

# Pseudoscalar Mediator Dark Matter Models at the LHC and Beyond

Jinmian Li

Korea Institute for Advanced Study



*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)*

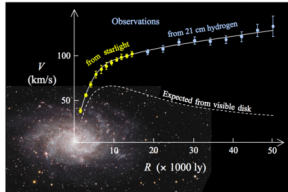
Nov. 10th, 2018

The 2nd BNU dark matter workshop

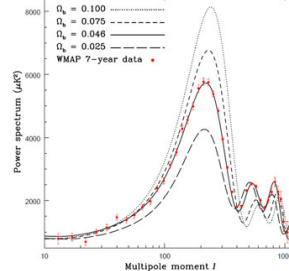
- 1 Motivation: why pseudoscalar?
- 2 Simplified fermion DM model with pseudoscalar mediator
- 3 A minimal UV completion
- 4 Conclusion

# DM experiments

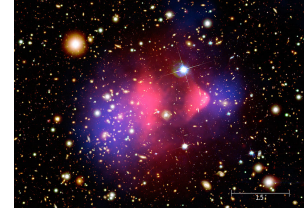
- The existence of dark matter is evident



Rotation curve

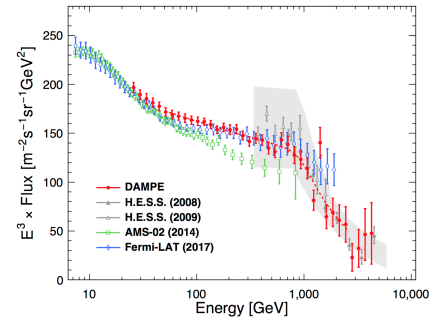
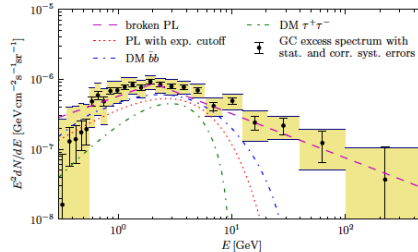
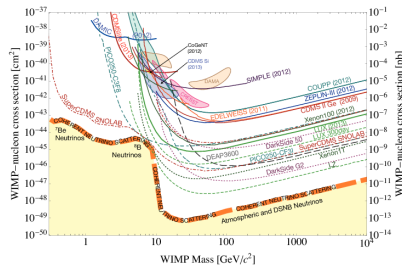


CMB Anisotropy



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

Pseudoscalar mediator meet the needs with simplest form.

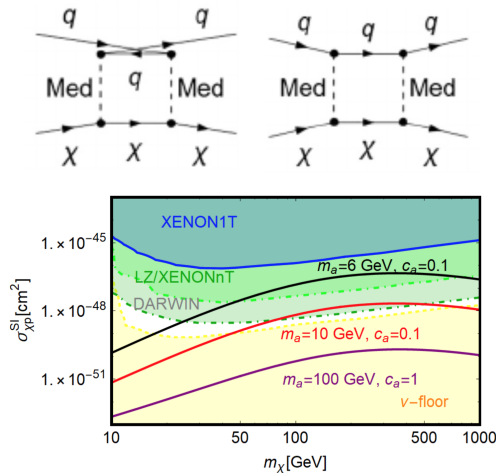
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- 1 Motivation: why pseudoscalar?
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- 3 A minimal UV completion
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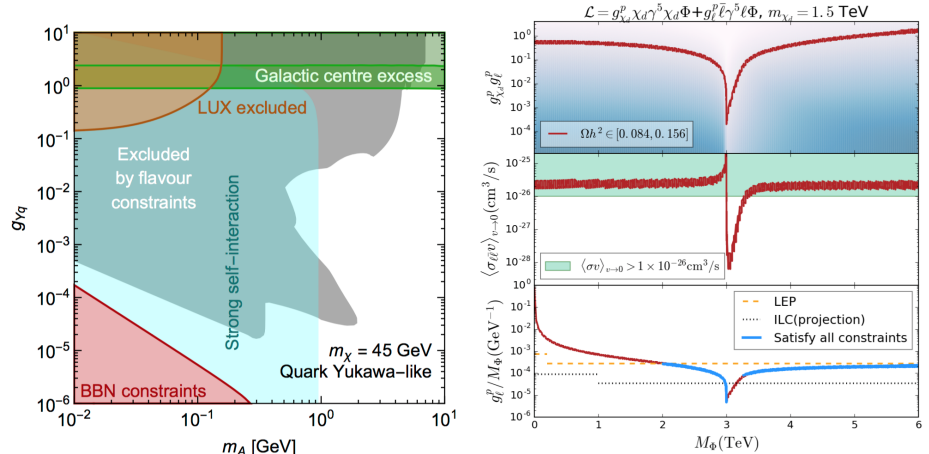
# Simplified model with pseudoscalar mediator

