

Exploring Multilepton Signatures From Dark Matter at the LHC

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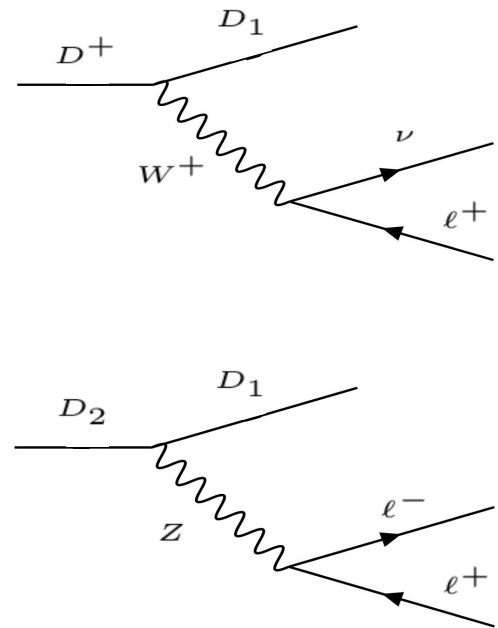
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COST Advanced School on Physics of Dark Matter and Hidden Sectors
18/10/21-21/10/21



Outline

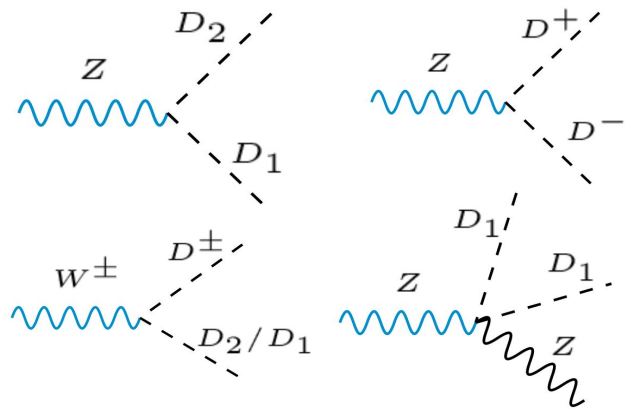
- Beyond mono-X searches \rightarrow multilepton+missing ET
- Cover the full (3D) parameter space relevant to LHC for two representative minimal consistent DM models: MFDM (spin 1/2) and i2HDM (spin 0)
- New parameterization to visualise the viable parameter space and related no-loose theorem
- New important and complementary LHC sensitivity from 3-lepton signature
- LHC limits and efficiencies for 2- and 3-lepton signatures for reinterpretation by the community



Inert 2 Higgs Doublet Model (I2HDM)

$$\mathcal{L}_\phi = |D_\mu \phi_1|^2 + |D_\mu \phi_2|^2 - V(\phi_1, \phi_2)$$

$$\phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix}, \quad \phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2} D^+ \\ D_1 + i D_2 \end{pmatrix}$$



$$[m_{D1}, m_{D+}, m_{D2}, \lambda_2, \lambda_{345}] \longrightarrow [m_{D1}, \Delta m^+, \Delta m^0]$$

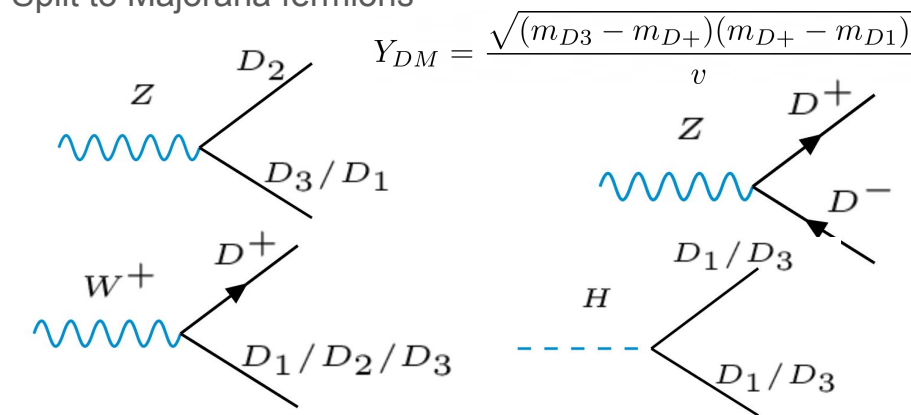
Minimal Fermion Dark Matter (MFDM)

$$\mathcal{L}_{FDM} = \mathcal{L}_{SM} + \bar{\psi}(i\not{D} - m_\psi)\psi + \frac{1}{2}\chi_s^0(i\not{D} - m_s)\chi_s^0 - (Y_{DM}\bar{\psi}\Phi\chi_s^0) + h.c.)$$

$$\psi = \begin{pmatrix} \chi^+ \\ \frac{1}{\sqrt{2}}(\chi_1^0 + i\chi_2^0) \end{pmatrix}$$

Split to Majorana fermions

Majorana singlet χ_s^0



$$[m_{D1}, m_{D2} = m_{D+}, m_{D3}] \longrightarrow [m_{D1}, \Delta m^+, \Delta m^0]$$

HEP Tools

- CalcHEP: Parton-level event production and decays: LHE file output
- CheckMATE (+ Pythia + Delphes): Decays, parton-showers, detector effects and analysis checks
- 8 TeV: written new analysis for final states with 2ℓ and E_T^{miss}
- 13 TeV: Check any available ATLAS and CMS analyses, lists 2ℓ and 3ℓ channels

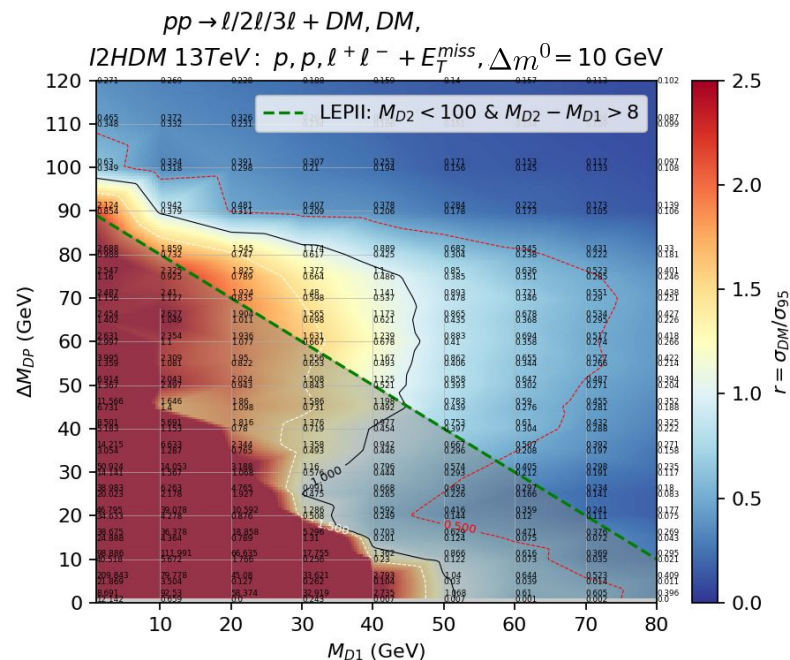
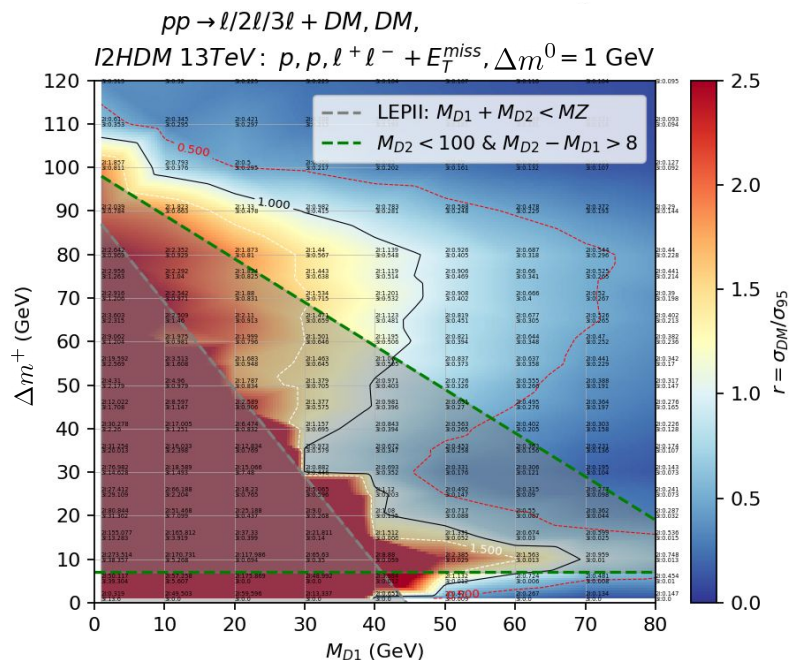
$$\mathcal{R} = \frac{\sigma_{DM}}{\sigma_{95}} \quad \begin{array}{l} \text{— Cross-section of DM events produced} \\ \text{— Cross-section required to exclude point at 95\% confidence level} \end{array}$$

