CP-violation in the dark sector

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LHC Higgs Working Group WG3 (BSM)
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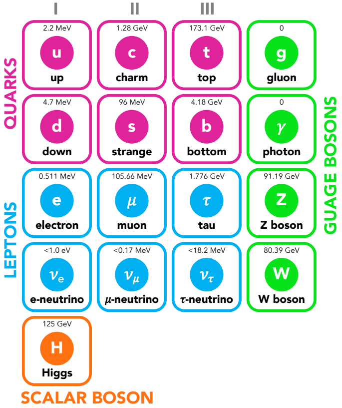
The Standard Model

Its current formulation was finalised in the 70's and predicted:

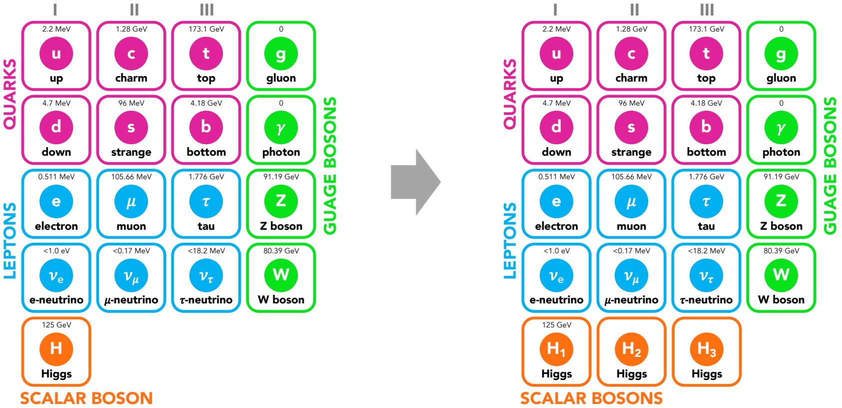
- the W & Z bosons
  discovered in 1983
- the top quark
  discovered in 1995
- the tau neutrino
  discovered in 2000
- the Brout-Englert-Higgs mechanism
  a scalar boson discovered in 2012



~~JFK~~ VK: Ask not what your ~~country~~ experiment can do for you - ask what you can do for your ~~country~~ experiment.

What the SM is missing

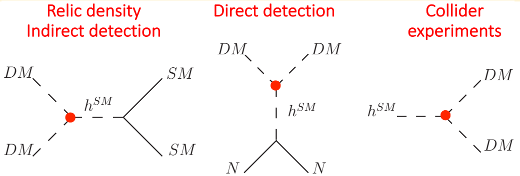
- a suitable Dark Matter candidate
- sufficient amount of CP-violation $\Rightarrow$ scalar extensions of the SM
- ...



Purely scalar extensions w/o a Z_2 symmetry:

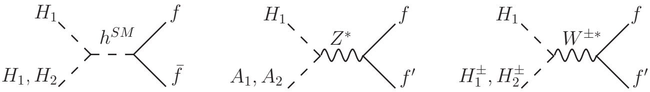
SM + singlet(s):

- $\phi_{SM}, S \Rightarrow$ DM, ~~CPV~~
- $\phi_{SM}, S_{1,2} \Rightarrow$ DM, ~~CPV~~



2HDMs:

- $\phi_1, \phi_2 \Rightarrow$ ~~DM~~, CPV
- $\phi_1, \phi_2 \Rightarrow$ DM, ~~CPV~~

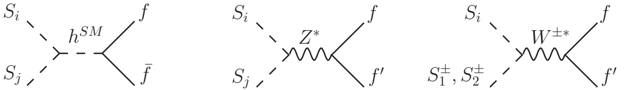


2HDM + singlet:

- $\phi_1, \phi_2, S \Rightarrow$ ~~DM~~, CPV
- $\phi_1, \phi_2, S \Rightarrow$ DM, ~~CPV~~
- $\phi_1, \phi_2, S \Rightarrow$ DM, CPV

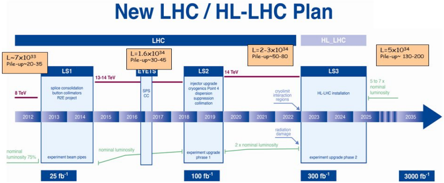
3HDMs:

