Exploring Multilepton Signatures From Dark Matter at the LHC

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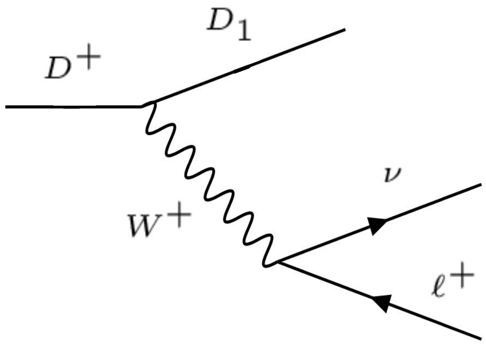
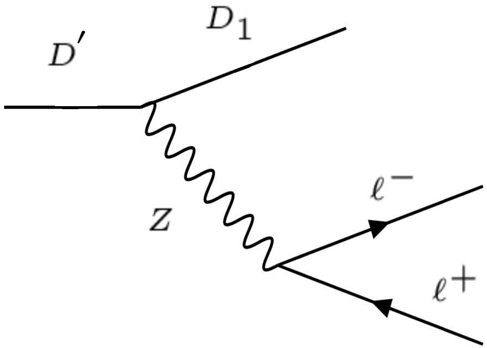
NExT

Outline

- Beyond mono-X searches ⟶ 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

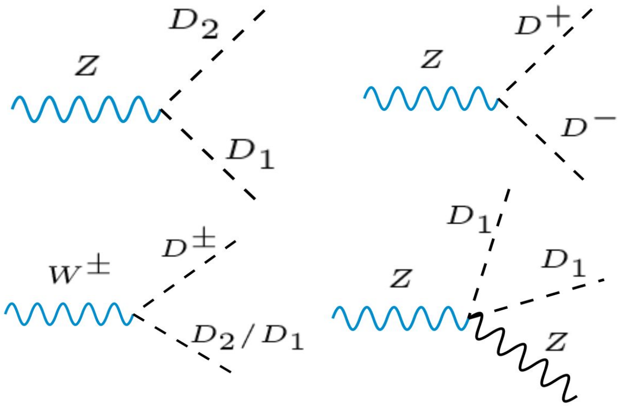




Inert 2 Higgs Doublet Model (I2HDM)

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

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



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

Minimal Fermion Dark Matter (MFDM)

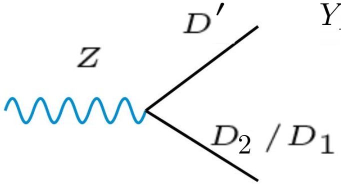
$$\mathcal{L}_{FDM} = \mathcal{L}_{SM} + \bar{\psi}(i\not{D} - m_\psi)\psi + \frac{1}{2}\bar{\chi}_s^0(i\not{\partial} - m_s)\chi_s^0 - (Y_{DM}(\bar{\psi}\Phi\chi_s^0) + h.c.)$$

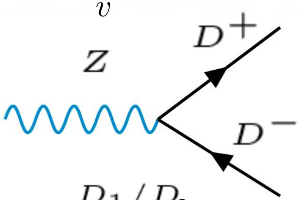
$$\psi = \begin{pmatrix} \chi^+ \\ \frac{1}{\sqrt{2}}(\chi_1^0 + i\chi_2^0) \end{pmatrix}$$

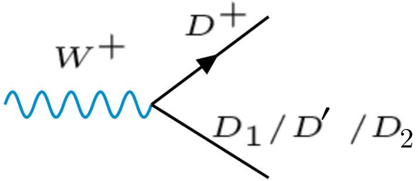
Majorana singlet χ_s^0

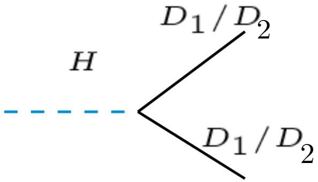
Split to Majorana fermions

$$Y_{DM} = \frac{\sqrt{(m_{D_2} - m_{D+})(m_{D+} - m_{D1})}}{v}$$









$$[m_{D1}, m_{D'} = m_{D+}, m_{D_2}] \rightarrow [m_{D1}, \Delta m^+, \Delta m^0]$$

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

$$r = \frac{\sigma_{DM}}{\sigma_{95}}$$

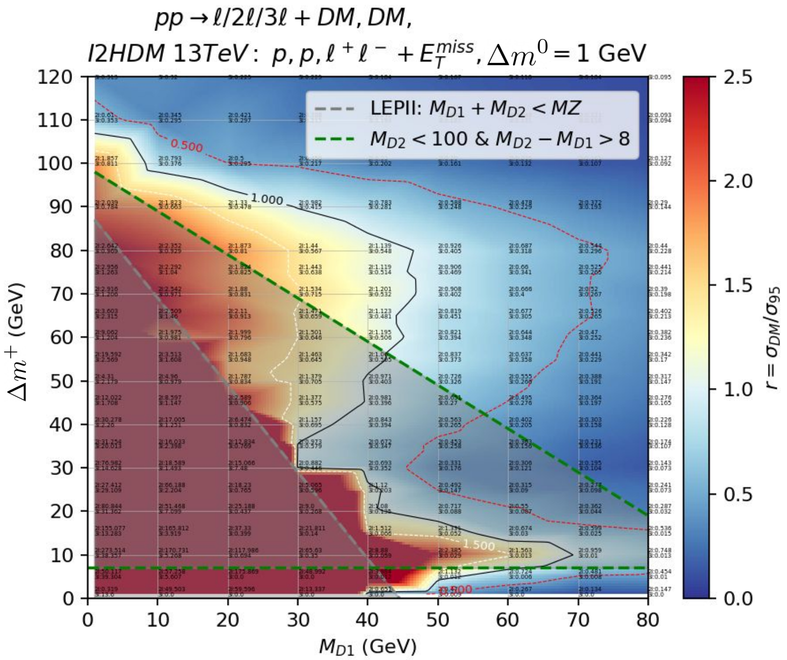
σ_{DM} — Cross-section of DM events produced

