3HDM Unveiled: From Theory to Smoking Gun Signals at Future Colliders

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- A Higgs boson discovered
- No significant deviation from the SM
- No signs of new physics

But no explanation for

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- Fermion mass hierarchy
- Vacuum stability
- Dark Matter & ...

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  Solutions:

  1. Beyond SM scenarios with extended scalar sectors, additional gauge sectors or presence of additional symmetries at higher energies.
  2. Precisely look for any missing signals at colliders.

BSMs to the rescue

Solution: Scalar extensions with a Z_2 symmetry:

- SM + scalar singlet $\Rightarrow$ DM, ~~CPV~~
- 2HDM: SM + scalar doublet
  - Type-I, Type-II, ...: $\phi_1, \phi_2 \Rightarrow$ CPV, ~~DM~~
  - IDM - I(1+1)HDM: $\phi_1, \phi_2 \Rightarrow$ DM, ~~CPV~~
- 3HDM: SM + 2 scalar doublets
  - Weinberg model: $\phi_1, \phi_2, \phi_3 \Rightarrow$ CPV, ~~DM~~
  - I(1+2)HDM: $\phi_1, \phi_2, \phi_3 \Rightarrow$ DM, CPV
  - I(2+1)HDM: $\phi_1, \phi_2, \phi_3 \Rightarrow$ CPV, DM

....This slide is borrowd from Venus Keus's presentation in HPNP2023

I(2+1)HDM: Literature on DM phenomenology and CP violation

- "Classification of finite reparametrization symmetry groups in the three-Higgs-doublet model", I. P. Ivanov, E. Vdovin.
- "Three-Higgs-doublet models: symmetries, potentials and Higgs boson masses", Venus Keus, Stephen F. King, Stefano Moretti.
- "CP violating scalar Dark Matter" and "Dark Matter Signals at the LHC from a 3HDM", A. Cordero-Cid, J. Hernandez-Sanchez, V. Keus, S. F. King, S. Moretti, D. Rojas, D. Sokolowska.
- "A smoking gun signature of the 3HDM", A. Dey, V. Keus, S. Moretti, C. Shepherd-Themistocleous
- "On the CP Properties of Spin-0 Dark Matter ", A. Dey, Jaime Hernandez-Sanchez, Venus Keus, Stefano Moretti, Tetsuo Shindou.

BSMs to the rescue

Scalar extensions with a Z_2 symmetry: 3HDM: SM + 2 scalar doublets

CP-conserving I(2+1)HDM

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

$$g_{Z_2} = diag(-1, -1, +1)$$

$$VEV = (0, 0, v)$$

[$JHEP$1401(2014)052], [$Phys.Rev.D$90, 075015(2014)], [$arXiV$: 1907.12522]

The scalar potential with explicit CPC

$$
\begin{aligned}
V_{3HDM} &= V_0 + V_{Z_2} \\
V_0 &= \sum_{i}^{3}\left[-\mu_i^2(\phi_i^\dagger\phi_i) + \lambda_{ii}(\phi_i^\dagger\phi_i)^2\right] \\
&+ \sum_{i,j}^{3}\left[\lambda_{ij}(\phi_i^\dagger\phi_i)(\phi_j^\dagger\phi_j) + \lambda'_{ij}(\phi_i^\dagger\phi_j)(\phi_j^\dagger\phi_i)\right] \\
V_{Z_2} &= -\mu_{12}^2(\phi_1^\dagger\phi_2) + \lambda_1(\phi_1^\dagger\phi_2)^2 + \lambda_2(\phi_2^\dagger\phi_3)^2 + \lambda_3(\phi_3^\dagger\phi_1)^2 + h.c.
\end{aligned}
$$

The Z_2 symmetry

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

[$Phys.Lett.B695(2011)459-462$]

....This slide is borrowd from Venus Keus's presentation in HPNP2023

Parameters of the model

- All parameters of the potential to be real
- "dark" parameters $\lambda_1, \lambda_{11}, \lambda_{22}, \lambda_{12}, \lambda'_{12}$ (values have been fixed in agreement with the theoretical constraints.)
- $\mu_1^2 = n\mu_2^2, \quad \lambda_3 = n\lambda_2, \quad \lambda_{31} = n\lambda_{23}, \quad \lambda'_{31} = n\lambda'_{23}$
- fixed by the Higgs mass $\mu_3^2 = v^2\lambda_{33} = m_h^2/2$

6 important parameters

- Mass splittings μ_{12}^2 , λ_2
- Higgs-DM coupling $\lambda_2, \lambda_{23}, \lambda'_{23}$
- Mass scale of inert particles μ_2^2

[*Eur.Phys.J.C*80(2020)2, 135]

