Anomalies in Particle Physics

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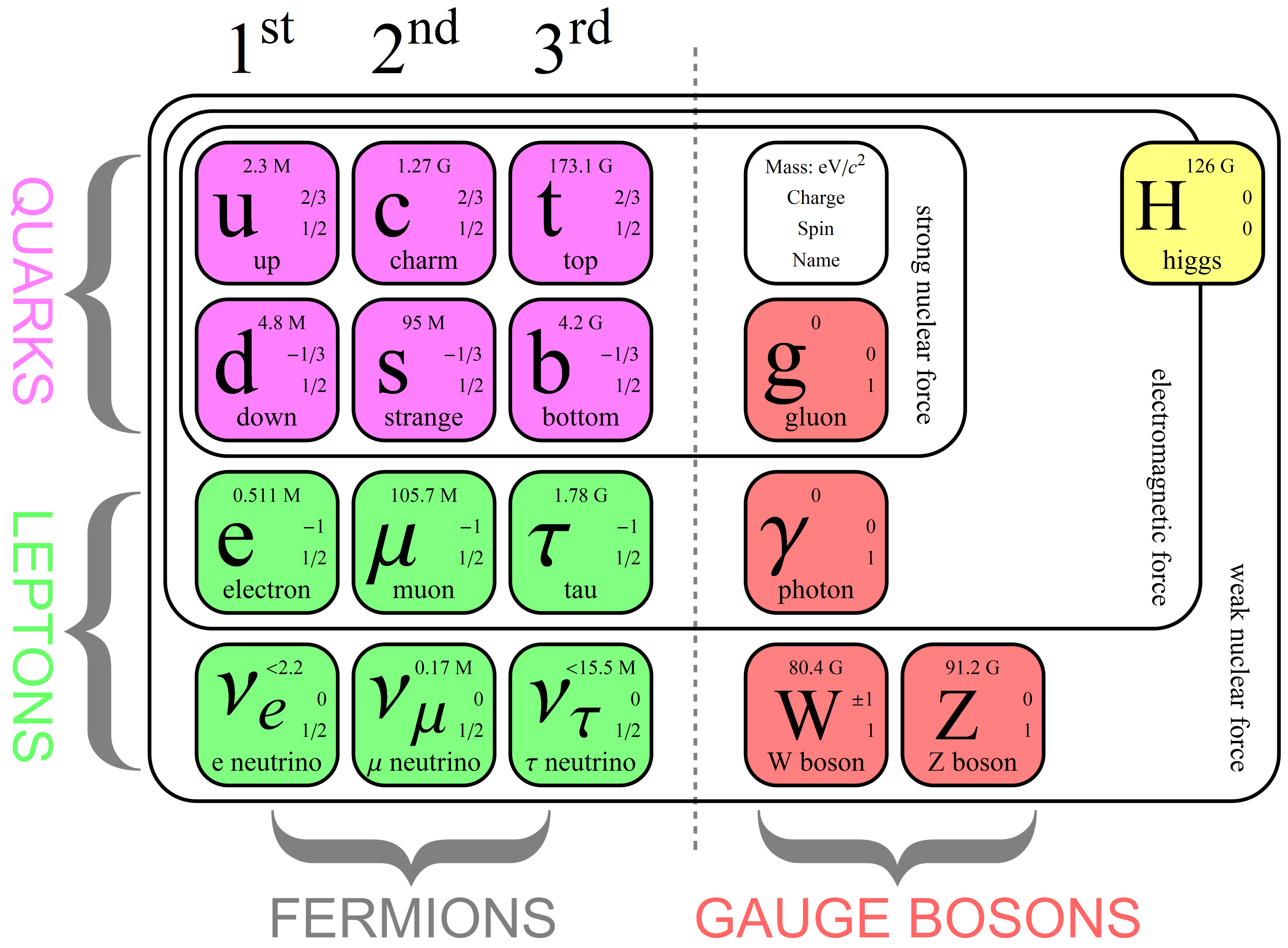
Outline

- Introduction
- Status of the anomalies
  - a_μ
  - Cabibbo Angle Anomaly
  - $b \to c\tau\nu$
  - $b \to s\mu\mu$
  - Non-resonant di-leptons
  - W mass and $Z \to bb$
  - .....
- Explanations of the Flavour anomalies
- Conclusions
- Future implications

Introduction

Standard Model



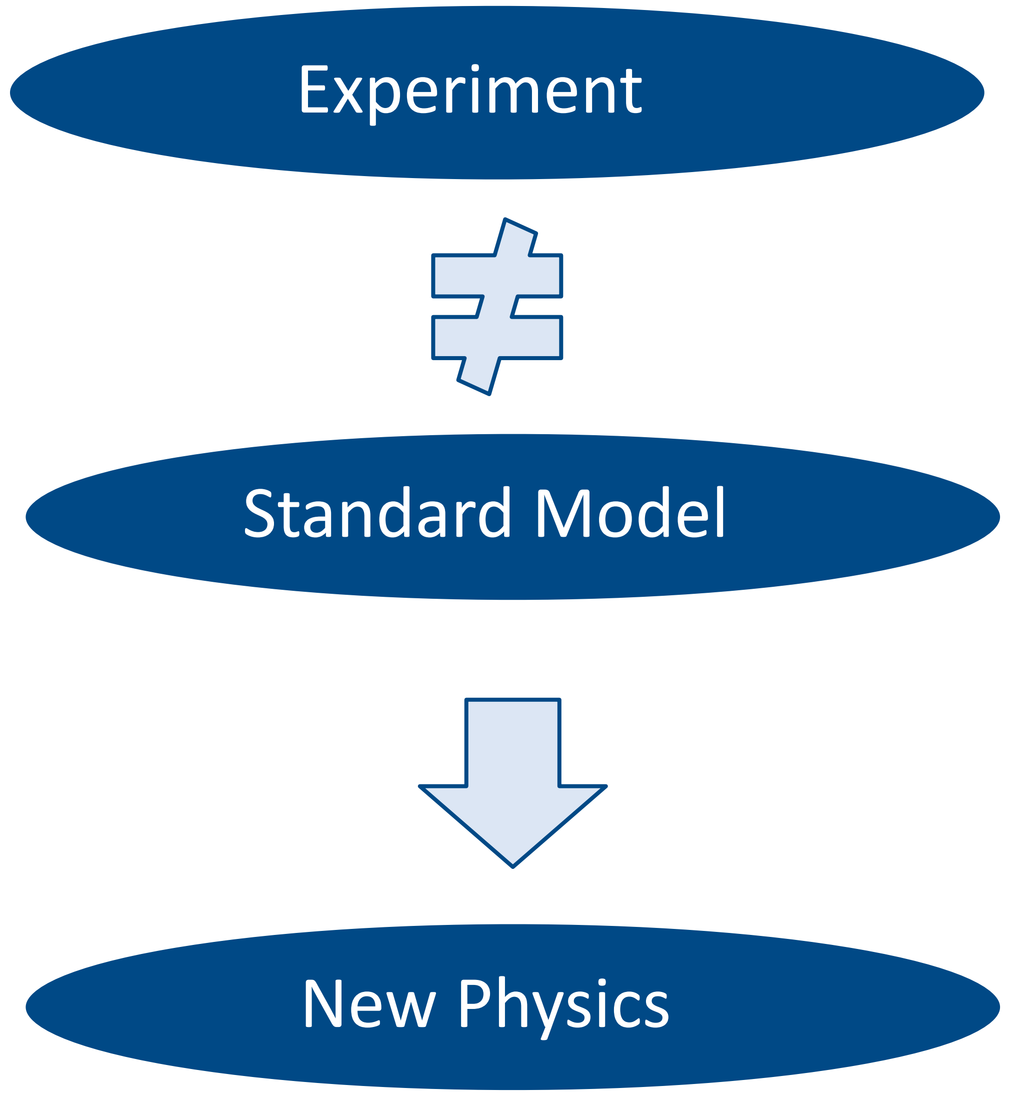
Physics Beyond the Standard Model

- Dark Matter existence established at cosmological scales
  - New weakly interacting particles
- Neutrinos not exactly massless
  - Right-handed (sterile) neutrinos
- Matter anti-matter asymmetry
  - Additional CP violating interactions

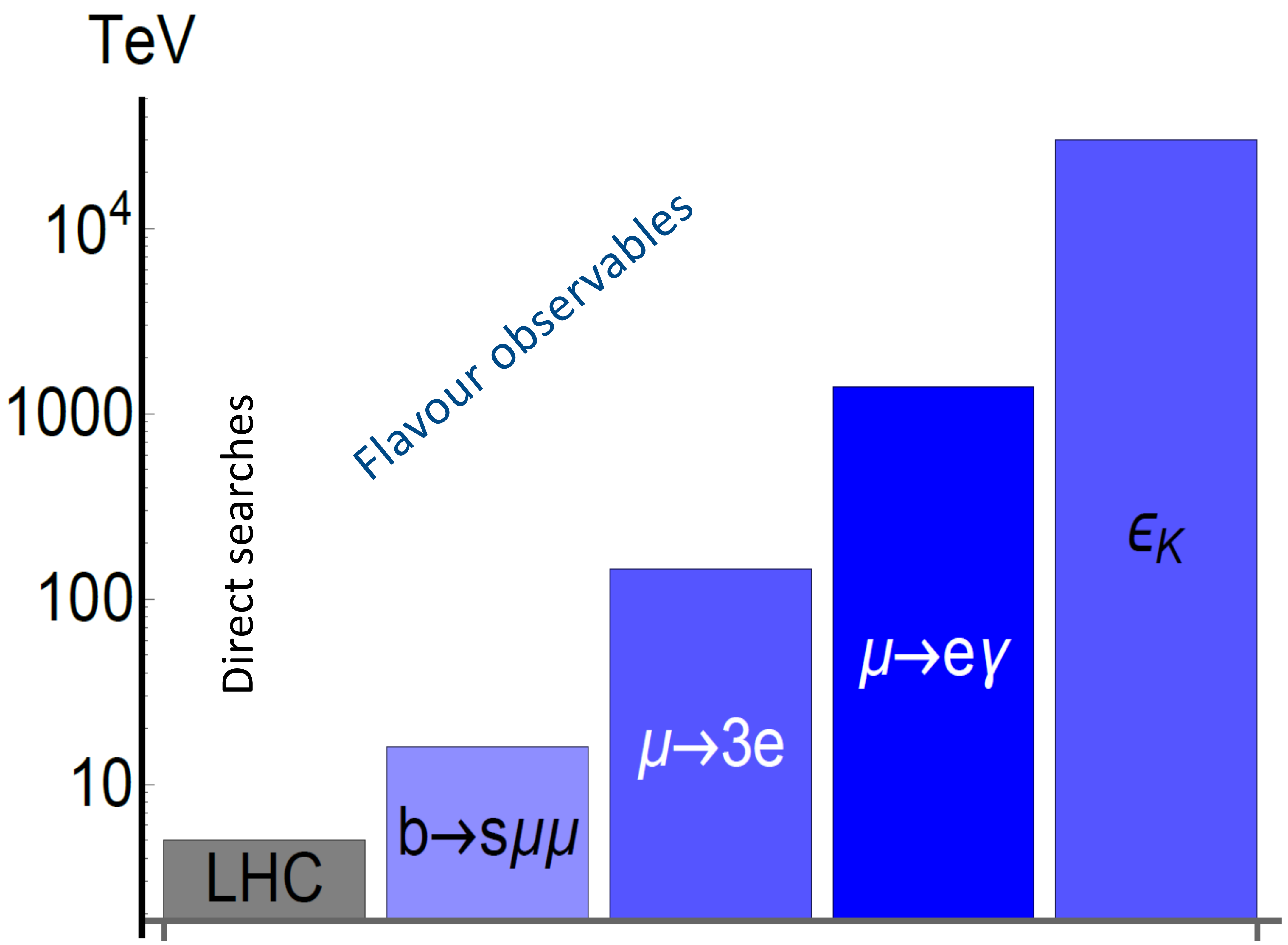
➡ The Standard Model must be extended!
What is the underlying fundamental theory?

The search for BSM physics

- Cosmic Frontier
  - Cosmic rays and neutrinos
  - Dark Matter
  - Dark Energy
- Energy Frontier
  - LHC
  - Future colliders
- Intensity Frontier
  - Flavour
  - Neutrino-less double-β decay
  - Test of fundamental symmetries
  - Proton decay

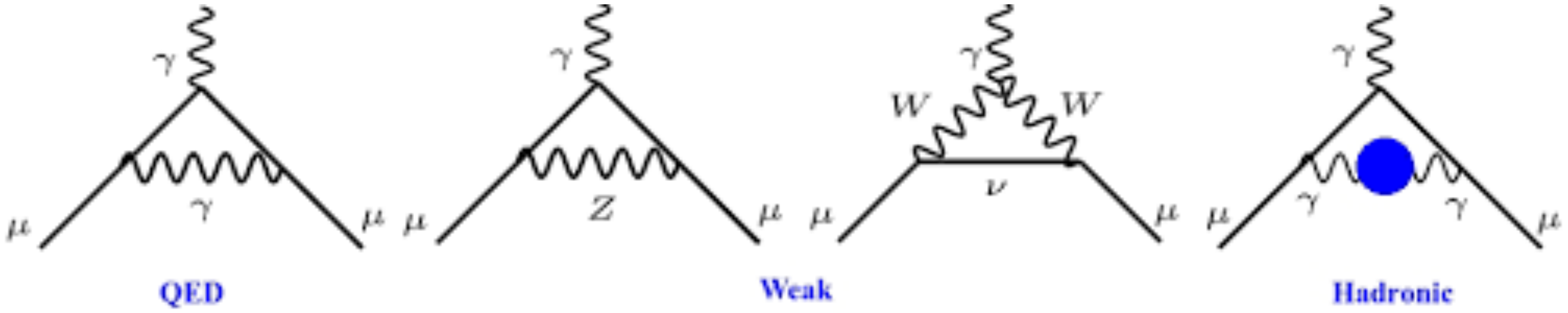


Perfrom high-statistics measurements to search for the quantum effects of new particles



Anomalies

Anomalous magnetic moment of the muon



5.0σ deviation from the SM prediction

- Theory prediction challenging (hadronic effects)
- $\Delta a_\mu = (251 \pm 49) \times 10^{-11}$
- Need NP of the order of the SM EW contribution
- Chiral enhancement necessary for heavy NP
- New results from Fermilab [2308.06230] : 116 592 057(25) × 10^-11 (0.21 ppm)
- New world average : 116592059(22)×10^-11 (0.19 ppm)

