Flavored B-L model and dark matter

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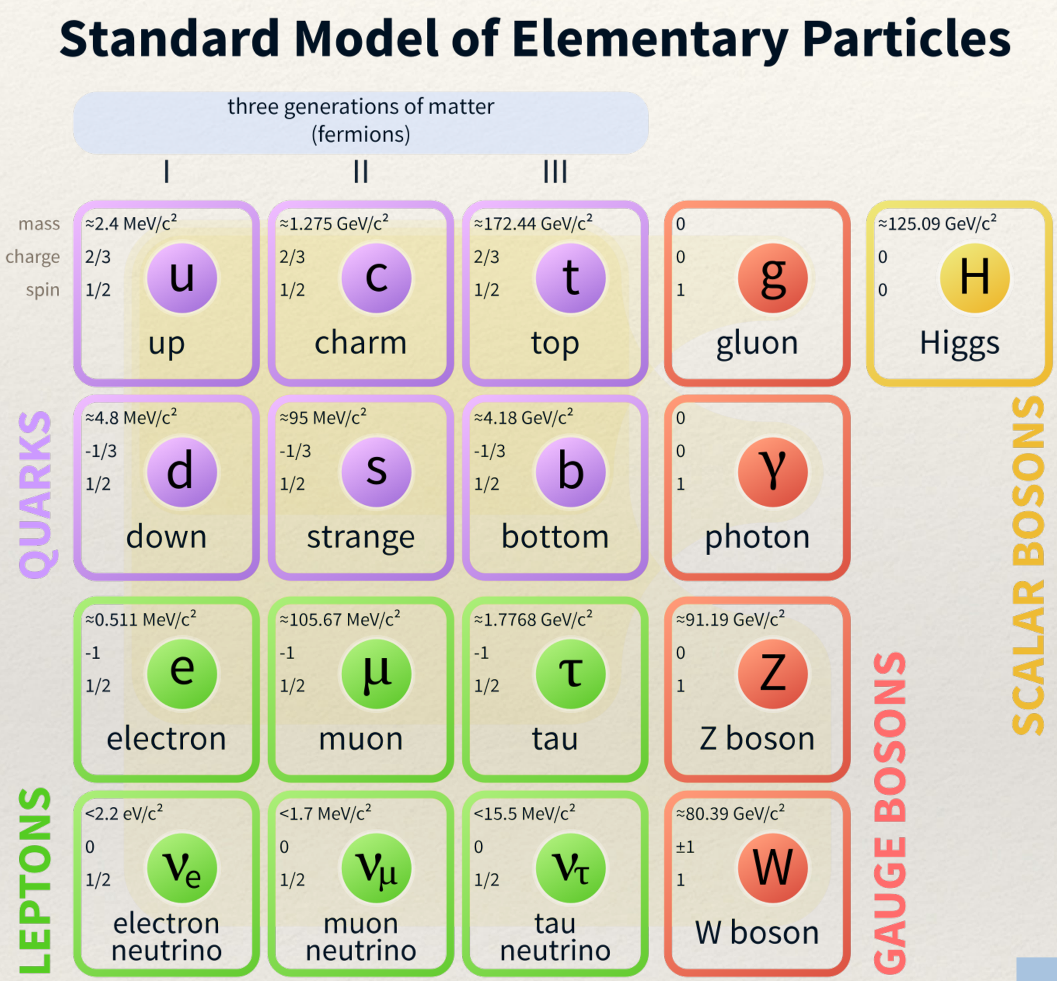
Based on arXiv:1710.01585, with Peter Cox and Tsutomu Yanagida

Outline

- Motivations for a flavored B-L model
- Right hand neutrino as a dark matter candidate
- Possible connection with flavor physics(if enough time)
- Summary

$SM + 3\nu_R$



Successful but can not explain

1. neutrino masses
2. Baryon asymmetry
3. dark matter ?

seesaw and leptogenesis

$+3\nu_R$ $\quad \mathcal{L} = \mathcal{L}_{SM} + y_\nu L \tilde{H} \nu_R - M_R \bar{\nu}_R^c \nu_R$

Natural extension of gauge sector

$$SU(3)_c \times SU(2)_L \times U(1)_Y \to SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$$

$SM + 3\nu_R$

$$SU(3)_c \times SU(2)_L \times U(1)_Y \times \not{U}(1)_{B-L}$$

$$m_{\nu_R} \sim 10^9 GeV$$

seesaw and leptogenesis

Minkowski, Yanagida Fukugita, Yanagida 1986'

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

Two right hand neutrinos are already enough to explain

1. neutrino data
2. Baryon asymmetry

$SM + 3\nu_R$

The last right hand neutrino as a dark matter candidate(TeV)?

- Unnatural yukawa coupling
- Baryon asymmetry washed out
- Stability?

← adding a Z2 symmetry

- We also need a mediator (B-L breaking at high energy scale)

$SM + 3\nu_R$

B-L to a flavored B-L, only couple to third generation

$$U(1)_{B-L} \to U(1)_{(B-L)_3}$$

- Breaking scale could be low(~TeV) ⟶ Mediators at low energy scale
- Naturally accommodate two heavy right neutrinos
- A dark matter candidate.
- Anomaly cancelation preserve(anomaly cancel by each generation)
- Survive under collider search and flavor physics, dark matter direct search.
- Or B meson decay anomaly.

Flavored B-L with dark matter

Matter contents

	$q_L^3,\, b_R,\, t_R$	$\ell_L^3,\, \tau_R,\, \nu_R^3$	H	Φ
$Q_{(B-L)_3}$	$+1/3$	-1	0	$+2$

- Breaking the new gauge symmetry
- Give majorana mass term ν_R^3

Additional couplings

- $h-\phi$mixing: $\lambda_{h\Phi} H^\dagger H \Phi^\dagger \Phi$

⟶ Important for dark matter direct detection

- Unavoidable kinetic mixing: $-\frac{\epsilon}{2} F'^{\mu\nu} B_{\mu\nu}$

⟶ Constrained by electroweak precision

Yukawa Structure

However, off-diagonal Yukawa couplings involving 3rd generation are now forbidden

$$Y_d = \begin{pmatrix} \hat{Y}_d & 0 \\ 0 & Y_b \end{pmatrix}$$

Two general possibilities:

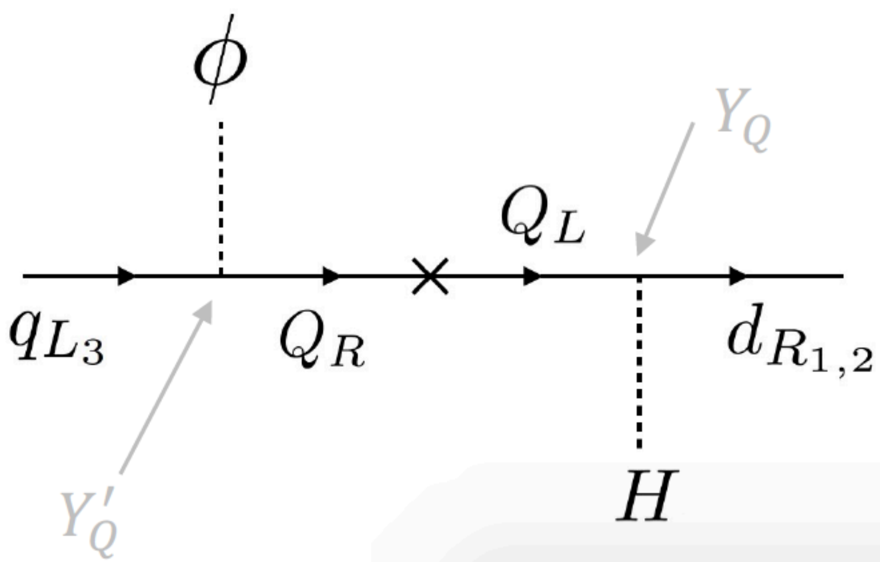
- Additional Higgs doublets charged under U(1)’
- New vector-like fermions and SM singlet scalars

