THEORY INTRODUCTION TO EXTENDED HIGGS MODELS

A dark matter phenomenology perspective

LCH DM 24 @ CERN

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Outline

01 MOTIVATIONS AND ASSUMPTIONS

- Many fermions but only 1 scalar discovered so far
- DM could be connected to SM through spin-0 or spin-1 particles
- New spin-1 resonances highly constrained
- Spin-1 with non-purely vector couplings requires new scalars
- Extended higgs sectors well motivated (MSSM/NMSSM, EW Baryogenesis, Neutrino masses)

- S-channel mediator
- Spin-0
- DM is SM singlet Fermion (scalar?)

↓

- DM can only couple to scalar that is SM singlet S
- SM fermions can only couple to SM higgs-like doublet ϕ

↓

- Need $S-\phi$ mixing!

02 MINIMAL MODELS: 2HDM+S/A

- One more assumption: CP-preserving → Cannot mix CP-even with C-odd
- Minimal: only one mixing

$$\mathcal{L} = -yS\bar{\chi}\chi$$

CP-Even

- Mix S with SM doublet ϕ?

Yes →

- DM search turns into higgs precision

No →

- Need <u>one additional doublet</u> for freedom on SM fermions-new scalar(s) couplings

$$\mathcal{L} = -iyP\bar{\chi}\gamma^5\chi$$

CP-Odd

- No pseudoscalar in the SM

→

- Need <u>one additional doublet</u>

02 MINIMAL MODELS: 2HDM+S/A

2HDM+s 1612.03475

CP-Even

- Mixing term $H_1^\dagger H_2 S$
- 3-scalar mixing $\rho_{1,2,3} \rightarrow h, H, s$
- 1 Pseudoscalar A
- 1 charged scalar $H^\pm$
- Only h, H, s can couple to both DM and SM fermions
- Rotation matrix for $\rho_{1,2,3} \rightarrow h, H, s$ constrained by higgs-strength

2HMD+a 1404.3716

CP-Odd

- Mixing term $H_1^\dagger H_2 P$
- 2-pseudoscalar mixing $\eta_{1,2} \rightarrow a, A$
- 2 Scalars h, H
- 1 charged scalar $H^\pm$
- Only a, A can couple to both DM and SM fermions
- Rotation matrix for $\rho_{1,2} \rightarrow |\cos(\alpha - \beta)| \ll 1$

02 MINIMAL MODELS: 2HDM+S/A

- 2HDM+a parameter space

$$V = m_{11} H_1^\dagger H_1 + m_{22} H_2^\dagger H_2 + m_{12}\left(H_1^\dagger H_2 + H_2^\dagger H_1\right) +$$
$$+ \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3\left(H_1^\dagger H_1\right)\left(H_2^\dagger H_2\right) + \lambda_4\left(H_1^\dagger H_2\right)\left(H_2^\dagger H_1\right)$$
$$+\lambda_5\left(\left(H_1^\dagger H_2\right)^2 + \left(H_2^\dagger H_1\right)^2\right)$$
$$+\frac{1}{2} m_{PP} P^2 + \lambda_P P^4 + \frac{1}{2}\lambda_{P1} P^2 H_1^\dagger H_1 + \frac{1}{2}\lambda_{P2} P^2 H_2^\dagger H_2 + i\mu P\left(H_1^\dagger H_2 - H_2^\dagger H_1\right)$$

- 13 parameters (CP-conserving, all real) +2 (DM yukawa and mass) – 2 constraints (v, m_h) = 13 free parameters
- Most DM phenomenology insensitive to λ_P ➡ Usually 12 parameters considered

02 MINIMAL MODELS: 2HDM+S/A

- 2HDM+a parameter space

$$m_{11}, m_{22}, m_{12}, \lambda_{1,2,3,4,5}, m_{PP}, \lambda_{P1}, \lambda_{P2}, \mu, y_\chi, m_\chi$$

Can be exchanged for

$$\boldsymbol{v}, \boldsymbol{m_h}, m_H, m_A, m_{H^\pm}, m_a, m_\chi, tan\beta, \cos(\alpha-\beta), sin\theta, y_\chi, \lambda_3, \lambda_{P1}, \lambda_{P2}$$

