Unusual WIMP Dark Matter

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(2) Direct Detection of WIMPs

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(5) Summary

Weakly Interacting Massive Particles (WIMPs)

χ: generic DM particle, n_χ its number density. Assume $\chi = \bar{\chi}$, i.e. $\chi\chi \leftrightarrow$SM particles is possible, but single production of χ is forbidden by some symmetry.

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Evolution of n_χ determined by Boltzmann equation:

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma_{\rm ann} v \rangle \left(n_\chi^2 - n_{\chi,\,\rm eq}^2 \right)$$

H Hubble parameter; $\langle \ldots \rangle$: Thermal averaging
$\sigma_{\rm ann} = \sigma(\chi\chi \to {\rm SM})$
v : relative velocity between χ's in their cms
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Gives

$$\Omega_\chi h^2 \propto \frac{1}{\langle v \sigma_{\rm ann} \rangle} \sim 0.1 \text{ for } \sigma_{\rm ann} \sim \text{pb}$$

Estimating the required coupling

Case 1: $m_\chi >$ mediator mass M_M

$\sigma_{\rm ann} \sim \frac{\alpha^2}{m_\chi}^2$ $\quad \alpha$: some couplings ($\neq \alpha_{\rm em}$, usually)

$\sigma_{\rm ann} \sim 1$ pb $\simeq 2.5 \cdot 10^{-9}\ {\rm GeV}^{-2} \Longrightarrow \alpha \sim 5 \cdot 10^{-3} \frac{m_\chi}{100\ {\rm GeV}}$

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Direct WIMP detection

Look for elastic scattering of ambient WIMPs off nuclei; signal: nuclear recoil. No (reproducable) signal has been found.

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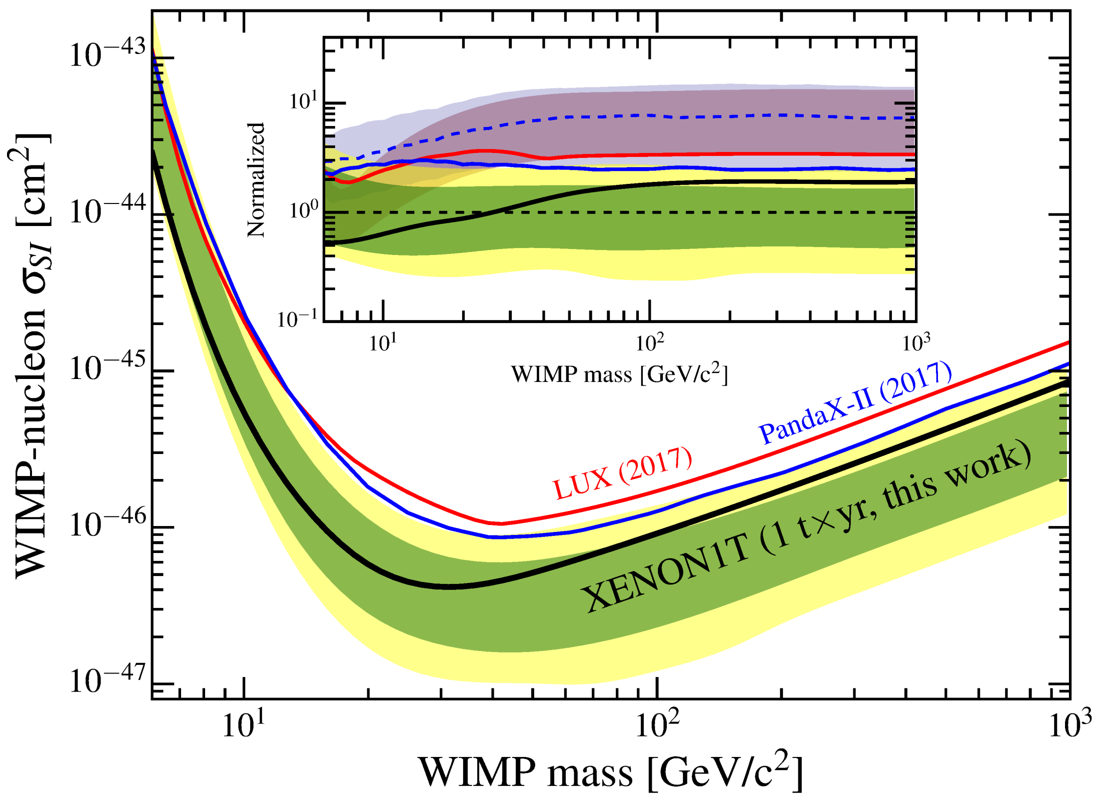
Current best bound: XENON1T collab., arXiv:1805.12562



