A Bound on the Dark Scale

Devin Walker
SLAC

arXiv:1306:XXXX

A (Very!) Brief History of New Physics

- Unitarity arguments dependably indicate when new physics will appear.

Fermi theory: Dimension six operators violate unitarity around 350 GeV.

Rescued: W boson at 80 GeV.

A (Very!) Brief History of New Physics

- Unitarity arguments dependably indicate when new physics will appear.

Pion effective theory: Light pion scattering violates unitarity around 1.2 GeV.

Resolved by the appearance of axial and vector resonances at 800 MeV.

A (Very!) Brief History of New Physics

- Unitarity arguments dependably indicate when new physics will appear.

Electroweak theory: WW scattering requires new physics around 1.2 TeV.

Rescued: SM higgs boson at 125.5 GeV.

New Physics?

- Basic Question: What is next?

  - Assuming thermal dark matter can we construct a unitarity argument to place a bound on when new physics must appear?

- Central Question for Snowmass:

  Is this scale/new physics obtainable for foreseeable searches? To what extent must existing/planned experiments probe (LHC, direct detection...)?

Today

- Focus on higgs portal dark matter annihilation from a hidden sector*.

  Very briefly ...

  1. Cover the simplest unitarity argument.

  2. Place bounds on the "dark" higgs which mixes with the SM higgs.

*See arXiv:1306:XXXX for more details and other scenarios.

Previous Work
(for Unitarity + Dark Matter)

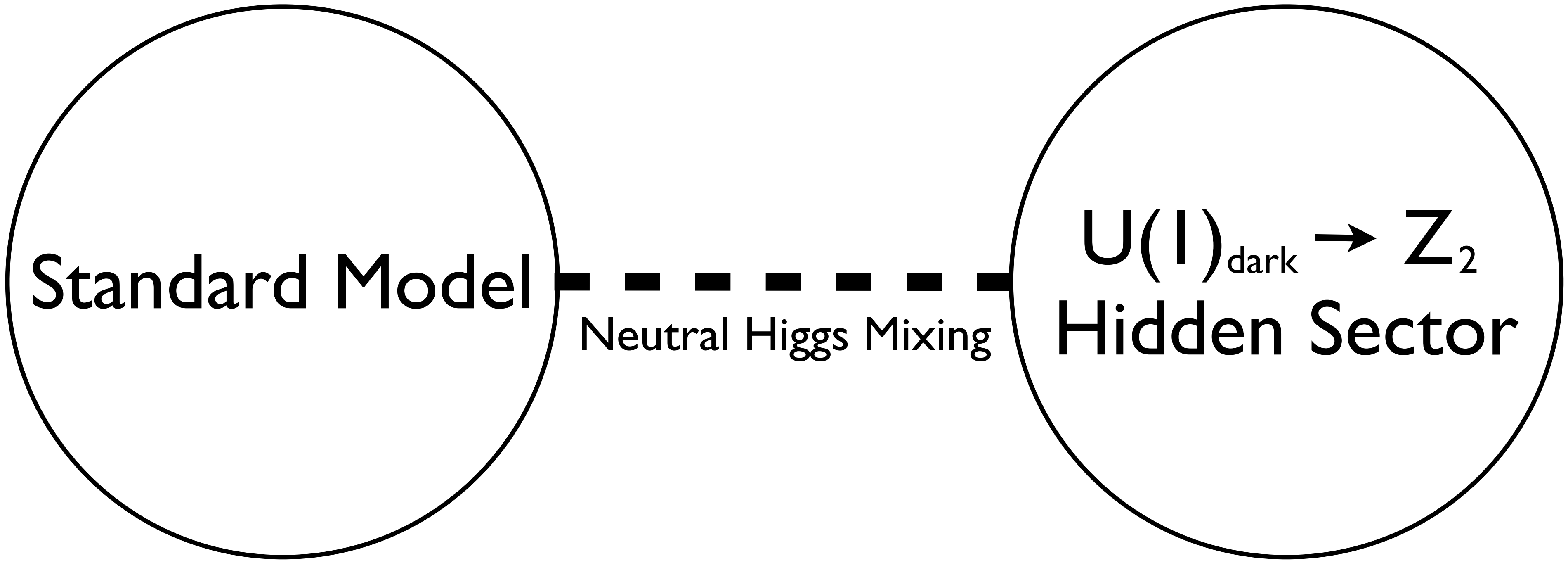
- Griest and Kamionkowski, PRL 64 (1990) 615.

  Basic bounds on thermal dark matter mass from the annihilation cross section and relic abundance. Maximum mass of the dark matter must be less than ~ 120 TeV.

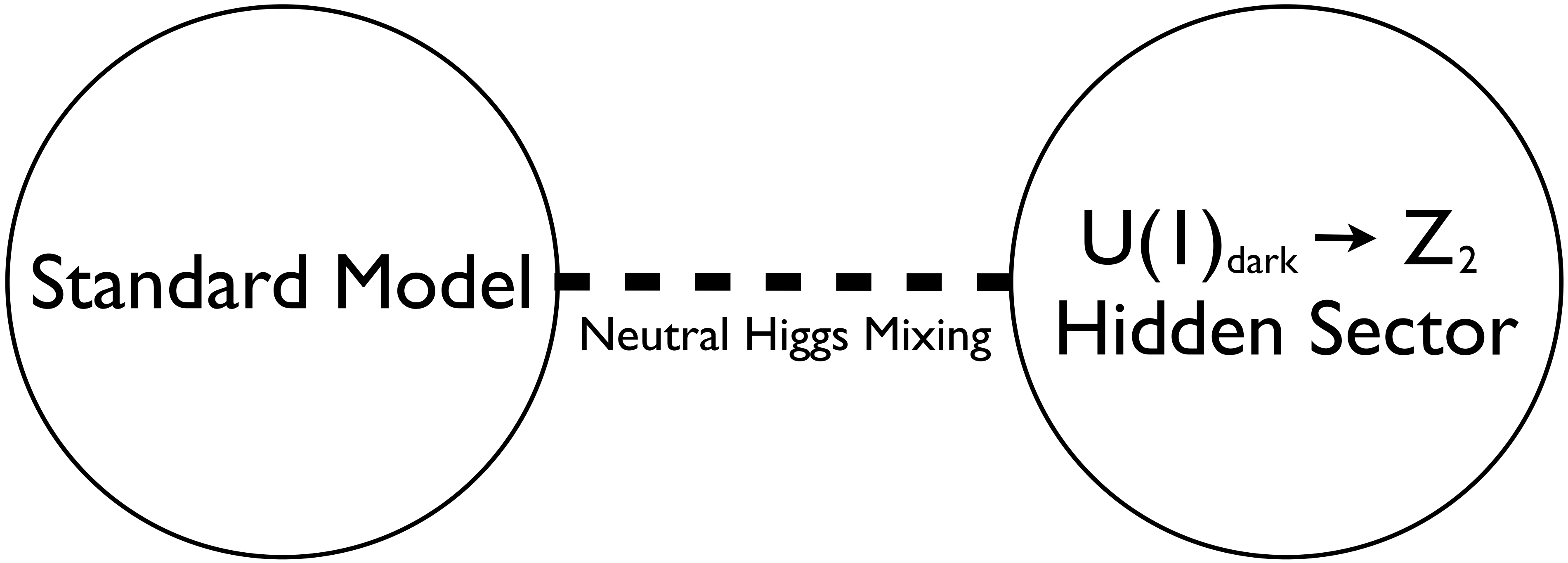
- Shoemaker and Vecchi, PRD 86 (2012) 015023.

  Focused on dark matter-quark and dark matter-gluon irrelevant operators. Use to constrain direct detection experiments and monojet searches.

