Pseudoscalar Portal Dark Matter

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Motivations & goal for the pseudoscalar portal

Question we want to ask in this talk:

How to fully explore thermal DM models with DM annihilating through the pseudoscalar portal?

Goal

$$g_\chi A \bar{\chi} i \gamma^5 \chi + g_f A \bar{f} i \gamma^5 f \xrightarrow{\text{if heavy A}} \frac{g_\chi g_f}{m_A^2} (\bar{\chi}\gamma^5\chi)(\bar{f}\gamma^5 f)$$

Why is the pseudoscalar portal interesting?

- The least constrained portal
  - s-wave annihilation (vs. p-wave for scalar mediators)
  - No spin independent scattering cross section (only spin dependent)
- Open parameter space for a quite light DM candidate, satisfying the galactic center excess

Based on A.Berlin, SG, T.Lin, L.T.Wang, 1502.06000

Motivations & goal for the pseudoscalar portal

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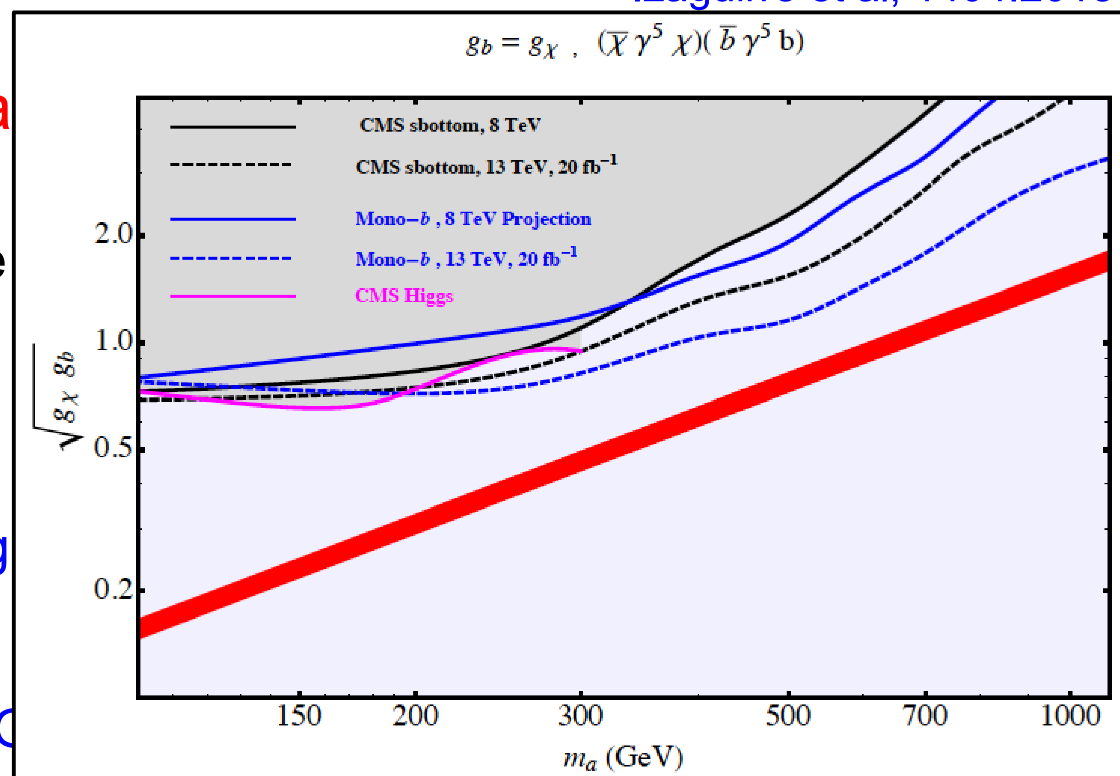
Izaguirre et al, 1404.2018



Based on A.Berlin, SG

Benchmark models for pseudoscalar portal

What UV completion can we write down?

- Based on minimality: 2HDM

1. Scalar DM:
- DM part of the 2HDM (if one doublet is inert)
- DM is an additional singlet scalar

2. **Fermion DM:**

A.Berlin, SG, T.Lin, L.T.Wang, 1502.06000

$$\mathcal{L}_{\rm DM} \supset -\frac{1}{2} M_S S^2 - M_D D_1 D_2 - y_1 S D_1 \Phi_1 - y_2 S \Phi_2^\dagger D_2 + \text{h.c.}$$

(2 neutral states, 2 charged states) + type II 2HDM

Name	Model
du	$\Phi_1 = \Phi_d,\ \Phi_2 = \Phi_u$
ud	$\Phi_1 = \Phi_u,\ \Phi_2 = \Phi_d$
dd	$\Phi_1 = \Phi_d,\ \Phi_2 = \Phi_d$
uu	$\Phi_1 = \Phi_u,\ \Phi_2 = \Phi_u$

2 Higgs doublets

(du, ud): Equivalent models: $y_1 \leftrightarrow y_2$

(dd, uu): Studied in details in eg. Cohen et al. 1109.2604; Cheung et al. 1311.5896

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Equivalent models: $y_1 \leftrightarrow y_2$ (du, ud)