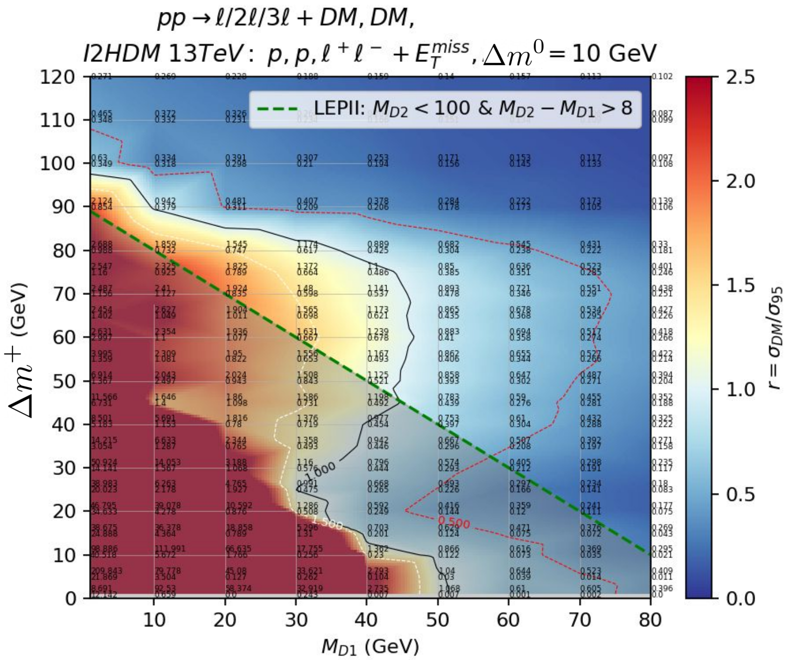
σ_{95} — Cross-section required to exclude point at 95% confidence level

- Point excluded if $r \geq 1$

New I2HDM Results

$$\Delta m^0 = m_{D2} - m_{D+}$$
$$\Delta m^+ = m_{D+} - m_{D1}$$





- Δm^0 = 1 GeV: Small wedge above $m_{D1} > 50$ GeV and below $\Delta m^+ < 8$ 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

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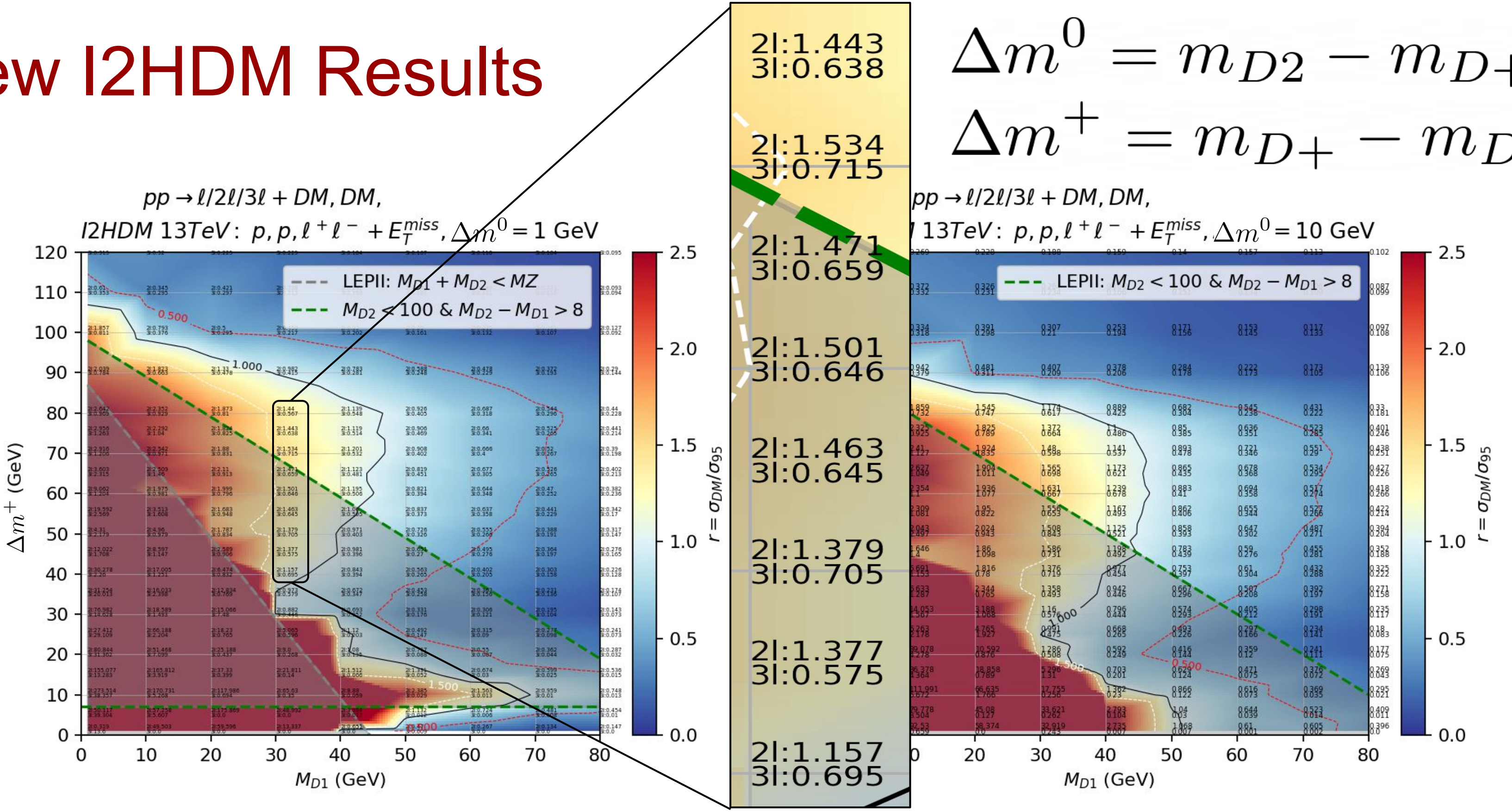