Yukawa Structure

$U(1)_{(B-L)_3}$ singlet vector fermions:

$$Q_{L,R}, U_{L,R}, D_{L,R}, L_{L,R}, E_{L,R}, N_{L,R}$$

SM singlet scalars: $\phi_q(+\frac{1}{3}), \phi_l(+1)$



$$\begin{pmatrix} \bar{q}_{L_{1,2}} & \bar{q}^3_L \end{pmatrix} H \begin{pmatrix} \hat{Y}_d^{2\times 2} & -\frac{Y'_D \phi_q^*}{M_D} Y_D \\ -\frac{Y'_Q \phi_q}{M_Q} Y_Q^T & Y_b \end{pmatrix} \begin{pmatrix} d_{R_{1,2}} \\ b_R \end{pmatrix}$$

Gauge Coupling

Generically mediate FCNC after rotation to mass basis

$$J^\mu = \bar{f} U_f^\dagger T_f U_f \gamma^\mu f \qquad T^q = \frac{1}{3}\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}, T^l = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1 \end{pmatrix}$$

Constraints from K-K and D-D mixing significantly reduced by construction (especially if CKM generated in up sector)

However, there can be new physical mixing angles involving the 3rd generation, beyond those present in the CKM and PMNS matrices

Right hand neutrino dark matter

To simplify our study, we assume $\langle \Phi \rangle \gg \langle \phi_{q,l} \rangle$

and in our analysis for the dark matter sector, $\phi_{q,l}$ is ignored

The related interactions:

$$\mathcal{L} = \frac{i}{2}\bar{\chi}\not{\partial}\chi + \frac{g}{2}Z'_{\mu}\bar{\chi}\gamma^5\gamma^{\mu}\chi - (\frac{y}{2}\bar{\chi}\Phi P_R\chi + h.c.)$$
$$+ (D^{\mu}\Phi)^{\dagger}(D_{\mu}\Phi) + \mu_{\Phi}^2\Phi^{\dagger}\Phi - \lambda_{\Phi}(\Phi^{\dagger}\Phi)^2 - \lambda_{H\Phi}(H^{\dagger}H)(\Phi^{\dagger}\Phi)$$
$$- \frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} - \frac{\epsilon}{2}F'^{\mu\nu}B_{\mu\nu} + \mathcal{L}_{SM}\,,$$

$\chi = (-\varepsilon\nu_R^{3*},\, \nu_R^3)^T$ is the majorana dark matter

Six free parameters: $g, y, \mu_{\Phi}, \lambda_{\Phi}, \lambda_{H\Phi}, \epsilon$

Right hand neutrino dark matter

After symmetry breaking:

$$\Phi = \frac{1}{\sqrt{2}}(w+\phi)\,, \quad H = \frac{1}{\sqrt{2}}(0,\, v+h)^T\,.$$

In the limit $\lambda_{H\Phi} \to 0 \quad w = \mu_\Phi / \sqrt{\lambda_\Phi}$

$$m_\chi = \frac{y}{\sqrt{2}} w,\;\; m_{Z'} = 2gw,\;\; m_\phi = \sqrt{2}\mu_\Phi$$

$\lambda_{H\Phi}$ induces mixing between $h-\phi$, this mixing is highly constrained by dark matter direct search.

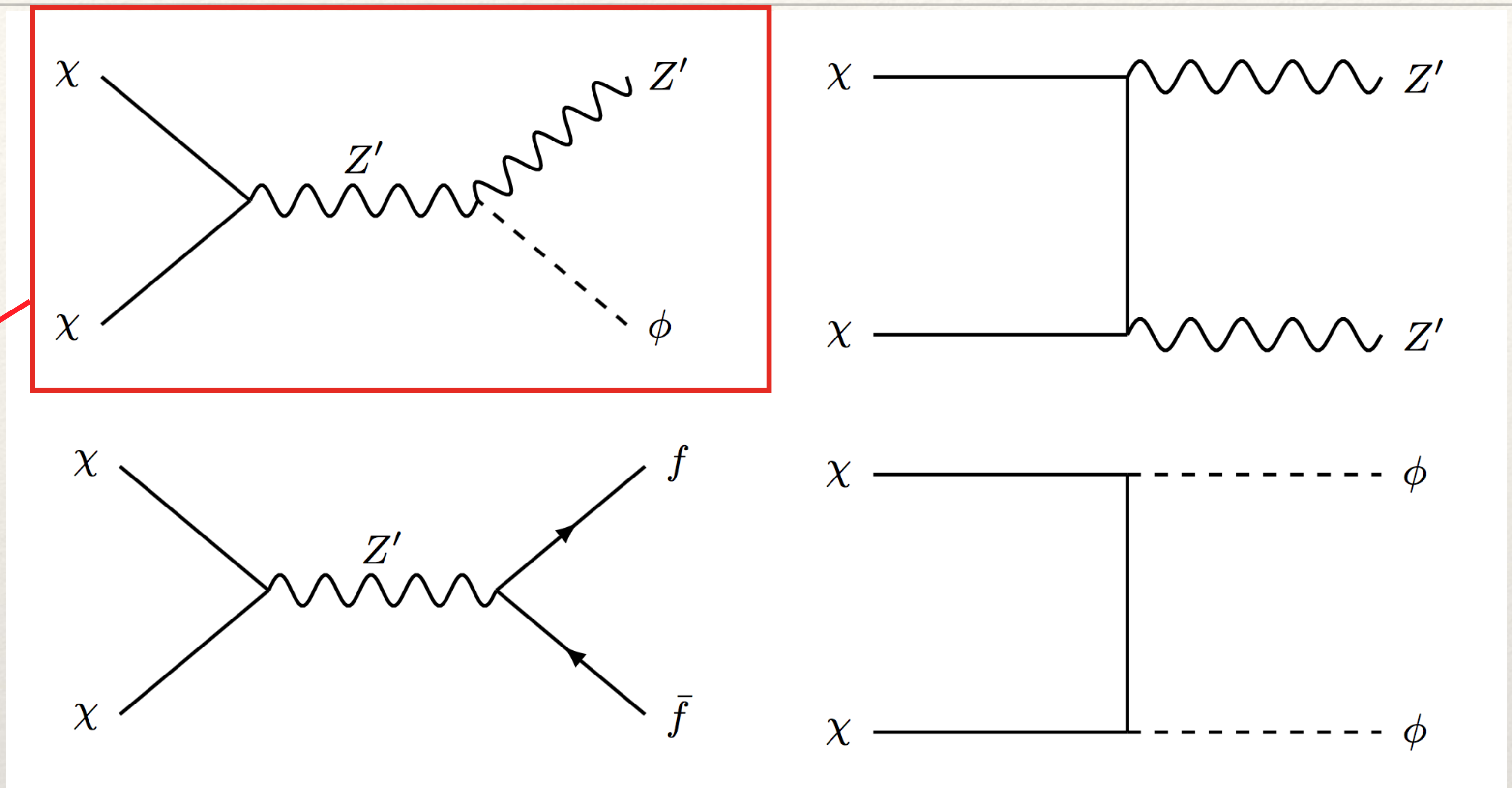
Changing into six more physical parameters:

$$(g, m_\chi, m_{Z'}, m_\phi, \theta, \epsilon)$$

θ → $h-\phi$ mixing

DM annihilation channels

In the small mixing limit:



