# A smoking gun signature of 3HDM

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In collaboration with

V. Keus & S. Moretti & C. Shepherd-Themistocleous

Based on

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**LHC Higgs Working Group WG3 (BSM) – Extended Higgs Sector subgroup meeting**
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# Table of Contents

# The Standard Model and its shortcomings

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- No significant deviation from the SM
- No signs of new physics

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  **The recently discovered 125-GeV scalar can be a portal to the dark sector.**
  **problem:** Current direct and indirect detection as well as relic density bound strongly constrain the simplistic possibilities.

# 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

*....for more details follow papers by Venus Keus*

# BSMs to the rescue

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

## CP-conserving I(2+1)HDM

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

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

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

[JHEP1401(2014)052], [Phys.Rev.D90, 075015(2014)], [arXiV : 1907.12522]

# The scalar potential with explicit CPC

$$V_{3HDM} = V_0 + V_{Z_2}$$

$$V_0 = \sum_{i}^{3}\left[-\mu_i^2(\phi_i^\dagger\phi_i) + \lambda_{ii}(\phi_i^\dagger\phi_i)^2\right] + \sum_{i,j}^{3}\left[\lambda_{ij}(\phi_i^\dagger\phi_i)(\phi_j^\dagger\phi_j) + \lambda'_{ij}(\phi_i^\dagger\phi_j)(\phi_j^\dagger\phi_i)\right]$$

$$V_{Z_2} = -\mu_{12}^2(\phi_1^\dagger\phi_2) + \lambda_1(\phi_1^\dagger\phi_2)^2 + \lambda_2(\phi_2^\dagger\phi_3)^2 + \lambda_3(\phi_3^\dagger\phi_1)^2 + h.c.$$

The $Z_2$ symmetry

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

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

# 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 $\mu_{12}^2$ , $\lambda_2$
- Higgs-DM coupling $\lambda_2, \lambda_{23}, \lambda'_{23}$
- Mass scale of inert particles $\mu_2^2$

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

# 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 $\theta_c$, $\theta_a$ and n.

# Constraints

- **Vacuum stability**: scalar potential $V$ bounded from below
- **Perturbative unitarity**: eigenvalues $\Lambda_i$ 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:
    $m_{H_i} + m_{H_j^\pm} \geq m_W, \; m_{A_i} + m_{H_j} \geq m_Z, \; 2\, m_{H^\pm_{1,2}} \geq m_Z$
  - Limits on charged scalar mass and lifetime:
    $m_{H_i^\pm} \geq 70 \text{ GeV}, \quad \tau \leq 10^{-7} \text{ s} \rightarrow \Gamma_{\text{tot}} \geq 10^{-18} \text{ GeV}$
  - Allowed by Higgs invisible branching ratio, $Br(h \rightarrow inv.) < 19\%$
  - 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 $A_1, H_1^\pm$:

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

# Relevant DM scenario

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

We are looking for:

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

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

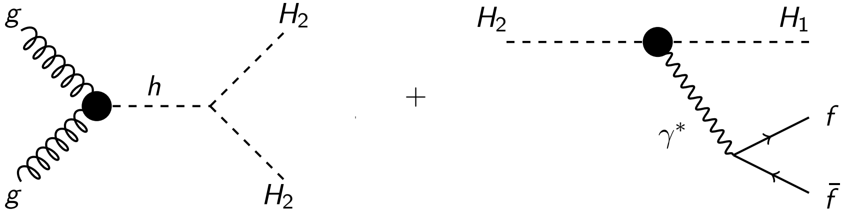
[*JHEP*09(2018)059]

## 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

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

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

# Smoking gun Signal

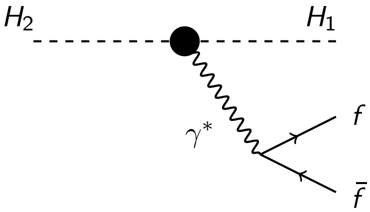



Figure: Radiative decay of the heavy neutral particle $H_2 \to H_1\gamma^* \to H_1 l^+ l^-$.