A Generic Higgs Portal



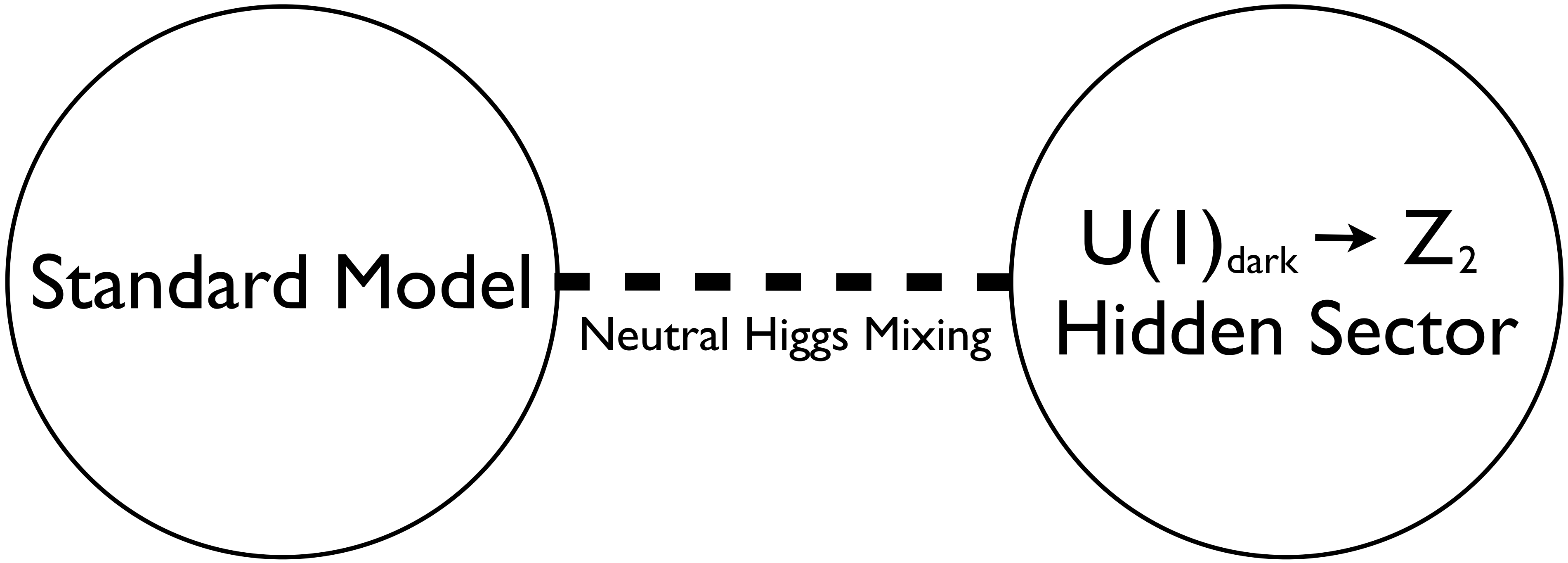
A Generic Higgs Portal



$$V = \lambda_1 \left(h^\dagger h - \frac{v^2}{2}\right)^2 + \lambda_2 \left(\phi^* \phi - \frac{u^2}{2}\right)^2 + \lambda_3 \left(h^\dagger h - \frac{v^2}{2}\right)\left(\phi^* \phi - \frac{u^2}{2}\right),$$

$$\mathcal{L} = \lambda_\chi \, \chi_L \, \chi_R \, \phi$$

A Generic Higgs Portal



Masses and mixing:

$$\begin{pmatrix} h' \\ \rho' \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h \\ \rho \end{pmatrix}$$

$$m_h^2 = 2\,\lambda_1 v^2 \left(1 - \frac{\lambda_3^2}{4\,\lambda_1 \lambda_2} + \ldots \right)$$

$$m_\rho^2 = 2\,\lambda_2\, u^2 \left(1 + \frac{\lambda_3^2}{4\,\lambda_2^2} \frac{v^2}{u^2} + \ldots \right)$$

$$\cos\theta \sim 1 - \frac{\lambda_3^2\, v^2}{8 \lambda_2^2\, u^2}$$

The Basic Unitarity Argument

- Consider WW scattering amplitudes:

$$
\begin{aligned}
\mathcal{M}_{\text{gauge}} &= \frac{g^2}{4\,m_W^2}(s+t) \\
\mathcal{M}_{\text{SM higgs}} &= -\frac{g^2}{4\,m_W^2}(s+t)\,\cos^2\theta \\
\mathcal{M}_{\text{dark higgs}} &= -\frac{g^2}{4\,m_W^2}(s+t)\,\sin^2\theta
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$$

Both higgses needed to unitarize WW scattering.

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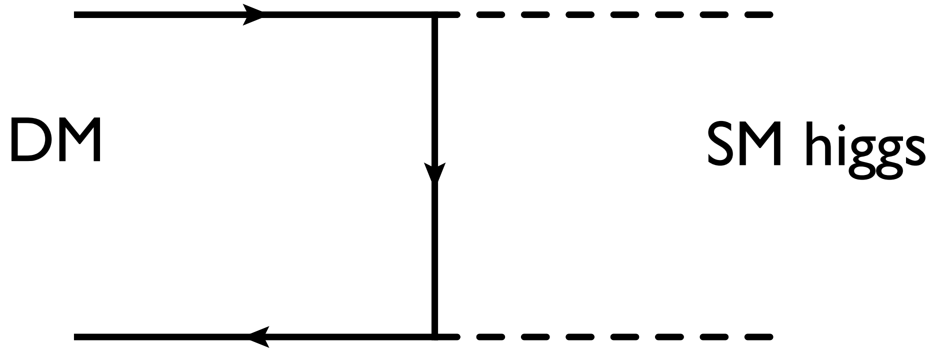
\end{aligned}
$$

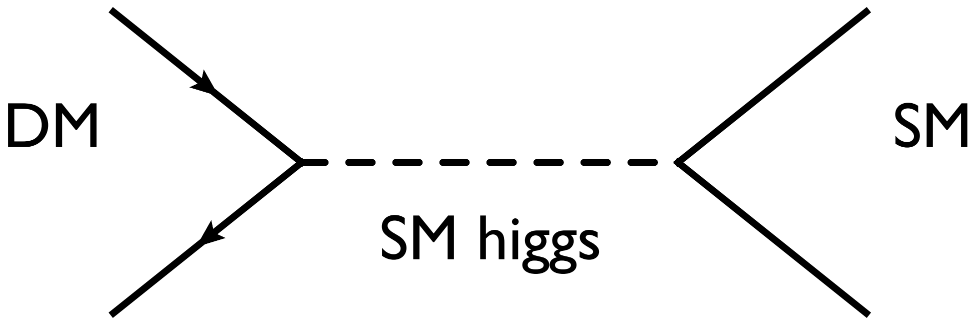
- Raise the dark higgs mass to be very large: $\sin\theta \to 0\,.$

However ... the Relic Abundance

- Dark higgs' mass is large: The correct relic abundance prevents $\sin\theta \to 0$.



$$\langle \sigma |v| \rangle \sim \frac{\sin^4\theta}{m_\chi^2}$$



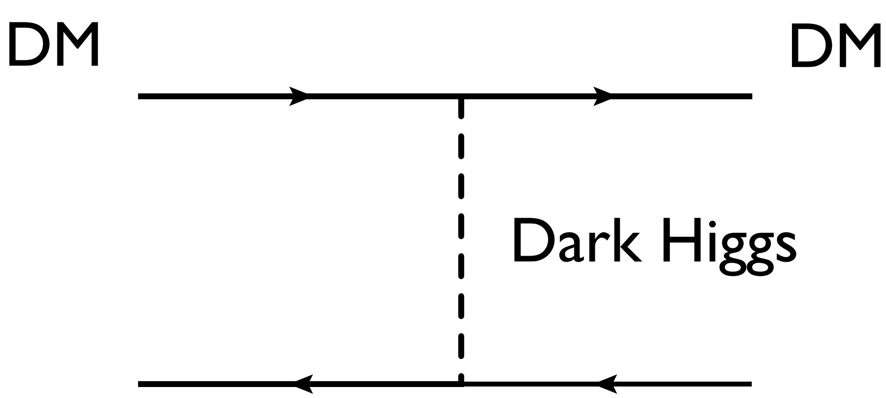
$$\langle \sigma |v| \rangle \sim \frac{\sin^2\theta\cos^2\theta}{m_\chi^2}$$

- Tension between unitarity and the relic abundance produces dark higgs mass bound.

Full Unitarity Considerations

- Dark matter - dark matter scattering

  (similar to Furman, Hinchliffe and Chanowitz's unitarity bounds on heavy 4th generation fermions)



Full Unitarity Considerations
(Goldstone Boson Limit)

$$\left(W_L^+W_L^-,\ \frac{Z_LZ_L}{\sqrt{2}},\ \frac{hh}{\sqrt{2}},\ \frac{\rho\rho}{\sqrt{2}},\ h\rho,\ hZ_L,\ \rho Z_L\right)$$

$$\mathcal{M}_I^{(0)} = -\frac{\lambda_1}{4\pi}\begin{pmatrix} 1 & \frac{1}{\sqrt{8}} & \frac{c^2}{\sqrt{8}} & \frac{s^2}{\sqrt{8}} & \frac{sc}{2} & 0 & 0 \\ \frac{1}{\sqrt{8}} & \frac{3}{4} & \frac{c^2}{4} & \frac{s^2}{4} & \frac{sc}{\sqrt{8}} & 0 & 0 \\ \frac{c^2}{\sqrt{8}} & \frac{c^2}{4} & \frac{3c^4}{4} & \frac{3s^2c^2}{4} & \frac{3\,sc^3}{\sqrt{8}} & 0 & 0 \\ \frac{s^2}{\sqrt{8}} & \frac{s^2}{4} & \frac{3\,s^2c^2}{4} & \frac{3s^4}{4} & \frac{3\,cs^3}{\sqrt{8}} & 0 & 0 \\ \frac{sc}{2} & \frac{sc}{\sqrt{8}} & \frac{3\,sc^3}{\sqrt{8}} & \frac{3\,cs^3}{\sqrt{8}} & \frac{3\,c^2s^2}{2} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{c^2}{2} & \frac{sc}{2} \\ 0 & 0 & 0 & 0 & 0 & \frac{sc}{2} & \frac{s^2}{2} \end{pmatrix} - \frac{\lambda_3}{4\pi}\begin{pmatrix} 0 & 0 & \frac{s^2}{\sqrt{32}} & \frac{c^2}{\sqrt{32}} & -\frac{sc}{4} & 0 & 0 \\ 0 & 0 & \frac{s^2}{8} & \frac{c^2}{8} & \frac{-sc}{\sqrt{32}} & 0 & 0 \\ \frac{s^2}{\sqrt{32}} & \frac{s^2}{8} & \kappa & \delta & \xi & 0 & 0 \\ \frac{c^2}{\sqrt{32}} & \frac{c^2}{8} & \delta & \alpha & \beta & 0 & 0 \\ -\frac{sc}{4} & -\frac{sc}{\sqrt{32}} & \xi & \beta & \eta & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{s^2}{4} & -\frac{sc}{4} \\ 0 & 0 & 0 & 0 & 0 & -\frac{sc}{4} & \frac{c^2}{4} \end{pmatrix}$$

