BSM & Flavour: life *after* the B anomalies?

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Astroparticle Theory

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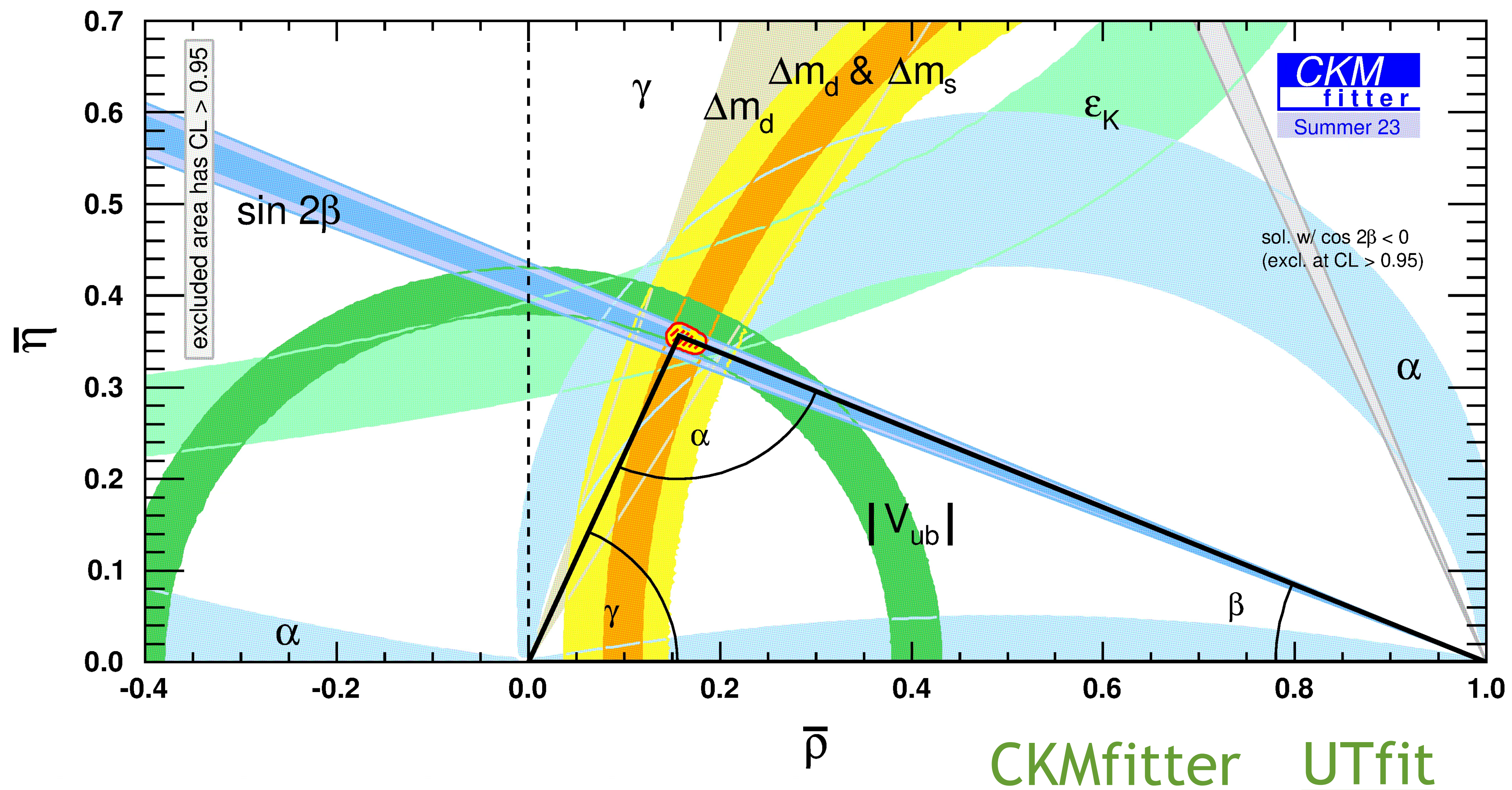
INVISIBLES24

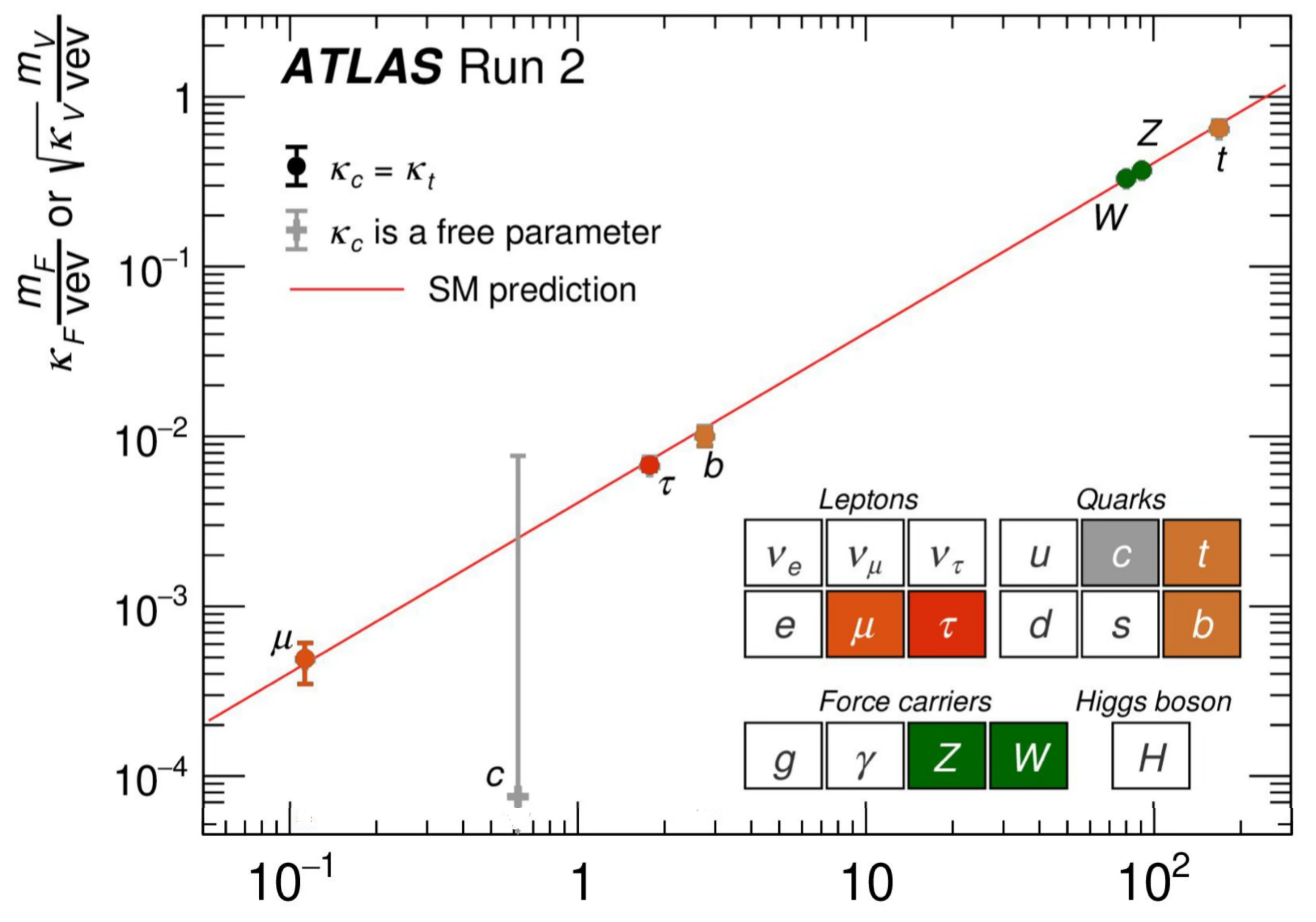
Flavor physics is a very mature field

Unitary triangle



CKMfitter UTfit

Yukawa couplings



Nature 607, 52-59 (2022)

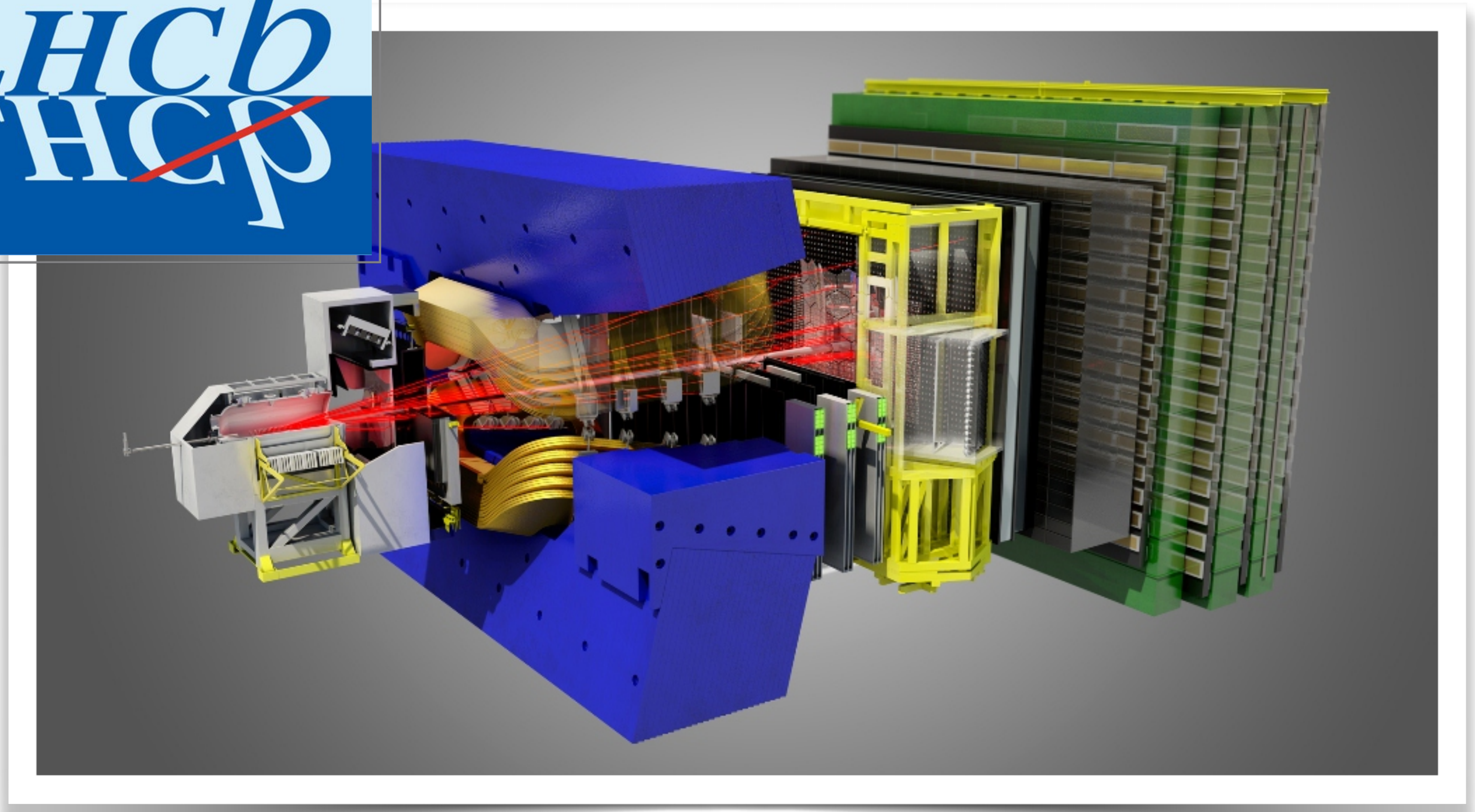
Flavor physics *well understood* within the SM

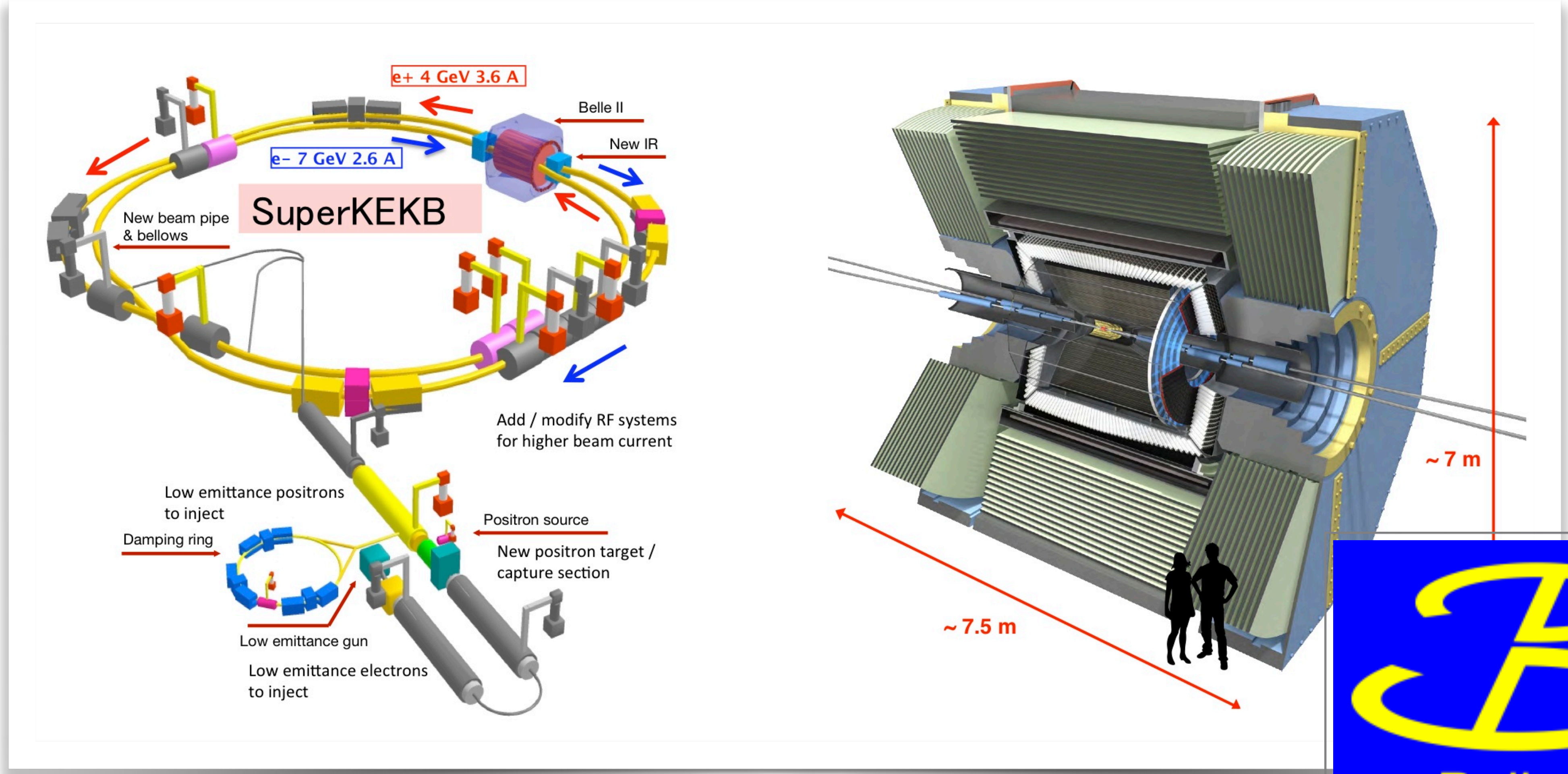
- Flavor mixing **well** parametrized by **Cabibbo-Kobayashi-Maskawa (CKM)**: 3 angles, 1 *CPV* phase
- Fermion masses parametrized by **Yukawa couplings**: 9 masses

We do not understand the hierarchy of masses/mixing angles ⇒ **Flavor puzzle**

Golden era: experiments

- "Multi-purpose" *B*-meson factories





- Many more flavor experiments at different scales

Kaons and muons

Taus, hyperons, charm

TeV scale

Golden era: hadron physics

- **Our Lagrangians are written in terms of quarks and our observables in terms of hadrons!**

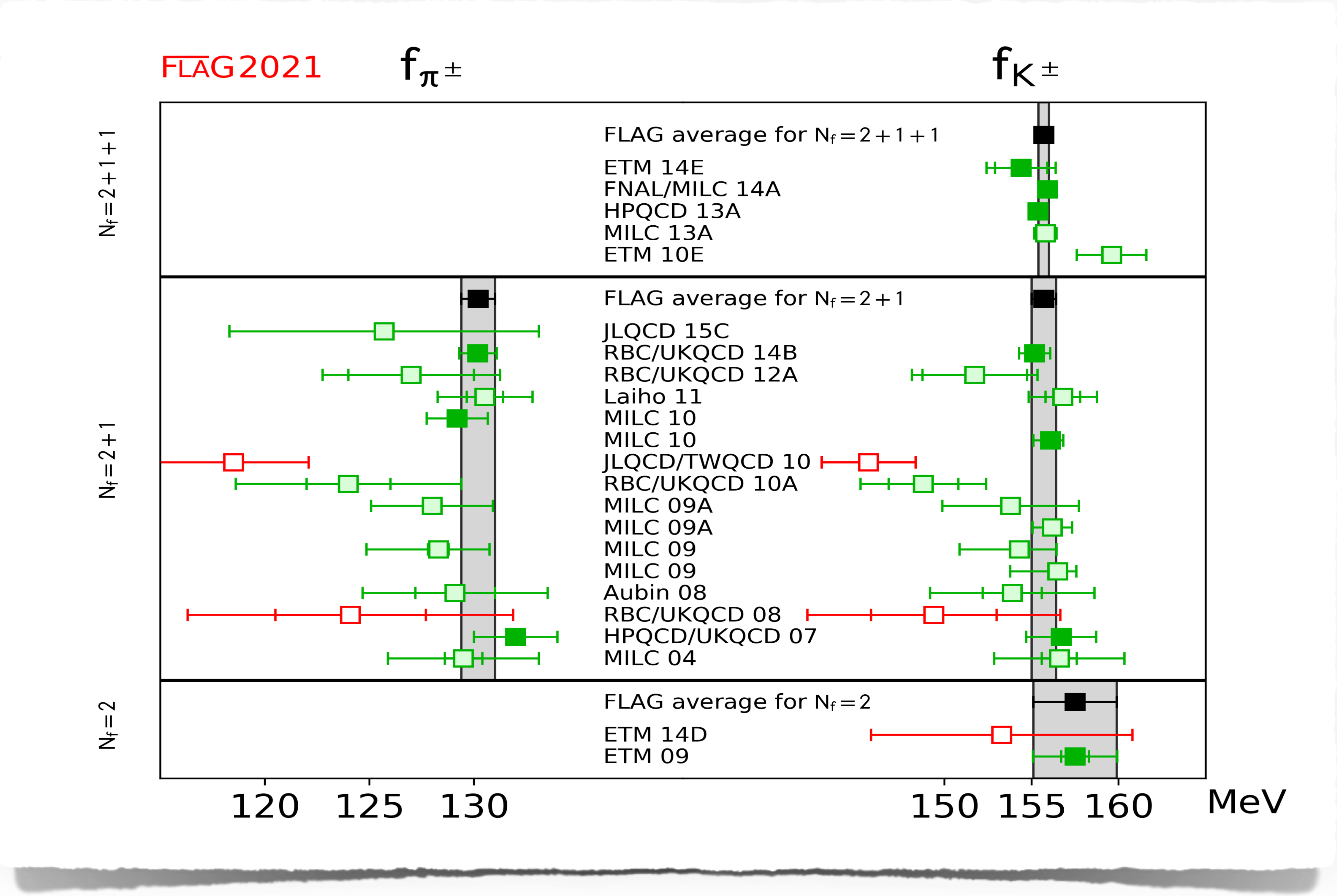
Interactions: $\mathscr{L}(u, d, s, c, b, e, \nu, G, F)$ ***Asymptotic* states:** $|\pi^{\pm}, \pi^{0}, K^{\pm}, D^{\pm}, B^{\pm}, p, n, \Lambda, \ldots\rangle$

- **Hadronic matrix elements:** Nonperturbative-QCD information of the transition

- **Many computational tools** $\Rightarrow$ **Only few from first principles (QCD)**
  - **Lattice QCD:** First principles but expensive and limited
  - **EFTs:** First principles vs proliferation of parameters
  - Analytic (QCD sum rules, quark models, etc)

