Scalar Mixing Dark Matter model and interface w/others

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A New Effort

- There are several efforts underway as to how to understand DM
  - LHC DM WG aims to centralize models across LHC
    - Additional goal is that this allows for comparison with ID/DD
  - Physics Beyond Colliders (PBC) aims to understand low mass DM
    - Goal is to organize low mass DM models
    - Ensure robust DM constraints in the low mass r3egion
- What is going on now?
  - There is an opportunity to consolidate limit plots
  - There is an active effort to consolidate spin-1 Dark Photon results
  - This talk will focus on the Scalar Mixing Portal (Higgs Invisible)

Comparisons w/PBC

$$\mathcal{L}_{\text{vector}} = -g_{\text{DM}}\, Z'_\mu\, \bar{\chi}\gamma^\mu\chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu\, \bar{q}\gamma^\mu q - g_\ell \sum_{\ell=e,\mu,\tau} Z'_\mu\, \bar{\ell}\gamma^\mu \ell\,,$$

Adding Mixing with photon

$$g_q = g_\ell = \frac{\epsilon}{2e\cos\theta_W}$$

Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2) H^\dagger H$
Axion, a	$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
Sterile Neutrino, N	$y_N L H N$

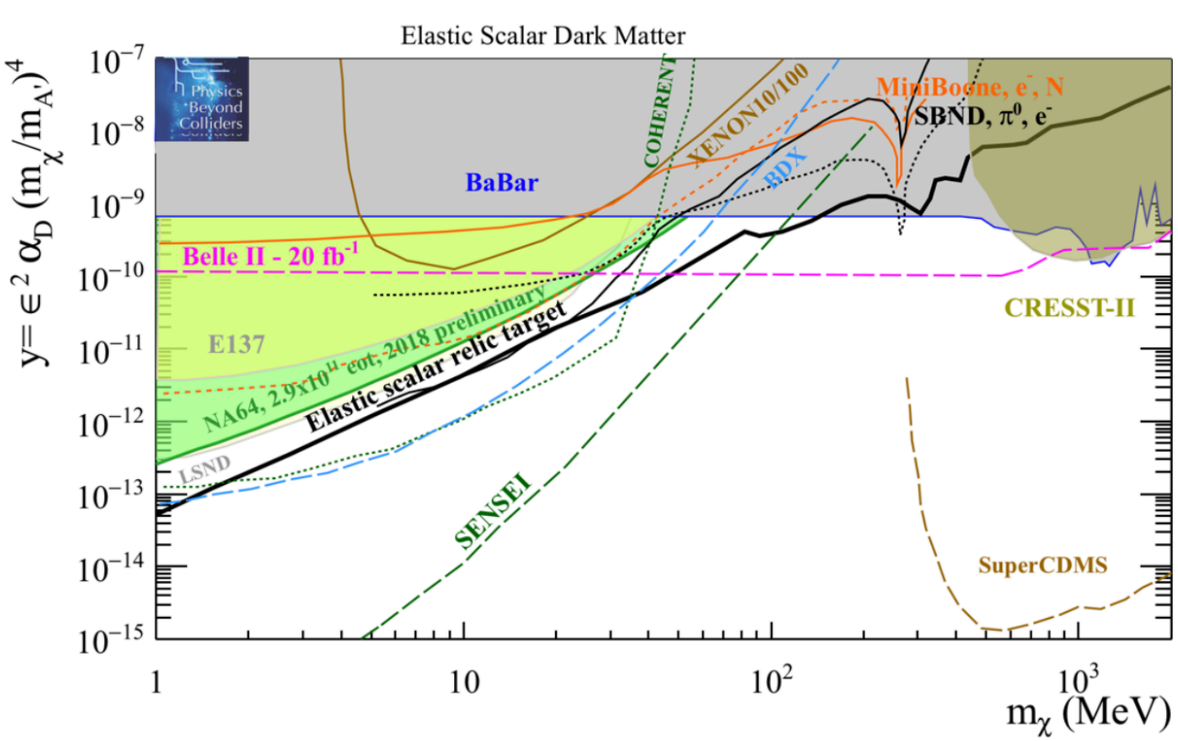
LHC Spin 1 results are very similar to Dark Photon in PBC
For the most part simple rescaling can allow for result comparisons

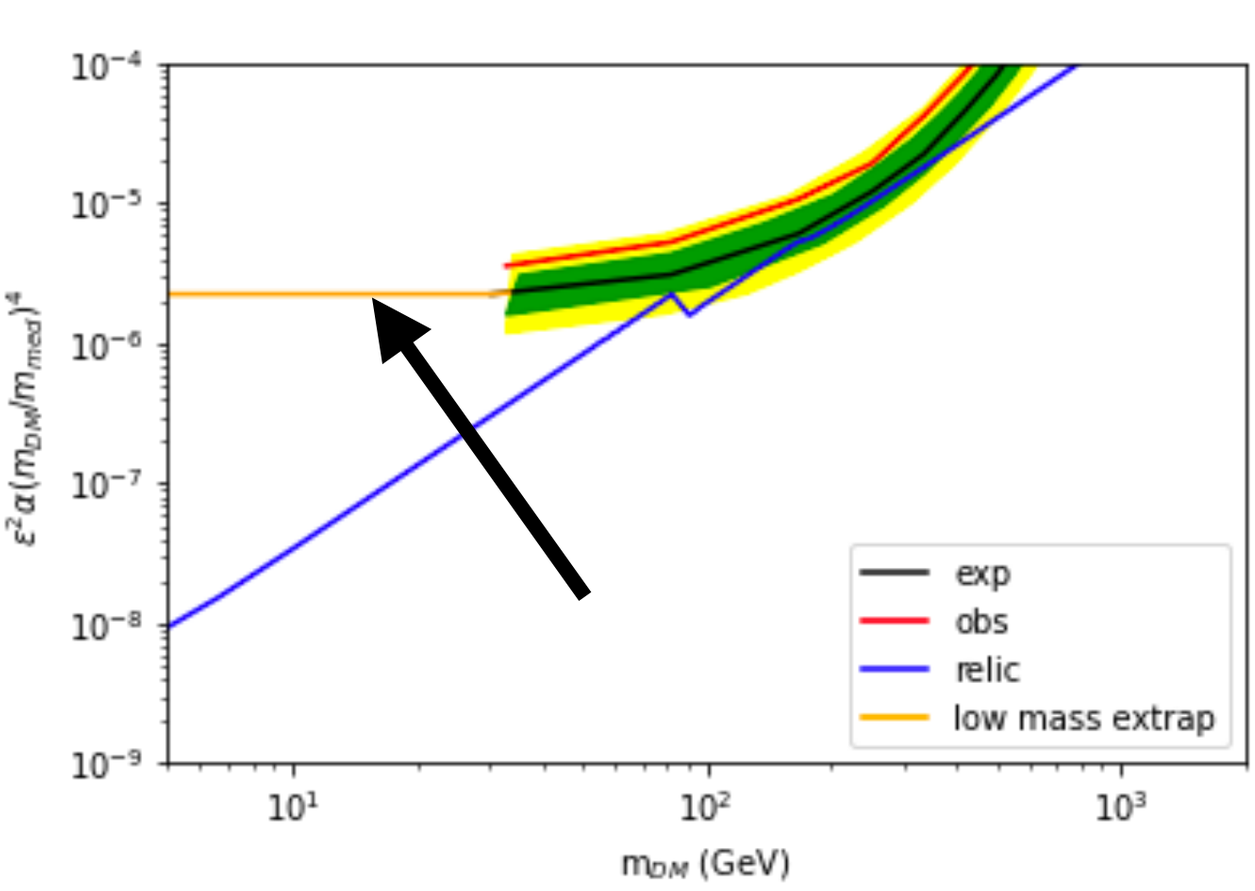
Dark Photon's have previously been discussed here https://indico.cern.ch/event/729789/