Direct WIMP Searches (cont'd)

If scattering proceeds via mediator with same coupling α:

$$\sigma(\chi N \to \chi N) \sim \frac{\alpha^2 \mu^2}{M_m^4} \qquad \mu = \frac{m_\chi m_N}{m_\chi + m_N} \simeq m_\chi$$

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Experimental bound

For $m_\chi \gtrsim 50$ GeV:

$$\sigma_{\chi N} \leq \frac{m_\chi}{100 \text{ GeV}} \cdot \begin{cases} 10^{-10} \text{ pb}, & \text{spin indep.} \\ 10^{-5} \text{ pb}, & \text{spin dep.} \end{cases}$$

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(*iii*) Decouple mediator from light quarks!

A Very Heavy Thermal WIMP

MD, F. Gomes Ferreira, JHEP 1904 (2019) 167

Enhance annihilation cross section through resonance: $m_\chi \simeq M_m/2$! For complex scalar WIMP: need scalar mediator. For Majorana fermion WIMP: need pseudoscalar mediator.

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Can be realized in [$E(6)$ motivated] $U(1)'$ extended MSSM!

$\tilde{\nu}_R$ in $U(1)$ Extended MSSM

(Reasonably) well motivated model:

MSSM $+\nu_R$ Superfield (SM singlet) $+E(6)$ inspired $U(1)$, broken by SM singlet N