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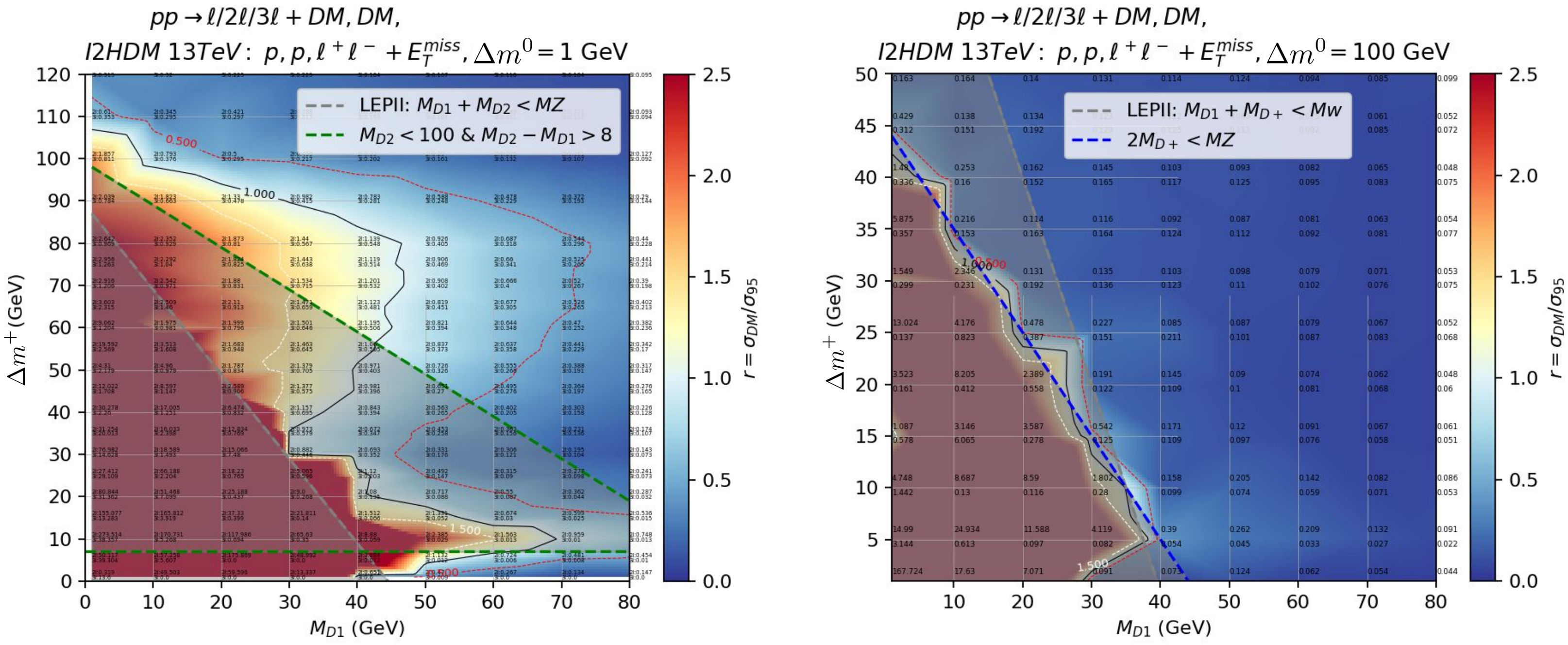
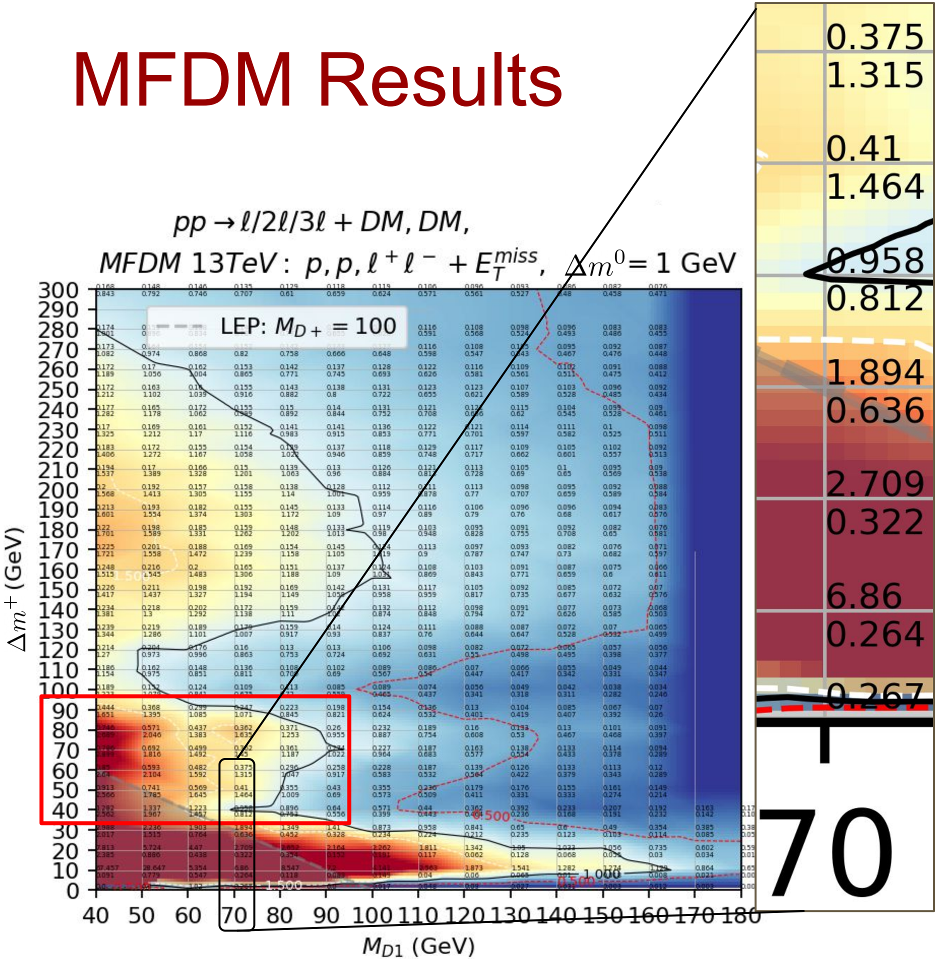
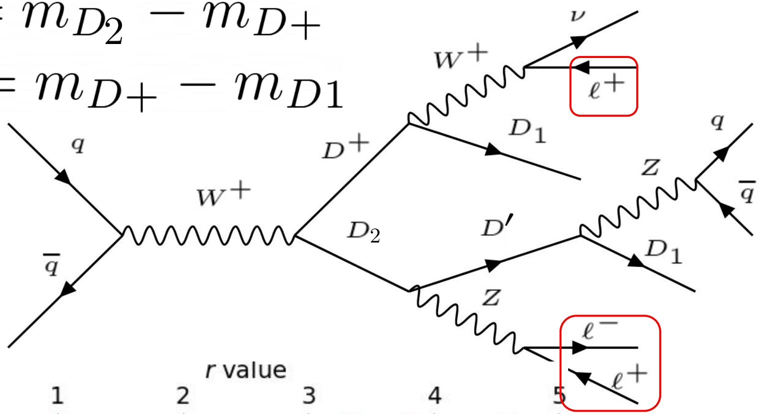