Can not be described by one mediator model

$$\sigma v(\chi\chi \to Z'\phi) = \frac{g^4}{64\pi m_\chi^4 m_{Z'}^4}\left(m_\phi^4 - 2m_\phi^2(4m_\chi^2 + m_{Z'}^2) + (4m_\chi^2 - m_{Z'}^2)^2\right)^{3/2},$$ s wave, always dominate when opens

$$\sigma v(\chi\chi \to Z'Z') = \frac{g^4}{16\pi m_\chi^2}\left(1 - \frac{m_{Z'}^2}{m_\chi^2}\right)^{1/2}\left(1 + \frac{4(8m_\chi^4 + m_\phi^4)}{3(4m_\chi^2 - m_\phi^2)^2}\frac{m_\chi^4}{m_{Z'}^4}v^2 + \mathcal{O}\left(\frac{m_{Z'}^2}{m_\chi^2}\right)\right),$$ s wave, p wave enhanced

$$\sigma v(\chi\chi \to \phi\phi) = \frac{3g^4 m_\chi^2}{8\pi m_{Z'}^4}\left(1 - \frac{m_\phi^2}{m_\chi^2}\right)^{1/2}\left(1 + \mathcal{O}\left(\frac{m_\phi^2}{m_\chi^2}\right)\right)v^2,$$ p wave

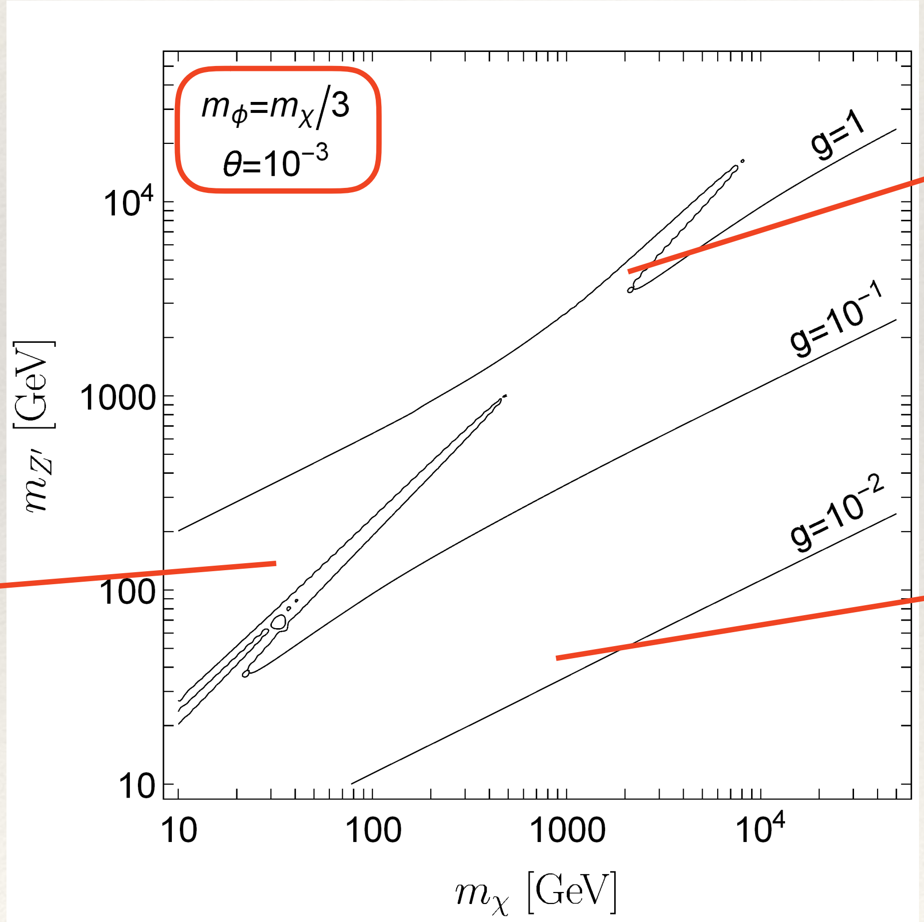
$$\sigma v(\chi\chi \to \bar{f}f) = \frac{g^4 N_c Q_f^2}{12\pi m_\chi^2}\left(1 - \frac{m_f^2}{m_\chi^2}\right)^{1/2}\frac{(2 + m_f^2/m_\chi^2)}{(4 - m_{Z'}^2/m_\chi^2)^2}v^2.$$ p wave

Relic density

Relic density calculated with Mircomega

Gauge coupling can be fixed to satisfy correct relic density

⟶ five parameters $m_\chi, m_{Z'}, m_\phi, \theta, \epsilon$



$m_\chi \sim \frac{1}{2} m_{Z'}$

resonance region

$\chi\chi \to \phi\phi$

$\chi\chi \to f\bar{f}$

$\chi\chi \to Z'\phi(Z'Z')$

Unitarity/perturbativity

Even in simplified models, partial wave perturbative unitarity gives strong bounds

$\phi\phi, Z'_L Z'_L$

$$m_\phi < \frac{\sqrt{\pi} m_{Z'}}{g} .$$

$\chi\chi \to \chi\chi$

$$m_\chi < \frac{\sqrt{\pi} m_{Z'}}{g} , \qquad g < \sqrt{4\pi}$$

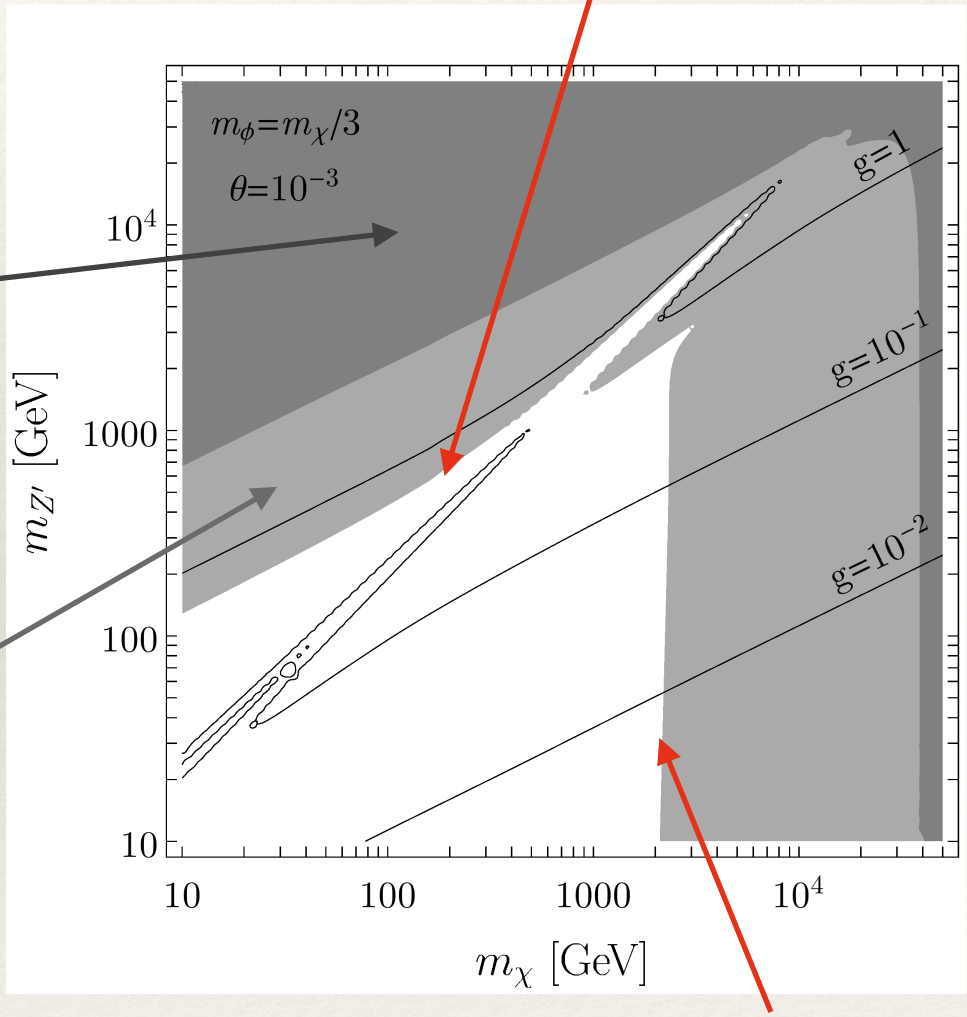
Impose perturbativity of couplings to high scales (i.e. no Landau pole below Mpl)