Big progress in LQCD and EFTs approach over the past 2 decades

  - Systematic **quality control!** FLAG 2021 Flavour Lattice Averaging Group

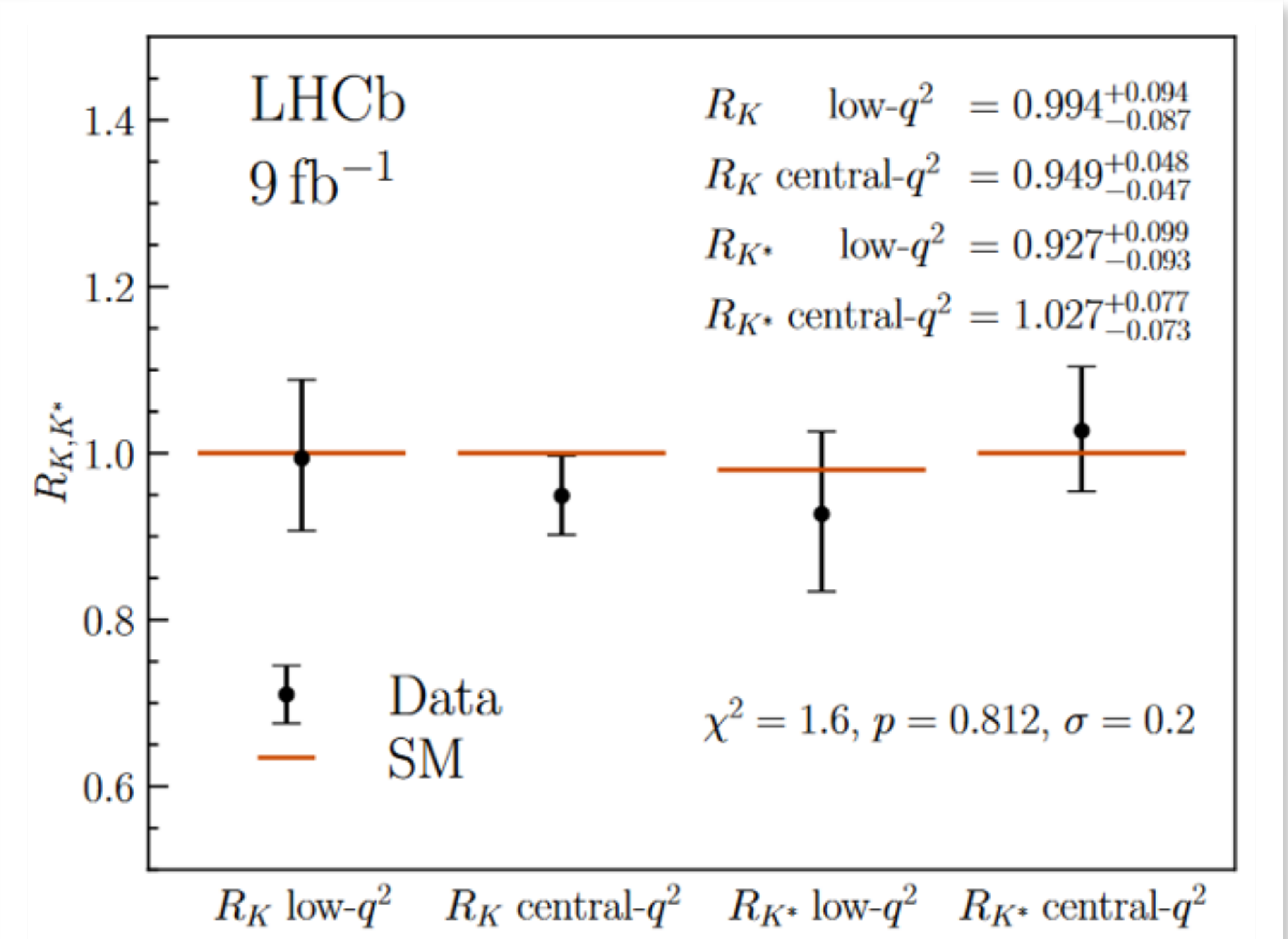


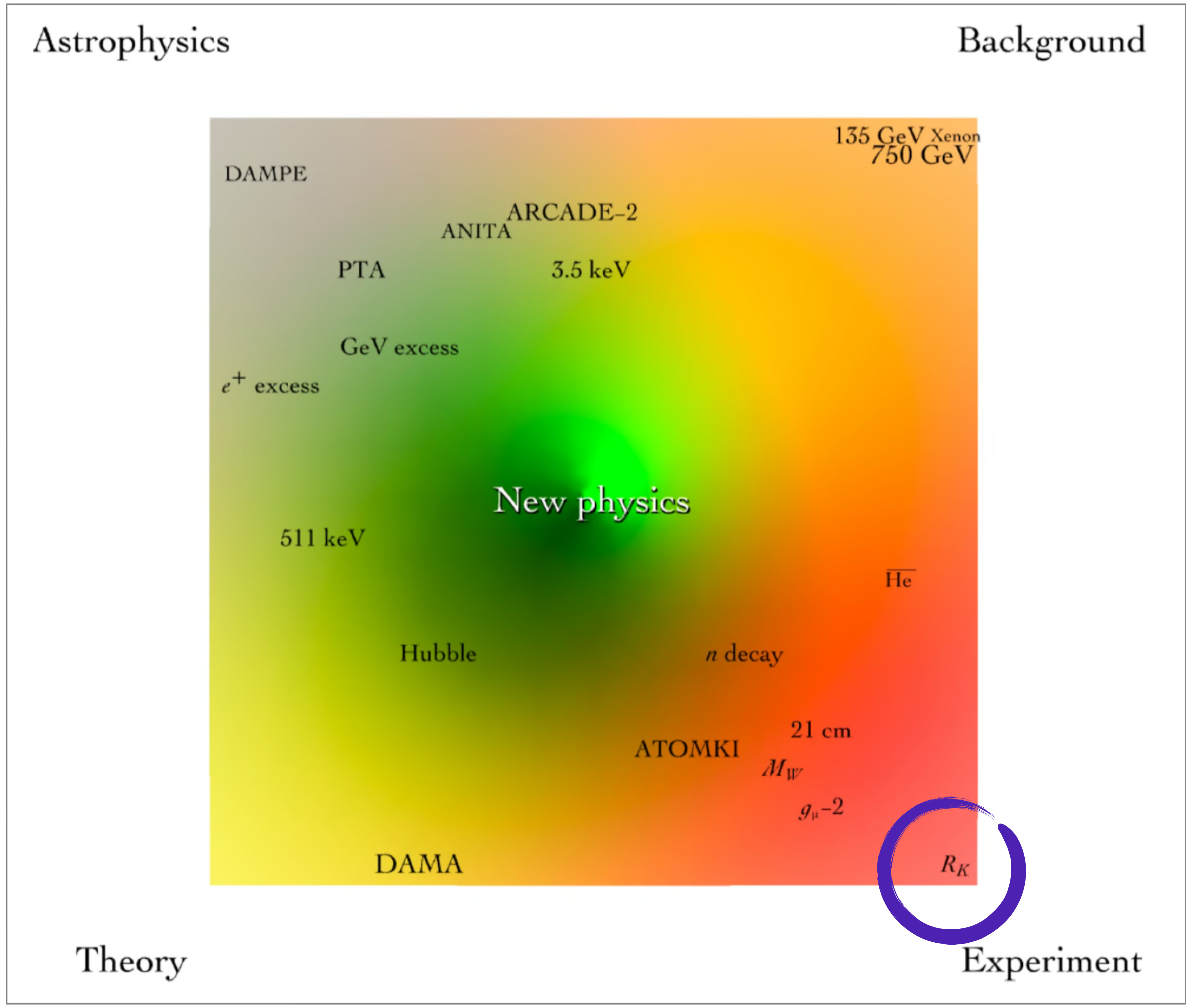
FLAG collaboration

The flavor anomalies

- **Rise and fall of the "R_K anomaly"**

  Long-standing (since 2014) **LHCb anomalies** refuted by **LHCb** in Dec 2022

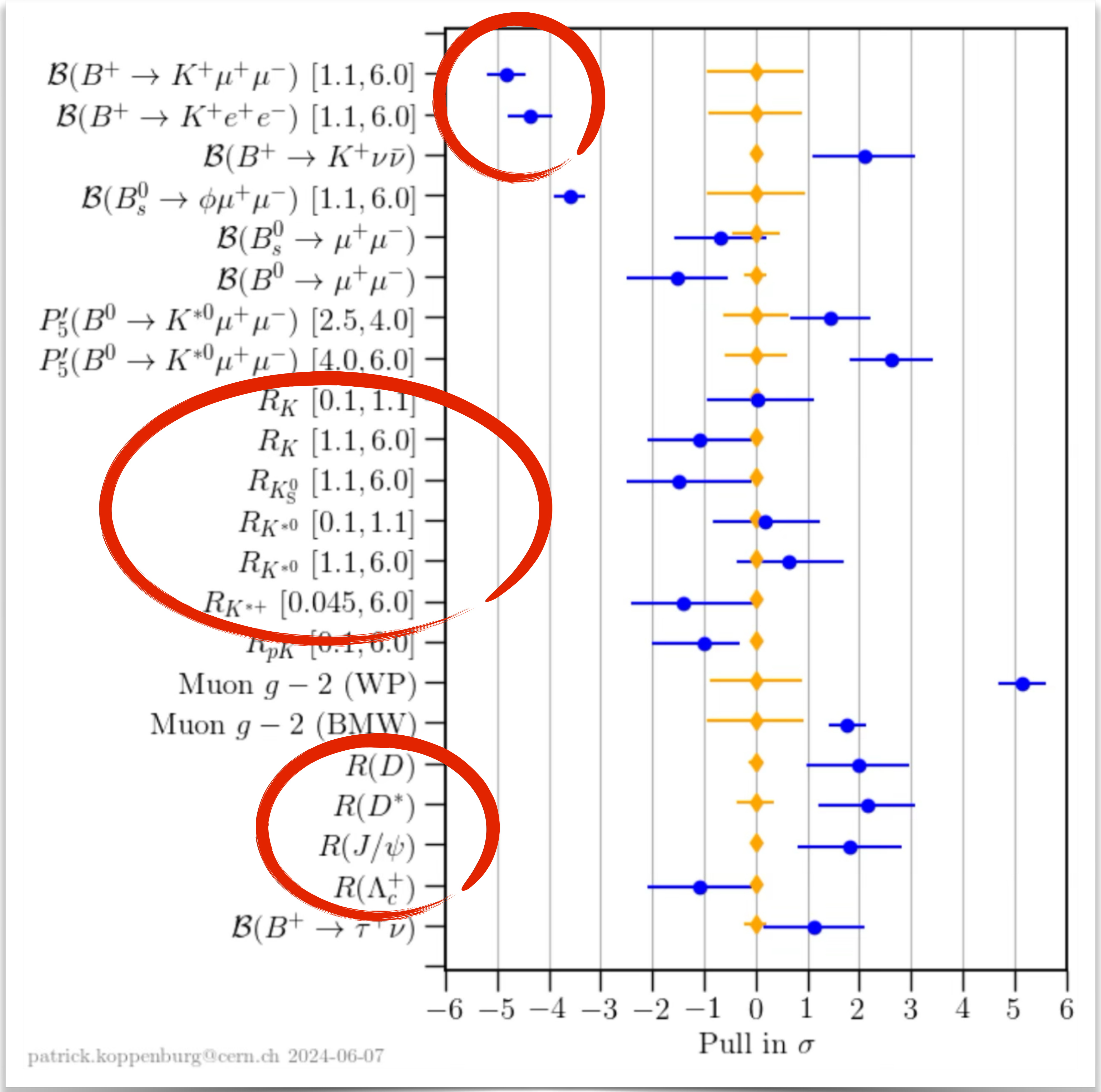




Cirelli, Strumia & Zupan, arXiv:2406.017056

The flavor anomalies

Anomalies still discussed **off scene**



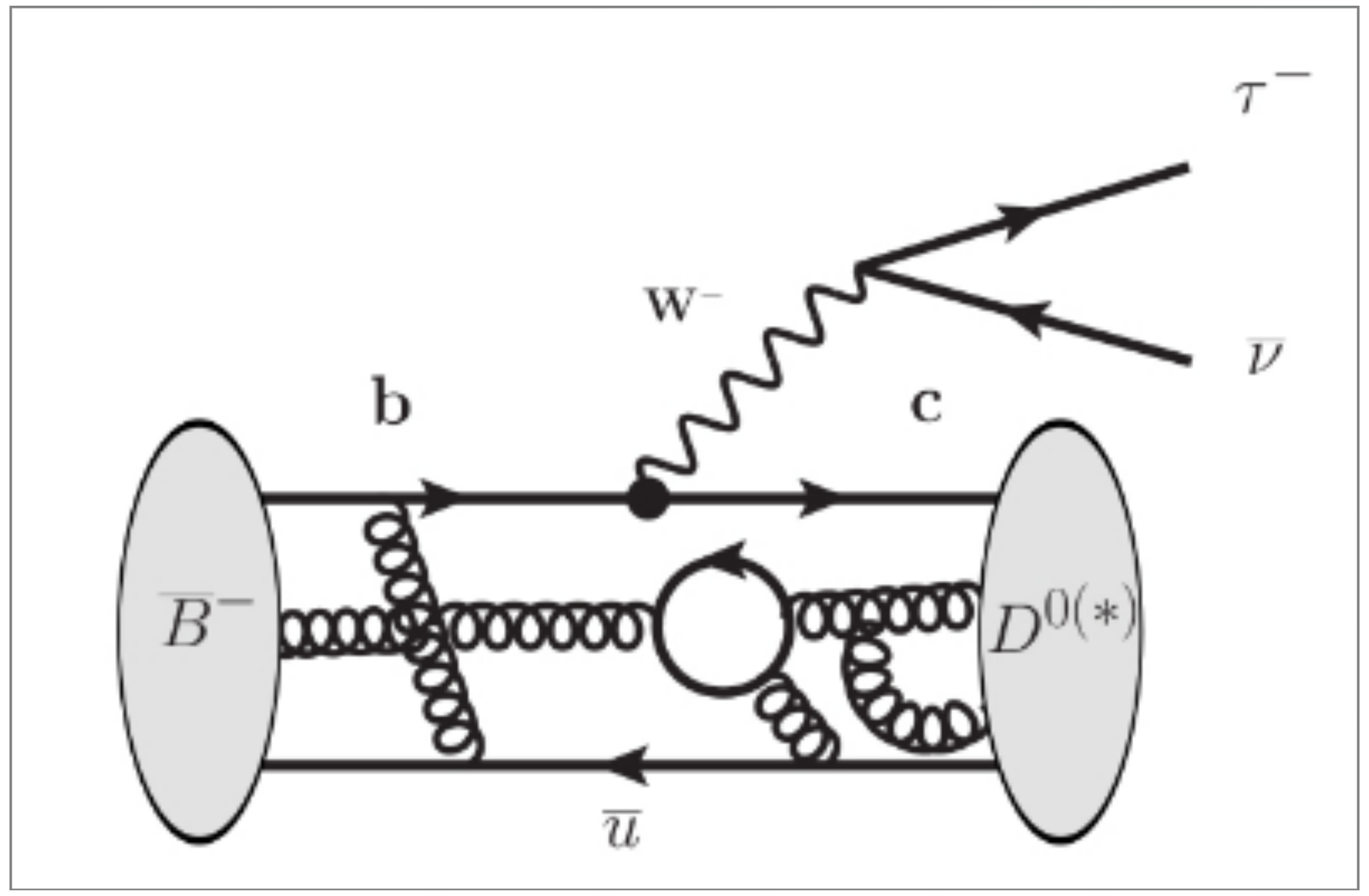
Patrick Koppenburg's website

Last update from June 07 2024

- Some tensions at the **5σ level**
- R_K measurements consistent with BSM
- Many of the anomalies predate original R_K anomaly (i.e. P_5' anomaly from 2013)
- What happened to the other R_D anomalies?

The R_D anomalies

Charged-current decays of B mesons into tau leptons



- **Semi-tauonic charged-current decay**
  - Governed by the weak amplitude $G_F V_{cb}$
  - Two main **hadronic** channels studied

$$B \to D \text{ with } J^P(D) = 0^-$$
$$B \to D^* \text{ with } J^P(D^*) = 1^+$$

- **Hadronic form factors**
  - Heavy-quark EFT with data light leptons and/or LQCD
  - Define **Lepton Universality** ratio to cancel uncertainties

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

→

HFLAV SM predictions

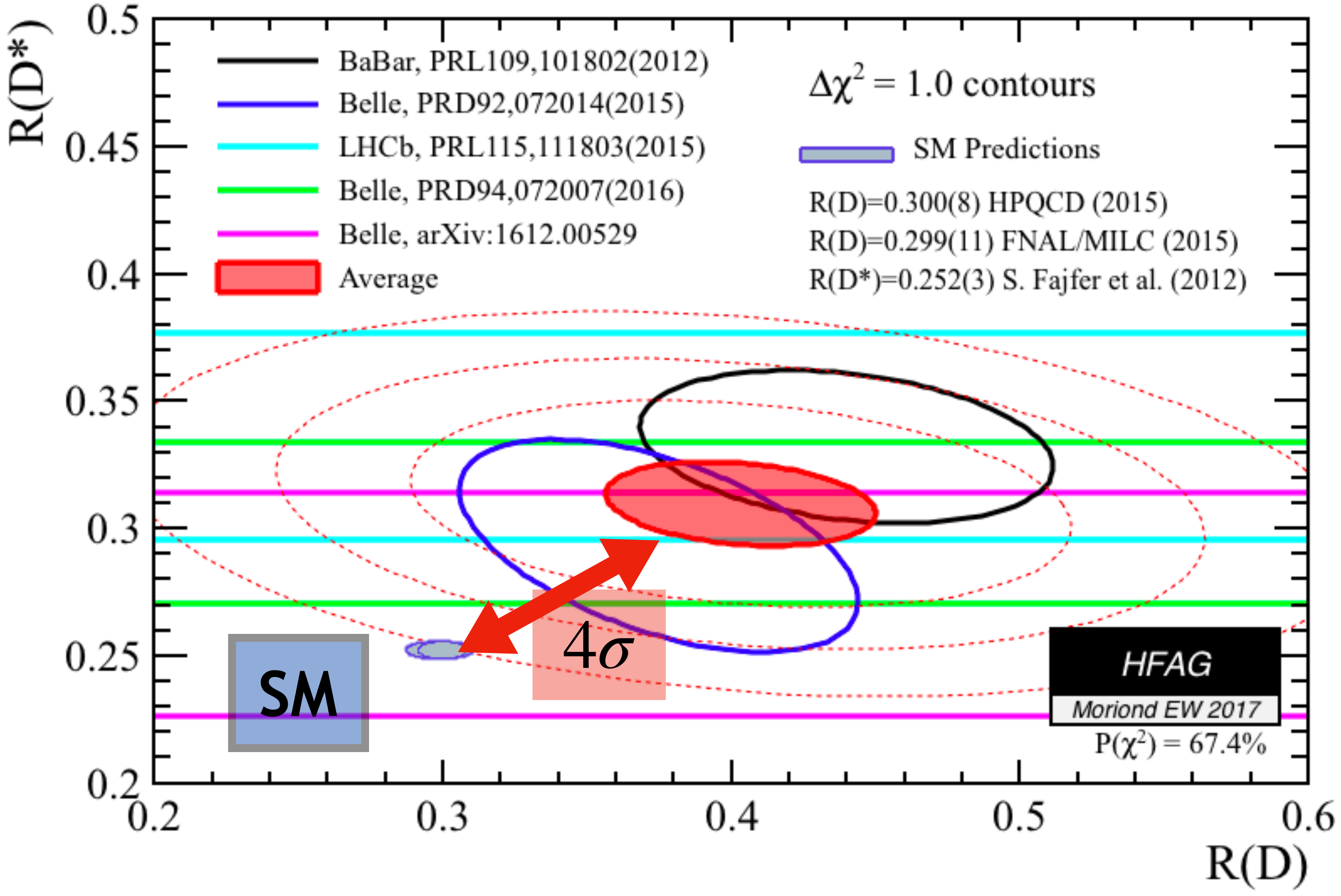
$$R_D = 0.298 \pm 0.004$$
$$R_{D*} = 0.254 \pm 0.005$$

HFLAV collaboration

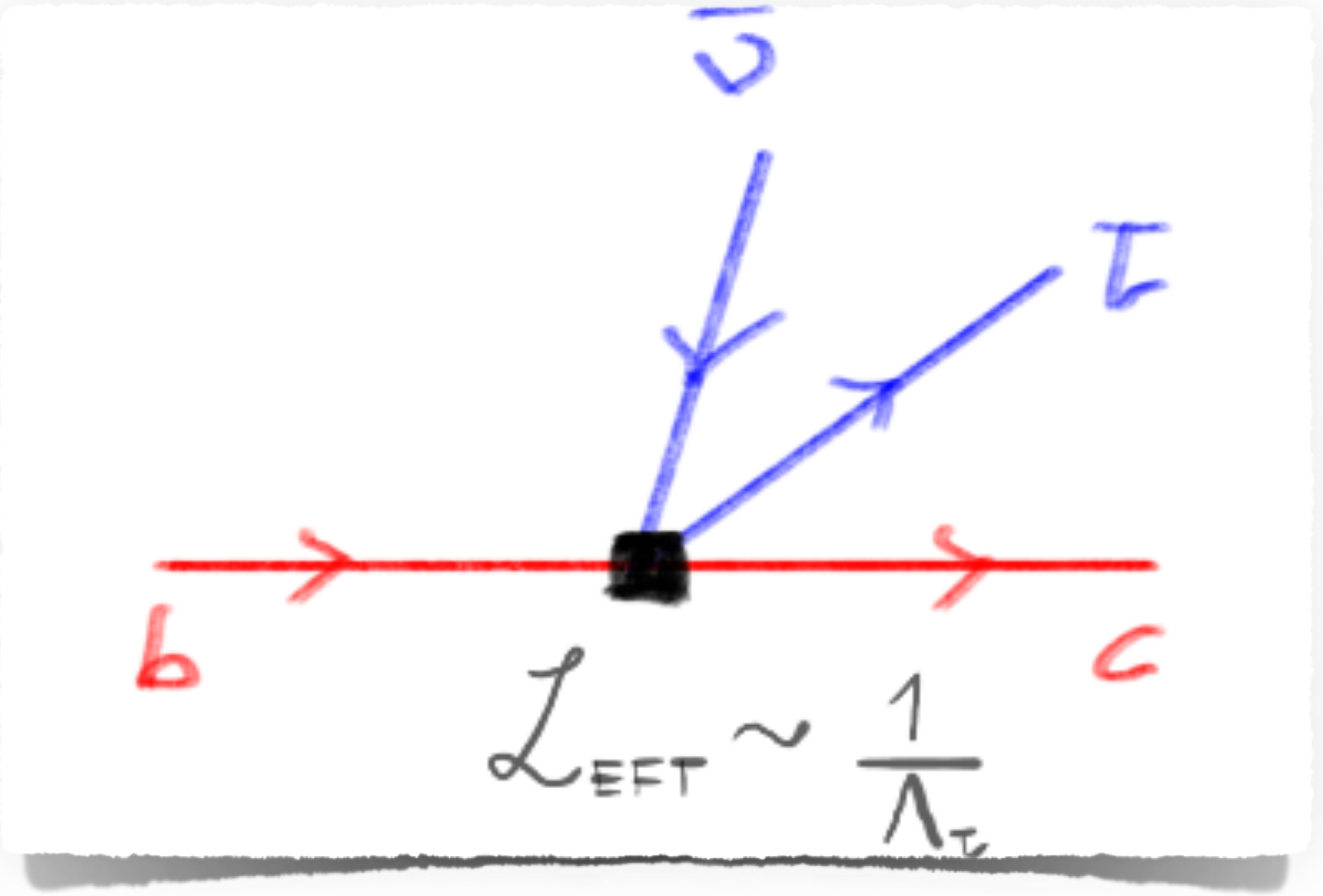
Theoretical errors well controlled at the 3 - 6% level

