Light New Particles Motivated by Flavour Anomalies

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Content

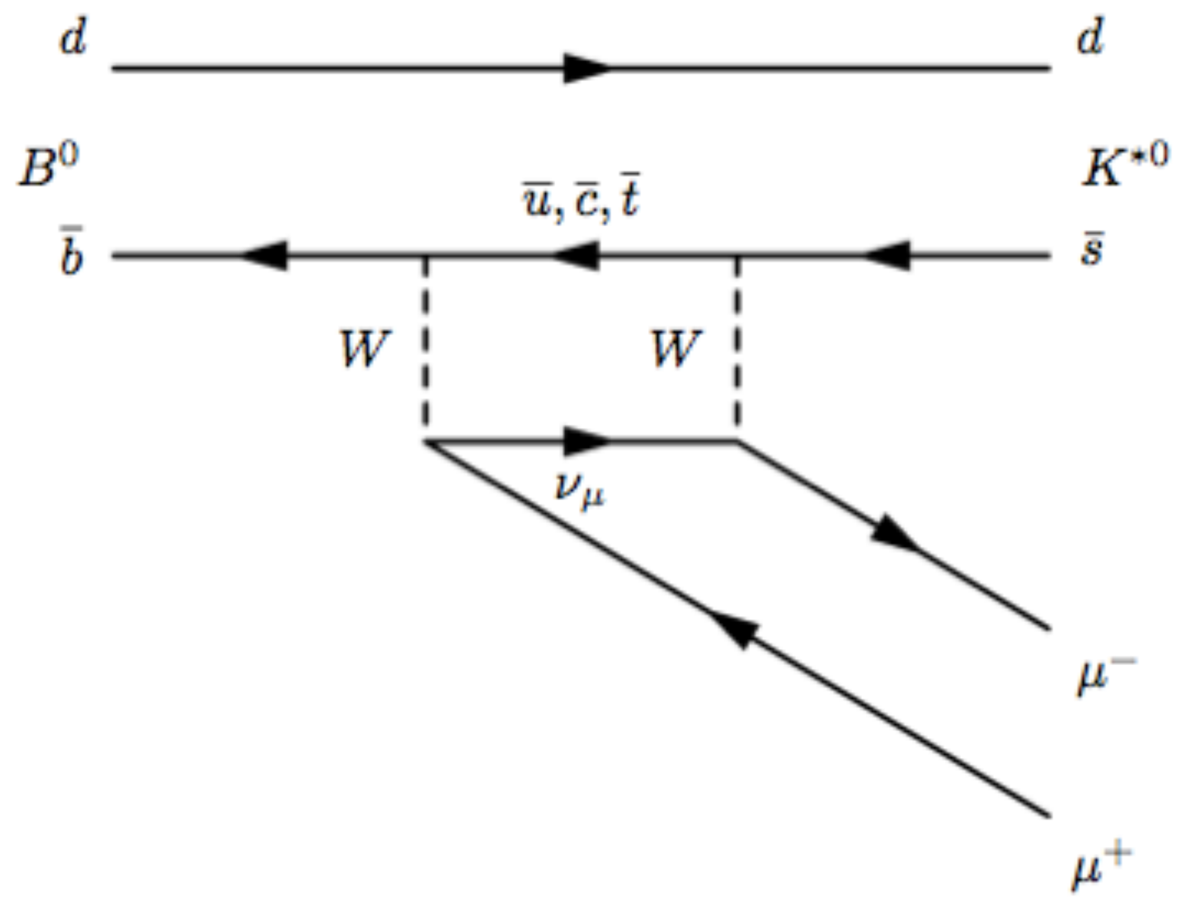
I. $b \to s\ell\ell$ **anomaly and** $(g-2)_\mu$

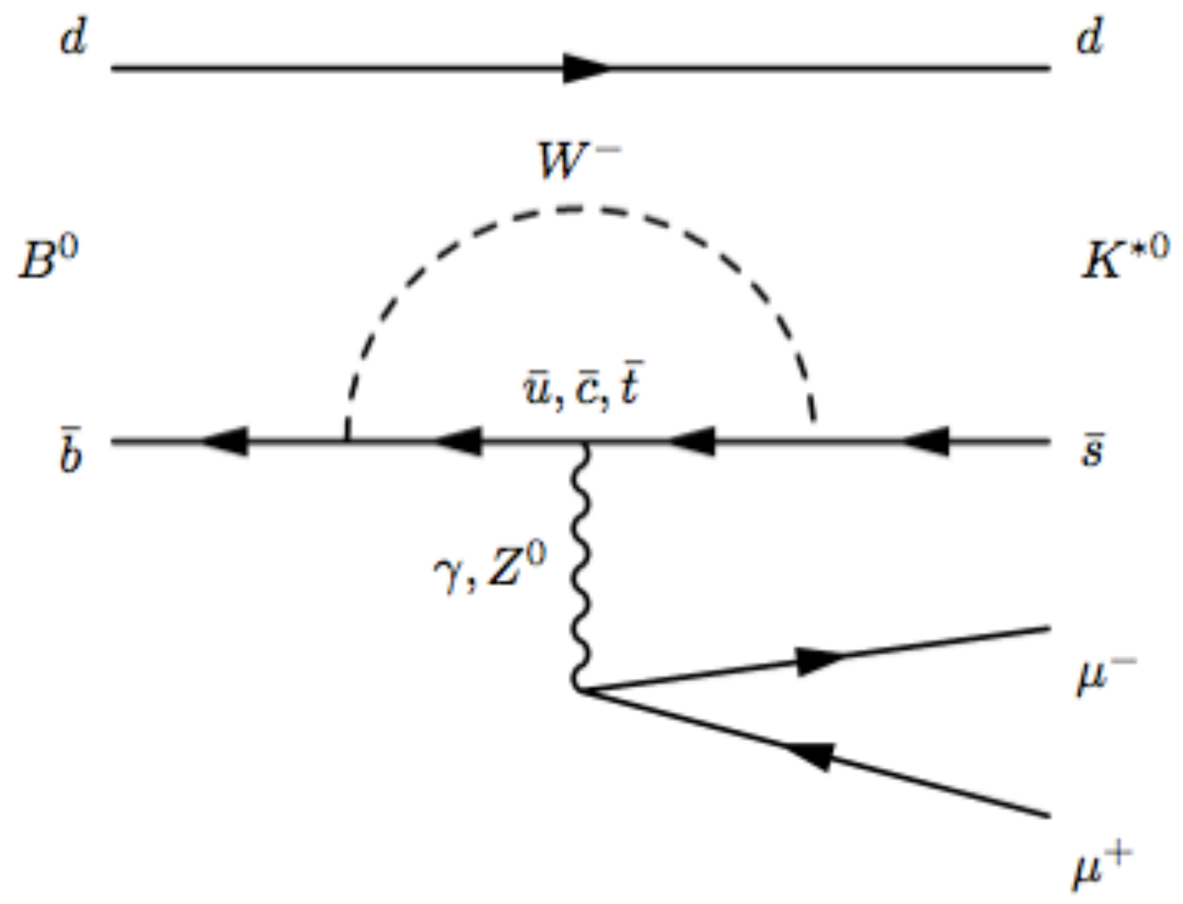
II. $B^+ \to K^+\nu\bar{\nu}$ **excess at Belle II**

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

see also Yue-hong Xie's talk

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





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

  $\Longrightarrow$ **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

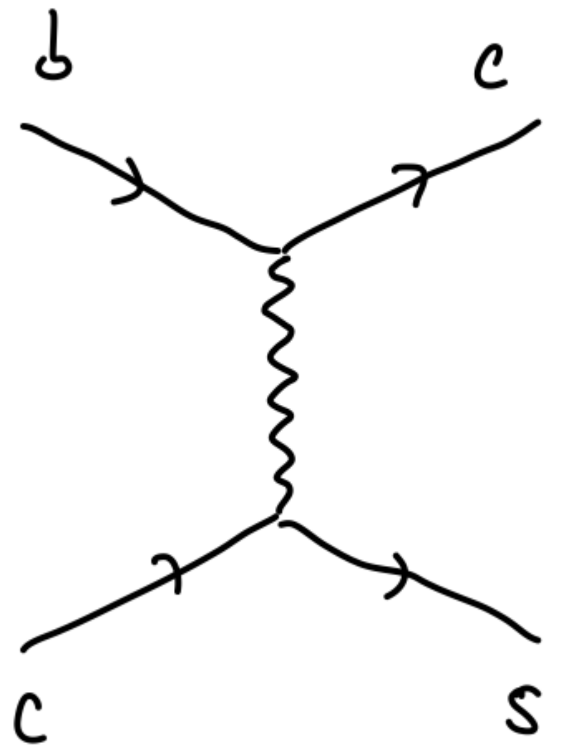
- **Effective Hamiltonian**

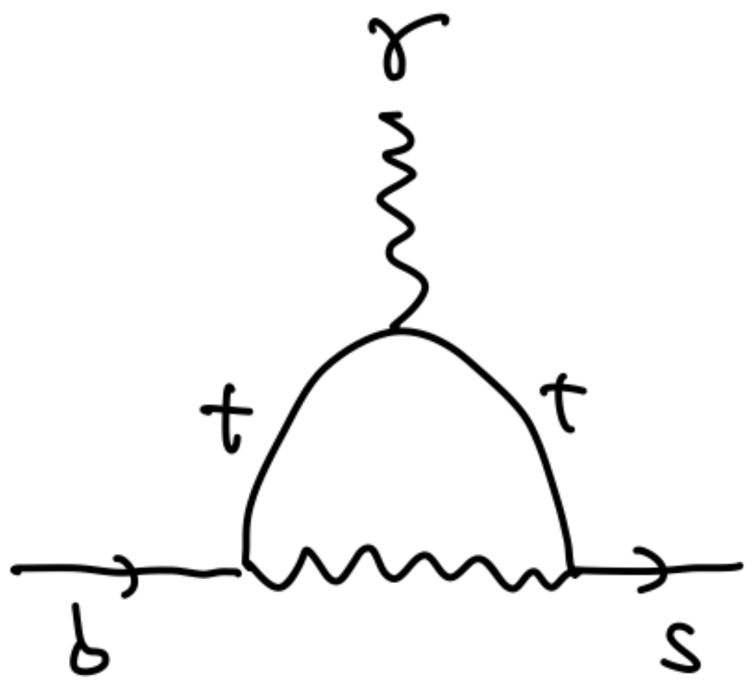
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \left(\sum_{i=1,\ldots,6} C_i O_i + C_{7\gamma} O_{7\gamma} + C_{8g} O_{8g} \sum_{\ell} \sum_{i=9,10,P,S} (C_i^\ell O_i^\ell + C_i'^\ell O_i'^\ell) \right)$$

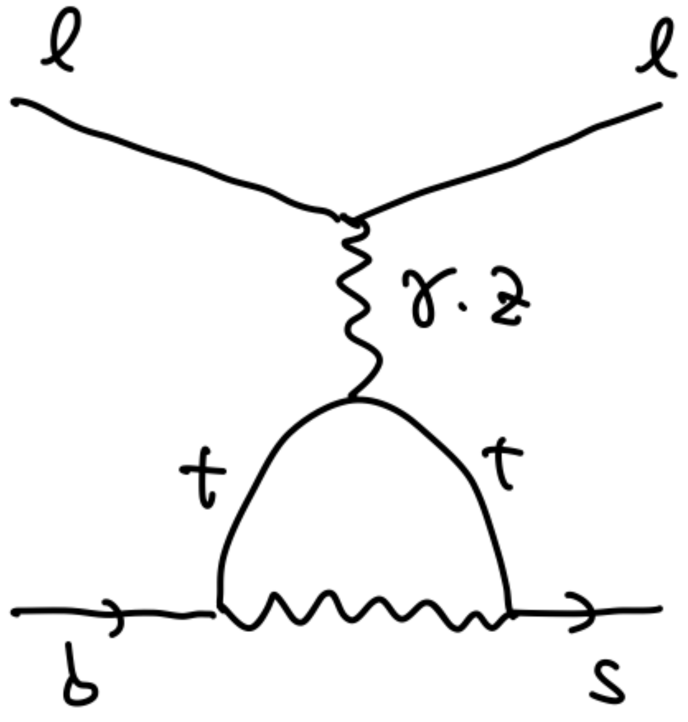
- **Effective operator**

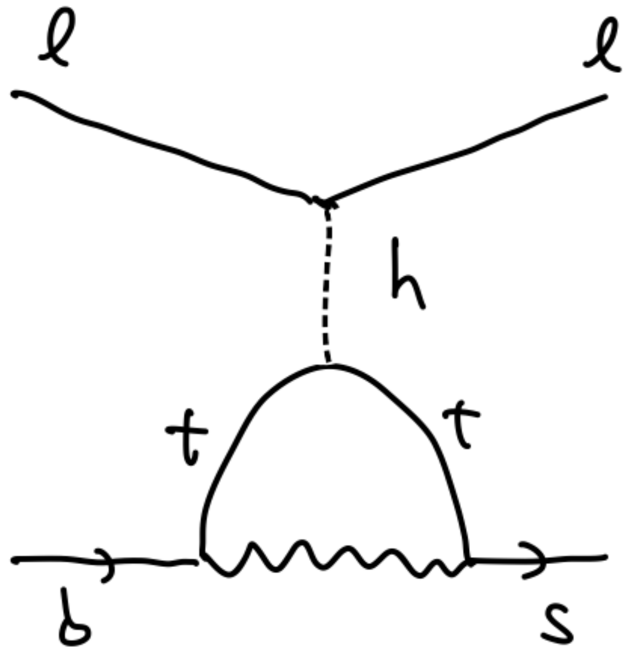
$$O_1 = (\bar{s}\gamma_\mu P_L T^a c)(\bar{c}\gamma^\mu P_L T^a b) \qquad O_7^{(\prime)} = \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}, \qquad O_9^{(\prime)\ell} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell), \qquad O_{10}^{(\prime)\ell} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu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

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









- **Feynman Diagram**

$b \to s\ell^+\ell^-$: 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 $B \to K\ell^+\ell^-$

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

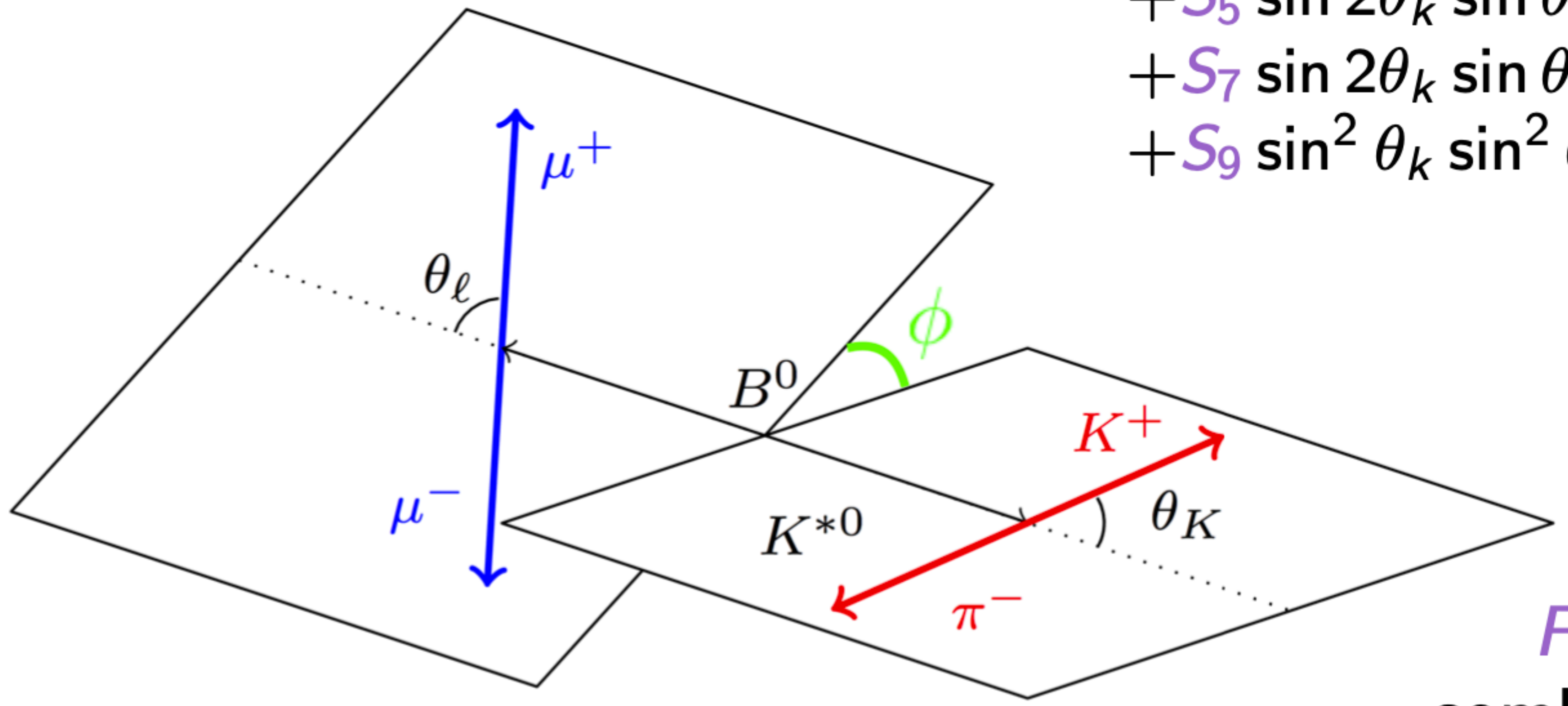
- $R_K^{\mathrm{SM}} \approx 1$
- **Hadronic uncertainties cancel**
- $\mathcal{O}(10^{-2})$ **QED correction**

deviation from unity

Physics beyond the SM

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

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



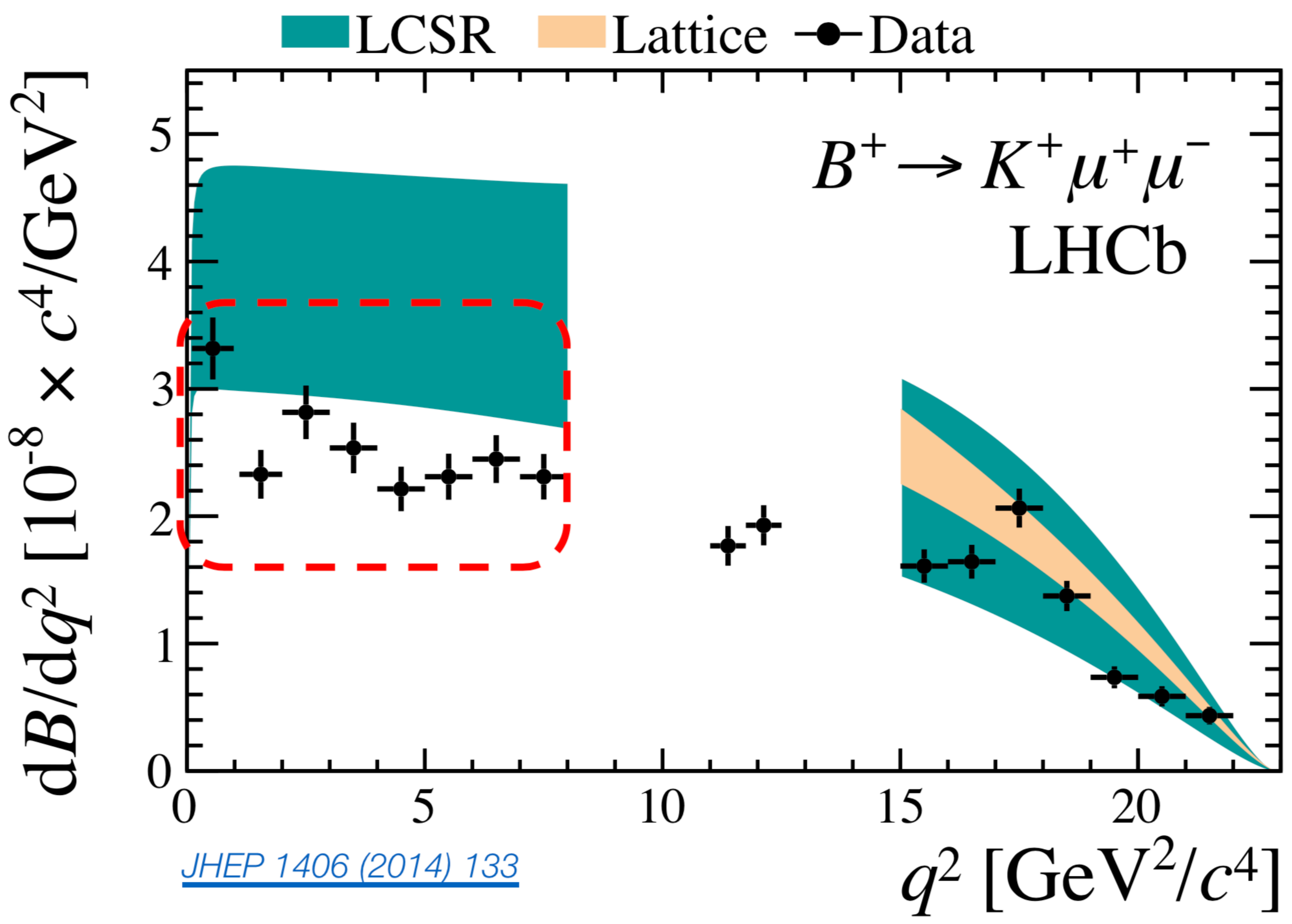
angular observables

$F_L,\ A_{FB},\ S_i = f(C_7, C_9, C_{10})$,

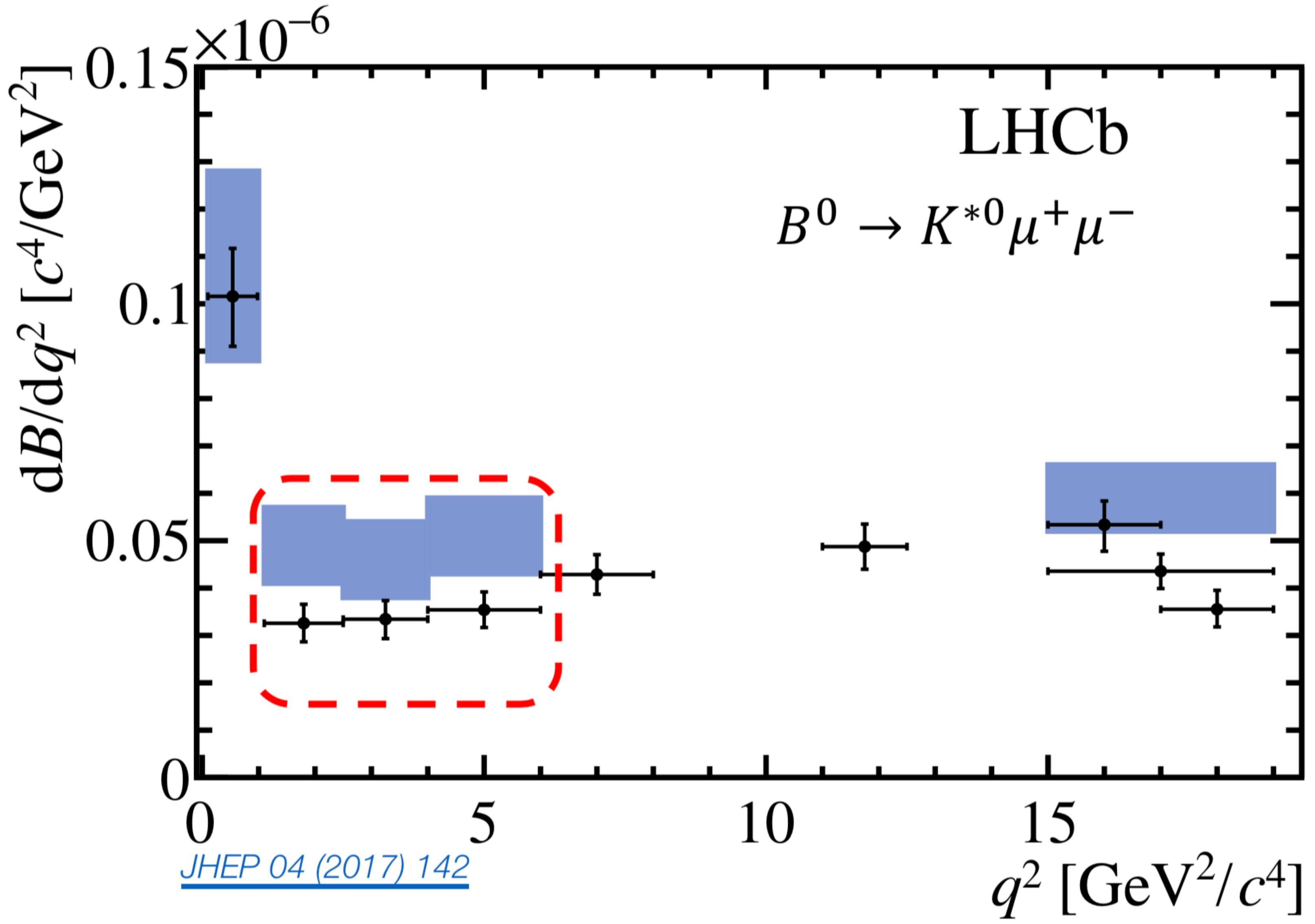
combinations of K^{*0} decay amplitudes

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

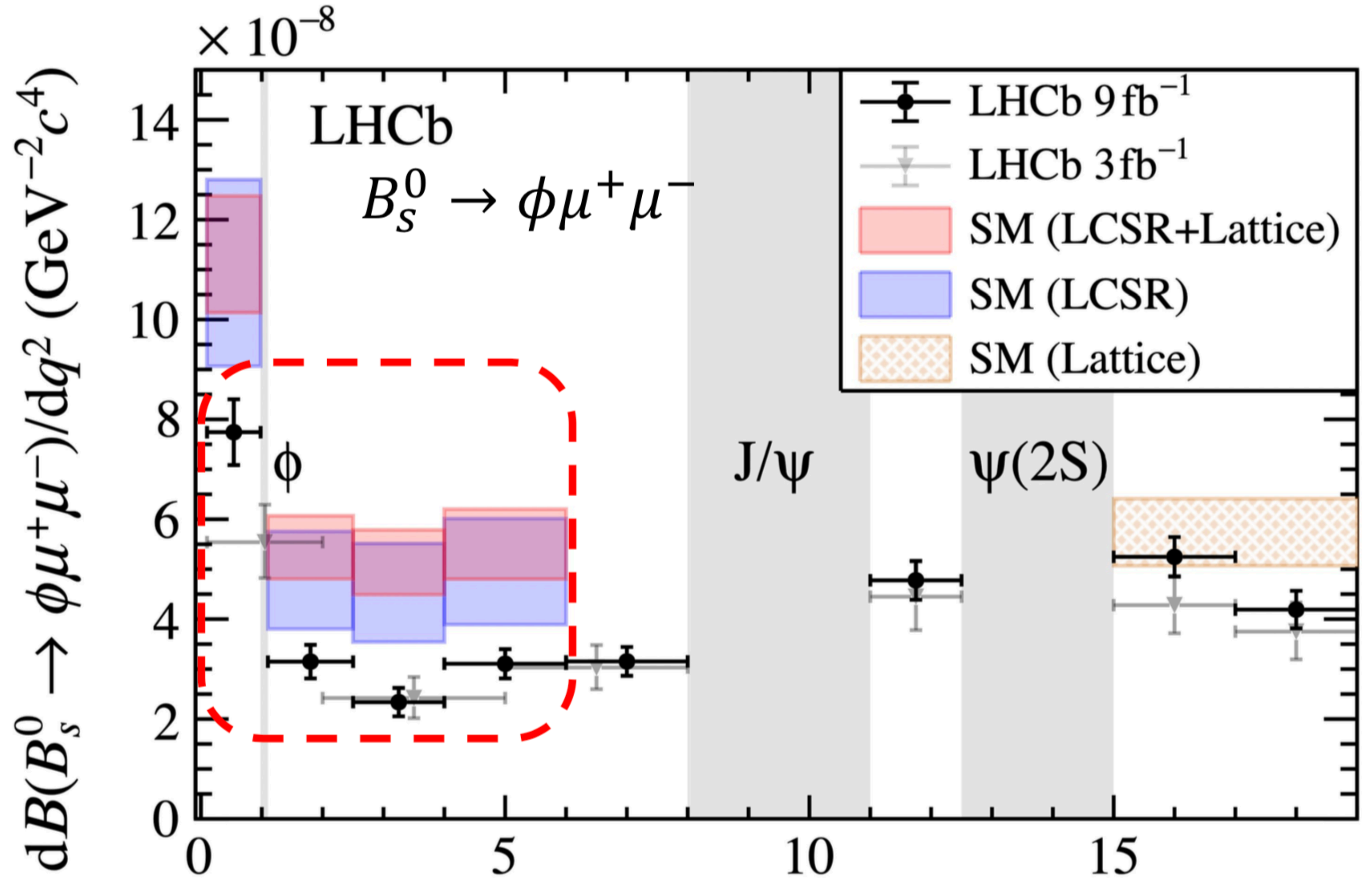
$b \to s\ell\ell$ anomalies@mid.2022: branching ratio



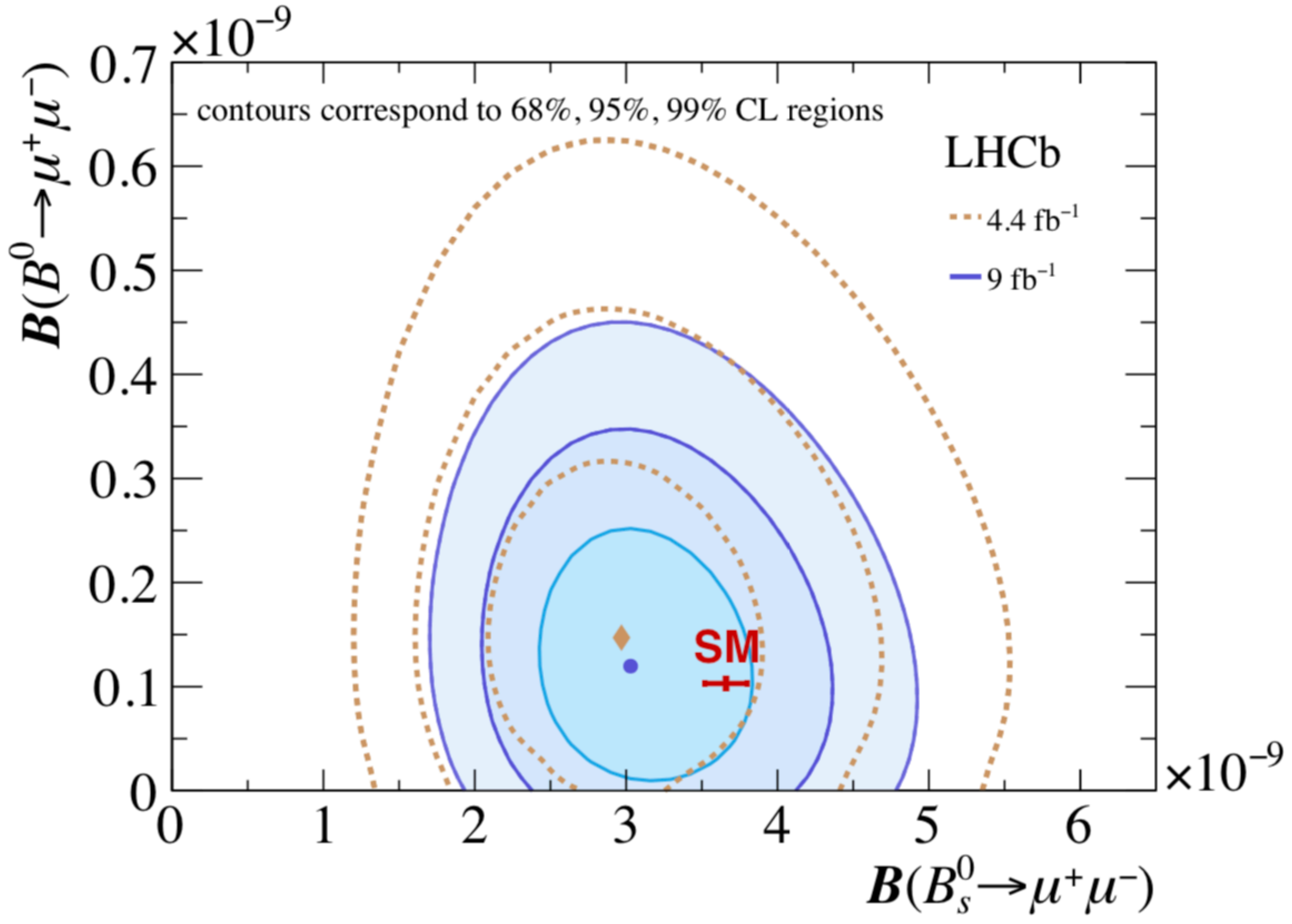
JHEP 1406 (2014) 133



JHEP 04 (2017) 142



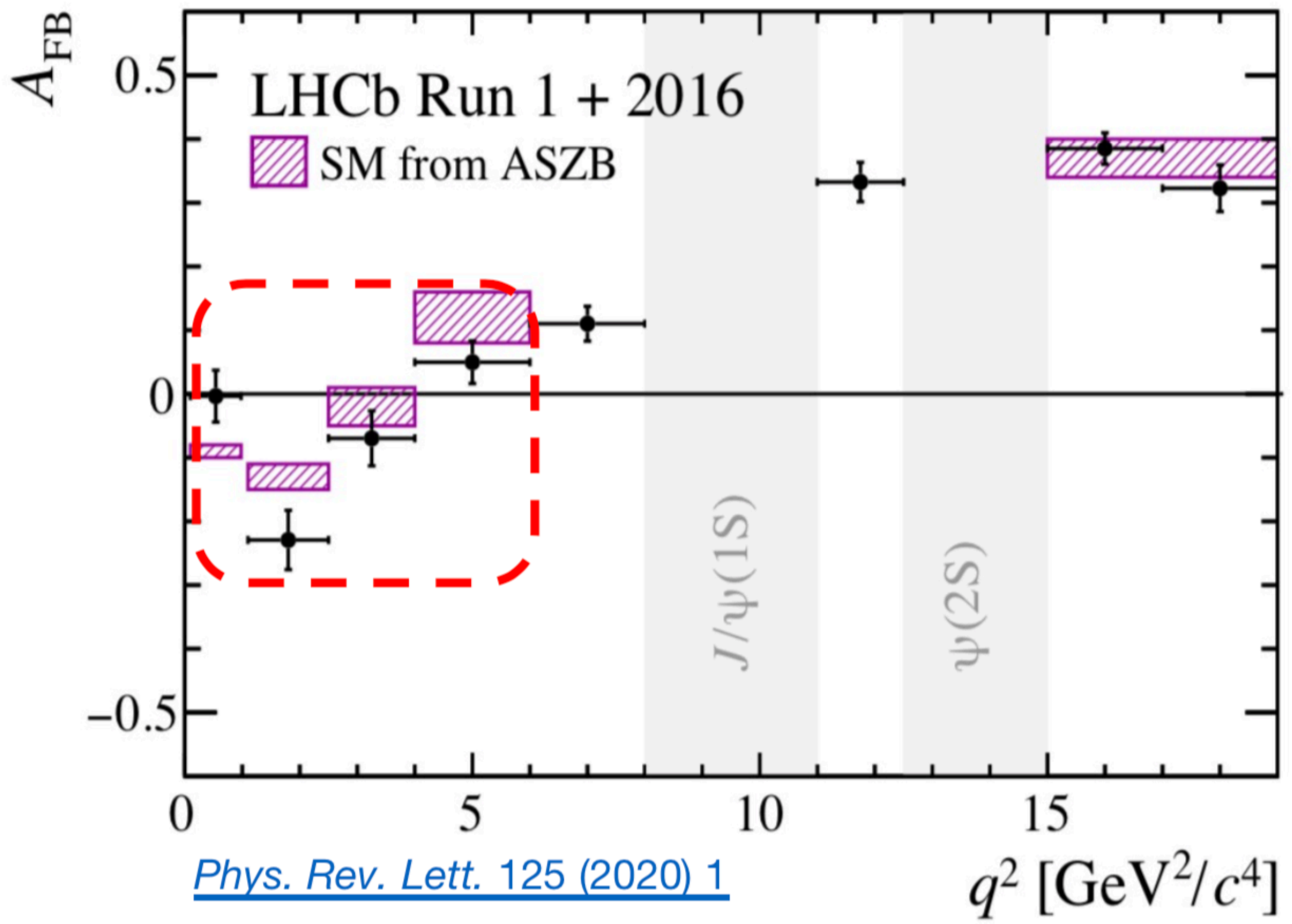
Phys. Rev. Lett. 127 (2021) 15



- **EXP below SM**
- **Low q^2**
- **Theoretical Uncertainties:** 😭

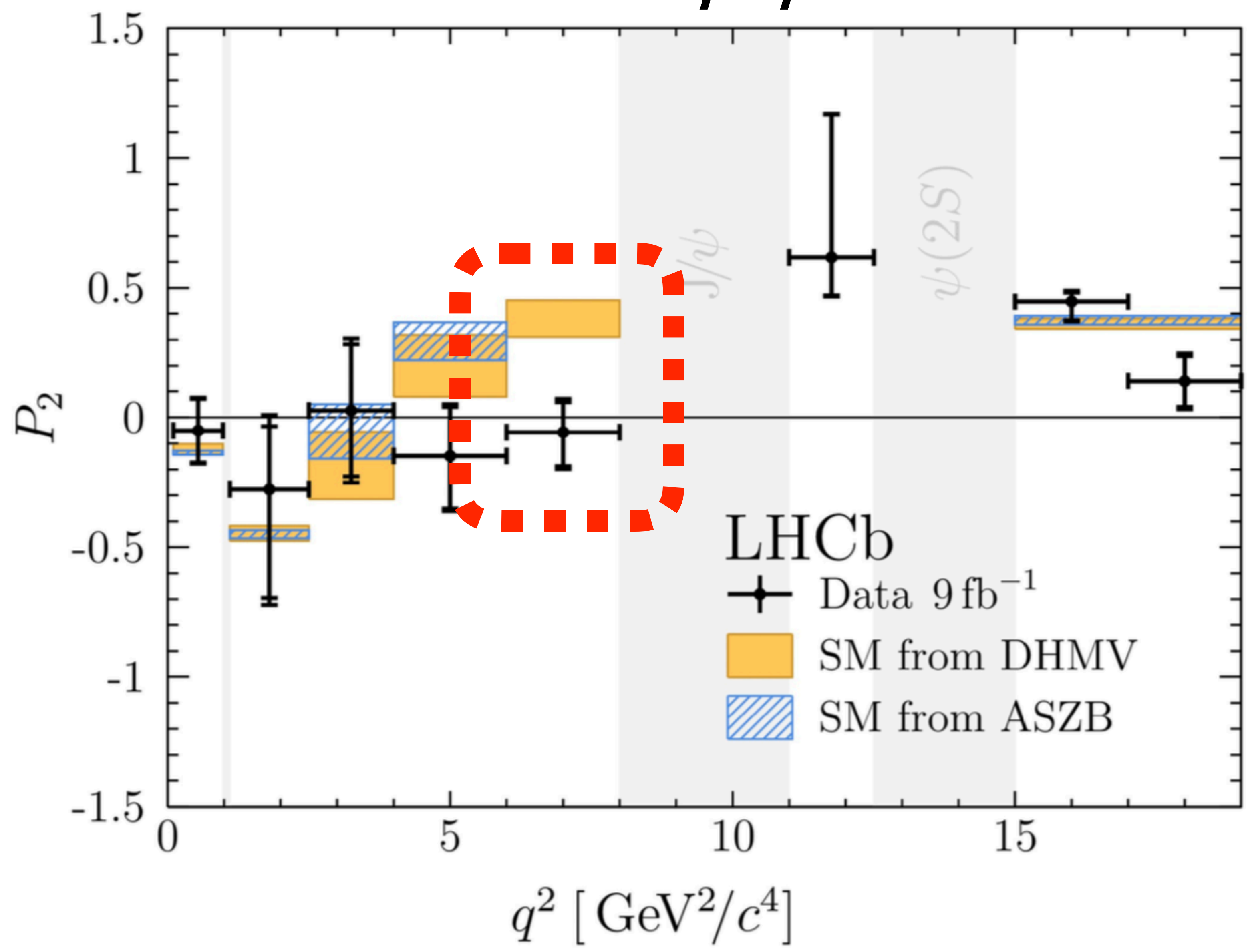
$b \to s\ell\ell$ anomalies@mid.2022: angular distribution

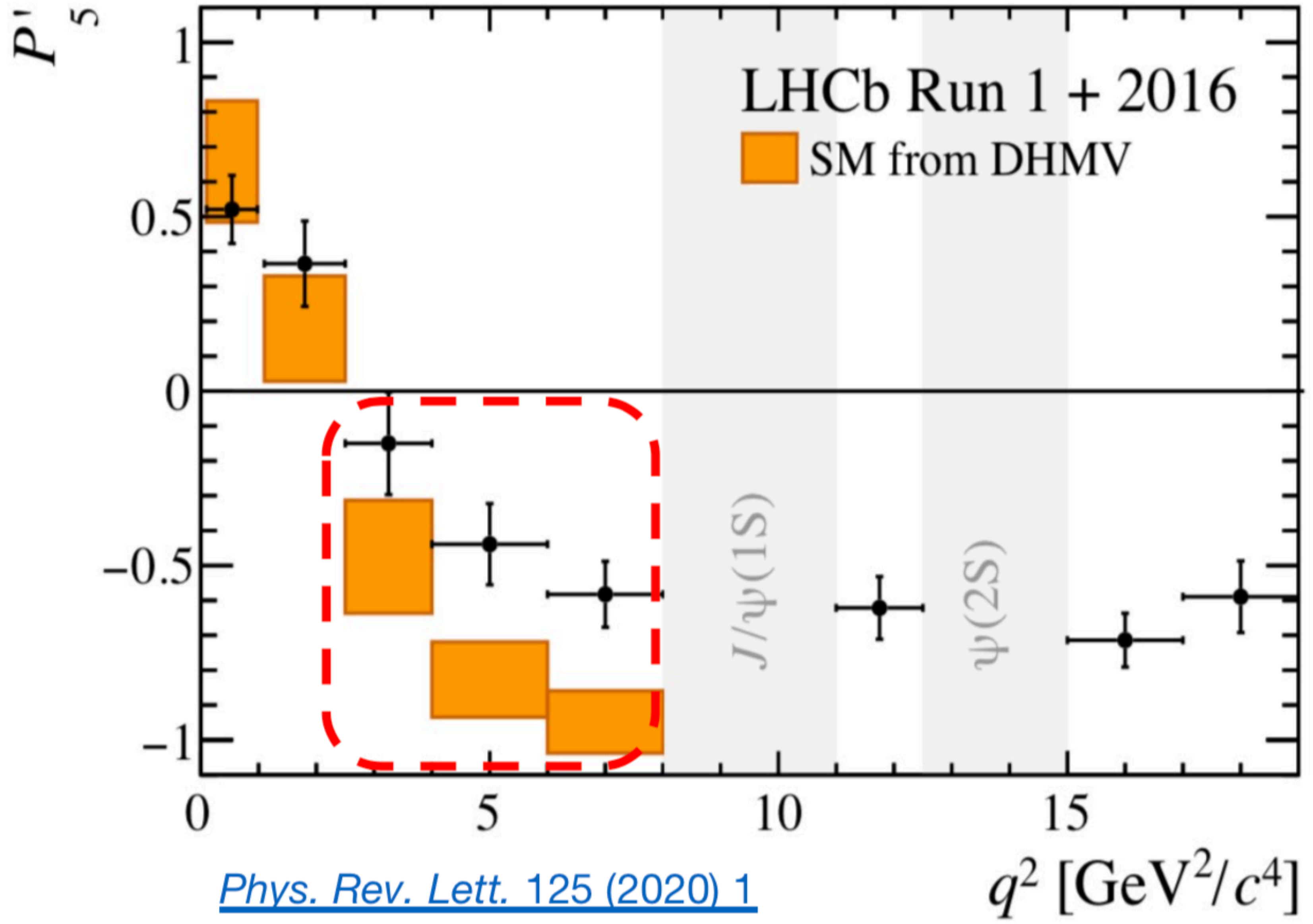
$B^0 \to K^{*0}\mu^+\mu^-$



Phys. Rev. Lett. 125 (2020) 1

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





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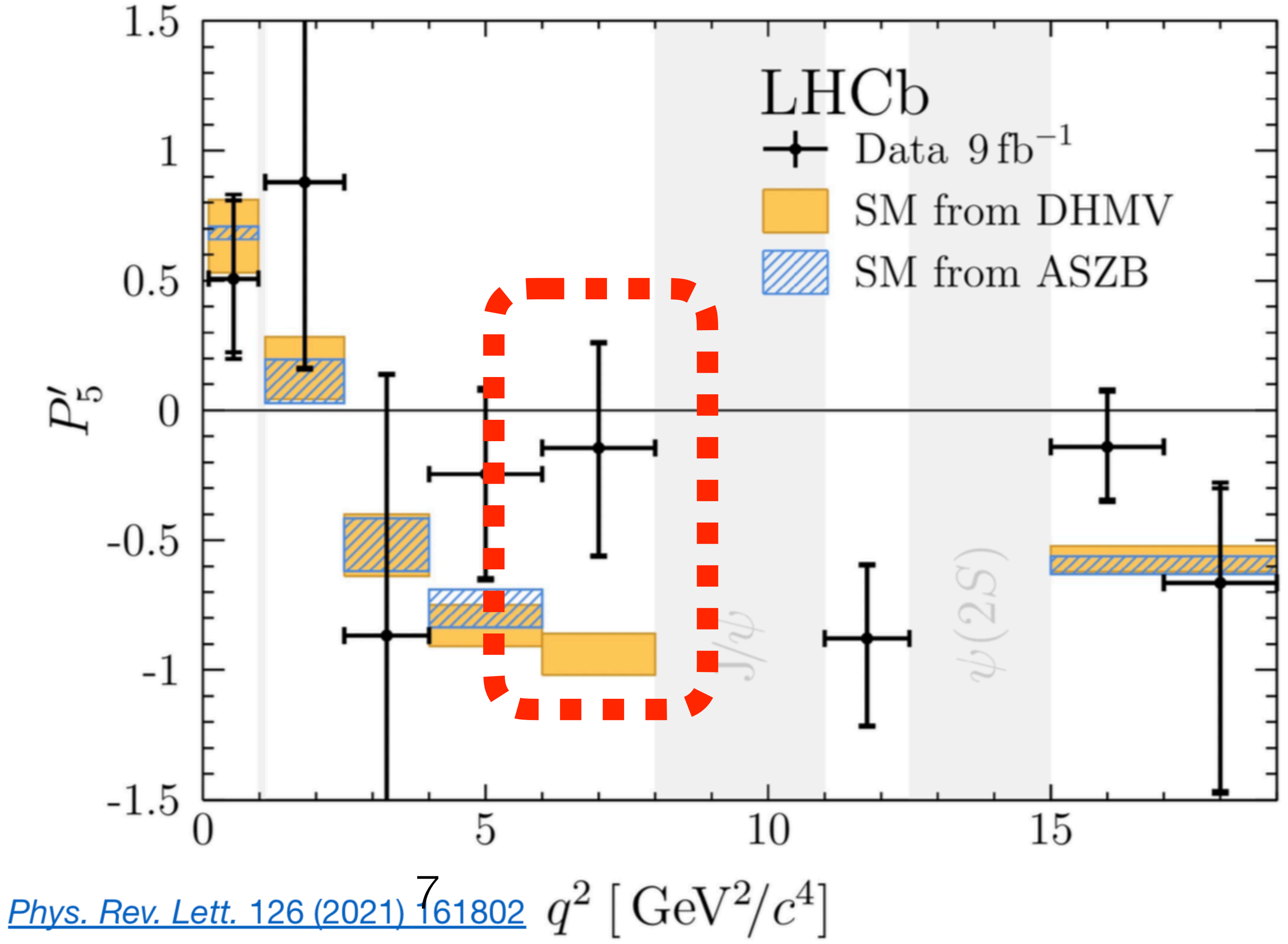
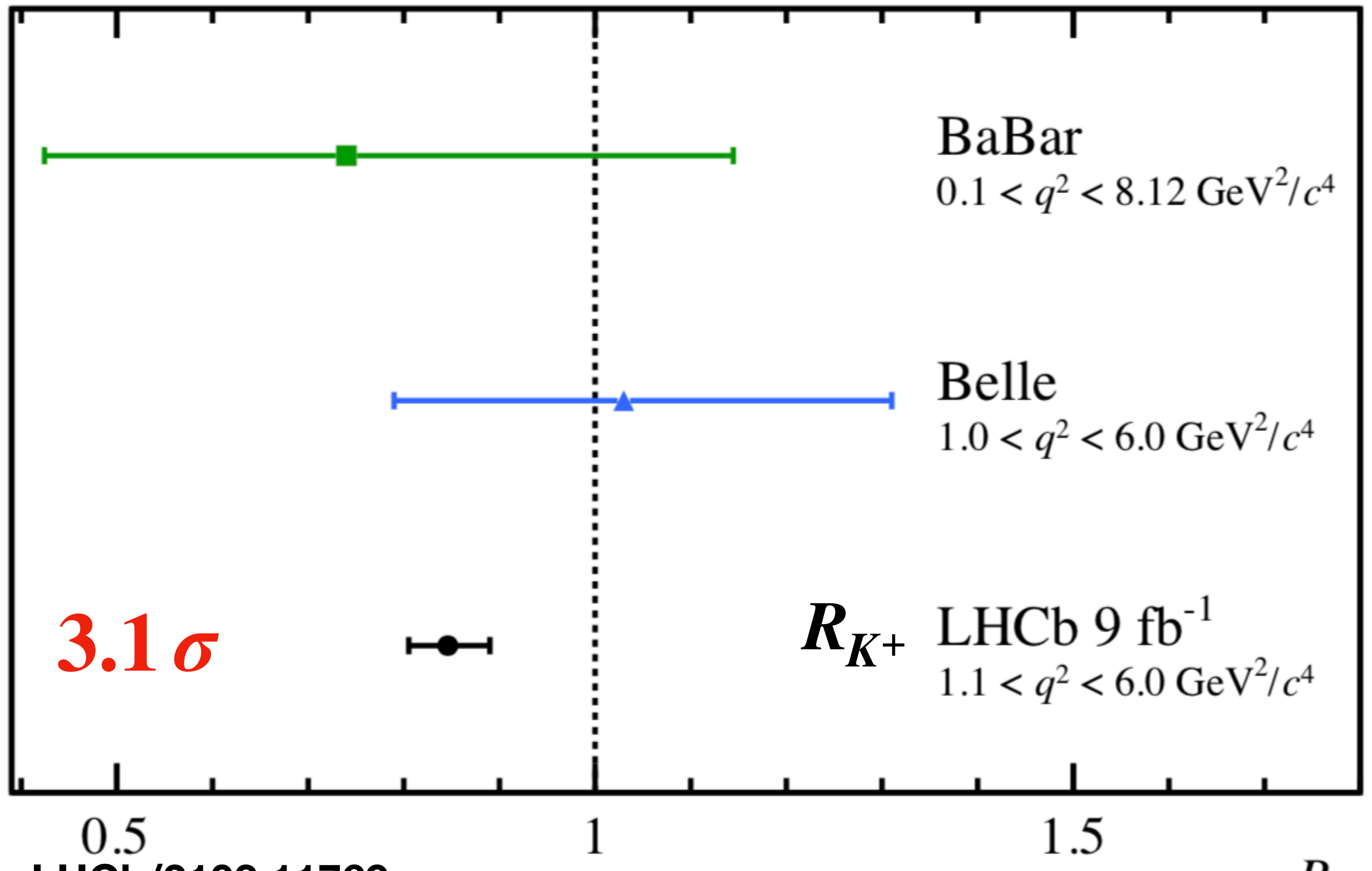


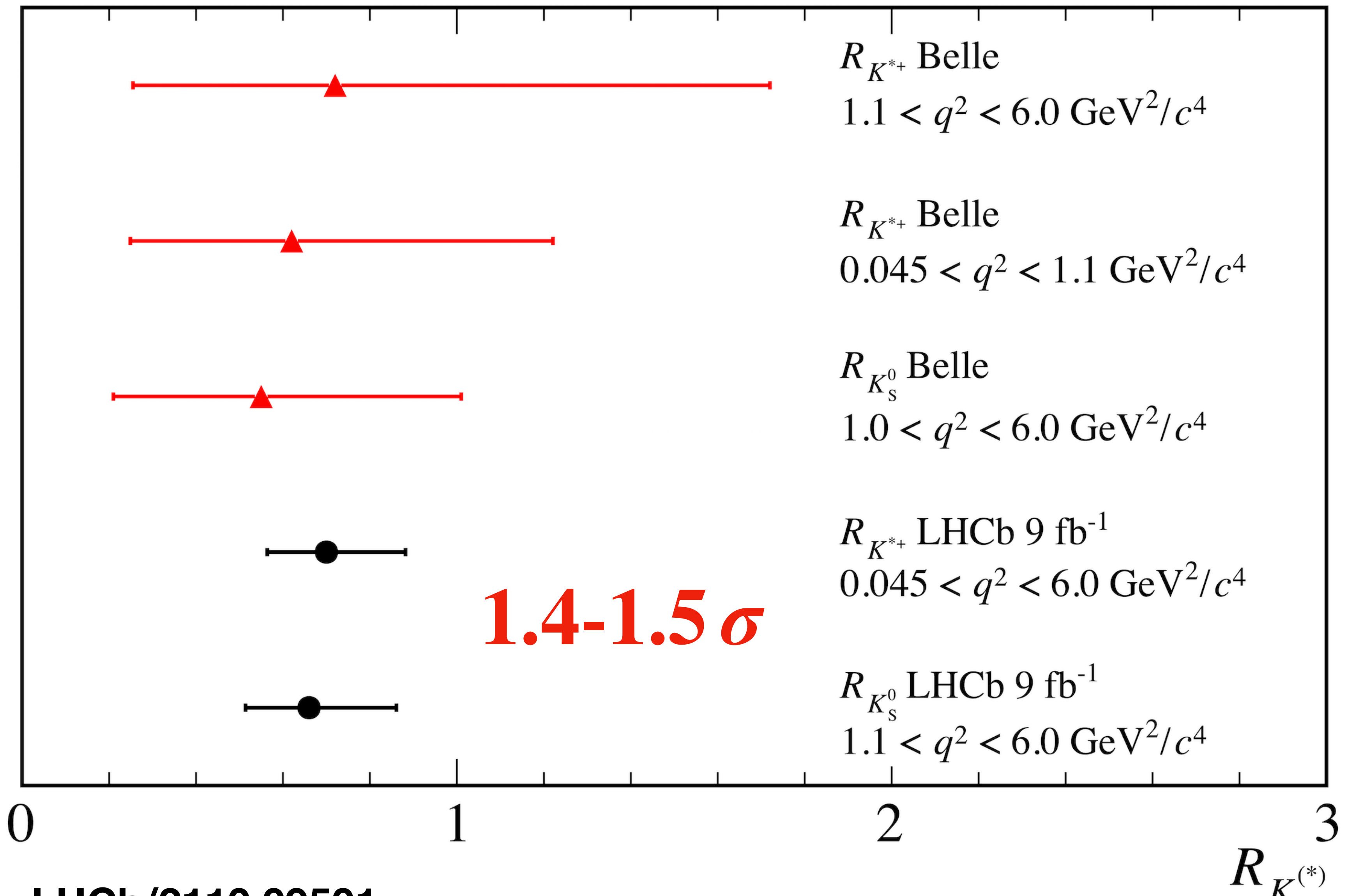
Phys. Rev. Lett. 126 (2021) 161802

- **Similar deviations in the 2 modes**
- **Theoretical Uncertainties:**
  - **branching ratio:** 😭
  - **angular distribution:** 😢

$b \to s\ell\ell$ anomalies@mid.2022: lepton flavour universality ratio



LHCb/2103.11769



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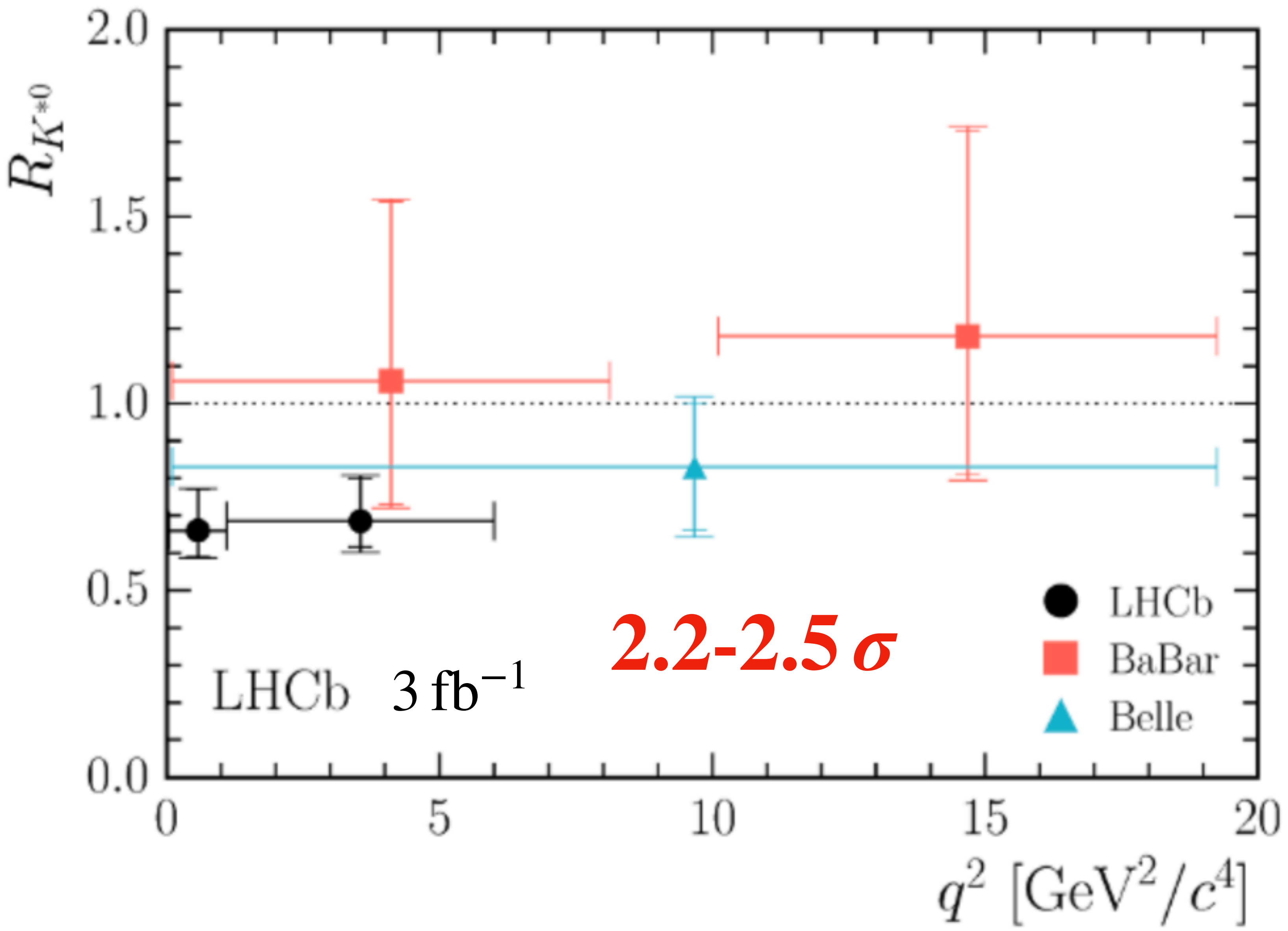
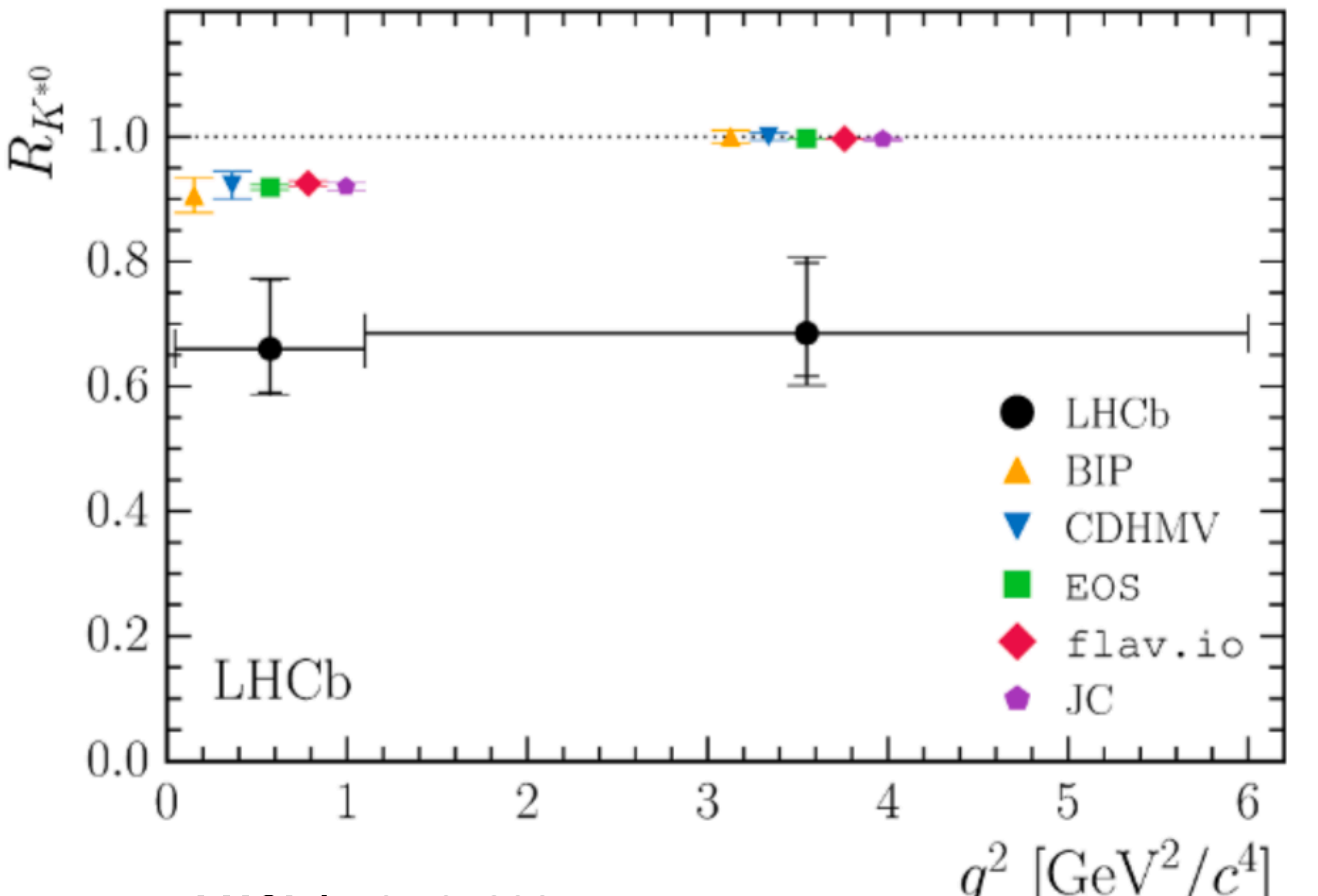




LHCb/1705.05802

$$R_{K^+} = \frac{\mathfrak{B}(B^+ \to K^+\mu^+\mu^-)}{\mathfrak{B}(B^+ \to K^+e^+e^-)}$$

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

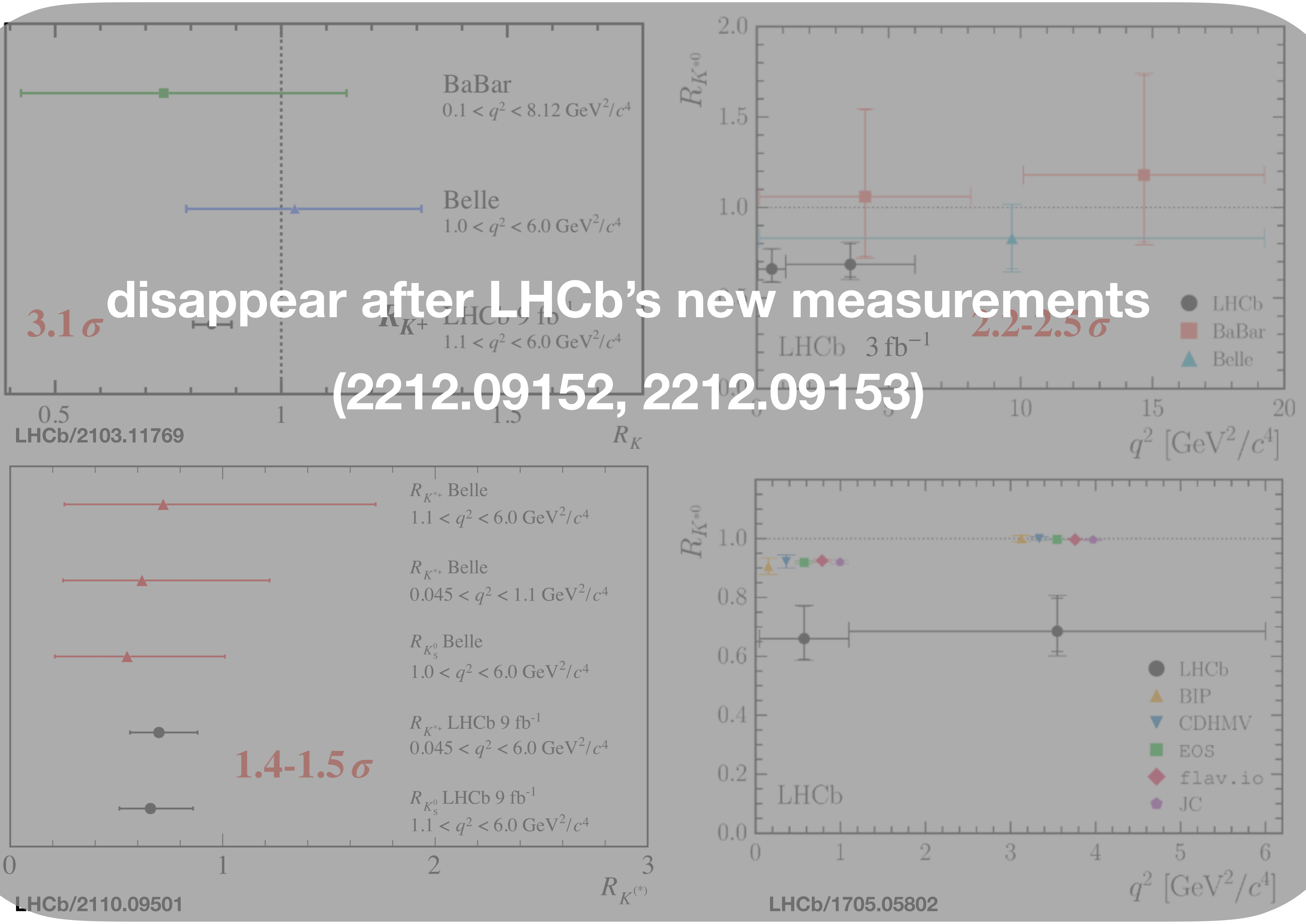
- **Theoretical Uncertainties:**
  - **branching ratio:** 😭
  - **angular distribution:** 😢
  - **LFV ratio:** 😀

deviation from unity

⬇

Physics beyond the SM

$b \to s\ell\ell$ anomalies@mid.2022: lepton flavour universality ratio



LHCb/2103.11769

LHCb/2110.09501

LHCb/1705.05802

disappear after LHCb's new measurements (2212.09152, 2212.09153)

$$R_{K^+} = \frac{\mathfrak{B}(B^+ \to K^+\mu^+\mu^-)}{\mathfrak{B}(B^+ \to K^+e^+e^-)}$$

- $R_H^{SM} \approx 1$
- Hadronic uncertainties cancel
- $\mathcal{O}(10^{-2})$ QED correction
- Theoretical Uncertainties:
  - branching ratio: 😭
  - angular distribution: 😢
  - LFV ratio: 😀

