(particle) Dark Matter theory in the era of future accelerators

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Science Foundation Ireland
IRISH RESEARCH COUNCIL
An Chomhairle um Thaighde in Éirinn

EISA European Institute for Sciences and Their Applications
Corfu Summer Institute
Hellenic School and Workshops on Elementary Particle Physics and Gravity
Corfu, Greece

April 28, 2023

Ireland is finally joining CERN

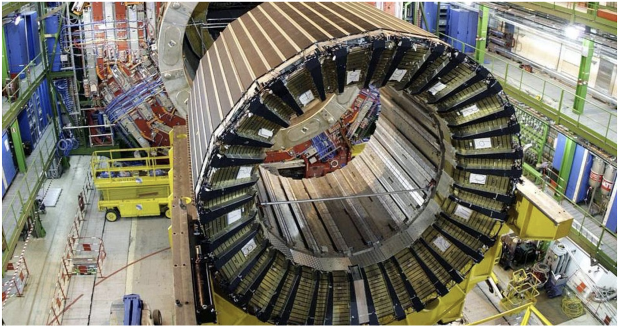
THE IRISH TIMES 12°

Science Analysis

A happy new year for Ireland and Cern

Irish scientists could at last participate in 'big science' experiments and work with the best in the world

Expand

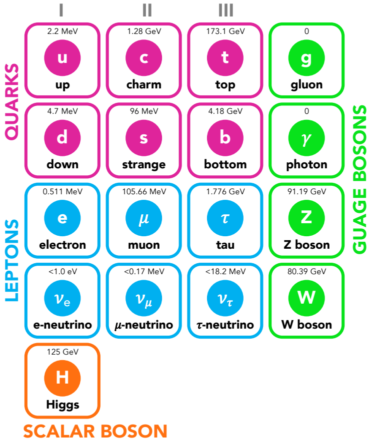


Stay tuned for the first Irish CERN conference in 2024

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



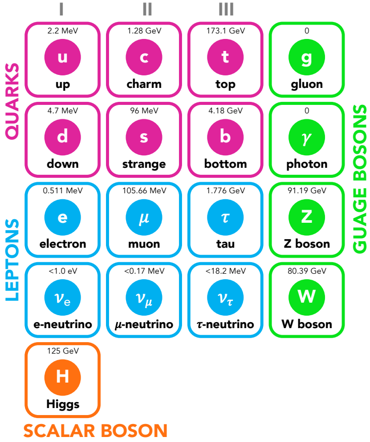
VK Theorists experiment experiment
~~JFK~~: My fellow ~~Americans~~, ask not what your ~~country~~ can do for you, ask what you can do for your ~~country~~.

··· 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

⇒ beyond the Standard Model



How do we know Dark Matter exists?

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

How do we know Dark Matter exists?

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.

How do we know Dark Matter exists?

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)."

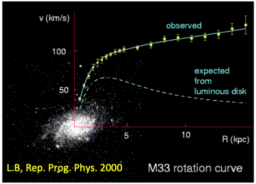


Tabelle 4.

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) see also

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

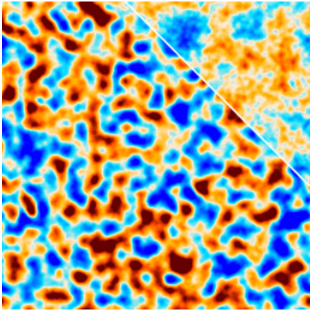
How do we know Dark Matter exists?

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.