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The mass eigenstates

The doublet compositions

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

The mass eigenstates

$$\begin{aligned} H_1 &= \cos\theta_h H_1^0 + \sin\theta_h H_2^0, \quad & A_1 &= \cos\theta_a A_1^0 + \sin\theta_a A_2^0 \\ H_2 &= \cos\theta_h H_2^0 - \sin\theta_h H_1^0, \quad & A_2 &= \cos\theta_a A_2^0 - \sin\theta_a A_1^0 \\ H_1^\pm &= \cos\theta_c \phi_1^\pm + \sin\theta_c \phi_2^\pm, \quad & H_2^\pm &= \cos\theta_c \phi_2^\pm - \sin\theta_c \phi_1^\pm \end{aligned}$$

H_1 is assumed to be the DM candidate

- **Input parameters:**

DM mass m_{H_1}, Mass of second CP-even scalar m_{H_2}, Higgs-DM coupling $g_{H_1 H_1 h}$, angles θ_c, θ_a and n.

Constraints

- **Vacuum stability**: scalar potential V bounded from below
- **Perturbative unitarity**: eigenvalues Λ_i of the high-energy scattering matrix fulfill the condition $|\Lambda_i| < 8\pi$
- **Collider**: bounds on masses of the scalars
  - Limits from gauge bosons width:
    $m_{H_i} + m_{H_j^\pm} \geq m_W, \; m_{A_i} + m_{H_j} \geq m_Z, \; 2\, m_{H_{1,2}^\pm} \geq m_Z$
  - Limits on charged scalar mass and lifetime:
    $m_{H_i^\pm} \geq 70 \text{ GeV}, \quad \tau \leq 10^{-7}\text{ s} \to \Gamma_{\text{tot}} \geq 10^{-18} \text{ GeV}$
  - Allowed by Higgs invisible branching ratio, $Br(h \to inv.) < 11\%$
  - Allowed by Higgs total decay width, $\mu^{tot}(h)$ as well as Higgs signal strength data.
- **DM constraints**: Relic density, Direct and indirect detection bounds.

Relevant DM scenario

In the low mass region ($m_{H_1} < m_Z$)

We can have multiple scenarios:

(A) **no coannihilation effects**:

$$M_{H_1} < M_{H_2,A_1,A_2,H_1^\pm,H_2^\pm}$$

(I) **coannihilation** with $H_2, A_{1,2}$:

$$M_{H_1} \approx M_{A_1} \approx M_{H_2} \approx M_{A_2}$$

(G) **coannihilation** with $H_2, A_{1,2}, H_{1,2}^\pm$:

$$M_{H_1} \approx M_{A_1} \approx M_{H_2} \approx M_{A_2} \approx M_{H_1^\pm,H_2^\pm}$$

(H) **coannihilation** with $A_1, H_1^\pm$:

$$M_{H_1} \approx M_{A_1} \approx, H_1^\pm < M_{H_2,A_2,H_2^\pm}$$

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Relevant DM scenario

In the low mass region ($m_{H_1} < m_Z$)

We are looking for:

[(I)] coannihilation with $H_2, A_{1,2}$:

$$M_{H_1} \approx M_{A_1} \approx M_{H_2} \approx M_{A_2}$$

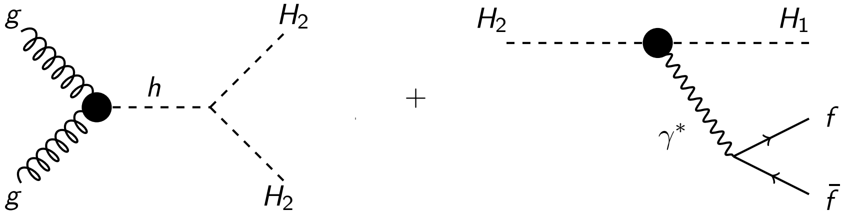
[*JHEP*09(2018)059]

CPC DM at the LHC

Looking for a **smoking-gun** signal of the 3HDM which is not allowed in the 2HDM with one inert doublet.

Smoking gun Signal

- We focused on,



In the CPC I(2+1)HDM, a process contributing to the $\not{E}_T l^+ l^+ l^- l^-$ signature is

$$gg \to h \to H_2 H_2 \to H_1 H_1 \gamma^* \gamma^* \to H_1 H_1 l^+ l^- l^+ l^-,$$

where the off-shell γ^* splits into $l^+ l^-$ and the H_1 states escape detection and will give $\not{E}_T$.

Smoking gun Signal

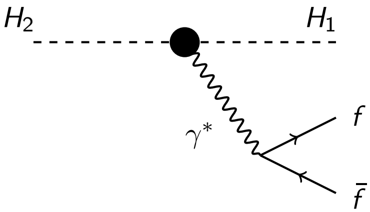


Figure: Radiative decay of the heavy neutral particle $H_2 \to H_1\gamma^* \to H_1 l^+ l^-$.