https://arxiv.org/pdf/1901.09966.pdf

Dark Photon Following up

- Looking to make a first set of limits with the dark photon
  - A goal for a first set of limits is next week at November
    - One possibility is to use MadAnalysis and re-run
    - Its not clear we can make it there





Comparisons w/PBC

$$\mathcal{L}_{\text{pseudo-scalar}} = -ig_{\text{DM}}\phi\bar{\chi}\gamma_5\chi - ig_q\frac{\phi}{\sqrt{2}}\sum_{q=u,d,s,c,b,t} y_q\bar{q}\gamma_5 q\,,$$

Pseudoscalar mediator again similar
Interpretation of couplings also similar

$$g_q = \frac{v}{f_a}$$

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Sterile Neutrino, N	$y_N LHN$

DMWG tends to present pseudoscalar results in two ways:
- A single mediator (as a simplified model)
- A mediator within a 2HDM

https://arxiv.org/pdf/1901.09966.pdf

Comparisons w/PBC

$$\mathcal{L}_{\text{scalar}} = -g_{\text{DM}}\,\phi\bar{\chi}\chi - g_q\,\frac{\phi}{\sqrt{2}}\sum_{q=u,d,s,c,b,t} y_q\,\bar{q}q$$

Enforcing a mixing with the Higgs
Higgs to Invisible dominates bounds (adds VBF channel)

$$g_q = -\sin\theta$$

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Sterile Neutrino, N	$y_N LHN$

DMWG presents results as a scalar w/o Higgs mixing
This eliminates the ϕ to SM vector boson coupling
Higgs to invisible is also presented

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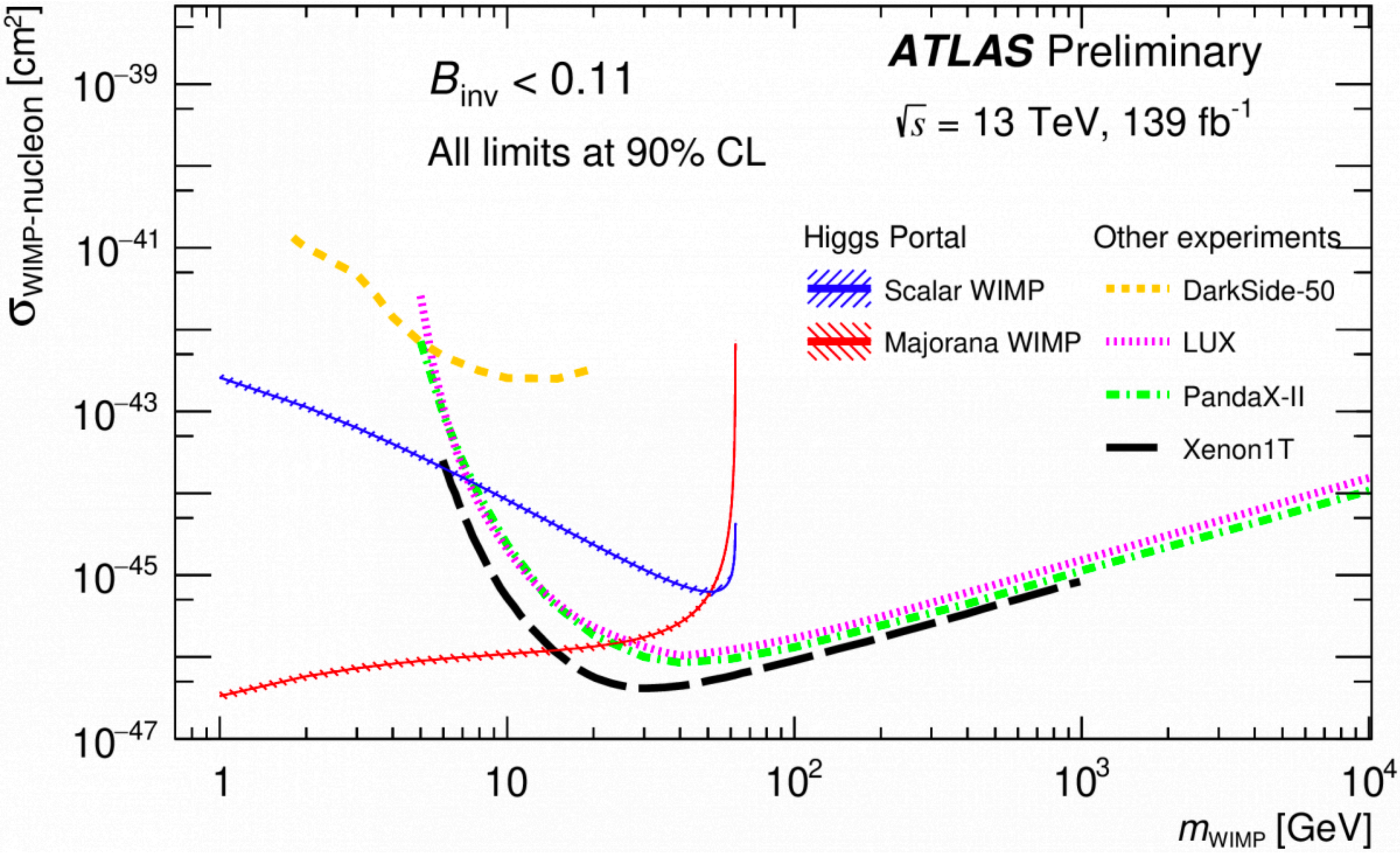
Higgs To Invisible



Why is Higgs invisible important

$$\mathcal{L} \supset -y_{\mathrm{DM}}\, s\, \bar{\chi}\chi - \mu\, s\, |H|^2$$

What if we make a complete singlet scalar model?

