Dark Matter models with extended scalar sectors

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Extended Scalar Sectors From All Angles

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CERN

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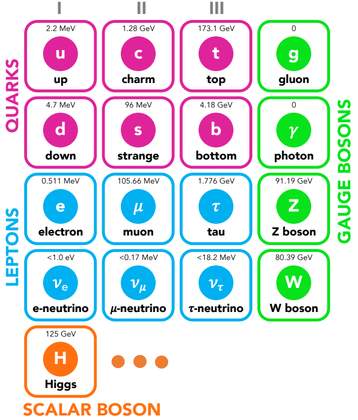
The need to go beyond the Standard Model (SM)

What is missing in SM:

- 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

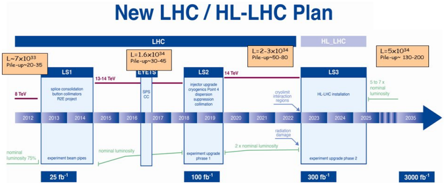
$\Rightarrow$ beyond the Standard Model

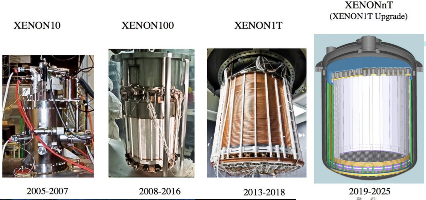
$\Rightarrow$ **scalar extensions of the SM**

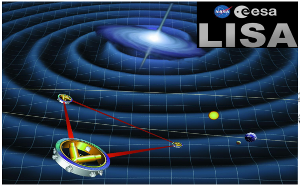


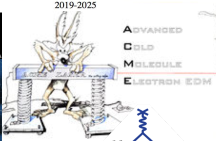
Complementary experimental probes of scalar extensions

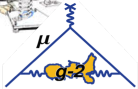
- Collider experiments
  - LHC-RUN-III
  - HL-LHC
  - CEPC
- DM experiments
  - XENONnT
  - CTA
- GW experiments
  - DECIGO
  - LISA mission
- Precision experiments
  - $(g-2)_\mu$
  - Advanced ACME











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."

$\Rightarrow$ 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)."

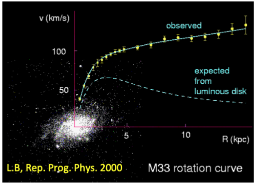


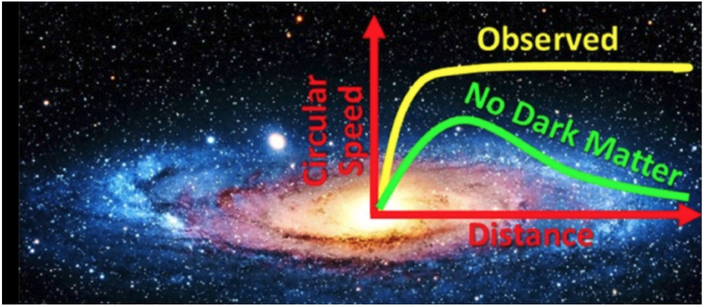
Tabelle 4.

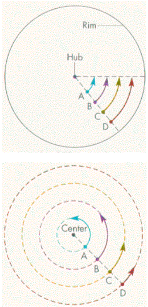
Objekt	Ratio: $\frac{\text{Luminous + Dark Matter}}{\text{Luminous Matter}}$
Messier 81	100:1 (?)
N. G. C. 4594	30:1
Andromedanebel	20:1
Messier 51	10:1
Milchstraßensystem	10:1
Messier 33	6:1

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

How do we know Dark Matter exists?

Galactic rotation curves:





Expectation: stars velocity to fall towards the edges.
Observation: stars velocity stays constant towards the edges.

$\Rightarrow$ a spread of Dark Matter throughout the galaxy

How do we know Dark Matter exists?

The Bullet cluster merger:

- Optical observations
- Gravitational observations

The visible matter is concentrated near the center.

The Dark Matter is concentrated in two pieces, just outside of the luminous matter.