Smoking gun Signal

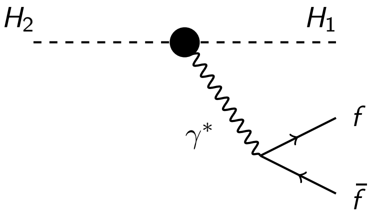
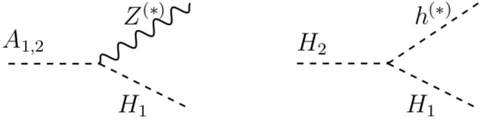


Figure: Radiative decay of the heavy neutral particle $H_2 \to H_1\gamma^* \to H_1 l^+ l^-$.

- $m_{H_2} - m_{H_1}$ is very small
- H_2, into the lightest inert state, H_1, and a virtual photon, which then would split into a light $l\bar{l}$ pair.

Inert cascade decays at the LHC

When there is a large mass splitting between DM and other inert particles:

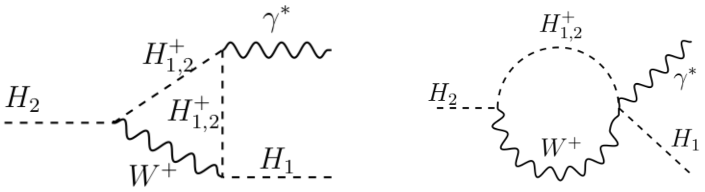


It can give the tree level process $E^T_{miss} + l^+ l^- l^+ l^-$:

$pp \to H_2 H_2 / A_{1,2} A_{1,2} \to H_1 H_1 Z^* Z^* \to H_1 H_1 l^+ l^- l^+ l^-$

Inert cascade decays at the LHC

When there is a small mass splitting between DM and other inert particles (winning scenarios):



It can give the loop level process $E^T_{miss} + l^+l^-l^+l^-$:

$pp \to H_2H_2/A_{1,2}A_{1,2} \to H_1H_1\gamma^*\gamma^* \to H_1H_1l^+l^-l^+l^-$

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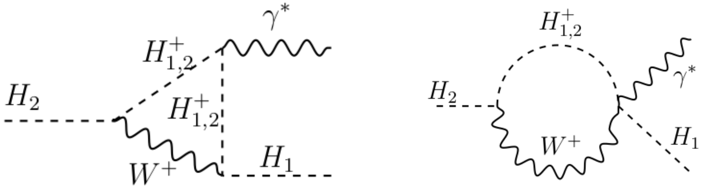


It can give the loop level process $E^T_{miss} + l^+l^-l^+l^-$:

$pp \to H_2H_2/A_{1,2}A_{1,2} \to H_1H_1\gamma^*\gamma^* \to H_1H_1l^+l^-l^+l^-$

The **smoking gun** channel

- We are looking for Benchmarks with small mass gap (Δm) between H_2 and H_1

BPs	m_{H_1}	m_{H_2}	Δm	n	$g_{H_1 H_1 h}$	θ_h	$\sigma(pp \to H_1 H_1 2\mu^+ 2\mu^-)$
$BP1 : I_5^{50}$	50	55	5	0.83	0.01	0.105	6.923 fb
$BP2 : I_{10}^{50}$	50	60	10	0.70	0.01	0.103	4.0 fb

Table: Parameter choices of our Benchmark points (BPs)

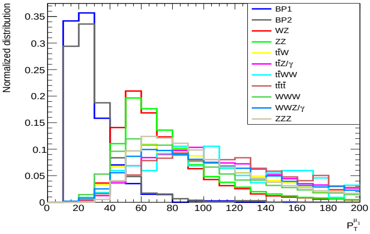
Signal and backgrounds

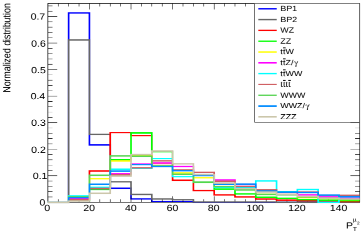
- **Signal:** At least 3−muon with at least one pair of Opposite sign $\mu + \not{E}_T$.

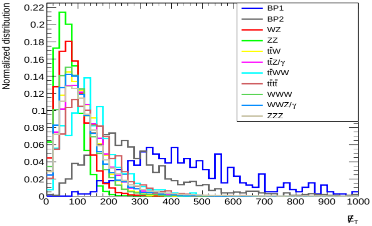
Signal and backgrounds

- **Signal:** At least 3−muon with at least one pair of Opposite sign $\mu + \not{E}_T$.
- **Backgrounds:** 1) **Di-boson**, $VV(V: W, Z, \gamma)$: Mainly WZ/γ and ZZ have large contribution where both V can decay leptonically.
  2) **Tri-boson**, $VVV(V: W, Z, \gamma)$: Mainly consider WWZ/γ, WWW and ZZZ. All vector bosons are supposed to decay leptonically.
  3) $t\bar{t}X$,(X: W, Z, γ, WW, $t\bar{t}$): The fully leptonic decay mode of $t\bar{t}X$ can give us atlast three lepton with at least one pair of μ with opposite charge.