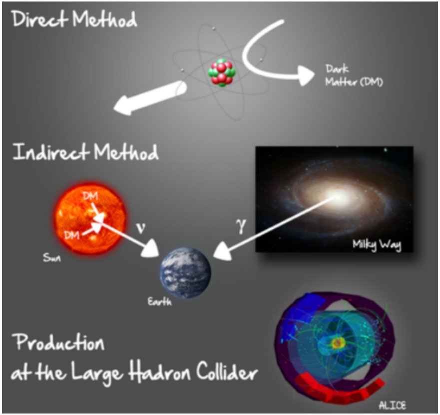


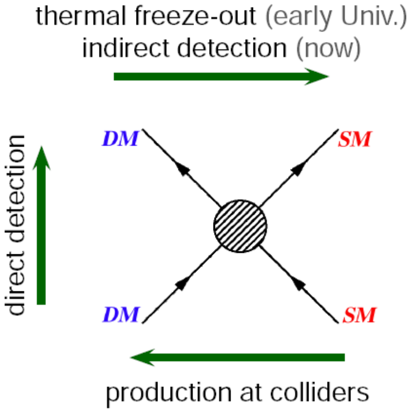
Planck CMB simulator

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)

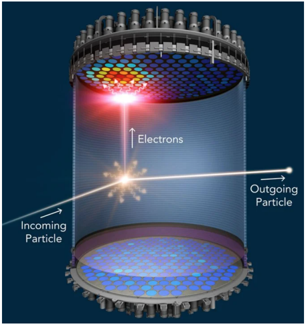
How do we look for Dark Matter?

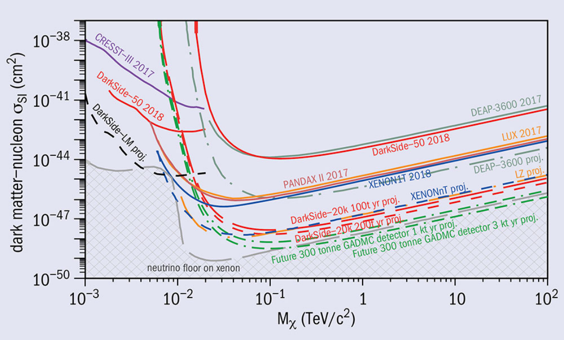




Direct Detection searches

In deep underground gigantic tanks of liquid gas



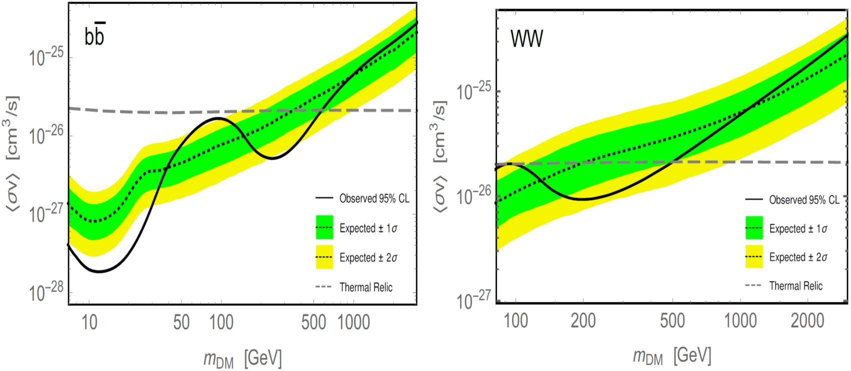


Constrain the spin-independent scattering cross section of DM off of nuclei

E. Aprile et al. [XENON], Phys. Rev. Lett. 121, no.11, 111302 (2018)

Indirect Detection observations

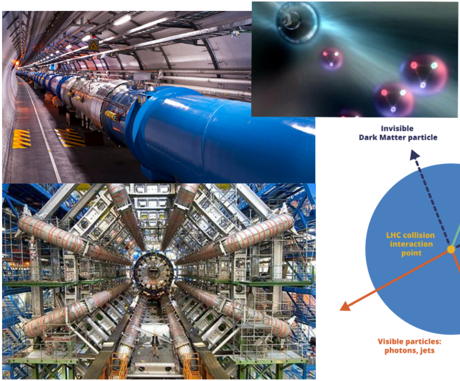
In dense regions of sky with telescopes in orbit $\mathrm{DMDM} \to bb/\tau\tau/WW$