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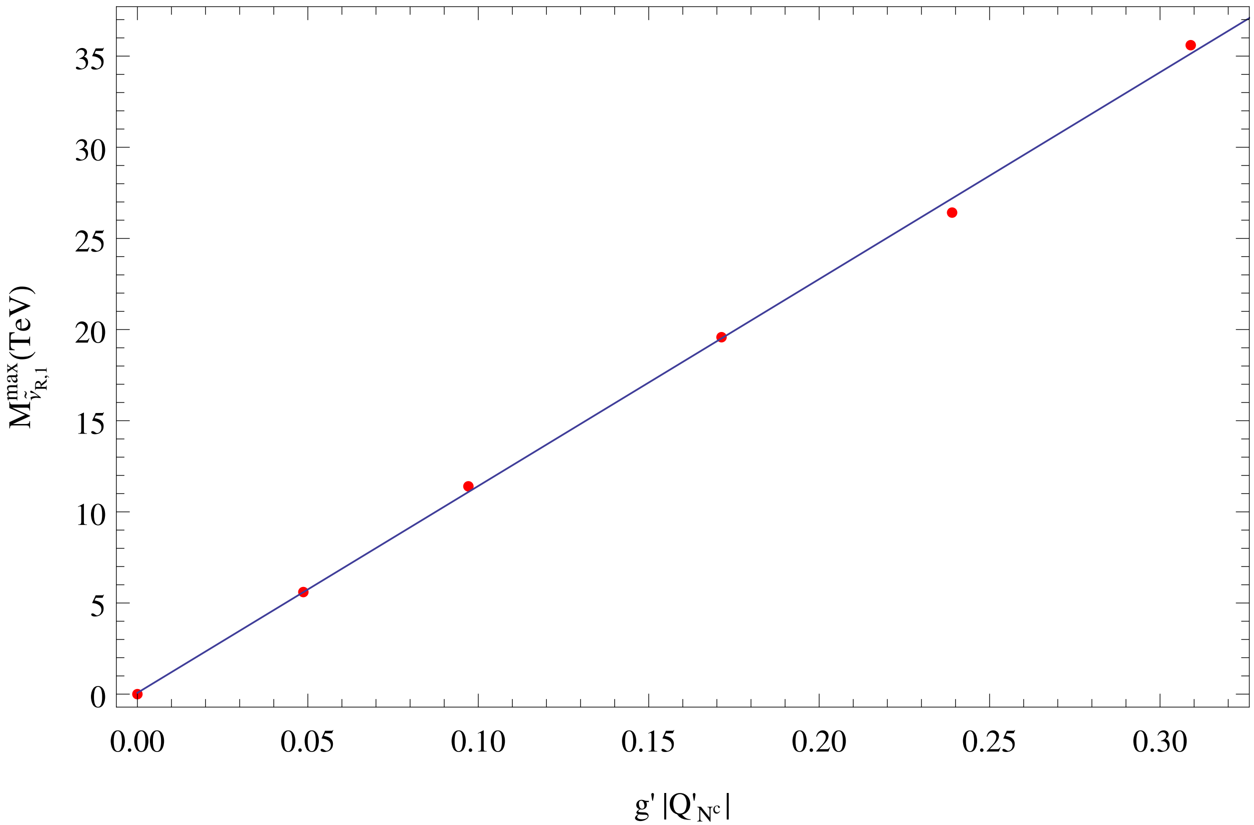
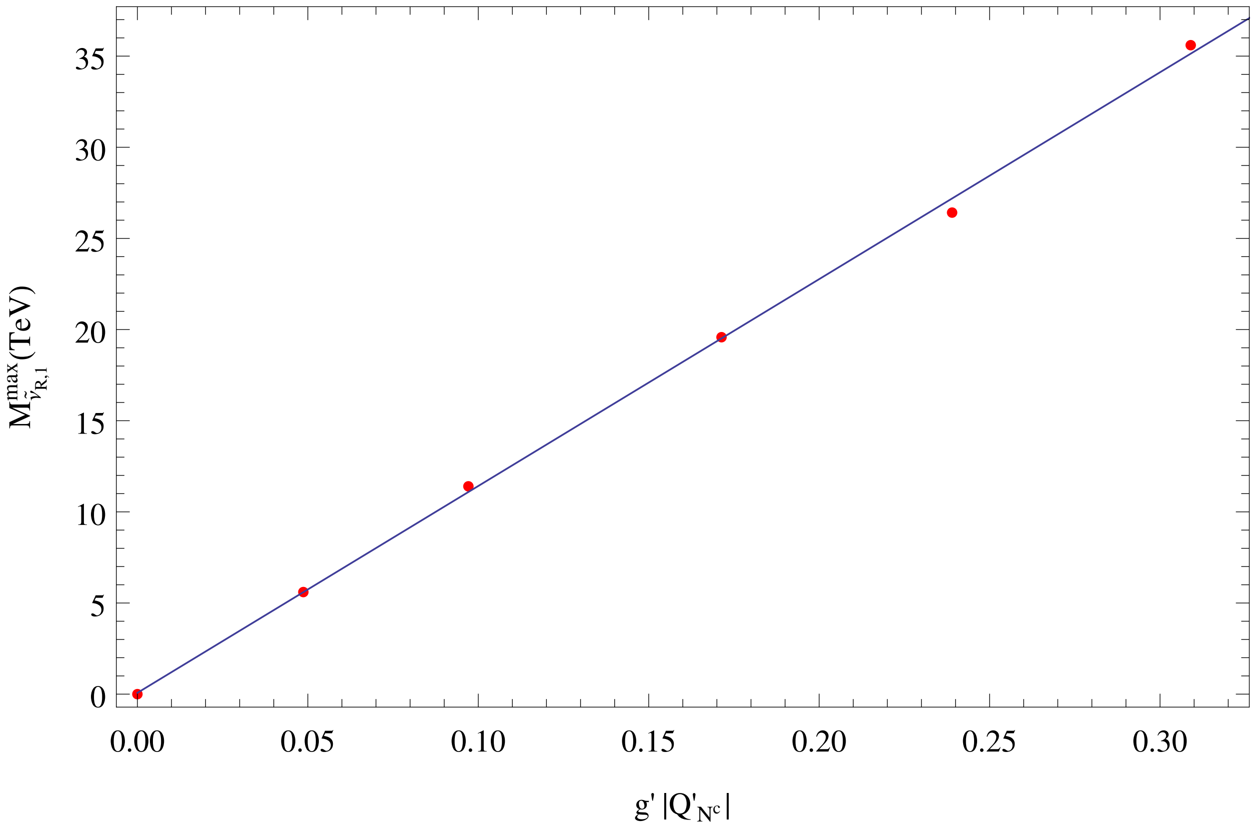
Relic density minimized, if N coupling to final state $\simeq g_{N\tilde{\nu}_R\tilde{\nu}_R^*}$: achieved by tuning doublet Higgs masses

Result



35
30
25
20
15
10
5
0
0.00
0.05
0.10
0.15
0.20
0.25
0.30
$M^{max}_{\tilde{\nu}_{R,1}}$(TeV)
g' |Q'$_{N^c}$|

Result



Allows $m_{\tilde{\nu}_R}$ up to 35 TeV!

