Explaining the CDF *W*-mass shift and $(g-2)_\mu$ in a Z' scenario and its implications for the $b \to s\ell^+\ell^-$ processes

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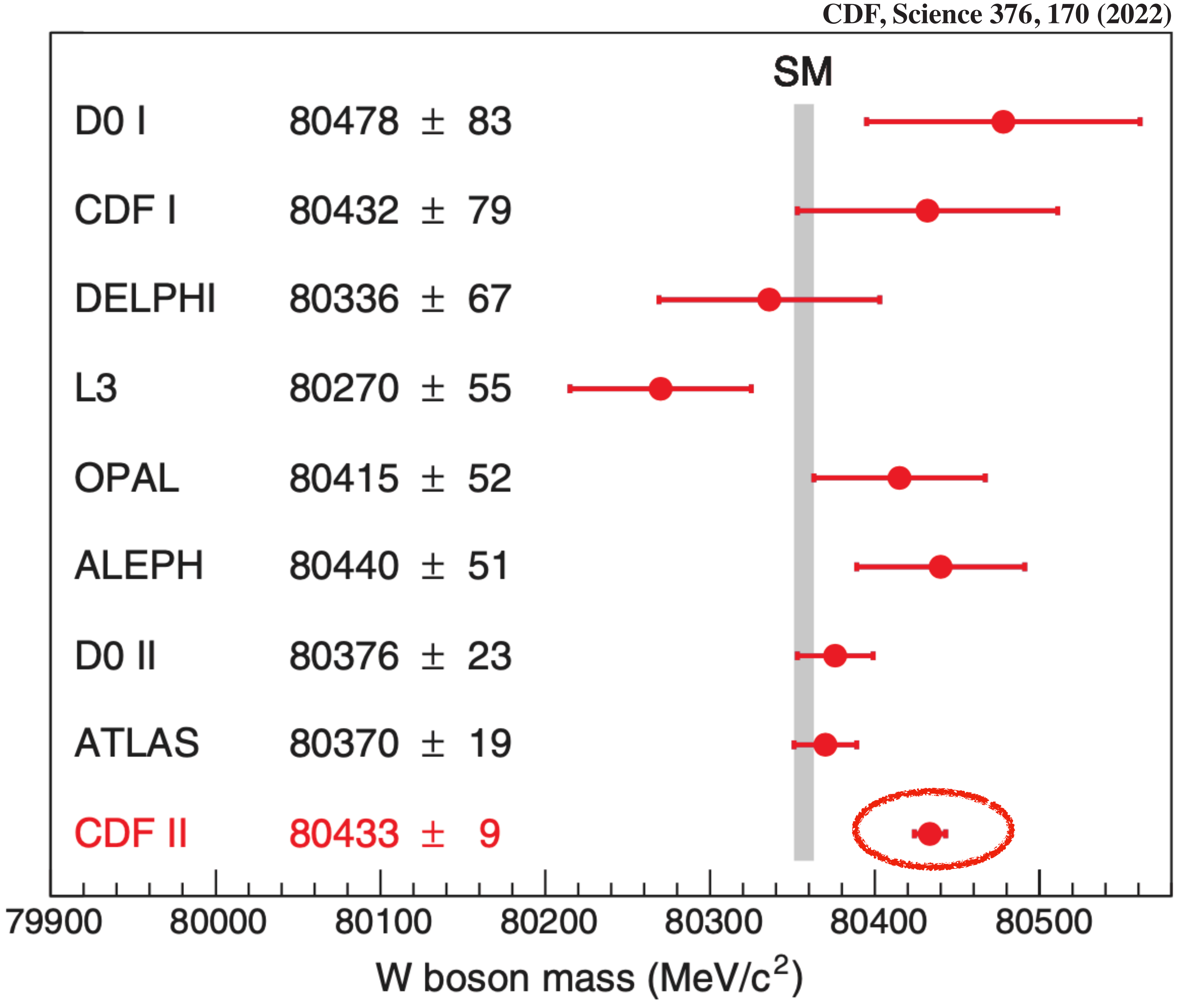
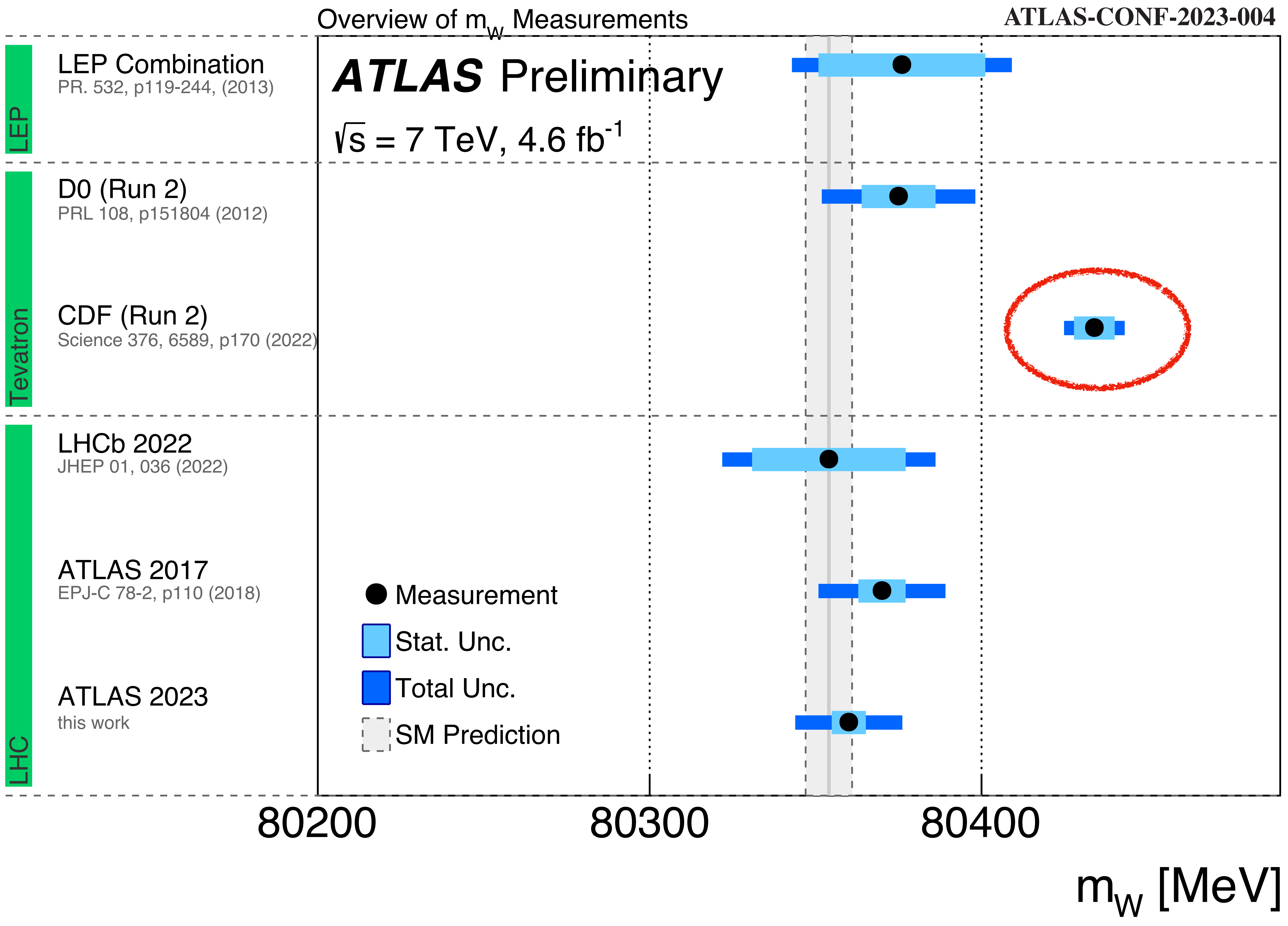
Central China Normal University (华中师范大学)

arXiv: 2205.02205, 2307.05290, Xin-Qiang Li (李新强)，Ze-Jun Xie (谢泽浚)，Ya-Dong Yang (杨亚东)，XBY
[PLB838(2023)137651]

W-boson mass





CDF: 80433 ± 9 GeV

EW fit: 80357 ± 6 GeV

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

PDG: 80387 ± 12 GeV

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

ATLAS: 80360 ± 16 GeV ATLAS-CONF-2023-004

W-boson mass

Global EW fit

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

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

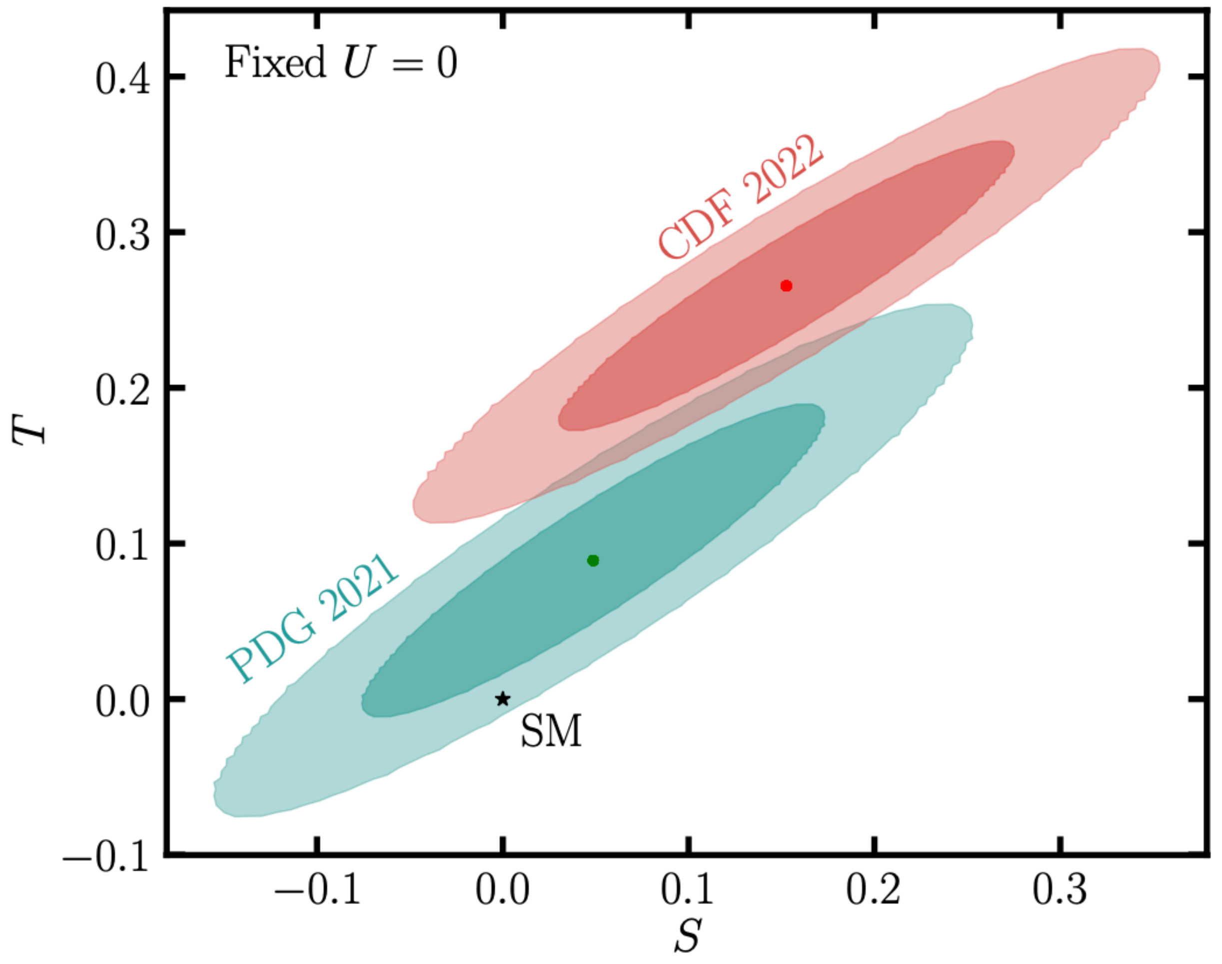
- S, T, U are related to the vacuum polarization of gauge bosons

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

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

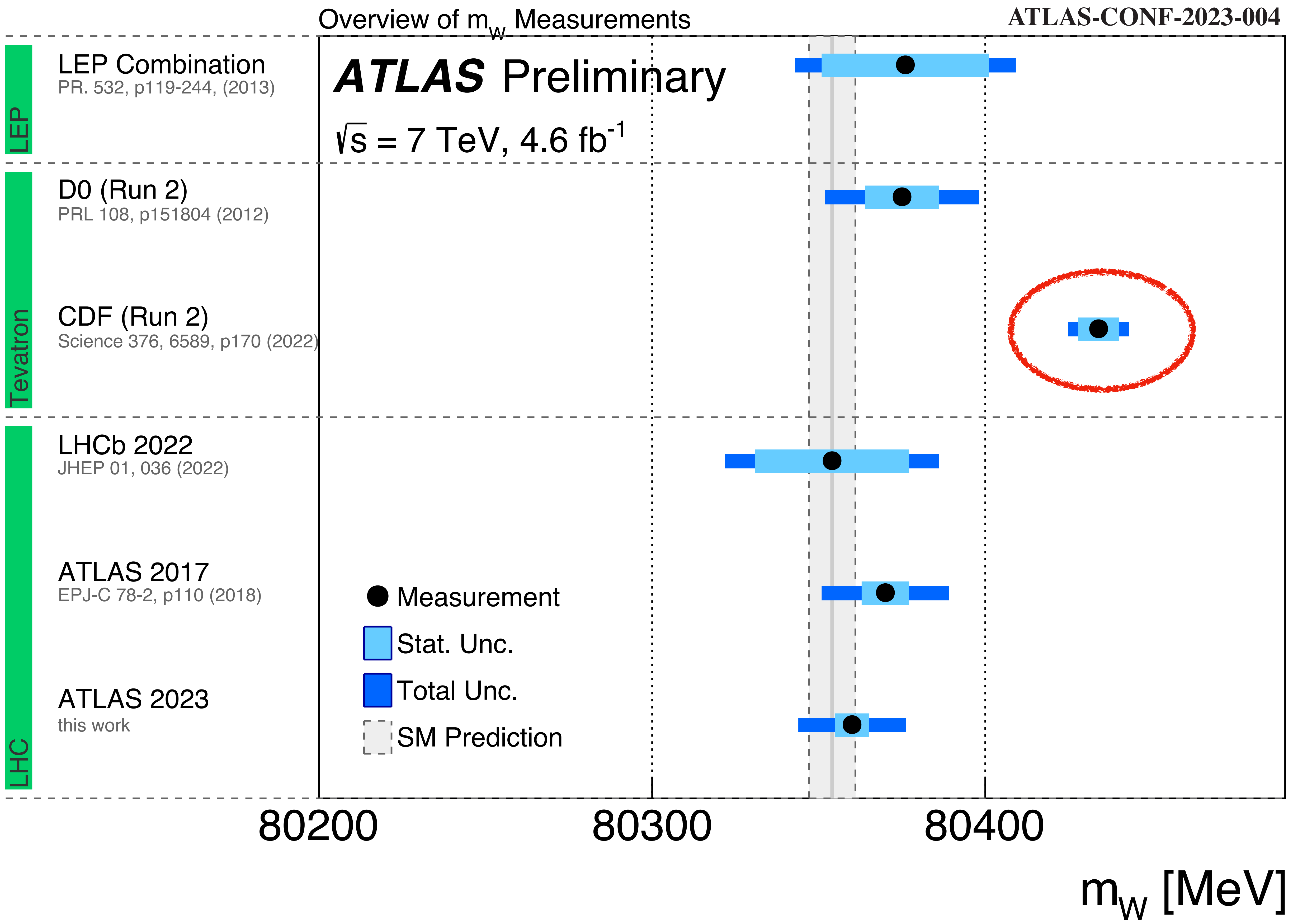
$$U = \frac{4 s_W^2}{\alpha_e}\left[\frac{\Pi_{WW}(m_W^2) - \Pi_{WW}(0)}{m_W^2} - \frac{c_W}{s_W}\Pi'_{Z\gamma}(0) - \Pi'_{\gamma\gamma}(0)\right] - S,$$

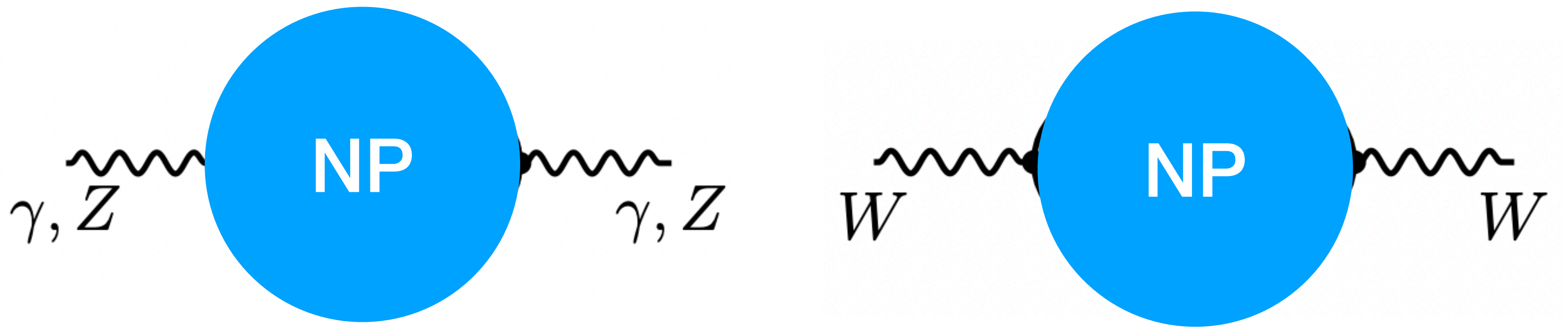
- A global EW fit is needed to explanation of the CDF m_W shift



By Gfitter

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





new particles in the vacuum polarizations of gauge bosons

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

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

theoretical cleanness

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

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

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

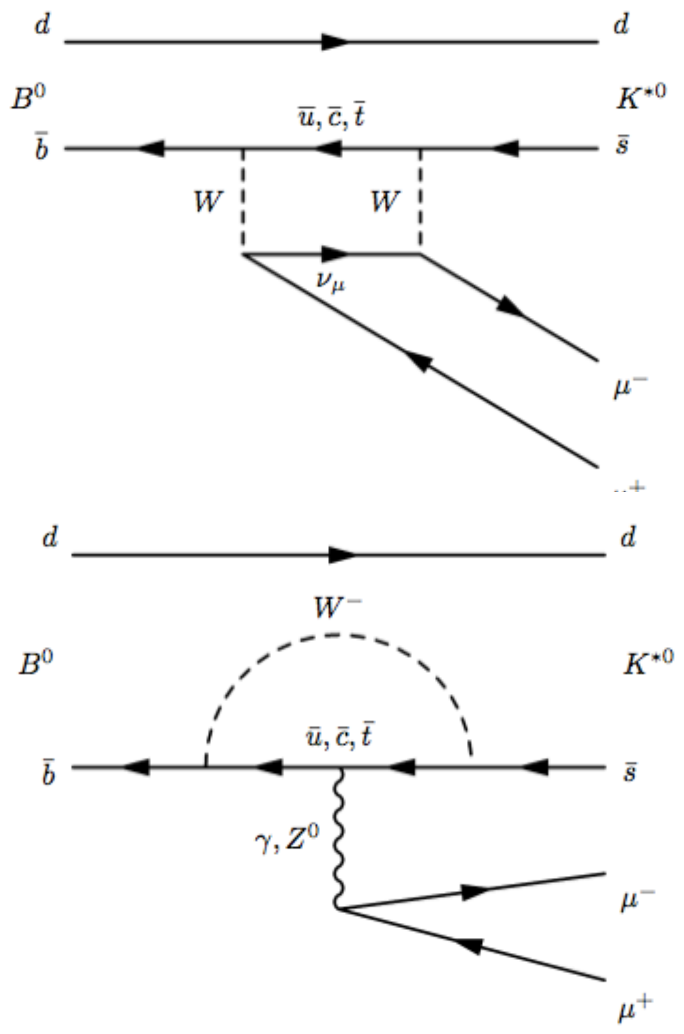
$$R_K = \frac{\mathscr{B}(B \to K\mu^+\mu^-)}{\mathscr{B}(B \to Ke^+e^-)}$$

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

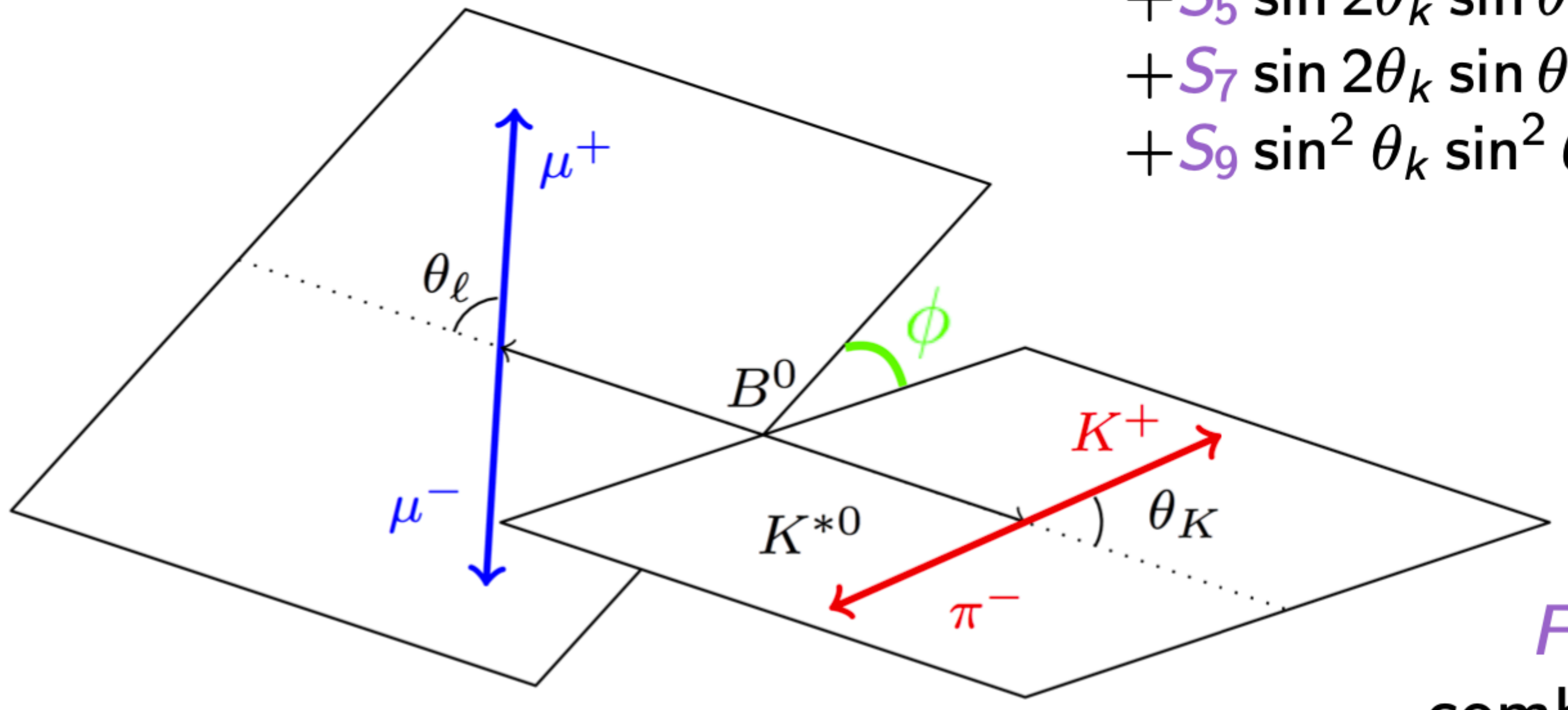
deviation from unity

Physics beyond the SM

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



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

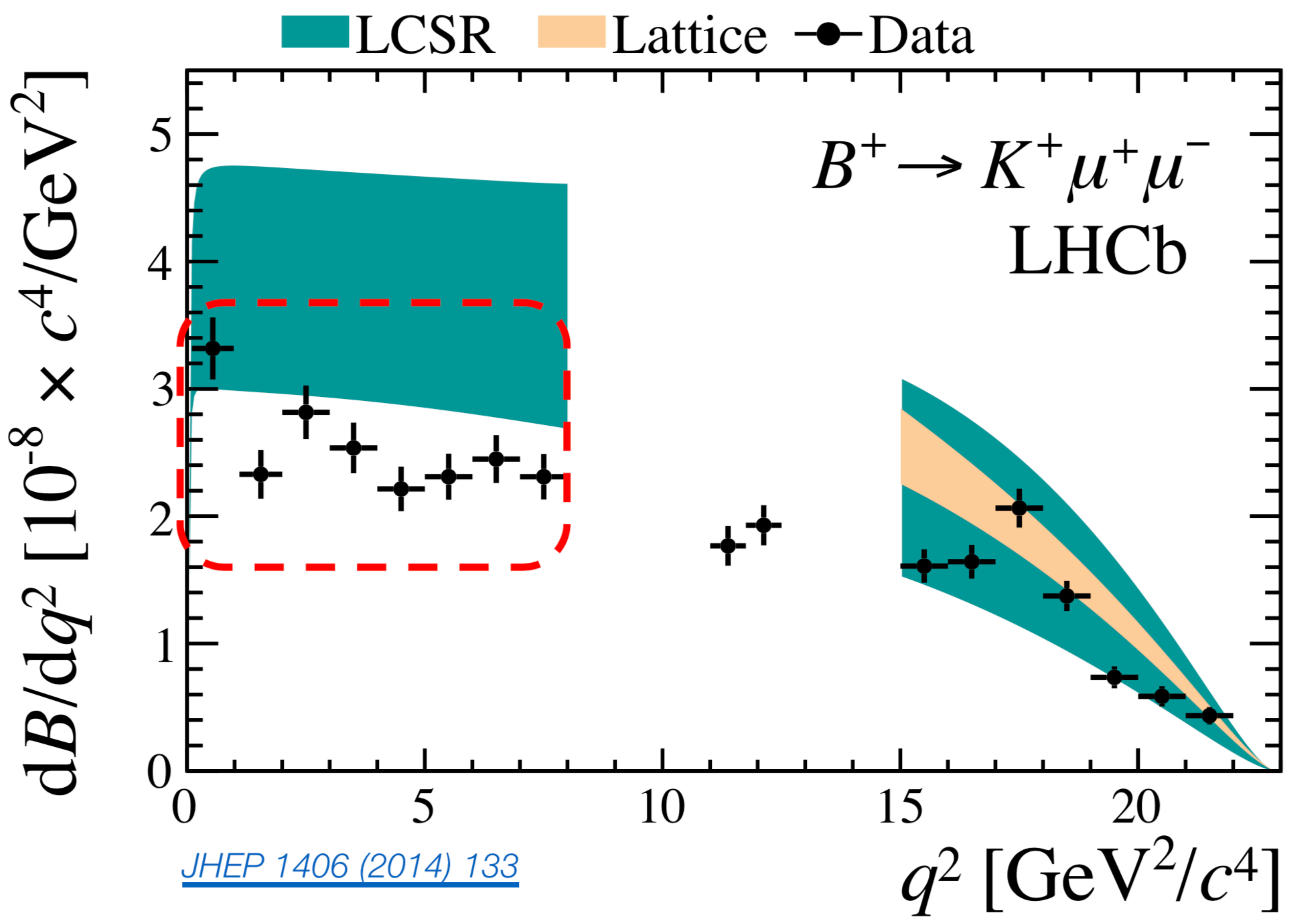


angular observables

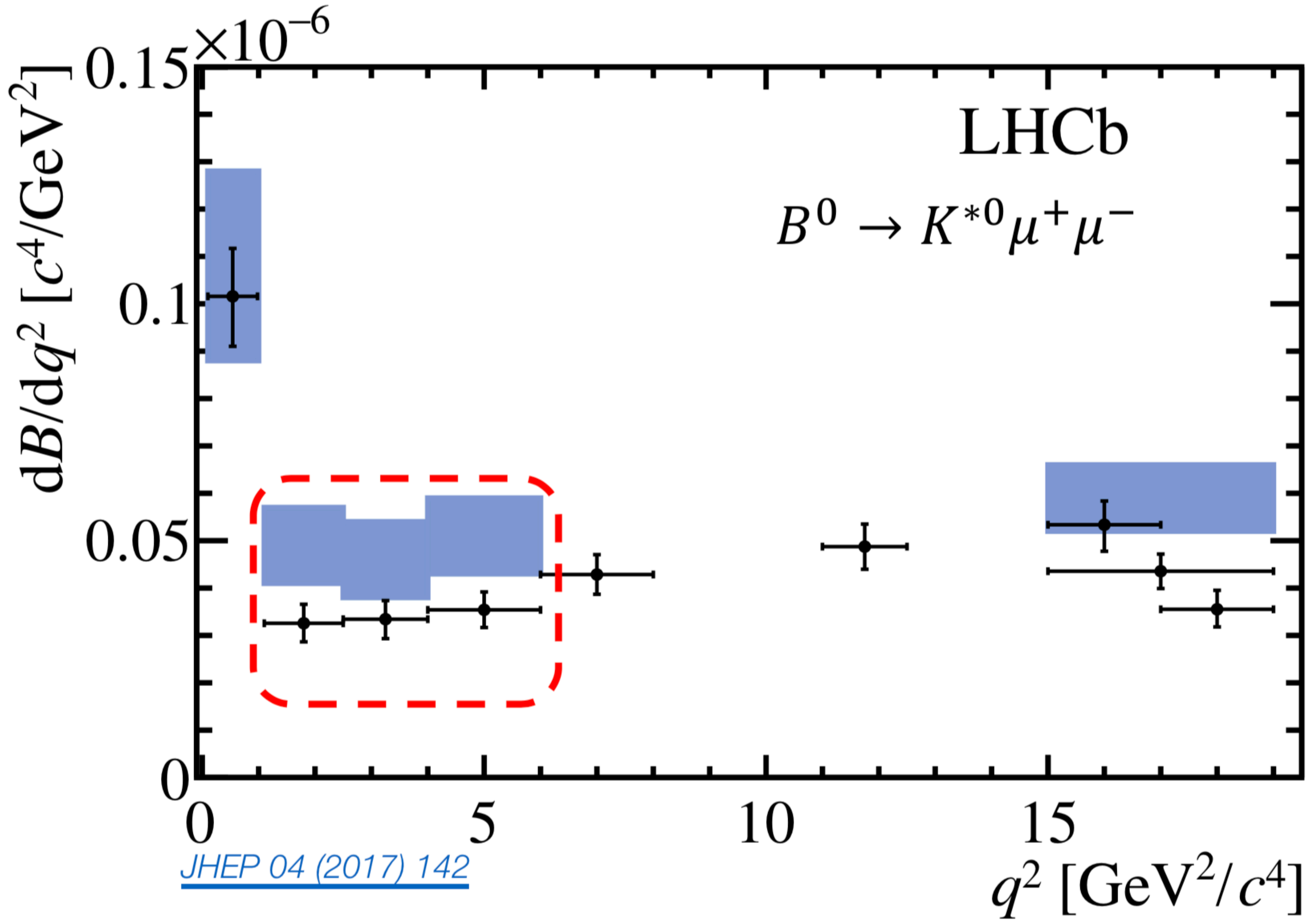
$F_L,\ A_{FB},\ S_i = f(C_7, C_9, C_{10}),$
combinations of K^{*0} decay amplitudes