Fixed

- Benchmark point for run 2:
- $\cos(\alpha-\beta) = 0$ (several reasons)
- $tan\beta, sin\theta$ free parameters
- $m_H = m_{H^\pm}$ (custodial symmetry)
- $m_H = m_A (= m_{H^\pm})$ also adopted in some cases
- λ_3 satisfying BFB condition
- $\lambda_{P1} = \lambda_{P2} = \lambda_3$ to keep $\Gamma(H \to aa), \Gamma(A \to ha)$ small
- y_χ large enough to allow $BR(a \to \chi\chi) \sim 100\%$ for $m_a < 2m_t$
- $m_\chi = 10 GeV$ small enough to allow $BR(a \to \chi\chi) \sim 100\%$ for $m_a > 100 GeV$

03 THEORY CONSTRAINTS

- Unitarity: will set upper bounds on λ_i
- Perturbativity: possibly, you want to stay away from the unitarity limit
- Bounded from Below: set of inequalities to guarantee that the potential has global minimum. Will give minimum and maximum values of λ_i
- Stable vacuum: the chosen minima is the global one: condition involving parameters of the potential

- In the limit of large masses for the heavy scalars, mass splittings will be forced to be small due to the upper bounds on the couplings.

04 EWPT, FLAVOUR

- EWPT: S, T, U Peskin-Takeuchi parameters, with $T \propto \Delta\rho$

Assumption $\boldsymbol{m_H = m_{H^\pm}}$

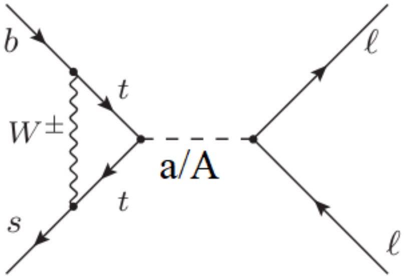
- For $\cos(\alpha-\beta)=0$, $\Delta\rho = \frac{1}{(4\pi)^2 v^2}\left(cos^2\theta f\left(m_{H^\pm}^2, m_A^2, m_H^2\right) + sin^2\theta f\left(m_{H^\pm}^2, m_a^2, m_H^2\right)\right)$
- $f(x,y,x)=0$ ➡ $m_H = m_{H^\pm}$ is sufficient to have $\Delta\rho = 0$
- Deviations from $m_H = m_{H^\pm}$ allowed as long as $\Delta\rho \in [-1.6\cdot 10^{-3}, 2\cdot 10^{-3}]$
- Some mass hierarchies can only give a certain sign of $\Delta\rho$

Assumption $\boldsymbol{cos(\alpha-\beta)=0}$

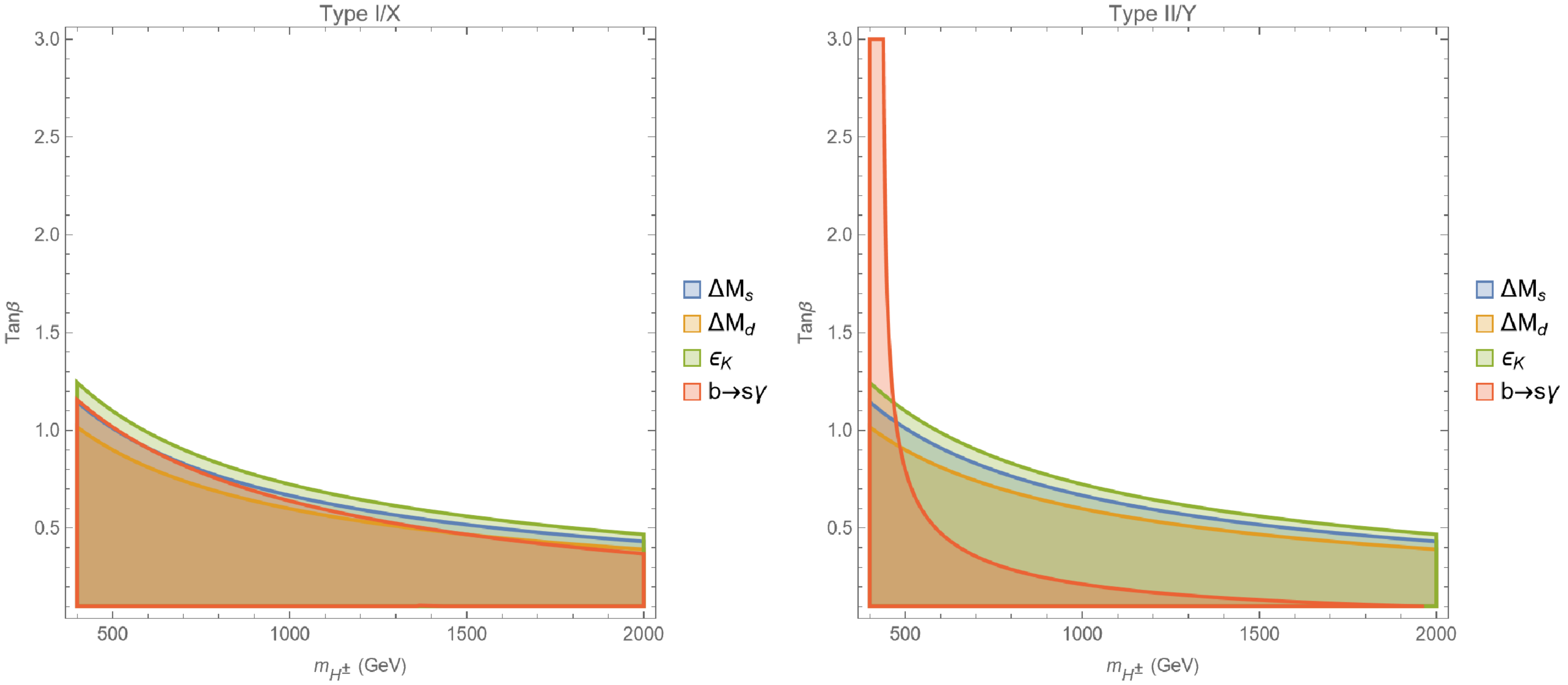
- For $m_H = m_{H^\pm}$ and $\cos(\alpha-\beta)\neq 0$, $\Delta\rho \propto cos^2(\alpha-\beta)$
- Small deviations from $\cos(\alpha-\beta)=0$ allowed