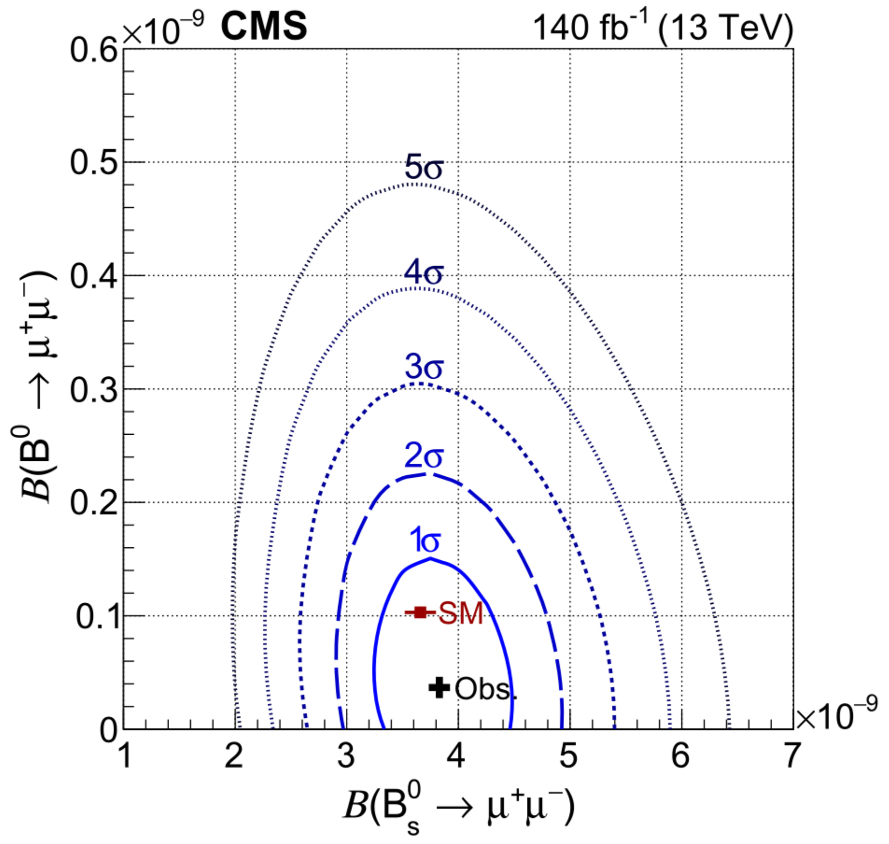
deviation from unity

⬇

Physics beyond the SM

$b \to s\ell\ell$ anomalies@2023

▶ **New CMS measurements on $B_s \to \mu^+\mu^-$** (axXiv: 2212.10311)

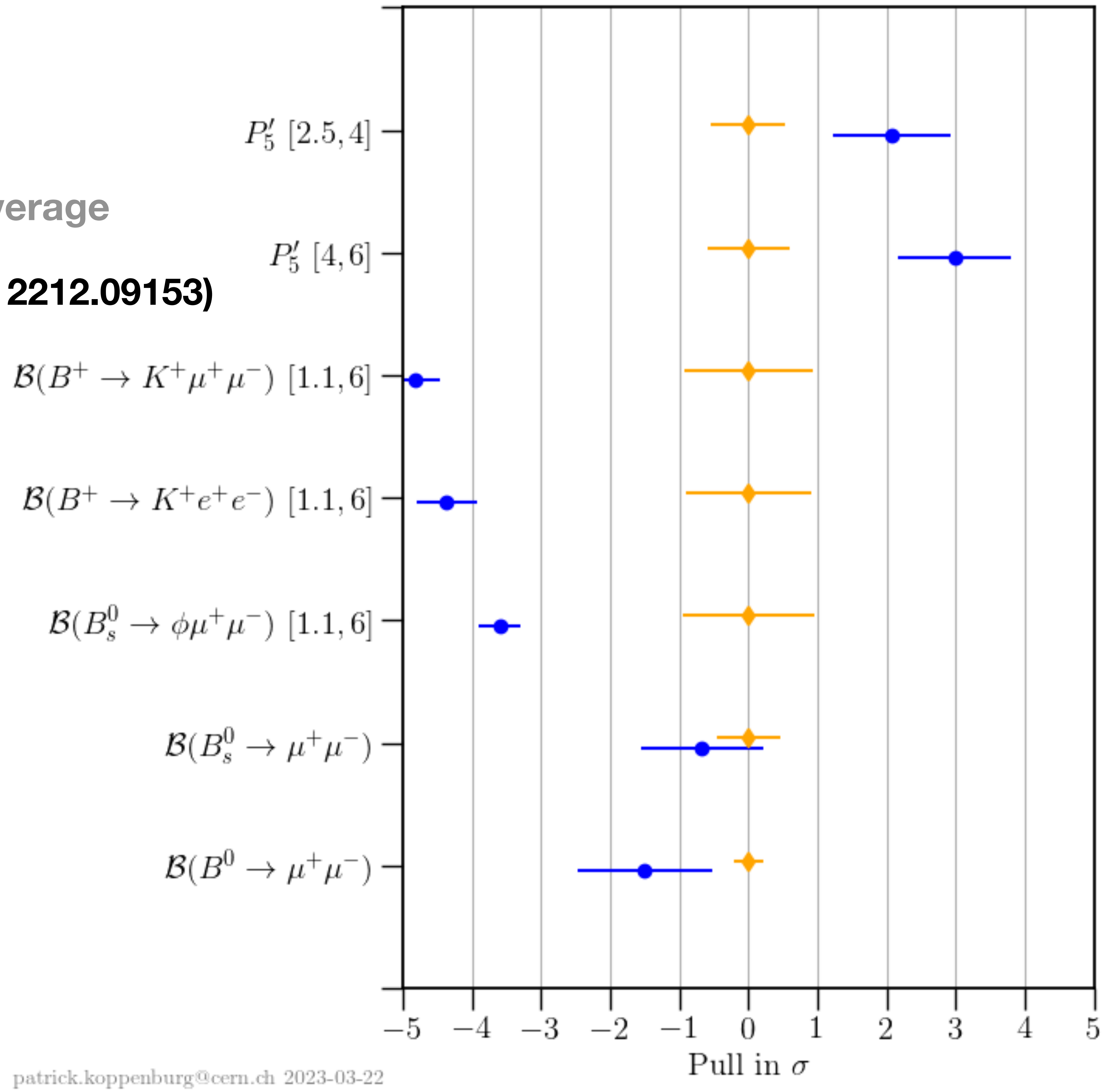


$$\mathcal{B}(B_s \to \mu^+\mu^-)_{\rm ATLAS} = (2.8^{+0.8}_{-0.7}) \times 10^{-9},$$
$$\mathcal{B}(B_s \to \mu^+\mu^-)_{\rm LHCb} = (3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9},$$
$$\mathcal{B}(B_s \to \mu^+\mu^-)_{\rm CMS} = (3.83^{+0.38+0.19+0.14}_{-0.36-0.16-0.13}) \times 10^{-9}.$$

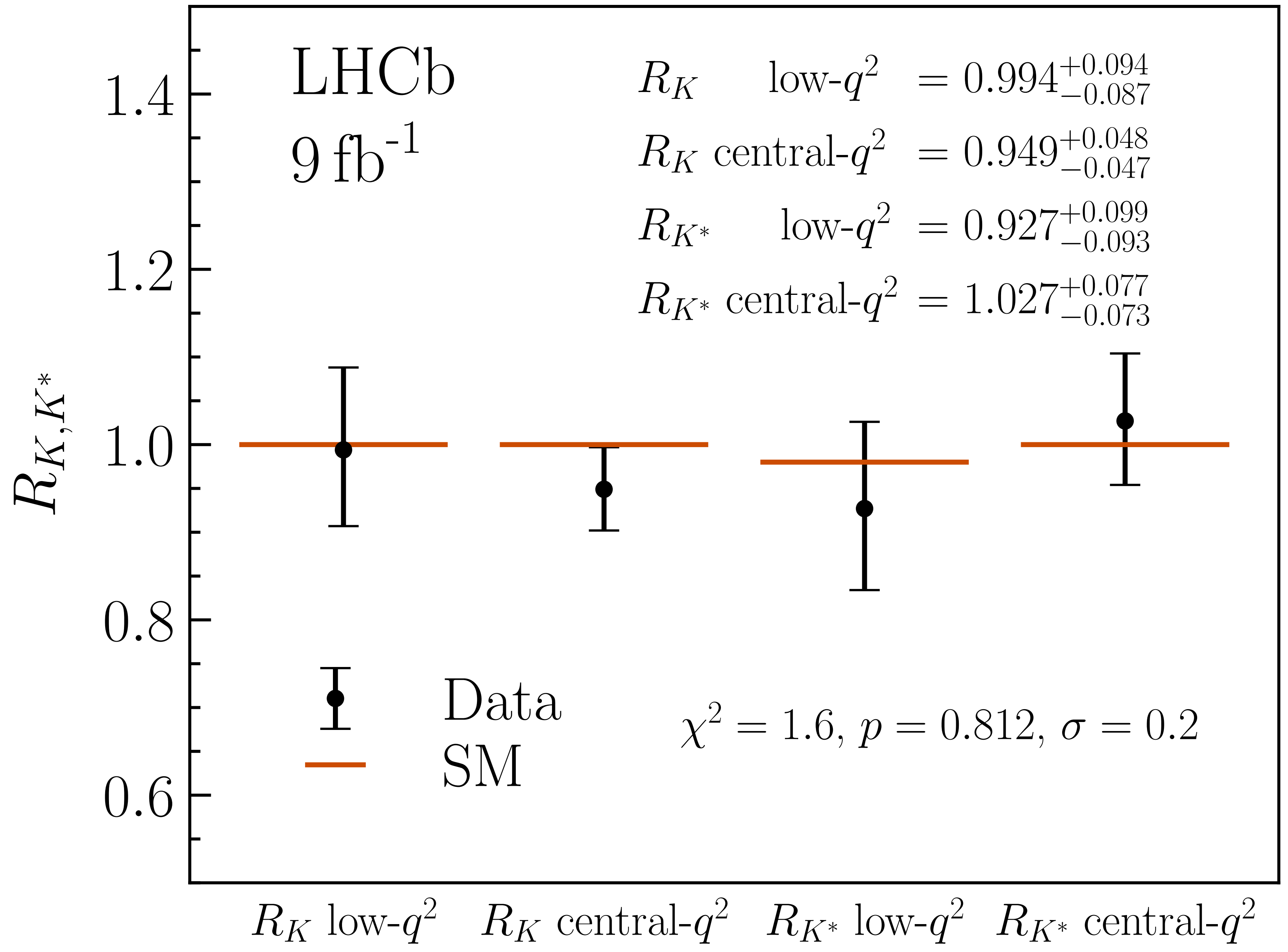
$$\mathcal{B}(B_s \to \mu^+\mu^-)_{\rm avg} = (3.52^{+0.32}_{-0.30}) \times 10^{-9}$$
$$\mathcal{B}(B_s \to \mu^+\mu^-)_{\rm SM} = (3.66 \pm 0.14) \times 10^{-9}$$

$$\mathcal{B}(B_s \to \mu^+\mu^-)_{\rm avg} = (2.93 \pm 0.35) \times 10^{-9}$$ old average

remaining discrepancies in $b \to s\ell^+\ell^-$



▶ **New LHCb measurements on R_K and R_{K^*}** (axXiv: 2212.09152, 2212.09153)



all consistent with SM

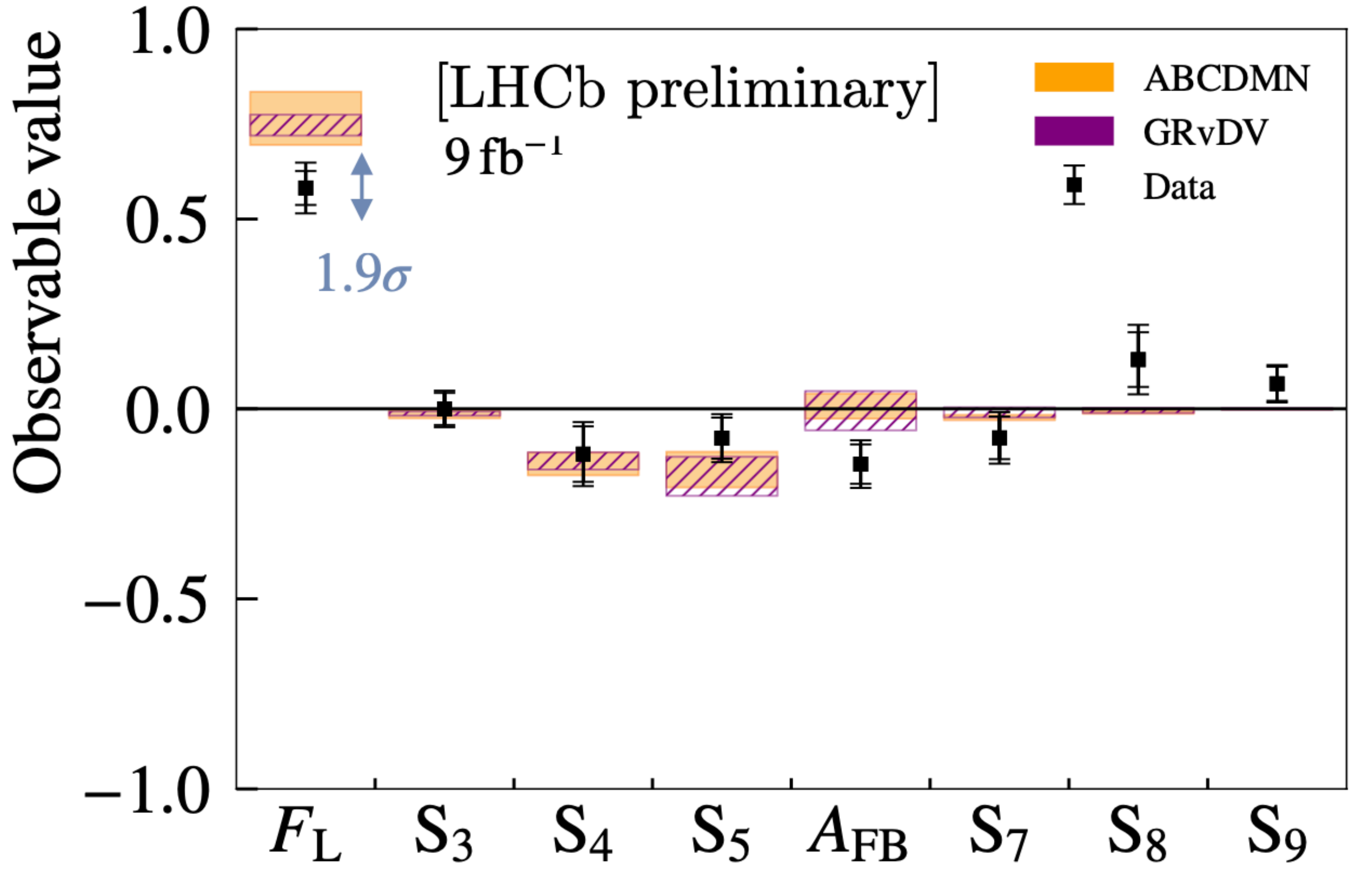
R_K and R_{K^*} anomaly disappear

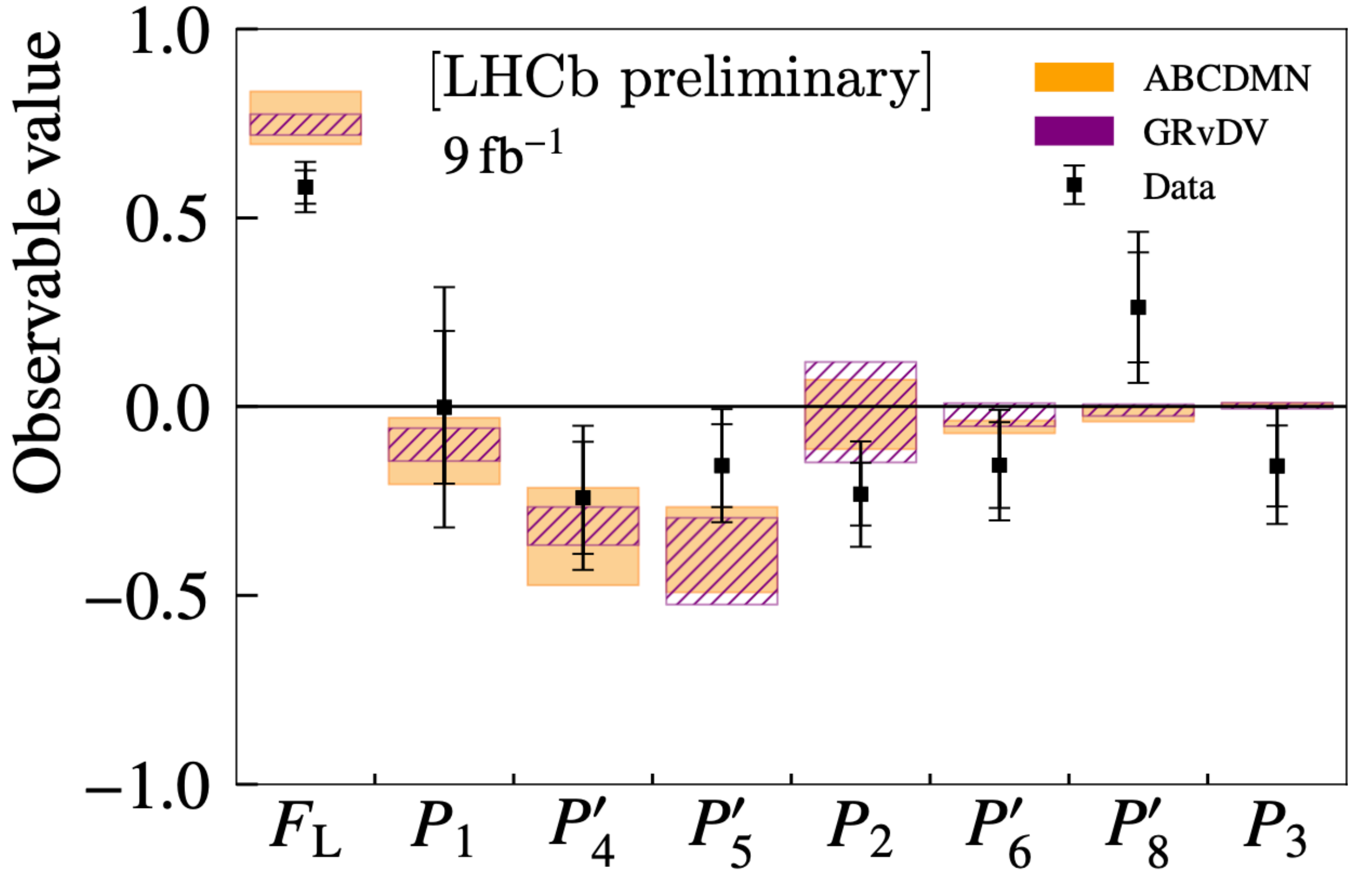
$b \to s\ell\ell$ anomalies@mid.2024

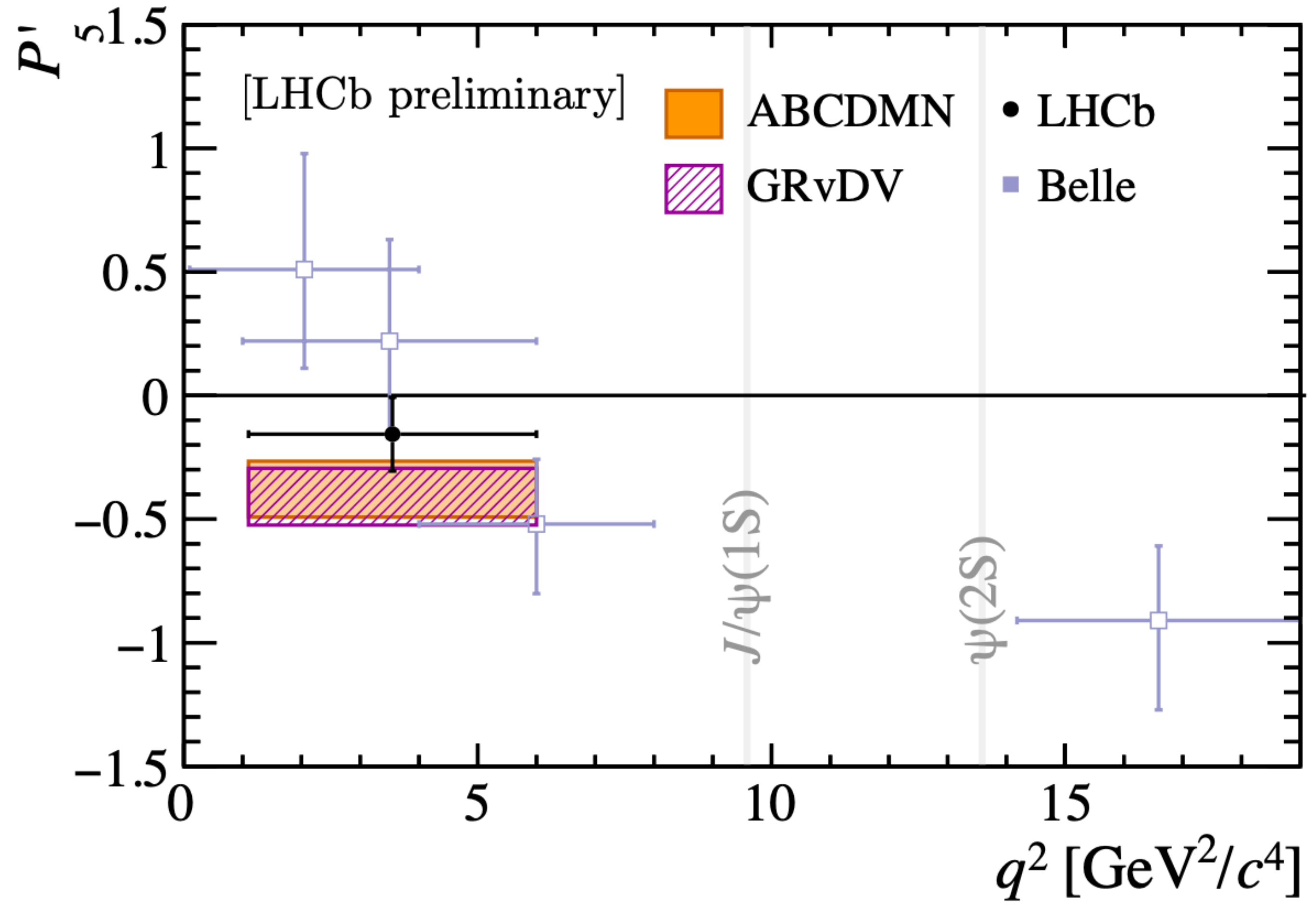
▶ Angular analysis of $B^0 \to K^{*0}e^+e^-$ at LHCb

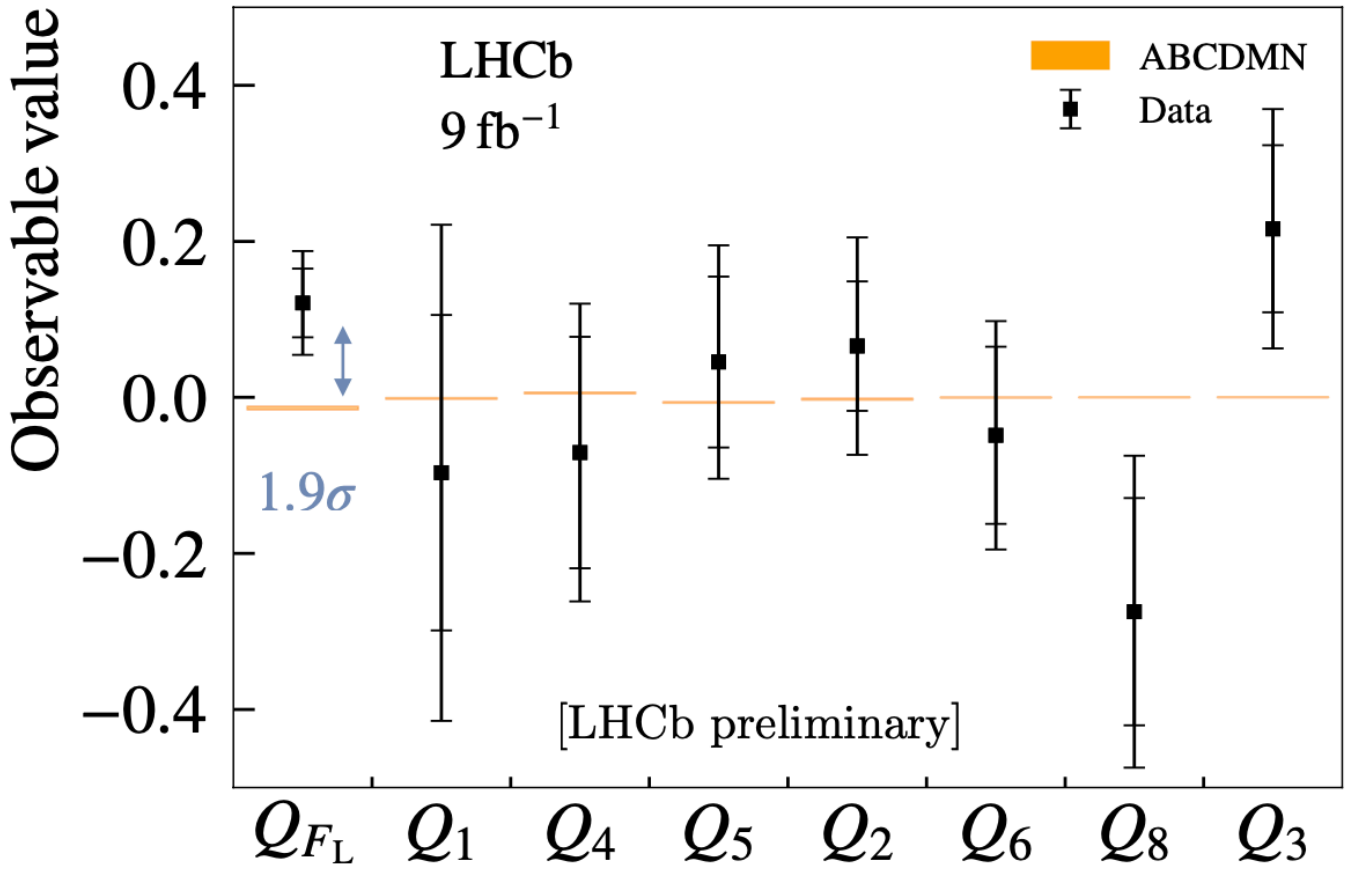
LHCb-Paper-2024-022
R.S.Coutinho's talk@ICHEP

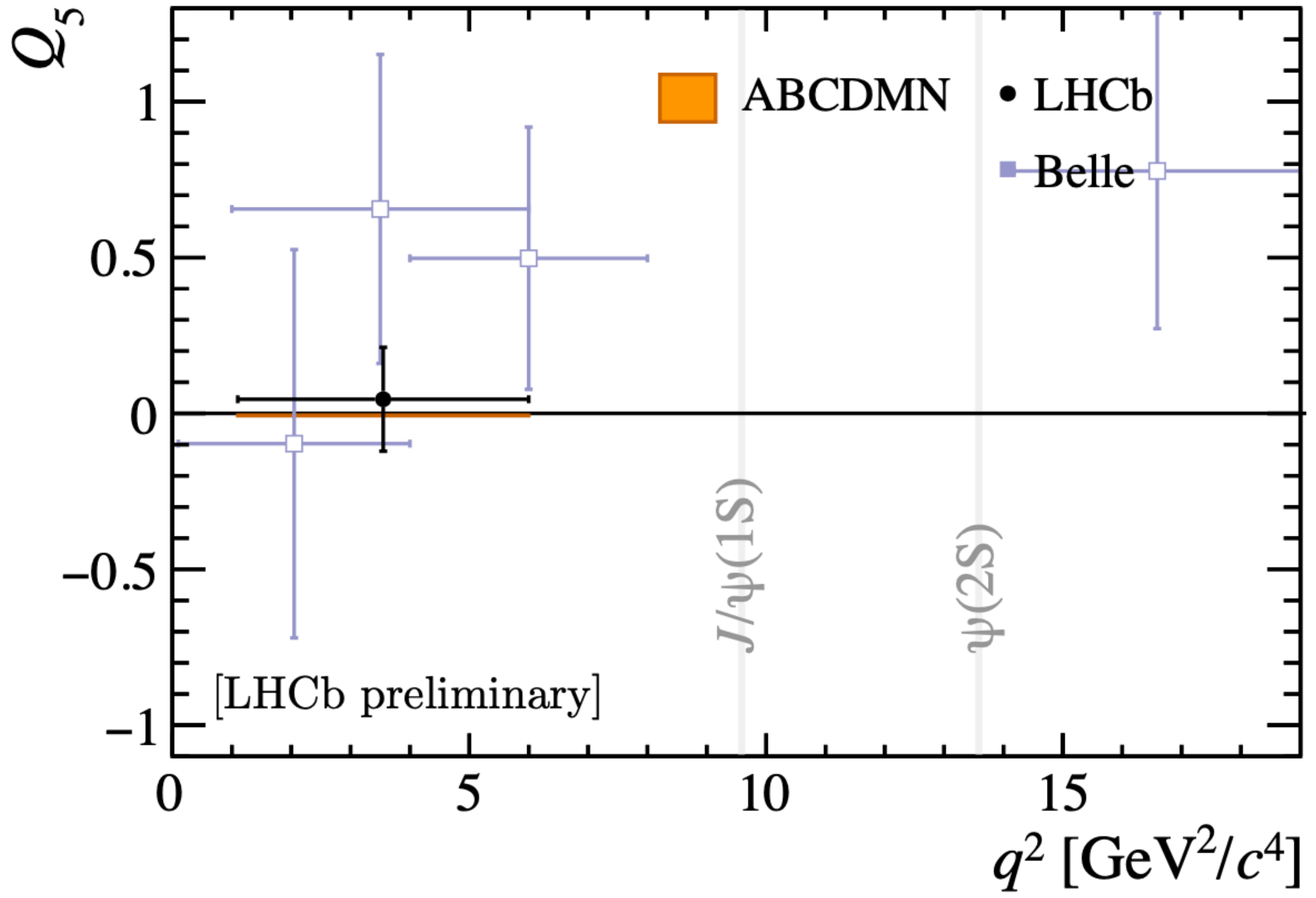
- Based on full Run I + II data
- Performed in $[1.1, 6.0\,(7.0)]\,\mathrm{GeV}^2$ region
- $Q_i = P_i^{(\mu)} - P_i^{(e)}$
- All consistent with SM





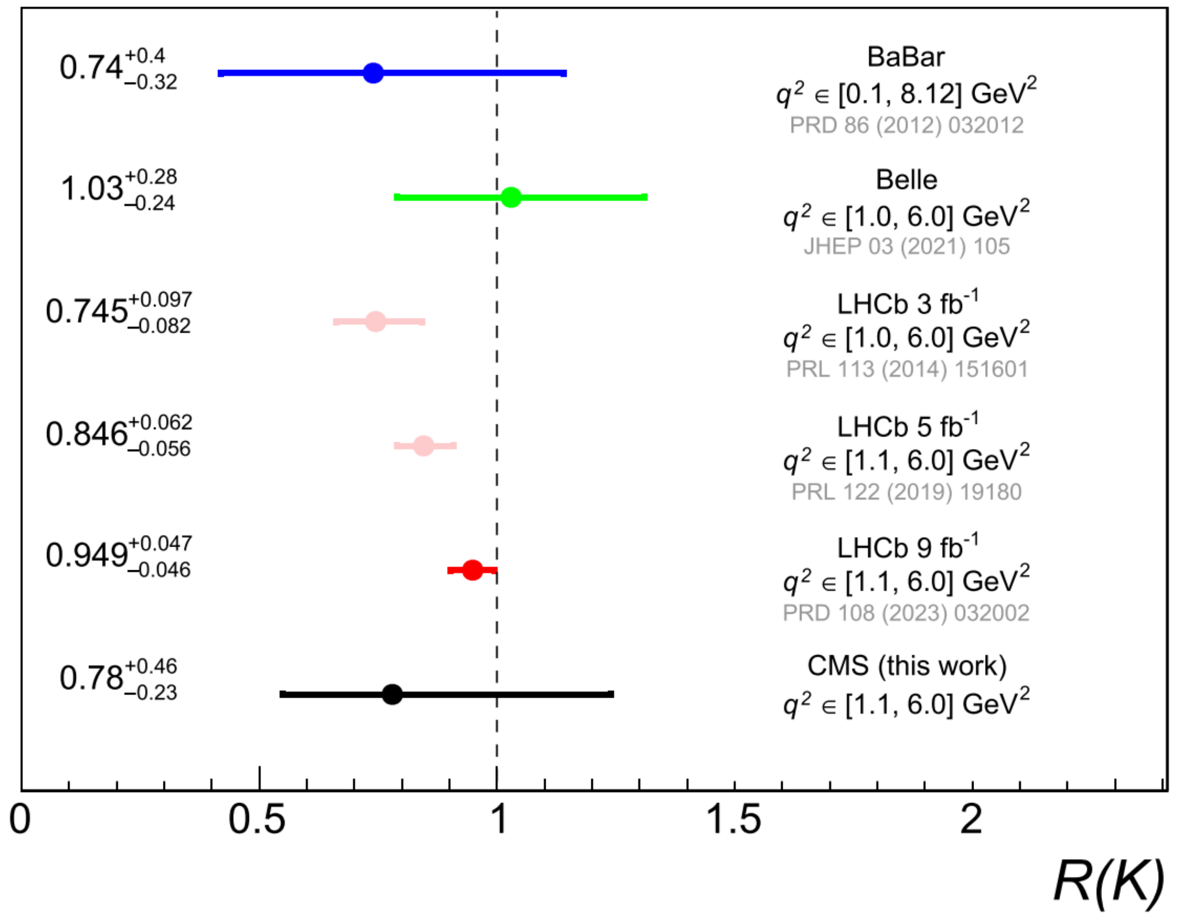






▶ R_K at CMS

Rep. Prog. Phys. 87 (2024) 077802



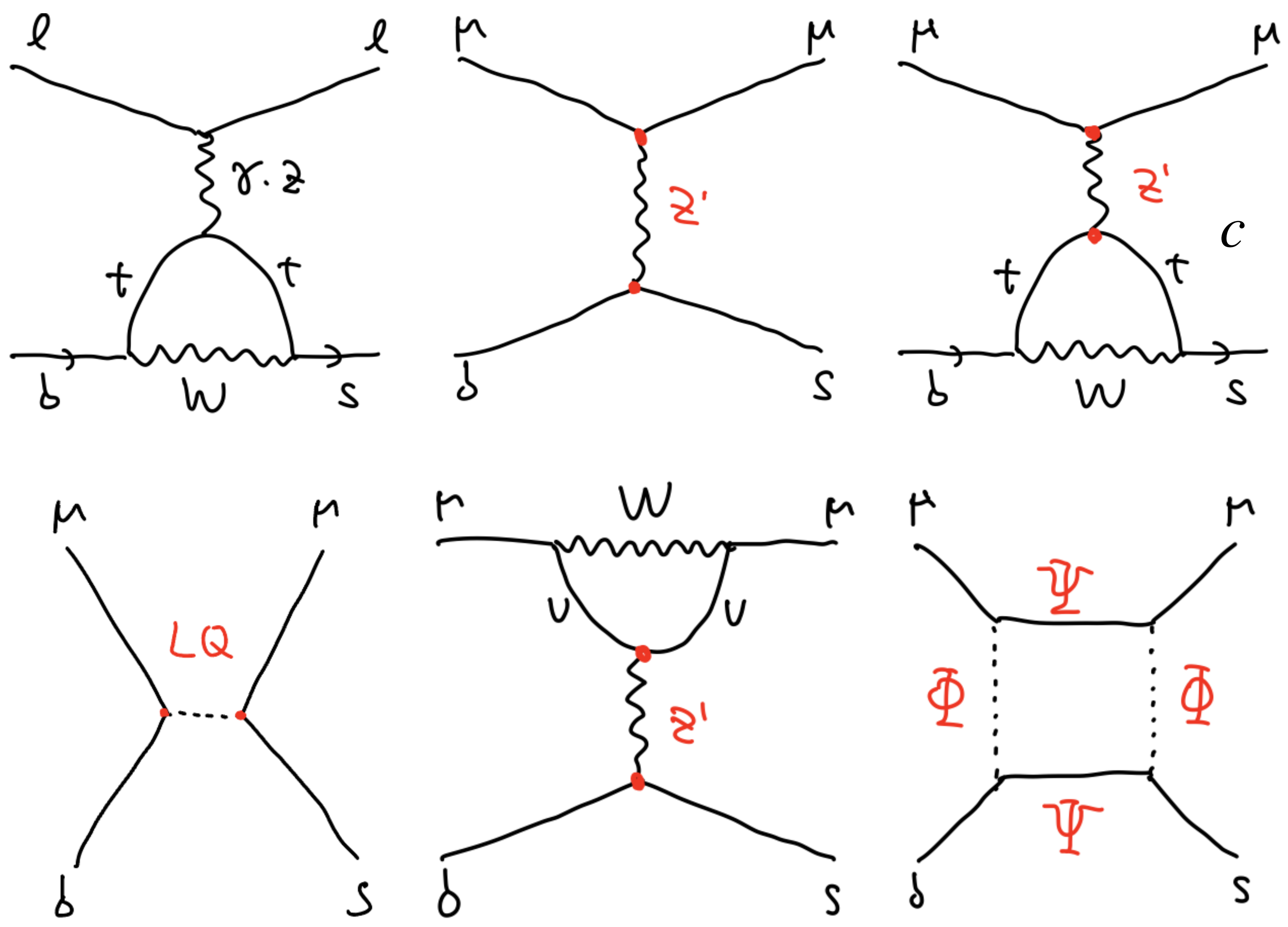
▶ Search for $B^0 \to K^{*0}\tau^+\tau^-$ at Belle II (Meihong Liu's talk@ICHEP)

$\mathscr{B}_{\rm exp} < 1.8 \times 10^{-3}$ is still far from the SM prediction 1.0×10^{-7}

Flavour anomalies: New Physics interpretation

- $b \to s\ell^+\ell^-$ anomalies
  - branching ratio: $\mathfrak{B}(B_s \to \phi\mu^+\mu^-)$, ...
  - angular distribution: P_5' in $B \to K^*\mu^+\mu^-$, ...
- $b \to s\ell^+\ell^-$ anomalies

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



$\mu_{\rm NP}$

???

?

?

$\mu_{\rm EW}$

SMEFT: SM Effective Field Theory

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

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

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

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

... ...

μ_b

LEFT: Low Energy Effective Field Theory

$$\mathscr{H}_{\rm eff} = (C_i^{\rm SM} + C_i^{\rm NP}) O_i^{\rm SM} + C_j^{\rm NP} O_j^{\rm NP}$$

$SU(3)_C \otimes U(1)_{\rm em}$

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

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

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

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

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

Recent Global Fit

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

	All		
2D Hyp.	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%

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	$\mathcal{C}_{9\mu}^{\text{V}}$ $\mathcal{C}_{10\mu}^{\text{V}}$ $\mathcal{C}_9^{\text{U}} = \mathcal{C}_{10}^{\text{U}}$	-1.02 -0.35 $+0.19$	$[-1.43, -0.61]$ $[-0.75, -0.00]$ $[-0.16, +0.58]$	4.1	21.0 %
Scenario 6	$\mathcal{C}_{9\mu}^{\text{V}} = -\mathcal{C}_{10\mu}^{\text{V}}$ $\mathcal{C}_9^{\text{U}} = \mathcal{C}_{10}^{\text{U}}$	-0.27 -0.41	$[-0.34, -0.20]$ $[-0.53, -0.29]$	4.0	18.0 %
Scenario 7	$\mathcal{C}_{9\mu}^{\text{V}}$ $\mathcal{C}_9^{\text{U}}$	-0.21 -0.97	$[-0.39, -0.02]$ $[-1.21, -0.72]$	5.6	40.3 %
Scenario 8	$\mathcal{C}_{9\mu}^{\text{V}} = -\mathcal{C}_{10\mu}^{\text{V}}$ $\mathcal{C}_9^{\text{U}}$	-0.08 -1.10	$[-0.14, -0.02]$ $[-1.27, -0.91]$	5.6	41.1 %

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

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

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

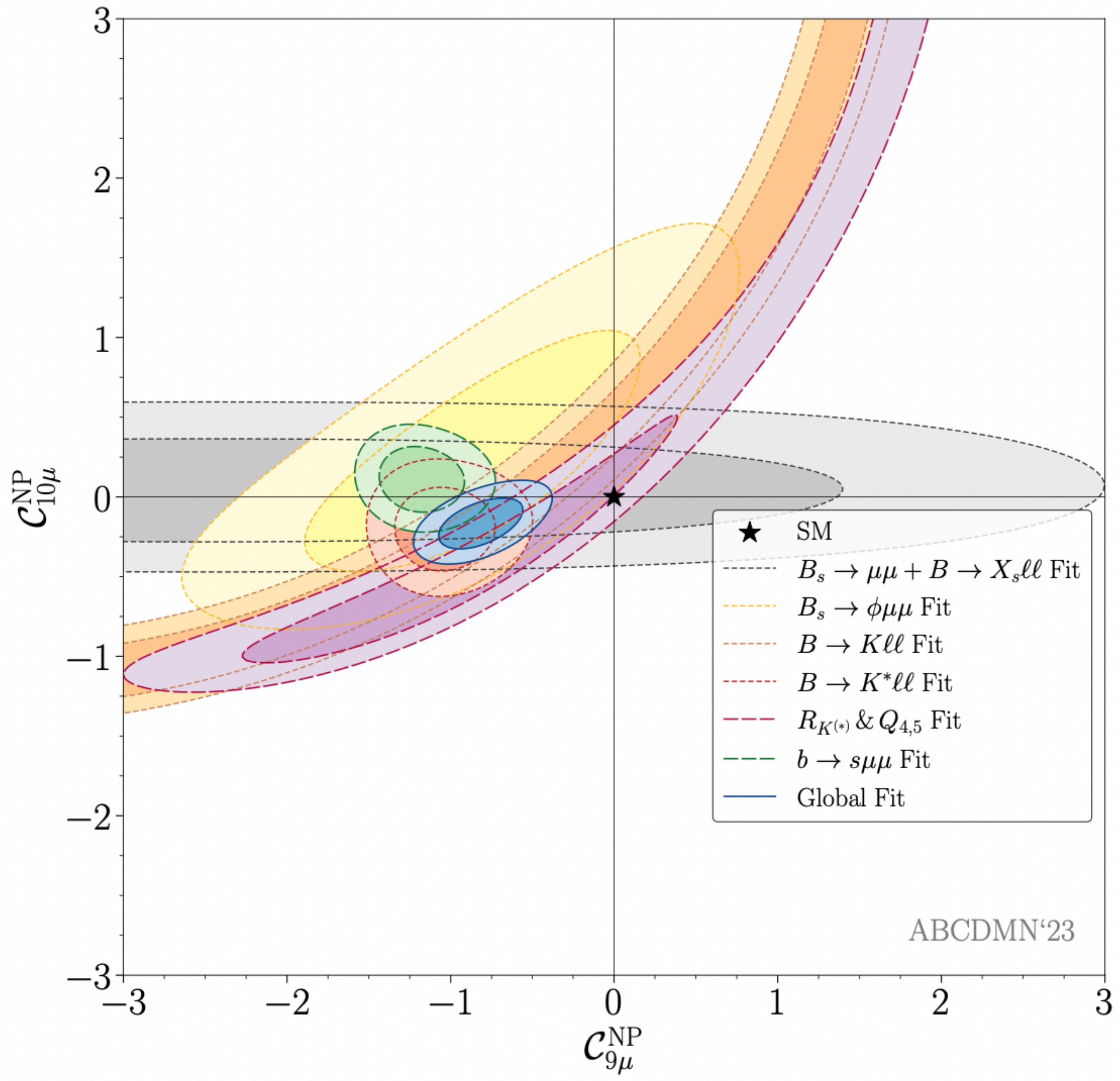
$\mathcal{B}(B_s \to \mu^+\mu^-)$ consistent with SM

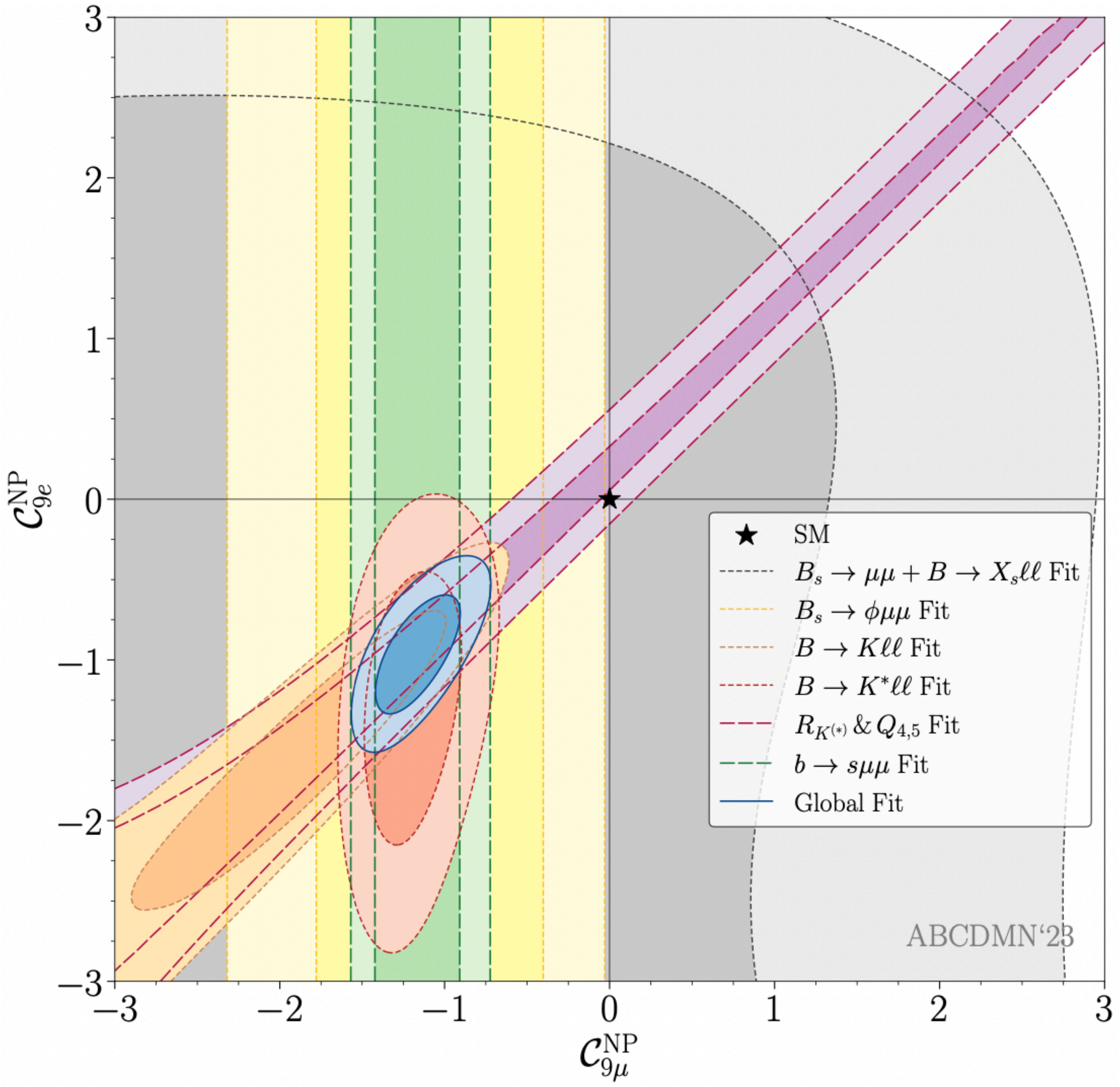
(C_{10} can't be too large)

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
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	All			
1D Hyp.	Best fit	$1\sigma/2\sigma$	Pull$_{\rm SM}$	p-value
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$\mathcal{C}_{9\mu}^{\rm NP}=-\mathcal{C}_{10\mu}^{\rm NP}$	-0.19	$[-0.25,-0.13]$ $[-0.32,-0.07]$	3.1	9.9 %

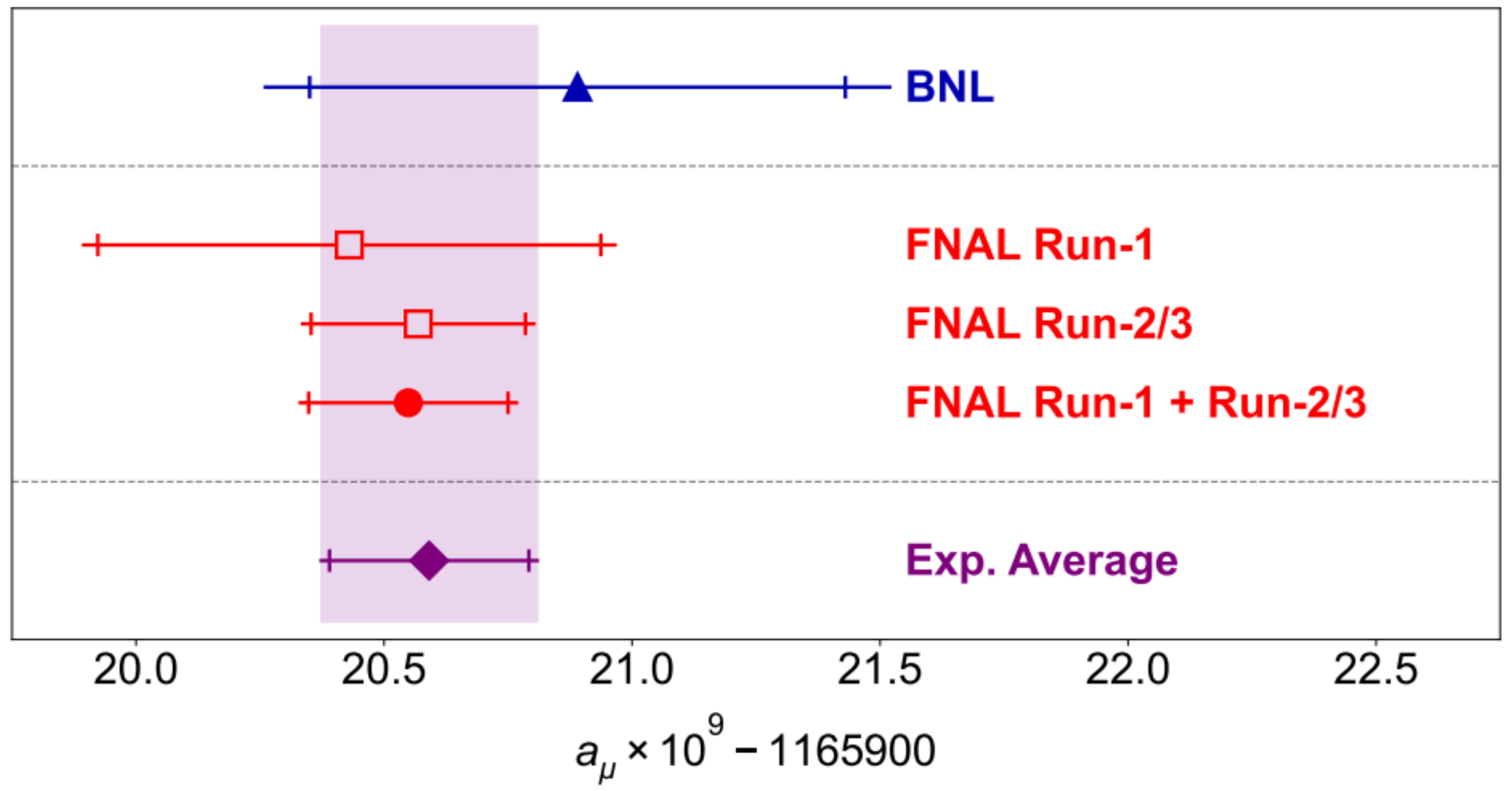
	All		
2D Hyp.	Best fit	Pull$_{\rm SM}$	p-value
$(\mathcal{C}_{9\mu}^{\rm NP},\mathcal{C}_{10\mu}^{\rm NP})$	$(-0.82,-0.17)$	4.4	21.9%
$(\mathcal{C}_{9\mu}^{\rm NP},\mathcal{C}_{7'})$	$(-0.68,+0.01)$	4.2	19.4%
$(\mathcal{C}_{9\mu}^{\rm NP},\mathcal{C}_{9'\mu})$	$(-0.78,+0.21)$	4.3	20.7%
$(\mathcal{C}_{9\mu}^{\rm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

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

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

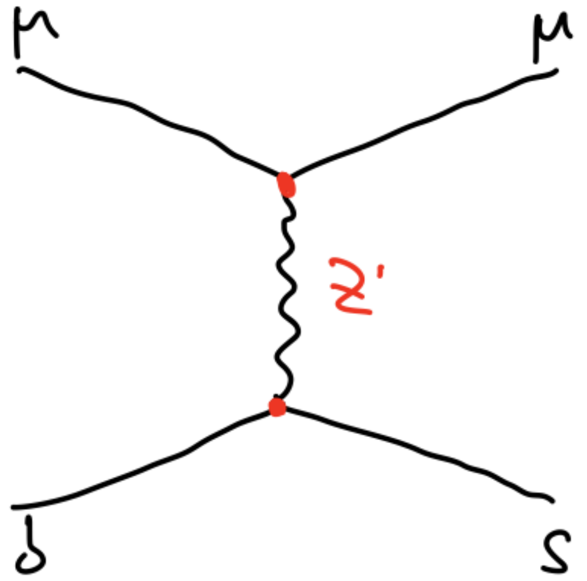
$$O_{10} = (\bar{b}\gamma^\mu P_L s)(\bar{\ell}\gamma_\mu\gamma_5 \ell)$$

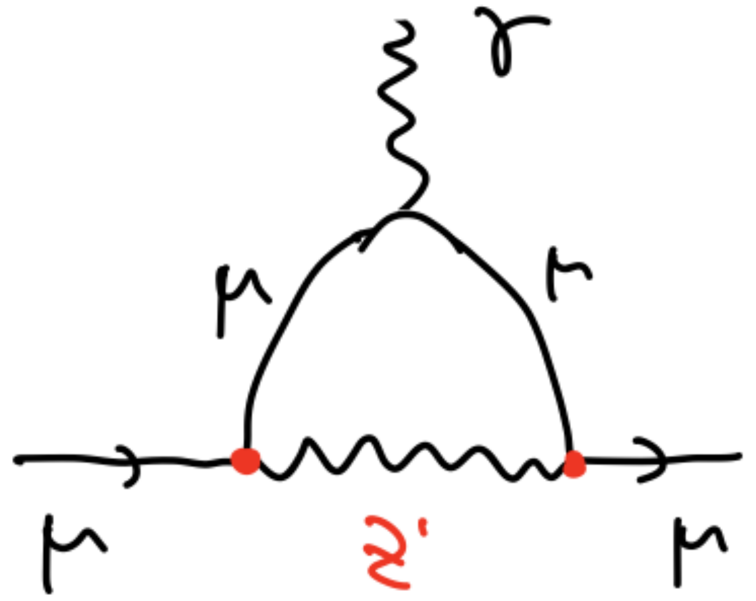
$\mathscr{B}(B_s \to \mu^+\mu^-)$ consistent with SM
(C_{10} can't be too large)



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

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





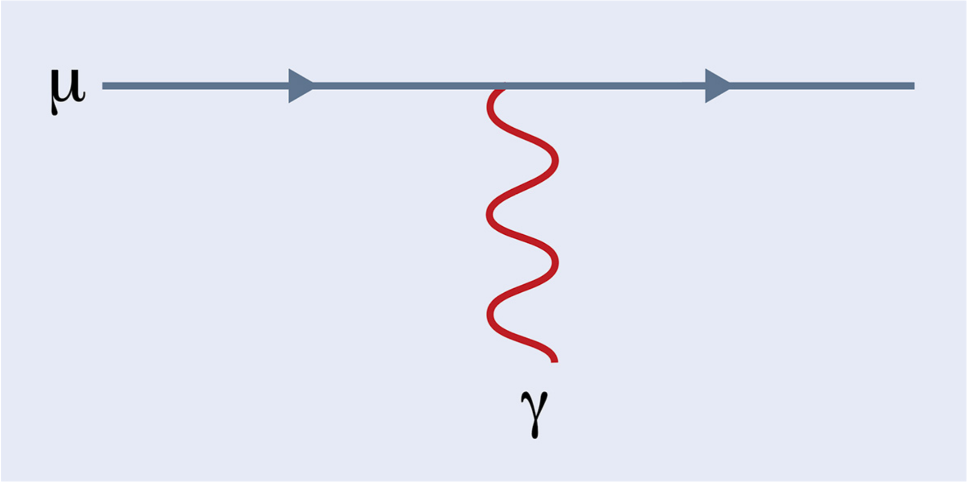
$$\Delta(g-2)_\mu \propto -5g_A^2 + g_V^2$$

$(g-2)_\mu$

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

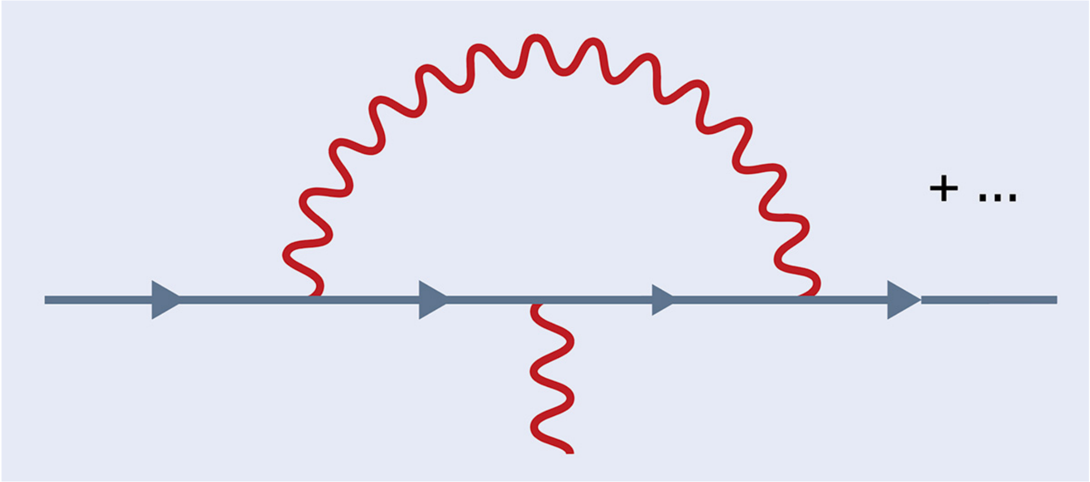
see also Shu-Min Zhao's talk

$g = 2$



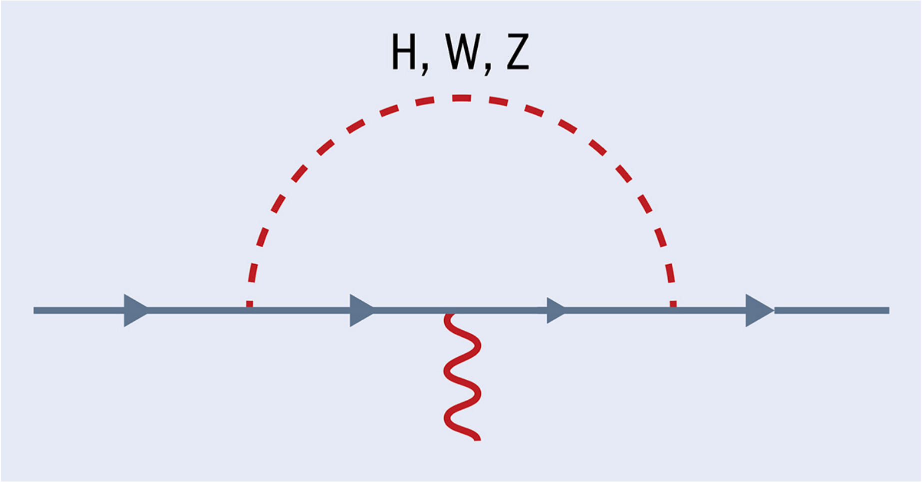
Bohr magneton

QED



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

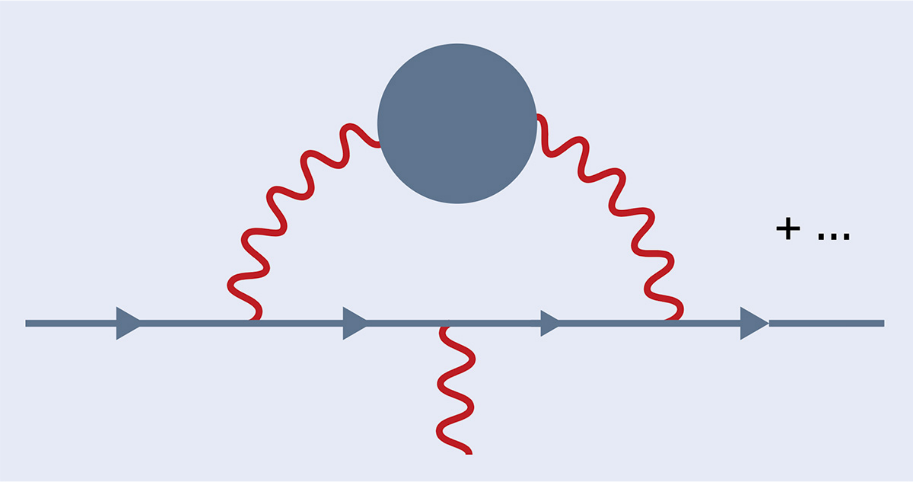
Electro-Weak



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

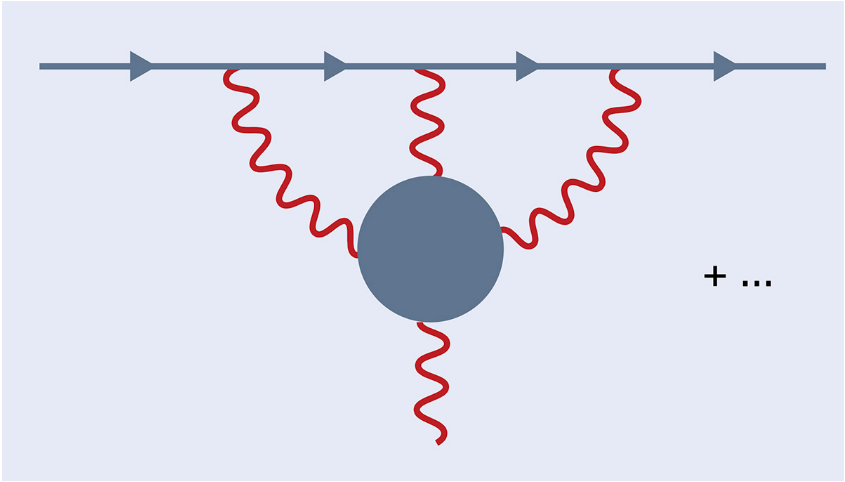
unit: 10^{-11}

hadronic vacuum polarisation



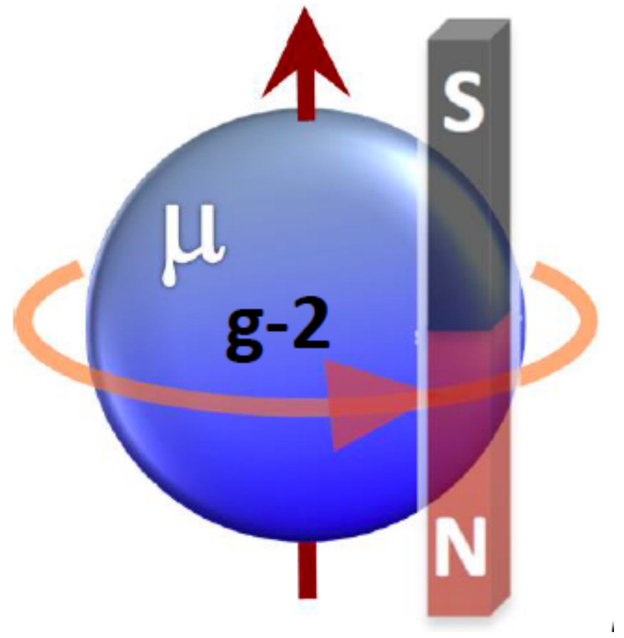
$a_\mu^{\rm HVP} \times 10^{11}$	LO	NLO	NNLO
e^+e^- data	6931 ± 40	−98 ± 7	12 ± 1
Lattice QCD	7116 ± 184		

Hadronic light-by-light scattering

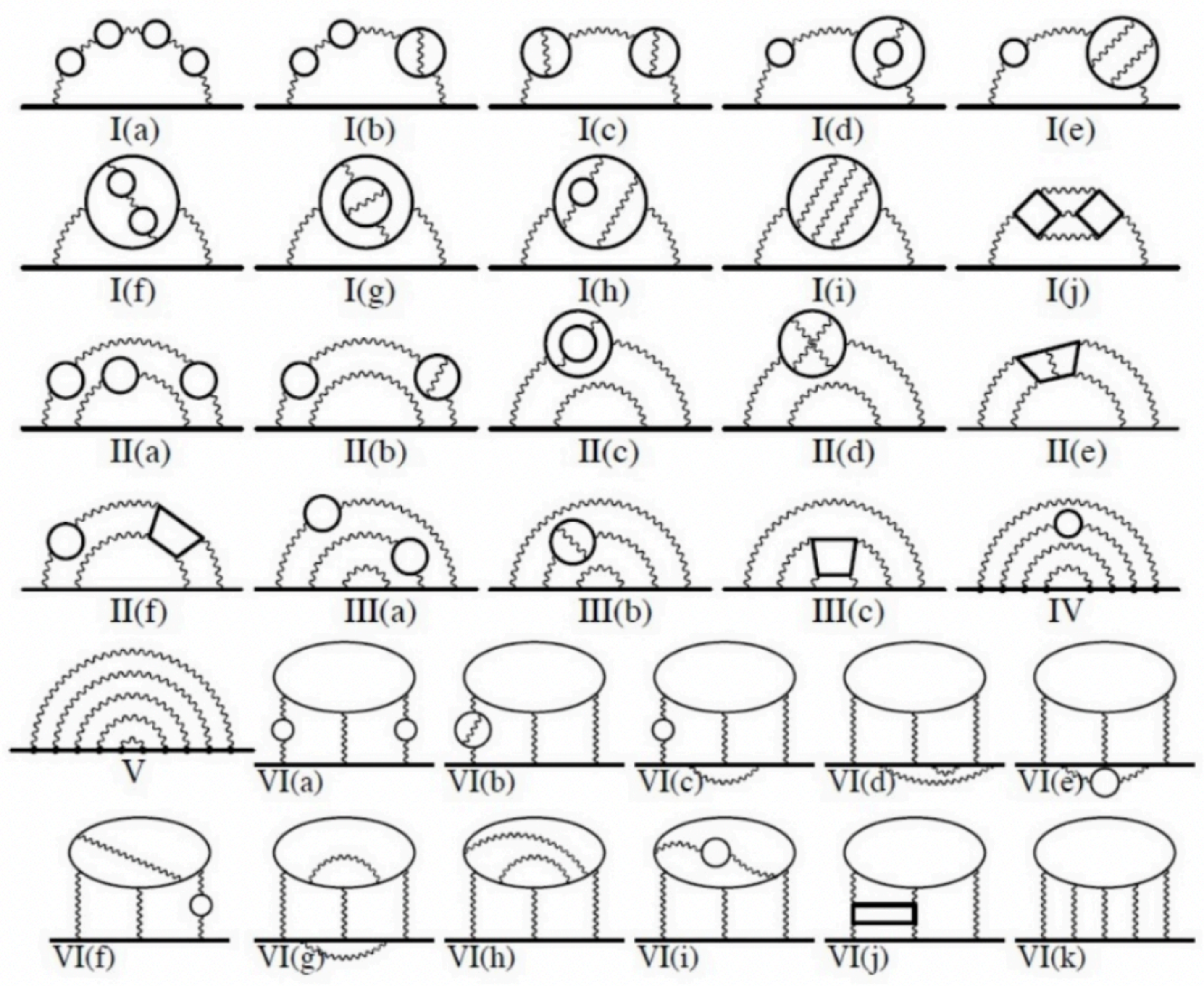


$a_\mu^{\rm HLbL} \times 10^{11}$	LO	NLO
Phenomenology	92 ± 19	2 ± 1
Lattice QCD	79 ± 35	

