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

Xing-Bo Yuan (袁兴博)

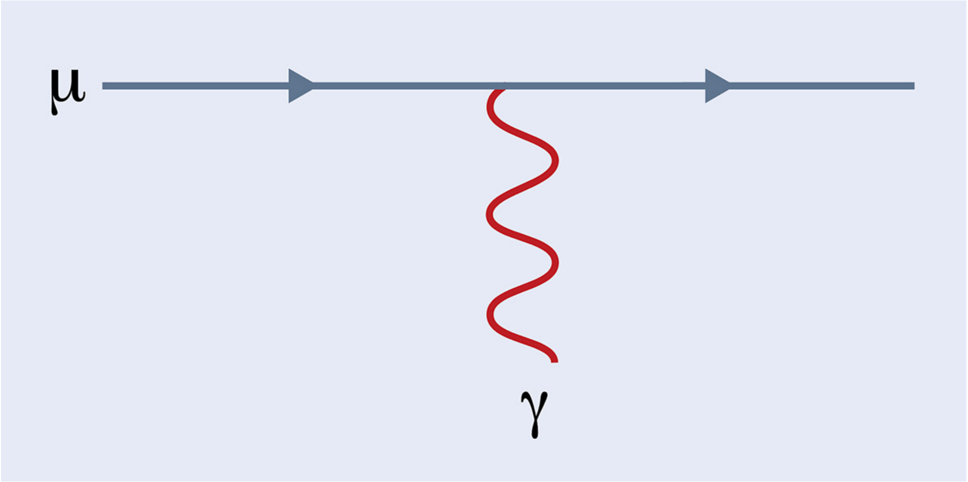
Central China Normal University (华中师范大学)

arXiv: 2205.02205, 2307.05290, 李新强，谢泽浚，杨亚东，袁兴博

$(g-2)_\mu$

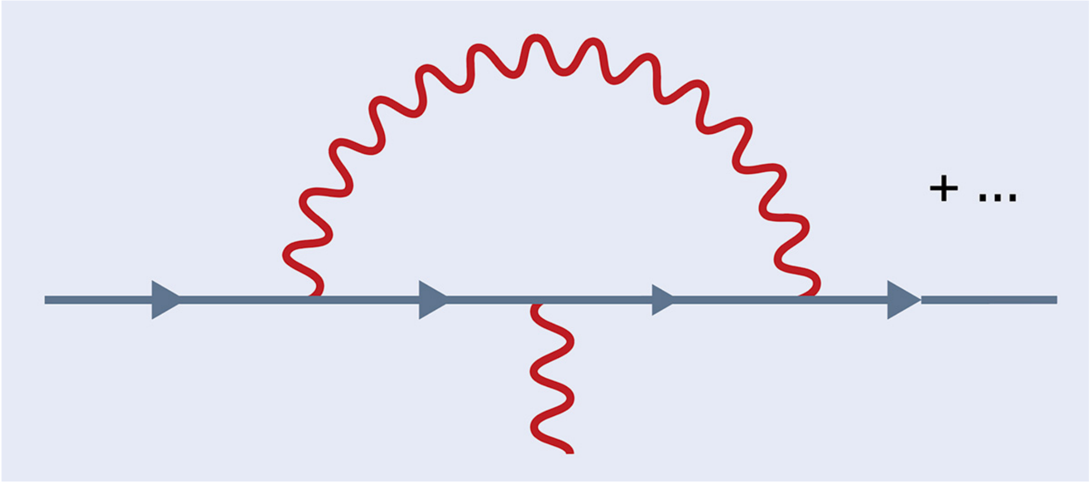
$a_\mu = (g-2)/2$

$g = 2$



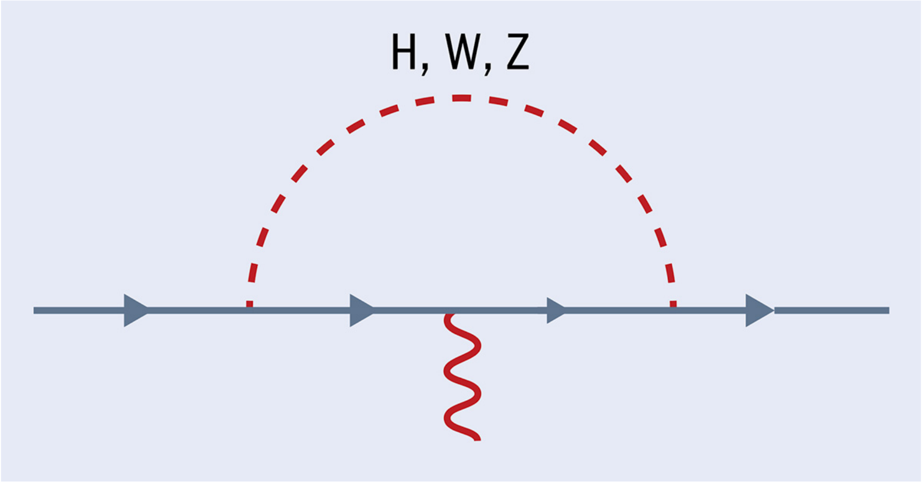
Bohr magneton

QED



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

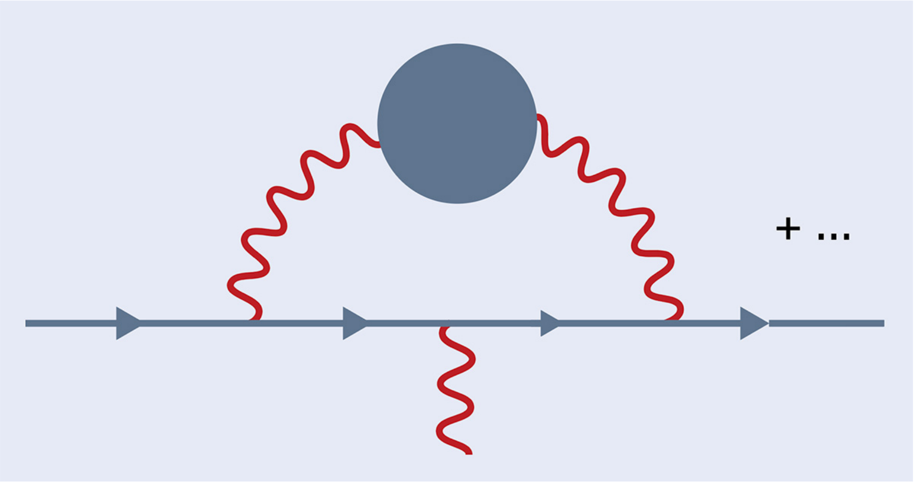
Electro-Weak



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

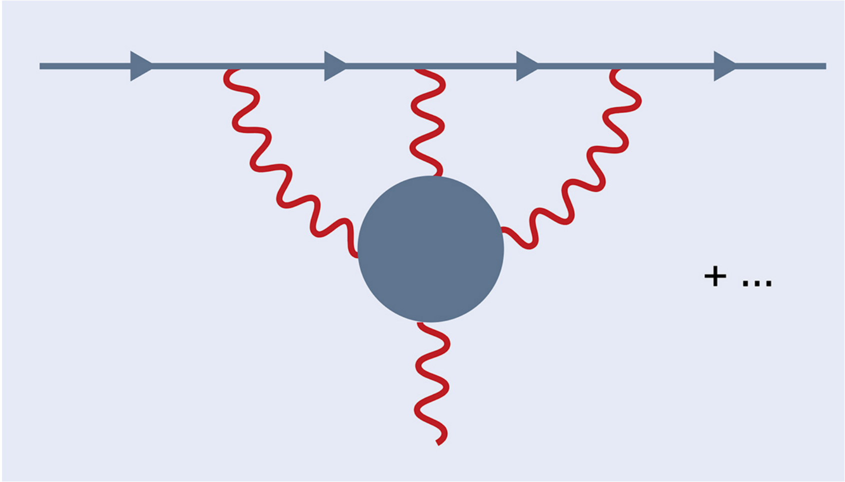
unit: 10^{-11}

hadronic vacuum polarisation



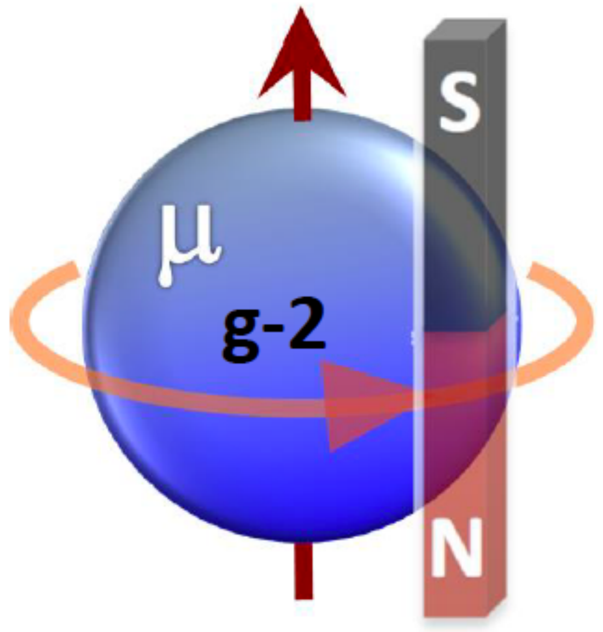
$a_\mu^{\mathrm{HVP}} \times 10^{11}$	LO	NLO	NNLO
e^+e^- data	6931 ± 40	−98 ± 7	12 ± 1
Lattice QCD	7116 ± 184		

Hadronic light-by-light scattering

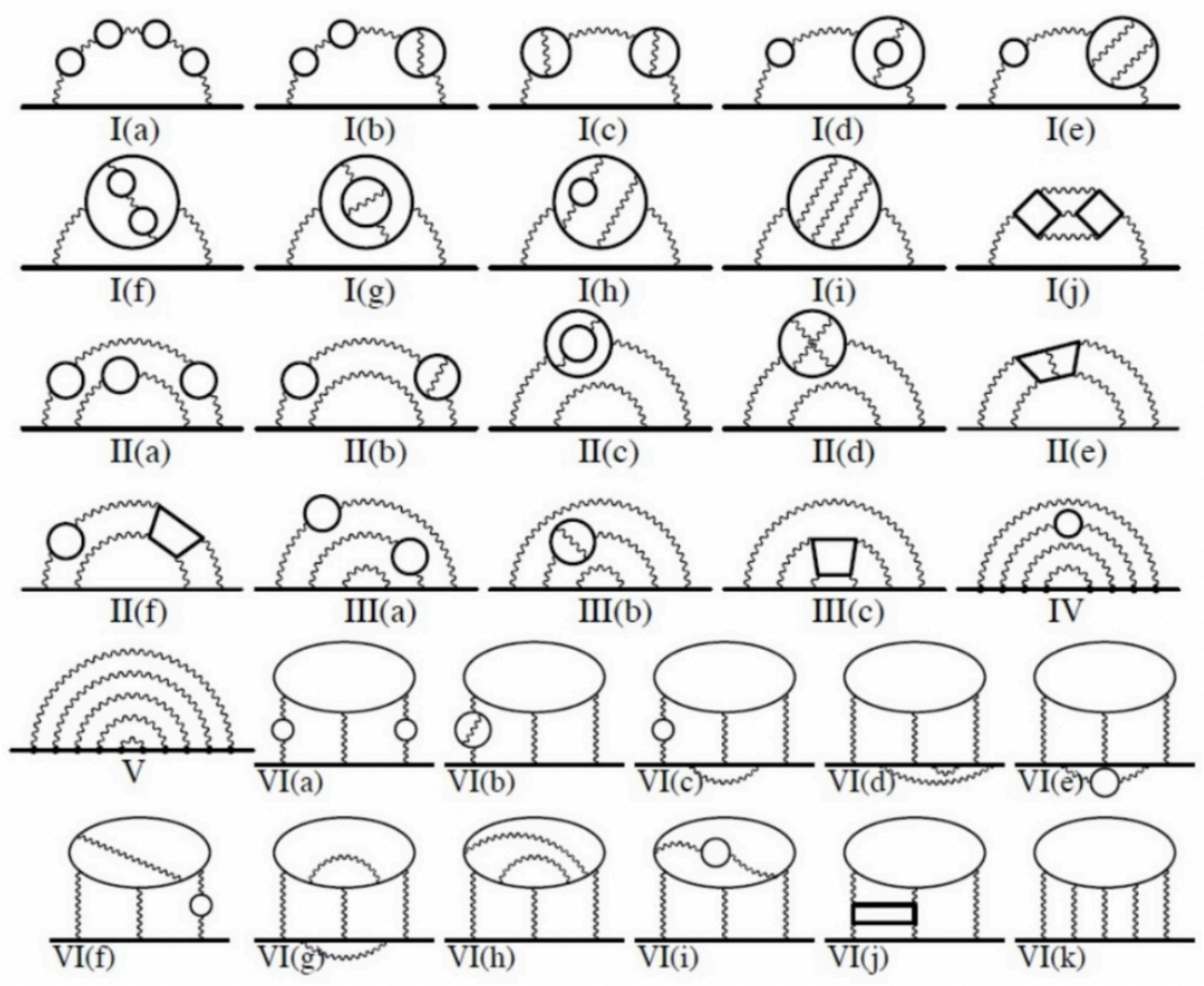


$a_\mu^{\mathrm{HLbL}} \times 10^{11}$	LO	NLO
Phenomenology	92 ± 19	2 ± 1
Lattice QCD	79 ± 35	

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



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



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

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

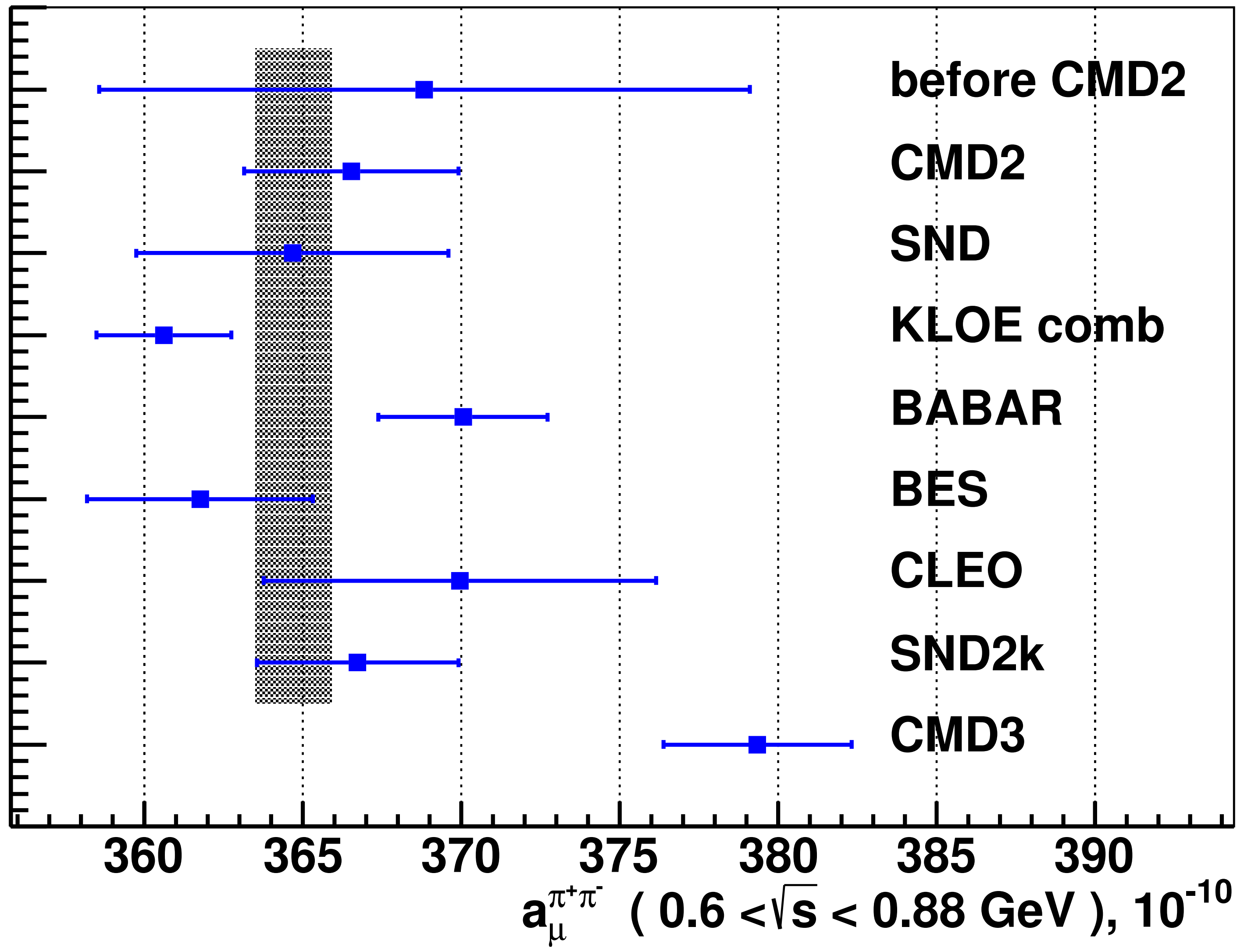
12000+ Feynman diagrams

Analytical calculation @ α^2, α^3

Partly analytical @ α^4

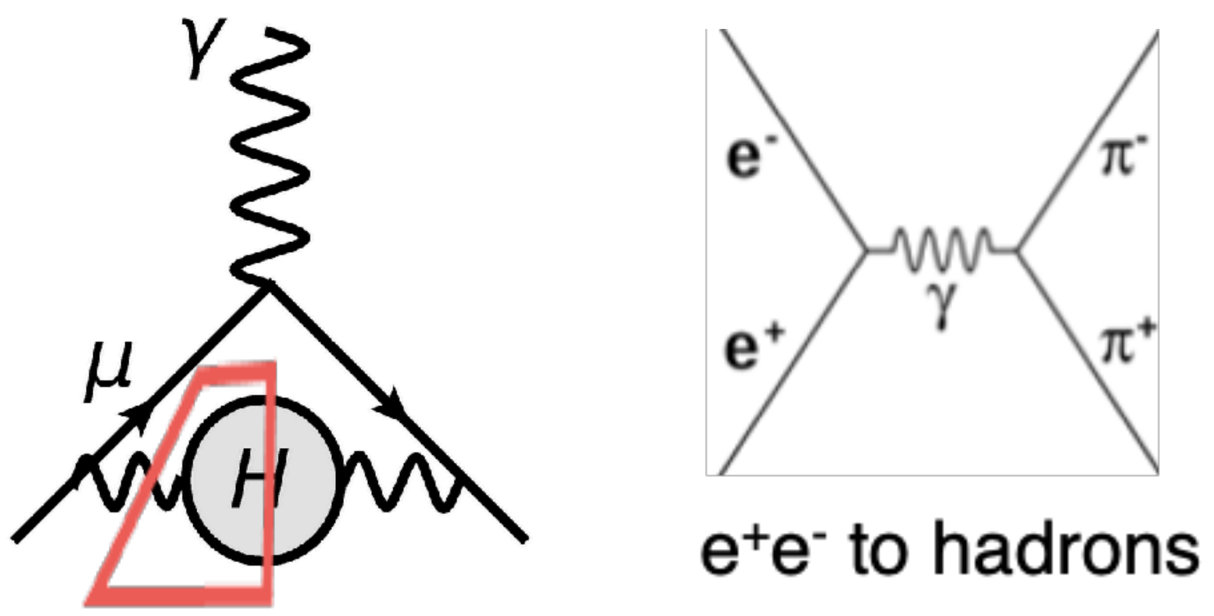
Numerical @ α^5

$(g-2)_\mu$

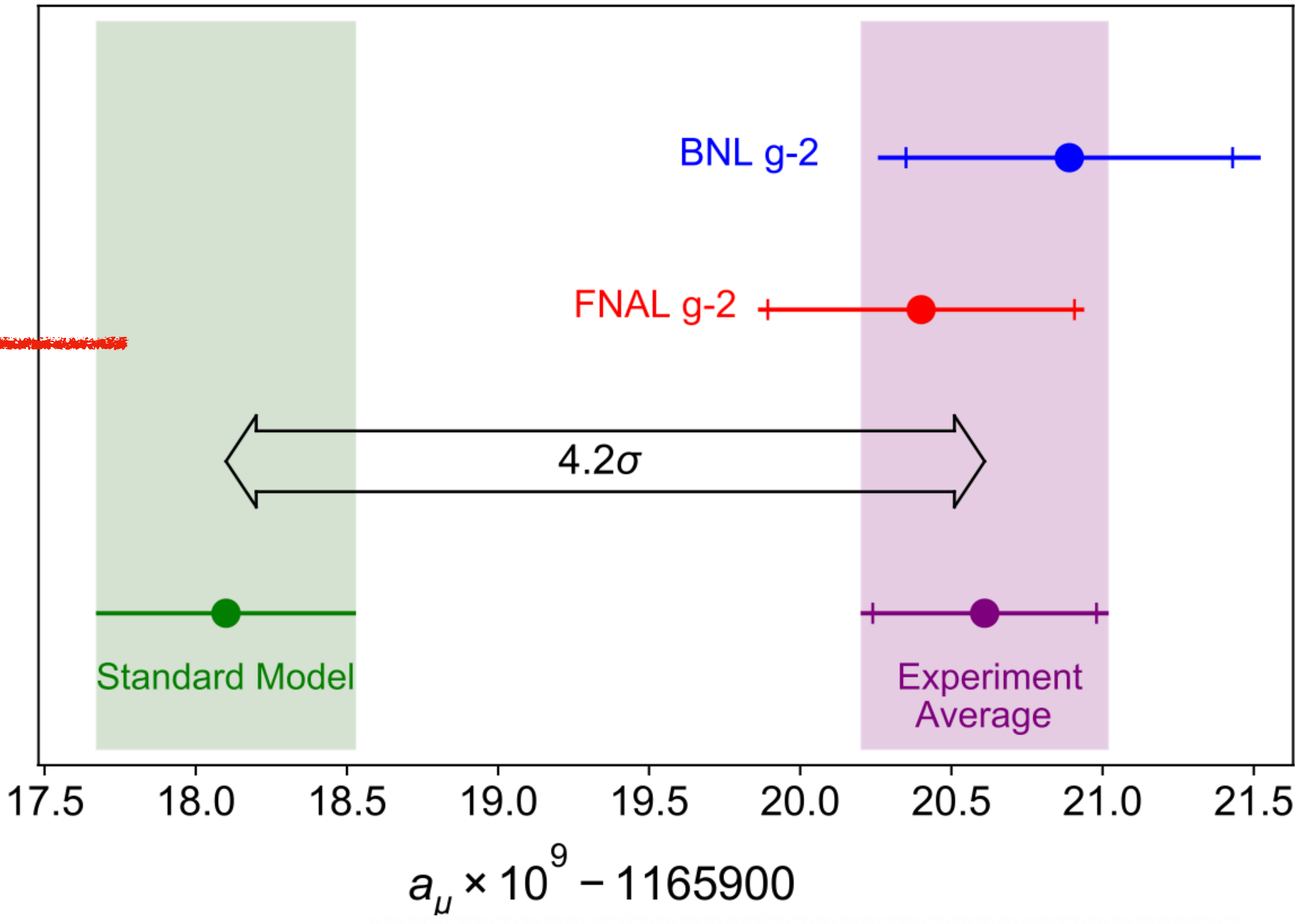


Data-driven

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



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



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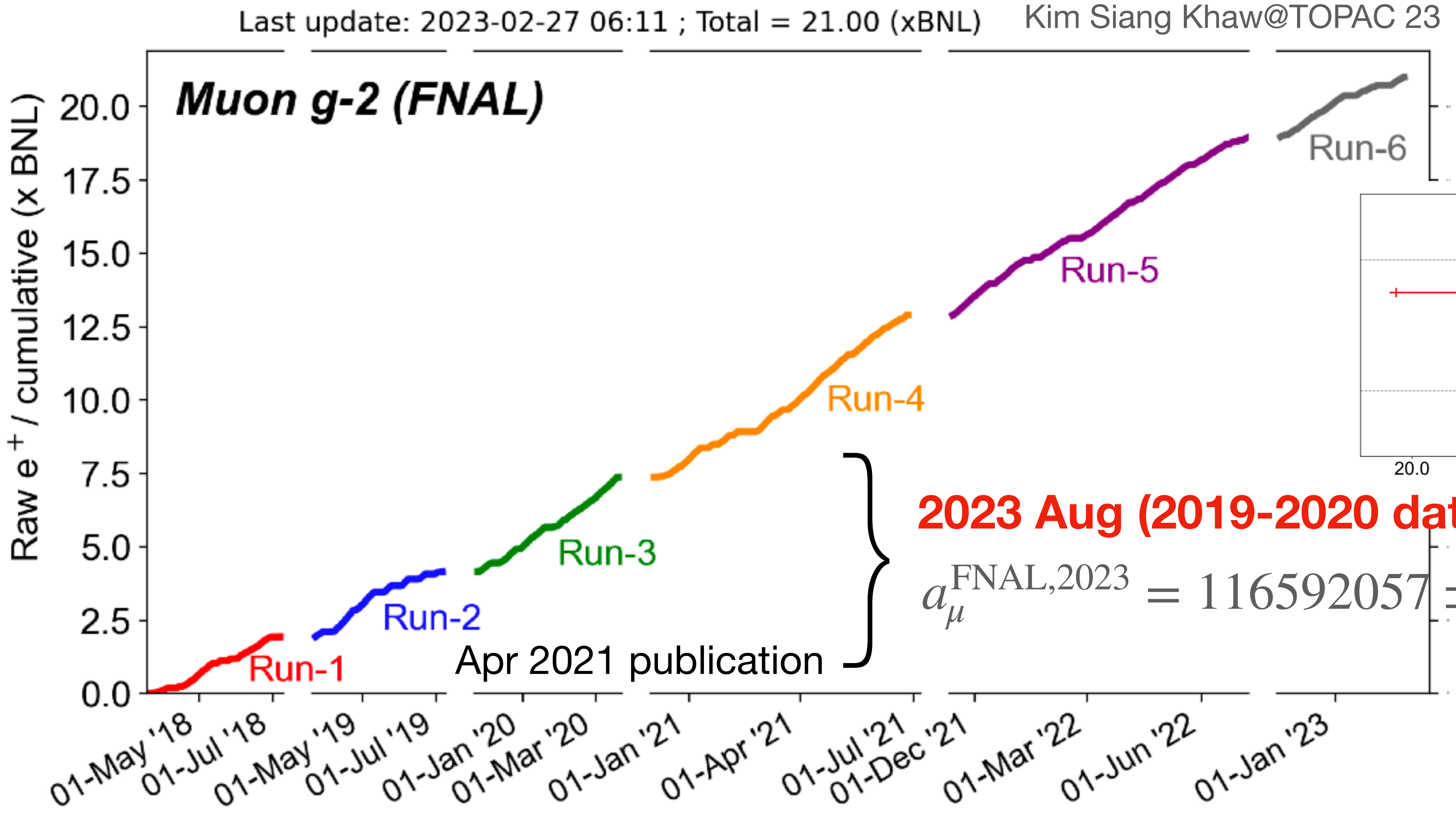
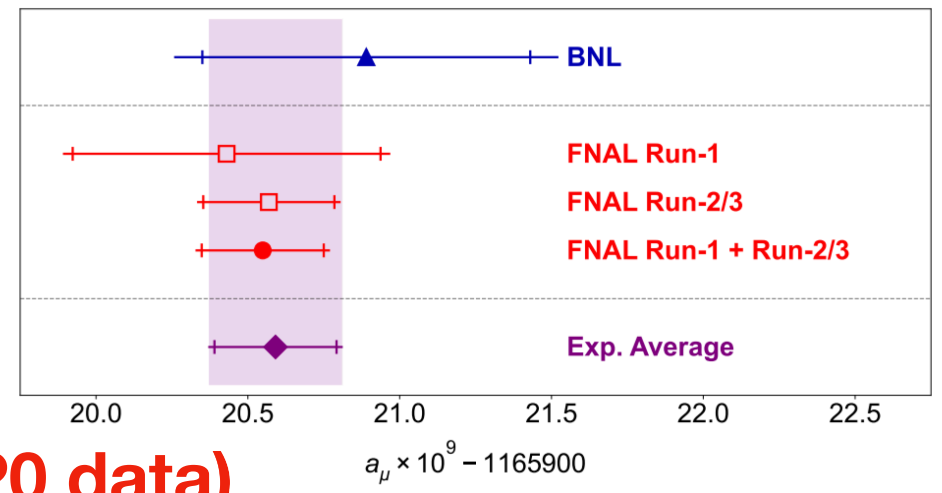
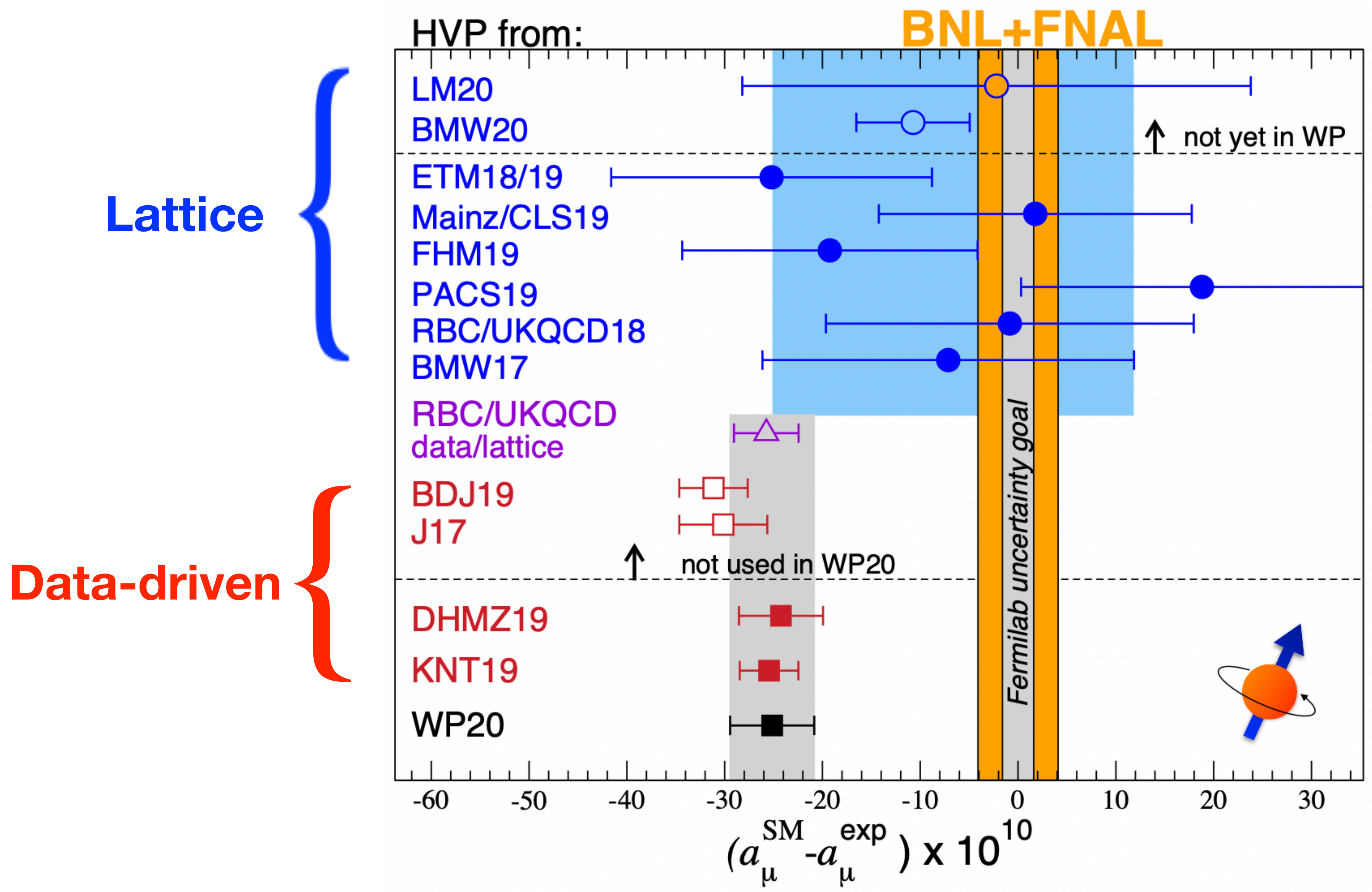