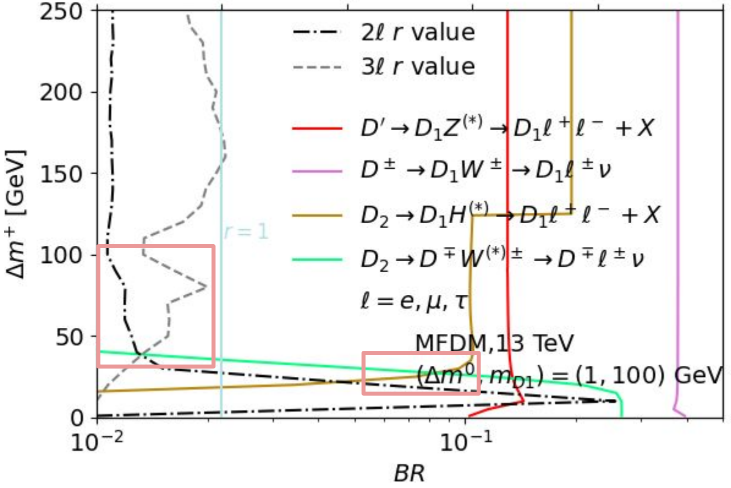
- Increasing Δm^0 to 100 GeV means the Z veto $m_{\ell\ell}$ > 100 GeV requirement by the analysis cut-flow can no longer be fulfilled as production cross-section of the heavier states has fallen

MFDM Results



$$\Delta m^0 = m_{D_2} - m_{D+}$$
$$\Delta m^+ = m_{D+} - m_{D1}$$

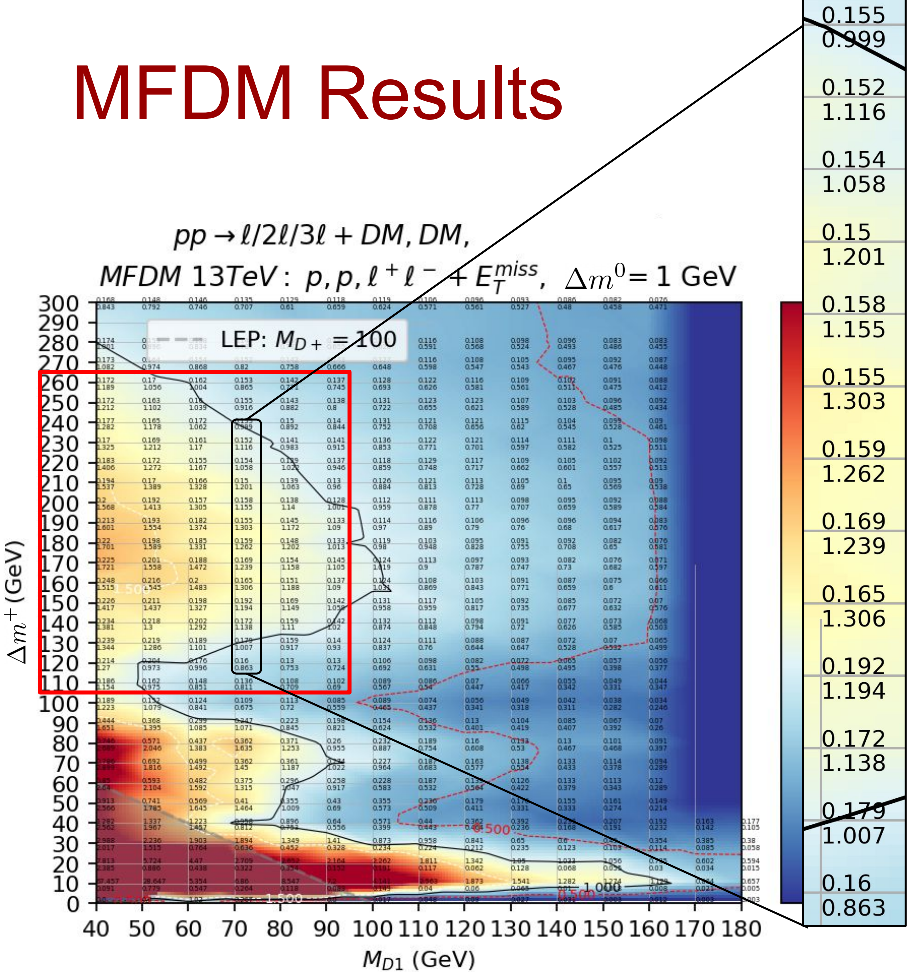


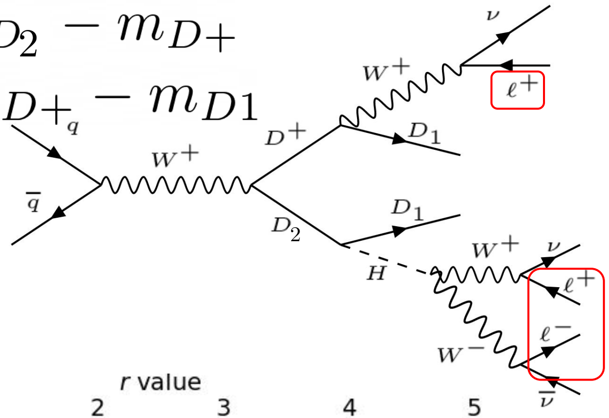


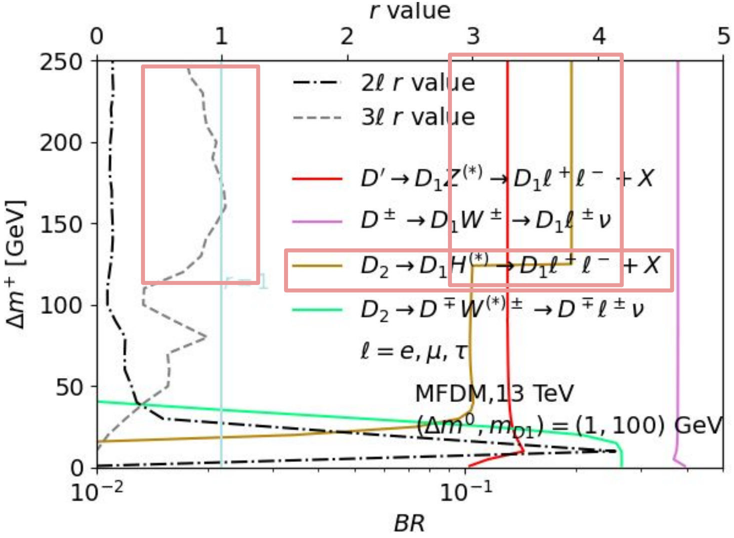
- Similar shapes to I2HDM, but 3-lepton channel sensitivity begins to dominate due to crossing between $D_2 \to \ell\nu D_1$ to $D_2 \to Z(\to \ell\ell)D'$ with production of $D^\pm(\to \ell\nu)D_2$, at $\Delta m^+ = 45$ GeV