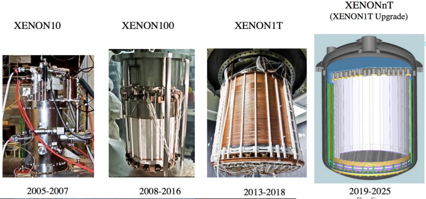
- $\phi_1, \phi_2, \phi_3 \Rightarrow$ ~~DM~~, CPV
- $\phi_1, \phi_2, \phi_3 \Rightarrow$ DM, CPV
- $\phi_1, \phi_2, \phi_3 \Rightarrow$ DM, CPV

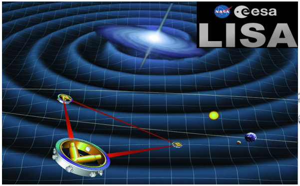


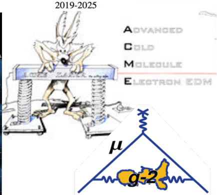
Experimental probes of 3HDMs

- Collider experiments
  - 2021: LHC-RUN-III
  - 2026: HL-LHC
  - 2028: CEPC
- DM experiments
  - 2020: XENONnT
  - 2022: CTA
- GW experiments
  - 2027: DECIGO
  - 2034: LISA mission
- Precision experiments
  - 2020: $(g-2)_\mu$
  - 2020: Advanced ACME









3HDMs: the crown jewel of scalar extensions

two scalar doublets + the SM Higgs doublet

ϕ_1, ϕ_2 ϕ_3

$$\phi_1 = \begin{pmatrix} H_1^+ \\ \frac{H_1+iA_1}{\sqrt{2}} \end{pmatrix}, \quad \phi_2 = \begin{pmatrix} H_2^+ \\ \frac{H_2+iA_2}{\sqrt{2}} \end{pmatrix}, \qquad \phi_3 = \begin{pmatrix} G^+ \\ \frac{h+iG^0}{\sqrt{2}} \end{pmatrix}$$

3HDM with dark CPV

DM ✓, CPV ✓

DM is protected by a Z_2 symmetry $(-,-,+)$:

$$\phi_1 \to -\phi_1, \quad \phi_2 \to -\phi_2, \quad \text{SM fields} \to \text{SM fields}, \quad \phi_3 \to \phi_3$$

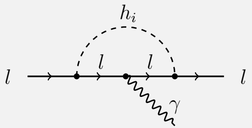
Z_2 symmetry respected by the vacuum $(0,0,v)$:

$$\phi_1 = \begin{pmatrix} H_1^+ \\ \frac{H_1+iA_1}{\sqrt{2}} \end{pmatrix}, \qquad \phi_2 = \begin{pmatrix} H_2^+ \\ \frac{H_2+iA_2}{\sqrt{2}} \end{pmatrix}, \qquad \phi_3 = \begin{pmatrix} G^+ \\ \frac{v+h+iG^0}{\sqrt{2}} \end{pmatrix}$$

DM candidate: the lightest state among $S_{1,2,3,4}$ (mixture of $H_{1,2}, A_{1,2}$)

Only ϕ_3 can couple to fermions $\phi_u = \phi_d = \phi_e = \phi_3$ and $h_i = h$

$$-\mathcal{L}_{Yukawa} = Y_u \bar{Q}'_L i\sigma_2 \phi_u^* u'_R + Y_d \bar{Q}'_L \phi_d d'_R + Y_e \bar{L}'_L \phi_e e'_R + \text{h.c.}$$



No contributions to electric dipole moments (EDMs)

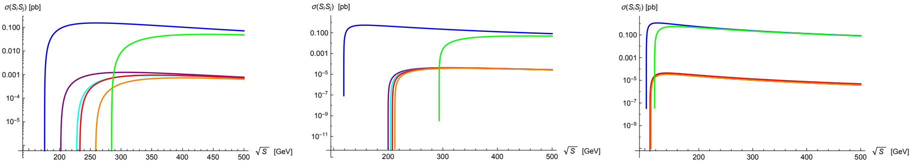
[JHEP 12, 014 (2016)], [Phys. Rev. D 101, 073007 (2020)]

