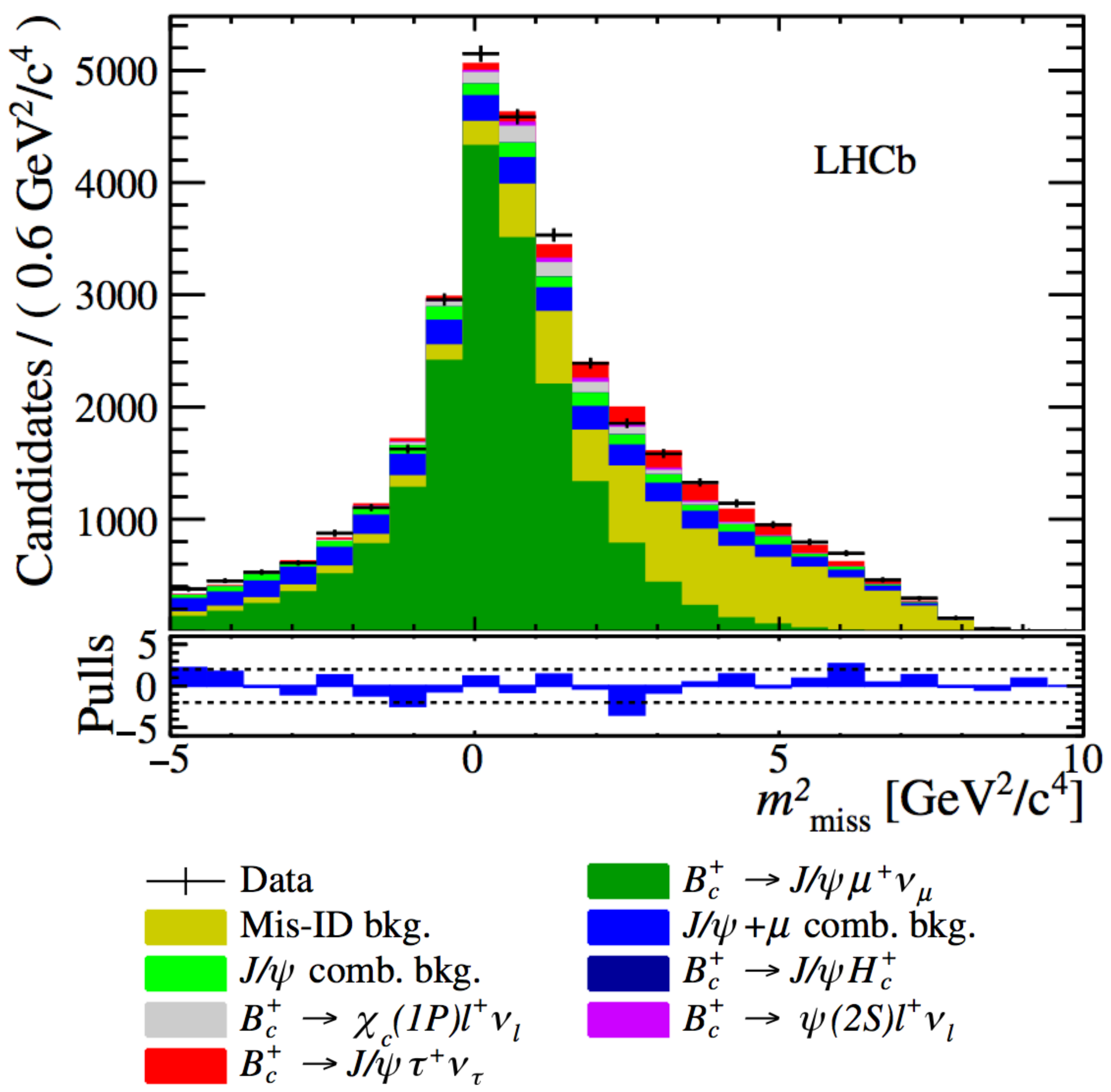
[*cf.* Angelescu, Bečirević, Faroughy, Jaffredo, Sumensari, 2103.12504; Athron, Balazs , Jacob , Kotlarski, Stockinger , Stockinger-Kim, 2104.03691]

- Leptoquarks that do not lead to proton decay and can contribute precision measurements

  [LQ* requires additional symmetry that forbids the proton decay, see 1603.04993]