Distributions







Distributions

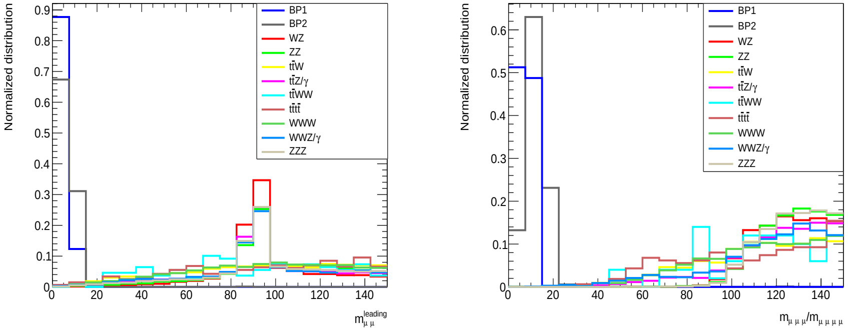


Figure: Normalized distribution of invariant mass of two leading muons and invariant mass of all muons fir signal BPs and backgrounds.

Results

Cuts:

1) **Pre-selection Cut**: We are looking for events where we can have at least three or four muons in final state with no $b-jet$.

2) **Cut-A**:

- $m_{\mu\mu}^{leading}$ and $m_{\mu\mu}^{\Delta R_{min}}$ has to be less than 50 GeV.
- $m_{\mu\mu\mu}/m_{\mu\mu\mu\mu}$ has to be less than 70 GeV and $\not{E}_T > 200$ GeV.

3) **Cut-B**:

- $m_{\mu\mu}^{leading}$ and $m_{\mu\mu}^{\Delta R_{min}}$ has to be less than 20 GeV.
- $m_{\mu\mu\mu}/m_{\mu\mu\mu\mu}$ has to be less than 30 GeV and $\not{E}_T > 200$ GeV.
- $\Delta R_{\mu\mu}^{leading,sub-leading} < 1.0$ and $\Delta R_{\mu\mu}^{leading,sub-sub-leading} < 1.2$.
- $\Delta \eta_{\mu\mu}^{leading,sub-leading} < 1.0$ and $\Delta \eta_{\mu\mu}^{leading,sub-sub-leading} < 1.0$.

Results($\geq 3\mu + \not{E}_T$)

Datasets	Cross-section (fb)	**Pre-selection Cut**	**Cut − A**	**Cut − B**
$BP1$	6.961	17	16	16
$BP2$	3.733	59	38	38
WZ	163.4068	97691	9	0
ZZ	16.554	22614	2	0
WWW	0.248862	185	3	0
WWZ/γ	0.04978	96	1	0
ZZZ	9.3516×10^{-3}	16	0	0
$t\bar{t}W$	0.606	114	2	0
$t\bar{t}Z/\gamma$	0.3045	136	1	0
$t\bar{t}WW$	1.279×10^{-3}	0	0	0
$t\bar{t}t\bar{t}$	1.51359×10^{-3}	0	0	0

Table: Signal and background events cross-section at and Number of Events after cuts at $\sqrt{s} = 14$ TeV and $\mathcal{L} = 3000 fb^{-1}$ for $\geq$ 3-μ + $\not{E}_T$ final state.

Significance

- we calculated the projected significance ($\mathcal{S}$) in the $3\mu + \not{E}_T$ channel for each benchmark point, for **14 TeV LHC** with **3000 fb**$^{-1}$. The significance $\mathcal{S}$ is defined as follows:

$$\mathcal{S} = \sqrt{2[(S+B)\mathrm{Log}(1+\frac{S}{B}) - S]}$$

$The' AsimovPaper' (Cowan, Cranmer, Gross, Vitells, EPJC71(2011)1-19$

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BP	$\mathcal{S}(Pre-selection)$	$\mathcal{S}(Cut-A)$
$BP1$	0.05 σ	3.77 σ
$BP2$	0.17 σ	9.0 σ

- with **Cut − B** we will end up with signal only events
- $L = 300\ fb^{-1}$ also can give us fully background elimaned signals after **Cut − A** itself.

Results($\geq 4\mu + \not{E}_T$)

Datasets	Cross-section (fb)	**Pre-selection Cut**	**Cut − A**	**Cut − B**
$BP1$	6.961	2	1	1
$BP2$	3.733	12	11	11
WZ	163.4068	20	0	0
ZZ	16.554	8871	0	0
WWW	0.248862	0	0	0
WWZ/γ	0.04978	41	0	0
ZZZ	9.3516×10^{-3}	6	0	0
$t\bar{t}W$	0.606	1	0	0
$t\bar{t}Z/\gamma$	0.3045	56	0	0
$t\bar{t}WW$	1.279×10^{-3}	0	0	0
$t\bar{t}t\bar{t}$	1.51359×10^{-3}	136	0	0

Table: Signal and background events cross-section at and Number of Events after cuts at $\sqrt{s} = 14$ TeV and $\mathcal{L} = 3000 fb^{-1}$ for $\geq$ 4-μ + $\not{E}_T$ final state.