Each eigenvalue satisfies: $\left|\mathrm{Re}\,\mathcal{M}^{(j)}\right| \leq \frac{1}{2}$

Full Unitarity Considerations
(Goldstone Boson Limit)

dark higgs

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Each eigenvalue satisfies: $\left|\mathrm{Re}\,\mathcal{M}^{(j)}\right| \leq \frac{1}{2}$

Parameter Scan

$$\{m_h, m_\rho, m_\chi, \sin\theta, u\}$$

$$\downarrow$$

$$\{\lambda_1, \lambda_2, \lambda_\chi, \lambda_3, u\}$$

Hidden sector symmetry breaking vev.

$$V = \lambda_1 \left(h^\dagger h - \frac{v^2}{2}\right)^2 + \lambda_2 \left(\phi^* \phi - \frac{u^2}{2}\right)^2 + \lambda_3 \left(h^\dagger h - \frac{v^2}{2}\right)\left(\phi^* \phi - \frac{u^2}{2}\right)$$

Parameter Scan

$$\{m_h, m_\rho, m_\chi, \sin\theta, u\}$$

$$\{\lambda_1, \lambda_2, \lambda_\chi, \lambda_3, u\}$$

Goldstone-higgs scattering produces unitarity constraints for higgs potential couplings.

$$V = \lambda_1 \left(h^\dagger h - \frac{v^2}{2}\right)^2 + \lambda_2 \left(\phi^* \phi - \frac{u^2}{2}\right)^2 + \lambda_3 \left(h^\dagger h - \frac{v^2}{2}\right)\left(\phi^* \phi - \frac{u^2}{2}\right)$$

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Goldstone-higgs scattering indirectly constrains the dark symmetry breaking scale.

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Parameter Scan

$$\{m_h, m_\rho, m_\chi, \sin\theta, u\}$$

$$\downarrow$$

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Dark matter-dark matter scattering produces unitarity constraints for these couplings .

$$V = \lambda_1 \left(h^\dagger h - \frac{v^2}{2}\right)^2 + \lambda_2 \left(\phi^*\phi - \frac{u^2}{2}\right)^2 + \lambda_3 \left(h^\dagger h - \frac{v^2}{2}\right)\left(\phi^*\phi - \frac{u^2}{2}\right)$$

Parameter Scan

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Parameter Scan

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$$\{\lambda_1, \lambda_2, \lambda_\chi, \lambda_3, u\}$$

Relic Abundance constrains these couplings and the dark symmetry breaking scale.

$$V = \lambda_1 \left(h^\dagger h - \frac{v^2}{2}\right)^2 + \lambda_2 \left(\phi^* \phi - \frac{u^2}{2}\right)^2 + \lambda_3 \left(h^\dagger h - \frac{v^2}{2}\right)\left(\phi^* \phi - \frac{u^2}{2}\right)$$

Parameter Scan

$$\{m_h, m_\rho, m_\chi, \sin\theta, u\}$$

$$\downarrow$$

$$\{\lambda_1, \lambda_2, \lambda_\chi, \lambda_3, u\}$$

SM higgs mass constraint relates

$$m_h^2 \;=\; 2\,\lambda_1 v^2 \left(1 - \frac{\lambda_3^2}{4\,\lambda_1 \lambda_2} + \ldots\right)$$

Parameter Scan

$$\{m_h, m_\rho, m_\chi, \sin\theta, u\}$$

$$\downarrow$$

$$\{\lambda_1, \lambda_2, \lambda_\chi, \lambda_3, u\}$$

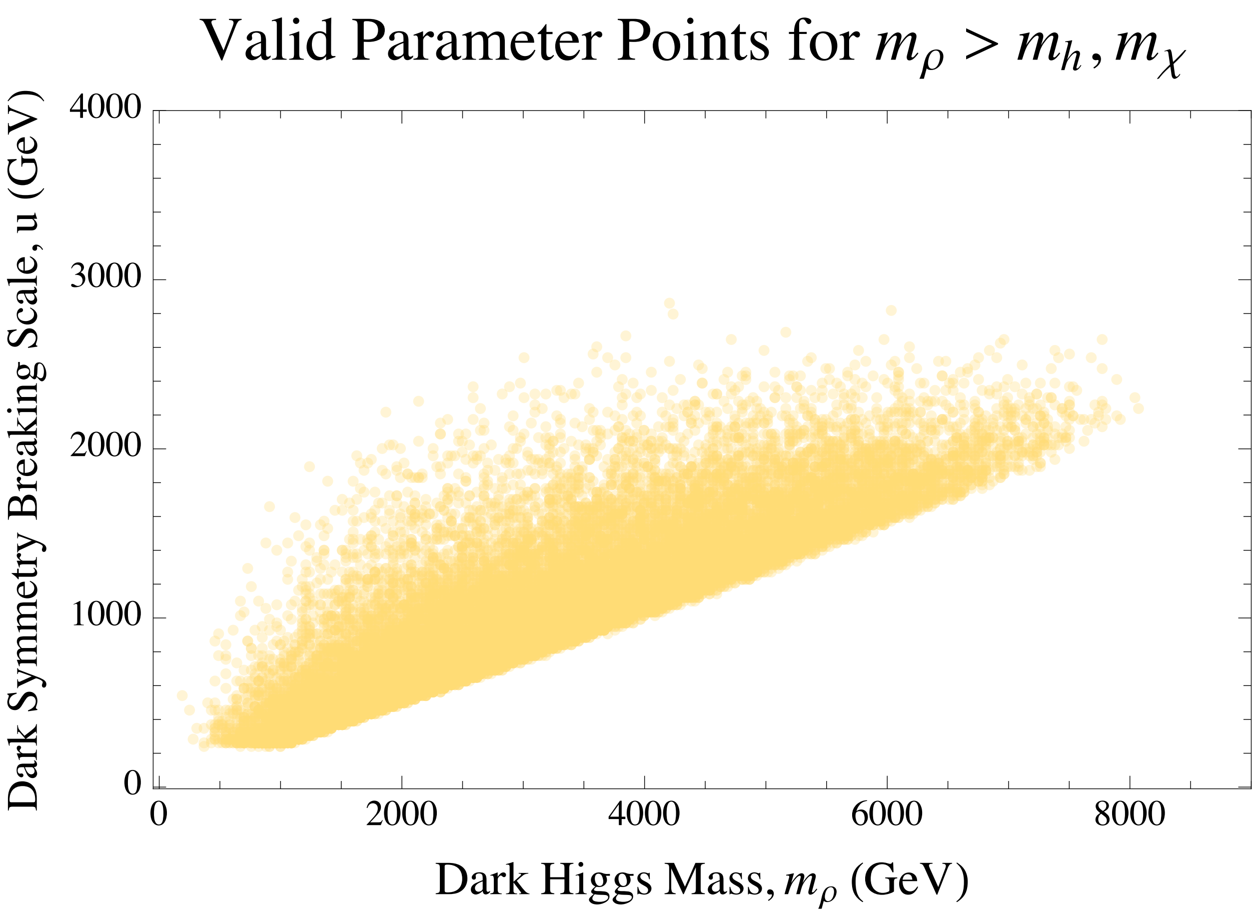
Additional considerations for the initial parameter scan:

1. Dark Matter must be cold.

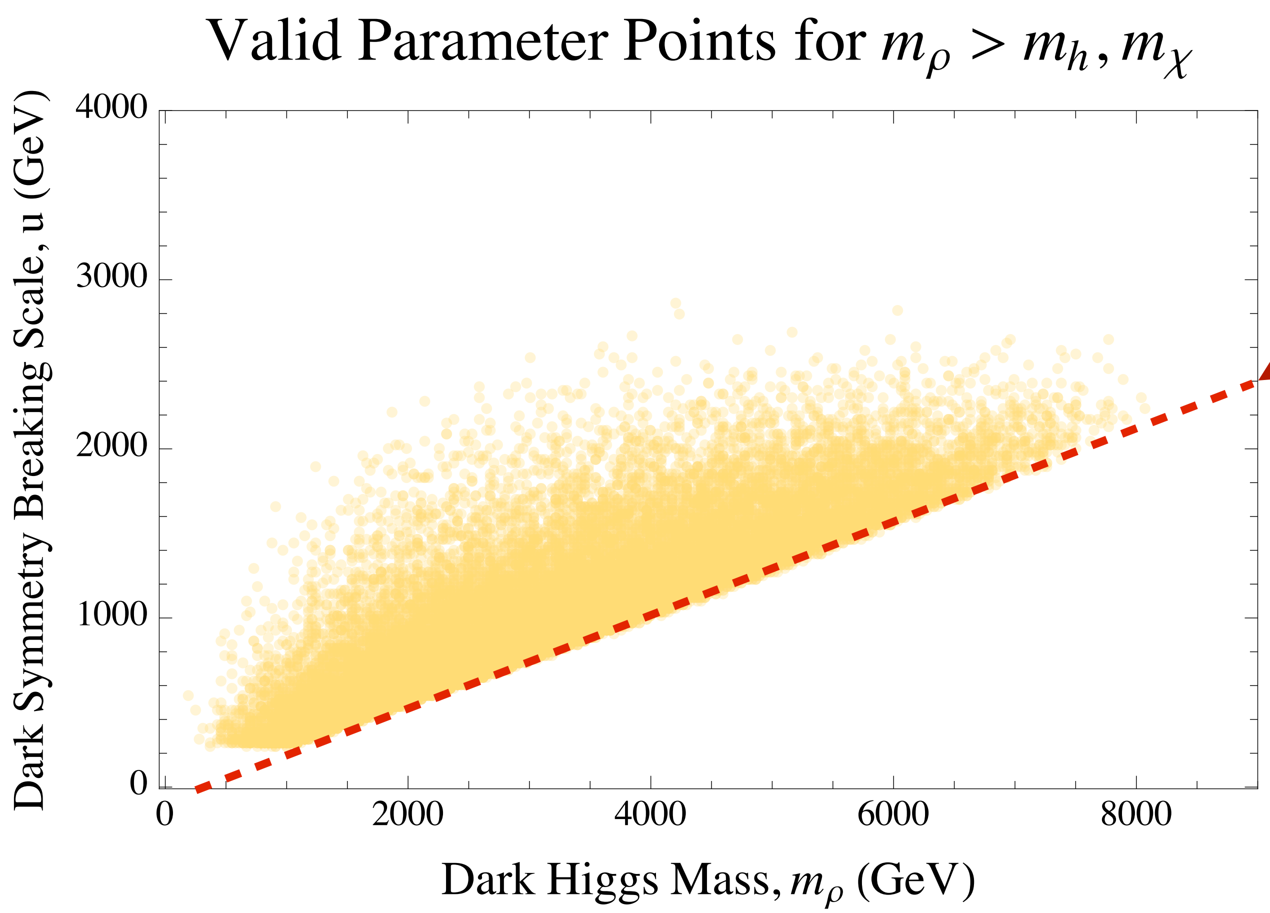
2. SM Higgs Mixing Constraints @ 95% c.l.

3. Invisible Higgs Decay (when applicable) ...

Unitarity Bounds



Unitarity Bounds



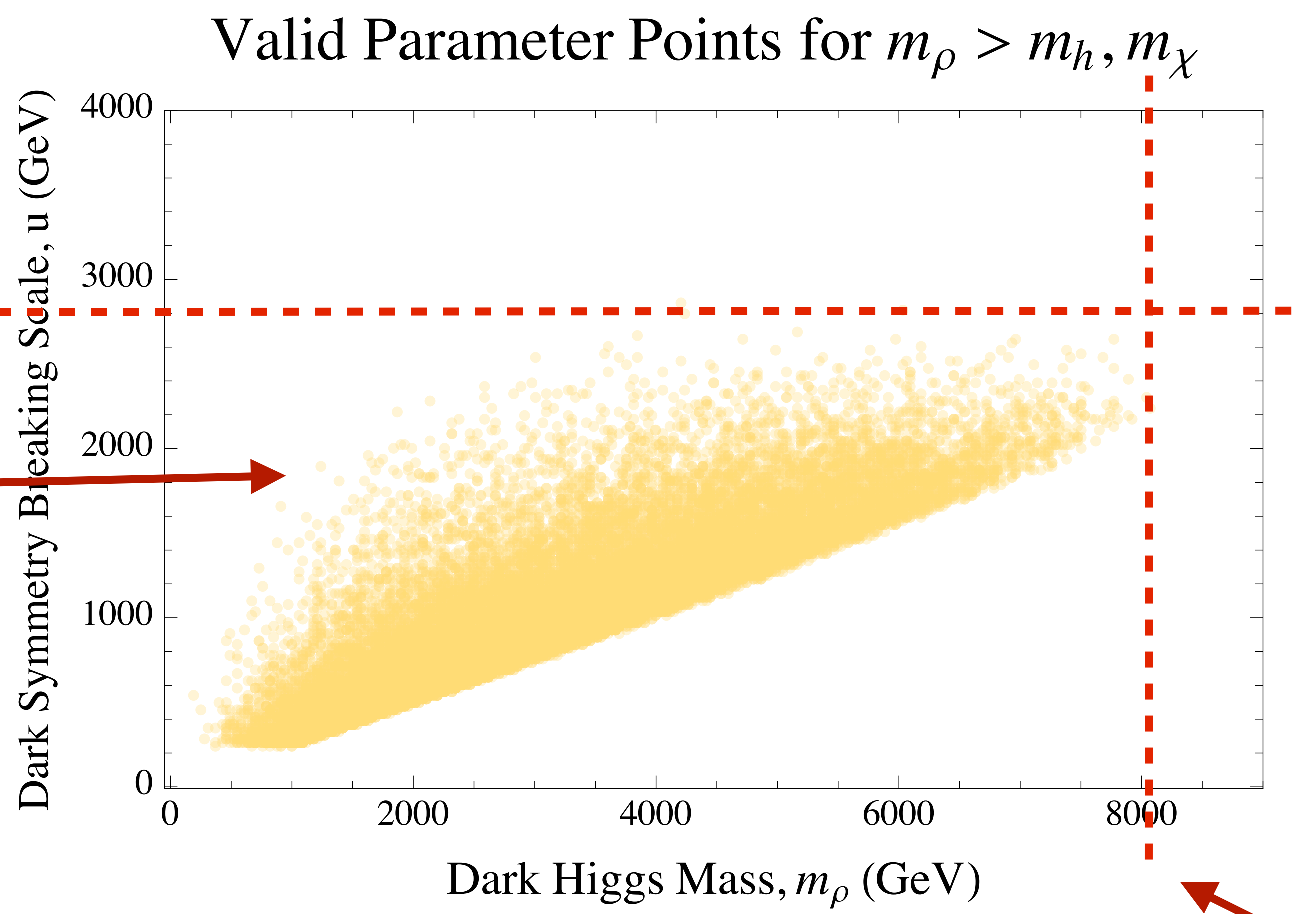
$m_\rho^2 \sim 2\lambda_2\, u^2$

Consistent w/
Lee, Quigg, Thacker

Unitarity Bounds

Upper bound on dark symmetry breaking vev.

Set by relic abundance constraint (upper 3σ limit)

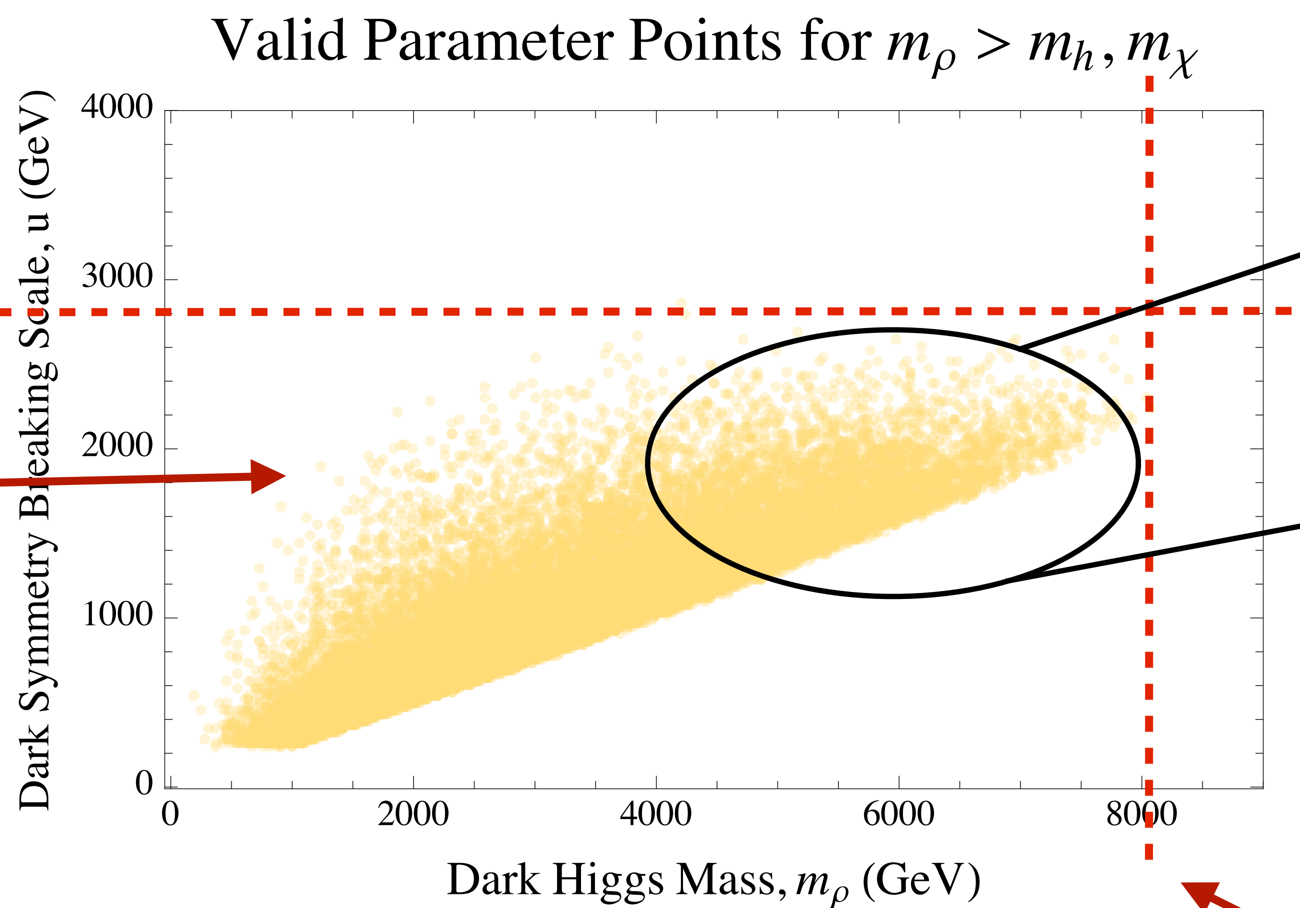


Upper bound on dark higgs mass

Unitarity Bounds

Upper bound on dark symmetry breaking vev.

