



# **Explaining the $b \rightarrow s\ell^+\ell^-$ anomalies in $Z'$ scenarios with top-FC/FCNC couplings**

## **and its implications for the $W$ -boson mass shift**

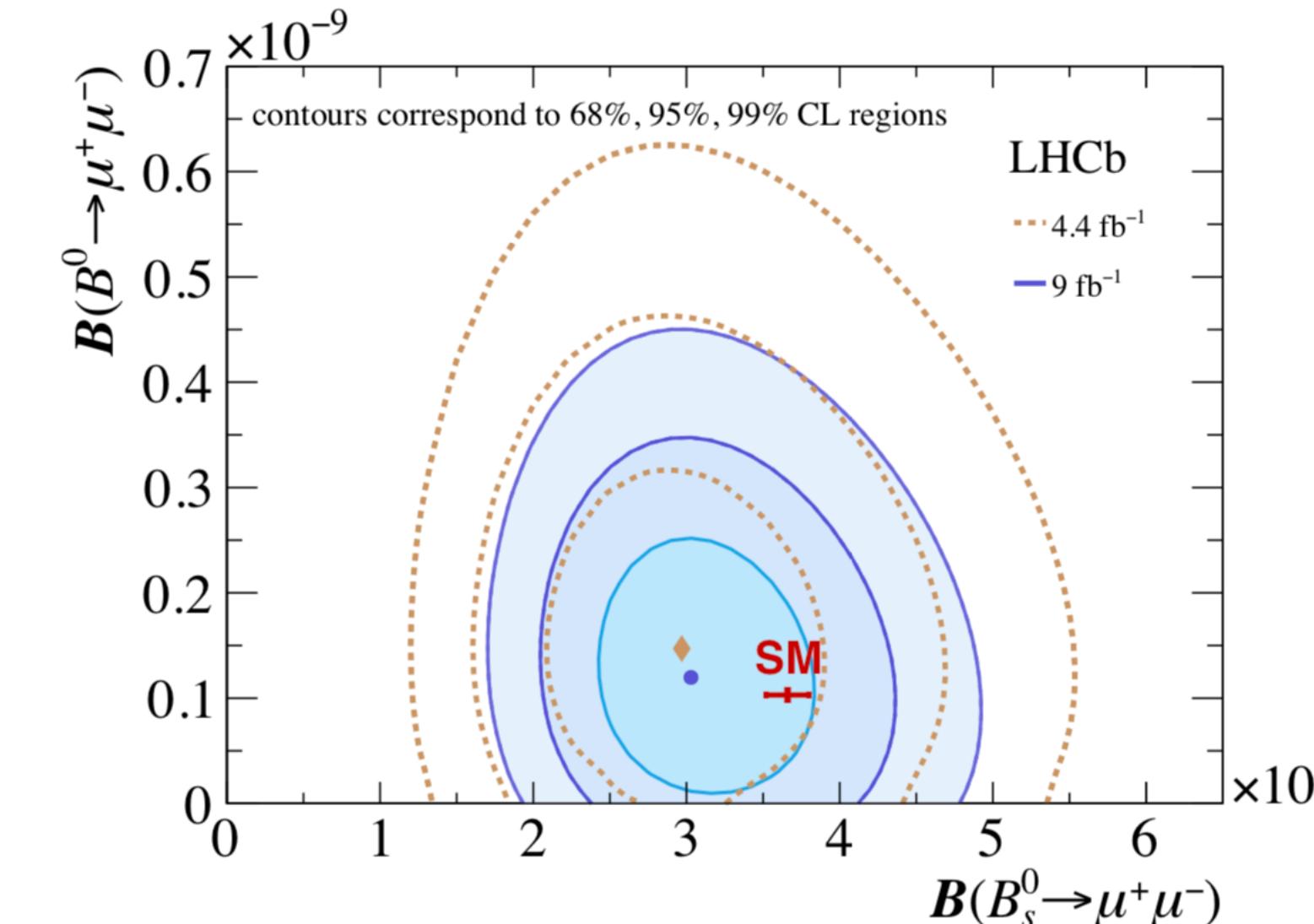
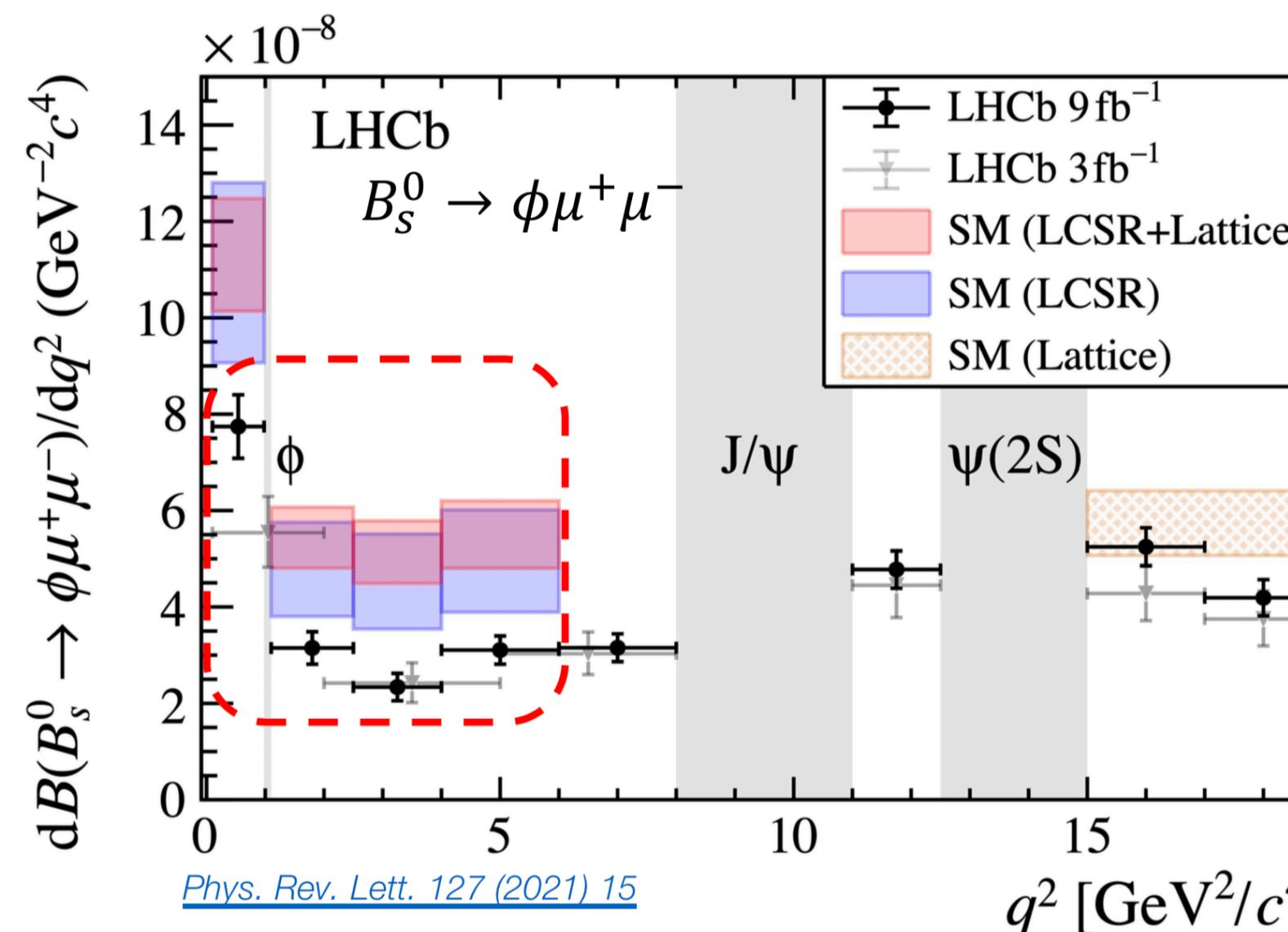
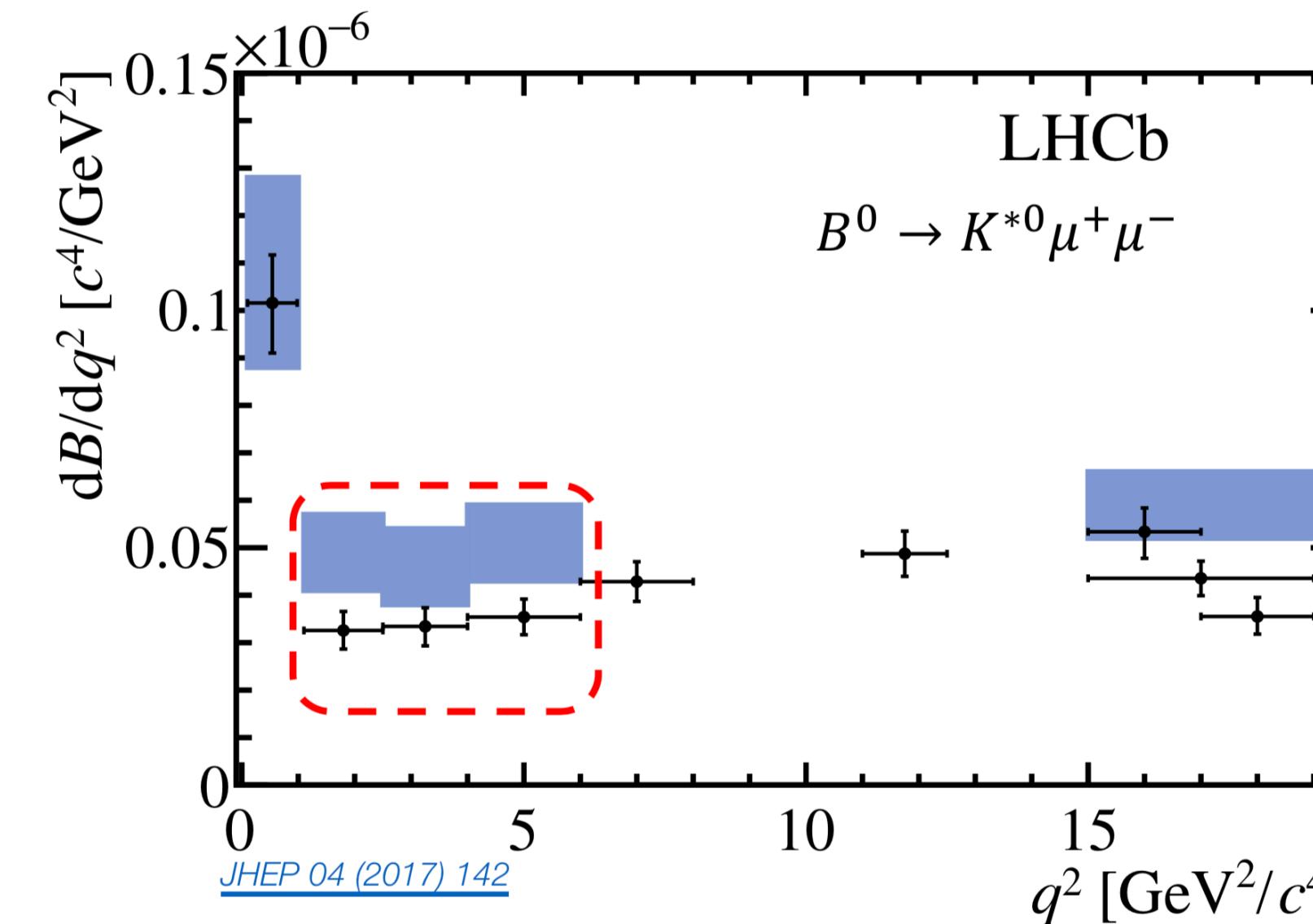
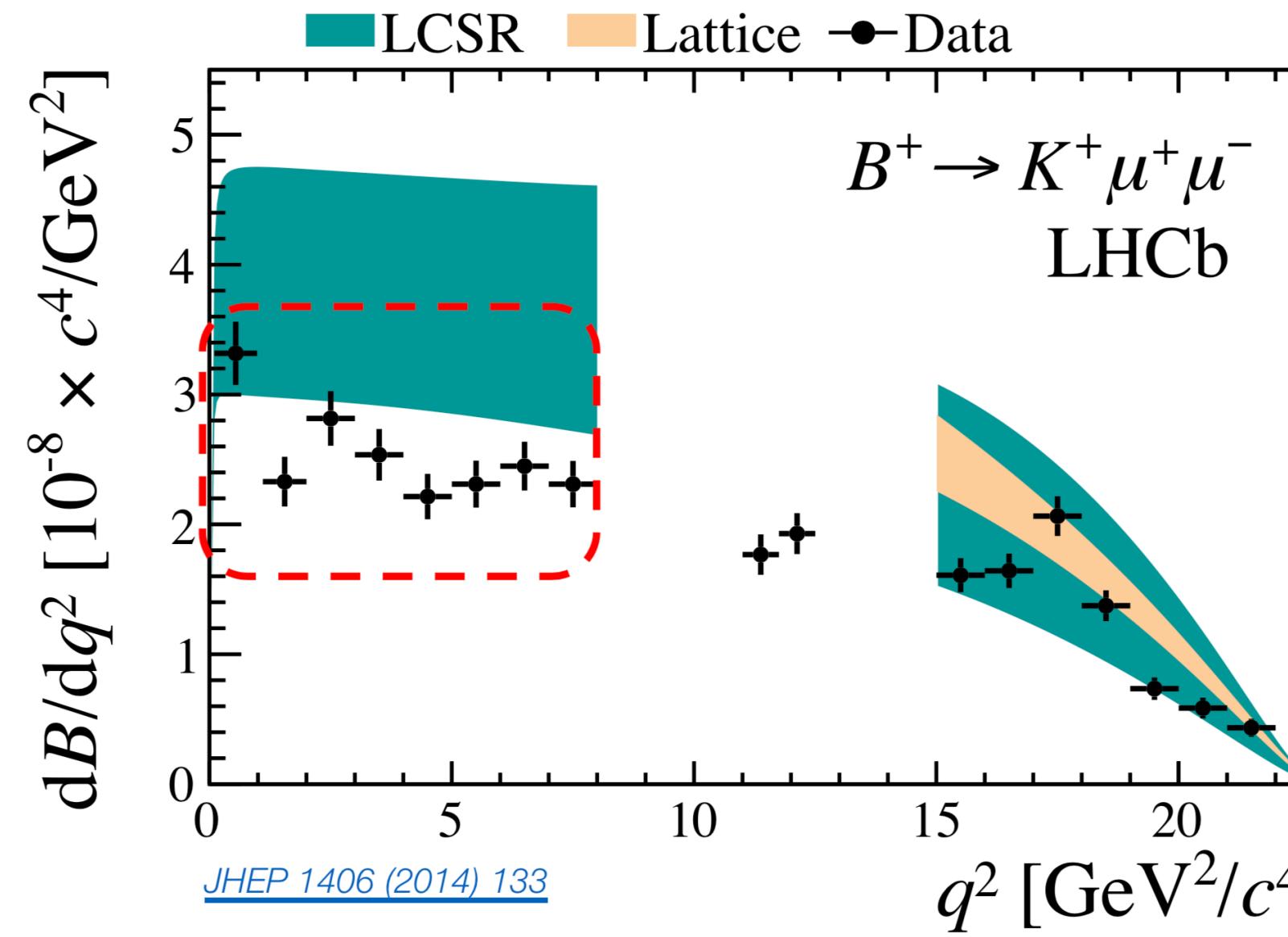
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**arXiv: 2112.14215**, 李新强, 沈萌, 王东洋, 杨亚东, 袁兴博

**arXiv: 2205.02205**, 李新强, 谢泽俊, 杨亚东, 袁兴博

**arXiv: 230x.xxxxx**, 李新强, 谢泽俊, 杨亚东, 袁兴博

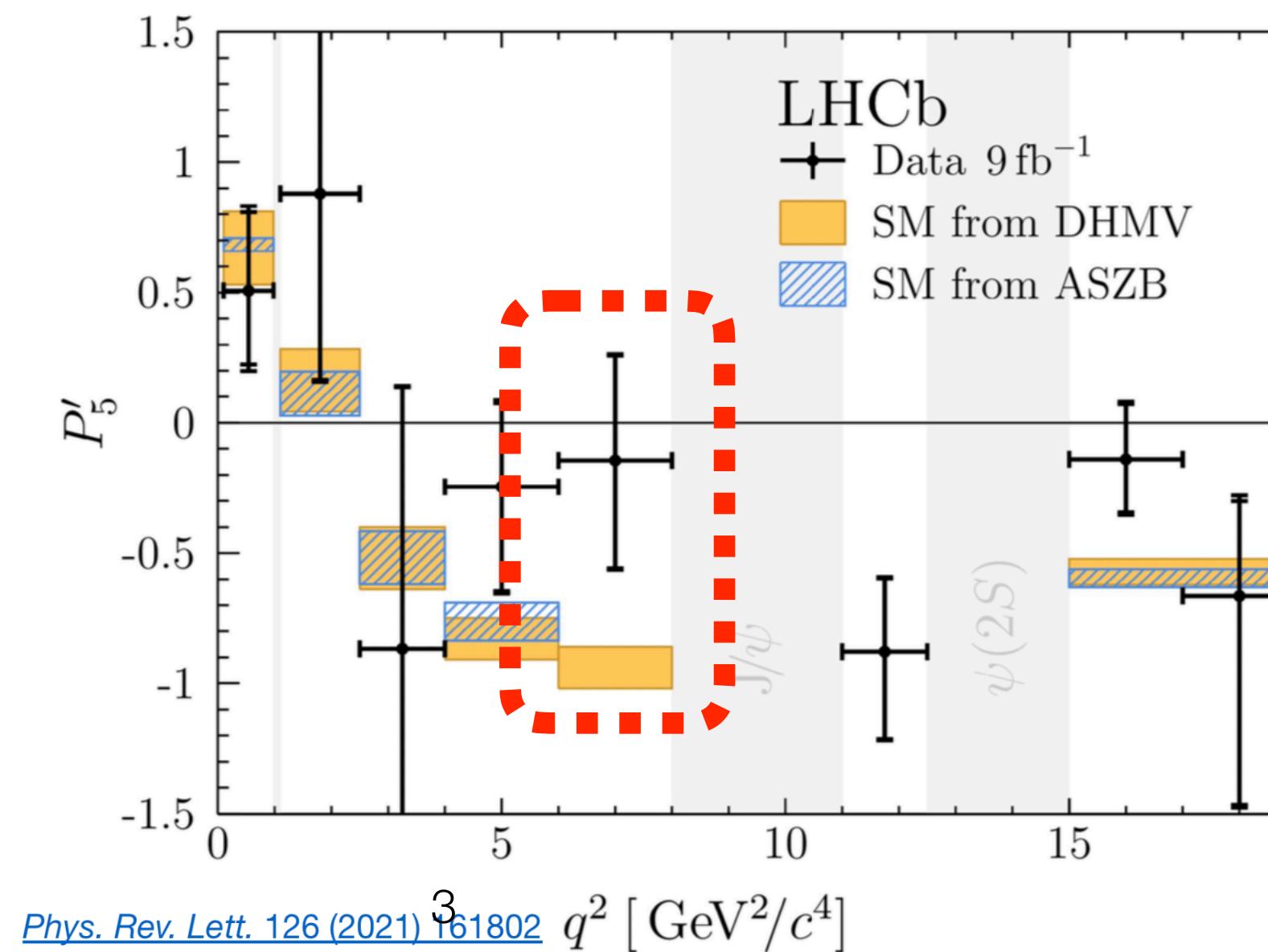
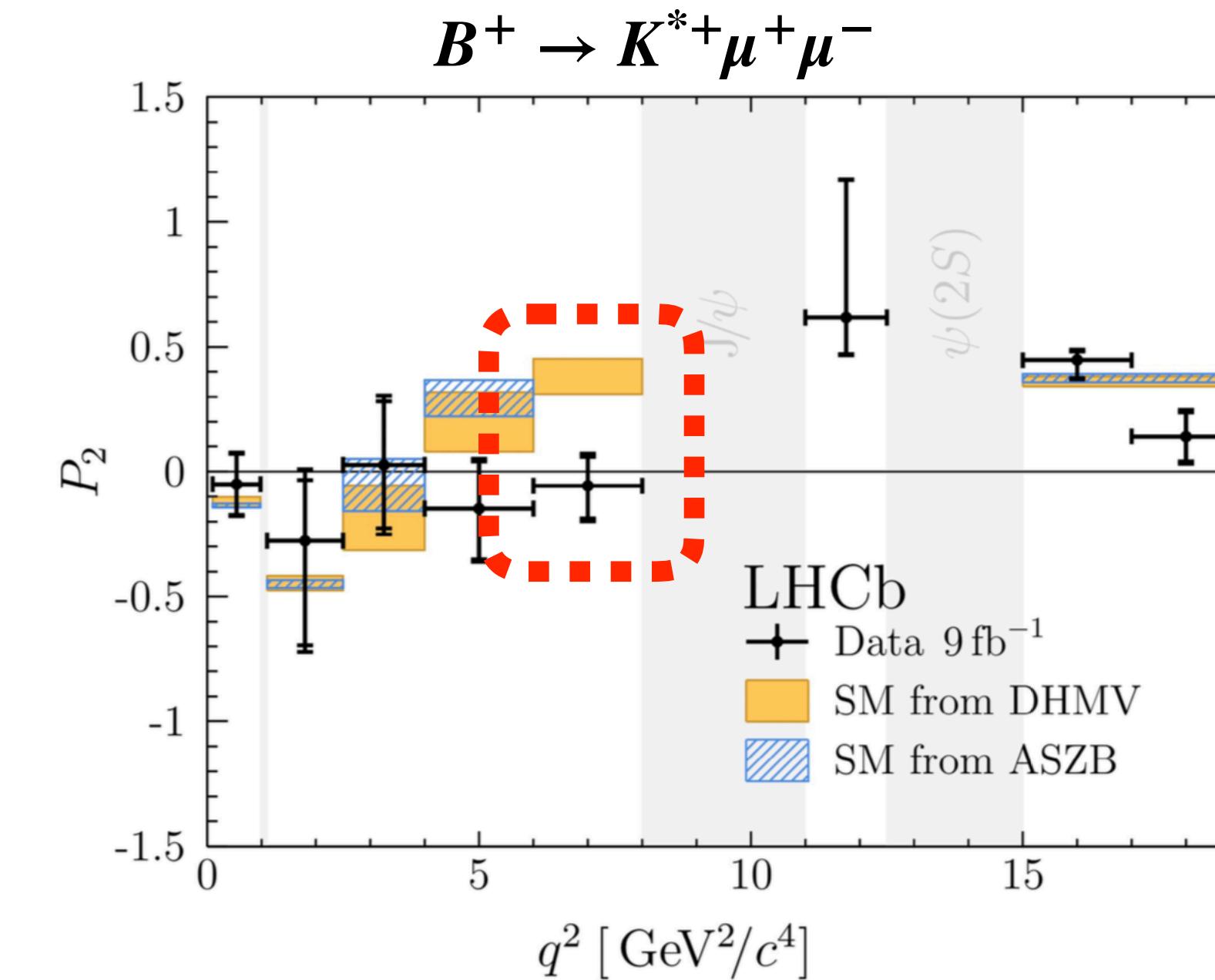
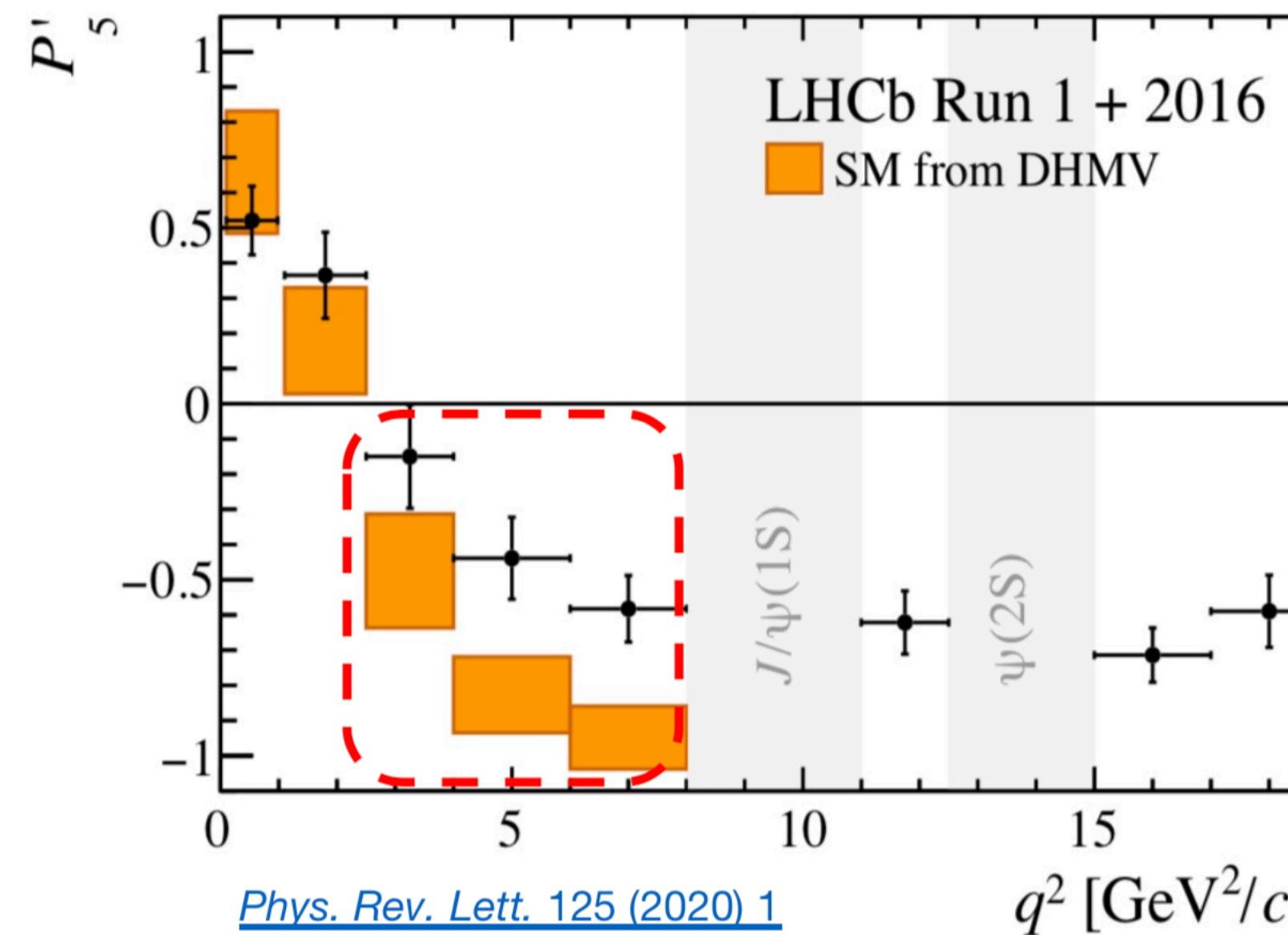
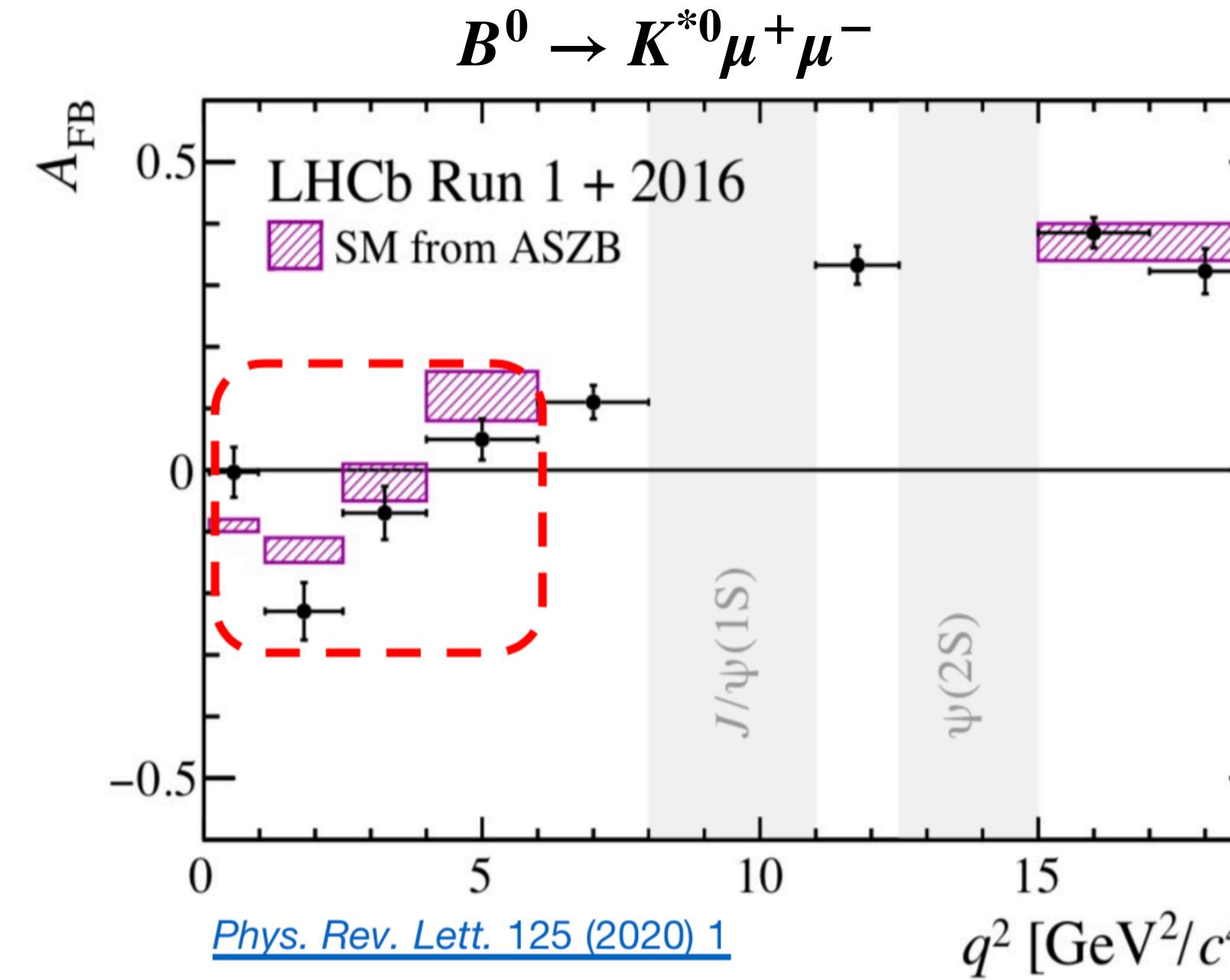
# $b \rightarrow s\ell\ell$ anomalies: branching ratio