Studied in details in eg. Cohen et al. 1109.2604; Cheung et al. 1311.5896 (dd, uu)

1. 2. We will study the **du** and **dd** models

- Counting the free parameters of these benchmark models:

$$m_H,\ m_A,\ m_{H^\pm},\ M_D,\ M_S,\ y,\ \tan\beta,\ \tan\theta \qquad (y_1 = y\cos\theta,\ y_2 = y\sin\theta)$$

For simplicity, we assume to be in the alignment limit: $\alpha = \beta - \pi/2$

Comparison with SUSY models

- The du model is a generalization of the MSSM, with Higgsino-Bino DM

$$\mathcal{L}_{\mathbf{DM}} \supset -\frac{1}{2} M_S S^2 - M_D D_1 D_2 - y \cos\theta S D_1 \Phi_u - y \sin\theta S \Phi_d^\dagger D_2 + \text{h.c.}$$

D_1, D_2 = Higgsinos, S = Bino

y = g', tanθ = -1, M_S = M_1, M_D = μ

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- More freedom in the Higgs spectrum

$$m_{H\pm}^2 - m_A^2 = \frac{v^2}{2}(\lambda_5 - \lambda_4),$$
$$m_H^2 - m_A^2 \simeq \lambda_5 v^2$$

large m_A, tanβ

MSSM

$$\lambda_4^{\rm MSSM} = -\frac{g^2}{2} \sim -0.21, \quad \lambda_5^{\rm MSSM} = 0$$
$$m_{H\pm}^2 - m_A^2 = m_W^2,$$
$$m_H^2 - m_A^2 \simeq m_Z^2 \sin^2(2\beta)$$

Some constraints from EW precision measurements.

In the alignment limit: α = β – π/2

$$\alpha T = \frac{g^2}{64\pi m_W^2}\left[\mathcal{F}(m_{H\pm}^2, m_A^2) + \mathcal{F}(m_{H\pm}^2, m_H^2) - \mathcal{F}(m_A^2, m_H^2)\right]$$

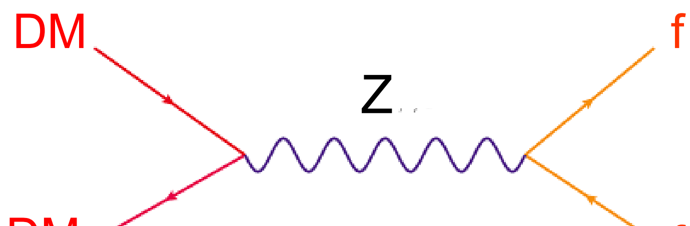
Nevertheless, it is easy to obtain sizable m_A - m_H,$m_{H\pm}$ splittings

Example: $m_H = m_{H\pm}$ → T = 0

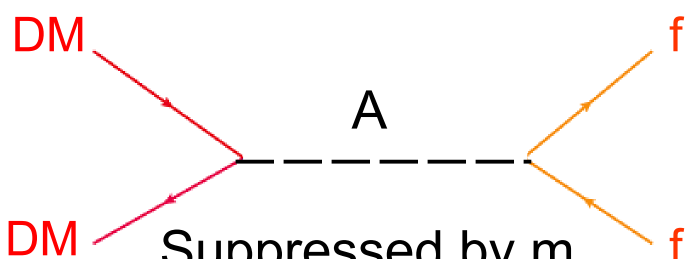
Direct and indirect DM detection

Thermal relic

tanβ

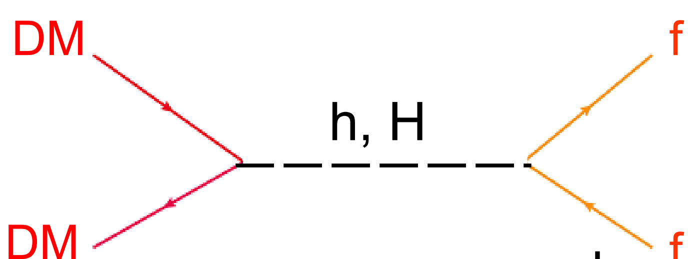


Suppressed by m_f



Suppressed by m_f

Can be enhanced by tanβ



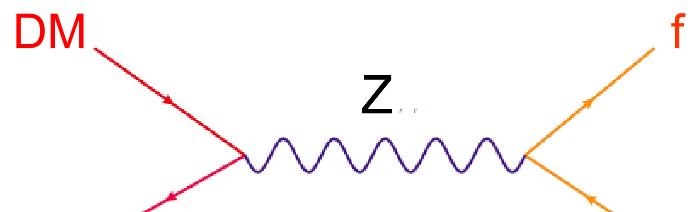
p-wave suppressed

<u>Conclusion:</u> at sizable **tanβ**, it is easier to get a thermal relic DM

Direct and indirect DM detection

Thermal relic

tanβ



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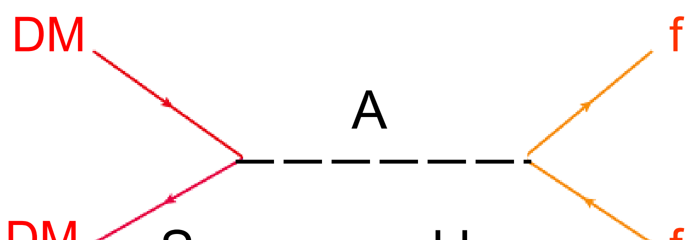