Charged-current decays of B mesons into tau leptons

- In 2017



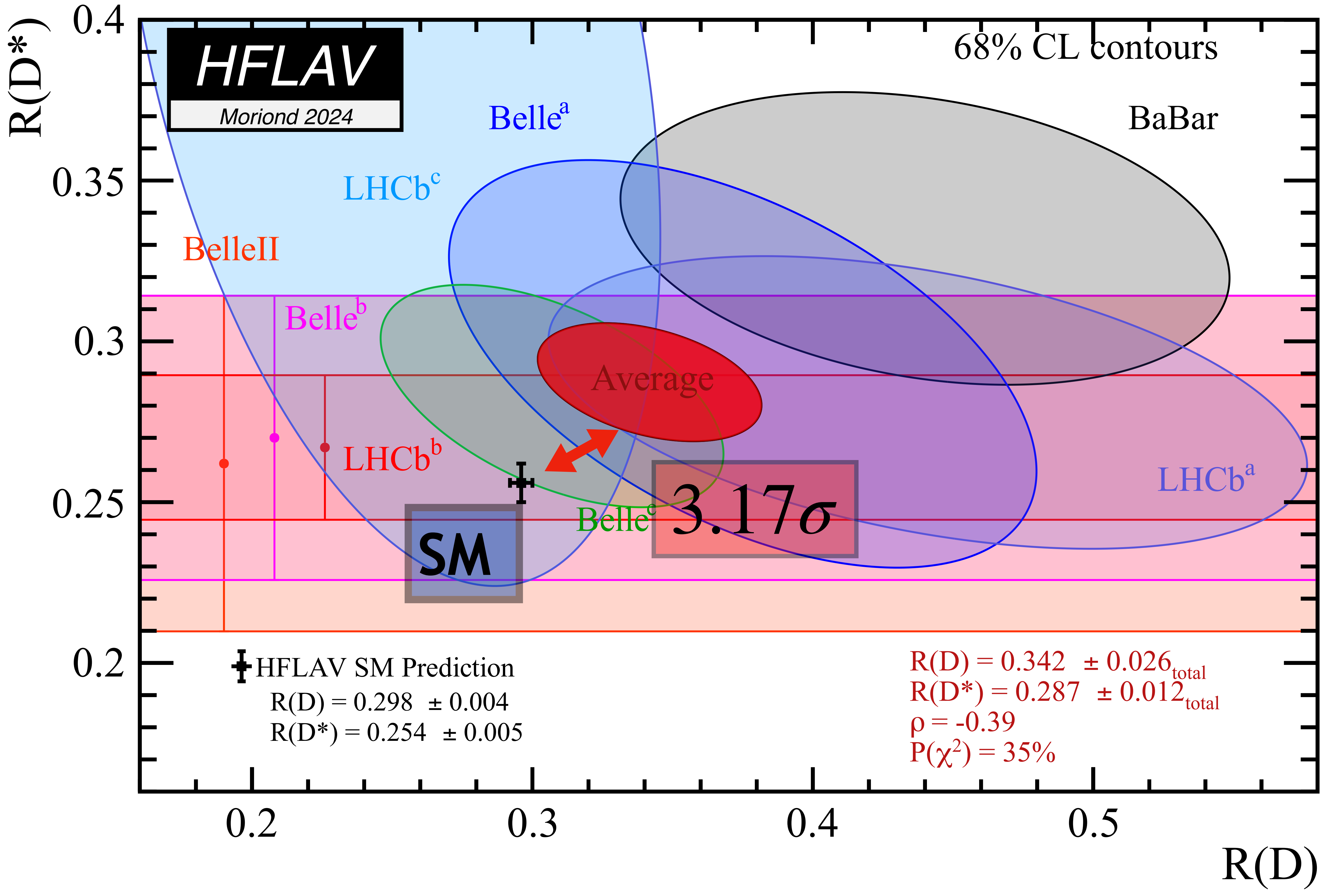
- General **excess** w.r.t. SM at 4σ
- Different experiments: BaBar, Belle,LHCb



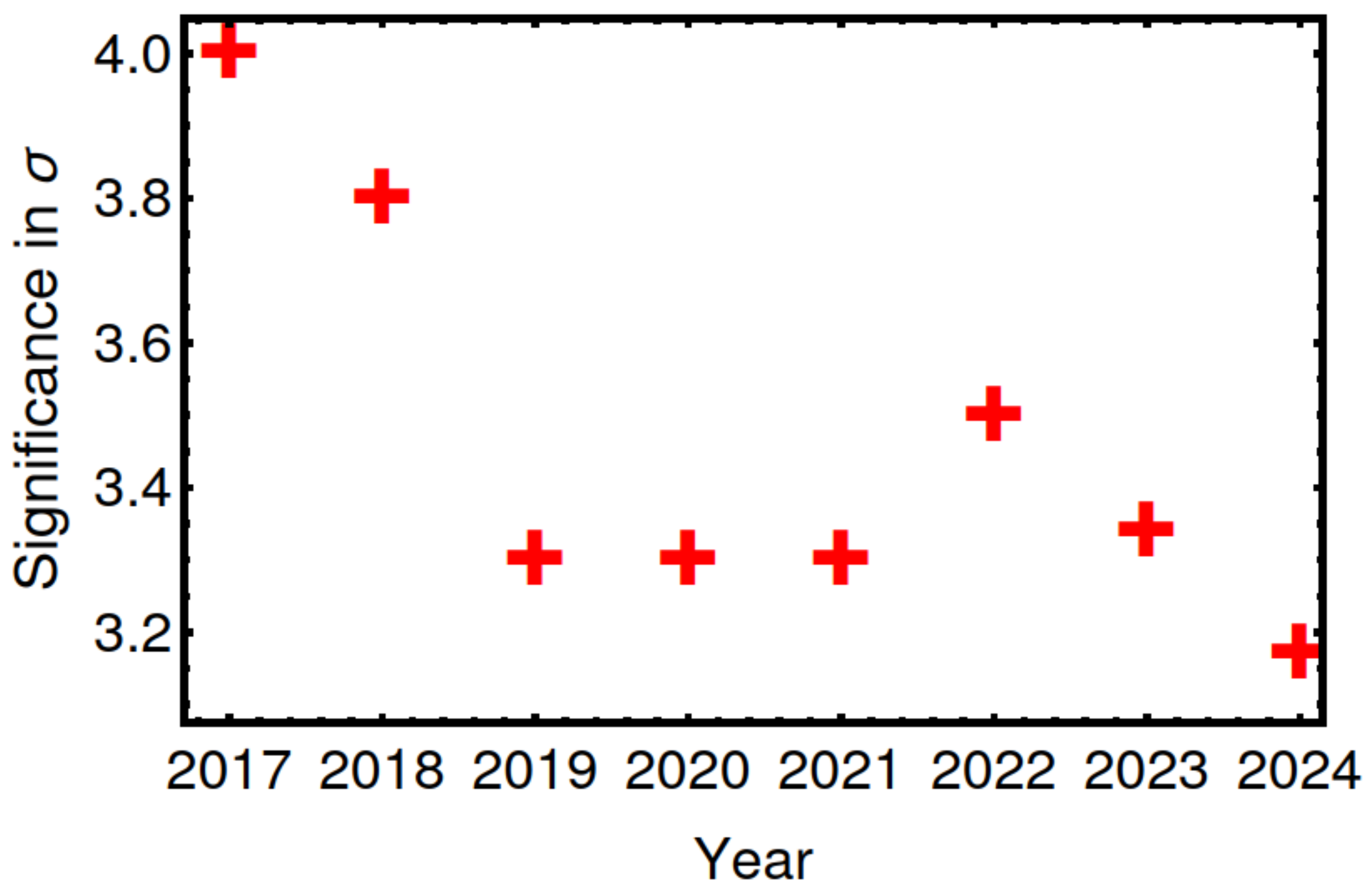
BSM interpretation: ~10% increase amplitude ⇒ New physics at $\Lambda_\tau \sim 3$ TeV (**LHC energies!**)

Charged-current decays of B mesons into tau leptons

- **7 years later in 2024**



- New measurements with 1st by **Belle II**
- Gradually descending to SM: Excess 3.17σ



- **BaBar** outlier? ⇒Down to ~ 2σ

Picture not getting any clearer ⇒ More data needed!

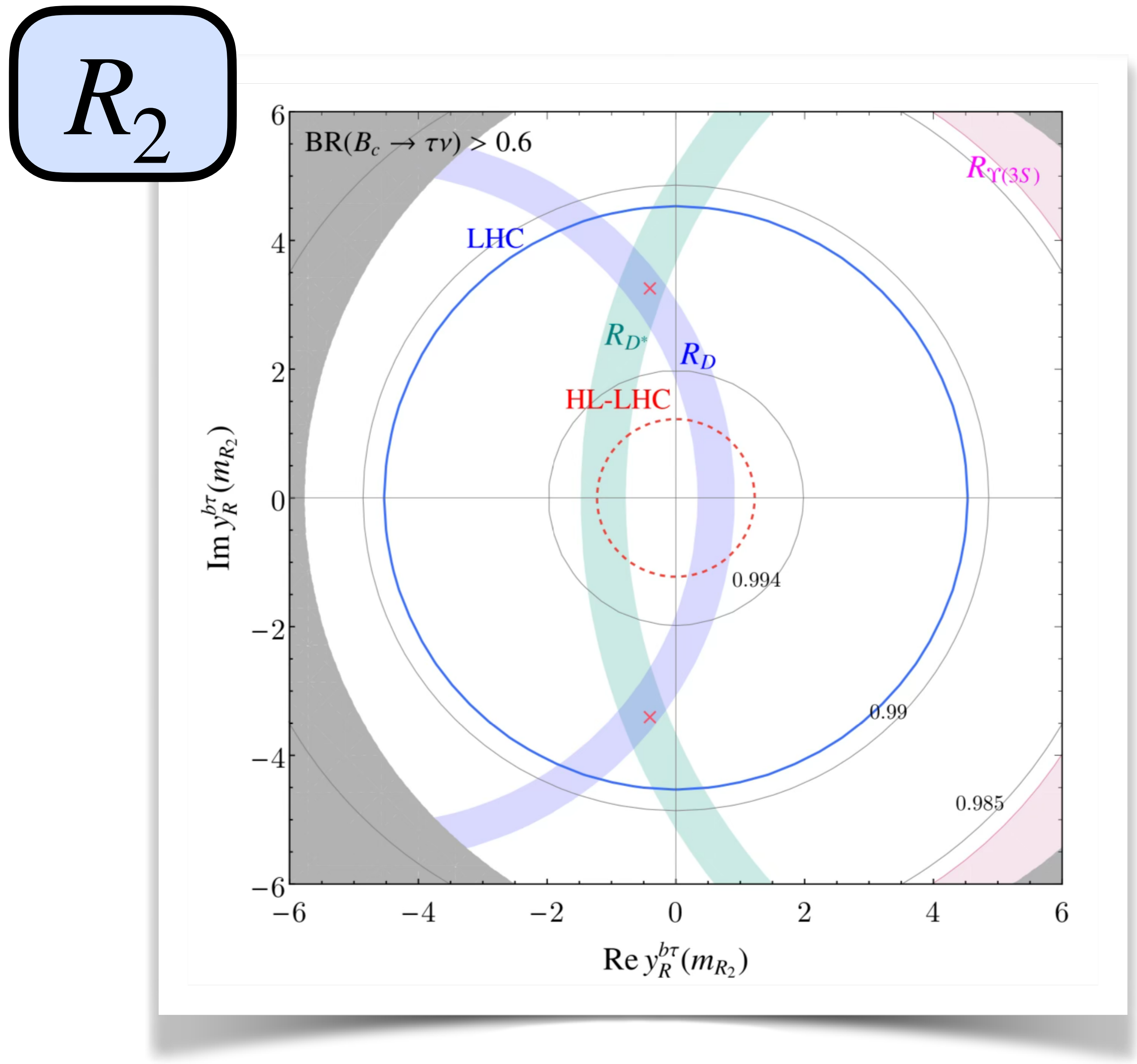
The BSM interpretation of the data in the EFT

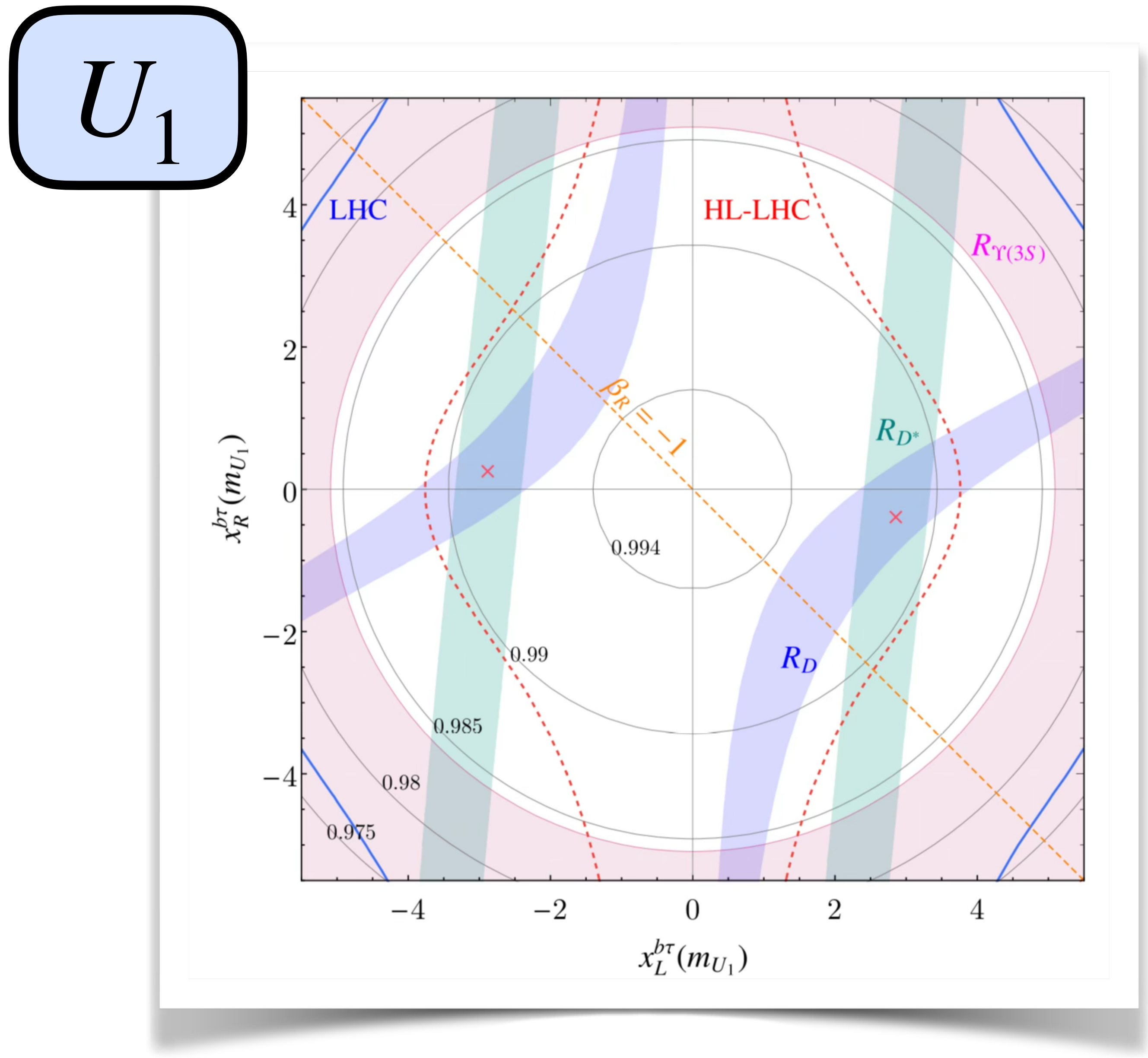
- **Bottom-up:** Different simplified models can describe the data

	Spin	Charge	Operators	R_D	R_{D^*}	LHC	Flavor
$H^\pm$	0	$(\mathbf{1},\mathbf{2},1/2)$	O_{S_L}	✓	✓	$b\tau\nu$	$B_c\to\tau\nu$, $F_L^{D^*}$, $P_\tau^{D^*}$, M_W
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, $B\to K^{(*)}\nu\nu$
$\mathrm{R}_2^{(2/3)}$	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
U_1	1	$(\mathbf{3},\mathbf{1},2/3)$	O_{V_L}, O_{S_R}	✓	✓	$b\tau\nu$, $\tau\tau$	$R_{K^{(*)}}$, $R_{\Upsilon(nS)}$, $B_s\to\tau\tau$
$\mathrm{V}_2^{(1/3)}$	1	$(\bar{\mathbf{3}},\mathbf{2},5/6)$	O_{S_R}	✓	2σ	$\tau\tau$	$B_s\to\tau\tau$, $B_u\to\tau\nu$, M_W

- **Leptoquarks** are the queens of the flavor anomalies

Iguro et al., arXiv: 2405.06062

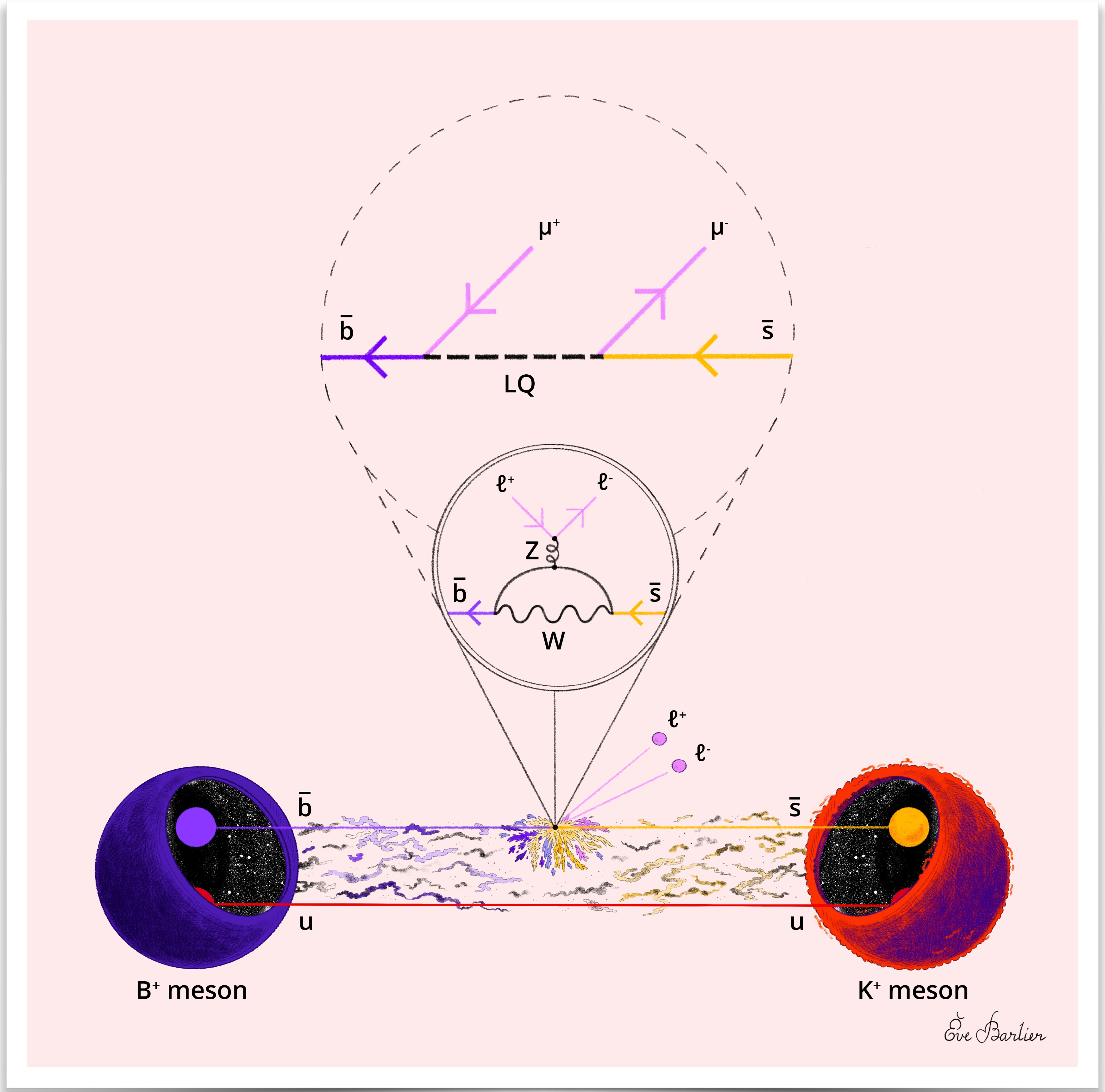




The $b \to s\ell\ell$ anomalies

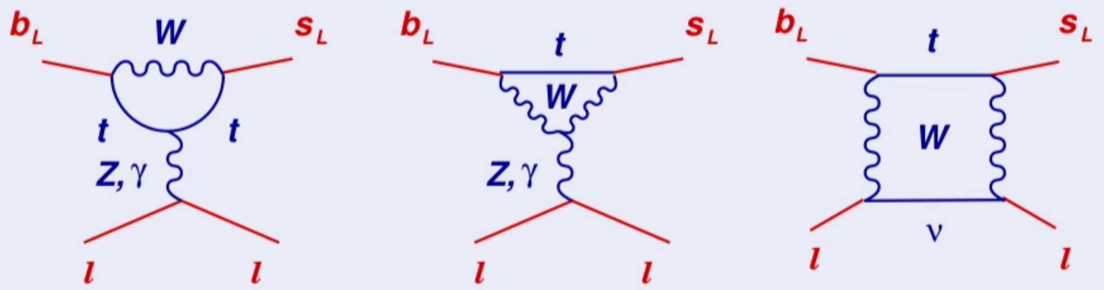
FCNC decays of B mesons into kaons and leptons