# Smoking gun Signal

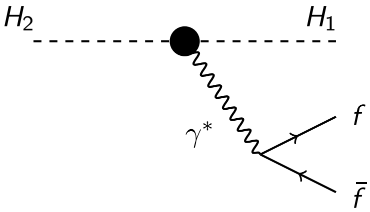
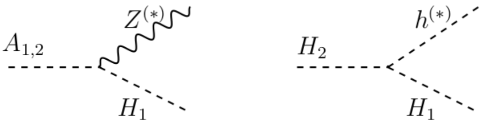



Figure: Radiative decay of the heavy neutral particle $H_2 \to H_1\gamma^* \to H_1 l^+ l^-$.

- $m_{H_2} - m_{H_1}$ 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:

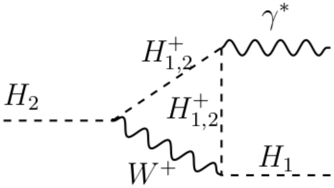


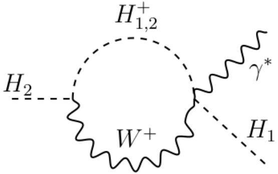

It can give the tree level process $E_{miss}^T + l^+ l^- l^+ l^-$:

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

# 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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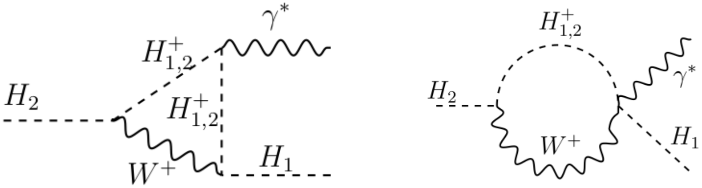


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$pp \to H_2 H_2 / A_{1,2} A_{1,2} \to H_1 H_1 \gamma^* \gamma^* \to H_1 H_1 l^+ l^- l^+ l^-$

The **smoking gun** channel

- We are looking for Benchmarks with small mass gap ($\Delta m$) between $H_2$ and $H_1$

| BPs | $m_{H_1}$ | $m_{H_2}$ | $\Delta m$ | $n$ | $g_{H_1 H_1 h}$ | $\theta_h$ | $\sigma(pp \to H_1 H_1 2\mu^+ 2\mu^-)$ |
|---|---|---|---|---|---|---|---|
| $BP1 : I_5^{50}$ | 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 $\mu + \not{E}_T$.

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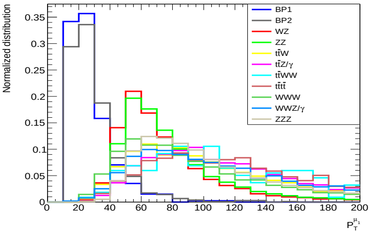
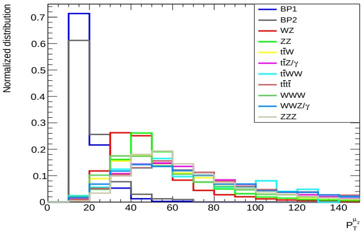
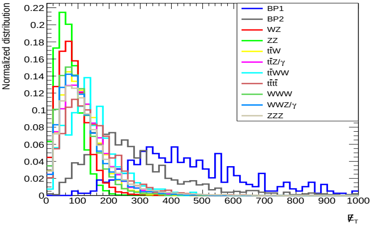
- **Signal:** At least 3−muon with at least one pair of Opposite sign $\mu + \not{E}_T$.
- **Backgrounds:** 1) **Di-boson**, $VV(V: W, Z, \gamma)$: Mainly $WZ/\gamma$ and $ZZ$ have large contribution where both $V$ can decay leptonically.
  2) **Tri-boson**, $VVV(V: W, Z, \gamma)$: Mainly consider $WWZ/\gamma$,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