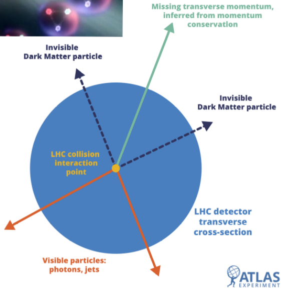


[M. Ackermann et al. [Fermi-LAT], Phys. Rev. Lett. 115, no.23, 231301 (2015)], [M. Cirelli and G. Giesen, JCAP 04, 015 (2013)], [Symmetry 2020, 12(10), 1648]

High energy collider experiments

Pair-producing it in high energy collider experiments

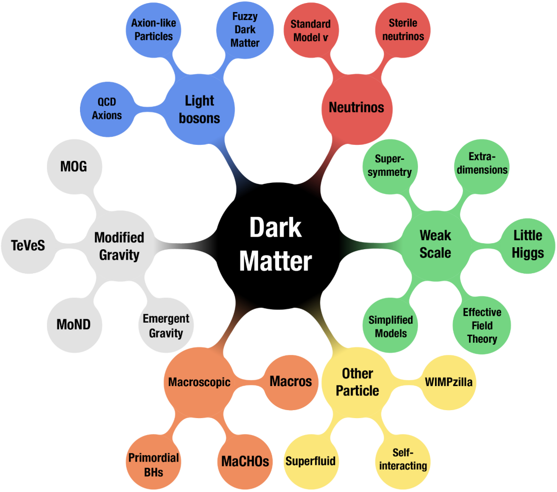




Looking for events with MET + model dependent objects

$$pp \rightarrow \mathrm{jets/leptons}/\gamma/\mathrm{W}/\mathrm{Z}/\mathrm{h} + \not{E}_T$$

What is Dark Matter?



(Image: G. Bertone and T. M. P. Tait)

How to make predictions for DM at colliders

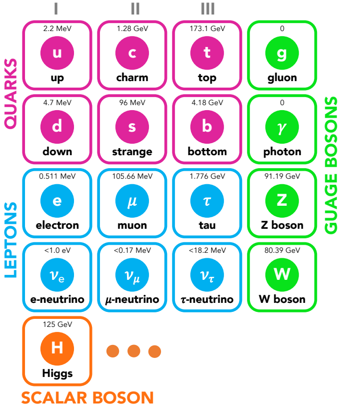
Top-down approach: a complete theory; UED, SUSY, etc.,
pros: distinct specific search strategies and signals
cons: many parameters, finite amount of data

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

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.

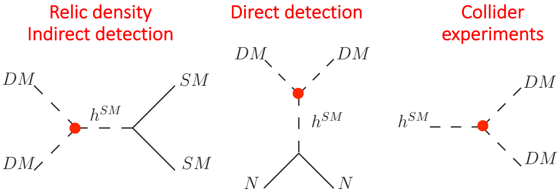
Higgs portal models: SM+ scalar singlet

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!

Higgs portal models: SM + scalar doublet

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

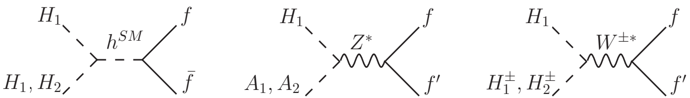
$$\text{SM fields} \to \text{SM fields}, \quad \phi_1 \to \phi_1, \quad \phi_2 \to -\phi_2$$

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!

Higgs portal models: SM + 2 scalar doublets

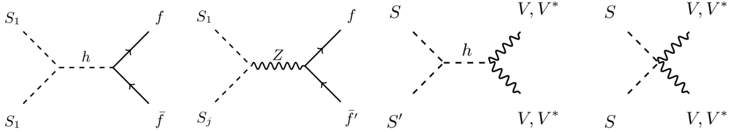
DM is protected by a Z_2 symmetry $(-,-,+)$:

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

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

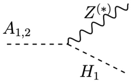


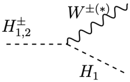
Tension released: the extended dark sector allows for annihilations, co-annihilations and CP-violation!