3HDMs: the crown jewel of scalar extensions

Collider probes of 3HDMs

Production thresholds of $S_i S_j$ at e^+e^- colliders

The $e^+e^- \to Z^* \to S_i S_j$ cross section for A, B and C scenarios



	Point-A	Point-B	Point-C	Point-D
m_{S_1}	72.3	55.4	50.9	63.2
m_{S_2}	103.3	63.2	51.7	78.0
$m_{S_1}^{\pm}$	106.2	79.1	99.1	106.3
m_{S_3}	129.4	144.3	58.5	185.0
m_{S_4}	155.1	148.8	59.4	213.1
$m_{S_2}^{\pm}$	157.5	159.2	111.1	204.3

a smoking gun signature of CP-violation in 3HDMs

Eur. Phys. J. C 80, no.2, 135 (2020)

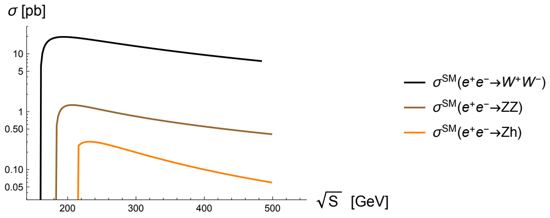
Significance of the signal over the SM background

For all our BPs, the final state of the $e^+e^- \to Z^* \to S_i S_j$ process is $\not{E}_T f\bar{f}$,

$$e^+e^- \to Z^* \to S_1 S_j \to S_1 S_1 Z^* \to S_1 S_1 \bar{f}f,$$
$$e^+e^- \to Z^* \to S_i S_j \to S_1 Z^* S_1 Z^* \to S_1 S_1 \bar{f}f\bar{f}f, \qquad (i,j = 2,3,4)$$

The main SM background is through

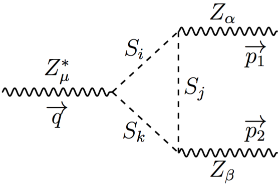
$$e^+e^- \to ZZ \to \bar{f}f\nu\bar{\nu}, \qquad e^+e^- \to W^+W^- \to l^-\bar{\nu}\, l^+\nu, \qquad e^+e^- \to Zh \to \bar{f}f\not{E}_T$$

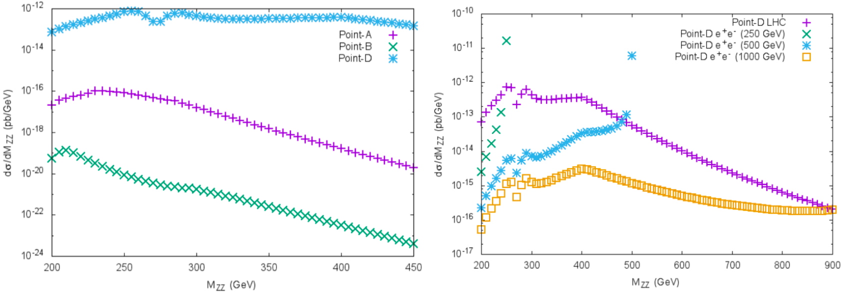


background decreases with increasing energy and is ≤ 1.8 pb

Eur. Phys. J. C 80, no.2, 135 (2020)

Dark CPV observables: the ZZZ vertex





The differential $f\bar{f} \to Z^* \to ZZ$ cross section at hadron and lepton colliders

[JHEP 12, 014 (2016)]

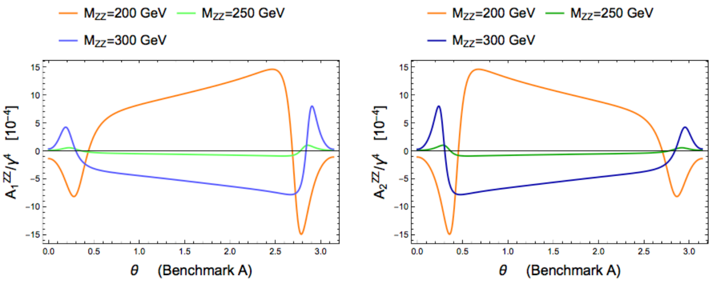
CP-violating asymmetries

In the cross section of the $\bar{f}f \to ZZ$ process

$$\sigma(f_\delta \bar{f}_{\bar{\delta}} \to Z_\eta Z_{\bar{\eta}}) \equiv \sigma_{\eta,\bar{\eta}} = \sum_{\delta,\bar{\delta}} \mathcal{M}^{\delta,\bar{\delta}}_{\eta,\bar{\eta}}[\Theta]\, \mathcal{M}^{\star\,\delta,\bar{\delta}}_{\eta,\bar{\eta}}[\Theta],$$

with $\delta, \bar{\delta}$: helicities of incoming $f, \bar{f}$ and $\eta, \bar{\eta}$: helicities of the outgoing ZZ we define