Cabibbo Angle Anomaly (CAA)

- Deficit in first row and first column CKM unitarity.
  [PDG]
  $$|V_{ud}^2| + |V_{us}^2| + |V_{ub}^2| = 0.9985 \pm 0.0005$$
  $$|V_{ud}^2| + |V_{cd}^2| + |V_{td}^2| = 0.9970 \pm 0.0018$$
- NP in the determination of V_{ud} from beta decays needed
- Can be interpreted as
  - NP in beta decays
  - NP in the Fermi constant
  - LFUV (modified W$\mu\nu$ coupling)

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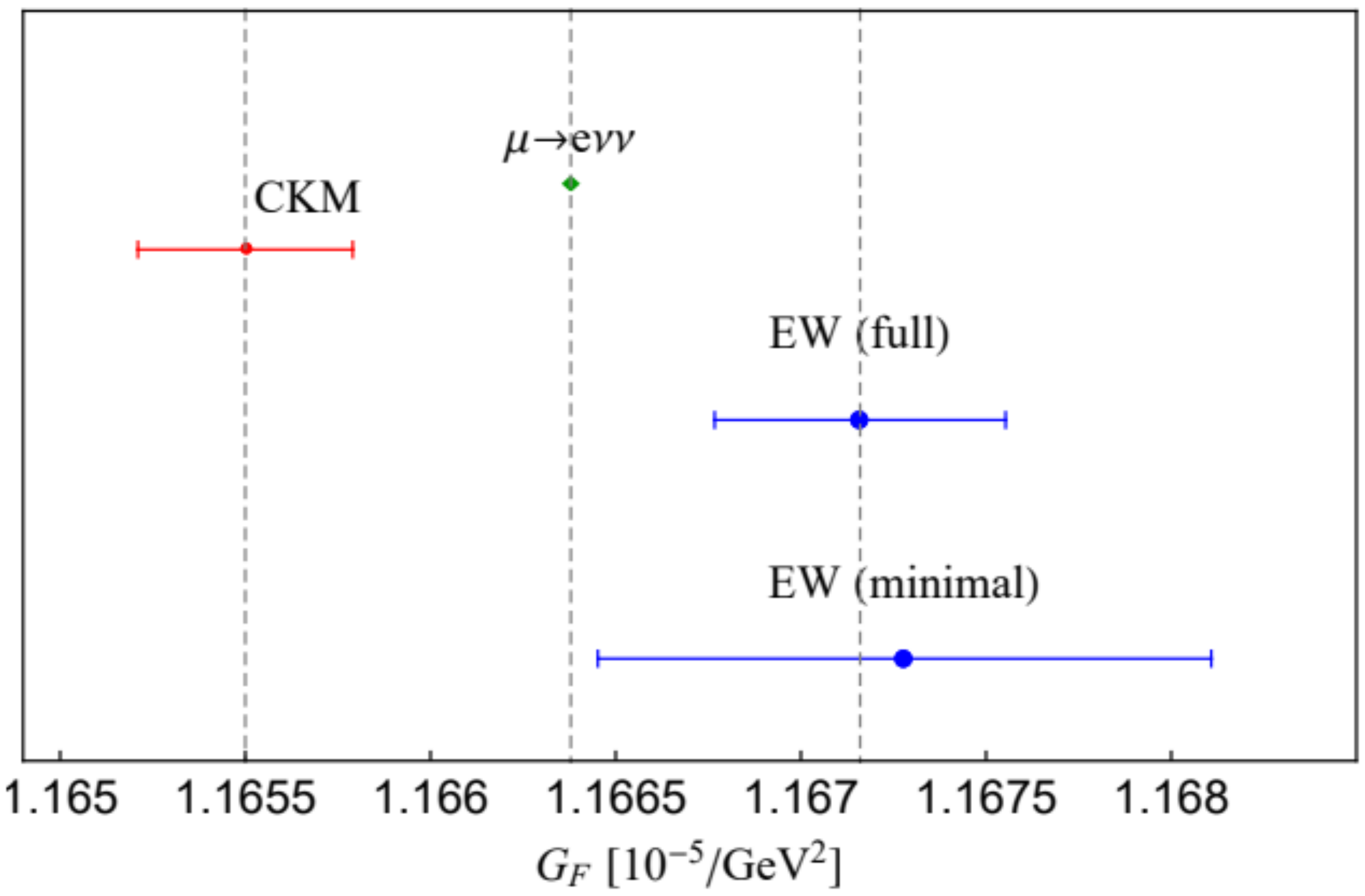
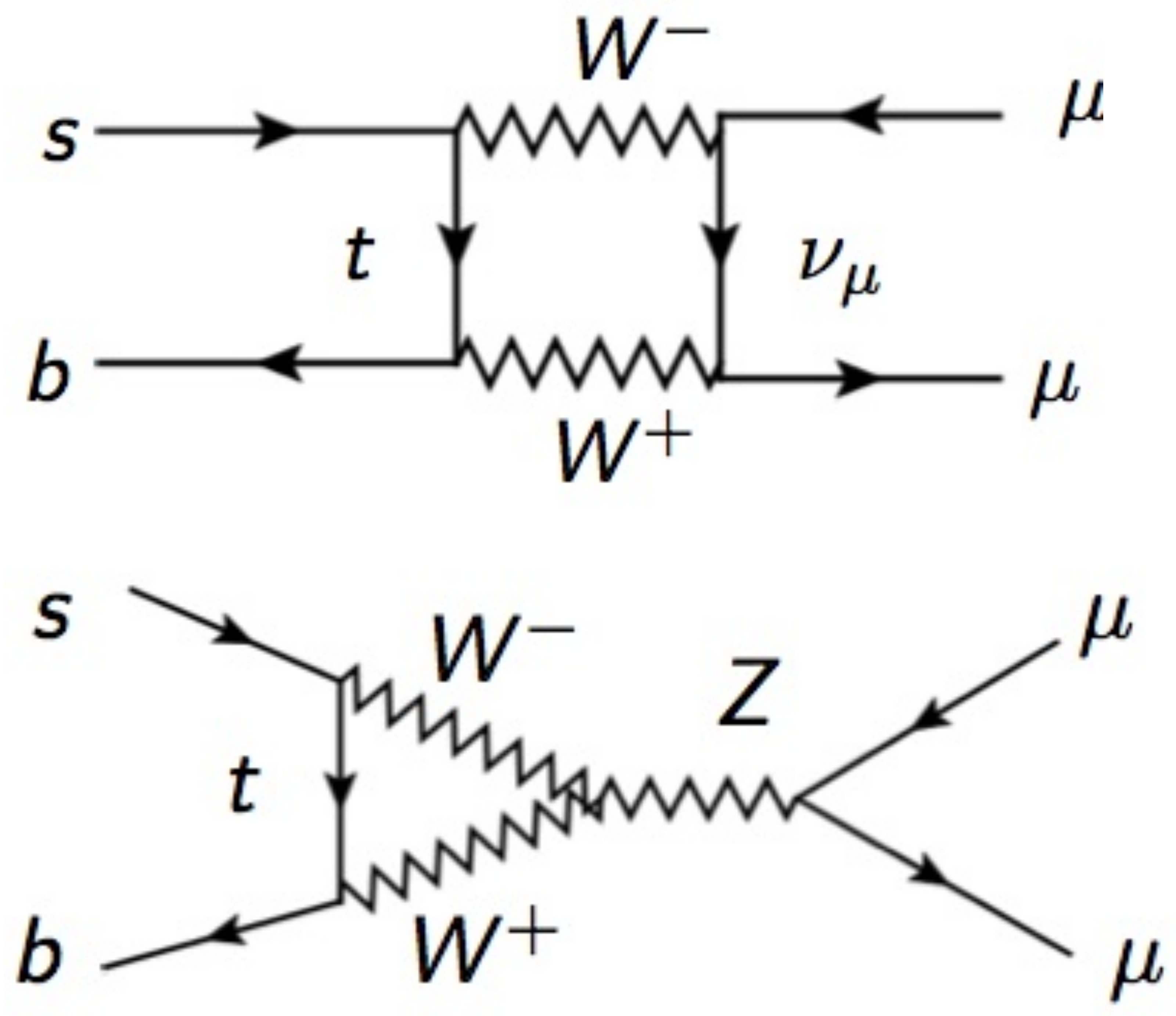


3σ tension, can be interpreted as LFUV

Flavour changing neutral current semi-leptonic B decays

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

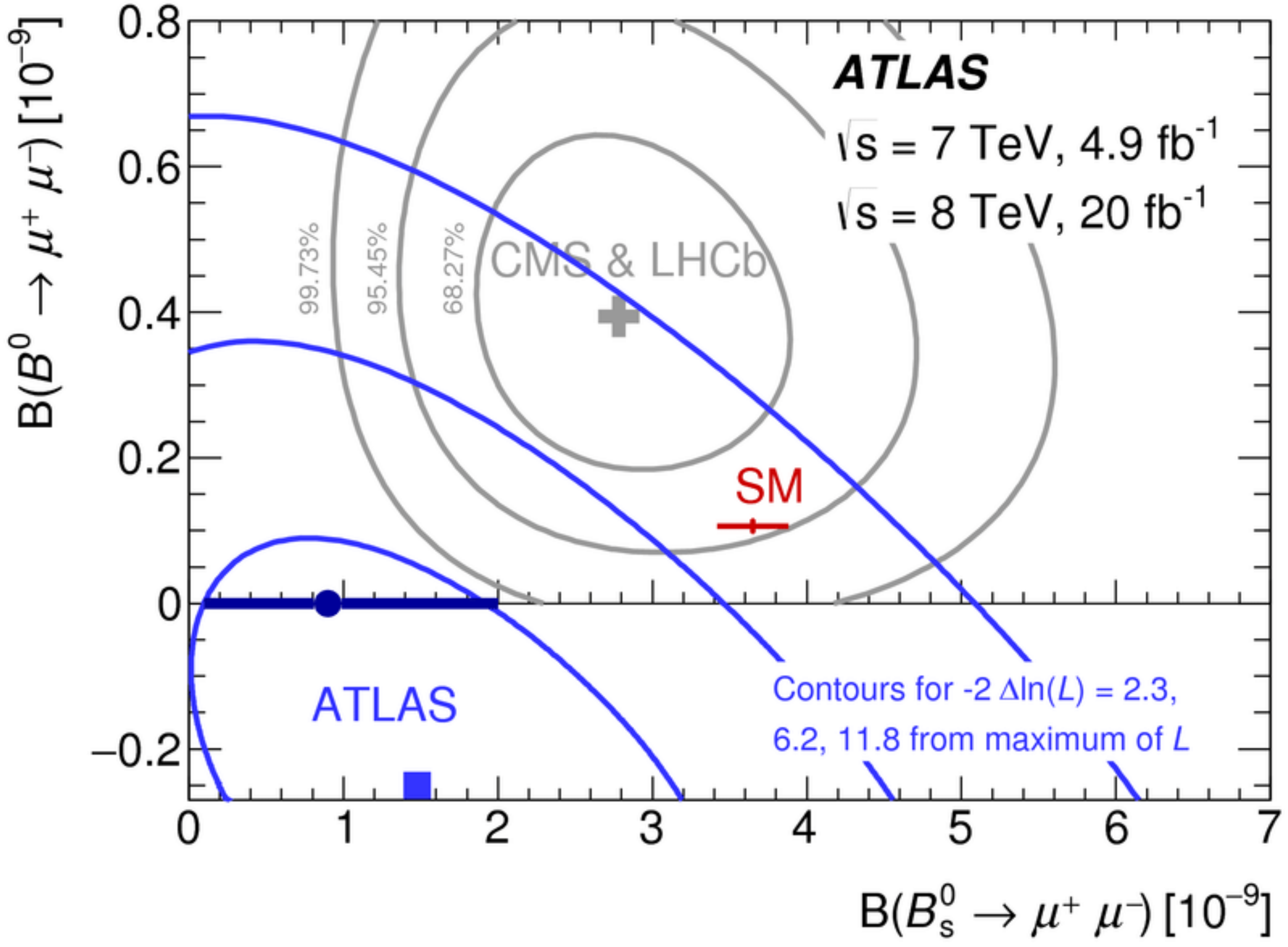
- Flavour Changing Neutral Current (FCNC)
- In the SM suppressed by
  - ➢ The CKM elements $V_{cb} \approx 0.04$
  - ➢ Electroweak scale
  - ➢ Loop-factor
- Wilson coefficients precisely known [Bobeth et al. PRD, 2013]



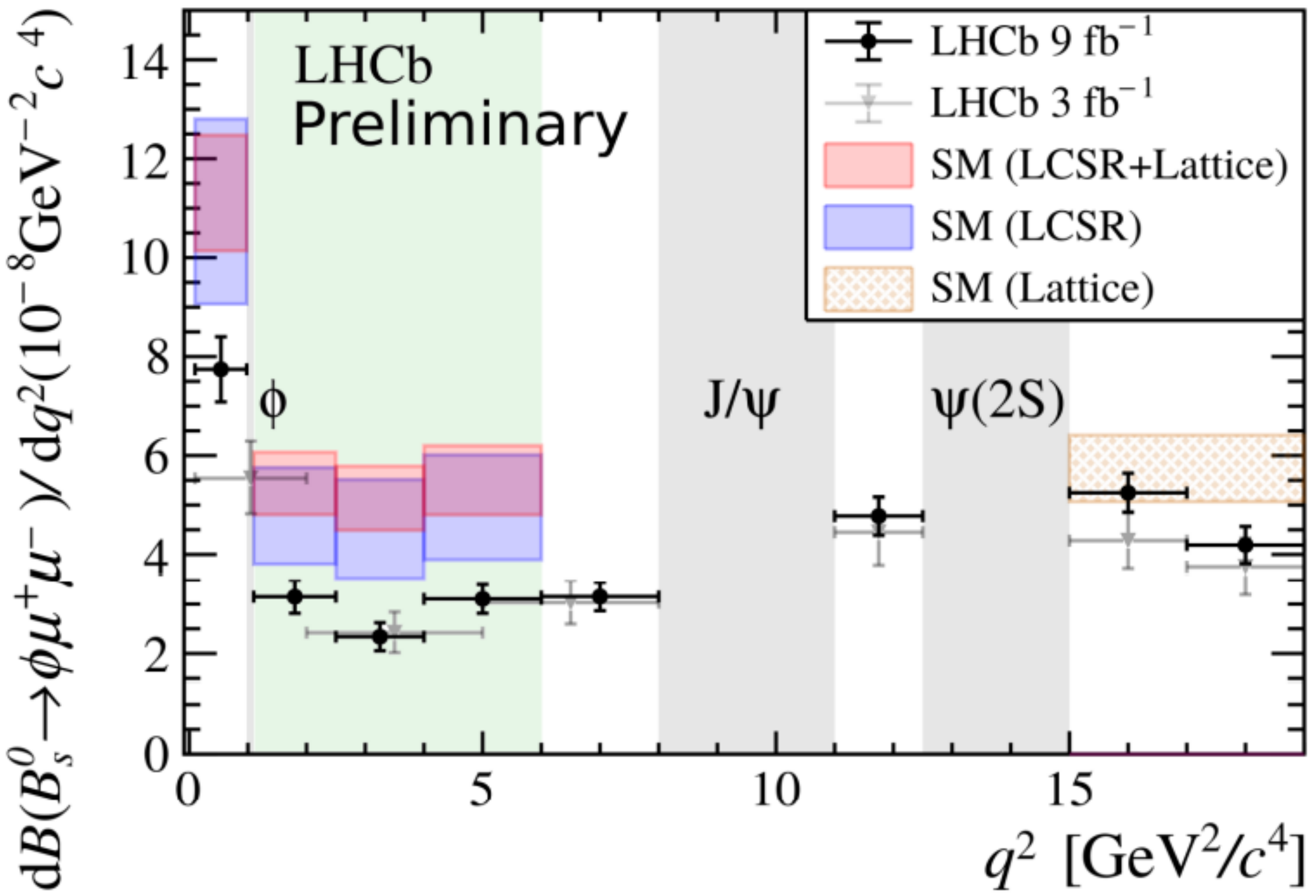
Rare processes; very sensitive to NP

$B_s \to \mu\mu$ and $B_s \to \varphi\mu\mu$

- $B_s \to \mu\mu$ theoretically clean but chirality suppressed and therefore statistically limited