- Point excluded if $\mathcal{R} \geq 1$

New I2HDM Results

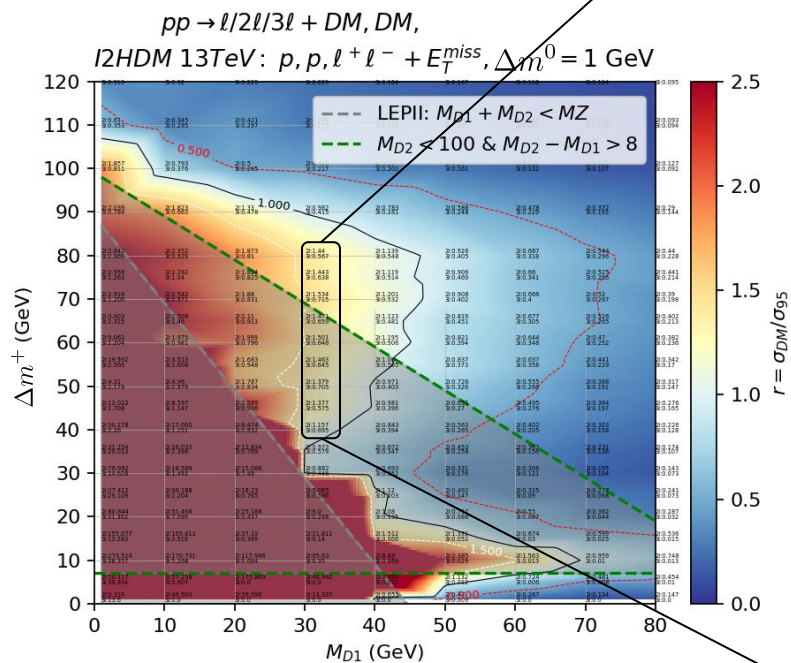
$$\Delta m^0 = m_{D2} - m_{D+}$$

$$\Delta m^+ = m_{D+} - m_{D1}$$



- $\Delta m^0 = 1 \text{ GeV}$: Small wedge above $m_{D1} > 50 \text{ GeV}$ and below $\Delta m^+ < 8 \text{ GeV}$ still allowed by LEP
- Δm^+ is a better variable than m_{D+} , results not dependent on m_{D2} , only require plane of 2 variables
- Important contributions from 3-lepton (up to 70%) which could be combined with 2-lepton

New I2HDM Results



2l:1.443
 3l:0.638

2l:1.534
 3l:0.715

2l:1.471
 3l:0.659

2l:1.501
 3l:0.646

2l:1.463
 3l:0.645

2l:1.379
 3l:0.705

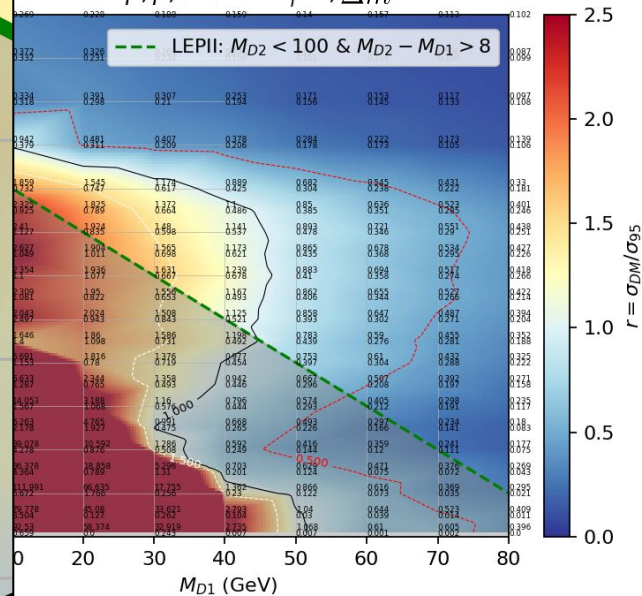
2l:1.377
 3l:0.575

2l:1.157
 3l:0.695

$$\Delta m^0 = m_{D2} - m_{D+}$$

$$\Delta m^+ = m_{D+} - m_{D1}$$

$pp \rightarrow l/2l/3l + DM, DM,$
 I2HDM 13TeV: $p, p, l^+l^- + E_T^{miss}, \Delta m^0 = 10 \text{ GeV}$

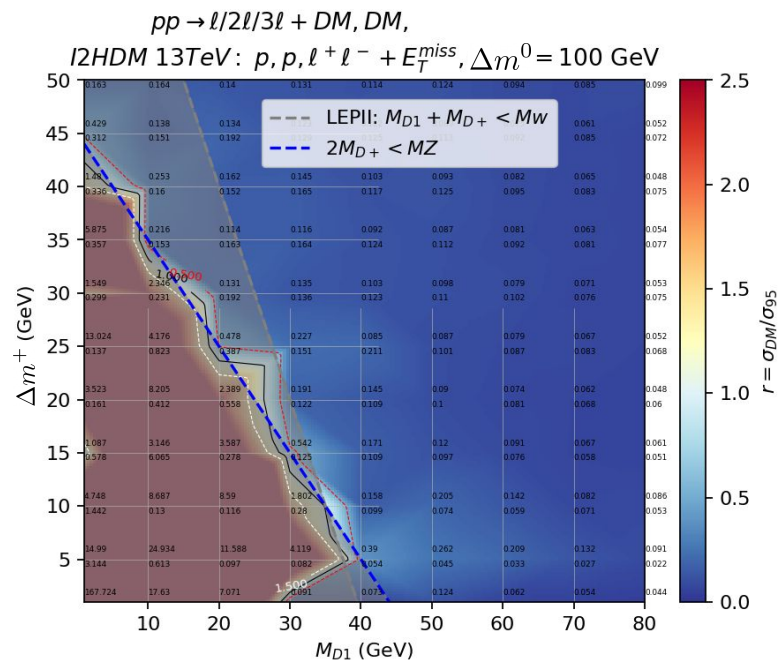
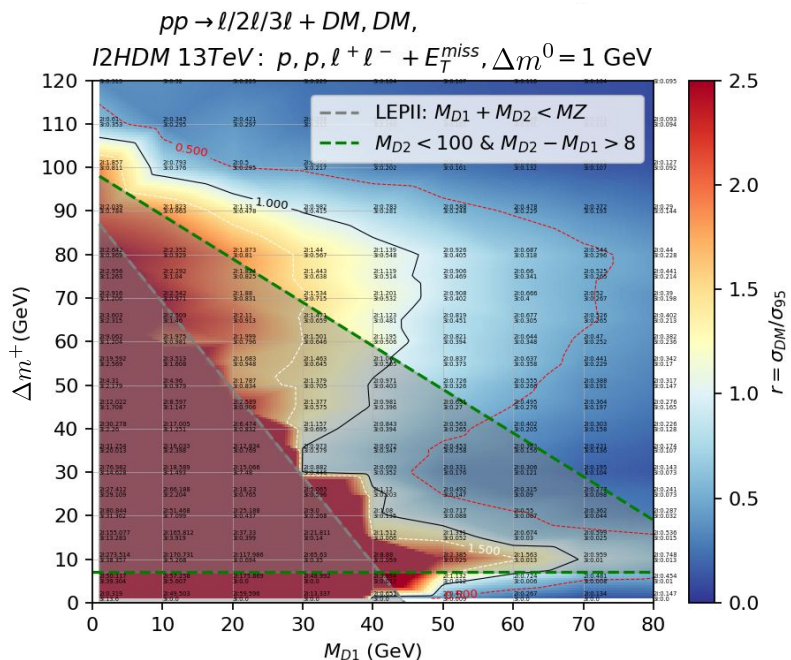


- $\Delta m^0 = 1 \text{ GeV}$: Small wedge above $m_{D1} > 50 \text{ GeV}$ and below $\Delta m^+ < 8 \text{ GeV}$ still allowed by LEP
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New I2HDM Results

$$\Delta m^0 = m_{D2} - m_{D+}$$

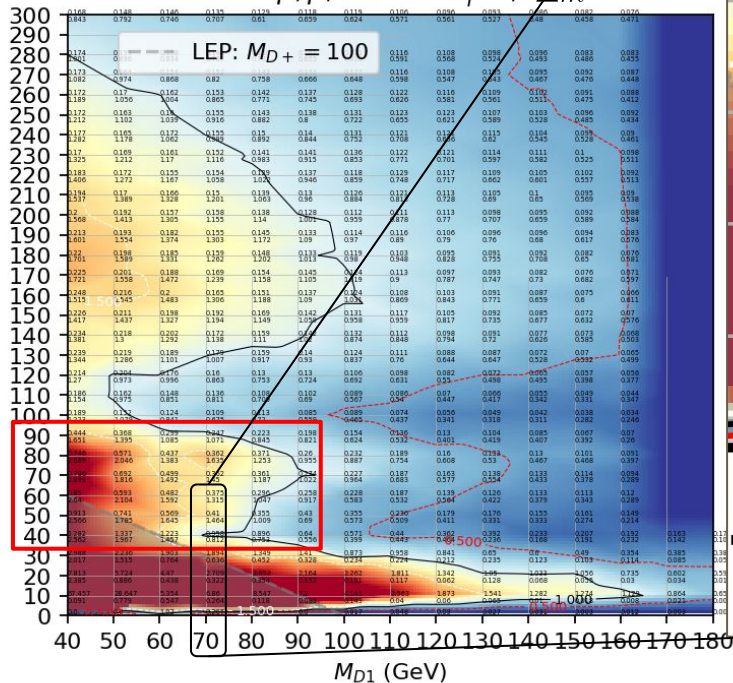
$$\Delta m^+ = m_{D+} - m_{D1}$$



- Increasing Δm^0 to 100 GeV means the Z veto $m_{\ell\ell} > 100 \text{ GeV}$ requirement by the analysis cut-flow can no longer be fulfilled as production cross-section of the heavier states has fallen

MFDM Results

$pp \rightarrow l/2l/3l + DM, DM,$
 MFDM 13TeV: $p, p, l^+ l^- + E_T^{miss}, \Delta m^0 = 1 \text{ GeV}$



