Explaining lepton-flavor non-universality and self-interacting dark matter with $L_\mu - L_\tau$

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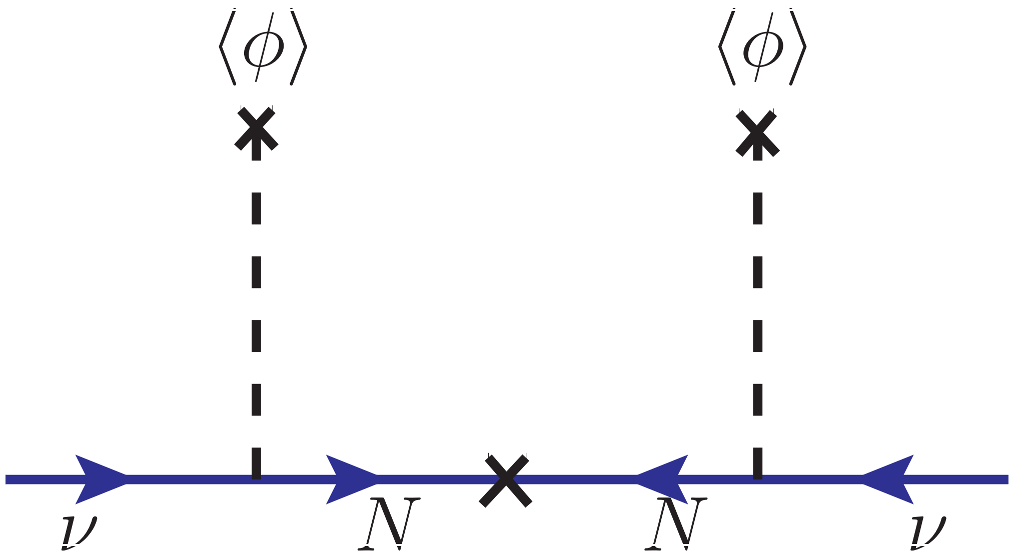
ν mass generation: Seesaw paradigm

- In Standard Model $M_\nu = 0$. But, ν flavor mix. $\nu_{aL} \leftrightarrow \nu_{bL}$

  $|\nu_\alpha\rangle = \sum U_{\alpha i} |\nu_i\rangle \Longrightarrow M_\nu \neq 0 \Longrightarrow$ New Physics beyond SM

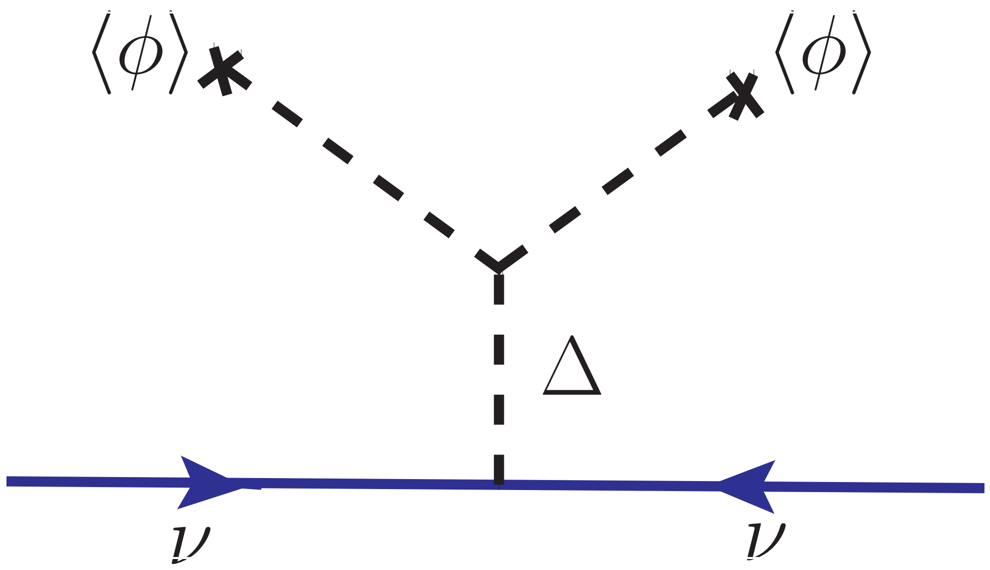
- Light neutrino mass is induced via Weinberg's dim-5 operator, $LL\phi\phi$
- Large Majorana mass scale Λ to suppress the neutrino mass via $\dfrac{\langle\phi\rangle^2}{\Lambda}$



Type I / Type III :