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



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

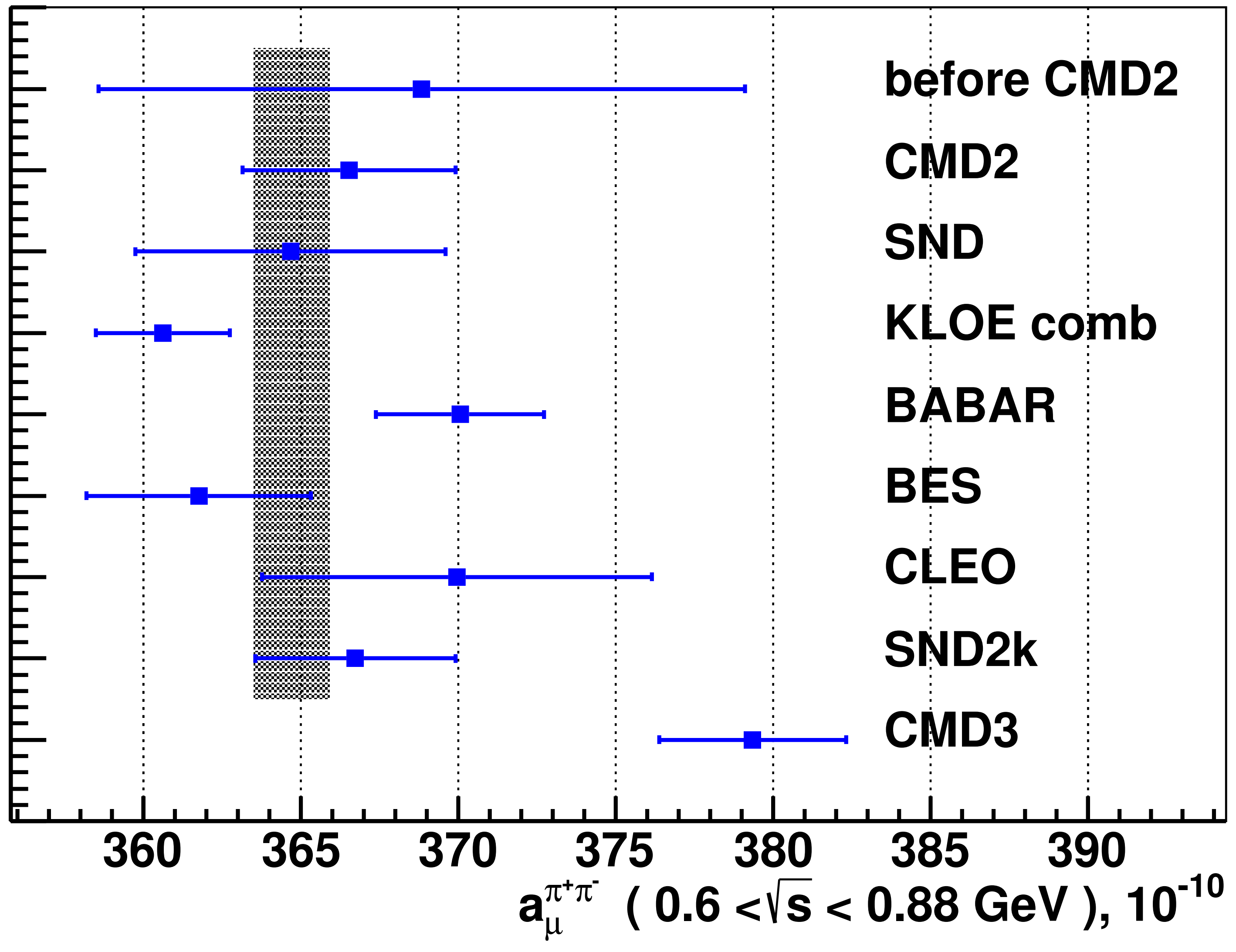


Aoyama, Hayakawa, Kinoshita, Nio (2012-2019)

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

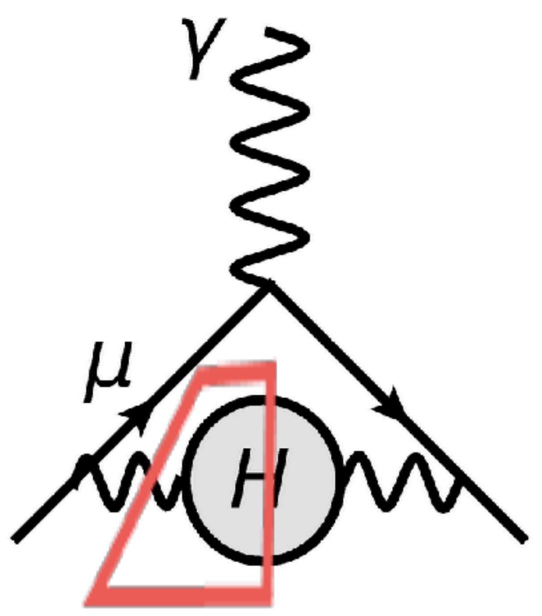
12000+ Feynman diagrams
Analytical calculation @ α^2, α^3
Partly analytical @ α^4
Numerical @ α^5

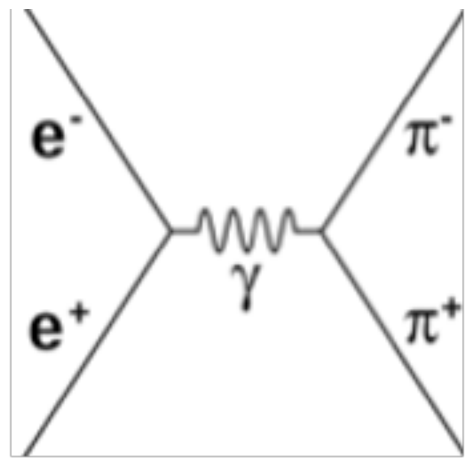
$(g-2)_\mu$



Data-driven

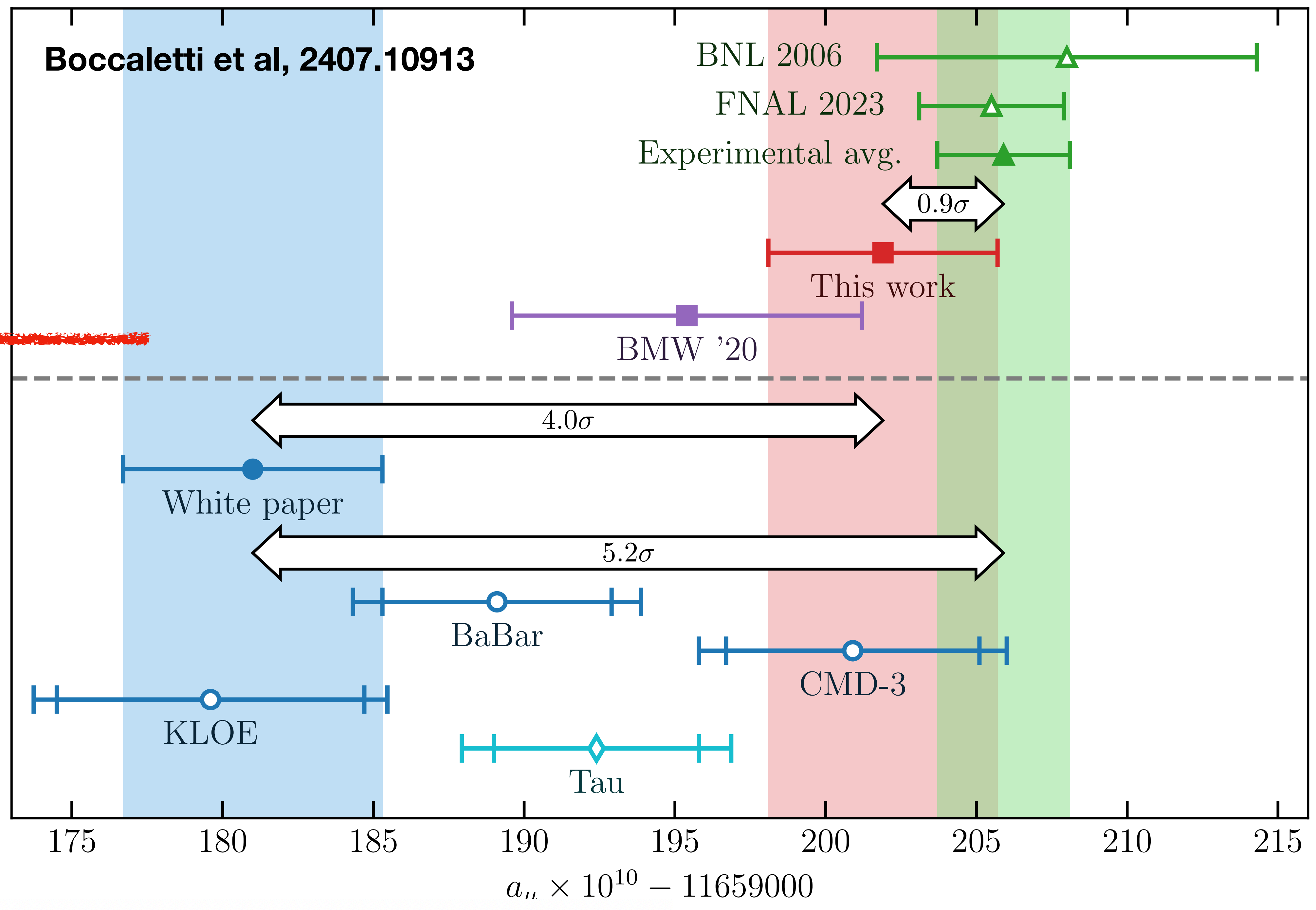
Dispersion relation + low energy e+e- -> hadrons



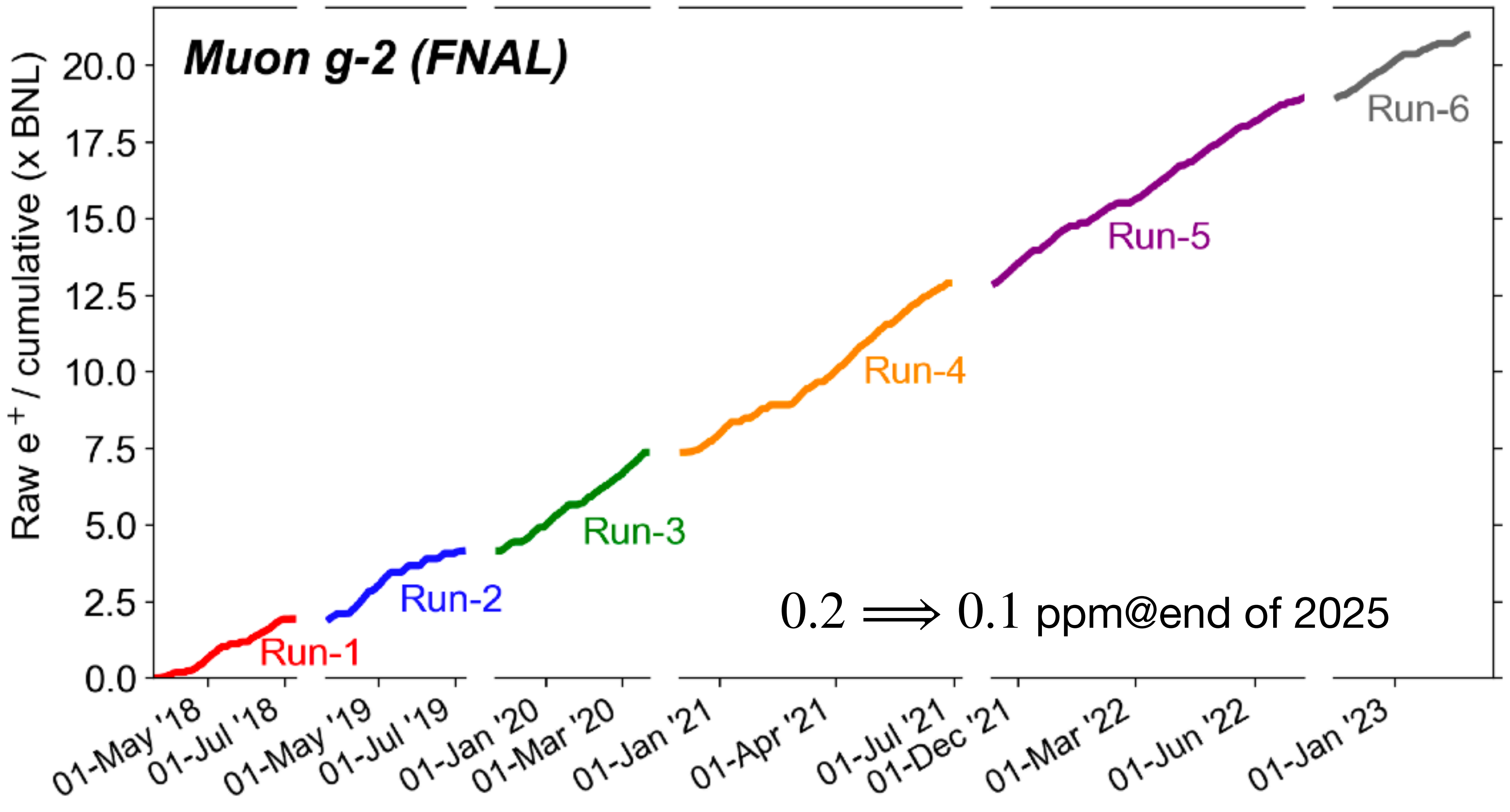


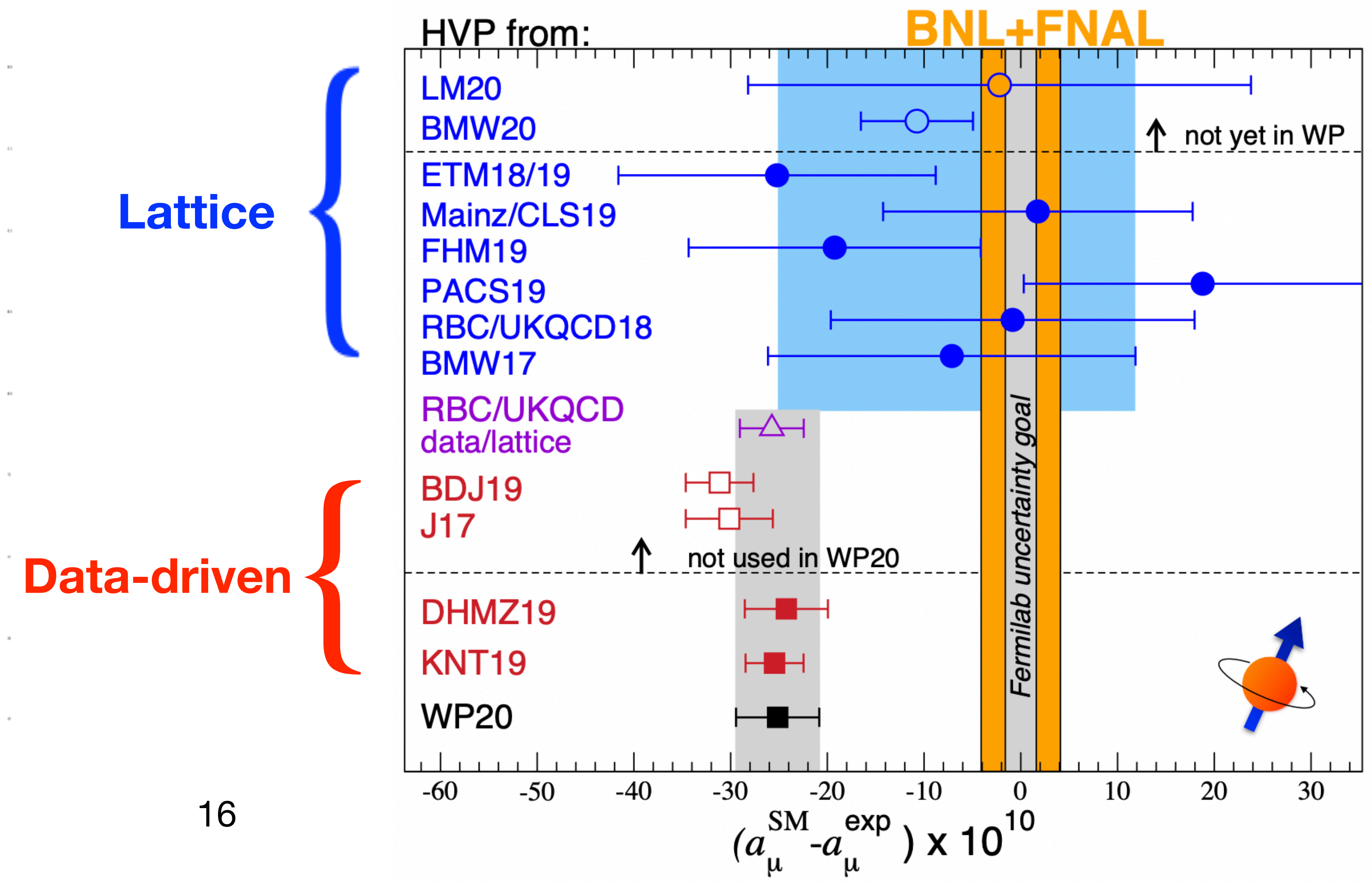
e+e- to hadrons

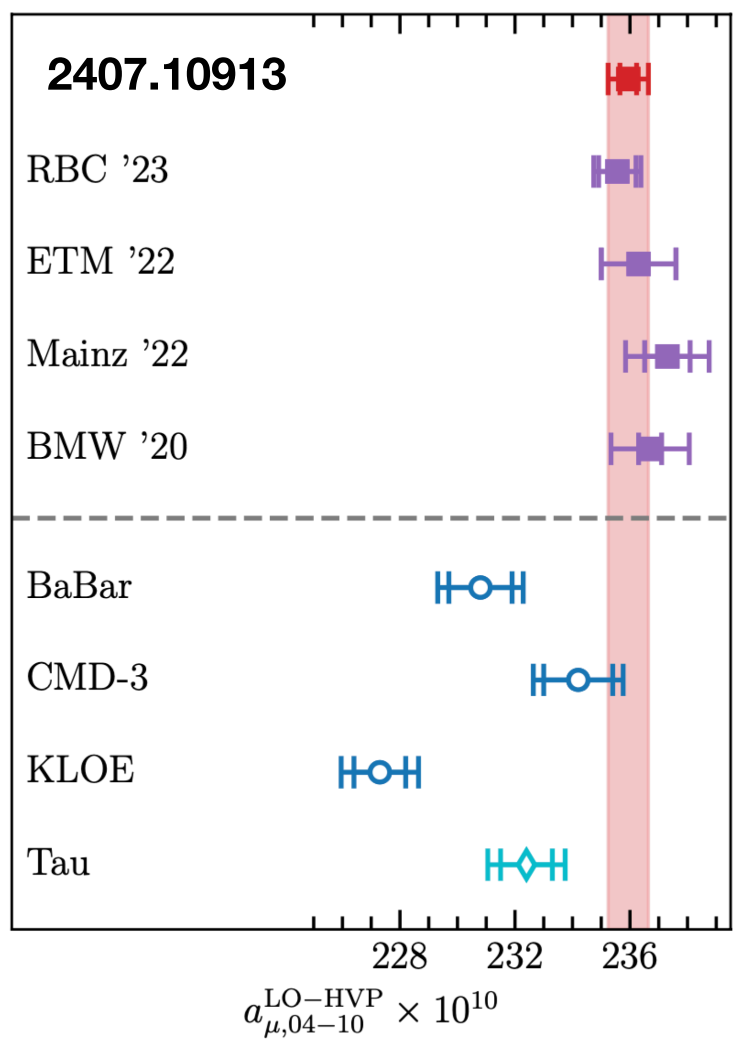
$$a_\mu^{\mathrm{had,LO}} = \frac{m_\mu^2}{12\pi^3}\int_{s_{\mathrm{th}}}^{\infty} ds\, \frac{1}{s}\hat{K}(s)\sigma_{\mathrm{had}}(s)$$



Last update: 2023-02-27 06:11 ; Total = 21.00 (xBNL) Kim Siang Khaw@TOPAC 23





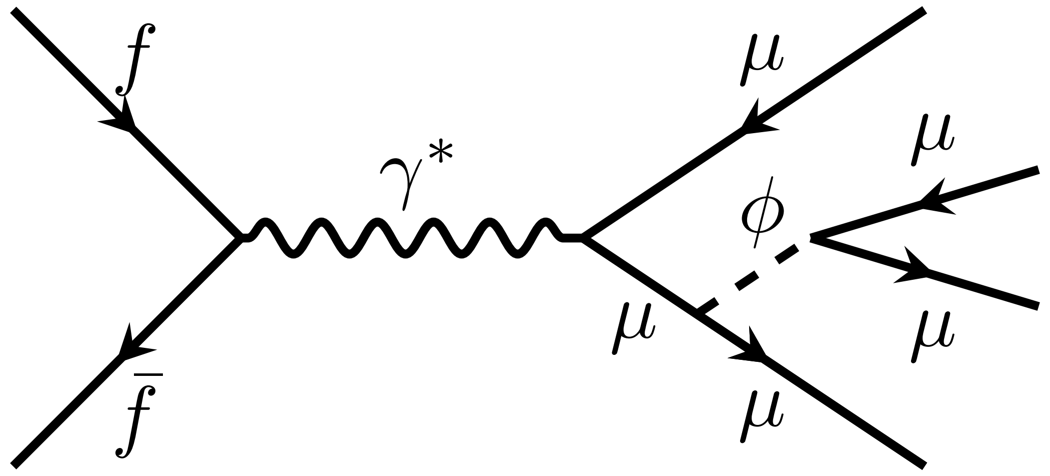


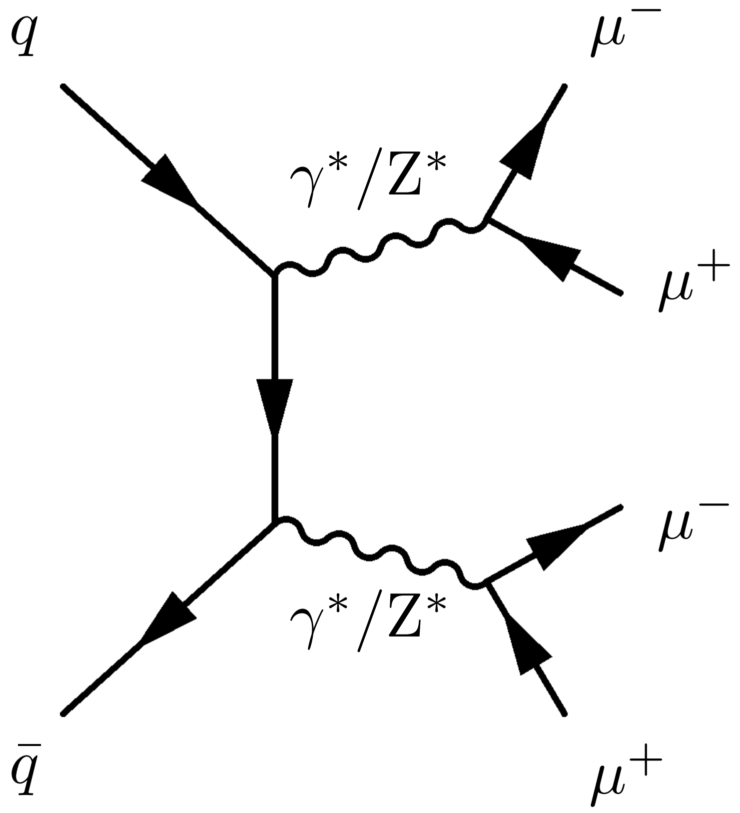
Collider Searches

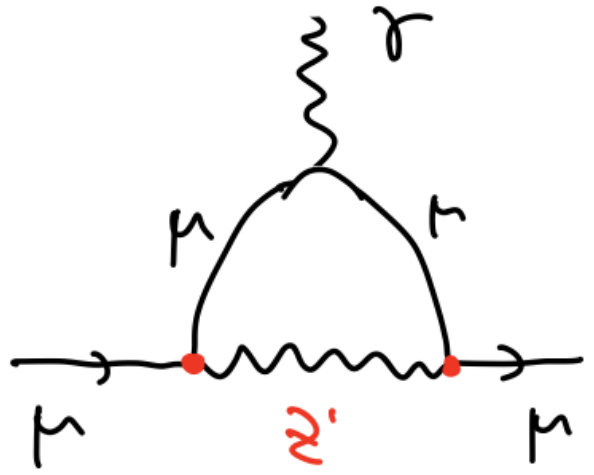
see also Zhi-Jun Li's talk

can be searched for at BESIII, Belle II, STCF

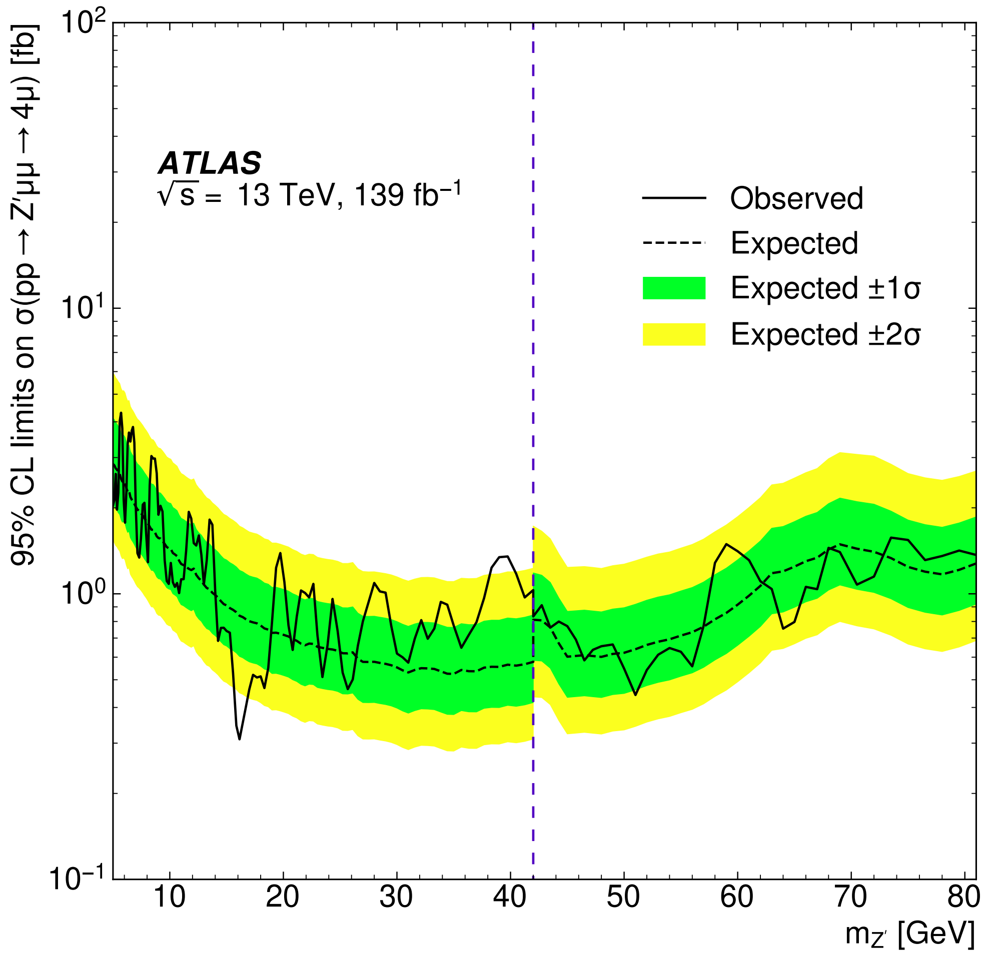
$e^+e^-(pp) \to \mu^+\mu^-\mu^+\mu^-$

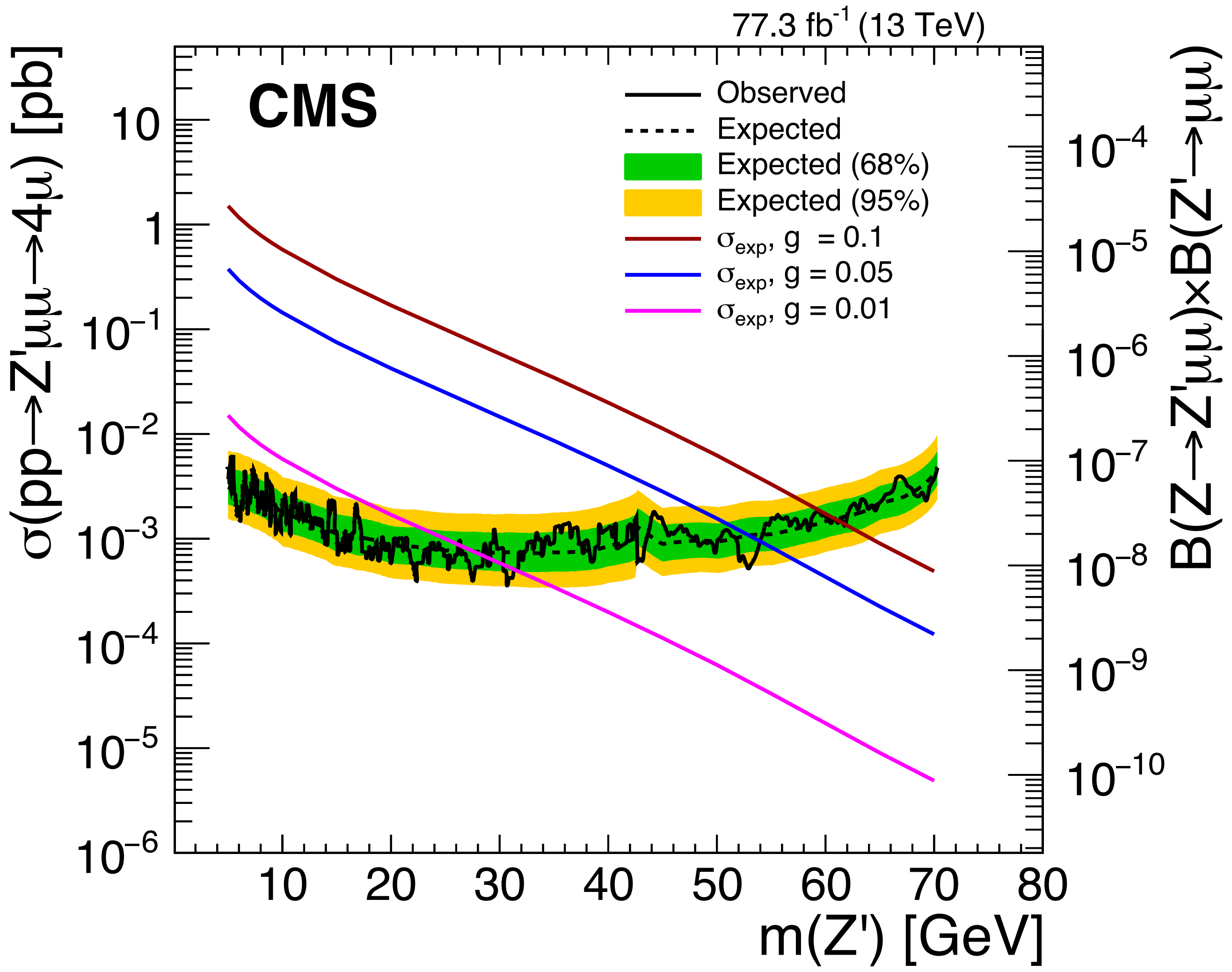




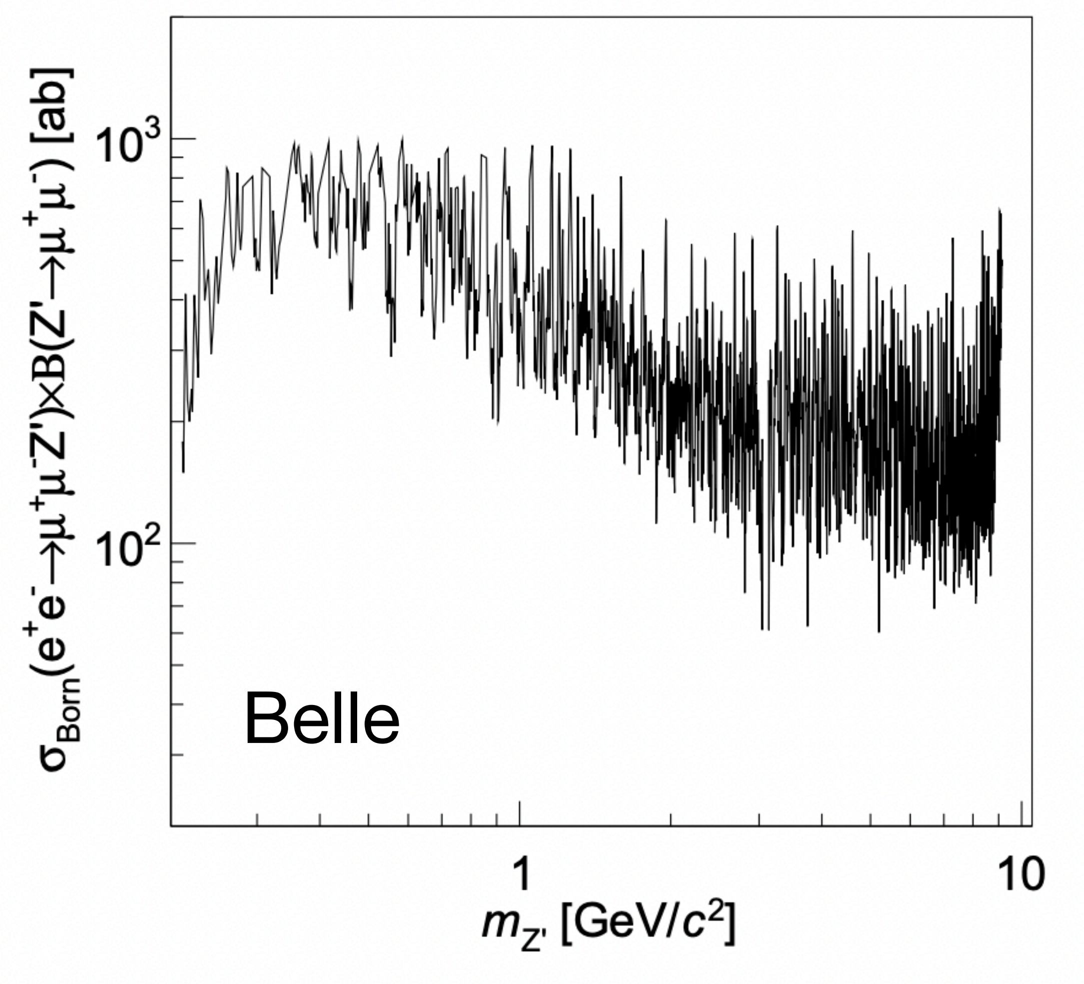


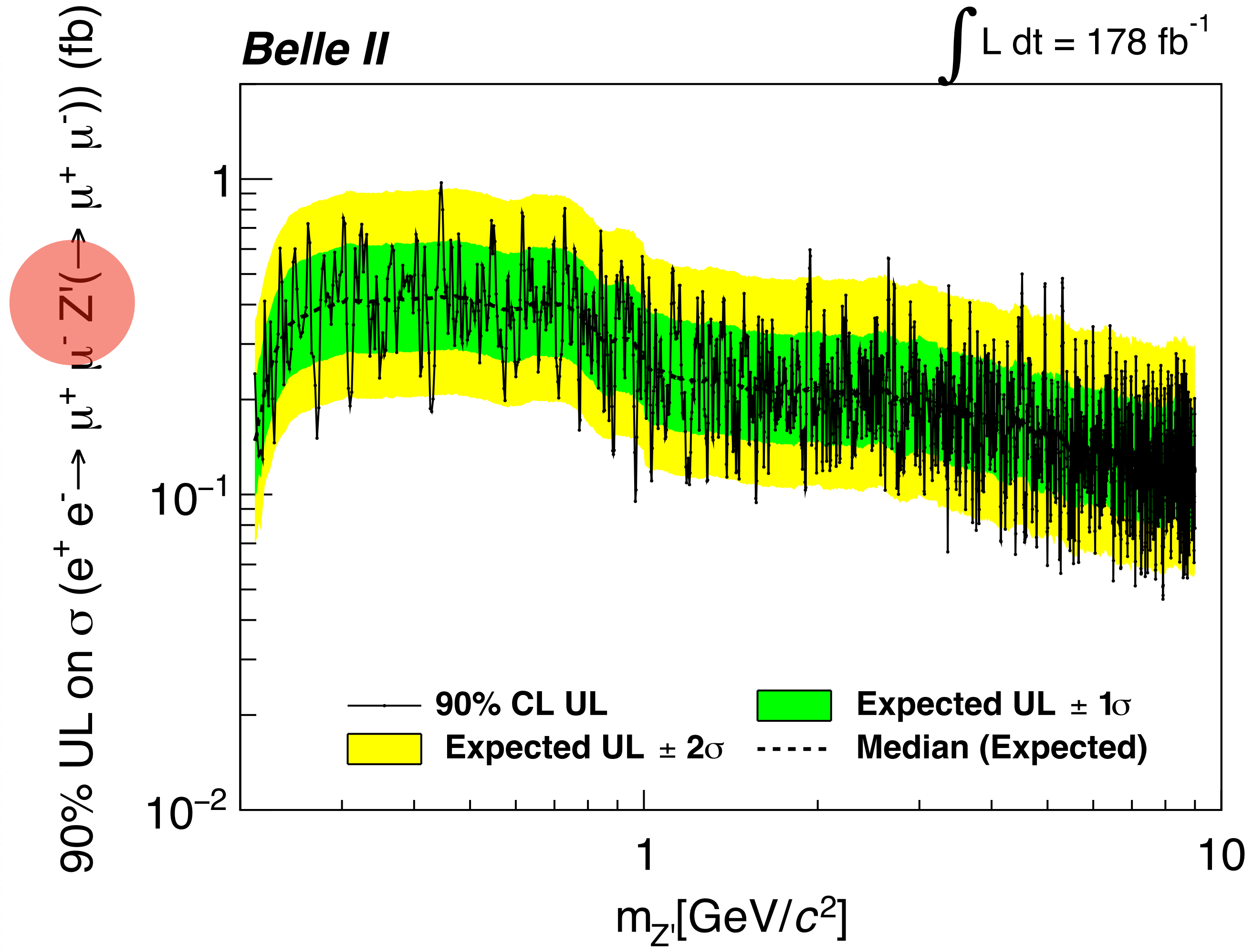
$(g-2)_\mu$

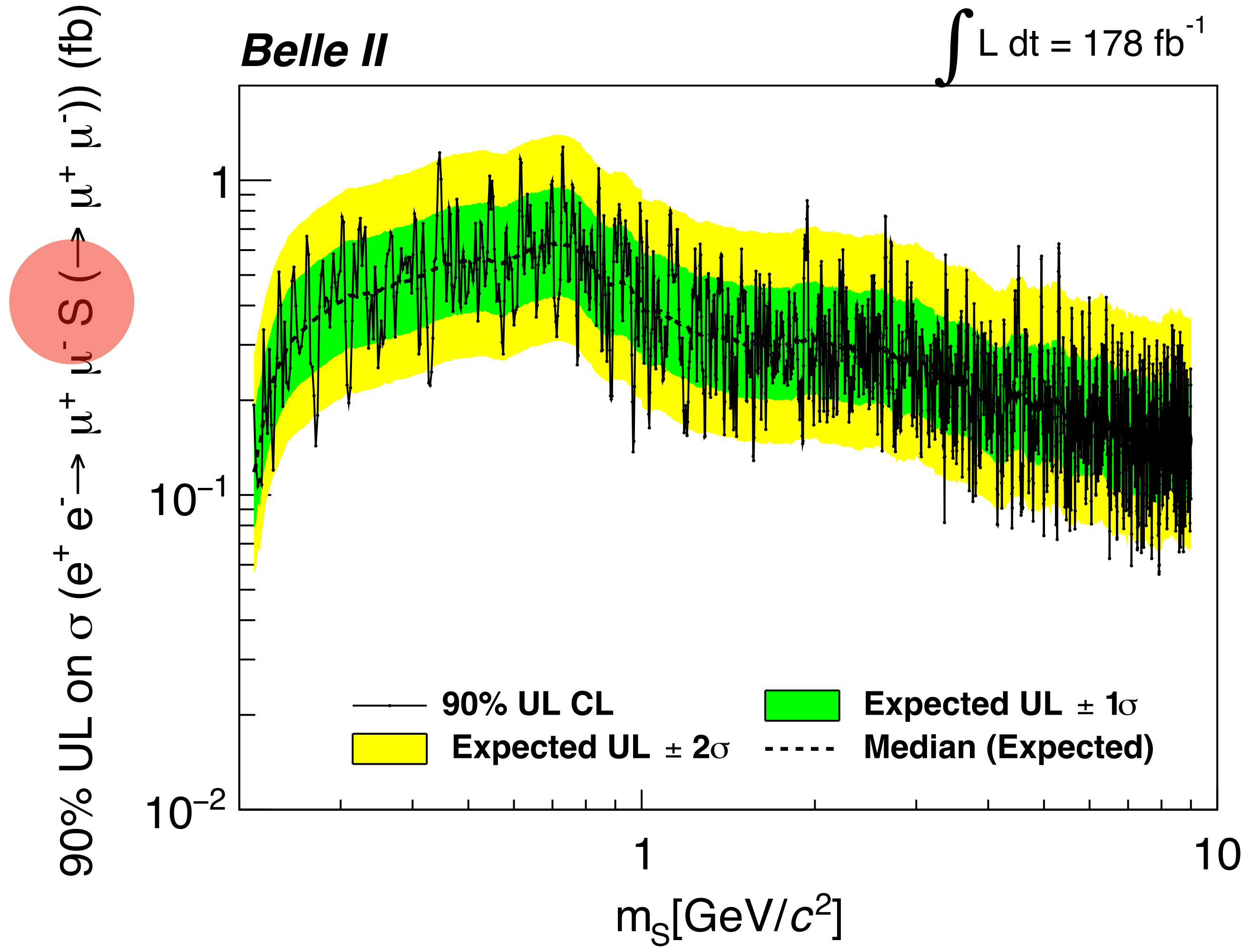




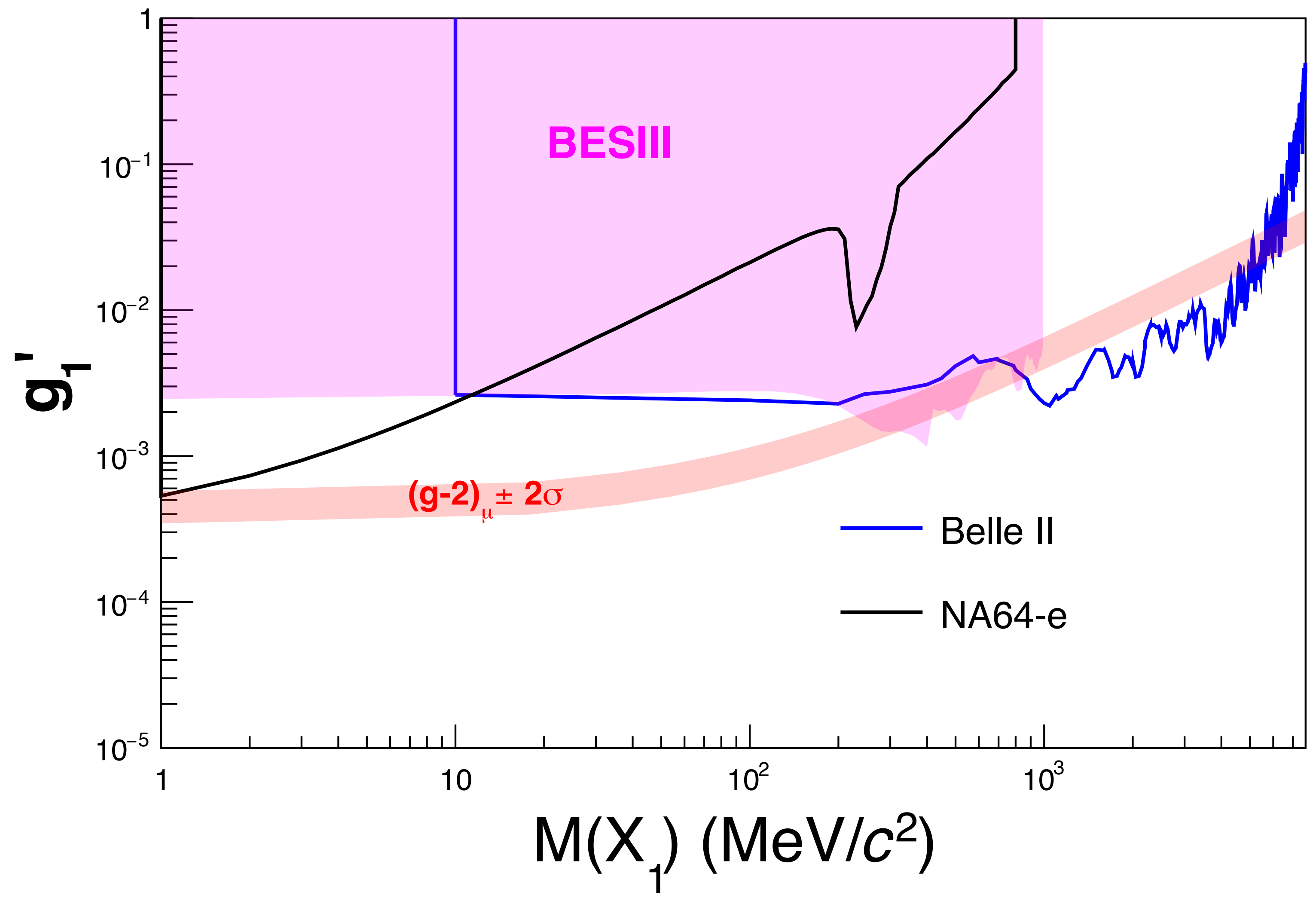
also at BESIII and BaBar

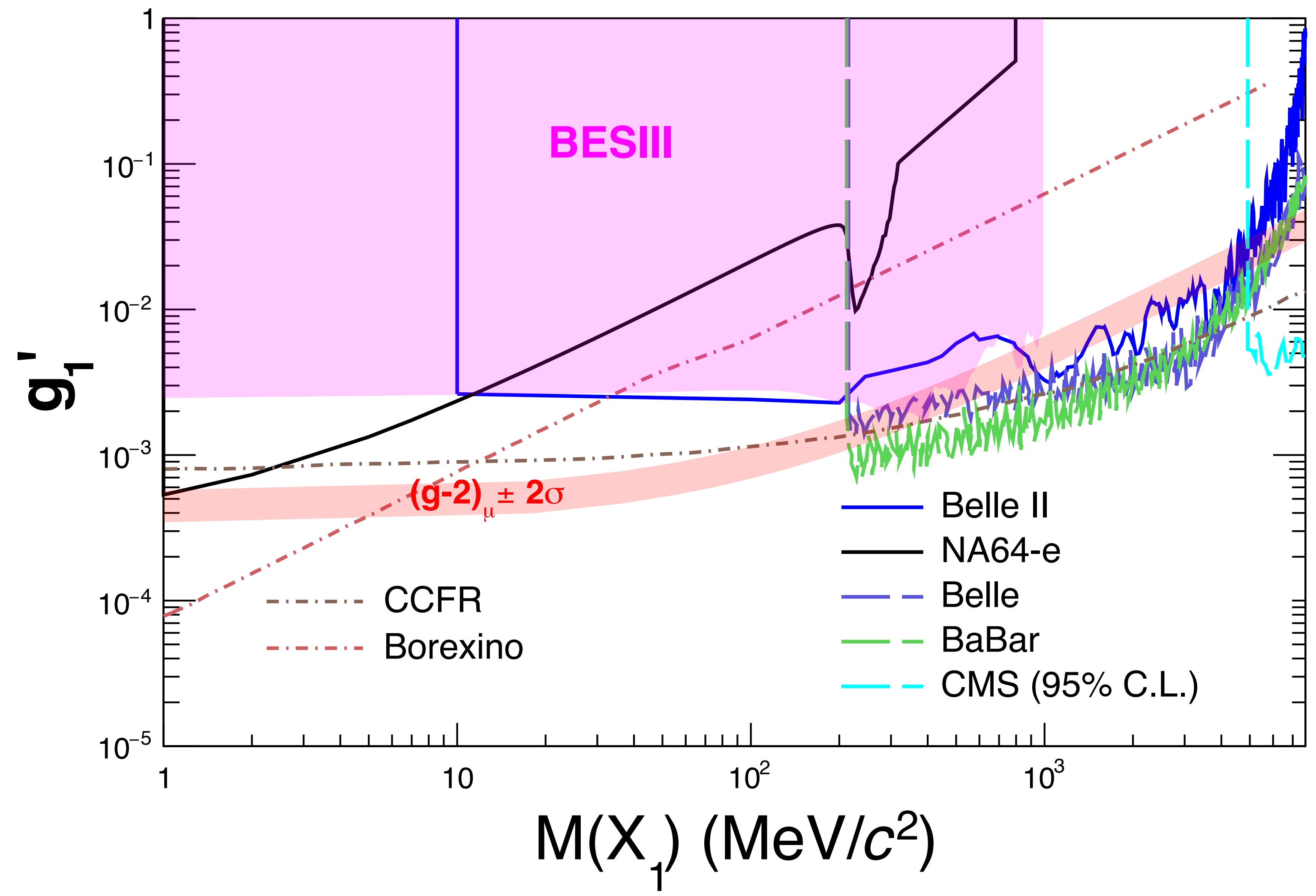


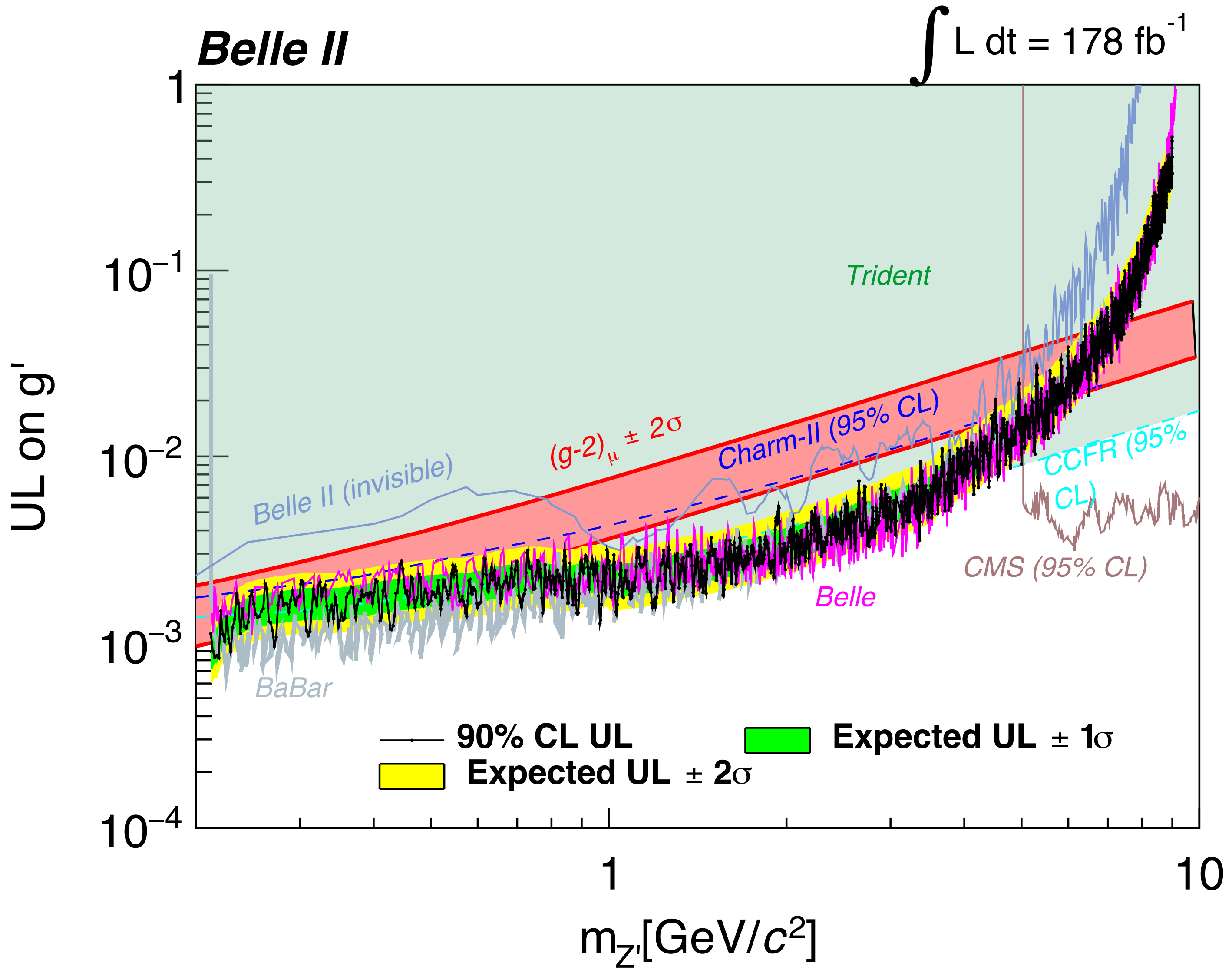


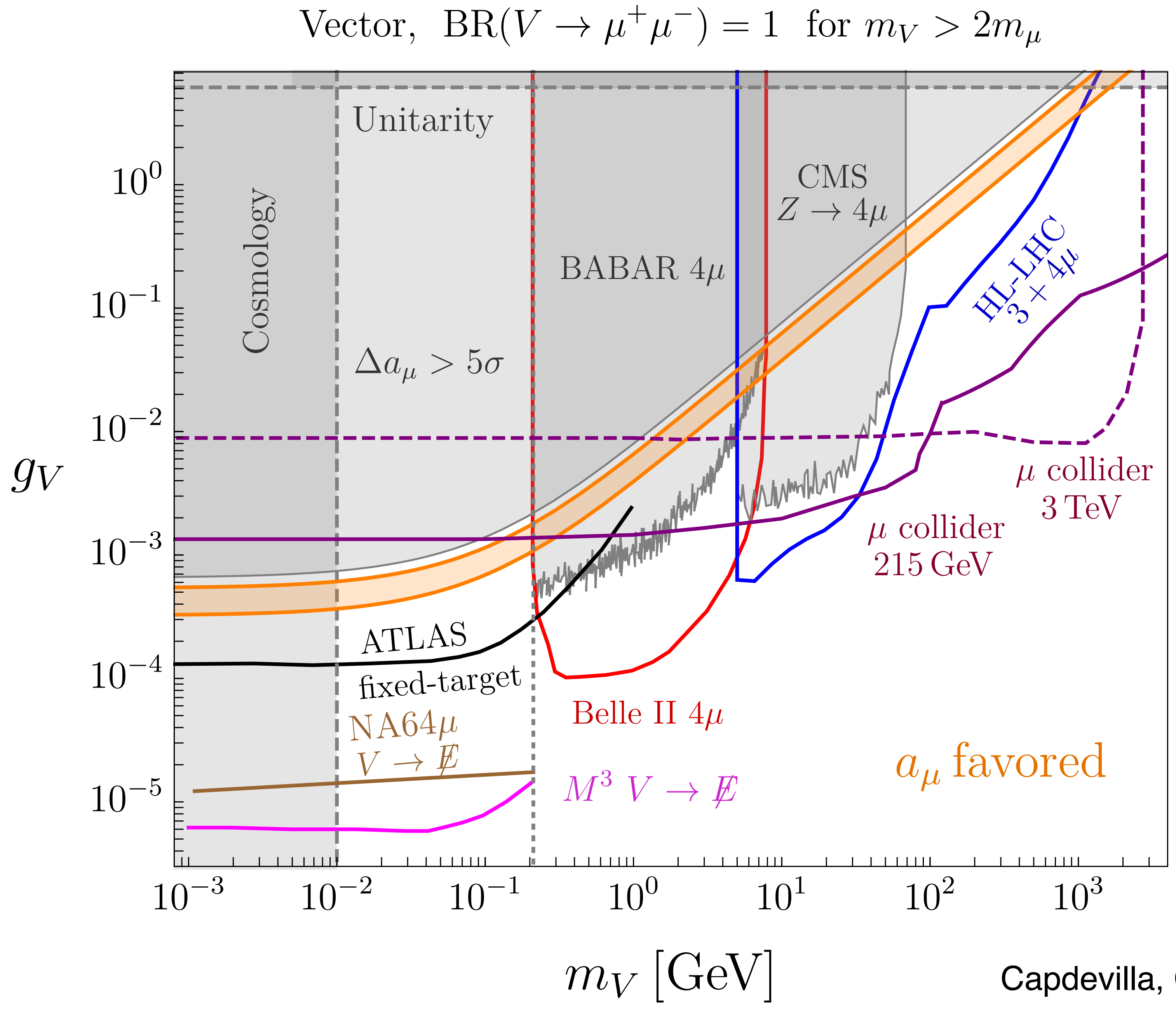


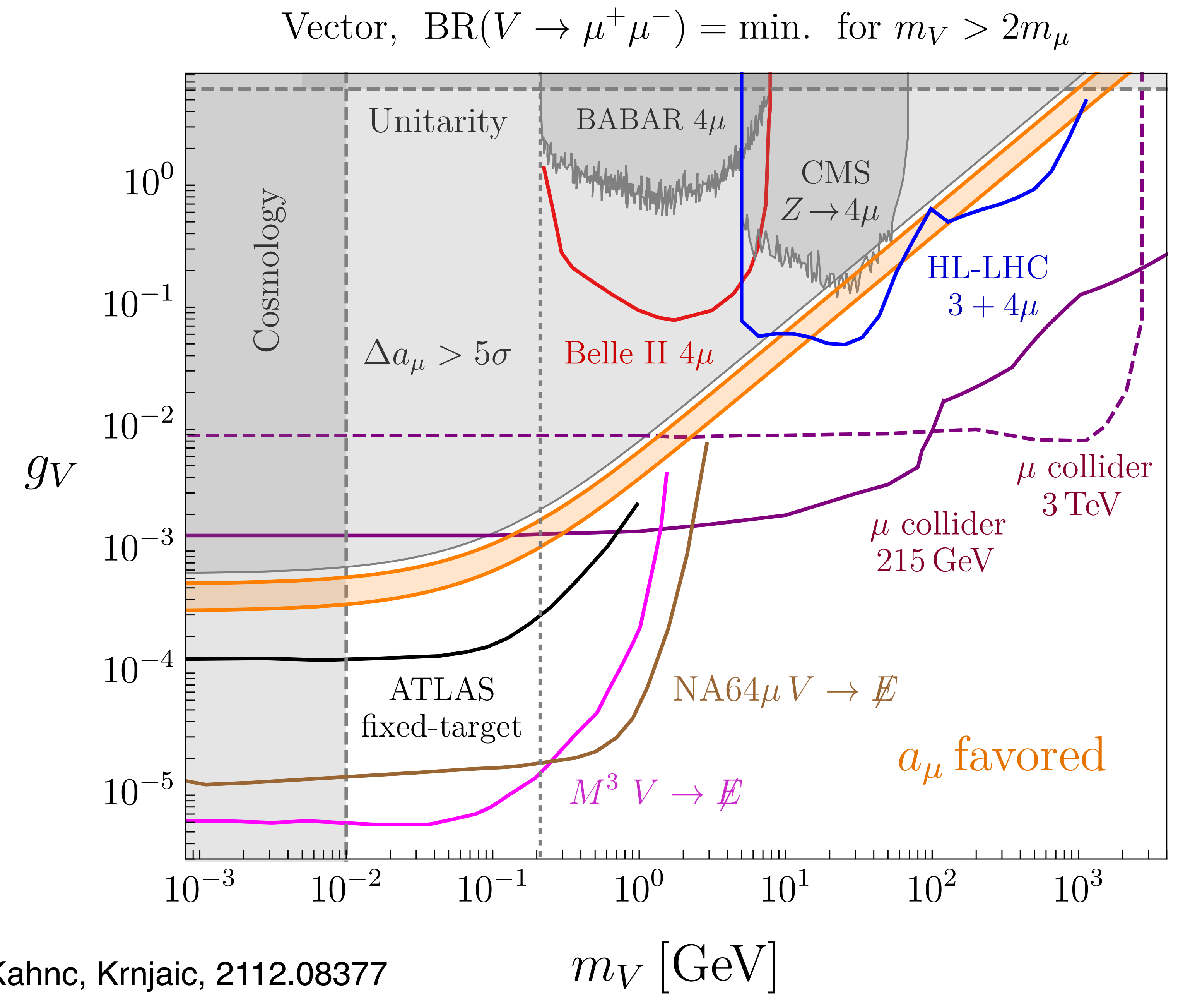
Collider Searches: vector



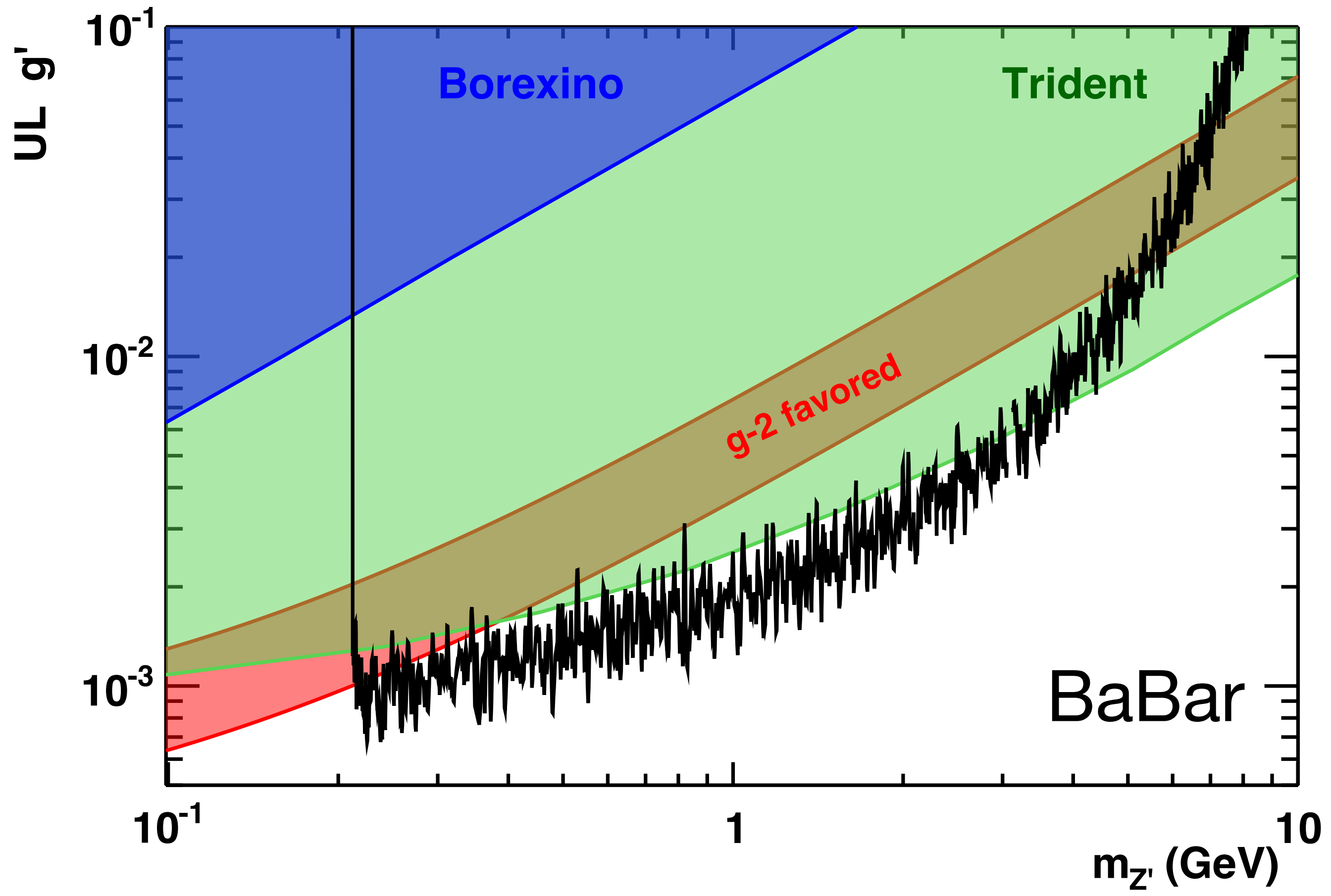




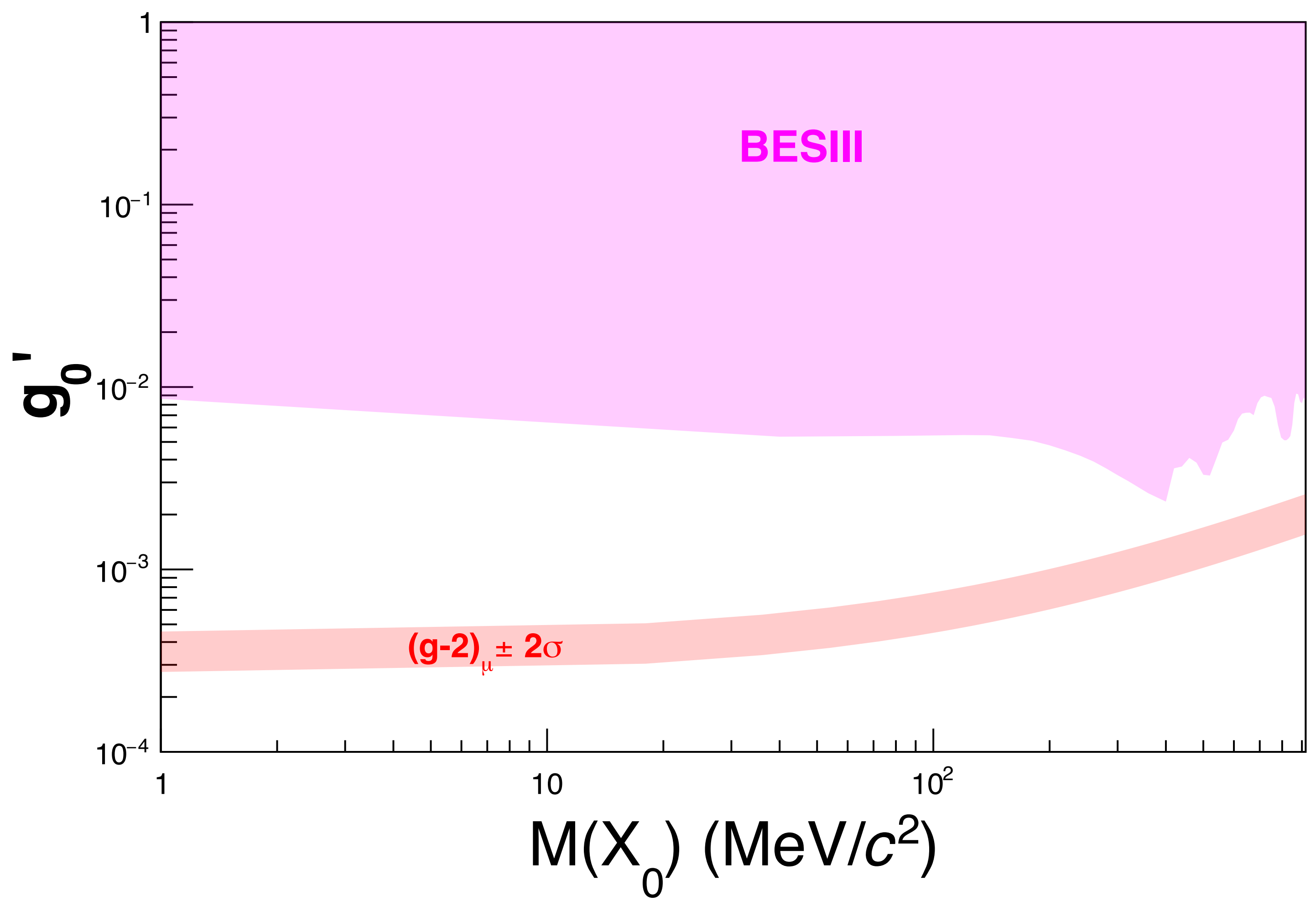


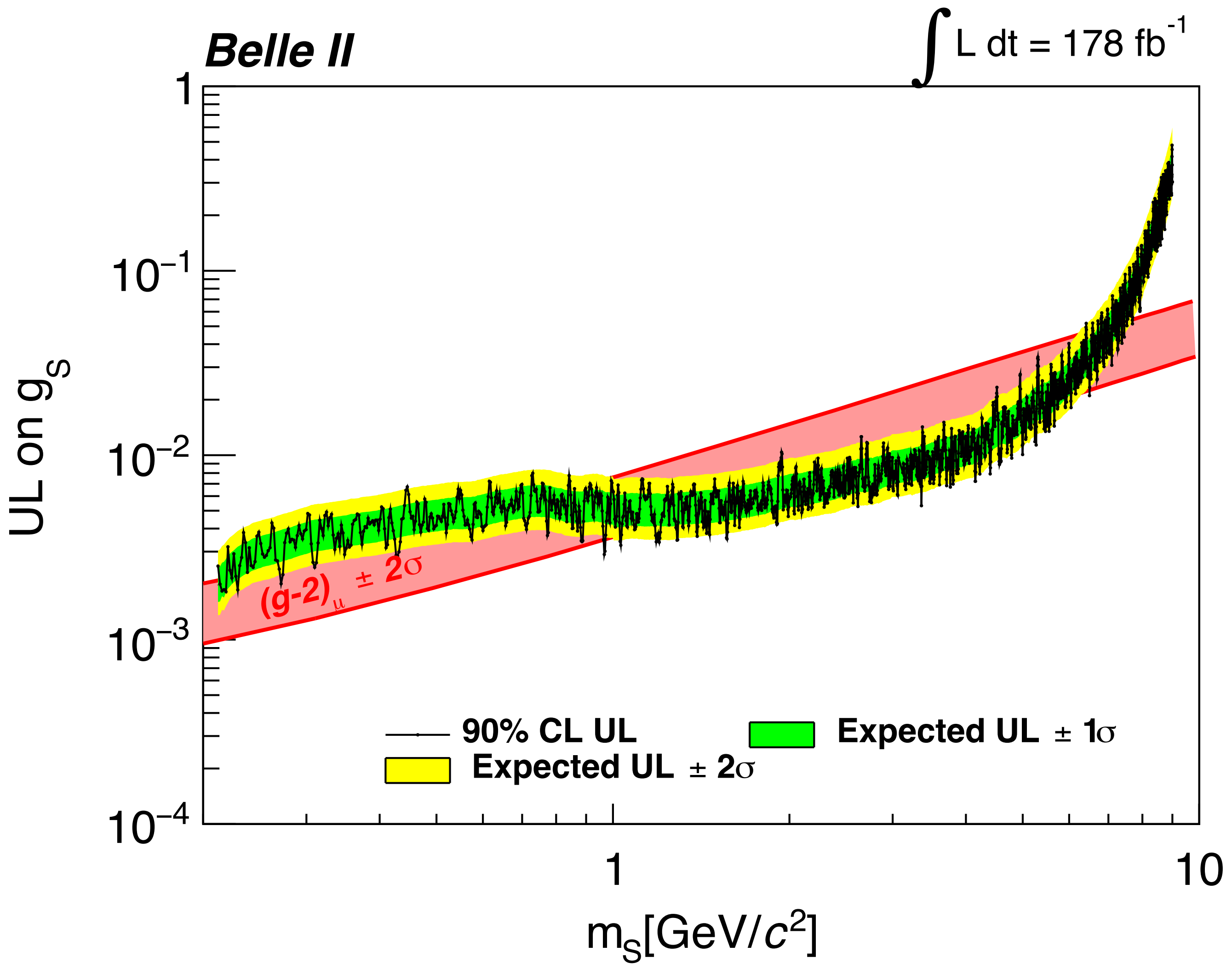


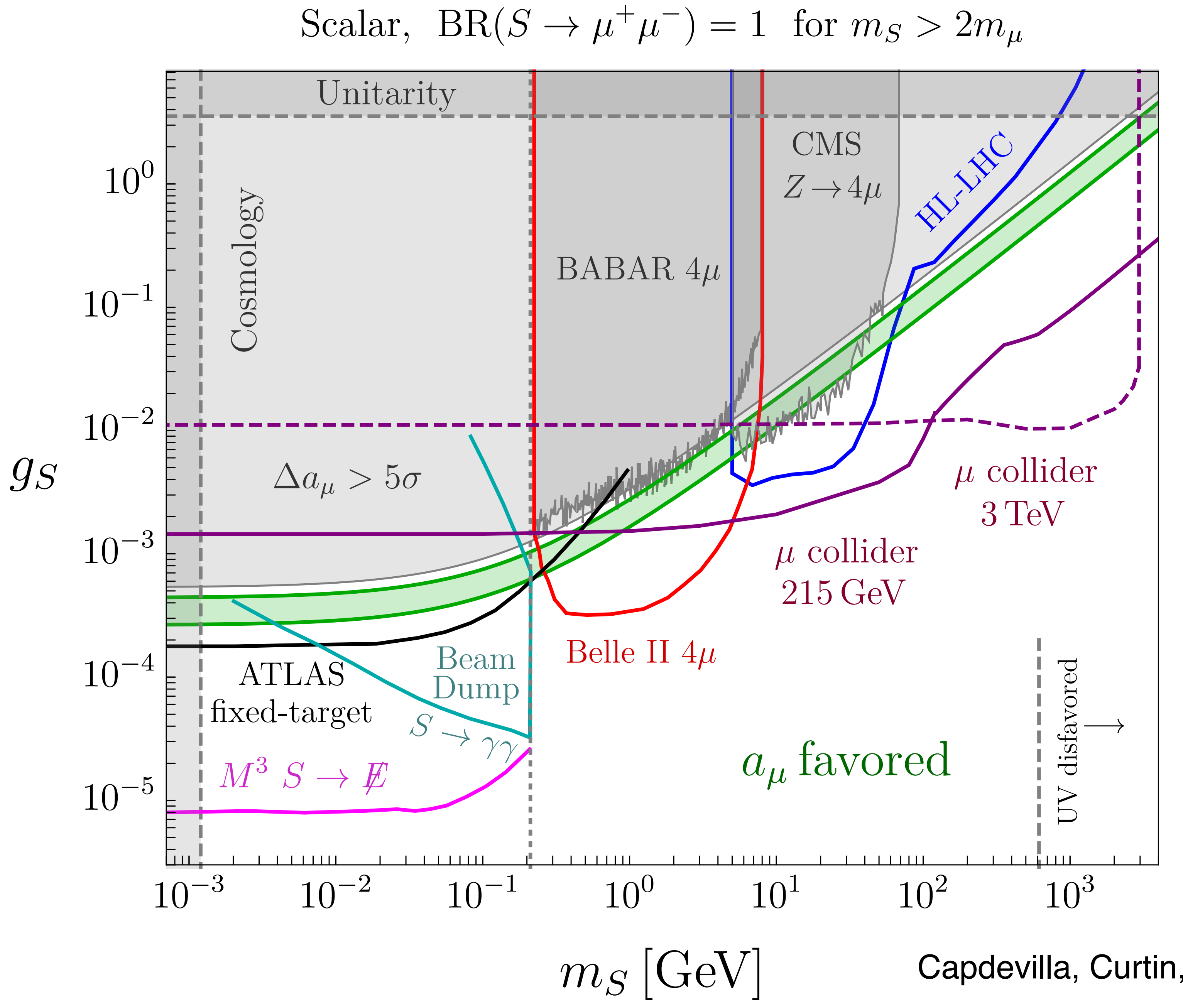
Capdevilla, Curtin, Kahnc, Krnjaic, 2112.08377



