Electroweak phase transition enhanced by a CP-violating dark sector

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DIAS

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IRISH RESEARCH COUNCIL
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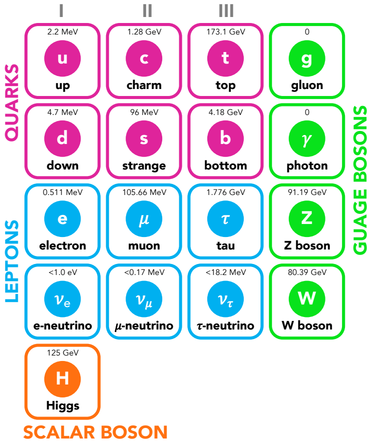
21.11.2025

The Standard Model of particle physics

Its current formulation was finalised in the 70's and <u>predicted</u>:

- the W & Z bosons
  discovered in 1983
- the top quark
  discovered in 1995
- the tau neutrino
  discovered in 2000
- the Brout-Englert-Higgs mechanism
  <u>a</u> 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.

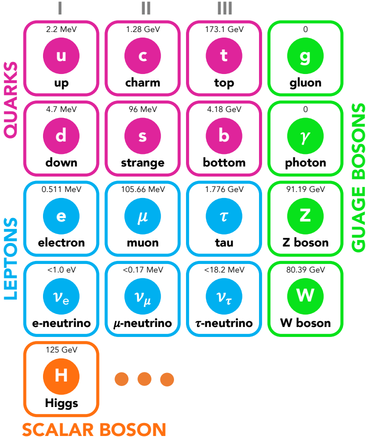
··· and the need to go beyond

What is missing:

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

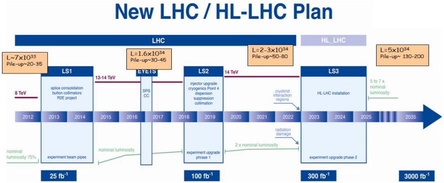
⇒ beyond the Standard Model

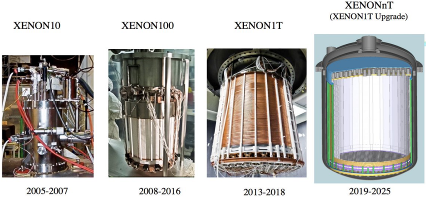
⇒ **scalar extensions of the SM**

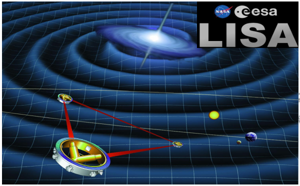


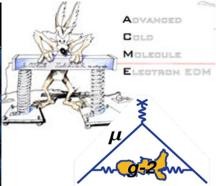
Current and upcoming experimental probes

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









Scalar extensions of the SM

SM + scalar singlets

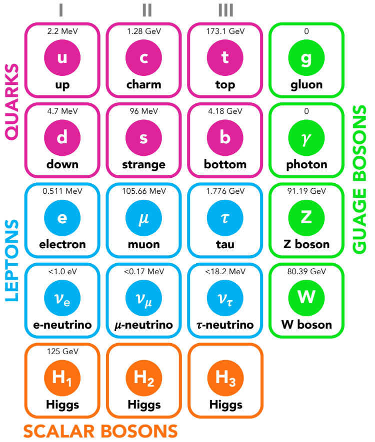
- Dark Matter severely constrained
- CP-violation not possible

2HDM: SM + a doublet

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

3HDM: SM + 2 doublets

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



Scalar singlet extension of SM

the SM Higgs doublet + a scalar singlet

ϕ S

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

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

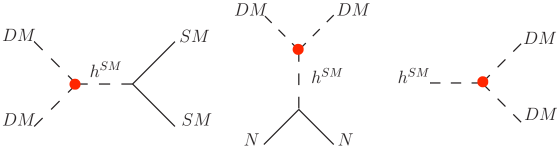
SM + scalar singlet DM ✓, CPV ×

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

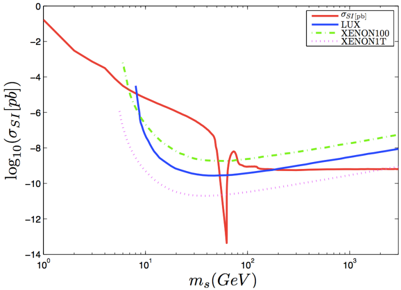
Direct detection

Collider
experiments

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

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



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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 ✓, CPV ×

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

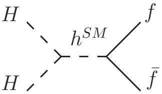
$$\text{SM fields} \rightarrow \text{SM fields}, \quad \phi_1 \rightarrow \phi_1, \quad \phi_2 \rightarrow -\phi_2$$

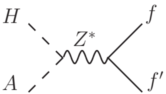
Z_2 symmetry: only ϕ_1 couples to fermions $\phi_u = \phi_d = \phi_e = \phi_1$

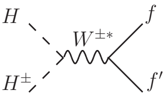
$$-\mathcal{L}_{Yukawa} = Y_u \bar{Q}'_L i\sigma_2 \phi_u^* u'_R + Y_d \bar{Q}'_L \phi_d d'_R + Y_e \bar{L}'_L \phi_e e'_R + \text{h.c.}$$

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







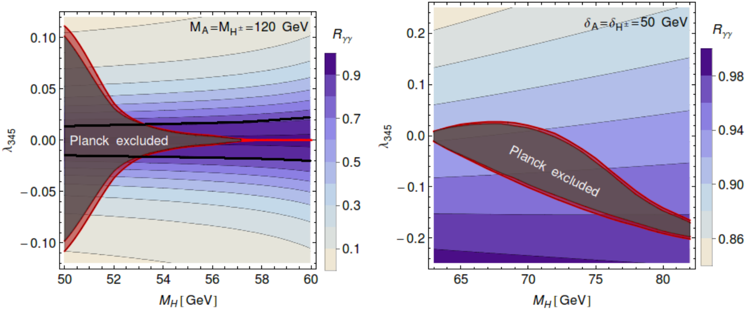
Tension: all scalar interactions are governed by the same coupling!
Gauge couplings are fixed!