$$-\mathcal{L}_\chi = ig_\chi A\bar{\chi}\gamma_5\chi + i\frac{g_q}{\sqrt{2}}\sum_f y_f Af\bar{f}\gamma_5f.$$

- Direct detection at loop level



- Explanations to ID hints

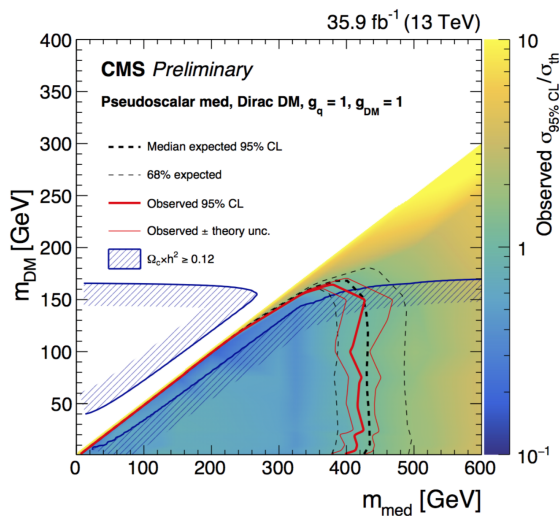
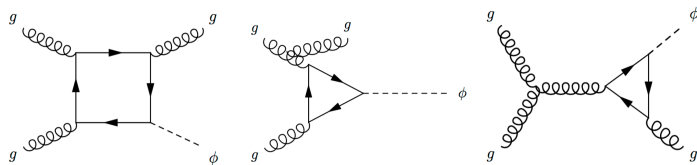


arXiv:1412.5174, 1711.11376

arXiv: 1711.02110 & T. Li's talk

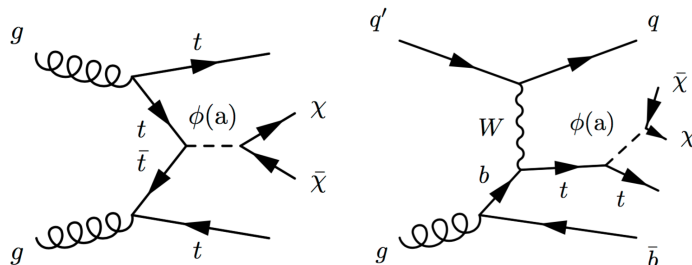
# LHC search for the simplified model

## • Mono-jet signature



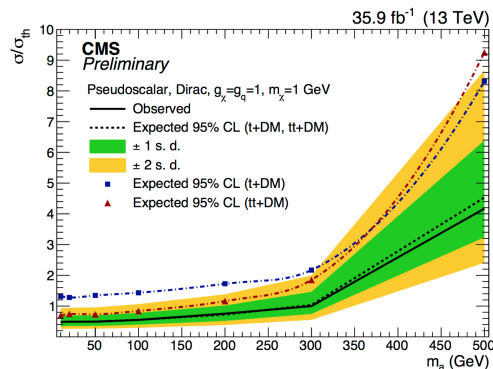
CMS PAS EXO-16-048

## • 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

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

- 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*)