MFDM Results

$$\Delta m^0 = m_{D_2} - m_{D+}$$
$$\Delta m^+ = m_{D+} - m_{D1}$$





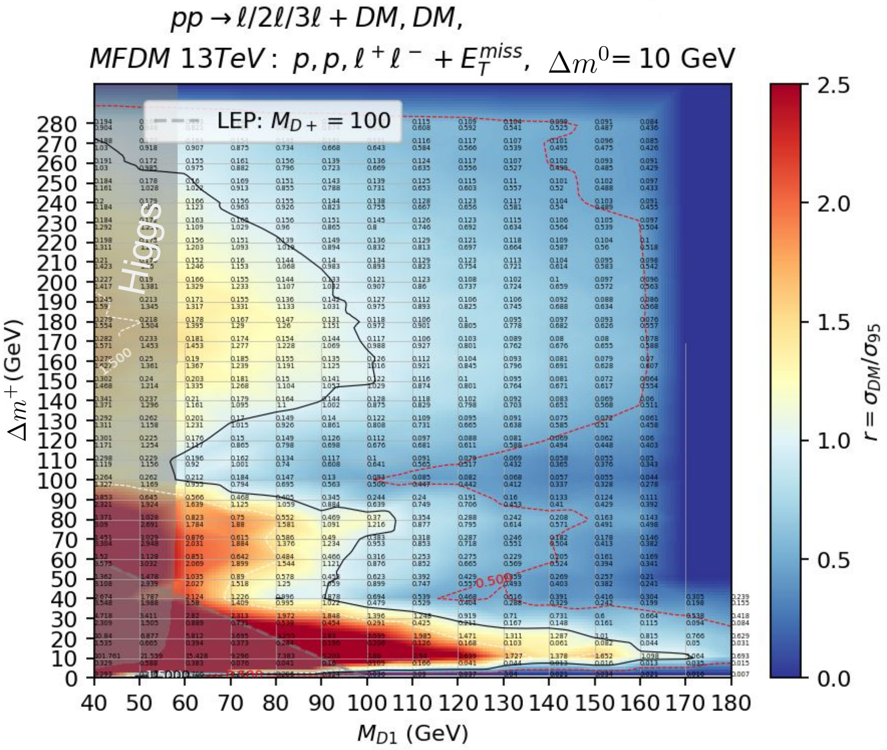


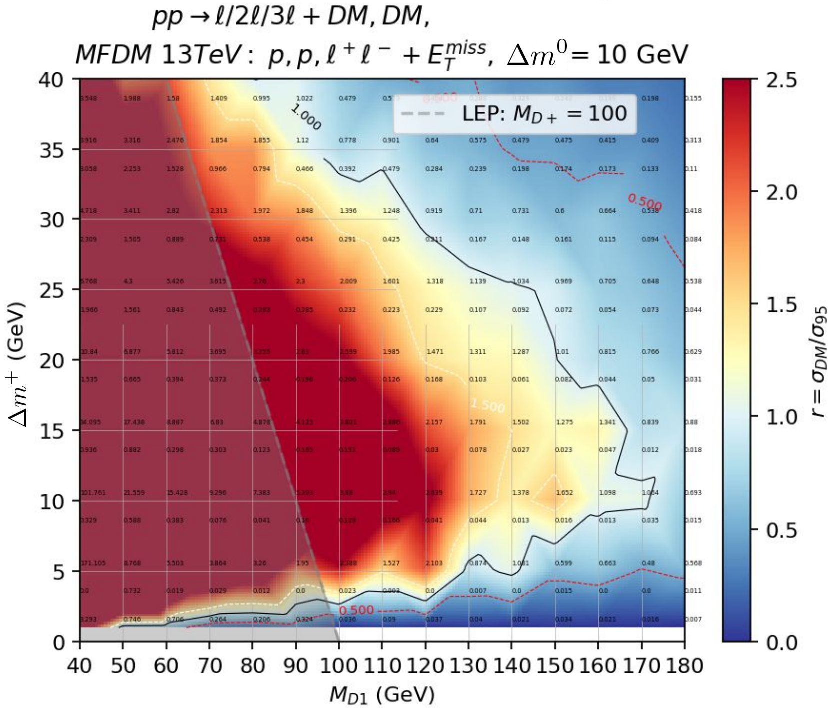
- Second shape due to 3-lepton channel sensitivity due to Higgs decay $D_2 \to H^*(\to \tau^+\tau^-)D_1$

$D_2 \to H(\to W^+W^-)D_1$ with production of $D^\pm(\to \ell\nu)D_2$, at $\Delta m^+ = 125$ GeV