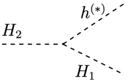
V. Keus, S. F. King, S. Moretti, D. Sokolowska, et al., [JHEP 12, 014 (2016)]

Inert cascade decays at the LHC

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



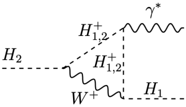


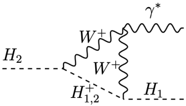


(may be possible in 2HDM)

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



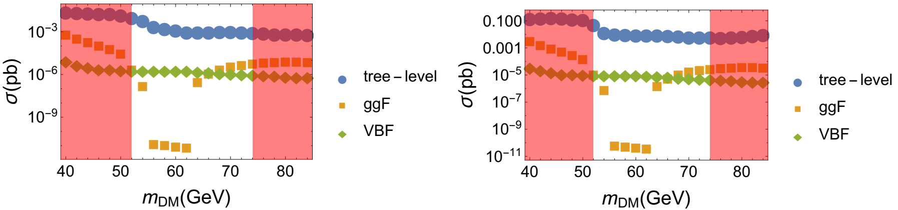


(smoking gun signature of 3HDM)

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)]

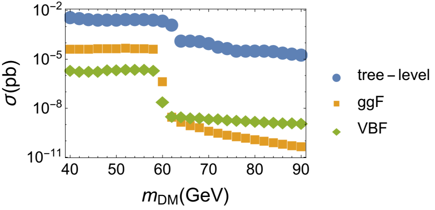
x-section for $\not{E}_T l\bar{l}$ and $\not{E}_T q\bar{q}$ for large $m_{H_2} - m_{H_1}$

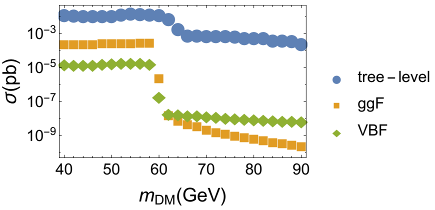


Decay channels	BR($H_2 \to H_1 X$)	tree-level	ggF	VBF
$H_2 \to b\bar{b}H_1$	1.88e-01	2.49e-03	1.18e-07	2.05e-06
$H_2 \to s\bar{s}H_1$	2.00e-01	1.97e-03	1.26e-07	2.19e-06
$H_2 \to c\bar{c}H_1$	2.00e-01	3.94e-03	1.26e-07	2.19e-06
$H_2 \to d\bar{d}H_1$	2.00e-01	3.54e-03	1.26e-07	2.19e-06
$H_2 \to u\bar{u}H_1$	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)]

x-section for $\not{E}_T l\bar{l}$ and $\not{E}_T q\bar{q}$ for small $m_{H_2} - m_{H_1}$



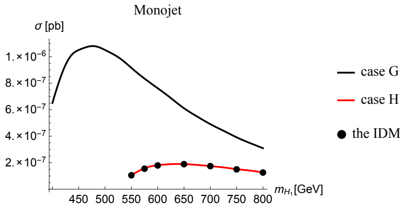


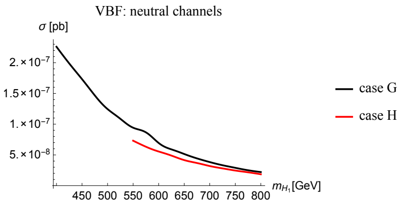
Decay channels	BR($H_2 \to H_1 X$)	tree-level	ggF	VBF
$H_2 \to s\bar{s}H_1$	2.22e-01	5.71e-03	9.70e-04	7.93e-06
$H_2 \to c\bar{c}H_1$	1.63e-01	1.52e-03	7.12e-05	5.82e-06
$H_2 \to d\bar{d}H_1$	2.28e-01	3.74e-03	9.96e-05	8.14e-06
$H_2 \to u\bar{u}H_1$	2.28e-01	4.80e-03	9.96e-05	8.14e-06
$H_2 \to \tau^+\tau^- H_1$	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