04 EWPT, FLAVOUR

- Flavour: $B_s \to \mu\mu, b \to s\gamma, \Delta M_{s,d}, \epsilon_K$
- $b \to s\gamma, \Delta M_{s,d}, \epsilon_K$ driven by $H^{\pm}$ ➡ only depend on $m_{H^{\pm}}, tan\beta$
- $B_s \to \mu\mu$ gets contributions from neutral scalars ➡ depends on all masses, $tan\beta, \cos(\alpha - \beta), sin\theta$
- $b \to s\gamma$ provides low limit on $m_{H^{\pm}}$ for Type II/Y
- $B_s \to \mu\mu$ provides a lower (Type II: also upper) limit on $tan\beta$ for fixed m_a



04 EWPT, FLAVOUR



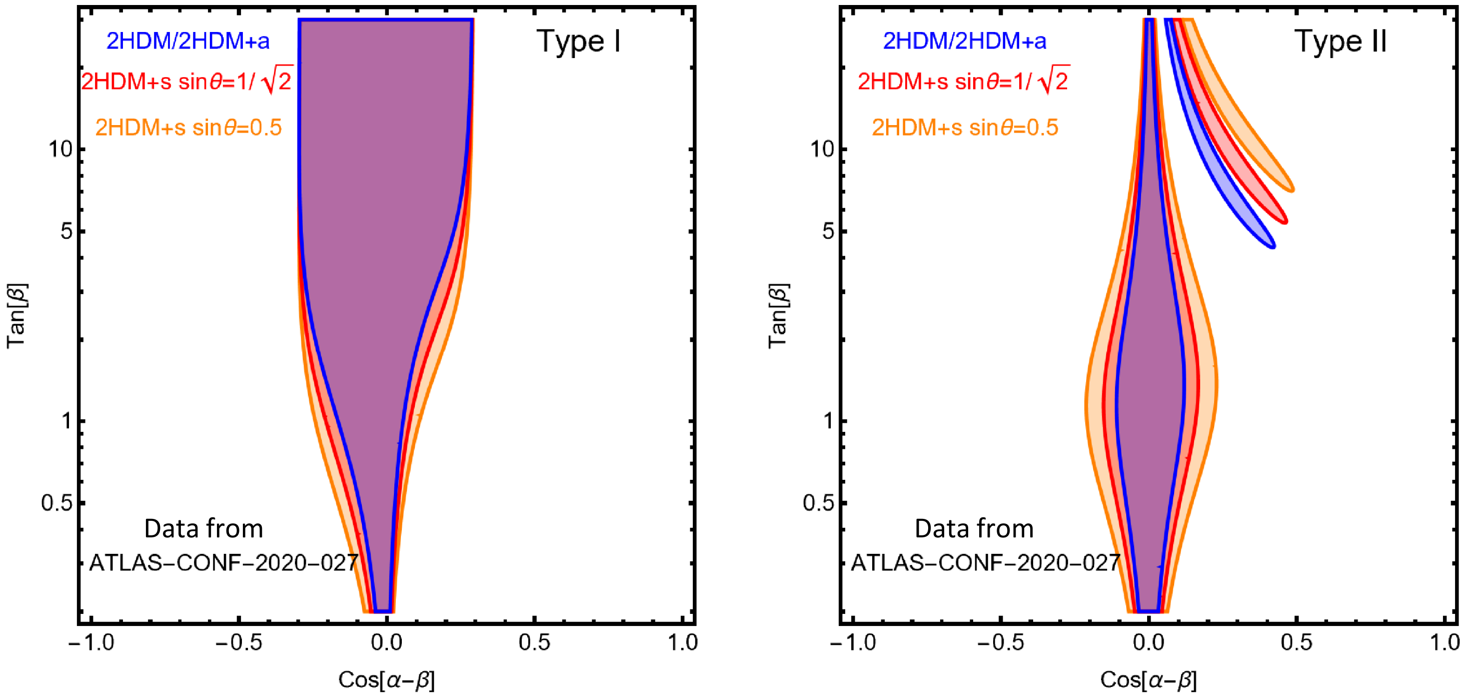
05 ALIGNMENT

- Measured strength of higgs couplings to fermions and gauge bosons requires to be close to alignment
- 2HDM+a: same constraints as in 2HDM, as hff, hVV are the same as in 2HDM
