Institute of Particle Physics
粒 子 物 理 研 究 所

轻子味普适性理论研究

一些个人的总结和理解

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see also talks by Keche Li, Haibo Li, Longke Li, Xiaorui Lyu, Liang Sun, Jiesheng Yu
Xinqiang Li, Fusheng Yu, Qin Qin, Yue-Long Shen, Qian Zhang

LFU: origin and observable

Experimental summary and implications for New Physics

LFU violation in New Physics

Summary

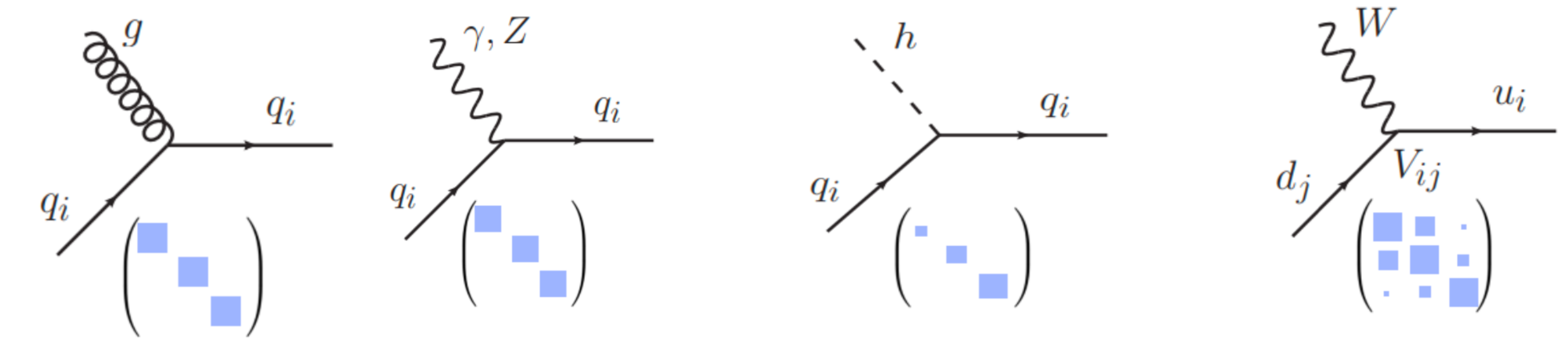
Flavour Physics

- **Flavour** **universal**
  - couplings $\propto \delta_{ij}$ in flavour space
  - example: strong and electromagnetic interactions
  - consequence of gauge invariance
- **Flavour** **diagonal**
  - couplings $\propto \lambda_i \delta_{ij}$ (diagonal, but not necessarily universal)
  - example: Yukawa interactions
- **Flavour** **violation** **(changing)**
  - couplings involve different quarks
  - no flavour violation in lepton sector ($m_\nu = 0$)
  - example: $W^\pm$ interactions in quark section
- **Flavour Changing Neutral Current (FCNC)**
  - absent at the tree-level
  - arise at the one-loop, but suppressed by GIM mechanism
- **Why flavour physics**
  - New physics $\Longleftarrow \mathcal{O}(10^9)$ $B\bar{B}$ events at BaBar and Belle
  - structure of CKM and mass
  - CP violation
  - strong interaction

experimental status

no evidence of NP	$> 5\,\sigma$
but, anomalies	$2 \sim 4\,\sigma$

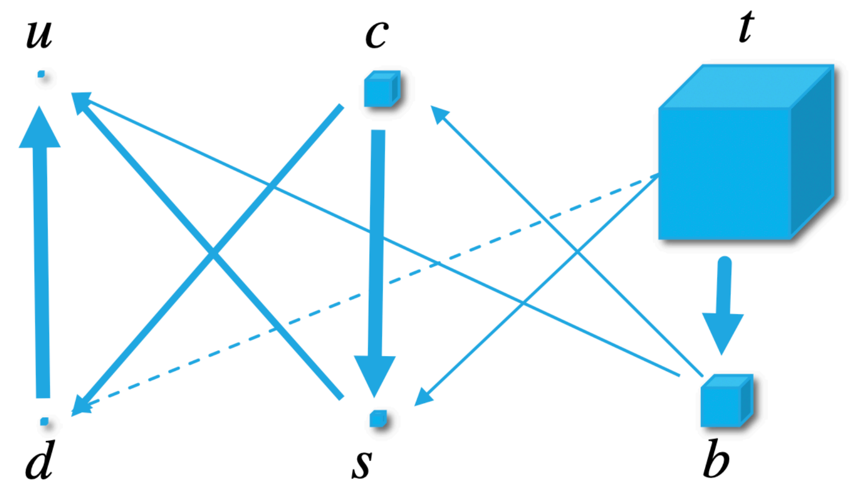
flavour universal | flavour diagonal | flavour violation



CKM matrix

- Cabibbo–Kobayashi–Maskawa matrix

$$\begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{bmatrix}$$



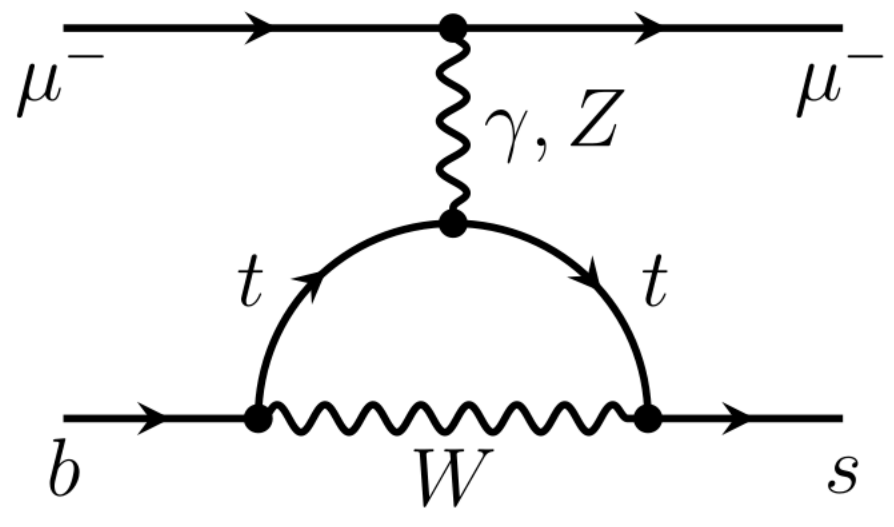
- 3 mixing angules and 1 CP phase
- CP violation in the Standard Model

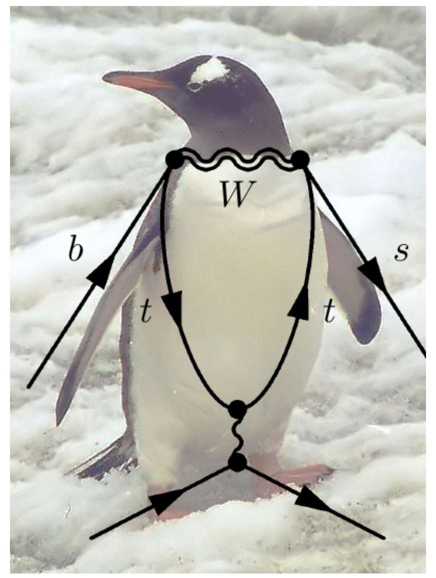
↓

not enough to explain the baryon asymmetry in our universe

↓

new CP violation sources





penguin diagram

Origin of LFU

accidental symmetry

i.e. symmetry holds for operators of dim=4, but broken by dim>4 operators

▶ Flavour universality in lepton sector

$$\bar{\ell}'_R \gamma^\mu Z_\mu Y \ell'_R \propto \begin{bmatrix} \bar{e}'_R & \bar{\mu}'_R & \bar{\tau}'_R \end{bmatrix} \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} e'_R \\ \mu'_R \\ \tau'_R \end{bmatrix} = \begin{bmatrix} \bar{e}_R & \bar{\mu}_R & \bar{\tau}_R \end{bmatrix} U_R^\dagger \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix} U_R \begin{bmatrix} e_R \\ \mu_R \\ \tau_R \end{bmatrix} = \begin{bmatrix} \bar{e}_R & \bar{\mu}_R & \bar{\tau}_R \end{bmatrix} \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} e_R \\ \mu_R \\ \tau_R \end{bmatrix}$$

interaction eigenbasis

mass eigenbasis

hypercharge of $U(1)_Y$

$Y_{e_R} = Y_{\mu_R} = Y_{\tau_R} = -1$

$\ell'_R = U_R \ell_R$

U_R: complex 3×3 unitary matrix

flavour universal

$$\bar{\ell}'_L \gamma^\mu W^-_\mu \nu'_L \propto \begin{bmatrix} \bar{e}'_L & \bar{\mu}'_L & \bar{\tau}'_L \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \nu'_{e,L} \\ \nu'_{\mu,L} \\ \nu'_{\tau,L} \end{bmatrix} = \begin{bmatrix} \bar{e}_L & \bar{\mu}_L & \bar{\tau}_L \end{bmatrix} U_\ell^\dagger \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} U_\nu \begin{bmatrix} \nu_{e,L} \\ \nu_{\mu,L} \\ \nu_{\tau,L} \end{bmatrix} = \begin{bmatrix} \bar{e}_L & \bar{\mu}_L & \bar{\tau}_L \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \nu_{e,L} \\ \nu_{\mu,L} \\ \nu_{\tau,L} \end{bmatrix}$$

neglecting neutrino masses, one can always choose $U_\nu = U_\ell$

flavour universal

▶ Flavour non-universality in quark sector

$$\bar{u}'_L \gamma^\mu W^+_\mu d'_L \propto \begin{bmatrix} \bar{u}'_L & \bar{c}'_L & \bar{t}'_L \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} d'_L \\ s'_L \\ b'_L \end{bmatrix} = \begin{bmatrix} \bar{u}_L & \bar{c}_L & \bar{t}_L \end{bmatrix} U_u^\dagger \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} U_d \begin{bmatrix} d_L \\ s_L \\ b_L \end{bmatrix} = \begin{bmatrix} \bar{u}_L & \bar{c}_L & \bar{t}_L \end{bmatrix} \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d_L \\ s_L \\ b_L \end{bmatrix}$$

flavour non-universal and non-diagonal

LFU Observable

- **Definition**

$$R_{\text{LFU}} \equiv \frac{\mathcal{O}\left(H \to \ell_1 (+\ell_1) + X\right)}{\mathcal{O}\left(H \to \ell_2 (+\ell_2) + X\right)}$$

Experimental uncertainty largely cancelled.

examples:

$$R_K = \frac{\mathcal{B}(B \to K\mu^+\mu^-)}{\mathcal{B}(B \to Ke^+e^-)} \qquad R(D^{(*)}) = \frac{\mathfrak{B}(B \to D^{(*)}\tau\nu)}{\mathfrak{B}(B \to D^{(*)}\ell\nu)}$$

$$\Delta_{\text{LFU}} \equiv \mathcal{O}\left(H \to \ell_1 (+\ell_1) + X\right) - \mathcal{O}\left(H \to \ell_2 (+\ell_2) + X\right)$$

- **General analysis within New Physics**

input parameter (mass, CKM, …)

$$R^{\mu/e}_{\text{LFU}} \equiv \frac{\mathcal{O}(H \to \mu (+\mu) + X)}{\mathcal{O}(H \to e (+e) + X)} \approx 1 + c \cdot h \cdot \left(g_\mu^{\text{NP}} - g_e^{\text{NP}}\right)$$

SM — hadronic (decay constant, form factor, …) and parameter (CKM factor, …) uncertainty largely cancelled in the SM part

hadronic parameter — hadronic uncertainty remains in the NP part

NP couplings

π, K, τ systems

A. Pich, Prog. Part. Nucl. Phys. 75 (2014) 41
B. Bryman, Cirigliano, Crivellin, Inguglia, Annu. Rev. Nucl. Part. Sci. 2022. 72:69-91

- **π decay**

$$R^P_{e/\mu} = \frac{\Gamma[P \to e\bar{\nu}_e(\gamma)]}{\Gamma[P \to \mu\bar{\nu}_\mu(\gamma)]} \qquad \left(\frac{A_\mu}{A_e}\right)_{R^\pi_{e/\mu}} = 1.0010 \pm 0.0009$$

- **K decay**

LFU holds @$\mathcal{O}(0.1\%)$

$$R^K_{e/\mu} = \frac{\Gamma\left[K^+ \to e^+\nu(\gamma)\right]}{\Gamma\left[K^+ \to \mu^+\nu(\gamma)\right]} \qquad \left(\frac{A_\mu}{A_e}\right)_{R^K_{e/\mu}} = 0.9978 \pm 0.0018$$

$$R^{K\to\pi}_{e/\mu} = \frac{\Gamma\left[K \to \pi e\nu(\gamma)\right]}{\Gamma\left[K \to \pi\mu\nu(\gamma)\right]} \qquad \left(\frac{A_\mu}{A_e}\right)_{R^{K_L\to\pi}_{e/\mu}} = 1.0022 \pm 0.0024, \qquad \left(\frac{A_\mu}{A_e}\right)_{R^{K^\pm\to\pi^\pm}_{e/\mu}} = 0.9995 \pm 0.0026$$

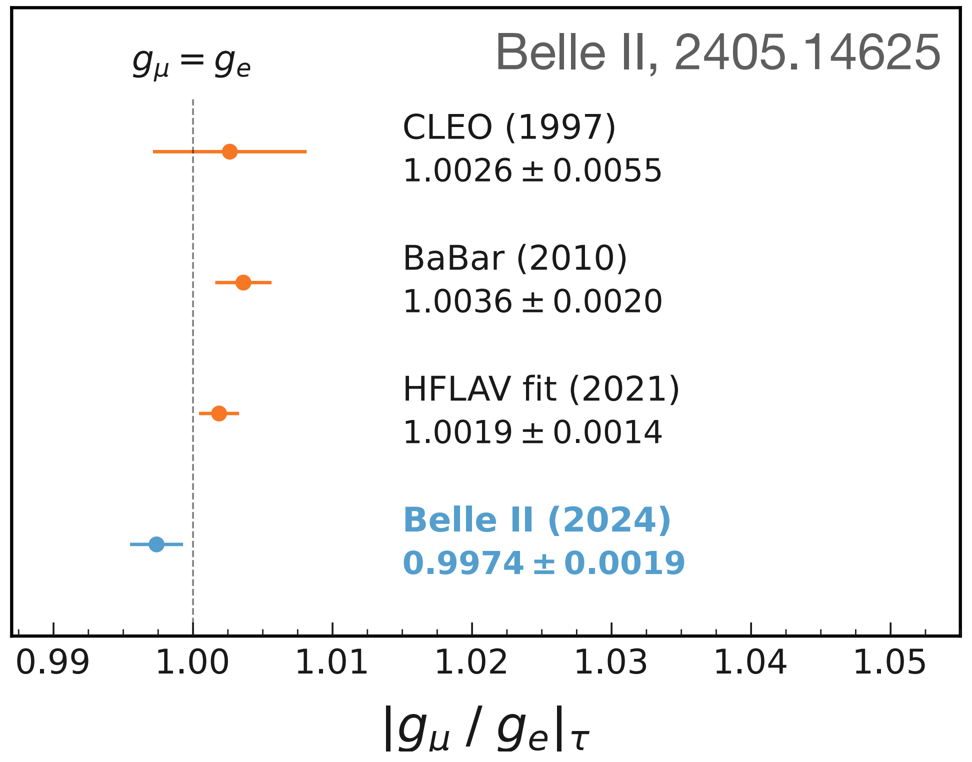
- **τ decay**

$$R^\tau_{\tau/e} = \frac{Br(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)}{Br(\mu^- \to e^-\bar{\nu}_e\nu_\mu)} \qquad \left(\frac{A_\tau}{A_e}\right)_\tau = 1.0029 \pm 0.0014$$

$$R^\tau_{\tau/\mu} = \frac{Br(\tau^- \to e^-\bar{\nu}_e\nu_\tau)}{Br(\mu^- \to e^-\bar{\nu}_e\nu_\mu)} \qquad \left(\frac{A_\tau}{A_\mu}\right)_\tau = 1.0010 \pm 0.0014$$

$$R^\tau_{\mu/e} = \frac{Br(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)}{Br(\tau^- \to e^-\bar{\nu}_e\nu_\tau)} \qquad \left(\frac{A_\mu}{A_e}\right)_\tau = 1.0018 \pm 0.0014$$

recent updates



$$R^{\tau\pi(K)}_{\tau/\mu} = \frac{Br[\tau \to \pi(K)\nu_\tau]}{Br[\pi(K) \to \mu\nu_\mu]} \qquad \left(\frac{A_\tau}{A_\mu}\right)_\pi = 0.9964 \pm 0.0038 \qquad \left(\frac{A_\tau}{A_\mu}\right)_K = 0.9857 \pm 0.0078$$

Z and W boson

▸ Z boson decay

$\Gamma(\mu^+\mu^-)/\Gamma(e^+e^-)$ — Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
1.0001±0.0024 OUR AVERAGE				
0.9974±0.0050	[1] AABOUD	17Q	ATLS	E^{pp}_{cm} = 7 TeV
1.0009±0.0028	[2] LEP-SLC	06		E^{ee}_{cm} = 88–94 GeV

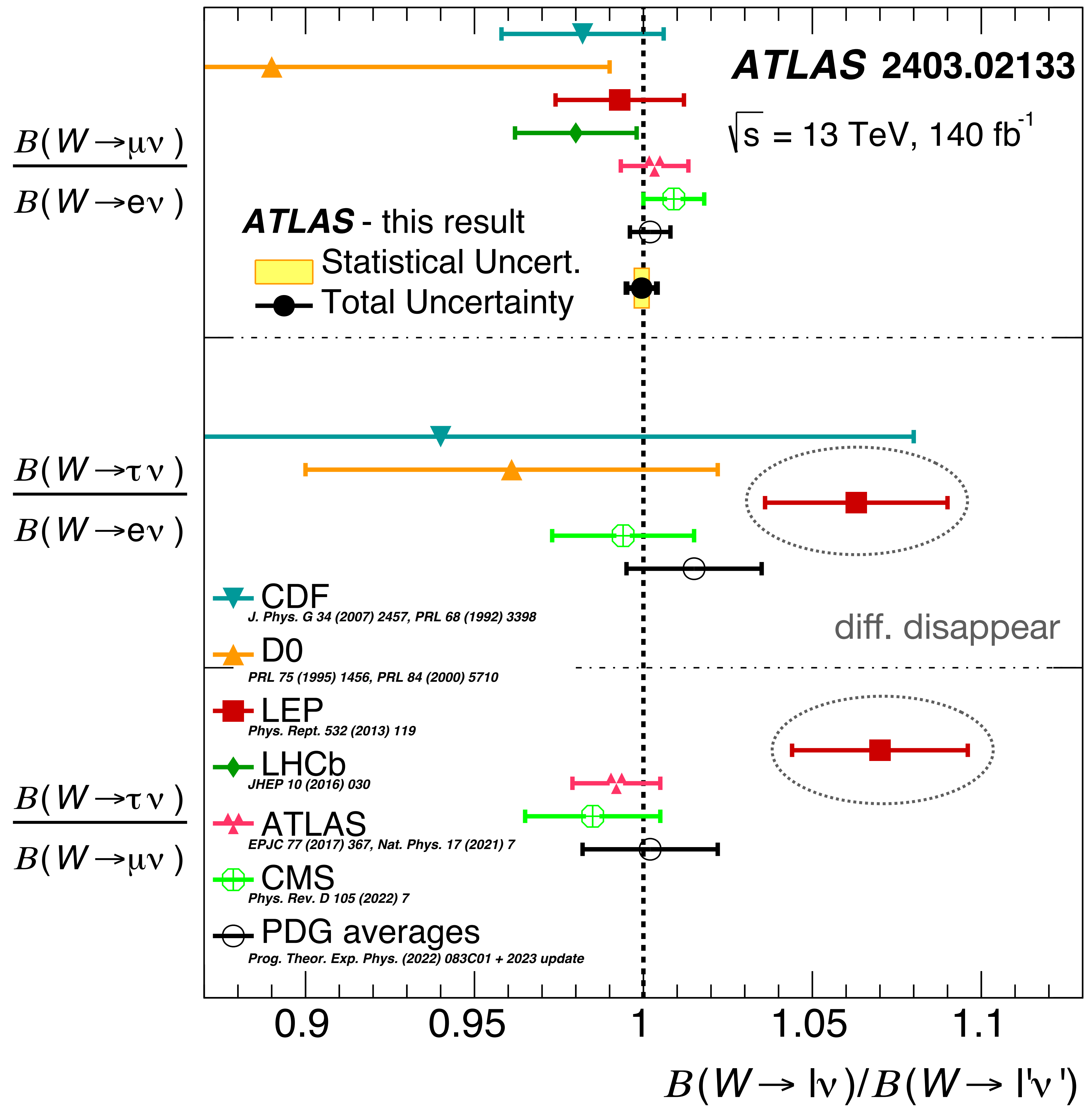
$\Gamma(\tau^+\tau^-)/\Gamma(e^+e^-)$ — Γ_3/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
1.0020±0.0032 OUR AVERAGE				
1.02 ±0.06	[1] AAIJ	18AR	LHCB	E^{pp}_{cm} = 8 TeV
1.0019±0.0032	[2] LEP-SLC	06		E^{ee}_{cm} = 88–94 GeV

$\Gamma(\tau^+\tau^-)/\Gamma(\mu^+\mu^-)$ — Γ_3/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
1.0010±0.0026 OUR AVERAGE				
1.01 ±0.05	[1] AAIJ	18AR	LHCB	E^{pp}_{cm} = 8 TeV
1.0010±0.0026	[2] LEP-SLC	06		E^{ee}_{cm} = 88–94 GeV

▸ W boson decay



Quarkonium

J/ψ — PDG

Γ_5	e^+e^-	(5.971 ± 0.032) %
Γ_7	$\mu^+\mu^-$	(5.961 ± 0.033) %

$\psi(2S)$

Γ_7	e^+e^-	$(7.94 \pm 0.22) \times 10^{-3}$
Γ_8	$\mu^+\mu^-$	$(8.0 \pm 0.6) \times 10^{-3}$
Γ_9	$\tau^+\tau^-$	$(3.1 \pm 0.4) \times 10^{-3}$

$$R_{\tau/\mu}^{\Upsilon(1S),\,\mathrm{BaBar}} = 1.005 \pm 0.013_{\mathrm{stat}} \pm 0.022_{\mathrm{syst}},$$
$$R_{\tau/\mu}^{\Upsilon(1S),\,\mathrm{CLEO}} = 1.02 \pm 0.02_{\mathrm{stat}} \pm 0.05_{\mathrm{syst}},$$
$$R_{\tau/\mu}^{\Upsilon(2S),\,\mathrm{CLEO}} = 1.04 \pm 0.04_{\mathrm{stat}} \pm 0.05_{\mathrm{syst}},$$
$$R_{\tau/\mu}^{\Upsilon(3S),\,\mathrm{CLEO}} = 1.05 \pm 0.08_{\mathrm{stat}} \pm 0.05_{\mathrm{syst}}.$$

$\Upsilon(1S)$ — PDG

Γ_1	$\tau^+\tau^-$	(2.60 ± 0.10) %
Γ_2	e^+e^-	(2.39 ± 0.08) %
Γ_3	$\mu^+\mu^-$	(2.48 ± 0.04) %

$\Upsilon(2S)$

Γ_3	$\tau^+\tau^-$	(2.00 ± 0.21) %
Γ_4	$\mu^+\mu^-$	(1.93 ± 0.17) %
Γ_5	e^+e^-	(1.91 ± 0.16) %

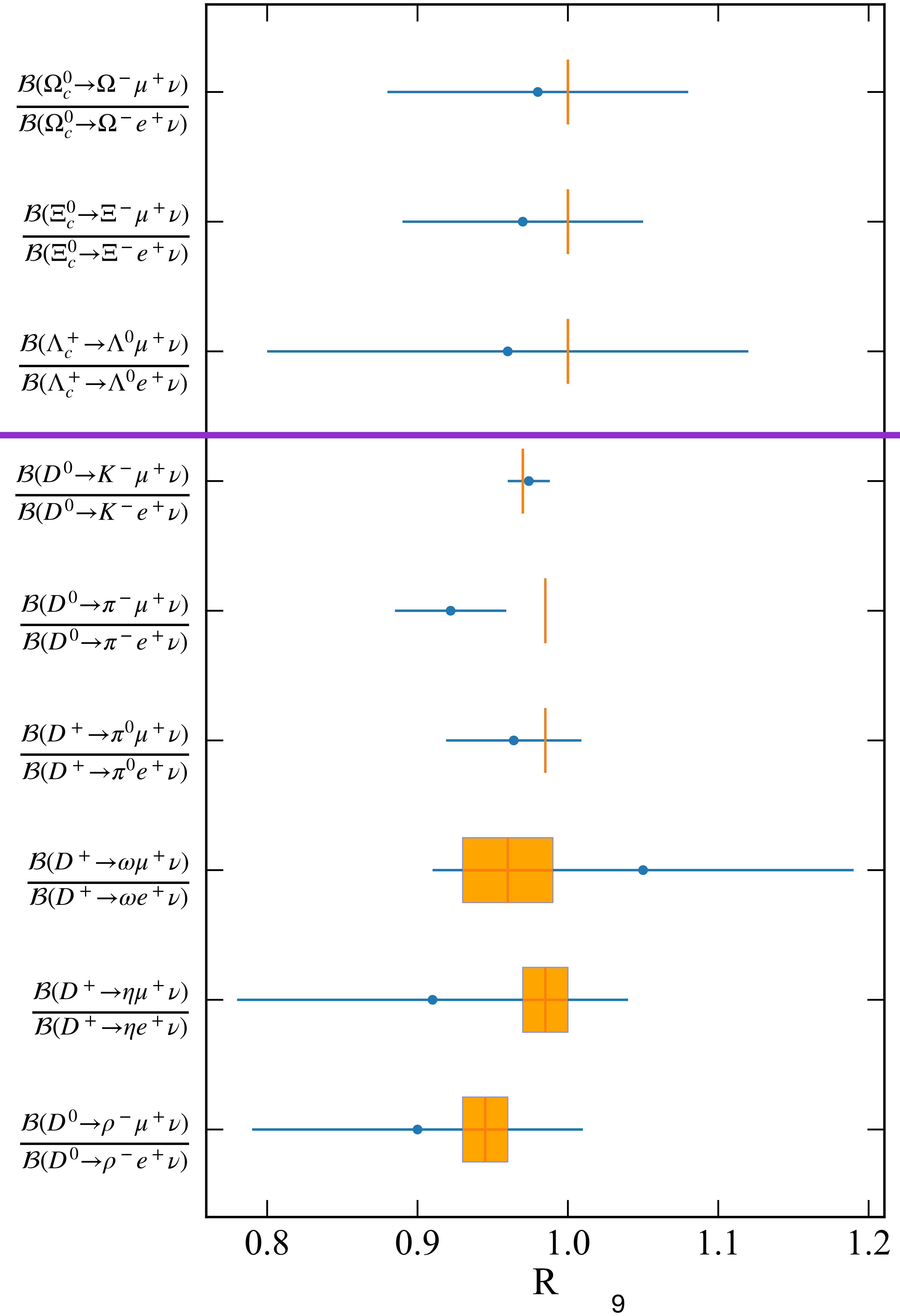
$\Upsilon(3S)$

Γ_{13}	$\tau^+\tau^-$	(2.29 ± 0.30) %
Γ_{14}	$\mu^+\mu^-$	(2.18 ± 0.21) %
Γ_{15}	e^+e^-	(2.18 ± 0.20) %

Charm sector: charged current

SL charm baryon decays

SL charm meson decays



Belle, Phys. Rev. D 105, L091101 (2022)

Belle, PRL127(2021)121803

BESIII, Phys. Lett. B, 767 (2017) p 42

BESIII, Phys. Rev. Lett. 122, 011804 (2019)

BESIII, Phys. Rev. Lett. 121, 171803 (2018)

BESIII, Phys. Rev. Lett. 121, 171803 (2018)

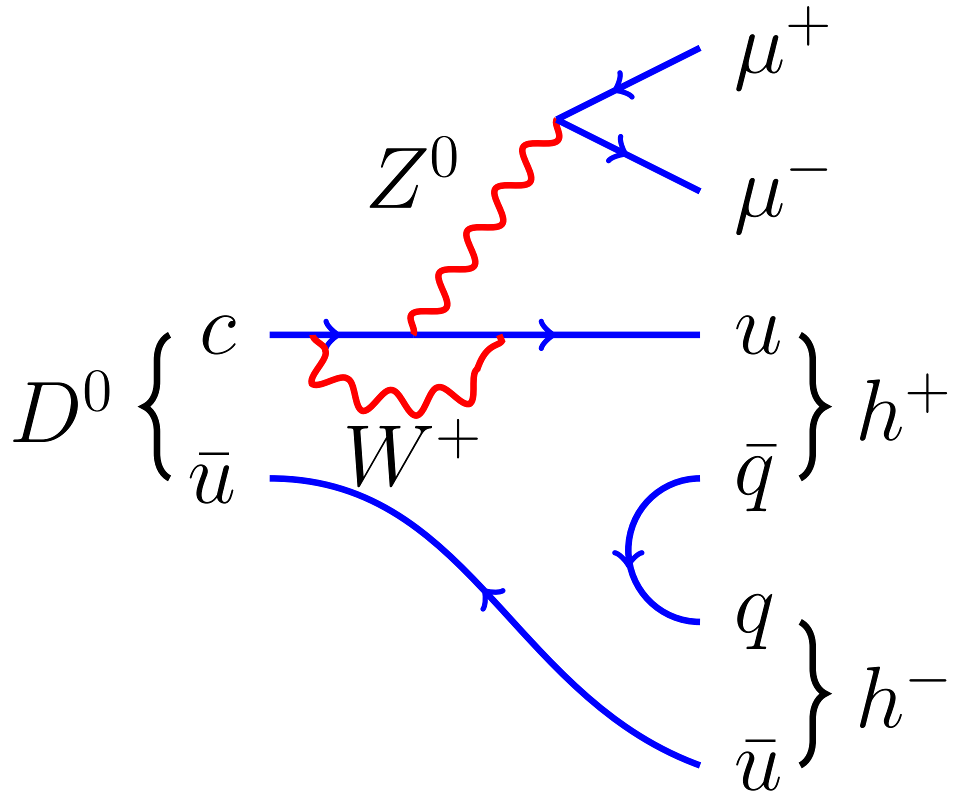
$$\mathscr{B}(D \to \mu^+\nu) = (3.74 \pm 0.17) \times 10^{-4}$$
$$\mathscr{B}(D \to \tau^+\nu) = (1.20 \pm 0.27) \times 10^{-3}$$

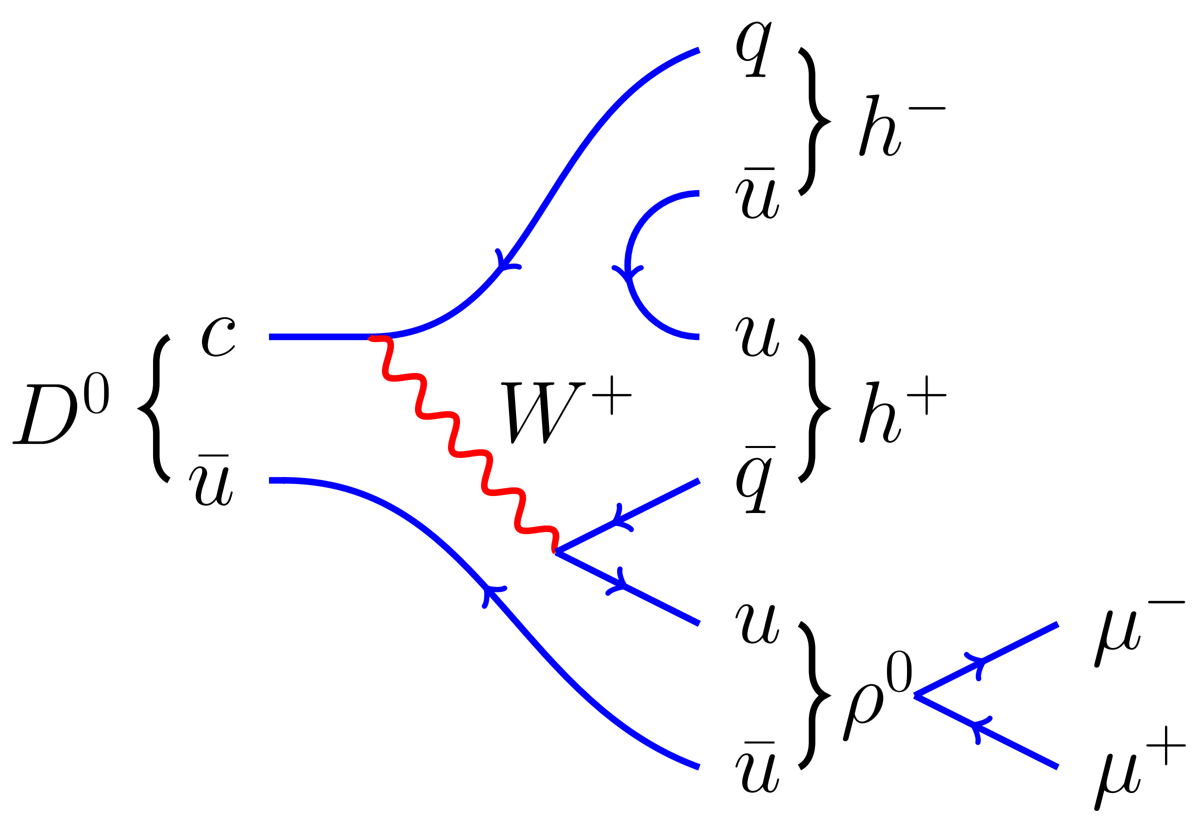
$$\mathscr{B}(D_s \to \mu^+\nu) = (5.35 \pm 0.12) \times 10^{-3}$$
$$\mathscr{B}(D_s \to \tau^+\nu) = (5.36 \pm 0.10) \times 10^{-2}$$

Image credit Adam Davis

Charm sector: neutral current

LHCb, 2412.09414
LHCb, Phys. Rev. Lett.119,181805 (2017)
see also talk by 吕晓睿





first "LFU test" in $c \to u$ decay

branching ratio	$D^0 \to \pi^+\pi^-\mu^+\mu^-$	$D^0 \to K^+K^-\mu^+\mu^-$	$D^0 \to \pi^+\pi^-e^+e^-$	$D^0 \to K^+K^-e^+e^-$
LHCb 17 NEW24	$(9.64 \pm 1.20) \times 10^{-7}$	$(1.54 \pm 0.33) \times 10^{-7}$	$(13.3 \pm 3.0) \times 10^{-7}$	n.a.
BESIII 18	–	–	$< 0.7 \times 10^{-5}$	$< 1.1 \times 10^{-5}$
resonant	$\sim 1 \times 10^{-6}$	$\sim 1 \times 10^{-7}$	$\sim 10^{-6}$	$\sim 10^{-7}$
non-resonant	$10^{-10} - 10^{-9}$	$\mathcal{O}(10^{-10})$	$10^{-10} - 10^{-9}$	$\mathcal{O}(10^{-10})$

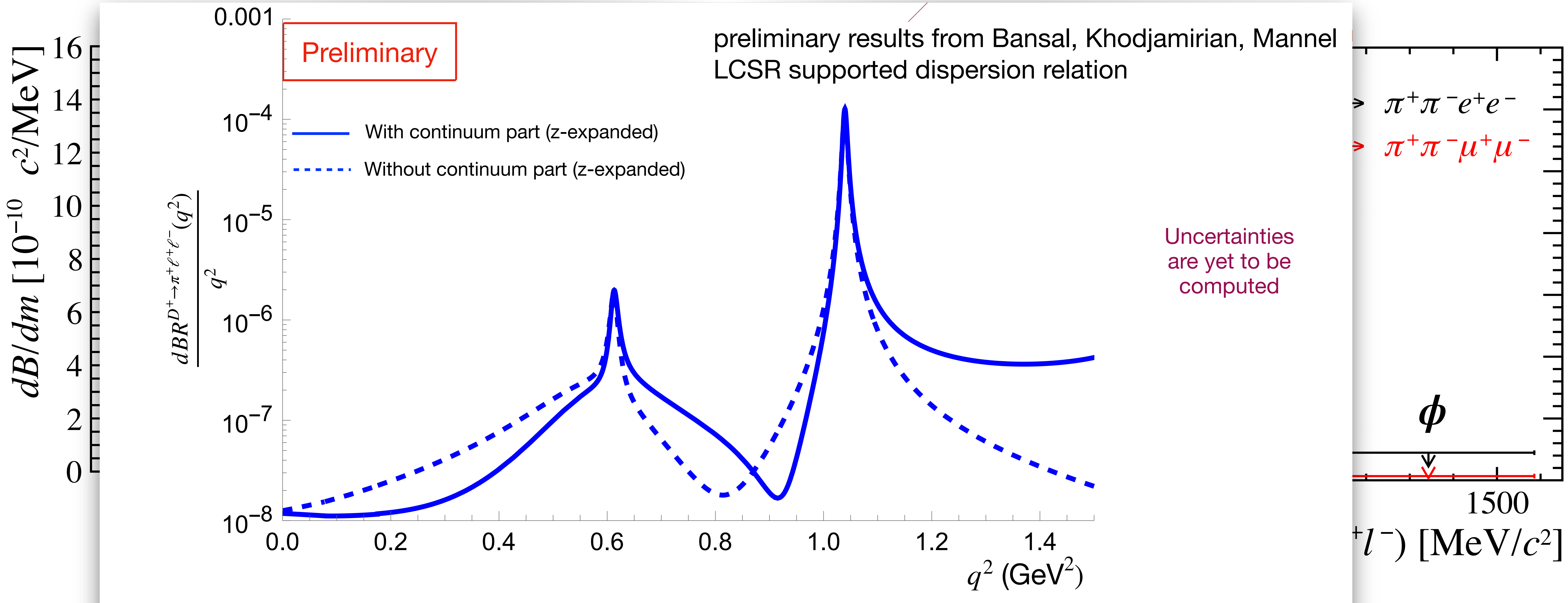
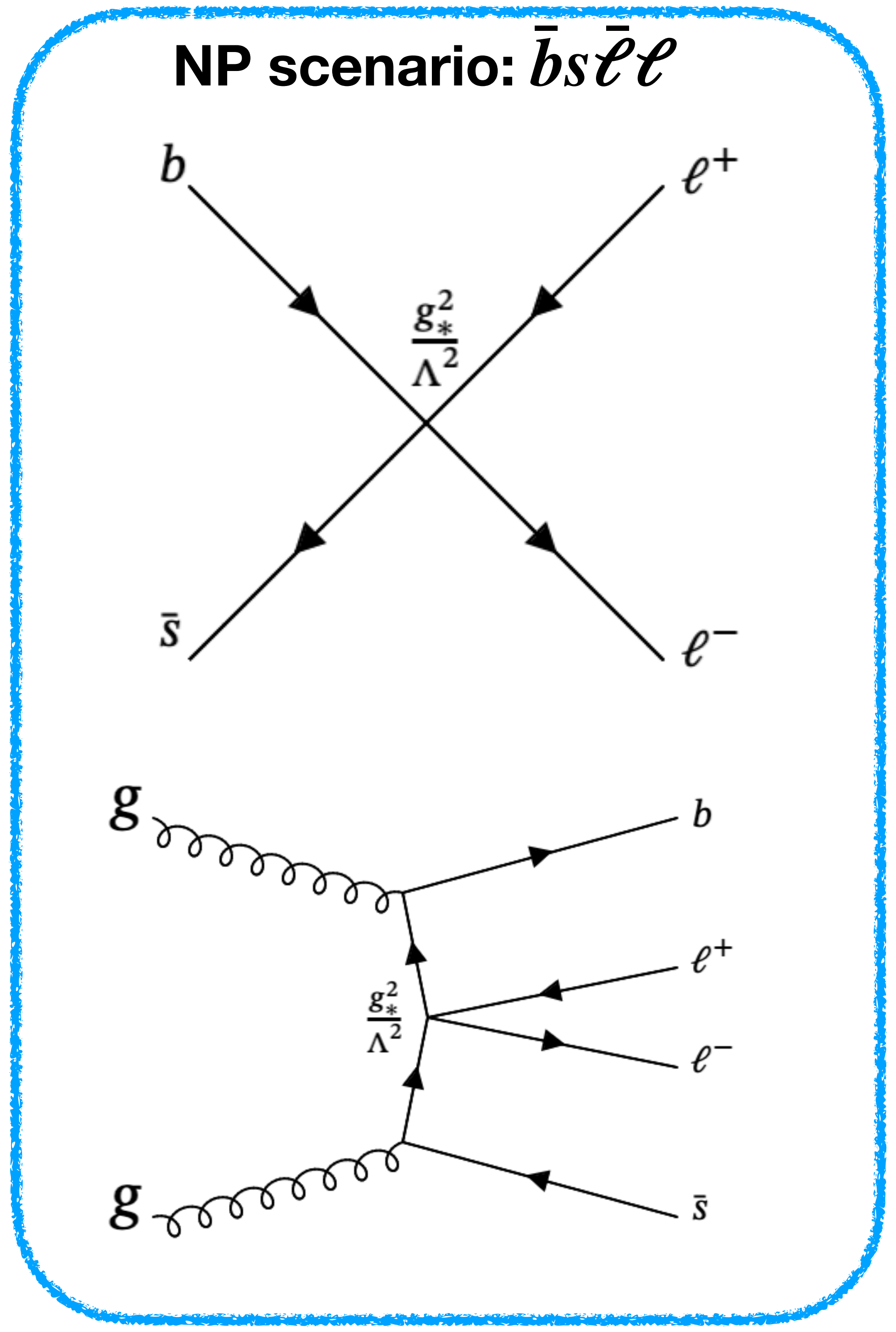
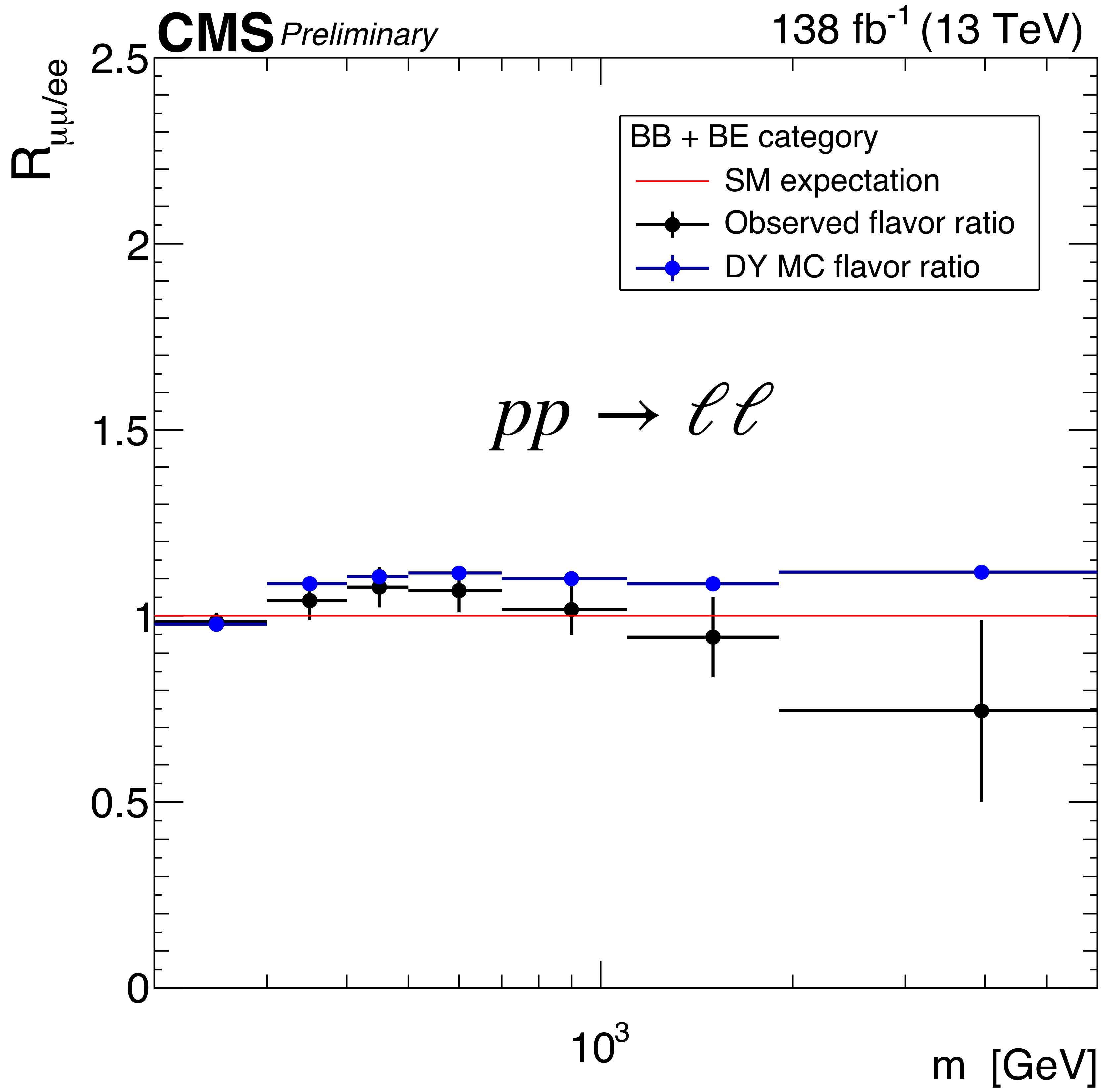
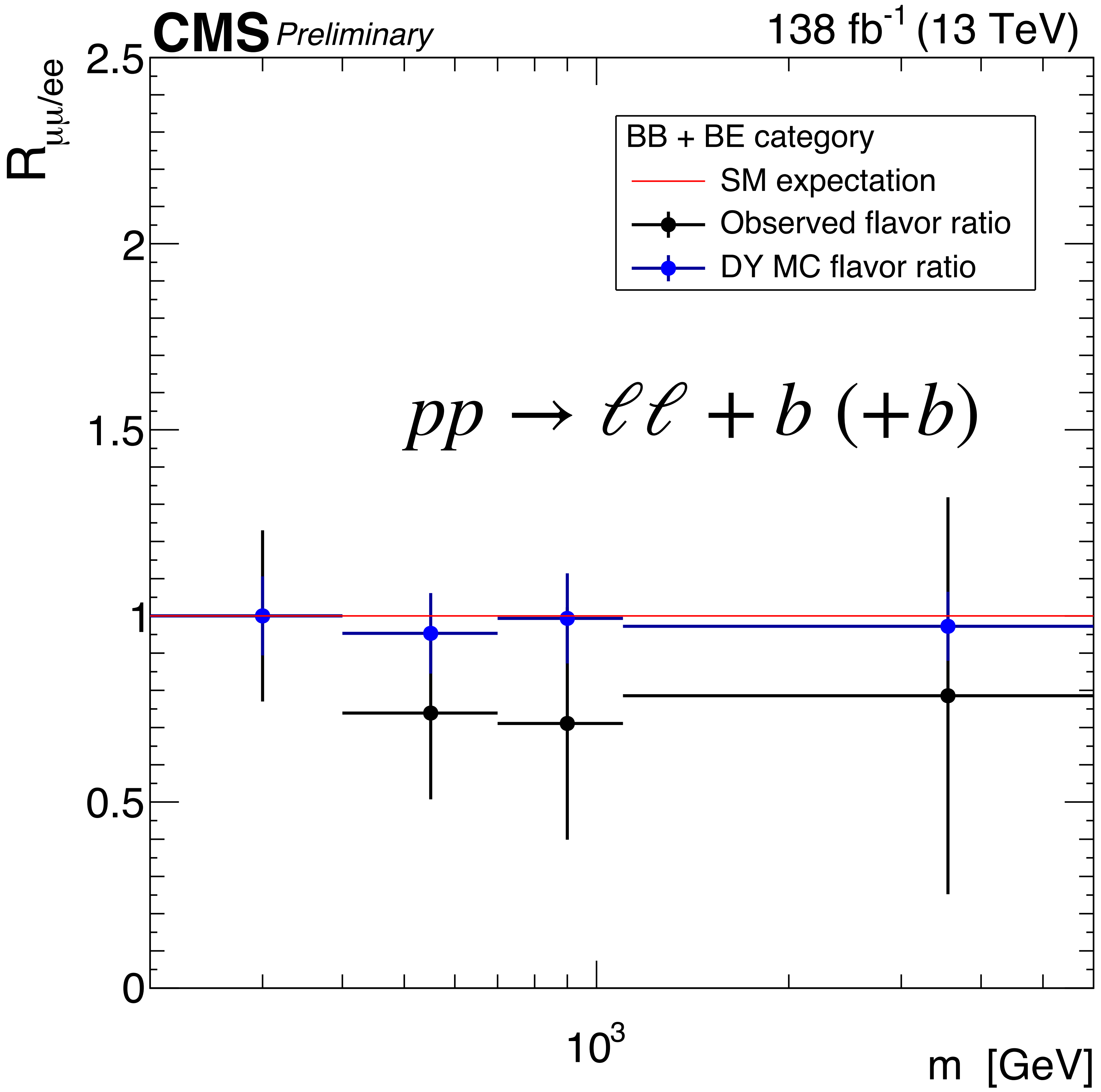