Set by relic abundance constraint (upper 3σ limit)

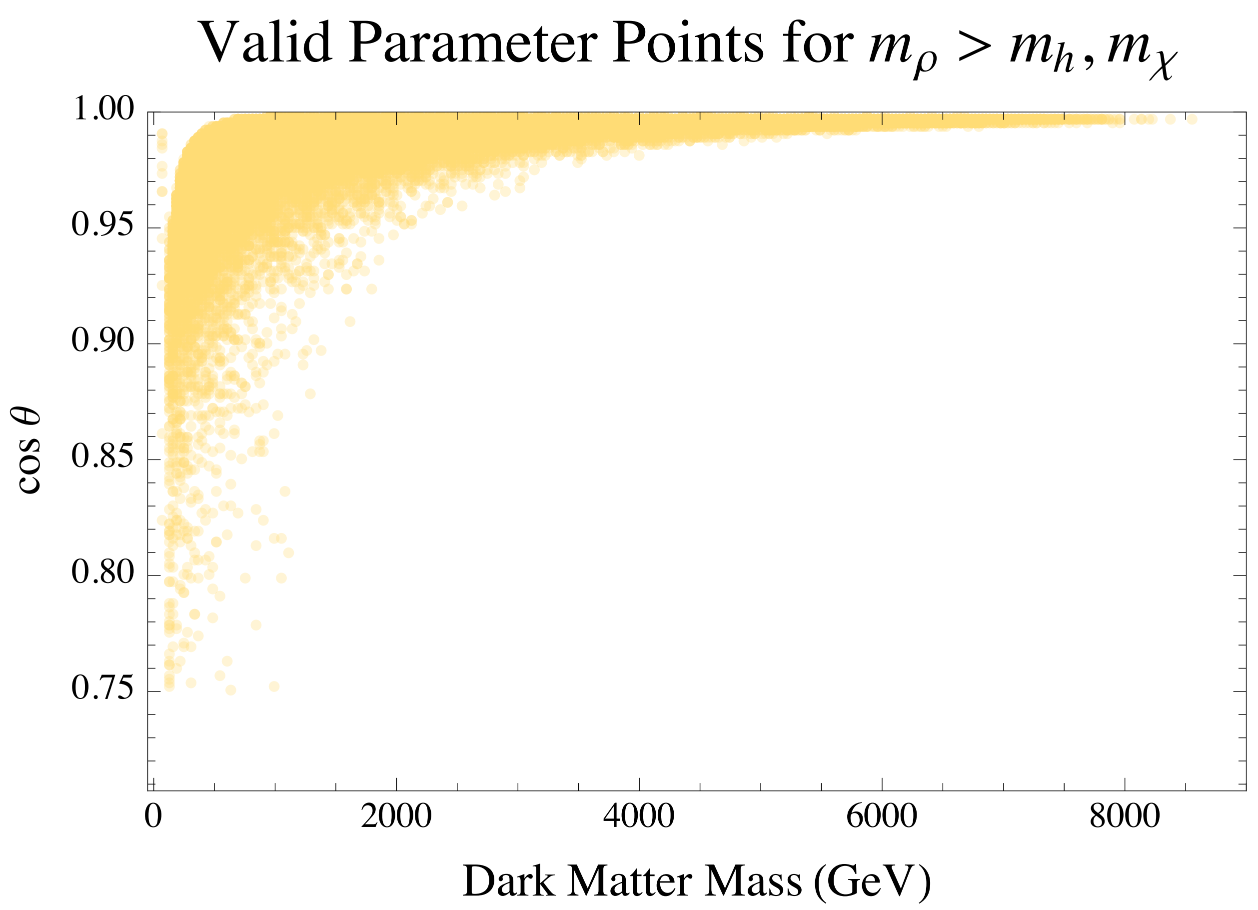


$\lambda_{2,3} \sim \{6, \lesssim 8.5\}$

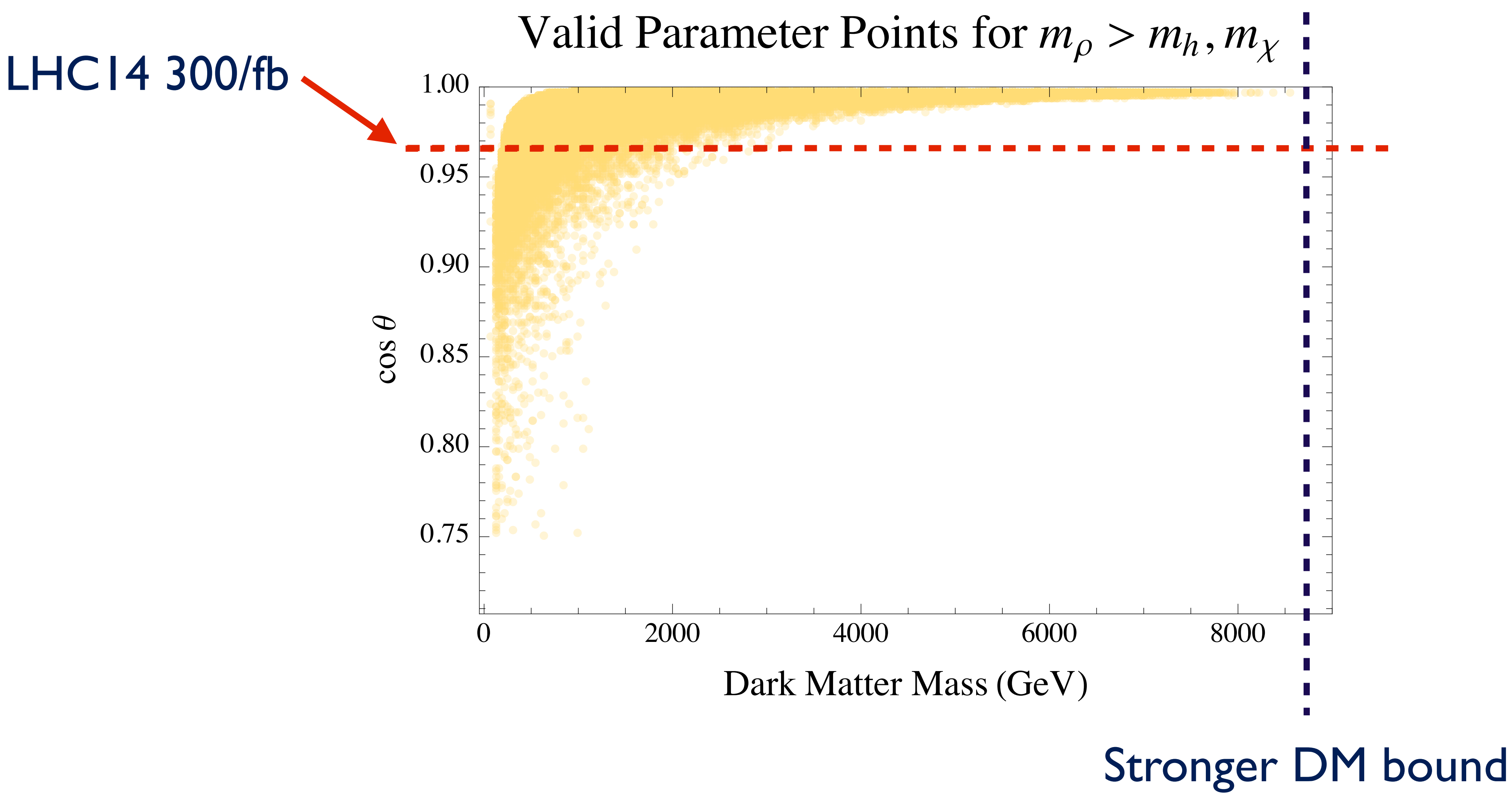
$\lambda_\chi \sim \{2.5, < 4\}$

Upper bound on dark higgs mass

Unitarity Bounds



Unitarity Bounds



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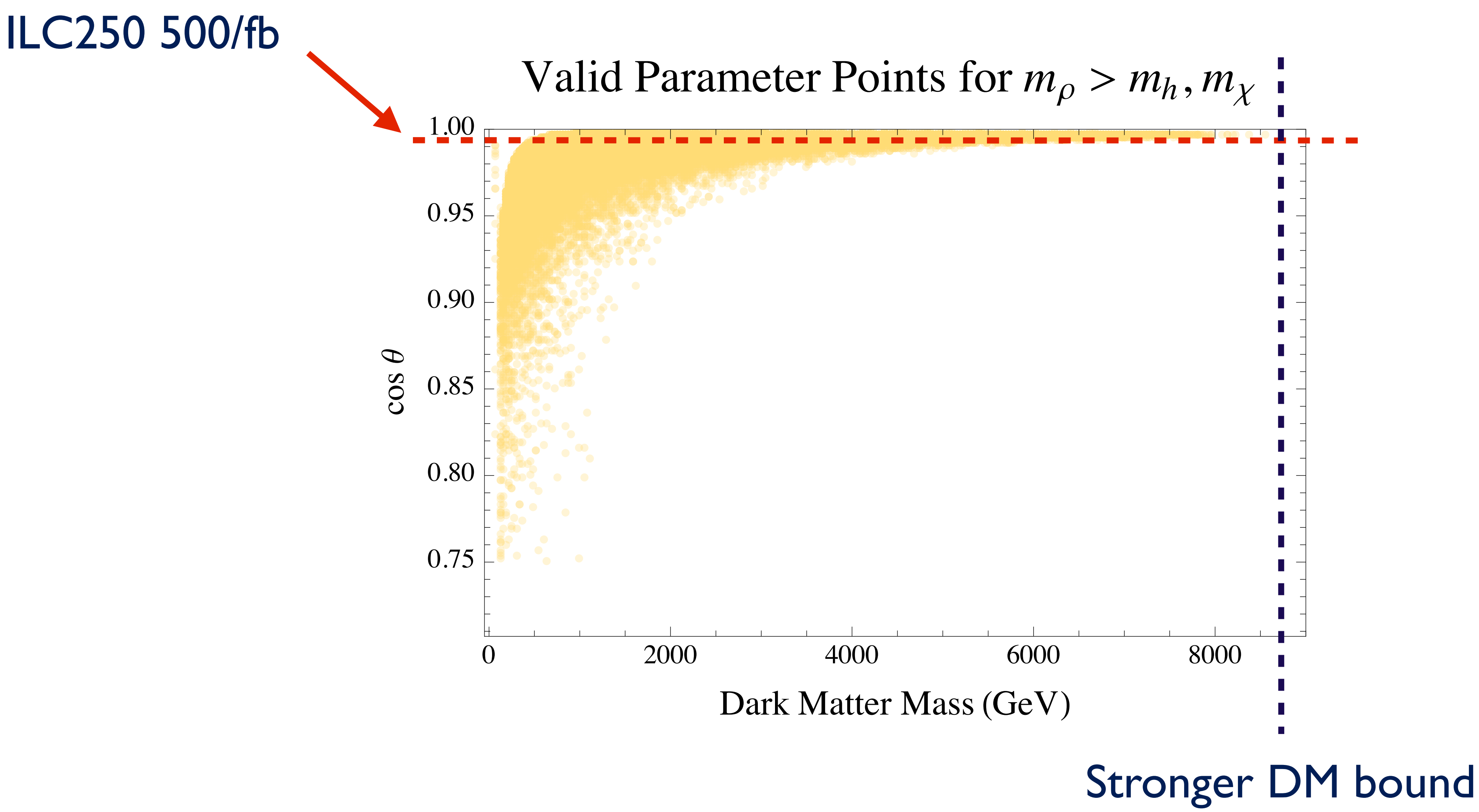

