Exotic Dark Matter in 3HDMs

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IRISH RESEARCH COUNCIL
An Chomhairle um Thaighde in Éirinn

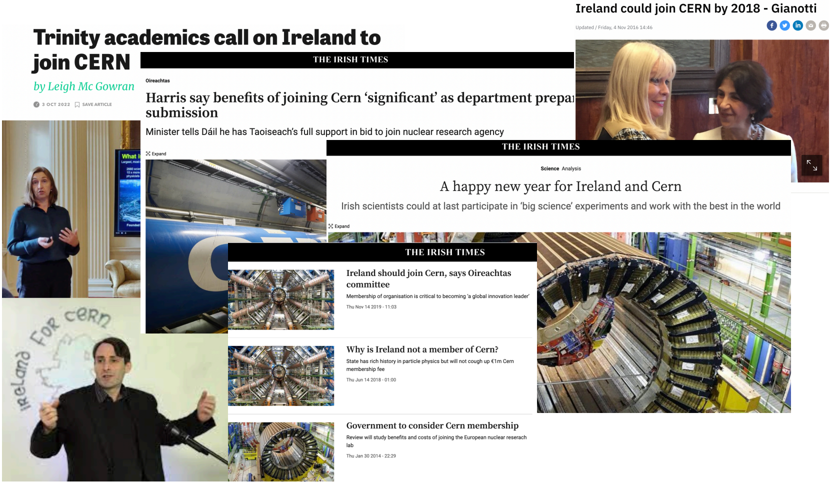
Scalars 2023
An opportunity to discuss various aspects of scalar particles.

Based on work published and in progress

In collaboration with S. King, S. Moretti, D. Sokolowska, D. Rojas, J. Hernandez, N. Koivunen, K. Tuominen, L. Niemi, H. Haber, R. Santos, M. Ramsey-Musolf, K. Rummukainen, A. Dey, J. Thomson-Cooke

13.09.2023

Ireland is finally joining CERN

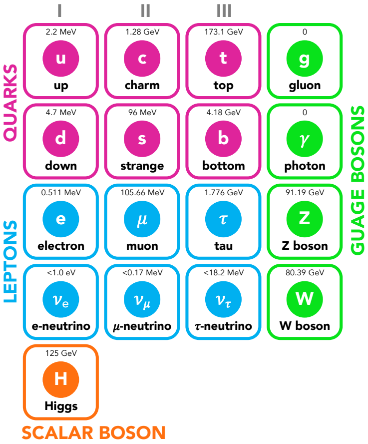


You are cordially invited to ...

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



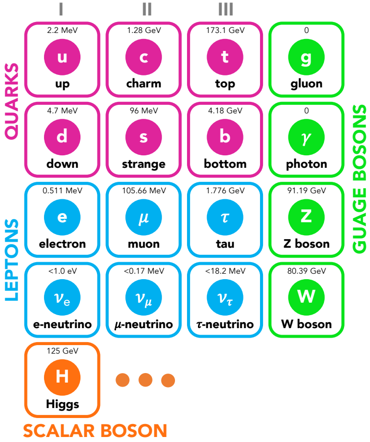
· · · and the need to go beyond

What is missing:

- a suitable Dark Matter candidate
- a successful baryogenesis mechanism
  - strong first order phase transition
  - sufficient amount of CP violation
- a natural inflation framework
- an explanation for the fermion mass hierarchy
- a stable electroweak vacuum

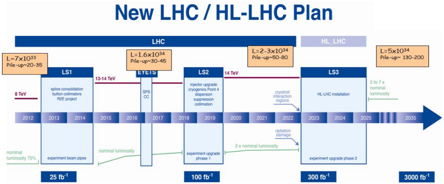
$\Rightarrow$ beyond the Standard Model

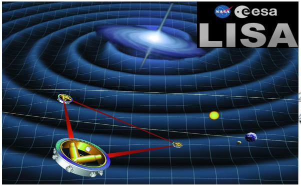
$\Rightarrow$ **scalar extensions of the SM**

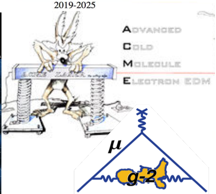


Complementary experimental probes of scalar extensions

- Collider experiments
  - LHC-RUN-III
  - HL-LHC
  - CEPC
- DM experiments
  - XENONnT
  - CTA
- GW experiments
  - DECIGO
  - LISA mission
- Precision experiments
  - $(g-2)_\mu$
  - Advanced ACME







The truth about Dark Matter

The common misinformation:

For the first time, Fritz Zwicky in 1933: "The Coma cluster moves too fast for its apparent gravitational pull (due to its luminous matter) to stay together."

⇒ Dark Matter within the cluster

The truth about Dark Matter

The common misinformation:

For the first time, Fritz Zwicky in 1933: “The Coma cluster moves too fast for its apparent gravitational pull (due to its luminous matter) to stay together.”