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

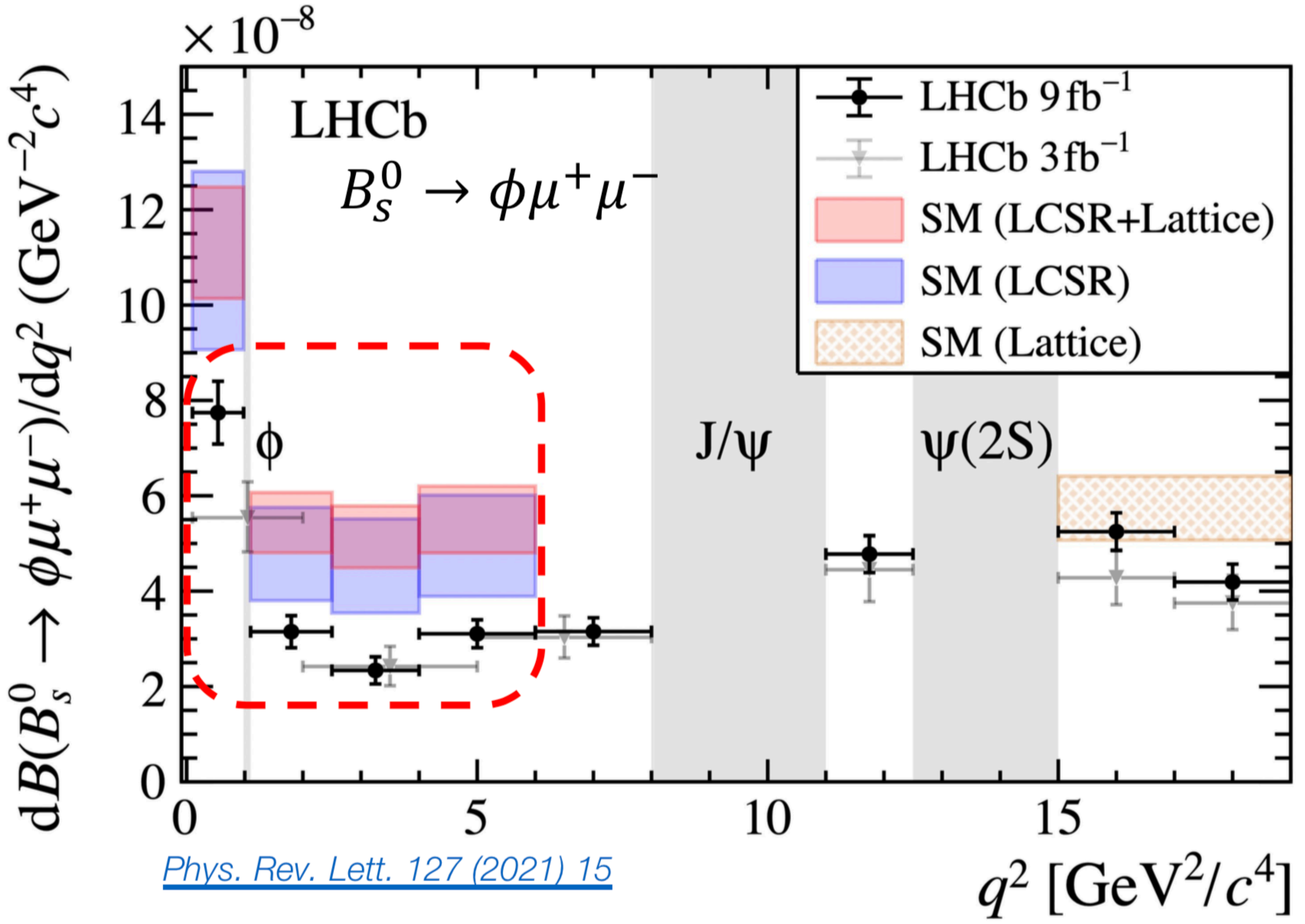
$b \to s\ell\ell$ anomalies@mid.2022: branching ratio



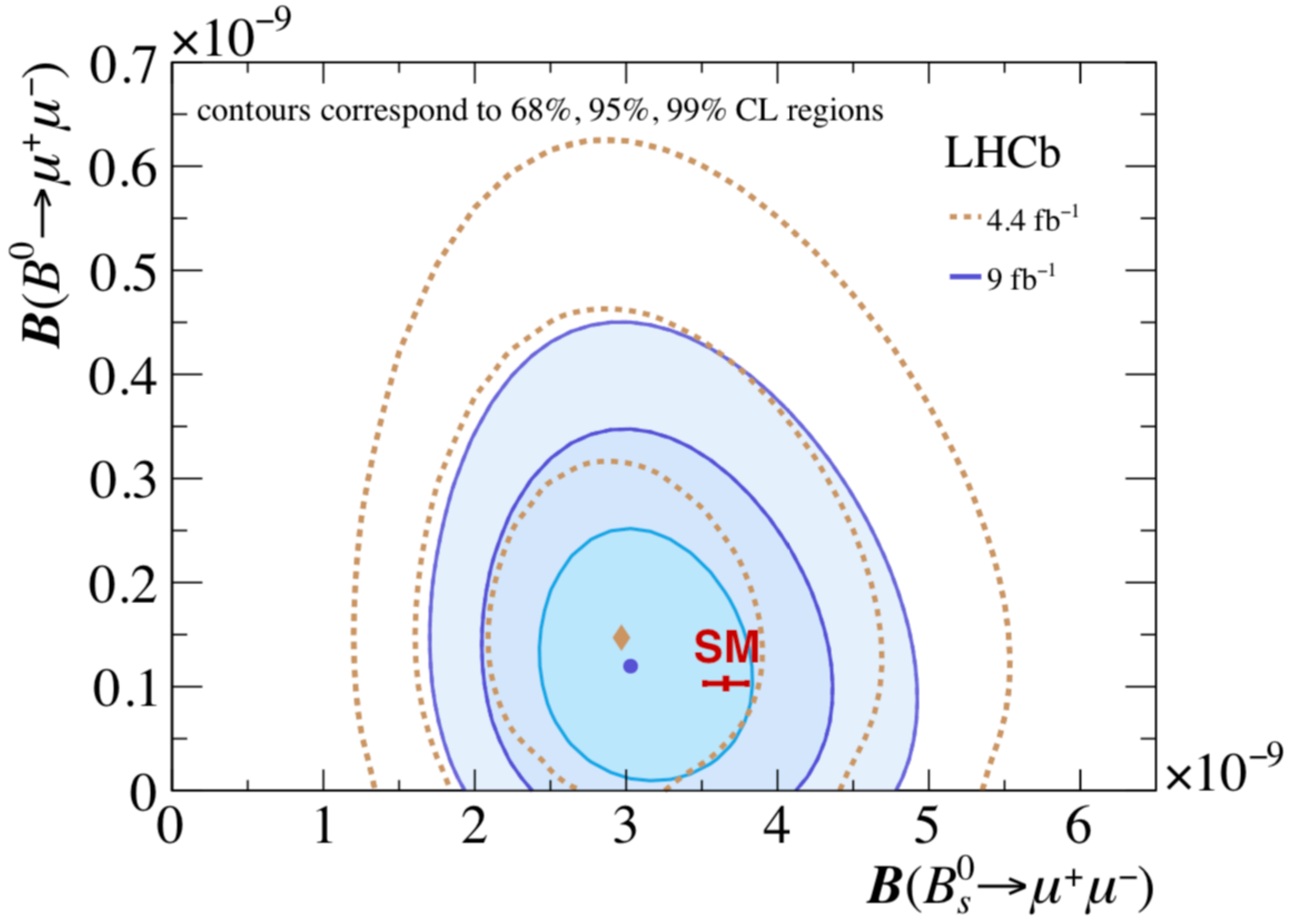
JHEP 1406 (2014) 133



JHEP 04 (2017) 142



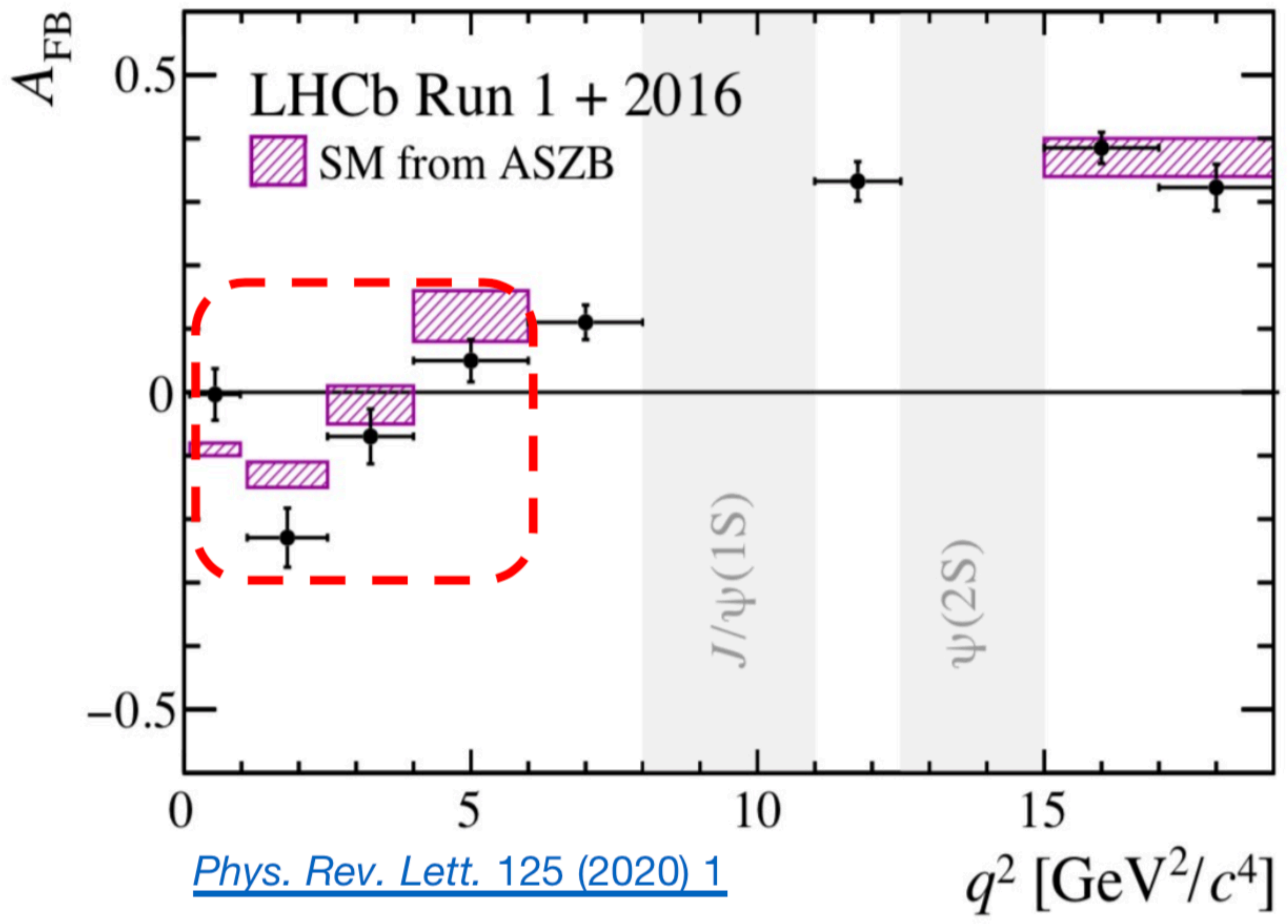
Phys. Rev. Lett. 127 (2021) 15



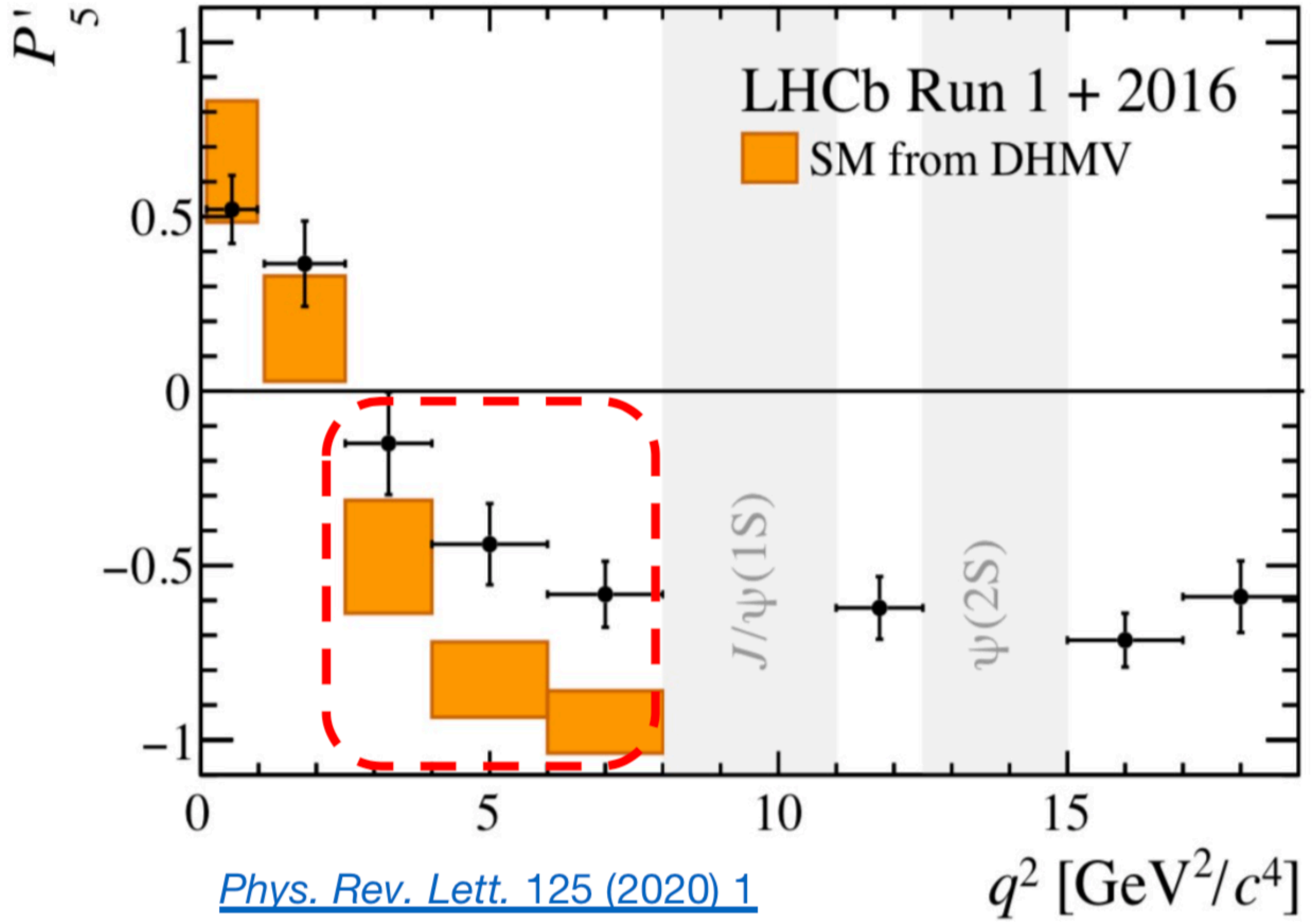
- **EXP below SM**
- **Low q^2**
- **Theoretical Uncertainties: 😭**

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

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

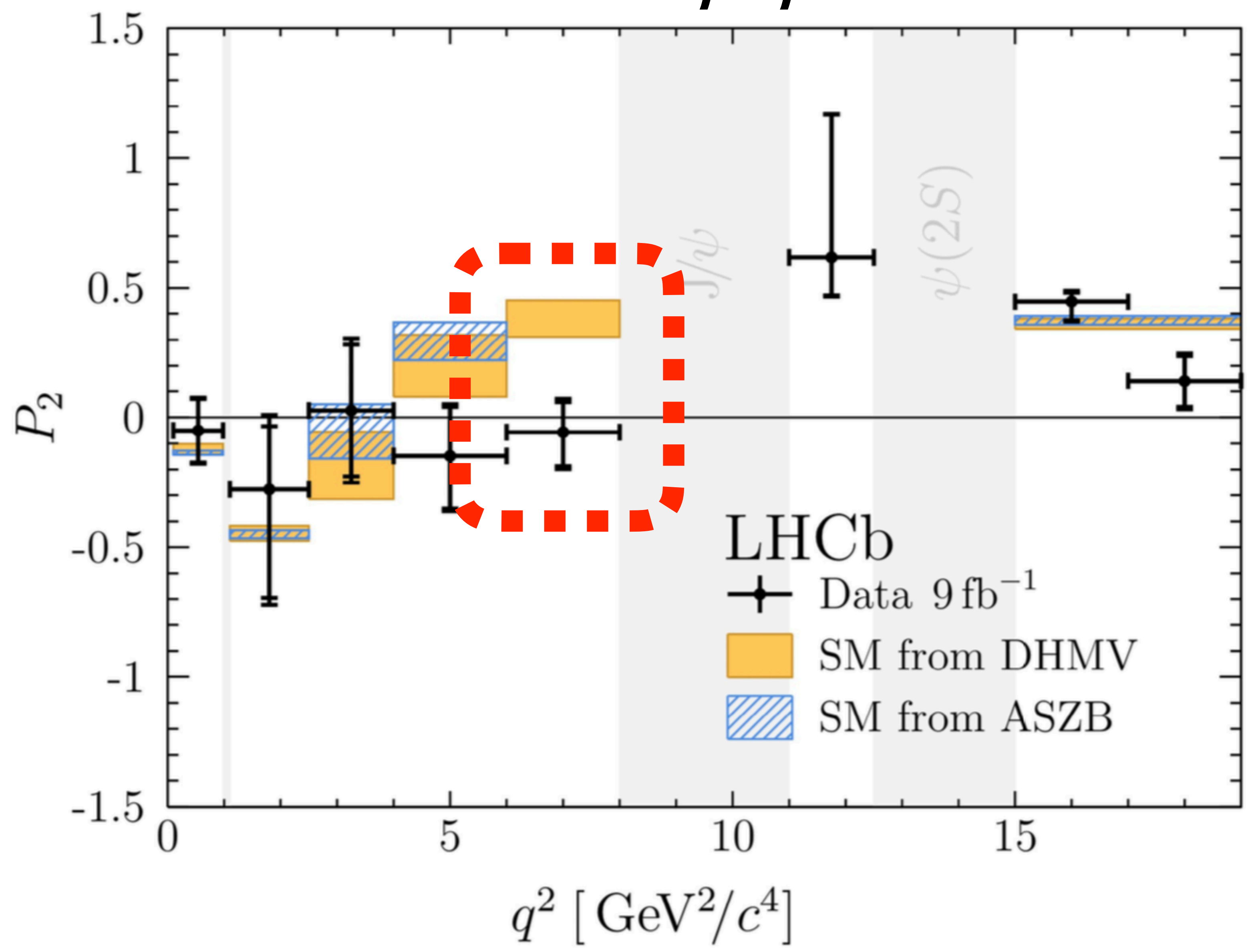


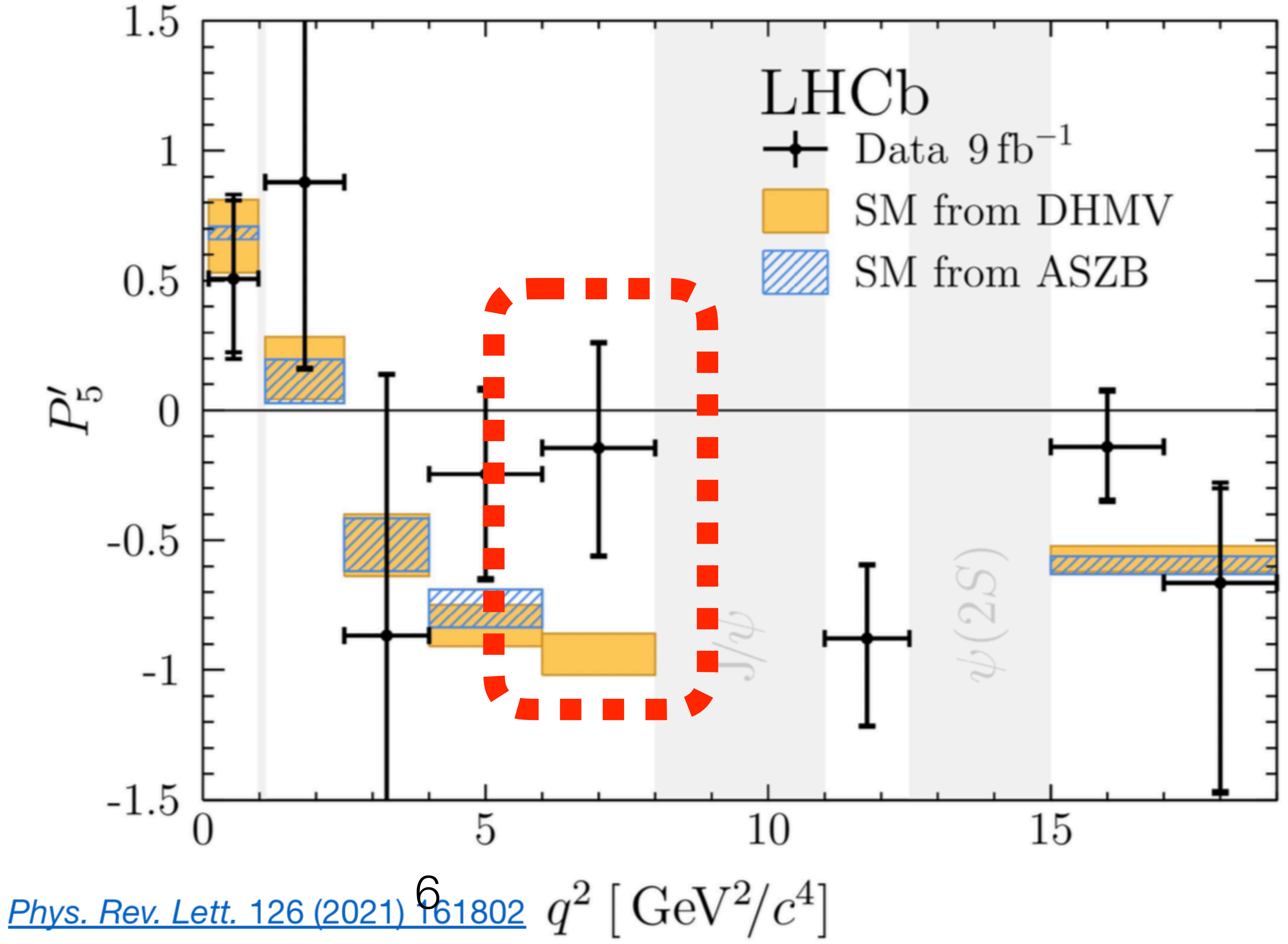
[Phys. Rev. Lett. 125 (2020) 1]



[Phys. Rev. Lett. 125 (2020) 1]

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

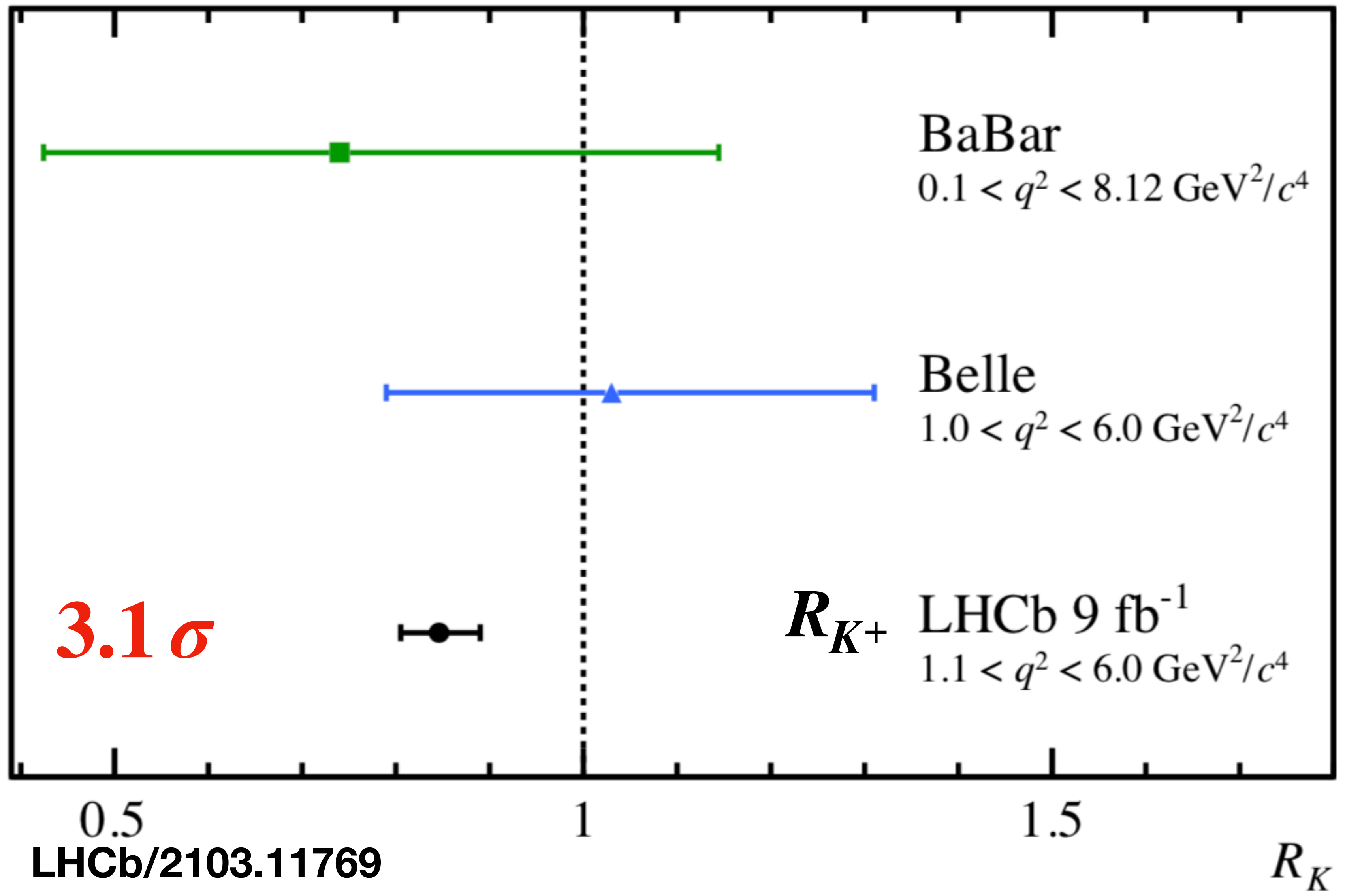




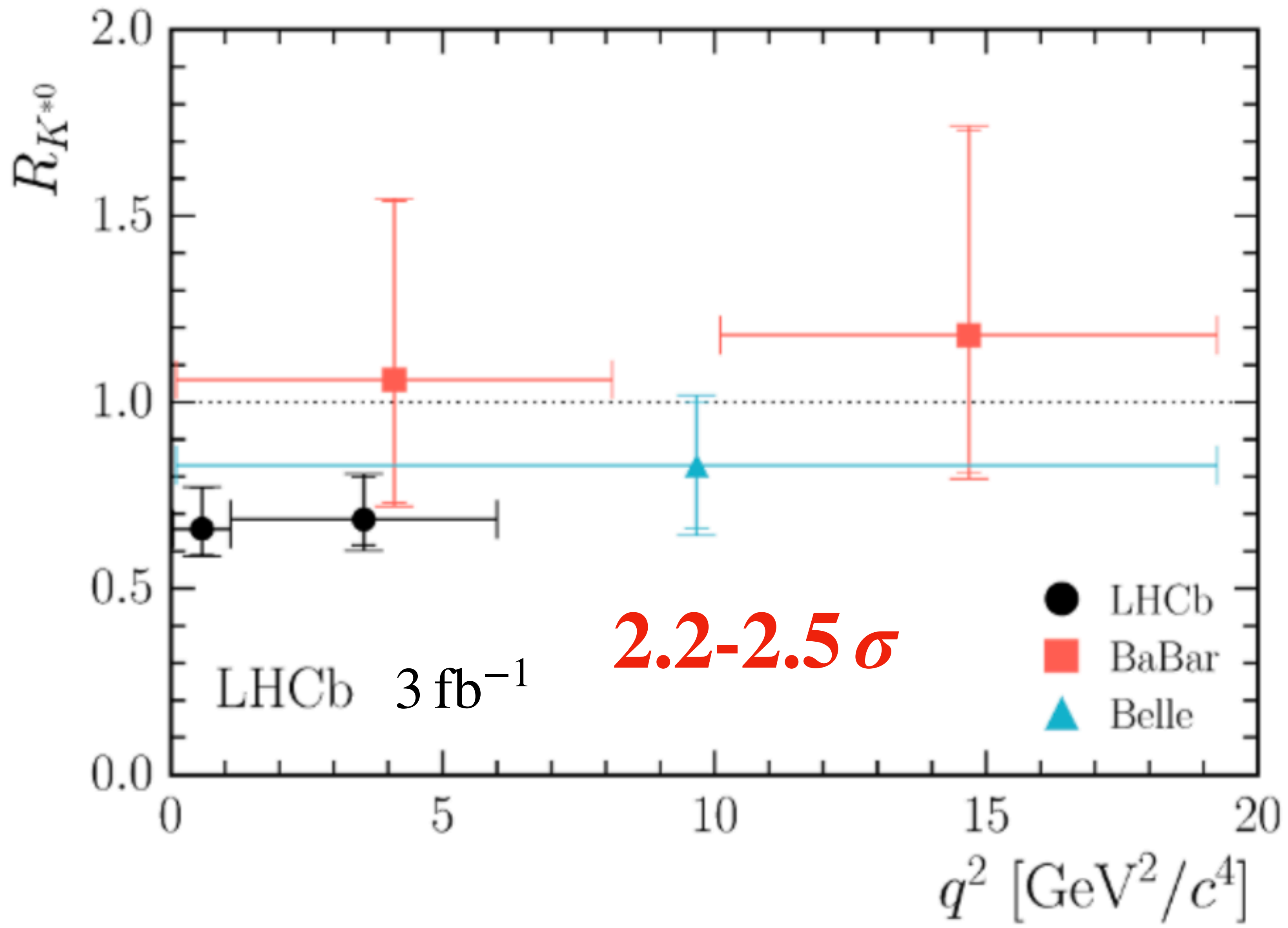
[Phys. Rev. Lett. 126 (2021) 161802]