$$V_{2\text{HDM}} = \mu_1^2 |H_1|^2 + \mu_2^2 |H_2|^2 - \mu^2 [H_1^\dagger H_2 + \text{h.c.}] + \frac{\lambda_1}{2} |H_1|^4 + \frac{\lambda_2}{2} |H_2|^4 \\ + \lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 |H_1^\dagger H_2|^2 + \frac{\lambda_5}{2} [(H_1^\dagger H_2)^2 + \text{h.c.}],$$

$$V_{\text{portal}} = i \kappa a_0 H_1^\dagger H_2 + \text{h.c.}$$

$$V_{\text{dark}} = \frac{m_{a_0}^2}{2} a_0^2 + m_\chi \bar{\chi} \chi + g_\chi a_0 \bar{\chi} i \gamma_5 \chi$$

- 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) | $\sigma^{\text{incl}}$ (pb) | $\epsilon(\geq 1j_b)$ | $\epsilon(\geq 2j_b)$ | $\epsilon(p_T(A) > 100 \text{ GeV})$ |
|-------------|-----------------------------|-----------------------|-----------------------|--------------------------------------|
| 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                                |

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

With b-jet  $p_T > 20 \text{ GeV}$  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  $E_T^{\text{miss}}$  distribution is difficult to model.

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

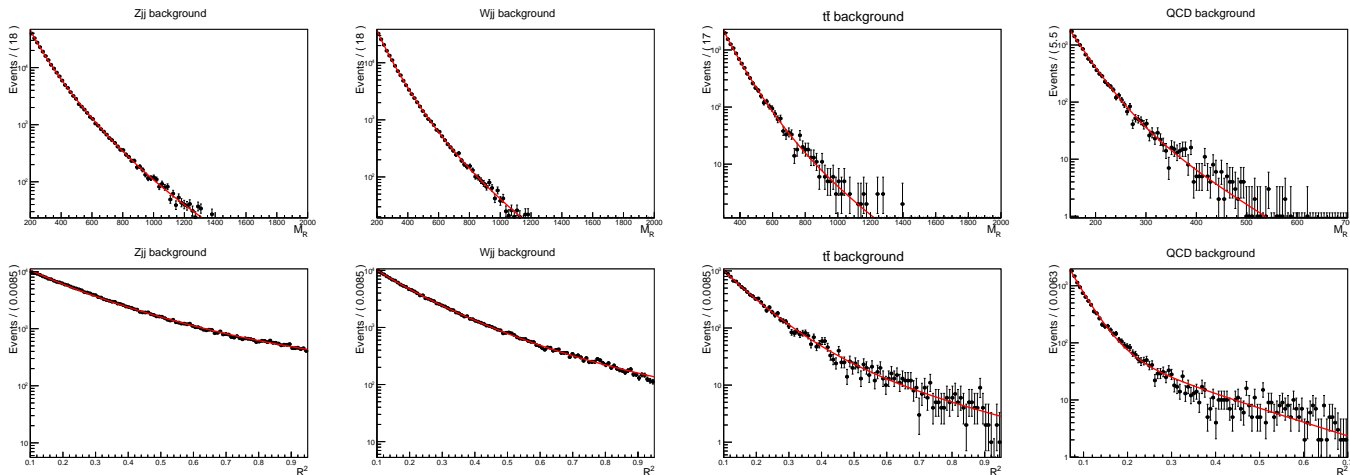
The partition that minimizes the sum of two megajets invariant mass square is chosen

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

$$M_R^T = \sqrt{\frac{\cancel{E}_T(p_T(J_1) + p_T(J_2)) - \vec{\cancel{E}}_T \cdot (\vec{p}_T(J_1) + \vec{p}_T(J_2))}{2}}$$