$\Rightarrow$ Dark Matter within the cluster

The correct information:

Three years prior, Knut Lundmark in 1930 had already found evidence for Dark Matter and coined the term.

The truth about Dark Matter

Knut Lundmark, Lund Medd. No125 (1930) 1 – 10 (Thanks to D.Dravins and A. L'Huillier, Lund University for digging out the original paper, in German, my translation):

"Under the condition that the mass-luminosity relation is valid for all stellar systems, the mass for the investigated systems can be computed using the total absolute magnitude M_{tot} which can be found when the distance is known and the total apparent m_{tot} is observed. The mass computed in this way, the luminous mass, does understandably not include the mass of the dark objects of the system (extinguished stars, dark clouds, meteors, comets, and so on). To determine the total mass or the gravitational mass, we need to rely on the five cases where one has detected an effect of rotation by spectrographical means. … A comparison between the two kinds of masses gives an estimate of the ratio of luminous and dark matter for some stellar systems (Table 4)."

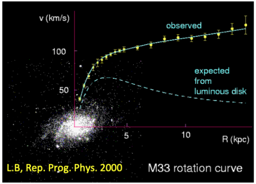


Tabelle 4.

Objekt	Ratio: Luminous + Dark Matter / Luminous Matter
Messier 81	100:1 (?)
N. G. C. 4594	30:1
Andromedanebel	20:1
Messier 51	10:1
Milchstraßensystem	10:1
Messier 33	6:1

From Lars Bergstrom's talk (modified) at the Workshop on Off-the-Beaten-Track Dark Matter and Astrophysical Probes of Fundamental Physics (April 2015)

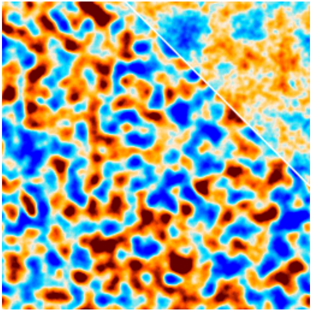
Dark Matter relic density

Patterns in the Cosmic Microwave Background (CMB):

Competition between

- the force of gravity causing matter to fall inward
- an outward pressure exerted by photons

Dark Matter feels the gravity but not the pressure from photons.

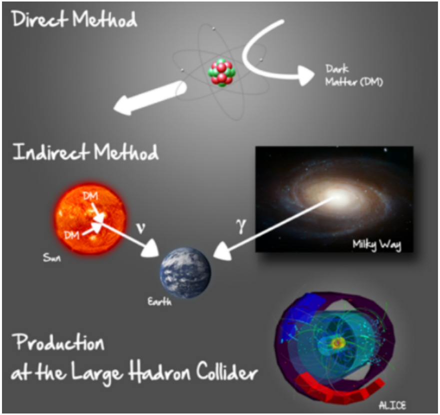


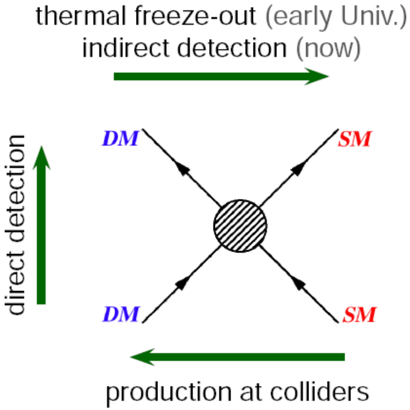
Planck CMB simulator

The total relic density by the Planck data: $\Omega_{\rm DM} h^2 = 0.1200 \pm 0.0012$

N. Aghanim et al. [Planck], Astron. Astrophys. 641, A6 (2020)

How do we look for Dark Matter?





Scalar extensions of the SM

SM + scalar singlets link

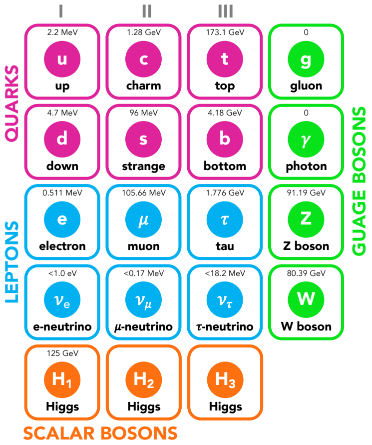
- Dark Matter severely constrained
- CP-violation not possible

2HDM: SM + a doublet link

- Dark Matter constrained & CPV incompatible
- CP-violation severely constrained & DM incompatible

3HDM: SM + 2 doublets link

- Dark Matter many exotic possibilities
- CP-violation unbounded dark CP-violation
- Inflation easily achieved + exotic possibilities
- Strong first order EWPT easily achieved
- Bonus: fermion mass hierarchy explanation



