Constraints on the Inert(1+2)HDM

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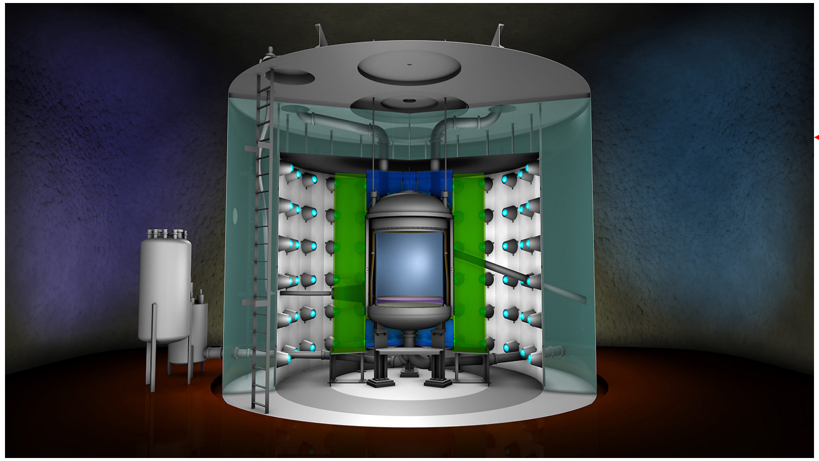
Motivation

- Necessary ingredient in other models, eg. SUSY, composite Higgs, twin Higgs, etc.
- Richer symmetry
- CP violation, [Sakharov ‘69]
- 1st order EW phase transition and Gravity Waves
- Dark Matter (DM) candidate: inert doublet models (this talk!)

Testability of Inert Models

Collider ⟷ Non-Collider

LHC



XENON 1T

The Inert(1+2)HDM

❖ Three Higgs doublets Φ_1, Φ_2, η

$$Z_2 : \quad \eta \to -\eta$$

Inert doublet: η

neutral $\chi, \ \chi_a$

charged $\chi^\pm$

Active doublets: Φ_1, Φ_2

CP-even $h, \ H$

CP-odd A

charged $H^\pm$

- Simplifying assumptions
  - No Flavor Changing Neutral Currents (FCNCs)
  - No CP violation (all parameters are real)
  - The scalar have relatively simple quartic couplings

- General Considerations
  - h is the SM Higgs boson and χ is the DM particle: $m_\chi < m_{\chi_a}, m_{\chi^\pm}$

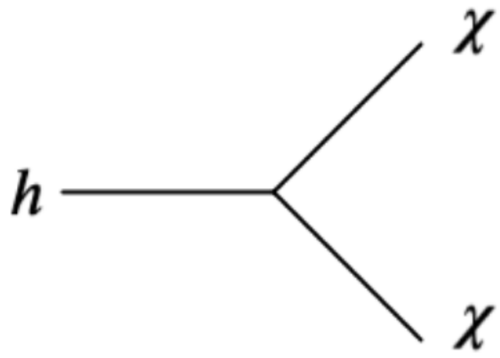
Potential

Potential between active and inert doublets

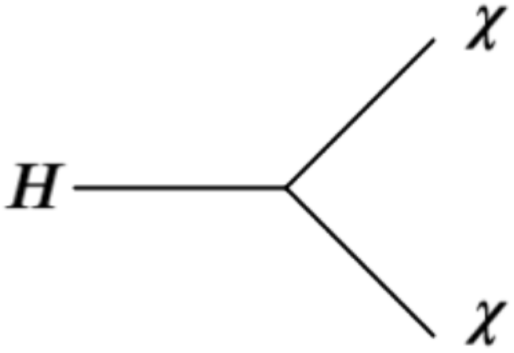
$$
\begin{aligned}
V_{123}(\Phi_1, \Phi_2, \eta) = \lambda_a & \left[(\Phi_1^\dagger \Phi_1)(\eta^\dagger \eta) + (\Phi_2^\dagger \Phi_2)(\eta^\dagger \eta)\right] \\
& + \lambda_b \left[(\Phi_1^\dagger \eta)(\eta^\dagger \Phi_1) + (\Phi_2^\dagger \eta)(\eta^\dagger \Phi_2)\right] \\
& + \frac{1}{2}\lambda_c \left[(\Phi_1^\dagger \eta)^2 + (\Phi_2^\dagger \eta)^2 + \text{h.c.}\right]
\end{aligned}
$$

