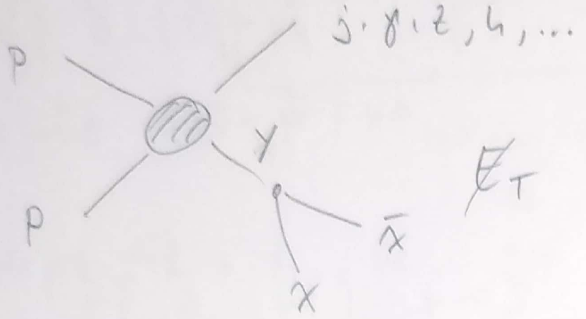
Dark Matter Pheno

Focus: DM models for collider searches

What does this mean?

Mediator masses with $M \sim 100$ GeV $- 1$ TeV



Assume: Fermion-DM

In ancient times: EFTs

Scalar $\quad \frac{c_S}{\Lambda^2} (\bar{q} q)(\bar{\chi}\chi)$

pseudoscalar $\quad \frac{c_P}{\Lambda^2} (\bar{q} \gamma_5 q)(\bar{\chi}\gamma_5\chi)$

vector $\quad \frac{c_V}{\Lambda^2} (\bar{q} \gamma_\mu q)(\bar{\chi}\gamma^\mu\chi)$

axial-vector $\quad \frac{c_A}{\Lambda^2} (\bar{q} \gamma_5\gamma_\mu q)(\bar{\chi}\gamma_5\gamma^\mu\chi)$

[Nuclear matrix elements:

S: $\langle \underset{s'}{\psi_f} | \bar{\psi}\psi | \underset{s}{\psi_i} \rangle \sim 2 m_\psi (\xi_\psi^{s'})^\dagger \xi_\psi^s$

P: $\langle \psi_f | \bar{\psi}\gamma_5 \psi | \psi_i \rangle \sim (\xi_\psi^{s'})^\dagger [\vec{p}_f - \vec{p}_i] \cdot \vec{\sigma}\, \xi_\psi^s$

$m_\psi (\vec{v}_f - \vec{v}_i) \quad \Delta\vec{v} = 10^{-3}$

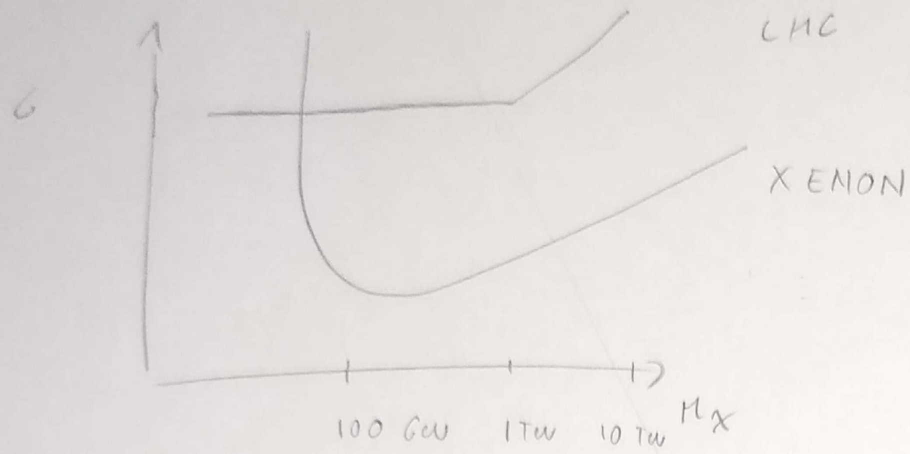
A: $\langle \psi_f | \bar{\psi}\gamma^0\gamma^5 \psi | \psi_i \rangle \sim 0$

$\langle \psi_f | \bar{\psi}\vec{\gamma}\gamma^5 \psi | \psi_i \rangle \sim 2 m_\psi\, (\xi_\psi^{s'})^\dagger \vec{\sigma}\, \xi_\psi^s$

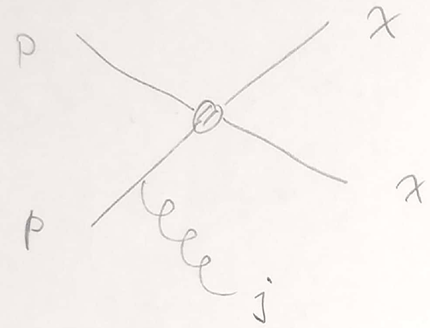
For $\psi = N$ (Nucleon) both pseudoscalars and axial-vectors lead to spin-dependent amplitudes.