Figure: The results for the differential branching fraction using the dispersion relation with the fitted parameters

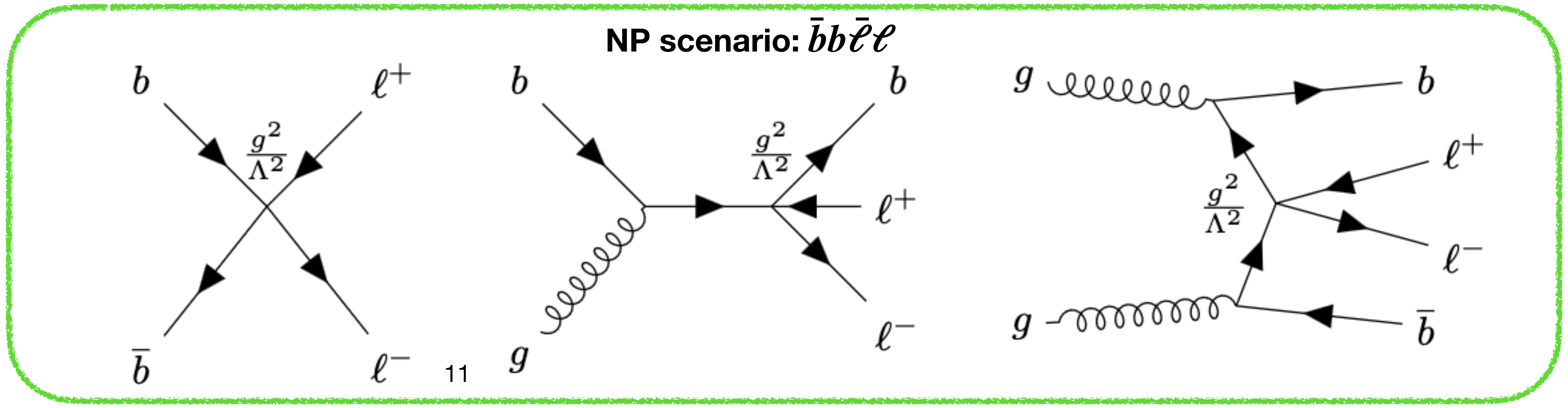
Drell-Yan + b jets



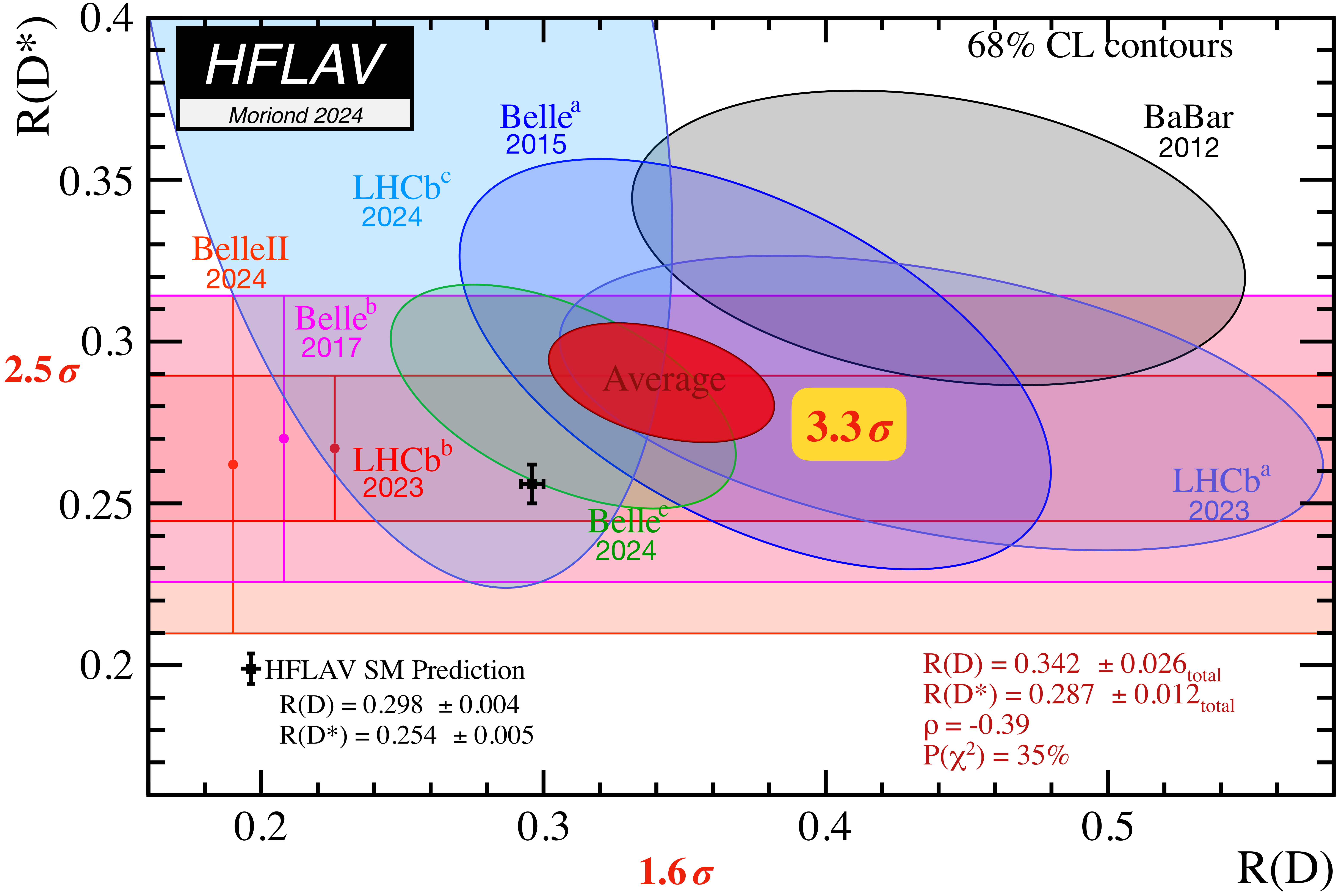




CMS PAS EXO-23-010 (2024 July)



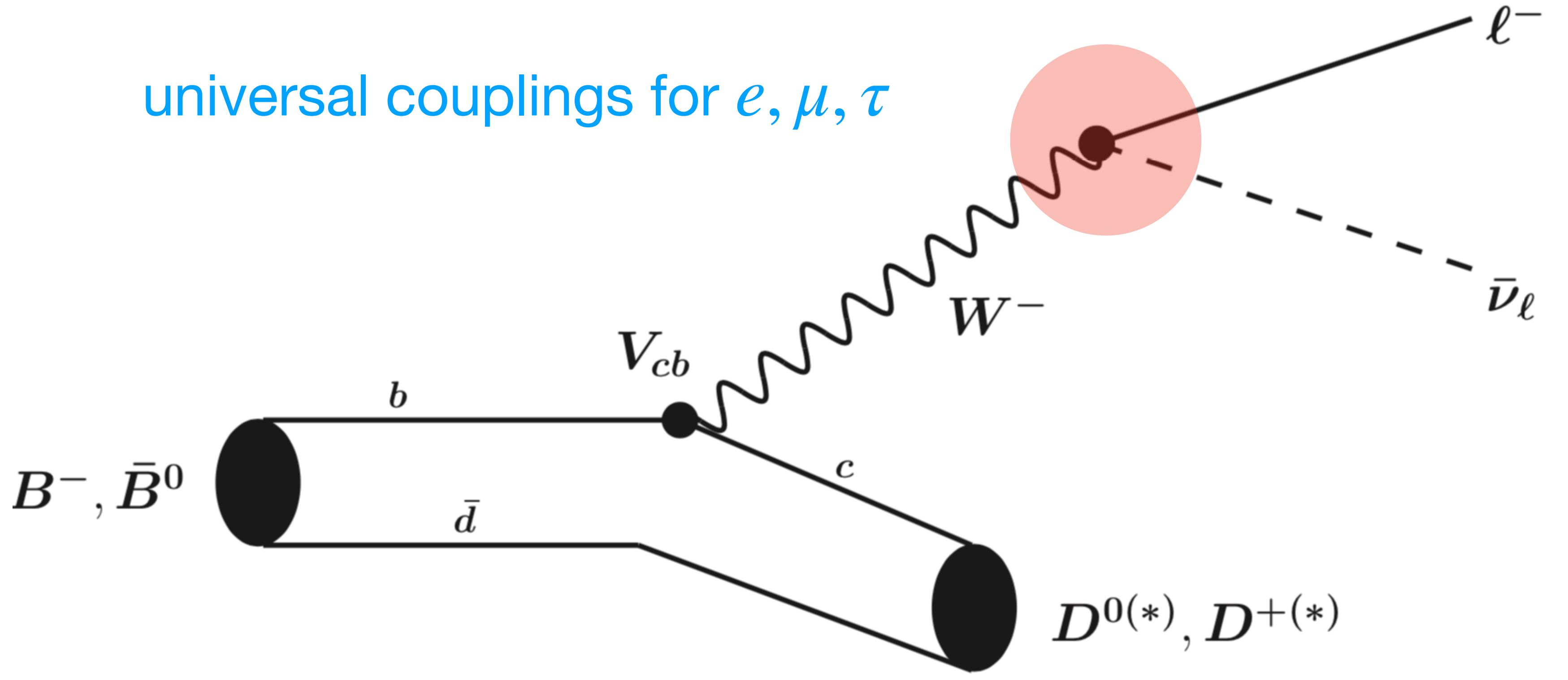
R_D and R_{D*} anomalies: exp

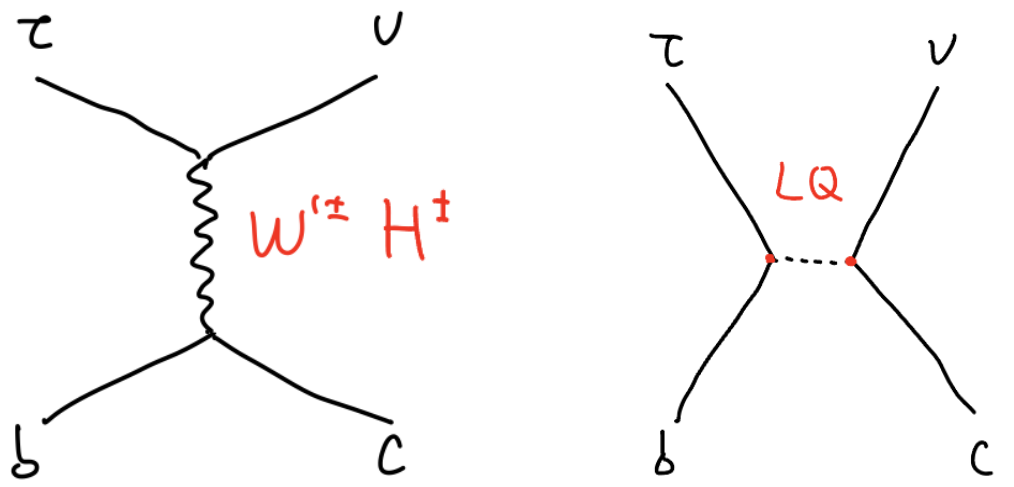


- **LFU Violation ratio:**

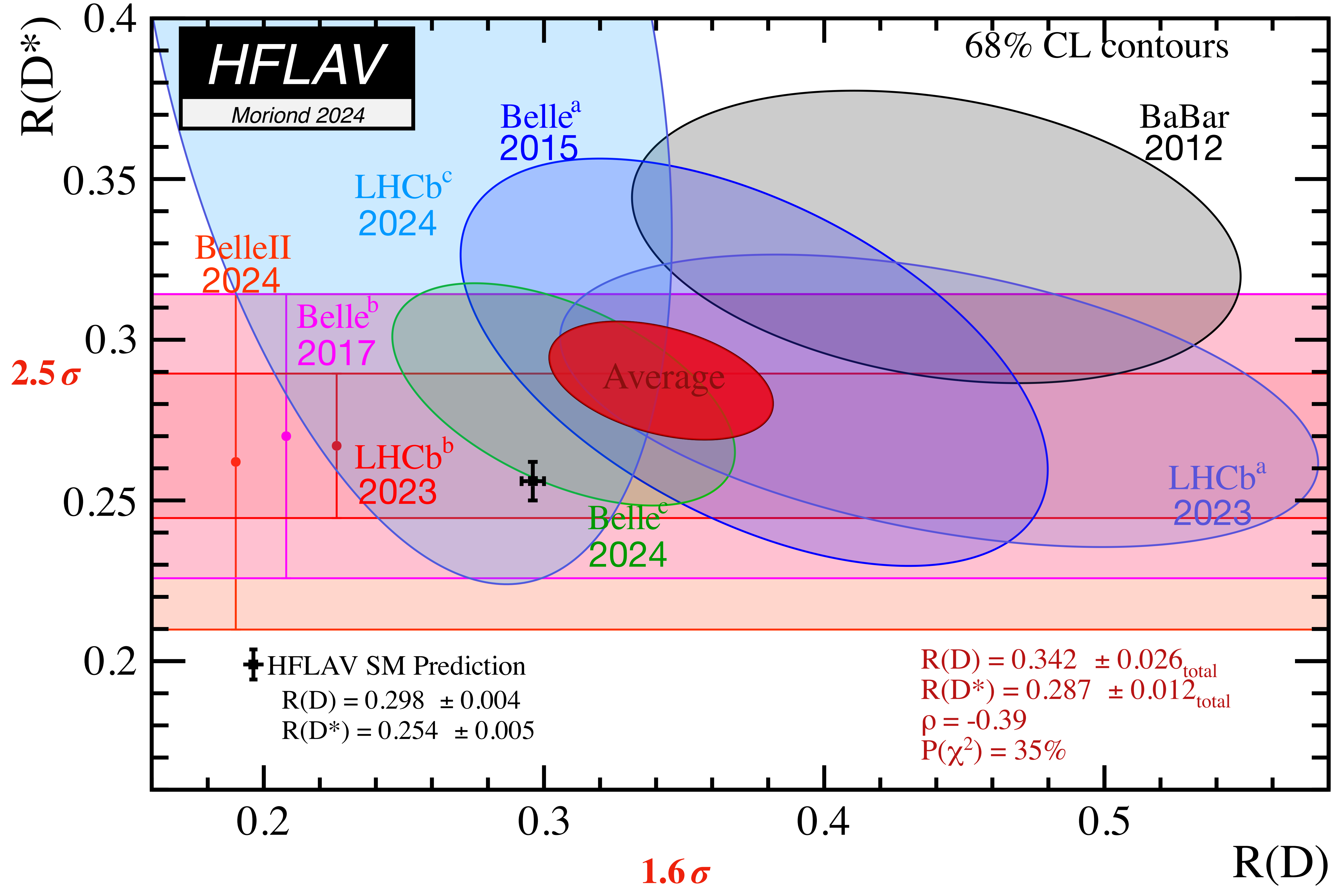
$$R(D^{(*)}) = \frac{\mathfrak{B}(B \to D^{(*)}\tau\nu)}{\mathfrak{B}(B \to D^{(*)}\ell\nu)} \quad (\ell = e, \mu)$$

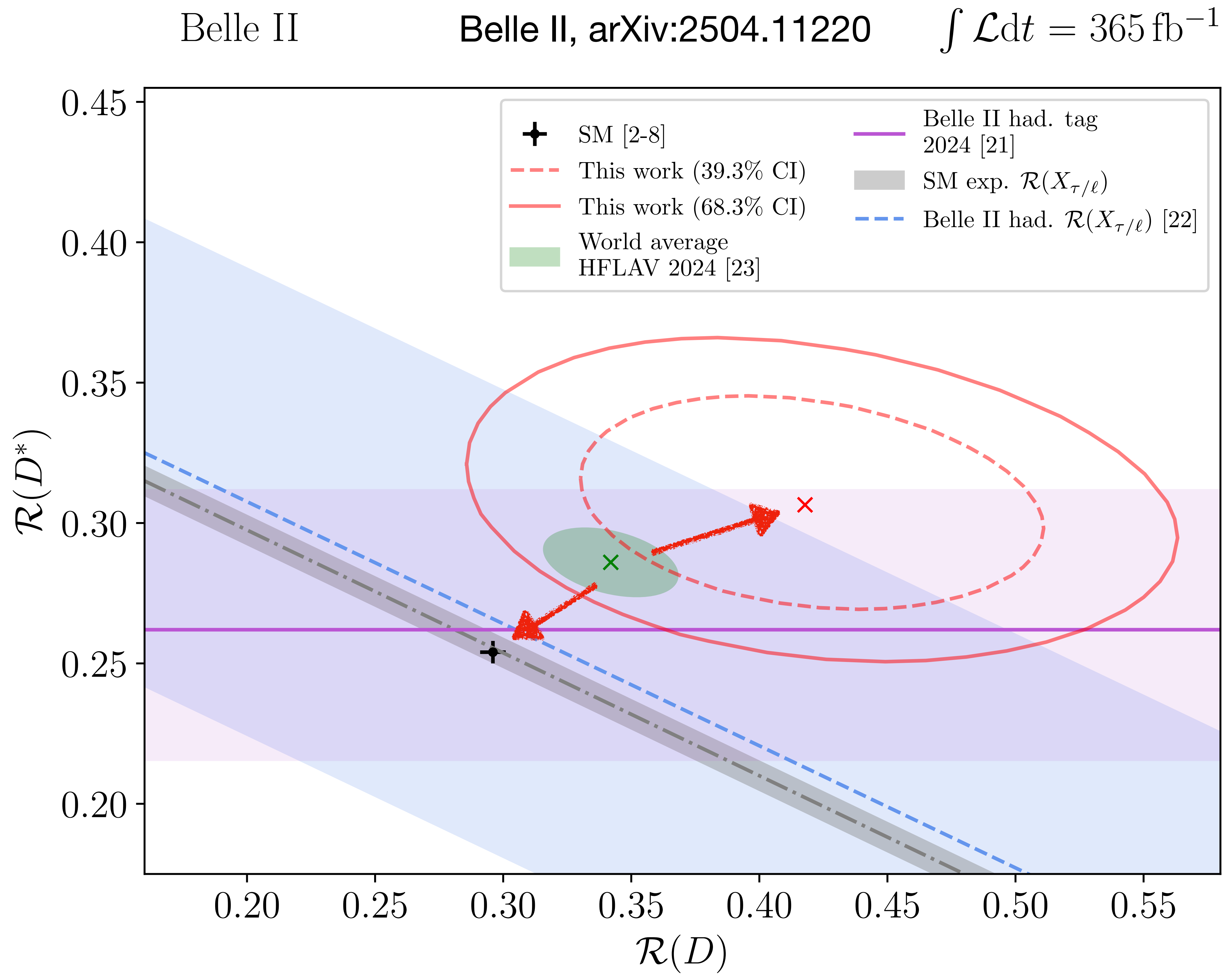
- **LFUV:** τ **v.s.** e, μ
- **QCD and EW contributions factorized**
- **hadronic and experimental uncertainties cancelled**
- **tiny theoretical uncertainties**





R_D and R_{D*} anomalies: exp





$$\mathcal{R}(D^+) = 0.418 \pm 0.074\ (\text{stat}) \pm 0.051\ (\text{syst})$$
$$\mathcal{R}(D^{*+}) = 0.306 \pm 0.034\ (\text{stat}) \pm 0.018\ (\text{syst})$$

3.3 σ deviation from SM

1.7 σ deviation from SM

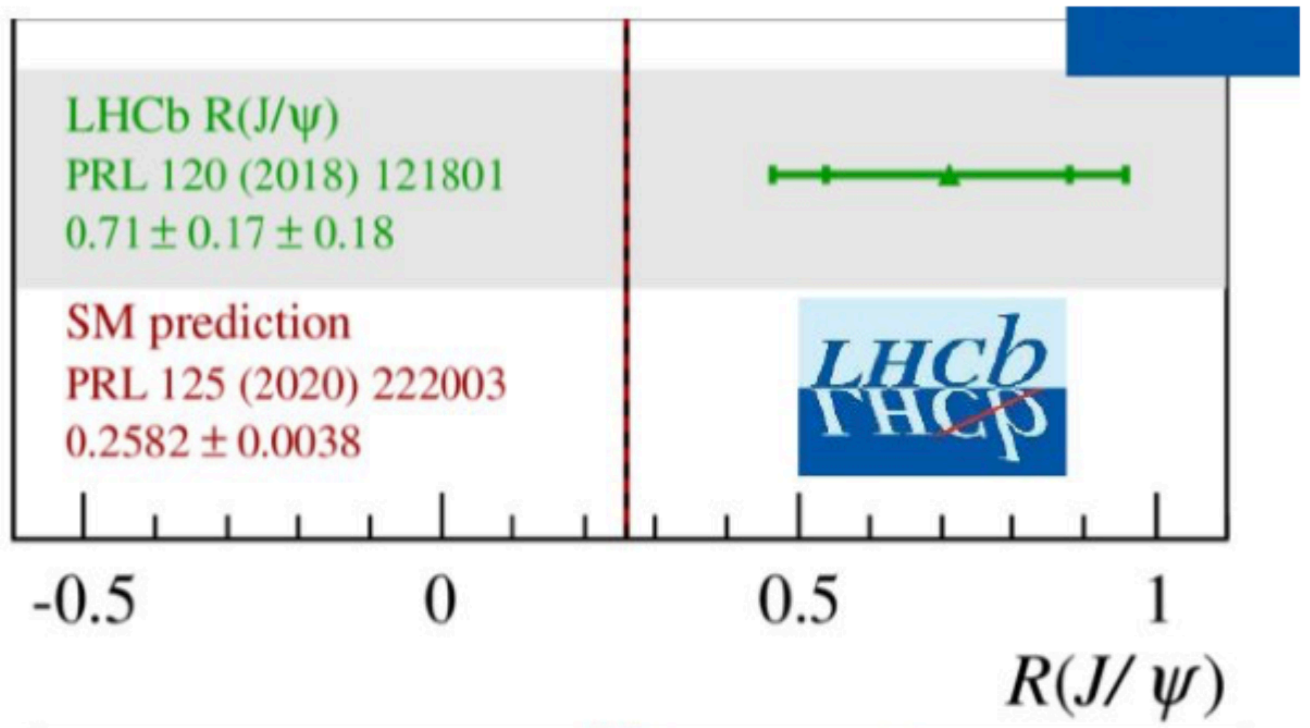
R_D and R_{D*} anomalies: exp

Belle II, arXiv:2504.11220

$$\mathcal{R}(D^{+}_{e/\mu}) = 1.07 \pm 0.05(\text{stat}) \pm 0.02(\text{syst})$$ **1.2 σ diff. from SM**

$$\mathcal{R}(D^{+*}_{e/\mu}) = 1.08 \pm 0.04(\text{stat}) \pm 0.02(\text{syst})$$ **1.6 σ diff. from SM**

$$\mathcal{R}(D^{**0}_{1,2}) = 0.13 \pm 0.03\,(\text{stat}) \pm 0.01\,(\text{syst}) \pm 0.02\,(\text{ext})$$ LHCb, arXiv: 2501.14943



$$R(J/\psi) = 0.17 \pm 0.33$$

CMS, PRD111(2025)L051102

$$R(X_{e/\mu}) = 1.007 \pm 0.009(\text{stat}) \pm 0.019(\text{syst})$$

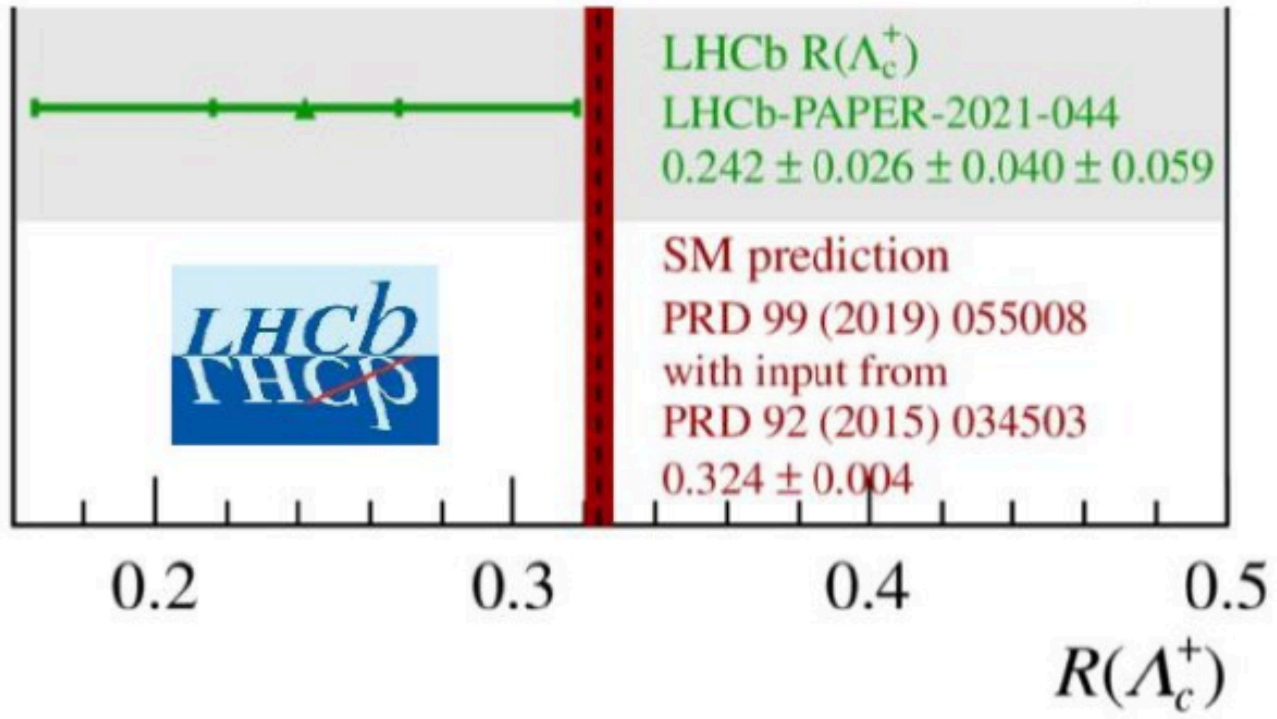
Belle II

PRL 131, 051804 (2023) e/μ
PRL 132, 211804 (2024) τ/ℓ

$$R(X_{\tau/e}) = 0.232 \pm 0.020(\text{stat}) \pm 0.037(\text{syst}),$$
$$R(X_{\tau/\mu}) = 0.222 \pm 0.027(\text{stat}) \pm 0.050(\text{syst}),$$

Combined

$$R(X_{\tau/\ell}) = 0.228 \pm 0.016(\text{stat}) \pm 0.036(\text{syst})$$



Duan, Iguro, Li, Watanabe, Yang, 2410.21384

$$\frac{R_{\Lambda_c}}{R^{\text{SM}}_{\Lambda_c}} = (0.272 \pm 0.015)\,\frac{R_D}{R^{\text{SM}}_D} + (0.728 \mp 0.015)\,\frac{R_{D^*}}{R^{\text{SM}}_{D^*}} + \delta_{\Lambda_c}$$

$$R^{\text{SR}}_{\Lambda_c} = 0.370 \pm 0.017|_{R_X^{\text{SM,exp}}} \pm (< 0.001)|_{\text{SR}}$$

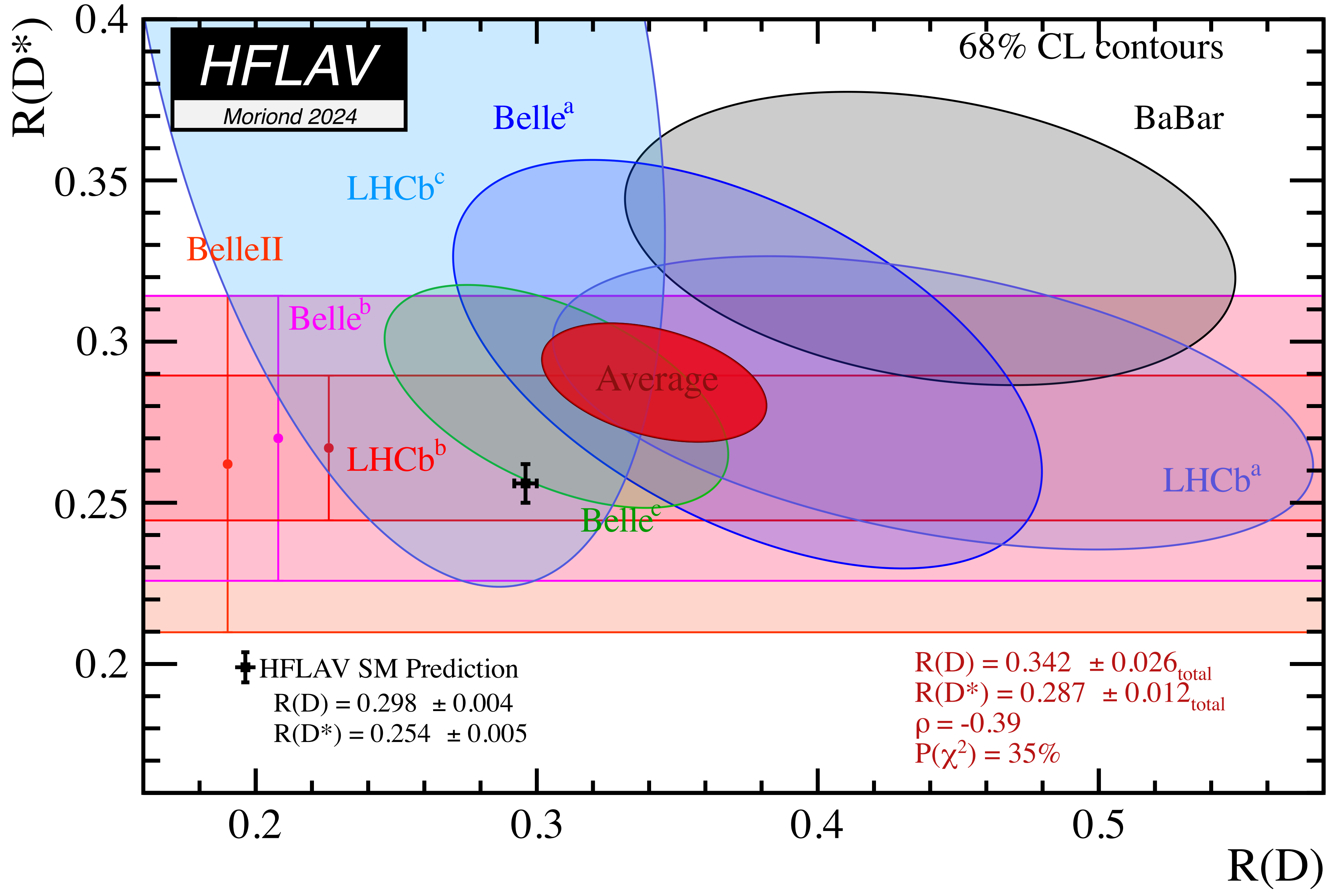
$$R^{\text{LHCb}}_{\Lambda_c} = 0.242 \pm 0.026 \pm 0.040 \pm 0.059$$

violation of the sum rules could be caused by right-handed neutrino, massive neutrino, …

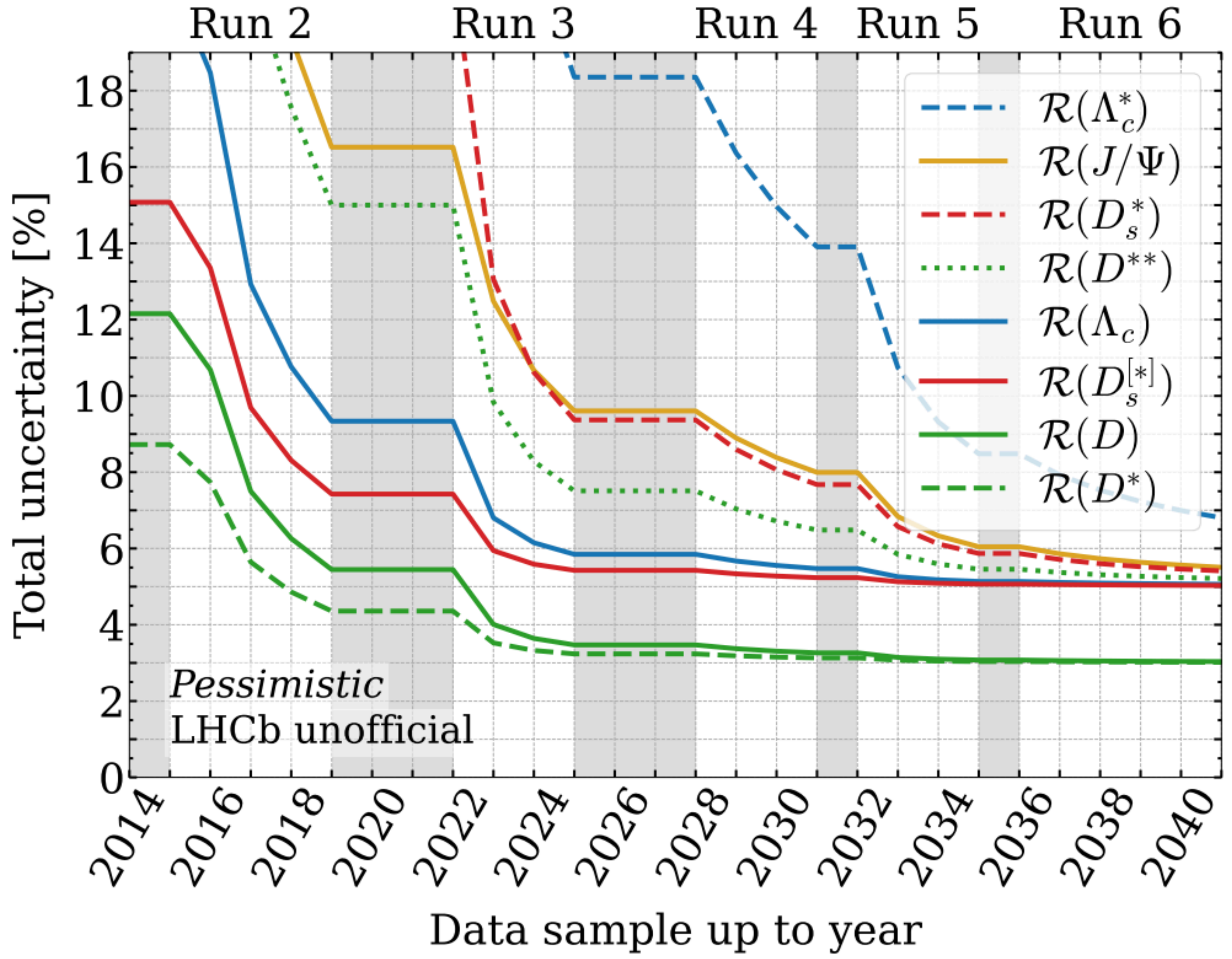
R_D and R_{D^*} anomalies

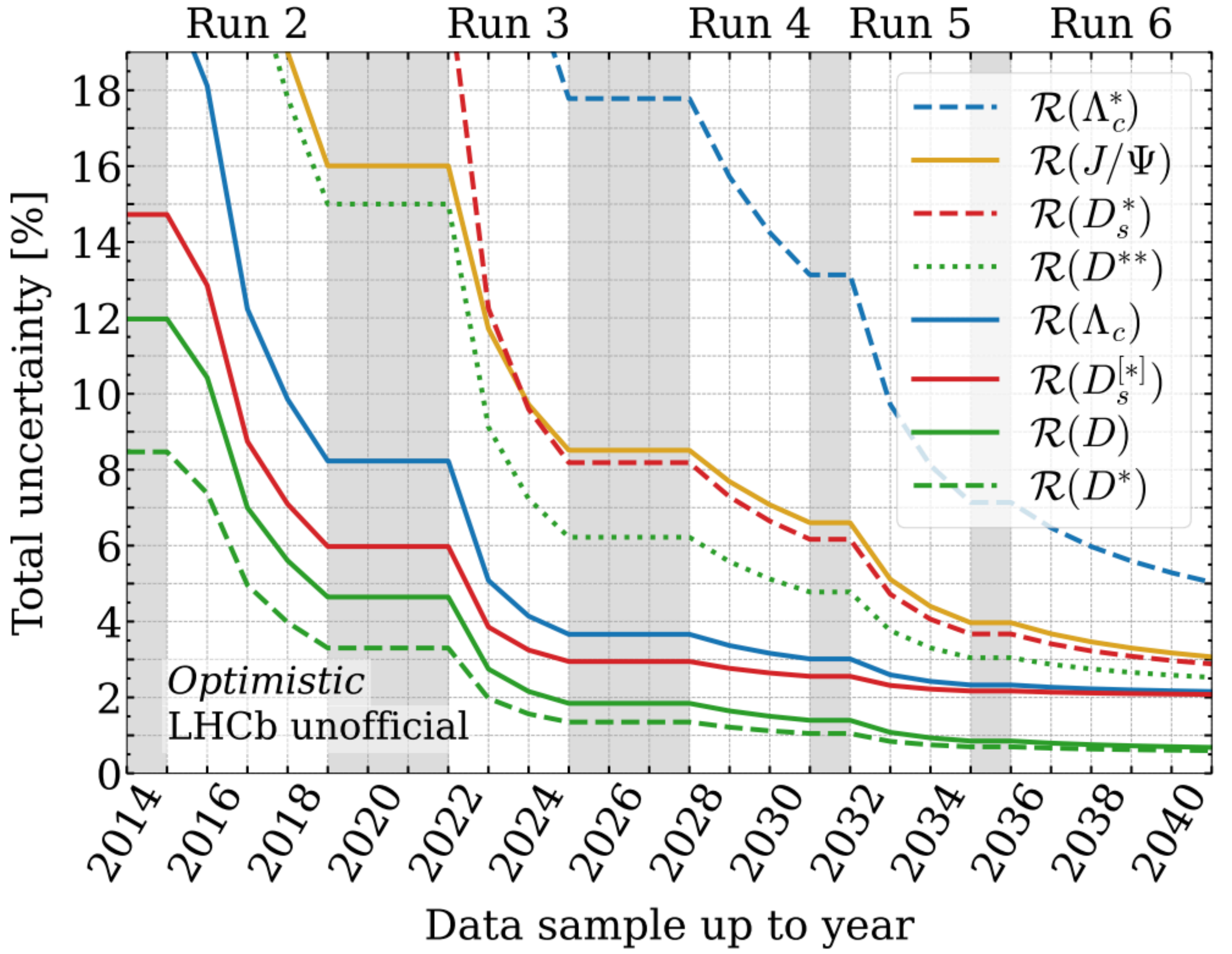
- **Anomalies mainly from BaBar measurement**
- **LHCb 2022: muonic tau, $3\,\mathrm{fb}^{-1}$@Run I**
- **LHCb 2023: hadronic tau, $2\,\mathrm{fb}^{-1}$@Run II**
- **Outlook**
  - Analysis based on Run I + II ($9\,\mathrm{fb}^{-1}$)
  - R_{Λ_c}, R_{D_s}, R_D
  - Belle II

current status

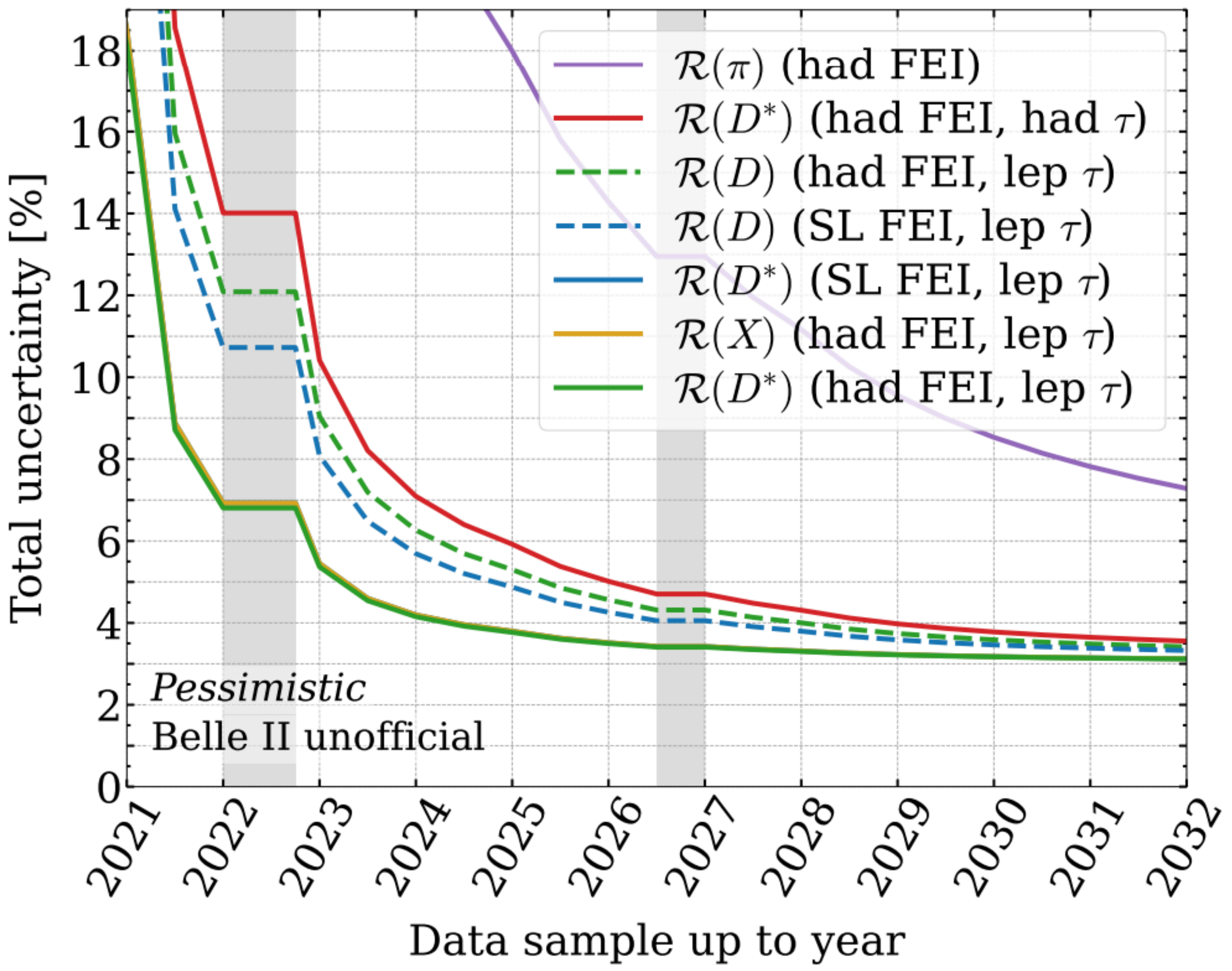


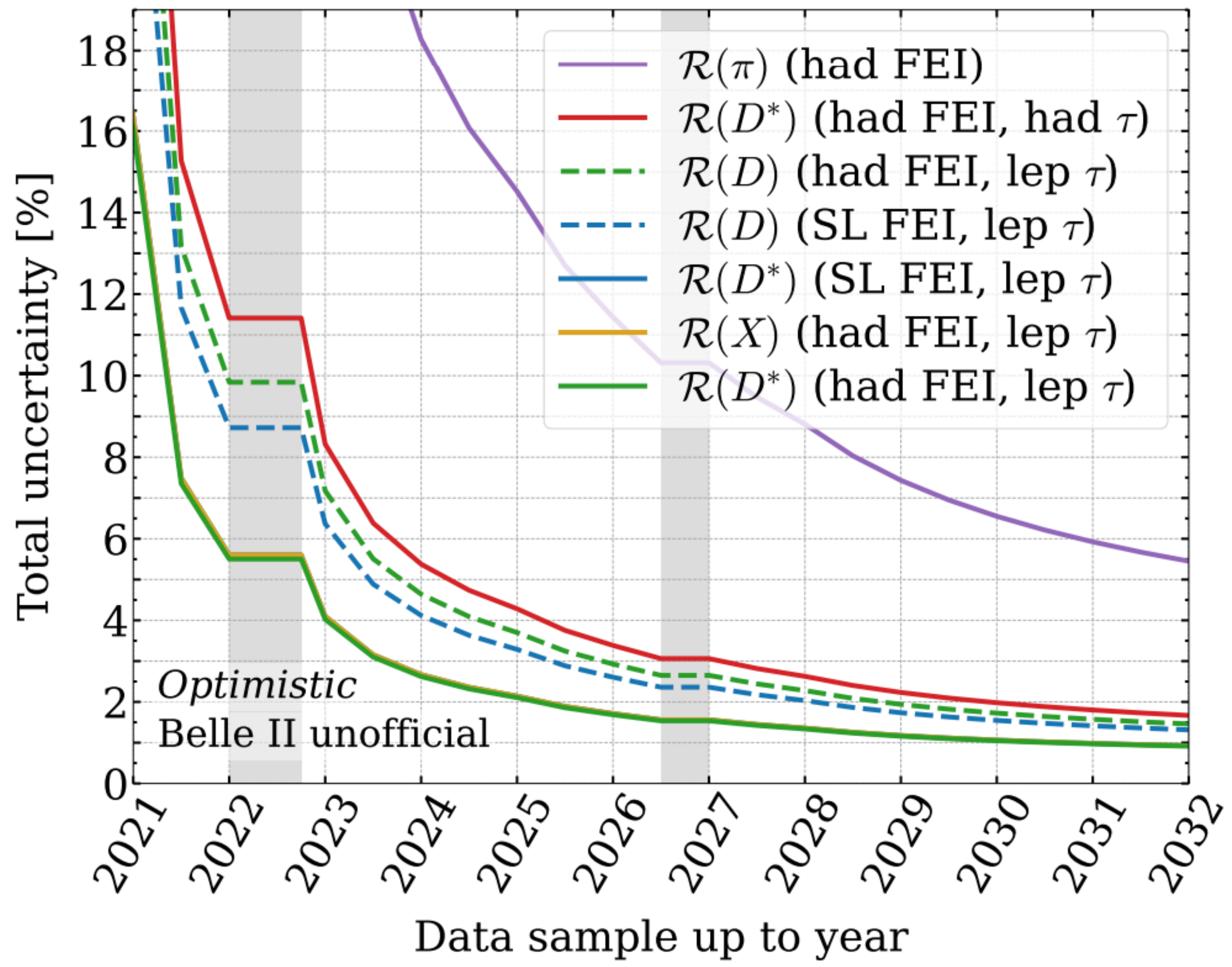
future exp uncertainty ~ $\mathcal{O}(2\%)$





