Anomalies in Flavor Physics

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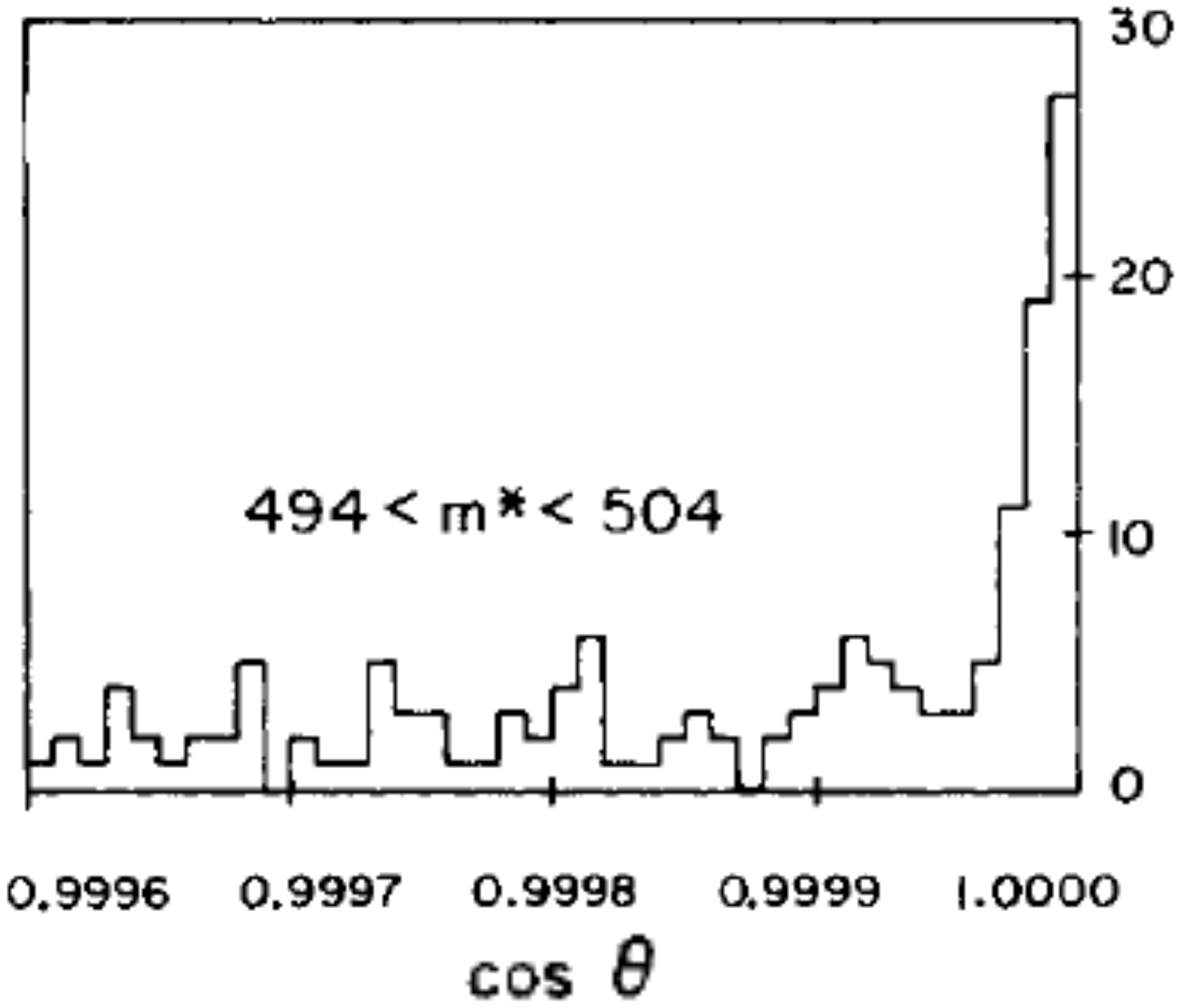
The 4th KMI school

- Statistical Data Analysis and Anomalies in Particle Physics and Astrophysics -

Nagoya University, December 17, 2022

A historic flavor anomaly



[Christenson, Cronin, Fitch, Turlay. ’64, PRL]

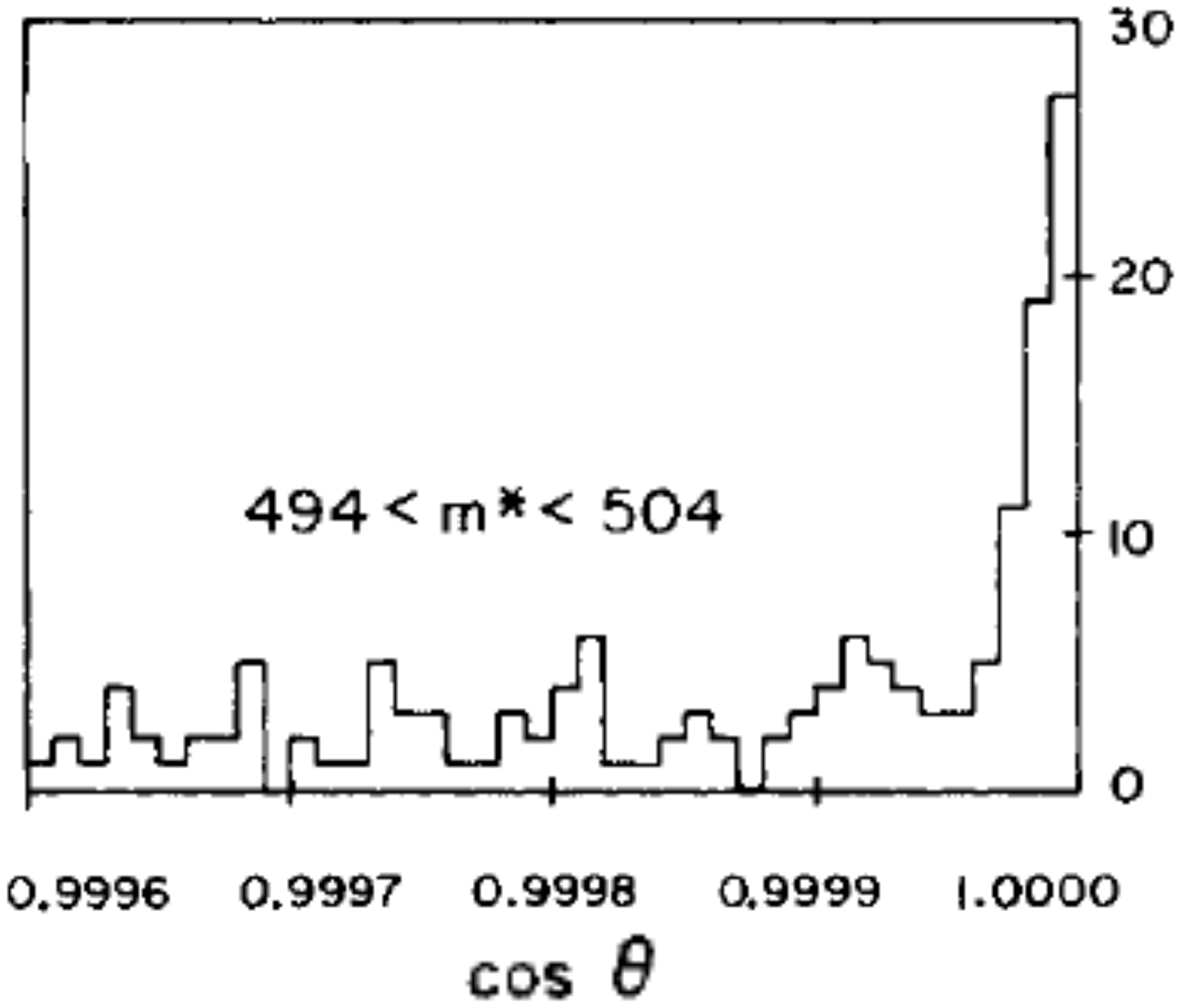
The relative efficiency for detection of the three-body K_2^0 decays compared to that for decay to two pions is 0.23. We obtain 45 ± 9 events in the forward peak after subtraction of background out of a total corrected sample of 22 700 K_2^0 decays.

22700 events → event selection
→ 45 signal with ±9 uncertainty

45/9 = 5σ peak in the last several bins

Then, what?

A historic flavor anomaly



[Christenson, Cronin, Fitch, Turlay. '64, PRL]

"Discovery of $K_L^0 \to \pi^+\pi^-$ decay"

corresponding to "discovery of CP violation"

inconsistent with Weinberg-Salam theory

Kobayashi and **Maskawa** introduced the CKM matrix

prediction of *c*,*b*,*t* + CPV

… and this building was built

Thus, *Anomaly* had provided us great breakthroughs!

Kobayashi-Maskawa Institute

Statistical fluctuation

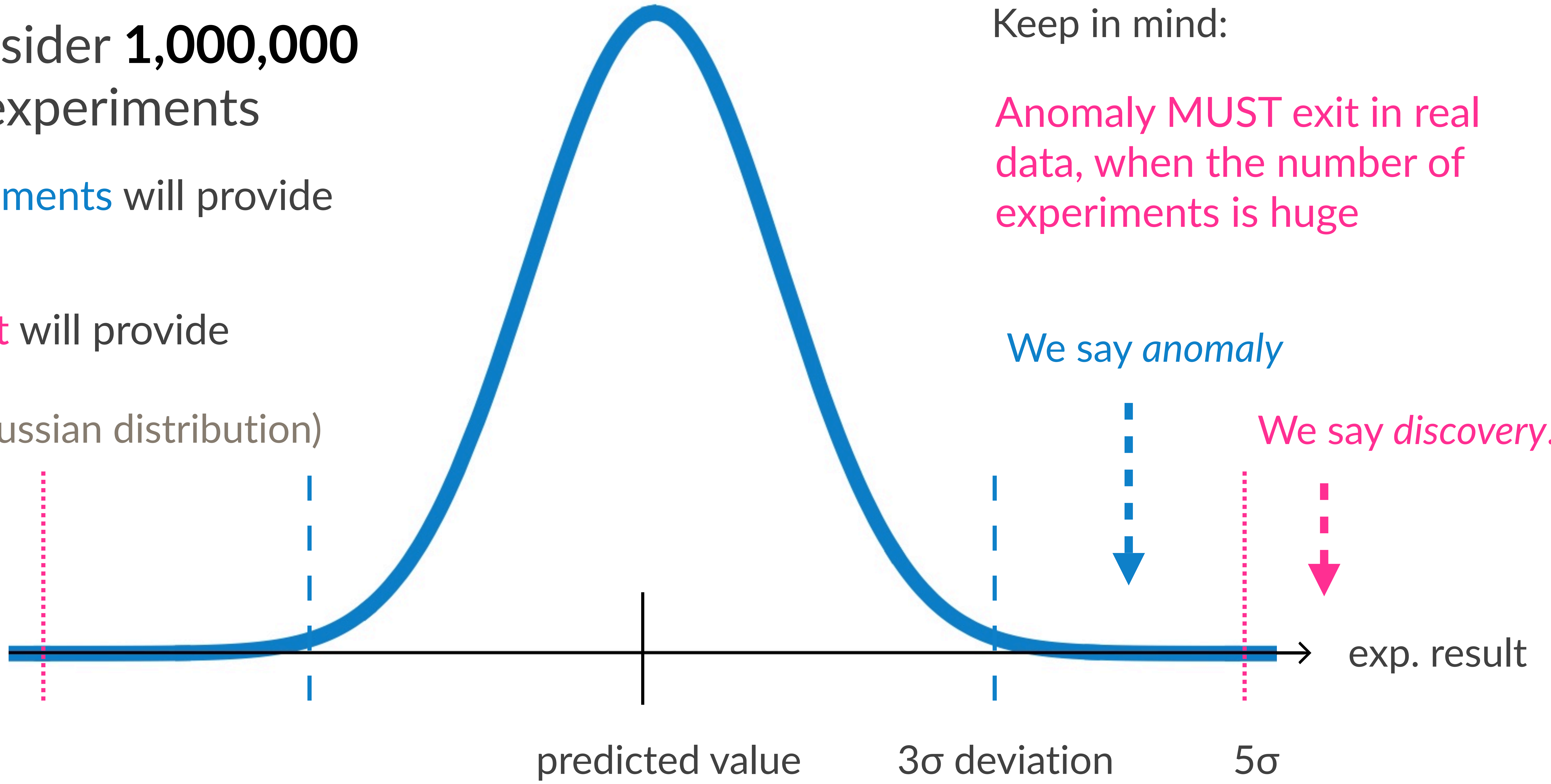
Let us consider **1,000,000** different experiments

2,700 experiments will provide 3σ deviation

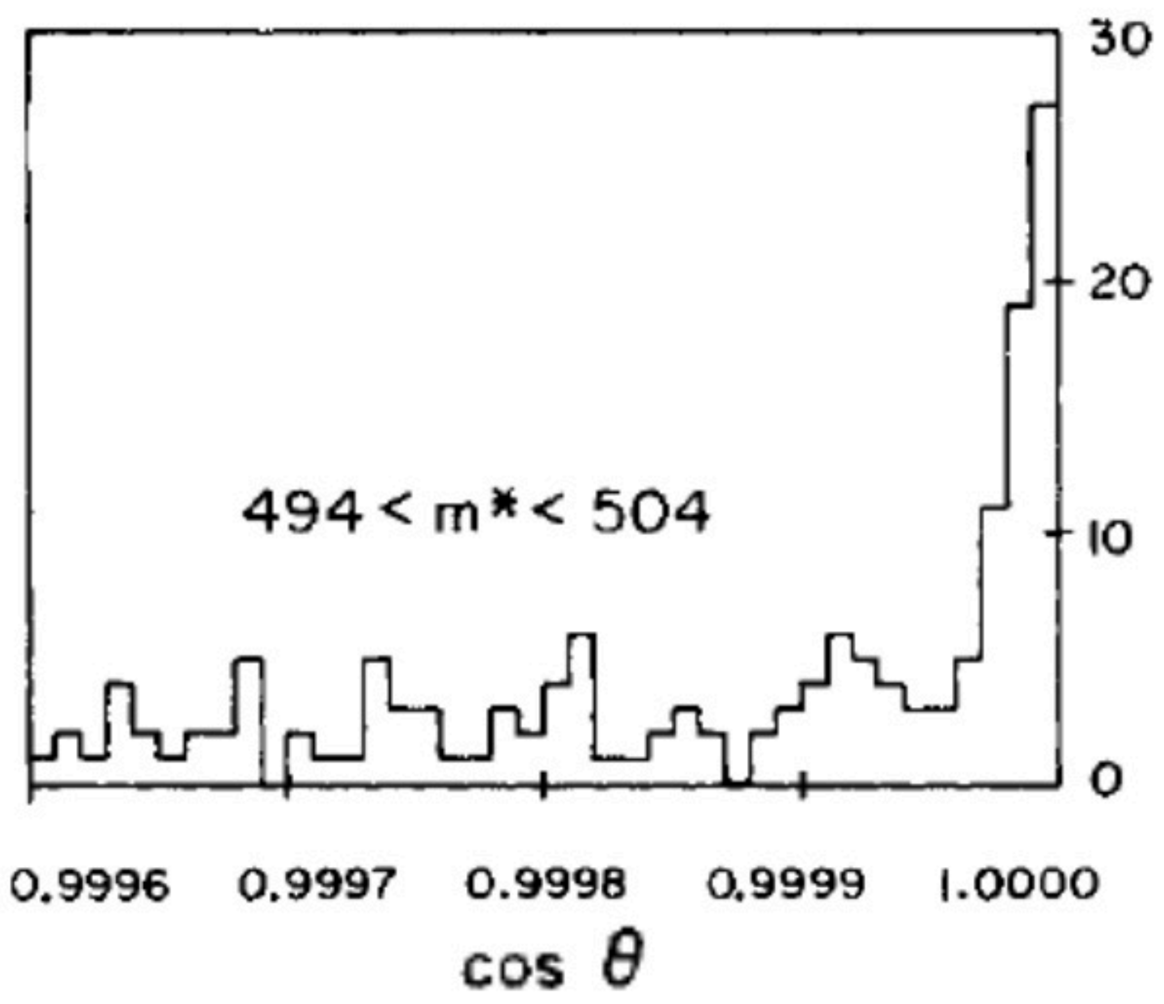
1 experiment will provide 5σ deviation
(assuming Gaussian distribution)

Keep in mind:

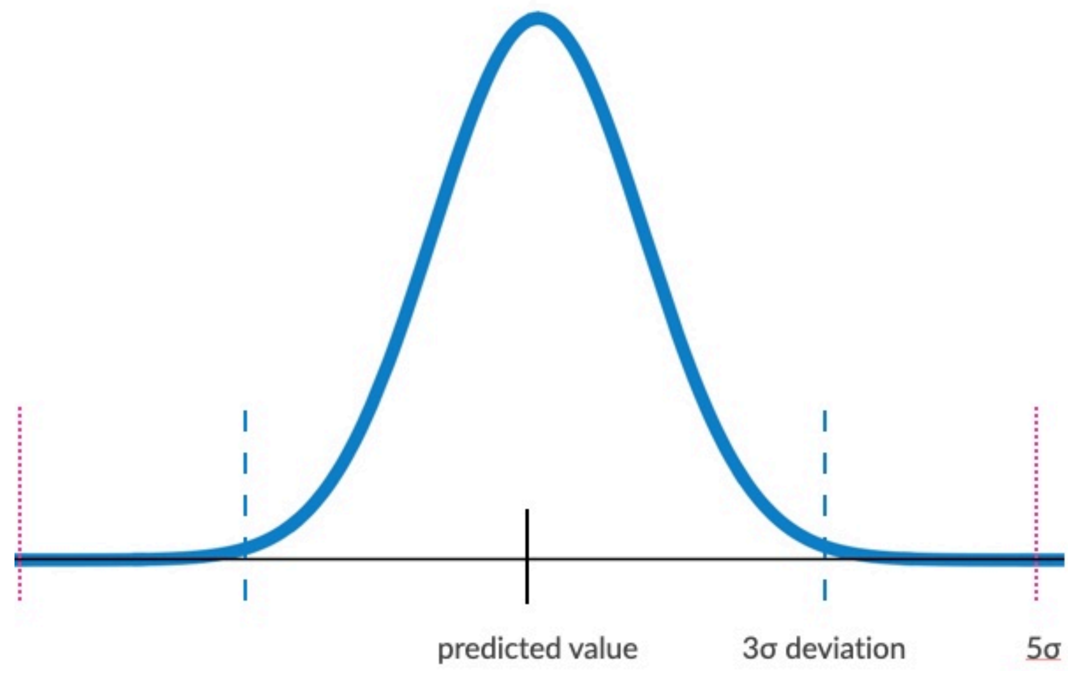
Anomaly MUST exit in real data, when the number of experiments is huge



Q. How to distinguish “new physics signal” from “fake anomaly”?



or



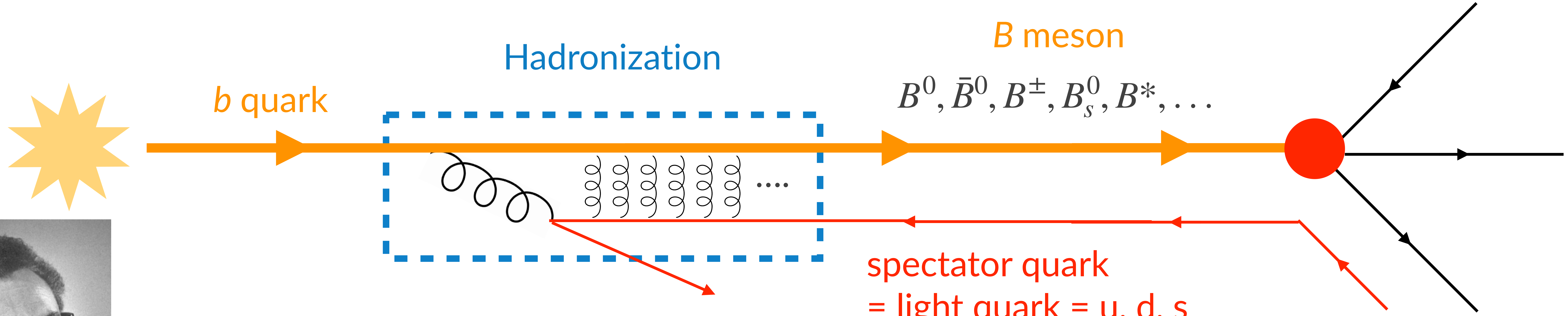
better strategies:

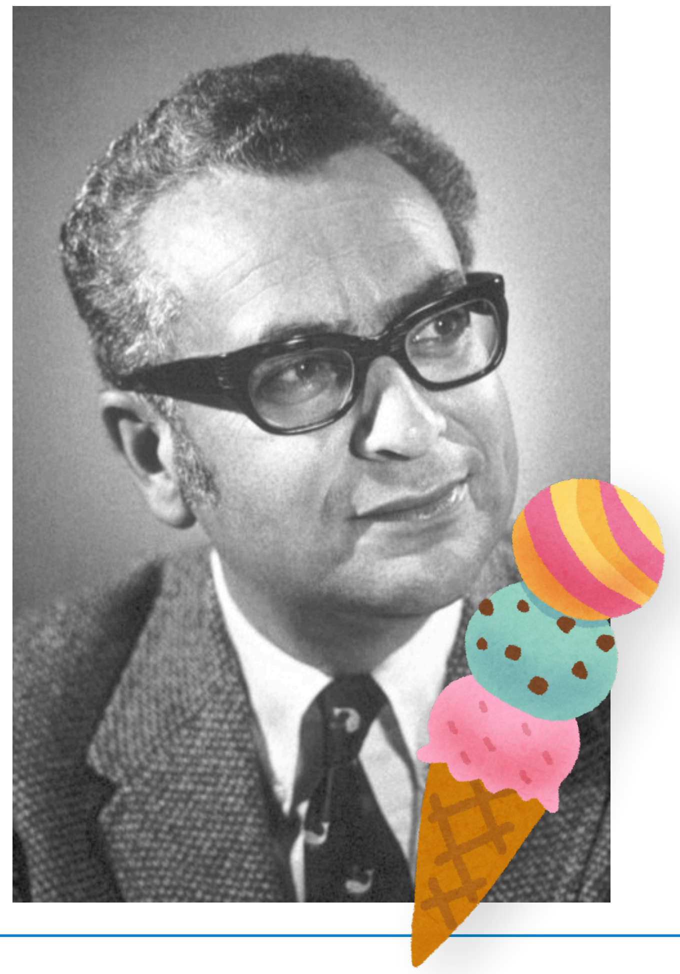
1, [exp-side] cross-checked by different collaborations or methods

2, [th-side] hidden theoretical correlation among several anomalies

What is flavor physics?

- Quarks cannot become the asymptotic field but must be contained in hadron=meson (or baryon) ***b* … *B* meson**, ***c* … *D* meson**, ***s* … *K* meson**





Gell-Mann named it "flavor" at an ice-cream store, just as ice-cream has both color and quark (cheese) flavor

Quark flavor physics means physics of meson (or baryon) transition;

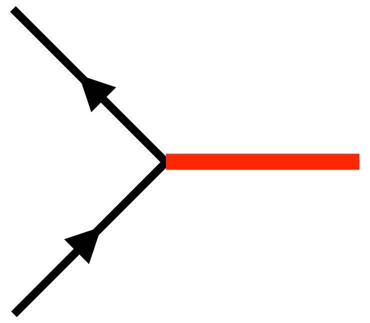
$B \to K + X(b \to s), D \to \pi + X(c \to u), K \to \pi + X(s \to d)$, etc.

High-energy vs. High-precision

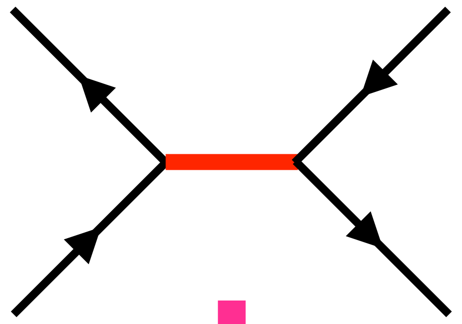
- High-energy experiments and high-precision experiments can probe new physics (NP) by different and complementary ways

hunt a new interaction

SM particle



New particle

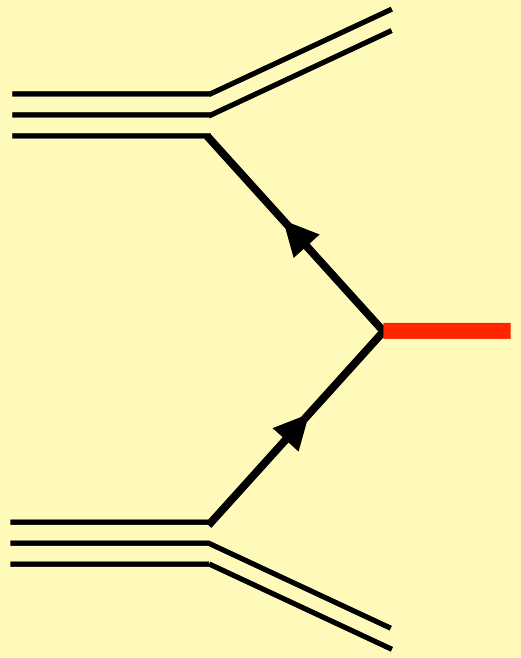


Effective field theory

Collider physics

High-energy frontier

$\sqrt{s} > m_{NP}$



ATLAS EXPERIMENT

CMS

comple-mentary

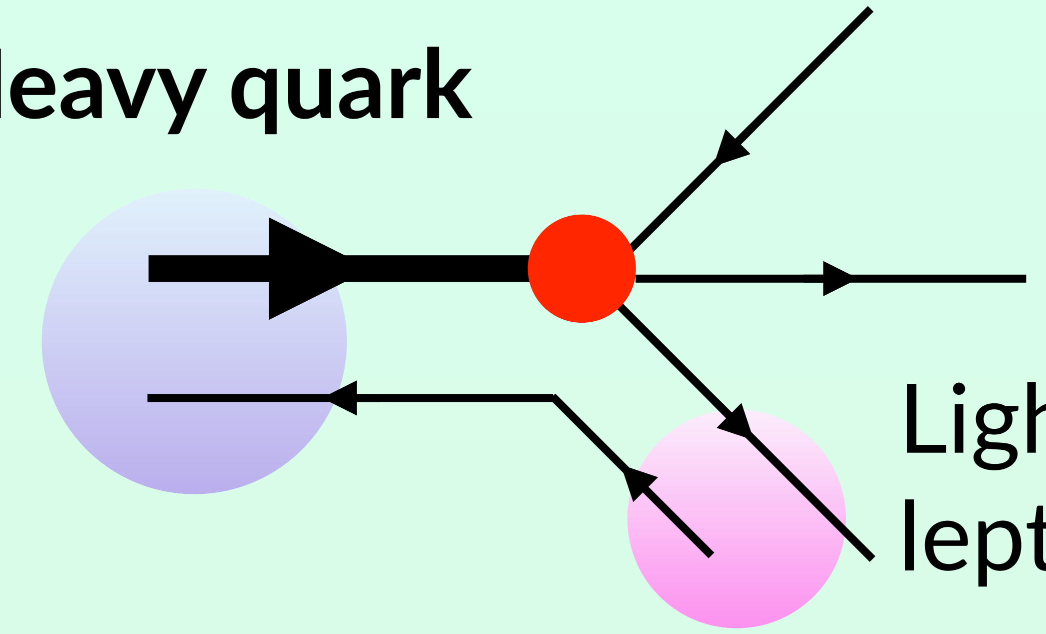
Precision measurement

High-intensity frontier

LHCb

Belle II

Heavy quark



Light meson, lepton

Small theoretical uncertainty → Good sensitivity to NP

B physics in B factory

- Rich phenomenology; CKM matrix, flavor-changing neutral current (FCNC), CP violation, tau lepton, Lepton-flavor universality (LFU), Hadron spectroscopy, dark sector, etc.

BaBar experiment @ **SLAC**, physics run **finished at 2008**

$e^+e^- \to \Upsilon \to B\bar{B}$ $10^8 B\bar{B}$ per year

Belle and Belle II experiments @ **KEK**, Belle II started at 2019

$e^+e^- \to \Upsilon \to B\bar{B}$ $10^{10} B\bar{B}$ per year

LHCb experiment @ **CERN**, Run 3 started at **2022**

$pp \to b\bar{b} \to B\bar{B}$ $10^{12} b\bar{b}$ per year (large event but large bkg)

newcomer!

CMS experiment will become B factory at Run 3 (called *B*-parking), Run 2 data [$10^{10}\,(b \to \mu X)\bar{b}$] will be shown near future

CKM matrix

- Cabibbo-Kobayashi-Maskawa (CKM) matrix arises the relative misalignment between the Yukawa matrices and gauge interactions:

$$\mathcal{L} \supset -\frac{g}{\sqrt{2}}\bar{u}_L^i \gamma^\mu d_L^i W_\mu^+ \xrightarrow{\text{mass-eigenbasis}} -\frac{g}{\sqrt{2}}\bar{u}_L^i \gamma^\mu (U_u^\dagger U_d)^{ij} d_L^j W_\mu^+$$

$$= -\frac{g}{\sqrt{2}}\bar{u}_L^i \gamma^\mu V_{\text{CKM}}^{ij} d_L^j W_\mu^+$$

- In the SM, the CKM matrix appears only through weak force

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

SM (Kobayashi-Maskawa) prediction:

must be unitary matrix

3 mixing angles and

1 CP-violating (CPV) phase

phase is here

Kobayashi-Maskawa Institute

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

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

SM NP?

