Pseudoscalar Mediator Dark Matter Models at the LHC and Beyond

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N. Chen, Z. Kang and JL, Phys. Rev. D ***95****, no. 1, 015003 (2017)*
S. Baek, P. Ko and JL, Phys. Rev. D ***95****, no. 7, 075011 (2017)*
B. Dutta, T. Kamon, P. Ko and JL, Eur. Phys. J. C ***78****, no. 7, 595 (2018)*

Oct. 3rd, 2018

Beyond the BSM

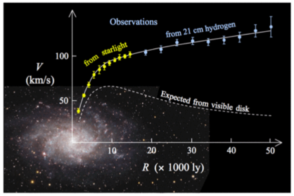
Hotel Tenbo

Outline

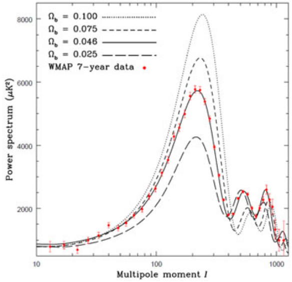
1. Motivation: why pseudoscalar?
2. Simplified fermion DM model with pseudoscalar mediator
3. A minimal UV completion
4. Conclusion

DM experiments

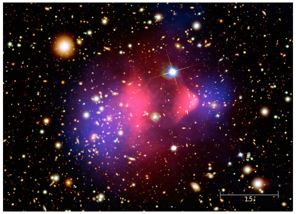
- The existence of dark matter is evident



Rotation curve

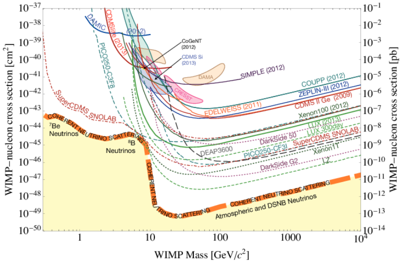


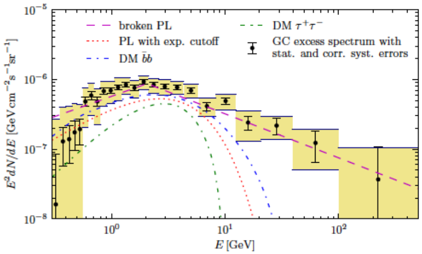
CMB Anisotropy

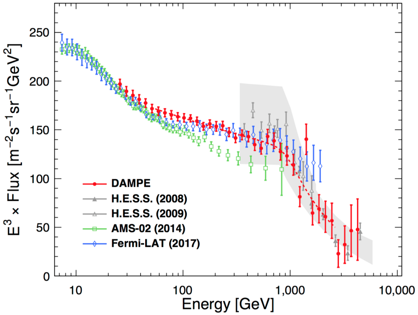


Bullet Cluster

- Null DM direct detection
- DM indirect detection hints







Matrix element analysis for fermion DM

Observations favor effective DM self-annihilation and suppressed DM-nucleon scattering cross section.

Interaction Structure	σ_{SI} suppression	s-wave annihilation
$\bar{\chi}\chi\ \bar{q}q$	1	no
$\bar{\chi}\gamma^5\chi\ \bar{q}q$	q^2	Yes
$\bar{\chi}\chi\ \bar{q}\gamma^5 q$	0	No
$\bar{\chi}\gamma^5\chi\ \bar{q}\gamma^5 q$	0	Yes
$\bar{\chi}\gamma^\mu\chi\ \bar{q}\gamma_\mu q$	1	Yes
$\bar{\chi}\gamma^\mu\gamma^5\chi\ \bar{q}\gamma_\mu q$	v^2	no
$\bar{\chi}\gamma^\mu\chi\ \bar{q}\gamma_\mu\gamma^5 q$	q^2	Yes
$\bar{\chi}\gamma^\mu\gamma^5\chi\ \bar{q}\gamma_\mu\gamma^5 q$	q^2v^2	$\propto m_f^2/m_\chi^2$

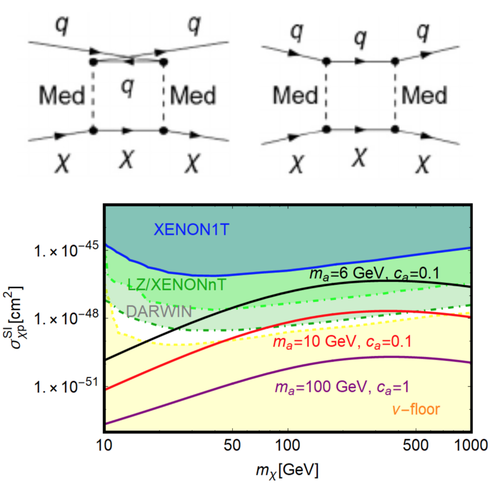
Pseudoscalar mediator meet the needs with simplest form.