→ Stronger bounds

→ $m_\chi \lesssim 2$ TeV

Except the resonance region

$g \lesssim 0.65$



$y \lesssim 1.2$

DM Direct Detection

Mediated by Z'

Suppressed: no coupling to light quarks

Can be introduced by RGE running to nuclear scale

$$\chi\gamma^5\gamma^\mu\bar{q}\gamma_\mu q \longrightarrow \text{velocity suppressed SI}$$

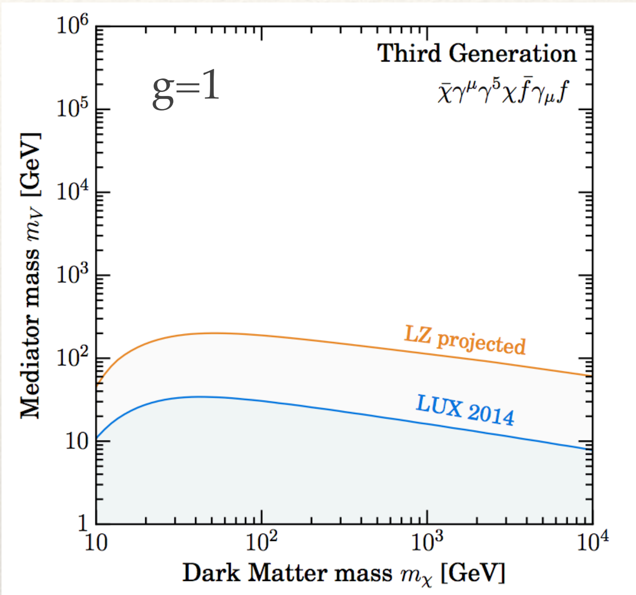
Limits are even weak in future!

Mediated by $h, \ \phi$

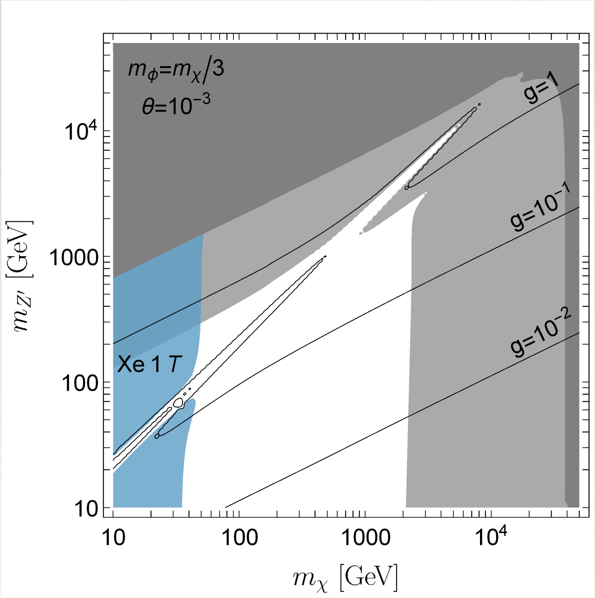
Highly depending on mixing angle

Even small mixing angle gets strong limit

Cancels when $m_h \sim m_\phi$



D'Eramo et al. 1605.04917



DM Indirect Detection

$\chi\chi \to \phi Z'$ $\chi\chi \to Z'Z'$ s wave

In principle lead gamma-ray signals

$\chi\chi \to Z'Z'$ p wave enhanced

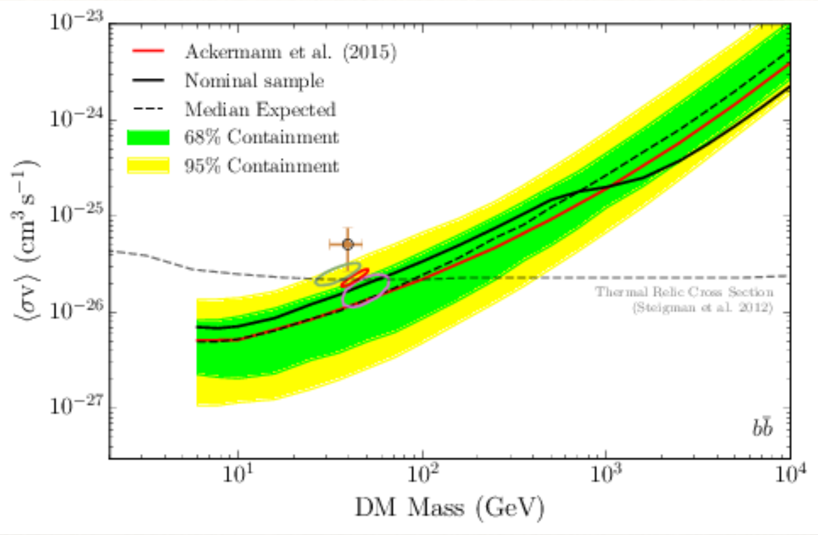
Annihilation xsec suppressed compared to the thermal relic xsec