0.375

1.315

0.41

1.464

0.958

0.812

1.894

0.636

2.709

0.322

6.86

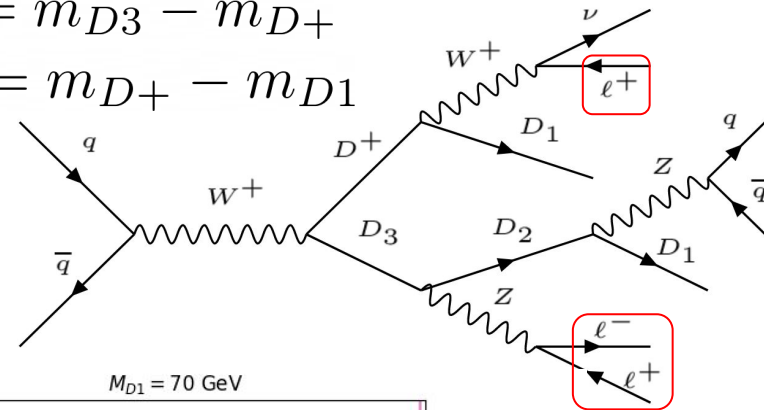
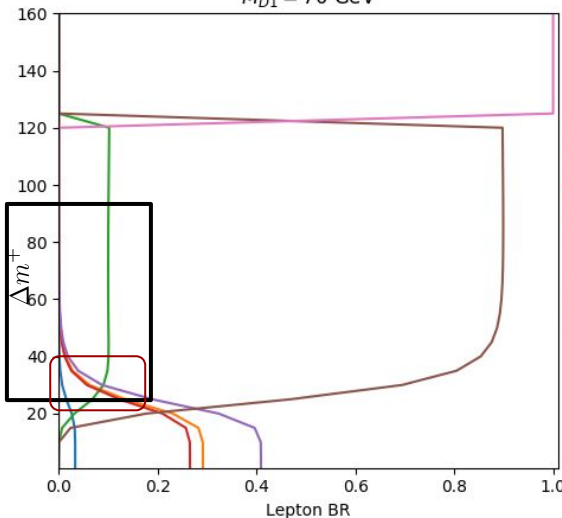
0.264

0.267

70

$$\Delta m^0 = m_{D3} - m_{D+}$$

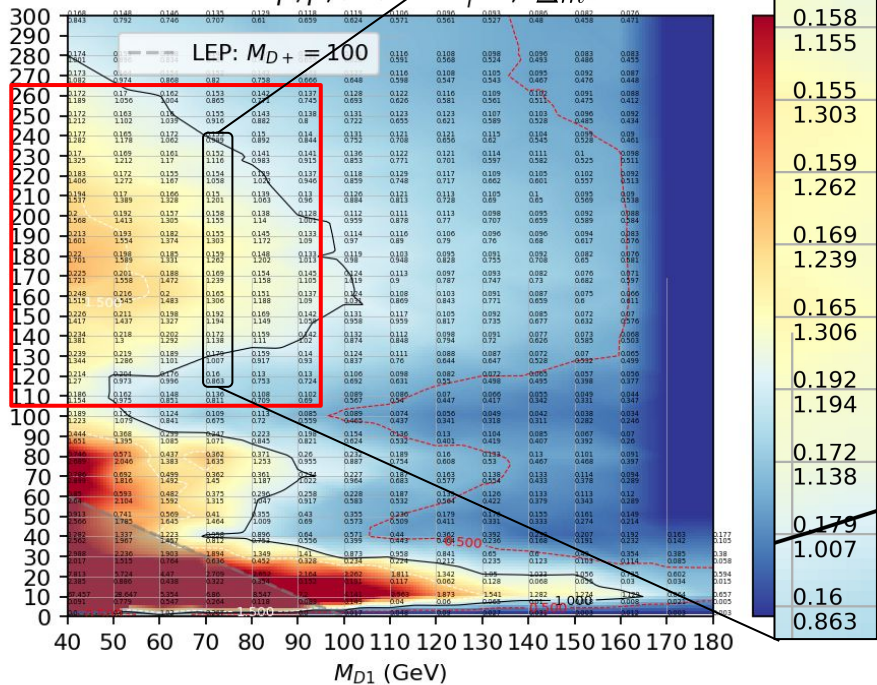
$$\Delta m^+ = m_{D+} - m_{D1}$$


 $M_{D1} = 70 \text{ GeV}$


- Similar shapes to I2HDM, but 3-lepton channel sensitivity begins to dominate due to crossing between
 - $D_3 \rightarrow \nu l D_1$
 - $D_3 \rightarrow Z(\rightarrow \ell \ell) D_1$
 - $D^\pm(\rightarrow \nu l D_1) D_3$
 - $\Delta m^+ = 45$

MFDM Results

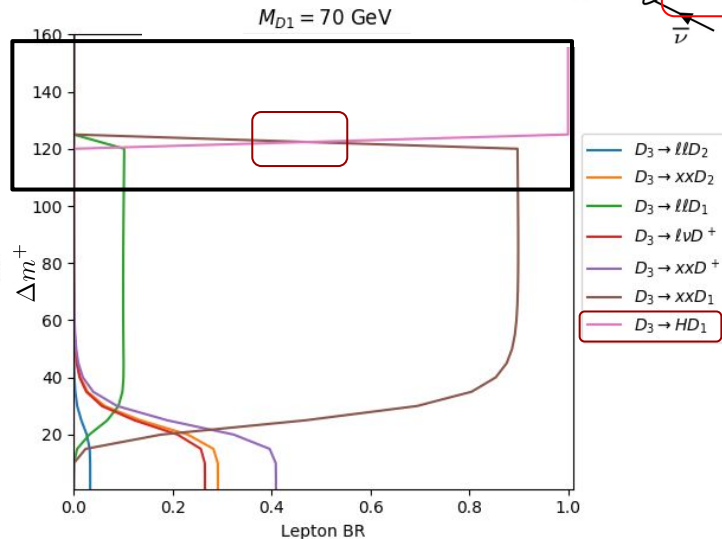
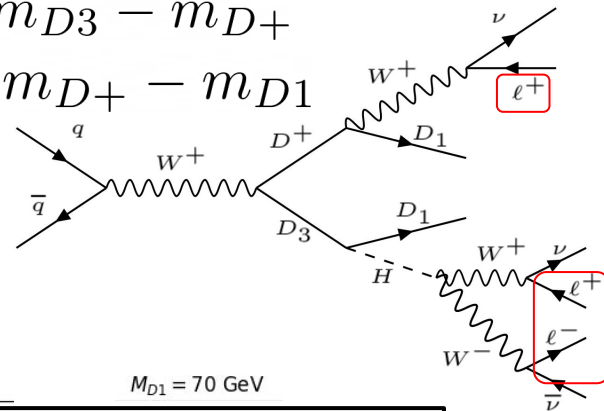
$pp \rightarrow l/2l/3l + DM, DM,$
 MFDM 13TeV: $p, p, l^+ l^- + E_T^{miss}, \Delta m^0 = 1 \text{ GeV}$



- Second shape due to 3-lepton channel sensitivity due to Higgs decay $D_3 \rightarrow Z(\rightarrow \ell\ell)D_1$ to $D_3 \rightarrow H(\rightarrow W^+W^-)D_1$ with production of $D^\pm(\rightarrow \ell\nu D_1)D_3$, at $\Delta m^+ = 125 \text{ GeV}$

$$\Delta m^0 = m_{D3} - m_{D+}$$

$$\Delta m^+ = m_{D+} - m_{D1}$$



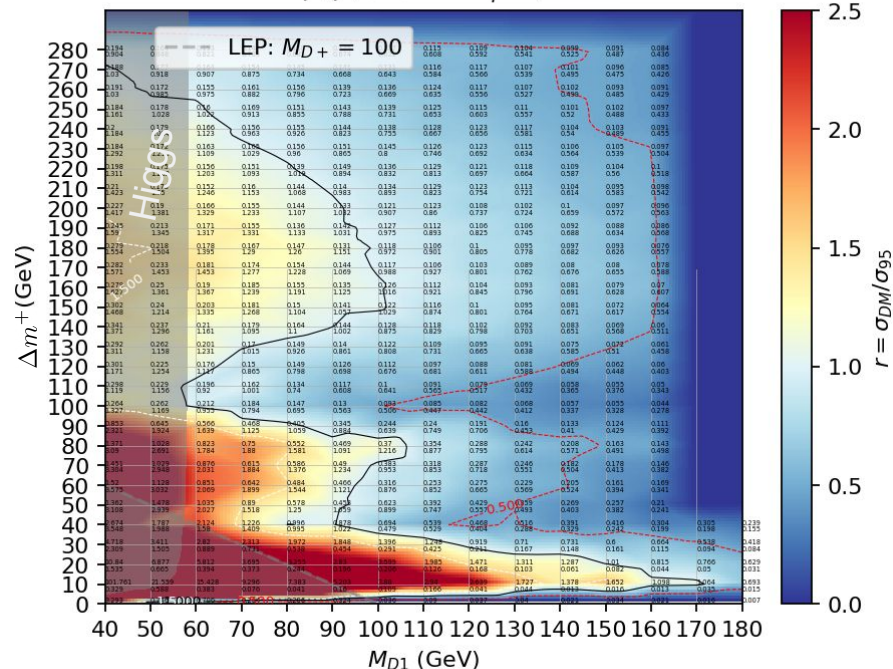
MFDM Results

$$\Delta m^0 = m_{D_3} - m_{D^+}$$

$$\Delta m^+ = m_{D^+} - m_{D_1}$$

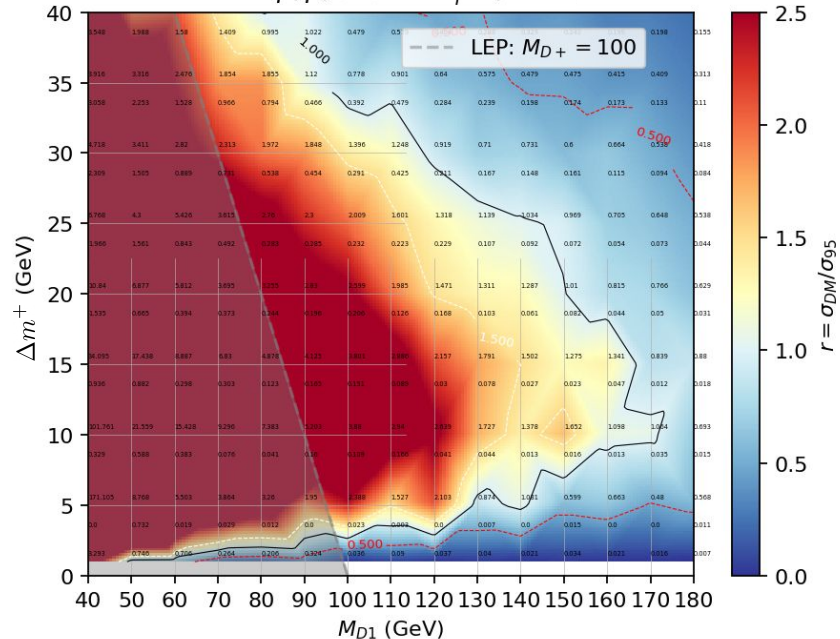
$pp \rightarrow \ell/2\ell/3\ell + DM, DM,$