Outline

Simplified model with pseudoscalar mediator

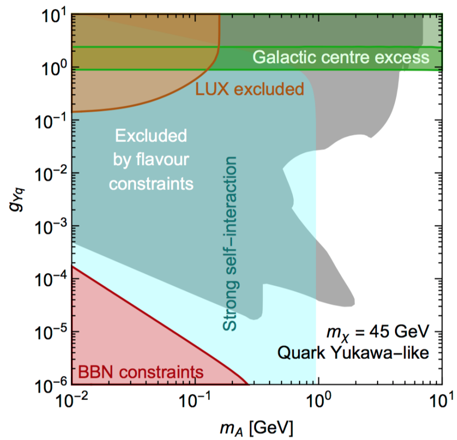
$$-\mathcal{L}_\chi = i g_\chi A \bar{\chi}\gamma_5\chi + i\frac{g_q}{\sqrt{2}}\sum_f y_f A\bar{f}\gamma_5 f.$$

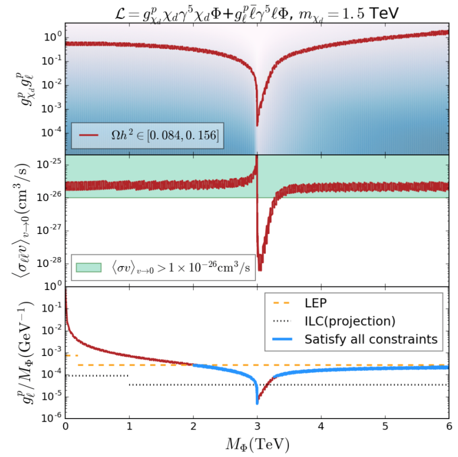
- Direct detection at loop level



arXiv: 1711.02110

- Explanations to ID hints

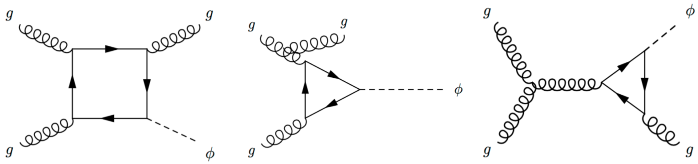


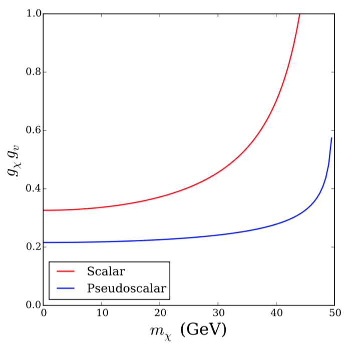


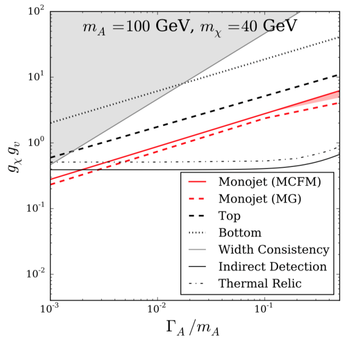
arXiv:1412.5174, 1711.11376

LHC search for the simplified model

- Mono-jet signature (only 8 TeV)

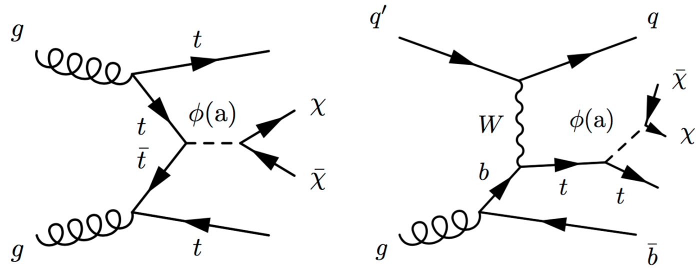






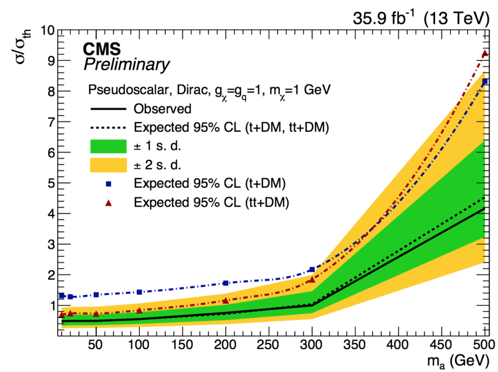
arXiv: 1410.6497, 8 TeV 19.5 fb^{-1}

- Top quark final state



(a) $t\bar{t}$ + DM

(b) $t/\bar{t}$ + DM, t-channel



CMS-PAS-EXO-18-010

Theoretical issues of the simplified model

$$-\mathcal{L}_\chi = i g_\chi A \bar{\chi}\gamma_5\chi + i\frac{g_q}{\sqrt{2}}\sum_f y_f A\bar{f}\gamma_5 f.$$

- SM fermions are chiral $\Rightarrow$ A is SM $SU(2)_L$ doublet
  $\Rightarrow$ DM is not SM singlet
- A solution: SM+DM with 2HDM+singlet pseudoscalar (*arXiv:1611.04593*)