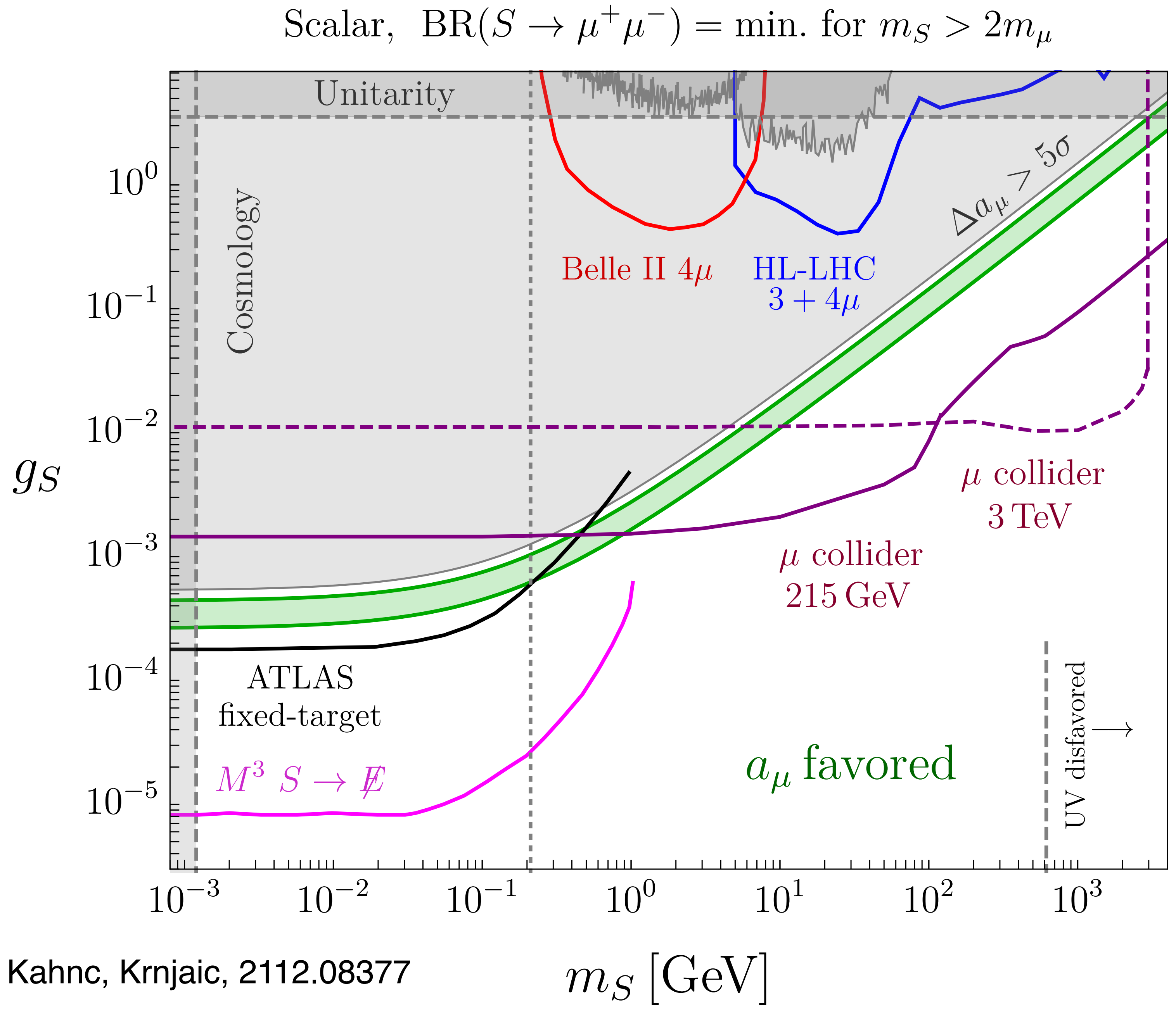
Collider Searches: scalar

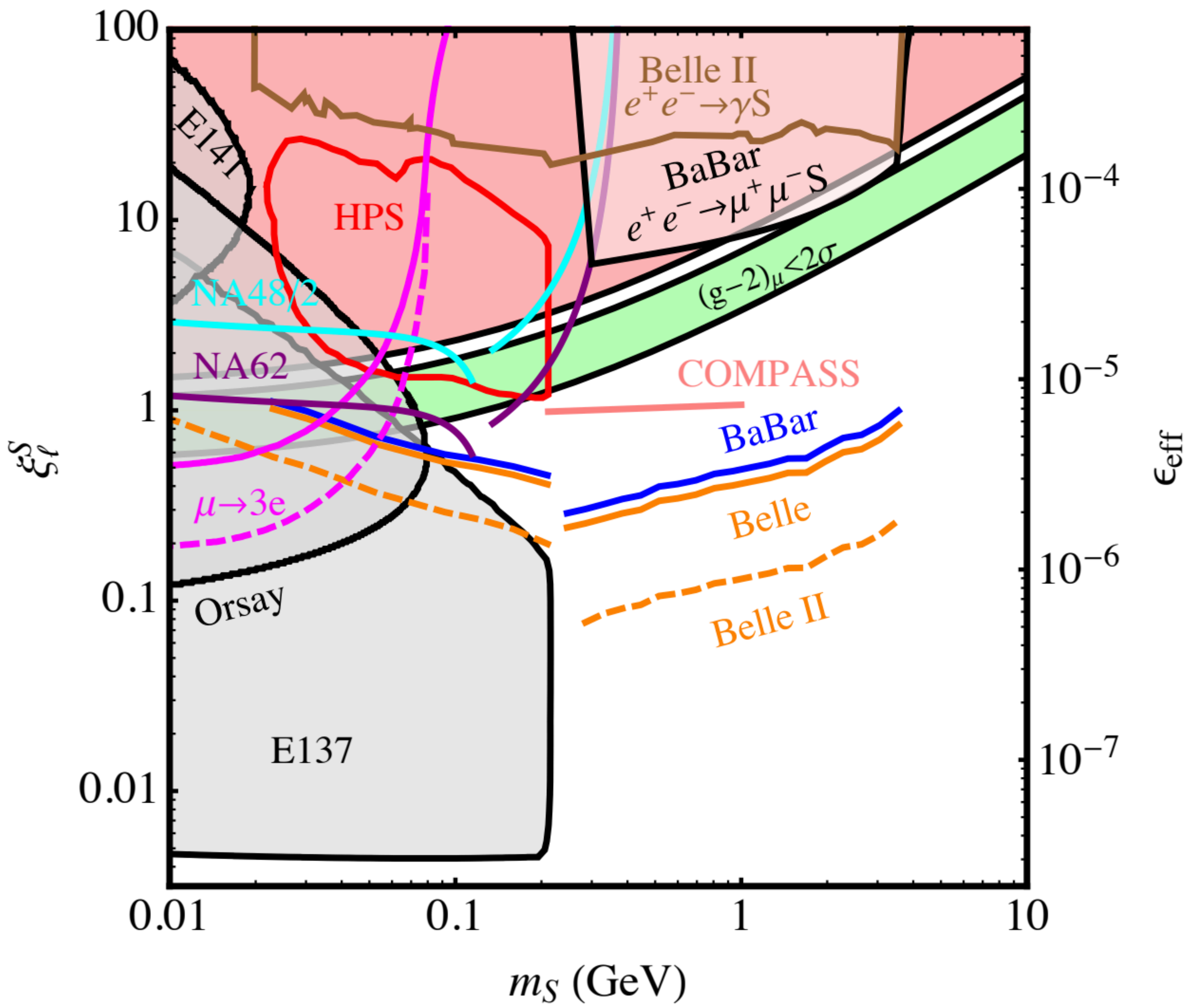






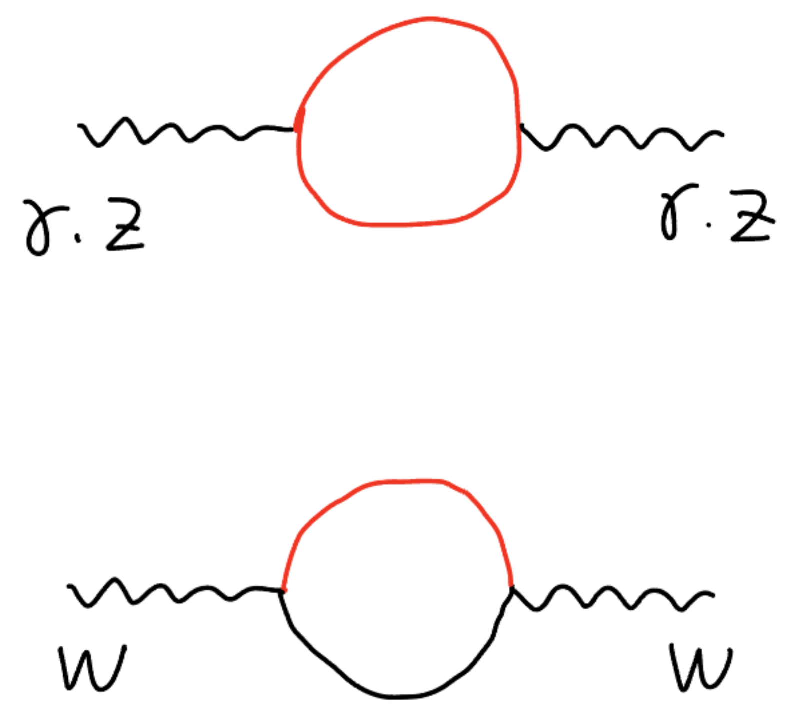
Capdevilla, Curtin, Kahnc, Krnjaic, 2112.08377



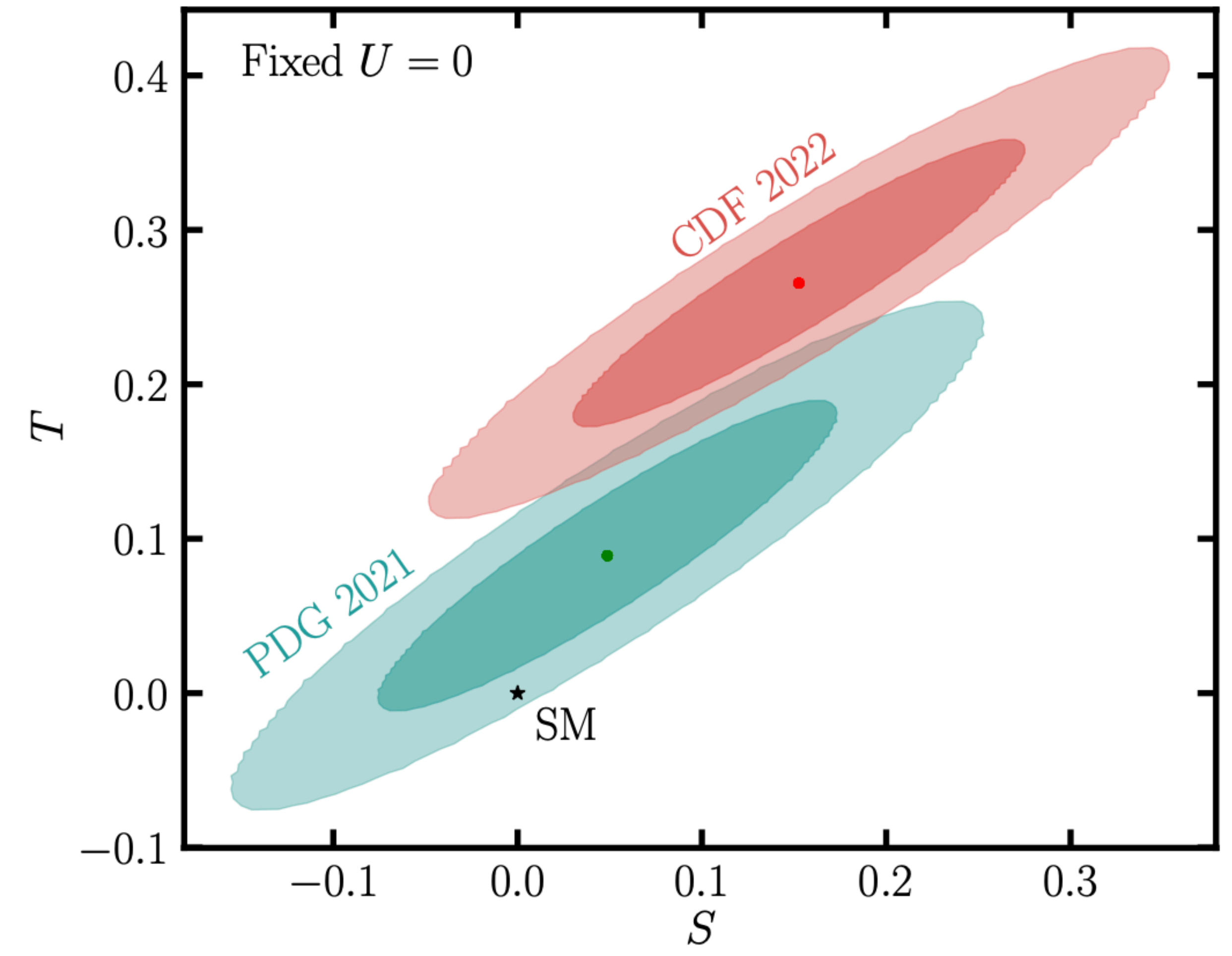


Batell, Lange, McKeen, Pospelov, Adam Ritz, 1606.04943

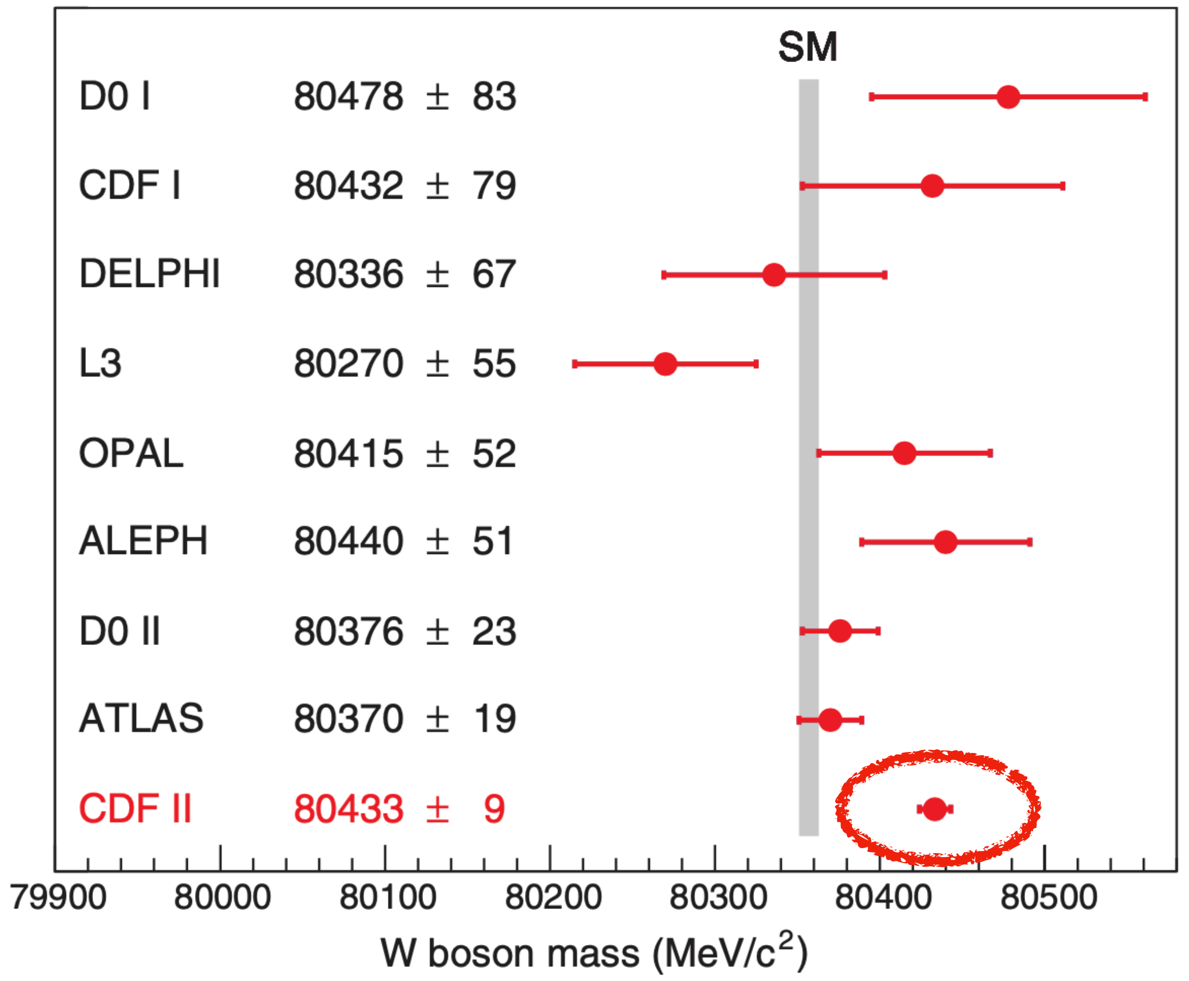
Motivation and idea



Chih-Ting Lu, Lei Wu, Yongcheng Wu, and Bin Zhu, 2204.03796

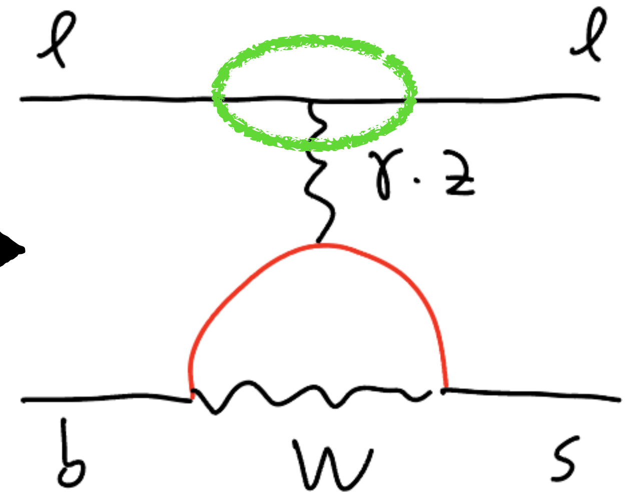


CDF W-mass shift

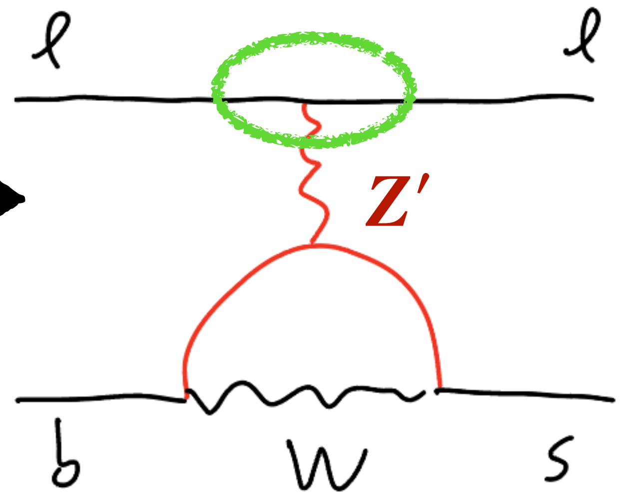


Fermion vector-like

LFUV ✗



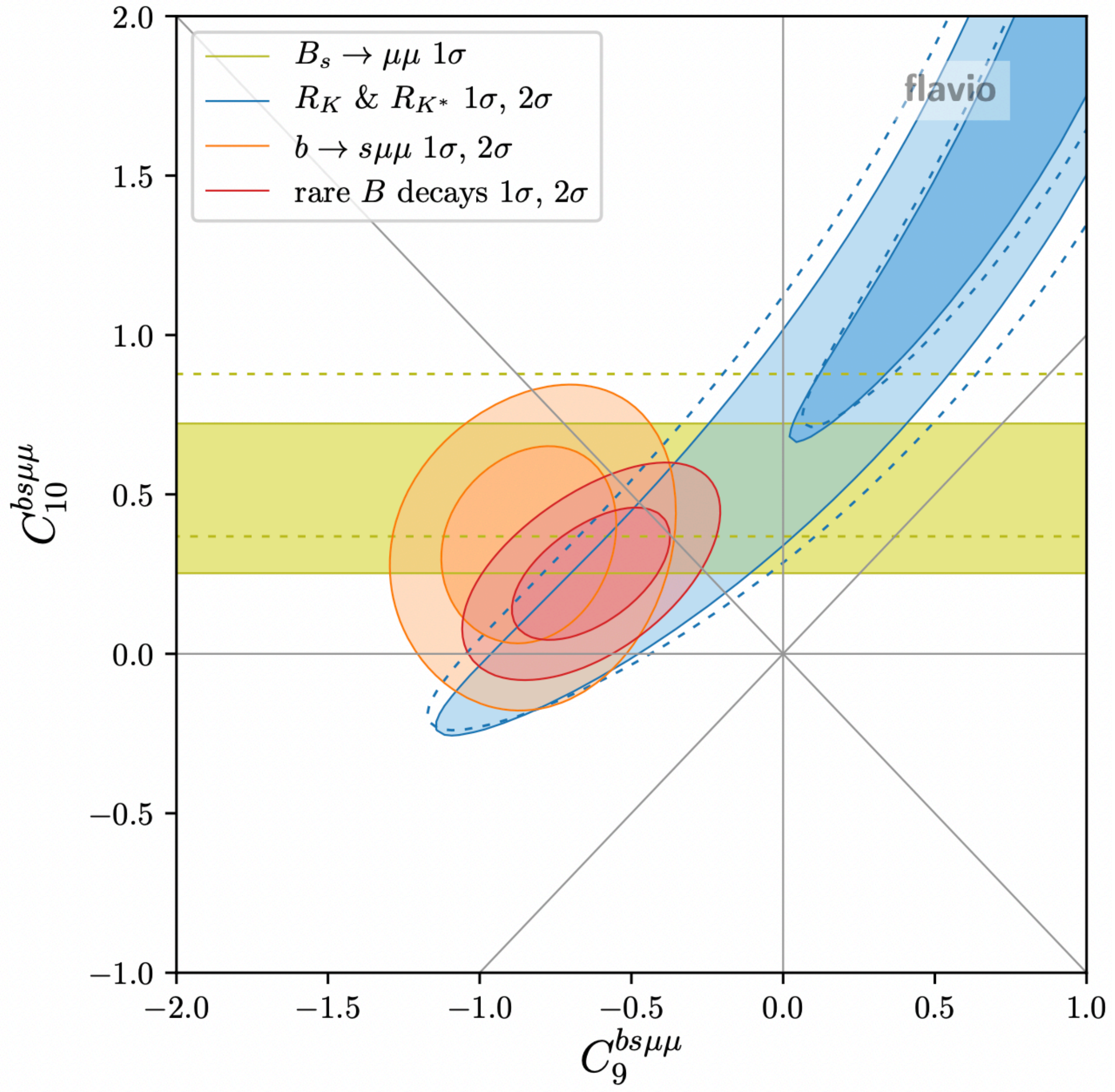
LFUV ✓



$U(1)'$

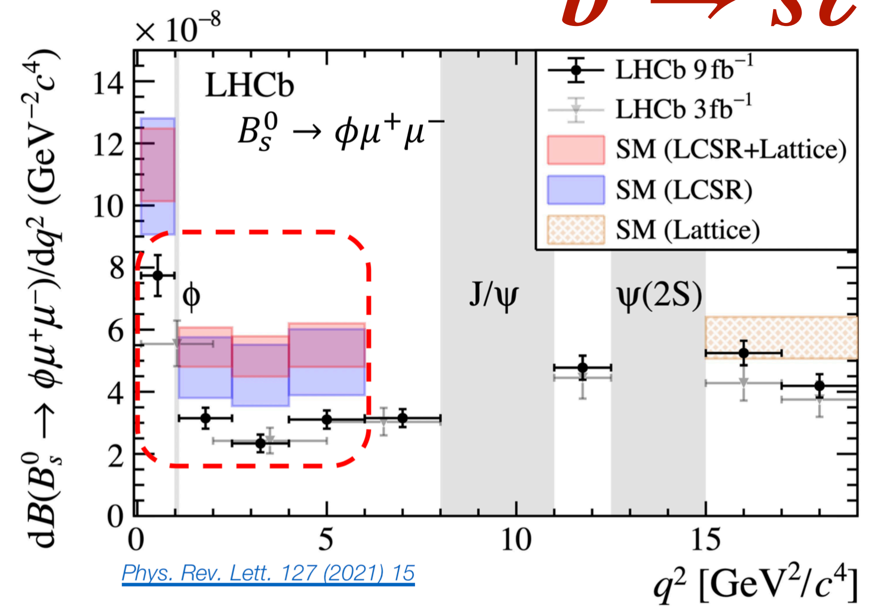
already introduced by J. F. Kamenik, Y. Soreq, J. Zupan, PRD97(2018)035002

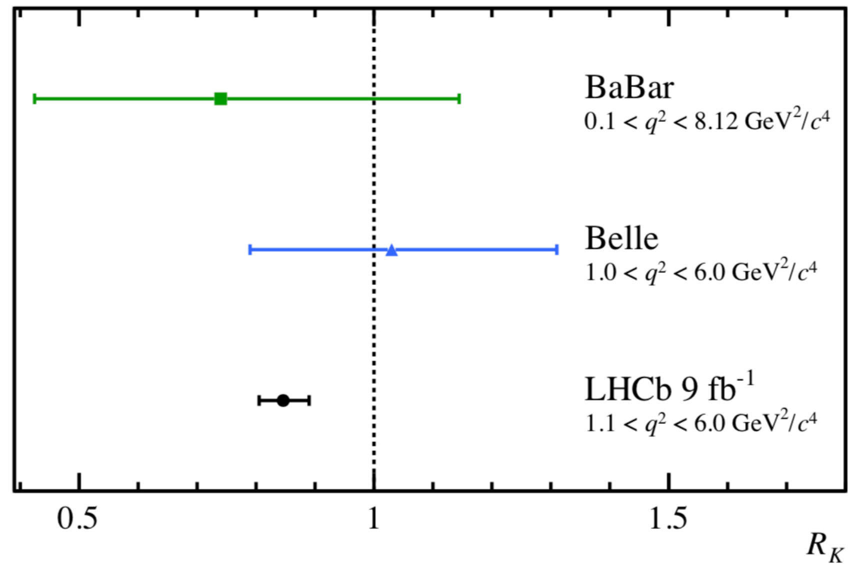
Altmannshofer, Stangl, 2103.1337

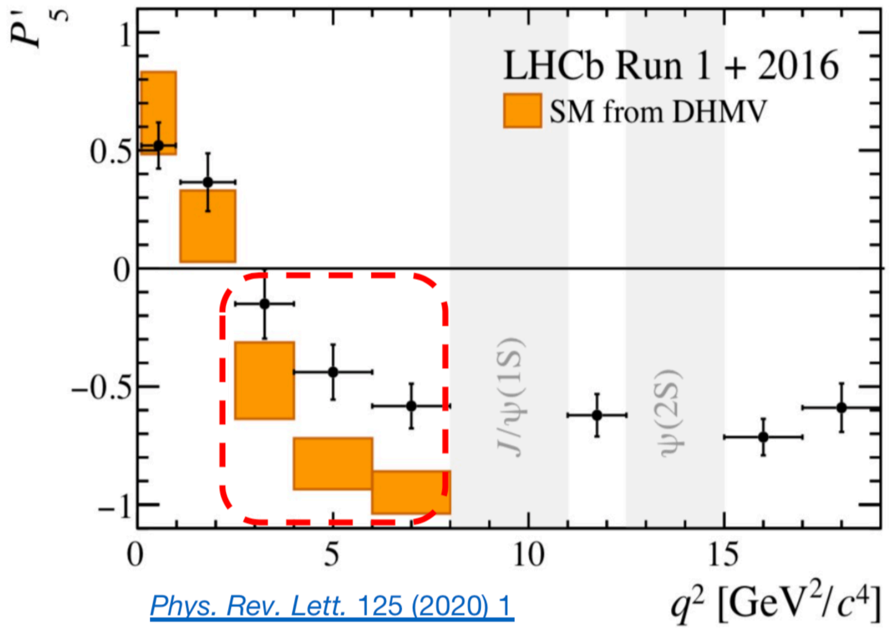


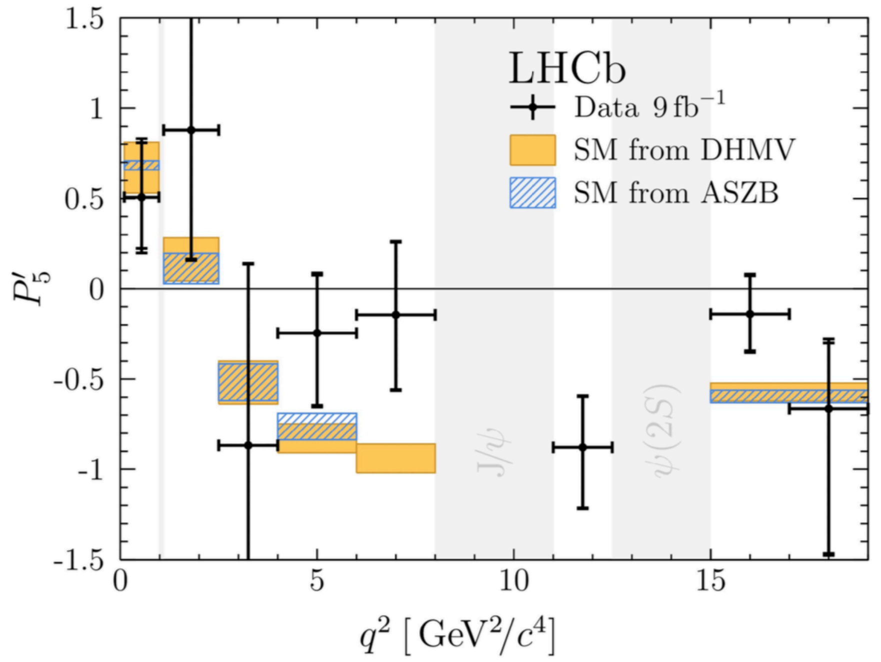
$$O_9 = (\bar{b}\gamma^\mu P_L s)(\bar{\ell}\gamma_\mu \ell) \quad O_{10} = (\bar{b}\gamma^\mu P_L s)(\bar{\ell}\gamma_\mu\gamma_5 \ell)$$

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









Top-philic Z' model

J. F. Kamenik, Y. Soreq, J. Zupan, PRD97 (3) (2018) 035002
P. J. Fox, I. Low, Y. Zhang, JHEP 03 (2018) 074
X.Q.Li, Z.J.Xie, Y.D.Yang, **XBY**, PLB 2023

- **Gauge group: $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)'$**
- **New fermions: vector-like top partner $U'_{L,R} \sim (3, 1, 2/3, q_t)$**
- **Lagrangian: quark sector**

$$\mathcal{L}_{\rm int} = \left(\lambda_H \bar{Q}_{3L} \tilde{H} u_{3R} + \lambda_\Phi \bar{U}'_L u_{3R} \Phi + \mu \bar{U}'_L U'_R + \text{h.c.}\right) + q_t g_t \left(\bar{U}'_L \gamma^\mu U'_L + \bar{U}'_R \gamma^\mu U'_R\right) Z'_\mu ,$$

- **Comments**
  - interaction eigenstates
  - Assuming only 3rd-gen SM quarks mix with the top partner
  - Vector-like top partner + Z'
- **Rotation from the interaction to the mass eigenstate**

$$\begin{pmatrix} t_L \\ T_L \end{pmatrix} = \begin{pmatrix} \cos\theta_L & -\sin\theta_L \\ \sin\theta_L & \cos\theta_L \end{pmatrix} \begin{pmatrix} u_{3L} \\ U'_L \end{pmatrix}$$

$$\begin{pmatrix} t_R \\ T_R \end{pmatrix} = \begin{pmatrix} \cos\theta_R & -\sin\theta_R \\ \sin\theta_R & \cos\theta_R \end{pmatrix} \begin{pmatrix} u_{3R} \\ U'_R \end{pmatrix}$$

mass **interaction**

$$\tan\theta_L = \frac{m_t}{m_T} \tan\theta_R$$

- **Mass matrix**

$$\begin{array}{cccc} u & c & t & T \end{array}$$

$$\begin{pmatrix} \lambda_{11} v_H & 0 & 0 & 0 \\ 0 & \lambda_{22} v_H & 0 & 0 \\ 0 & 0 & \lambda_H v_H & 0 \\ 0 & 0 & \lambda_{\Phi_t} v_{\Phi_t} & \sqrt{2}\mu \end{pmatrix}$$

mixing between t and T

Top-philic Z' model

J. F. Kamenik, Y. Soreq, J. Zupan, PRD97 (3) (2018) 035002
P. J. Fox, I. Low, Y. Zhang, JHEP 03 (2018) 074
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mass **interaction**

$$\tan\theta_L = \frac{m_t}{m_T} \tan\theta_R$$

- **Interactions**

$$\mathcal{L}_\gamma = \frac{2}{3} e \bar{t} \not{A} t + \frac{2}{3} e \bar{T} \not{A} T\,, \quad (7)$$

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} V_{td_i} \left(c_L \bar{t} \not{W} P_L d_i + s_L \bar{T} \not{W} P_L d_i\right) + {\rm h.c.}\,, \quad (8)$$

$$\mathcal{L}_Z = \frac{g}{c_W} (\bar{t}_L, \bar{T}_L) \begin{pmatrix} \frac{1}{2}c_L^2 - \frac{2}{3}s_W^2 & \frac{1}{2}s_L c_L \\ \frac{1}{2}s_L c_L & \frac{1}{2}s_L^2 - \frac{2}{3}s_W^2 \end{pmatrix} \not{Z} \begin{pmatrix} t_L \\ T_L \end{pmatrix} + \frac{g}{c_W} (\bar{t}_R, \bar{T}_R) \left(-\frac{2}{3}s_W^2\right) \not{Z} \begin{pmatrix} t_R \\ T_R \end{pmatrix}, \quad (9)$$

$$\mathcal{L}_{Z'} = q_t g_t (\bar{t}_L, \bar{T}_L) \begin{pmatrix} s_L^2 & -s_L c_L \\ -s_L c_L & c_L^2 \end{pmatrix} \not{Z}' \begin{pmatrix} t_L \\ T_L \end{pmatrix} + (L \to R)\,, \quad (10)$$

- **lepton sector** (effective coupling)

$$\mathcal{L}_\mu = \bar{\mu} \not{Z}' \left(g_\mu^L P_L + g_\mu^R P_R\right) \mu$$

- **NP parameters**

$$(\cos\theta_L,\, m_T,\, g_\mu^L,\, g_\mu^R,\, g_t,\, q_t,\, m_{Z'})$$

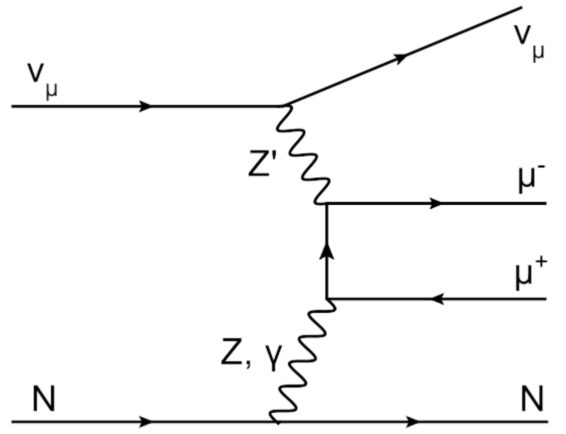
Z' model with UV-complete lepton sector

X.Q.Li, Z.J.Xie, Y.D.Yang, **XBY**, NPB 2024

Requirements

lepton sector: $\mathcal{L}_\mu = \bar{\mu} \not{Z}' \left(g_\mu^L P_L + g_\mu^R P_R\right) \mu$

- **anomaly free**
- **almost vector type $Z'\ell\ell$ int. ($\Longleftarrow b \to s\ell\ell$ global fit)**
- **explain $(g-2)_\mu$**
- **satisfy neutrino trident production**
- **provide neutrino masses**



Altmannshofer, Gori, Pospelov, Yavin, 2014

Constructions

- **Gauge group: $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)'$**

$$L_{2L} = (\mathbf{1},\, \mathbf{2},\, -1/2,\, +q_\ell) \qquad e_{2R} = (\mathbf{1},\, \mathbf{1},\, -1,\, +q_\ell)$$
$$L_{3L} = (\mathbf{1},\, \mathbf{2},\, -1/2,\, -q_\ell) \qquad e_{3R} = (\mathbf{1},\, \mathbf{1},\, -1,\, -q_\ell)$$

i.e., $L_\mu - L_\tau$

- **New vector-like muon partner**

$$E_{L/R} = (\mathbf{1},\, \mathbf{1},\, -1,\, 0)$$

- **Two complex scalars**

$$\phi = (\mathbf{1},\, \mathbf{1},\, 0,\, 0) \qquad \Phi_\ell = (\mathbf{1},\, \mathbf{1},\, 0,\, -q_\ell)$$

generate muon partner mass | **induce muon partner-muon mixing**

Lagrangian

$$\Delta\mathcal{L}_\ell = -\left(\eta_H \bar{L}_{2L}\tilde{H} e_{2R} + \lambda_{\Phi_\ell}\bar{E}_L e_{2R}\Phi_\ell + \lambda_\phi \bar{E}_L E_R \phi + \text{h.c.}\right) + q_\ell g' \left(\bar{L}_{2L}\gamma^\mu L_{2L} + \bar{e}_{2R}\gamma^\mu e_{2R} - \bar{L}_{3L}\gamma^\mu L_{3L} - \bar{e}_{3R}\gamma^\mu e_{3R}\right) Z'_\mu$$

Diagonalize mass matrix

$$\tan\delta_L = \frac{m_\mu}{m_M}\tan\delta_R$$

$$\begin{pmatrix}\mu_L\\ M_L\end{pmatrix} = R(\delta_L)\begin{pmatrix}e_{2L}\\ E_L\end{pmatrix} \qquad \begin{pmatrix}\mu_R\\ M_R\end{pmatrix} = R(\delta_R)\begin{pmatrix}l_{2R}\\ E_R\end{pmatrix}$$

mass **interaction** **mass** **interaction**

Interaction

$s_L = sin\delta_L,\ c_L = cos\delta_L$

$$\mathcal{L}_\gamma^\ell = -e\bar{\mu}\not{A}\mu - e\bar{M}\not{A}M,$$

$$\mathcal{L}_W^\ell = \frac{g}{\sqrt{2}}\left(\hat{c}_L \bar{\mu}\not{W} P_L \nu_\mu + \hat{s}_L \bar{M}\not{W} P_L \nu_\mu\right) + \text{ h.c.},$$

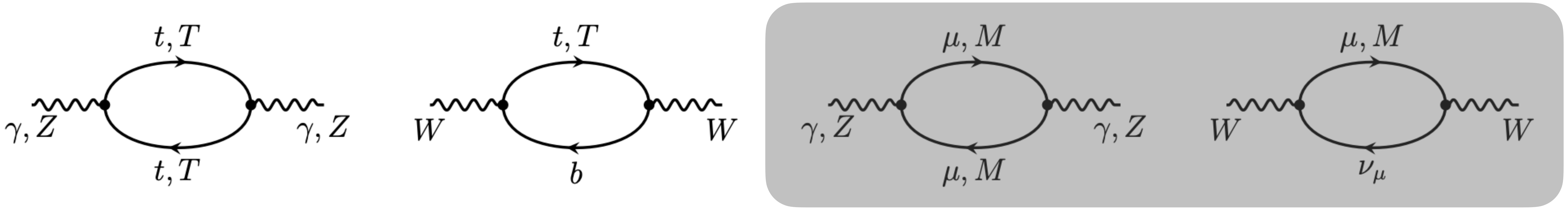
$$\mathcal{L}_Z^\ell = \frac{g}{c_W}\left(\bar{\mu}_L, \bar{M}_L\right)\begin{pmatrix}-\frac{1}{2}\hat{c}_L^2 + s_W^2 & -\frac{1}{2}\hat{s}_L\hat{c}_L\\ -\frac{1}{2}\hat{s}_L\hat{c}_L & -\frac{1}{2}\hat{s}_L^2 + s_W^2\end{pmatrix}\not{Z}\begin{pmatrix}\mu_L\\ M_L\end{pmatrix} + \frac{g}{c_W}s_W^2\left(\bar{\mu}_R, \bar{M}_R\right)\not{Z}\begin{pmatrix}\mu_R\\ M_R\end{pmatrix}$$

$$\mathcal{L}_{Z'}^\ell = q_\ell g'\left(\bar{\mu}_L, \bar{M}_L\right)\begin{pmatrix}\hat{c}_L^2 & \hat{s}_L\hat{c}_L\\ \hat{s}_L\hat{c}_L & \hat{s}_L^2\end{pmatrix}\not{Z}'\begin{pmatrix}\mu_L\\ M_L\end{pmatrix} + (L \to R)$$

$$sin\delta_L < 0.01$$

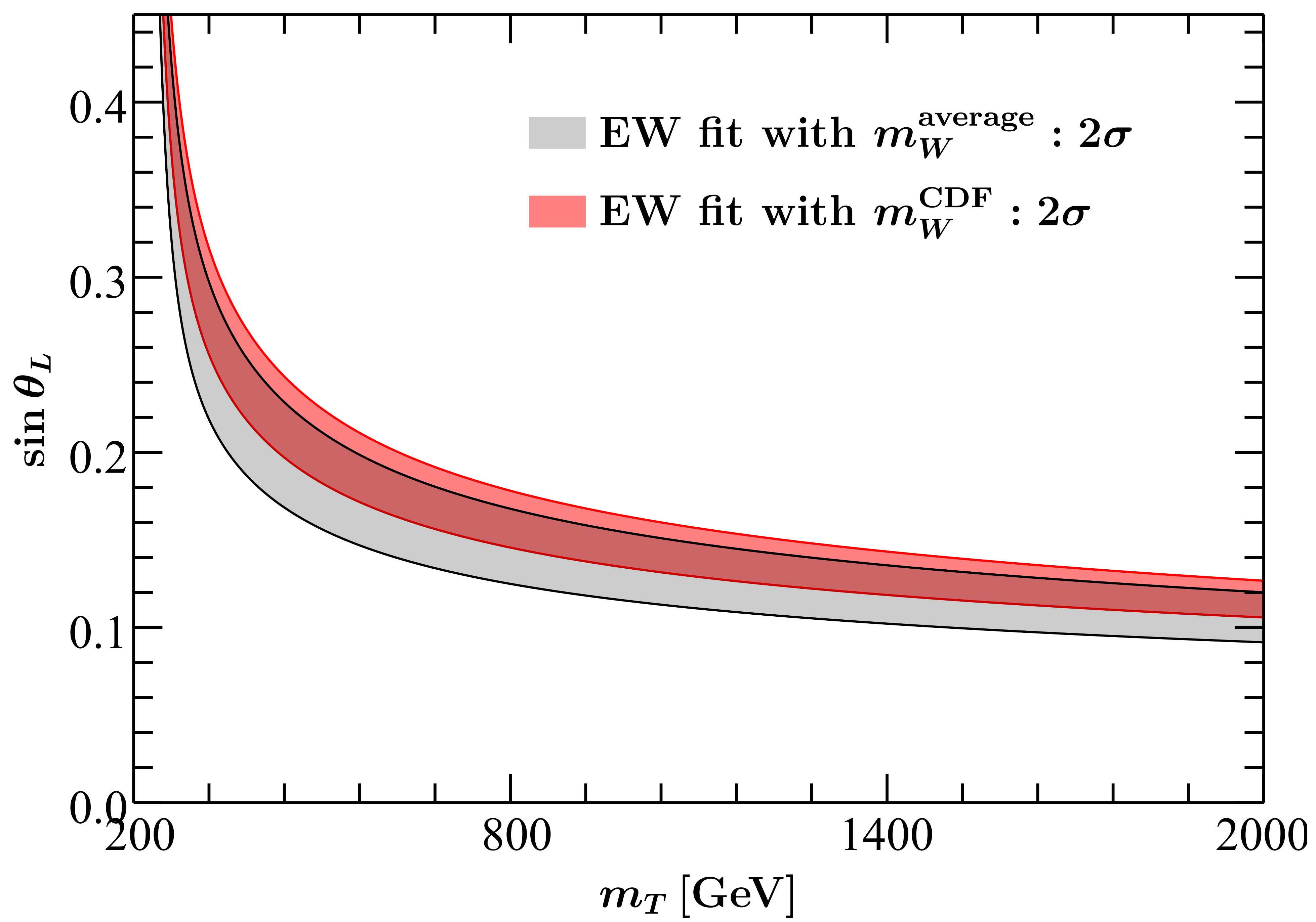
W-boson mass shift

- **Feynman diagrams**



highly suppressed by small δ_L

- **Result**



same with the previous work

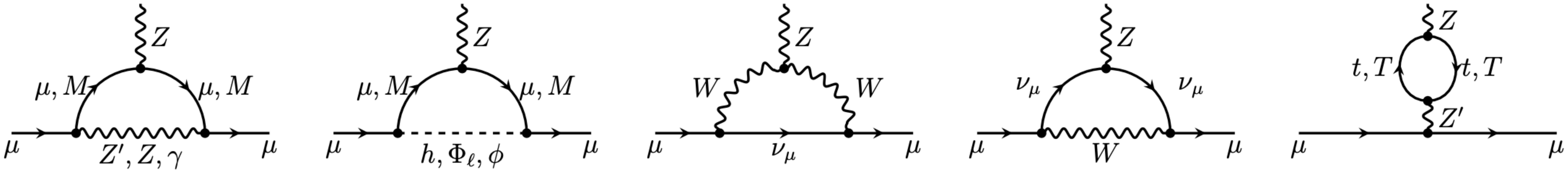
$Z \to \mu^+\mu^-$

$$\begin{pmatrix} \mu_L \\ M_L \end{pmatrix} = \begin{pmatrix} \cos\delta_L & -\sin\delta_L \\ \sin\delta_L & \cos\delta_L \end{pmatrix} \begin{pmatrix} e_{2L} \\ E_L \end{pmatrix}$$

mass **interaction**

To cancel the UV divergences, the mixing angle δ_L should be renormalized.

- **Feynman diagrams**



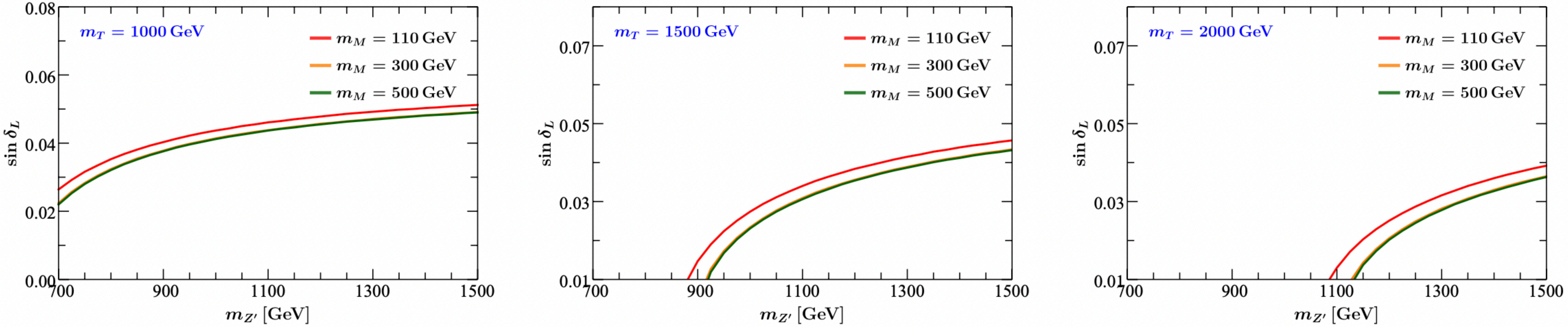
- **Effective couplings**

$$\mathcal{L} = \frac{g}{c_W}\bar{\ell}\not{Z}(g_{L\ell}P_L + g_{R\ell}P_R)\ell$$

- **Observables** $R_{\mu/e} = \Gamma(Z \to \mu^+\mu^-)/\Gamma(Z \to e^+e^-)$

$$\mathcal{A}_\mu = \frac{\Gamma(Z \to \mu_L^+\mu_L^-) - \Gamma(Z \to \mu_R^+\mu_R^-)}{\Gamma(Z \to \mu^+\mu^-)}$$

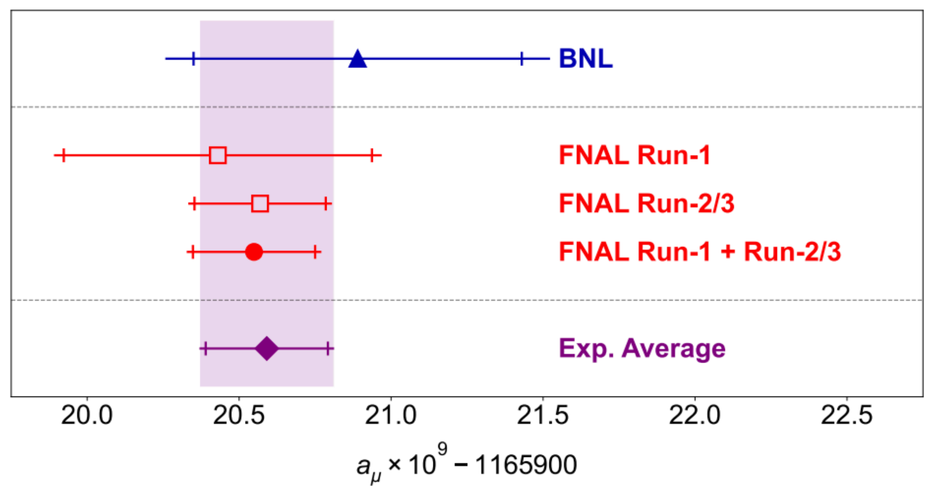
- **Constraints: m_W and $Z \to \mu^+\mu^-$**

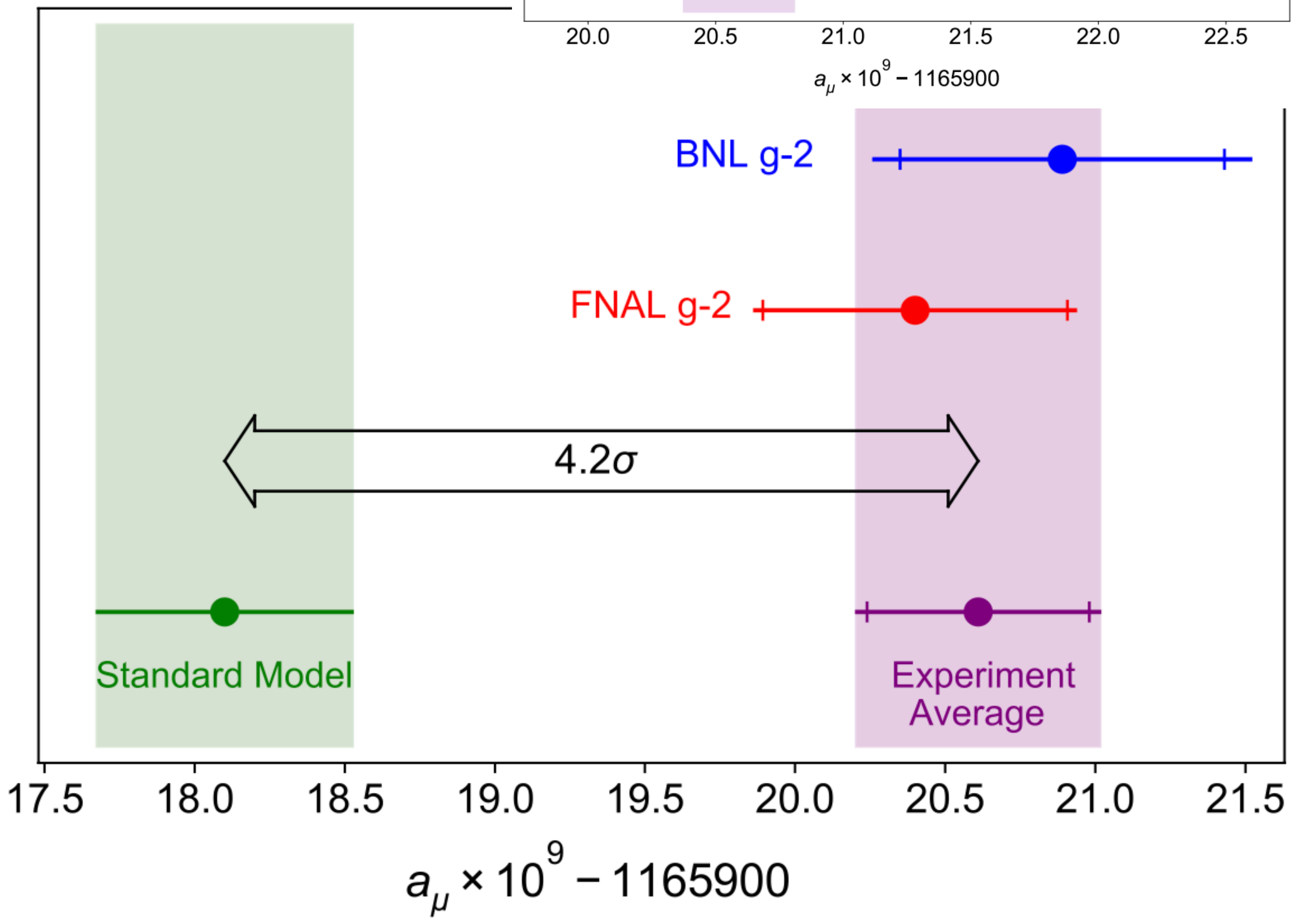


$\sin\delta_L < 0.05$ is obtained. However, $\sin\delta_L < 0.01$ is considered for simplicity.