Collision of two galaxy clusters

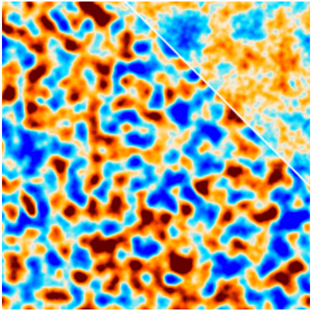
How do we know Dark Matter exists?

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.

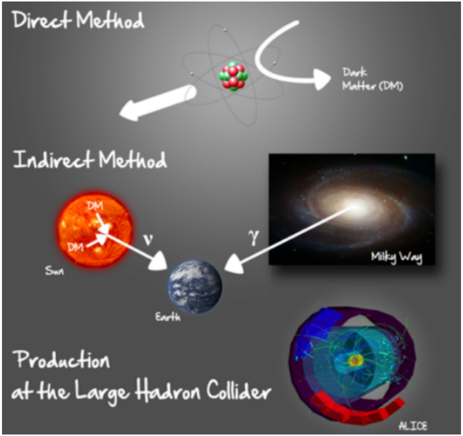


Planck CMB simulator

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

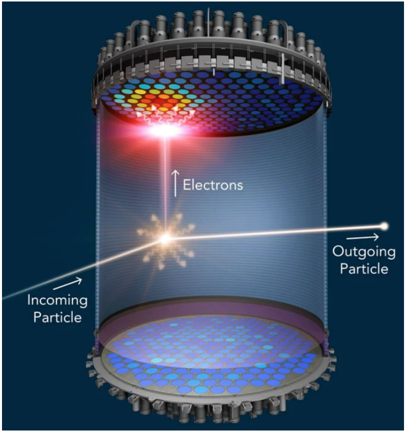
N. Aghanim et al. [Planck], Astron. Astrophys. 641, A6 (2020)

How do we look for Dark Matter?



Direct Detection searches

In deep underground gigantic tanks of liquid gas

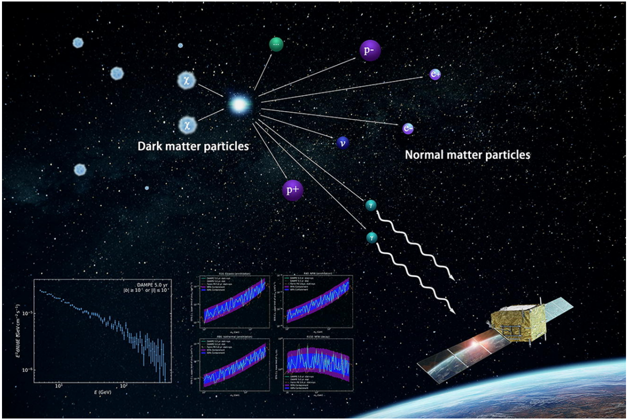


Constrain the scattering cross section of DM off of nuclei

XENON collaboration

Indirect Detection searches

In dense regions of sky with telescopes in orbit

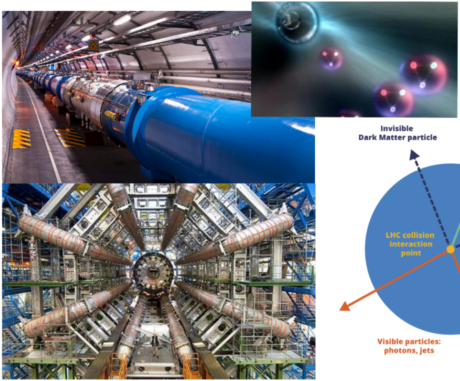


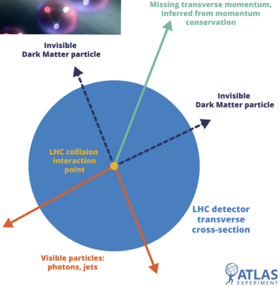
Constrain the annihilation rate of DM to SM particles