MFDM 13TeV: $p, p, \ell^+ \ell^- + E_T^{miss}, \Delta m^0 = 10 \text{ GeV}$



$pp \rightarrow \ell/2\ell/3\ell + DM, DM,$

MFDM 13TeV: $p, p, \ell^+ \ell^- + E_T^{miss}, \Delta m^0 = 10 \text{ GeV}$



- As Δm^0 increases, coupling between $D_1 - D^\pm$ increases, while heavy D_3 leads to suppressed production cross-section - 'no-lose' theorem

MFDM Results

$$\Delta m^0 = m_{D3} - m_{D+}$$

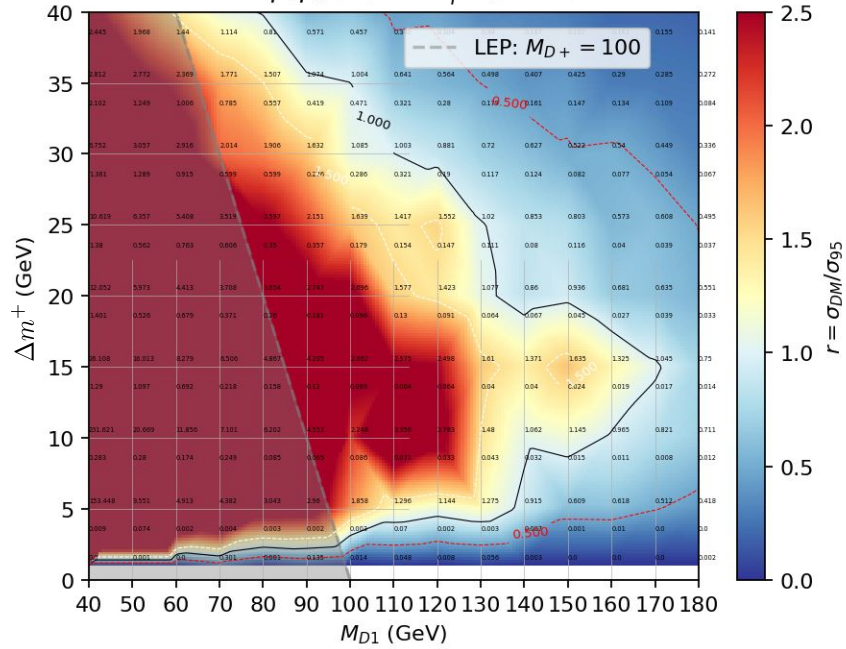
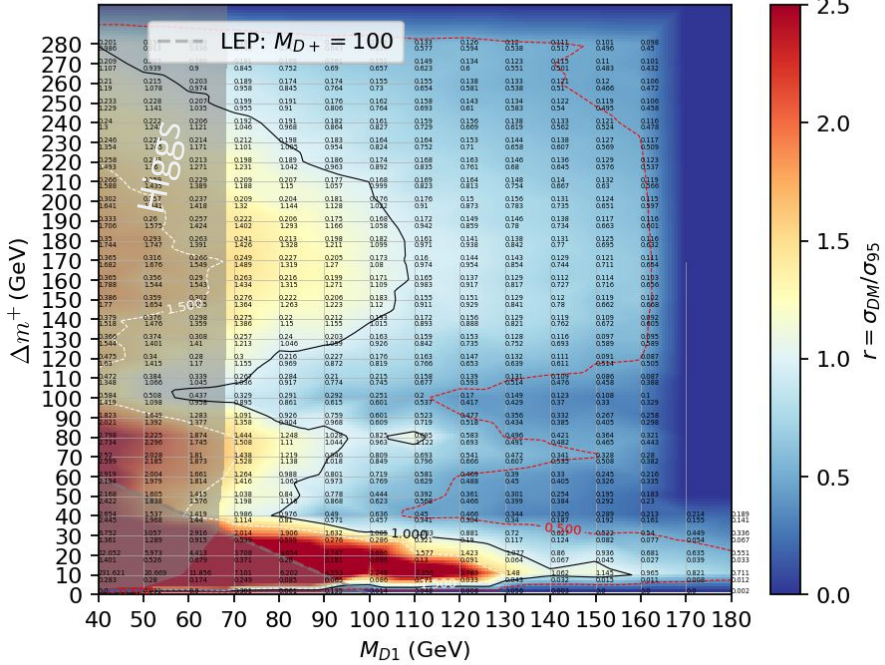
$$\Delta m^+ = m_{D+} - m_{D1}$$

$pp \rightarrow \ell/2\ell/3\ell + DM, DM,$

MFDM 13TeV: $p, p, \ell^+ \ell^- + E_T^{miss}, \Delta m^0 = 100 \text{ GeV}$

$pp \rightarrow \ell/2\ell/3\ell + DM, DM,$

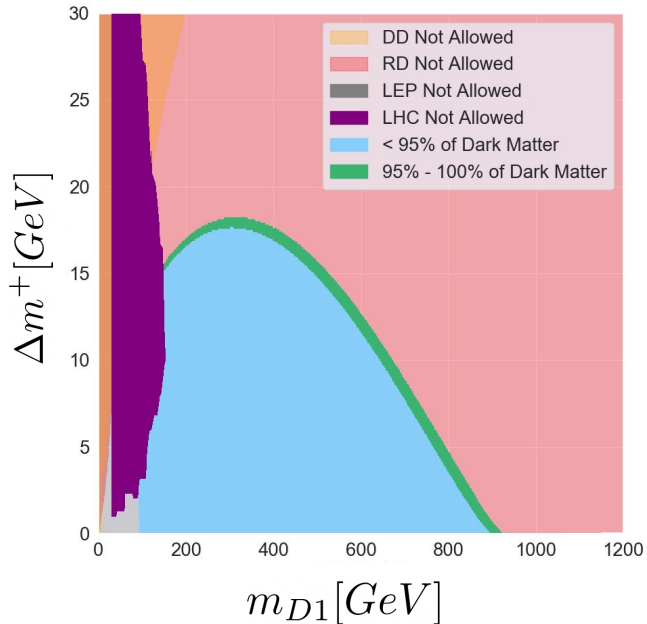
MFDM 13TeV: $p, p, \ell^+ \ell^- + E_T^{miss}, \Delta m^0 = 100 \text{ GeV}$



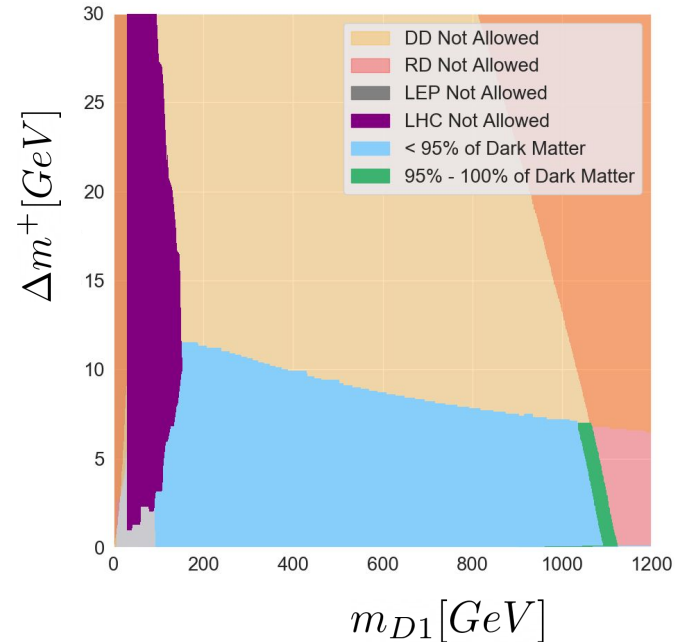
- With increasing Δm^0 , Higgs to invisible limit covers larger m_{D1} upto $m_{D1} = m_H/2$

Combined Limits: MFDM

$$\Delta m^0 = 1 \text{ GeV}$$



$$\Delta m^0 = 100 \text{ GeV}$$



- Under abundance of relic density in light blue region, is 'just right' in green line
- As Δm^+ increases, co-annihilation between the D,D+ is suppressed, due to the greater mass difference; so the relic density becomes too large (pink region)

Conclusions

1. **New sensitivity results for MCDM models at the LHC (beyond mono-X)**
2. **Better parameterization in terms of DM couplings to visualise the viable parameter space and no-loose theorem**
3. **Show important role from 3-lepton final states, with leading role in MFDM (\sim SUSY Higgsino) via Higgs decays $D_3 \rightarrow H(\rightarrow W^+W^-)D_1$**
4. **Provide limits and efficiencies for re-interpretation of any scalar or fermion DM model by the community**

Backup

Re-interpretation: Providing Cross-section Limits

I2HDM

	Sample A	Sample B	Sample C
No# Events:	50,000	150,000	100,000
Production:	$pp \rightarrow D^+ D^-$ $pp \rightarrow D_2 D_1$	$pp \rightarrow D^\pm D_2$	$pp \rightarrow Z D_1 D_1$
Decays:	$D^\pm \rightarrow (W^\pm \rightarrow \ell^\pm \nu) D_1$ $D_2 \rightarrow (Z \rightarrow \ell^+ \ell^-) D_1$	$D_2 \rightarrow (Z \rightarrow \ell^+ \ell^-) D_1$	$Z \rightarrow \ell^+ \ell^-$

- While the genuine 2-2 process $pp \rightarrow D_2 D_1$ is separate to 3-body decay $pp \rightarrow Z D_1 D_1$, width of D_2 is small, so expected interference between these diagrams is small


