‘Anomaly’ in current low-energy data

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Strings and Fields 2021

August 26, 2021, online talk

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ANOMALY

Two types of ‘Anomaly’ in high-energy physics

1. Quantum anomaly

Measure in the path integral is changed by quantum corrections

Two types of 'Anomaly' in high-energy physics

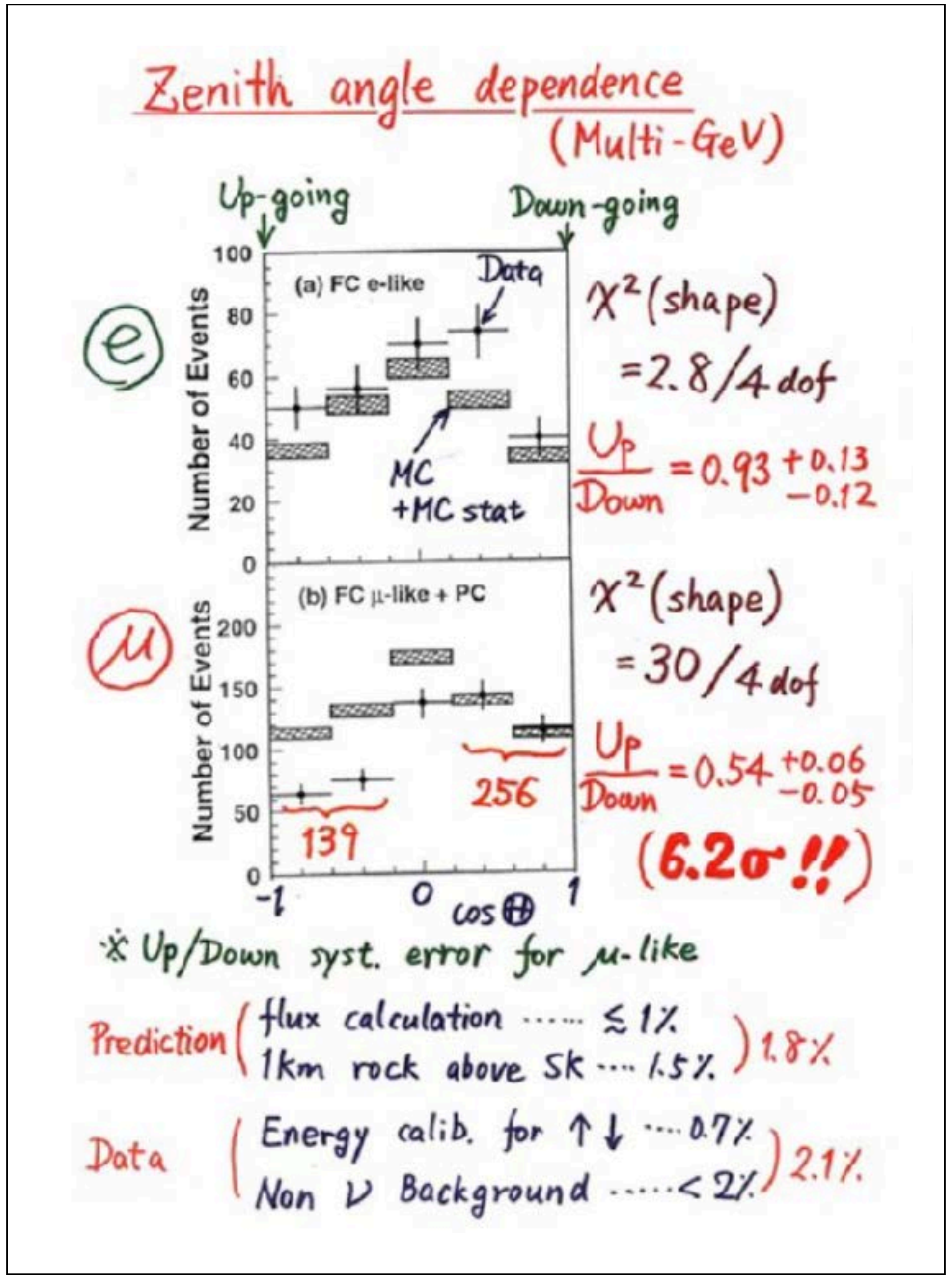
1. Quantum anomaly

   Measure in the path integral is changed by quantum corrections

2. Experimental anomaly (this talk)

   Measurement is inconsistent with a theory prediction

Famous experimental anomaly 1



From *slide* of Kajita [Super-Kamiokande collaboration], 1998

"Atmospheric neutrino anomaly"

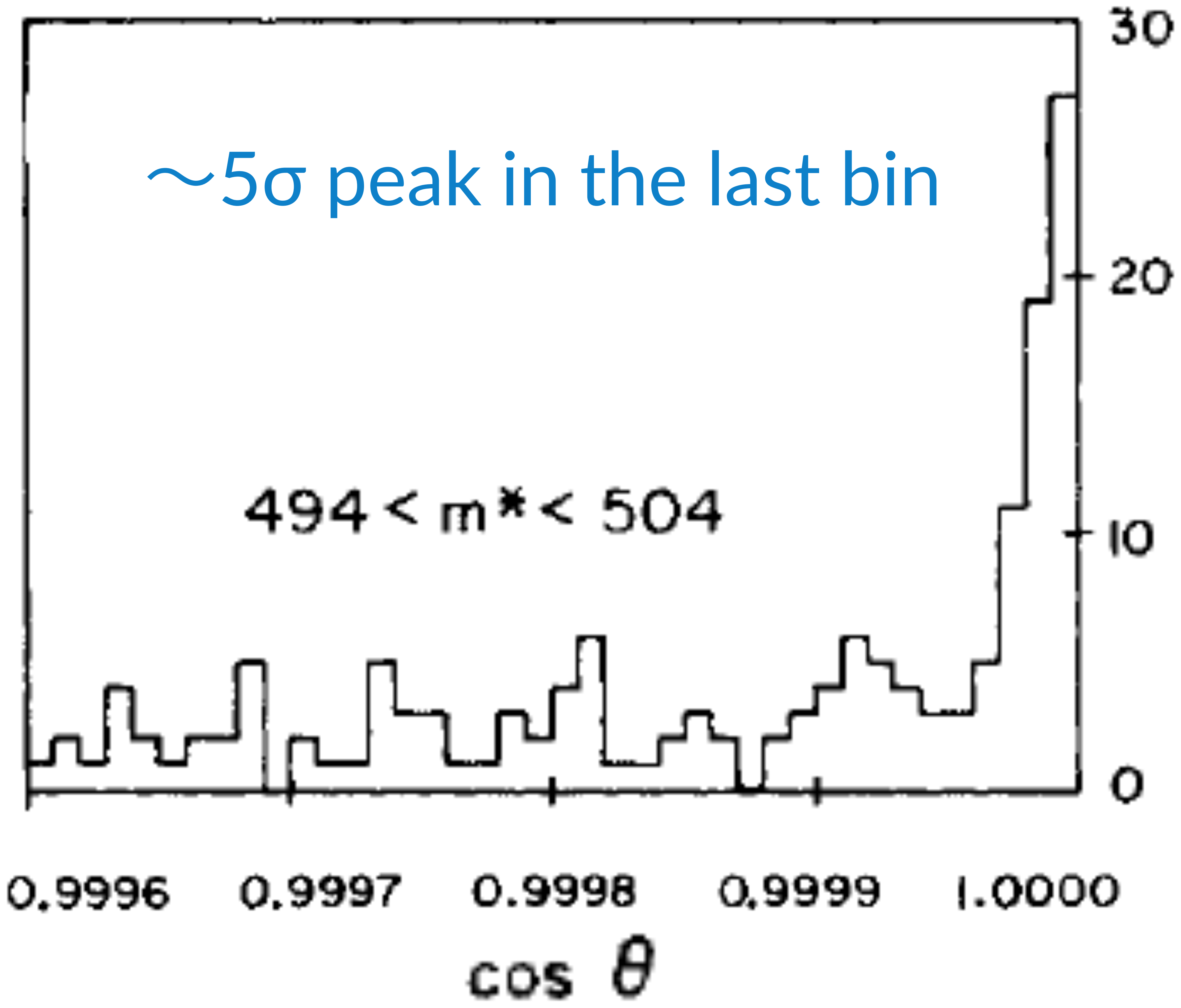
= significant direction-dependence of μ neutrino

Neutrino oscillation and Neutrino mass.

[Nobel Lecture, 2015, Kajita]

Famous experimental anomaly 2

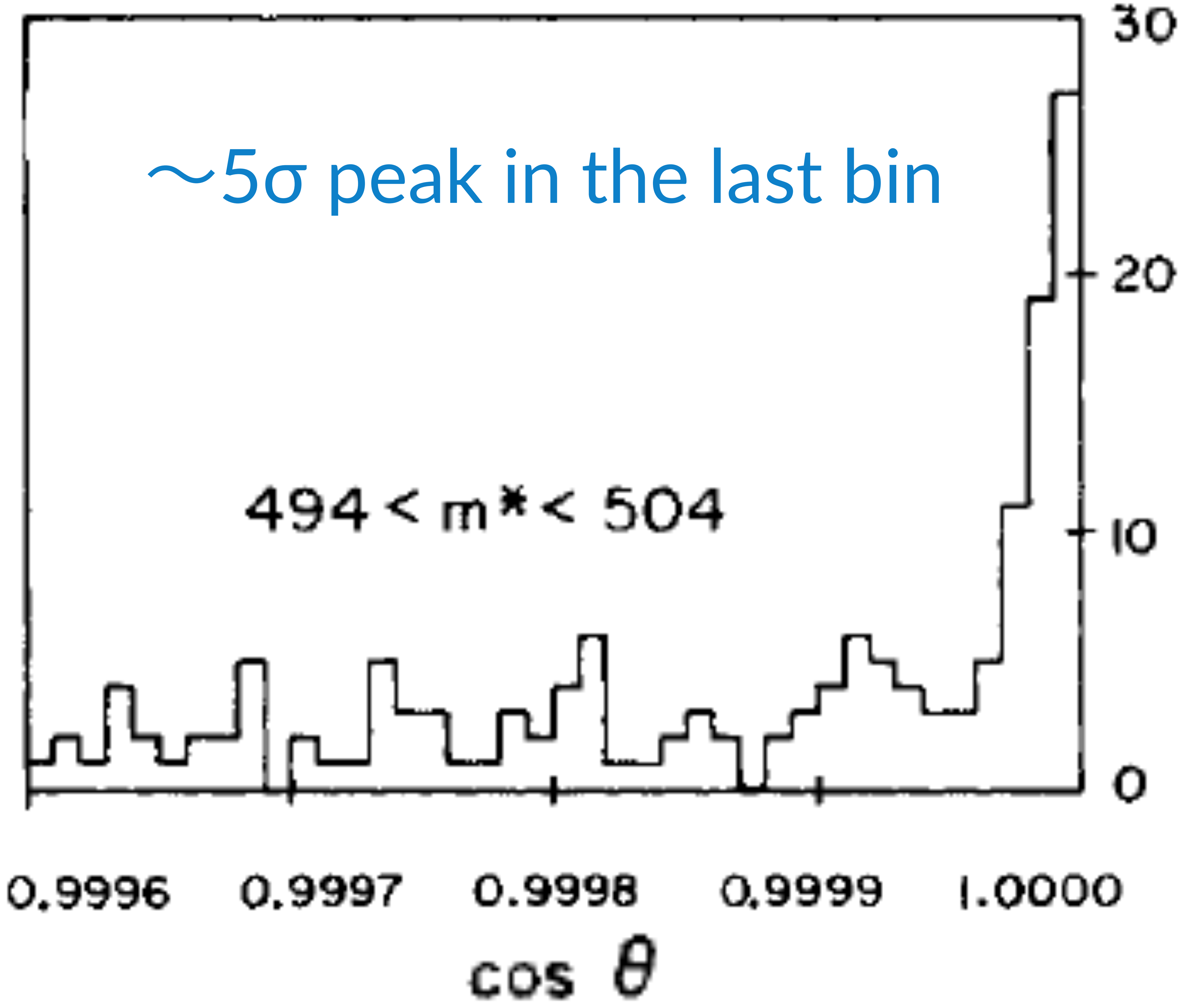
~5σ peak in the last bin



… what?

[Cronin, Fitch et al, '64, PRL]

Famous experimental anomaly 2



[Cronin, Fitch et al, '64, PRL]

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

immediately leads to "discovery of CP violation"

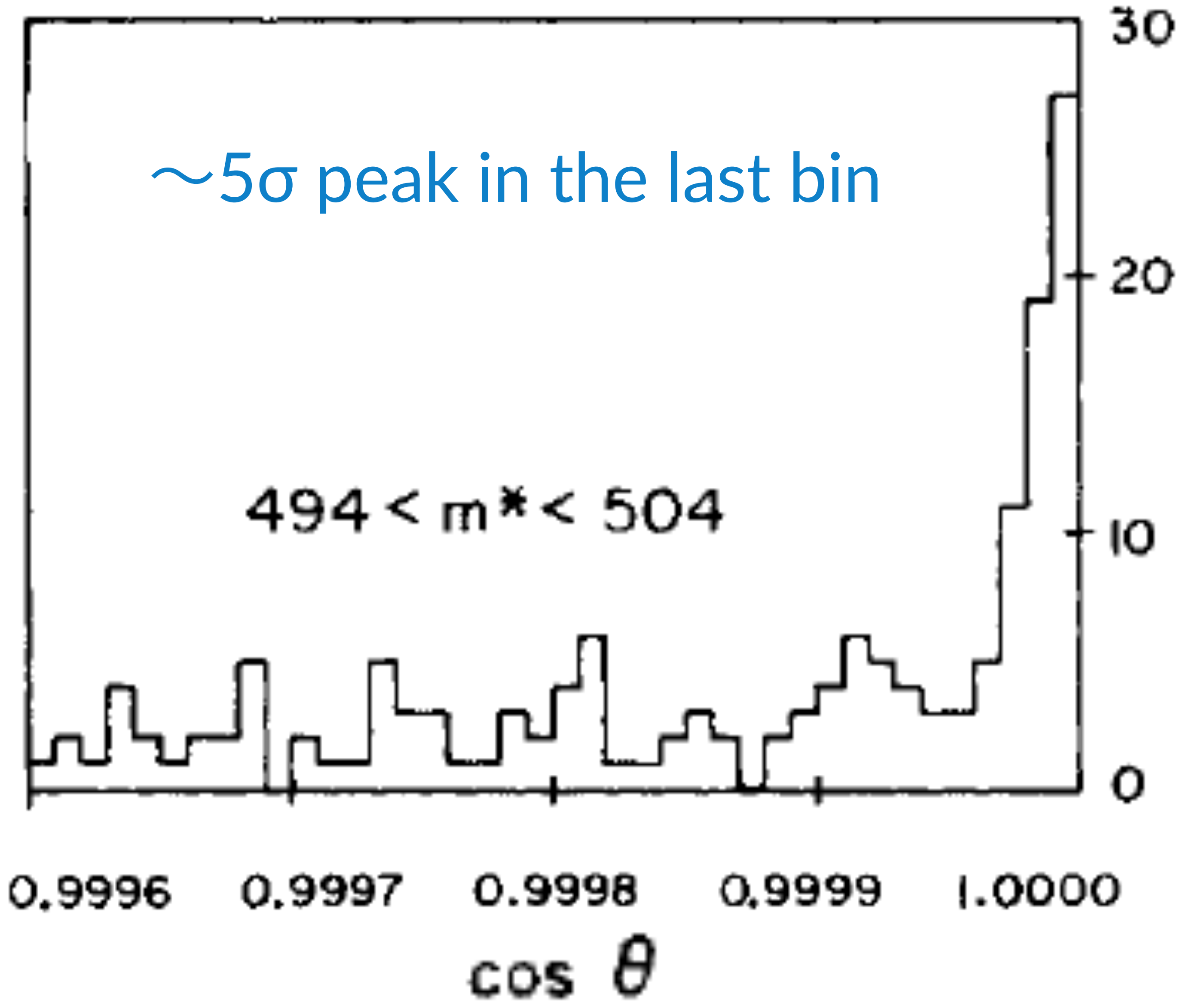
BUT, inconsistent with Weinberg-Salam theory

Kobayashi and **Maskawa** predicted charm, bottom and top quarks in 1973 before their discoveries

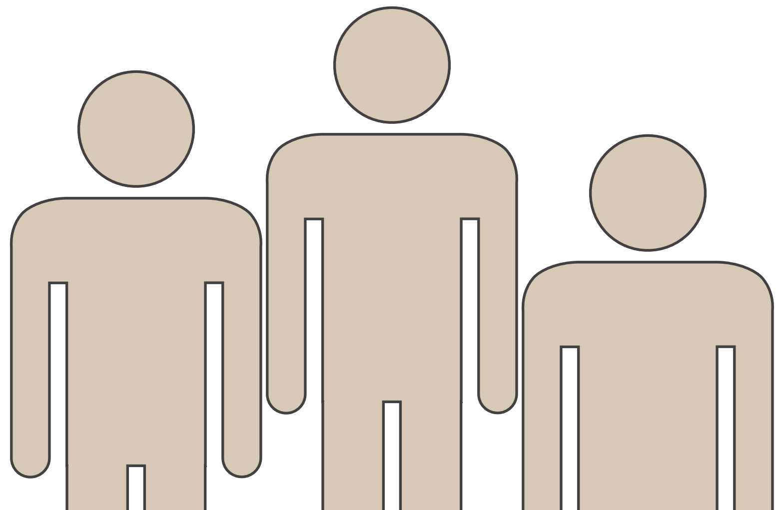
Third generation

Thus, 'anomaly' has provided us great breakthroughs!

An interesting side story (source: Prof. Hagiwara)



I would think this peak is fake/ underestimate of uncertainty/ etc...



Even after the exp. paper was published, many theoretical researchers (except for Kobayashi and Maskawa) did not believe the experimental results, but believed CP-conserving theory.

(I'm surprised to hear this)

Serious contradiction! Theorists want to investigate new physics, but at the same time want to maintain "SM"

Why does this contradiction happen?

Statistical fluctuation

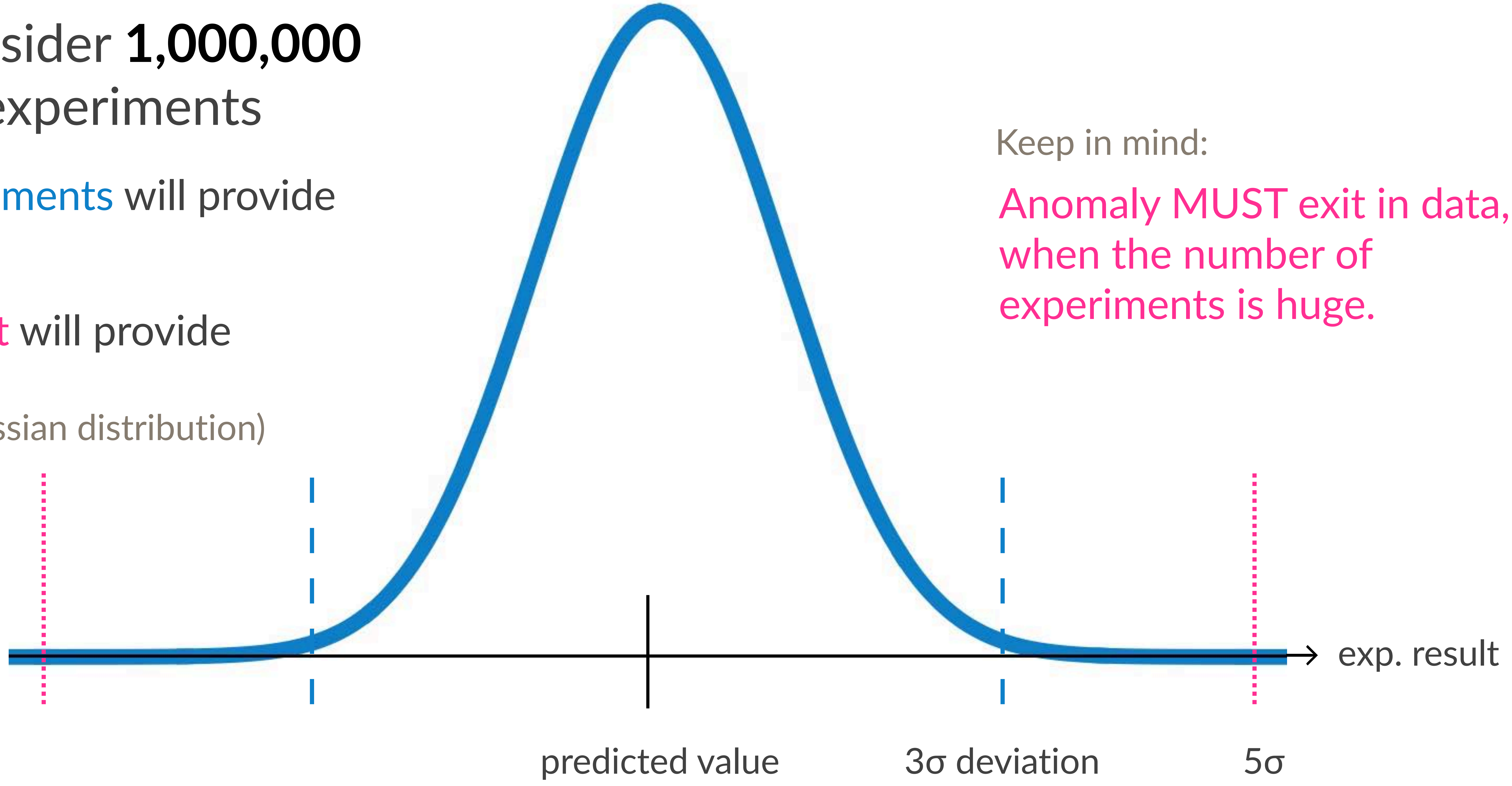
Let us consider **1,000,000** different experiments

2,700 experiments will provide 3σ deviation

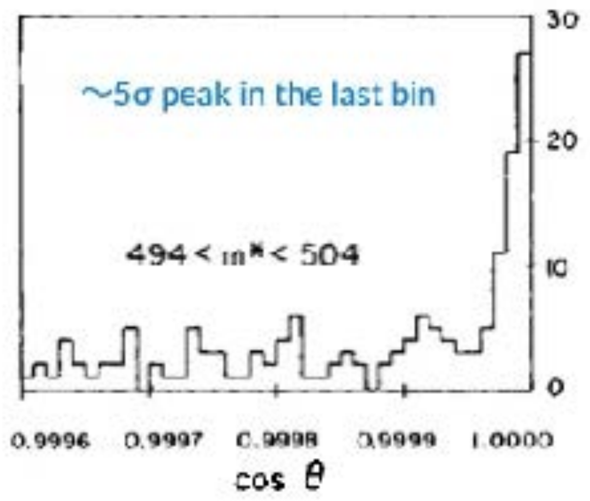
1 experiment will provide 5σ deviation
(assuming Gaussian distribution)

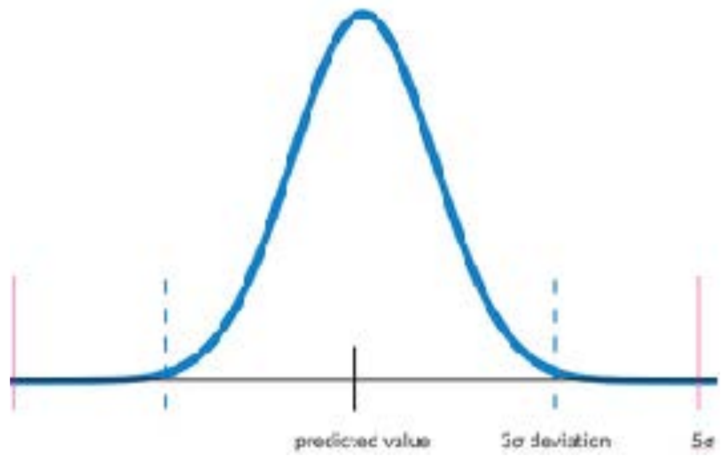
Keep in mind:

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



How to distinguish ‘real anomaly’ from ‘fake anomaly’?