- 2HDM+s: $3x3$ mixing gives fore freedom, 3 mixing angles instead of 1

- 2HDM+s: hff measurements can be less constraining on $\cos(\alpha - \beta)$

05 ALIGNMENT

2HDM+s vs 2HDM+a comparison



05 ALIGNMENT

2HDM/2HDM+a constraints

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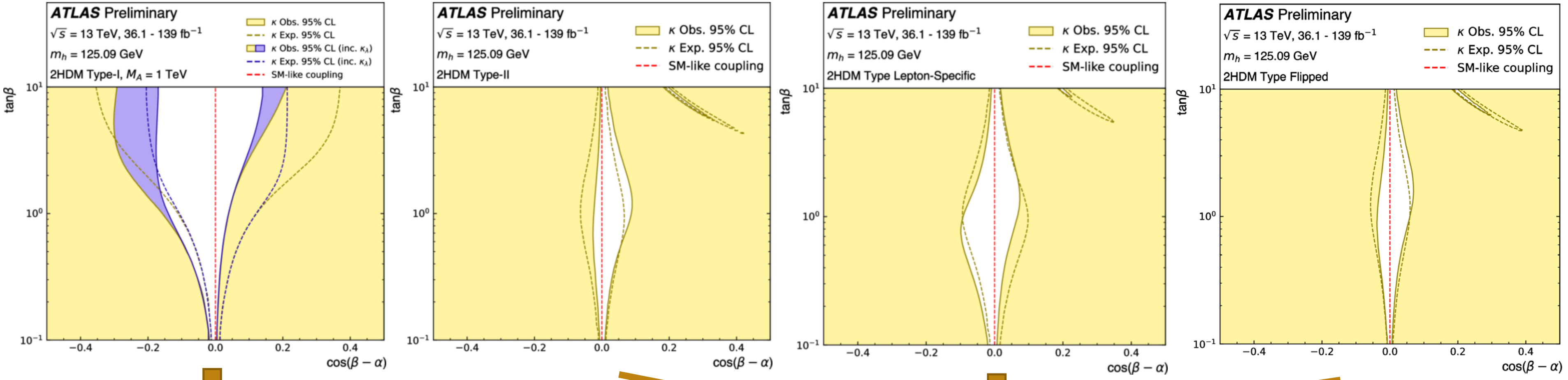


$$|\cos(\alpha - \beta)| \lesssim 0.2$$

$$|\cos(\alpha - \beta)| \lesssim 0.1$$

05 THEORY+EWPT+FLAVOUR+ALIGNMENT

Dropping Assumption $m_H = m_{H^\pm} = m_A$

- Allows for more freedom on λ_3, allowing it to be $\mathcal{O}(1)$
- One might still need to be forced to consider particular hierarchies arising from the BFB and global minima conditions