2023 Aug (2019-2020 data)

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

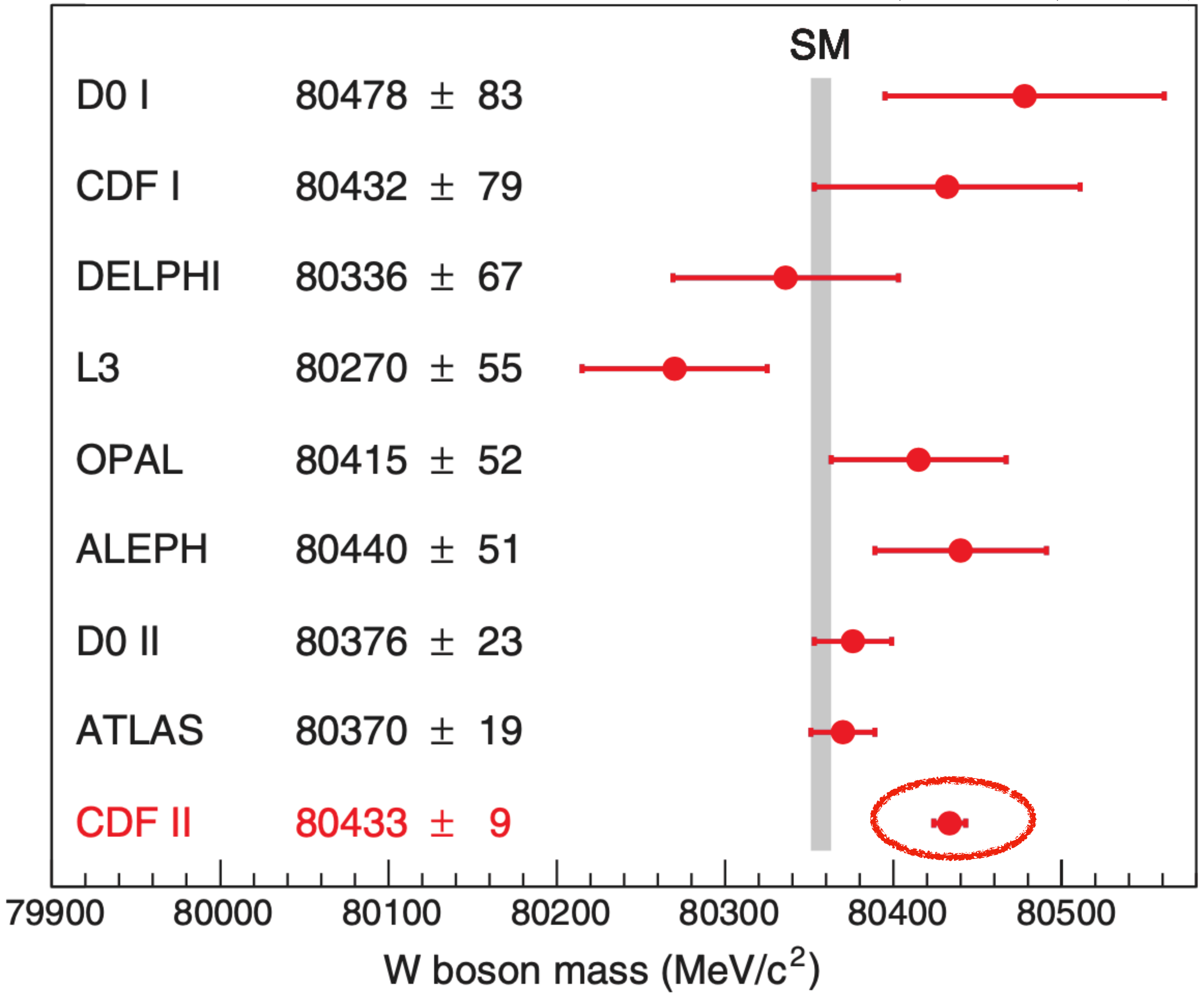
Exp vs SM: 5.2 σ



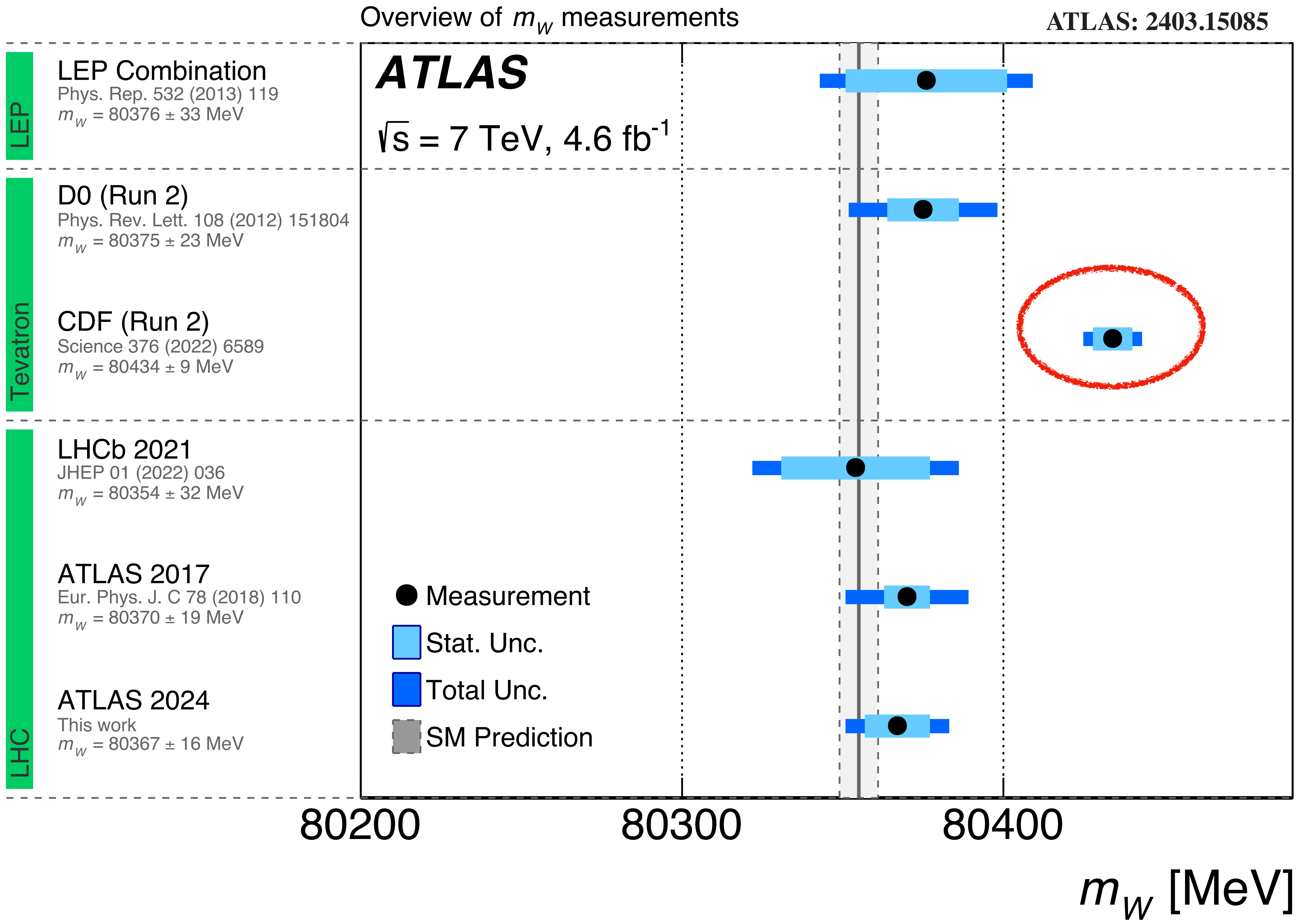
W-boson mass

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

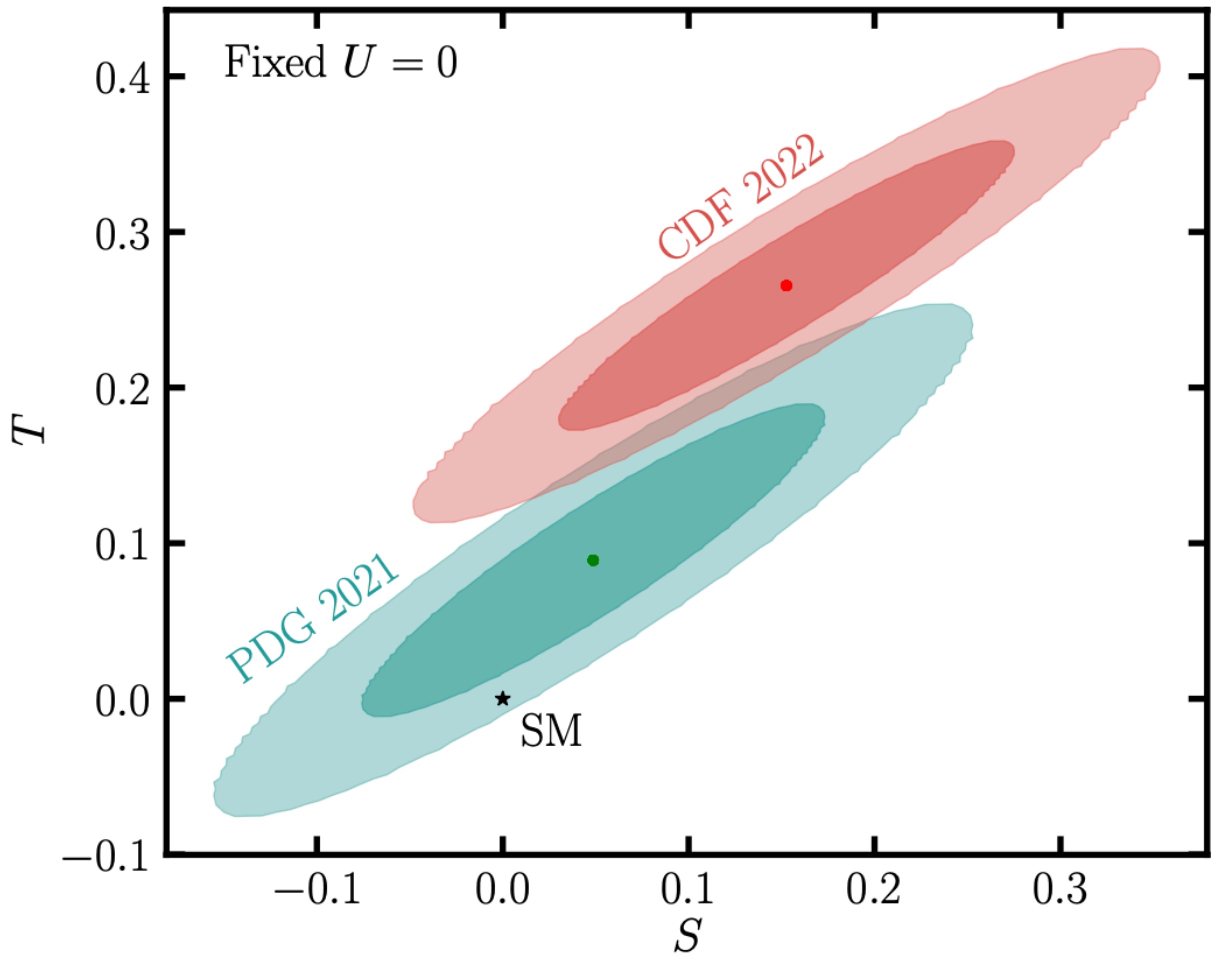
- Most NP effects on the EW sector can be parameterized by S, T, U, e.g.,

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

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

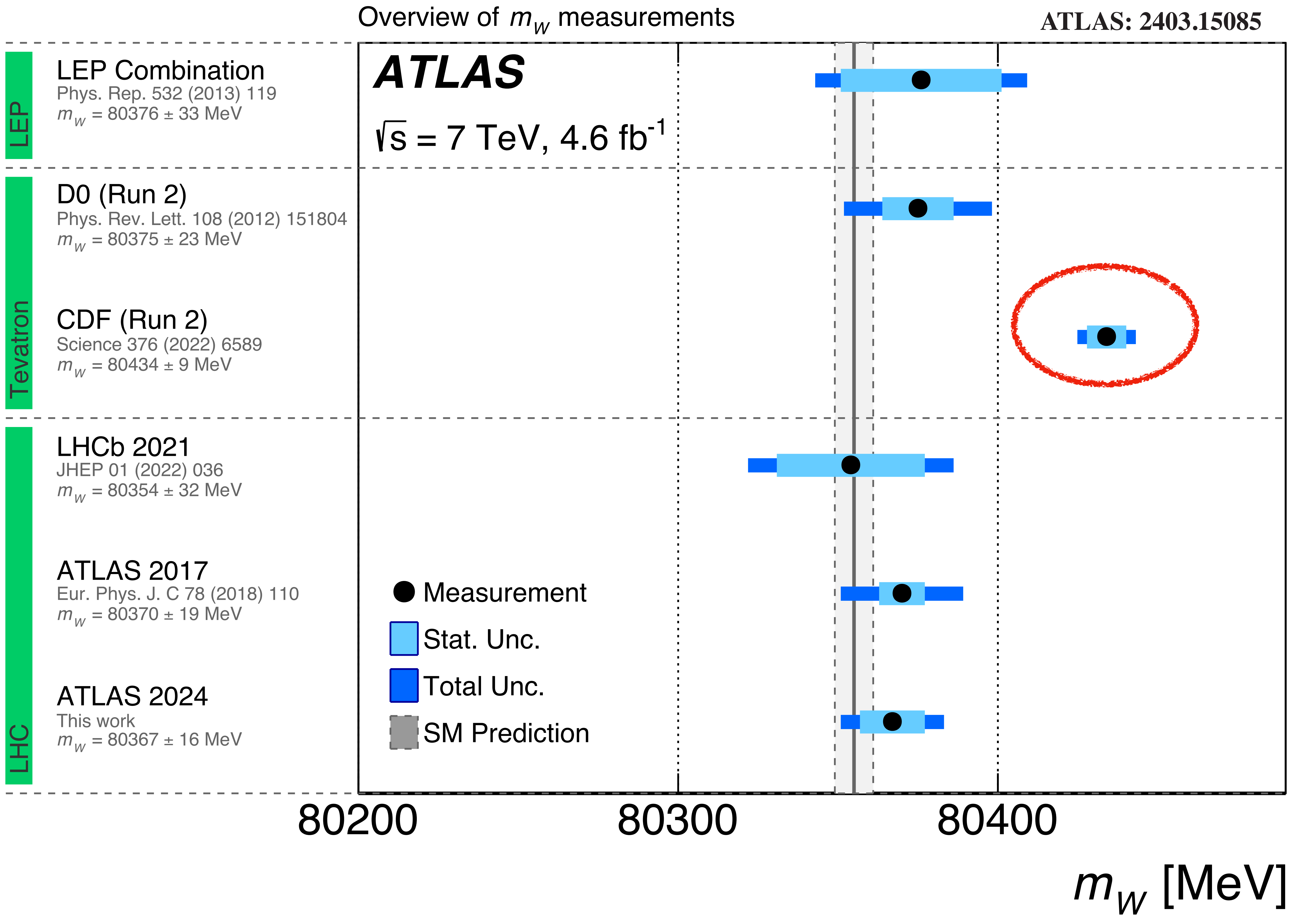
$$S = \frac{4 s_W^2 c_W^2}{\alpha_e}\left[\frac{\Pi_{ZZ}(m_Z^2) - \Pi_{ZZ}(0)}{m_Z^2} - \frac{c_W^2 - s_W^2}{s_W c_W}\Pi'_{Z\gamma}(0) - \Pi'_{\gamma\gamma}(0)\right],$$
$$T = \frac{1}{\alpha_e}\left[\frac{\Pi_{WW}(0)}{m_W^2} - \frac{\Pi_{ZZ}(0)}{m_Z^2}\right],$$
$$U = \frac{4 s_W^2}{\alpha_e}\left[\frac{\Pi_{WW}(m_W^2) - \Pi_{WW}(0)}{m_W^2} - \frac{c_W}{s_W}\Pi'_{Z\gamma}(0) - \Pi'_{\gamma\gamma}(0)\right] - S,$$

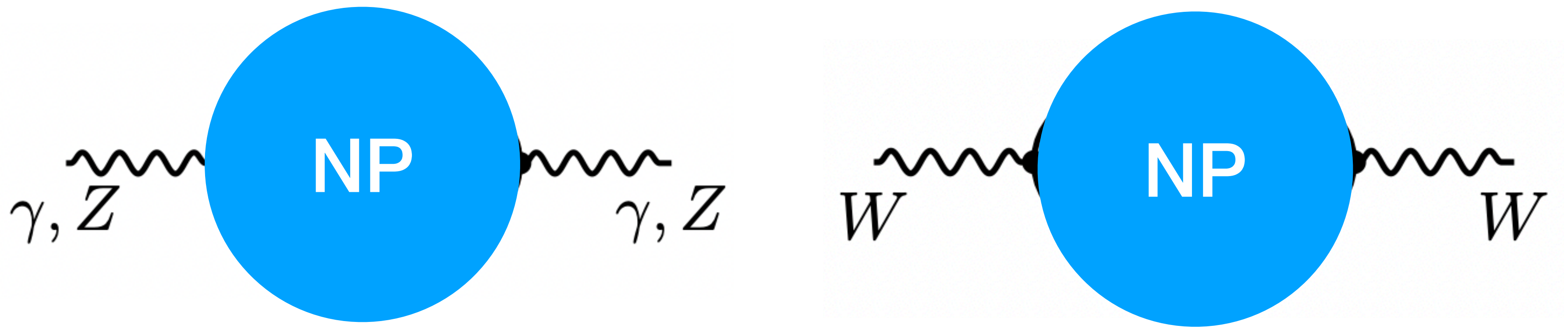
- A global EW fit is needed to explanation of the CDF m_W shift



By Gfitter

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





new particles in the vacuum polarizations of gauge bosons

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

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

theoretical cleanness

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

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

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

see also 何吉波's talk

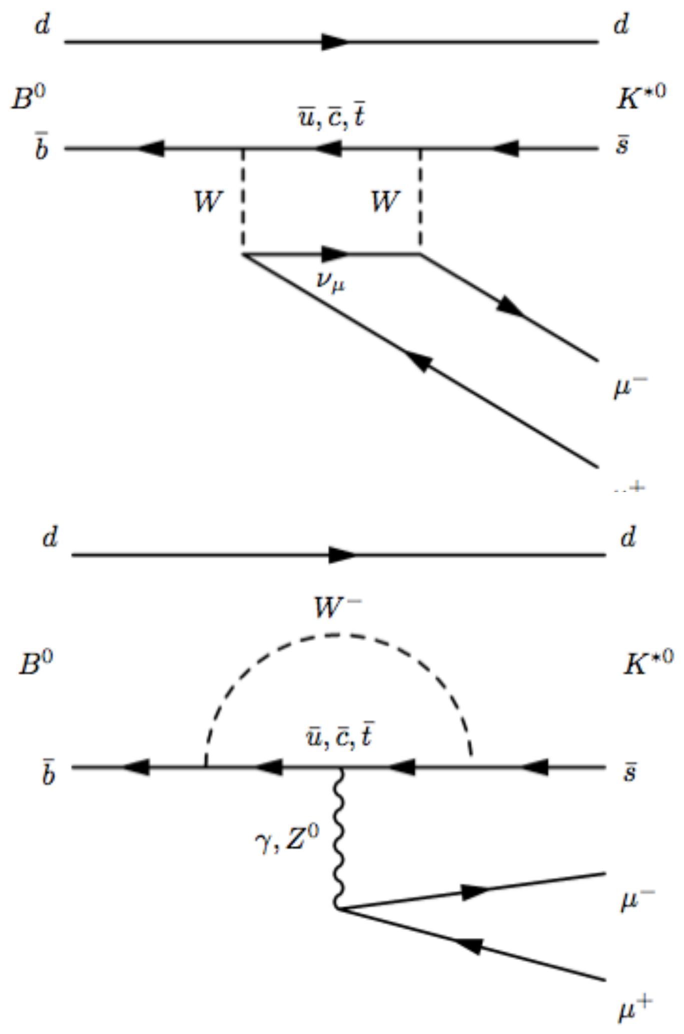
$$R_K = \frac{\mathcal{B}(B \to K\mu^+\mu^-)}{\mathcal{B}(B \to Ke^+e^-)}$$