Testing this model

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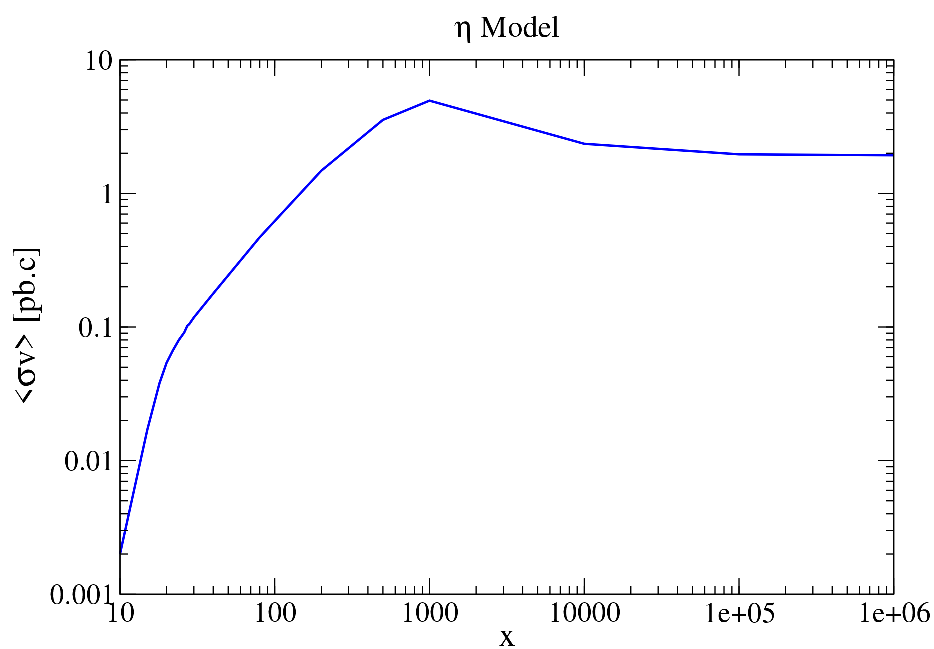
- Cross section for indirect detection (WIMP annihilation in halo of galaxies) can be enhanced!



Mediator Coupling to Heavy Quarks

MD, Z. Zhang, arXiv:1903.00496

- Vector couplings: Leads to spin–indep. interaction
  $\Longrightarrow$ Only couplings to u, d have to vanish
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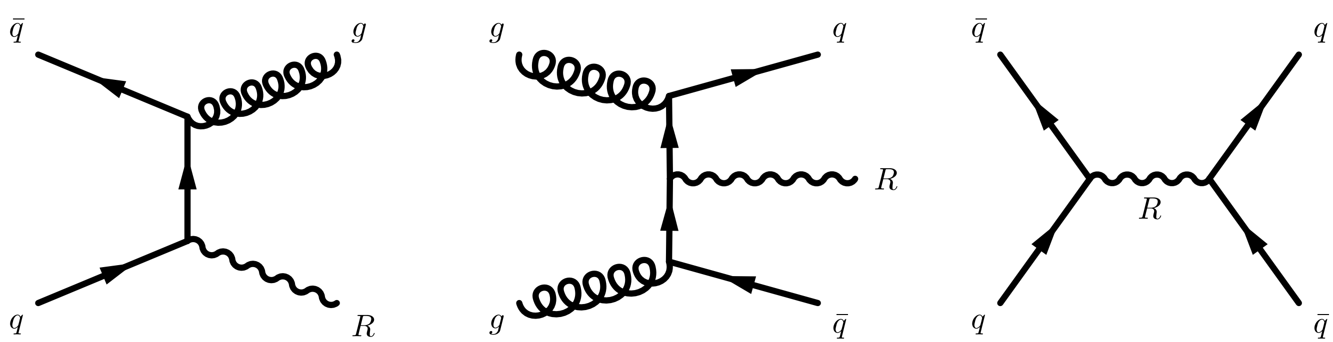
- Best way to test this: LHC!