DIENES, KUMAR 1312.7772
HOOPER, MCDERMOTT 1404.0022

LHC Bounds



independent of the DM mass, because $\cancel{E}_T$ is determined by the boost



Resolve ⊘ : Simplified models (Jeon Age)

Scalar : $y_\chi \bar{\chi} S \chi + y_q \bar{q} S q + \frac{1}{2} M_S^2 S^2$

Pseudoscalar : $y_\chi \bar{\chi} P \gamma_5 \chi + y_q \bar{q} P \gamma_5 q + \frac{1}{2} M_P^2 P^2$

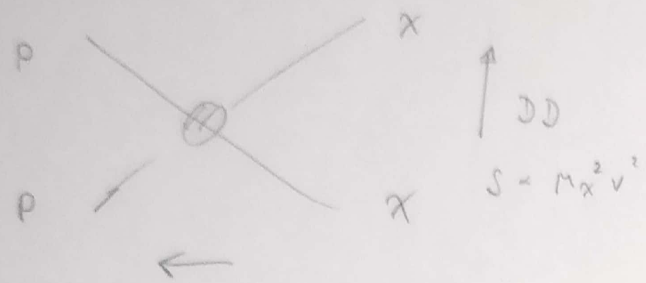
Vector : $g' Q_\chi \bar{\chi} Z'^\mu \gamma_\mu \chi + g' Q_q \bar{q} Z'^\mu \gamma_\mu q + M_{Z'}^2 Z'^2$

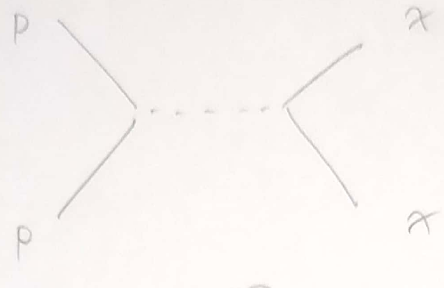
axial-vector : $g' Q_\chi \bar{\chi} A^\mu \gamma_\mu \gamma_5 \chi + g' Q_q \bar{q} A^\mu \gamma_\mu \gamma_5 q + M_A^2 A^2$

$C_P \sim y_\chi y_q \qquad \Lambda^2 \sim M_P^2$

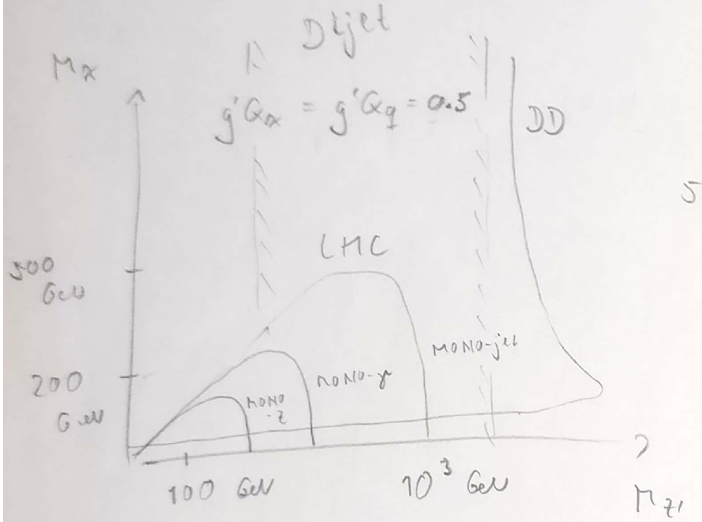
$C_V \sim g'^2 Q_\chi Q_q \qquad \Lambda^2 \sim M_{Z'}^2$