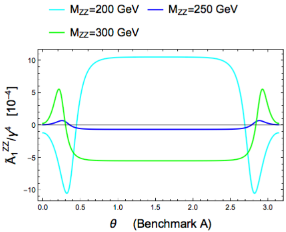
$$A_1^{ZZ} \equiv \frac{\sigma_{+,0} - \sigma_{0,-}}{\sigma_{+,0} + \sigma_{0,-}}, \qquad A_2^{ZZ} \equiv \frac{\sigma_{0,+} - \sigma_{-,0}}{\sigma_{0,+} + \sigma_{-,0}},$$

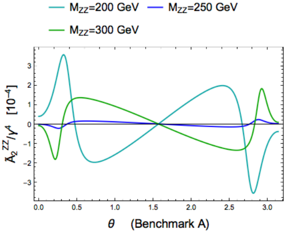


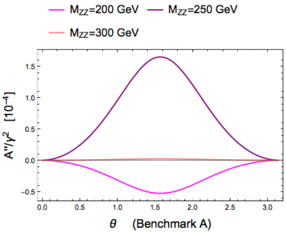
Phys. Rev. D 101, 095023 (2020)

Other CP-violating asymmetries

$$\widetilde{A}_1^{ZZ} \equiv \frac{\sigma_{+,0} + \sigma_{0,+} - \sigma_{0,-} - \sigma_{-,0}}{\sigma_{+,0} + \sigma_{0,+} + \sigma_{0,-} + \sigma_{-,0}}, \qquad \widetilde{A}_2^{ZZ} \equiv \frac{\sigma_{+,0} - \sigma_{0,+} - \sigma_{0,-} + \sigma_{-,0}}{\sigma_{+,0} + \sigma_{0,+} + \sigma_{0,-} + \sigma_{-,0}}.$$

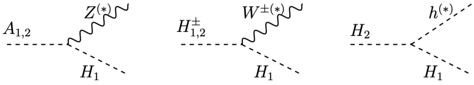






Inert cascade decays at the LHC

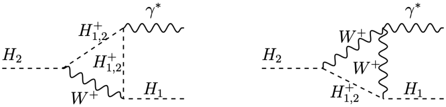
Tree level process: $q\bar{q} \to Z^* \to H_1 A_{1,2} \to H_1 H_1 Z^* \to H_1 H_1 f\bar{f}$



(may be possible in 2HDM)

Loop level ggF process: $gg \to h \to H_1 H_2 \to H_1 H_1 \gamma^* \to H_1 H_1 f\bar{f}$

Loop level VBF process: $q_i q_j \to H_1 H_2 \to H_1 H_1 \gamma^* \to H_1 H_1 f\bar{f}$

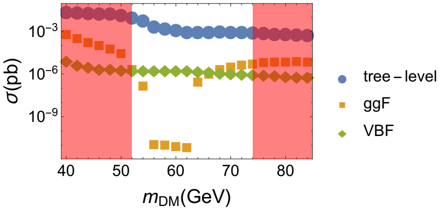


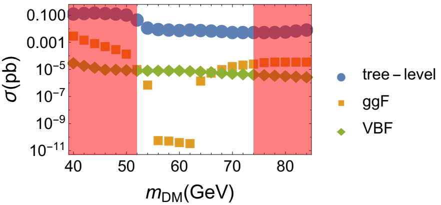
(smoking gun signature of 3HDM)

Benchmark	$m_{H_2} - m_{H_1}$	$m_{A_1} - m_{H_1}$	$m_{A_2} - m_{H_1}$	$m_{H_1^\pm} - m_{H_1}$	$m_{H_2^\pm} - m_{H_1}$
A50	50	75	125	75	125
I5	5	10	15	90	95

[JHEP 05, 030 (2018)]

LHC cross section for $\not{E}_T l\bar{l}$ and $\not{E}_T q\bar{q}$ for scenario A50