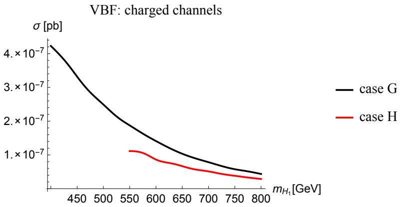
[JHEP 05, 030 (2018)]

Observable heavy scalar DM

Monojet and dijet channels in the heavy DM mass region:

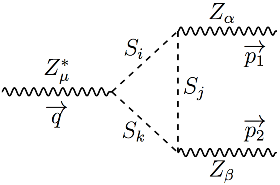


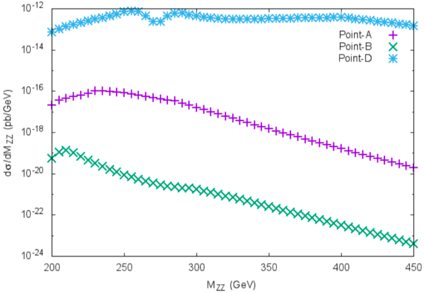


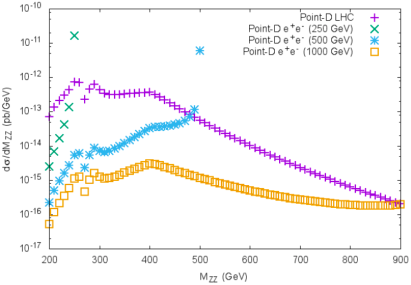


[JHEP 1511 (2015) 003]

Dark CPV observables: the ZZZ vertex



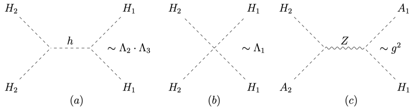


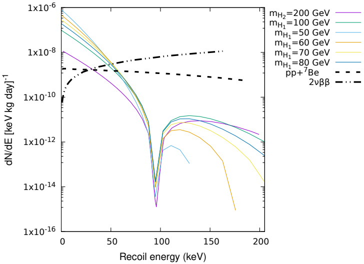


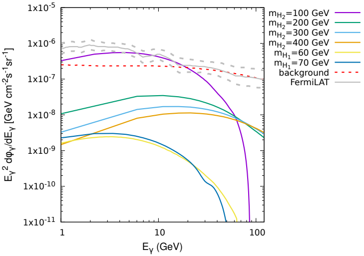
The differential $f\bar{f} \to Z^* \to ZZ$ cross section at hadron and lepton colliders

Two-component Dark Matter: H_1, H_2

The conversion processes play an important role in DM production.





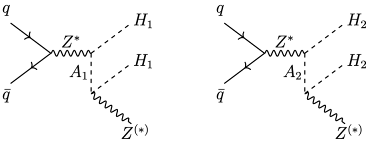


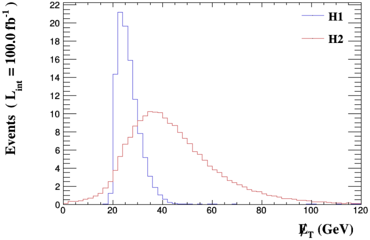
Light DM: probed by the nuclear recoil energy in DD experiments
Heavy DM: contributes to the photon flux in ID experiments

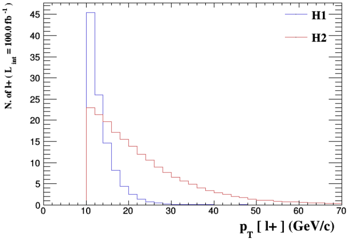
[JHEP 03 (2023) 045], [arXiv: 2012.11621]

Two-component Dark Matter: H_1, H_2

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





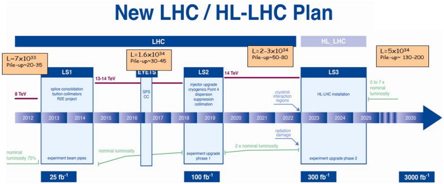


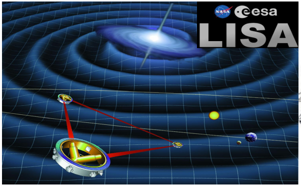
Missing transverse energy and transverse momentum of either lepton