$$
\boxed{\lambda_{abc} \equiv \lambda_a + \lambda_b + \lambda_c}
$$

Feynman Rules



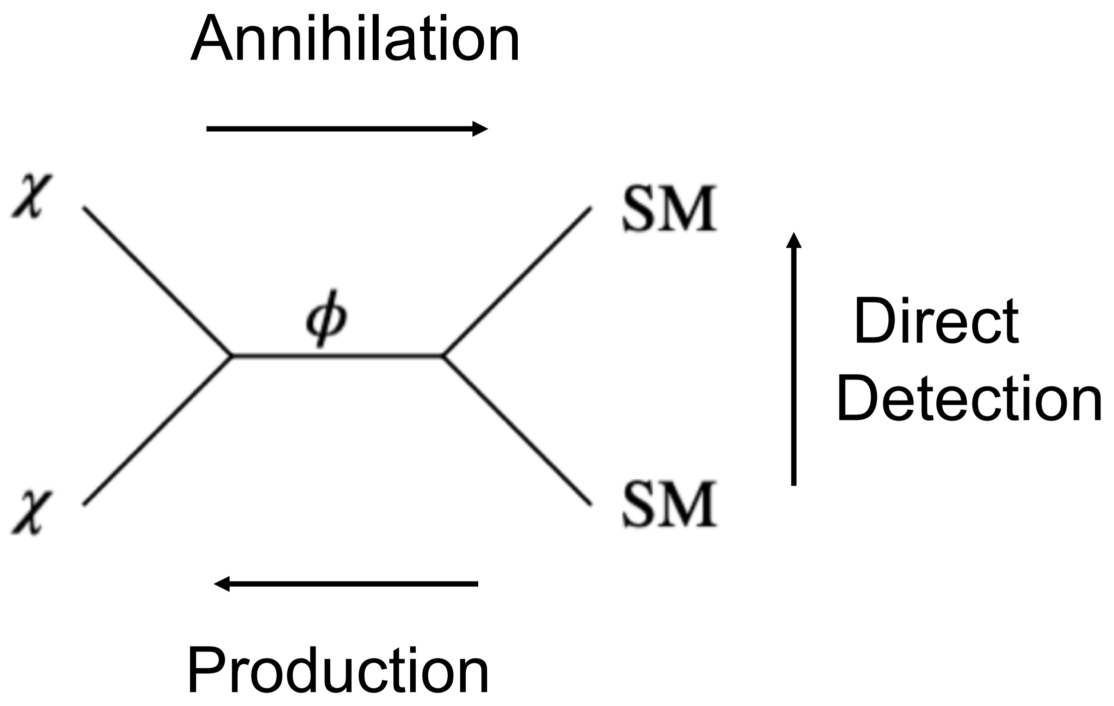
$$= i\ \lambda_{abc} v \sin(\beta - \alpha)$$ → Mixing Angles