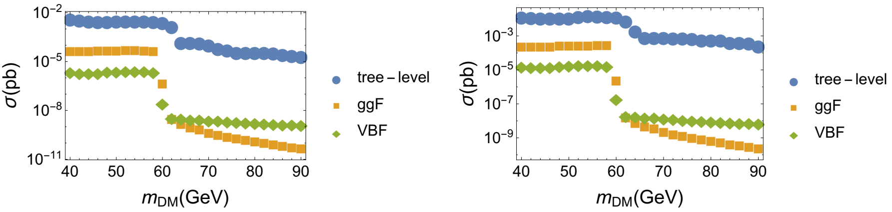




Decay channels	BR($H_2 \to H_1 X$)	tree-level	ggF	VBF
$H_2 \to b\bar{b}H_1$	1.88e-01	2.49e-03	1.18e-07	2.05e-06
$H_2 \to s\bar{s}H_1$	2.00e-01	1.97e-03	1.26e-07	2.19e-06
$H_2 \to c\bar{c}H_1$	2.00e-01	3.94e-03	1.26e-07	2.19e-06
$H_2 \to d\bar{d}H_1$	2.00e-01	3.54e-03	1.26e-07	2.19e-06
$H_2 \to u\bar{u}H_1$	2.00e-01	1.97e-03	1.26e-07	2.19e-06
$H_2 \to \tau^+\tau^- H_1$	6.56e-02	8.09e-04	4.13e-08	7.15e-07
$H_2 \to \mu^+\mu^- H_1$	6.69e-02	8.22e-04	4.21e-08	7.29e-07
$H_2 \to e^+e^- H_1$	6.69e-02	1.34e-03	4.21e-08	7.29e-07

[JHEP 05, 030 (2018)]

LHC cross section for $\not{E}_T l\bar{l}$ and $\not{E}_T q\bar{q}$ for scenario I5

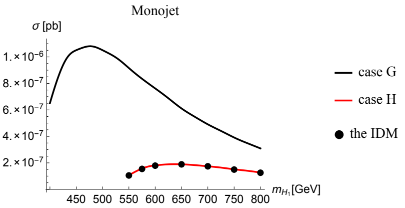


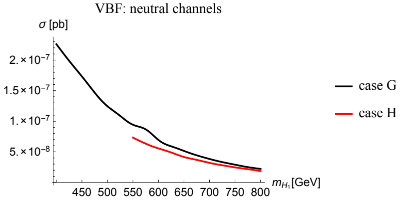
Decay channels	BR($H_2 \to H_1 X$)	tree-level	ggF	VBF
$H_2 \to s\bar{s}H_1$	2.22e-01	5.71e-03	9.70e-04	7.93e-06
$H_2 \to c\bar{c}H_1$	1.63e-01	1.52e-03	7.12e-05	5.82e-06
$H_2 \to d\bar{d}H_1$	2.28e-01	3.74e-03	9.96e-05	8.14e-06
$H_2 \to u\bar{u}H_1$	2.28e-01	4.80e-03	9.96e-05	8.14e-06
$H_2 \to \tau^+\tau^- H_1$	7.55e-03	1.13e-03	3.30e-06	2.70e-07
$H_2 \to \mu^+\mu^- H_1$	7.54e-02	7.47e-04	3.30e-05	2.69e-06
$H_2 \to e^+e^- H_1$	7.59e-02	1.73e-03	3.32e-05	2.71e-06

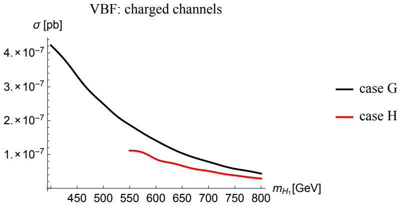
[JHEP 05, 030 (2018)]

Observable heavy scalar DM

Monojet and dijet channels in the heavy DM mass region:







[JHEP 1511 (2015) 003]

Summary

3HDMs are very well motivated and accessible through

- Production thresholds of $S_i S_j$ at $e^+ e^-$ colliders
- The $\bar{f}f \to Z^* \to ZZ$ with the ZZZ vertex
- CP-violating asymmetries
- Inert cascade decays
- Observable heavy scalar DM

and many non-collider complementary observables.