Observed mass eigenstates

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$$

With vector boson interactions it will mix w/Higgs

$$\mathcal{L} \supset -y_{\mathrm{DM}} \left(\sin\theta\, h_1 + \cos\theta\, h_2\right) \bar{\chi}\chi$$

Higgs to Invisible

$$+ \left(\cos\theta\, h_1 - \sin\theta\, h_2\right) \left(\frac{2M_W^2}{v} W_\mu^+ W^{-\mu} + \frac{M_Z^2}{v} Z_\mu Z^\mu - \sum_f \frac{m_f}{v} \bar{f} f \right)$$

https://arxiv.org/pdf/1607.06680.pdf

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Modified Higgs Vector Boson Couplings

$$\mathcal{L} \supset -y_{\mathrm{DM}} \left(\sin\theta\, h_1 + \cos\theta\, h_2\right) \bar{\chi}\chi$$

$$+ \left(\cos\theta\, h_1 - \sin\theta\, h_2\right) \left(\frac{2M_W^2}{v} W_\mu^+ W^{-\mu} + \frac{M_Z^2}{v} Z_\mu Z^\mu - \sum_f \frac{m_f}{v} \bar{f} f \right)$$

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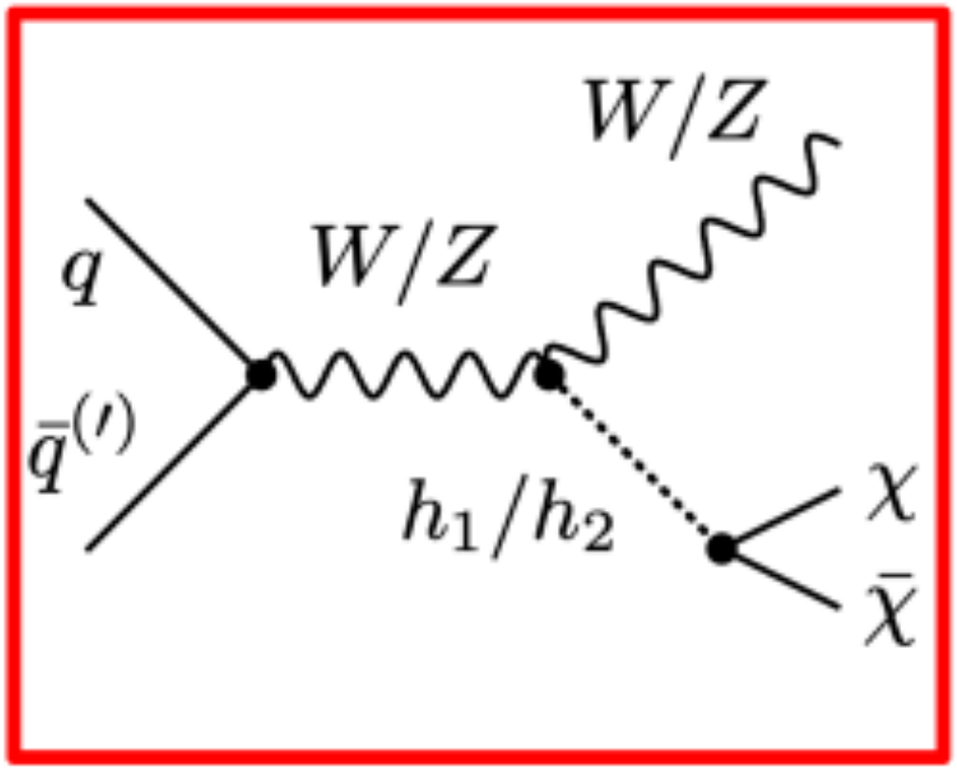
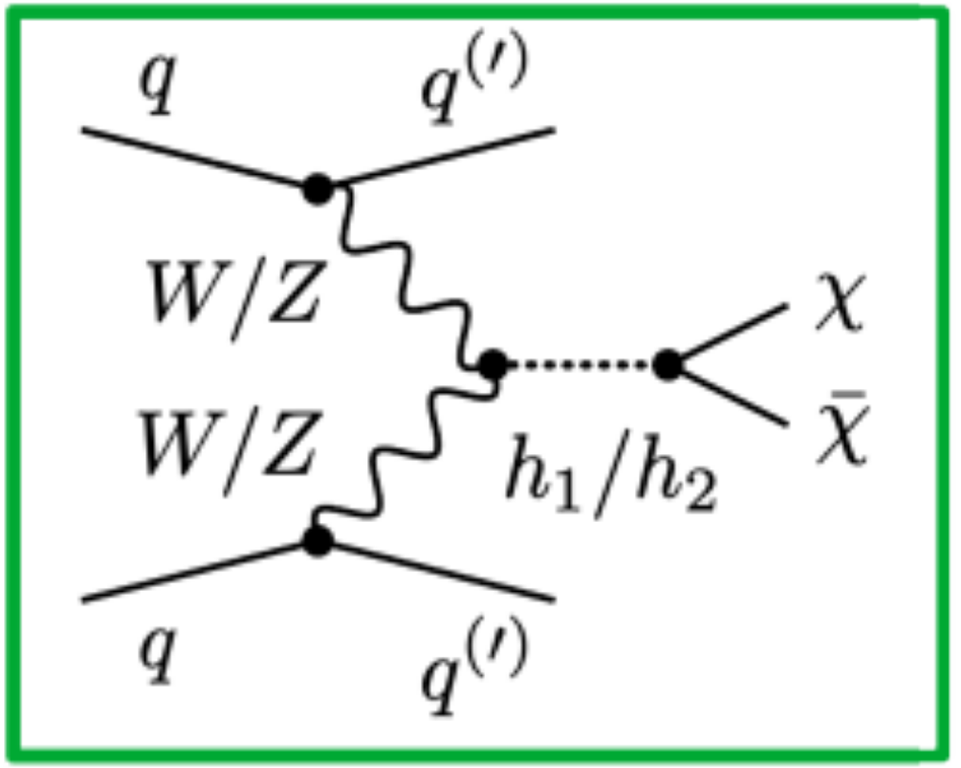
What are the scale of Modifications?

$$\Gamma(h_1 \to \chi\bar{\chi}) = \frac{y_{\mathrm{DM}}^2 \sin^2\theta\, m_{h_1}}{8\pi}\left(1 - \frac{4m_\chi^2}{m_{h_1}^2}\right)^{3/2}$$