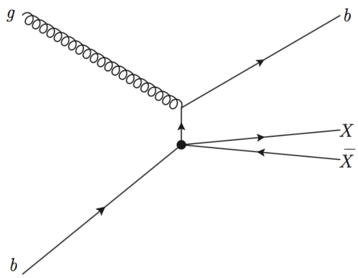
$$V_{\rm 2HDM} = \mu_1^2 |H_1|^2 + \mu_2^2 |H_2|^2 - \mu^2 \left[H_1^\dagger H_2 + \text{h.c.}\right] + \frac{\lambda_1}{2}|H_1|^4 + \frac{\lambda_2}{2}|H_2|^4$$
$$+ \lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 \left|H_1^\dagger H_2\right|^2 + \frac{\lambda_5}{2}\left[\left(H_1^\dagger H_2\right)^2 + \text{h.c.}\right],$$
$$V_{\rm portal} = i\,\kappa\, a_0\, H_1^\dagger H_2 + \text{h.c.}$$
$$V_{\rm dark} = \frac{m_{a_0}^2}{2}\, a_0^2 + m_\chi\,\bar{\chi}\chi + g_\chi\, a_0\,\bar{\chi} i\gamma^5\chi$$

- Consequence: enhanced $A\bar{b}\gamma^5 b$ at large/small $\tan\beta$ region.

Mono-b jet versus two b-jets searches

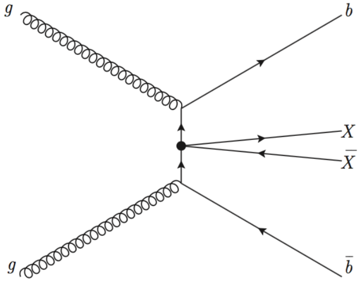
arXiv: 1608.00421, N. Chen, Z. Kang, ***JL***

$$-\mathcal{L}_\chi = \frac{m_\chi}{2}\bar{\chi}\chi + \frac{m_A^2}{2}A^2 + iY_\chi A\bar{\chi}\gamma_5\chi + iY_b A\bar{b}\gamma_5 b.$$



Cross sections at the 14 TeV LHC ($Y_b = 1$):

m_A (GeV)	$\sigma^{\rm incl}$ (pb)	$\epsilon(\geq 1 j_b)$	$\epsilon(\geq 2 j_b)$	$\epsilon(p_T(A) > 100$ GeV)
125	1562	0.374	0.0472	0.0257
500	6.83	0.602	0.131	0.177
1000	0.2115	0.662	0.170	0.298
2000	0.002748	0.696	0.199	0.409



- $\sigma(t\bar{t}) = 920$ pb
- $\sigma(\mathrm{QCD}) = 3.4 \times 10^7$ pb
- $\sigma(W(\to \ell\nu)jj) = 3360$ pb
- $\sigma(Z(\to \nu\nu)jj) = 714$ pb

With b-jet $p_T > 20$ GeV and $|\eta| < 2.5$; the b-tagging efficiency of 60 %, the corresponding mis-tagging rates for the charm- and light-flavor jets are 0.15 and 0.008.

Difficulty: tails of the E_T^{miss} distribution is difficult to model.

Shape analysis of $b\bar{b}$+MET final state

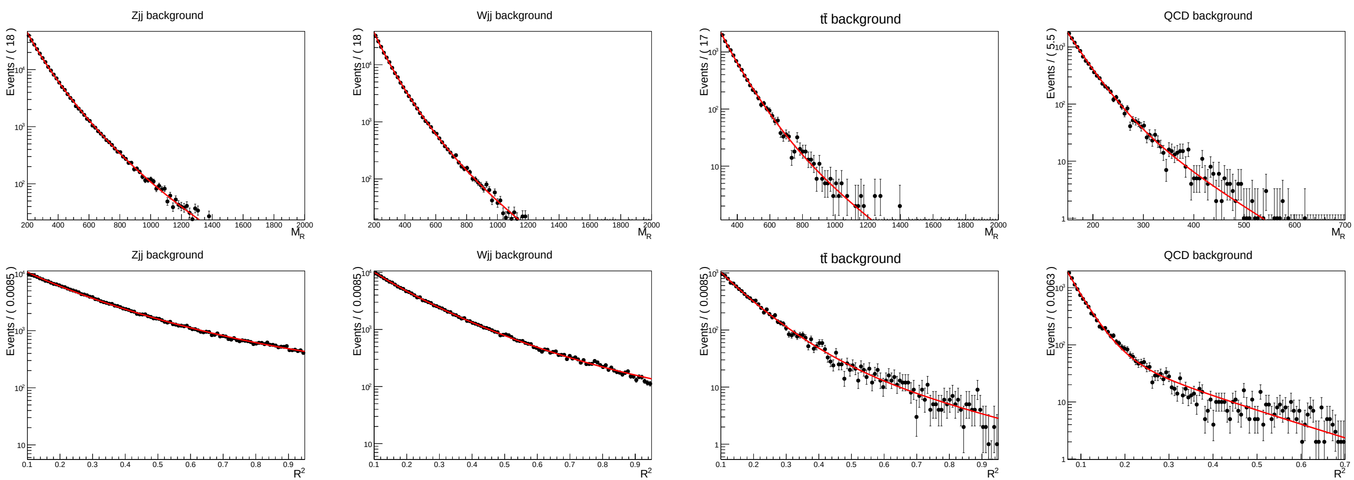
The partition that minimizes the sum of two megajets invariant mass square is chosen