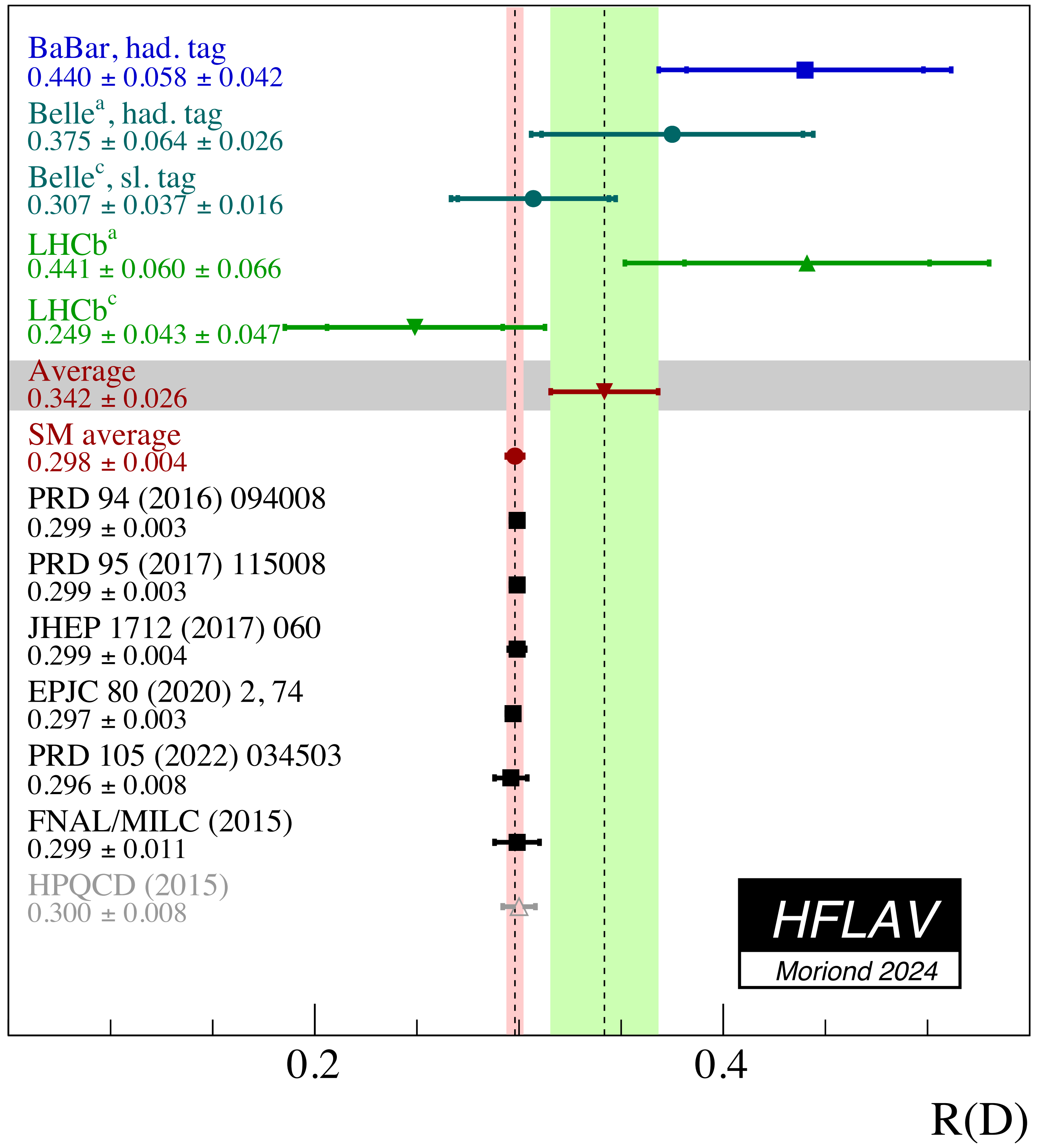
Bernlochner, Sevilla, Robinson, Wormser, 2101.08326

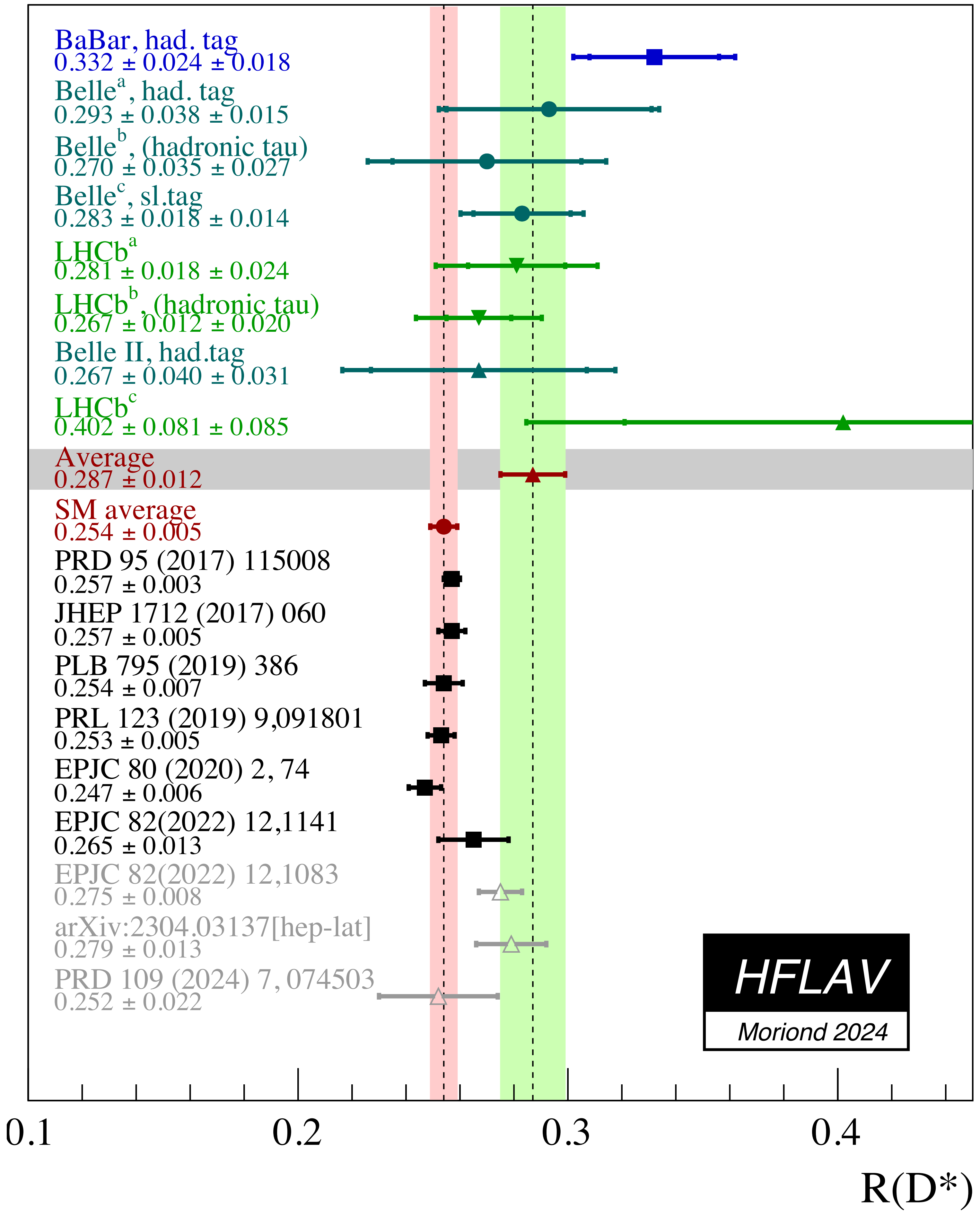


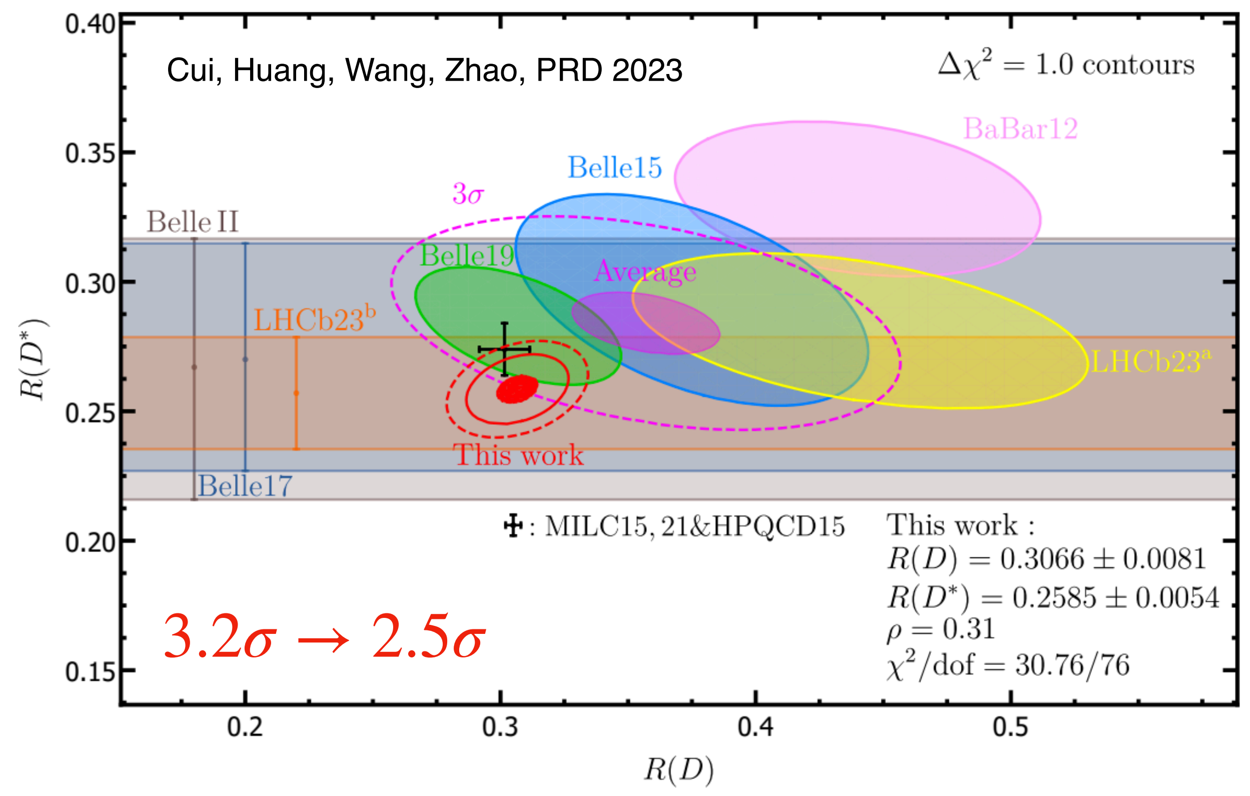


R_D and R_{D^*} anomalies: theory

uncertainty: current theo ≈ exp@2040







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

$$R_D = \frac{\int_{m_\tau^2}^{q^2_{\max}} \frac{d\Gamma(B \to D\tau\nu)}{dq^2}}{\int_{m_\ell^2}^{q^2_{\max}} \frac{d\Gamma(B \to D\ell\nu)}{dq^2}}$$

form factor in $q^2 \in (m_\ell^2, m_\tau^2)$ not cancelled

$$\tilde{R}_D = \frac{\int_{m_\tau^2}^{q^2_{\max}} \frac{d\Gamma(B \to D\tau\nu)}{dq^2}}{\int_{m_\tau^2}^{q^2_{\max}} \frac{d\Gamma(B \to D\ell\nu)}{dq^2}}$$

form factors in the same region

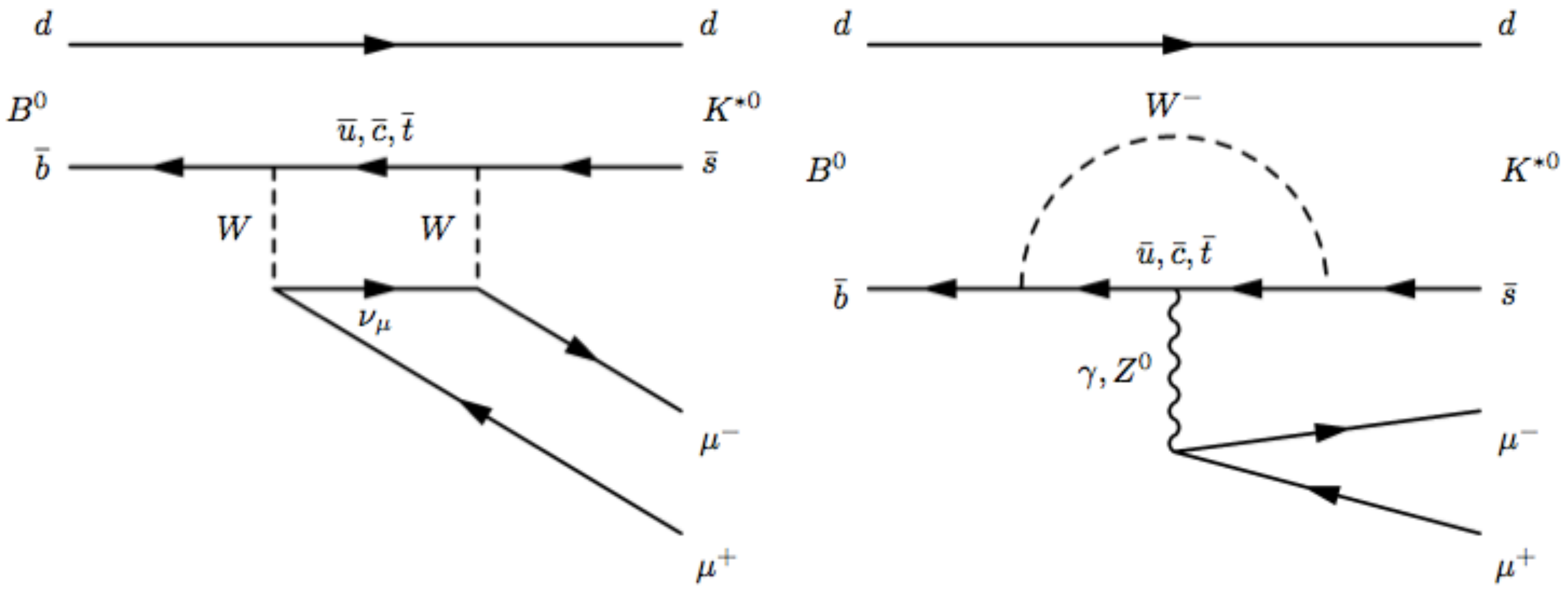
$$r_D(q^2) = \frac{\frac{d\Gamma(B \to D\tau\nu)}{dq^2}}{\frac{d\Gamma(B \to D\ell\nu)}{dq^2}}$$

form factor fully cancelled, for large data samples

Form factors could not be a problem for $R_{D^{(*)}}$ in the future,
but still important for angular observables e.g., $P_\tau(D^*)$ and $F_{L,\tau}(D^*)$.

$b \to s\ell^+\ell^-$ decays

- $B_s \to \ell^+\ell^-$
- $B \to X_s\ell^+\ell^-$
- $B \to K\ell^+\ell^-$
- $B \to K^*\ell^+\ell^-$
- $B_s \to \phi\ell^+\ell^-$
- $\Lambda_b \to \Lambda\ell^+\ell^-$



- **Flavour-Changing Neutral Current (FCNC)**
  - Tree-level: forbidden
  - Loop-level: suppressed by GIM, $\mathscr{B} \lesssim \mathcal{O}(10^{-6})$

  $\Longrightarrow$ **Sensitive to New Physics**
- **Many observables: branching ratio, angular distribution, LFV ratio**
- **NP effects can be sizable compared to the SM amplitude**
- **This transition is LFU in the SM**

$b \to s\ell^+\ell^-$: theory

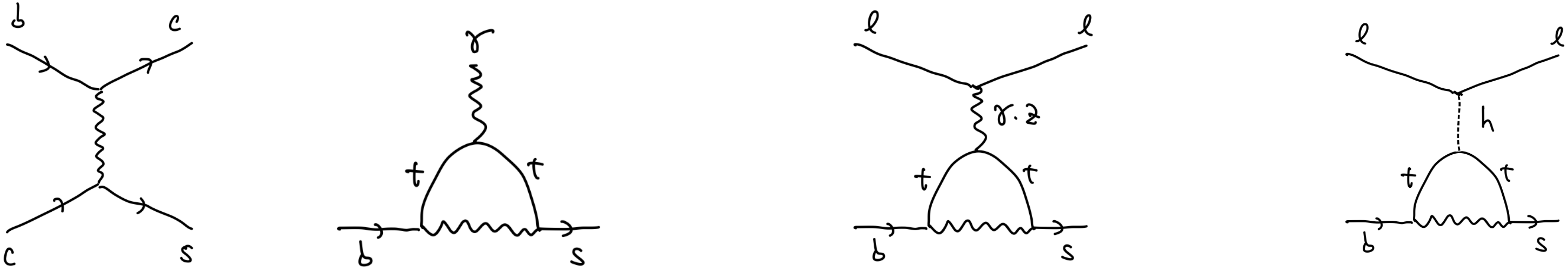
- **Effective Hamiltonian**

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \frac{e^2}{16\pi^2}\left(\sum_{i=1,\ldots,6} C_i O_i + C_{7\gamma}O_{7\gamma} + C_{8g}O_{8g} \sum_{\ell}\sum_{i=9,10,P,S}(C_i^\ell O_i^\ell + C_i'^\ell O_i'^\ell)\right)$$

- **Effective operator**

$$O_1 = (\bar{s}\gamma_\mu P_L T^a c)(\bar{c}\gamma^\mu P_L T^a b) \qquad O_7^{(\prime)} = \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_{R(L)}b)F^{\mu\nu}\,, \qquad O_9^{(\prime)\ell} = (\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\ell}\gamma^\mu\ell)\,, \qquad O_{10}^{(\prime)\ell} = (\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\ell}\gamma^\mu\gamma_5\ell) \qquad O_S^{(\prime\ell)} = (\bar{s}P_{R(L)}b)(\bar{\ell}\ell)$$

$$O_2 = (\bar{s}\gamma_\mu P_L c)(\bar{c}\gamma^\mu P_L b) \qquad C_7^{\rm SM} \simeq -0.3\,, \qquad C_9^{\rm SM} \simeq 4\,, \qquad C_{10}^{\rm SM} \simeq -4\,. \qquad O_P^{(\prime\ell)} = (\bar{s}P_{R(L)}b)(\bar{\ell}\gamma_5\ell)$$



- **Feynman Diagram**

$b \to s\ell^+\ell^-$: theory

- **Effective Hamiltonian**

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \frac{e^2}{16\pi^2}\left(\sum_{i=1,\ldots,6} C_i O_i + C_{7\gamma}O_{7\gamma} + C_{8g}O_{8g} \sum_{\ell}\sum_{i=9,10,P,S}(C_i^\ell O_i^\ell + C_i'^\ell O_i'^\ell)\right)$$

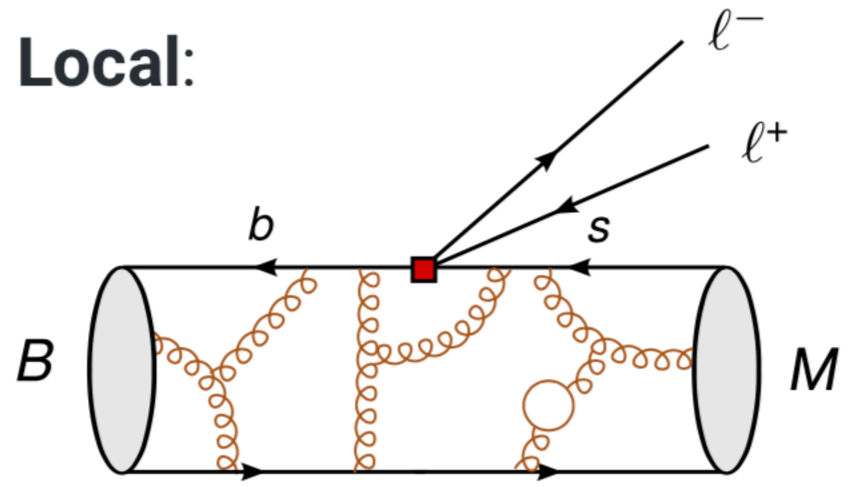
- **Effective operator**

$$O_1 = (\bar{s}\gamma_\mu P_L T^a c)(\bar{c}\gamma^\mu P_L T^a b) \quad O_7^{(\prime)} = \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_{R(L)}b)F^{\mu\nu}, \quad O_9^{(\prime)\ell} = (\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\ell}\gamma^\mu\ell), \quad O_{10}^{(\prime)\ell} = (\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\ell}\gamma^\mu\gamma_5\ell) \quad O_S^{(\prime\ell)} = (\bar{s}P_{R(L)}b)(\bar{\ell}\ell)$$

$$O_2 = (\bar{s}\gamma_\mu P_L c)(\bar{c}\gamma^\mu P_L b) \quad C_7^{\rm SM} \simeq -0.3, \quad C_9^{\rm SM} \simeq 4, \quad C_{10}^{\rm SM} \simeq -4. \quad O_P^{(\prime\ell)} = (\bar{s}P_{R(L)}b)(\bar{\ell}\gamma_5\ell)$$

- **Amplitude:** $\mathcal{M}(B \to M\ell\ell) = \langle M\ell\ell|\mathcal{H}_{\rm eff}|B\rangle = \mathcal{N}\left[(\mathcal{A}_V^\mu + \mathcal{H}^\mu)\,\bar{u}_\ell\gamma_\mu v_\ell + \mathcal{A}_A^\mu\,\bar{u}_\ell\gamma_\mu\gamma_5 v_\ell + \mathcal{A}_S\,\bar{u}_\ell v_\ell + \mathcal{A}_P\,\bar{u}_\ell\gamma_5 v_\ell\right]$

Local:

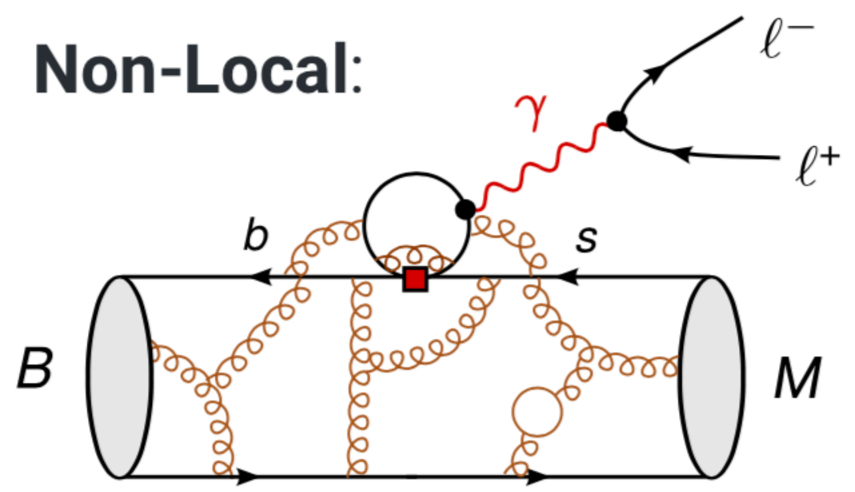


$$\mathcal{A}_V^\mu = -\frac{2im_b}{q^2} C_7\langle M|\bar{s}\,\sigma^{\mu\nu}q_\nu\,P_R\,b|B\rangle + C_9\langle M|\bar{s}\,\gamma^\mu\,P_L\,b|B\rangle + (P_L \leftrightarrow P_R, C_i \to C_i')$$

$$\mathcal{A}_A^\mu = C_{10}\langle M|\bar{s}\,\gamma^\mu\,P_L\,b|B\rangle + (P_L \leftrightarrow P_R, C_i \to C_i')$$

$$\mathcal{A}_{S,P} = C_{S,P}\langle M|\bar{s}\,P_R\,b|B\rangle + (P_L \leftrightarrow P_R, C_i \to C_i')$$

Non-Local:



$$\mathcal{H}^\mu = \frac{-16i\pi^2}{q^2}\sum_{i=1,\ldots,6,8} C_i\int dx^4 e^{iq\cdot x}\langle M|T\{j^\mu_{\rm em}(x), O_i(0)\}|B\rangle$$

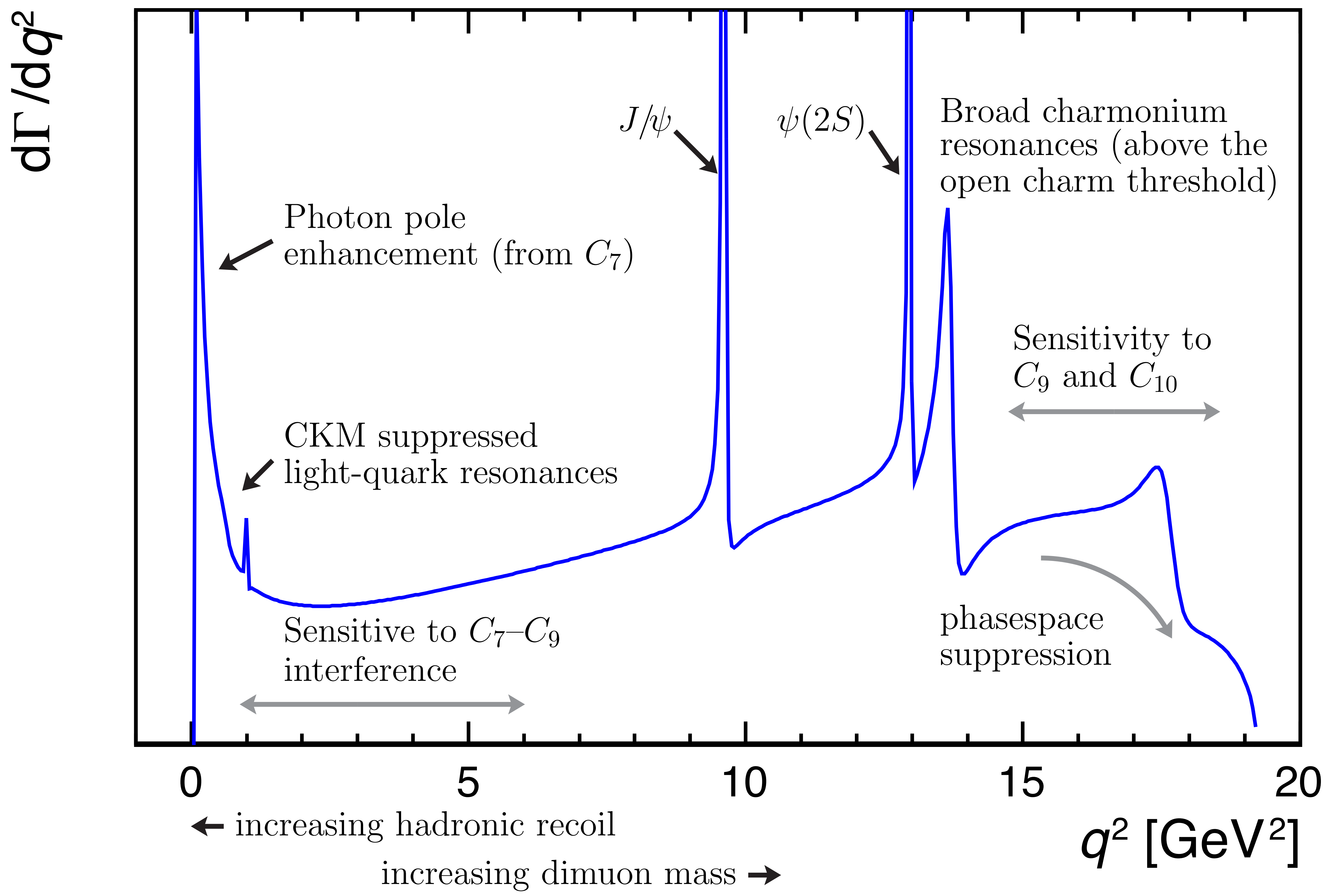
$$j^\mu_{\rm em} = \sum_q Q_q\,\bar{q}\gamma^\mu q$$

- **Wilson Coefficient**
  - perturbative
  - short-distance physics
  - q^2 independent
  - NNLO QCD + NLO EW@SM
  - parameterization of heavy NP
  - $C_i = C_i^{\rm SM} + C_i^{\rm NP}$

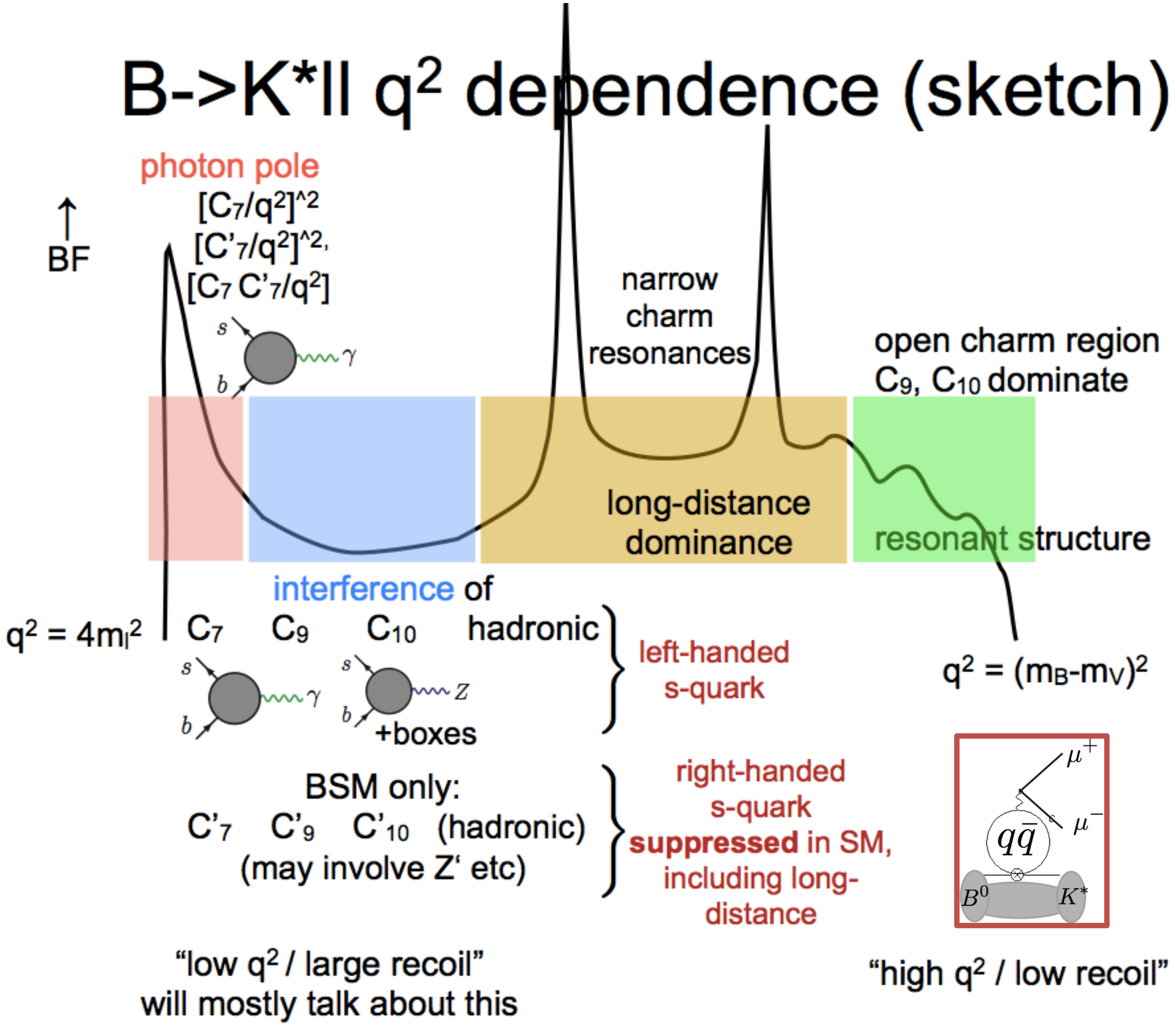
- **Matrix Element**
  - non-perturbative
  - long-distance physics
  - q^2 dependent
  - theoretically challenging
  - main source of uncertainties

From talk by B. Capdevila, M. Fedele, S. Neshatpour, P. Stangl

$b \to s\ell^+\ell^-$: theory



T.Blake, G.Lanfranchi, D.Straub, 1606.00916



From S.Jager's talk

$b \to s\ell^+\ell^-$: observables

- $B_s \to \ell^+\ell^-$
- $B \to X_s\ell^+\ell^-$
- $B \to K\ell^+\ell^-$
- $B \to K^*\ell^+\ell^-$
- $B_s \to \phi\ell^+\ell^-$
- $\Lambda_b \to \Lambda\ell^+\ell^-$

theoretical cleanness

- Branching Ratio
- Angular Distribution
- Lepton Flavour Universality (LFU) ratio

function of $(C_{7\gamma}, C_9, C_{10})$

LFU ratio in $B \to K\ell^+\ell^-$

$$R_K = \frac{\mathcal{B}(B \to K\mu^+\mu^-)}{\mathcal{B}(B \to Ke^+e^-)}$$

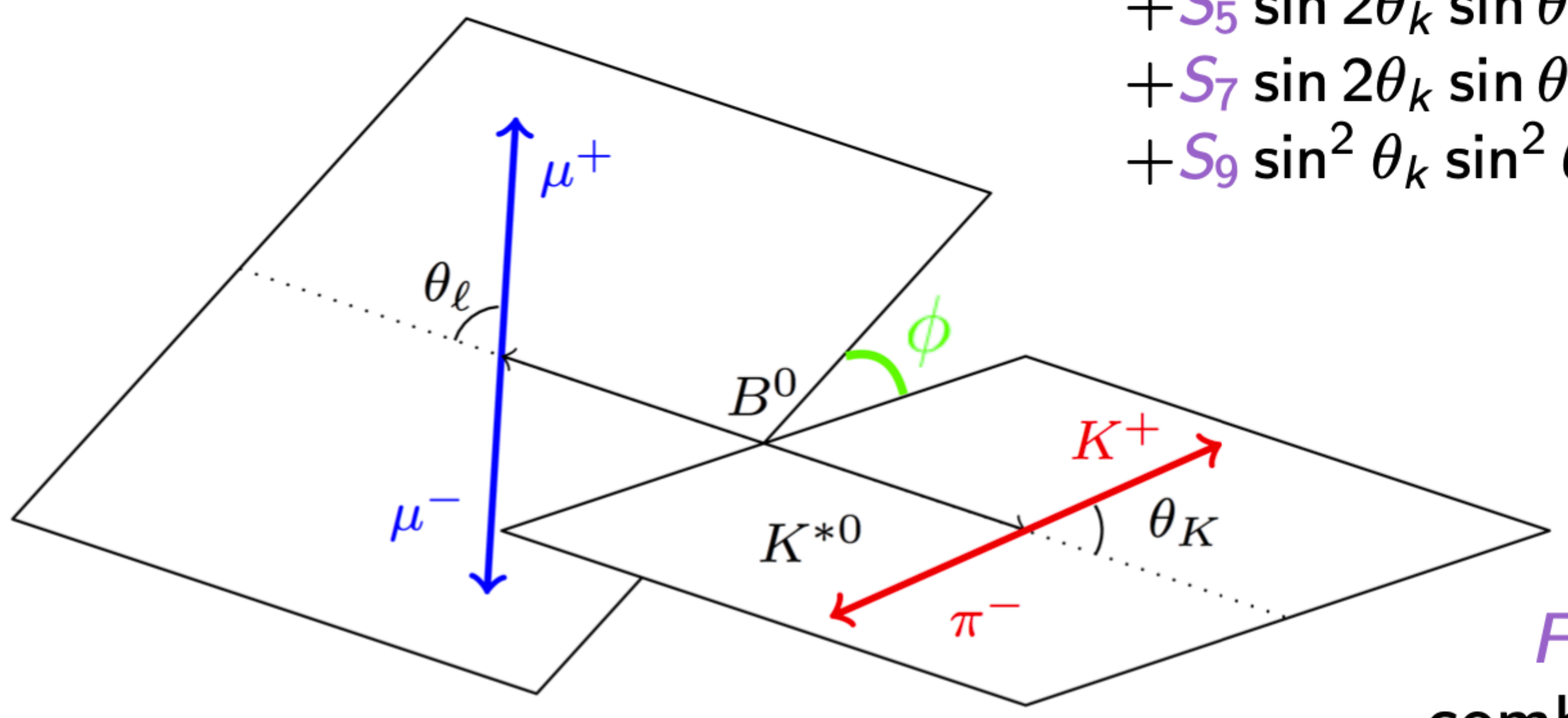
- $R_K^{\rm SM} \approx 1$
- **Hadronic uncertainties cancel**
- $\mathcal{O}(10^{-2})$ **QED correction**

deviation from unity

Physics beyond the SM

Angular distribution of $B \to K^*(\to K\pi)\mu^+\mu^-$

$$\frac{1}{d(\Gamma+\bar{\Gamma})/dq^2}\frac{d^4(\Gamma+\bar{\Gamma})}{d\vec{\Omega}dq^2} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_L)\sin^2\theta_k + F_L\cos^2\theta_k + \tfrac{1}{4}(1-F_L)\sin^2\theta_k\cos 2\theta_\ell - F_L\cos^2\theta_k\cos 2\theta_\ell + S_3\sin^2\theta_k\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_k\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_k\sin\theta_\ell\cos\phi + \tfrac{4}{3}A_{FB}\sin^2\theta_k\cos\theta_\ell + S_7\sin 2\theta_k\sin\theta_\ell\sin\phi + S_8\sin 2\theta_k\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_k\sin^2\theta_\ell\sin 2\phi\Big],$$

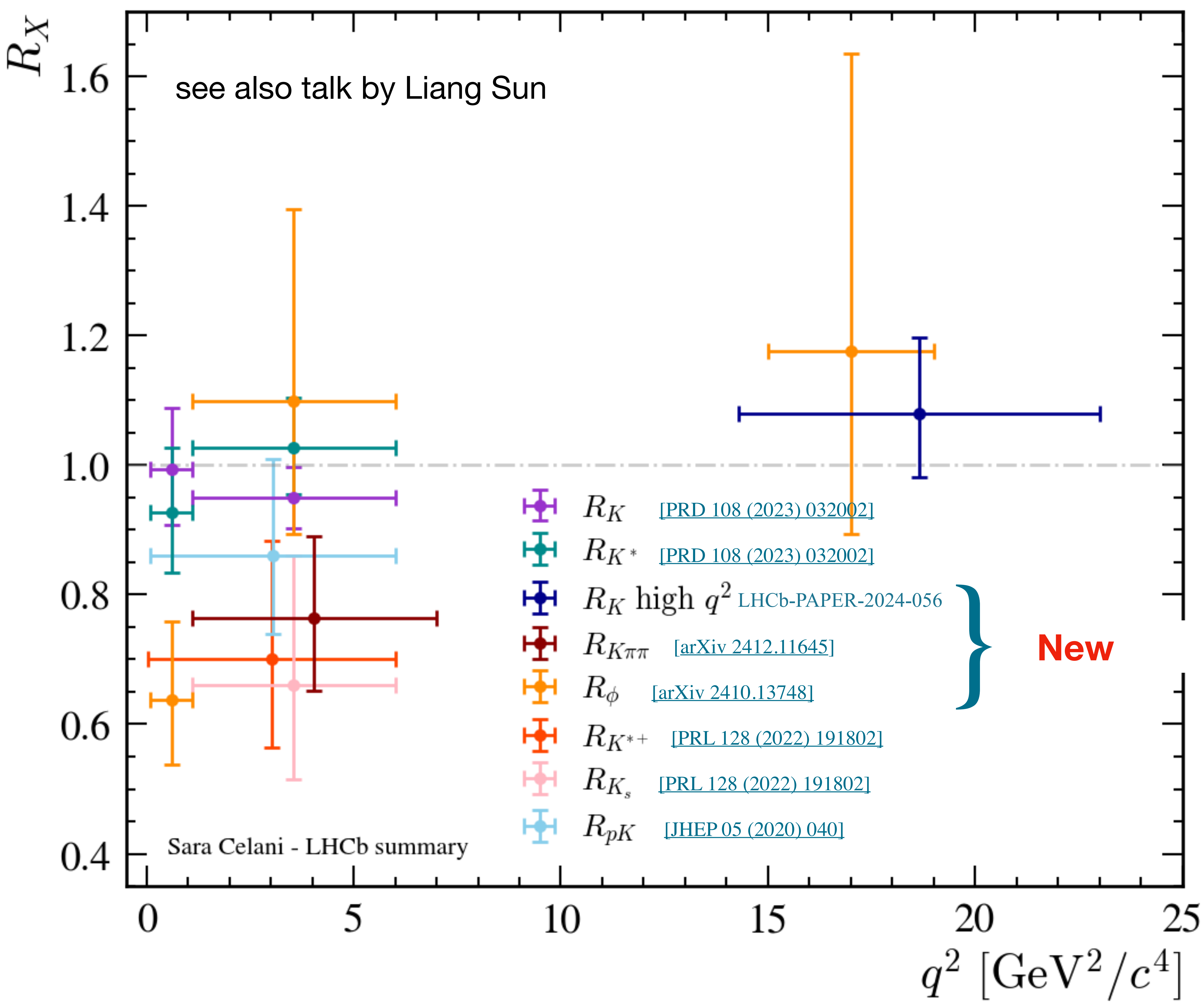


angular observables

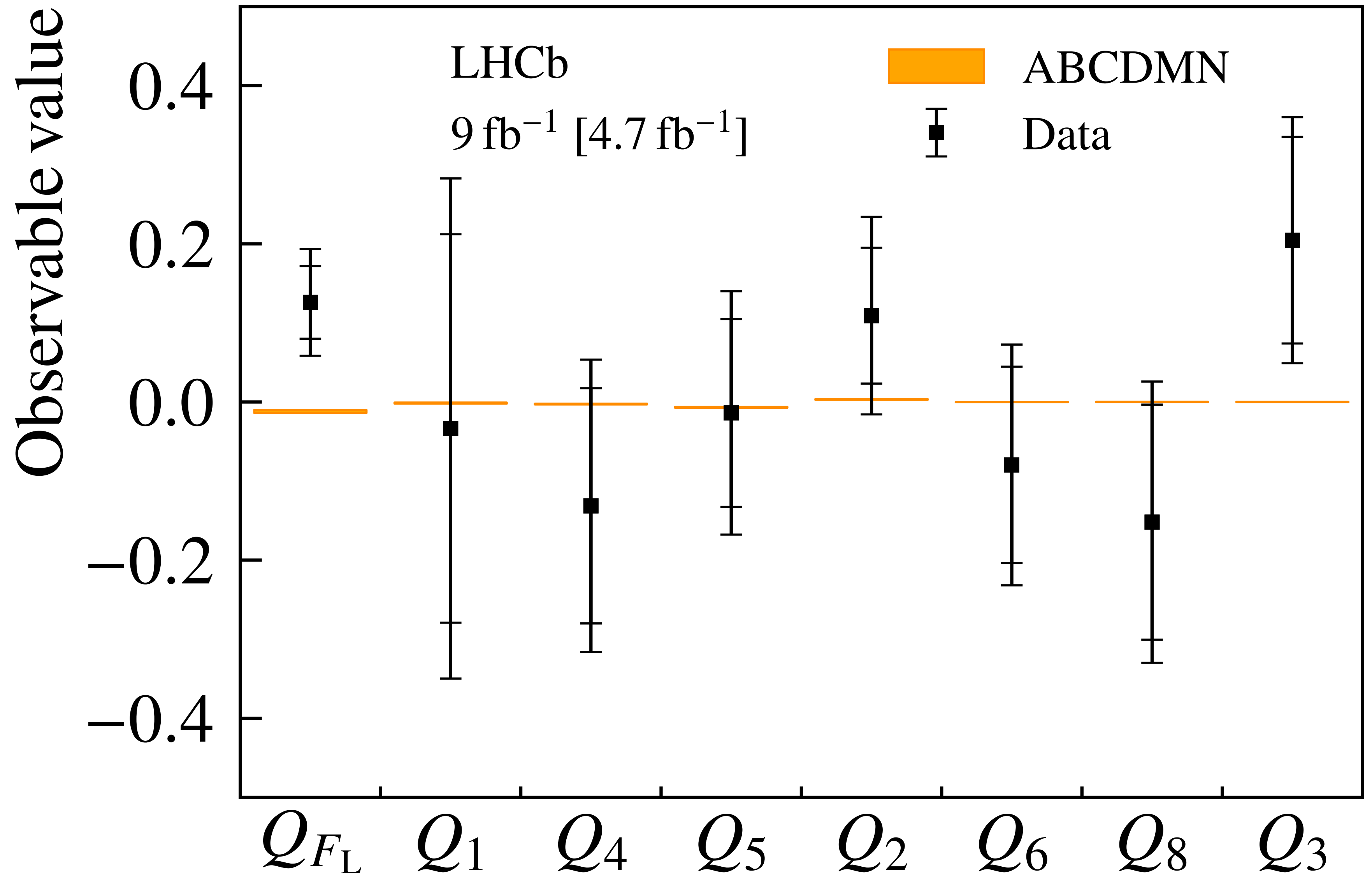
F_L, A_{FB}, $S_i = f(C_7, C_9, C_{10})$,
combinations of K^{*0} decay amplitudes

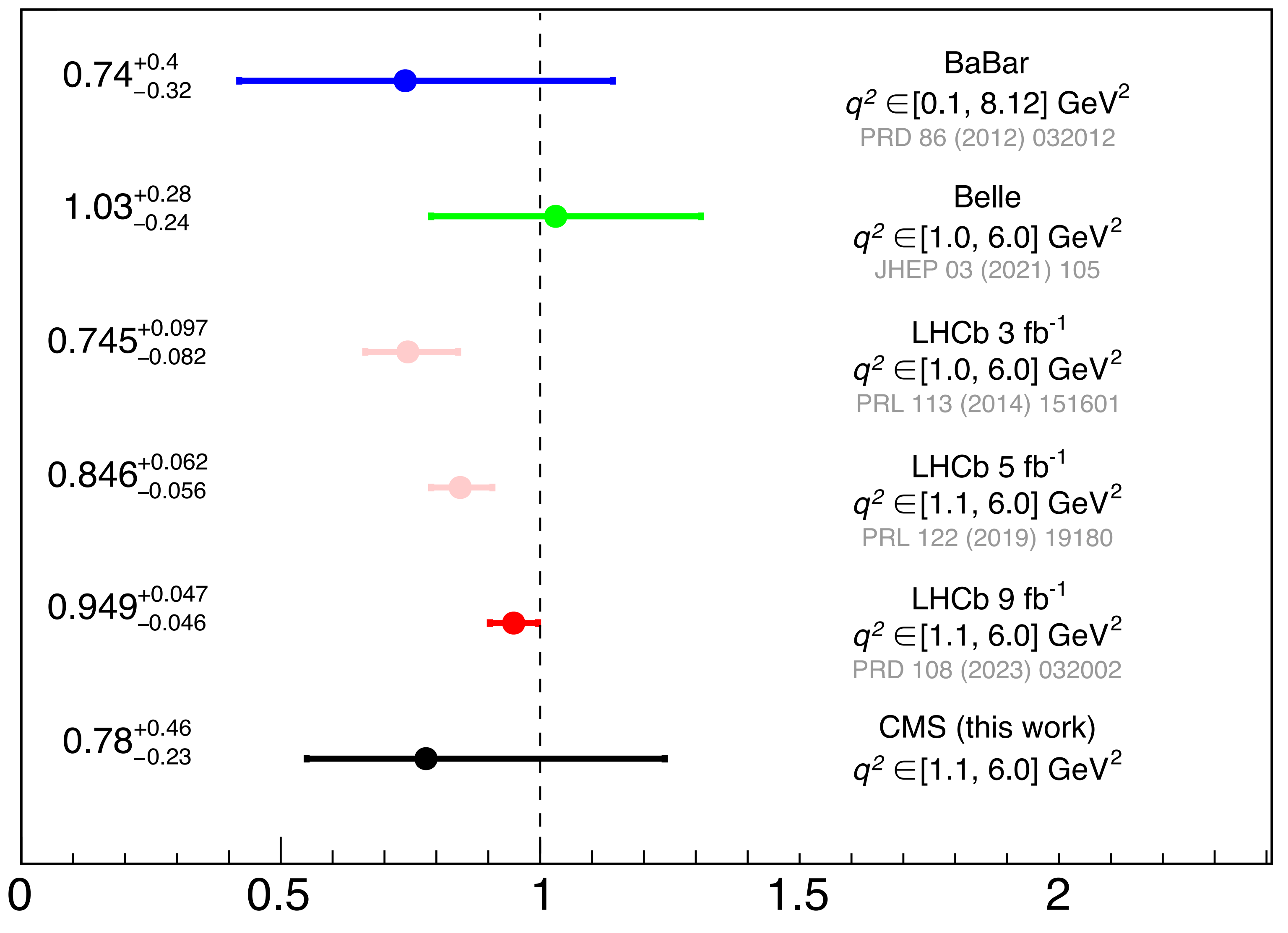
$$P_1 = \frac{2S_3}{1-F_L}$$
$$P_2 = \frac{2}{3}\frac{A_{\rm FB}}{1-F_L}$$
$$P_3 = -\frac{S_9}{1-F_L}$$
$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}.$$

$b \to s\ell^+\ell^-$: LFU



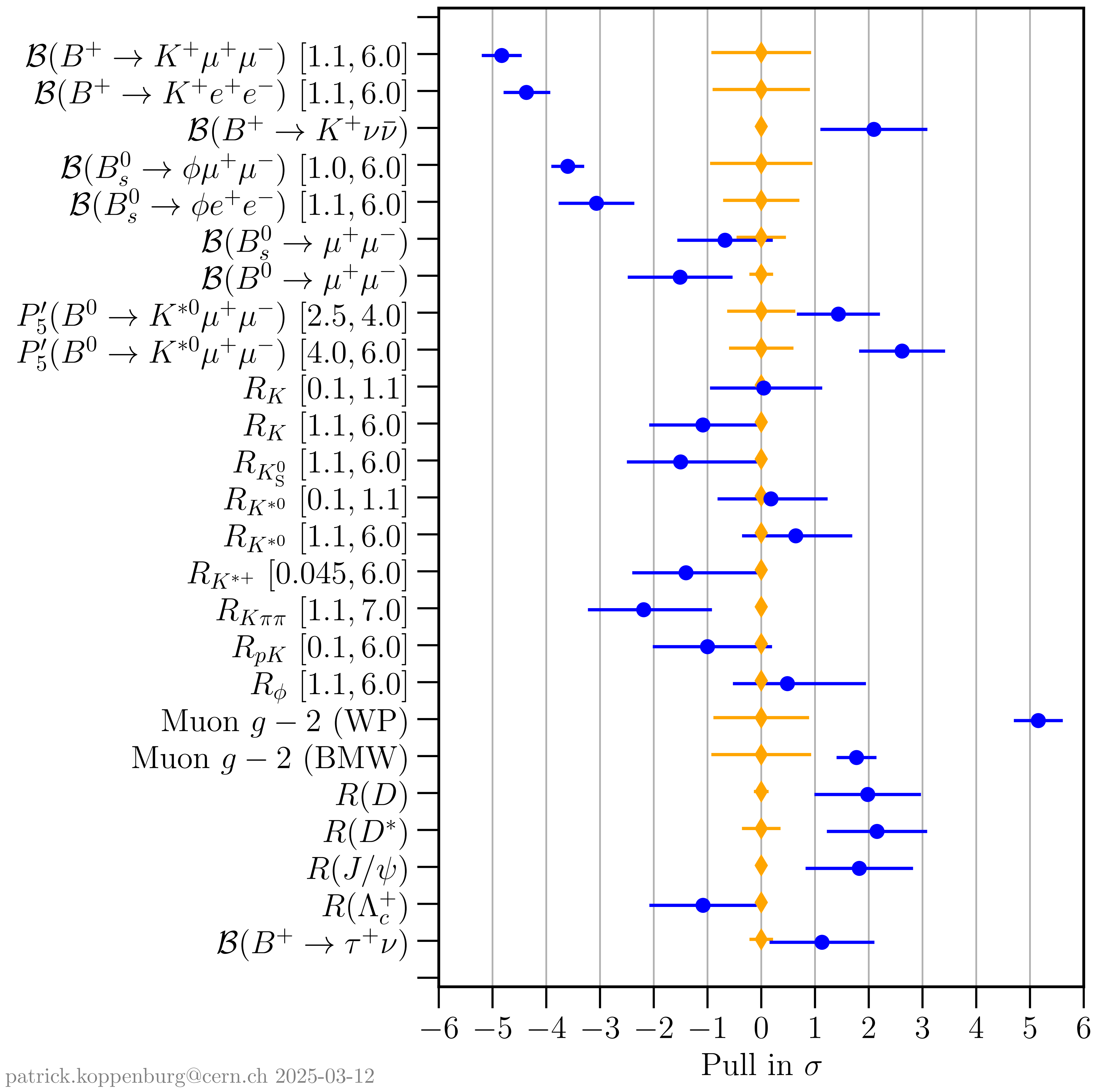
LHCb, arXiv: 2502.10291





CMS, Rep.Prog.Phys.87(2024)077802

Flavour anomalies: New Physics interpretation



μ_{NP} — ???