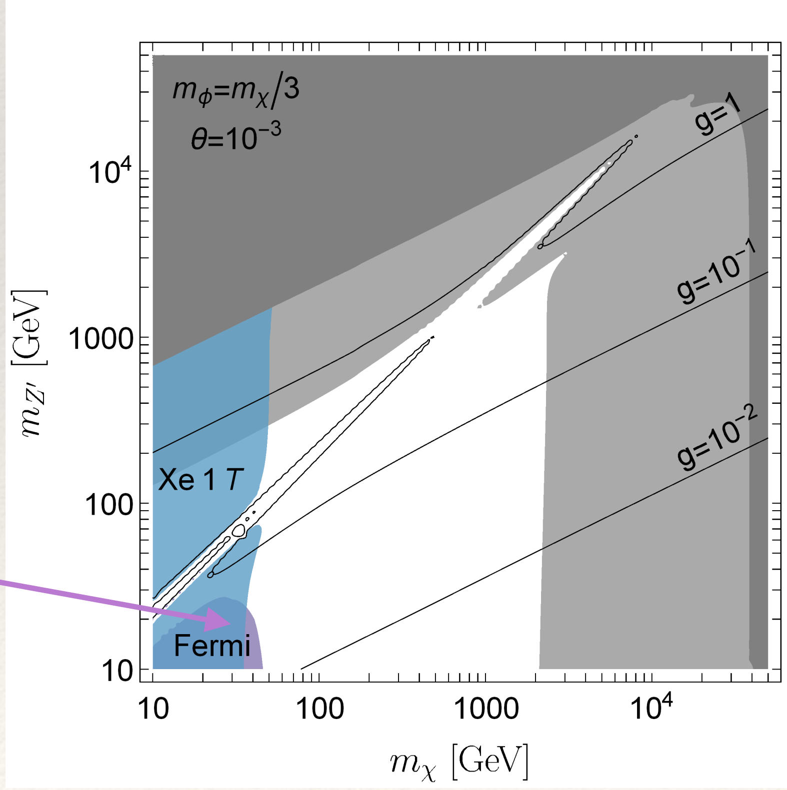
For $\chi\chi \to \phi Z'$

- Multibody SM final state(eg. bbbb)
- Significant Br into neutrino

→ Current Fermi dwarf limits very weak

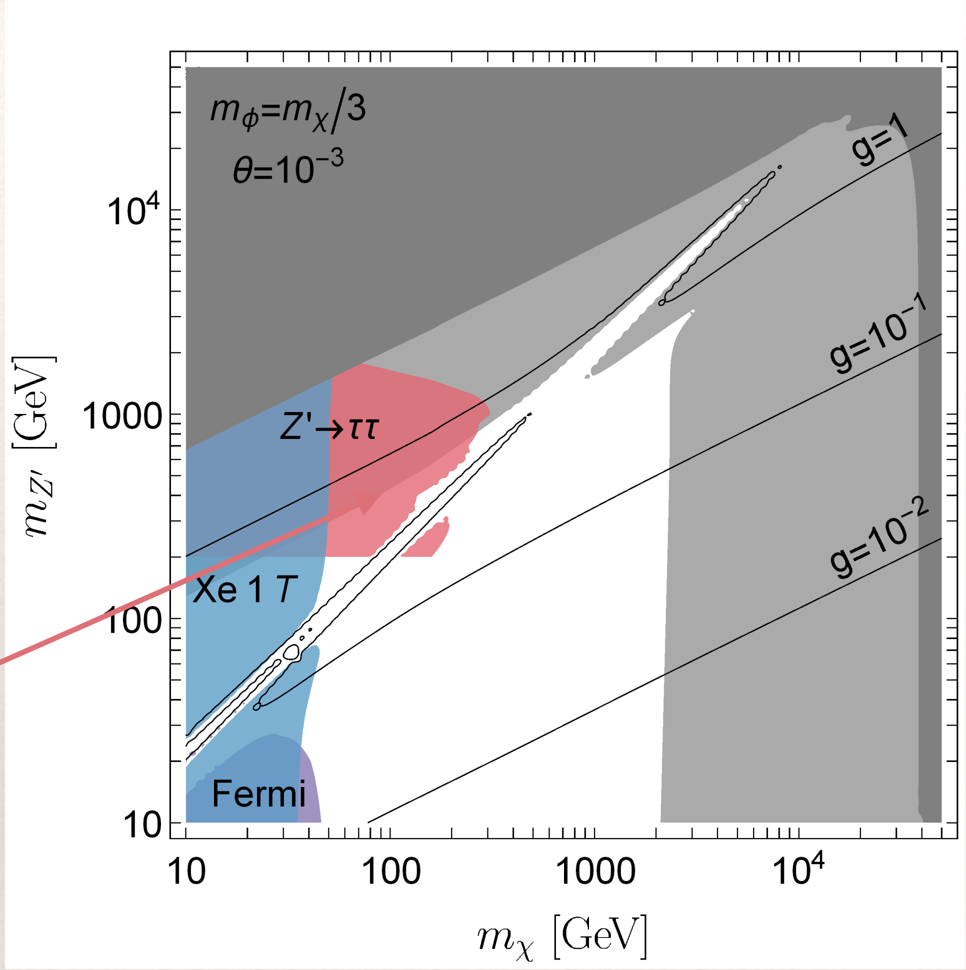
Fermi-LAT 1611.03184





Collider searches

- Cross section is suppressed. Main production channels from $b\bar{b} \to Z'$
- tau tau channel is less sensitive to the normal dilepton search(assuming small mixing in lepton sector)



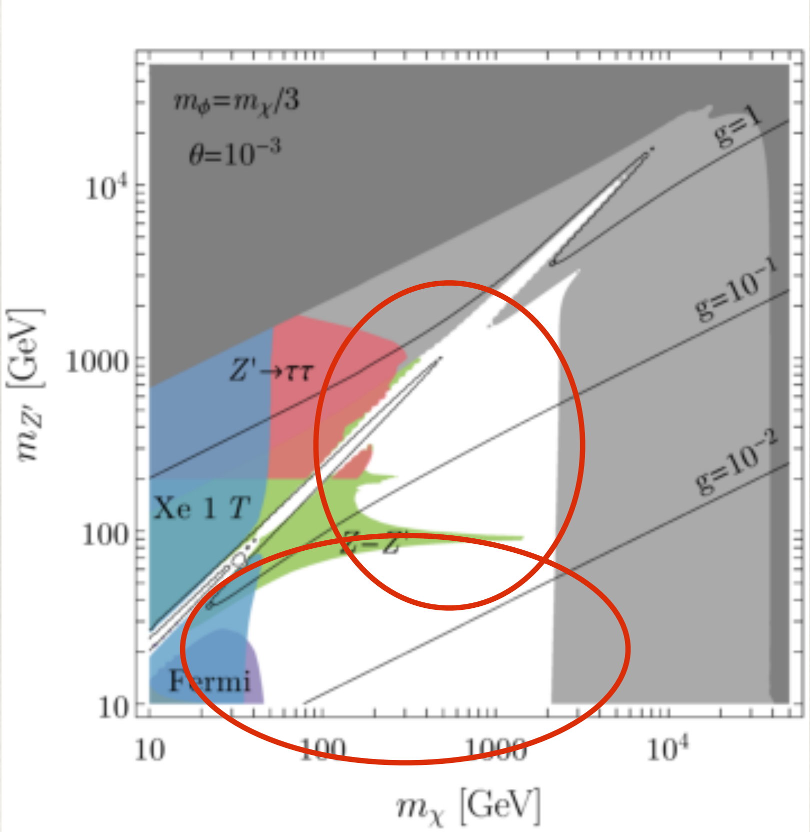
$Z - Z'$ mixing

- Kinematics mixing:

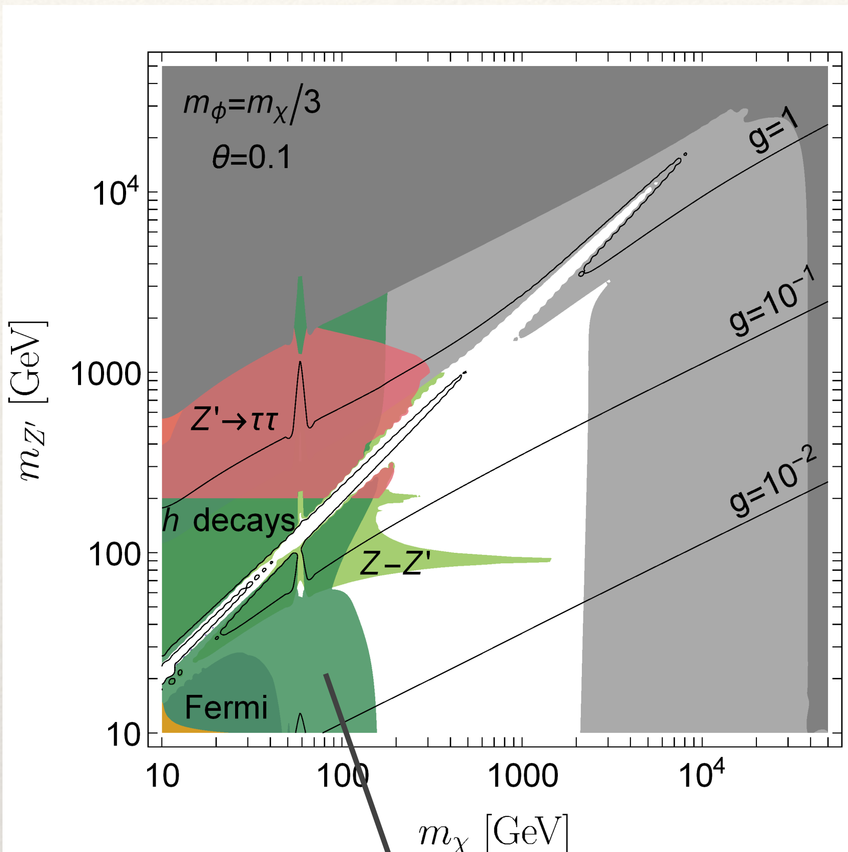
- Generated by RGE evolution, even if vanishing at high scales