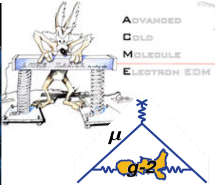
[JHEP 03 (2023) 045], [arXiv: 2012.11621]

Complementary experimental probes

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







Final remarks

- Cosmology and particle physics are joined at the hip; particle accelerators complement telescopes and vice versa.
- To uncover the particle properties of DM, we need to work together.

~~JFK~~ (VK): My fellow ~~Americans~~ (Theorists), ask not what your ~~country~~ (Experiment) can do for you, ask what you can do for your ~~country~~ (Experiment).

My fellow ~~citizens of the world~~ (Cosmo/Astro/Particle physicists), ask not what ~~America~~ (the next accelerator) will do for you, but together what we can do for the freedom of man.

and for the advancement of our understanding of fundamental physics

BACKUP SLIDES

Who discovered the expansion of the universe?

Common lore: Edwin Hubble discovered the expansion of the Universe, in 1929. Fritz Zwicky discovered Dark Matter, in 1933.

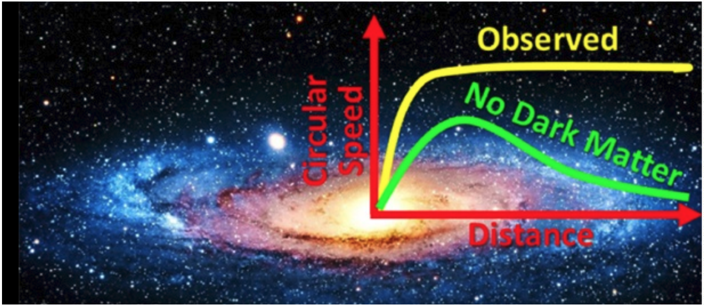
Forgotten pioneer: Knut Lundmark, Sweden (1889 – 1958)

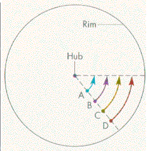
" … measurements by a Swedish astronomer, Knut Lundmark, were much more advanced than formerly appreciated. Lundmark was the first person to find observational evidence for expansion, in 1924 — three years before Lemaître and five years before Hubble. Lundmark's extragalactic distance estimates were far more accurate than Hubble's…"

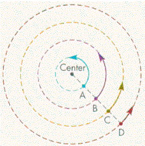
Ian Steer, NASA/IPAC, Pasadena, arxiv:1212.1359; J. R. Astron. Soc. Can. 105 (2011) 18

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

Galactic rotation curves



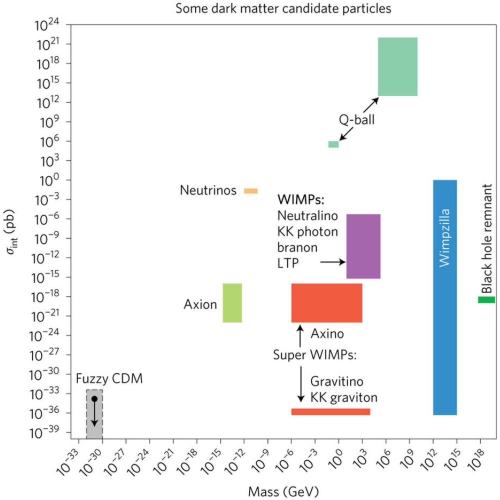




Expectation: stars velocity to fall towards the edges.
Observation: stars velocity stays constant towards the edges.

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

What is Dark Matter?