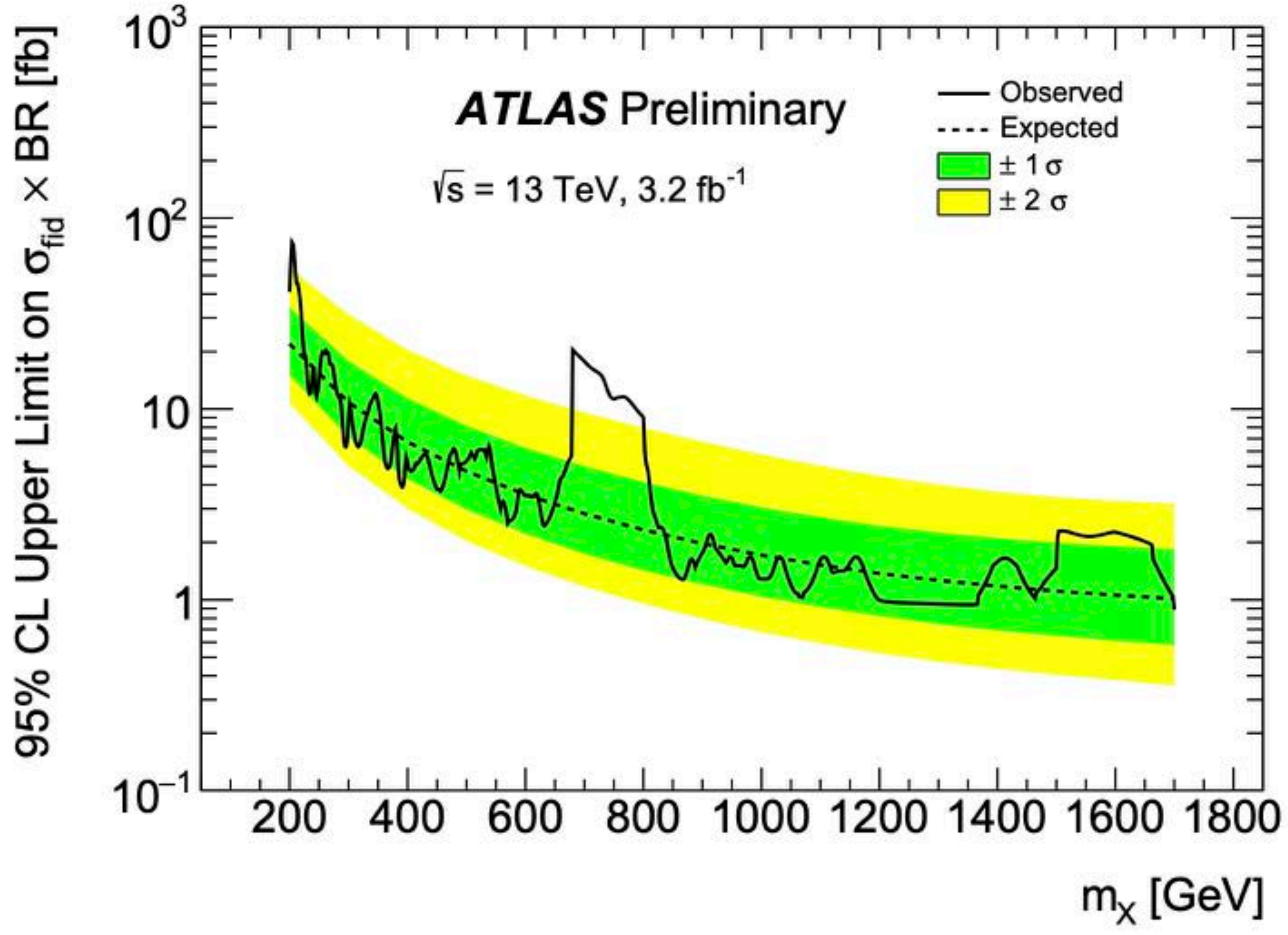
Would-be better strategy is:

1, cross-checked by the second experiment

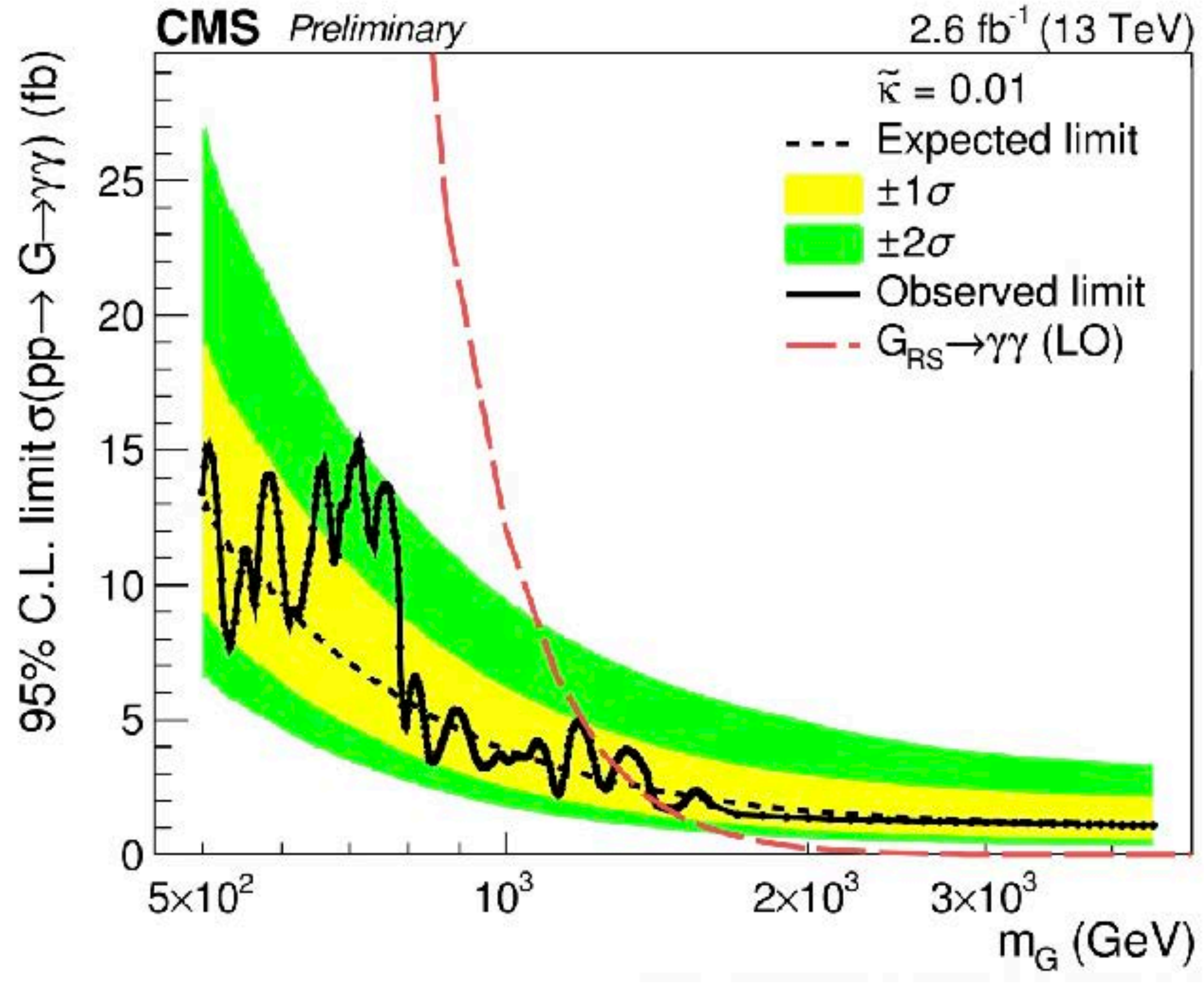
2, hidden theoretical correlation between several anomalies

A counter-example!

“750 GeV anomaly” had been observed by two different experiments.
But, very unfortunately, both were just fluctuations, and disappeared.

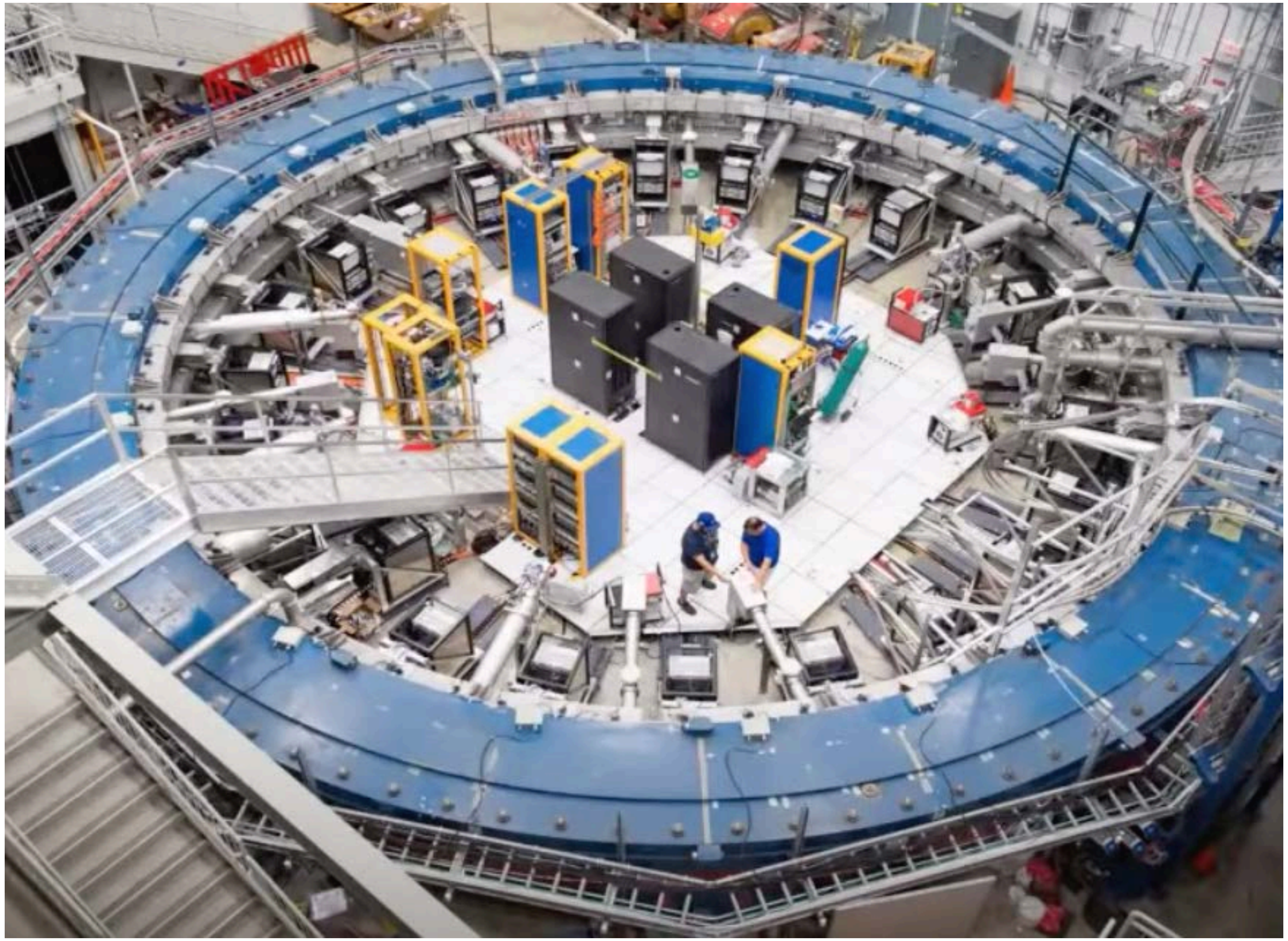


[ATLAS-CONF-2015-081]



[CMS-PAS-EXO-15-004]

muon *g*-2 anomaly



The experimental ring at Fermilab

Definition: Magnetic Dipole Moment (g-2)

- Details definitions

$$\mathcal{L} = -\frac{eQ_\ell}{8m_\ell} g_\ell \bar{\ell}\sigma_{\mu\nu}\ell F^{\mu\nu} = -\frac{eQ_\ell}{2m_\ell} g_\ell \bar{\ell}(S^\mu B_\mu)\ell$$

$$\Rightarrow \quad \mathcal{H} = -\frac{eQ_\ell}{2m_\ell} g_\ell \vec{S}\cdot\vec{B} = -\vec{\mu}_\ell \cdot \vec{B}$$

spin-magnetic interaction

magnetic field four-vector:

$$B_\mu = -\frac{1}{2m_\ell}\epsilon_{\mu\nu\rho\sigma} p_\ell^\nu F^{\rho\sigma}$$

spin operator:

$$S_\mu = \frac{1}{2m_\ell}\epsilon_{\mu\nu\rho\sigma} p_\ell^\nu J^{\rho\sigma}$$

$$J^{\rho\sigma} = \frac{i}{4}[\gamma^\rho, \gamma^\sigma]$$

spin magnetic moment:

$$\vec{\mu}_\ell = g_\ell \frac{eQ_\ell}{2m_\ell}\vec{S}$$

$$\mathcal{L} = -\frac{eQ_\ell}{4m_\ell}\bar{\ell}\sigma_{\mu\nu}\ell F^{\mu\nu} - \frac{eQ_\ell}{4m_\ell} a_\ell \bar{\ell}\sigma_{\mu\nu}\ell F^{\mu\nu} = -\frac{eQ_\ell}{8m_\ell}(2+2a_\ell)\bar{\ell}\sigma_{\mu\nu}\ell F^{\mu\nu}$$

Equation of motion

Dirac equation: $\mathcal{L} = \bar{\ell}(i\not{D} - m_\ell)\ell$ tree level "$F_1(0)$"

radiative corrections "$F_2(0)$"

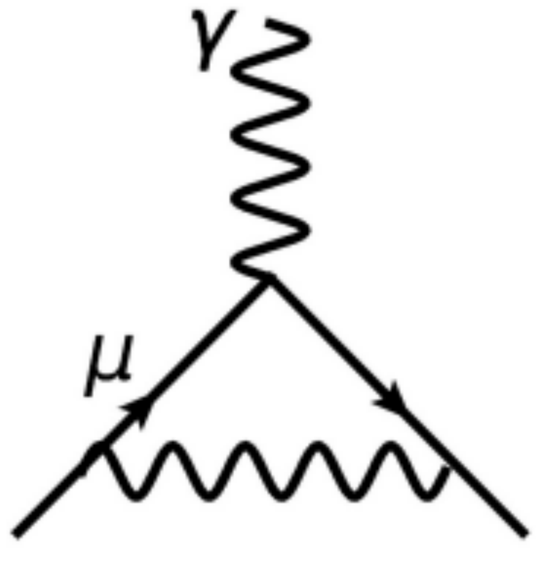
$$\Rightarrow \quad g_\ell = 2 + 2a_\ell$$

$$g\text{-}2: \quad a_\ell = \frac{g_\ell - 2}{2}$$

✓

Muon g-2

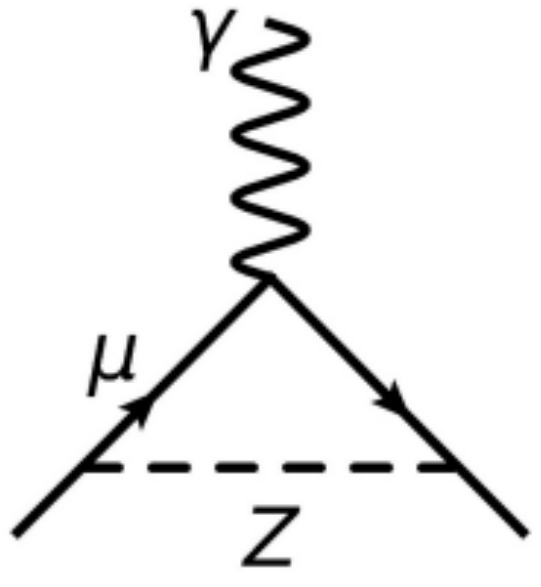
Theory (four *g*-2 contributions)



QED

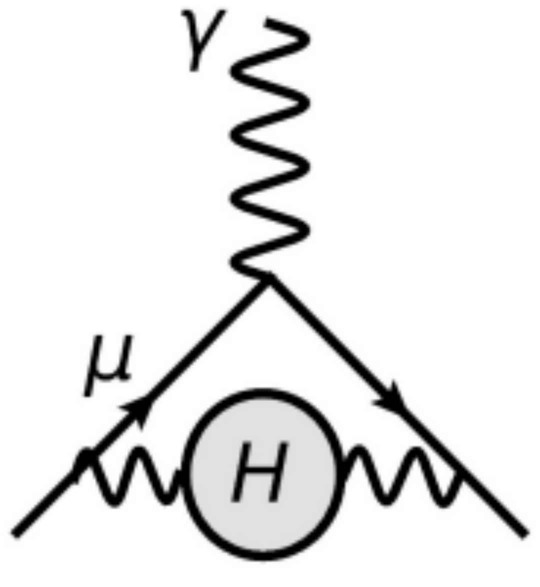
4-loop analytic

5-loop numeric



EW

2-loop analytic

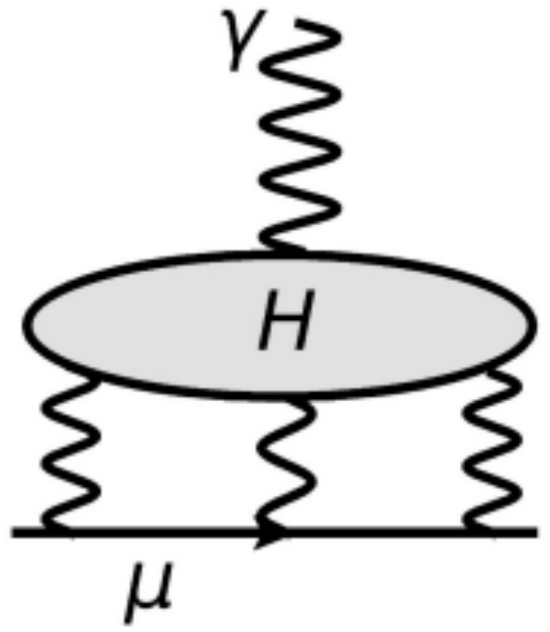


Hadronic vacuum polarization **(HVP)**

Phenomenological

Lattice

Problematic



Hadronic light-by-light **(HLbL)**

Pheno.

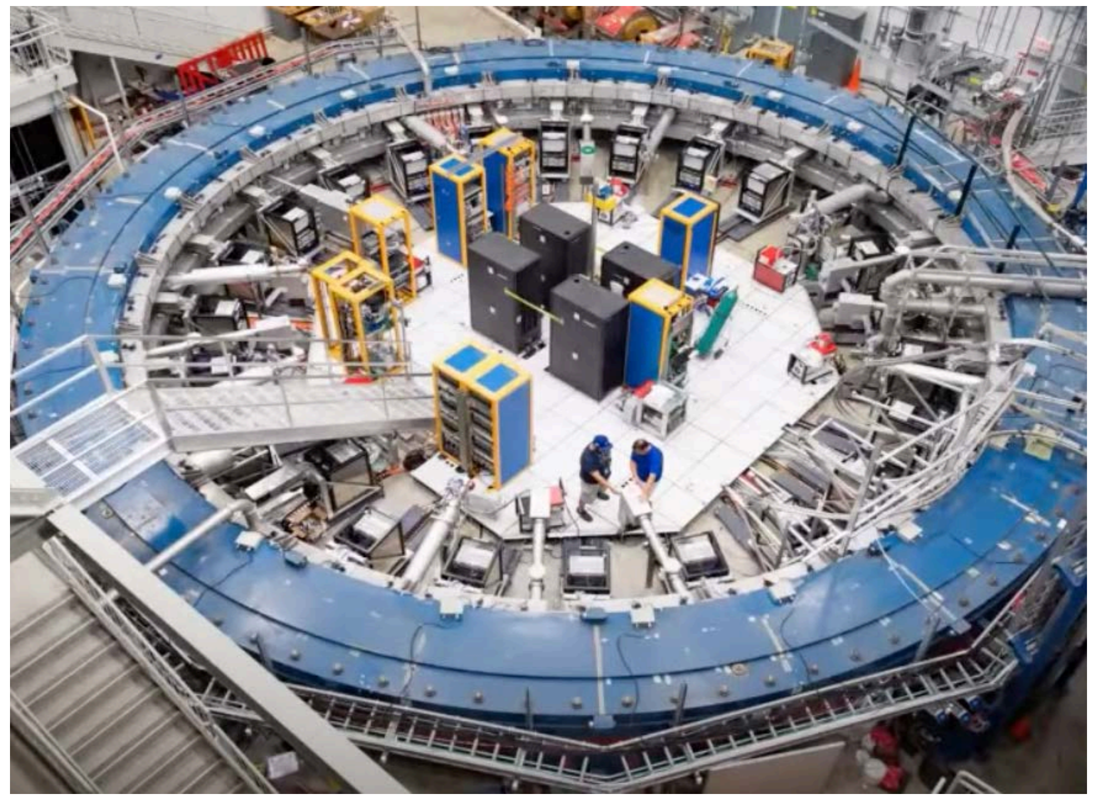
Lattice

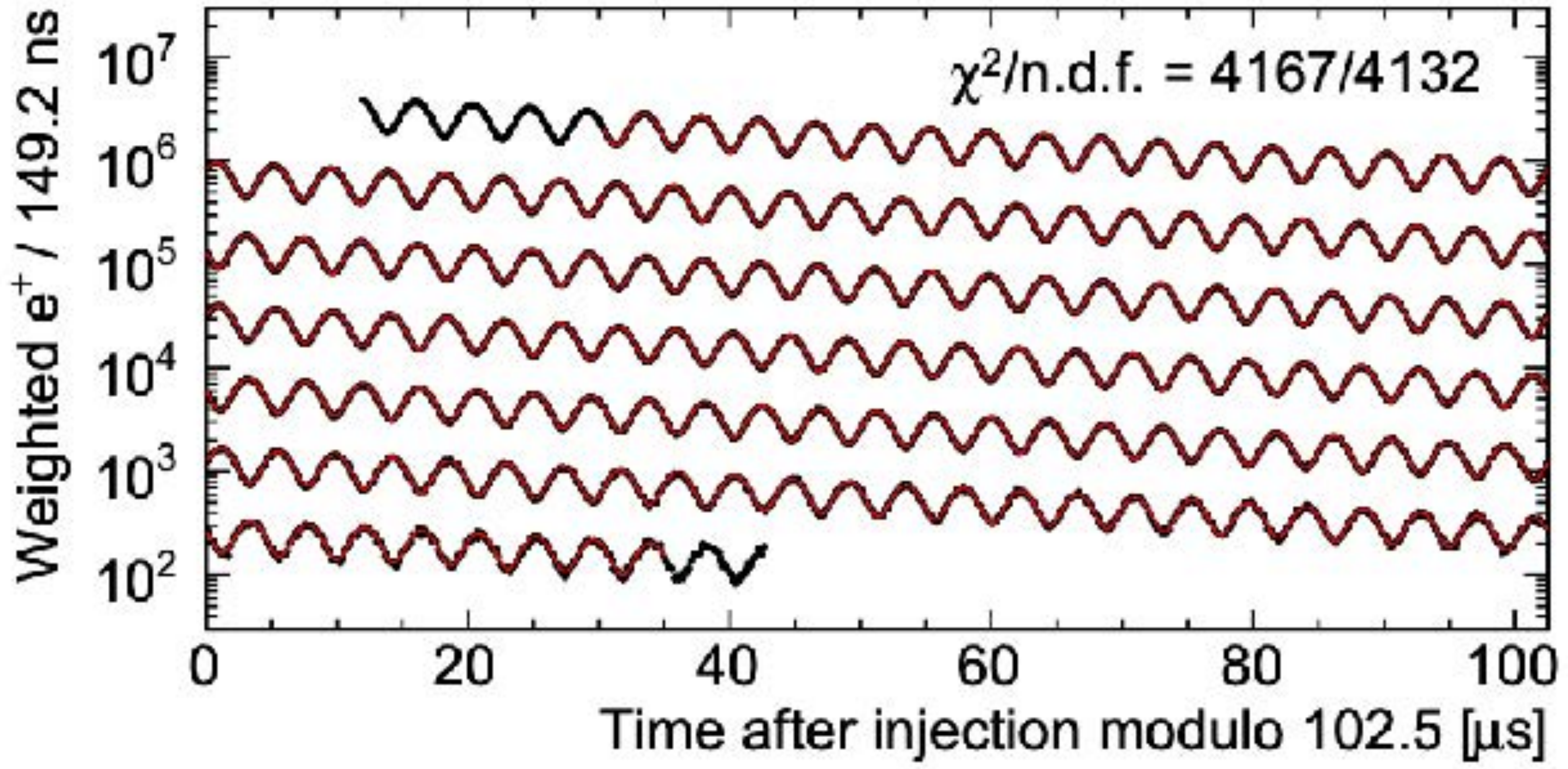
Exp.

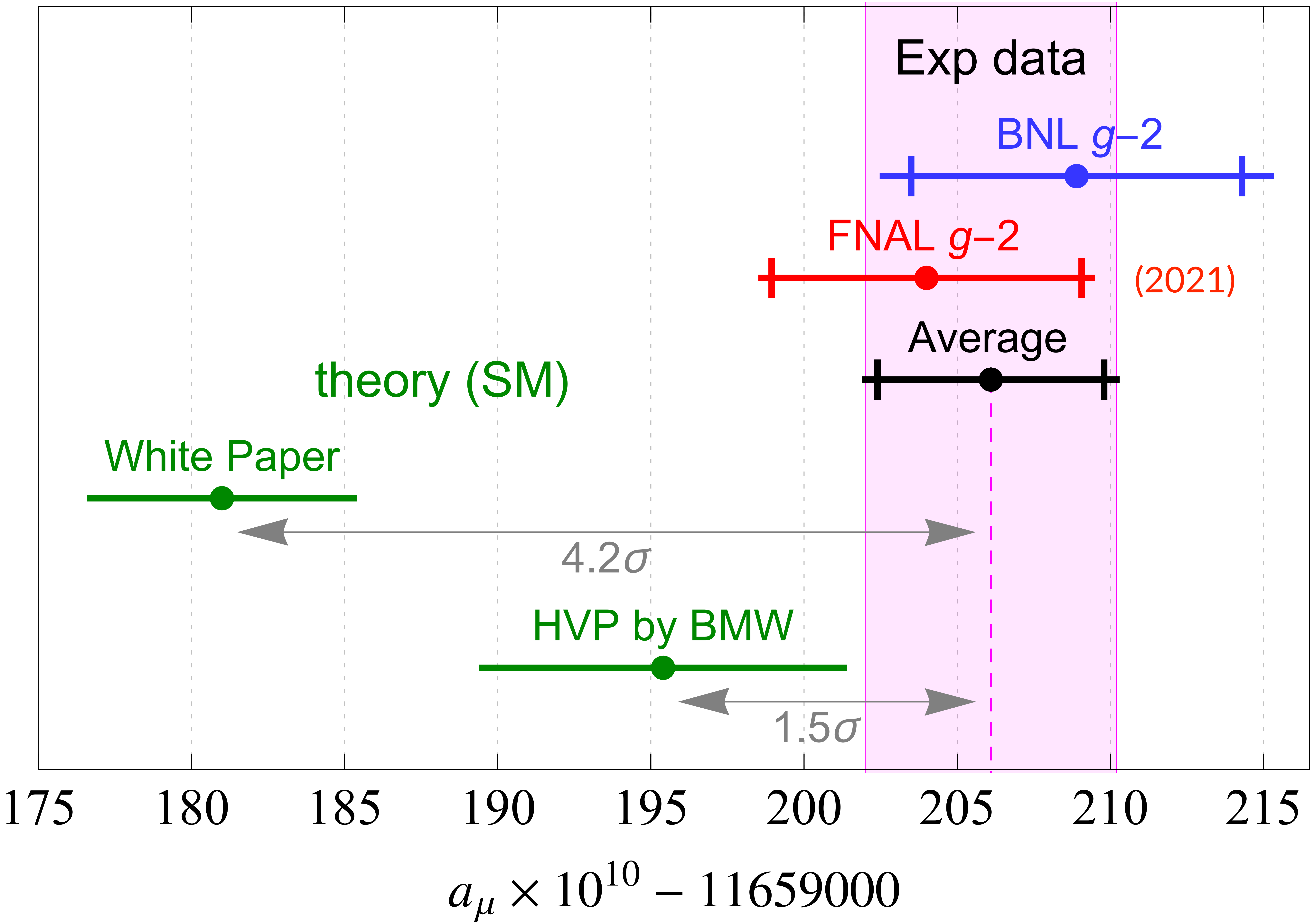
BNL ’97-‘01

FNAL ongoing

J-PARC
near future







The previous data is checked

The latest lattice result for HVP significantly reduces tension [BMW, Nature '21]