$$M_R = \sqrt{(E(J_1) + E(J_2))^2 - (p_z(J_1) + p_z(J_2))^2}\ , \quad R = \frac{M_R^T}{M_R}\ ,$$

$$M_R^T = \sqrt{\frac{\not{E}_T(p_T(J_1) + p_T(J_2)) - \vec{\not{E}}_T \cdot (\vec{p}_T(J_1) + \vec{p}_T(J_2))}{2}}$$

The distributions of the razor variables over a wide range can be well described by a probability function with two exponential components:

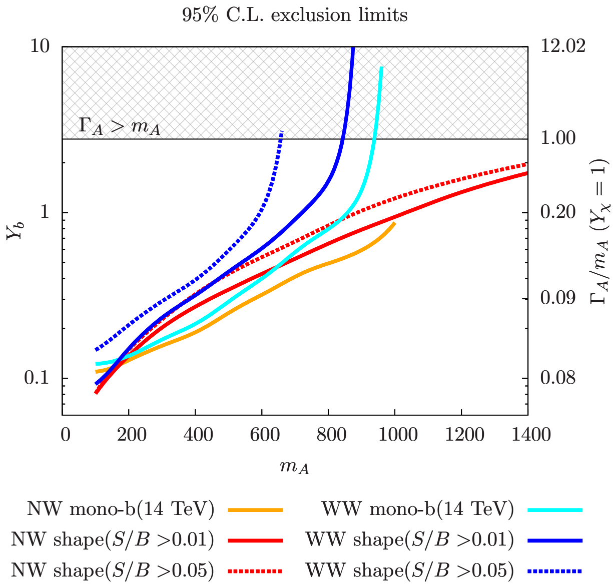
$$P(R^2, M_R) = f \times e^{-k(M_R - x_0)(R^2 - y_0)} + (1-f)e^{-k'(M_R - x_0')(R^2 - y_0')}\ .$$

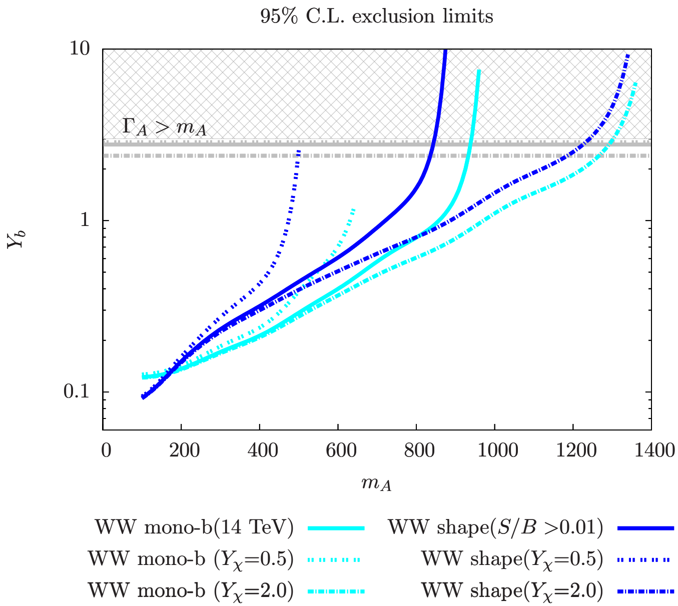


Shape analysis of $b\bar{b}$+MET final state

Preselection: (i) no isolated electron or muon; (ii) $|\Delta\phi(J_1, J_2)| < 2.5$; (iii) exactly one b-tagged anti-k_t jet in each megajet; (iv) $M_R > 300$ GeV and $R^2 > 0.1$.

Optimization: razor variables to have $M_R > M_R'$ and $R^2 > R^{2\prime}$ that maximize the signal significance.





Outline

Minimal pseudoscalar portal with gauge symmetry

arXiv: 1701.04131, S. Baek, P. Ko and ***JL***

DM χ is a SM singlet Dirac fermion that couples to an singlet pseudoscalar a (Remove tadpole for a and assume $\langle a \rangle = 0$):

$$\mathcal{L} = \bar{\chi}(i\partial \cdot \gamma - m_\chi - i g_\chi a \gamma^5)\chi + \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2$$
$$- (\mu_a a + \lambda_{Ha} a^2)\left(H^\dagger H - \frac{v_h^2}{2}\right) - \frac{\mu_a'}{3!}a^3 - \frac{\lambda_a}{4!}a^4 - \lambda_H \left(H^\dagger H - \frac{v_h^2}{2}\right)^2$$