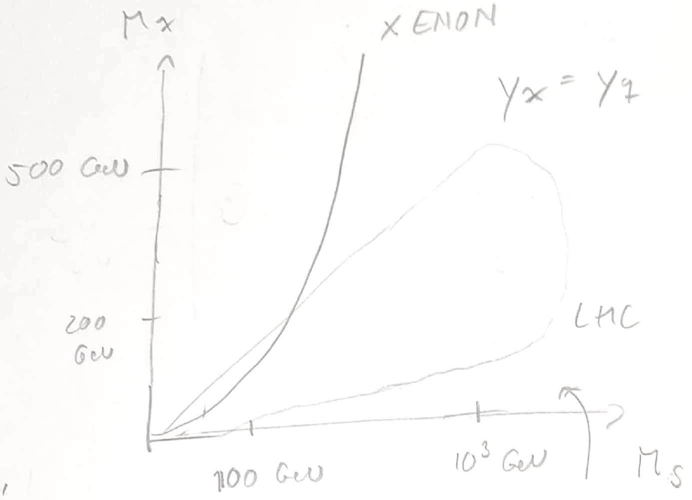
If $M_p < \sqrt{s}$ the mediator is produced on-shell at colliders. (This is likely for WIMP-like models)





DD, $s \propto 4M_\chi^2$ Col, s = com energy





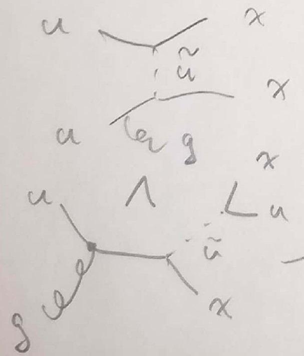
gap if $y_\chi \propto \frac{M_\chi}{v}$

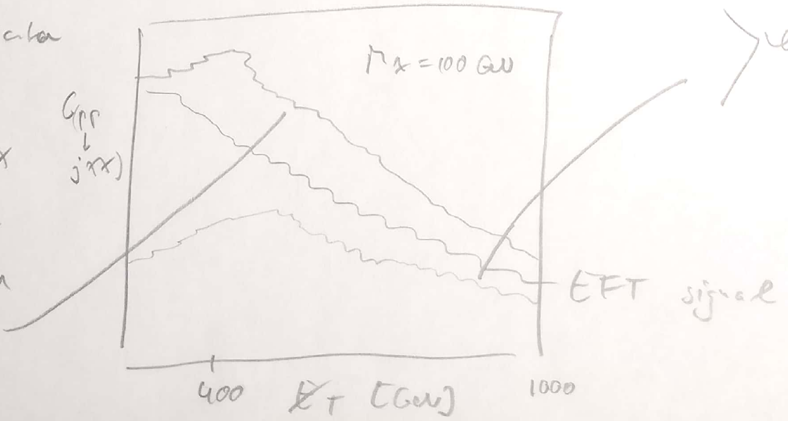
EG: [1411.0535 SPANNOWSKY, KHOZE]

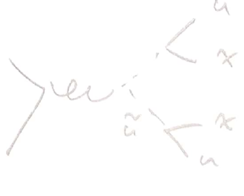
$\frac{\alpha}{\alpha_s}\frac{Q^2 s_w^2}{C_F}$ BR(Z→ll) $\sim 10^{-4}$ including Z-loss

Changes the signal beyond s-channel resonances [MB, BUTTER, DESAI et al. 1611.09908]

t-channel mediator







BUT, simplified models are inconsistent

Scalar: $y_q \bar{q} S q \leftarrow y_q \bar{Q} S q$ breaks $SU(2)$

either $y \frac{S}{\Lambda} \bar{Q} H q \to \left(y \frac{v}{\Lambda}\right) \bar{Q} S q$

$\qquad\qquad\qquad\qquad\qquad \overset{\shortparallel}{y_q} \ll 1$

or Higgs-Portal

$$y_\chi \bar{\chi} S \chi + \mu S H^\dagger H + y_q \bar{Q} H q$$

$$S \to -s_\alpha h + c_\alpha s \qquad \left(s_\alpha \sim \frac{\mu v}{m_S^2 - m_h^2} \right)$$

$$y_q = \sin\alpha \frac{m_q}{v}$$

$$g_{h\gamma\gamma} = \cos\alpha \, g_{h\gamma\gamma}^{SM} \Rightarrow \cos\alpha \gtrsim 0.9$$

stronger constraint than $\not{E}_T$ searches.

