Consistent Models of Dark Matter at the LHC

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arXiv:1712.06597

DM@LHC Heidelberg
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INTERNATIONAL MAX PLANCK RESEARCH SCHOOL

PTFS FOR PRECISION TESTS OF FUNDAMENTAL SYMMETRIES

Model Landscape

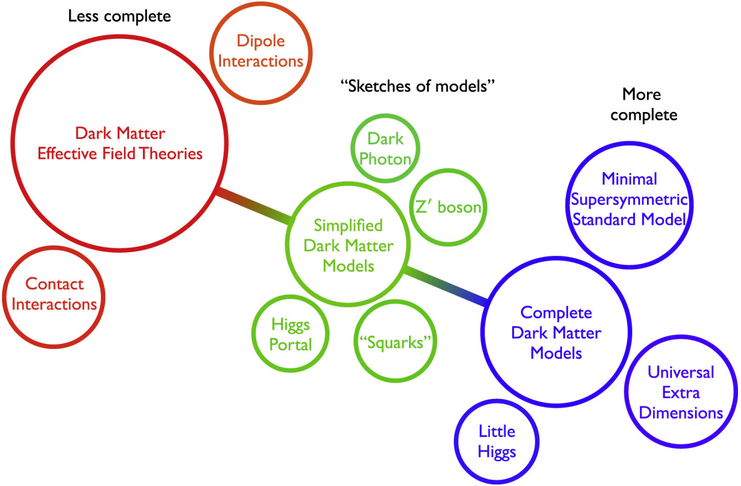
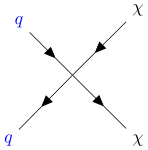


Image: doi.org/10.1016/j.dark.2015.08.001

DM EFT vs. Simplified Models

$$\mathcal{L}_{\mathsf{EFT}} = \frac{1}{\Lambda^2}\,\bar{q}\gamma_5 q\bar{\chi}\gamma_5\chi$$



$$p^2 \ll \Lambda^2$$

Break down @LHC
→ Restore Mediator
[Talk by K. Schmidt-Hoberg]

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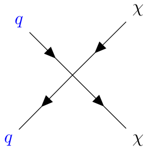

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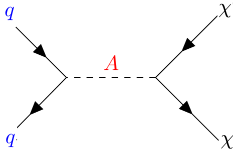
[Talk by K. Schmidt-Hoberg]

$$\mathcal{L}_{\mathsf{simp}} = g_q A\bar{q}_L\gamma_5 q_R + g_\chi A\bar{\chi}_L\gamma_5\chi_R$$



$$\propto \frac{g_q g_\chi}{p^2 - M^2}$$

Not gauge invariant

→ Violate Unitarity

[Talks by F. Kahlhoefer, G. Polesello]

Consistent Model for Pseudoscalar

(One) minimal solution to restore Gauge Invariance
→ Embedding the Pseudoscalar in a 2nd Higgs Doublet

Universal signals → Coupling to DM via effective operators

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$$+ \frac{c_\chi}{\Lambda} H_u^\dagger H_d \bar{\chi}\chi + \frac{c_5}{\Lambda} H_u^\dagger H_d \bar{\chi}\gamma_5\chi + h.c.$$

Free (physical) Parameters:

$$M_A,\ M_H,\ M_{H^\pm},\ \tan\beta,\ \cos(\beta-\alpha),\ c_\chi,\ c_5,\ m_\chi$$

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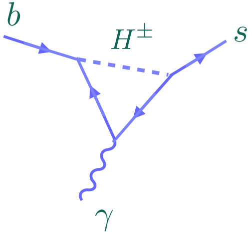
Flavour & Electroweak Precision Bounds

Flavour observables lead to:

$$M_{H^\pm} > 480 \text{ GeV}$$

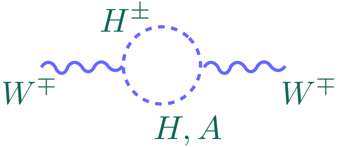
Phys. Lett. B 302, 435 (1993)



