Exploring Multilepton Signatures From Dark Matter at the LHC

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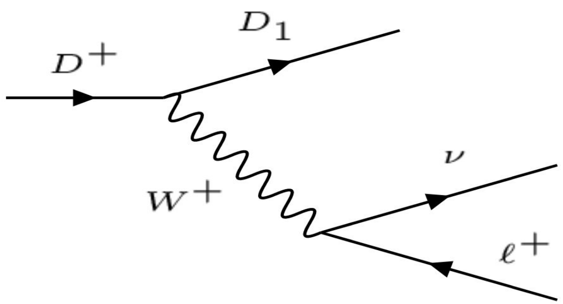
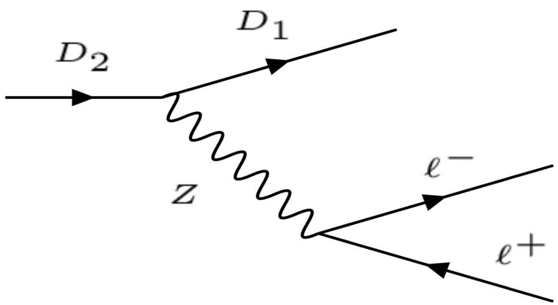
19/02/21

Outline

- Motivations for beyond mono-X searches, e.g. multilepton+missing ET
- Two representative examples of Minimal consistent Dark Matter Models (MCDM)
- Multilepton+missing ET is complementary to LLP signature from weak multiplet DM
- We validate our own analysis code against previous analyses
- New limits for I2HDM and MFDM and suggestion for a better parameterisation
- The map of 2&3 lepton channel cross-section limits and efficiencies using CheckMATE for a wider DM re-interpretation analysis for our community





Inert 2 Higgs Doublet Model (I2HDM)

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

$$V = -m_1^2(\phi_1^\dagger \phi_1) - m_2^2(\phi_2^\dagger \phi_2) + \lambda_1(\phi_1^\dagger \phi_1)^2 + \lambda_2(\phi_2^\dagger \phi_2)^2 + \lambda_3(\phi_1^\dagger \phi_1)(\phi_2^\dagger \phi_2) + \lambda_4(\phi_2^\dagger \phi_1)(\phi_1^\dagger \phi_2) + \frac{\lambda_5}{2}[(\phi_1^\dagger \phi_2)^2 + (\phi_2^\dagger \phi_1)^2]$$

$$M_H^2 = 2\lambda_1 v^2 = 2m_1^2 \qquad M_{D+}^2 = \frac{1}{2}\lambda_3 v^2 - m_2^2$$

$$M_{D_1}^2 = \frac{1}{2}(\lambda_3 + \lambda_4 - |\lambda_5|)v^2 - m_2^2 \qquad M_{D_2}^2 = \frac{1}{2}(\lambda_3 + \lambda_4 + |\lambda_5|)v^2 - m_2^2 > M_{D_1}^2$$

1. λ_2 is quartic inert doublet self-coupling **2.** $\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5$ is Higgs-DM coupling: HD_1D_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: $[M_{D_1}, M_{D_2}, M_{D_+}, \lambda_2, \lambda_{345}] \rightarrow [M_{D_1}, M_{D_2}, M_{D_+}]$

Parameterisations which are more physical for our analysis: $\Delta M_{D2} = M_{D2} - M_{D+}$

$[M_{D1}, \Delta M_{DP}, \Delta M_{D2}]$ $\qquad \Delta M_{DP} = M_{D+} - M_{D1}$

Minimal Fermion Dark Matter (MFDM)

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

- Minimal model with an EW fermion DM doublet
- To provide 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

$$Y_{DM} = \frac{\sqrt{(M_{D3} - M_{DP})(M_{DP} - M_{D1})}}{v}$$

1. M_{D1} is DM mass 2. $M_{DP} = M_{D2}$ is chargino mass 3. M_{D3} is third lightest, neutralino mass

$$M_{D3} > M_{DP} = M_{D2} > M_{D1}$$

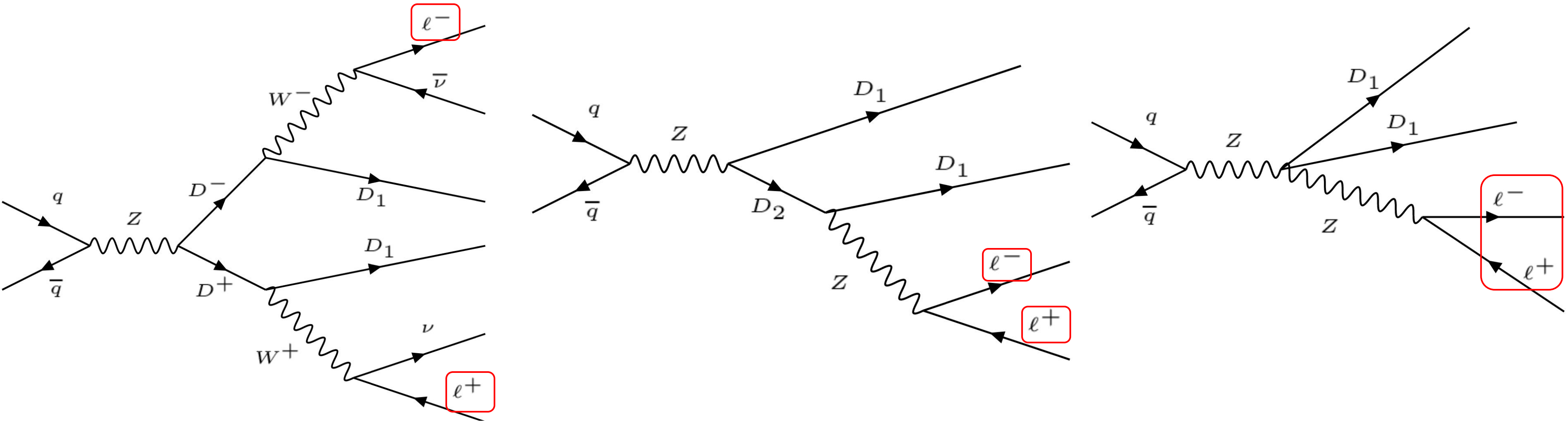
Parameterisations which are more physical for our analysis:

$$[M_{D1}, \Delta M_{DP}, \Delta M_{D3}]$$

$$\Delta M_{D3} = M_{D3} - M_{DP}$$
$$\Delta M_{DP} = M_{DP} - M_{D1}$$

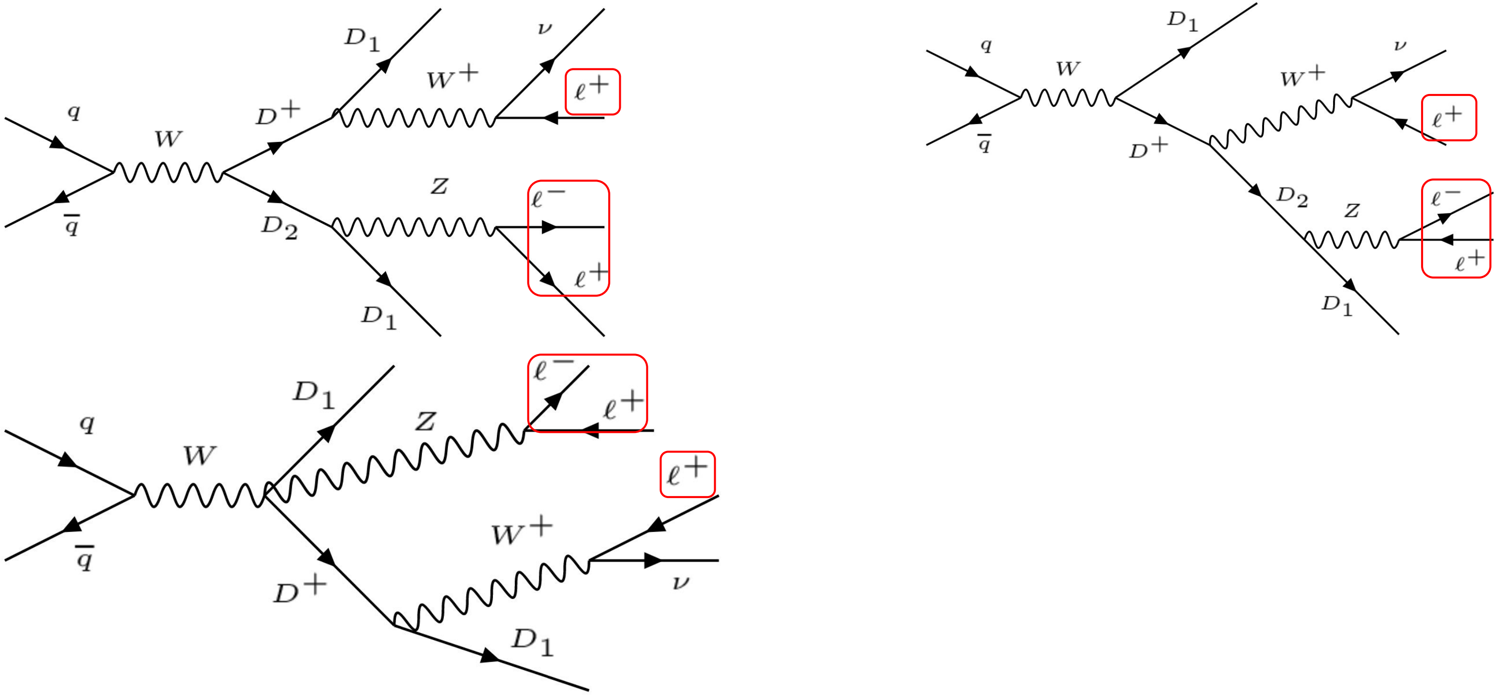
$$Y_{DM} = \frac{\sqrt{\Delta M_{D3}\Delta M_{DP}}}{v}$$

