From Light to Heavy Z' to explain $b \to s\ell^+\ell^-$ data

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PSI

Heavy Z'

https://inspirehep.net/literature/2014092

M. Alguero, A. Crivellin, C.A.M., J. Matias

Heavy Z'

Setup

- Simple patterns where NP couples solely to muons can explain the discrepancies between the SM and experiment very well.
- Structures with additional LFU contributions can describe data even better…

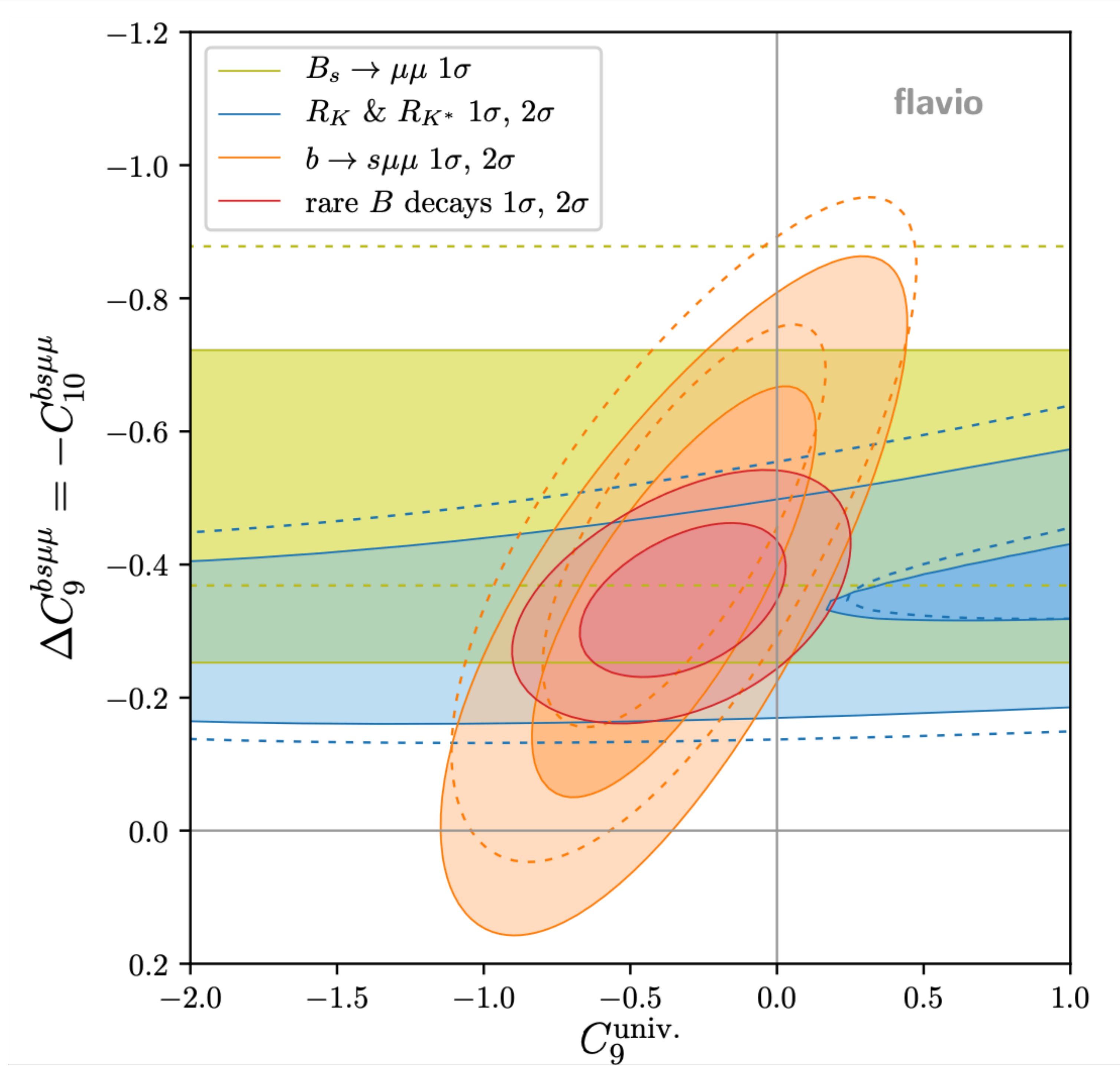
I. 2HDMs

II. Leptoquarks

III. $SU(2)_L$ Vector Bosons Triplets

IV. Vector-like quarks

V. Vector Boson Singlet



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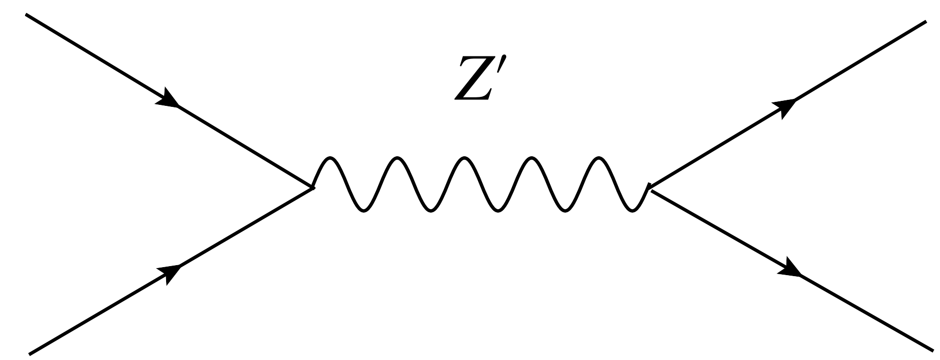
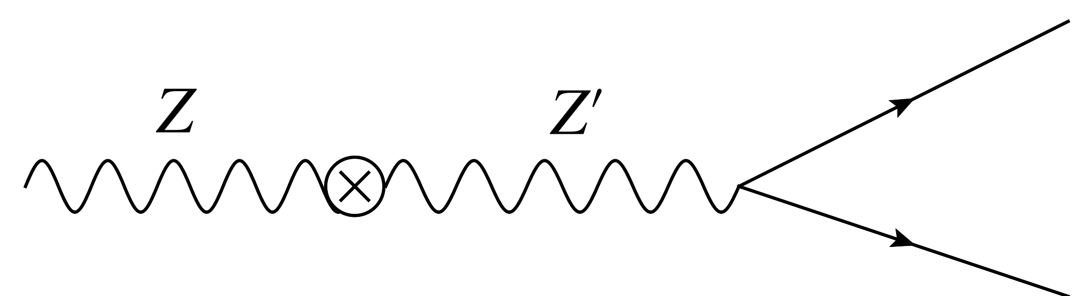
LFUV & LFU

LFUV in $b \to s\ell^+\ell^-$	
LFU effects via $Z - Z'$ mixing	

Impact on the EW Fit!