CKM unitarity triangle

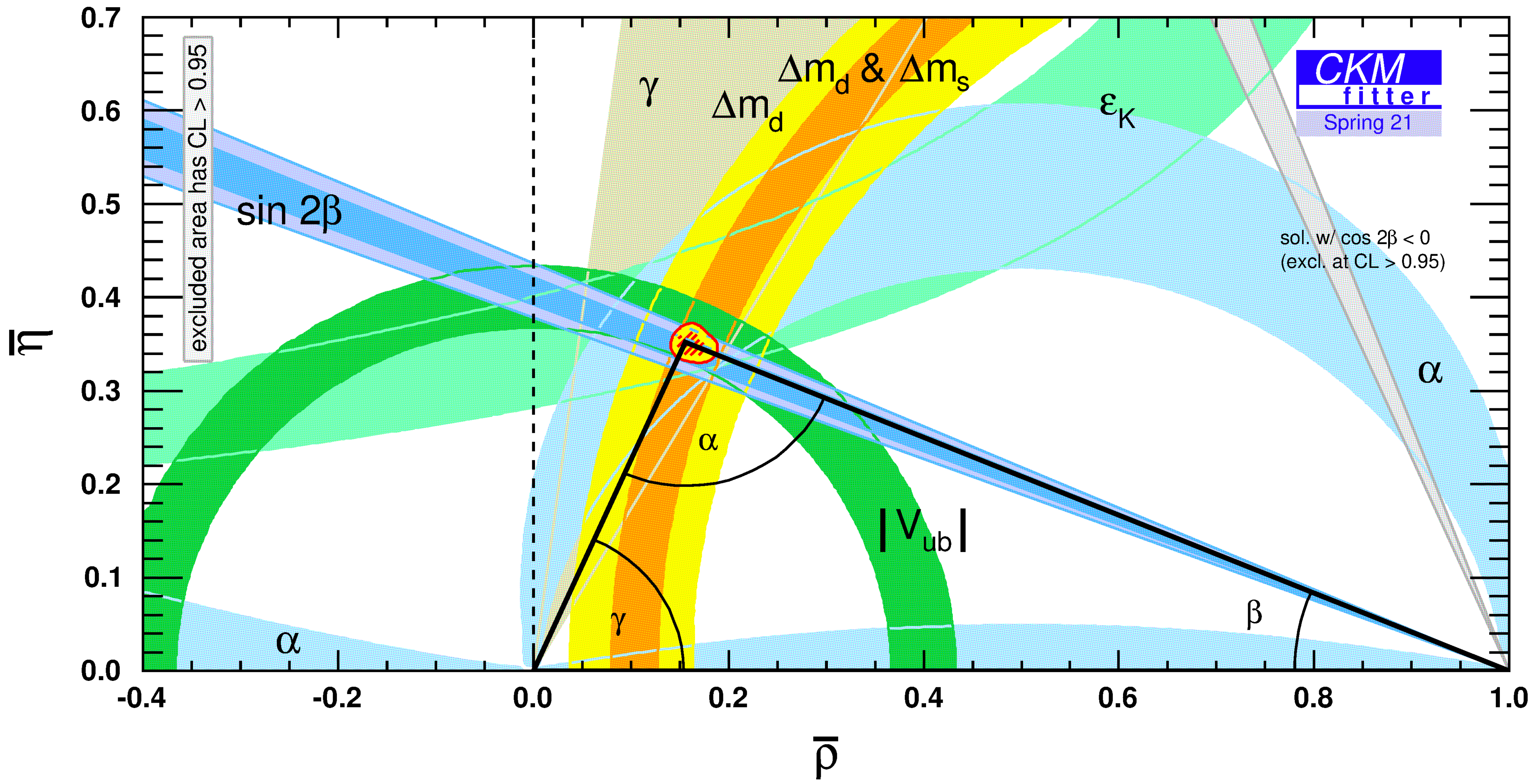
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Unitarity condition

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

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

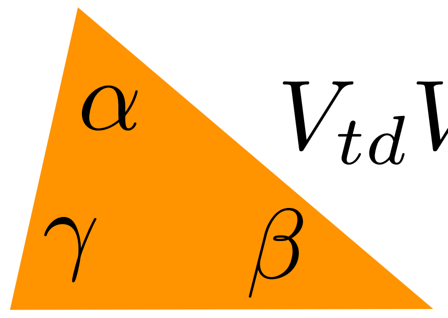
A triangle can be drawn on a complex plane



[CKM fitter 2021]

B triangle

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



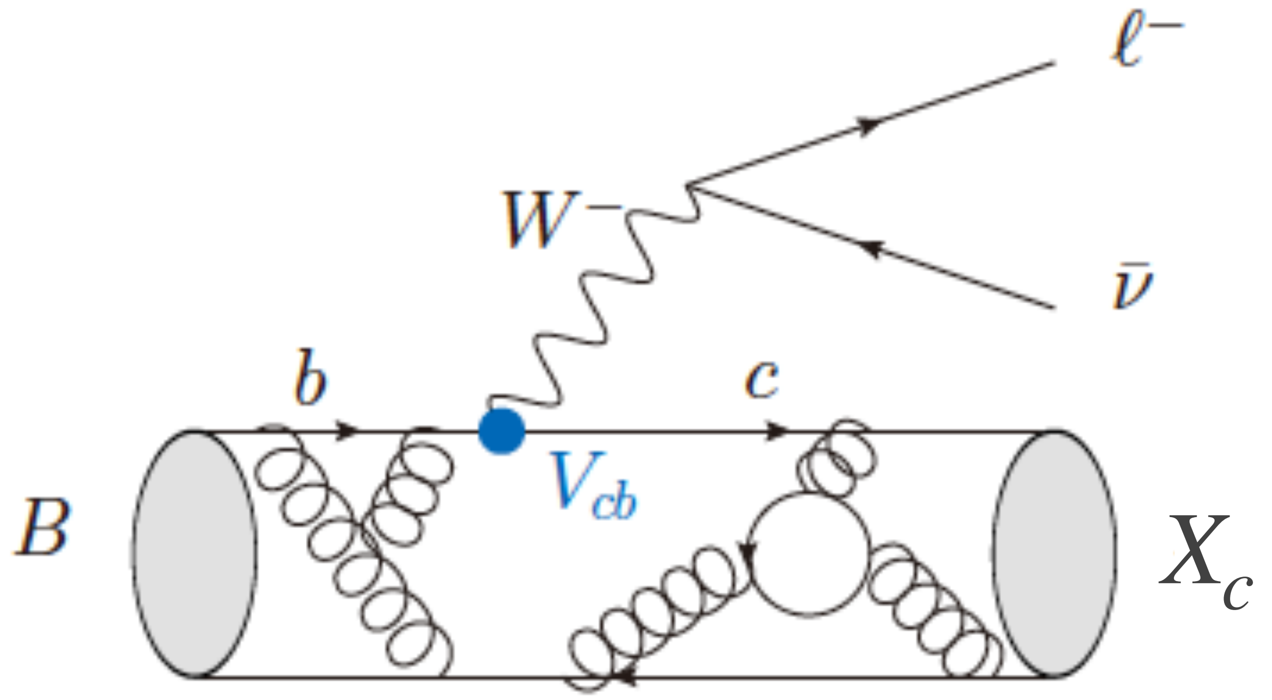
$V_{td}V_{tb}^* \sim \lambda^3$

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

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

$b \to c$ $[B \to X_c, D, D^*]$ semileptonic decays

- Comparing measured BR to the theoretical formulae **determines $|V_{cb}|$**
- Inclusive decays: $B \to X_c \ell \nu$
  - The heavy quark effective theory: $b \to c\ell\nu + \mathcal{O}(\alpha_s\,,\ \Lambda_{\rm QCD}/m_b)$ with non-perturbative elements
  - Last data in 2010 (BaBar) & no lattice → Belle II result coming soon [Belle II, 2205.06372], the first lattice study [Gambino, Hashimoto, '20]
- Exclusive decays: $B \to D\ell\nu, B \to D^*\ell\nu$
  - Hadronization is relevant; channel-dependent form factor, difficult SM prediction
  - Many data and many lattice results are available



$\ell = e, \mu + \tau$

Inclusive hadron states

X_c = D^{**}, D^*, D, $D\pi$, $D\pi\pi$...

Exclusive decays: $B \to D\ell\nu, B \to D^*\ell\nu$ [HFLAV 2021; based on CLN]

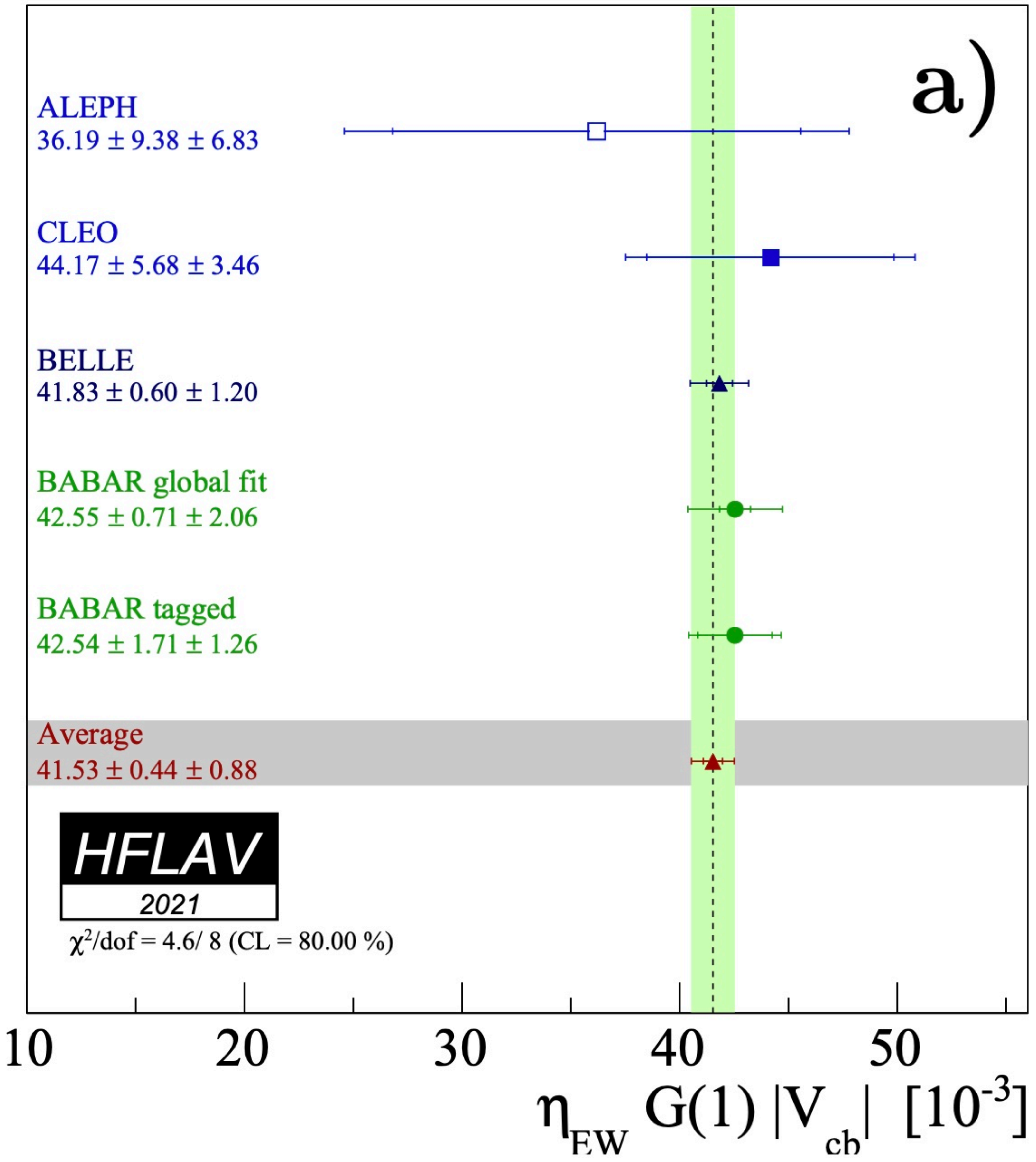
$B \to D\ell\nu$

χ^2/dof = 4.6/ 8 (CL = 80.00 %)

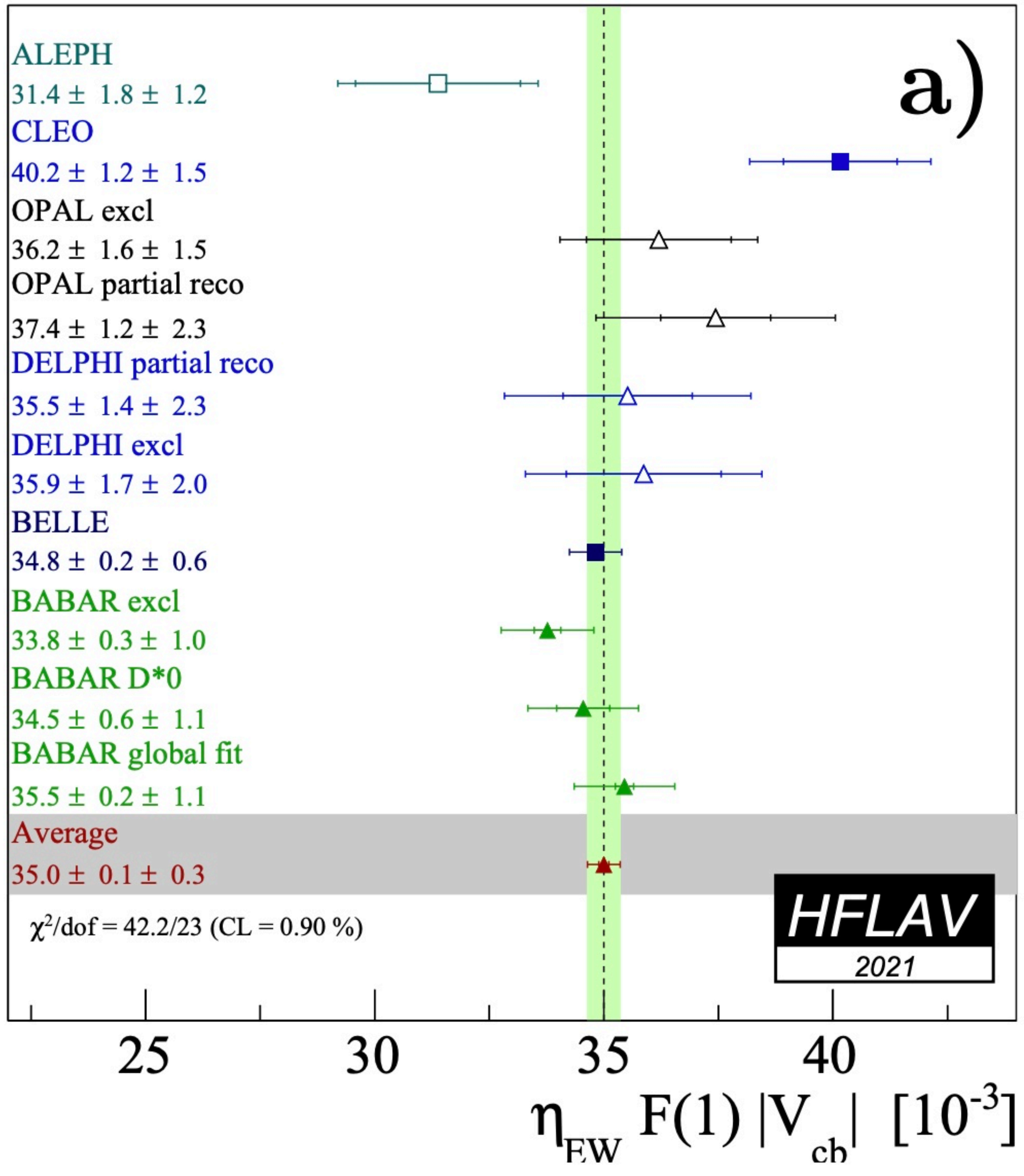
9 input data
(D^0 and $D^\pm$)
1 parameter fit
→ dof = 9-1=8

total χ^2 = 4.6

P value= 0.80



$B \to D^*\ell\nu$



χ^2/dof = 42.2/23 (CL = 0.90 %)

24 input data
(D^{*0} and $D^{*\pm}$)
→ dof = 23

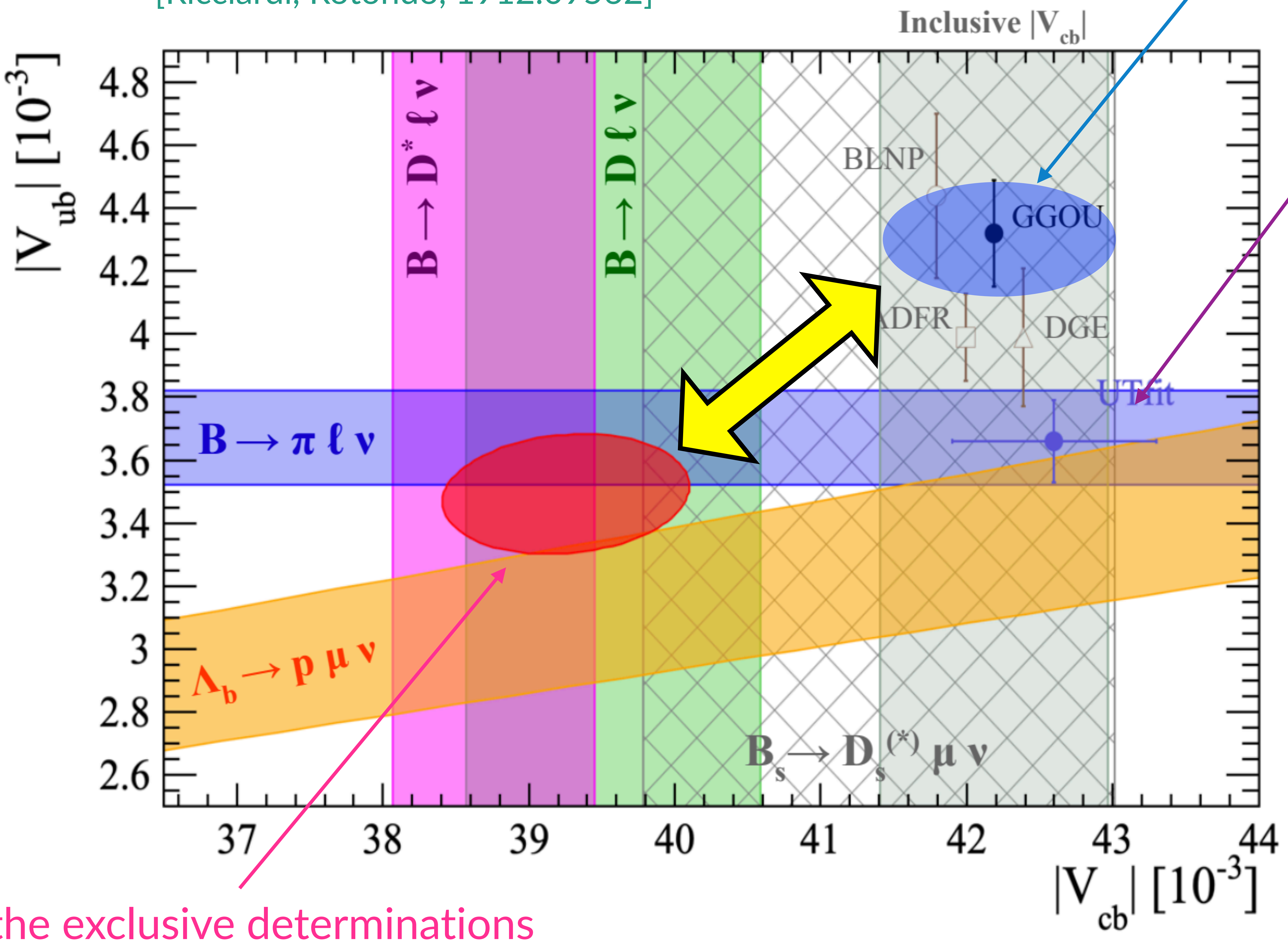
total χ^2 = 42.2

P value= 0.009

[Ricciardi, Rotondo, 1912.09562]

Average of the inclusive determinations

CKM unitarity



Kaon physics prefers inclusive V_{cb}

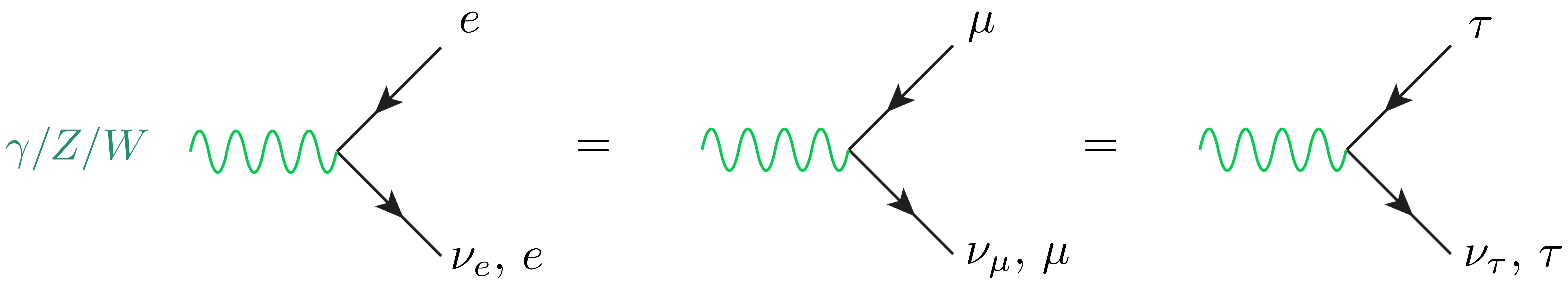
3.3σ tension between inclusive vs exclusive determinations of V_{cb} and V_{ub} (exclusive violates the CKM unitarity condition)

But, NP interpretation is not easy

Average of the exclusive determinations

Test of Lepton Flavor Universality (LFU)

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



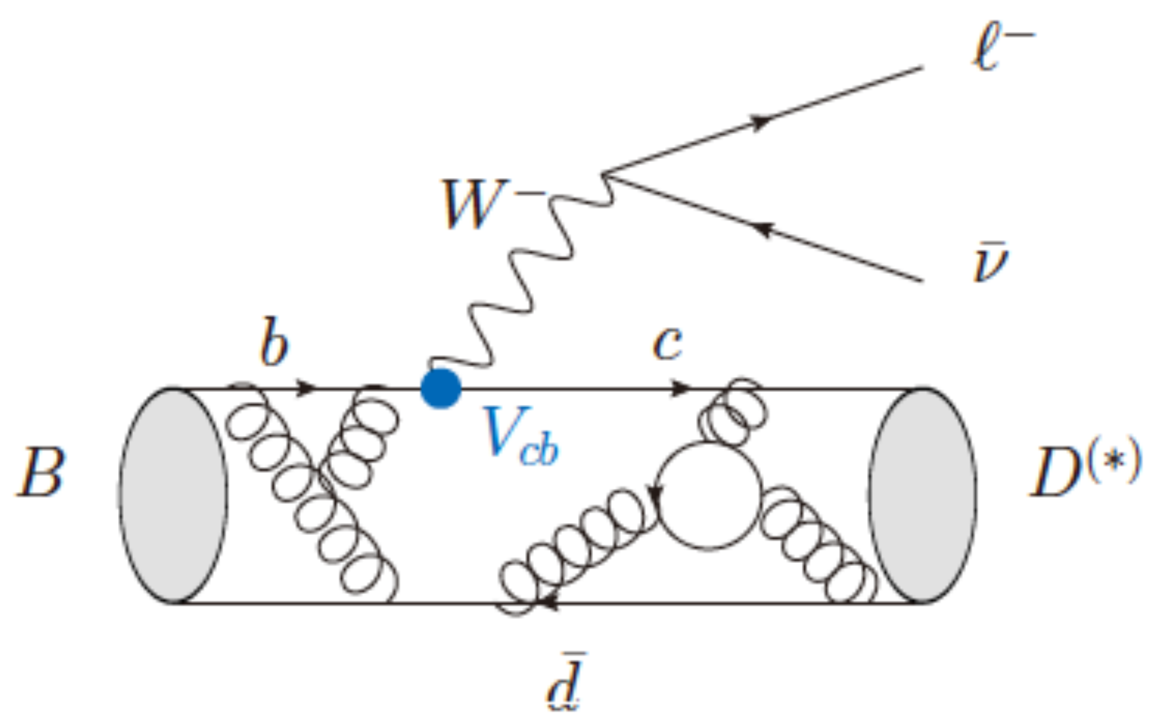
- Only **charged-lepton mass** violates the LFU within the SM

$$m_e = 0.5\,\text{MeV}\,, \qquad m_\mu = 105\,\text{MeV}\,, \qquad m_\tau = 1776\,\text{MeV}$$

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

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

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



[HFLAV 2022+, [Iguro, **TK,** Watanabe, 2210.10751]]

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	$0.280 \pm 0.018 \pm 0.029$	–	–
LHCb	$0.281 \pm 0.018 \pm 0.024$	$0.441 \pm 0.060 \pm 0.066$	-0.43
World average	$0.285 \pm 0.010 \pm 0.008$	$0.358 \pm 0.025 \pm 0.012$	-0.29

10 measurements with correlations and 2 parameter fit
→ dof = 10 - 2 = 8

total $\chi^2 = 9.2$

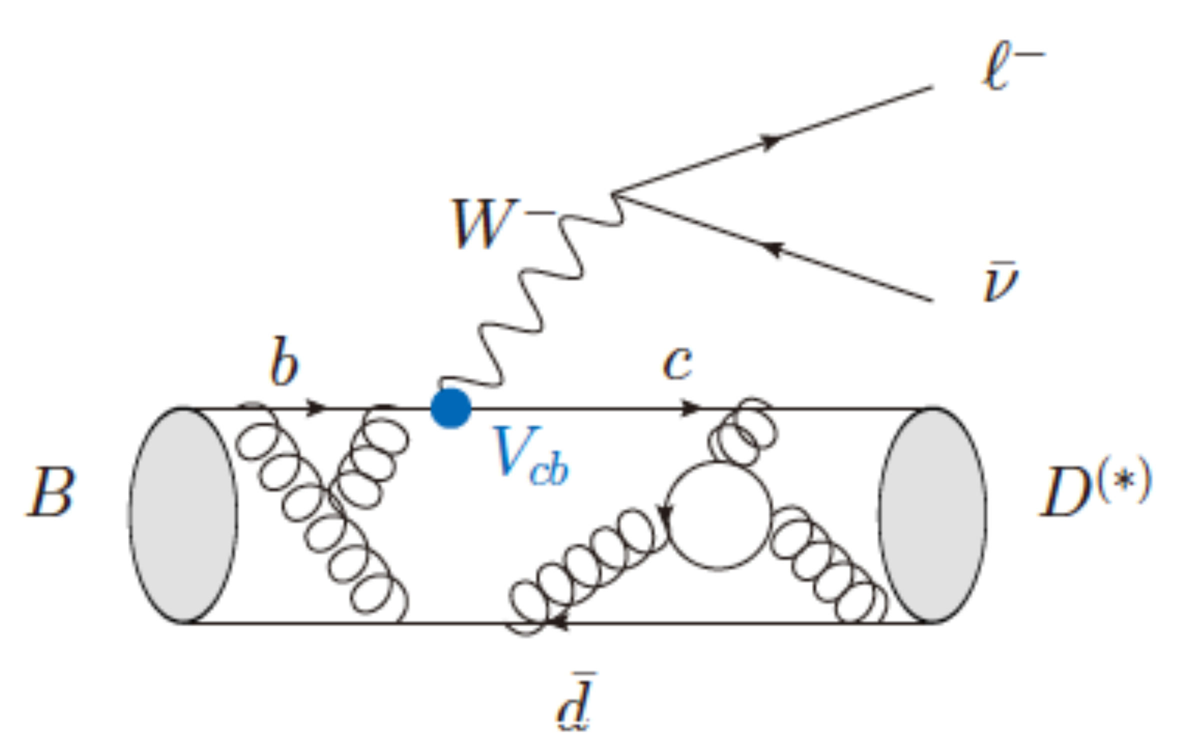
P value= 0.32 ; means data are consistent

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

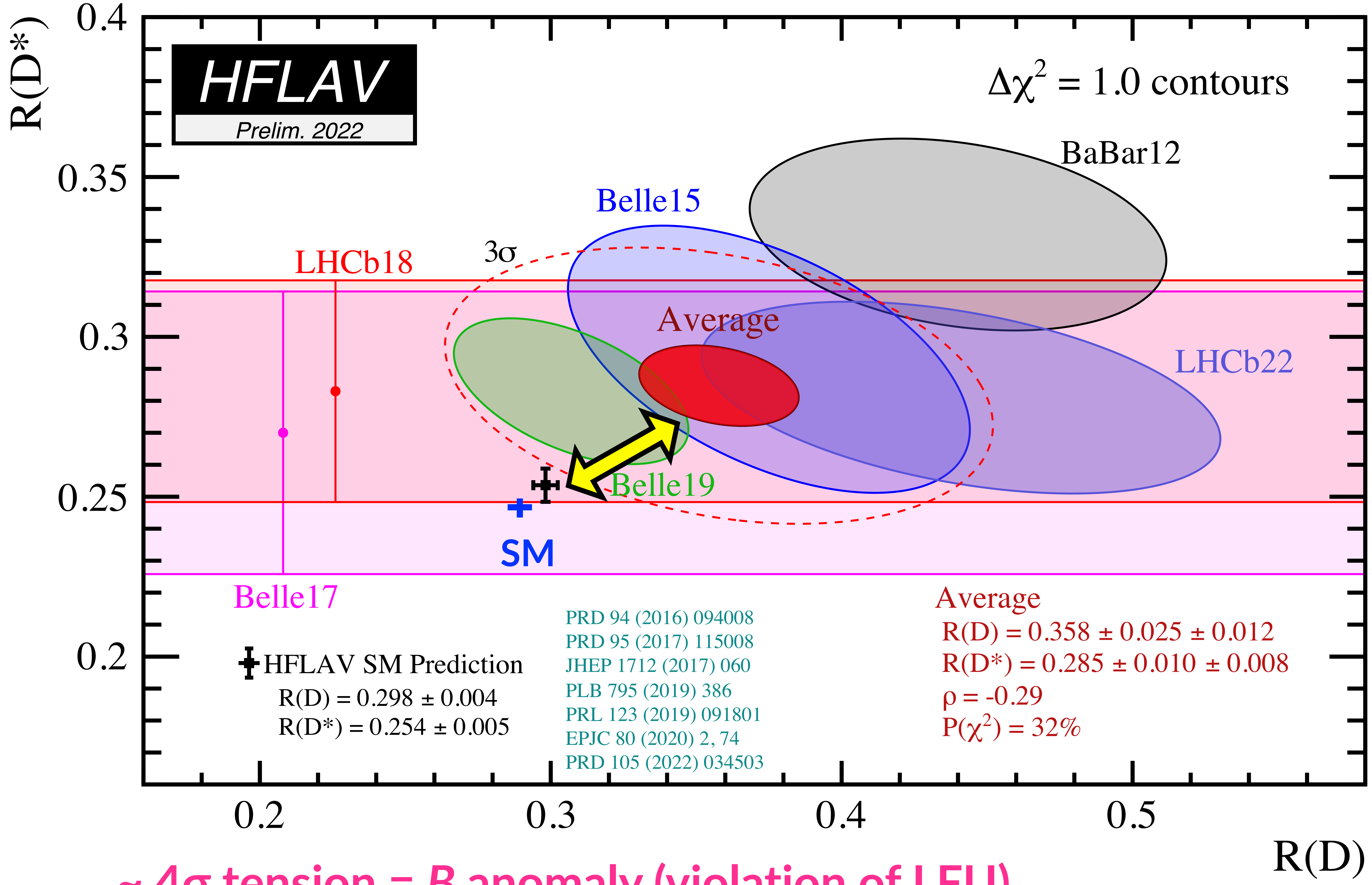
[HFLAV 2022+]