Scalar singlet extension of SM

the SM Higgs doublet + a scalar singlet

ϕ S

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

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

back

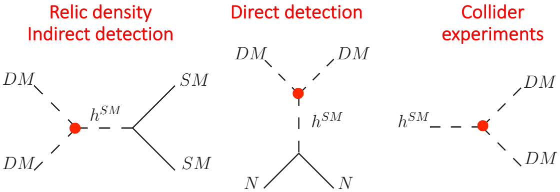
SM + scalar singlet — DM ✓, CPV ×

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: $\langle\phi\rangle = v$, $\langle S\rangle = 0$

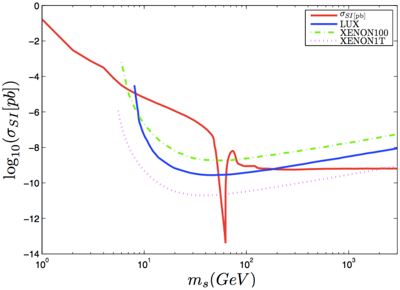
$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}(\partial S)^2 - m_s^2 S^2 - \lambda_s S^4 - \lambda_{hs}\phi^2 S^2$$



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

SM + scalar singlet DM ✓, CPV ×

- Bounded from below potential:
  $h, s \to \infty \;\; \Rightarrow V > 0$
- Vacuum stability:
  $\tau_{v_{EW}} >$ age of the universe
- Perturbative unitarity:
  $|\lambda_i| \leq 4\pi, \;\; |\Lambda_i| \leq 8\pi$
- Higgs decays:
  $BR(h \to inv.) < 20\% \;\; \Rightarrow \lambda_{hs}$ small
- Relic density:
  λ_{hs} large
- Direct and indirect detection:
  λ_{hs} small



H. Han, S. Zheng, [JHEP 12 (2015) 044]

2-Higgs doublet models (2HDMs)

the SM Higgs doublet + 1 scalar doublet

ϕ_1 ϕ_2

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

back

Z_2-symmetric 2HDM DM ✓, CPV ×

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

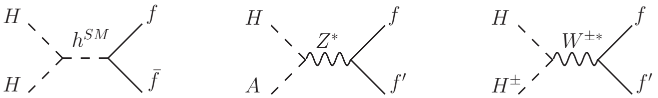
$$\text{SM fields} \to \text{SM fields}, \quad \phi_1 \to \phi_1, \quad \phi_2 \to -\phi_2$$

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

<u>DM candidate:</u> the lightest neutral particle from the dark doublet



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

More constraints in scalar doublet extensions of SM

Electroweak precision observables:

$$S,\ T,\ U \text{parameters}$$

Flavour observables:

$$BR(B \to X_s\gamma), \quad B^0 - \bar{B}^0 \text{mixing}$$
$$D_s \to \tau\nu_\tau, \quad D_s \to \mu\nu_\mu, \quad B \to D\tau\nu_\tau$$

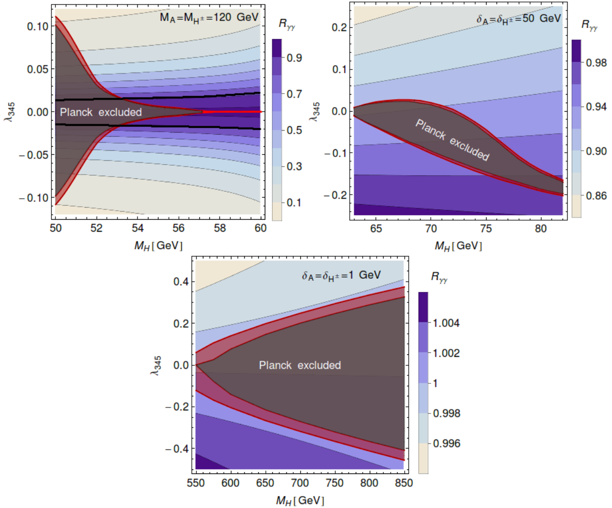
LEP bounds:

$$m_{H^\pm} + m_{H,A} > m_{W^\pm}, \qquad m_H + m_A > m_Z, \qquad 2m_{H^\pm} > m_Z$$
$$m_{H^\pm} \gtrsim 70 - 90 \text{ GeV}$$
$$\text{if } M_H < 80 \text{ GeV and } M_A < 100 \text{ GeV} \Rightarrow M_A - M_H < 8 \text{ GeV}$$

LHC bound on the total decay signal strength:

$$\mu_{tot} = \frac{\text{BR}(h \to XX)}{\text{BR}(h_{\text{SM}} \to XX)} = 1.17 \pm 0.17$$