- Semi-leptonic rare decays
  - Governed by the weak/loop/CKM suppressed amplitude $G_F V_{tb} V_{ts}^* \frac{\alpha}{4\pi}$



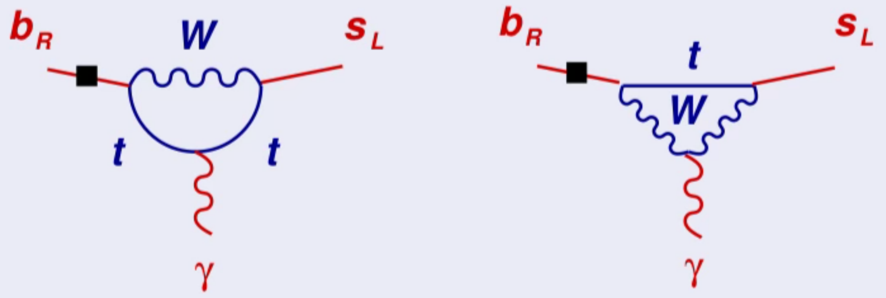
The $b \to s\ell\ell$ transition in the SM

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



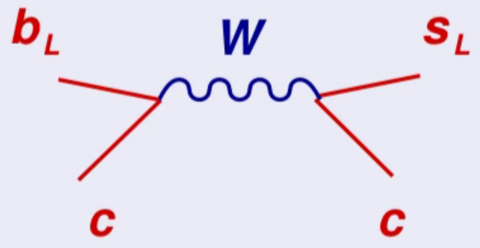
$$\frac{\alpha}{4\pi} C_{9(10)}\, \bar{s}_L \gamma^\mu b_L\, \bar{\ell}\gamma_\mu(\gamma_5)\ell$$

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



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

- **CC @ 1 loop**

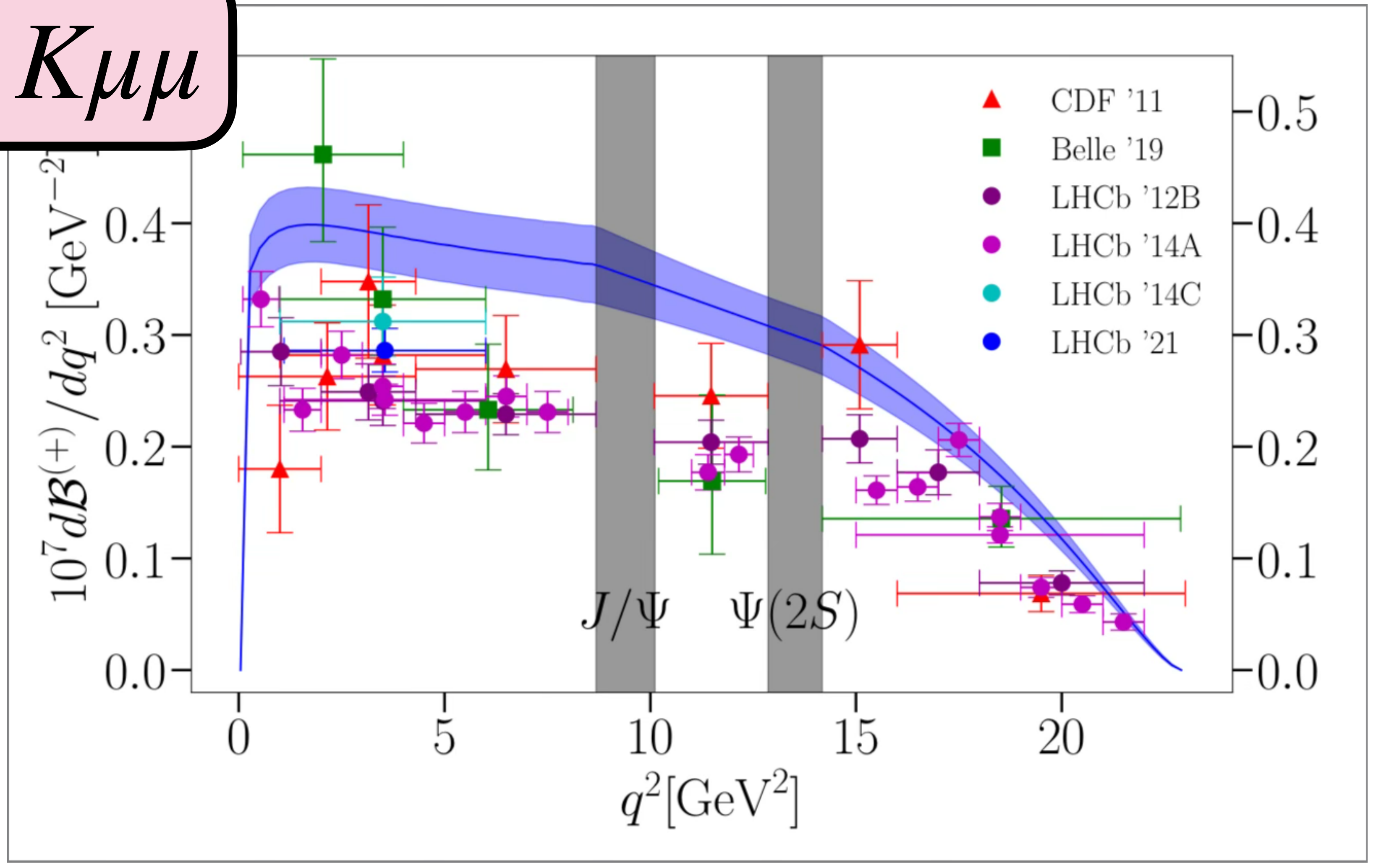


$$C_2\, \bar{c}_L \gamma^\mu b_L\, \bar{s}_L \gamma_\mu c_L$$

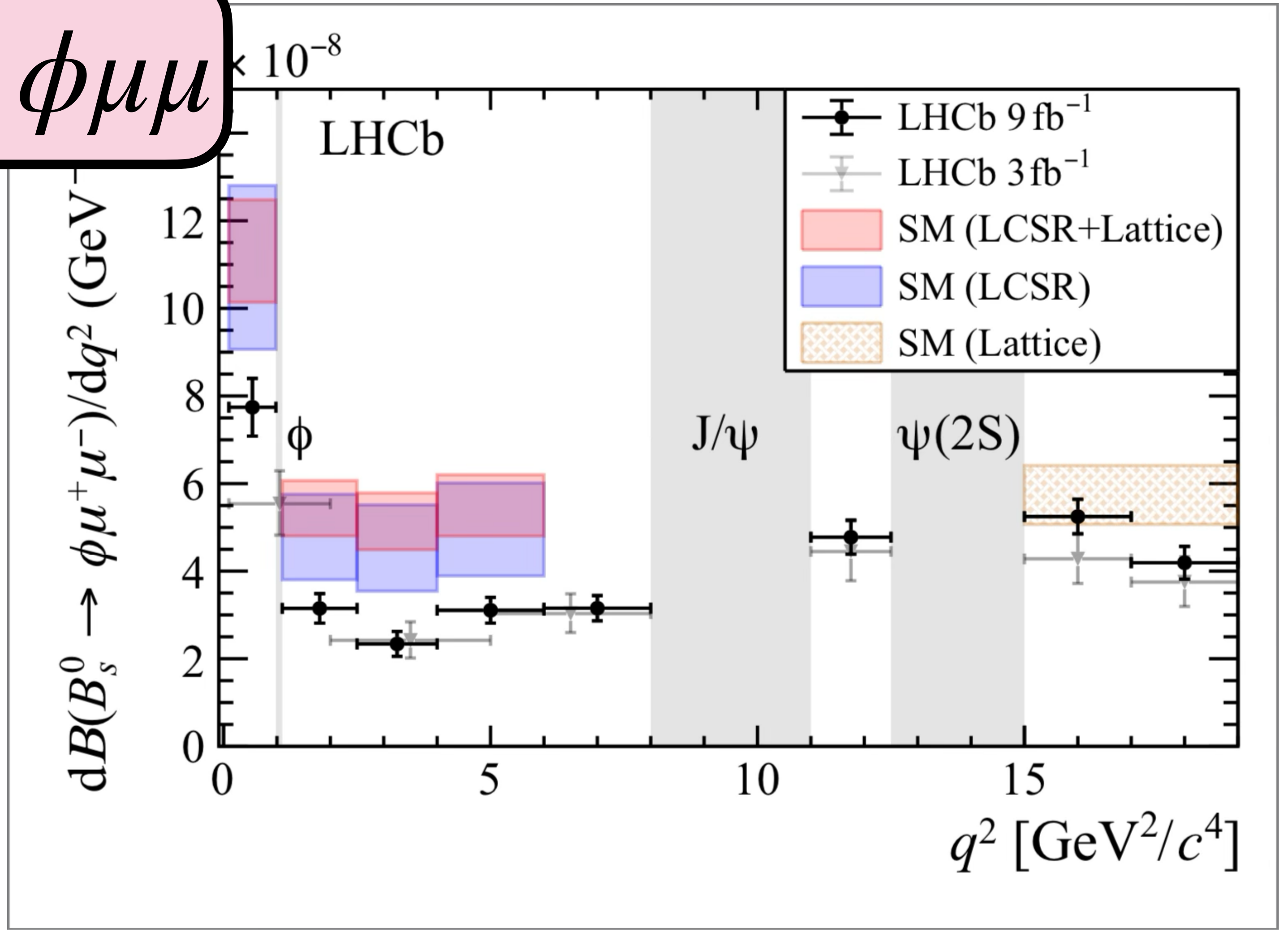
Processes studied to search for BSM at Λ~10's of TeV

The $b \to s\ell\ell$ anomalies: the branching fractions

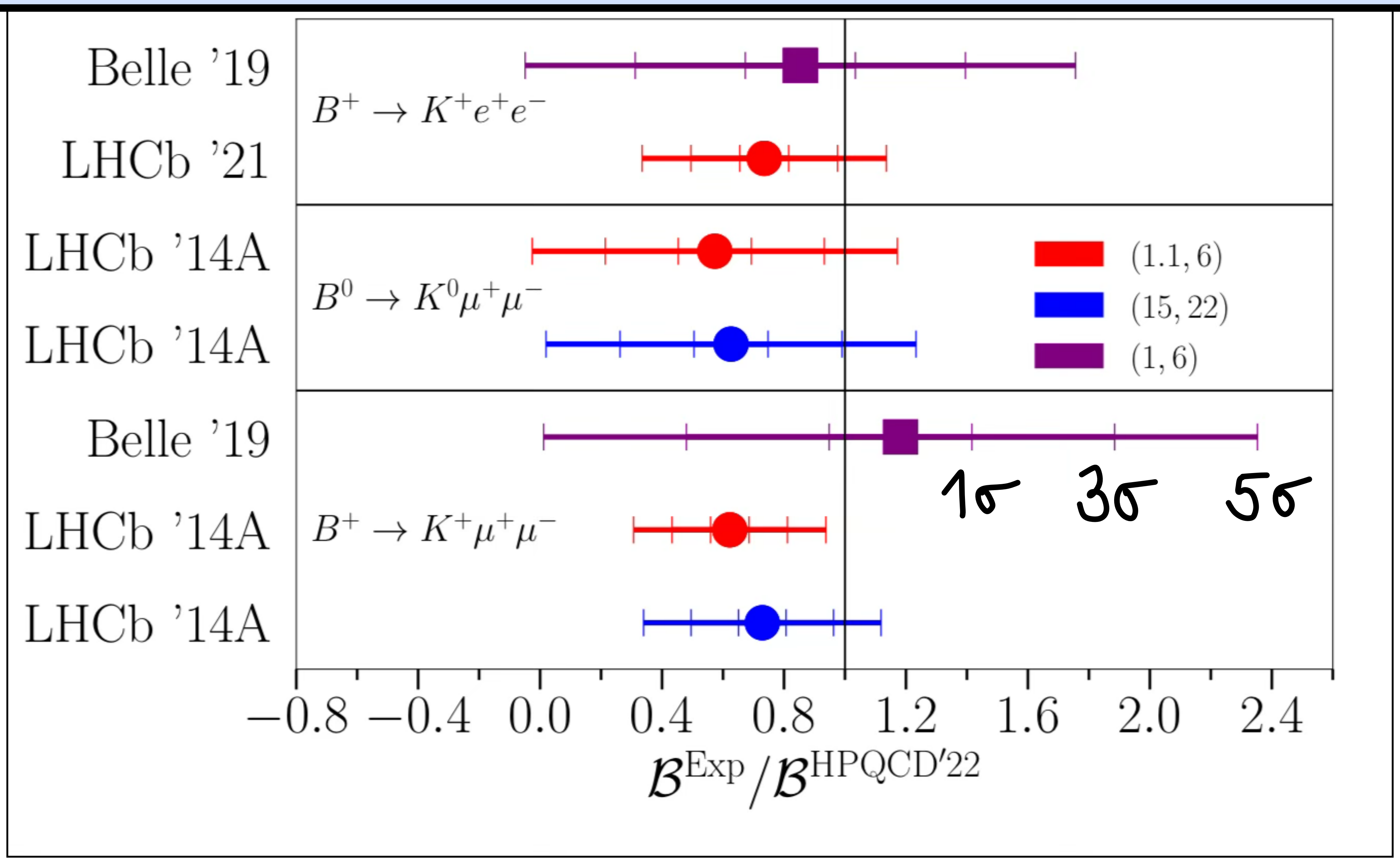
$B \to K\mu\mu$



$B_s \to \phi\mu\mu$



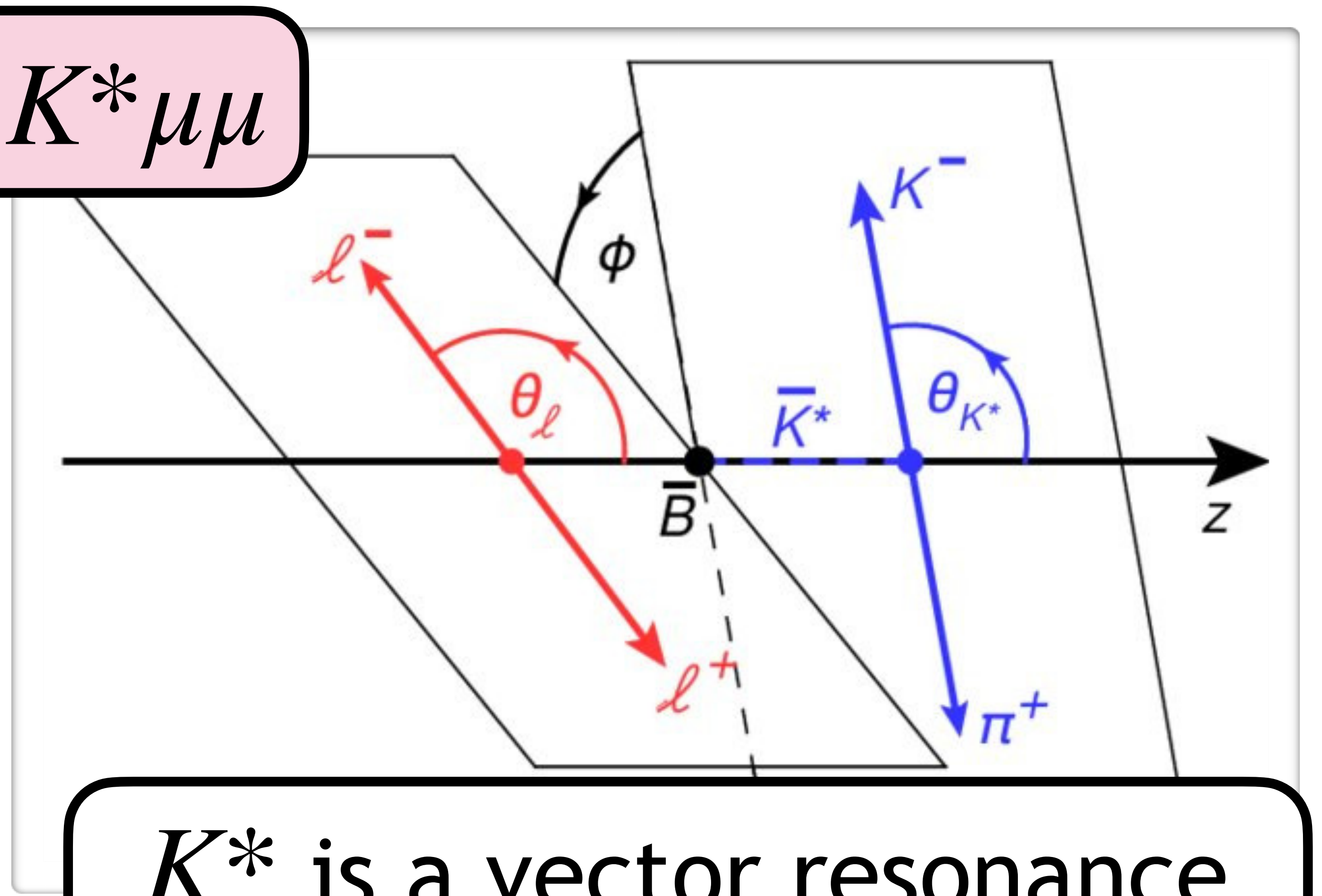
Data significantly below SM by 3σ - 4σ *individually*



HPQCD, PRD107 (2023) 1, 014511

The $b \to s\ell\ell$ anomalies: the angular analysis

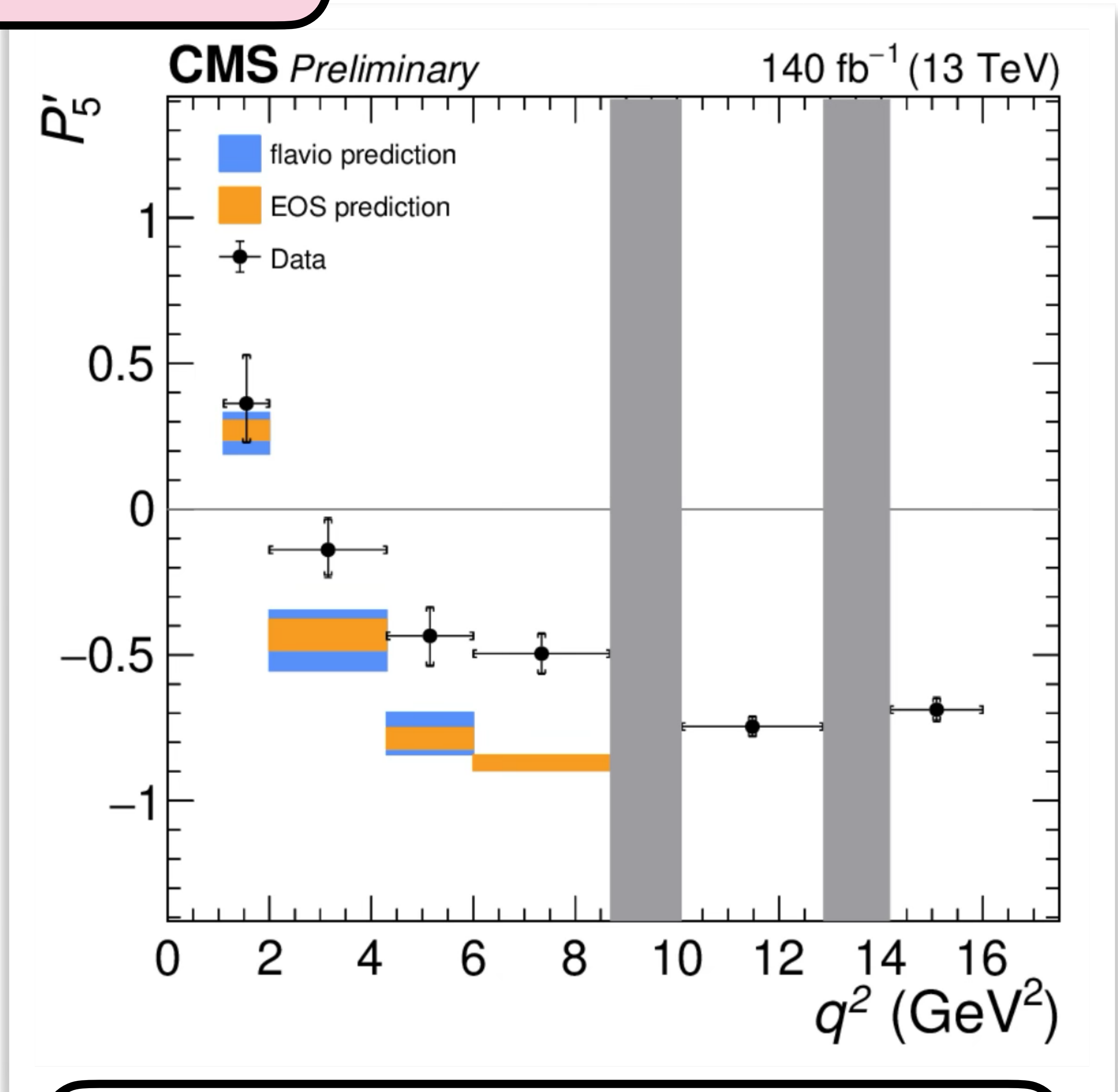
$B \to K^*\mu\mu$



K^* is a vector resonance

- **4-body decay:** Very rich phenomenology
  - 11 angular observables $I_i(q^2)$ which are q^2-dependent
  - One, $I_5(q^2)$, is related to an observable called P'_5