MFDM Results

$$\Delta m^0 = m_{D_2} - m_{D+}$$
$$\Delta m^+ = m_{D+} - m_{D1}$$

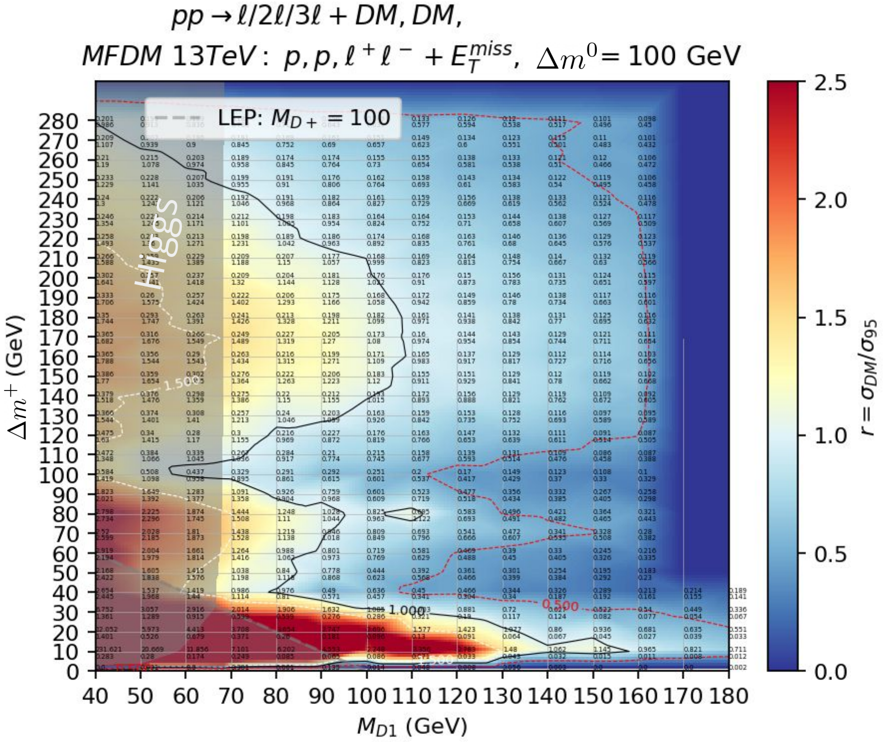


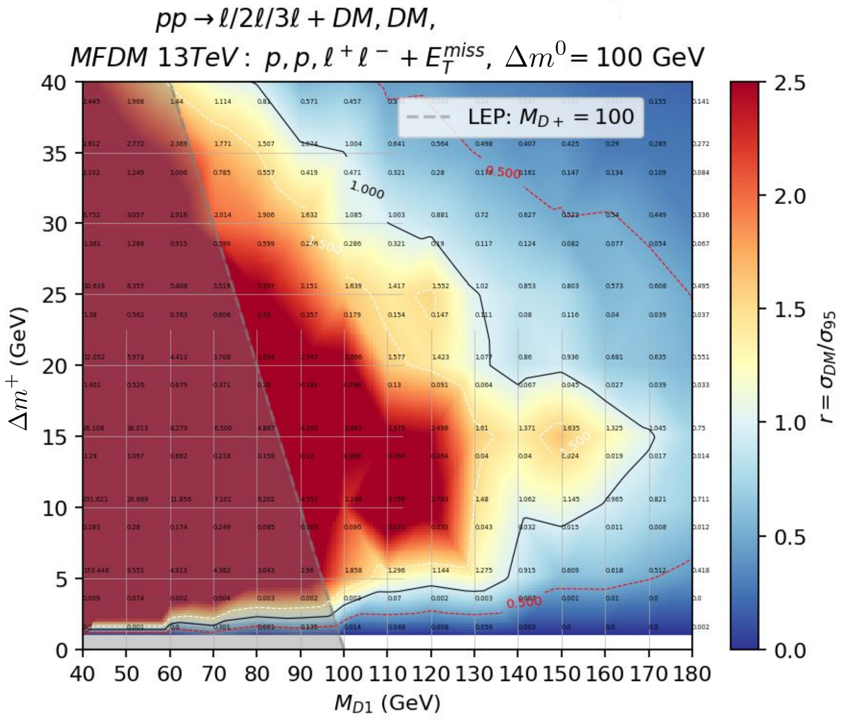


- As Δm^0 increases, coupling between $D_1 - D^{\pm}$ increases, while heavy D_2 leads to suppressed production cross-section - 'no-lose' theorem

MFDM Results

$$\Delta m^0 = m_{D_2} - m_{D+}$$
$$\Delta m^+ = m_{D+} - m_{D1}$$

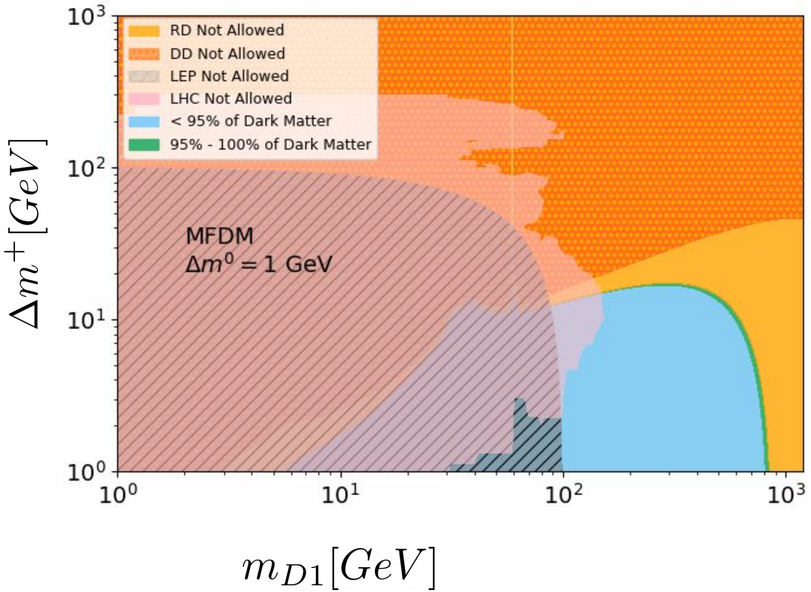




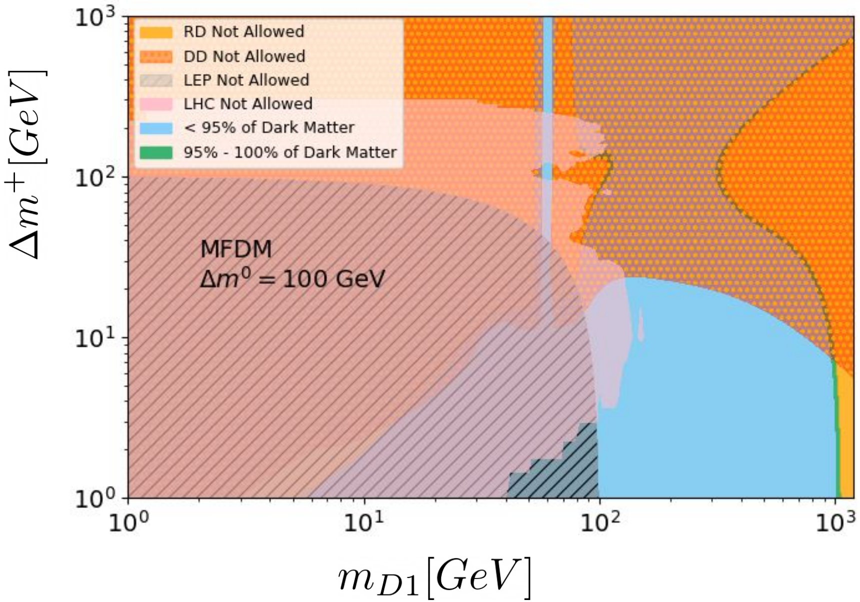
- With increasing Δm^0, Higgs to invisible limit covers larger m_{D1} upto $m_{D1} = m_H/2$