LHC constraints

Mediator couples to $b\bar{b} \Longrightarrow$ searches with $b-$tag are most sensitive! (`CheckMate` says so.)

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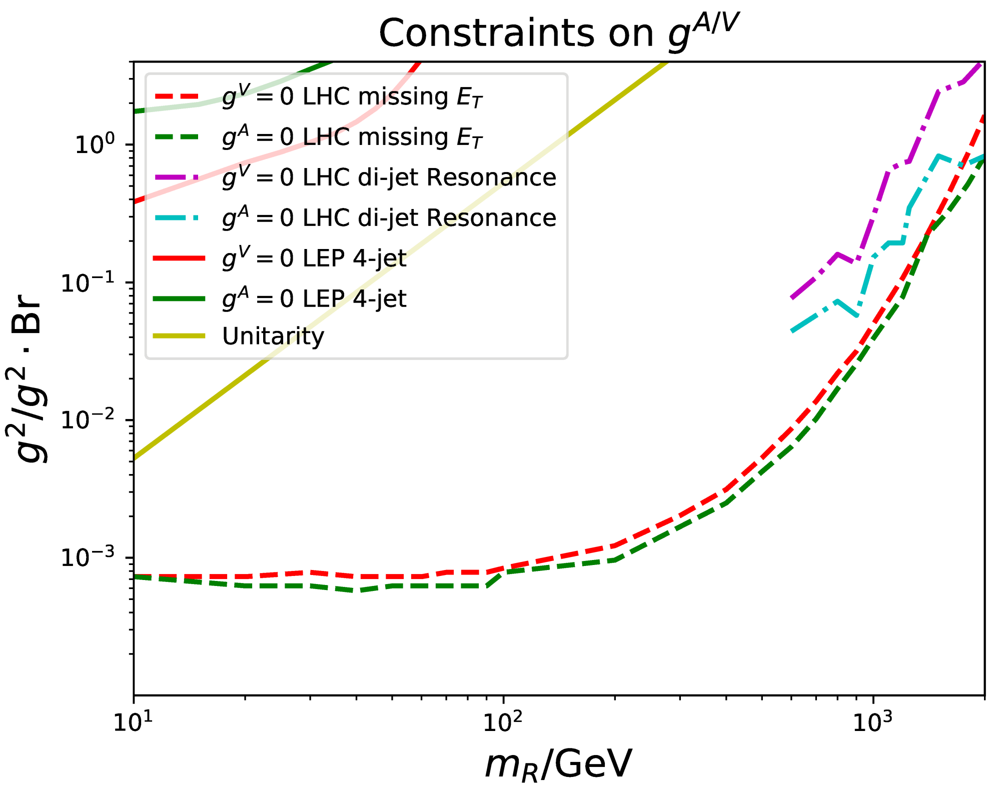
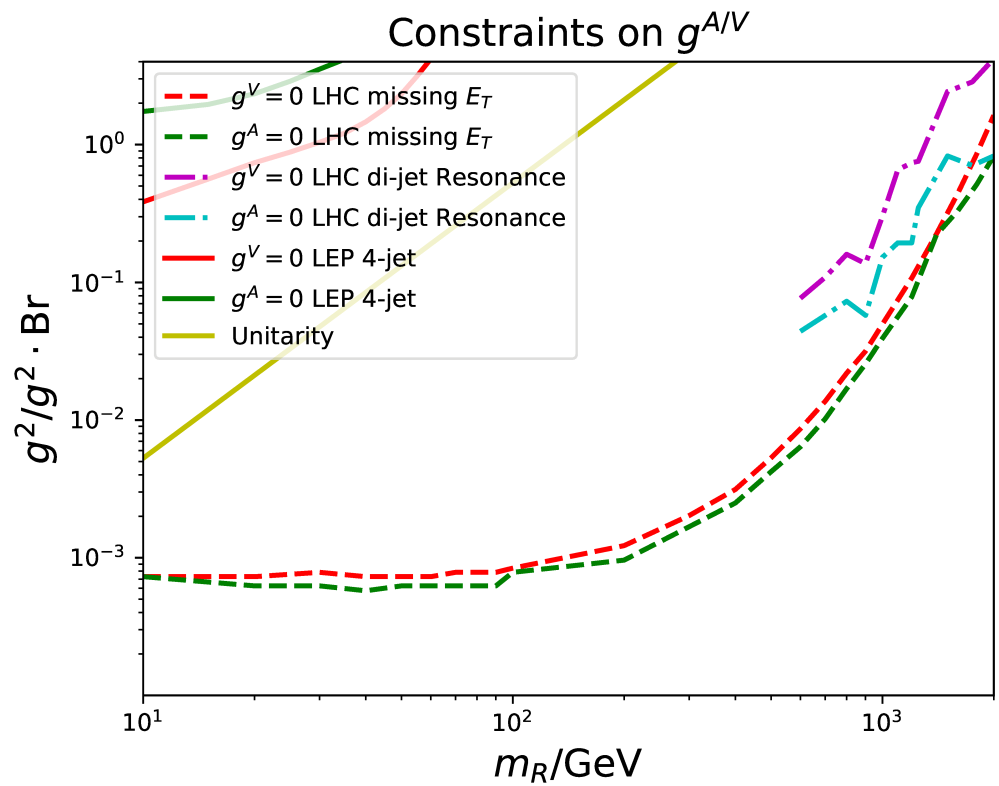
- For mediator decay into $b\bar{b}$: Search for $b\bar{b}$ resonance (ATLAS)
- For mediator decay into WIMPs: Search for $b\bar{b}$ plus missing E_T (ATLAS)