$$= i\lambda_{abc} v \cos(\beta - \alpha)$$

Alignment Limit: $\cos(\beta - \alpha) \to 0$

Freeze Out Production



Relic density: $\Omega_{\rm DM} h^2 \simeq 0.120$

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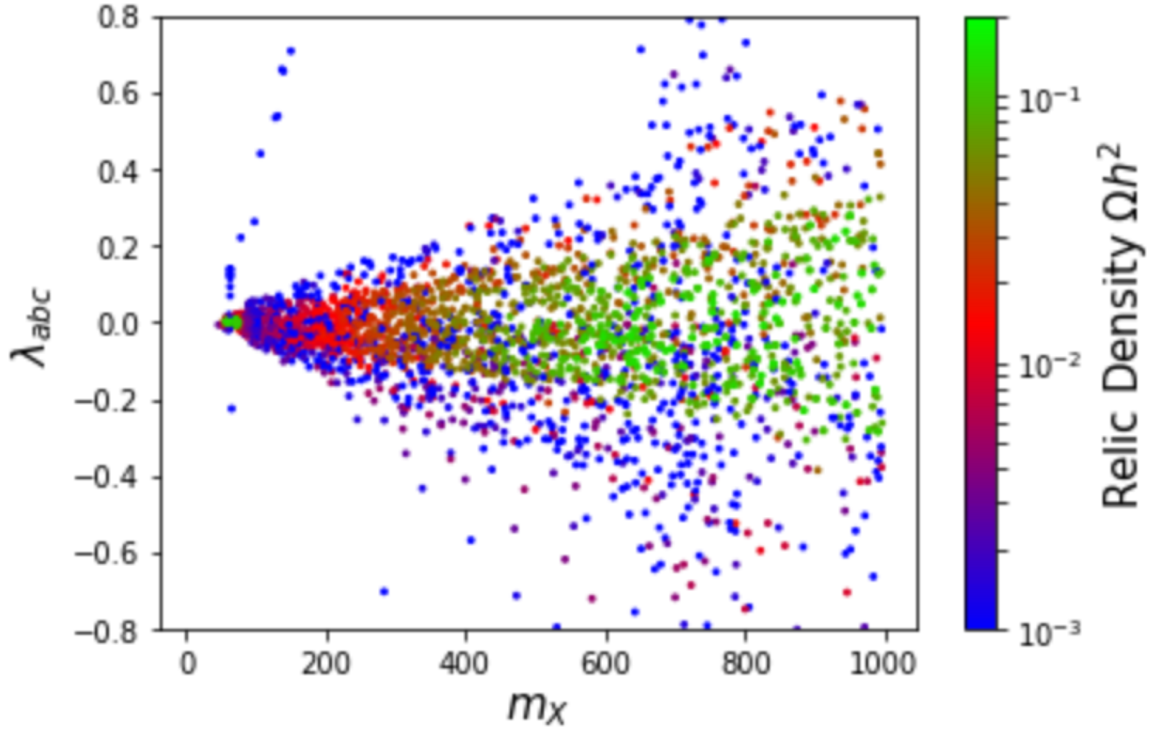
Results



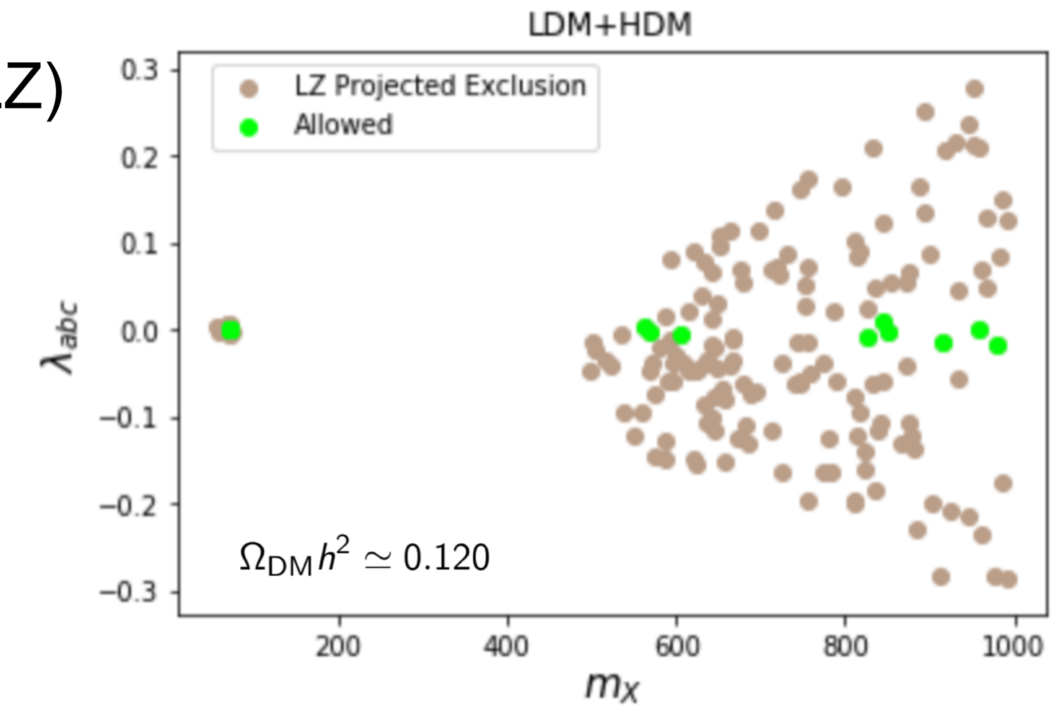
$$\Omega_{\mathrm{DM}} h^2 \simeq 0.120$$