Combined Limits: MFDM

$\Delta m^0 = 1\ GeV$

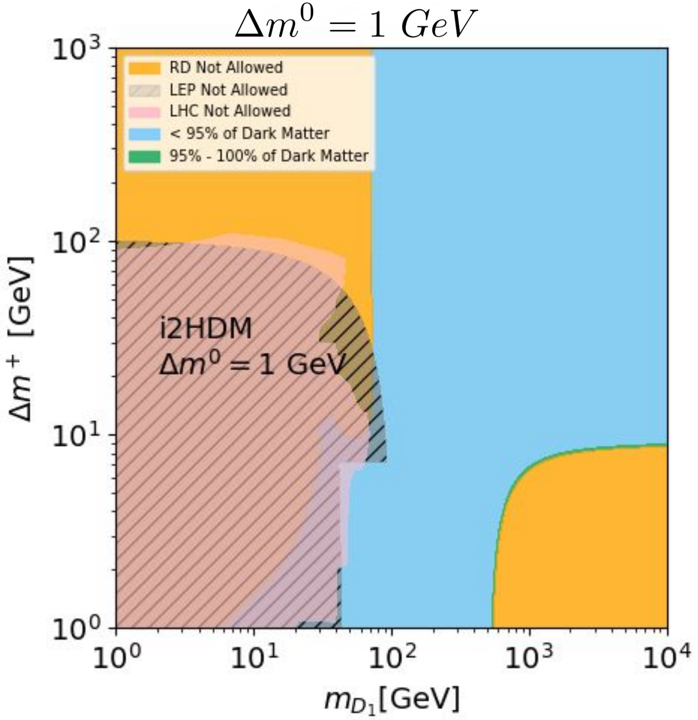


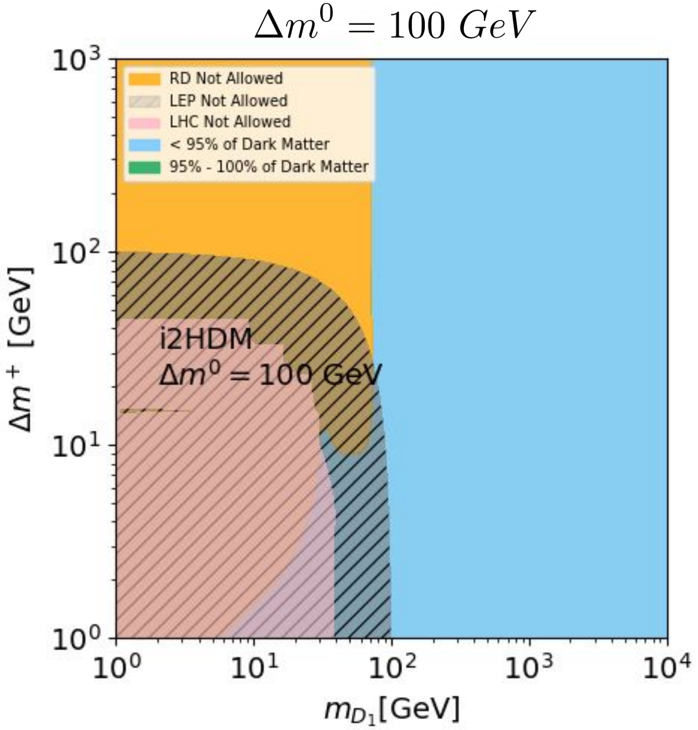
$\Delta m^0 = 100\ GeV$



- Under abundance of relic density in light blue region, is ‘just right’ in green line
- As Δm^+ increases, co-annihilation between the $D_1 D^{\pm}$ is suppressed, due to the greater mass difference; so the relic density becomes too large
- Significant new contributions from LHC limit (pink region)

Combined Limits: i2HDM





- New LHC limits provide constraints to $\Delta m^0 = 1$ GeV region
- No Direct detection (DD), due to Higgs-funnel assumption

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 (~SUSY Higgsino) via Higgs decays** $D_2 \to H(\to W^+W^-)D_1$
4. **Provide limits and efficiencies for re-interpretation of any scalar of 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:	$pp \to D^+D^-$ $pp \to D_2D_1$	$pp \to D^{\pm}D_2$	$pp \to ZD_1D_1$
Decays:	$D^{\pm} \to (W^{\pm} \to \ell^{\pm}\nu)D_1$ $D_2 \to (Z \to \ell^+\ell^-)D_1$	$D_2 \to (Z \to \ell^+\ell^-)D_1$	$Z \to \ell^+\ell^-$

- While the genuine 2-2 process $pp \to D_2D_1$ is separate to 3-body decay $pp \to ZD_1D_1$, 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:	$pp \to D^+D^-$ $pp \to D'D_1$	$pp \to D'D_2$	$pp \to D^{\pm}D'$ $pp \to D^{\pm}D_2$
Decays:	$D^{\pm} \to (W^{\pm} \to \ell^{\pm}\nu)D_1$ $D' \to (Z \to \ell^+\ell^-)D_1$	Any	$D' \to (Z \to \ell^+\ell^-)D_1$ $D_2 \to (W^{\pm} \to \ell^{\pm}\nu)D^{\pm}$ $D_2 \to (Z \to \ell^+\ell^-)D'$

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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Re-interpretation: Providing Cross-section Limits

Cross-section limit (95% cl) for 3 lepton channel of sample A,B,C

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Re-interpretation: Providing Cross-section Limits

$$\frac{100}{\sqrt{\text{Number of Monte Carlo events survived}}}\%$$

- 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)	$\frac{100}{\sqrt{N_{MC}}}$
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