ν- mass induced from fermion exchange

$N^1 \sim (1,1,0) \quad N^3 \sim (1,3,0)$



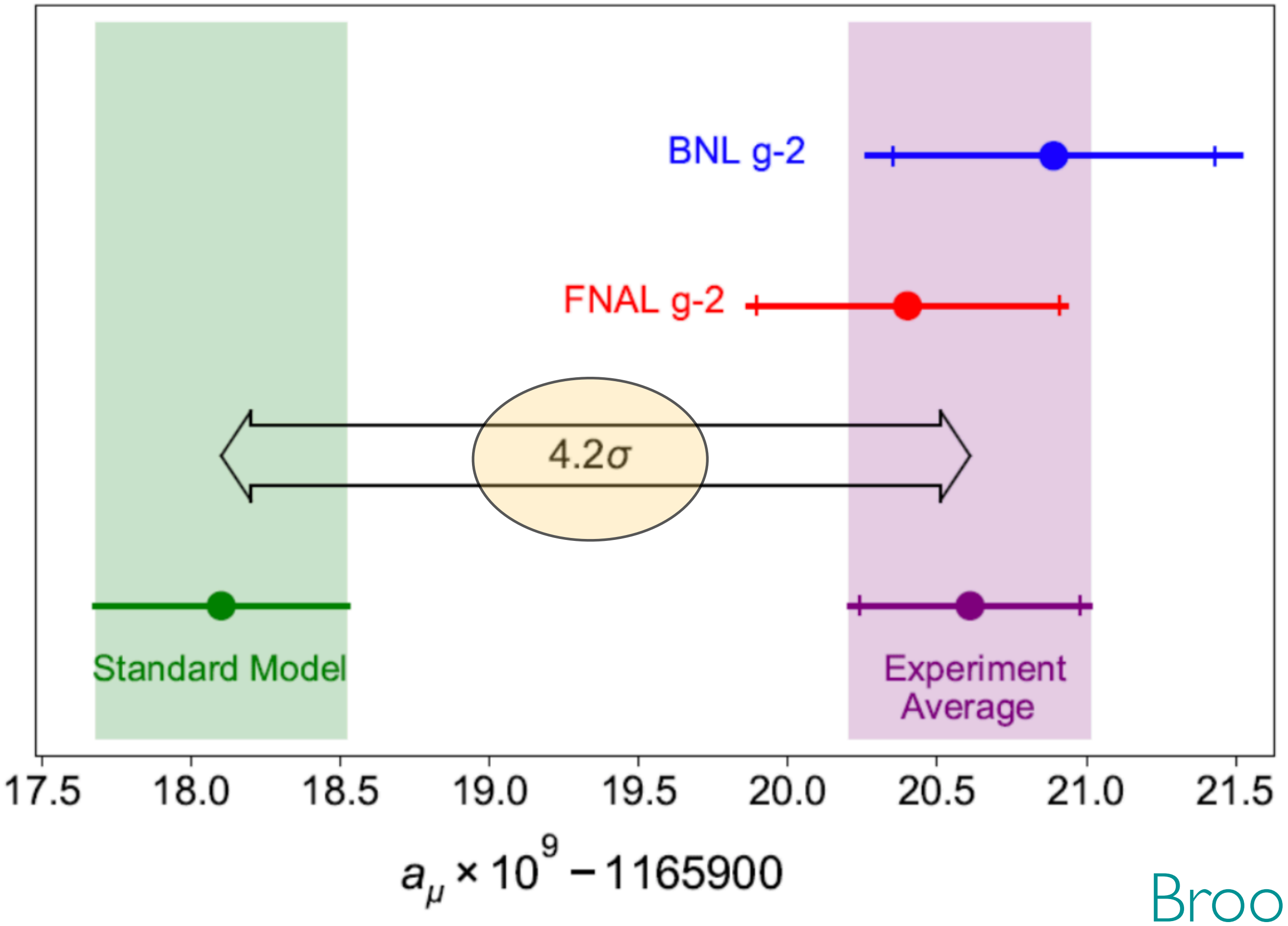
Type II :

ν- mass induced from scalar exchange

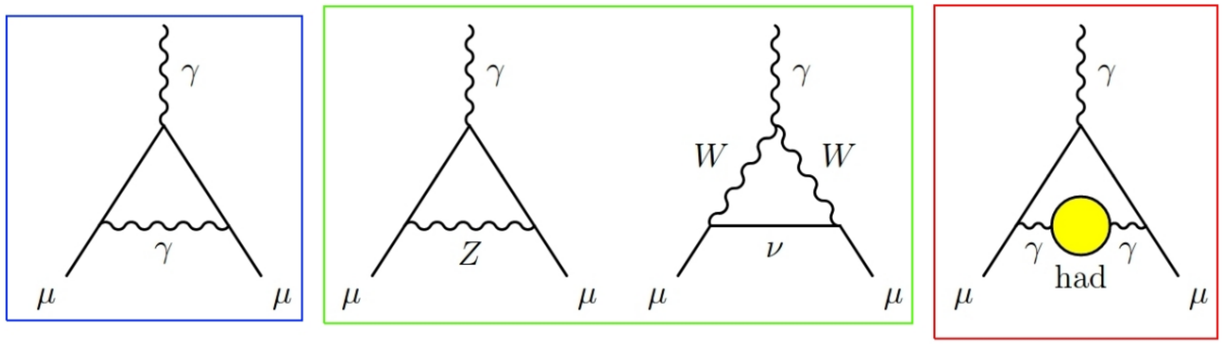
$\Delta \sim (1,3,1)$

$(g-2)_\mu$

- Intrinsic magnetic property of a lepton is characterized by dimensionless number, called g-factor $H = -\vec{\mu}\cdot\vec{B}, \quad \vec{\mu} = g\frac{e}{2m}\vec{s}$
- Anomaly, $a_\mu \equiv (g_\mu - 2)/2$, is a consequence of quantum nature of elementary particles. R. Kusch and H. M. Foley 1948, J. Schwinger 1948
- The Standard Model contribution to the lepton $g-2$:



$$a_\ell = a_\ell(\text{QED}) + a_\ell(\text{ weak }) + a_\ell(\text{ hadron })$$



$$\boxed{a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (251 \pm 59)\times 10^{-11}\,.}$$

Brookhaven (2006); Fermilab (2021)

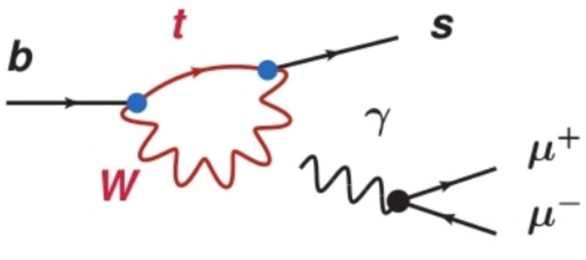
B anomalies

$b \to s$ anomalies

Observables: R_K and $R_{K^\star}$

Neutral current

1-loop in the SM



$\sim 3.1\sigma$

$$R_{K^{(\star)}} = \frac{\Gamma\left(\bar{B} \to \bar{K}^{(\star)}\mu^+\mu^-\right)}{\Gamma\left(\bar{B} \to \bar{K}^{(\star)}e^+e^-\right)}$$

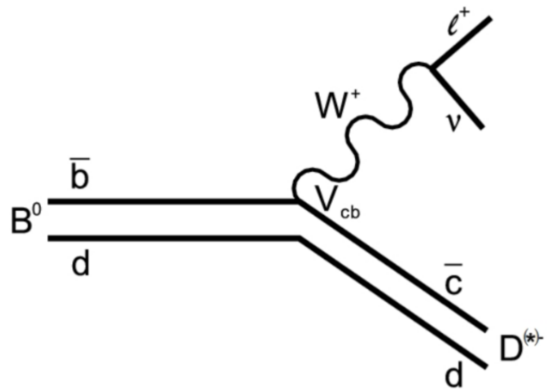
The New Physics can be heavy

$b \to c$ anomalies

Observables: R_D and $R_{D^\star}$

Charged current

Tree-level in the SM



$\sim 3.4\sigma$

$$R_{D^{(\star)}} = \frac{\Gamma(\bar{B} \to D^{(\star)}\tau\nu)}{\Gamma(\bar{B} \to D^{(\star)}\ell\nu)}$$