2ℓ + E_T^{miss} I2HDM Final States



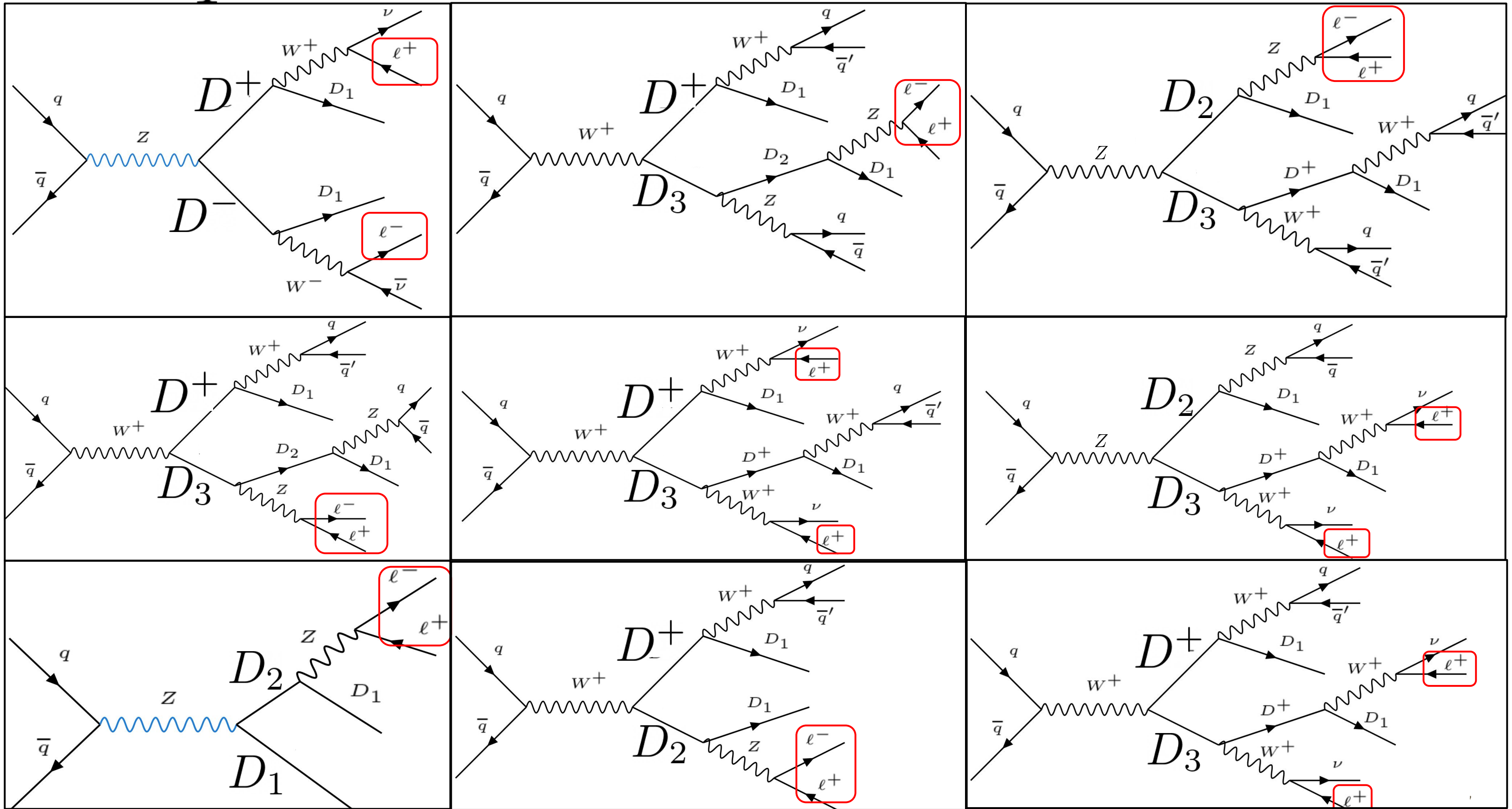
- DM decays via Z production
- Looking at Higgs funnel: λ_{345} ~ 0, and λ_2 not relevant

3ℓ + E_T^{miss} I2HDM Final States



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

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



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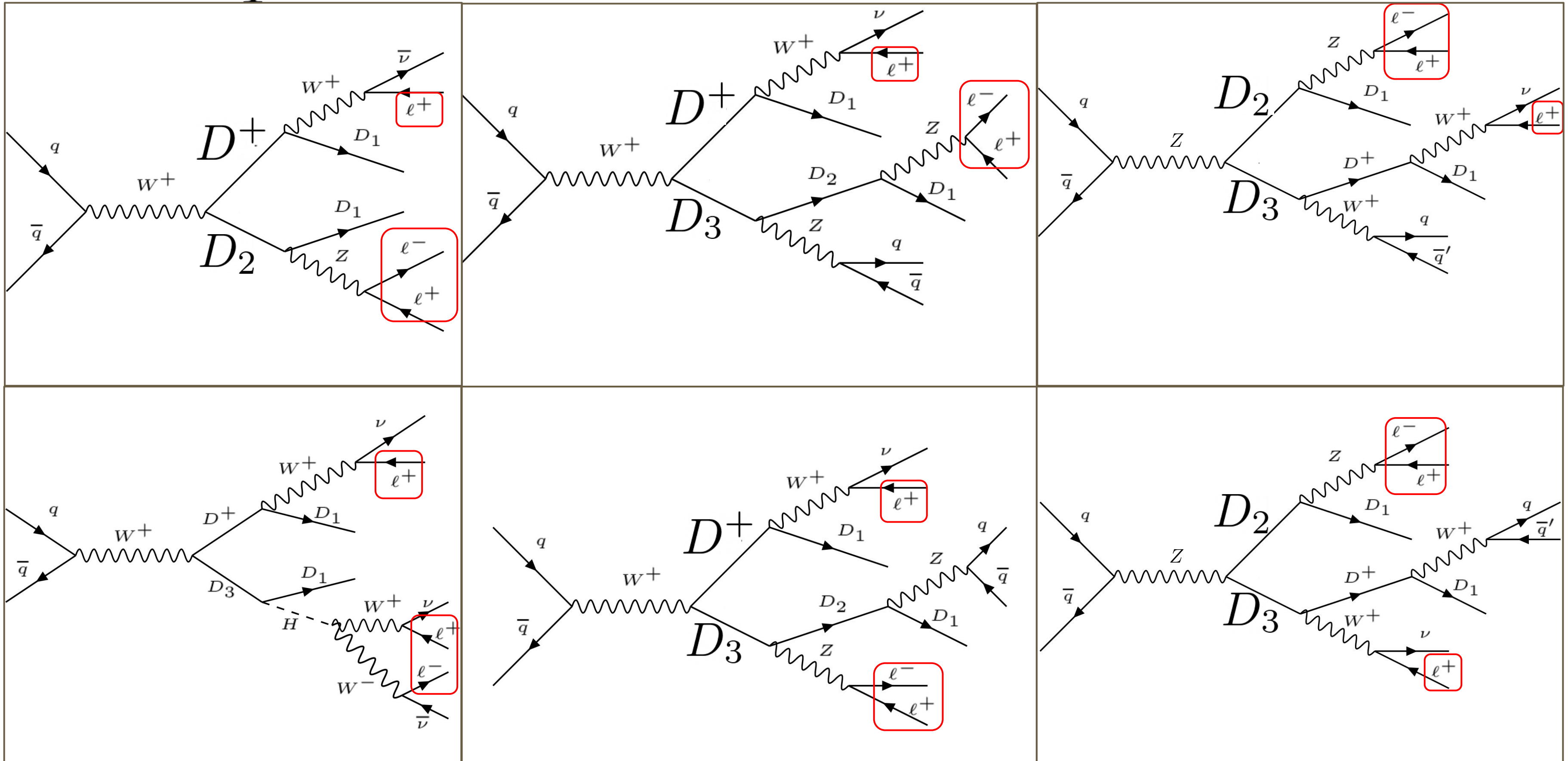


HEP Tools

- 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

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

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

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

- Point excluded if $\mu \geq 1$

8 TeV Analysis Cuts

- 8 TeV ATLAS SUSY analysis arXiv:1403.5294 cutflows for dilepon+MET finals states, implemented in CheckMATE