Scalar extensions of the SM

SM + scalar singlets link

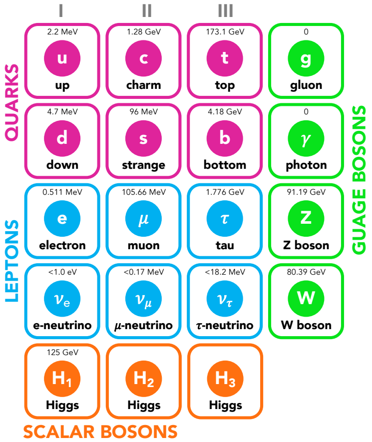
- Dark Matter severely constrained
- CP-violation not possible
- Inflation DM incompatible

2HDM: SM + a doublet link

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

3HDM: SM + 2 doublets link

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



Scalar singlet extension of SM

the SM Higgs doublet + a scalar singlet

ϕ S

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

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

back

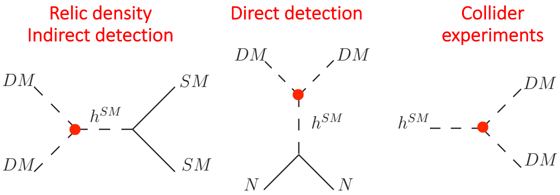
SM + scalar singlet DM ✓, CPV ×

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!

back

2-Higgs doublet models (2HDMs)

the SM Higgs doublet + a scalar doublet

ϕ_1 ϕ_2

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

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

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!

back

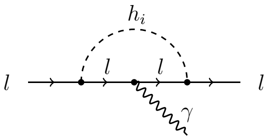
CP-violating 2HDM DM ×, CPV ✓

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!

back

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

3-Higgs doublet models (3HDMs)

two scalar doublets + the SM Higgs doublet

ϕ_1, ϕ_2 ϕ_3

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

back

Z_2-symmetric 3HDM with dark CPV DM ✓, CPV ✓

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

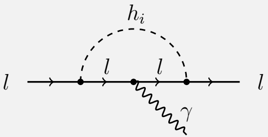
$$\phi_1 \to -\phi_1, \quad \phi_2 \to -\phi_2, \quad \text{SM fields} \to \text{SM fields}, \quad \phi_3 \to \phi_3$$

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

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

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

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



No contributions to electric dipole moments (EDMs)

back

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

Z_2-symmetric 3HDM with dark CPV DM ✓, CPV ✓

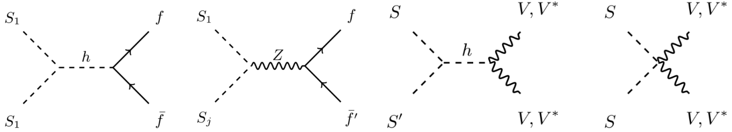
DM is protected by a Z_2 symmetry $(-,-,+)$:

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

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

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

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!

back

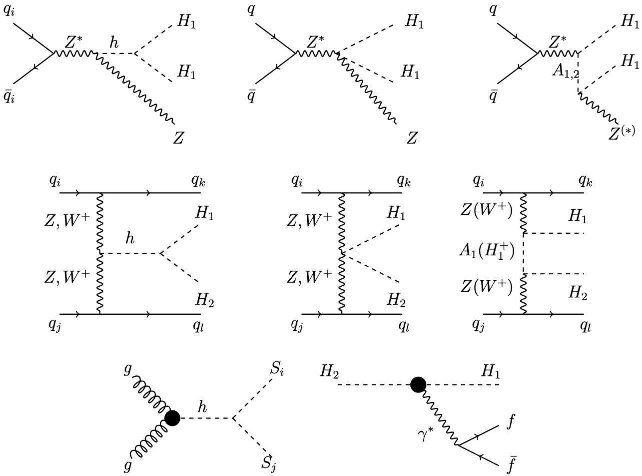
V. Keus, S. F. King, S. Moretti, D. Sokolowska, et al., [JHEP 12, 014 (2016)]