DAMPE collaboration

High energy collider experiments

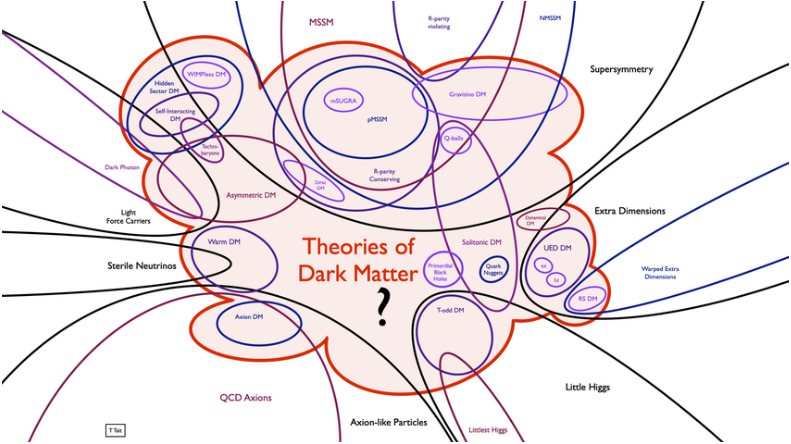
Pair-producing it in high energy collider experiments





Looking for events with MET + model dependent objects

What is Dark Matter?

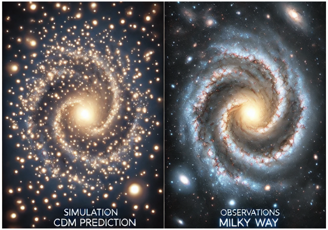


(Image: T. M. P. Tait)

Categorisation based on the velocity of DM

This affects how it clusters and impacts structure formation:

- Cold Dark Matter (CDM): WIMPs
- Warm Dark Matter (WDM): Sterile neutrinos
- Hot Dark Matter (HDM): SM-neutrinos



Categorisation based on the velocity of DM

Dark Matter Type	Examples	Pros	Cons
Cold Dark Matter (CDM)	WIMPs, Axions, MACHOs, Primordial Black Holes	- Explains large-scale structures (galaxies, clusters). - Matches cosmic microwave background (CMB) and galaxy data well.	- May overpredict small-scale structures (e.g., dwarf galaxies). - No direct detection yet (for WIMPs).
Warm Dark Matter (WDM)	Sterile Neutrinos, Thermal Relics (keV scale)	- Helps resolve the overabundance of small structures in CDM. - Fits both large- and small-scale observations better than CDM.	- Lacks strong evidence for WDM candidates. - May not completely solve all small-scale problems.
Hot Dark Matter (HDM)	Light Neutrinos (Standard Model), Hypothetical Light Particles	- Explains suppression of small-scale structures in the early universe.	- Cannot form galaxies and clusters. - Contradicts observed galaxy and structure formation.

Categorisation based on DM production mechanism

This affects how DM could have formed and evolved:

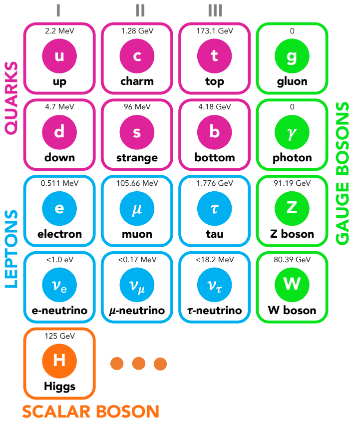
- Thermal Production
  - Freeze-out: Weakly Interacting Massive Particles (WIMPs)
  - Freeze-in: Feebly Interacting Massive Particles (FIMPs)
  - Asymmetric Dark Matter (ADM)
- Non-Thermal Production
  - Misalignment, produced though oscillations of a scalar field: ALPs
  - Decay of a heavy parent particle: WIMPzillas
  - Primordial Black Holes (PBHs): formed from density fluctuations
  - Inflationary production: ultralight scalar fields (Fuzzy DM)
  - Gravitational production