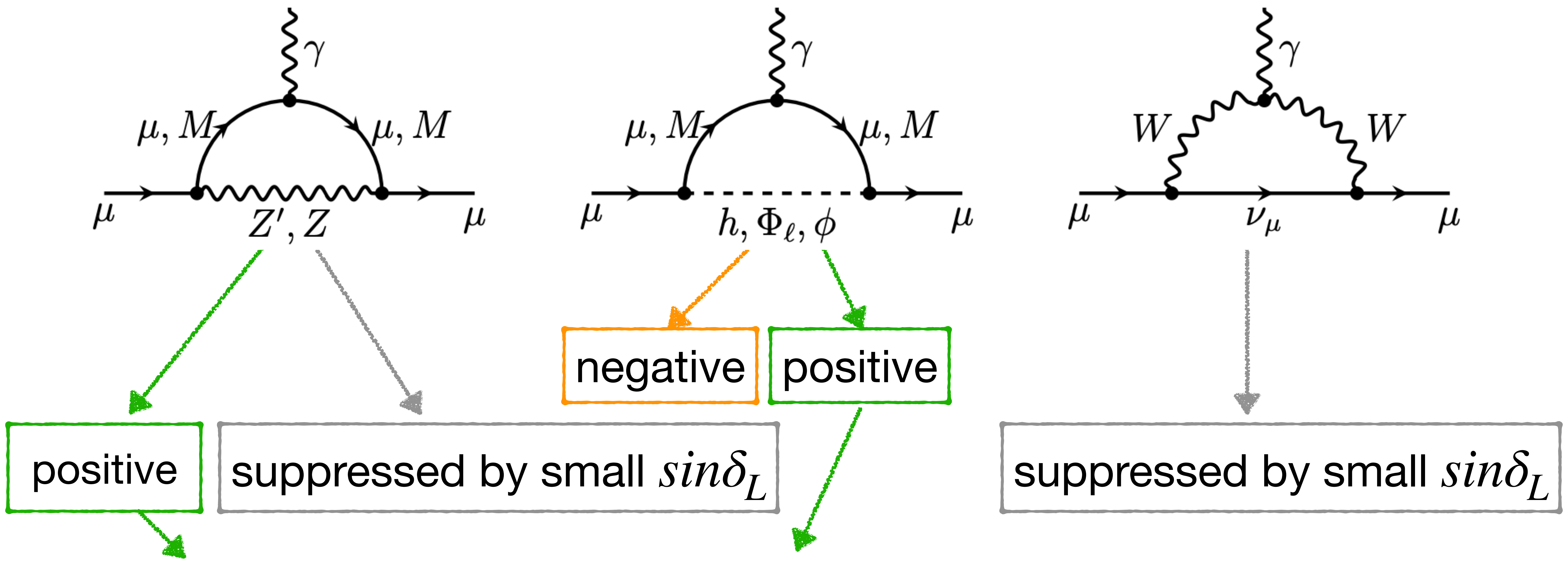
$(g-2)_\mu$

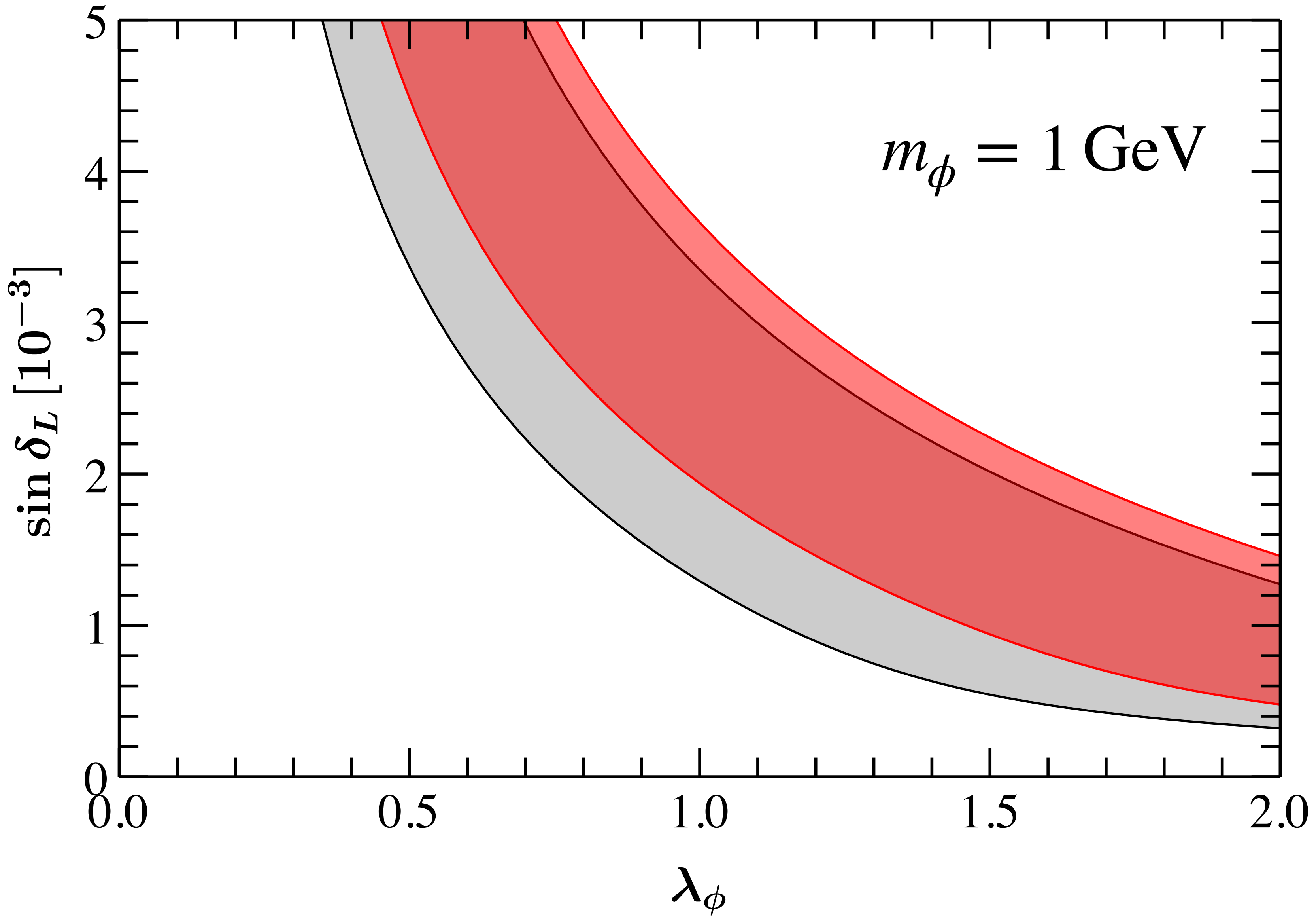
$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = 251 \pm 59$





- **Feynman diagrams**





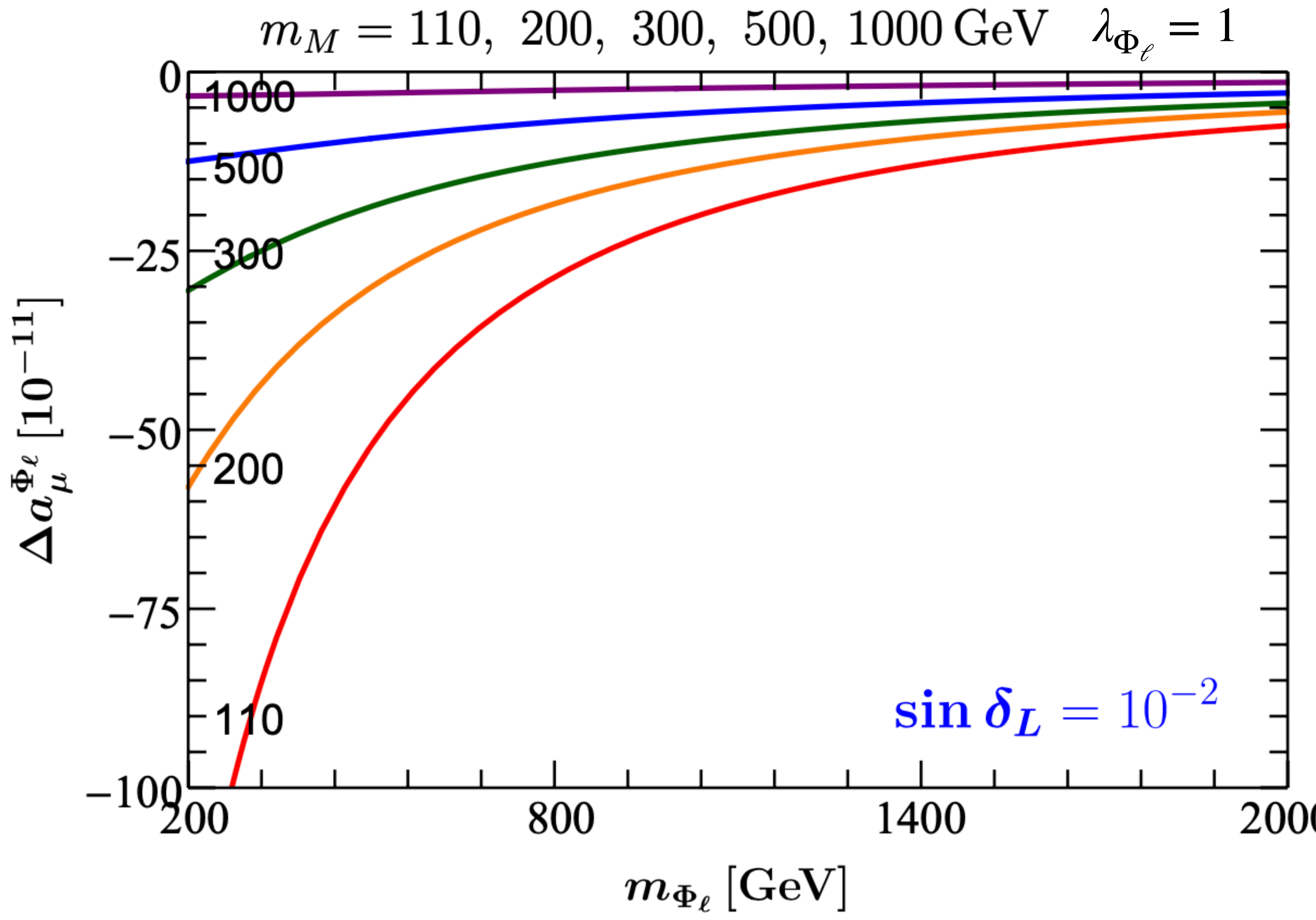
$2\,\sigma$ allowed region

- ϕ
- $\phi + Z'$ (**ν trident prod. Included**)

ϕ **alone can explain $(g-2)_\mu$ anomaly**

$\sin\delta_L$ is lower bounded

$3.2 \times 10^{-4} < \sin\delta_L < 1.0 \times 10^{-2}$



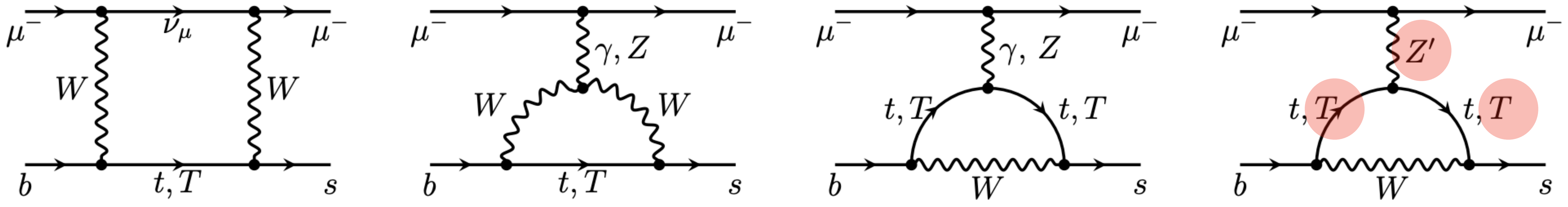
choose $m_{\Phi_\ell} > 2\,\mathrm{TeV}$ to suppress this negative contribution

Global fit: $b \to s\ell^+\ell^-$

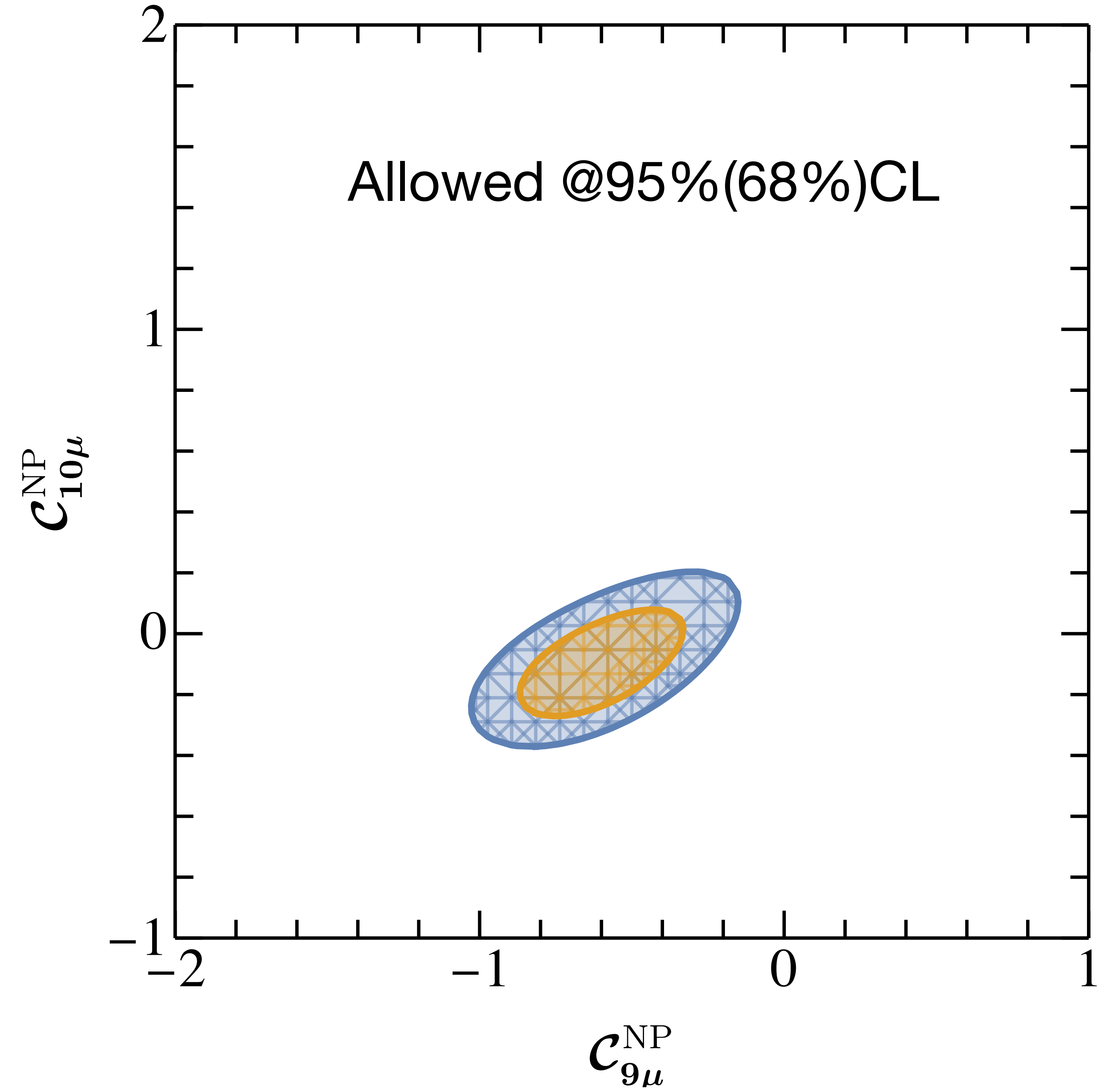
Recent LHCb results in LHCb-PAPER-2023-032, 033 not considered in our work

▶ Global fit

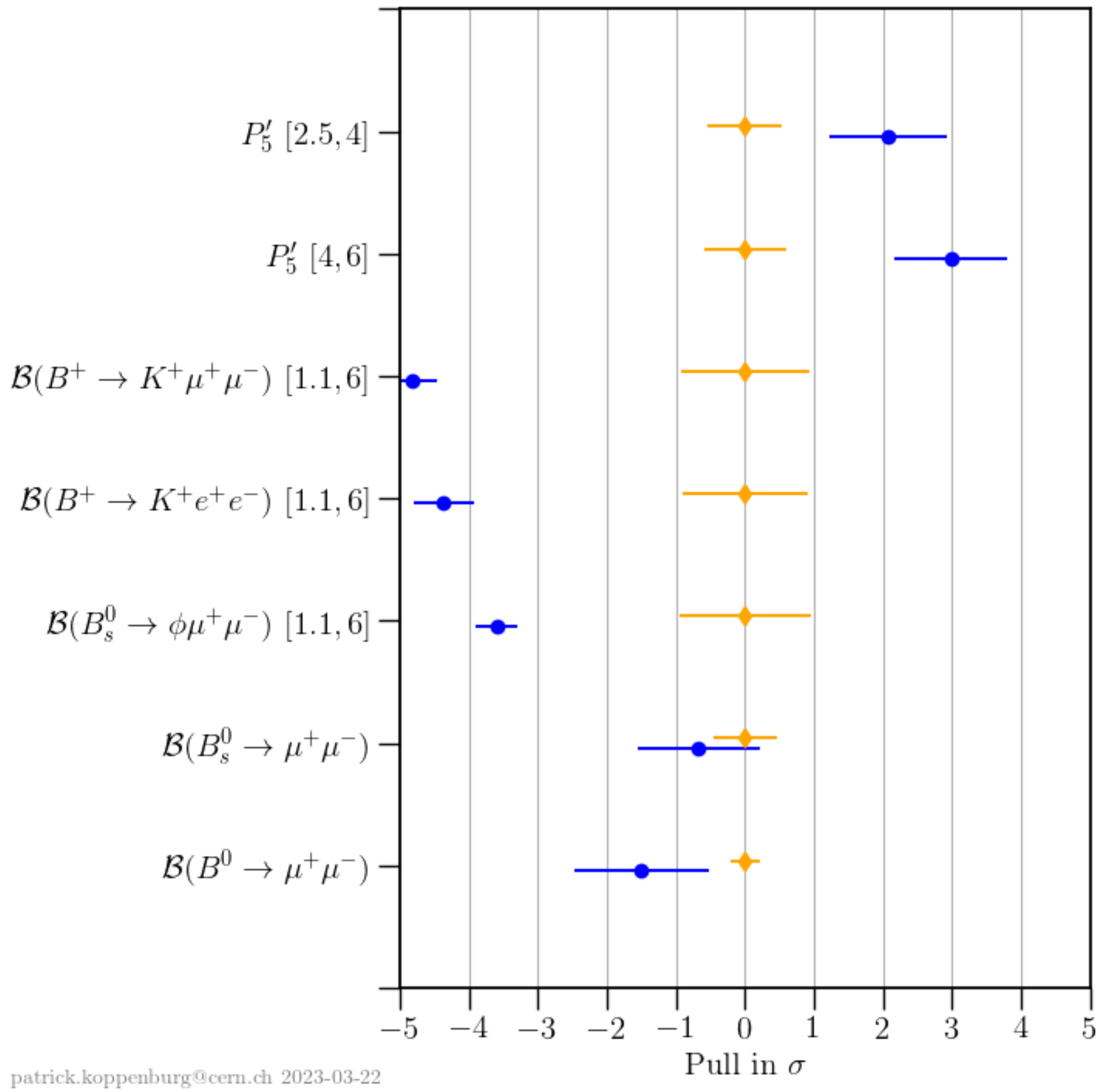
- Inclusive decays
  - $B \to X_s\gamma$
  - $B \to X_s\ell^+\ell^-$
- Exclusive leptonic decays
  - $B_{s,d} \to \ell^+\ell^-$
- Exclusive radiative/semileptonic decays
  - $B \to K^*\gamma$
  - $B^{(0,+} \to K^{(0,+)}\ell^+\ell^-$
  - $B^{(0,+} \to K^{*(0,+)}\ell^+\ell^-$
  - $B_s \to \phi\mu^+\mu^-$
  - $\Lambda_b \to \Lambda\mu^+\mu^-$
- Including about 200 observables (almost all available measurements from BaBar, Belle, CDF, ATLAS, CMS, and LHCb)
- performed using an extended version of the package **`flavio`**



▶ Fit result



▶ Current discrepancies



CMS and LHCb's new measurements included

Global constraints

- $Z\mu\mu$ couplings
- W-boson mass
- $b \to s\mu\mu$
- ν trident production

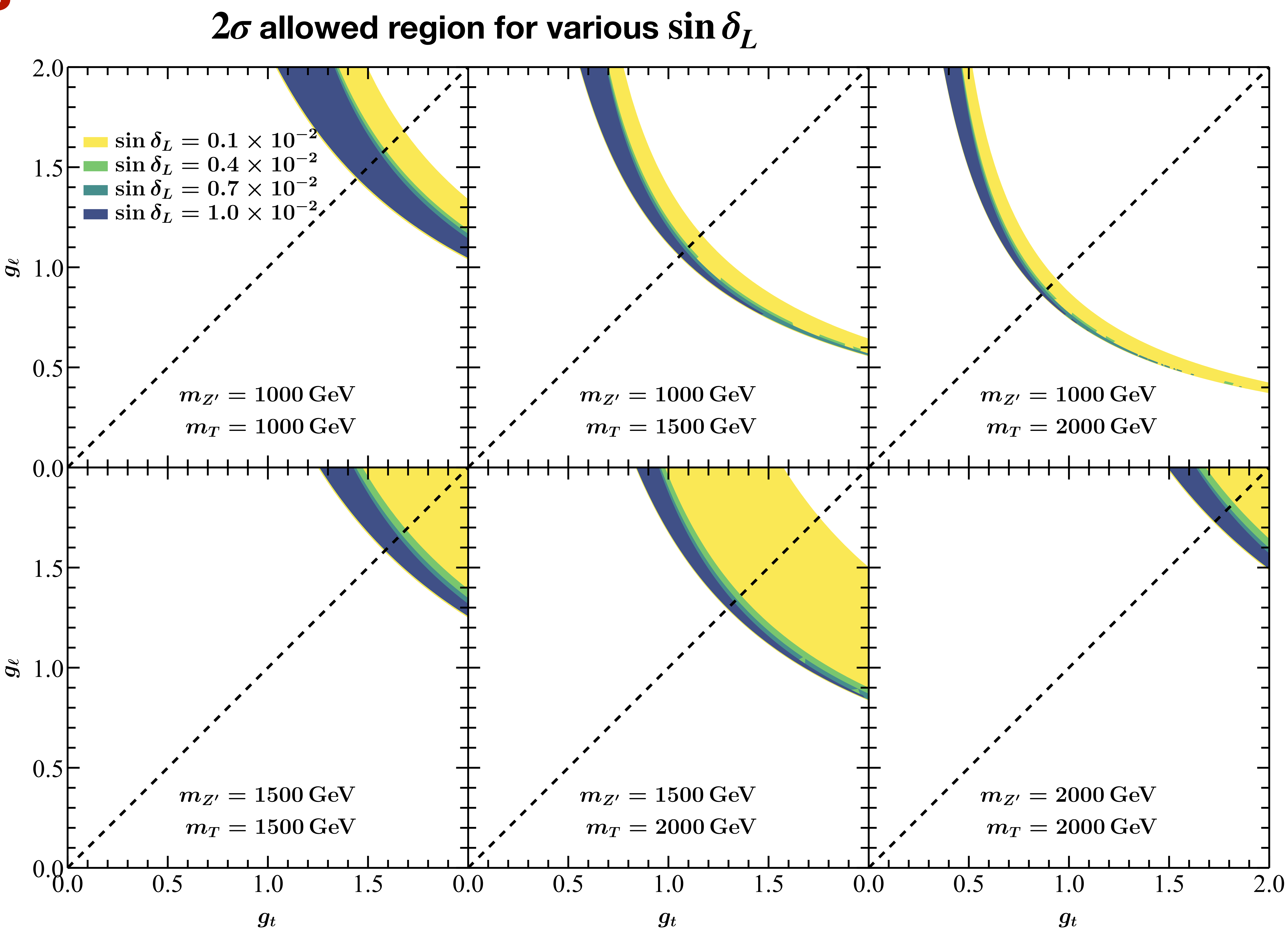
- Fixed parameters

$$m_\phi = 1\,\text{GeV} \qquad \lambda_\phi = 1$$
$$m_{\Phi_\ell} = 2\,\text{TeV} \qquad \lambda_{\Phi_\ell} = 0.1$$

- Free parameters

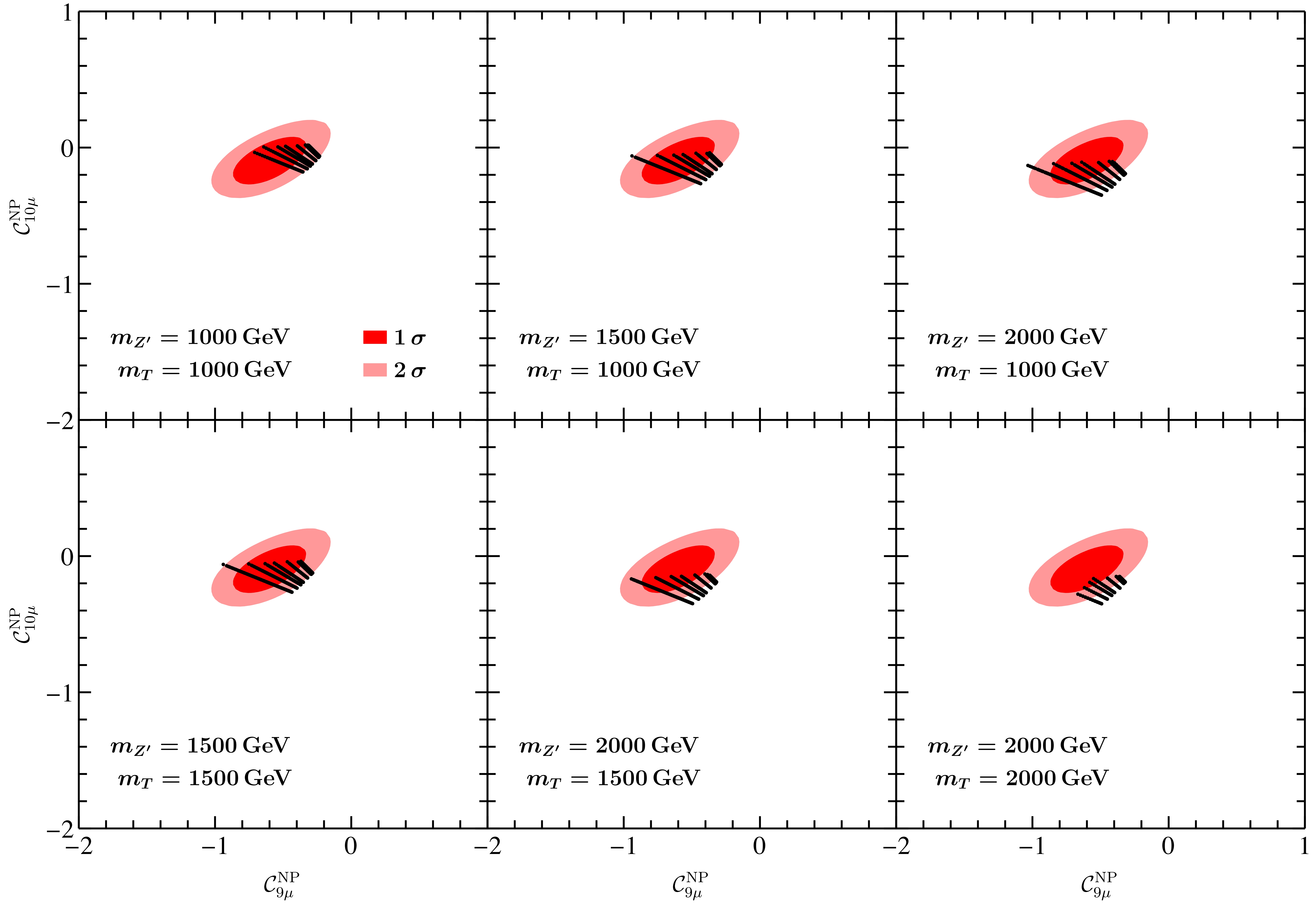
$$(m_T, \sin\theta_L, m_M, \sin\delta_L, m_{Z'}, g_t, g_\ell)$$

$$g_t \equiv q_t g' \quad g_\ell \equiv q_\ell g'$$



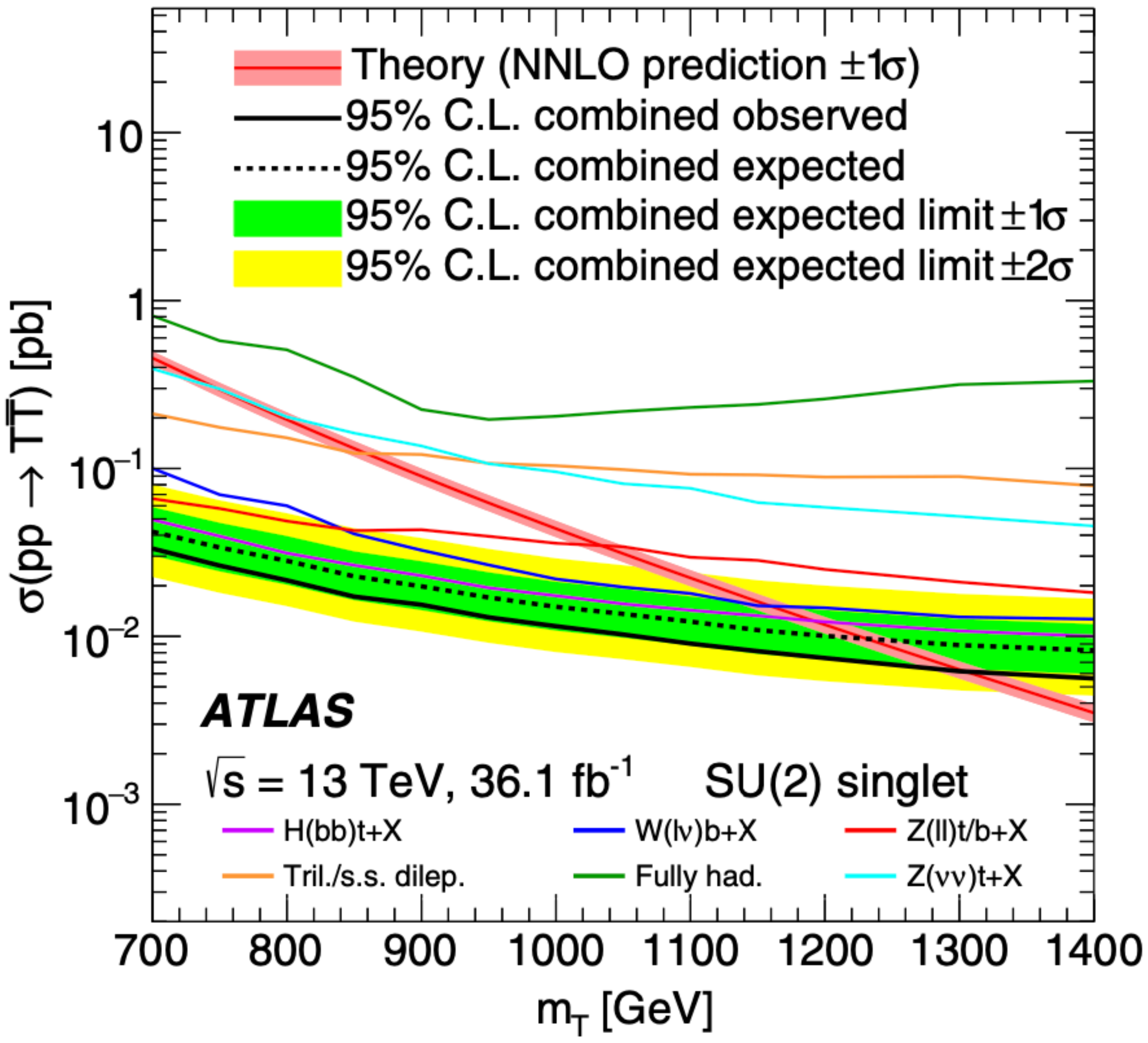
Predictions on (C_9, C_{10}) in $b \to s\ell^+\ell^-$

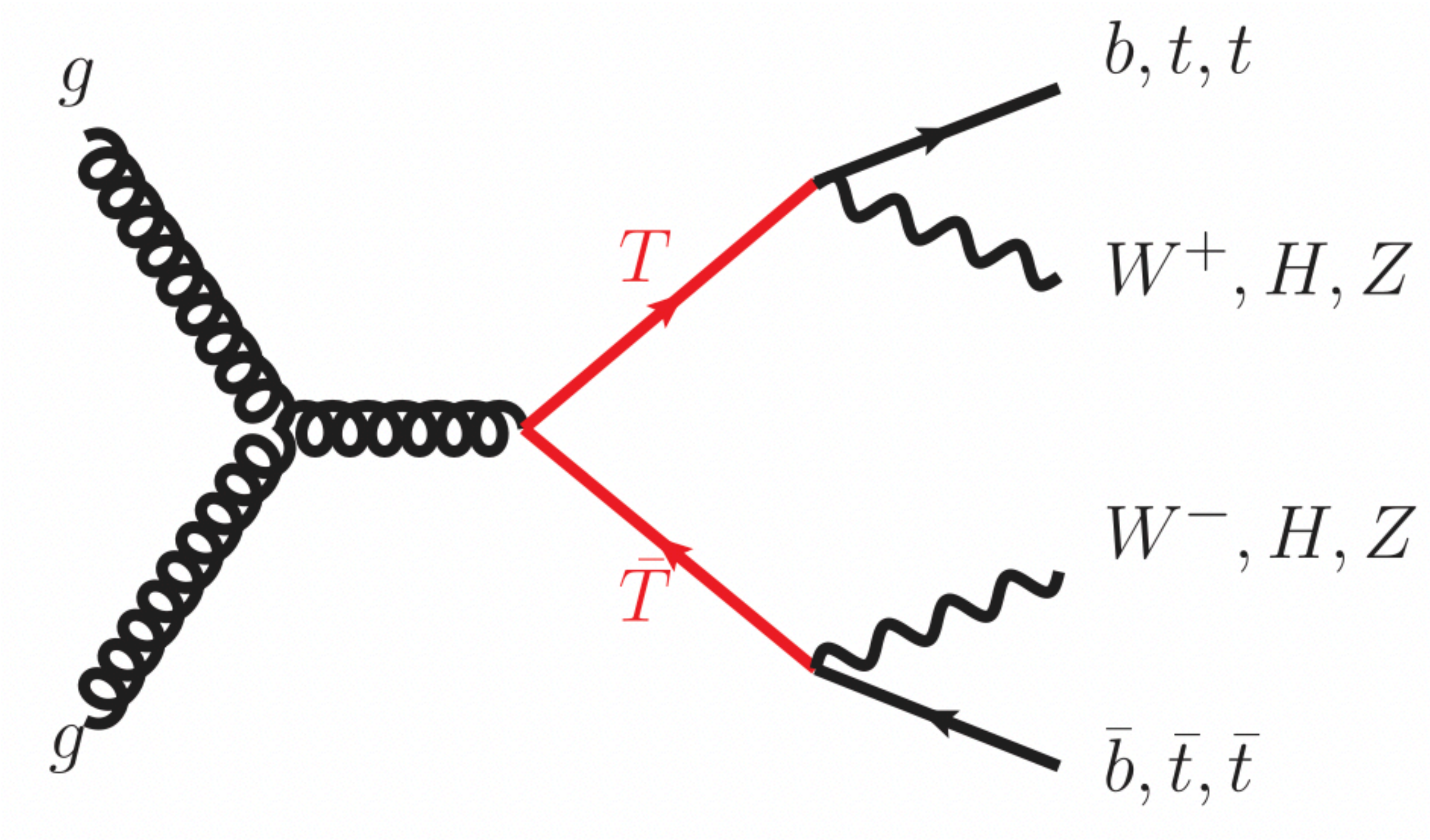
predictions shown in the black points



Collider Searches: $m_T < m_{Z'}$

ATLAS, Phys. Rev. Lett. 121 (2018), no. 21 211801



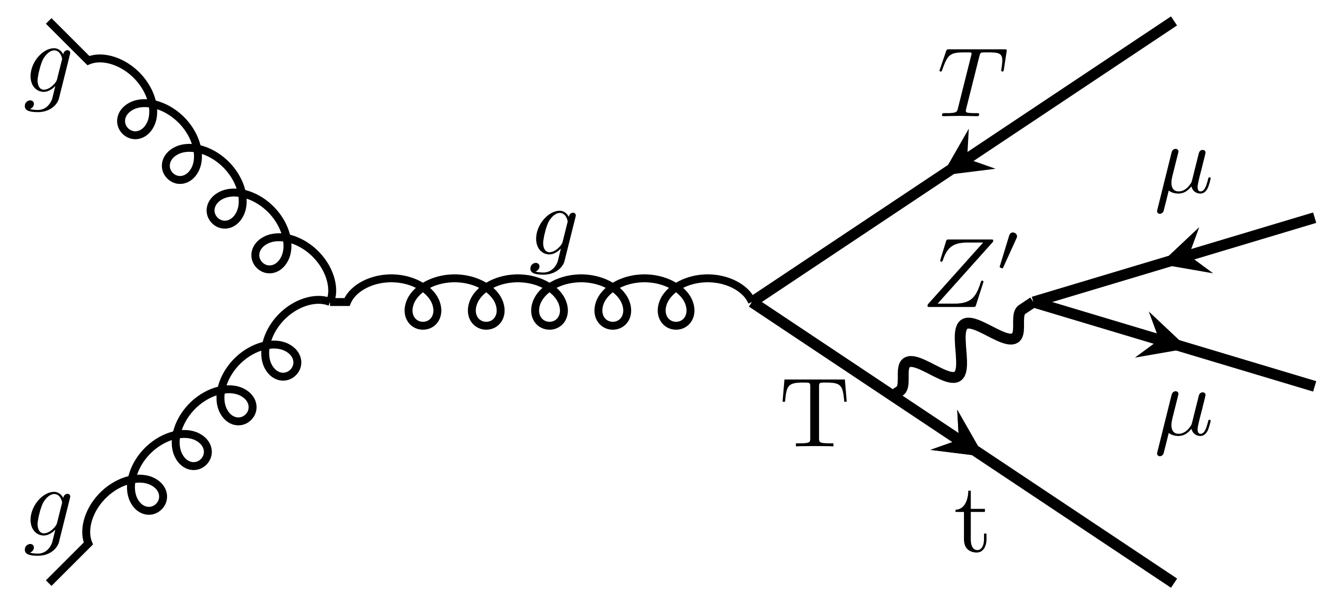


$m_T > 1.3\,\mathrm{TeV}$

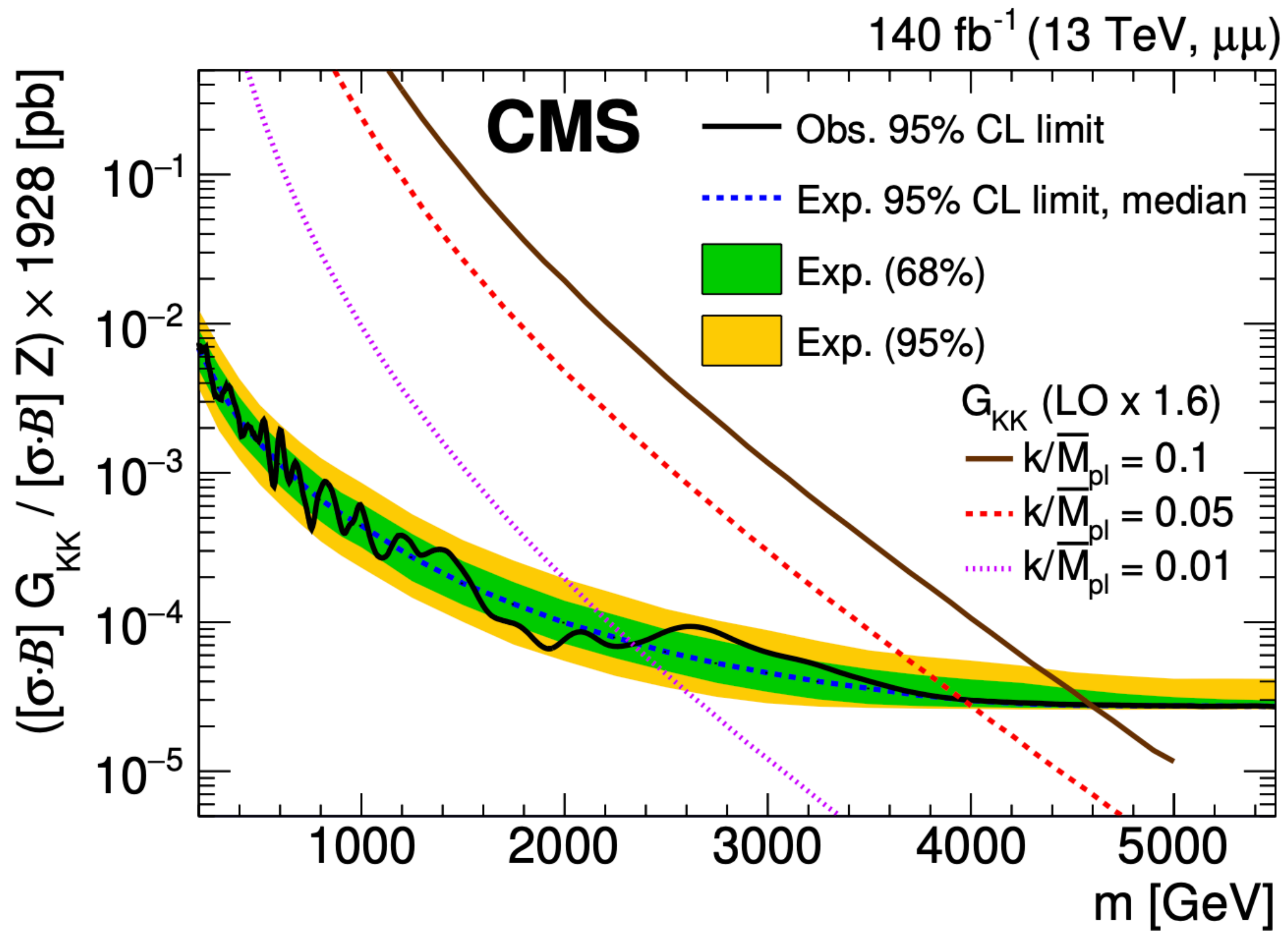
same with the regular top partner scenarios

Collider Searches: $m_T > m_{Z'}$

$pp \to \mu^+\mu^- + X$



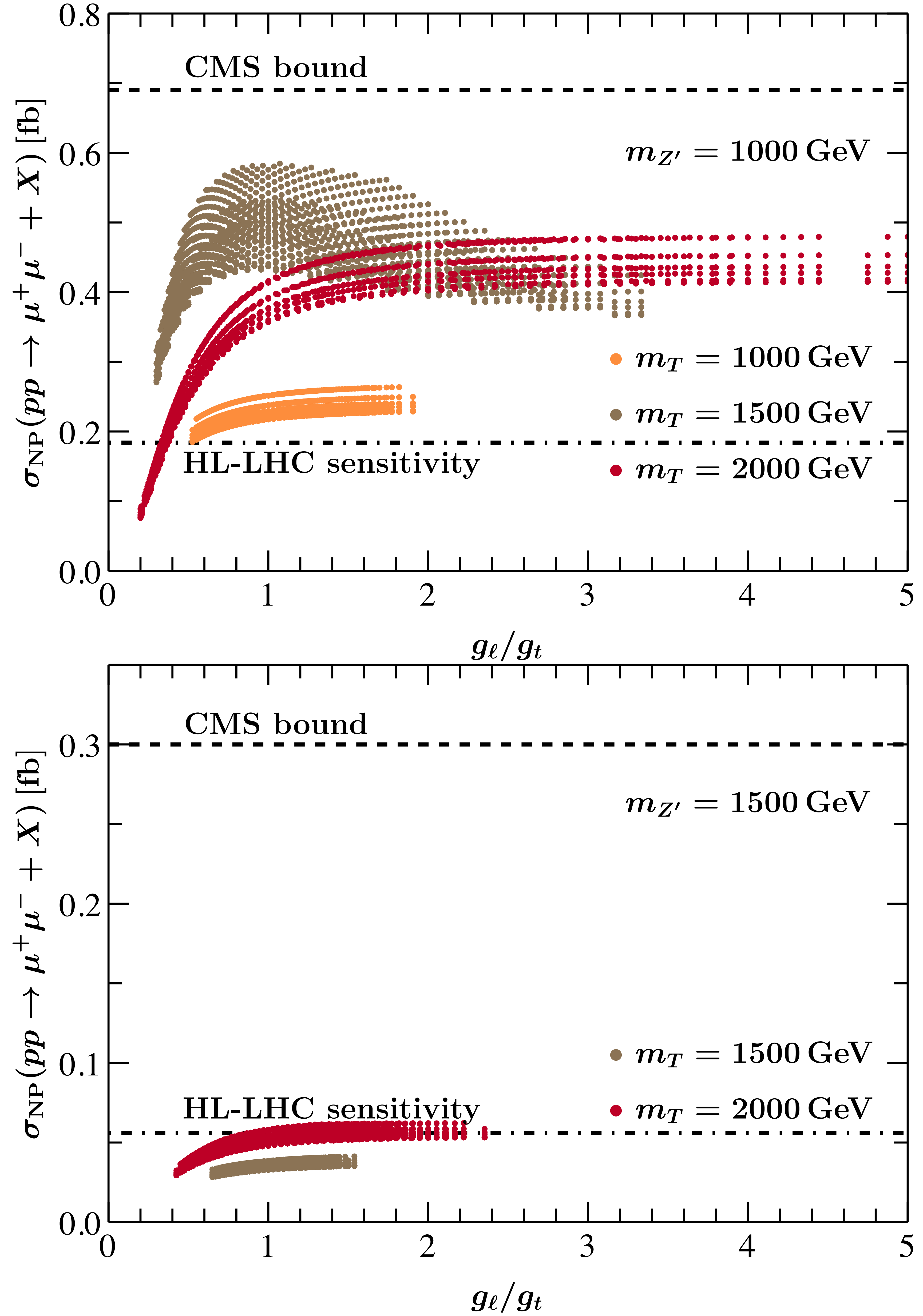
$\sigma(pp \to T\bar{T}) \cdot 2 \cdot \mathcal{B}(T \to tZ') \cdot \mathcal{B}(Z' \to \mu^+\mu^-)$



CMS 137 fb^{-1} @ 13 TeV, JHEP07(2021)208

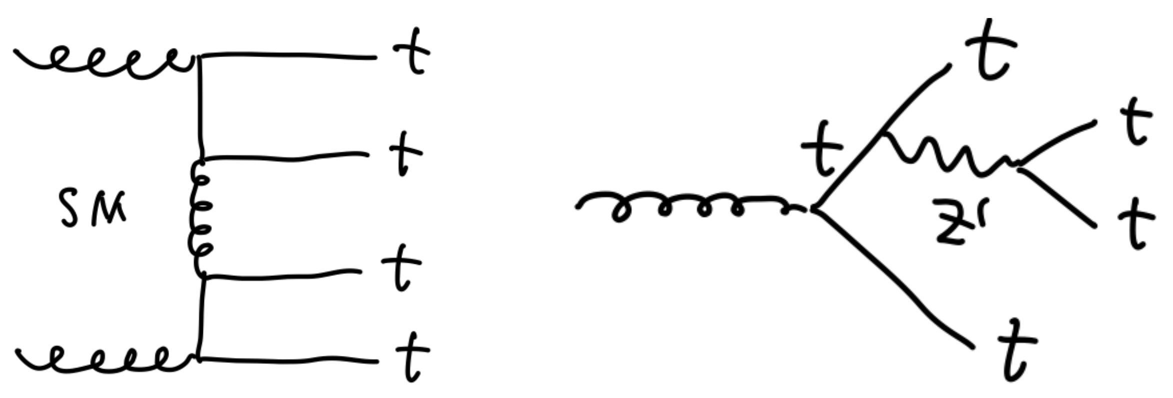
$T \to tZ, tZ', bW, th$

$Z' \to MM, M\mu, \mu\mu, \tau\tau, \nu\bar{\nu}, t\bar{t}$



Collider Searches

$pp \to t\bar{t}t\bar{t}$



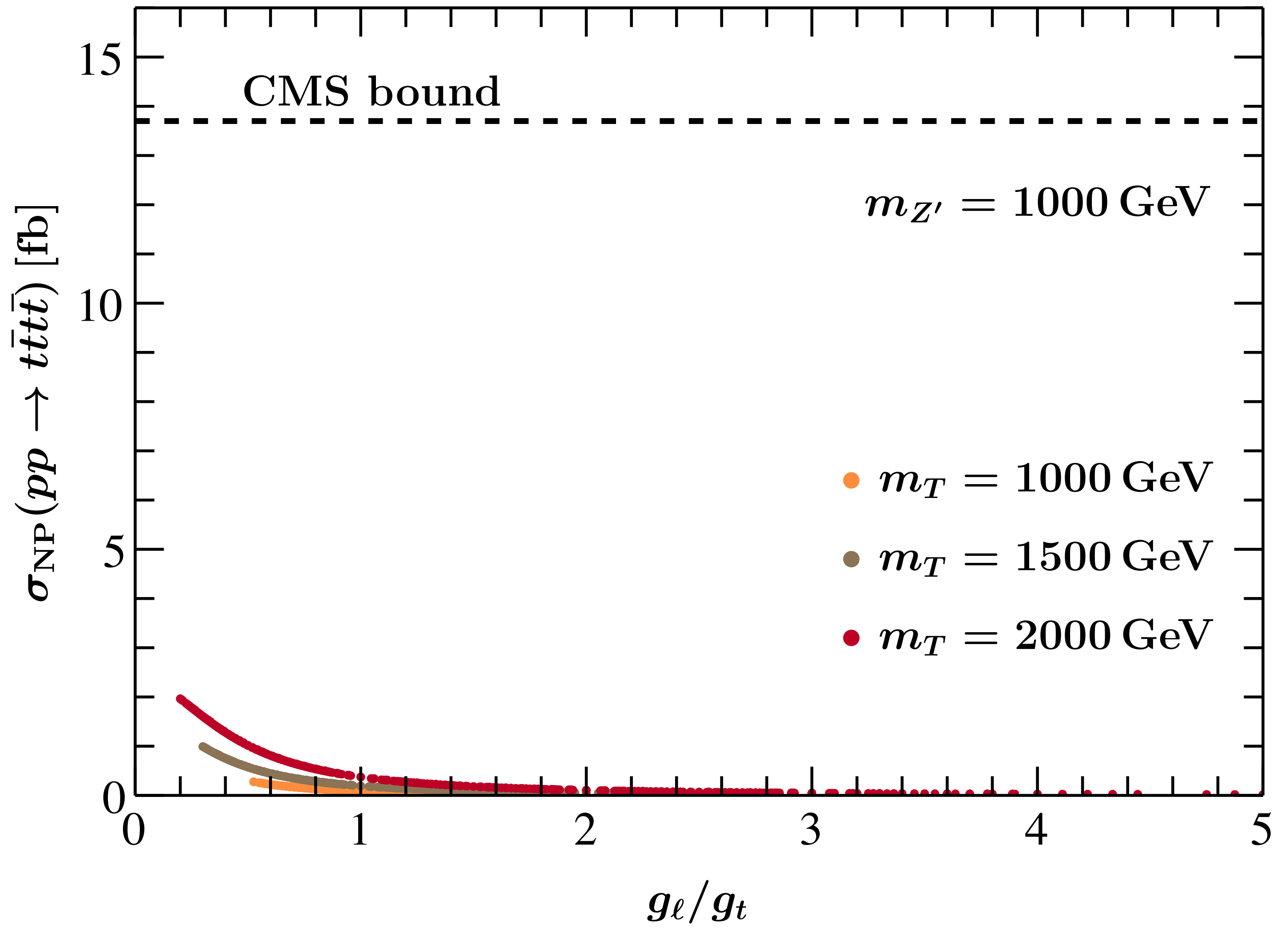
$$\sigma_{\text{exp}} = 12.6^{+5.8}_{-5.2}\,\text{fb}$$

CMS 137 fb^{-1} @ 13 TeV, 1908.06463

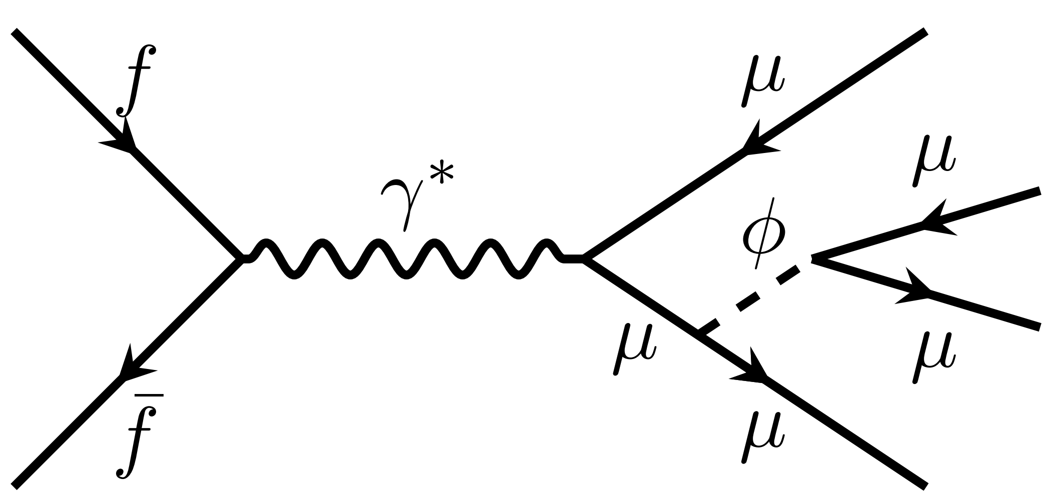
$$\sigma_{\text{NLO}} = 12.0^{+2.2}_{-2.5}\,\text{fb}$$

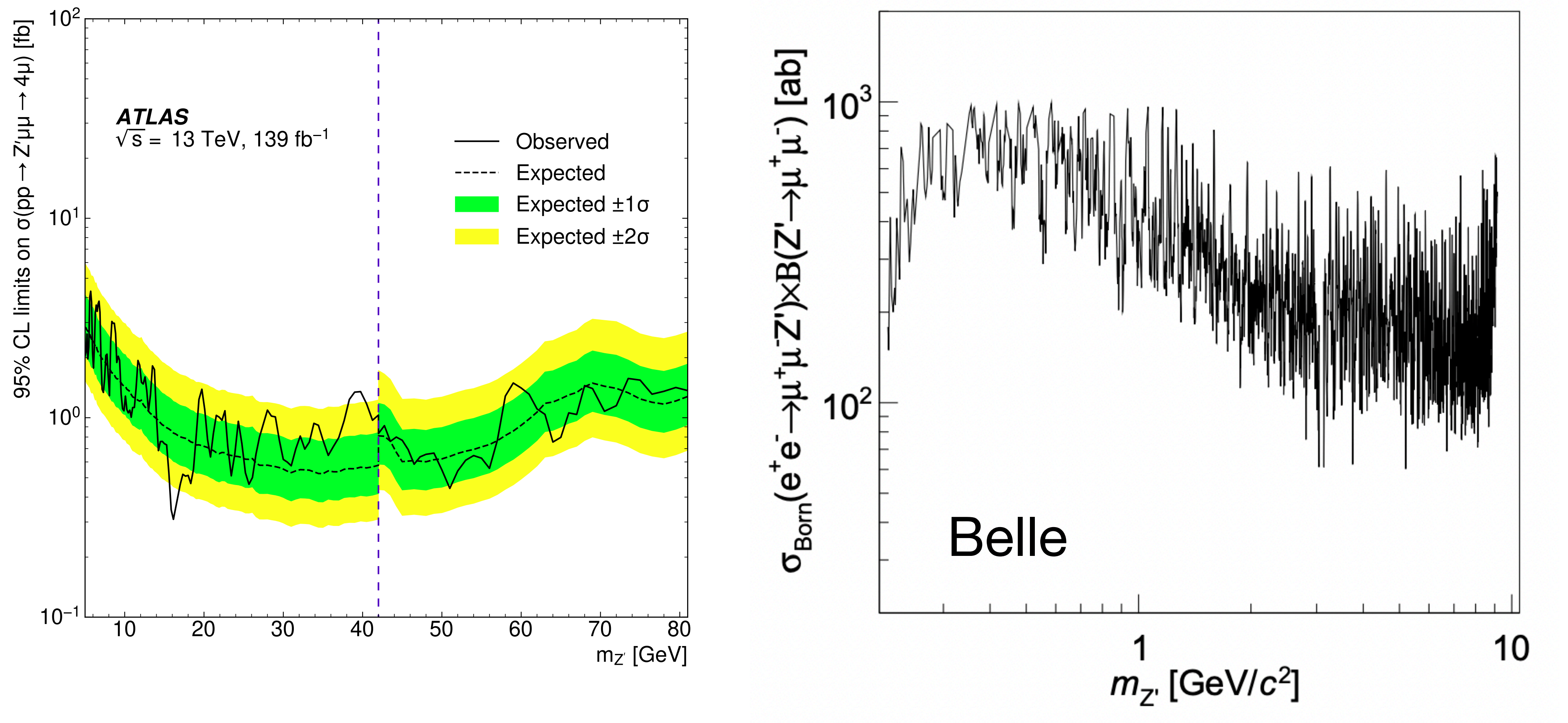
Frederix, D. Pagani, M. Zaro 1711.02116

$\sigma(pp \to t\bar{t}Z') \cdot \mathcal{B}(Z' \to t\bar{t})$

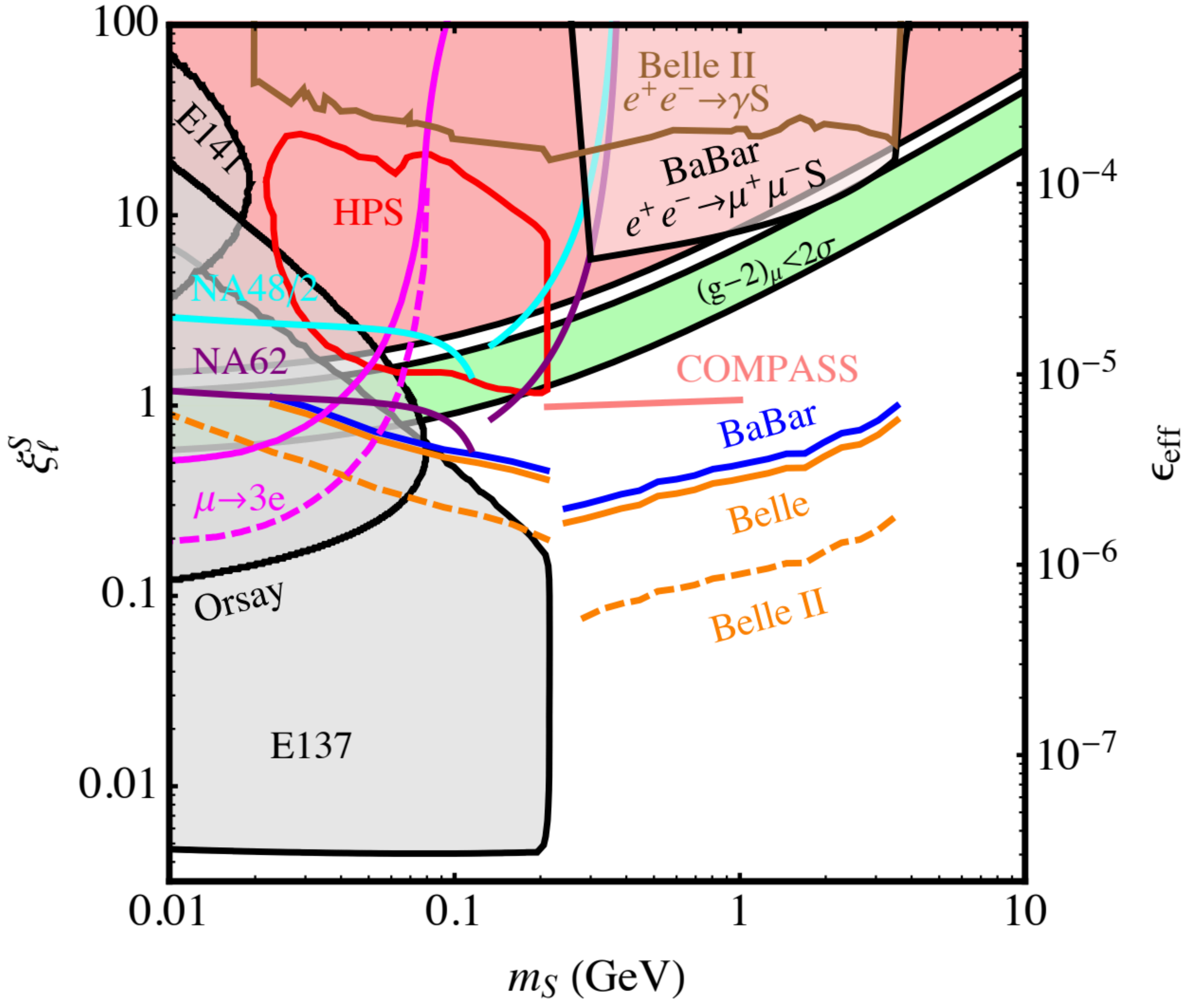


$e^+e^-(pp) \to \mu^+\mu^-\mu^+\mu^-$





Batell, Lange, McKeen, Pospelov, Adam Ritz, 1606.04943



$m_\phi \sim 1\,\text{GeV}$

can be searched for at BESIII, Belle II, STCF

Summary

Conclusions

- Our model can explain $(g-2)_\mu$, CDF m_W measurement, and the $b \to s\ell^+\ell^-$ data
- And satisfy many other constraints, e.g., $Z \to \mu^+\mu^-, \nu$ trident production, ...
- $pp \to \mu^+\mu^- + X$ at LHC and $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$ at BESIII/Belle II are sensitive to the NP particles

Issues

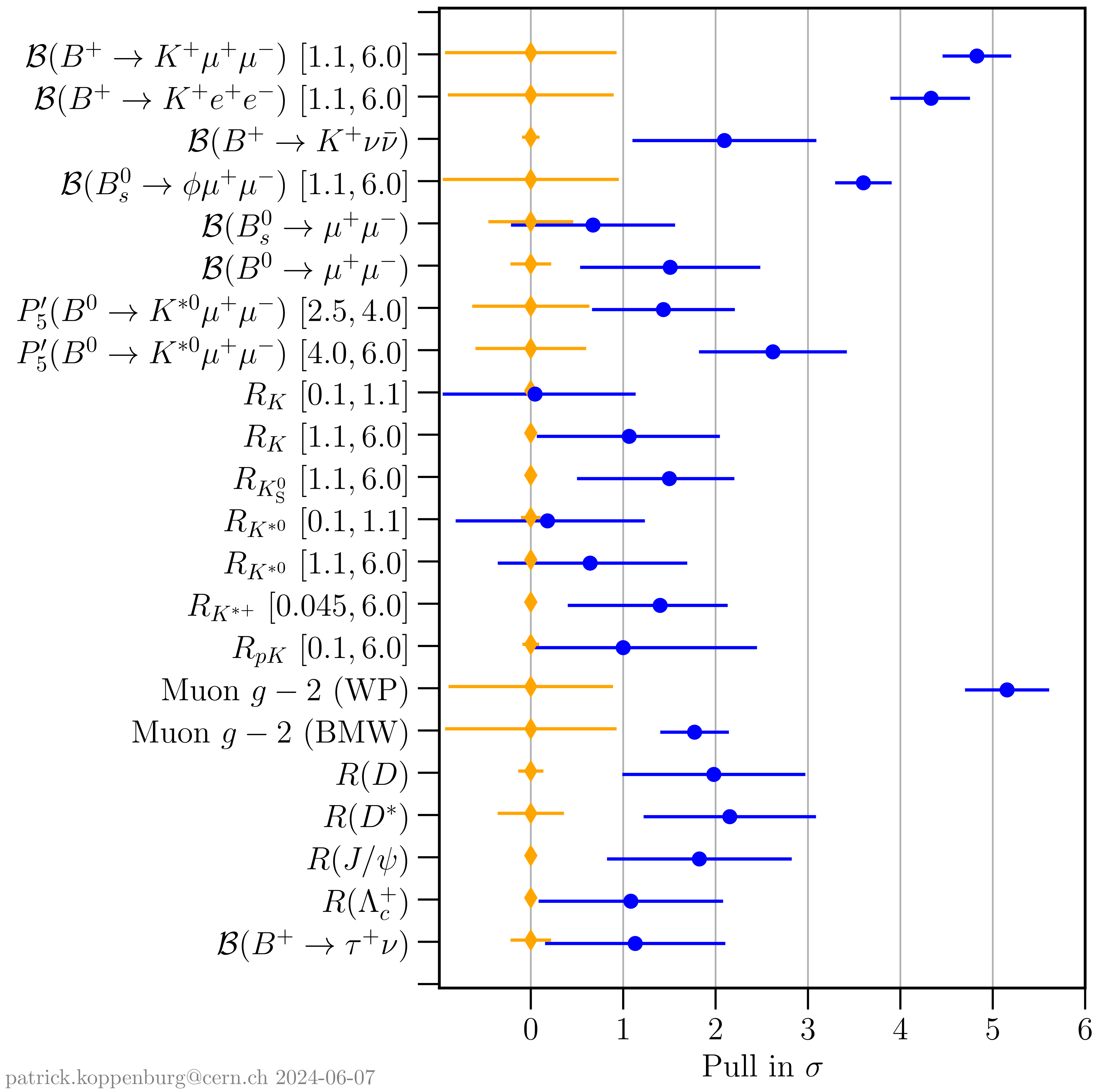
- Top partner mixing with 1st and 2nd generation is also possible — G.C. Branco et al, arXiv:2103.13409
- EW baryogenesis ?
- Z' contributions to the global EW fit is not included — J. Berger, J. Hubisz and M. Perelstein, arXiv: 1205.0013
- Naturalness from the top partner not discussed

Future works

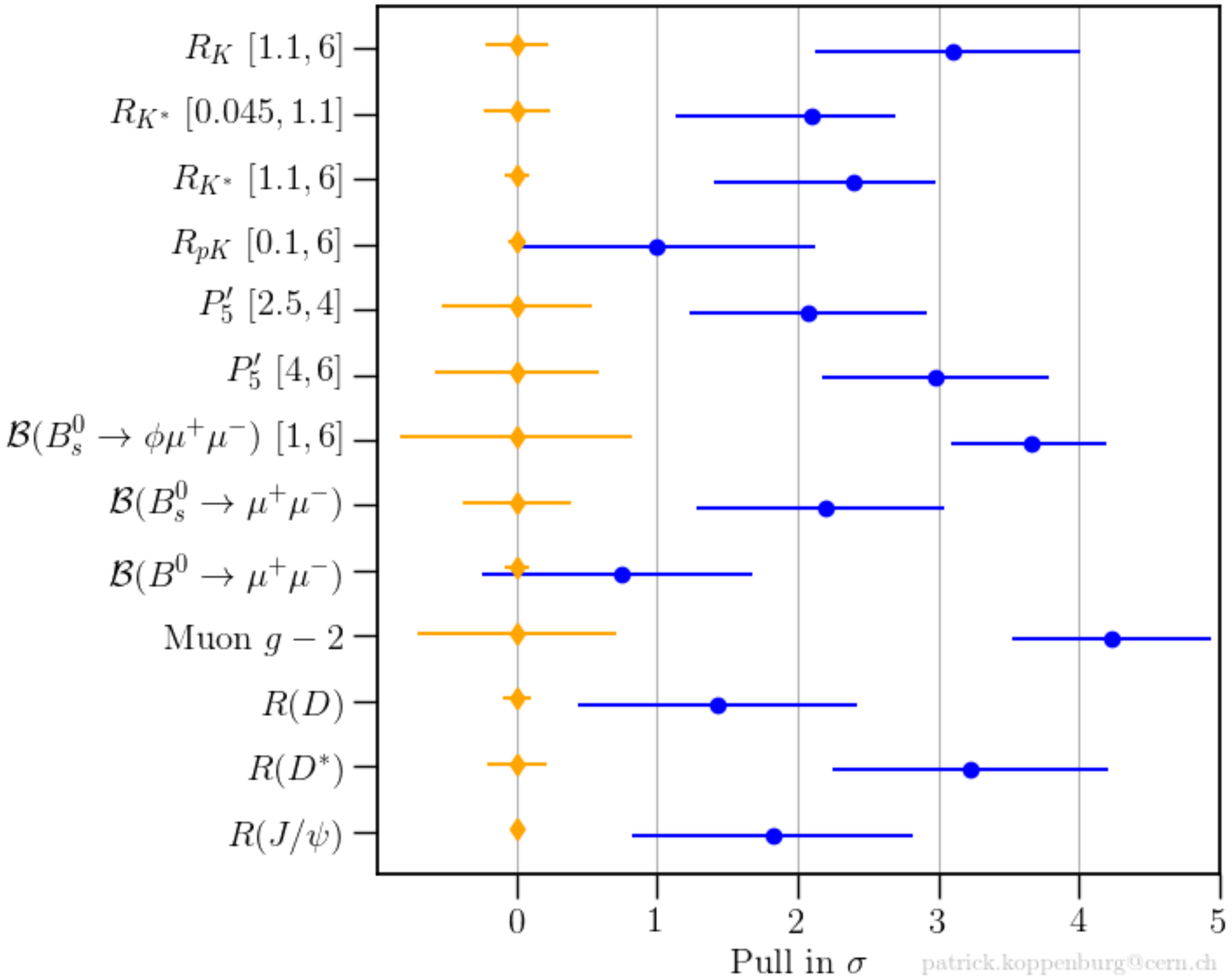
- Z' contributions to EW fit | mixing with 1st and 2nd gen | Naturalness
- detailed collider simulation