Z_2-symmetric 2HDM DM ✓, CPV ×

More constraints:

Higgs invisible decays: $\mathrm{BR}(h \to HH) < 0.2$

$h \to \gamma\gamma$ signal strength: $\mu_{\gamma\gamma} = 1.16^{+0.20}_{-0.18}$



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

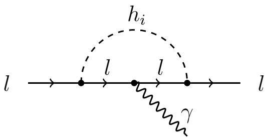
CP-violating 2HDM DM ×, CPV ✓

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).

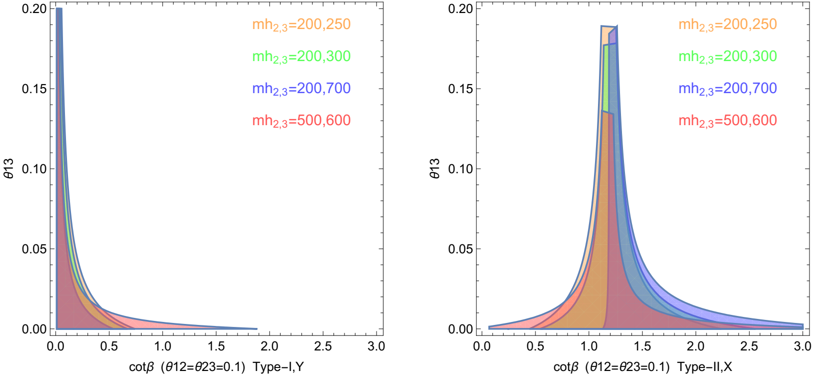
CP-violation is very constrained!

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)]

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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 $(-,-,+)$:

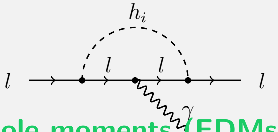
$$\phi_1 \to -\phi_1, \quad \phi_2 \to -\phi_2, \quad \text{SM fields} \to \text{SM fields}, \quad \phi_3 \to \phi_3$$

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 $h_i = h$

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



No contributions to electric dipole moments (EDMs)

Observable heavy scalar DM

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

Z_2-symmetric 3HDM with dark CPV

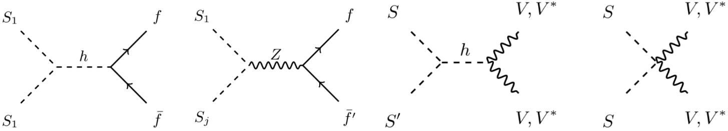
DM is protected by a Z_2 symmetry $(-,-,+)$:

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

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

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

DM candidate: the lightest CP-mixed state $S_{1,2,3,4}$ (mixtures of $H_{1,2}, A_{1,2}$)

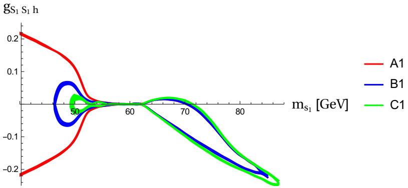


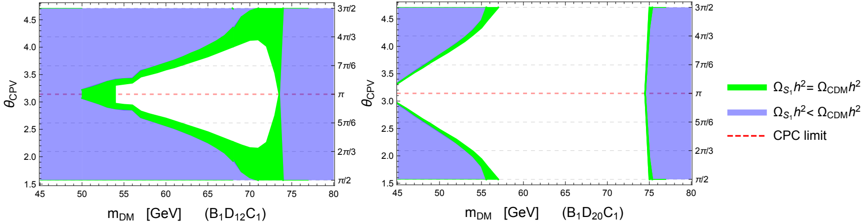
Tension released: the extended dark sector allows for annihilations, co-annihilations and CP-violation!

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



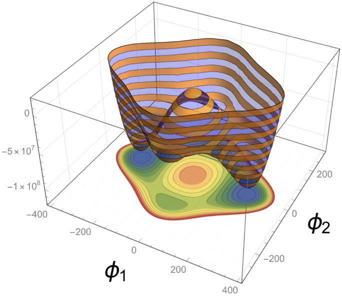


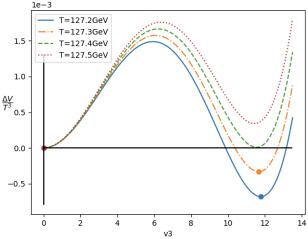
V. Keus, S. F. King, S. Moretti, D. Sokolowska, et al., [JHEP 12, 014 (2016)], V. Keus, [Phys. Rev. D 101, 073007 (2020)]

Dark CPV observables

Electroweak phase transition in 3HDMs

Scanning $V(\phi_1, \phi_2, \phi_3)$ at different temperatures





Introducing BLOOP

BLOOP: Beyond one LOOp Phase transition

The very first 2-loop analysis on the market

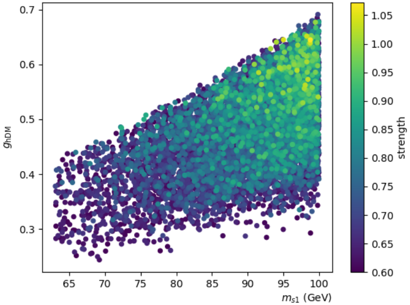
https://github.com/MOREHIGGS/BLOOP

`BLOOP: Beyond one LOOp Phase transition`

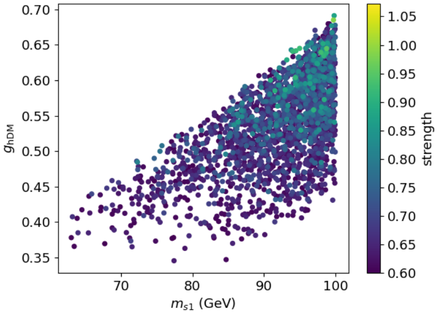
- Using dimensional reduction to get V_{eff} at 2-loop level from `DRalgo` (Mathematica based)
- `BLOOP` handles the complicated numerics of `DRalgo` in python
- Useful for many other codes such as `WallGo` (computes v_w)
- Generates benchmarks passing theoretical & experimental constraints
- Follows the dimensional reduction pipeline (matching, running couplings)
- Numerically minimises the potential over a range of temperatures
- Finds T_c and computes the strength of the phase transition