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

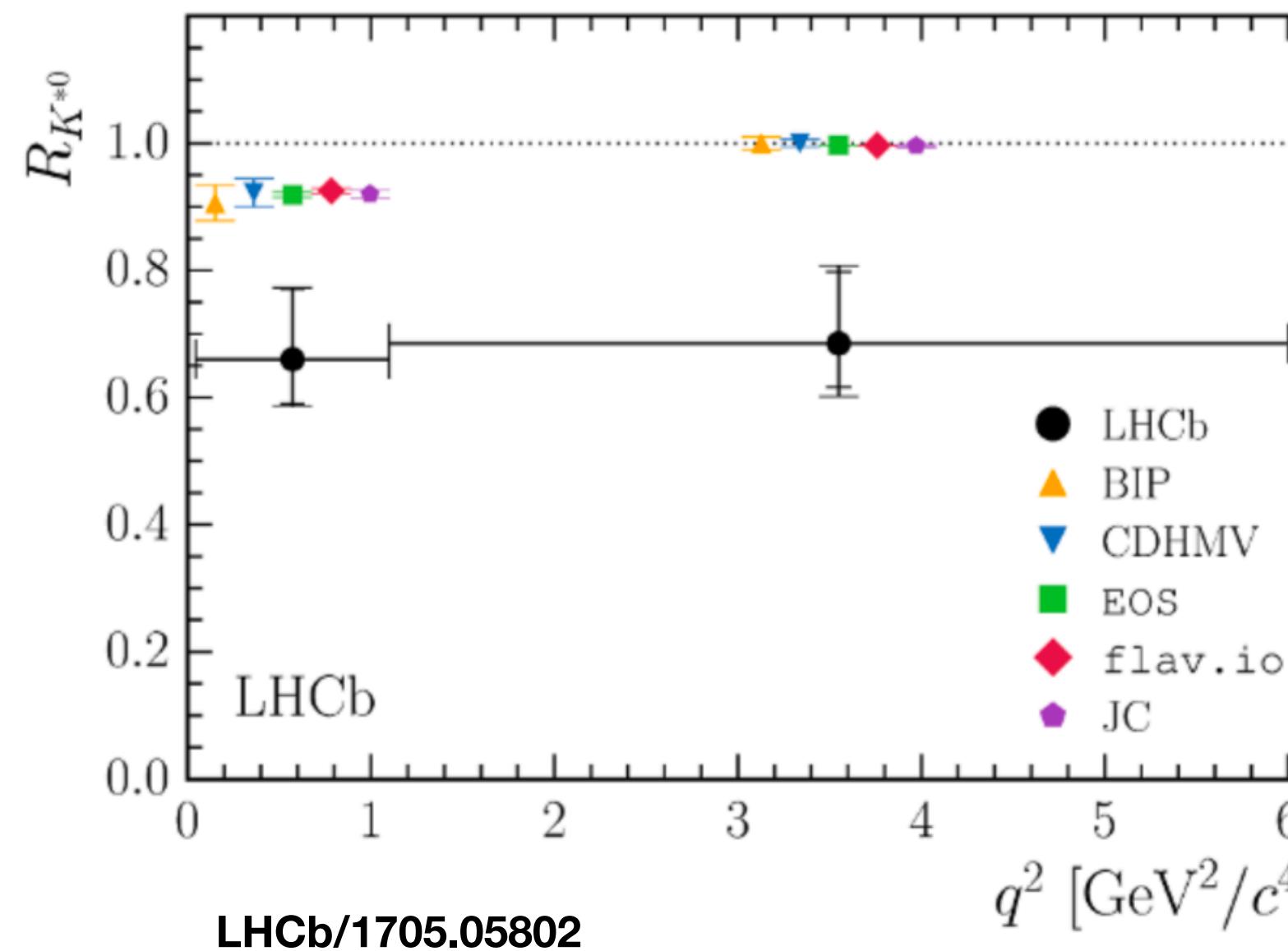
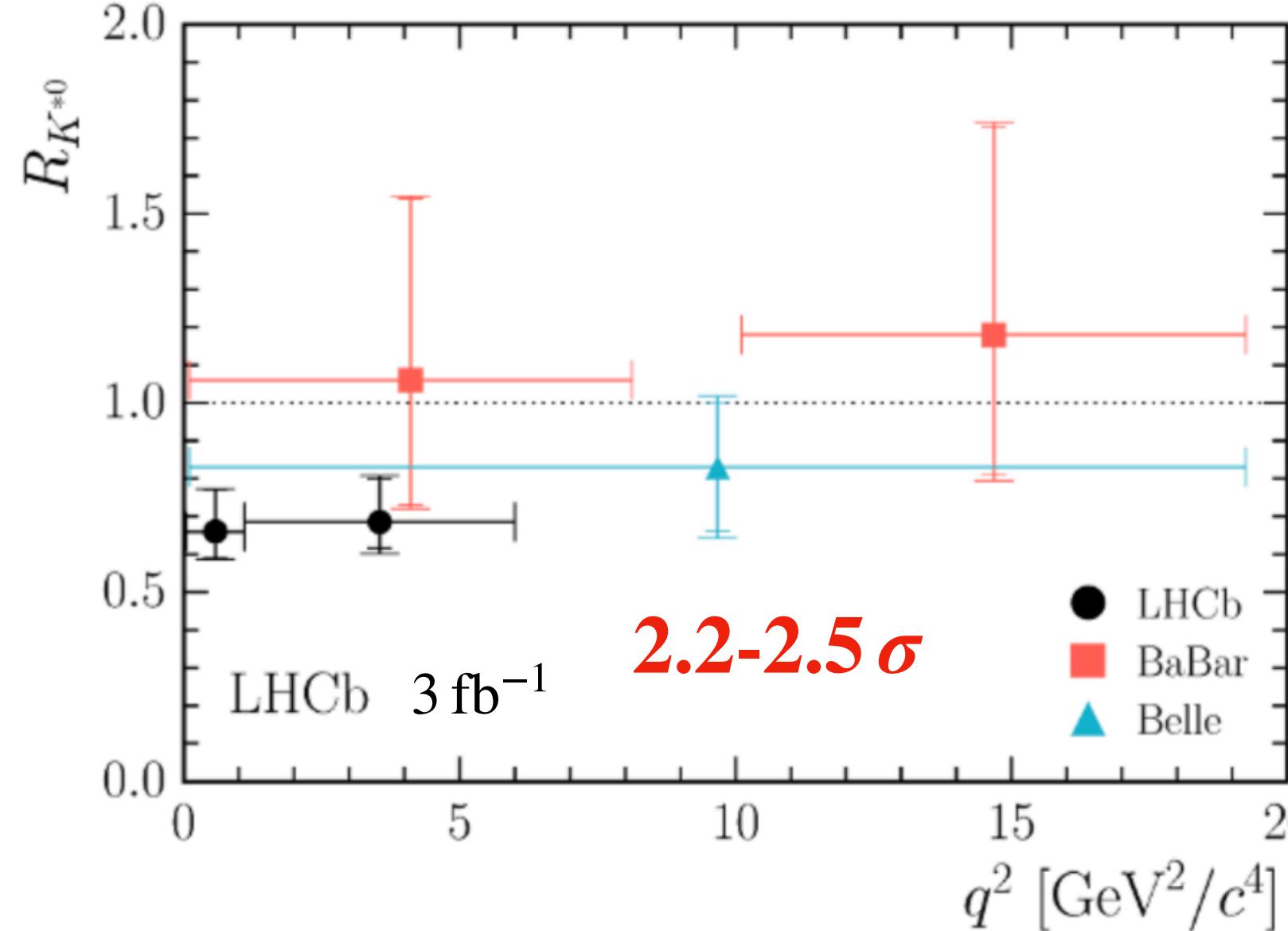
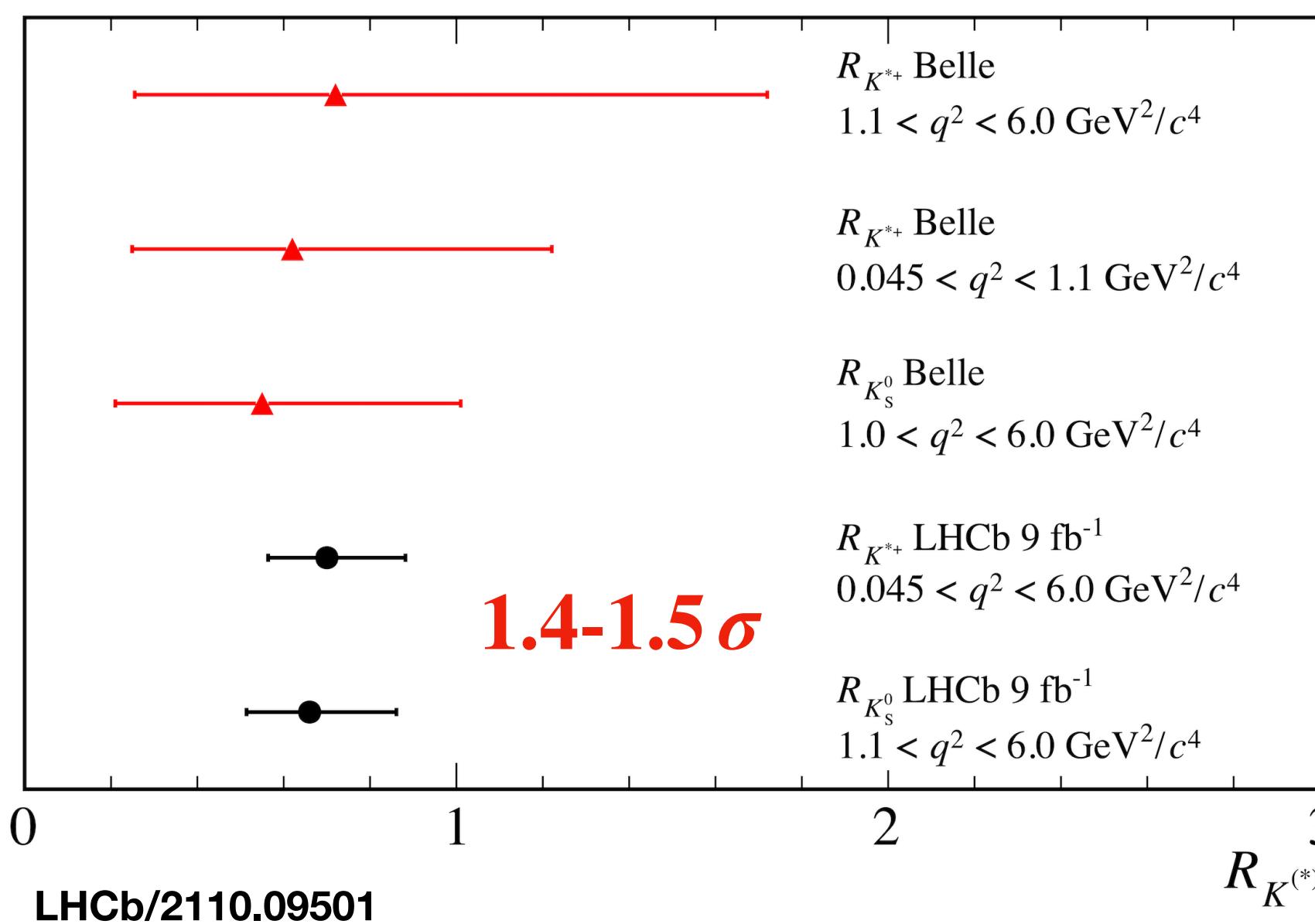
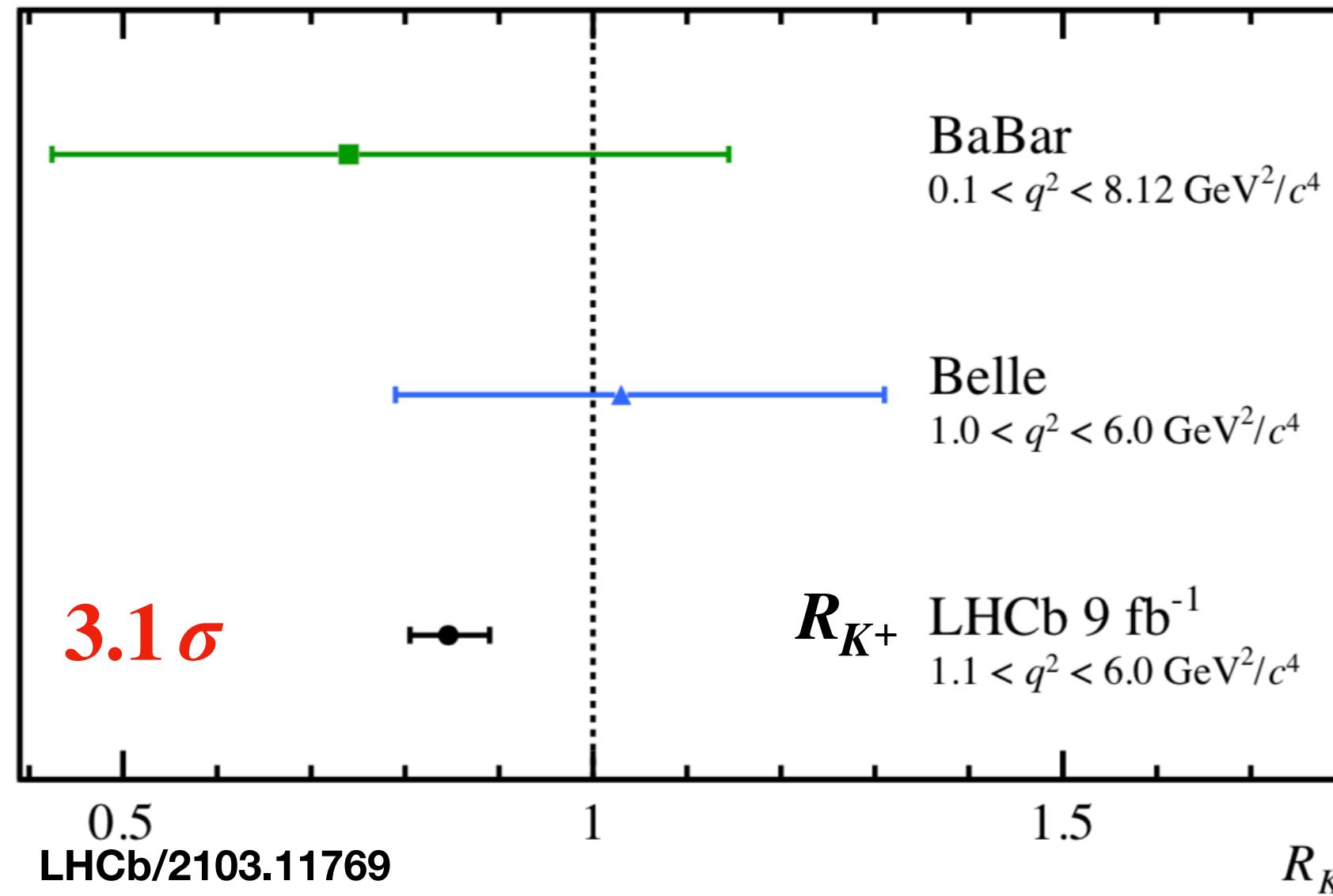
详见张艳席, 何吉波等老师的报告