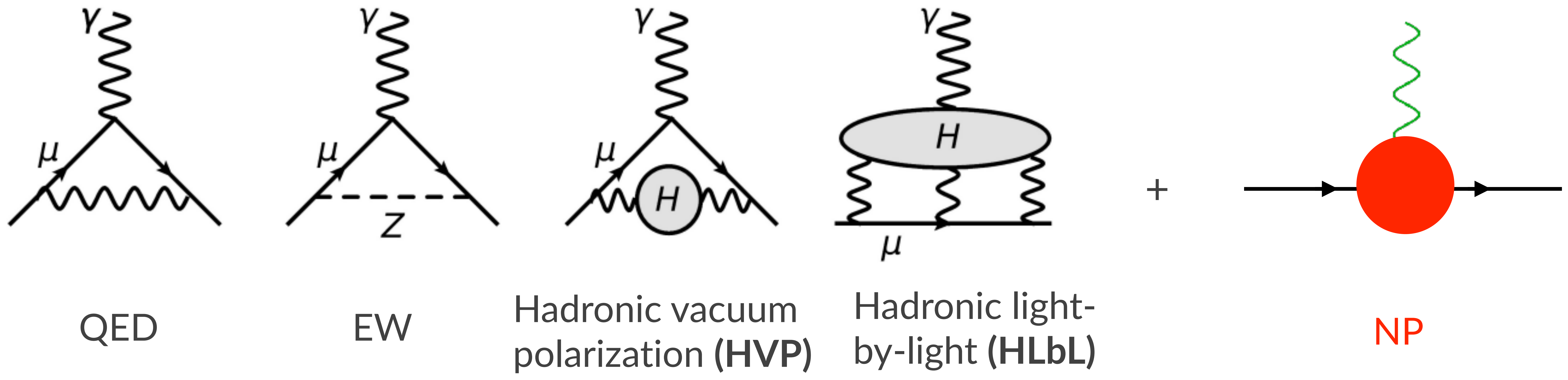
Problematic

This leads to other tensions

New physics models

https://publicdomainq.net/

Naive NP energy scale



- Muon g-2 anomaly implies that NP mass scale is around the electroweak scale.

$$\Delta a_\mu \equiv a_\mu^{\mathrm{BNL+FNAL}} - a_\mu^{\mathrm{SM}} = (25.1 \pm 5.9) \times 10^{-10} \quad (4.2\sigma)$$

$$= \frac{m_\mu^2}{16\pi^2} \frac{g_{\mathrm{NP}}^2}{M_{\mathrm{NP}}^2} \quad \Rightarrow \quad M_{\mathrm{NP}} \sim g_{\mathrm{NP}} \times 150\,\mathrm{GeV}$$

Naive NP energy scale

muon g-2 anomaly → $M_{\rm NP} \sim g_{\rm NP} \times 150\,{\rm GeV}$

- NP scale $M_{\rm NP}$ is determined by size of the NP couplings to muon $g_{\rm NP}$
  - Large $g_{\rm NP}$ by certain mechanisms (*e.g.*, chiral enhancement)

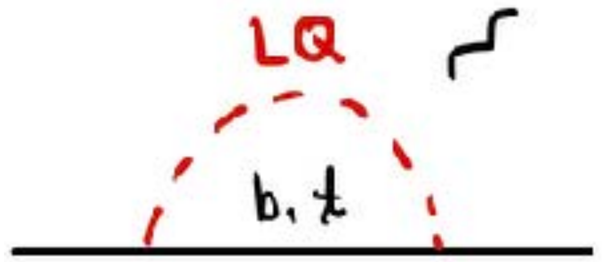
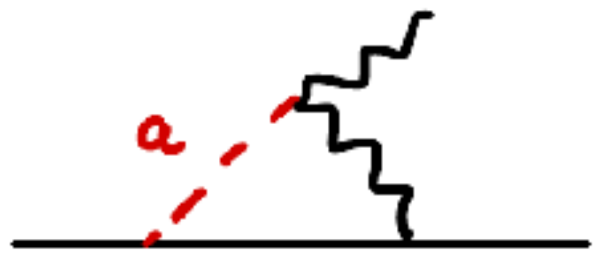
    → TeV scale NP models
  - Small $g_{\rm NP}$ (*e.g.*, $g \sim 10^{-3}$)

    → MeV scale NP models

Point: MeV scale NP search is difficult at the LHC because of so much QCD background noise

New physics interpretations

[Refs: Athron et al, 2104.03691; Buen-Abad et al, 2104.03267; Krnjaic et al, 1902.07715; Dermisek et al, 2103.05645]

NP type	diagrams	mass range	probe
Supersymmtery		200〜500 GeV	$\tilde{\chi}_2^0\tilde{\chi}_1^\pm \to (h\tilde{\chi}_1^0)\,(W^\pm\tilde{\chi}_1^0)$ $pp \to \gamma\gamma \to \widetilde{\ell\ell^*}$
Leptoquark		1.5〜2.1 TeV	$pp \to \mathrm{LQ}\overline{\mathrm{LQ}}$ $Z \to \mu^+\mu^-$
Vector-like lepton		100 GeV〜1 TeV	$h \to \mu^+\mu^-$
Scalar extensions		10〜100 GeV (A), 150〜300 GeV (H)	$Z \to \tau^+\tau^-$ $pp \to HA \to 4\tau$
Axion-like particle		40 MeV〜200 GeV	$e^+e^- \to \gamma a \to 3\gamma$
U(1) Lμ-Lτ		10〜200 MeV	$e^+e^- \to \mu^+\mu^- Z'$ $K^- \to \mu^-\bar{\nu}Z'$

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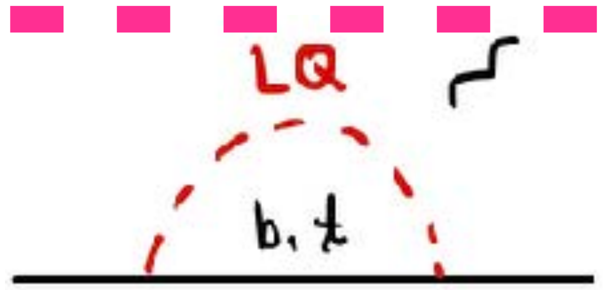
Leptoquark		1.5〜2.1 TeV	$pp \to \mathrm{LQ}\overline{\mathrm{LQ}}$ $Z \to \mu^+\mu^-$
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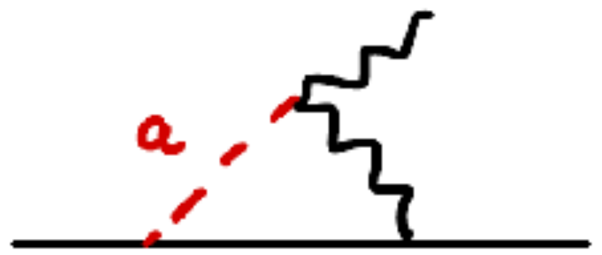
Axion-like particle		40 MeV〜200 GeV	$e^+e^- \to \gamma a \to 3\gamma$
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An example: $\mathcal{N} = 1$ Supersymmetric Interpretation

- Crucial point: SM possesses one Higgs-doublet, while the minimal SUSY requires two Higgs/Higgsino-doublet. **Holomorphy of superpotential** and **gauge anomaly cancelation**
- So, the electroweak symmetry breaking must occur **by two Higgs vevs**

$$\begin{pmatrix} H^+ \\ v + H^0 \end{pmatrix}_{\rm SM} \rightarrow \begin{pmatrix} H_u^+ \\ v_u + H_u^0 \end{pmatrix}, \begin{pmatrix} v_d + H_d^0 \\ H^- \end{pmatrix}_{\rm SUSY}$$

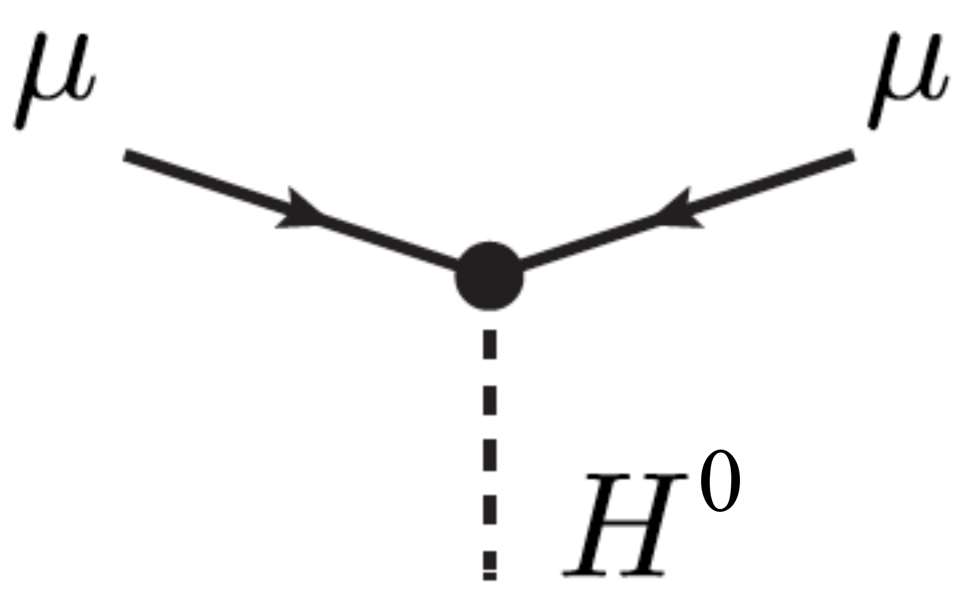
+ two Higgsino doublets

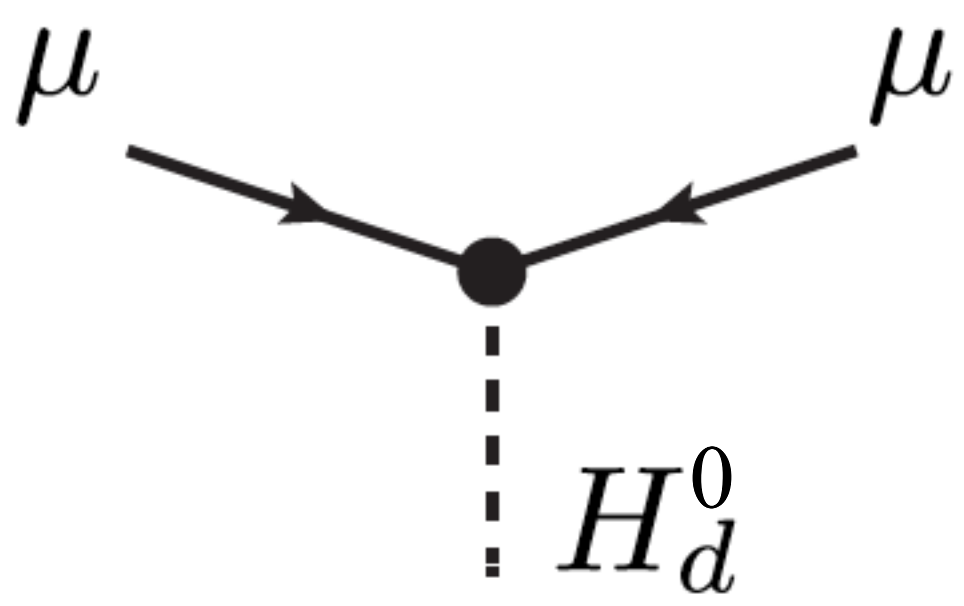
- **Then,** $\tan\beta \equiv v_u/v_d$ **is a free parameter, where** $v_{\rm SM} = \sqrt{v_u^2 + v_d^2}$

"$\tan\beta$ enhancement"

- One encounters "$\tan\beta$ enhancement" via the muon Yukawa interaction

SM





SUSY

$$m_\mu = y_\mu^{\rm SM} v \qquad\qquad m_\mu = y_\mu^{\rm SUSY} v_d$$

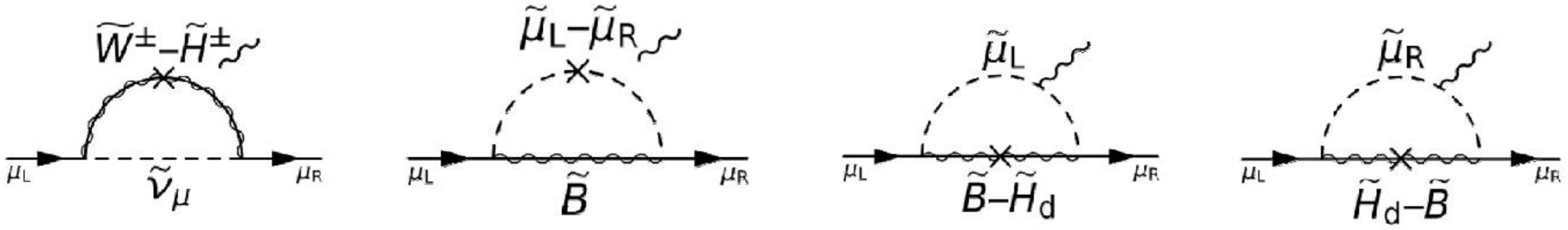
$$\Rightarrow\quad y_\mu^{\rm SUSY} = y_\mu^{\rm SM}\frac{v}{v_d} = y_\mu^{\rm SM}\frac{1}{\cos\beta} \simeq y_\mu^{\rm SM}\tan\beta$$

- When $v_d \ll v = \sqrt{v_u^2 + v_d^2}$, the muon Yukawa is enhanced by $\tan\beta\ (\gg 1)$

$\mathcal{N} = 1$ Supersymmetric Interpretation

- Four types of one-loop diagrams are responsible to explain the anomaly:

1, WHL scenario   2, BLR scenario   3, BHL scenario   4, BHR scenario



- These diagrams are proportional to $\tan\beta = 1 \sim 60 \rightarrow$ effectively large $g_{\mathrm{NP}} \rightarrow$ TeV scale NP
- 1, WHL and 2, BLR $\rightarrow$ next slide
- 3, BHL and 4, BHR are constrained from dark matter direct detection (XENON1T experiment)

  [Endo, Hamaguchi, Iwamoto, Yanagi 1704.05287; Baum, Carena, Shah, Wagner 2104.03302]

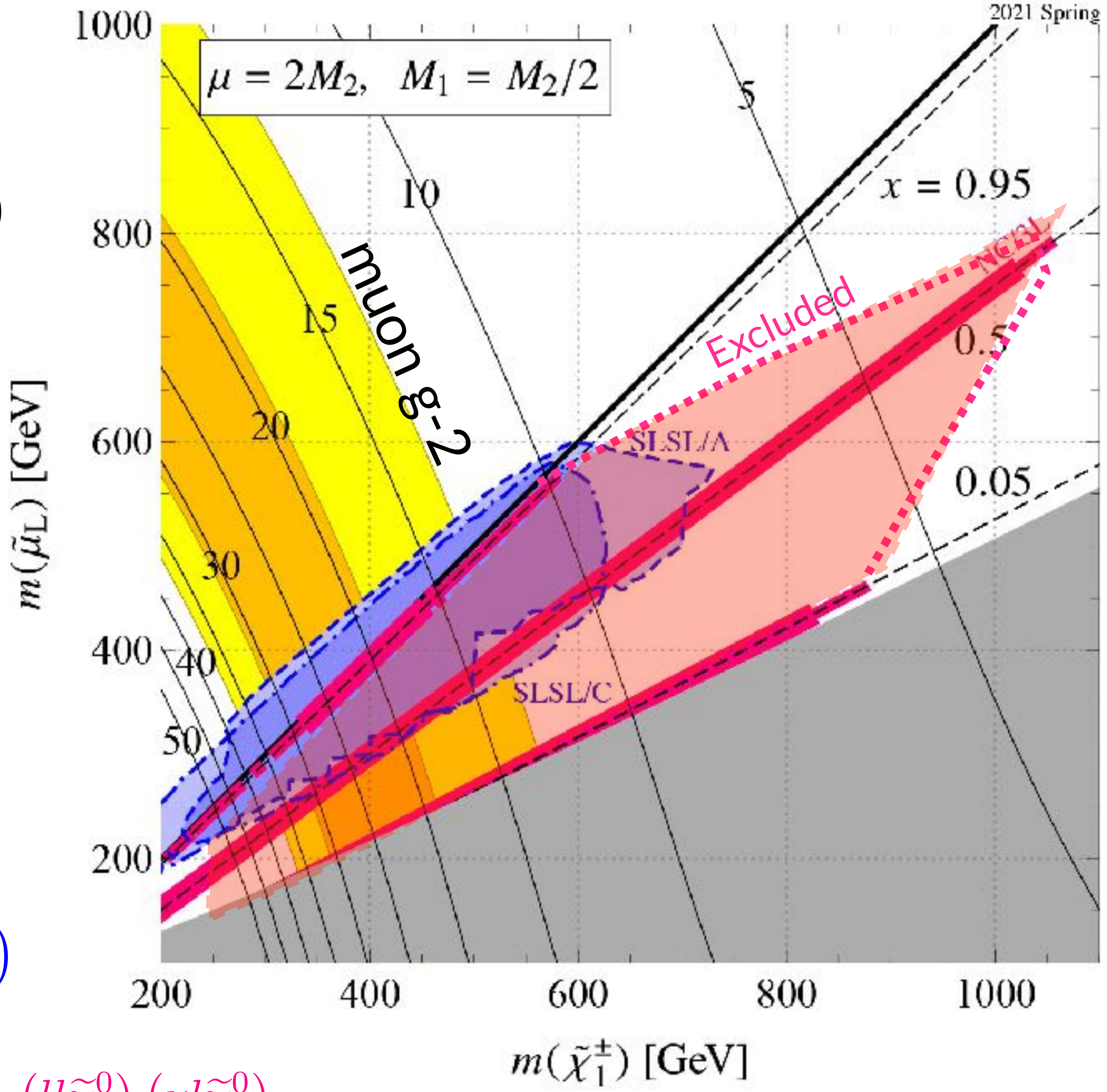
$\mathcal{N}=1$ SUSY example [Endo, Hamaguchi, Iwamoto, TK, 2104.03217]

1, chargino contribution

$\tilde{\chi}_2^0\tilde{\chi}_1^\pm \to (h\tilde{\chi}_1^0)\,(W^\pm\tilde{\chi}_1^0)$

will be able to probe

Point: $\tilde{W}^0$ decays into h not Z

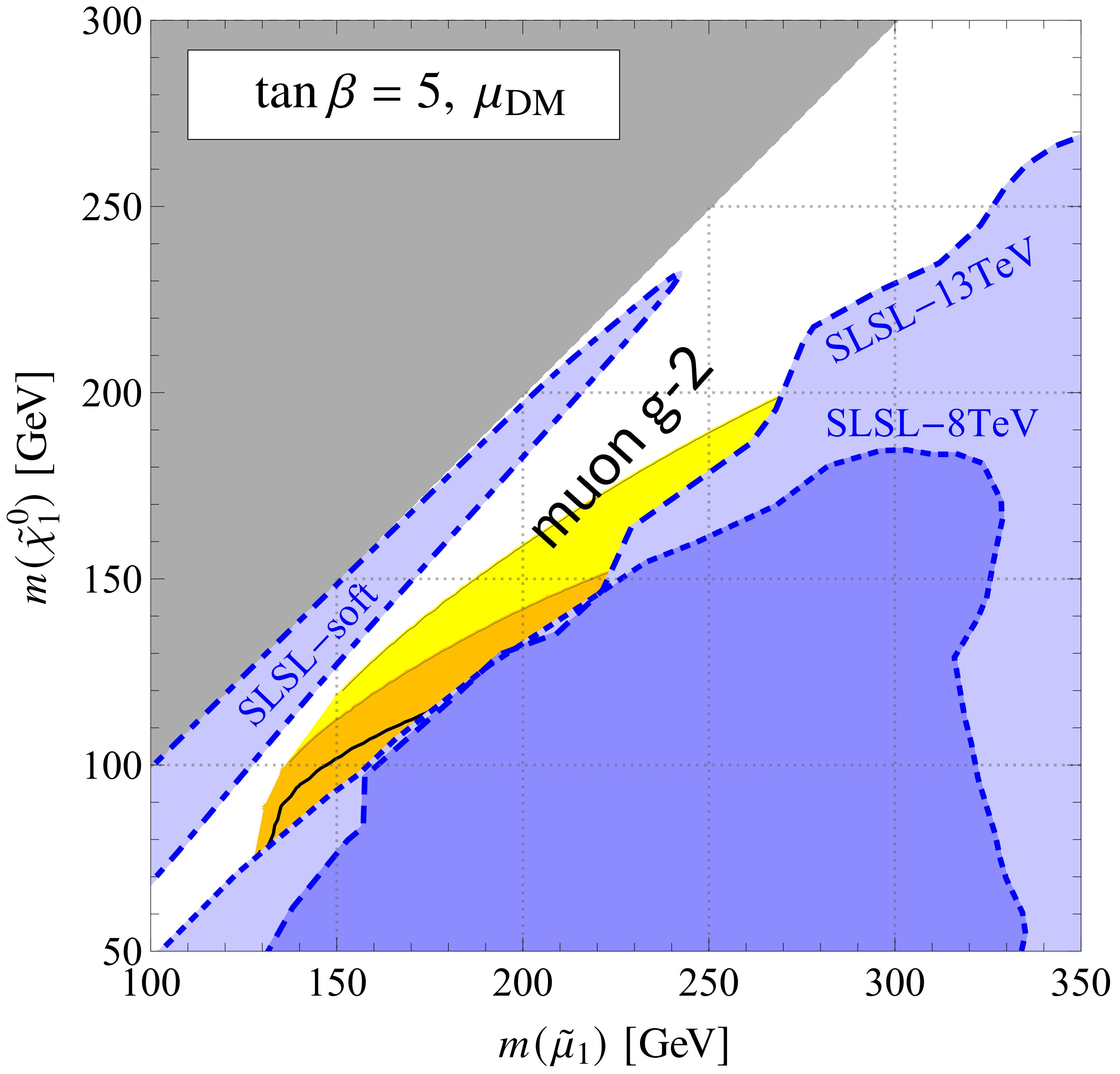


strong bound from:

$\widetilde{\ell}_L\widetilde{\ell}_L^* \to (\ell\widetilde{\chi}_1^0)\,(\bar{\ell}\widetilde{\chi}_1^0)$

$\tilde{\chi}_2^0\tilde{\chi}_1^\pm \to (\tilde{l}_L)\,(\nu\tilde{l}_L) \to (ll\tilde{\chi}_1^0)\,(\nu l\tilde{\chi}_1^0)$

2, pure-bino contribution with correct $\Omega_{\rm DM}$



Low tanβ is preferred(!)

Good target for ILC

XENONnT (DM direct detection) can also probe this scenario

Photon collision $pp \to \gamma\gamma \to \widetilde{\ell}\widetilde{\ell}^* \to (\ell\widetilde{\chi}_1^0)\,(\bar{\ell}\widetilde{\chi}_1^0)$

will be able to probe [Beresford, Liu, PRL '19]

New physics interpretations

[Refs: Athron et al, 2104.03691; Buen-Abad et al, 2104.03267; Krnjaic et al, 1902.07715; Dermisek et al, 2103.05645]

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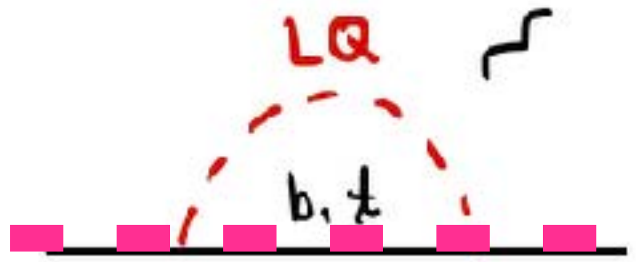
Leptoquark		1.5〜2.1 TeV	$pp \to \mathrm{LQ}\overline{\mathrm{LQ}}$ $Z \to \mu^+\mu^-$
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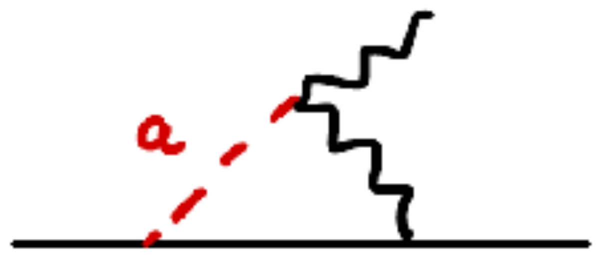
Axion-like particle		40 MeV〜200 GeV	$e^+e^- \to \gamma a \to 3\gamma$
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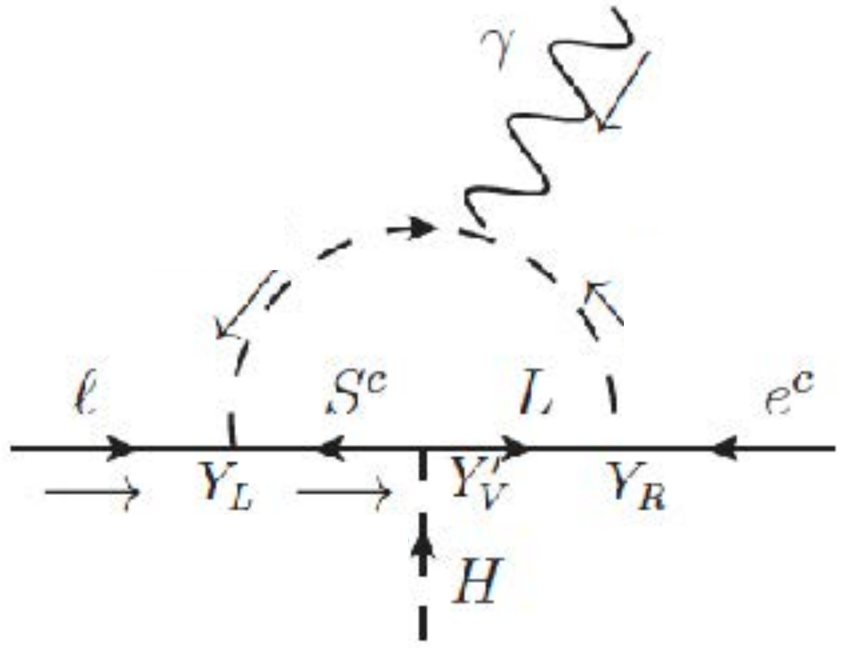
Novel theoretical finding: Violation of Wilsonian (1/2)

[Arkani-Hamed, Harigaya, 2106.01373]

- Using **a vector-like lepton model**, the authors discover "violation of Wilsonian naturalness" following from "total derivative phenomenon"
- Two vector-like leptons are introduced: SU(2)$_L$ doublet L and singlet S (motivation: $h\mu^+\mu^-$ is SM-like)
- Dimension-six one-loop contributions are canceled out without symmetry reason, independently of mass spectrum! The reason is that the loop function is "total derivative"

Σ 

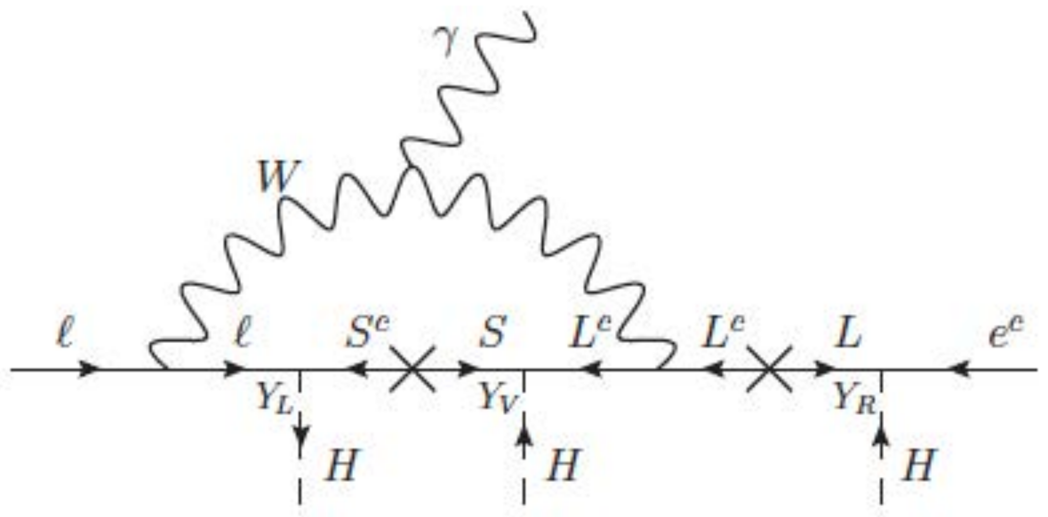
etc. $= 0$

total derivative!