Axial-vector $\bar{q} A^\mu \gamma_\mu q \leftarrow \bar{q}_L A^\mu \gamma_\mu q_L - \bar{q}_R A^\mu \gamma_\mu q_R$

$$Q[q_L] = -Q[q_R] = +1$$

$$[\bar{q}_L H q_R] = [\bar{q}_L][H][q_R]$$

$$\qquad\qquad\qquad -1 \quad +2 \quad -1$$

couples to everything (dileptons, dijets, ...)

and there is no $U(1)_A$. Where can a single axial-vector come from?

$U(1)_L \times U(1)_R \to U(1)_A$ ↯

[This is also the reason why the axion is the axion]

$SU(2) \to U(1)_A$ ↯

$SU(2) \to \emptyset$ includes a Z', but what about the other states?

× Pseudoscalar $\quad \bar{Q}\, P \gamma_5 q \quad$ breaks $SU(2)$

either $\quad \dfrac{P}{\Lambda}\, \bar{Q} \gamma_5 H q \quad \supset \quad \dfrac{\partial_\mu P}{\Lambda} \left(\bar{Q} \gamma_\mu Q + \bar{q} \gamma_\mu q \right)$

$$Q \to e^{iP/2\Lambda}\, Q$$

Axion $\quad y_\chi \propto \dfrac{m_q}{\Lambda} \ll 1$

$$q \to e^{-iP/2\Lambda}\, q$$

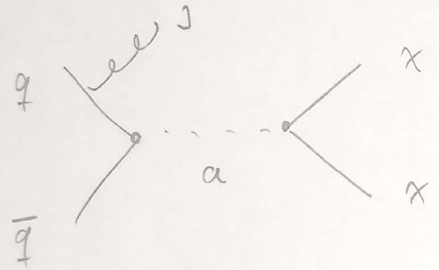
"pseudoscalar portal"

$$y_u \bar{u}_L H_1 u_R + y_d \bar{d}_L H_2 d_R + \mu P H_1 H_2 + \bar{\chi} P \chi$$

→ 2 pseudoscalars a, A and 2 scalars h, H

+ 1 charged scalar $H^\pm$

Now



vs.

or

The resonant enhancement makes the Mono-Higgs or Mono-Z the most important signal.

[Phase-space]

$$\sigma(q\bar{q} \to j a)\, BR(a \to \bar{\chi}\chi)$$

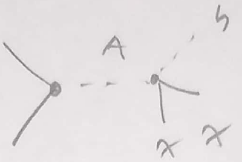
$$\sigma(q\bar{q} \to H)\, BR(H \to a Z)\, BR(a \to \bar{\chi}\chi)$$

[TB, HAISCH, KAHLHOEFER, 1701.07427]

Can it be decoupled?

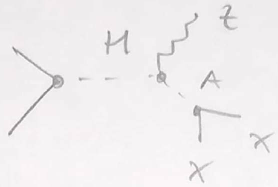
$M_P \to \infty$:

$$\mu P H_1 H_2 + y_\chi \bar\chi P \gamma_5 \chi + \tfrac{1}{2} M_P^2 \bar\chi \chi$$



$$\downarrow \quad \Lambda = \frac{\mu}{M_P^2} y_\chi$$

$$\frac{H_1 H_2}{\Lambda} \bar\chi \gamma_5 \chi$$



$$\uparrow \quad \Lambda = \frac{y_\chi y_\chi'}{M_\psi}$$

$$y_\chi \bar\chi H_1 \psi + y_\chi' \bar\chi \tilde H_2 \psi + M_\psi \bar\psi \psi$$

[MD, 1712.06597]

$M_\psi \to \infty$

But the mono-Z signal remains.

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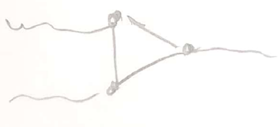
* Vectors $\quad \bar q Z'^\mu \gamma_\mu q \leftarrow \bar q_L Z'^\mu \gamma_\mu q_L + \bar q_R Z'^\mu \gamma_\mu q_R$

$Q[q_L] = Q[q_R] \Rightarrow$ Yukawa couplings ok.

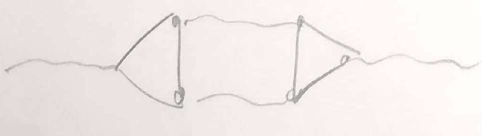
For a gauge boson $U(1)_X$ needs to be anomaly-free

$$\sum_{\text{fermions}}$$



$\overset{!}{=} 0$ for all gauge groups!