Z_2-symmetric 2HDM DM ✓, CPV ×



M. Krawczyk, D. Sokolowska, P. Swaczyna and B. Swiezewsk, [JHEP 09 (2013) 055]

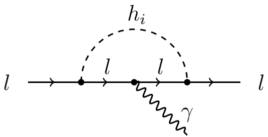
CP-violating 2HDM   DM ×, CPV ✓

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



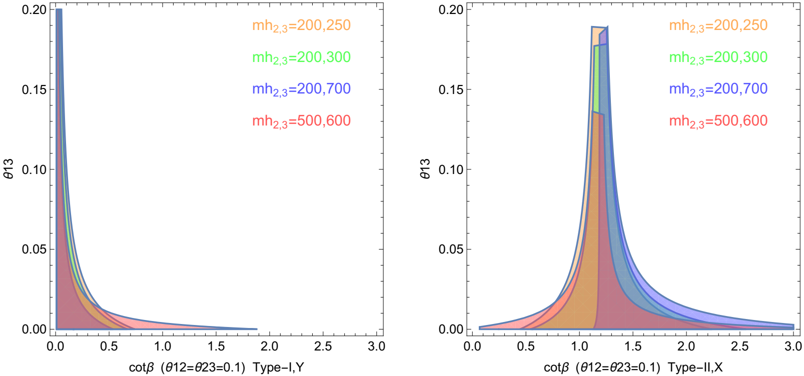
contributing to electric dipole moments (EDMs).

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)]

CP-violating 2HDM DM ×, CPV ✓

Parameter space allowed by the EDM bounds implications for $(g-2)_\mu$



V. Keus, N. Koivunen, K. Tuominen, [JHEP 09, 059 (2018)]

3-Higgs doublet models (3HDMs)

2 scalar doublets + the SM Higgs doublet

ϕ_1, ϕ_2 ϕ_3

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

back

Z_2-symmetric 3HDM with dark CPV

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

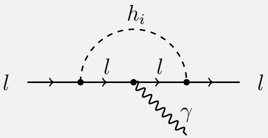
$$\phi_1 \to -\phi_1, \quad \phi_2 \to -\phi_2, \quad \text{SM fields} \to \text{SM fields}, \quad \phi_3 \to \phi_3$$

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

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

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)

Observable heavy scalar DM

V. Keus, [Phys. Rev. D 101, 073007 (2020)]

Z_2-symmetric 3HDM with dark CPV

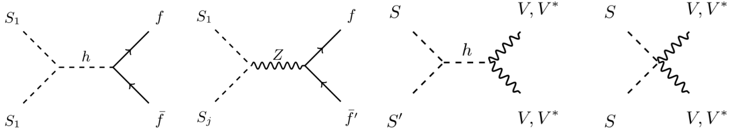
DM is protected by a Z_2 symmetry $(-,-,+)$:

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

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 CP-mixed state $S_{1,2,3,4}$ (mixtures of $H_{1,2}, A_{1,2}$)

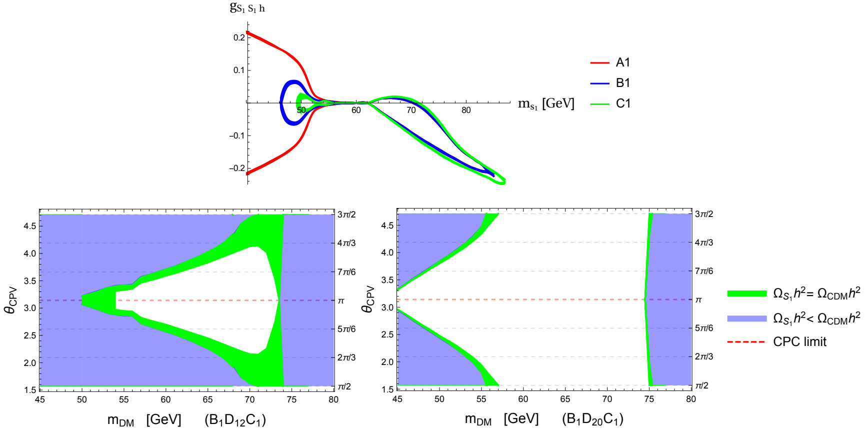


Tension released: the extended dark sector allows for annihilations, co-annihilations and CP-violation!

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

Z_2-symmetric 3HDM with dark CPV

Due to co-annihilation with other dark particles



V. Keus, S. F. King, S. Moretti, D. Sokolowska, et al., [JHEP 12, 014 (2016)], V. Keus, [Phys. Rev. D 101, 073007 (2020)]

Dark CPV observables

Multi-component Dark Matter in 3HDMs

2 scalar doublets + the SM Higgs doublet

$\phi_1, \ \phi_2 \qquad\qquad \phi_3$

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

3HDM with a $Z_2 \times Z'_2$ symmetry

DM protected by a Z_2 symmetry $(-,+,+)$, and 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 $(0,0,v)$:

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

The lightest neutral field from each doublet is a viable DM candidate:

$$m_{H_1} < m_{A_1} < m_{H_1^\pm} \qquad m_{H_2} < m_{A_2} < m_{H_2^\pm}$$

Z_2 symmetry: only ϕ_3 couples to fermions $\phi_u = \phi_d = \phi_e = \phi_3$

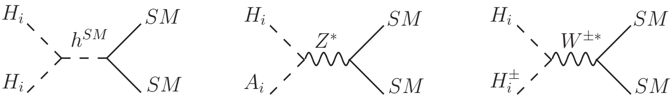
$$-\mathcal{L}_{Yukawa} = Y_u \, \bar{Q}'_L \, i\sigma_2 \, \phi_u^* \, u'_R + Y_d \, \bar{Q}'_L \, \phi_d \, d'_R + Y_e \, \bar{L}'_L \, \phi_e \, e'_R + \text{h.c.}$$

No FCNCs

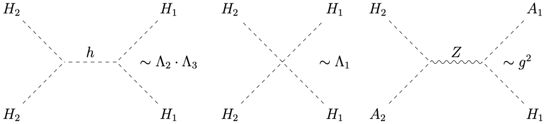
J. Hernandez, V. Keus, S. Moretti, D. Rojas, D. Sokolowska, [JHEP 03, 045 (2023)] and [arXiv:2012.11621]

Two-component light H_1 and heavy H_2 DM

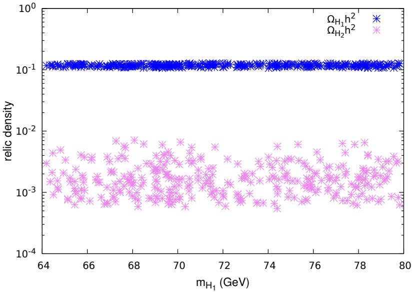
(Co)annihilations:



Conversions:

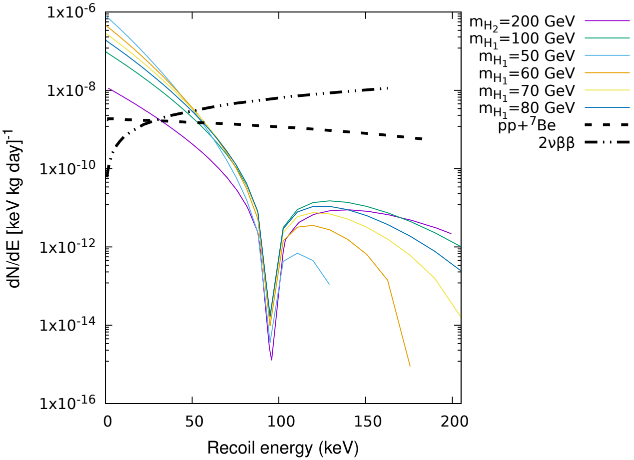


Relic density contributions:



Astrophysical probes: Direct detection at XENONnT/LZ

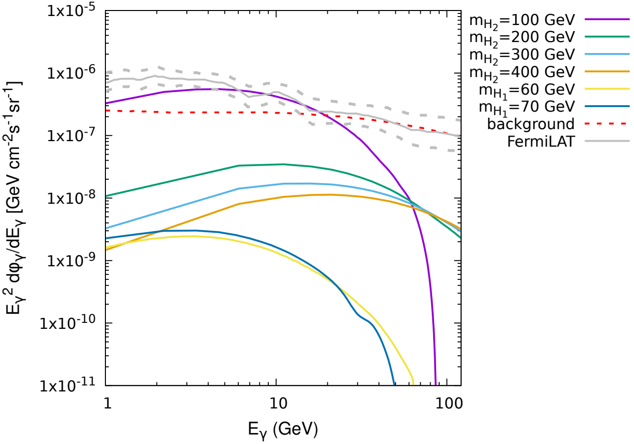
Light DM H_1: probed in the nuclear recoil energy event rate



J. Hernandez, V. Keus, S. Moretti, D. Rojas, D. Sokolowska, [JHEP 03, 045 (2023)] and [arXiv:2012.11621]

Astrophysical probes: Indirect detection at Fermi-LAT

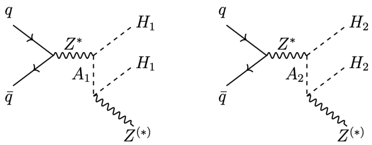
Heavy DM H_2: contributes to the photon flux from the galactic center

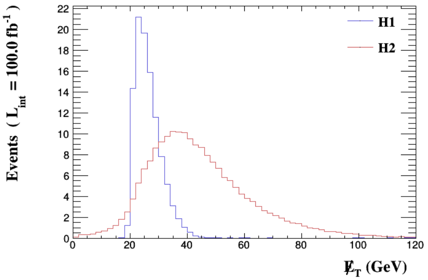


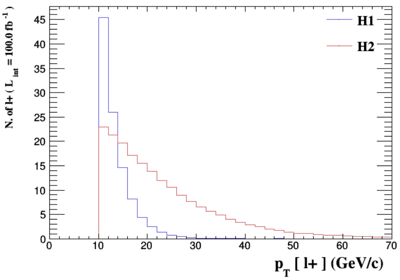
J. Hernandez, V. Keus, S. Moretti, D. Rojas, D. Sokolowska, [JHEP 03, 045 (2023)] and [arXiv:2012.11621]

