Perturbative Unitarity Constraints on Thermal Dark Matter Portals

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with K. Betre, M. Cahill-Rowley, S. El Hedri and W. Shepherd

Dark matter represents (perhaps) the strongest case for new physics beyond the Standard Model.

Simplest thermal dark matter models ruled out.
DM portals are not.

What's Dark Matter Portal?

DM Portal = DM + mediator particles

"Mediator" particles help the dark matter get the right relic abundance yet avoid stringent direct/indirect detection constraints.

Mediator particles couple directly to dark matter but mix with SM particles.

What's Dark Matter Portal?

A Classification:

Higgs Portal

Gauge Portal

Charged/Colored
Portal

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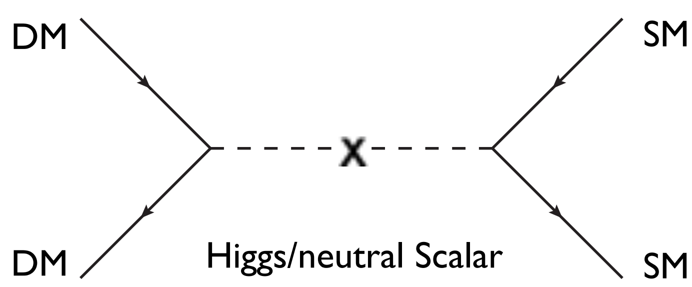

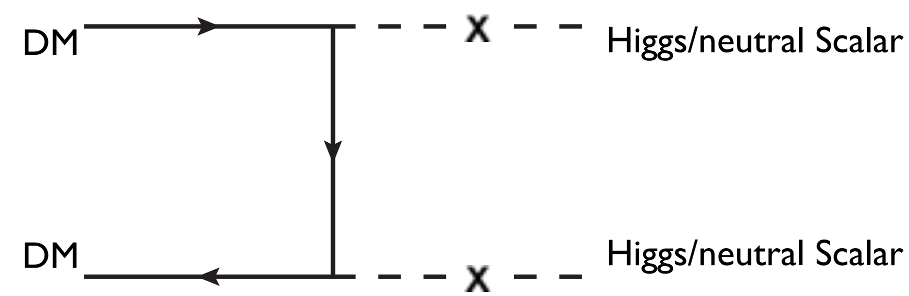

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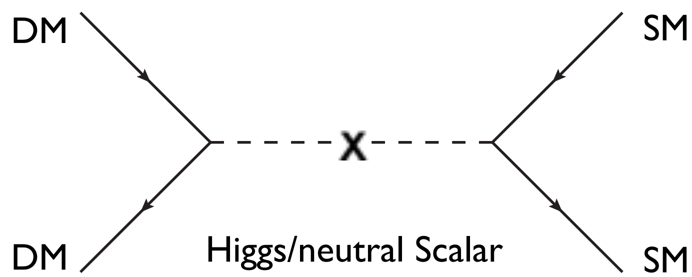