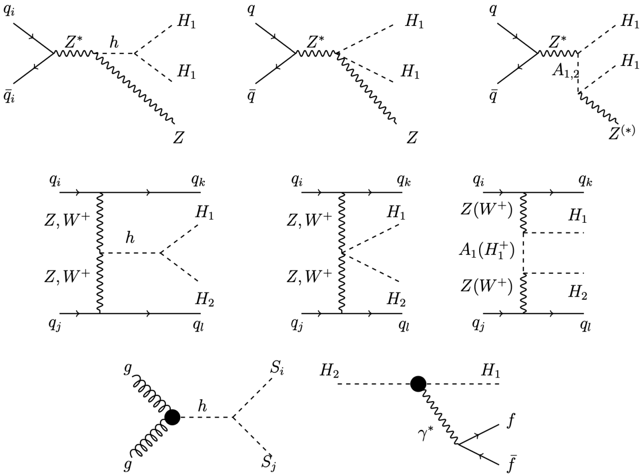
BACKUP SLIDES

The background to the inert cascade decay

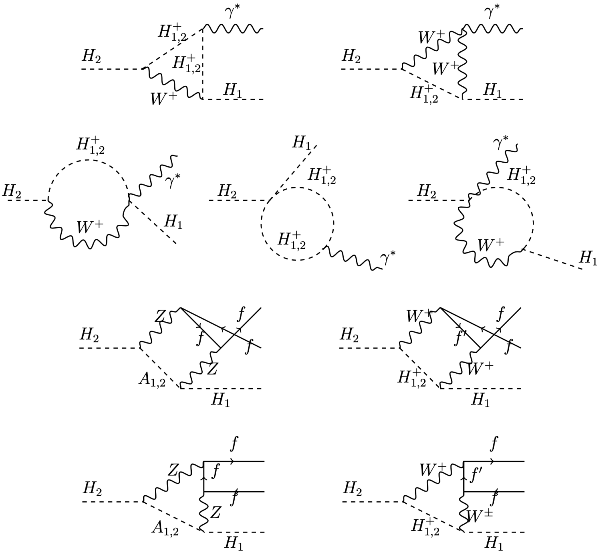
The background process, h decay into two charged scalars, cross section for $m_{DM} = 54$ GeV.

scenario	cross section (pb)
A50	6.77e-09
I5	7.91e-08
I10	4.19e-08

HS, VBS and ggF processes in inert cascade decays

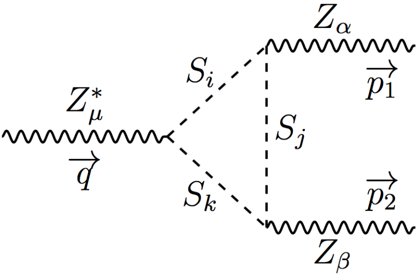


$H_2 \to H_1 f\bar{f}$ processes in inert cascade decays



Dark CPV observables: the ZZZ vertex

$$e\Gamma^{\alpha\beta\mu}_{ZZZ} = ie\frac{q^2 - M_Z^2}{M_Z^2}[f_4(q^\alpha g^{\mu\beta} + q^\beta g^{\mu\alpha}) + f_5\epsilon^{\mu\alpha\beta\rho}(p_1 - p_2)_\rho]$$



$$f_4 = \frac{M_Z^2 |g_{ZS_2S_3}|\ |g_{ZS_1S_3}|\ |g_{ZS_1S_2}|}{2\pi^2 e(q^2 - M_Z^2)} \sum_{i,j,k}^{4} \epsilon_{ijk} C_{002}(M_Z^2, M_Z^2, q^2, m_i^2, m_j^2, m_k^2)$$

V. Keus, S. F. King, S. Moretti, D. Sokolowska, et al., [JHEP 12, 014 (2016)]

Scalar singlet extension of SM

the SM Higgs doublet + a scalar singlet

ϕ $\qquad$ S

$$\phi = \begin{pmatrix} G^+ \\ \frac{h+iG^0}{\sqrt{2}} \end{pmatrix} \qquad S = \left(\frac{s}{\sqrt{2}} \right)$$

$$\underbrace{S\ S \to \mathrm{SM\ SM}}_{\text{pair annihilation}}, \qquad \underbrace{S \not\to \mathrm{SM\ SM}}_{\text{stable}}$$