Results



Constraints on $g^{A/V}$
$g^V = 0$ LHC missing E_T
$g^A = 0$ LHC missing E_T
$g^V = 0$ LHC di-jet Resonance
$g^A = 0$ LHC di-jet Resonance
$g^V = 0$ LEP 4-jet
$g^A = 0$ LEP 4-jet
Unitarity
$g^2/g^2 \cdot \mathrm{Br}$
10^0
10^{-1}
10^{-2}
10^{-3}
10^1
10^2
10^3
m_R/GeV

Results



Search for WIMP pair final state competitive with “pure mediator” search!

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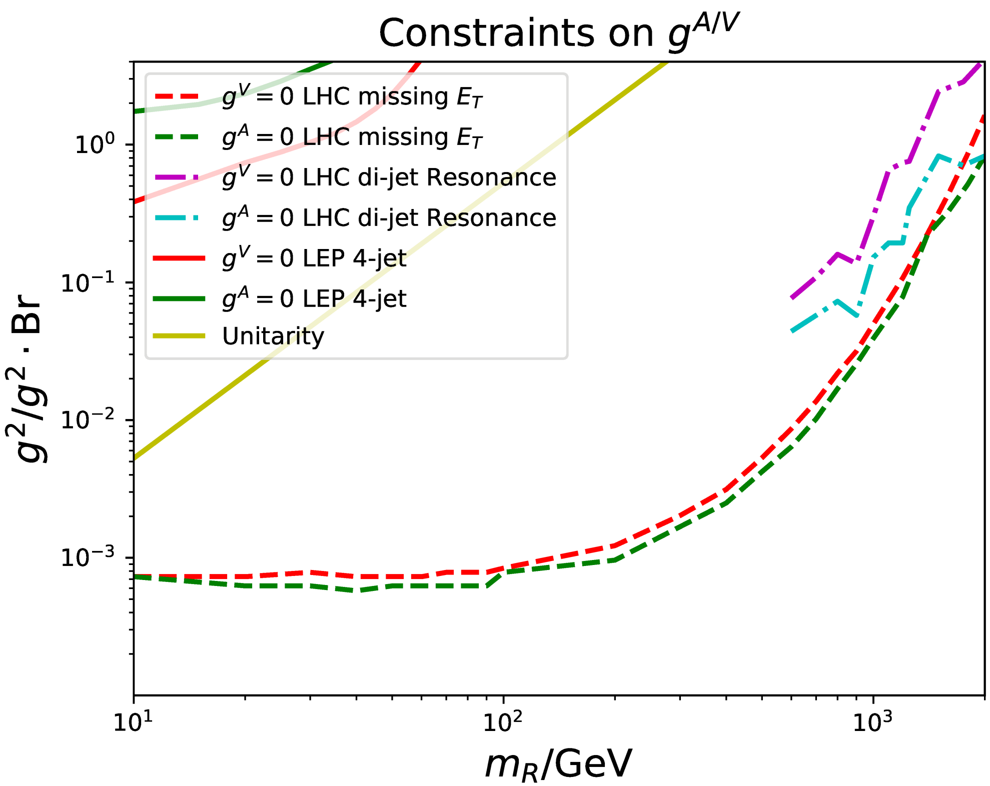

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Search for boosted $b\bar{b}$ resonance $+$jet would be helpful for $m_R < 0.6$ TeV.