8 TeV Analysis Cuts

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

- 8 TeV ATLAS SUSY analysis arXiv:1403.5294 cutflows for dilepton+MET finals states, implemented in CheckMATE: 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
$\lvert M_{\ell\ell} - M_Z \rvert$	> 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 (WWb, WWc)

8 TeV Analysis Cuts

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

- 8 TeV ATLAS SUSY analysis arXiv:1403.5294 cutflows for dilepton+MET finals states, implemented in CheckMATE: https://checkmate.hepforge.org/validationNotes/atlas_1403_5294.pdf

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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 ATLAS Z+Higgs->invisible analysis arXiv:1402.3244 cutflows for dilepton+MET finals states, implemented in CheckMATE: https://checkmate.hepforge.org/validationNotes/atlas_higg_2013_03.pdf

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
$\lvert \frac{E_T^{miss} - p_T(\ell\ell)}{p_T(\ell\ell)} \rvert$	> 0.2
jets	0

- Validated against MadAnalysis (Belanger et.al paper arXiv:1503.07367)

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 $m\ell\ell > 20$ 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 mT2¿90 GeV	0.00136	4.6	92%	5.3	92%	4.5	92%
09 ee WWb $m\ell\ell < 170$ 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 $m\ell\ell > 20$ 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 mT2¿90 GeV	0.00273	9.2	93%	10.5	93%	8	93%
09 emu WWb $m\ell\ell < 170$ 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 $m\ell\ell > 20$ 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 mT2¿90 GeV	0.00182	6.2	92%	6.8	92%	5.2	92%
09 mumu WWb $m\ell\ell < 170$ 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 mT2¿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 mT2¿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 mT2¿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

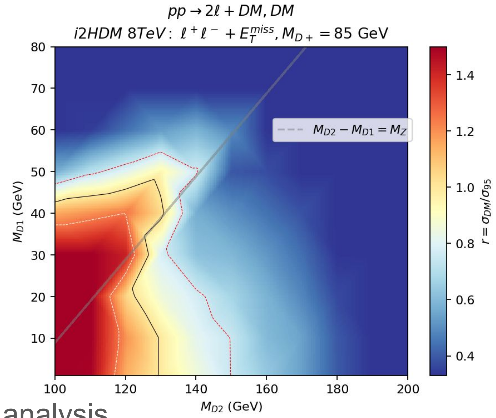
https://checkmate.hepforge.org/AnalysesList/ATLAS_8TeV.html

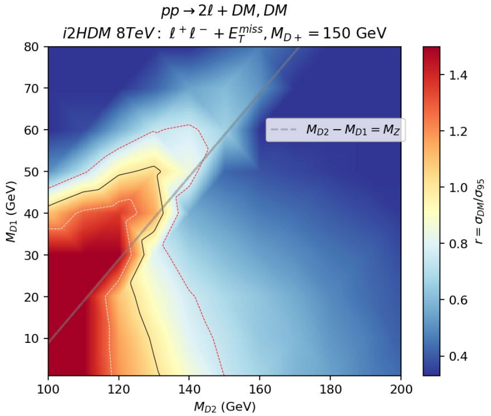
Cut	Acc	Weighted	Change	MadAnalysis	Change	Official	Change
01 Initial	1.00	838.9		838.9			
02 OS leptons	0.40	336.1	60%	256.2	69%		
03 Zwindow	0.38	317.7	5%	244.1	5%	243	
04 MET> 90	0.15	122.8	61%	105.1	57%	103	58%
05 dilepton-MET separation	0.12	104.3	15%	91.7	13%		
06 lepton-lepton separation	0.10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

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

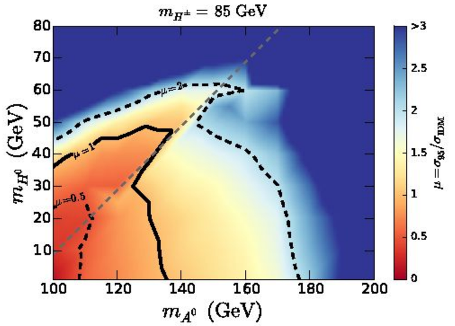
I2HDM Validations

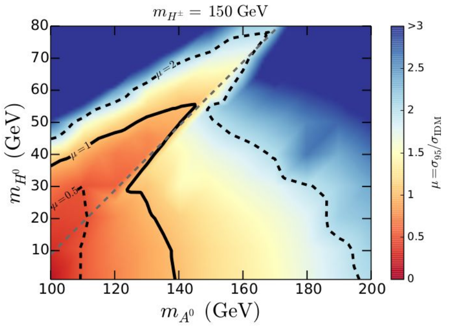
8 TeV





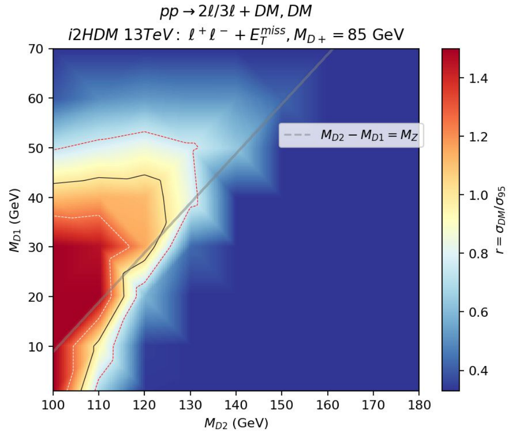
Our analysis

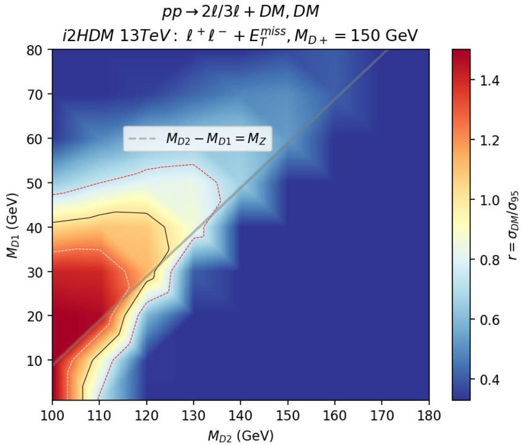




Bélanger, et al. “Dilepton Constraints in the Inert Doublet Model from Run 1 of the LHC.” Physical Review D 91.11 (2015) [arXiv:1503.07367]

13 TeV





Our analysis