No UV div.

$$\propto \int_0^\infty dk^2 f'(k^2) = 0 \text{ with } f(\infty) = f(0) = 0$$

- Leading contribution comes from dimension-eight one-loop

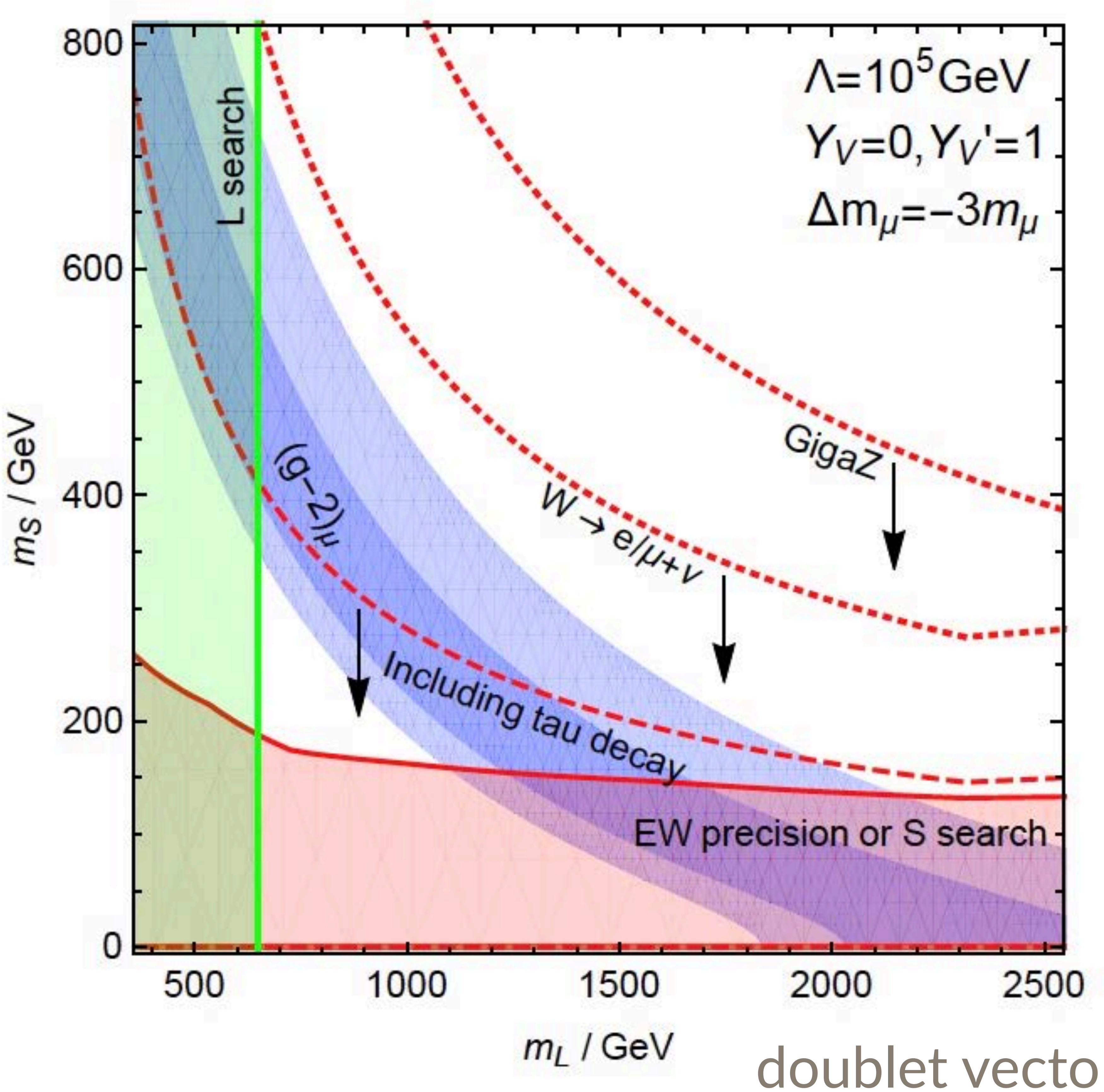


Novel theoretical finding: Violation of Wilsonian (2/2)

- Prediction. Viable parameter space will be fully proved by future lepton colliders.

Excluded by LHC search

[Arkani-Hamed, Harigaya, 2106.01373]



singlet vector-like lepton mass

doublet vector-like lepton mass

$Z \to \mu^+ \mu^-$

$W \to \mu \bar{\nu}$

$\tau \to \mu \nu \bar{\nu}$

Excluded by electroweak fit

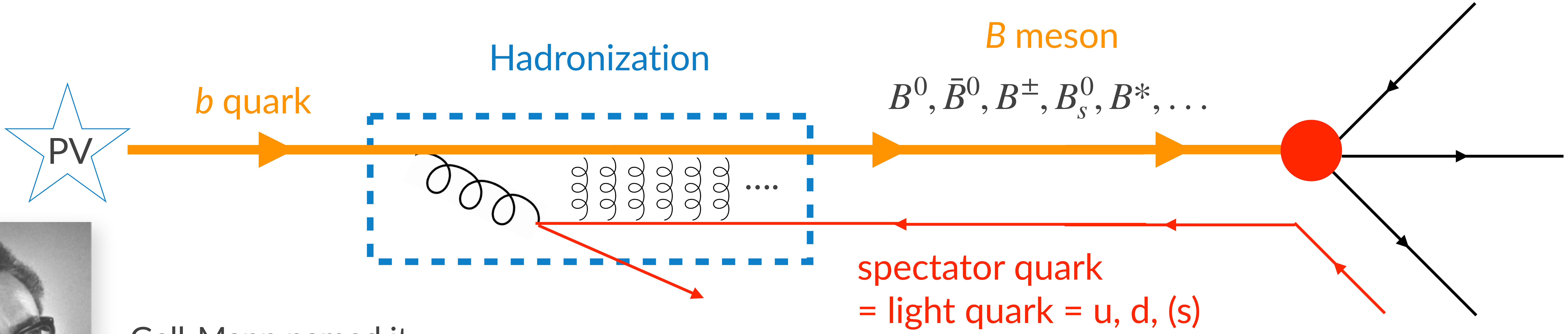
B anomaly

http://www.wallcoo.net/

What is flavor physics?

- Quarks can not become asymptotic field, but must be contained in hadron=meson or baryon

  ***b* … *B* meson**, ***c* … *D* meson**, ***s* … *K* meson**, or heavy baryons.



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/baryon transition;

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

B physics

- **Main stream of the flavor physics.** There are **three big experiments** for *B* physics.
- Rich phenomenology; CKM, FCNC, CP violation, tau lepton, LFU, Hadron spectroscopy, dark sector

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

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

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

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

LHCb experiment @ **CERN**, Run 1 and 2 were done, Run 3 will start at **2022**

$pp \to b\bar{b} \to B\bar{B}$ $\quad 10^{12} b\bar{b}$ per year

CKM matrix

- CKM matrix arises the relative misalignment between the Yukawa matrices and gauge interactions:

$$\mathcal{L} \supset -\frac{g}{\sqrt{2}}\bar{u}^i_L\gamma^\mu d^i_L W^+_\mu \xrightarrow{\text{mass-eigenbasis}} -\frac{g}{\sqrt{2}}\bar{u}^i_L\gamma^\mu (U_u^\dagger U_d)^{ij} d^j_L W^+_\mu$$

$$= -\frac{g}{\sqrt{2}}\bar{u}^i_L\gamma^\mu V^{ij}_{\text{CKM}} d^j_L W^+_\mu$$

- Wolfenstein parametrization

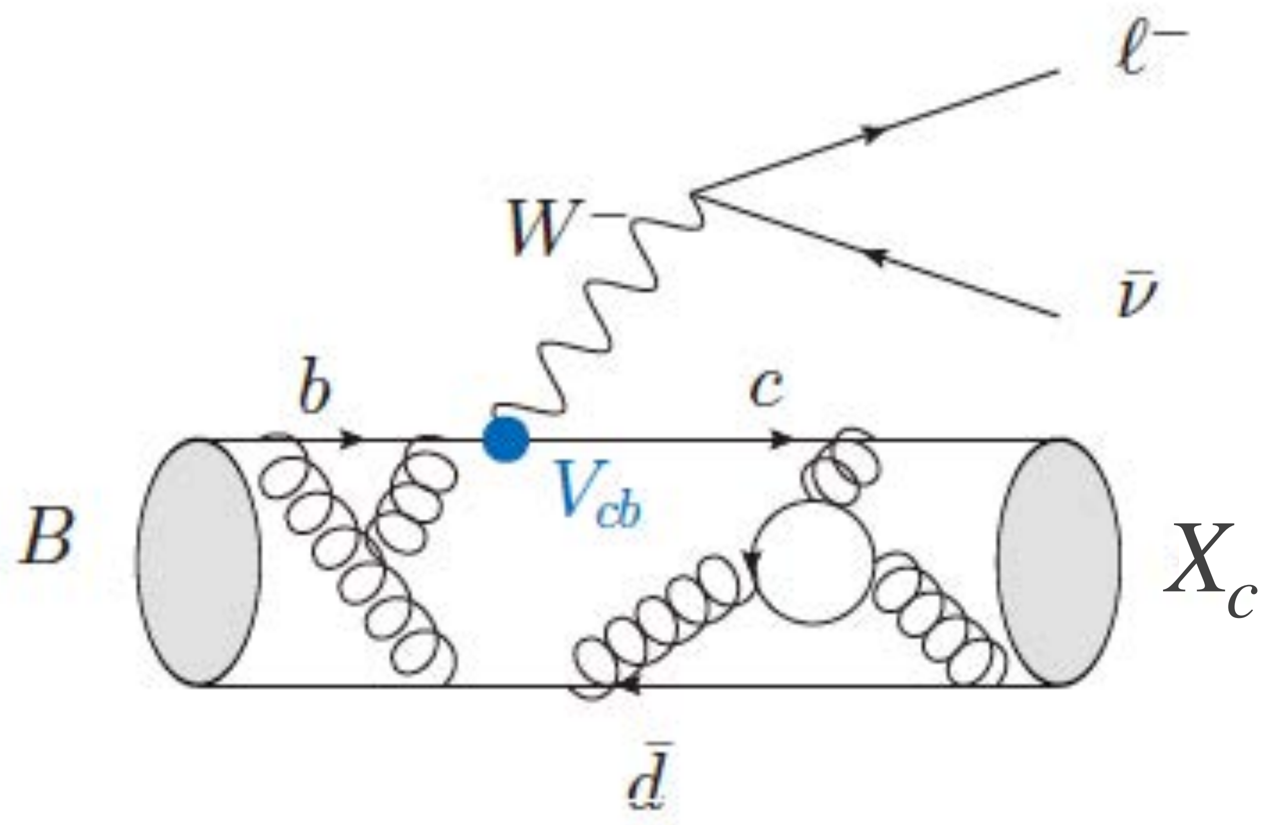
K physics *B* physics

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

- Parameter A is determined by *B* physics

Measurements of $|V_{cb}|$

- For determination of $|V_{cb}|$, one measures branching ratios of *B*-meson semileptonic decay modes, and compare TH



Semileptonic mode $\ell = e, \mu$

Hadron states X_c (=*D***, *D**, *D*, *Dπ*, *Dππ*...)

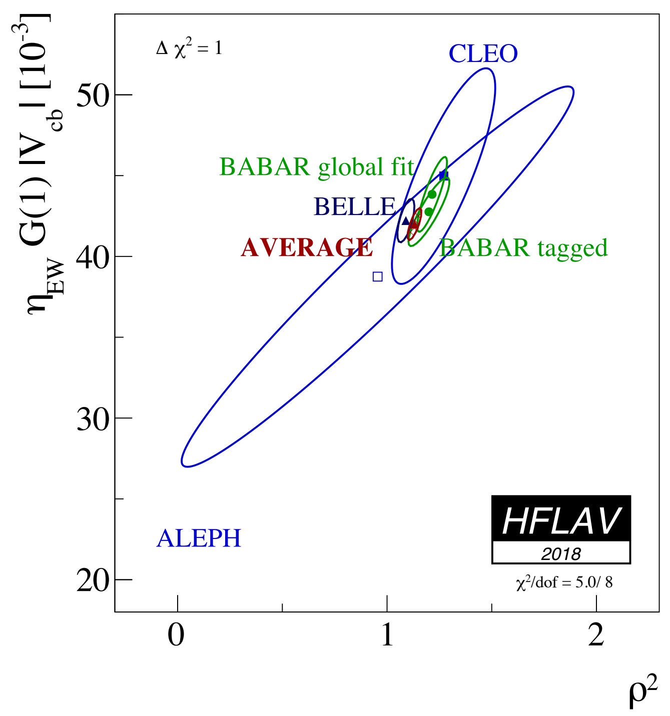
- Inclusive decays: $B \to X_c \ell \nu$
  - It corresponds to quark level decay rate ($b \to c \ell \nu$) + α_s, $\Lambda_{\rm QCD}/m_b$ corrections
  - Last data in 2010 → Belle II result coming soon; No lattice → the first lattice study [Gambino, Hashimoto, PRL '20]
- Exclusive decays: $B \to D \ell \nu, B \to D^* \ell \nu$
  - Many data with different schemes. One can use lattice simulations.

~3σ tension between inclusive vs. exclusive determinations of V_{cb} and V_{ub}

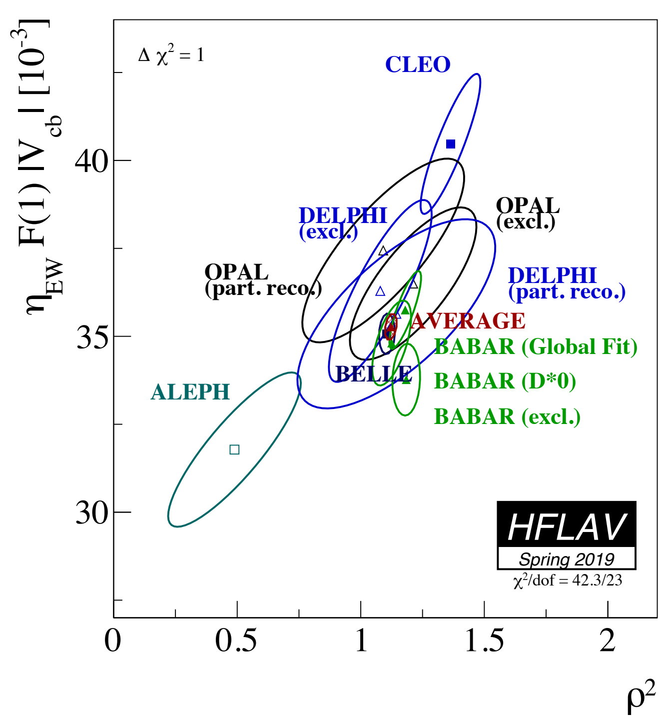
NP interpretation is difficult [Iguro, Watanabe, 2004.10208]

[HFLAV averages 2019, based on CLN]

$B \to D\ell\nu$



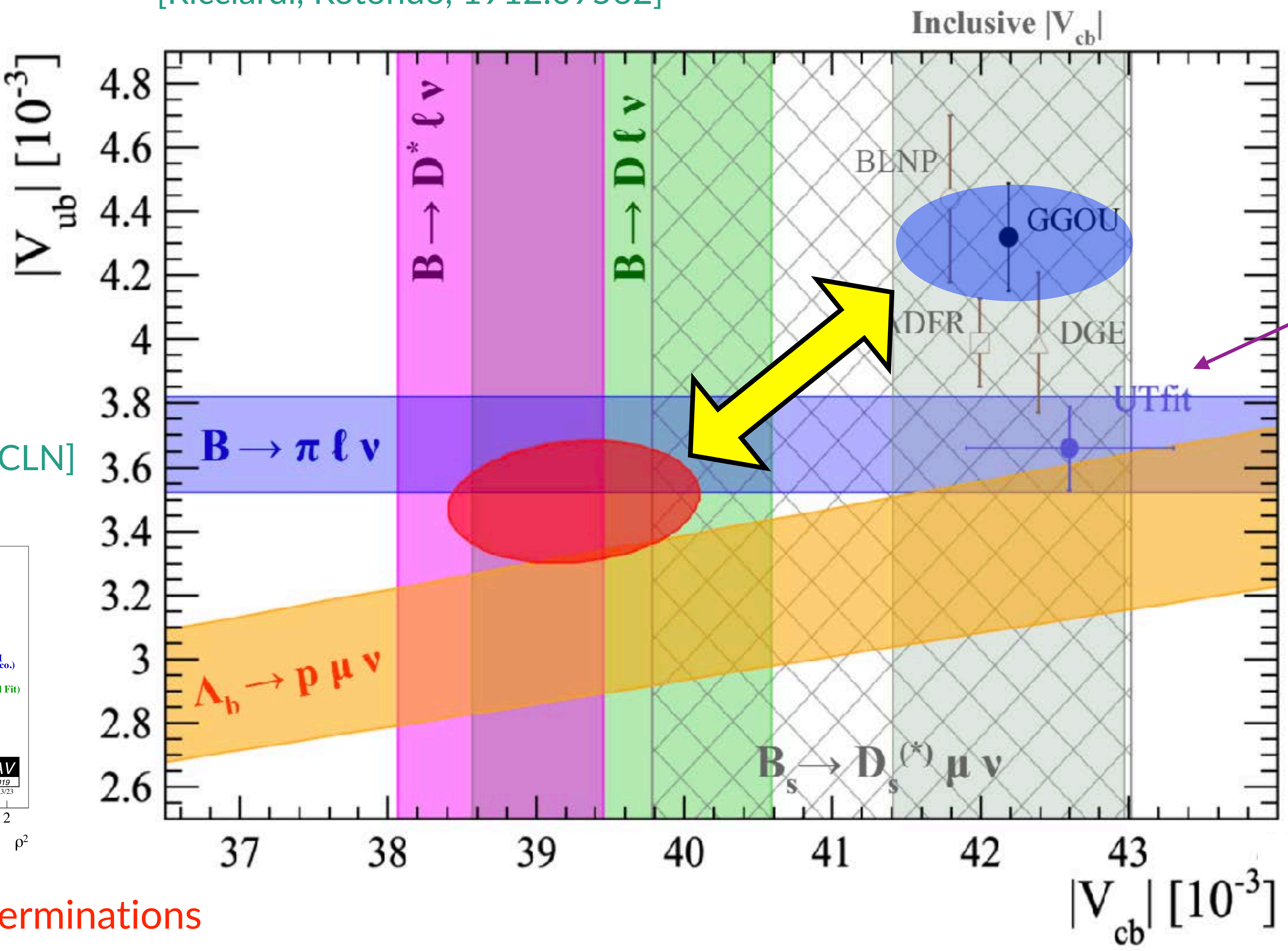
$B \to D^*\ell\nu$



Average of the exclusive determinations

Average of the inclusive determinations

[Ricciardi, Rotondo, 1912.09562]



CKM unitarity

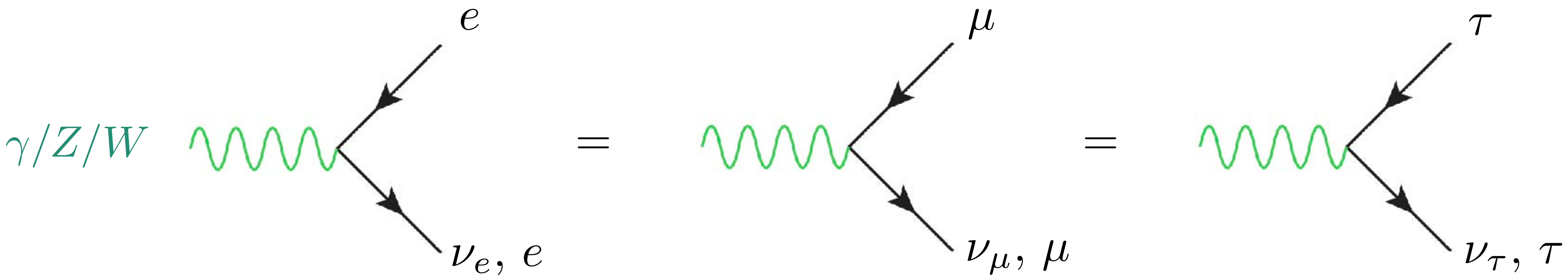
Kaon physics prefers inclusive V_{cb} (→ page 36)

Belle II preliminary result [Moriond2021]

Inclusive Vcb = 41.7 (12) x 10^{-3}

Lepton flavor universality (LFU)

- Gauge symmetry predicts lepton flavor universal phenomena

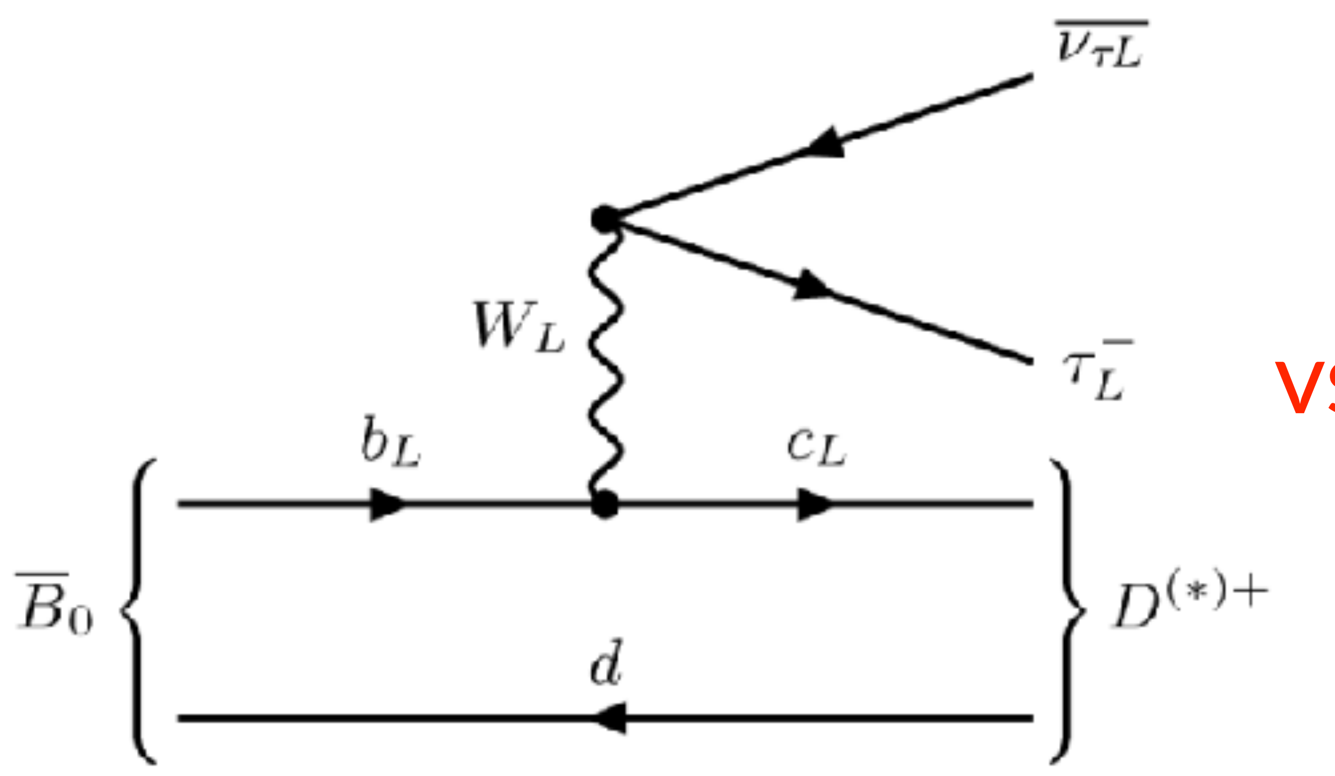


- **Charged lepton mass** changes **kinematics** and modifies **scalar form factors in the hadronization**, which eventually violates the lepton flavor universality
- Long-distance QED correction (beyond PHOTOS) could violate the lepton flavor universality [de Boer, TK, Nisandzic, PRL '18; Isidori, Nabeebaccus, Zwicky, '20]

LFU observable *R*(*D*)

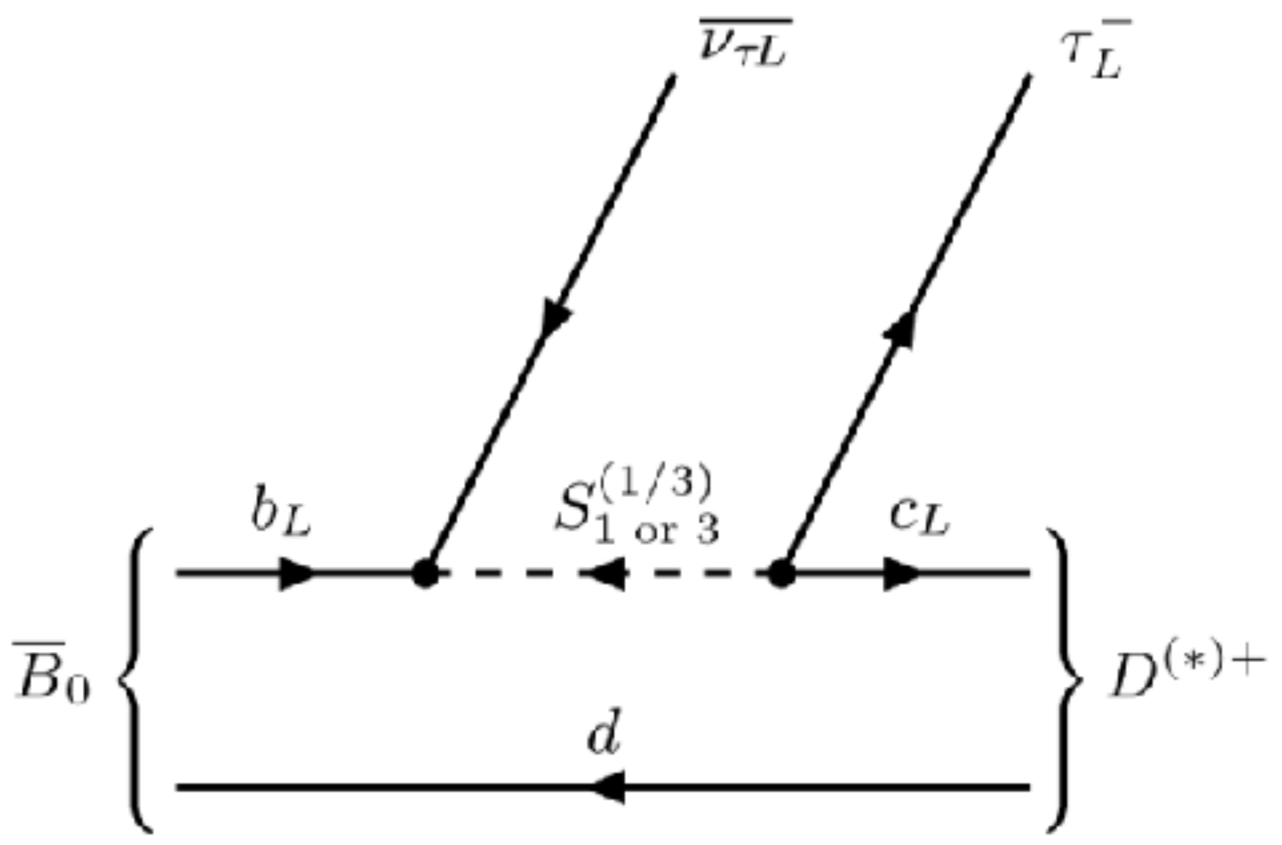
$$R(D^{(*)}) = \frac{\mathrm{BR}(B \to D^{(*)}\bar{\tau}\nu_\tau)}{\mathrm{BR}(B \to D^{(*)}\bar{\ell}\nu_\ell)}$$

V_{cb} dependence is dropped



SM

vs.