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

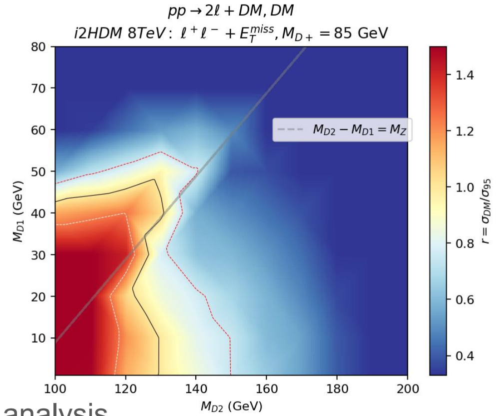
- 8 TeV ATLAS Higgs analysis arXiv:1402.3244 cutflows for dilepon+MET finals states, implemented in CheckMATE

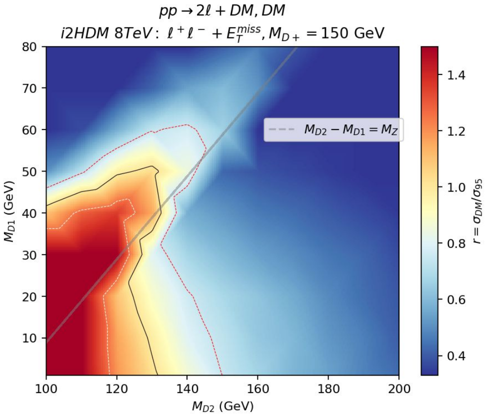
Global Cut	
Base leptons	2
Lepton p_T	> 20 GeV
Z-window	$76 < M_{\ell\ell} < 106$ GeV
E_T^{miss}	> 90 GeV
$d\phi(E_T^{miss}, p_T^{miss})$	< 0.2
$\Delta\phi(p_T(\ell\ell), E_T^{miss})$	> 2.6
$\Delta\phi(\ell,\ell)$	< 1.7
$\left\|\frac{E_T^{miss} - p_T(\ell\ell)}{p_T(\ell\ell)}\right\|$	> 0.2
jets	0

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

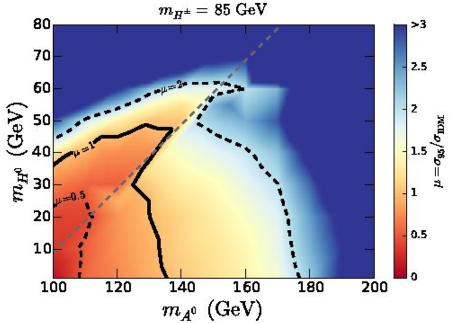
I2HDM Validations

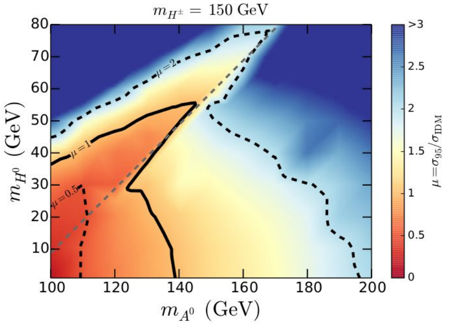
8 TeV





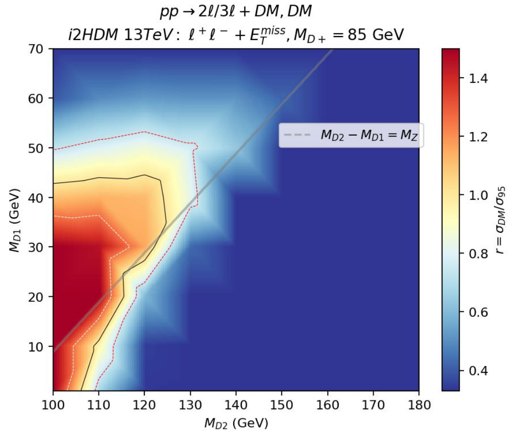
Our analysis

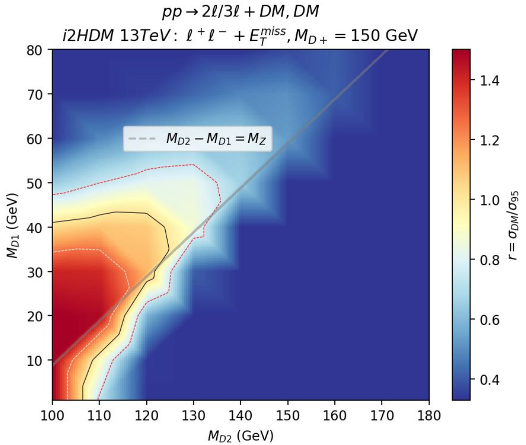




Bélanger, et al. "Dilepton Constraints in the Inert Doublet Model from Run 1 of the LHC." Physical Review D 91.11 (2015) [arXiv:1503.07367]