`https://github.com/MOREHIGGS/BLOOP`

The importance of 2-loop analysis



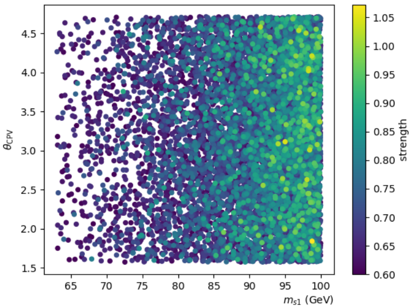
1-loop



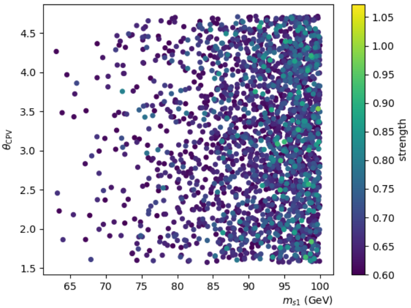
2-loop

V. Keus, L. Lewis, J. Thomson-Cooke [2511.04636 [hep-ph]]

The importance of 2-loop analysis



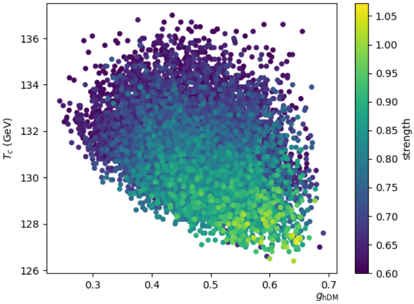
1-loop



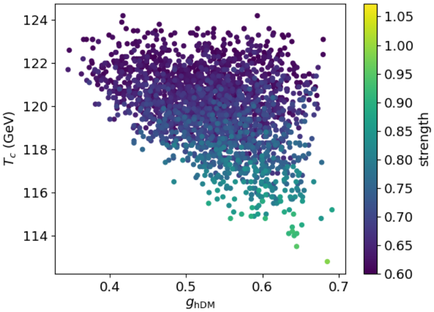
2-loop

V. Keus, L. Lewis, J. Thomson-Cooke [2511.04636 [hep-ph]]

The importance of 2-loop analysis



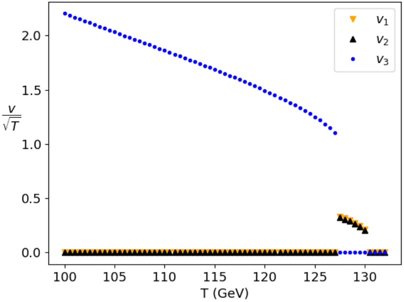
1-loop



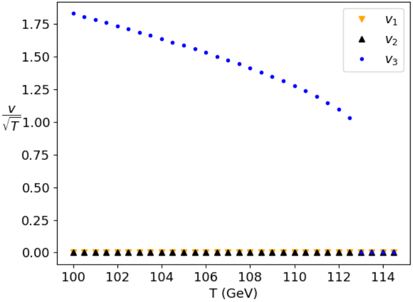
2-loop

V. Keus, L. Lewis, J. Thomson-Cooke [2511.04636 [hep-ph]]

The importance of 2-loop analysis



1-loop



2-loop

Analysis at 1-loop vs. 2-loop shows:

$\sim$ 27% reduction in mean strength, $\sim$ 7% reduction in mean T_c

V. Keus, L. Lewis, J. Thomson-Cooke [2511.04636 [hep-ph]]

Baryogenesis from primordial CP violation

Three scalar doublets:

$$\phi_1 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ h_1 + i\eta_1 \end{pmatrix}, \quad \phi_2 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ h_2 + i\eta_2 \end{pmatrix}, \quad \phi_{SM} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_h + h_3 \end{pmatrix}$$

Inflaton

SM-Higgs

The potential:

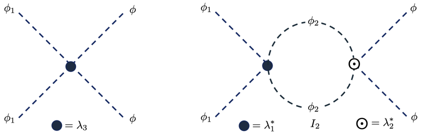
$$V_0 = -\mu_i^2(\phi_i^\dagger\phi_i) + \lambda_{ii}(\phi_i^\dagger\phi_i)^2 + \lambda_{ij}(\phi_i^\dagger\phi_i)(\phi_j^\dagger\phi_j) + \lambda'_{ij}(\phi_i^\dagger\phi_j)(\phi_j^\dagger\phi_i)$$

$$V_{Z_2} = -\mu_{12}^2(\phi_1^\dagger\phi_2) + \lambda_1(\phi_1^\dagger\phi_2)^2 + \lambda_2(\phi_2^\dagger\phi_{SM})^2 + \lambda_3(\phi_{SM}^\dagger\phi_1)^2 + h.c.$$

The sources of CP-violation are $\lambda_1 = |\lambda_1|e^{i\theta_1}$ and $\xi_4 = |\xi_4|\, e^{i\theta_4}$

The action:

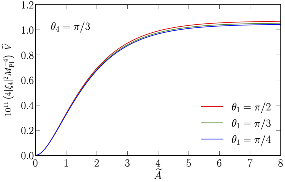
$$S_J = \int d^4x\sqrt{-g}\Big[-\frac{1}{2}M_{pl}^2 R - D_\mu\phi_i^\dagger D^\mu\phi_i - V - \Big(\xi_i|\phi_i|^2 + \underbrace{\xi_4(\phi_1^\dagger\phi_2)}_{Z_2-\mathrm{symmetric}} + h.c.\Big)R\Big]$$

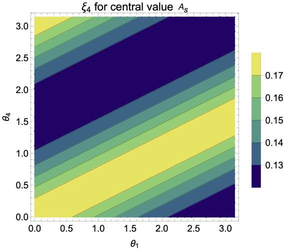


CP-violating inflation → Baryogenesis

The inflationary potential:

$$\widetilde{V}(\widetilde{A}) = \frac{\widetilde{\lambda}}{4}\frac{M_{\rm Pl}^4}{\widetilde{\xi}^2}\left(1 - e^{-2\widetilde{A}/\sqrt{6}}\right)^2$$