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

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



$b \to c\tau\nu$ anomaly

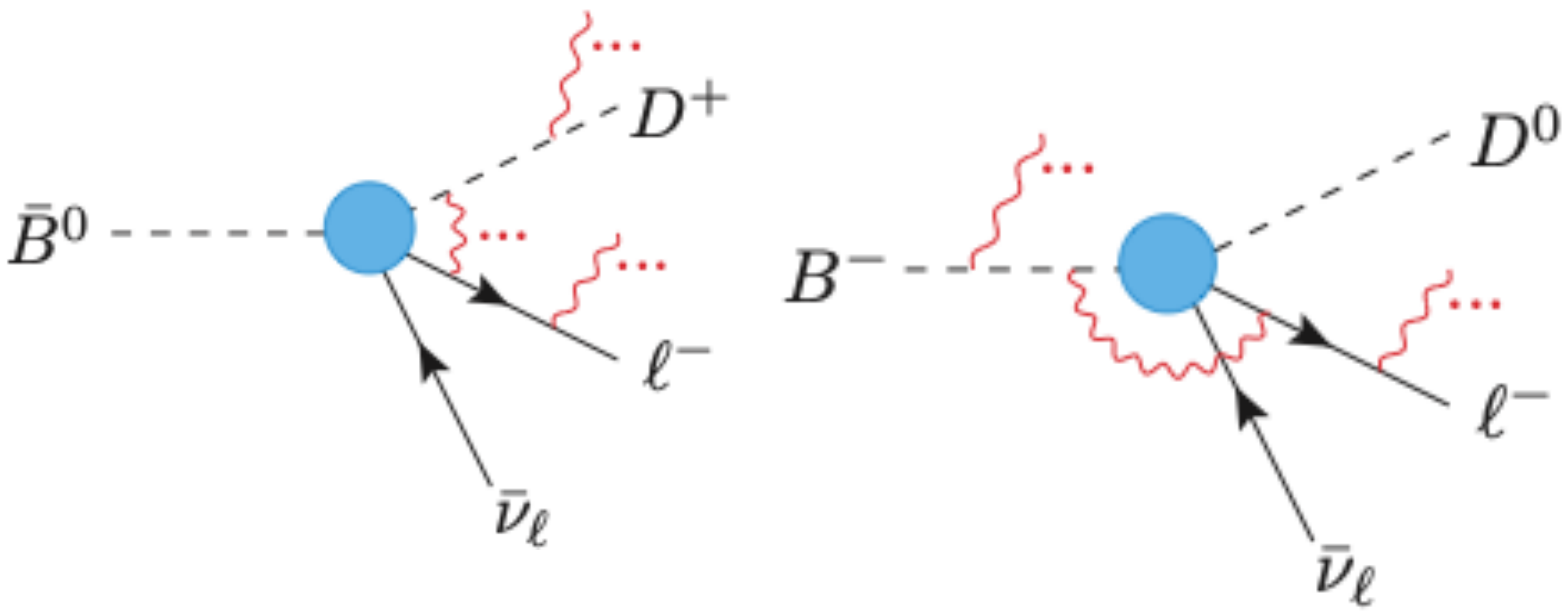


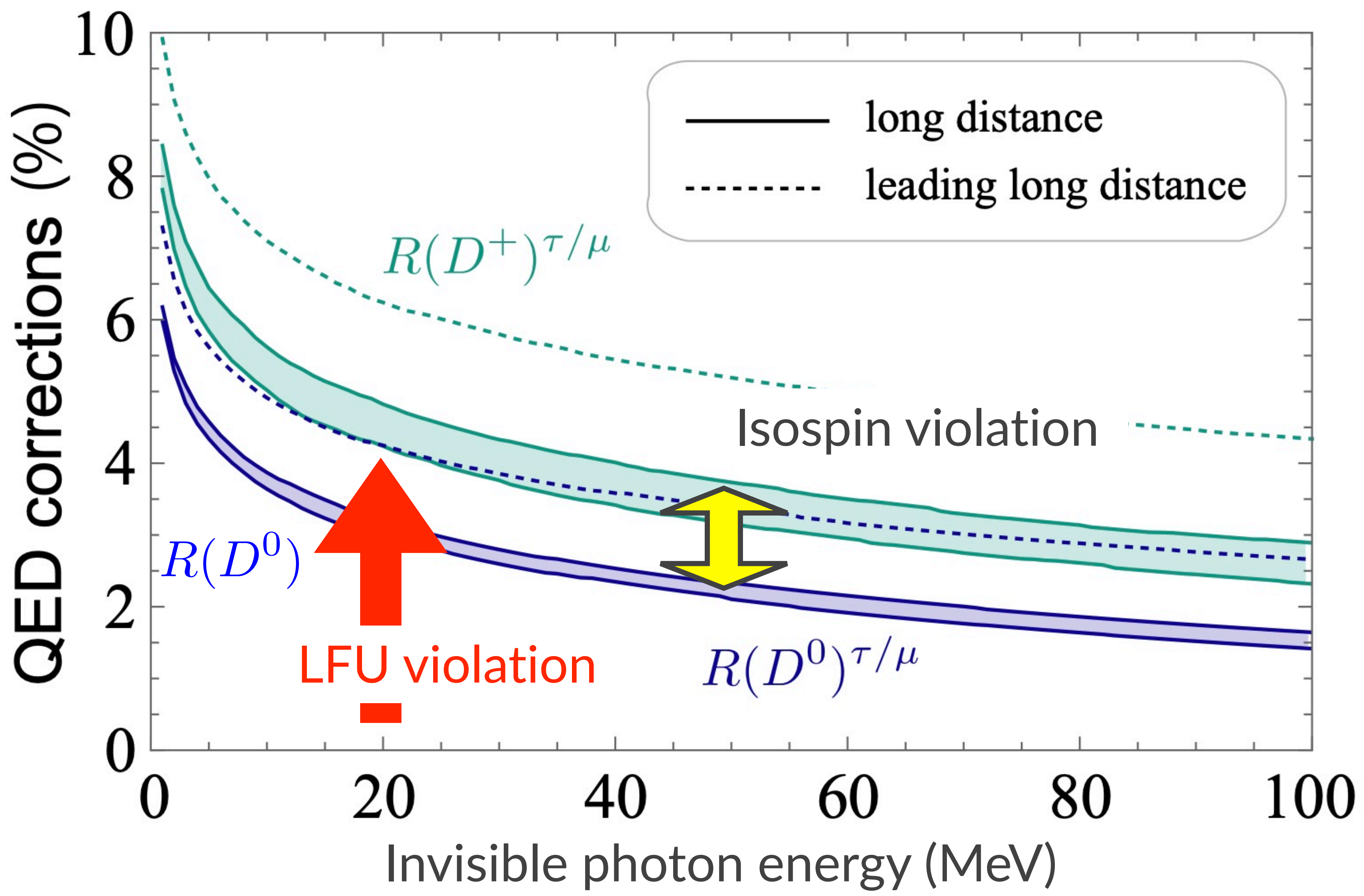
~ 4σ tension = *B* anomaly (violation of LFU)

QED correction within the SM

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

[de Boer, **TK**, Nisandzic, Phys.Rev.Lett. '18] + [Calí, Klaver, Rotondo, Sciascia, '19; Isidori, Nabeebaccus, Zwicky, '20]





We found that the QED corrections depend on the lepton velocities; non-rela τ vs relativistic μ

Improvement on theory (SM) prediction

[de Boer, **TK**, Nisandzic, Phys.Rev.Lett. '18]

Single new-particle interpretations

- **W'**
  - Severely constrained from ΔM_s, $W' \to \tau\nu$ search [Abdullah, Calle, Dutta, Flores, Restrepo, 1805.01869] and $Z' \to \tau\tau$ search [Faroughy, Greljo, Kamenik, 1609.07138]
- **Charged-Higgs with generic flavor structure**
  - Constrained from $B_c \to \tau\nu$ and $H^\pm \to \tau\nu$ search but still allowed [Iguro, Tobe, 1708.06176; Iguro, 2201.06565]
- **Leptoquark**
  - Collider bound comes from $gg \to \mathrm{LQ}\ \mathrm{LQ}^*$, and broad parameter regions are still allowed

Single new-particle interpretations

[Iguro, **TK,** Watanabe, 2210.10751]

		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_τ^D, M_W
LQ	S_1	0	$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	O_{V_L}, O_{S_L}, O_T	✓	✓	$\tau\tau$	ΔM_s, P_τ^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	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}	✓	2σ	$\tau\tau$	$B_s \to \tau\tau$, M_W

One can distinguish each model by these channels

New idea: LFU violation in Υ (Upsilon) decay

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

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

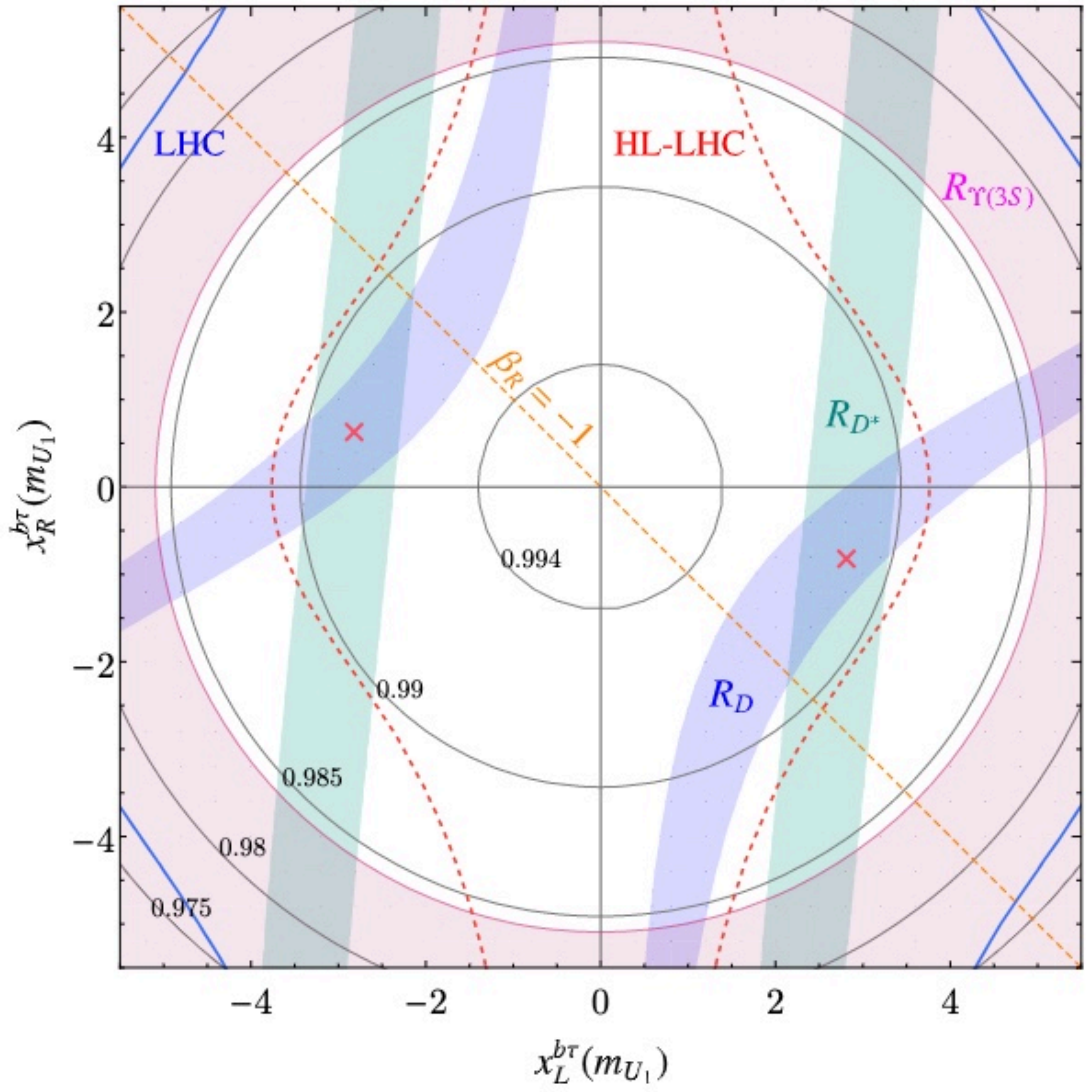
$$R^{\rm SM}_{\Upsilon(3S)} = 0.9948 \pm \mathcal{O}(10^{-5}),$$

$$R^{\rm exp}_{\Upsilon(3S)} = 0.968 \pm 0.016.$$ [CLEO+BaBar data]

- Belle II will measure it [n=2] very precisely
- less than 1% accuracy is needed

Correlation in the U_1 LQ scenario

[Iguro, **TK**, Watanabe, 2210.10751]



Sum rule between $R(\Lambda_c)$ and $R(D)$, $R(D^*)$

- 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)

$$\frac{R(\Lambda_c)}{R(\Lambda_c)_{\rm SM}} \simeq 0.26\frac{R(D)}{R(D)_{\rm SM}} + 0.74\frac{R(D^*)}{R(D^*)_{\rm SM}}$$

[Fedele, Blanke, Crivellin, Iguro, **TK**, Nierste, Watanabe, 2211.14172]

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

R(D(*)) anomaly →

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

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

$$R(\Lambda_c)_{\rm exp} = 0.242 \pm 0.075$$ [LHCb: 2201.03497]

A slight (~2σ) inconsistency appeared


hunt a new interaction
SM particle
New particle
Effective
field theory
Collider physics
$\sqrt{s} > m_{NP}$
ATLAS
EXPERIMENT
CMS
comple-
mentary
Precision measurement
Heavy quark
LHCb
Belle II
Light meson,
lepton
Small theoretical uncertainty
Good new physics sensitivity
p
b
ν
p
c
τ
Crossing symmetry
Direct connection
B
b
ν
τ
c
D
non-resonance search
→ new study direction
B anomaly!

LQ indirect collider search

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

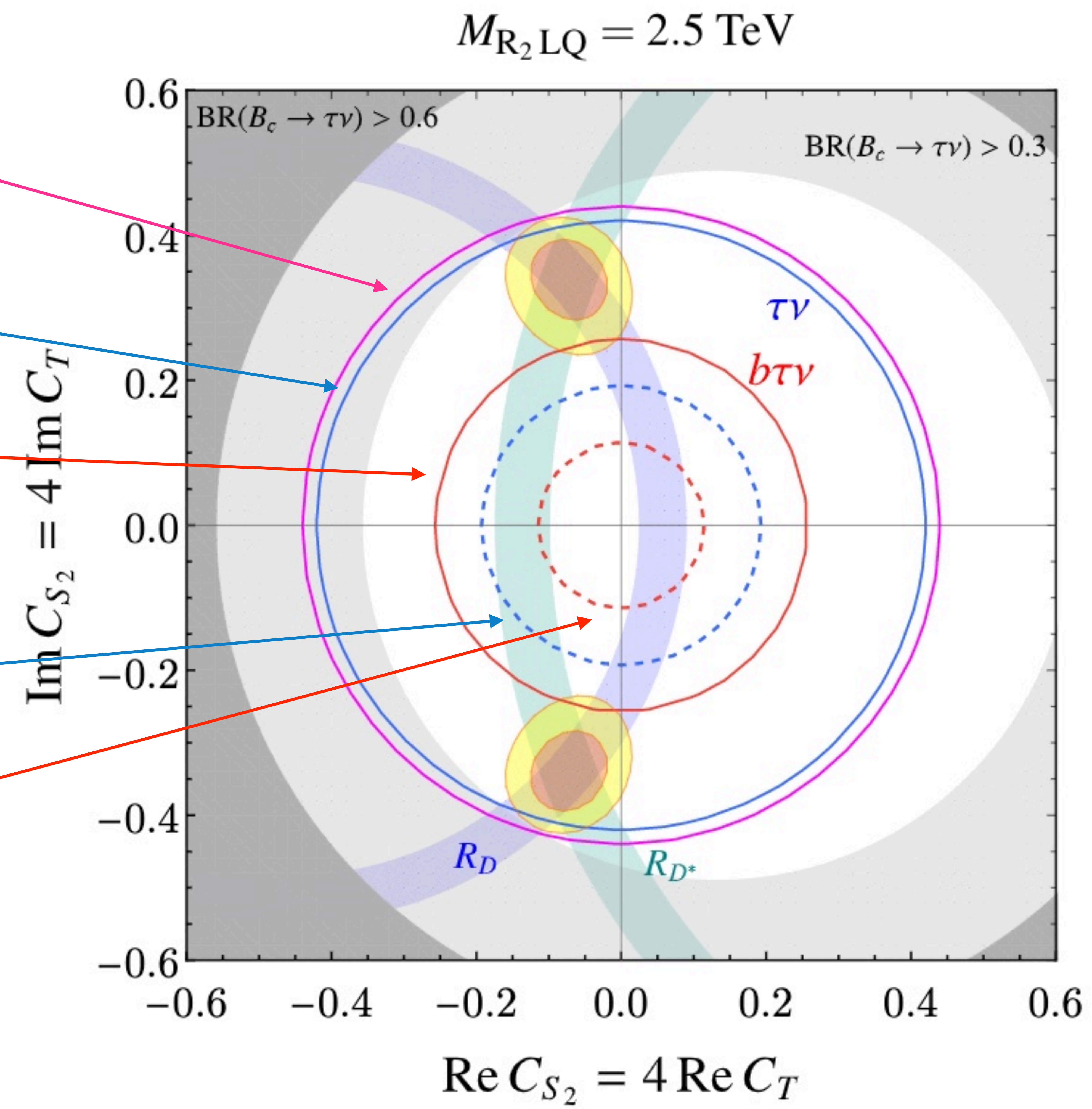
τ+MET search
$36fb^{-1}$ exclusion

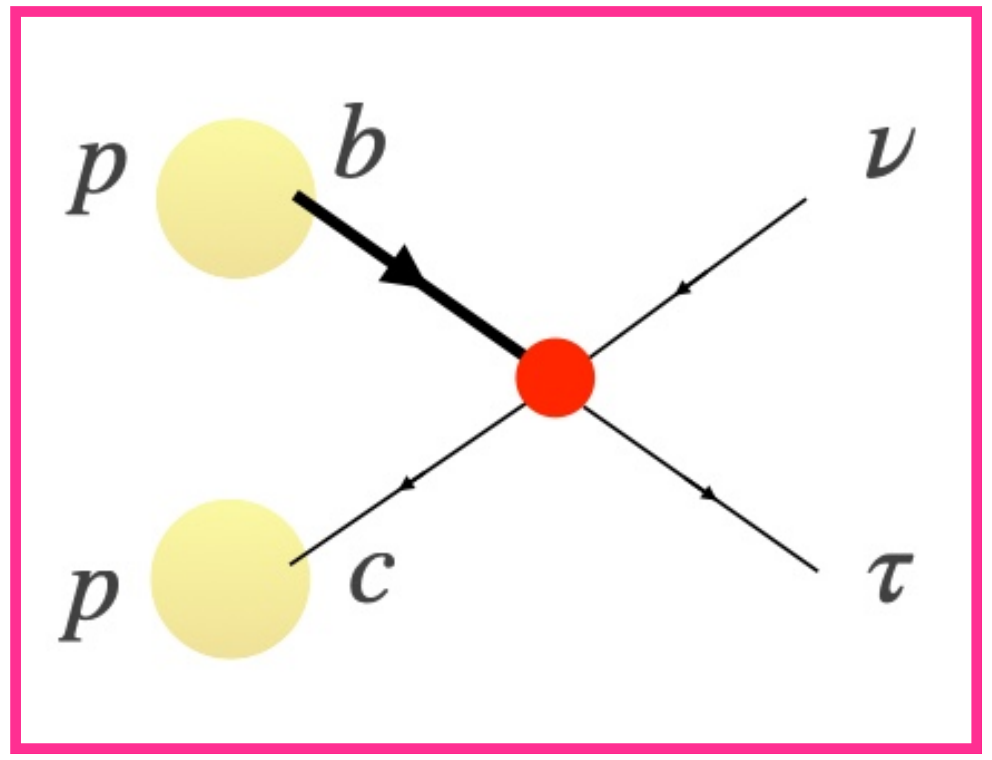
τ+MET search
$139fb^{-1}$ sensitivity

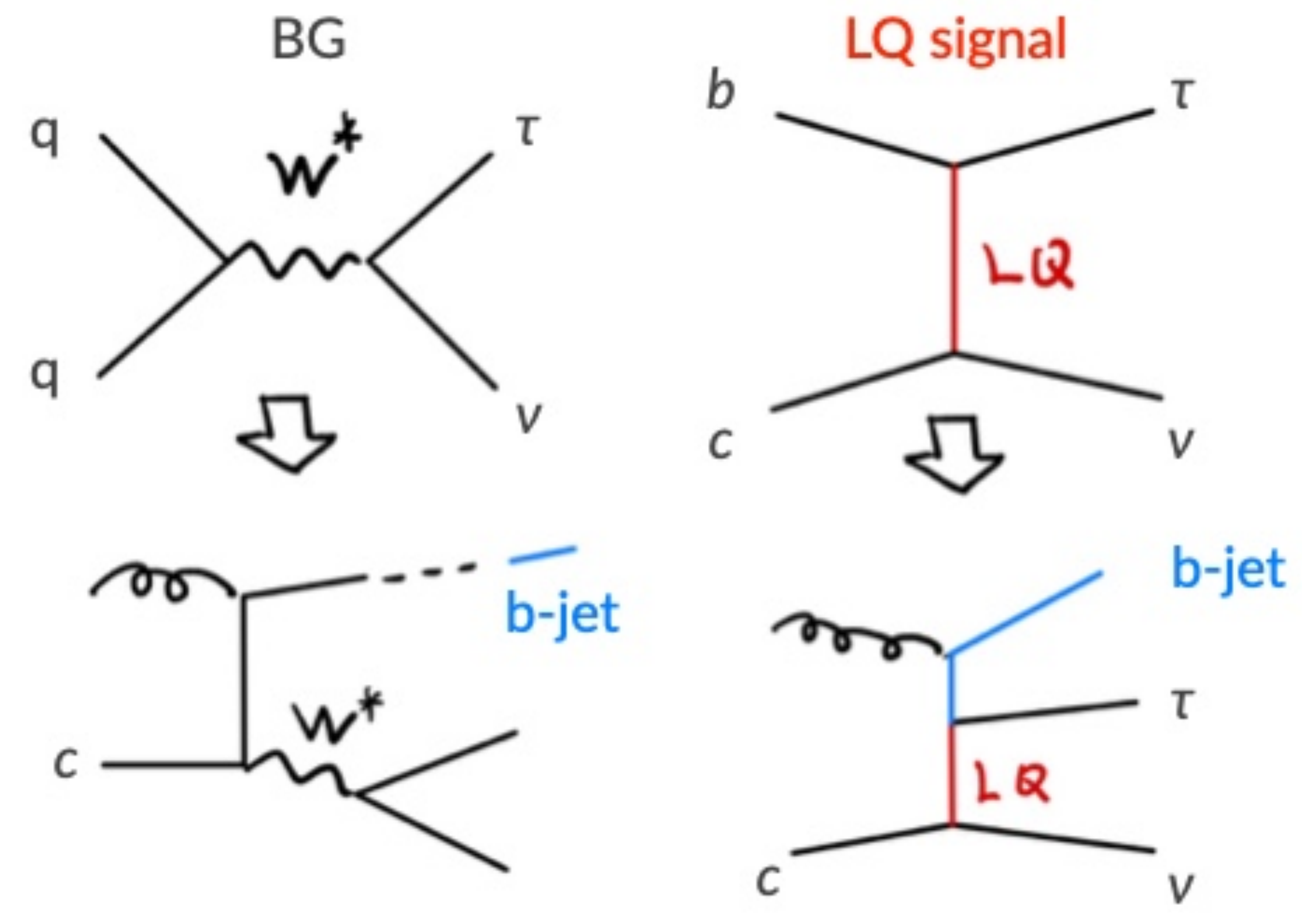
τ+MET+b search
$139fb^{-1}$ sensitivity

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

U_1 Leptoquark scenario: comparison

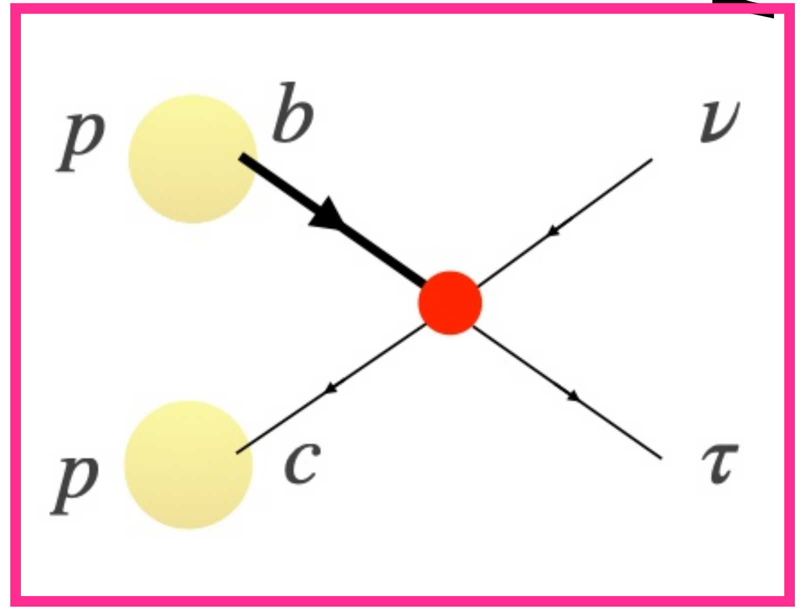
See also Nobe-san's talk

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

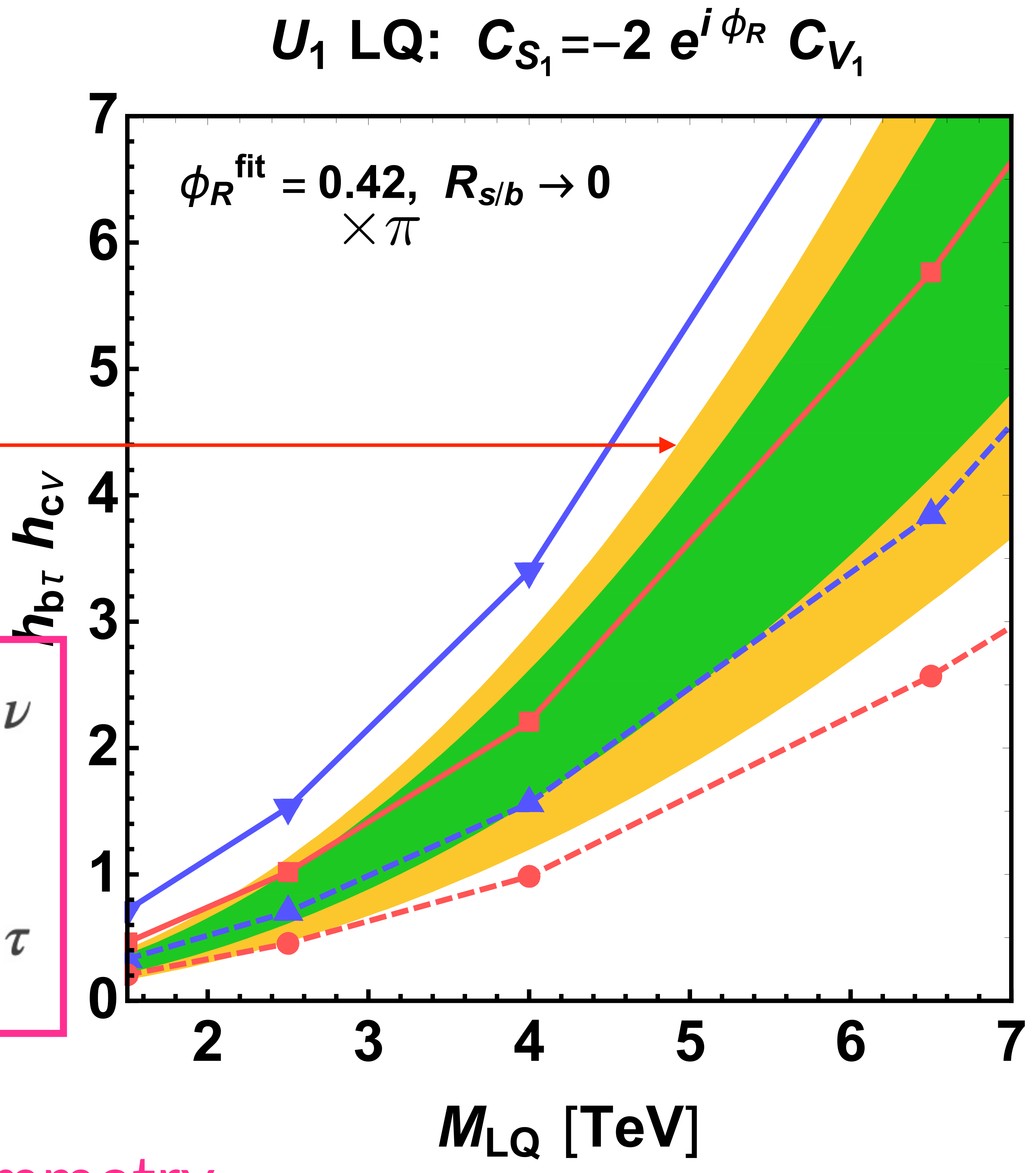
[CMS, CMS PAS HIG-21-001]