- Constraints from $Z \to \ell^+\ell^-$, etc.
- Prediction of the W mass altered with respect to the SM

Heavy Z'

Couplings of the Z'

$$\mathscr{L}^{\text{int.}}_{Z'_0} = \bar{u}_j\gamma_\mu(g^{uL}_{ji}P_L + g^{uR}_{ji}P_R)u_i\,Z'^{\mu}_0 + \bar{d}_j\gamma_\mu(g^{dL}_{ji}P_L + g^{dR}_{ji}P_R)d_i\,Z'^{\mu}_0$$

$$+g^{\ell L}_{ji}(\bar{\nu}_j\gamma_\mu P_L\nu_i)\,Z'^{\mu}_0 + \bar{\ell}_j\gamma_\mu(g^{\ell L}_{ji}P_L + g^{\ell R}_{ji}P_R)\ell_i\,Z'^{\mu}_0$$

Let simplify: the one dimensional scenario with the best fit to data is obtained from a left-handed b−s coupling and a vectorial muon coupling

$$\mathscr{L}^{\text{int.}}_{Z'_0} = \left[g^{dL}_{23}\,\bar{s}\gamma_\mu P_L b + g^{dL*}_{23}\,\bar{b}\gamma_\mu P_L s + g^{\ell V}_{ii}\,\bar{\ell}_i\gamma_\mu\ell_i\right] Z'^{\mu}_0$$

Heavy Z'

Mixing

$$\mathscr{L}_{Z_0'} = -\frac{1}{4} Z'_{0,\mu\nu} Z_0'^{\mu\nu} + \frac{\mu_Z'^2}{2} Z'_{0\mu} Z_0'^{\mu} + g_{Z'} Z'_{0\mu} Z_0'^{\mu} \phi^\dagger \phi - i g_{Z'}^{\phi} Z_0'^{\mu} \phi^\dagger \overleftrightarrow{D}_\mu \phi$$

$$\mathscr{M}^2 = \begin{pmatrix} m_{Z_0}^2 & -\frac{y}{c_W} \\ -\frac{y}{c_W} & m_{Z_0'}^2 \end{pmatrix}, \qquad y \equiv \frac{v^2}{2} g_2 \, g_{Z'}^{\phi}$$

$$\boxed{\sin \xi \simeq \frac{y}{c_W m_{Z_0'}^2}}$$

$$\begin{pmatrix} Z \\ Z' \end{pmatrix} = \begin{pmatrix} Z_0' \sin \xi + Z_0 \cos \xi \\ Z_0' \cos \xi \ - Z_0 \sin \xi \end{pmatrix}$$

$$m_Z^2 \simeq m_{Z_0}^2 - \sin \xi^2 m_{Z_0'}^2$$

Heavy Z'

Electroweak Fit

EW sector completely parametrized by 3 parameters (+ fermion masses)

$$\alpha, \quad M_{Z_0}, \quad G_F$$

+

Parameter	Prior
$\Delta\alpha_{\text{had}} \times 10^4$ [16, 17]	276.1(1.1)
$\alpha_s(M_Z)$ [8, 33]	0.1179(10)
M_H [GeV] [8, 38–40]	125.10(14)
m_t [GeV] [8, 41–44]	172.76(30)

Needed for higher order corrections

Observable	Measurement	Observable	Measurement
M_W [GeV]	80.379(12)	σ_h^0 [nb]	41.541(37)
Γ_W [GeV]	2.085(42)	R_e^0	20.804(50)
BR($W \to$ had)	0.6741(27)	R_μ^0	20.785(33)
$\sin^2\theta^e_{\text{eff(CDF)}}$	0.23248(52)	R_τ^0	20.764(45)
$\sin^2\theta^e_{\text{eff(D0)}}$	0.23146(47)	$A_{FB}^{0,e}$	0.0145(25)
$\sin^2\theta^\mu_{\text{eff(CDF)}}$	0.2315(20)	$A_{FB}^{0,\mu}$	0.0169(13)
$\sin^2\theta^\mu_{\text{eff(CMS)}}$	0.2287(32)	$A_{FB}^{0,\tau}$	0.0188(17)
$\sin^2\theta^\mu_{\text{eff(LHCb)}}$	0.2314(11)	R_b^0	0.21629(66)
P_τ^{pol}	0.1465(33)	R_c^0	0.1721(30)
A_e	0.1516(21)	$A_{FB}^{0,b}$	0.0992(16)
A_μ	0.142(15)	$A_{FB}^{0,c}$	0.0707(35)
A_τ	0.136(15)	A_b	0.923(20)
Γ_Z [GeV]	2.4952(23)	A_c	0.670(27)

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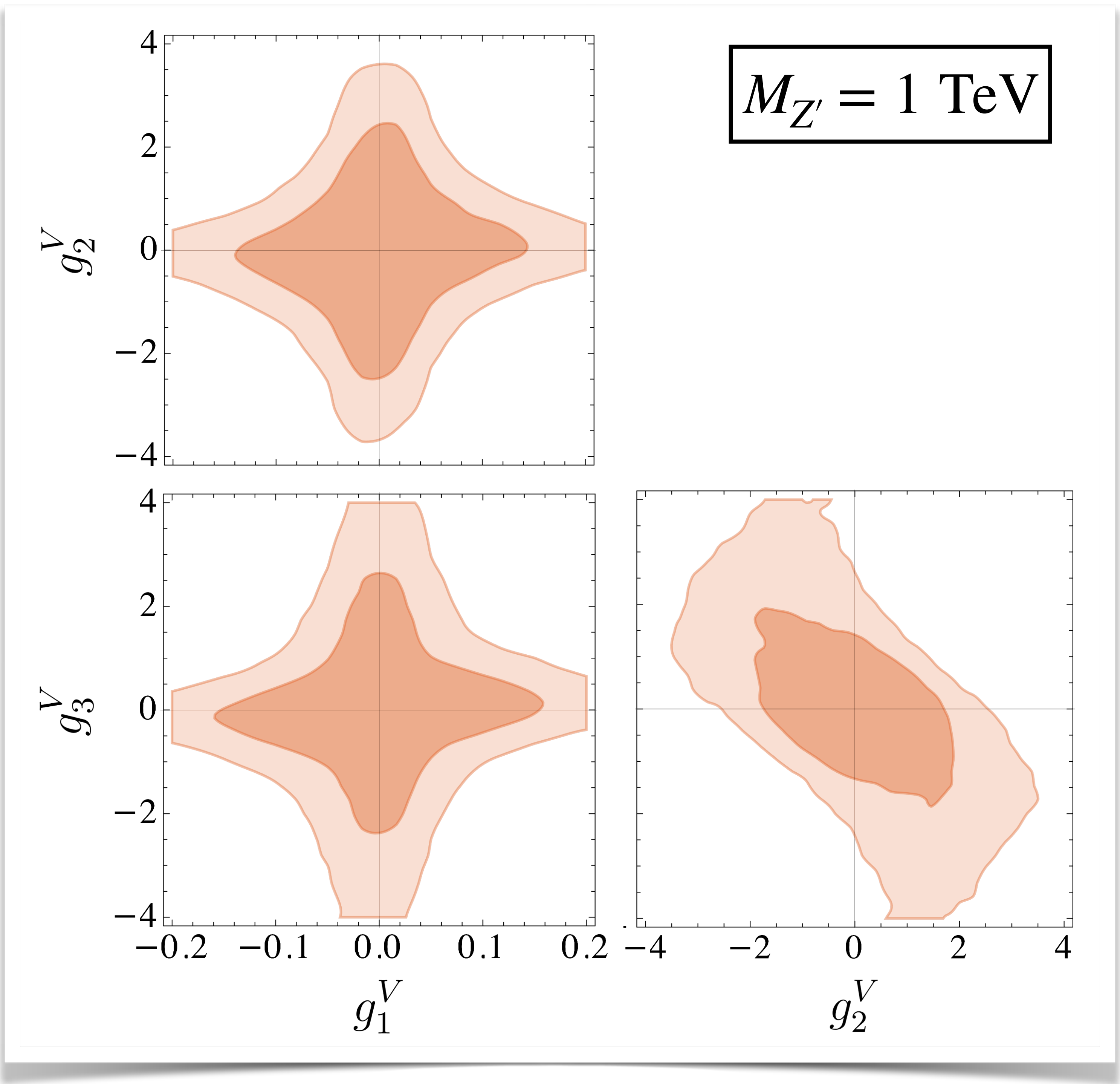
Couplings to Leptons