V. Keus, E. W. Kolb [JHEP 07 (2025) 156]

Summary

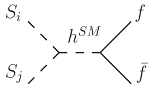
- SM + scalar singlets
  - Dark Matter severely constrained
  - CP-violation not possible
  - Strong first order EWPT DM incompatible
- 2HDM: SM + a doublet
  - Dark Matter constrained & CPV incompatible
  - CP-violation severely constrained & DM incompatible
  - Strong first order EWPT severely constrained
- 3HDM: SM + 2 doublets
  - Dark Matter many exotic possibilities
  - CP-violation unbounded dark CP-violation
  - Strong first order EWPT easily achieved
  - Inflaton easily achieved + exotic possibilities

BACKUP SLIDES

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

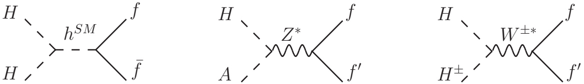
SM + singlet(s):

- $\phi_{SM}, S \Rightarrow$ 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~~

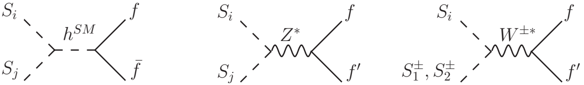


2HDM + singlet:

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

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."

⇒ Dark Matter within the cluster

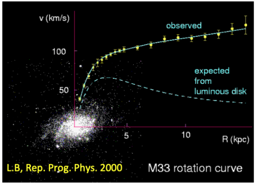
The correct information:

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)."



L.B, Rep. Prog. Phys. 2000

M33 rotation curve

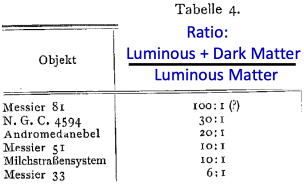


Tabelle 4.

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

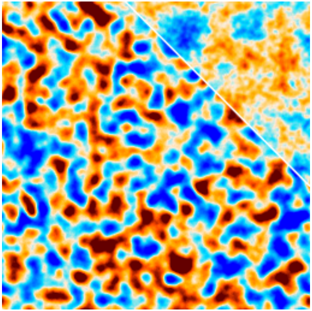
How do we know Dark Matter exists?

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

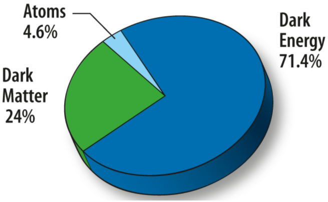
The total relic density by the Planck data: $\Omega_{\rm DM}h^2 = 0.1200 \pm 0.0012$

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

How much Dark Matter?

Characteristics:

- cold (non-relativistic at the onset of galaxy formation)
- non-baryonic
- neutral & weakly interacting
- stable due to a discrete symmetry



None of the SM particles are suitable DM candidates.

$\Rightarrow$ Beyond the SM

Weakly Interacting Massive Particles (WIMPs)

$$\underbrace{\text{DM DM} \to \text{SM SM},}_{\text{pair annihilation}} \quad \underbrace{\text{DM} \not\to \text{SM}, \ldots}_{\text{stable}}$$

back

Baryon asymmetry in the universe

Sakharov's conditions for a successful baryogenesis mechanism:

- B-violation
- C & CP-violation
- Departure from thermal equilibrium

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

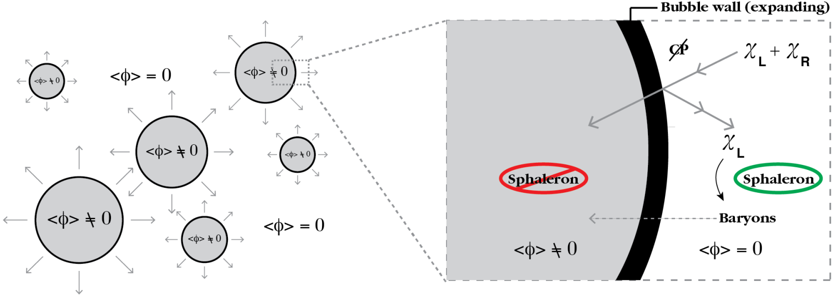
$$V_{ub} \neq V_{ub}^{*}; V_{td} \neq V_{td}^{*} \Rightarrow \mathbf{CPV}$$

Observation $\frac{N(B)}{N(\gamma)} \approx 10^{-9} \quad \gg \quad 10^{-20}$ provided by the SM

$\Rightarrow$ New sources of CPV needed.

back

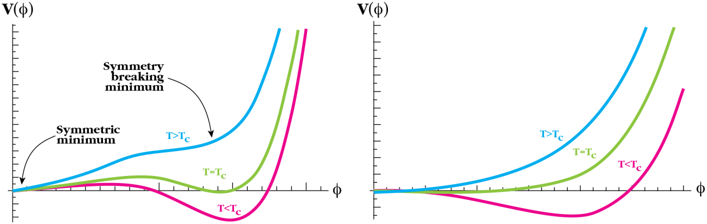
A strong first order phase transition



- New physics accessible by the LHC
- Gravitational waves from first-order EWPT detectable by LISA

back

A strong first order phase transition



- Difficult to achieve in a singlet extension

T. Alanne, N. Benincasa, M. Heikinheimo, K. Kannike, V. Keus, N. Koivunen, K. Tuominen, [JHEP 10, 080 (2020)]

- Current calculations can not be trusted in 2HDMs

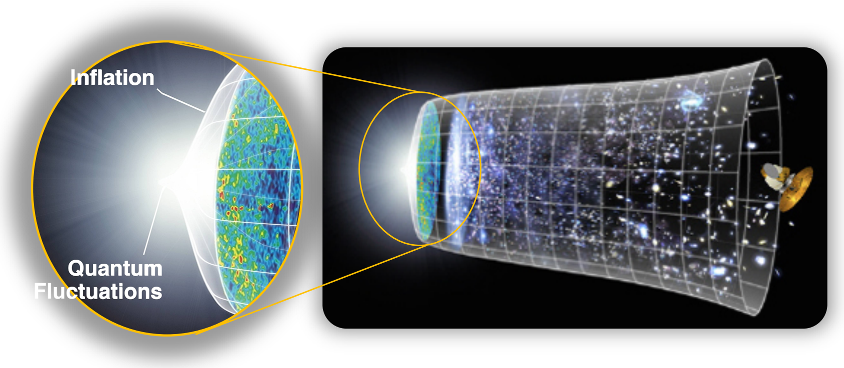
K. Kainulainen, V. Keus, L. Niemi, K. Rummukainen, T. V. I. Tenkanen, V. Vaskonen, [JHEP 06, 075 (2019)]