Higgstrahlung



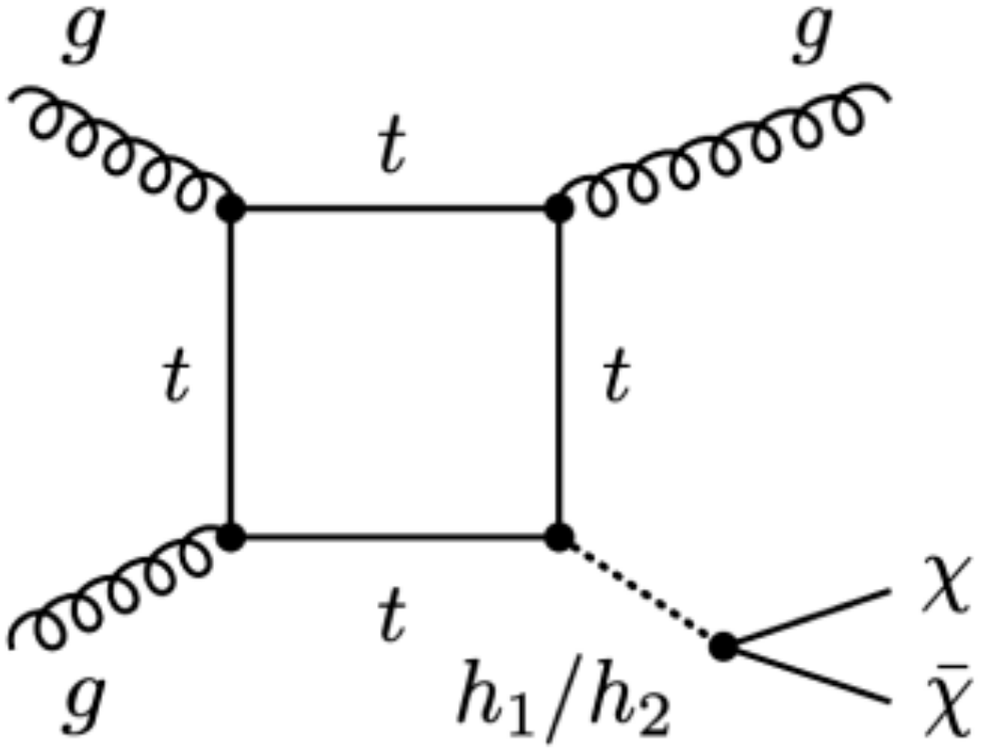
VBF Higgs to invisible

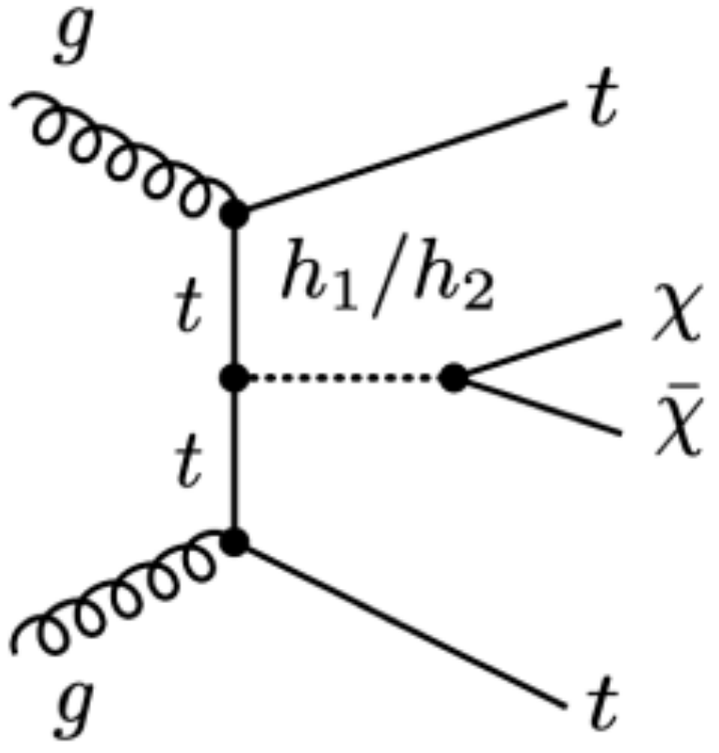
https://arxiv.org/pdf/1607.06680.pdf

What are the scale of Modifications?

$$g_{\mathrm{DM}} \longrightarrow y_{\mathrm{DM}} \cos\theta$$

$$g_{\mathrm{SM}} \longrightarrow -\sin\theta$$





In addition have the usual Scalar simplified models

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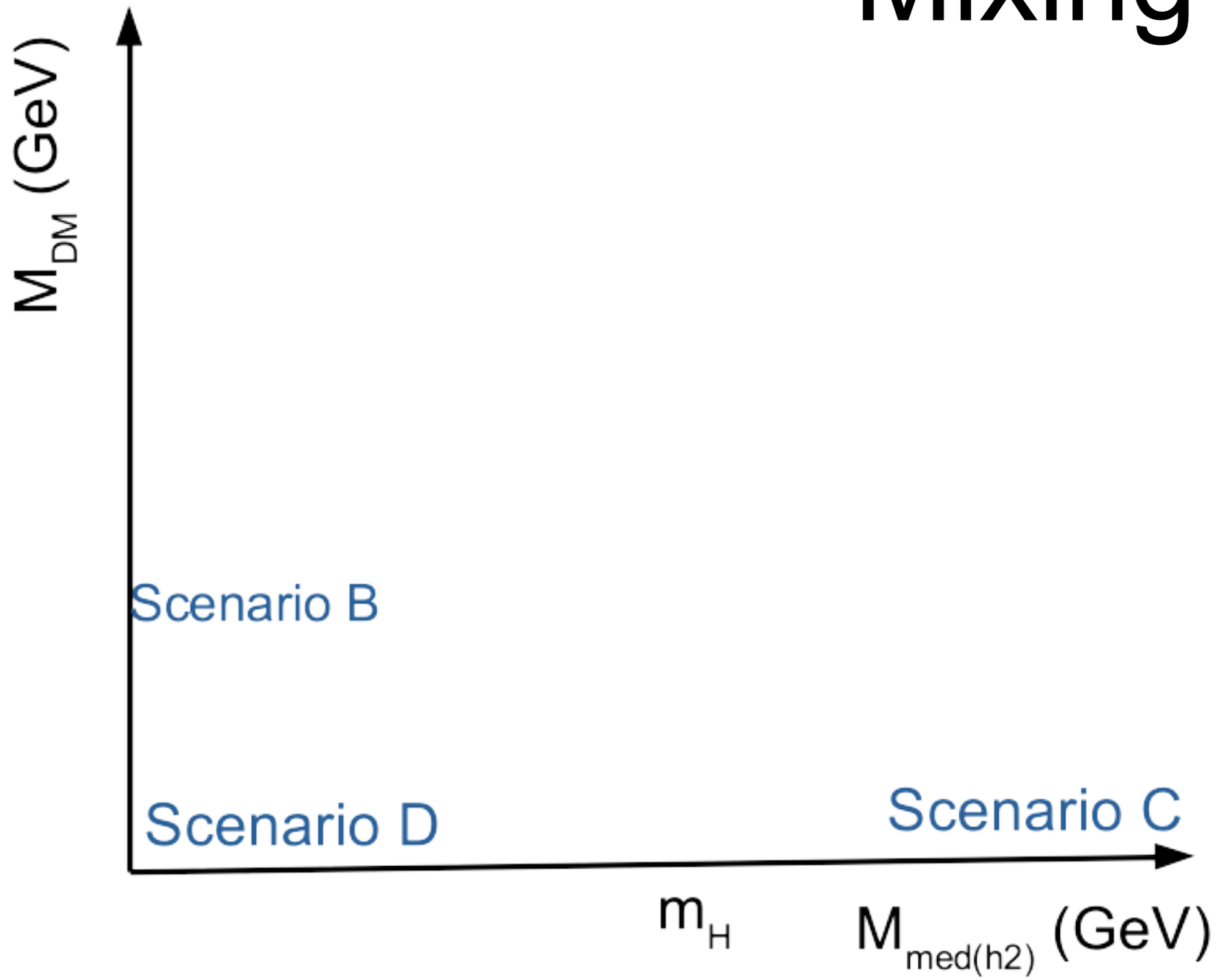
Parametrizing the Single Mixing Model