13 TeV

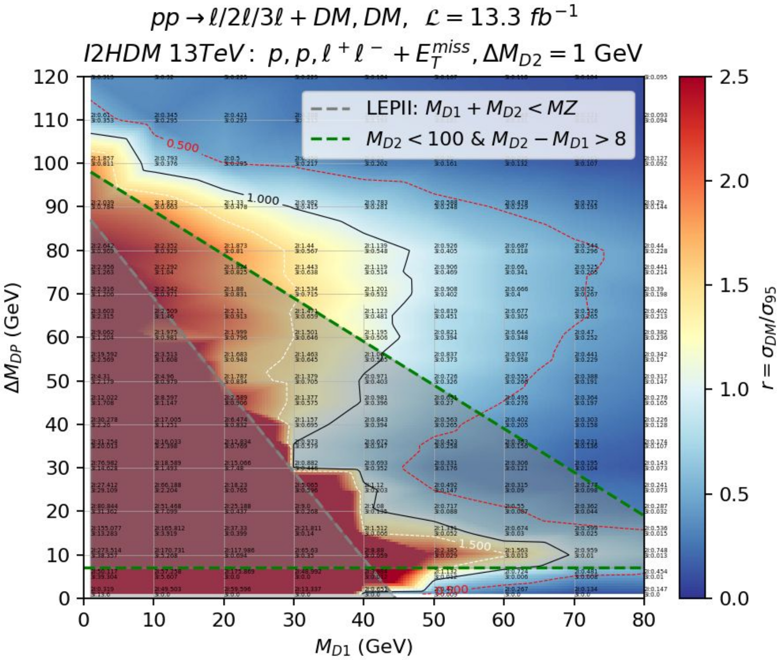


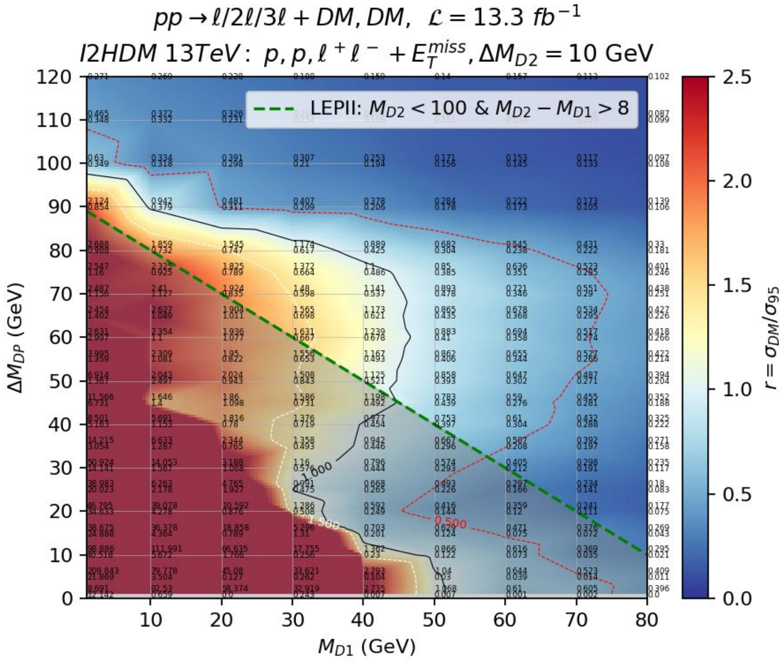


Our analysis

$$\Delta M_{D2} = M_{D2} - M_{D+}$$
$$\Delta M_{DP} = M_{D+} - M_{D1}$$

New I2HDM Results





- ΔM_{D2} = 1 GeV: Small wedge above $M_{D1} > 50$ GeV and below $\Delta M_{DP} < 8$ GeV still allowed by LEP
- M_{DP} is a better variable, 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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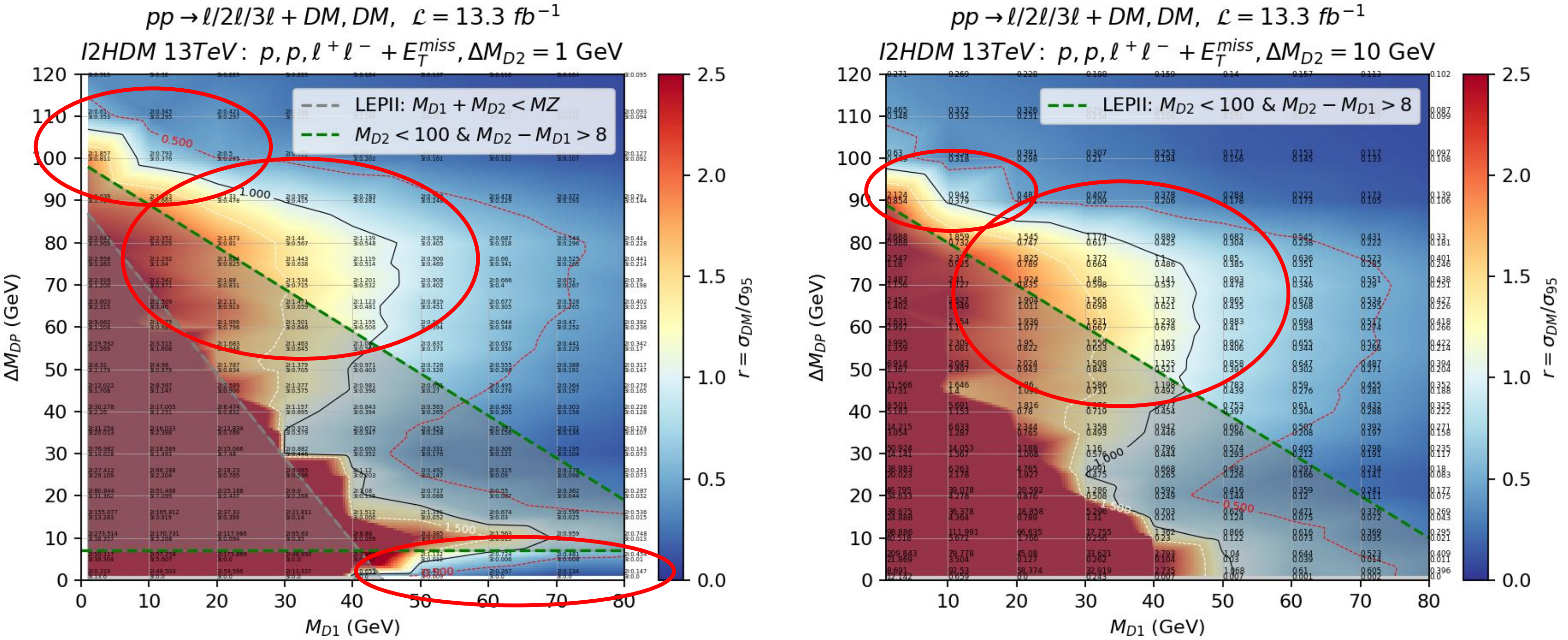

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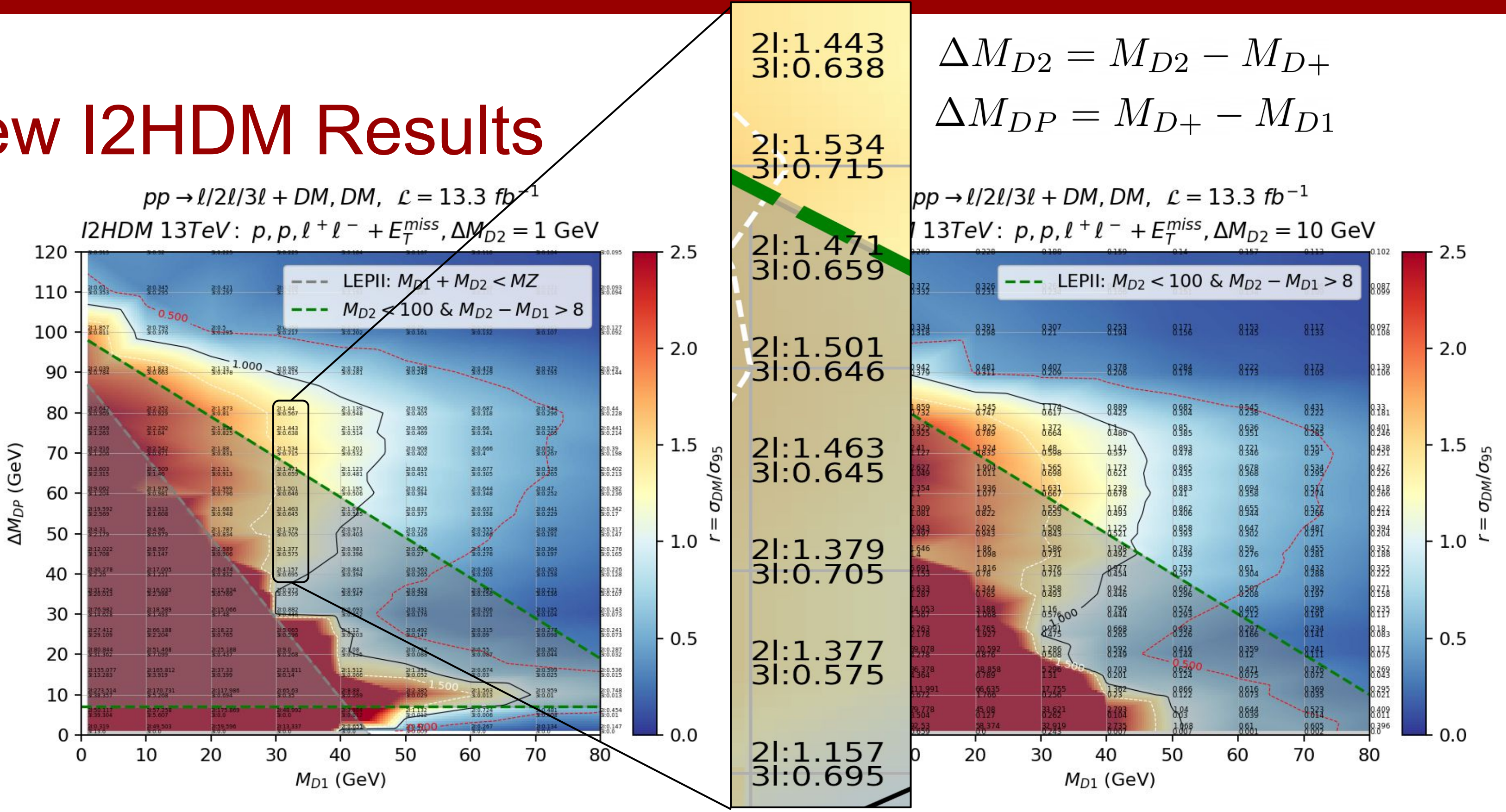

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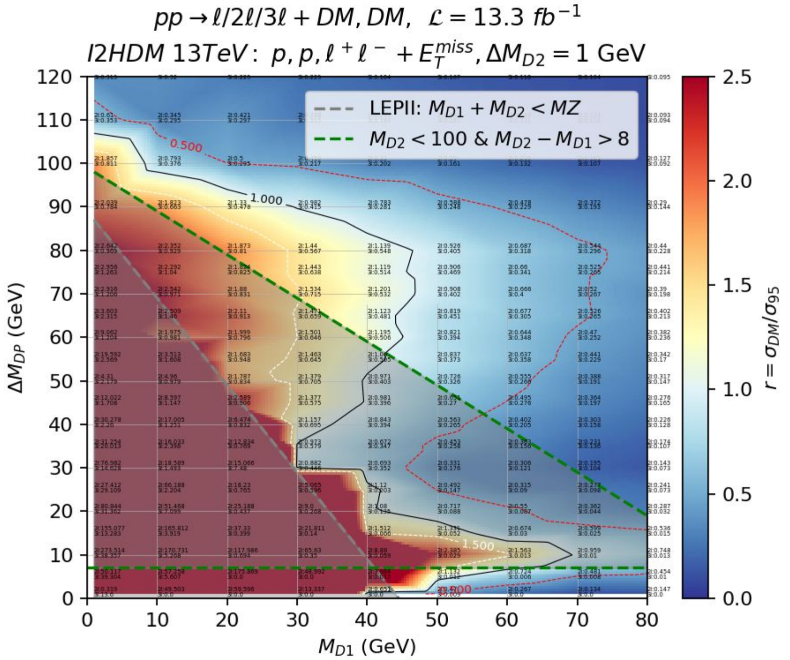
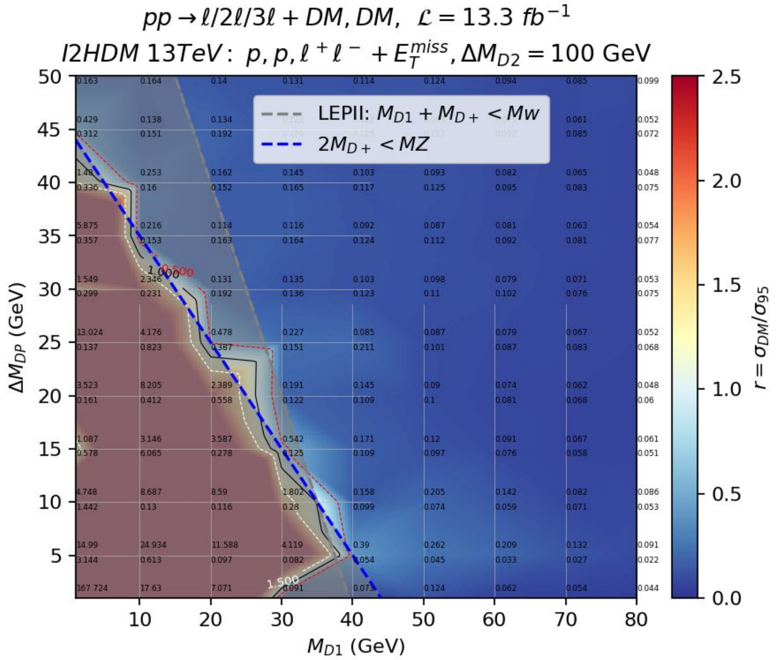