Flavour anomalies: one last comment

Aug 2024



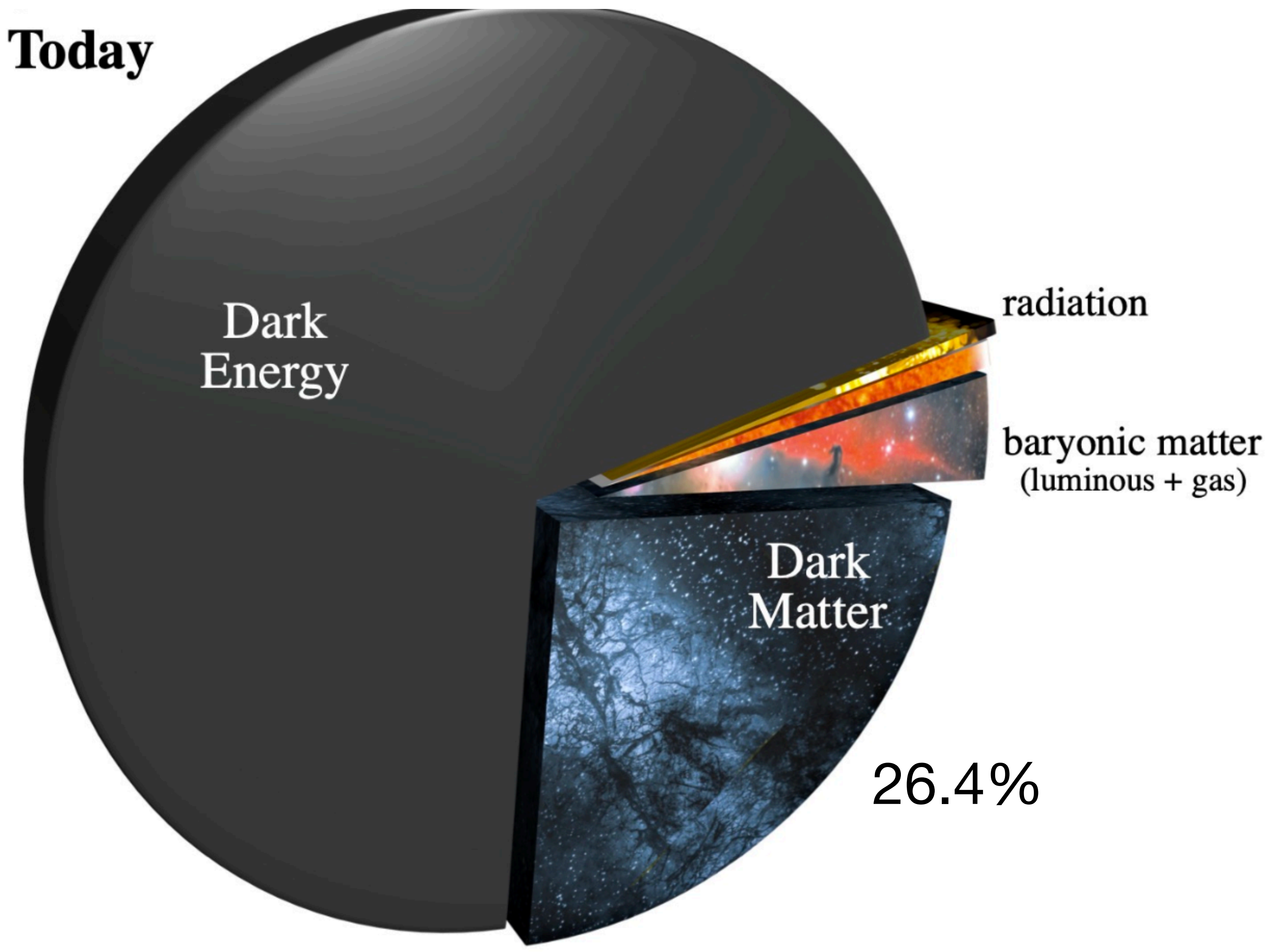
Apr 2021



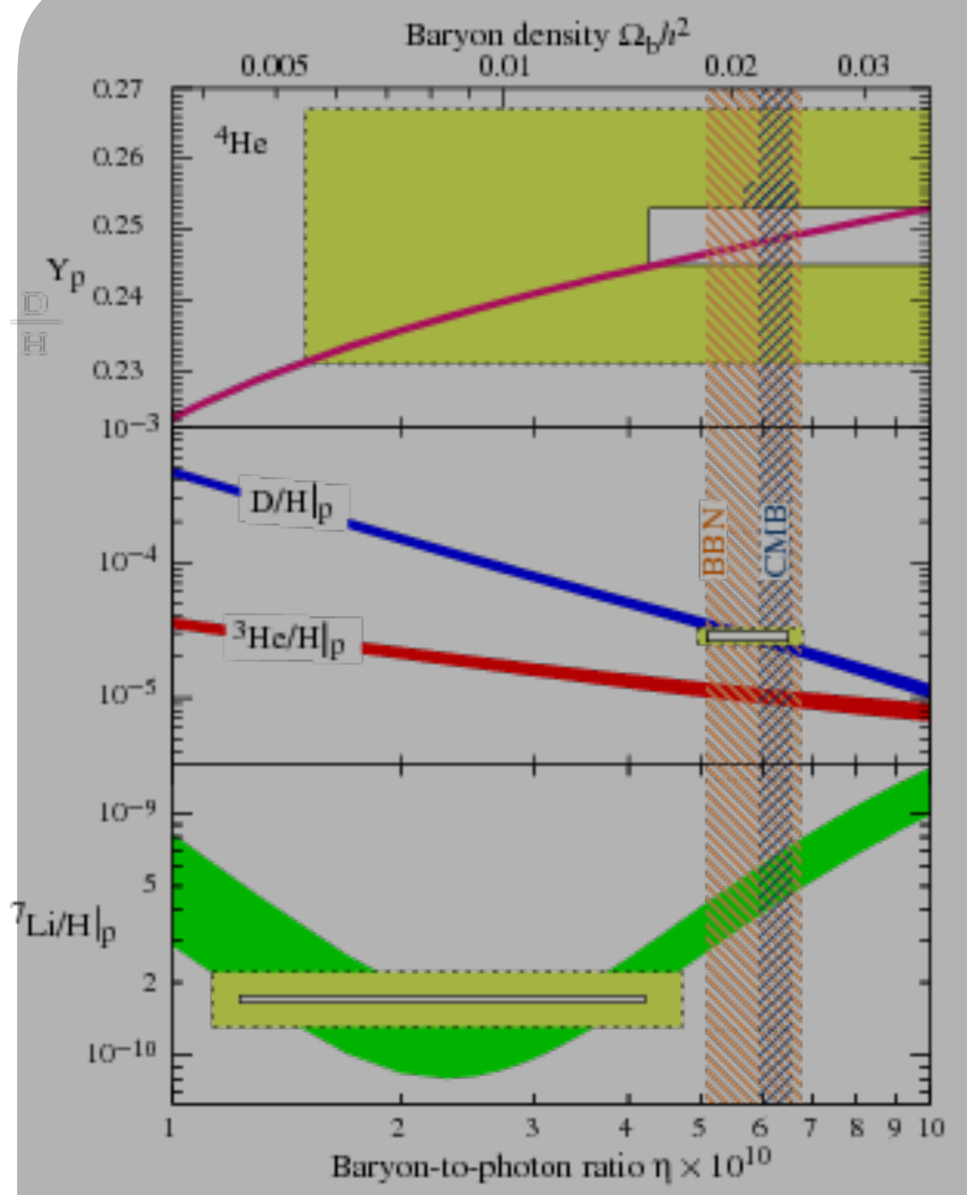
A Possible Flavour Path to New Physics

Dark Matter

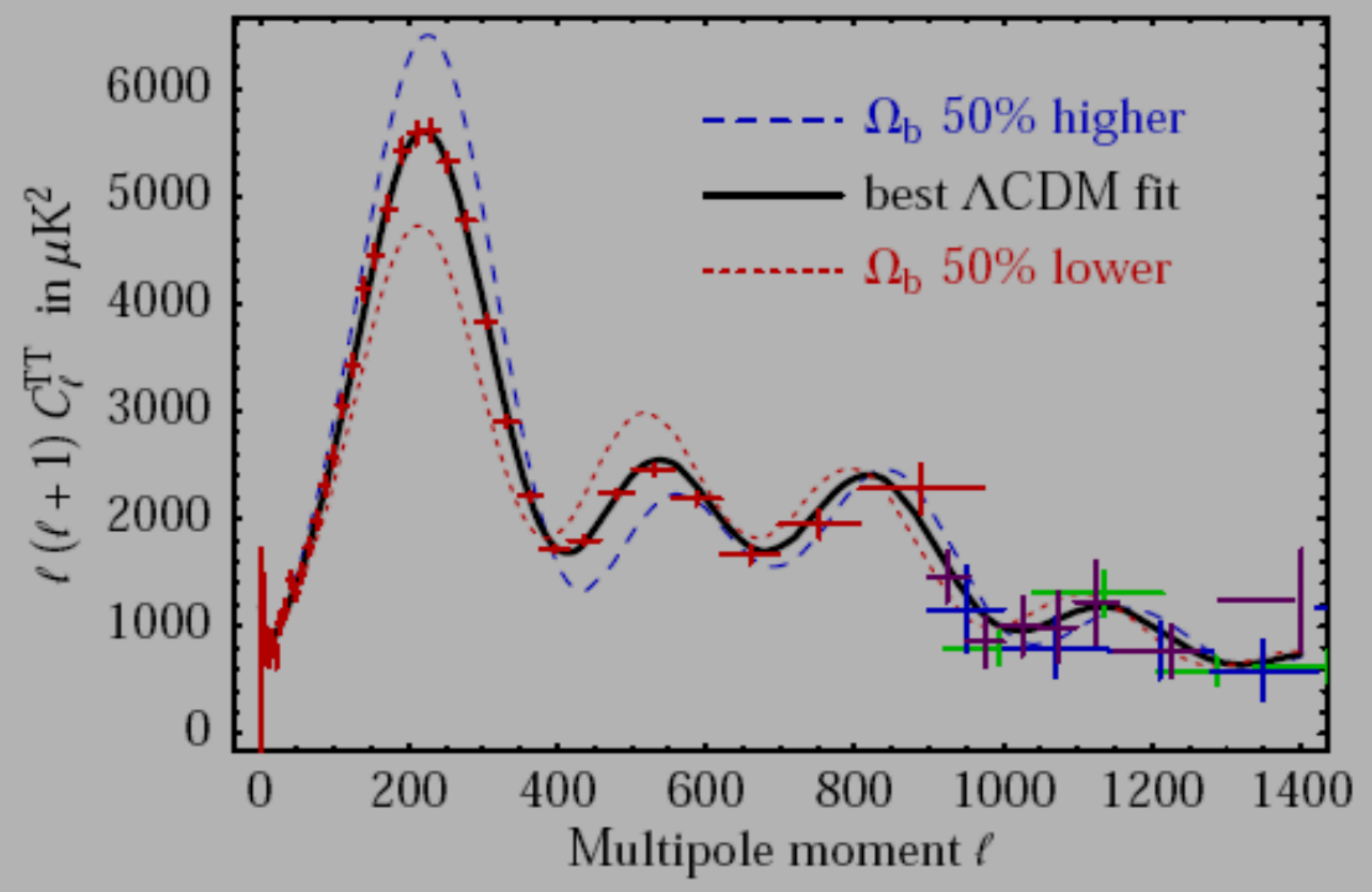
Matter-antimatter Asymmetry



Cirelli, Strumia, Zupan/2406.01705



Rubakov/1804.11230



Blanchet/0807.1408

not covered in this talk

A Possible Flavour Path to New Physics

DM is electrically neutral ! $\Longrightarrow$ DM only have FC or FCNC couplings to quarks !

	d	s	b
d	DD	NA62/KOTO	Belle II
s		DD	Belle II
b			

	u	c	t
u	DD	BES/STCF	
c			
t			

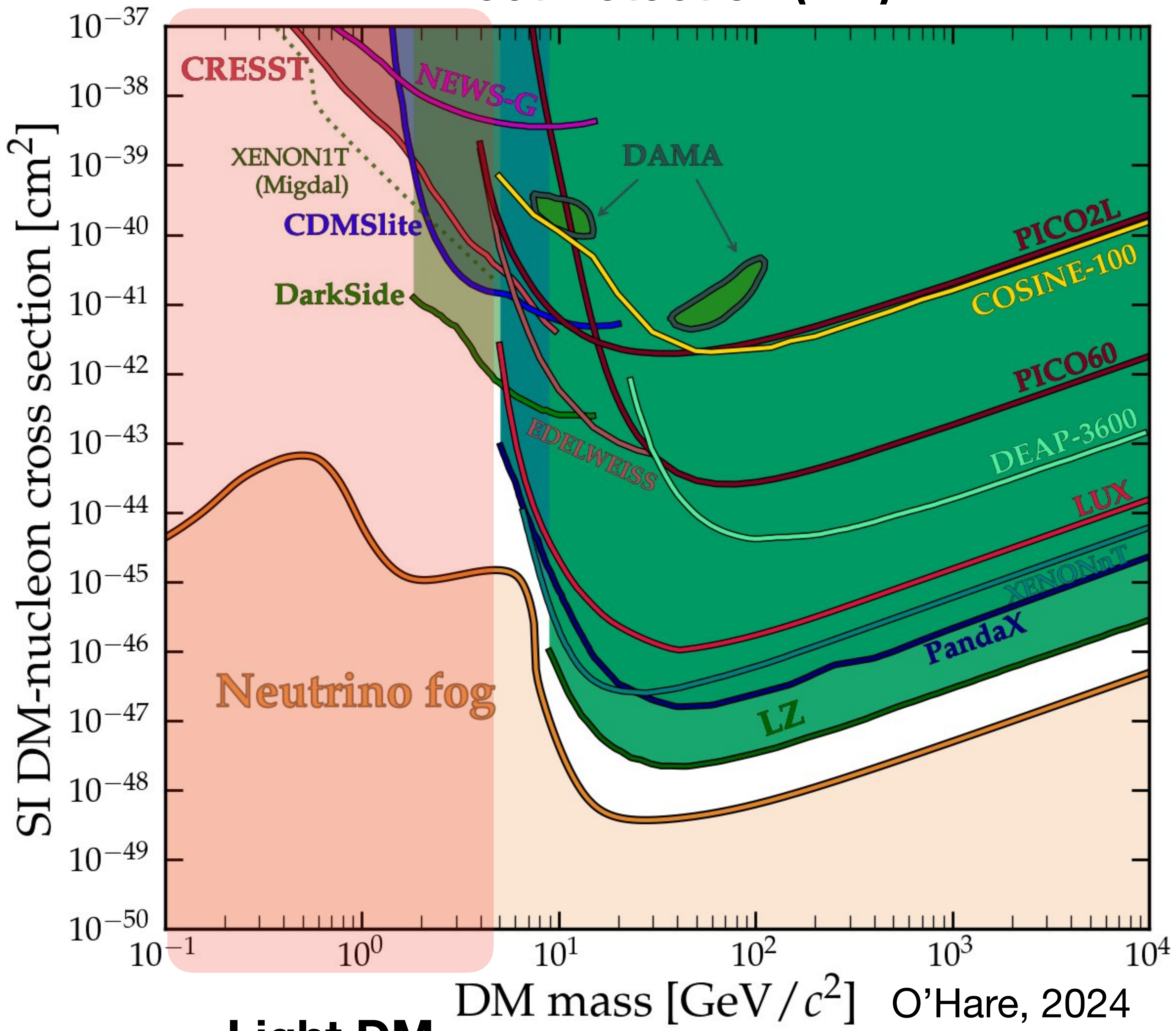
example:

$B^+ \to K^+ + \mathrm{DM}$

$K^+ \to \pi^+ + \mathrm{DM}$

$D^0 \to \pi^0 + \mathrm{DM}$

Direct Detection (DD)



Light DM

see also Yue Meng's talk

means related to the DM relic density

Effective Field Theory approach to combine the various experimental searches

In EFT, DM is a just singlet under the SM gauge group.

Dark SMEFT

$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$, all the SM particles

example

$$\mathcal{Q}_{d\phi^2} = (\bar{q}_p d_r H)\phi^2$$

$$\mathcal{Q}_{d\chi} = (\bar{d}_p \gamma_\mu d_r)(\bar{\chi}\gamma^\mu \chi)$$

$$\mathcal{Q}_{dX^2} = (\bar{q}_p d_r H) X_\mu X^\mu$$

$$\mathcal{Q}_{qa} = (\bar{q}_p \gamma_\mu q_r)\partial^\mu a$$

2011 Kamenik, Smith
2014 Duch, Grzadkowski, Wudka
2017 Brod, Gootjes-Dreesbach, Tammaro, Zupan
2021 Criado, Djouadi, Perez-Victoria, Santiago
2022 Aebischer, Altmannshofer, Jenkins, Manohar (basis@dim-6)
2023 Song, Sun, Yu (basis@dim-8)

Axion-like particle, see also H.Y.Cheng, Phys.Rept 1988

2020 Bauer, Neubert, Renner, Schnubel, Thamm
2023 Song, Sun, Yu (basis@dim-8)

$\mu_{\rm EW}$

Dark LEFT

$SU(3)_C \otimes U(1)_{\rm em}$, W, Z, h, t have been integrated out

$$\mathcal{O}_{d\phi^2} = (\bar{d}_{Lp} d_{Rr})\phi^2$$

$$\mathcal{O}_{d\chi}^{V,LR} = (\bar{d}_{Lp}\gamma_\mu d_{Lr})(\bar{\chi}_a \gamma^\mu \chi_b)$$

$$\mathcal{O}_{dXX}^{L} = (\bar{d}_{Lp}\gamma_\mu d_{Lr}) X^{\mu\nu} X_\nu$$

$$\mathcal{O}_{da}^{L} = (\bar{d}_{Lp}\gamma_\mu d_{Lr})\partial^\mu a$$

example

2022 Aebischer, Altmannshofer, Jenkins, Manohar (basis@dim-6)
2022 He, Ma, Valencia (basis@dim-6)
2023 Liang, Liao, Ma, Wang (basis@dim-8)

μ_b

μ_c

1 GeV

NRET/HDMET/Chiral EFT

$$\chi(x) = e^{-im_\chi v\cdot x}(\chi_v(x) + X_v(x))$$

2011 Hill, Solon
2012 Fitzpatrick, Haxton, Katz, Lubbers, Xu
2013 Hill, Solon
2013 Anand, Fitzpatrick, Haxton
2016 Bishara, Brod, Grinstein, Zupan

$H_1 \to H_2 + \mathrm{DM}$ theoretical calculation and experimental searches

- **$d_i \to d_j + \phi + \phi$**

  2011 Kamenik, Smith
  2004 Bird, Jackson, Kowalewski, Pospelov
  2019 G.Li, J.Y. Su, Tandean
  $\Lambda \to n + \phi\phi$, $\Sigma^+ \to p + \phi\phi$, $\Xi^0 \to \Lambda + \phi\phi$, $\Xi^- \to \Sigma^-\phi\phi$, $\Omega^- \to \Sigma^- + \phi\phi$
  2020 X.G. He, X.D. Ma, Tandean, Valencia
  2020 C.Q.Geng, Tandean, $K \to \pi\pi + \phi\phi$
  2021 G. Li, T. Wang, J.B. Zhang, G.L. Wang
  2022 Kling, S. Li, H. Song, S. Su, W. Su

- **$d_i \to d_j + \chi + \chi$**

  2011 Kamenik, Smith
  2019 J.Y. Su, Tandean
  2020 G. Li, T. Wang, Y. Jiang, J.B. Zhang, G.L. Wang
  2021 Felkl, S. L. Li, Schmidt

- **$d_i \to d_j + X + X$**

  2011 Kamenik, Smith
  2021 G. Li, T. Wang, J.B. Zhang, G.L. Wang
  2022 X.G. He, X.D. Ma, Valencia

- **$d_i \to d_j + a$**

  2020 Camalich, Pospelov, Vuong, Ziegler, Zupan,
  2021 Bauer, Neubert, Renner, Schnubel, Thamm
  2022 Guerrera and S. Rigolin

- theoretically clean: $A \propto C \cdot \langle H_1 | O | H_2 \rangle$ (tiny LD contribution)
- no GIM suppression
- possibly two-body decay

} **enhancement**

Observable
$\mathcal{B}(B^+ \to K^+\nu\bar{\nu})$
$\mathcal{B}(B^0 \to K^0\nu\bar{\nu})$
$\mathcal{B}(B^+ \to K^{*+}\nu\bar{\nu})$
$\mathcal{B}(B^0 \to K^{*0}\nu\bar{\nu})$
$\mathcal{B}(B_s \to \phi\nu\bar{\nu})$
$\mathcal{B}(B^+ \to \pi^+\nu\bar{\nu})$
$\mathcal{B}(B^0 \to \pi^0\nu\bar{\nu})$
$\mathcal{B}(B^+ \to \rho^+\nu\bar{\nu})$
$\mathcal{B}(B^0 \to \rho^0\nu\bar{\nu})$
$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$
$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$
$\mathcal{B}(B_s \to \nu\bar{\nu})$
$\mathcal{B}(B^0 \to \nu\bar{\nu})$
$\nu \to \mathrm{DM}$

- **$c \to u + \mathrm{DM}$**

  2022 C.Q.Geng, G.Li
  2023 G.Li, Tandean

$D^0 \to \mathrm{s}\bar{\mathrm{s}}'$
$D^0 \to \gamma\mathrm{s}\bar{\mathrm{s}}'$
$D^0 \to \pi^0\mathrm{s}\bar{\mathrm{s}}'$
$D^+ \to \pi^+\mathrm{s}\bar{\mathrm{s}}'$
$D_s^+ \to K^+\mathrm{s}\bar{\mathrm{s}}'$
$D^0 \to \rho^0\mathrm{s}\bar{\mathrm{s}}'$
$D^+ \to \rho^+\mathrm{s}\bar{\mathrm{s}}'$
$D_s^+ \to K^{*+}\mathrm{s}\bar{\mathrm{s}}'$
$\Lambda_c^+ \to p\mathrm{s}\bar{\mathrm{s}}'$
$\Xi_c^+ \to \Sigma^+\mathrm{s}\bar{\mathrm{s}}'$
$\Xi_c^0 \to \Sigma^0\mathrm{s}\bar{\mathrm{s}}'$
$\Xi_c^0 \to \Lambda\mathrm{s}\bar{\mathrm{s}}'$

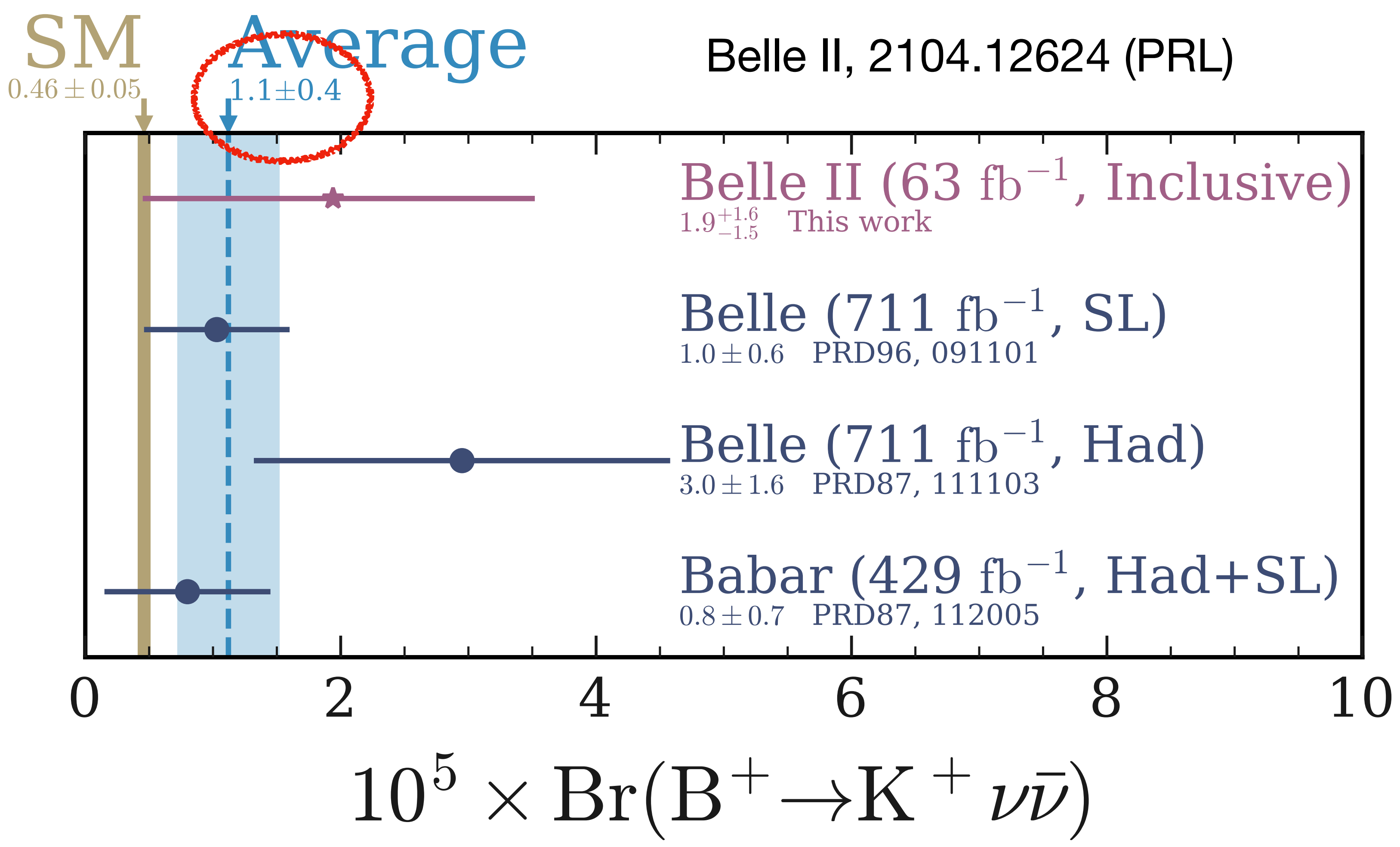
`HadronToNP`: a package to calculate decay of hadron to new particles
B.F. Hou, X.Q. Li, H.Yan, Y.D. Yang, **XBY** *to be finished*

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

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

- **2021 Apr**

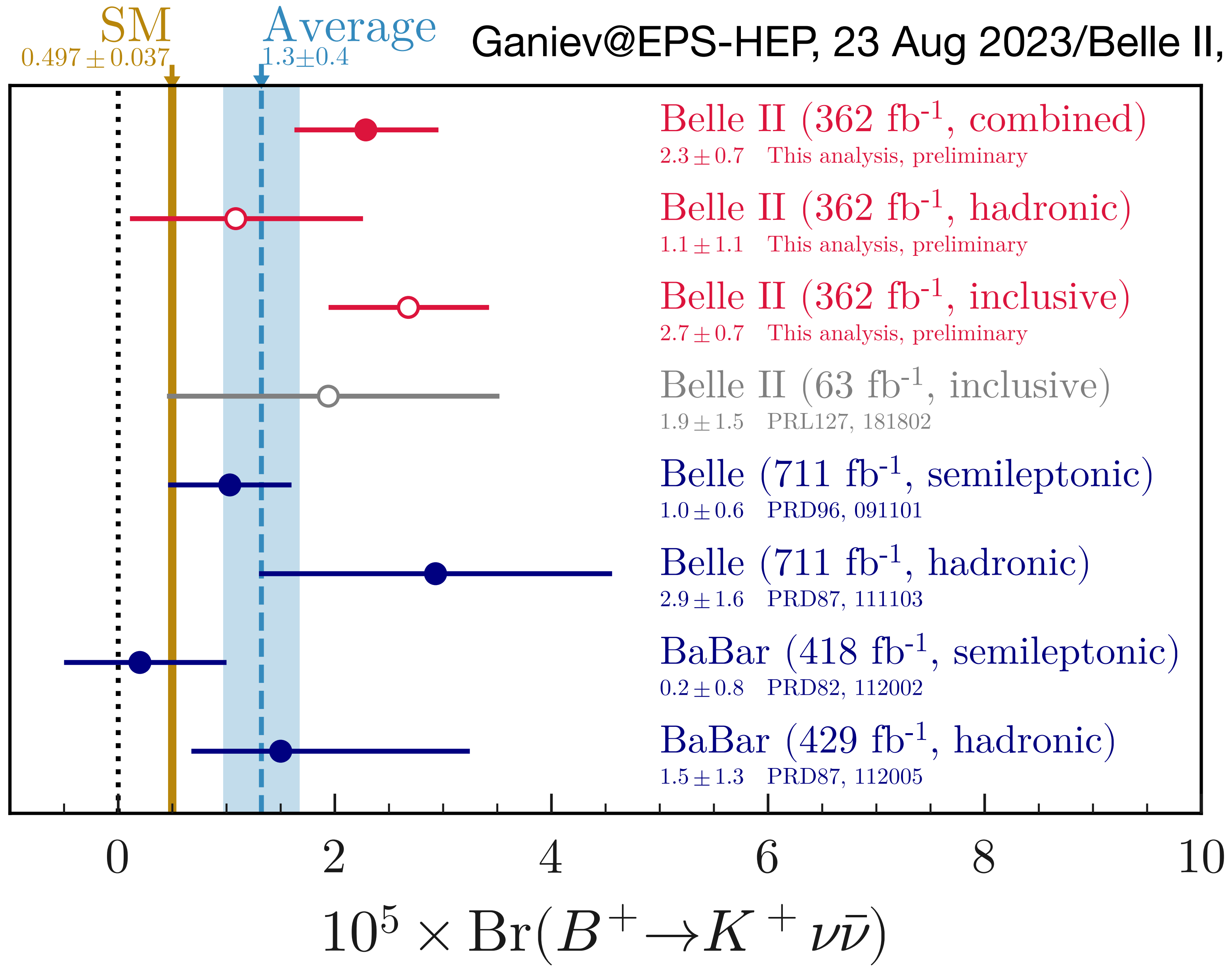
Belle II, 2104.12624 (PRL)



- **2023 Aug**

see also Tao Luo's talk

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



Impact of B→Kνν¯ 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

30+ theory papers !

Phenomenological study of a gauged L_μ - L_τ 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]
pdf cite claim reference search 4 citations

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

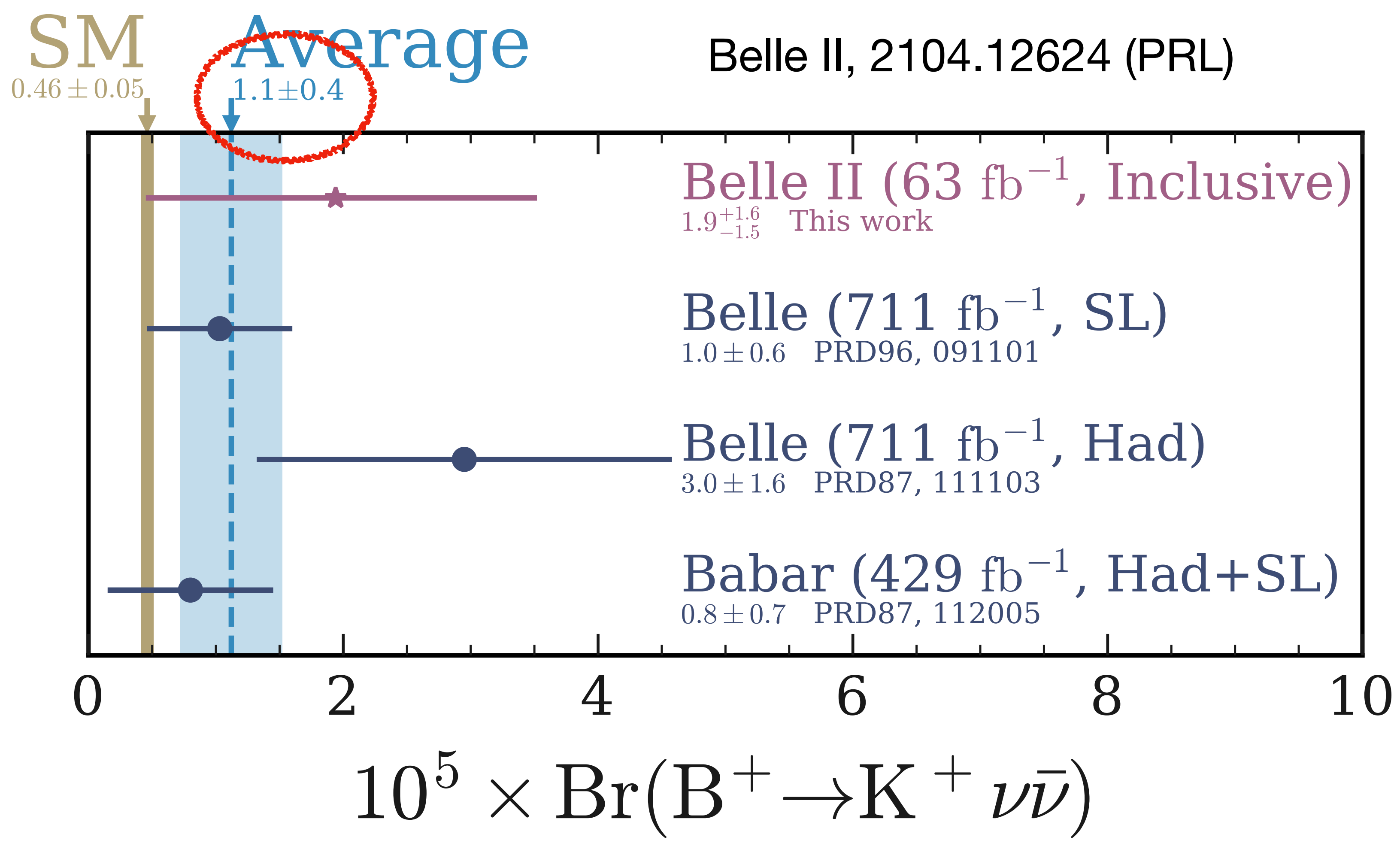
Status and prospects of rare decays at Belle-II #10
Elisa Manoni (Mar 12, 2024)
Published in: *PoS* WIFAI2023 (2024) 024 • Contribution to: WIFAI 2023, 024
pdf DOI cite claim reference search 0 citations

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**

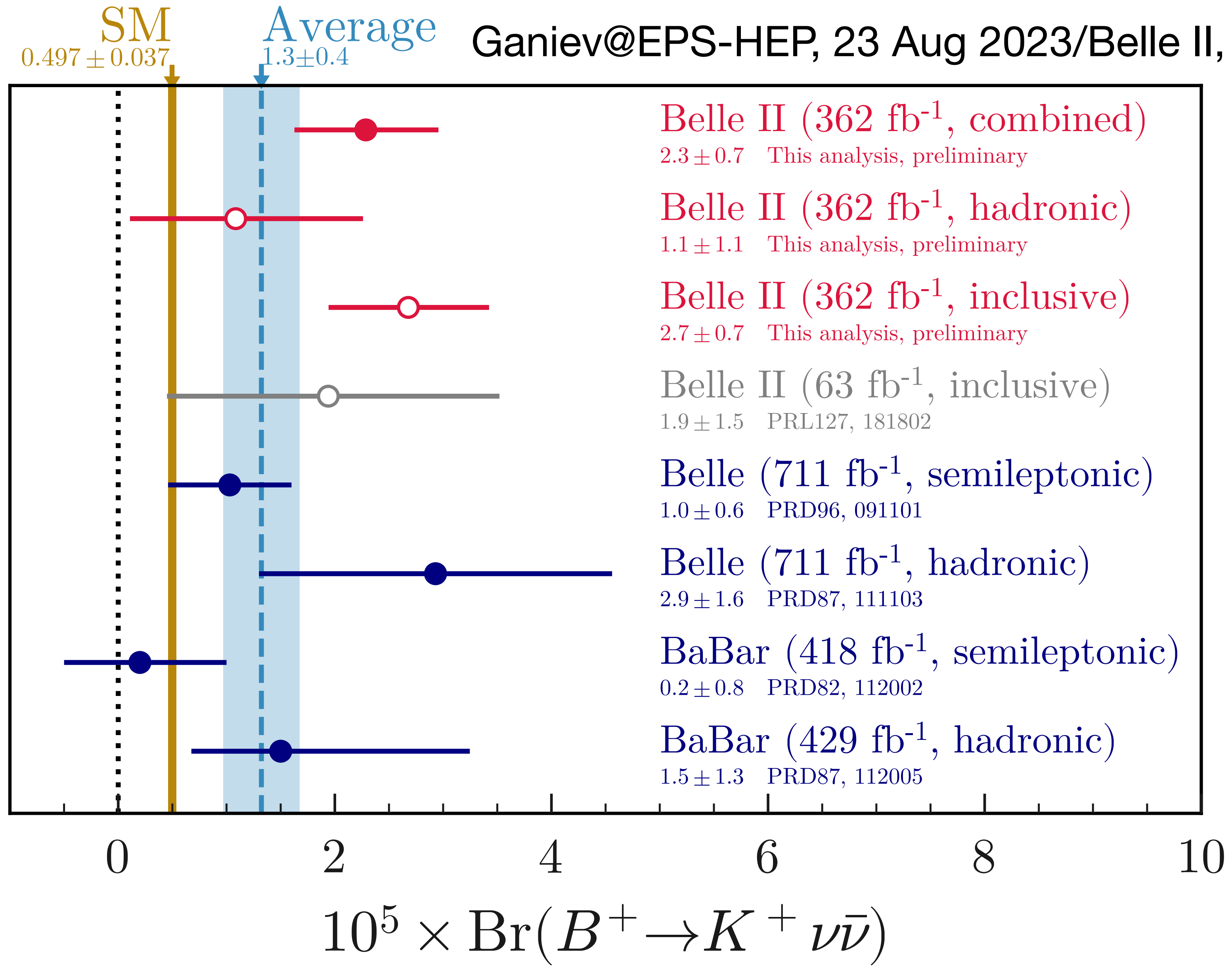
Belle II, 2104.12624 (PRL)

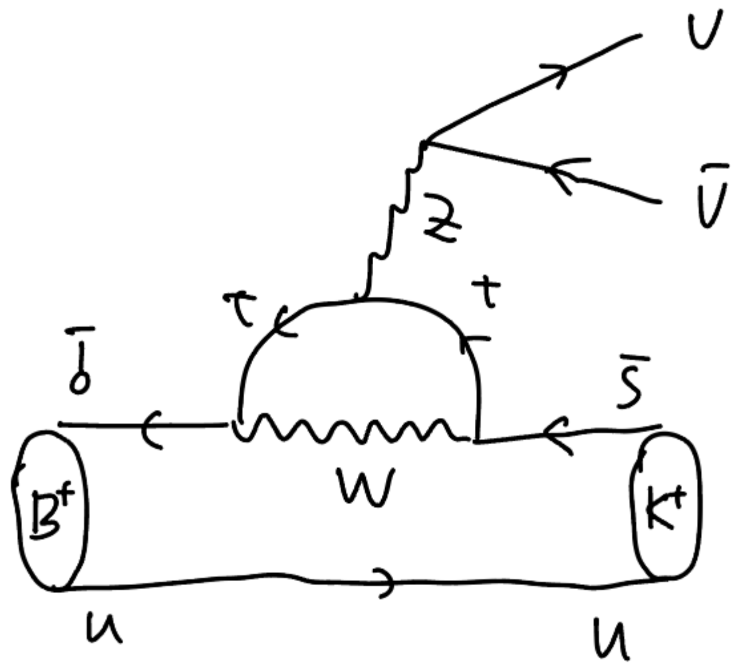


- **2023 Aug**

see also Tao Luo's talk

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**

$\mathcal{O}_L = (\bar{s}P_L b)(\bar{\nu}P_L \nu)$ ✘

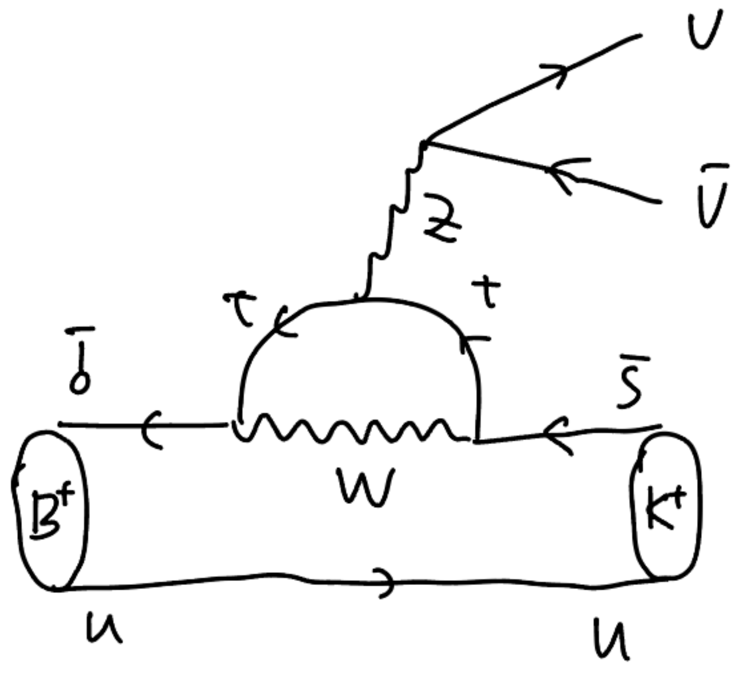
$\mathcal{O}_R = (\bar{s}P_R b)(\bar{\nu}P_R \nu)$ ✘

$\mathcal{O}_T = (\bar{s}\sigma_{\mu\nu} b)(\bar{\nu}\sigma^{\mu\nu} \nu)$ ✘

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

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}

Why such a large NP effect has not shown up in other $b \to s$ decays ? in $b \to d, s \to d$ decays ?

▶ Exp vs SM $[10^{-6}]$

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

2.7σ difference
NP/SM $\gtrsim 2$

$$\mathscr{B}(B^+ \to K^+\nu\bar{\nu})_{exp} \gtrsim 10$$ (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**

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

$\mathcal{O}_L = (\bar{s}P_L b)(\bar{\nu}P_L \nu)$ ✘

$\mathcal{O}_R = (\bar{s}P_R b)(\bar{\nu}P_R \nu)$ ✘

$\mathcal{O}_T = (\bar{s}\sigma_{\mu\nu} b)(\bar{\nu}\sigma^{\mu\nu} \nu)$ ✘

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

operator structure highly constrained by LH neutrino

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

SMEFT

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

$\mu_{\rm EW}$

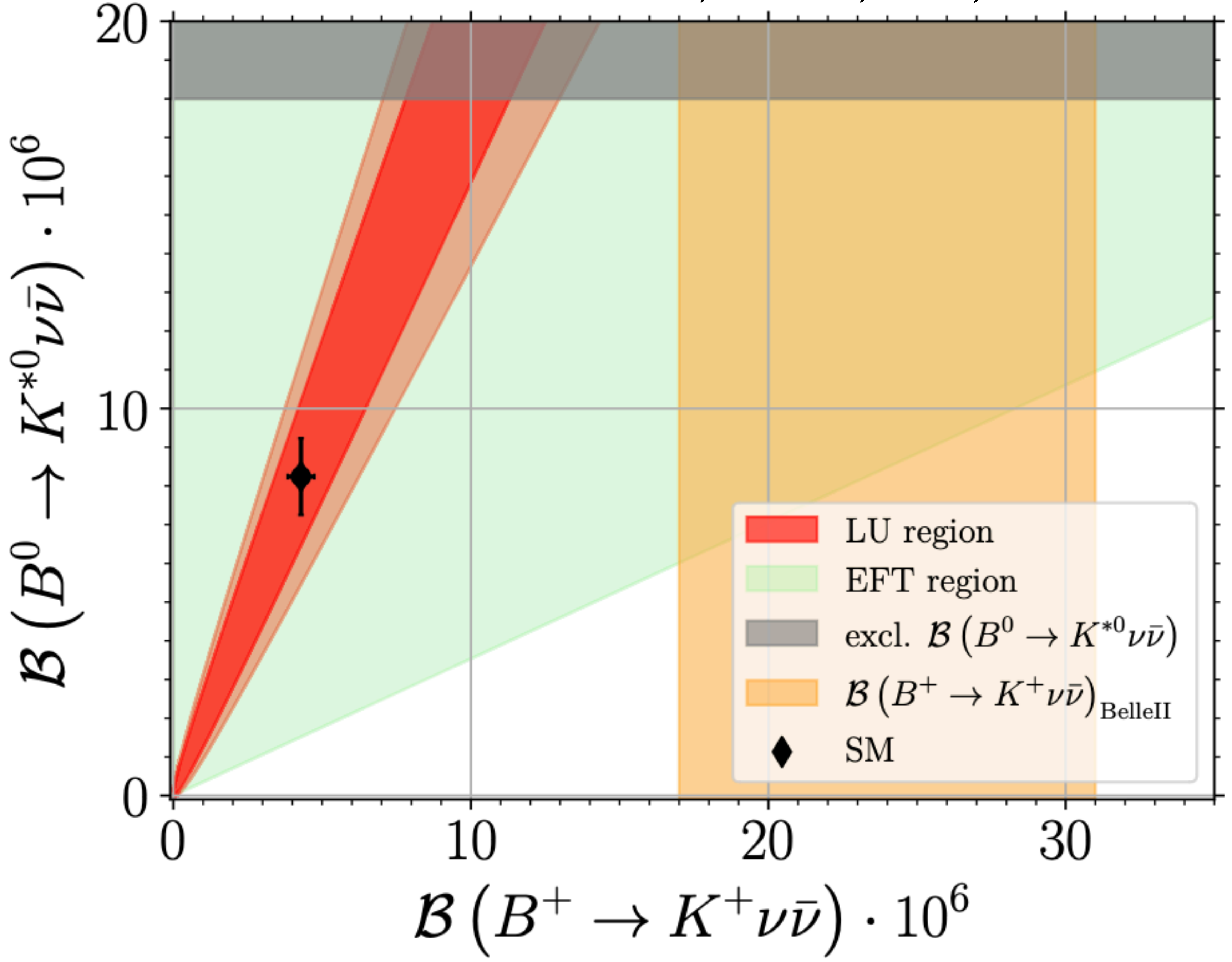
LEFT

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

μ_b

operator structure highly constrained by Left-handed neutrino

Bause, Gisbert, Hiller, 2309.00075



$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) = A_+^{BK}\, x^+ ,$$
$$\mathcal{B}(B^0 \to K^{*0}\nu\bar{\nu}) = A_+^{BK^*}\, x^+ + A_-^{BK^*}\, x^- ,$$
$$x^\pm = \sum_{\nu,\nu'} |C_L^{\nu\nu'} \pm C_R^{\nu\nu'}|^2 ,$$

Bause, Gisbert, Hiller, 2309.00075
Allwicher, Becirevic, Piazza, Rosauro-Alcaraz, Sumensari, 2309.02246
Chen, Wen, Xu, 2401.11552

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

SMEFT

$$\mathcal{Q}_{Hq}^{(1)} = \left(H^\dagger i \overleftrightarrow{D}_\mu H\right)\left(\bar{q}_p \gamma^\mu q_r\right),$$

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

$$\mathcal{Q}_{Hd} = \left(H^\dagger i \overleftrightarrow{D}_\mu H\right)\left(\bar{d}_p \gamma^\mu d_r\right),$$

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

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

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

$\mu_{\rm EW}$

LEFT

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

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

μ_b

operator structure highly constrained by Left-handed neutrino

	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}
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	$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$	3.41 ± 0.45	< 300	10^{-11}

Why such a large NP effect has not shown up
in other $b \to s$ decays ?
in $b \to d, s \to d$ decays ? NP flavour structure

Minimal Flavour Violation

- Flavour symmetry without Yukawa

$$G_{\rm QF} = SU(3)_q \otimes SU(3)_u \otimes SU(3)_d$$

- Flavour symmetry breaking only from SM Yukawa

$$-\mathcal{L}_Y = \bar{q}\, Y_d H d + \bar{q}\, Y_u \tilde{H} u + \text{h.c.}$$

- Flavour symmetry recovering: Yukawa coupling $\Longrightarrow$ spurion field

$$Y_u \sim (\mathbf{3}, \bar{\mathbf{3}}, \mathbf{1}) \qquad\qquad Y_d \sim (\mathbf{3}, \mathbf{1}, \bar{\mathbf{3}})$$

D'Ambrosio, Giudice, Isidori, Strumia, 2009

- EFT with MFV: operators, constructed from SM and Yukawa spurion fields, are invariant under CP and $G_{\rm QF}$

$$\mathcal{C}^{\rm MFV} = \begin{cases} f(\mathsf{A},\mathsf{B}) & \text{for } \; \bar{q}\gamma^\mu \mathcal{C} q, \\ f(\mathsf{A},\mathsf{B}) Y_d & \text{for } \; \bar{q}\mathcal{C} d,\ \bar{q}\sigma^{\mu\nu}\mathcal{C} d, \\ \epsilon_0 \mathbb{1} + Y_d^\dagger g(\mathsf{A},\mathsf{B}) Y_d & \text{for } \; \bar{d}\gamma^\mu \mathcal{C} d, \end{cases}$$

$$f(\mathsf{A},\mathsf{B}) = \epsilon_0 1 + \epsilon_1 \mathsf{A} + \epsilon_2 \mathsf{B} + \epsilon_3 \mathsf{A}^2 + \epsilon_4 \mathsf{B}^2 + \epsilon_5 \mathsf{A}\mathsf{B} + \ldots$$

$$\mathsf{A} = Y_u Y_u^\dagger$$

$$\mathsf{B} = Y_d Y_d^\dagger$$

Minimal Flavour Violation

- Spurion function

$$f(\mathsf{A},\mathsf{B}) = \epsilon_0 1 + \epsilon_1 \mathsf{A} + \epsilon_2 \mathsf{B} + \epsilon_3 \mathsf{A}^2 + \epsilon_4 \mathsf{B}^2 + \epsilon_5 \mathsf{AB} + \ldots\ldots$$

- Cayley-Hamilton identity for 3×3 invertible matrix X

$$X^3 = \mathrm{Det}X \cdot \mathbb{1} + \frac{1}{2}[\mathrm{Tr}X^2 - (\mathrm{Tr}X)^2] \cdot X + \mathrm{Tr}X \cdot X^2$$

- Spurion function after resummation

Colangelo, Nikolidakis, Smith, 2009
Mercolli, Smith, 2009

$$\begin{aligned} f(\mathsf{A},\mathsf{B}) = \epsilon_0 \mathbb{1} &+ \epsilon_1 \mathsf{A} + \epsilon_3 \mathsf{A}^2 + \epsilon_5 \mathsf{AB} + \epsilon_7 \mathsf{ABA} + \epsilon_{10} \mathsf{AB}^2 + \epsilon_{12} \mathsf{A}^2\mathsf{B}^2 + \epsilon_{14} \mathsf{B}^2\mathsf{AB} + \epsilon_{15} \mathsf{AB}^2\mathsf{A}^2 \\ &+ \epsilon_2 \mathsf{B} + \epsilon_4 \mathsf{B}^2 + \epsilon_6 \mathsf{BA} + \epsilon_9 \mathsf{BAB} + \epsilon_8 \mathsf{BA}^2 + \epsilon_{13} \mathsf{B}^2\mathsf{A}^2 + \epsilon_{11} \mathsf{ABA}^2 + \epsilon_{16} \mathsf{B}^2\mathsf{A}^2\mathsf{B}. \end{aligned}$$

- assumption #1: neglect tiny imaginary parts of ϵ_i
- assumption #2: neglect spurion B (suppressed by $\mathcal{O}(\lambda_d^2)$)

$$f(\mathsf{A},\mathsf{B}) \approx \epsilon_0 \mathbb{1} + \epsilon_1 \mathsf{A} + \epsilon_2 \mathsf{A}^2$$

Minimal Flavour Violation

- MFV coupling   **FCNC controlled by CKM**

$$C^{\rm MFV} = \begin{cases} \epsilon_0 1 + \epsilon_1 \Delta_q & \text{for } \bar{d}_L \gamma^\mu C d_L \\ \epsilon_0 \hat{\lambda}_d + \epsilon_1 \Delta_q \hat{\lambda}_d & \text{for } \bar{d}_L C d_R,\ \bar{d}_L \sigma^{\mu\nu} C d_R \\ \epsilon_0 1 & \text{for } \bar{d}_R \gamma^\mu C d_R \end{cases} \qquad \Delta_q = V^\dagger \hat{\lambda}_u^2 V$$

No Right-handed down-type FCNC !

- Numerics

$$\Delta_q = \begin{pmatrix} 0.8 & -3.3-1.5i & 79.3+35.4i \\ -3.3+1.5i & 16.6 & -397.5+8.1i \\ 79.3-35.4i & -397.5-8.1i & 9839.0 \end{pmatrix} \times 10^{-4}$$

$$\Delta_q \hat{\lambda}_d = \begin{pmatrix} 0.0021 & -0.18-0.08i & 191.3+85.4i \\ -0.009+0.004i & 0.88 & -958.7+19.6i \\ 0.21-0.10i & -21.1-0.4i & 23728.1 \end{pmatrix} \times 10^{-6}$$

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

- **Prediction**

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

$$\frac{\mathcal{B}(B^+ \to K^+\nu\bar{\nu})}{\mathcal{B}(B^+ \to \pi^+\nu\bar{\nu})} = \frac{\mathcal{B}(B^+ \to K^+\nu\bar{\nu})_{\rm SM}}{\mathcal{B}(B^+ \to \pi^+\nu\bar{\nu})_{\rm SM}} = 29.7 \pm 5.6$$

- **prediction**

$$\mathscr{B}(B^0 \to K^{*0}\nu\bar{\nu})_{\rm SM} = (9.00 \pm 0.87) \times 10^{-6}$$
$$\mathscr{B}(B^0 \to K^{*0}\nu\bar{\nu})_{\rm MFV} = \left(50^{+17}_{-16}\right) \times 10^{-6}$$
$$\mathscr{B}(B^0 \to K^{*0}\nu\bar{\nu})_{\rm exp} < 18 \times 10^{-6}$$

$$\mathscr{B}(B^+ \to \pi^+\nu\bar{\nu})_{\rm SM} = (1.40 \pm 0.18) \times 10^{-7}$$
$$\mathscr{B}(B^+ \to \pi^+\nu\bar{\nu})_{\rm MFV} = \left(7.8^{+2.8}_{-2.6}\right) \times 10^{-7}$$
$$\mathscr{B}(B^+ \to \pi^+\nu\bar{\nu})_{\rm exp} < 140 \times 10^{-7}$$

SMEFT

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

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

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

forbidden by MFV

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

$\mu_{\rm EW}$

LEFT

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

one LEFT operator !
just the SM operator

μ_b

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

- **Prediction**

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

$$\frac{\mathcal{B}(B^+ \to K^+\nu\bar{\nu})}{\mathcal{B}(B^+ \to \pi^+\nu\bar{\nu})} = \frac{\mathcal{B}(B^+ \to K^+\nu\bar{\nu})_{\rm SM}}{\mathcal{B}(B^+ \to \pi^+\nu\bar{\nu})_{\rm SM}} = 29.7 \pm 5.6$$

- **prediction**

$$\mathscr{B}(B^0 \to K^{*0}\nu\bar{\nu})_{\rm SM} = (9.00 \pm 0.87) \times 10^{-6}$$
$$\mathscr{B}(B^0 \to K^{*0}\nu\bar{\nu})_{\rm MFV} = \left(50^{+17}_{-16}\right) \times 10^{-6}$$
$$\mathscr{B}(B^0 \to K^{*0}\nu\bar{\nu})_{\rm exp} < 18 \times 10^{-6}$$

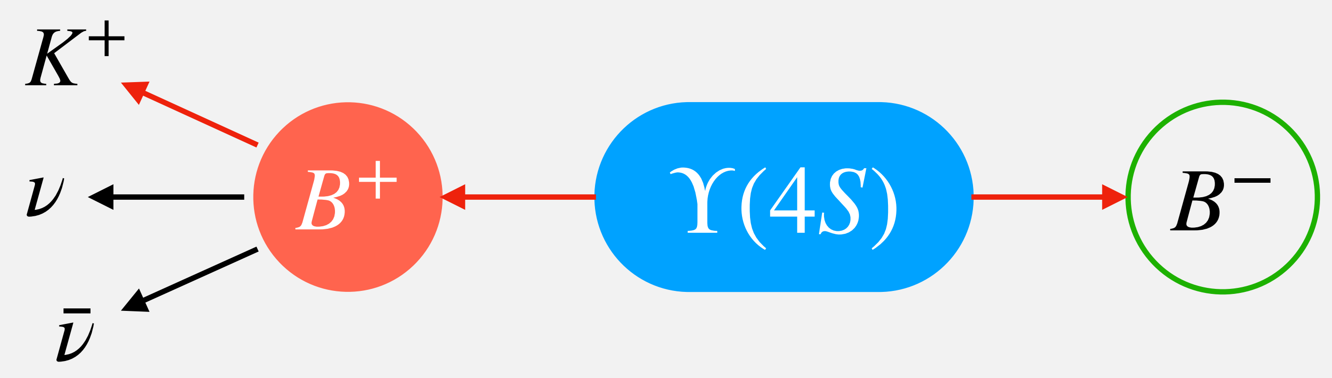
Inconsistent →

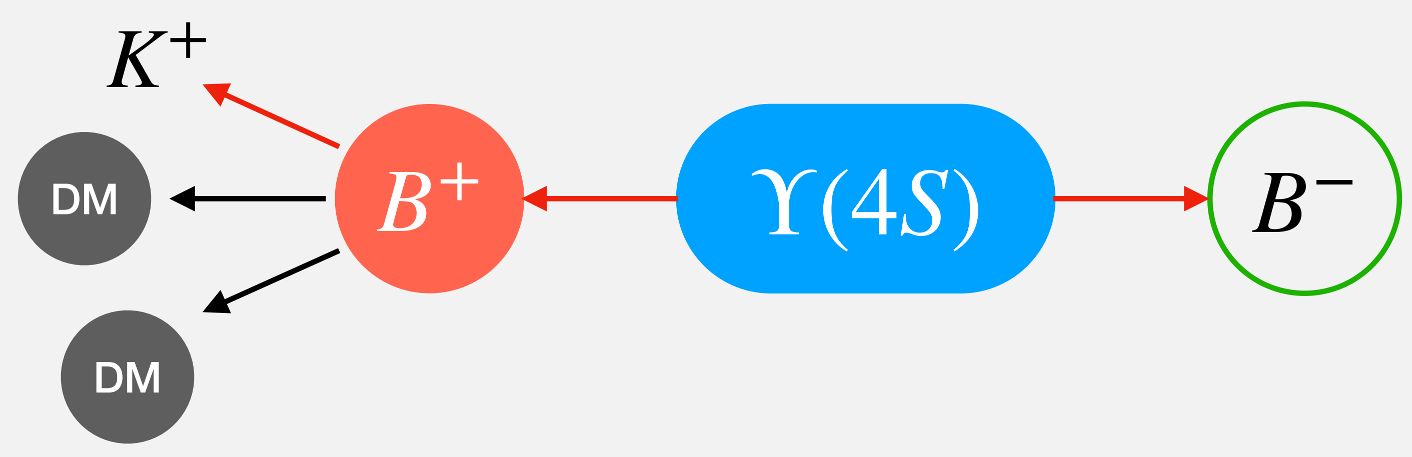
$$\mathscr{B}(B^+ \to \pi^+\nu\bar{\nu})_{\rm SM} = (1.40 \pm 0.18) \times 10^{-7}$$
$$\mathscr{B}(B^+ \to \pi^+\nu\bar{\nu})_{\rm MFV} = \left(7.8^{+2.8}_{-2.6}\right) \times 10^{-7}$$
$$\mathscr{B}(B^+ \to \pi^+\nu\bar{\nu})_{\rm exp} < 140 \times 10^{-7}$$

Belle II excess (if confirmed in the future) implies:
- impossible to explain in SMEFT with MFV
- NP flavour structure is highly non-trivial
- **NP structure in quark sector is beyond MFV**
- **flavour violation is beyond Yukawa coupling**

This conclusion only assumes the quark MFV.
No lepton flavour structure is assumed.

$b \to s\nu\bar{\nu}$: exp picture





SMEFT

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

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

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

$\mu_{\rm EW}$

LEFT

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

μ_b

Dark SMEFT

example

$$\mathcal{Q}_{d\phi^2} = (\bar{q}_p d_r H)\phi^2$$
$$\mathcal{Q}_{d\chi} = (\bar{d}_p\gamma_\mu d_r)(\bar{\chi}\gamma^\mu\chi)$$
$$\mathcal{Q}_{dX^2} = (\bar{q}_p d_r H)X_\mu X^\mu$$
$$\mathcal{Q}_{qa} = (\bar{q}_p\gamma_\mu q_r)\partial^\mu a$$

2011 Kamenik, Smith
2014 Duch, Grzadkowski, Wudka
2017 Brod, Gootjes-Dreesbach, Tammaro, Zupan
2021 Criado, Djouadi, Perez-Victoria, Santiago
2022 Aebischer, Altmannshofer, Jenkins, Manohar (basis@dim-6)
2023 Song, Sun, Yu (basis@dim-8)

Axion-like particle, see also H.Y.Cheng, Phys.Rept 1988

2020 Bauer, Neubert, Renner, Schnubel, Thamm
2023 Song, Sun, Yu (basis@dim-8)

Dark LEFT

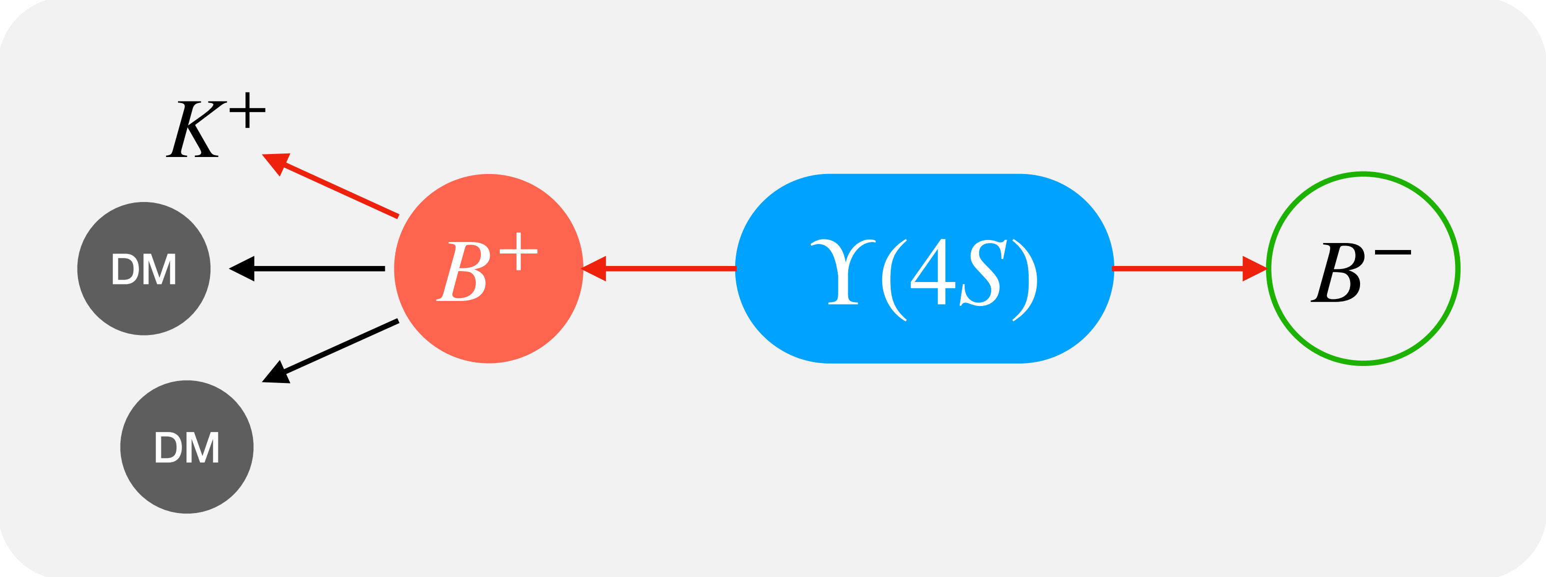
$$\mathcal{O}_{d\phi^2} = (\bar{d}_{Lp}d_{Rr})\phi^2$$
$$\mathcal{O}_{d\chi}^{V,LR} = (\bar{d}_{Lp}\gamma_\mu d_{Lr})(\bar{\chi}_a\gamma^\mu\chi_b)$$
$$\mathcal{O}_{dXX}^{L} = (\bar{d}_{Lp}\gamma_\mu d_{Lr})X^{\mu\nu}X_\nu$$
$$\mathcal{O}_{da}^{L} = (\bar{d}_{Lp}\gamma_\mu d_{Lr})\partial^\mu a$$

example

2022 Aebischer, Altmannshofer, Jenkins, Manohar (basis@dim-6)
2022 He, Ma, Valencia (basis@dim-6)
2023 Liang, Liao, Ma, Wang (basis@dim-8)

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

Can DSMEFT operators explain the Belle II excess, while satisfy other $b \to s$ bounds ?