$\Rightarrow$ non-perturbative calculation of the EWPT strength is needed

$\Rightarrow$ further scalar extensions are needed

back

Inflation: an exponential expansion in the early universe



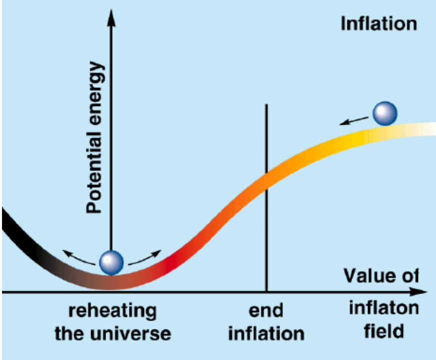
Explains: generation of primordial density fluctuations seeding structure formation, the flatness, homogeneity and isotropy of the universe

back

Simplest and best in agreement with observation

Slow roll inflation:

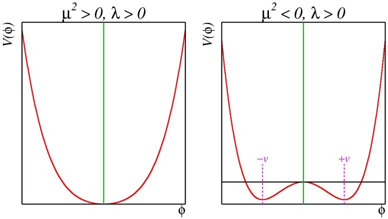
driven by a scalar field (inflaton) slowly rolling down its smooth potential



J. Garcia-Bellido, [arXiv:hep-ph/0303153 [hep-ph]]

back

The Higgs inflation model

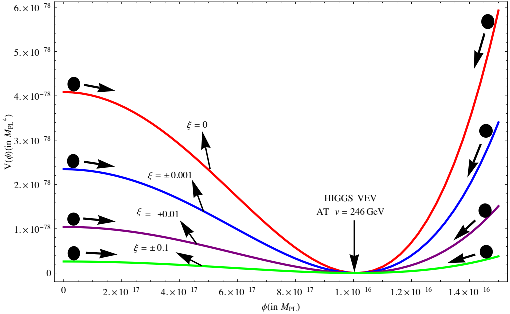


The SM Higgs potential:

$$V(\phi) = -\mu_h^2 \phi^\dagger \phi + \lambda_h (\phi^\dagger \phi)^2$$

Introducing a non-minimal coupling to gravity ξ:

$$\mathcal{L}_J = \frac{\sqrt{-g_J}}{2}\left[(\xi\phi^2 + M_{pl}^2)R + (\partial_\mu \phi)^2 - V(\phi)\right]$$



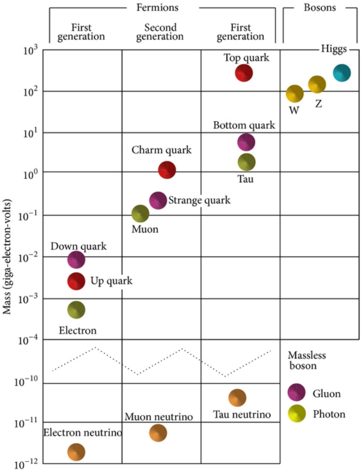
back

S. Choudhury, T. Chakraborty, S. Pal, [Nucl. Phys. B 880, 155-174 (2014)]

Fermion mass hierarchy in the SM

No explanation for

- $m_t/m_e \approx 10^6$
- $m_t/m_\nu \approx 10^{11}$



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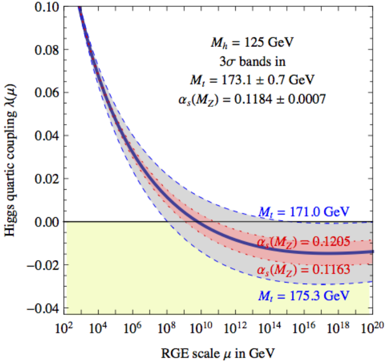
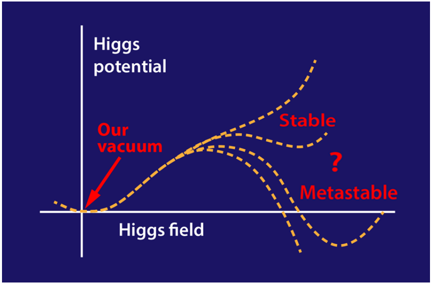
The SM electroweak vacuum is not stable





$$V = -\mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2$$

$\Rightarrow$ Scalar extensions can stabilise the EW vacuum.

back

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.

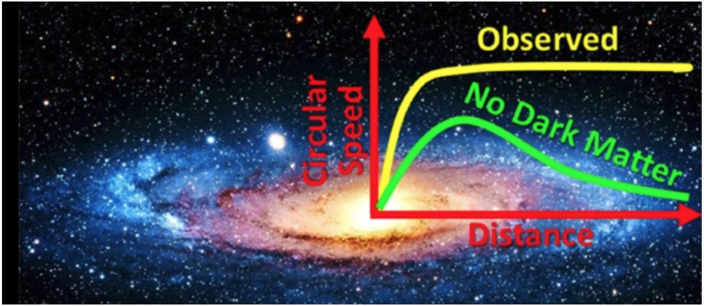
Forgotten pioneer: Knut Lundmark, Sweden (1889 – 1958)

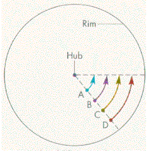
" … measurements by a Swedish astronomer, Knut Lundmark, were much more advanced than formerly appreciated. Lundmark was the first person to find observational evidence for expansion, in 1924 — three years before Lemaître and five years before Hubble. Lundmark's extragalactic distance estimates were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

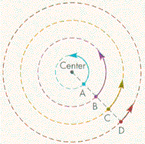
Ian Steer, NASA/IPAC, Pasadena, arxiv:1212.1359; J. R. Astron. Soc. Can. 105 (2011) 18

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.