Mixing between H_0 and A:

$$H_0 = h\cos\alpha + a\sin\alpha \ ,$$
$$A = -h\sin\alpha + a\cos\alpha \ .$$

Interaction Lagrangian $\bar{\chi}\gamma^5\chi\ \bar{q}q$:

$$\mathcal{L}_{\rm int} = -i g_\chi (H_0 \sin\alpha + A\cos\alpha)\ \bar{\chi}\gamma^5\chi - (H_0\cos\alpha - A\sin\alpha)$$
$$\times \left[\sum_f \frac{m_f}{v_h}\bar{f}f - \frac{2m_W^2}{v_h}W_\mu^+ W^{-\mu} - \frac{m_Z^2}{v_h}Z_\mu Z^\mu\right]$$

DM properties

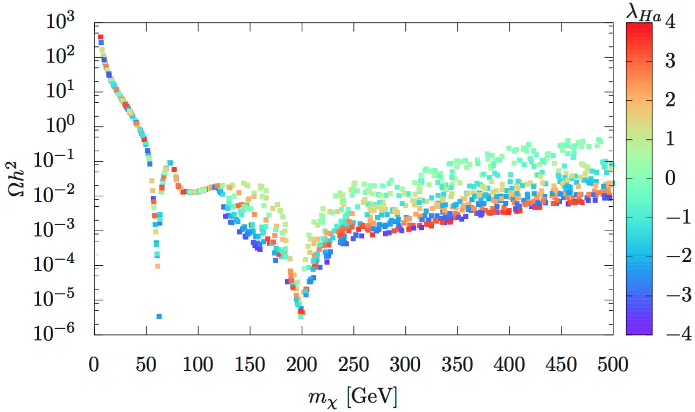
Seven free parameters of the model$_{(m_{H_0} = 125 \text{ GeV})}$:

$$m_A, \; g_\chi, \; \alpha, \; m_\chi, \; \lambda_{Ha}, \; \mu'_a, \; \lambda_a$$

Parameter scanning strategy:

- Constraints: singlet-doublet scalar mixing, Higgs invisible decay
- $\lambda_{Ha} \in \pm[10^{-3}, \sqrt{4\pi}], \; \mu'_a \in [5, 300]$ GeV, $\lambda_a \in [10^{-3}, \sqrt{4\pi}], m_\chi$
- Fix $g_\chi = 1, \; \alpha = 0.3, \; m_A = 400$ GeV

DM relic density:



- In $m_\chi < m_h$, $\chi\chi > \bar{f}f, VV$, only m_χ is relevant.
- In $m_\chi > m_h$, $\chi\chi > A/hA/h$, the scalar self-couplings are important.
- Two resonant poles at $m_\chi \sim m_h/2$ and m_A.
- Varying the g_χ and α can only lead to a total rescaling.
- Changing m_A renders different pole position.

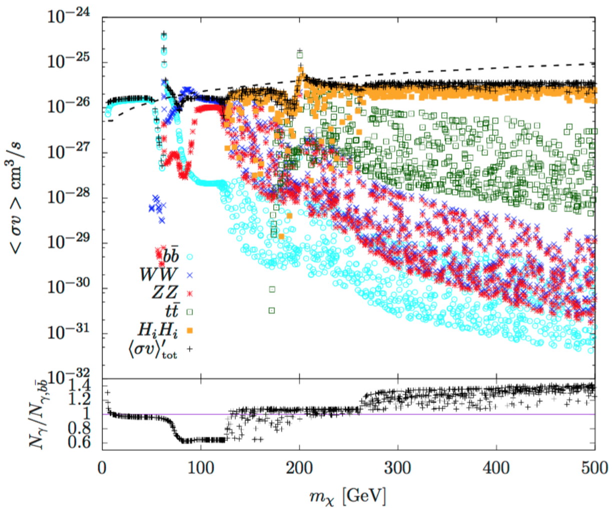
DM direct and indirect constraints

DM indirect detection:

The s-wave annihilation is permitted:

$$\mathcal{M}_\chi = \bar{\chi_1}\gamma^5\chi_2 = -\frac{(E_1+m_1)(E_2+m_2)+\vec{k}^2}{\sqrt{(E_1+m_1)(E_2+m_2)}}\xi^\dagger_{\chi_1}\xi_{\chi_2}$$

Varying g_χ to obtain correct Ωh^2



The 95%CL exclusion limit from Milky Way Dwarf Spheroidal Galaxies (6 years)

DM direct detection (Tree level):

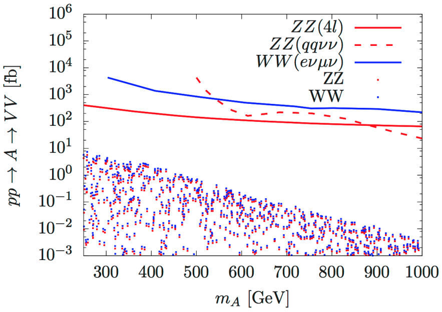
$$\mathcal{M} \propto \mathcal{M}_\chi \cdot \mathcal{M}_f = -2q^i(\xi^\dagger_\chi \hat{S}^i \xi_\chi)\times$$
$$[2m_f(\xi^\dagger_f\xi_f) + i\frac{\mu}{m_f}\epsilon^{ijk}q^i v^j(\xi^\dagger_f\hat{S}^k\xi_f)]$$

- The SI DM-nucleon cross section is suppressed by the $|\vec{q}|^2$; the SD cross section is $\propto |\vec{q}|^4$.
- The relative velocity between the DM and nuclear is given by the orbital speed of the Sun $\sim \mathcal{O}(10^{-3})$; the typical $\sigma^{SI}_{\chi N}$ of our model is suppressed by a factor of $\mathcal{O}(10^{-6})$.