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

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



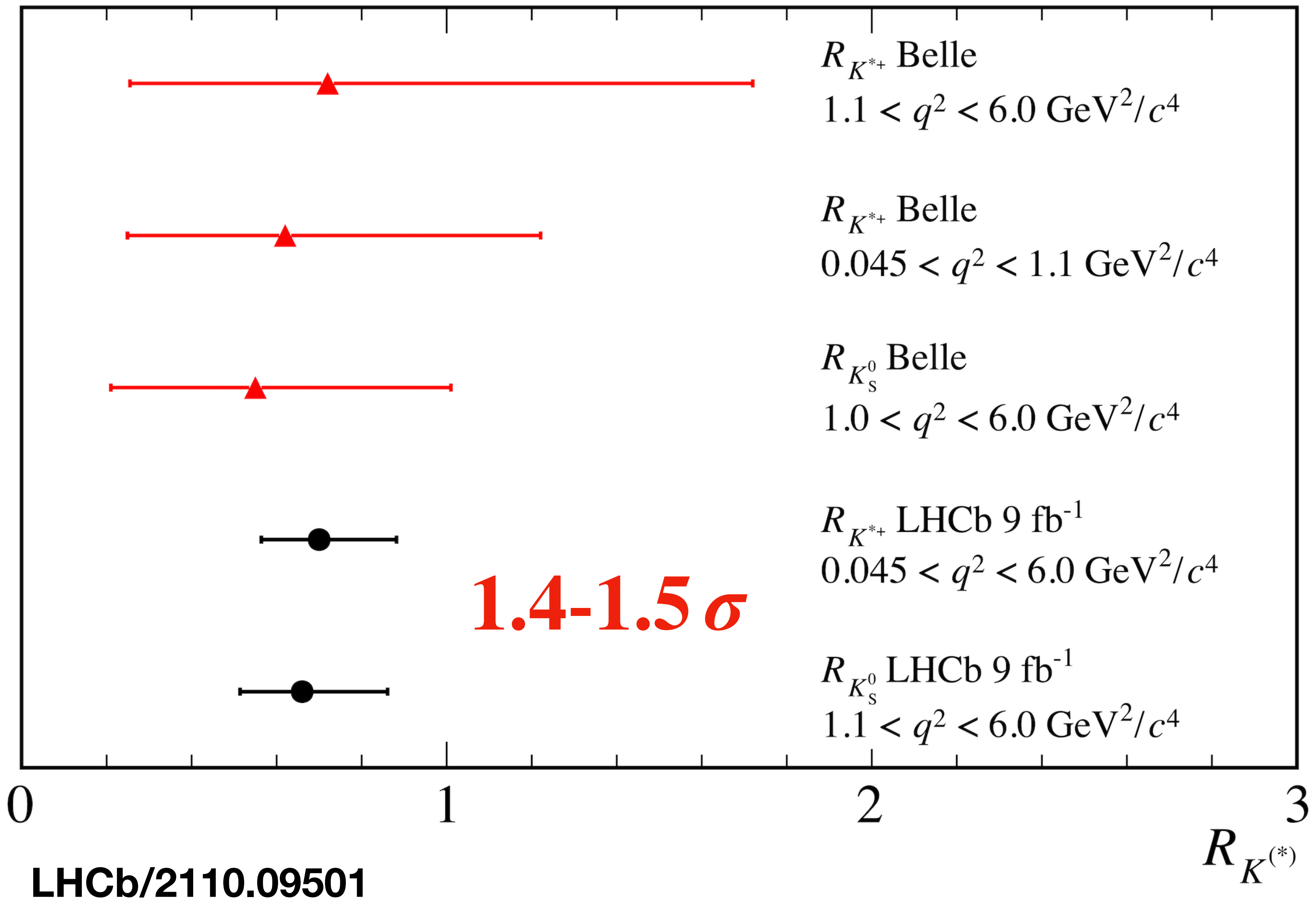
LHCb/2103.11769



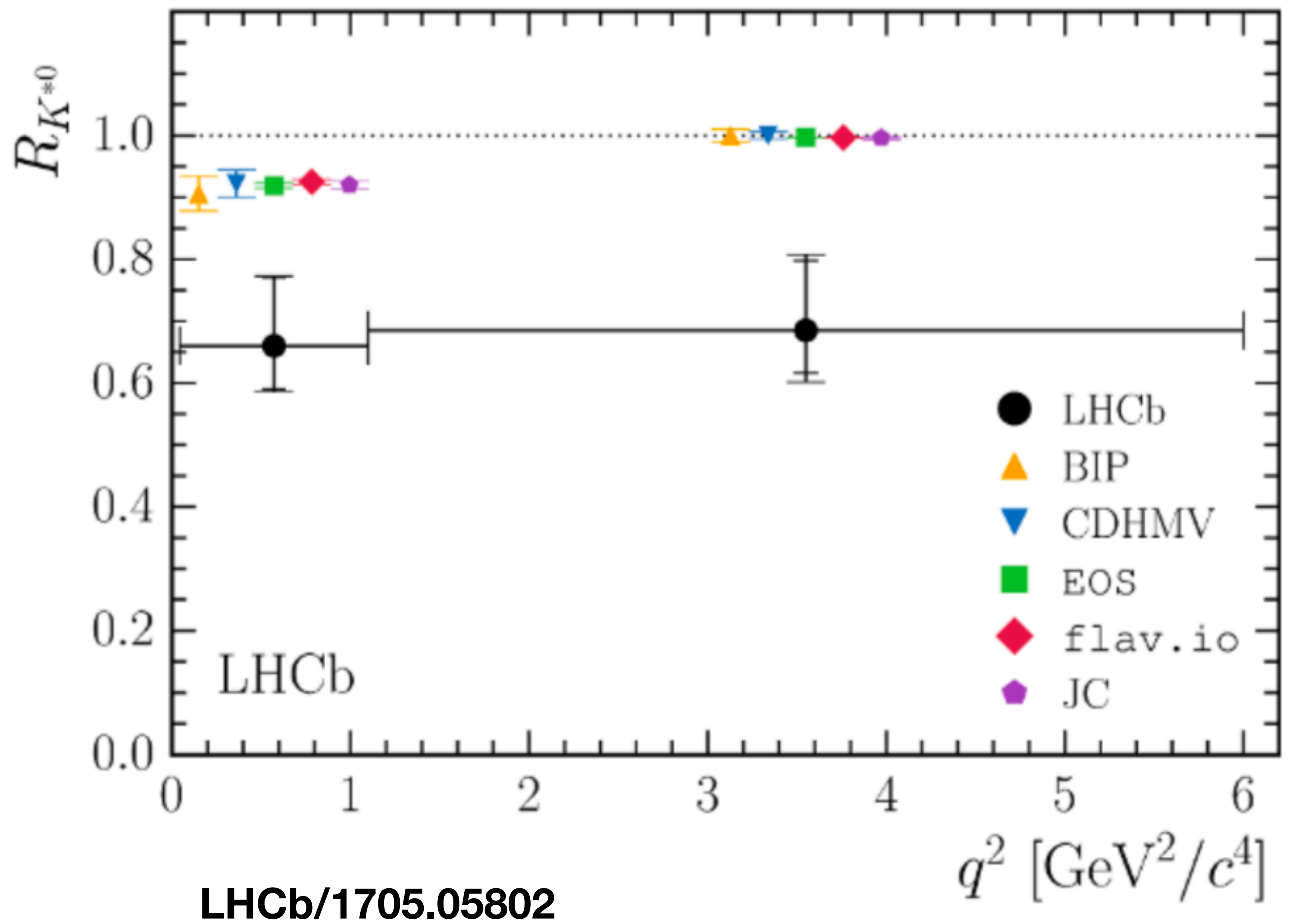
$$R_{K^+} = \frac{\mathfrak{B}(B^+ \to K^+\mu^+\mu^-)}{\mathfrak{B}(B^+ \to K^+e^+e^-)}$$

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

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



LHCb/2110.09501



LHCb/1705.05802

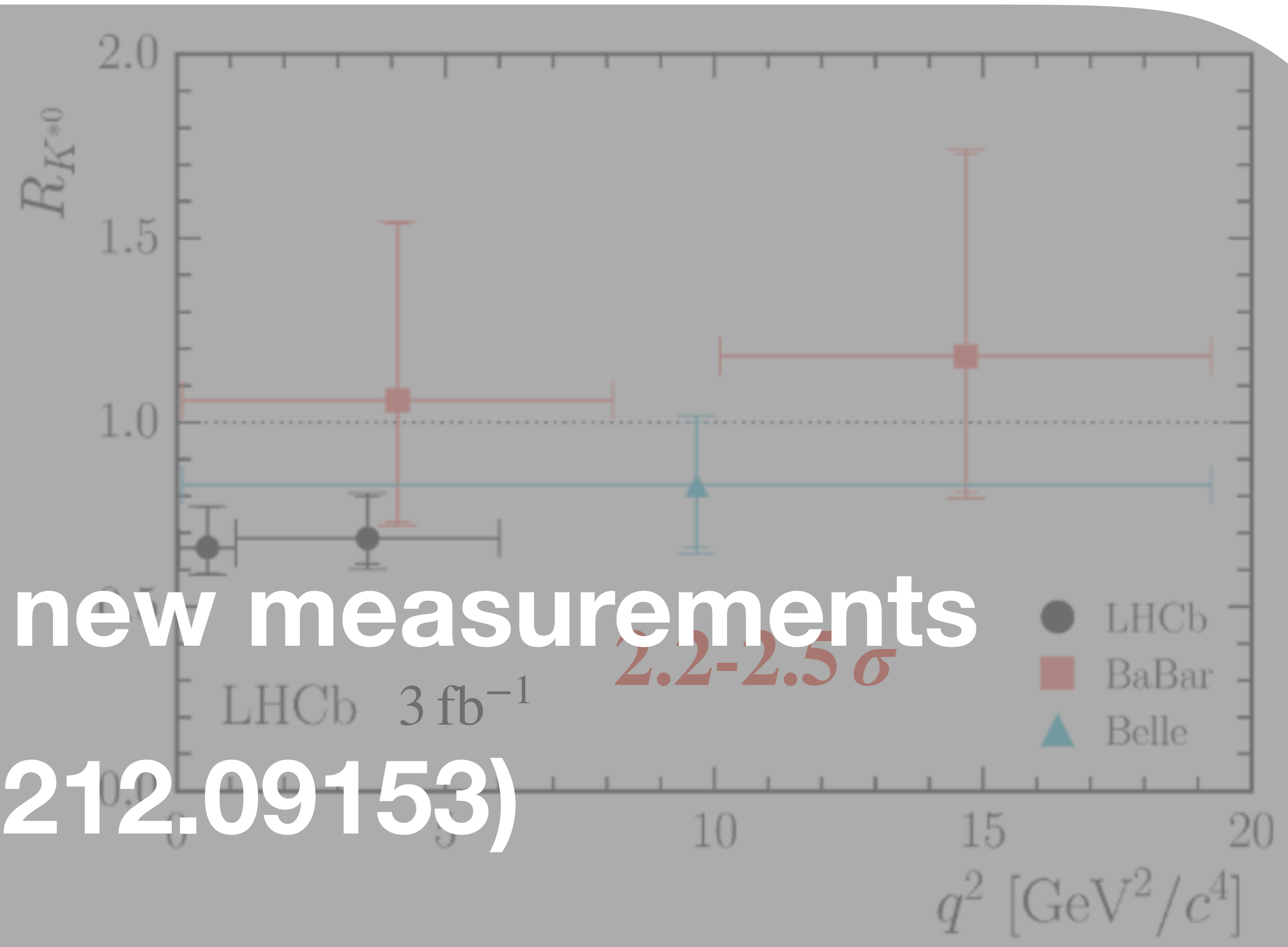
deviation from unity

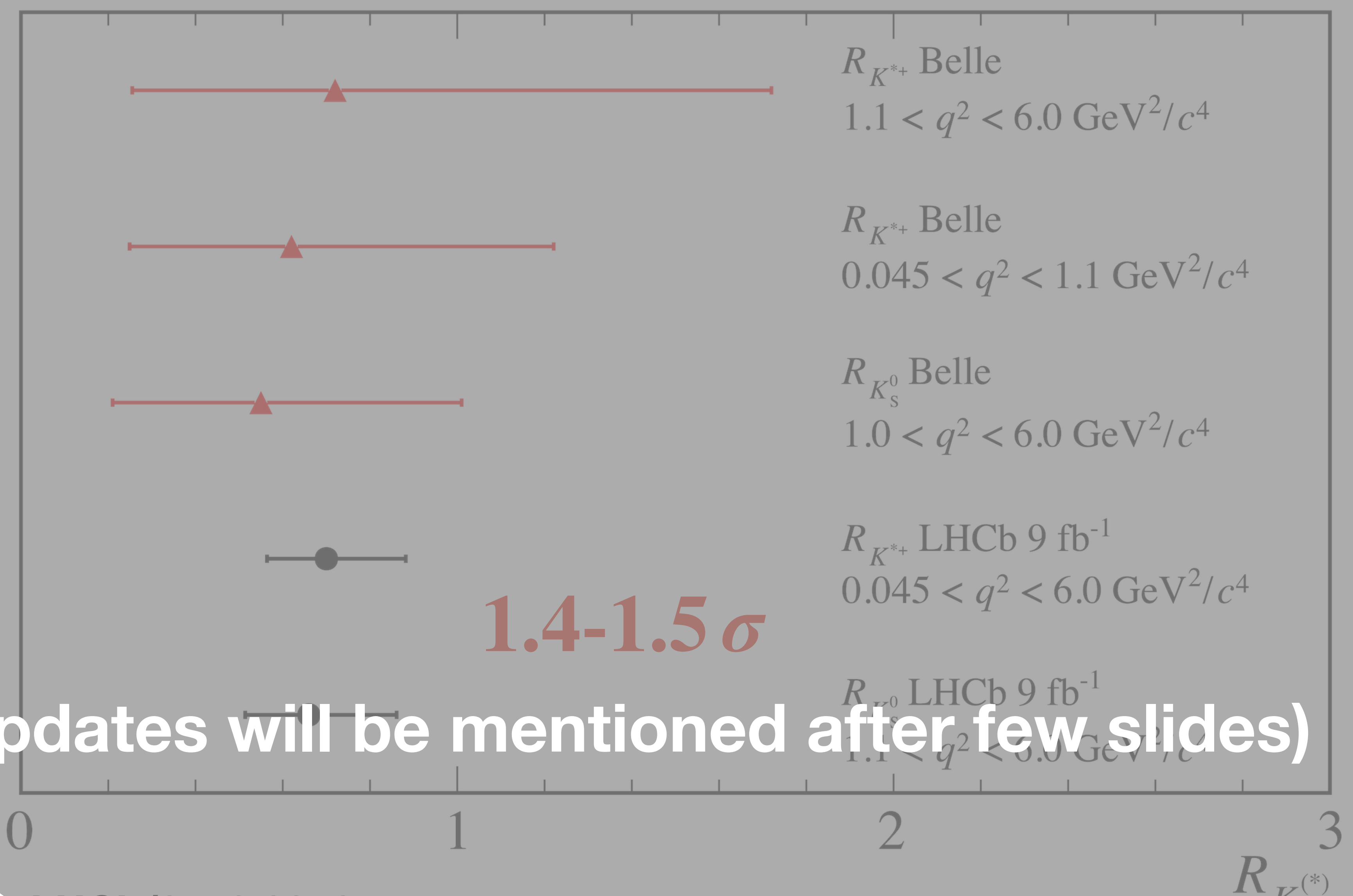
⬇

Physics beyond the SM

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

LHCb/2103.11769





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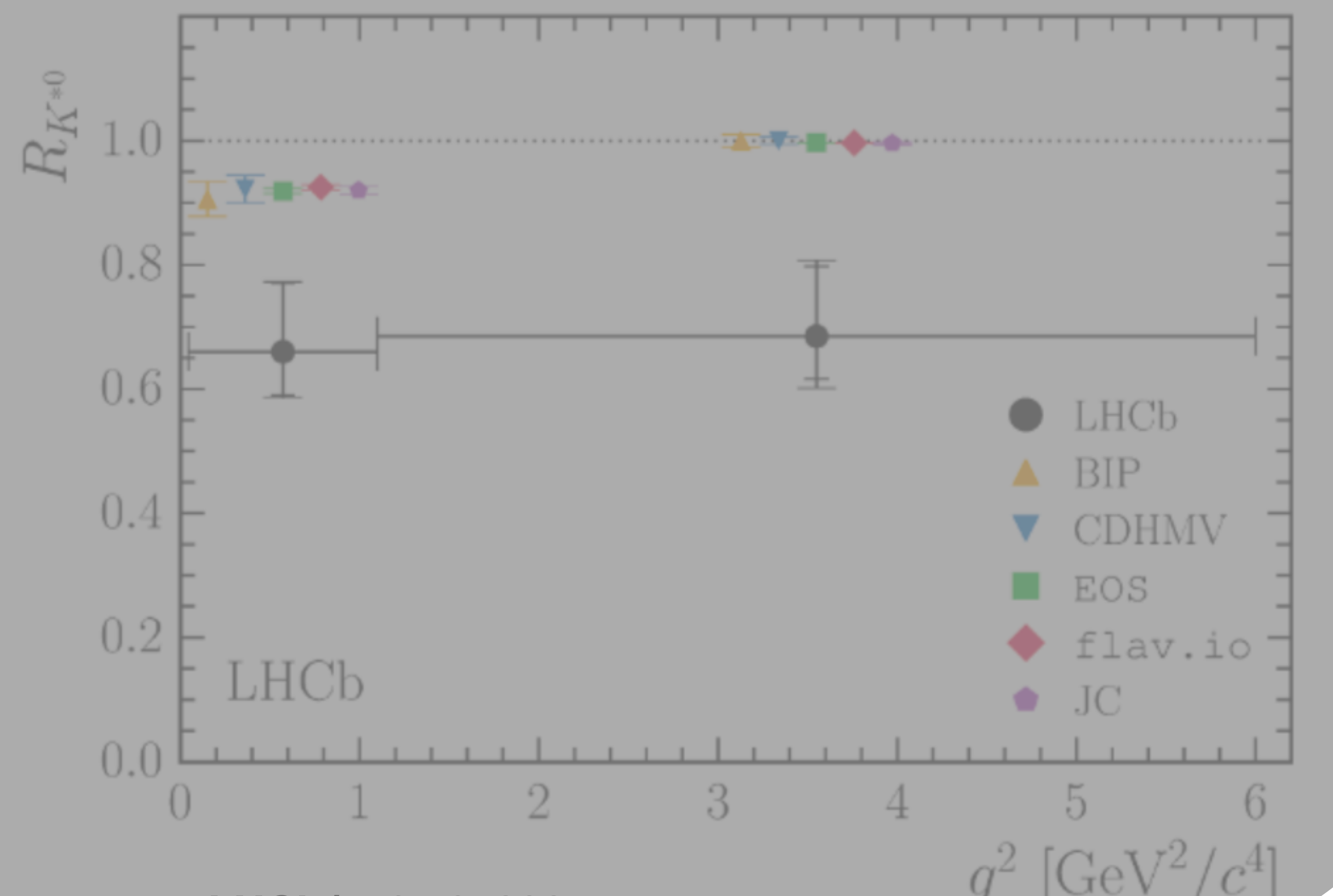


LHCb/1705.05802

disappear after LHCb's new measurements

(2212.09152, 2212.09153)

(updates will be mentioned after few slides)

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

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

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

deviation from unity

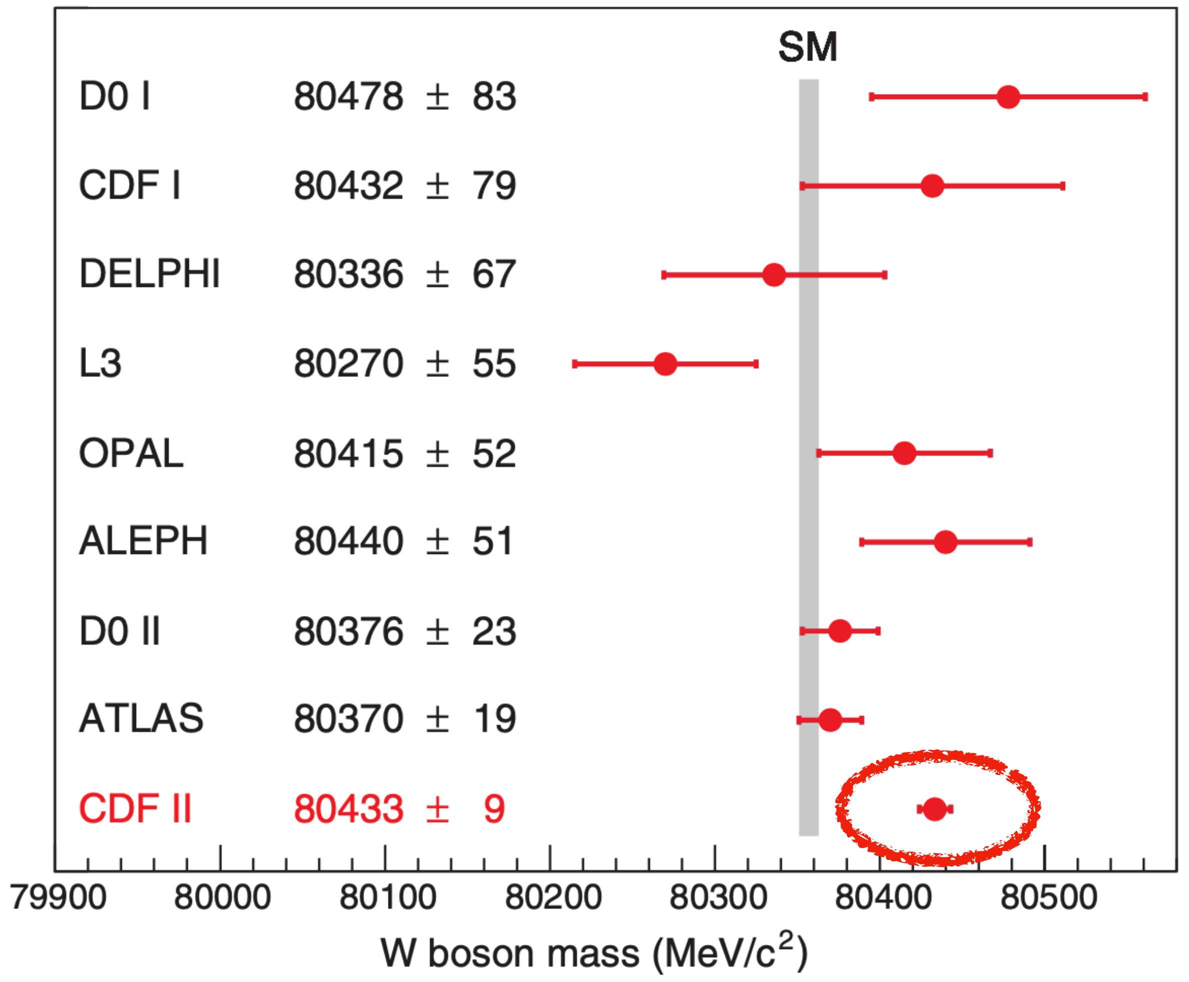
⬇

Physics beyond the SM

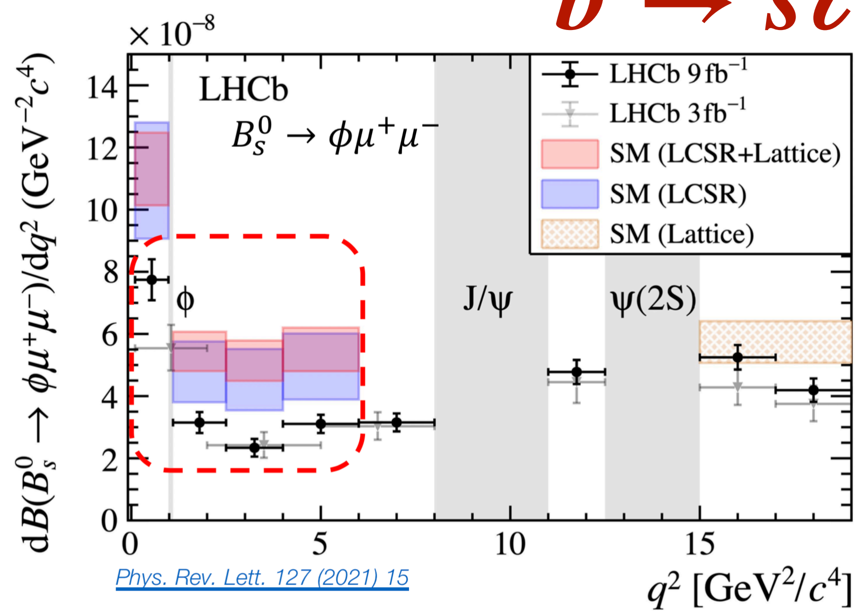
Motivation of this work (arXiv:2205.02205)

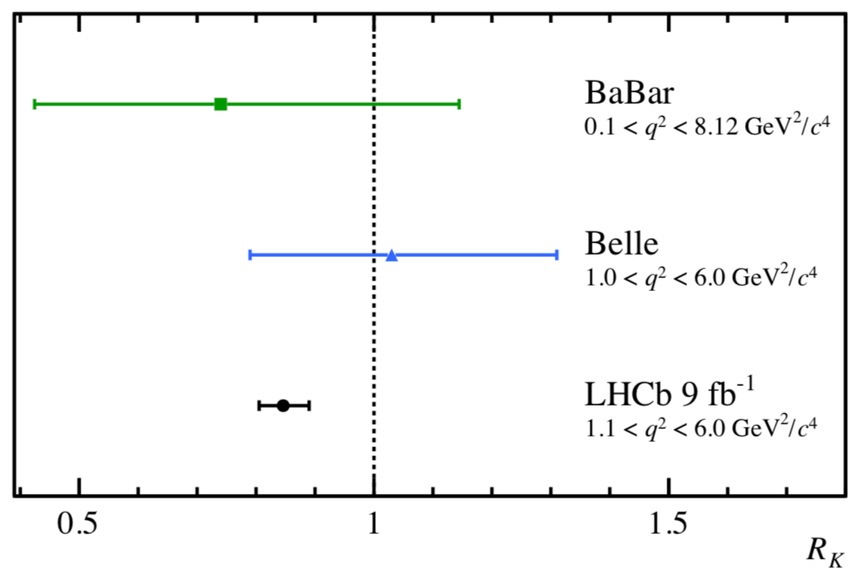
Explain the CDF W-mass shift and $b \to s\ell^+\ell^-$ anomaly in a model simultaneously ?