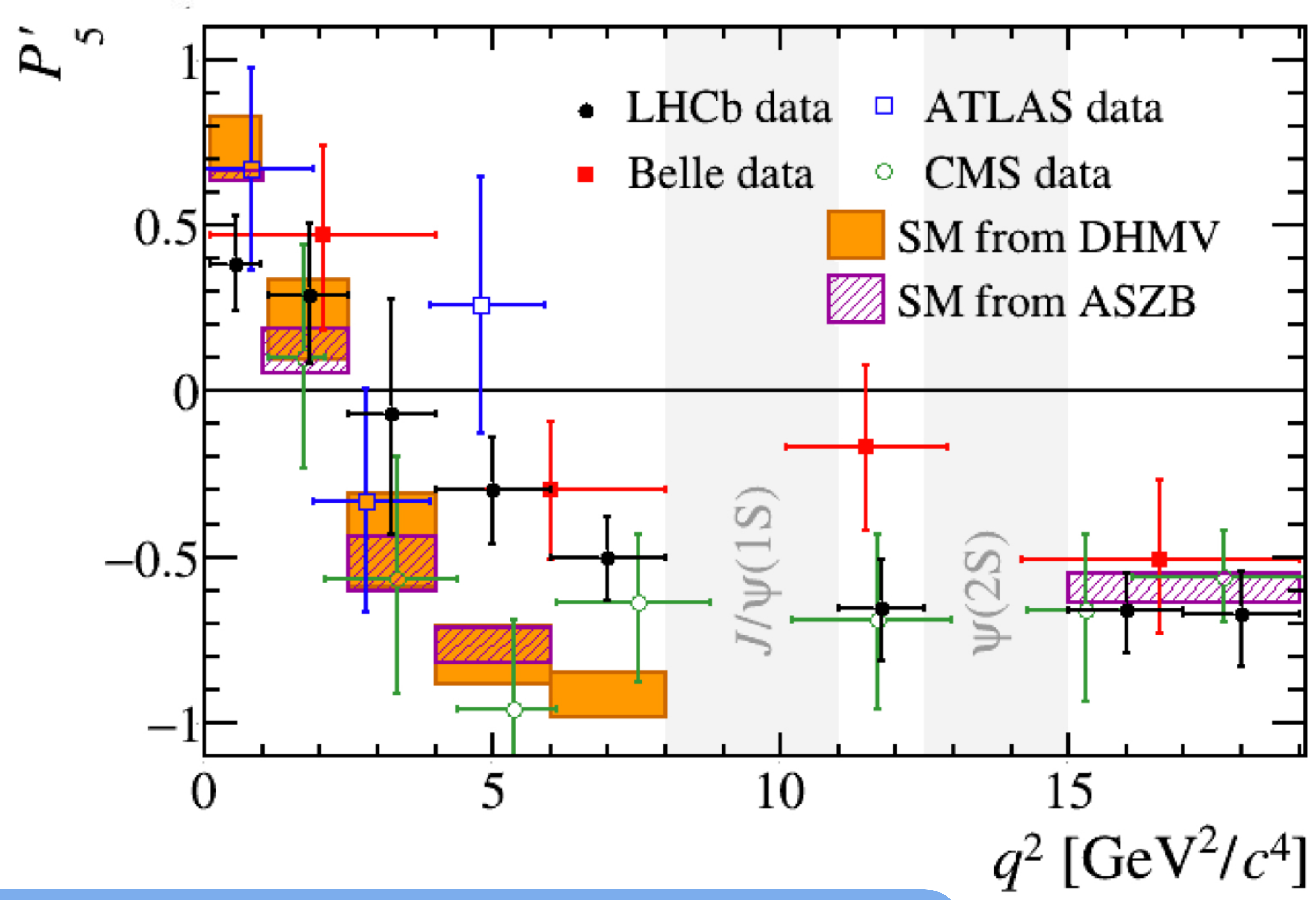
- $B_s \to \phi\mu\mu$ has a higher Br, but knowledge of the form-factor needed



Br's ≈ 20% below SM expectations

The P_5' Anomaly

- P_5´ angular observables in $B \to K^* \mu\mu$
- Constructed in such a way that the form factor dependence is minimized
- Confirmed by latest LHCb analysis for the charged mode



>3σ deviation from the SM prediction

$$R(K^*) = B \to K^*\mu^+\mu^- / B \to K^* e^+ e^-$$

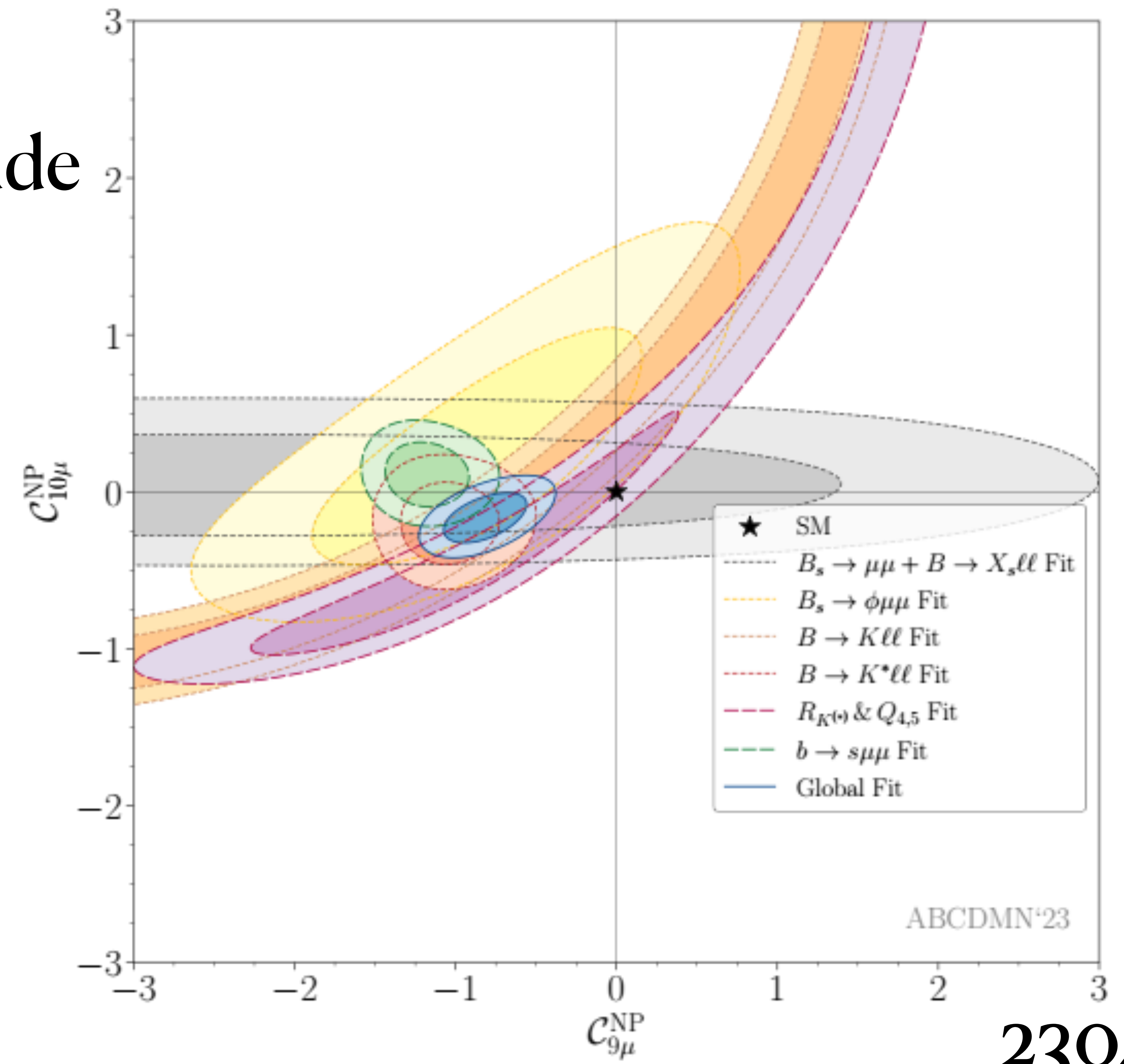
$$R(K) = B \to K\mu^+\mu^- / B \to K e^+ e^-$$

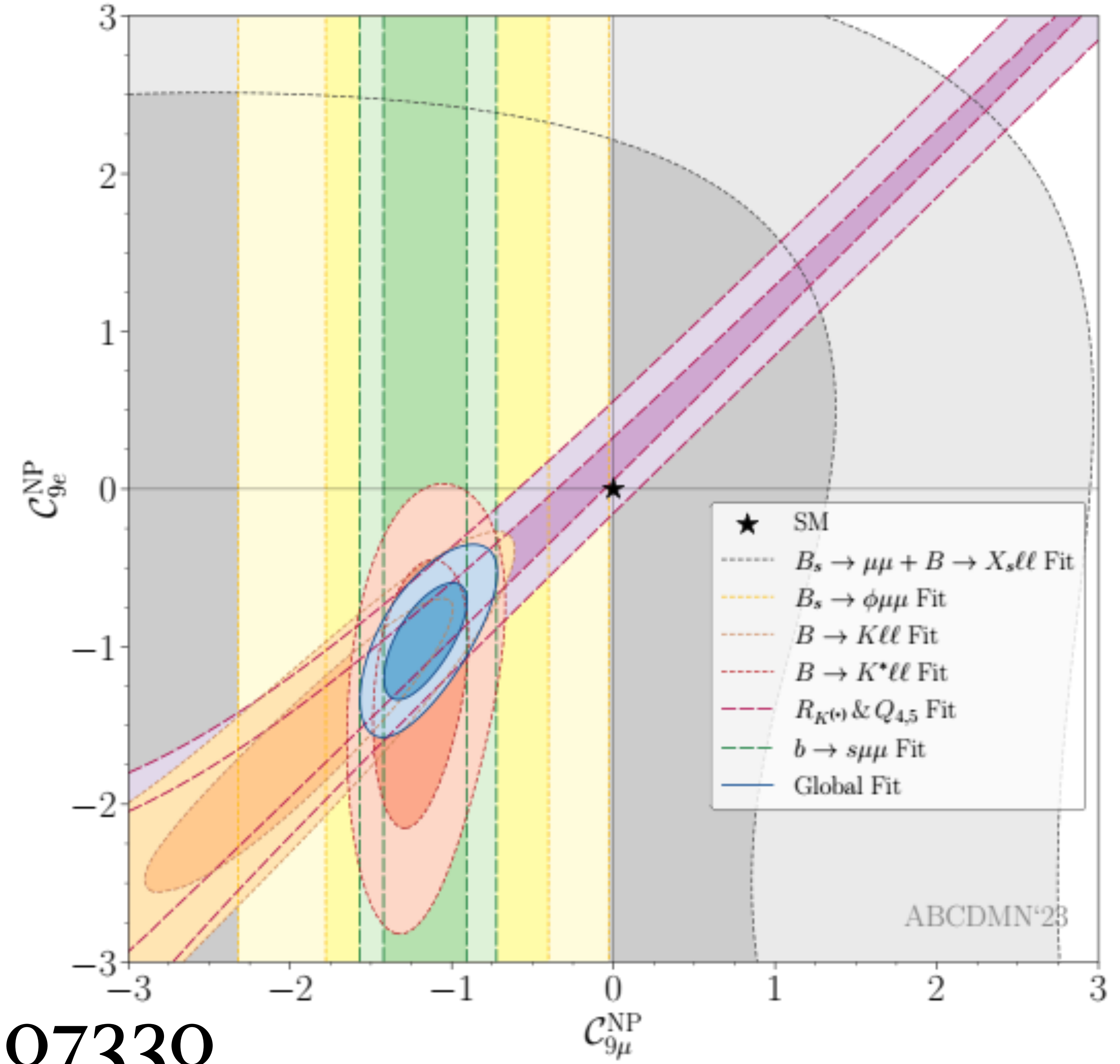
Theoretically absolutely clean observable (in the SM)

Lepton Flavour Violation were not confirmed
[2212.09152]

Global Fit to $b \to s\mu^+\mu^-$ Data

- Perform global model independent fit to include all observables (≈150)
- Several NP hypothesis are significantly preferred over the SM hypothesis
- Study via effective interactions