The background to the inert cascade decay

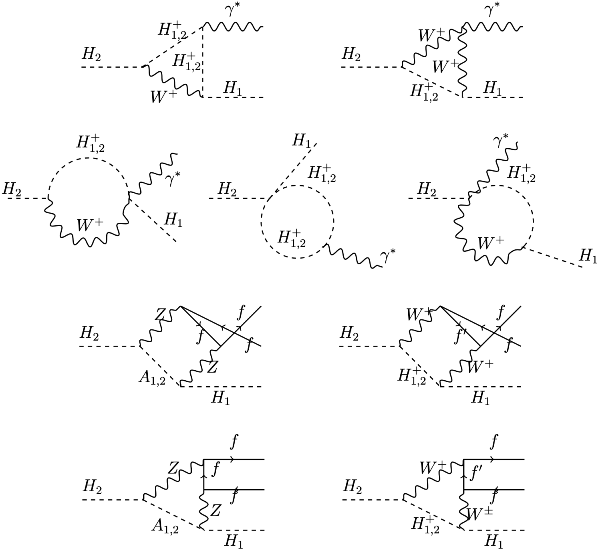
The background process, h decay into two charged scalars, cross section for $m_{DM} = 54$ GeV.

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

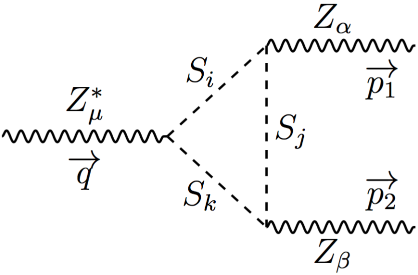


$H_2 \to H_1 f \bar{f}$ processes in inert cascade decays



Dark CPV observables: the ZZZ vertex

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

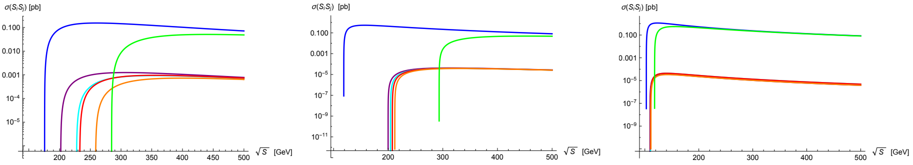


$$f_4 = \frac{M_Z^2|g_{ZS_2S_3}|\,|g_{ZS_1S_3}|\,|g_{ZS_1S_2}|}{2\pi^2 e(q^2 - M_Z^2)}\sum_{i,j,k}^{4}\epsilon_{ijk}C_{002}(M_Z^2, M_Z^2, q^2, m_i^2, m_j^2, m_k^2)$$

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

Production thresholds of S_iS_j at e^+e^- colliders

The $e^+e^- \to Z^* \to S_iS_j$ 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
$m^{\pm}_{S_1}$	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
$m^{\pm}_{S_2}$	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)

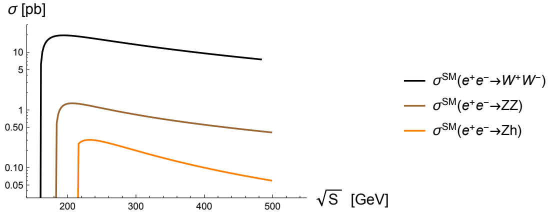
Significance of the signal over the SM background

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

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

The main SM background is through

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



background decreases with increasing energy and is ≤ 1.8 pb

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

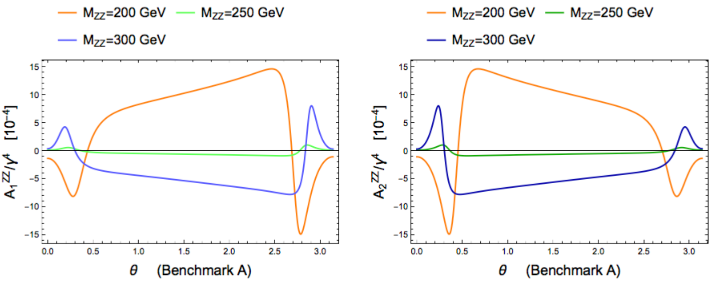
CP-violating asymmetries

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

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