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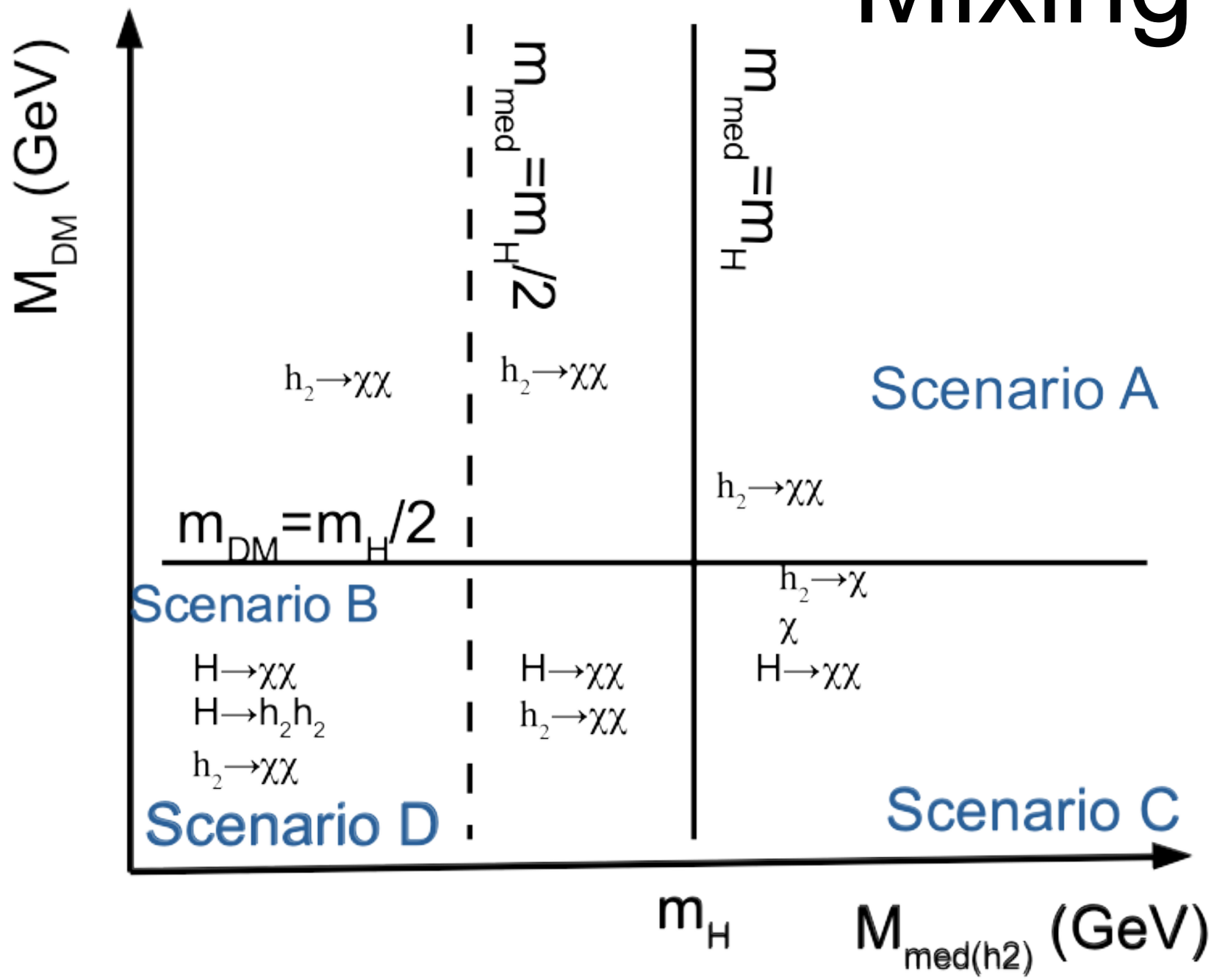
Parametrizing the Single Mixing Model