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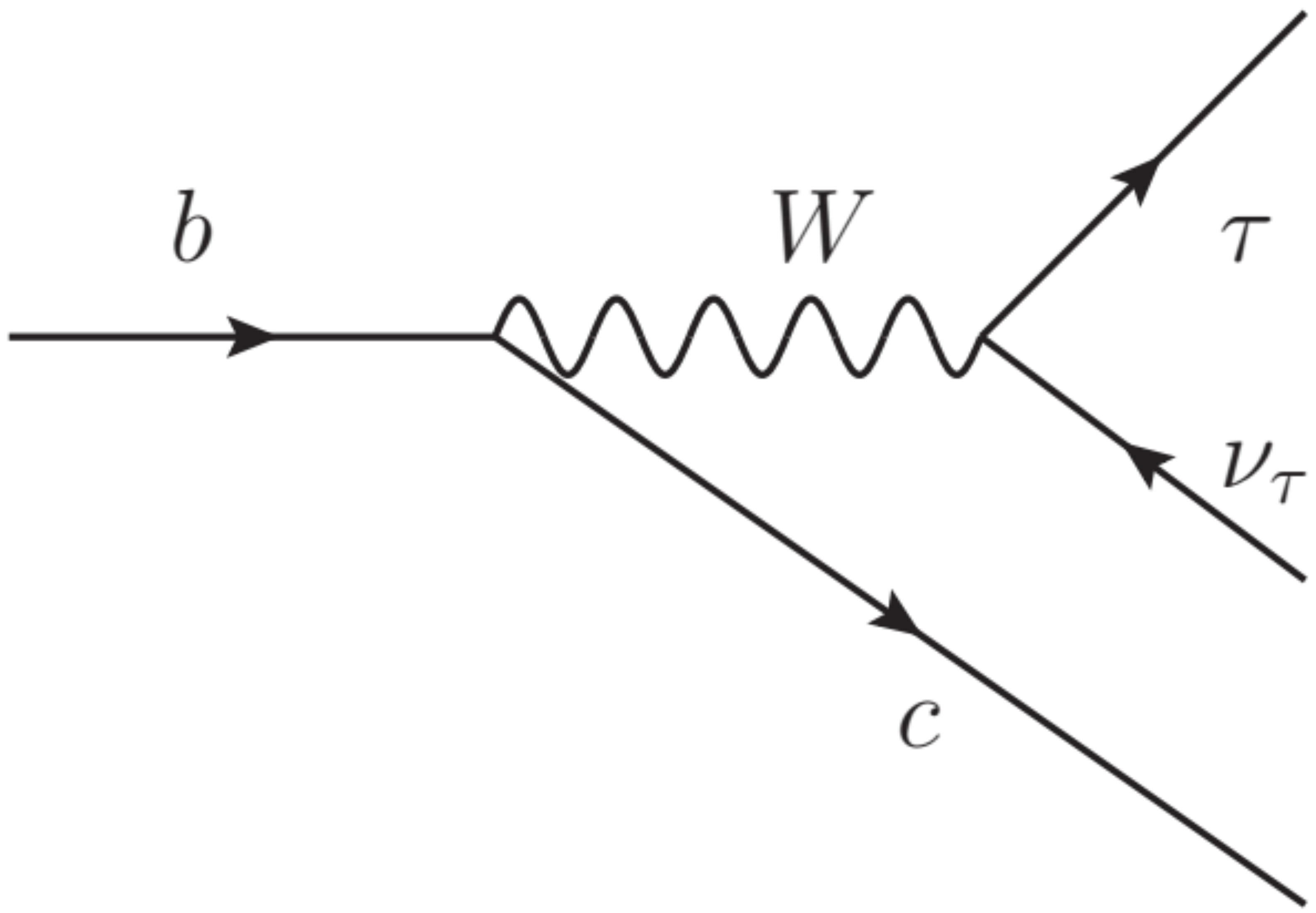
Fit is >5 σ better than the SM

Charged current tauonic B decays

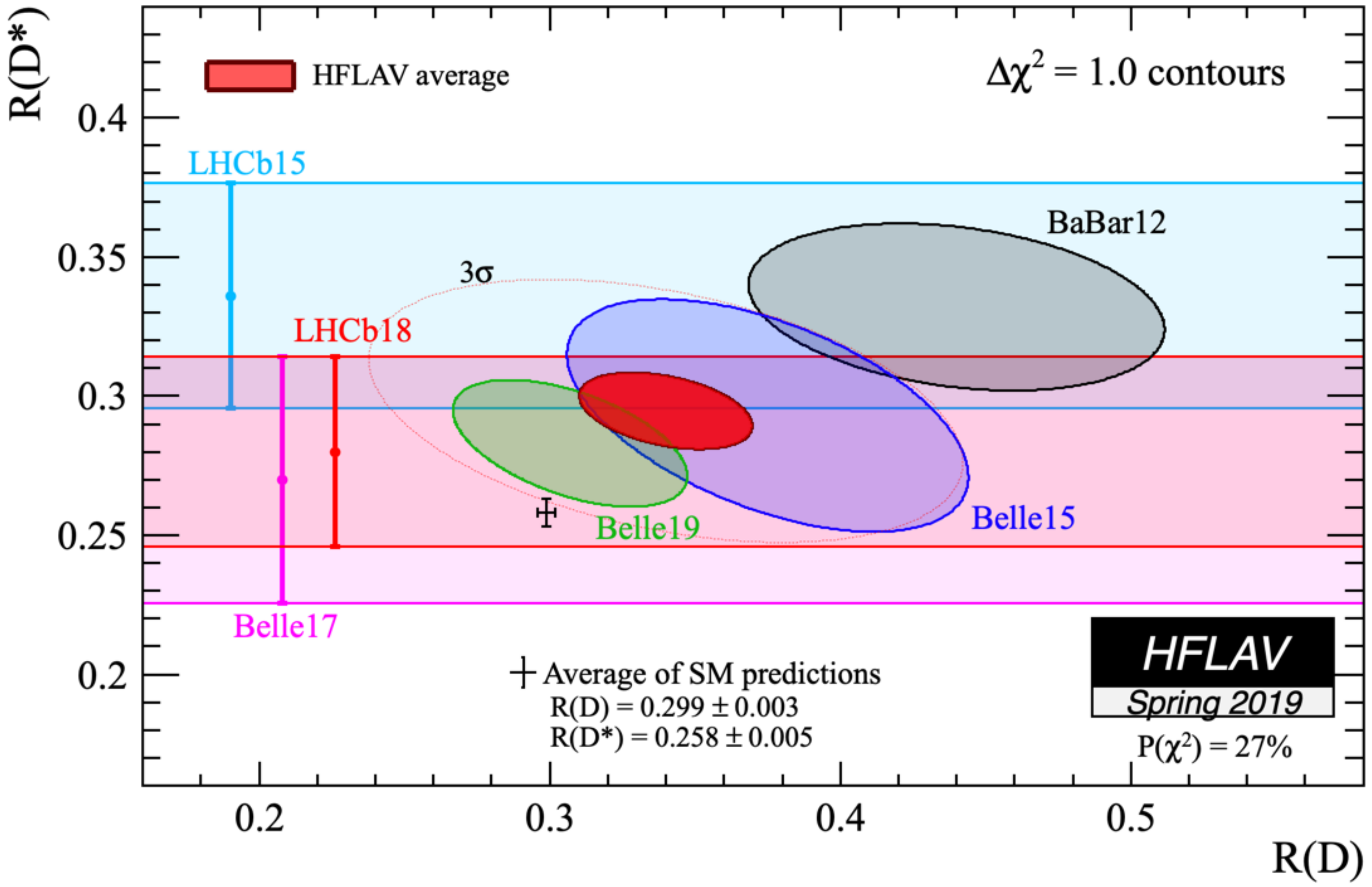
- $B \to D\tau\nu$, $B \to D^*\tau\nu$
- Tree-level decays in the SM
- Form factors needed
- With light leptons (μ, e) used to determine the CKM elements
- CKM fit works very well, i.e. tree-level in agreement with $\Delta F=2$ processes



Largest B branching ratios, used to determine the CKM elements, usually assumed to be free of NP