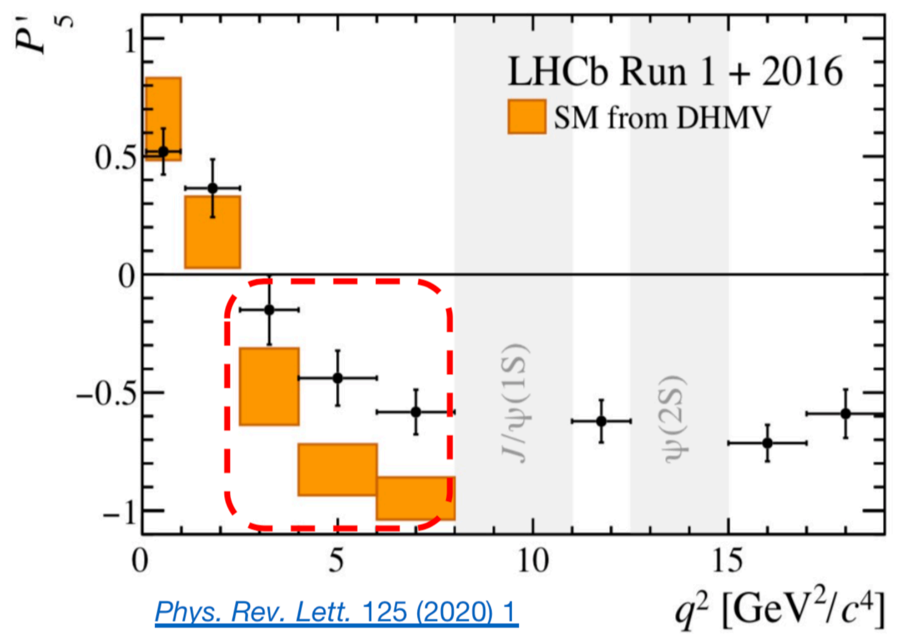
CDF W-mass shift

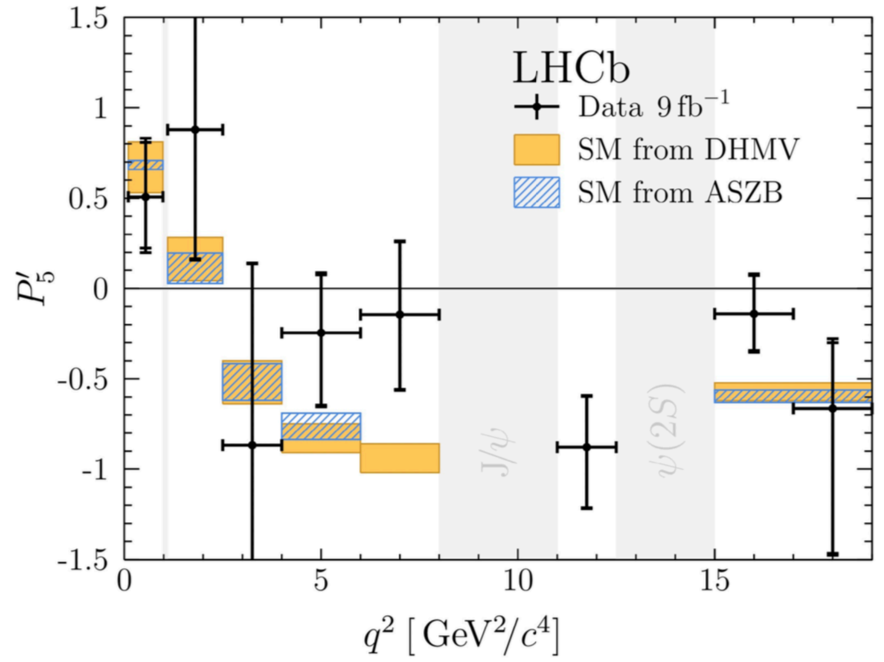


$b \to s\ell^+\ell^-$ anomaly

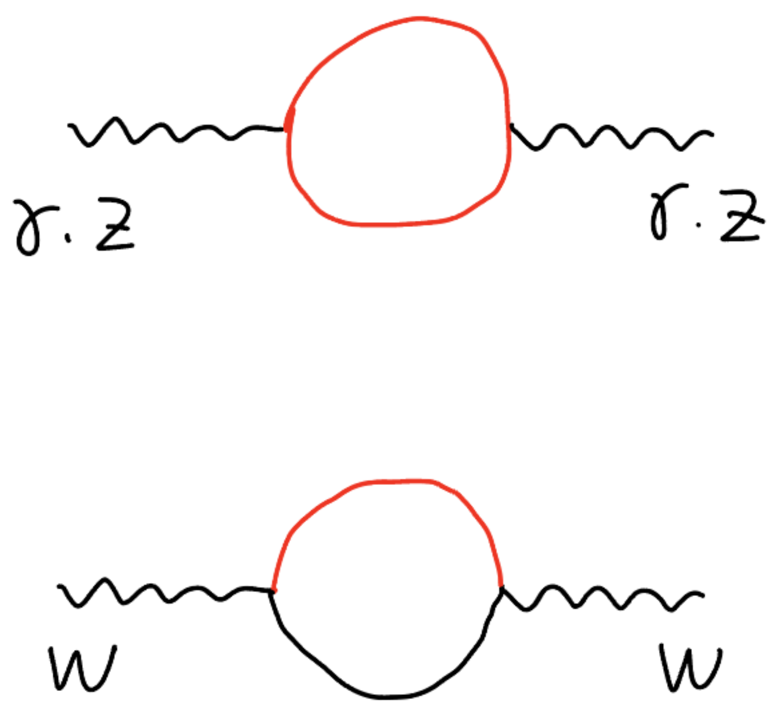






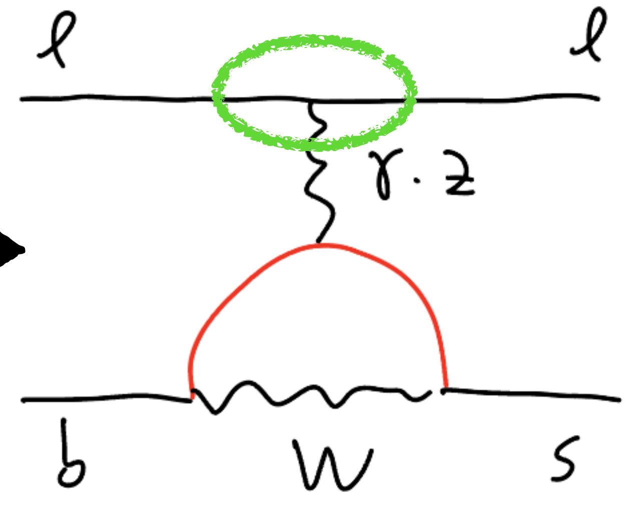


Motivation and idea



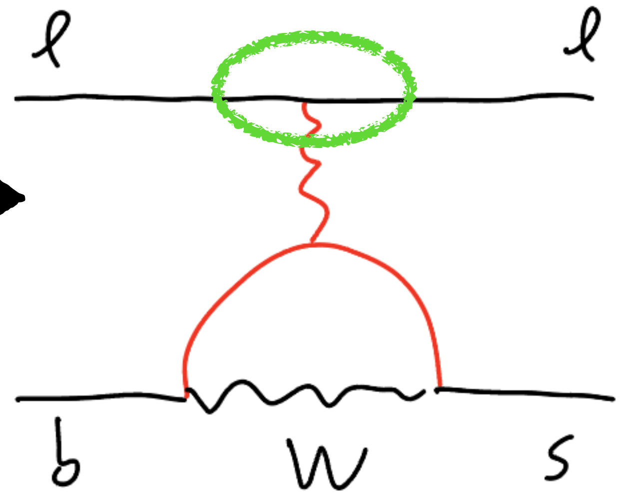
Fermion vector-like

LFUV ✗

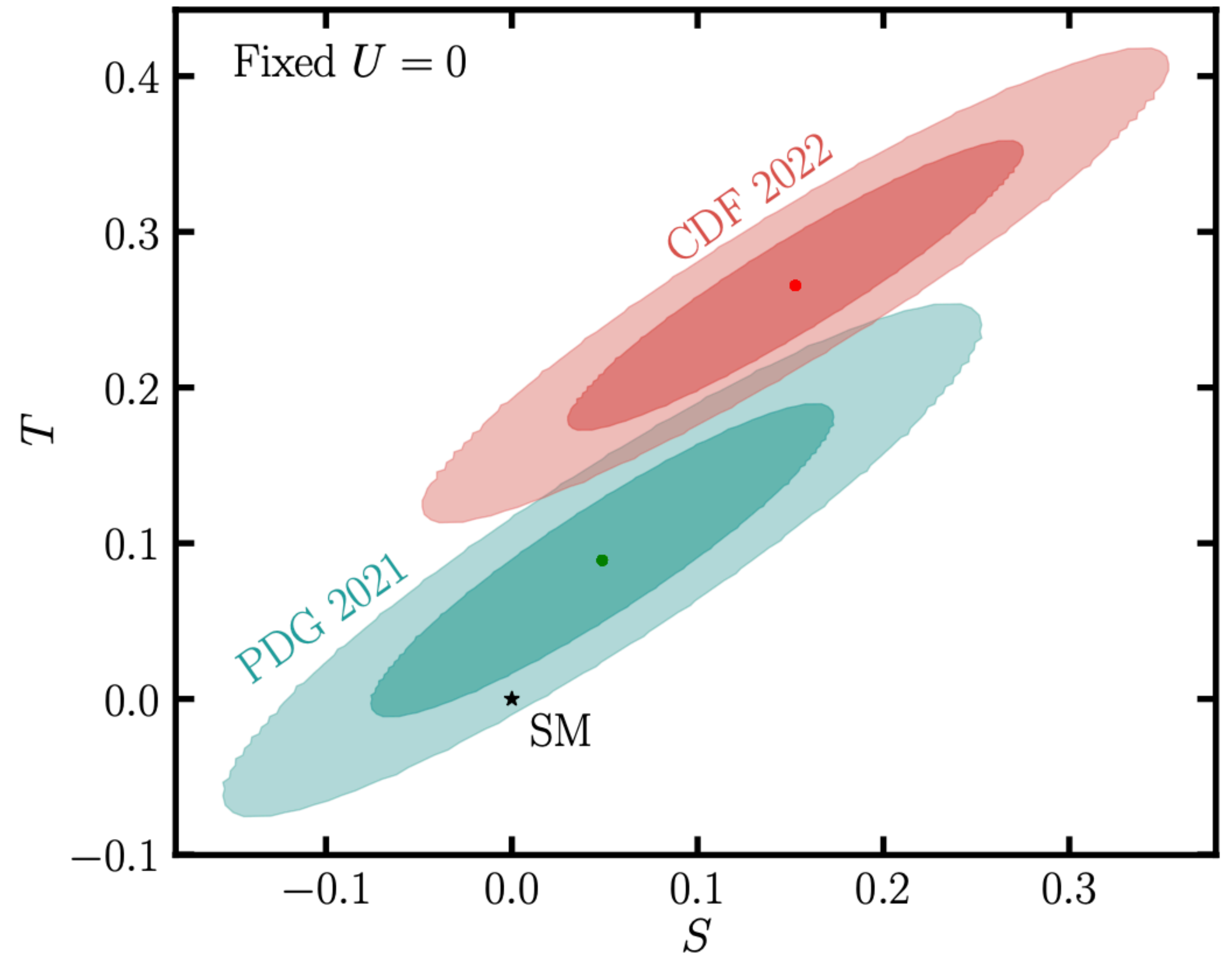


$U(1)'$

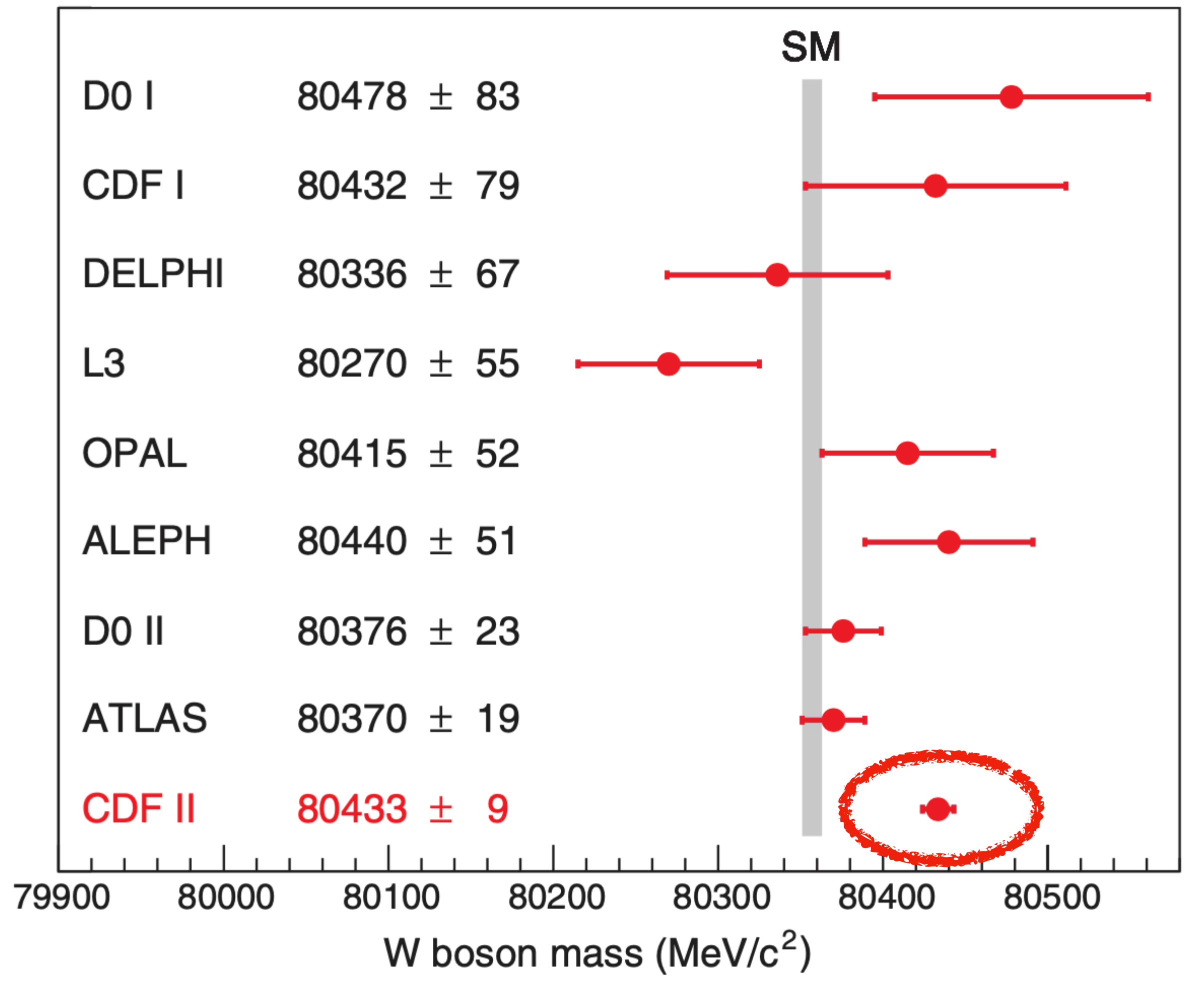
LFUV ✓



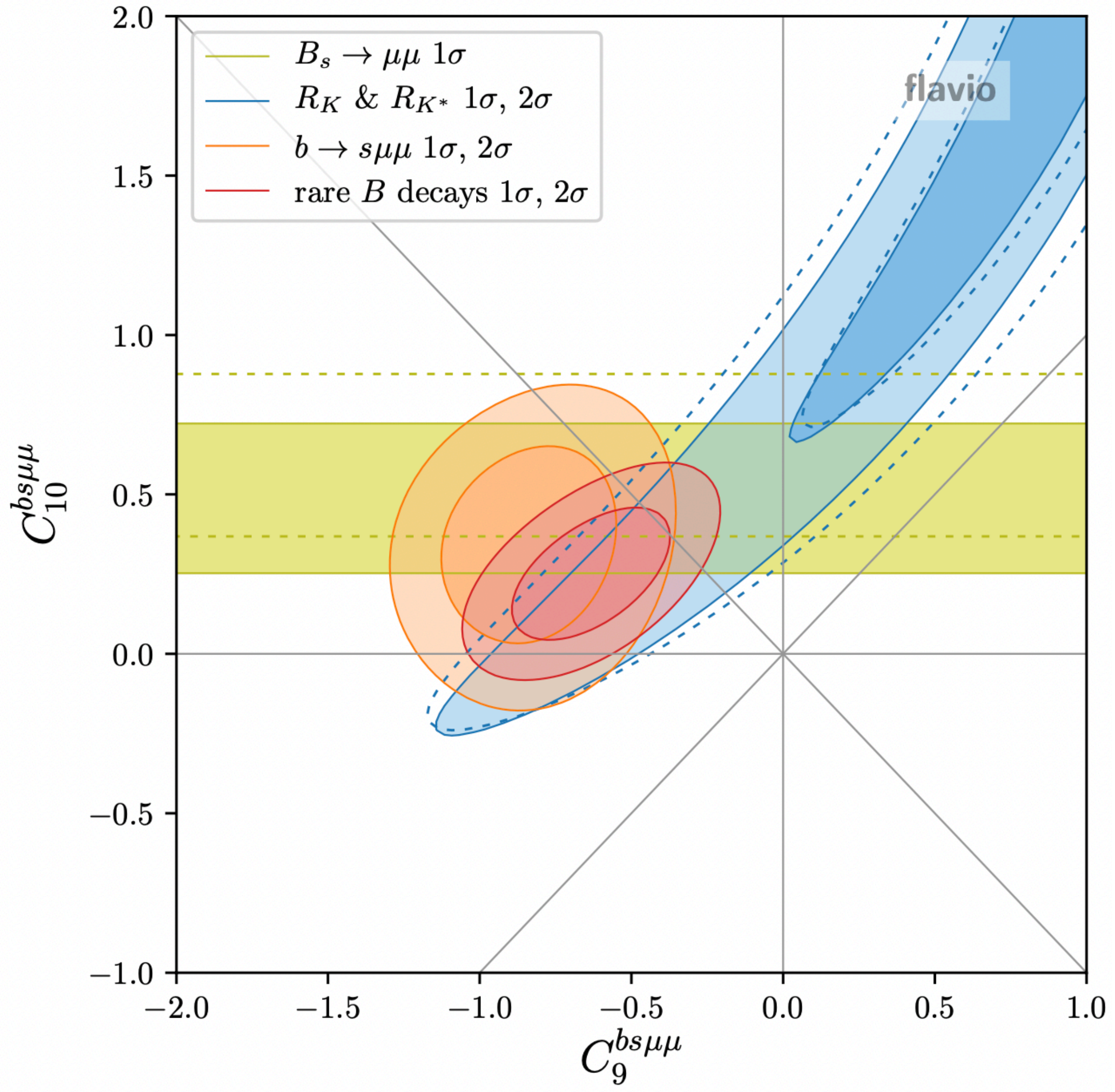
Chih-Ting Lu, Lei Wu, Yongcheng Wu, and Bin Zhu, 2204.03796



CDF W-mass shift

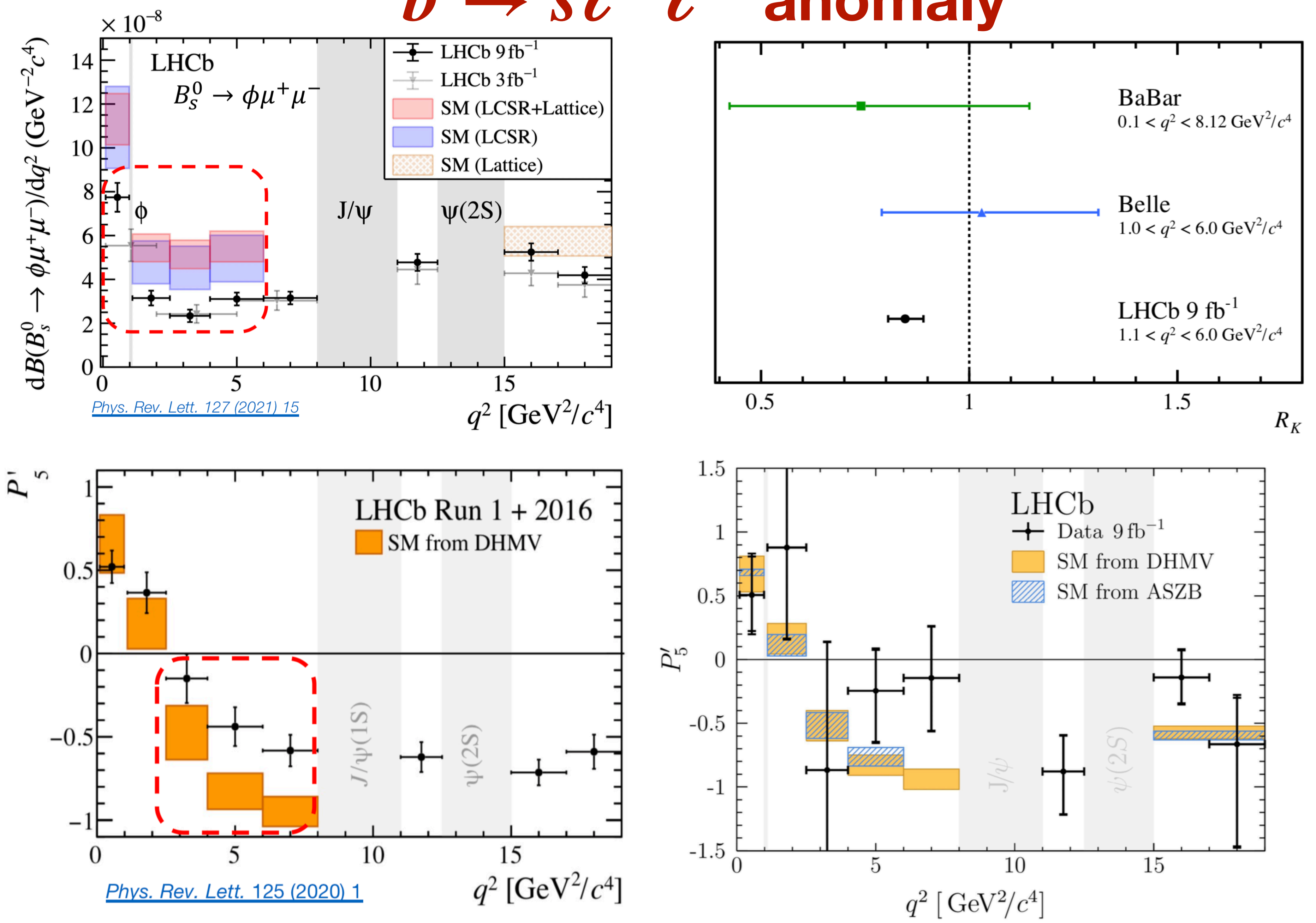


Altmannshofer, Stangl, 2103.1337

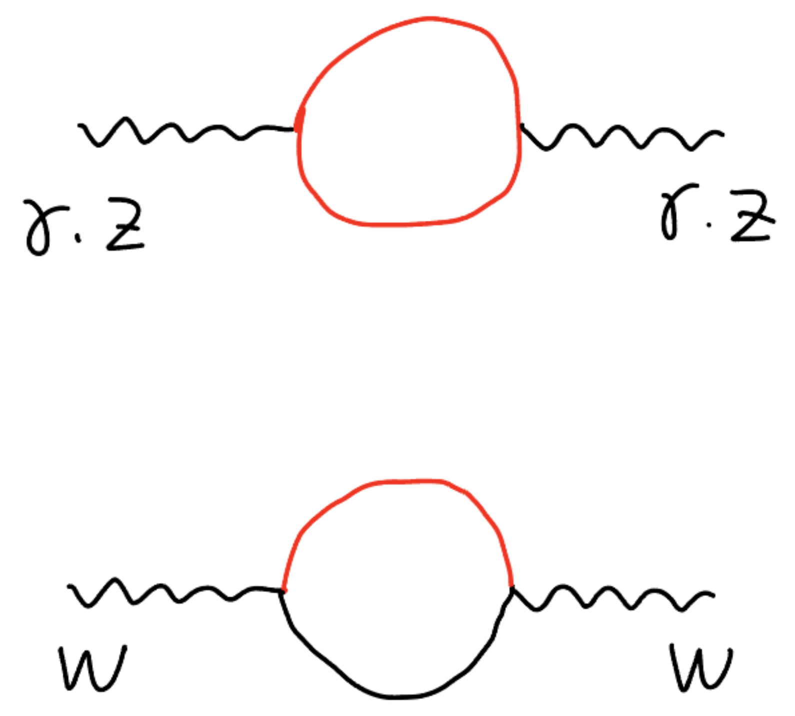


$O_9 = (\bar{b}\gamma^\mu P_L s)(\bar{\ell}\gamma_\mu \ell)$ $O_{10} = (\bar{b}\gamma^\mu P_L s)(\bar{\ell}\gamma_\mu\gamma_5 \ell)$

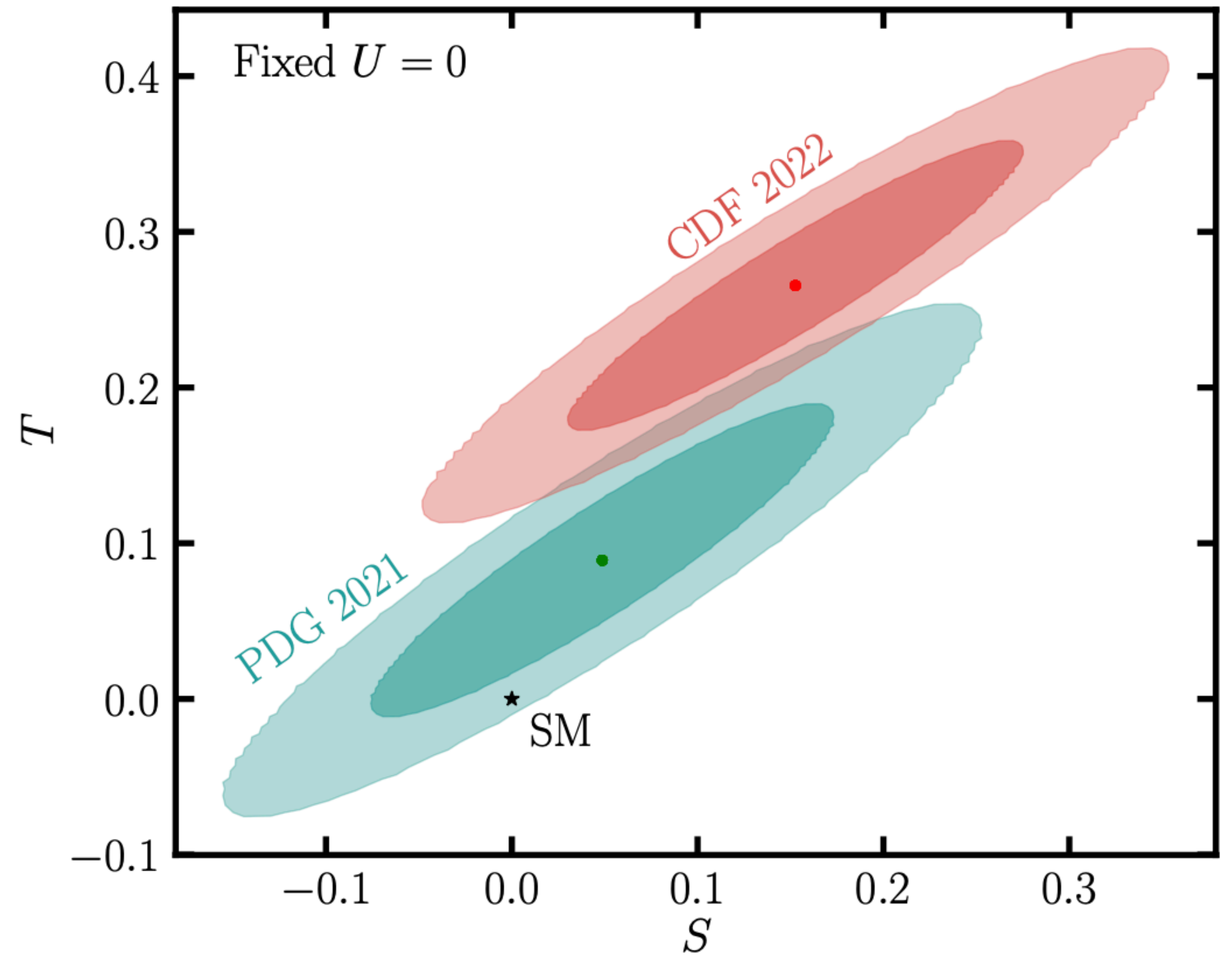
$b \to s\ell^+\ell^-$ **anomaly**



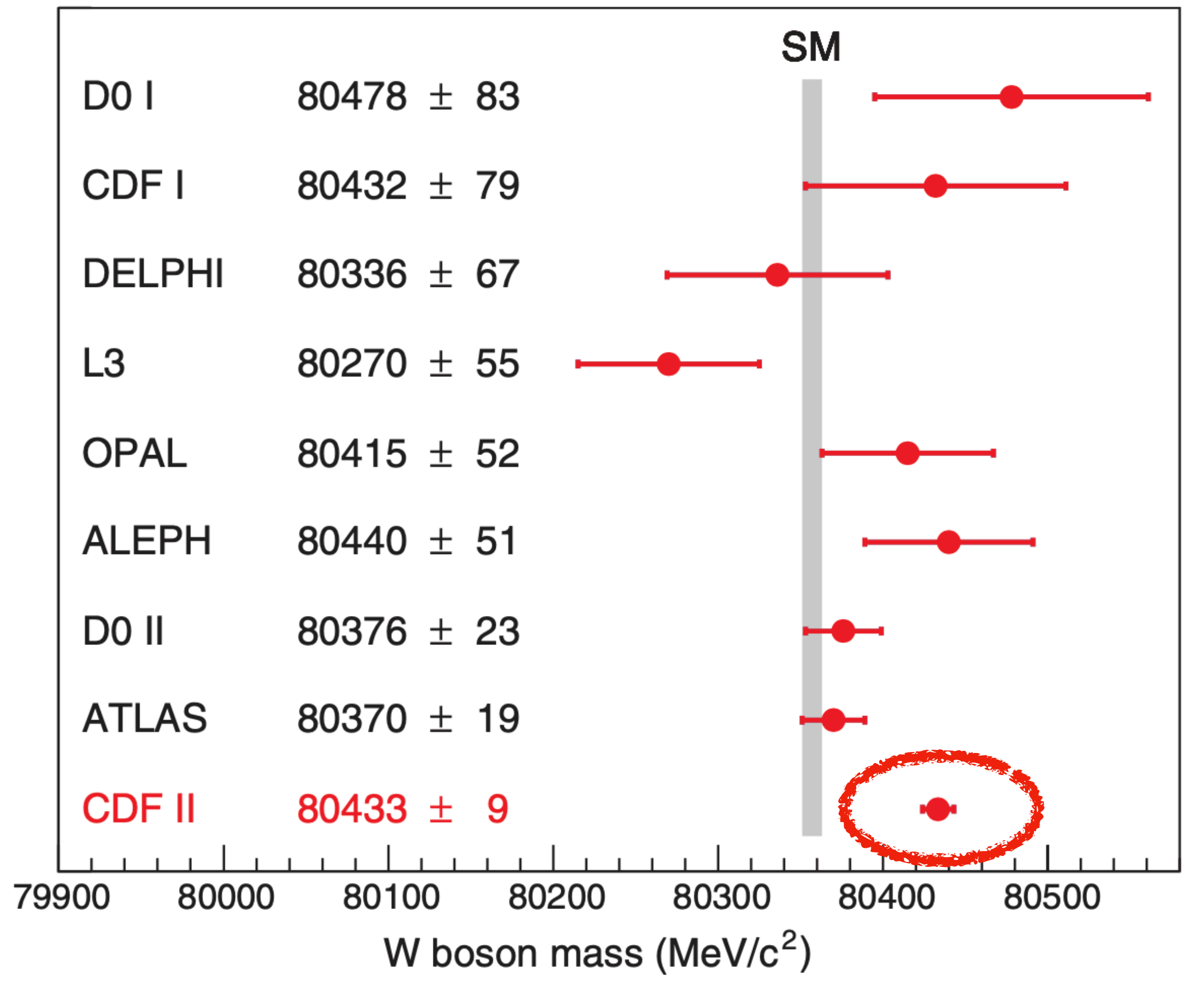
Motivation and idea



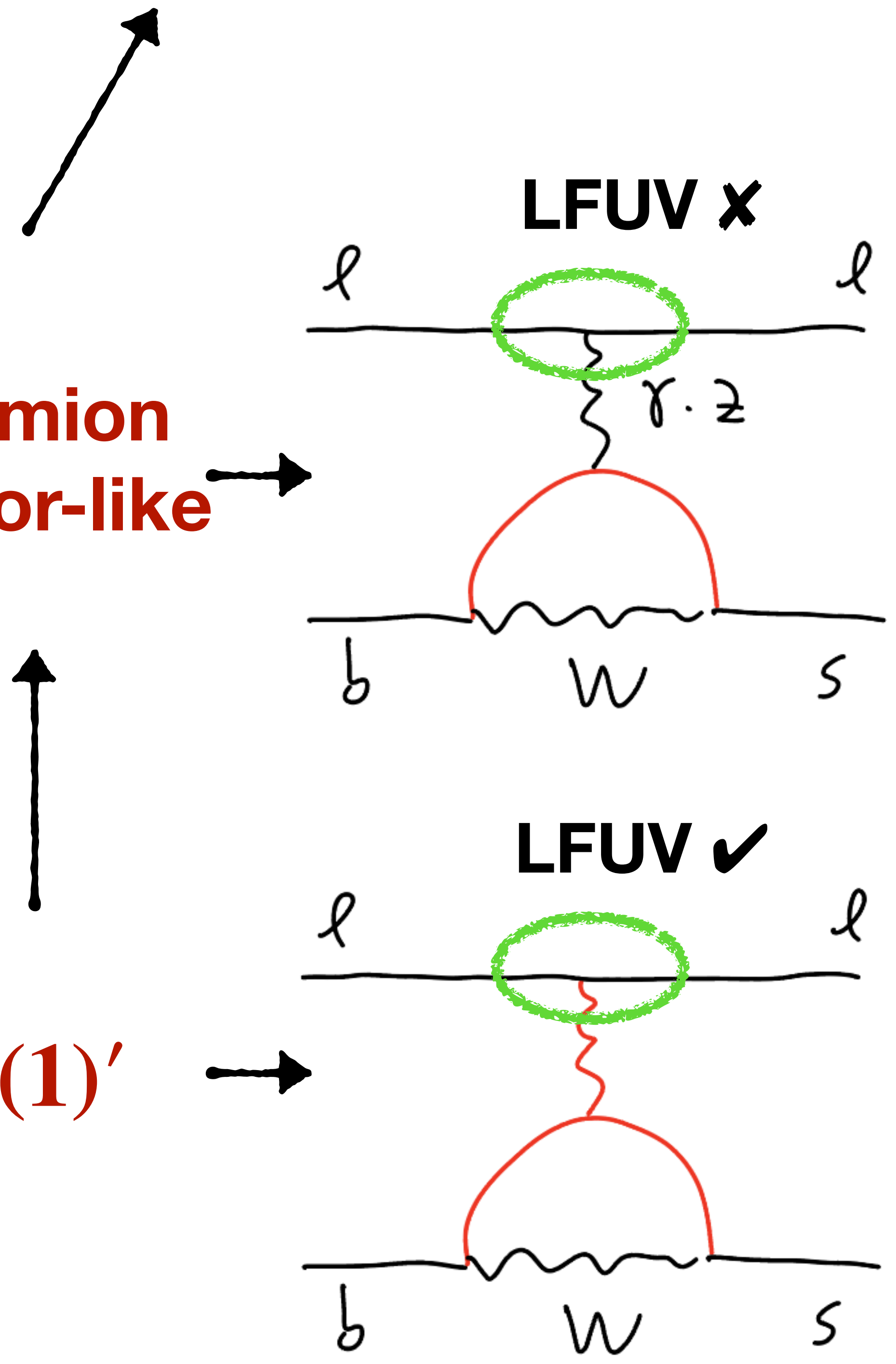
Chih-Ting Lu, Lei Wu, Yongcheng Wu, and Bin Zhu, 2204.03796