SM + scalar singlet DM ✓, CPV ×

DM protected by a Z_2 symmetry $(+, -)$ from decaying to SM particles.

$$\text{SM fields} \to \text{SM fields}, \quad \phi \to \phi, \quad S \to -S$$

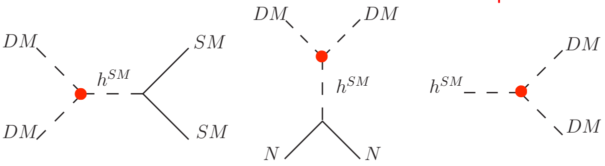
The Lagrangian and the vacuum are Z_2 symmetric: $\langle \phi \rangle = v$, $\langle S \rangle = 0$

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}(\partial S)^2 - m_s^2 S^2 - \lambda_s S^4 - \lambda_{hs}\phi^2 S^2$$

Relic density
Indirect detection

Direct detection

Collider
experiments



Tension: all relevant interactions are governed by the same coupling!

2-Higgs doublet models (2HDMs)

the SM Higgs doublet + a scalar doublet

ϕ_1 ϕ_2

$$\phi_1 = \begin{pmatrix} G^+ \\ \frac{h+iG^0}{\sqrt{2}} \end{pmatrix} \qquad \phi_2 = \begin{pmatrix} H^+ \\ \frac{H+iA}{\sqrt{2}} \end{pmatrix}$$

Z_2-symmetric 2HDM DM ✓, CPV ×

DM is protected by a Z_2 symmetry $(+,-)$ from decaying to SM particles:

$$\text{SM fields} \to \text{SM fields}, \quad \phi_1 \to \phi_1, \quad \phi_2 \to -\phi_2$$

Z_2 symmetry: only ϕ_1 couples to fermions $\phi_u = \phi_d = \phi_e = \phi_1$

$$-\mathcal{L}_{Yukawa} = Y_u \bar{Q}'_L i\sigma_2 \phi_u^* u'_R + Y_d \bar{Q}'_L \phi_d d'_R + Y_e \bar{L}'_L \phi_e e'_R + \text{h.c.}$$

Z_2 symmetry respected by the vacuum: $\phi_1 = \begin{pmatrix} G^+ \\ \frac{v+h+iG^0}{\sqrt{2}} \end{pmatrix}, \quad \phi_2 = \begin{pmatrix} H^+ \\ \frac{H+iA}{\sqrt{2}} \end{pmatrix}$

DM candidate: the lightest neutral particle from the dark doublet

$$HH \to h \to \text{SM}, \quad HA \to Z \to \text{SM}, \quad HH^\pm \to W^\pm \to \text{SM}$$

Tension: all scalar interactions are governed by the same coupling! Gauge couplings are fixed!

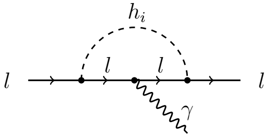
CP-violating 2HDM DM $\times$, CPV $\checkmark$

Break the Z_2 symmetry and let the two doublets mix

$$\phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{v_1 + h_1^0 + i a_1^0}{\sqrt{2}} \end{pmatrix}, \quad \phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{v_2 + h_2^0 + i a_2^0}{\sqrt{2}} \end{pmatrix}$$

No Dark Matter candidate!

Mixing doublets means h_i (mixtures of $h^0_{1,2}, a^0_{1,2}$) are CP-mixed states

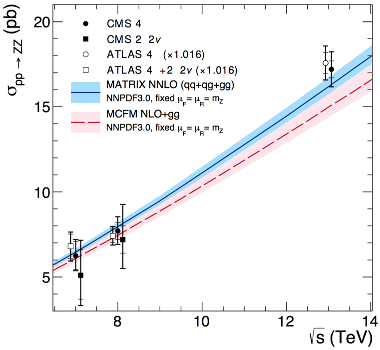


contributing to electric dipole moments (EDMs).

CP-violation is very constrained!

V. Keus, S. F. King, S. Moretti, K. Yagyu, [JHEP 04, 048 (2016)] V. Keus, N. Koivunen, K. Tuominen, [JHEP 09, 059 (2018)]

The $f\bar{f} \to Z^* \to ZZ$ process at the LHC



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