τ+MET+b search

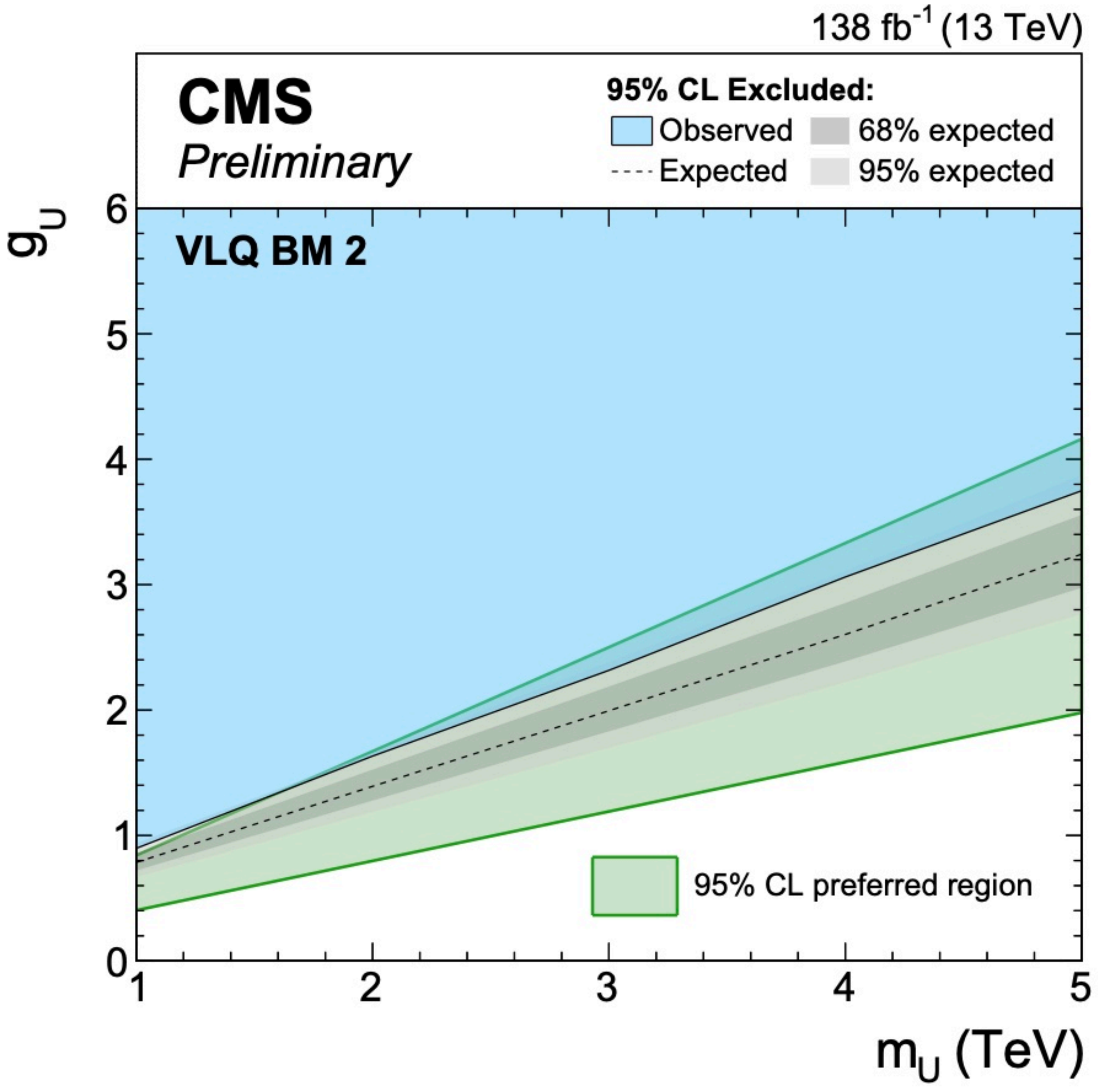
139fb-1 sensitivity



direct bound
via crossing symmetry

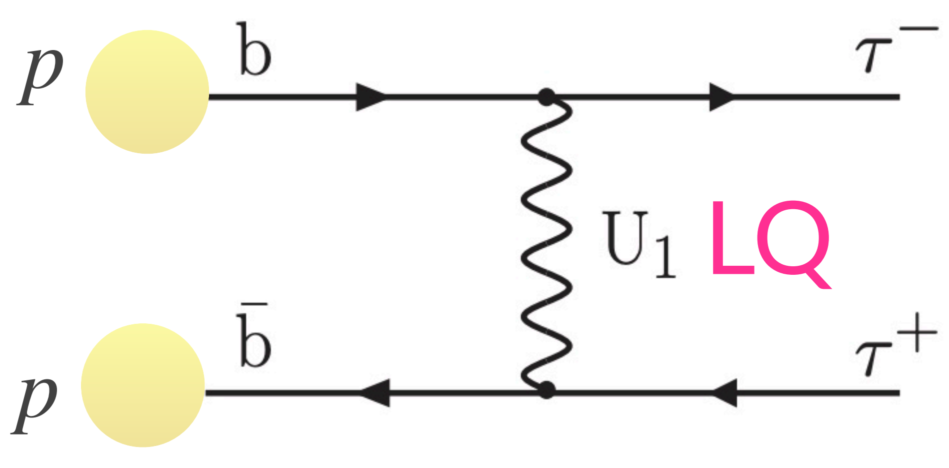


τb + MET $(139\,\mathrm{fb}^{-1})$



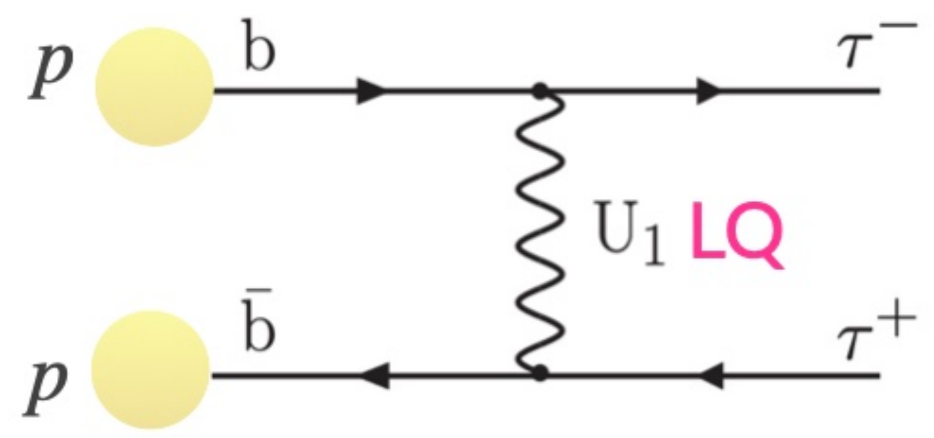
$\tau\,\tau$ $(138\,\mathrm{fb}^{-1})$ (+b is included)

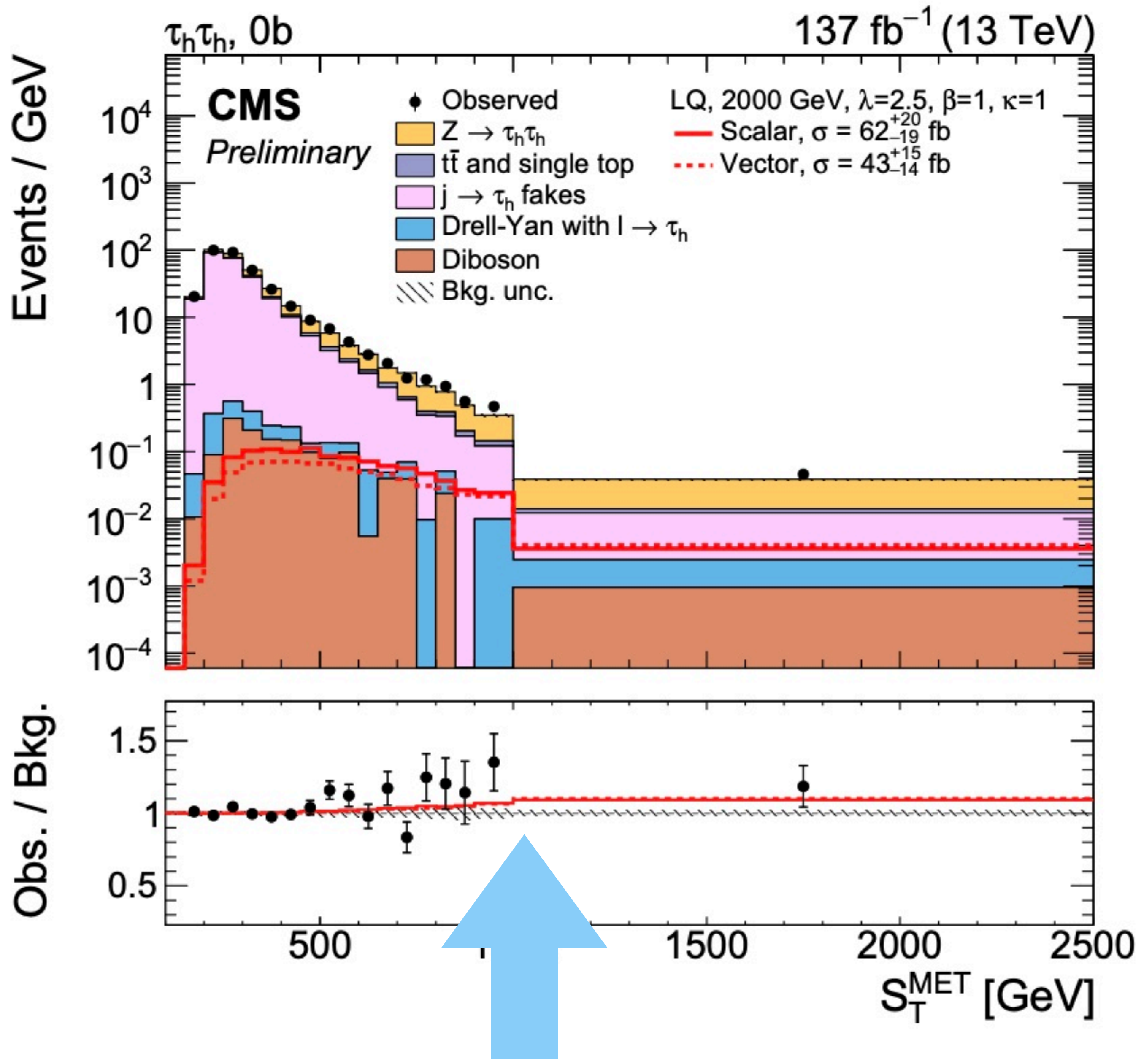
Both are comparable sensitivity

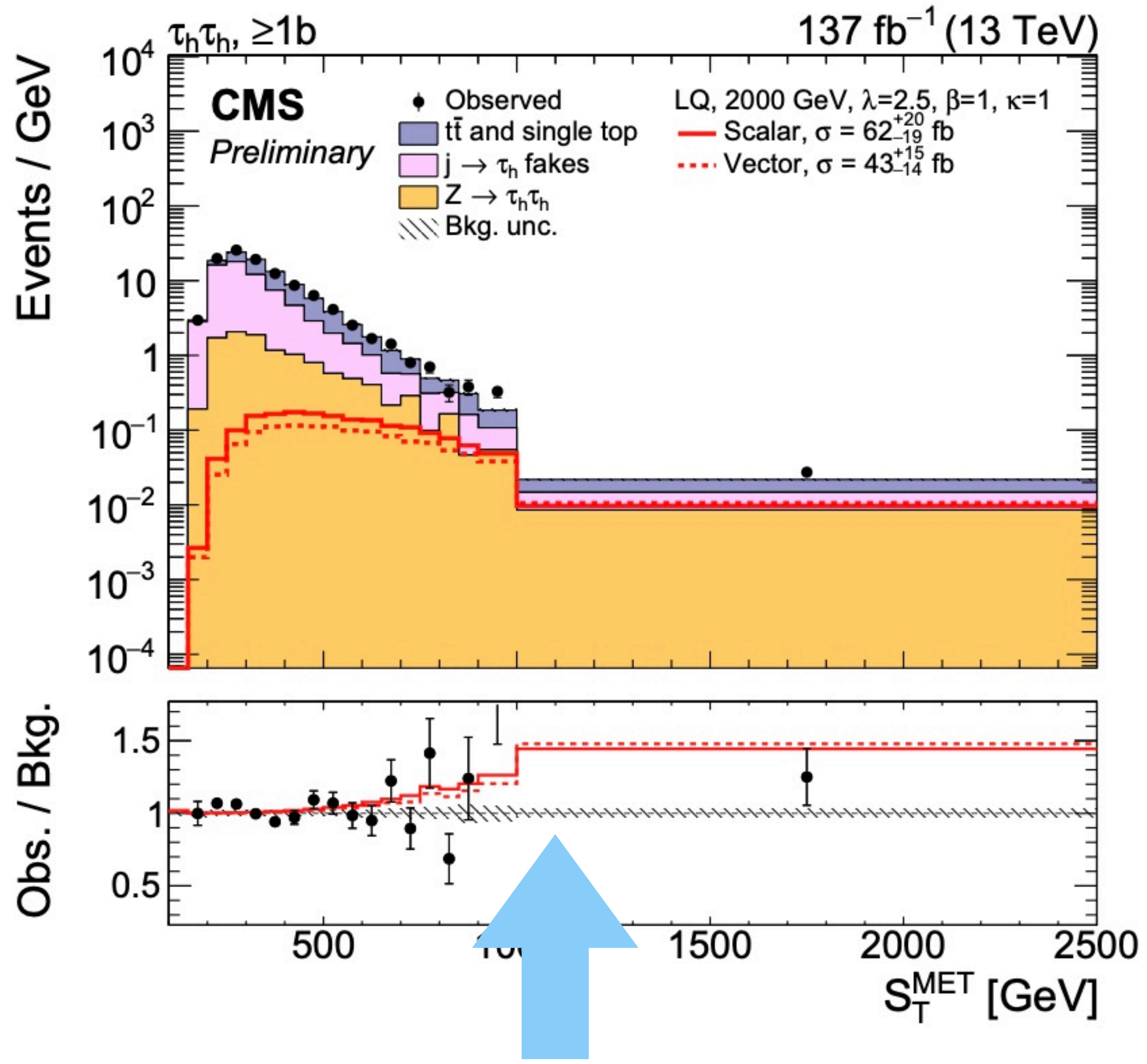


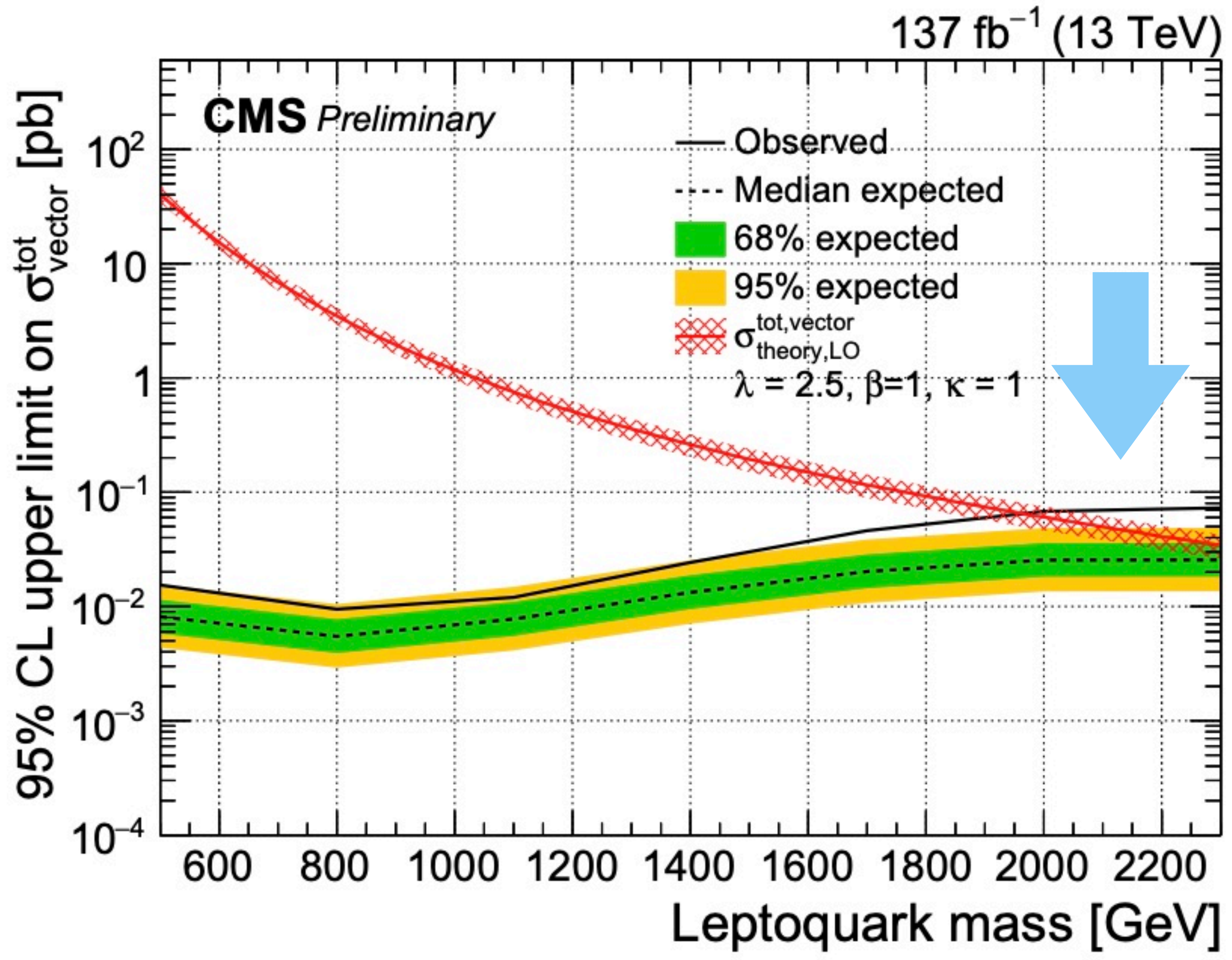
model-dependent bound

New LQ anomaly from CMS @ICHEP2022





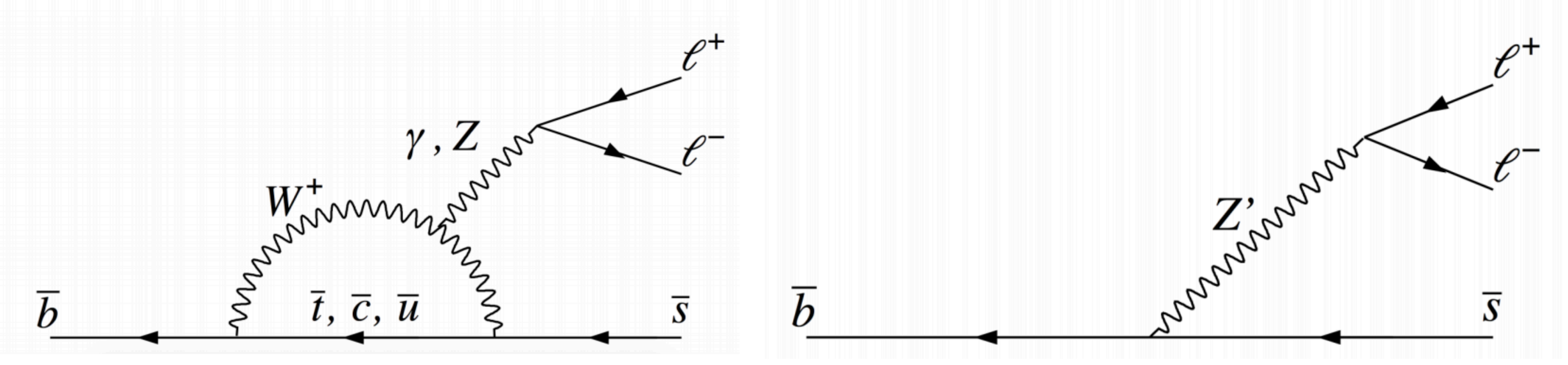




3.4σ level excess at $M_{LQ} \sim 2$ TeV was reported from CMS [CMS, CMS-PAS-EXO-19-016]

Other LFU observables: *R*(*K*) and *R*(K*)

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

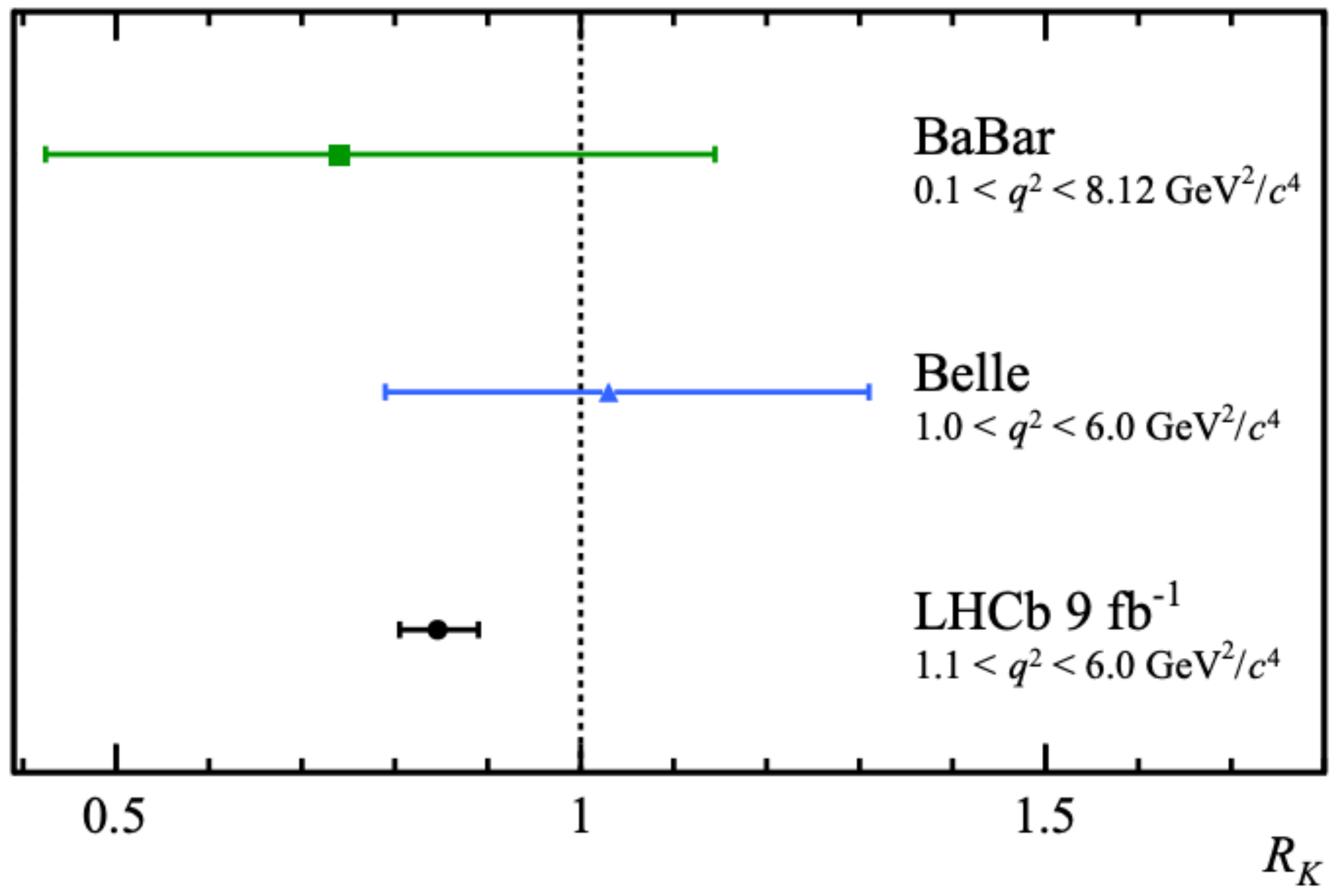


SM vs. NP, *e.g.*, Z' boson

SM: $R(K) \simeq R(K^*) \simeq 1$

data: $R(K) \simeq R(K^*) \approx 0.8$

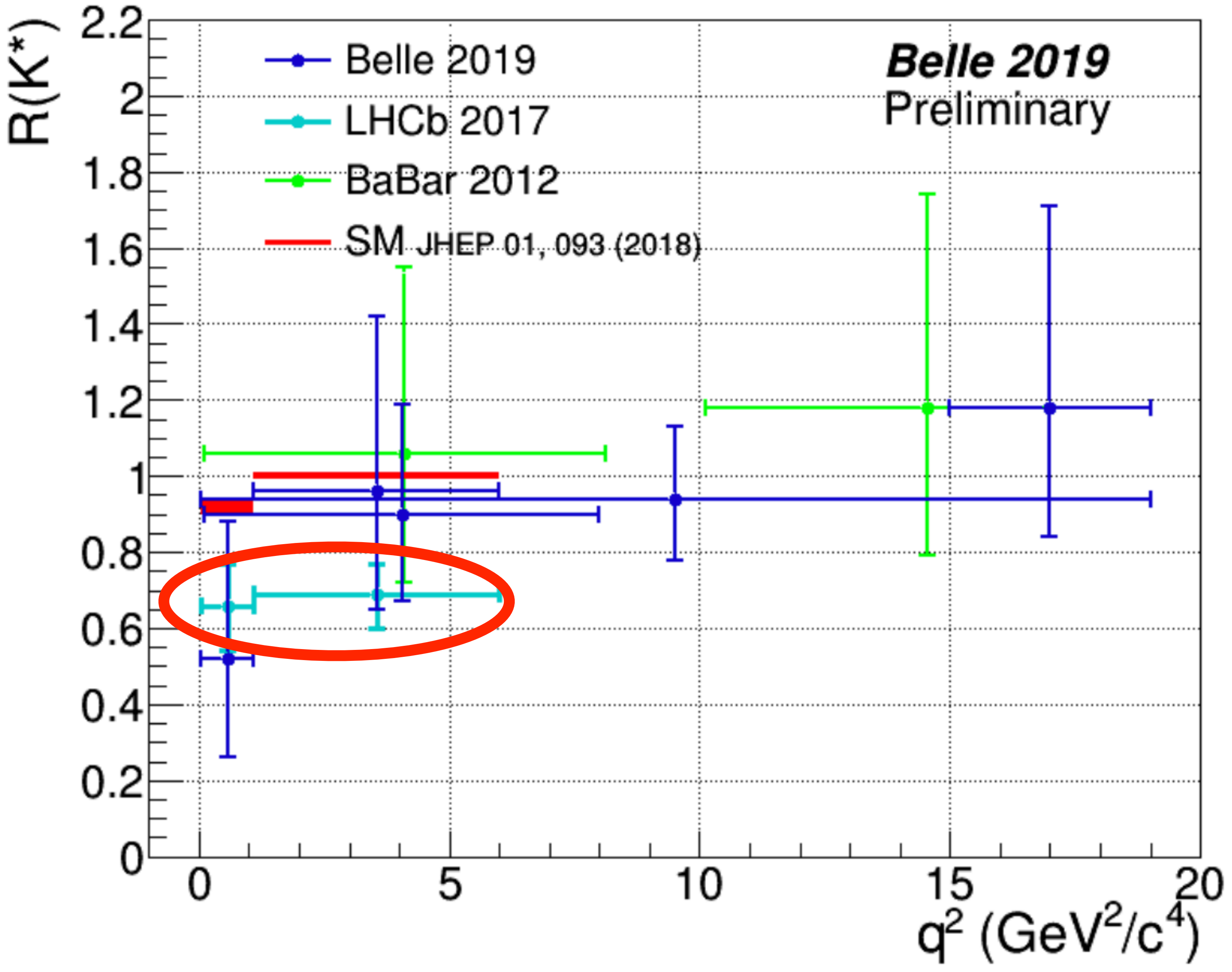
R(*K*)



~ 3.1σ below the SM

$b \to s\mu\mu$ anomaly

R(*K**)

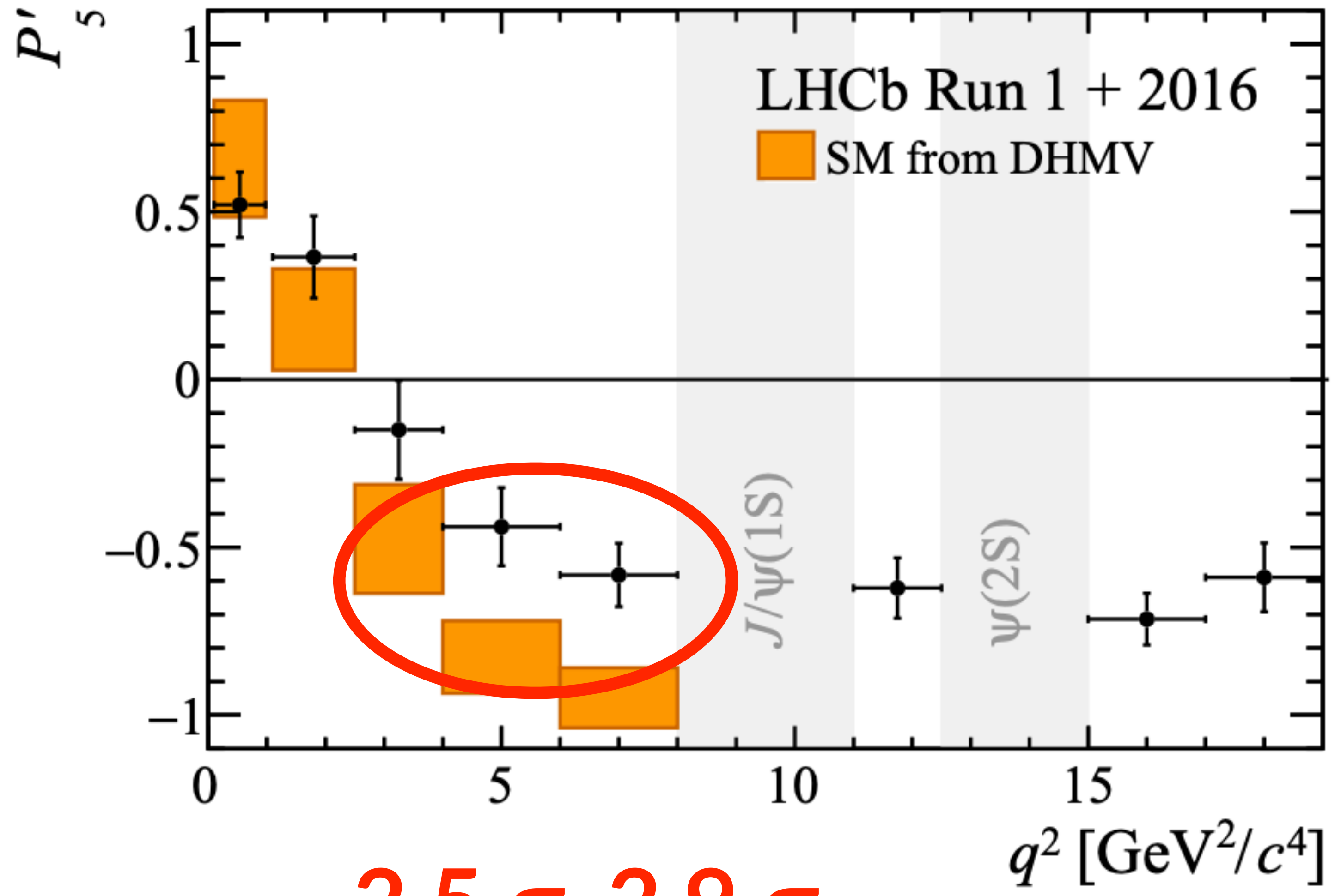


~ 2.5σ below the SM

$b \to s\mu^+\mu^-$ anomalies

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

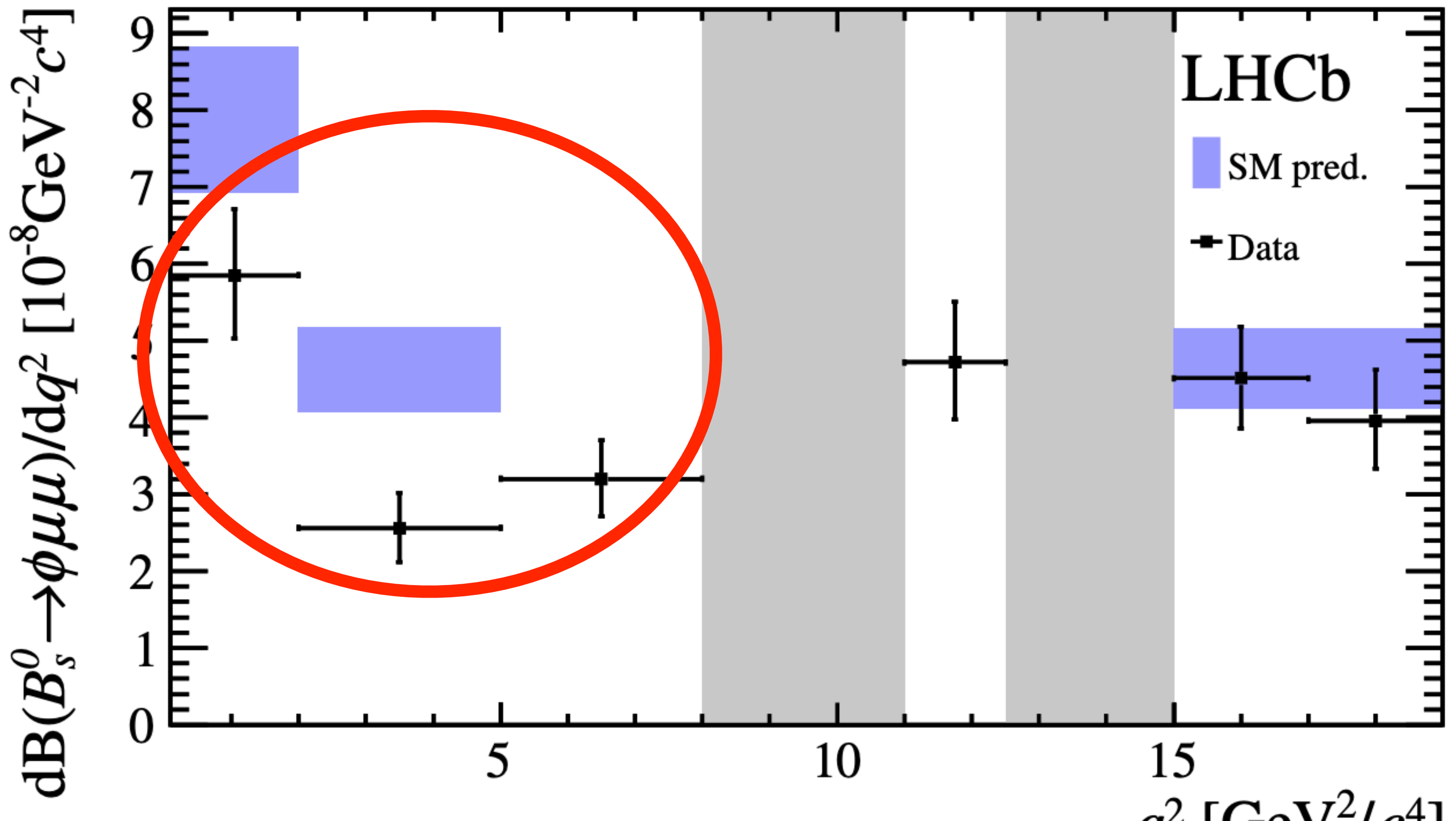
[LHCb, 2003.04831]