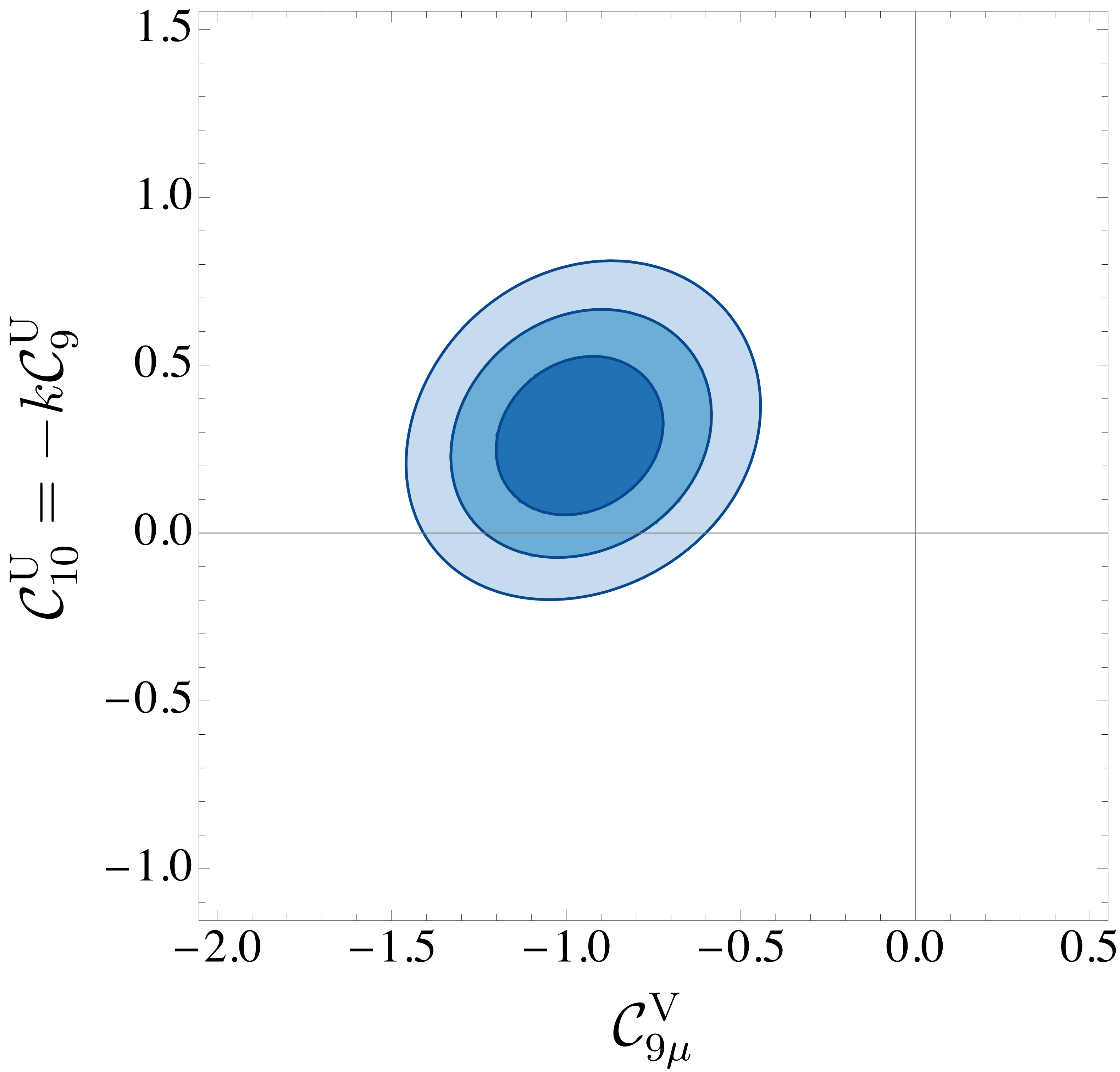
- EW Precision Observables
- Neutrino Trident Production
- LEP-II
- Lepton decays:
  $\tau \to \mu \nu_\tau \bar{\nu}_\mu , \tau \to e \nu_\tau \bar{\nu}_e , \mu \to e \nu_\mu \bar{\nu}_e$

$$g_1^V \ll g_{2,3}^V \quad \& \quad g_2^V \simeq -g_3^V \equiv g'$$

$$L_\mu - L_\tau$$

Heavy Z'

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



$$C_{9\mu}^{V} = -\frac{\pi^2}{e^2}\frac{4\sqrt{2}g_{23}^{dL}g_{22}^{\ell V}}{G_F m_{Z'}^2 V_{tb}V_{ts}^*}$$

$$C_{10}^{U} = -\,k\,C_9^{U}$$

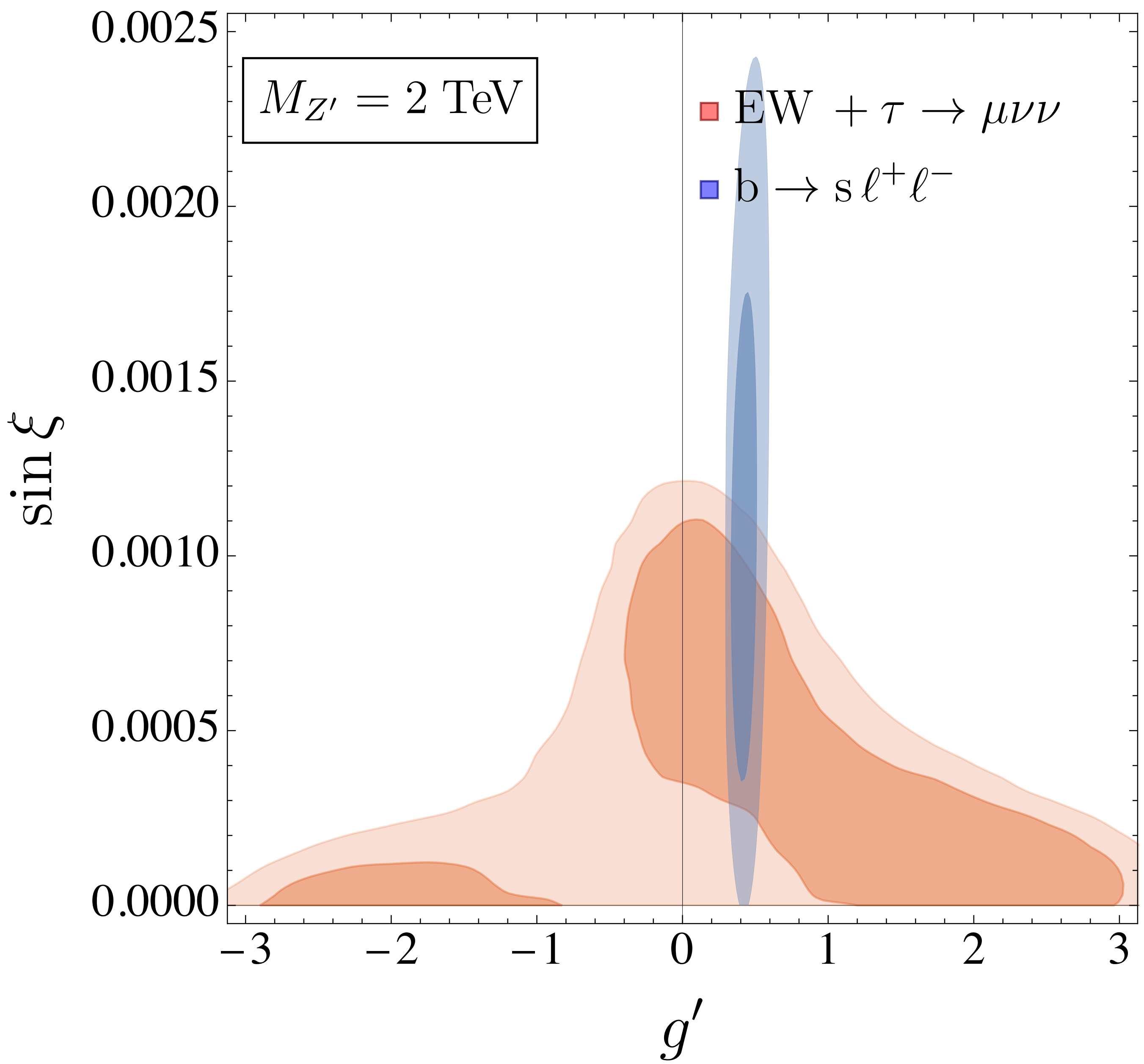
$$= -\frac{\pi^2}{e^2}\frac{\sqrt{2}g_{23}^{dL}\,g_2\,sin\xi}{c_W G_F m_Z^2 V_{tb}V_{ts}^*}$$

$$k = \frac{1}{1-4\,s_W^2}$$

Heavy Z'