$L_\mu - L_\tau$ **Mediator**

MD, M. Shi, Z. Zhang, Phys. Lett. B791 (2019) 130

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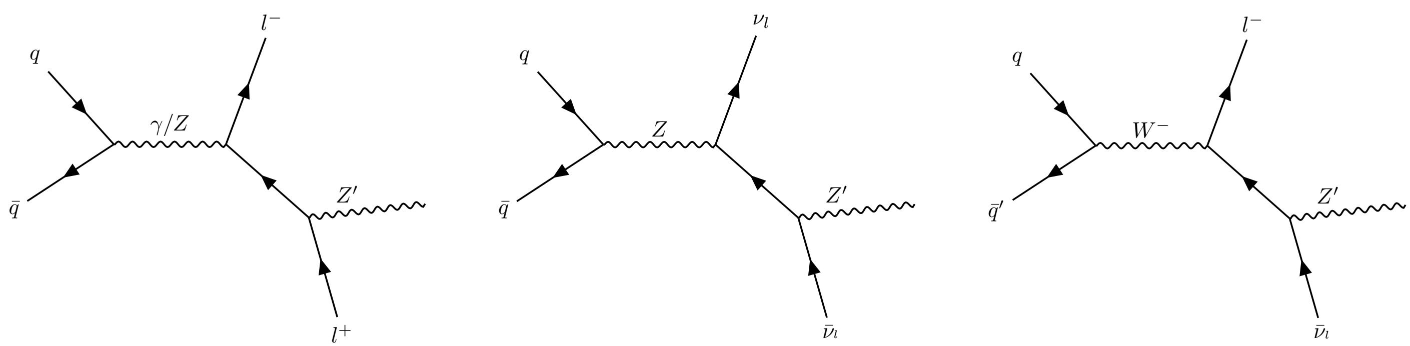
- No significant constraint from e^+e^- colliders
- Hence, search at LHC again!