2.5 σ, 2.9 σ

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

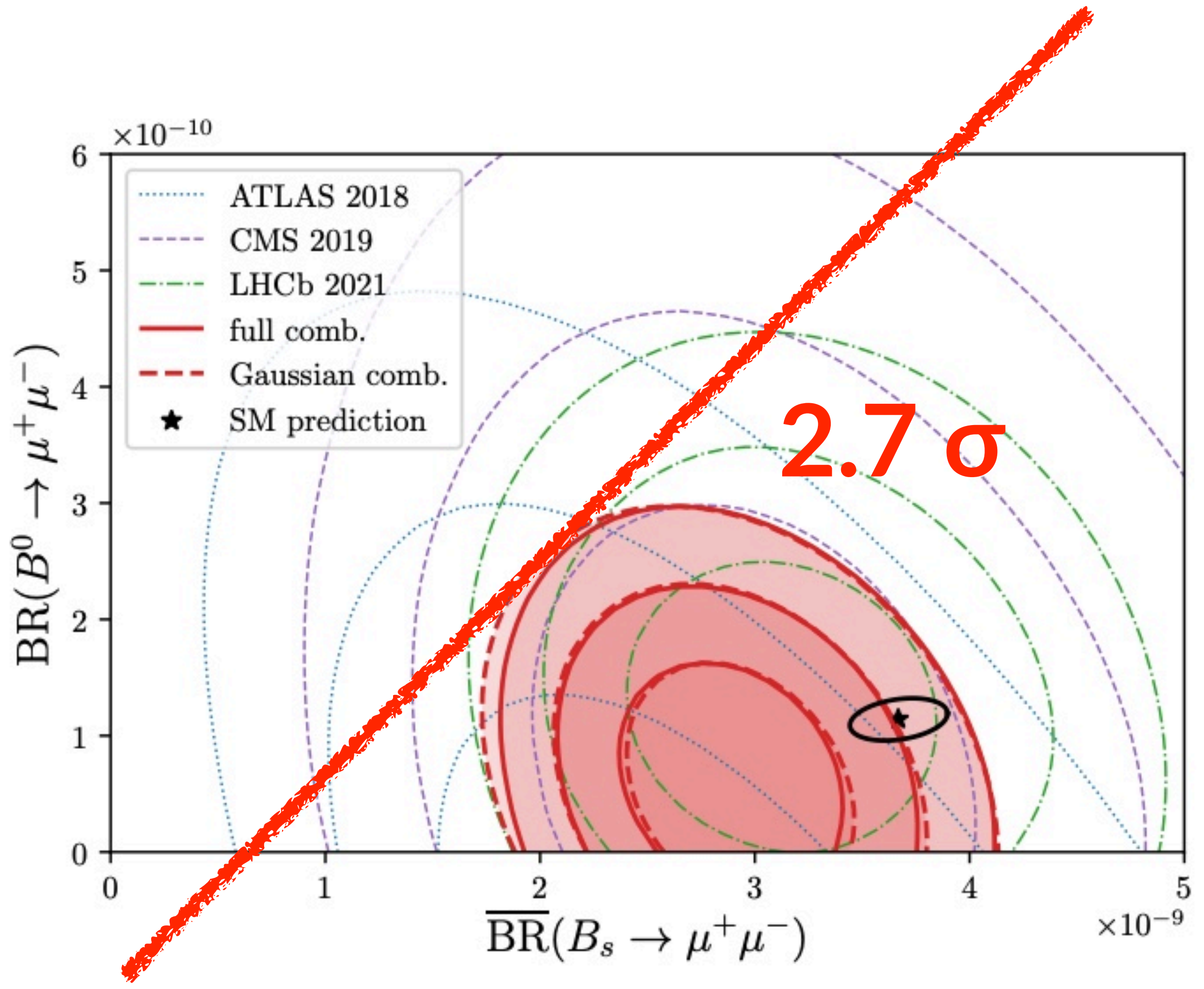
[LHCb, 1506.08777]



3.3 σ

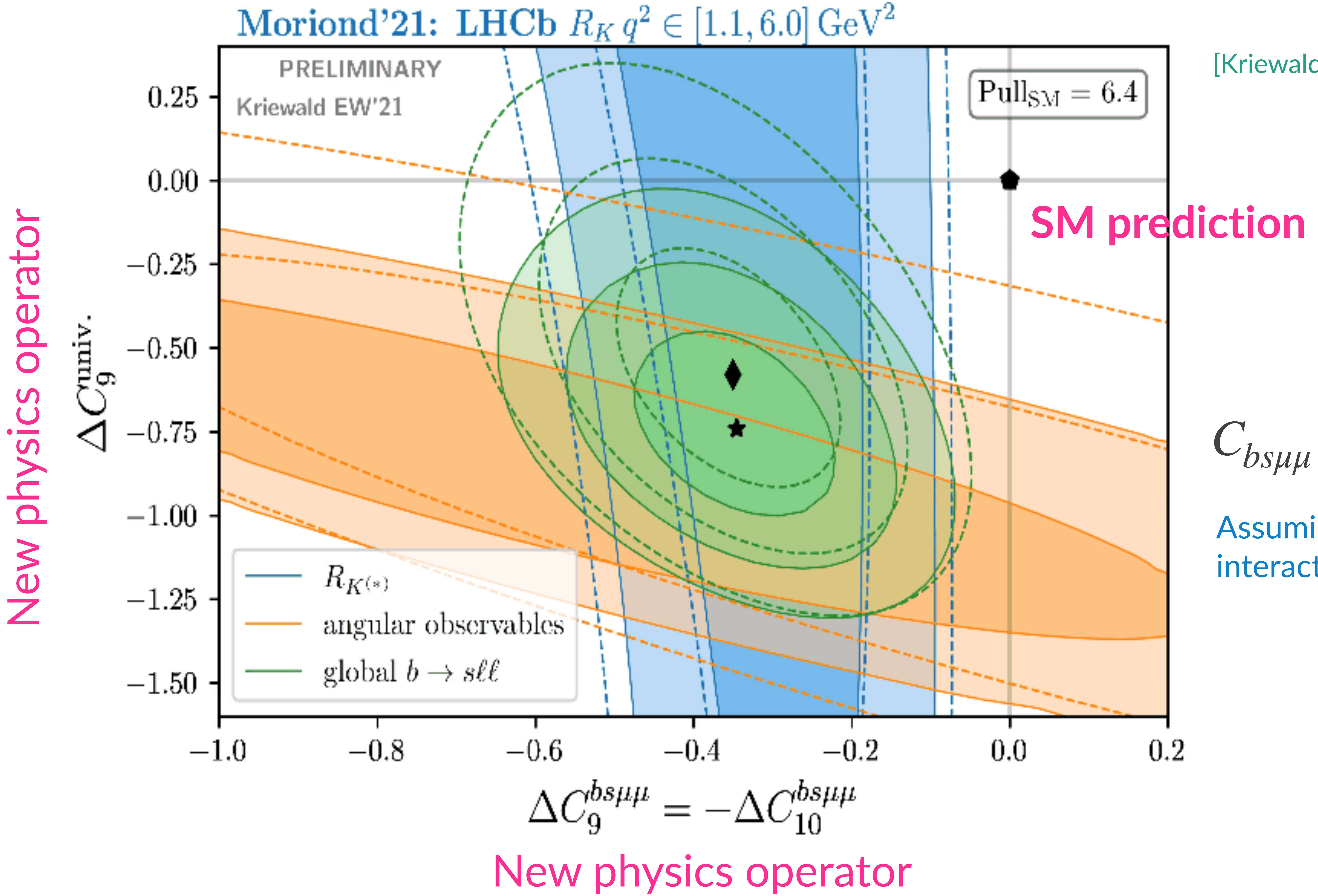
$B_s \to \mu^+\mu^-$

[Altmannshofer, Stangl, 2103.13370; Buras, 2205.01118]



gone [CMS, ICHEP2022]

- Global significance of $b \to s\mu\mu$ anomaly is **4.3σ level** taking into account the look-elsewhere effect (evaluated via pseudo-experiment) [Isidori, Lancierini, Owen, Serra 2104.05631]



[Kriewald, et al, 2104.00015]

$$C_{bs\mu\mu} \approx (39\ \mathrm{TeV})^{-2}$$

Assuming all dimensionless interactions = 1

New result will be presented next Tuesday! You cannot miss it.

LHC Seminar

Measurements of $R(K)$ and $R(K^*)$ with the full LHCb Run 1 and 2 data

by Renato Quagliani (EPFL - Ecole Polytechnique Federale Lausanne (CH))

Tuesday Dec 20, 2022, 11:00 AM → 12:00 PM Europe/Zurich

500/1-001 - Main Auditorium (CERN)

Description In this seminar we present the first simultaneous test of muon-electron universality in $B^+ \to K^+\ell^+\ell^-$ and $B^0 \to K^{*0}\ell^+\ell^-$ decays, known as $R(K)$ and $R(K^*)$, in two regions of di-lepton invariant mass squared.
The analysis operates at a higher signal purity compared with previous analyses and implements a data-driven treatment of residual hadronic backgrounds. The analysis uses the full LHCb Run 1 and 2 data recorded in 2011-2012 and 2015-2018, corresponding to an integrated luminosity of 9 fb^{-1}. This analysis is the most sensitive lepton universality test in rare b-decays and the results obtained supersede the previous LHCb measurements of $R(K)$ and $R(K^{*0})$.

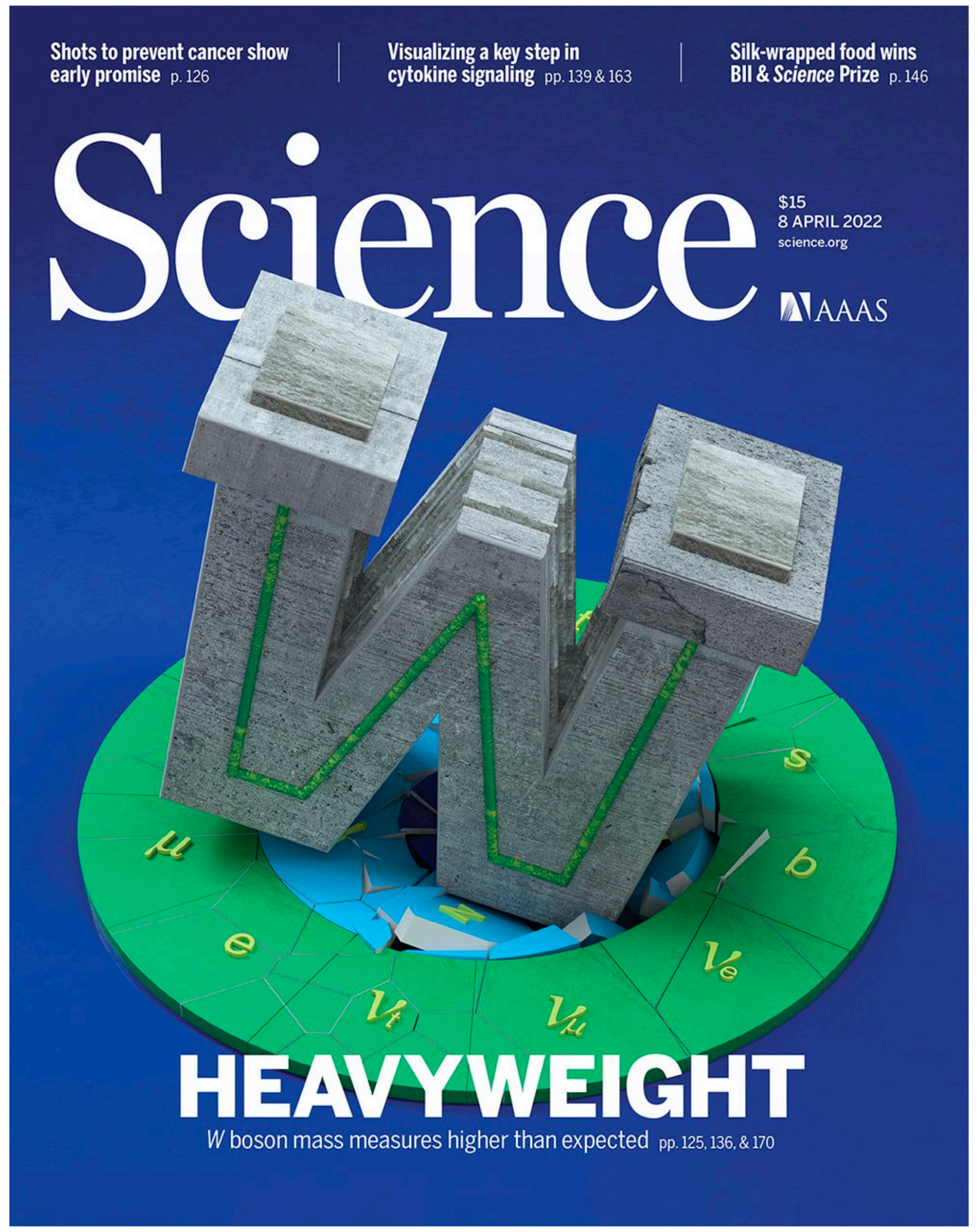
Organized by Michelangelo Mangano, Jan Fiete Grosse-Oetringhaus and Pedro Silva.....Refreshments will be served at 10h30

Videoconference zoom LHC seminar - 20 December - LHCb Join

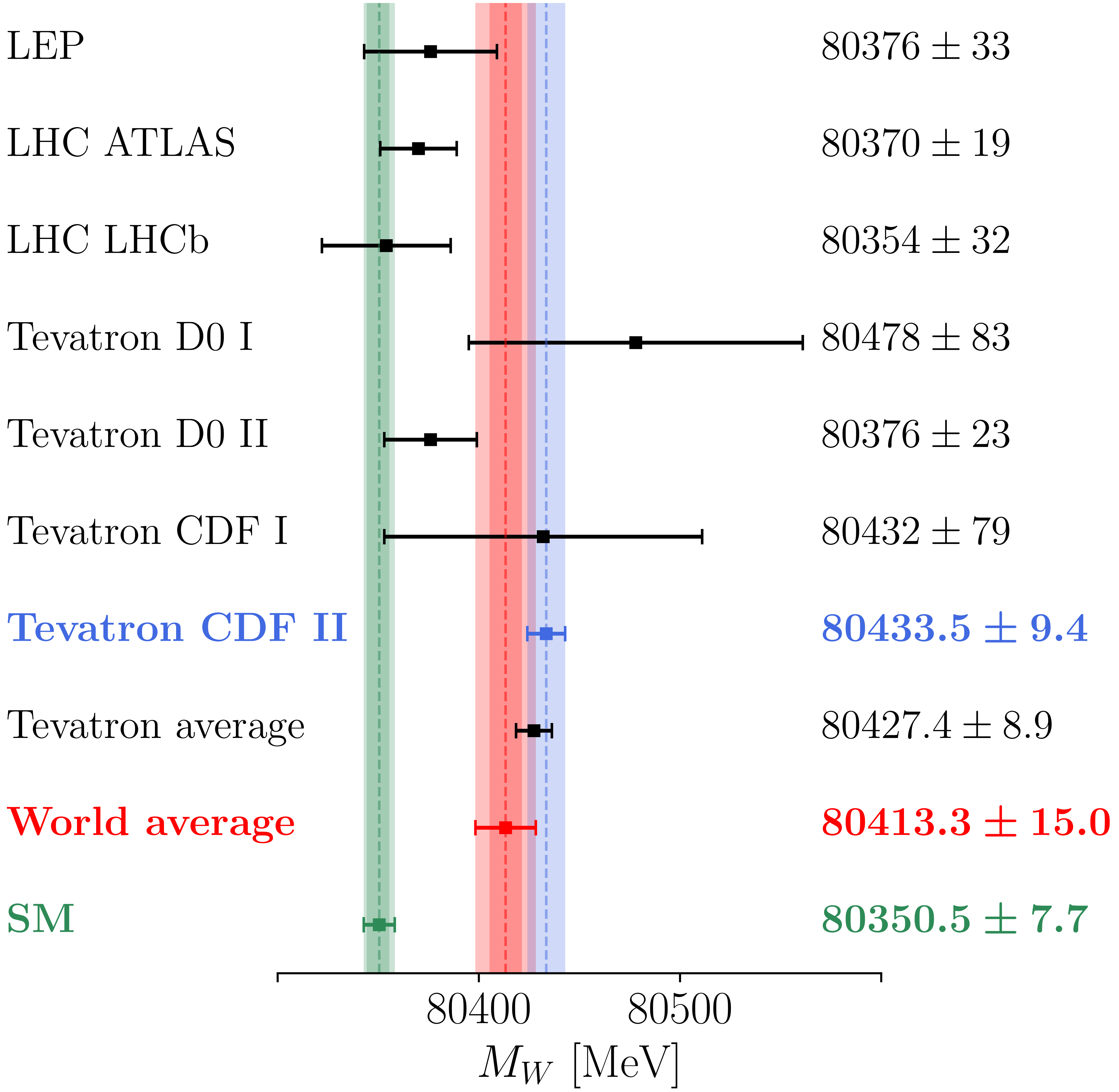
Webcast There is a live webcast for this event Watch

W boson mass anomaly

Review [Endo, **TK**, Yagyu, High Energy News, 2022, Link]



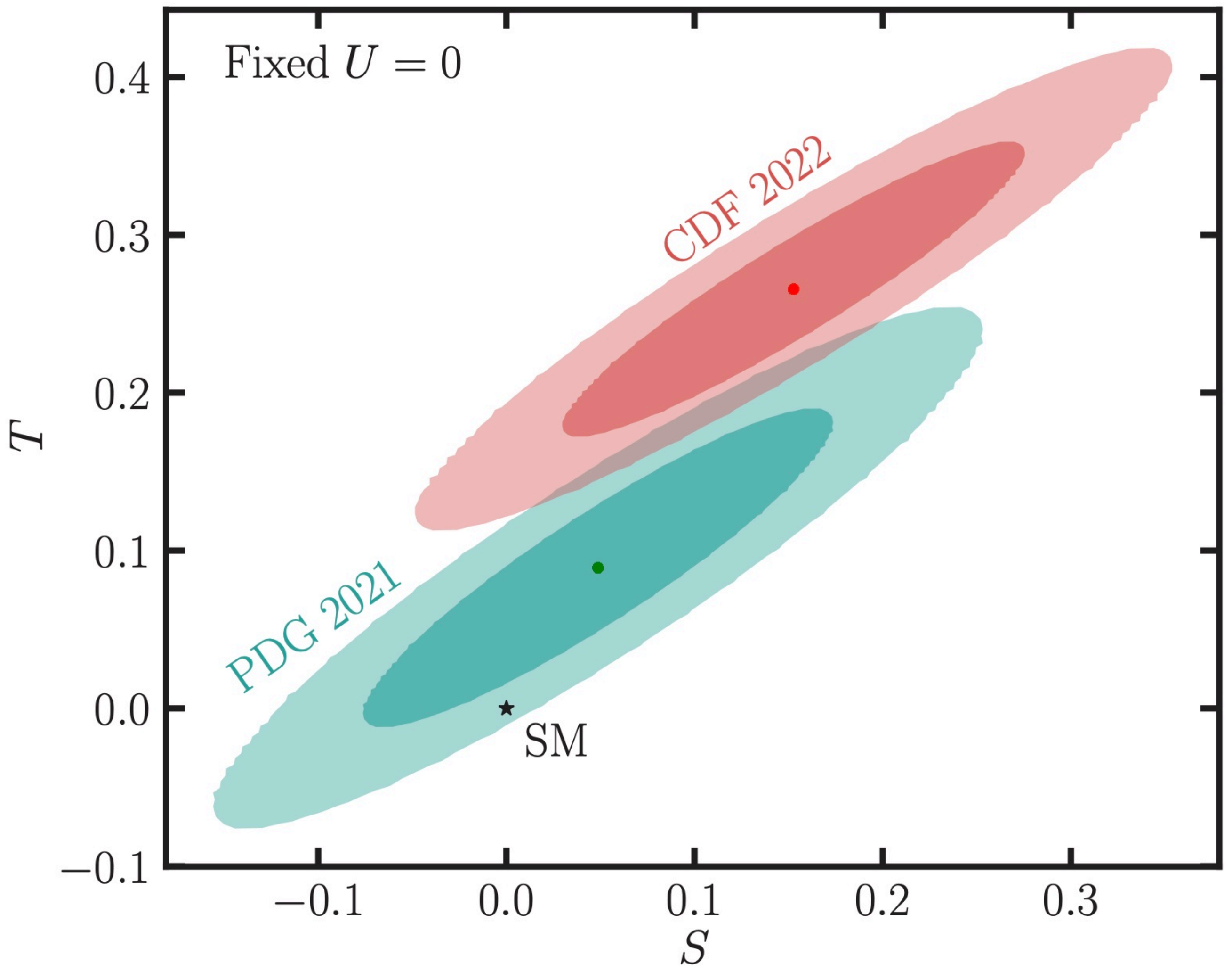
[CDF Collaboration, Science 376 (2022)].



"Scale factor" is included in the world average

Most conservatively, the tension is **3.7 σ**

Oblique parameter fit

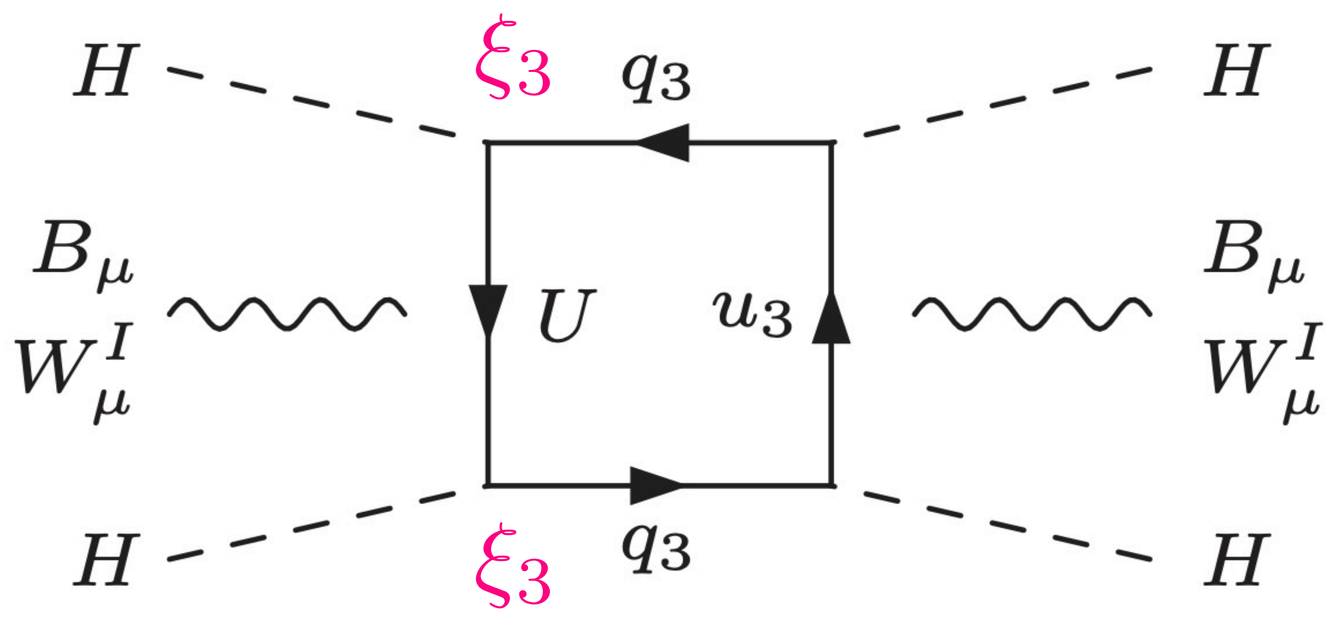


[Lu, Wu, Wu, Zhu, 2204.03796]

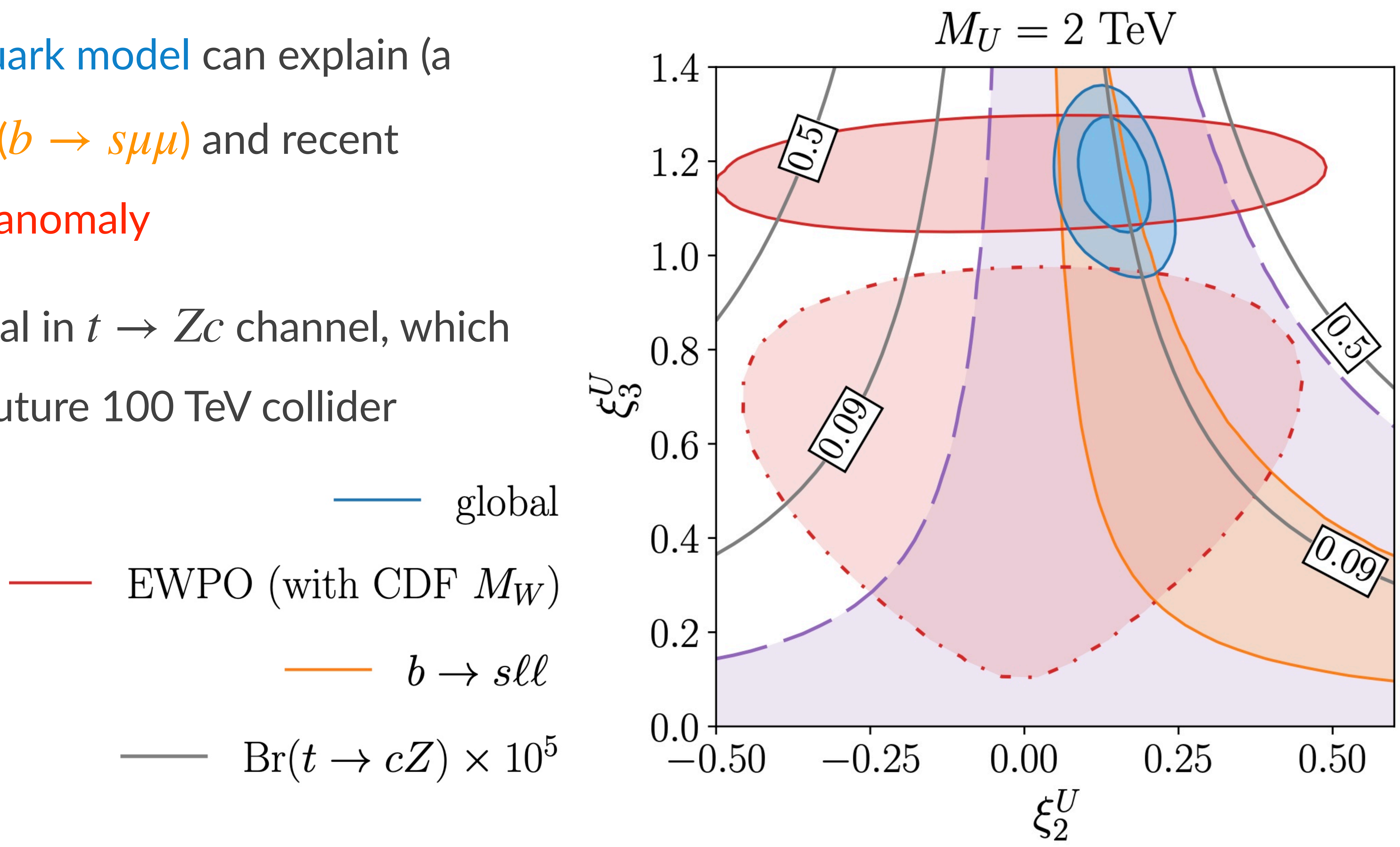
B anomaly ($b \to s\mu\mu$) vs W boson mass

[Crivellin, Kirk, **TK**, Mescia, 2204.05962]

- SM + vector-like quark model can explain (a part of) B anomaly ($b \to s\mu\mu$) and recent measured W mass anomaly
- Predict unique signal in $t \to Zc$ channel, which can be probed by future 100 TeV collider



T parameter



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	$(\bar{3}, 2, 5/6)$	Small	△	Small	✓
S_3 LQ (*)	0	$(\bar{3}, 3, 1/3)$	✗	✓	✗	With S_1
U_3 LQ	1	(3, 3, 2/3)	✗	✓	✗	?