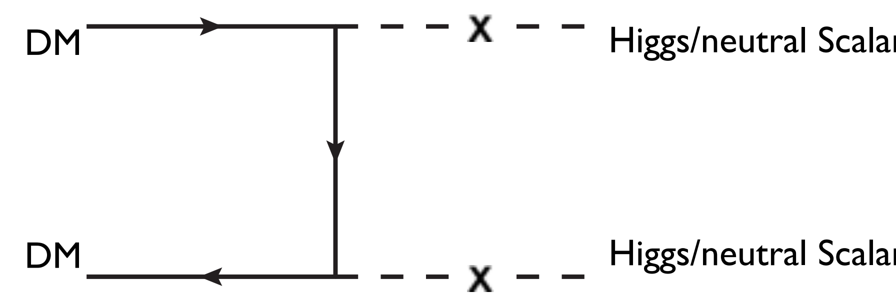

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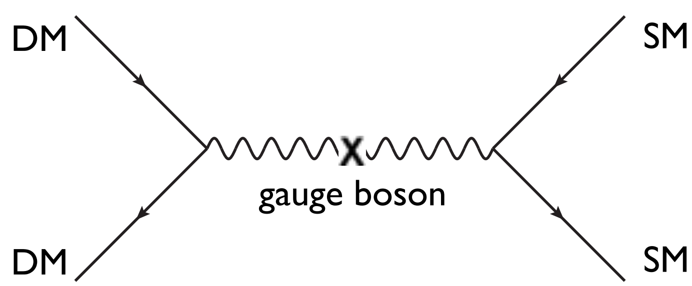

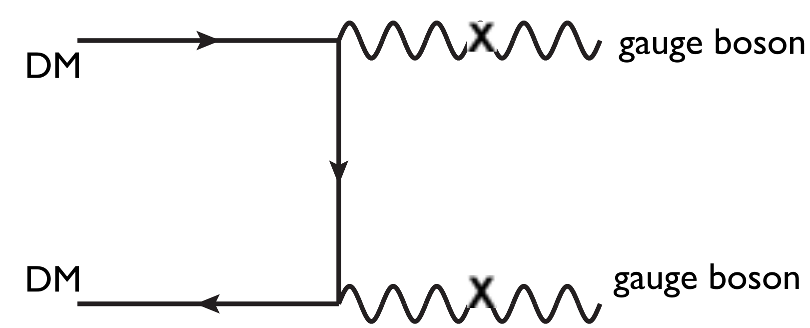

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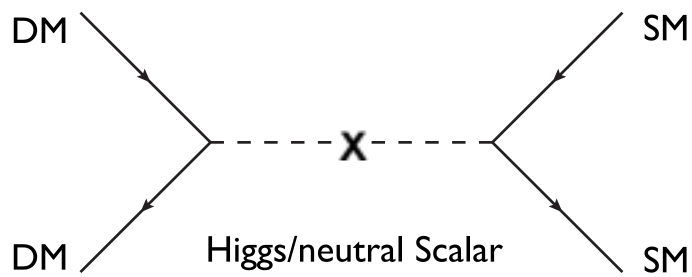

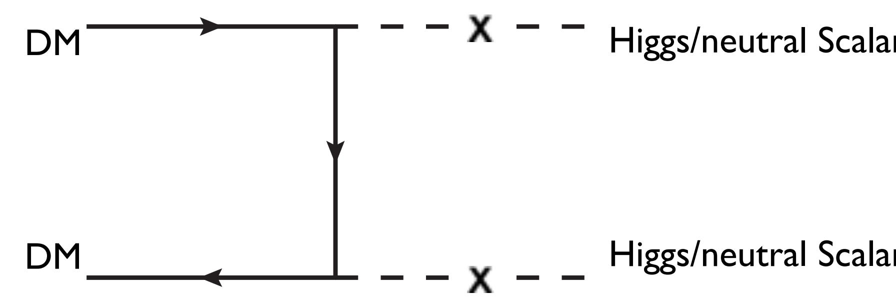

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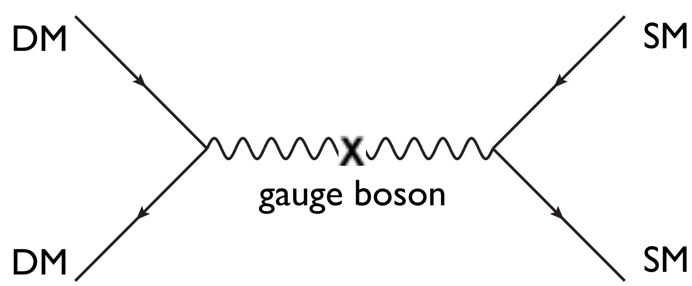