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

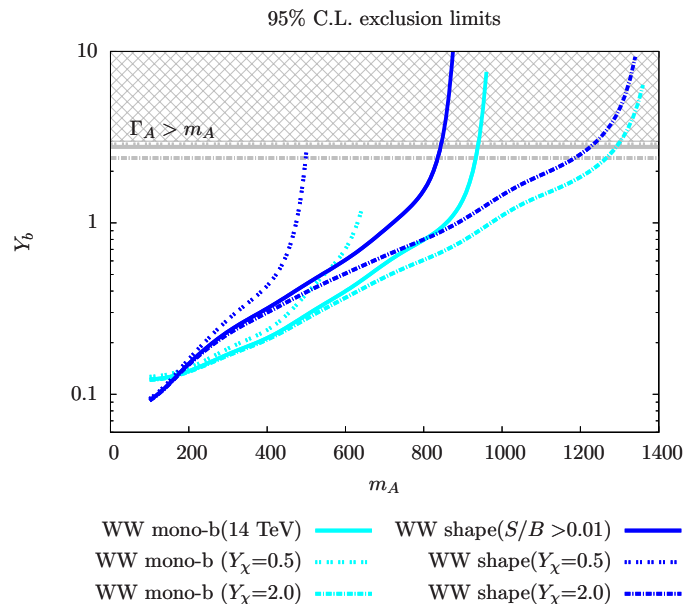
$$P(R^2, M_R) = f \times e^{-k(M_R - x_0)(R^2 - y_0)} + (1 - f)e^{-k'(M_R - x'_0)(R^2 - y'_0)}.$$



# Shape analysis of $b\bar{b}+\text{MET}$ 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  $R^2 > R^{2'}$  that maximize the signal significance.



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# Minimal pseudoscalar portal with gauge symmetry

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

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

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

Mixing between  $H_0$  and  $A$ :

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

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

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

# DM properties

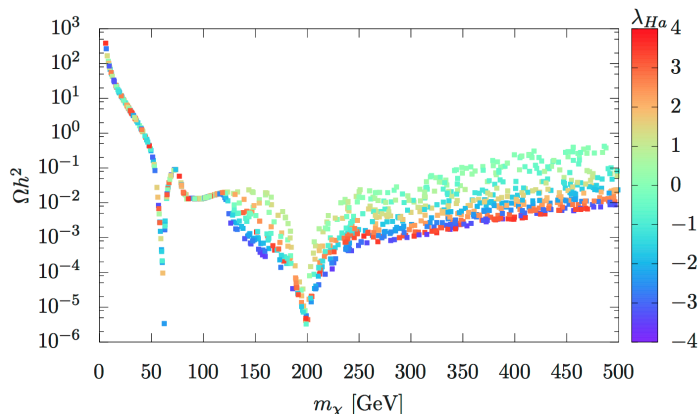
Seven free parameters of the model ( $m_{H_0} = 125 \text{ GeV}$ ) :

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

Parameter scanning strategy:

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

DM relic density:



- In  $m_\chi < m_h$ ,  $\chi\chi > \bar{f}f, VV$ , only  $m_\chi$  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  $g_\chi$  and  $\alpha$  can only lead to a total rescaling.
- Changing  $m_A$  renders different pole position.

# DM direct and indirect constraints

## DM direct detection (Tree level):

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

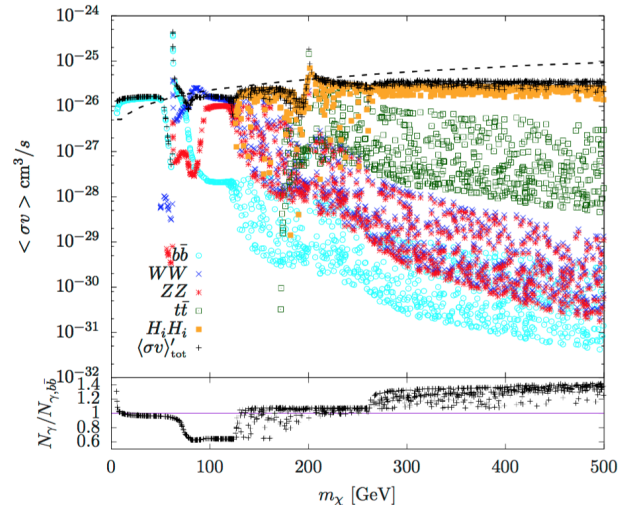
- The SI DM-nucleon cross section is suppressed by the  $|\vec{q}|^2$ ; the SD cross section is  $\propto |\vec{q}|^4$ .
- The relative velocity between the DM and nuclear is given by the orbital speed of the Sun  $\sim \mathcal{O}(10^{-3})$ ; the typical  $\sigma_{\chi N}^{SI}$  of our model is suppressed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