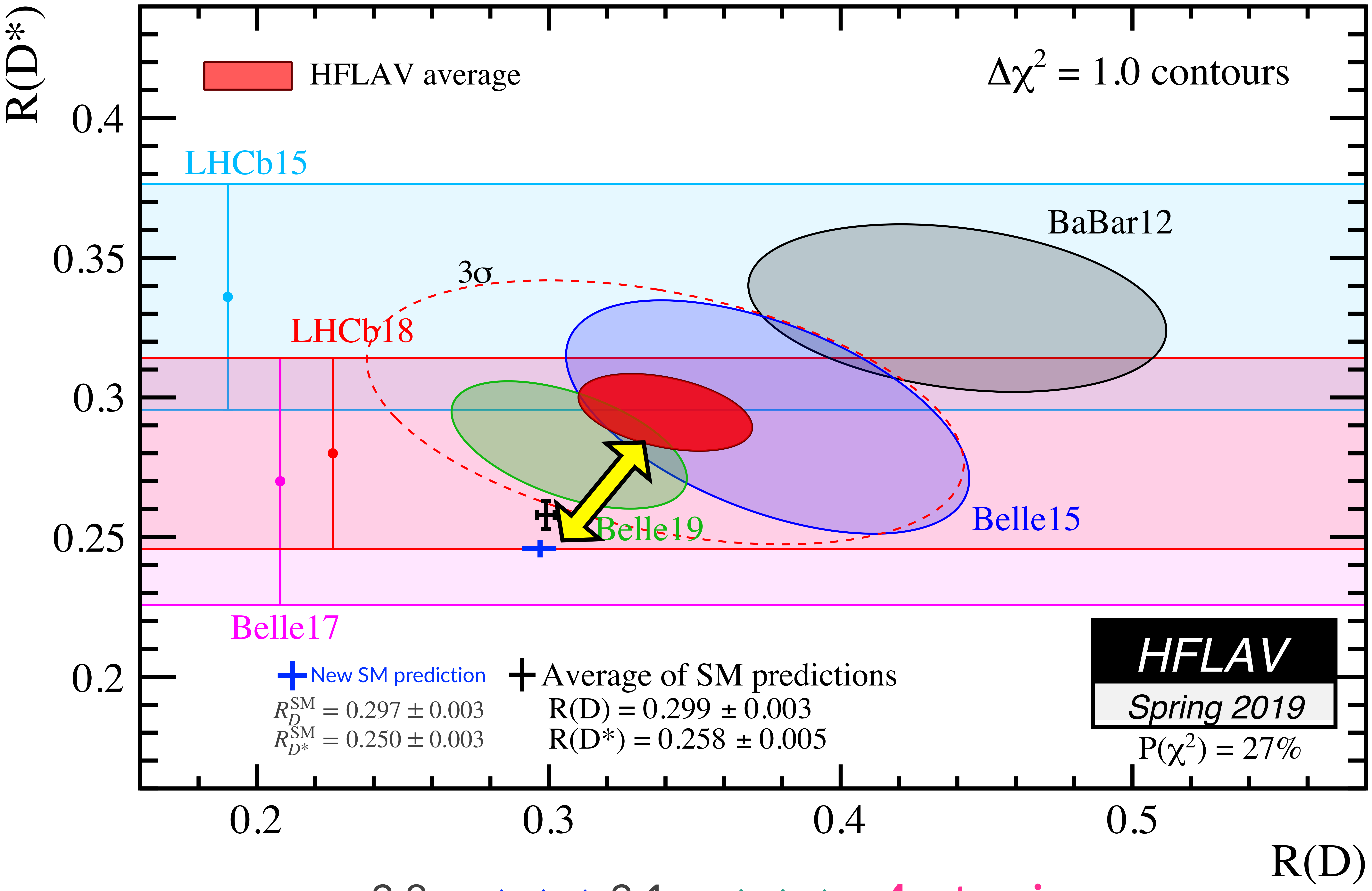


NP, *e.g.*, Leptoquark

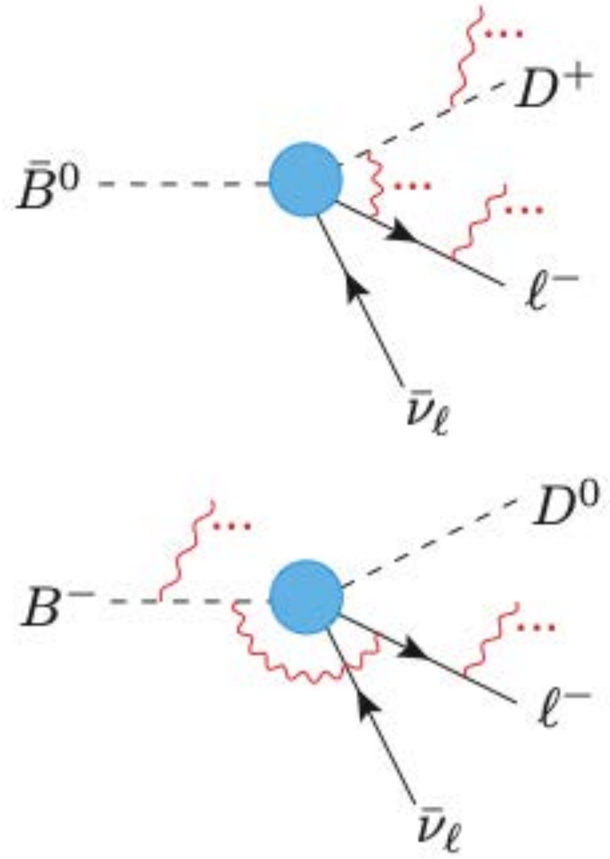
$\mathcal{B}(B \to D\ell\nu) = 2\%,\ \mathcal{B}(B \to D^*\ell\nu) = 5\%,$

[HFLAV averages 2019]

Average of the experimental data



Soft-photon QED corrections could change these tensions



It was shown that the QED correction violates LFU at a few % level

[de Boer, TK, Nisandzic, PRL '18]

3.8 σ →→→ 3.1 σ →→→ **~ 4 σ tension**

New Belle data '19 New SM '20 [Bordone, Jung, van Dyk, '20; Iguro Watanabe, '20]

EFT global fit

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

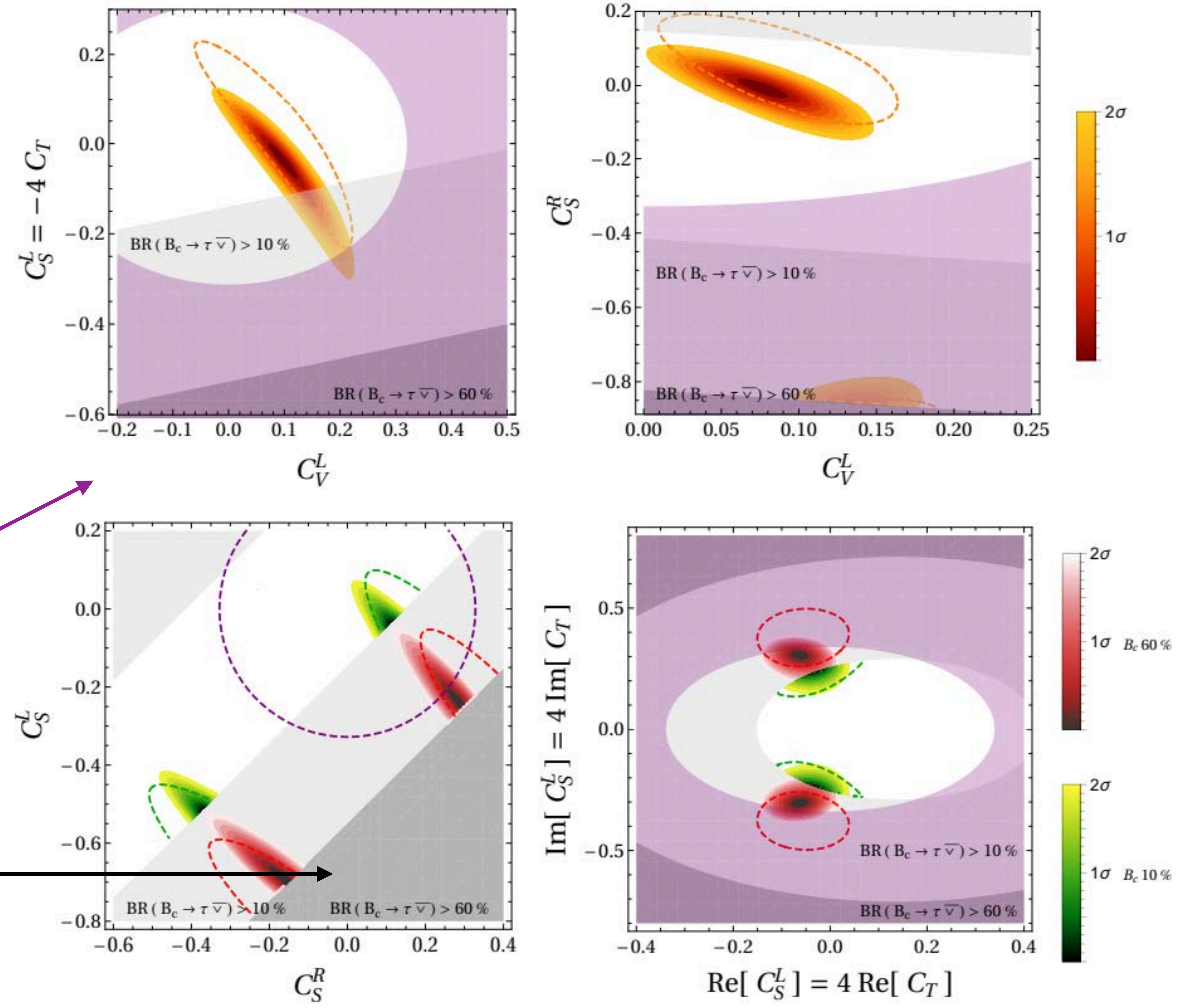
- Relevant effective Hamiltonian

$$\mathcal{H}_{\rm eff} = 2\sqrt{2} G_F V_{cb} \left[(1 + C_V^L) O_V^L + C_S^R O_S^R + C_S^L O_S^L + C_T O_T \right],$$

$$O_V^L = (\bar{c}\gamma^\mu P_L b)(\bar{\tau}\gamma_\mu P_L \nu_\tau)$$
$$O_S^R = (\bar{c} P_R b)(\bar{\tau} P_L \nu_\tau)$$
$$O_S^L = (\bar{c} P_L b)(\bar{\tau} P_L \nu_\tau)$$
$$O_T = (\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\tau}\sigma_{\mu\nu} P_L \nu_\tau)$$

- Collider bound
- Bound from BR($B_c^+ \to \tau^+ \nu$) < 60%

10% bound is too stringent



Single particle interpretations

- One WC scenarios
  - C_V^L: W', SU(2)$_L$-singlet vector **LeptoQuark (LQ)**, SU(2)$_L$-triplet and/or -singlet scalar LQ
  - C_S^R: Charged Higgs, SU(2)$_L$-doublet vector LQ (V_2)
  - C_S^L: Charged Higgs with generic flavour structure
  - $C_S^L = 4C_T$: scalar SU(2)$_L$-doublet LQ (R_2) ("4" is modified by RG evolution)

- Two WCs scenarios
  - $(C_V^L, C_S^L = -4C_T)$: SU(2)$_L$-singlet scalar LQ (S_1)
  - (C_V^L, C_S^R): SU(2)$_L$-singlet vector LQ (U_1)
  - (C_S^R, C_S^L): Charged Higgs with generic flavour structure
  - (Re$[C_S^L = 4C_T]$, Im$[C_S^L = 4C_T]$): scalar SU(2)$_L$-doublet LQ (R_2)

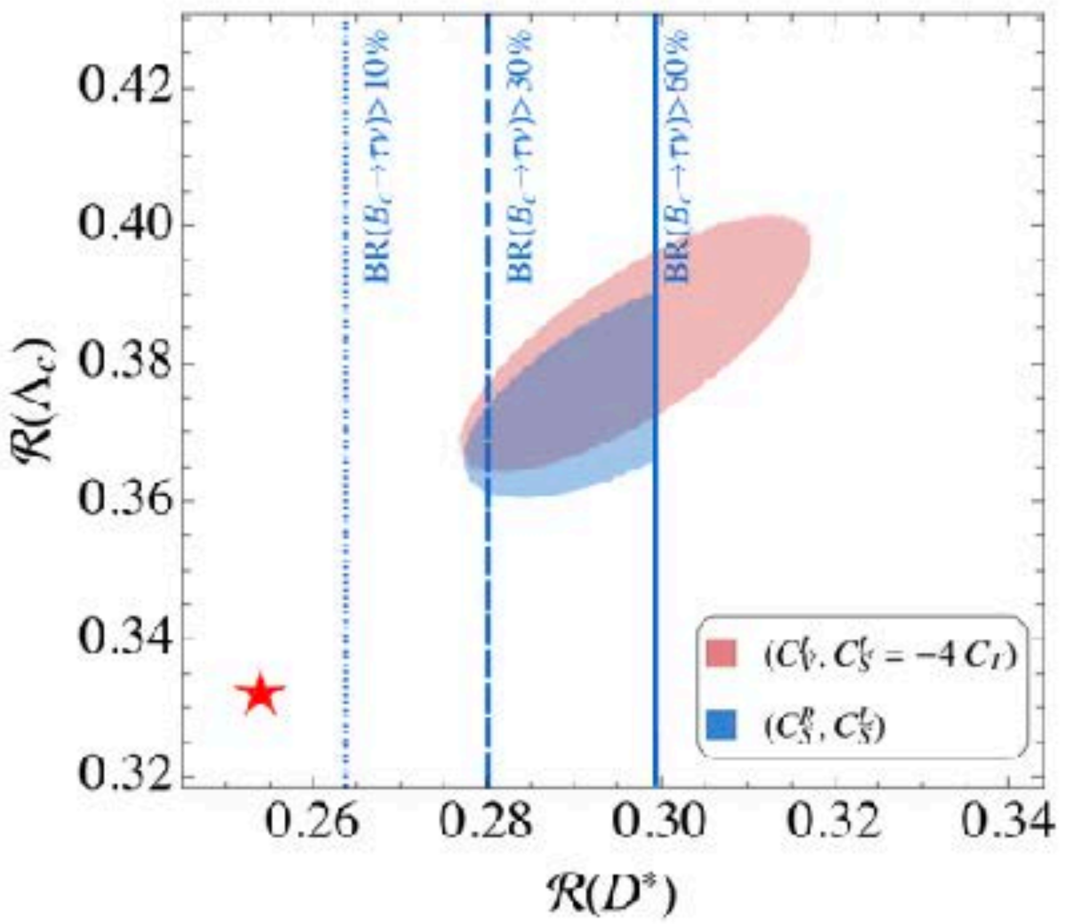
- There are so many detailed studies for **each** single particle scenarios
- There are also "two LQs" scenarios

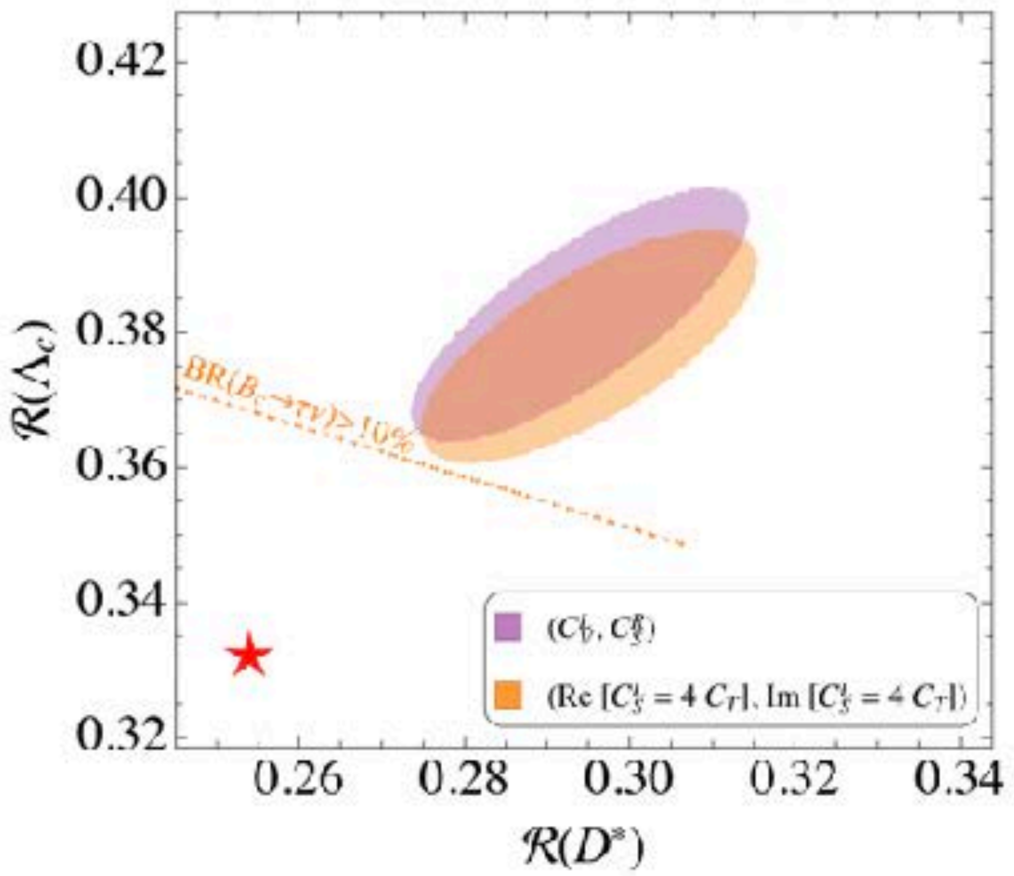
Model-independent prediction: $R(\Lambda_c)$

- Baryonic counterpart: $\mathcal{R}(\Lambda_c) = \dfrac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \ell^- \bar{\nu}_\ell)}$ @ LHCb [Bernlochner, Liegt, Robinson, Sutcliffe, PRL '18]

SU(2)L-singlet scalar LQ (S_1)

Charged Higgs





SU(2)L-singlet vector LQ (U_1)

SU(2)L-doublet scalar LQ (R_2)

Similar ellipses!

- Sum rule for $R(\Lambda_c)$ prediction from the form factor analysis

Model-independent sum rule
(also valid for RH neutrino scenarios)

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

Crosscheck of $R(D^{(*)})$ anomaly is possible by $R(\Lambda_c)$

$$R(\Lambda_c) = 0.38 \pm 0.01_{R(D^{(*)})} \pm 0.01_{\rm FF}$$

There is no data yet, but soon?

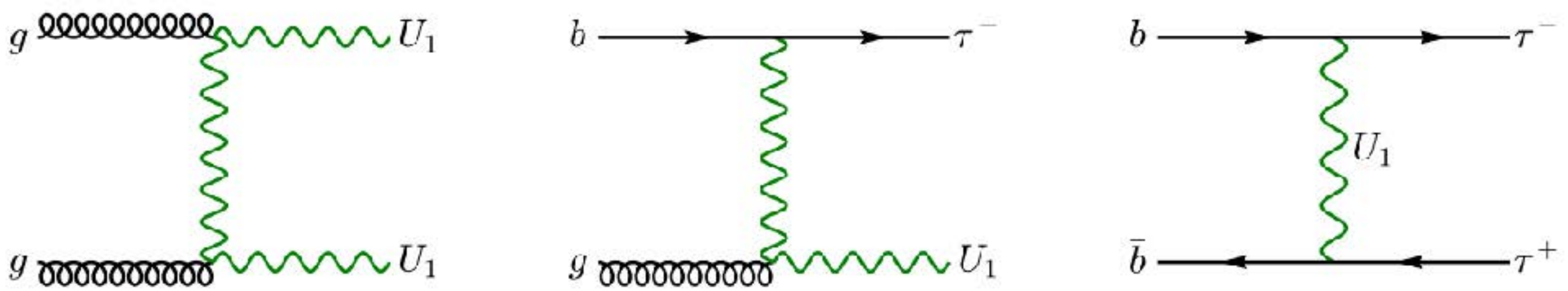
$$R(\Lambda_c)_{\rm SM} = 0.324 \pm 0.004$$

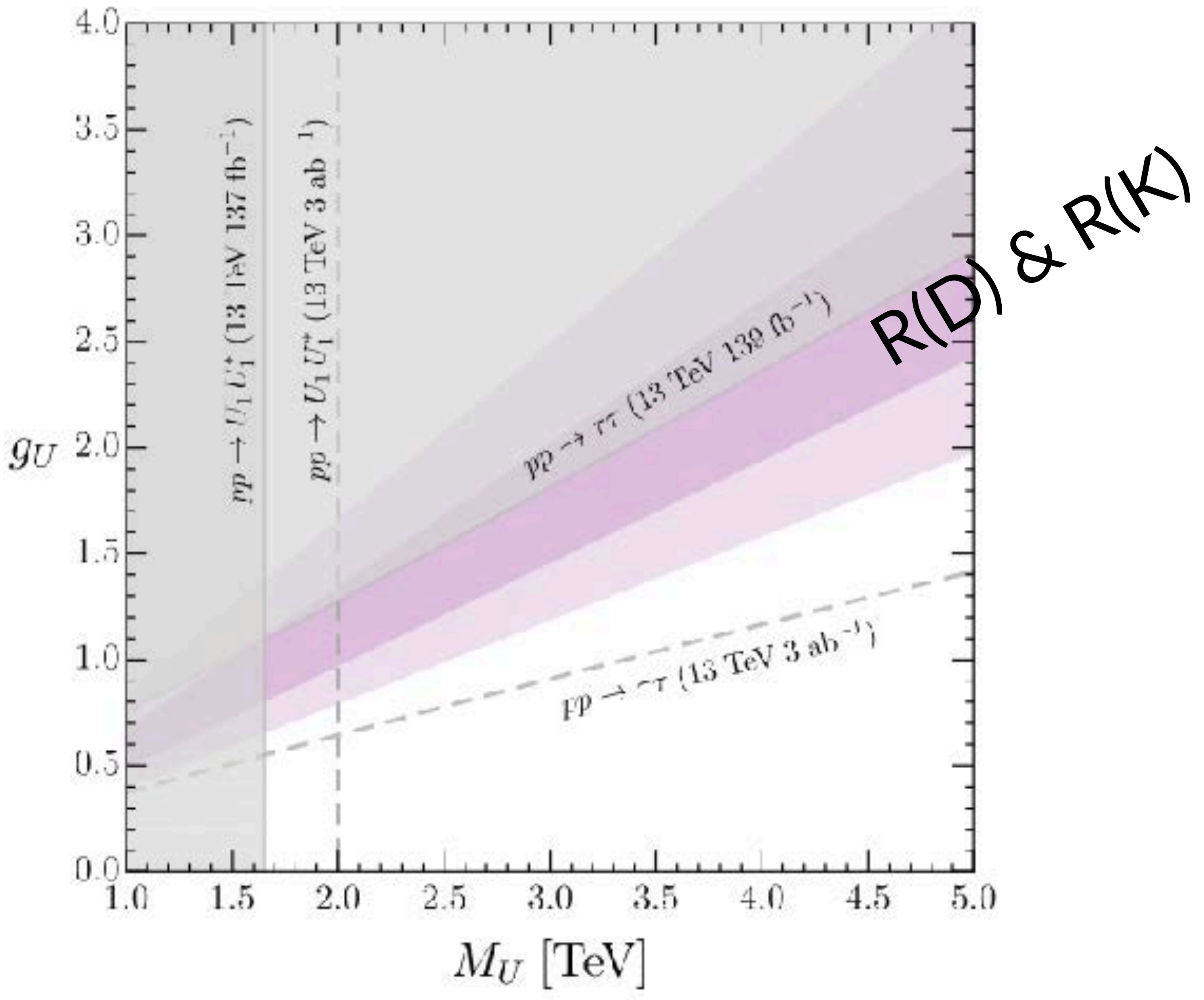
[Blanke, Crivellin, TK, Moscati, Nierste, Nisandzic, '19]