# $b \rightarrow s\ell\ell$ anomalies: angular distribution



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

# $b \rightarrow s\ell\ell$ anomalies: lepton flavour universality ratio



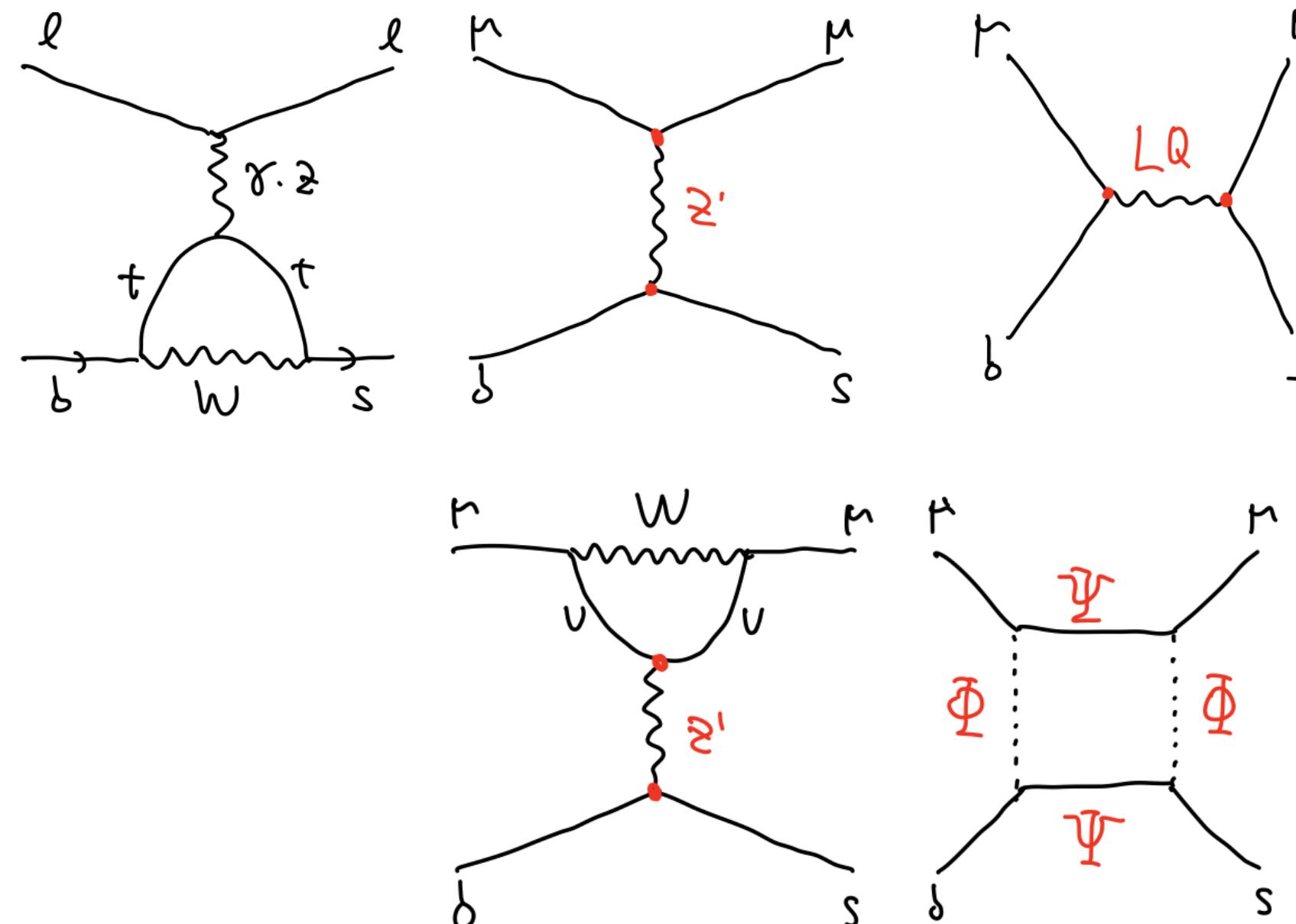
$$R_{K^+} = \frac{\mathfrak{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\mathfrak{B}(B^+ \rightarrow K^+ e^+ e^-)}$$

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

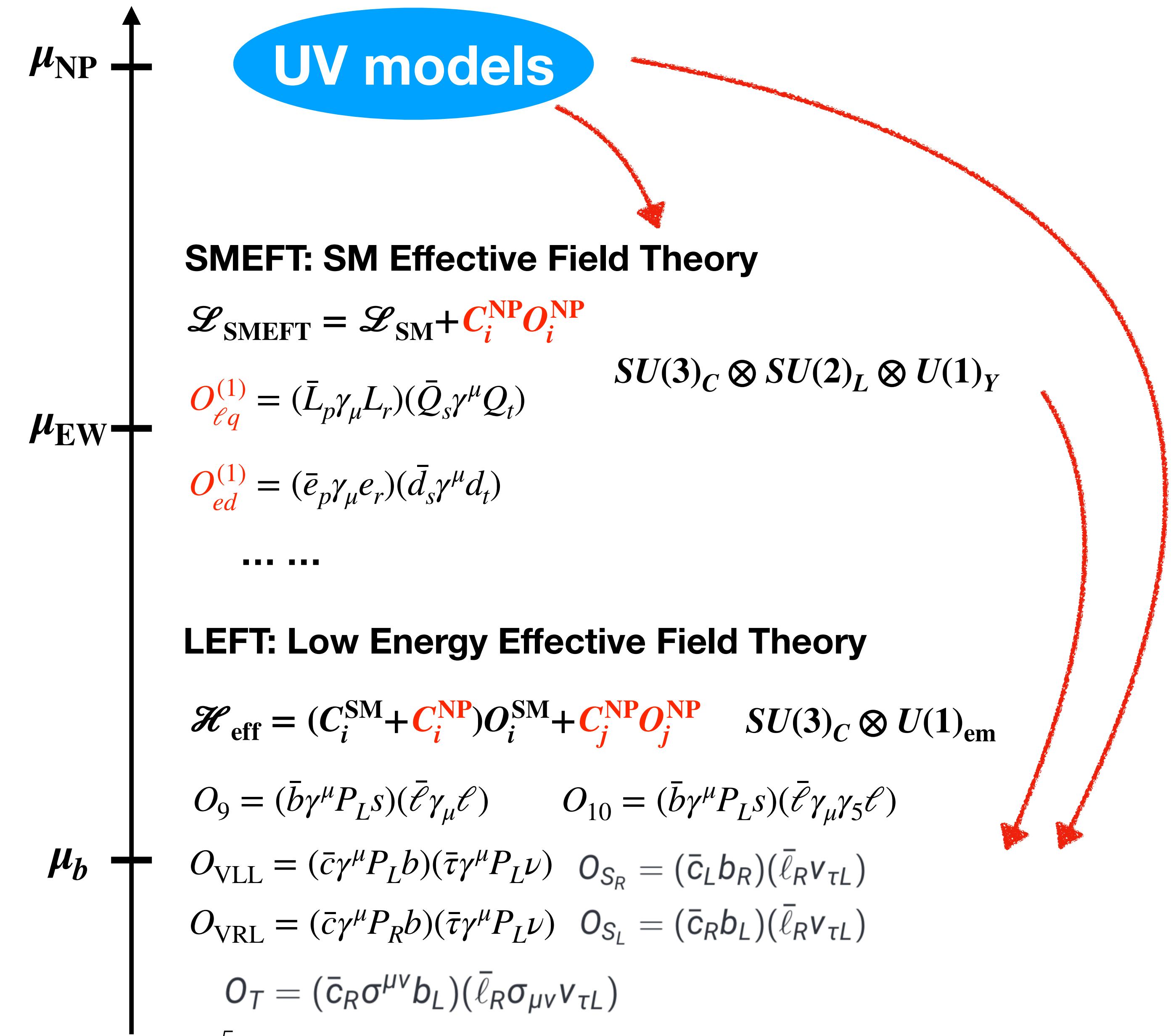
- ▶ Theoretical Uncertainties:
  - branching ratio: 😢
  - angular distribution: 😢
  - LFV ratio: 😊

# Flavour anomalies: theoretical interpretation

## ► $b \rightarrow s\ell^+\ell^-$ anomalies

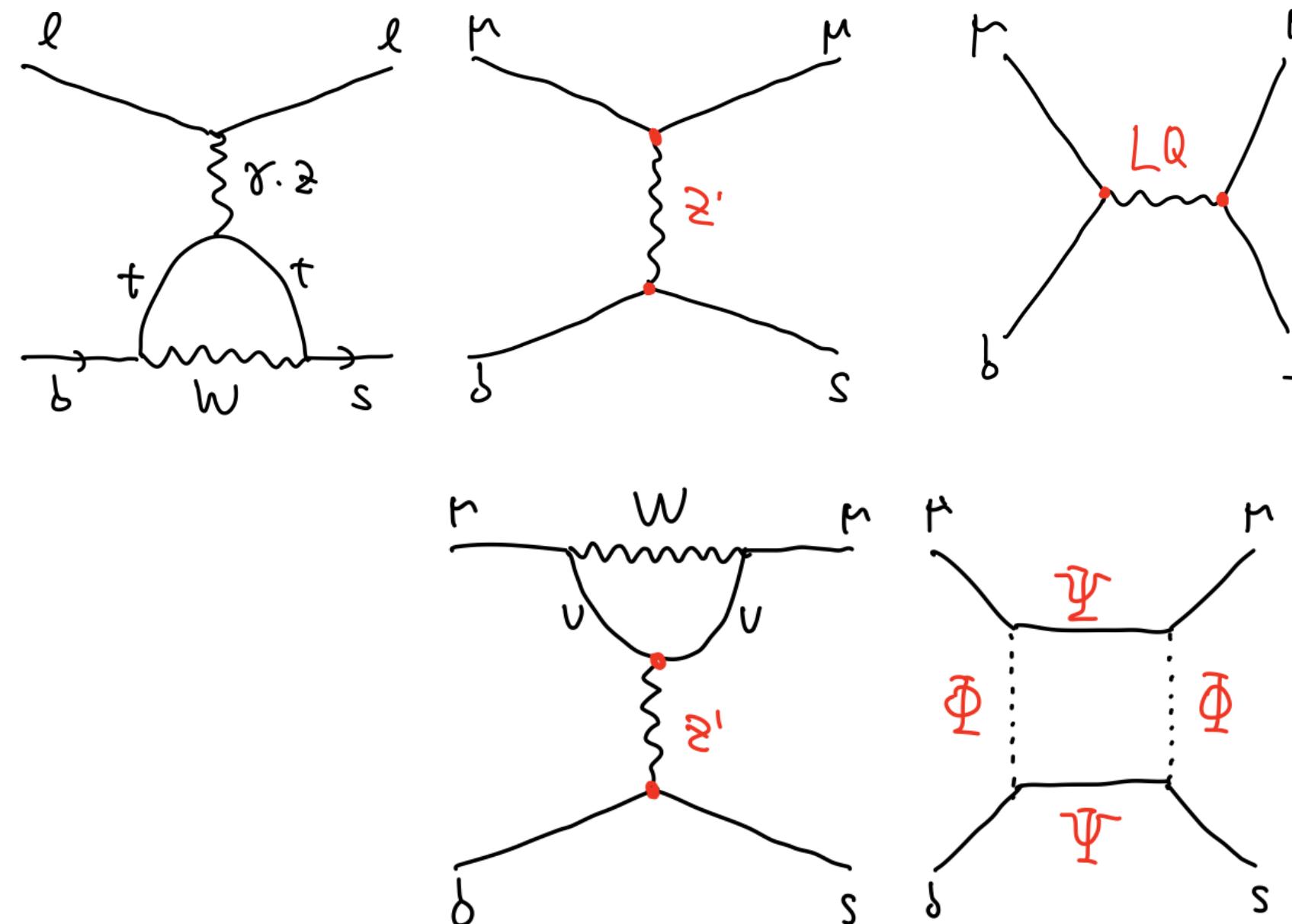


Altmannshofer, Gori, Pospelov, Yavin; 1403.1269,  
 Crivellin, D'Ambrosio, Heeck; 1501.00993,  
 Celis, Fuentes-Martin, Jung, Serodio; 1505.03079,  
 Crivellin, Fuentes-Martin, AG, Isidori; 1611.02703,  
 Alonso, Cox, Han, Yanagida; 1705.03858,  
 Bonilla, Modak, Srivastava, Valle; 1705.00915,  
 Ellis, Fairbairn, Tunney; 1705.03447;  
 Allanach, Davighi; 1809.01158,  
 Altmannshofer, Davighi, Nardecchia; 1909.02021,  
 Allanach; 2009.02197,  
 + many more ...

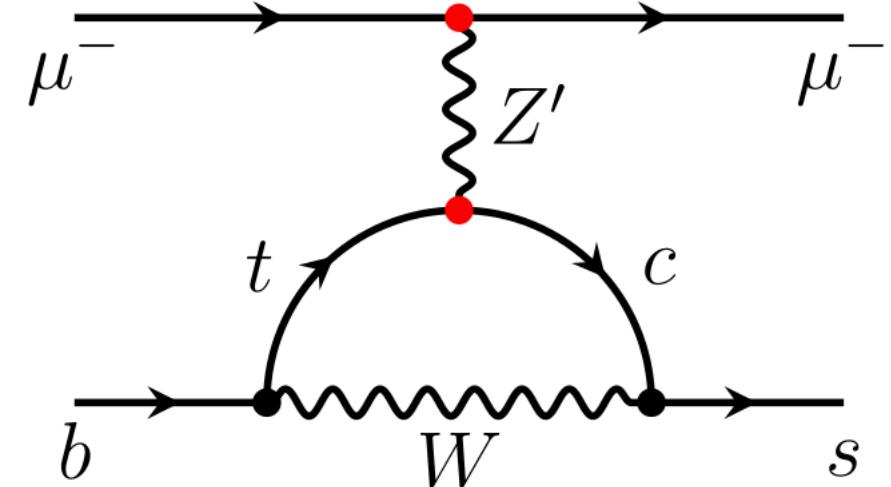


# Flavour anomalies: theoretical interpretation

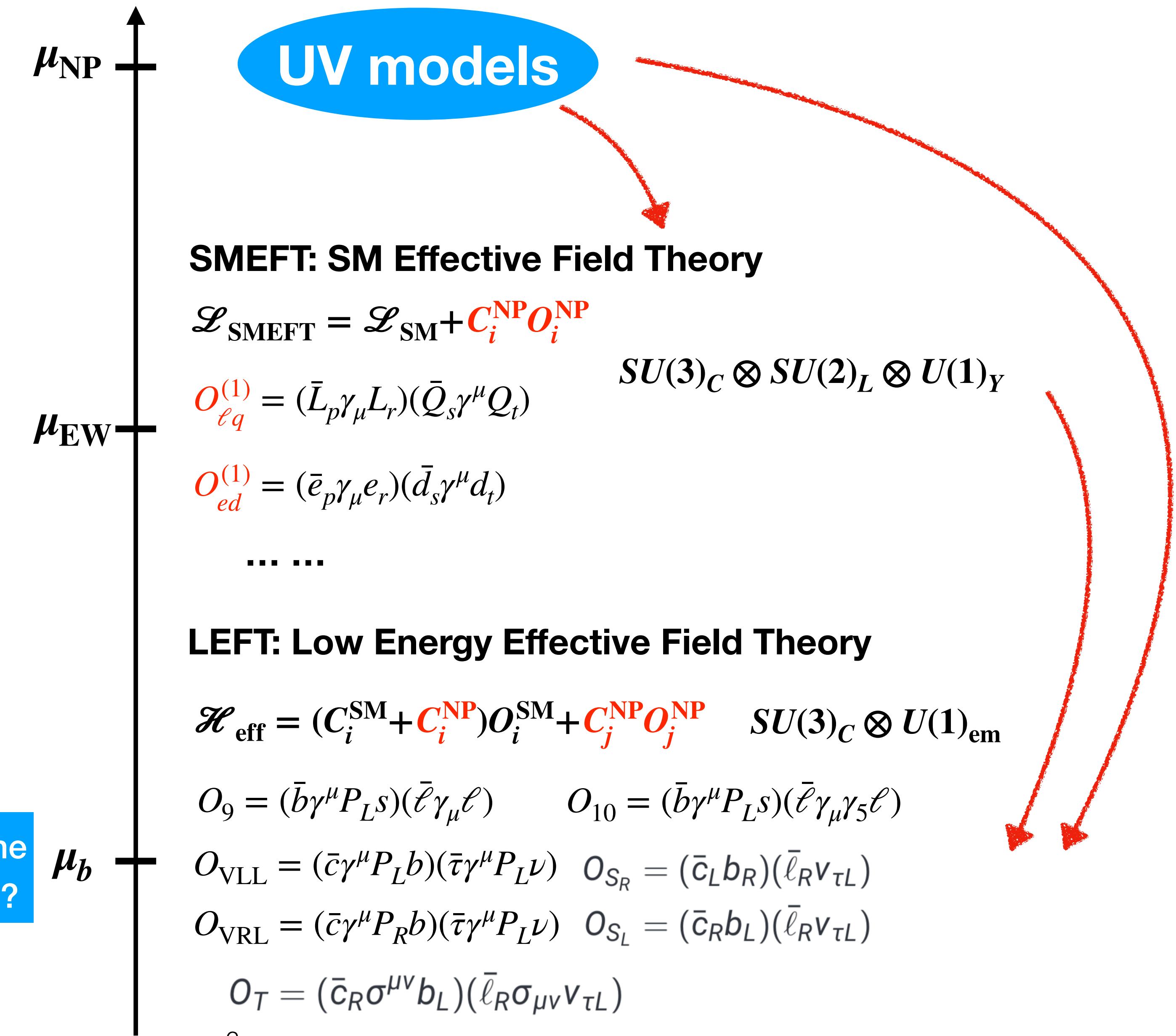
## ► $b \rightarrow s\ell^+\ell^-$ anomalies



## ► New possibility ?



Explain  $b \rightarrow s\ell^+\ell^-$  by the NP with  $t \rightarrow c$  transition ?



# Z' scenarios with top-FCNC couplings

## ► Lagrangian (mass eigenstates)

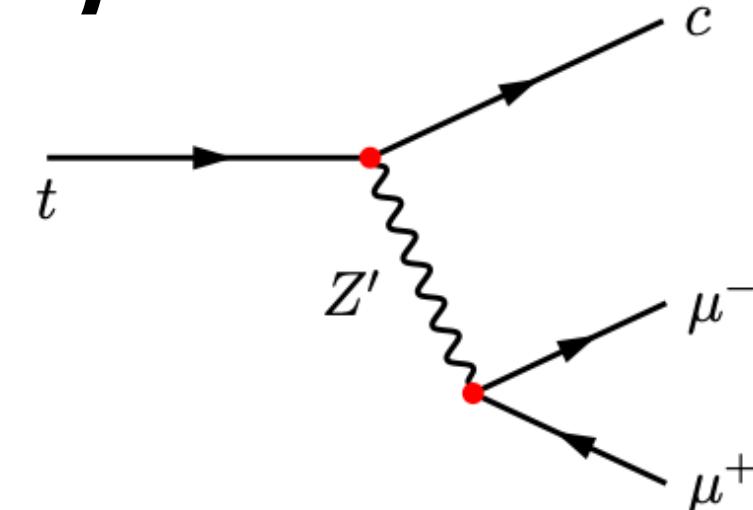
$$\mathcal{L}_{Z'}^I = \left( X_{ct}^L \bar{c} \gamma^\mu P_L t Z'_\mu + \text{h.c.} \right) + \lambda_{\mu\mu}^L \bar{\mu} \gamma^\mu P_L \mu Z'_\mu$$

## ► Comments

- Phenomenological scenarios (simple, but not UV complete)
- 2 parameters  $X_{ct}^L$  (complex) and  $\lambda_{\mu\mu}^L$  (real)
- Right-handed  $\mu^+ \mu^- Z'$  interaction can be added  $\implies (g-2)_\mu$
- $e^+ e^- Z'$  instead of  $\mu^+ \mu^- Z'$  is also possible  $\implies$  pheno@ $e^+ e^-$  collider
- $\bar{t} u Z'$  instead of  $\bar{t} c Z'$  is also possible
- Models with right-handed  $\bar{t} c Z'$  couplings

R. Coy, M. Frigerio, F. Mescia, O. Sumensari, EPJC 2020.  
 H.J. He, T.M.P. Tait, C.P. Yuan, PRD 2000  
 X.F. Wang, C. Du, H.J. He, PLB 2013

## ► $t \rightarrow c \mu^+ \mu^-$

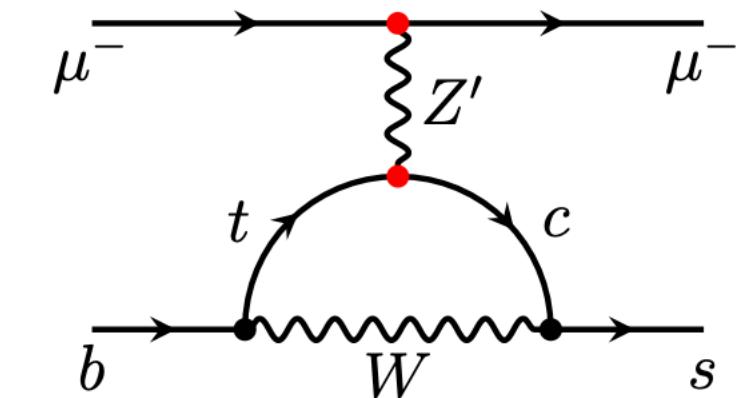
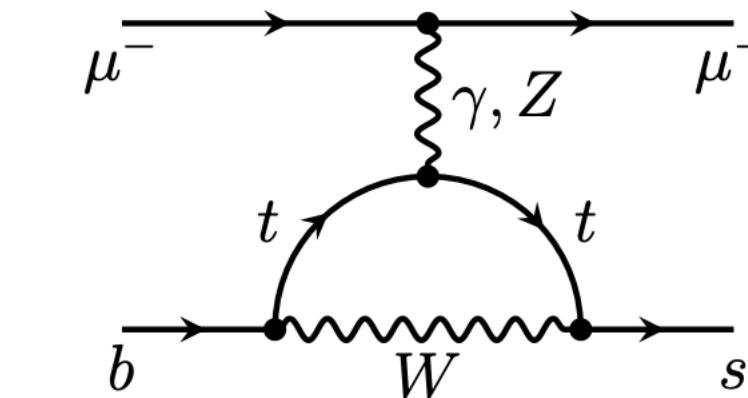


SM branching ratio  $\sim \mathcal{O}(10^{-10})$

clean NP signal

## ► $b \rightarrow s \mu^+ \mu^-$

### ► Feynman diagram



### ► Effective Hamiltonian

$$\mathcal{H}_{\text{eff}}^{b \rightarrow s \mu^+ \mu^-} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i=1}^{10} \mathcal{C}_i \mathcal{O}_i$$