Z-$W^\pm$ - mass relation leads to

$$M_H^\pm \approx M_A$$

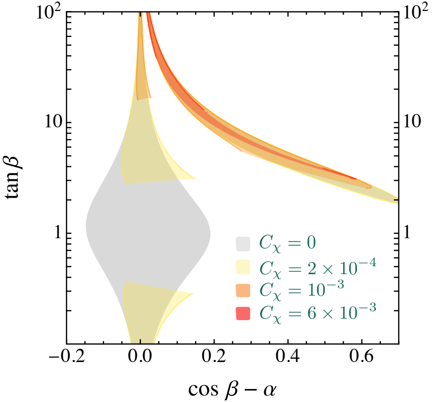
or $$M_H^\pm \approx M_H$$



hep-ph/0703051, 1011.5228

$$M_A,\ M_H,\ M_{H^\pm},\ \tan\beta,\ \cos(\beta-\alpha),\ c_\chi,\ c_5,\ m_\chi$$

Higgs Signal Strength

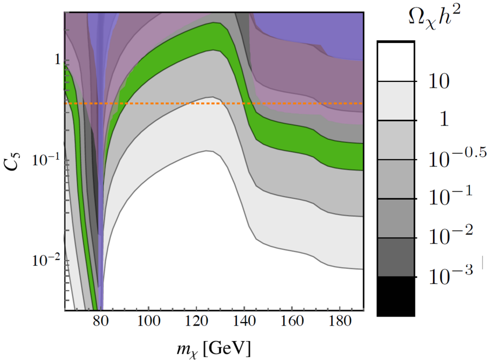


- 2HDM of Type II
- $m_\chi = 0$
- Disfavors scalar DM couplings
- Alignment limit $\cos(\beta-\alpha)\approx 0$

$M_A,\ M_H,\ M_{H^\pm},\ \tan\beta,\ \cos(\beta-\alpha),\ c_\chi,\ c_5,\ m_\chi$

1606.02266 (ATLAS & CMS), 1509.00672 (ATLAS), 1610.09218 (CMS)

Relic Density & Indirect Detection



- $m_A = 160$ GeV
- $\tan\beta = 1$
- $c_\chi = 0$
- $\cos(\beta - \alpha) = 0$
- $M_H = M_{H^\pm} = 500$ GeV

Choose: $C_5 = 0.37 \quad \rightarrow \quad m_\chi \approx 70$ GeV

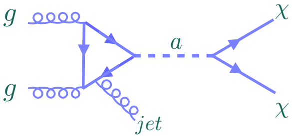
$M_A,\ M_H,\ M_{H^\pm},\ \tan\beta,\ \cos(\beta-\alpha),\ c_\chi,\ c_5,\ m_\chi$

1609.04026 (CMB), 1706.01505 (CTA Prospects)

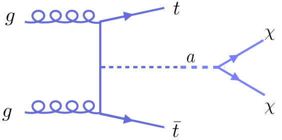
Collider Channels

Intital State Radiation:

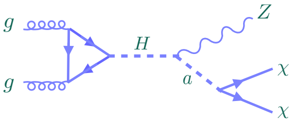
mono-jet $>$ mono-γ $>$ mono-Z $>$ mono-h