Observable	SM	Exp	Unit
$\mathcal{B}(B^+ \to K^+\nu\bar{\nu})$	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}
$\mathcal{B}(B^+ \to \pi^+\nu\bar{\nu})$	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}
$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$	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}

$\mu_{\rm EW}$

Dark SMEFT

$$\mathcal{Q}_{d\phi} = (\bar{q}_p d_r H)\phi + \text{h.c.}, \qquad \mathcal{Q}_{d\phi^2} = (\bar{q}_p d_r H)\phi^2 + \text{h.c.},$$
$$\mathcal{Q}_{\phi q} = (\bar{q}_p\gamma_\mu q_r)(i\phi_1 \overleftrightarrow{\partial^\mu}\phi_2), \quad \mathcal{Q}_{\phi d} = (\bar{d}_p\gamma_\mu d_r)(i\phi_1 \overleftrightarrow{\partial^\mu}\phi_2),$$

scalar: 4

$$\mathcal{Q}_{q\chi} = (\bar{q}_p\gamma_\mu q_r)(\bar{\chi}\gamma^\mu\chi), \qquad \mathcal{Q}_{d\chi} = (\bar{d}_p\gamma_\mu d_r)(\bar{\chi}\gamma^\mu\chi),$$

fermion: 2

$$\mathcal{Q}_{dHX} = (\bar{q}_p\sigma_{\mu\nu}d_r)HX^{\mu\nu} \qquad \mathcal{Q}_{dX^2} = (\bar{q}_p d_r H)X_\mu X^\mu$$

vector: 1+13

$$\mathcal{Q}_{qa} = (\bar{q}_p\gamma_\mu q_r)\partial^\mu a \qquad \mathcal{Q}_{da} = (\bar{d}_p\gamma_\mu d_r)\partial^\mu a$$

ALP: 2

Dark LEFT

$$\mathcal{O}_{d\phi} = (\bar{d}_{Lp}d_{Rr})\phi + \text{h.c.}, \qquad \mathcal{O}^L_{\phi d} = (\bar{d}_{Lp}\gamma_\mu d_{Lr})(i\phi_1 \overleftrightarrow{\partial^\mu}\phi_2),$$

scalar: 4

$$\mathcal{O}^{V,LR}_{d\chi} = (\bar{d}_{Lp}\gamma_\mu d_{Lr})(\bar{\chi}_a\gamma^\mu\chi_b), \mathcal{O}^{V,RR}_{d\chi} = (\bar{d}_{Rp}\gamma_\mu d_{Rr})(\bar{\chi}_a\gamma^\mu\chi_b),$$

fermion: 5

$$\mathcal{O}^T_{dX} = (\bar{d}_{Lp}\sigma_{\mu\nu}d_{Rr})X^{\mu\nu}_a \qquad \mathcal{O}^L_{dXX} = (\bar{d}_{Lp}\gamma_\mu d_{Lr})X^{\mu\nu}X_\nu$$

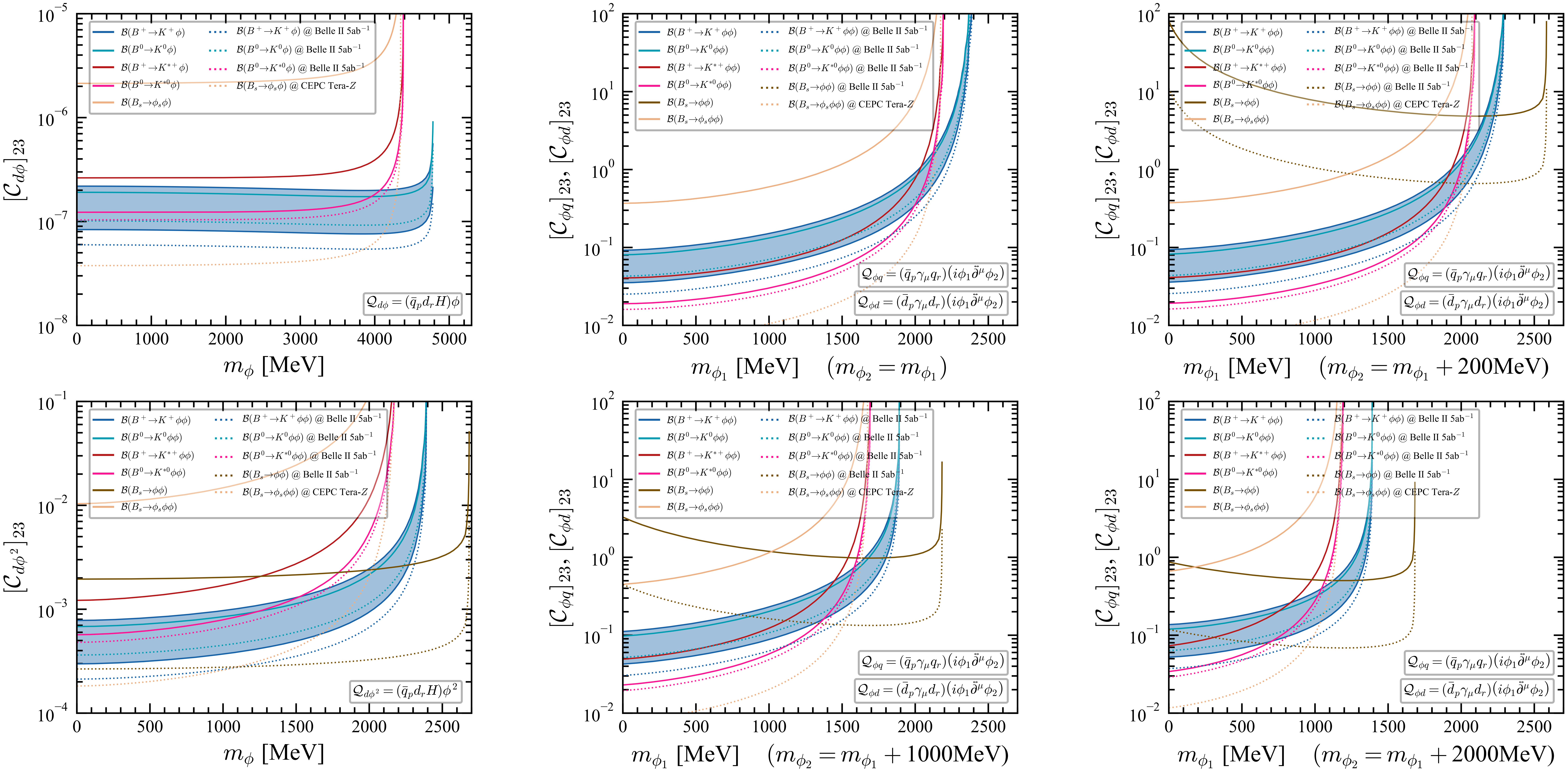
vector: 1+10

$$\mathcal{O}^L_{da} = (\bar{d}_{Lp}\gamma_\mu d_{Lr})\partial^\mu a, \qquad \mathcal{O}^R_{da} = (\bar{d}_{Rp}\gamma_\mu d_{Rr})\partial^\mu a$$

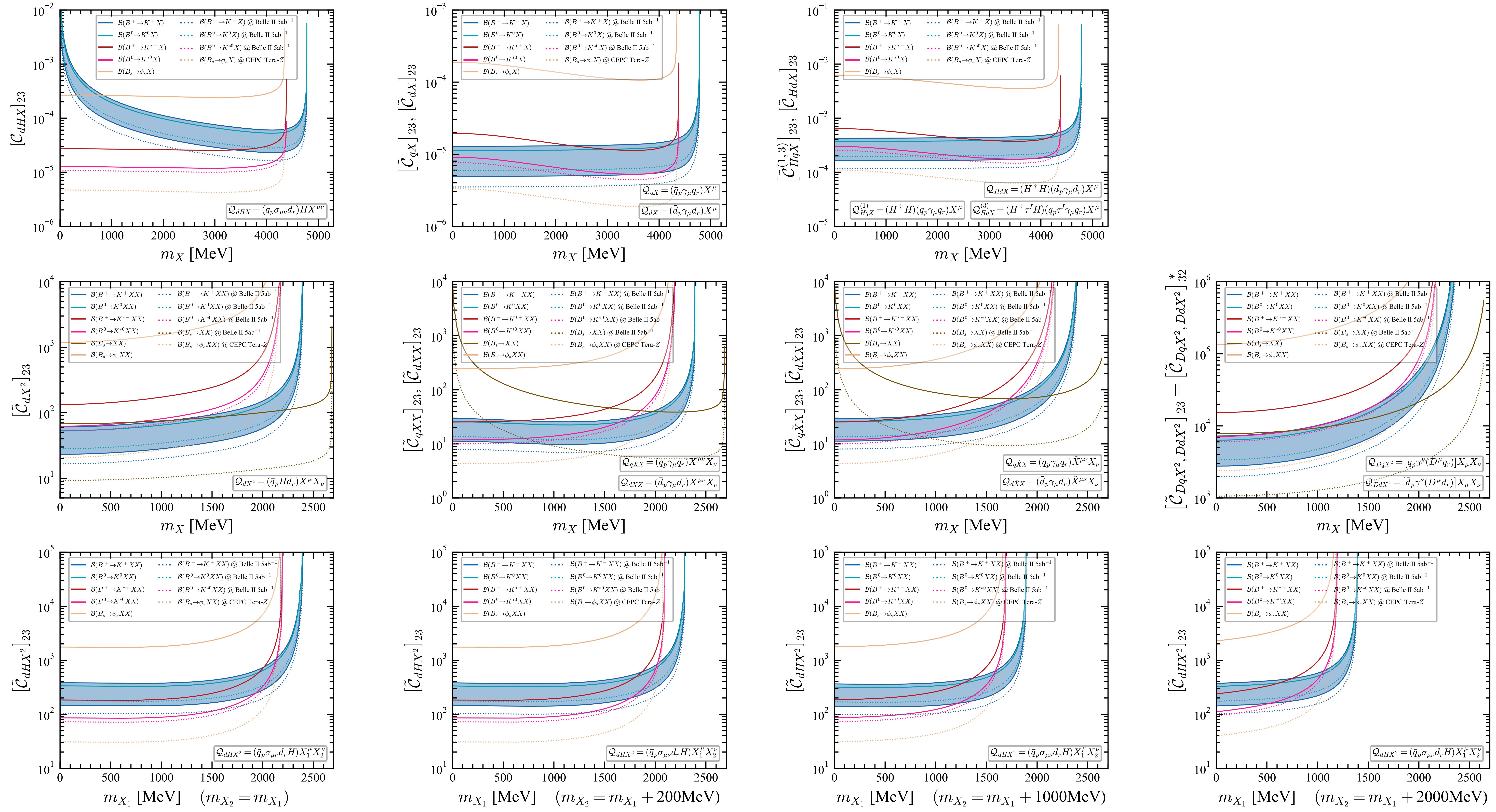
ALP: 2

μ_b

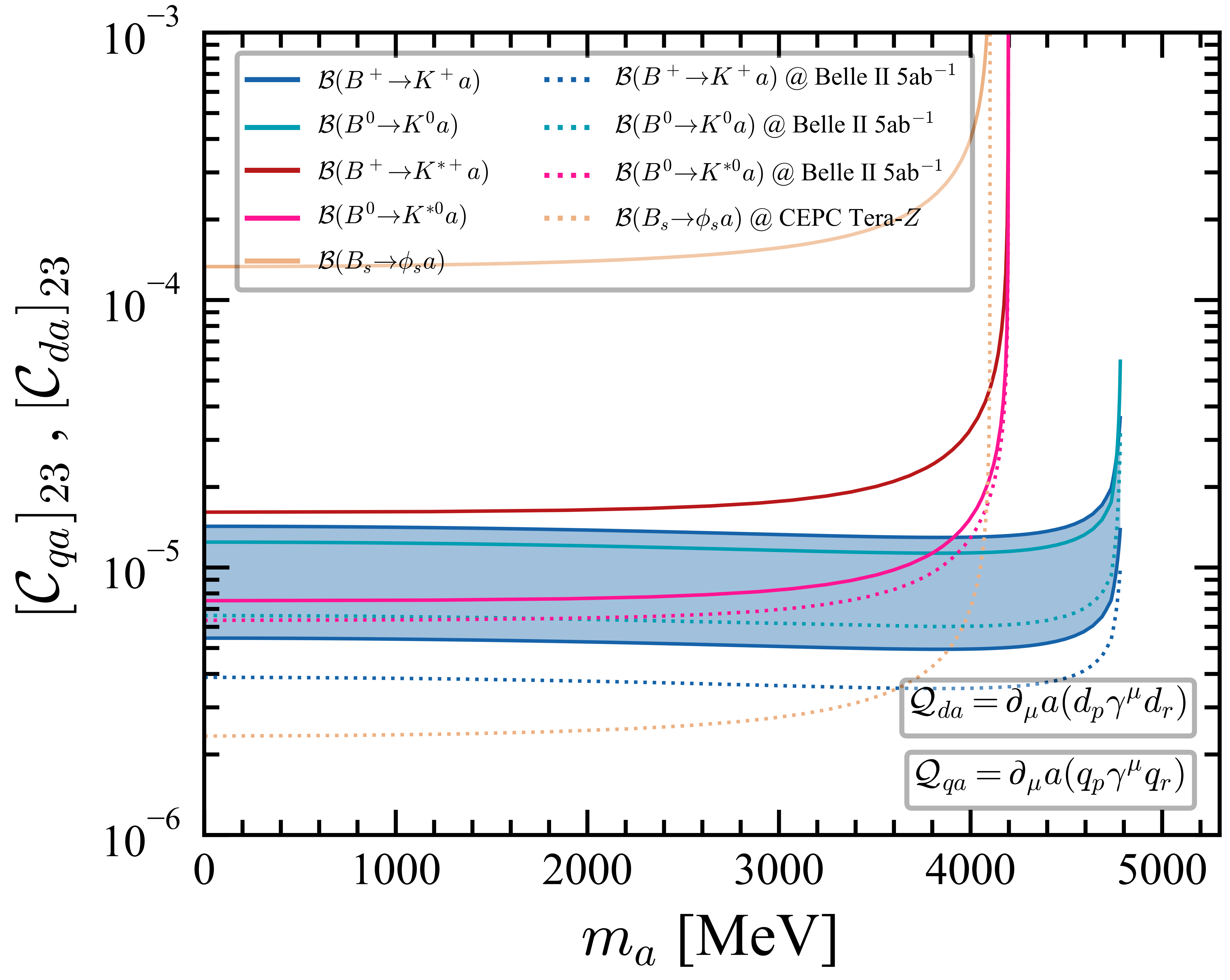
Dark SMEFT: Scalar

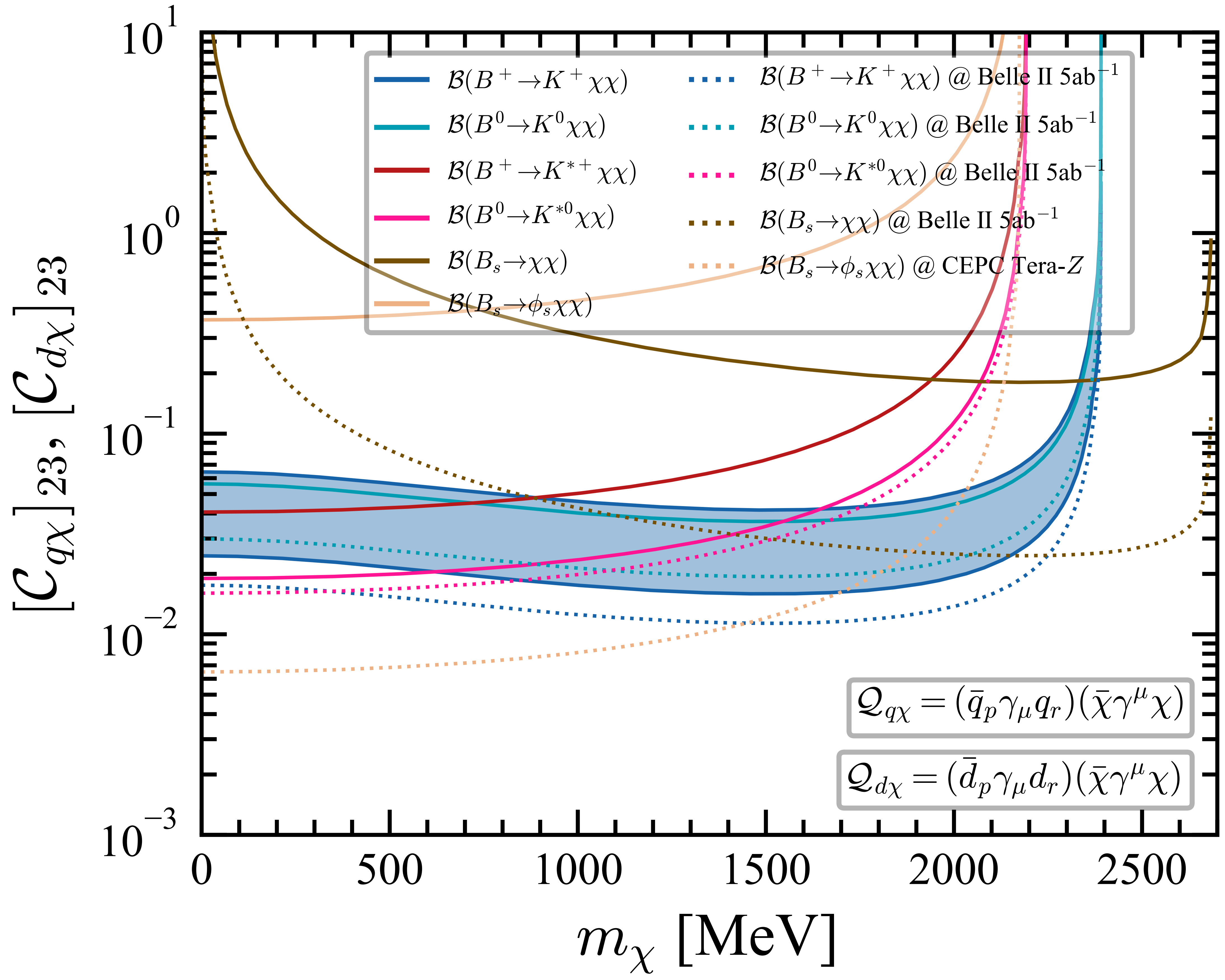


Dark SMEFT: Vector



Dark SMEFT: Fermion, ALP





All the operators survive from the constraints of the various FCNC decays.

In the future, all the parameter space to explain the Belle II anomaly can be covered by combing the Belle II (e.g., $B^0 \to K^0 + \text{inv}$) and CEPC (e.g., $B_s \to \phi + \text{inv}$ and $B_s \to \text{inv}$) measurements.

Dark SMEFT with MFV

- MFV coupling **$b \to s, b \to d, s \to d$ are connected with each other.**

$$\mathcal{C}_i^{\rm MFV} = \begin{cases} \epsilon_0^i \hat{\lambda}_d + \epsilon_1^i \Delta_q \hat{\lambda}_d & \text{for } \mathcal{Q}_i = \mathcal{Q}_{d\phi}, \mathcal{Q}_{d\phi^2}, \mathcal{Q}_{dHX}, \mathcal{Q}_{dHX^2}, \mathcal{Q}_{dX^2}, \\ \epsilon_0^i \mathbb{1} + \epsilon_1^i \Delta_q & \text{for } \mathcal{Q}_i = \mathcal{Q}_{\phi q}, \mathcal{Q}_{q\chi}, \mathcal{Q}_{qXX}, \mathcal{Q}_{q\tilde{X}X}, \mathcal{Q}_{DqX^2}, \mathcal{Q}_{qX}, \mathcal{Q}_{HqX}^{(1,3)}, \mathcal{Q}_{qa}, \\ \epsilon_0^i \mathbb{1} & \text{for } \mathcal{Q}_i = \mathcal{Q}_{\phi d}, \mathcal{Q}_{d\chi}, \mathcal{Q}_{dXX}, \mathcal{Q}_{d\tilde{X}X}, \mathcal{Q}_{DdX^2}, \mathcal{Q}_{dX}, \mathcal{Q}_{HdX}, \mathcal{Q}_{da}, \end{cases}$$

8 operators are eliminated

- Numerics

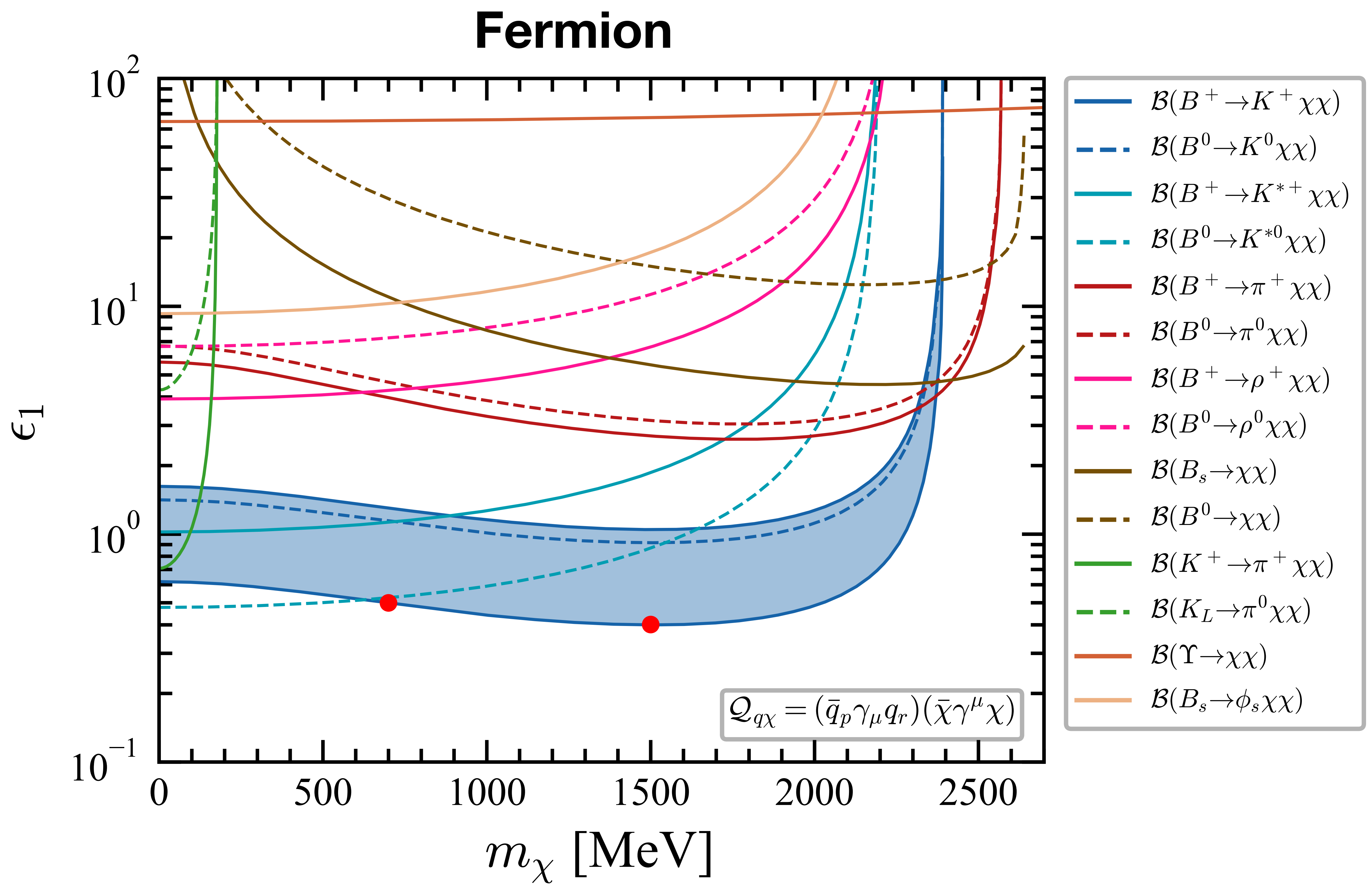
$$\Delta_q = \begin{pmatrix} 0.8 & -3.3 - 1.5i & 79.3 + 35.4i \\ -3.3 + 1.5i & 16.6 & -397.5 + 8.1i \\ 79.3 - 35.4i & -397.5 - 8.1i & 9839.0 \end{pmatrix} \times 10^{-4}$$

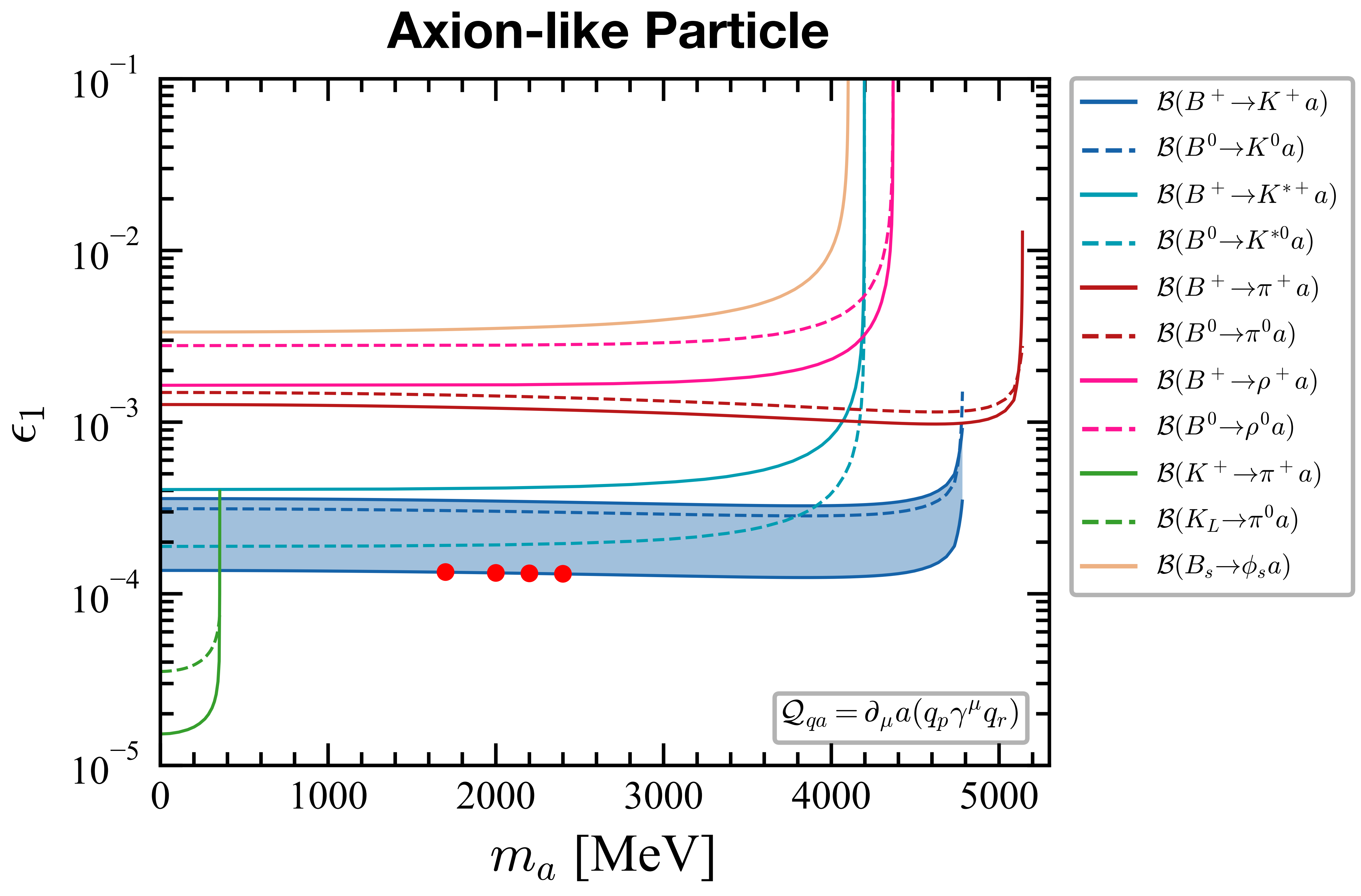
$$\Delta_q \hat{\lambda}_d = \begin{pmatrix} 0.0021 & -0.18 - 0.08i & 191.3 + 85.4i \\ -0.009 + 0.004i & 0.88 & -958.7 + 19.6i \\ 0.21 - 0.10i & -21.1 - 0.4i & 23728.1 \end{pmatrix} \times 10^{-6}$$

Dark SMEFT with MFV: Scalar

all the operators survive
some ones highly constrained

Dark SMEFT with MFV: Fermion, ALP



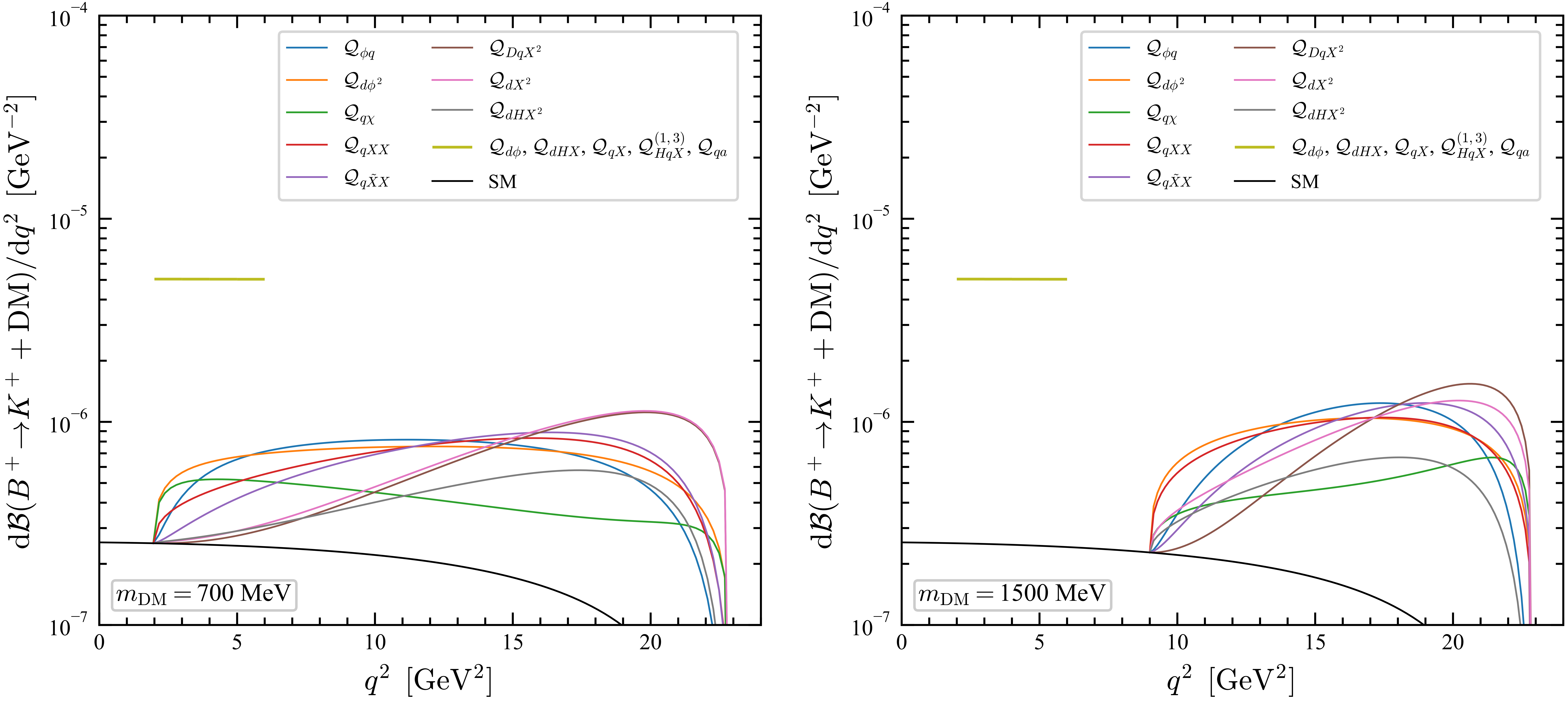


all the operators survive

Dark SMEFT with MFV: Vector

all the operators survive, some ones highly constrained

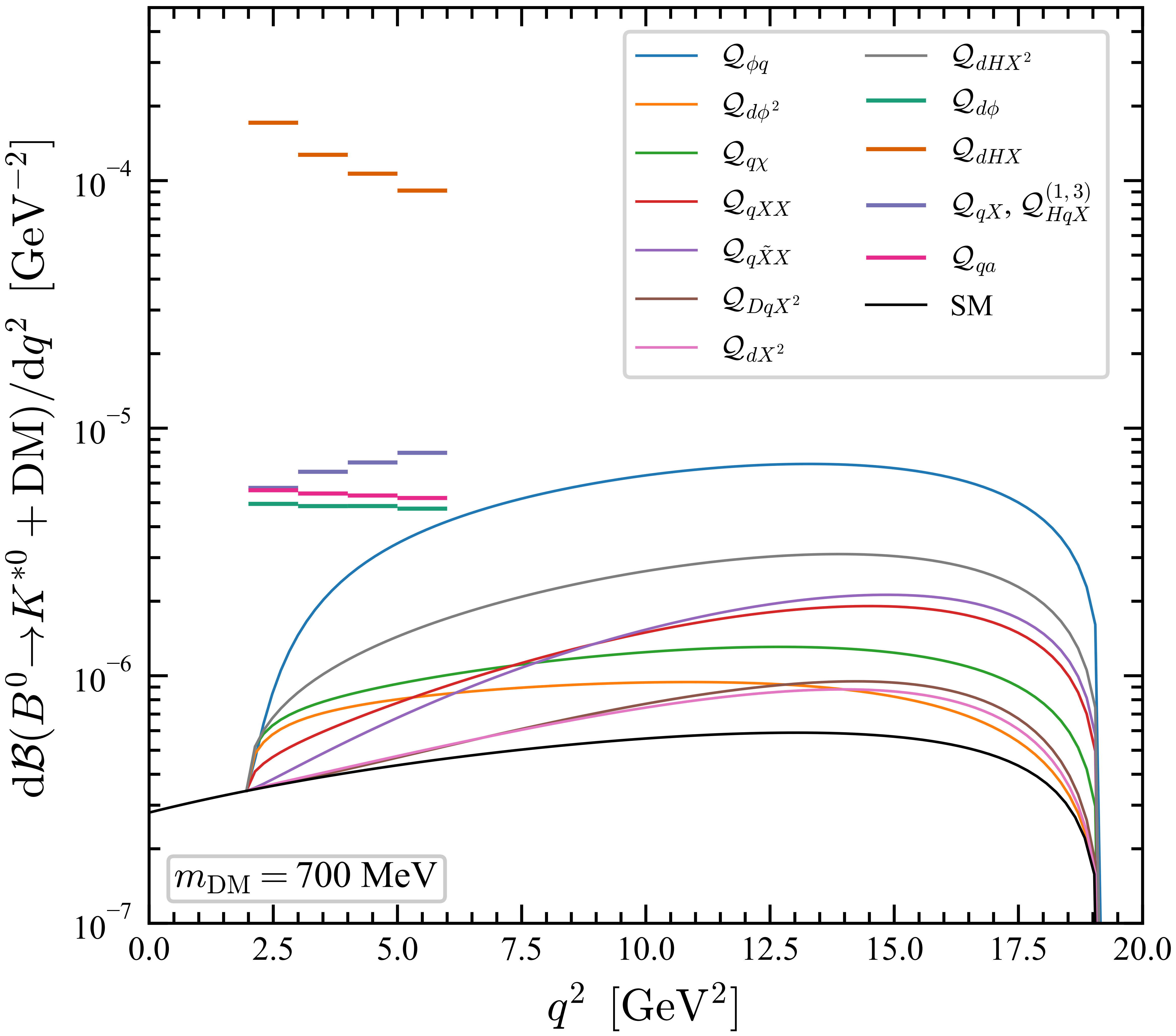
Dark SMEFT: $\mathrm{d}B/\mathrm{d}q^2$

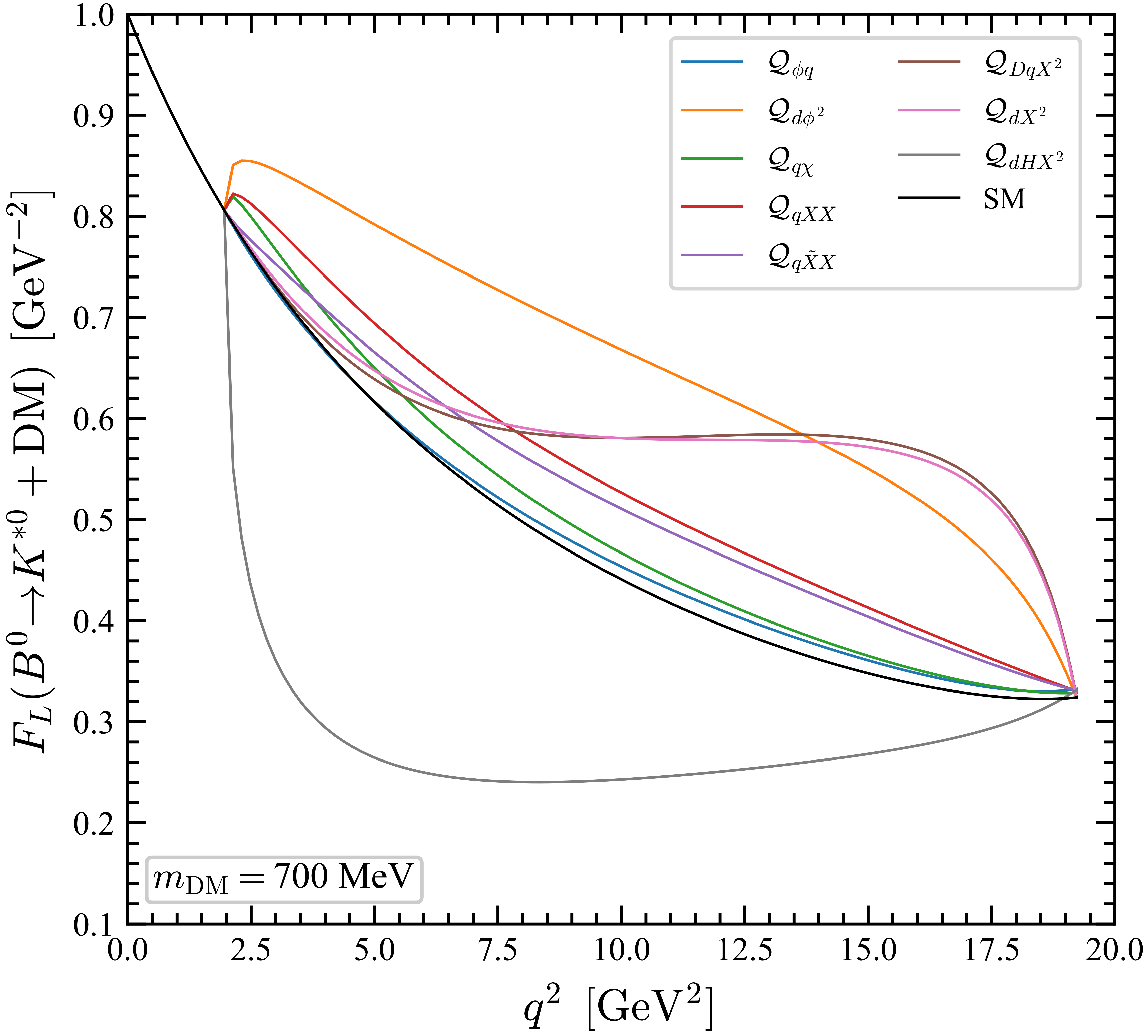


Difficult to distinguish the DSMEFT operators by considering only the $B^+ \to K^+\nu\bar{\nu}$ decay. However,

Dark SMEFT: $\mathrm{d}\mathcal{B}/\mathrm{d}q^2$, F_L

$m_{\mathrm{DM}} = 700\,\mathrm{MeV}$

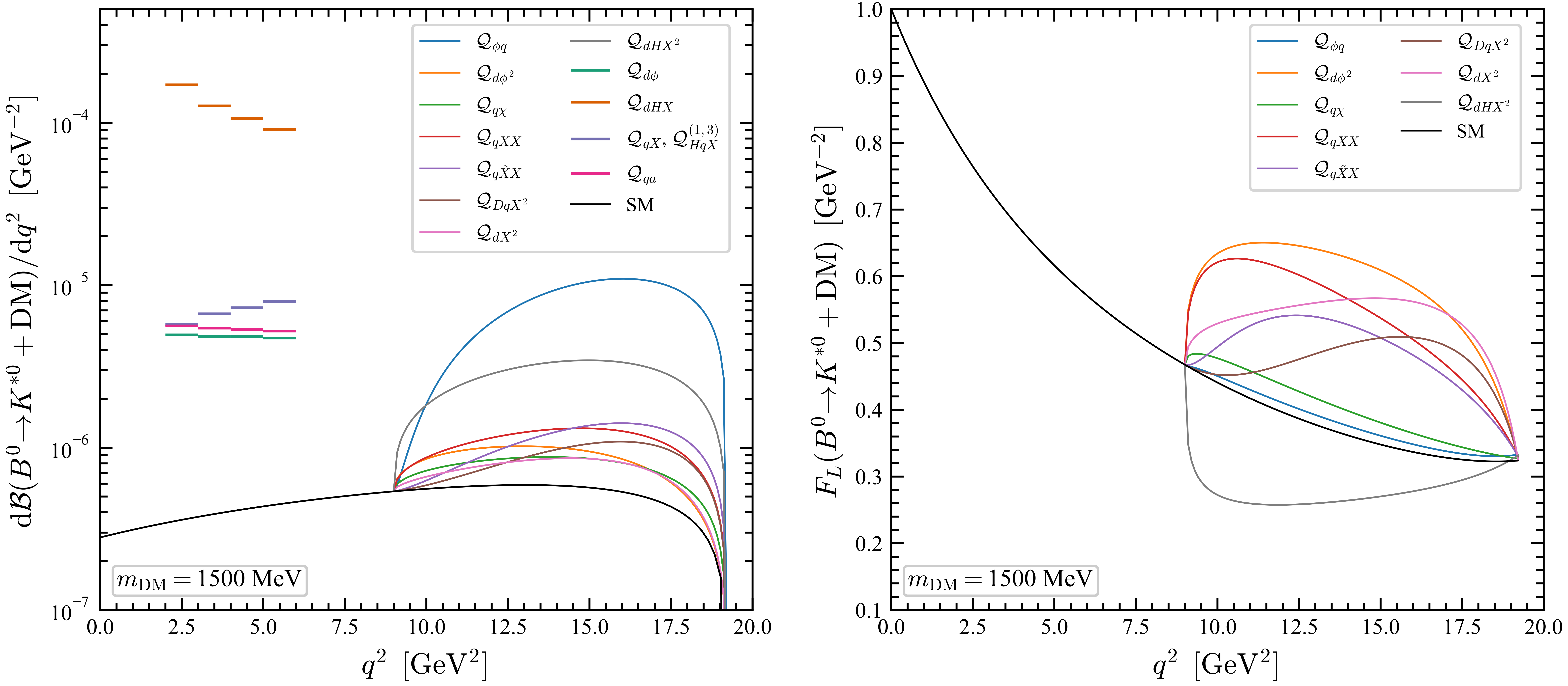




All the operators are distinguishable from each other by combing these observables, except Q_{qXX} **and** $Q_{qX\tilde{X}}$, Q_{dX^2} **and** Q_{DqX}

Dark SMEFT: $\mathrm{d}B/\mathrm{d}q^2, F_L$

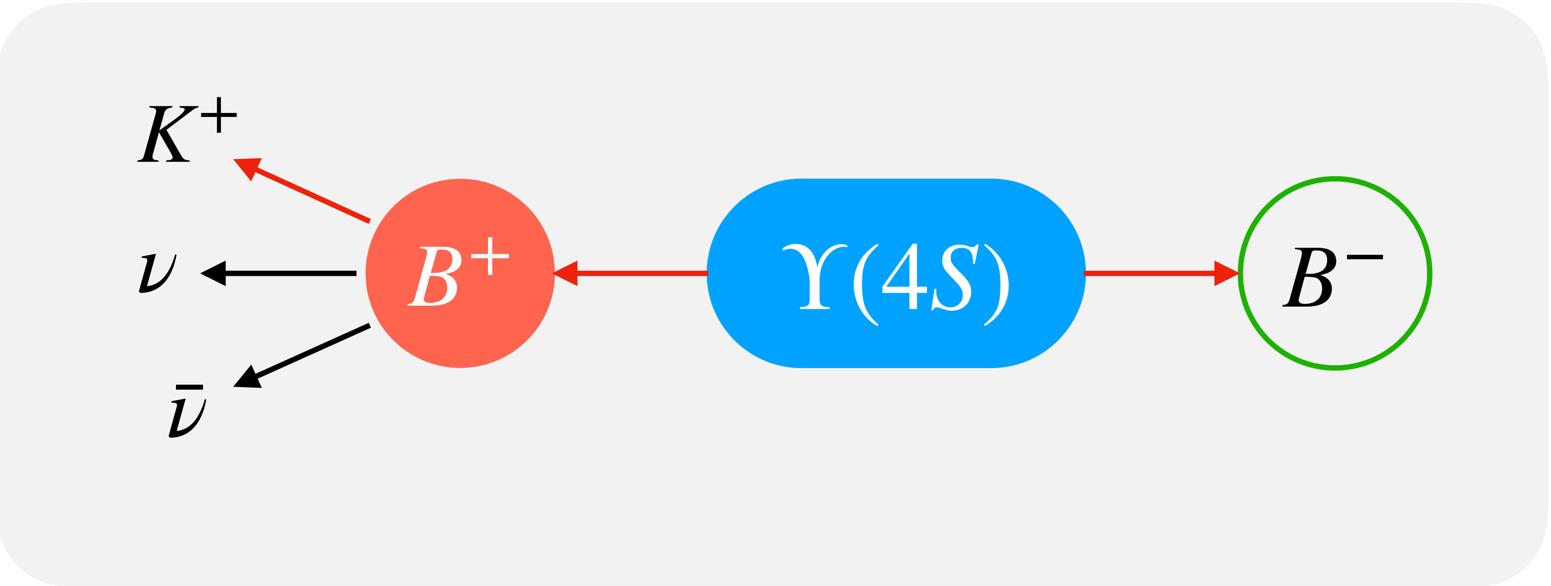
$m_{\mathrm{DM}} = 1500\,\mathrm{MeV}$

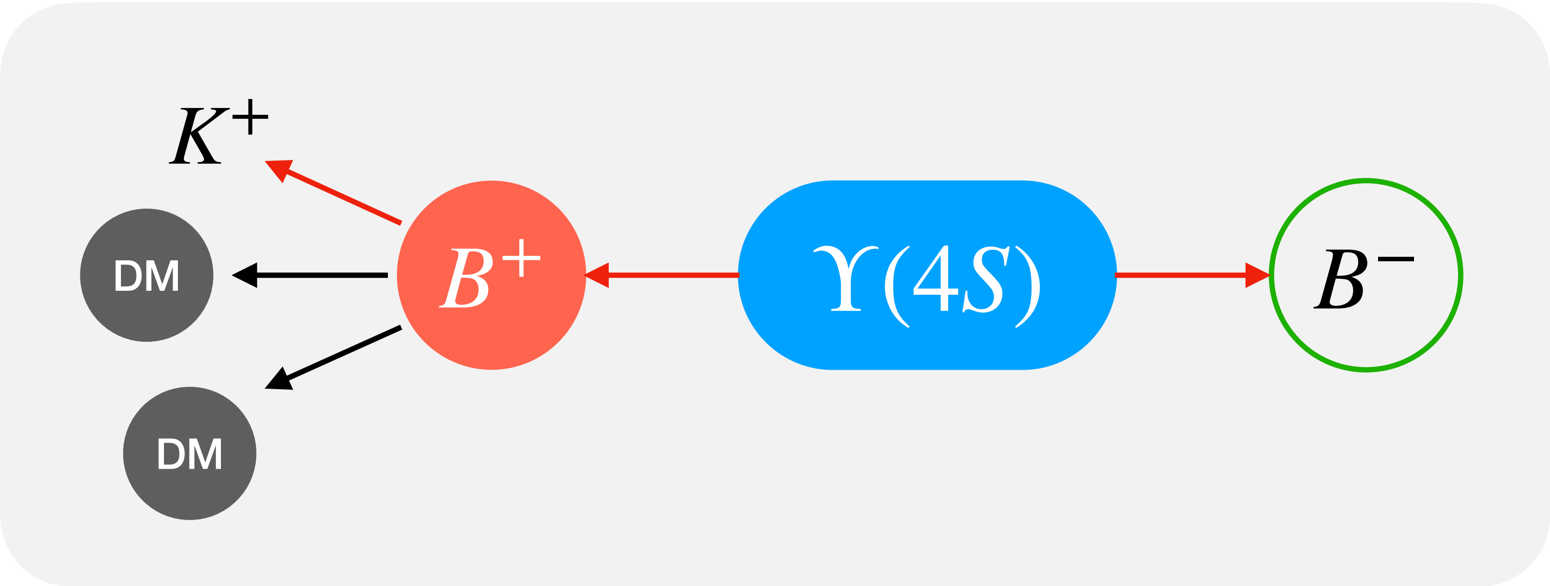


All the operators are distinguishable from each other by combing these observables, except ~~Q_{qXX} and $Q_{qX\tilde{X}}$~~ ~~Q_{dX^2} and Q_{DqX}~~

Conclusion of this work

HadronToNP: a package to calculate decay of hadron to new particles
$B \to K + \text{DM},\ B \to \rho + \text{DM},\ \Lambda_b \to \Lambda + \text{DM}, \Upsilon \to \text{DM}, \ldots$
$D \to \pi + \text{DM},\ D \to \rho + \text{DM},\ \Xi_c \to \Xi + \text{DM},\ J/\psi \to \text{DM}, \ldots$
to be finished





SMEFT

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

$$\frac{\mathcal{B}(B^+ \to K^+\nu\bar{\nu})}{\mathcal{B}(B^+ \to \pi^+\nu\bar{\nu})} = \frac{\mathcal{B}(B^+ \to K^+\nu\bar{\nu})_{\text{SM}}}{\mathcal{B}(B^+ \to \pi^+\nu\bar{\nu})_{\text{SM}}} = 29.7 \pm 5.6$$

Belle II excess (if confirmed in the future) implies:
- impossible to explain in SMEFT with MFV
- NP flavour structure is highly non-trivial
- **NP structure in quark sector is beyond MFV**
- **flavour violation is beyond Yukawa coupling**

μ_{EW}

LEFT

μ_b

Dark SMEFT

All DSMEFT operators survive in general and MFV flavour structure
$\mathrm{d}B/\mathrm{d}q^2$ and F_L are useful to distinguish them
future work: interplay with DM direct detection and relic density

Dark LEFT

Observable	SM	Exp	Unit
$\mathcal{B}(B^+ \to K^+\nu\bar{\nu})$	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}
$\mathcal{B}(B^+ \to \pi^+\nu\bar{\nu})$	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}
$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$	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}

Conclusion

- a possible approach to detect light DM and constrain its flavour structure.
- branching ratios could be much higher than the SM value.
- EFT can be used to combine the various experimental searches.
- missing invariant mass distribution and angular observables are important.

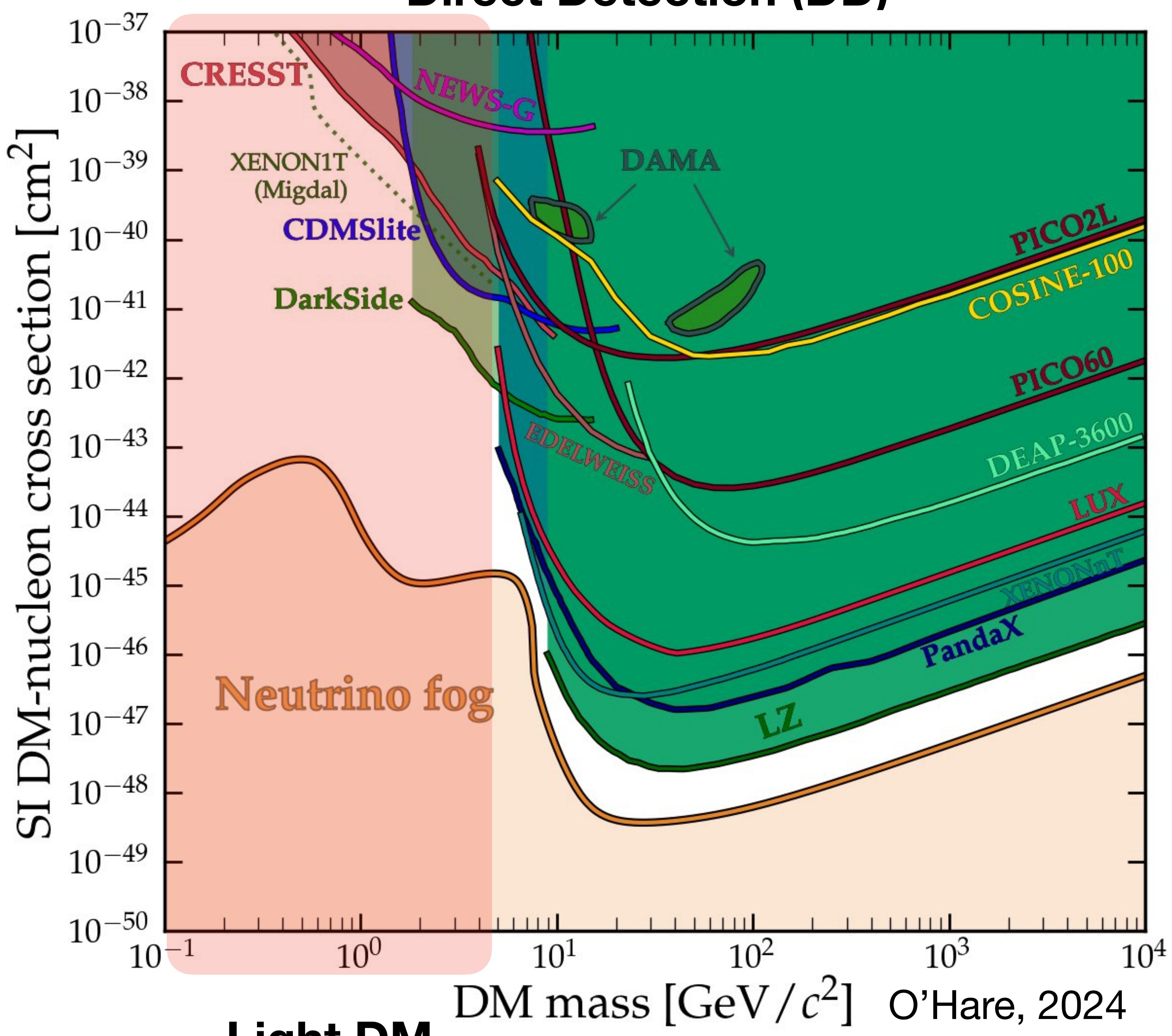
	d	s	b
d	DD	NA62/KOTO	Belle II
s		DD	Belle II
b			

	u	c	t
u	DD	BES/STCF	
c			
t			

example:

$B^+ \to K^+ + \mathrm{DM}$
$K^+ \to \pi^+ + \mathrm{DM}$
$D^0 \to \pi^0 + \mathrm{DM}$

Direct Detection (DD)



O'Hare, 2024

Light DM

see also Yue Meng's talk

Thank You !

Backup

$b \to s\nu\bar{\nu}$ and $b \to s\ell\ell$

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

- **$\mathcal{O}_{ld}$ 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.

SMEFT

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

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

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

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

$\mu_{\rm EW}$

LEFT

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

one LEFT operator !
just the SM operator

μ_b

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

Backup

$$\mathcal{Q}_{d\phi} = \big(\bar{q}_p d_r H\big)\phi + \text{h.c.}, \qquad \mathcal{Q}_{d\phi^2} = \big(\bar{q}_p d_r H\big)\phi^2 + \text{h.c.},$$
$$\mathcal{Q}_{\phi q} = \big(\bar{q}_p \gamma_\mu q_r\big)\big(i\phi_1 \overleftrightarrow{\partial^\mu} \phi_2\big), \qquad \mathcal{Q}_{\phi d} = \big(\bar{d}_p \gamma_\mu d_r\big)\big(i\phi_1 \overleftrightarrow{\partial^\mu} \phi_2\big), \qquad (4.2)$$

$$\mathcal{Q}_{q\chi} = \big(\bar{q}_p \gamma_\mu q_r\big)\big(\bar{\chi}\gamma^\mu \chi\big), \qquad \mathcal{Q}_{d\chi} = \big(\bar{d}_p \gamma_\mu d_r\big)\big(\bar{\chi}\gamma^\mu \chi\big), \qquad (4.3)$$

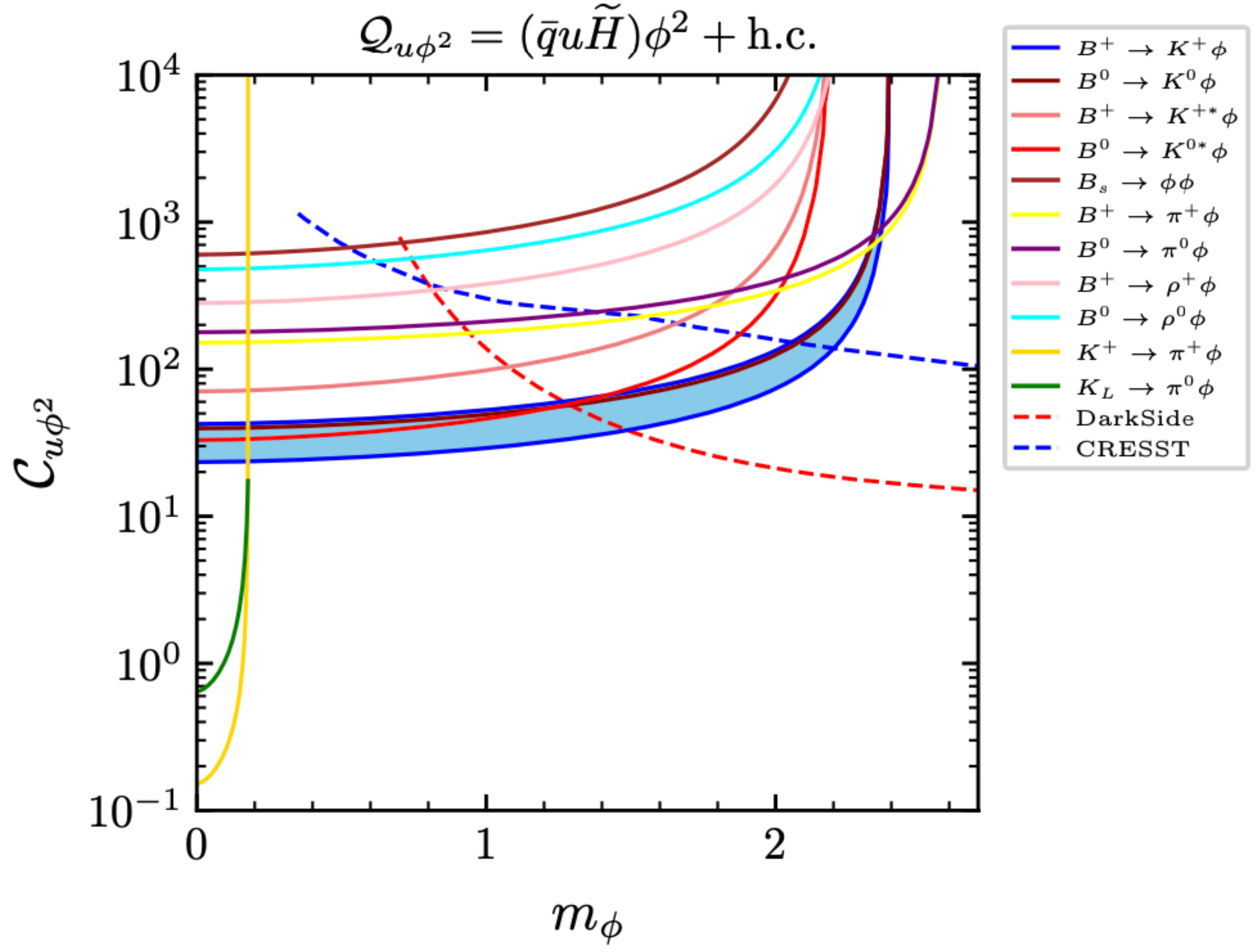
$$\mathcal{Q}_{dHX} = \big(\bar{q}_p \sigma_{\mu\nu} d_r\big) H X^{\mu\nu} + \text{h.c.}, \qquad (4.4)$$

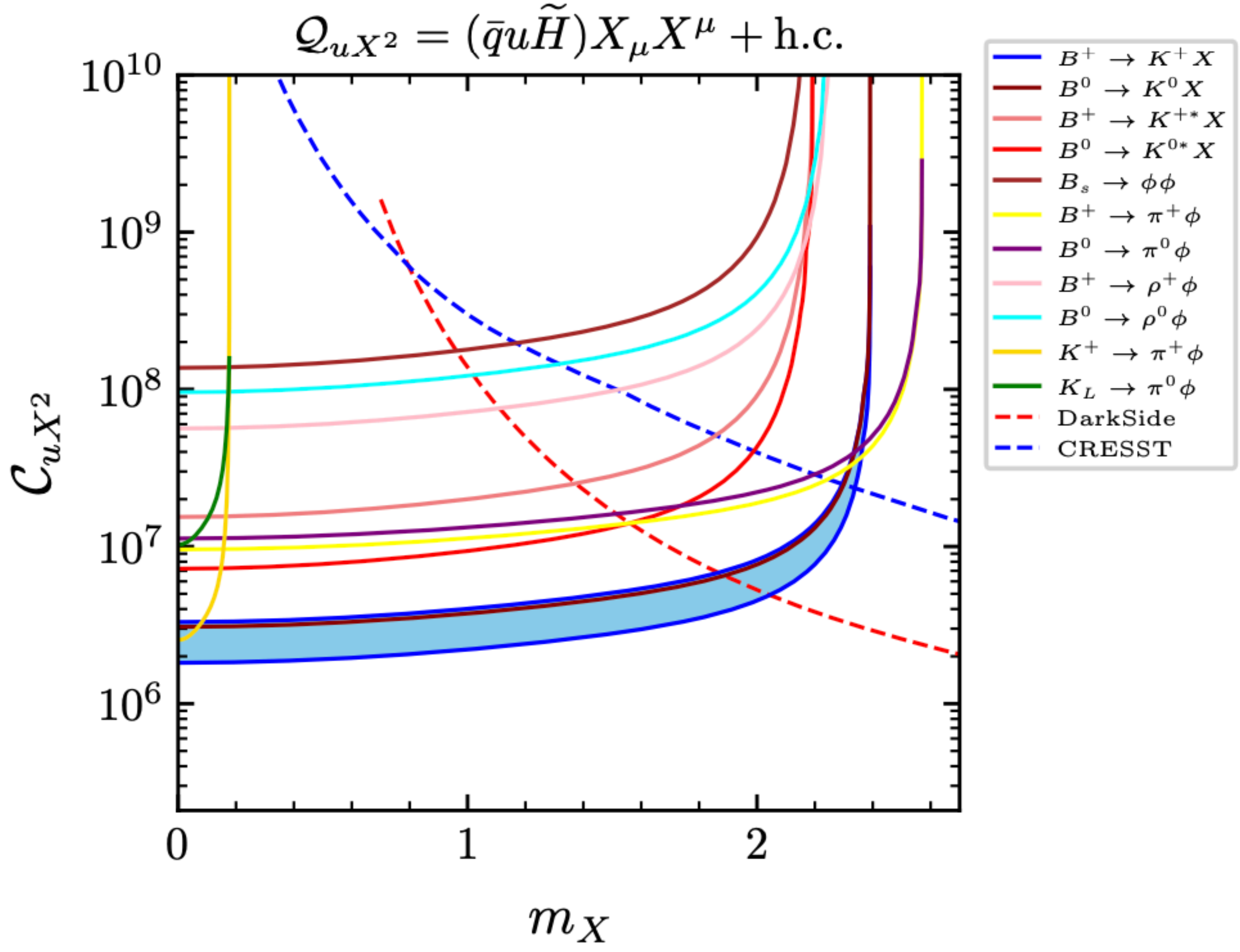
$$\begin{aligned}
\mathcal{Q}_{dX} &= \big(\bar{d}_p \gamma_\mu d_r\big) X^\mu, & \mathcal{Q}_{HdX} &= \big(H^\dagger H\big)\big(\bar{d}_p \gamma^\mu d_r\big) X_\mu, \\
\mathcal{Q}_{qX} &= \big(\bar{q}_p \gamma_\mu q_r\big) X^\mu, & \mathcal{Q}^{(1)}_{HqX} &= \big(H^\dagger H\big)\big(\bar{q}_p \gamma^\mu q_r\big) X_\mu, \\
\mathcal{Q}_{dX^2} &= \big(\bar{q}_p d_r H\big) X_\mu X^\mu + \text{h.c.}, & \mathcal{Q}^{(3)}_{HqX} &= \big(H^\dagger \tau^I H\big)\big(\bar{q}_p \tau^I \gamma^\mu q_r\big) X_\mu, \\
\mathcal{Q}_{qXX} &= \big(\bar{q}_p \gamma_\mu q_r\big) X^{\mu\nu} X_\nu\,, & \mathcal{Q}_{dXX} &= \big(\bar{d}_p \gamma_\mu d_r\big) X^{\mu\nu} X_\nu, \\
\mathcal{Q}_{q\tilde{X}X} &= \big(\bar{q}_p \gamma_\mu q_r\big) \tilde{X}^{\mu\nu} X_\nu\,, & \mathcal{Q}_{d\tilde{X}X} &= \big(\bar{d}_p \gamma_\mu d_r\big) \tilde{X}^{\mu\nu} X_\nu\,, \\
\mathcal{Q}_{DqX^2} &= i\big(\bar{q}_p \gamma^\mu D^\nu q_r\big) X_\mu X_\nu + \text{h.c.}, & \mathcal{Q}_{DdX^2} &= i\big(\bar{d}_p \gamma^\mu D^\nu d_r\big) X_\mu X_\nu + \text{h.c.}, \\
\mathcal{Q}_{dHX^2} &= \big(\bar{q}_p \sigma_{\mu\nu} d_r H\big) X_1^\mu X_2^\nu + \text{h.c.}, & & \qquad (4.5)
\end{aligned}$$

$$\mathcal{C}_i = \tilde{\mathcal{C}}_i \cdot \begin{cases} (m_X/\Lambda)^2 & \text{for } \mathcal{Q}_i = \mathcal{Q}_{dX^2}, \mathcal{Q}_{DdX^2}, \mathcal{Q}_{DqX^2}, \mathcal{Q}_{dHX^2}, \\ (m_X/\Lambda) & \text{for } \mathcal{Q}_i = \text{others.} \end{cases}$$

$$\mathcal{Q}_{qa} = \big(\bar{q}_p \gamma_\mu q_r\big)\partial^\mu a, \qquad \mathcal{Q}_{da} = \big(\bar{d}_p \gamma_\mu d_r\big)\partial^\mu a, \qquad (4.7)$$

Backup





very preliminary result for top-philic DM

Backup

One can also apply the MFV hypothesis to the lepton sector. However, since the mechanism of neutrino mass generation is still unknown, there are different approaches to formulate the leptonic MFV [73–79]. Here, we consider the realization of leptonic MFV within the so-called minimal field content [73, 74], in which the neutrino masses are generated by the Weinberg operator. In this case, the Yukawa interactions in the lepton sector can be written as

$$-\Delta\mathcal{L} = \bar{e}\,Y_e H^\dagger l + \frac{1}{2\Lambda_{\rm LN}}\left(\bar{l}^c\tau_2 H\right)Y_\nu\left(H^T\tau_2 l\right) + \text{h.c.}, \tag{2.18}$$

where l denotes the left-handed lepton doublet with the charge conjugated field given by $l^c = -i\gamma_2 l^*$, and e is the right-handed charged lepton singlet. $\Lambda_{\rm LN}$ denotes the breaking scale of the lepton number symmetry $U(1)_{\rm LN}$. Y_e and Y_ν stand for the 3×3 Yukawa coupling matrices in flavour space. In the absence of these Yukawa couplings, the lepton sector respects the flavour symmetry

$$G_{\rm LF} = SU(3)_l \otimes SU(3)_e. \tag{2.19}$$

finite polynomial of A_ℓ and B_ℓ. After neglecting all the terms involving B_ℓ, which are suppressed by the small lepton Yukawa couplings Y_e, we obtain

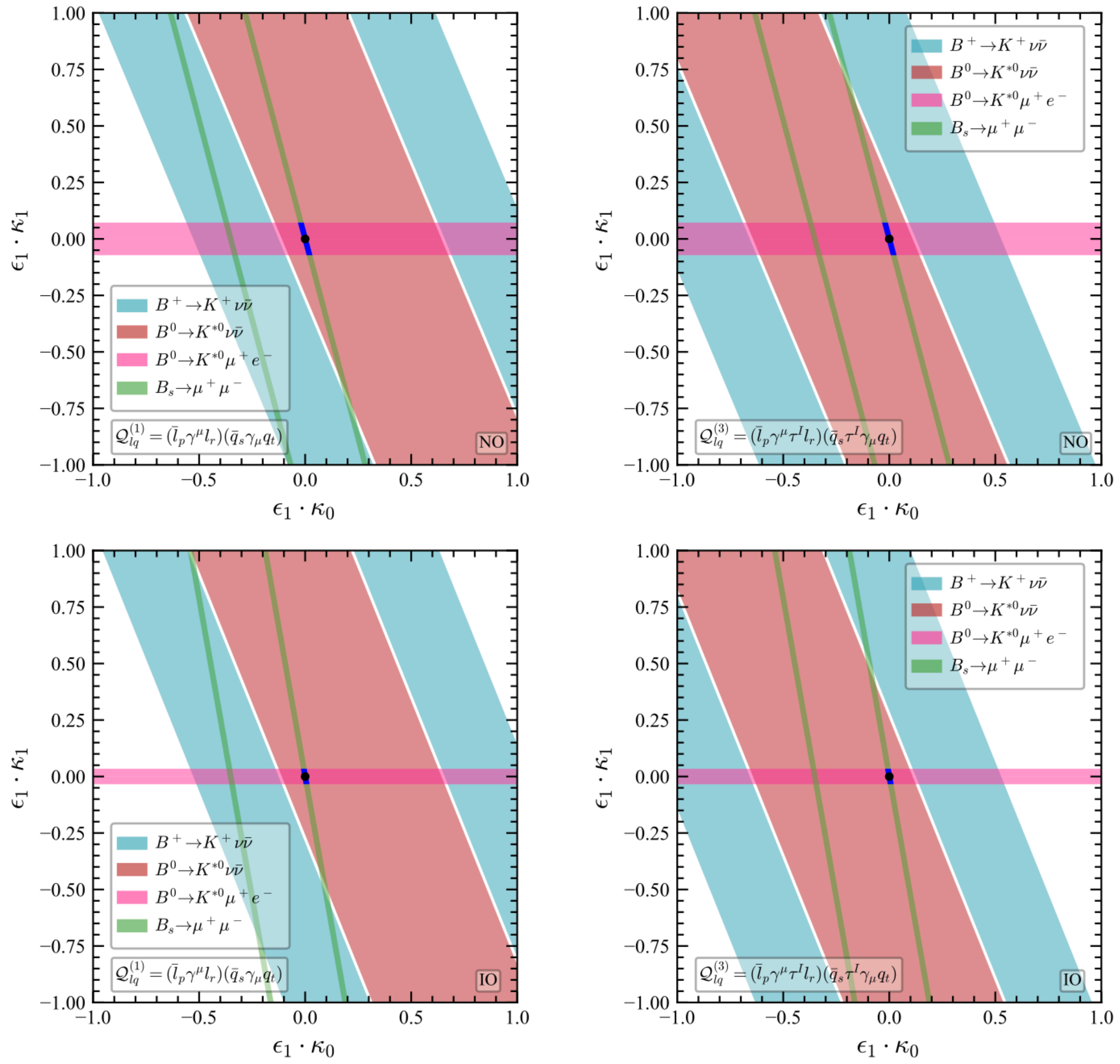
$$\mathcal{C}_{\rm MFV} \approx \kappa_0 + \kappa_1\mathsf{A}_\ell + \kappa_2\mathsf{A}_\ell^2, \tag{2.21}$$

where the coefficients $\kappa_{0,1,2}$ are free real parameters. In the numerical analysis, we keep only the leading lepton flavour violation term A_ℓ for simplicity, i.e., $\kappa_2 = 0$. Turning to the lepton mass eigenbasis, the current $\bar{l}\gamma^\mu\mathcal{C}l$ gives in the MFV hypothesis the following interactions:

$$\bar{e}_L\gamma^\mu(\kappa_0\mathbb{1} + \kappa_0\Delta_\ell)e_L + \bar{\nu}_L\gamma^\mu(\kappa_0\mathbb{1} + \kappa_0\hat{\lambda}_\nu^2)\nu_L, \tag{2.22}$$

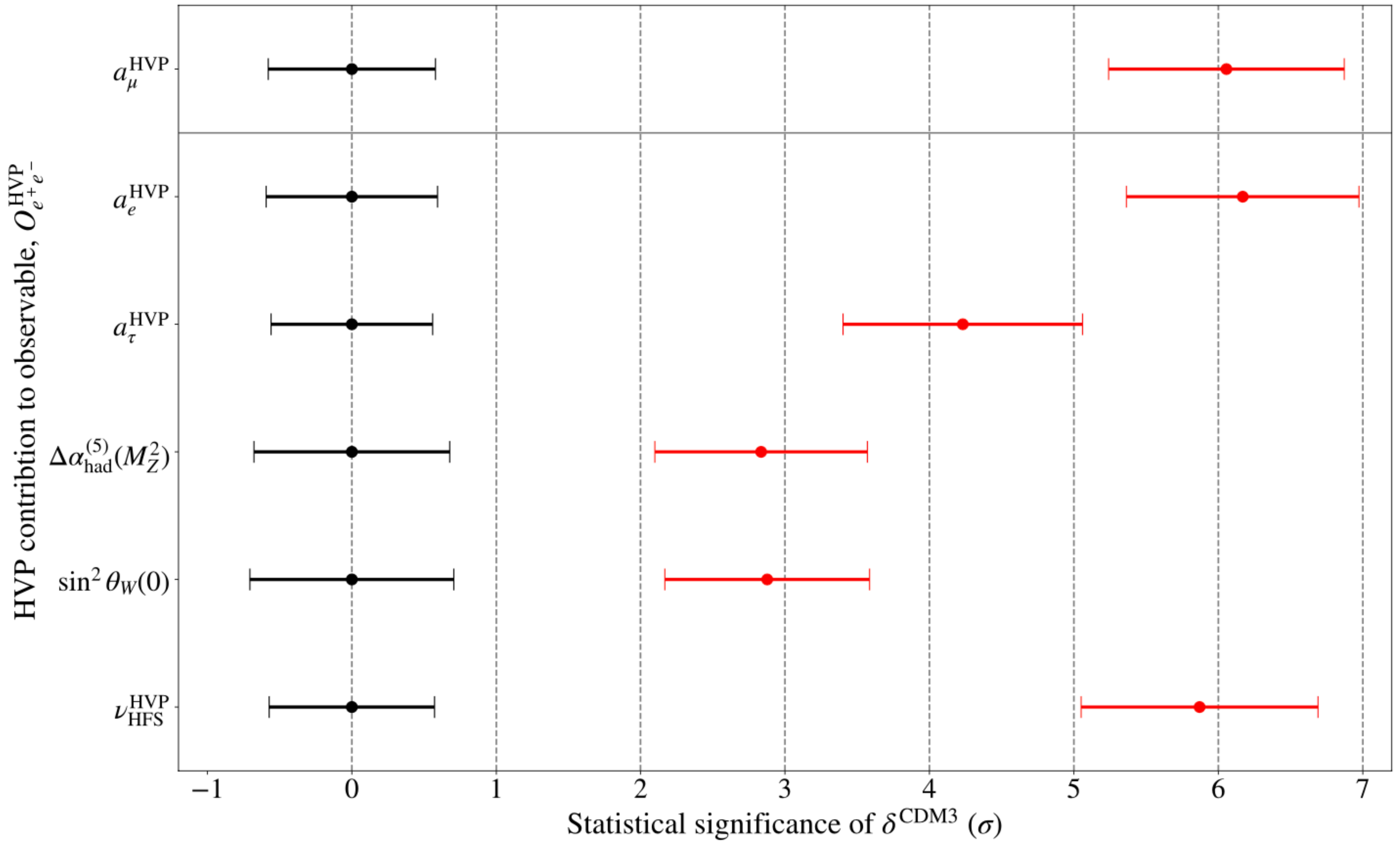
where the basic LFV coupling Δ_ℓ can be obtained from A_ℓ and takes the form

$$\Delta_\ell = U\hat{\lambda}_\nu^2 U^\dagger, \tag{2.23}$$



$$\Delta_\ell^{\rm NO} = \begin{pmatrix} -0.19-0.01i & -0.25-0.02i & 0.31-0.04i \\ 0.12+0.01i & 0.28-0.00i & 0.29+0.04i \\ -0.37-0.01i & 0.21-0.05i & -0.03+0.01i \end{pmatrix}, \quad \Delta_\ell^{\rm IO} = \begin{pmatrix} 0.21+0.09i & -0.34+0.05i & 0.03+0.11i \\ 0.31+0.12i & 0.19+0.00i & -0.15-0.14i \\ 0.12-0.02i & 0.04-0.19i & 0.34-0.10i \end{pmatrix}$$