P'_5 anomaly



New data confirms LHCb

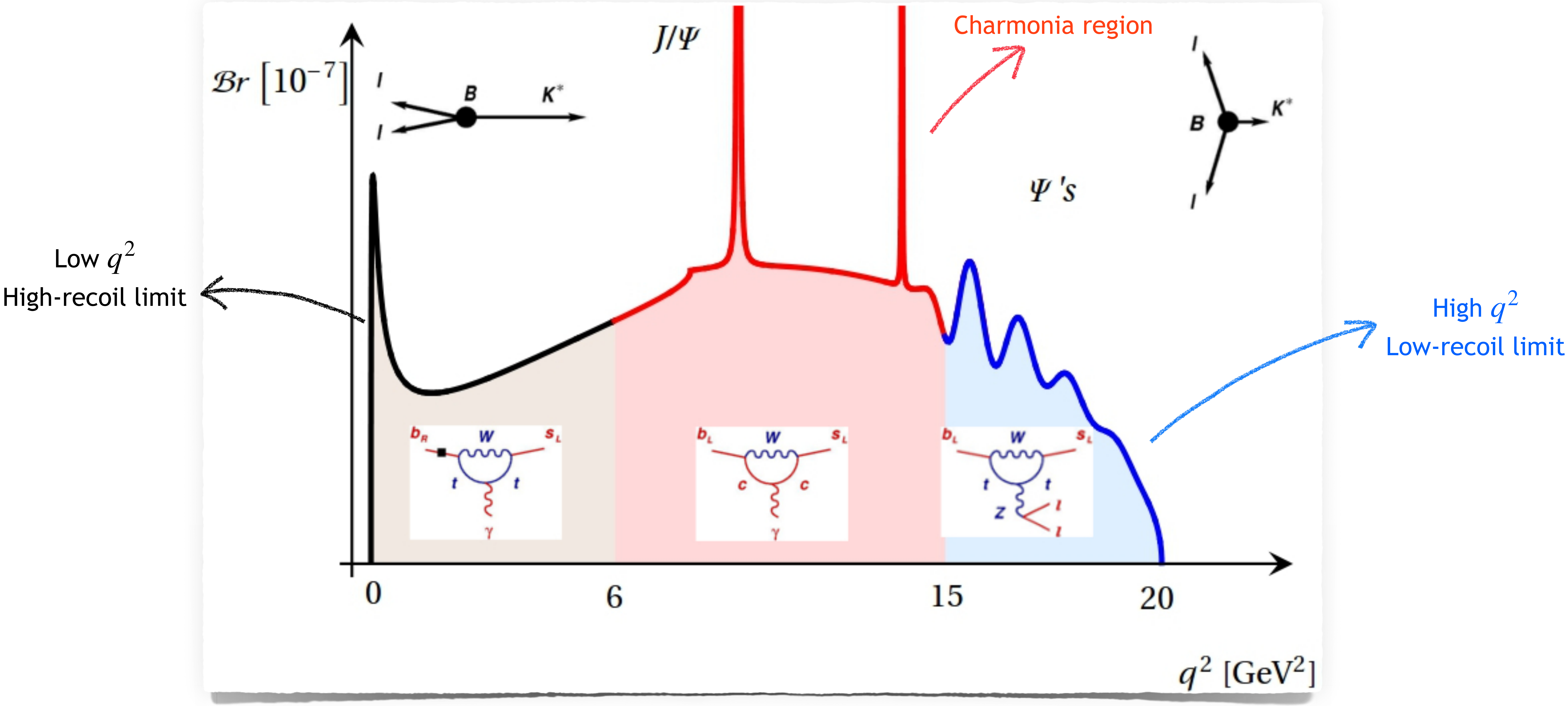
BSM hypothesis

$$C_9^{\mathrm{BSM}} \simeq -1$$

Explains all $b \to s\ell\ell$ anomalies

Descotes-Genon et al.,PRD88 (2013) 074002

Kinematic regions in the $B \to K^*\ell\ell$ decay

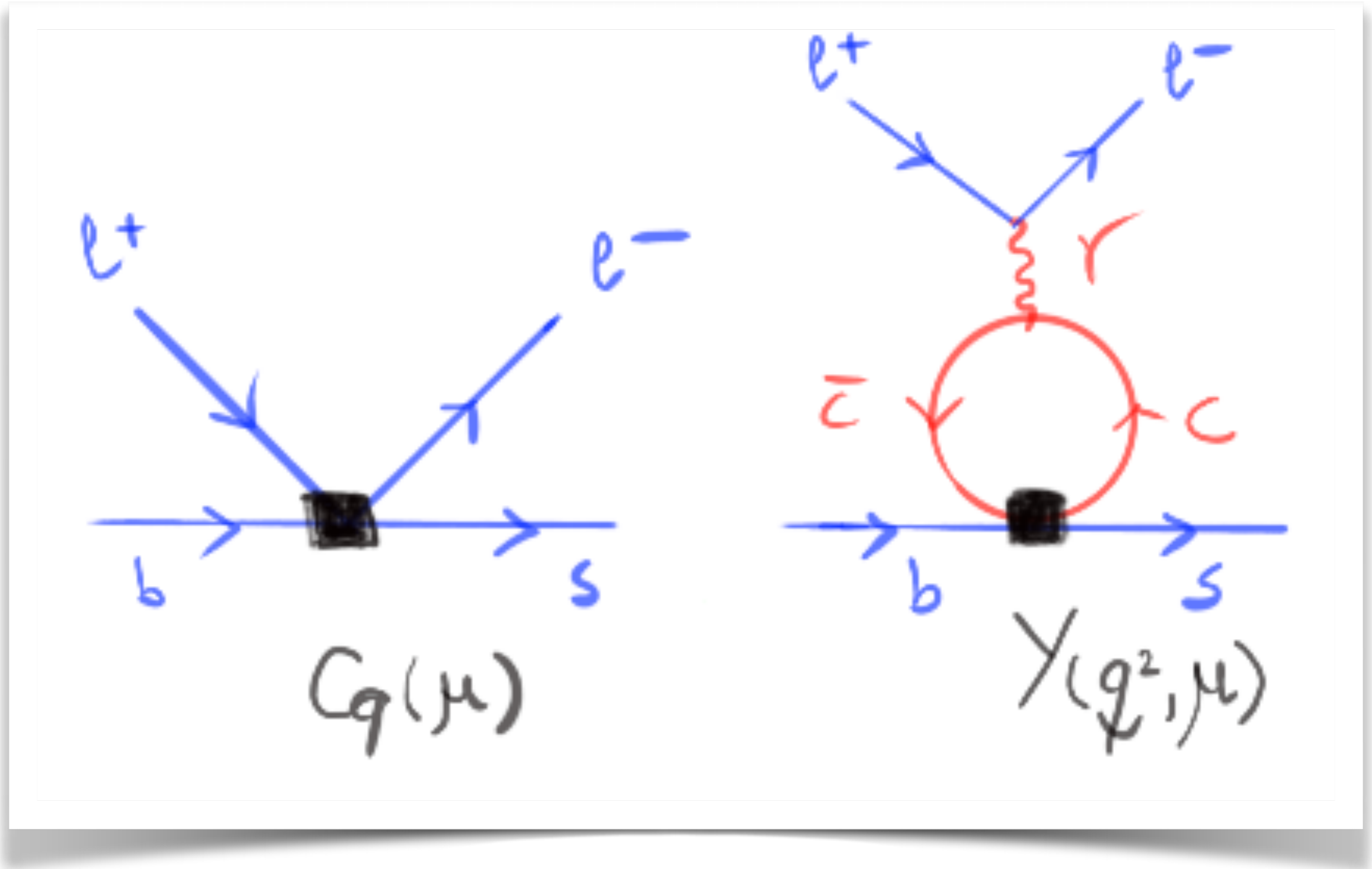


Anatomy of the vectorial $B \to K^{(*)}\ell\ell$ amplitude

- Helicity amplitudes

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

- 7 (local) form factors (independent) and 3 non-local form factors
- **Vector amplitude!** $\Rightarrow$ Sensitive to the charm contributions!



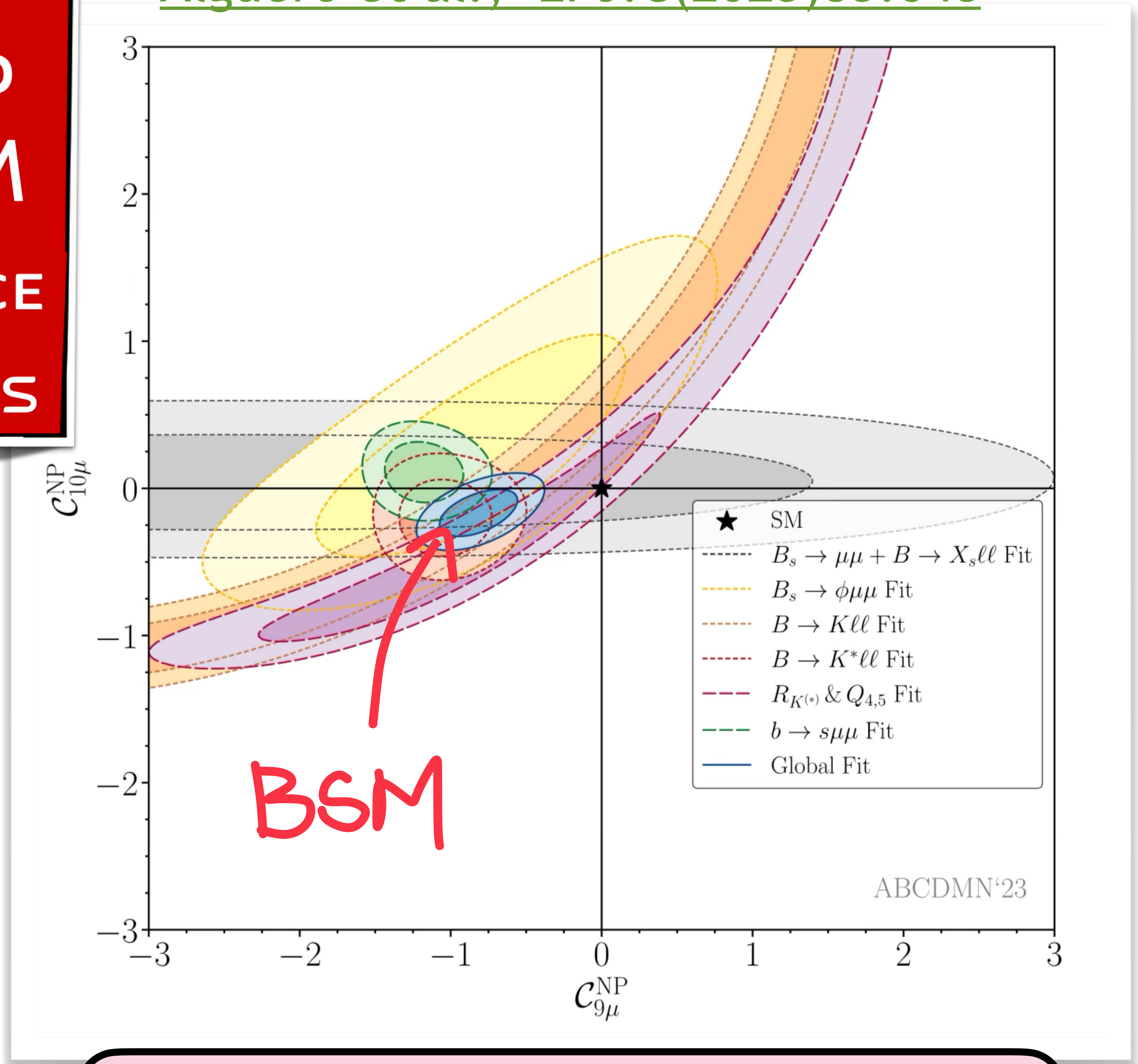
- **At leading order** $C_9^{\rm eff} = C_9(\mu) + Y(q^2, \mu)$
  - In fact $C_9^{\rm eff}$ is observable $\Rightarrow$ **Scale independent**
  - **One cannot disentangle** C_9 **from** $C_9^{\rm eff}$ **without** h_λ

Jäger and JMC, JHEP 05 (2013) 043 Ciuchini et al., JHEP 06 (2016) 116

The $b \to s\ell\ell$ anomalies: two approaches to life

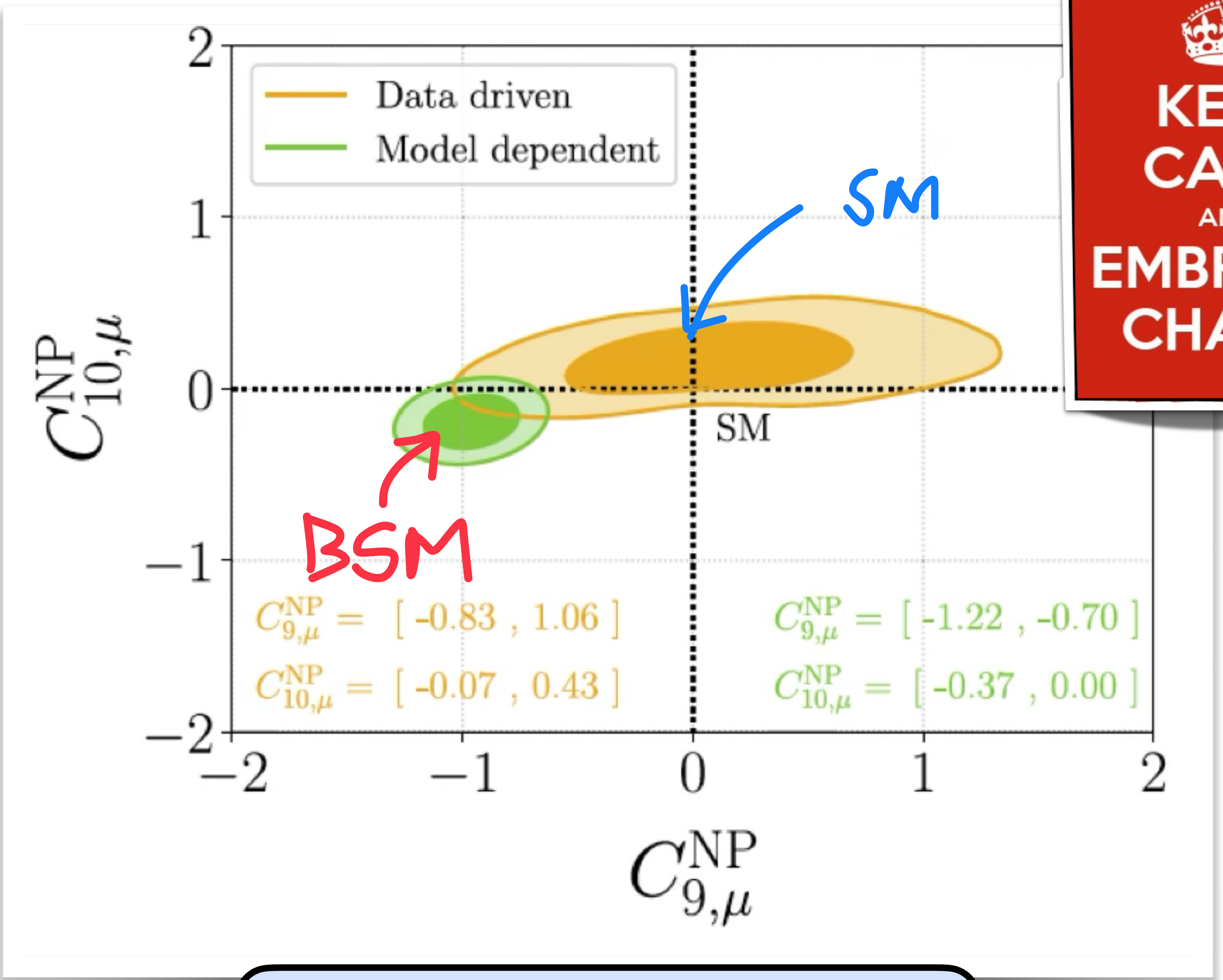
- Interpretation of data depends on **prior beliefs** about "charm"

Algueró et al., EPJ.C(2023)83:648



Tension with SM at $> 6\sigma$

Ciuchini et al., PRD107 (2023) 5, 055036



Consistent within 1σ

Key of R_K excitement: Charm cancels in the ratio!!!

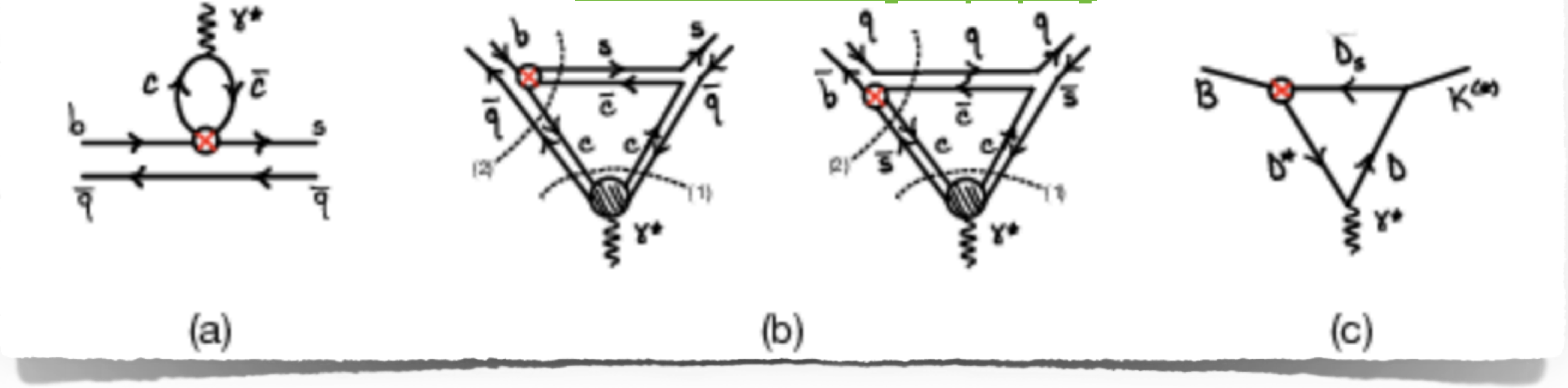
Taming the charm

- Calculate this effect at unphysical low-q^2 in QCD and sum rules: Superseed (?) standard SCET/QCDF

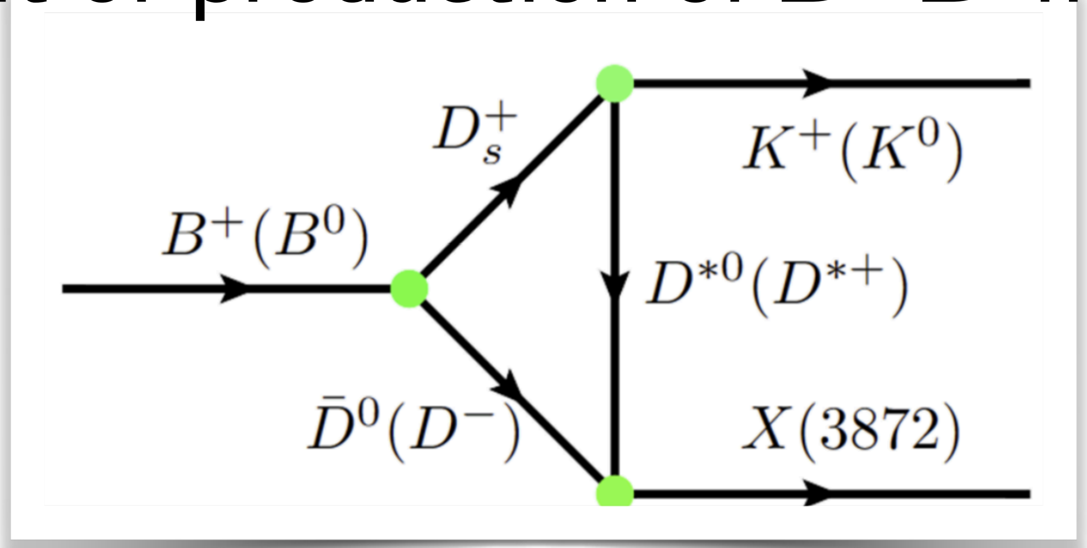
  JHEP 09 (2010) 089 JHEP 02 (2021) 088 J.Virto's talk at Zurich 204

- Estimate additional hadronic contributions

2405.17551 [hep-ph]



- Reminiscent of production of $D^*\bar{D}$ molecules



2304.05269 [hep-ph]

- **Data driven:** Amplitude analyses of data including model
- **High q^2:** Typically plagued by broad charmonia in $B \to K^{(*)}\ell\ell$ $\Rightarrow$ **Theoretically hopeless** (?!)