CDF W-mass shift



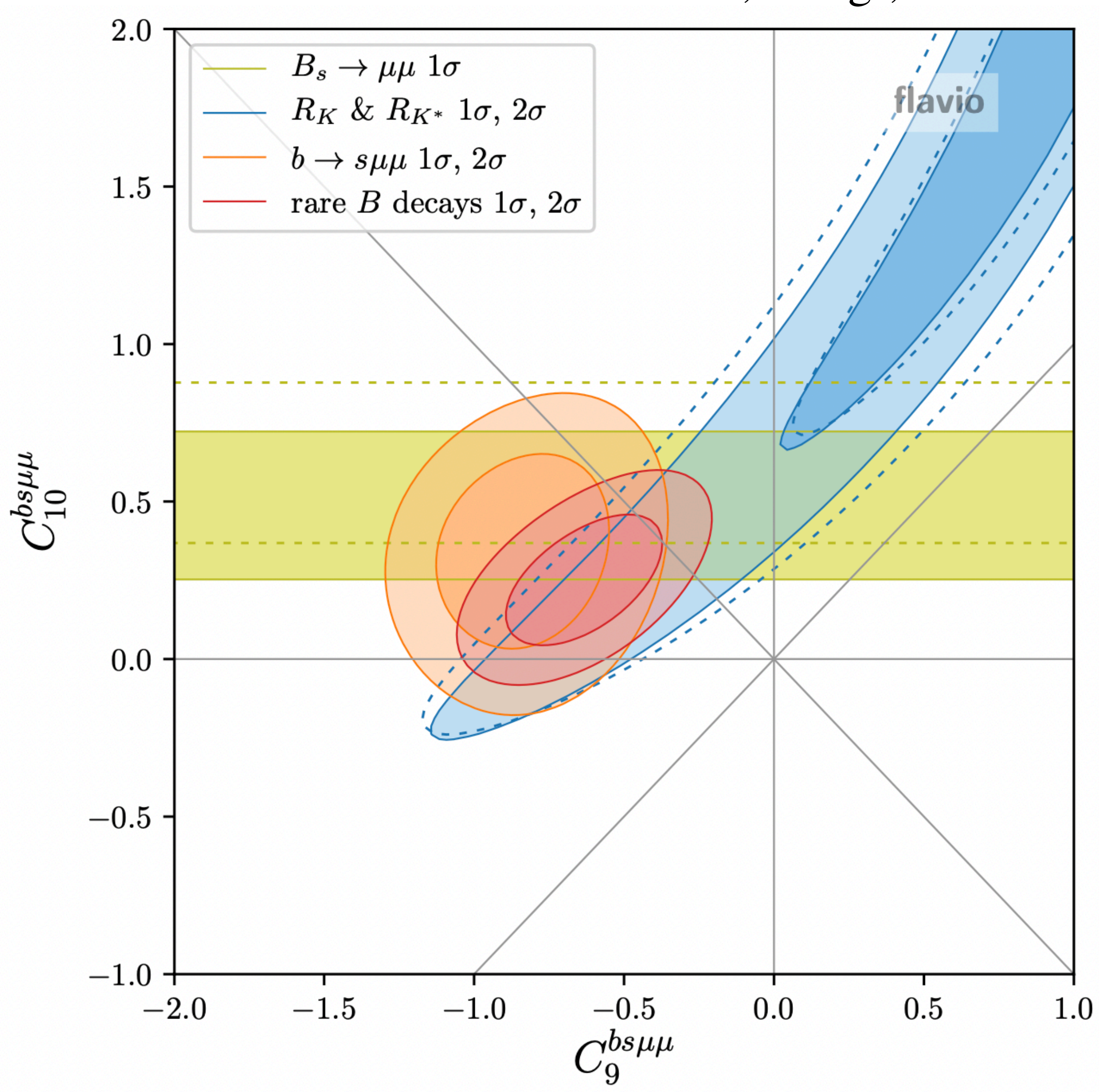
already introduced by J. F. Kamenik, Y. Soreq, J. Zupan, PRD97(2018)035002



Fermion vector-like

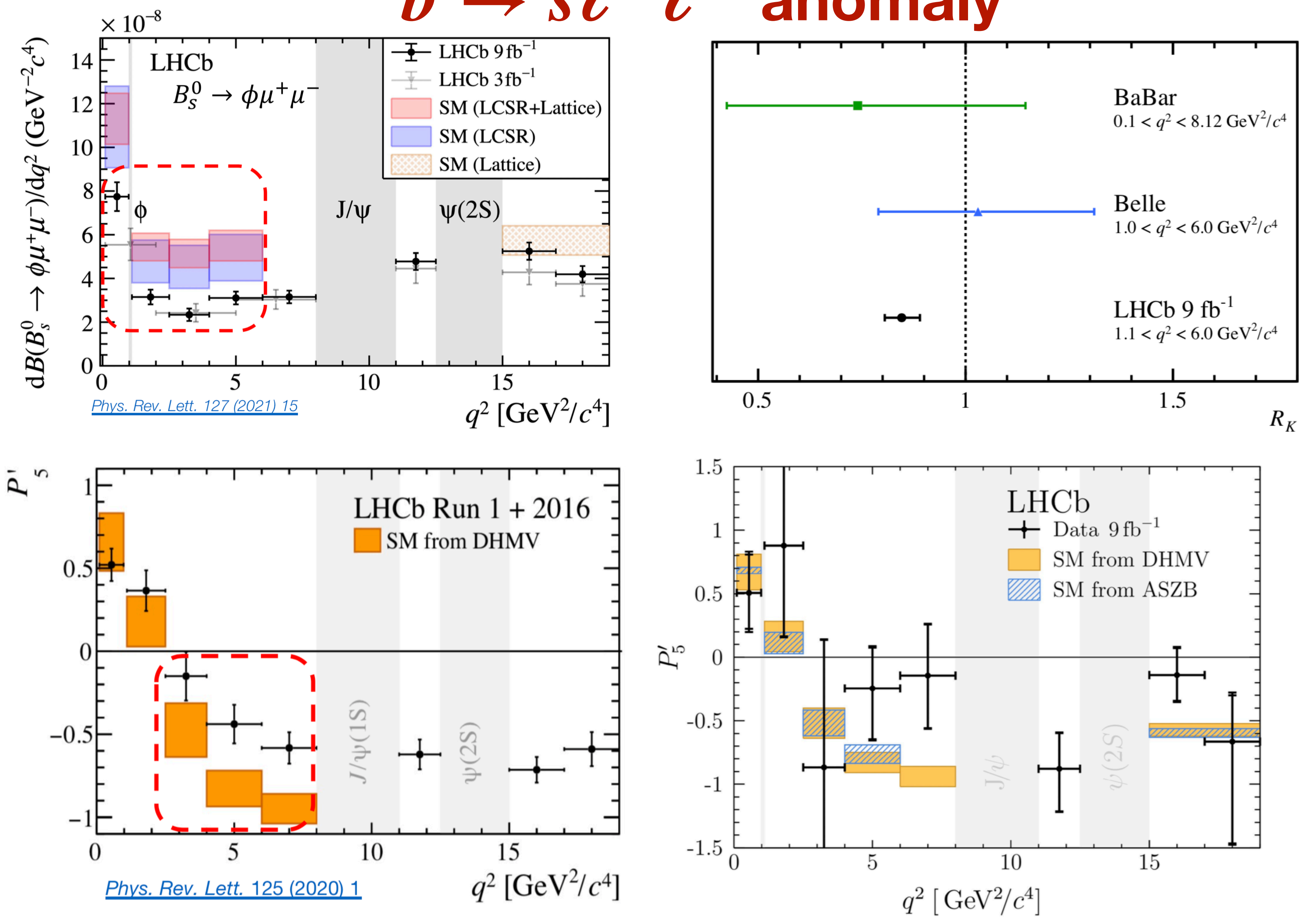
$U(1)'$

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

- **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**

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

- **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**

$$\begin{array}{c} \begin{array}{cccc} \quad u \quad & \quad c \quad & \quad t \quad & \quad T \quad \end{array} \\ \begin{pmatrix} \lambda_{11} v_H & 0 & 0 & 0 \\ 0 & \lambda_{22} v_H & 0 & 0 \\ 0 & 0 & \lambda_H v_H & 0 \\ 0 & 0 & \lambda_{\Phi_t} v_{\Phi_t} & \sqrt{2}\mu \end{pmatrix} \end{array}$$

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

- **Comments**
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$$\tan\theta_L = \frac{m_t}{m_T} \tan\theta_R$$

mass **interaction**

- **Interactions**

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

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

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

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

- **lepton sector (effective coupling)**

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

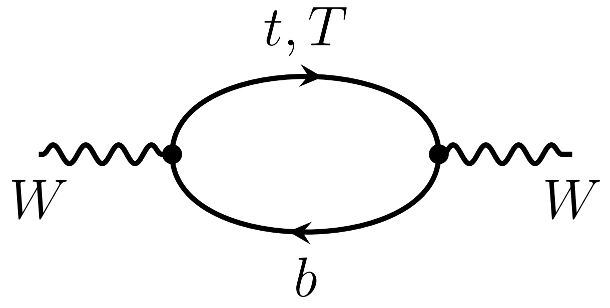
- **NP parameters**

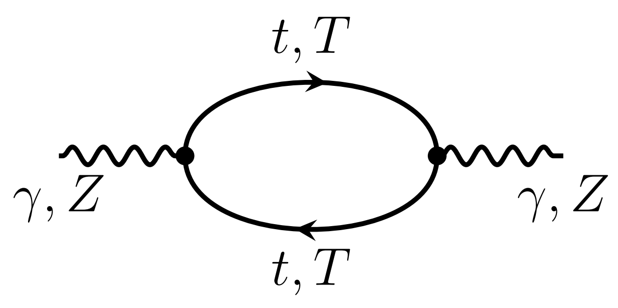
$$(\cos\theta_L,\, m_T,\, g_\mu^L,\, g_\mu^R,\, g_t,\, q_t,\, m_{Z'})$$

W-boson mass shift and oblique parameters

Explanation in top-philic Z' scenario

- NP contributions to vacuum polarizations





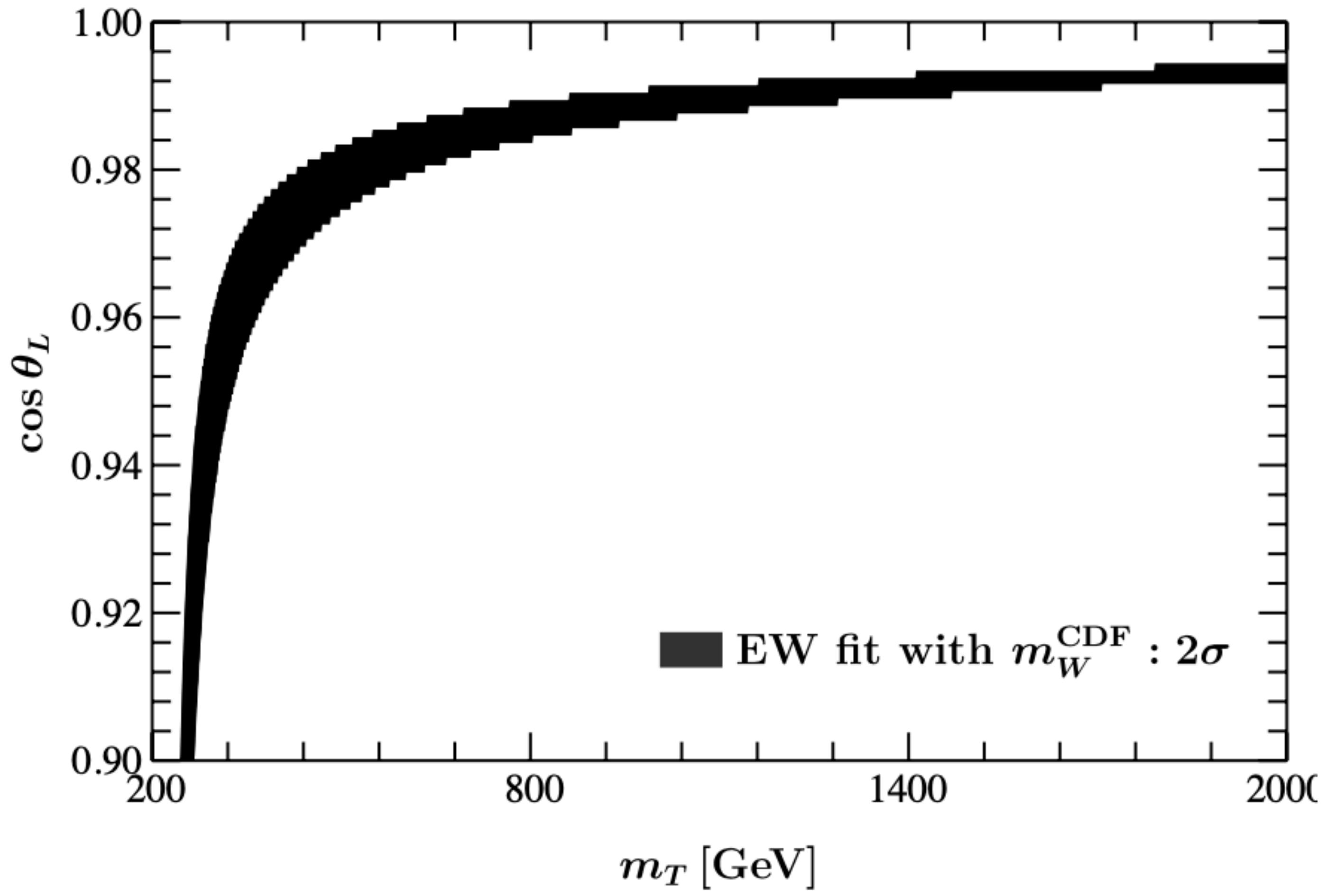
- S, T, U are affected

$$S_T = \frac{s_L^2}{12\pi}\Big[K_1(y_t, y_T) + 3c_L^2 K_2(y_t, y_T)\Big],$$

$$T_T = \frac{3s_L^2}{16\pi s_W^2}\left[x_T - x_t - c_L^2\left(x_T + x_t + \frac{2x_t x_T}{x_T - x_t}\ln\frac{x_t}{x_T}\right)\right]$$

$$U_T = \frac{s_L^2}{12\pi}\Big[K_3(x_t, y_t) - K_3(x_T, y_T)\Big] - S,$$

- Allowed parameter space



★ $m_W^{\rm CDF}$ can be explained by the top-parter effects

★ small θ_L is allowed

Global EW fit

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

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

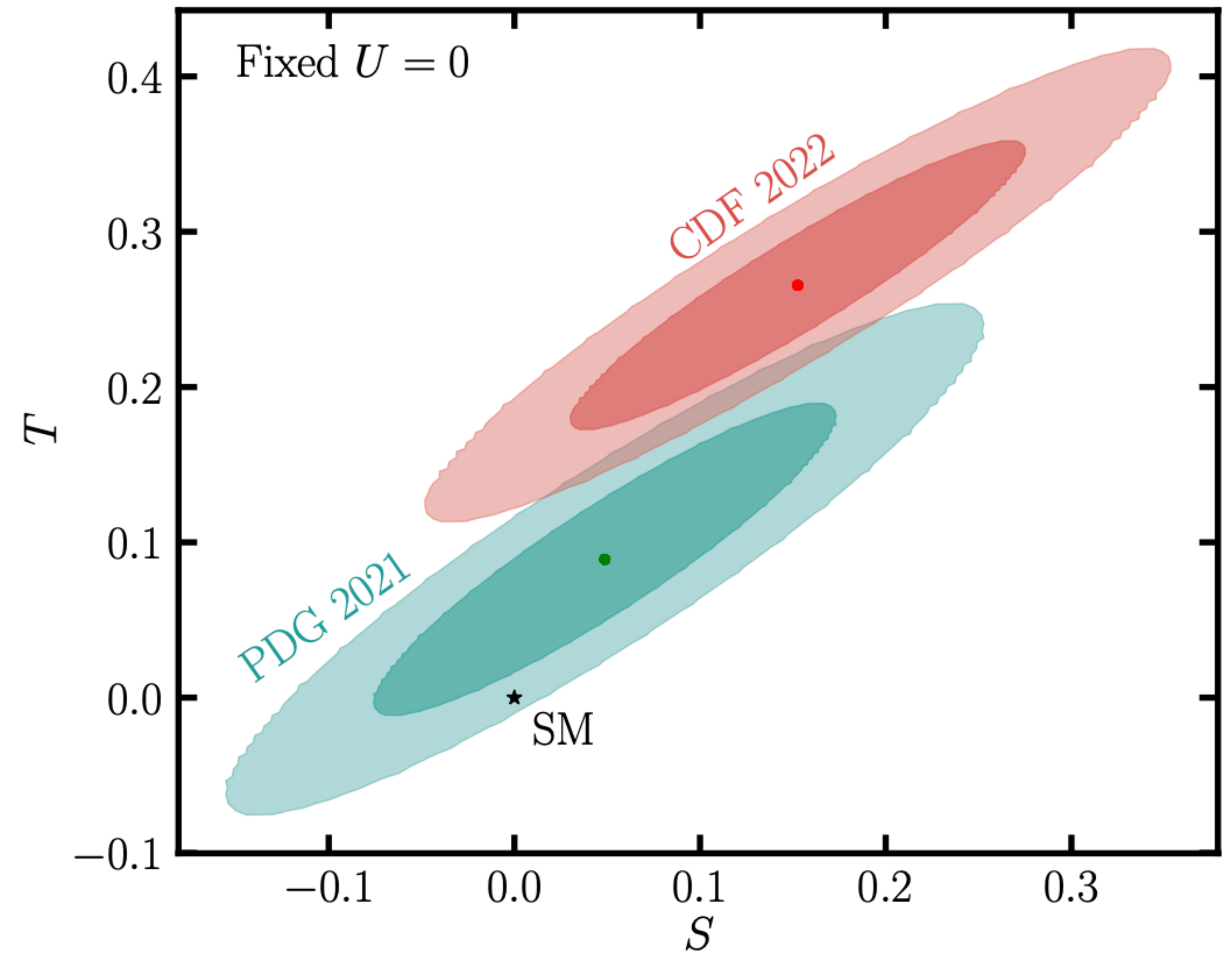
- S, T, U are related to the vacuum polarization of gauge bosons

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

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

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

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

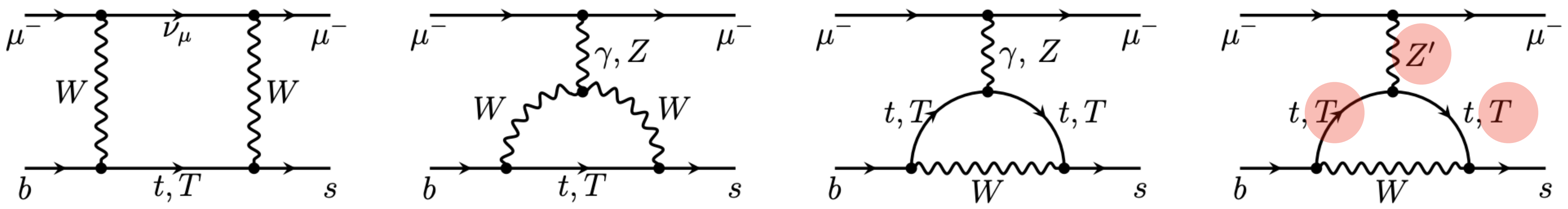


By Gfitter

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

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

▶ NP contributions



dominated

▶ Effective Hamiltonian

$$\mathcal{H}_{\rm eff} \supset -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha}{4\pi} \left(\mathcal{C}_9^\mu \mathcal{O}_9^\mu + \mathcal{C}_{10}^\mu \mathcal{O}_{10}^\mu\right) + \text{ h.c.} \,,$$

▶ Wilson coefficients

$$\mathcal{C}_9^{\rm NP} = s_L^2 I_1 + s_L^2 \left(1 - \frac{1}{4 s_W^2}\right)\left(I_2 + c_L^2 I_3\right) + \Delta\mathcal{C}_+^{Z'}$$

$$\mathcal{C}_{10}^{\rm NP} = \frac{s_L^2}{4 s_W^2}\left(I_2 + c_L^2 I_3\right) + \Delta\mathcal{C}_-^{Z'} \,,$$

$$\Delta\mathcal{C}_\pm^{Z'} = \frac{(g_L \pm g_R) q_t g_t}{e^2} \frac{m_W^2}{m_{Z'}^2} c_L^2 s_R^2 \left(I_4 - \frac{c_L^2}{c_R^2} I_5\right)$$

▶ NP parameters

$$\left(\cos\theta_L,\, m_T,\, \frac{q_t g_t g_\mu^{L,R}}{m_{Z'}^2}\right)$$

Without loss of generality

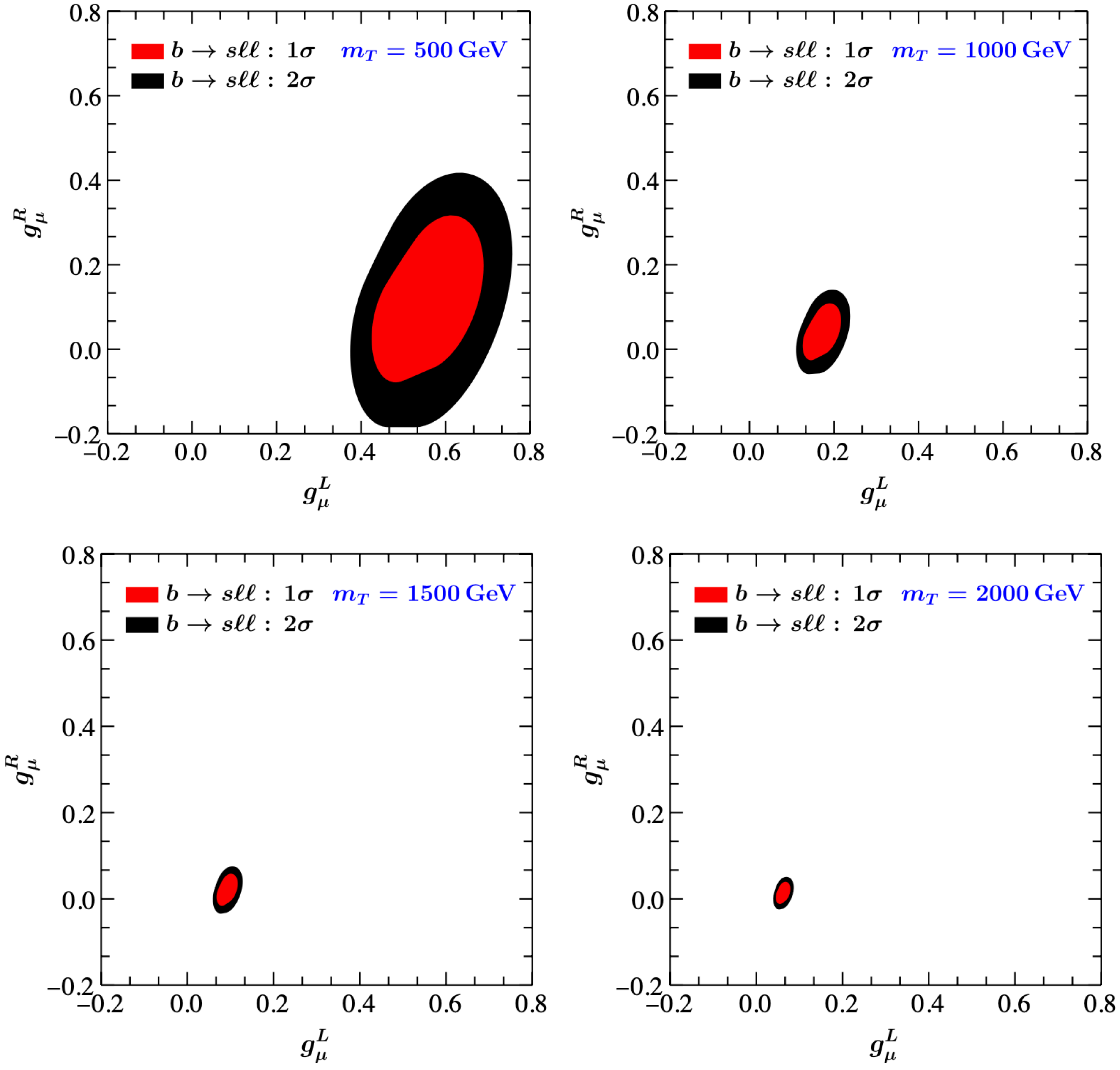
$$q_t = 1,\, g_t = 1,\, m_{Z'} = 200\,\text{GeV}$$

$$(\cos\theta_L,\, m_T,\, g_\mu^L,\, g_\mu^R)$$

★ The W-box, γ- and Z- penguin diagrams are highly suppressed (proportional to $\sin^2\theta_L$)

★ The Z' penguins do not suffer from this suppression and may affect the $b \to s\ell^+\ell^-$ processes

$b \to s\ell^+\ell^-$ anomalies and the CDF m_W shift



- ▶ $b \to s\ell^+\ell^-$ $(\cos\theta_L, m_T, g_\mu^L, g_\mu^R)$
- ▶ m_W shift $(\cos\theta_L, m_T)$

★ $m_W^{\rm CDF}$ and $b \to s\ell^+\ell^-$ anomalies simultaneously explained at $2\,\sigma$ level

★ the couplings are safely in the perturbative region

Constraints on (g_μ^L, g_μ^R) from the $b \to s\ell^+\ell^-$ processes, in the $2\,\sigma$ allowed regions of $(\cos\theta_L, m_T)$ obtained from the global EW fit

Problems in this work (arXiv:2205.02205)

- **lepton sector is based on effective couplings, not UV-complete**

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

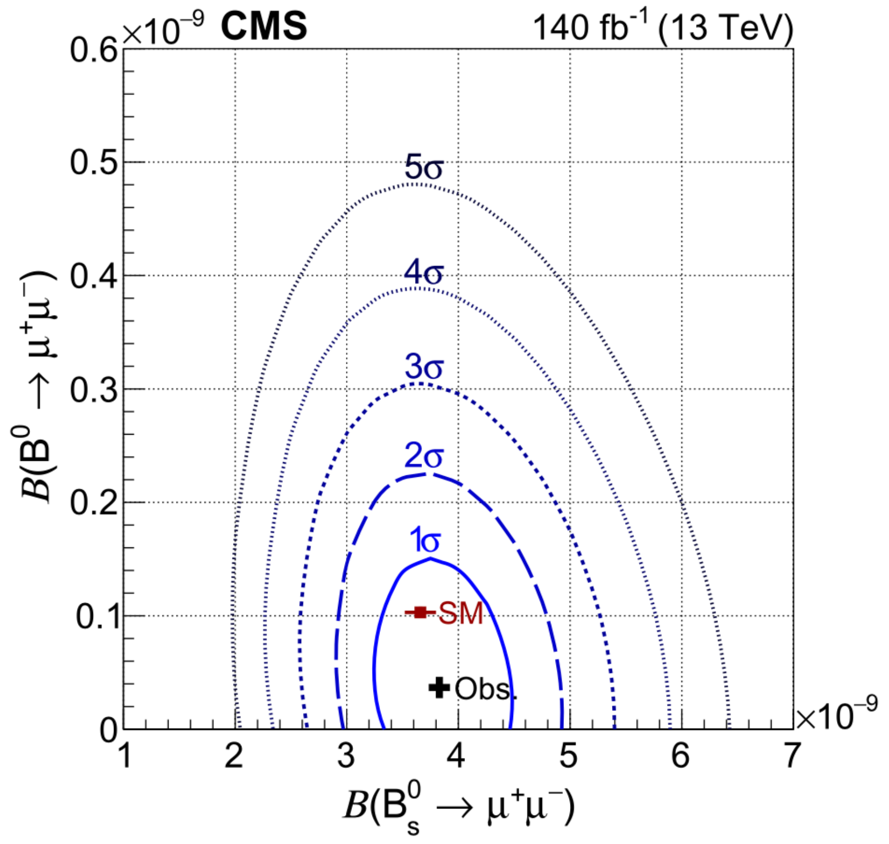
  - can't explain $(g-2)_\mu$
  - collider (depending the Z' decay)
  - $Z - Z'$ mixing (NP particles in the lepton sector can enter the loop)

- **New CMS measurements on $B_s \to \mu^+\mu^-$**

- **New LHCb measurements on R_K and R_{K*}**

Problems in this work (arXiv:2205.02205)

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



$$\mathcal{B}(B_s \to \mu^+\mu^-)_{\rm ATLAS} = \left(2.8^{+0.8}_{-0.7}\right) \times 10^{-9},$$

$$\mathcal{B}(B_s \to \mu^+\mu^-)_{\rm LHCb} = \left(3.09^{+0.46+0.15}_{-0.43-0.11}\right) \times 10^{-9},$$

$$\mathcal{B}(B_s \to \mu^+\mu^-)_{\rm CMS} = \left(3.83^{+0.38+0.19+0.14}_{-0.36-0.16-0.13}\right) \times 10^{-9}.$$