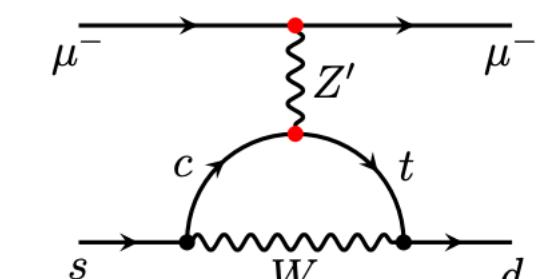
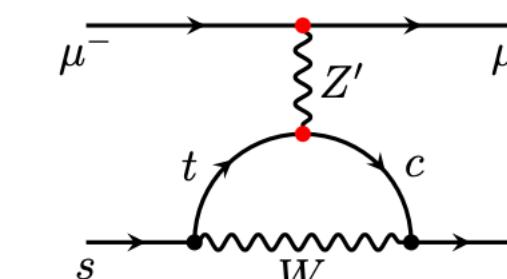
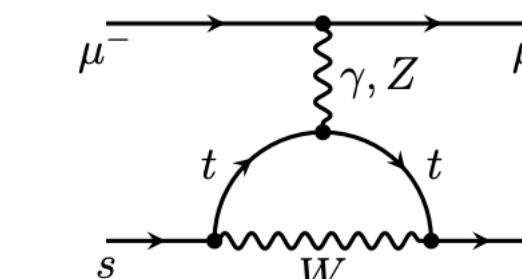
$$\mathcal{O}_{9\ell} = \frac{e^2}{16\pi^2} (\bar{s} \gamma_\mu P_L b)(\bar{\ell} \gamma^\mu \ell) \quad \mathcal{O}_{10\ell} = \frac{e^2}{16\pi^2} (\bar{s} \gamma_\mu P_L b)(\bar{\ell} \gamma^\mu \gamma_5 \ell)$$

### ► Wilson coefficient: NP effect

$$\mathcal{C}_{9\mu}^{\text{NP}, I} = -\mathcal{C}_{10\mu}^{\text{NP}, I} = \frac{1}{8\sqrt{2}G_F s_W^2} \frac{V_{cs}^*}{V_{ts}^*} \frac{X_{ct}^L \lambda_{\mu\mu}^L}{m_{Z'}^2} f(x_t)$$

- enhanced by  $V_{cs}/V_{ts}$
- favored by  $b \rightarrow s \ell^+ \ell^-$  global fits

## ► $s \rightarrow d \mu^+ \mu^-$



# Numerical analysis: $b \rightarrow s\ell^+\ell^-$

## ► Global fit

### ► Inclusive decays

- $B \rightarrow X_s \gamma$
- $B \rightarrow X_s \ell^+ \ell^-$

### ► Exclusive leptonic decays

- $B_{s,d} \rightarrow \ell^+ \ell^-$

### ► Exclusive radiative/semileptonic decays

- $B \rightarrow K^* \gamma$

e.g., LHCb, Nature Phys. 18 (2022) 3, 277 | PRL128(2022)19, 191802

- $B^{(0,+)} \rightarrow K^{(0,+)} \ell^+ \ell^-$

e.g., LHCb PRL126(2021), 16161802

- $B_s \rightarrow \phi \mu^+ \mu^-$

e.g., LHCb, PRL127(2021)15, 151801, JHEP11(2021)043

- $\Lambda_b \rightarrow \Lambda \mu^+ \mu^-$

e.g., LHCb JHEP 09 (2018) 146

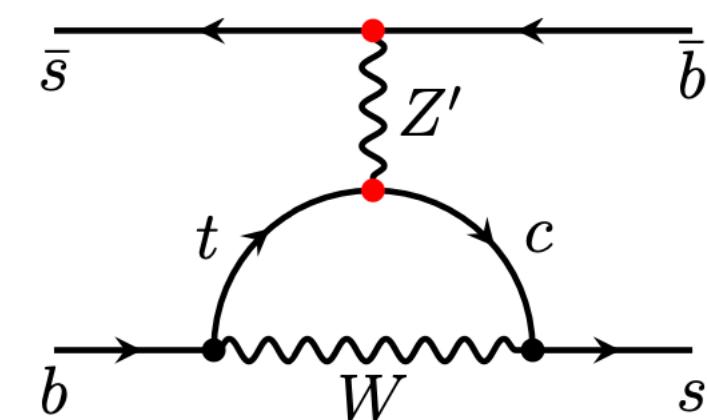
### ► Including about 200 observables (almost all available measurements

from BaBar, Belle, CDF, ATLAS, CMS, and LHCb)

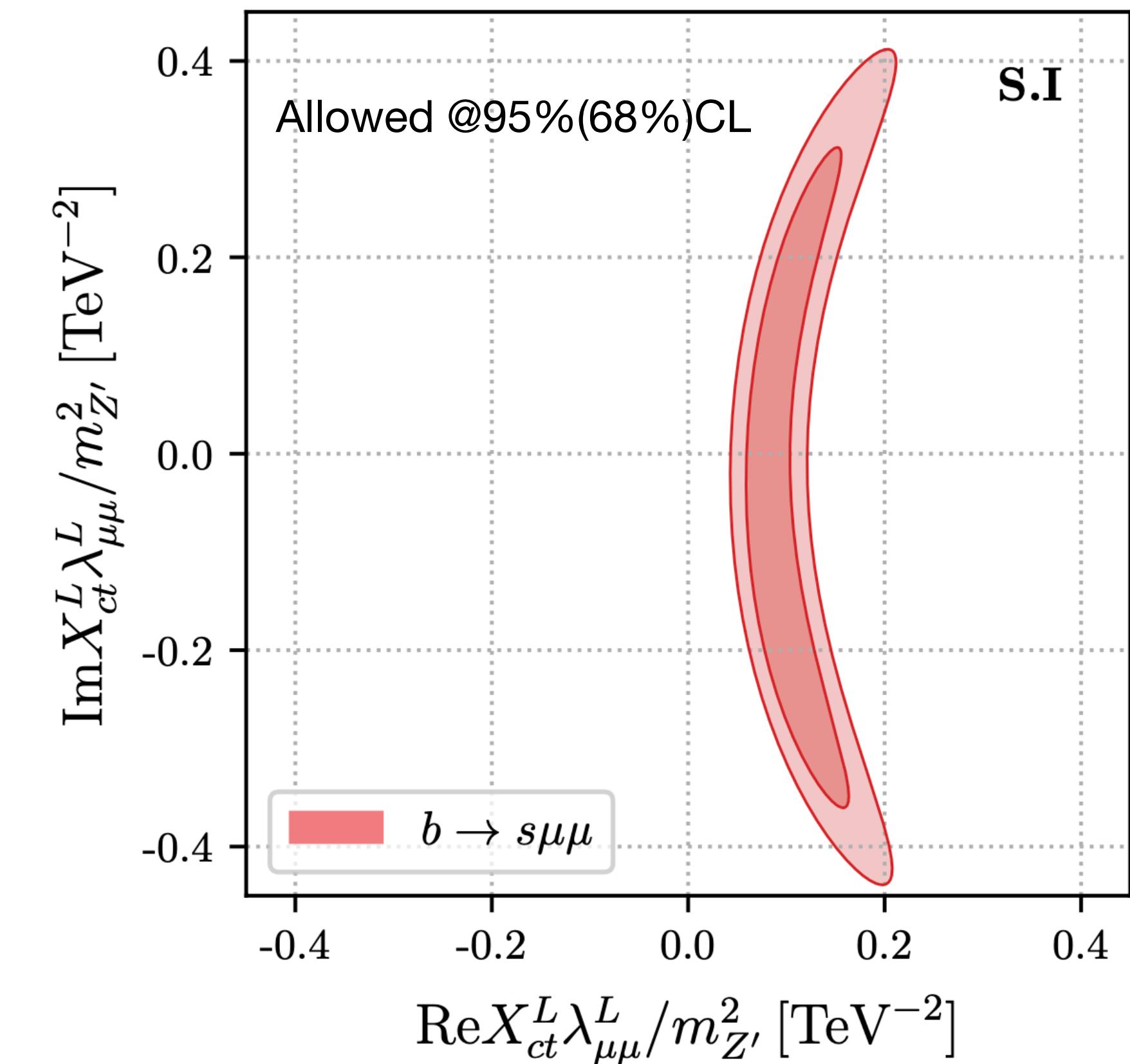
### ► performed using an extended version of the package **flavio**

## ► Parameters

$$\frac{\text{Re}X_{ct}^L \lambda_{\mu\mu}^L}{m_{Z'}^2} \quad \frac{\text{Im}X_{ct}^L \lambda_{\mu\mu}^L}{m_{Z'}^2}$$



## ► Fit result



- ★ can explain  $b \rightarrow s\ell^+\ell^-$  anomalies at 95% CL.
- ★ for  $m_{Z'} < \mathcal{O}(5)$  TeV, both  $X_{ct}^L$  and  $\lambda_{\mu\mu}^L$  are in the perturbative region

# Numerical analysis: $t \rightarrow c\mu^+\mu^-$

$m_{Z'} < m_t$

►  $t \rightarrow c\mu^+\mu^-$

- ▶ Currently, no direct experimental bounds
- ▶ LHC searches performed at the  $Z$  peak,  $|m_{\mu\mu} - m_Z| < 15$  GeV
- ▶ Detailed analysis with the signal shape could be used to derive constraints
- ▶ We concentrate on the mass region  $105$  GeV  $< m_{Z'} < m_t$

►  $t \rightarrow cZ'$

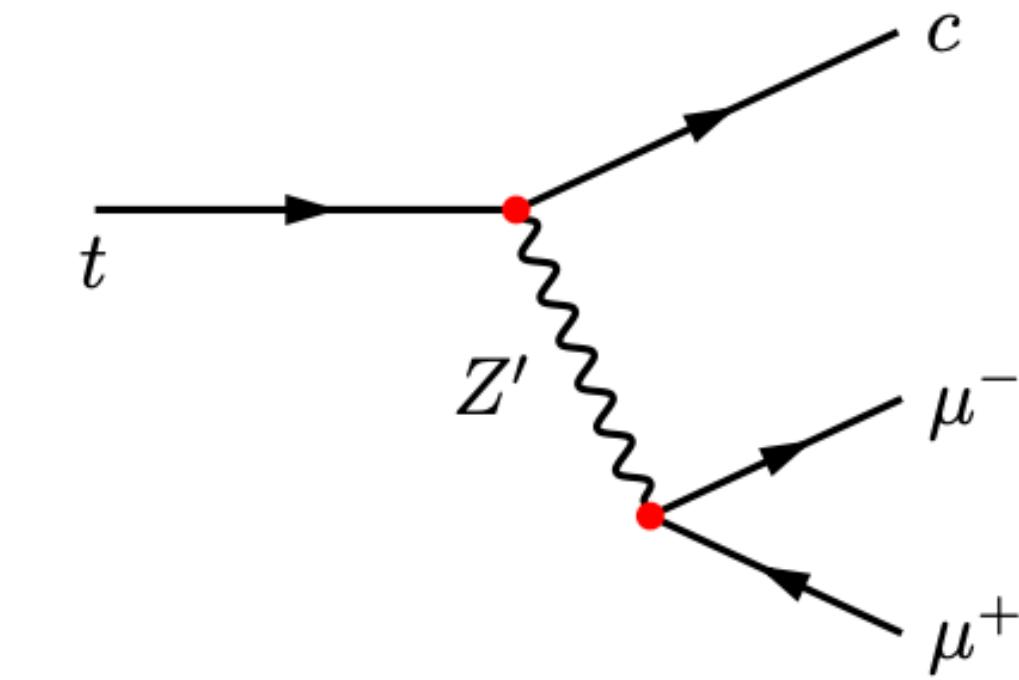
- ▶ Currently, no direct experimental bounds
- ▶ Contribute to the top-quark width
- ▶  $\Gamma_t^{\text{SM}} = 1.3$  GeV v.s.  $\Gamma_t^{\text{exp}} = 1.42^{+0.19}_{-0.15}$  GeV leaves  $\mathcal{O}(20\%)$  room for  $Z'$
- ▶ ★ Top-quark provides a unique constraint on the  $\bar{t}cZ'$  coupling

$m_{Z'} > m_t$

►  $t \rightarrow c\mu^+\mu^-$

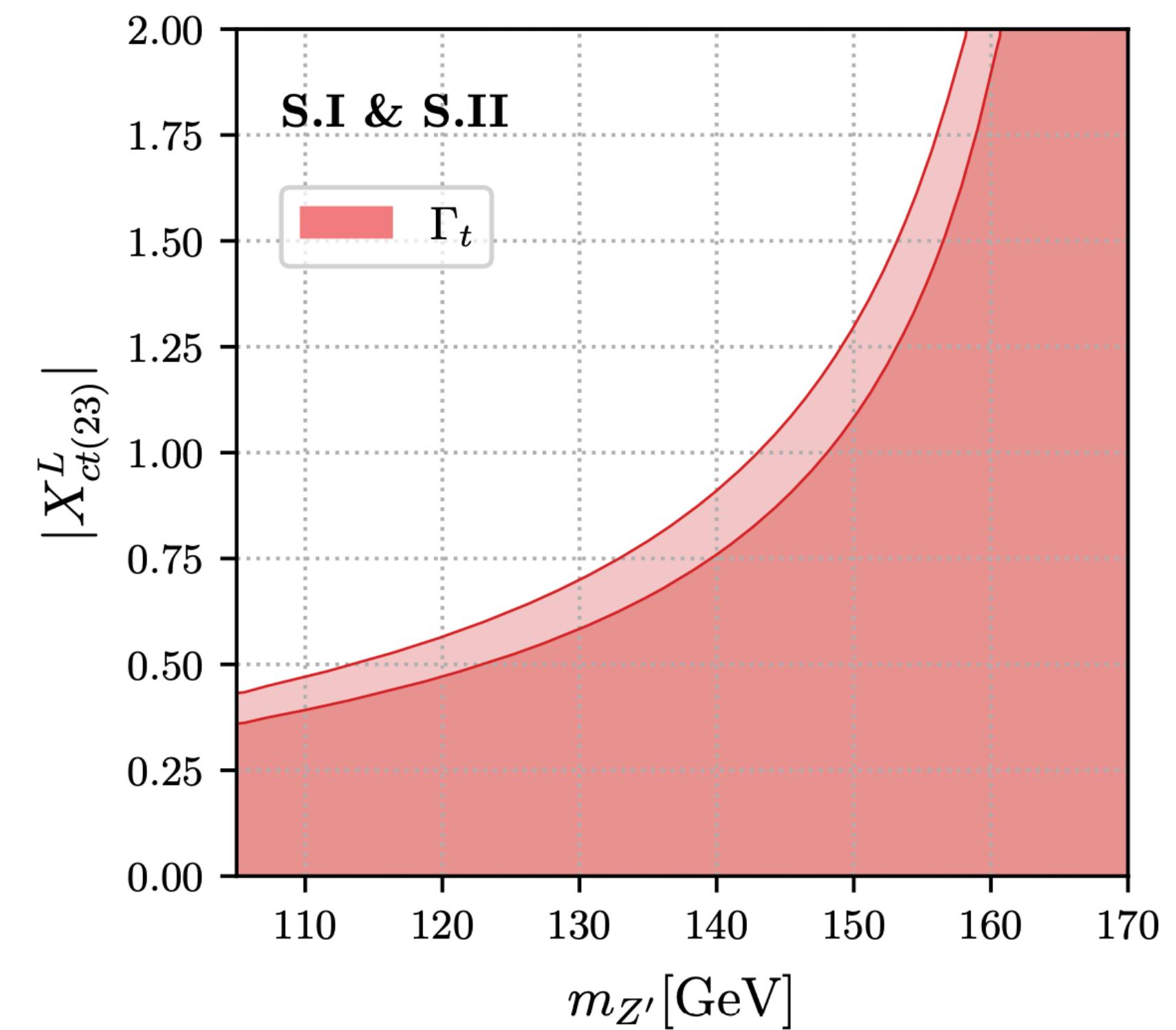
- ▶ Currently, no direct experimental bounds
- ▶ No constraints, similar as the  $m_{Z'} < m_t$  case

►  $pp \rightarrow tZ'$



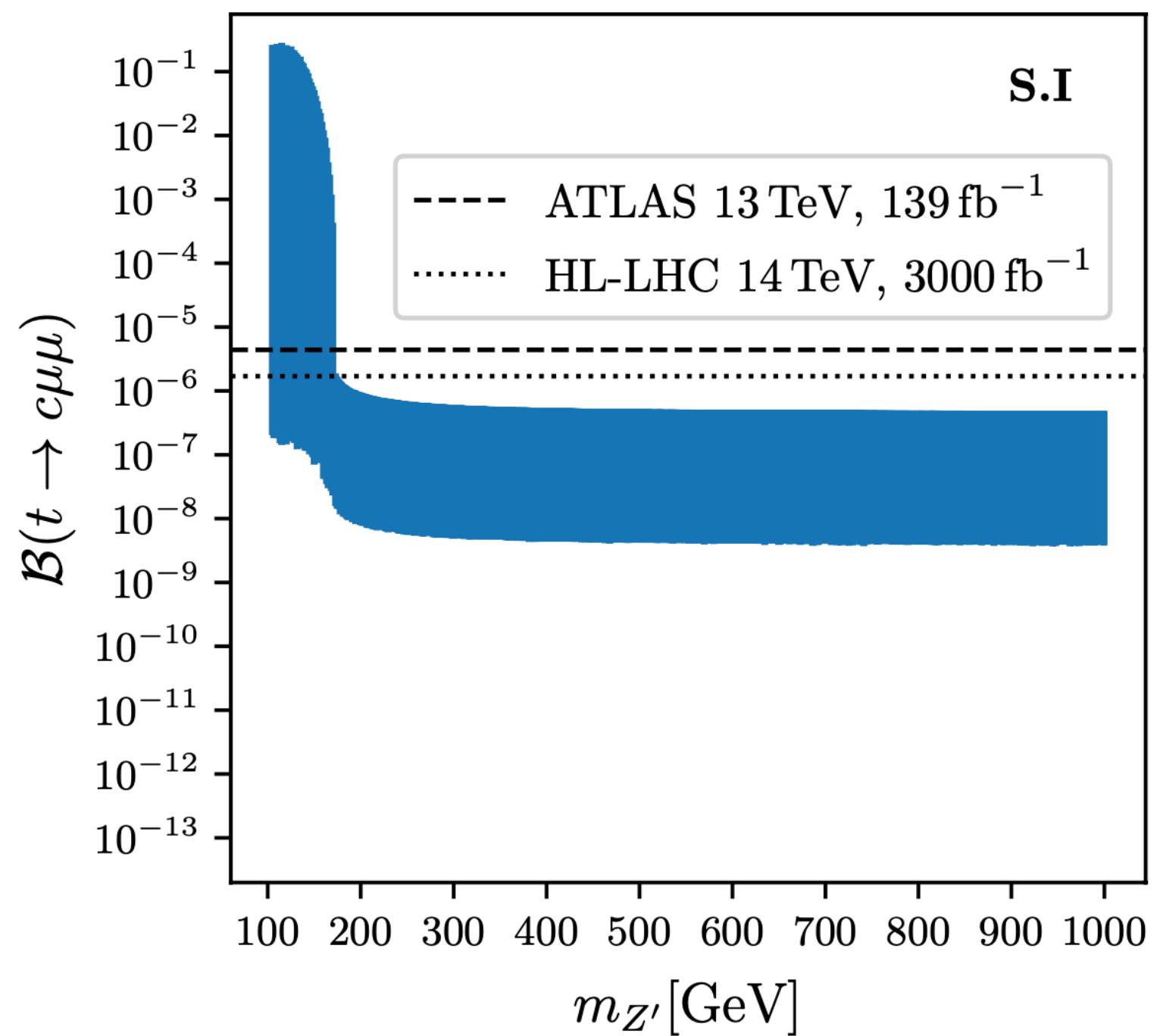
ATLAS, JHEP07(2018)176; CMS, JHEP07(2017)003

M. Chala, J. Santiago, and M. Spannowsky, JHEP04(2019)014



# Numerical analysis: $t \rightarrow c\mu^+\mu^-$

## ► Prediction on $Br(t \rightarrow c\mu^+\mu^-)$



- Upper bound on  $Br(t \rightarrow c\mu^+\mu^-)$  is estimated by the bound on  $Br(t \rightarrow cZ)$  and  $Br(Z \rightarrow \mu^+\mu^-) = 3.37\%$

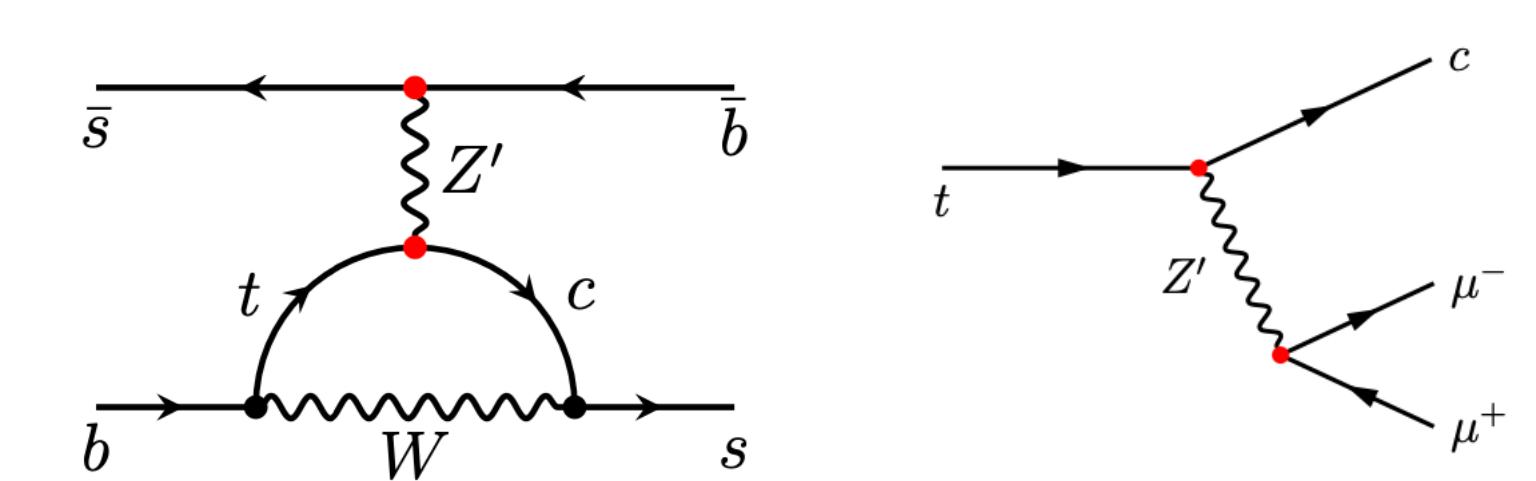
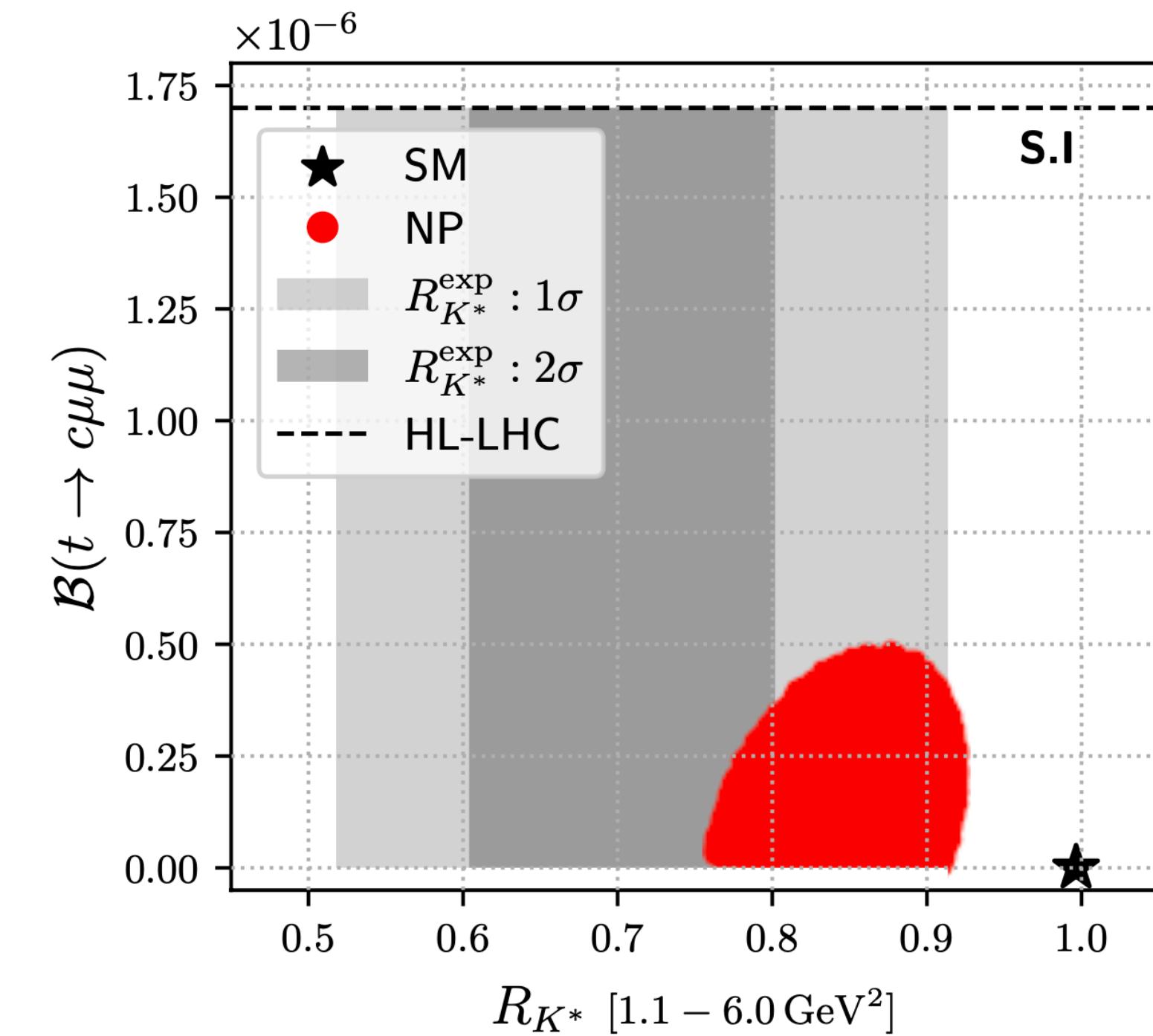
★  $m_{Z'} < m_t$ :  $t \rightarrow c\mu^+\mu^-$  can serve as a sensitive probe of the  $Z'$  boson