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

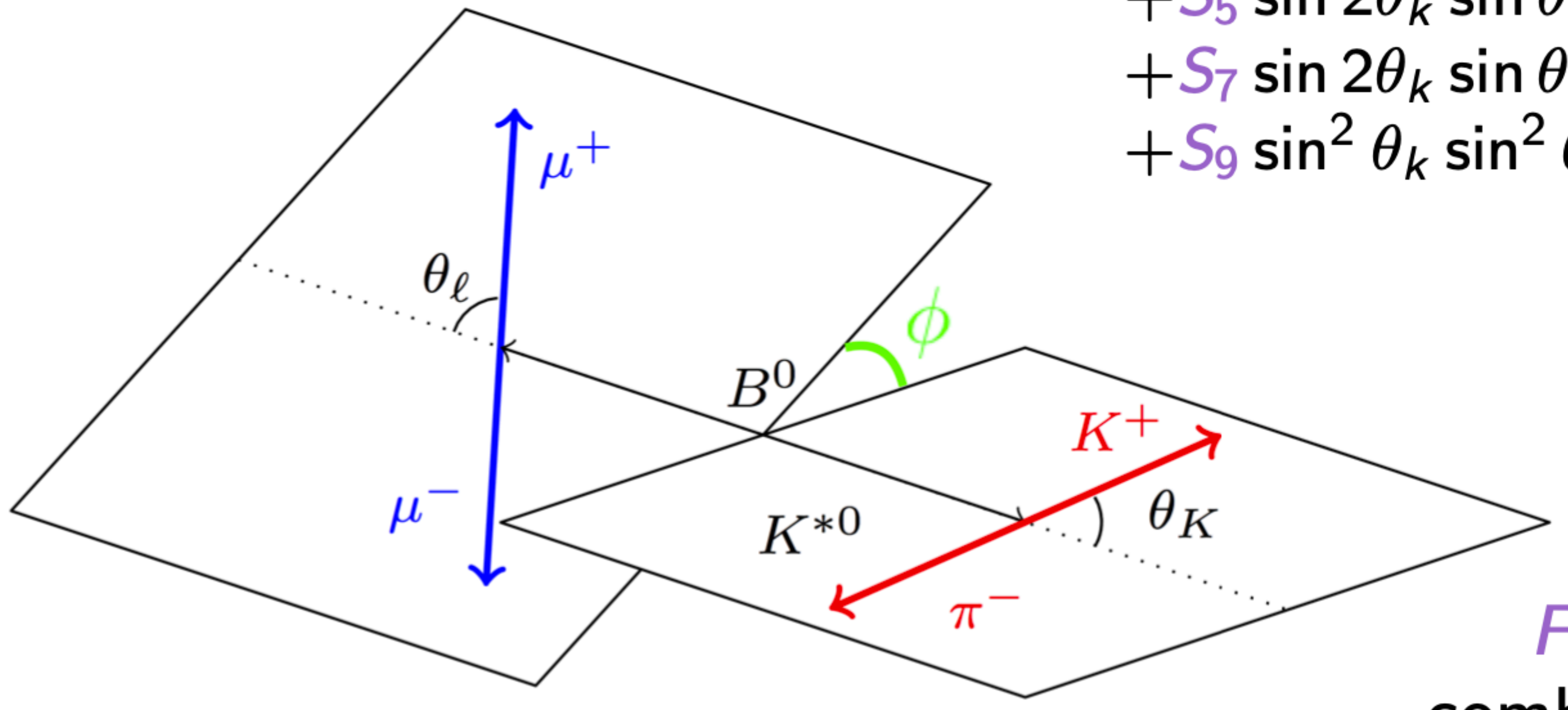
deviation from unity

Physics beyond the SM

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



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



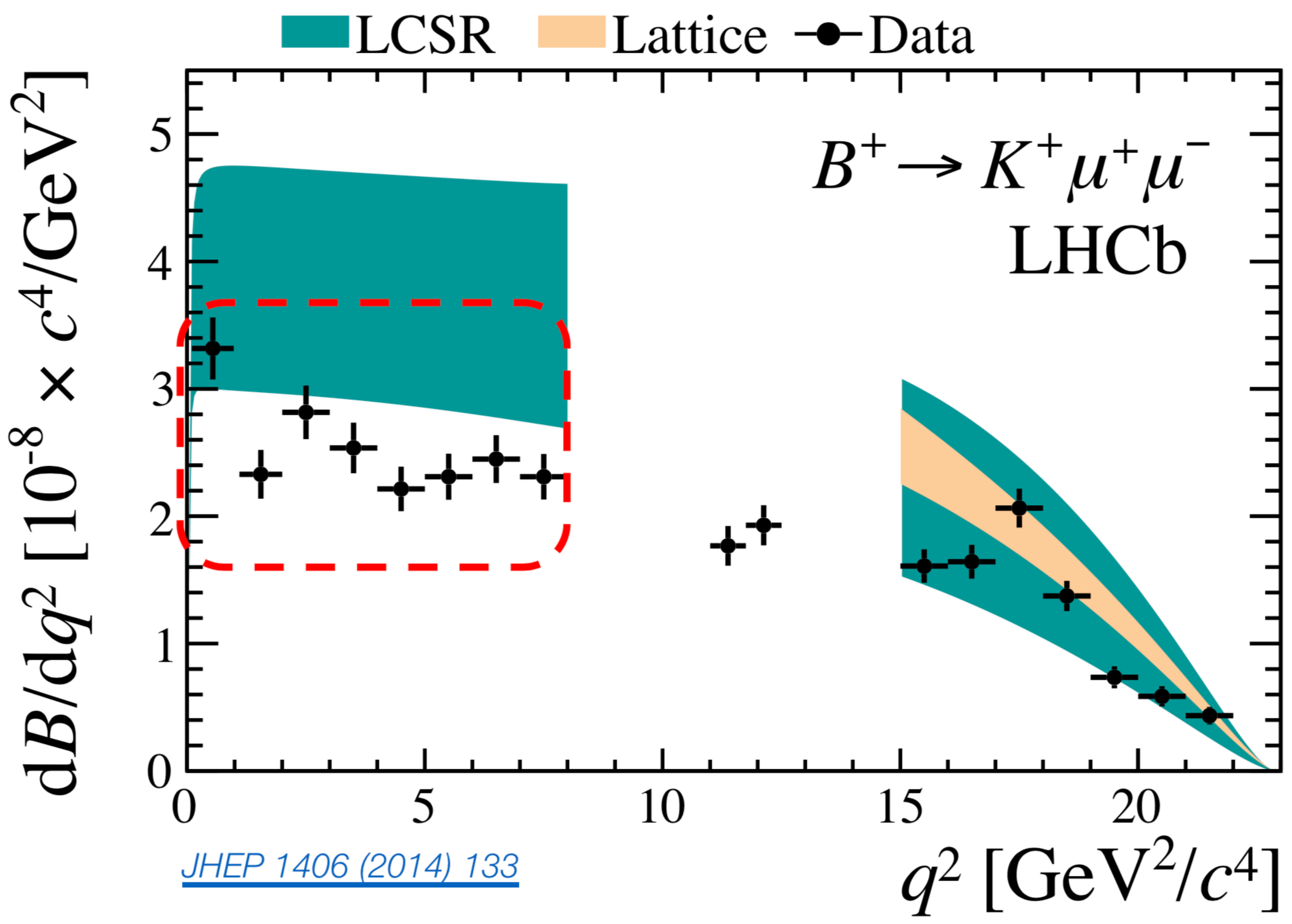
angular observables

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

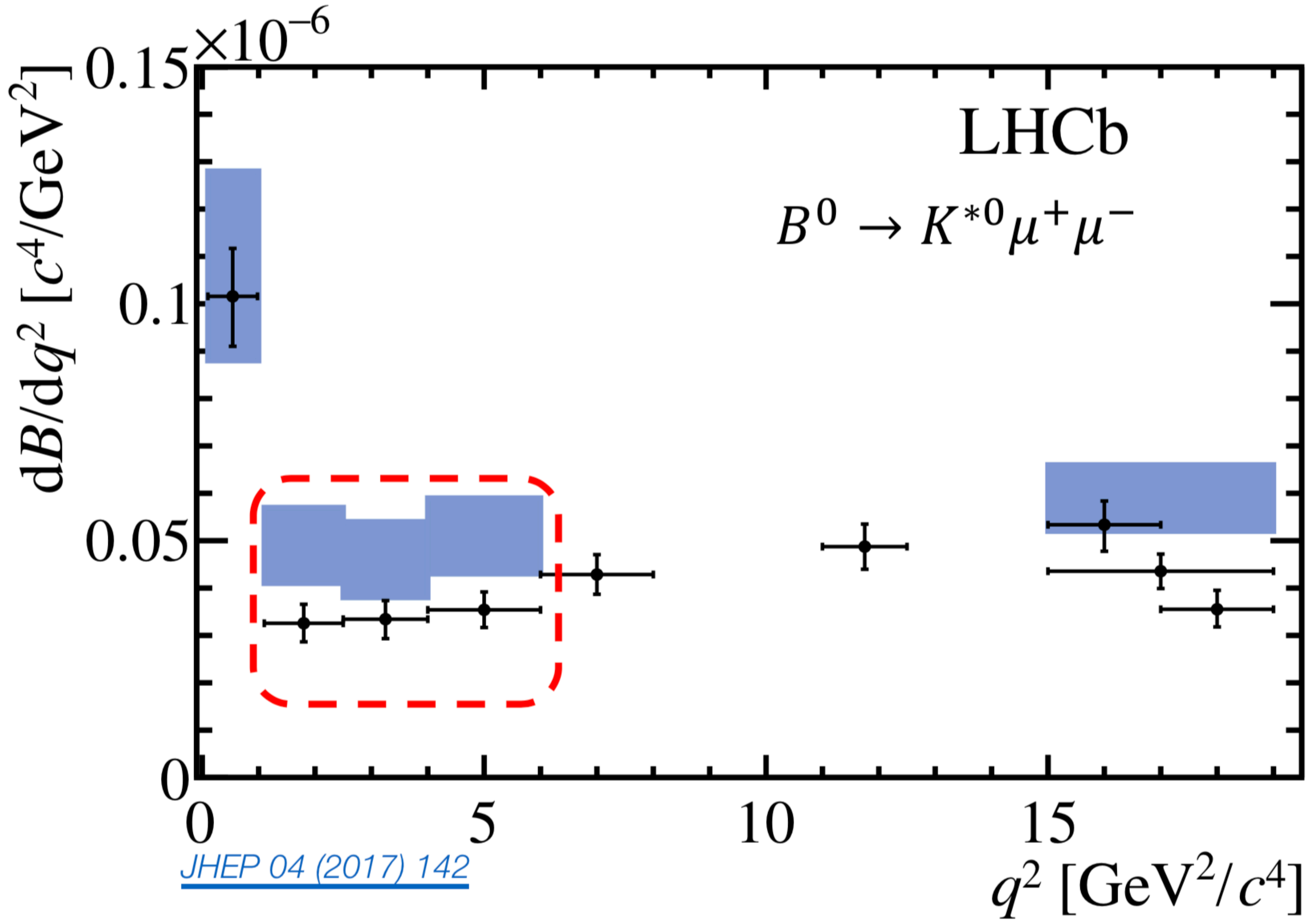
combinations of K^{*0} decay amplitudes

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

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

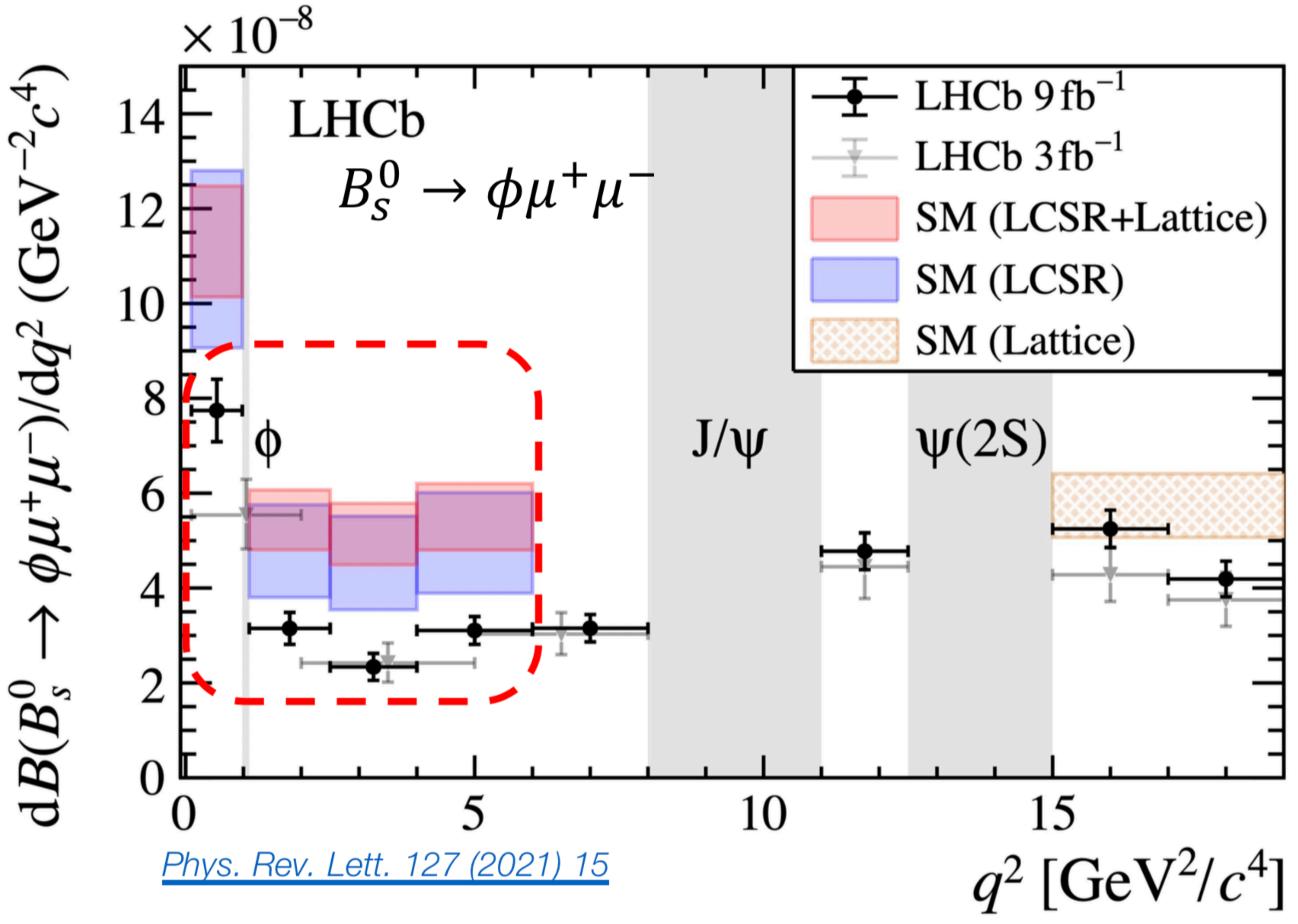


JHEP 1406 (2014) 133

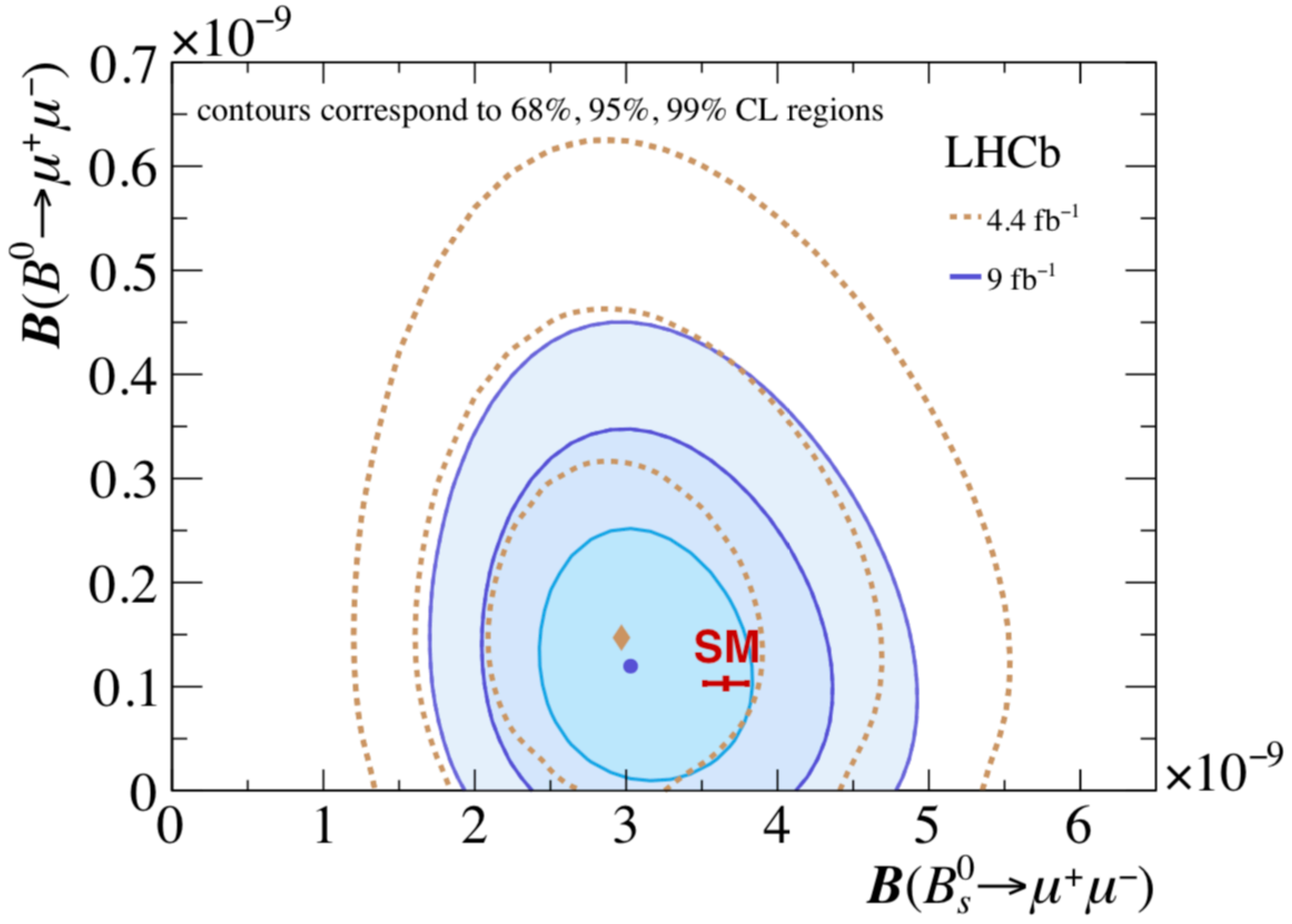


JHEP 04 (2017) 142

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

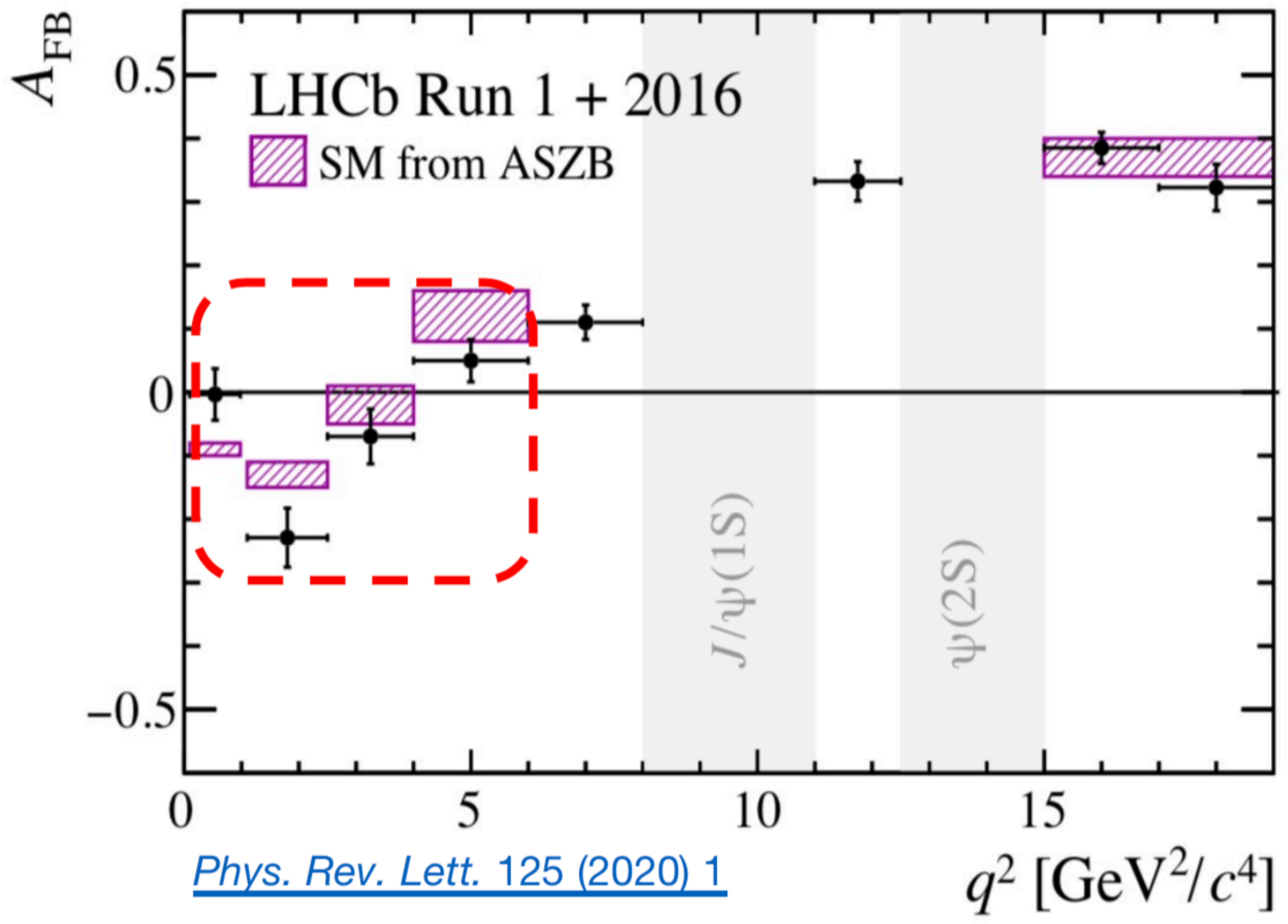


Phys. Rev. Lett. 127 (2021) 15



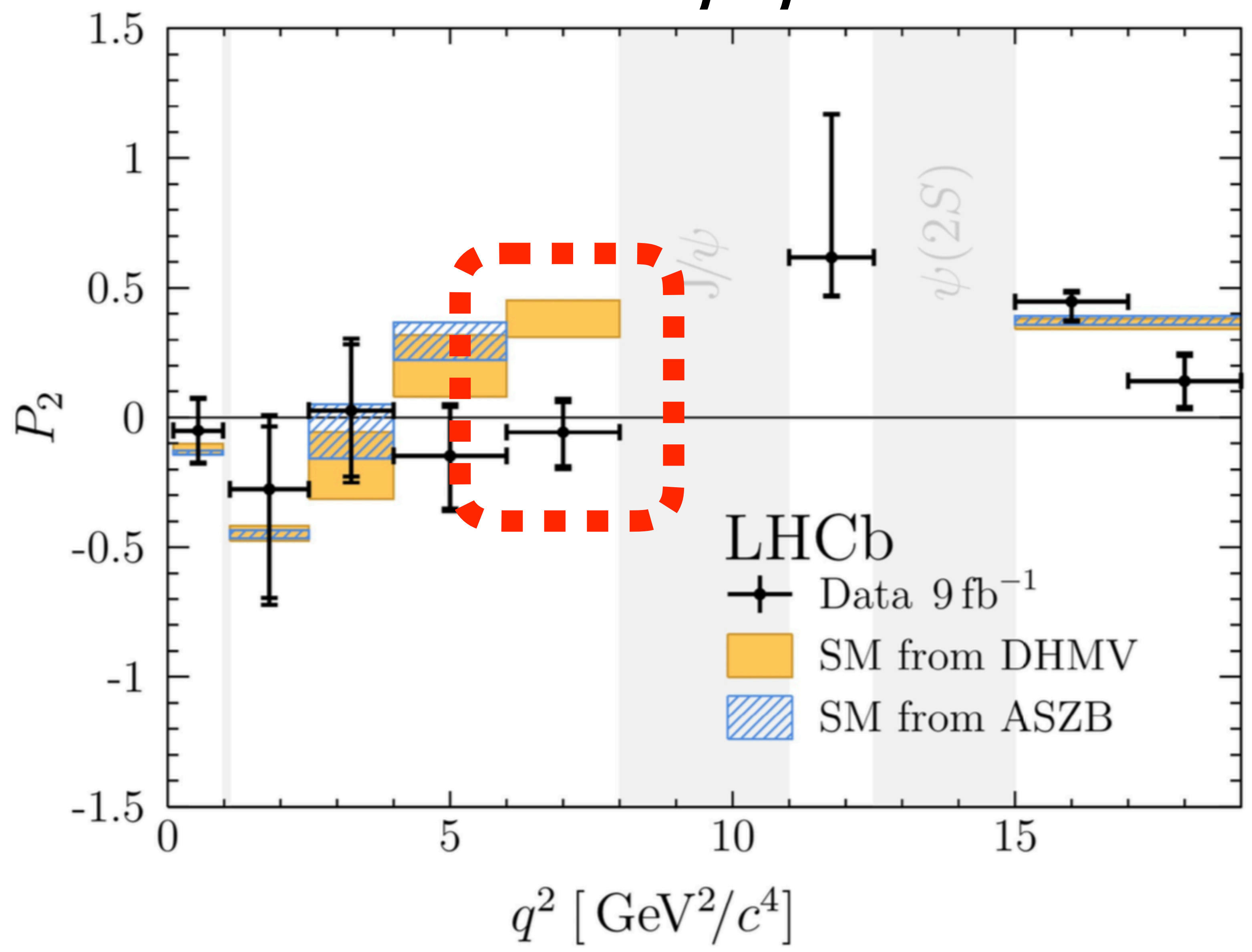
$b \to s\ell\ell$ anomalies@mid.2022: angular distribution

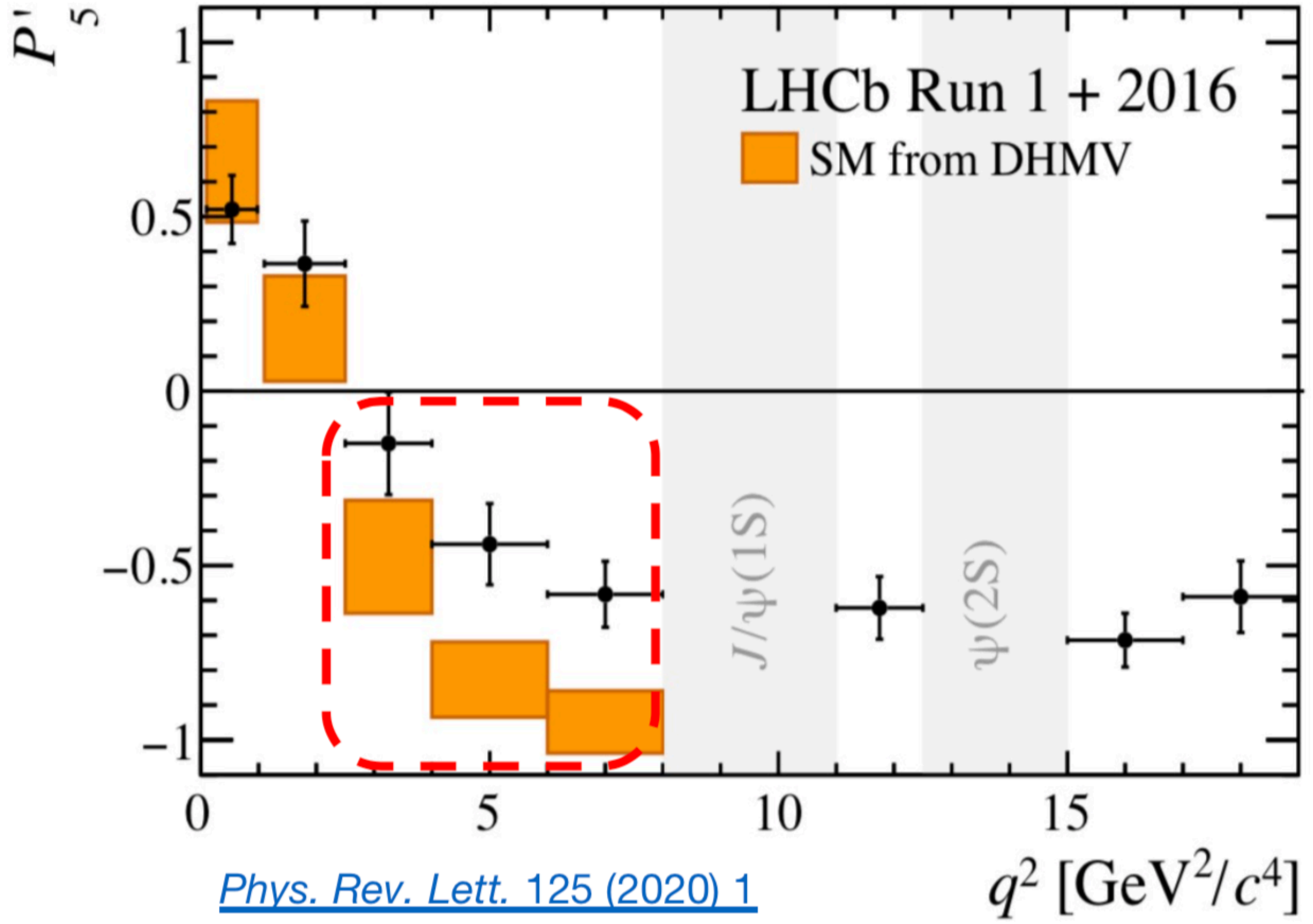
$B^0 \to K^{*0}\mu^+\mu^-$



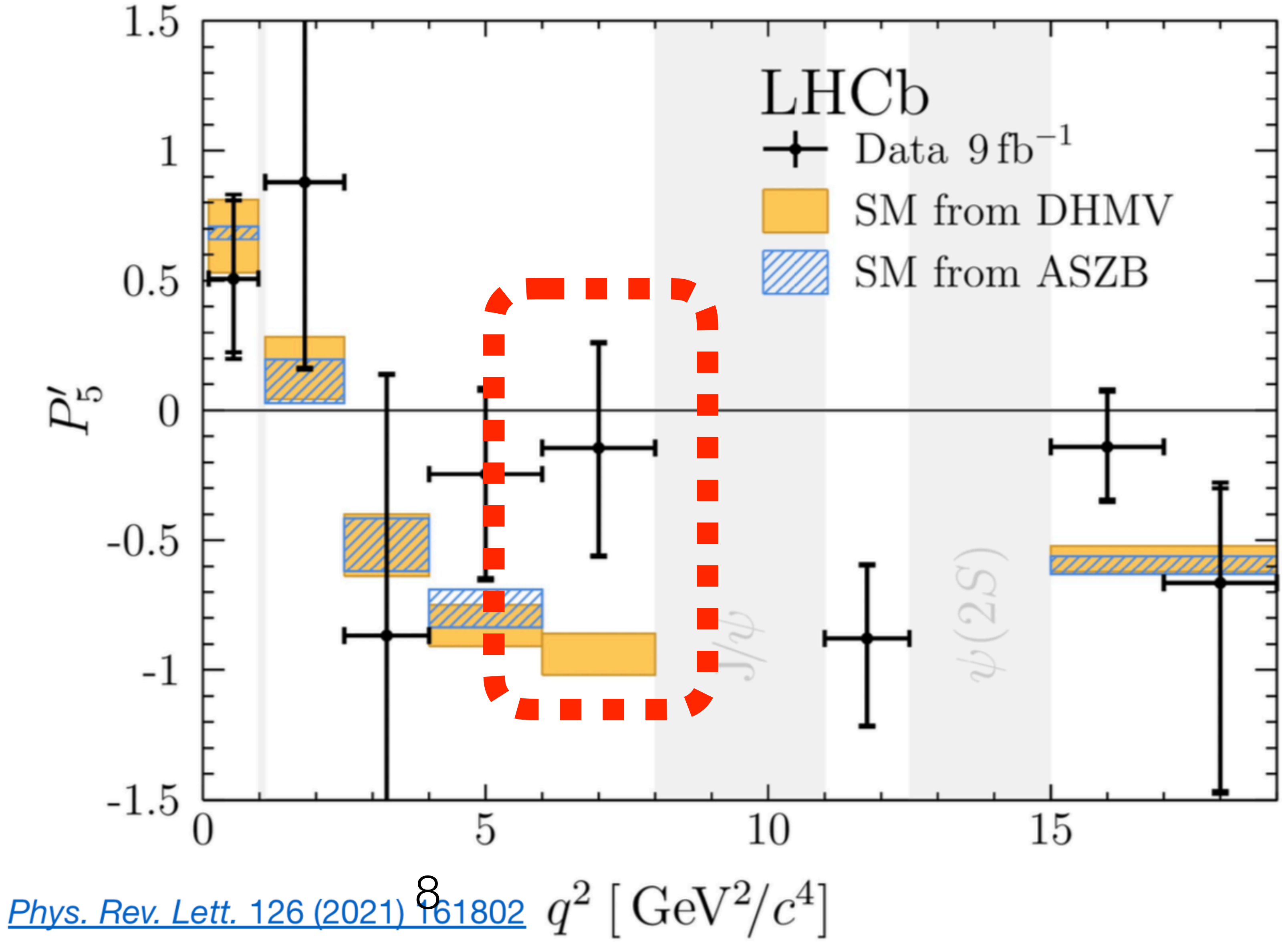
[Phys. Rev. Lett. 125 (2020) 1]

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





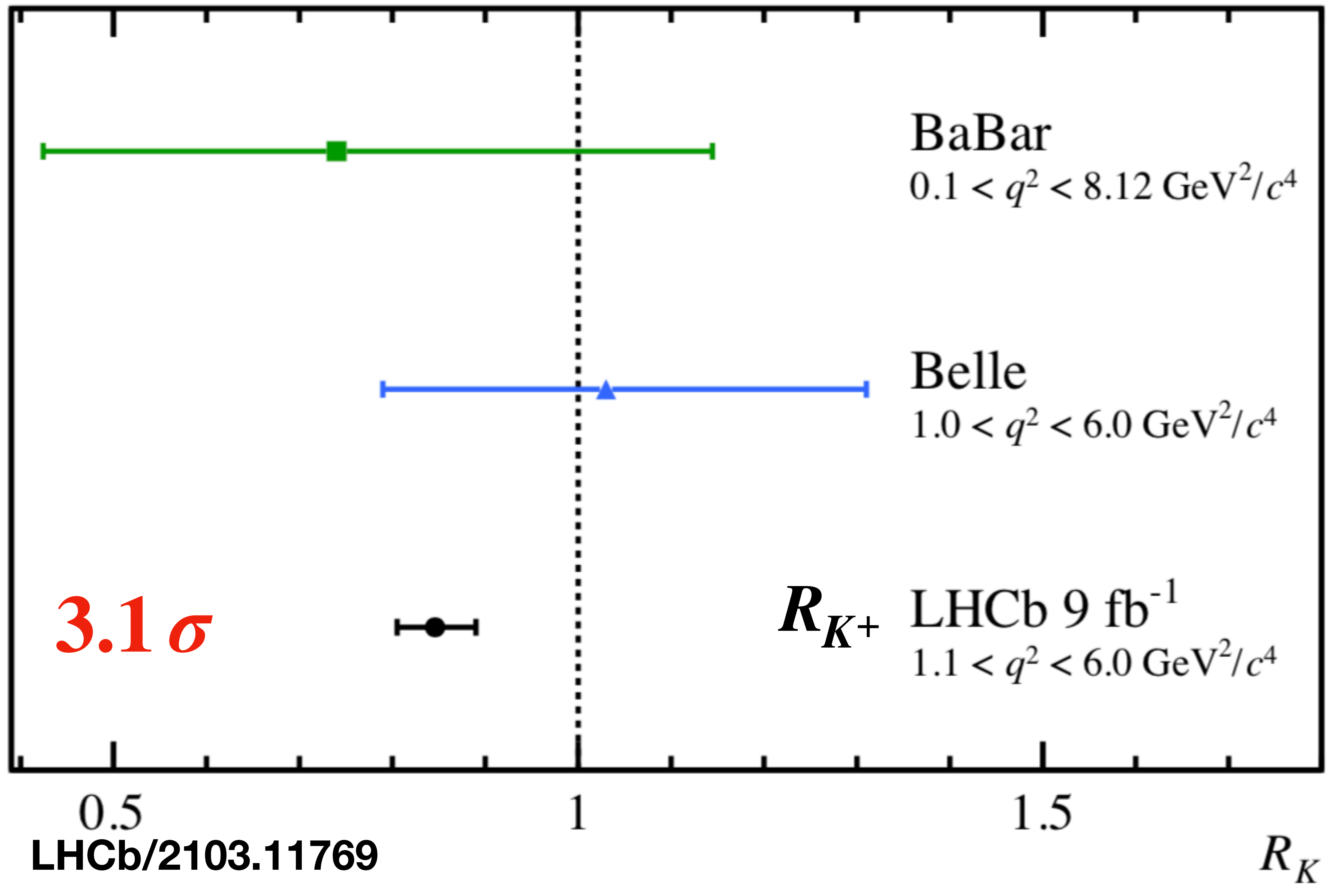
[Phys. Rev. Lett. 125 (2020) 1]



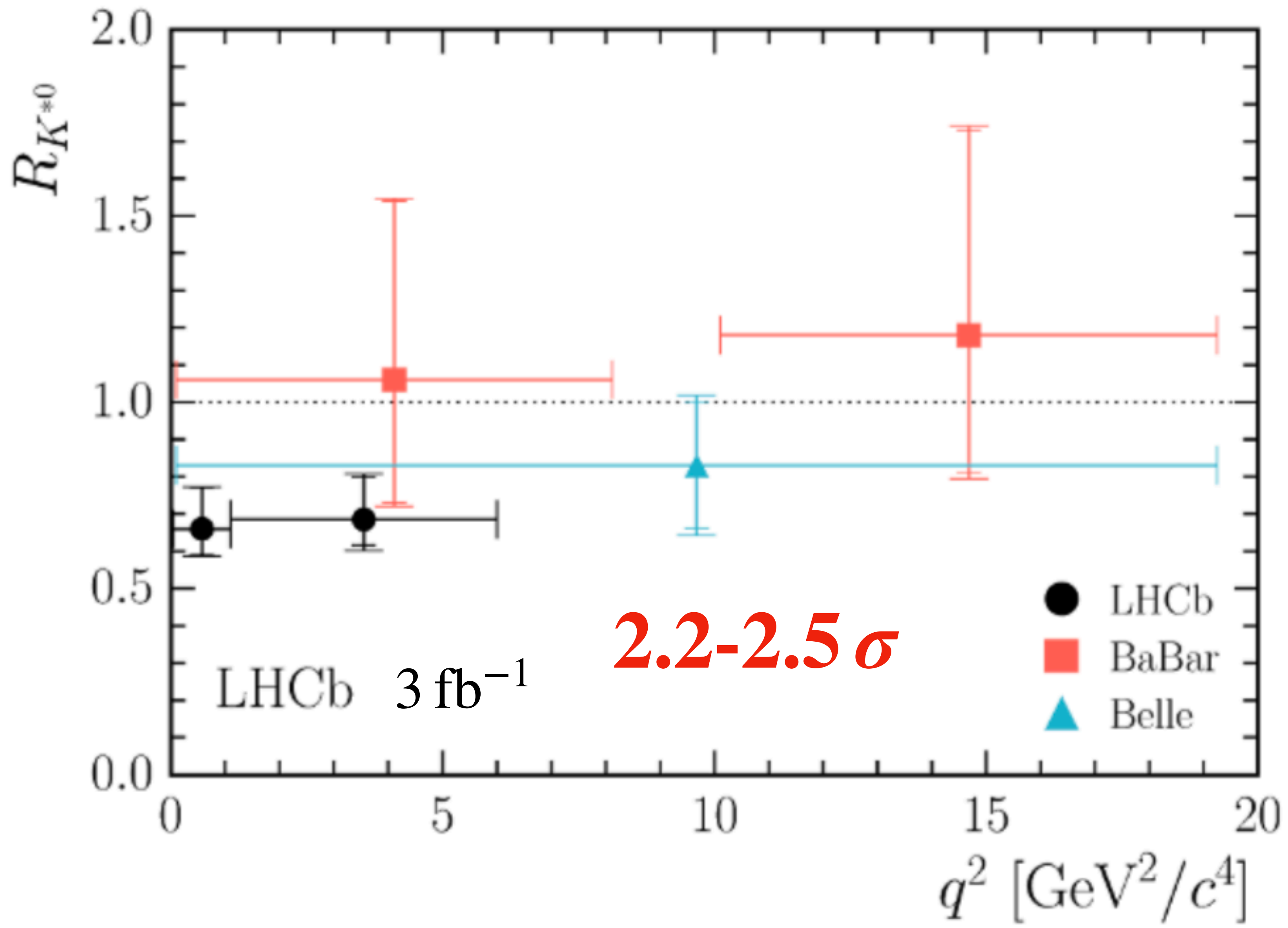
[Phys. Rev. Lett. 126 (2021) 161802]

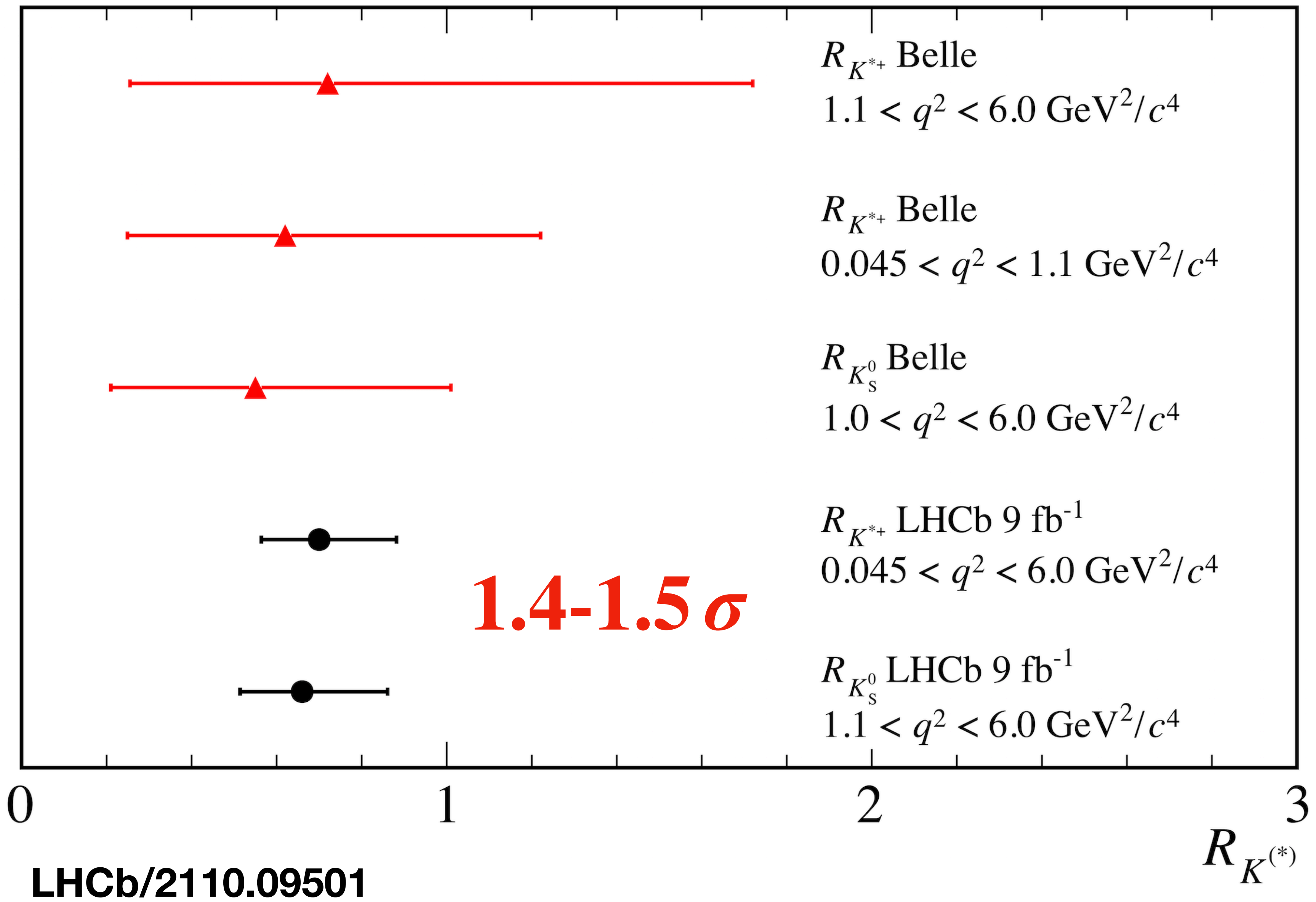
- Similar deviations in the 2 modes
- Theoretical Uncertainties:
  - branching ratio: 😭
  - angular distribution: 😢

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

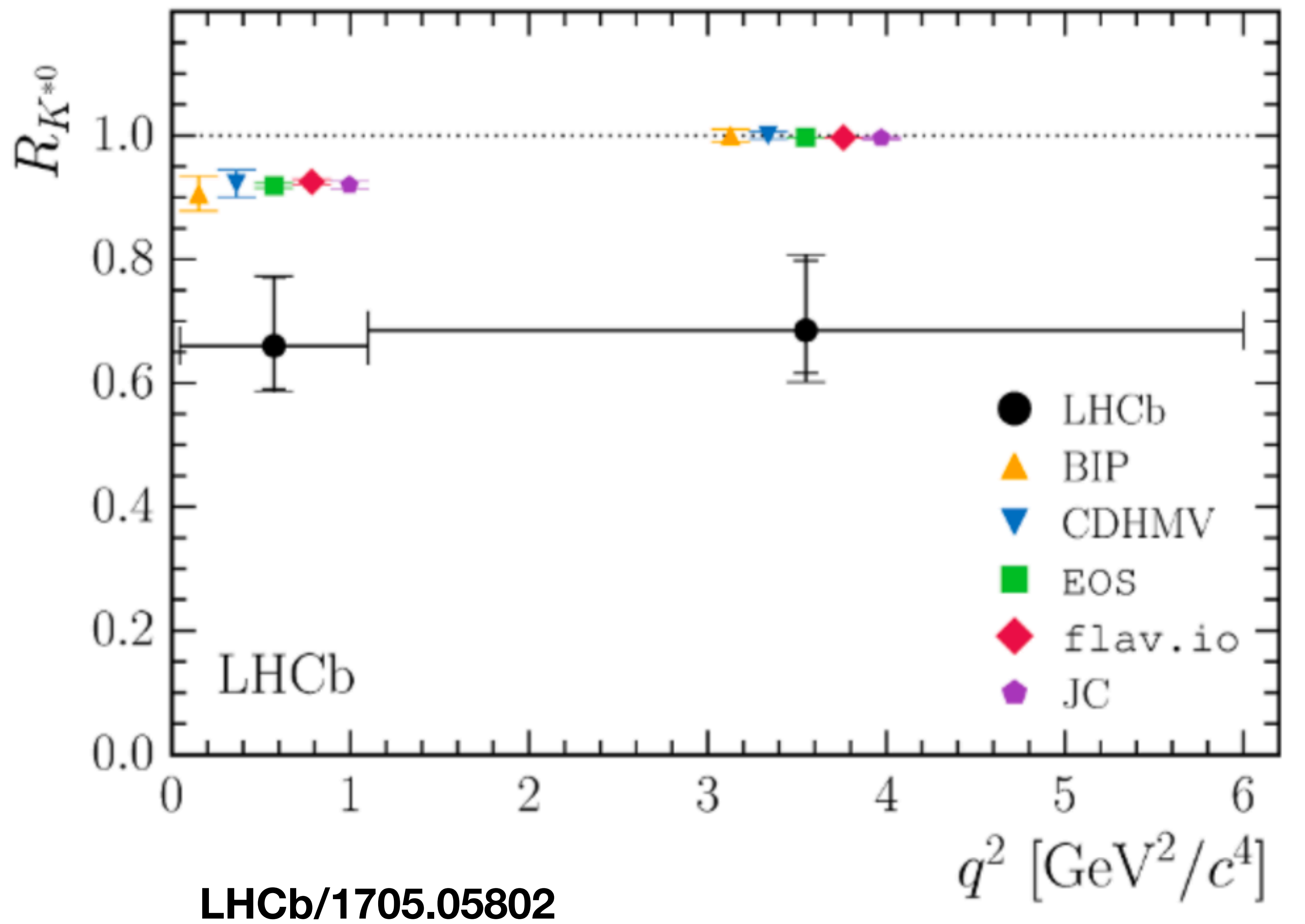


LHCb/2103.11769





LHCb/2110.09501



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**

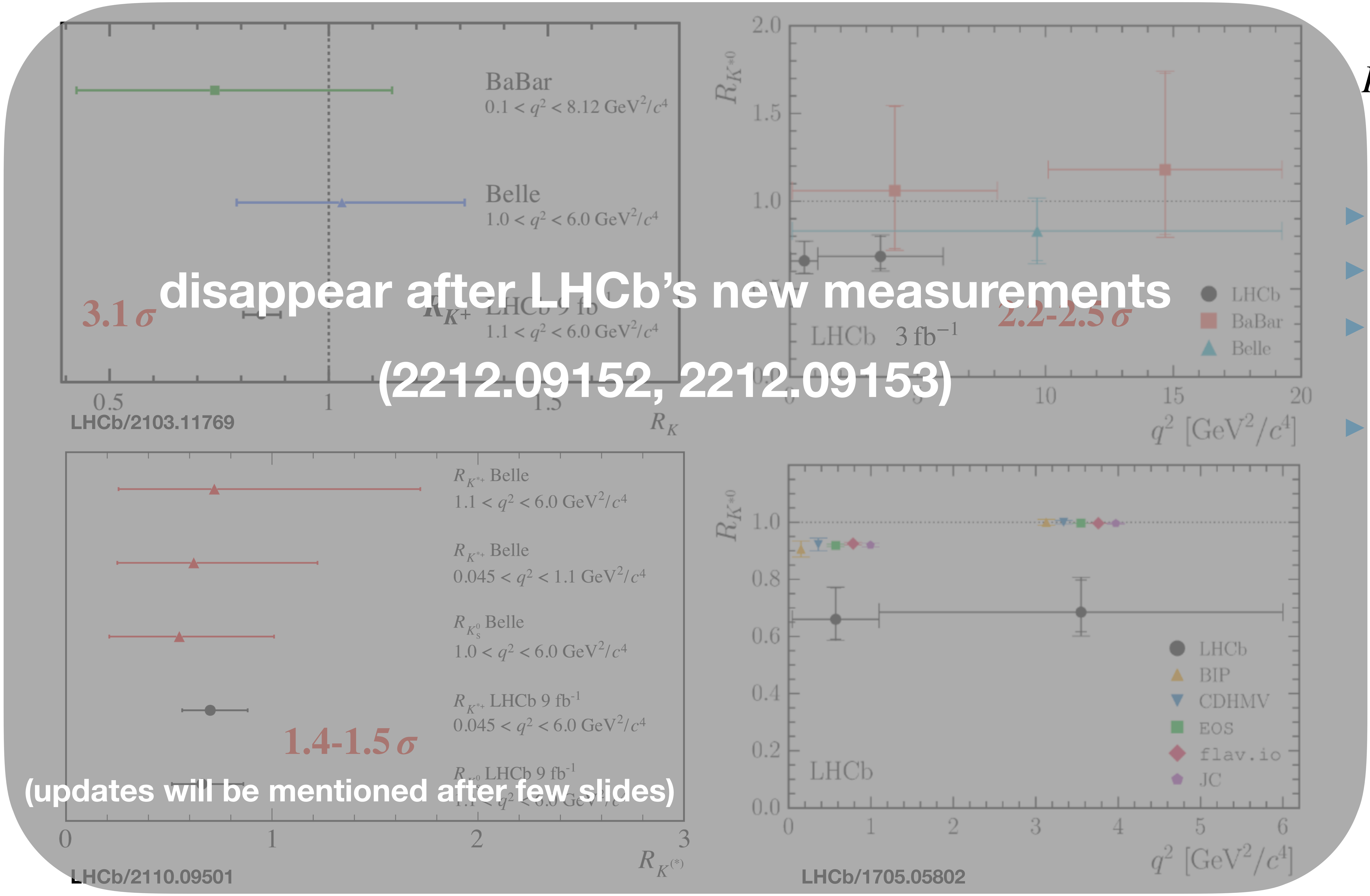
- **Theoretical Uncertainties:**
  - **branching ratio:** 😭
  - **angular distribution:** 😢
  - **LFV ratio:** 😀

deviation from unity

⬇

Physics beyond the SM

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



disappear after LHCb's new measurements

(2212.09152, 2212.09153)