- Increasing ΔM_{D2} to 200 GeV means the Z veto $M_{\ell\ell} > 100$ GeV requirement can no longer be fulfilled as production cross-section of the heavier states has fallen

Re-interpretation: Providing Cross-section Limits

I2HDM

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

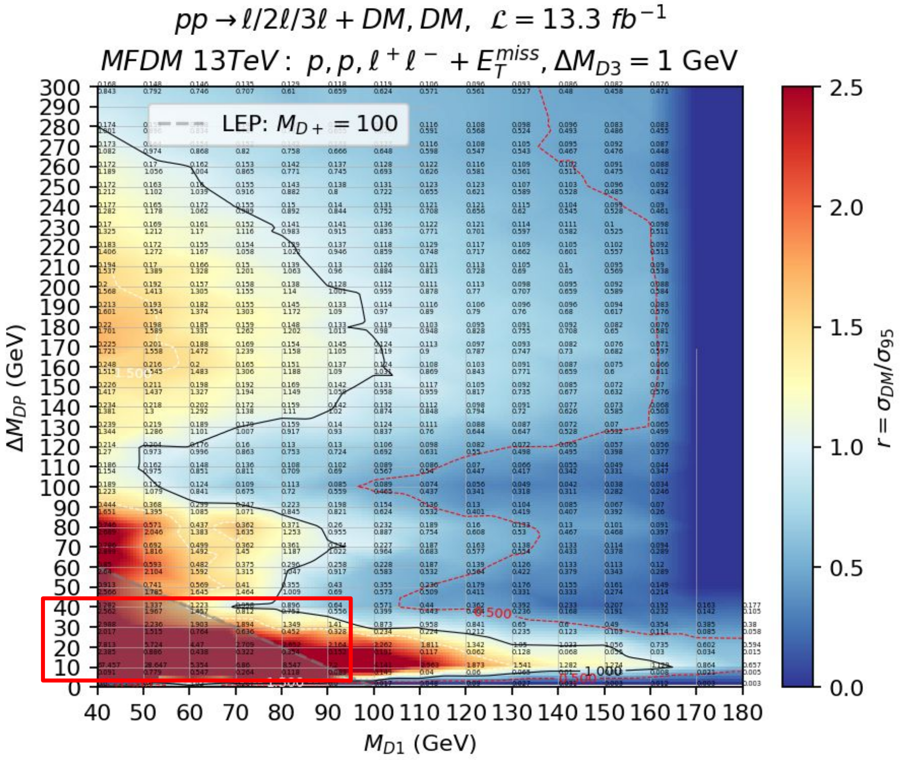
- While the genuine 2-2 process $pp \to D_2 D_1$ is separate to 3-body decay $pp \to Z D_1 D_1$, width of D_2 is small, so expected interference between these diagrams is small

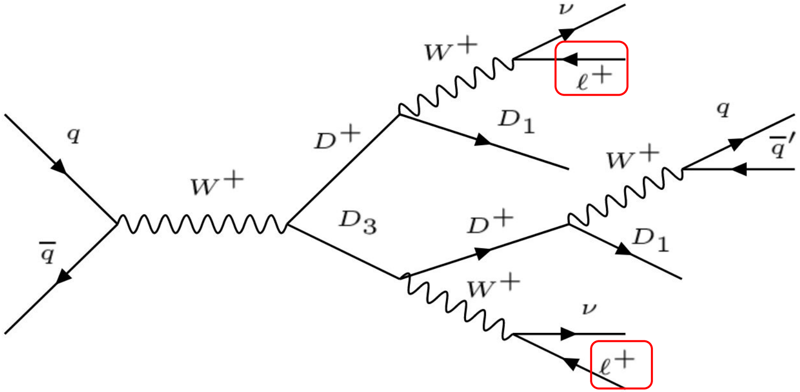
Re-interpretation: Providing Cross-section Limits

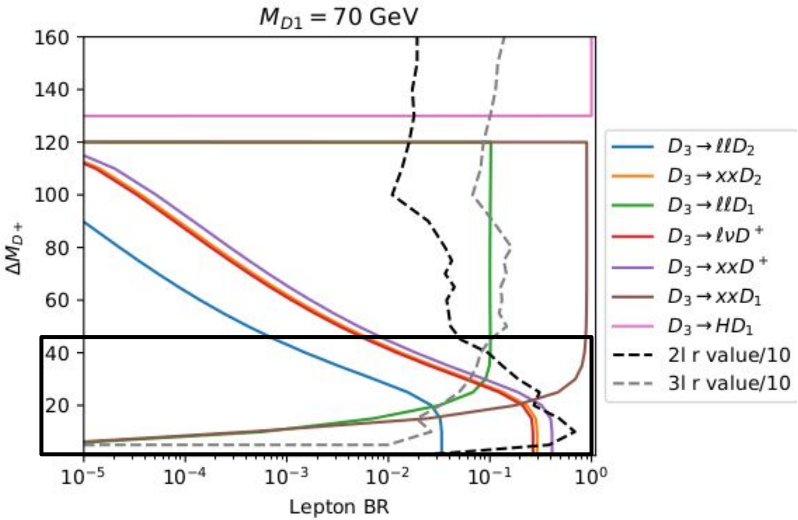
MFDM

	Sample A	Sample B	Sample C
No# Events:	50,000	150,000	100,000
Production:	$pp \to D^+D^-$ $pp \to D_2D_1$	$pp \to D_2D_3$	$pp \to D^\pm D_2$ $pp \to D^\pm D_3$
Decays:	$D^\pm \to (W^\pm \to \ell^\pm\nu)D_1$ $D_2 \to (Z \to \ell^+\ell^-)D_1$	Any	$D_2 \to (Z \to \ell^+\ell^-)D_1$ $D_3 \to (W^\pm \to \ell^\pm\nu)D^\pm$ $D_3 \to (Z \to \ell^+\ell^-)D_2$