Re-interpretation: Providing Cross-section Limits

MFDM

	Sample A	Sample B	Sample C
No# Events:	50,000	150,000	100,000
Production:	$pp \rightarrow D^+ D^-$ $pp \rightarrow D_2 D_1$	$pp \rightarrow D_2 D_3$	$pp \rightarrow D^\pm D_2$ $pp \rightarrow D^\pm D_3$
Decays:	$D^\pm \rightarrow (W^\pm \rightarrow \ell^\pm \nu) D_1$ $D_2 \rightarrow (Z \rightarrow \ell^+ \ell^-) D_1$	Any	$D_2 \rightarrow (Z \rightarrow \ell^+ \ell^-) D_1$ $D_3 \rightarrow (W^\pm \rightarrow \ell^\pm \nu) D^\pm$ $D_3 \rightarrow (Z \rightarrow \ell^+ \ell^-) D_2$

Re-interpretation: Providing Cross-section Limits


Mass parameter points



m_{D1}	Δm^+	Δm^0	$2\ell \sigma_A^{95}$ (fb)	$\frac{100}{\sqrt{N_{MC}}}$	$2\ell \sigma_B^{95}$ (fb)	$\frac{100}{\sqrt{N_{MC}}}$	$2\ell \sigma_C^{95}$ (fb)	$\frac{100}{\sqrt{N_{MC}}}$	$3\ell \sigma_A^{95}$ (fb)	$\frac{100}{\sqrt{N_{MC}}}$	$3\ell \sigma_B^{95}$ (fb)	$\frac{100}{\sqrt{N_{MC}}}$	$3\ell \sigma_C^{95}$ (fb)	$\frac{100}{\sqrt{N_{MC}}}$
1	5	1	3.26×10^3	71	-	100	6.51×10^4	71	-	-	1.21×10^3	24	-	-
1	10	1	97.0	41	-	100	-	-	-	-	1.21×10^3	24	-	100
1	20	1	1.47×10^3	58	6.63×10^3	71	-	100	-	-	933	21	-	-
1	40	1	1.02×10^5	35	8.17×10^4	58	8.17×10^4	71	-	-	1.2×10^3	8	-	-
1	60	1	8.84×10^3	45	5.3×10^3	20	2.94×10^4	58	-	-	220	6	-	100
1	80	1	783	11	326	4	1.15×10^3	9	-	-	93.0	6	-	-
10	5	1	698	58	3.14×10^3	71	-	100	-	-	-	-	-	-
10	10	1	161	38	674	45	-	-	-	-	-	-	-	-
10	20	1	287	45	-	100	1.43×10^4	71	-	-	1.87×10^3	30	-	100
10	40	1	1.40×10^4	50	1.29×10^4	28	2.23×10^4	45	-	-	531	5	6.82×10^4	71
10	60	1	4.44×10^3	26	507	5	604	7	-	-	165	5	-	-
10	80	1	150	5	248	4	630	7	-	-	80.0	5	-	-
10	120	1	281	6	1.32×10^3	8	411	6	-	-	62.0	4	-	-
20	5	1	97.0	41	877	71	-	-	-	-	-	-	-	-
20	10	1	140	35	562	41	-	-	-	-	-	-	-	-
20	20	1	4.78×10^3	58	1.08×10^4	50	-	-	-	-	9.32×10^3	21	-	-
20	40	1	6.31×10^3	38	6.02×10^3	21	1.76×10^4	45	-	-	366	7	-	-
20	60	1	247	6	377	4	438	6	-	-	148	5	-	-
20	80	1	91.0	4	230	3	534	6	-	-	62.0	5	-	-
20	120	1	247	6	1.50×10^3	9	321	5	-	100	58.0	4	9.40×10^3	58

Re-interpretation: Providing Cross-section Limits


Cross-section limit (95% cl) for 2
lepton channel of sample A,B,C



m_{D1}	Δm^+	Δm^0	$2\ell \sigma_A^{95}$ (fb)	$\frac{100}{\sqrt{N_{MC}}}$	$2\ell \sigma_B^{95}$ (fb)	$\frac{100}{\sqrt{N_{MC}}}$	$2\ell \sigma_C^{95}$ (fb)	$\frac{100}{\sqrt{N_{MC}}}$	$3\ell \sigma_A^{95}$ (fb)	$\frac{100}{\sqrt{N_{MC}}}$	$3\ell \sigma_B^{95}$ (fb)	$\frac{100}{\sqrt{N_{MC}}}$	$3\ell \sigma_C^{95}$ (fb)	$\frac{100}{\sqrt{N_{MC}}}$
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1	40	1	1.02×10^5	35	8.17×10^4	58	8.17×10^4	71	-	-	1.2×10^3	8	-	-
1	60	1	8.84×10^3	45	5.3×10^3	20	2.94×10^4	58	-	-	220	6	-	100
1	80	1	783	11	326	4	1.15×10^3	9	-	-	93.0	6	-	-
10	5	1	698	58	3.14×10^3	71	-	100	-	-	-	-	-	-
10	10	1	161	38	674	45	-	-	-	-	-	-	-	-
10	20	1	287	45	-	100	1.43×10^4	71	-	-	1.87×10^3	30	-	100
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Re-interpretation: Providing Cross-section Limits

Cross-section limit (95% cl) for 3
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m_{D1}	Δm^+	Δm^0	$2\ell \sigma_A^{95}$ (fb)	$\frac{100}{\sqrt{N_{MC}}}$	$2\ell \sigma_B^{95}$ (fb)	$\frac{100}{\sqrt{N_{MC}}}$	$2\ell \sigma_C^{95}$ (fb)	$\frac{100}{\sqrt{N_{MC}}}$	$3\ell \sigma_A^{95}$ (fb)	$\frac{100}{\sqrt{N_{MC}}}$	$3\ell \sigma_B^{95}$ (fb)	$\frac{100}{\sqrt{N_{MC}}}$	$3\ell \sigma_C^{95}$ (fb)	$\frac{100}{\sqrt{N_{MC}}}$
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10	10	1	161	38	674	45	-	-	-	-	-	-	-	-
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Re-interpretation: Providing Cross-section Limits

100

$\frac{100}{\sqrt{\text{Number of Monte Carlo events survived}}}$ % • Gives a percentage uncertainty

m_{D1}	Δm^+	Δm^0	$2\ell \sigma_A^{95}$ (fb)	$\frac{100}{\sqrt{N_{MC}}}$	$2\ell \sigma_B^{95}$ (fb)	$\frac{100}{\sqrt{N_{MC}}}$	$2\ell \sigma_C^{95}$ (fb)	$\frac{100}{\sqrt{N_{MC}}}$	$3\ell \sigma_A^{95}$ (fb)	$\frac{100}{\sqrt{N_{MC}}}$	$3\ell \sigma_B^{95}$ (fb)	$\frac{100}{\sqrt{N_{MC}}}$	$3\ell \sigma_C^{95}$ (fb)	$\frac{100}{\sqrt{N_{MC}}}$
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1	20	1	1.47×10^3	58	6.63×10^3	71	-	100	-	-	933	21	-	-
1	40	1	1.02×10^5	35	8.17×10^4	58	8.17×10^4	71	-	-	1.2×10^3	8	-	-
1	60	1	8.84×10^3	45	5.3×10^3	20	2.94×10^4	58	-	-	220	6	-	100
1	80	1	783	11	326	4	1.15×10^3	9	-	-	93.0	6	-	-
10	5	1	698	58	3.14×10^3	71	-	100	-	-	-	-	-	-
10	10	1	161	38	674	45	-	-	-	-	-	-	-	-
10	20	1	287	45	-	100	1.43×10^4	71	-	-	1.87×10^3	30	-	100
10	40	1	1.40×10^4	50	1.29×10^4	28	2.23×10^4	45	-	-	531	5	6.82×10^4	71
10	60	1	4.44×10^3	26	507	5	604	7	-	-	165	5	-	-
10	80	1	150	5	248	4	630	7	-	-	80.0	5	-	-
10	120	1	281	6	1.32×10^3	8	411	6	-	-	62.0	4	-	-
20	5	1	97.0	41	877	71	-	-	-	-	-	-	-	-
20	10	1	140	35	562	41	-	-	-	-	-	-	-	-
20	20	1	4.78×10^3	58	1.08×10^4	50	-	-	-	-	9.32×10^3	21	-	-
20	40	1	6.31×10^3	38	6.02×10^3	21	1.76×10^4	45	-	-	366	7	-	-
20	60	1	247	6	377	4	438	6	-	-	148	5	-	-
20	80	1	91.0	4	230	3	534	6	-	-	62.0	5	-	-
20	120	1	247	6	1.50×10^3	9	321	5	-	100	58.0	4	9.40×10^3	58

Inert 2 Higgs Doublet Model (I2HDM)

$$\mathcal{L}_\phi = |D_\mu \phi_1|^2 + |D_\mu \phi_2|^2 - V(\phi_1, \phi_2) \quad \phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix}, \quad \phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2} D^+ \\ D_1 + i D_2 \end{pmatrix}$$

$$V = -m_1^2(\phi_1^\dagger \phi_1) - m_2^2(\phi_2^\dagger \phi_2) + \lambda_1(\phi_1^\dagger \phi_1)^2 + \lambda_2(\phi_2^\dagger \phi_2)^2 + \lambda_3(\phi_1^\dagger \phi_1)(\phi_2^\dagger \phi_2) + \lambda_4(\phi_2^\dagger \phi_1)(\phi_1^\dagger \phi_2)$$

$$m_H^2 = 2\lambda_1 v^2 = 2m_1^2 \quad m_{D^+}^2 = \frac{1}{2}\lambda_3 v^2 - m_2^2 \quad + \frac{\lambda_5}{2}[(\phi_1^\dagger \phi_2)^2 + (\phi_2^\dagger \phi_1)^2]$$

$$m_{D1}^2 = \frac{1}{2}(\lambda_3 + \lambda_4 - |\lambda_5|)v^2 - m_2^2 \quad m_{D2}^2 = \frac{1}{2}(\lambda_3 + \lambda_4 + |\lambda_5|)v^2 - m_2^2 > m_{D1}^2$$