Results

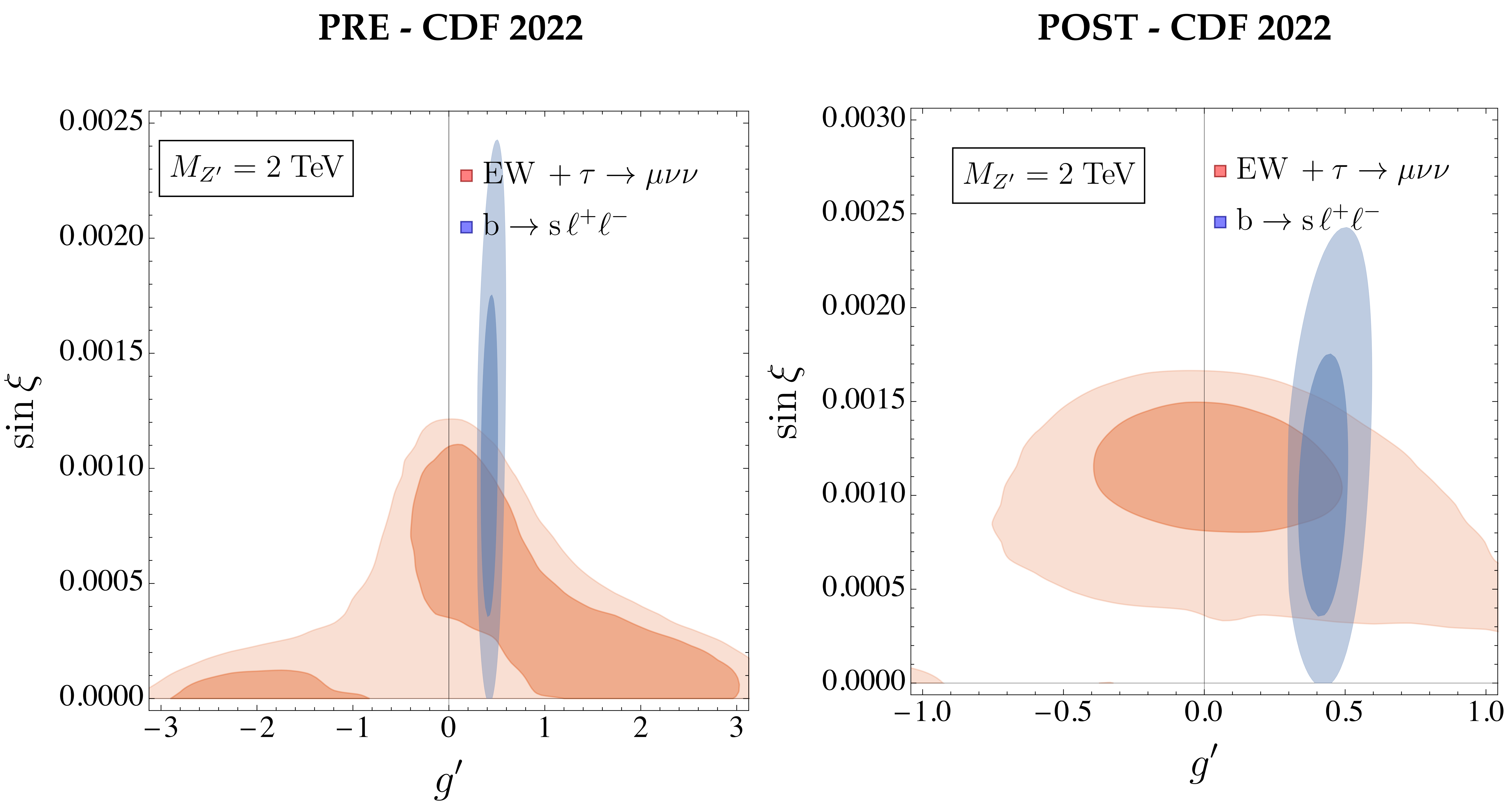
PRE - CDF 2022



$$m_W^2 \simeq m_Z^2 c_W^2 + \sin\xi^2 m_{Z_0'}^2 c_W^2$$

Heavy Z'

Results



Light Z'

https://inspirehep.net/literature/2039365

W. Altmannshofer, A. Crivellin, C.A.M., G. Inguglia, P. Feichtinger, J.M. Camalich

Light Z'

Setup

$m_{Z'} \lesssim 6 \text{ GeV}$

$$\mathcal{L}_{Z'} \supset \left[\bar{\mu}\left(g^V_{\mu\mu}\gamma^\mu + g^A_{\mu\mu}\gamma^\mu\gamma_5\right)\mu + g^L_{sb}\bar{s}\gamma^\mu P_L b + g_\chi\bar{\chi}\gamma^\mu\chi\right] Z'_\mu$$

Observables

- $b \to s\ell^+\ell^-$
- $(g-2)_\mu$
- $B \to K^{(*)} + \text{invisible}$
- $pp \to \mu^+\mu^- + \text{ invisible}$
- $B_s - \bar{B}_s$ mixing
- $e^+e^- \to \mu^+\mu^- + \text{ invisible}$

Light Z'

$m_{Z'} \lesssim 6$ GeV

$b \to s\ell^+\ell^-$ **&** $(g-2)_\mu$

$$\mathcal{L}_{Z'} \supset \left[\bar{\mu}\left(g^V_{\mu\mu}\gamma^\mu + g^A_{\mu\mu}\gamma^\mu\gamma_5\right)\mu + g^L_{sb}\bar{s}\gamma^\mu P_{L,R} b + g_\chi \bar{\chi}\gamma^\mu \chi\right] Z'_\mu$$

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

$(g-2)_\mu$

$$C_{9(10)} = \frac{g^L_{sb} g^{V(A)}_{\mu\mu}}{q^2 - m^2_{Z'} + i m_{Z'}\Gamma_{Z'}}$$

$$\Delta a_\mu = \frac{m^2_\mu}{12\pi^2 M^2_{Z'}} \mathrm{Re}\left[(g^V_{\mu\mu})^2 - 5(g^A_{\mu\mu})^2\right]$$