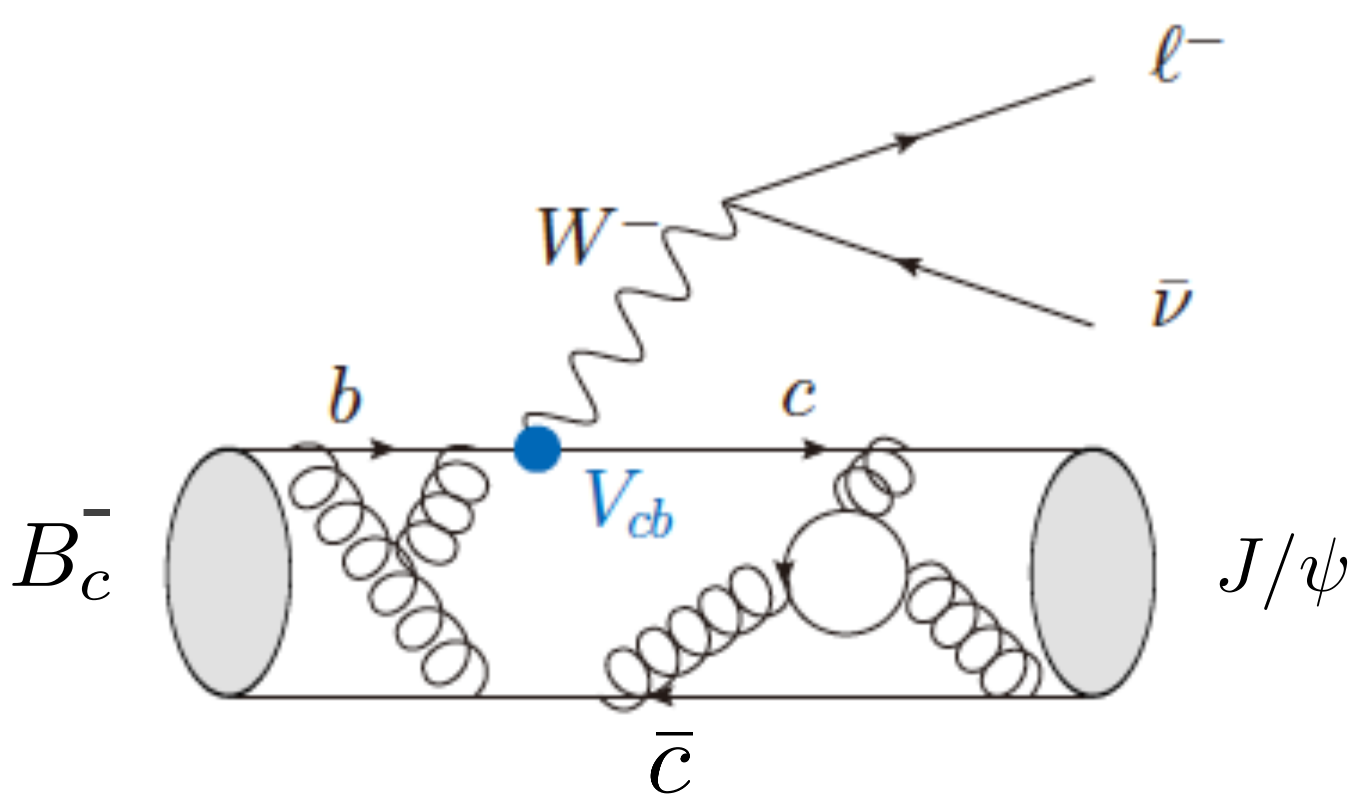
| Label | Spin | Charge | $R(D^{(*)})$ | $R(K^{(*)})$ | muon g-2 | $M_W$ |
|---|---|---|---|---|---|---|
| $S_1$ LQ (*) | 0 | $(\bar{3}, 1, 1/3)$ | ✓ | Loop | ✓ | With $S_3$ |
| $U_1$ LQ | 1 | (3, 1, 2/3) | ✓ | ✓ | ✗ | ✗ |
| $R_2$ LQ | 0 | (3, 2, 7/6 [1/6]) | ✓ | Loop | ✓ | ✓ |
| $V_2$ LQ (*) | 1 | $(\bar{3}, 2, 5/6)$ | only R(D) | Small | Small | ✓ |
| $S_3$ LQ (*) | 0 | $(\bar{3}, 3, 1/3)$ | ✗ | ✓ | ✗ | With $S_1$ |
| $U_3$ LQ | 1 | (3, 3, 2/3) | ✗ | ✓ | ✗ | ? |

# Related channel: $R(J/\psi)$




- The LFU violation was also observed in $B_c^- \to J/\psi$

$$\mathcal{R}(J/\psi) = \frac{\mathcal{B}(B_c^- \to J/\psi \tau^- \bar{\nu}_\tau)}{\mathcal{B}(B_c^- \to J/\psi \ell^- \bar{\nu}_\ell)}$$




$R(J/\psi)_{\rm exp} = 0.71 \pm 0.17_{\rm stat} \pm 0.18_{\rm syst}$ [LHCb, 1711.05623]