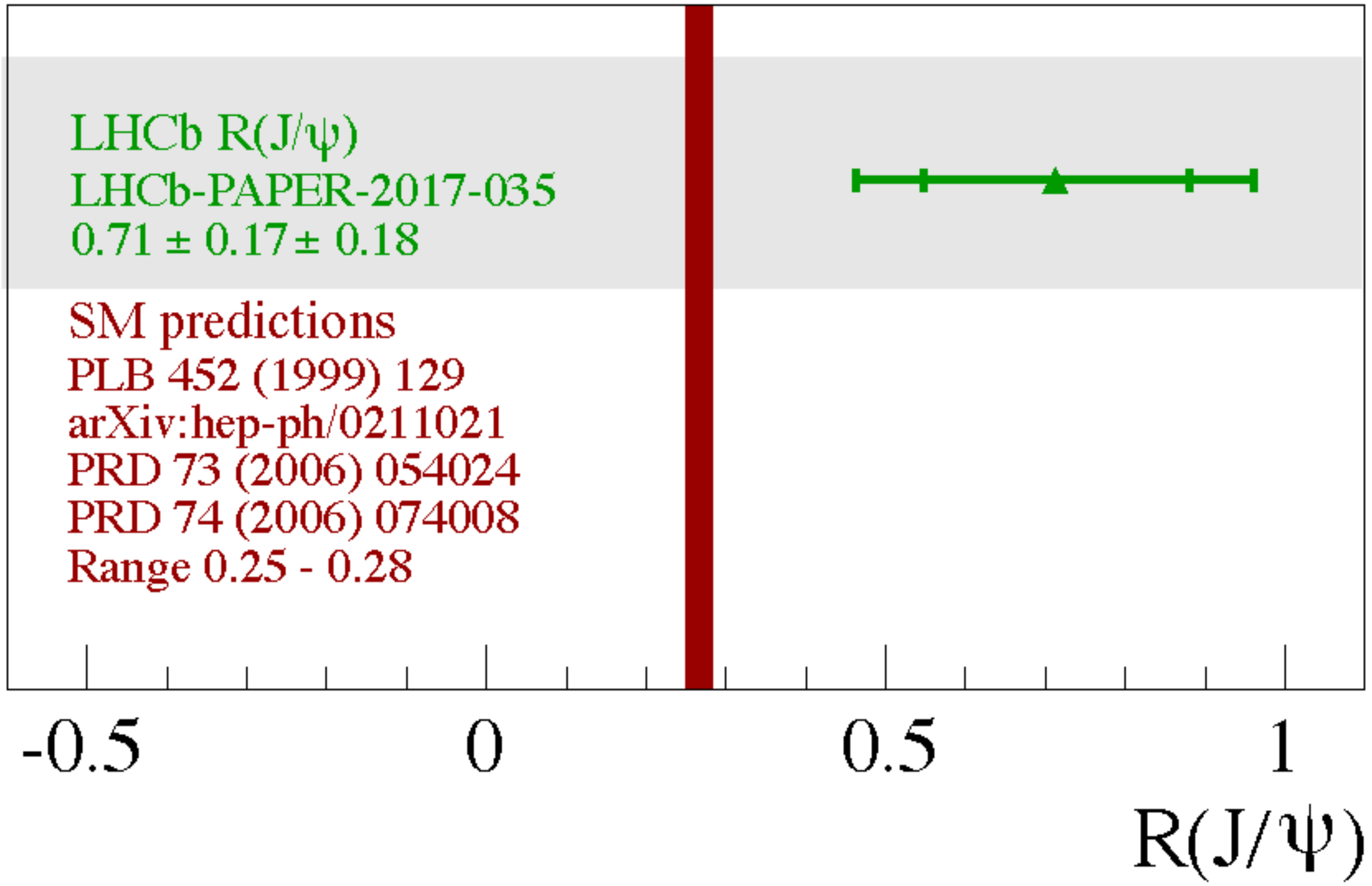
$b \to c\tau\nu$ Measurements

- $R\left(D^{(*)}\right) = B \to D^{(*)}\tau\nu / B \to D^{(*)}l\nu$



All measurements above the SM prediction
O(20%) constructive effect at >3σ

- $R(J/\Psi) = B_c \to J/\Psi\tau\nu / B_c \to J/\Psi l\nu$

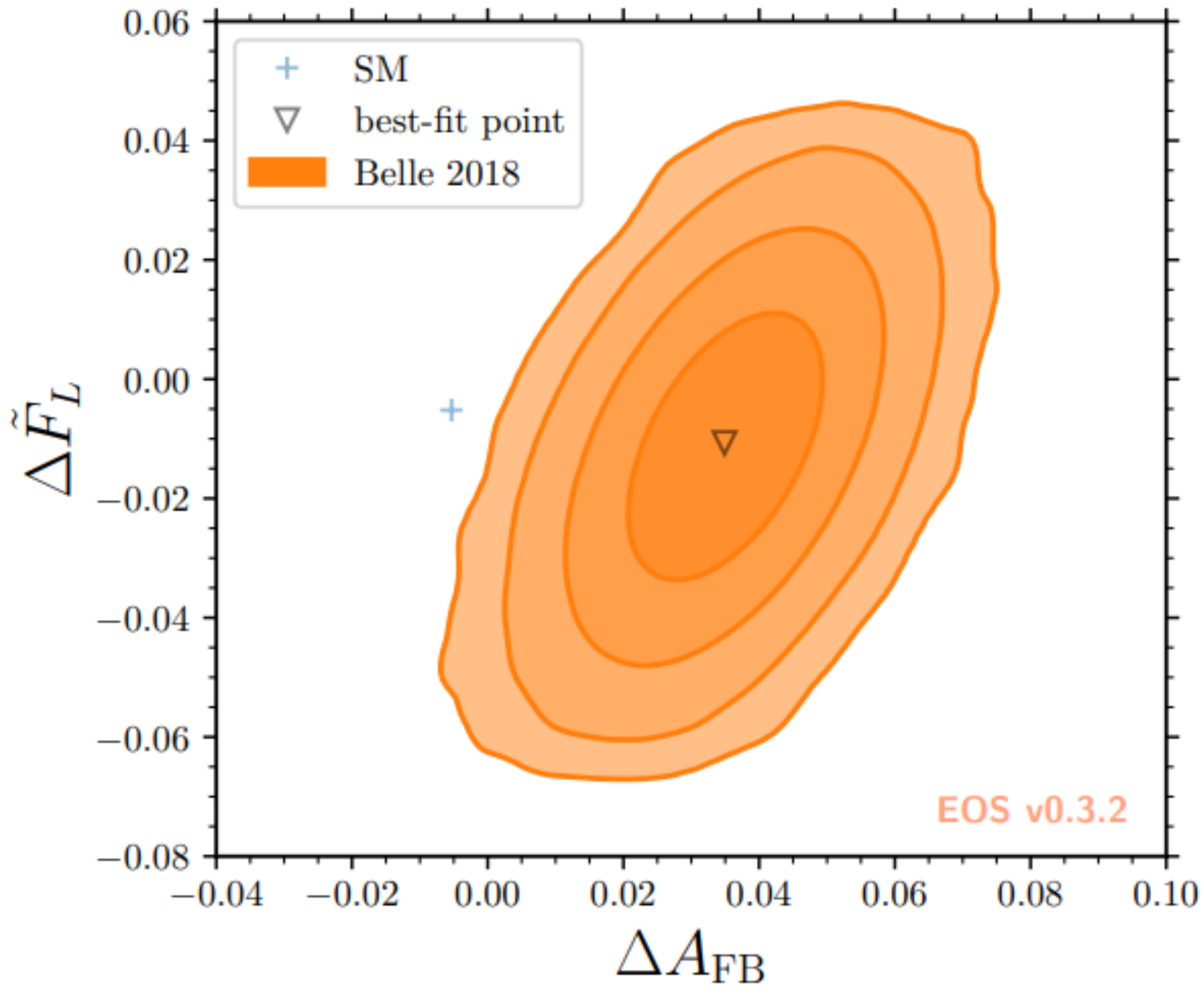


Supports R(D) & R(D*) preferred

ΔA_{FB} in $B \to D^* l\nu$

$$\Delta A_{FB} = A_{FB}(b \to c\mu\nu) - A_{FB}(b \to ce\nu)$$

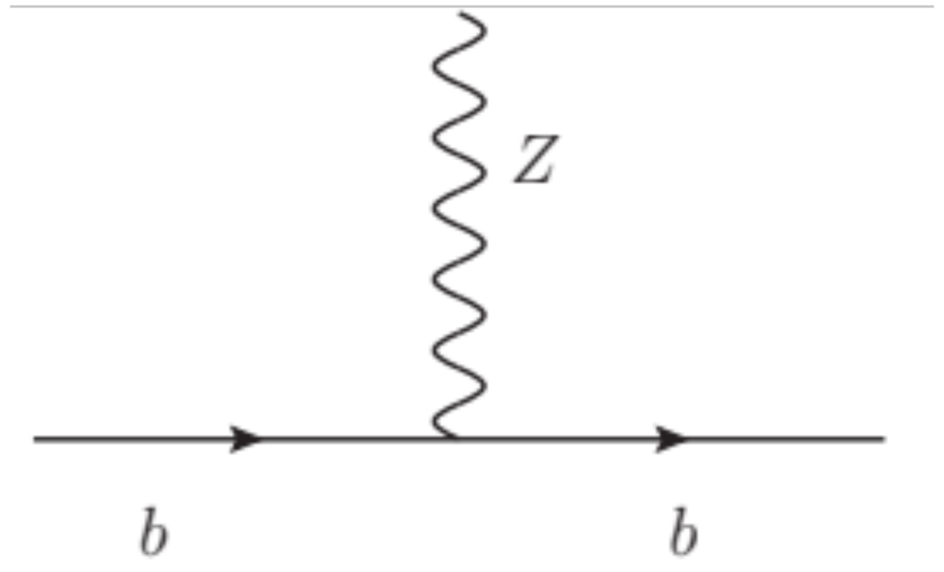
- 4σ deviation found by 2104.02094 based on BELLE data 1809.03290
- Scalar and/or tensor operators required for an angular asymmetry
- g-2 and $b \to s\mu\mu$ motivate new physics related to muons

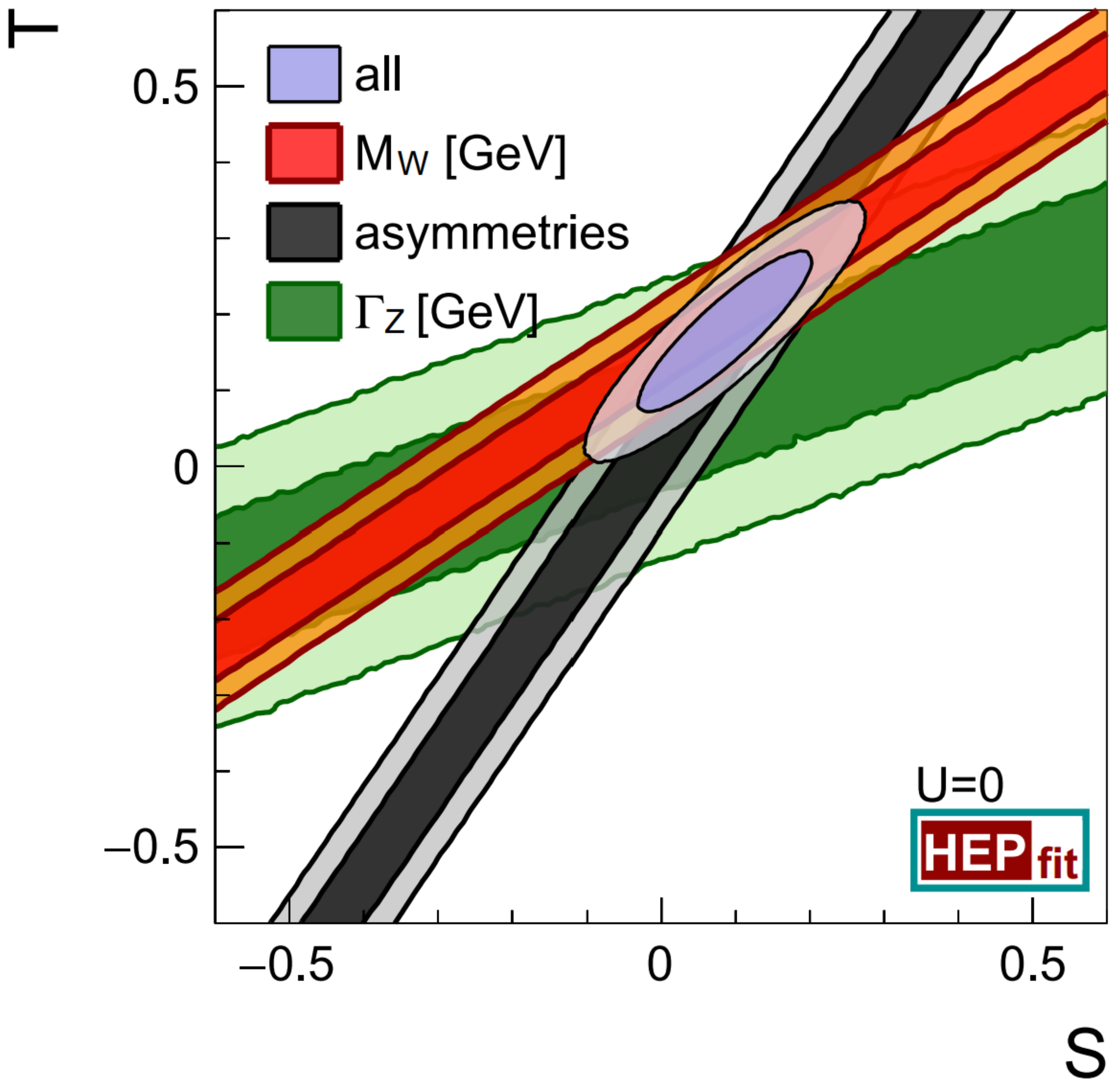


Hint for scalar/tensor NP

W mass and Z→bb

- 3.7 σ tension in the W mass using a conservative error combination
- 2 σ tension in Z→bb from LEP





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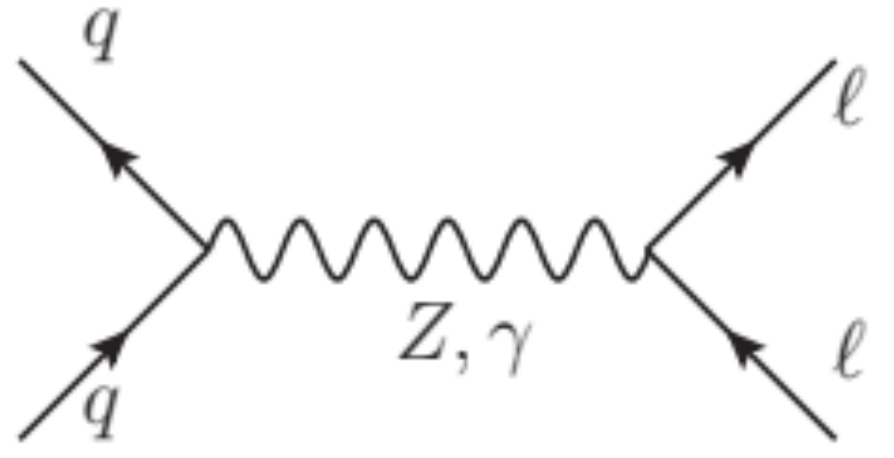
Related to LFUV?

Non-resonant di-electrons ($q\bar{q} \to e^+e^-$)

- CMS and ATLAS observe more electrons than expected in the SM [2103.02708]
- model-independent fit: NP scale of 10 TeV with order one couplings can improve over the SM hypothesis by $\approx 3\sigma$ [2103.12003]



Lepton flavour universality violation in tau decays $\tau \to \mu\nu\bar{\nu}$

- Combining the ratios of branching ratios $\mathrm{Br}(\tau \to \mu(e)\nu\bar{\nu})/\mathrm{Br}(\mu \to e\nu\bar{\nu})$ and $\mathrm{Br}(\tau \to \mu\nu\bar{\nu})/\mathrm{Br}(\tau \to e\nu\bar{\nu})$ [2206.07501], leads to an $\approx 2\sigma$ preference for constructive new physics (NP) at the per-mille level in $\tau \to \mu\nu\bar{\nu}$ [2111.05338]

LHC Multi-Lepton Anomalies (eμ(+b))

Final state	Characteristics	SM backgrounds	Significance
$\ell^+\ell^-$+(b-jets)[62,65,66]	$m_{\ell\ell} < 100$ GeV, $(1b, 2b)$	$t\bar{t}, Wt$	$> 5\sigma$
$\ell^+\ell^-$+(no jet)[61,67]	$m_{\ell\ell} < 100$ GeV	W^+W^-	$\approx 3\sigma$
$\ell^\pm\ell^\pm, 3\ell$ + (b-jets)[64,68,69]	Moderate H_T	$t\bar{t}W^\pm, t\bar{t}t\bar{t}$	$> 3\sigma$
$\ell^\pm\ell^\pm, 3\ell$, (no b-jet)[63,70,71]	In association with h	$W^\pm h(125), WWW$	$\gtrapprox 4\sigma$
$Z(\to \ell\ell)\ell$, (no b-jet)[62,72]	$p_T^Z < 100$ GeV	$ZW^\pm$	$> 3\sigma$

Higgs-like signals

- 95 GeV: di-taus, ZH($H \to b\bar{b}$), WW: 3.8σ
- 152 GeV [2104.13240]: γγ + missing energy, WW+missing energy: 4.9σ
- 680 GeV [2102.13405]

(di-)di-jet resonances (j j(−j j))

- CMS [2206.09997] finds hints for the (non-resonant) pair production of di-jet resonances with a mass of ≈ 950 GeV with a local (global) significance of 3.6σ (2.5σ) ($pp \to Y(*) \to XX \to (jj)(jj)$)
- [2208.12254] global 3.2σ significance at mY ≈ 3.6TeV
- ATLAS [2307.14944] finds a di-di-jet excesses at ≈ 3.3TeV with a di-jet mass of 850GeV

Hints for NP

- LFV:
  - CAA
  - (g-2)
  - $b \to s\mu^+\mu^-$
  - $b \to c\tau\nu$
  - $qq \to ee$
- EW observables:
  - W mass
  - $Z \to bb$
- Direct searches:
  - $\gamma\gamma$
  - $\tau\tau$
  - 4b
  - $bb\tau\tau$

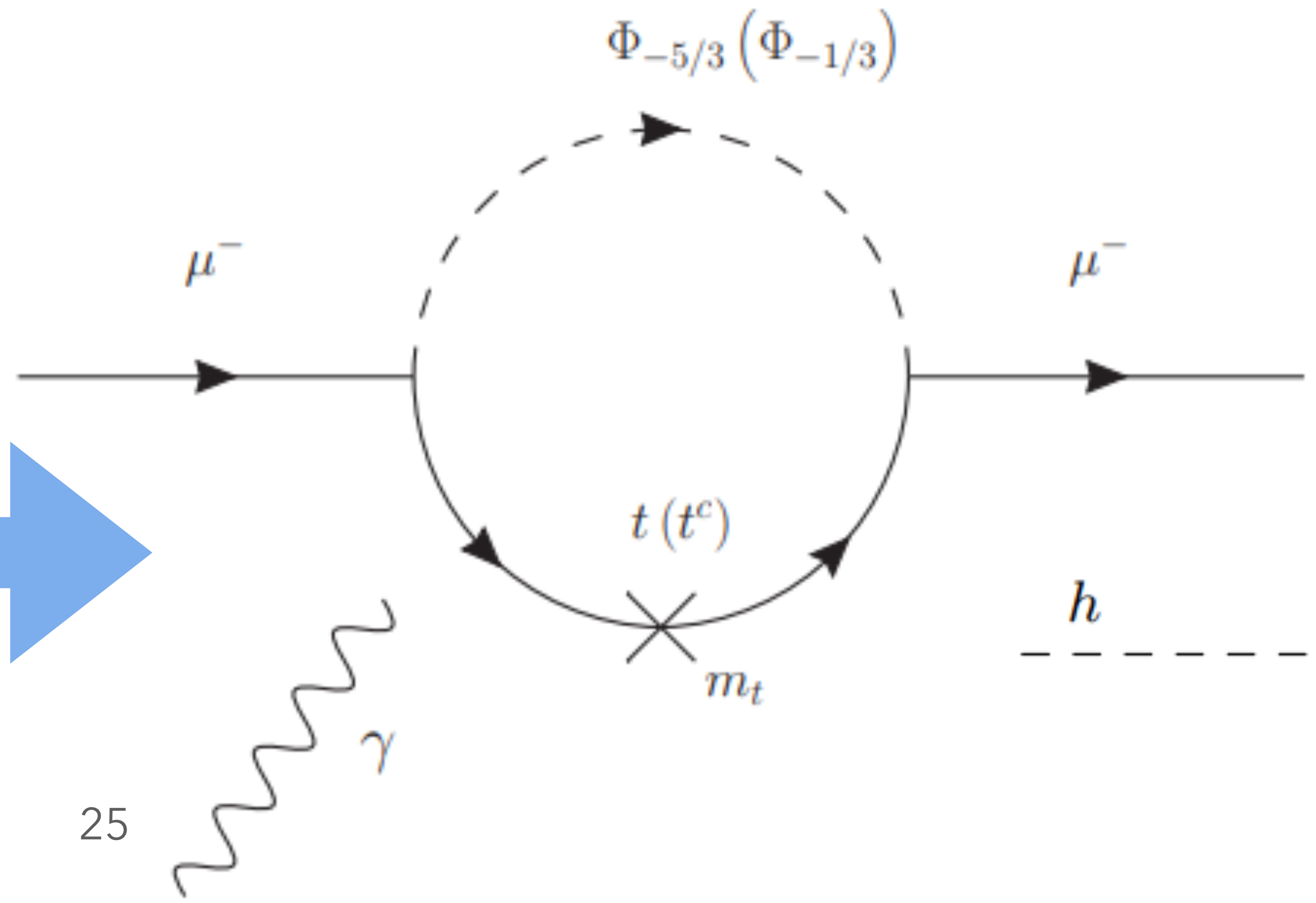
New Physics
Explanations of the Anomalies