(updates will be mentioned after few slides)

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

- $R_H^{\text{SM}} \approx 1$
- **Hadronic uncertainties cancel**
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- **Theoretical Uncertainties:**
  - **branching ratio:** 😭
  - **angular distribution:** 😢
  - **LFV ratio:** 😀

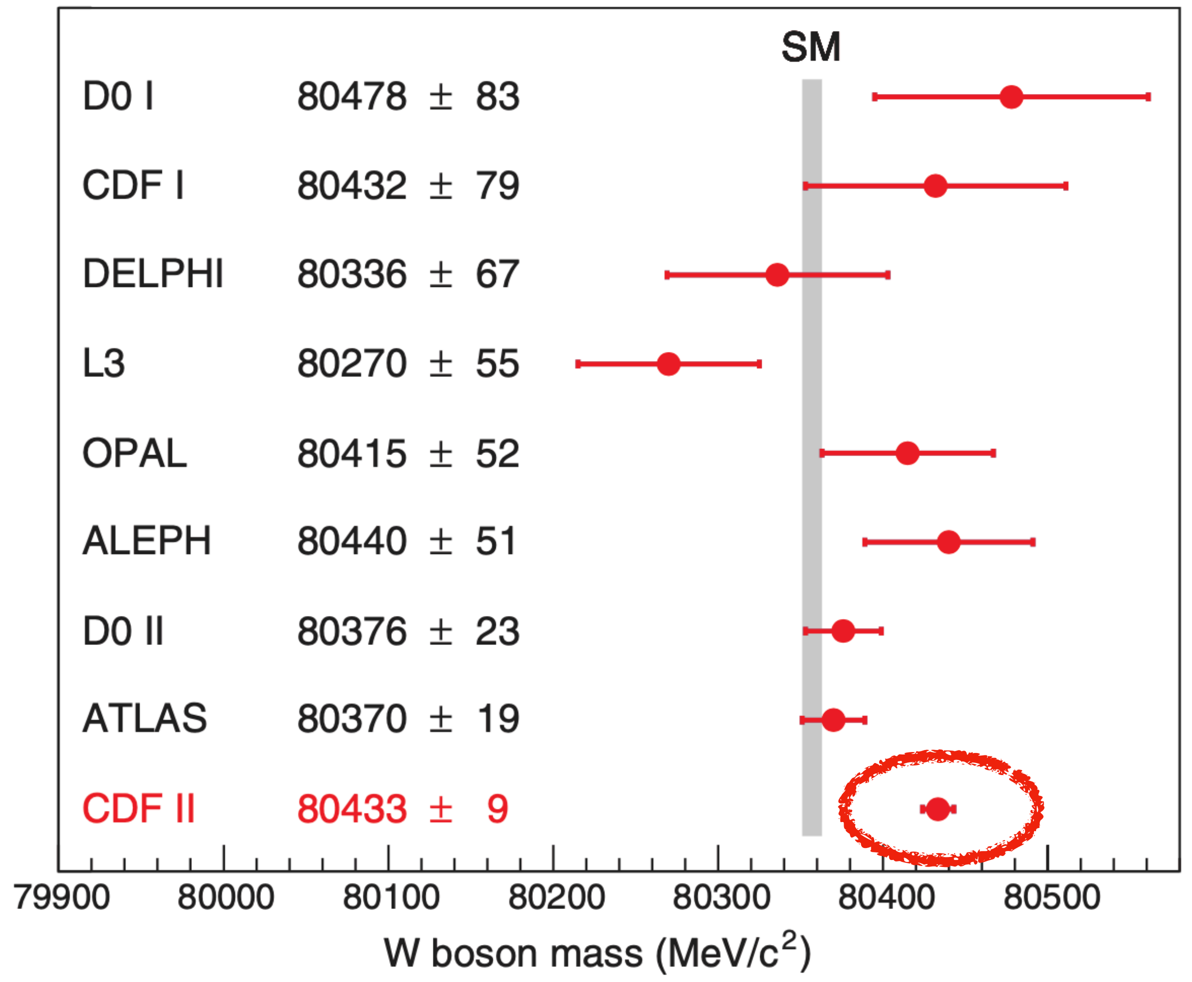
deviation from unity

⬇

Physics beyond the SM

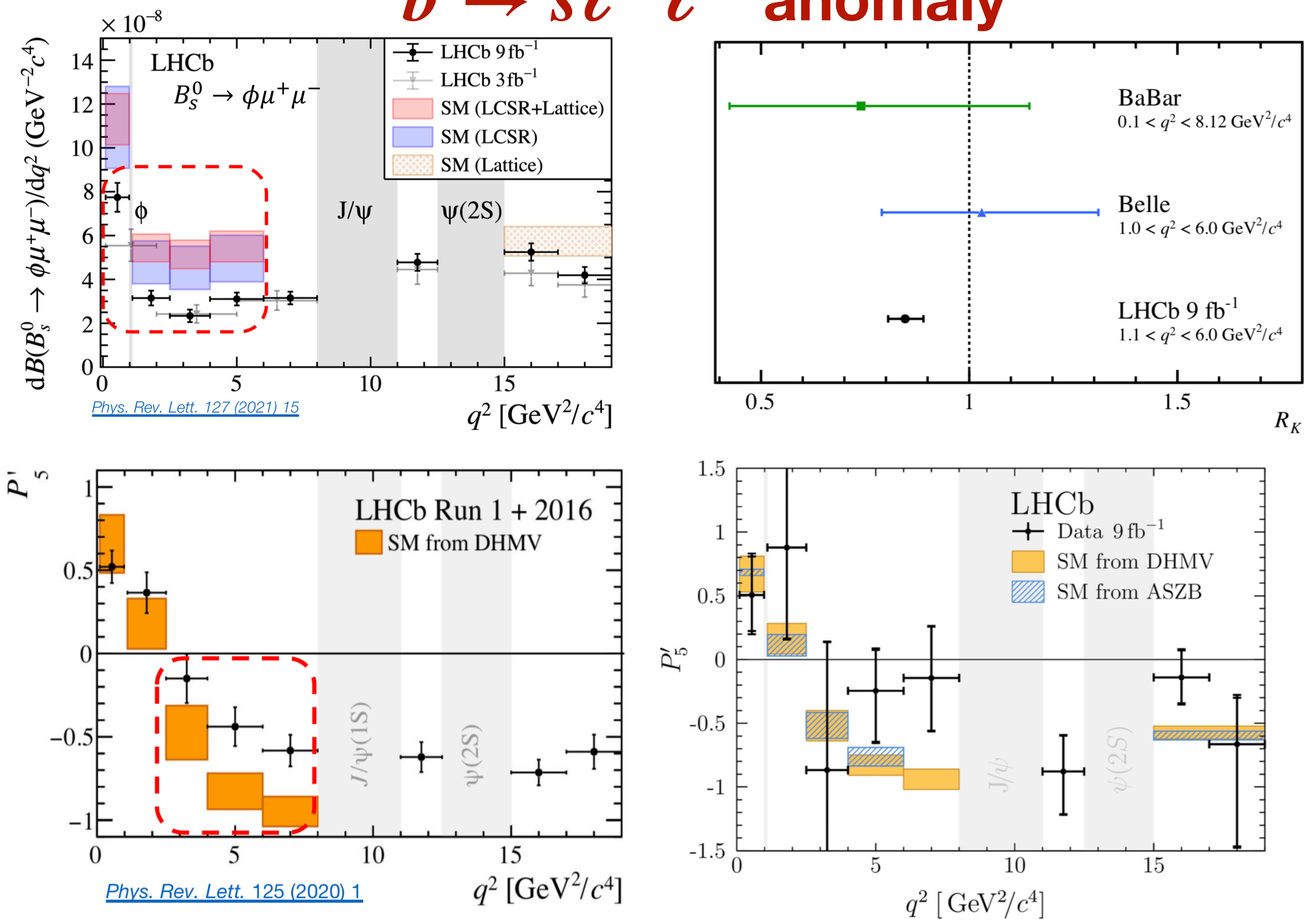
Motivation of this work (arXiv:2205.02205)

CDF W-mass shift

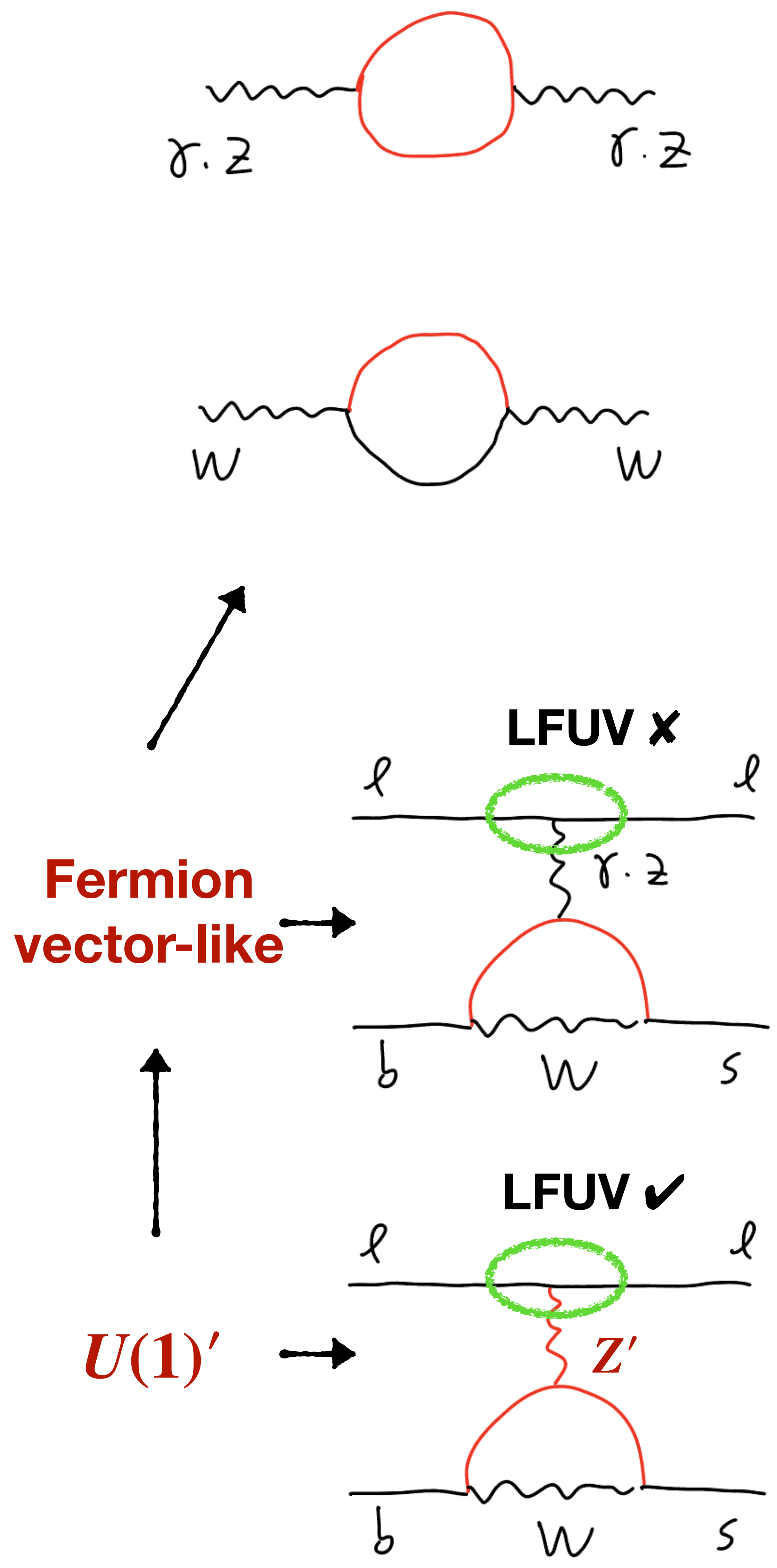


Explain the CDF W-mass shift and $b \to s\ell^+\ell^-$ anomaly in a model simultaneously ?

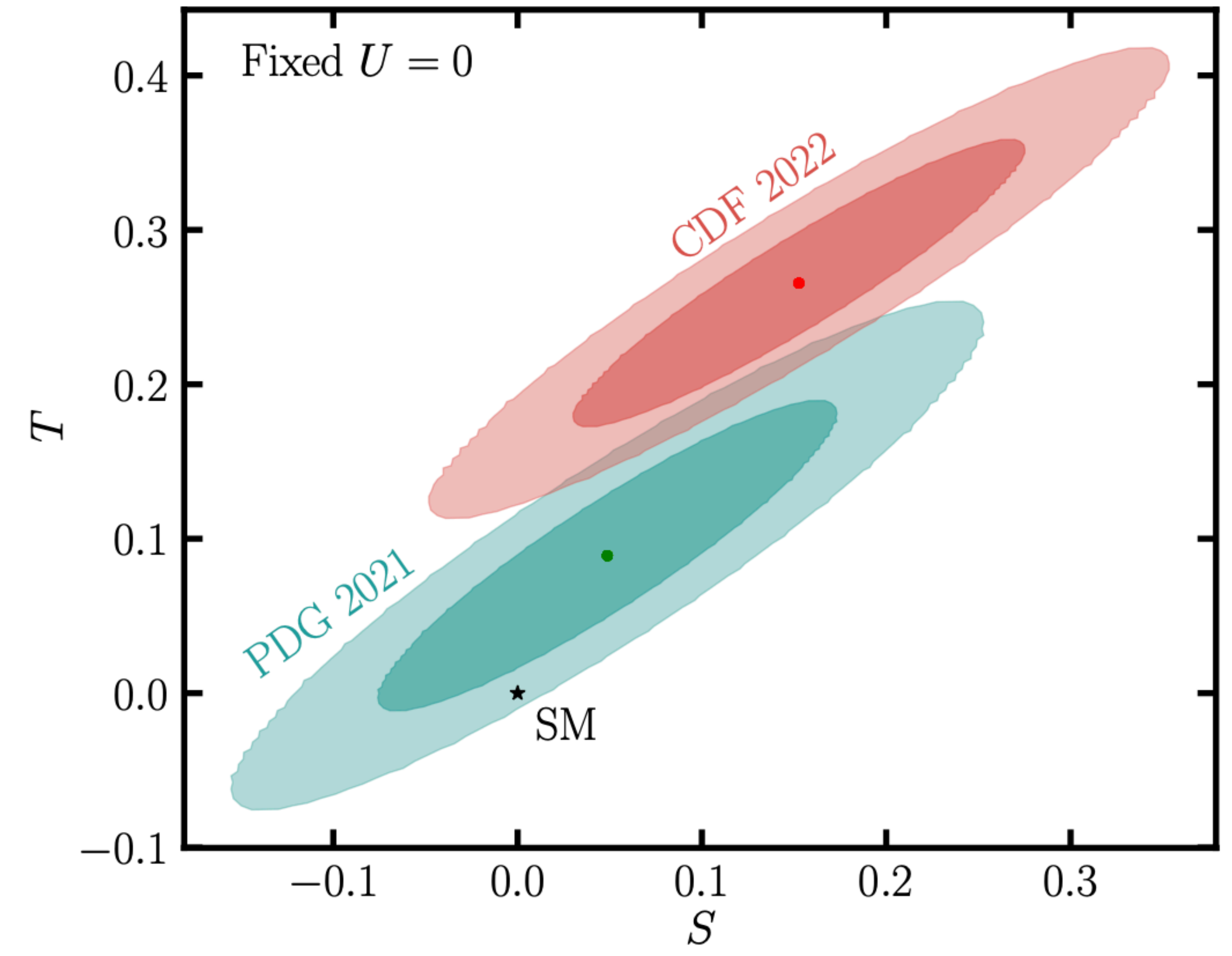
$b \to s\ell^+\ell^-$ anomaly



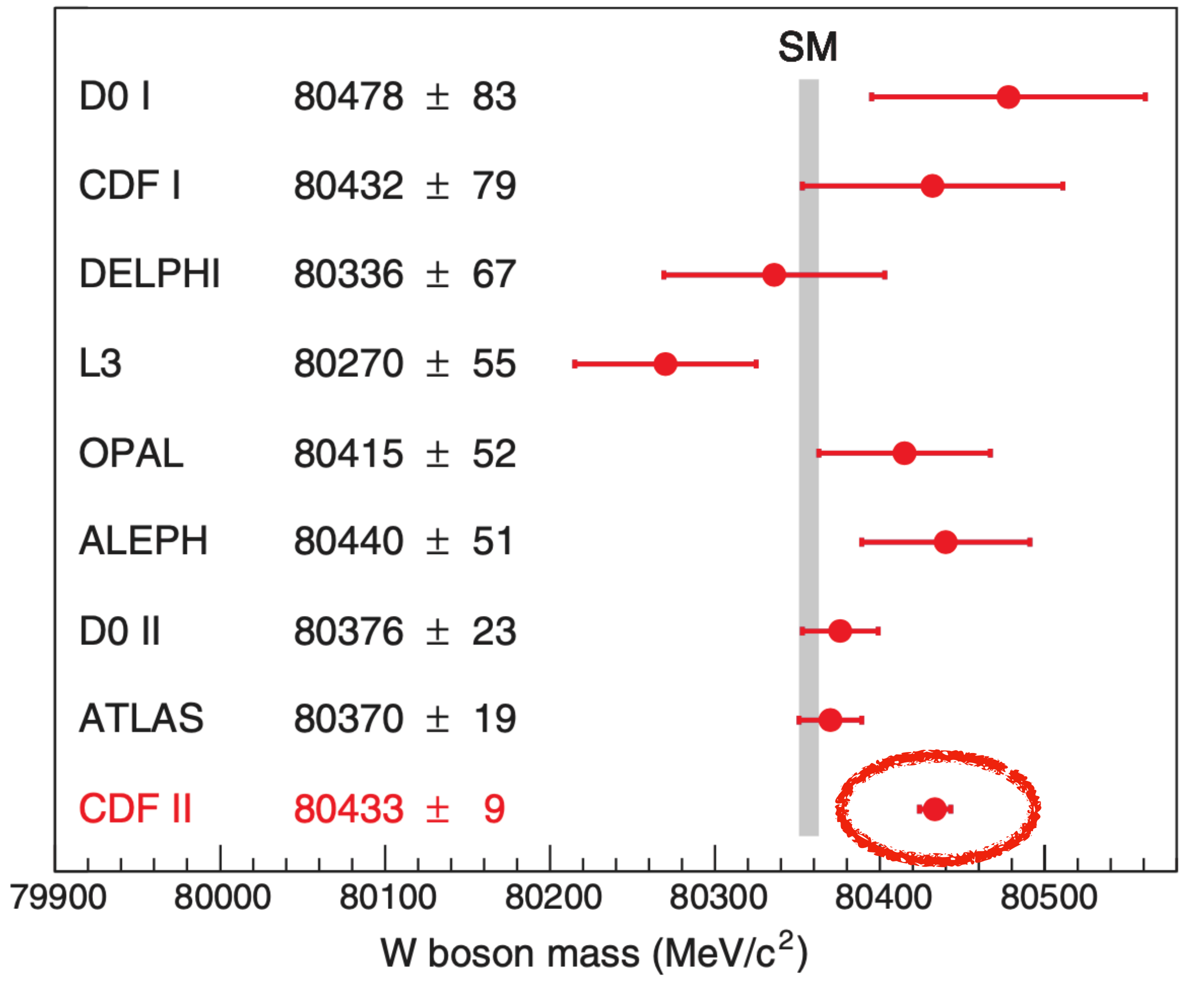
Motivation and idea



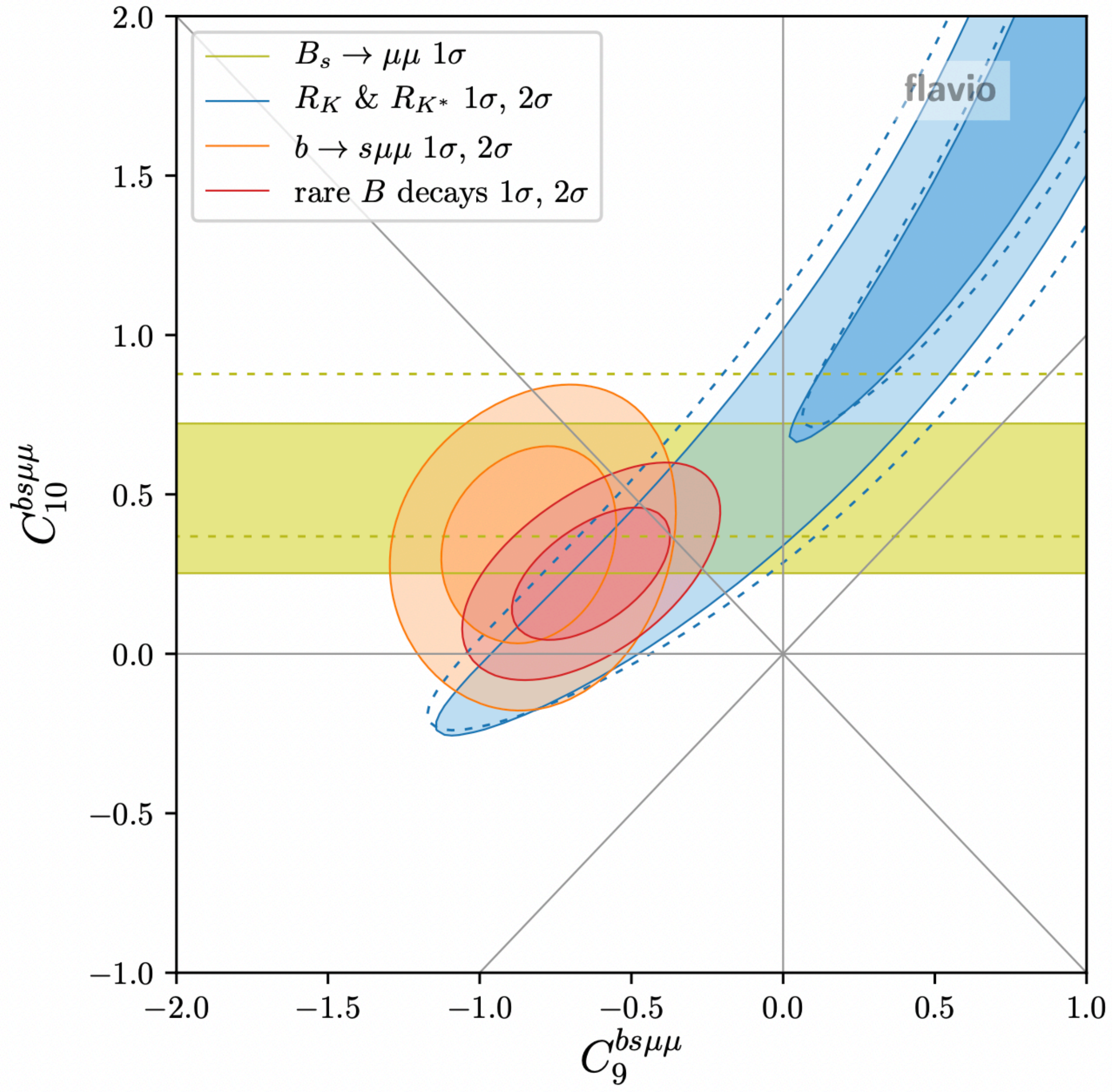
Chih-Ting Lu, Lei Wu, Yongcheng Wu, and Bin Zhu, 2204.03796



CDF W-mass shift

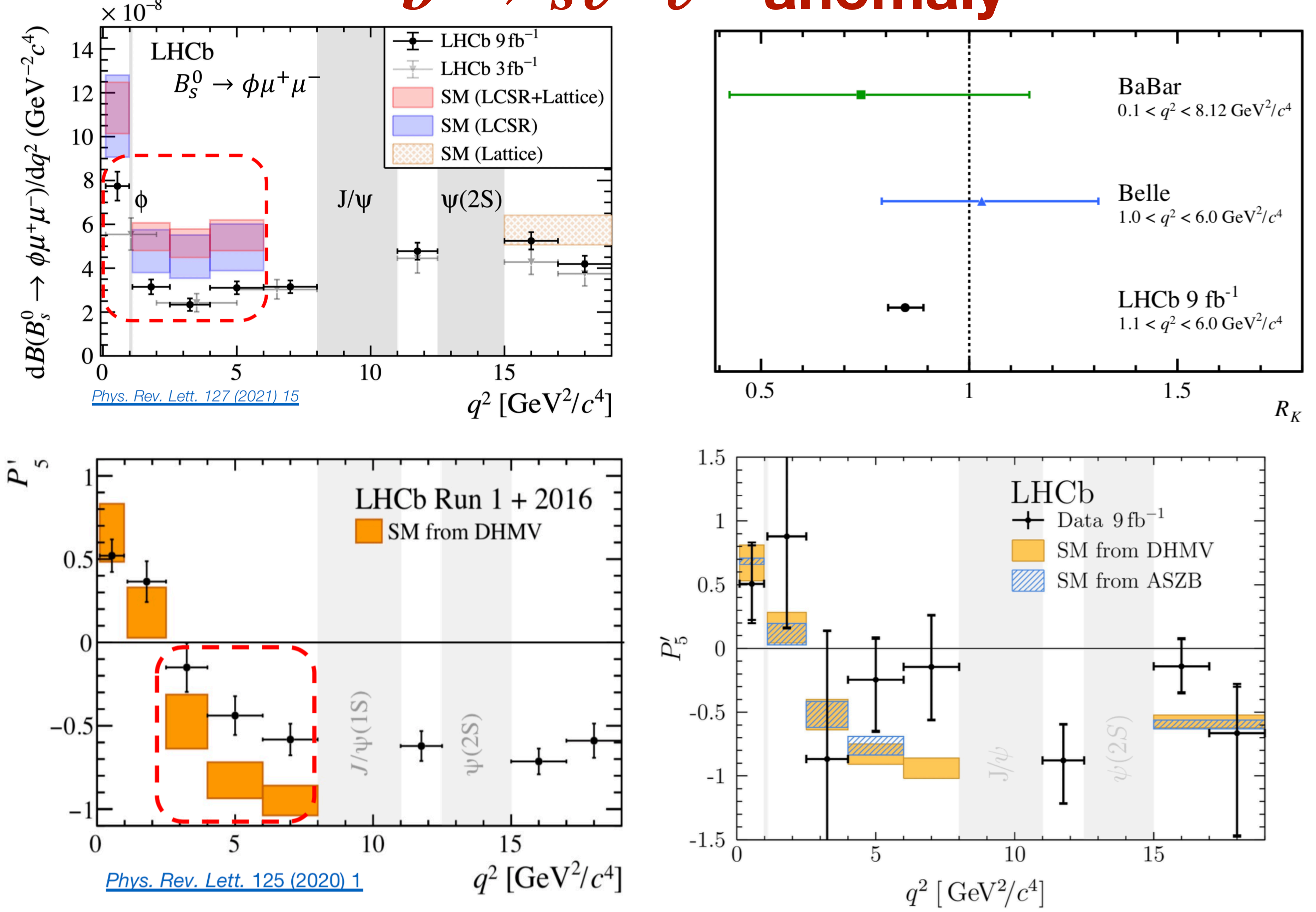


Altmannshofer, Stangl, 2103.1337

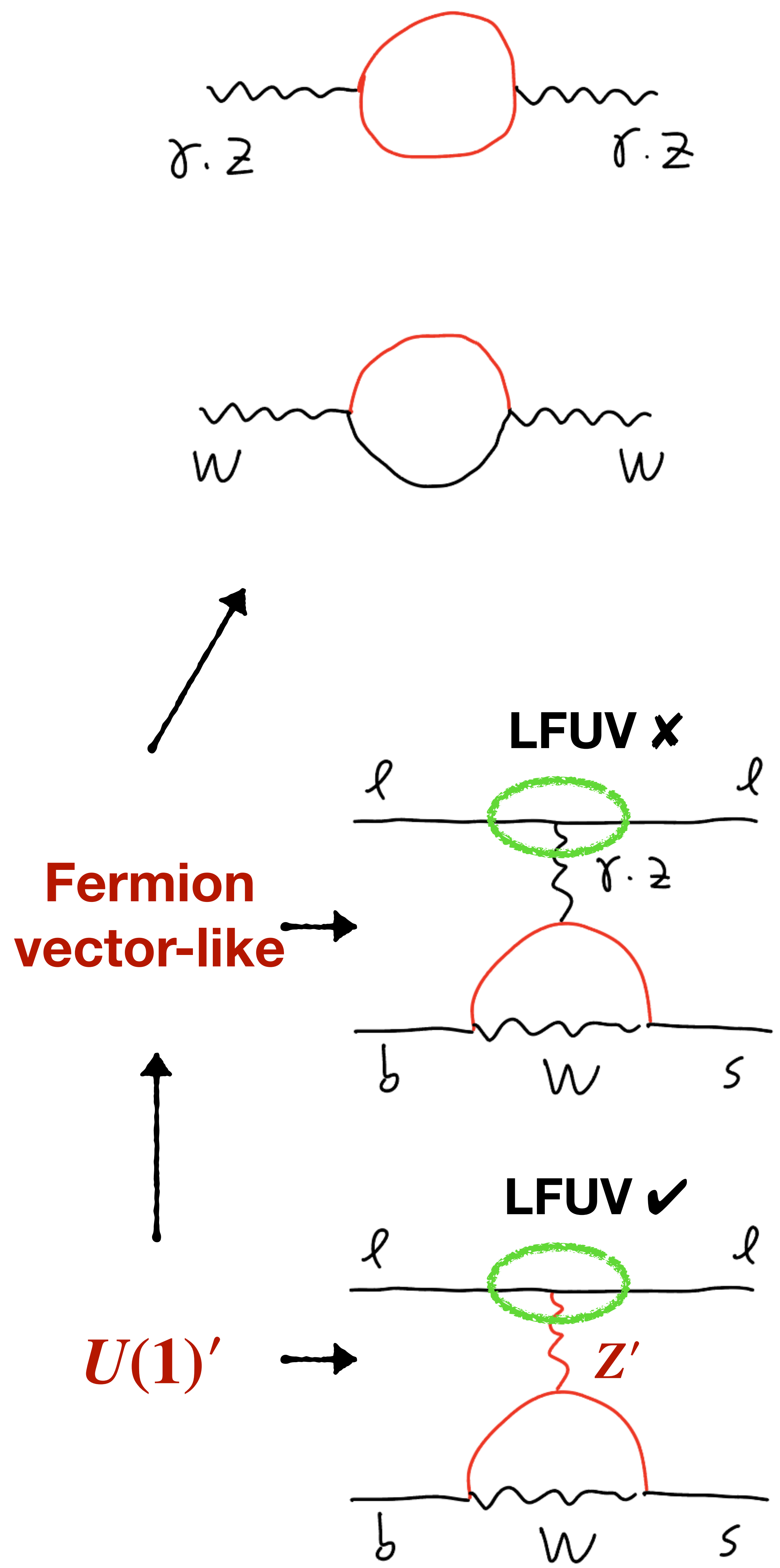


$$O_9 = (\bar{b}\gamma^\mu P_L s)(\bar{\ell}\gamma_\mu \ell) \quad O_{10} = (\bar{b}\gamma^\mu P_L s)(\bar{\ell}\gamma_\mu\gamma_5 \ell)$$