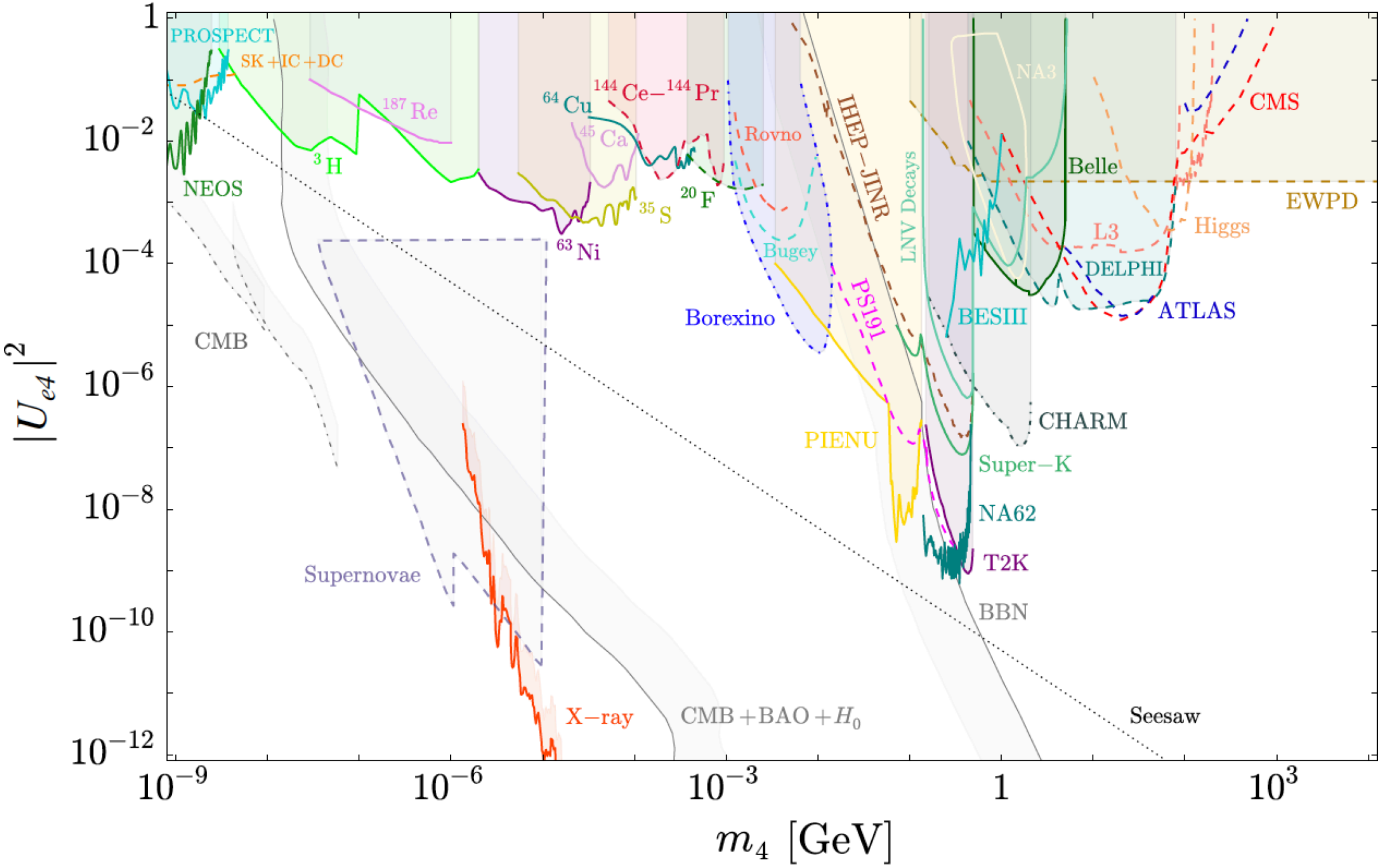
$R(J/\psi)_{\rm SM} = 0.258 \pm 0.004$ Based on first lattice result [HPQCD, 2007.06956]

using $N_f$=2+1+1, with "HISQ" *c* and heavy quark *b*

**1.8σ consistent**

**Same-direction tension** as R(D) and R(D*) anomalies

[Bolton, Deppisch, Dev, 1912.03058]



# Operators for CAA

$$Q_{Hq}^{(1)ij} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_i\gamma^\mu P_L q_j)\,, \qquad Q_{Hq}^{(3)ij} = (H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_i\tau^I\gamma^\mu P_L q_j)\,,$$

$$Q_{Hu}^{ij} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_i\gamma^\mu P_R u_j)\,, \qquad Q_{Hd}^{ij} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_i\gamma^\mu P_R d_j)\,,$$

$$Q_{Hud}^{ij} = i(\tilde{H}^\dagger D_\mu H)(\bar{u}_i\gamma^\mu P_R d_j)\,.$$

$$\begin{aligned}\mathcal{L}_{W,Z} = & -\frac{g_2}{\sqrt{2}}W_\mu^+\,\bar{u}_i\gamma^\mu\left(\left[V\cdot\left(\mathbb{1}+v^2C_{Hq}^{(3)}\right)\right]_{ij}P_L+\frac{v^2}{2}\left[C_{Hud}\right]_{ij}P_R\right)d_j+\text{h.c.}\\ & -\frac{g_2}{6c_W}Z_\mu\,\bar{u}_i\gamma^\mu\left(\left[(3-4s_W^2)\mathbb{1}+3v^2\,V\cdot\left\{C_{Hq}^{(3)}-C_{Hq}^{(1)}\right\}\cdot V^\dagger\right]_{ij}P_L\right.\\ & \qquad\left.-\left[4s_W^2\mathbb{1}+3v^2C_{Hu}\right]_{ij}P_R\right)u_j\\ & -\frac{g_2}{6c_W}Z_\mu\,\bar{d}_i\gamma^\mu\left(\left[(2s_W^2-3)\mathbb{1}+3v^2\left\{C_{Hq}^{(3)}+C_{Hq}^{(1)}\right\}\right]_{ij}P_L\right.\\ & \qquad\left.+\left[2s_W^2\mathbb{1}+3v^2C_{Hd}\right]_{ij}P_R\right)d_j\,,\end{aligned}$$