- with **Cut − A** and **Cut − B** we will end up with signal only events by eliminating all background in the signal region.

Summary

- Inert Doublet Model
  - a good DM model with rich phenomenology, however, very constrained.
- CP-Conserving in I(2+1)HDM
  - SM-like active sector: $H_3 \equiv h^{SM}$
  - The inert sector: $H_{1,2}, A_{1,2}, H^{\pm}_{1,2}$, $H_1 \rightarrow$ DM
  - less constrained DM sector with low mass DM particle
  - New **Smoking-gun** signature at the LHC: m_{H_2} and m_{H_1} are close
  - Good signal significance in $3\mu + \not{E}_T$ and $4\mu + \not{E}_T$ channel over backgrounds at HL-LHC.

Thank you for your attaintion....

Back-up slides

BSMs to the rescue

Solution: Scalar extensions with a Z_2 symmetry:

- 2HDM: SM + scalar doublet
  - Type-I, Type-II, ...: $\phi_1, \ \phi_2 \ \Rightarrow$ CPV, ~~DM~~
  - IDM - I(1+1)HDM: $\phi_1, \ \phi_2 \ \Rightarrow$ DM, ~~CPV~~
- 3HDM: SM + 2 scalar doublets
  - Weinberg model: $\phi_1, \ \phi_2, \ \phi_3 \ \Rightarrow$ CPV, ~~DM~~
  - I(1+2)HDM: $\phi_1, \ \phi_2, \ \phi_3 \ \Rightarrow$ DM, CPV
  - I(2+1)HDM: $\phi_1, \ \phi_2, \ \phi_3 \ \Rightarrow$ CPV, DM

Dark Matter (DM)

around 25 % of the Universe is:

- cold
- non-baryonic
- neutral
- very weakly interacting

$\Rightarrow$ **W**eakly **I**nteracting **M**assive **P**article

- stable due to the discrete symmetry

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

Higgs-portal DM

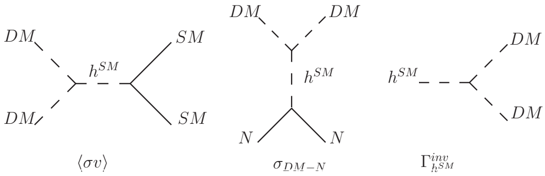
Simplest realisation: the SM with Φ_{SM} + Z_2-odd scalar S:

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

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}(\partial S)^2 - \frac{1}{2}m_{DM}^2 S^2 - \lambda_{DM} S^4 - \lambda_{hDM}\Phi_{SM}^2 S^2$$

Higgs-portal interaction:

$$\text{SM sector} \xleftrightarrow{\text{Higgs}} \text{DM sector}$$



given by the same coupling

2HDM with CP-violation (~~DM~~)

The general scalar potential

$$\begin{aligned} V &= \mu_1^2(\phi_1^\dagger\phi_1) + \mu_2^2(\phi_2^\dagger\phi_2) - \left[\mu_3^2(\phi_1^\dagger\phi_2) + h.c.\right] \\ &+ \frac{1}{2}\lambda_1(\phi_1^\dagger\phi_1)^2 + \frac{1}{2}\lambda_2(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) \\ &+ \left[\frac{1}{2}\lambda_5(\phi_1^\dagger\phi_2)^2 + \lambda_6(\phi_1^\dagger\phi_1)(\phi_1^\dagger\phi_2) + \lambda_7(\phi_2^\dagger\phi_2)(\phi_1^\dagger\phi_2) + h.c.\right]. \end{aligned}$$

$$Z_2 \text{ symmetry} \Rightarrow \lambda_6 = \lambda_7 = 0$$

The doublets composition with $\tan\beta = v_2/v_1$

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

CP-mixed mass eigenstates

- 2×2 charged mass-squared matrix

$$\begin{pmatrix} \phi_1^\pm \\ \phi_2^\pm \end{pmatrix} \Rightarrow \begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix}$$

- 4×4 neutral mass-squared matrix

$$\begin{pmatrix} a_1^0 \\ h_1^0 \\ a_2^0 \\ h_2^0 \end{pmatrix} \Rightarrow \begin{pmatrix} G^0 \\ H_1 \\ H_2 \\ H_3 \end{pmatrix}$$

CPV severely constrained from SM data

The Inert Doublet Model (~~CPV~~)