LHC searches constraining the mediator

Fix $m_\chi = 80$ GeV, $g_\chi = 1$, vary $m_A \in [0, 1000]$ GeV, $\alpha \in [0, 0.3]$

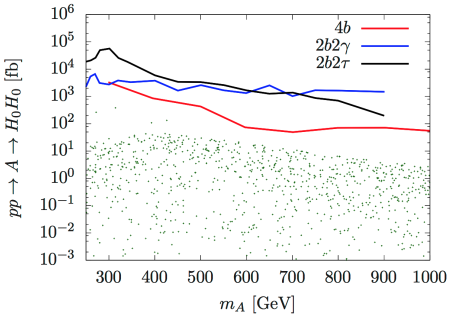
- Vector boson pair production at NNLO ($\sigma \propto \sin^4 \alpha$)
- Lines obtained with ATLAS run-II ~ 13 fb^{-1}.
- At least two orders of magnitude below the current LHC search sensitivities



- Resonance Higgs pair production is $\propto \sin^2 \alpha$

$$\lambda_{Ahh} \sim -\mu_a \cos^3 \alpha$$

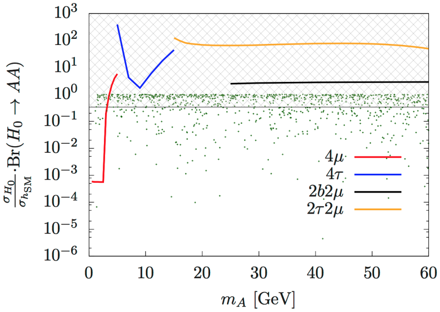
- Lines obtained with ATLAS run-II ~ 13 fb^{-1}
- 4b final state provides the best sensitivity



- Higgs exotic decay is not suppressed by α

$$\lambda_{hAA} \sim -2\lambda_{Ha} v_h \cos^3 \alpha$$

- Lines obtained with CMS 8 TeV 20 fb^{-1}.
- Shaded region is excluded by $\mathrm{Br}_{\mathrm{BSM}} > 34\%$.



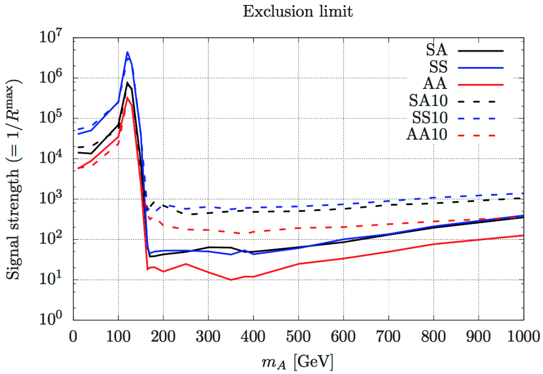
LHC searches for the DM signals (mono-jet/V)

$$\mathcal{L}_{\rm int}^{\rm SA} = -ig_\chi(H_0 \sin\alpha + A\cos\alpha)\ \bar\chi\gamma^5\chi - (H_0\cos\alpha - A\sin\alpha)\left[\sum_f \frac{m_f}{v_h}\bar f f - \frac{2m_W^2}{v_h}W_\mu^+ W^{-\mu} - \frac{m_Z^2}{v_h}Z_\mu Z^\mu\right]$$

$$\mathcal{L}_{\rm int}^{\rm AA} = -ig_\chi(a \sin\alpha + A\cos\alpha)\ \bar\chi\gamma^5\chi - i(a\cos\alpha - A\sin\alpha)\sum_f \frac{m_f}{v_h}\bar f \gamma^5 f$$

$$\mathcal{L}_{\rm int}^{\rm SS} = -g_\chi(H_1 \sin\alpha + H_2\cos\alpha)\ \bar\chi\chi - (H_1\cos\alpha - H_2\sin\alpha)\left[\sum_f \frac{m_f}{v_h}\bar f f - \frac{2m_W^2}{v_h}W_\mu^+ W^{-\mu} - \frac{m_Z^2}{v_h}Z_\mu Z^\mu\right]$$

Fixing $\alpha = 0.3$, $g_\chi = 1$, $m_\chi = 80$ GeV and $m_{H_{0,1}/a} = 125$ GeV.