- The less restrictive $m_H = m_{H^\pm}$ assumption can allow for (some of) these decays:
  - $A \to Ha$
  - $A \to HZ$
  - $H \to Aa$
  - $H \to AZ$
  - $H \to AA$ (this one requires large mass splitting ⇒ not too large $m_{H,A}$)

05 THEORY+EWPT+FLAVOUR+ALIGNMENT

Dropping Assumption $\boldsymbol{m_H = m_{H^\pm}}$

- Allows for more decay channels to open (depending on mass hierarchy):
- $A \to H^\pm W^\mp$
- $H \to H^\pm W^\mp$
- $H \to H^\pm H^\mp$ (requires low $m_{H^\pm}$ ➡ Type I/X)
- $H^\pm \to H W^\pm$
- $H^\pm \to A W^\pm$

Dropping Assumption $\boldsymbol{cos(\alpha - \beta) = 0}$

- Allows several couplings to be non-zero, opening decay channels:
- $HW^+W^-, H \to W^\pm W^\mp$
- $HZZ, \mathrm{H} \to \mathrm{ZZ}$
- $hH^\pm W^\mp, H^\pm \to hW^\pm$
- $hAZ, A \to hZ$
- $haZ, a \to hZ$
- $Hhh, H \to hh$
- $HhW^+W^-, H \to hW^+W^-$
- $HhZZ, H \to hZZ$
- …..

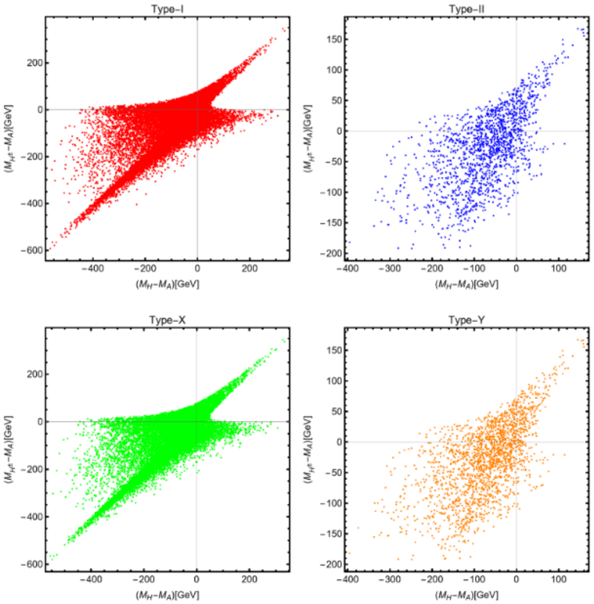
05 THEORY+EWPT+FLAVOUR+ALIGNMENT

Possible Mass splitting for $M_A, M_H, M_{H^\pm}$?

EWPT: at least one mass splitting needs to be small

- $M_H \sim M_{H^\pm}$
- Any of the other 2 together with an upper bound on $sin\theta$
- Unitarity/perturbativity: hard upper bound on any mass splitting
- Ballpark upper bound from perturbativity $(M_A, M_H, M_{H^\pm})$:

$$\frac{\Delta M}{100GeV} \lesssim \frac{TeV}{M}$$



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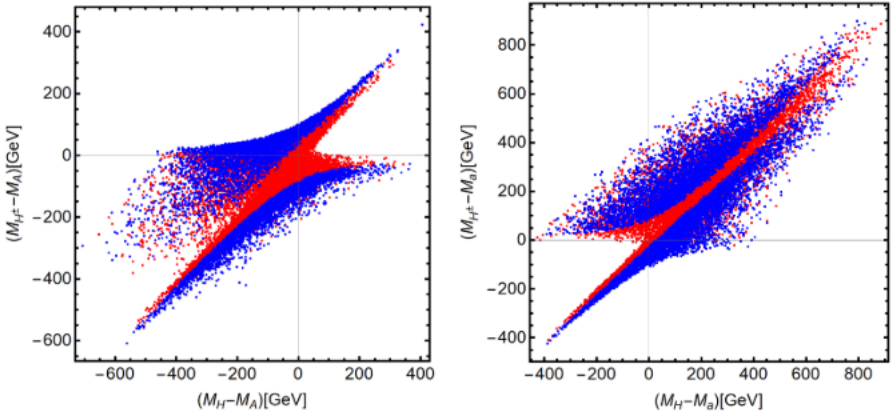
05 THEORY+EWPT+FLAVOUR+ALIGNMENT

New CDF II measurement?