The New Physics must be light

$L_\mu - L_\tau$ **Model**

- Promote anomaly-free global symmetry $U(1)_{L_\mu - L_\tau}$ to gauge symmetry
- Z' only talks to second and third generation leptons, constraints are weak and allow light Z' that can explain $(g-2)_\mu$

Fermions		Bosons	
$N_{R,e}$	$(\mathbf{1},\mathbf{1},0,0)$	ϕ_1	$(\mathbf{1},\mathbf{1},0,1)$
$N_{R,\mu}$	$(\mathbf{1},\mathbf{1},0,1)$	S_3	$(\overline{\mathbf{3}},\mathbf{3},\frac{1}{3},-1)$
$N_{R,\tau}$	$(\mathbf{1},\mathbf{1},0,-1)$	S_1	$(\overline{\mathbf{3}},\mathbf{1},\frac{1}{3},+1)$
χ	$(\mathbf{1},\mathbf{1},0,q)$ or	χ	$(\mathbf{1},\mathbf{1},0,q)$

Julian, **AT**, '22

- Resolve $R_{K^{(\star)}}$ via S_3 and S_1 resolve $R_{D^{(\star)}}$. Automatically eliminate dangerous proton and LFV decays.
- No need for ad-hoc discrete symmetry for DM. The light Z' can mediate a large velocity dependent DM self-interaction that resolve small scale problems.

Neutrino Mass Generation

Neutrino masses are induced at tree level via type-I seesaw mechanism

$$m_\nu \simeq -\, m_D\, m_R^{-1} m_D^T \qquad m_D = v/\sqrt{2}\ \mathrm{Diag}\ (\lambda_e, \lambda_\mu, \lambda_\tau)$$

$$m_R = \begin{pmatrix} M_1 & a_{12}\langle\phi_1\rangle & a_{13}\langle\phi_1\rangle \\ a_{12}\langle\phi_1\rangle & 0 & M_2 \\ a_{13}\langle\phi_1\rangle & M_2 & 0 \end{pmatrix}$$

Lead to two vanishing minors,

$$(m_\nu^{-1})_{22} = (m_\nu^{-1})_{33} = 0$$

Predicts Normal Hierarchy

$$\sum_j m_j = [0.124 - 0.17]\ \mathrm{eV}\,,\ m_{\beta\beta} = 0.036\ \mathrm{eV}\,,\ \delta_{\mathrm{CP}} = 246^\circ \text{ or } 114^\circ$$

Cosmological constraints: $\sum_j m_j = [0.12 - 0.16]\ \mathrm{eV}$

If lower bound confirmed,

Excluded but add second scalar $\phi_2 \sim (1,1,0,2)$

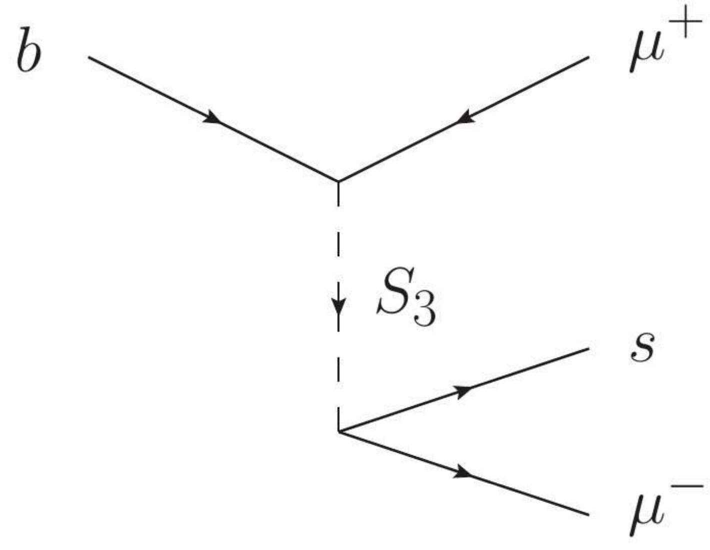
But not prediction!

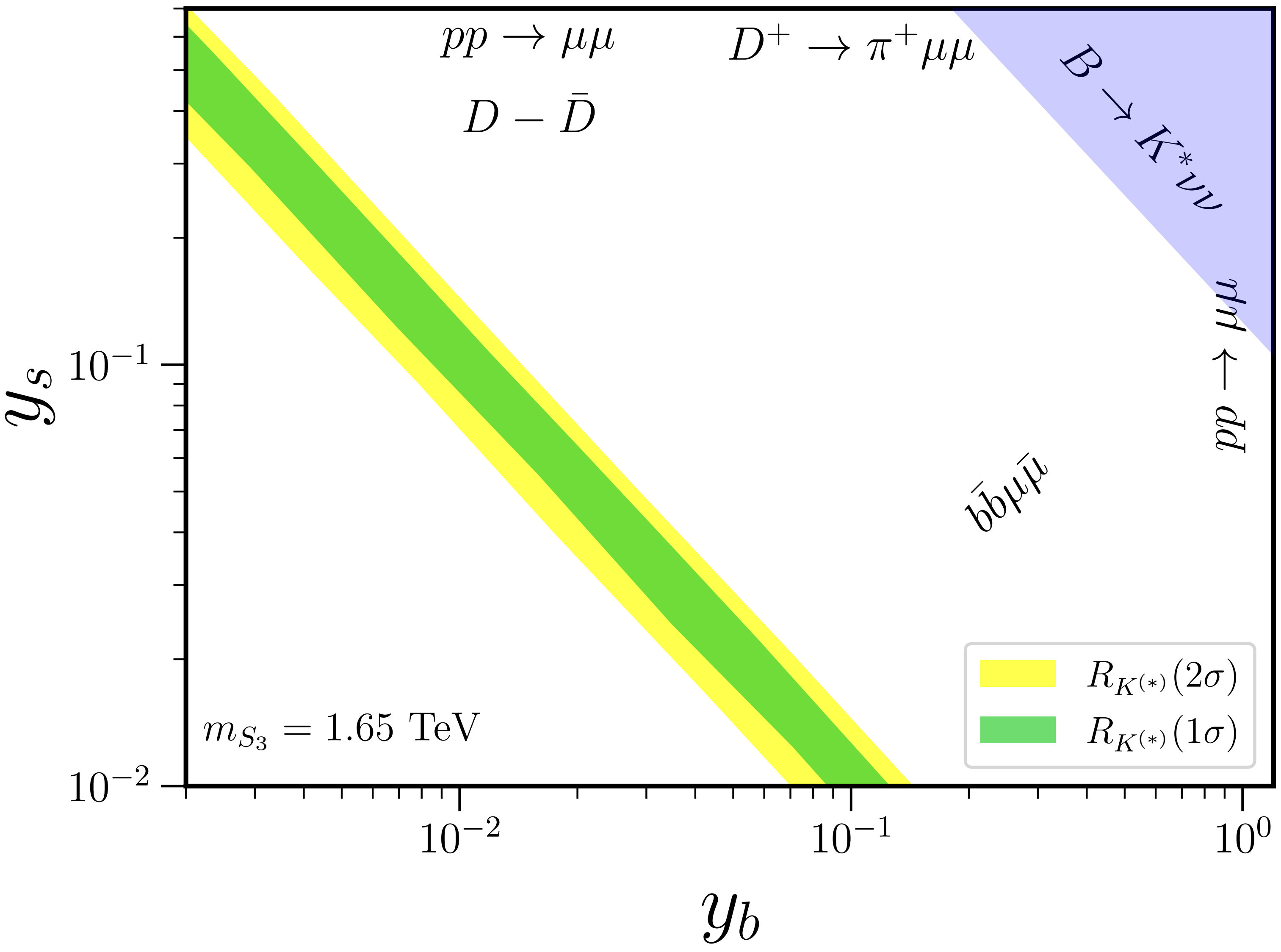
Neutral Current Anomaly: $R_K, R_{K^\star}$