LQ vs LHC

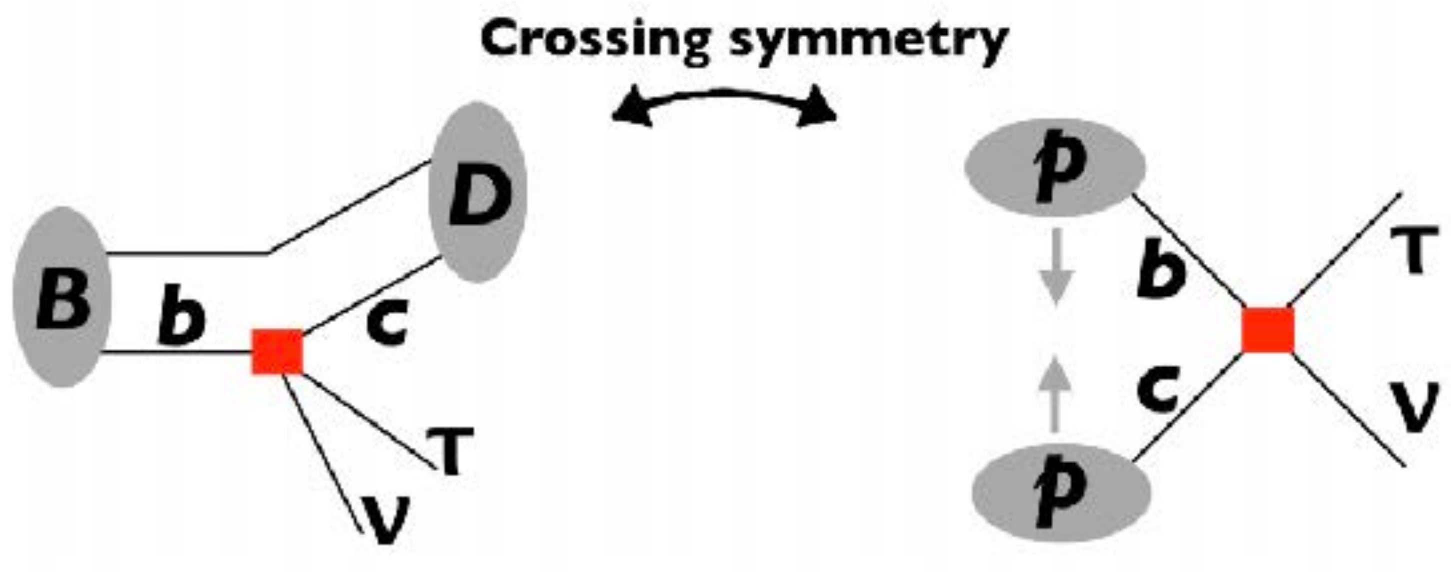
- LQ can be probed by LHC directly and indirectly

  Vector leptoquark scenario [Cornella et al, 2103.16558]





- The direct bound comes from high-p_T tails in mono-τ searches



[Greljo, Camalich, Ruiz-Alvarez PRL '19; Marzocca, Min, Son, '20; Iguro, Takeuchi, Watanabe 2011.02486]

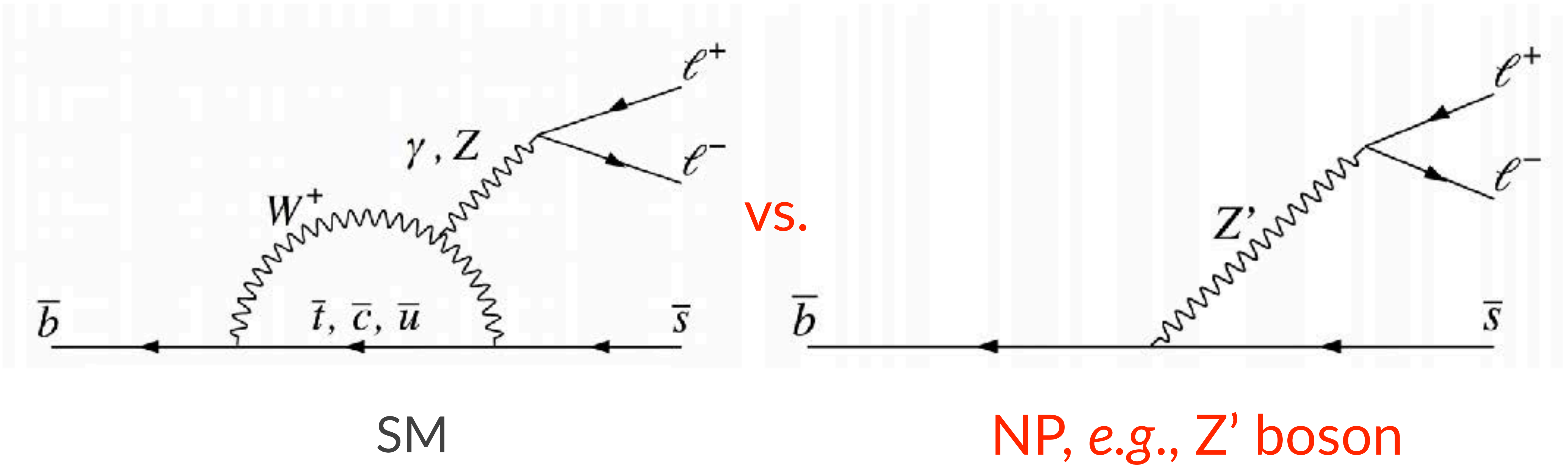
Current bounds:

EFT: $|C_V^L| < 0.32, \quad |C_S^{L(R)}| < 0.55, \quad |C_T| < 0.17$

2TeV LQ: $|C_V^L| < 0.42, \quad |C_S^{L(R)}| < 0.8, \quad |C_T| < 0.35$

LFU observable *R*(*K*)

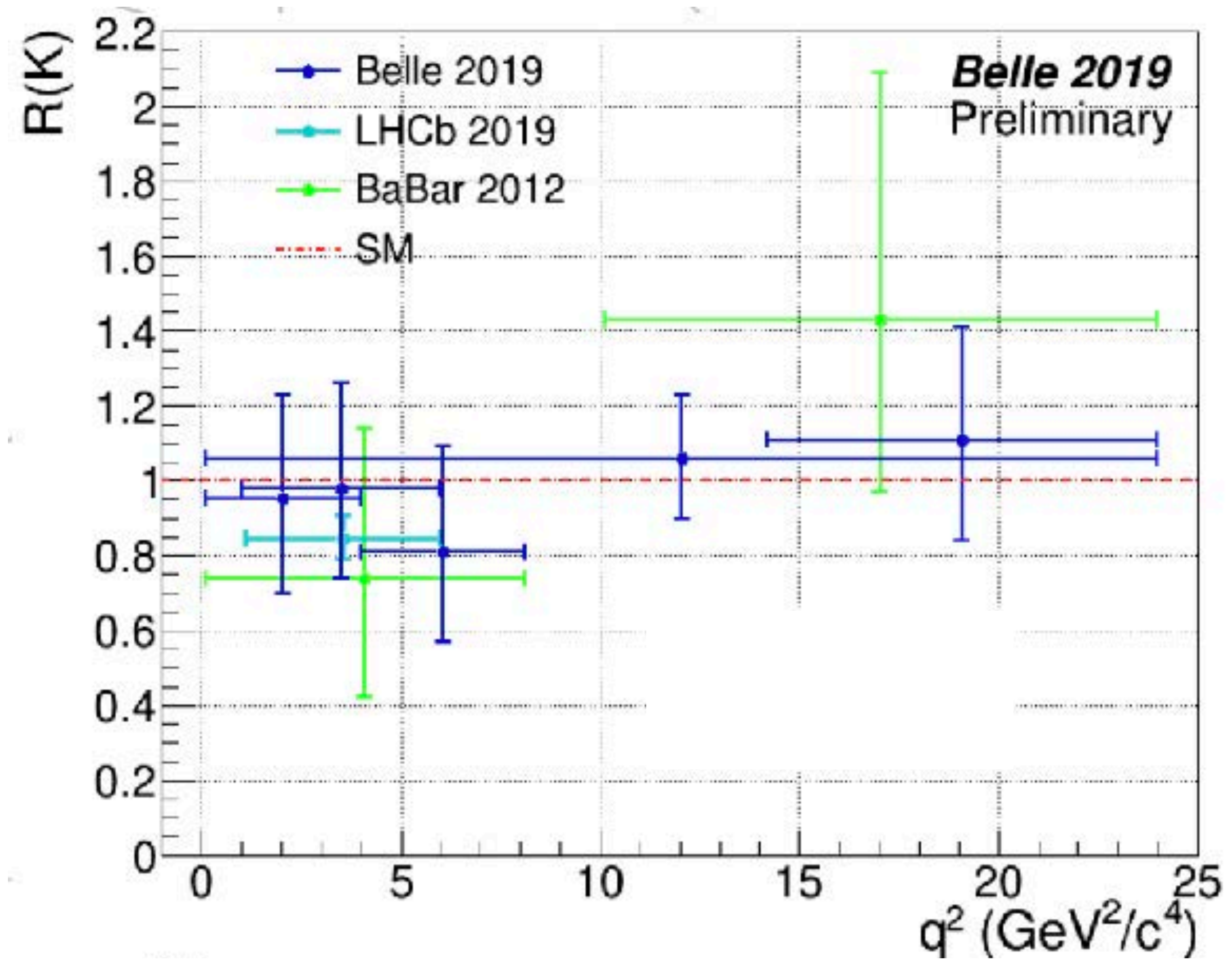
$$R(K^{(*)}) = \frac{\mathrm{BR}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{BR}(B \to K^{(*)}e^+e^-)}$$

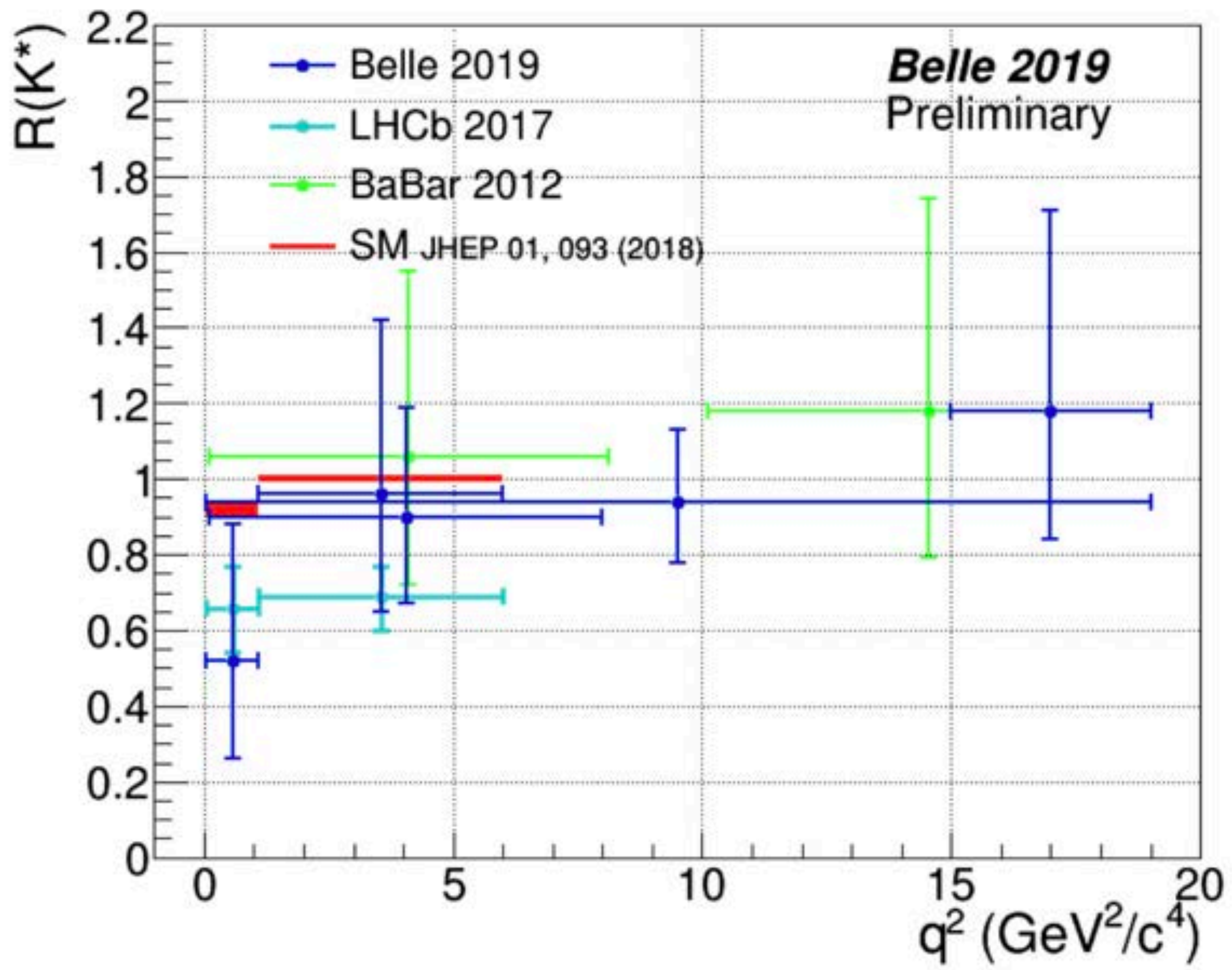


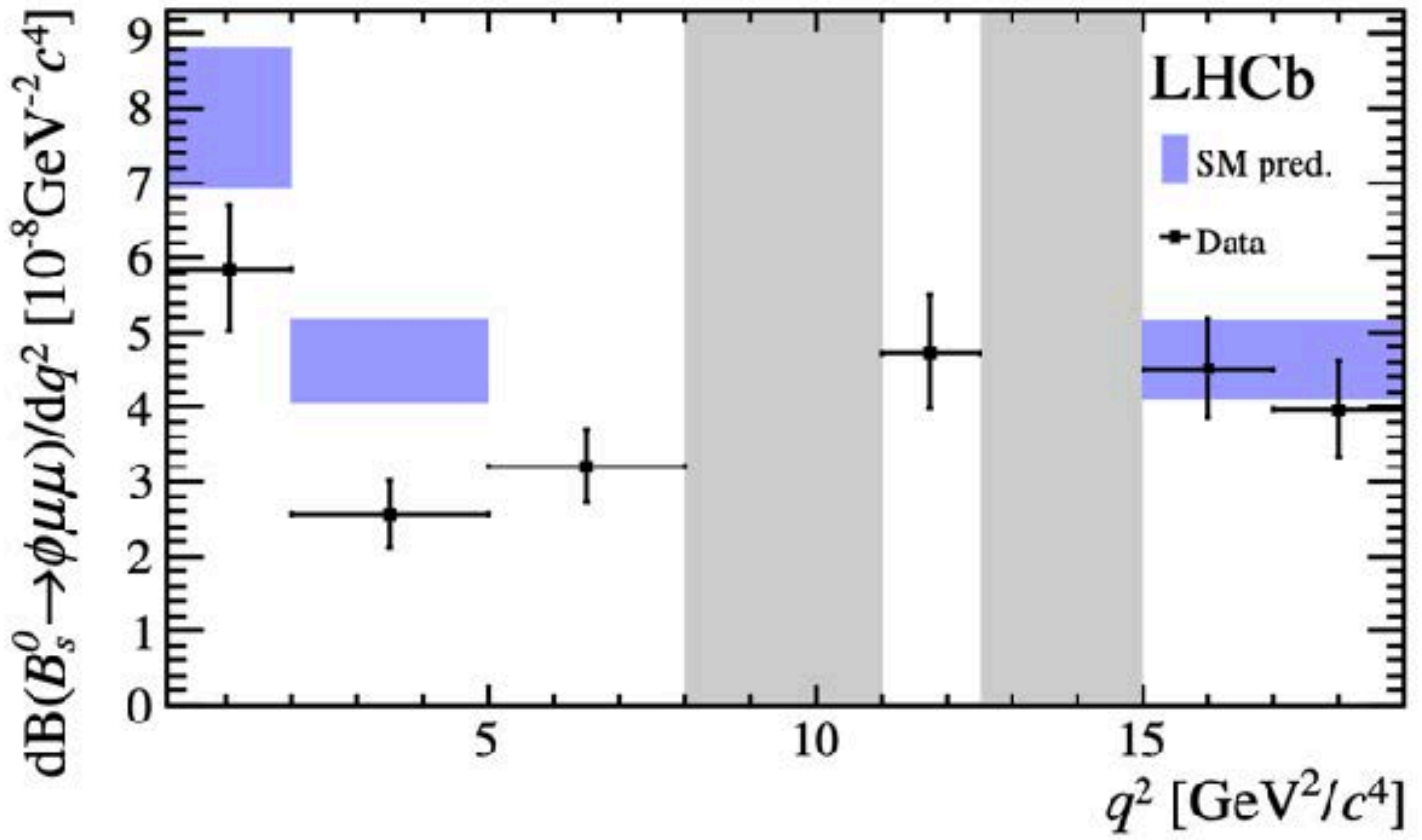
$$\mathcal{B}(B \to K\ell^+\ell^-) = \mathcal{O}(10^{-7}),\ \mathcal{B}(B \to K^*\ell^+\ell^-) = \mathcal{O}(10^{-6})$$