1. λ_2 is quartic inert doublet self-coupling
2. $\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5$ is Higgs-DM coupling: $HD_1 D_1$
3. m_{D1} is DM mass
4. m_{D2} is second lightest, neutral Higgs mass
5. m_{D^+} is charged Higgs mass

Relevant parameters for our study: $[m_{D1}, m_{D^+}, m_{D2}, \lambda_2, \lambda_{345}] \rightarrow [m_{D1}, m_{D^+}, m_{D2}]$

Parameterisations which are more physical for our analysis:

$$[m_{D1}, \Delta m^+, \Delta m^0]$$

$$\Delta m^0 = m_{D2} - m_{D^+}$$

$$\Delta m^+ = m_{D^+} - m_{D1}$$

Minimal Fermion Dark Matter (MFDM)

$$\mathcal{L}_{FDM} = \mathcal{L}_{SM} + \bar{\psi}(i\not{D} - m_{\psi})\psi + \frac{1}{2}\chi_s^0(i\not{D} - m_s)\chi_s^0 - (Y(\bar{\psi}\Phi\chi_s^0) + h.c.)$$

- Minimal model with an EW fermion DM doublet
- To provide the correct amount of relic density, suppress DM scattering through intermediate Z/Higgs boson:

- Majorana neutral D-odd particles χ_1^0, χ_2^0
- additional Majorana singlet fermion χ_s^0

$$\psi = \begin{pmatrix} \chi^+ \\ \frac{1}{\sqrt{2}}(\chi_1^0 + i\chi_2^0) \end{pmatrix}$$

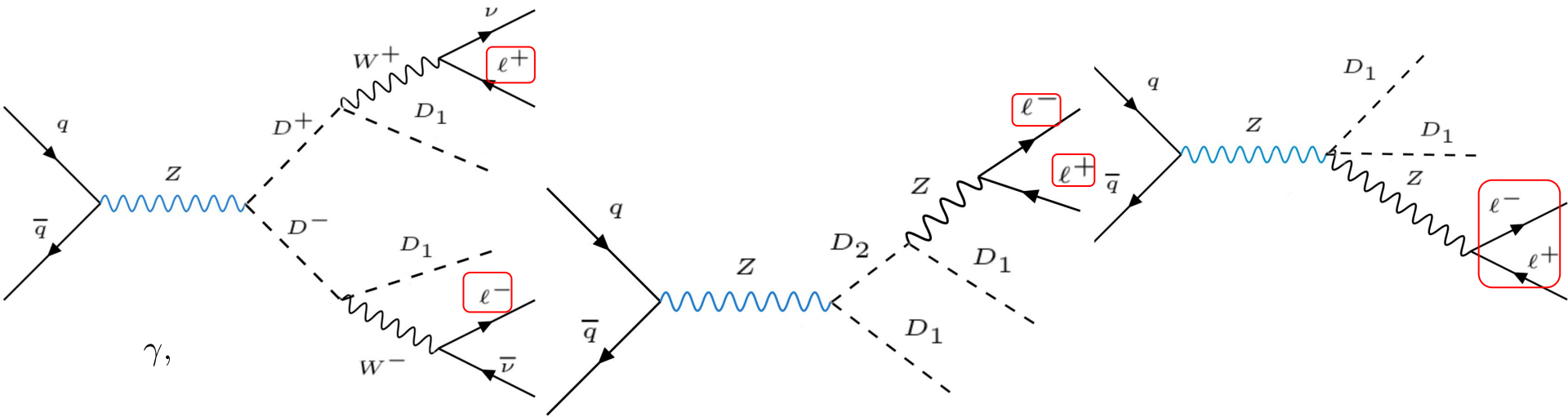
- χ_1^0 and χ_s^0 mix via Yukawa coupling, χ_2^0 and χ^+ are mass degenerate $Y_{DM} = \frac{\sqrt{(m_{D3} - m_{D+})(m_{D+} - m_{D1})}}{v}$

1. m_{D1} is DM mass 2. $m_{D+} = m_{D2}$ is chargino mass 3. m_{D3} is third lightest, neutralino mass

$$m_{D3} > m_{D+} = m_{D2} > m_{D1}$$

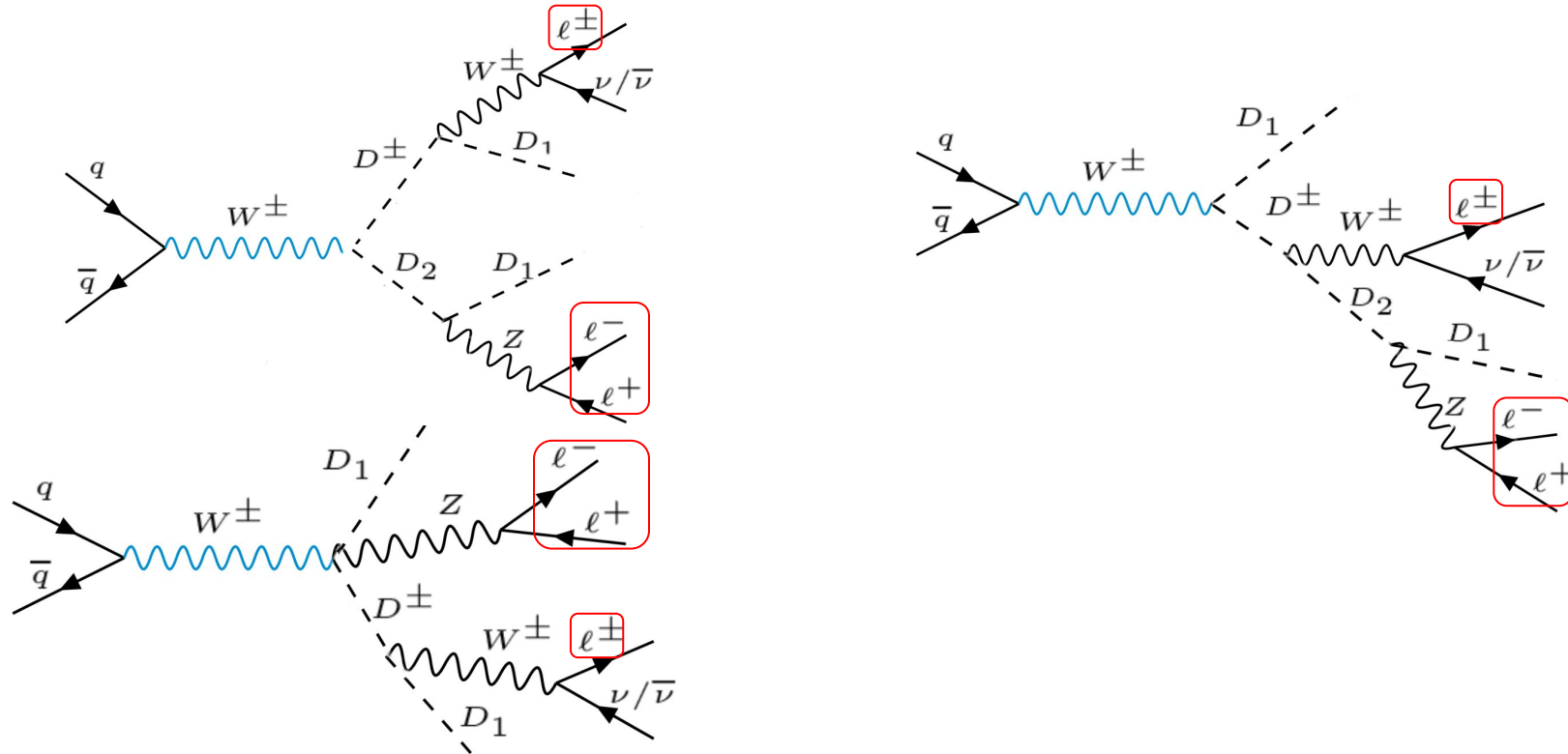
Parameterisations which are more physical for our analysis: $\Delta m^0 = m_{D3} - m_{D+}$ $Y_{DM} = \frac{\sqrt{\Delta m^0 \Delta m^+}}{v}$
 $[m_{D1}, \Delta m^+, \Delta m^0]$ $\Delta m^+ = m_{D+} - m_{D1}$