?

?

μ_{EW}

SMEFT: SM Effective Field Theory

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + C_i^{\text{NP}} O_i^{\text{NP}}$$

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$$

$$O_{\ell q}^{(1)} = (\bar{L}_p \gamma_\mu L_r)(\bar{Q}_s \gamma^\mu Q_t)$$

$$O_{ed}^{(1)} = (\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$$

… …

LEFT: Low Energy Effective Field Theory

$$\mathcal{H}_{\text{eff}} = (C_i^{\text{SM}} + C_i^{\text{NP}}) O_i^{\text{SM}} + C_j^{\text{NP}} O_j^{\text{NP}} \quad SU(3)_C \otimes U(1)_{\text{em}}$$

μ_b

$$O_9 = (\bar{b}\gamma^\mu P_L s)(\bar{\ell}\gamma_\mu \ell) \qquad O_{10} = (\bar{b}\gamma^\mu P_L s)(\bar{\ell}\gamma_\mu\gamma_5 \ell)$$

$$O_{\text{VLL}} = (\bar{c}\gamma^\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu) \qquad O_{S_R} = (\bar{c}_L b_R)(\bar{\ell}_R \nu_{\tau L})$$

$$O_{\text{VRL}} = (\bar{c}\gamma^\mu P_R b)(\bar{\tau}\gamma^\mu P_L \nu) \qquad O_{S_L} = (\bar{c}_R b_L)(\bar{\ell}_R \nu_{\tau L})$$

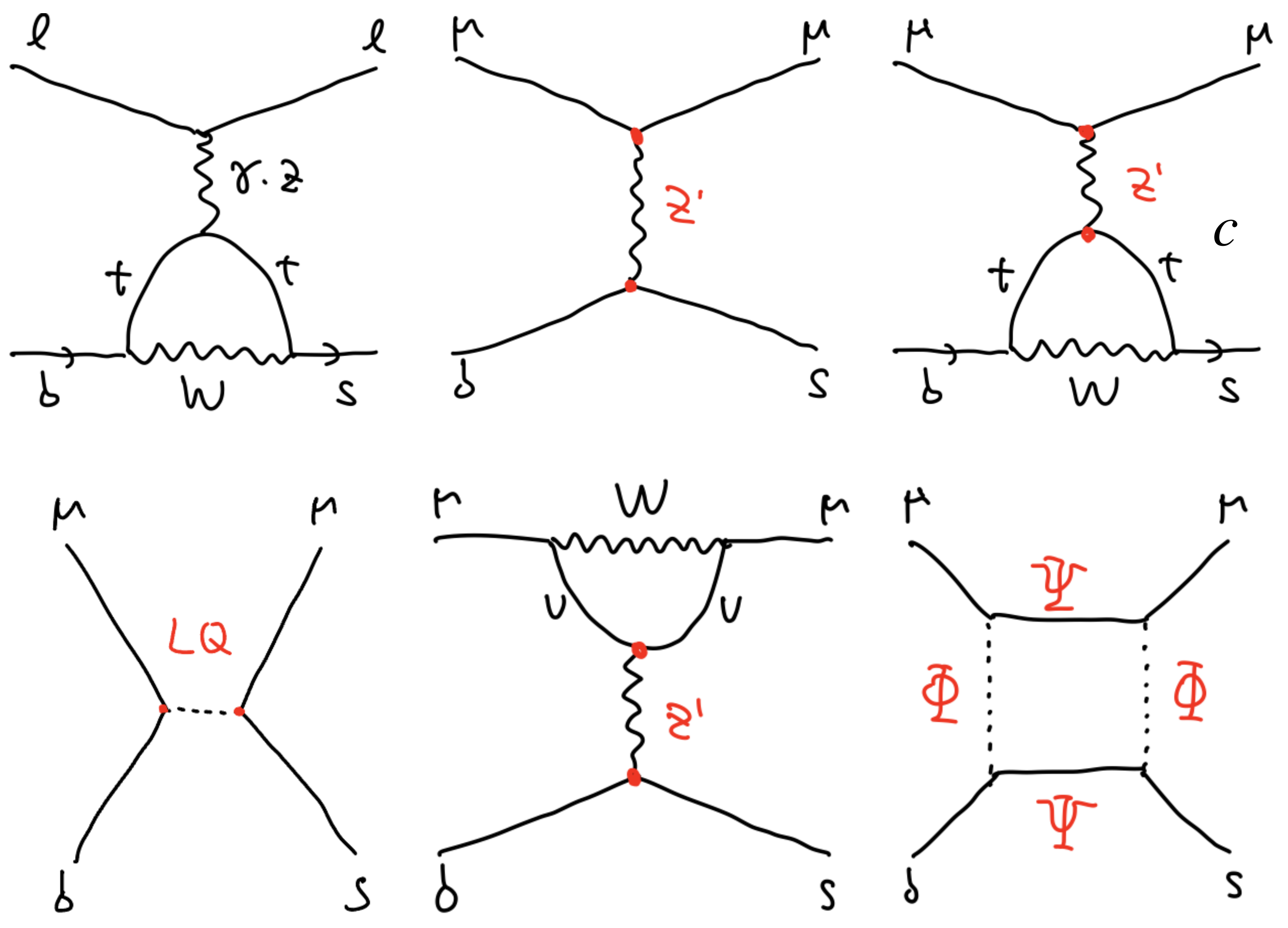
$$O_T = (\bar{c}_R \sigma^{\mu\nu} b_L)(\bar{\ell}_R \sigma_{\mu\nu} \nu_{\tau L})$$

Flavour anomalies: New Physics interpretation

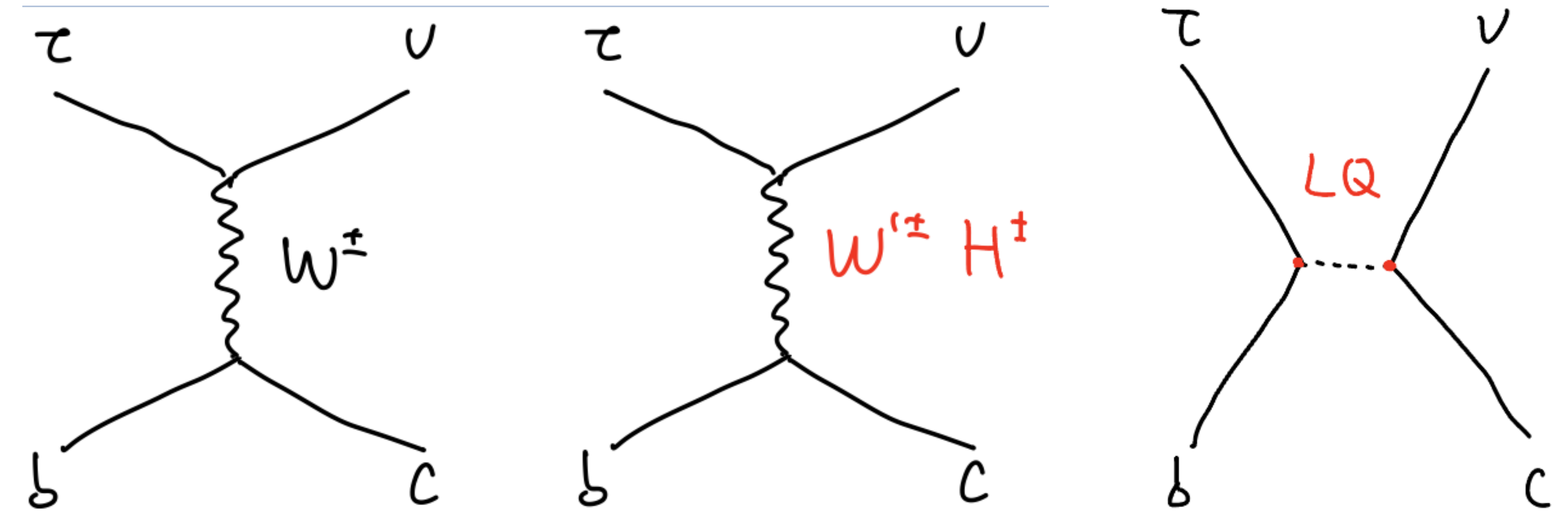
Ying Li, Cai-Dian Lu, 1808.02990

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

X.Q.Li, Y.D.Yang, **XBY**, et al, 2112.14215, 2205.02205, 2307.05290



- $b \to c\tau\nu$ anomalies



$\mu_{\rm NP}$

???

?

?

SMEFT: SM Effective Field Theory

$$\mathscr{L}_{\rm SMEFT} = \mathscr{L}_{\rm SM} + C_i^{\rm NP} O_i^{\rm NP}$$

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$$

$\mu_{\rm EW}$

$$O_{\ell q}^{(1)} = (\bar{L}_p \gamma_\mu L_r)(\bar{Q}_s \gamma^\mu Q_t)$$

$$O_{ed}^{(1)} = (\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$$

… …

LEFT: Low Energy Effective Field Theory

$$\mathscr{H}_{\rm eff} = (C_i^{\rm SM} + C_i^{\rm NP}) O_i^{\rm SM} + C_j^{\rm NP} O_j^{\rm NP} \qquad SU(3)_C \otimes U(1)_{\rm em}$$

$$O_9 = (\bar{b}\gamma^\mu P_L s)(\bar{\ell}\gamma_\mu \ell) \qquad O_{10} = (\bar{b}\gamma^\mu P_L s)(\bar{\ell}\gamma_\mu\gamma_5 \ell)$$

μ_b

$$O_{\rm VLL} = (\bar{c}\gamma^\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu) \qquad O_{S_R} = (\bar{c}_L b_R)(\bar{\ell}_R \nu_{\tau L})$$

$$O_{\rm VRL} = (\bar{c}\gamma^\mu P_R b)(\bar{\tau}\gamma^\mu P_L \nu) \qquad O_{S_L} = (\bar{c}_R b_L)(\bar{\ell}_R \nu_{\tau L})$$

$$O_T = (\bar{c}_R \sigma^{\mu\nu} b_L)(\bar{\ell}_R \sigma_{\mu\nu} \nu_{\tau L})$$

$b \to s\ell\ell$ global fit

Recent Global Fit

1D Hyp.	Best fit	$1\sigma/2\sigma$ (All)	$\mathrm{Pull}_{\mathrm{SM}}$ (All)	p-value (All)
$\mathcal{C}_{9\mu}^{\mathrm{NP}}$	-0.67	$[-0.82,-0.52]$ $[-0.98,-0.37]$	4.5	20.2 %
$\mathcal{C}_{9\mu}^{\mathrm{NP}}=-\mathcal{C}_{10\mu}^{\mathrm{NP}}$	-0.19	$[-0.25,-0.13]$ $[-0.32,-0.07]$	3.1	9.9 %

Ciuchini et al 2212.10516
Alguero et al 2304.07330
Qiaoyi Wen, Fanrong Xu 2305.19038

$$O_9=(\bar b\gamma^\mu P_L s)(\bar\ell\gamma_\mu\ell)$$

$$O_{10}=(\bar b\gamma^\mu P_L s)(\bar\ell\gamma_\mu\gamma_5\ell)$$

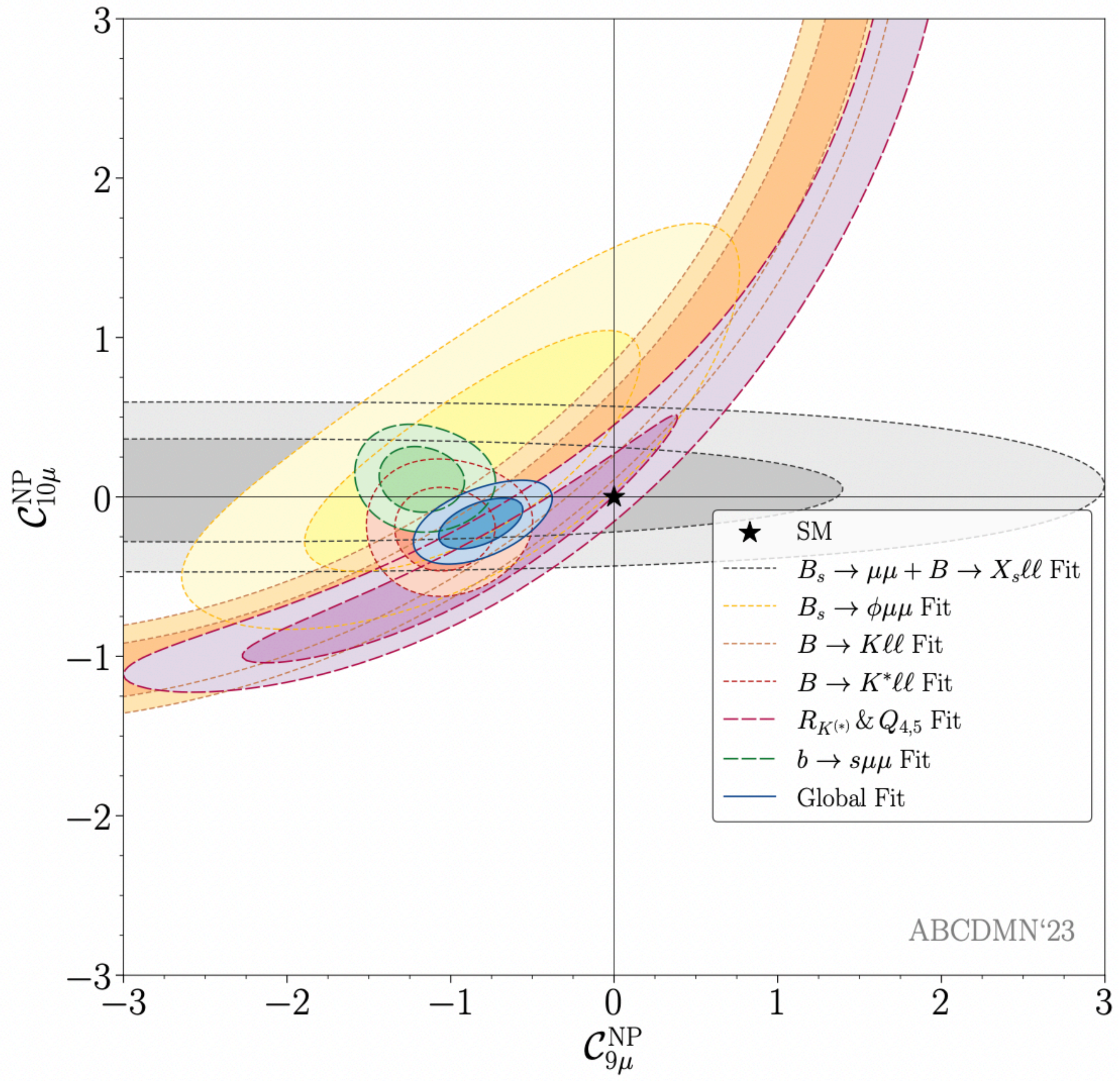
$\mathscr{B}(B_s\to\mu^+\mu^-)$ consistent with SM
(C_{10} can't be too large)

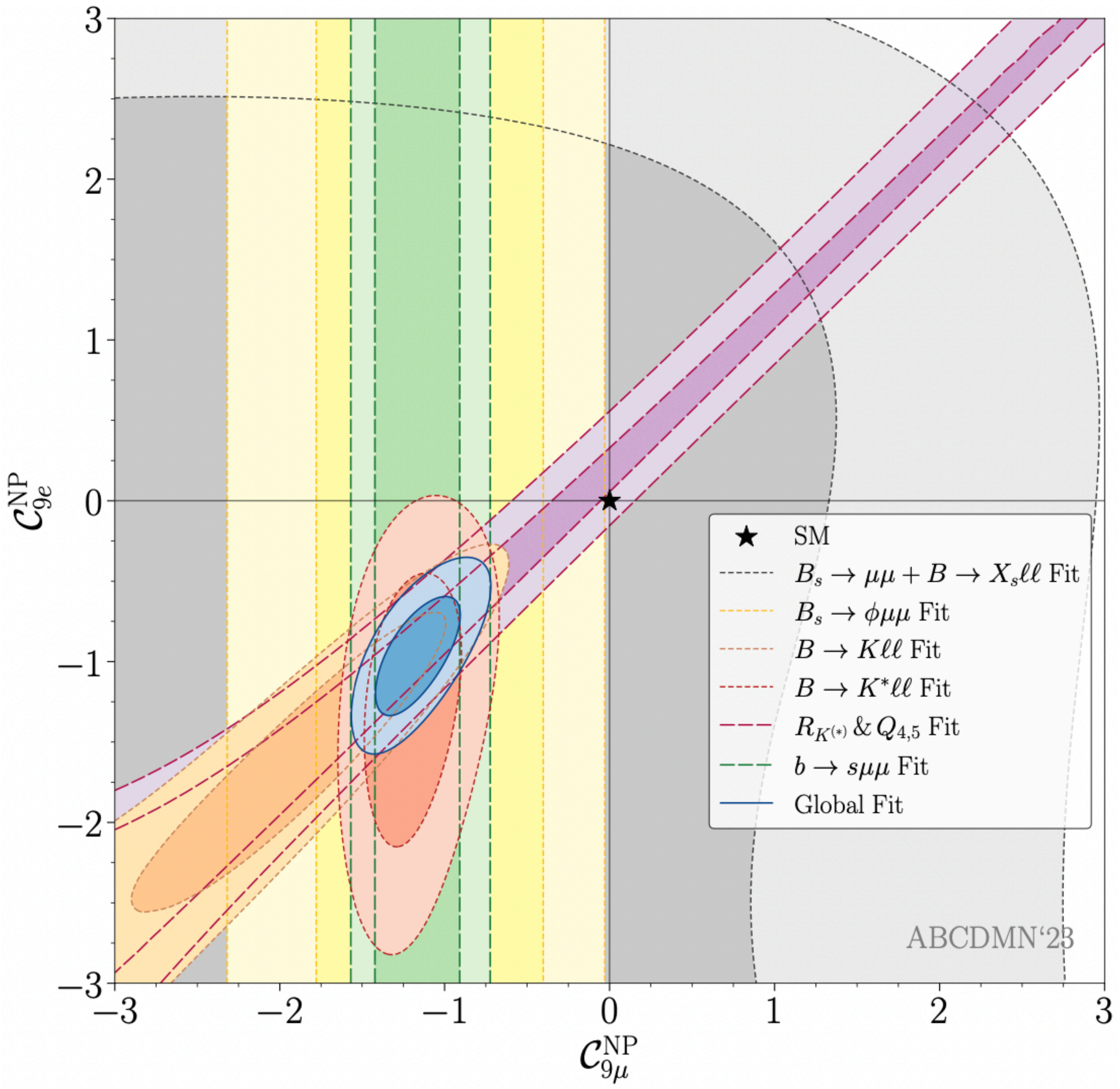
2D Hyp.	Best fit (All)	$\mathrm{Pull}_{\mathrm{SM}}$ (All)	p-value (All)
$(\mathcal{C}_{9\mu}^{\mathrm{NP}},\mathcal{C}_{10\mu}^{\mathrm{NP}})$	$(-0.82,-0.17)$	4.4	21.9%
$(\mathcal{C}_{9\mu}^{\mathrm{NP}},\mathcal{C}_{7'})$	$(-0.68,+0.01)$	4.2	19.4%
$(\mathcal{C}_{9\mu}^{\mathrm{NP}},\mathcal{C}_{9'\mu})$	$(-0.78,+0.21)$	4.3	20.7%
$(\mathcal{C}_{9\mu}^{\mathrm{NP}},\mathcal{C}_{10'\mu})$	$(-0.76,-0.12)$	4.3	20.5%
$(\mathcal{C}_{9\mu}^{\mathrm{NP}},\mathcal{C}_{9e}^{\mathrm{NP}})$	$(-1.17,-0.97)$	5.6	40.3%

Scenario		Best-fit point	1σ	$\mathrm{Pull}_{\mathrm{SM}}$	p-value
Scenario 0	$\mathcal{C}_{9\mu}^{\mathrm{NP}}=\mathcal{C}_{9e}^{\mathrm{NP}}=\mathcal{C}_{9}^{\mathrm{U}}$	-1.17	$[-1.33,-1.00]$	5.8	39.9 %
Scenario 5	$\mathcal{C}_{9\mu}^{\mathrm{V}}$	-1.02	$[-1.43,-0.61]$	4.1	21.0 %
	$\mathcal{C}_{10\mu}^{\mathrm{V}}$	-0.35	$[-0.75,-0.00]$		
	$\mathcal{C}_{9}^{\mathrm{U}}=\mathcal{C}_{10}^{\mathrm{U}}$	$+0.19$	$[-0.16,+0.58]$		
Scenario 6	$\mathcal{C}_{9\mu}^{\mathrm{V}}=-\mathcal{C}_{10\mu}^{\mathrm{V}}$	-0.27	$[-0.34,-0.20]$	4.0	18.0 %
	$\mathcal{C}_{9}^{\mathrm{U}}=\mathcal{C}_{10}^{\mathrm{U}}$	-0.41	$[-0.53,-0.29]$		
Scenario 7	$\mathcal{C}_{9\mu}^{\mathrm{V}}$	-0.21	$[-0.39,-0.02]$	5.6	40.3 %
	$\mathcal{C}_{9}^{\mathrm{U}}$	-0.97	$[-1.21,-0.72]$		
Scenario 8	$\mathcal{C}_{9\mu}^{\mathrm{V}}=-\mathcal{C}_{10\mu}^{\mathrm{V}}$	-0.08	$[-0.14,-0.02]$	5.6	41.1 %
	$\mathcal{C}_{9}^{\mathrm{U}}$	-1.10	$[-1.27,-0.91]$		

No R_K, R_{K^*} anomalies now !

$$C_{9e}=C_9^U$$
$$C_{9\mu}=C_9^U+C_9^V$$





$b \to s\ell\ell$ global fit and $(g-2)_\mu$

Recent Global Fit

Ciuchini et al 2212.10516
Alguero et al 2304.07330
Qiaoyi Wen, Fanrong Xu 2305.19038

1D Hyp.	Best fit	All: $1\sigma/2\sigma$	Pull_{SM}	p-value
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$$O_9 = (\bar{b}\gamma^\mu P_L s)(\bar{\ell}\gamma_\mu \ell)$$

$$O_{10} = (\bar{b}\gamma^\mu P_L s)(\bar{\ell}\gamma_\mu\gamma_5 \ell)$$

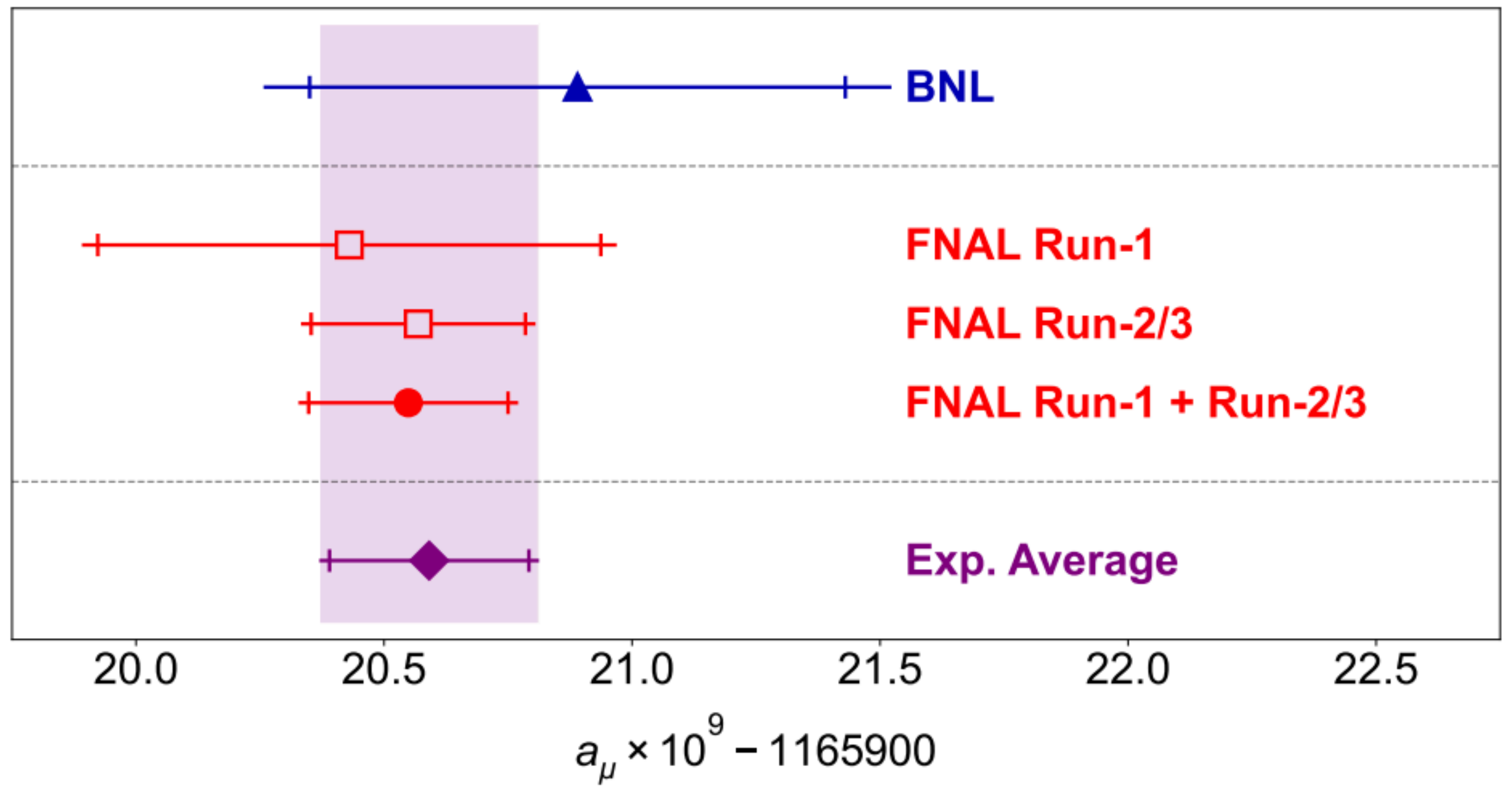
$\mathcal{B}(B_s \to \mu^+\mu^-)$ consistent with SM
(C_{10} can't be too large)

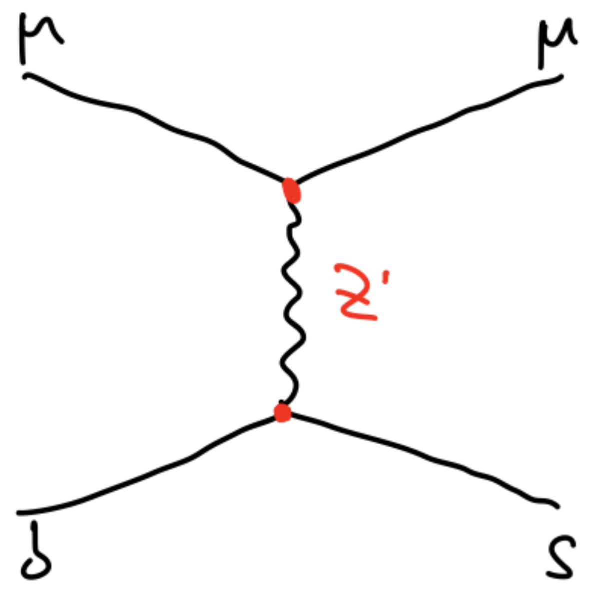
2D Hyp.	All: Best fit	Pull_{SM}	p-value
$(\mathcal{C}_{9\mu}^{\text{NP}},\mathcal{C}_{10\mu}^{\text{NP}})$	$(-0.82,-0.17)$	4.4	21.9%
$(\mathcal{C}_{9\mu}^{\text{NP}},\mathcal{C}_{7'})$	$(-0.68,+0.01)$	4.2	19.4%
$(\mathcal{C}_{9\mu}^{\text{NP}},\mathcal{C}_{9'\mu})$	$(-0.78,+0.21)$	4.3	20.7%
$(\mathcal{C}_{9\mu}^{\text{NP}},\mathcal{C}_{10'\mu})$	$(-0.76,-0.12)$	4.3	20.5%
$(\mathcal{C}_{9\mu}^{\text{NP}},\mathcal{C}_{9e}^{\text{NP}})$	$(-1.17,-0.97)$	5.6	40.3%

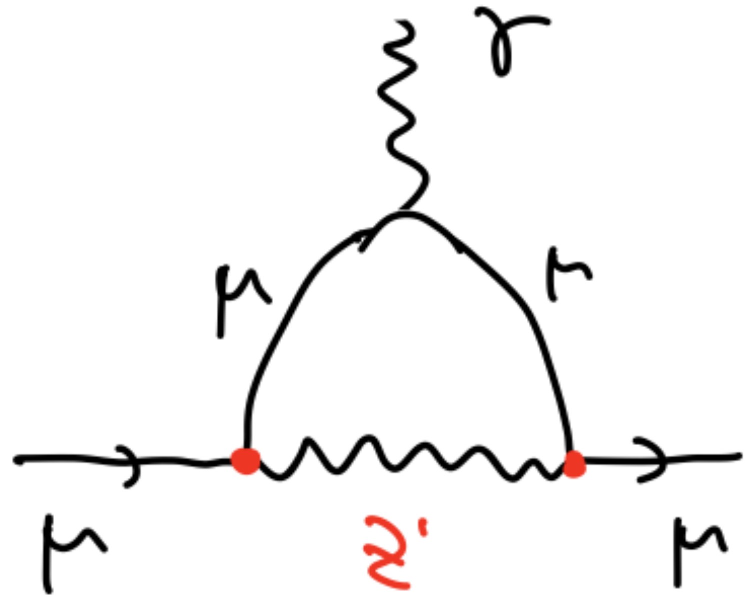
Current global fit implies non-zero C_9^{NP}

Scenario		Best-fit point	1σ	Pull_{SM}	p-value
Scenario 0	$\mathcal{C}_{9\mu}^{\text{NP}}=\mathcal{C}_{9e}^{\text{NP}}=\mathcal{C}_9^{\text{U}}$	-1.17	$[-1.33,-1.00]$	5.8	39.9 %
Scenario 5	$\mathcal{C}_{9\mu}^{\text{V}}$	-1.02	$[-1.43,-0.61]$	4.1	21.0 %
	$\mathcal{C}_{10\mu}^{\text{V}}$	-0.35	$[-0.75,-0.00]$		
	$\mathcal{C}_9^{\text{U}}=\mathcal{C}_{10}^{\text{U}}$	$+0.19$	$[-0.16,+0.58]$		
Scenario 6	$\mathcal{C}_{9\mu}^{\text{V}}=-\mathcal{C}_{10\mu}^{\text{V}}$	-0.27	$[-0.34,-0.20]$	4.0	18.0 %
	$\mathcal{C}_9^{\text{U}}=\mathcal{C}_{10}^{\text{U}}$	-0.41	$[-0.53,-0.29]$		
Scenario 7	$\mathcal{C}_{9\mu}^{\text{V}}$	-0.21	$[-0.39,-0.02]$	5.6	40.3 %
	$\mathcal{C}_9^{\text{U}}$	-0.97	$[-1.21,-0.72]$		
Scenario 8	$\mathcal{C}_{9\mu}^{\text{V}}=-\mathcal{C}_{10\mu}^{\text{V}}$	-0.08	$[-0.14,-0.02]$	5.6	41.1 %
	$\mathcal{C}_9^{\text{U}}$	-1.10	$[-1.27,-0.91]$		

$Z'\ell^+\ell^-$ interaction should be almost vector-type







$$\Delta(g-2)_\mu \propto -5g_A^2 + g_V^2$$

Charm-loop contribution

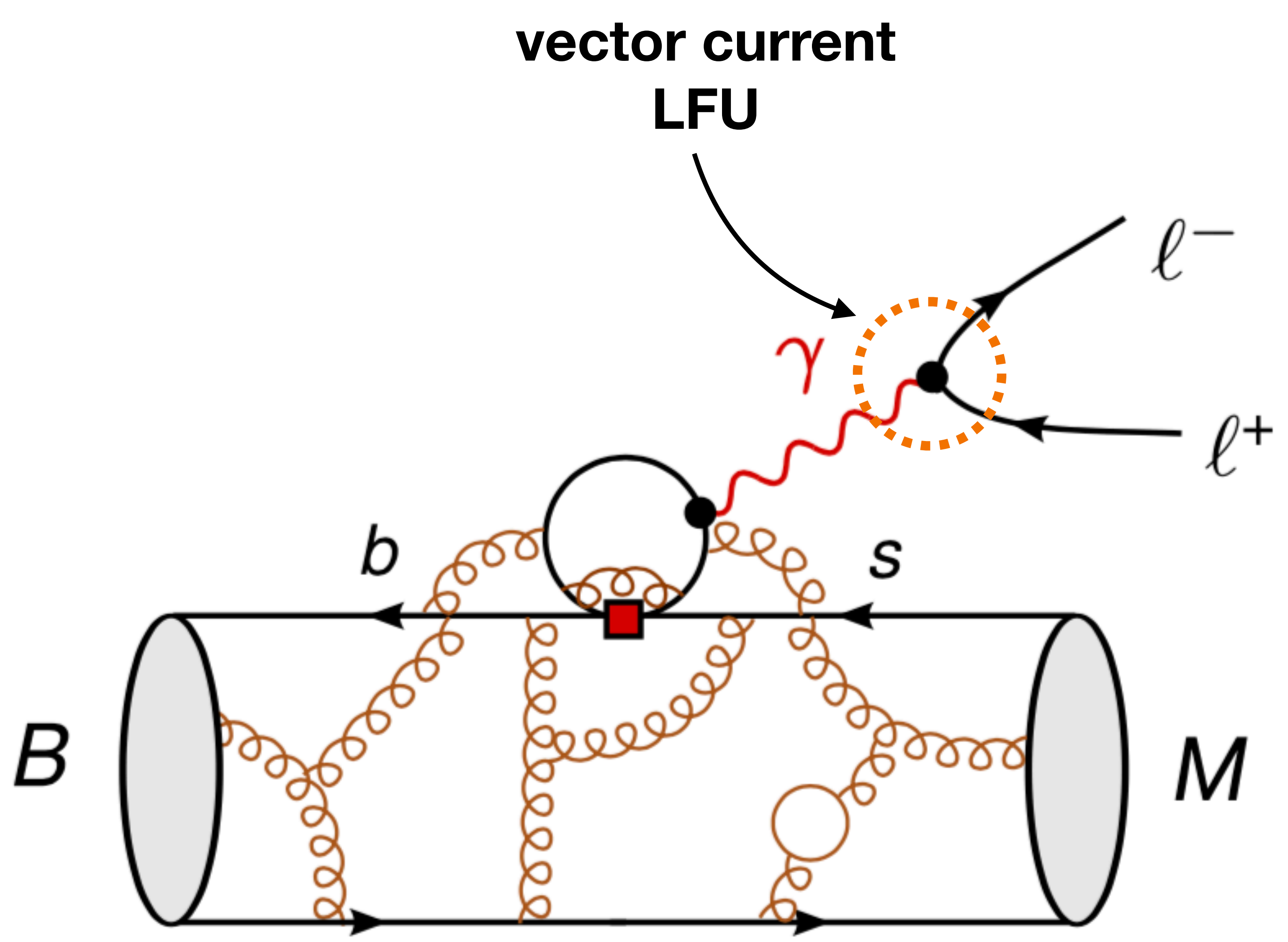
- ▶ **Global fit prefer to $C_{9e} = C_{9\mu} \neq C_9^{SM}$** $\Longleftarrow \mathscr{B}(B_s \to \mu^+\mu^-)_{exp}$ **is consistent with SM**
- ▶ **Charm-loop could mimic $C_{9e} = C_{9\mu}$**

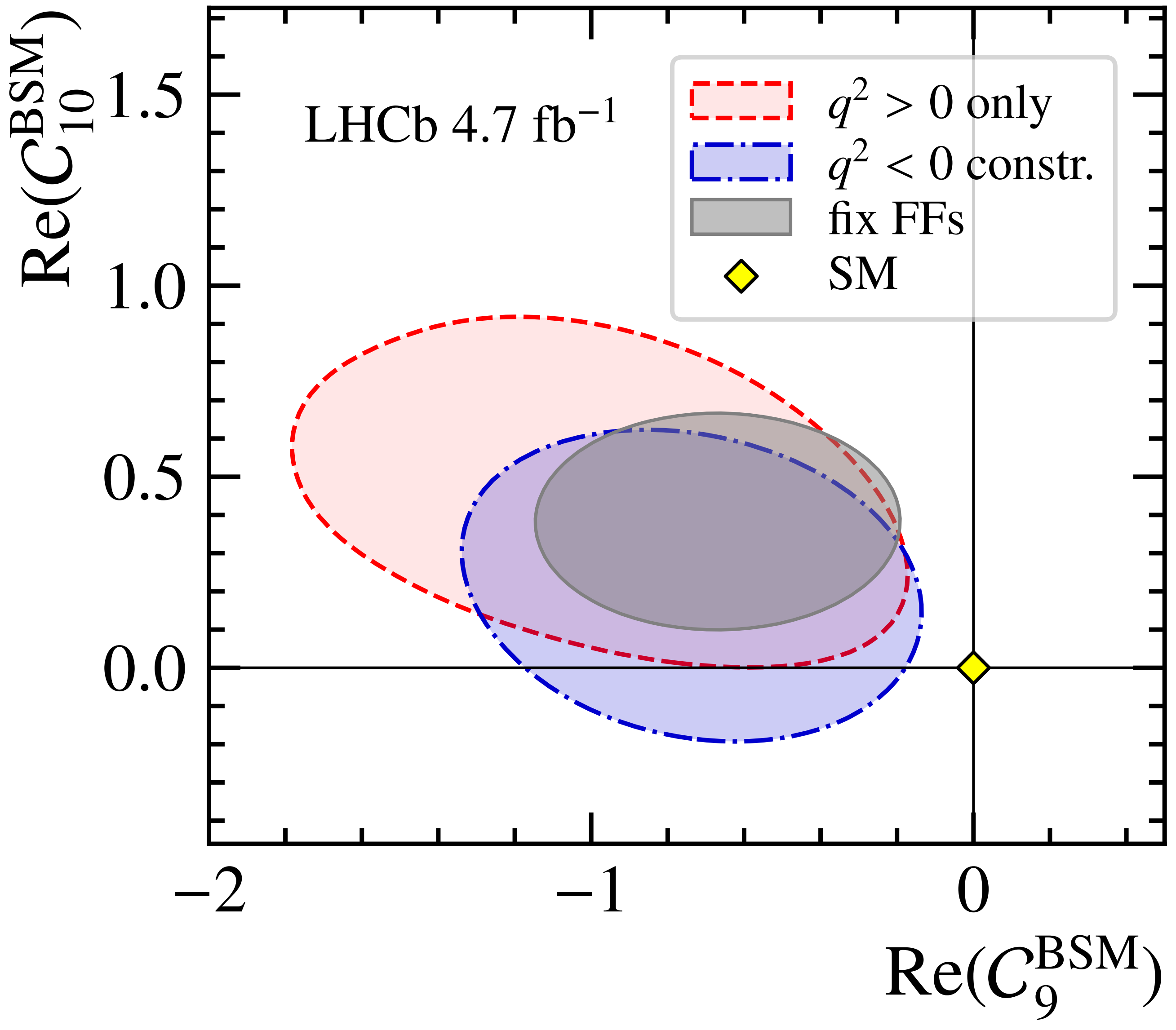
$$O_9 = (\bar{b}\gamma^\mu P_L s)(\bar{\ell}\gamma_\mu \ell)$$