Categorisation based on DM production mechanism

Production Mechanism	Examples	Pros	Cons
Thermal Freeze-out	WIMPs	Naturally explains relic density	No detection despite extensive searches
Thermal Freeze-in	FIMPs	Explains dark matter abundance	Weak interactions, hard to detect
Asymmetric Dark Matter (ADM)	Asymmetric Dark Matter	Explains baryon-to-dark matter ratio	Requires specific model-building
Non-thermal Misalignment	Axions	Solves the strong CP problem	Difficult to detect axions
Out-of-equilibrium Decays	Sterile Neutrinos, Gravitinos	Non-thermal production, no equilibrium	Model-dependent, challenging detection
Superheavy Dark Matter (WIMPzillas)	Supermassive particles	Explains absence of detection signals	Extremely hard to detect
Primordial Black Holes (PBHs)	Primordial Black Holes	No new particle physics required	Limited mass range, astrophysical limits
Inflationary Production	Ultralight Scalars, Scalar Fields	Inflation models are well-motivated	Hard to detect very light particles

Higgs portal models and extra scalars

Scalar extensions are a common characteristic of almost all BSM scenarios.



The scalar sector is the least understood and experimentally least constrained sector.

Scalar singlet extension of SM

the SM Higgs doublet + a scalar singlet

ϕ S

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

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

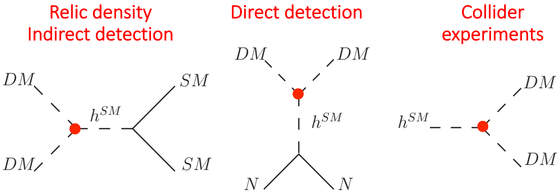
SM + scalar singlet

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

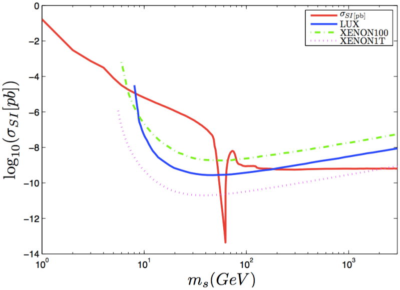
$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}(\partial S)^2 - m_s^2 S^2 - \lambda_s S^4 - \lambda_{hs} \phi^2 S^2$$



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

SM + scalar singlet

- 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

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

Z_2-symmetric 2HDM

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

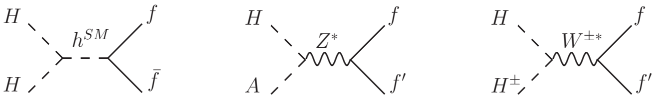
$$\text{SM fields} \to \text{SM fields}, \quad \phi_1 \to \phi_1, \quad \phi_2 \to -\phi_2$$

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



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:

$$m_{H^\pm} + m_{H,A} > m_{W^\pm}, \qquad m_H + m_A > m_Z, \qquad 2m_{H^\pm} > m_Z$$

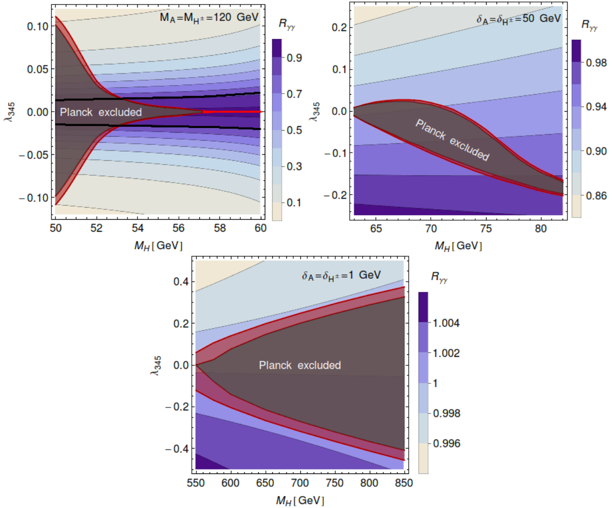
$$m_{H^\pm} \gtrsim 70 - 90 \text{ GeV}$$

$$\text{if } M_H < 80 \text{ GeV and } M_A < 100 \text{ GeV} \Rightarrow M_A - M_H < 8 \text{ GeV}$$

LHC bound on the total decay signal strength:

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

Z_2-symmetric 2HDM



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

3-Higgs doublet models (3HDMs)

2 scalar doublets + the SM Higgs doublet

ϕ_1, ϕ_2 ϕ_3

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

Z_2-symmetric 3HDM with dark CPV

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

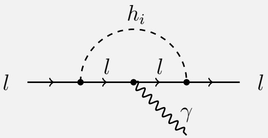
$$\phi_1 \to -\phi_1, \quad \phi_2 \to -\phi_2, \quad \text{SM fields} \to \text{SM fields}, \quad \phi_3 \to \phi_3$$