Test of unitarity 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

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

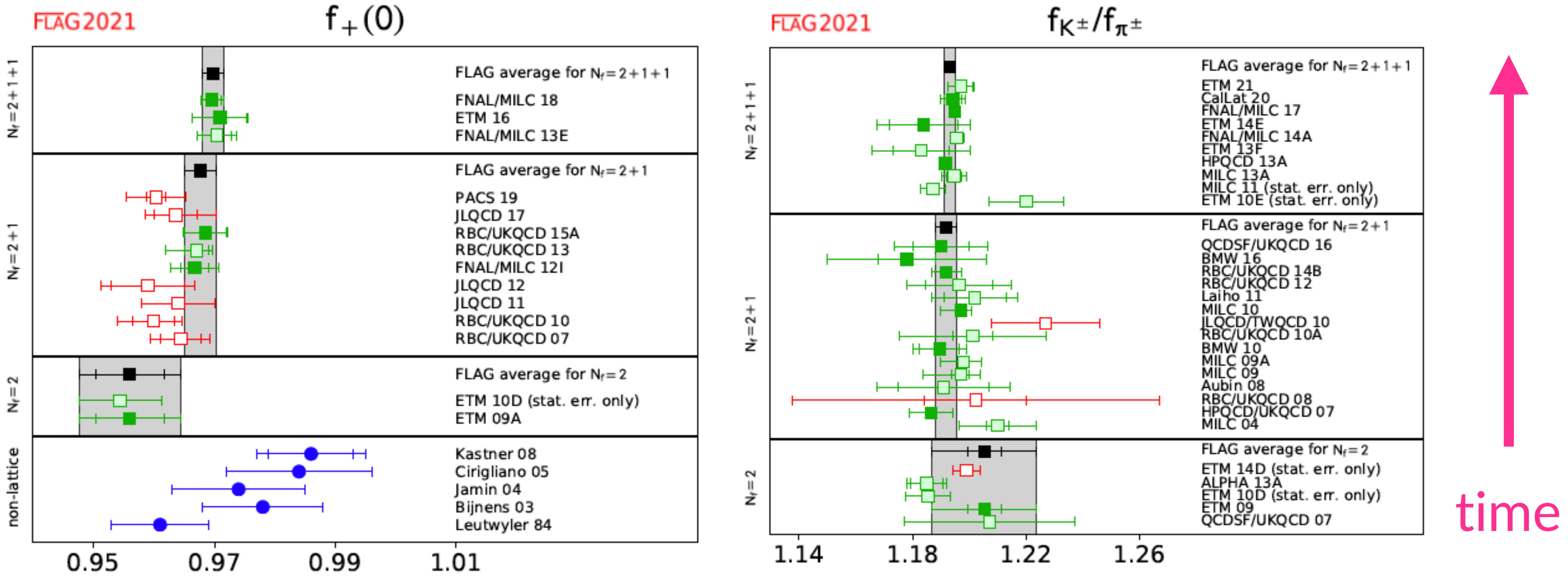
1st row unitarity condition

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

Sum of the absolute values must become 1

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

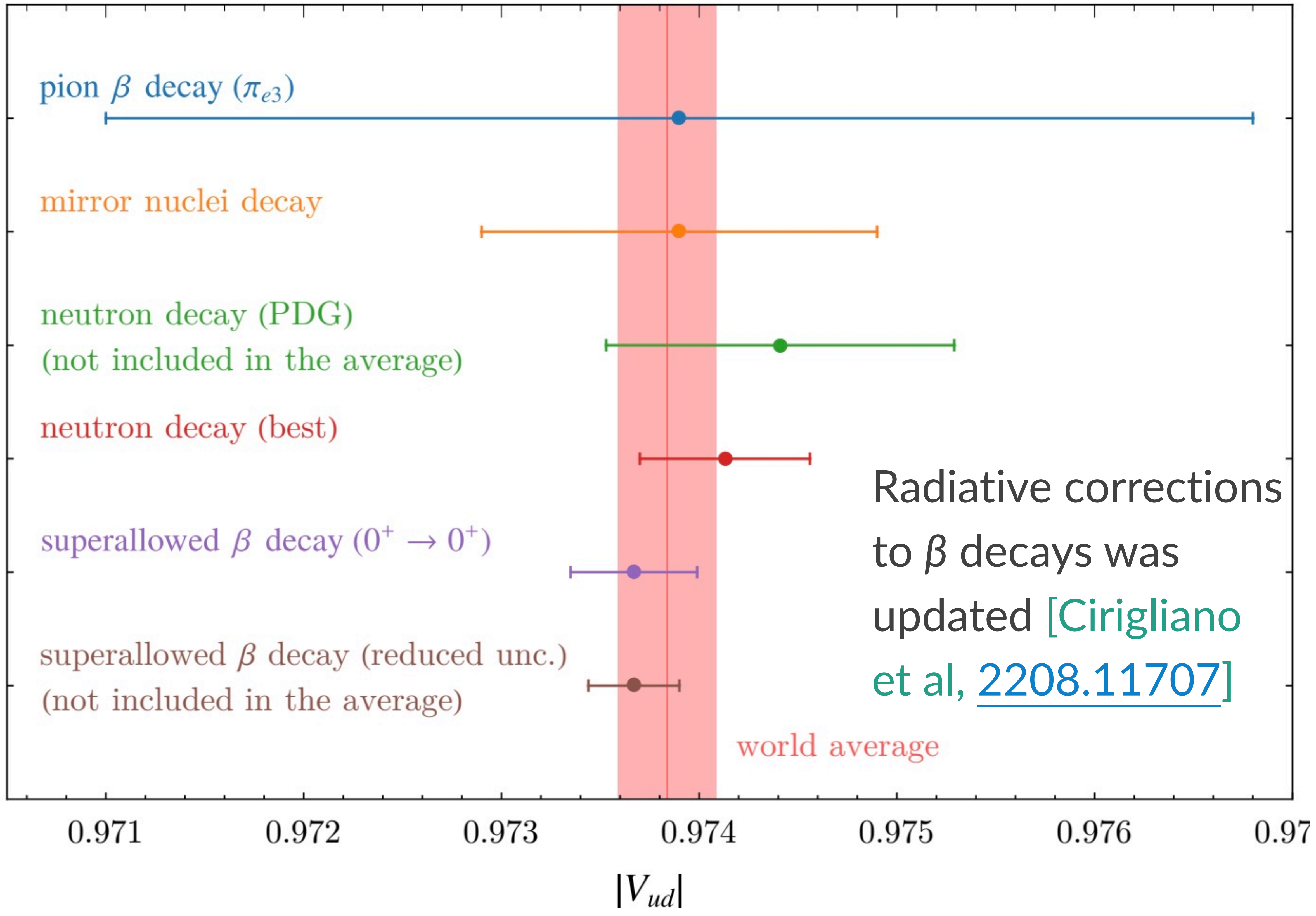
[FLAG2021, 2111.09849]



Vud and Vus determinations

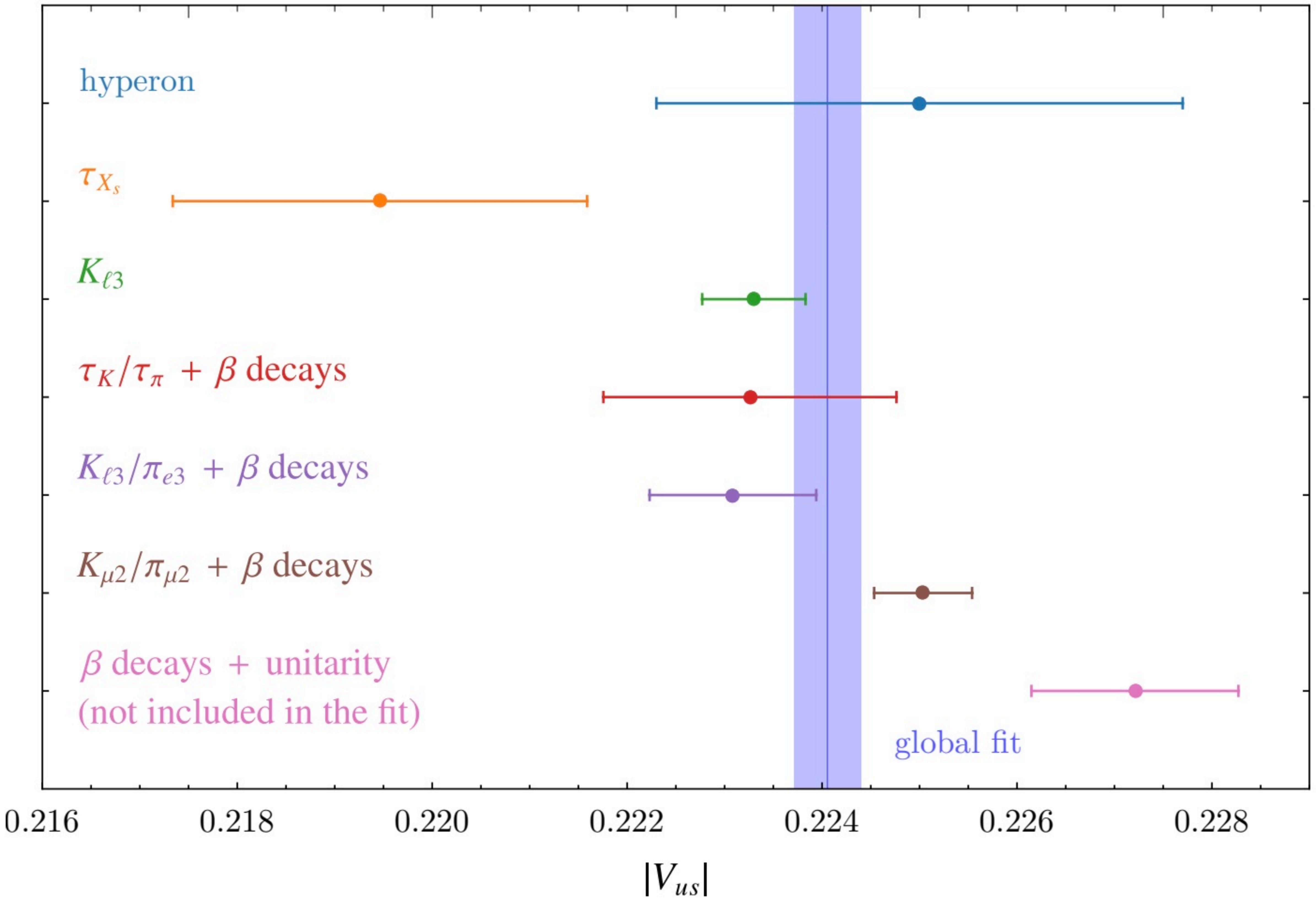
See also Young-san's talk

[Crivellin, Kirk, **TK,** Mescia, 2212.06862]



Radiative corrections to β decays was updated [Cirigliano et al, 2208.11707]

All data are consistent



One can see several tensions

Cabibbo-angle anomaly (CAA) [Crivellin, Kirk, **TK,** Mescia, 2212.06862]

$K_{\ell 3}$

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

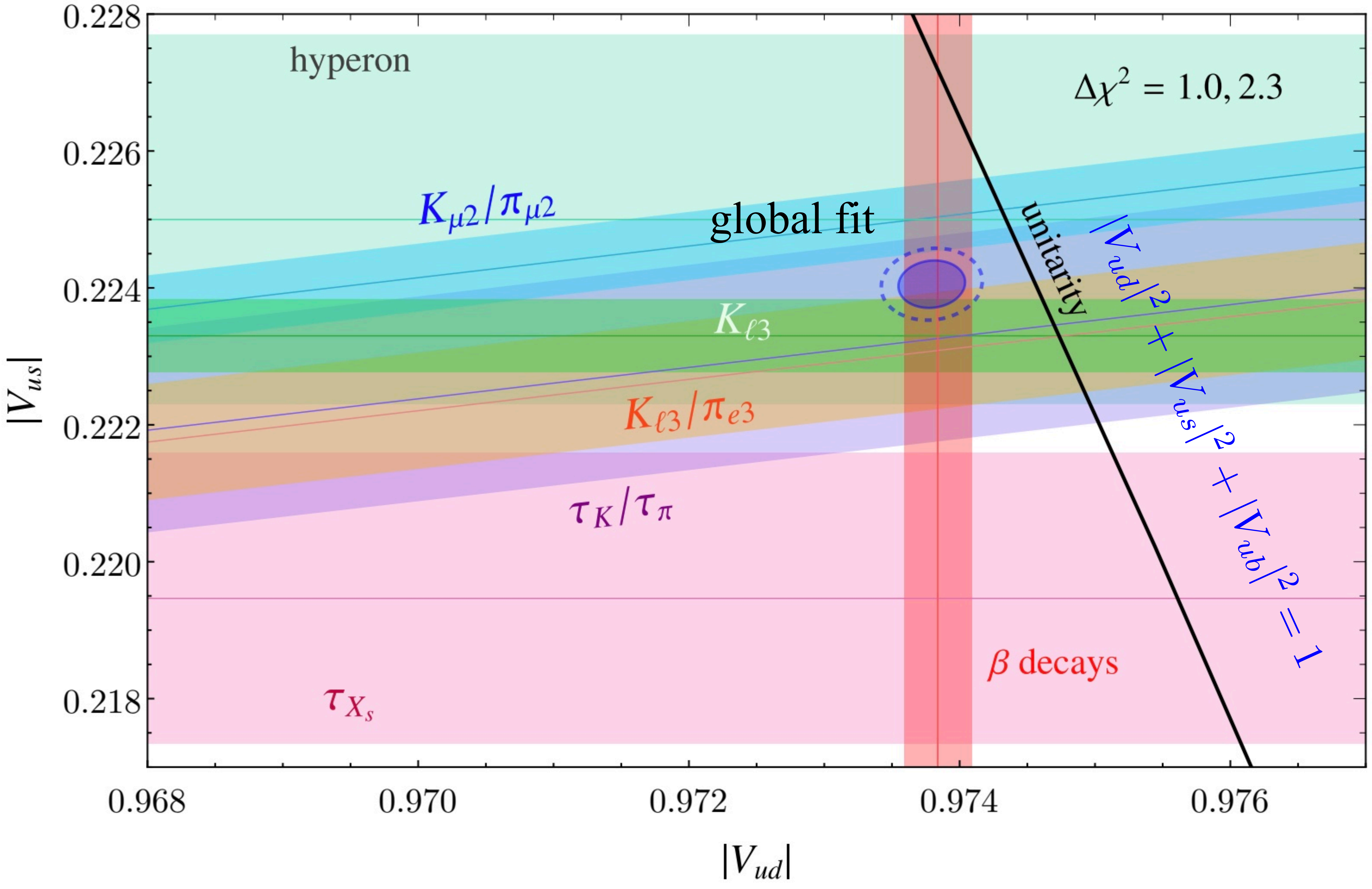
$K^- \to \pi^0 \ell \bar{\nu}$

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

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 CAA

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

$$|V_{ud}|_{\rm global} = 0.973\,79(25)\,, \quad |V_{us}|_{\rm global} = 0.224\,05(35)\,, \qquad \rho(V_{ud}, V_{us}) = 0.09$$

$$\Delta_{\rm CKM}^{\rm global} \equiv |V_{ud}|^2_{\rm global} + |V_{us}|^2_{\rm global} + |V_{ub}|^2 - 1 = -0.001\,51(53)\,,$$

2.8σ level deviation from the unitarity condition

- Another precise combination (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

EFT fitting

[Crivellin, Kirk, **TK**, Mescia, 2212.06862]

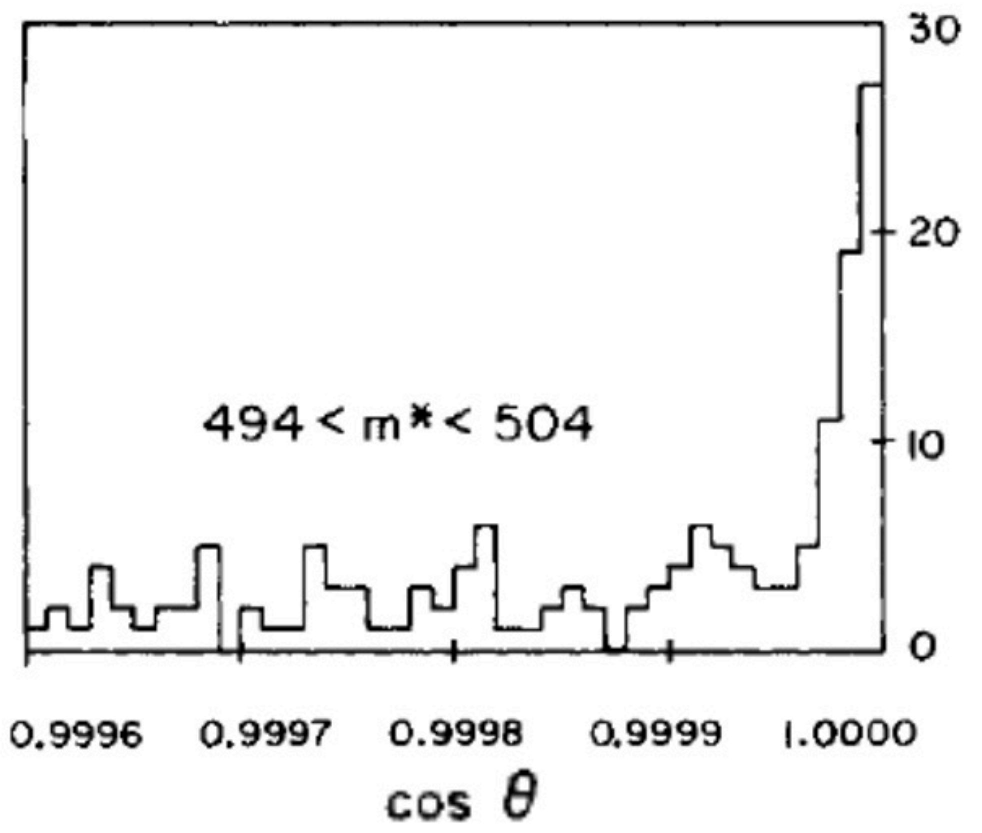
- EFT global fitting implies that right-handed W-u-d and W-u-s new physics is preferred

EFT Scenario	Best fit point	$-\Delta\chi^2$	Pull
$\left[C_{Hq}^{(3)}\right]_{11}$	-0.49	3.3	$1.8\,\sigma$
$\left[C_{Hq}^{(3)}\right]_{11} = \left[C_{Hq}^{(3)}\right]_{22}$	-0.26	1.1	$1.1\,\sigma$
$\left[C_{Hq}^{(3)}\right]_{11} = \left[C_{Hq}^{(1)}\right]_{11}$	-0.53	3.6	$1.9\,\sigma$
$[C_{Hud}]_{11}$	-1.1	3.3	$1.8\,\sigma$
$[C_{Hud}]_{12}$	-2.5	8.2	$2.9\,\sigma$
$([C_{Hud}]_{11}, [C_{Hud}]_{12})$	$(-1.6, -3.1)$	15	$3.5\,\sigma$
$\left(\left[C_{Hq}^{(3)}\right]_{11}, [C_{Hud}]_{12}\right)$	$(-0.59, -2.7)$	12	$3.1\,\sigma$
$\left(\left[C_{Hq}^{(3)}\right]_{11}, [C_{Hud}]_{11}, [C_{Hud}]_{12}\right)$	$(0.25, -2.1, -3.2)$	16	$3.2\,\sigma$
$\left(\left[C_{Hq}^{(3)}\right]_{11}, \left[C_{Hq}^{(3)}\right]_{22}, [C_{Hud}]_{11}, [C_{Hud}]_{12}\right)$	$(0.59, 0.78, -2.8, -3.3)$	18	$3.3\,\sigma$
$\left(\left[C_{Hq}^{(3)}\right]_{11}, \left[C_{Hq}^{(1)}\right]_{11}, [C_{Hud}]_{11}, [C_{Hud}]_{12}\right)$	$(0.27, 0.11, -2.1, -3.2)$	16	$2.9\,\sigma$

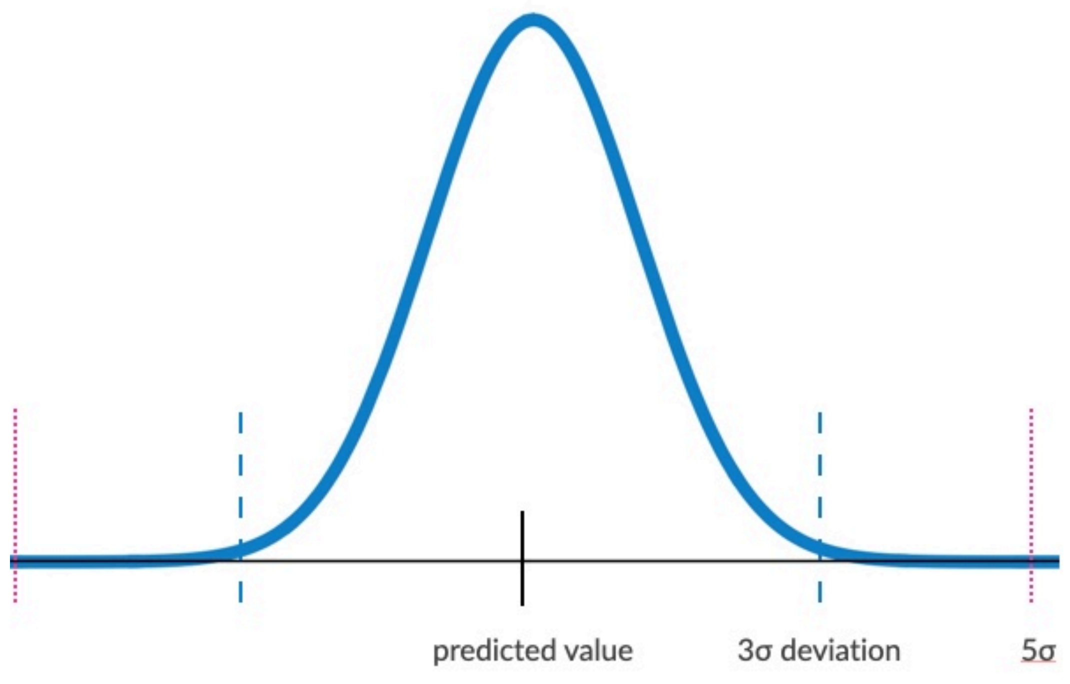
nice pull

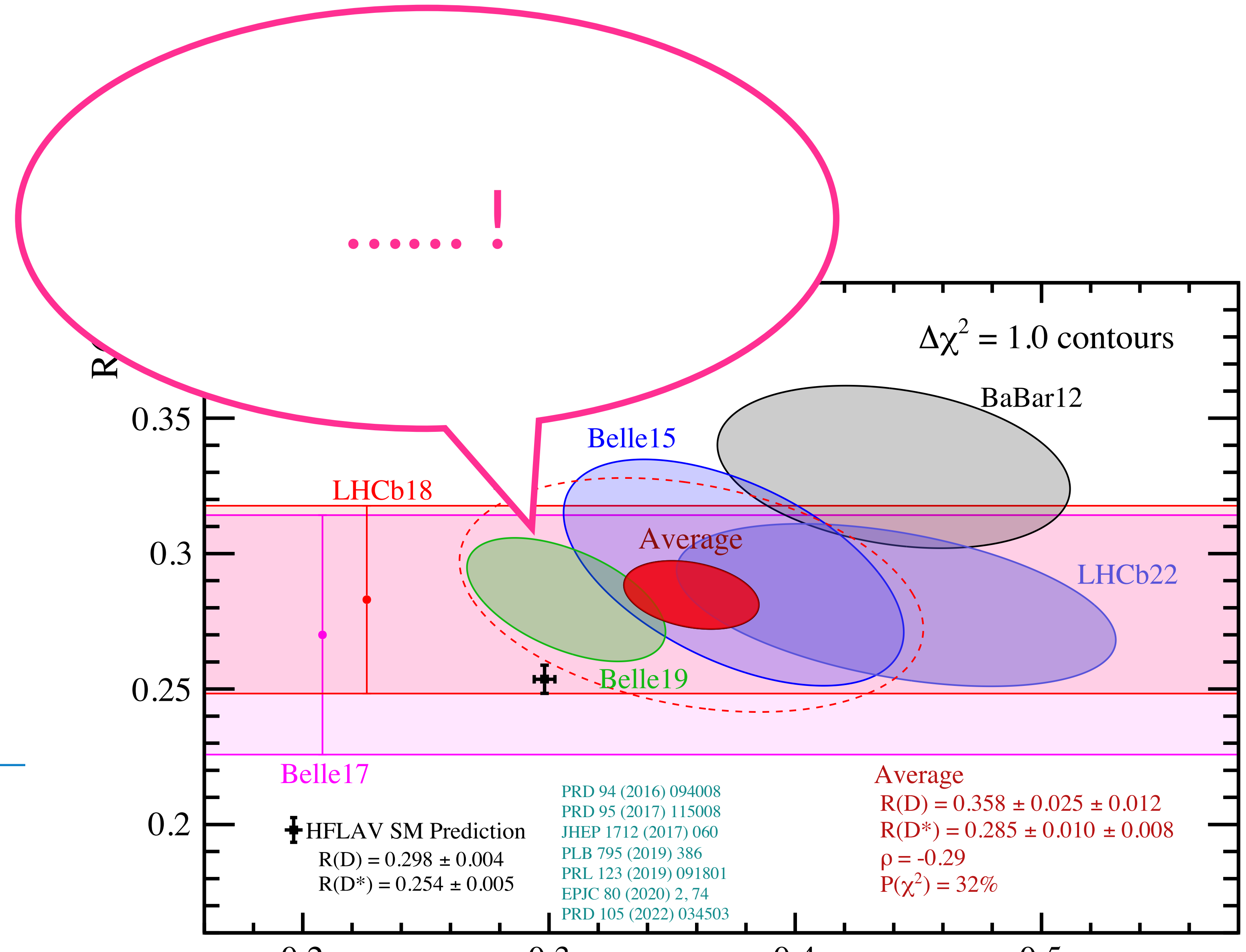
Conclusions

- Flavor physics is an essential approach to investigate new physics beyond the SM
- Currently, several flavor anomalies are found. There, the statistical data analysis plays an important role
- Beyond the statistical data analysis, it is important to investigate *hidden theoretical correlation among several observables*

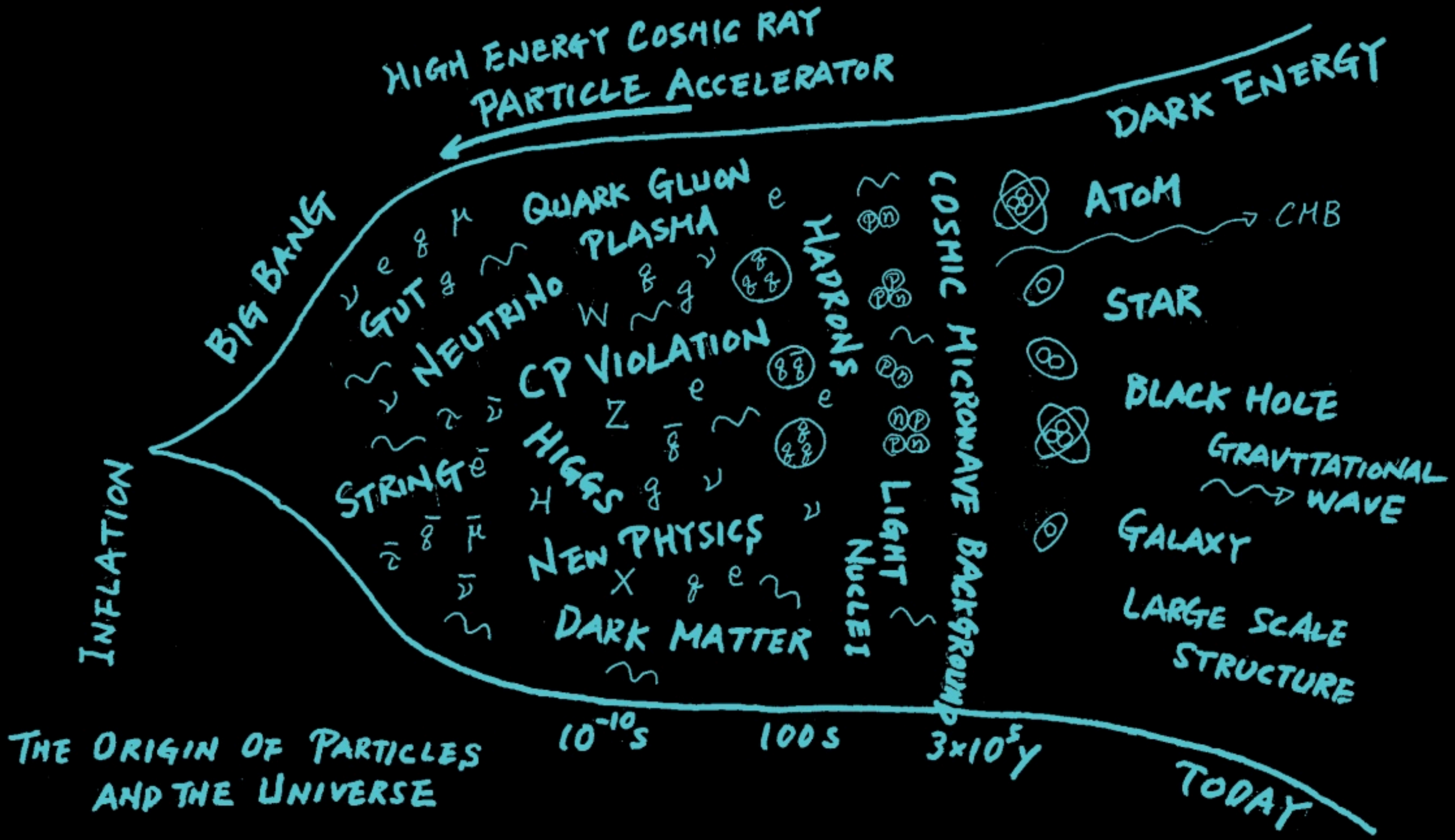


or





Backup slides



(c) KMI/Nagoya-U

Operators for CAA

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

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

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

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

Operators for R(D$^{(*)}$) anomaly

$$\mathcal{H}_{\rm eff} = 2\sqrt{2} G_F V_{cb} \Big[(1 + C_{V_L}) O_{V_L} + C_{V_R} O_{V_R} + C_{S_L} O_{S_L} + C_{S_R} O_{S_R} + C_T O_T \Big] ,$$

with

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

$$O_{S_L} = (\bar{c} P_L b)(\bar{\tau} P_L \nu_\tau) , \qquad O_{S_R} = (\bar{c} P_R b)(\bar{\tau} P_L \nu_\tau) ,$$