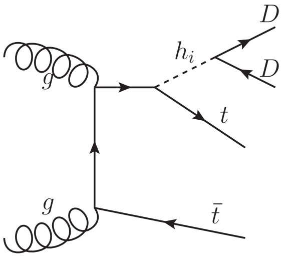


- Recasted limits from the ATLAS mono-jet search at 13 TeV 3.2 fb^{-1}.
- In the region $m_A \gtrsim 2m_\chi$, $\mathrm{Br}(A \to \bar\chi\chi)$ is already close to one, larger g_χ will not increase the signal rate.
- AA scenario has the best search sensitivity
- Dashed lines: ten times larger total width of A than Γ_{min}, due to the opening of new decay channels
- The interference effect is more significant for larger A decay width, it can lead to distinguished signal reaches for SS and SA scenarios.

Studies on distinguishing AA and SS scenario

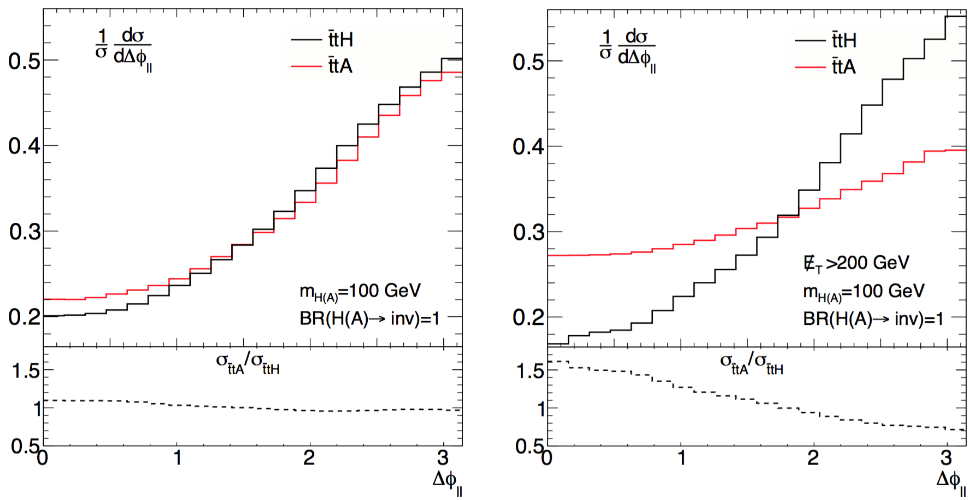
arXiv: 1511.06451, M. Buckley and D. Goncalves

arXiv: 1611.09841, U. Haisch, P. Pani and G. Polesello



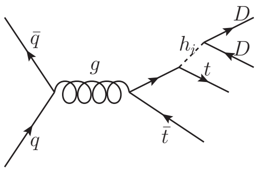
$$f_{t\to\phi}(x) = \frac{g_t^2}{(4\pi)^2}\left[\frac{4(1-x)}{x} + x\ln\left(\frac{s}{m_t^2}\right)\right]$$

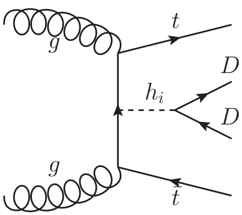
$$f_{t\to a}(x) = \left[x\ln\left(\frac{s}{m_t^2}\right)\right]$$

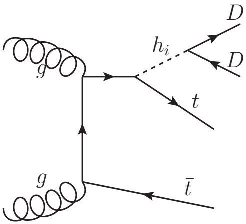


Distinguish between scalar ($S\bar{\chi}\chi$) and pseudoscalar couplings ($A\bar{\chi}\gamma^5\chi$) at collider?

Consider $\bar{t}t\chi\chi$ production channel (100 TeV)



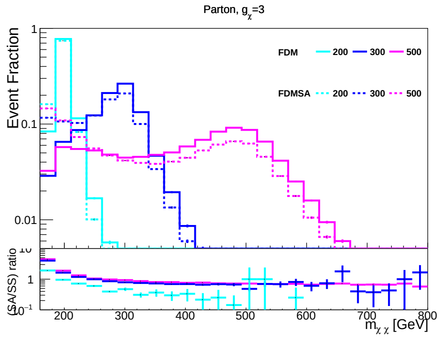


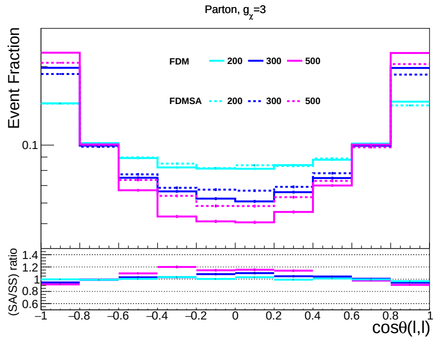


$$\frac{d\sigma_{\rm FDMSS}}{dt} \propto \sigma^{h^*}_{\rm FDM} \cdot \left(2t - 8m_\chi^2\right), \qquad \frac{d\sigma_{\rm FDMSA}}{dt} \propto \sigma^{h^*}_{\rm FDMSA} \cdot 2t$$