MFDM Results



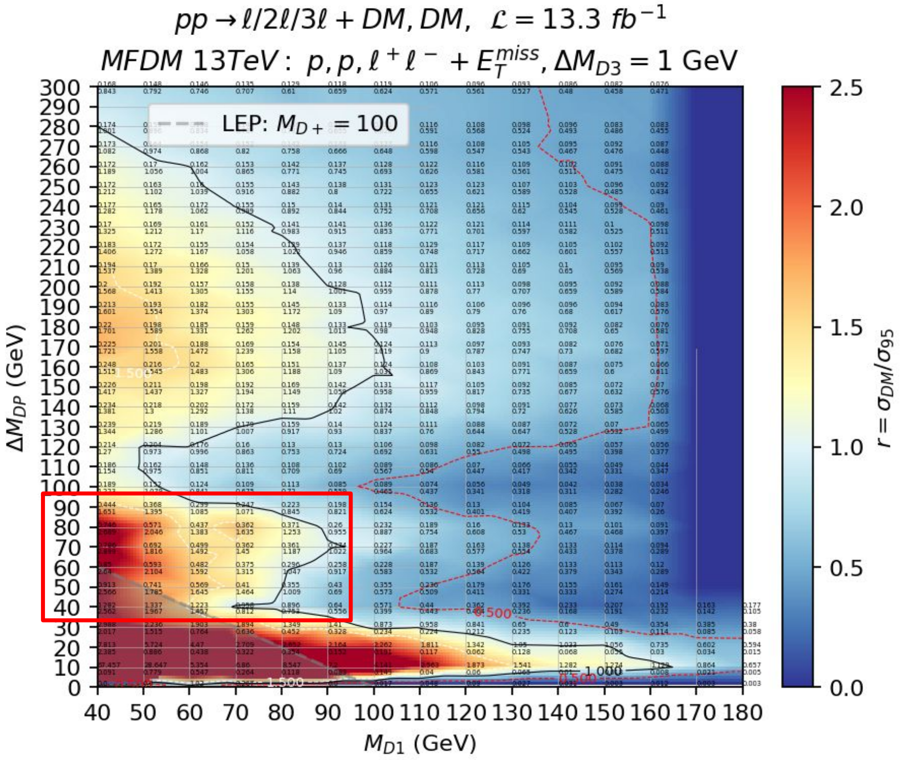


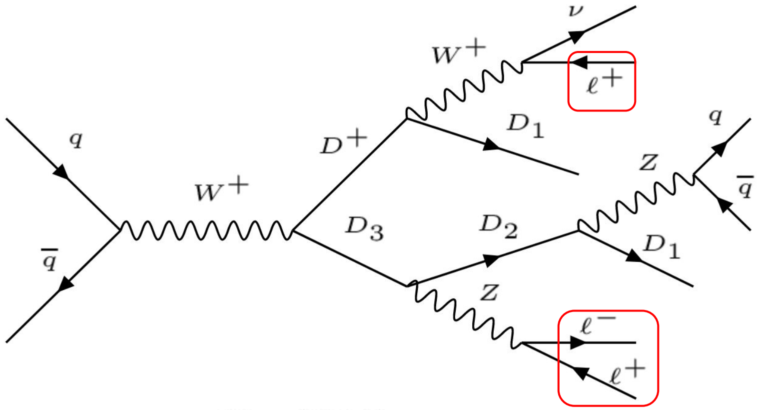


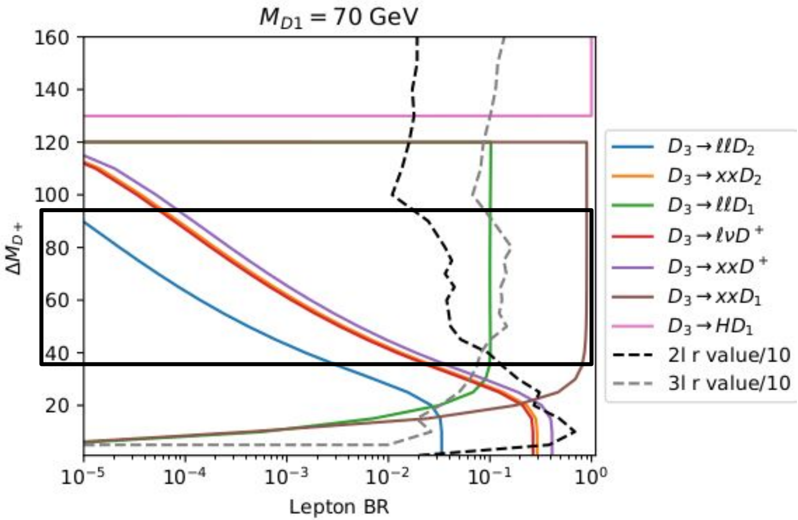
- Similar shapes to I2HDM, but with 3-lepton channel sensitivity due to crossing between

$D_3 \to \ell\nu D_1$ $D_3 \to Z(\to \ell\ell)D_1$ $D^\pm(\to \ell\nu D_1)D_3$ $\Delta M_{DP} = 45$

MFDM Results

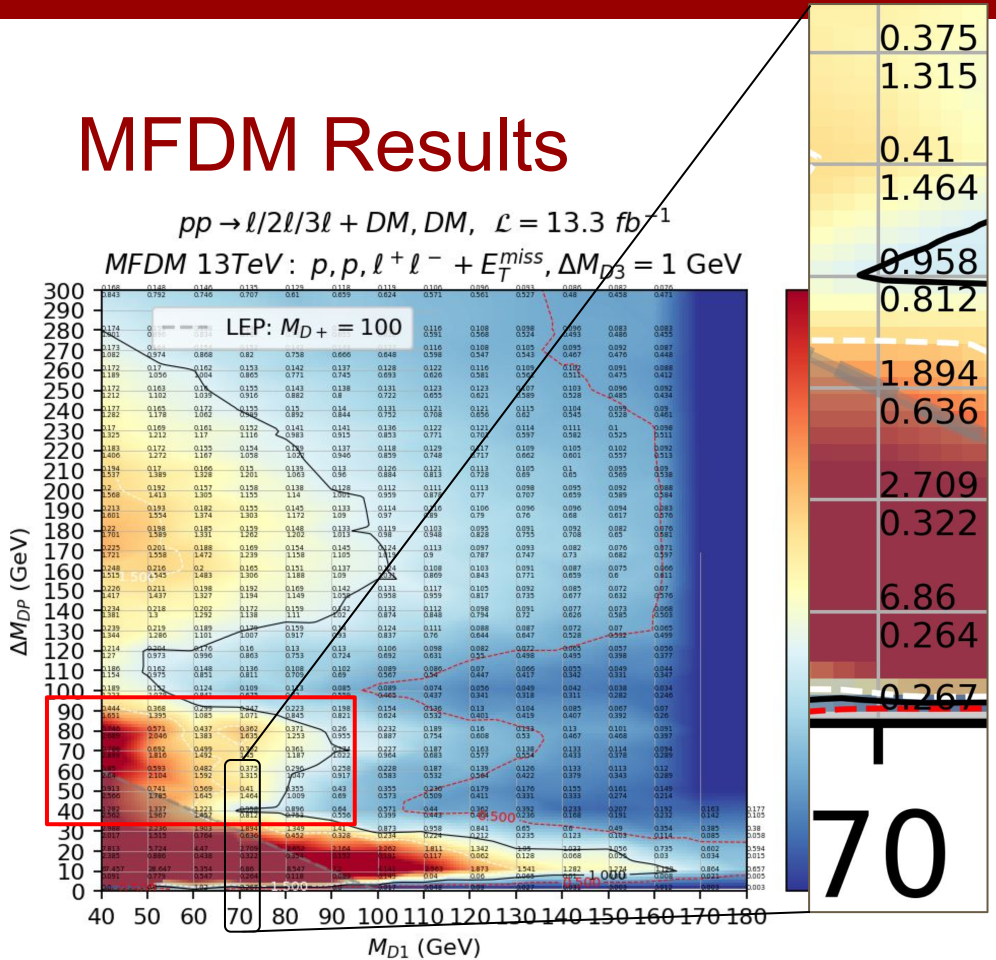


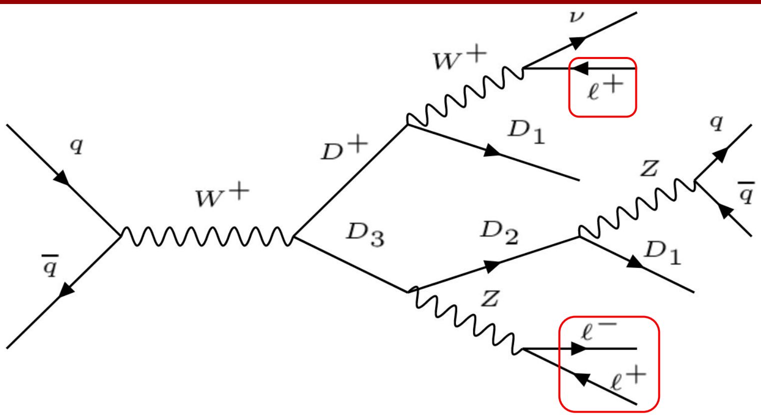


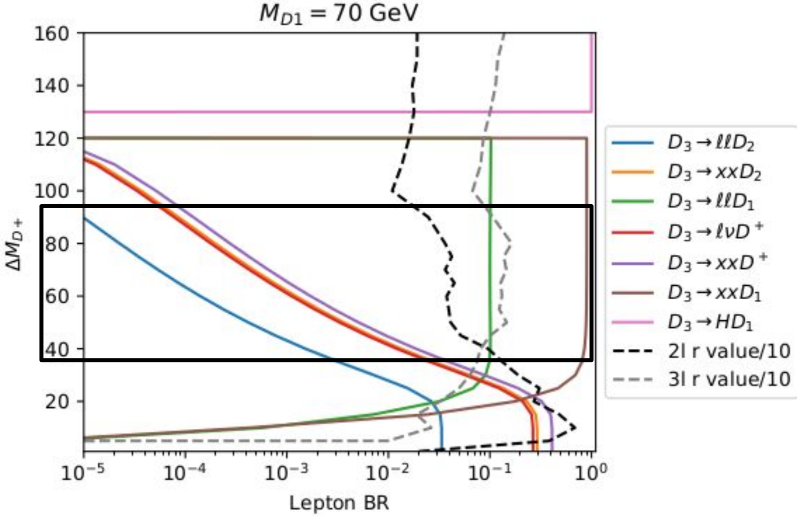


- Similar shapes to I2HDM, but 3-lepton channel sensitivity begins to dominate due to crossing between $D_3 \to \ell\nu D_1$ $D_3 \to Z(\to \ell\ell)D_1$ $D^\pm(\to \ell\nu D_1)D_3$ $\Delta M_{DP} = 45$