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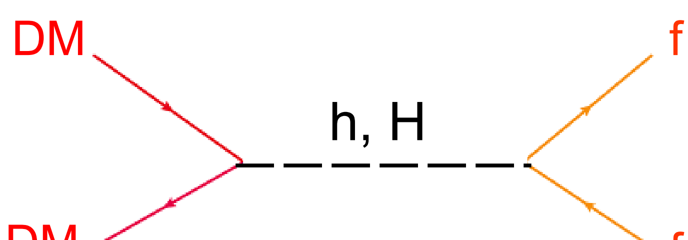

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Conclusion: at sizable **tanβ**, it is easier to get a thermal relic DM

Direct detection

tanθ

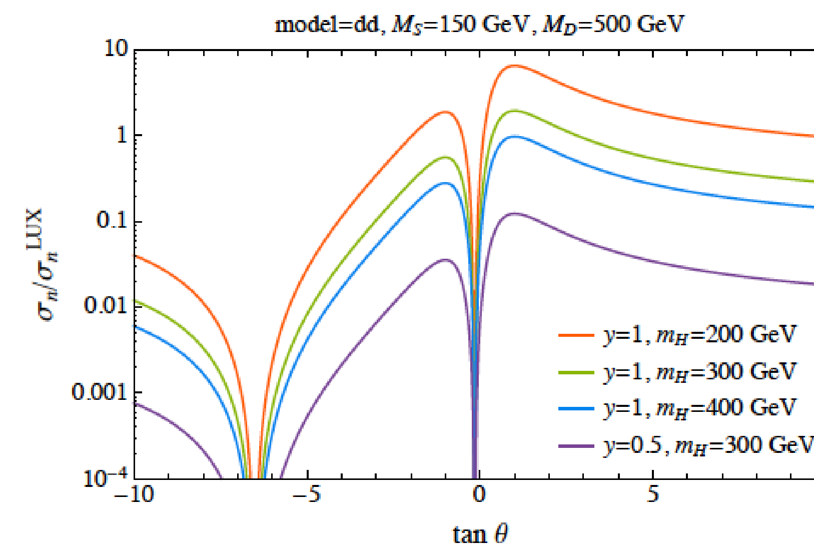
- Spin independent: h, H mediated

$$\sigma_0 \propto \mu^2_{\chi,h}\left(-\frac{\lambda_{\chi h}}{m_h^2}+\frac{\lambda_{\chi H} q_{\beta H}}{m_H^2}\right)$$

$$q_{u(d)H} = \frac{1}{\tan\beta}\;(-\tan\beta)$$

Several blind spots arise for **tanθ < 0**

Eg. in the dd model, both contributions are 0 for $m_\chi + M_D \sin(2\theta) = 0$