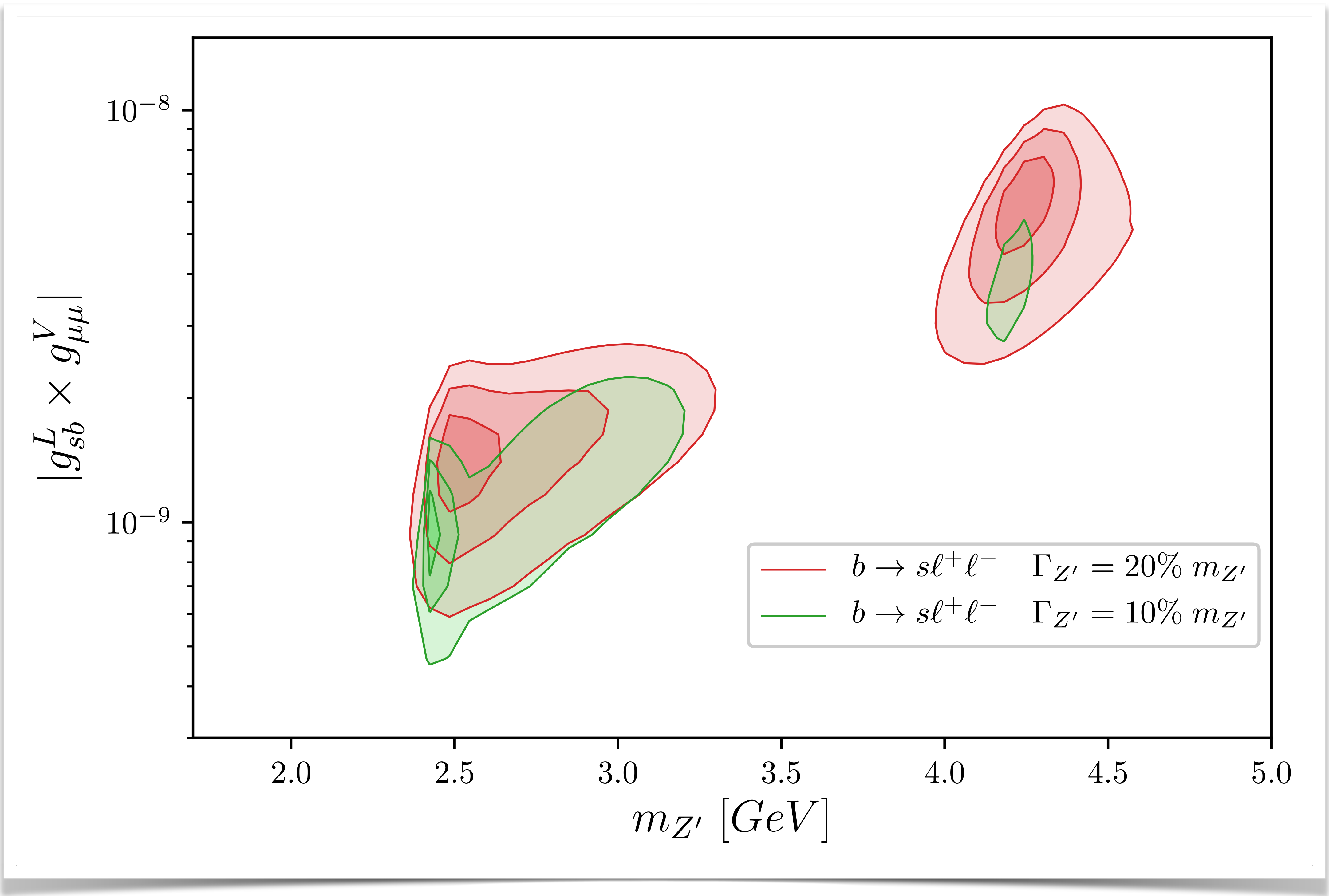
$$g_V = -\sqrt{5} g_A$$

$m_{Z'} \gtrsim 2.5$ GeV   F. Sala, D. Straub hep/1704.06188.pdf

Light Z'

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

$C_9 = -\sqrt{5}C_{10}$



Light Z'

$B \to K^{(*)}\nu\nu$

$$\mathcal{B}(B \to K^{(*)}\chi\bar{\chi}) = \mathcal{B}(Z' \to \bar{\chi}\chi) \int_{s_{\min}}^{s_{\max}} ds\, \Gamma_{Z'}(s)\, \mathrm{BW}(s)\, \mathcal{B}(B \to K^{(*)}Z')(s)$$

$$s_{\min} = 4m_\chi^2$$

$$s_{\max} = \left(m_B - m_{K^{(*)}}\right)^2$$

$$\mathrm{BW}(s) = \frac{\sqrt{s}}{\pi} \frac{1}{(s - m_{Z'}^2)^2 + \Gamma_{Z'}(s)^2 m_{Z'}^2}$$

$$\Gamma_{Z'}(s) = \frac{g_\chi^2}{12\pi\sqrt{s}} \sqrt{1 - 4\frac{m_\chi^2}{s}}\,(s + 2m_\chi^2)$$

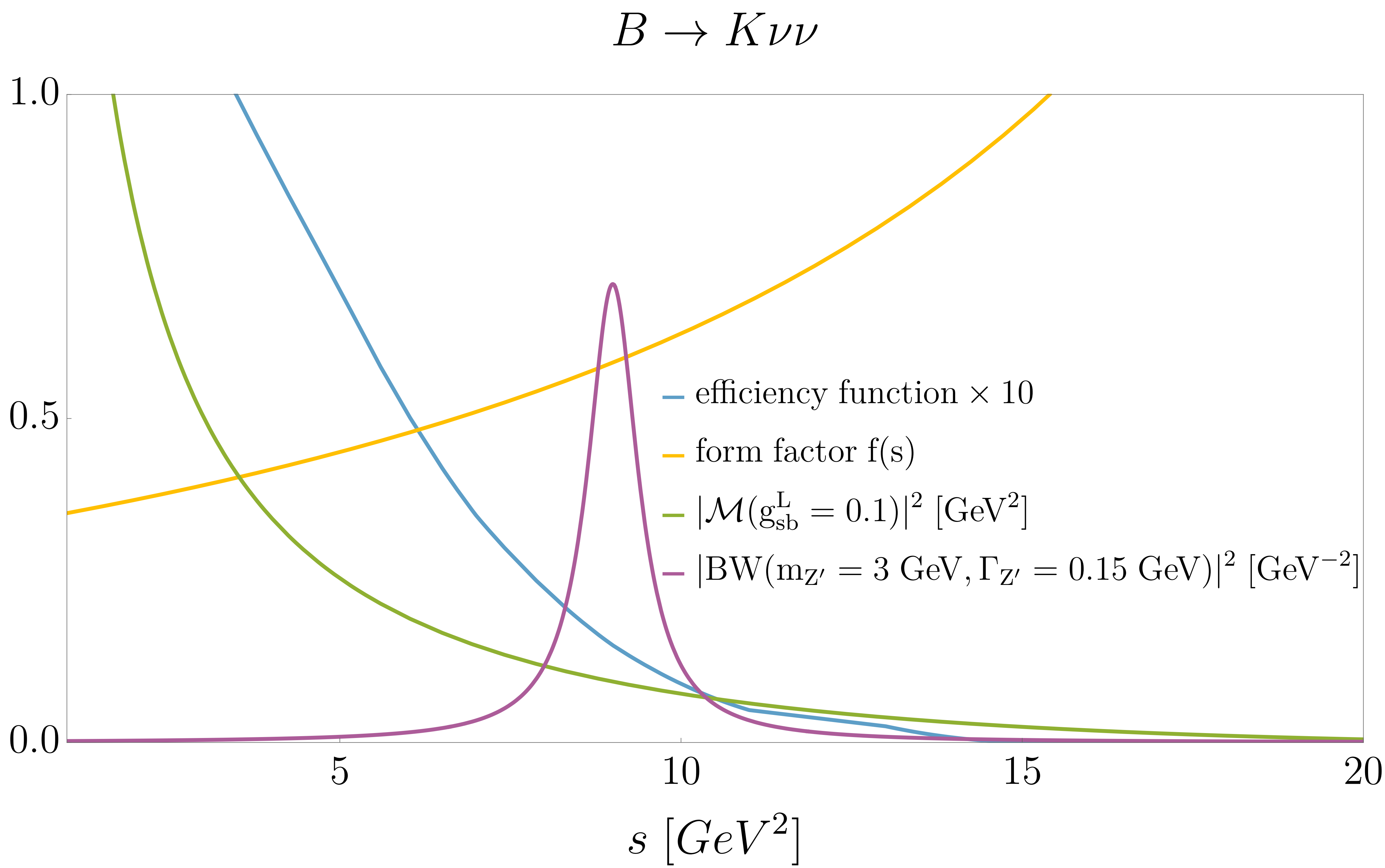
Belle II:

$\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) < 4.1 \times 10^{-5}$

Others: Babar, Belle

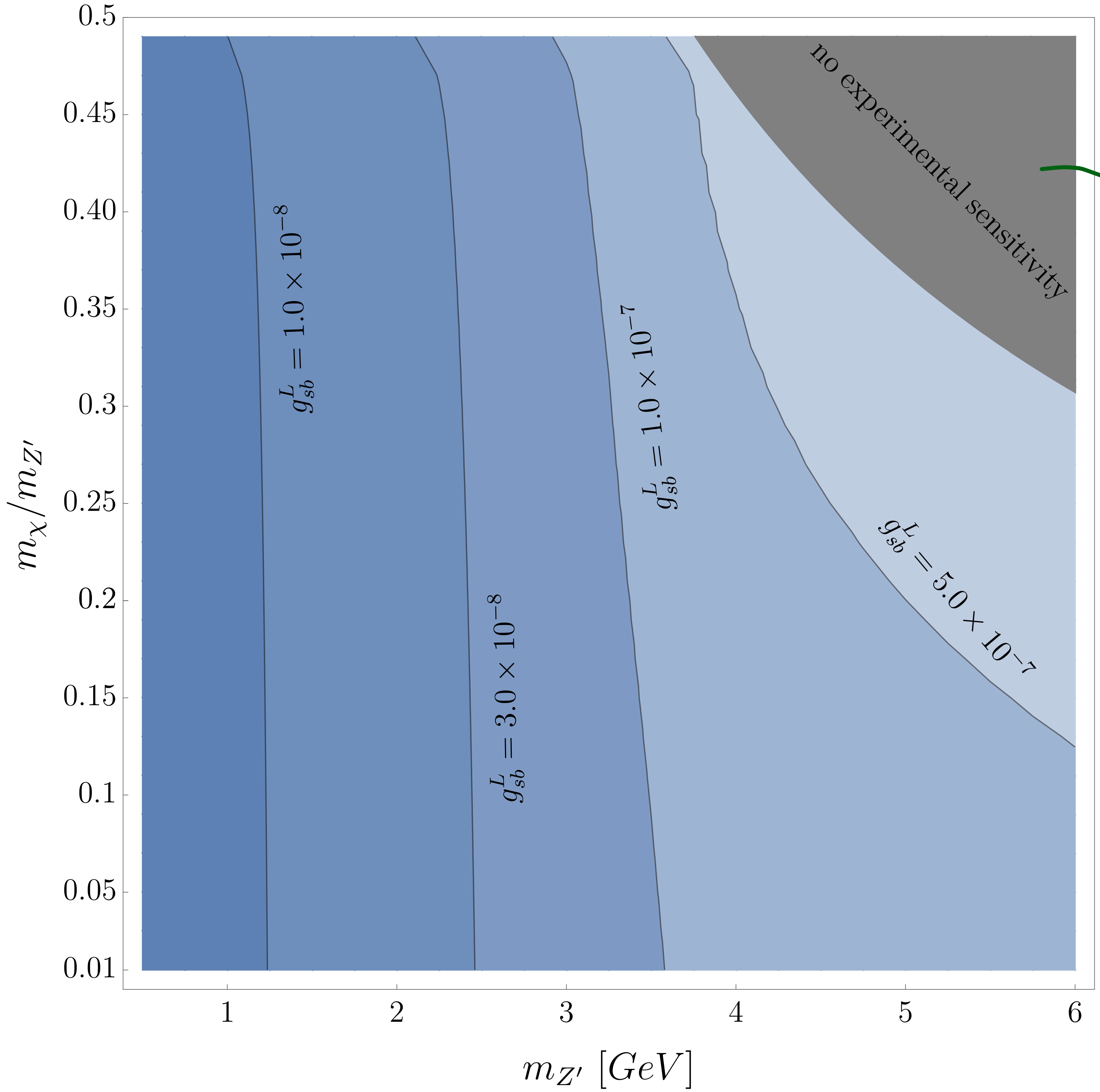
Light Z'

$B \to K^{(*)}\nu\nu$



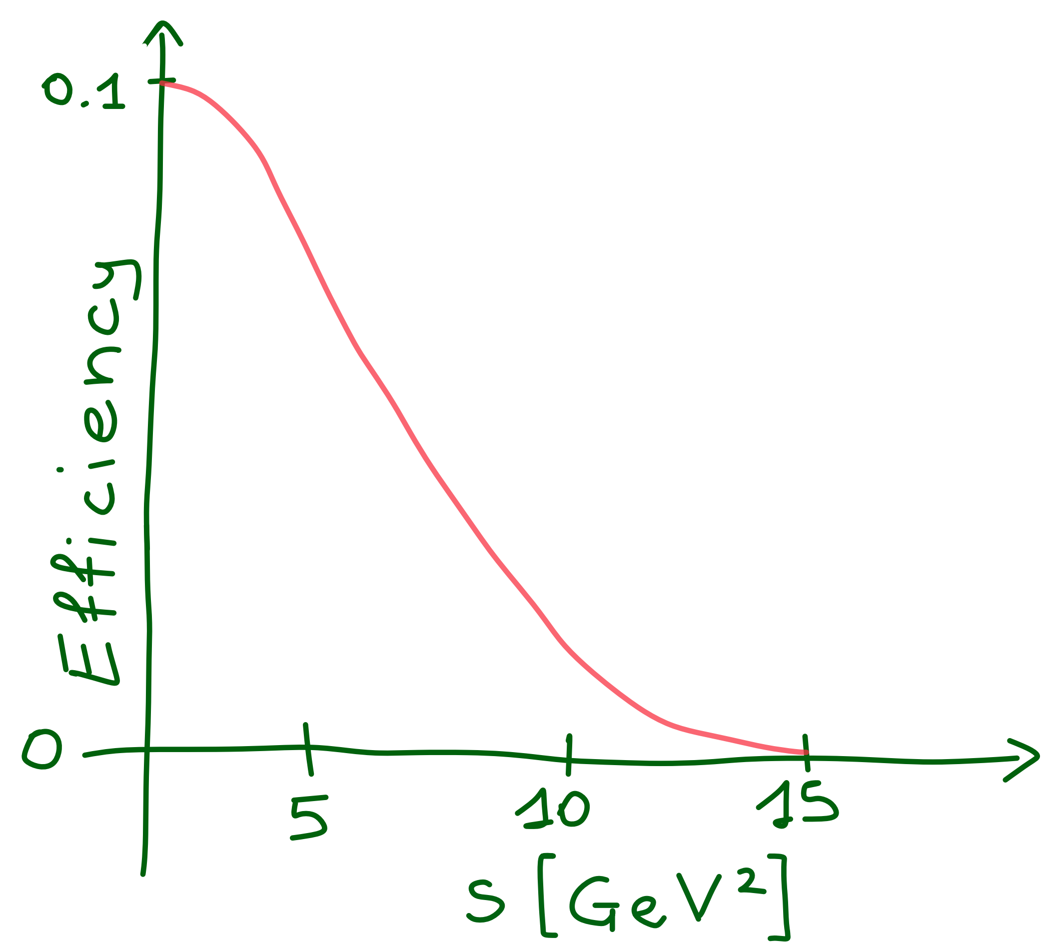
Light Z'