★  $m_{Z'} > m_t$ :  $pp \rightarrow tZ'$  reaches the sensitivity of the HL-LHC ( $3000 \text{ fb}^{-1}$ )

► Sensitivity is  $\Lambda_{tc\mu\mu} = 1.5 \text{ TeV}$  from an EFT analysis

►  $1.4 < \Lambda_{tc\mu\mu} < 4.8 \text{ TeV}$  obtained from the  $b \rightarrow s\ell^+\ell^-$  global fit

## ► Correlation for $m_{Z'} = 1 \text{ TeV}$



# Summary: $Z'$ scenarios with top-FCNC couplings

## Conclusions

- ▶ A phenomenological  $Z'$  scenario is considered, in which a  $Z'$  couples only to  $t\bar{c}$  and  $\mu^+\mu^-$  with left-handed chirality
- ▶ The  $Z'$  effects on the  $b \rightarrow s\mu^+\mu^-$  automatically induce  $C_9^{\text{NP}} = -C_{10}^{\text{NP}}$ , which is favored by the global fit
- ▶ The  $Z'$  scenario can address the  $b \rightarrow s\mu^+\mu^-$  anomalies, which satisfying other flavour and collider constraints
- ▶ For  $m_{Z'} < m_t$ : resonance searches in  $t \rightarrow c\mu^+\mu^-$  can serve as a sensitive probe of the  $Z'$  boson
- ▶ For  $m_{Z'} > m_t$ :  $pp \rightarrow tZ'$  reaches the sensitivity of the HL-LHC ( $3000 \text{ fb}^{-1}$ )

## Issues

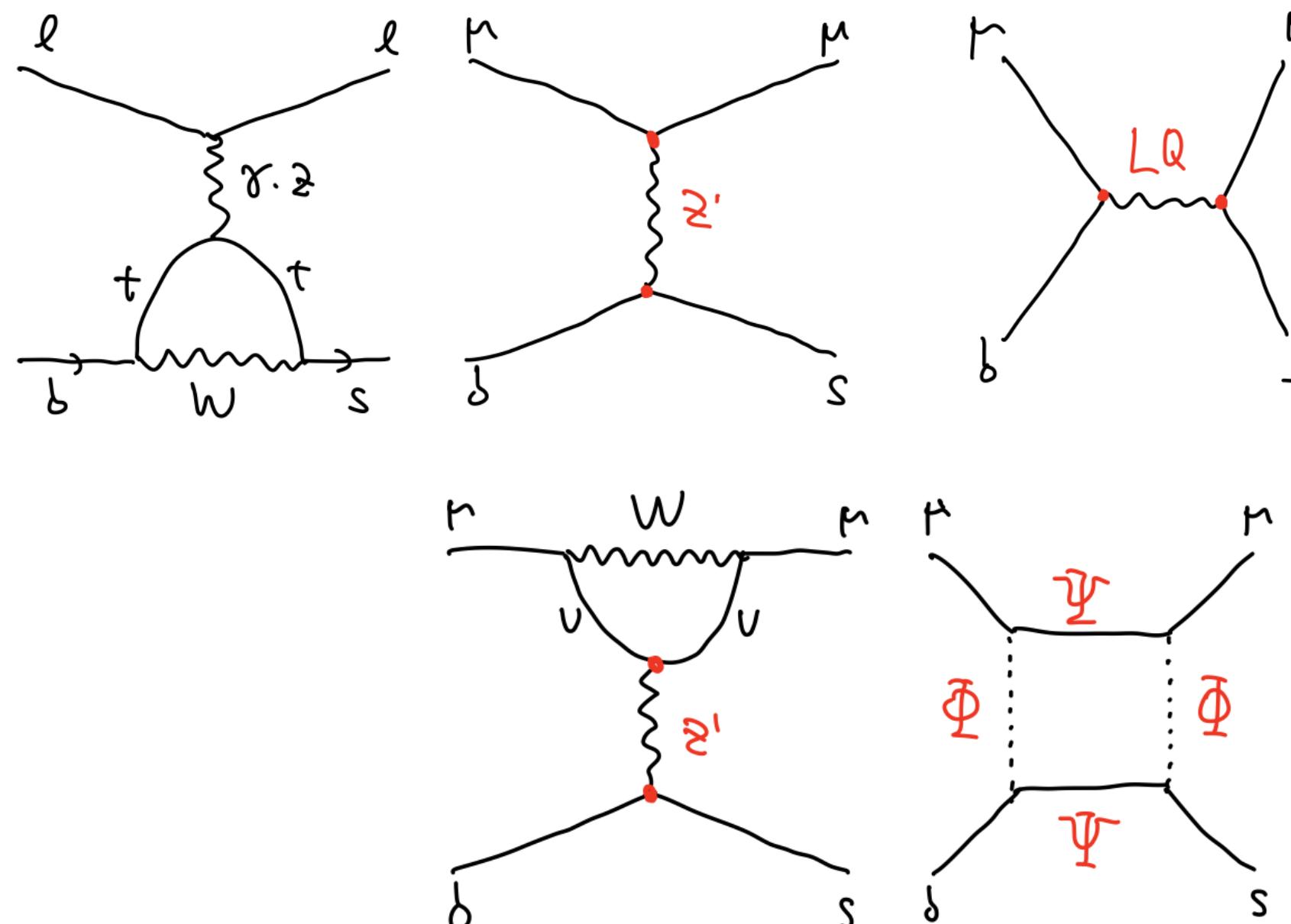
- ▶ NOT UV complete
- ▶ SU(2) invariance
  - ▶ same coupling for  $\bar{b}sZ'$  (considered in our work). For  $b \rightarrow s\mu^+\mu^-$ , effects from  $\bar{b}sZ'$  is dominated)
  - ▶ SU(2) is constructed in the interaction eigenstate. However, the rotation matrices from the interaction to the mass eigenstate are different for  $b_L$  and  $t_L$ . Therefore, the couplings of  $\bar{b}sZ'$  and  $\bar{t}cZ'$  could be different and should depend on the flavour structure of the UV theory.
  - ▶ In the case of a light  $Z'$  (e.g.,  $m_{Z'} < \mu_{\text{EW}}$ ), the  $\bar{t}cZ'$  could be an effective interaction and SU(2) can be broken

## Future works

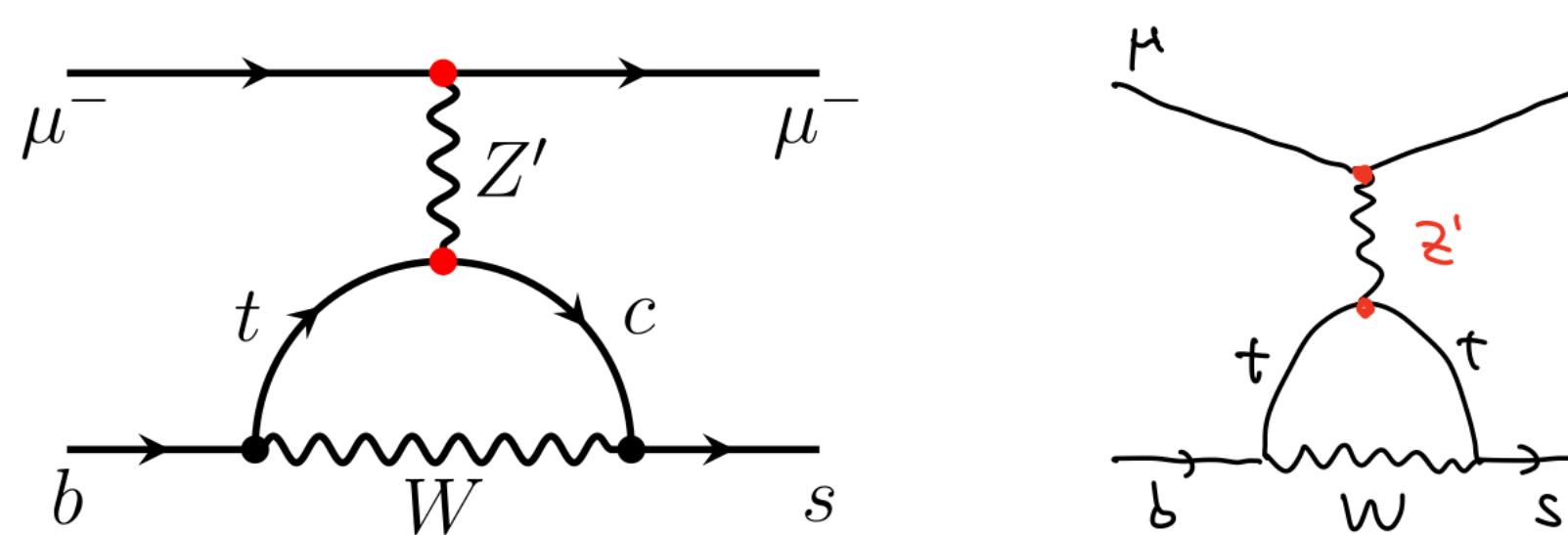
- ▶ UV complete model | (ultra) light  $Z'$  |  $e^+e^-Z'$  | detailed collider simulation

# Flavour anomalies: theoretical interpretation

## ► $b \rightarrow s\ell^+\ell^-$ anomalies

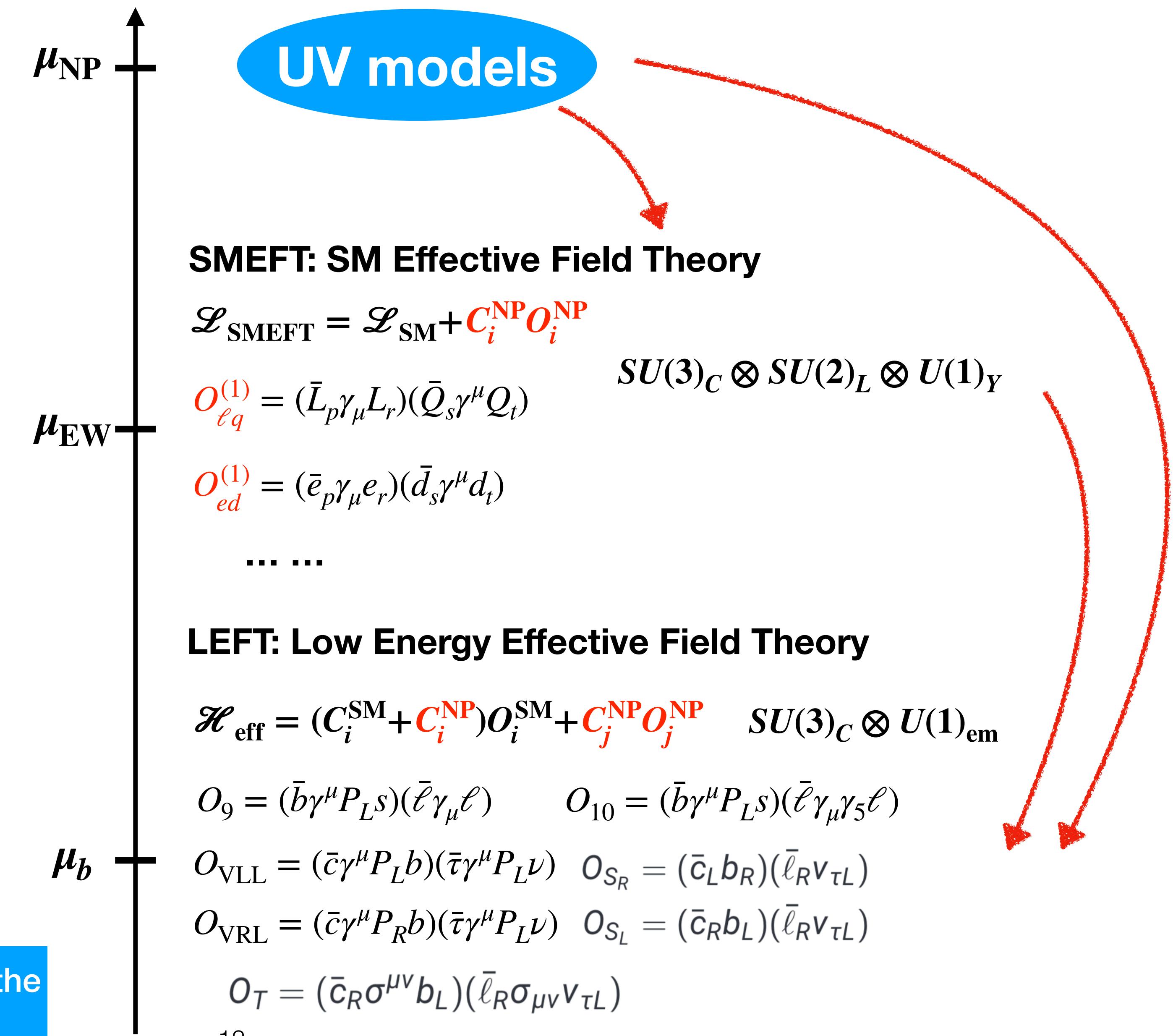


## ► New possibility ?

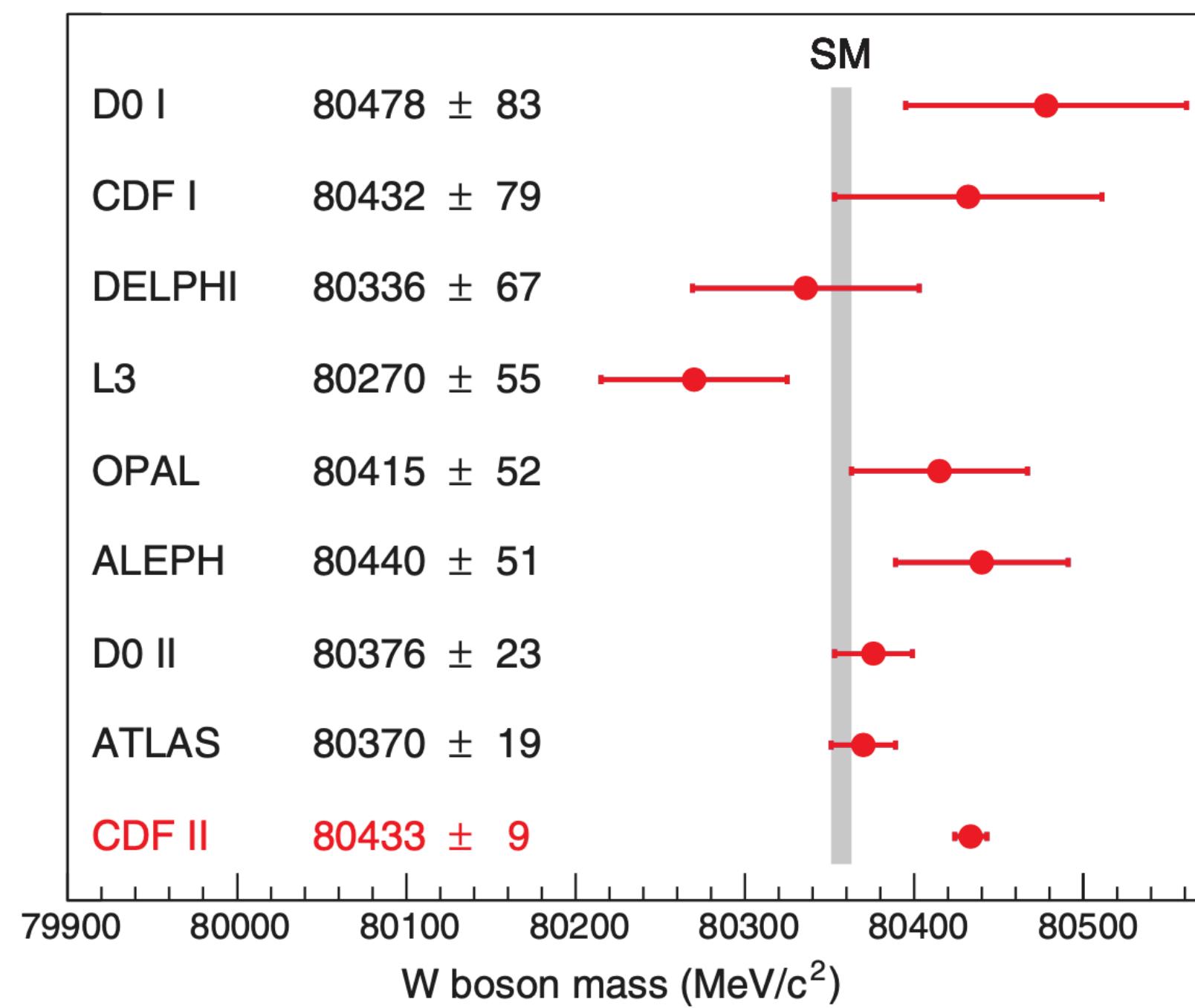


J. F. Kamenik, Y. Soreq, J. Zupan,  
PRD97 (3) (2018) 035002

Explain  $b \rightarrow s\ell^+\ell^-$  by the  
NP without FCNC ?



# W-boson mass shift and oblique parameters



CDF:  $80433 \pm 9 \text{ GeV}$

EW fit:  $80357 \pm 6 \text{ GeV}$

About  $7\sigma$  deviation !!!

PDG:  $80387 \pm 12 \text{ GeV}$

LHCb:  $80354 \pm 31 \text{ GeV}$  LHCb, JHEP01(2022)036

## Global EW fit

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

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

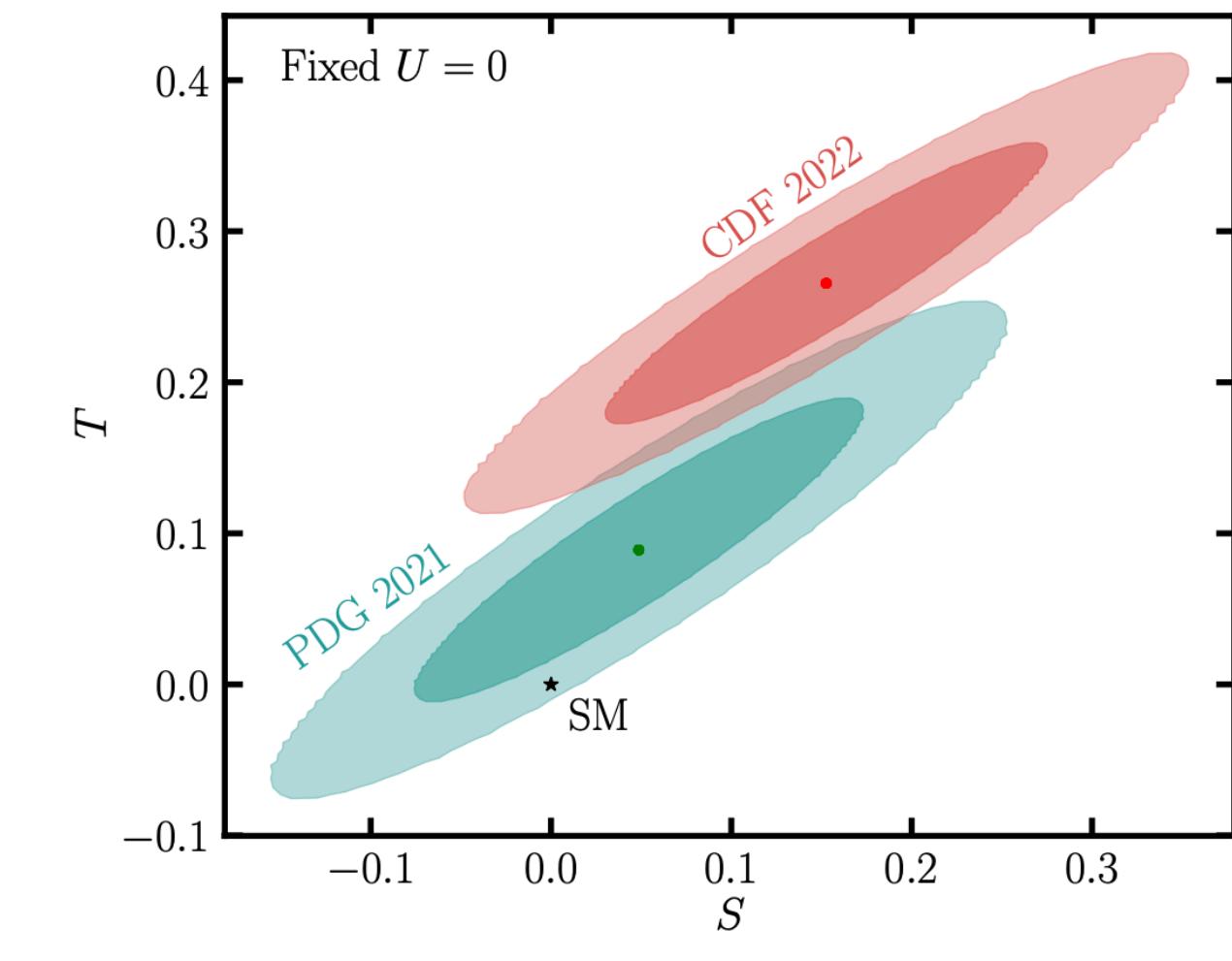
- $S, T, U$  are related to the vacuum polarization of gauge bosons