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)

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

Z_2-symmetric 3HDM with dark CPV

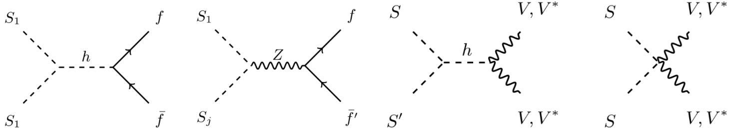
DM is protected by a Z_2 symmetry $(-,-,+)$:

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

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 $H_{1,2}$, $A_{1,2}$)

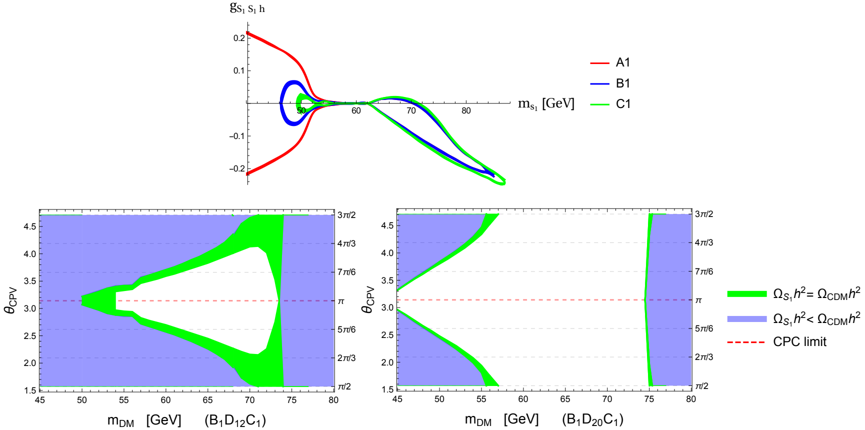


Tension released: the extended dark sector allows for annihilations, co-annihilations and CP-violation!

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)]

Multi-component Dark Matter in 3HDMs

2 scalar doublets + the SM Higgs doublet

ϕ_1, ϕ_2 ϕ_3

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

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 $\phi_u = \phi_d = \phi_e = \phi_3$

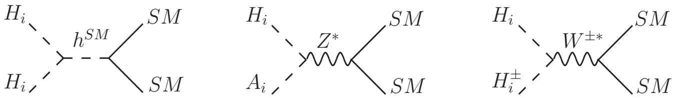
$$-\mathcal{L}_{Yukawa} = Y_u\, \bar{Q}_L'\, i\sigma_2\, \phi_u^*\, u_R' + Y_d\, \bar{Q}_L'\, \phi_d\, d_R' + Y_e\, \bar{L}_L'\, \phi_e\, e_R' + \text{h.c.}$$

No FCNCs

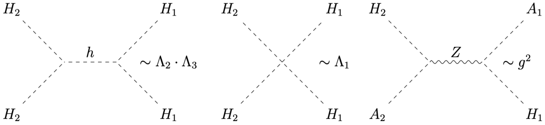
J. Hernandez, V. Keus, S. Moretti, D. Rojas, D. Sokolowska, [JHEP 03, 045 (2023)] and [arXiv:2012.11621]

Two-component light H_1 and heavy H_2 DM

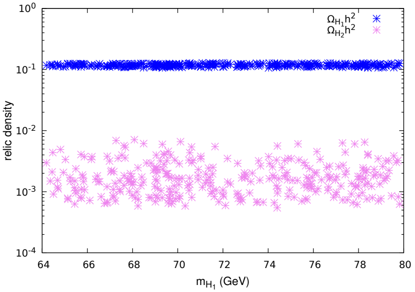
(Co)annihilations:



Conversions:

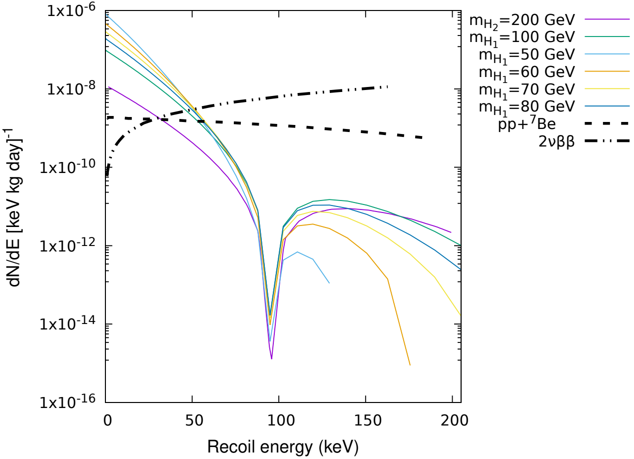


Relic density contributions:



Astrophysical probes: Direct detection at XENONnT/LZ

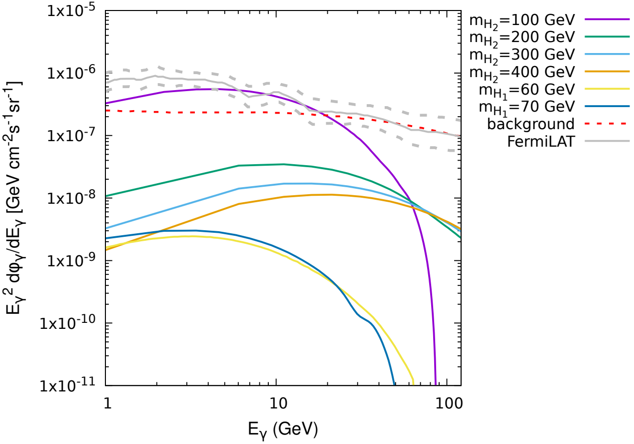
Light DM H_1: probed in the nuclear recoil energy event rate



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

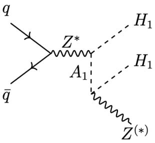
Heavy DM H_2: contributes to the photon flux from the galactic center

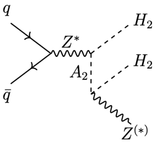


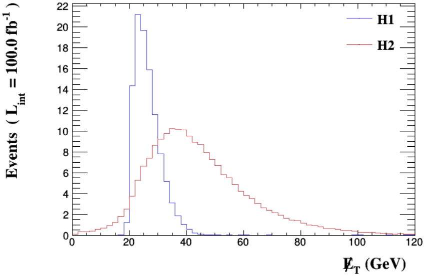
J. Hernandez, V. Keus, S. Moretti, D. Rojas, D. Sokolowska, [JHEP 03, 045 (2023)] and [arXiv:2012.11621]

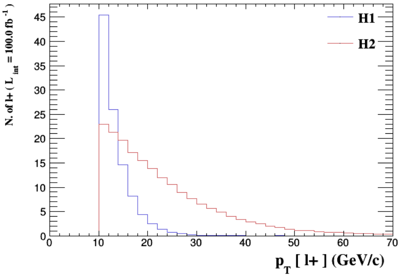
Collider probes: distributions of observables

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







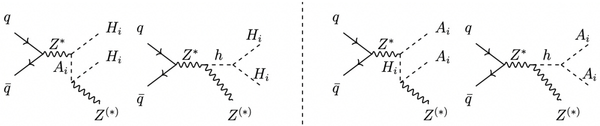


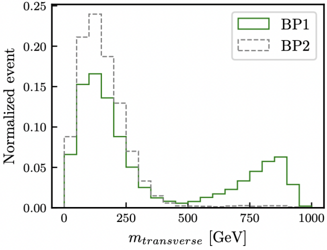
Missing transverse energy and transverse momentum of either lepton

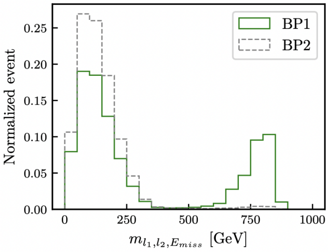
J. Hernandez, V. Keus, S. Moretti, D. Rojas, D. Sokolowska, [JHEP 03, 045 (2023)] and [arXiv:2012.11621]