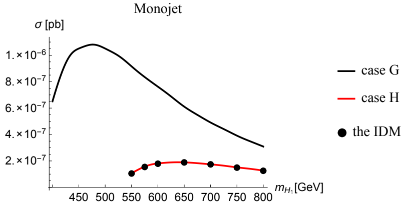
Observation: stars velocity stays constant towards the edges.

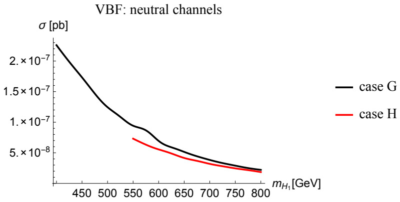
⇒ a spread of Dark Matter throughout the galaxy

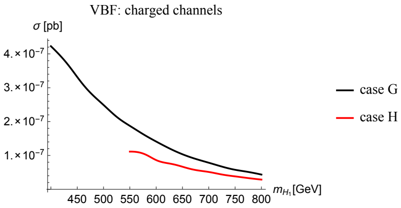
back

Observable heavy scalar DM

Monojet and dijet channels in the heavy DM mass region:



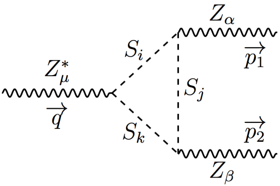


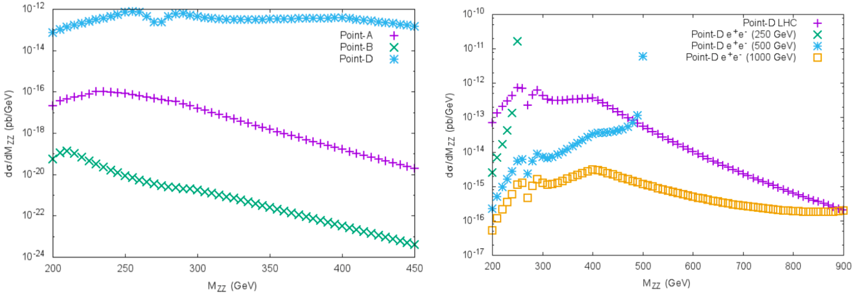


back

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

Dark CPV observables: the ZZZ vertex





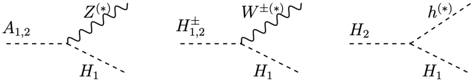
Differential $f\bar{f} \to Z^* \to ZZ$ cross section at hadron and lepton colliders

back

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

Inert cascade decays at the LHC

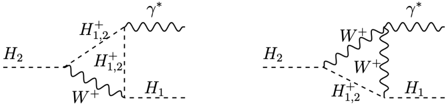
Tree level process: $q\bar{q} \to Z^* \to H_1 A_{1,2} \to H_1 H_1 Z^* \to H_1 H_1 f\bar{f}$



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



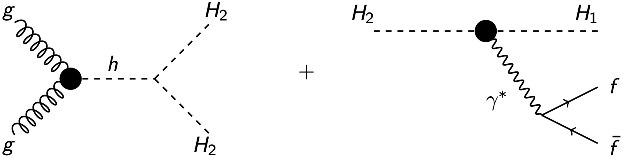
(smoking gun signature of 3HDM)

back

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

The smoking gun signature

MET+ 4μ: $gg \to h \to H_2H_2 \to H_1H_1\gamma^*\gamma^* \to H_1H_1\ell^+\ell^-\ell^+\ell^-$



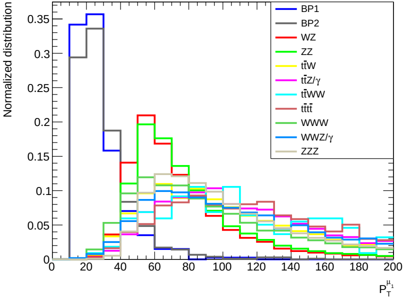
Benchmark	m_{H_1}	m_{H_2}	m_{A_1}	m_{A_2}	$m_{H_1^\pm}$	$m_{H_2^\pm}$	n	θ_h	$\sigma_{2\mu}$	$\sigma_{4\mu}$
BP1	50	55	95	104	116	127	0.83	0.105	0.02224	6.923
BP2	50	60	94	112	115	137	0.70	0.103	0.06	4.0

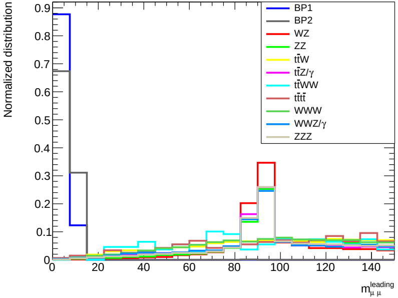
- Signal: ≥ 3 -μ with at least one pair of opposite sign μ with $\not{E}_T$.
- Background: VV, VVV $(V = W^\pm, Z, \gamma)$ and
  $t\bar{t}X$ $(X = W^\pm, Z, \gamma, W^\pm W^\mp, t\bar{t})$

back

A. Dey, V. Keus, S. Moretti, C. Shepherd-Themistocleous [arXiv:2310.06593 [hep-ph]] (to appear in JHEP)

Distributions and significance





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

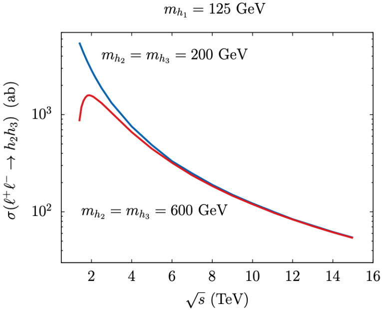
back

A. Dey, V. Keus, S. Moretti, C. Shepherd-Themistocleous [arXiv:2310.06593 [hep-ph]] (to appear in JHEP)

P-conserving, CP-violating observables at future colliders

Undoubtable signal of CPV: simultaneous observation of

1. $h_2H^+H^-\,,\quad h_3H^+H^-\,,\quad Zh_2h_3\,,$
2. $h_2h_kh_k\,,\quad h_3H^+H^-\,,\quad Zh_2h_3\,,\quad$ (for $k=2$ or 3),
3. $h_3h_kh_k,\,,\quad h_2H^+H^-\,,\quad Zh_2h_3\,,\quad$ (for $k=2$ or 3),
4. $h_2h_kh_k\,,\quad h_3h_\ell h_\ell\,,\quad Zh_2h_3\,,\quad$ (for $k,\ell=2$ or 3).