Mono-jet



$t\bar{t}A$ Production



Mono-Z

Resonantly enhanced if

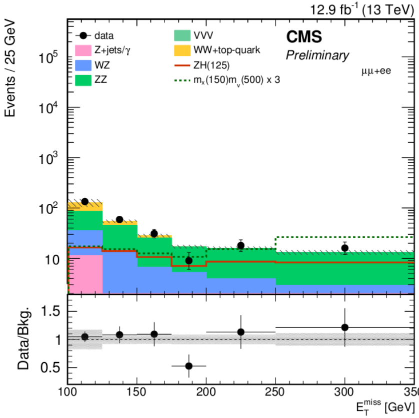
$M_H \geqslant M_A + M_Z$

CMS Mono-Z at 12.9fb^{-1} CMS PAS EXO-16-038

DM signal via t-loop only

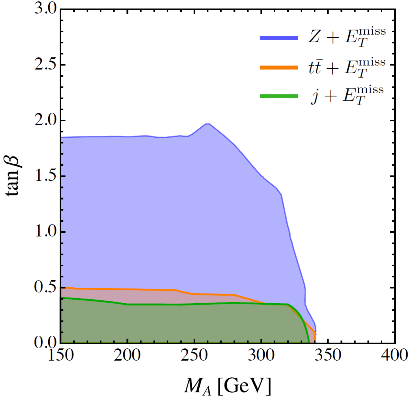
Cuts:

	Variable	Requirements
Preselection	p_T^ℓ	$>25/20$ GeV (electrons)
		>20 GeV (muons)
	Dilepton mass	$m_Z - 15 < m_{ll} < m_Z + 10$
	Jet counting	≤ 1 jets with $p_T^j > 30$ GeV
	$p_T^{\ell\ell}$	>60 GeV
	3rd-lepton veto	$p_T^{e,\mu} > 10$ GeV
	Top quark veto	0 b jets with $p_T > 20$ GeV
Selection	$\Delta\phi_{\ell\ell,\vec{p}_T^{\,miss}}$	> 2.8 rad
	$\lvert E_T^{miss} - p_T^{\ell\ell}\rvert / p_T^{\ell\ell}$	< 0.4
	$\Delta\phi(\text{jet}, E_T^{miss})$	> 0.5 rad
	E_T^{miss}	>100 GeV
	τ_h veto	0 τ_h candidates with $p_T^\tau > 18$ GeV



Implementation checked against $ZZ \to ee + E_T^{\text{miss}}$

Collider Bounds



- $m_\chi = 70$ GeV
- $C_5 = 0.37$
- $c_\chi = 0$
- $\cos(\beta - \alpha) = 0$
- $M_H = M_{H^\pm} = 500$ GeV

Resonantly enhanced Mono-Z production provides the strongest bounds!

CMS PAS EXO-16-038 ($Z + E_T^{\text{miss}}$), CMS PAS EXO-16-005 ($t\bar{t} + E_T^{\text{miss}}$), ATLAS-CONF-2017-060 ($j + E_T^{\text{miss}}$)

Summary and Outlook

- Consistent model for Pseudoscalar-mediator @LHC
- Universal signal: Resonantly enhanced Mono-Z

- Constraints lead to similar parameter region
- Left over region testable by future LHC runs!

- Also relevant $H^\pm \to tW^\pm A \to tW^\pm \bar{\chi}\chi$
  [Talk by P.Pani] 1712.03874

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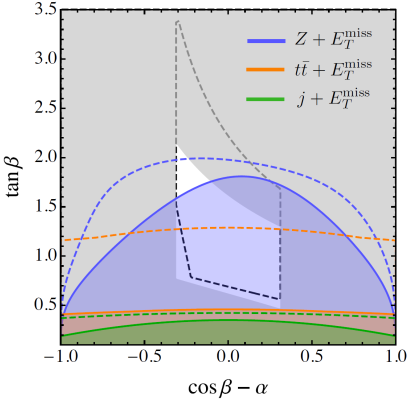
Thanks for your attention!

Final Result



Mono-Z searches have the potential to exclude almost all of the parameter space!