$$\boxed{S_3 \sim (\bar{3}, 3, 1/3, -1)}$$

$$y_j \overline{Q}^c_j S_3 P_L L_\mu + h.c.$$

$$\cancel{QQS_3^\star}$$





$$\boxed{C_9 = -C_{10} = \frac{\pi v^2}{V_{tb}V_{ts}^\star \alpha_{\text{em}}} \frac{y_b y_s^\star}{m_{S_3}^2}}$$

$$C_9^{\mu\mu} = -C_{10}^{\mu\mu} = -0.41 \pm 0.09$$

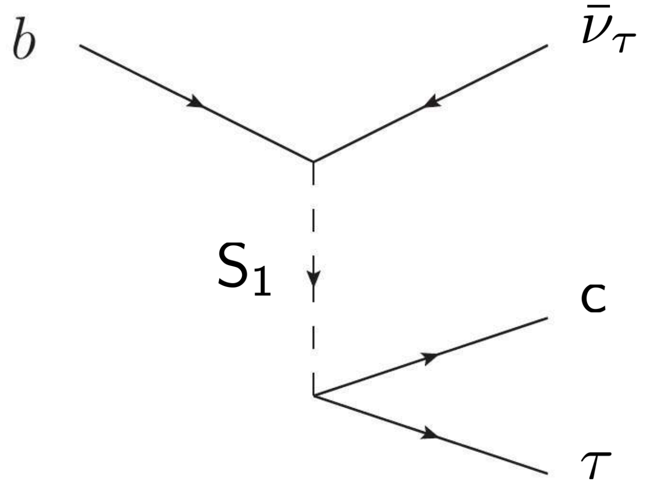
[Aebischer, et. al, '19; Becirevic et. al, '21]

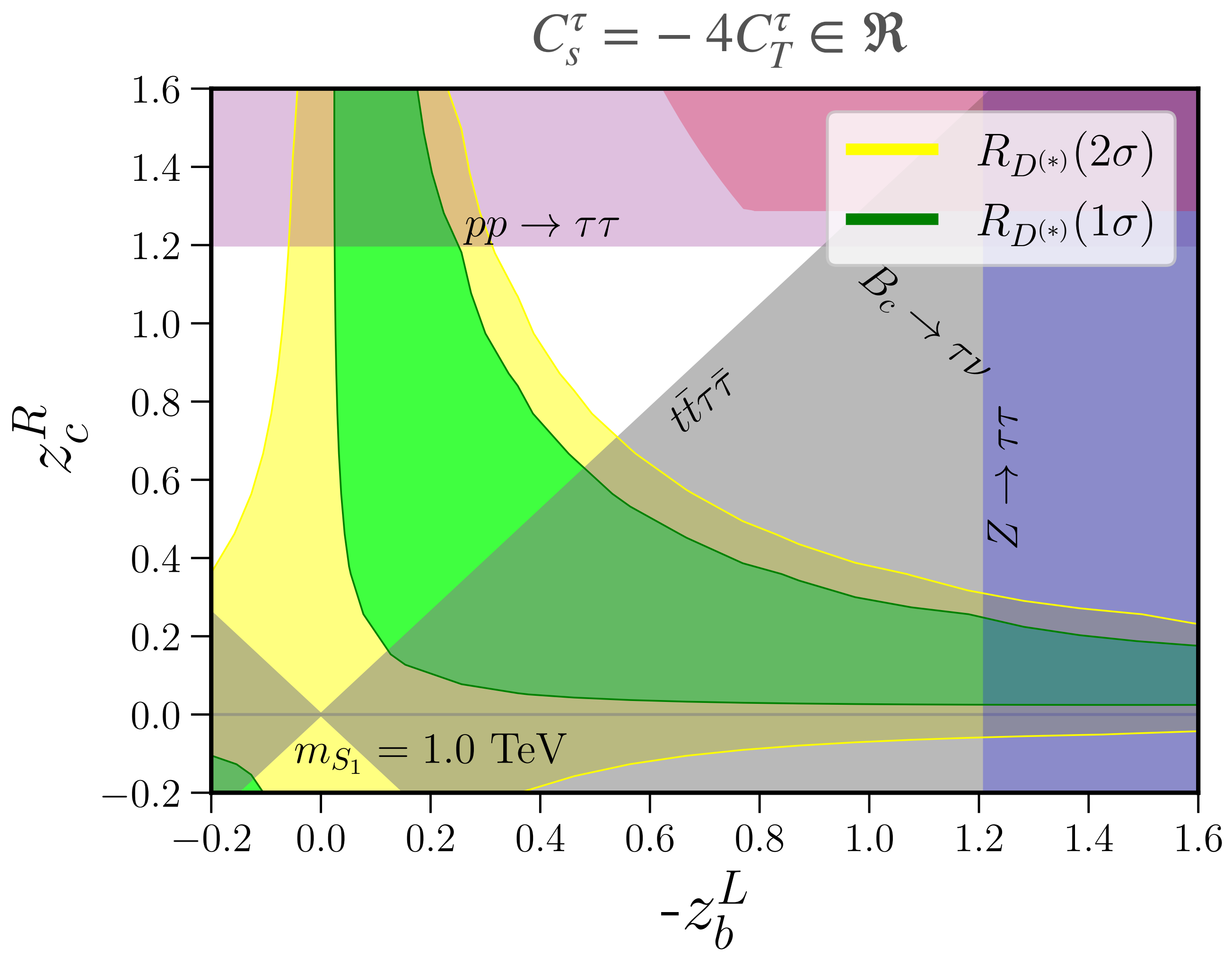
$$m_{S_3} \sim 40 \text{ TeV} \times \sqrt{|y_b y_s|}$$