SM FIT
CDF II

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05 THEORY+EWPT+FLAVOUR+ALIGNMENT

Mass splitting: $M_A - M_a$

There is no hard limit, but will be limited by EWPT

$$sin2\theta = \frac{2\mu v}{M_A^2 - M_a^2}$$

As this relation holds, having a large $M_A^2 - M_a^2$ without a small mixing angle pushed the new coupling μ to large values

μ becomes a “new physics scale”

05 THEORY+EWPT+FLAVOUR+ALIGNMENT

Masses: how large/small can they be?

- 2HDM has decoupling limit, no hard upper limit

↓

- Upper limit driven by other considerations, like ggF production cross sections

- Lower limit on M_a driven by invisible higgs:
- $M_a > \frac{M_h}{2}$ from 2-body decay $h \to aa$
- $M_a \gtrsim 75 GeV$ from 3 body decay $h \to aa^*$

06 (IN)DIRECT DETECTION

Direct Detection

- Very sensitive to y_χ, m_χ → Complementary to collider

- 2HDM+S: has SI cross section at tree level

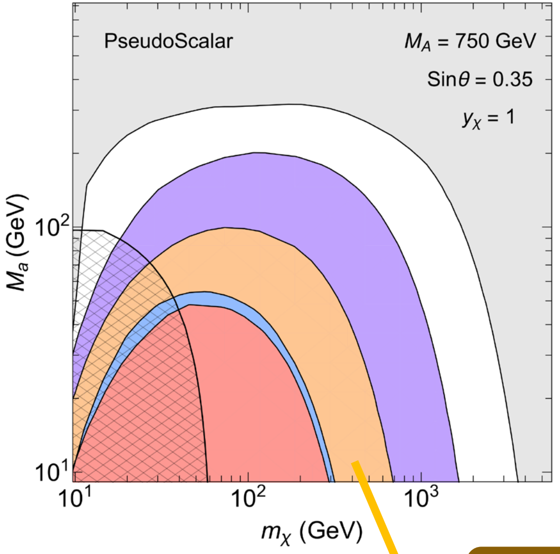
Evading constraints usually requires:

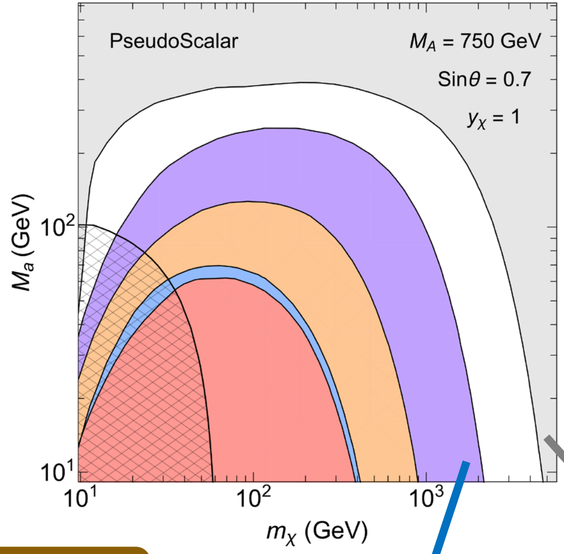
- A fine-tunes cancellation of couplings and/or
- A fine-tuned cancellation of diagrams and/or
- Small DM yukawa y_χ and/or
- A light DM mass

- 2HDM+a: has a q^4 suppressed SD cross section at tree level
- Dominant DD contribution is loop level SI cross section
- Couplings $\lambda_{P1}, \lambda_{P2}$ substantially enhance σ at small $sin\theta$
- σ becomes smaller for small values of $\lambda_{P1}, \lambda_{P2}$, $sin\theta$, or small y_χ or $m_\chi \ll M_a$ or $m_\chi \gg M_a$