Recasted Belle II analysis



- A large m_χ weakens the bounds on g_{sb}^L

$$s_{\min} = 4m_\chi^2$$



Light Z'

Other bounds

$B_s - \bar{B}_s$ mixing

- Light Z' masses: OPE in $m_{Z'}/m_B$ $\rightarrow$ weaker than $B \rightarrow K^{(*)}\nu\nu$
- For $m_{Z'} \sim m_B$: no reliable treatment yet

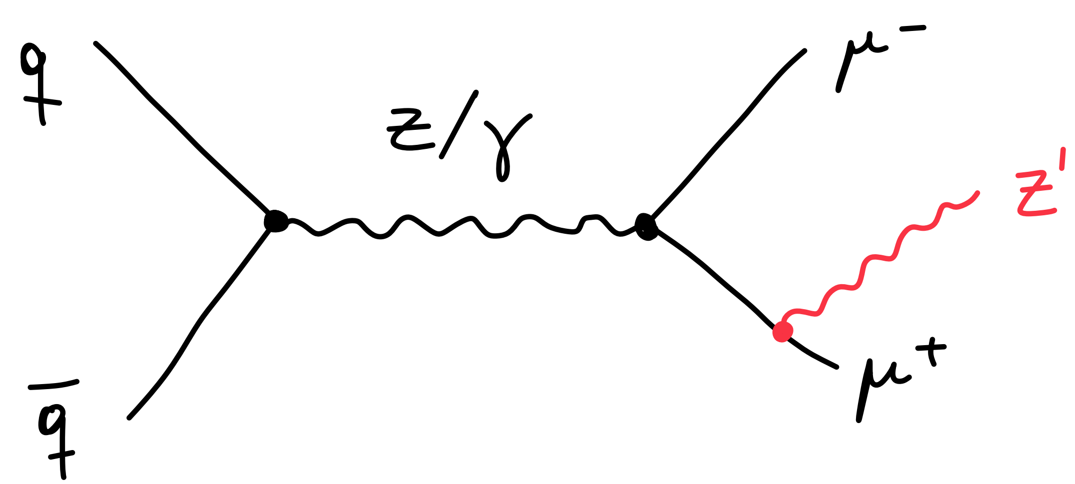
$e^+e^- \rightarrow \mu^+\mu^- + \text{invisible}$

- Recasted Belle II analysis for a sizeable Z' width:
  - $276\ \text{pb}^{-1}$ hep/1912.11276
  - $50\ \text{fb}^{-1}$
  - $5\ \text{ab}^{-1}$

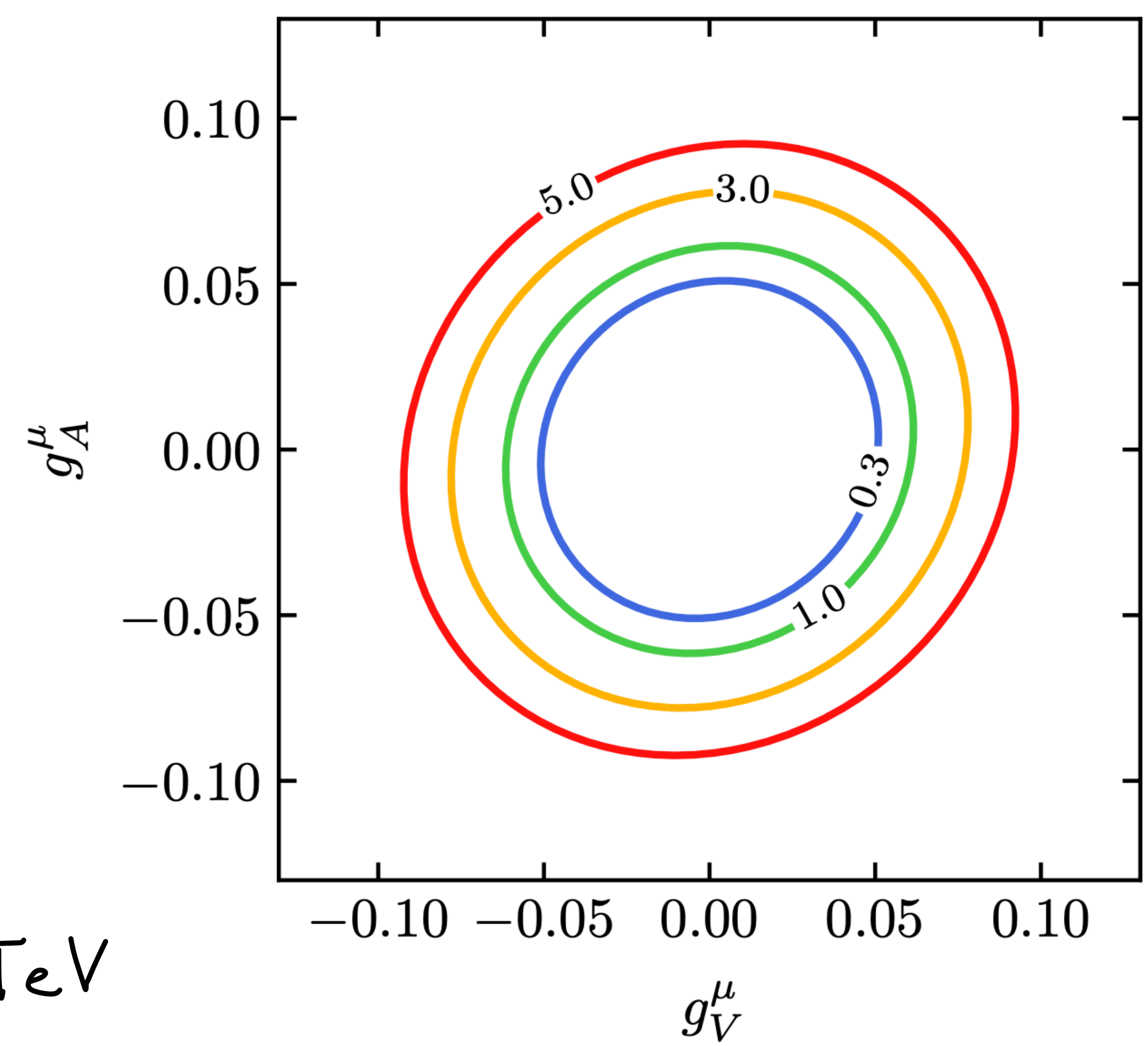
Limits on $g^V_{\mu\mu}$ of the order $10^{-1} - 10^{-2}$