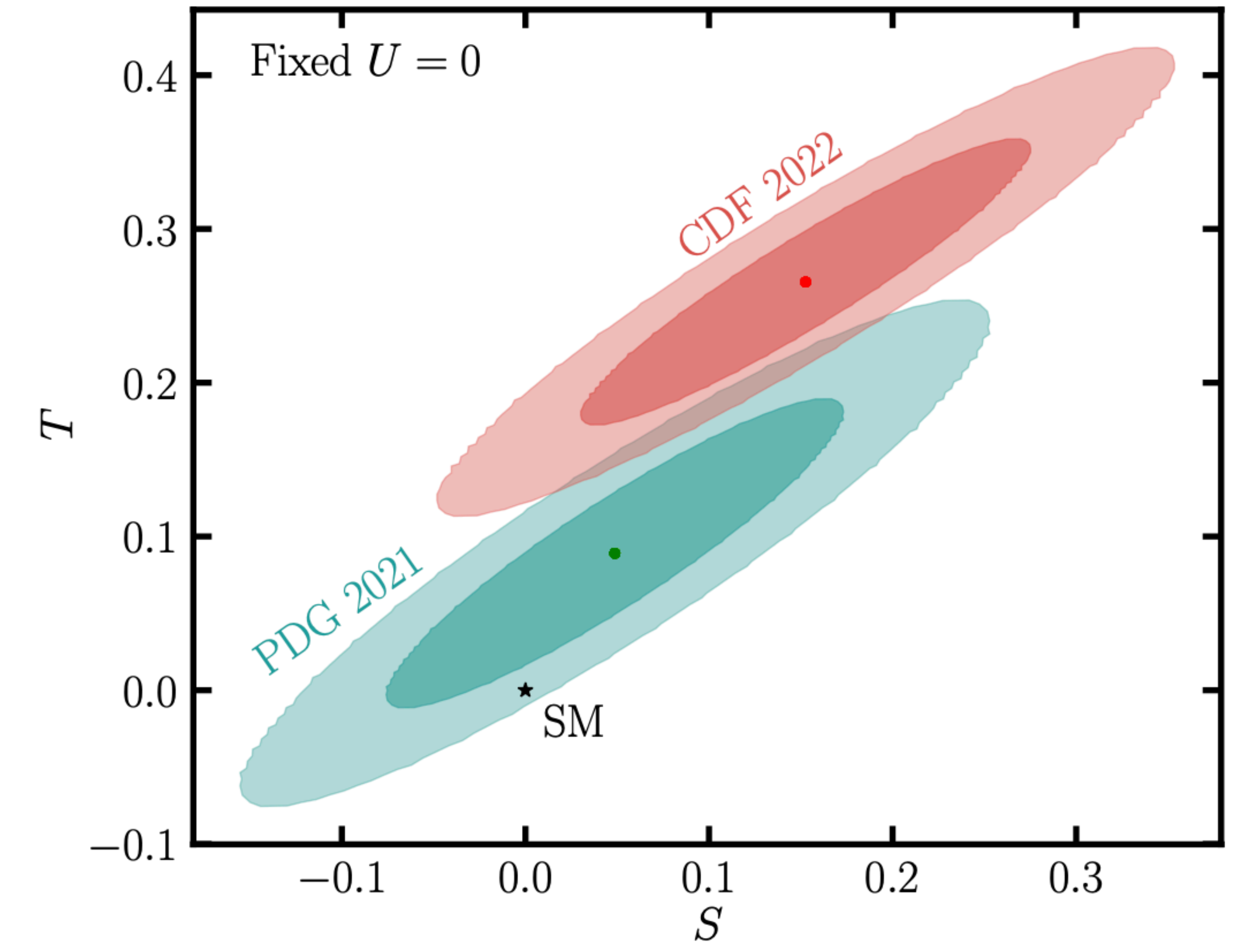
$b \to s\ell^+\ell^-$ anomaly



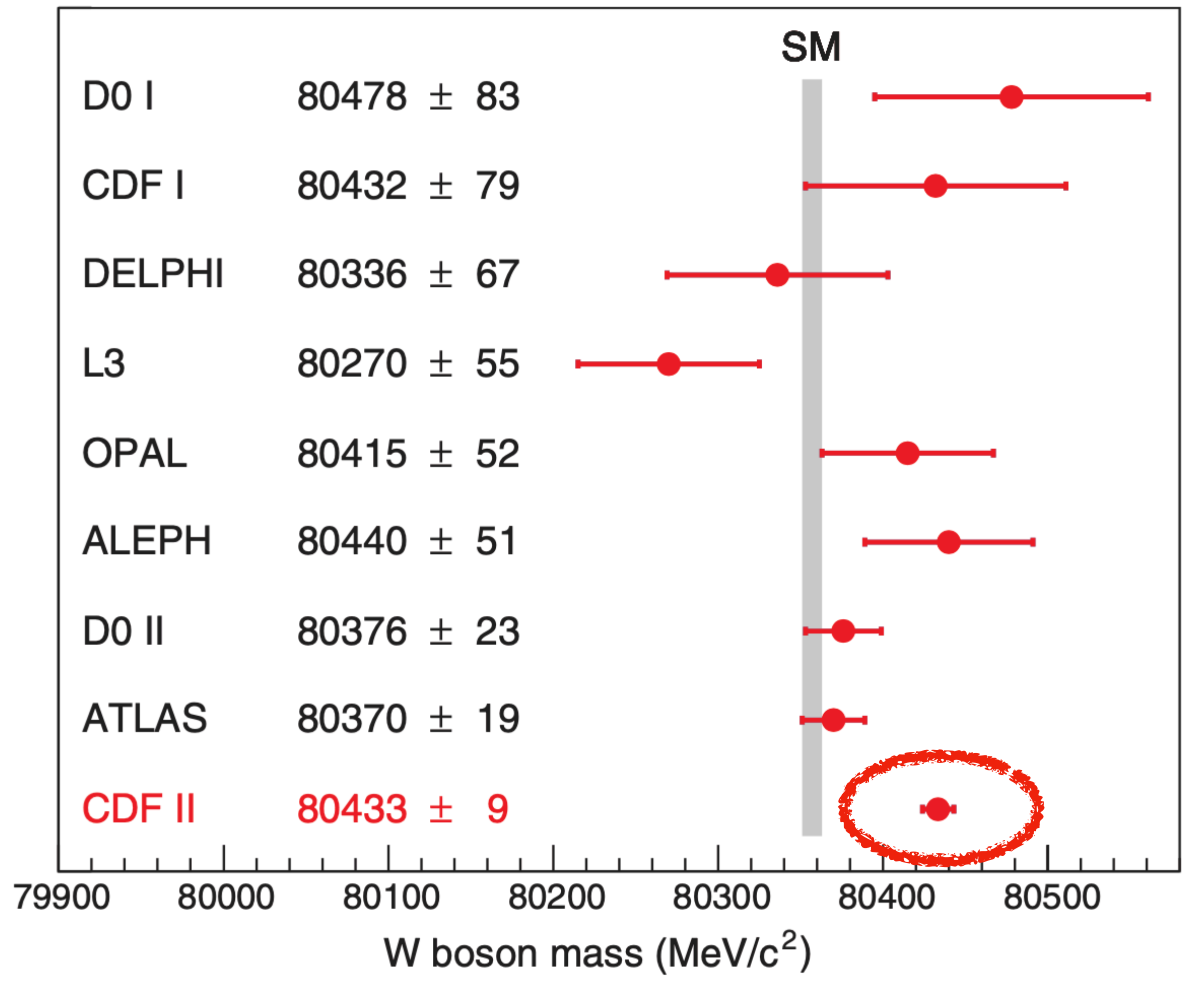
Motivation and idea



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

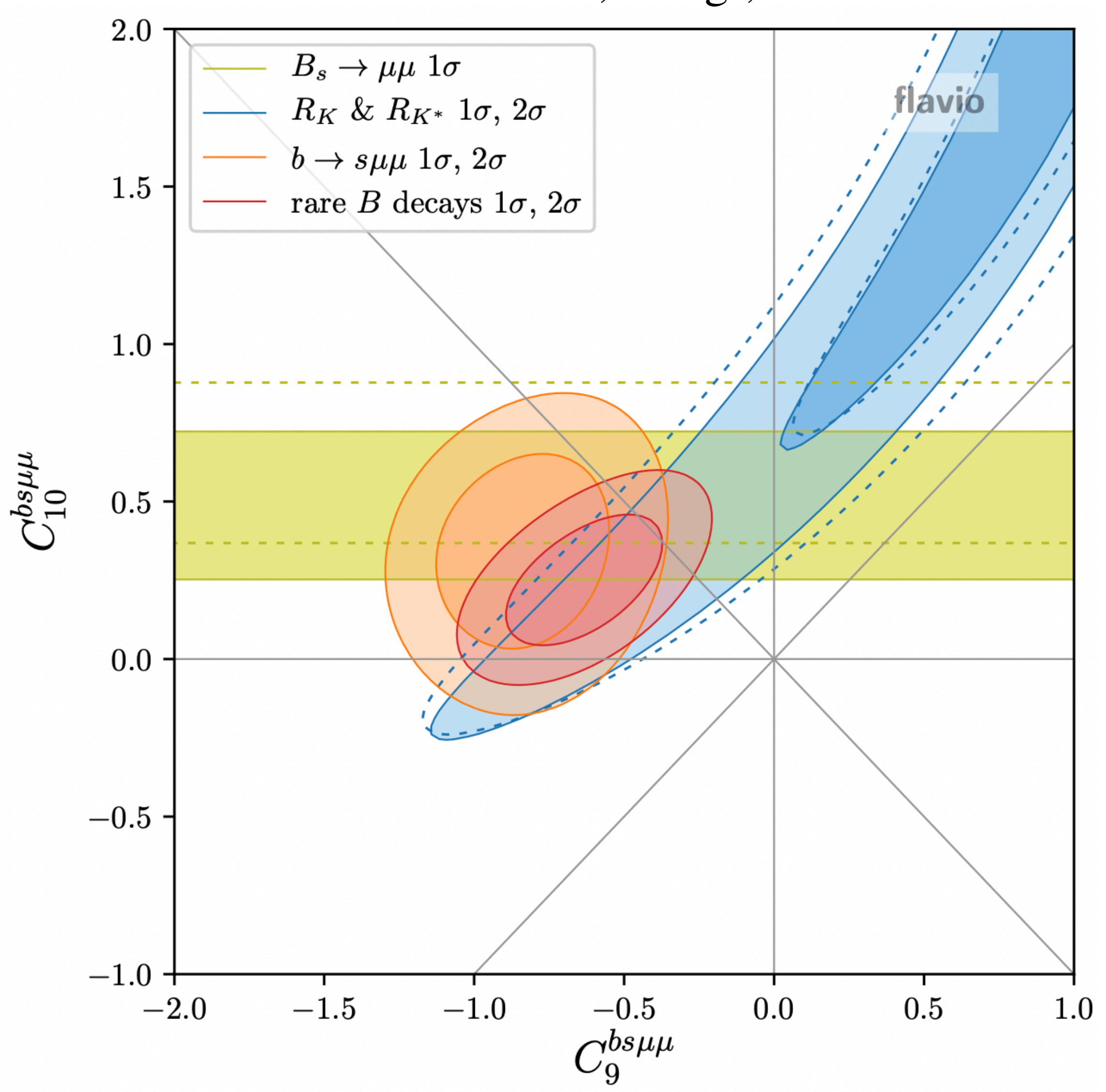


CDF W-mass shift



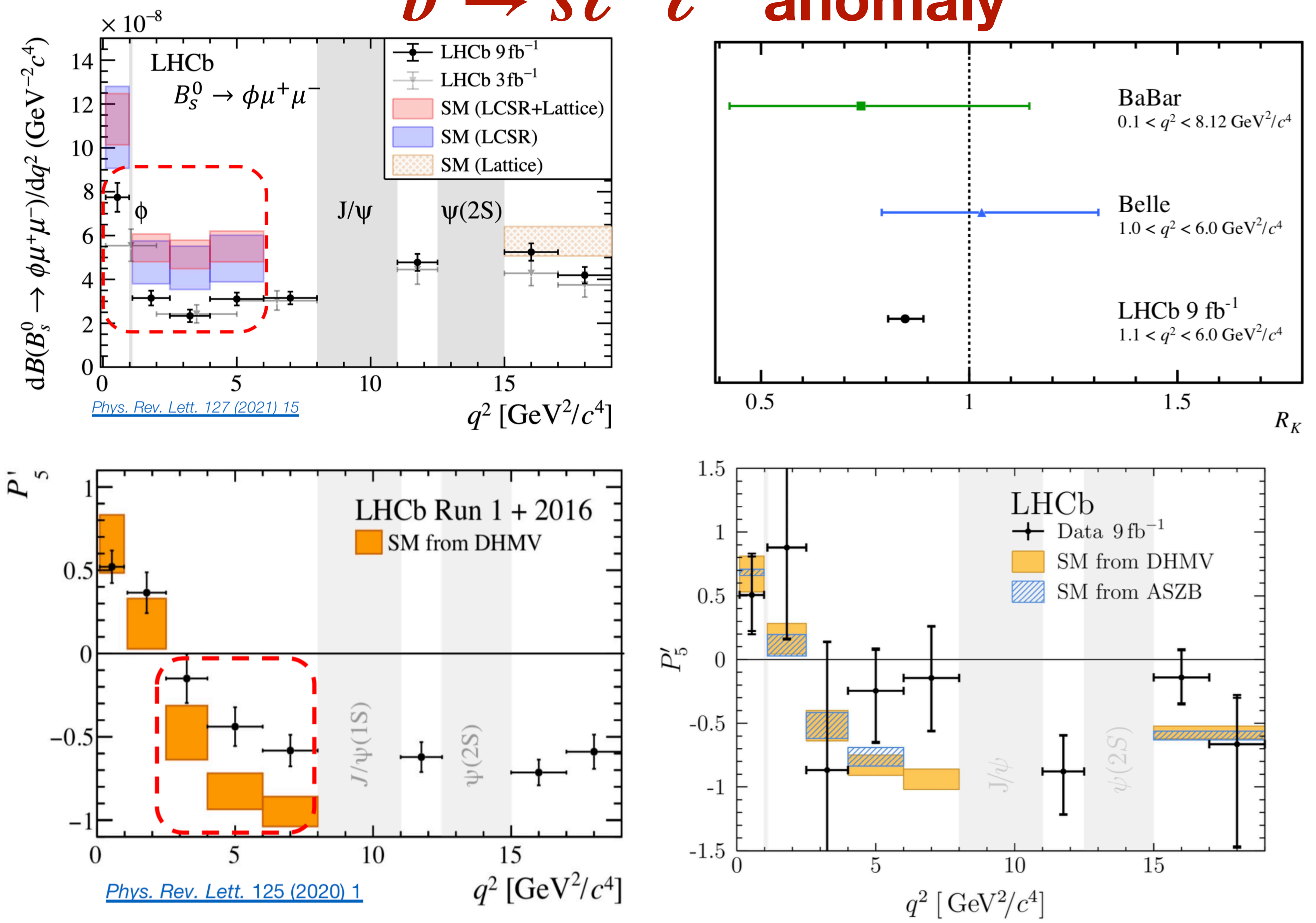
already introduced by J. F. Kamenik, Y. Soreq, J. Zupan, PRD97(2018)035002

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**

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

- **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

- **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**

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

- **Interactions**

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

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

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

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

- **lepton sector (effective coupling)**

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

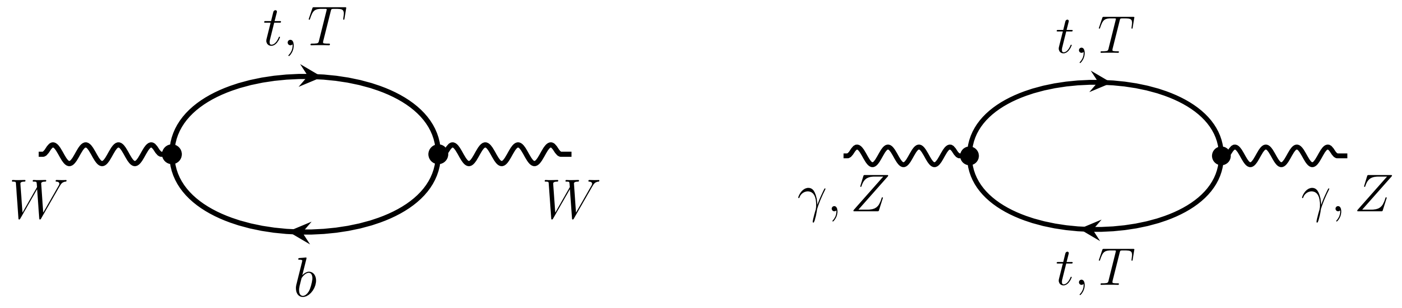
- **NP parameters**

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

W-boson mass shift and oblique parameters

Explanation in top-philic Z' scenario

- NP contributions to vacuum polarizations



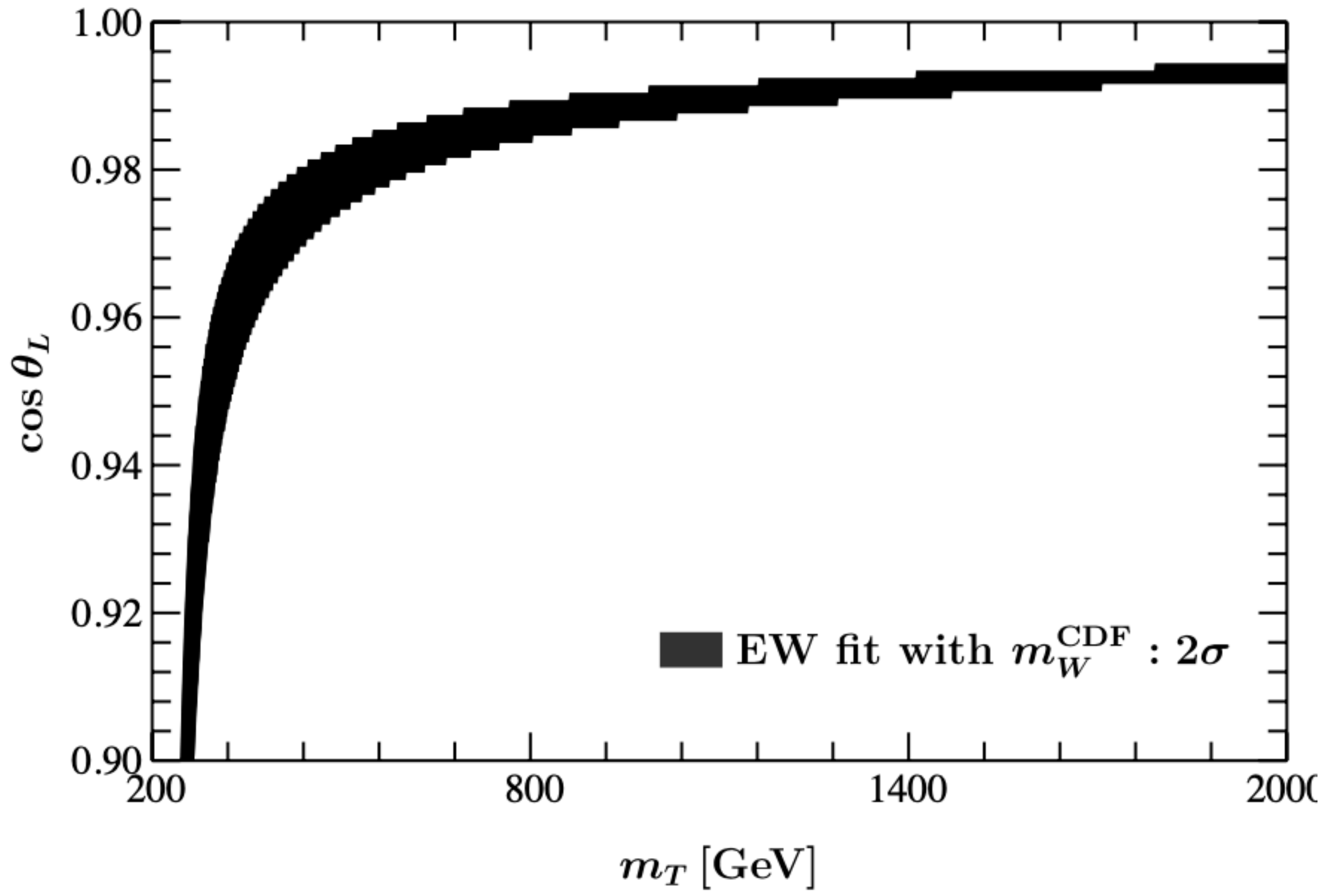
- S, T, U are affected

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

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

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

- Allowed parameter space



J. Cao, L. Meng, L. Shang, S. Wang, B. Yang, 2022
H.M. Lee, K. Yamashita, 2022
A. Crivellin, M. Kirk, T. Kitahara, F. Mescia, 2022
M. Endo, S. Mishima, 2022
R. Balkin, E. Madge, T. Menzo, G. Perez, Y. Soreq, J. Zupan, 2022

★ $m_W^{\rm CDF}$ 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.,

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

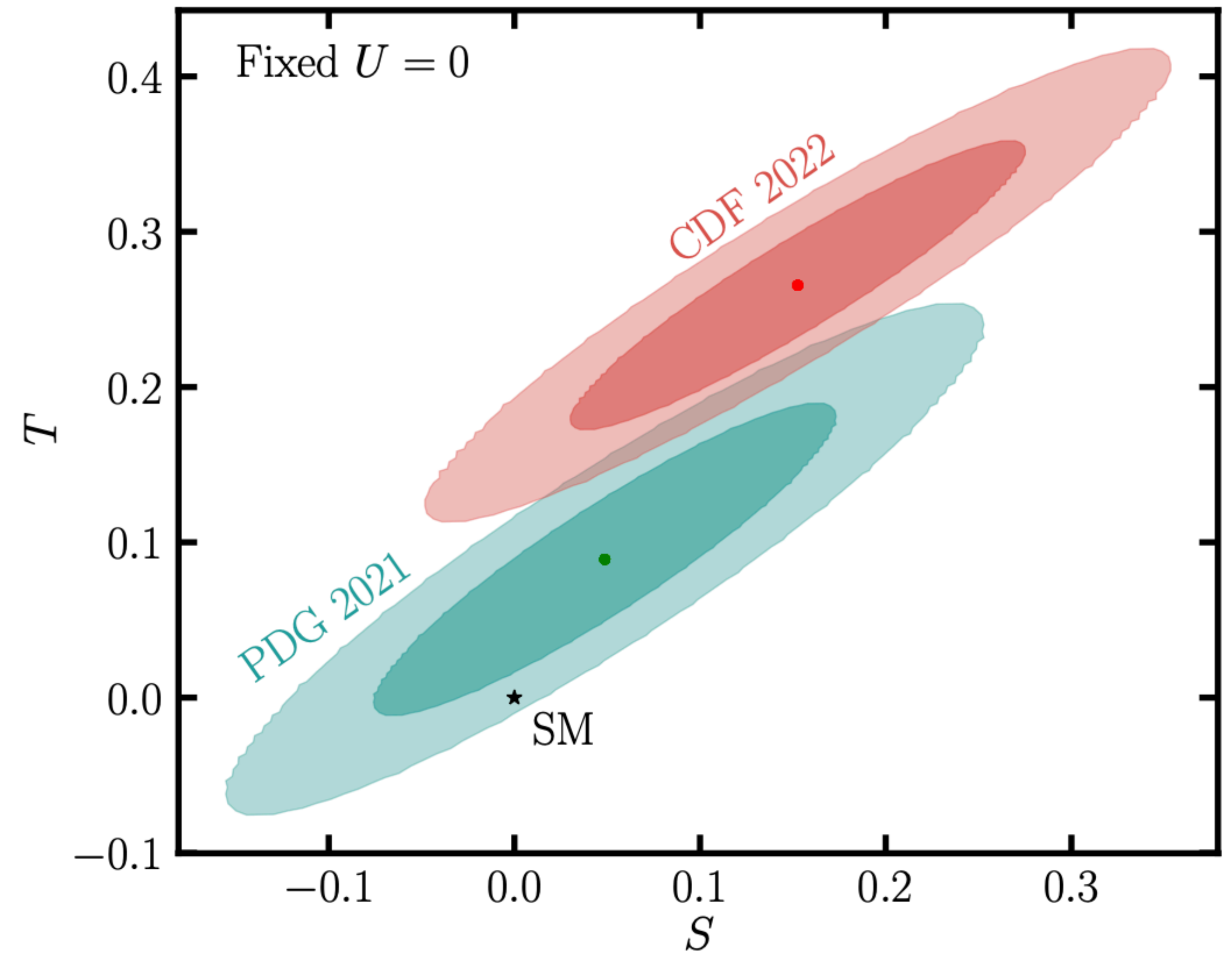
- S, T, U are related to the vacuum polarization of gauge bosons

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

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

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

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

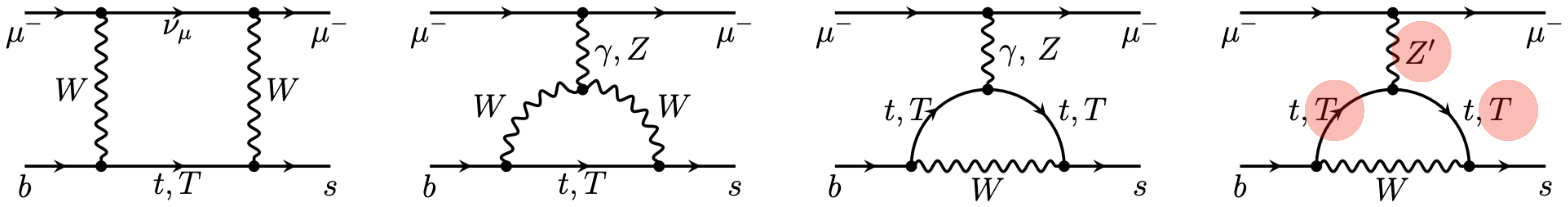


By Gfitter

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

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

- **NP contributions**



dominated

- **Effective Hamiltonian**

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

- **Wilson coefficients**

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

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

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

★ 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

- **NP parameters**

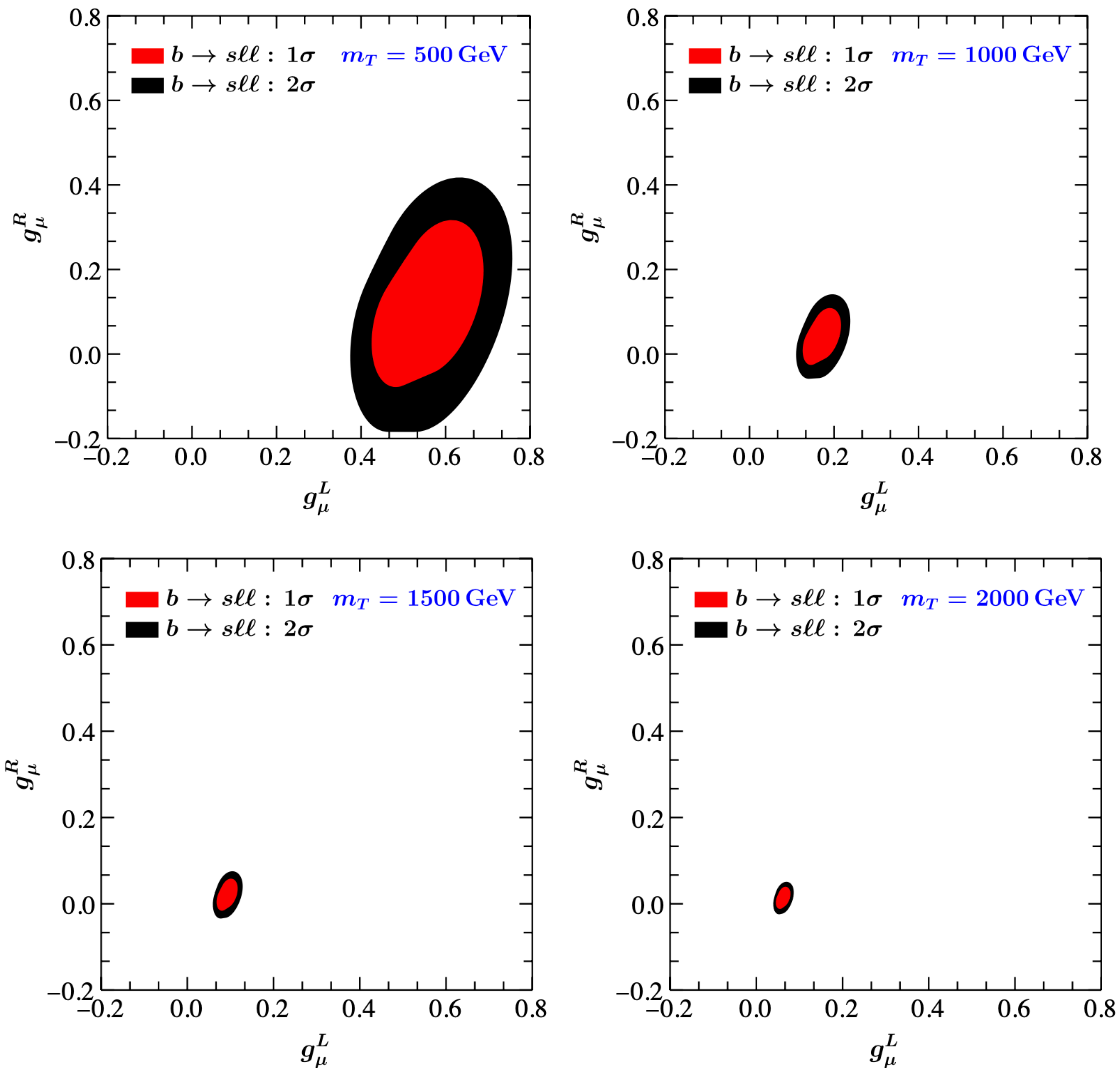
$$\left(\cos\theta_L,\, m_T,\, \frac{q_t g_t g_\mu^{L,R}}{m_{Z'}^2}\right)$$

Without loss of generality

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

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

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

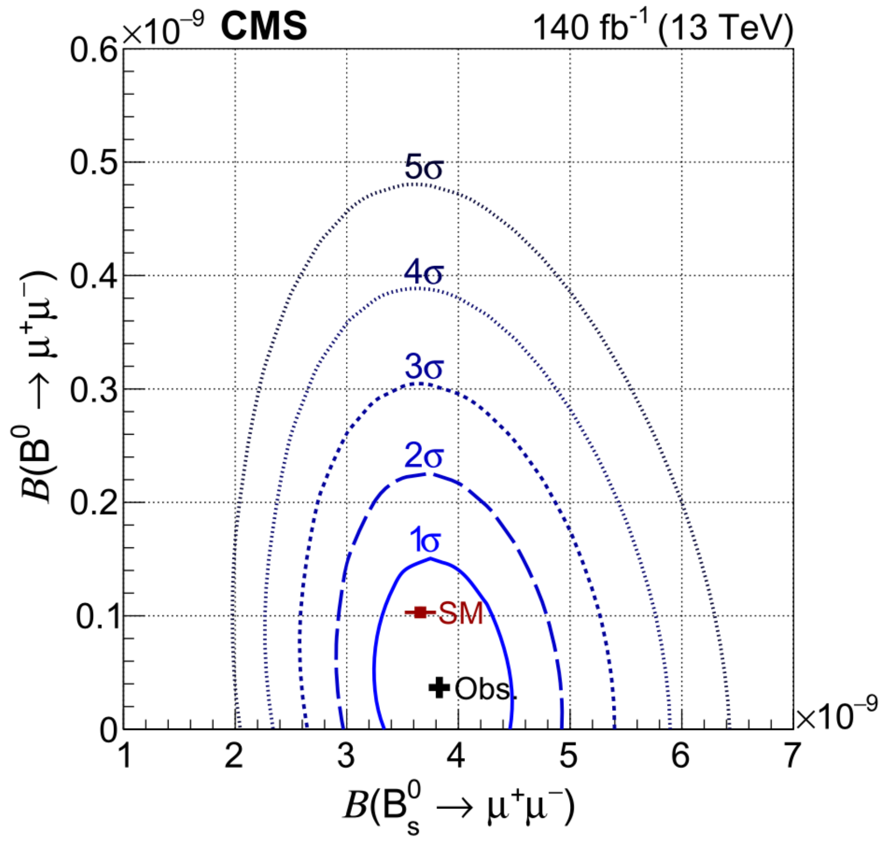
- **New CMS measurements on $B_s \to \mu^+\mu^-$**