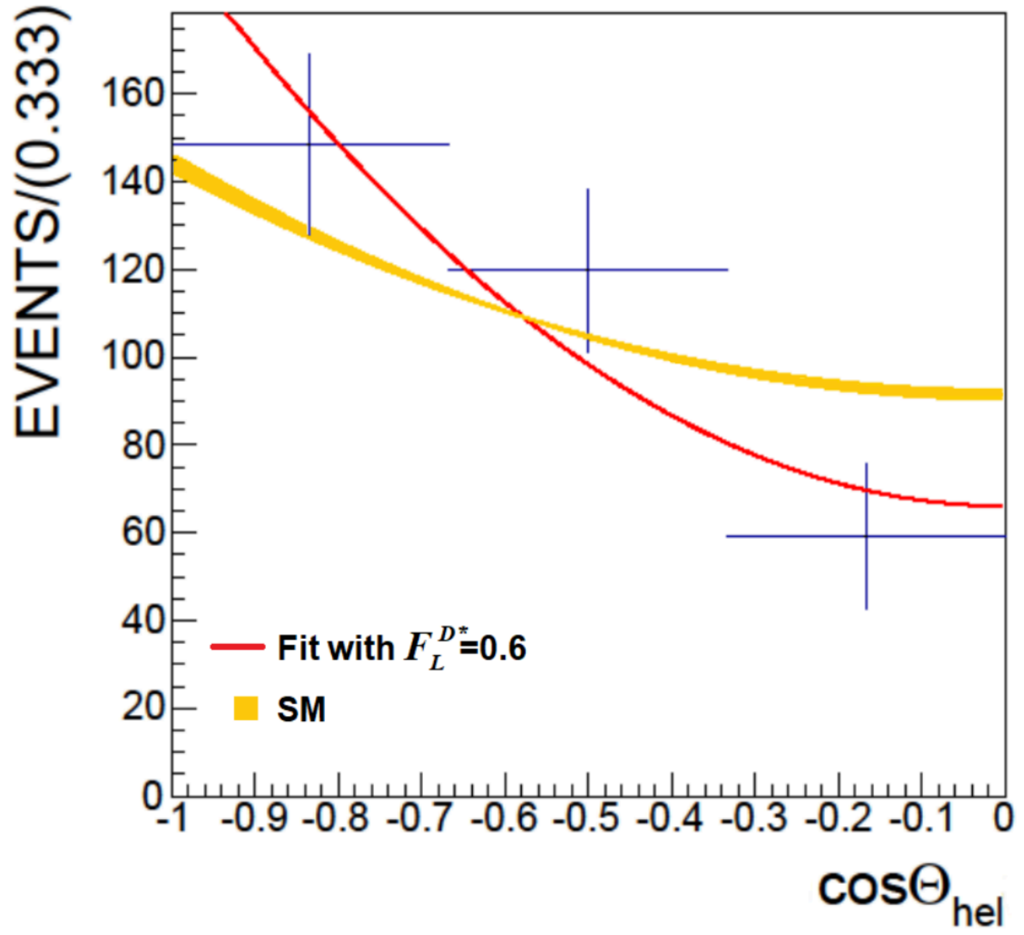
$$O_T = (\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\tau}\sigma_{\mu\nu} P_L \nu_\tau) ,$$

Polarization observables in $b \to c\tau\nu$

- The following two polarization observables could be important to confirm/distinguish new physics
  - Longitudinal D^* polarization ($D^* \to D\pi$)

$$F_L(D^*) = \frac{\Gamma(B \to D_L^* \tau\nu)}{\Gamma(B \to D^* \tau\nu)}$$

θ_{hel} is the angle between D and B in the D^* rest frame



[Belle, 1903.03102]

1.4 σ consistent

  - τ polarization asymmetry along the longitudinal directions of τ ($\tau \to \pi\nu,\ \rho\nu$) [Tanaka, ZPC '95]

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

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

[Blanke, Crivellin, **TK**, Moscati, Nierste, Nisandzic '19]

B anomaly prediction

Charged Higgs

SU(2)$_L$-singlet scalar LQ (S_1)

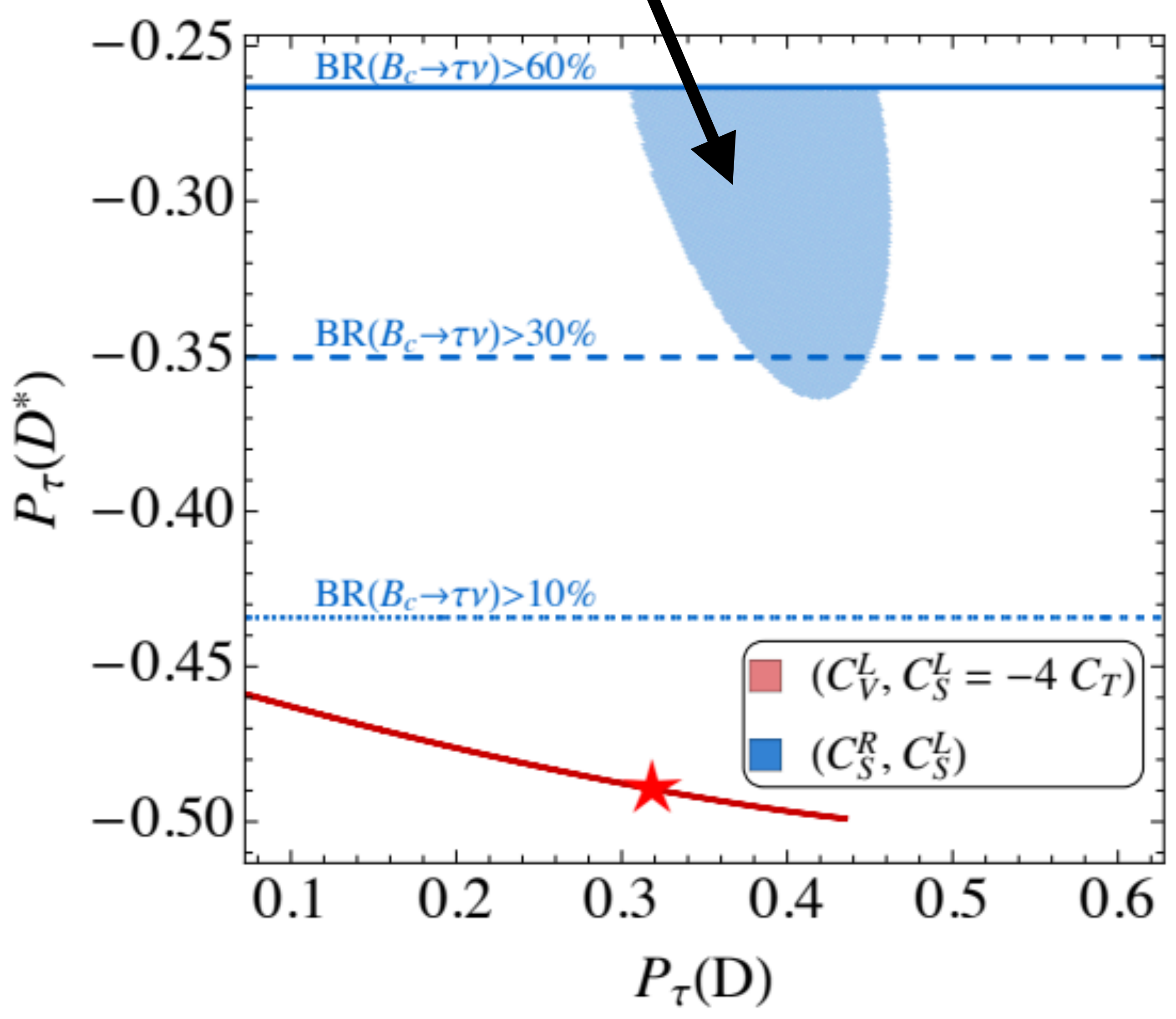
$P_\tau(D)$ vs. $P_\tau(D^*)$

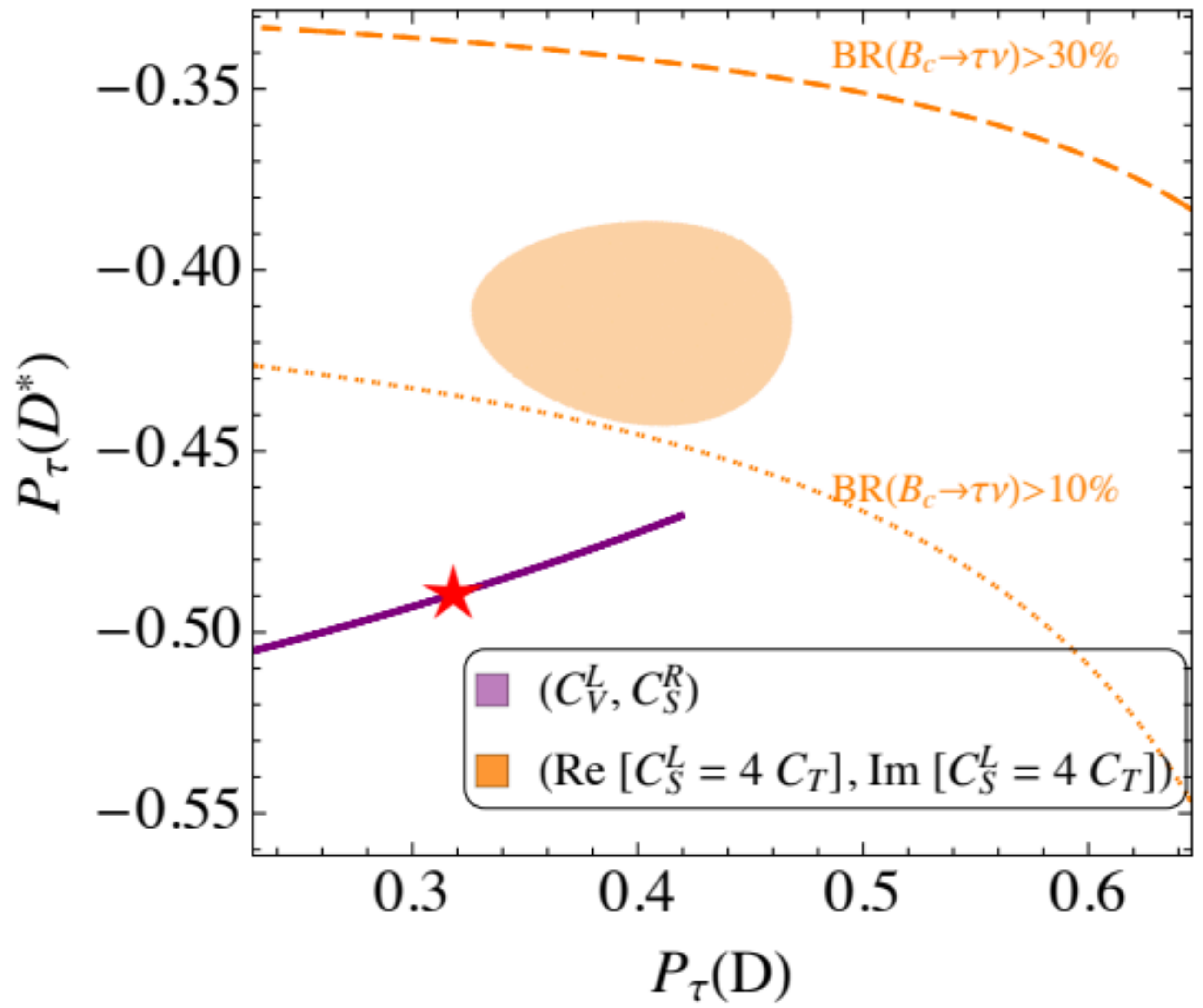
↑

Polarization observables in $B \to D^{(*)}\tau\nu$, which will be probed by Belle II

↓

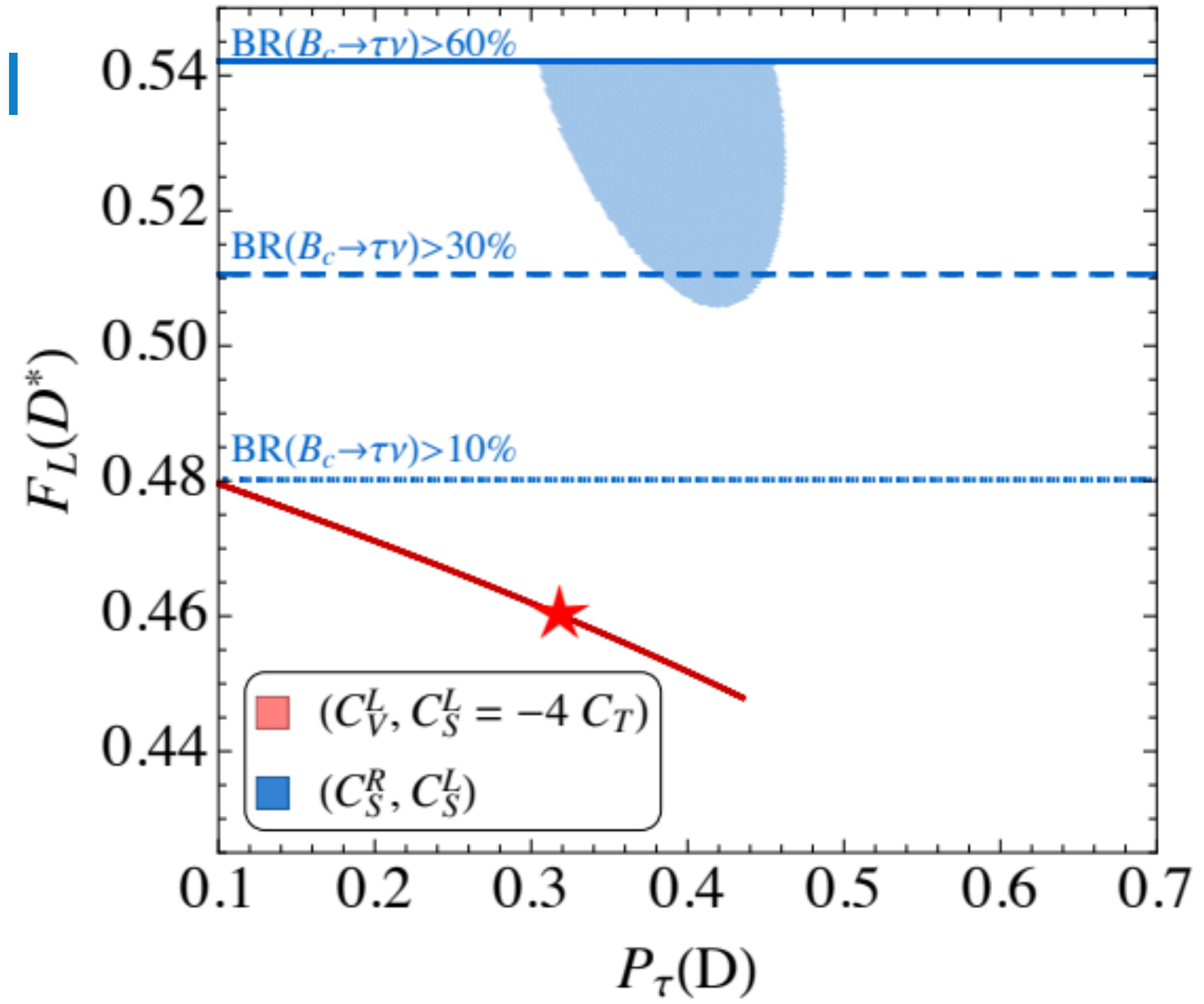
$P_\tau(D)$ vs. $F_L(D^*)$

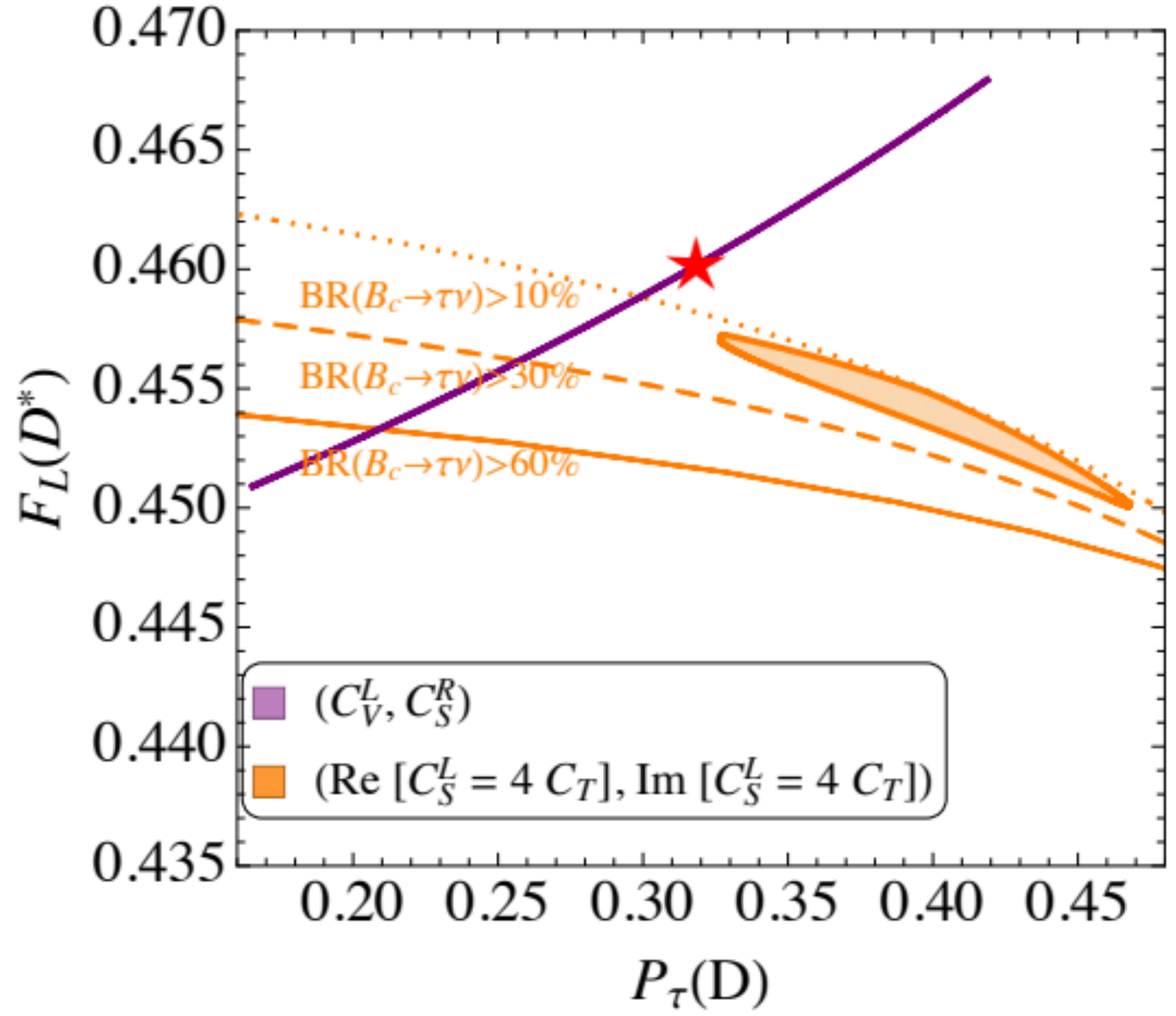




SU(2)$_L$-doublet scalar LQ (R_2)

SU(2)$_L$-singlet vector LQ (U_1)





$P_\tau(D)$ can discriminate the new physics

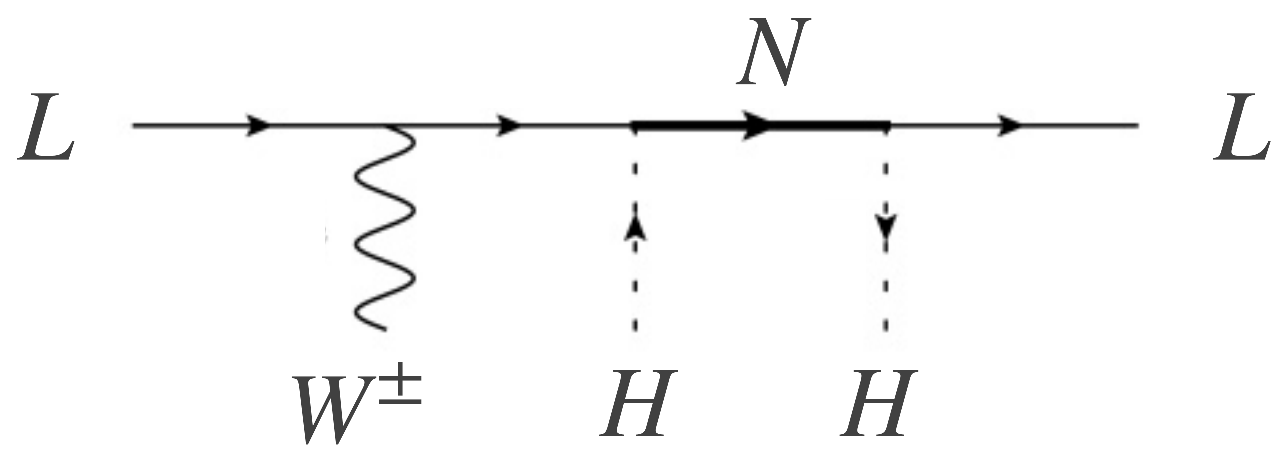
$P_\tau(D^*)$ could discriminate the new physics

One can distinguish each new physics scenario

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-ℓ-ν fit [Crivellin, et al, 2002.07184]; G_F fit [Crivellin, et al, 2102.02825]
- 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]
- Vector-like Lepton (1-2 TeV) [Endo, Mishima, 2005.03933; Crivellin, et al, 2008.01113; Kirk, 2008.03261
  - **Heavy right-handed neutrino** (type I seesaw) can not explain the tension, but the unphysical region [$(\text{mixing})^2 < 0$] is favored



W-ℓ-ν coupling

Light NP?

- How about **a light sterile neutrino**?

Neutrino anomalies on the market

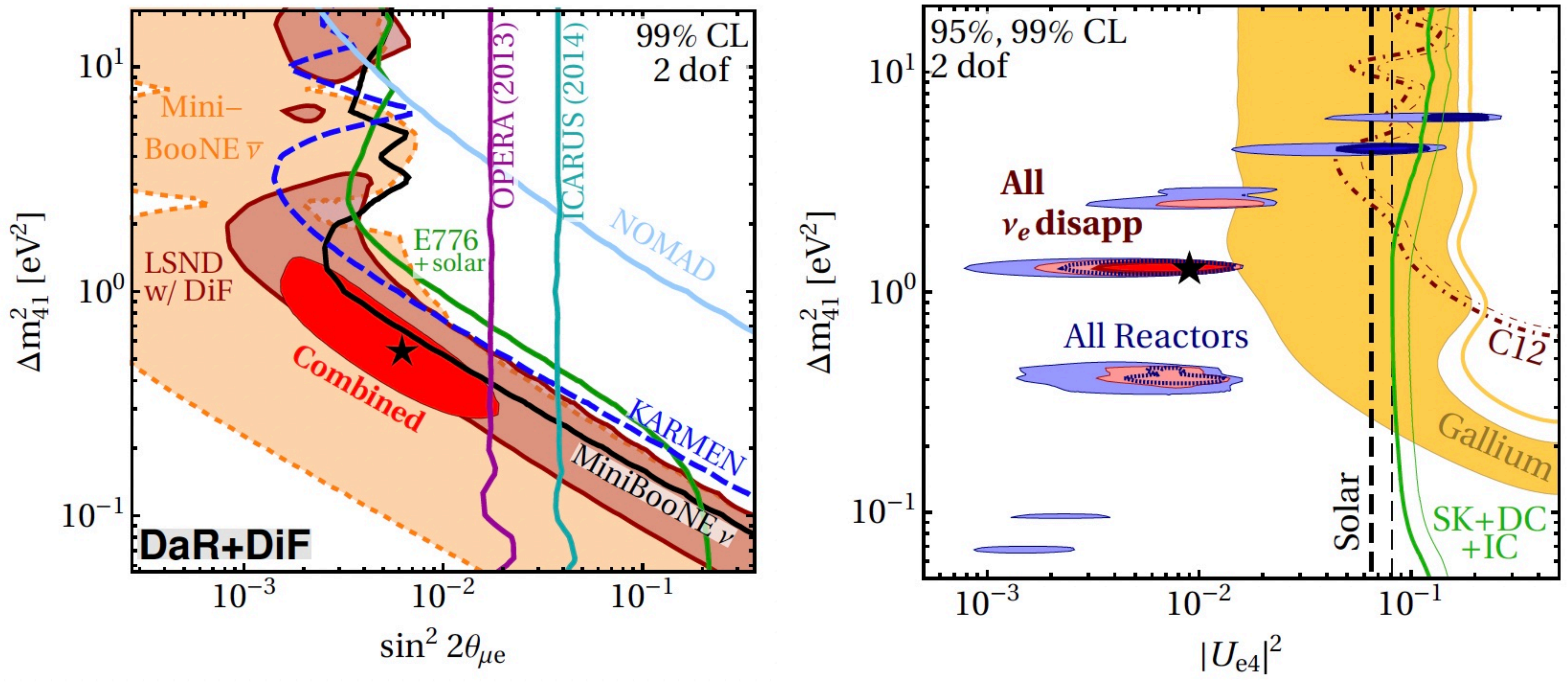
- O(1) eV sterile neutrino (neutrino oscillations from LSND, MiniBooNE, Gallium Anomaly, Reactor Antineutrino Anomaly)

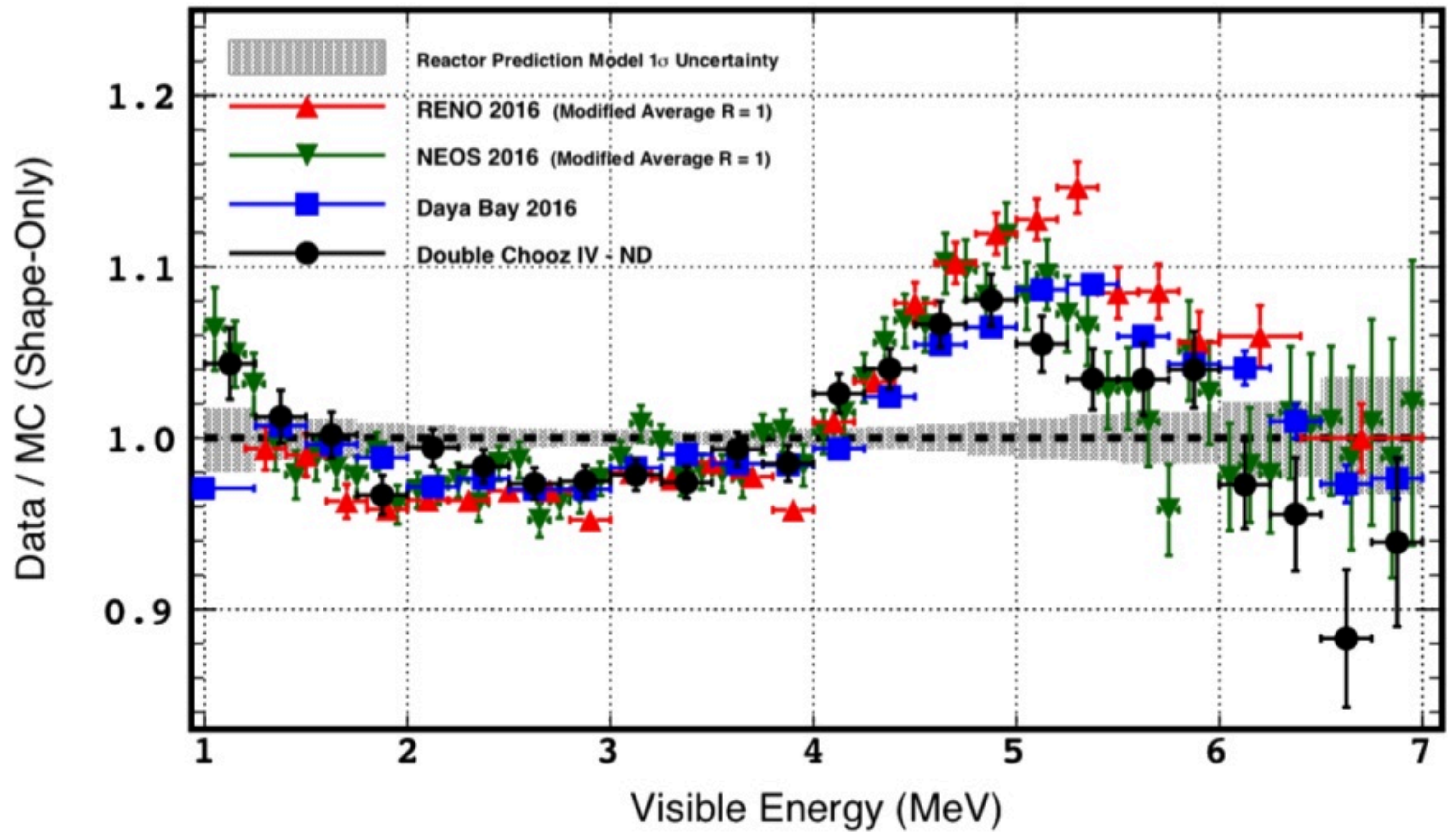
- 7 keV decaying sterile neutrino (3.5 keV photon emission from galaxy clusters)

- 5 MeV bump in antineutrino energy spectrum (RENO, NEOS, Daya Bay, Double Chooz)

- But, no conclusive measurements yet

[Dentler et al, 1803.10661]



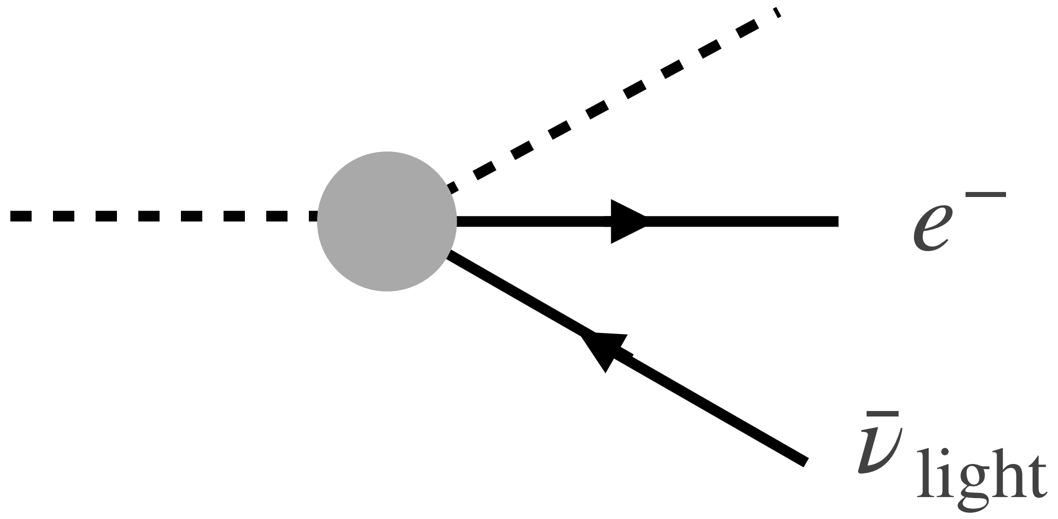


[Double Chooz, 1901.09445]