2408.01123



$a_\mu^{\rm HVP}$
$a_e^{\rm HVP}$
$a_\tau^{\rm HVP}$
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$
$\sin^2\theta_W(0)$
$\nu^{\rm HVP}_{\rm HFS}$
HVP contribution to observable, $O^{\rm HVP}_{e^+e^-}$
−1
0
1
2
3
4
5
6
7
Statistical significance of $\delta^{\rm CDM3}$ (σ)

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

- **Effective Hamiltonian**

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

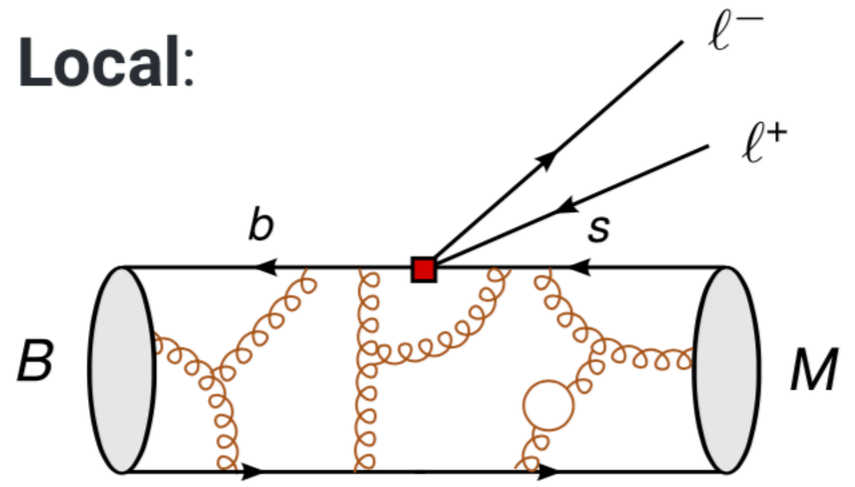
- **Effective operator**

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

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

- **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:

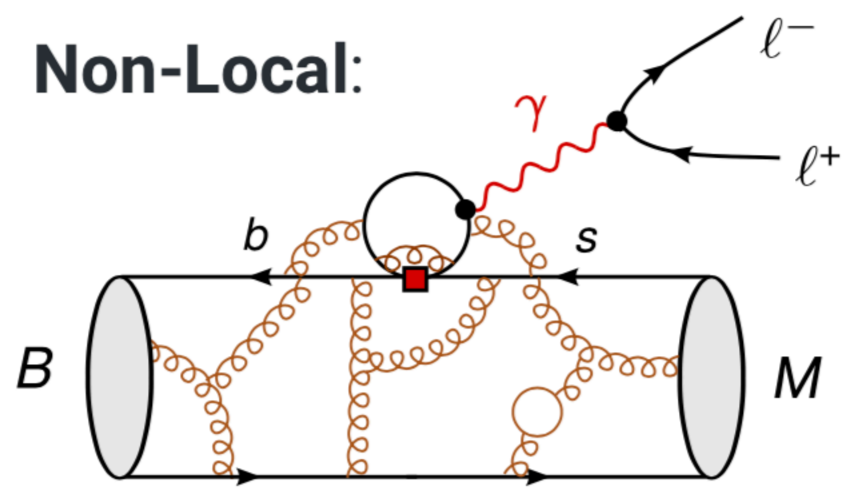


$$\mathcal{A}_V^\mu = -\frac{2im_b}{q^2}C_7\langle M|\bar s\,\sigma^{\mu\nu}q_\nu\,P_R\,b|B\rangle + C_9\langle M|\bar s\,\gamma^\mu\,P_L\,b|B\rangle + (P_L\leftrightarrow P_R, C_i\to C_i')$$

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

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

Non-Local:



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

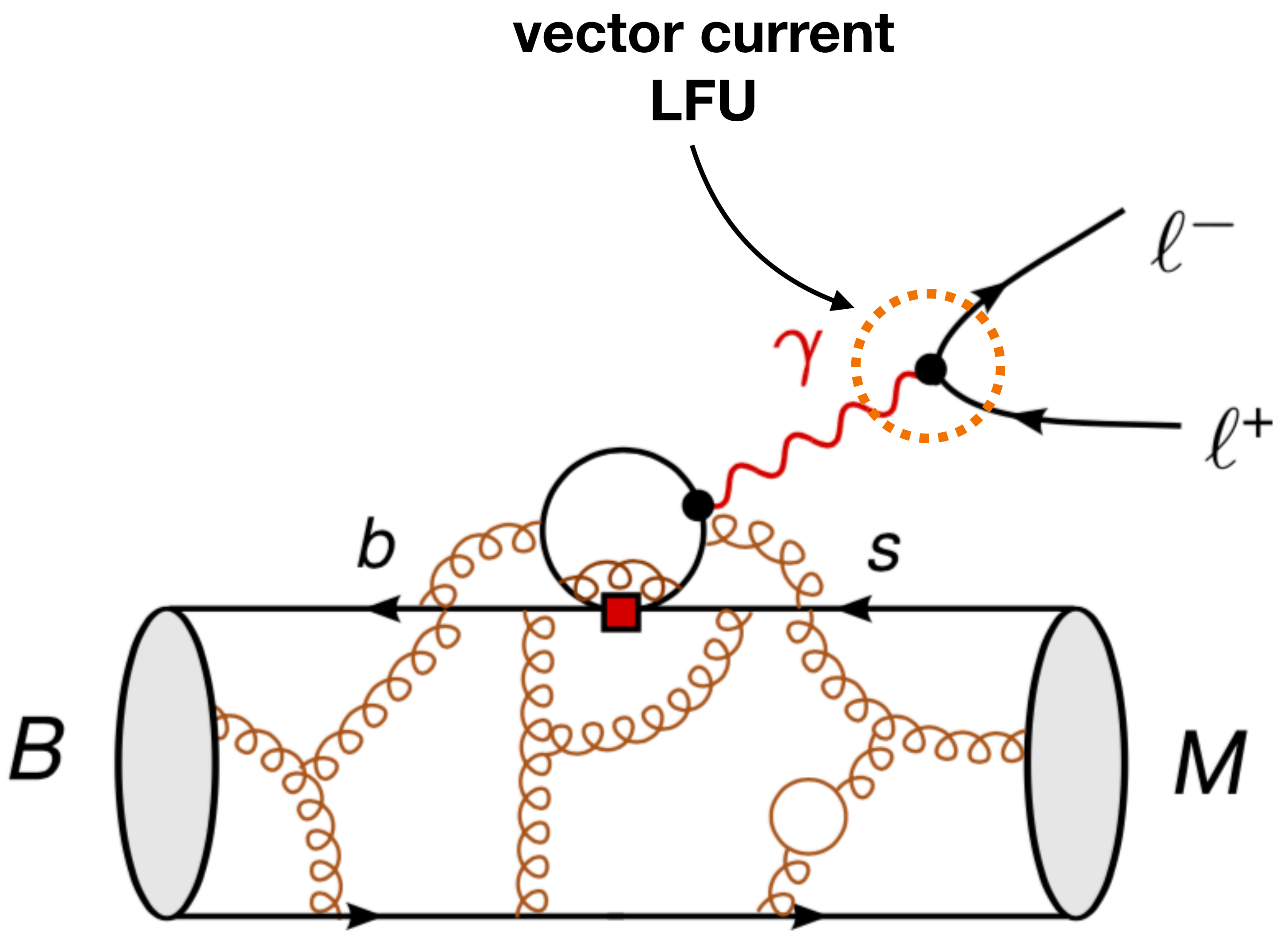
$$j^\mu_{\rm em} = \sum_q Q_q\,\bar q\gamma^\mu q$$

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

- **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

Charm-loop contribution



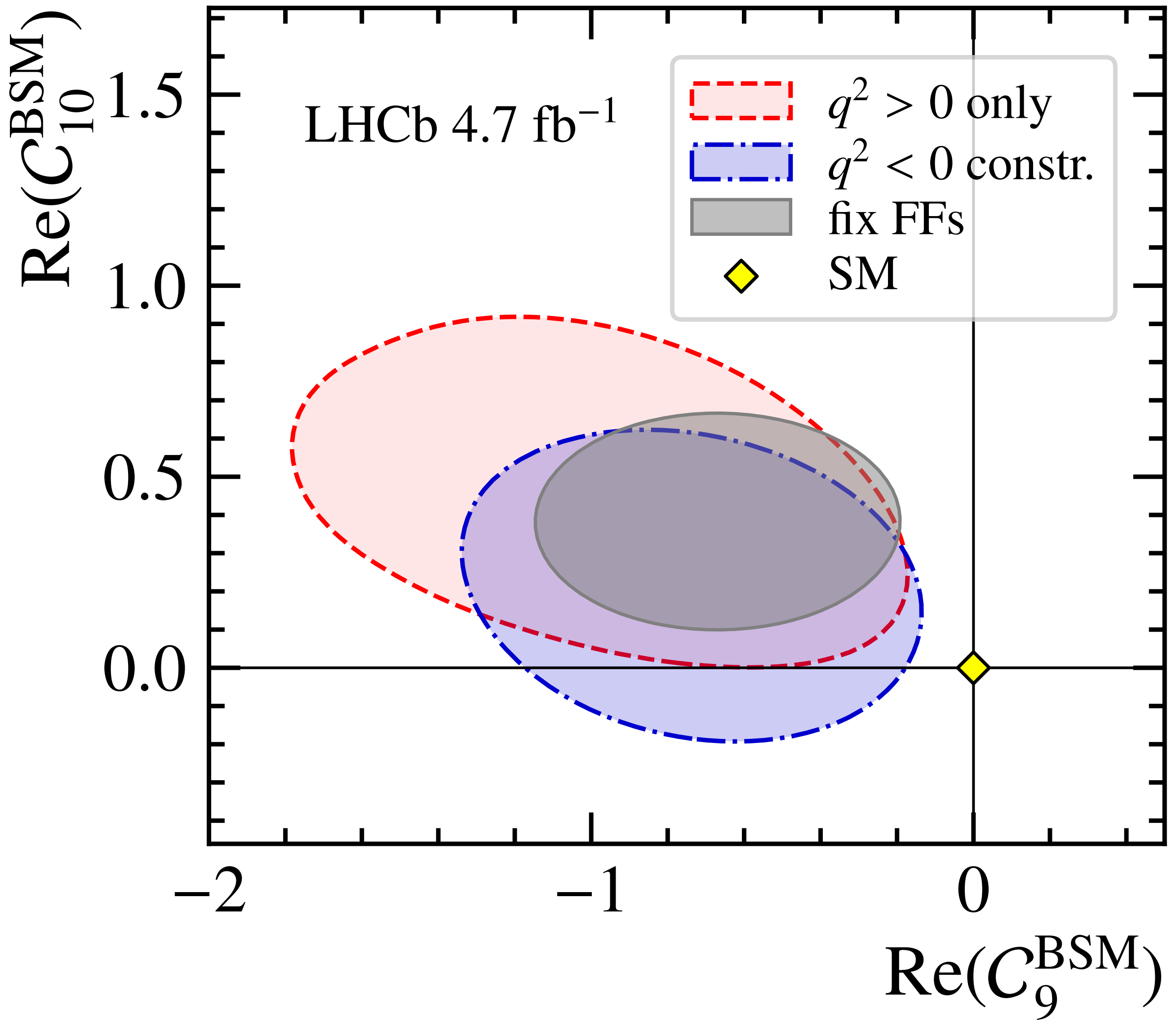
- **Global fit prefer to $C_{9e} = C_{9\mu} \neq C_9^{\mathrm{SM}}$** $\Longleftarrow \mathcal{B}(B_s \to \mu^+\mu^-)_{\mathrm{exp}}$ **is consistent with SM**
- **Charm-loop could mimic $C_{9e} = C_{9\mu}$**

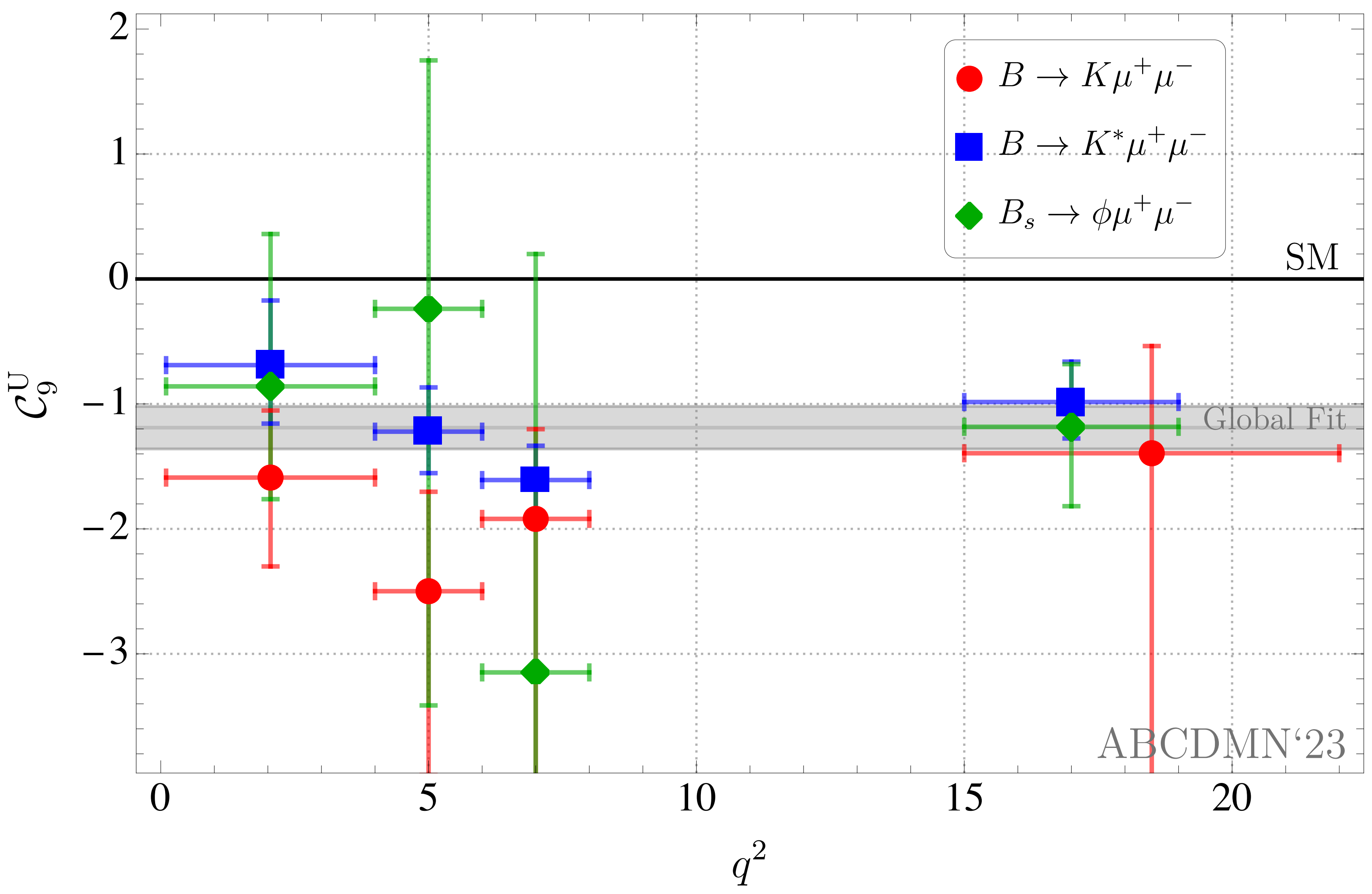
$$C_{9e} = C_{9\mu} = C_9^{\mathrm{SM}} + \Delta C_9^{U,\,\text{charm loop}} + \Delta C_9^{U,\,\mathrm{NP}}$$

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

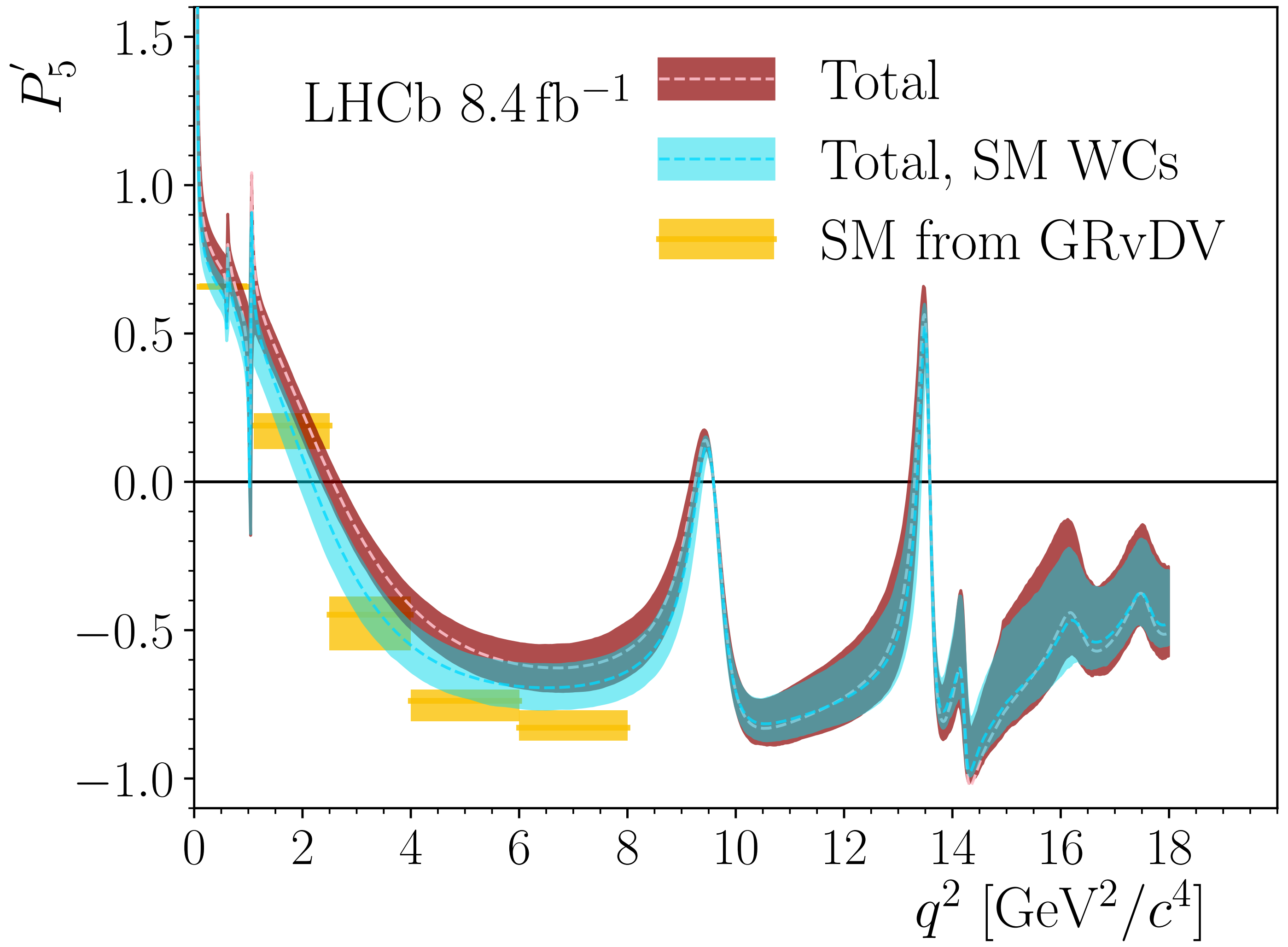
$$O_{10} = (\bar{b}\gamma^\mu P_L s)(\bar{\ell}\gamma_\mu \gamma_5 \ell)$$

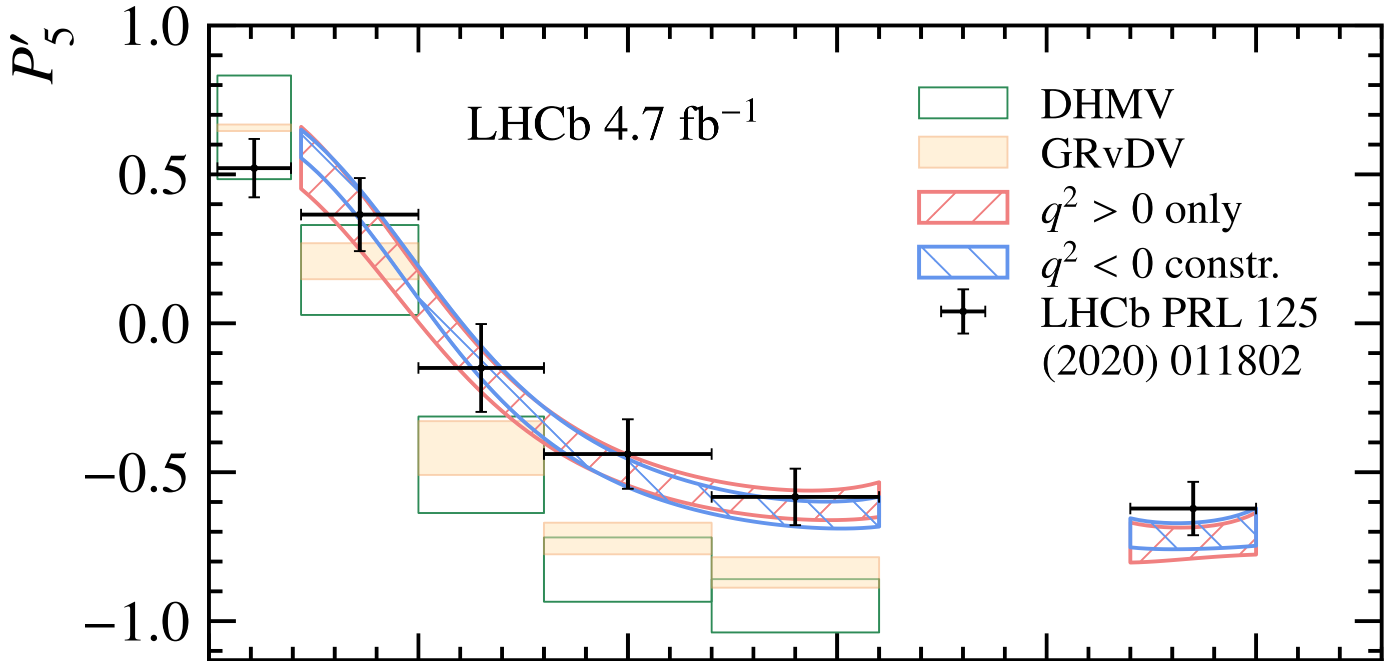
- **Charm-loop contribution is expected to be $\Delta C_9^U(q^2)$, but not ΔC_9^U**



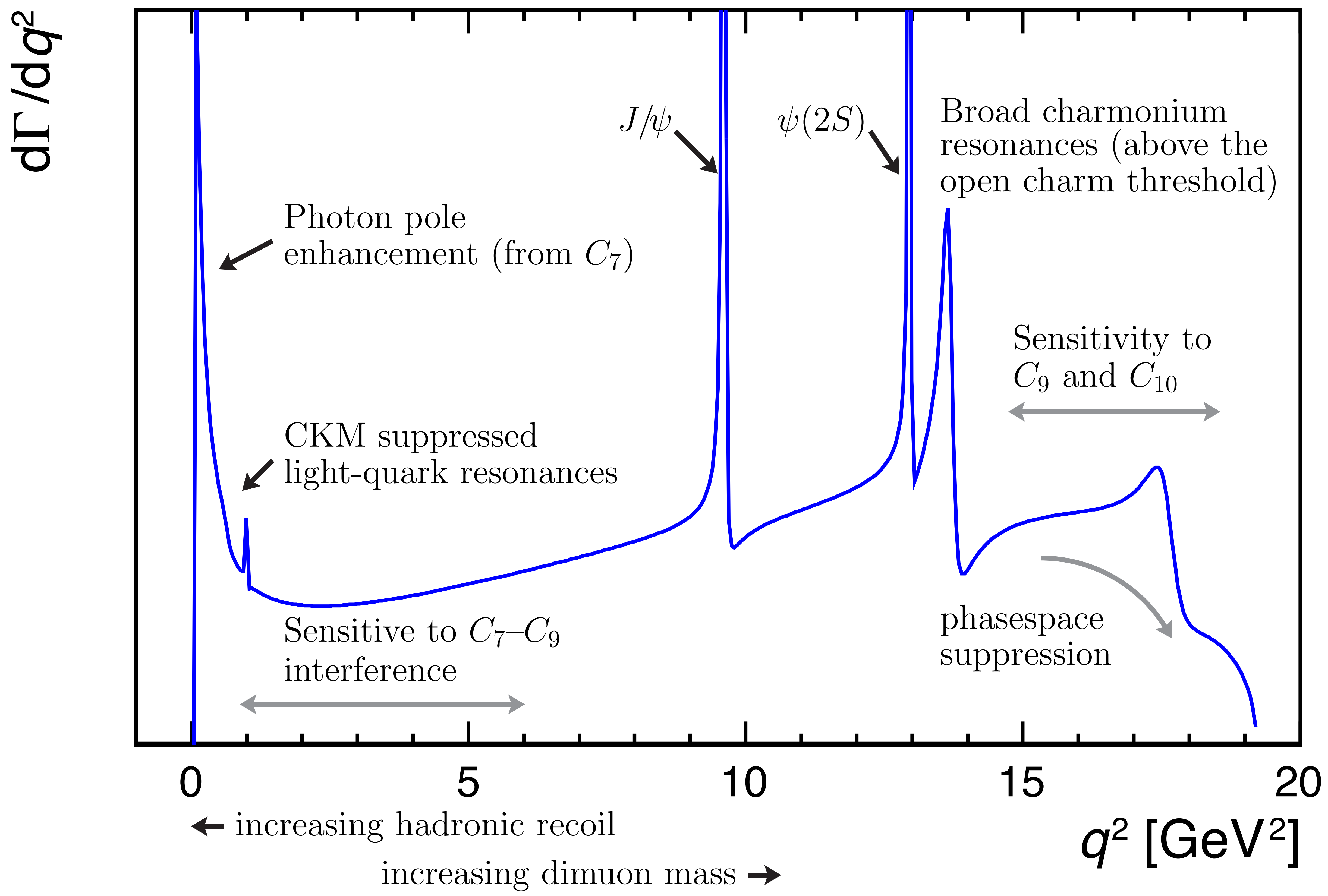


LHCb, PRL132(2024)131801
LHCb, PRD109(2024)052009
LHCb, 2405.17347 (charmonium region is open)

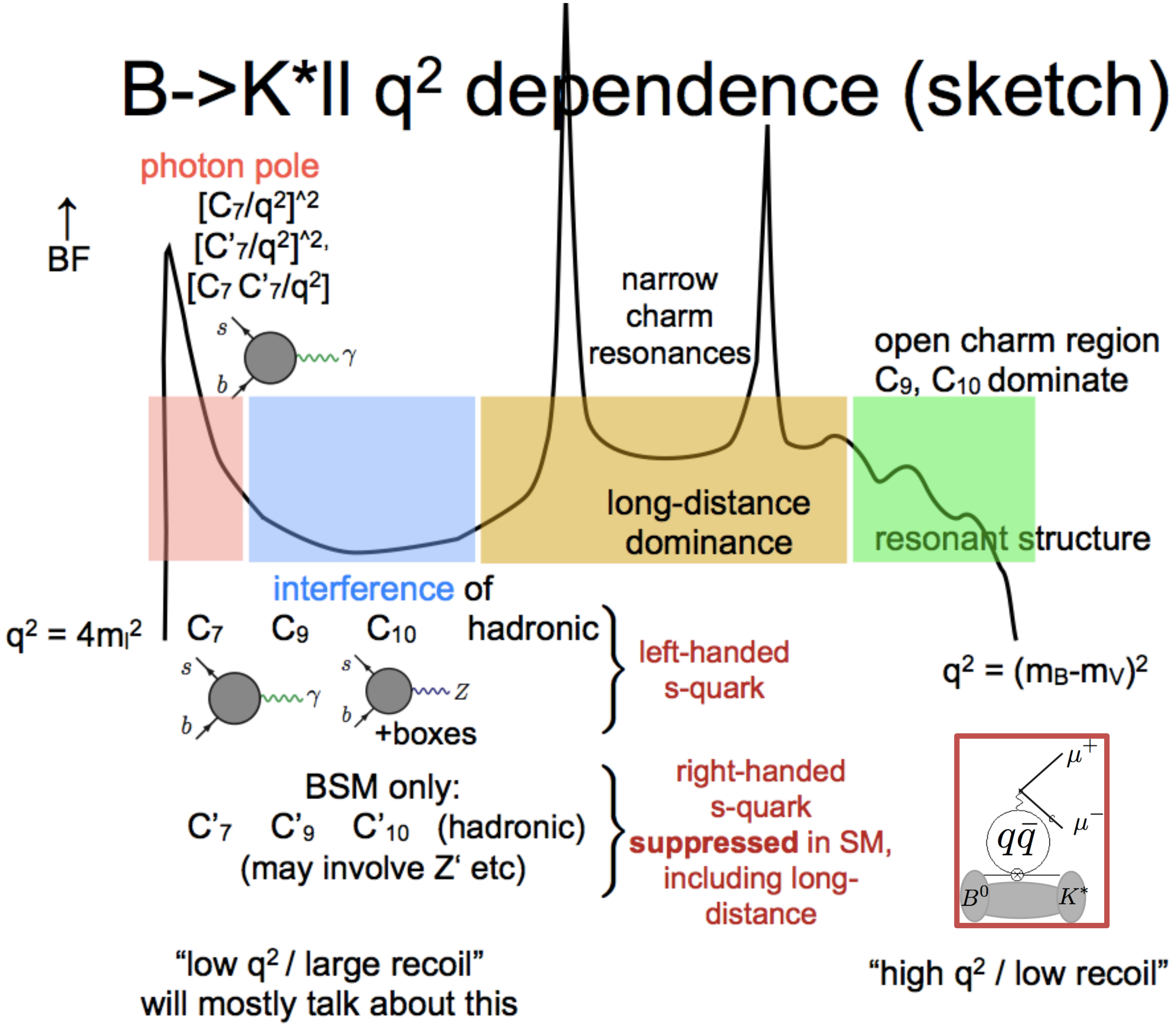




$b \to s\ell^+\ell^-$: theory



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



From S.Jager's talk

Charm-loop contribution

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

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

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

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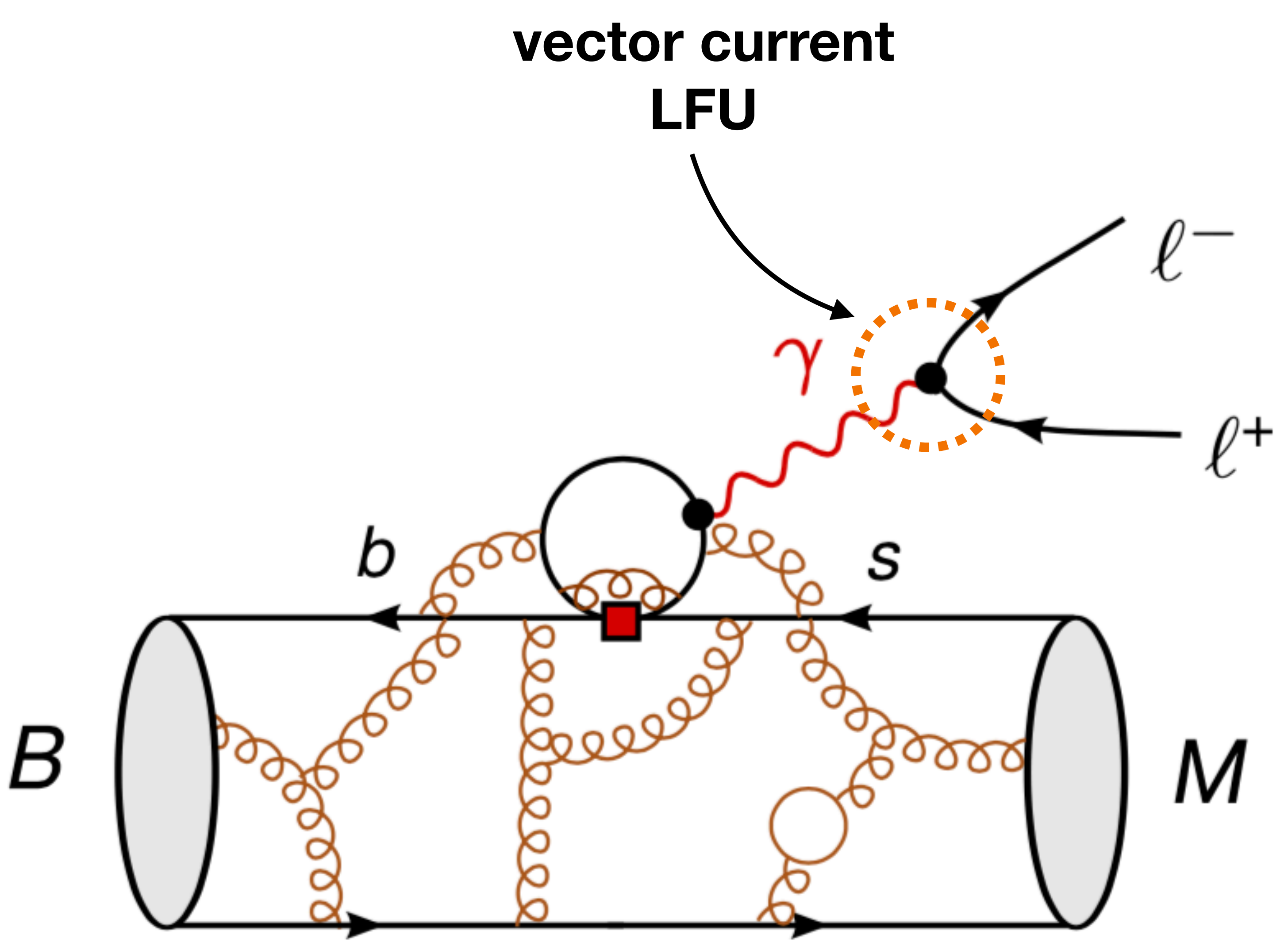
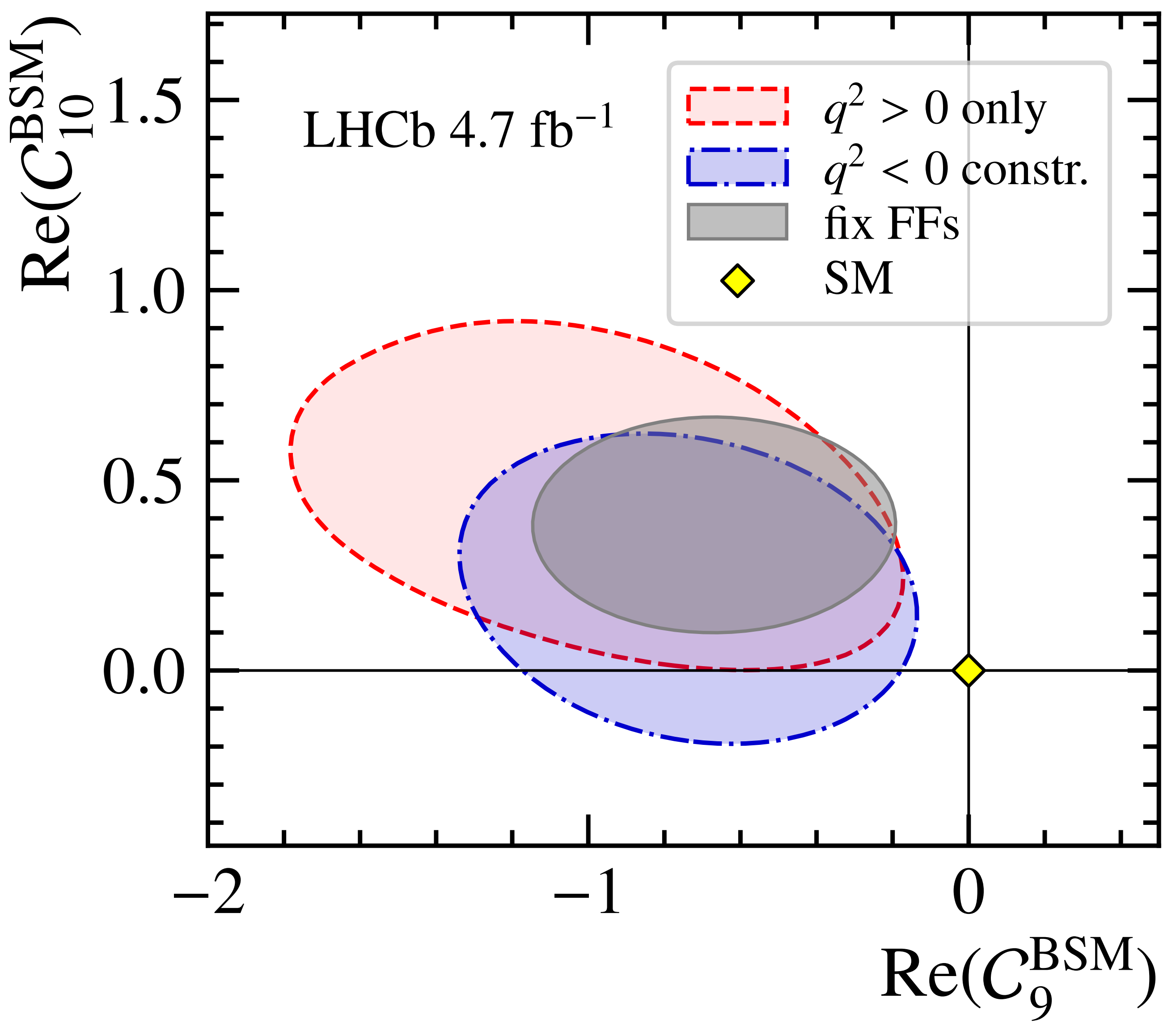
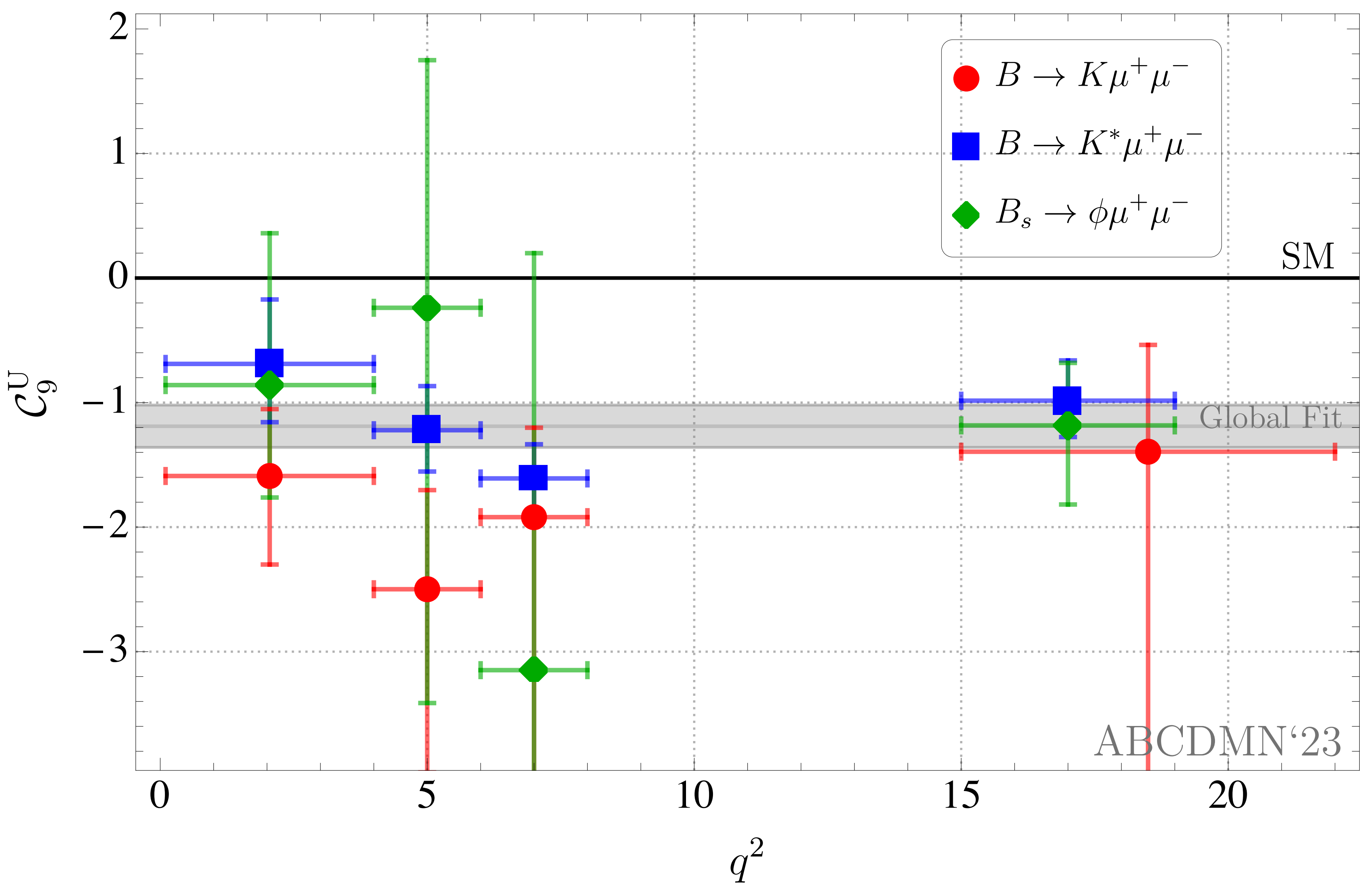
- **Charm-loop contribution is expected to be $\Delta C_9^U(q^2)$, but not ΔC_9^U**







LHCb, PRL132(2024)131801
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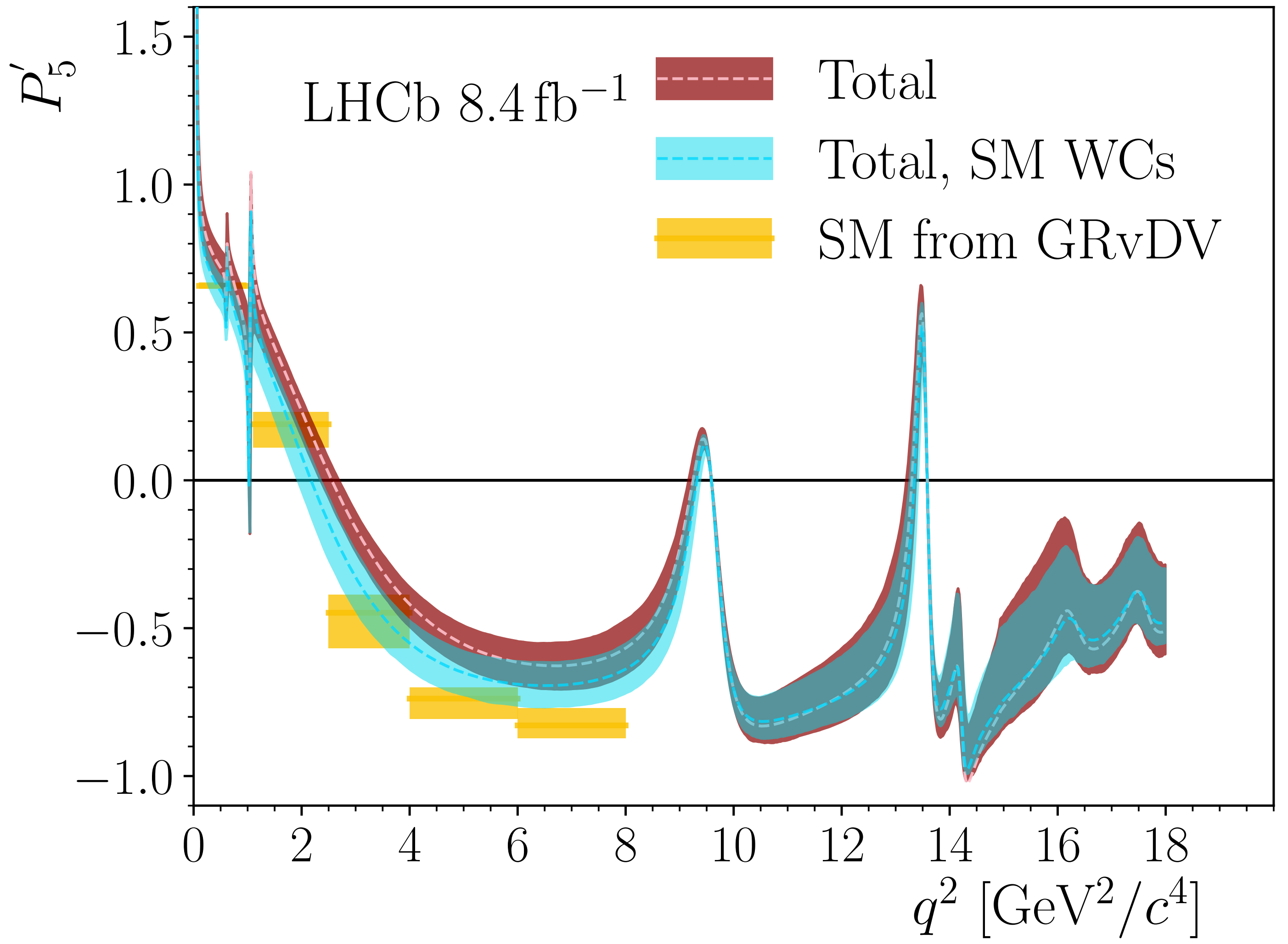
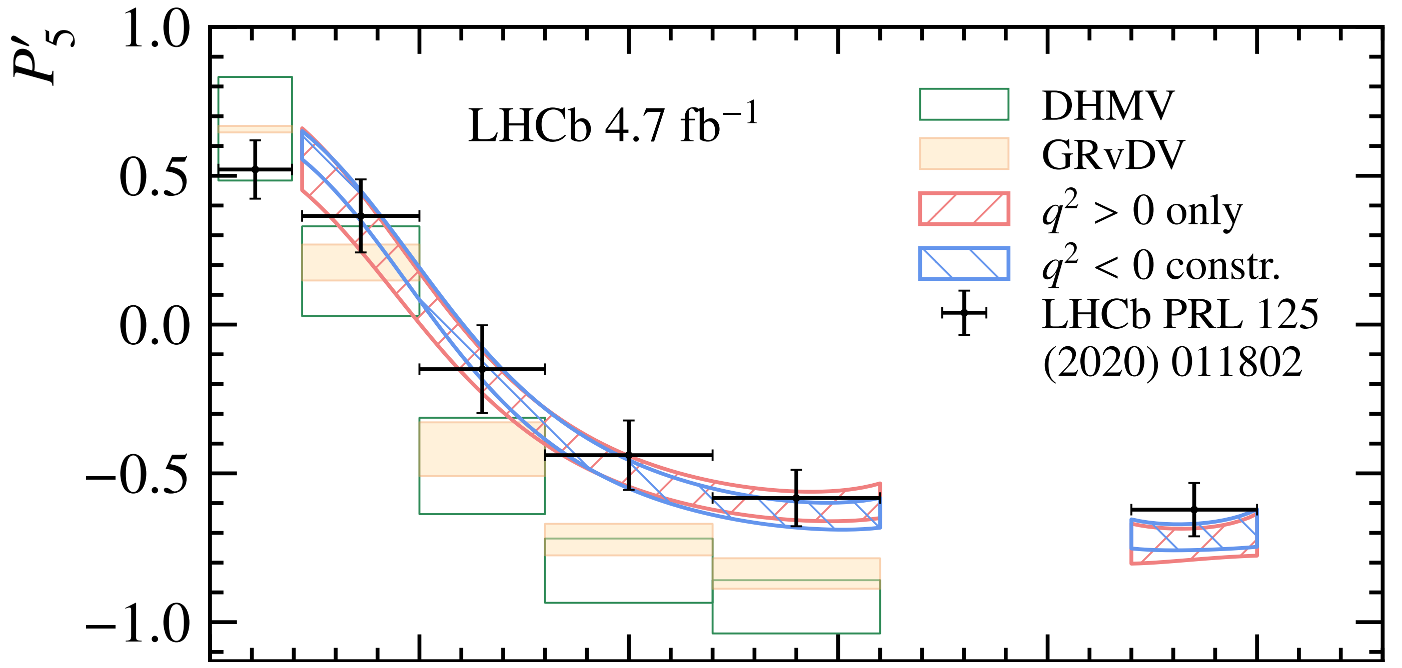
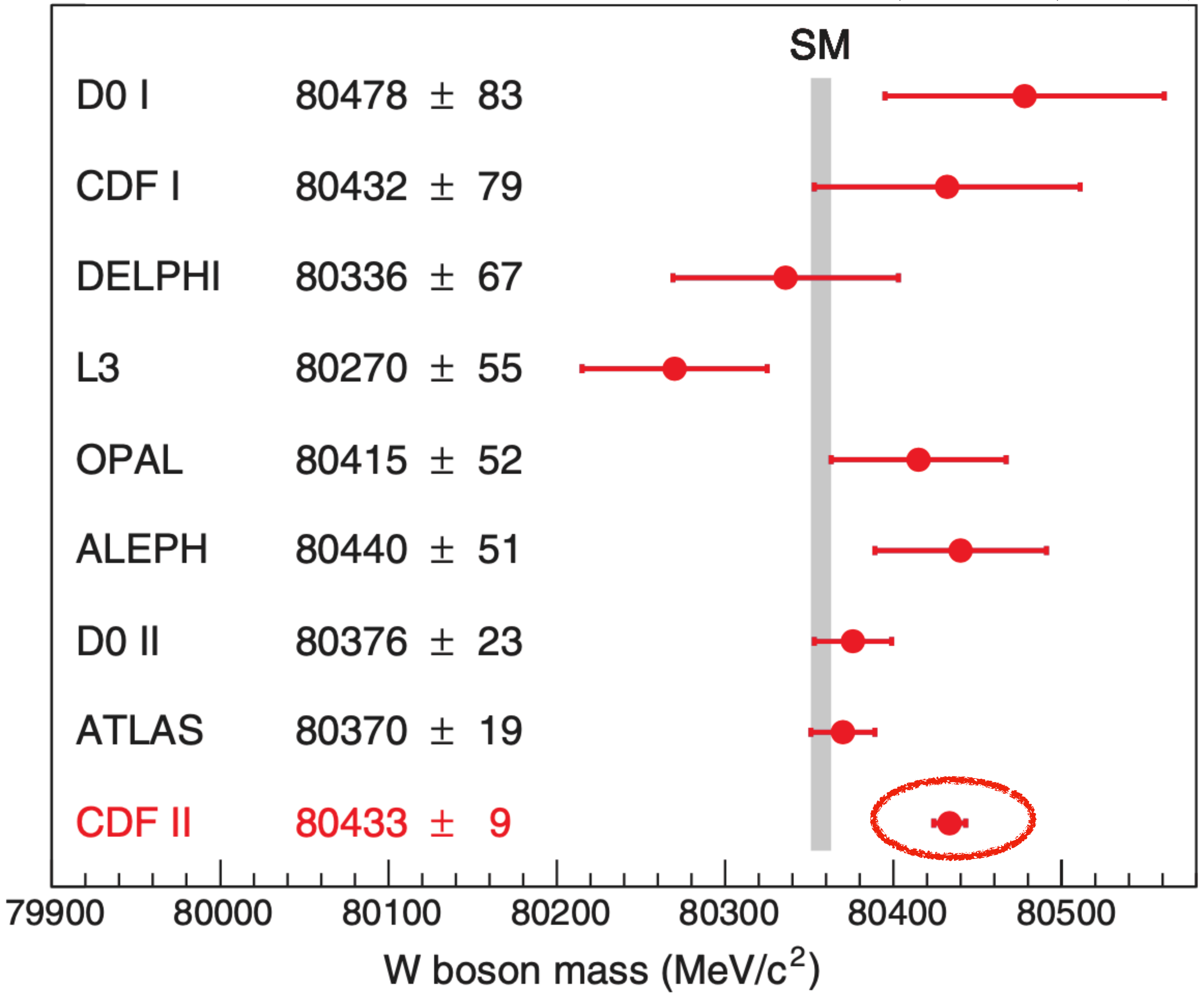




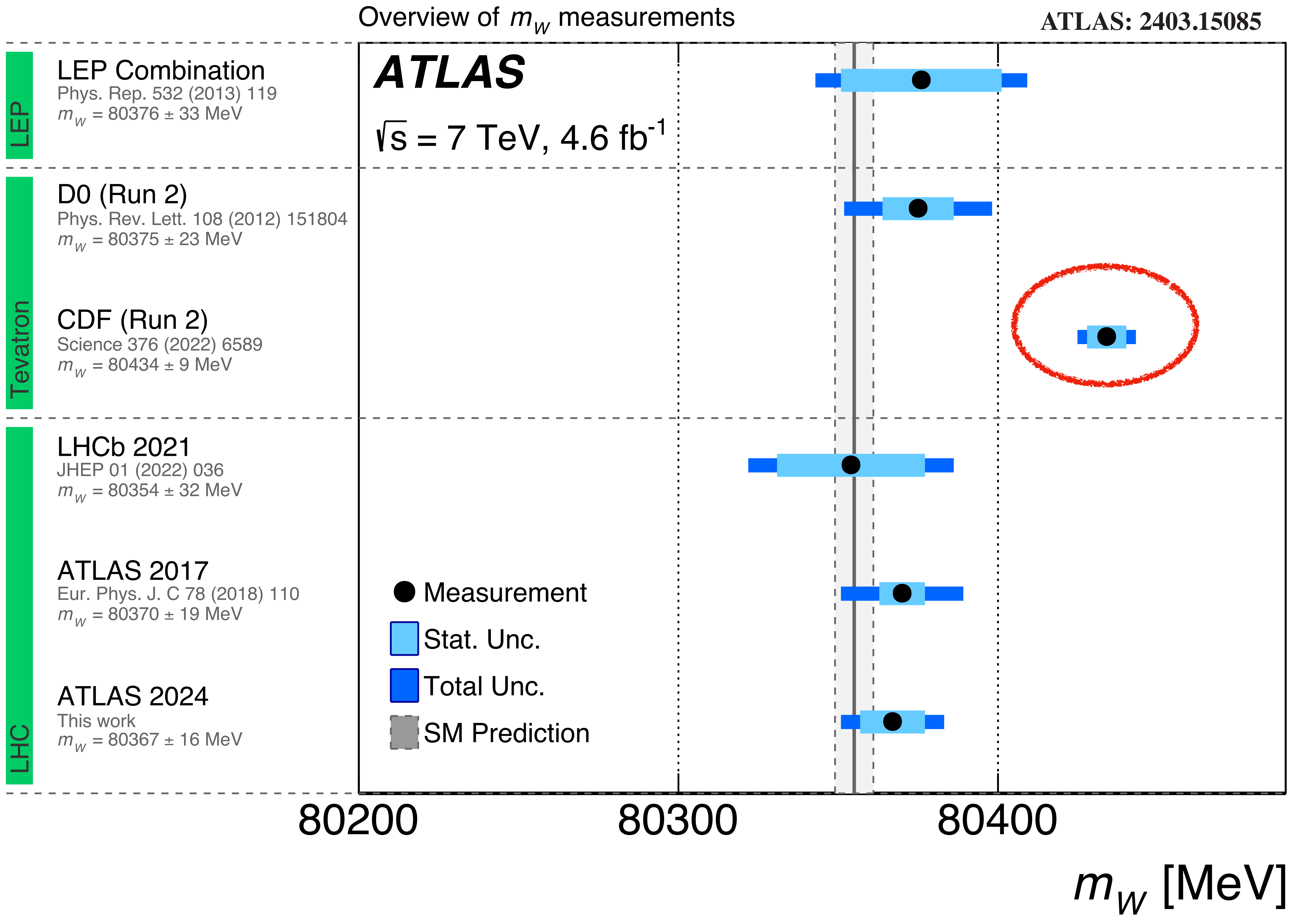
W-boson mass

see also 何吉波, 吴雨生 's talk

CDF, Science 376, 170 (2022)



ATLAS: 2403.15085



CDF: 80433 ± 9 MeV

EW fit: 80357 ± 6 MeV

About $7\,\sigma$ deviation ! ! !

PDG: 80387 ± 12 MeV

LHCb: 80354 ± 31 MeV LHCb, JHEP01(2022)036

ATLAS: 80366.5 ± 15.9 MeV ATLAS, 2403.15085

W-boson mass

Global EW fit

- Most NP effects on the EW sector can be parameterized by S, T, U, e.g.,

$$\Delta m_W^2 = \frac{\alpha c_W^2 m_Z^2}{c_W^2 - s_W^2}\left[-\frac{S}{2} + c_W^2 T + \frac{c_W^2 - s_W^2}{4 s_W^2} U\right]$$

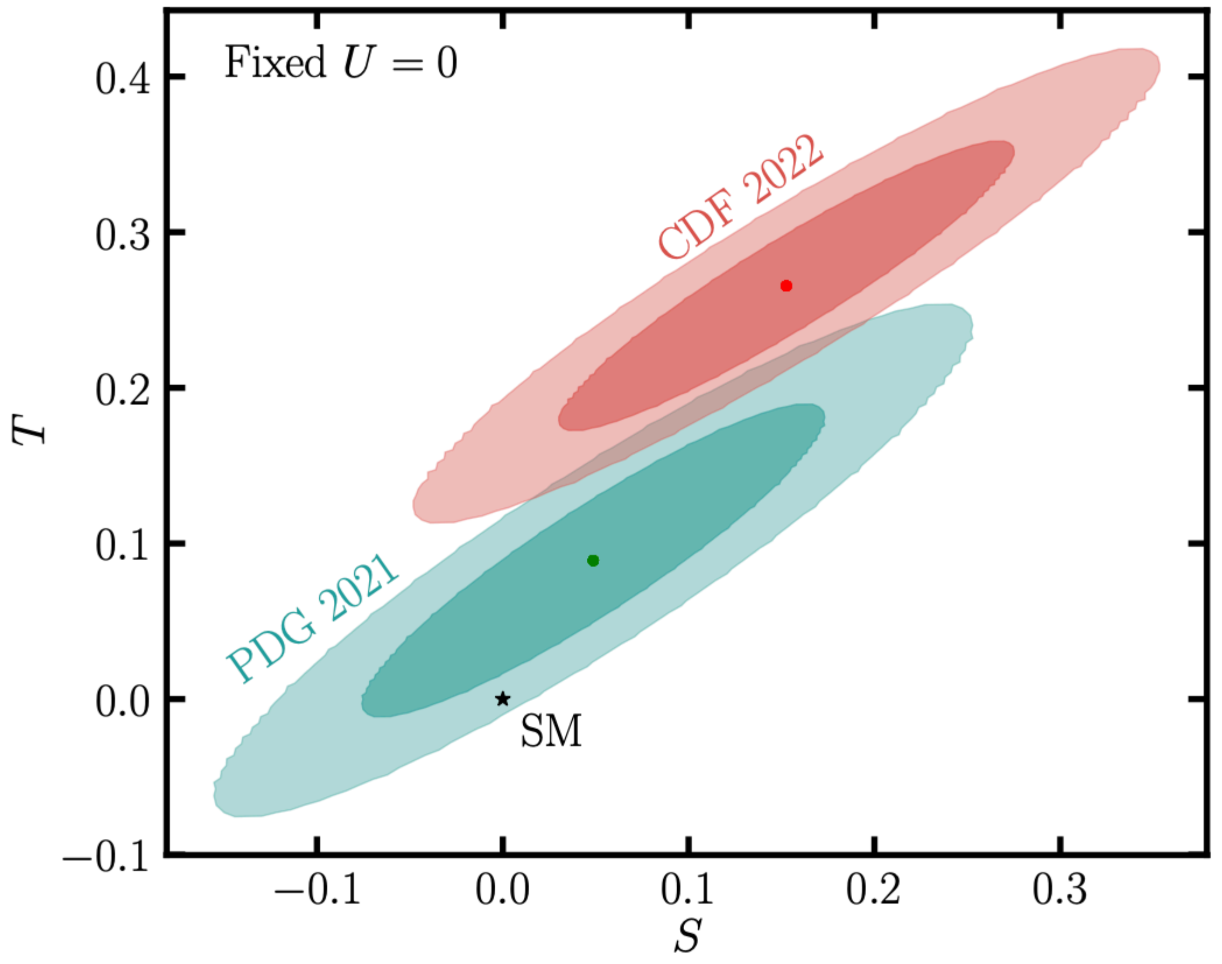
- S, T, U are related to the vacuum polarization of gauge bosons

$$S = \frac{4 s_W^2 c_W^2}{\alpha_e}\left[\frac{\Pi_{ZZ}(m_Z^2) - \Pi_{ZZ}(0)}{m_Z^2} - \frac{c_W^2 - s_W^2}{s_W c_W}\Pi'_{Z\gamma}(0) - \Pi'_{\gamma\gamma}(0)\right],$$

$$T = \frac{1}{\alpha_e}\left[\frac{\Pi_{WW}(0)}{m_W^2} - \frac{\Pi_{ZZ}(0)}{m_Z^2}\right],$$

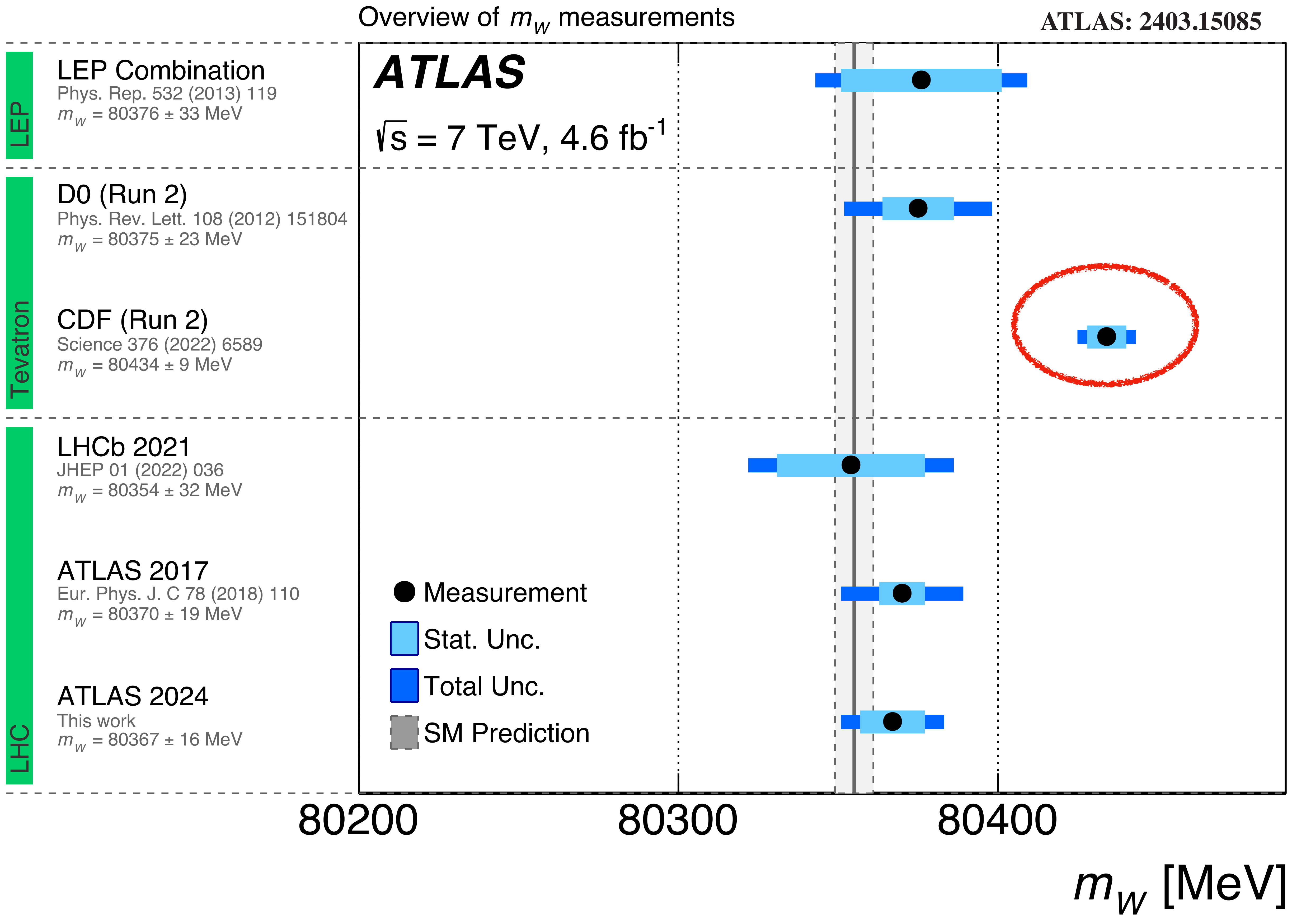
$$U = \frac{4 s_W^2}{\alpha_e}\left[\frac{\Pi_{WW}(m_W^2) - \Pi_{WW}(0)}{m_W^2} - \frac{c_W}{s_W}\Pi'_{Z\gamma}(0) - \Pi'_{\gamma\gamma}(0)\right] - S,$$

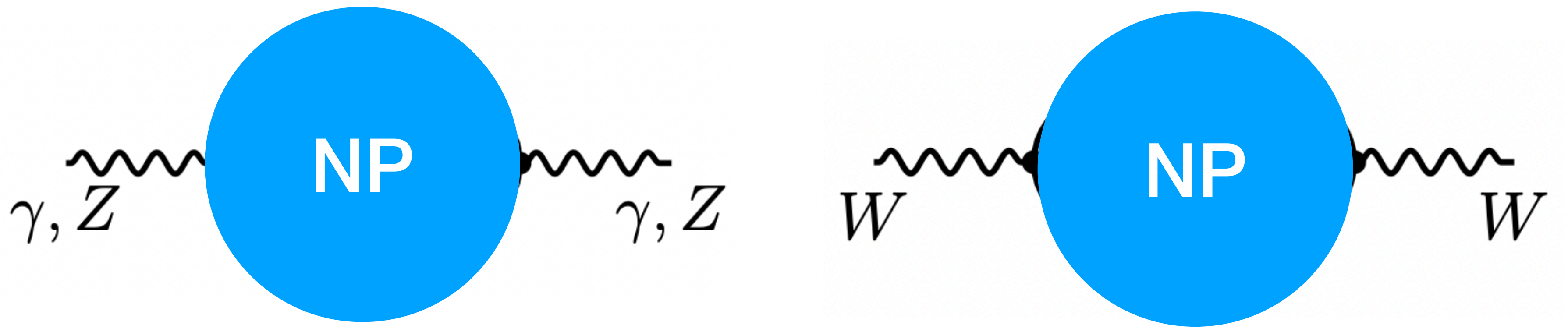
- A global EW fit is needed to explanation of the CDF m_W shift



By Gfitter

Chih-Ting Lu, Lei Wu, Yongcheng Wu, and Bin Zhu, arXiv: 2204.03796





new particles in the vacuum polarizations of gauge bosons