Collider probes: distributions of observables

$m_{H_2} - m_{H_1} > \not{E}_T$ resolution $\Rightarrow$ visible effect in different distributions







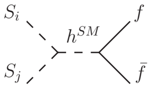
Missing transverse energy and transverse momentum of either lepton

J. Hernandez, V. Keus, S. Moretti, D. Rojas, D. Sokolowska, [JHEP 03, 045 (2023)] and [arXiv:2012.11621]

Purely scalar extensions w/o a $Z_2 \times Z_2'$ symmetry:

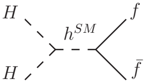
SM + singlet(s):

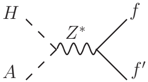
- $\phi_{SM}, S \Rightarrow$ DM, ~~CPV~~
- $\phi_{SM}, S_{1,2} \Rightarrow$ DM, ~~CPV~~

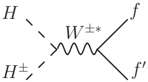


2HDMs:

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





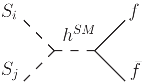


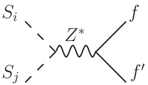
2HDM + singlet:

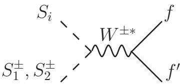
- $\phi_1, \phi_2, S \Rightarrow$ ~~DM~~, CPV
- $\phi_1, \phi_2, S \Rightarrow$ DM, ~~CPV~~
- $\phi_1, \phi_2, S \Rightarrow$ DM, CPV

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





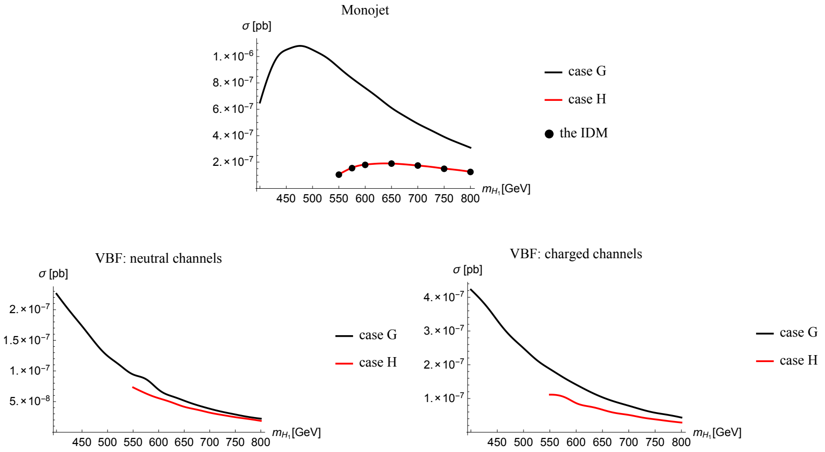


more

BACKUP SLIDES

Observable heavy scalar DM

Monojet and dijet channels in the heavy DM mass region:



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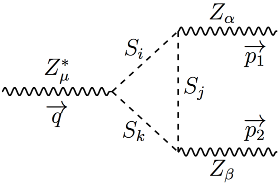
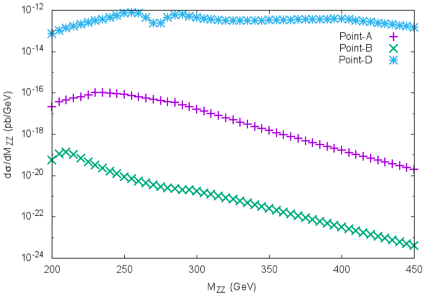
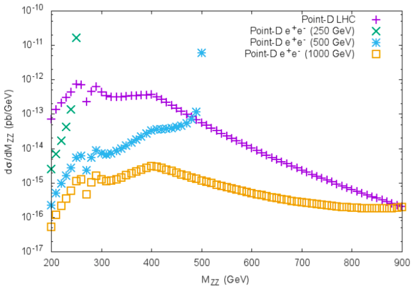
V. Keus, S. F. King, S. Moretti, D. Sokolowska, [JHEP 1511 (2015) 003]

Dark CPV observables: the ZZZ vertex







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

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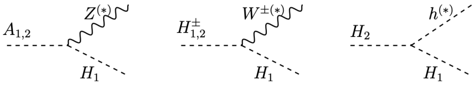
J. Hernandez, V. Keus, S. Moretti, D. Rojas-Ciofalo, D. Sokolowska, [Phys. Rev. D 101, 095023 (2020)]

Inert cascade decays at the LHC

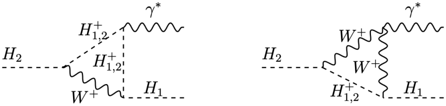
Tree level process: $q\bar{q} \to Z^* \to H_1 A_{1,2} \to H_1 H_1 Z^* \to H_1 H_1 f\bar{f}$