# Distributions



# Distributions

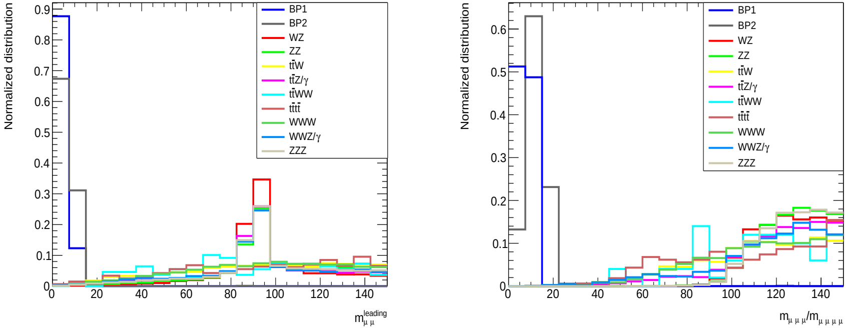



Figure: Normalized distribution of invariant mass of two leading muons and invariant mass of all muons fir signal BPs and backgrounds.

# 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 |
| $WWZ/\gamma$ | 0.04978 | 96 | 1 | 0 |
| $ZZZ$ | $9.3516 \times 10^{-3}$ | 16 | 0 | 0 |
| $t\bar{t}W$ | 0.606 | 114 | 2 | 0 |
| $t\bar{t}Z/\gamma$ | 0.3045 | 136 | 1 | 0 |
| $t\bar{t}WW$ | $1.279 \times 10^{-3}$ | 0 | 0 | 0 |
| $t\bar{t}t\bar{t}$ | $1.51359 \times 10^{-3}$ | 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-$\mu$ + $\not{E}_T$ 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:

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

*The′AsimovPaper′(Cowan, Cranmer, Gross, Vitells, EPJC71(2011)1 − 19*

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

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

- 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 |
| $WWZ/\gamma$ | 0.04978 | 41 | 0 | 0 |
| $ZZZ$ | $9.3516 \times 10^{-3}$ | 6 | 0 | 0 |
| $t\bar{t}W$ | 0.606 | 1 | 0 | 0 |
| $t\bar{t}Z/\gamma$ | 0.3045 | 56 | 0 | 0 |
| $t\bar{t}WW$ | $1.279 \times 10^{-3}$ | 0 | 0 | 0 |
| $t\bar{t}t\bar{t}$ | $1.51359 \times 10^{-3}$ | 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 $\geq 4$-$\mu$ + $\not{E}_T$ 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

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

# Higgs-portal DM

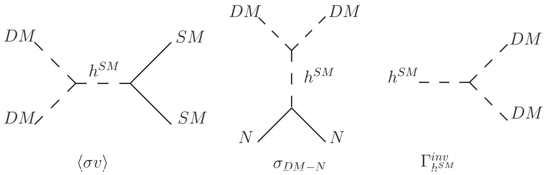
Simplest realisation: the SM with $\Phi_{SM}$ + $Z_2$-odd scalar $S$:

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

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

Higgs-portal interaction:

$$\text{SM sector} \overset{\text{Higgs}}{\longleftrightarrow} \text{DM sector}$$




given by the same coupling

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

The general scalar potential

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

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

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

- $2 \times 2$ charged mass-squared matrix

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

- $4 \times 4$ 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 $\to$ no CP violation
- Only $\phi_1$ couples to fermions
- The whole Lagrangian is explicitly $Z_2$-symmetric

# DM in the IDM

The Inert minimum

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

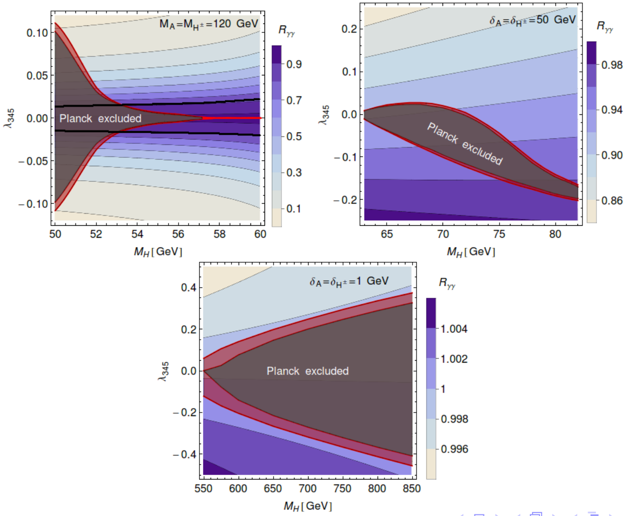
- $Z_2$-symmetry survives the EWSB

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

- $\phi_1$ is active (plays the role of the SM-Higgs)
- $\phi_2$ is “dark” or inert (with 4 dark scalars $H, A, H^{\pm}$)