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

Problems in this work (arXiv:2205.02205)

see also 何吉波's talk

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



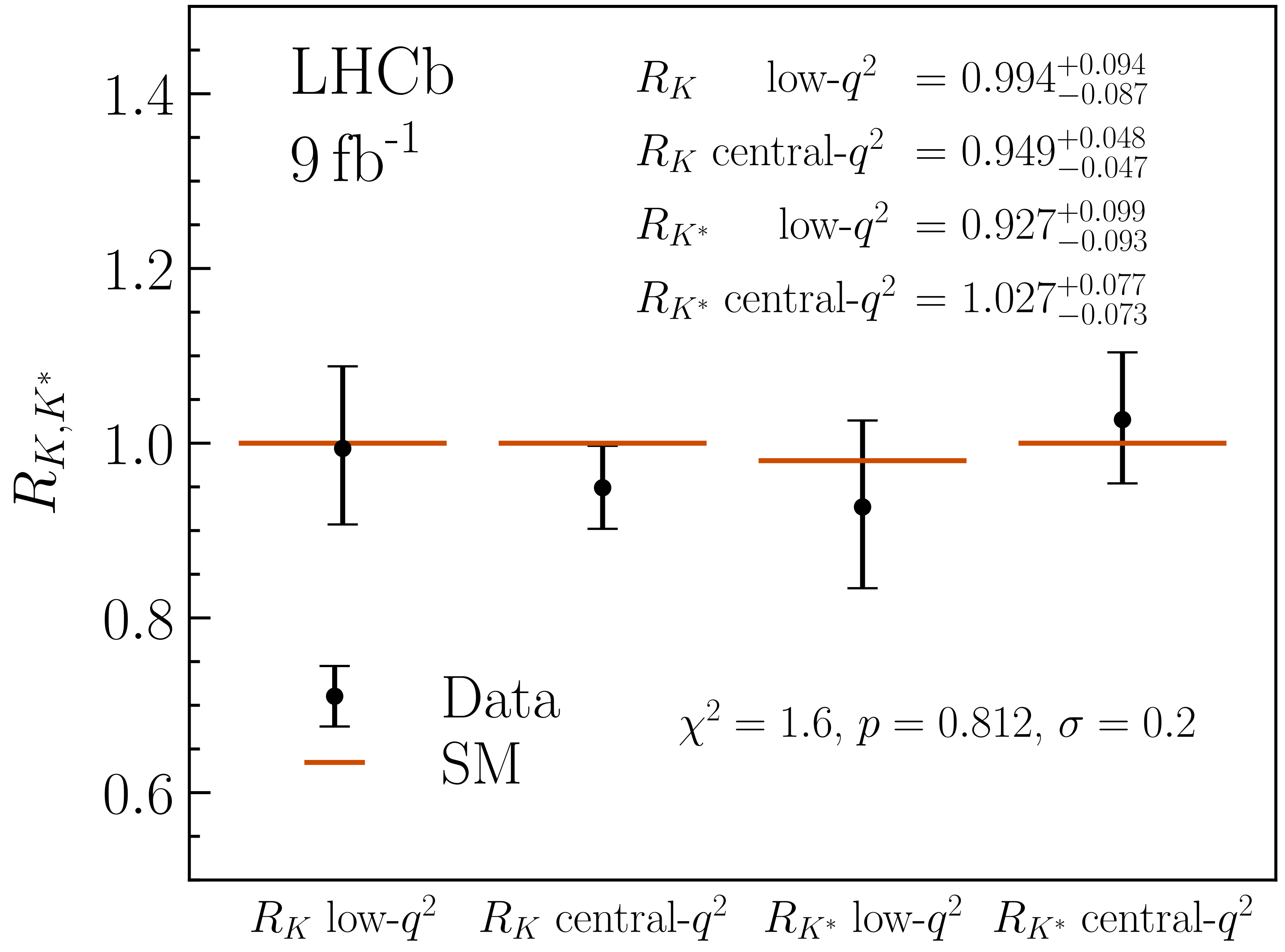
$$\mathcal{B}(B_s \to \mu^+\mu^-)_{\rm ATLAS} = (2.8^{+0.8}_{-0.7}) \times 10^{-9},$$
$$\mathcal{B}(B_s \to \mu^+\mu^-)_{\rm LHCb} = (3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9},$$
$$\mathcal{B}(B_s \to \mu^+\mu^-)_{\rm CMS} = (3.83^{+0.38+0.19+0.14}_{-0.36-0.16-0.13}) \times 10^{-9}.$$

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

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

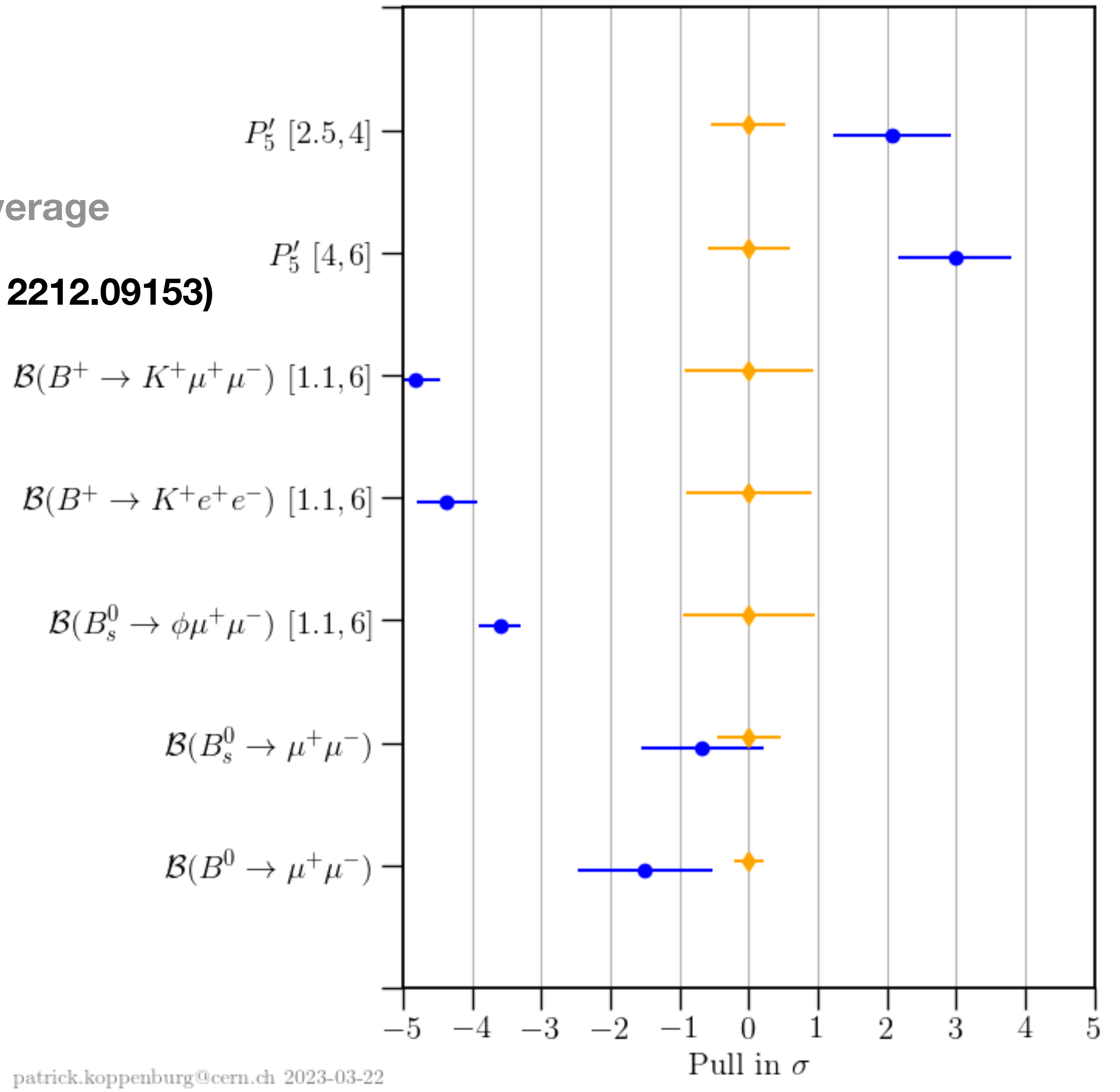
old average

- **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

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



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

1D Hyp.	All: Best fit	All: $1\sigma/2\sigma$	All: Pull_{SM}	All: 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 %

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

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

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

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

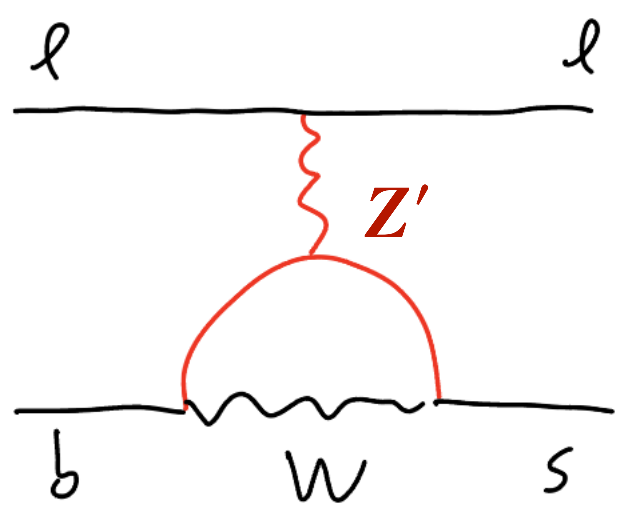
2D Hyp.	All: Best fit	All: Pull_{SM}	All: p-value
$(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{10\mu}^{\text{NP}})$	$(-0.82, -0.17)$	4.4	21.9%
$(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{7'})$	$(-0.68, +0.01)$	4.2	19.4%
$(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{9'\mu})$	$(-0.78, +0.21)$	4.3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

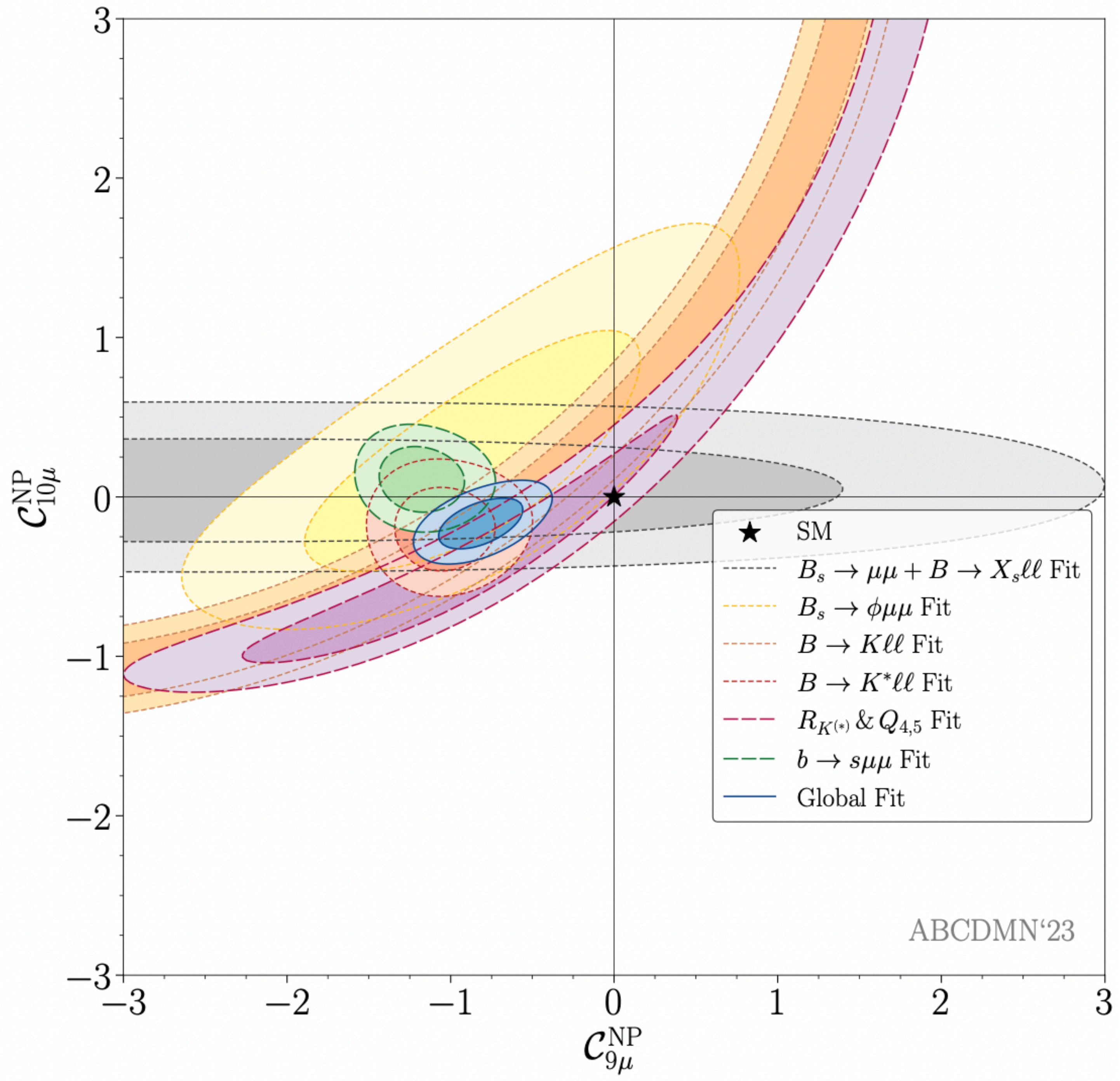
Current global fit implies $Z'\ell^+\ell^-$ interaction should be almost vector-type

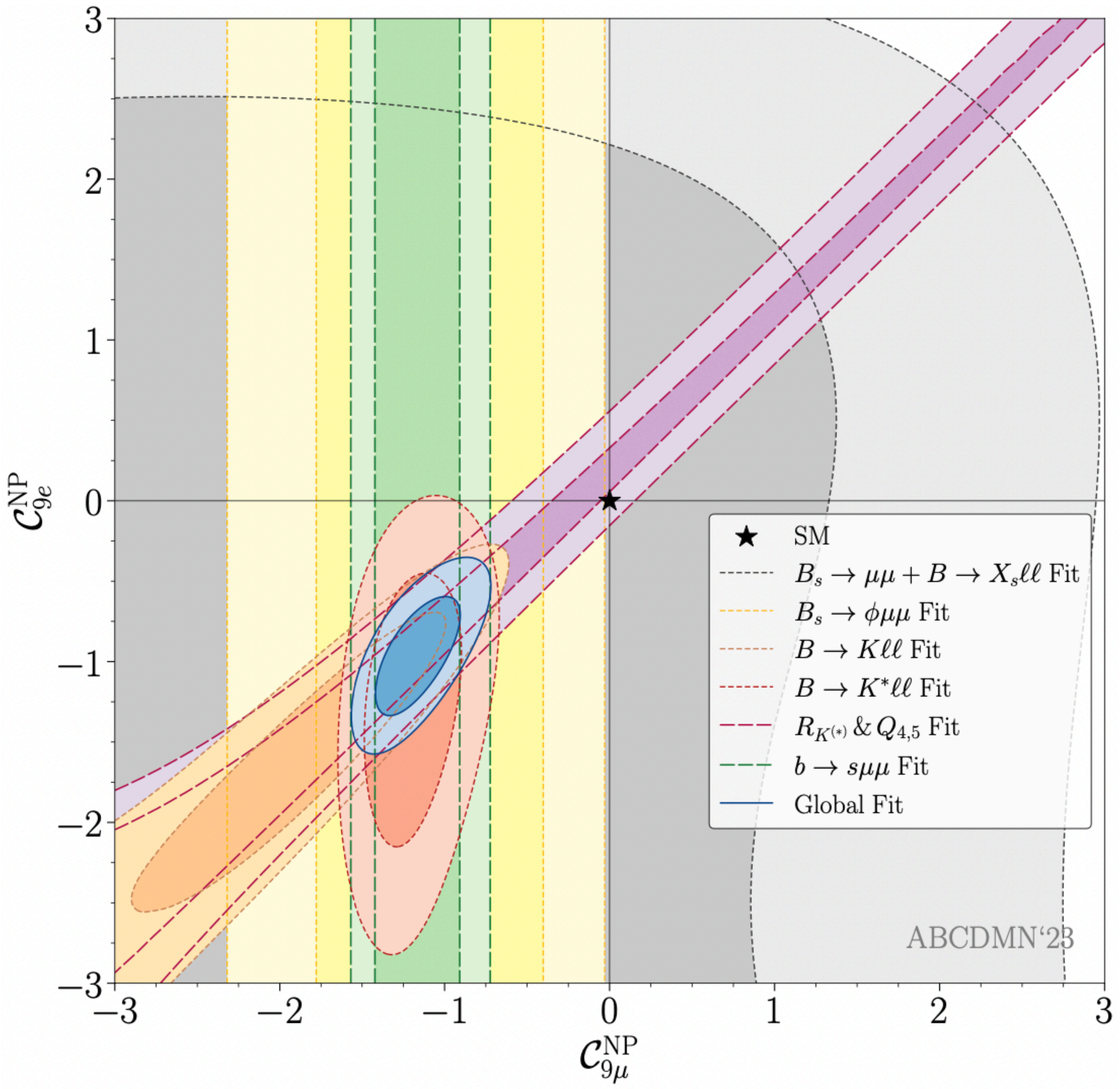
one-loop Z' contribution: $(g-2)_\mu \propto -5g_A^2 + g_V^2$

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

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





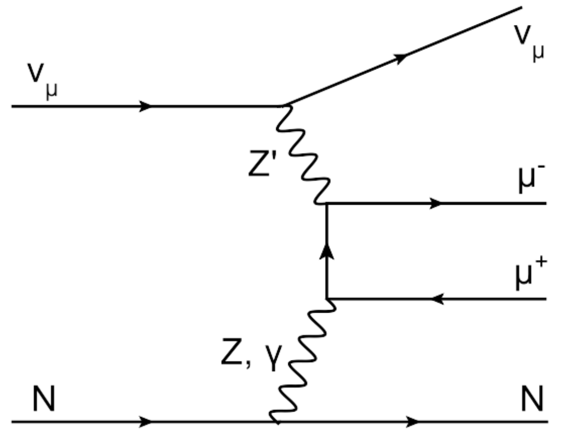


Z' model with UV-complete lepton sector

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 (for ϕ) — **induce muon partner-muon mixing** (for Φ_ℓ)

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

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

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

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

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

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

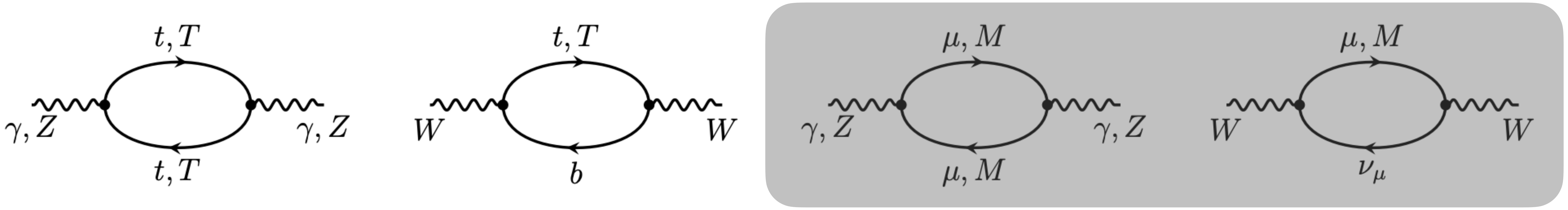
$$\mathcal{L}_Z^\ell = \frac{g}{c_W} \left(\bar{\mu}_L, \bar{M}_L \right) \begin{pmatrix} -\frac{1}{2}\hat{c}_L^2 + s_W^2 & -\frac{1}{2}\hat{s}_L\hat{c}_L \\ -\frac{1}{2}\hat{s}_L\hat{c}_L & -\frac{1}{2}\hat{s}_L^2 + s_W^2 \end{pmatrix} \not{Z} \begin{pmatrix} \mu_L \\ M_L \end{pmatrix} + \frac{g}{c_W}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

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

$$sin\delta_L < 0.01$$

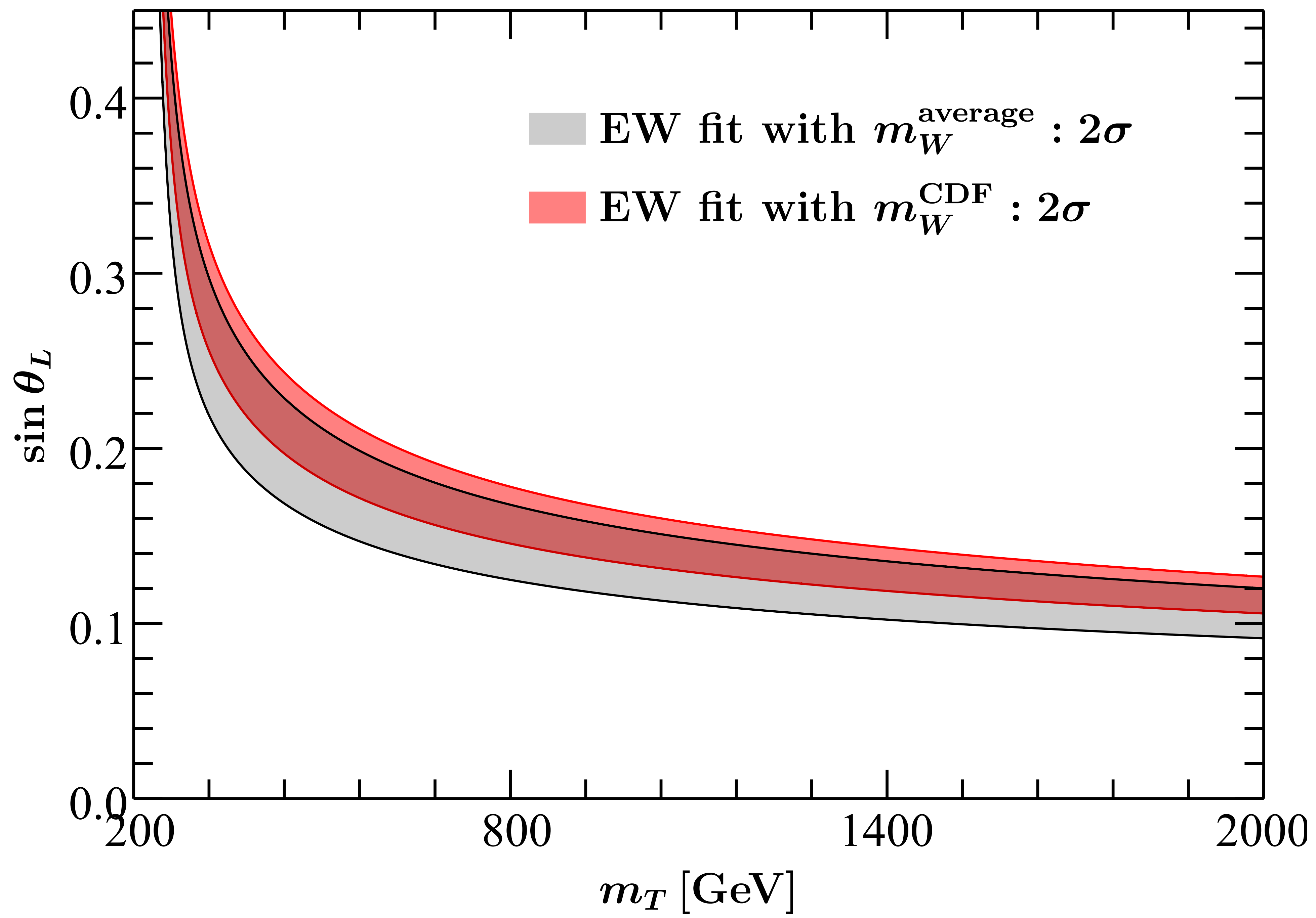
W-boson mass shift

- **Feynman diagrams**



highly suppressed by small δ_L

- **Result**



same with the previous work

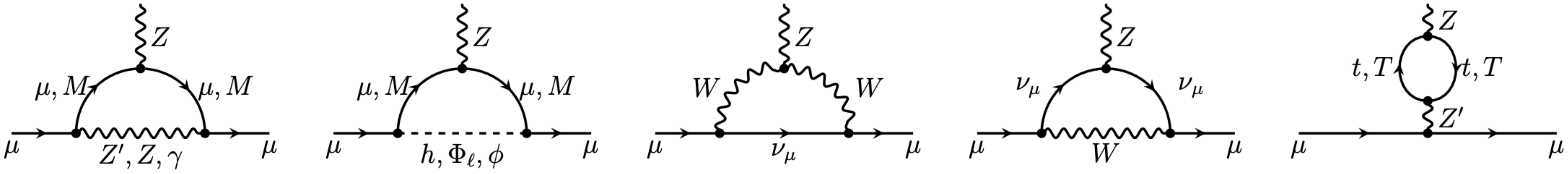
$Z \to \mu^+\mu^-$

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

mass **interaction**

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

- **Feynman diagrams**



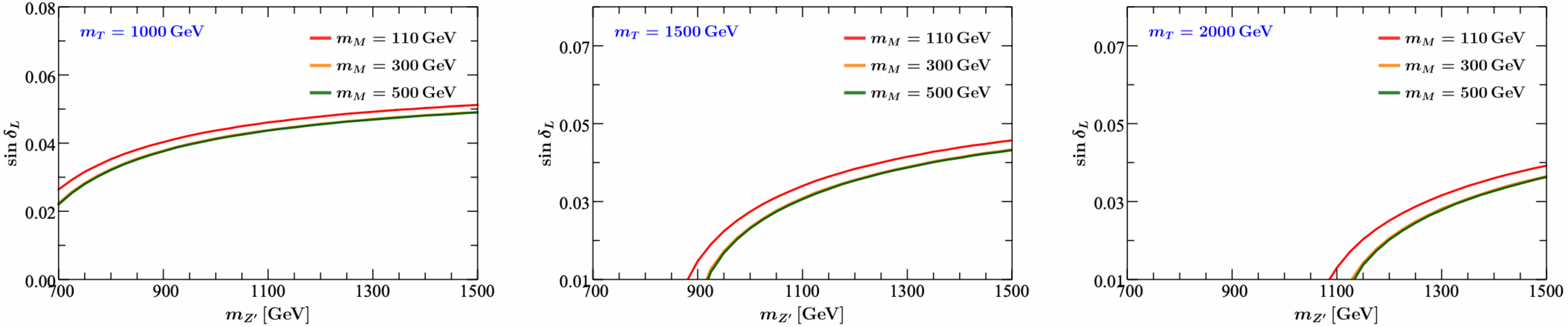
- **Effective couplings**

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

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

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

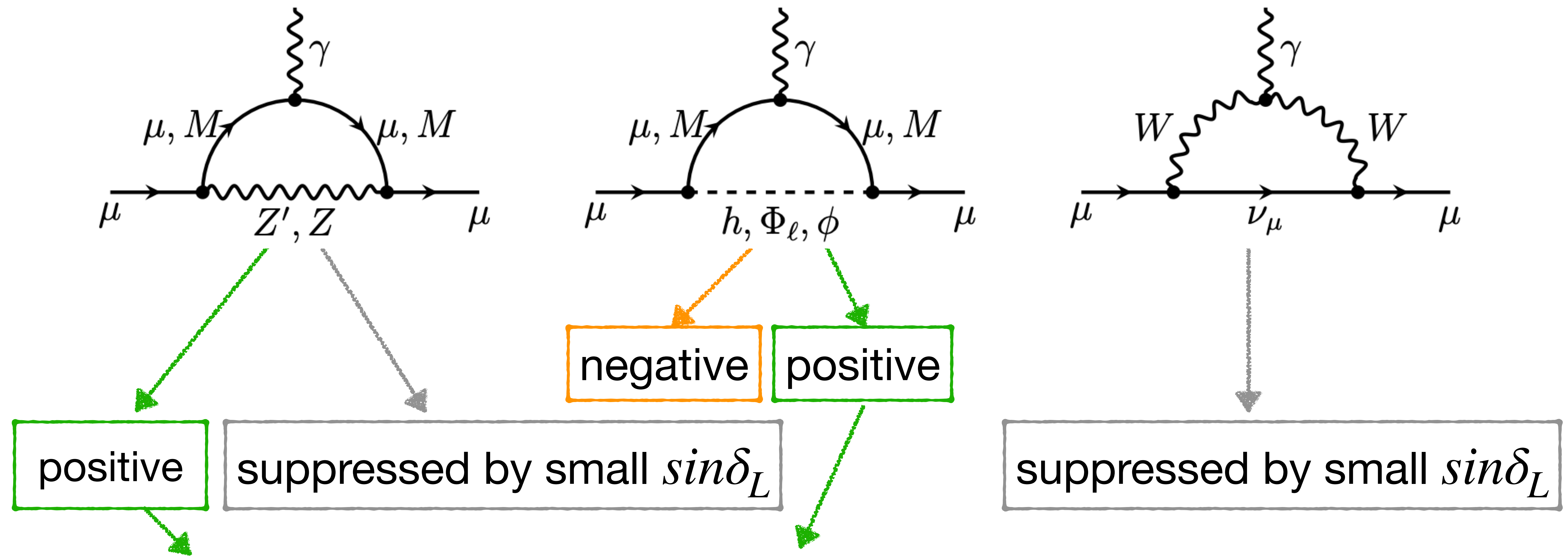
- **Constraints: m_W and $Z \to \mu^+\mu^-$**



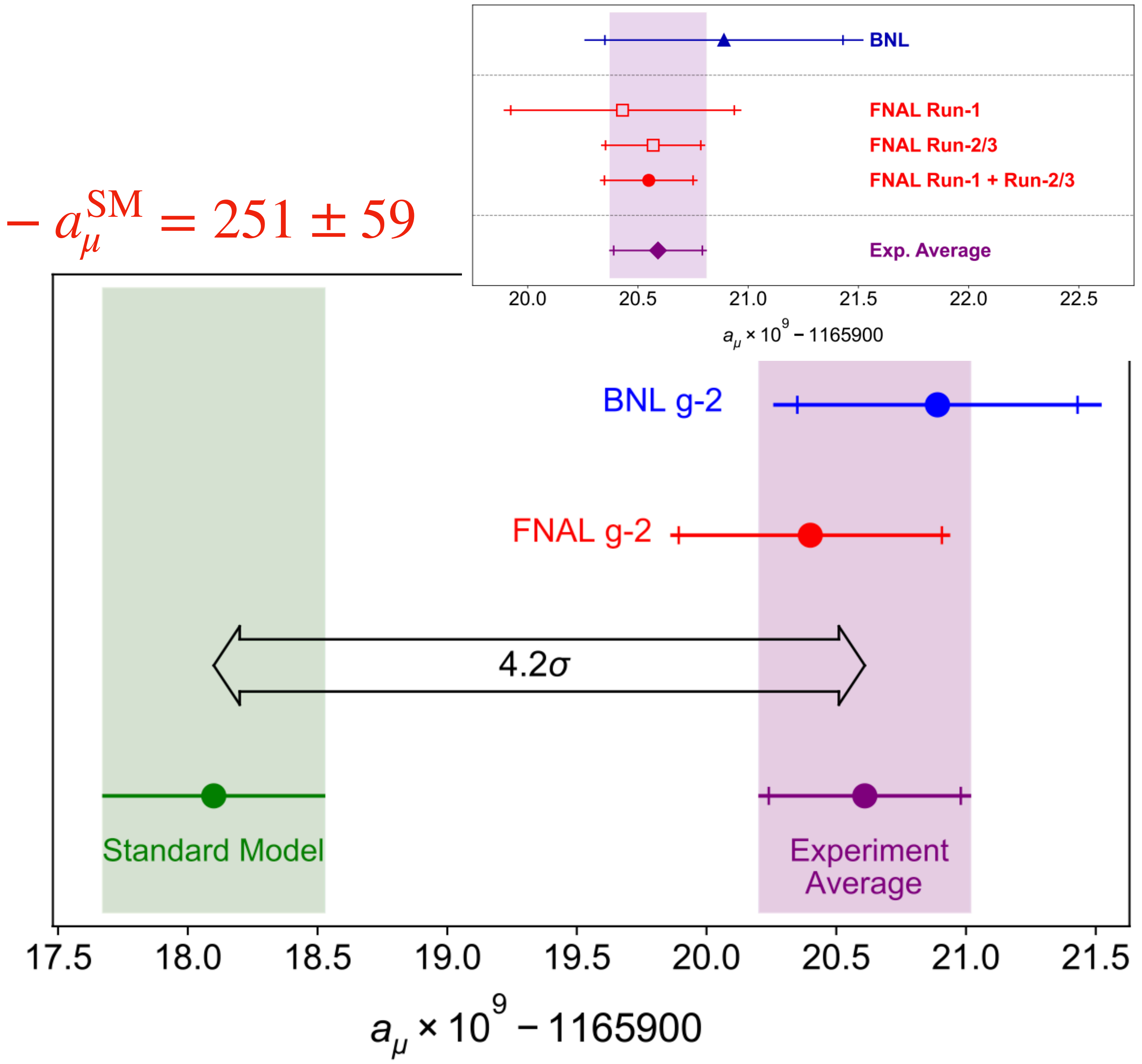
$\sin\delta_L < 0.05$ is obtained. However, $\sin\delta_L < 0.01$ is considered for simplicity.