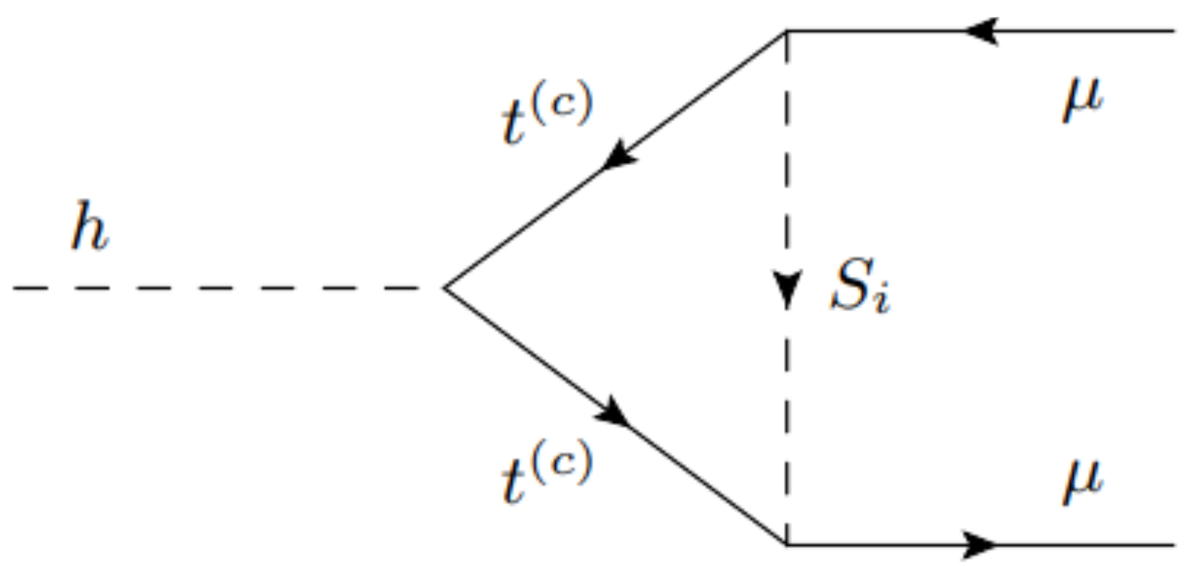
The SM extensions

- Leptoquarks (LQs)
- Diquarks (DQs)
- Z' bosons
- W' bosons
- Vector-like Quarks (VLQs)
- Vector-like Leptons (VLLs)
- New scalars (S)

a_μ explanations

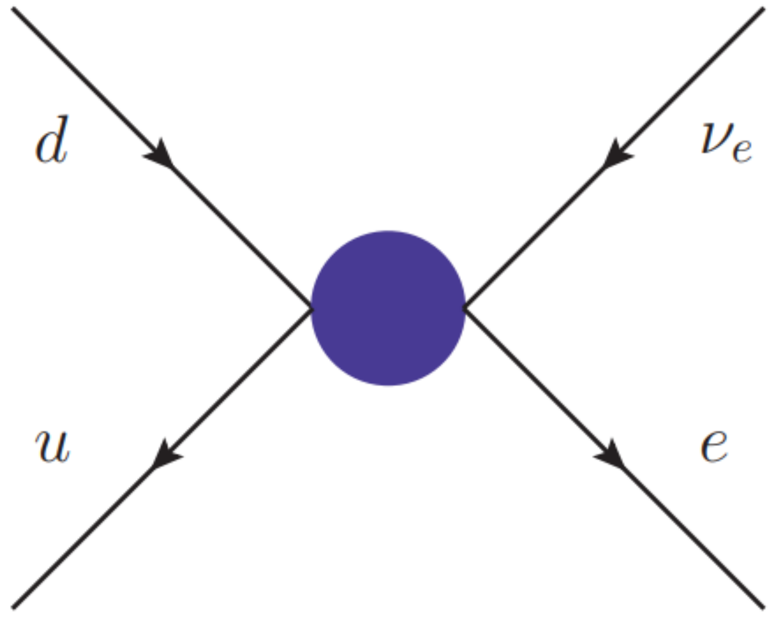
- MSSM [0102145], [0102146]
  - tan(ß) enhanced slepton loops
- Scalars
  - Light scalar with enhanced muon couplings
- Z'
  - Very light with τμ couplings (m_τ enhancement) [0104141]
  - Heavy (TeV scale): chiral enhancement factor [2104.03691]
- New scalars and fermions [1807.11484]
  - $\varkappa/Y_\mu$
- Leptoquarks [1511.01900]
  - m_t/m_μ enhanced effects in $h \to \mu\mu$
  - m_t^2/m_Z^2 enhanced effects in $Z \to \mu\mu$





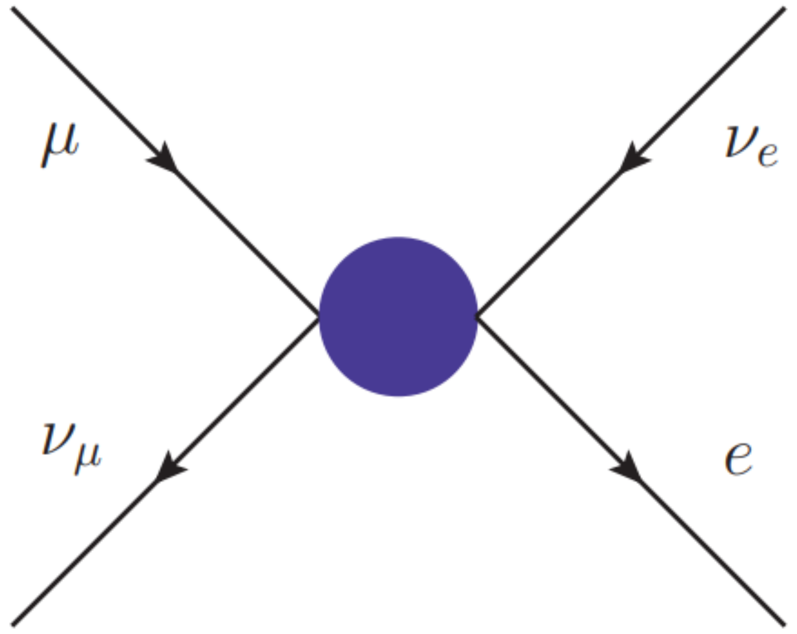
Cabibbo Angle Anomaly [2102.02825]

- LQs [2104.06417]
- W' [2005.13542]



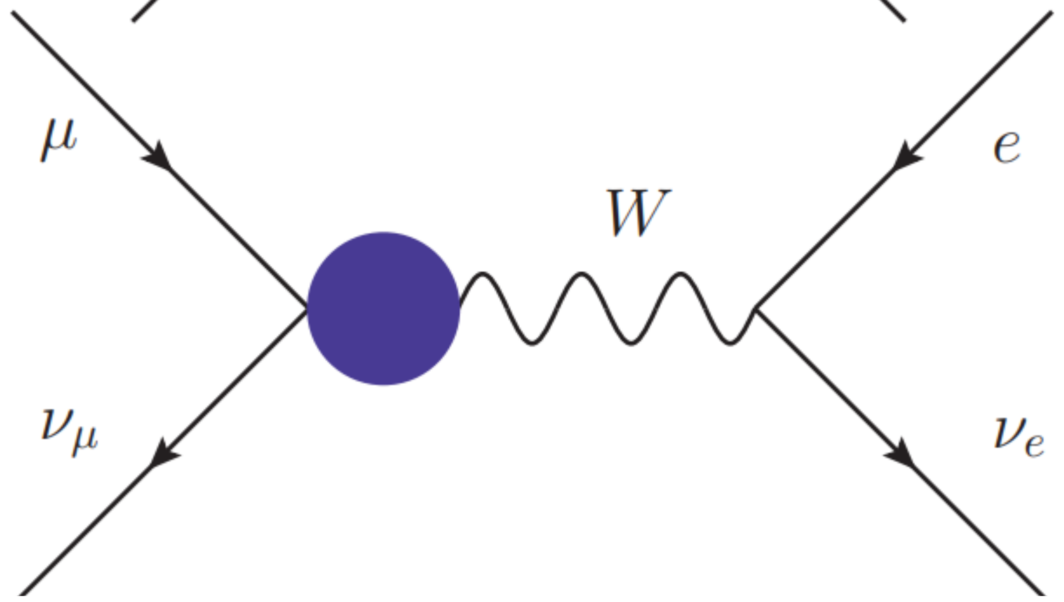
- a direct (tree-level) modification of beta decays

- W' [2005.13542]
- Z' [2104.07680]
- Singly charged scalar [2012.09845]



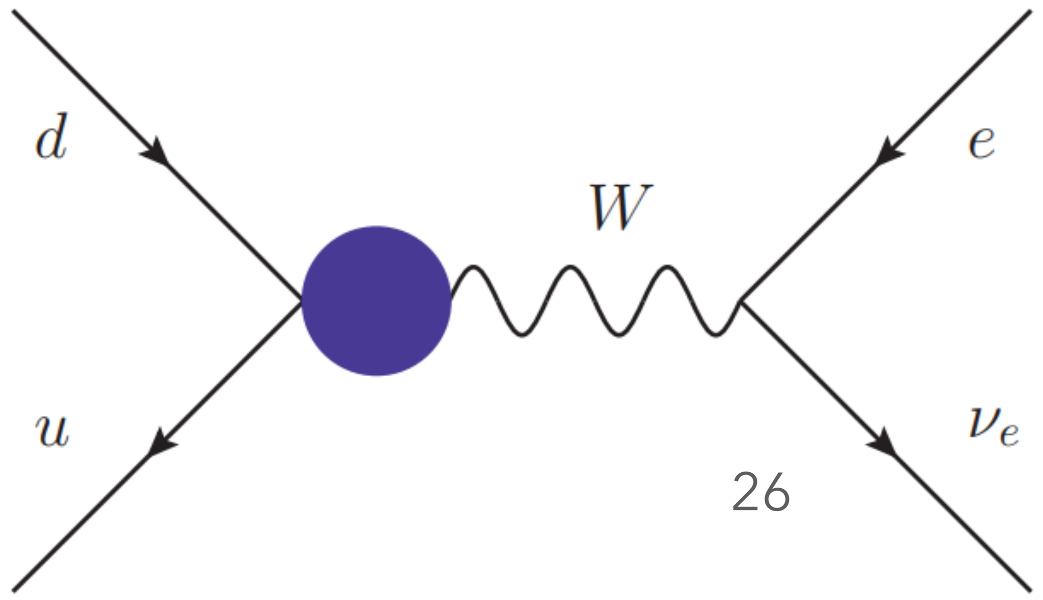
- a direct (tree-level) modification of muon decay

- Vector-like leptons [1912.08823]



- a modified W-μ-ν coupling entering muon decay

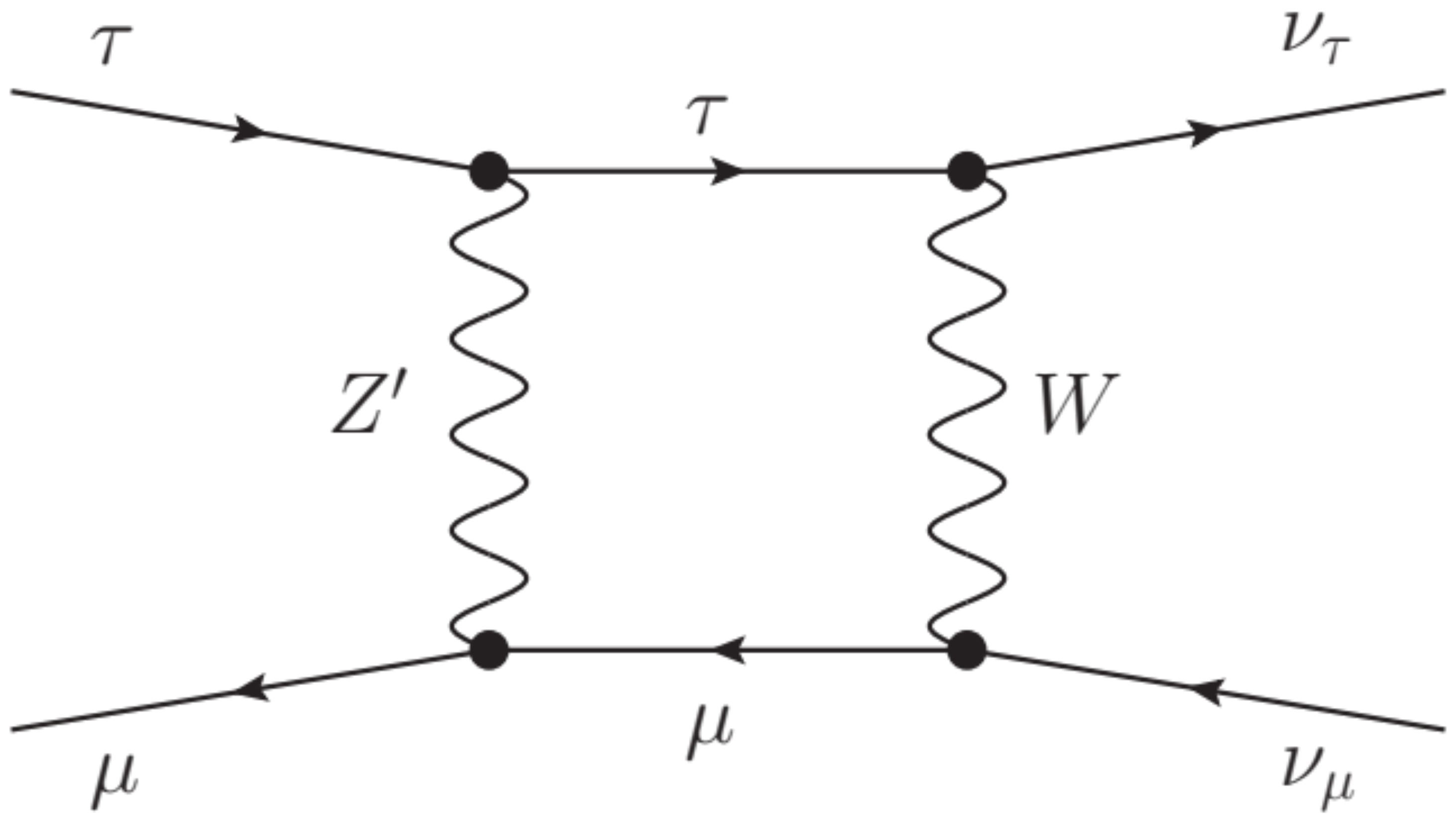
- Vector-like quarks [1906.02714]