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

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

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

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



# 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

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

## 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

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

## Interactions

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

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

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

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

## Lagrangian: lepton section

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

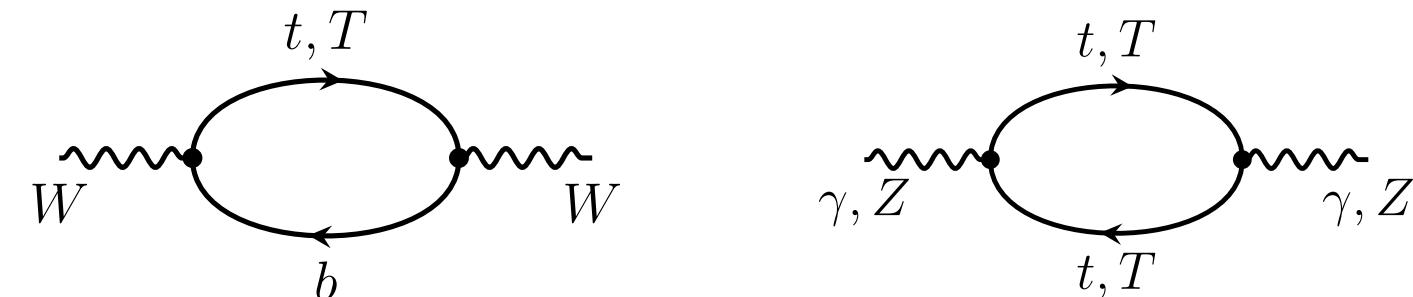
## NP parameters

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

# W-boson mass shift and oblique parameters

## Explanation in top-philic $Z'$ scenario

- NP contributions to vacuum polarizations



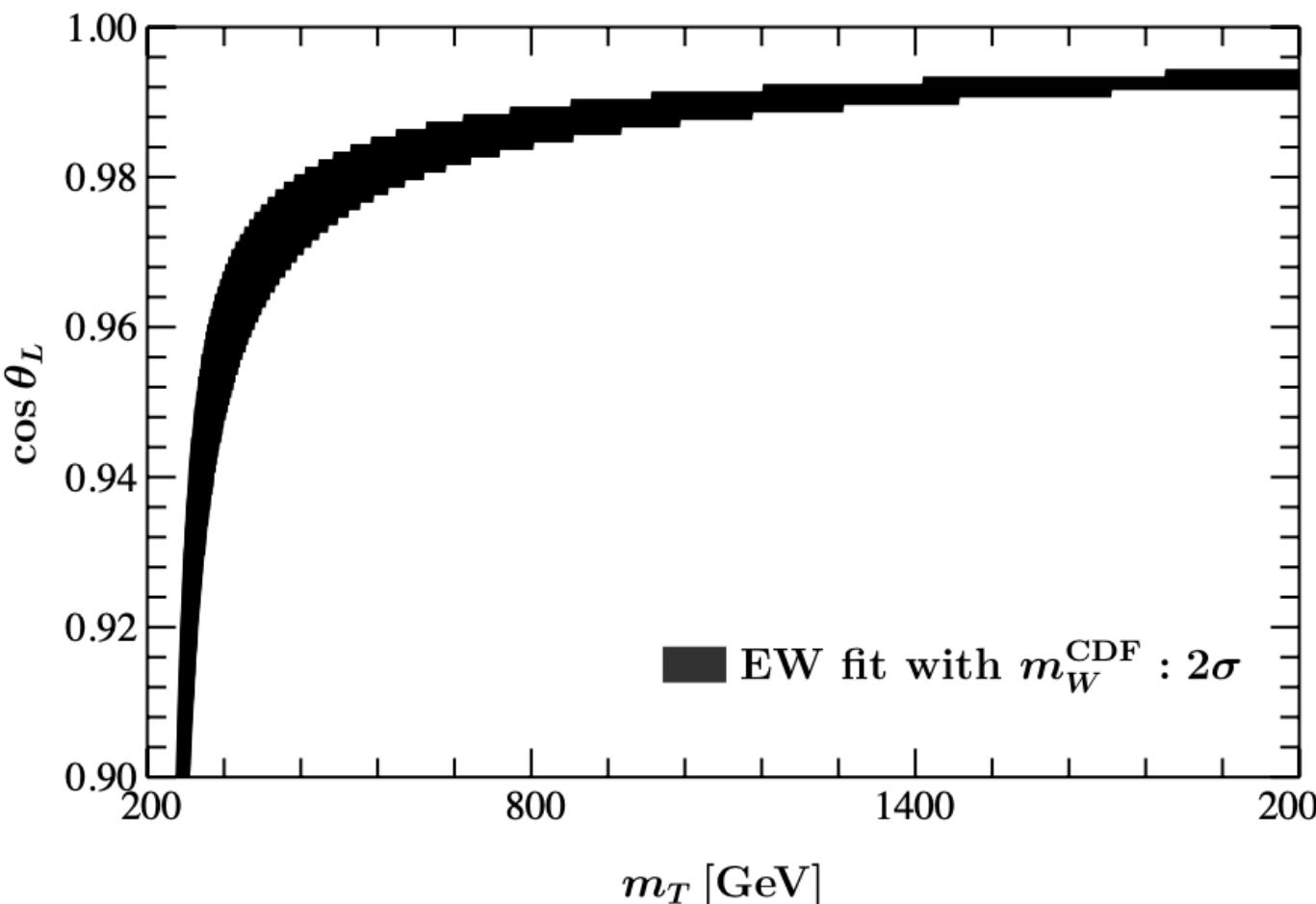
- $S, T, U$  are affected

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

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

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

- Allowed parameter space



- ★  $m_W^{\text{CDF}}$  can be explained by the top-parter effects
- ★ small  $\theta_L$  is allowed

## Global EW fit

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

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

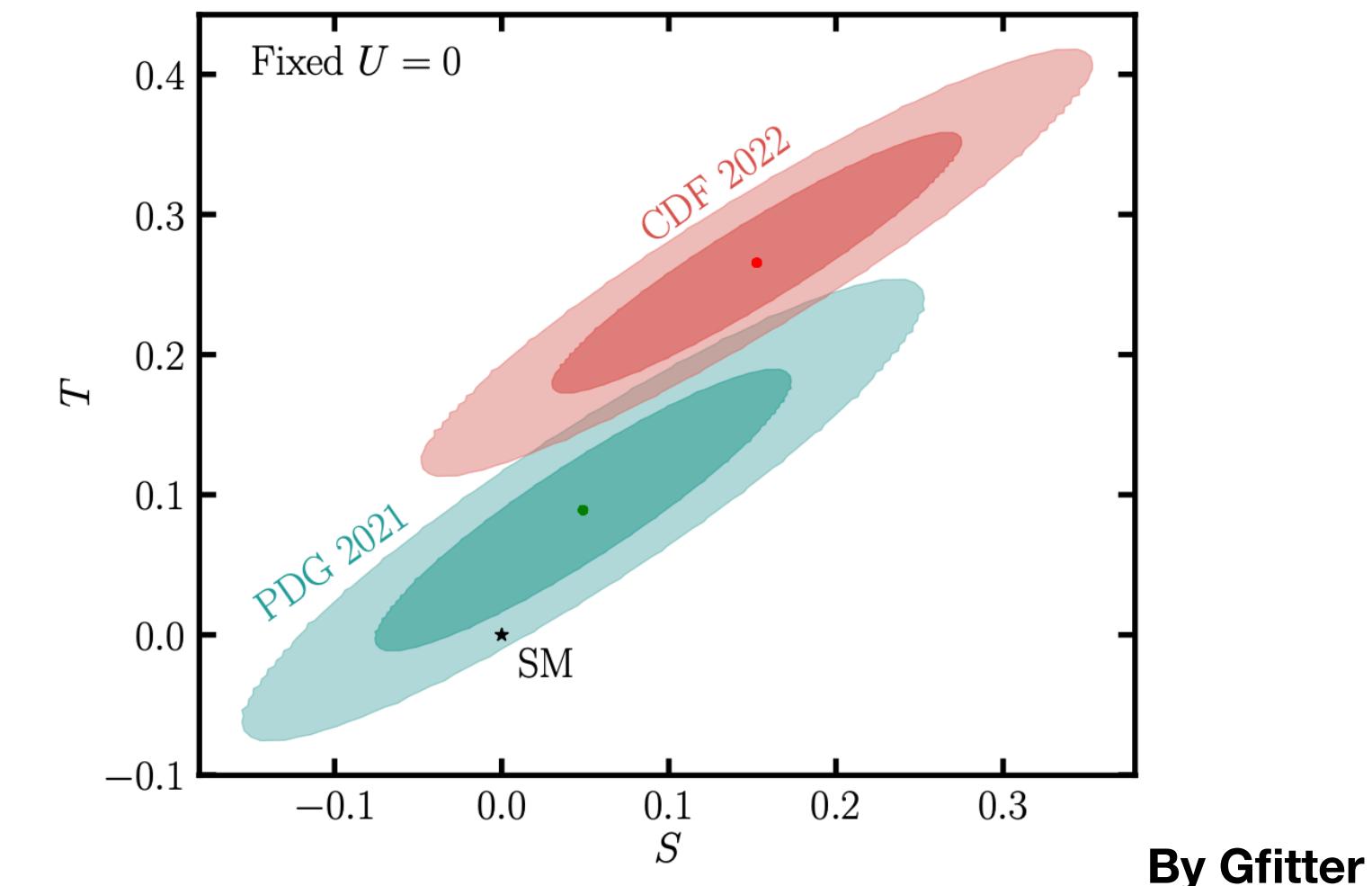
- $S, T, U$  are related to the vacuum polarization of gauge bosons

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

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

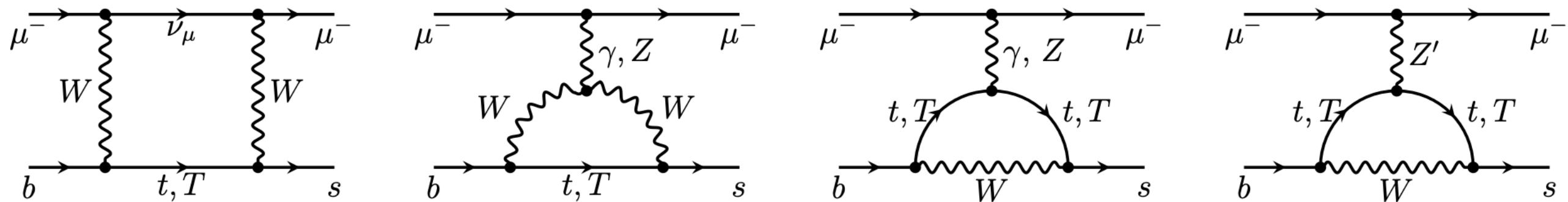
$$U = \frac{4s_W^2}{\alpha_e} \left[ \frac{\Pi_{WW}(m_W^2) - \Pi_{WW}(0)}{m_W^2} - \frac{c_W}{s_W} \Pi'_{Z\gamma}(0) - \Pi'_{\gamma\gamma}(0) \right] - S,$$

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



# $b \rightarrow s\ell^+\ell^-$ anomalies

## ► NP contributions



## ► 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,  $\gamma$ - 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  $b \rightarrow s\ell^+\ell^-$  processes

## ► NP parameters

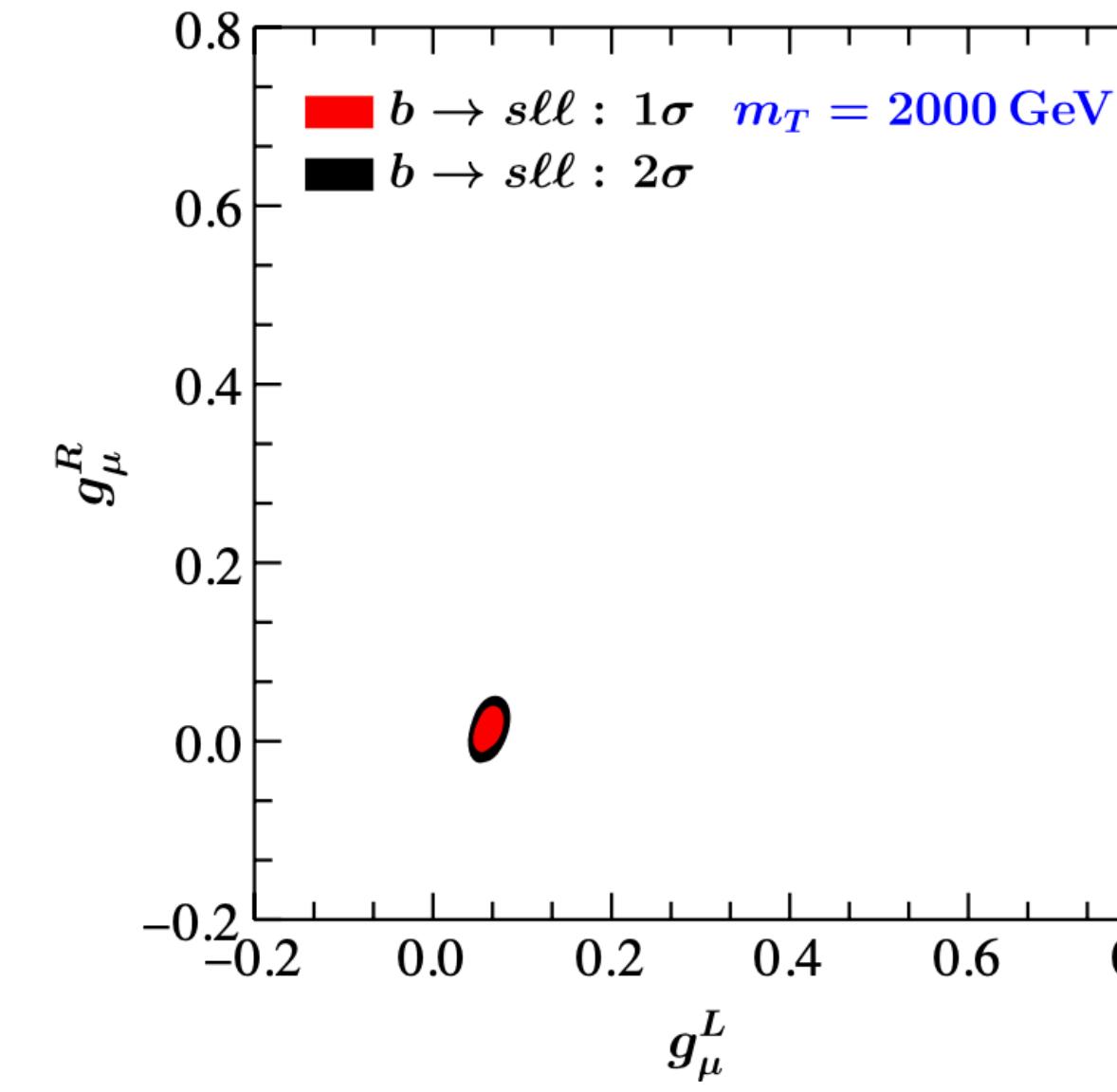
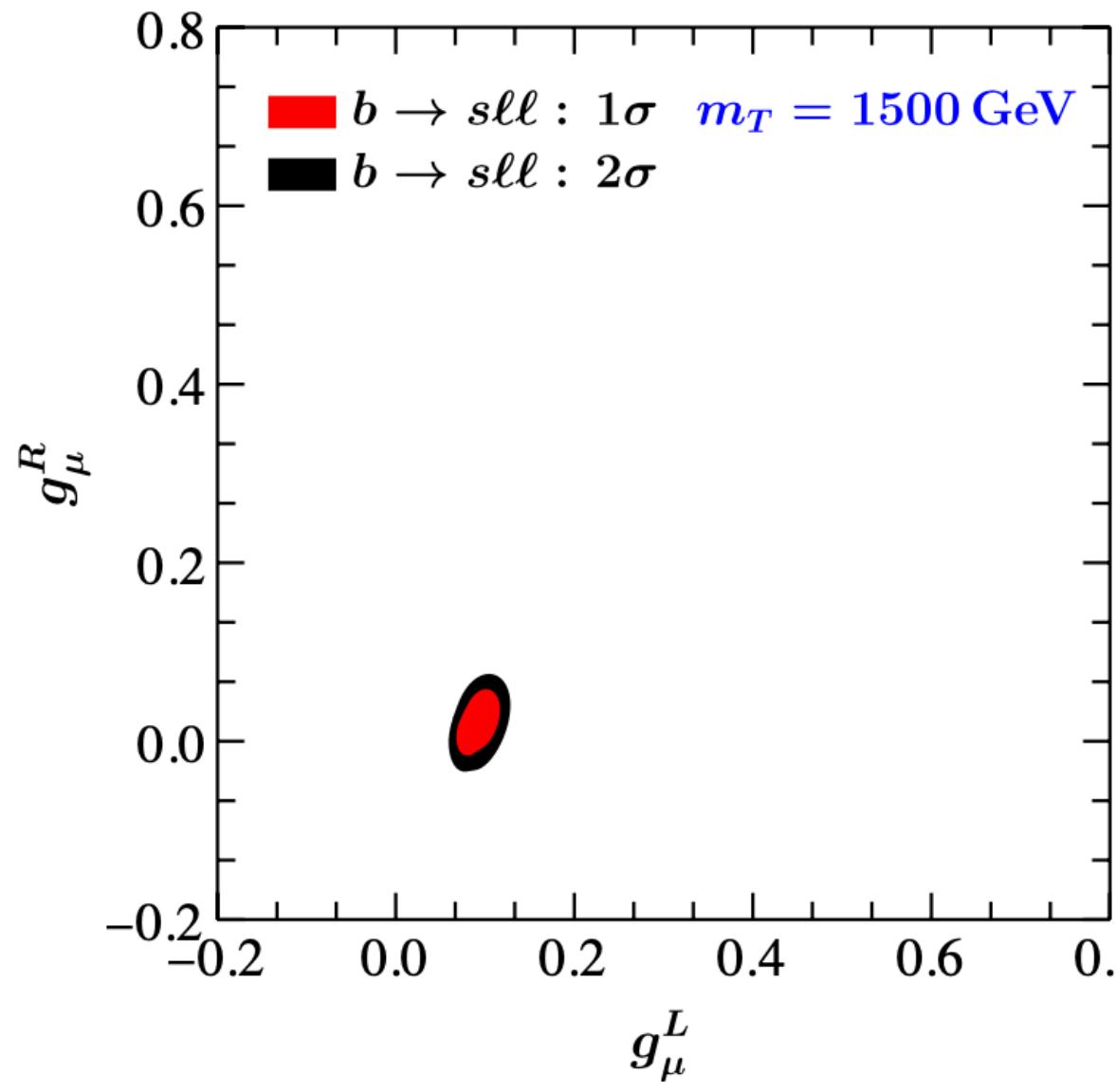
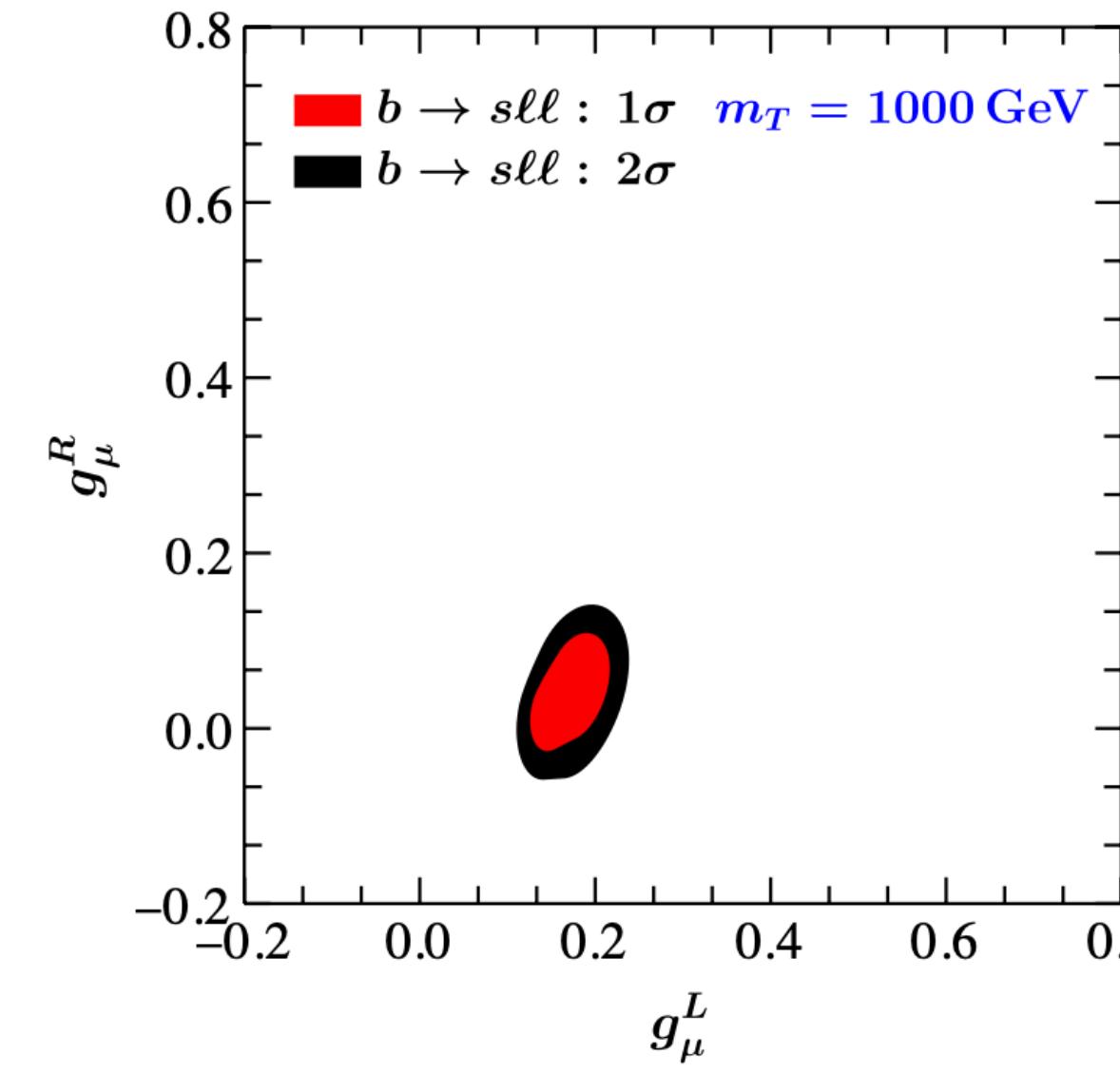
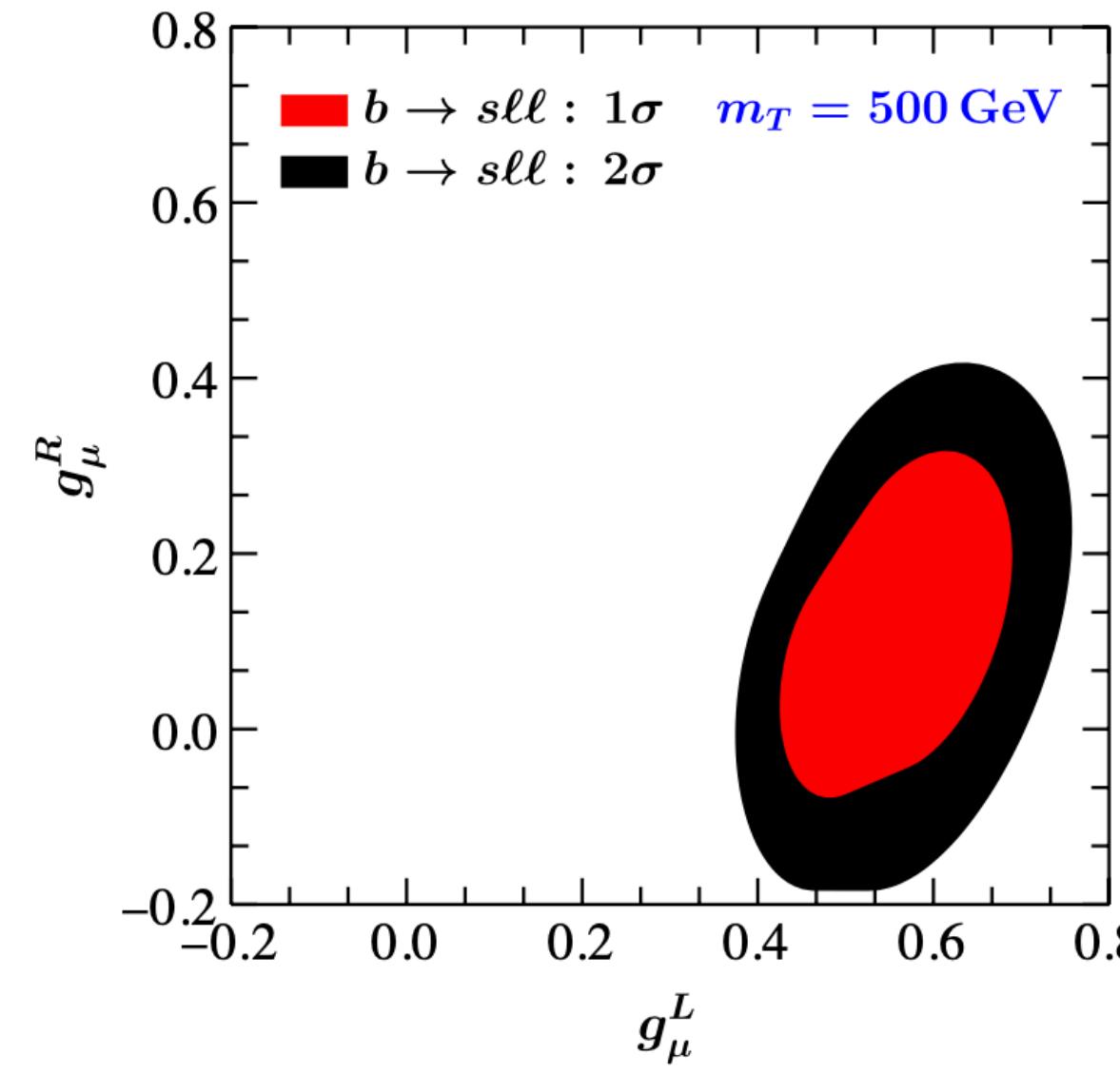
$$\left( \cos \theta_L, m_T, \frac{q_t g_t g_\mu^{L,R}}{m_{Z'}^2} \right)$$