## DM indirect detection:

The s-wave annihilation is permitted:

$$\mathcal{M}_\chi = \bar{\chi}_1 \gamma^5 \chi_2 = - \frac{(E_1 + m_1)(E_2 + m_2) + \vec{k}^2}{\sqrt{(E_1 + m_1)(E_2 + m_2)}} \xi_{\chi_1}^\dagger \xi_{\chi_2}$$

Varying  $g_\chi$  to obtain correct  $\Omega h^2$

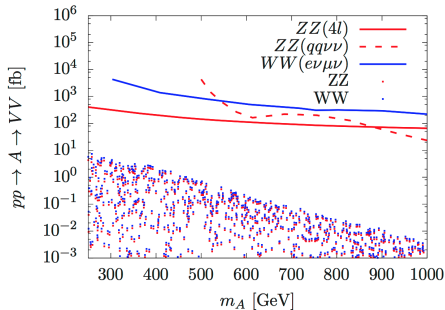


The 95%CL exclusion limit from Milky Way Dwarf Spheroidal Galaxies (6 years)

# LHC searches constraining the mediator

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

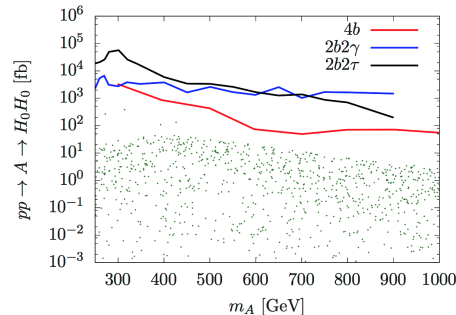
- **Vector boson pair production** at NNLO ( $\sigma \propto \sin^4 \alpha$ )
- Lines obtained with ATLAS run-II  $\sim 13$  fb $^{-1}$ .
- At least two orders of magnitude below the current LHC search sensitivities



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

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

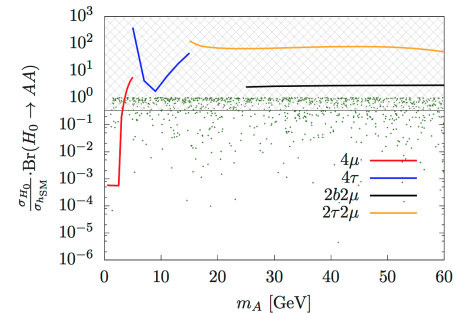
- Lines obtained with ATLAS run-II  $\sim 13$  fb $^{-1}$
- 4b final state provides the best sensitivity



- **Higgs exotic decay** is not suppressed by  $\alpha$

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

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





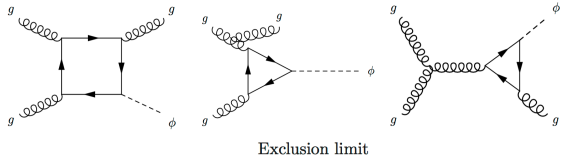
# LHC searches for the DM signals (mono-jet/V)

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

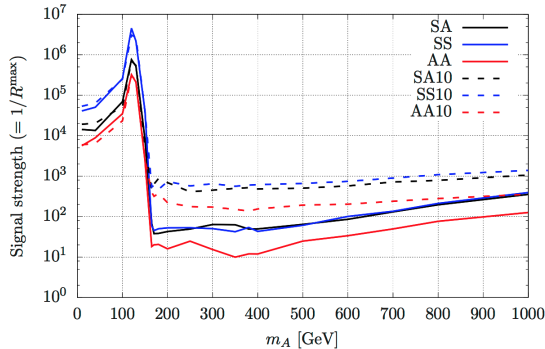
$$\mathcal{L}_{\text{int}}^{\text{AA}} = -ig_{\chi}(a \sin \alpha + A \cos \alpha) \bar{\chi}\gamma^5\chi - i(a \cos \alpha - A \sin \alpha) \sum_f \frac{m_f}{v_h} \bar{f}\gamma^5 f$$