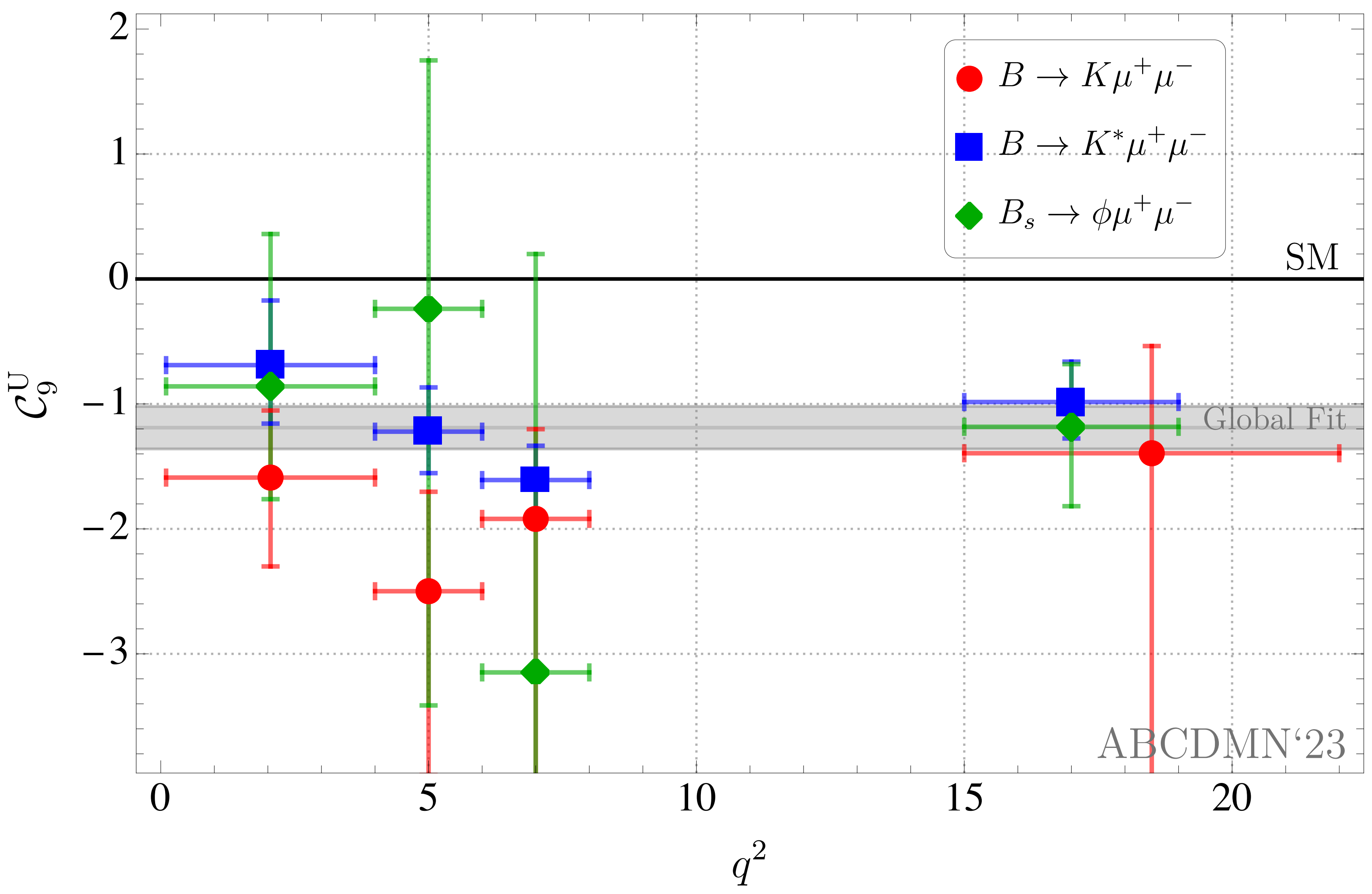
$$O_{10} = (\bar{b}\gamma^\mu P_L s)(\bar{\ell}\gamma_\mu \gamma_5 \ell)$$

$$C_{9e} = C_{9\mu} = C_9^{SM} + \Delta C_9^{U,\text{ charm loop}} + \Delta C_9^{U,\text{ NP}}$$

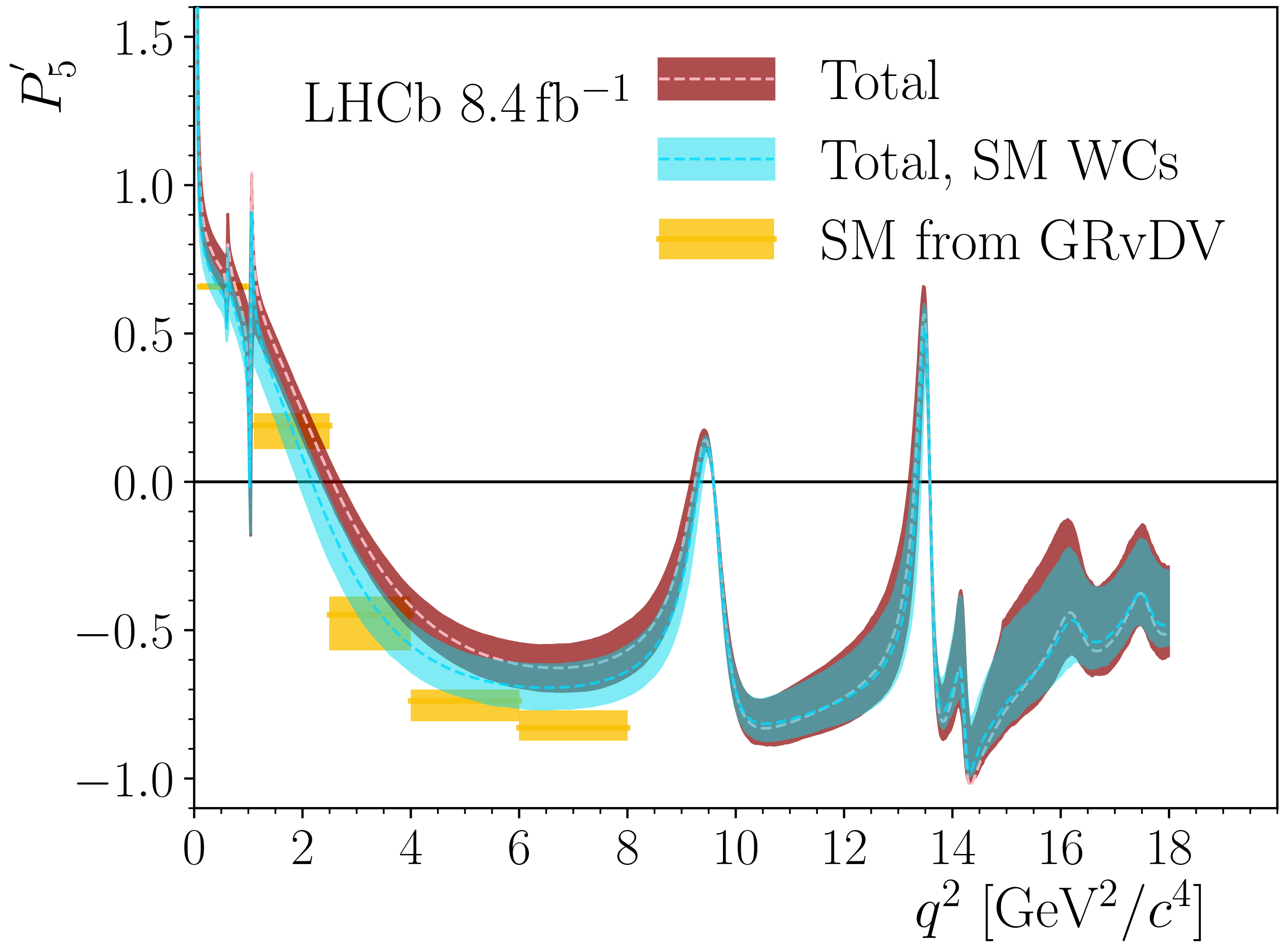
- ▶ **Charm-loop contribution is expected to be $\Delta C_9^U(q^2)$, but not ΔC_9^U**

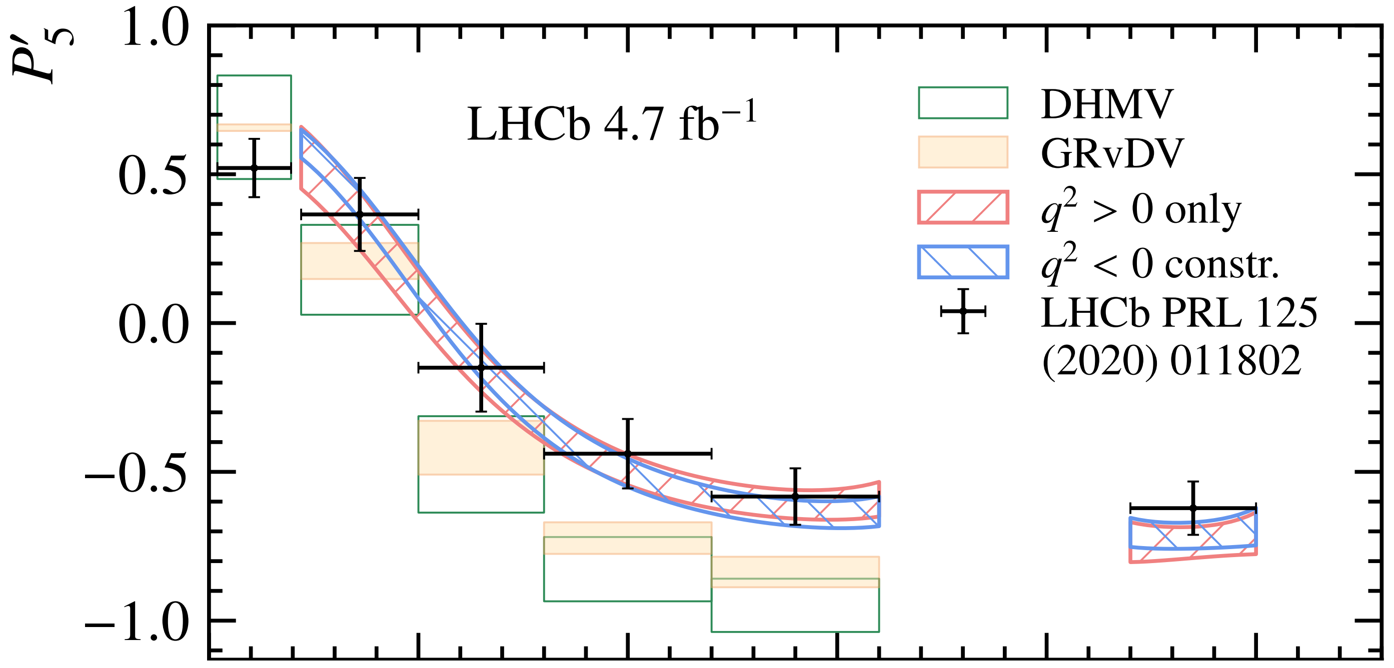






LHCb, PRL132(2024)131801
LHCb, PRD109(2024)052009
LHCb, 2405.17347 (charmonium region is open)





LFU violation in NP

LFU in SM

$$\bar{\ell}'_R \gamma^\mu Z_\mu Y \ell'_R \propto \begin{bmatrix}\bar{e}'_R & \bar{\mu}'_R & \bar{\tau}'_R\end{bmatrix} \begin{bmatrix}-1 & 0 & 0\\ 0 & -1 & 0\\ 0 & 0 & -1\end{bmatrix} \begin{bmatrix}e'_R\\ \mu'_R\\ \tau'_R\end{bmatrix} = \begin{bmatrix}\bar{e}_R & \bar{\mu}_R & \bar{\tau}_R\end{bmatrix} U_R^\dagger \begin{bmatrix}-1 & 0 & 0\\ 0 & -1 & 0\\ 0 & 0 & -1\end{bmatrix} U_R \begin{bmatrix}e_R\\ \mu_R\\ \tau_R\end{bmatrix} = \begin{bmatrix}\bar{e}_R & \bar{\mu}_R & \bar{\tau}_R\end{bmatrix} \begin{bmatrix}-1 & 0 & 0\\ 0 & -1 & 0\\ 0 & 0 & -1\end{bmatrix} \begin{bmatrix}e_R\\ \mu_R\\ \tau_R\end{bmatrix}$$

interaction eigenbasis

mass eigenbasis

hypercharge of $U(1)_Y$

$Y_{e_R} = Y_{\mu_R} = Y_{\tau_R} = -1$

$\ell'_R = U_R \ell_R$

U_R: complex 3×3 unitary matrix

flavour universal

LFU violation in NP

$$\bar{\ell}'_R \gamma^\mu Z'_\mu Y' \ell'_R \propto \begin{bmatrix}\bar{e}'_R & \bar{\mu}'_R & \bar{\tau}'_R\end{bmatrix} \begin{bmatrix}Y'_{e_R} & 0 & 0\\ 0 & Y'_{\mu_R} & 0\\ 0 & 0 & Y'_{\tau_R}\end{bmatrix} \begin{bmatrix}e'_R\\ \mu'_R\\ \tau'_R\end{bmatrix} = \begin{bmatrix}\bar{e}_R & \bar{\mu}_R & \bar{\tau}_R\end{bmatrix} U_R^\dagger \begin{bmatrix}Y'_{e_R} & 0 & 0\\ 0 & Y'_{\mu_R} & 0\\ 0 & 0 & Y'_{\tau_R}\end{bmatrix} U_R \begin{bmatrix}e_R\\ \mu_R\\ \tau_R\end{bmatrix} = \begin{bmatrix}\bar{e}_R & \bar{\mu}_R & \bar{\tau}_R\end{bmatrix} \begin{bmatrix}\epsilon_{11} & \epsilon_{12} & \epsilon_{13}\\ \epsilon_{21} & \epsilon_{22} & \epsilon_{23}\\ \epsilon_{31} & \epsilon_{32} & \epsilon_{33}\end{bmatrix} \begin{bmatrix}e_R\\ \mu_R\\ \tau_R\end{bmatrix}$$

hypercharge of $U(1)'$

$Y'_{e_R} \neq Y'_{\mu_R} \neq Y'_{\tau_R}$

flavour non-universality is generated, but flavour violation usually can't be avoided.

We learn that

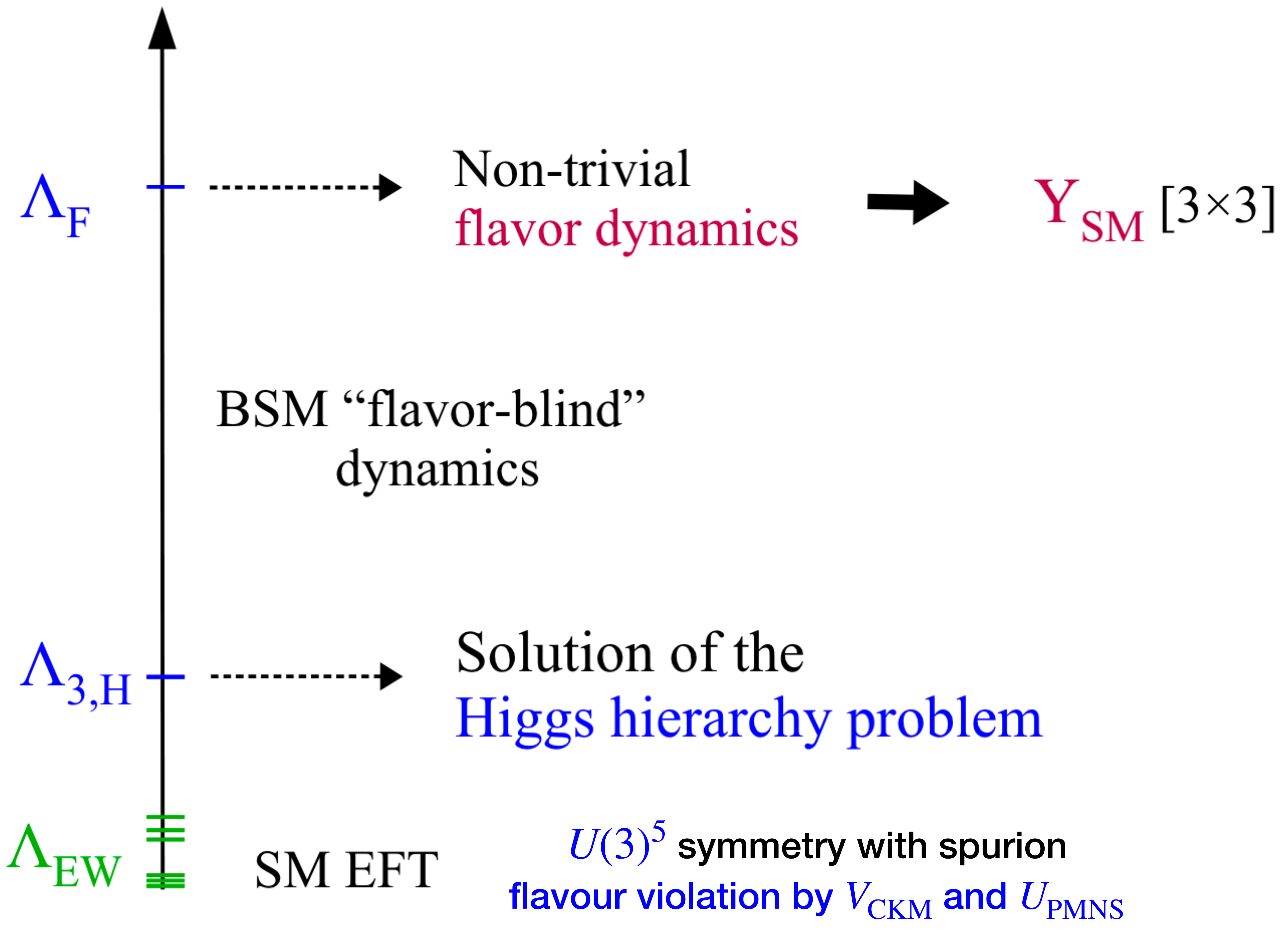
$b \to s\mu\mu / b \to see \neq$ SM $\Longrightarrow \begin{cases} b \to se\mu,\ b \to se\tau,\ b \to s\mu\tau \\ b \to d\mu\mu / b \to dee,\ s \to d\mu\mu / s \to dee,\ b\bar{b} \to \mu\mu / b\bar{b} \to ee, \ldots \end{cases}$

$b \to c\tau\nu / b \to c\mu\nu \neq$ SM $\Longrightarrow b \to u\tau\nu / b \to u\mu\nu,\ c \to s\tau\nu / c \to s\mu\nu, \ldots$

What's the magnitude of NP effects in these related channels? Can they satisfy the current exp bound? Flavour structure !

Origin of LFUV: connection to flavour structure

- **Minimal Flavour Violation**



	Branching fractions		
	Measured upper limit at 90% CL [8,84]	Prediction maximum [or range]	
Decay mode		NO	IO
$B \to K e^\pm \mu^\mp$	3.8×10^{-8}	2.9×10^{-9}	3.0×10^{-9}
$B \to K^* e^\pm \mu^\mp$	5.1×10^{-7}	7.8×10^{-9}	7.8×10^{-9}
$B_s \to e^\pm \mu^\mp$	1.1×10^{-8}	8.6×10^{-12}	9.0×10^{-12}
$B \to \pi e^\pm \mu^\mp$	9.2×10^{-8}	1.2×10^{-10}	1.3×10^{-10}
$B \to \rho e^\pm \mu^\mp$	3.2×10^{-6}	3.1×10^{-10}	3.2×10^{-10}
$B^0 \to e^\pm \mu^\mp$	2.8×10^{-9}	2.6×10^{-13}	2.7×10^{-13}

C.W.Chiang, X.G.He, J.Tandean, **XBY**, 1706.02696
C.S.Kim, **XBY**, Y.J.Zheng, 1602.08107

LFU violation in NP

▶ LFU in SM

$$\bar{\ell}'_R\gamma^\mu Z_\mu Y \ell'_R \propto \begin{bmatrix}\bar{e}'_R & \bar{\mu}'_R & \bar{\tau}'_R\end{bmatrix}\begin{bmatrix}-1 & 0 & 0\\ 0 & -1 & 0\\ 0 & 0 & -1\end{bmatrix}\begin{bmatrix}e'_R\\ \mu'_R\\ \tau'_R\end{bmatrix} = \begin{bmatrix}\bar{e}_R & \bar{\mu}_R & \bar{\tau}_R\end{bmatrix} U_R^\dagger \begin{bmatrix}-1 & 0 & 0\\ 0 & -1 & 0\\ 0 & 0 & -1\end{bmatrix} U_R \begin{bmatrix}e_R\\ \mu_R\\ \tau_R\end{bmatrix} = \begin{bmatrix}\bar{e}_R & \bar{\mu}_R & \bar{\tau}_R\end{bmatrix}\begin{bmatrix}-1 & 0 & 0\\ 0 & -1 & 0\\ 0 & 0 & -1\end{bmatrix}\begin{bmatrix}e_R\\ \mu_R\\ \tau_R\end{bmatrix}$$

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mass eigenbasis

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$\ell'_R = U_R \ell_R$

U_R: complex 3×3 unitary matrix

flavour universal

▶ LFU violation in NP

$$\bar{\ell}'_R\gamma^\mu Z'_\mu Y' \ell'_R \propto \begin{bmatrix}\bar{e}'_R & \bar{\mu}'_R & \bar{\tau}'_R\end{bmatrix}\begin{bmatrix}Y'_{e_R} & 0 & 0\\ 0 & Y'_{\mu_R} & 0\\ 0 & 0 & Y'_{\tau_R}\end{bmatrix}\begin{bmatrix}e'_R\\ \mu'_R\\ \tau'_R\end{bmatrix} = \begin{bmatrix}\bar{e}_R & \bar{\mu}_R & \bar{\tau}_R\end{bmatrix} U_R^\dagger \begin{bmatrix}Y'_{e_R} & 0 & 0\\ 0 & Y'_{\mu_R} & 0\\ 0 & 0 & Y'_{\tau_R}\end{bmatrix} U_R \begin{bmatrix}e_R\\ \mu_R\\ \tau_R\end{bmatrix} = \begin{bmatrix}\bar{e}_R & \bar{\mu}_R & \bar{\tau}_R\end{bmatrix}\begin{bmatrix}\epsilon_{11} & \epsilon_{12} & \epsilon_{13}\\ \epsilon_{21} & \epsilon_{22} & \epsilon_{23}\\ \epsilon_{31} & \epsilon_{32} & \epsilon_{33}\end{bmatrix}\begin{bmatrix}e_R\\ \mu_R\\ \tau_R\end{bmatrix}$$

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$b \to s\mu\mu / b \to see \neq$ SM $\Longrightarrow \begin{cases} b \to se\mu,\ b \to se\tau,\ b \to s\mu\tau \\ b \to d\mu\mu / b \to dee,\ s \to d\mu\mu / s \to dee,\ b\bar{b} \to \mu\mu / b\bar{b} \to ee,\ \ldots \end{cases}$

$b \to c\tau\nu / b \to c\mu\nu \neq$ SM $\Longrightarrow b \to u\tau\nu / b \to u\mu\nu,\ c \to s\tau\nu / c \to s\mu\nu,\ \ldots$

What's the magnitude of NP effects in these related channels? Can they satisfy the current exp bound? Flavour structure !

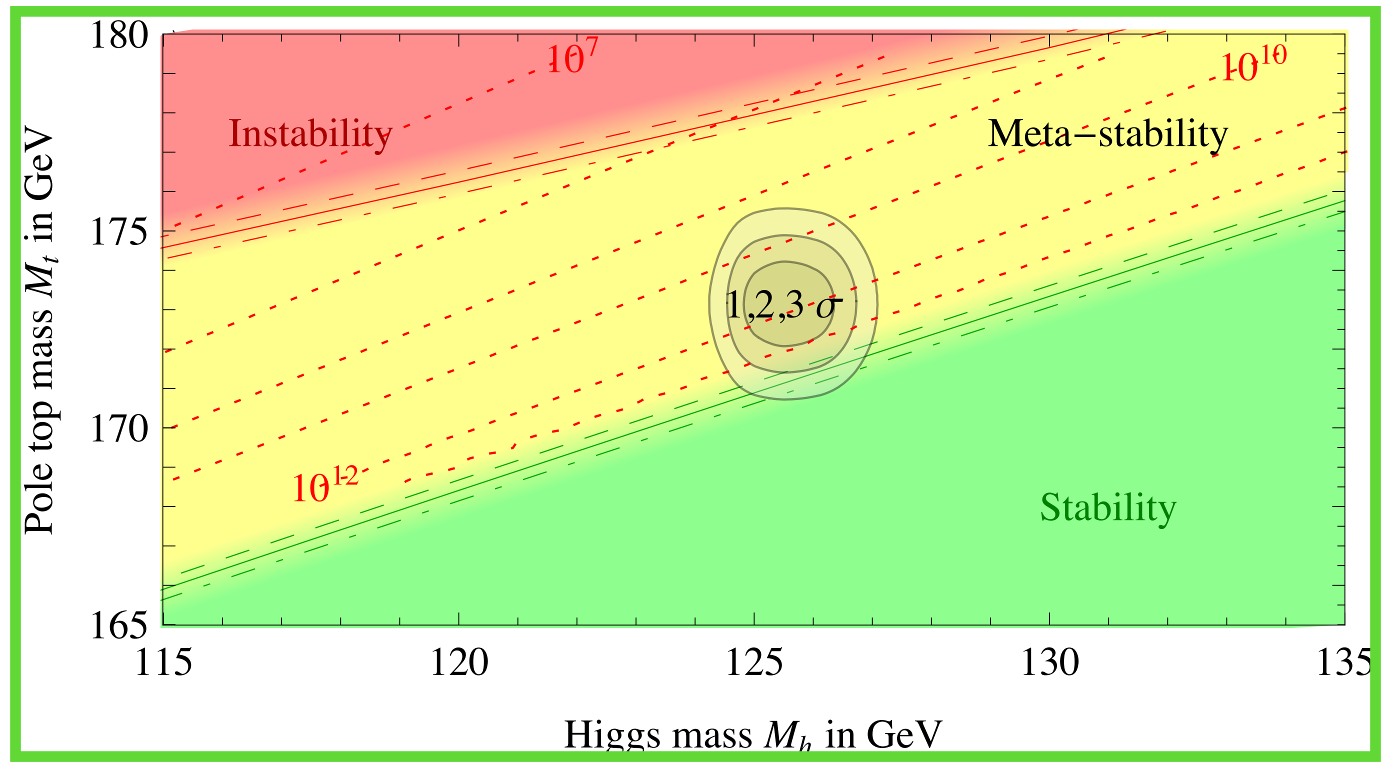
Physics beyond the Standard Model

Problems of the SM ⟹ Physics beyond the SM

experimental

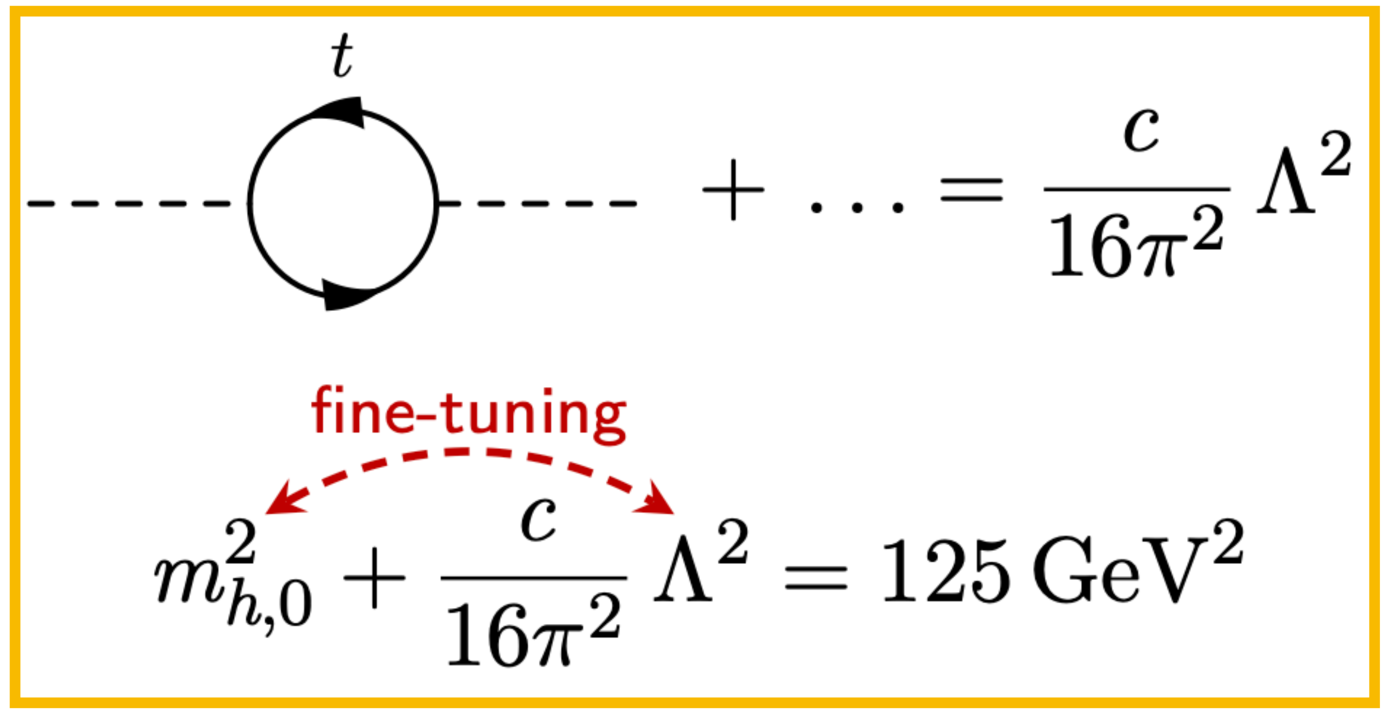
- Dark Matter (26%)
- Dark Energy (69%)
- Matter-antimatter asymmetry
- Anomalies in experimental data

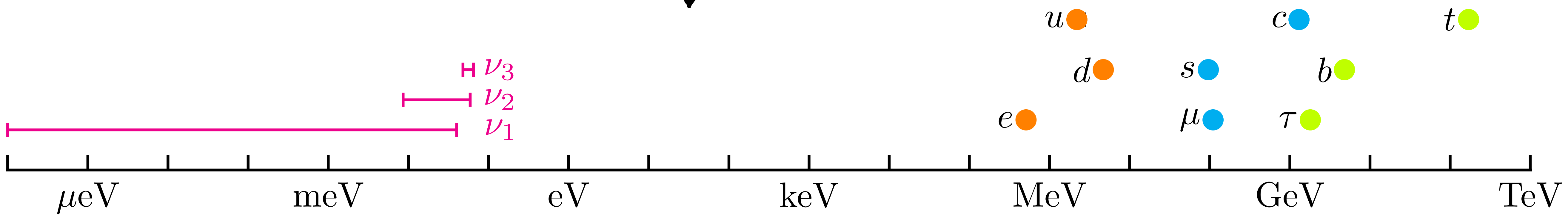
- Neutrino masses
- Strong CP problem
- Vacuum metastability



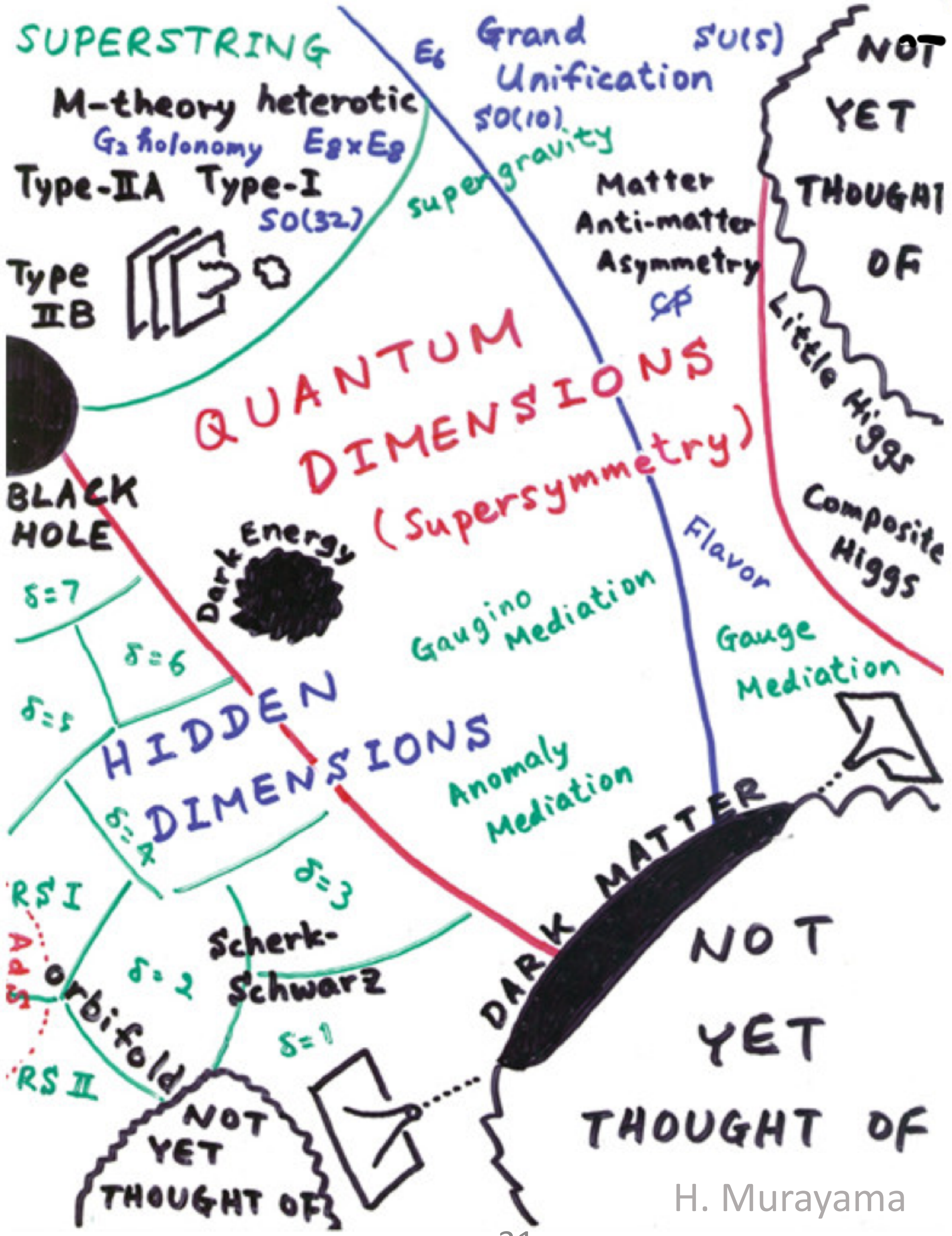
conceptual

- Gravity
- Hierarchy problem
- Number of parameters
- Family replication ...





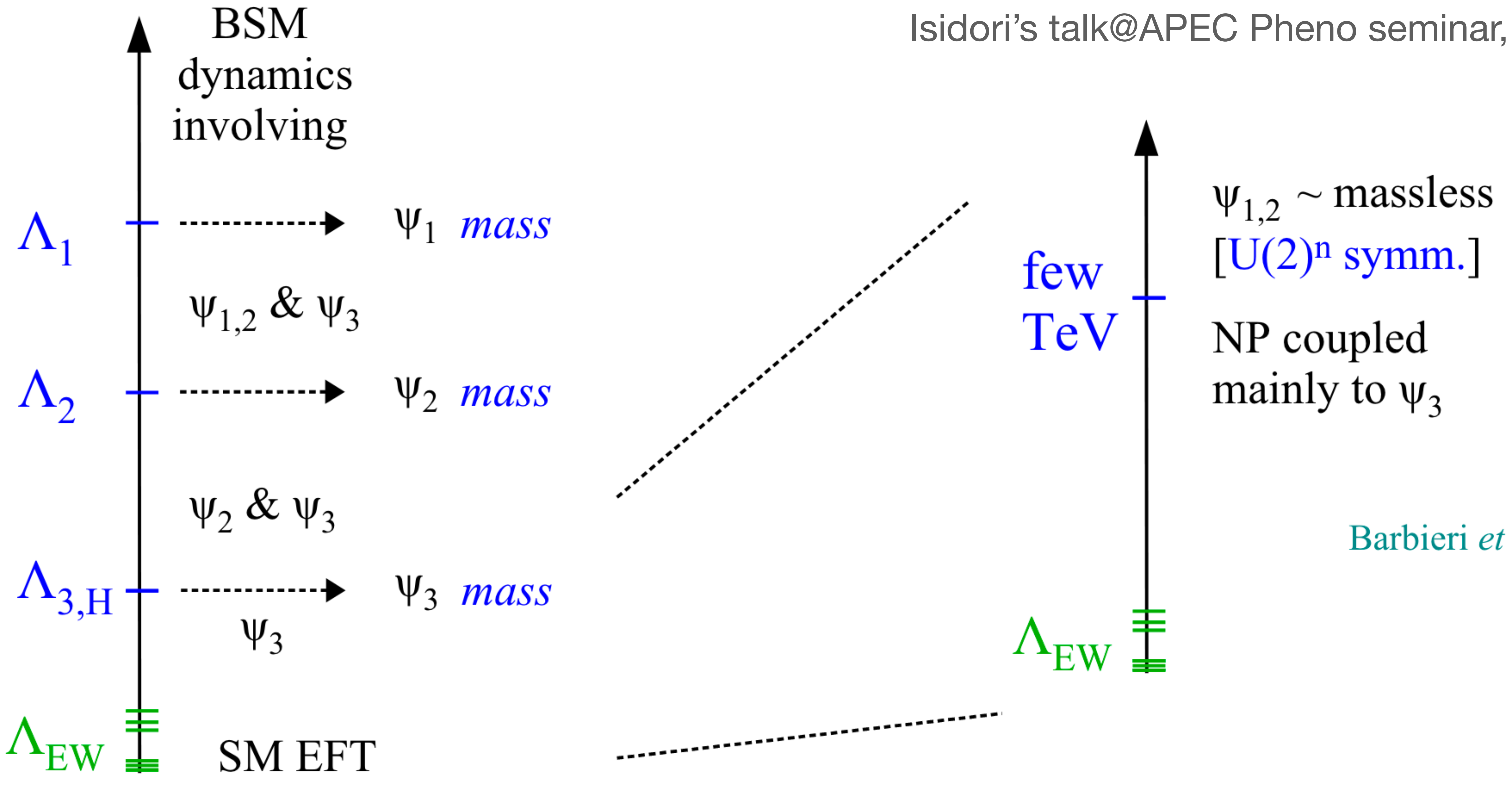
Theories beyond the SM



H. Murayama

Origin of LFU violation

▶ Flavour deconstruction



Isidori's talk@APEC Pheno seminar, 2021

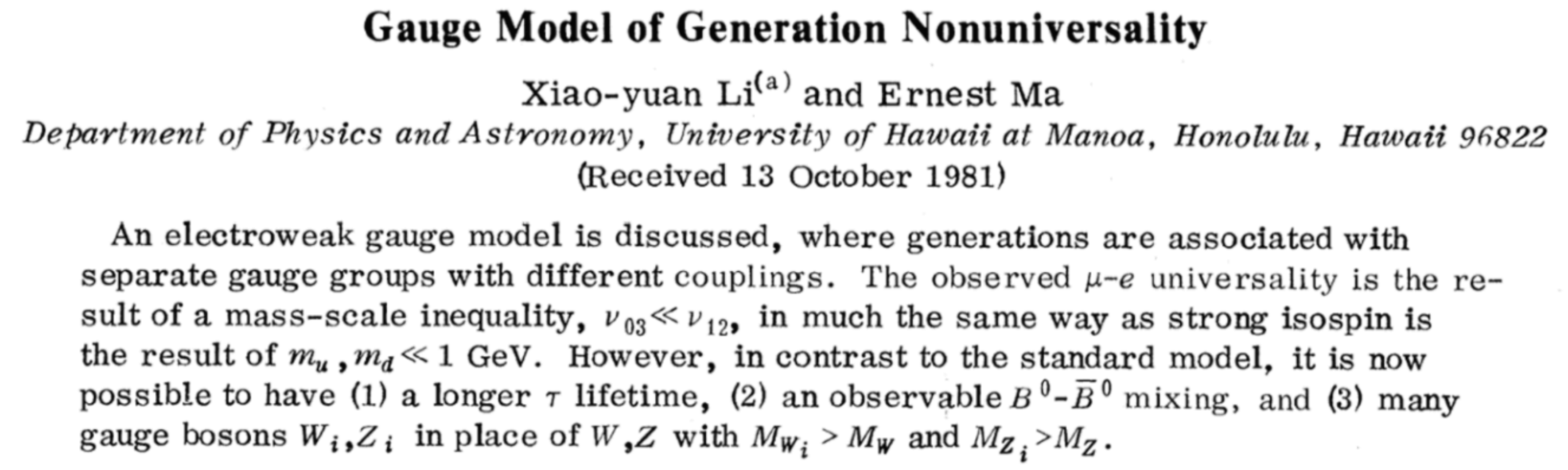
to connect NP flavour problem and Higgs hierarchy problem

SM is embedded in a gauge symmetry that contains a separate factor for each fermion family

$$G_{\text{universal}} \times G_1 \times G_2 \times G_3$$

$$SU(3)_c \times SU(2)_L \times U(1)_{Y_1} \times U(1)_{Y_2} \times U(1)_{Y_3}$$

q_1	q_2	q_3
u_1^c	u_2^c	u_3^c
d_1^c	d_2^c	d_3^c
ℓ_1	ℓ_2	ℓ_3
e_1^c	e_2^c	e_3^c


Gauge Model of Generation Nonuniversality

Xiao-yuan Li[(a)] and Ernest Ma

Department of Physics and Astronomy, University of Hawaii at Manoa, Honolulu, Hawaii 96822

(Received 13 October 1981)

An electroweak gauge model is discussed, where generations are associated with separate gauge groups with different couplings. The observed μ-e universality is the result of a mass-scale inequality, $v_{03} \ll v_{12}$, in much the same way as strong isospin is the result of $m_u, m_d \ll 1$ GeV. However, in contrast to the standard model, it is now possible to have (1) a longer τ lifetime, (2) an observable B^0-$\bar{B}^0$ mixing, and (3) many gauge bosons W_i, Z_i in place of W, Z with $M_{W_i} > M_W$ and $M_{Z_i} > M_Z$.

Arkani-Hamed, Cohen, Georgi, hep-th/0104005
Craig, Green, Katz, 1103.3708

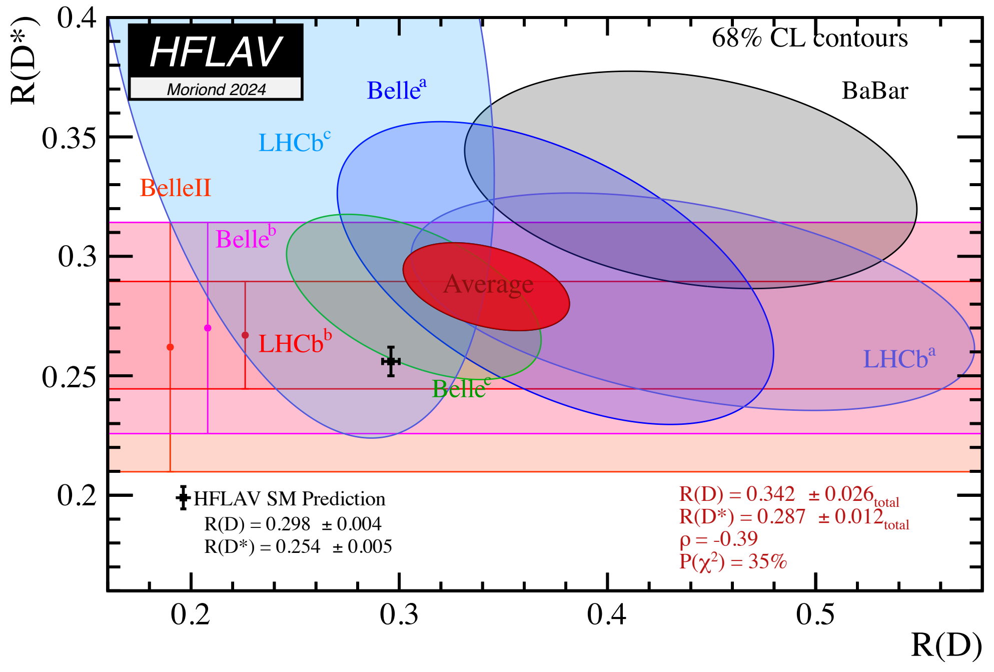
- Flavour non-universal interactions already at the TeV scale.
- 1st and 2nd gen have small masses due to couple to NP at heavier scales.
- 3 gens are not identical copies up to high scales.

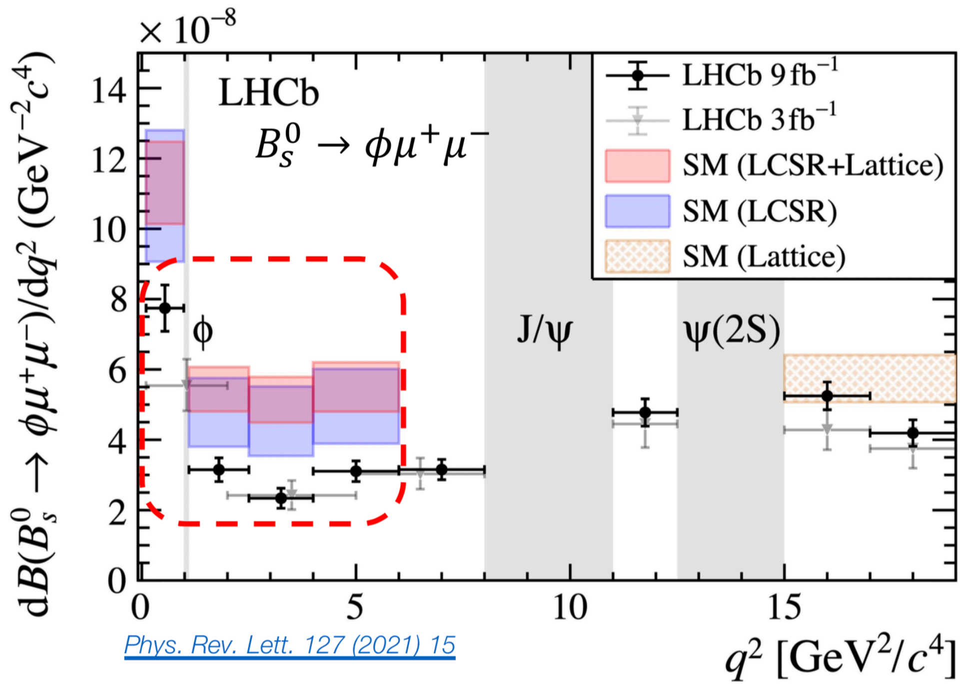
Covone, Davighi, Isidori, Pesut/2407.10950
Fuentes-Martín, Lizana/2402.09507
Davighi, Gosnay, Miller, Renner/2312.13346
Barbieri, Isidori/2312.14004
Isidori/2308.11612
Navarro, King/2305.07690
Davighi, Stefanek/2305.16280
Davighi, Isidori/2303.01520

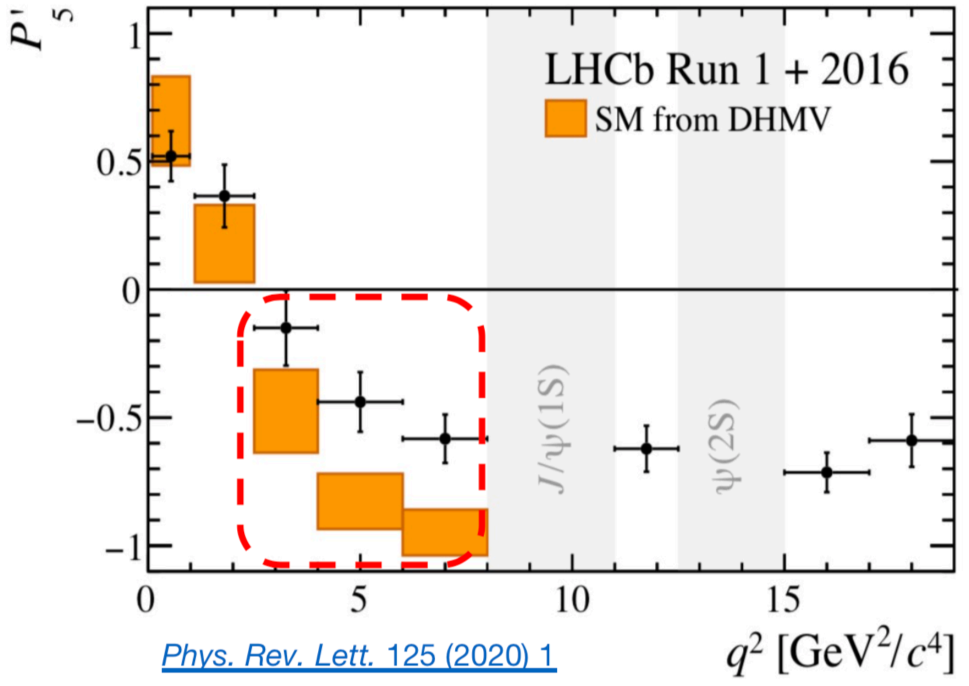
… …

Summary

exp measurement







… …

more precise data needed !