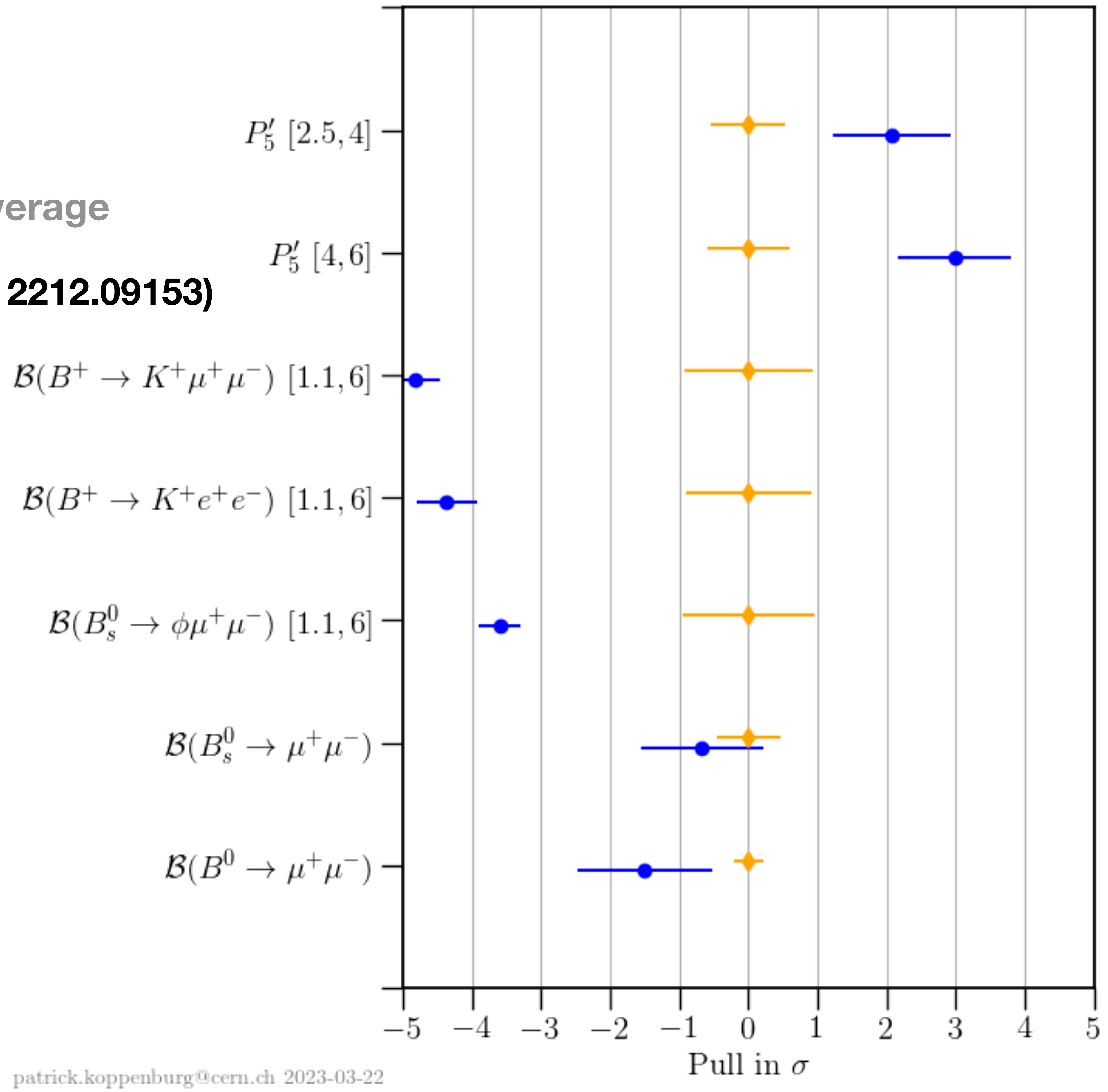
$$\mathcal{B}(B_s \to \mu^+\mu^-)_{\rm avg} = \left(3.52^{+0.32}_{-0.30}\right) \times 10^{-9}$$

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

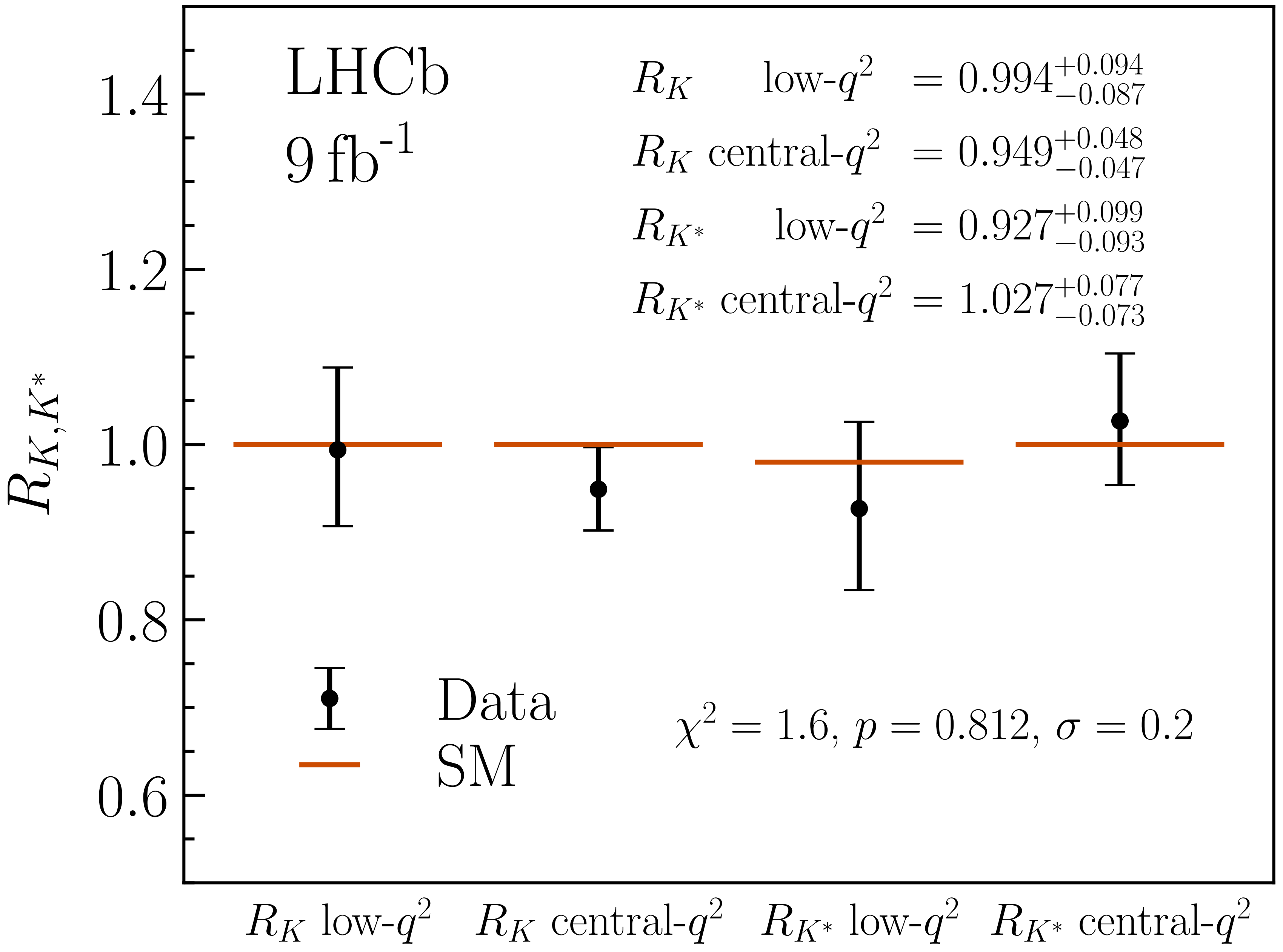
$$\mathcal{B}(B_s \to \mu^+\mu^-)_{\rm avg} = (2.93 \pm 0.35) \times 10^{-9}.$$

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

Problems in this work (arXiv:2205.02205)

Recent Global Fit

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

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

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

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

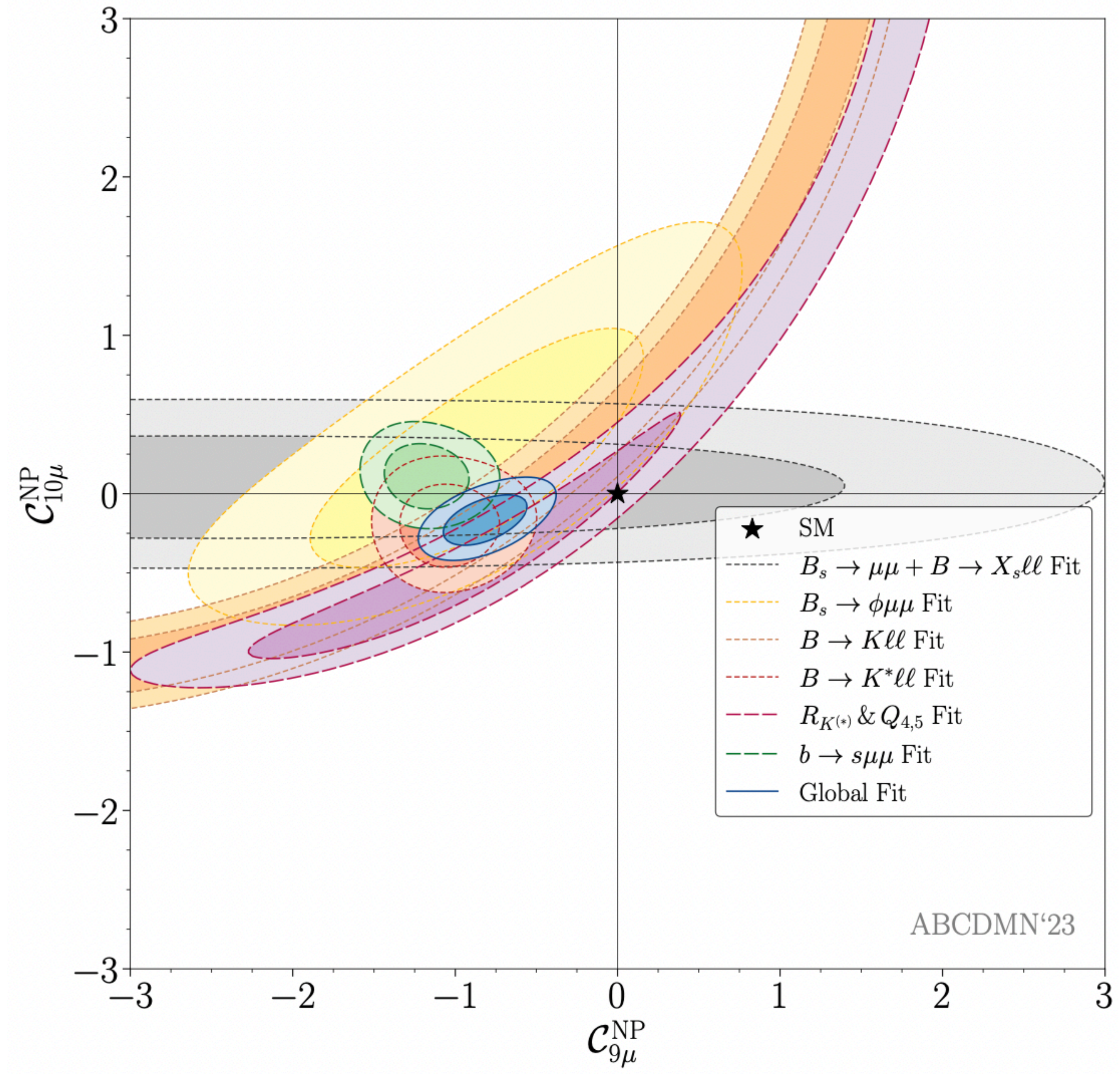
$$O_9 = (\bar{b}\gamma^\mu P_L s)(\bar{\ell}\gamma_\mu \ell)$$

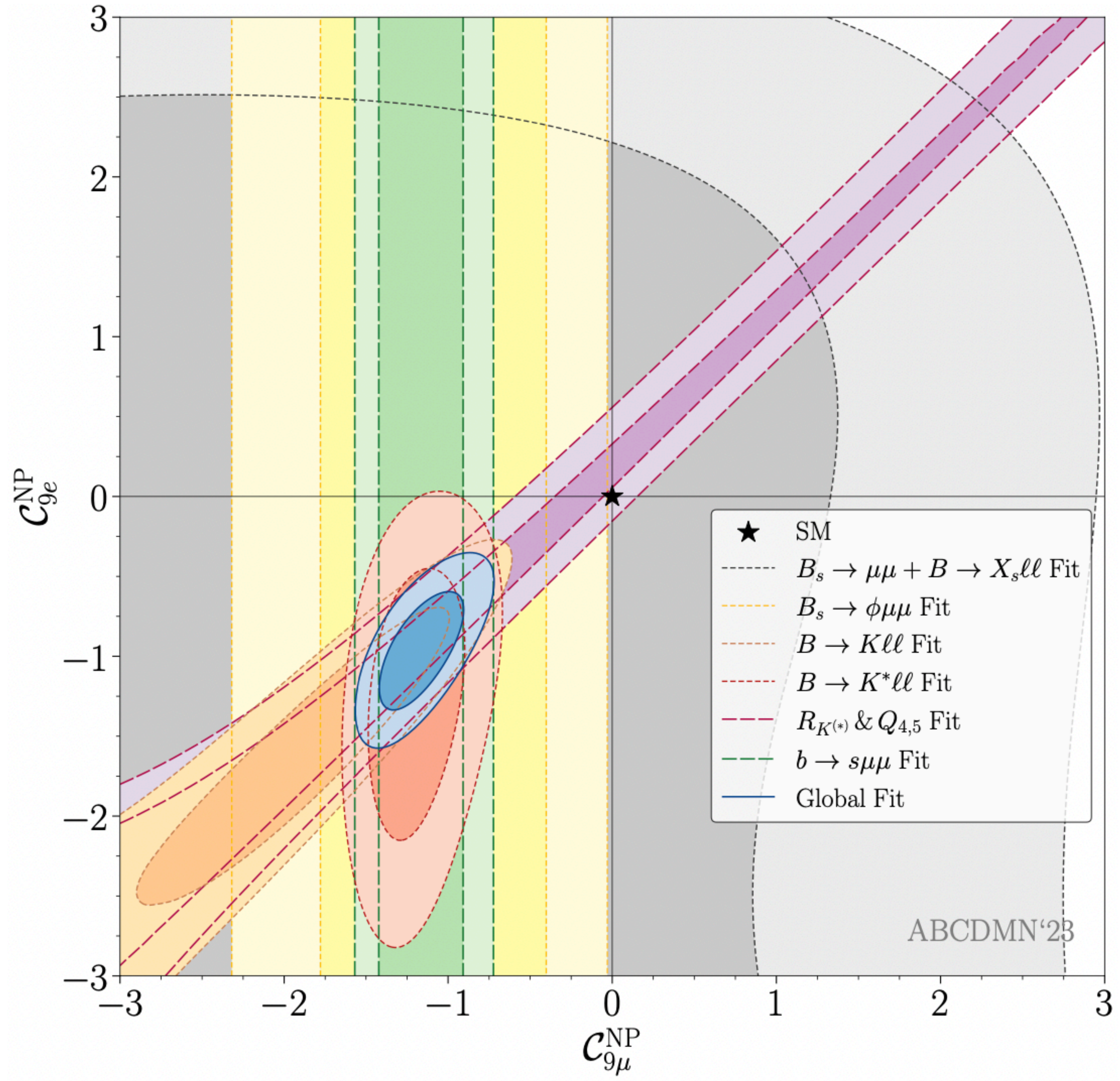
$$O_{10} = (\bar{b}\gamma^\mu P_L s)(\bar{\ell}\gamma_\mu \gamma_5 \ell)$$

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

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

Current global fit implies $Z'\ell^+\ell^-$ interaction should be almost vector-type

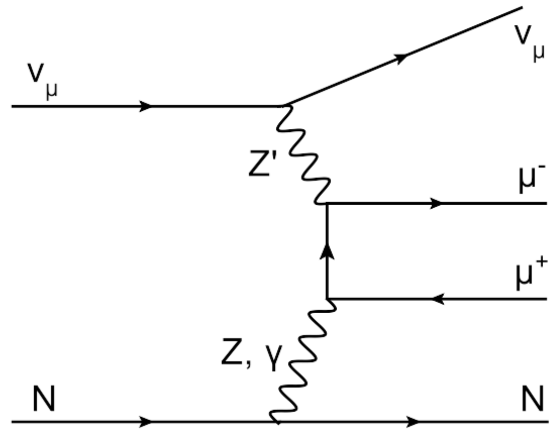




Z' model with UV-complete lepton sector

Requirements

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

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

mass — **interaction** — **mass** — **interaction**

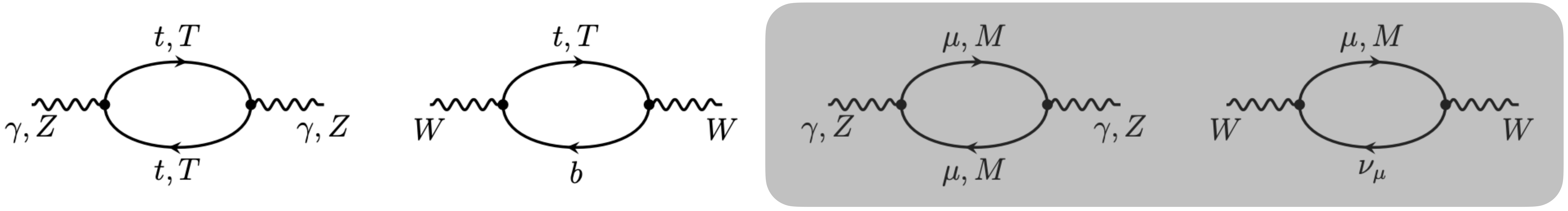
- **Interaction** $\quad s_L = sin\delta_L,\ c_L = cos\delta_L$

$$\mathcal{L}_\gamma^\ell = -e \bar{\mu} \not{A} \mu - e \bar{M} \not{A} M,$$
$$\mathcal{L}_W^\ell = \frac{g}{\sqrt{2}} \left(\hat{c}_L \bar{\mu} \not{W} P_L \nu_\mu + \hat{s}_L \bar{M} \not{W} P_L \nu_\mu \right) + \text{ h.c.}\,,$$
$$\mathcal{L}_Z^\ell = \frac{g}{c_W} \left(\bar{\mu}_L, \bar{M}_L \right) \begin{pmatrix} -\frac{1}{2} \hat{c}_L^2 + s_W^2 & -\frac{1}{2} \hat{s}_L \hat{c}_L \\ -\frac{1}{2} \hat{s}_L \hat{c}_L & -\frac{1}{2} \hat{s}_L^2 + s_W^2 \end{pmatrix} \not{Z} \begin{pmatrix} \mu_L \\ M_L \end{pmatrix} + \frac{g}{c_W} s_W^2 \left(\bar{\mu}_R, \bar{M}_R \right) \not{Z} \begin{pmatrix} \mu_R \\ M_R \end{pmatrix}$$
$$\mathcal{L}_{Z'}^\ell = q_\ell g' \left(\bar{\mu}_L, \bar{M}_L \right) \begin{pmatrix} \hat{c}_L^2 & \hat{s}_L \hat{c}_L \\ \hat{s}_L \hat{c}_L & \hat{s}_L^2 \end{pmatrix} \not{Z}' \begin{pmatrix} \mu_L \\ M_L \end{pmatrix} + (L \to R)$$

$$\boxed{sin\delta_L < 0.01}$$

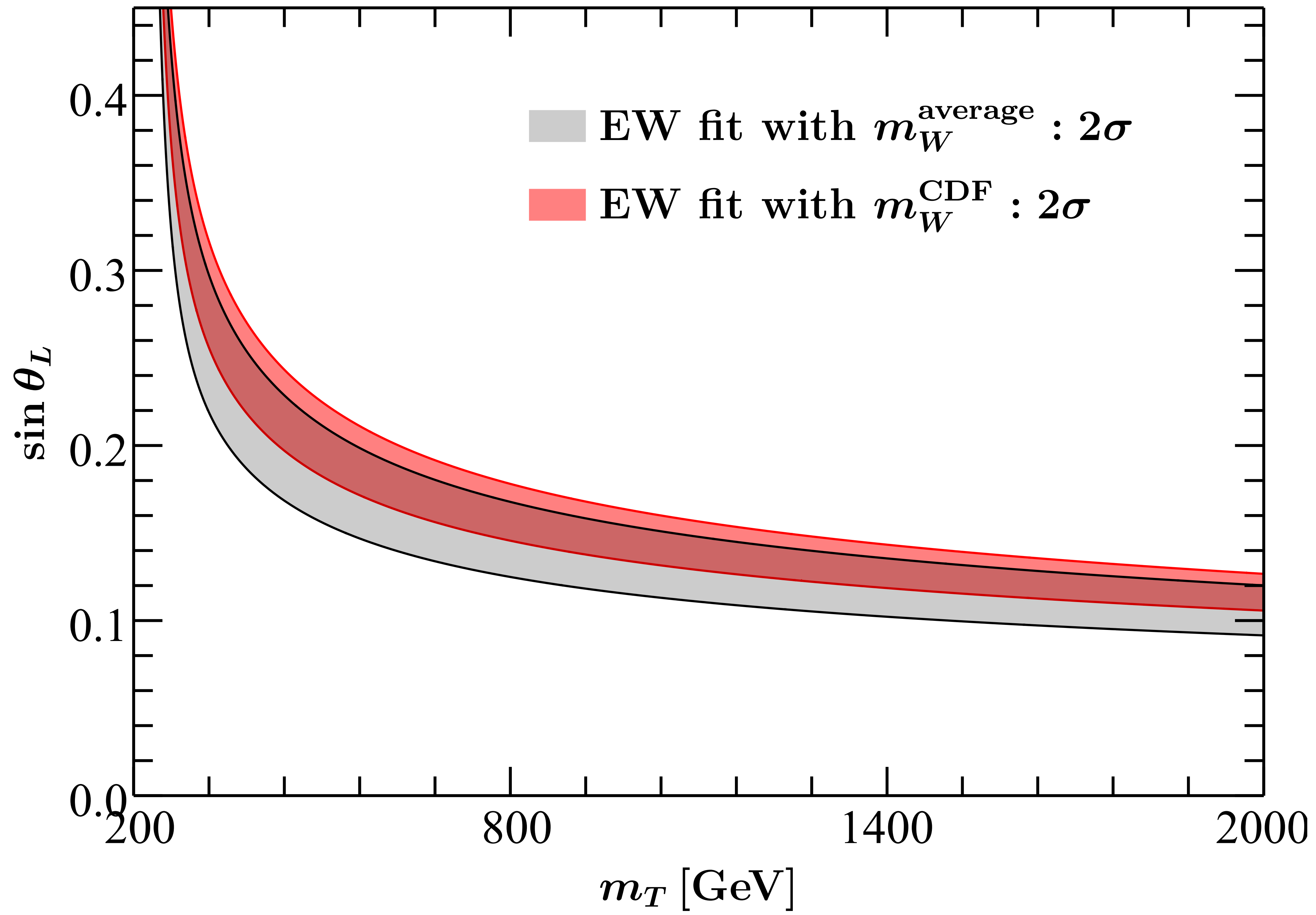
W-boson mass shift

- **Feynman diagrams**



highly suppressed by small δ_L

- **Result**



same with the previous work

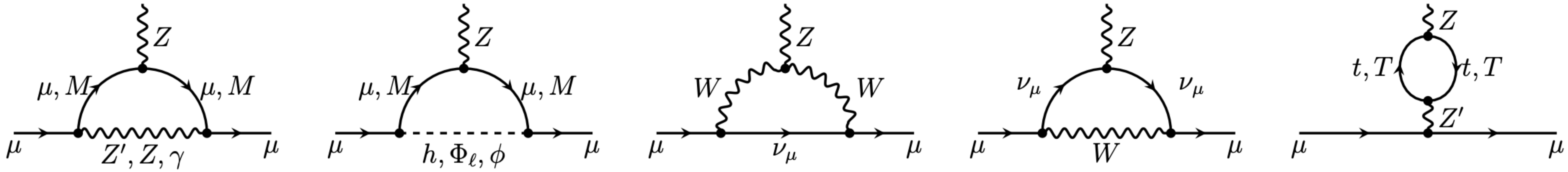
$Z \to \mu^+\mu^-$

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

mass **interaction**

- **Feynman diagrams**

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



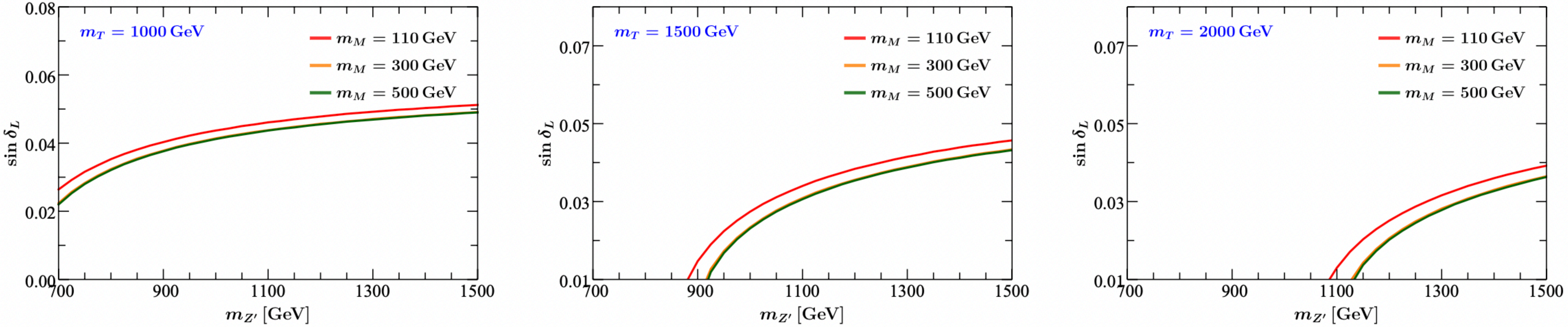
- **Effective couplings**

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

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

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

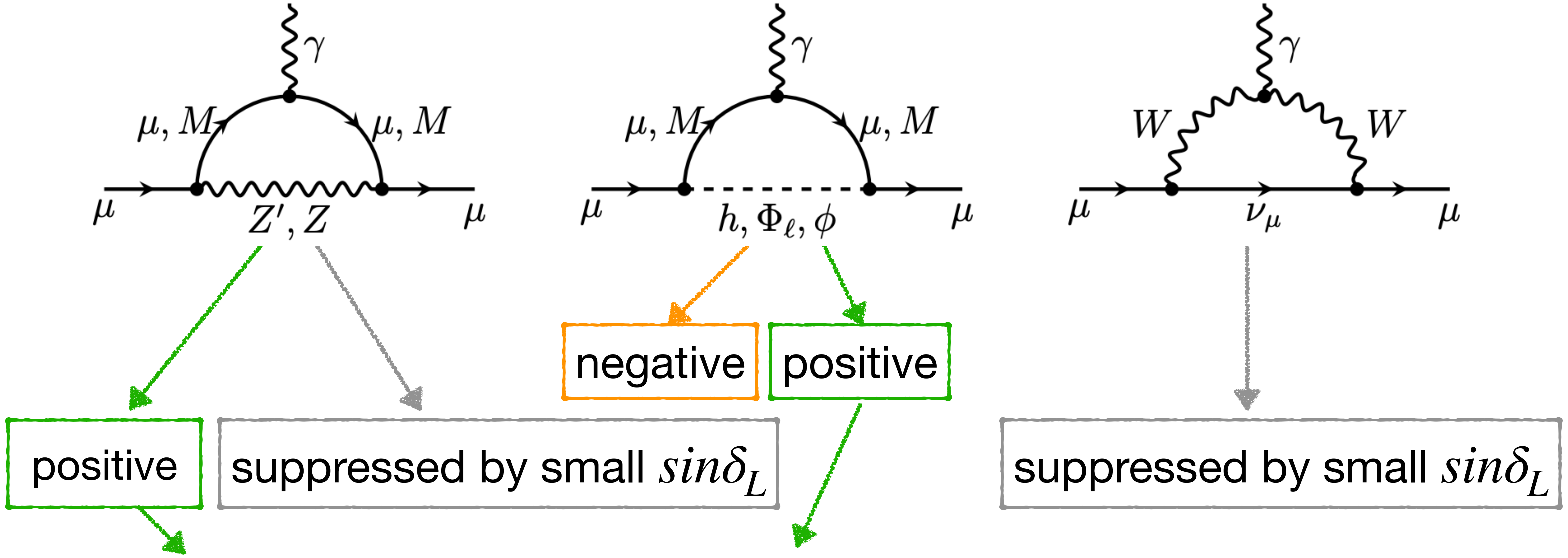
- **Constraints: m_W and $Z \to \mu^+\mu^-$**



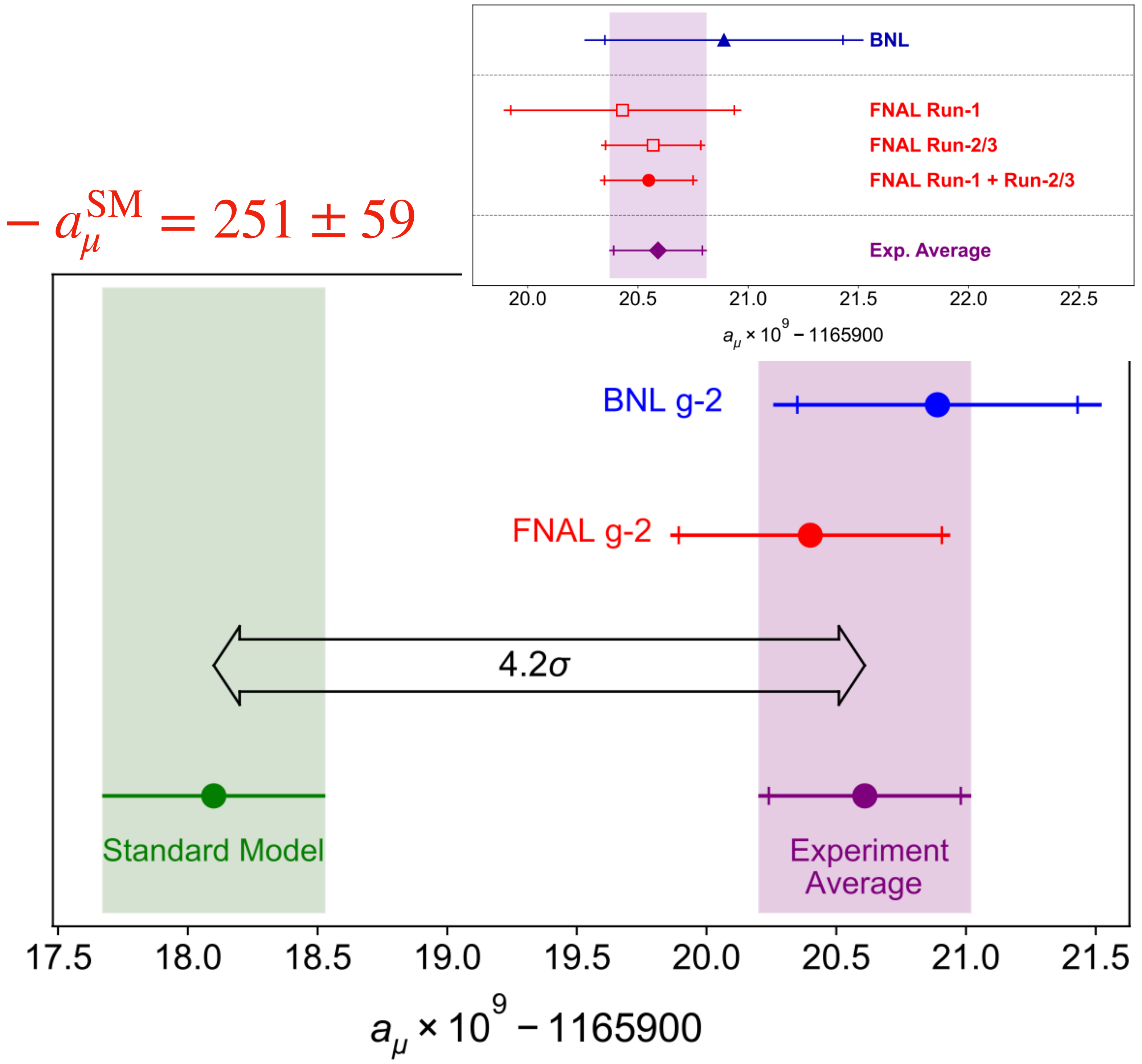
$\sin\delta_L < 0.05$ is obtained. However, $\sin\delta_L < 0.01$ is considered for simplicity.