06 (IN)DIRECT DETECTION

Direct Detection





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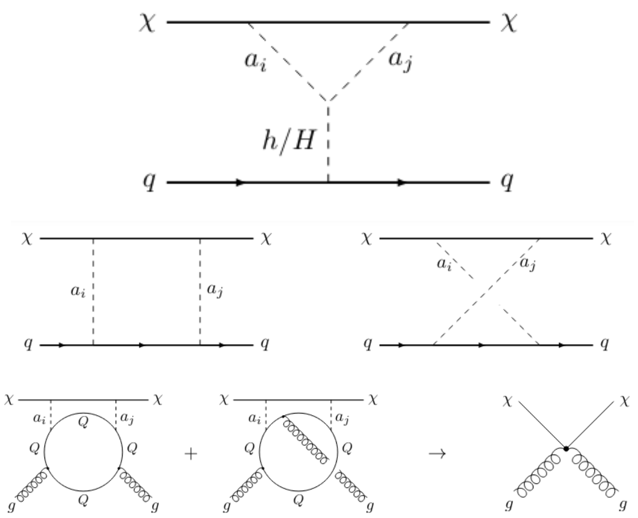
XENON1T 2ty

XENONnT 20ty

Neutrino Floor



Improved expressions

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06 (IN)DIRECT DETECTION

Indirect Detection

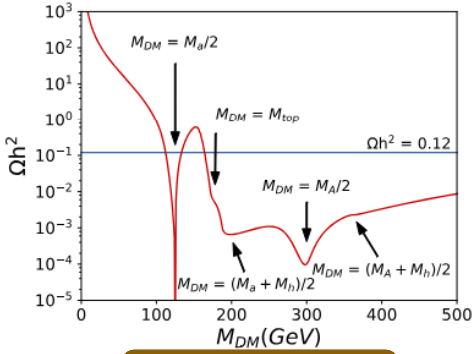
- Very sensitive to y_χ, m_χ → Complementary to collider

- 2HDM+S: has p-wave suppressed annihilations
  ↓
- Annihilations for ID are highly suppressed
- Still possible to reproduce relic density if annihilation to boson is allowed 1710.10764
- Annihilation cross section can become very large once $t\bar{t}$ or scalar/vector boson annihilation channels open up →

- 2HDM+a: has s wave annihilations
  ↓
- Annihilation cross section can become very large once $t\bar{t}$ or scalar/vector boson annihilation channels open up
  ↓
- Evading ID constraints easy if y_χ, m_χ are small enough, but
- Achieving the right relic density usually requires either fine-tuning m_χ or choosing very large/small values or y_χ

06 (IN)DIRECT DETECTION

ID/Relic Density



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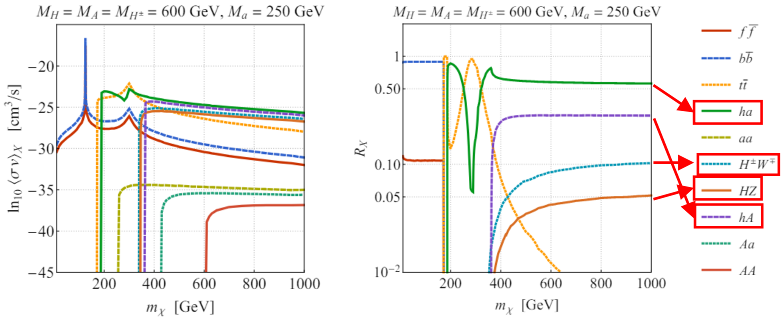
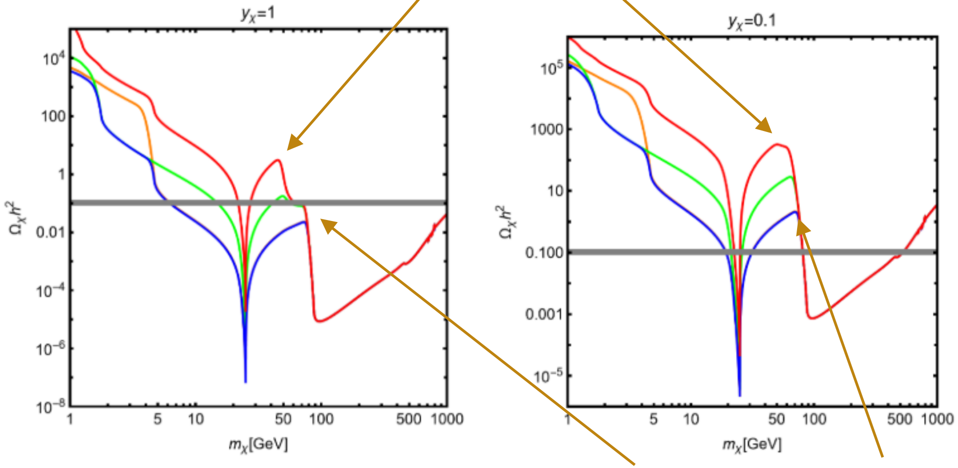