# A $\mathrm{SU(2)}_1 \times \mathrm{SU(2)}_2 \times \mathrm{U(1)}_Y$ model

- We consider an extended electroweak gauge group $\mathrm{SU(2)}_1 \times \mathrm{SU(2)}_2 \times \mathrm{U(1)}_Y$ model, which contains heavy vector-like quarks and heavy SU(2) gauge multiplet
- After integrating out the vector-like quarks, the following effective Lagrangian is generated

[Boucenna, Celis, Fuentes-Martin, Vicente, Virto, 1608.01349]

$$\mathcal{L} = + \frac{g_{ij}}{2} Z'_\mu \bar{d}^i_L \gamma^\mu d^j_L - \frac{(VgV^\dagger)_{ij}}{2} Z'_\mu \bar{u}^i_L \gamma^\mu u^j_L - \frac{(Vg)_{ij}}{\sqrt{2}} W'^+_\mu \bar{u}^i_L \gamma^\mu d^j_L + \text{H.c.}\,,$$

$g_{ij}$ basis is defined by the first term

$$\Rightarrow \quad C_2^{q,W'}(M_V) = \frac{1}{4\sqrt{2} G_F M_V^2} \frac{(Vg)_{23}(Vg)^*_{1q}}{V_{cb} V^*_{uq}}\,.$$

# Three scenarios

- We consider the fowling three scenarios

$$\mathcal{L} = + \frac{g_{ij}}{2} Z'_\mu \bar{d}^i_L \gamma^\mu d^j_L - \frac{(V g V^\dagger)_{ij}}{2} Z'_\mu \bar{u}^i_L \gamma^\mu u^j_L - \frac{(V g)_{ij}}{\sqrt{2}} W'^+_\mu \bar{u}^i_L \gamma^\mu d^j_L + \text{H.c.}\,,$$

$$g_{ij} = \begin{pmatrix} g_{11} & 0 & 0 \\ 0 & g_{11} & 0 \\ 0 & 0 & g_{33} \end{pmatrix}, \quad g_{ij} = \begin{pmatrix} g_{11} & 0 & 0 \\ 0 & g_{11} & g_{23} \\ 0 & g_{23} & 0 \end{pmatrix}, \quad g_{ij} = \begin{pmatrix} g_{11} & 0 & 0 \\ 0 & g_{11} & g_{23} \\ 0 & g_{23} & g_{33} \end{pmatrix},$$

Scenario1 Scenario2 Scenario3

Here, U(2) symmetry is imposed to avoid strong constraints from *K*- and *D*-meson mixings