Unitarity Bounds

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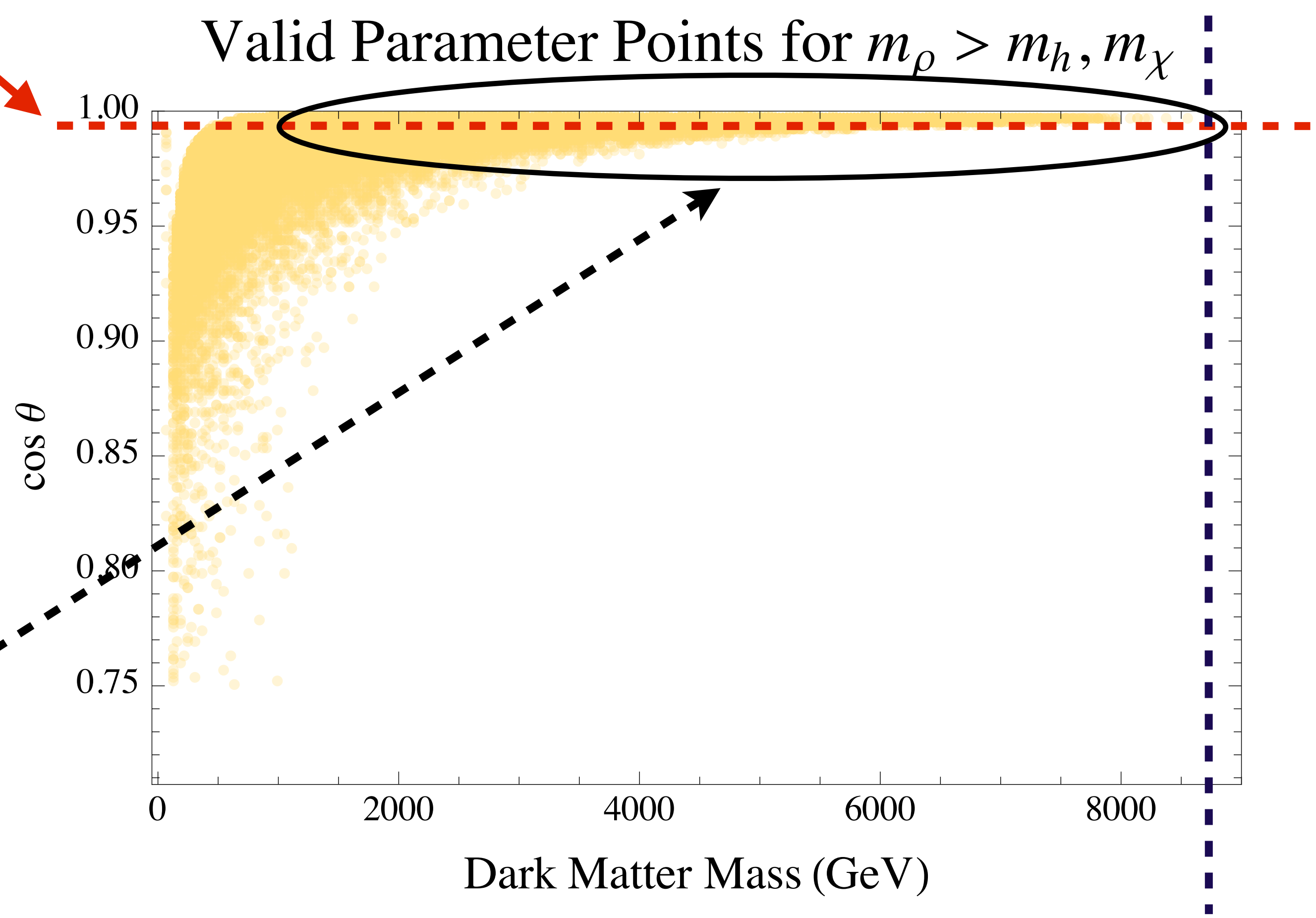


$\lambda_{2,3} \sim \{6, \lesssim 8.5\}$

$\lambda_\chi \sim \{2.5, < 4\}$

Stronger DM bound

Unitarity Bounds + Perturbativity?

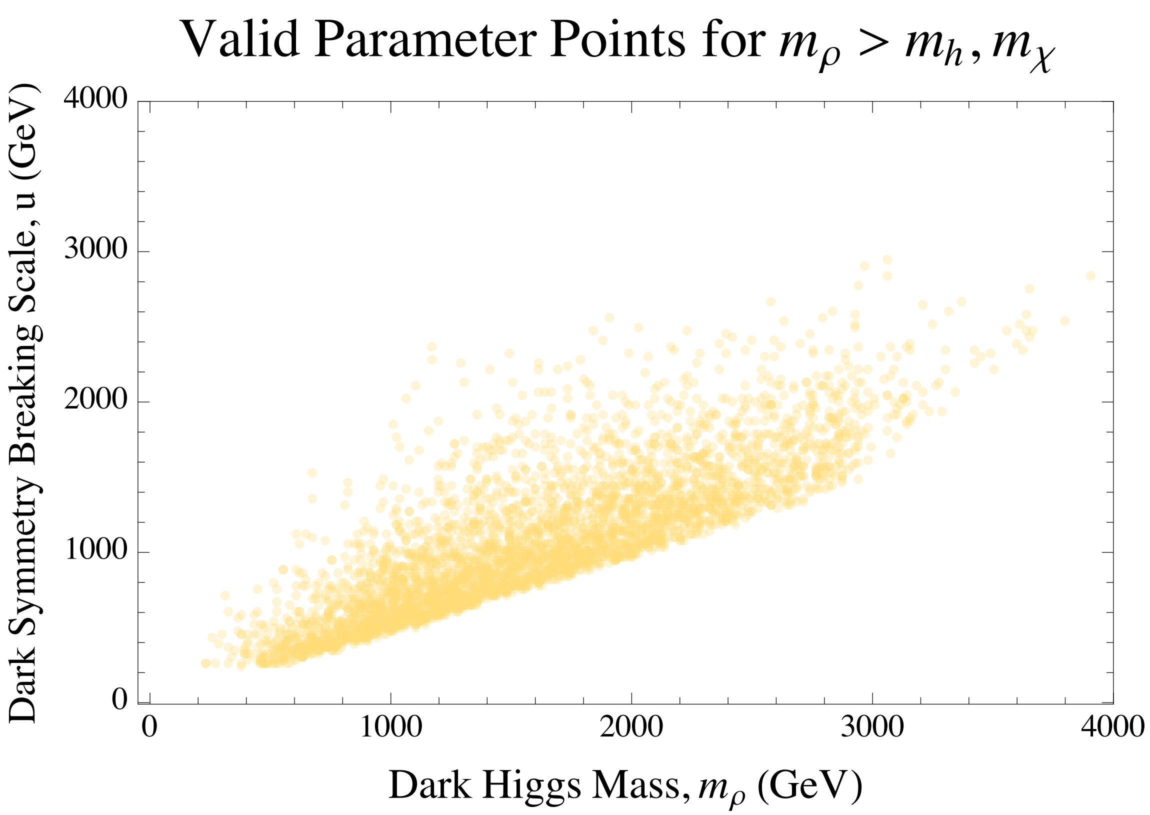
- Can we refine the parameter space?