MFDM Results







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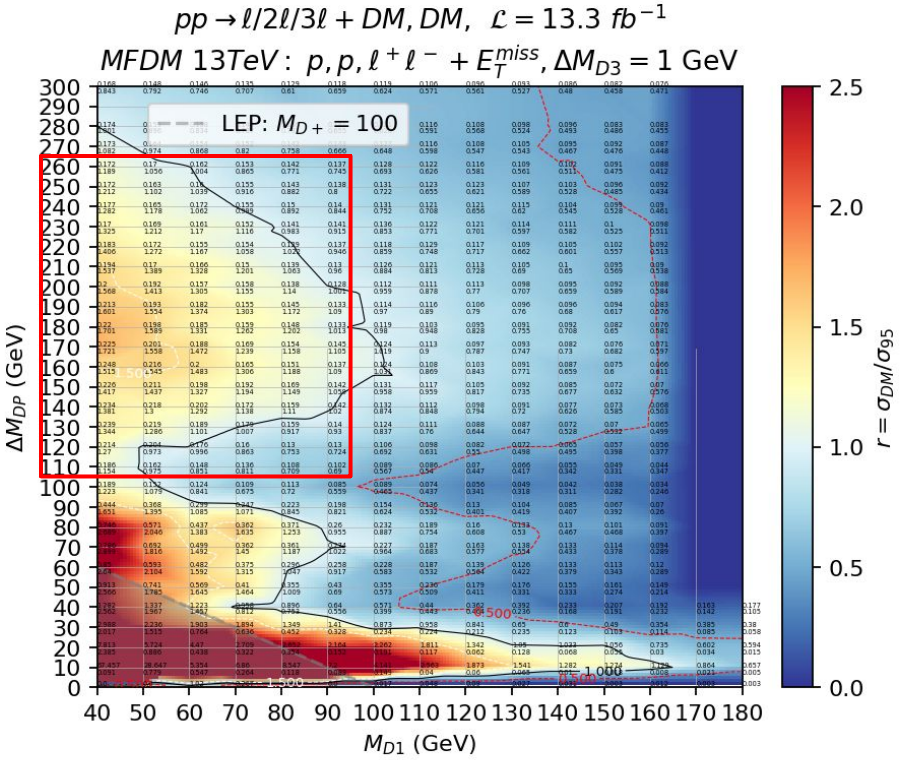
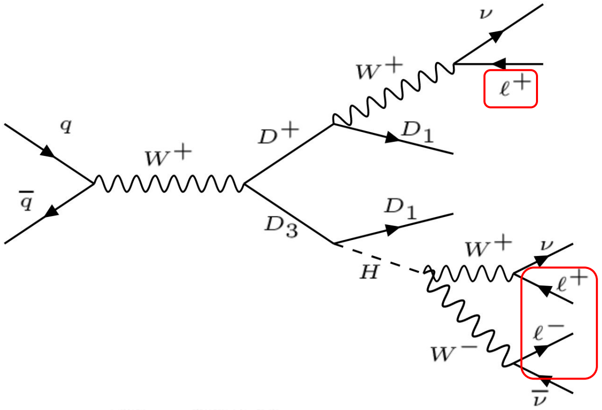
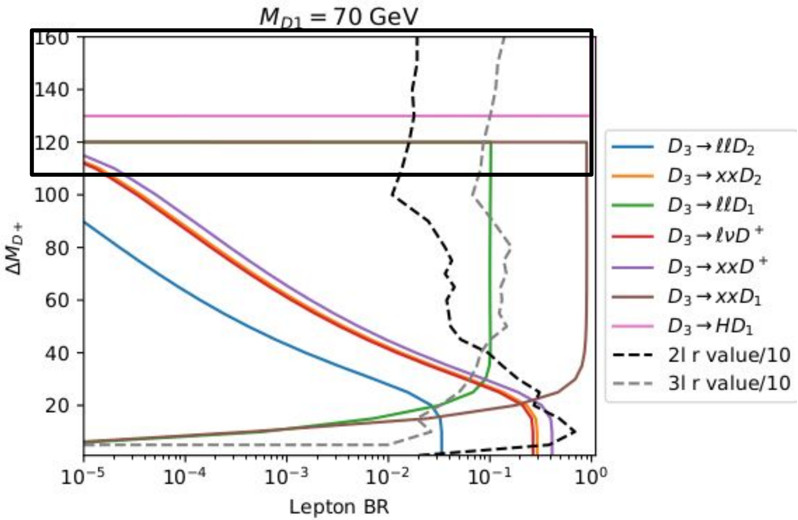
MFDM Results

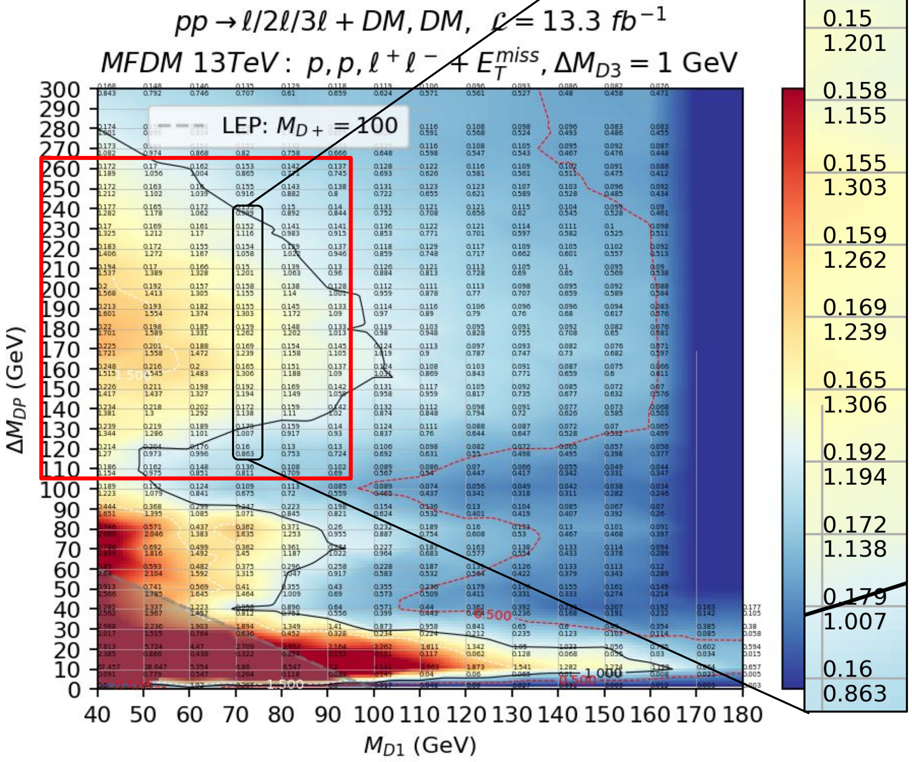


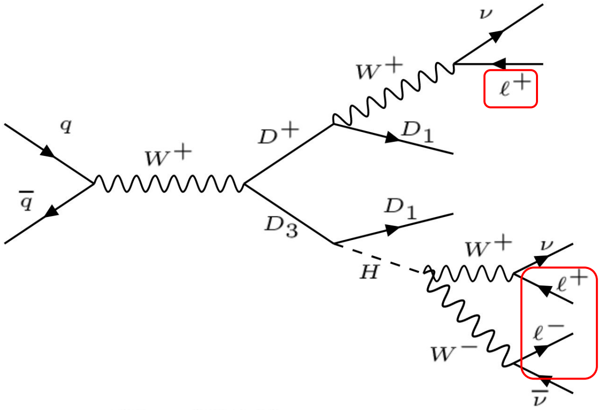


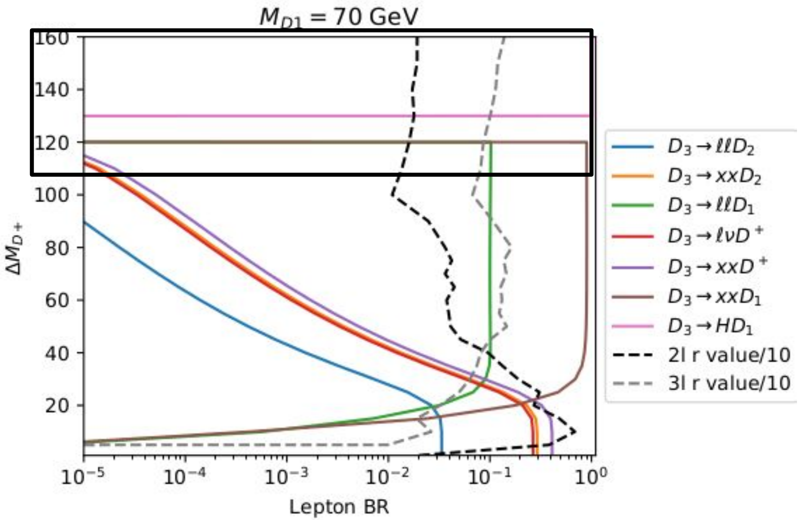


- Second shape due to 3-lepton channel sensitivity due to Higgs decay $D_3 \rightarrow Z(\rightarrow \ell\ell)D_1$ to $D_3 \rightarrow H(\rightarrow W^+W^-)D_1$ with production of $D^{\pm}(\rightarrow \ell\nu D_1)D_3$, at $\Delta M_{DP} = 125$ GeV