(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)

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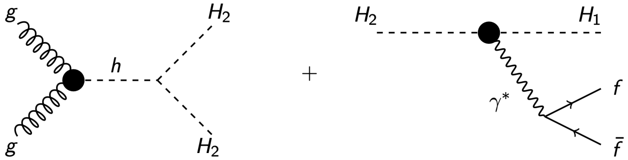
J. Hernandez, V. Keus, S. F. King, S. Moretti, D. Rojas, D. Sokolowska, [JHEP 05, 030 (2018)]

The smoking gun signature (see Atri Dey's talk)

MET+ 4μ: $gg \to h \to H_2 H_2 \to H_1 H_1 \gamma^* \gamma^* \to H_1 H_1 \ell^+ \ell^- \ell^+ \ell^-$



Benchmark	m_{H_1}	m_{H_2}	m_{A_1}	m_{A_2}	$m_{H_1^\pm}$	$m_{H_2^\pm}$	n	θ_h	$\sigma_{2\mu}$	$\sigma_{4\mu}$
BP1	50	55	95	104	116	127	0.83	0.105	0.02224	6.923
BP2	50	60	94	112	115	137	0.70	0.103	0.06	4.0

- Signal: ≥ 3 -μ with at least one pair of opposite sign μ with $\not{E}_T$.
- Background: VV, VVV $(V = W^\pm, Z, \gamma)$ and
  $t\bar{t}X$ $(X = W^\pm, Z, \gamma, W^\pm W^\mp, t\bar{t})$

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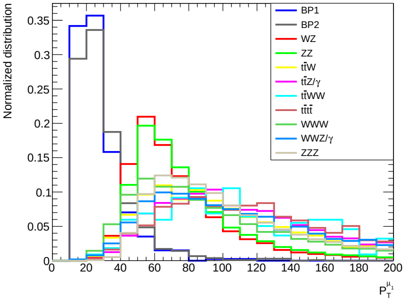
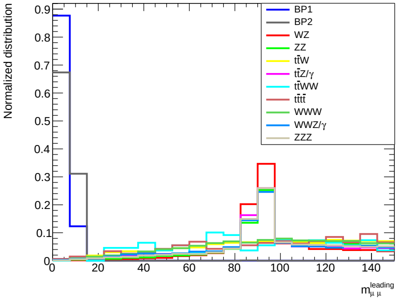
A. Dey, V. Keus, S. Moretti, C. Shepherd-Themistocleous [arXiv:2309.XXXX]

Distributions and significance (see Atri Dey's talk)





BP	$\mathcal{S}(Pre-selection)$	$\mathcal{S}(Cut-A)$
$BP1$	$0.05\ \sigma$	$3.77\ \sigma$
$BP2$	$0.17\ \sigma$	$13.67\ \sigma$

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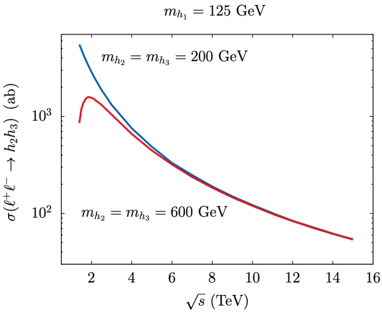
A. Dey, V. Keus, S. Moretti, C. Shepherd-Themistocleous [arXiv:2309.XXXX]

P-conserving, CP-violating observables at future colliders

Undoubtable signal of CPV: simultaneous observation of

1. $h_2 H^+ H^-$, $h_3 H^+ H^-$, $Z h_2 h_3$,
2. $h_2 h_k h_k$, $h_3 H^+ H^-$, $Z h_2 h_3$, (for $k = 2$ or 3),
3. $h_3 h_k h_k$, , $h_2 H^+ H^-$, $Z h_2 h_3$, (for $k = 2$ or 3),
4. $h_2 h_k h_k$, $h_3 h_\ell h_\ell$, $Z h_2 h_3$, (for $k, \ell = 2$ or 3).



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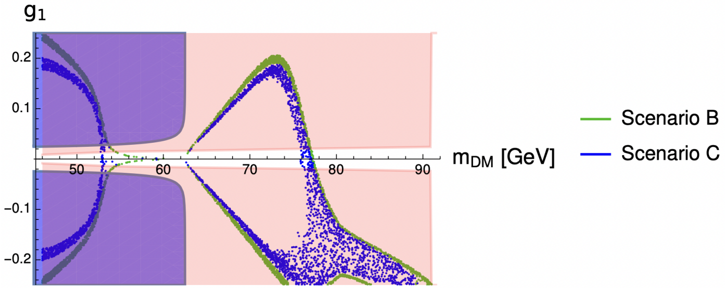
H. Haber, V. Keus, R. Santos, [Phys. Rev. D 106, 095038 (2022)]