back

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

More constraints in scalar doublet extensions of SM

Electroweak precision observables:

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

Flavour observables:

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

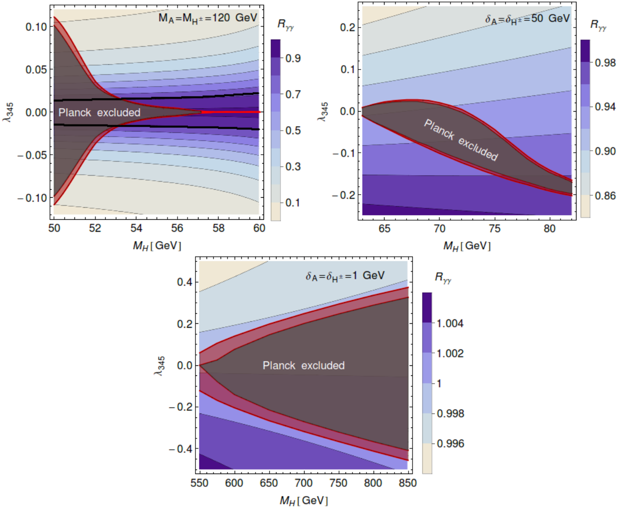
LEP bounds:

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

LHC bound on the total decay signal strength:

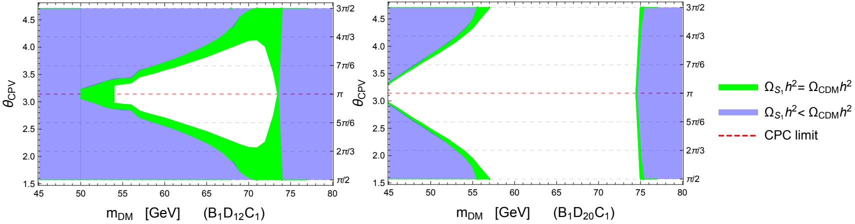
$$\mu_{tot} = \frac{\text{BR}(h \to XX)}{\text{BR}(h_{\text{SM}} \to XX)} = 1.17 \pm 0.17$$

Z_2-symmetric 2HDM DM ✓, CPV ×



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

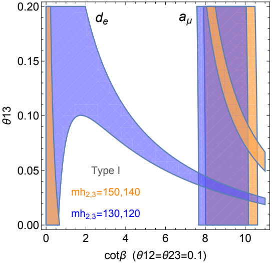
Type 1 benchmarks: $m_{S_1} \sim m_{S_3} \sim m_{S_2} \sim m_{S_4} \ll m_{S_1^\pm} \sim m_{S_2^\pm}$

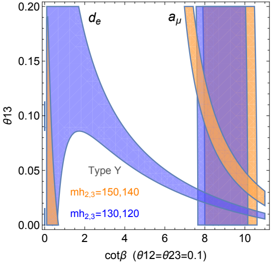


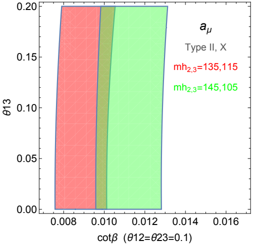
$$\mathbf{B}_1\mathbf{D}_4\mathbf{C}_1 : \ \delta_{12} = 4 \text{ GeV}, \quad \delta_c = 1 \text{ GeV}, \quad \delta_{1c} = 50 \text{ GeV},$$

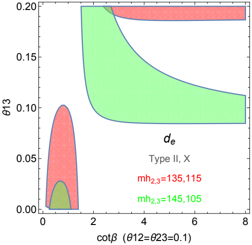
$$\mathbf{B}_1\mathbf{D}_8\mathbf{C}_1 : \ \delta_{12} = 8 \text{ GeV}, \quad \mathbf{B}_1\mathbf{D}_{12}\mathbf{C}_1 : \ \delta_{12} = 12 \text{ GeV}, \quad \mathbf{B}_1\mathbf{D}_{20}\mathbf{C}_1 : \ \delta_{12} = 20 \text{ GeV}$$

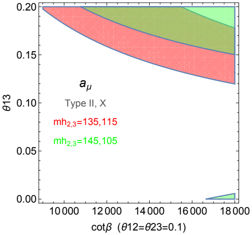
Overlap between d_e and a_μ regions in 2HDMs