QCD corrections
form factor
non-local matrix element

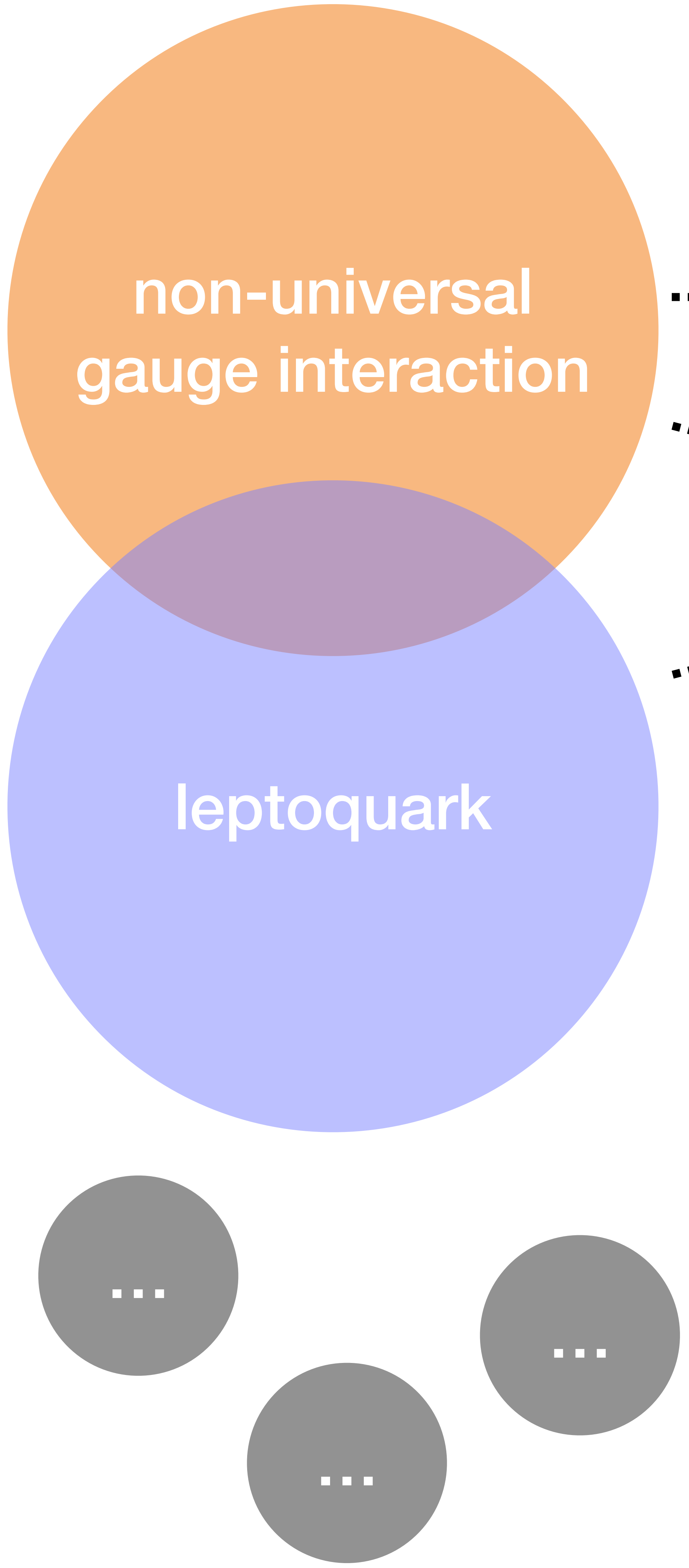
LEFT/WET

RGE
(well understood !)

SMEFT

inverse problem
(e.g., Fermi theory to SM)

NP model



big question

- flavour structure in the SM
- EW hierarchy problem
- Grand Unified Theory
- Dark matter
- Strong CP
- Neutrino mass

Backup

Definition of Pull

To quantify the level of agreement between a given hypothesis and the data, we compute the corresponding p-value of *goodness-of-fit*:

$$p = \int_{\chi^2_{\rm min}}^{\infty} d\chi^2 \, f(\chi^2; n_{\rm dof}), \tag{8}$$

where $n_{\rm dof} = N_{\rm obs} - n$. Finally, to compare the descriptions offered by two different nested hypotheses H_0 and H_1 (with $n_{\rm H_0}$, $n_{\rm H_1}$ the respective number of degrees of freedom and $n_{\rm H_0} < n_{\rm H_1}$), we compute their relative Pull, measured in units of Gaussian standard deviations (σ):

$$\mathrm{Pull}_{H_0 H_1} = \sqrt{2}\,\mathrm{Erf}^{-1}\left[F(\Delta\chi^2_{H_0 H_1}; n_{\rm H_0 H_1})\right], \tag{9}$$

with $\Delta\chi^2_{H_0H_1} = \chi^2_{H_0,{\rm min}} - \chi^2_{H_1,{\rm min}}$, $n_{\rm H_0H_1} = n_{\rm H_1} - n_{\rm H_0}$, F the χ^2 cumulative distribution function and Erf^{-1} the inverse error function. Most of the time, we compare a given NP scenario with the SM case, denoting the result as $\mathrm{Pull}_{\rm SM}$ unless there is a risk of ambiguity. Our statistical

Non-local matrix element

$$\mathcal{A}_\lambda^{L,R} = \mathcal{N}\left\{\left[(\mathcal{C}_9 \pm \mathcal{C}_9') \mp (\mathcal{C}_{10} \pm \mathcal{C}_{10}')\right]\mathcal{F}_\lambda(q^2,k^2) + \frac{2m_b M_B}{q^2}\left[(\mathcal{C}_7 \pm \mathcal{C}_7')\mathcal{F}_\lambda^T(q^2,k^2) - 16\pi^2 \frac{M_B}{m_b}\mathcal{H}_\lambda(q^2,k^2)\right]\right\}$$

A. $(g-2)_\mu$ and $(g-2)_e$

According to the window observable theory [53, 54] and the SM prediction [55], the current disagreement concerning the Δa_μ designations has emerged as follows [55–58]:

Me/m_mu=0.5MeV/105.6MeV=5*10^-3

$$\Delta a_\mu^{\text{window}} = (1.81 \pm 0.47) \times 10^{-9}, \tag{17}$$

On the other hand, the electron magnetic dipole moment [59] with its experiment measurement through Rb in 2020 [60, 61], the discrepancy with SM prediction can be expressed as follows:

$$\Delta a_e^{\text{Rb}} = 34(16) \times 10^{-14}, \tag{18}$$

whereas the Cs atoms measurement method search has obtained a lower bound [62],

$$\Delta a_e^{\text{Cs}} = -102(26) \times 10^{-14}, \tag{19}$$

PIONEER goal

Phase I

- $R^{\pi}_{e/\mu} = \Gamma(\pi \to e\bar{\nu}_e(\gamma)/\Gamma(\pi \to \mu\bar{\nu}_\mu(\gamma))$
  Improvement by a factor of 15
- Comparable with the theoretical uncertainty
- NP at the PeV scale can be probed

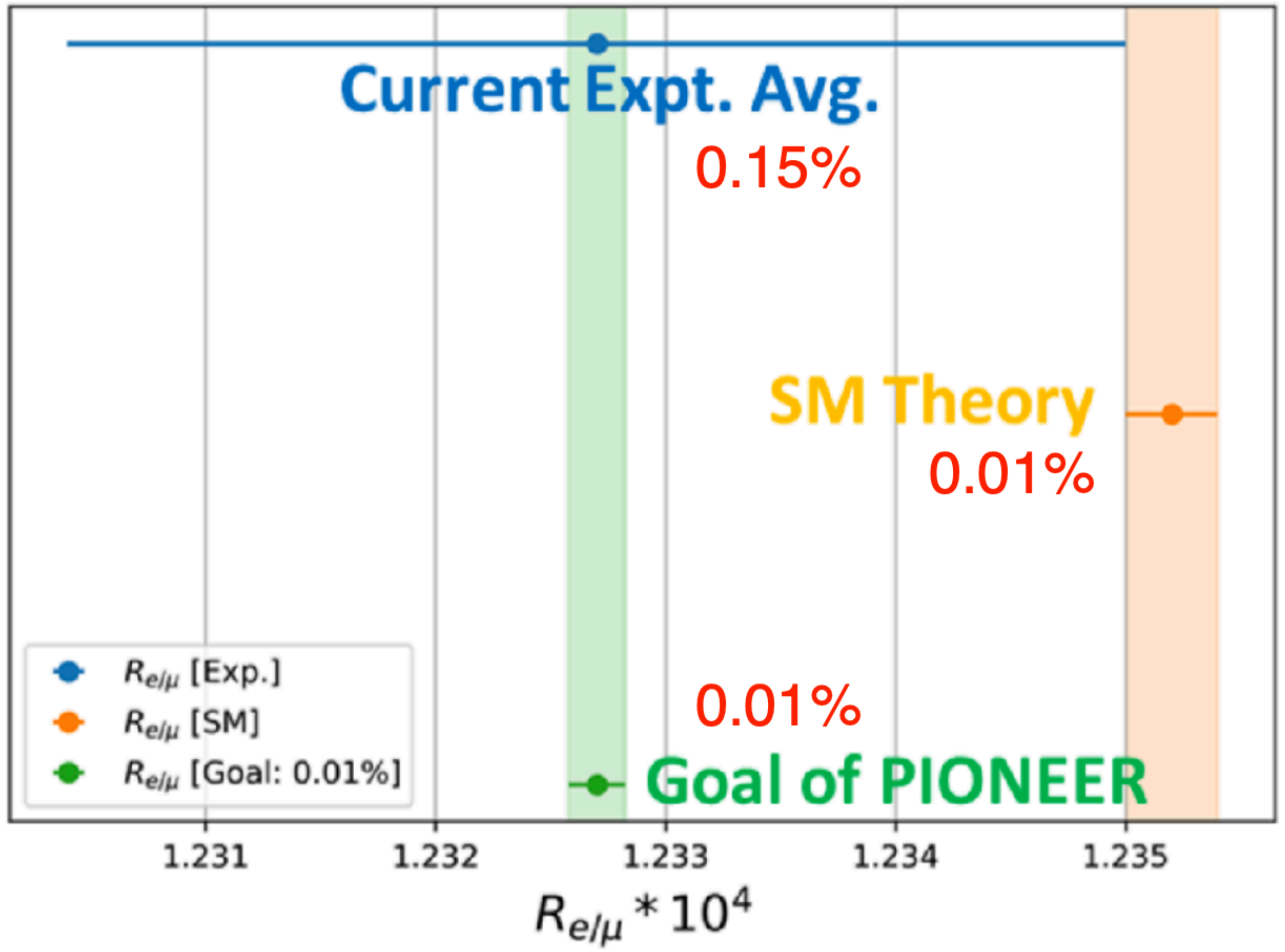
Phase II & III

- $\frac{\Gamma(\pi^+ \to \pi^0 e^+ \nu)}{\Gamma(\mathrm{Total})}$ with a precision < 0.2%
- Improvement by a factor of 3 (Phase II) / 10(Phase III)
- CKM unitarity check by theoretically cleanest $|V_{ud}|$

Exotic searches

- Heavy neutral lepton

PIONEER experiment is approved by Paul Scherrer Institute in Switzerland in 2022



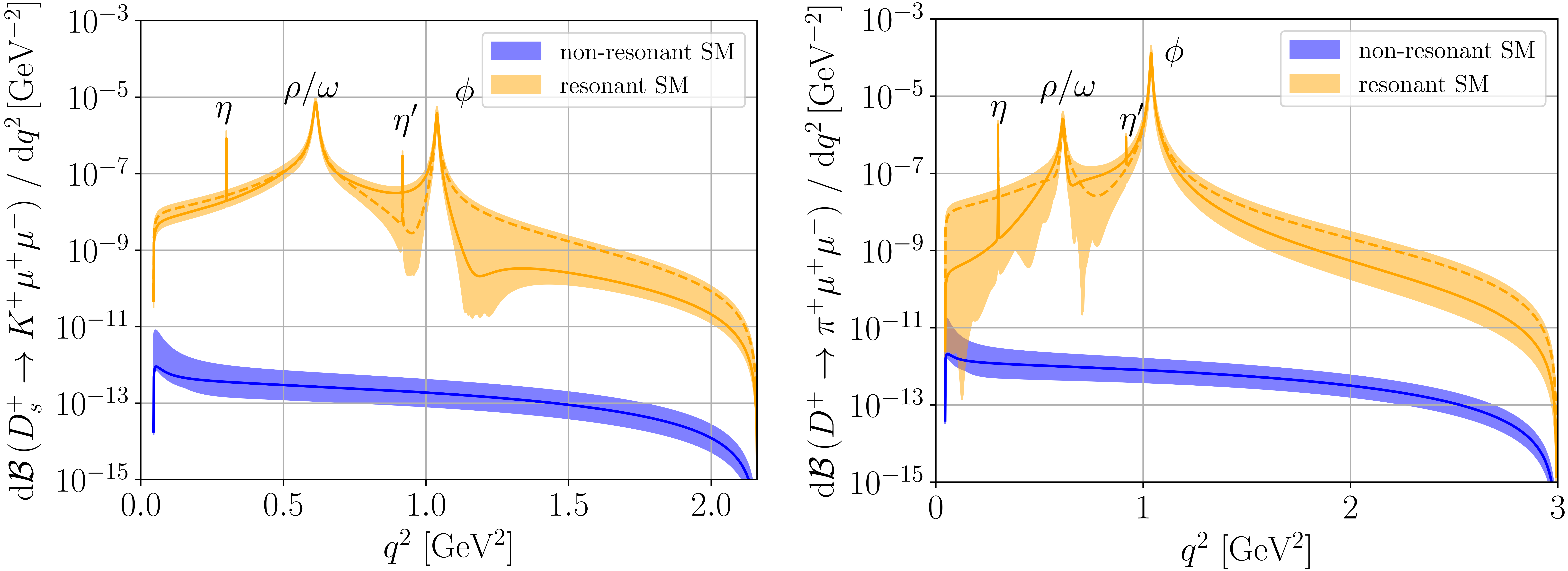
Overview of LFU results with charm meson decays

Mode	Measured $\mathcal{B}(\ell)/\mathcal{B}(\ell')$	SM Prediction
$D^+ \to \frac{\tau}{\mu}\nu$	3.21 ± 0.77	2.66
$D_s^+ \to \frac{\tau}{\mu}\nu$	9.72 ± 0.37	9.75
$D^0 \to \rho^- \frac{\mu}{e}\nu$	0.90 ± 0.11	$0.93 - 0.96$
$D^+ \to \eta \frac{\mu}{e}\nu$	0.91 ± 0.13	$0.97 - 1.00$
$D^+ \to \omega \frac{\mu}{e}\nu$	1.05 ± 0.14	$0.93 - 0.99$
$D^+ \to \pi^0 \frac{\mu}{e}\nu$	0.964 ± 0.045	~ 0.985
$D^0 \to \pi^+ \frac{\mu}{e}\nu$	0.922 ± 0.037	~ 0.985
$D^0 \to K^+ \frac{\mu}{e}\nu$	0.974 ± 0.014	~ 0.970

Credit Alex Gilman

Values deviate from 1 because of the different available phase space

- No tensions with the SM expectation within the current precision

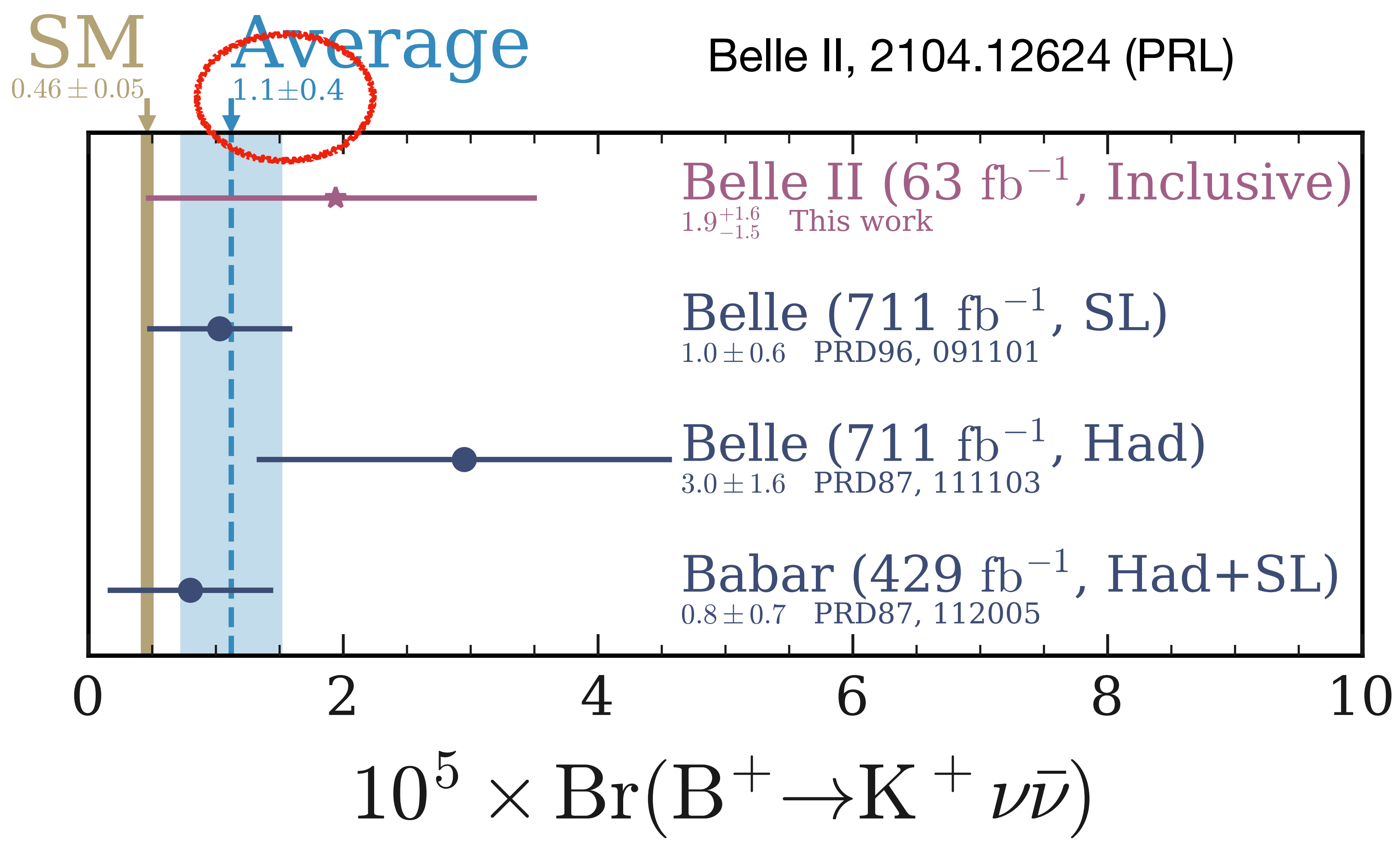


non-resonant SM
resonant SM
η
ρ/ω
η'
ϕ
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
0.0
0.5
1.0
1.5
2.0
q^2 [GeV^2]
$\mathrm{d}\mathcal{B}(D_s^+ \to K^+\mu^+\mu^-)$ / $\mathrm{d}q^2$ [GeV^{-2}]
0
1
2
3
$\mathrm{d}\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-)$ / $\mathrm{d}q^2$ [GeV^{-2}]

$b \to s\nu\bar{\nu}$: exp & theory

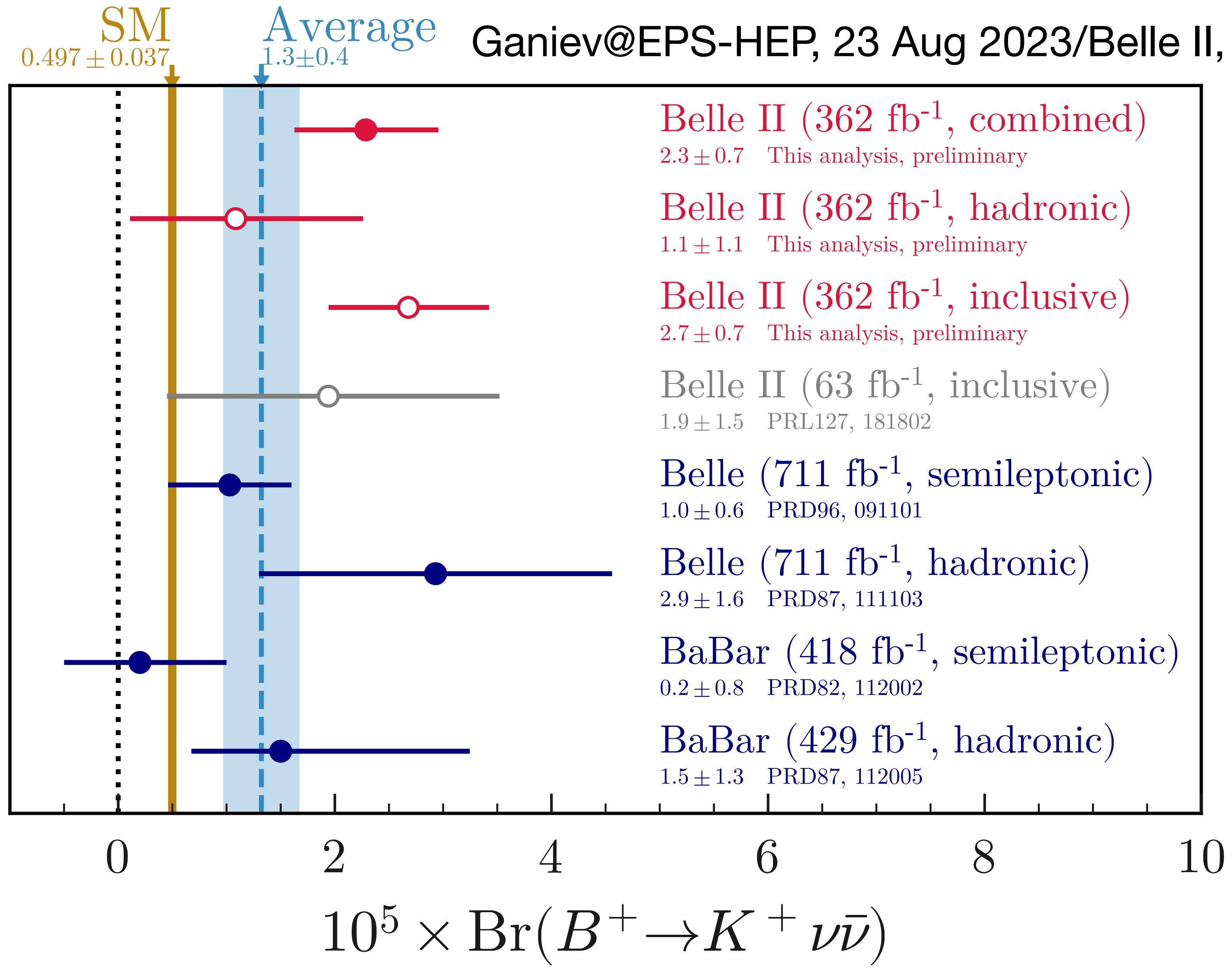
- **2021 Apr**

Belle II, 2104.12624 (PRL)



- **2023 Aug**

Ganiev@EPS-HEP, 23 Aug 2023/Belle II, 2311.14647



30+ theory papers !

Impact of B→Kνν̄ measurements on beyond the Standard Model theories #69
Thomas E. Browder (Hawaii U.), Nilendra G. Deshpande (Oregon U.), Rusa Mandal (Siegen U.), Rahul Sinha (IMSc, Chennai and Bhubaneswar, Inst. Phys.) (Jul 2, 2021)
Published in: Phys.Rev.D 104 (2021) 5, 053007 • e-Print: 2107.01080 [hep-ph]
pdf DOI cite claim reference search 34 citations

Phenomenological study of a gauged $L_\mu - L_\tau$ model with a scalar leptoquark #42
Chuan-Hung Chen (Taiwan, Natl. Cheng Kung U. and NCTS, Taipei), Cheng-Wei Chiang (Taiwan, Natl. Taiwan U. and NCTS, Taipei), Chun-Wei Su (Taiwan, Natl. Taiwan U.) (May 16, 2023)
Published in: Phys.Rev.D 109 (2024) 5, 5 • e-Print: 2305.09256 [hep-ph]
pdf DOI cite claim reference search 3 citations

Higgs portal interpretation of the Belle II $B^+ \to K^+\nu\nu$ measurement #29
David McKeen (TRIUMF), John N. Ng (TRIUMF), Douglas Tuckler (TRIUMF and Simon Fraser U.) (Dec 1, 2023)
Published in: Phys.Rev.D 109 (2024) 7, 075006 • e-Print: 2312.00982 [hep-ph]
pdf DOI cite claim reference search 10 citations

Light new physics in $B \to K^{(*)}\nu\bar{\nu}$? #30
Wolfgang Altmannshofer (UC, Santa Cruz, Inst. Part. Phys.), Andreas Crivellin (Zurich U.), Huw Haigh (Vienna, OAW), Gianluca Inguglia (Vienna, OAW), Jorge Martin Camalich (IAC, La Laguna) (Nov 24, 2023)
Published in: Phys.Rev.D 109 (2024) 7, 075008 • e-Print: 2311.14629 [hep-ph]
pdf DOI cite claim reference search 15 citations

$B \to K\nu\bar{\nu}$, MiniBooNE and muon g - 2 anomalies from a dark sector #31
Alakabha Datta (Mississippi U. and SLAC and UC, Santa Cruz), Danny Marfatia (Hawaii U.), Lopamudra Mukherjee (Nankai U.) (Oct 23, 2023)
Published in: Phys.Rev.D 109 (2024) 3, L031701 • e-Print: 2310.15136 [hep-ph]
pdf DOI cite claim reference search 11 citations

$B \to K^* M_X$ vs $B \to K M_X$ as a probe of a scalar-mediator dark matter scenario #33
Alexander Berezhnoy (SINP, Moscow), Dmitri Melikhov (SINP, Moscow and Dubna, JINR and Vienna U.) (Sep 29, 2023)
Published in: EPL 145 (2024) 1, 14001 • e-Print: 2309.17191 [hep-ph]
pdf DOI cite claim reference search 10 citations

Flavor anomalies in leptoquark model with gauged $U(1)_{L_\mu - L_\tau}$ #34
Chuan-Hung Chen (Taiwan, Natl. Cheng Kung U. and Unlisted, TW), Cheng-Wei Chiang (Taiwan, Natl. Taiwan U. and Unlisted, TW) (Sep 22, 2023)
Published in: Phys.Rev.D 109 (2024) 7, 075004 • e-Print: 2309.12904 [hep-ph]
pdf DOI cite claim reference search 9 citations

Revisiting models that enhance $B^+ \to K^+\nu\bar{\nu}$ in light of the new Belle II measurement #35
Belle-II Collaboration • Xiao-Gang He (Tsung-Dao Lee Inst., Shanghai and Taiwan, Natl. Taiwan U.) et al. (Sep 22, 2023)
Published in: Phys.Rev.D 109 (2024) 7, 075019 • e-Print: 2309.12741 [hep-ph]
pdf DOI cite claim reference search 16 citations

A new look at $b \to s$ observables in 331 models #18
Francesco Loparco (Jan 22, 2024)
e-Print: 2401.11999 [hep-ph]
pdf cite claim reference search 1 citation

Correlating $B \to K^{(*)}\nu\bar{\nu}$ and flavor anomalies in SMEFT #19
Feng-Zhi Chen, Qiaoyi Wen, Fanrong Xu (Jan 21, 2024)
e-Print: 2401.11552 [hep-ph]
pdf cite claim reference search 8 citations

Recent $B^+ \to K^+\nu\bar{\nu}$ Excess and Muon $g-2$ Illuminating Light Dark Sector with Higgs Portal #20
Shu-Yu Ho, Jongkuk Kim, Pyungwon Ko (Jan 18, 2024)
e-Print: 2401.10112 [hep-ph]
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A tale of invisibility: constraints on new physics in b → sνν #65
Tobias Felkl (New South Wales U.), Sze Lok Li (New South Wales U.), Michael A. Schmidt (New South Wales U.) (Nov 8, 2021)
Published in: JHEP 12 (2021) 118 • e-Print: 2111.04327 [hep-ph]
pdf DOI cite claim reference search 24 citations

Explaining the $B^+ \to K^+\nu\bar{\nu}$ excess via a massless dark photon #16
E. Gabrielli, L. Marzola, K. Müürsepp, M. Raidal (Feb 8, 2024)
e-Print: 2402.05901 [hep-ph]
pdf cite claim reference search 4 citations

Decoding the $B \to K\nu\nu$ excess at Belle II: kinematics, operators, and masses #27
Kåre Fridell, Mitrajyoti Ghosh, Takemichi Okui, Kohsaku Tobioka (Dec 19, 2023)
e-Print: 2312.12507 [hep-ph]
pdf cite claim reference search 10 citations

Understanding the first measurement of $B(B \to K\nu\bar{\nu})$ #38
Lukas Allwicher (Zurich U.), Damir Becirevic (IJCLab, Orsay), Gioacchino Piazza (IJCLab, Orsay), Salvador Rosauro-Alcaraz (IJCLab, Orsay), Olcyr Sumensari (IJCLab, Orsay) (Sep 5, 2023)
Published in: Phys.Lett.B 848 (2024) 138411 • e-Print: 2309.02246 [hep-ph]
pdf DOI cite claim reference search 26 citations

Implications of an enhanced $B \to K\nu\bar{\nu}$ branching ratio #39
Rigo Bause (Tech. U., Dortmund (main)), Hector Gisbert (INFN, Padua and Padua U.), Gudrun Hiller (Tech. U., Dortmund (main) and Sussex U.) (Aug 31, 2023)
Published in: Phys.Rev.D 109 (2024) 1, 015006 • e-Print: 2309.00075 [hep-ph]
pdf DOI cite claim reference search 31 citations

B meson anomalies and large $B^+ \to K^+\nu\bar{\nu}$ in non-universal U(1)′ models #40
Peter Athron (Nanjing Normal U.), R. Martinez (Colombia, U. Natl.), Cristian Sierra (Nanjing Normal U.) (Aug 25, 2023)
Published in: JHEP 02 (2024) 121 • e-Print: 2308.13426 [hep-ph]
pdf DOI cite claim reference search 22 citations

SMEFT predictions for semileptonic processes #4
Siddhartha Karmakar, Amol Dighe, Rick S. Gupta (Apr 15, 2024)
e-Print: 2404.10061 [hep-ph]
pdf cite claim reference search 0 citations

Implications of $B \to K\nu\bar{\nu}$ under Rank-One Flavor Violation hypothesis #5
David Marzocca, Marco Nardecchia, Alfredo Stanzione, Claudio Toni (Apr 9, 2024)
e-Print: 2404.06533 [hep-ph]
pdf cite claim reference search 0 citations

The quark flavor-violating ALPs in light of B mesons and hadron colliders #20
Tong Li (Nankai U.), Zhuoni Qian (Hangzhou Normal U.), Michael A. Schmidt (Sydney U. and New South Wales U.), Man Yuan (Nankai U.) (Feb 21, 2024)
Published in: JHEP 05 (2024) 232 • e-Print: 2402.14232 [hep-ph]
pdf DOI cite claim reference search 3 citations

Scalar dark matter explanation of the excess in the Belle II B^+\to K^+ + \mbox{invisible} measurement #9
Xiao-Gang He, Xiao-Dong Ma, Michael A. Schmidt, German Valencia, Raymond R. Volkas (Mar 19, 2024)
e-Print: 2403.12485 [hep-ph]
pdf cite claim reference search 2 citations

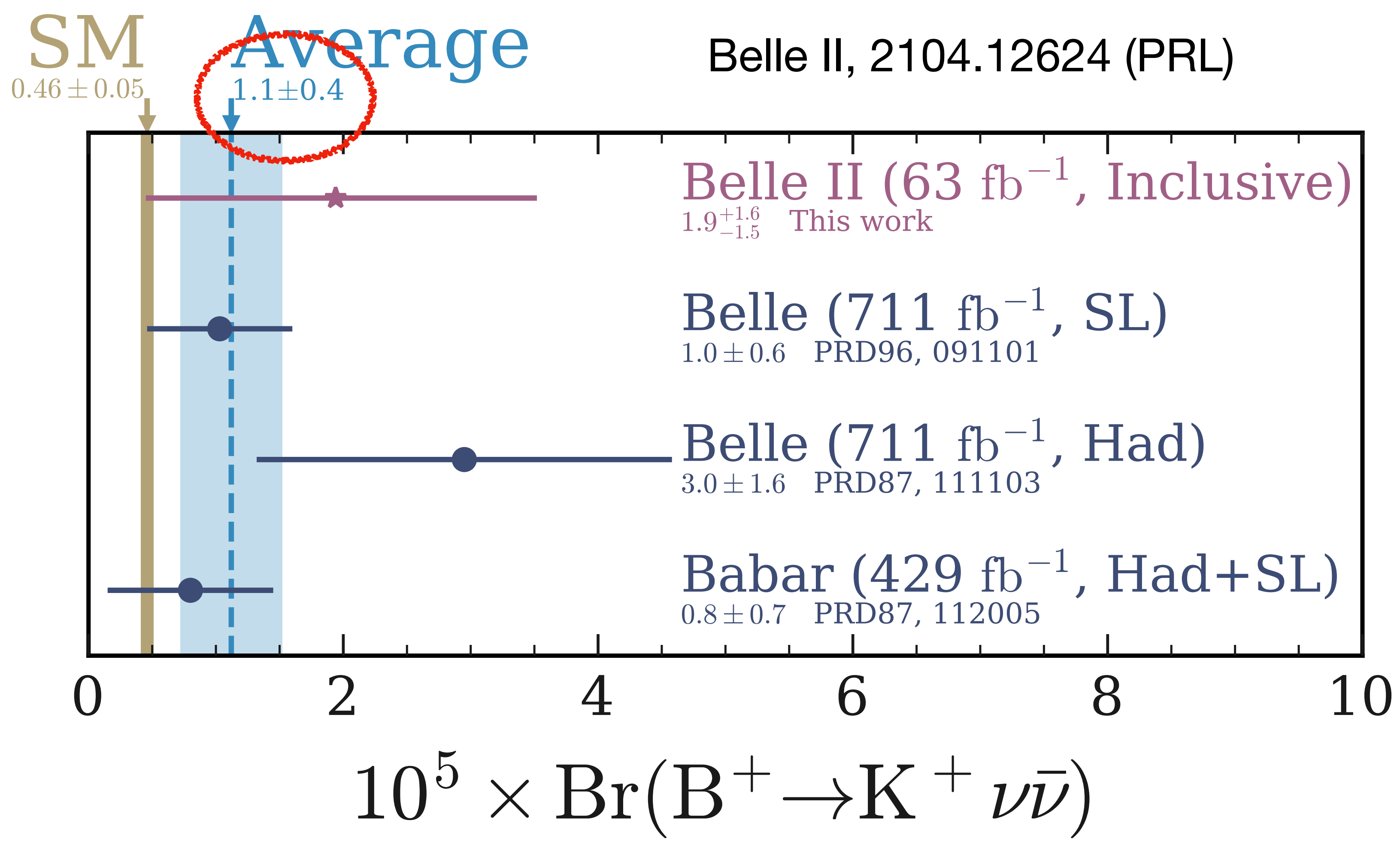
Status and prospects of rare decays at Belle-II #10
Elisa Manoni (Mar 12, 2024)
Published in: PoS WIFAI2023 (2024) 024 • Contribution to: WIFAI 2023, 024
pdf DOI cite claim reference search 0 citations

Rare B and K decays in a scotogenic model #11
Chuan-Hung Chen, Cheng-Wei Chiang (Mar 5, 2024)
e-Print: 2403.02897 [hep-ph]
pdf cite claim reference search 2 citations

$b \to s\nu\bar{\nu}$: exp & theory

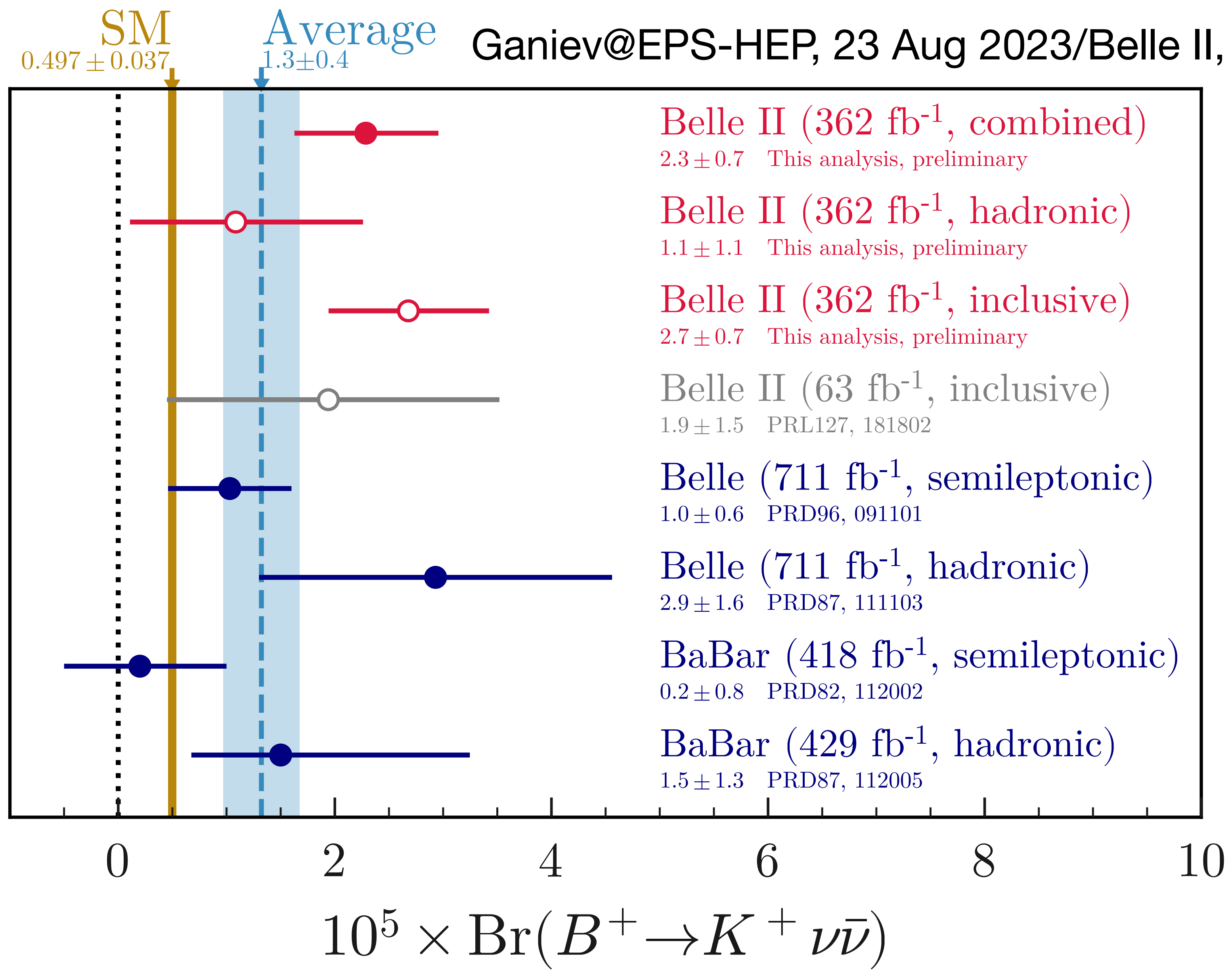
- **2021 Apr**

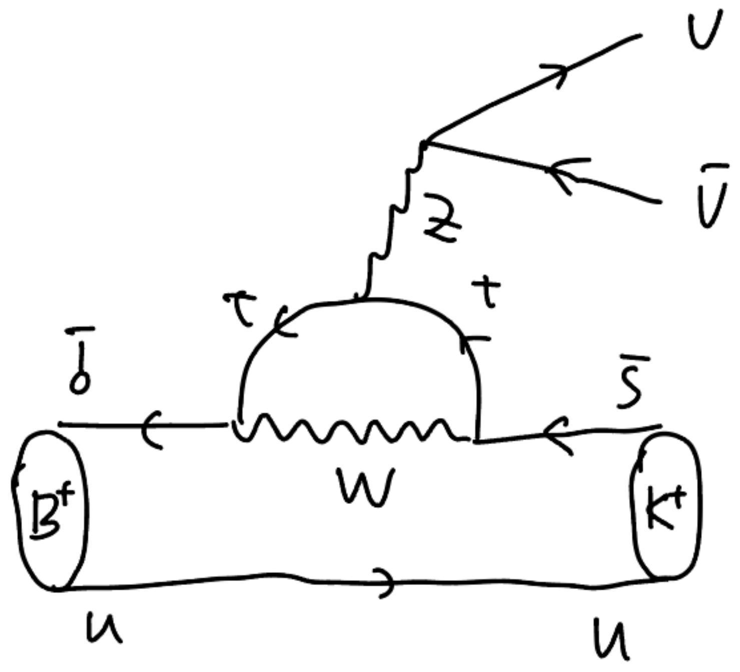
Belle II, 2104.12624 (PRL)



- **2023 Aug**

Ganiev@EPS-HEP, 23 Aug 2023/Belle II, 2311.14647





- **Exp vs SM** $[10^{-6}]$

$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu})_{\rm SM} = 4.16 \pm 0.57$$
$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu})_{\rm exp} = 23 \pm 7$$

2.7σ difference
NP/SM $\gtrsim 2$

$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu})_{\rm exp} \gtrsim 10$$ (2σ lower bound)

- **Theoretical prediction**

Factorization

$$\mathcal{A} \propto C_L \cdot \langle K | \bar{s}\gamma^\mu b | \bar{B} \rangle \cdot \bar{\nu}\gamma_\mu \nu$$

Wilson coef **quark current** **neutrino current**

theoretically, simple and clean
one of the cleanest channels in flavour physics

$\mathcal{O}_L = (\bar{s}\gamma_\mu P_L b)(\bar{\nu}\gamma^\mu P_L \nu)$ in the SM

$\mathcal{O}_R = (\bar{s}\gamma_\mu P_R b)(\bar{\nu}\gamma^\mu P_L \nu)$ possible in BSM

simple interaction but complicated flavour

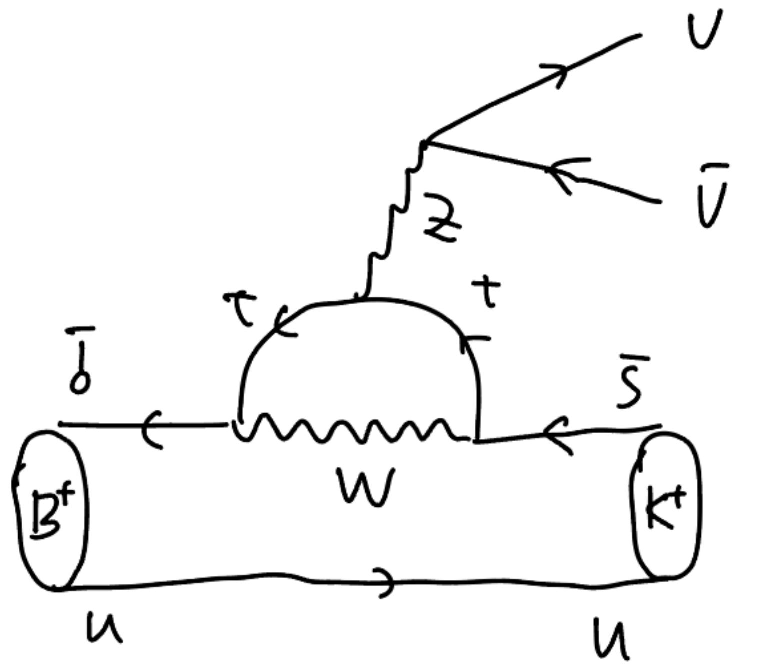
$\mathcal{O}_L = (\bar{s}P_L b)(\bar{\nu}P_L \nu)$ ✘
$\mathcal{O}_R = (\bar{s}P_R b)(\bar{\nu}P_R \nu)$ ✘
$\mathcal{O}_T = (\bar{s}\sigma_{\mu\nu} b)(\bar{\nu}\sigma^{\mu\nu} \nu)$ ✘
$\mathcal{O}_{T5} = (\bar{s}\sigma_{\mu\nu}\gamma_5 b)(\bar{\nu}\sigma^{\mu\nu} \nu)$ ✘

operator structure highly constrained by LH neutrino

$b \to s\nu\bar{\nu}$: exp & theory

	Observable	SM	Exp	Unit
$b \to s$	$\mathcal{B}(B^+ \to K^+\nu\bar{\nu})$	4.16 ± 0.57	$23 \pm 5^{+5}_{-4}$	10^{-6}
	$\mathcal{B}(B^0 \to K^0\nu\bar{\nu})$	3.85 ± 0.52	< 26	10^{-6}
	$\mathcal{B}(B^+ \to K^{*+}\nu\bar{\nu})$	9.70 ± 0.94	< 61	10^{-6}
	$\mathcal{B}(B^0 \to K^{*0}\nu\bar{\nu})$	9.00 ± 0.87	< 18	10^{-6}
	$\mathcal{B}(B_s \to \phi\nu\bar{\nu})$	9.93 ± 0.72	< 5400	10^{-6}
	$\mathcal{B}(B_s \to \nu\bar{\nu})$	≈ 0	< 5.9	10^{-4}
$b \to d$	$\mathcal{B}(B^+ \to \pi^+\nu\bar{\nu})$	1.40 ± 0.18	< 140	10^{-7}
	$\mathcal{B}(B^0 \to \pi^0\nu\bar{\nu})$	6.52 ± 0.85	< 900	10^{-8}
	$\mathcal{B}(B^+ \to \rho^+\nu\bar{\nu})$	4.06 ± 0.79	< 300	10^{-7}
	$\mathcal{B}(B^0 \to \rho^0\nu\bar{\nu})$	1.89 ± 0.36	< 400	10^{-7}
	$\mathcal{B}(B^0 \to \nu\bar{\nu})$	≈ 0	< 1.4	10^{-4}
$s \to d$	$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$	8.42 ± 0.61	$10.6^{+4.0}_{-3.4} \pm 0.9$	10^{-11}
	$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$	3.41 ± 0.45	< 300	10^{-11}

$B^0 \to K^{*0}\nu\bar{\nu}$ can put strong constraints on related BSM effects.



