Correlating the CDF W-boson mass shift with the $b \to s\ell^+\ell^-$ anomalies

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X.-Q. Li, Z.-J. Xie, Y.-D. Yang, and X.-B. Yuan arXiv:2205.02205.

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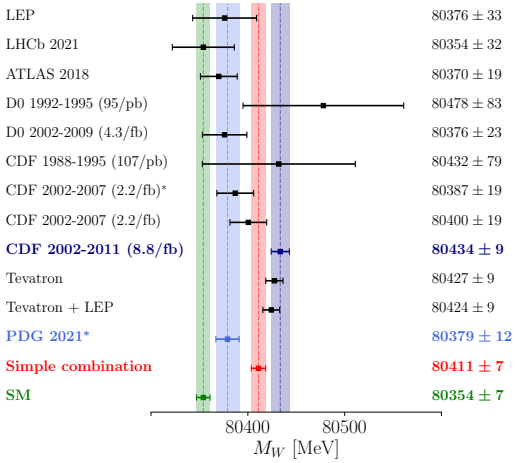
CDF m_W anomalies



* Does not include 13.5 MeV shift in CDF 2002-2007 (2.2/fb)

P. Athron, A. Fowlie, C. T. Lu, L. Wu, Y. Wu and B. Zhu, [arXiv:2204.03996 [hep-ph]]

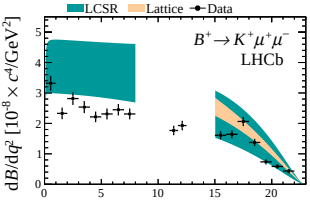
T. Aaltonen *et al.* [CDF], Science **376**, no.6589, 170-176 (2022)

CDF: 80433 ± 9 GeV

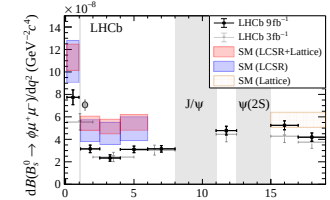
On April 8, CDF announced the most precise W mass to date, a 7σ tension with SM

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

branching ratio EXP below SM at low q^2.

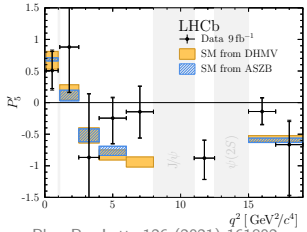


JHEP 04 (2017) 142.

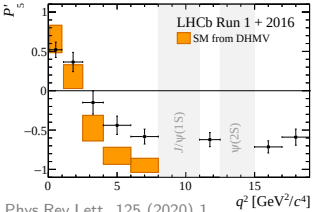


Phys.Rev.Lett. 127 (2021) 15.

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



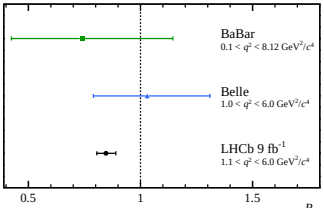
Phys.Rev.Lett. 126 (2021) 161802.



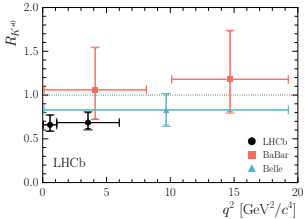
Phys.Rev.Lett. 125 (2020) 1.

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

lepton flavour universality violation ratio



LHCb/2103.11769 3.1σ



LHCb/1705.05802 $2.2 - 2.5\sigma$

$$R_{K^{(*)}} \equiv \frac{\mathrm{Br}(B^{+(0*)} \to K^{+(0*)}\mu^+\mu^-)}{\mathrm{Br}(B^{+(0*)} \to K^{+(0*)}e^+e^-)}$$

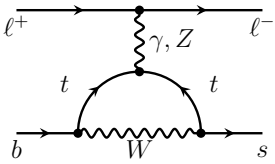
- $R_H^{SM} \approx 1$
- Hadronic uncertainties cancel
- $\mathcal{O}(10^{-2})$ QED correction

branching ratio
angular distribution
LFV ratio

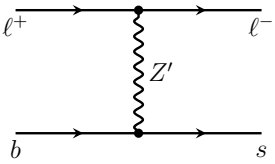
$\Rightarrow$Physics beyond the SM

Search for NP

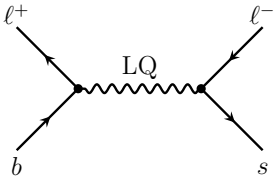
- Explain $b \to s\ell^+\ell^-$ anomalies



(SM)

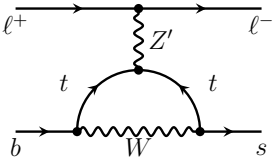


(NP with FCNC)



(NP with FCCC)

- Explain CDF m_W and $b \to s\ell^+\ell^-$ anomalies with Z'



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

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

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

	SM			NP	
	Q_{3L}	u_{3R}	H	$U'_{L/R}$	Φ
$SU(3)$	3	3	1	3	1
$SU(2)$	2	1	2	1	1
$U(1)$	1/6	2/3	$-1/2$	2/3	0
$U(1)'$	0	0	0	q_t	q_t