$m_\chi = m_a$



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$m_\chi = (m_a + m_h)/2$

$$\tan\beta = 5, \cos(\alpha - \beta) = 0, \theta = \pi/4$$

$$m_a = 50GeV, M_{H,A,H^\pm} = 800GeV$$

07 COLLIDER SIGNATURES

New possible Decays/couplings

Drop degenerate mass assumption

- $A \to Ha$
- $A \to HZ$
- $H \to Aa$
- $H \to AZ$
- $H \to AA$
- $A \to H^{\pm}W^{\mp}$
- $H \to H^{\pm}W^{\mp}$
- $H \to H^{\pm}H^{\mp}$
- $H^{\pm} \to HW^{\pm}$
- $H^{\pm} \to AW^{\pm}$

Drop alignment assumption

- $H \to W^{\pm}W^{\mp}$
- $\mathrm{H} \to \mathrm{ZZ}$
- $H^{\pm} \to hW^{\pm}$
- $A \to hZ$
- $a \to hZ$
- $H \to hh$
- $H \to hW^{+}W^{-}$
- $H \to hZZ$

07 COLLIDER SIGNATURES

Signature	Run 2	No degen. mass	No alignment
$h + E_T$	✓	+	
$Z + E_T$	✓	+	
$tW^- + E_T$	✓		
$t\bar{t} + E_T$	✓	+	?
$b\bar{b} + E_T$	✓	+	
$j + E_T$	✓	+	
$b\bar{b}Z$	✗	✓	
$ZZ + E_T$	✗	✓	
$hh + E_T$	✗	✓	

2404.05704

07 COLLIDER SIGNATURES

A few collider anomalies…

2309.03870

Final state	Characteristics	SM backgrounds	Significance
$\ell^+\ell^-$+(b-jets)[243, 246, 247]	$m_{\ell\ell} < 100$ GeV	$t\bar{t}, Wt$	$> 5\sigma$
$\ell^+\ell^-$+(no jet)[242, 248]	$m_{\ell\ell} < 100$ GeV	W^+W^-	$\approx 3\sigma$
$\ell^\pm\ell^\pm, 3\ell$ + (b-jets)[245, 249, 250]	Moderate H_T	$t\bar{t}W^\pm, t\bar{t}t\bar{t}$	$\approx 3\sigma$
$\ell^\pm\ell^\pm, 3\ell$, (no b-jet)[244, 251, 252]	In association with h	$W^\pm h(125), WWW$	$\gtrsim 4\sigma$
$Z(\to \ell\ell)\ell$, (no b-jet)[243, 253]	$p_T^Z < 100$ GeV	$ZW^\pm$	$> 3\sigma$

Suggesting

$$gg \to t\bar{t}\phi_1, \phi_1 \to \phi_2\phi_3, \phi_2 \to WW, \phi_3 \to b\bar{b}$$

ϕ_2 needs to be a scalar to have WW coupling and $m_2 \sim 150 GeV$
WW coupling requires non-alignment in 2HDM and usually implies mixing also in a generic scalar sector

2HDM+a interpretation: $\phi_1 = A, \phi_2 = H, \phi_3 = a$ (requires non-alignment!)
However, no ZZ signal is observed ⟹ prefers models without $ZZ\phi_2$ coupling

07 COLLIDER SIGNATURES

A few collider anomalies…

2309.03870

- Hints of $\gamma\gamma$ at $95GeV, 152GeV, 680GeV$
- $\gamma\gamma$ at $95GeV$ supported by $\tau\tau$ and $b\bar{b}$ (LEP) → Many papers!
- $\gamma\gamma, ZZ$ hints at $680GeV$
- $b\bar{b}\gamma\gamma$ hint at $680GeV$, with $\gamma\gamma$ compatible with $95GeV$

All pointing towards extended scalar sector!

07 COLLIDER SIGNATURES

Some thoughts/questions for discussion time:

- Consider signatures coming from non-alignment?
- $WW, ZZ, VV + X$ signatures? VBF?
- Other Yukawa types? Non-alignment prefers Type I
- Going down to $m_a \sim 95 GeV$ or even $m_a \sim 80 GeV$?
- Lower and upper limits for M_A?
- What if $2m_\chi > m_a$? All $+E_T$ signatures would turn into $+b\bar{b}$
- Origin and workaround of large Γ problem?
- Higher order corrections available for scalars, not pseudoscalars!

THANK YOU

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