▶ Exp vs SM $[10^{-6}]$

$$\mathscr{B}(B^+ \to K^+\nu\bar{\nu})_{\rm SM} = 4.16 \pm 0.57$$
$$\mathscr{B}(B^+ \to K^+\nu\bar{\nu})_{\rm exp} = 23 \pm 7$$

2.7σ difference
NP/SM $\gtrsim 2$

$$\mathscr{B}(B^+ \to K^+\nu\bar{\nu})_{\rm exp} \gtrsim 10$$ (2σ lower bound)

▶ Theoretical prediction

Factorization

$$\mathscr{A} \propto C_L \cdot \langle K | \bar{s}\gamma^\mu b | \bar{B} \rangle \cdot \bar{\nu}\gamma_\mu\nu$$

Wilson coef **quark current** **neutrino current**

theoretically, simple and clean
one of the cleanest channels in flavour physics

$\mathscr{O}_L = (\bar{s}\gamma_\mu P_L b)(\bar{\nu}\gamma^\mu P_L \nu)$ in the SM

$\mathscr{O}_R = (\bar{s}\gamma_\mu P_R b)(\bar{\nu}\gamma^\mu P_L \nu)$ possible in BSM

simple interaction but complicated flavour

$\mathscr{O}_L = (\bar{s}P_L b)(\bar{\nu}P_L \nu)$ ✘
$\mathscr{O}_R = (\bar{s}P_R b)(\bar{\nu}P_R \nu)$ ✘
$\mathscr{O}_T = (\bar{s}\sigma_{\mu\nu} b)(\bar{\nu}\sigma^{\mu\nu} \nu)$ ✘
$\mathscr{O}_{T5} = (\bar{s}\sigma_{\mu\nu}\gamma_5 b)(\bar{\nu}\sigma^{\mu\nu} \nu)$ ✘

operator structure highly constrained by LH neutrino

$b \to s\nu\bar{\nu}$: SMEFT

B.F.Hou, X.Q.Li, M.Shen, Y.D.Yang, **XBY**, 2402.19208

SMEFT notation: $l = \begin{pmatrix} \nu \\ e \end{pmatrix}_L, q = \begin{pmatrix} u \\ d \end{pmatrix}_L, d = d_R$

- **Prediction**

$$\frac{\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})}{\mathcal{B}(B^0 \to K^{*0}\nu\bar{\nu})} = \frac{\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})_{\rm SM}}{\mathcal{B}(B^0 \to K^{*0}\nu\bar{\nu})_{\rm SM}} = 0.46 \pm 0.07$$

- **prediction**

$$\mathscr{B}(B^0 \to K^{*0}\nu\bar{\nu})_{\rm SM} = (9.00 \pm 0.87) \times 10^{-6}$$

$$\mathscr{B}(B^0 \to K^{*0}\nu\bar{\nu})_{\rm SMEFT} = \left(50^{+17}_{-16}\right) \times 10^{-6}$$

$$\mathscr{B}(B^0 \to K^{*0}\nu\bar{\nu})_{\rm exp} < 18 \times 10^{-6}$$

conflict

- **Only $\mathcal{O}_{lq}^{(3)}$ is relevant with $R_{D^{(*)}}$**

SMEFT

$$\mathcal{Q}_{Hq}^{(1)} = \left(H^\dagger i \overleftrightarrow{D}_\mu H\right)\left(\bar{q}_p \gamma^\mu q_r\right),$$
$$\mathcal{Q}_{Hq}^{(3)} = \left(H^\dagger i \overleftrightarrow{D}^I_\mu H\right)\left(\bar{q}_p \tau^I \gamma^\mu q_r\right),$$
$$\mathcal{Q}_{Hd} = \left(H^\dagger i \overleftrightarrow{D}_\mu H\right)\left(\bar{d}_p \gamma^\mu d_r\right),$$

induce $\bar{s}bZ$ interaction, Thus, universally affect $b \to se^+e^-, \mu^+\mu^-, \tau^+\tau^-$

$$\mathcal{Q}_{ld} = \left(\bar{l}_p \gamma^\mu l_r\right)\left(\bar{d}_s \gamma_\mu d_t\right),$$

$$\mathcal{Q}_{lq}^{(1)} = \left(\bar{l}_p \gamma^\mu l_r\right)\left(\bar{q}_s \gamma_\mu q_t\right),$$
$$\mathcal{Q}_{lq}^{(3)} = \left(\bar{l}_p \gamma^\mu \tau^I l_r\right)\left(\bar{q}_s \tau^I \gamma_\mu q_t\right),$$

$\mu_{\rm EW}$

LEFT

$$\mathcal{O}_L^{\nu_i\nu_j} = \left(\bar{s}\gamma_\mu P_L b\right)\left(\bar{\nu}_i \gamma^\mu P_L \nu_j\right)$$

one LEFT operator ! **just the SM operator**

$$\mathcal{O}_R^{\nu_i\nu_j} = \left(\bar{s}\gamma_\mu P_R b\right)\left(\bar{\nu}_i \gamma^\mu P_L \nu_j\right)$$

μ_b

- **$\mathcal{O}_{ld}$ can explain the $B^+ \to K^+\nu\bar{\nu}$ data**
- **$\mathcal{O}_{ld}$ also induce $O'_{9,ij}$ and $O'_{10,ij}$**
- **They can't improve the $b \to s\ell\ell$ fit**
  - O'_{9e} and $O'_{10\mu}$ worsen the fit. weird (LFV, $\tau\tau \gg ee, \mu\mu$)
  - $O'_{9,ij}$ and $O'_{10,ij}$ with $i = j = \tau$ has no effect.
  - $O'_{9,ij}$ and $O'_{10,ij}$ with $i \neq j$ (i.e. LFV) has no effect.

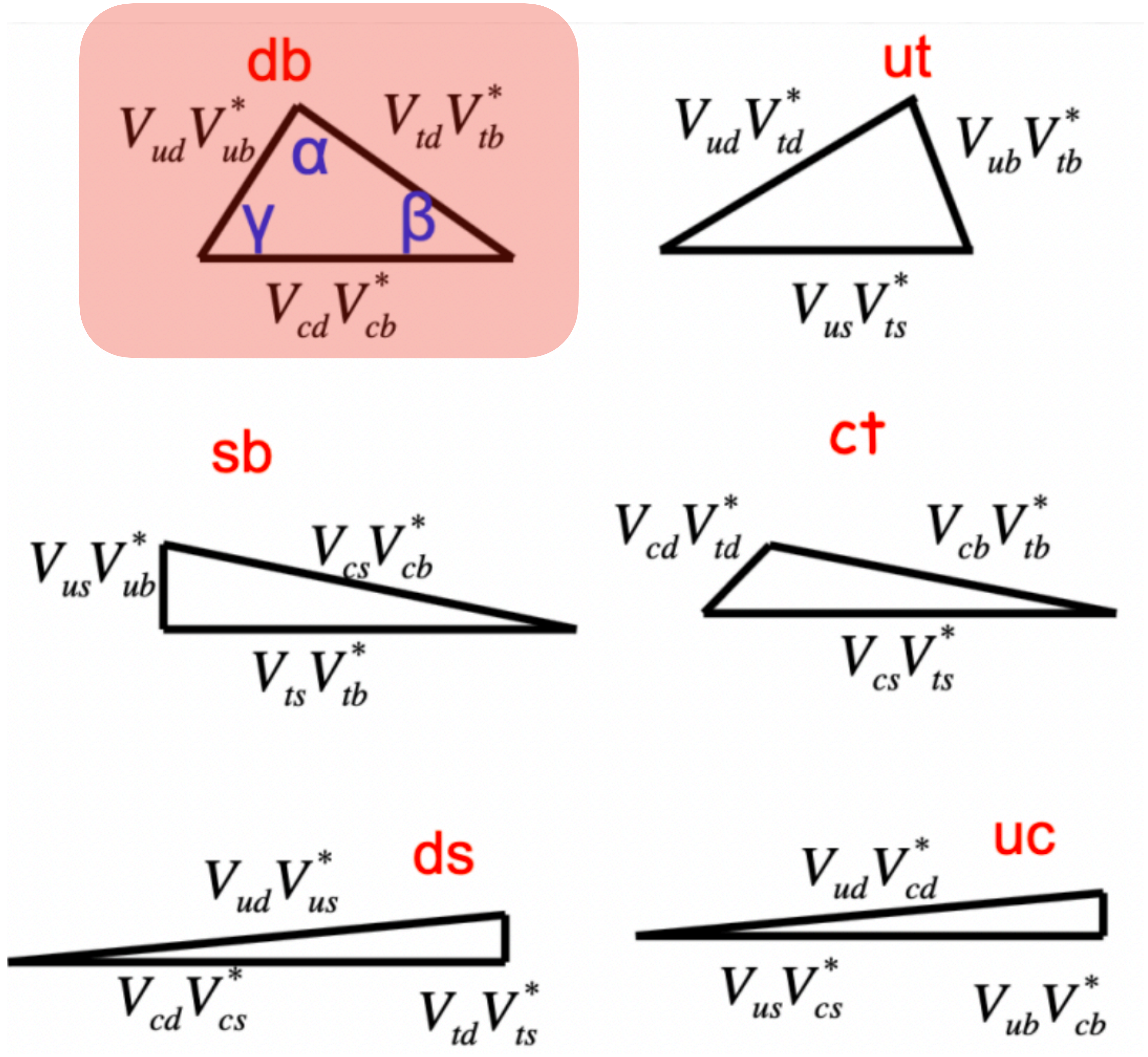
$$O'_{9,ij} = (\bar{b}\gamma^\mu P_R s)(\bar{\ell}_i \gamma_\mu \ell_j)$$
$$O'_{10,ij} = (\bar{b}\gamma^\mu P_R s)(\bar{\ell}_i \gamma_\mu \gamma_5 \ell_j)$$

Cabibbo Angle Anomaly

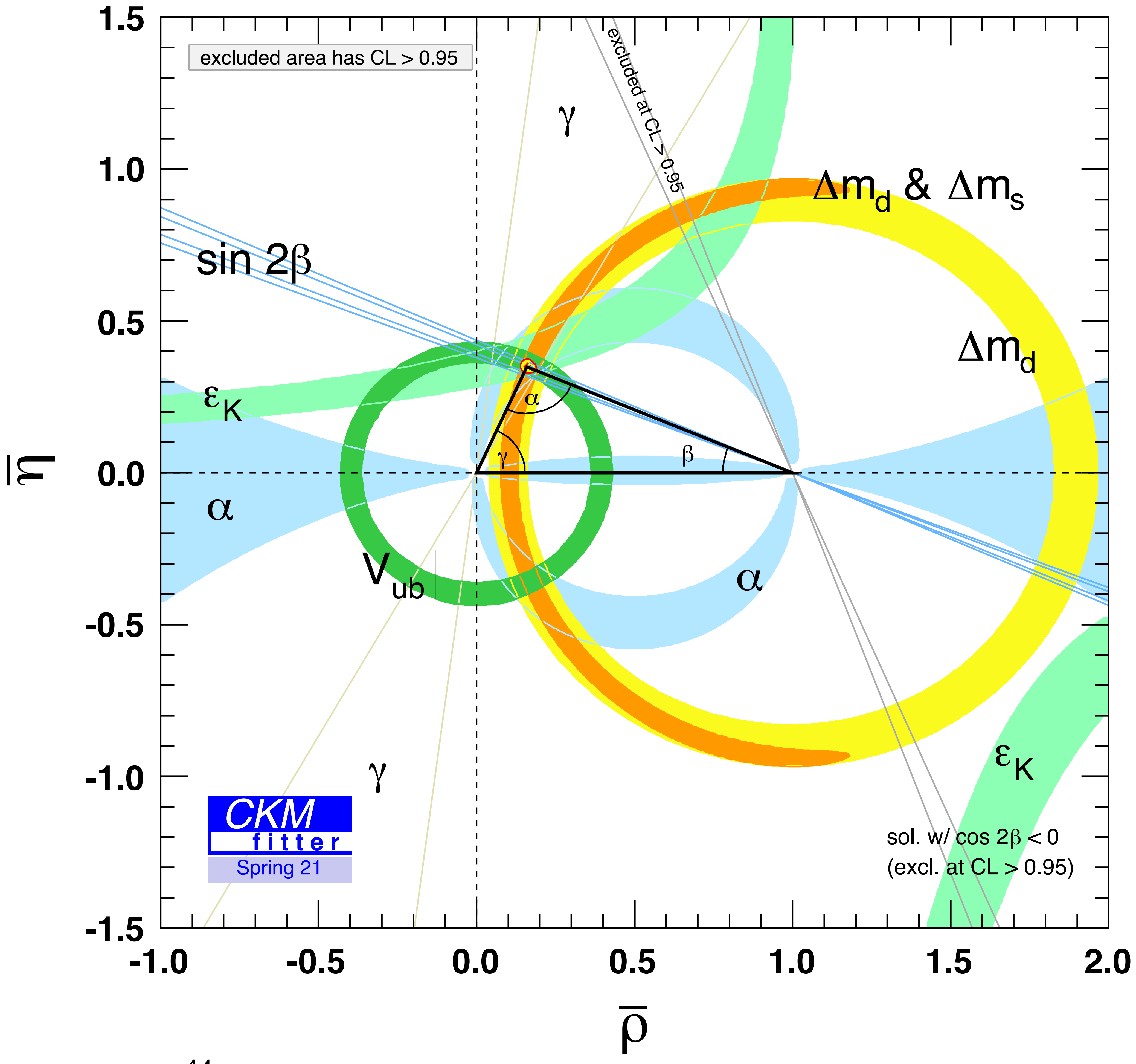
- unitarity of CKM: $VV^\dagger = V^\dagger V = 1$

$$V_{\text{CKM}} = \begin{bmatrix} V_{\text{ud}} & V_{\text{us}} & V_{\text{ub}} \\ V_{\text{cd}} & V_{\text{cs}} & V_{\text{cb}} \\ V_{\text{td}} & V_{\text{ts}} & V_{\text{tb}} \end{bmatrix} \longrightarrow \begin{array}{l} \sum_i V_{ij}V^*_{ik} = \delta_{jk} \\ \sum_i V_{ji}V^*_{ki} = \delta_{jk} \end{array}$$

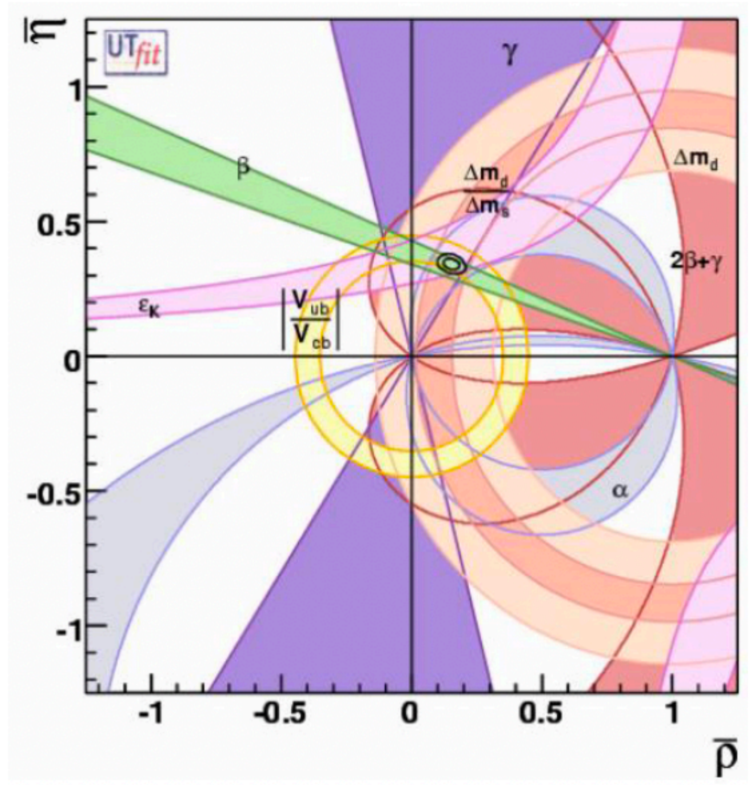
- unitarity triangle



All measurements agree with the CKM picture in the SM !!! However, …



- Semileptonic decay $B \to D\ell\nu$
- "Charmed" decays $B \to DK$
- CP violation in K mesons
- ΔM in B_d–$\overline{B}_d$ system
- ΔM in B_s–$\overline{B}_s$ system
- Decays to π and K
- CP asymmetry in $B \to J/\psi K_S$



Cabibbo Angle Anomaly

Belfatto, Beradze, Berezhiani 1906.02714

- From unitarity for the first row of CKM ($|V_{ub}|^2 \sim 10^{-5}$)

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

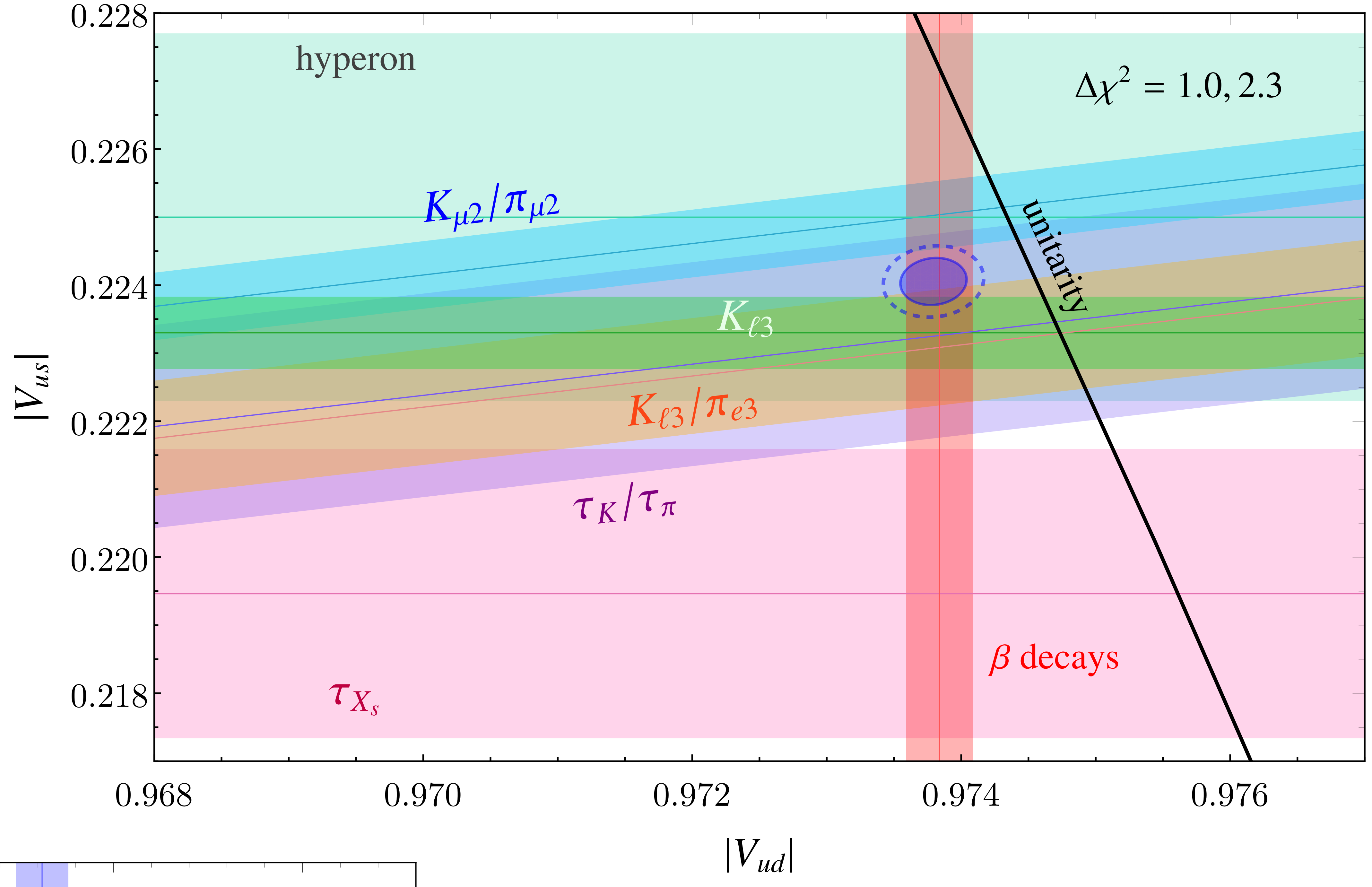
Crivellin, Kirk, Kitahara, Mescia, 2212.06862

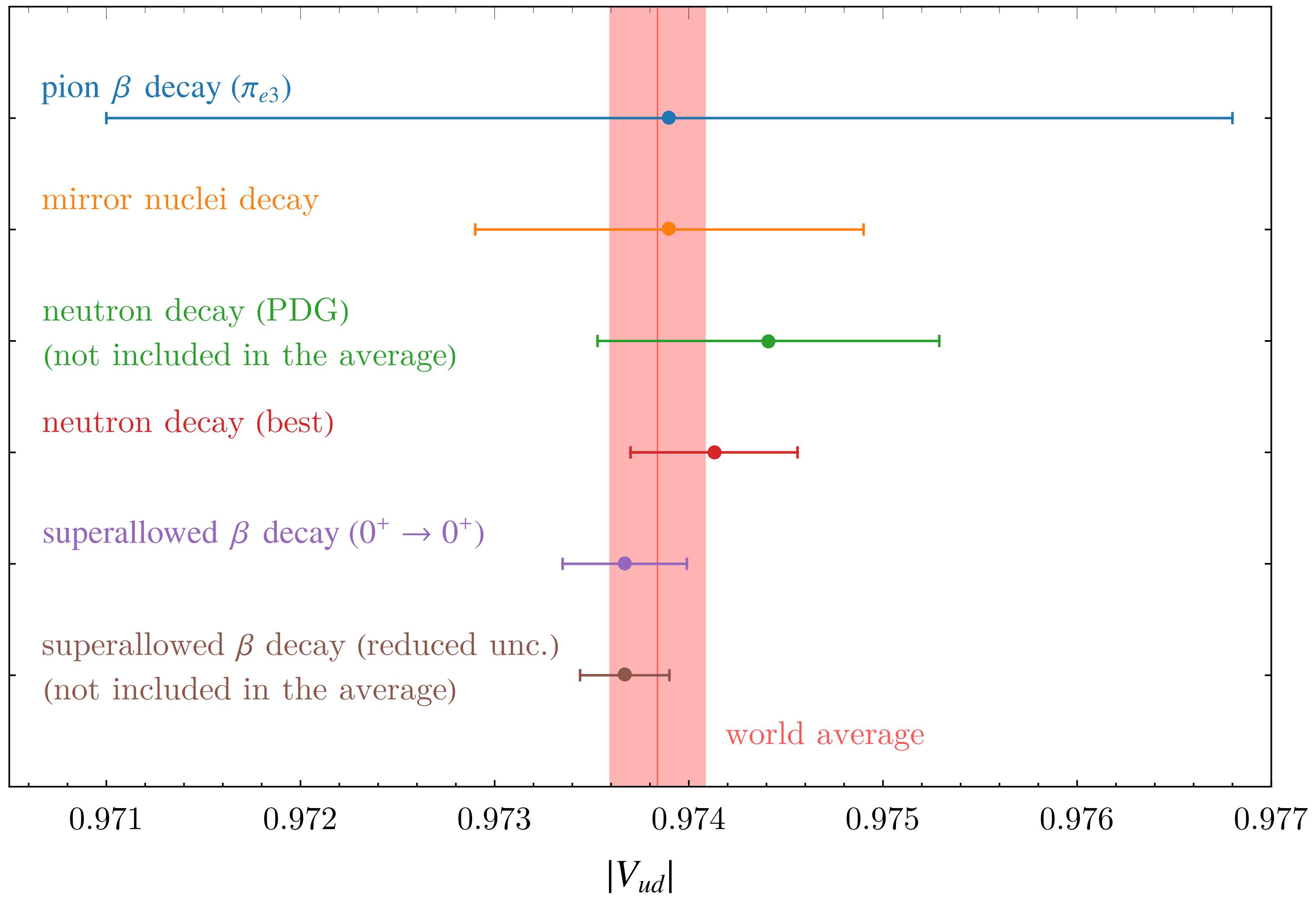
- $|V_{ud}|^2_{\text{global}} + |V_{us}|^2_{\text{global}} + |V_{ub}|^2 - 1 = -0.001\,51(53)$ $\quad 2.8\,\sigma$

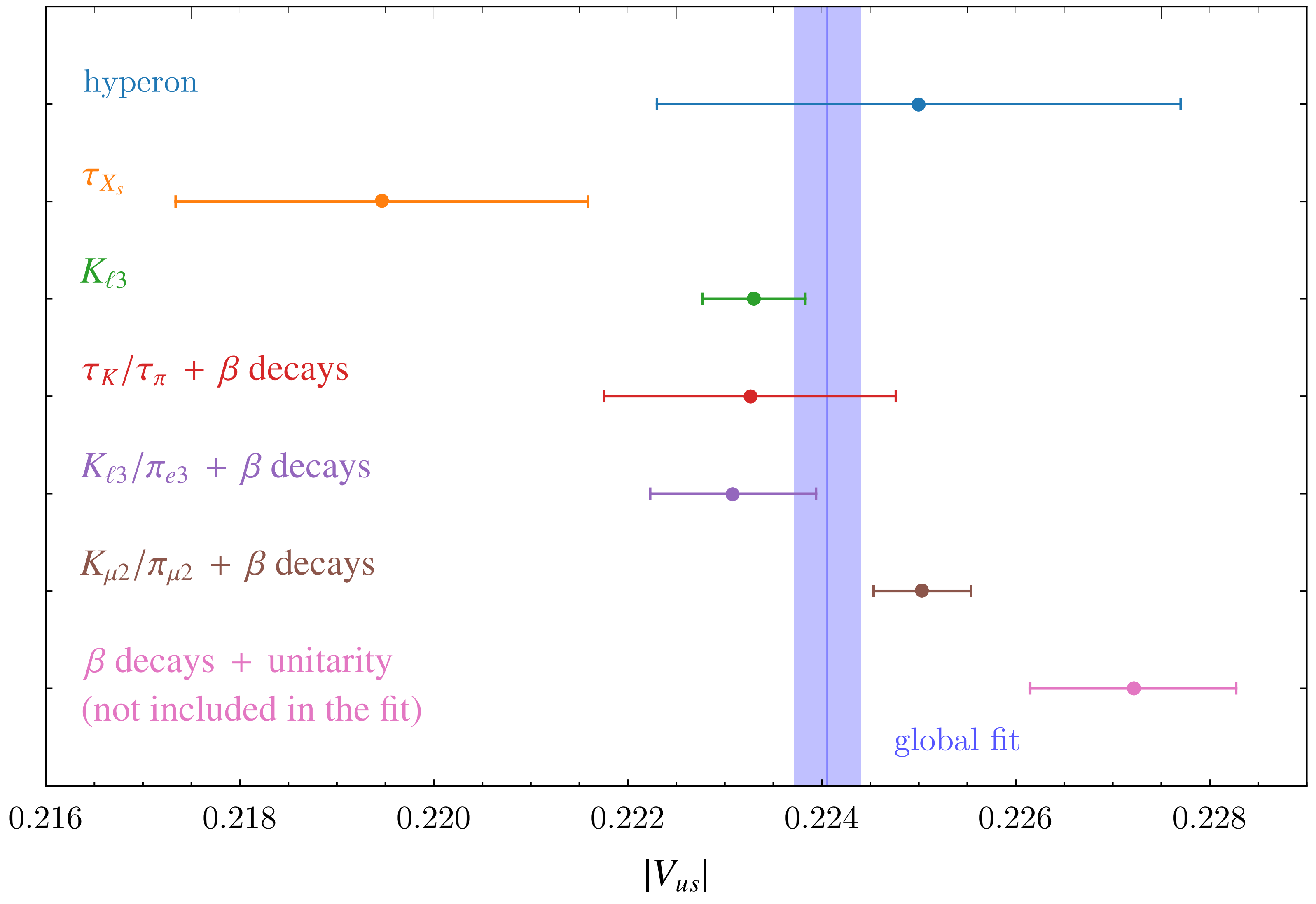
$$|V_{ud}|^2_{\beta} + |V_{us}|^2_{K_{\ell 3}} + |V_{ub}|^2 - 1 = -0.001\,76(54)\,, \quad 3.3\,\sigma$$

$$|V_{ud}|^2_{\beta} + |V_{us}|^2_{K_{\mu 2}/\pi_{\mu 2},\beta} + |V_{ub}|^2 - 1 = -0.000\,98(56)\,, \quad 1.8\,\sigma$$

$$|V_{ud}|^2_{K_{\mu 2}/\pi_{\mu 2},K_{\ell 3}} + |V_{us}|^2_{K_{\ell 3}} + |V_{ub}|^2 - 1 = -0.0163(62)\,, \quad 2.6\,\sigma$$







$$K_{\mu 2}/\pi_{\mu 2} = \Gamma(K^+ \to \mu^+\nu)/\Gamma(\pi^+ \to \mu^+\nu)$$

$$\tau_K/\tau_\pi = \Gamma(\tau \to K^-\nu)/\Gamma(\tau \to \pi^-\nu)$$

$$K_{\ell 3}/\pi_{e3} = \Gamma(K \to \pi\ell\nu)/\Gamma(\pi^+ \to \pi^0 e^+\nu)$$

Cabibbo Angle Anomaly

Belfatto, Beradze, Berezhiani 1906.02714

- From unitarity for the first row of CKM ($|V_{ub}|^2 \sim 10^{-5}$)

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

- From data

Crivellin, Kirk, Kitahara, Mescia, 2212.06862

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

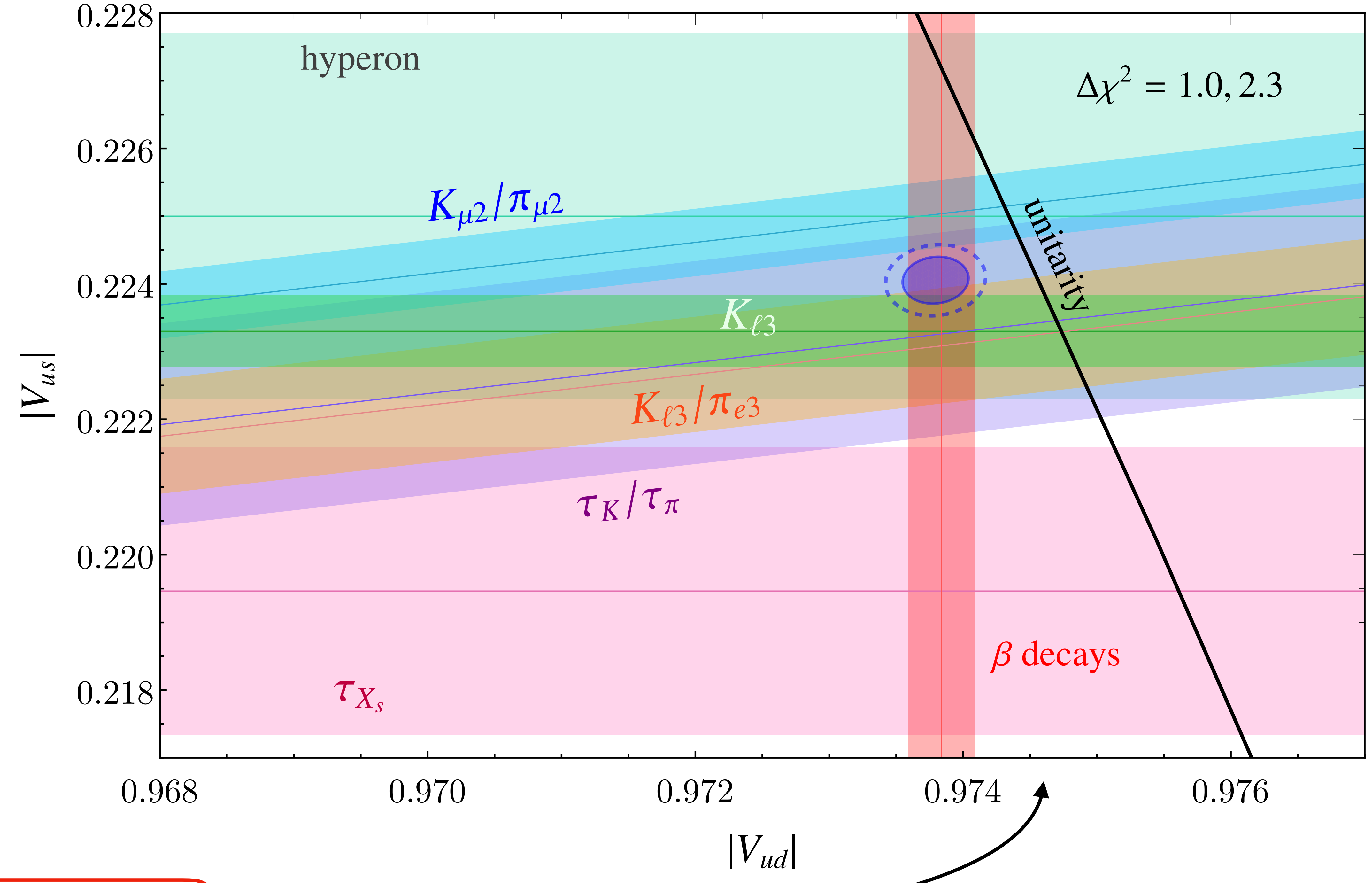
$2.8\,\sigma$

- Connection to LFUV

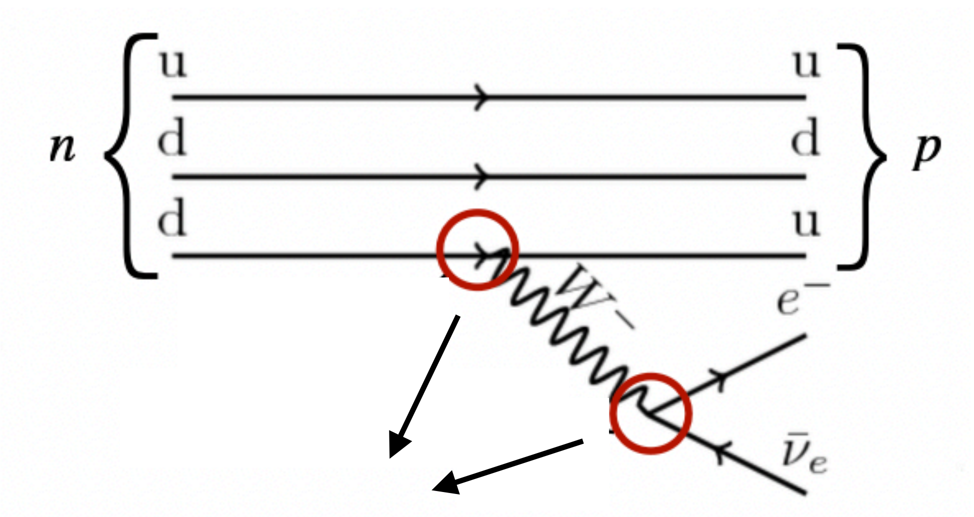
Crivellin, Hoferichter, 2002.07184

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

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



V_{ud} from β decay:

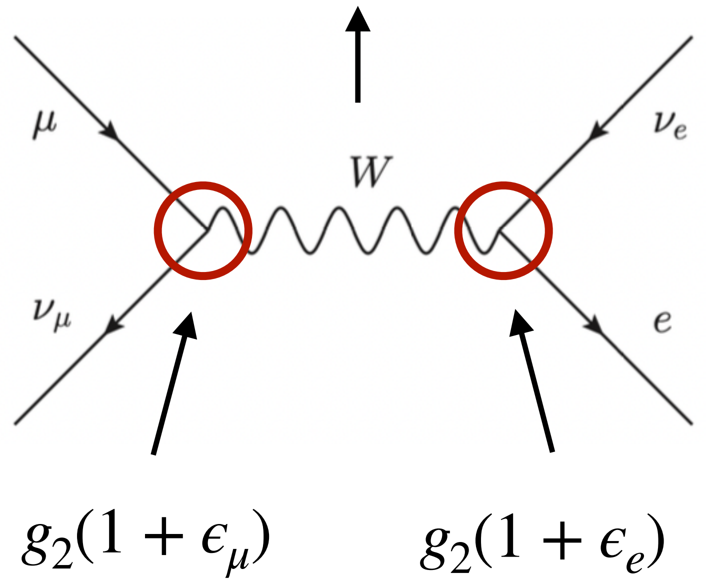


$$G_F^0 \cdot (1+\epsilon_e) \cdot V_{ud}^0 = G_F \cdot (1-\epsilon_\mu) \cdot V_{ud}^0 \longrightarrow V_{ud}^\beta = V_{ud}^0 \cdot (1-\epsilon_\mu)$$

$$G_F = G_F^0(1+\epsilon_e+\epsilon_\mu)$$

V_{ud}^β can receive the contribution from ϵ_μ, but no ϵ_e

G_F from μ decay:

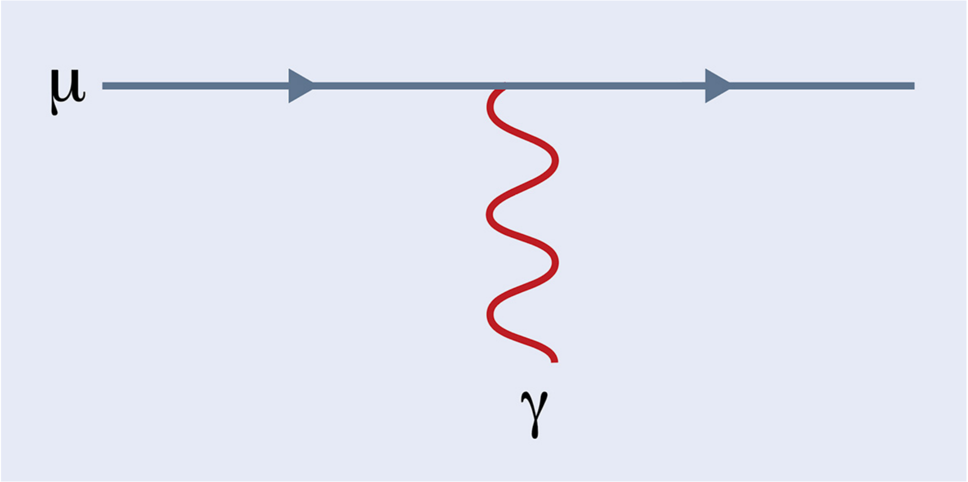


Observable	Measurement
$\frac{K\to\pi\mu\bar\nu}{K\to\pi e\bar\nu} \simeq 1+\varepsilon_{\mu\mu}-\varepsilon_{ee}$	1.0010(25) [77]
$\frac{K\to\mu\nu}{K\to e\nu} \simeq 1+\varepsilon_{\mu\mu}-\varepsilon_{ee}$	0.9978(18) [3, 78, 79]
$\frac{\pi\to\mu\nu}{\pi\to e\nu} \simeq 1+\varepsilon_{\mu\mu}-\varepsilon_{ee}$	1.0010(9) [3, 80–82]
$\frac{\tau\to\mu\nu\bar\nu}{\tau\to e\nu\bar\nu} \simeq 1+\varepsilon_{\mu\mu}-\varepsilon_{ee}$	1.0018(14) [3, 32]
$\frac{W\to\mu\bar\nu}{W\to e\bar\nu} \simeq 1+\varepsilon_{\mu\mu}-\varepsilon_{ee}$	0.9960(100) [83, 84]
$\frac{B\to D^{(*)}\mu\nu}{B\to D^{(*)}e\nu} \simeq 1+\varepsilon_{\mu\mu}-\varepsilon_{ee}$	0.9890(120) [85]
$R(V_{us}) \simeq 1-\left(\frac{V_{ud}}{V_{us}}\right)^2\varepsilon_{\mu\mu}$	0.9891(33) [11]
	0.9927(39) [14]

$(g-2)_\mu$

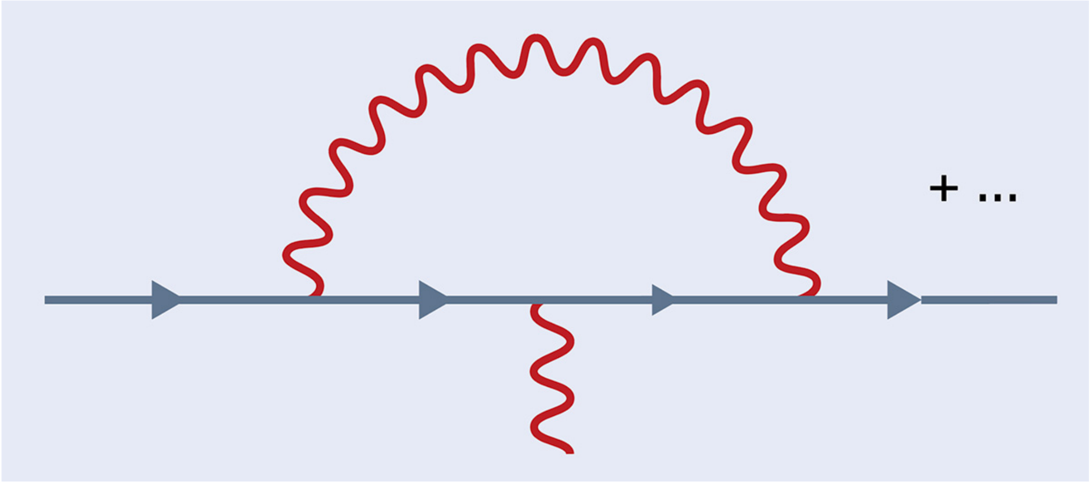
$$a_\mu = (g-2)/2$$

$g = 2$



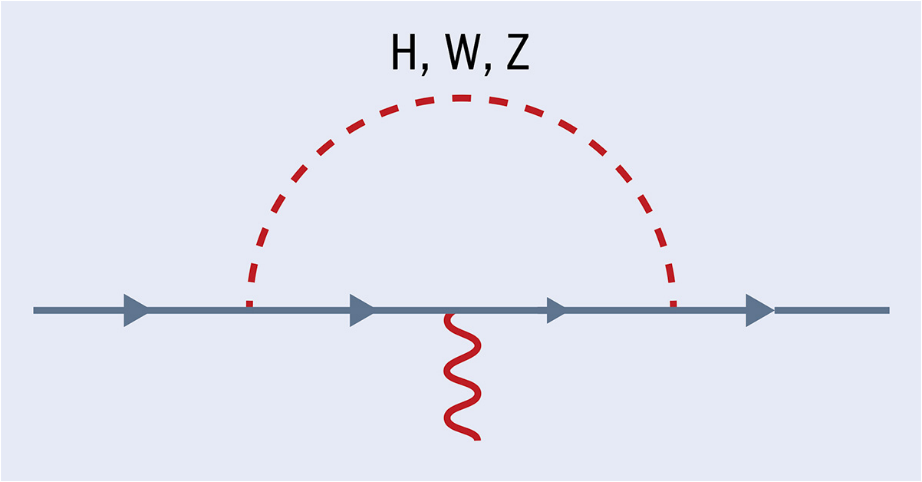
Bohr magneton

QED



$$a_\mu^{\text{QED}} = 116584718.931 \pm 0.104$$

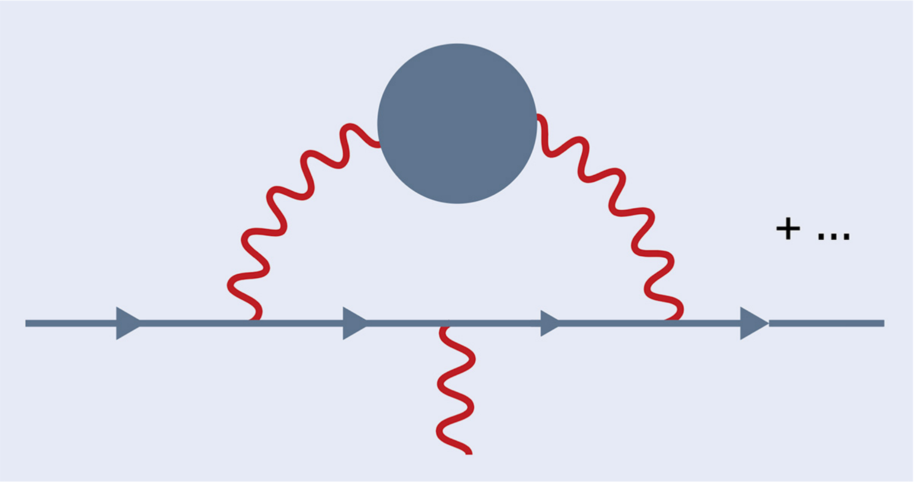
Electro-Weak



$$a_\mu^{\text{EW}} = 153.6 \pm 1.0$$

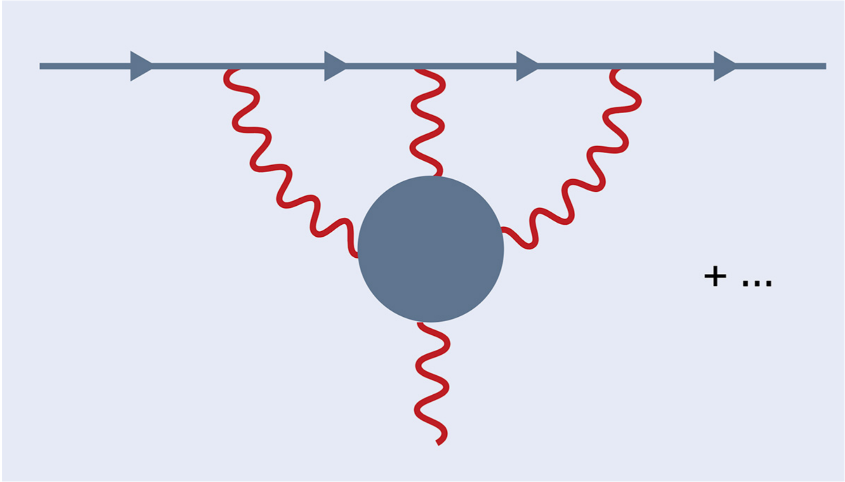
unit: 10^{-11}

hadronic vacuum polarisation



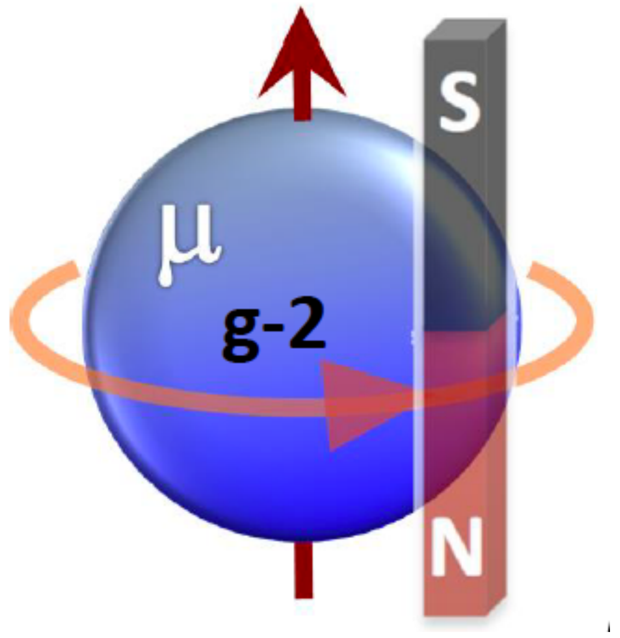
$a_\mu^{\text{HVP}} \times 10^{11}$	LO	NLO	NNLO
e^+e^- data	6931 ± 40	-98 ± 7	12 ± 1
Lattice QCD	7116 ± 184		