$2\ell + E_T^{miss}$ 12HDM Final States



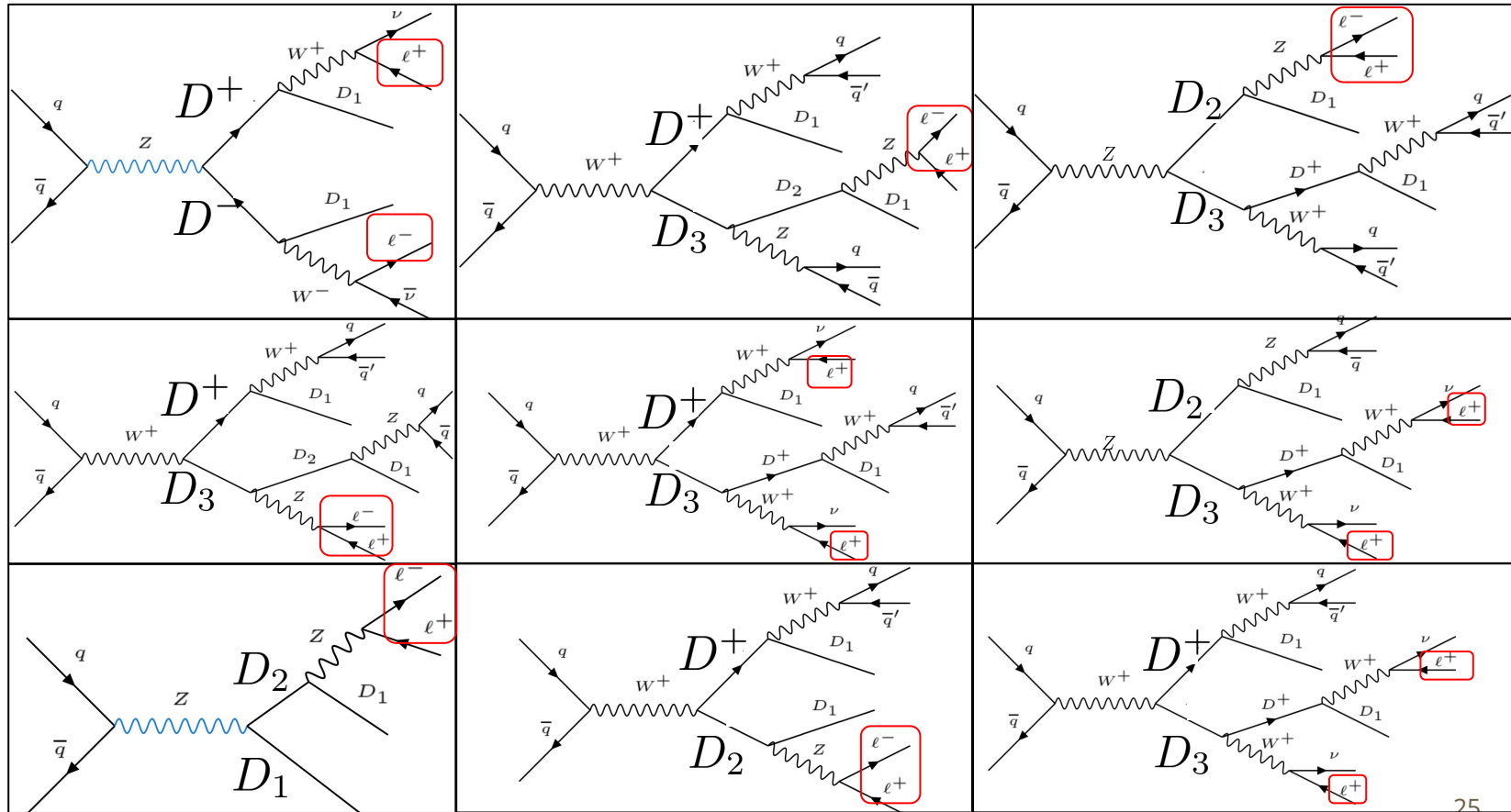
- DM decays via Z production
- Looking at Higgs funnel: $\lambda_{345} \sim 0$, and λ_2 not relevant

$3\ell + E_T^{miss}$ 12HDM Final States

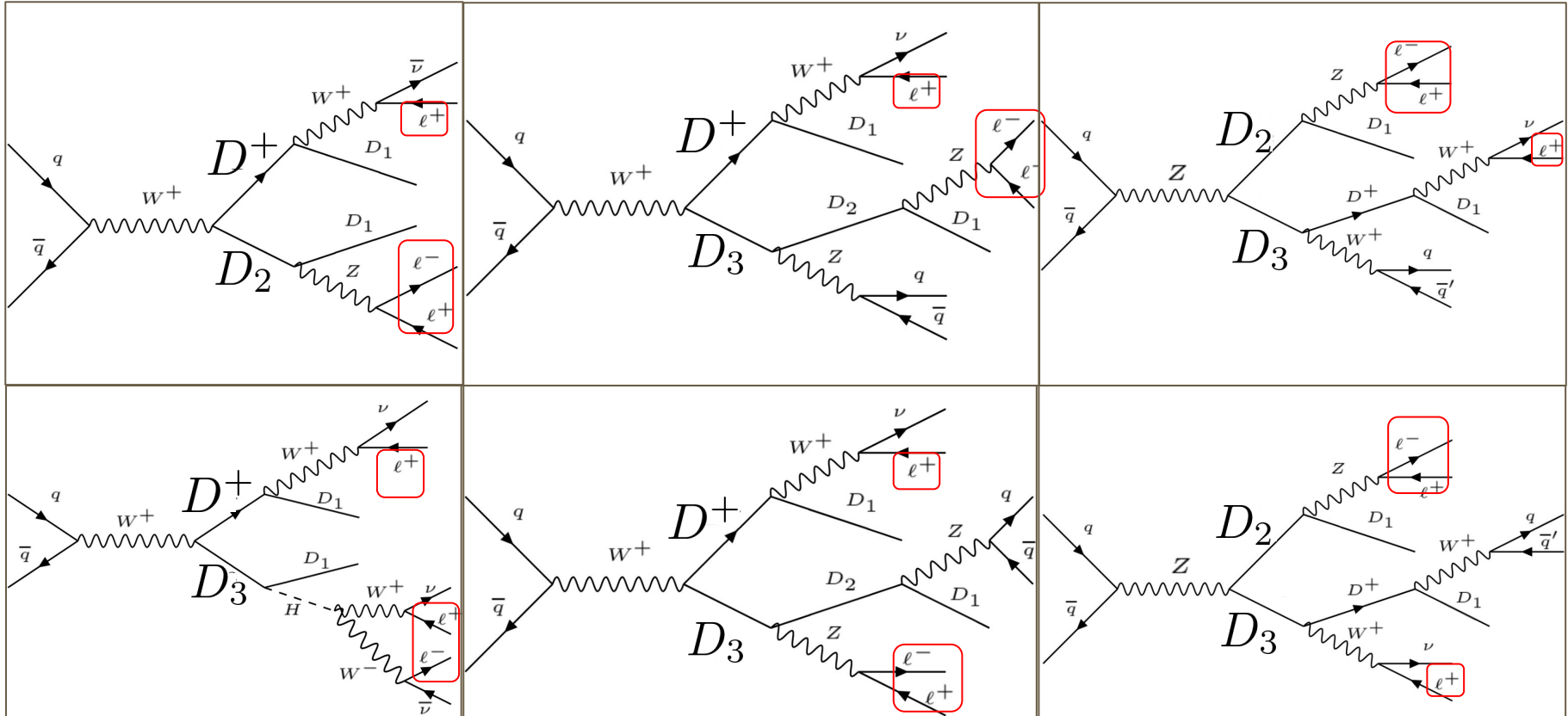


- DM decays via W production, x2 for the +/- processes

$2\ell + E_T^{miss}$ MFDM Final States



$3\ell + E_T^{miss}$ MFDM Final States



8 TeV Analysis Cuts

https://checkmate.hepforge.org/AnalysesList/ATLAS_8TeV.html

- 8 TeV ATLAS SUSY analysis [arXiv:1403.5294](https://arxiv.org/abs/1403.5294)

cutflows for dilepton+MET finals states,

implemented in CheckMATE:

https://checkmate.hepforge.org/validationNotes/atlas_1403_5294.pdf

[as_1403_5294.pdf](https://checkmate.hepforge.org/validationNotes/atlas_1403_5294.pdf)

Global Cut	
E_T^{miss}	> 0 GeV
Base leptons	2
$e + e^-$ trigger	97%
$\mu^+ \mu^-$ trigger	89%
$e\mu$ trigger	75%
Signal leptons	2
Leading lepton p_T	> 35 GeV
sub-leading lepton p_T	> 20 GeV
$M_{\ell\ell}$	> 20 GeV
jets	0
$ M_{\ell\ell} - M_Z $	> 10 GeV

SR	m_{T2}^{90}	m_{T2}^{120}	m_{T2}^{150}	WWa	WWb	WWc	Zjets
$M_{\ell\ell}$				< 120	< 170		
$p_T(\ell\ell)$				> 80			> 80
$E_T^{miss,rel}$				> 80			> 80
m_{T2}	> 90	> 120	> 150		> 90	> 100	

best for
these results

8 TeV Analysis Cuts

https://checkmate.hepforge.org/AnalysesList/ATLAS_8TeV.html

- 8 TeV ATLAS SUSY analysis [arXiv:1403.5294](https://arxiv.org/abs/1403.5294)

cutflows for dilepton+MET finals states,
implemented in CheckMATE:

https://checkmate.hepforge.org/validationNotes/atlas_1403_5294.pdf

- 8 TeV ATLAS Z+Higgs->invisible analysis [arXiv:1402.3244](https://arxiv.org/abs/1402.3244) cutflows for dilepton+MET finals states, implemented in CheckMATE:
https://checkmate.hepforge.org/validationNotes/atlas_higg_2013_03.pdf
- Validated against MadAnalysis (Belanger et.al paper [arXiv:1503.07367](https://arxiv.org/abs/1503.07367))

Global Cut	
E_T^{miss}	> 0 GeV
Base leptons	2
$e + e^-$ trigger	97%
$\mu^+ \mu^-$ trigger	89%
$e\mu$ trigger	75%
Signal leptons	2
Leading lepton p_T	> 35 GeV
sub-leading lepton p_T	> 20 GeV
$M_{\ell\ell}$	> 20 GeV
jets	0
$ M_{\ell\ell} - M_Z $	> 10 GeV

SR	m_{T2}^{90}	m_{T2}^{120}	m_{T2}^{150}	WWa	WWb	WWc	Zjets
$M_{\ell\ell}$				< 120	< 170		
$p_T(\ell\ell)$				> 80			> 80
$E_T^{miss,rel}$				> 80			> 80
m_{T2}	> 90	> 120	> 150		> 90	> 100	

best for
these results

Global Cut	
Base leptons	2
Lepton p_T	> 20 GeV
Z-window	$76 < M_{\ell\ell} < 106$ GeV
E_T^{miss}	> 90 GeV
$d\phi(E_T^{miss}, p_T^{miss})$	< 0.2
$\Delta\phi(p_T(\ell\ell), E_T^{miss})$	> 2.6
$\Delta\phi(\ell, \ell)$	< 1.7
$ \frac{E_T^{miss} - p_T(\ell\ell)}{p_T(\ell\ell)} $	> 0.2
jets	0

CheckMATE 8 TeV Sample Validation Tables

https://checkmate.hepforge.org/AnalysesList/ATLAS_8TeV.html

Cut	Acc	Weighted	Change	MadAnalysis	Change	Official	Change
01 Initial	1	3375.0		3375			
02 2 OS leptons	0.16405	553.7	84%	545.8	84%		
03 $m_{ll} > 20$ GeV	0.16119	544.0	2%	537.8	1%		
04 tau veto	0.16100	544.0	0%	537.8	0%		
05 ee leptons	0.03680	124.2	77%	132.4	75%	139.6	
06 ee jet veto	0.02018	68.1	45%	79.2	40%	65.7	53%
07 ee Z veto	0.01690	57.0	16%	67.3	15%	55.5	16%
08 ee WWb $m_{T2;90}$ GeV	0.00136	4.6	92%	5.3	92%	4.5	92%
09 ee WWb $m_{ll} < 170$ GeV	0.00115	3.9	15%	4.3	19%	3.9	13%