# Scenario1

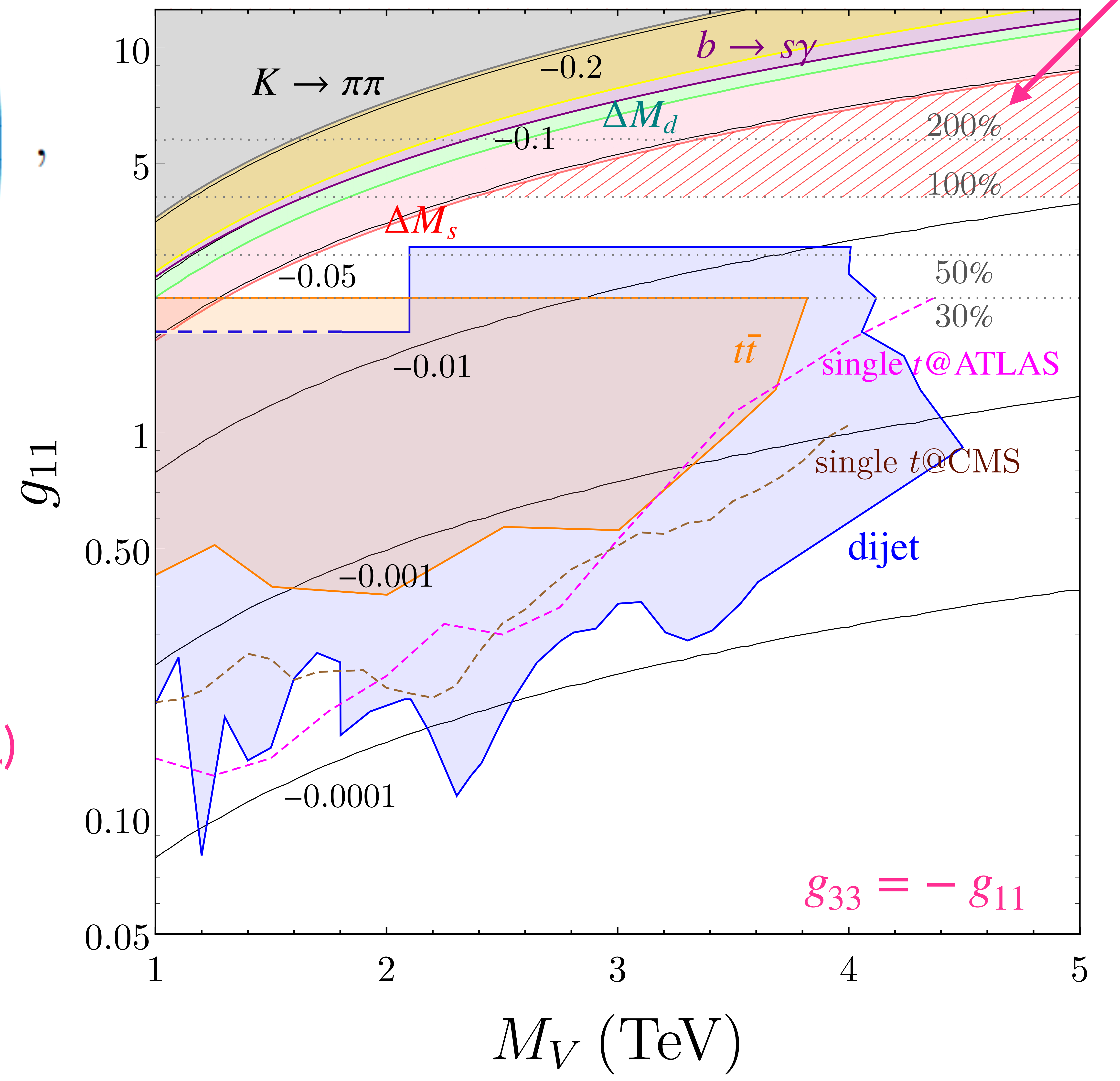
$$g_{ij} = \begin{pmatrix} g_{11} & 0 & 0 \\ 0 & g_{11} & 0 \\ 0 & 0 & g_{33} \end{pmatrix},$$

Black contours:

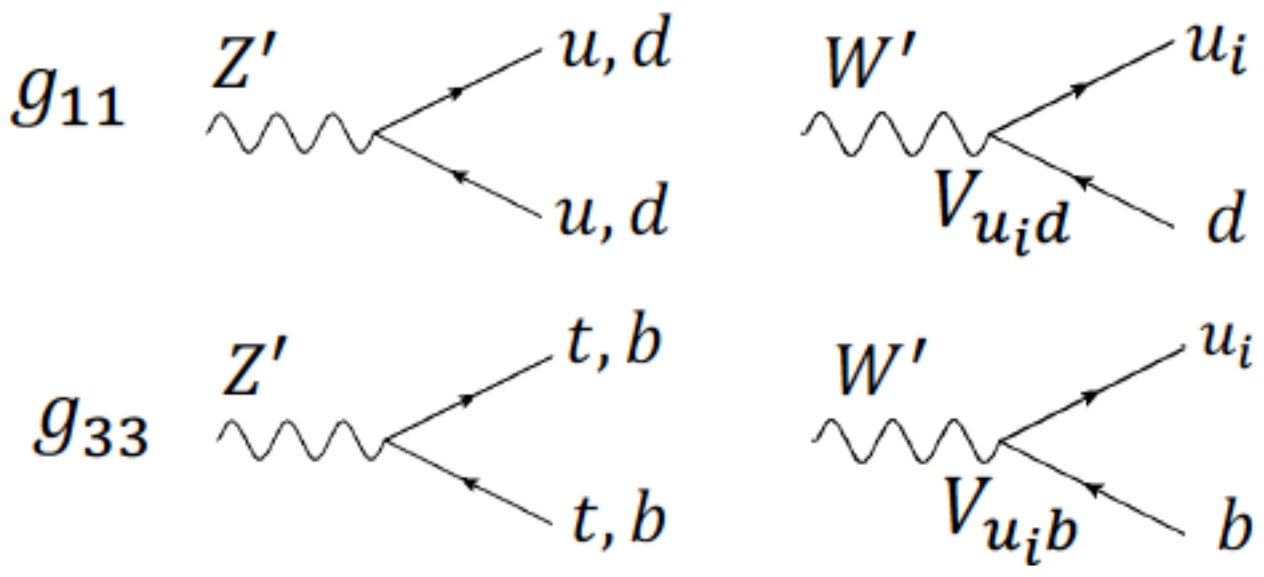
$$\frac{C_2^{\rm NP}(m_b)}{C_2^{\rm SM}(m_b)}$$

Flavor constraint ($\Delta M_s$) comes from $W$-$W'$ box $\propto g_{11} \times g_{33}$