$pp \rightarrow \mu^+\mu^- + \text{invisible}$

F. Bishara, U. Haisch, P.F. Monni hep/1705.03465



ATLAS 3.2 fb⁻¹ √s = 13 TeV

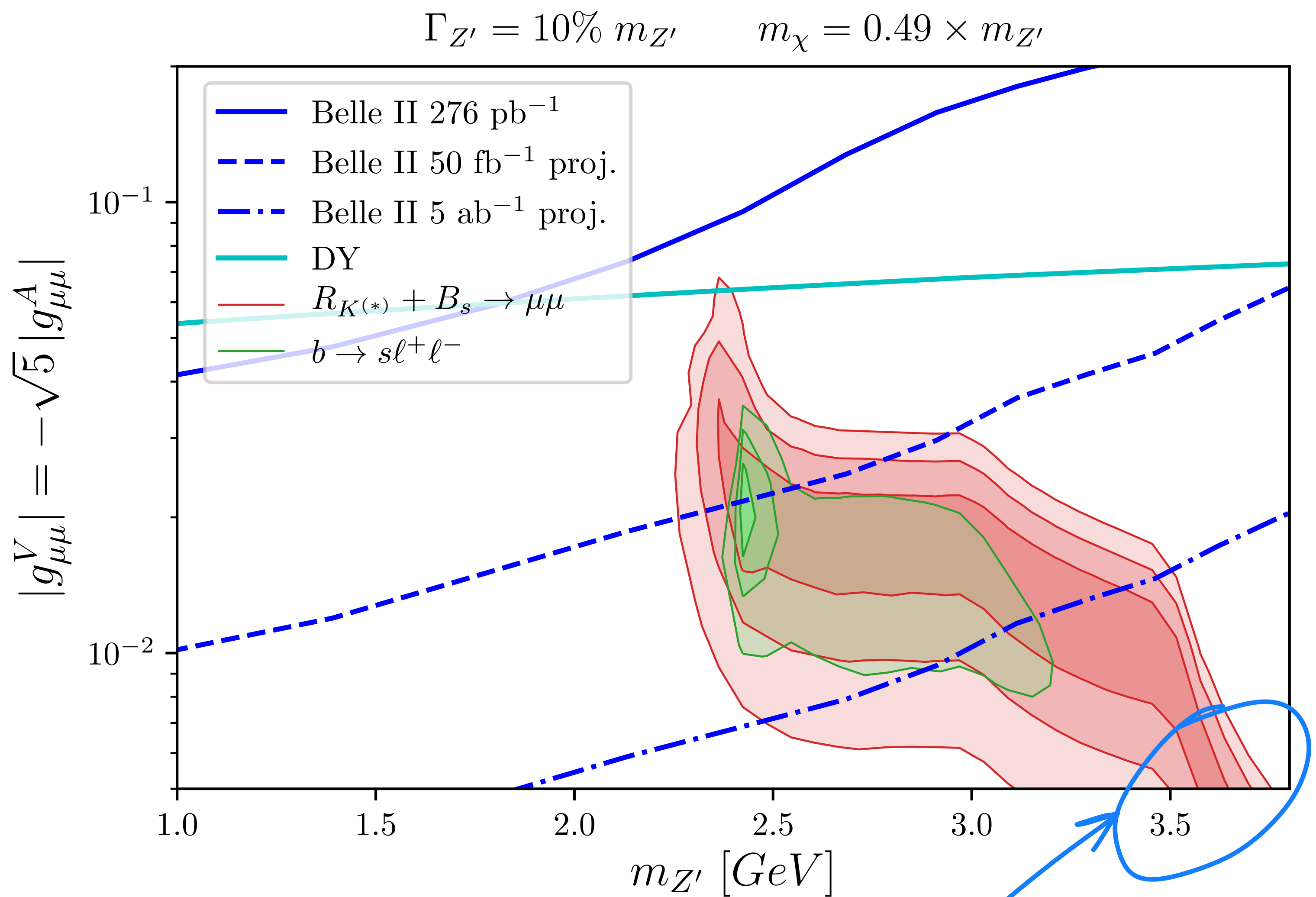


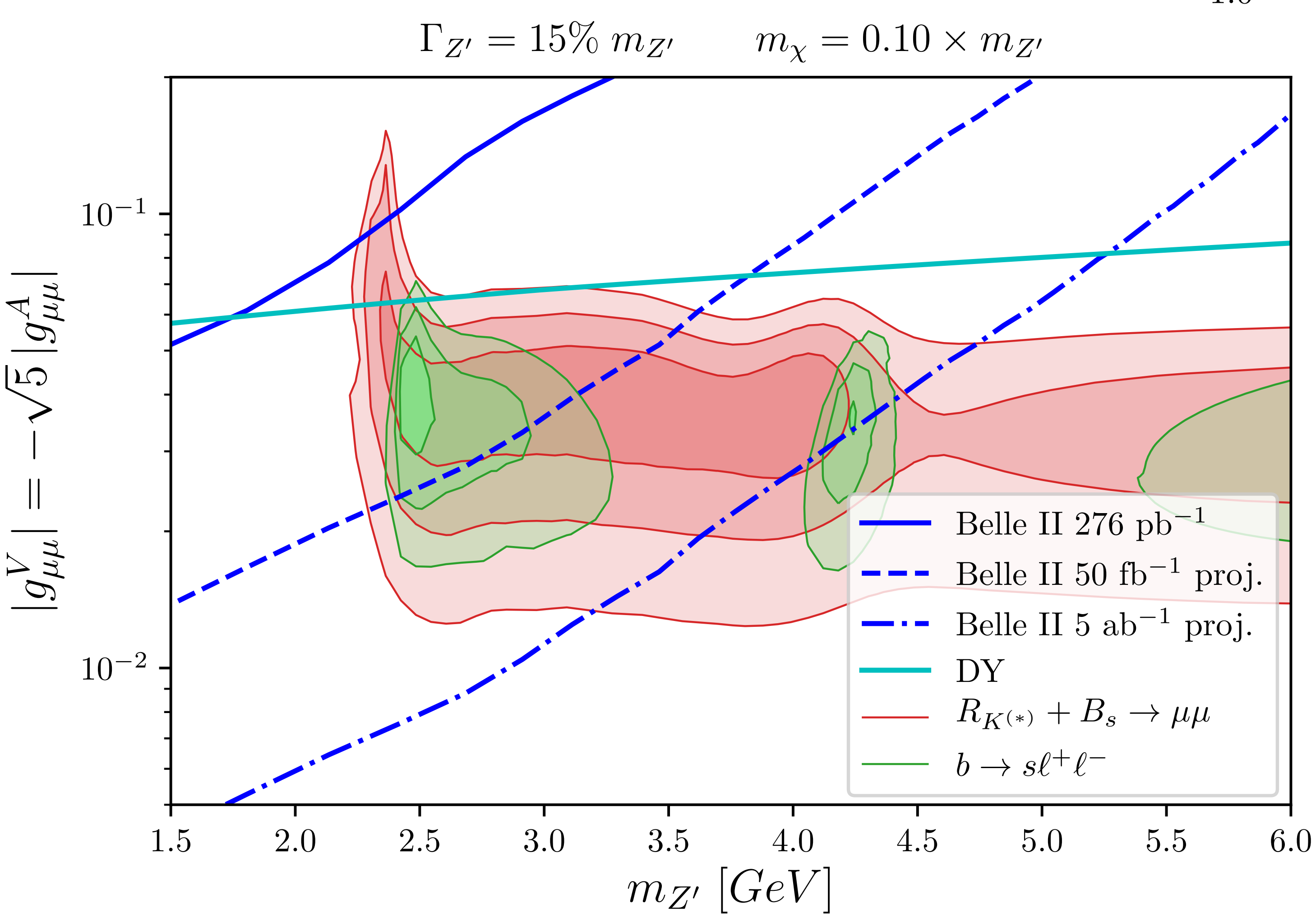
Light Z'

Bounds on $g^V_{\mu\mu}$

Maximum g^L_{bs} allowed by $B \to K^{(*)}\nu\nu$

Cannot exclude a light Z' yet





Belle efficiency drops

$\Longrightarrow g^L_{bs}$ can be very large

- **Future Belle II analysis can exclude**

$$m_{Z'} \sim 2.5 \text{ GeV}$$

- $m_{Z'} \sim 4$ GeV **would not lead to**

$R(K^{(*)}) > 1$ **in high-q^2 bins**

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Light Z'

Bounds on g_{sb}^L

Alternatively we can maximize $g_{\mu\mu}^V$ from $e^+e^- \to \mu^+\mu^- + \text{invisible}$