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

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



Exclusion limit

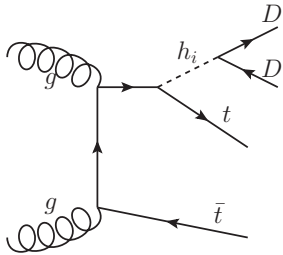


- Recasted limits from the ATLAS mono-jet search at 13 TeV  $3.2 \text{ fb}^{-1}$ .
- In the region  $m_A \gtrsim 2m_{\chi}$ ,  $\text{Br}(A \rightarrow \bar{\chi}\chi)$  is already close to one, larger  $g_{\chi}$  will not increase the signal rate.
- AA scenario has the best search sensitivity
- Dashed lines: ten times larger total width of A than  $\Gamma_{\text{min}}$ , 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

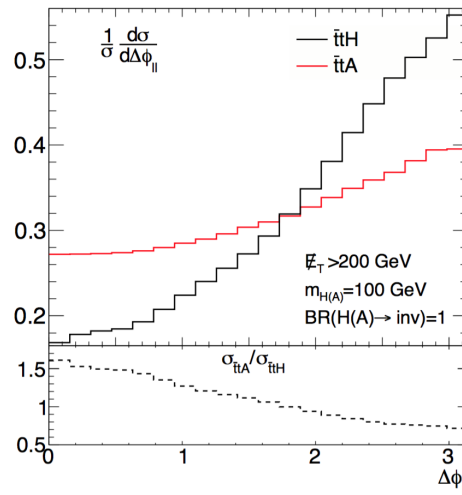
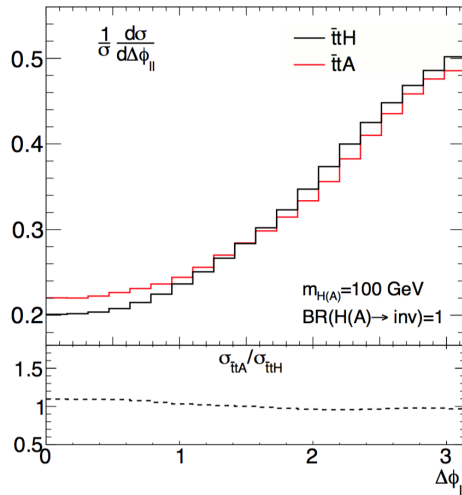
*arXiv: 1511.06451, M. Buckley and D. Goncalves*

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



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

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



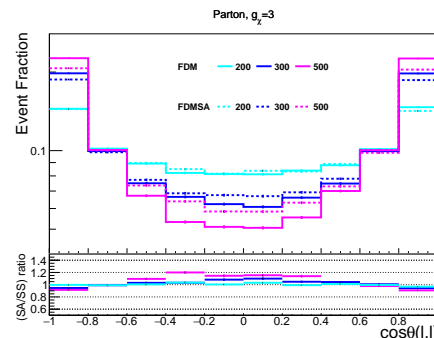
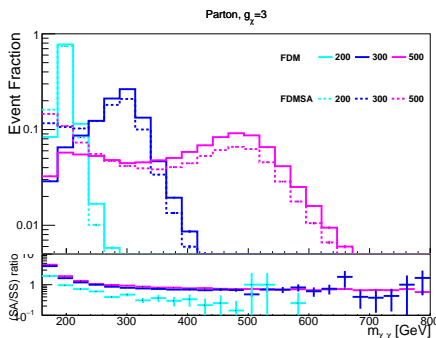
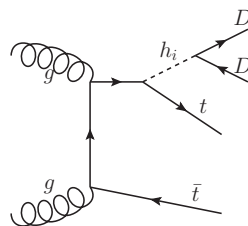
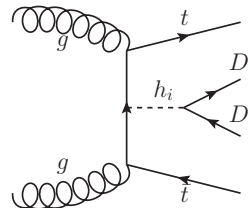
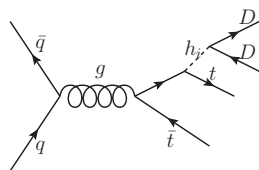
Distinguish between scalar ( $S\bar{\chi}\chi$ ) and pseudoscalar couplings ( $A\bar{\chi}\gamma^5\chi$ ) at collider?