CP properties of DM

DM components with same CP vs. DM components with opposite CP





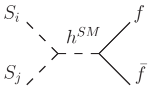


A. Dey, J. Hernandez, V. Keus, S. Moretti, T. Shindou,[arXiv:2409.16360]

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

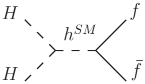
SM + singlet(s):

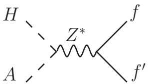
- $\phi_{SM}, S \Rightarrow$ DM, ~~CPV~~
- $\phi_{SM}, S_{1,2} \Rightarrow$ DM, ~~CPV~~

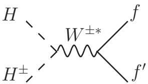


2HDMs:

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





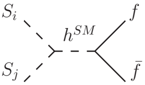


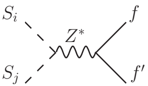
2HDM + singlet:

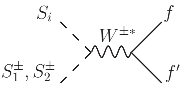
- $\phi_1, \phi_2, S \Rightarrow$ ~~DM~~, CPV
- $\phi_1, \phi_2, S \Rightarrow$ DM, ~~CPV~~
- $\phi_1, \phi_2, S \Rightarrow$ DM, CPV

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







BACKUP SLIDES

How to make predictions for DM at colliders

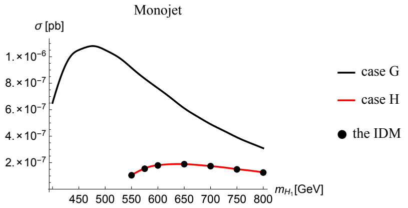
Top-down approach: a complete theory; UED, SUSY, etc.,
pros: distinct specific search strategies and signals
cons: many parameters, finite amount of data

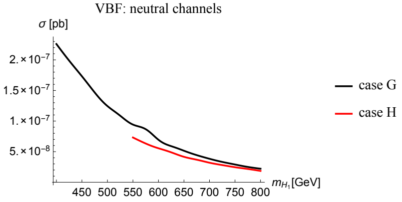
Bottom-up approach: interactions of DM with SM are approximated

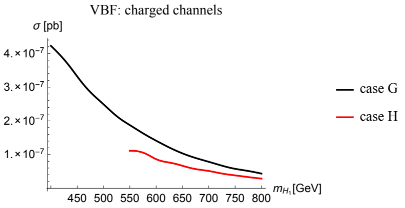
- Effective Field Theories (EFT): assuming the mediators, connecting DM with SM, are heavy and integrated out
  pros: useful when DM is the only light new physics state
  cons: inappropriate for colliders if the mediator is produced on-shell
- Simplified models: devised to mediate between a complete model description of a DM theory and an EFT description
  pros: can describe the full kinematics of DM production

Observable heavy scalar DM

Monojet and dijet channels in the heavy DM mass region:



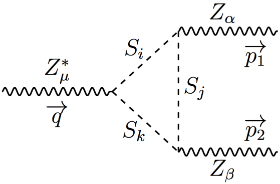


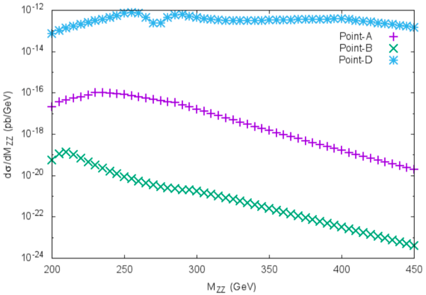


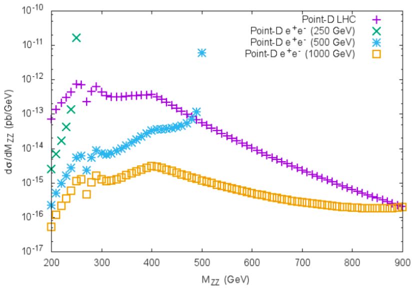
back

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

Dark CPV observables: the ZZZ vertex







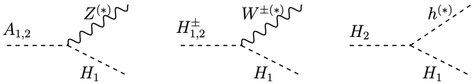
Differential $f\bar{f} \to Z^* \to ZZ$ cross section at hadron and lepton colliders

back

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

Inert cascade decays at the LHC

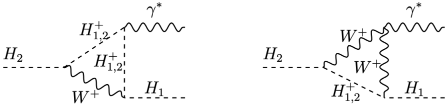
Tree level process: $q\bar{q} \to Z^* \to H_1 A_{1,2} \to H_1 H_1 Z^* \to H_1 H_1 f \bar{f}$