$$\epsilon(\mu) = \frac{2 g_Y g}{9\pi^2} \log\left(\frac{\Lambda}{\mu}\right),$$

Large viable parameter region except the resonance region

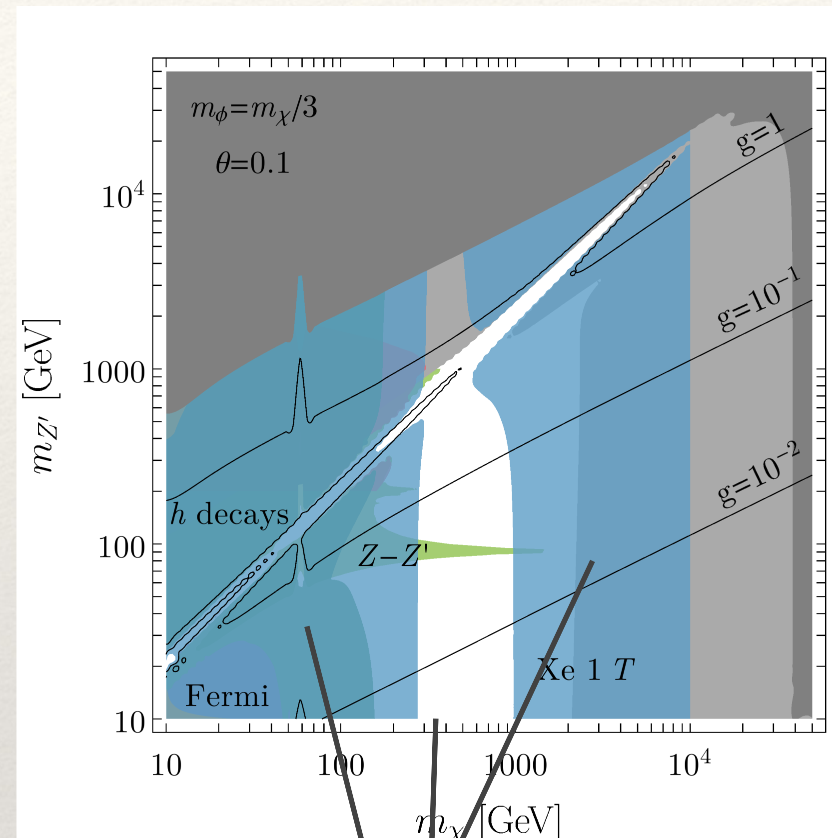


Different mixing angle



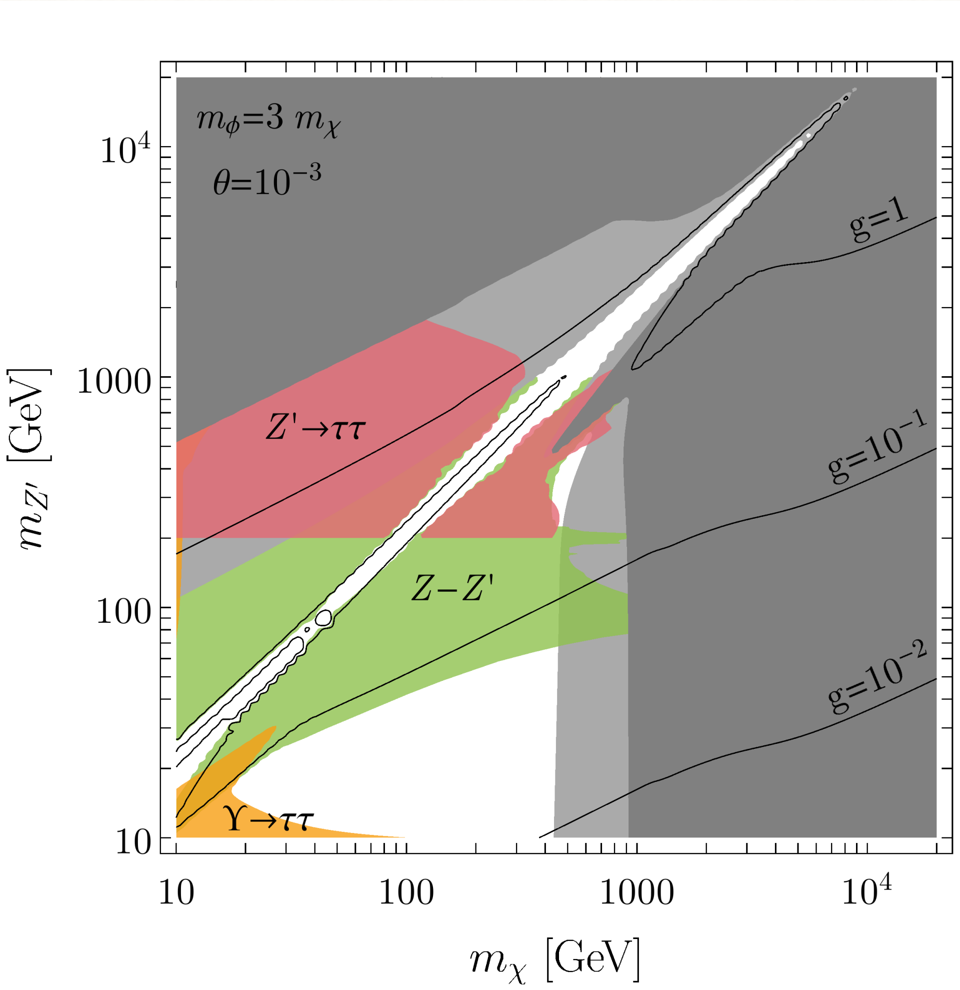
Higgs decay

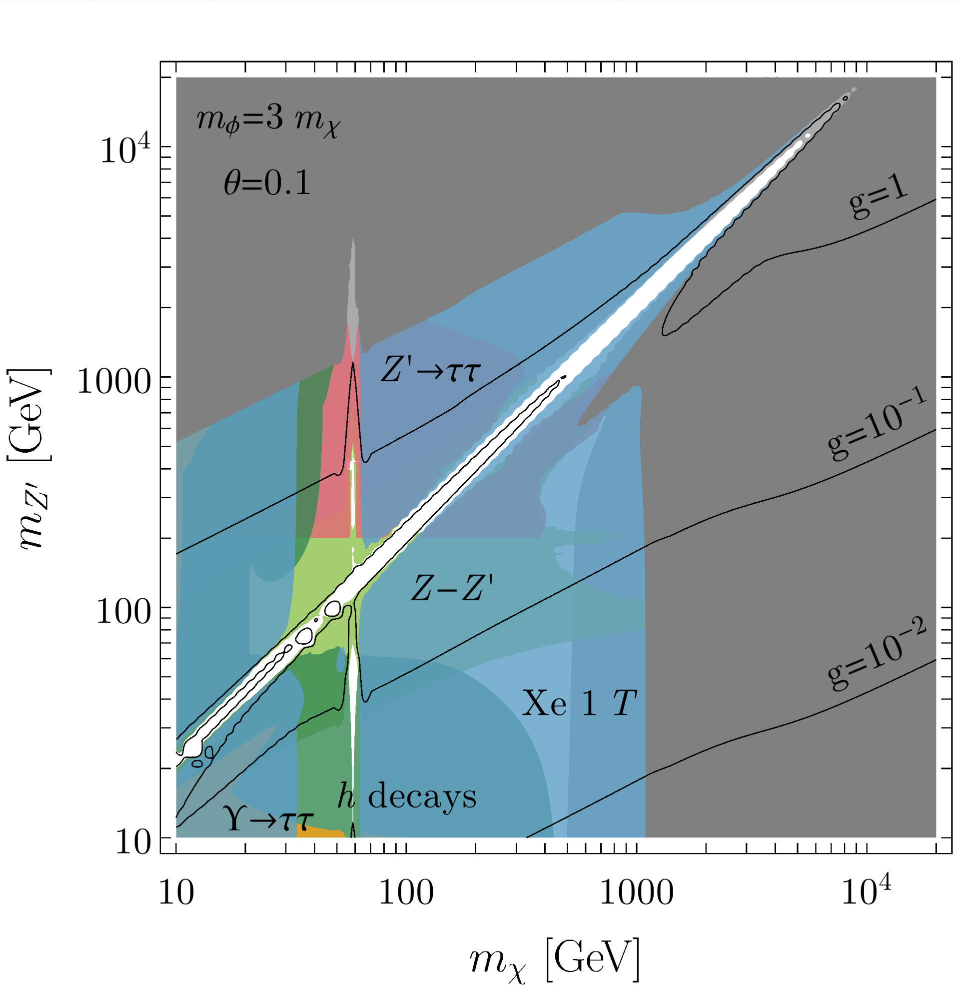
Direct search



Direct search rather strong cancelation when $m_h \sim m_\phi$

Different mass relation

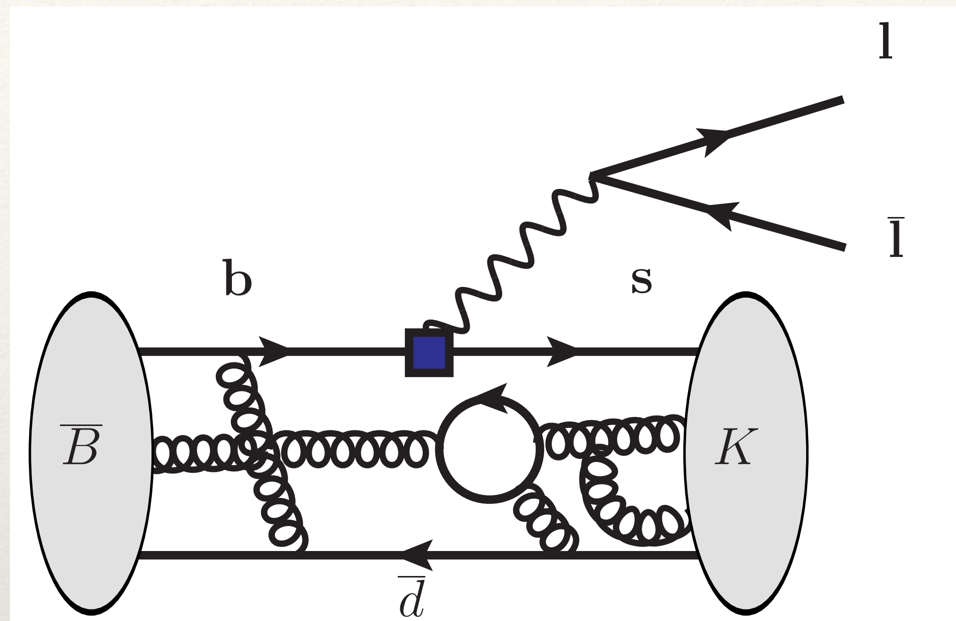




Larger gauge coupling is needed. Stronger limit.

Connection with flavor physics

B decay anomaly



$$R_K = \frac{Br(B \to K\mu\mu)}{Br(B \to Kee)}_{[1,6]} = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036((\text{syst})$$

LHCb arXiv:1406.6482

$$R_{K^*} = \frac{Br(B \to K^*\mu\mu)}{Br(B \to K^*ee)}_{[1,6]} = 0.69^{+0.11}_{-0.07}(\text{stat}) \pm 0.05((\text{syst})$$

LHCb arXiv:1705.05802

$$_{[0.05,1]} = 0.66^{+0.11}_{-0.07}(\text{stat}) \pm 0.024(\text{syst})$$

Combined ~4sigma tension with SM(RSM=1)

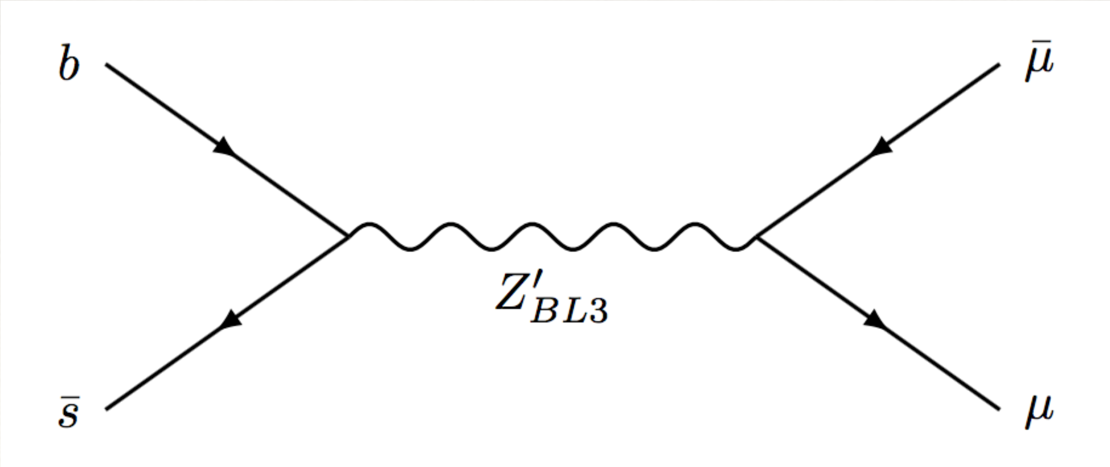