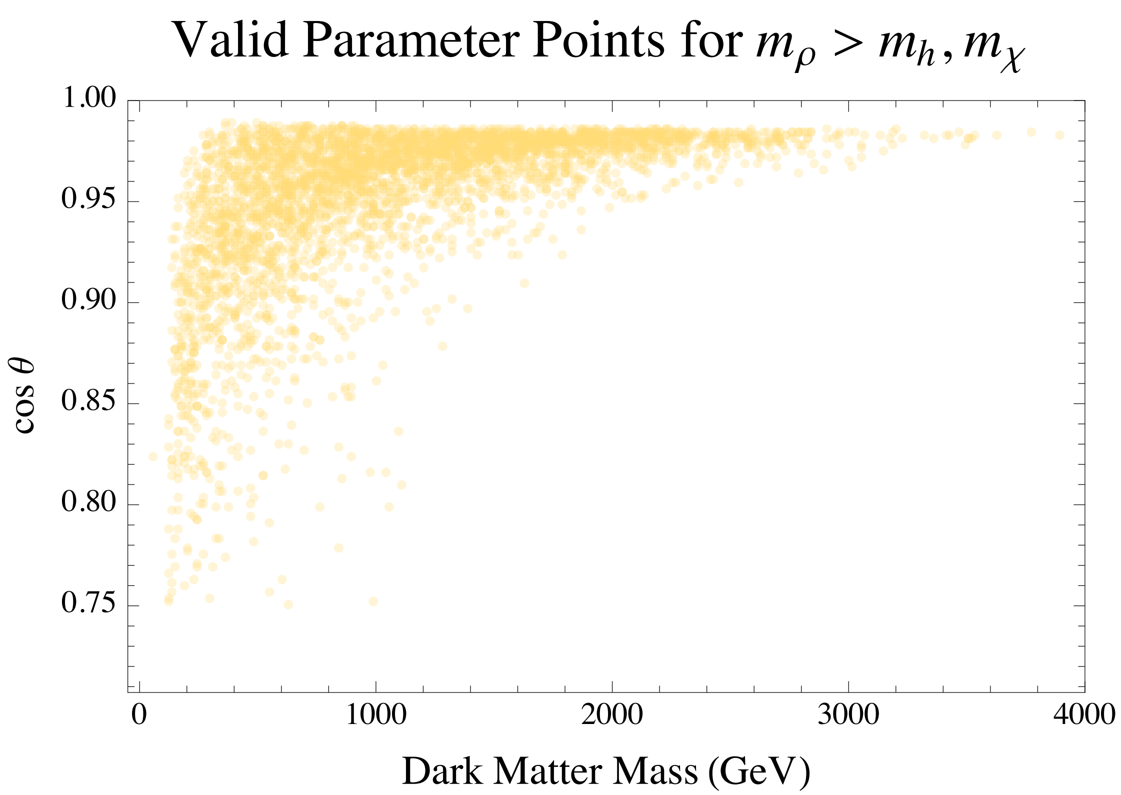
  Today consider requiring an absence of Landau poles up to 10 TeV.*

  Require a triviality bound for the points with a dominant dark yukawa coupling.

*Applied 1-loop RGEs and modified the perturbativity arguments in Barbieri, Hall and Rychkov. Modifications were for this higgs portal scenario.

Unitarity Bound + Perturbativity*





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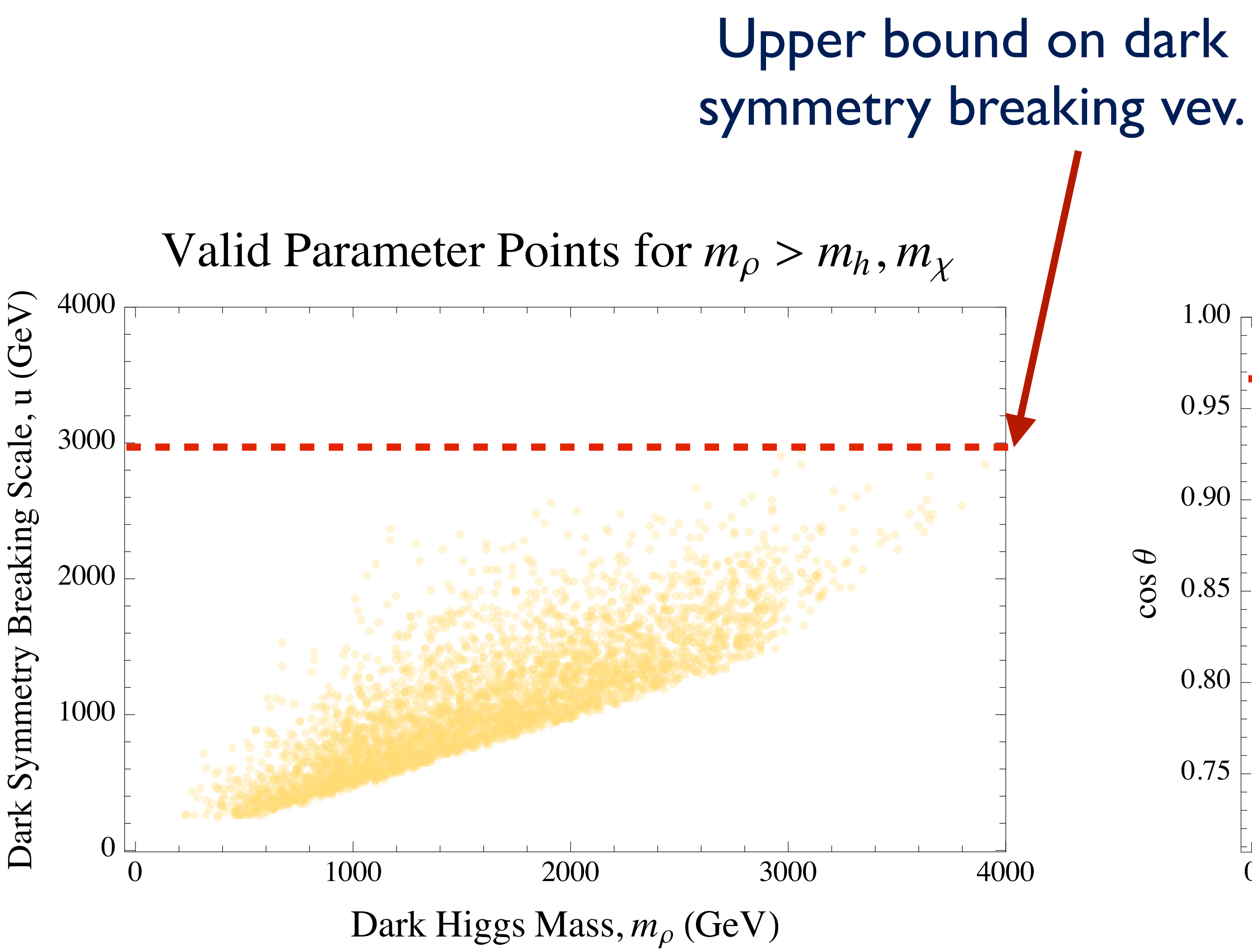
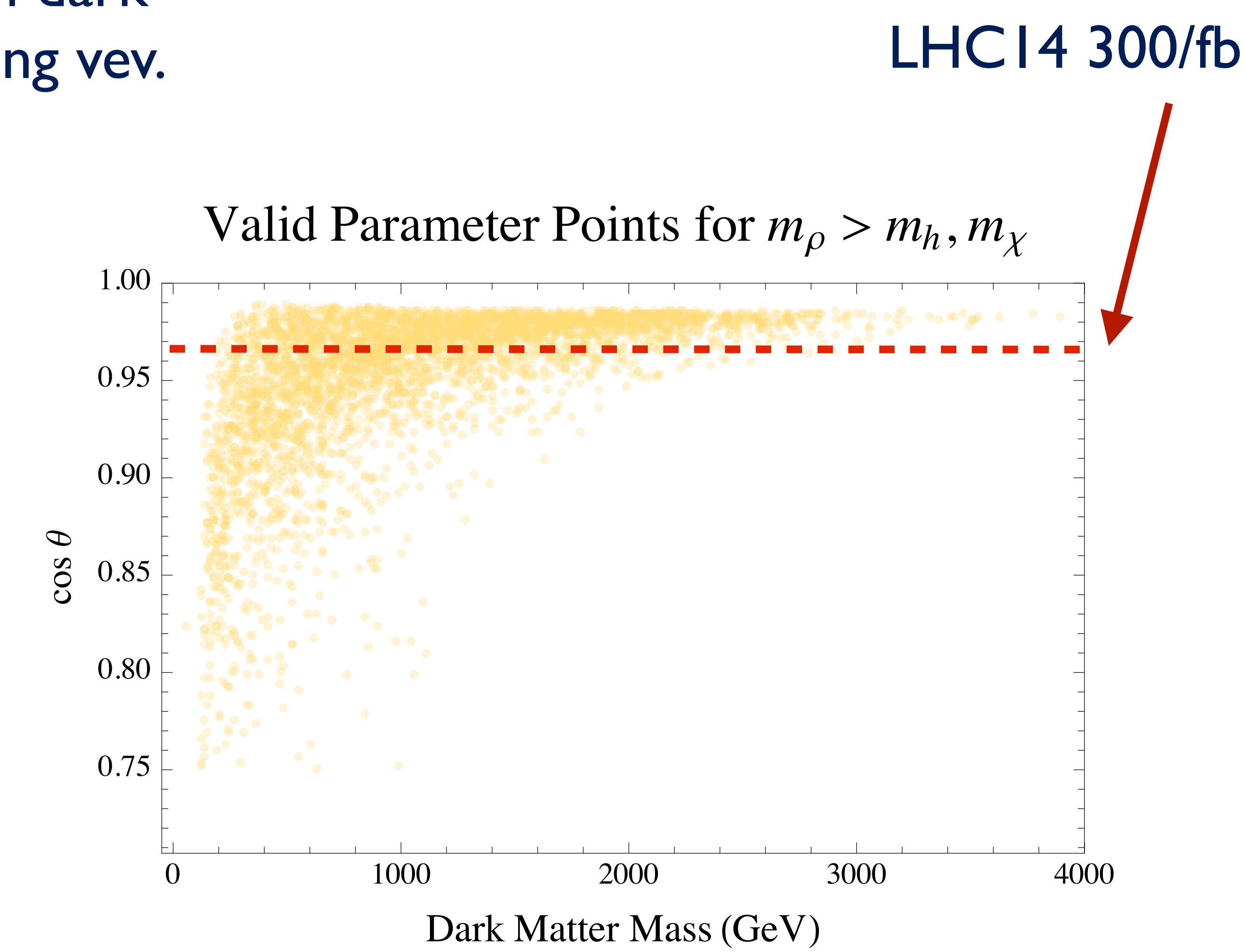
Unitarity Bound + Perturbativity*