Table 4: $\chi + \chi^-$ (140/20), Wwbee

Cut	Acc	Weighted	Change	MadAnalysis	Change	Official	Change
01 Initial	1	3375.0		3375			
02 2 OS leptons	0.16405	553.7	84%	545.8	84%		
03 $m_{ll} > 20$ GeV	0.16119	544.0	2%	537.8	1%		
04 tau veto	0.16100	544.0	0%	537.8	0%		
05 emu leptons	0.07158	241.6	56%	239.9	55%	253.8	
06 emu jet veto	0.03899	131.6	46%	142.6	41%	118.6	53%
08 emu WWb $m_{T2;90}$ GeV	0.00273	9.2	93%	10.5	93%	8	93%
09 emu WWb $m_{ll} < 170$ GeV	0.00245	8.3	10%	9.3	11%	7.2	10%

Table 5: $\chi + \chi^-$ (140/20), Wwbemu

Cut	Acc	Weighted	Change	MadAnalysis	Change	Official	Change
01 Initial	1	3375.0		3375			
02 2 OS leptons	0.16405	553.7	84%	545.8	84%		
03 $m_{ll} > 20$ GeV	0.16119	544.0	2%	537.8	1%		
04 tau veto	0.16100	544.0	0%	537.8	0%		
05 mumu leptons	0.05281	178.2	67%	165.5	69%	168.7	
06 mumu jet veto	0.02877	97.1	46%	100.7	39%	78.2	54%
07 mumu Z veto	0.02408	81.3	16%	84.2	16%	65.5	16%
08 mumu WWb $m_{T2;90}$ GeV	0.00182	6.2	92%	6.8	92%	5.2	92%
09 mumu WWb $m_{ll} < 170$ GeV	0.00169	5.7	7%	6.2	9%	4.5	13%

Table 6: $\chi + \chi^-$ (140/20), Wwbmumu

CheckMATE 8 TeV Sample Validation Tables

https://checkmate.hepforge.org/AnalysesList/ATLAS_8TeV.html

Cut	Acc	Weighted	Change	MadAnalysis	Change	Official	Change
01 Initial	1	835.5		835.5			
02 2 OS leptons	0.19479	162.7	81%	155.4	81%		
03 $m_{\ell\ell} > 20$ GeV	0.19232	160.7	1%	153.3	1%		
04 tau veto	0.19232	160.7	0%	153.3	0%		
05 ee leptons	0.04540	38.0	76%	39	75%	40.9	
06 ee jet veto	0.02291	19.1	50%	22.8	42%	17.5	57%
07 ee Z veto	0.02005	16.8	12%	19.9	13%	15.5	11%
08 ee WWc $m_{T2_i} > 100$ GeV	0.00302	2.5	85%	3.1	84%	2.4	85%

Table 7: $\chi + \chi - (200/0)$, Wwcee

Cut	Acc	Weighted	Change	MadAnalysis	Change	Official	Change
01 Initial	1	835.5		835.5			
02 2 OS leptons	0.19479	162.7	81%	155.4	81%		
03 $m_{\ell\ell} > 20$	0.19232	160.7	1%	153.3	1%		
04 tau veto	0.19232	160.7	0%	153.3	0%		
05 emu leptons	0.08430	70.4	56%	67.6	56%	71.1	
06 emu jet veto	0.04308	36.0	49%	39.9	41%	30.8	57%
08 emu WWc $m_{T2_i} > 100$ GeV	0.00612	5.1	86%	6.7	83%	4.6	85%

Table 8: $\chi + \chi - (200/0)$, Wwcemu

Cut	Acc	Weighted	Change	MadAnalysis	Change	Official	Change
01 Initial	1	835.5		835.5			
02 2 OS leptons	0.19479	162.7	81%	155.4	81%		
03 $m_{\ell\ell} > 20$ GeV	0.19232	160.7	1%	153.3	1%		
04 tau veto	0.19232	160.7	0%	153.3	0%		
05 mumu leptons	0.06259	52.3	67%	46.7	70%	46.3	
06 mumu jet veto	0.03230	27.0	48%	26.9	42%	20.7	55%
07 mumu Z veto	0.02764	23.1	14%	23.4	13%	18	13%
08 mumu WWc $m_{T2_i} > 100$ GeV	0.00416	3.5	85%	3.7	84%	2.8	84%

Table 9: $\chi + \chi - (200/0)$, Wwcmumu

CheckMATE 8 TeV Sample Validation Tables

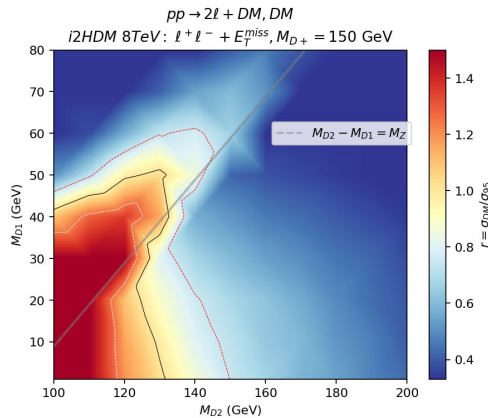
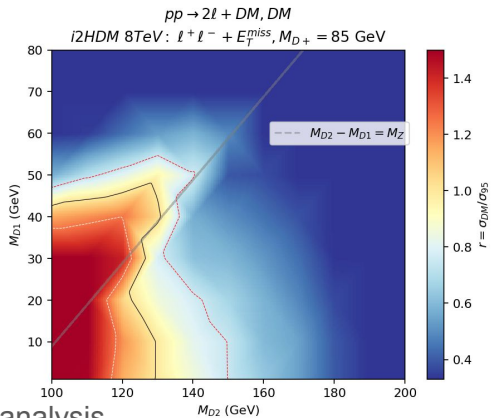
https://checkmate.hepforge.org/AnalysesList/ATLAS_8TeV.html

Cut	Acc	Weighted	Change	MadAnalysis	Change	Official	Change
01 Initial	1.00	838.9		838.9			
02 OS leptons	0.40	336.1	60%	256.2	69%		
03 Zwindow	0.38	317.7	5%	244.1	5%	243	
04 MET > 90	0.15	122.8	61%	105.1	57%	103	58%
05 dilepton-MET separation	0.12	104.3	15%	91.7	13%		
06 lepton-lepton separation	0.10	86.4	17%	82.9	10%		
07 pT _{miss} -MET separation	0.10	81.5	6%	76.5	8%		
08 pT _{ll} -MET similarity	0.07	60.4	26%	63.2	17%		
09 jetveto	0.06	51.1	15%	54.8	13%	44 ± 1 ± 3	

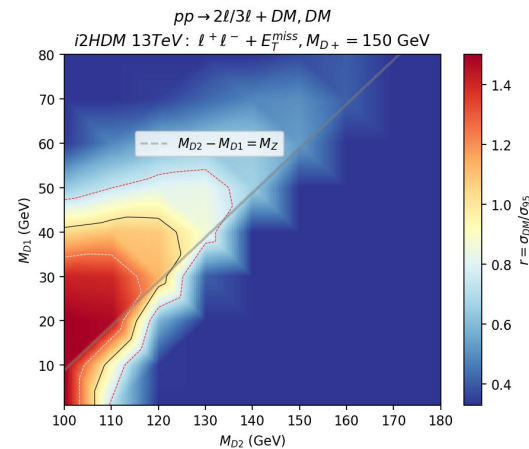
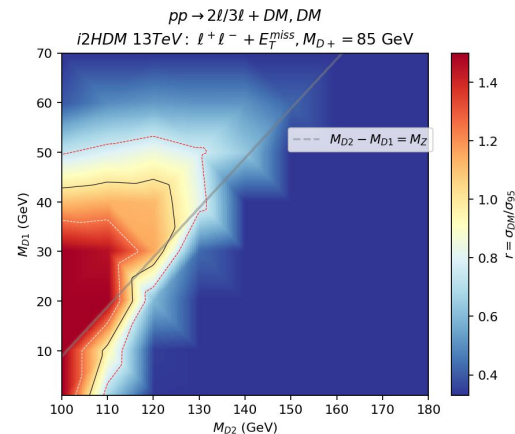
Table 1: Cutflow table for benchmark point of the process $HZ \rightarrow \nu\nu\nu\ell\ell$, for $M_H = 125.5$ GeV

I2HDM Validations

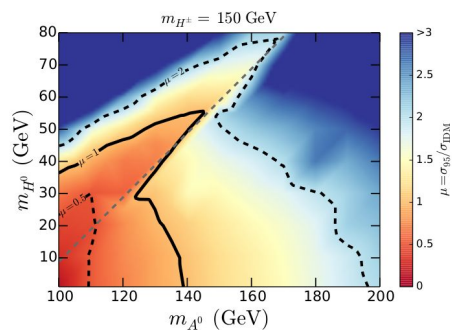
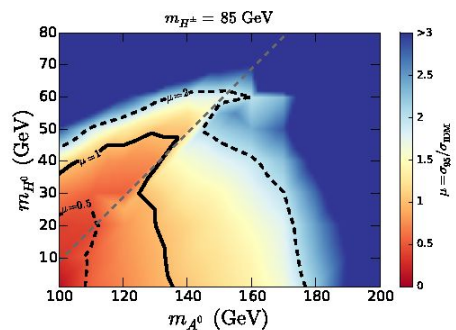
8 TeV



13 TeV



Our analysis



Our analysis

Bélanger, et al. "Dilepton Constraints in the Inert Doublet Model from Run 1 of the LHC."

Physical Review D 91.11 (2015) [arXiv:1503.07367]