Without loss of generality

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

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

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

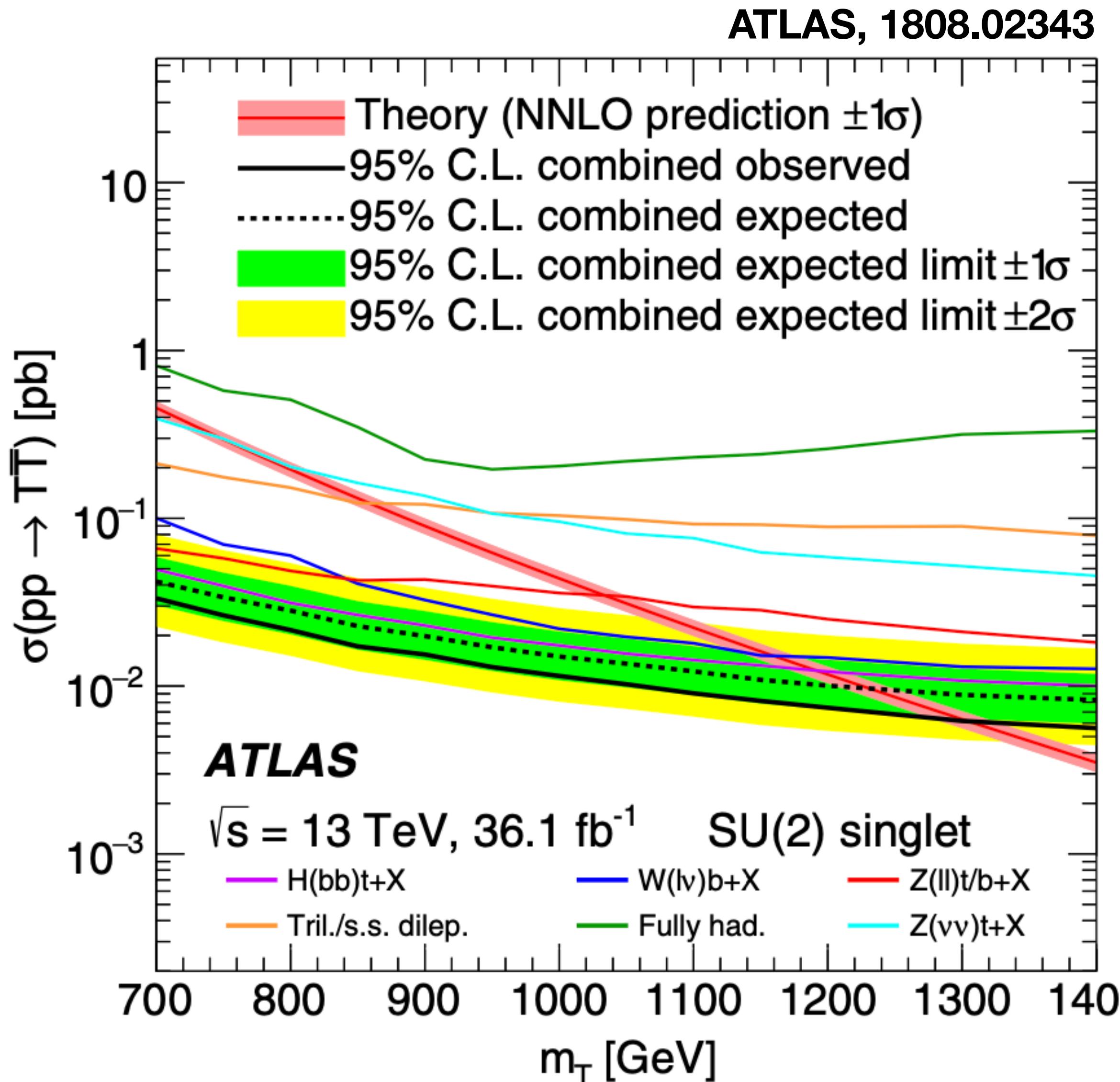


- ▶  $b \rightarrow s\ell^+\ell^-$  ( $\cos \theta_L, m_T, g_\mu^L, g_\mu^R$ )
- ▶  $m_W$  shift ( $\cos \theta_L, m_T$ )

★  $m_W^{\text{CDF}}$  and  $b \rightarrow s\ell^+\ell^-$  anomalies simultaneously explained at  $2\sigma$  level  
 ★ the couplings are safely in the perturbative region

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

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

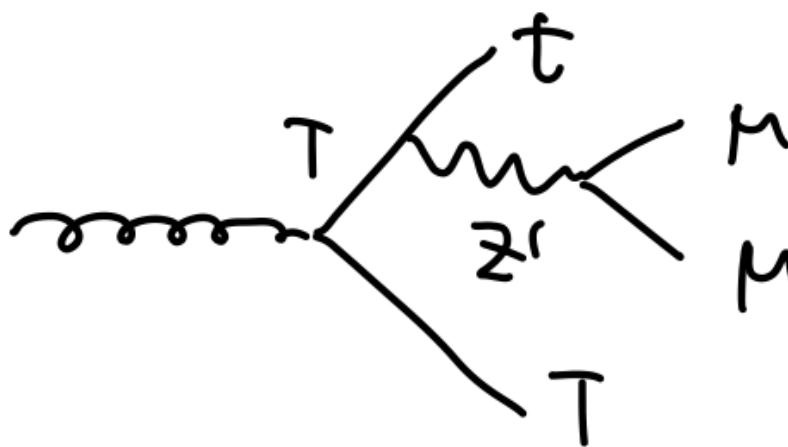


$m_T > 1.3 \text{ TeV}$

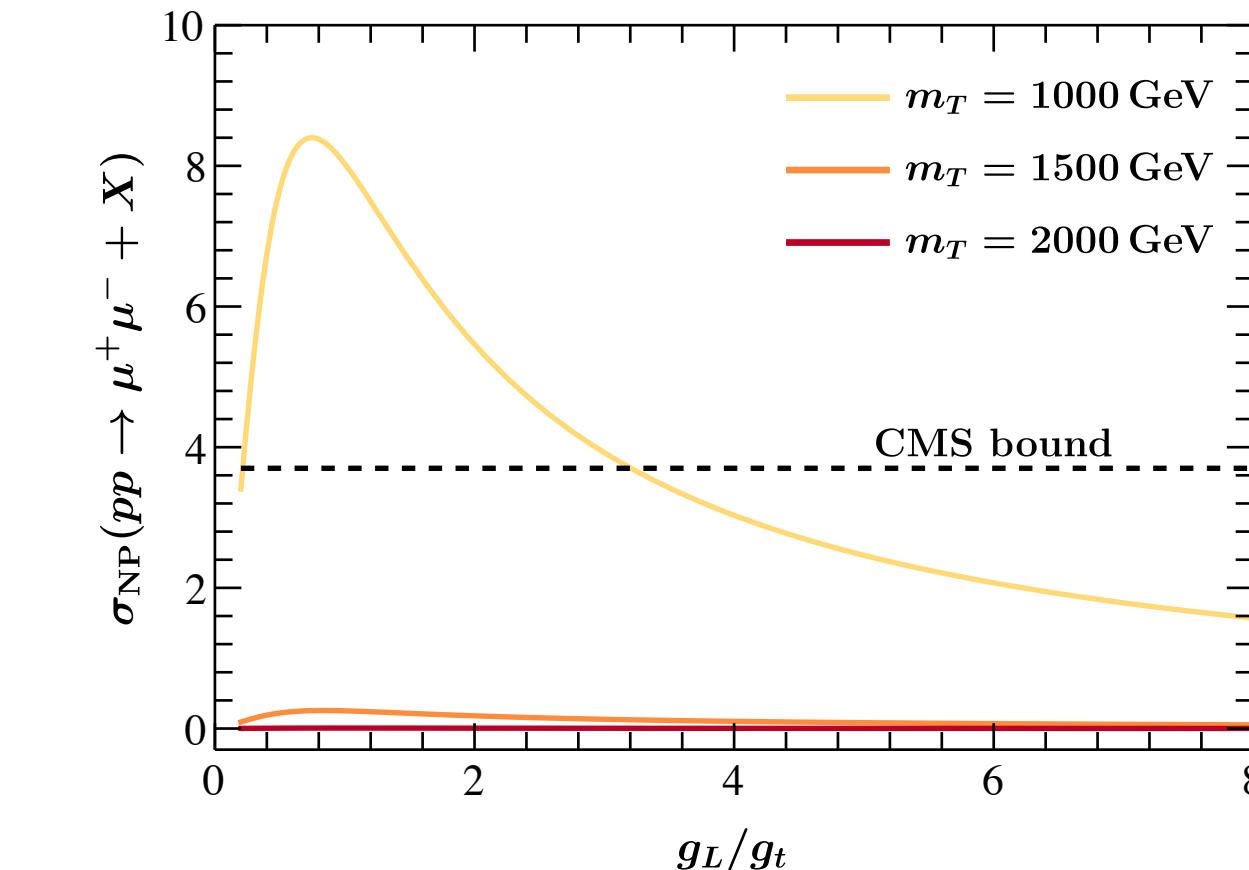
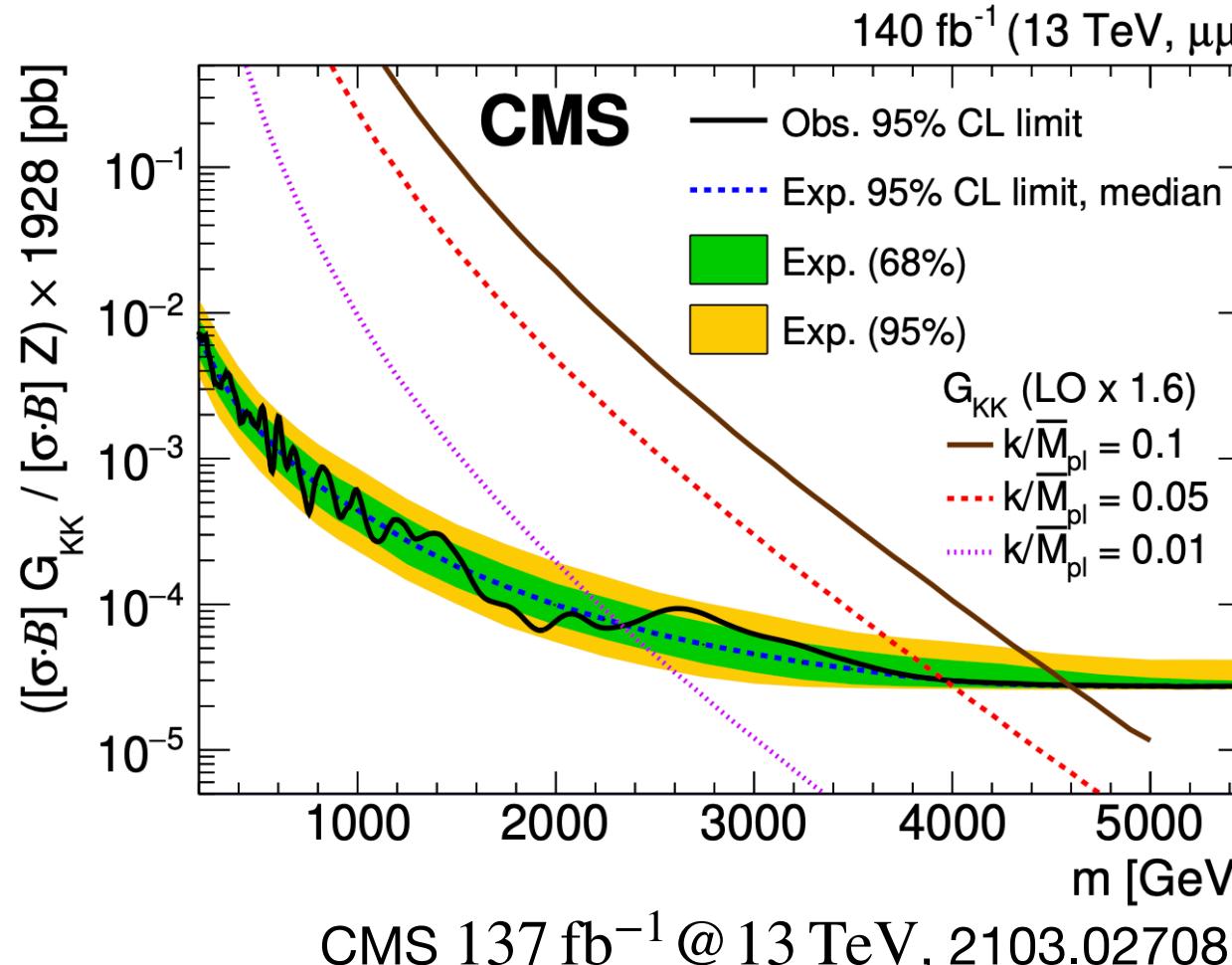
same with the regular top partner scenarios

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

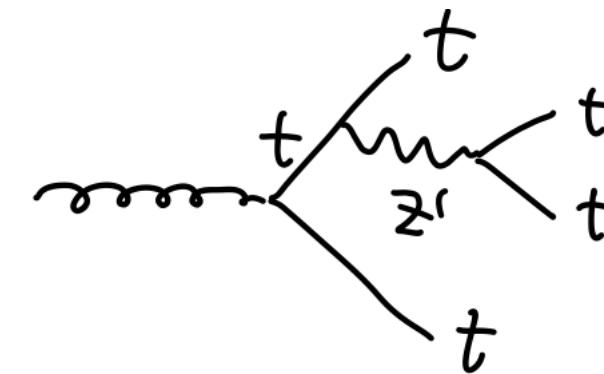
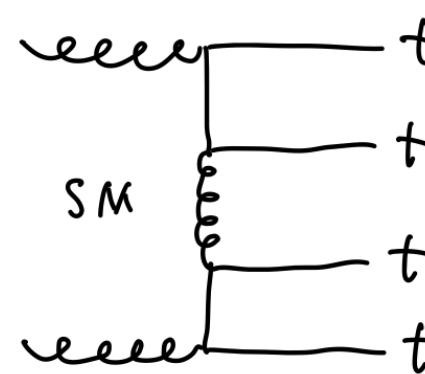
$$pp \rightarrow \mu^+ \mu^- + X$$



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

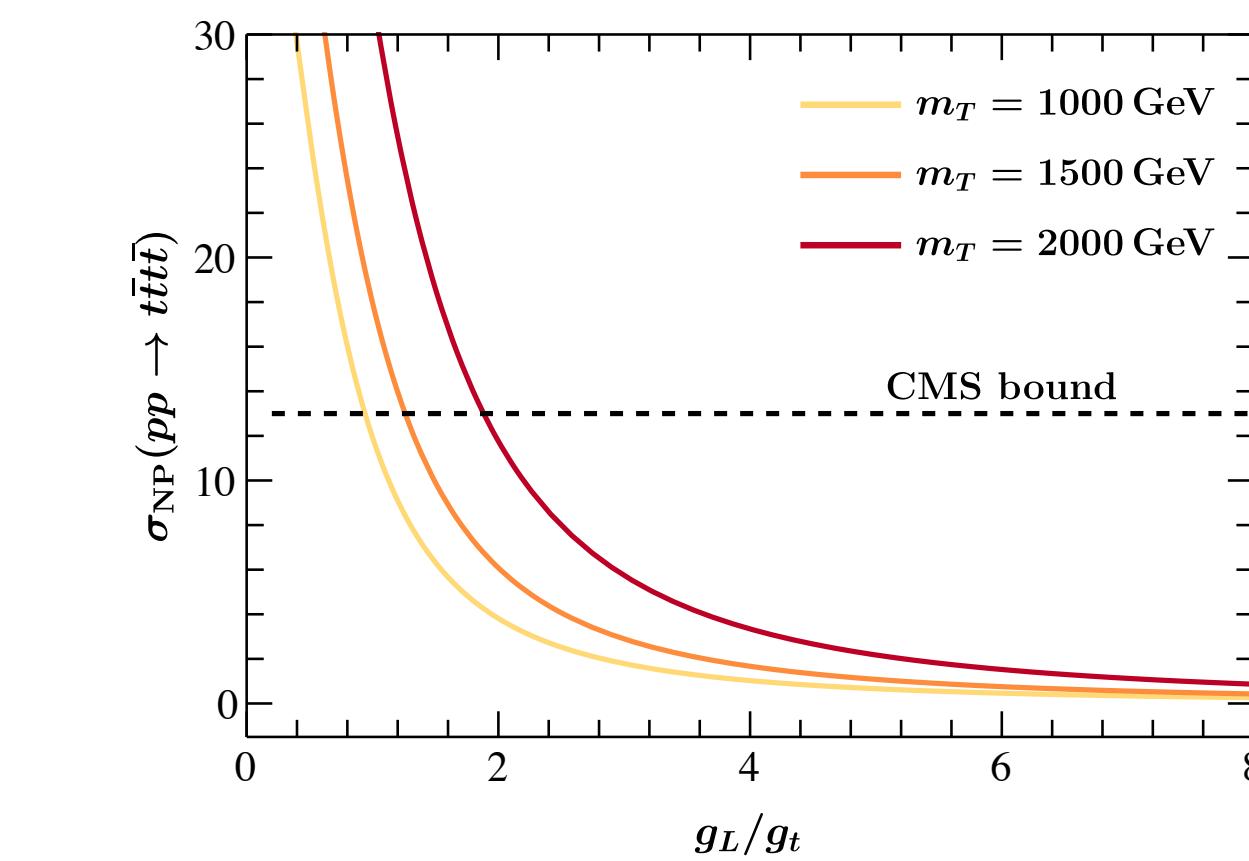


$$pp \rightarrow t\bar{t}t\bar{t}$$



$$\begin{aligned} \sigma_{\text{exp}} &= 12.6^{+5.8}_{-5.2} \text{ fb} \\ &\text{CMS } 137 \text{ fb}^{-1} @ 13 \text{ TeV, 1908.06463} \\ \sigma_{\text{NLO}} &= 12.0^{+2.2}_{-2.5} \text{ fb} \\ &\text{Frederix, D. Pagani, M. Zaro 1711.02116} \end{aligned}$$

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



In a realistic model,  $Z'$  could also couple to  $e, \tau, \nu$  and NP particles, which suppress  $\mathcal{B}(Z' \rightarrow \mu^+\mu^-/t\bar{t})$  and relax the above collider bounds.