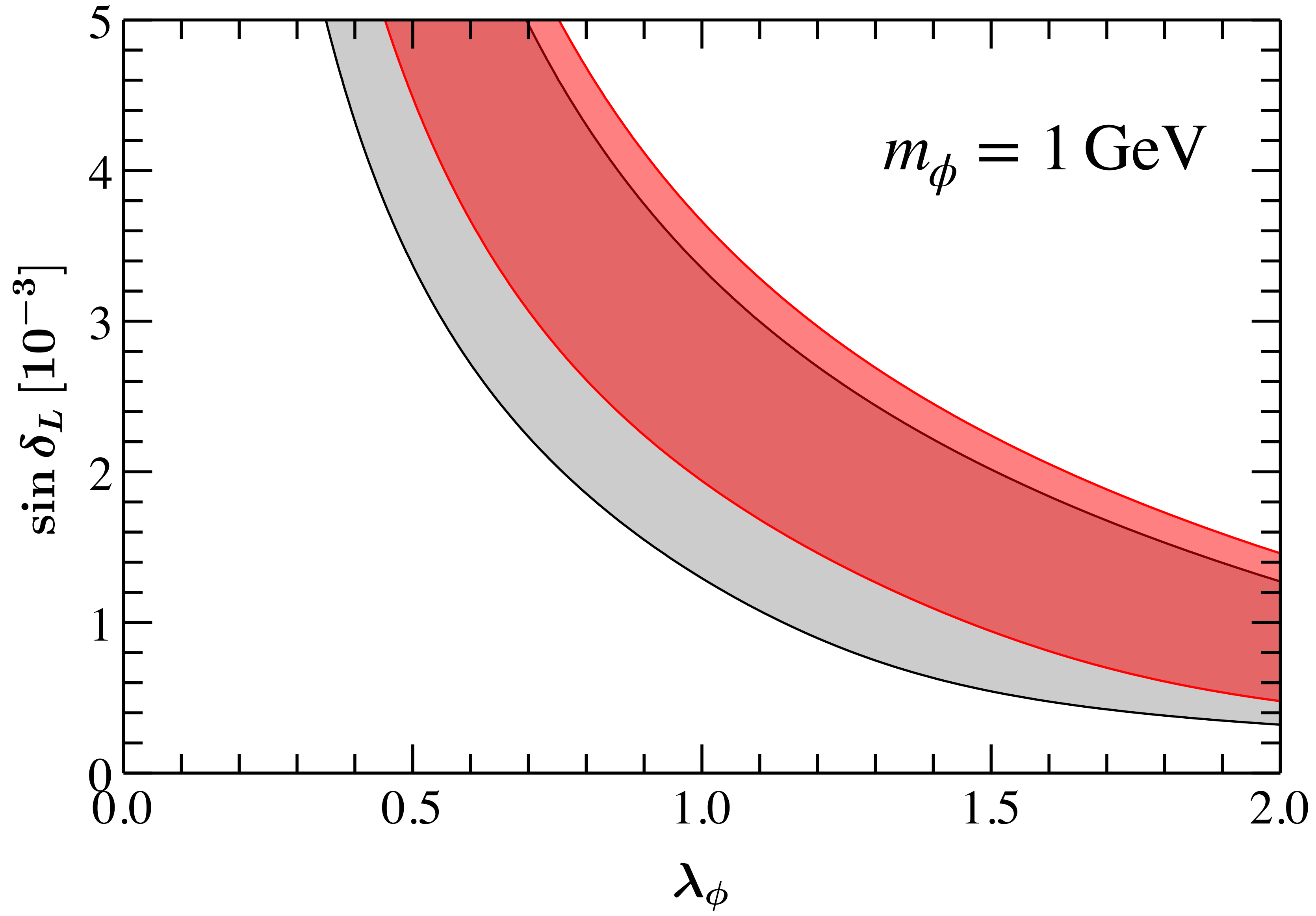
$(g-2)_\mu$

- **Feynman diagrams**



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





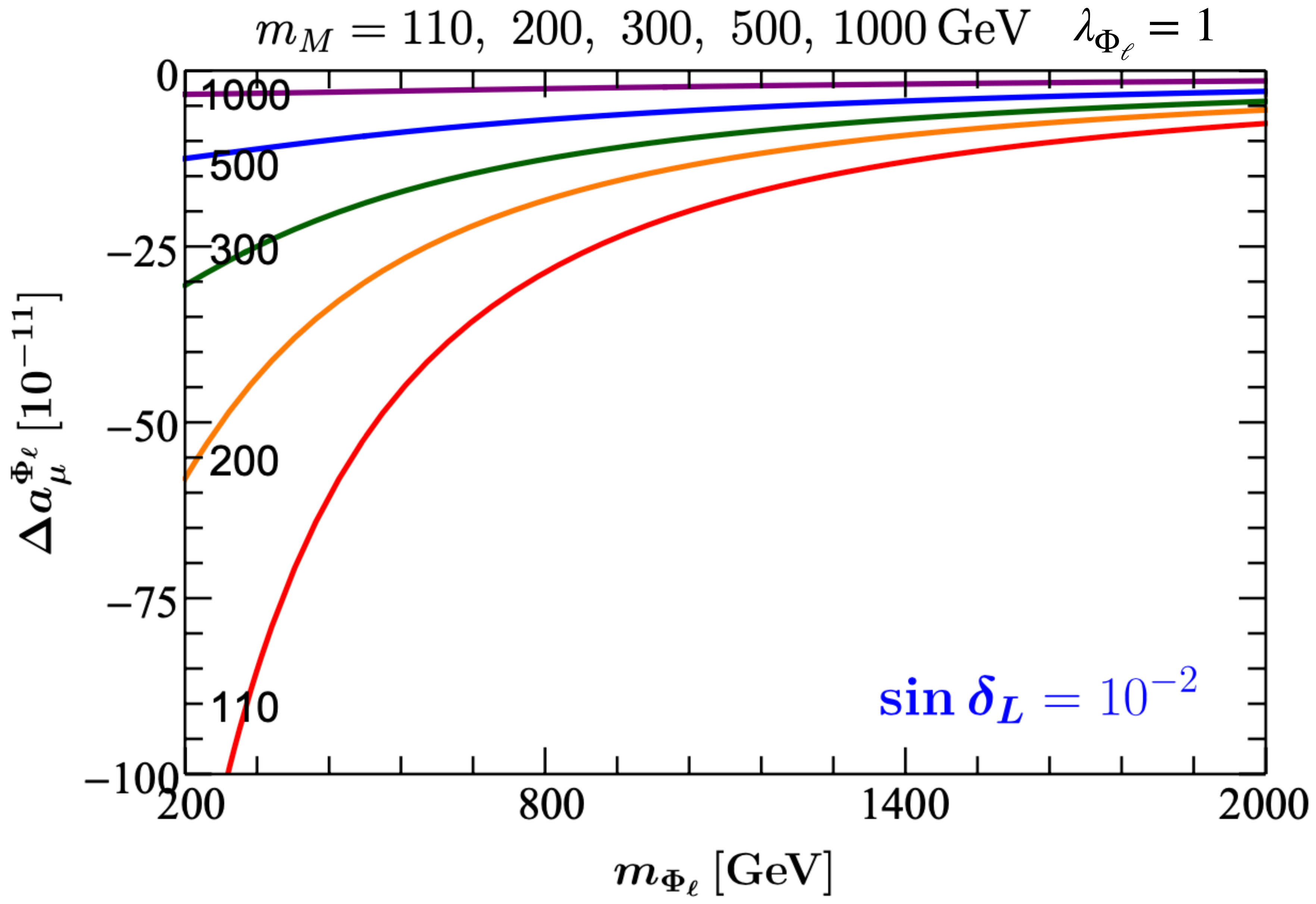
$2\,\sigma$ **allowed region**

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

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

$\sin\delta_L$ is lower bounded

$3.2\times10^{-4} < \sin\delta_L < 1.0\times10^{-2}$



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

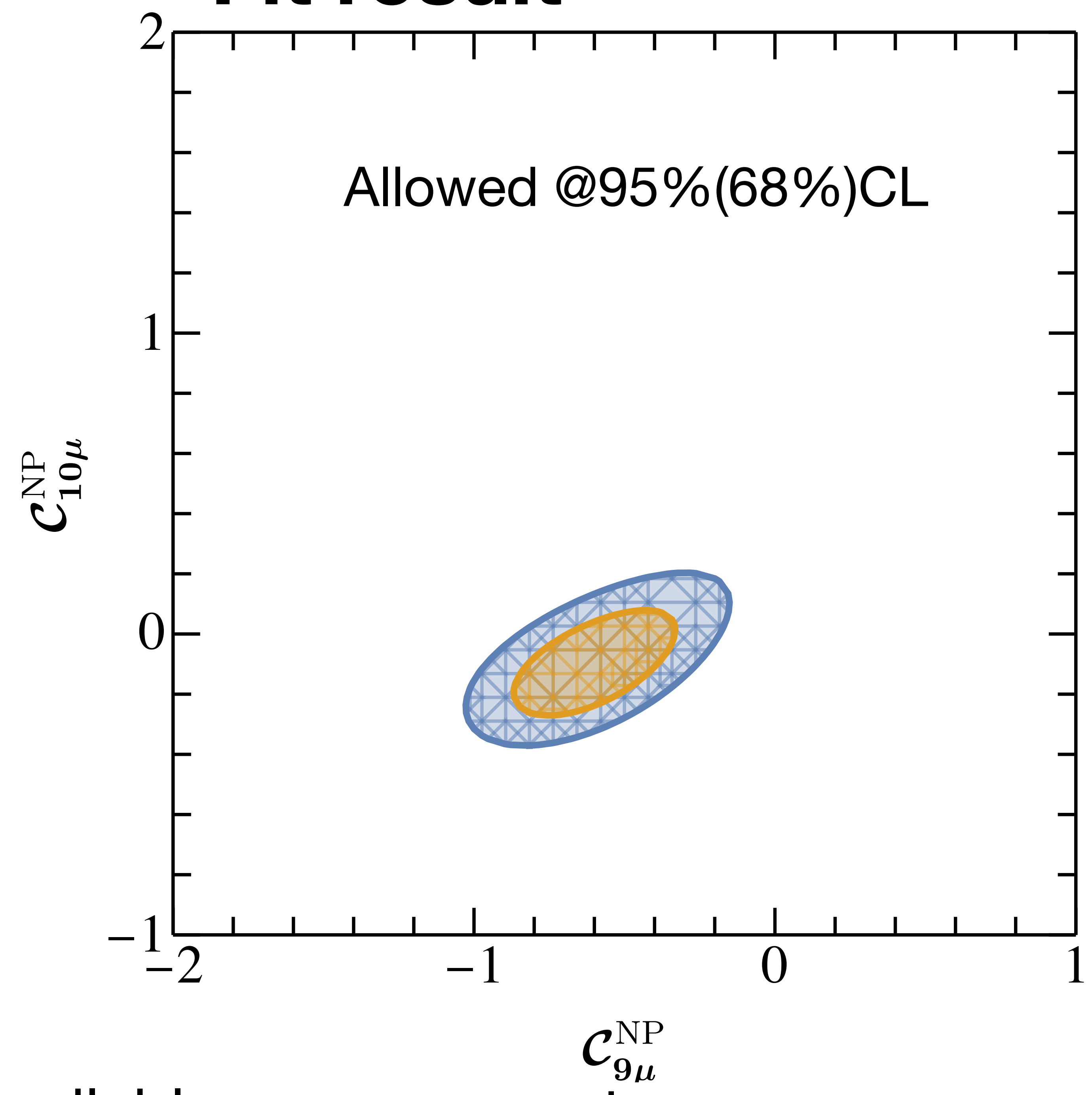
Global fit: $b \to s\ell^+\ell^-$

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

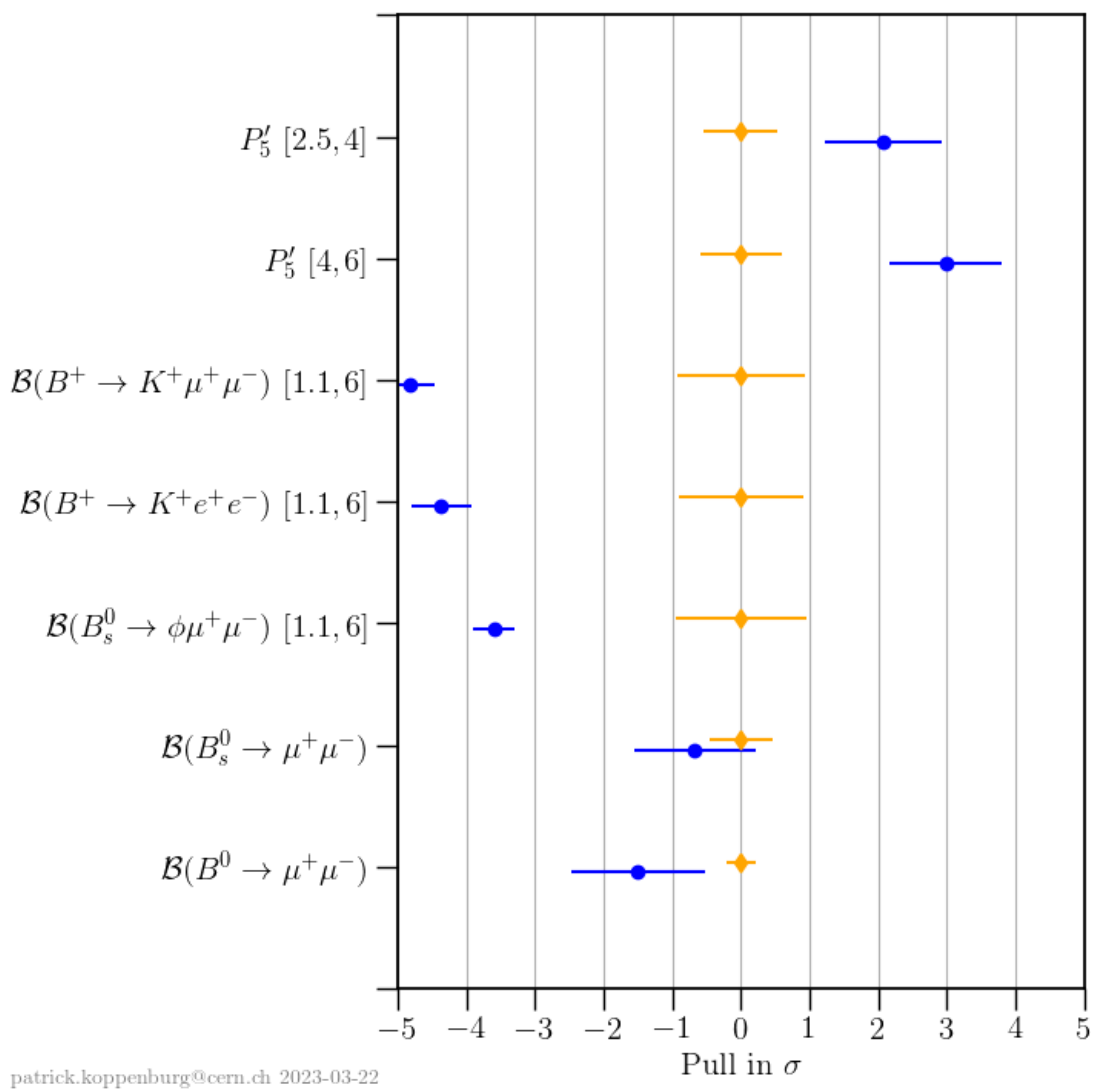
Global fit

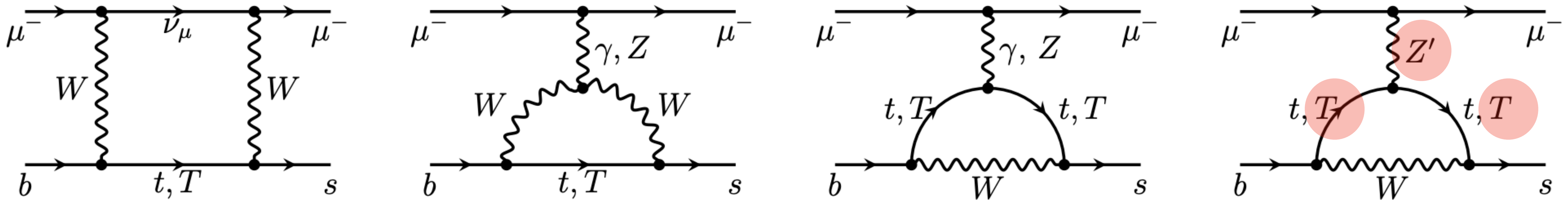
- Inclusive decays
  - $B \to X_s\gamma$
  - $B \to X_s\ell^+\ell^-$
- Exclusive leptonic decays
  - $B_{s,d} \to \ell^+\ell^-$
- Exclusive radiative/semileptonic decays
  - $B \to K^*\gamma$
  - $B^{(0,+} \to K^{(0,+)}\ell^+\ell^-$
  - $B^{(0,+} \to K^{*(0,+)}\ell^+\ell^-$
  - $B_s \to \phi\mu^+\mu^-$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





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

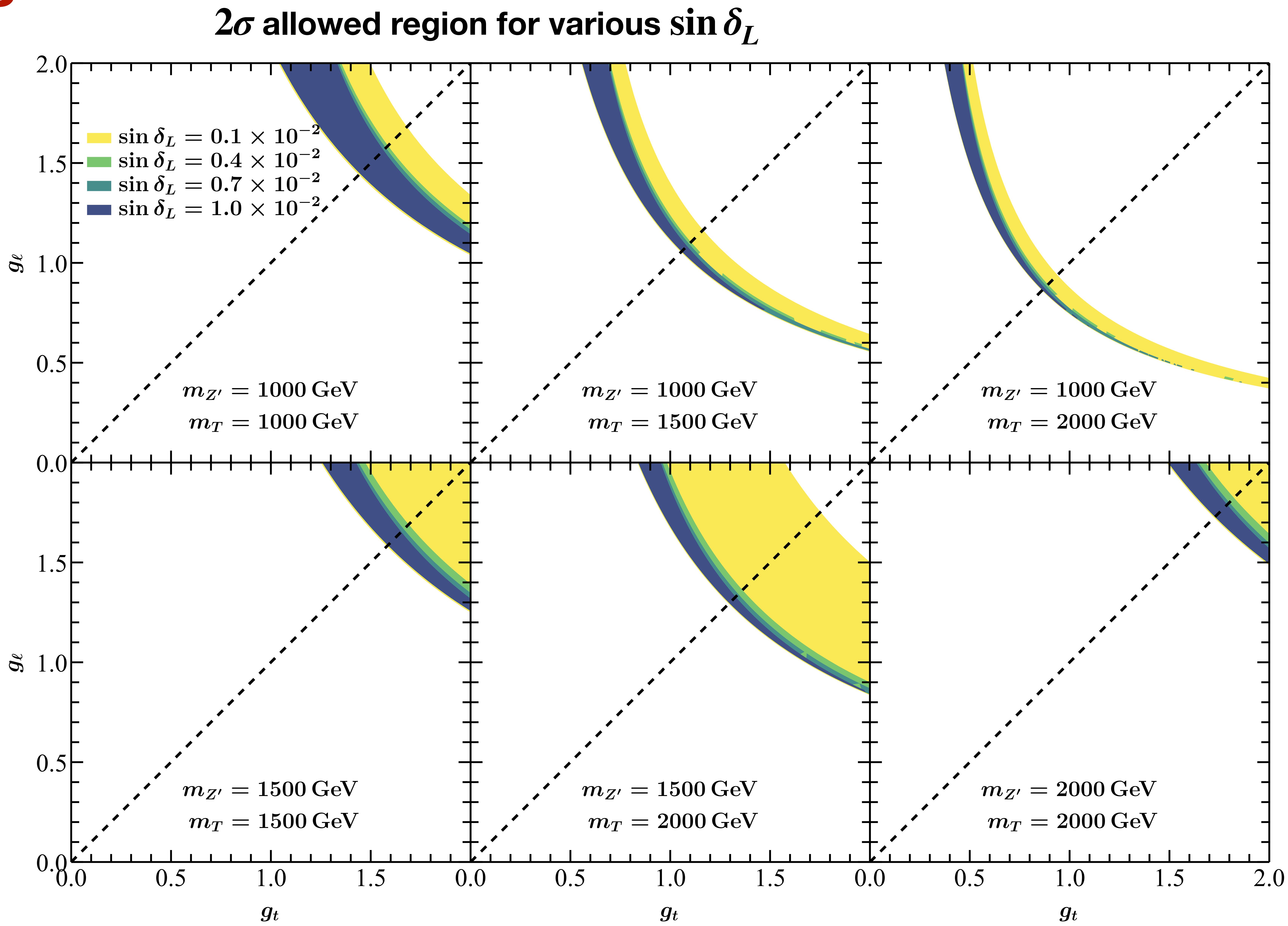
- Fixed parameters

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

- Free parameters

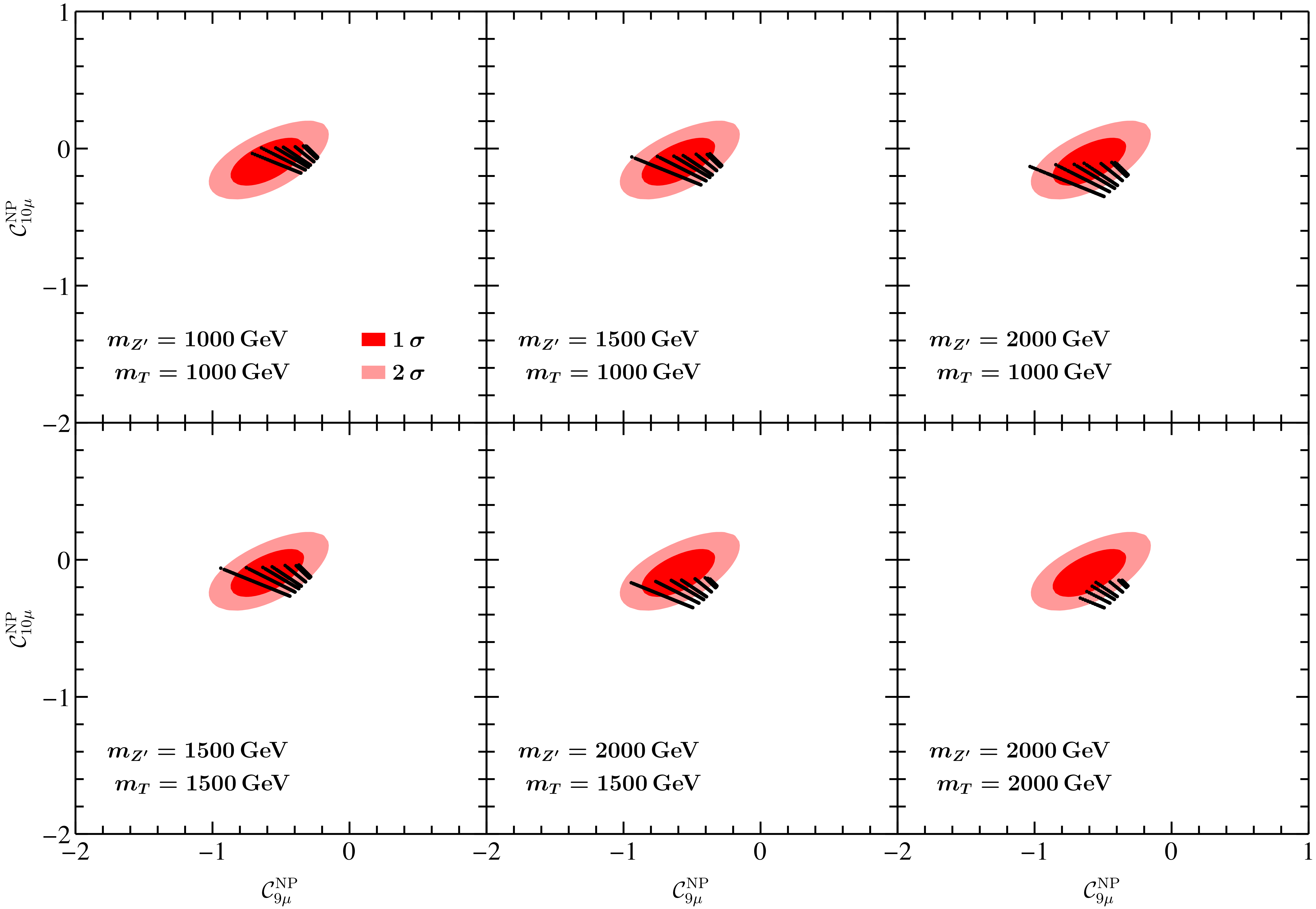
$$(m_T, \sin\theta_L, m_M, \sin\delta_L, m_{Z'}, g_t, g_\ell)$$

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



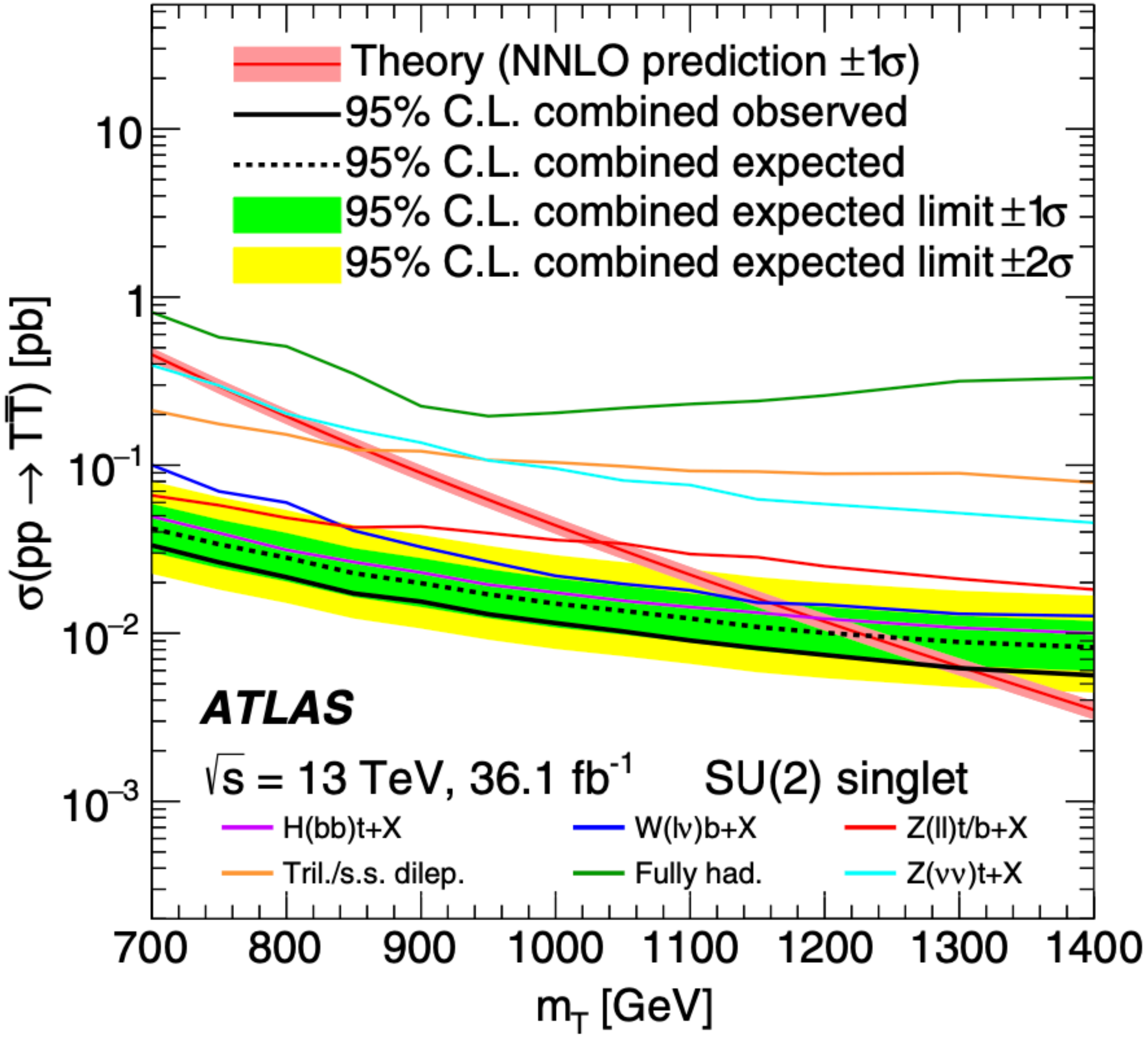
Predictions on (C_9, C_{10}) in $b \to s\ell^+\ell^-$

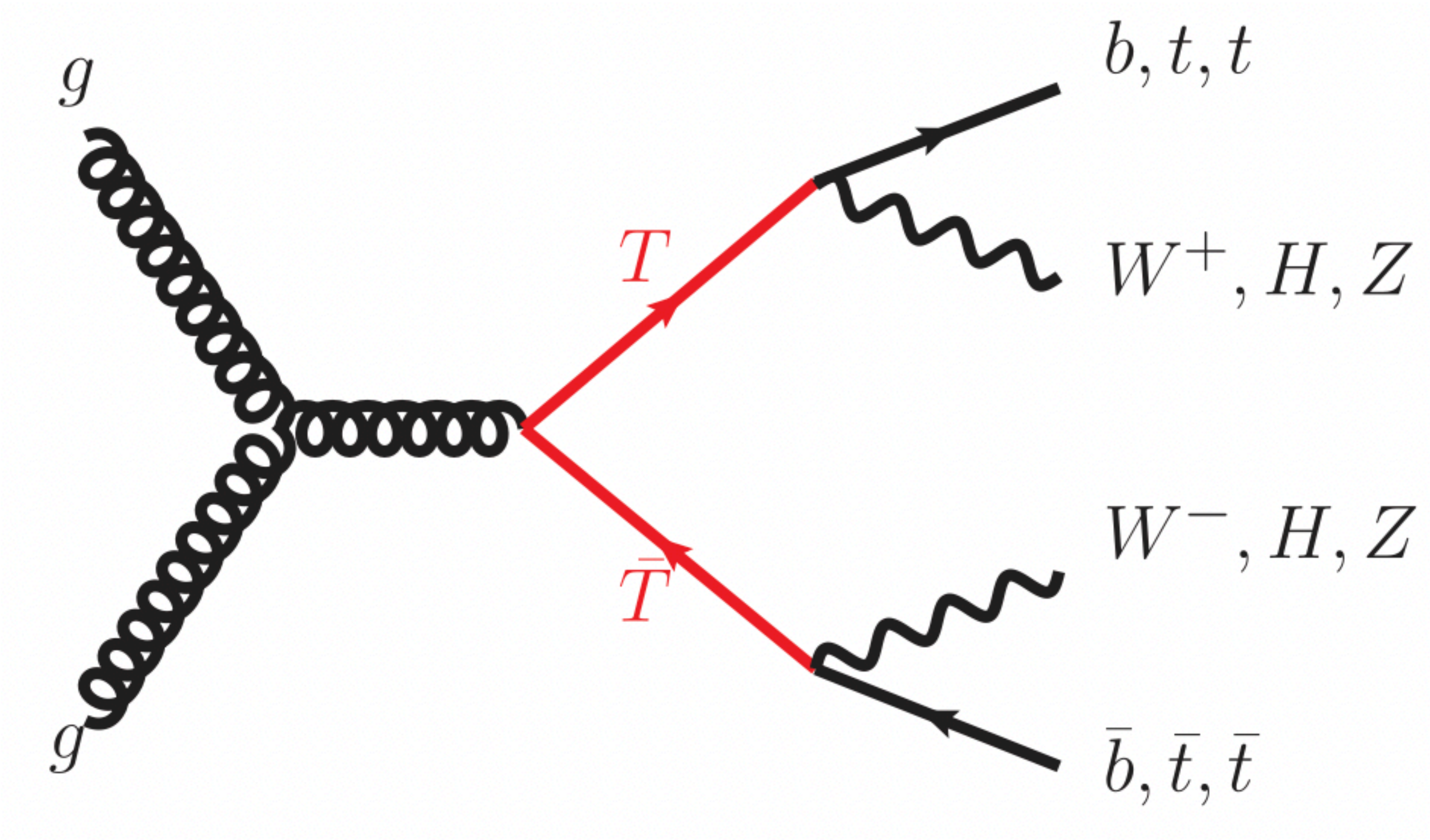
predictions shown in the black points



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

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



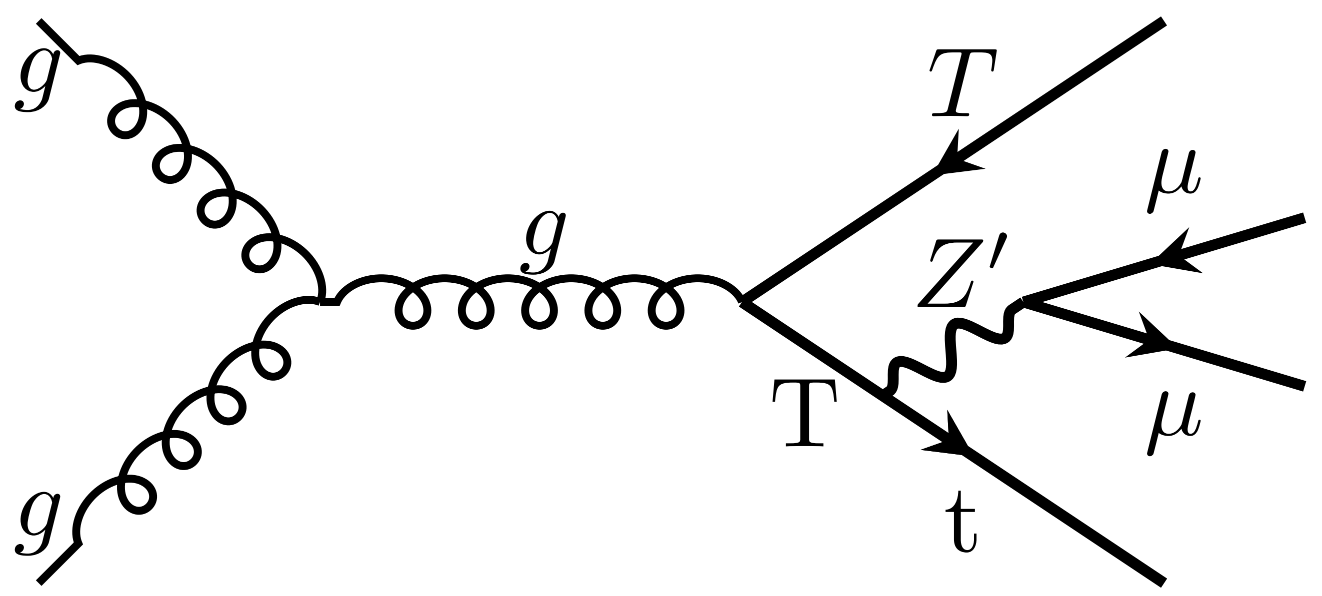


$m_T > 1.3\,\mathrm{TeV}$

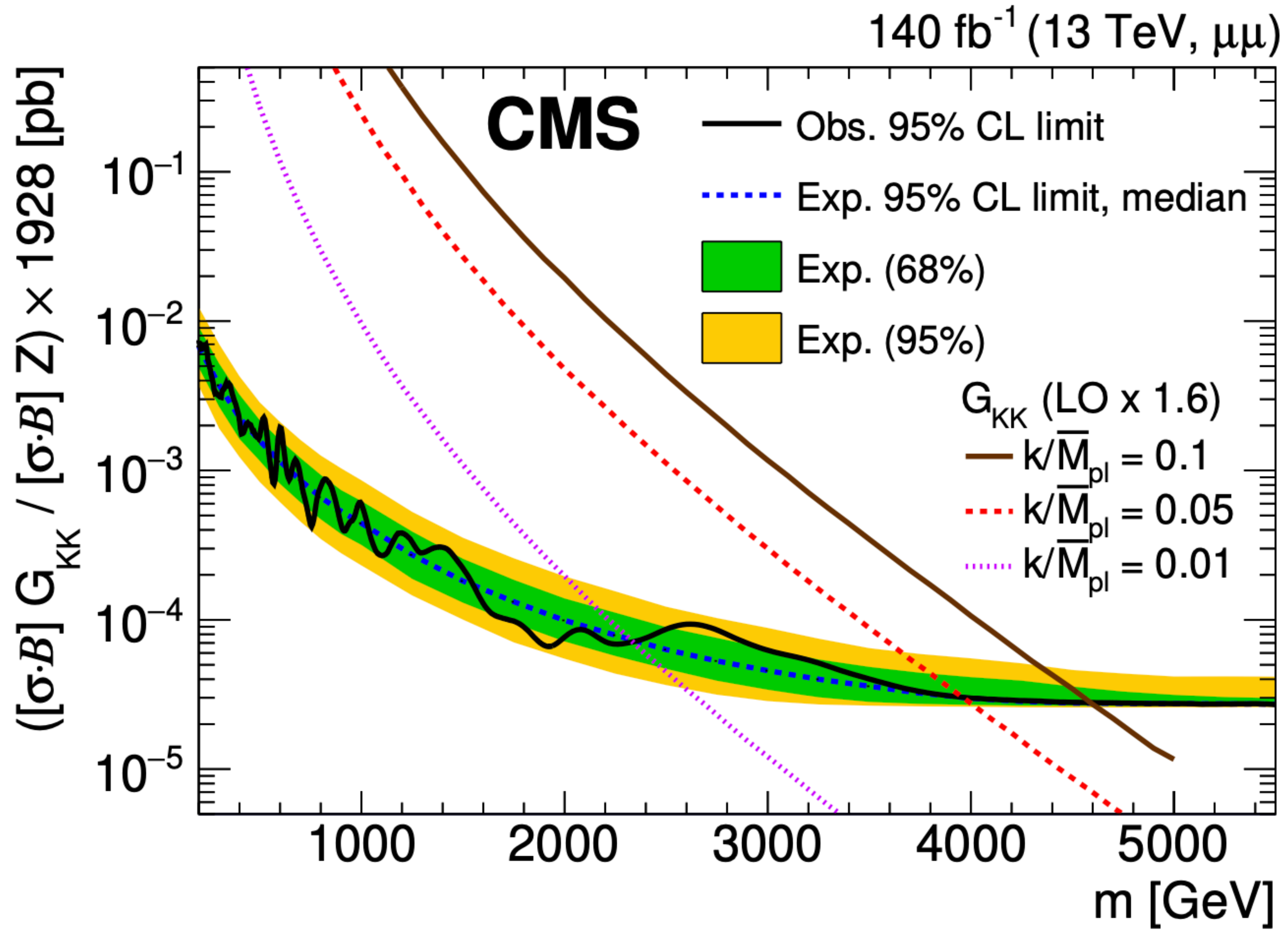
same with the regular top partner scenarios