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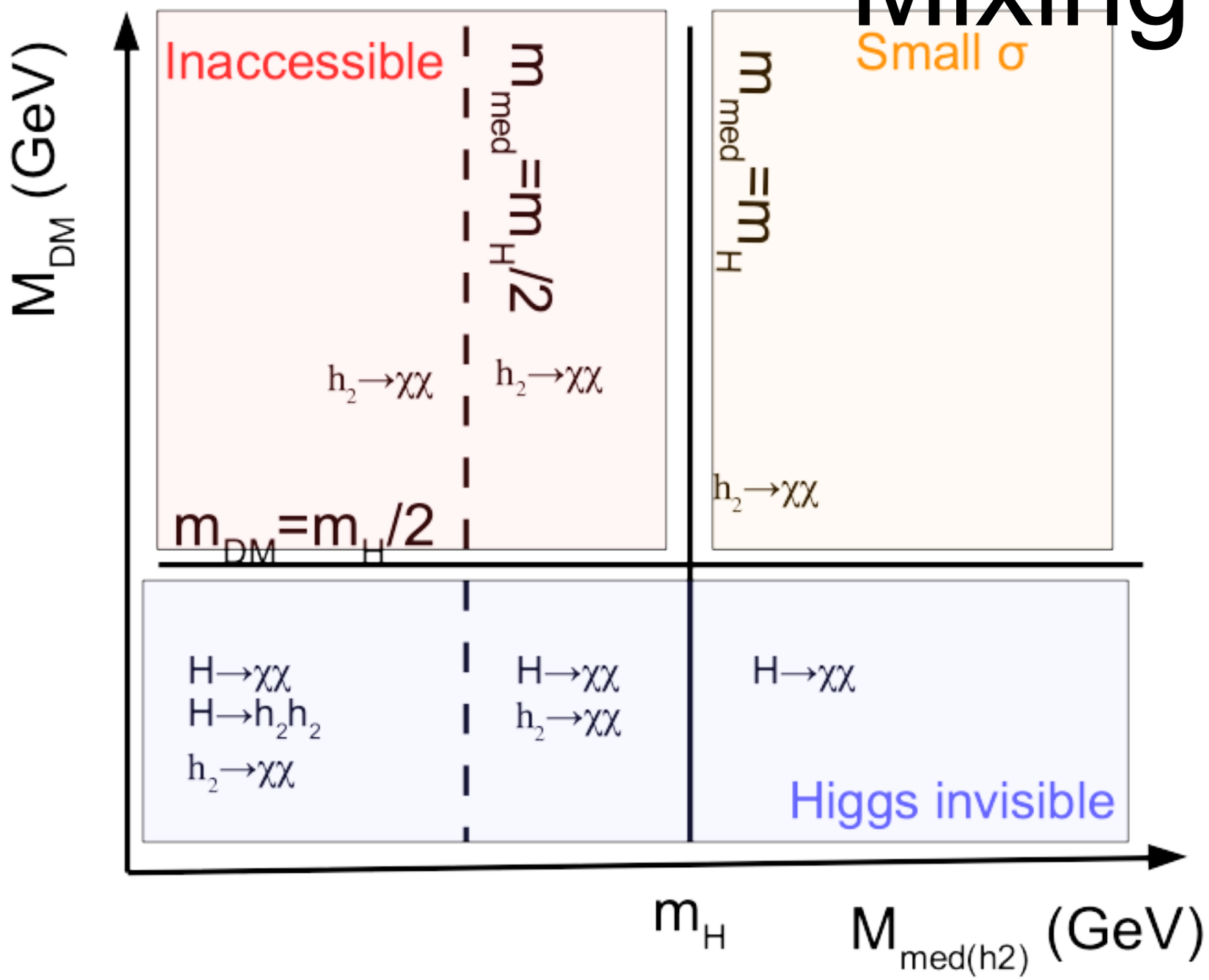