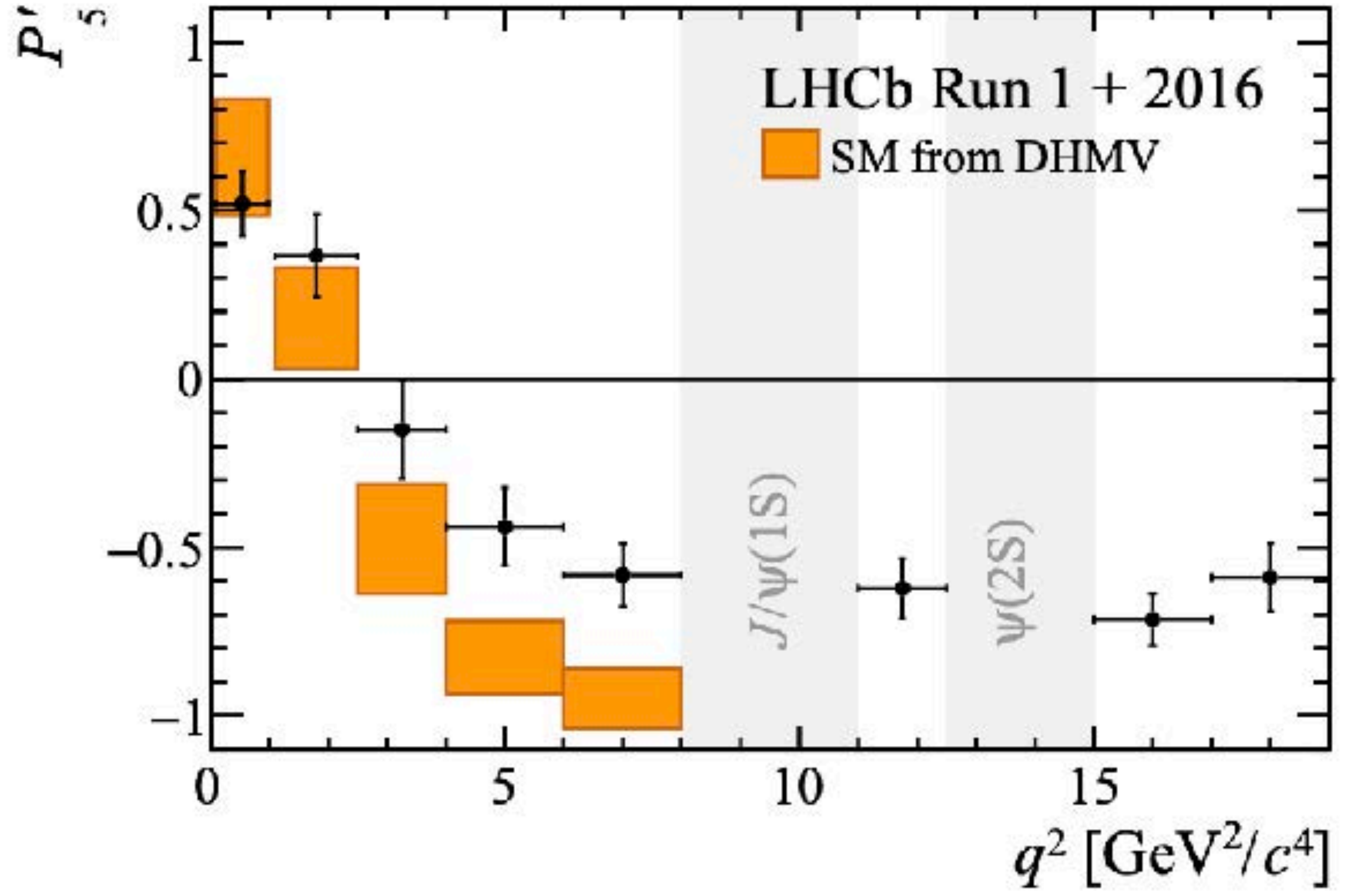
$b \to s\mu^+\mu^-$ anomalies

- In 2019 and 2020, LHCb and Belle presented new results





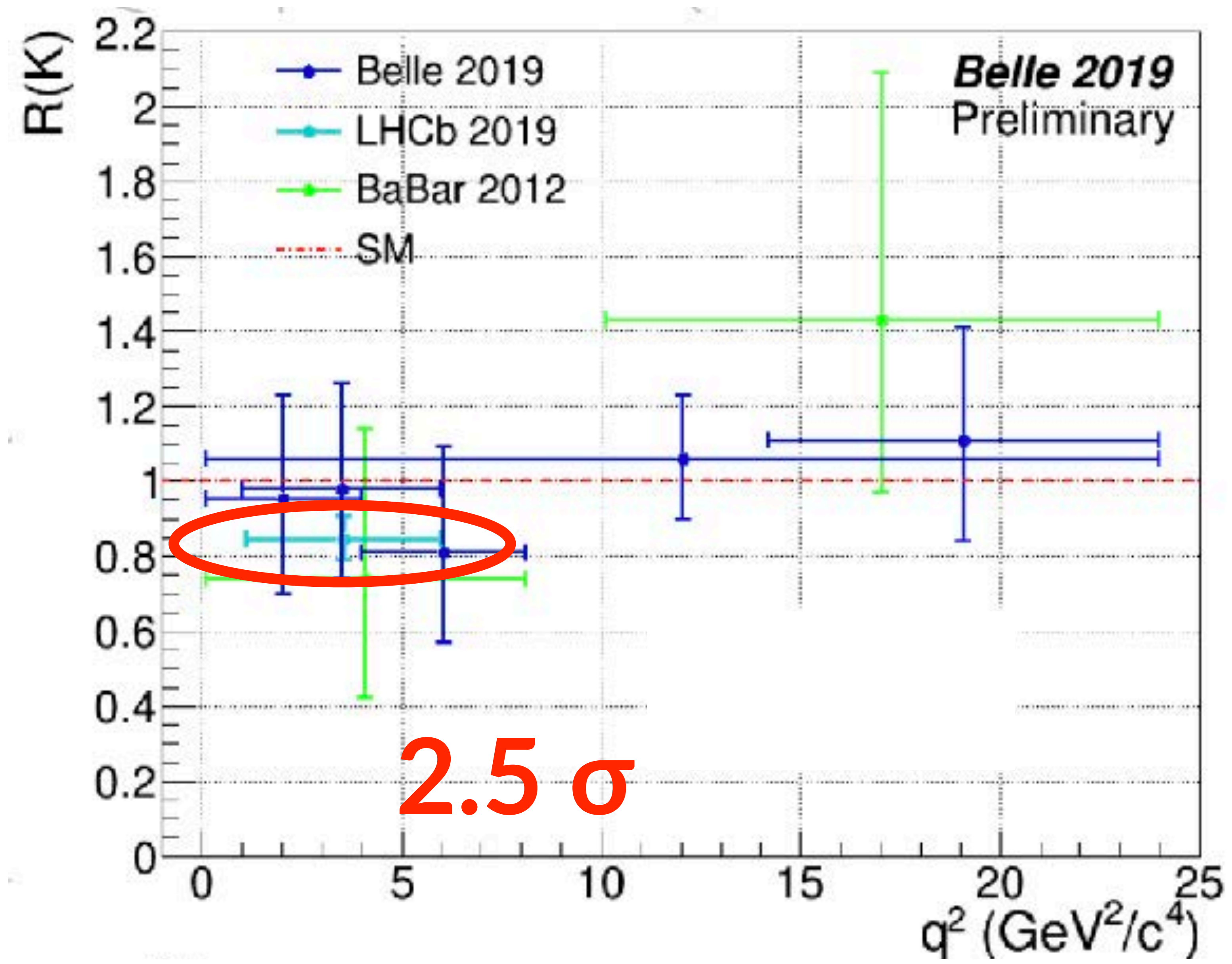


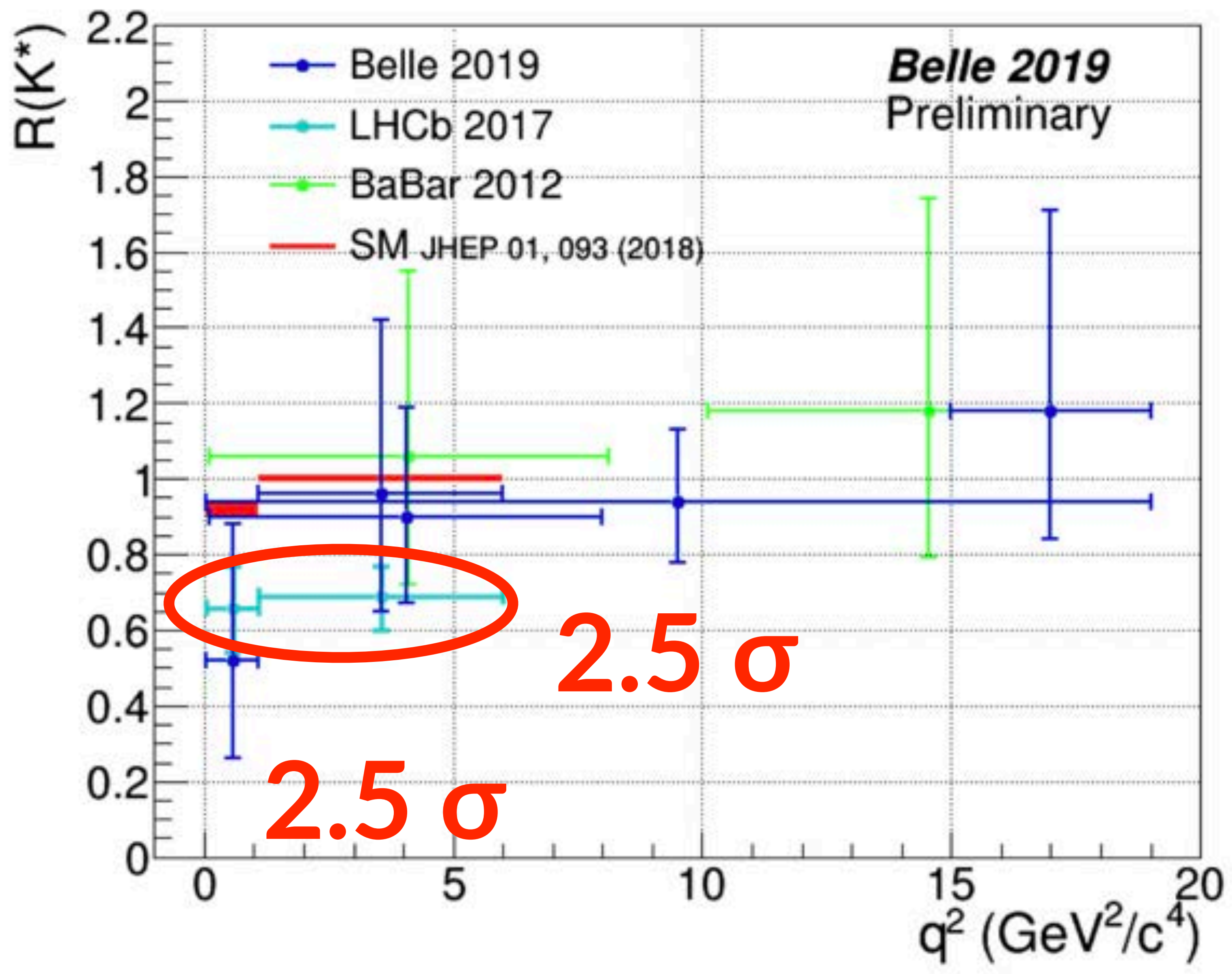


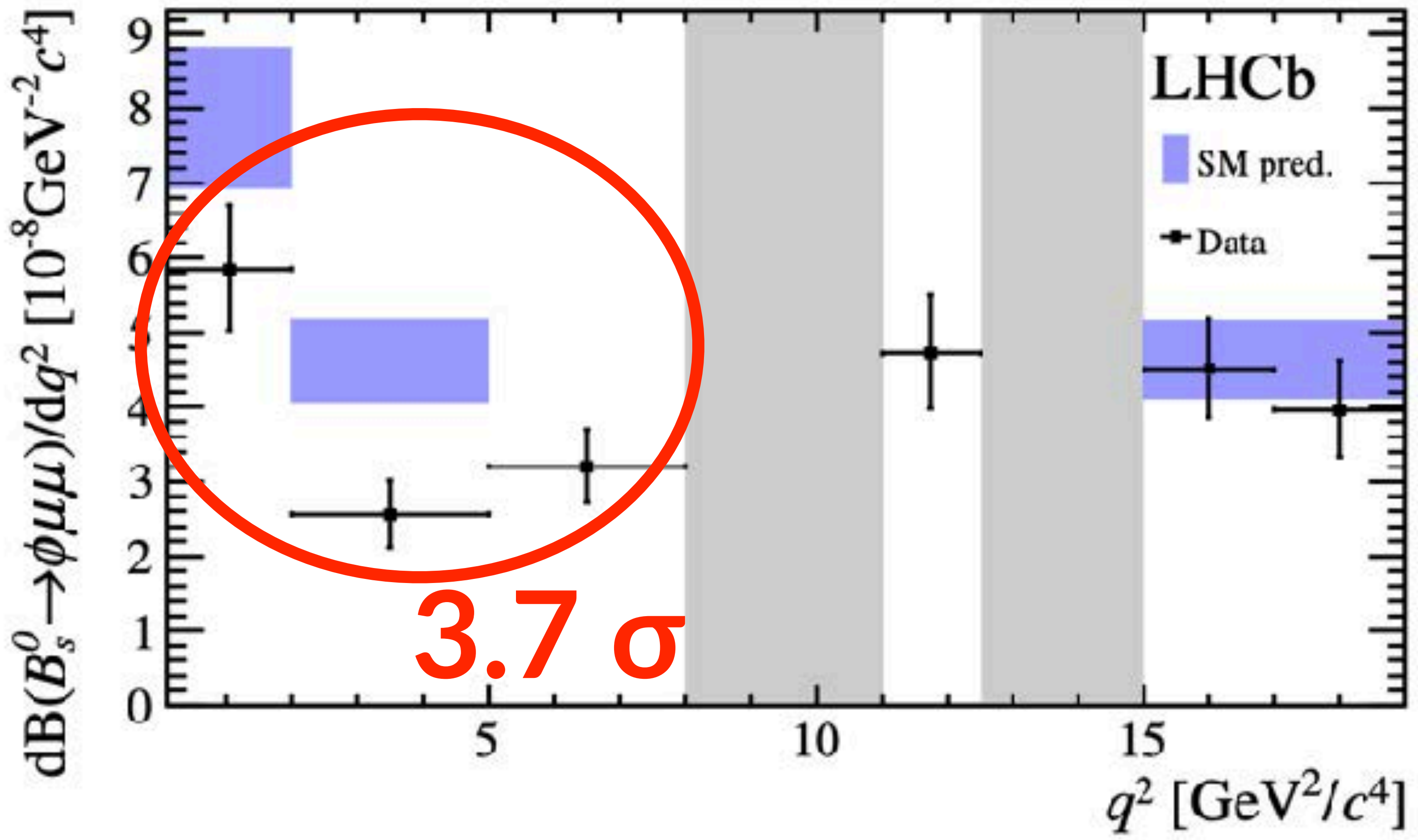
[LHCb, 2003.04831]

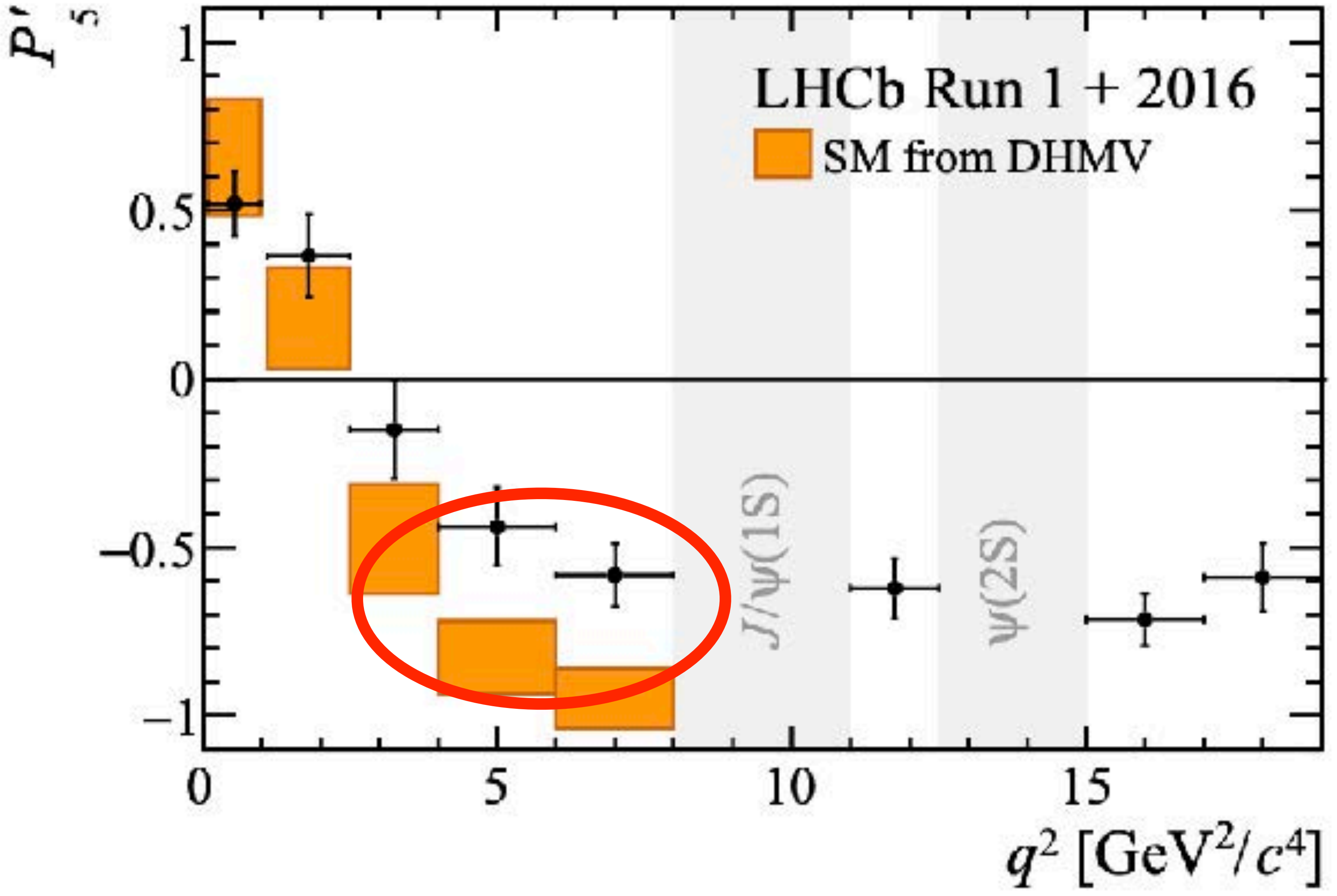
$b \to s\mu^+\mu^-$ anomalies

- In 2019 and 2020, LHCb and Belle presented new results









[LHCb, 2003.04831]

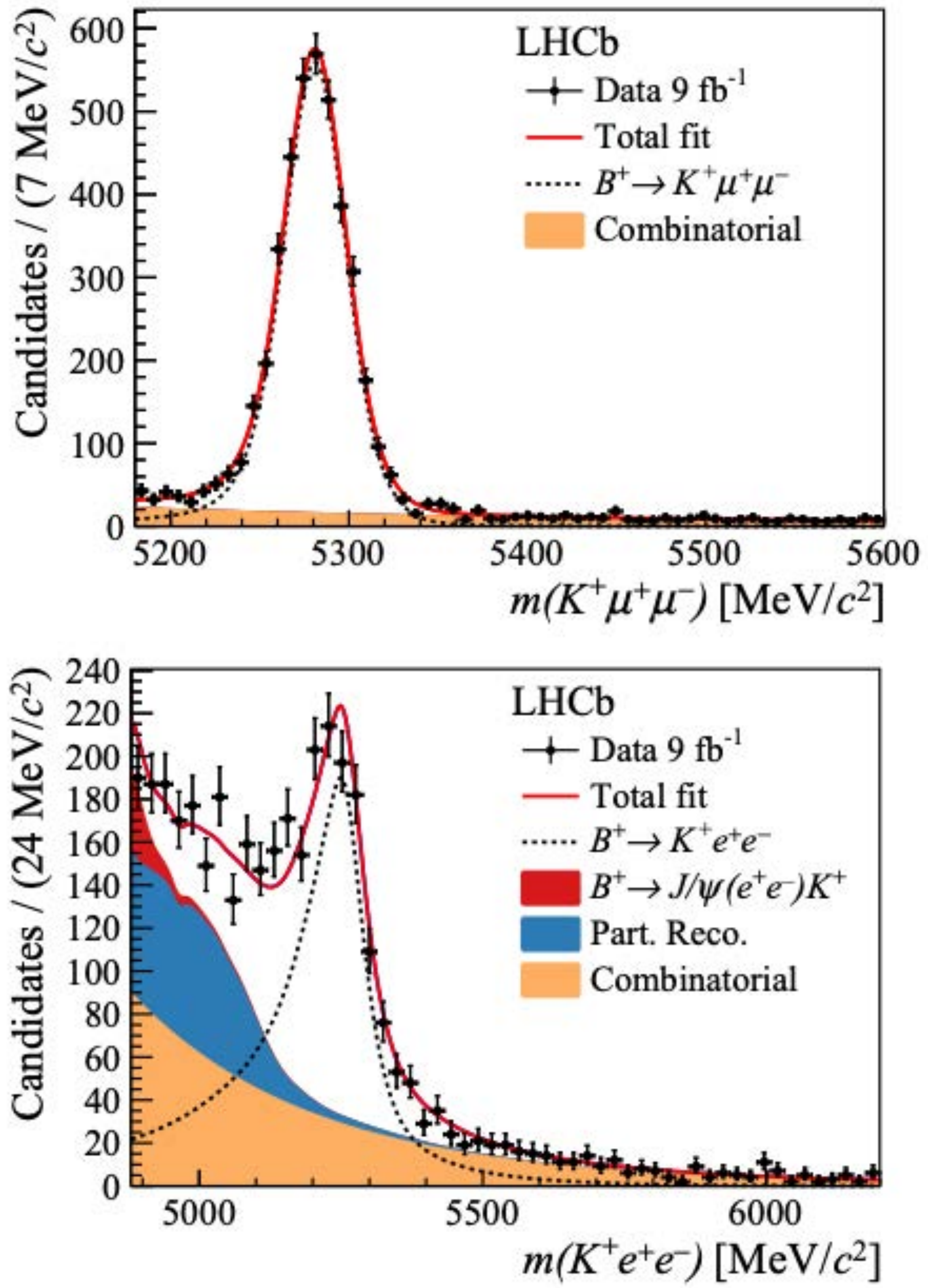
2.5 σ, 2.9 σ

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

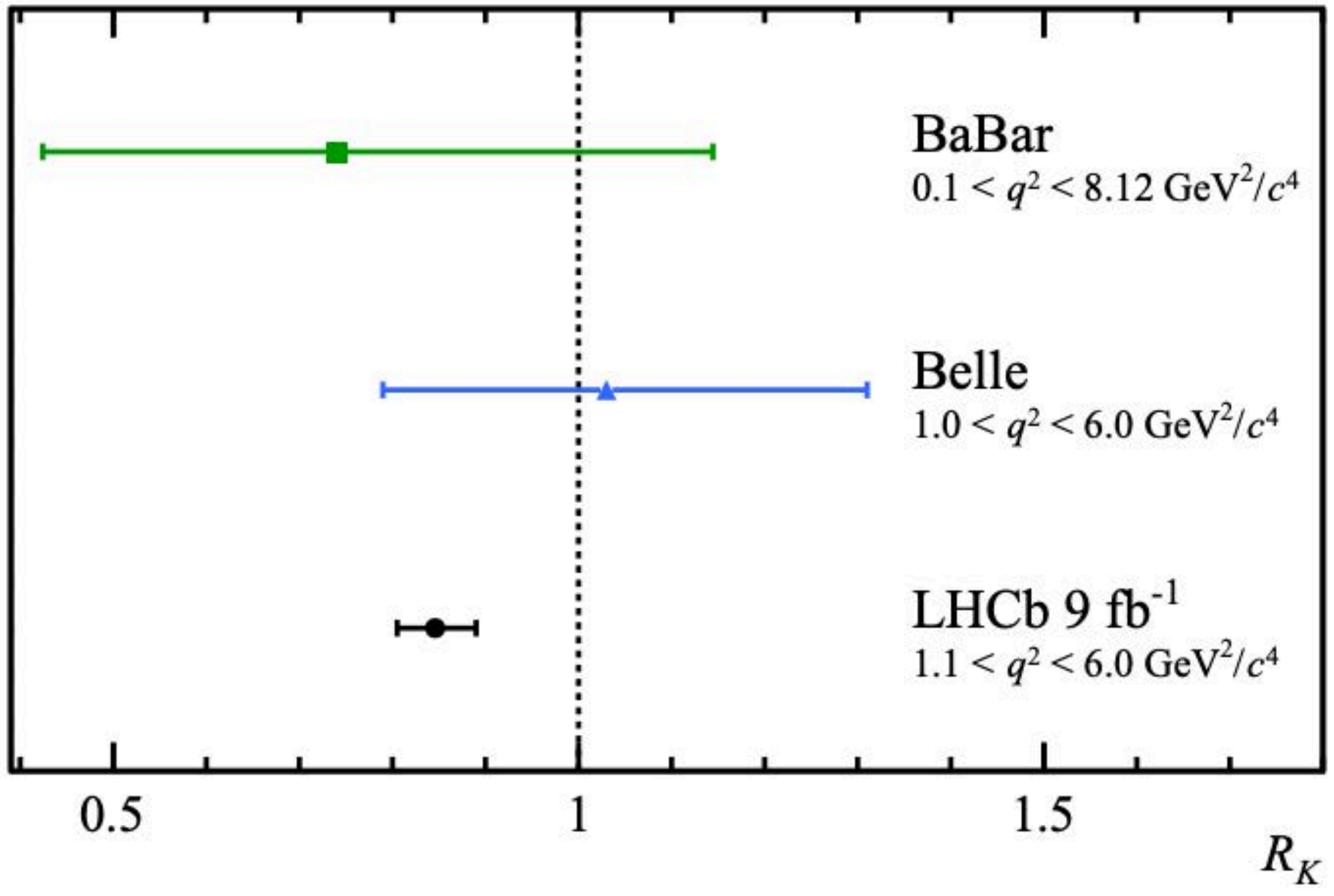
  at 2.6 σ [LHCb, 1808.00264]

R(K) in Moriond2021

- Last month, R(K) was confirmed by using full Run 2 data [LHCb Moriond2021, 2103.11769]

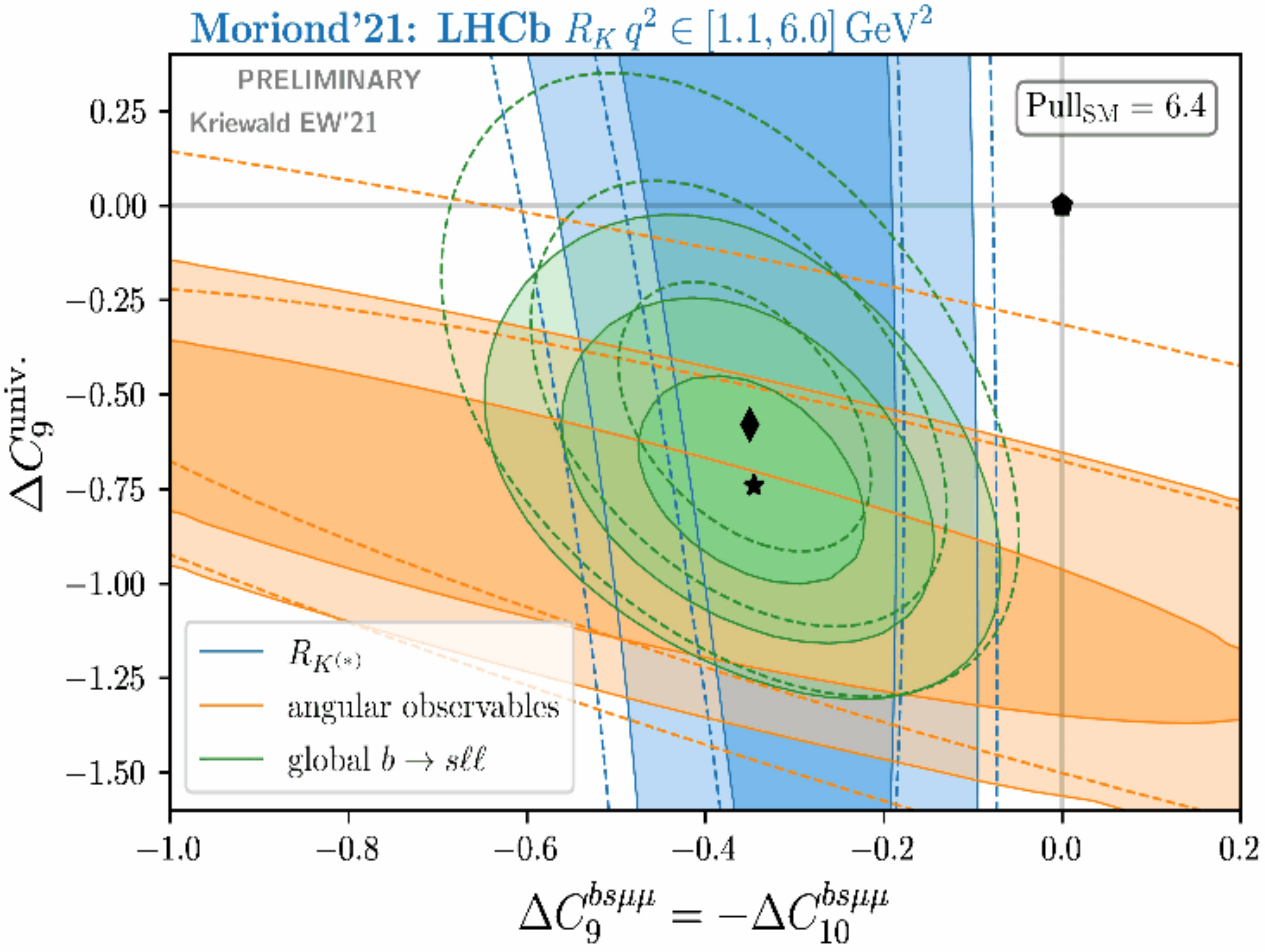


$$R_K = 0.846\,^{+0.042}_{-0.039}\,(\text{stat.})\,^{+0.013}_{-0.012}\,(\text{syst.})$$



R(K) only

2.5 σ → **3.1σ**



[Kriewald, Hat, Orloff, Teixeira, 2104.00015]

SMEFT global fit

[Geng et al, 2103.12738;
Altmannshofer et al, 2103.13370;
Cornella et al, 2103.16558;
Alguero et al, 2104.08921;
Hurth et al, 2104.10058]

- Relevant effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i C_i \mathcal{O}_i$$

$$\mathcal{O}_7 = (\bar{s}\sigma_{\mu\nu} P_R b)\, F^{\mu\nu}$$

$$\mathcal{O}_9 = (\bar{s}\gamma_\mu P_L b)\,(\bar{\ell}\gamma^\mu \ell)$$

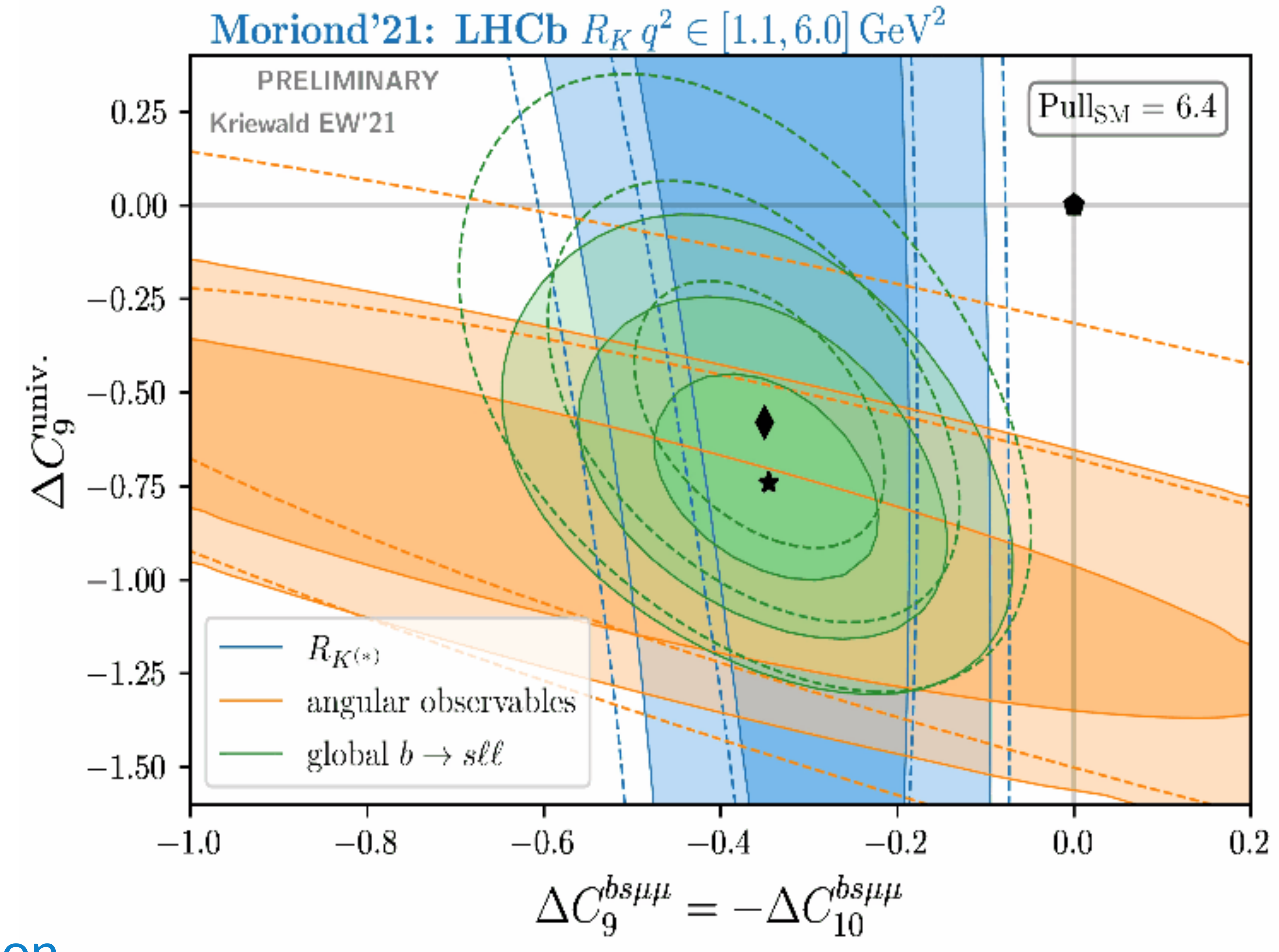
$$\mathcal{O}_{10} = (\bar{s}\gamma_\mu P_L b)\,(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

Including the *look-elsewhere effect* and conservative theoretical error from charm loops, **the global significance of $b \to s\ell^+\ell^-$ is 3.9σ**