- a modified W-u-d coupling entering beta decays

Lepton flavour universality violation in tau decays ($\tau \to \mu \nu \nu$) [1403.1269]

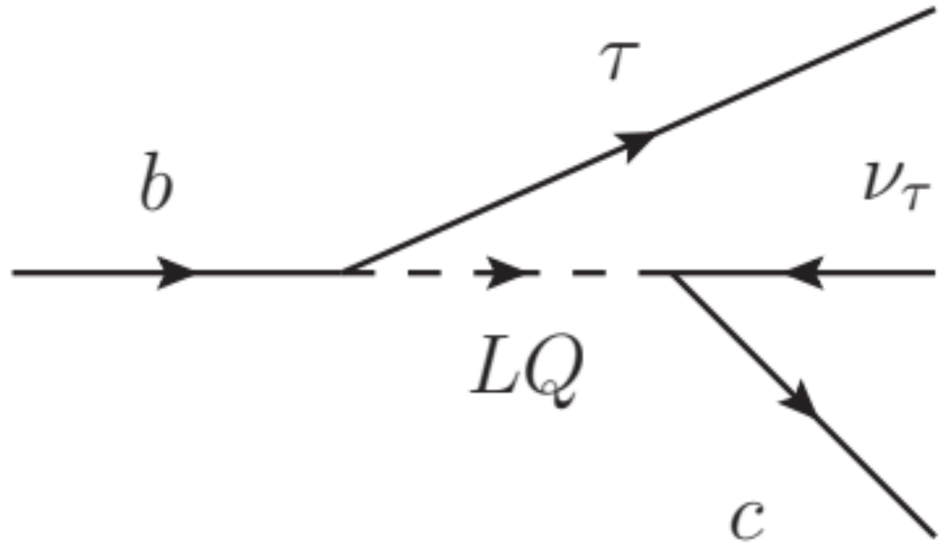
- Modified Fermi constant
- Z' boson coupling to muons and tau leptons



Charged current tauonic B decays ($b \to c \ell \nu$) [1403.1269]

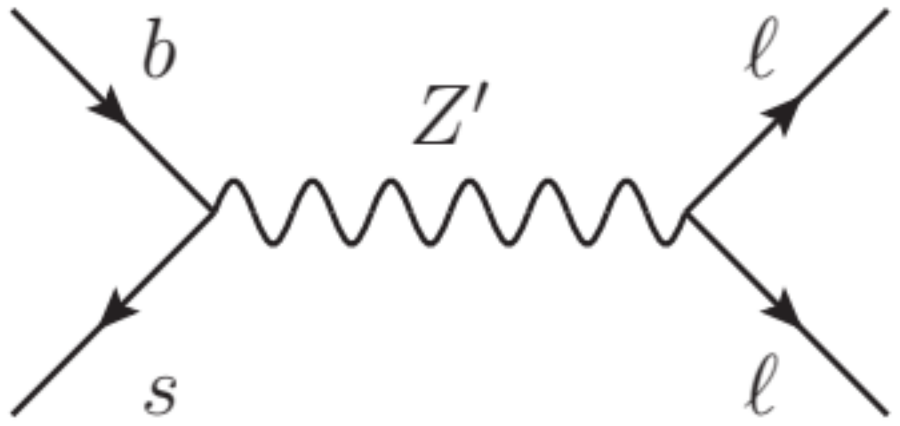
- charged Higgses [1206.2634]: Problems with distributions and B_c lifetime
- W' bosons [1412.7164]: Strong constraints from direct LHC searches
- LQs [1309.0301, 1506.08896 , 1511.06024]: Strong signals in $qq \to \tau\tau$ searches

CMS, 1809.05558; ATLAS, 1902.08103



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

- Z' [W. Altmannshofer, S. Gori, M. Pospelov and I. Yavin 1403.1269, ….]
  - Necessary effects in B_s mixing
  - Collider constraints



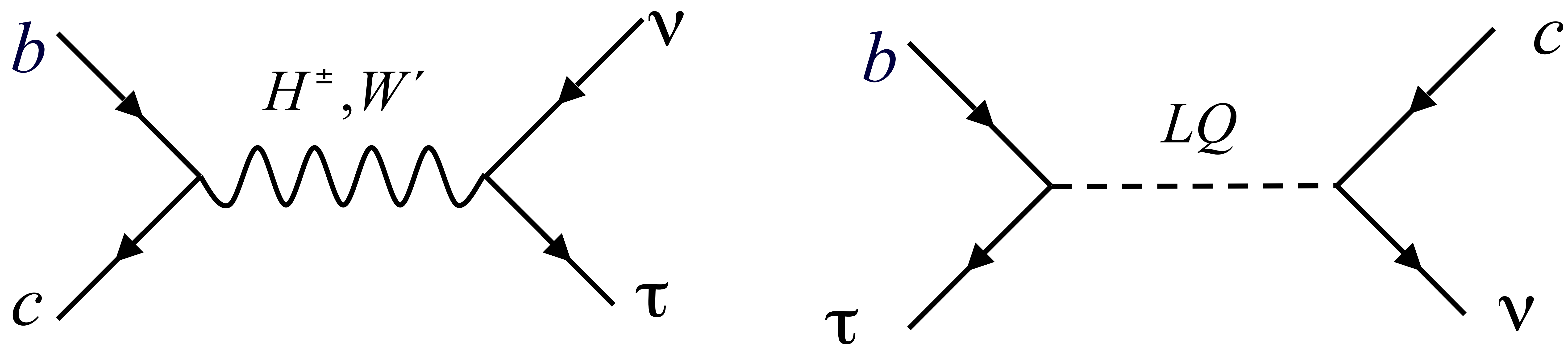
- Loop contributions [1408.1627, 1503.09024, …]
  - Scalars and vector-like fermions [B. Gripaios, M. Nardecchia, S. A. Renner, JHEP 2016]
  - 2HDM [1903.10440]
  - R_2 Leptoquark [1704.05835]
  - Z' coupling to tops [1704.06005]
- LQs [2203.10111, 1807.02068]

ΔA_{FB} explanation

- Right-handed vector operators LFU
- Good fit requires the tensor operator

→ **scalar LQ**

R(D) & R(D*)



- Charged scalars: Problems with distributions and B_c lifetime

  A. Celis, M. Jung, X. Q. Li, A. Pich, PLB 2017
  R. Alonso, B. Grinstein, J. Martin Camalich, PRL 2017

- W': Strong constraints from direct LHC searches

  D. Buttazzo, A. Greljo, G. Isidori, D. Marzocca, JHEP 2017

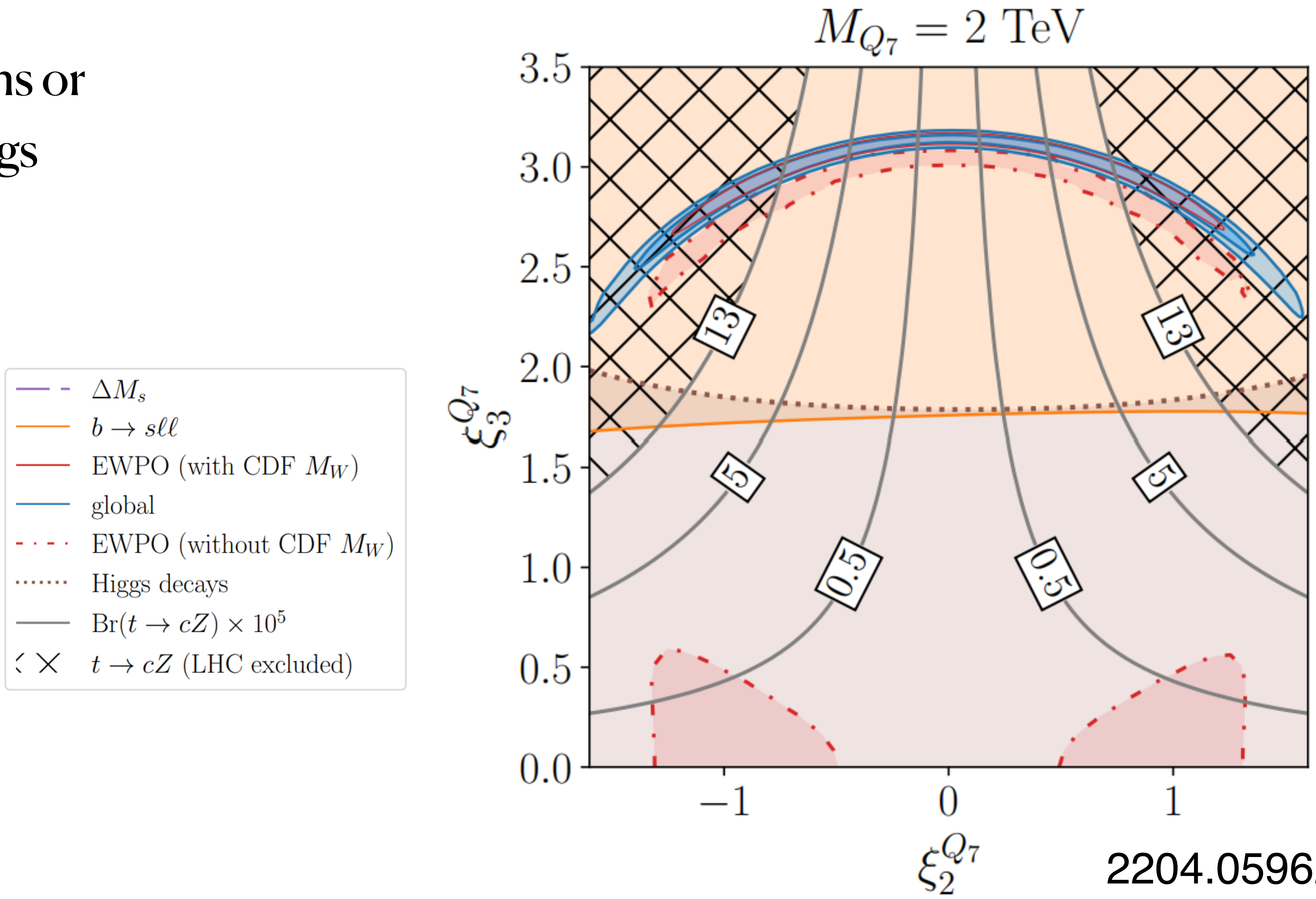
- Leptoquark: Strong signals in $qq \to \tau\tau$ searches

  CMS, 1809.05558; ATLAS, 1902.08103

Explanation difficult but possible with Leptoquarks

W boson mass

- Loop effects of fermions or scalars with sizable Higgs couplings
- Z-Z' mixing
- SU(2) triplet scalar
- Leptoquarks



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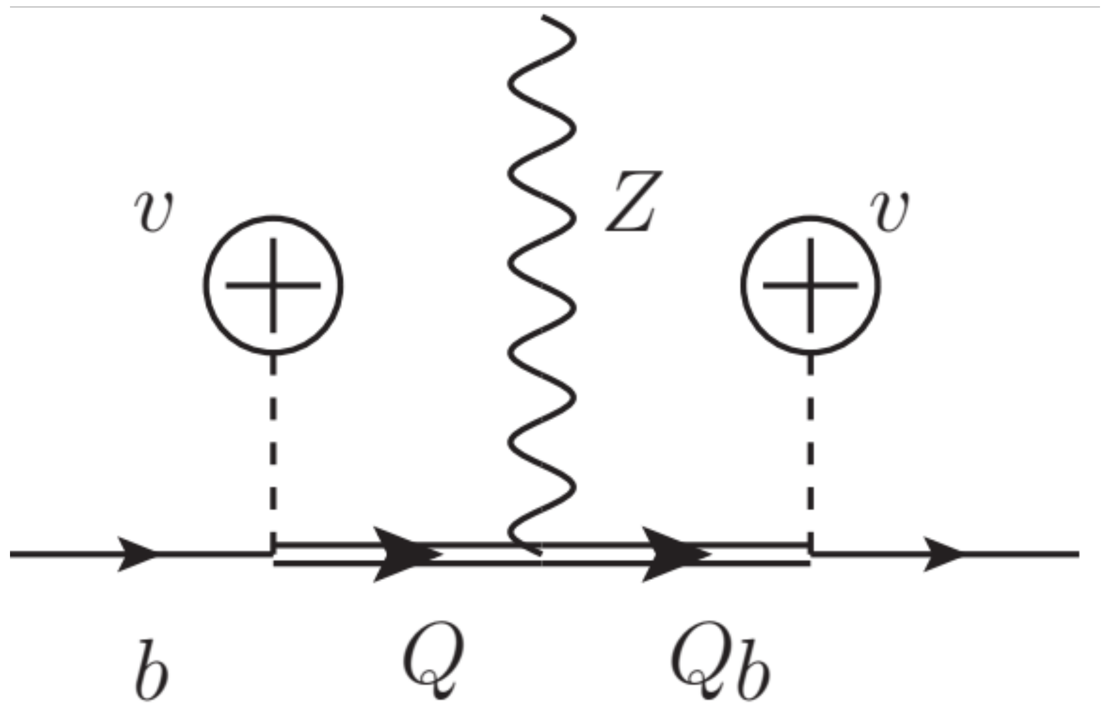
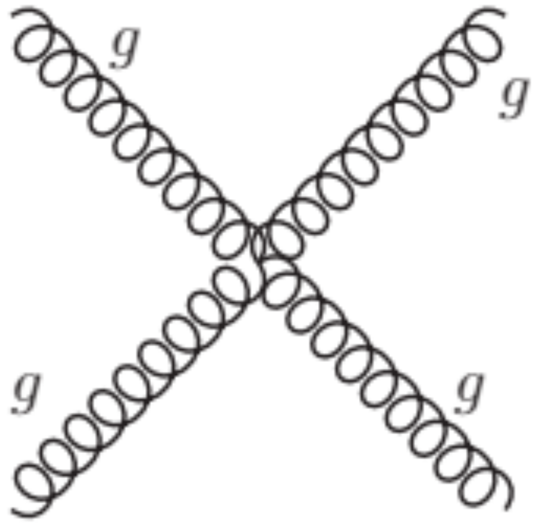
Asymmetries in Z decays ($Z \to b\bar{b}$)