$B_s^* \to \ell\ell$

Grinstein & JMC, PRL116,141801

Khodjamirian et al. JHEP 11 (2015) 142

- Charm in the **perturbative regime**
- **Very challenging:** $BR \simeq 10^{-11}$
- **Upgraded HL-LHCb:** $BR \lesssim 1.2 \times 10^{-9}$

Abudinen et al., EPJ.C 82 (2022) 5, 459

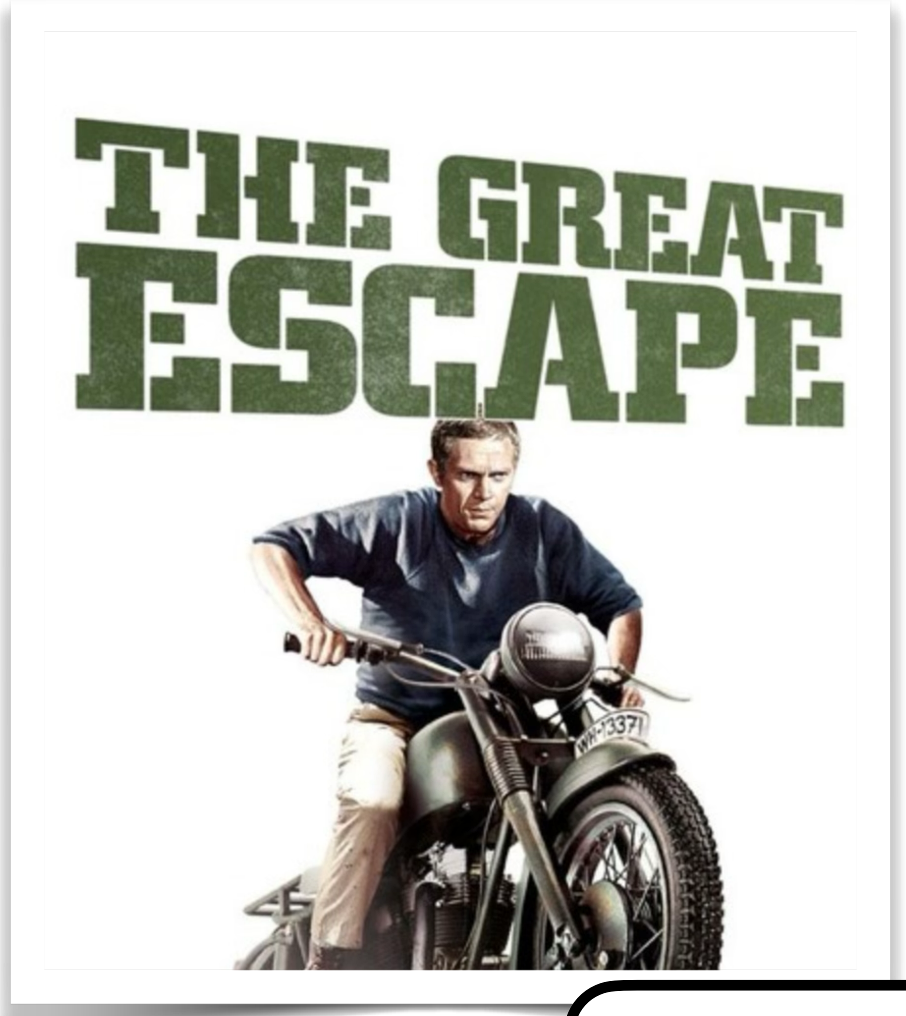
$B_s \to \gamma\ell\ell$

- Accesible at LHCb - challenging at high q^2 !
- Not completely out from charmonia region

D. Guadagnoli's talk at ALPS2023

Guadagnoli et al., JHEP 10 (2023) 102

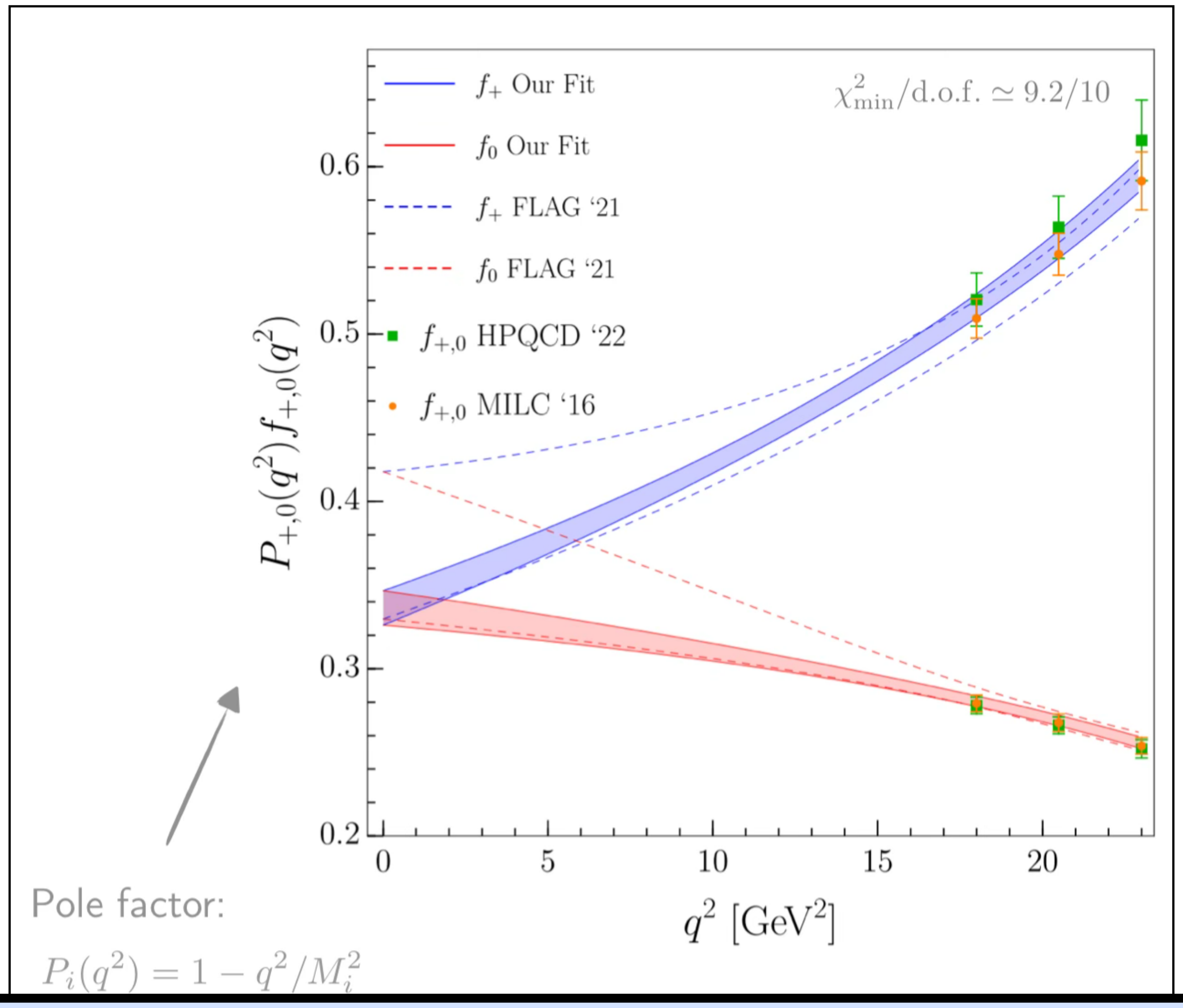
The $B \to K^{(*)}\nu\bar{\nu}$ decay



- Couple to neutrinos $\Rightarrow$ **Escape from the charm!**
- Potentially (<u>not necessarily</u>) linked to the $b \to s\ell\ell$ anomalies
- Only accessible in B factories (Belle, Belle II and BaBar)
- Under theoretical control (**LQCD**)

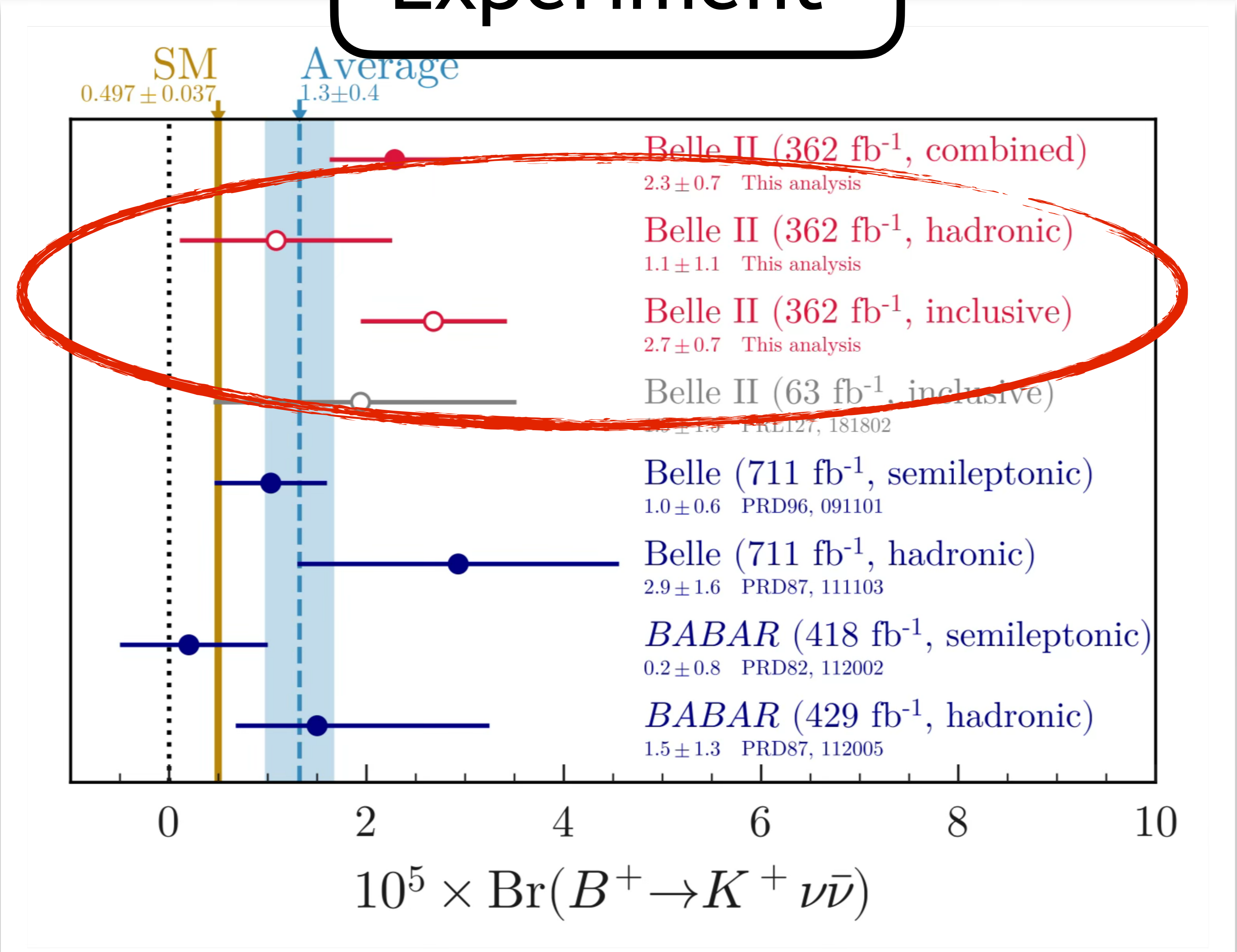
Theory

Becirevic et al., EPJC83,3,252



Form factors $B \to K$ from LQCD

Experiment

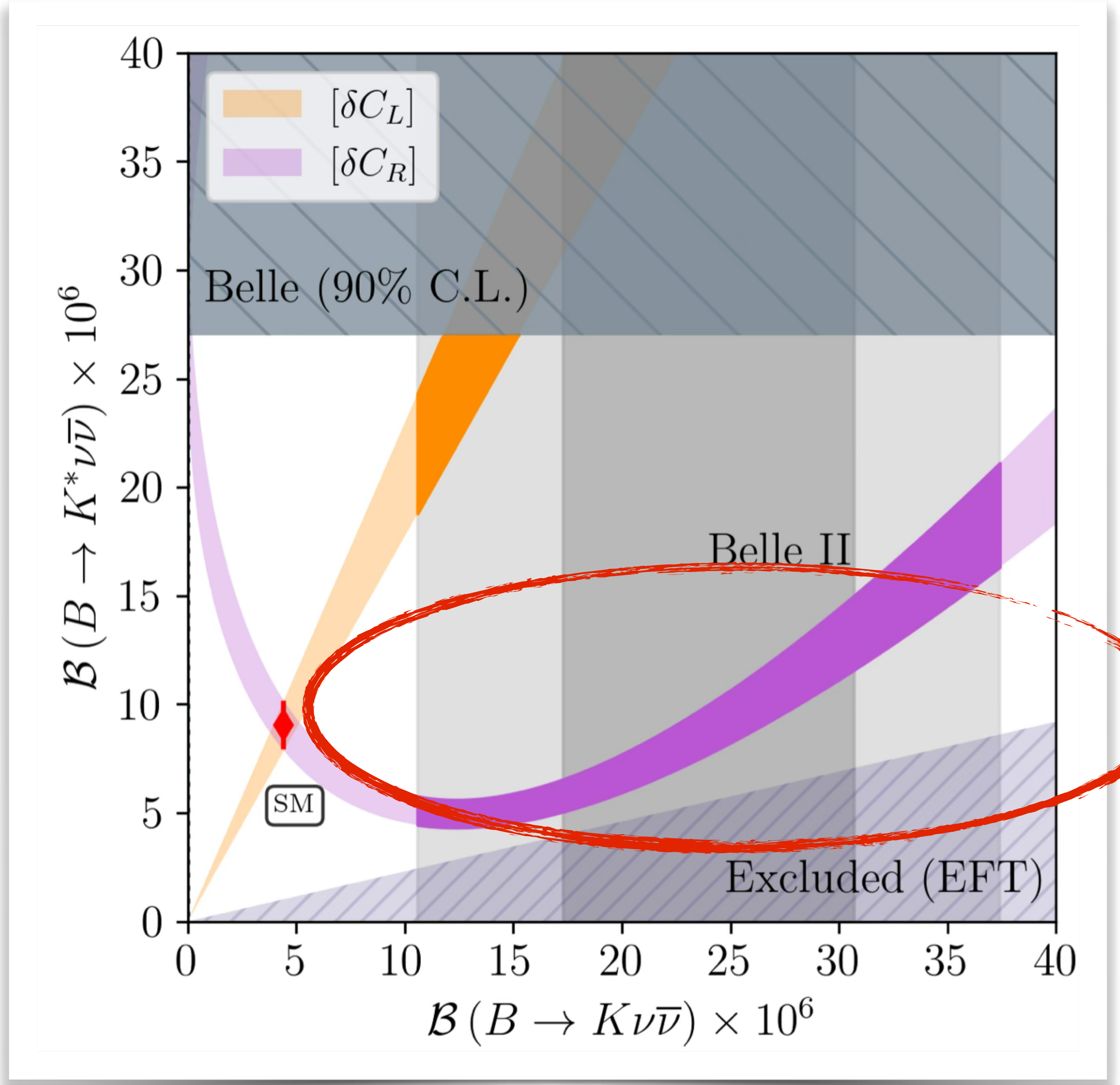


Belle excess in $B^+ \to K^+\nu\bar{\nu}$ at 2.6σ

Belle 2, PRD109(2024)11,112006

Explaining $B \to K^{(*)}\nu\bar{\nu}$ decay

- **Heavy BSM**



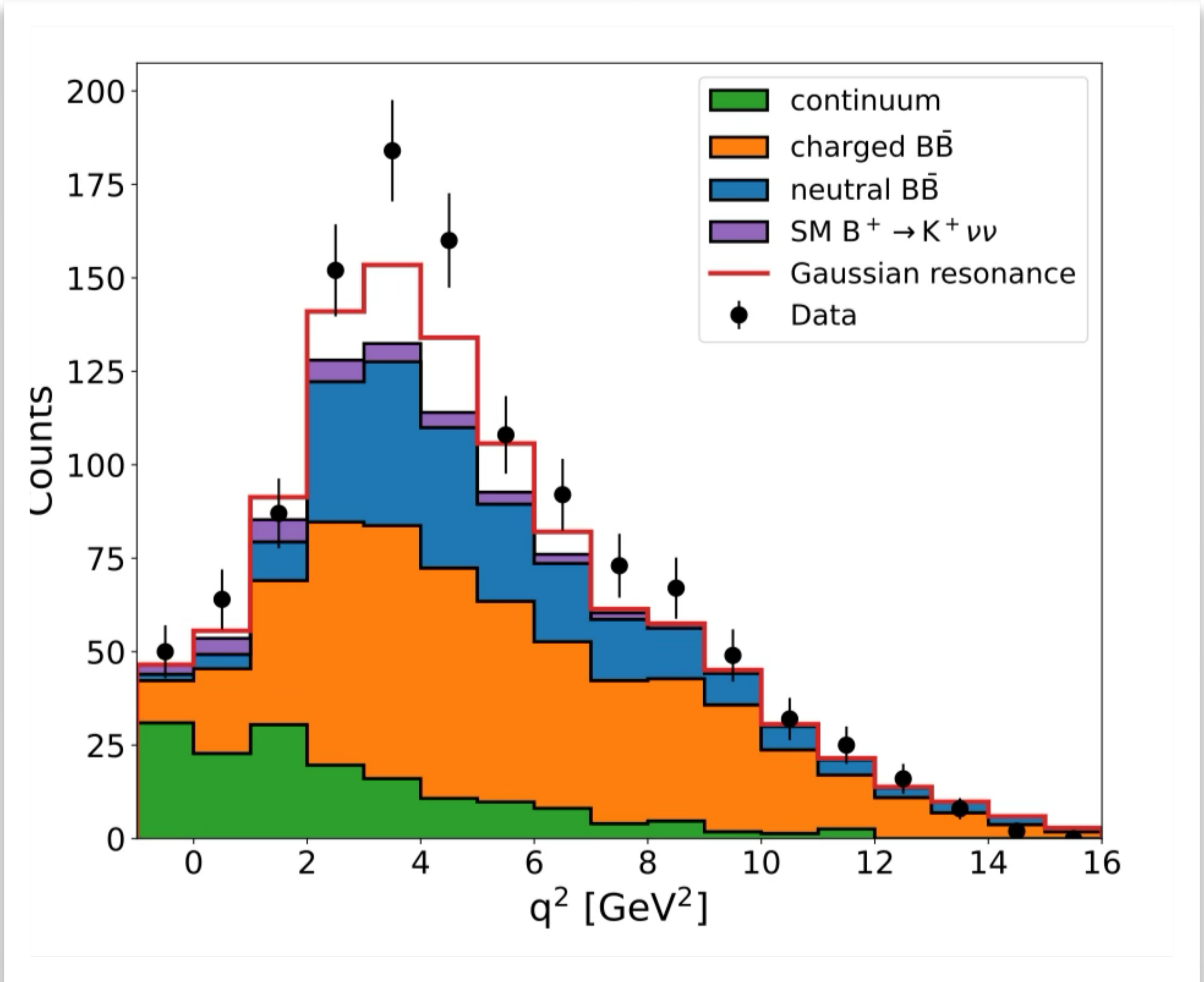
Allwicher et al., PLB848 (2024)138411

  - Potential interconection with $b \to s\ell\ell$

    Not with this result ⇒ RH currents!

  - Need LFV ⇒ **Coupling to taus**

- **Light BSM**



Altmanshofer et al., PRD109(2024) 7, 075008

  - Excess concentrated in $q^2 \simeq 4$ GeV^2
  - **Two-body $B^+ \to K^+X^0$**
  - **Connections to light dark flavored sectors!**

Very interesting measurements for the future

Conclusions

- The R_D anomalies
  - **Difficult measurements:** experimental situation **highly unclear**
  - Interest on **consistency tests** with **new observables** etc in the SM and BSM
  - Unclear motivation for BSM interpretations? ...

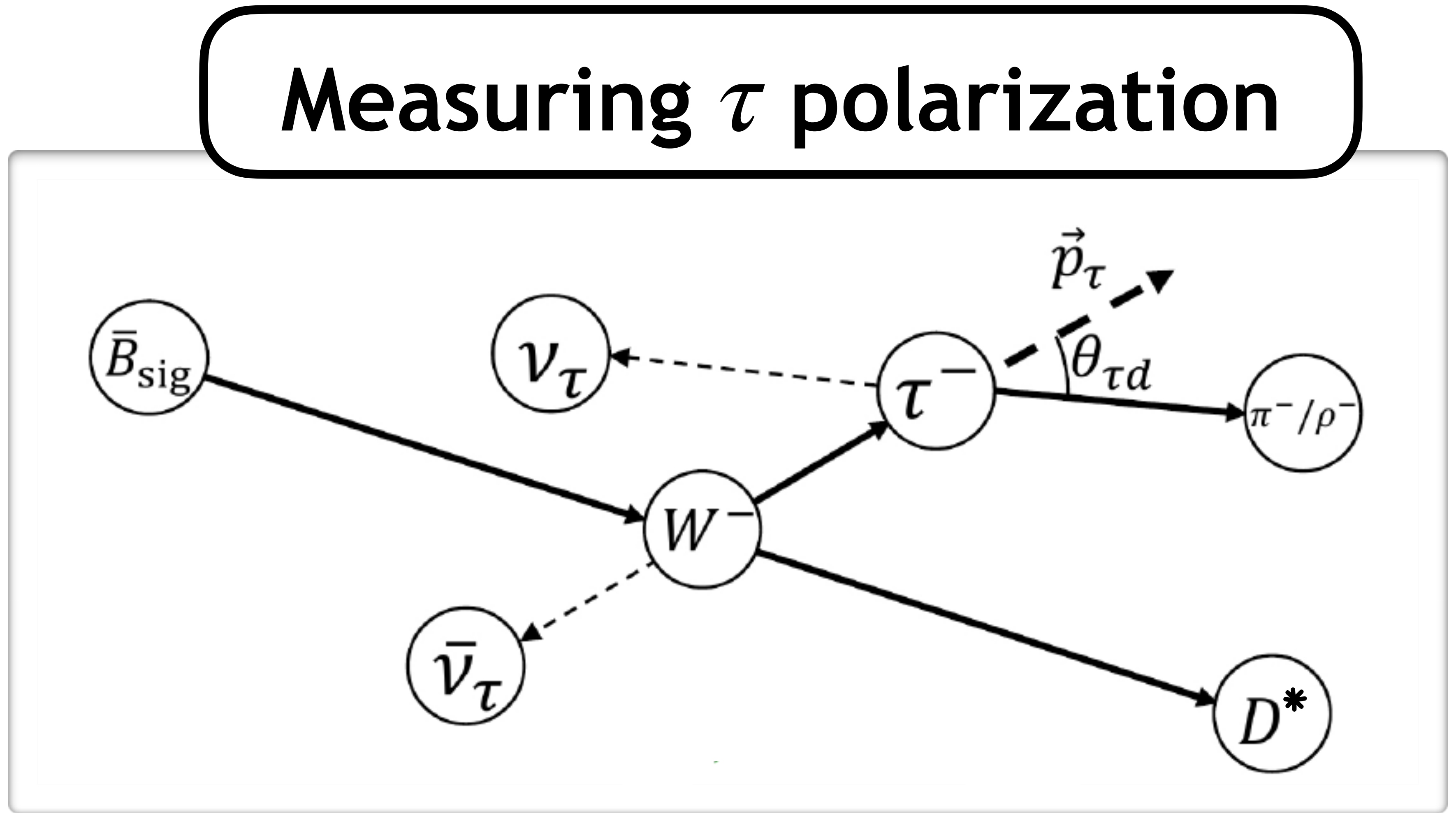
- The $b \to s\ell\ell$ anomalies
  - **Difficult theory:** understanding of the "charm" **highly unclear**
  - Interest on **hadronic physics** and interplay with weak interactions
  - New observales or decay channels ...