B decay anomaly

$$\mathcal{O}_9^l = \frac{\alpha}{4\pi} (\bar{s}\gamma_\mu b_L)(\bar{l}\gamma_\mu l) \,,$$

$$\mathcal{O}_{10}^l = \frac{\alpha}{4\pi} (\bar{s}\gamma_\mu b_L)(\bar{l}\gamma_\mu \gamma^5 l) \,,$$

$$\mathcal{O}_\nu^{ij} = \frac{\alpha}{2\pi} (\bar{s}\gamma_\mu b_L)\left(\bar{\nu}^i \gamma_\mu \nu_L^j\right) \,.$$

Coeff.	best fit	1σ	2σ	pull
C_9^μ	-1.59	$[-2.15,\ -1.13]$	$[-2.90,\ -0.73]$	4.2σ
C_{10}^μ	$+1.23$	$[+0.90,\ +1.60]$	$[+0.60,\ +2.04]$	4.3σ
C_9^e	$+1.58$	$[+1.17,\ +2.03]$	$[+0.79,\ +2.53]$	4.4σ
C_{10}^e	-1.30	$[-1.68,\ -0.95]$	$[-2.12,\ -0.64]$	4.4σ
$C_9^\mu = -C_{10}^\mu$	-0.64	$[-0.81,\ -0.48]$	$[-1.00,\ -0.32]$	4.2σ
$C_9^e = -C_{10}^e$	$+0.78$	$[+0.56,\ +1.02]$	$[+0.37,\ +1.31]$	4.3σ
$C_9'^\mu$	-0.00	$[-0.26,\ +0.25]$	$[-0.52,\ +0.51]$	0.0σ
$C_{10}'^\mu$	$+0.02$	$[-0.22,\ +0.26]$	$[-0.45,\ +0.49]$	0.1σ
$C_9'^e$	$+0.01$	$[-0.27,\ +0.31]$	$[-0.55,\ +0.62]$	0.0σ
$C_{10}'^e$	-0.03	$[-0.28,\ +0.22]$	$[-0.55,\ +0.46]$	0.1σ



B decay anomaly

To explain the anomaly, we just naive assume:

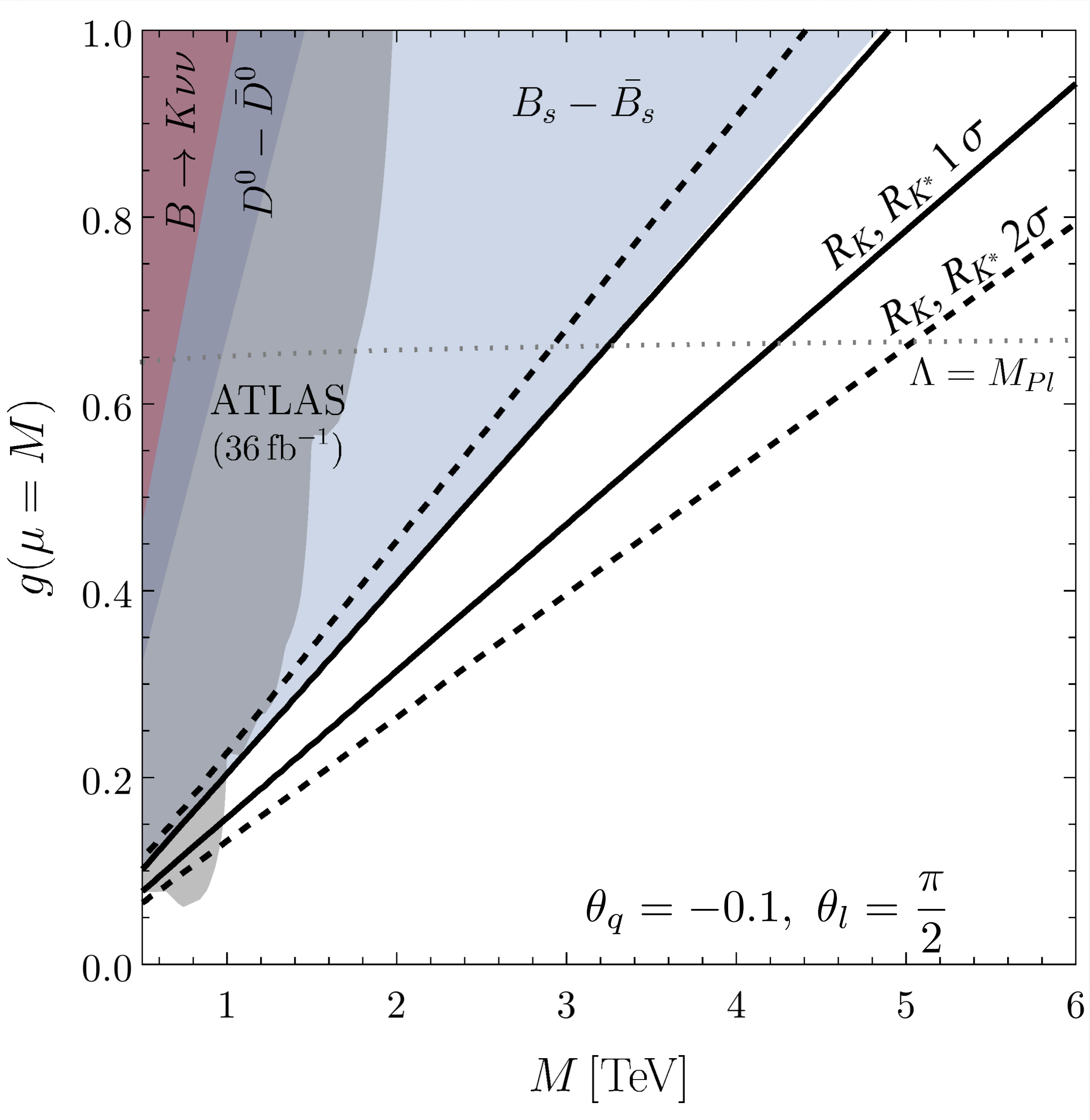
$$U_{e_L} = R^{23}(\theta_l), \quad U_{\nu_L} = R^{23}(\theta_l) U_{PMNS},$$
$$U_{d_L} = R^{23}(\theta_q), \quad U_{u_L} = R^{23}(\theta_q) V^\dagger_{CKM}$$

$$T_{d_L} = U^\dagger_{d_L} T^q U_{d_L} = \frac{1}{3} \begin{pmatrix} 0 & 0 & 0 \\ 0 & s^2_{\theta_q} & \boxed{-s_{\theta_q} c_{\theta_q}} \\ 0 & -s_{\theta_q} c_{\theta_q} & c^2_{\theta_q} \end{pmatrix}$$

$$T_{e_L} = U^\dagger_{e_L} T^l U_{e_L} = -1 \begin{pmatrix} 0 & 0 & 0 \\ 0 & \boxed{s^2_{\theta_l}} & -s_{\theta_l} c_{\theta_l} \\ 0 & -s_{\theta_l} c_{\theta_l} & c^2_{\theta_l} \end{pmatrix}$$

- To explain the B anomaly, we need opposite sign coupling with b-s and mu-mu
- If assuming $U_{d_L} = V_{CKM}$, it will give wrong sign!

Results

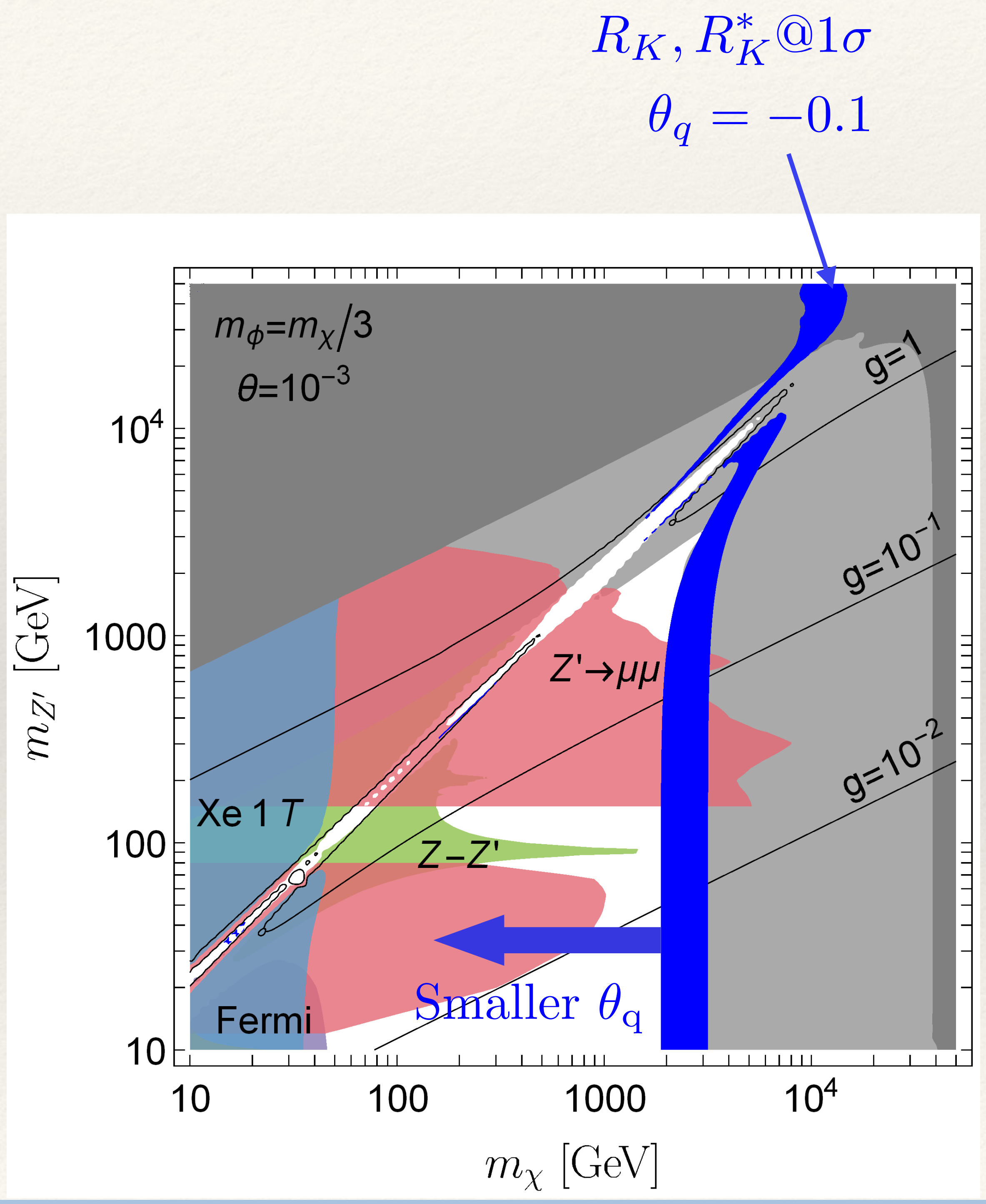


Rodrigo Alonso, Peter Cox, Chengcheng Han, Tsutomu T. Yanagida, arXiv:1705.03858

Dark matter & B anomaly

Can we explain B anomaly & dark matter

- smaller mixing angle is preferred
- stronger limits from mu mu channel



Summary

- A simple gauge extension of SM still survive.
- The right hand neutrino could be the dark matter candidate.
- The collider search and dark matter direct search are weak in this model. Dark matter indirect search may help.
- It could explain the B anomaly at the same time

The end!

Thanks!