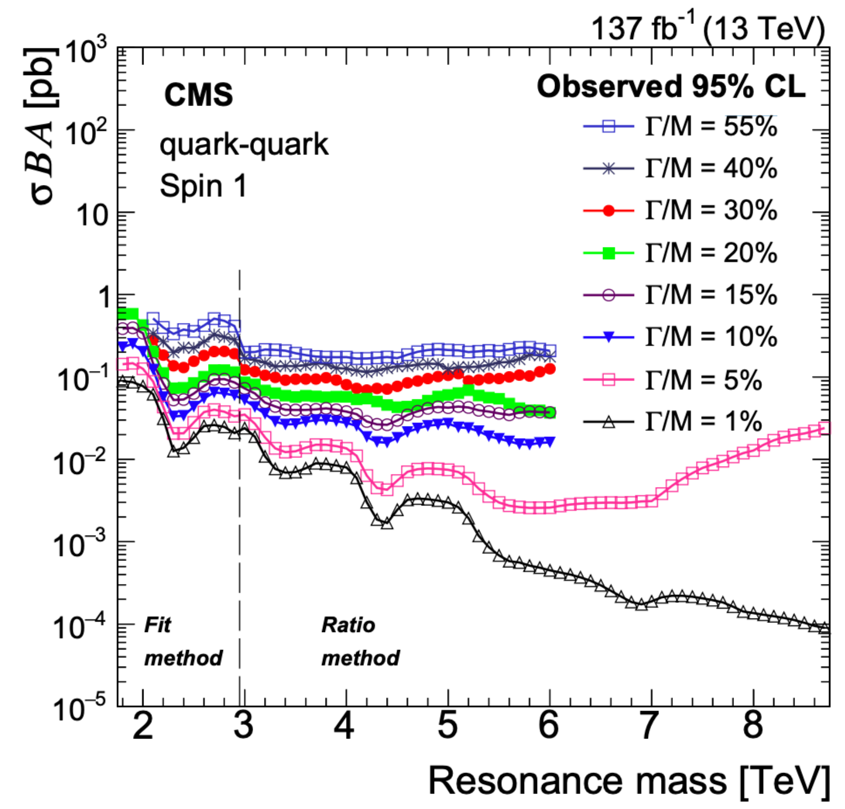
Width > 100%




Strong bounds comes from direct search by LHC




We rescaled the width-dependent limit




[CMS 1911.03947]

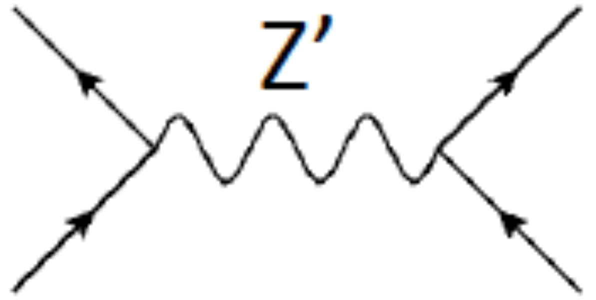
# Scenario2

$$g_{ij} = \begin{pmatrix} g_{11} & 0 & 0 \\ 0 & g_{11} & g_{23} \\ 0 & g_{23} & 0 \end{pmatrix},$$