$g_L/g_t > 1.5 \sim 3.2$

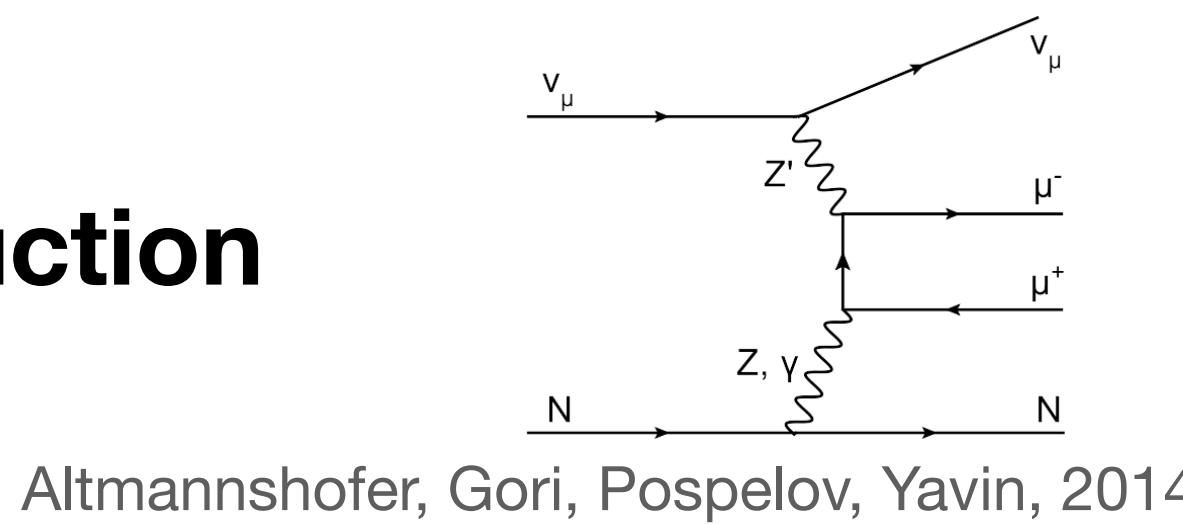
$m_{Z'} = 500 \text{ GeV}$ ,  $m_\Phi = 150 \text{ GeV}$ ,  $q_t = 1$ , and  $g_R = 0$   
 $(m_T, \sin \theta_L, g_L g_t) = (1.0 \text{ TeV}, 0.988, 0.72)$   
 $(1.5 \text{ TeV}, 0.993, 0.54)$   
 $(2.0 \text{ TeV}, 0.994, 0.35)$

# Top-philic Z' model with UV-complete lepton sector

## Requirements

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

- **Explain  $(g - 2)_\mu$**
- **Satisfy neutrino-trident production**
- **Provide neutrino masses**



## Constructions

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

$$L_{2L} = (1, 2, -1/2, +q_\ell)$$

$$e_{2R} = (1, 1, -1, +q_\ell)$$

$$L_{3L} = (1, 2, -1/2, -q_\ell)$$

$$e_{3R} = (1, 1, -1, -q_\ell)$$

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

- **New vector-like muon partner**

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

- **Two complex scalars**

$$\phi = (1, 1, 0, 0)$$

$$\Phi_\ell = (1, 1, 0, q_\ell)$$

## ► Lagrangian

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

## ► Diagonalize mass matrix

$$\begin{array}{ll} \begin{pmatrix} \mu_L \\ M_L \end{pmatrix} = R(\delta_L) \begin{pmatrix} e_{2L} \\ E_L \end{pmatrix} & \begin{pmatrix} \mu_R \\ M_R \end{pmatrix} = R(\delta_R) \begin{pmatrix} l_{2R} \\ E_R \end{pmatrix} \\ \text{mass} & \text{interaction} \end{array} \quad \begin{array}{ll} \text{mass} & \text{interaction} \end{array}$$

## ► Interaction

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

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

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

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

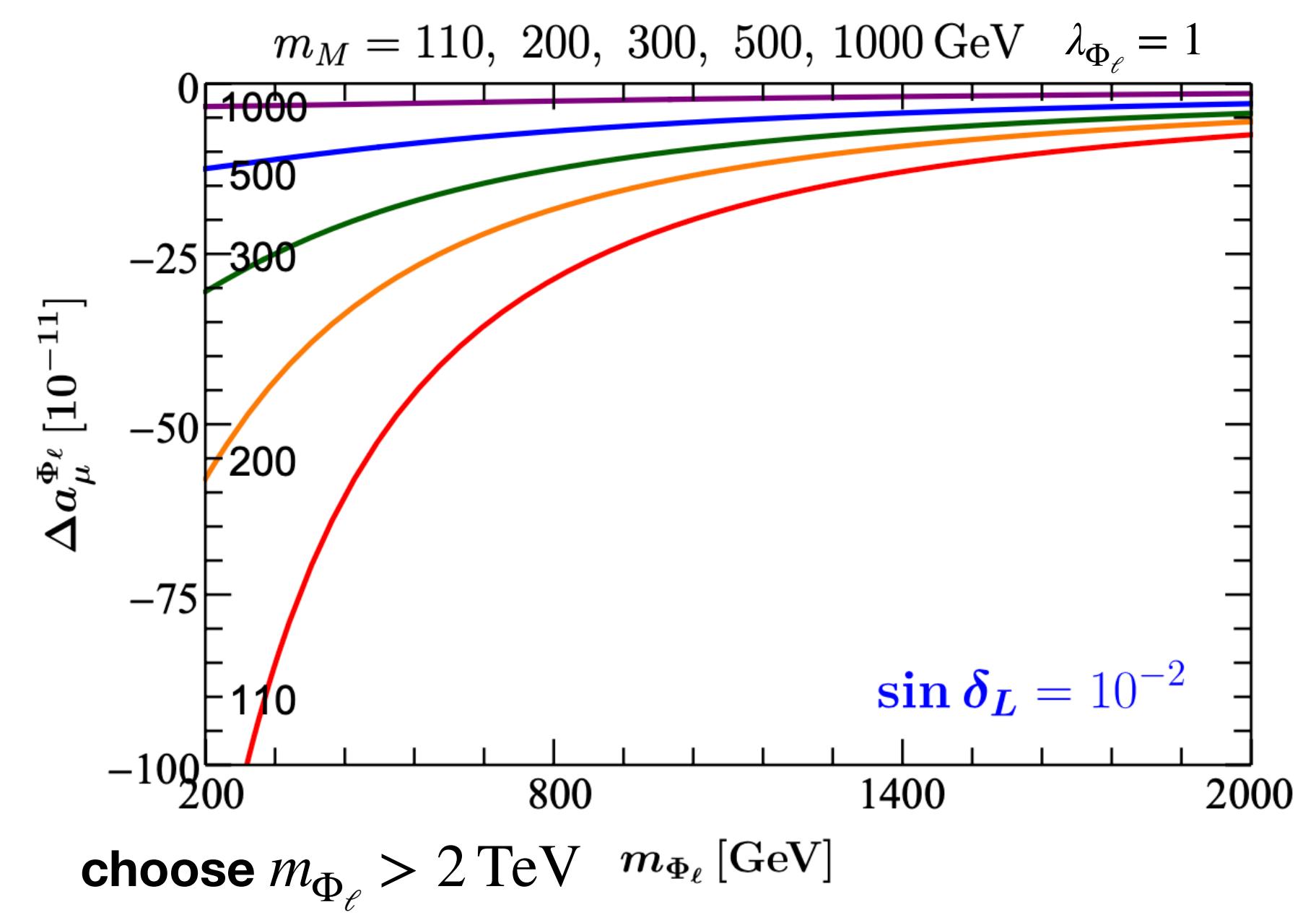
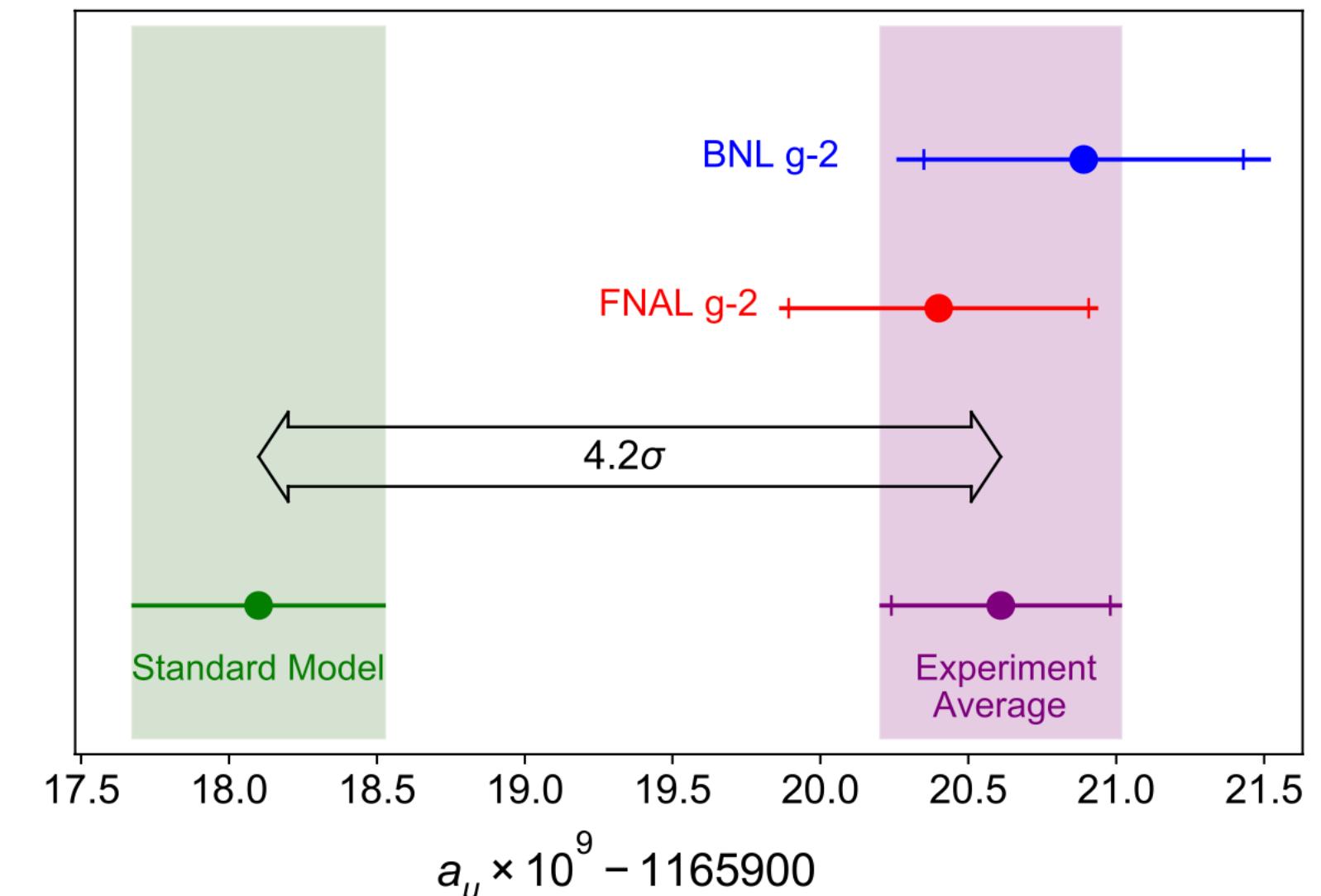
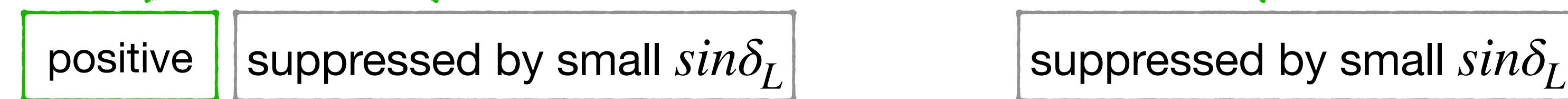
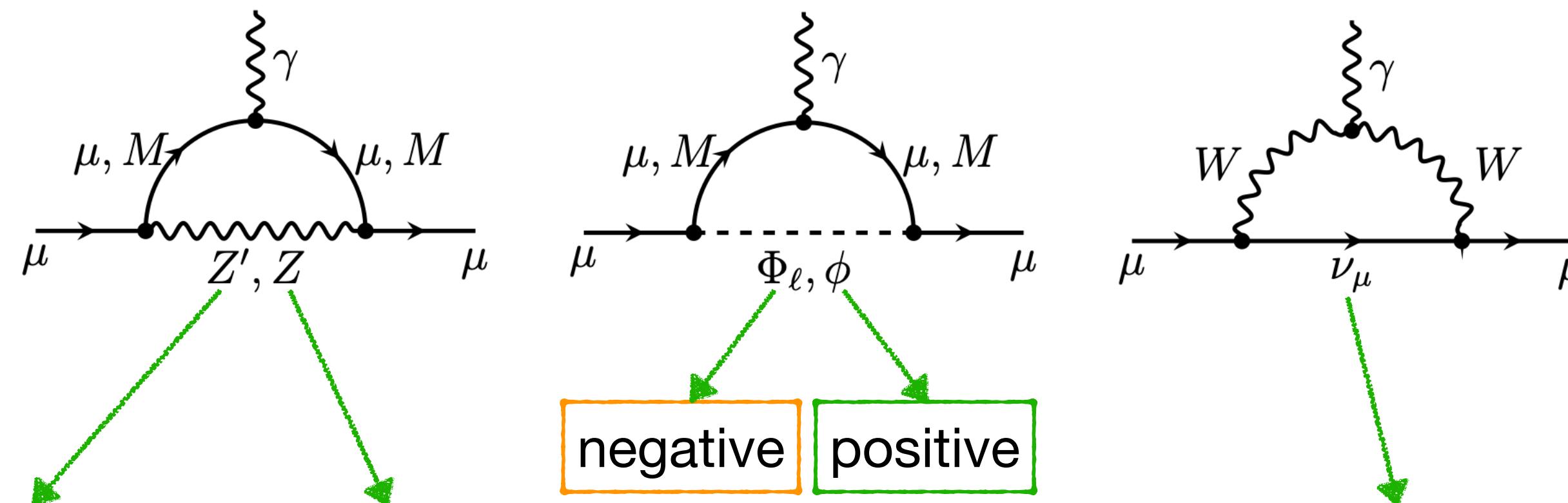
$$+ \frac{g}{c_W} s_W^2 (\bar{\mu}_R, \bar{M}_R) \not{Z} \begin{pmatrix} \mu_R \\ M_R \end{pmatrix}$$

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

$Z \rightarrow \mu^+ \mu^- @ \text{LEP} \implies \sin \delta_L < 0.1$

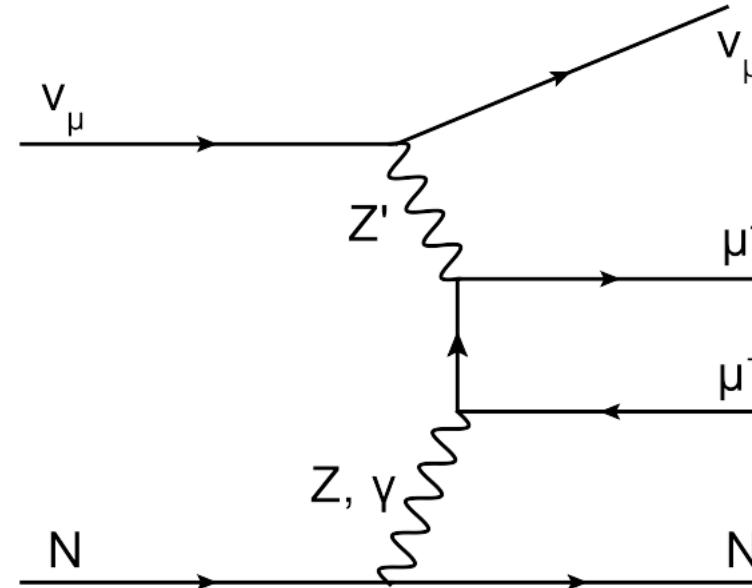
# $(g - 2)_\mu$

## ► Feynman diagrams



# $\nu$ trident production

## ► Feynman diagrams



## ► Exp constraint: CHARM-II, CCFR, NuTeV

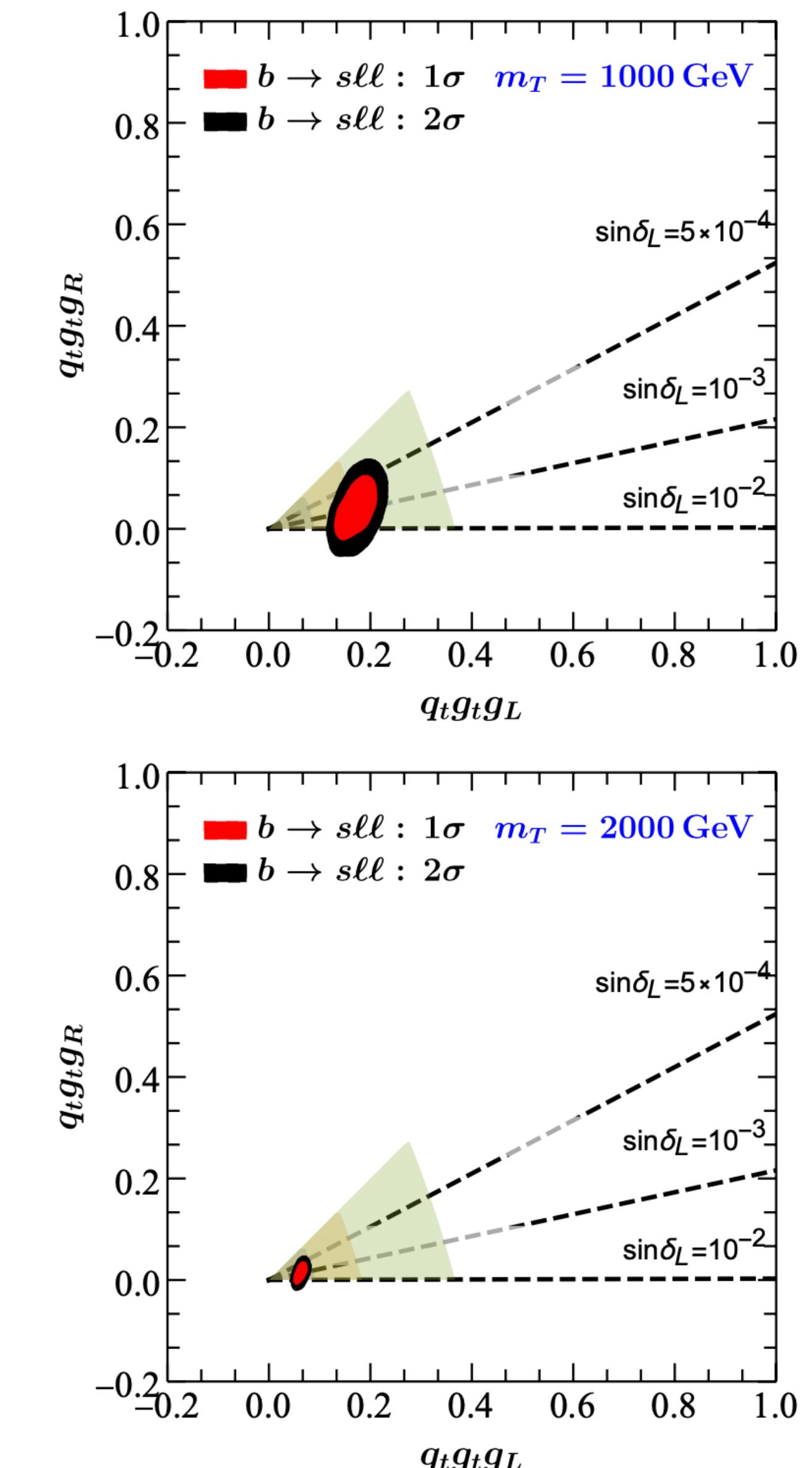
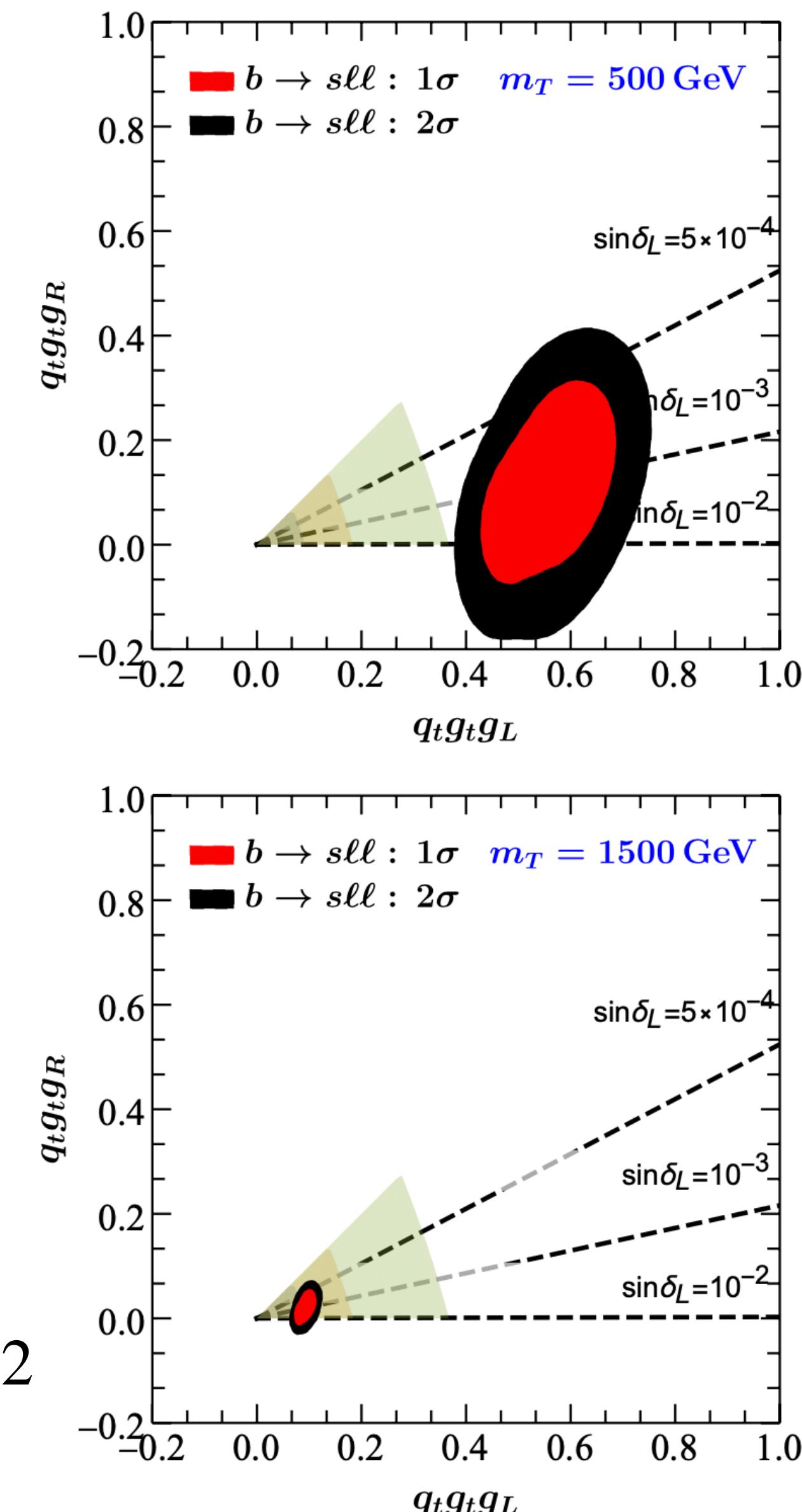
$$\sigma_{\text{exp}}/\sigma_{\text{SM}} = 0.95 \pm 0.25$$

## ► combined constraints

$$(\sin \theta_L, m_M, q_t g' g_L, q_t g' g_R)$$

explain  $b \rightarrow s\ell^+\ell^-$  anomalies while satisfying other constraints

$$q_t/q_\ell = 1/2, 1, 2$$



# Summary

## Conclusions

- ▶ Oblique parameters  $S$ ,  $T$ ,  $U$  and Wilson coefficients  $C_9$  and  $C_{10}$  calculated in a topophilic  $Z'$  model
- ▶ It is found that the model can simultaneously explain the CDF  $m_W$  measurement and the  $b \rightarrow s\ell^+\ell^-$  anomalies

## 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

- ▶ UV complete model |  $Z'$  contributions to EW fit | mixing with 1st and 2nd gen | Nautralness
- ▶ detailed collider simulation

谢谢