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

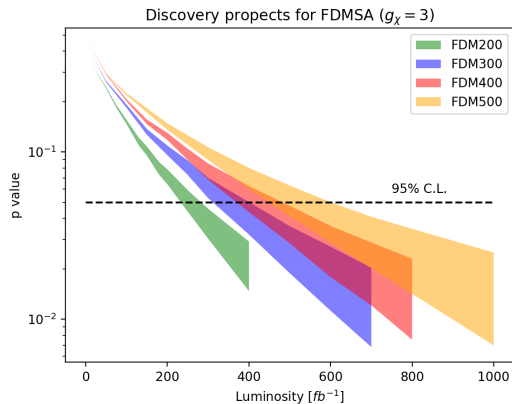
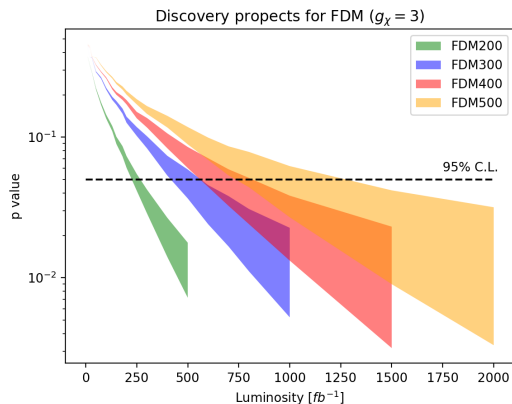
$$\frac{d\sigma_{\text{FDMSS}}}{dt} \propto \sigma_{\text{FDM}}^{h^*} \cdot (2t - 8m_\chi^2), \quad \frac{d\sigma_{\text{FDMSA}}}{dt} \propto \sigma_{\text{FDMSA}}^{h^*} \cdot 2t$$

$\frac{2t_2 - 8m_\chi^2}{2t_1 - 8m_\chi^2} > \frac{2t_2}{2t_1}$  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

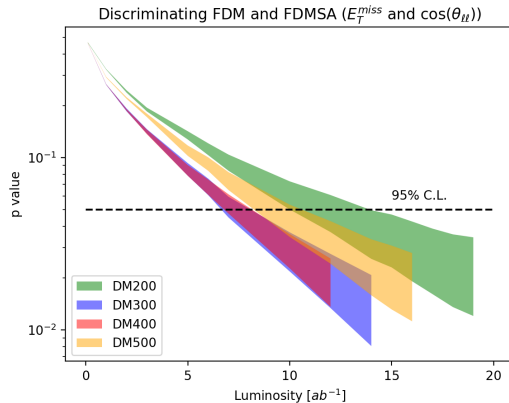
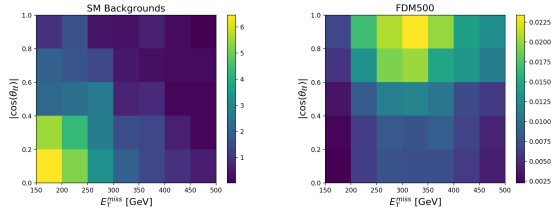


- Dominant backgrounds:

|                   | Cross section (NLO) |
|-------------------|---------------------|
| $t\bar{t}$        | 1316.5 pb           |
| $t\bar{t}W$       | 20.5 pb             |
| $t\bar{t}Z$       | 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).  $m_{\ell\ell} \notin [85, 95] \text{ GeV}$ ; (3).  $E_T^{miss} > 150 \text{ GeV}$ ; (4).  $m_{T2}(l, l) > 150 \text{ GeV}$ .
- 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  $E_T^{\text{miss}}$  and  $\cos(\theta_{ll})$ :

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

with  $t_{ij}$  and  $n_{ij}$  being the expected and observed event number in  $ij$ th 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  $15 \text{ ab}^{-1}$ .
- 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  $b\bar{b}+\text{MET}$  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.