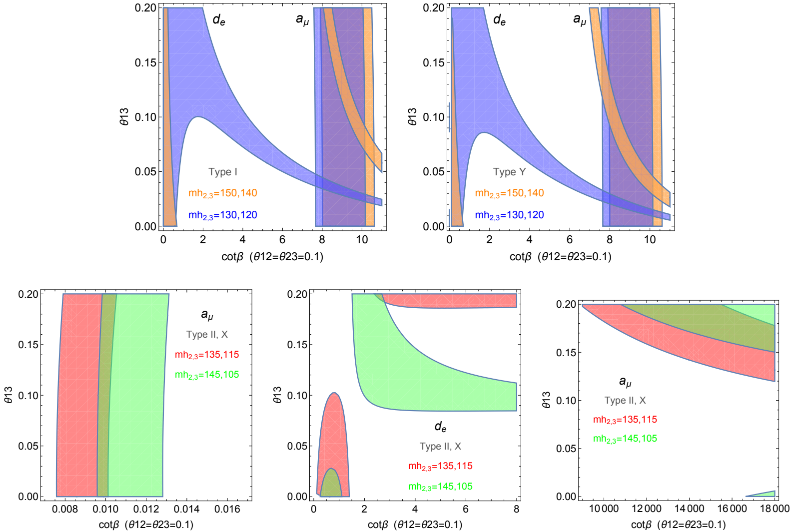
Z_3 3HDM: Hermaphrodite DM $N_1 = H_1 + A_1$

Scenario B: $m_{H_1} = m_{A_1} \ll m_{A_2} = m_{H_2} \ll m_{H_1^\pm} \sim m_{H_2^\pm}$
Scenario C: $m_{H_1} = m_{A_1} \sim m_{A_2} = m_{H_2} \ll m_{H_1^\pm} \sim m_{H_2^\pm}$



back A. Aranda, D. Hernández-Otero, J. Hernández-Sanchez, V. Keus, S. Moretti, D. Rojas-Ciofalo, T. Shindou, [Phys. Rev. D 103, no.1, 015023 (2021)]

Overlap between d_e and a_μ regions in 2HDMs



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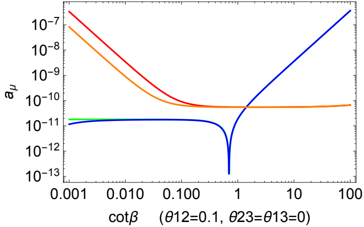
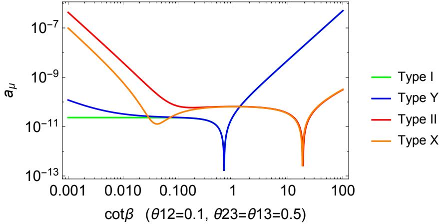
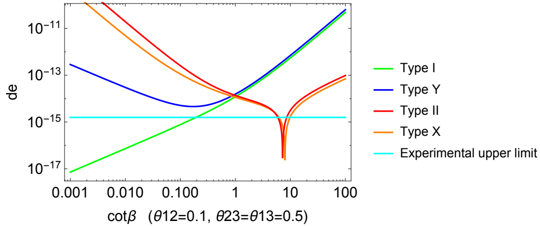
V. Keus, N. Koivunen, K. Tuominen, [JHEP 09, 059 (2018)]

a_μ with/without CPV and d_e







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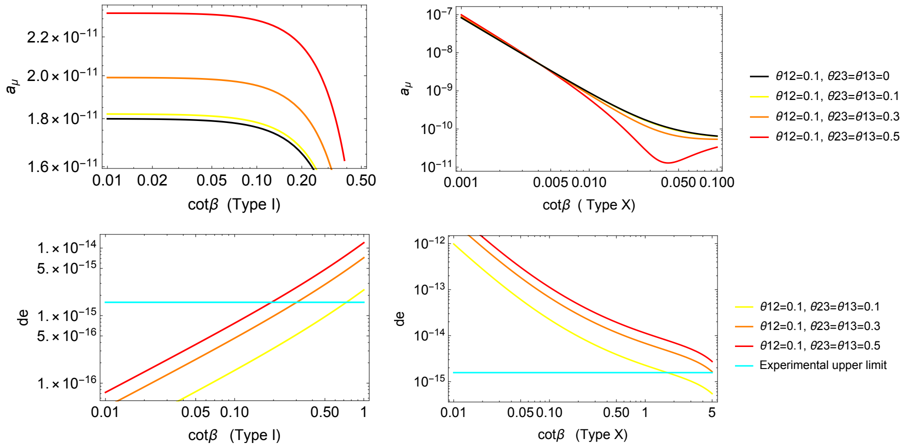
V. Keus, N. Koivunen, K. Tuominen, [JHEP 09, 059 (2018)]

A closer look



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V. Keus, N. Koivunen, K. Tuominen, [JHEP 09, 059 (2018)]