Hadronic light-by-light scattering

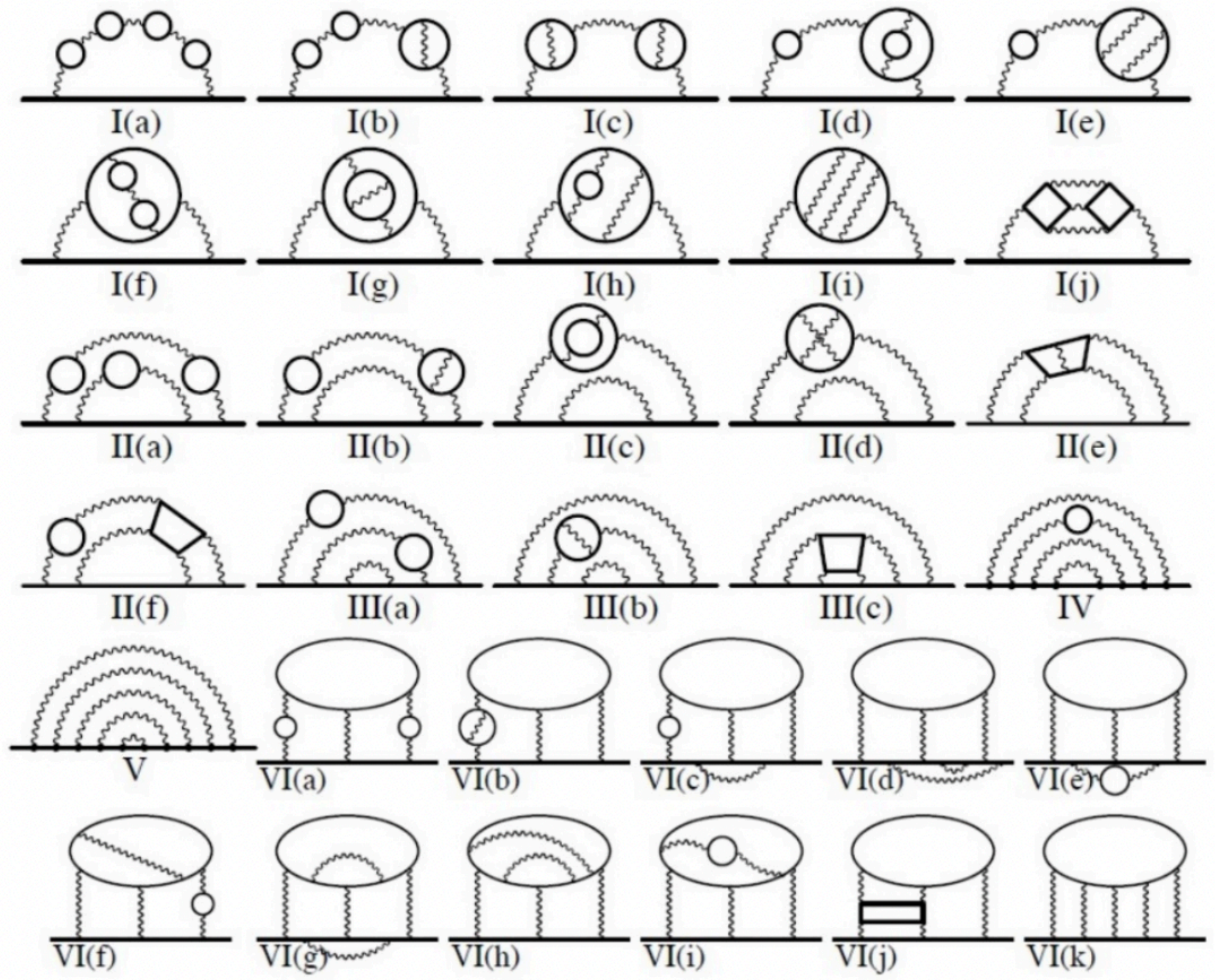


$a_\mu^{\text{HLbL}} \times 10^{11}$	LO	NLO
Phenomenology	92 ± 19	2 ± 1
Lattice QCD	79 ± 35	

$$a_\mu^{\text{SM}} = 116591810 \pm 43$$



$$\vec{\mu} = g\frac{e}{2m}\vec{s}$$



Aoyama, Hayakawa, Kinoshita, Nio (2012-2019)

$$
\begin{aligned}
a_\mu^{\text{QED}} = \; & 116\,140\,973.321\,(23) && \alpha \\
+ \; & 413\,217.626\,(7) && \alpha^2 \\
+ \; & 30\,141.902\,(33) \quad (\times 10^{-11}) && \alpha^3 \\
+ \; & 381.004\,(17) && \alpha^4 \\
+ \; & 5.078\,(6) && \alpha^5 \\
= \; & 116\,584\,718.931\,(104)
\end{aligned}
$$

12000+ Feynman diagrams

Analytical calculation @ α^2, α^3

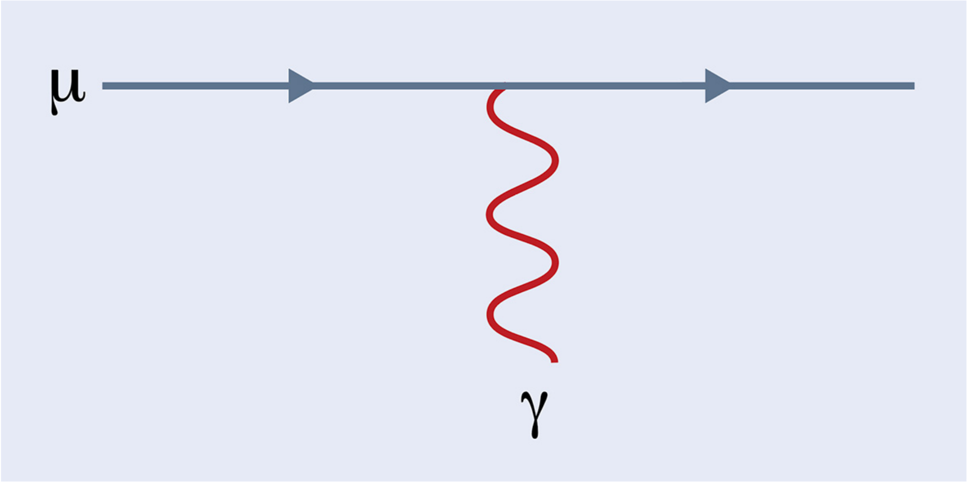
Partly analytical @ α^4

Numerical @ α^5

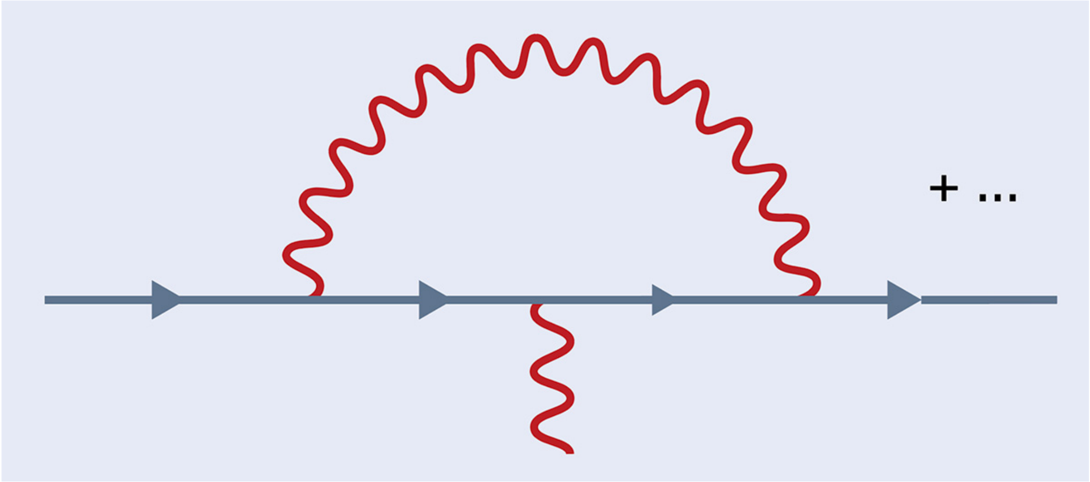
$(g-2)_\mu$

$a_\mu = (g-2)/2$

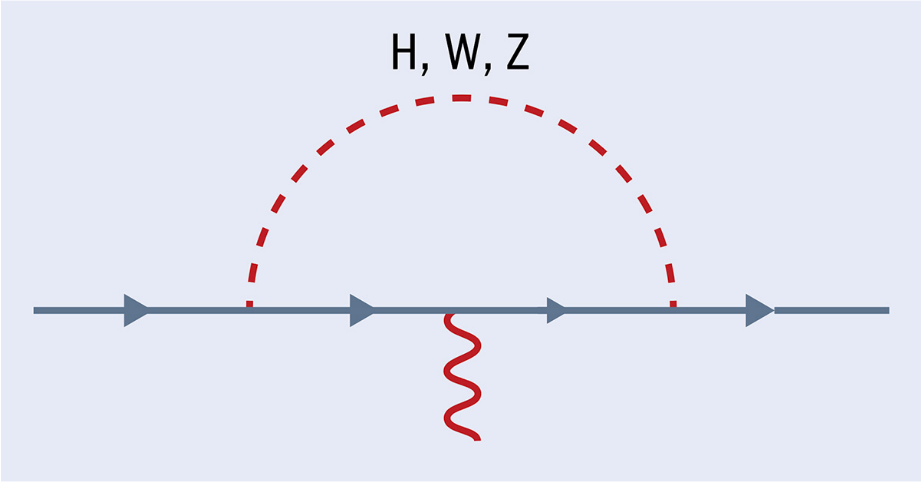
$g=2$



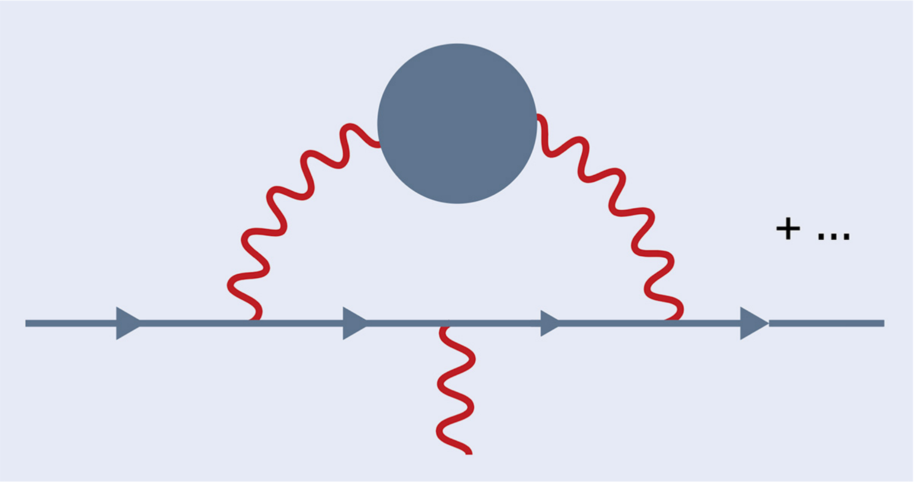
QED



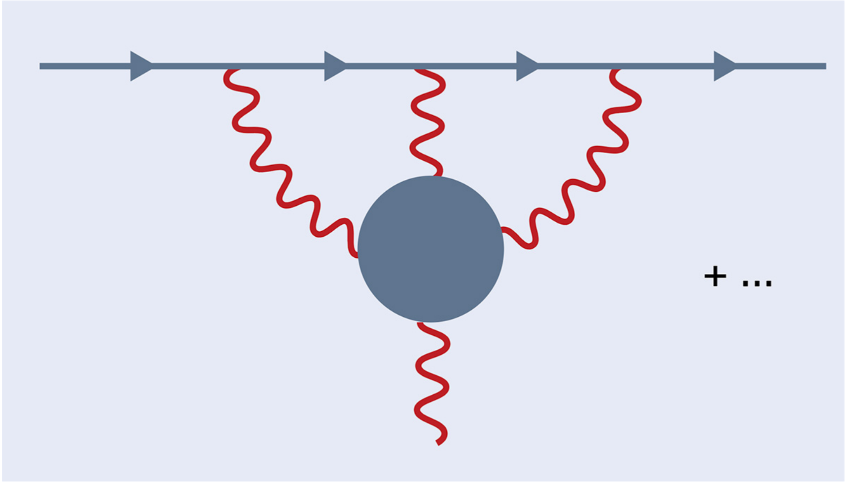
Electro-Weak



hadronic vacuum polarisation



Hadronic light-by-light scattering



Bohr magneton

$a_\mu^{\text{QED}} = 116584718.931 \pm 0.104$

$a_\mu^{\text{EW}} = 153.6 \pm 1.0$

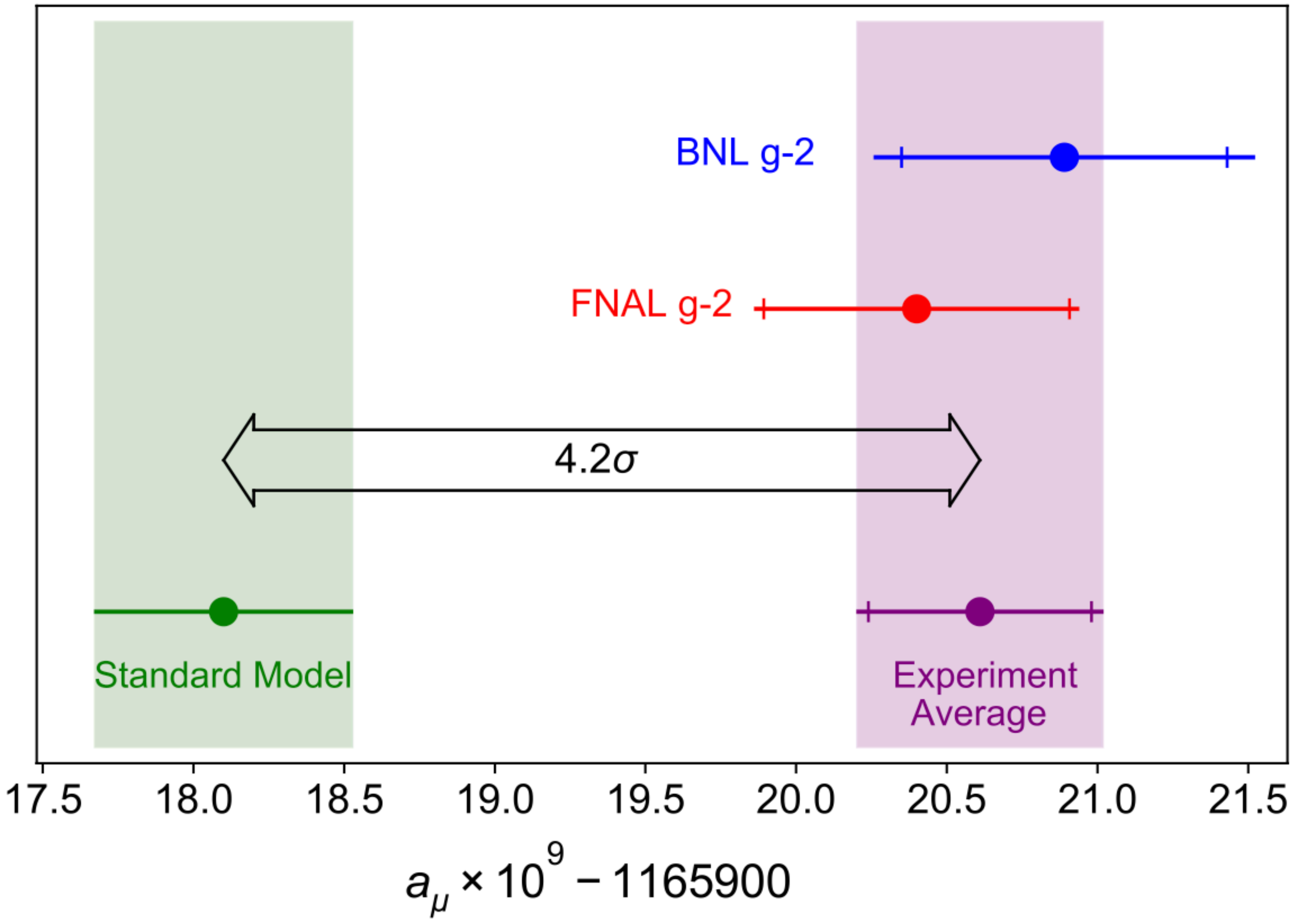
unit: 10^{-11}

$a_\mu^{\text{HVP}} \times 10^{11}$	LO	NLO	NNLO
e^+e^- data	6931 ± 40	-98 ± 7	12 ± 1
Lattice QCD	7116 ± 184		

$a_\mu^{\text{HLbL}} \times 10^{11}$	LO	NLO
Phenomenology	92 ± 19	2 ± 1
Lattice QCD	79 ± 35	

$a_\mu^{\text{SM}} = 116591810 \pm 43$ $a_\mu^{\text{exp}} = 116592061 \pm 41$ → $\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 251 \pm 59$

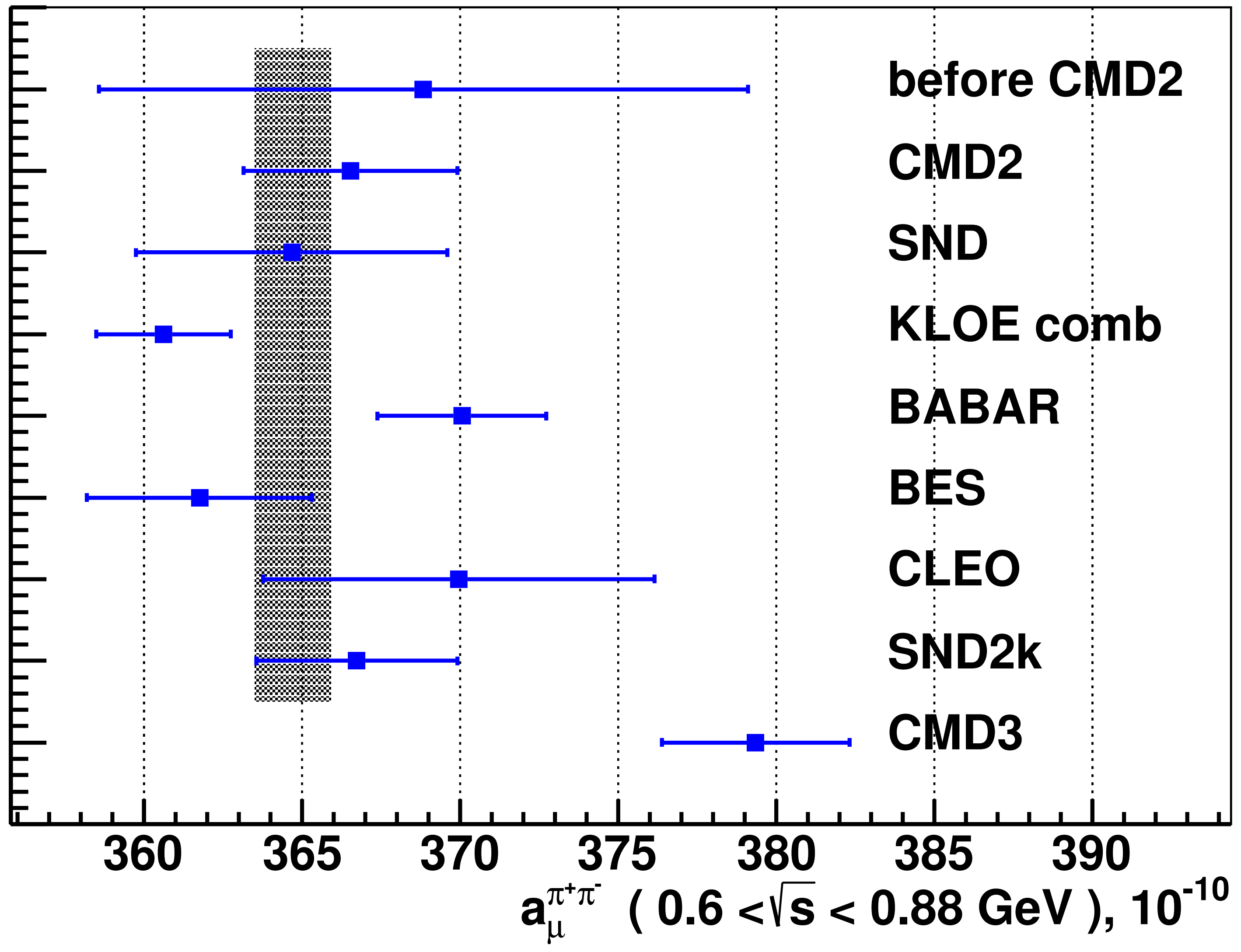
4.2 sigma difference !!!



Experiment	Beam	Measurement	$\delta a_\mu / a_\mu$	Required th. terms
Columbia-Nevis (57)	μ^+	g=2.00±0.10		g=2
Columbia-Nevis (59)	μ^+	0.001 13(+16)(−12)	12.4%	α/π
CERN 1 (61)	μ^+	0.001 145(22)	1.9%	α/π
CERN 1 (62)	μ^+	0.001 162(5)	0.43%	$(\alpha/\pi)^2$
CERN 2 (68)	μ^+	0.001 166 16(31)	265 ppm	$(\alpha/\pi)^3$
CERN 3 (75)	$\mu^\pm$	0.001 165 895(27)	23 ppm	$(\alpha/\pi)^3$ + had
CERN 3 (79)	$\mu^\pm$	0.001 165 911(11)	7.3 ppm	$(\alpha/\pi)^3$ + had
BNL E821 (00)	μ^+	0.001 165 919 1(59)	5 ppm	$(\alpha/\pi)^3$ + had
BNL E821 (01)	μ^+	0.001 165 920 2(16)	1.3 ppm	$(\alpha/\pi)^4$ + had + weak
BNL E821 (02)	μ^+	0.001 165 920 3(8)	0.7 ppm	$(\alpha/\pi)^4$ + had + weak + ?
BNL E821 (04)	μ^-	0.001 165 921 4(8)(3)	0.7 ppm	$(\alpha/\pi)^4$ + had + weak + ?
FNAL Run1 (21)	μ^+	0.001 165 920 40(54)	0.46 ppm	$(\alpha/\pi)^4$ + had + weak + ?

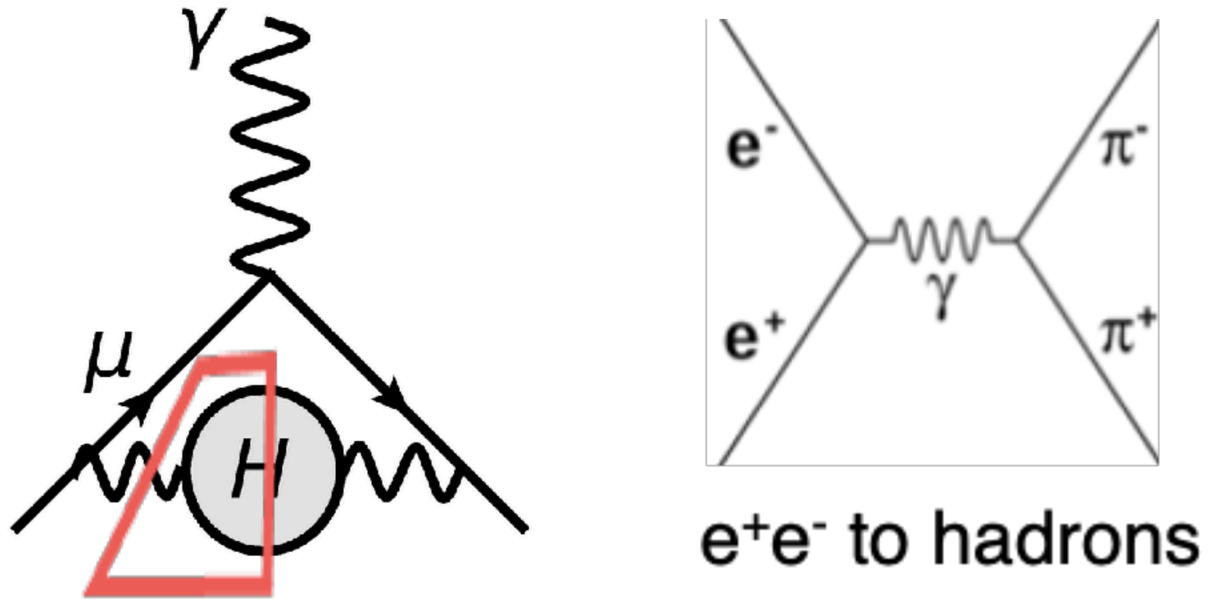
60 years of g-2 measurements

$(g-2)_\mu$

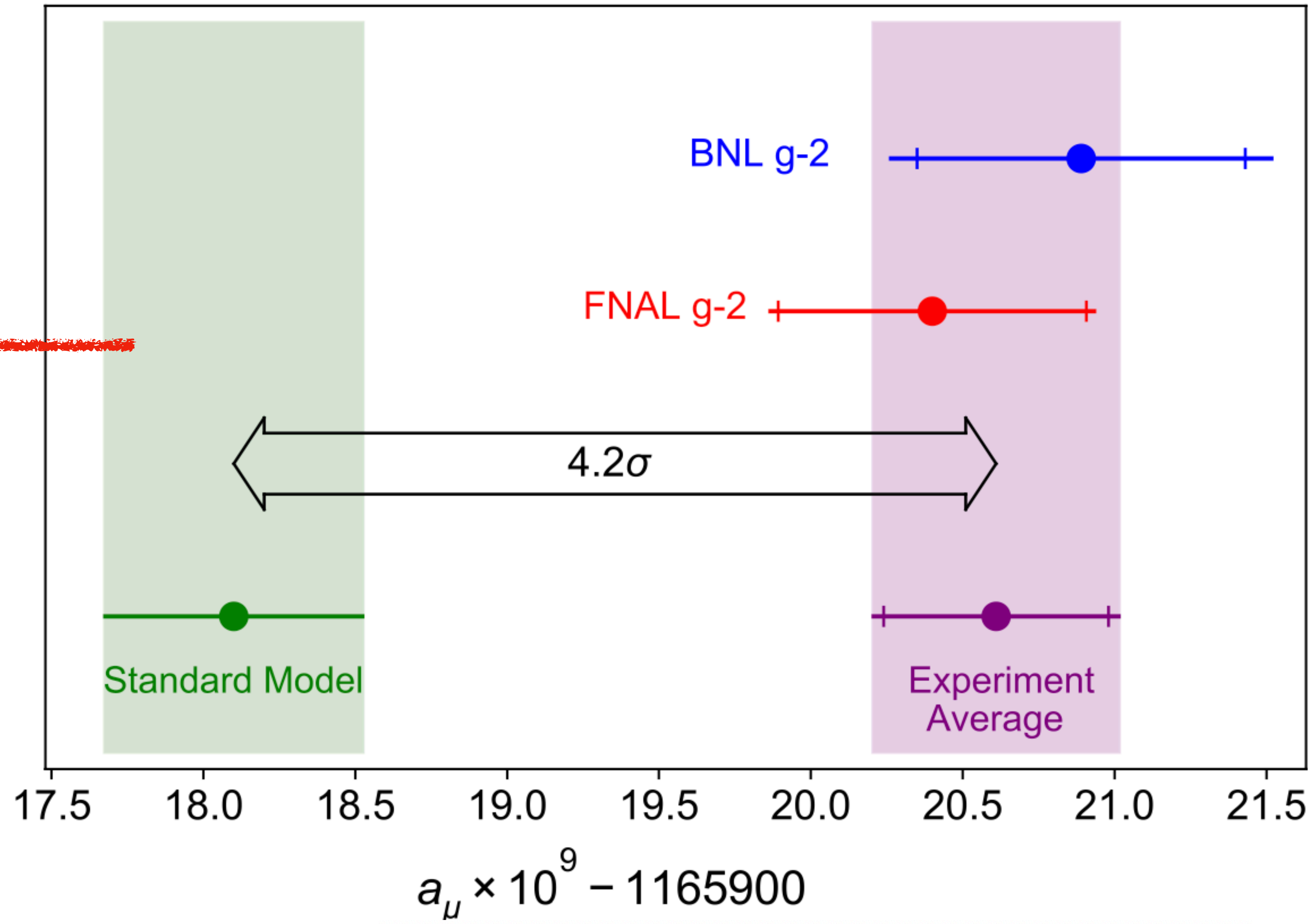


Data-driven

Dispersion relation + low energy e+e- -> hadrons



$$a_\mu^{\mathrm{had,LO}} = \frac{m_\mu^2}{12\pi^3}\int_{s_{\mathrm{th}}}^{\infty} ds\, \frac{1}{s}\hat{K}(s)\sigma_{\mathrm{had}}(s)$$

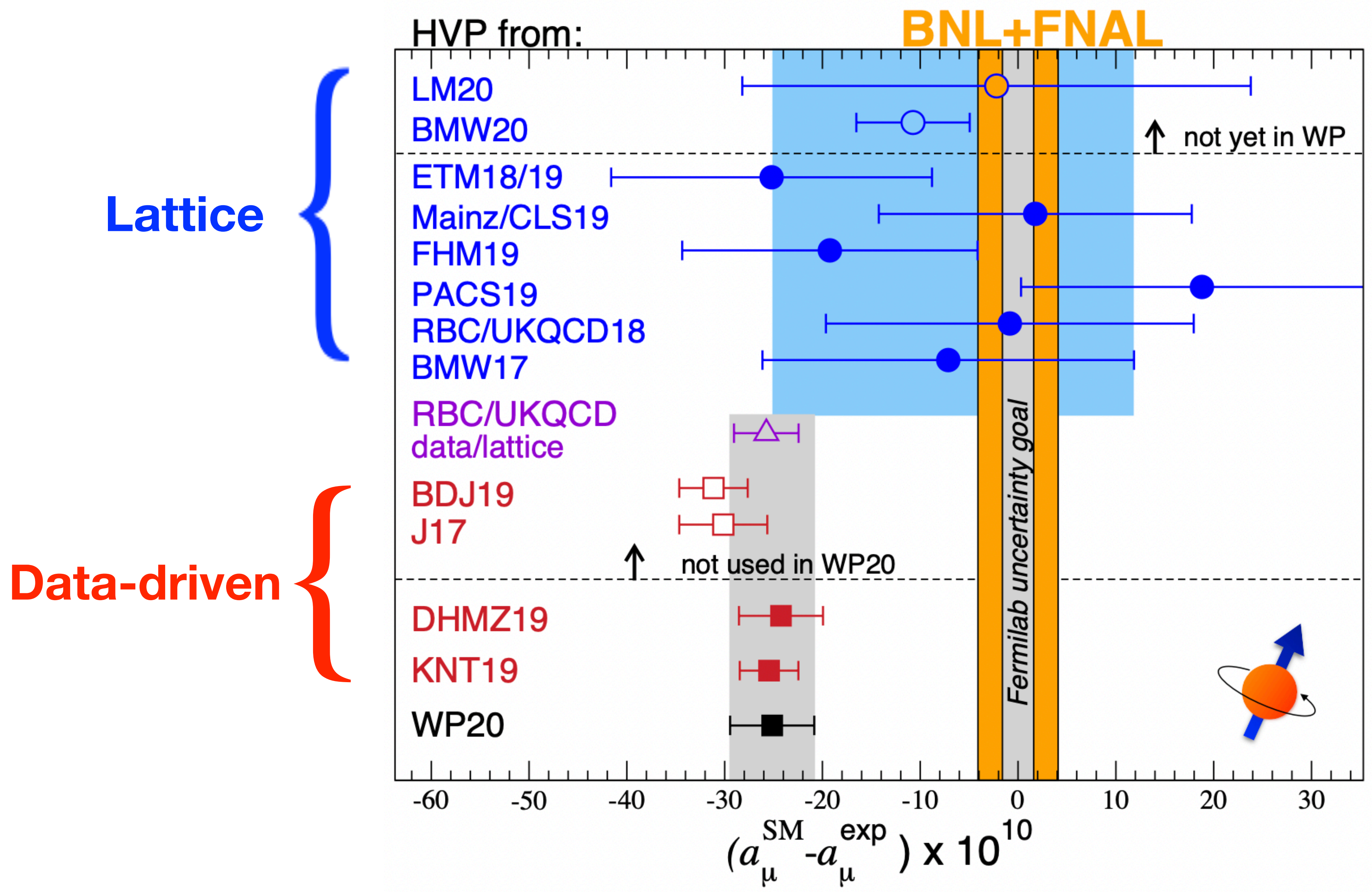


- CMD-3 different from CDM-2 and others
- New results from BES-III, Belle II, STCF expected !!!
- More time needed to resolve these puzzles

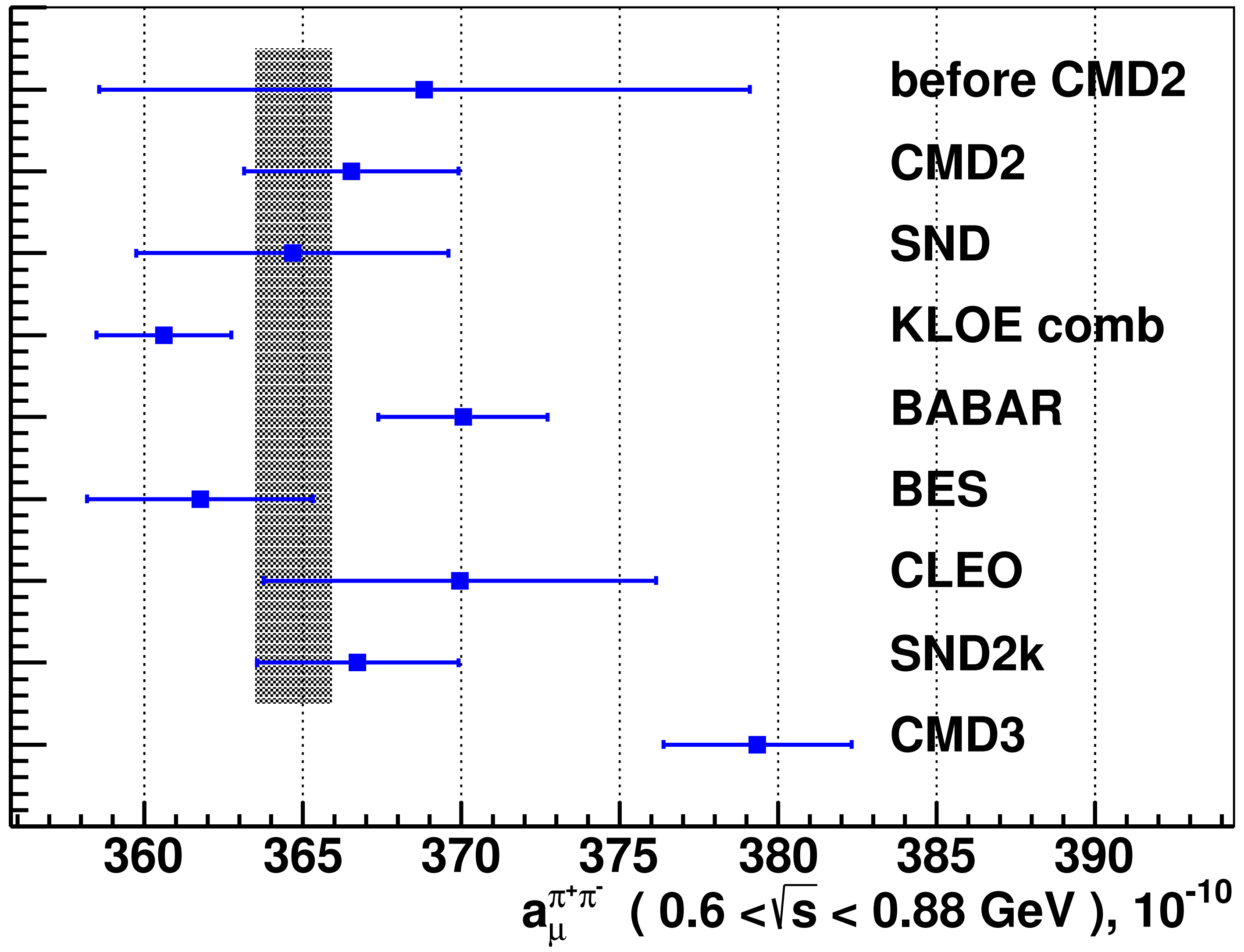
Tension between data-driven and lattice

- Uncertainty in BMW20 much smaller than others (huge computing power)
- Central value closer to experimental measurement
- Discrepancy between BMW20 and Data-driven
- Require more checks among the several Lattice groups
- Recent progress

M. Ce et al, 2206.06582
ETMC, 2206.15084
Fermilab Lattice, HPQCD, and MILC, 2301.08274
RBC and UKQCD, 2301.08696

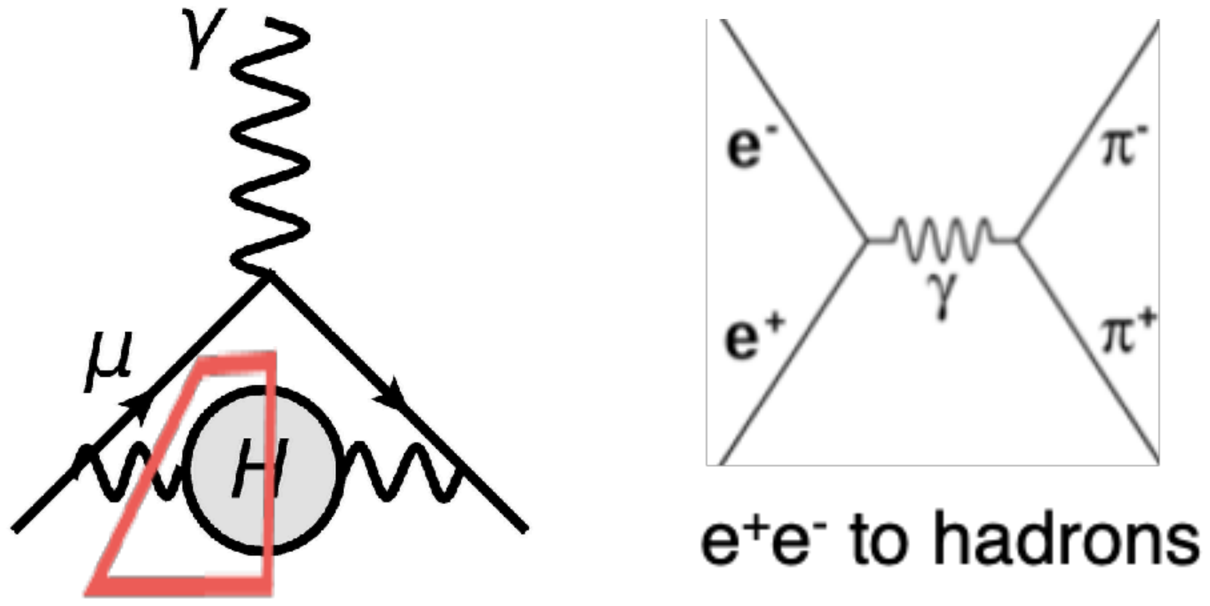


$(g-2)_\mu$



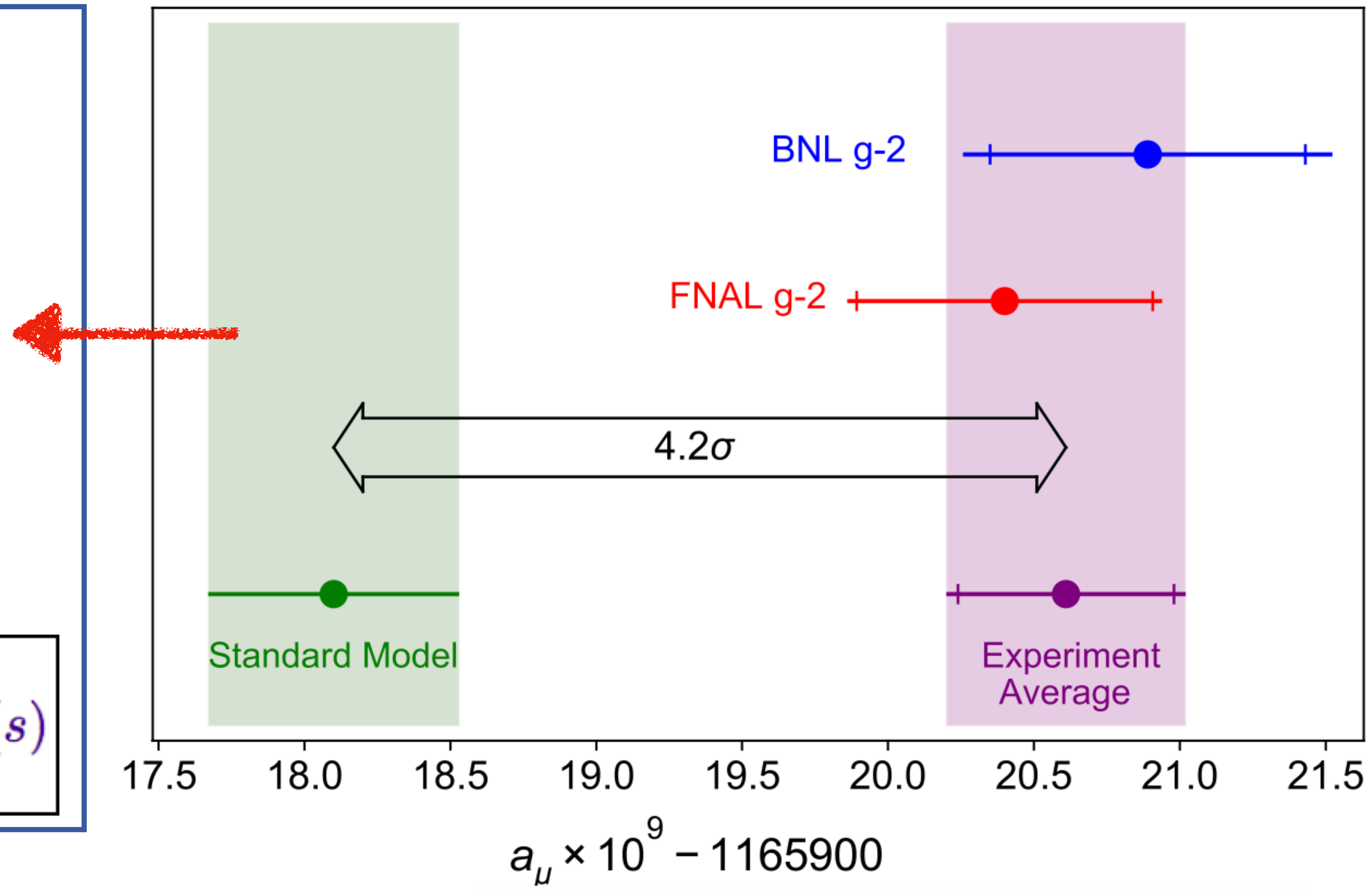
Data-driven

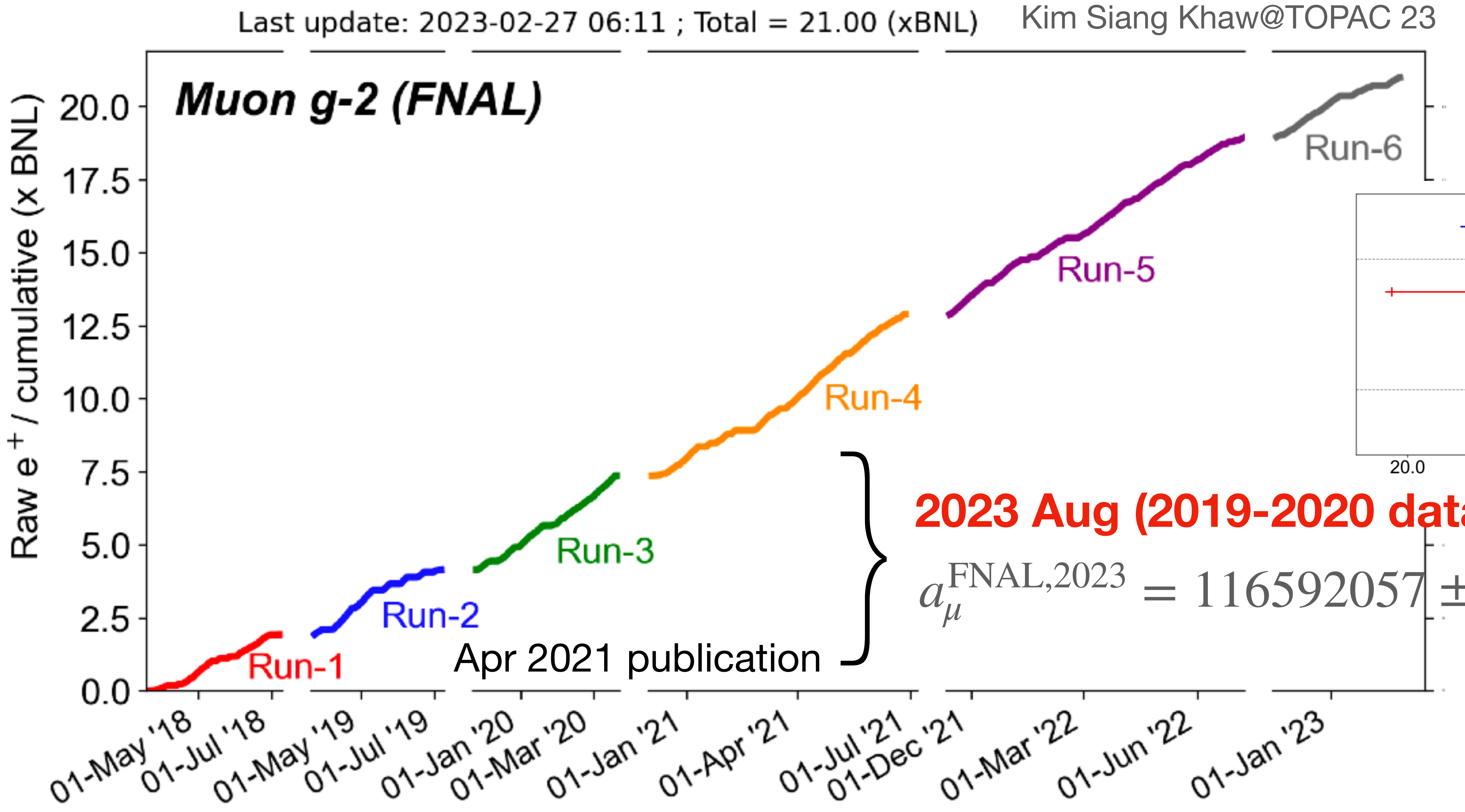
Dispersion relation + low energy e⁺e⁻ -> hadrons



e⁺e⁻ to hadrons

$$a_\mu^{\mathrm{had,LO}} = \frac{m_\mu^2}{12\pi^3}\int_{s_{\mathrm{th}}}^{\infty} ds\, \frac{1}{s}\hat{K}(s)\sigma_{\mathrm{had}}(s)$$





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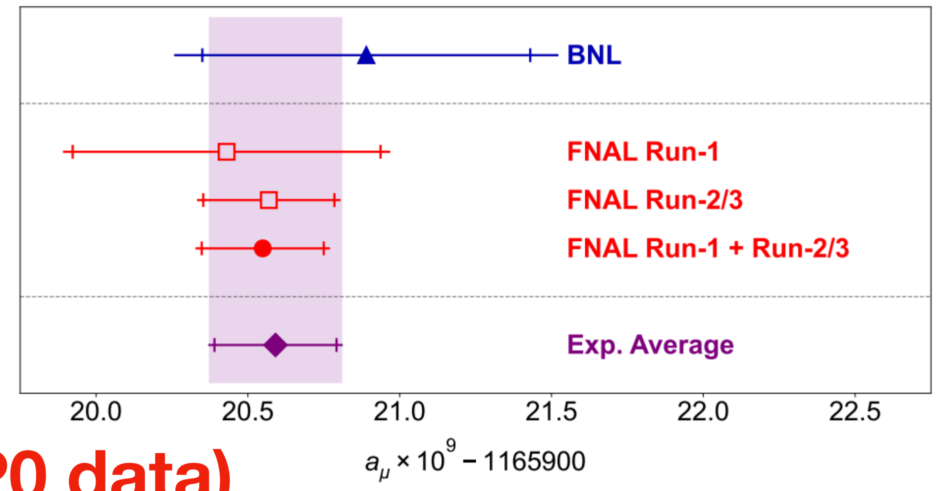

2023 Aug (2019-2020 data)

$$a_\mu^{\mathrm{FNAL,2023}} = 116592057 \pm 25$$

Exp vs SM: 5.2 σ