$$m_\chi \in [53, 73] \;\; \mathrm{GeV}$$

$$m_\chi \in [500, 1000] \;\; \mathrm{GeV}$$

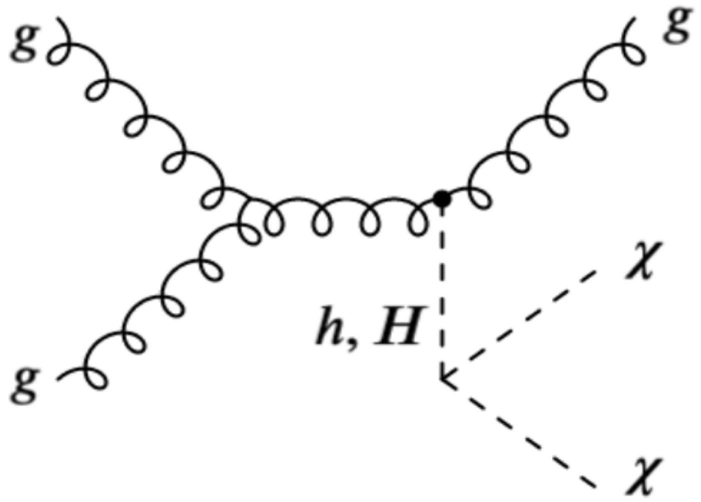
Projected Exclusions

- Projected bounds from LUX-ZEPLIN (LZ)
- Low mass $|\lambda_{abc}| \leq 5 \times 10^{-4}$
- High mass $|\lambda_{abc}| \leq 0.02$
- Best chance to discover DM!



Mono-object signals

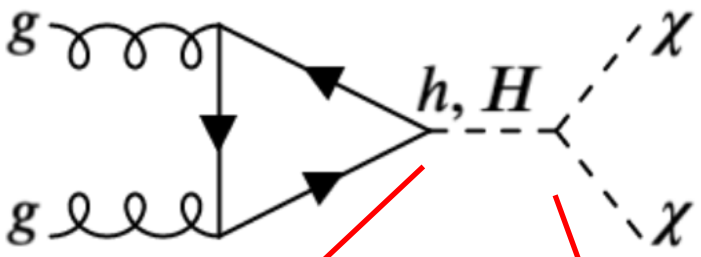
- Production of several final states in association with large missing transverse momentum.



Mono-jet production

- We calculated cross sections for mono-jet, mono-Z, mono-h
- Mono-jet production yields the strongest effects