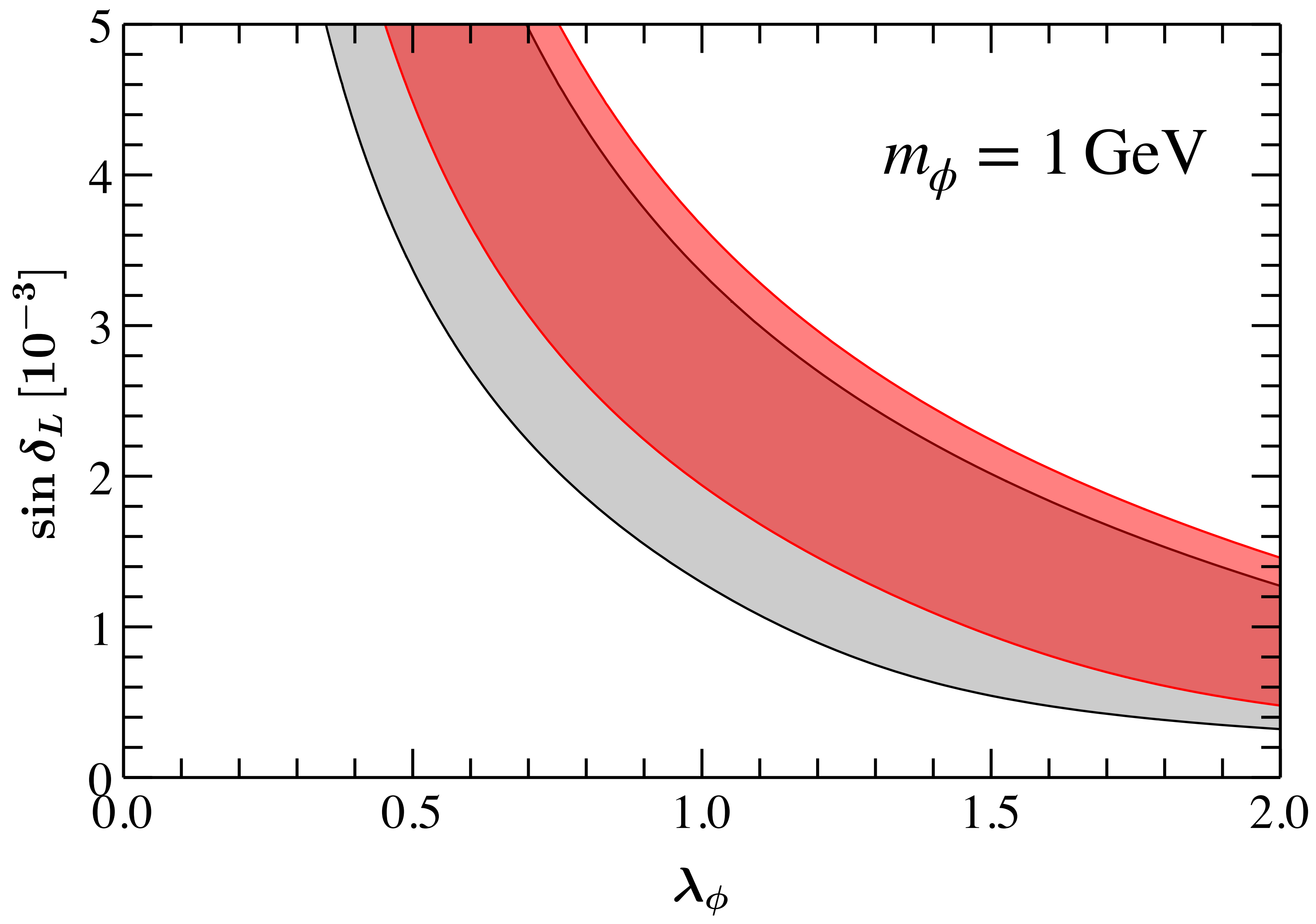
$(g-2)_\mu$

▶ Feynman diagrams



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





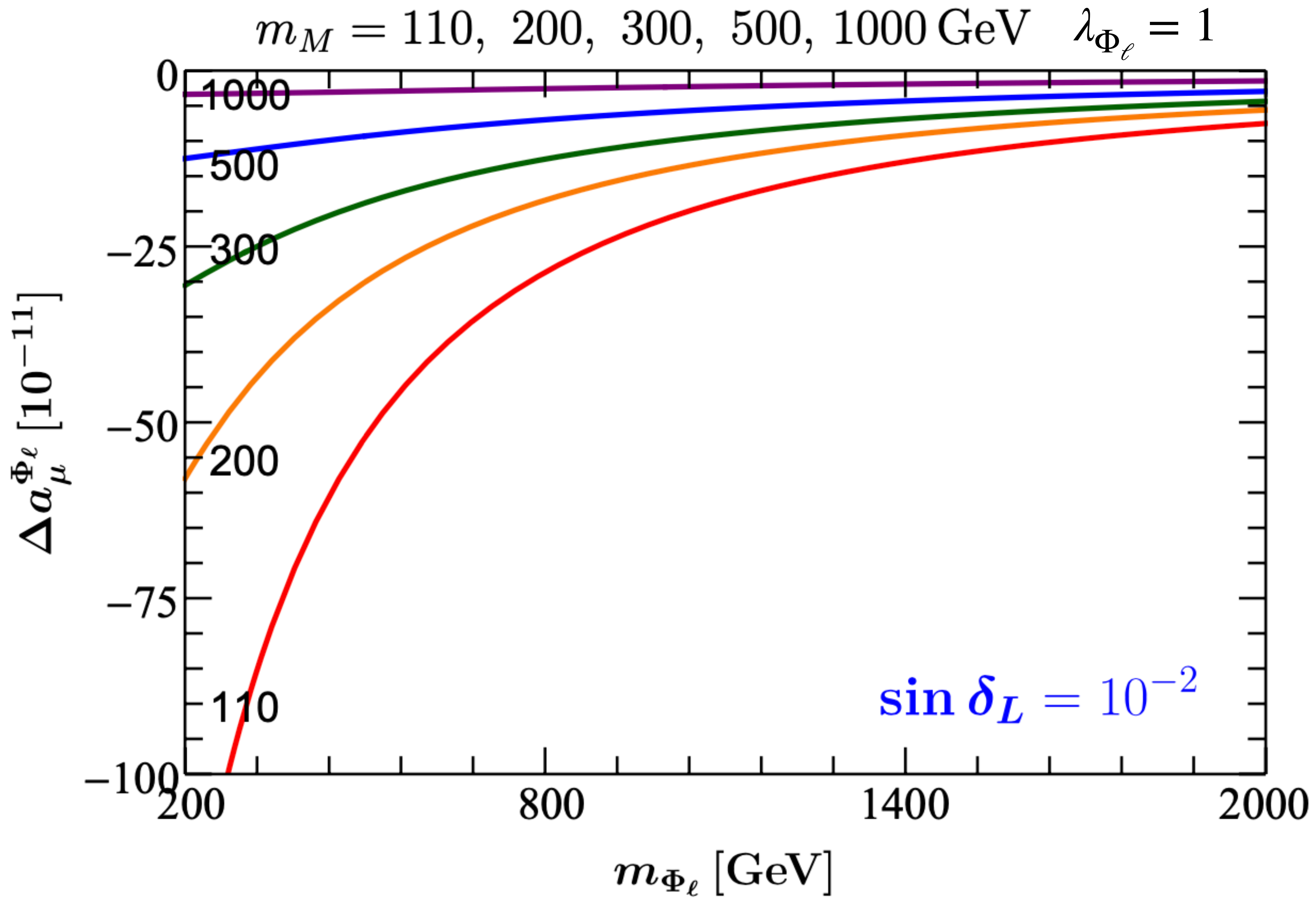
$2\,\sigma$ **allowed region**

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

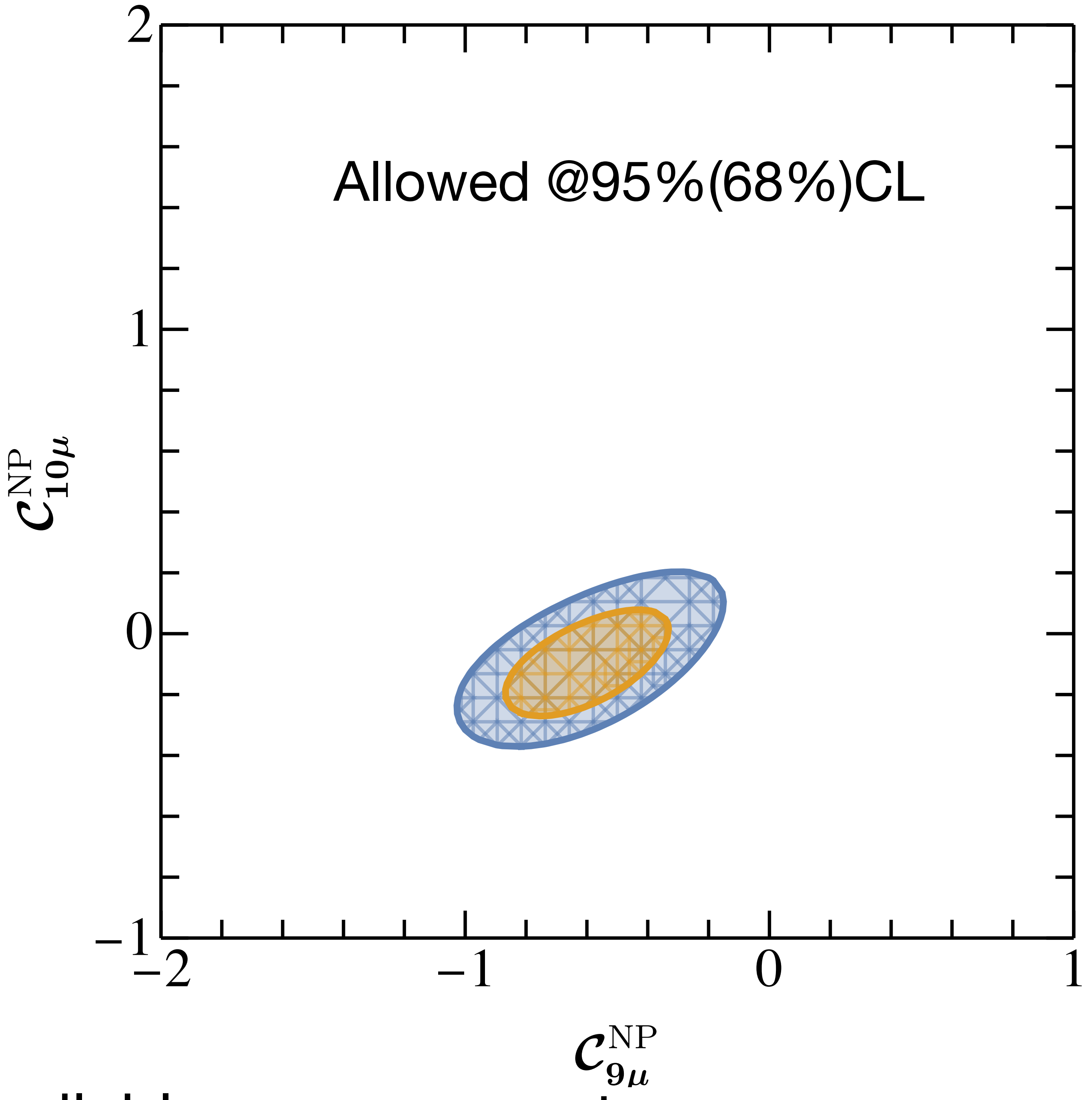
Global fit: $b \to s\ell^+\ell^-$

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

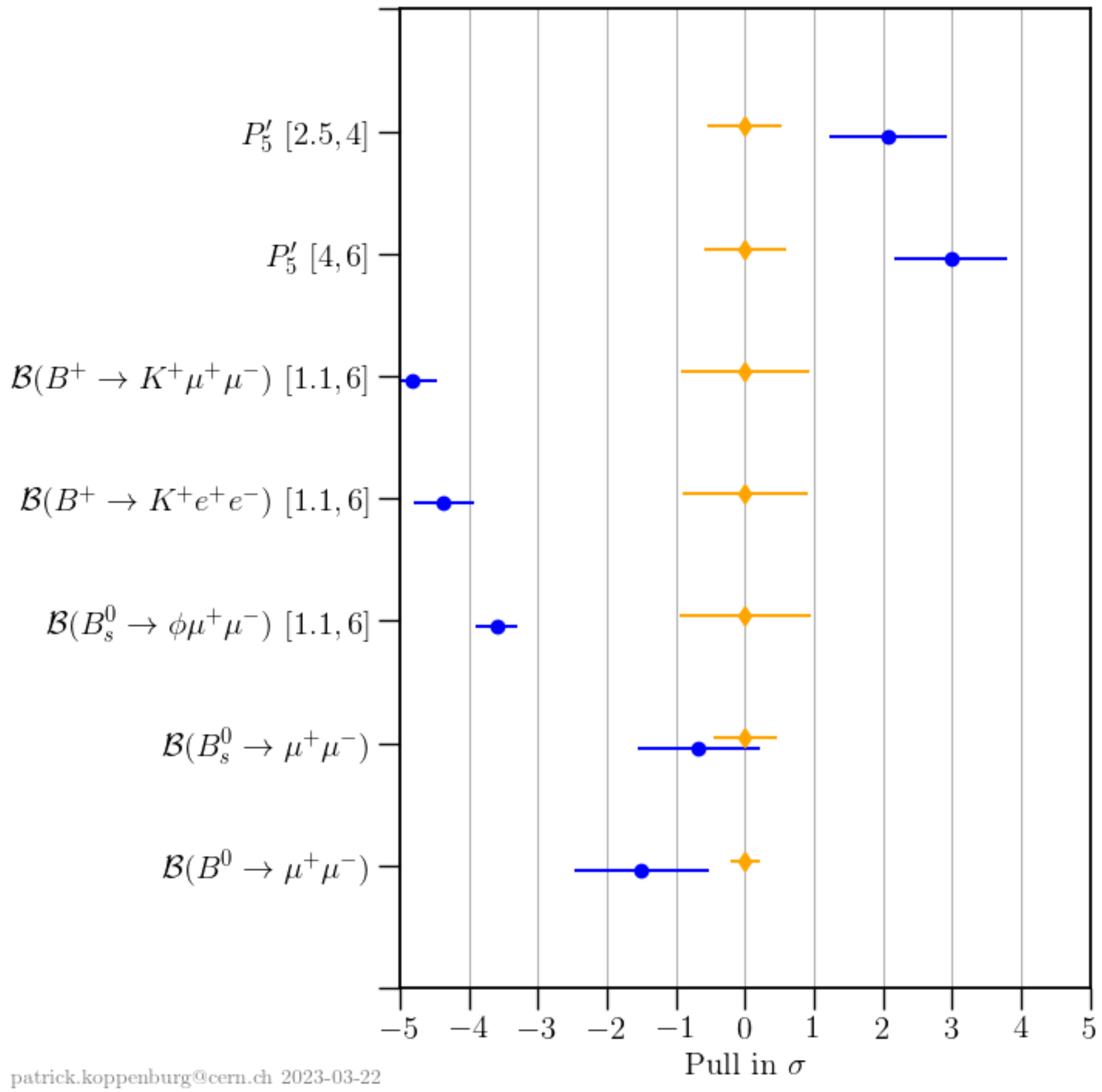
Global fit

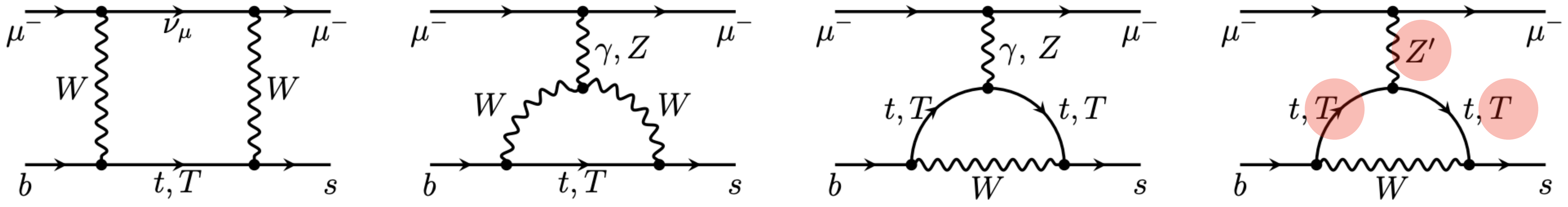
- Inclusive decays
  - $B \to X_s\gamma$
  - $B \to X_s\ell^+\ell^-$
- Exclusive leptonic decays
  - $B_{s,d} \to \ell^+\ell^-$
- Exclusive radiative/semileptonic decays
  - $B \to K^*\gamma$
  - $B^{(0,+} \to K^{(0,+)}\ell^+\ell^-$
  - $B^{(0,+} \to K^{*(0,+)}\ell^+\ell^-$
  - $B_s \to \phi\mu^+\mu^-$
  - $\Lambda_b \to \Lambda\mu^+\mu^-$
- 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





dominated

CMS and LHCb's new measurements included

Global constraints

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

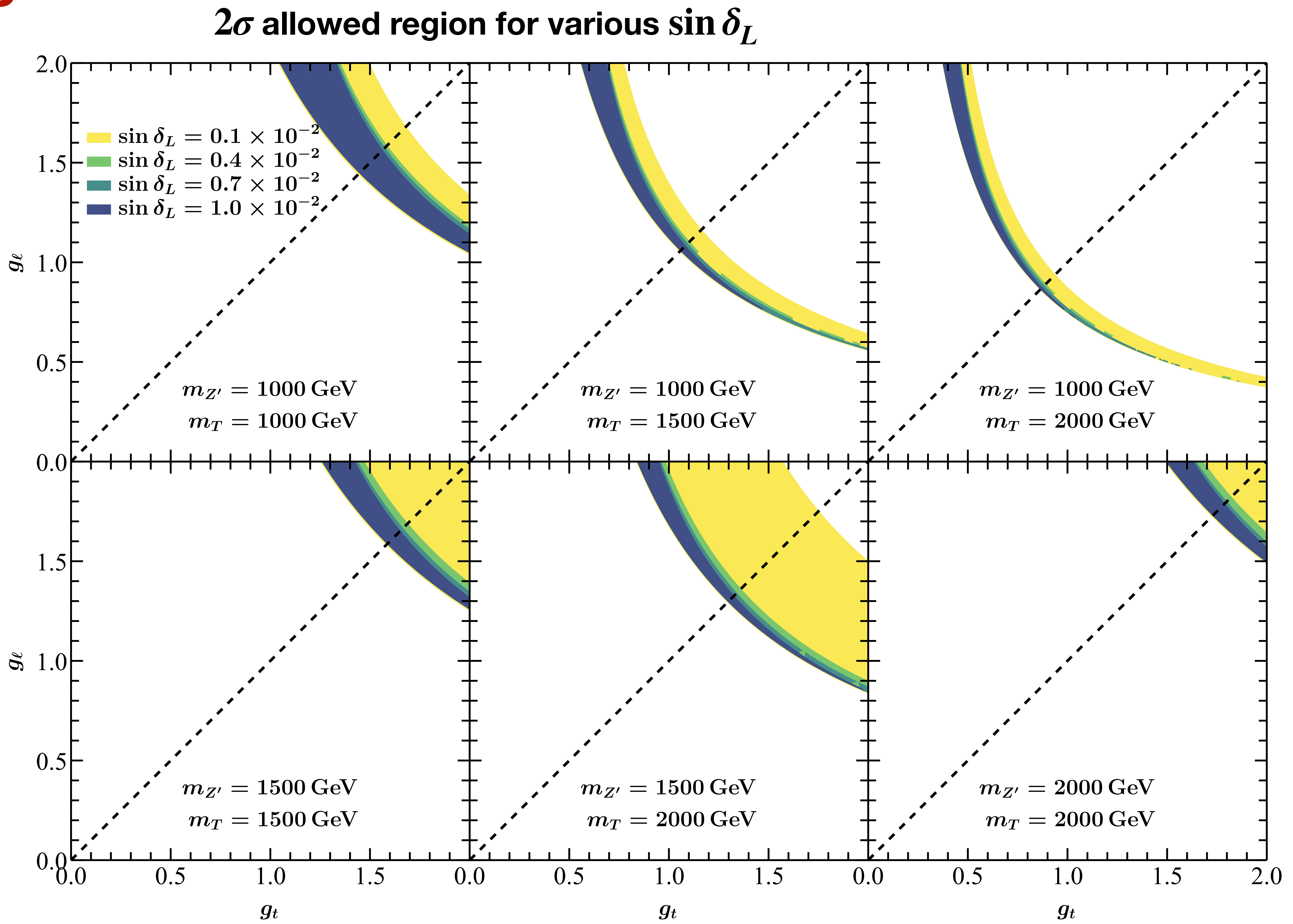
- Fixed parameters

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

- Free parameters

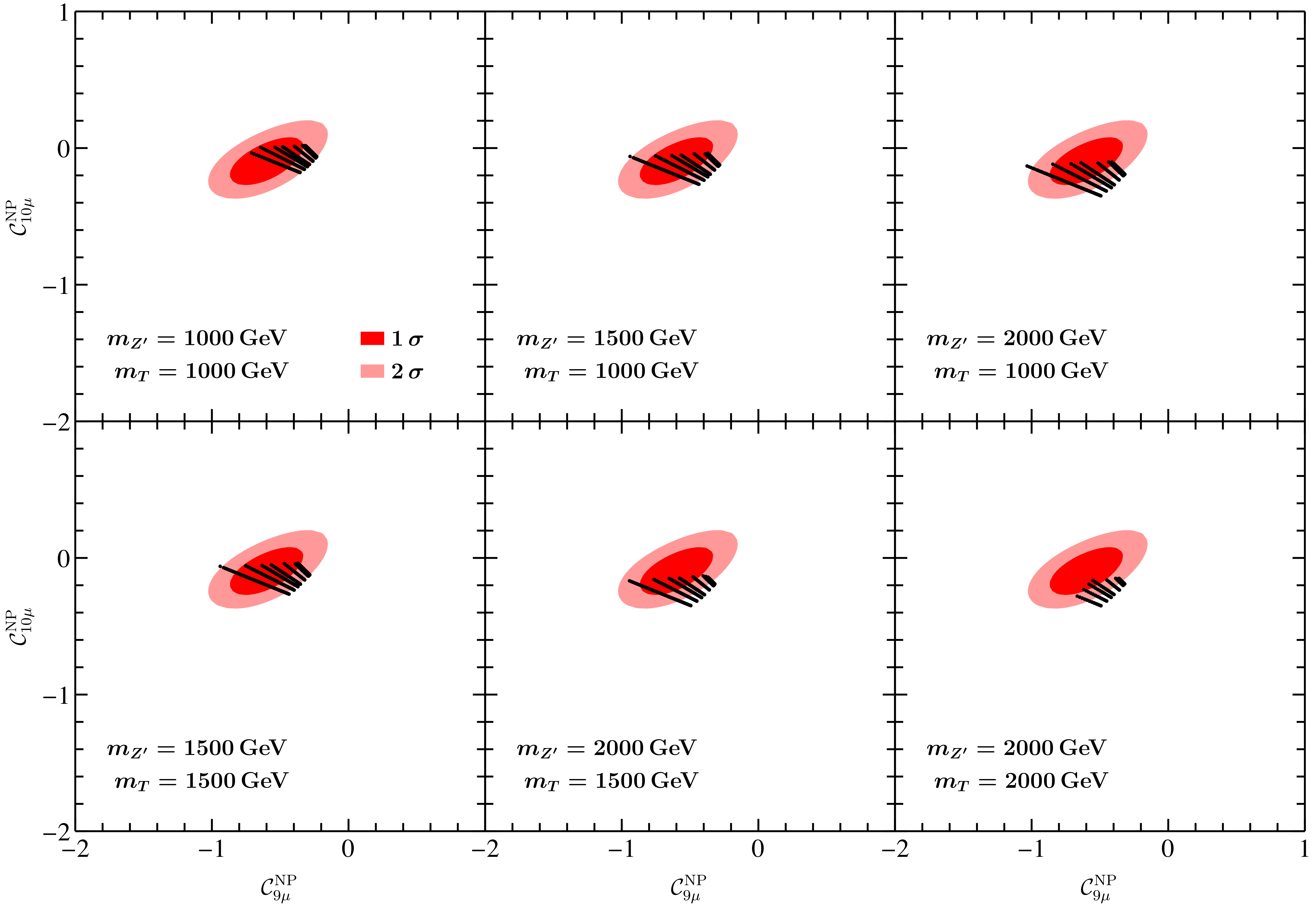
$$(m_T, \sin\theta_L, m_M, \sin\delta_L, m_{Z'}, g_t, g_\ell)$$

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



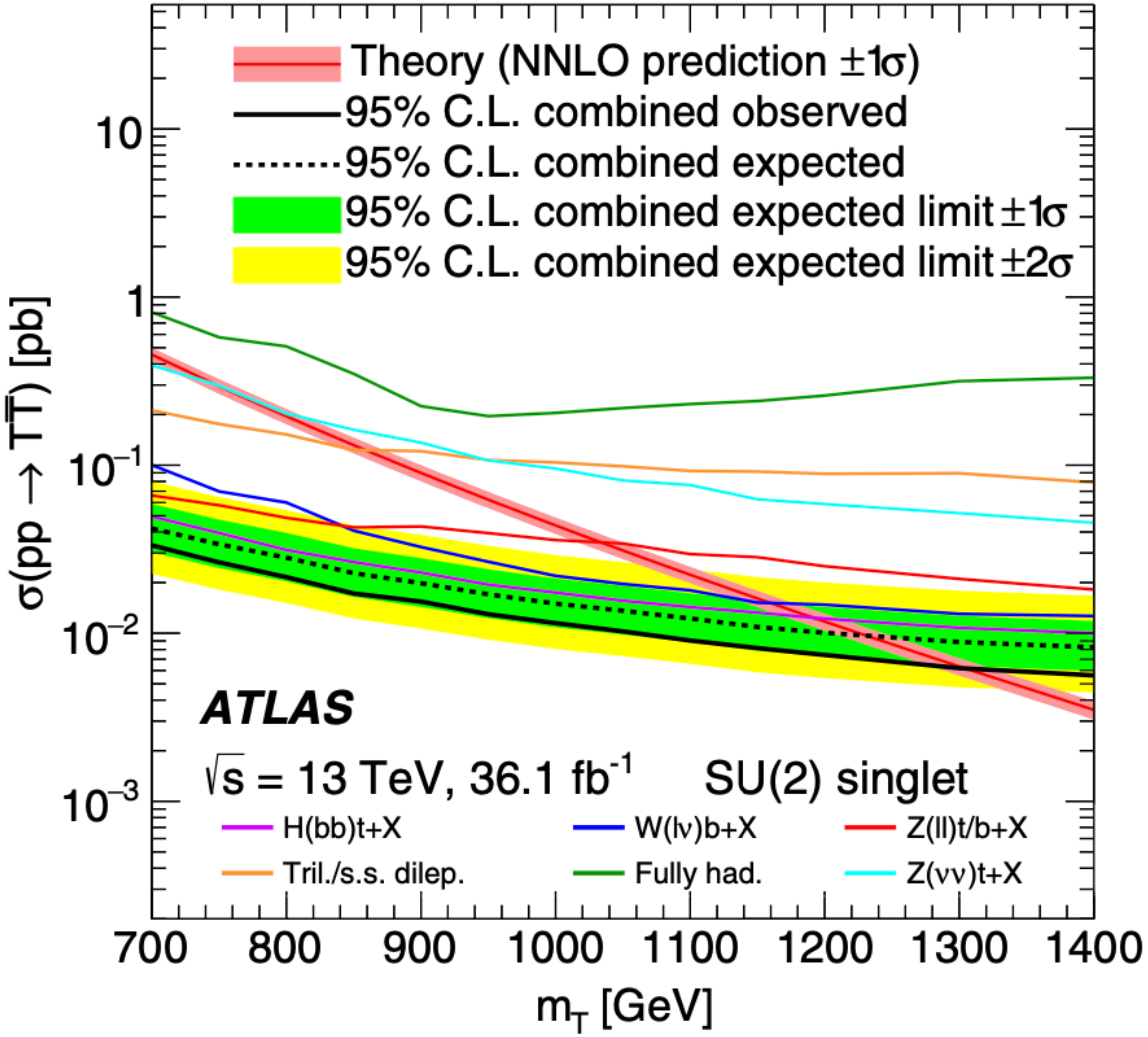
Predictions on (C_9, C_{10}) in $b \to s\ell^+\ell^-$