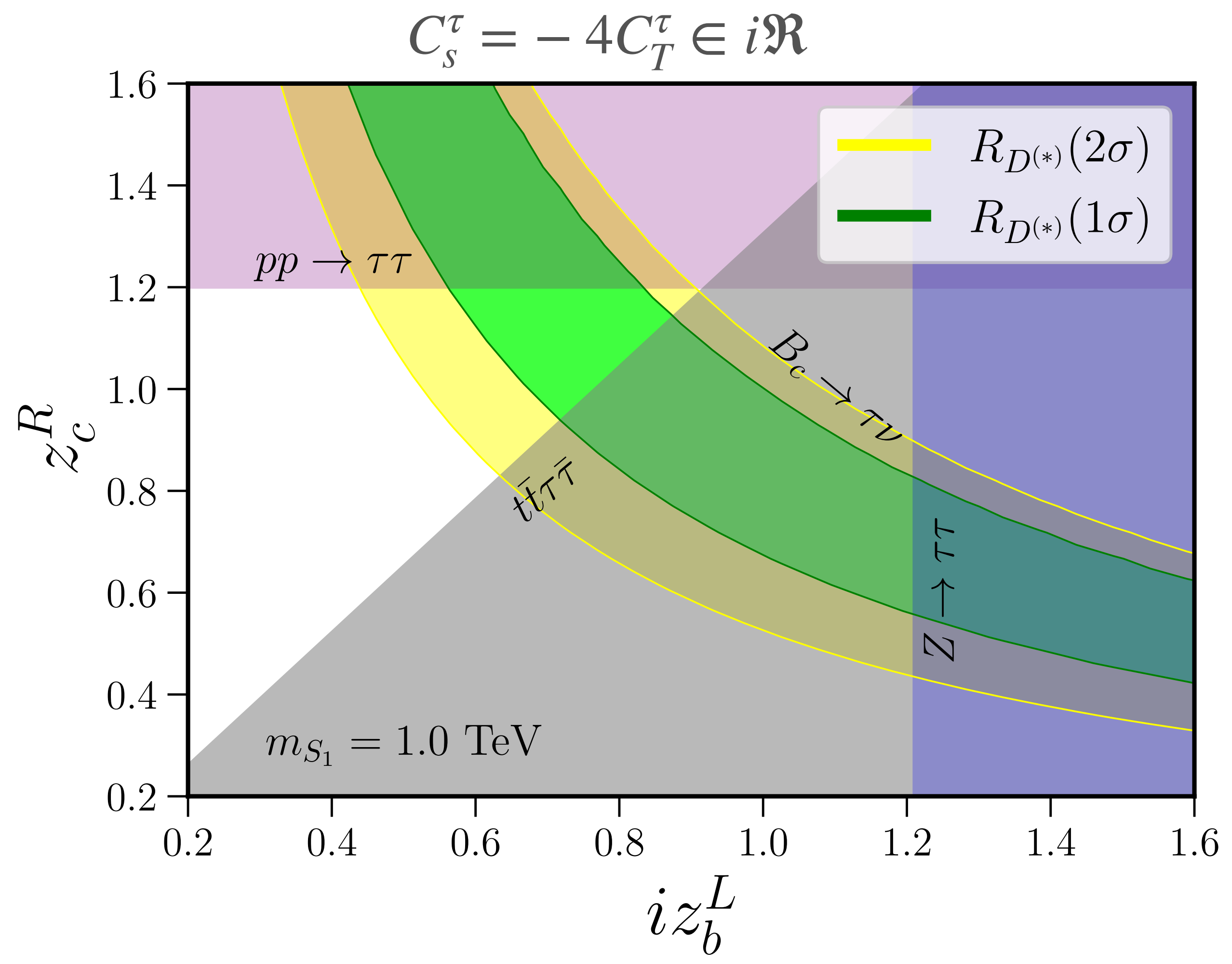
Charged Current Anomaly: $R_D, R_{D^\star}$

$$\boxed{S_1 \sim (\bar{3}, 1, 1/3, +1)}$$

$$z_j^L \overline{Q}_j^c S_1 P_L L_\tau + z_j^R \overline{u}_j^c S_1 P_R \tau + z_j^N \overline{d}_j^c S_1 P_R N_{R,\tau} + h.c.$$