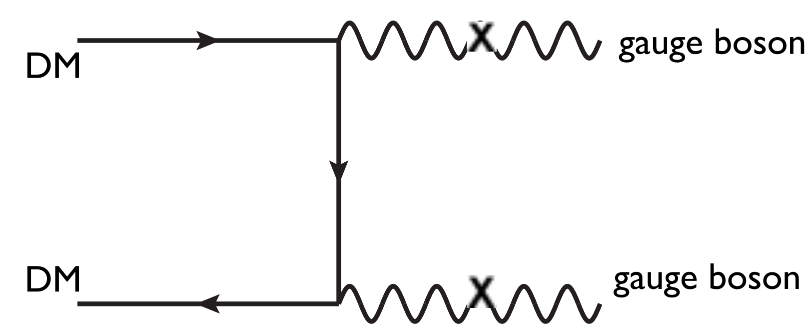

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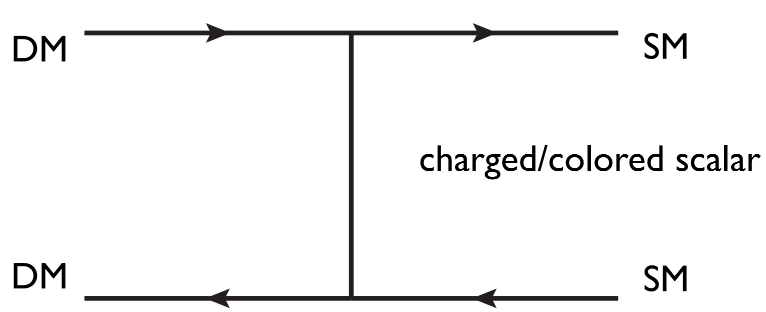

(also known as DM SUSY processes)

Today's Talk

Higgs Portal

Gauge Portal

Charged/Colored
Portal

Focus on theory constraints on these models. Want the basic arguments.

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Higgs Portal

Focus on theory constraints on these models. Want the <u>basic arguments</u>.

Gauge Portal

Charged/Colored Portal

Discuss theory constraints only if time permits.

Today's Talk

- Basic Higgs Portal Arguments

- A Higgs Portal (in more detail)

- Why Perturbativity Matters

- Conclusions/Other Portals

Basic Higgs Portal Arguments*

* Walker, 2013

The Problem in Particle Physics

No large coefficients of dimension six operators to tell us when (and what) new physics will appear.

So What Did Physicists Do Historically?

Dimension Six Operators + Perturbative Unitarity Constraints =

Reasonable Expectation of the Scale of New Physics

Examples from History

Fermi theory: Dimension six operators violate unitarity around 350 GeV. Rescued: W boson at 80 GeV.

Light pion effective theory: Pion scattering violates unitarity around 1.2 GeV. Rescued: Axial and vector resonances at 800 MeV.

Electroweak Theory: WW scattering requires new physics around 1.2 TeV. Rescued: SM Higgs boson at 125.5 GeV.

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PHYSICAL REVIEW D VOLUME 16, NUMBER 5 1 SEPTEMBER 1977

Weak interactions at very high energies: The role of the Higgs-boson mass

Benjamin W. Lee,* C. Quigg,† and H. B. Thacker
Fermi National Accelerator Laboratory,‡ Batavia, Illinois 60510
(Received 20 April 1977)

We give an S-matrix-theoretic demonstration that if the Higgs-boson mass exceeds $M_c = (8\pi\sqrt{2}/3G_F)^{1/2}$, parital-wave unitarity is not respected by the tree diagrams for two-body scattering of gauge bosons, and the weak interactions must become strong at high energies. We exhibit the relation of this bound to the structure of the Higgs-Goldstone Lagrangian, and speculate on the consequences of strongly coupled Higgs-Goldstone systems. Prospects for the observation of massive Higgs scalars are noted.

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Central Claim and Question

If Higgs portals exist (thermal dark matter), the SM Higgs does not fully cancel WW/WZ divergences.

Can perturbative unitarity give us a *reasonable* expectation of the new dark scale of physics?