MFDM Results







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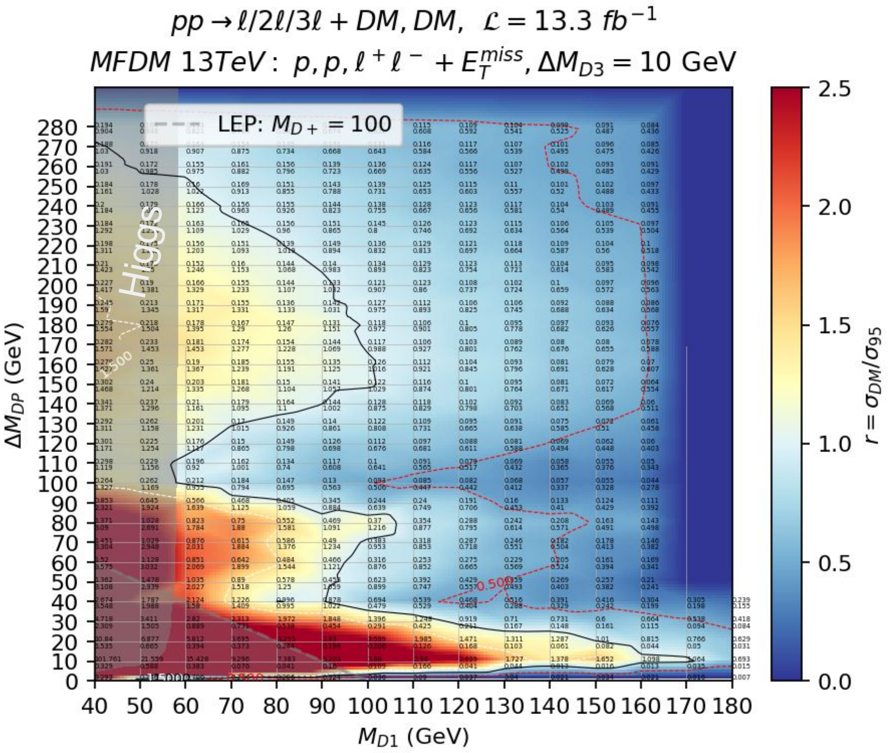
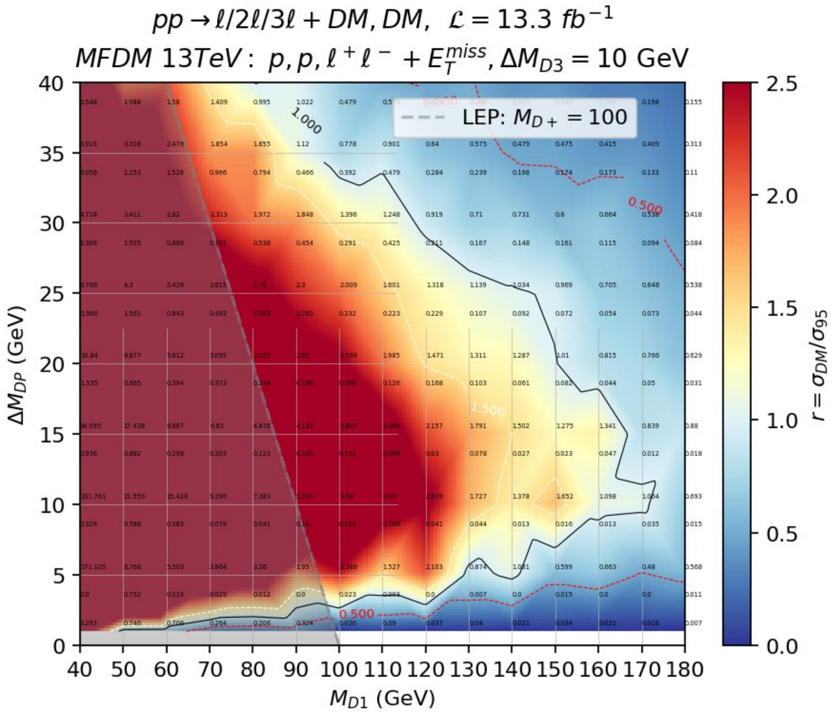
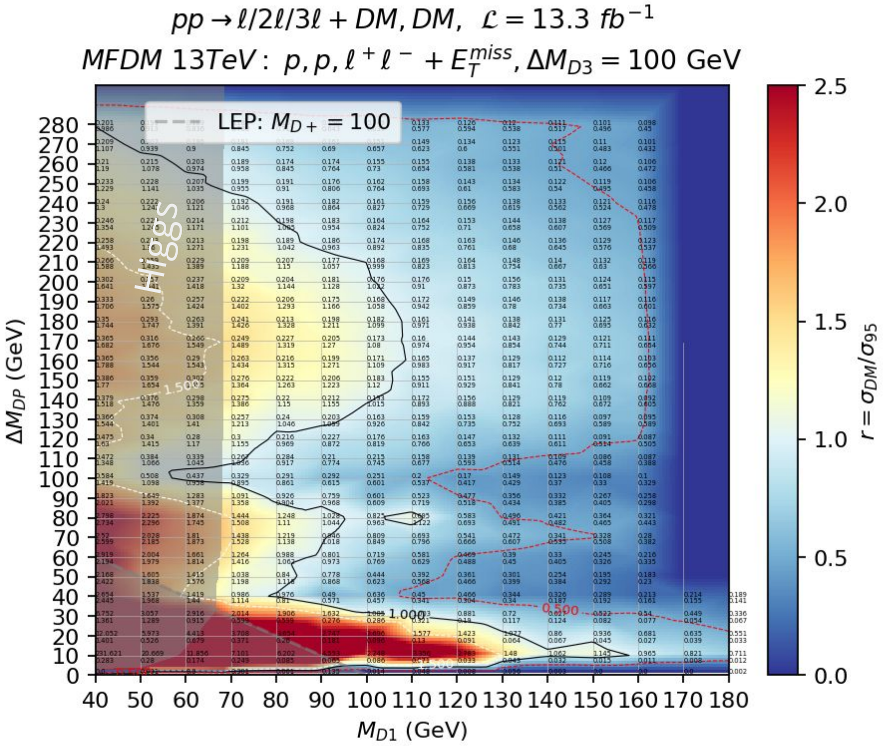
MFDM Results

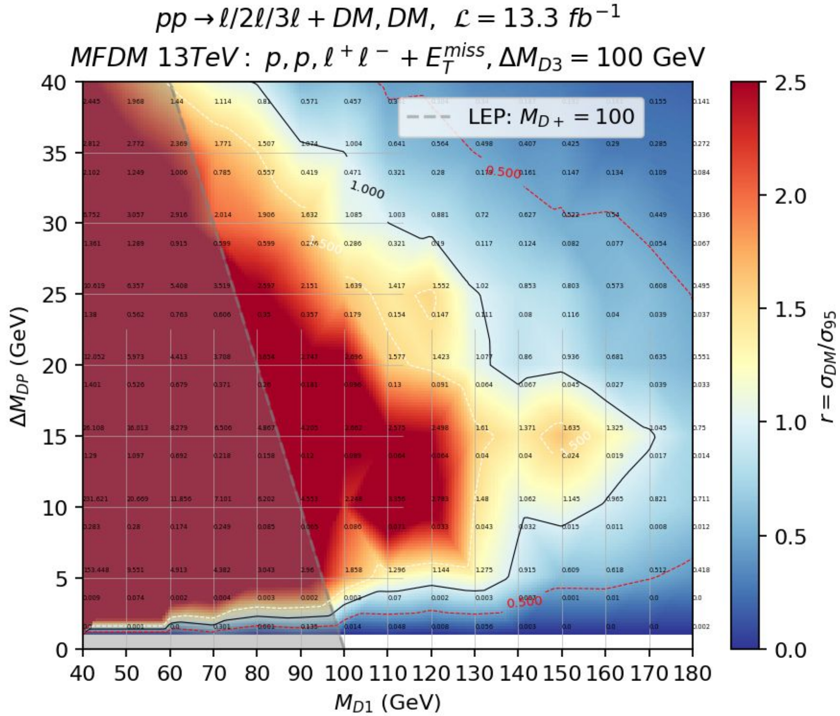




- As ΔM_{D3} increases, coupling between $D_1 - D^{\pm}$ increases, while heavy D_3 leads to suppressed production cross-section - ‘no-lose’ theorem

MFDM Results





- With increasing ΔM_{D3}, Higgs to invisible limit covers larger M_{D1}

Re-interpretation: Providing Cross-section Limits

Mass parameter points

M_{D1}	ΔM_{D+}	ΔM_{D2}	$2\ell\ \sigma^{95}_A$ (fb)	$\frac{100}{\sqrt{N_{MC}}}$	$2\ell\ \sigma^{95}_B$ (fb)	$\frac{100}{\sqrt{N_{MC}}}$	$2\ell\ \sigma^{95}_C$ (fb)	$\frac{100}{\sqrt{N_{MC}}}$	$3\ell\ \sigma^{95}_A$ (fb)	$\frac{100}{\sqrt{N_{MC}}}$	$3\ell\ \sigma^{95}_B$ (fb)	$\frac{100}{\sqrt{N_{MC}}}$	$3\ell\ \sigma^{95}_C$ (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_{D+}	ΔM_{D2}	$2\ell\ \sigma_A^{95}$ (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 3 lepton channel of sample A,B,C

M_{D1}	ΔM_{D+}	ΔM_{D2}	$2\ell\ \sigma_A^{95}$ (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

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

- Gives a percentage uncertainty

M_{D1}	ΔM_{D+}	ΔM_{D2}	$2\ell\ \sigma_A^{95}$ (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

Conclusions

- Validated previous 8 TeV results from MadAnalysis, in CheckMATE
- New 13 TeV limits on DM mass splittings, beyond mono-jet for:
    - I2HDM: Important contributions from 3-lepton final states
    - MFDM: 3-lepton channel becomes leading role via $D_3 \to Z(\to \ell\ell)D_1$ and Higgs becomes important for $D_3 \to H(\to W^+W^-)D_1$
- Map of 2&3 lepton channel cross-section limits and efficiencies using CheckMATE for a wider DM re-interpretation analysis for our community