Otherwise the photon picks up a mass



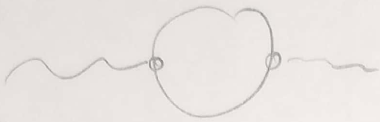
$\Rightarrow m_\gamma \neq 0$

[PRESKILL 1991]

No gauge-symmetry.

Easy $U(1)_X$, no SM-charges

$$\mathcal{L} \supset -\frac{1}{4} F_{\mu\nu}F^{\mu\nu} - \frac{\epsilon}{2} F_{\mu\nu}X^{\mu\nu} - \frac{1}{4} X_{\mu\nu}X^{\mu\nu}$$



Z $\quad$ Z' $\qquad$ $\epsilon \propto e g' Q_X Q_e \log\left(\frac{m_1}{m_2}\right)$

no strong suppression unless $g' \ll 1$

Z' couples like the Z. In this case: Dijet searches dominate.

What about charged SM fields?

(Anomaly cancellation is a strong constraint, otherwise new fermions at $M_N \propto y\langle S\rangle$, $M_{Z'} \propto g'\langle S\rangle$)

Baryon number $\quad U(1)_B \quad$ ↯

Lepton number $\quad U(1)_L \quad$ ↯

$U(1)_{B-L}$ + 3 right-handed neutrinos

Pheno of a $U(1)_{B-L}$ Z' is very similar to the $U(1)_X$ Z'.

Also $\quad U(1)_{B_2-B_3}$ ✓

but...

$$\mathcal{L} \supset \bar{Q}_i \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & \times \end{pmatrix} H q_j$$

$U_L, D_L \sim \mathbb{1} \qquad U_R, D_R \sim \mathbb{1}$

$V_{CKM} \propto U_L^\dagger D_L = \mathbb{1}$ ↯

Needs extra scalars & extra fermions at $M_N \approx y\langle S\rangle$ again.

For leptons $\quad U(1)_{L_\mu - L_\tau}$ ✓

$$\mathcal{L} \supset \bar{L}_i \begin{pmatrix} \times & & \\ & \times & \\ & & \times \end{pmatrix} \tilde{H}\, \ell_j$$

add right-handed neutrinos

$$+ \; \bar{L}_i \begin{pmatrix} \times & & \\ & \times & \\ & & \times \end{pmatrix} H\, N_R$$

$$+ \; \frac{1}{2} N_i^T C^{-1} \begin{pmatrix} X & 0 & 0 \\ 0 & 0 & Y \\ 0 & Y & 0 \end{pmatrix} N_j$$

$$+ \; \frac{1}{2} \langle S\rangle N_i^T C^{-1} \begin{pmatrix} 0 & z & z \\ z & 0 & 0 \\ z & 0 & 0 \end{pmatrix} N_j$$

$$M_R = \begin{pmatrix} X & \langle S\rangle & \langle S\rangle \\ \langle S\rangle & 0 & Y \\ \langle S\rangle & Y & 0 \end{pmatrix}$$

U_R not diagonal!

[HEECK, RODEJOHANN 1107.5238]

but

$$\bar{L} \; Z' g' \begin{pmatrix} 0 & & \\ & 1 & \\ & & -1 \end{pmatrix} L$$

$$\downarrow$$

$$\bar{L}' \; Z' g' \underbrace{U_L}_{\approx \mathbb{1}} \begin{pmatrix} 0 & & \\ & 1 & \\ & & -1 \end{pmatrix} \underbrace{U_L^\dagger}_{\approx \mathbb{1}} L$$

Only FCNCs in the neutrino sector!

Attractive model for DM-mediator.