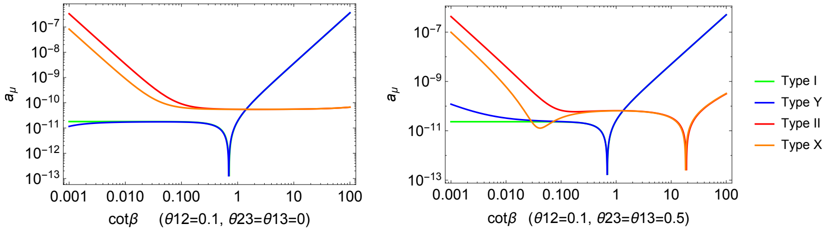


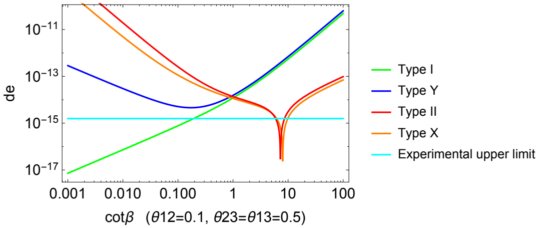


back

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

a_μ with/without CPV and d_e





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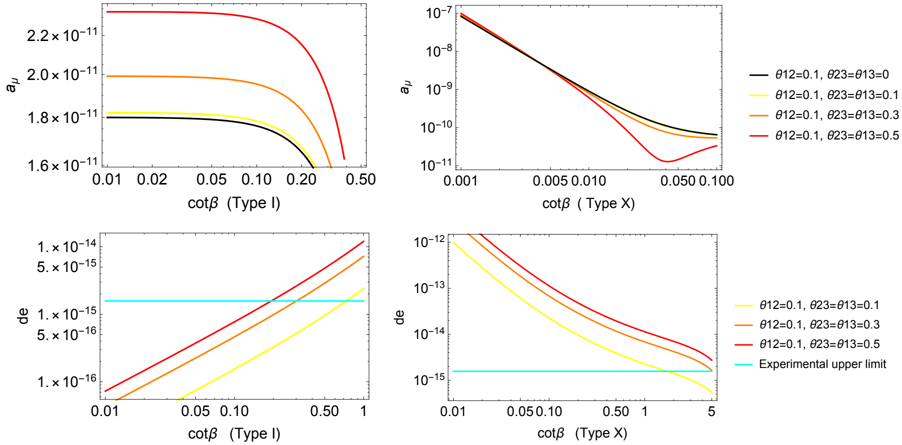
V. Keus, N. Koivunen, K. Tuominen, [JHEP 09, 059 (2018)]

A closer look



back

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

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

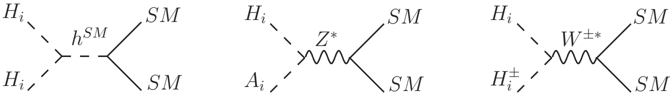
$$-\mathcal{L}_{Yukawa} = Y_u\, \bar{Q}_L'\, i\sigma_2\, \phi_u^*\, u_R' + Y_d\, \bar{Q}_L'\, \phi_d\, d_R' + Y_e\, \bar{L}_L'\, \phi_e\, e_R' + \text{h.c.}$$

No FCNCs

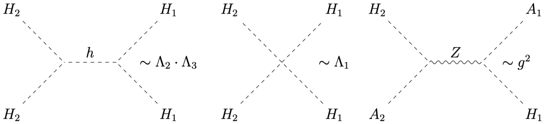
J. Hernandez, V. Keus, S. Moretti, D. Rojas, D. Sokolowska, [JHEP 03, 045 (2023)] and [arXiv:2012.11621]

Two-component light H_1 and heavy H_2 DM

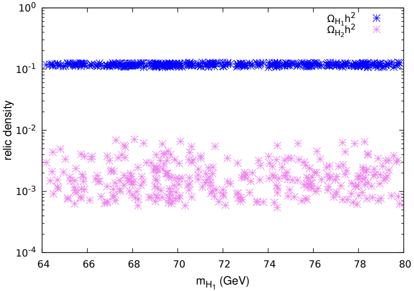
(Co)annihilations:



Conversions:

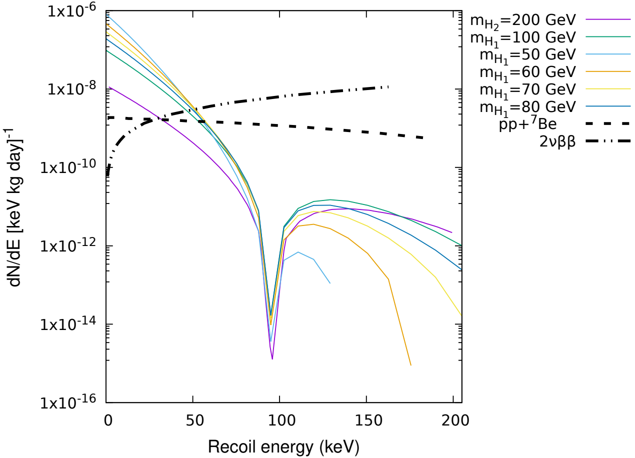


Relic density contributions:



Astrophysical probes: Direct detection at XENONnT/LZ

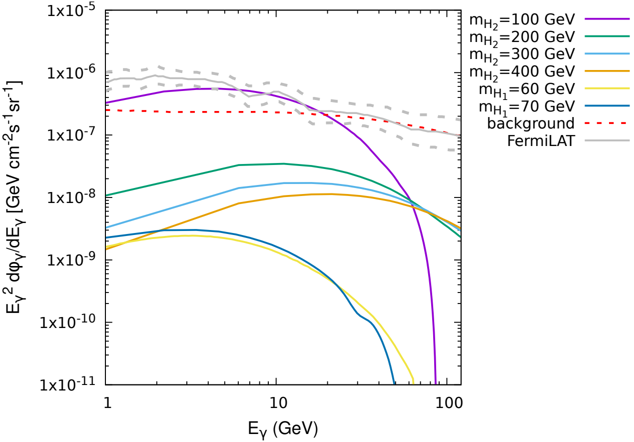
Light DM H_1: probed in the nuclear recoil energy event rate



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

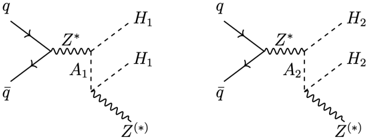
Heavy DM H_2: contributes to the photon flux from the galactic center

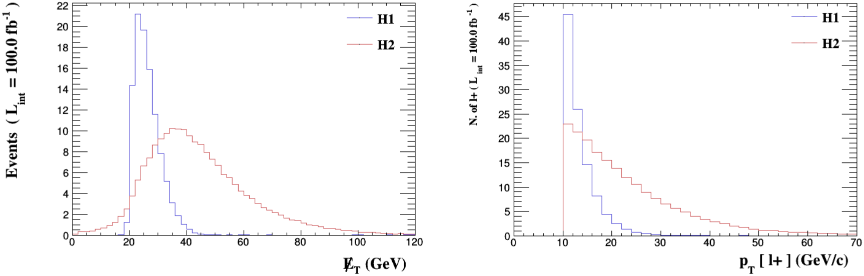


J. Hernandez, V. Keus, S. Moretti, D. Rojas, D. Sokolowska, [JHEP 03, 045 (2023)] and [arXiv:2012.11621]

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]