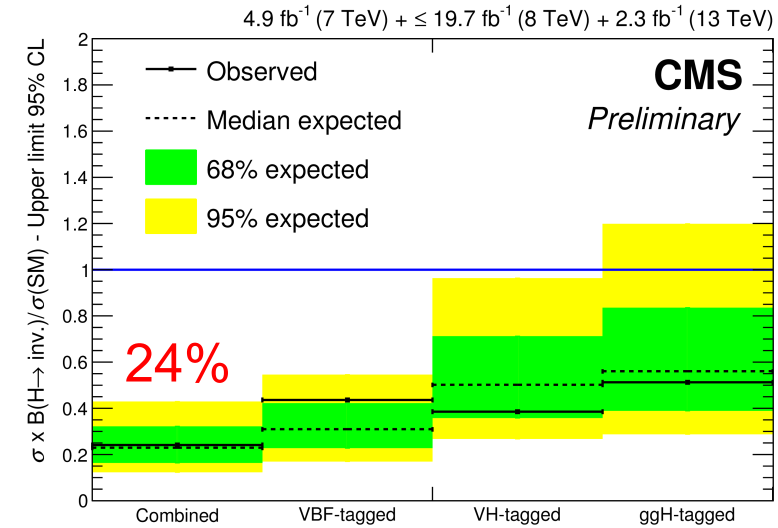


- Spin dependent: Z (and A) mediated

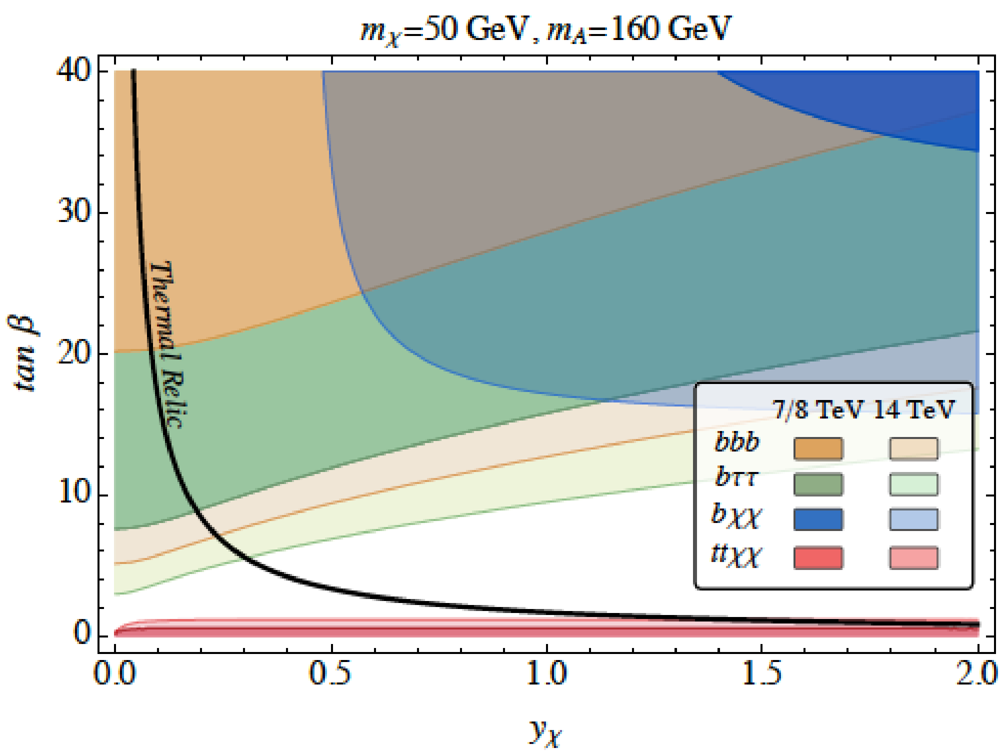
Additional probes (scalar sector)

- **Higgs (and Z) invisible decays.**
  Constraints from the LHC and from LEP

$$\Gamma(Z \to \chi\chi) \lesssim 2\ \mathrm{MeV}$$



- **Direct (LHC) and indirect (flavor experiments) searches for new scalars**



Flavor constraints mainly for the charged Higgs boson

eg. from b → sγ

$$m_{H^\pm} \gtrsim 480\ \mathrm{GeV}$$

Misiak, 1503.01789

Possible plane to be used for the interpretation of the LHC searches

Additional probes (EW-ino sector, 1)

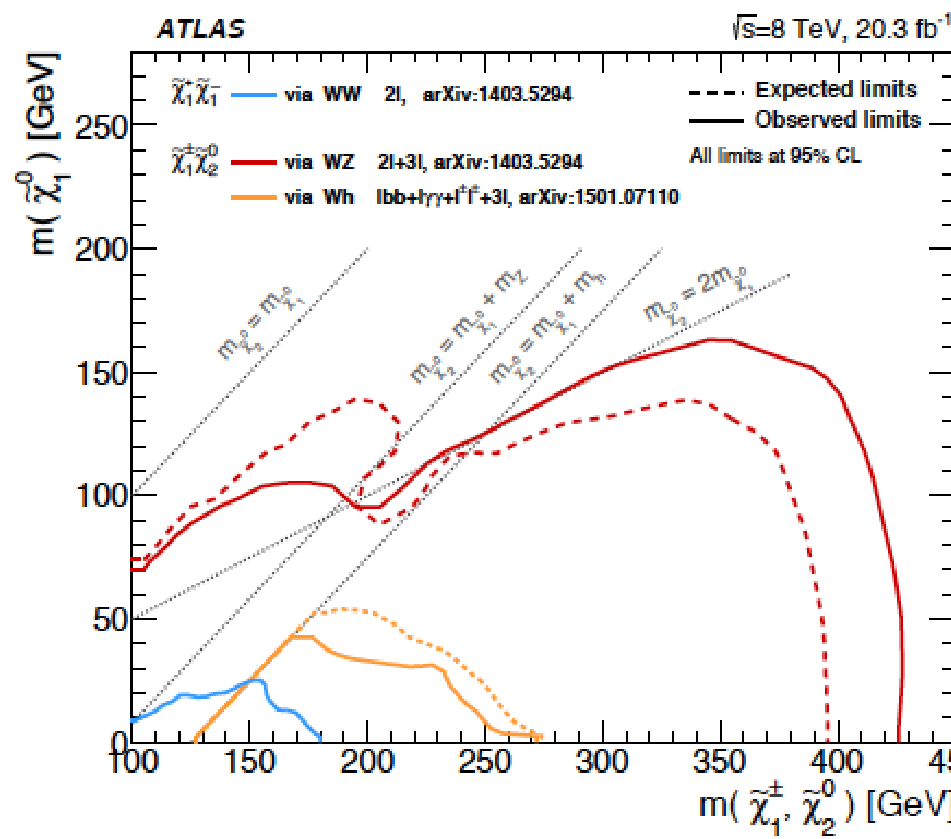
- LHC electro-weakino searches

- These bounds are for Wino-like NLSPs

In our case (~Higgsino-like) the bound on the mass will be weaker

- Also, in our model, new decay modes can be open (eg. $X_2 \to A\, X_1$) and this will affect the bound