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

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



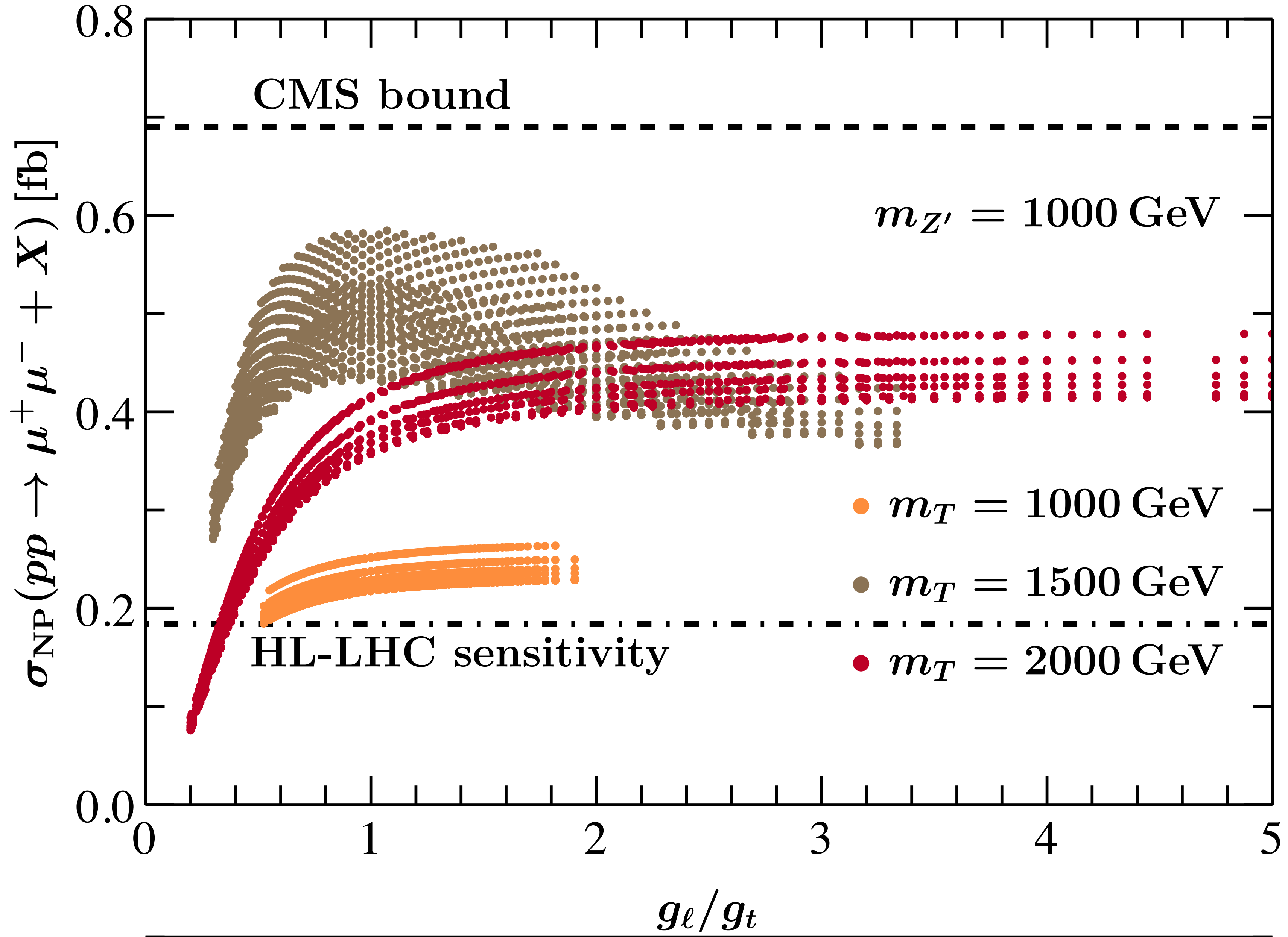
$$\sigma(pp \to T\bar{T}) \cdot 2 \cdot \mathcal{B}(T \to tZ') \cdot \mathcal{B}(Z' \to \mu^+\mu^-)$$

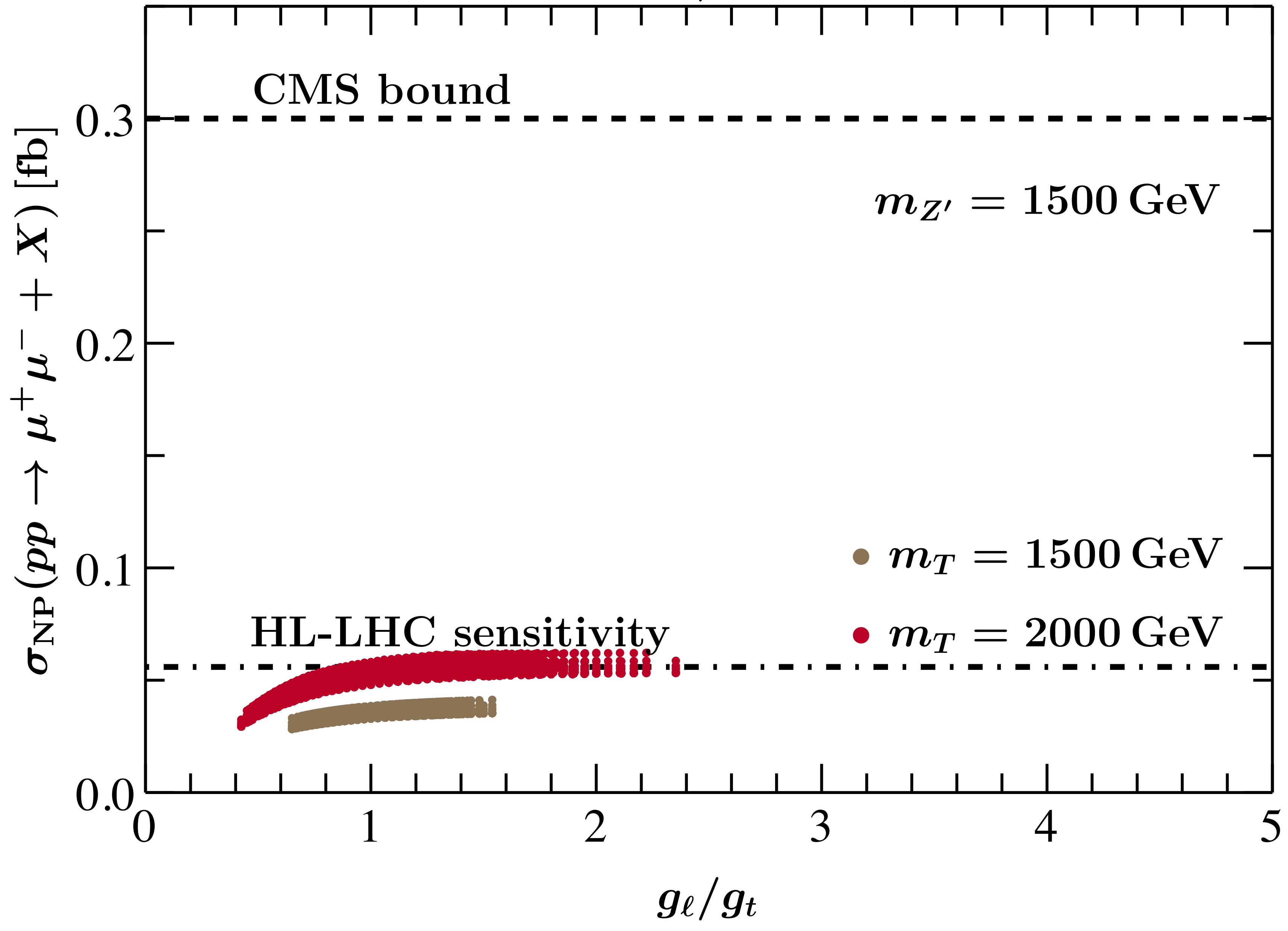


CMS 137 fb^{-1} @ 13 TeV, JHEP07(2021)208

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

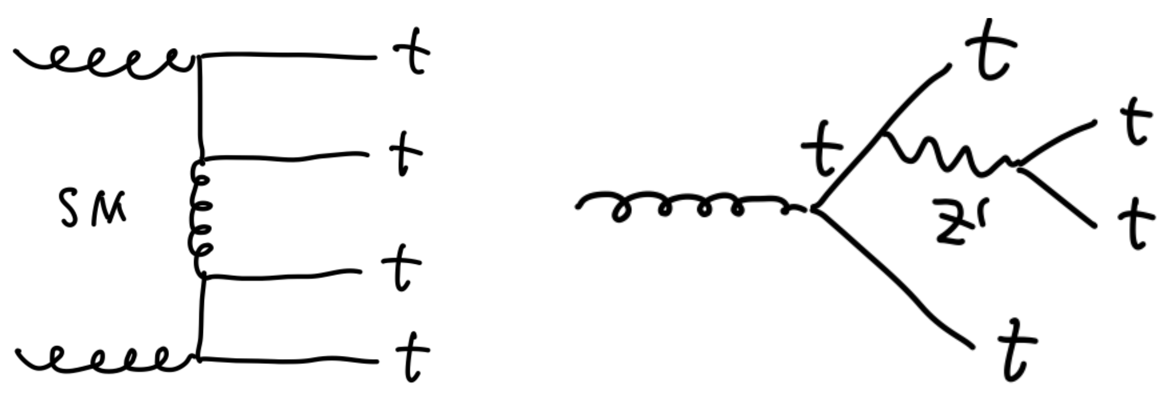
$Z' \to MM, M\mu, \mu\mu, \tau\tau, \nu\bar{\nu}, t\bar{t}$





Collider Searches

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



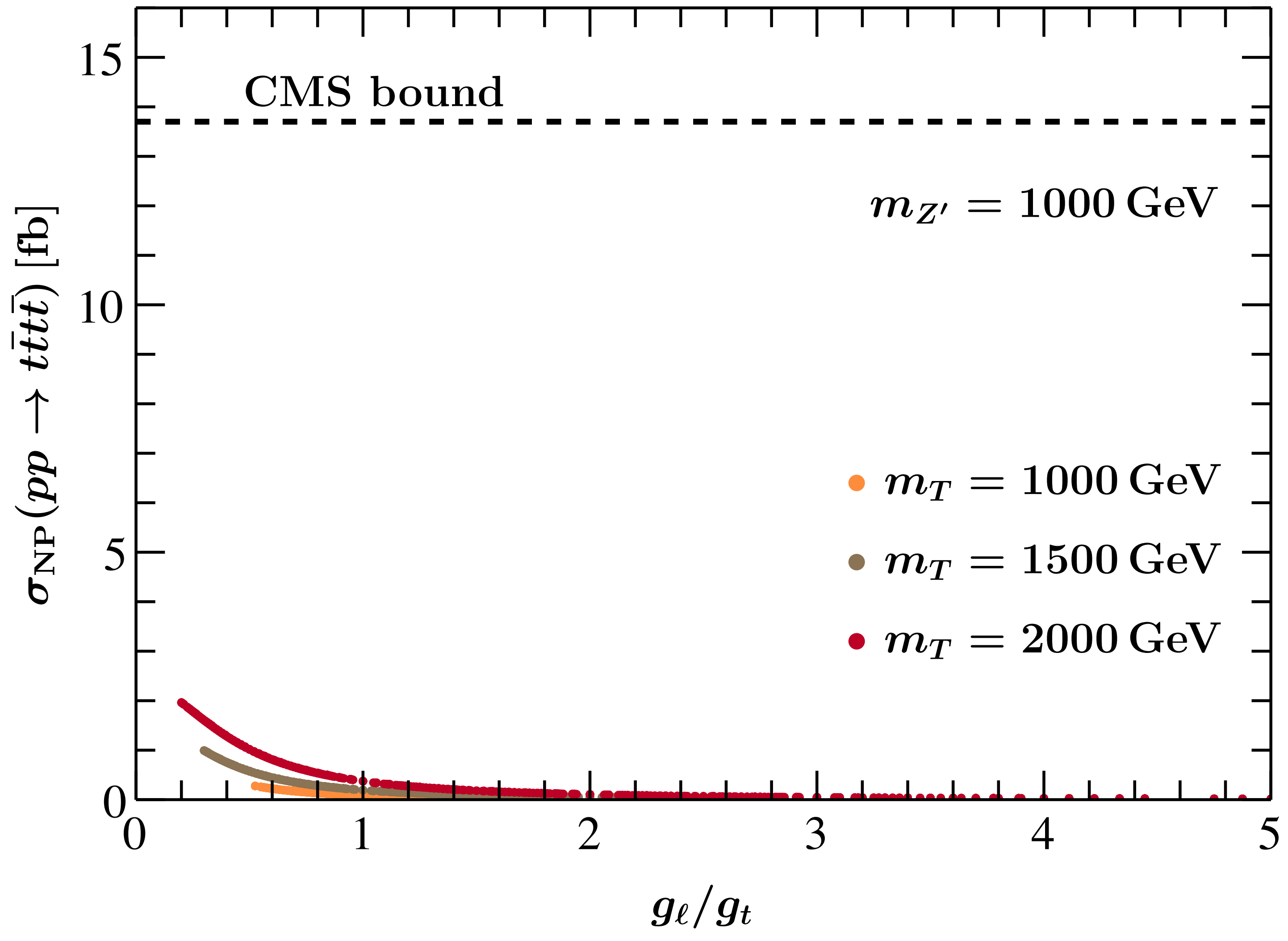
$$\sigma_{\text{exp}} = 12.6^{+5.8}_{-5.2}\,\text{fb}$$

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

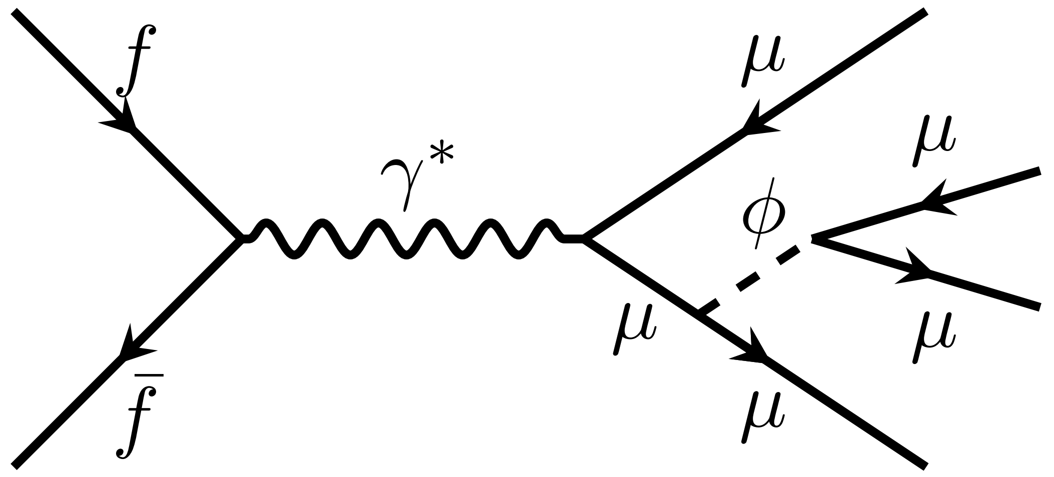
$$\sigma_{\text{NLO}} = 12.0^{+2.2}_{-2.5}\,\text{fb}$$

Frederix, D. Pagani, M. Zaro 1711.02116

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

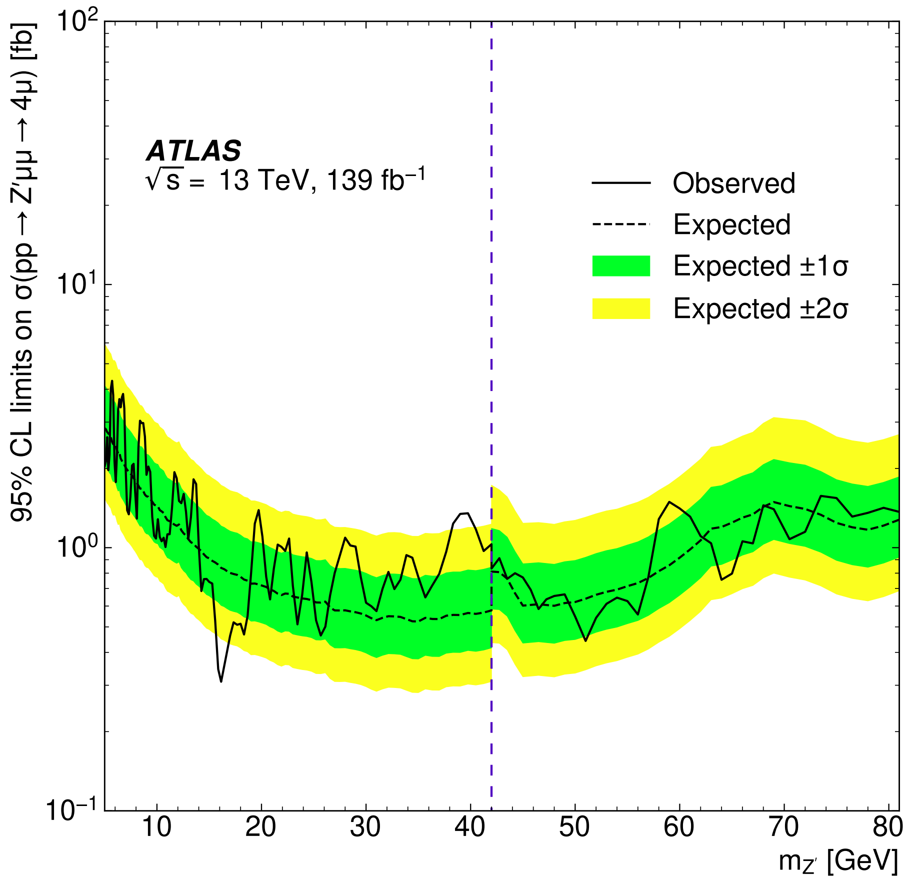


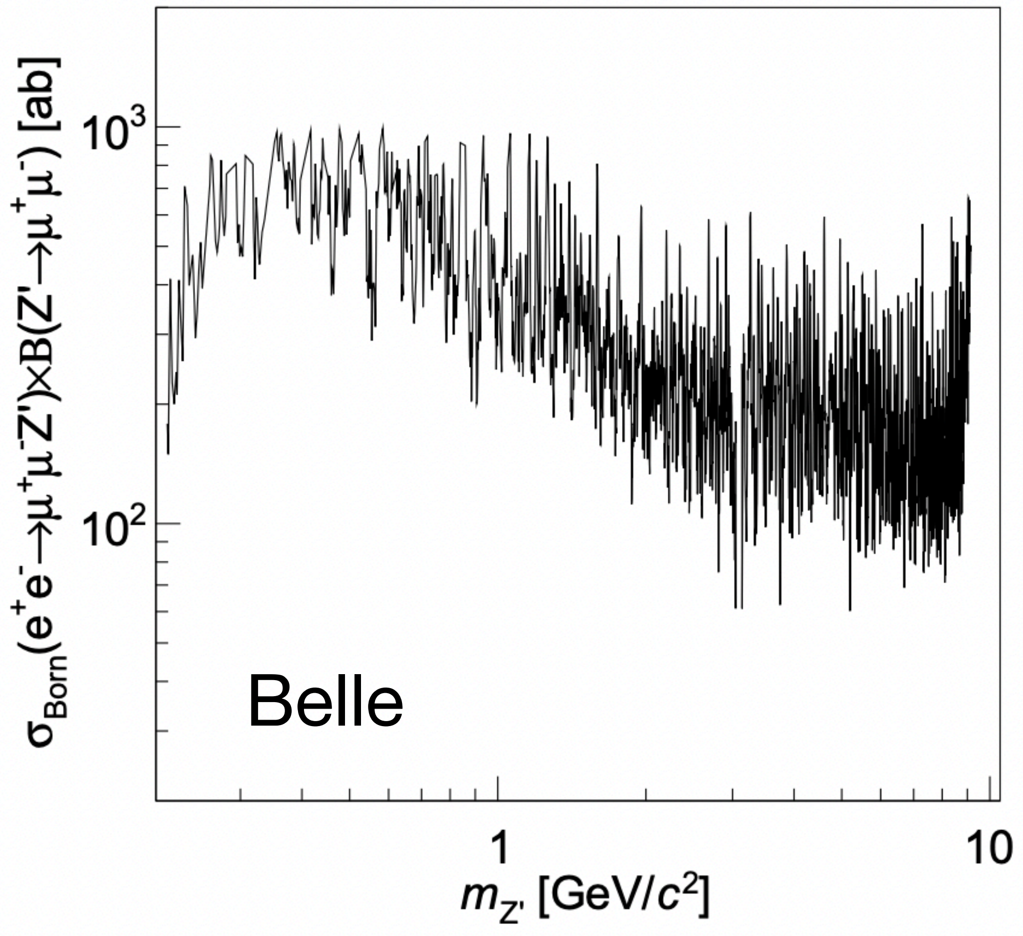
$e^+e^-(pp) \to \mu^+\mu^-\mu^+\mu^-$



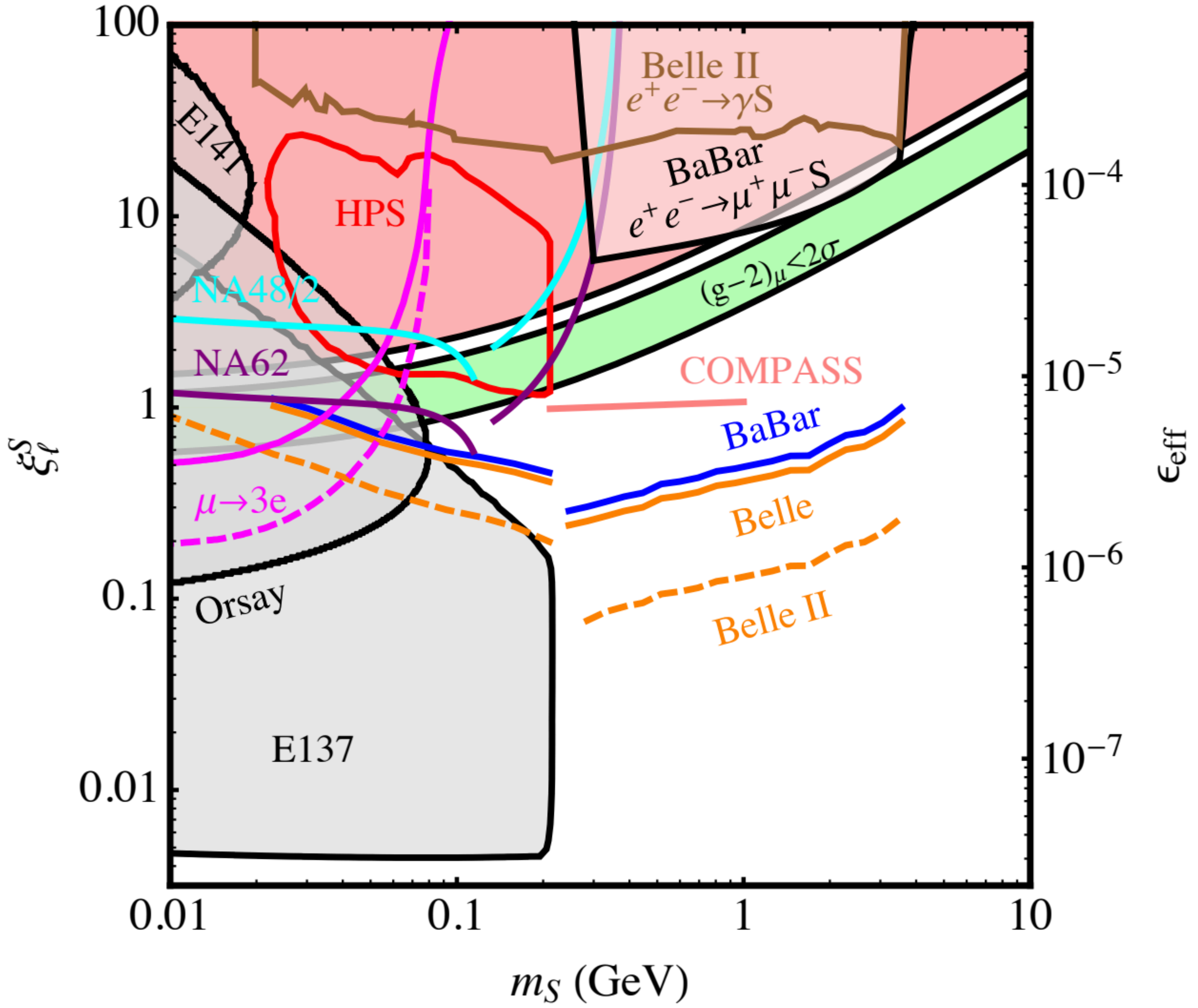
$m_\phi \sim 1\,\text{GeV}$

can be searched for at BES, Belle II, STCF





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



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
- 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

Thank You !

Backup

	SM							NP				
	Q_{3L}	u_{3R}	L_{2L}	L_{3L}	e_{2R}	e_{3R}	H	$U'_{L/R}$	$E_{L/R}$	Φ_ℓ	Φ_t	ϕ
$SU(3)_C$	3	3	1	1	1	1	1	3	1	1	1	1
$SU(2)_L$	2	1	2	2	1	1	2	1	1	1	1	1
$U(1)_Y$	$1/6$	$2/3$	$-1/2$	$-1/2$	-1	-1	$1/2$	$2/3$	-1	0	0	0
$U(1)'$	0	0	q_ℓ	$-q_\ell$	q_ℓ	$-q_\ell$	0	q_t	0	$-q_\ell$	q_t	0

$$\mathcal{L} \supset q_t g' \left(\bar{U}'_L \gamma^\mu U'_L + \bar{U}'_R \gamma^\mu U'_R\right) Z'_\mu - \left(\sum_i \lambda_{ii} \bar{Q}_{iL} \tilde{H} u_{iR} + \lambda_{4i} \bar{U}'_L u_{iR} \Phi_t + \mu \bar{U}'_L U'_R + \text{h.c.}\right)$$

$$\begin{aligned} \mathcal{L} \supset\ & q_\ell g' \left(\bar{L}_{2L} \gamma^\mu L_{2L} + \bar{e}_{2R} \gamma^\mu e_{2R} - \bar{L}_{3L} \gamma^\mu L_{3L} - \bar{e}_{3R} \gamma^\mu e_{3R}\right) Z'_\mu \\ & - \Big[\sum_i \lambda^\ell_{ii} \bar{L}_{iL} H e_{iR} + \lambda^\ell_{42} \bar{E}_L e_{2R} \Phi_\ell + \lambda^\ell_{43} \bar{E}_L e_{3R} \Phi^*_\ell + \left(\lambda^\ell_{41} \bar{E}_L e_{1R} + \lambda^\ell_{44} \bar{E}_L E_R\right) \phi + \text{h.c.}\Big], \end{aligned} \tag{2.19}$$

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

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

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

$$\mathcal{L}_{Z'}^\ell = g_\ell\left(\bar{\mu}_L, \bar{M}_L\right)\begin{pmatrix}\hat{c}_L^2 & \hat{s}_L\hat{c}_L \\ \hat{s}_L\hat{c}_L & \hat{s}_L^2\end{pmatrix}\not{Z}'\begin{pmatrix}\mu_L \\ M_L\end{pmatrix} - g_\ell\bar{\tau}_L\not{Z}'\tau_L + (L\to R) + g_\ell\left(\bar{\nu}_\mu\not{Z}'P_L\nu_\mu - \bar{\nu}_\tau\not{Z}'P_L\nu_\tau\right)$$

$$\mathcal{L}_h = -\frac{m_\mu}{v_H}\left(\bar{\mu}_L, \bar{M}_L\right)\begin{pmatrix}\hat{c}_L^2 & \hat{c}_L^2\tan\delta_R \\ \hat{s}_L\hat{c}_L & \hat{s}_L\hat{c}_L\tan\delta_R\end{pmatrix} h\begin{pmatrix}\mu_R \\ M_R\end{pmatrix} + \text{h.c.},$$

$$\mathcal{L}_{\Phi_\ell} = -\frac{\lambda_{\Phi_\ell}}{\sqrt{2}}\left(\bar{\mu}_L, \bar{M}_L\right)\begin{pmatrix}-\hat{s}_L\hat{c}_R & -\hat{s}_L\hat{s}_R \\ \hat{c}_L\hat{c}_R & \hat{c}_L\hat{s}_R\end{pmatrix}\Phi_\ell\begin{pmatrix}\mu_R \\ M_R\end{pmatrix} + \text{h.c.},$$

$$\mathcal{L}_\phi = -\frac{\lambda_\phi}{\sqrt{2}}\left(\bar{\mu}_L, \bar{M}_L\right)\begin{pmatrix}\hat{s}_L\hat{s}_R & -\hat{s}_L\hat{c}_R \\ -\hat{c}_L\hat{s}_R & \hat{c}_L\hat{c}_R\end{pmatrix}\phi\begin{pmatrix}\mu_R \\ M_R\end{pmatrix} + \text{h.c.}.$$

$$\mathcal{L}_h^t = -\frac{m_t}{v_H}\left(\bar{t}_L, \bar{T}_L\right)\begin{pmatrix}c_L^2 & c_L^2\tan\theta_R \\ s_Lc_L & s_Lc_L\tan\theta_R\end{pmatrix} h\begin{pmatrix}t_R \\ T_R\end{pmatrix} + \text{h.c.},$$

$$\mathcal{L}_{\Phi_t} = -\frac{\lambda_{\Phi_t}}{\sqrt{2}}\left(\bar{t}_L, \bar{T}_L\right)\begin{pmatrix}-s_Lc_R & s_Ls_R \\ c_Lc_R & c_Ls_R\end{pmatrix} h\begin{pmatrix}t_R \\ T_R\end{pmatrix} + \text{h.c.}.$$

$$\begin{aligned}\mathcal{V} = &\sum_S \mu_S^2|S|^2 + \mathrm{Re}\left(\lambda_S^{(3)}\phi\right)|S|^2 - \lambda_S^{(4)}|S|^4 \\ &+ \left(\lambda_{H\phi}|\phi|^2 + \lambda_{H\Phi_t}|\Phi_t|^2 + \lambda_{H\Phi_\ell}|\Phi_\ell|^2\right)H^\dagger H + \left(\lambda_{\phi\Phi_t}|\Phi_t|^2 + \lambda_{\phi\Phi_\ell}|\Phi_\ell|^2\right)|\phi|^2 + \lambda_{\Phi_t\Phi_\ell}|\Phi_t|^2|\Phi_\ell|^2,\end{aligned} \tag{2.34}$$