Examples of possible UV completions

Additional SM singlet pseudoscalar [1]

$$\mathcal{L} = \sum_{i,j=1}^{3} y^u_{ij} \bar{Q}_i H_u u_j + \sum_{i,j=1}^{3} y^d_{ij} \bar{Q}_i H_d d_j + \sum_{i,j=1}^{3} y^l_{ij} \bar{L}_i H_d l_j$$
$$+ \kappa a H_u^\dagger H_d + c_a a \bar{\chi} \gamma_5 \chi + h.c.$$

Additional electroweak fermion doublet $\psi = (\chi^+ \chi^0)$ [2]

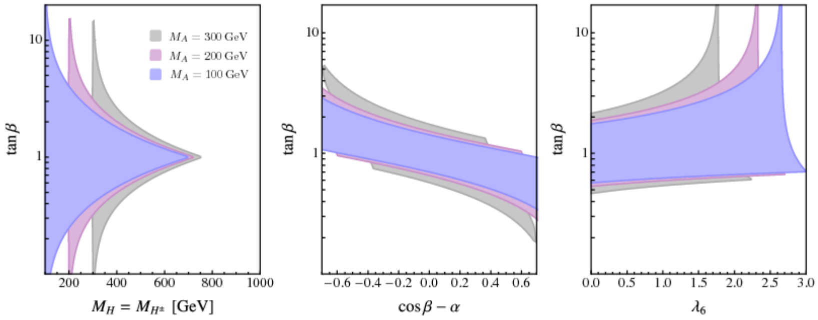
$$\mathcal{L} = \sum_{i,j=1}^{3} y^u_{ij} \bar{Q}_i H_u u_j + \sum_{i,j=1}^{3} y^d_{ij} \bar{Q}_i H_d d_j + \sum_{i,j=1}^{3} y^l_{ij} \bar{L}_i H_d l_j$$
$$+ c_1 \bar{\psi} H_u^\dagger \chi + c_2 \bar{\psi} \tilde{H}_d \chi + h.c.$$

[1] M. Bauer, U. Haisch, F. Kahlhoefer, 1701.07427

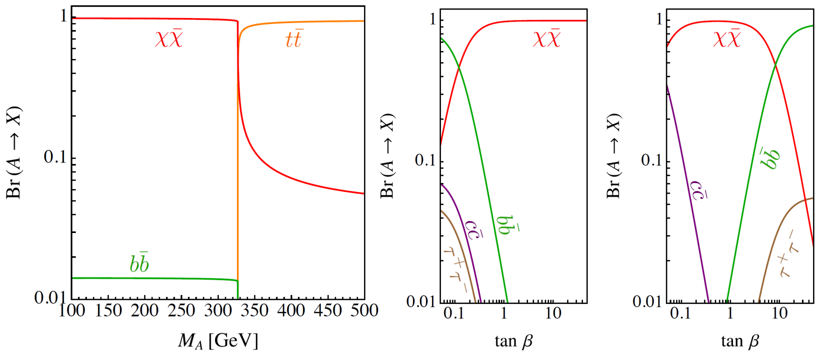
[2] A. Freitas, S. Westhoff, J. Zupan, 1506.04149

Unitarity, Perturbativity & Stability Requirements

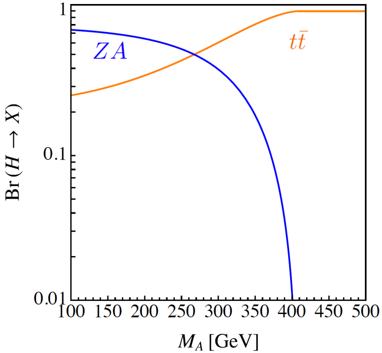
$$\lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_3 > -\sqrt{\lambda_1 \lambda_2}, \quad \lambda_3 + \lambda_4 + \sqrt{\lambda_1 \lambda_2} > 0$$

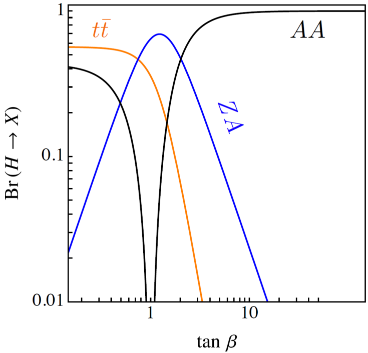


Branching Ratios A



Branching Ratios H





Branching Ratios $H^\pm$