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Unitarity Bound + Perturbativity*

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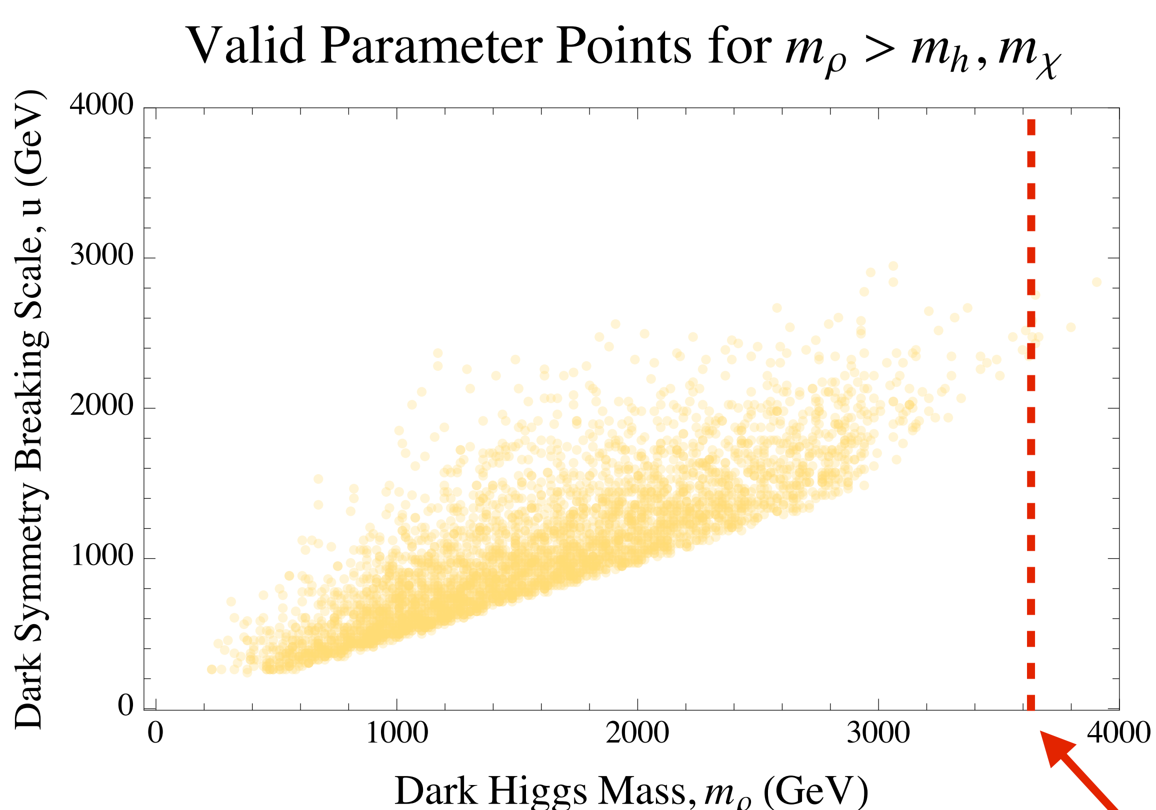

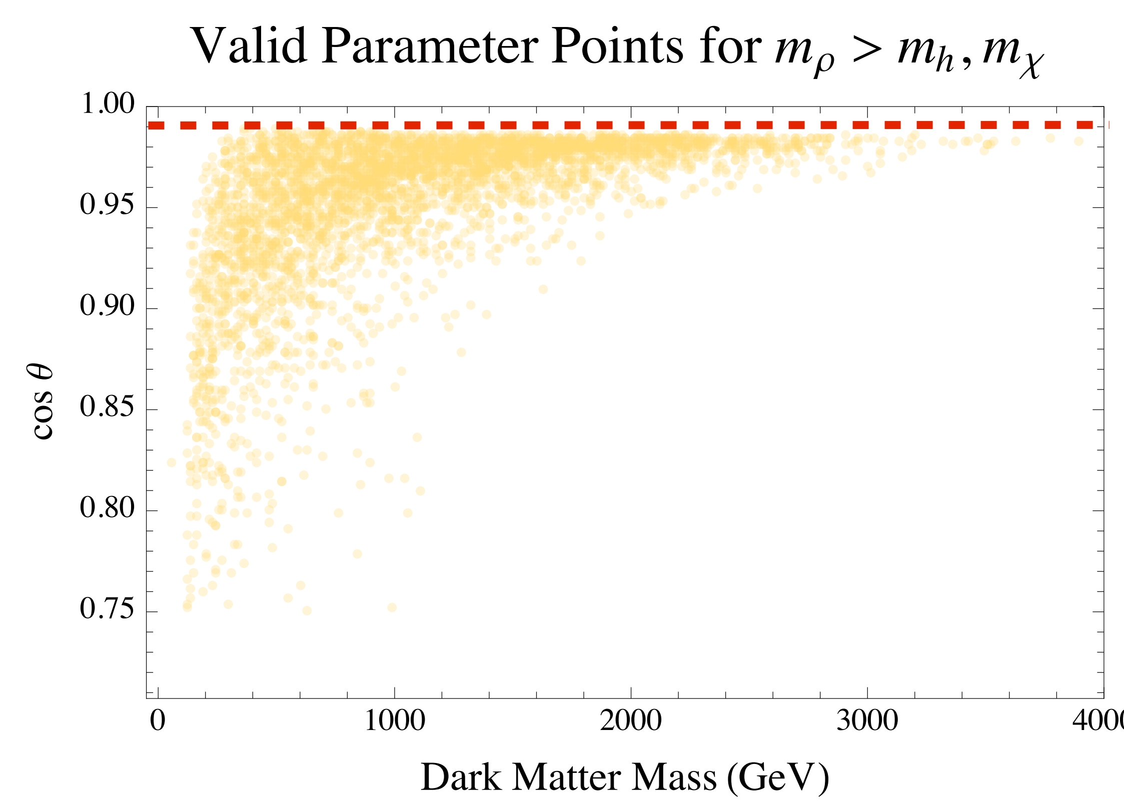

LHC14 300/fb

Upper bound on dark higgs mass

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Takeaways...

- It may be possible for new physics to be "around the corner" for (well motivated) thermal dark matter + mediators.

- Questions for the Snowmass Contribution:

  Connection between new scale/new physics obtainable for foreseeable searches? To what extent must existing/planned experiments probe (LHC, direct detection...)?

Thank you!

A Perspective

- Today: Focus on higgs portal dark matter annihilation from a hidden sector.

Many reasons for mediators:

1. Direct detection largely rules out Z boson dark matter/nucleon scattering (heavy neutrino).

2. Precision electroweak gives strong constraints on dark matter that obtains mass solely from EWSB.*

3. Implies new mediator particles and a new physics scale associated with the dark matter mass.

   and more . . .

*E.g., Cotta, Hewett, Tait and DW, to appear.

Previous Work
(for Unitarity + Dark Matter)

- Cynolter, Lendvai and Pocsik, Acta Phys. Polon. B36 827

  Constrains scalar dark matter-higgs couplings. No bound on dark matter mass.