Sterile neutrino contributions

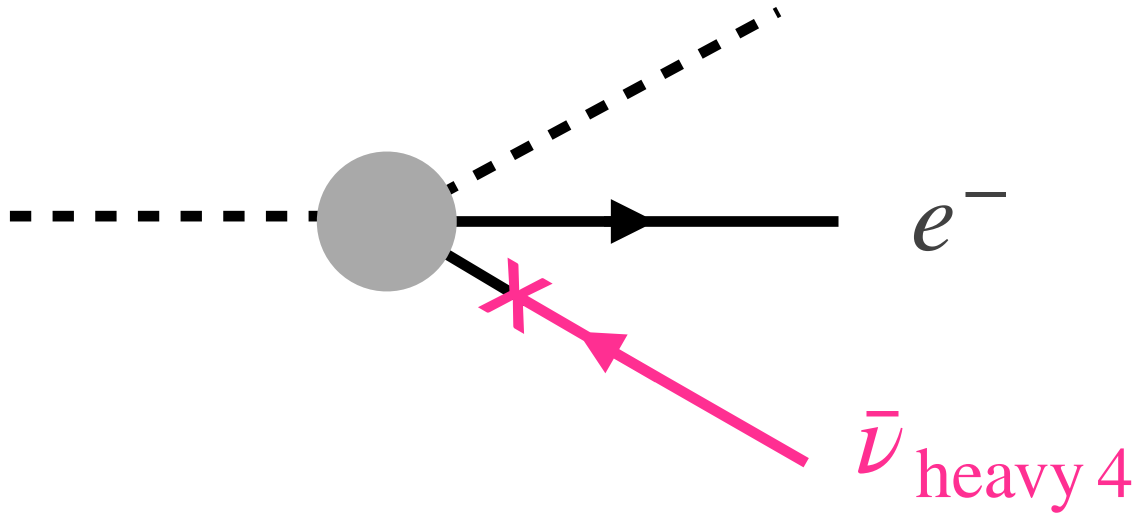
- **Two contributions** to the leptonic and semi-leptonic decays

1. modifies active neutrino coupling



$\propto \cos\theta_e$

2. decay into sterile neutrino if kinematically possible



$\propto \sin\theta_e^{(4)}$ with phase space suppression

- When the sterile neutrino masses are much smaller than the decay Q-value ($M_N \ll Q$), **the total contribution from 1+2 is canceled**

$$|\mathcal{M}|^2 = |\mathcal{M}_{\rm SM}|^2 \cos^2\theta_e + |\mathcal{M}_{\rm SM}|^2 \sin^2\theta_e \times f(M_N, Q)$$

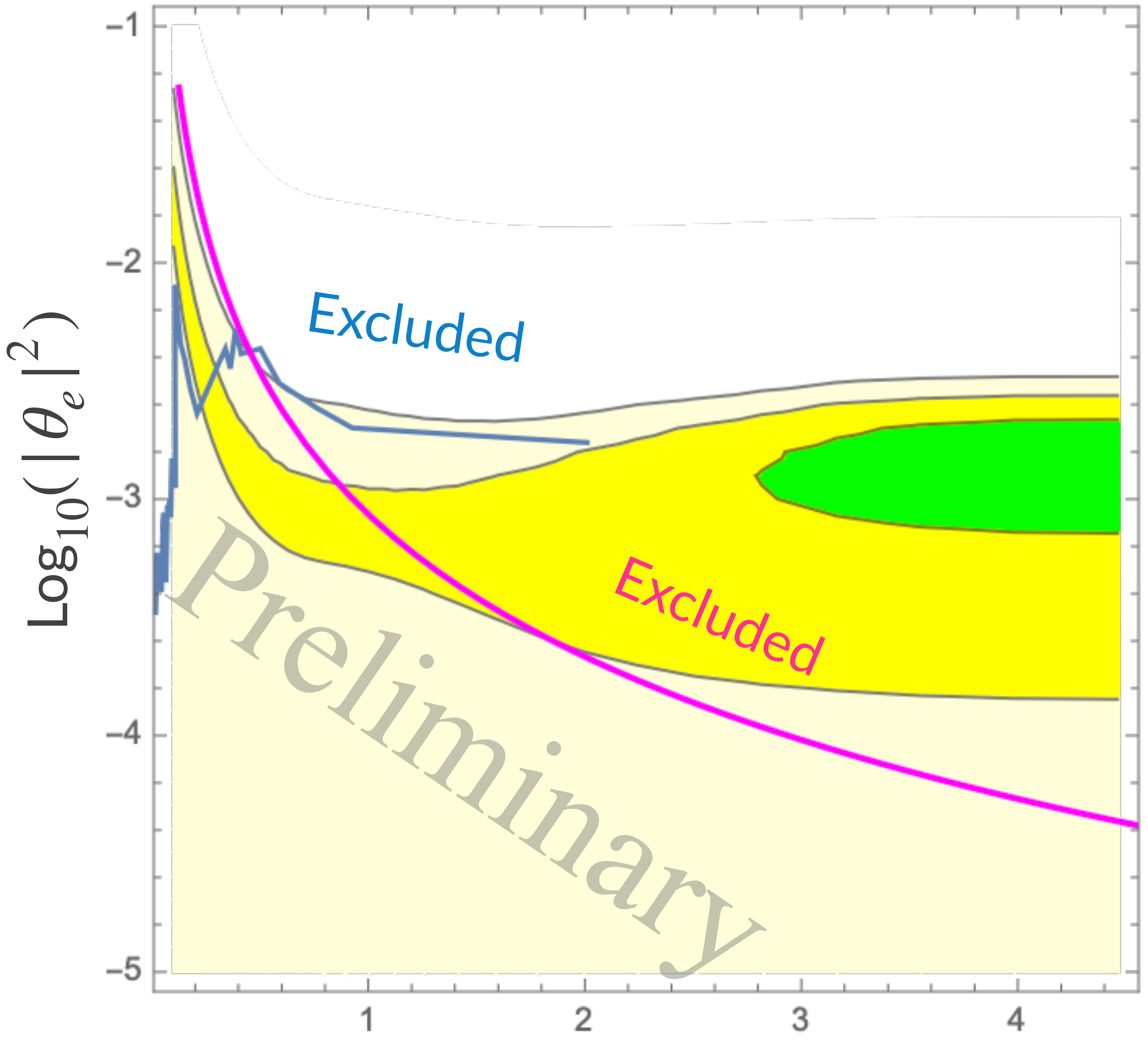
$$\simeq |\mathcal{M}_{\rm SM}|^2 (\cos^2\theta_e + \sin^2\theta_e) = |\mathcal{M}_{\rm SM}|^2$$

[Isakov, Strikman, ’86; Deutxh, Lebrun, Prieels, '90]

sterile-neutrino contributions are suppressed when $M_N \ll Q$

Sterile neutrino fitting

Favored parameter regions (1σ/2σ) in a MeV sterile neutrino model **with assuming CKM unitarity**



[Kitahara, Tobioka, in progress]

Kink search in the energy spectrum of the isotope β decays [Bolton, et al, 1912.03058]

$$E_{\mathrm{kink}} = Q - M_N$$

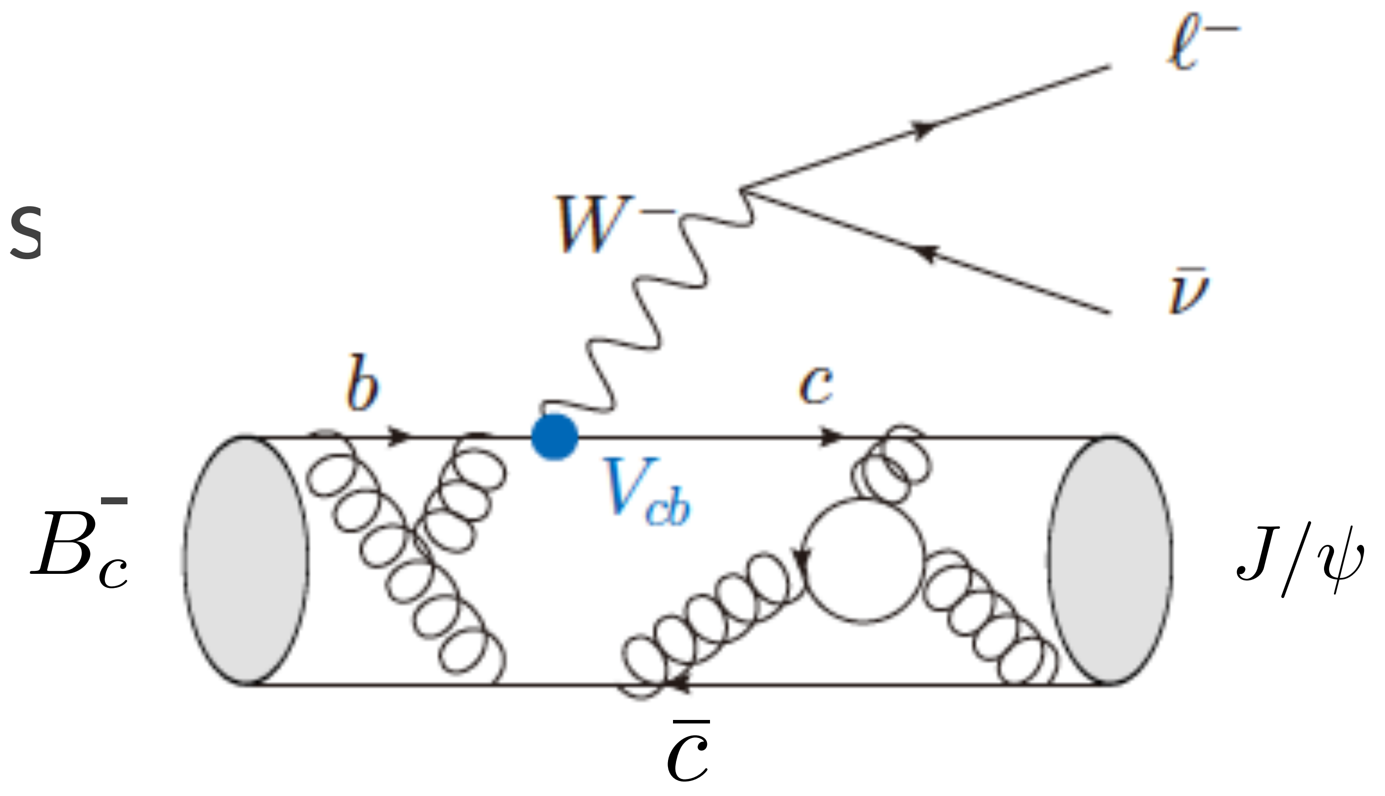
PIENU experiment:
1506.05845, 1909.11198

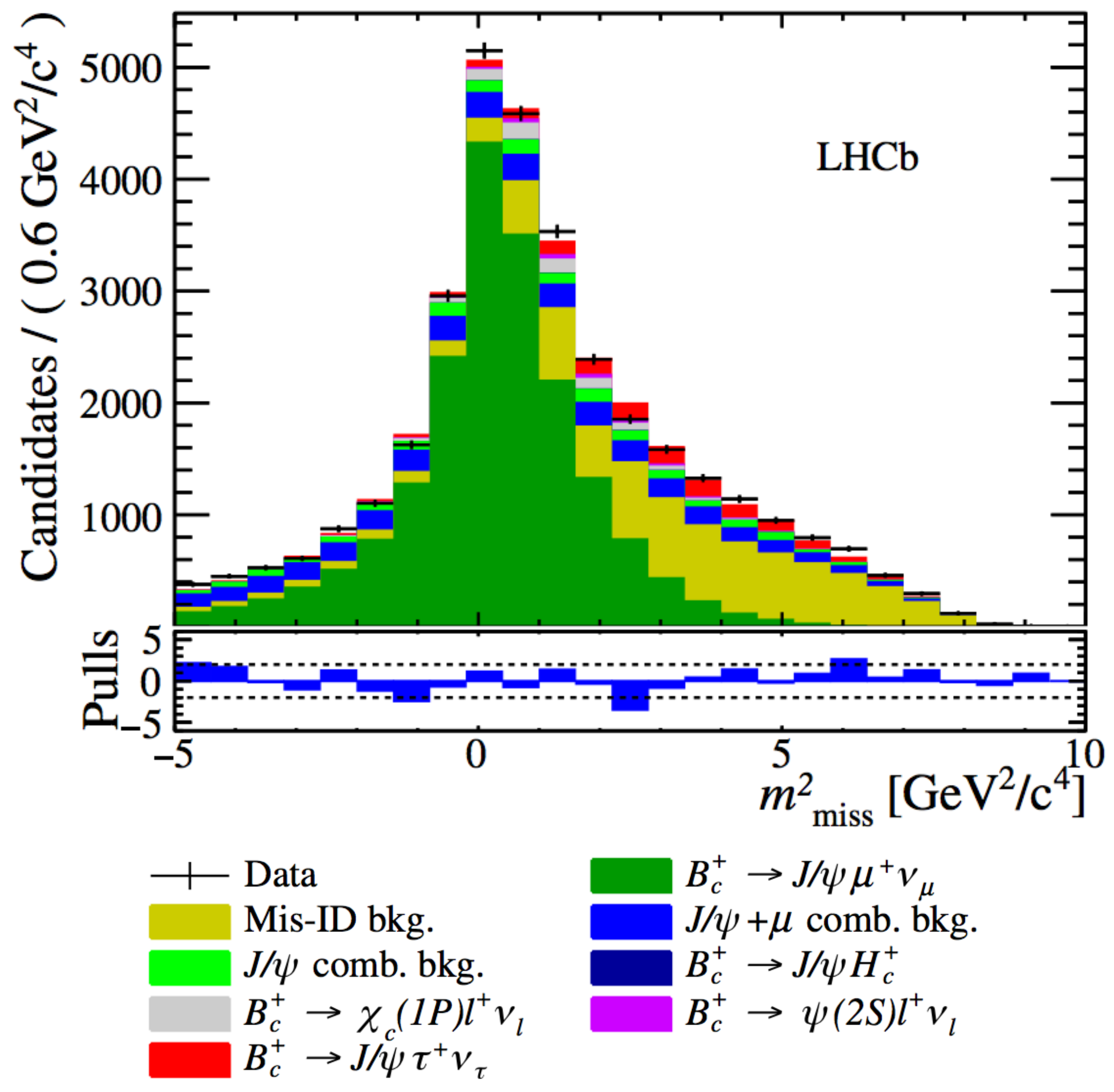
$$\frac{\mathrm{BR}(\pi^+ \to e^+\nu_e)}{\mathrm{BR}(\pi^+ \to \mu^+\nu_\mu)}$$

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

- The LFU violation was measured in $B_c^- \to J/\psi$ transitions

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





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

$R(J/\psi)_{\rm SM} = 0.2582 \pm 0.0038$ Based on first lattice result [HPQCD, 2007.06956]

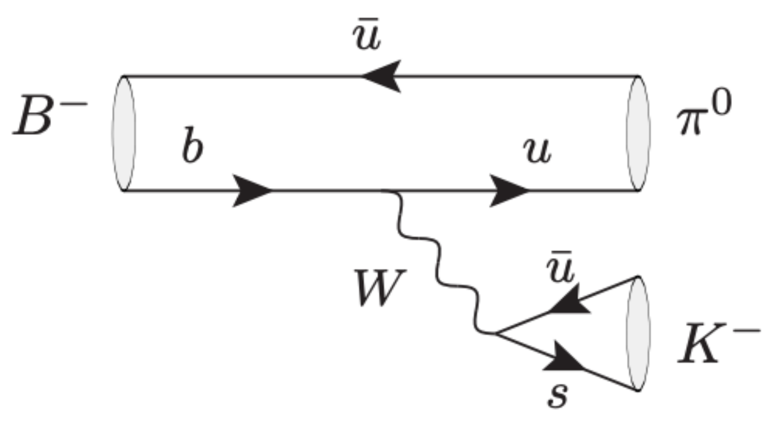
1.8σ consistent using N_f=2+1+1, with “HISQ” c and heavy quark b

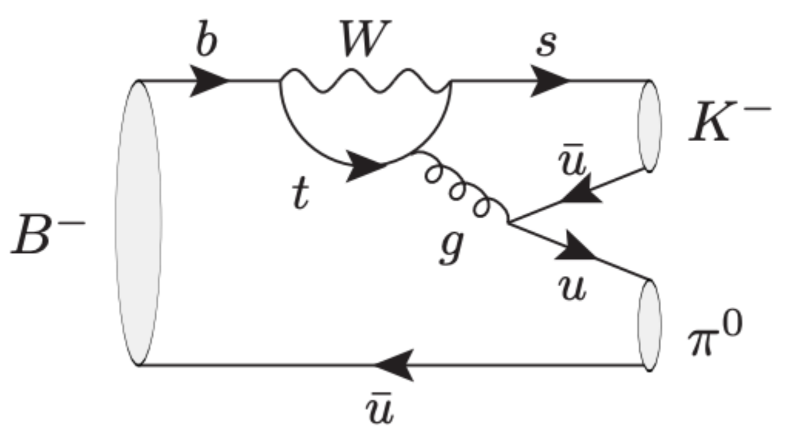
Same-direction tension as R(D) and R(D*) anomalies

New physics study, *e.g.*, [Watanabe, PLB ’18; Alok, Kumar, Kumar, Kumbhakar, Sankar, JHEP ’18]

Signal reconstructed with tau leptonic decays and LHCb Run 1 data (3fb^{-1})

“$K\pi$ puzzle”: Direct CPV in $B \to K\pi$ modes





- Direct CP asymmetry is obtained by

$$A_{CP} = \frac{\Gamma(\bar{B} \to \bar{f}) - \Gamma(B \to f)}{\Gamma(\bar{B} \to \bar{f}) + \Gamma(B \to f)}$$

- The difference between two direct CP asymmetries [note that $\mathcal{B}(B \to K\pi) = \mathcal{O}(10^{-5})$]

$$\Delta A_{CP}(K\pi) = A_{CP}(B^+ \to \pi^0 K^+) - A_{CP}(B^0 \to \pi^- K^+)$$ = 0 @ SM leading order

$$\Delta A_{CP}|_{\rm SM}(K\pi) = (1.8^{+4.1}_{-3.2})\,\%$$

[Hofer, Scherer, Vernazza, JHEP ’11; Crivellin, Gross, Pokorski, Vernazza, PRD '20]

All data are in agreement with each other

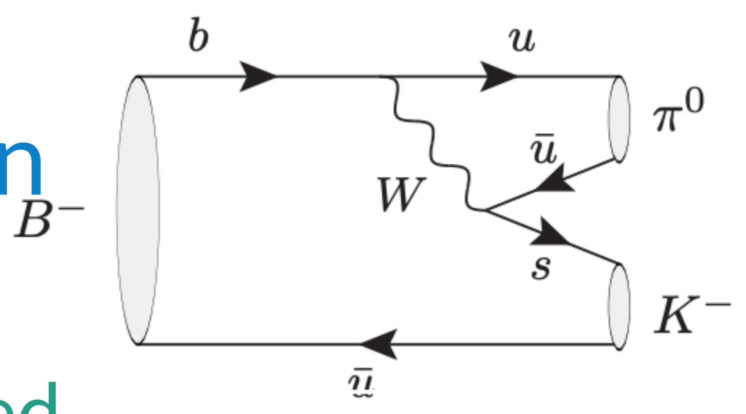
$$A_{CP}|_{\rm BaBar}(B^+ \to \pi^0 K^+) = (3.0 \pm 3.9 \pm 1.0)\,\%$$
$$A_{CP}|_{\rm Belle}(B^+ \to \pi^0 K^+) = (4.3 \pm 2.4 \pm 0.2)\,\%$$

$$A_{CP}|_{\rm BaBar}(B^0 \to \pi^- K^+) = (-10.7 \pm 1.6^{+0.6}_{-0.4})\,\%$$
$$A_{CP}|_{\rm Belle}(B^0 \to \pi^- K^+) = (-6.9 \pm 1.4 \pm 0.7)\,\%$$
$$A_{CP}|_{\rm CDF}(B^0 \to \pi^- K^+) = (-8.3 \pm 1.3 \pm 0.4)\,\%$$
$$A_{CP}|_{\rm LHCb}(B^0 \to \pi^- K^+) = (-8.4 \pm 0.4 \pm 0.3)\,\%$$

2.3σ tension

$$\Delta A_{CP}|_{\rm exp}(K\pi) = (12.4 \pm 2.1)\,\%$$ [HFLAV averages 2019]

SM explanation can be possible, if this contribution is bigger than the NLO prediction by a factor of 2



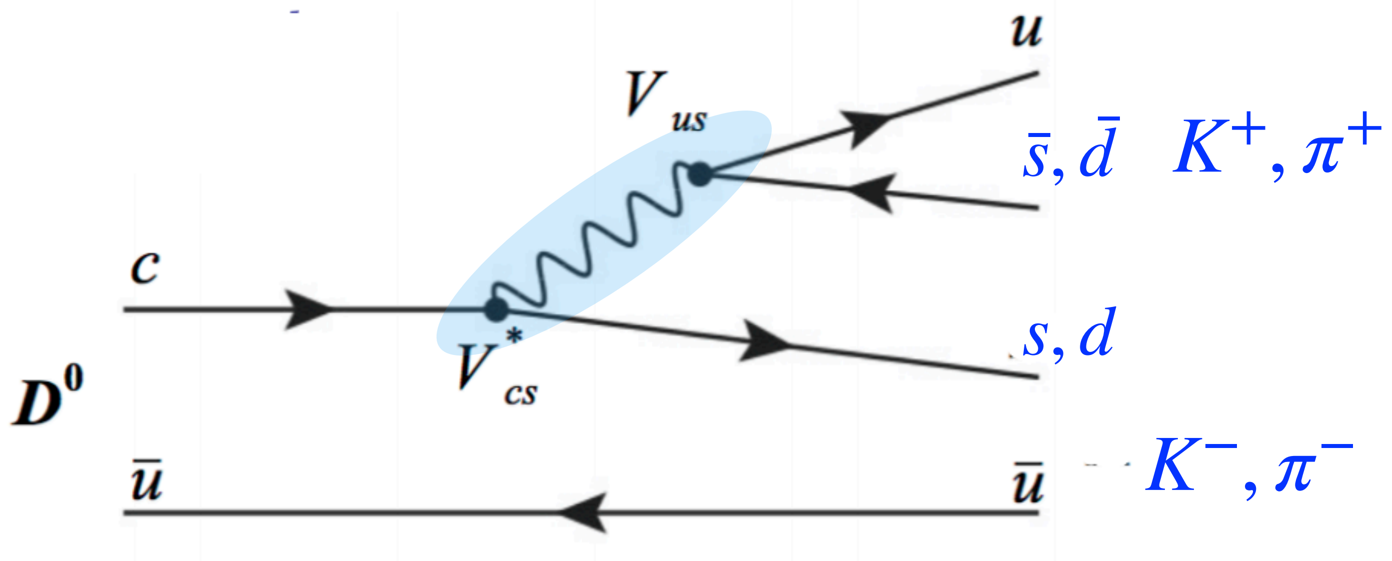
[Li, Mishima, PRD '11; Beaudry, Datta, London, Rashed, Roux, JHEP '18]

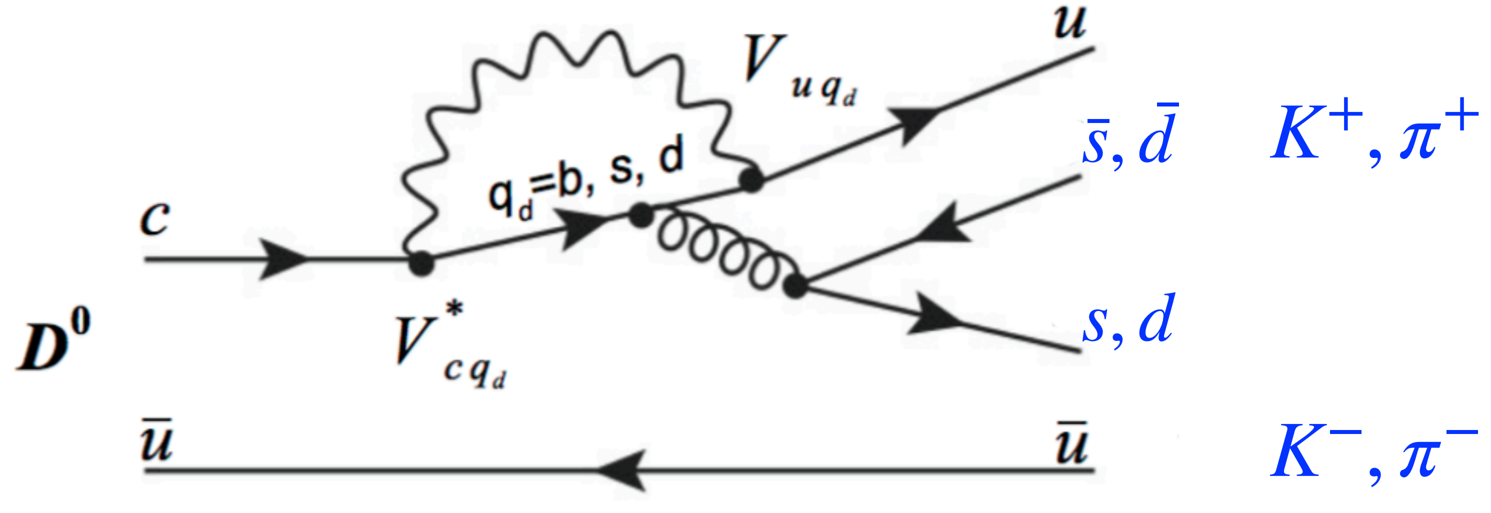
The first observation of CPV in *D*-meson

- Difference of Difference of $D^0 \to h^- h^+$ and $\bar{D}^0 \to h^- h^+$

Direct CPV $A_{CP}(D^0 \to K^- K^+) \equiv \frac{\#(D^0(t=0) \to K^- K^+) - \#(\bar{D}^0(t=0) \to K^- K^+)}{\#(D^0(t=0) \to K^- K^+) + \#(\bar{D}^0(t=0) \to K^- K^+)}$

Observable $\Delta A_{CP} = A_{CP}(D^0 \to K^- K^+) - A_{CP}(D^0 \to \pi^- \pi^+)$



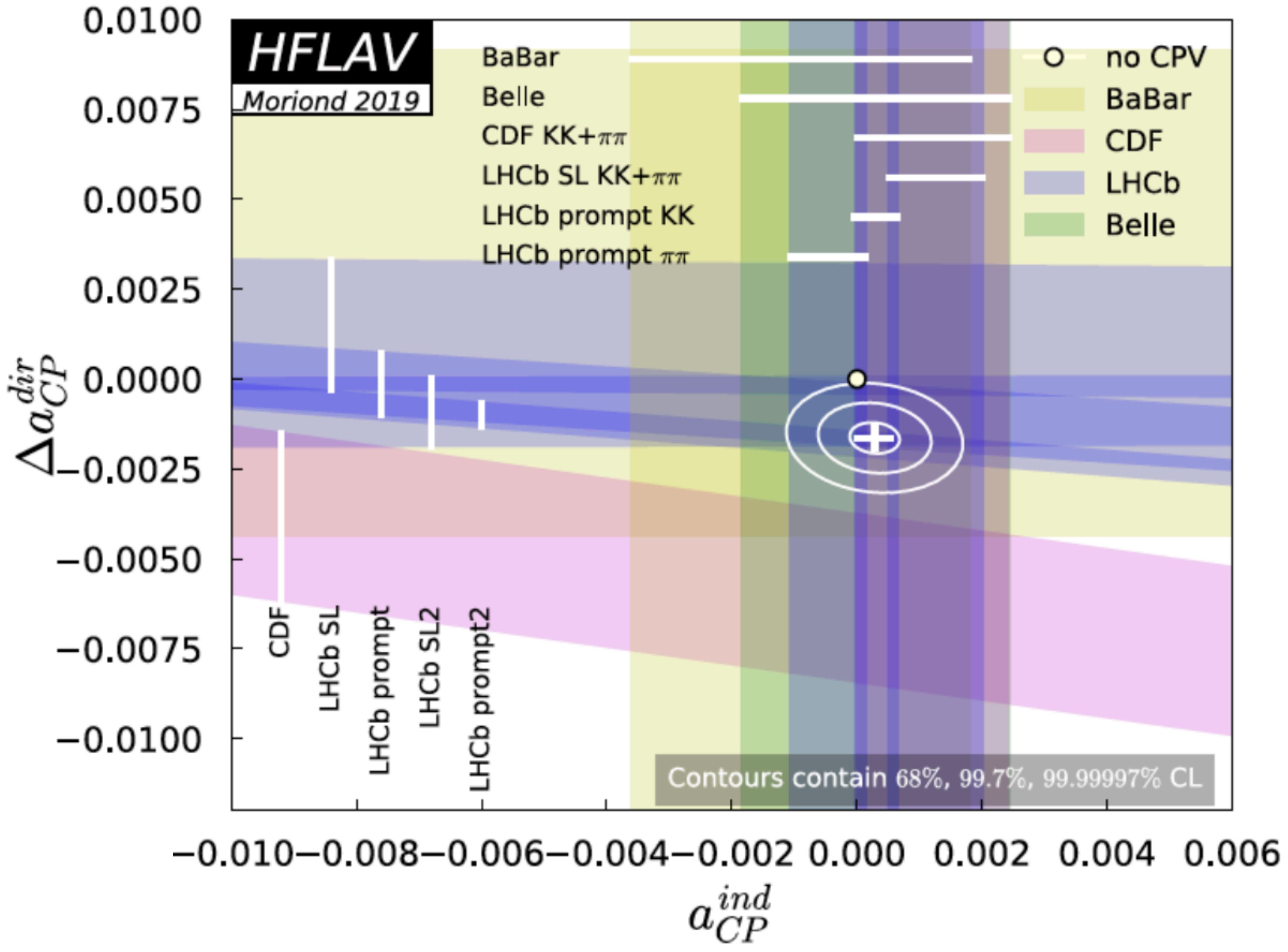


The Direct CPV is ***amplified*** in the difference! $V_{cd} : V_{us} \simeq -1 : 1$

Detection asymmetry and final-state independent uncertainty are dropped!

Direct *CP* violation in *D*

World average



Latest result [LHCb, 1903.08726]

$$\Delta a_{CP}^{dir} = (-15.7 \pm 2.9) \times 10^{-4}$$ 5.3σ discovery of CPV!

But, need confirmation by Belle II

A reliable SM prediction [QCD sum rule]

$$\left|\Delta a_{CP}^{dir}\right| < (2.0 \pm 0.3) \times 10^{-4}$$ [Khodjamirian, Petrov, PLB '17]

Smaller than the data by a factor of 7; 4.7σ tension

(QCD sum rule works well in *B* physics)

SM explanation could be possible by QCD re scattering
$D^0 \to$ "$\pi\pi$" $\to K^- K^+$ [Grossman, FPCP2020]

New physics implications; 2HDM, MSSM, vector-like quark
[Dery, Nir, JHEP '19]