Keep and eye on Belle II and its neutrino modes!

Thank You

Angular observables

- Semi-tauonic decays are very complex to measure



- Lifetime of τ ~$10^{-13}s$
- Reconstruct τ decay products with missing neutrinos
  - Leptonic mode $\tau \to \ell \nu_\tau \bar{\nu}_\ell$
  - Hadronic modes $\tau \to \pi\nu_\tau$, $\tau \to \rho\nu_\tau$, $\tau \to 3\pi\nu_\tau$

Angular observables and τ properties!

Asadi, Hallin, JMC, Shih, Westhoff, PRD102(2020)9,095028

- **Polarization of the τ**

$$P_\tau^{D^*}\text{(Belle)} = -0.38 \pm 0.51 \pm 0.18$$

vs.

$$P_\tau^{D^*}\text{(SM)} = +0.497 \pm 0.007$$

Consistent within 1.6σ

- **Polarization of the D^***

$$F_L\text{(LHCb)} = 0.43 \pm 0.06 \pm 0.03$$

vs.

$$F_L\text{(SM)} = 0.464 \pm 0.03$$

Consistent within 1σ

Other decay channels

- Fundamental $b \to c\tau\nu$ transition triggers decays of other beautiful hadrons

$\Lambda_b \to \Lambda_c \tau\nu$

Valid in *any* BSM scenario!

- Channels connected by **model independent** "sum rules" $\Rightarrow$ **Tests consistency of measurements!**

$$\frac{R_{\Lambda_c}}{R_{\Lambda_c^{SM}}} = 0.28\frac{R_D}{R_D^{SM}} + 0.72\frac{R_{D^*}}{R_{D^*}^{SM}}$$

$\Rightarrow$

R_{Λ_c}(SR) $= 0.376 \pm 0.013$

vs.

R_{Λ_c}(LHCb) $= 0.242 \pm 0.076$

1.7σ failure consistency test

Blanke et al.,PRD99(2019) 7, 075006

$B_c \to J/\psi\tau\nu$

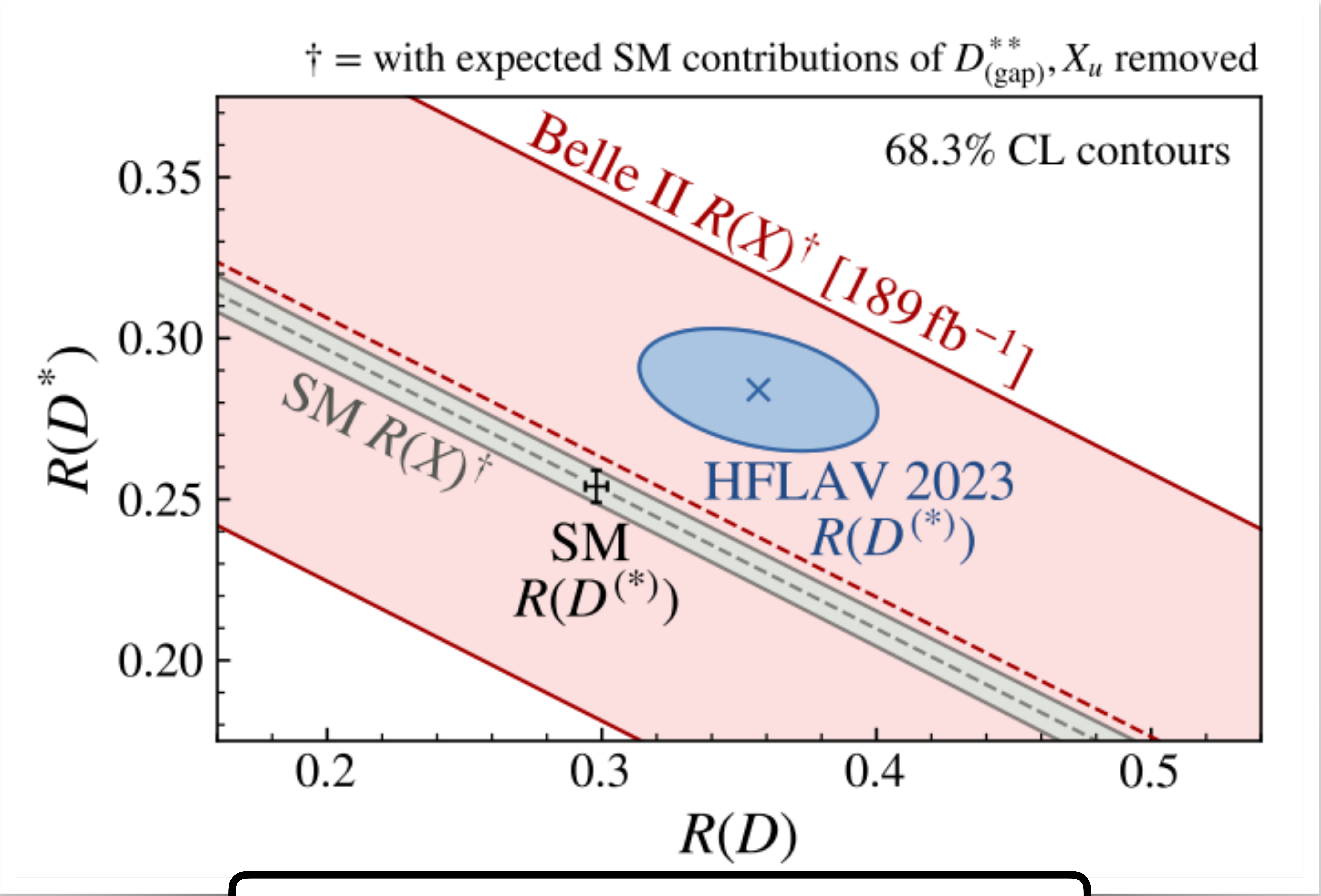
- New (preliminary) measurement by **CMS** not completely consistent with **LHCb's**

$B \to X_c\tau\nu$

- Novel **inclusive measurement** by **Belle II** consistent with both SM and BSM

Inclusive B

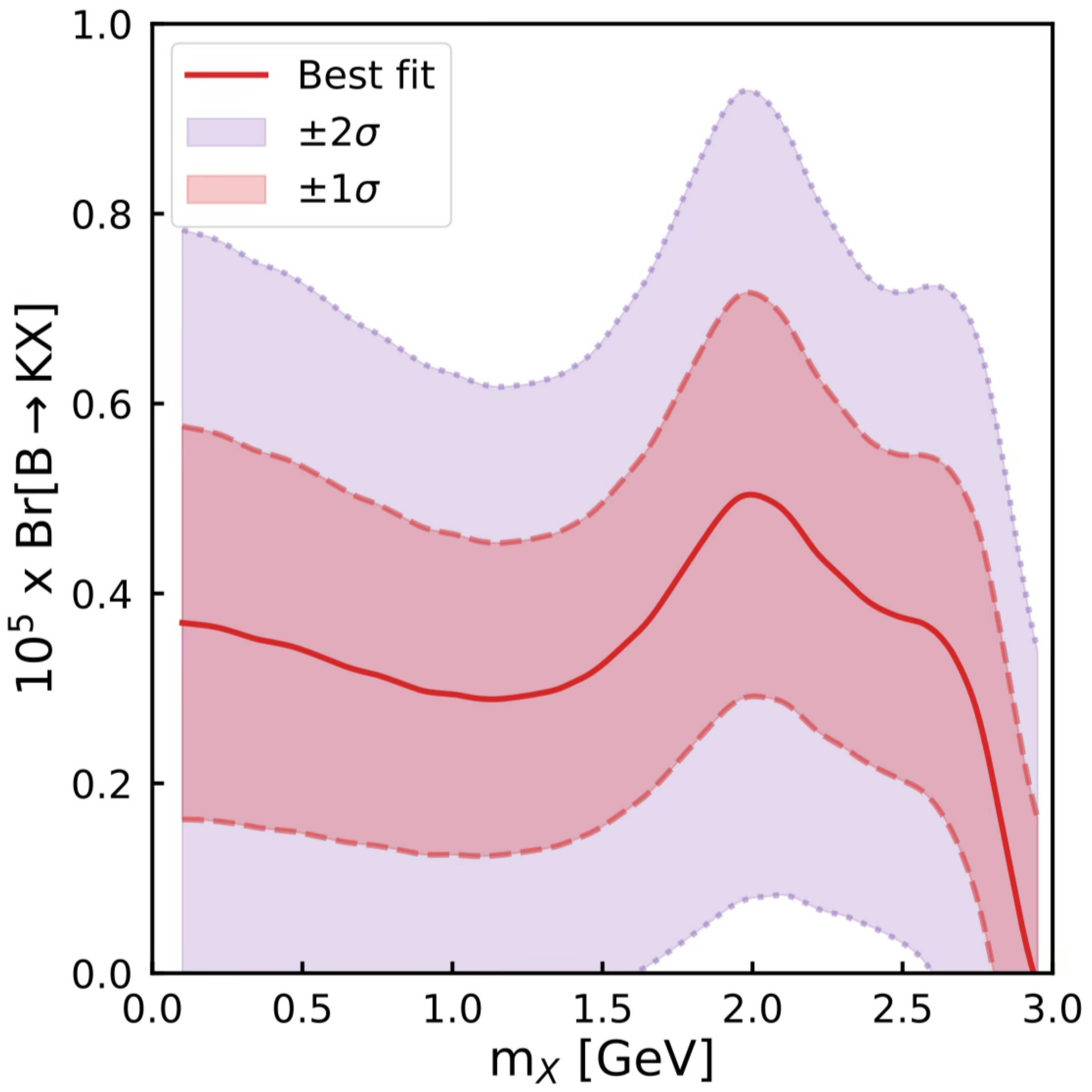
- Fundamental $b \to c\tau\nu$ transition triggers decays of other beautiful hadrons
  - **Inclusive** $B \to X_c\tau\nu$

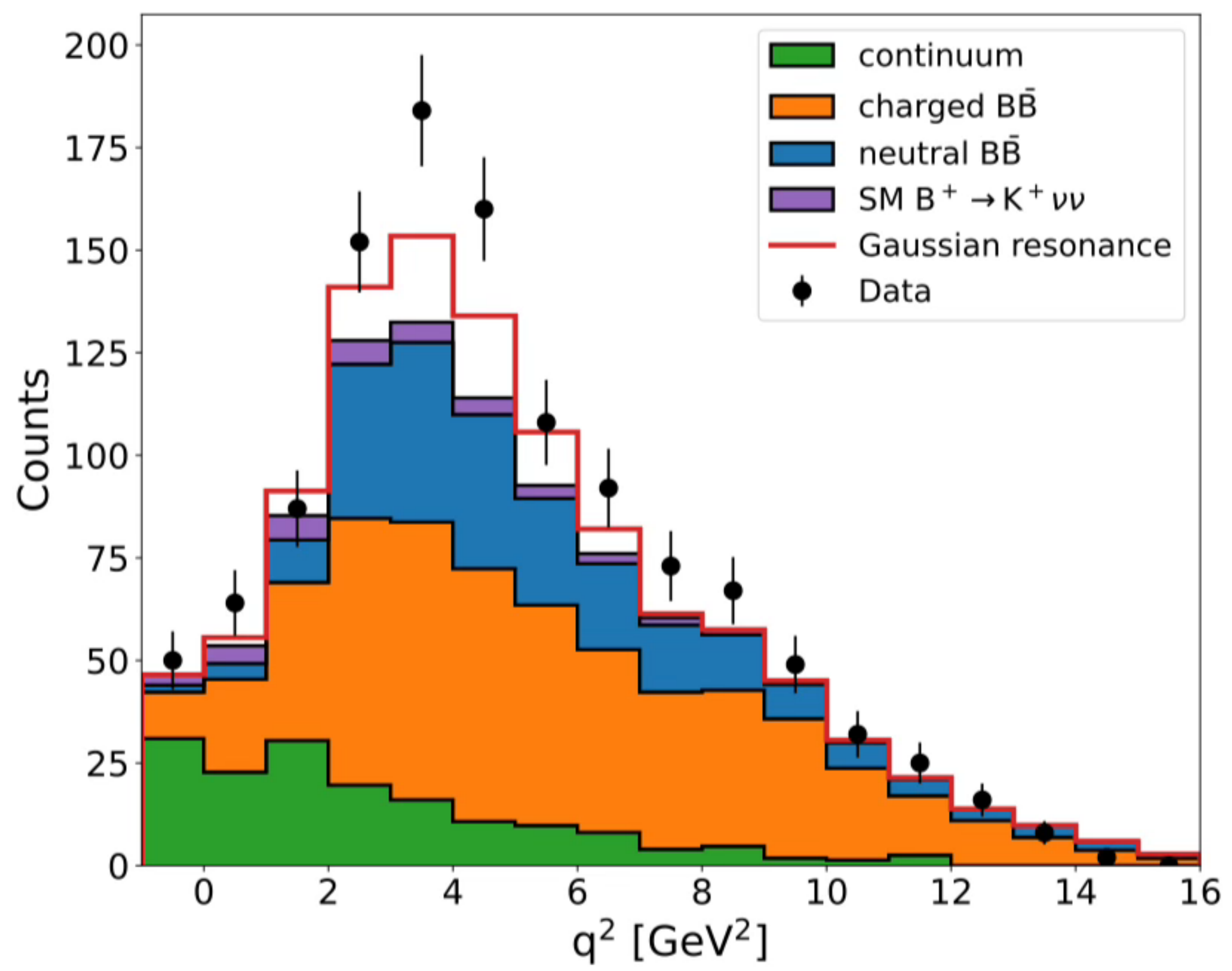


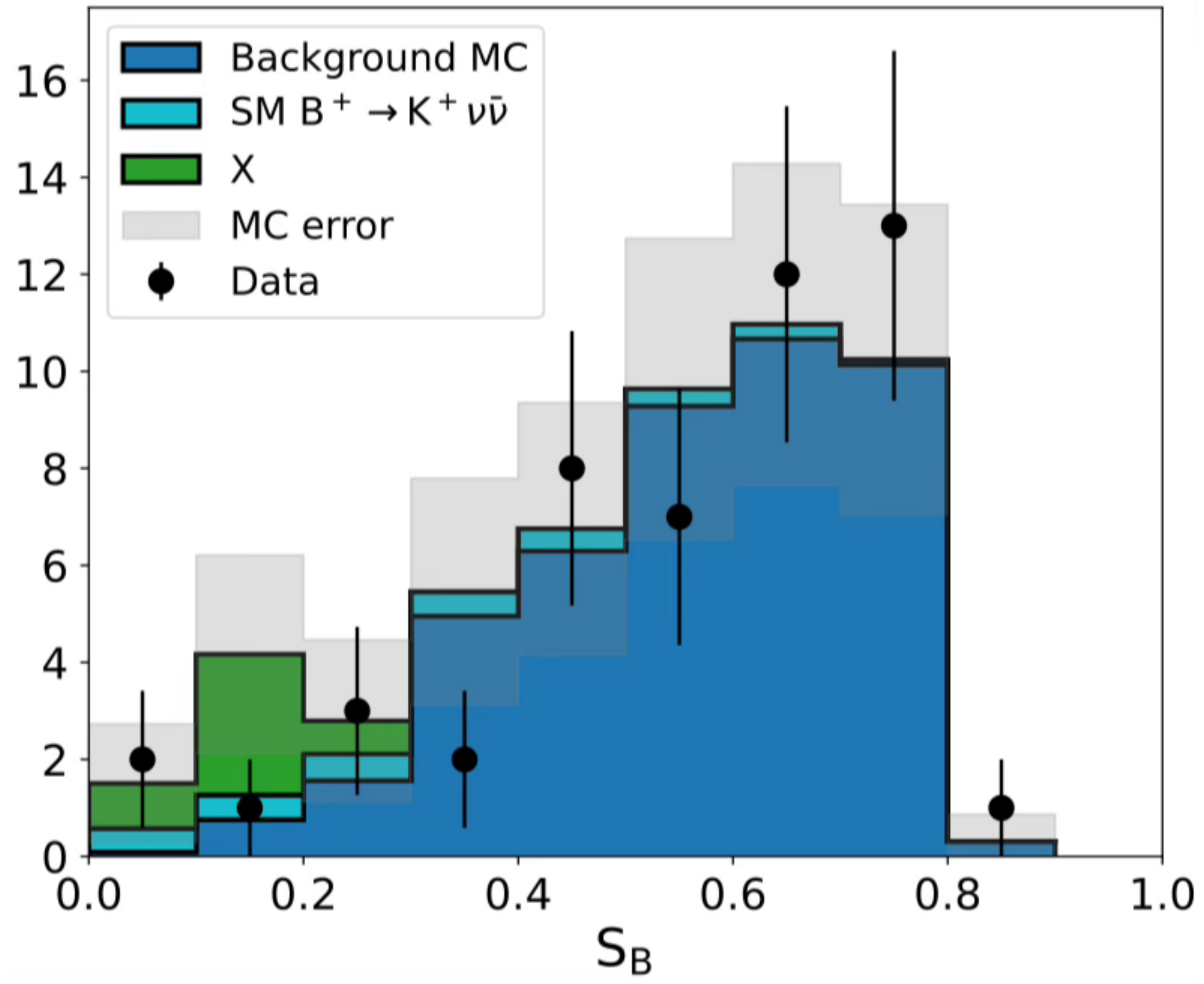
Consistent with both SM and BSM

$B^+ \to K^+ X^0$

- **Significance as a function of mass**
- **Belle II vs BaBar**

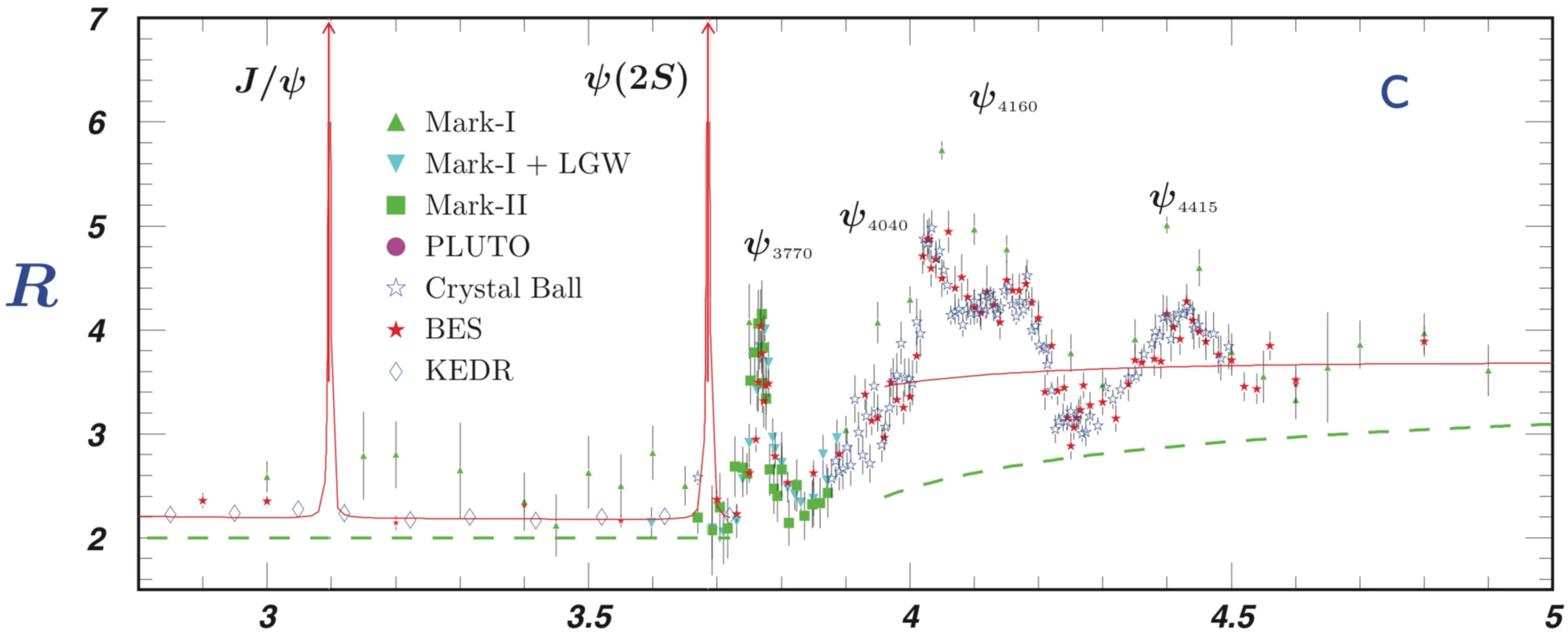




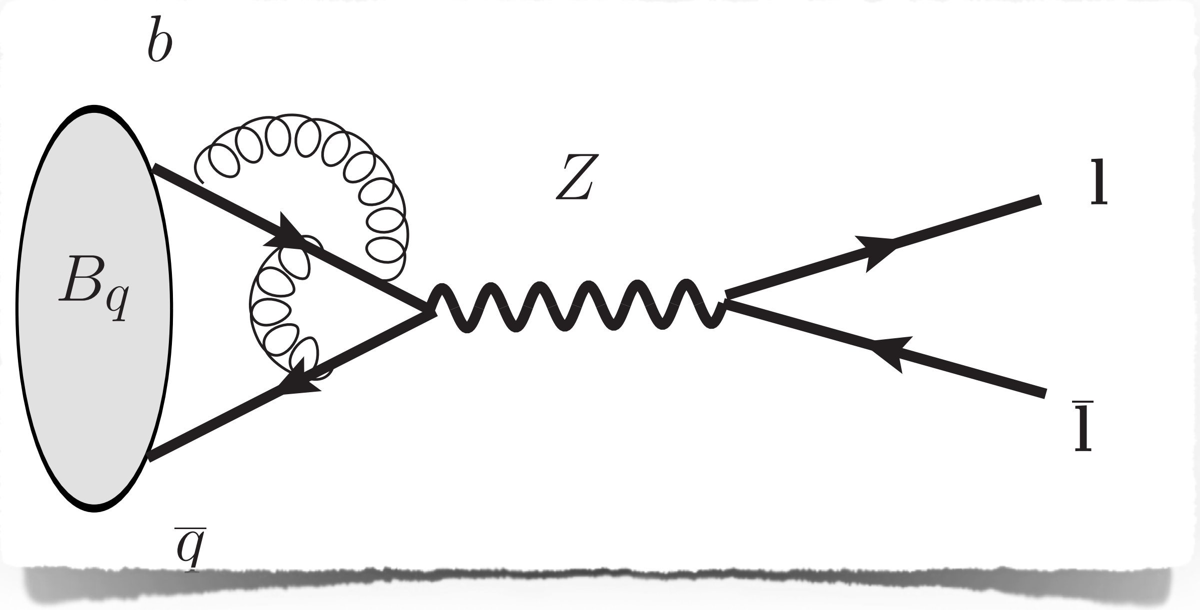


The R-factor

$$R = \frac{\sigma^{(0)}(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)},$$