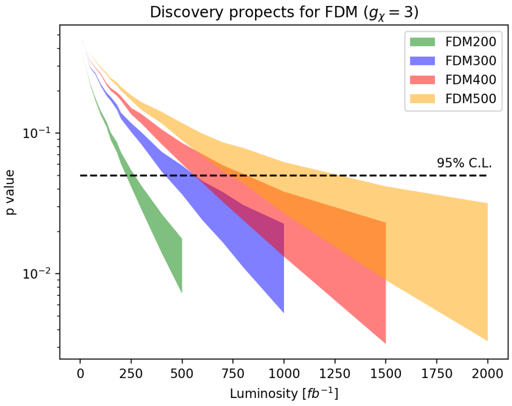
$\frac{2t_2 - 8m_\chi^2}{2t_1 - 8m_\chi^2} > \frac{2t_2}{2t_1}$ for $t_2 > t_1 \Rightarrow m_{\chi\chi}$ spectrum in scalar mediator model will be harder than that in pseudoscalar model $\Rightarrow$ more spread angular distribution

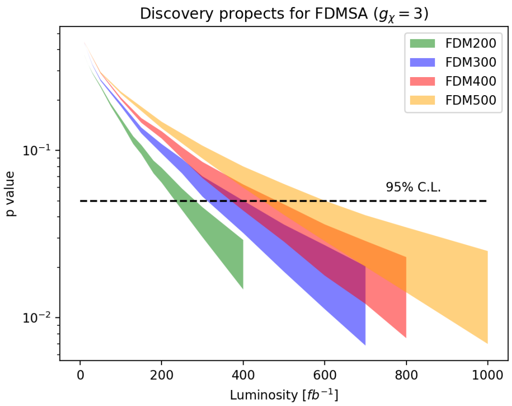
- Take $g_\chi = 3$, $\sin\alpha = 0.3$, $m_\chi = 80$ GeV and four different $m_{H_2/A} = \{200,\ 300,\ 400,\ 500\}$ GeV





Probing the SS and SA scenarios



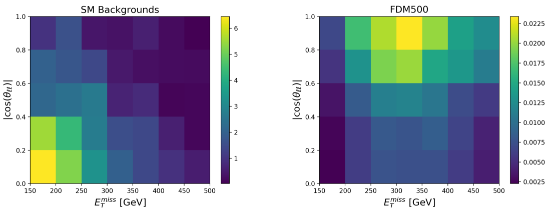


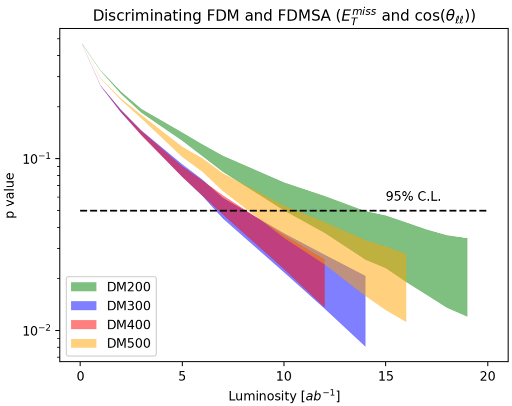
- Dominant backgrounds:

	Cross section (NLO)
$\bar{t}t$	1316.5 pb
$\bar{t}tW$	20.5 pb
$\bar{t}tZ$	64.2 pb
$W_\ell W_\ell b$	128.4 pb

- Event selections: (1). Preselection: Exactly two opposite sign lepton and at least one b jet in the final state; (2). $m_{\ell\ell} \notin [85, 95]$ GeV; (3). $E_T^{miss} > 150$ GeV; (4). $m_{T_2}(l, l) > 150$ GeV.
- FDMSA scenario has better discovery prospects (for heavier mediator mass), mainly due to larger production cross section.
- The widths of bands correspond to 1% systematic uncertainty.

Discriminating the SS and SA scenarios





- The two dimensional binned log-likelihood analysis on E_T^{miss} and $\cos(\theta_{\ell\ell})$:

$$\mathcal{L}(\text{data}|\mathcal{H}_\alpha) = \prod_{i,j} \frac{t_{ij}^{n_{ij}} e^{-t_{ij}}}{n_{ij}!}$$

  with t_{ij} and n_{ij} being the expected and observed event number in ijth bin.

- Testing hypotheses $\mathcal{H}_0 = \text{SM} + \text{SS}$, $\mathcal{H}_1 = \text{SM} + \text{SA}$.
- The discrimination can be made with an integrated luminosity of around 15 ab^{-1}.
- The widths of bands correspond to 0.5% systematic uncertainty.

Conclusion

- Pseudoscalar provides rich phenomena, better consistent with current observations.
- A simplified model of some possible UV completions, predict $b\bar{b}$+MET signal.
- The razor variables which have well behaved tails are useful in realistic analyses.
- A minimal UV completion is proposed: correct relic density, suppressed direct detection rate, indirect detection efficient.
- At collider, higher collision energy and higher luminosity are required to probe the minimal model.
- It is possible to discriminate between the pseudoscalar and scalar mediator coupling at future colliders.