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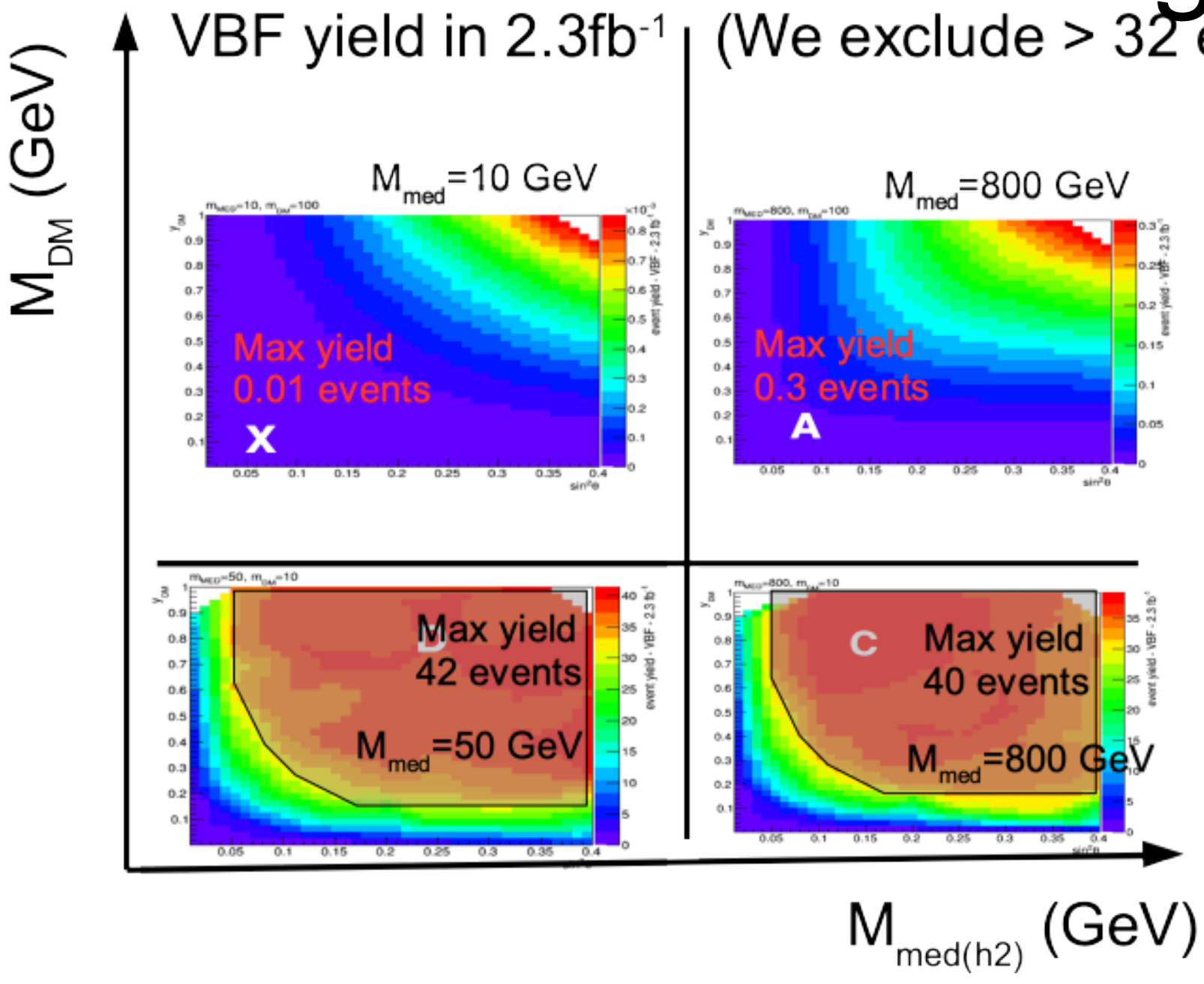
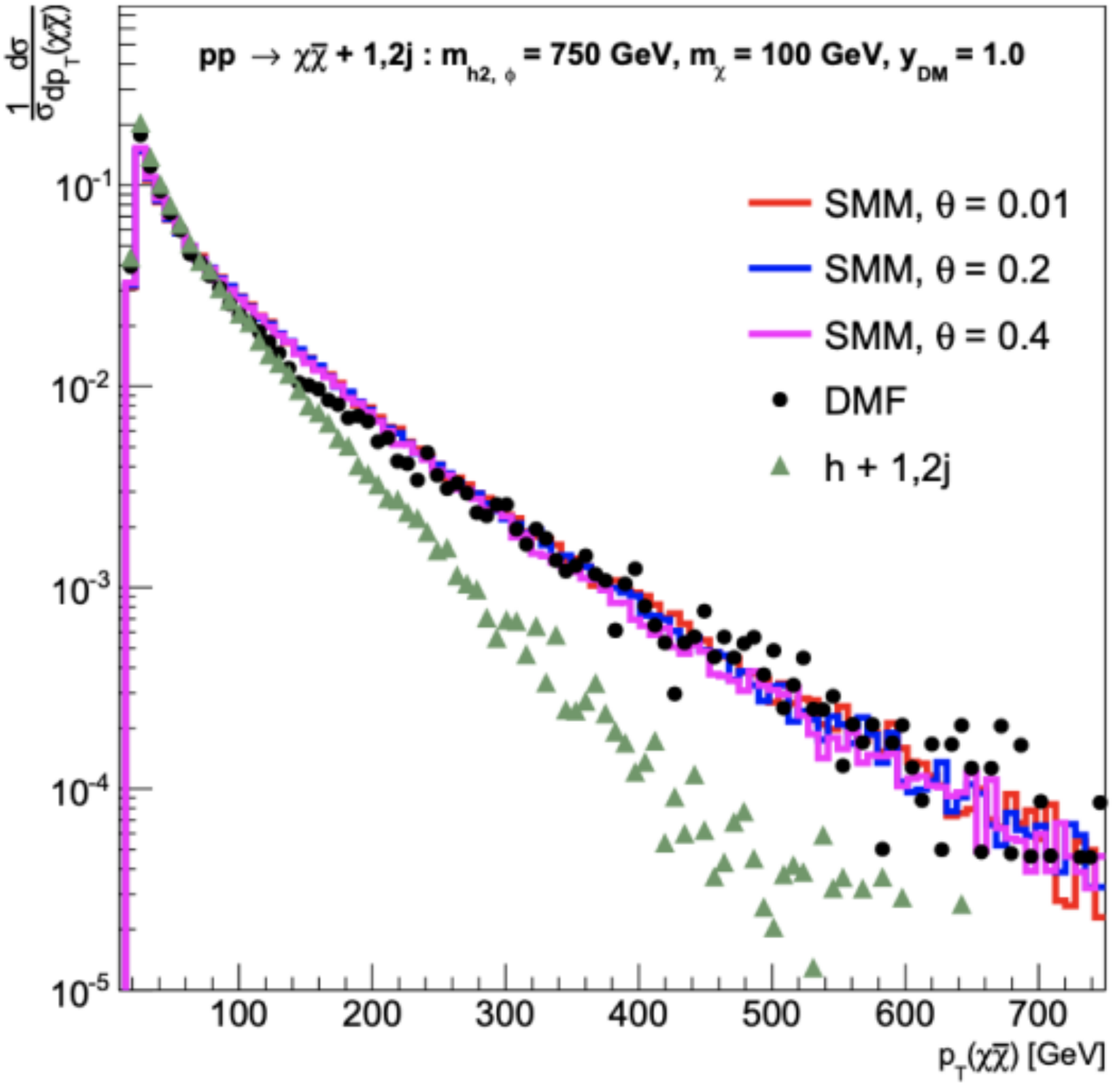
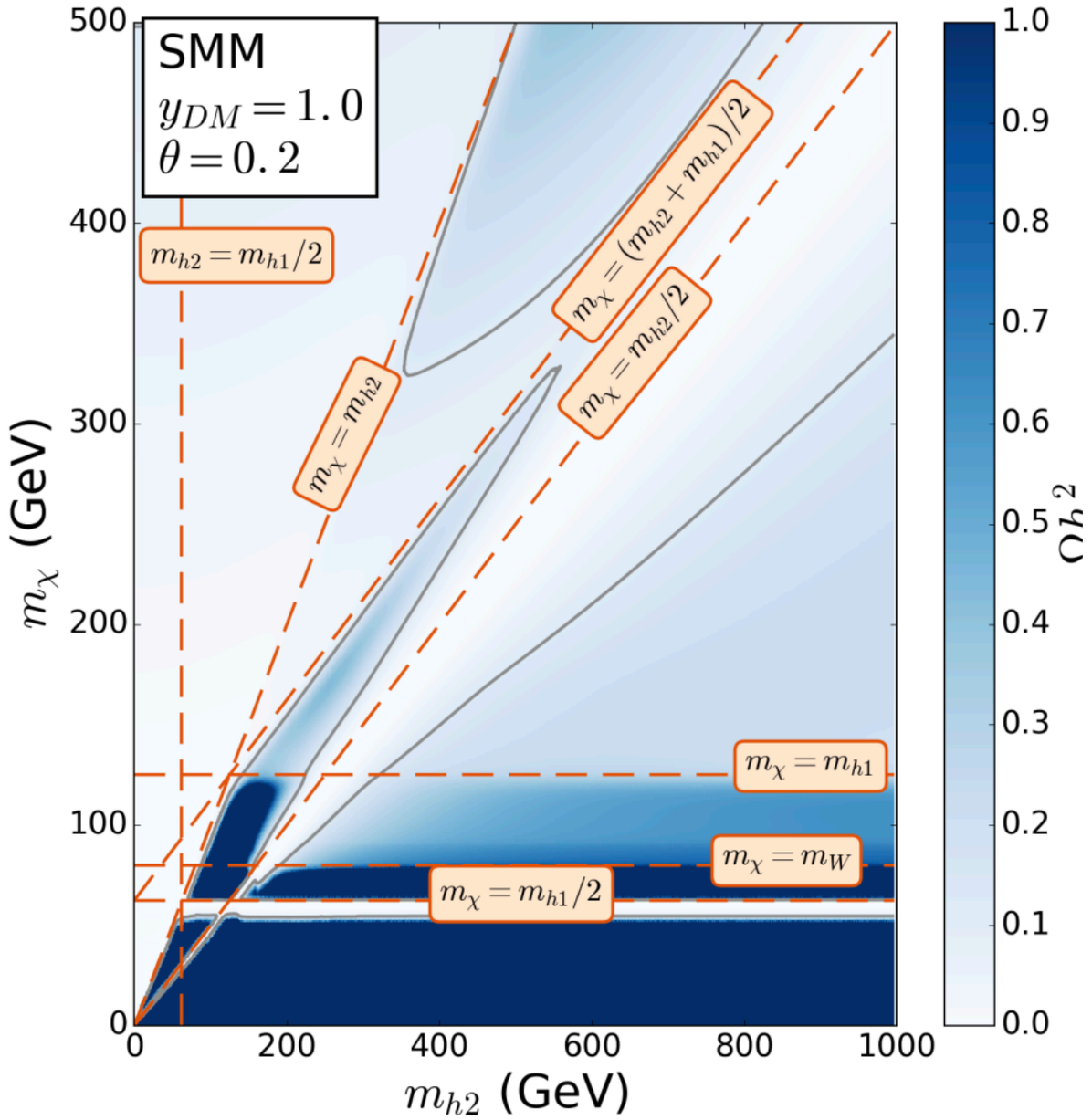