Basic Higgs Portal Unitarity Arguments

$$
\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 \\
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Both Higgses needed to unitarize WW scattering because of the mixing.

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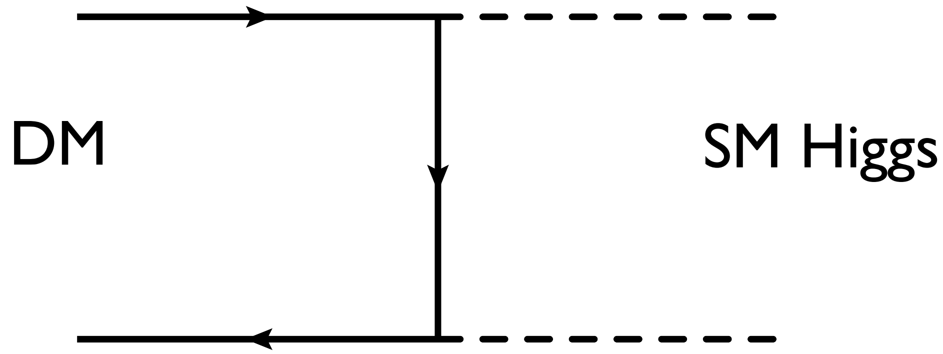
Raise dark Higgs mass? $\theta \to 0$ to satisfy unitarity.

Basic Higgs Portal Relic Abundance Arguments



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

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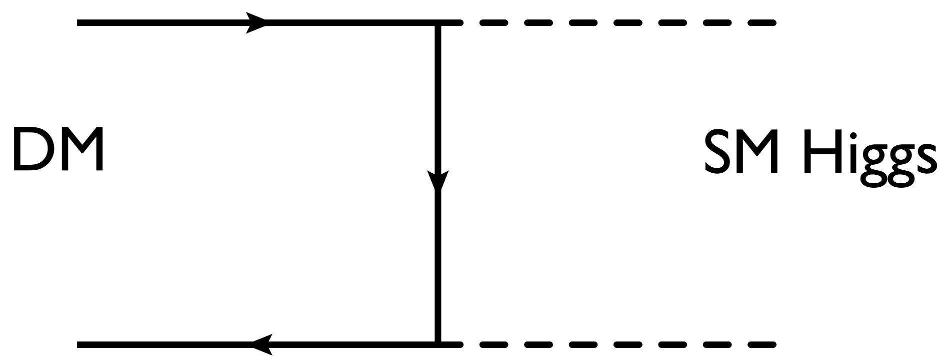

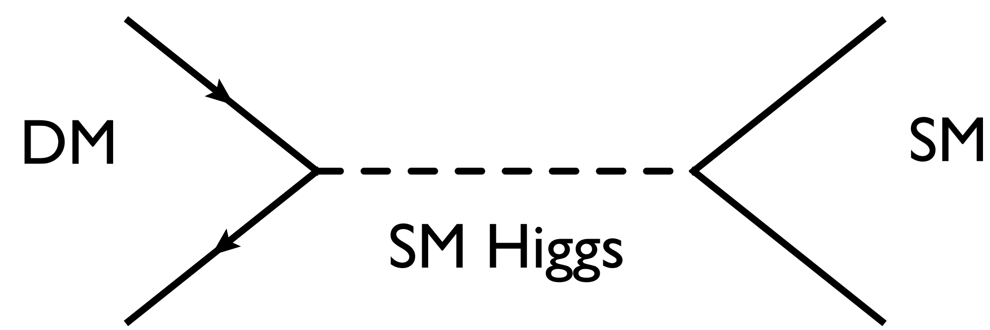

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Relic abundance prevents $\sin \theta \rightarrow 0.$