Benchmark points

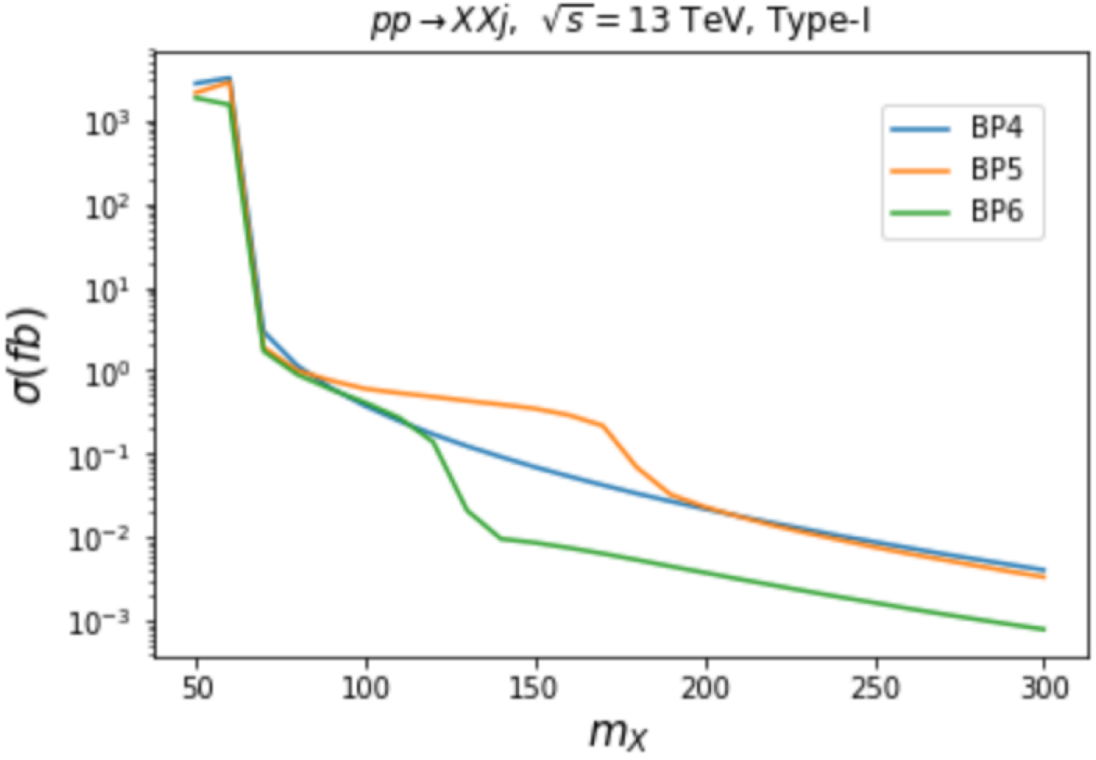


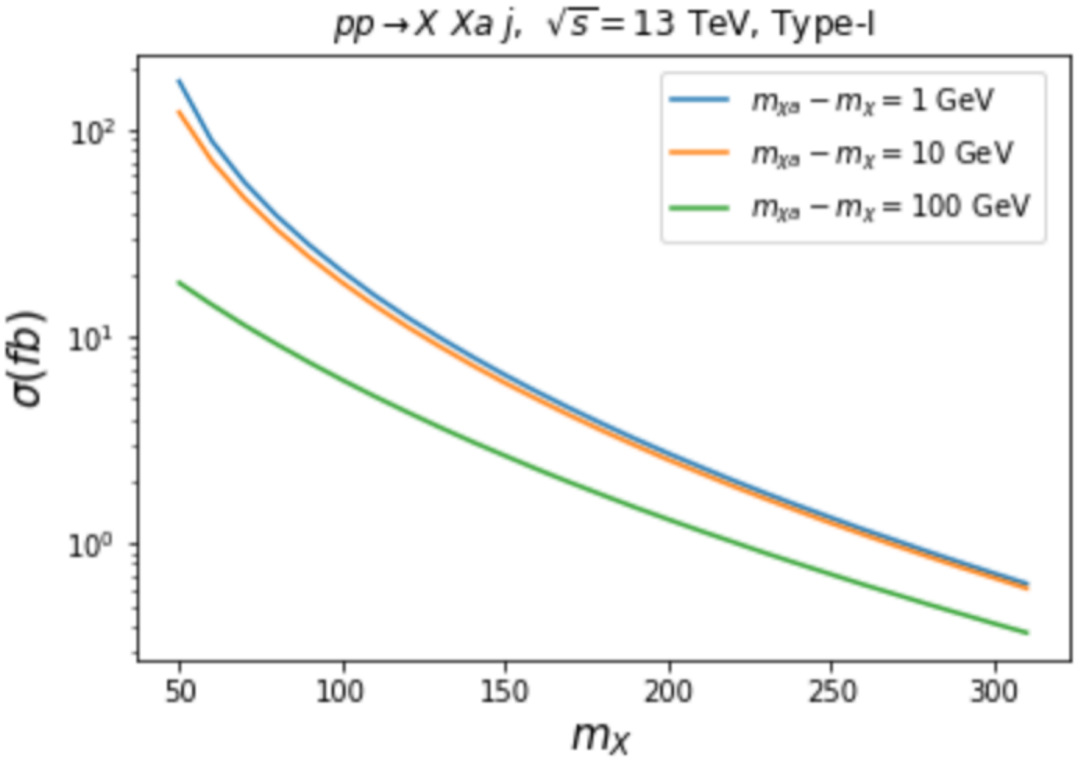
$$g_{htt}, g_{Htt} \propto \frac{1}{\tan\beta}$$

$$g_{h\chi\chi} \propto \lambda_{abc} \sin(\beta - \alpha)$$

$$g_{H\chi\chi} \propto \lambda_{abc} \cos(\beta - \alpha)$$

Mono-jet production





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Summary

- A reassessment of the CPC I(1+2)HDM has been performed with the most current experimental data.
- We have identified the regions of parameter space that give the right amount of relic abundance
- Presented the projected impact of DD experiments on the parameter space.
- Benchmark points for mono-object production have been provided and its signals investigated.
- The model is hard to test at LHC with current data

Thank you for your attention!