Scalar potential V invariant under a Z_2-transformation:

$$Z_2 : \quad \phi_1 \to \phi_1, \quad \phi_2 \to -\phi_2, \quad \text{SM fields} \to \text{SM fields}$$

$$\begin{aligned} V &= -\frac{1}{2}\left[m_{11}^2 \phi_1^\dagger \phi_1 + m_{22}^2 \phi_2^\dagger \phi_2\right] + \frac{1}{2}\left[\lambda_1 \left(\phi_1^\dagger \phi_1\right)^2 + \lambda_2 \left(\phi_2^\dagger \phi_2\right)^2\right] \\ &+ \lambda_3 \left(\phi_1^\dagger \phi_1\right)\left(\phi_2^\dagger \phi_2\right) + \lambda_4 \left(\phi_1^\dagger \phi_2\right)\left(\phi_2^\dagger \phi_1\right) + \frac{1}{2}\lambda_5 \left[\left(\phi_1^\dagger \phi_2\right)^2 + \left(\phi_2^\dagger \phi_1\right)^2\right] \end{aligned}$$

- All parameters are real → no CP violation
- Only ϕ_1 couples to fermions
- The whole Lagrangian is explicitly Z_2-symmetric

DM in the IDM

The Inert minimum

$$\langle \phi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad \langle \phi_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

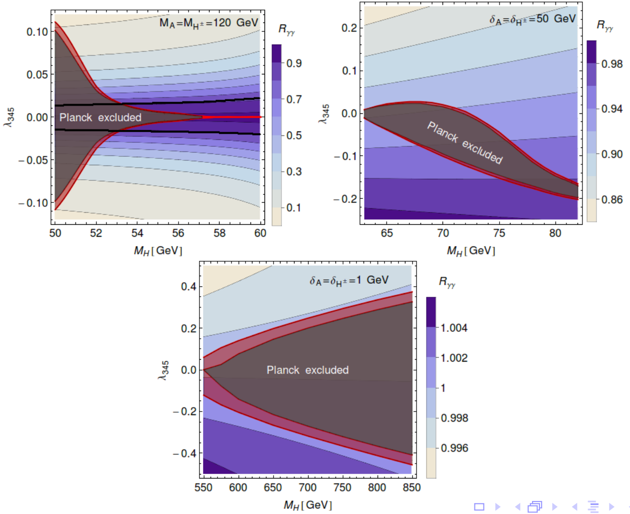
- Z_2-symmetry survives the EWSB

$$g_{Z_2} = diag(+1, -1)$$
$$VEV = (v, 0)$$

- ϕ_1 is active (plays the role of the SM-Higgs)
- ϕ_2 is “dark” or inert (with 4 dark scalars $H, A, H^\pm$)

$\rightarrow$ the lightest scalar is **a candidate for the DM**

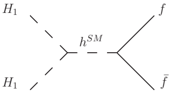
$h \to \gamma\gamma$ signal strength (JHEP 09 (2013) 055)



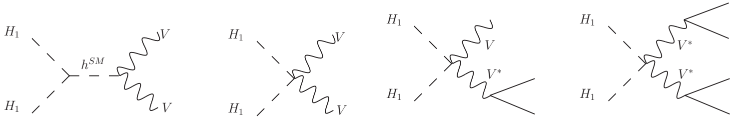
CP-conserving I(2+1)HDM

Dark Matter Annihilation

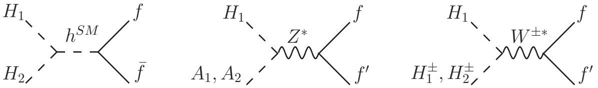
- annihilation through Higgs into fermions; dominant channel for $M_{DM} < M_h/2$



- annihilation to gauge bosons; crucial for heavy masses



- coannihilation; when particles have similar masses



DM Annihilation Scenarios

(A) **no coannihilation effects**:

$$M_{H_1} < M_{H_2,A_1,A_2,H_1^\pm,H_2^\pm}$$

(I) **coannihilation** with $H_2, A_{1,2}$:

$$M_{H_1} \approx M_{A_1} \approx M_{H_2} \approx M_{A_2} < M_{H_1^\pm,H_2^\pm}$$

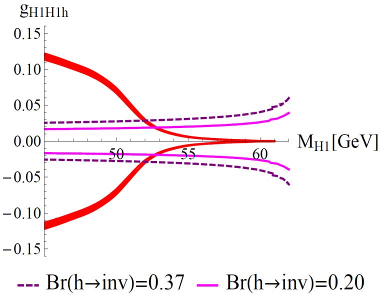
(G) **coannihilation** with $H_2, A_{1,2}, H_{1,2}^\pm$:

$$M_{H_1} \approx M_{A_1} \approx M_{H_2} \approx M_{A_2} \approx M_{H_1^\pm,H_2^\pm}$$

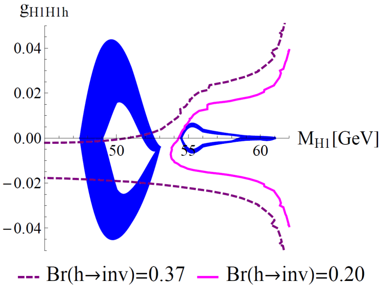
(H) **coannihilation** with $A_1, H_1^\pm$:

$$M_{H_1} \approx M_{A_1} \approx, H_1^\pm < M_{H_2,A_2,H_2^\pm}$$

LHC vs Planck $M_{DM} < M_h/2$



case A



case I

- $Br(h \to inv) < 37\%$ & $\Omega_{DM} h^2 \Rightarrow$
  - Case A: $M_{DM} \gtrsim 53\,\text{GeV}$
  - Case I: most masses are OK