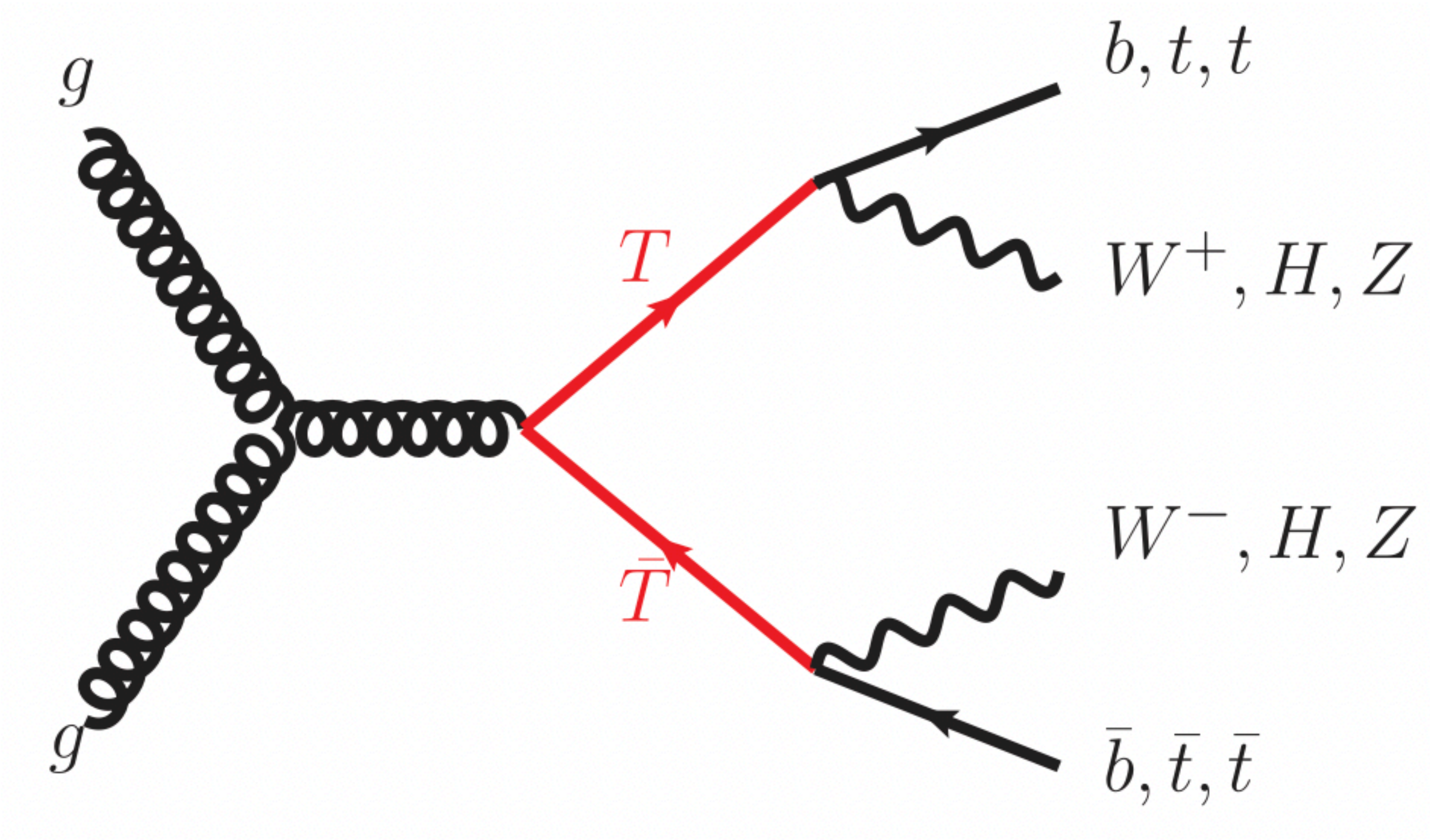
predictions shown in the black points



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

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



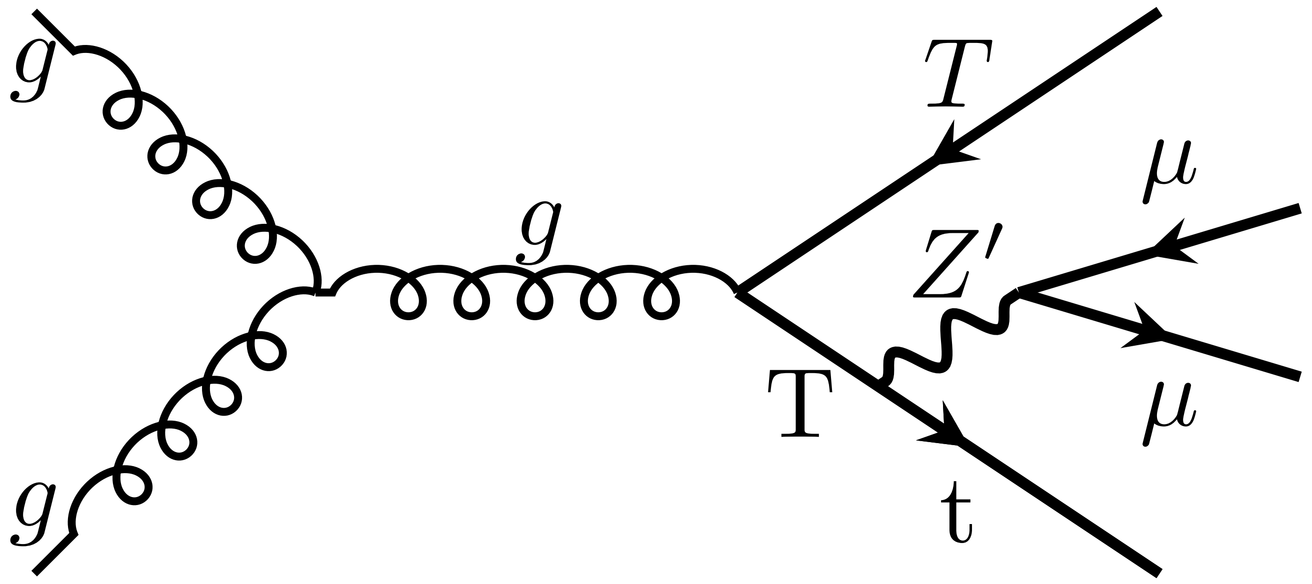


$\boldsymbol{m_T > 1.3\,\mathrm{TeV}}$

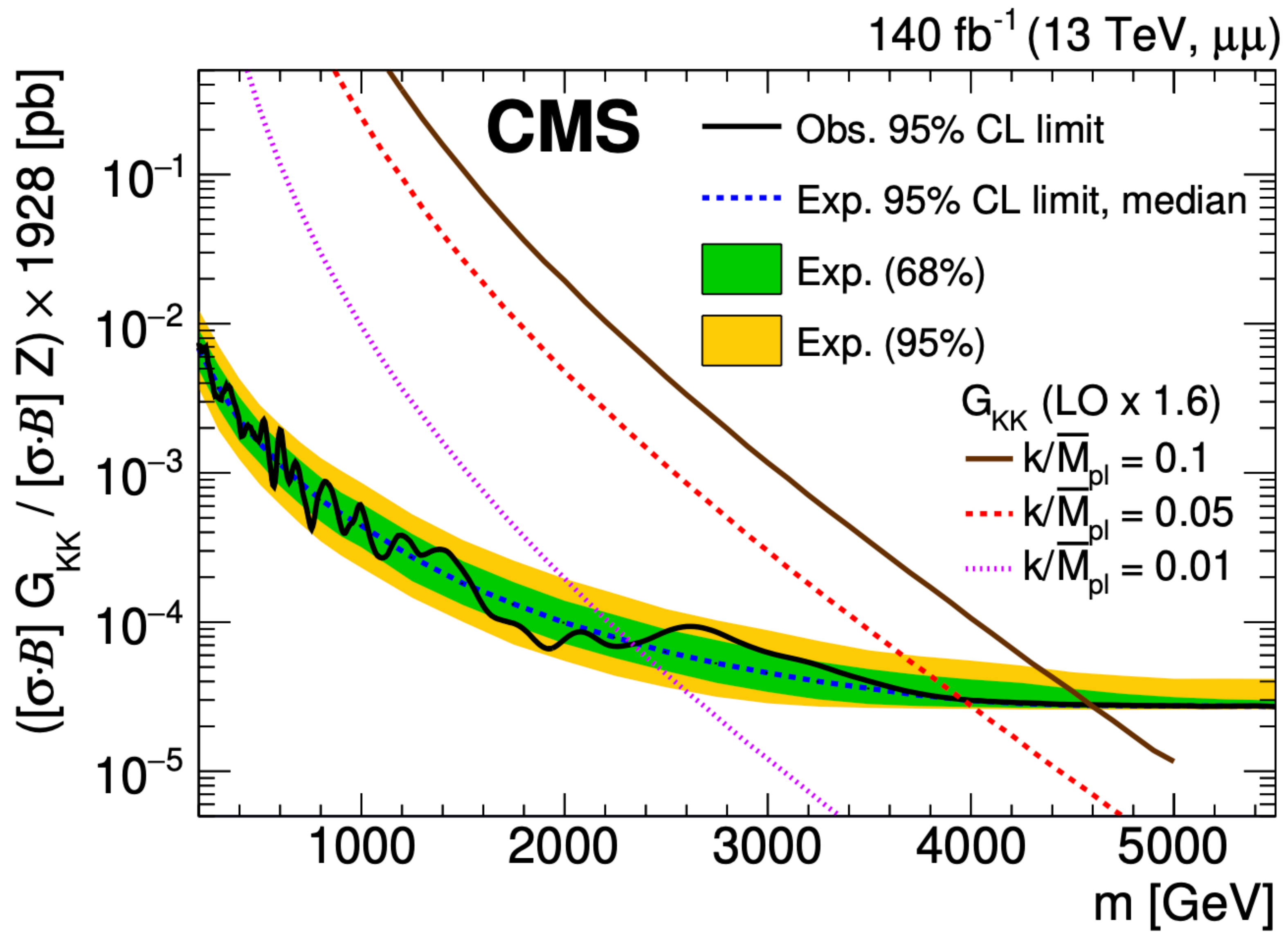
same with the regular top partner scenarios

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

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



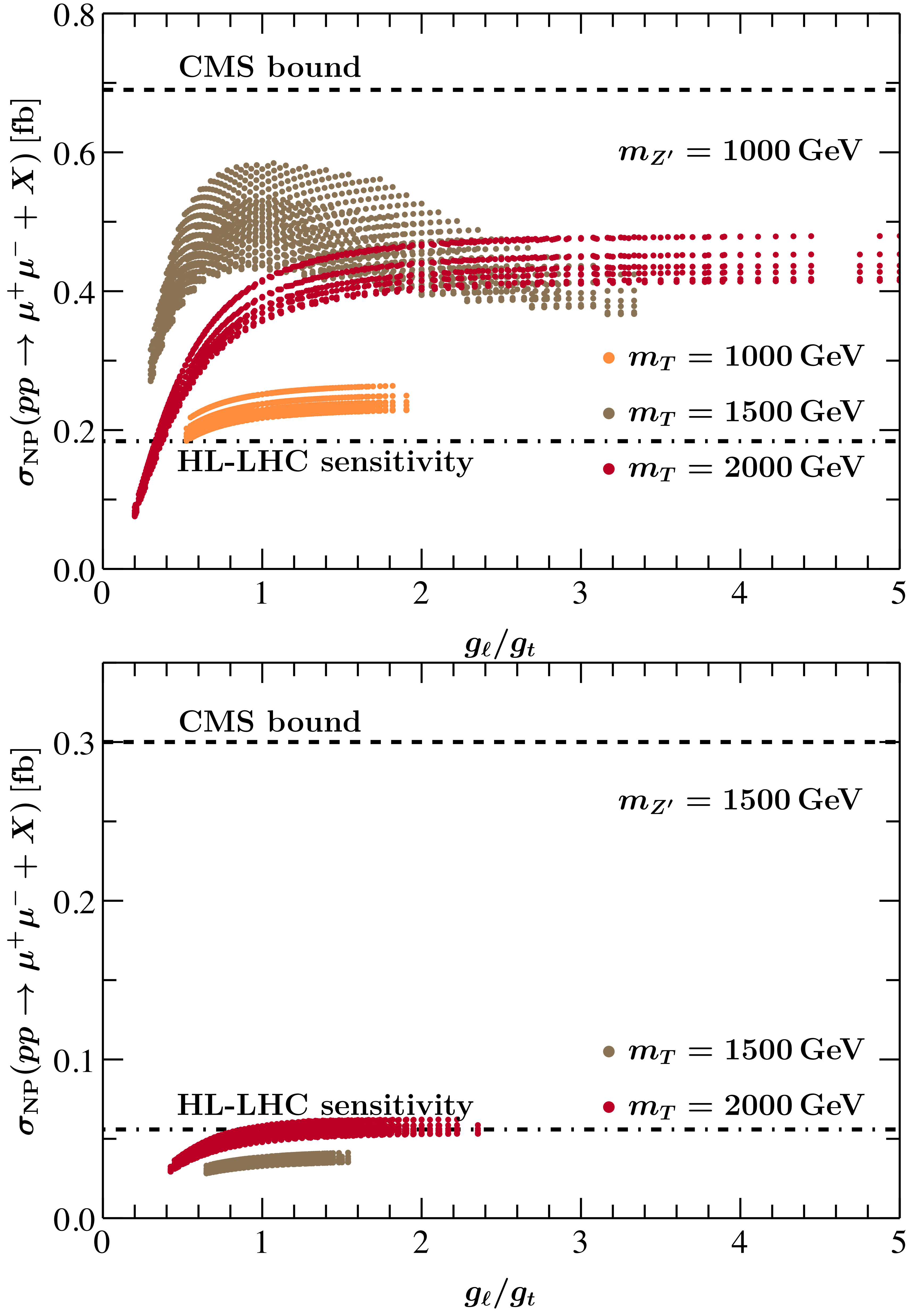
$\sigma(pp \to T\bar{T}) \cdot 2 \cdot \mathcal{B}(T \to tZ') \cdot \mathcal{B}(Z' \to \mu^+\mu^-)$



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

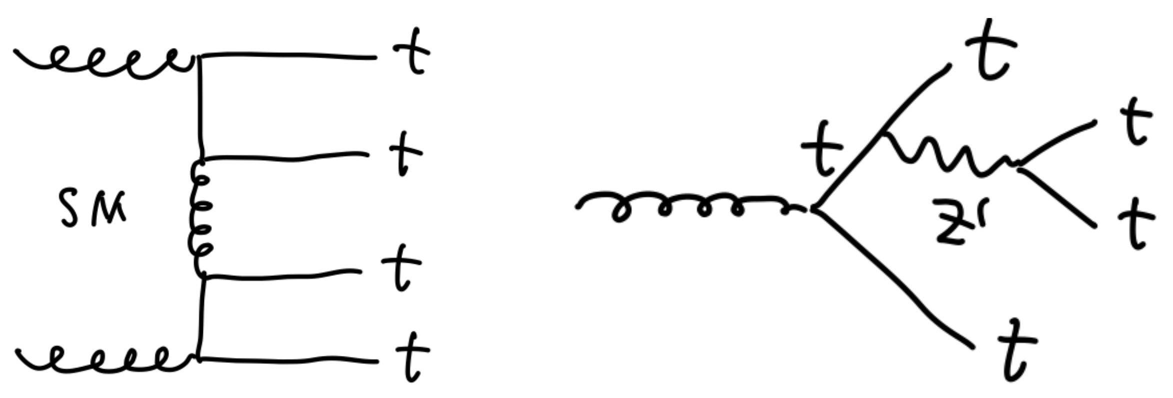
$T \to tZ, tZ', bW, th$

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



Collider Searches

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



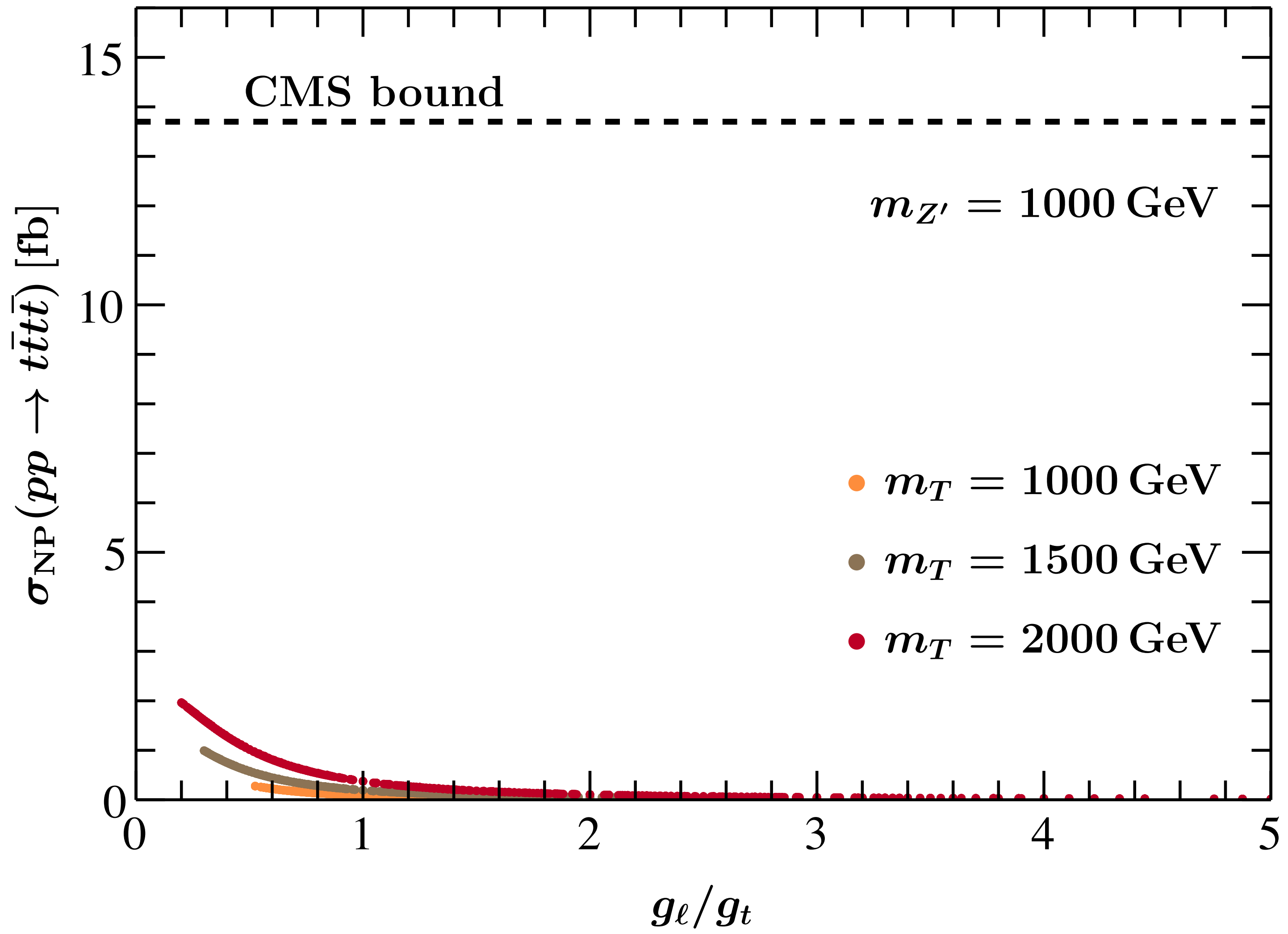
$$\sigma_{\rm exp} = 12.6^{+5.8}_{-5.2}\,{\rm fb}$$

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

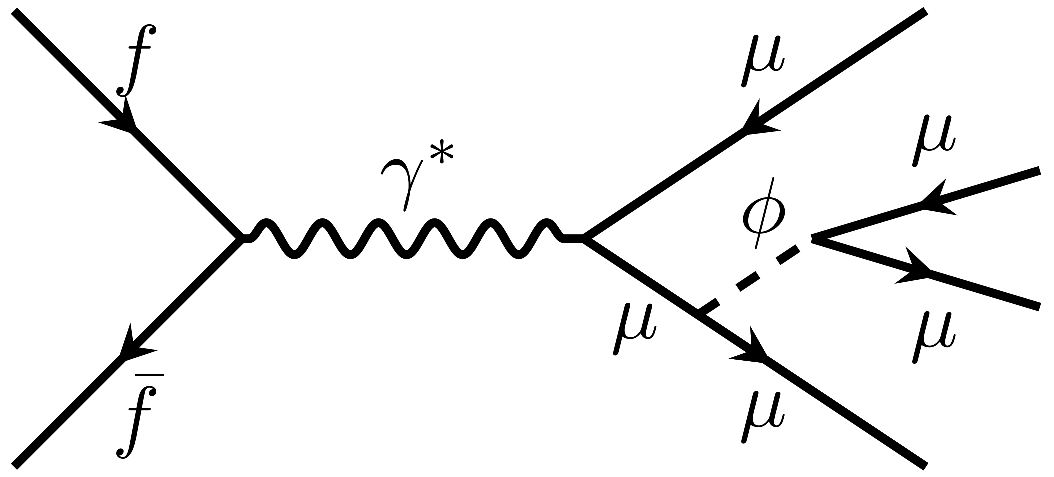
$$\sigma_{\rm NLO} = 12.0^{+2.2}_{-2.5}\,{\rm fb}$$

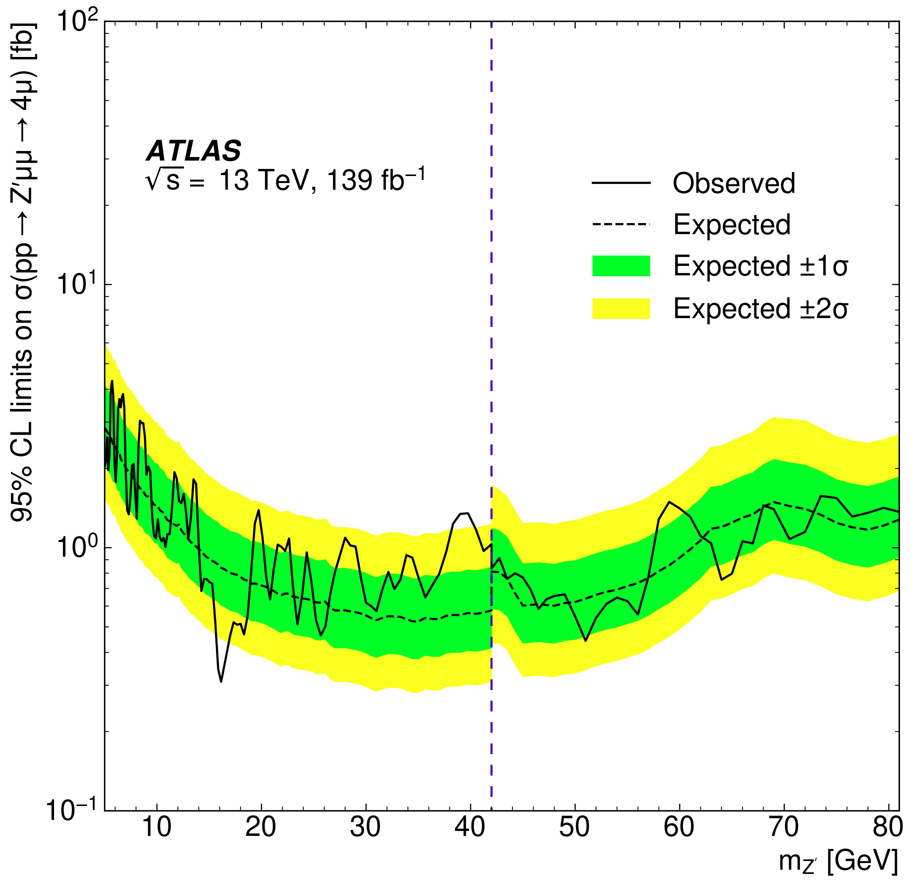
Frederix, D. Pagani, M. Zaro 1711.02116

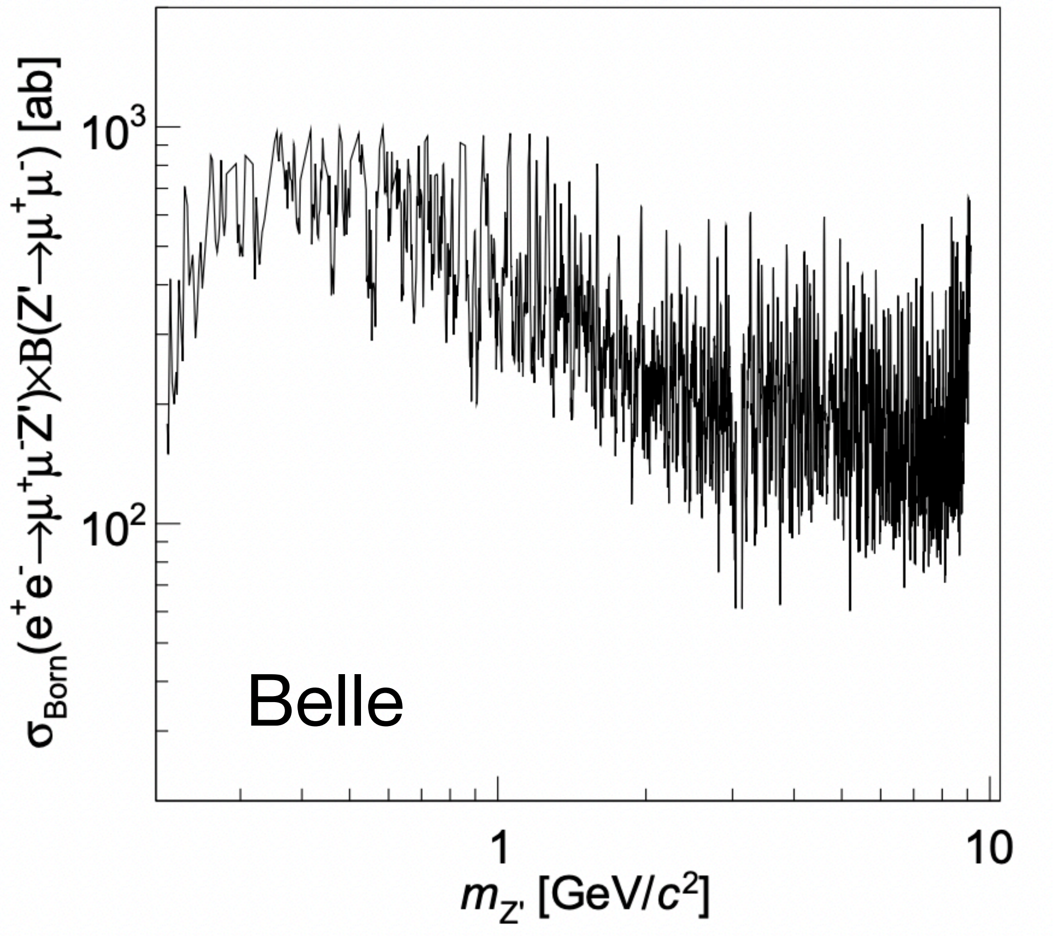
$$\sigma(pp \to t\bar{t}Z') \cdot \mathcal{B}(Z' \to t\bar{t})$$

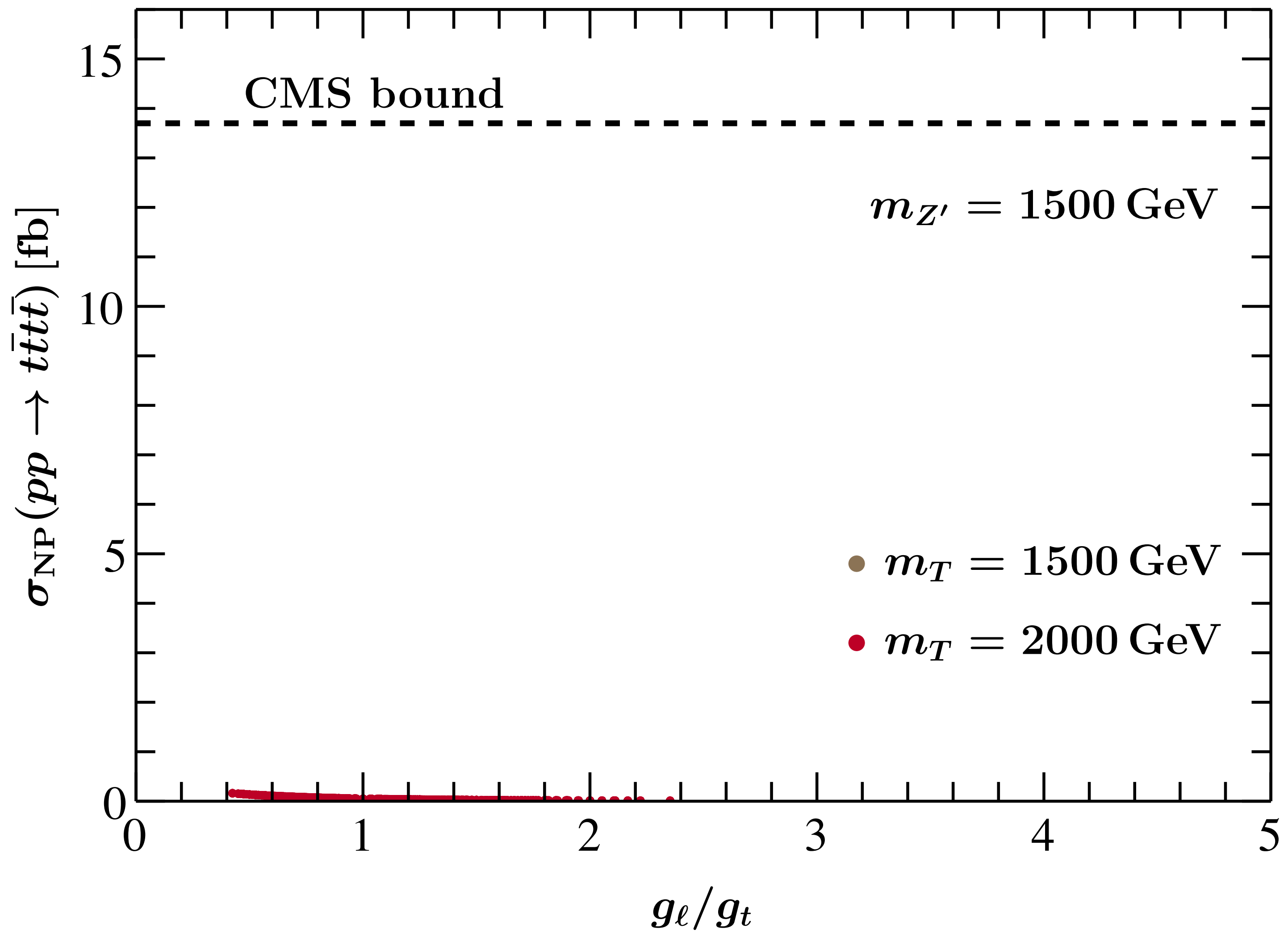


$e^+e^-(pp) \to \mu^+\mu^-\mu^+\mu^-$









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

can be searched for at BES, 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 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
- Z' contributions to the global EW fit is not included
- Naturalness from the top partner not discussed J. Berger, J. Hubisz and M. Perelstein, arXiv: 1205.0013

Future works

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

Thank You !