- No bound beyond LEP for DM with masses above ~150 GeV



Available

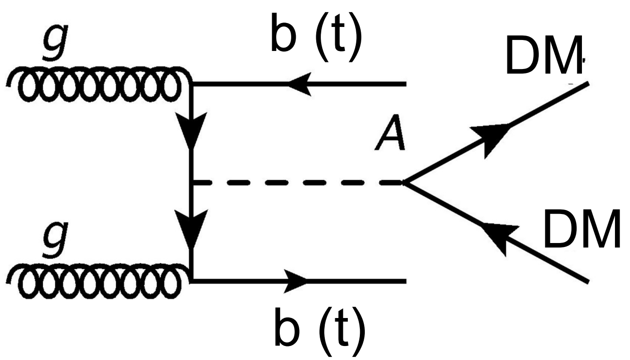
For the re-interpretation, we can provide the MadGraph model for our scenario

Additional probes (EW-ino sector, 2)

- **Mono-X searches**

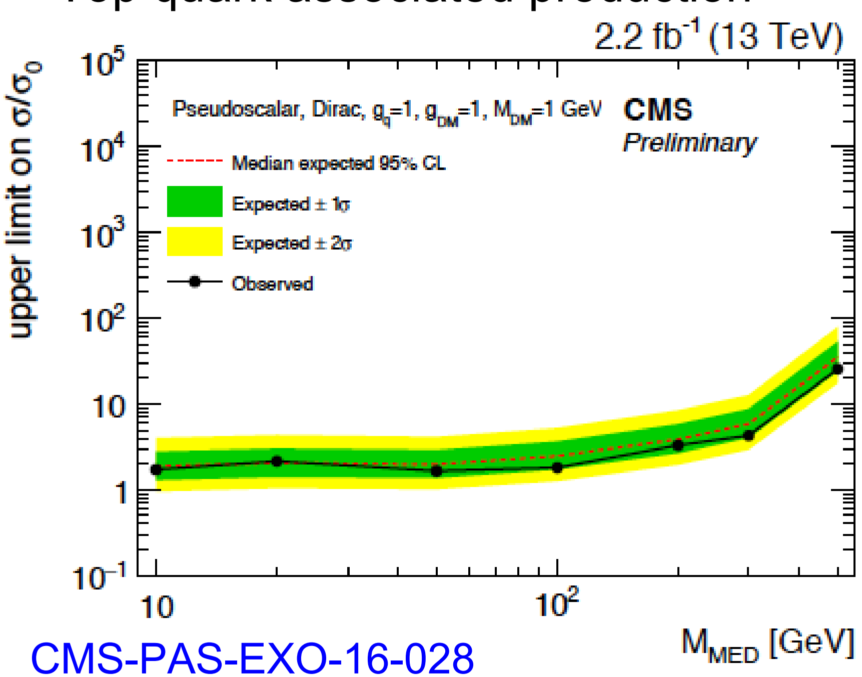
Mono-b and mono-top searches are particularly interesting

See eg. Cheung et al, 1207. 4930
Lin, Kolb, Wang, 1303.6638



Example:

Top quark associated production



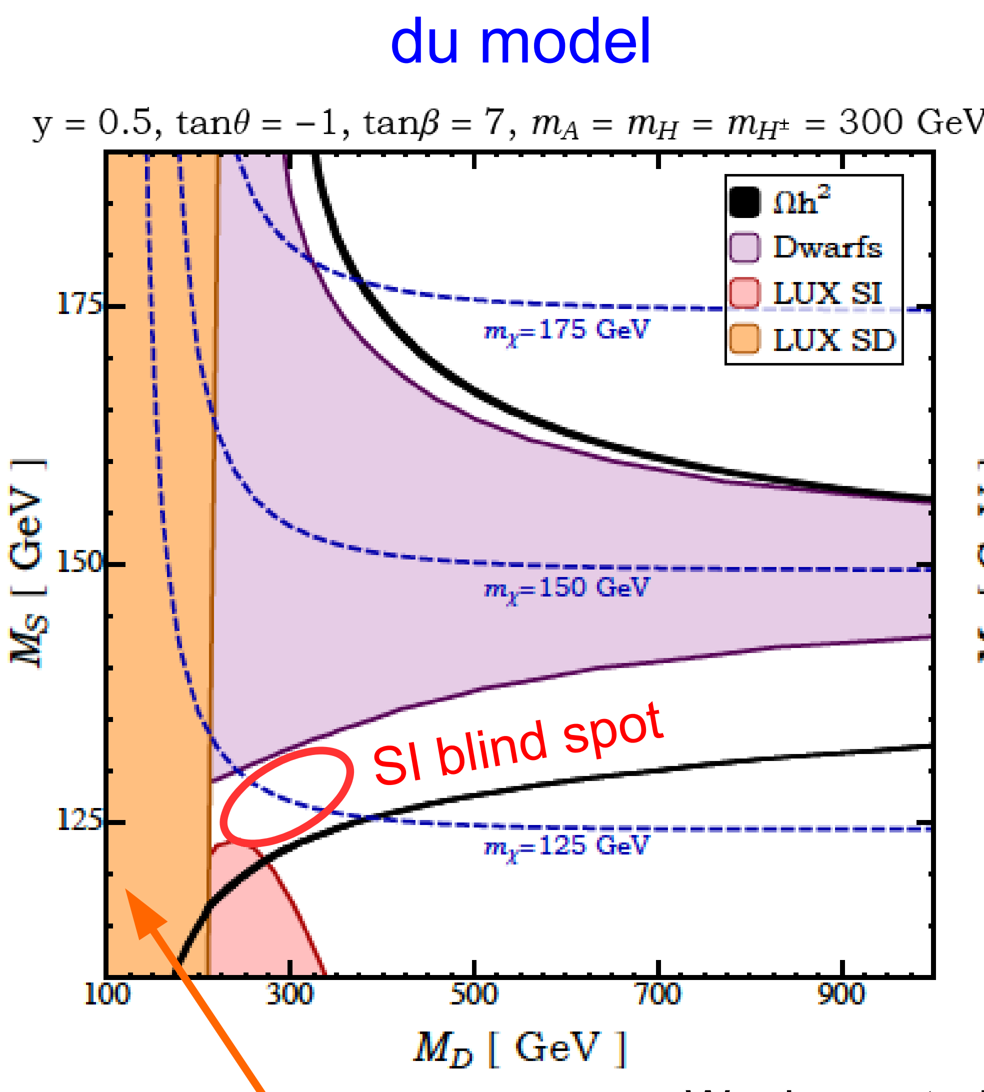
CMS-PAS-EXO-16-028

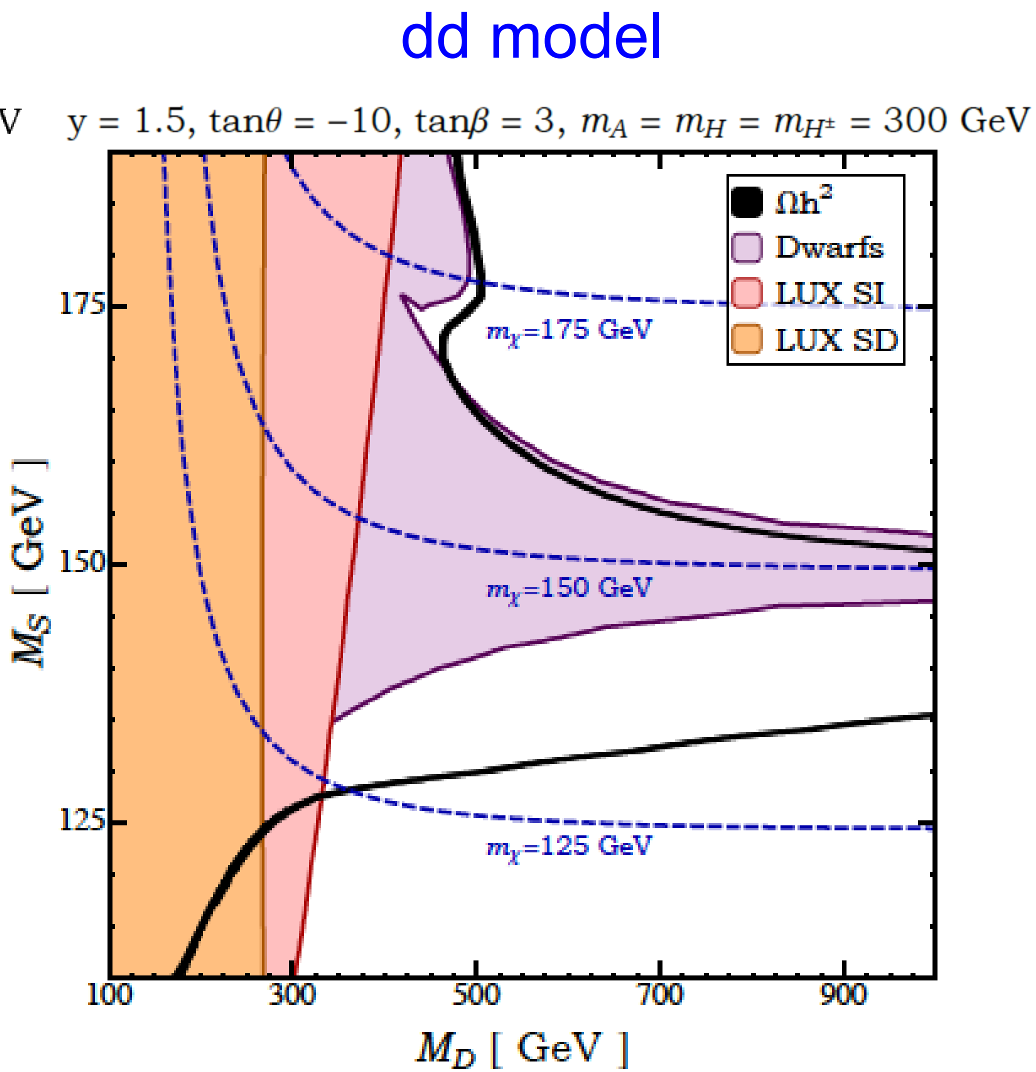
Still relatively weak limits, but they will get there...