At colliders $M_{Z'} \propto g' \langle S \rangle$

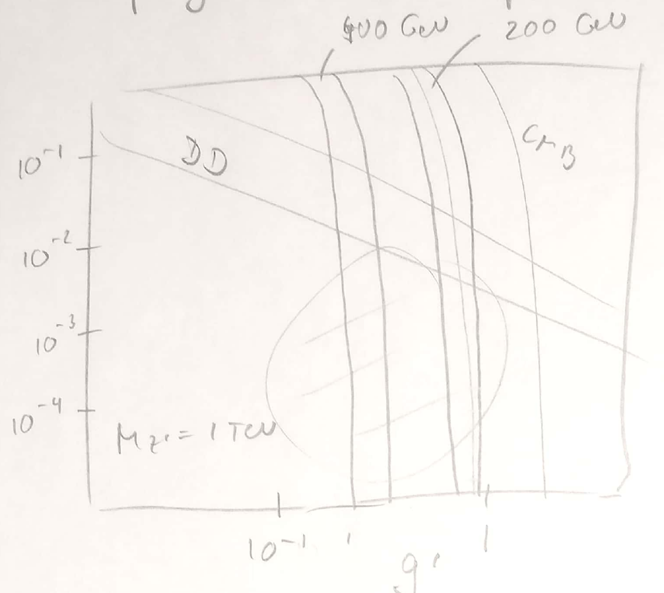
$M_S \propto \lambda \langle S \rangle$

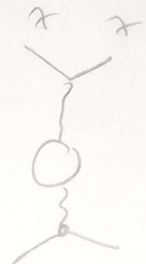
So $M_S \gtrsim M_{Z'}$.

$U(1)_{L_\mu - L_e}$ and $U(1)_{L_\tau - L_e}$ is constrained because of tree-level couplings to leptons.

In

[M.B., DIEFENBACHER et. al] 1805.01904)





at the LHC: production goes through mixing: $\epsilon \lesssim 10^{-2}$

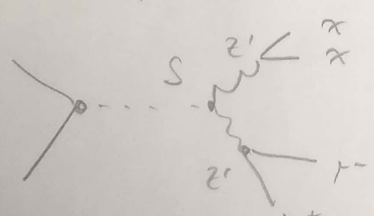
Di-muon search the most promising unless

$Q_\chi \gg Q_\mu$

Measure Z' width, problematic because of muon energy resolution (few %)

Note that the scalar mixing angle is not constrained by DD, and $BR(S \to Z'Z') \approx 100\%$ if $M_S > 2M_{Z'}$

For $\epsilon < 10^{-2}$, $S_\alpha \gtrsim 0.2$ the most promising signal is



Discovers the whole model at once.

Mono - Z'

FULL EMBEDDING

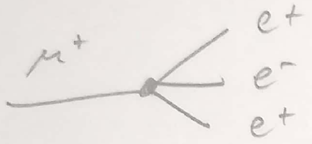
[BERNREUTHER, BUTTER, et al. 1805.11637]

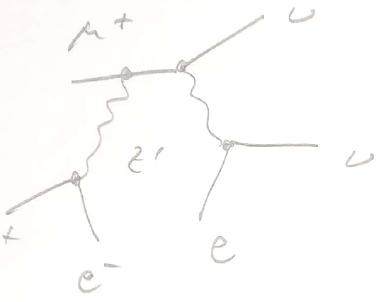
g

Consistent models can lead to unexpected (hierarchies of) signatures.

Also for non-LHC searches (Non-WIMP)

Light $U(1)_{L_\mu - L_\tau}$? Displaced vertices at Mu3E





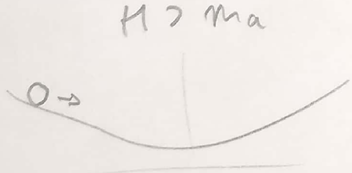
[FOLDENAUER, PEDREGVOORT]
1808.03647 1812.00741
1903.05466

Very, very light bosons: $m_a \simeq 10^{-22}$ eV — can be DM themselves (otherwise $a \to \gamma\gamma$)

Halo = wavelength of a

Classical background field

Relic density by misalignment $\ddot{a} + H\dot{a} + V'(a) = 0$



Friction dominates

Oscillating

$$a = a_0 \cos(\omega t) \Rightarrow \frac{a}{\Lambda} F\tilde{F} \Rightarrow \alpha = \alpha_0\left(1 + \frac{a_0}{\Lambda}\cos(\omega t)\right)$$

Measure variations of fund. constants $\Rightarrow$ QSFP

$$10 \qquad m_a = \frac{\mu^2}{F} = \frac{(100\text{ eV})^2}{M_P}$$