- 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

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

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

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

Top-philic Z' model

- Interactions

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

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

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

$$+ \frac{g}{c_W} \left(\bar{t}_R, \bar{T}_R \right) \left(- \frac{2}{3} s_W^2 \right) \not{Z} \begin{pmatrix} t_R \\ T_R \end{pmatrix} ,$$

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

$$+ (L \to R) ,$$

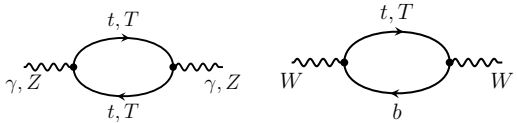
- Lagrangian: lepton section

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

- 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

- NP contributions to vacuum polarizations



- S, T, U are affected

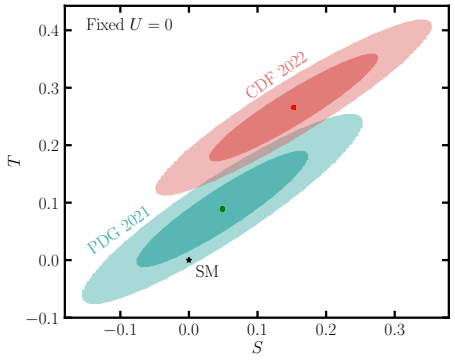
$$\Delta S = \frac{s_L^2}{12\pi}\Big[K_1(y_t, y_T) + 3c_L^2 K_2(y_t, y_T)\Big],$$

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

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

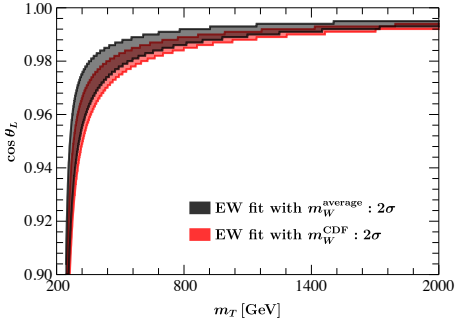
W-boson mass shift and oblique parameters

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



C. T. Lu, L. Wu, Y. Wu and B. Zhu, Phys. Rev. D **106**, no.3, 035034 (2022)

- Allowed parameter space



- m_W^{CDF} can be explained by the top-parter effects
- small θ is allowed

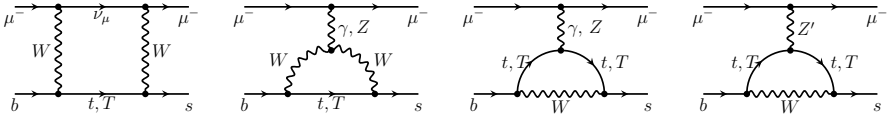
$b \to s\ell^+\ell^-$ anomalies

- Effective Hamiltonian

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

  with $\mathcal{O}_{9\ell} = (\bar{s}\gamma^\mu P_L b)\left(\bar{\ell}\gamma_\mu \ell\right)$ and $\mathcal{O}_{10\ell} = (\bar{s}\gamma^\mu P_L b)\left(\bar{\ell}\gamma_\mu\gamma_5 \ell\right)$

- NP contributions



- Wilson coefficients

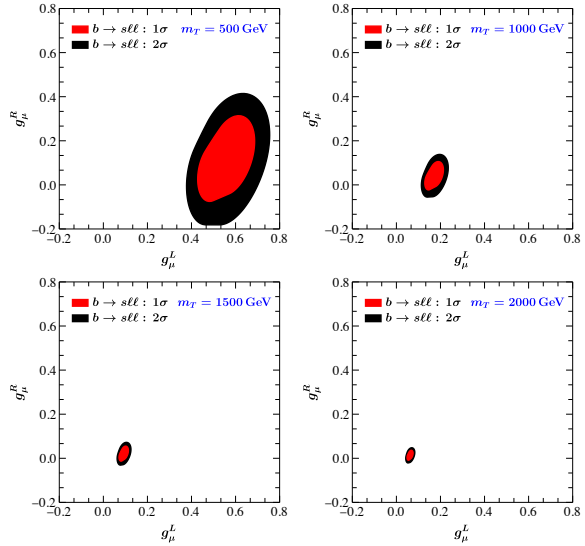
$$\mathcal{C}_9^{\text{NP}} = s_L^2 I_1 + s_L^2\left(1 - \frac{1}{4s_W^2}\right)\left(I_2 + c_L^2 I_3\right) + \Delta\mathcal{C}_+^{Z'}$$

$$\mathcal{C}_{10}^{\text{NP}} = \frac{s_L^2}{4s_W^2}\left(I_2 + c_L^2 I_3\right) + \Delta\mathcal{C}_-^{Z'} \qquad \Delta\mathcal{C}_\pm^{Z'} = \frac{(g_L \pm g_R) q_t g_t}{e^2}\frac{m_W^2}{m_{Z'}^2} c_L^2 s_R^2\left(I_4 - \frac{c_L^2}{c_R^2} I_5\right)$$