(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: $q_i q_j \to H_1 H_2 \to H_1 H_1 \gamma^* \to H_1 H_1 f \bar{f}$



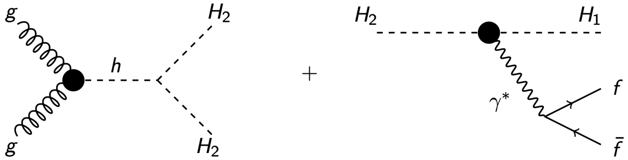
(smoking gun signature of 3HDM)

back

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



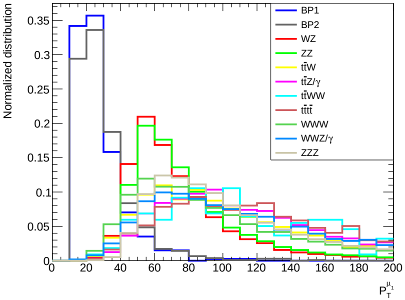
Benchmark	m_{H_1}	m_{H_2}	m_{A_1}	m_{A_2}	$m_{H_1^\pm}$	$m_{H_2^\pm}$	n	θ_h	$\sigma_{2\mu}$	$\sigma_{4\mu}$
BP1	50	55	95	104	116	127	0.83	0.105	0.02224	6.923
BP2	50	60	94	112	115	137	0.70	0.103	0.06	4.0

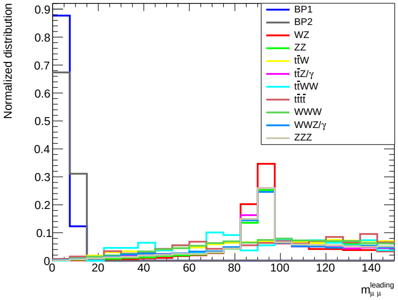
- Signal: ≥ 3 -μ with at least one pair of opposite sign μ with $\not{E}_T$.
- Background: VV, VVV $(V = W^\pm, Z, \gamma)$ and $t\bar{t}X$ $(X = W^\pm, Z, \gamma, W^\pm W^\mp, t\bar{t})$

back

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

Distributions and significance (see Atri Dey's talk)





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

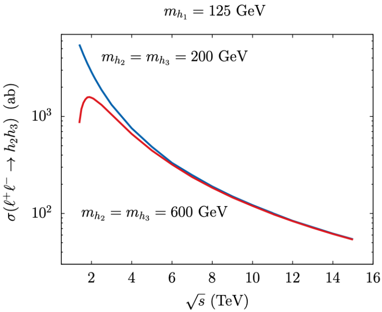
back

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. $h_2 H^+ H^-$, $h_3 H^+ H^-$, $Zh_2 h_3$,
2. $h_2 h_k h_k$, $h_3 H^+ H^-$, $Zh_2 h_3$,   (for $k = 2$ or 3),
3. $h_3 h_k h_k$, , $h_2 H^+ H^-$, $Zh_2 h_3$,   (for $k = 2$ or 3),
4. $h_2 h_k h_k$, $h_3 h_\ell h_\ell$, $Zh_2 h_3$,   (for $k, \ell = 2$ or 3).

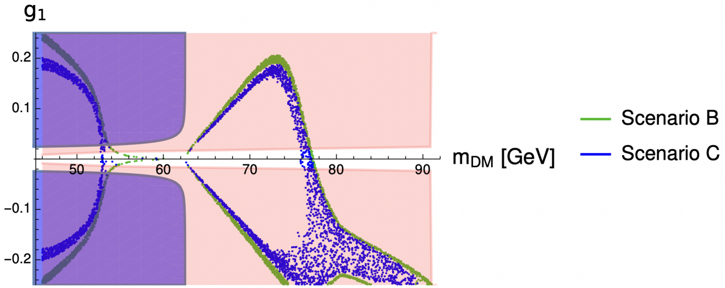


back

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)]