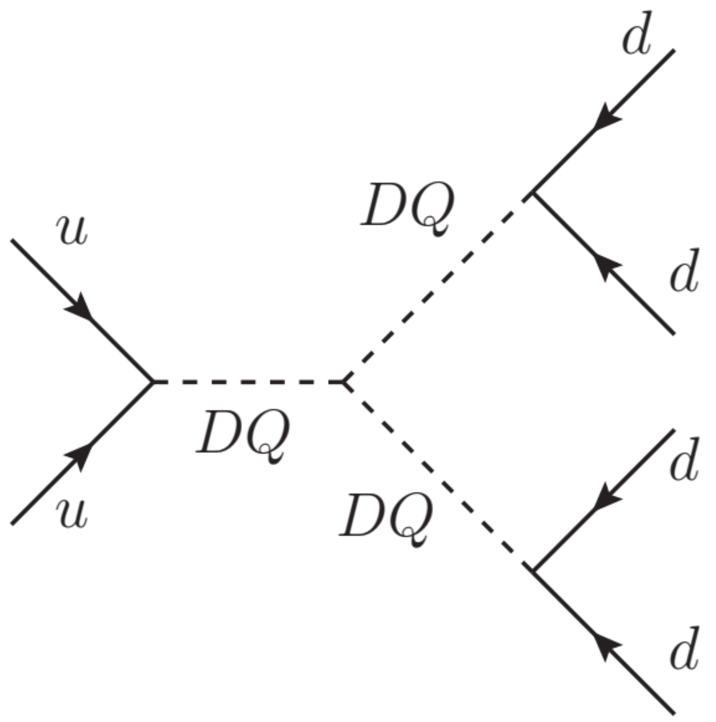
- Vector-like leptons
- Z-Z' mixing



(di-)di-jet resonances (j j(−j j))

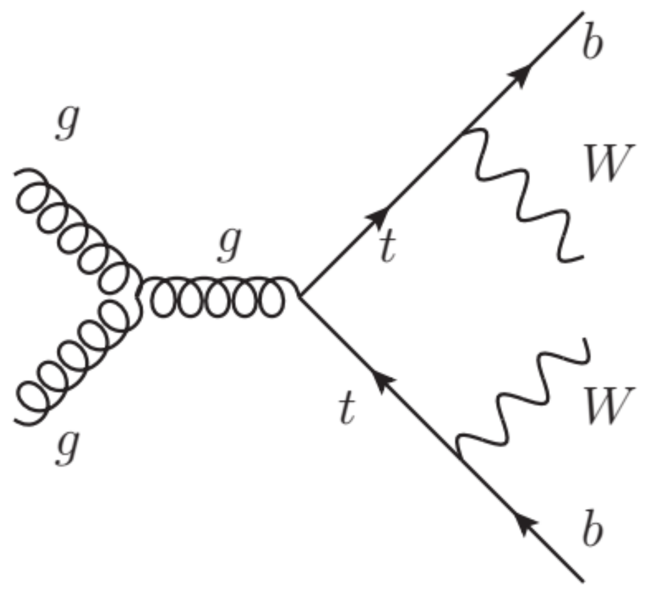
- two scalar DQ [2208.12254]
- new massive gluons

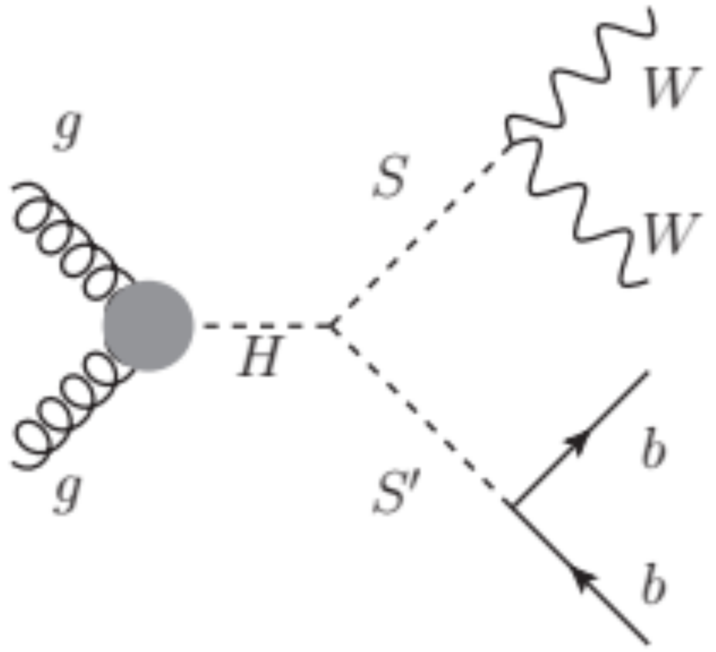




Multi-lepton anomalies ($e\mu$ (+b))

- Production of new scalars [2308.07953]
- Z-Z' mixing



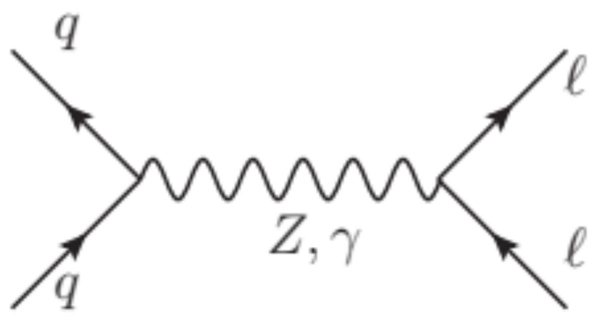


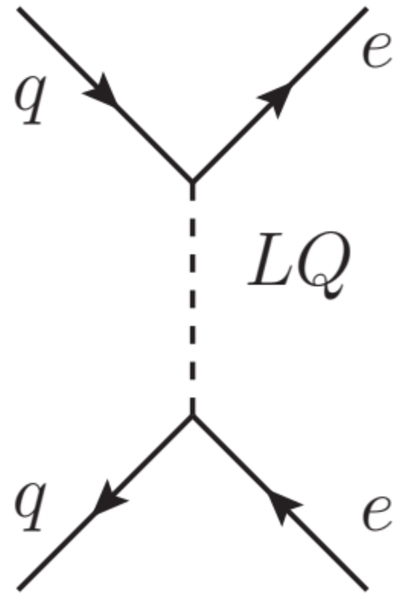
Higgs-like signals (yy = γγ,ττ,WW,ZZ)

- New scalar [2303.11351]
  $650\text{GeV} \to b\bar{b}(90\text{GeV}) + \gamma\gamma(125\text{GeV})$
- $pp \to H \to (S \to \gamma\gamma, WW) + (S' \to \text{invisible})$

Non-resonant di-electrons ($q\bar{q} \to e+e-$)

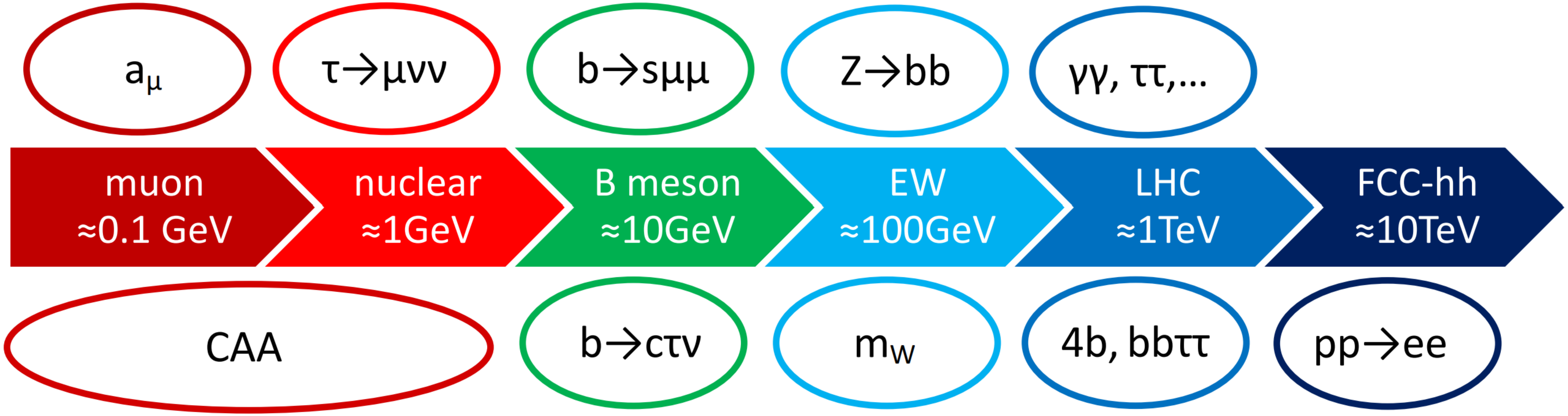
- Z′ bosons [2107.13569]
- LQs [2104.06417]



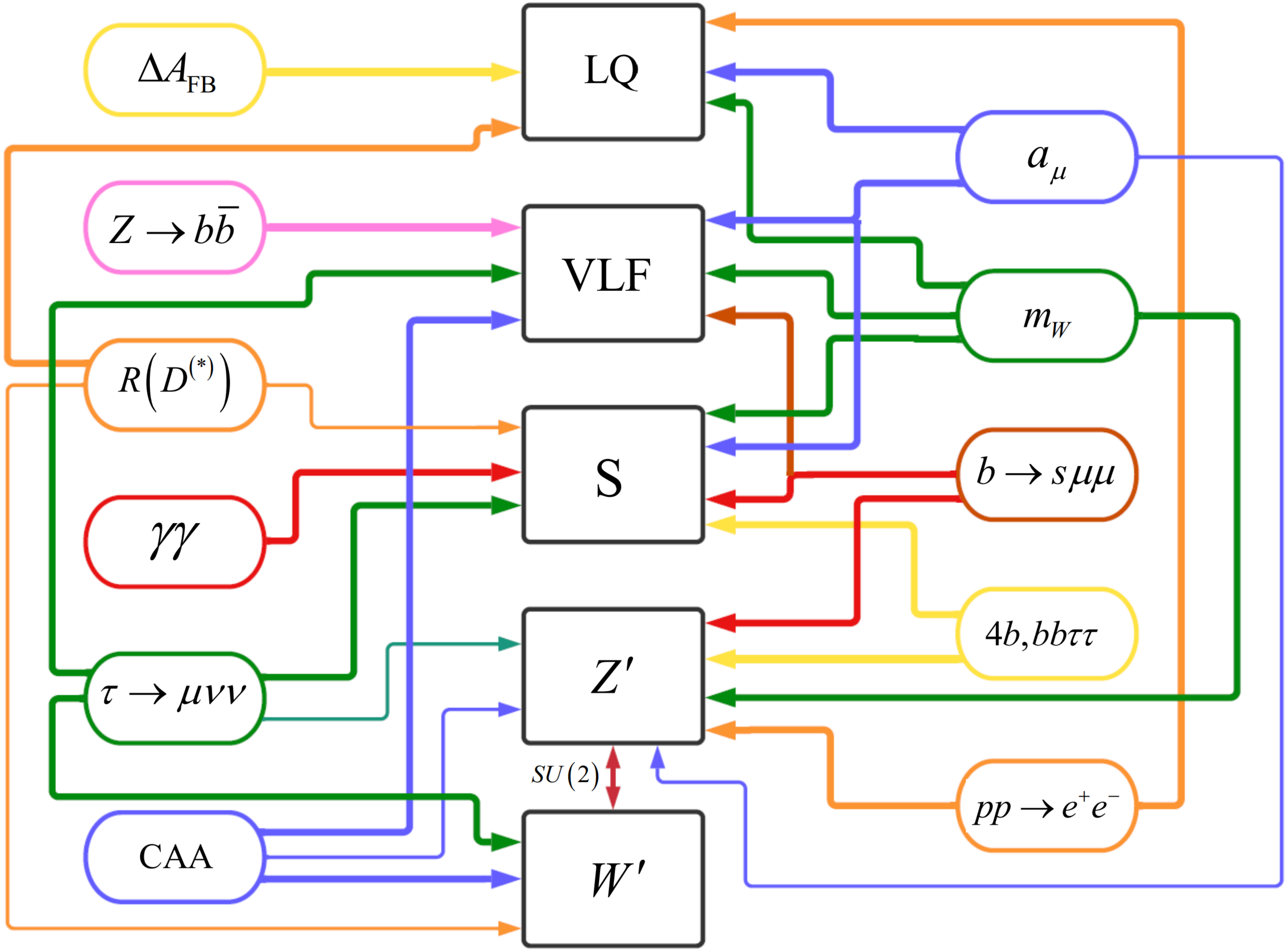


Conclusions

- Many intriguing anomalies emerged in the last years:
  - EW observables
  - LFUV
  - Direct LHC searches



Outlook: Beyond the Standard Model



Future implications

- a_μ: Belle-II and MUonE, lattice QCD
- CAA: NA62 $(K \to \mu\nu)/(K \to \pi\mu\nu)$ and PIONEER pion beta decay
- $\tau \to \mu\nu\nu$: Belle II, FCC-ee, CEPC
- $b \to c\ell\nu$: $R(D^{(*)})$ Belle II, LHCb run 3, CMS
- $b \to s\ell^+\ell^-$: non-perturbative methods like dispersion relations
- m_W : ILC, CLIC, FCC-ee or CEPC
- $e\mu$ (+b): NNLO effects helps to determine SM background, LHC
- $jj(-jj)$ & $q\bar{q} \to e^+e^-$: LHC run 3