BACK UP

The Inert Doublet Model (IDM)

DM is stable ⟷ Exact Z_2 symmetry

Odd: $\eta = \begin{pmatrix} \chi^{\pm} \\ (\chi + i\chi_a)/\sqrt{2} \end{pmatrix}$ SM Higgs: $\Phi = \begin{pmatrix} 0 \\ (v + h)/\sqrt{2} \end{pmatrix}$

DM candidates (χ, χ_a)

IDM potential:

$$V = -m_{11}^2 \Phi^\dagger \Phi + m_{22}^2 \eta^\dagger \eta + \frac{\lambda_1}{2}(\Phi^\dagger \Phi)^2 + \frac{\lambda_2}{2}(\eta^\dagger \eta)^2 + \lambda_3 (\Phi^\dagger \Phi)(\eta^\dagger \eta) + \lambda_4 (\Phi^\dagger \eta)(\eta^\dagger \Phi) + \frac{1}{2}\left[\lambda_5 (\Phi^\dagger \eta)^2 + \text{h.c.}\right]$$

- Very well studied
- Five free parameters
- No CP violation allowed
- No tree-level FCNCs

Eigenstates

$$\eta = \begin{pmatrix} \chi^+ \\ (\chi + i\chi_a)/\sqrt{2} \end{pmatrix}$$

Physical

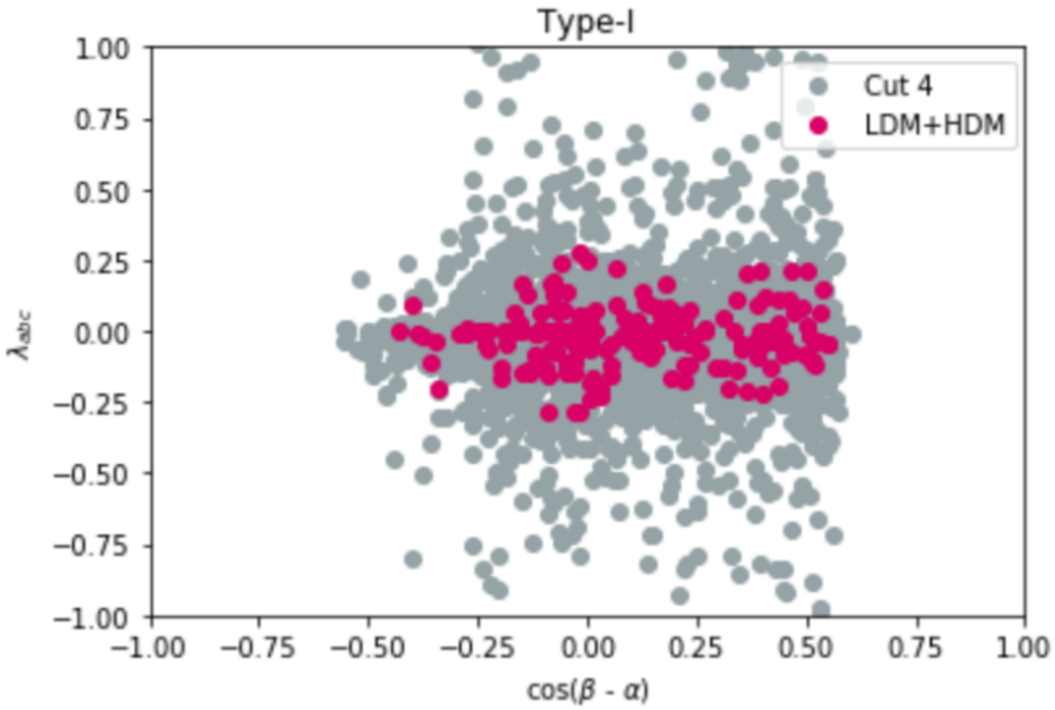
$$\Phi_i = \begin{pmatrix} \varphi_i^\pm \\ (v_i + \rho_i + \chi_i)/\sqrt{2} \end{pmatrix}$$