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

- 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 $(\cos\theta_L, m_T, q_t g_t g_\mu^{L,R}/m_{Z'}^2)$
  Without loss of generality $q_t = 1, g_t = 1, m_{Z'} = 200$ GeV
  $\Rightarrow (\cos\theta_L, m_T, g_\mu^L, g_\mu^R)$

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



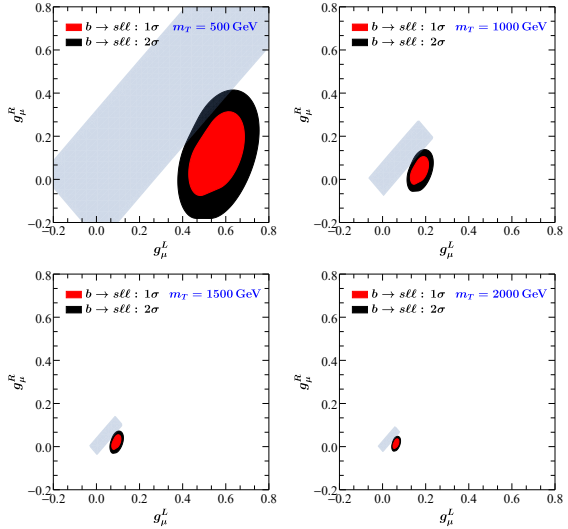
- $b \to s\ell^+\ell^-$ $(\cos\theta_L, m_T, g_\mu^L, g_\mu^R)$
- m_W shift $(\cos\theta_L, m_T)$

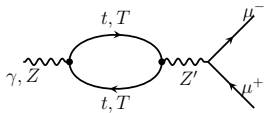
∗ m_W shift and $b \to s\ell^+\ell^-$ anomalies simultaneously explained at 2σ level

∗ the couplings are safely in the perturbative region

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

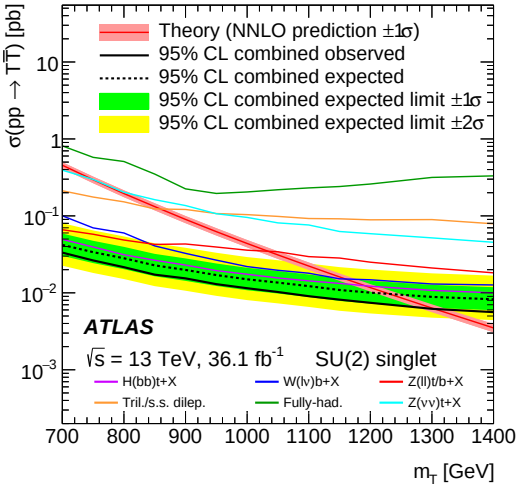
Loop-induced $Z - Z'$ mixing





- loop-induced $Z - Z'$ mixing
- affect $Z \to \mu^+\mu^-$ decays
- allowed region: dark rectangle
- small overlap with other constraints
- In a realistic model, other particles (SM or NP) could provide vertex corrections, which is hard to include in our framework

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



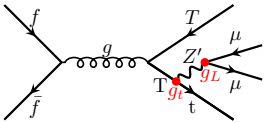
ATLAS, 1808.02343

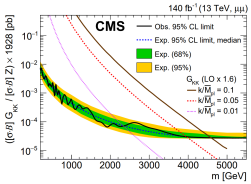
- same with the regular top partner scenarios
- $m_T > 1.3$ GeV

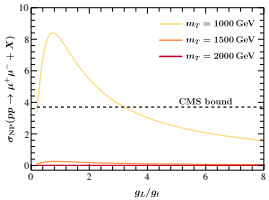
Collider Searches: $m_T > m_{Z'}$

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

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



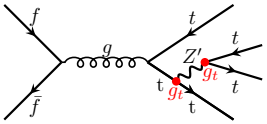




$\sigma(pp \to T\bar{T}) \cdot 2 \cdot \mathcal{B}(T \to tZ') \cdot \mathcal{B}(Z' \to \mu^+\mu^-)$

CMS 137fb^{-1}@13 TeV, 2103.02708

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



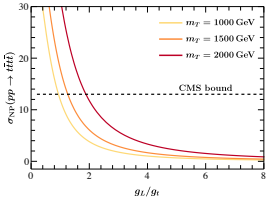
$\sigma_{exp} = 12.6^{+5.8}_{-5.2}$fb

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

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

Frederix, D. Pagani, M. Zaro 1711.02116

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



- Conclusion: $g_L/g_t > 1.5 \sim 3.2$

In a realistic model, Z' could also couple to e, τ, ν and NP particles, which suppress and relax the above collider bounds.

Conclusion

Conclusion

- Oblique parameters S, T, U and Wilson coefficients C_9 and C_{10} calculated in a top-philic model
- It is found that the model can simultaneously explain the CDF m_W measurement and the $b \to s\ell^+\ell^-$ anomalies

Future works

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

1. X.-Q. Li, **Z.-J. Xie**, Y.-D. Yang, and X.-B. Yuan, "Correlating the CDF W-boson mass shift with the $b \to s\ell^+\ell^-$ anomalies," arXiv:2205.02205.

谢谢！