$C_s^\tau = -4C_T^\tau \in \Re$

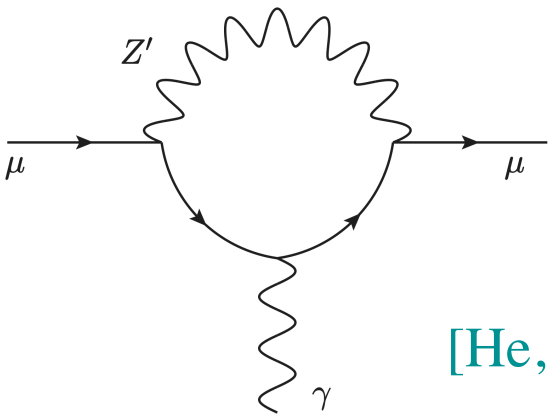

$C_s^\tau = -4C_T^\tau \in i\Re$

$$C_s^\tau = -4C_T^\tau = -\frac{v^2}{4V_{cb}}\frac{z_b^L z_c^{R*}}{m_{S_1}^2}$$

$$C_V^\tau = \frac{v^2}{4V_{cb}}\frac{z_b^L (V z^{L*})_c}{m_{S_1}^2}$$

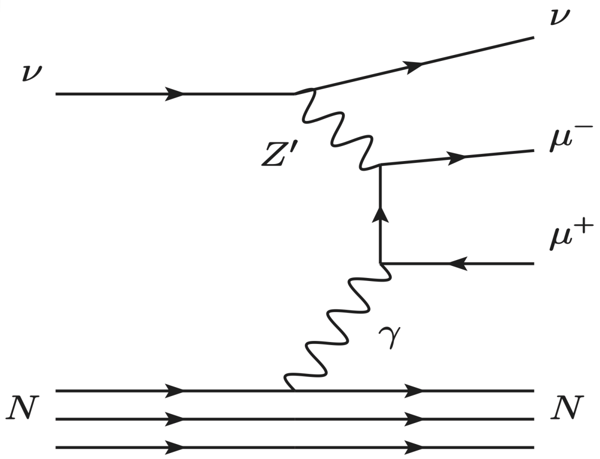
Anomalous Magnetic Moment

$(g-2)_\mu$

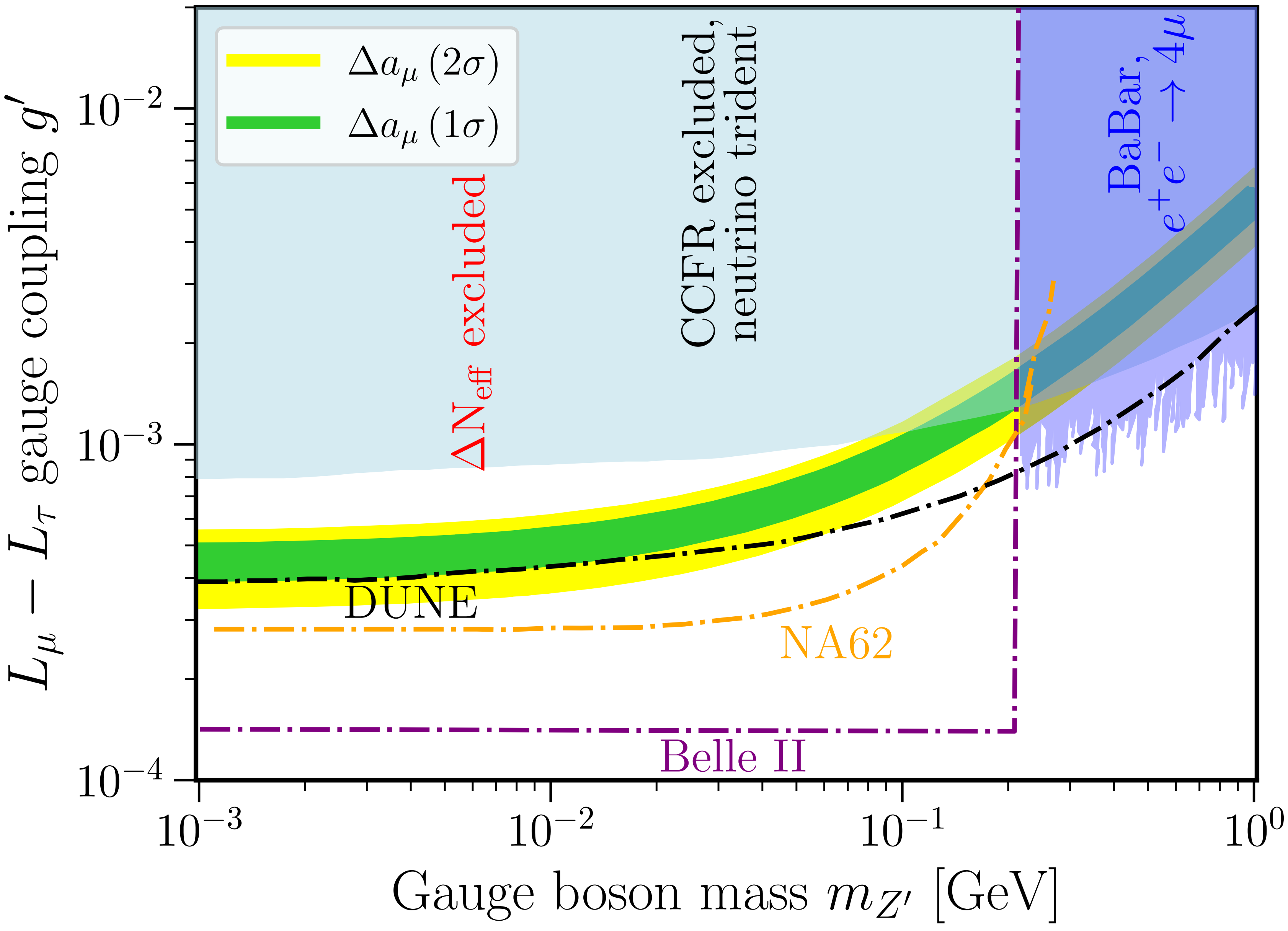


[He, Joshi, Lew, Volkas, '91]

ν trident



[Altmannshofer, Gori, Pospelov, Yavin, '14]



To be improved by DUNE

[Altmannshofer et al, '19; Ballettet al, '19]

Invisible Z'

$e^+e^- \to \mu^+\mu^- Z'$ at Belle II

[Jho++, 1904.1305]

$K \to \mu\nu Z'$ at NA62

[Krnjaic++, 1904.1305]

Dark Matter

$$\boxed{\chi \sim (1,1,0,q)}$$

- $(g-2)_\mu \Longrightarrow m_{Z'} = \mathcal{O}(10-100)$ MeV, relevant hierarchy $m_{Z'} \ll m_\chi$
- Dominant annihilation channel $\bar{\chi}\chi \to Z'Z'$:

$$\boxed{qg' \simeq 0.02\sqrt{\frac{m_\chi}{\text{GeV}}}}$$

- $\bar{\chi}\chi \to$ leptons suppressed by $1/q^2$

- Large DM-DM self interactions mediated by the light Z'
- Same combination $(g_X = qg')$ enters the DM-DM self-interactions cross sections describe by Yukawa potential:

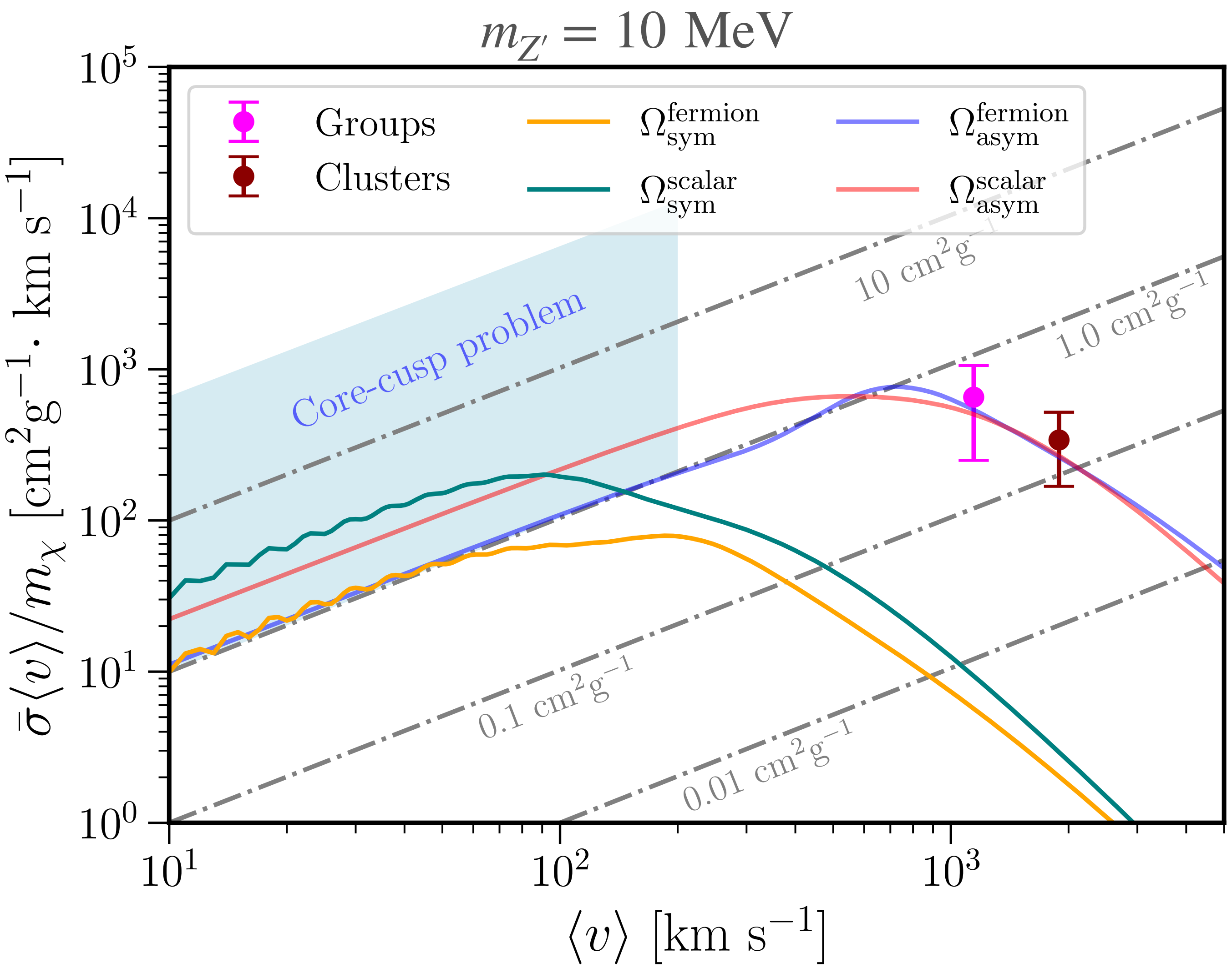
$$g_X \bar{\chi}\gamma^\mu \chi Z_\mu \qquad V(r) = \pm \frac{\alpha_X}{r} e^{-m_{Z'} r}$$

[Tulin et al, '20]

- Typical cross section needed to flatten the cores to explain small structure formation:

$$\boxed{\sigma \sim 10^{-24}\ \text{cm}^2 \frac{m_\chi}{\text{GeV}} \approx 1\text{cm}^2/\text{g}}$$

Typical WIMP cross section: $\sigma \sim 10^{-36}\ \text{cm}^2$



Dwarf galaxies:

velocity of DM ~ [10 – 100] km/s,

$\sigma/m \sim 1\ \text{cm}^2/\text{g}$

[Tulin et al, '20]

Clusters:

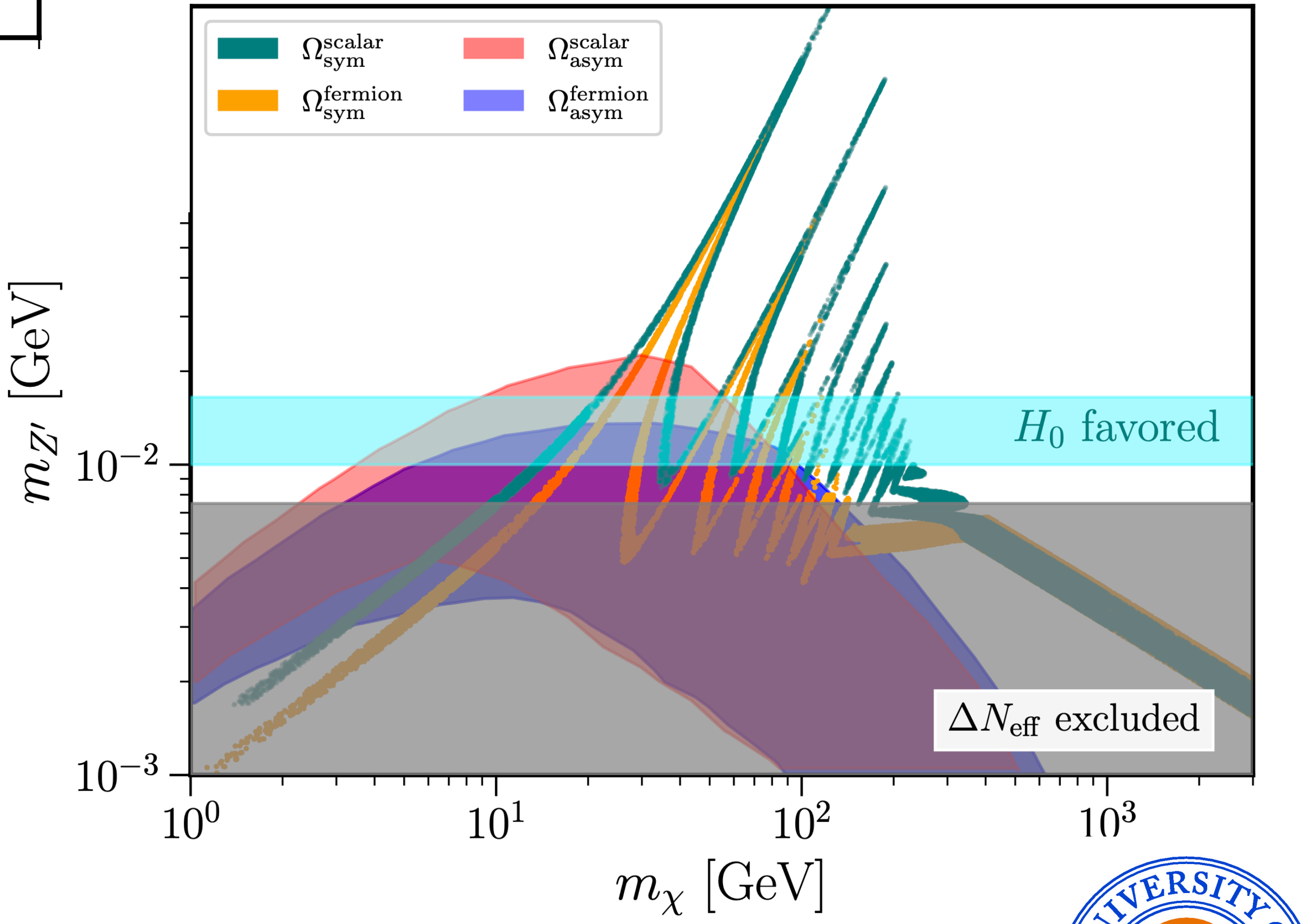
velocity of DM ~ 1000 km/s,

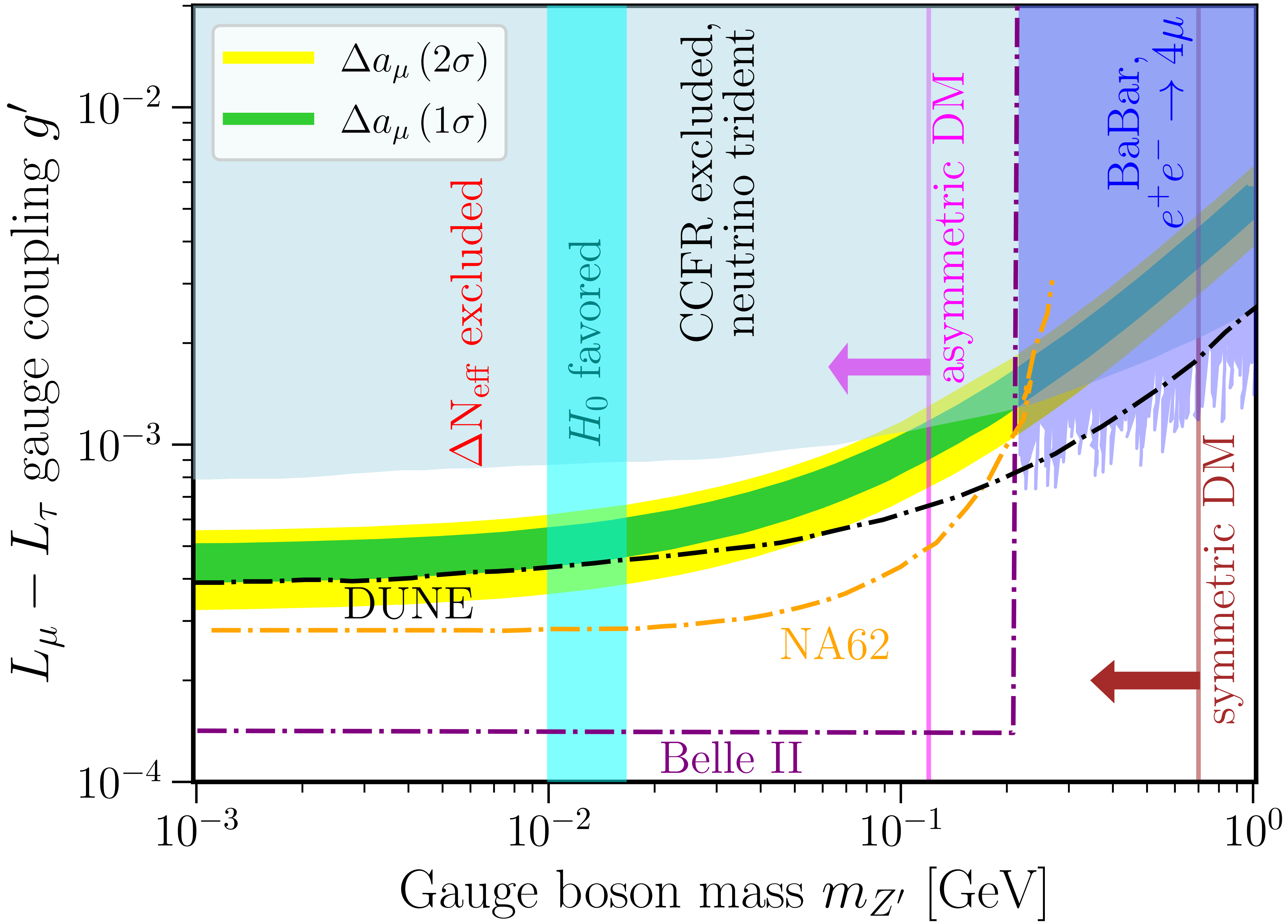
$\sigma/m \sim 0.1\ \text{cm}^2/\text{g}$.

$m_\chi = 4$ GeV
asymmetric DM

$m_\chi = 15$ GeV
symmetric DM

Z' mass falls precisely in the region in which the Z' can explain the $(g-2)_\mu$ anomaly




$\Delta a_\mu\,(2\sigma)$
$\Delta a_\mu\,(1\sigma)$
ΔN_{eff} excluded
H_0 favored
CCFR excluded, neutrino trident
asymmetric DM
BaBar, $e^+e^- \to 4\mu$
symmetric DM
DUNE
NA62
Belle II
$L_\mu - L_\tau$ gauge coupling g'
10^{-2}
10^{-3}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
Gauge boson mass $m_{Z'}$ [GeV]

Conclusion

- Simple gauged $U(1)_{L_\mu - L_\tau}$ resolves B- anomalies, muon $g-2$ and leads to velocity-dependent dark-matter self-interactions that can ameliorate current small-scale structure-formation discrepancies.
- The models are consistent with observed neutrino oscillation data and predicts NH.