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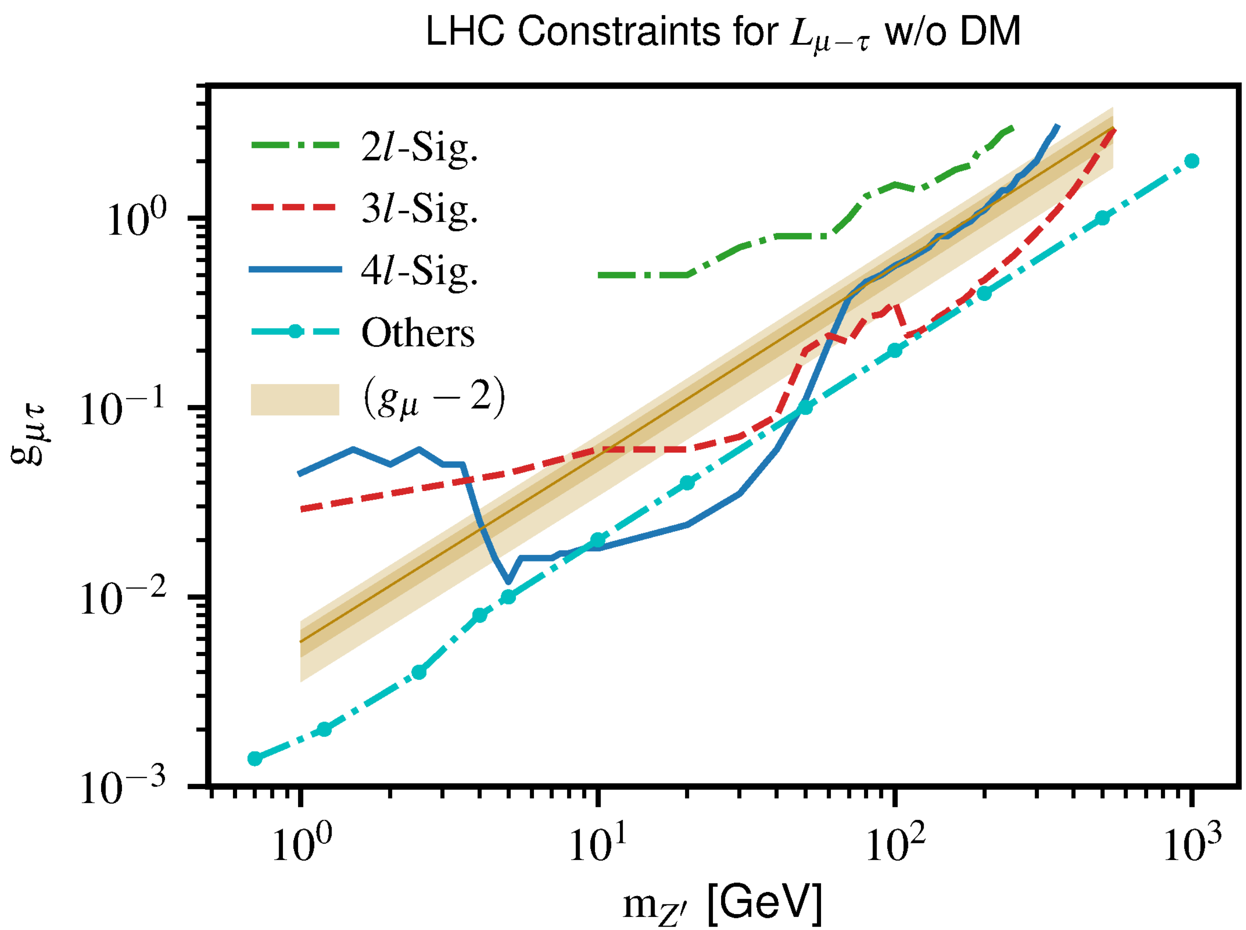
- Final states with single charged lepton useless (huge Drell–Yan background)
- Replacing $\mu^\pm$ by $\tau^\pm$ makes things worse $\Longrightarrow$ maximize number of muons!

Results


LHC Constraints for $L_{\mu-\tau}$ w/o DM
$2l$-Sig.
$3l$-Sig.
$4l$-Sig.
Others
$(g_\mu - 2)$
$g_{\mu\tau}$
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{0}
10^{1}
10^{2}
10^{3}
$m_{Z'}$ [GeV]

Results (cont'd)

- Except $Z \to \mu^+\mu^- Z' \to 4\mu$ search (CMS), searches are not optimized: no better than old "trident" search, $\nu_\mu N \to \nu_\mu \mu^+\mu^- N$ (CHARM, CCFR).

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- Sensitivity to invisible Z' decays, in particular $Z' \to$ WIMPs, is not very good
- Model might also be testable through heating of old neutron stars! R. Garani, J. Heeck, arXiv:1906.10145

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MD, R. Mehra

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- More generally, 13 different non–relativistic operators can contribute up to $\mathcal{O}(v^2)$ Fan, Reece, Wang 2010; Fitzpatrick et al. 2013; ...
- Some operators scale like $3-$mom. transfer $q/m_p \sim 0.1$, not like $v \sim 10^{-3}$: constraint can be comparable to usual spin–dep. one!

However...

- Lorentz–invariant operators that generate these new operators in non–relat. limit generically also generate traditional spin–indep. operator: completely dominates unless its coefficient is "accidentally" suppressed *by cancellation* by about 1 part in 10^3.

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- Relevant operators are $P-$ and $T-$odd $\Longrightarrow$ corresponding Lorentz–invariant operators violate CP, often give rise to neutron EDM; resulting bound makes WIMP scattering unobservable.

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- $U(1)'$ extended MSSM allows thermal $\tilde{\nu}_R$ WIMP with mass in excess of 30 TeV
- LHC searches for mediators not coupling to first generation quarks are not very strong; few dedicated searches as yet $\Longrightarrow$ can quite easily build models with $\mathcal{O}(100)$ GeV WIMPs!
- Motivation for “general WIMP NREFT” is weak.