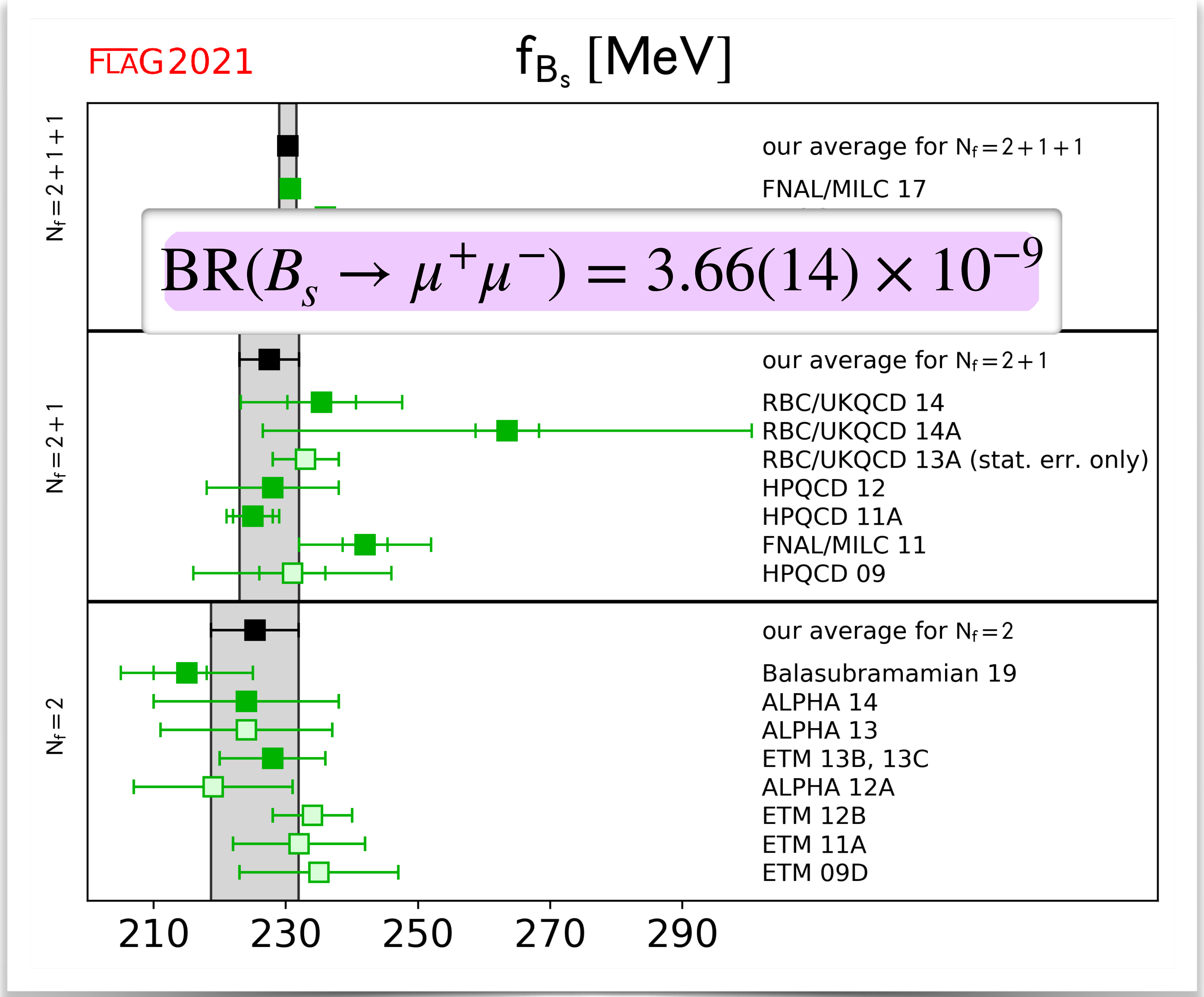


The pure leptonic $B_s \to \mu\mu$ decay



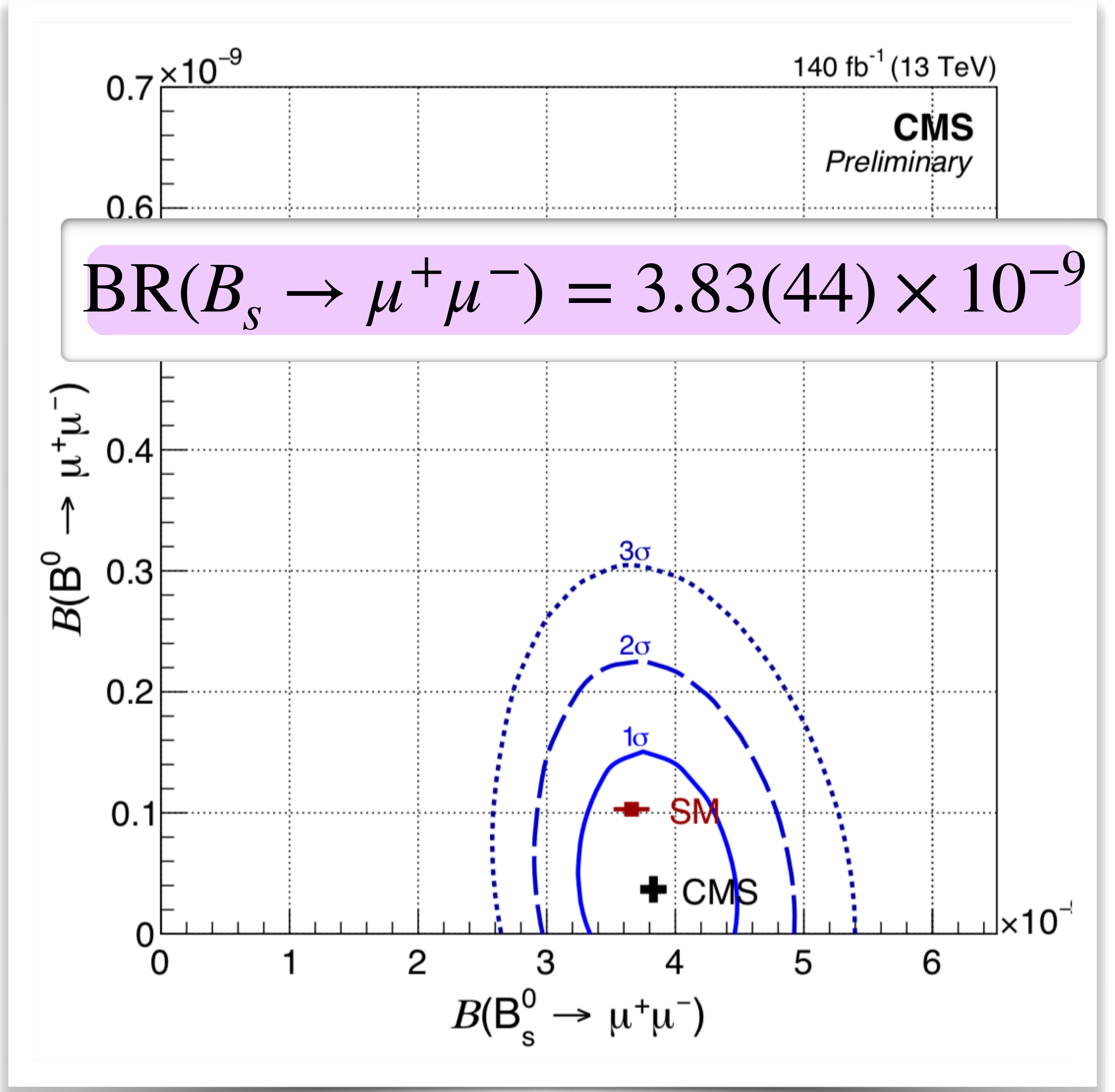
$$\mathrm{BR}(B_s \to \mu^+\mu^-) = \frac{G_F^2\alpha^2}{64\pi^3}\tau_{B_s} m_{B_s}^3 f_{B_s}^2 |V_{tb}V_{ts}^*|^2 \times \Big\{ \overbrace{|C_S - C_S'|^2 + |C_S + C_S'}^{\text{Scalar operators}} - 2\underbrace{\frac{m_\mu}{m_{B_s}}(C_{10}}_{\text{SM}} - \overbrace{C_{10}'}^{\text{RHC}})|^2 \Big\}$$

- Can be predicted accurately with LQCD inputs



$$\mathrm{BR}(B_s \to \mu^+\mu^-) = 3.66(14) \times 10^{-9}$$

- Measurement by CMS consistent with SM

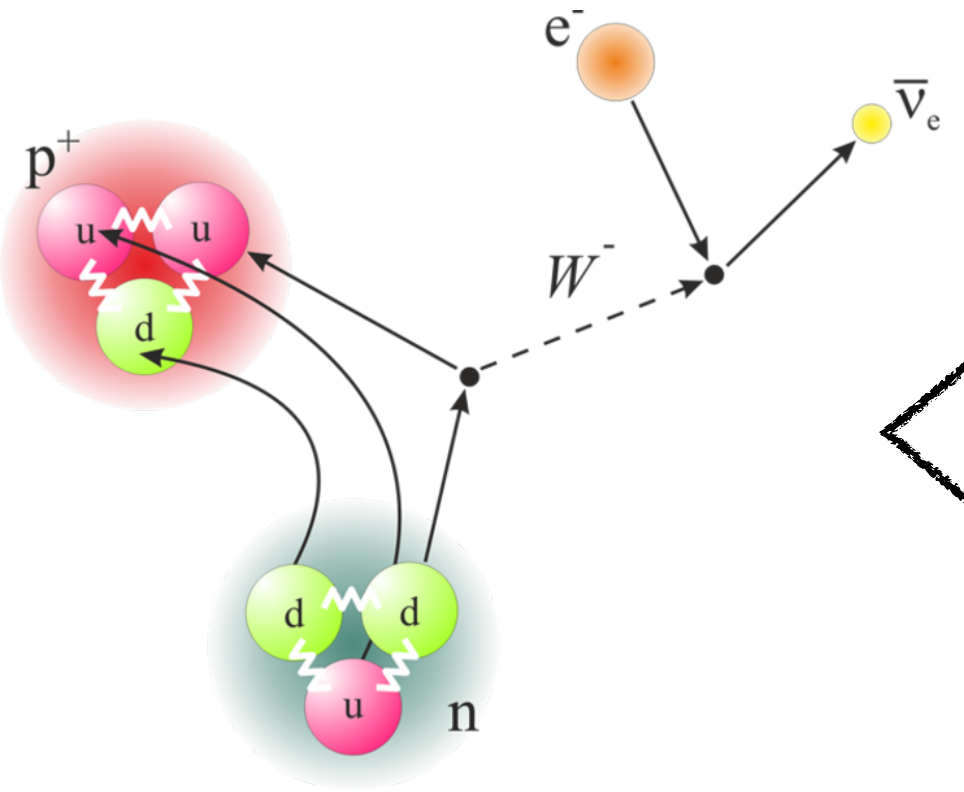


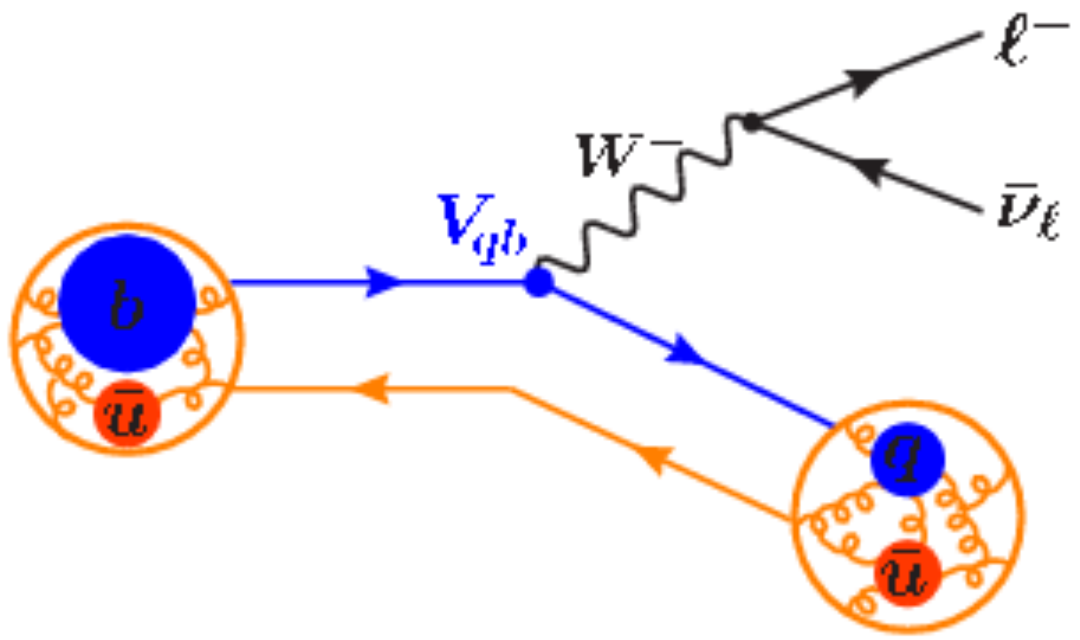
$$\mathrm{BR}(B_s \to \mu^+\mu^-) = 3.83(44) \times 10^{-9}$$

Flavor physics in the quark sector

Only weak interactions *violate* flavor

- **Classic:** Nuclear (neutron) β decay
- **Contemporary:** B meson decay



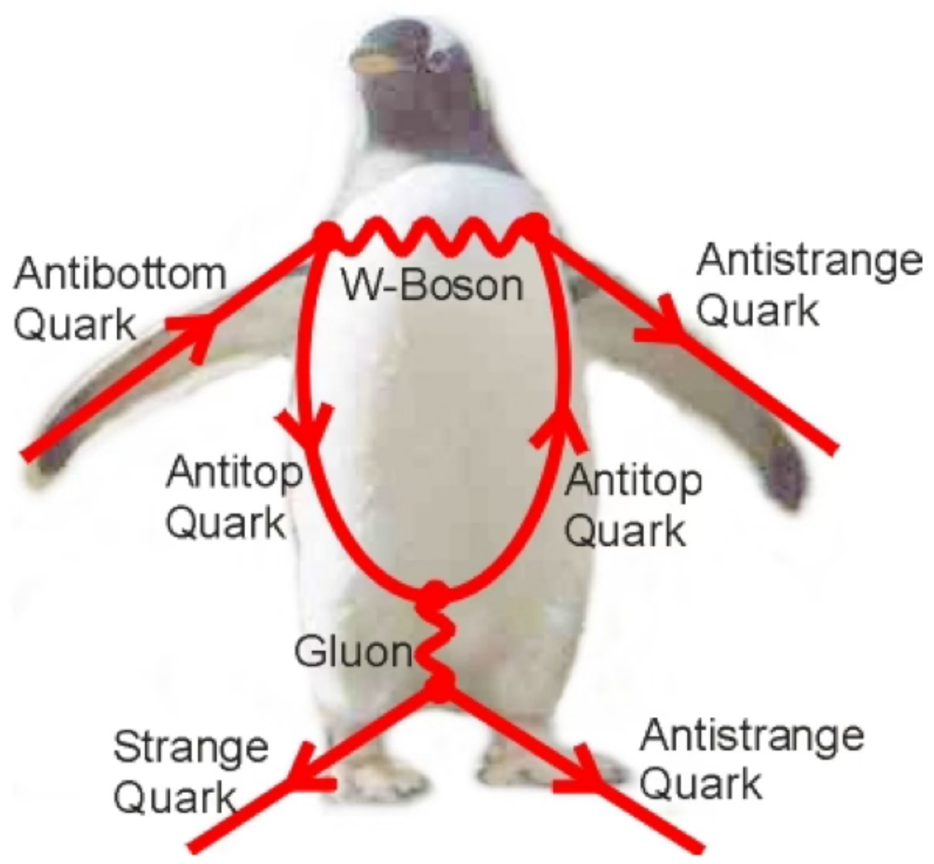


- **Nuclear β decay:** Discovery of **weak interactions** and the **neutrinos**
- **Rare kaon decays:** Discovery of **charm quark**
- **Kaon decays:** Discovery of ***CP* violation** → Discovery of **3 generations**

Flavor Physics spearheaded the discovery of the SM when the SM was the New Physics!

Flavor physics is a sensitive probe of new physics

Penguin diagram

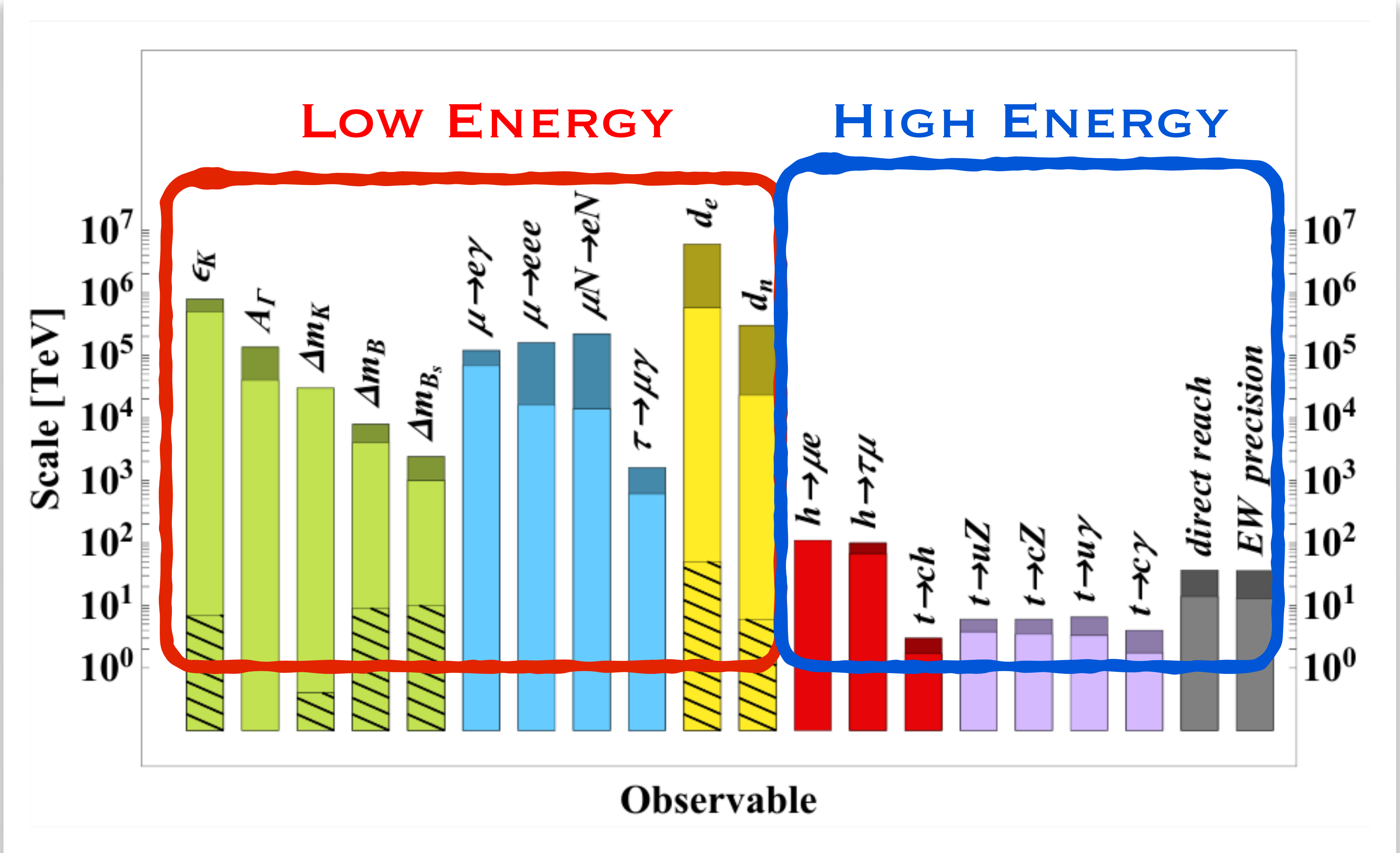


- Flavor-changing neutral currents (FCNC)
  - In the SM, FCNCs occur only at **1-loop level!**
  - In addition, they receive a **flavor suppression**

GIM mechanism

$$\text{Amplitude} \approx \underbrace{G_F}_{\text{Weak}} \underbrace{\frac{y_t^2}{8\pi}}_{\text{Loop}} \underbrace{V_{tb}V_{ts}^*}_{\text{Flavor}}$$

- FCNCs are very sensitive to BSM
  - Searching for FCNCs in experiment could herald the discovery of New Physics!
  - Null searches are typically expressed as lower-bounds on mass scales of the putative BSM



European Strategy for Particle Physics Update 2020