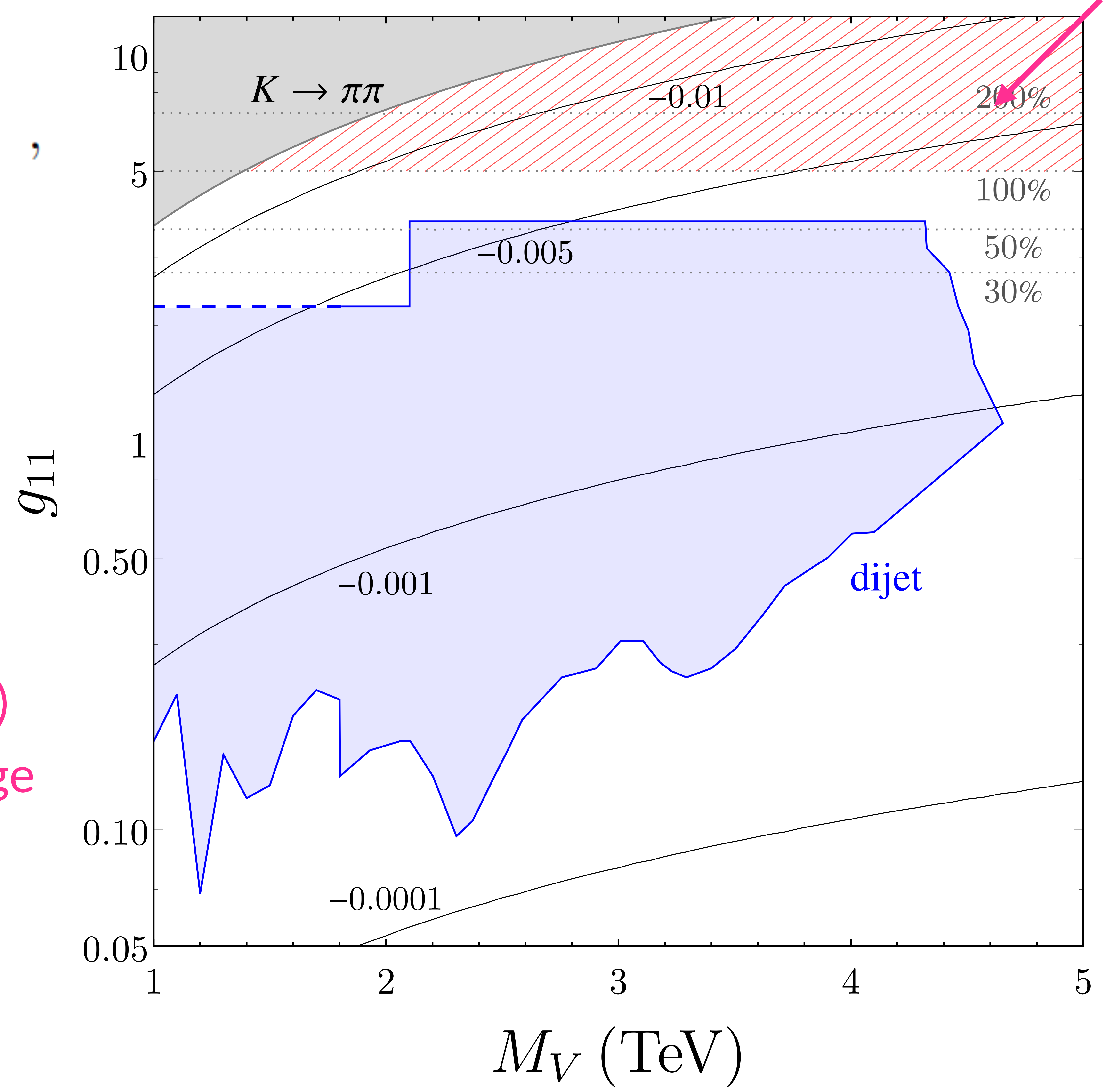
Black contours:

$$\frac{C_2^{\rm NP}(m_b)}{C_2^{\rm SM}(m_b)}$$

Flavor constraint ($\Delta M_s$) comes from $Z'$-exchange $\propto |g_{23}|^2$




Width > 100%




$$\frac{C_2^{NP}(\Lambda_{NP})}{C_2^{SM}} \sim \frac{g_{11}\times g_{23}}{4\sqrt{2}G_F M_V^2 V_{cb}}$$

Enhancement by $\frac{1}{V_{cb}} \sim 25$

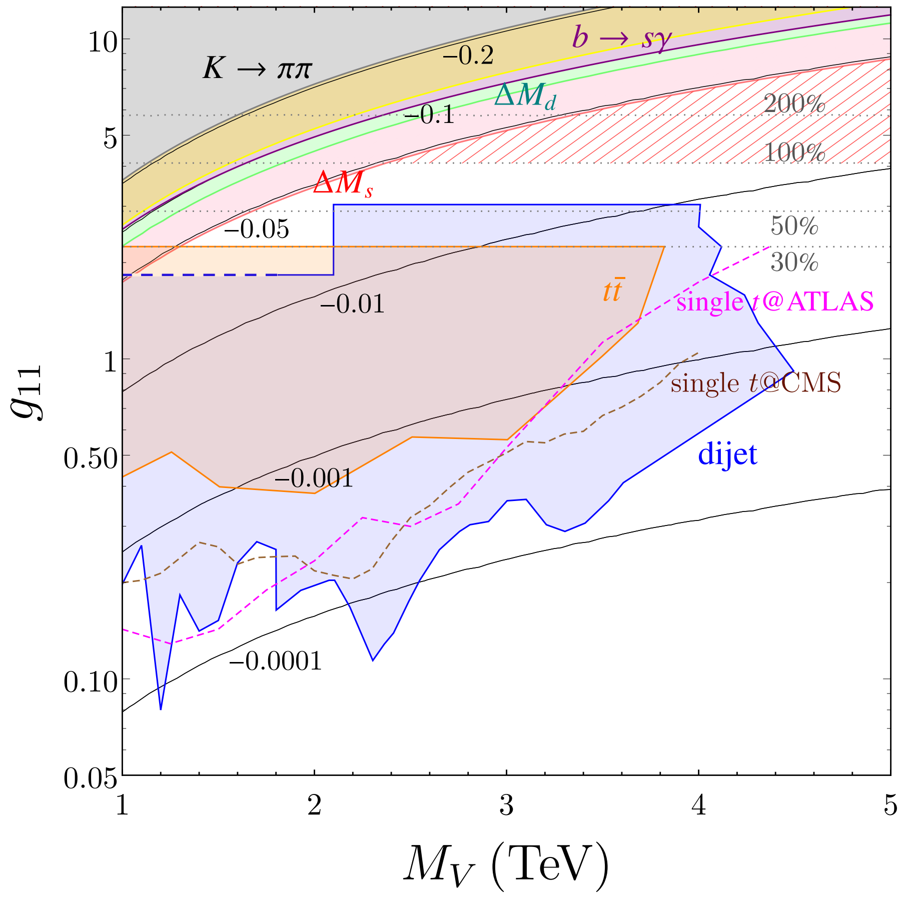
$g_{23}$ is saturated under the flavor constraints on this plane