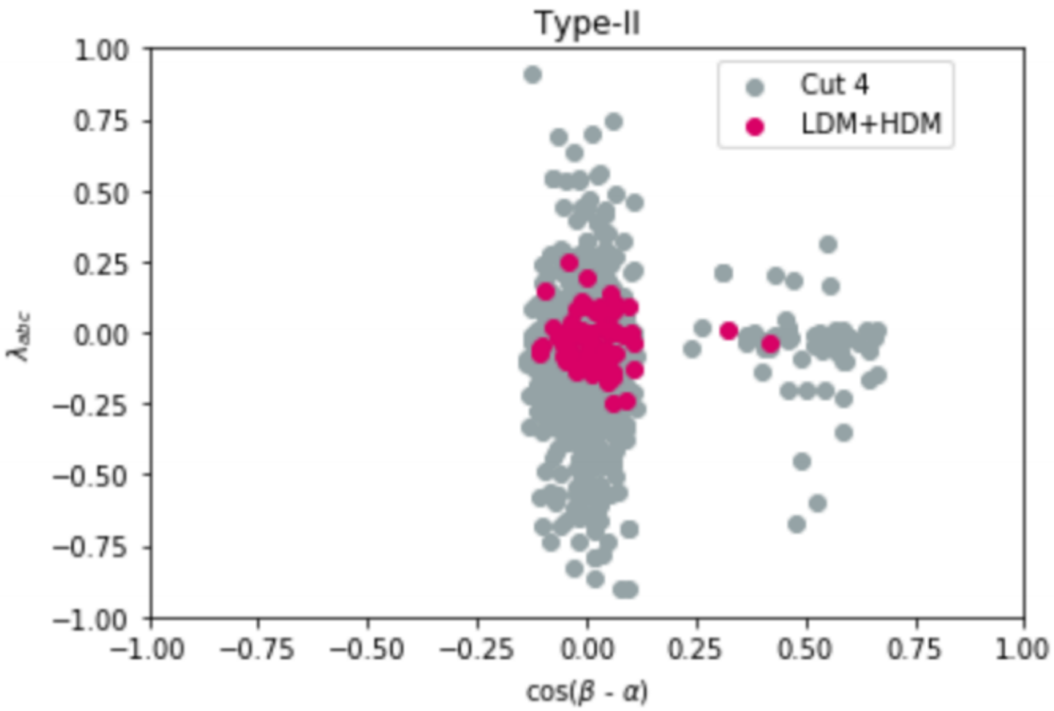
$$\begin{pmatrix} \varphi_1^+ \\ \varphi_2^+ \end{pmatrix} = \begin{pmatrix} c_\beta & -s_\beta \\ s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} G^+ \\ H^+ \end{pmatrix}$$

$$\begin{pmatrix} \chi_1 \\ \chi_2 \end{pmatrix} = \begin{pmatrix} c_\beta & -s_\beta \\ s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} G^0 \\ A \end{pmatrix}$$

$$\begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix} = \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$$

Mixing Angles





- Lower bound on relic density only at $|\lambda_{abc}|$
- Alignment lim $\cos(\beta - \alpha) \to 0$ h has SM couplings

Theoretical and experimental constraints

1. Positivity of the potential
2. Unitarity
3. Electroweak Precision Observables (EWPO)
4. B meson decays
5. LEP bounds
6. Higgs boson signal strengths and invisible decays
7. Heavy scalar searches
8. DM overabundance
9. Spin independent cross sections of DM with nucleons

Model Parameters

- The model has 12 free parameters:

Active $S_1 = \{m_h, m_H, m_A, m_{H^\pm}, m_{12}^2, \alpha, \beta\}$

Inert $S_2 = \{m_\chi, m_{\chi_a}, m_{\chi^\pm}, m_\eta^2, \lambda_\eta\}$

- General Considerations

h is the SM Higgs boson
and

$m_\chi < m_{\chi_a}, m_{\chi^\pm}$

Bounds on I2HDM

arXiv:1809.00933

- Need a more dedicated analysis but one can compare with derived limits for similar models
- The mono-jet production can be tested at the high luminosity LHC in the low mass region.