Masses and mixing angles

- **The CP-even neutral inert fields**
  The pair of inert neutral scalar gauge eigenstates, H_1^0, H_2^0, are rotated by

$$R_{\theta_h} = \begin{pmatrix} \cos\theta_h & \sin\theta_h \\ -\sin\theta_h & \cos\theta_h \end{pmatrix}, \text{with} \quad \tan 2\theta_h = \frac{2\mu_{12}^2}{\mu_1^2 - \Lambda_{\phi_1} - \mu_2^2 + \Lambda_{\phi_2}}$$

into the mass eigenstates, H_1, H_2, with squared masses

$$m_{H_1}^2 = (-\mu_1^2 + \Lambda_{\phi_1})\cos^2\theta_h + (-\mu_2^2 + \Lambda_{\phi_2})\sin^2\theta_h - 2\mu_{12}^2 \sin\theta_h \cos\theta_h,$$
$$m_{H_2}^2 = (-\mu_1^2 + \Lambda_{\phi_1})\sin^2\theta_h + (-\mu_2^2 + \Lambda_{\phi_2})\cos^2\theta_h + 2\mu_{12}^2 \sin\theta_h \cos\theta_h,$$
$$\text{where} \quad \Lambda_{\phi_1} = \frac{1}{2}(\lambda_{31} + \lambda'_{31} + 2\lambda_3)v^2, \quad \Lambda_{\phi_2} = \frac{1}{2}(\lambda_{23} + \lambda'_{23} + 2\lambda_2)v^2.$$

Masses and mixing angles

- **The charged inert fields**
  The pair of inert charged gauge eigenstates, $\phi_1^\pm, \phi_2^\pm$, are rotated by

$$R_{\theta_c} = \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix}, \text{with} \quad \tan 2\theta_c = \frac{2\mu_{12}^2}{\mu_1^2 - \Lambda'_{\phi_1} - \mu_2^2 + \Lambda'_{\phi_2}}$$

  into the mass eigenstates, $H_1^\pm, H_2^\pm$, with squared masses

$$m^2_{H_1^\pm} = (-\mu_1^2 + \Lambda'_{\phi_1})\cos^2\theta_c + (-\mu_2^2 + \Lambda'_{\phi_2})\sin^2\theta_c - 2\mu_{12}^2 \sin\theta_c \cos\theta_c,$$

$$m^2_{H_2^\pm} = (-\mu_1^2 + \Lambda'_{\phi_1})\sin^2\theta_c + (-\mu_2^2 + \Lambda'_{\phi_2})\cos^2\theta_c + 2\mu_{12}^2 \sin\theta_c \cos\theta_c,$$

  where $\Lambda'_{\phi_1} = \frac{1}{2}(\lambda_{31})v^2, \quad \Lambda'_{\phi_2} = \frac{1}{2}(\lambda_{23})v^2.$

Masses and mixing angles

- **The CP-odd neutral inert fields**
  The pair of inert pseudo-scalar gauge eigenstates, A_1^0, A_2^0, are rotated by

$$R_{\theta_a} = \begin{pmatrix} \cos\theta_a & \sin\theta_a \\ -\sin\theta_a & \cos\theta_a \end{pmatrix}, \text{with} \quad \tan 2\theta_a = \frac{2\mu_{12}^2}{\mu_1^2 - \Lambda''_{\phi_1} - \mu_2^2 + \Lambda''_{\phi_2}},$$

into the mass eigenstates, A_1, A_2, with squared masses

$$m_{A_1}^2 = (-\mu_1^2 + \Lambda''_{\phi_1})\cos^2\theta_a + (-\mu_2^2 + \Lambda''_{\phi_2})\sin^2\theta_a - 2\mu_{12}^2 \sin\theta_a\cos\theta_a,$$
$$m_{A_2}^2 = (-\mu_1^2 + \Lambda''_{\phi_1})\sin^2\theta_a + (-\mu_2^2 + \Lambda''_{\phi_2})\cos^2\theta_a + 2\mu_{12}^2 \sin\theta_a\cos\theta_a,$$
$$\text{where} \quad \Lambda''_{\phi_1} = \frac{1}{2}(\lambda_{31} + \lambda'_{31} - 2\lambda_3)v^2, \quad \Lambda''_{\phi_2} = \frac{1}{2}(\lambda_{23} + \lambda'_{23} - 2\lambda_2)v^2.$$