# Scenario3

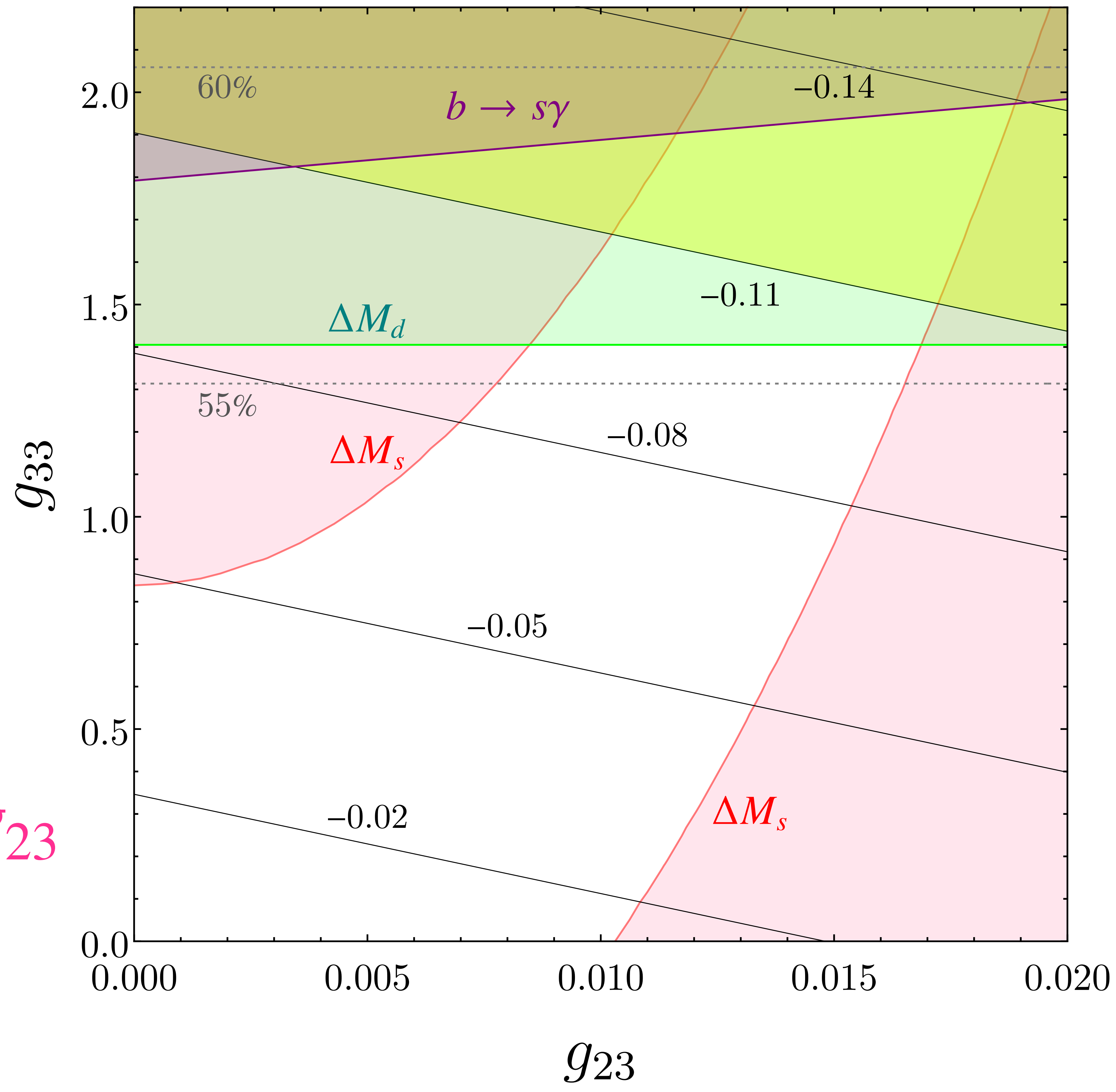
$$g_{ij} = \begin{pmatrix} g_{11} & 0 & 0 \\ 0 & g_{11} & g_{23} \\ 0 & g_{23} & g_{33} \end{pmatrix},$$

$$M_V = 1\,\text{TeV and } g_{11} = -3.6.$$

Scenario1




non-zero $g_{23}$




Contribution to $\Delta M_s$ can be cancelled

$$\Delta M_s^{W'} < 0, \quad \Delta M_s^{Z'} > 0$$

W-W' box Z' tree level

Then constraint from $\Delta M_d$ is important!

$\Delta M_d / \Delta M_s$ would give additional bound

$C_2(NP)/C_2(SM) \sim -0.10$

would be possible