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

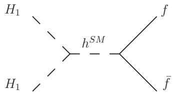
# $h \to \gamma\gamma$ signal strength (JHEP 09 (2013) 055)



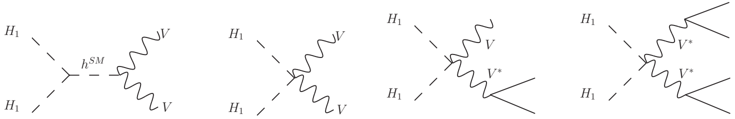
# CP-conserving I(2+1)HDM

# Dark Matter Annihilation

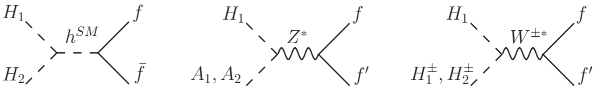
- annihilation through Higgs into fermions; dominant channel for $M_{DM} < M_h/2$




- 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 $H_2, A_{1,2}$:

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

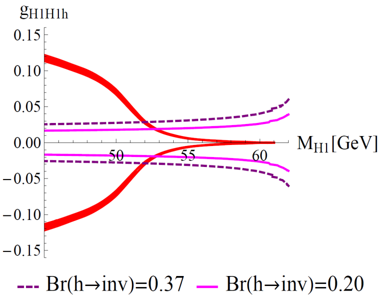
(G) **coannihilation** with $H_2, A_{1,2}, H_{1,2}^\pm$:

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

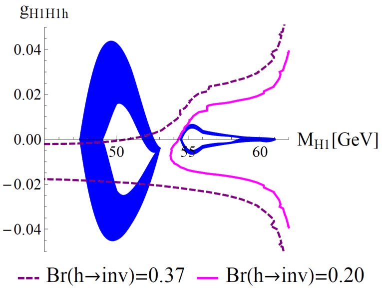
(H) **coannihilation** with $A_1, H_1^\pm$:

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

# 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

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

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

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

# 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

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

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

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

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

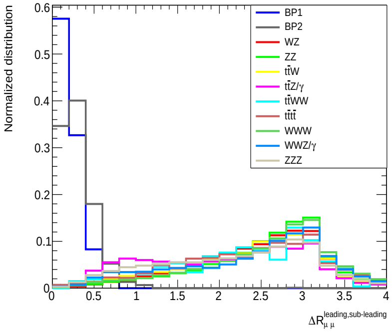
$$\mu_{12}^2 = \frac{1}{2}\sqrt{(m_{H_1}^2 - m_{H_2}^2)^2 - (-1+n)^2(\Lambda_{\phi_2} - \mu_2^2)^2},$$

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

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

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

# Distributions



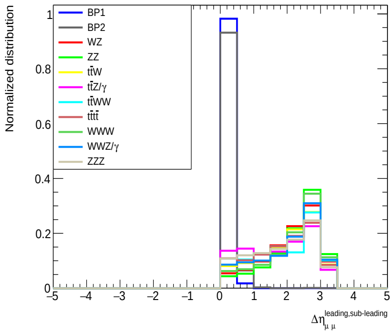




Figure: Normalized Distribution of $\Delta R$ and $\Delta\eta$ of leading and sub-leading muon for signal BPs and backgrounds.

# 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 $s + b$, $n \rightarrow x \sim$ Gaussian($\mu$,$\sigma$) , $\mu = s + b$, $\sigma = \sqrt{(s + b)}$.

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

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

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 $s$: $$\hat{s} = n - b$$

*Takenfromtheslides′ Asimovestimatefordiscoverysignificanceincountingexperiment′ byGlenCowan*)1 − 19

## 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 $n \to s + b$ (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.

*Takenfromtheslides′ Asimovestimatefordiscoverysignificanceincountingexperiment′ byGlenCowan*)1 − 19