In our model, (small) changes in the re-interpretation since additional Z-mediated contributions

For the re-interpretation, we can provide the MadGraph model for our scenario

Open parameter space (~heavy DM)





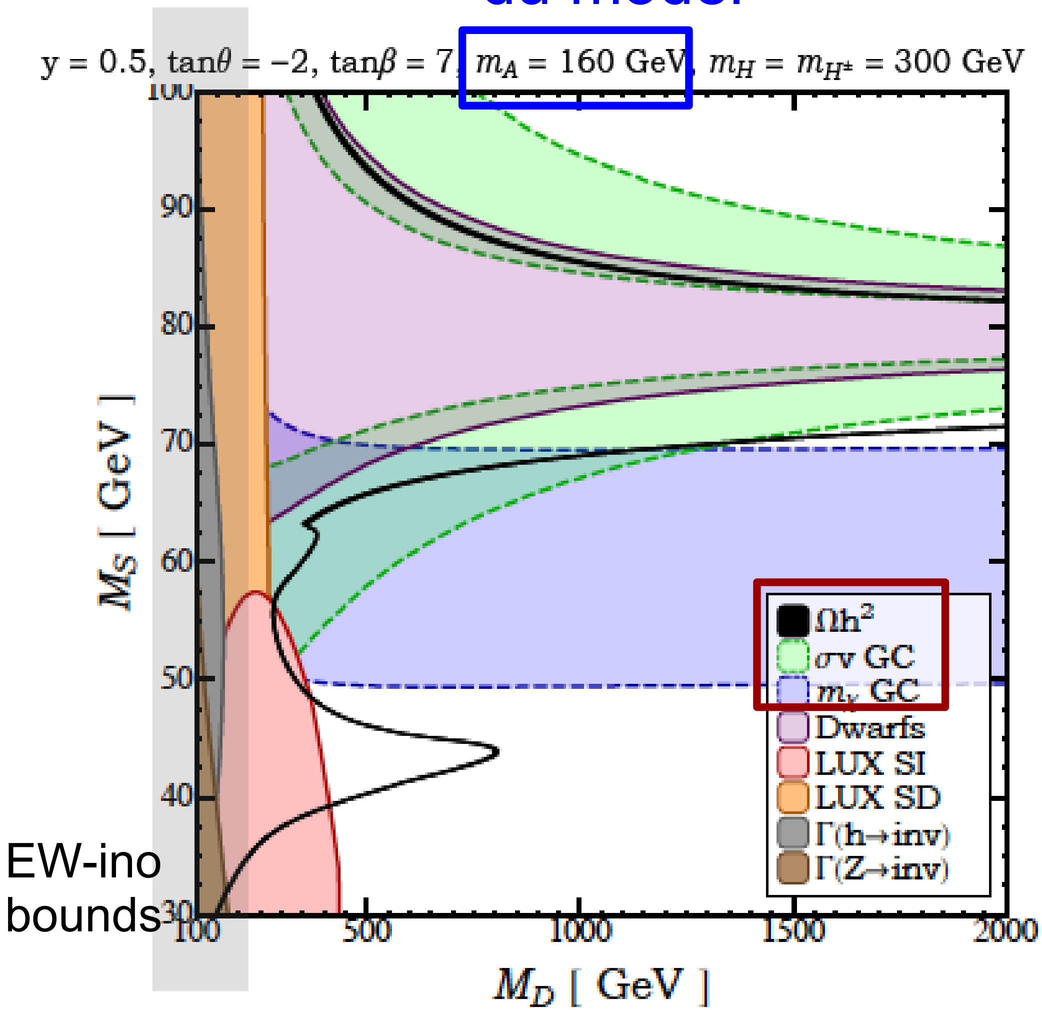
SD direct detection
at large doublet-component