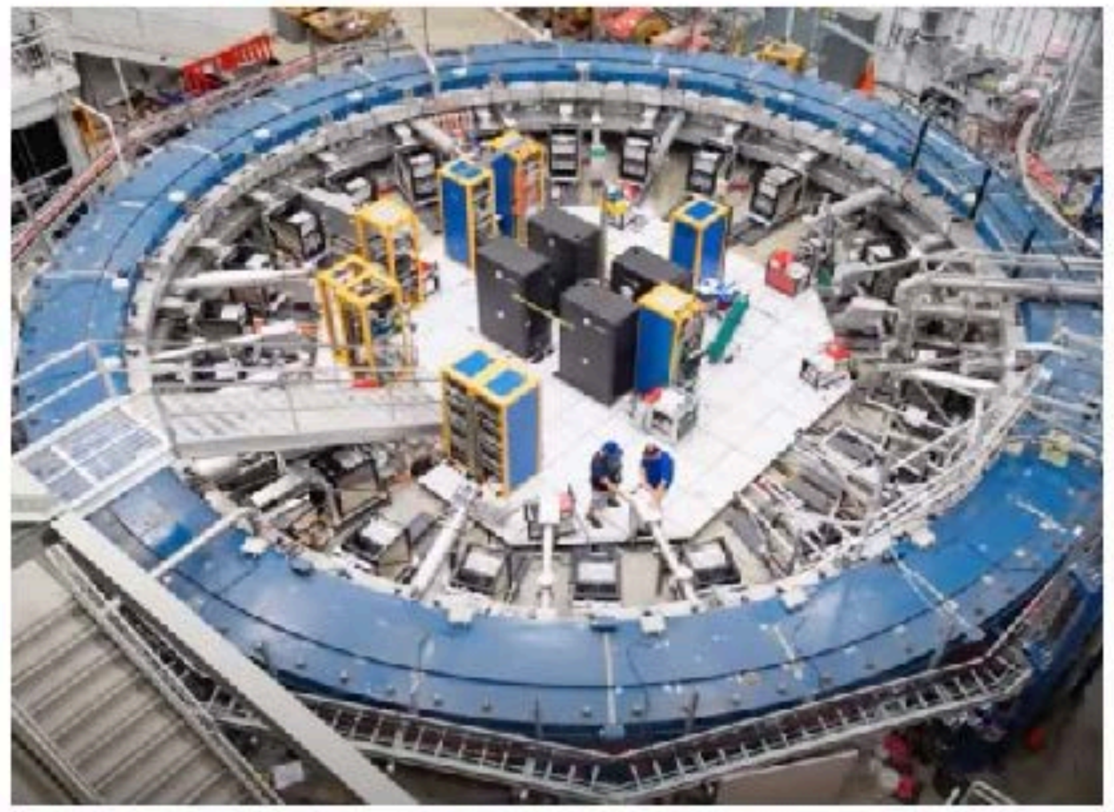
[Lancierini, Isidori, Owen, Serra, 2104.05631]

→ $\Lambda_{\rm NP} = \mathcal{O}(10)\text{TeV}$

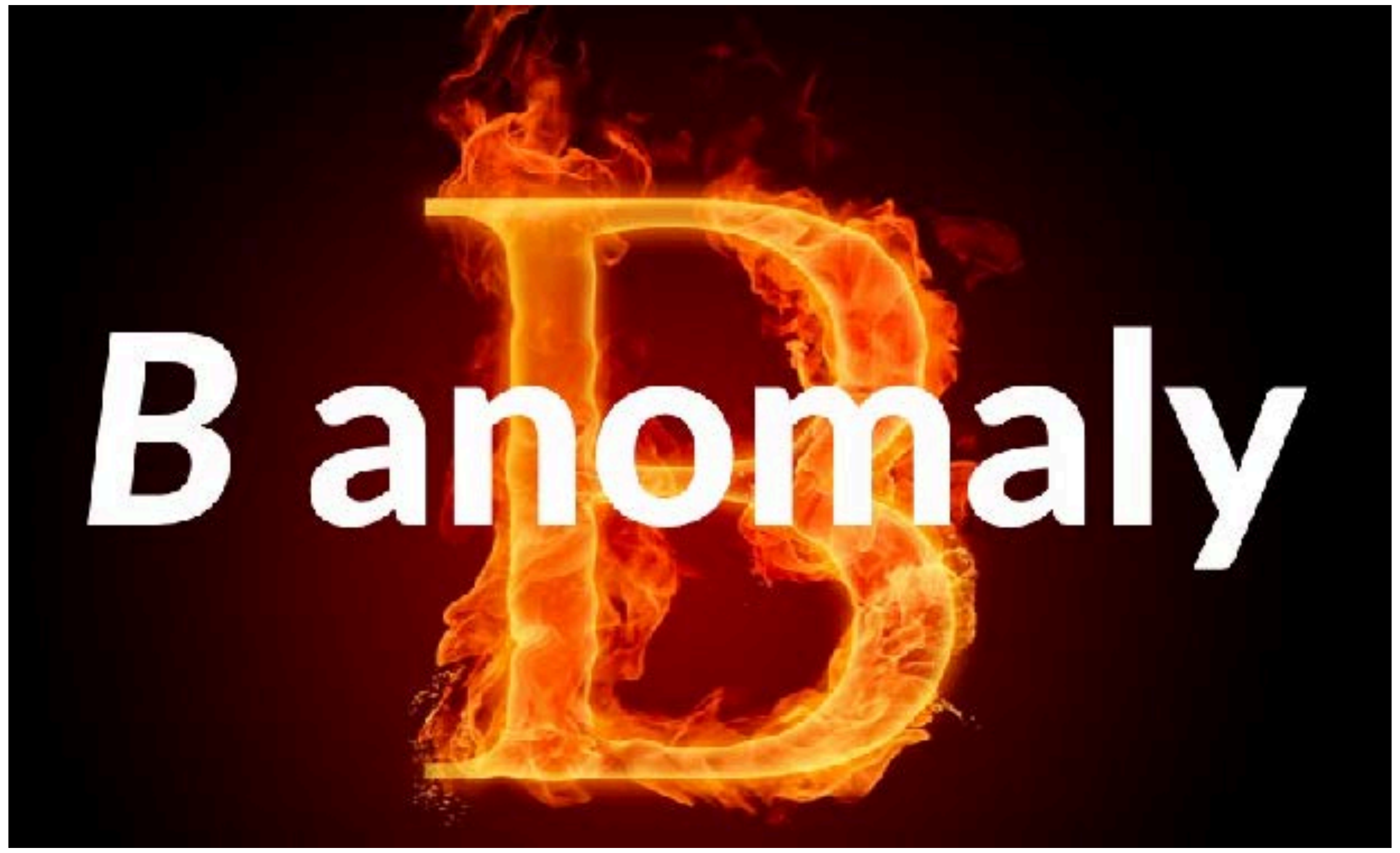
[Kriewald, Hat, Orloff, Teixeira, 2104.00015]



All deviations in $b \to s\mu^+\mu^-$ are the same direction muon g-2 anomaly



+



= ?

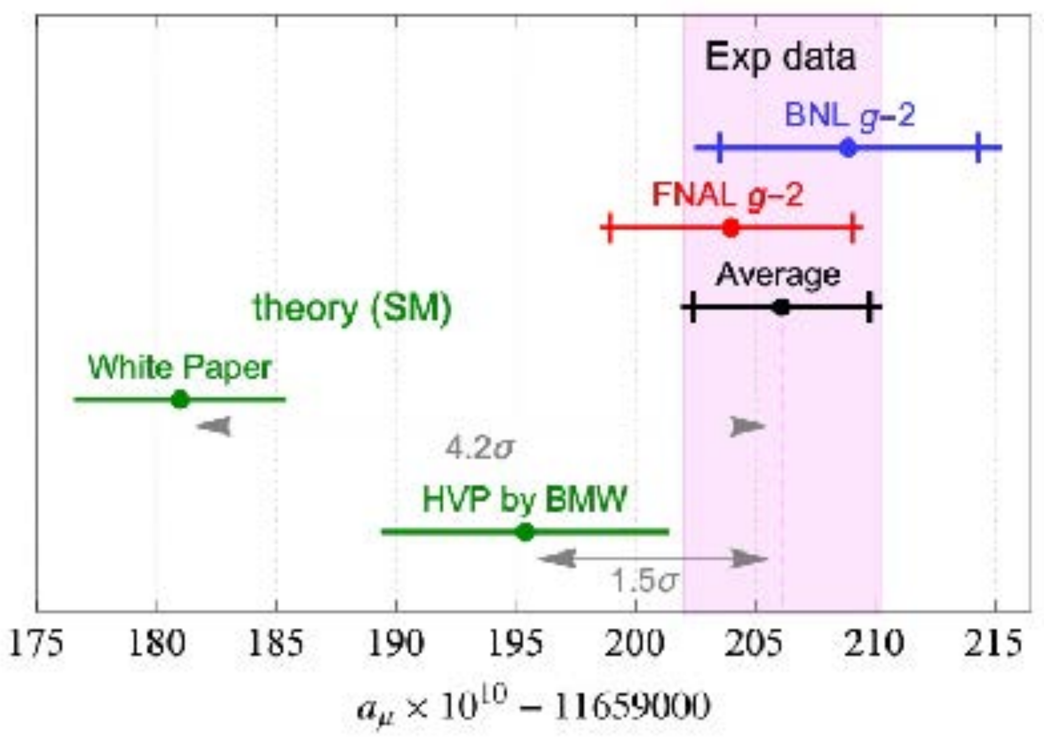
(B + muon g-2) anomaly =?

Refs	particles	solve	mass scale
Arcadi et al, 2104.03228	Vector-like fermion + scalars	muon g-2, R(K), DM	0.1〜1 TeV VL
Nomura, Okada 2104.03248	Scalar LeptoQuark (LQ)	muon g-2, R(K), m_ν	〜5 TeV LQ
Bhattacharya et al, 2104.03947	ALP	muon g-2, $K\pi$ puzzle	〜140 MeV ALP
Marzocca, Trifinopoulos, 2104.05730	Scalar LQ + scalar	muon g-2, R(K), R(D), CAA	〜5 TeV LQ
Du et al, 2104.05685; Ban et al, 2104.06656	Vector LQ	muon g-2, R(K), R(D)	〜2 TeV LQ

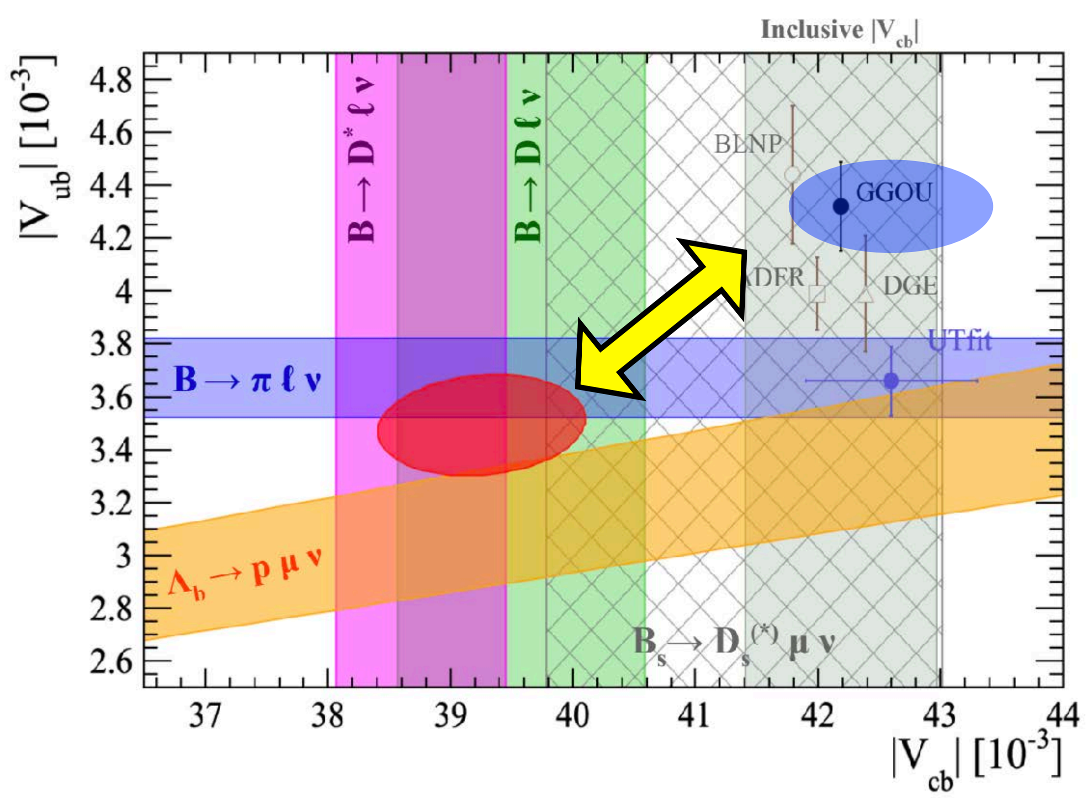
⋮

Summary of anomalies —fake or real? —

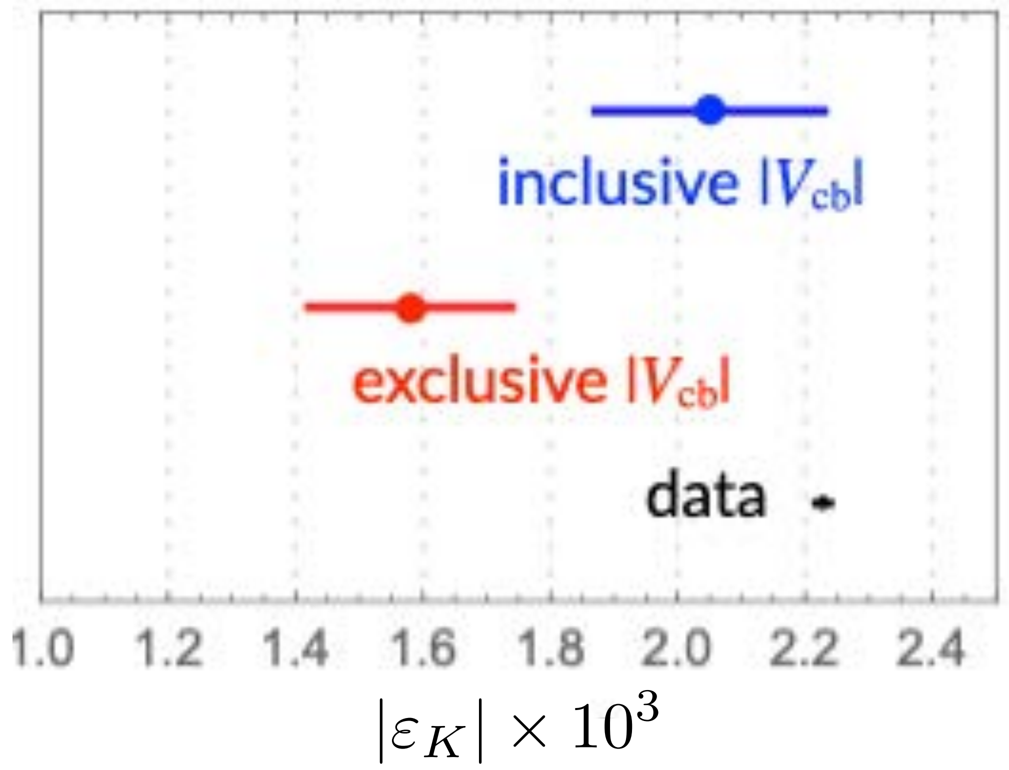
4.2σ?



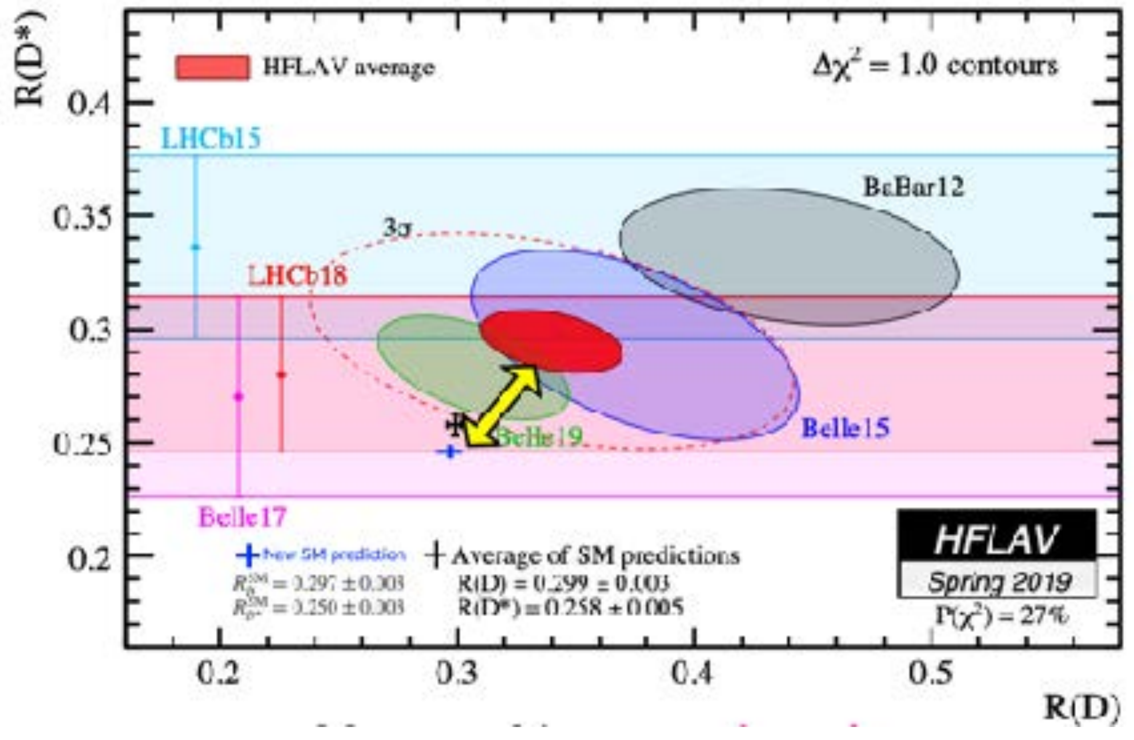
~3σ



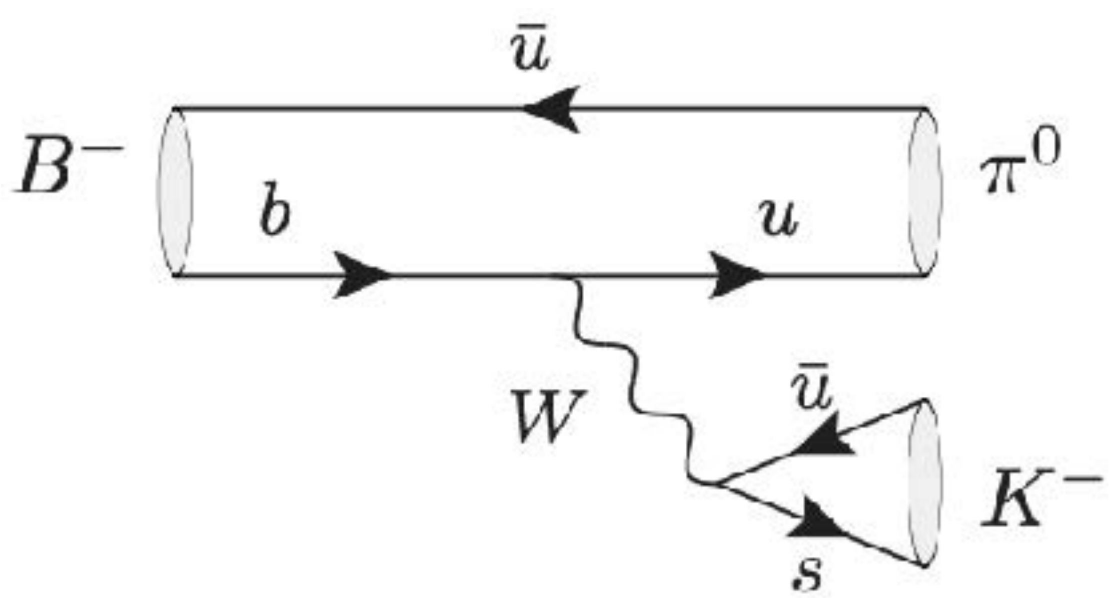
4.2σ?



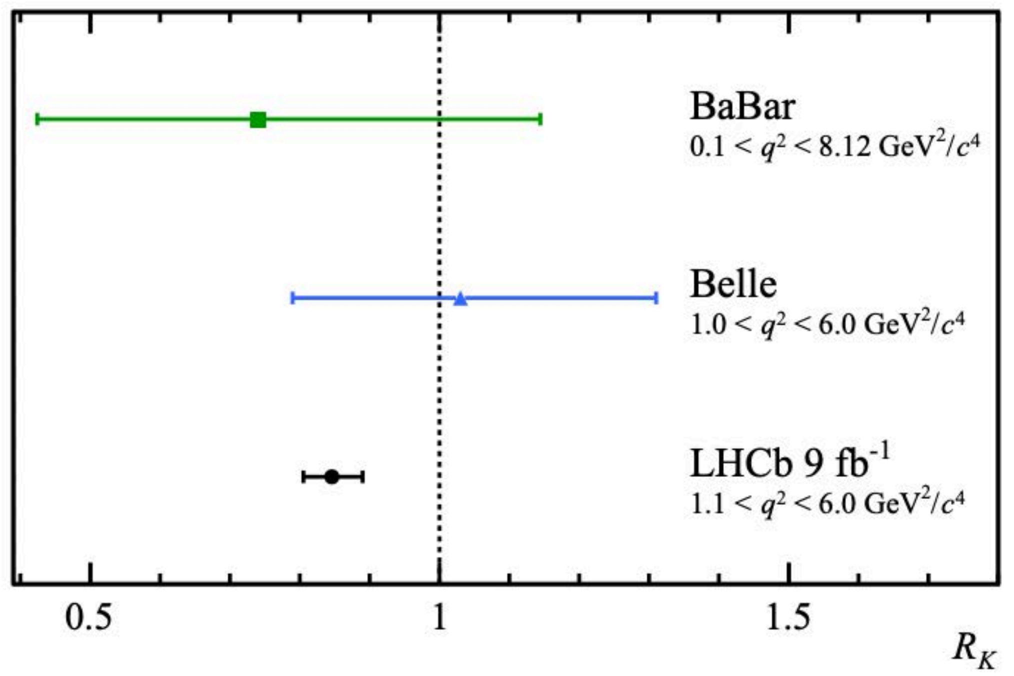
~4σ



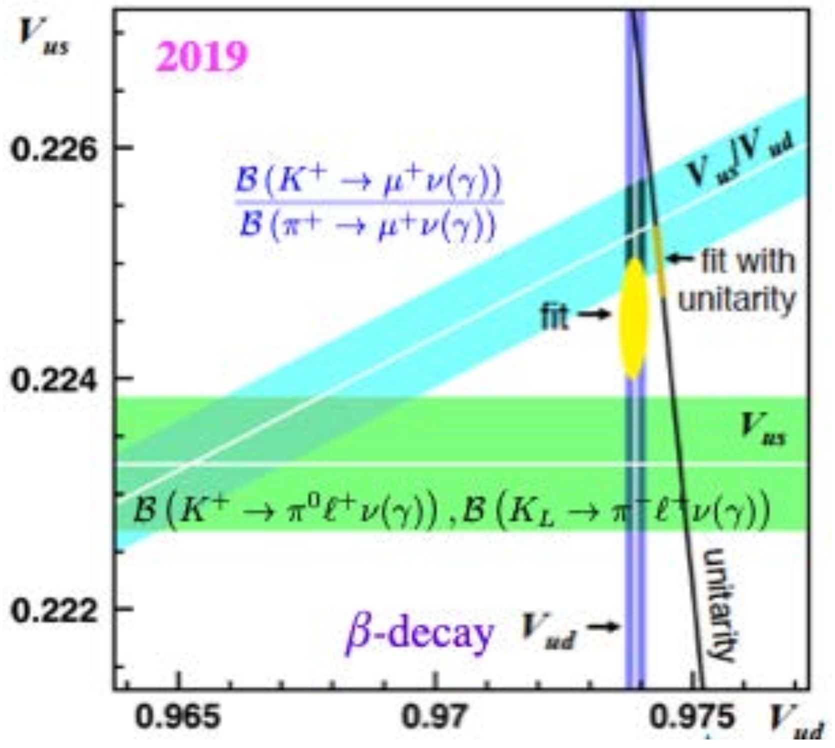
2.2σ?



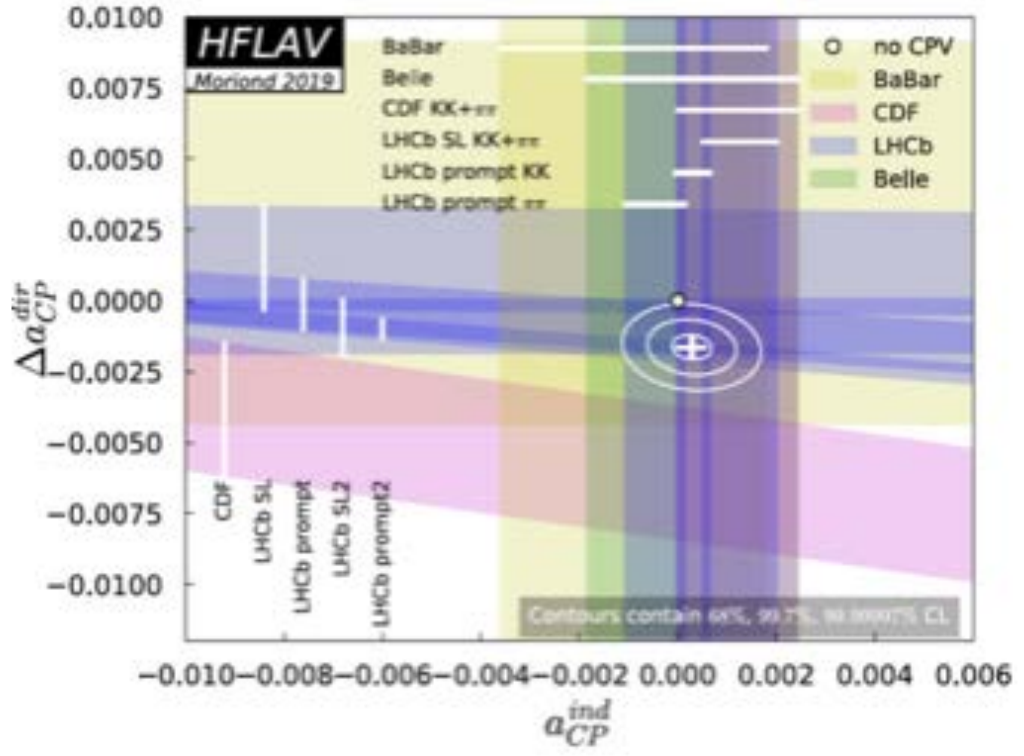
3.9σ



3-4σ



4.7σ?



SUSY? Leptoquark? Axion-like particle? Z’? Vector-like fermion?