Singlet Scenarios



DM Relic Density



- Light DM region
  - Naively has strong constraints
- Most interesting relic bound
  - From Heavy Dark Matter
  - The region hardest to probe
- Higgs Couplings might still help

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What Drives Constraints

$$\Gamma(h_1 \to \chi\bar{\chi}) = \frac{y_{\mathrm{DM}}^2 \sin^2\theta\, m_{h_1}}{8\pi}\left(1 - \frac{4m_\chi^2}{m_{h_1}^2}\right)^{3/2}$$

Higgs to invisible bounds puts constraints

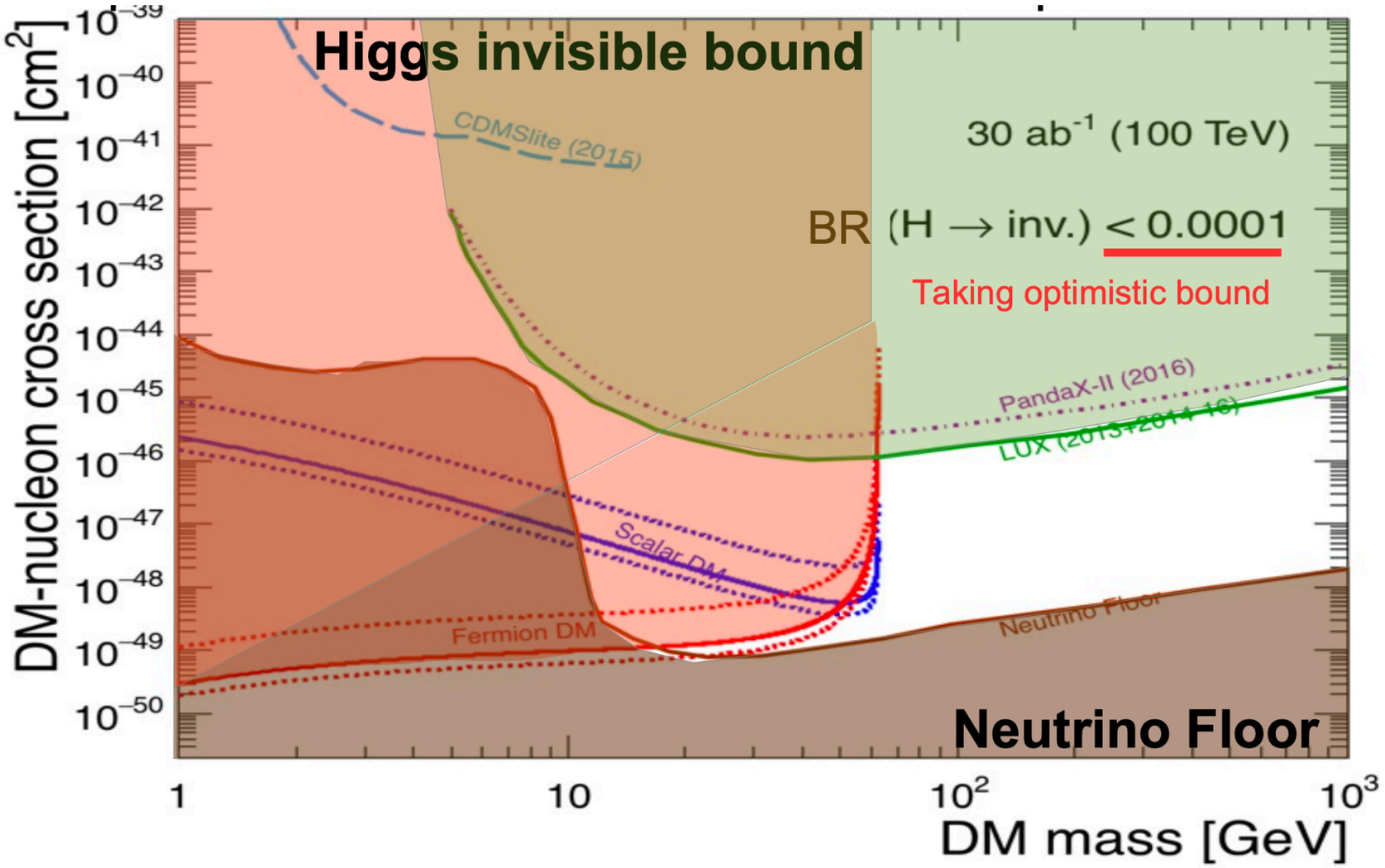
10% bound equates to ~ sin θ < 0.7 for 5 GeV DM

Higgs to boson coupling puts strong constraints

10% bound equates to ~ sin θ < 0.3 for any DM

Both invisible decay and Couplings play a critical role

Higgs to Invisible extrapolated



- In the long term we expect a Higgs to invisible limit of
  - Roughly 1-2% at the LHC
  - Roughly 10^{-4} at a 100 TeV machine

Going Forward

- The scalar singlet model provides an interesting model
  - It is a complete model that adds a new scalar to the SM
  - This scalar can be observed if it is light
    - If its not, the best way to see it is through Higgs mixing
      - Higgs to invisible can provide the strongest constraint
      - Higgs couplings to standard model also can
- A full study of this model would be interesting
  - Would help to benchmark future High Energy DM searches