Dependent parameters in terms of input parameters

$$\Lambda_{\phi_2} = \frac{v^2 g_{H_1 H_1 h}}{4(\sin^2\theta_h + n\cos^2\theta_h)},$$

$$\Lambda'_{\phi_2} = \frac{2\mu_{12}^2}{(1-n)\tan 2\theta_c} + \mu_2^2,$$

$$\Lambda''_{\phi_2} = \frac{2\mu_{12}^2}{(1-n)\tan 2\theta_a} + \mu_2^2,$$

$$\mu_2^2 = \Lambda_{\phi_2} - \frac{m_{H_1}^2 + m_{H_2}^2}{1+n},$$

$$\mu_{12}^2 = \frac{1}{2}\sqrt{(m_{H_1}^2 - m_{H_2}^2)^2 - (-1+n)^2(\Lambda_{\phi_2} - \mu_2^2)^2},$$

$$\lambda_2 = \frac{1}{2v^2}(\Lambda_{\phi_2} - \Lambda''_{\phi_2}),$$

$$\lambda_{23} = \frac{2}{v^2}\Lambda'_{\phi_2},$$

$$\lambda'_{23} = \frac{1}{v^2}(\Lambda_{\phi_2} + \Lambda''_{\phi_2} - 2\Lambda'_{\phi_2})$$

Distributions

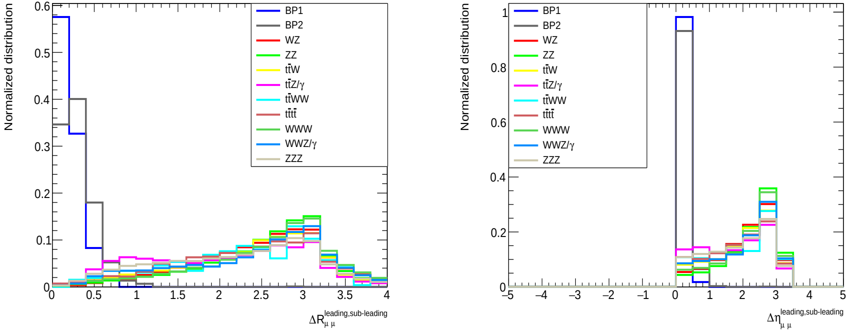


Figure: Normalized Distribution of ΔR and $\Delta\eta$ of leading and sub-leading muon for signal BPs and backgrounds.

Asimov estimate for discovery significance in counting experiment

Discovery significance for $n \sim \text{Poisson}(s + b)$

Consider the case where we observe n events, model as following Poisson distribution with mean $s + b$.

Here assume b is known.

1) For an observed n, what is the significance Z_0 with which we would reject the $s = 0$ hypothesis?

2) What is the expected (or more precisely, median) Z_0 if the true value of the signal rate is s?

Takenfromtheslides′ Asimovestimatefordiscoverysignificanceincountingexperiment′ byGlenCowan)1 − 19

Gaussian approximation for Poisson significance

For large $s + b$, $n \to x \sim$ Gaussian(μ,σ) , $\mu = s + b$, $\sigma = \sqrt{(s + b)}$.

For observed value $x_{\rm obs}$, p-value of $s = 0$ is Prob($x > x_{\rm obs} \mid s = 0$),:

$$p_0 = 1 - \Phi\left(\frac{x_{\rm obs} - b}{\sqrt{b}}\right)$$

Significance for rejecting $s = 0$ is therefore

$$Z_0 = \Phi^{-1}(1 - p_0) = \frac{x_{\rm obs} - b}{\sqrt{b}}$$

Expected (median) significance assuming signal rate s is

$$\text{median}[Z_0|s + b] = \frac{s}{\sqrt{b}}$$

*Takenfromtheslides′ Asimovestimatefordiscoverysignificanceincountingexperiment′ byGlenCowan)*1 − 19

Better approximation for Poisson significance

Likelihood function for parameter s is

$$L(s) = \frac{(s+b)^n}{n!} e^{-(s+b)}$$

or equivalently the log-likelihood is

$$\ln L(s) = n \ln(s+b) - (s+b) - \ln n!$$

Find the maximum by setting $\frac{\partial \ln L}{\partial s} = 0$

gives the estimator for s: $\hat{s} = n - b$

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Approximate Poisson significance (continued)

The likelihood ratio statistic for testing $s = 0$ is

$$q_0 = -2\ln\frac{L(0)}{L(\hat{s})} = 2\left(n\ln\frac{n}{b} + b - n\right) \quad \text{for } n > b,\ 0 \text{ otherwise}$$

For sufficiently large $s + b$, (use Wilks' theorem),

$$Z_0 \approx \sqrt{q_0} = \sqrt{2\left(n\ln\frac{n}{b} + b - n\right)} \quad \text{for } n > b,\ 0 \text{ otherwise}$$

To find median[$Z_0|s+b$], let $n \longrightarrow s + b$ (i.e., the Asimov data set):

$$\text{median}[Z_0|s+b] \approx \sqrt{2\left((s+b)\ln(1+s/b) - s\right)}$$

This reduces to $s/\sqrt{b}$ for s << b.

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