Weak constraints from
EW-ino and mono-X
searches

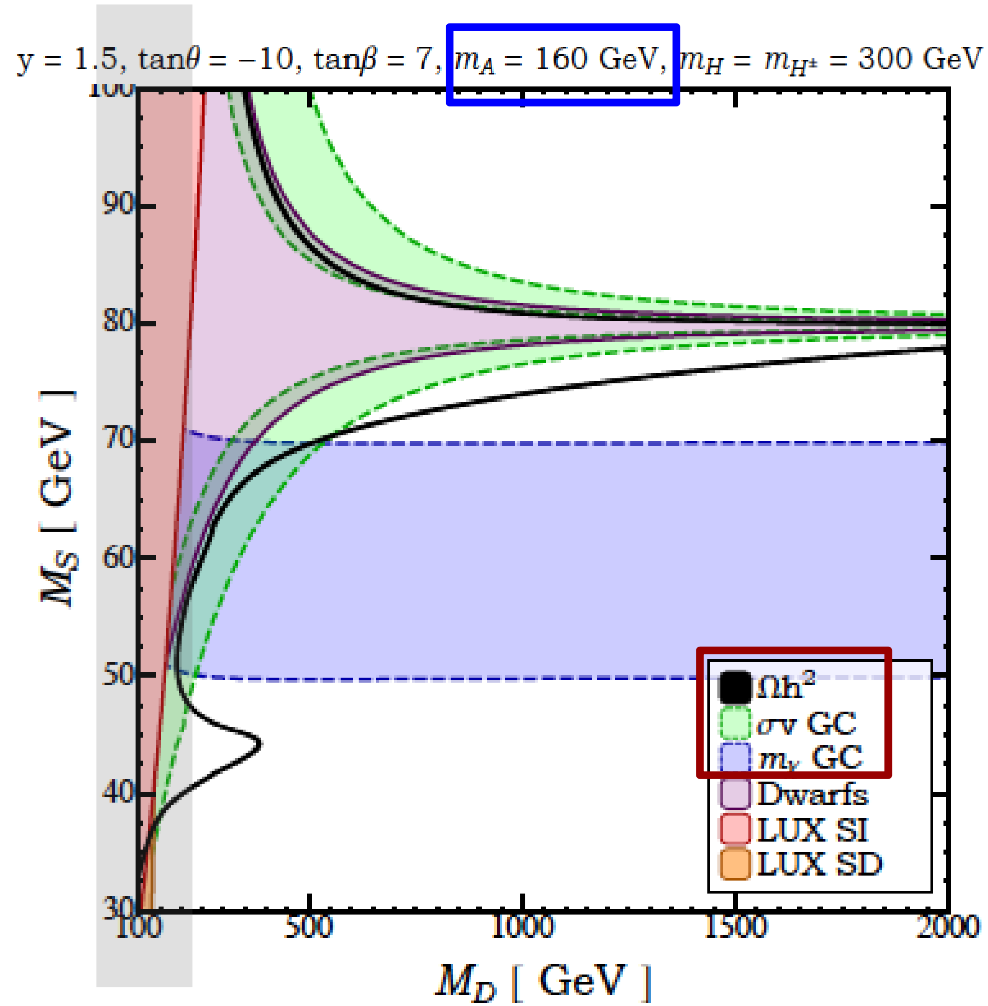
Region not too far away from
the "A-funnel" is favored

Open parameter space (~light DM)

du model



dd model



A light DM with mass below 100GeV can be accommodated, if the pseudoscalar has a mass below ~200GeV.

Also the galactic center excess can be fitted

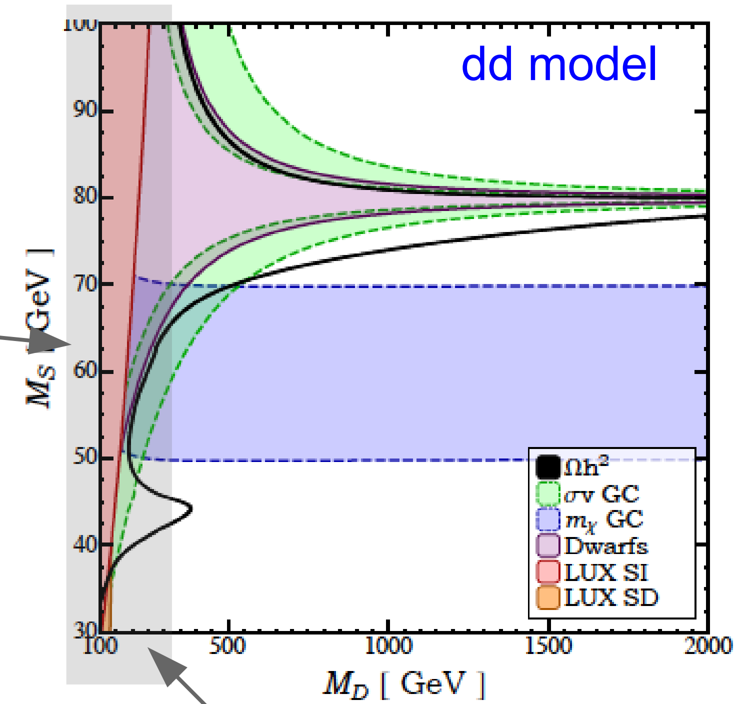
Note: for our study, we take the GCE best fit has shown in Calore et al. 1411.4647

Future tests of the model

✖ Future stages of

- direct detection experiments (Xenon1T, LZ, …)
- LHC EW-ino searches

will probe additional regions of parameter space (especially in the light DM case)



Recasting the "prospect paper" ATL-PHYS-PUB-2014-010, 300fb^{-1}

✖ Mono-heavy quark searches will start to be sensitive (interesting new interpretation in terms of our model)

✖ New interesting searches could be performed at the LHC:

- new EW-ino searches: eg. $pp \to X^\pm X_2 \to (WA)\, X_1 X_1$, $A \to bb, \tau\tau$, …
- new heavy Higgs searches: eg. $H^\pm \to X^\pm X_1$, $H \to X_1 X_2$, …

Work in progress with Zhen Liu and Bibhushan Shakya

Summary & Conclusions

- Very interesting DM benchmark models arising from 2HDMs
- Requiring minimality: DM = mixture of singlet and doublet states
- uu, dd, du and ud benchmark models with free parameters

$$m_H, \ m_A, \ m_{H^\pm}, \ M_D, \ M_S, \ y, \ \tan\beta, \ \tan\theta$$

generalization of the MSSM
Bino-Higgsino scenario

The Madgraph model
is available

- Interesting complementarity of
  - Mono-X searches (in particular, mono-heavy quark searches)
  - searches for additional Higgs bosons
  - searches for new EW states
  - DM direct and indirect detection
- Large set of new signatures for the additional Higgs bosons & for the new EW states