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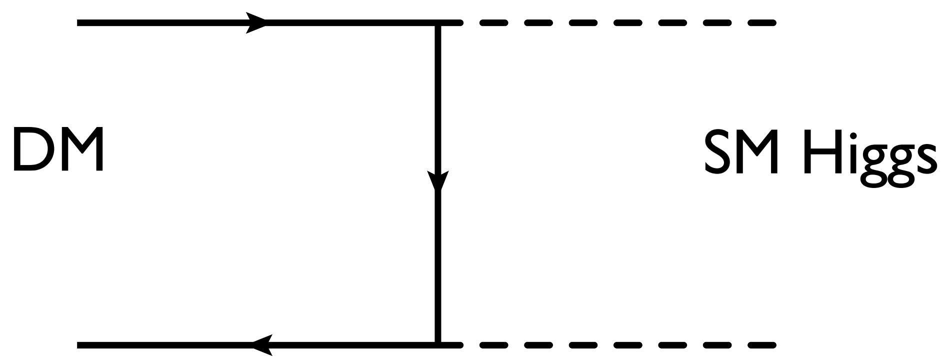

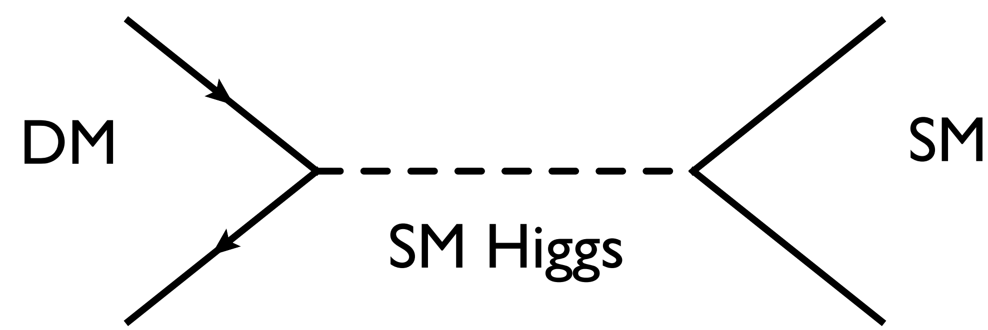

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$$\Omega_\chi h^2 \simeq \frac{0.1 \text{ pb} \cdot c}{\langle \sigma v \rangle}$$

$$\Omega_\chi h^2 = 0.1199 \pm 0.0027$$

Basic Philosophy

- Relic abundance constraints (WIMP dark matter) +

  dark sector and SM Unitarity constraints =

  Perturbative Unitarity bounds

- Argument is roughly same for the other portals.

A Higgs Portal (in more detail)*

* Walker, 2013

- Higgs sector:

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

mixing term

Generic for all Higgs portals so long as there is dark/SM Higgs mixing

- Masses and mixings:

$$\phi = (\rho + u/\sqrt{2})\, e^{i\theta}$$

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

$$\begin{aligned} m_h^2 &= 2\,\lambda_1 v^2 \left(1 - \frac{\lambda_3^2}{4\,\lambda_1\lambda_2} + \ldots\right) \\ m_\rho^2 &= 2\,\lambda_2\, u^2 \left(1 + \frac{\lambda_3^2}{4\,\lambda_2^2}\frac{v^2}{u^2} + \ldots\right) \end{aligned}$$

$$\sin\theta \sim \frac{\lambda_3\, v}{2\lambda_2\, u}$$

dark Higgs

mixing angle

- Mixing angle and dark Higgs mass have different parametric dependencies.

- Dark matter sector:

$$\mathcal{L} = \overline{\chi} \left(\lambda_{\chi_V} + i\, \lambda_{\chi_A} \gamma_5 \right) \Phi\, \chi$$

dark matter

Pseudo-scalar coupling for Model 2*.

- Two models: **Model 1:** $\lambda_{\chi\, A} = 0,$

  Model 2: $\lambda_{\chi\, A}$ and $\lambda_{\chi\, V}$ are non-zero

*Lopez-Honorez, Schwetz and Zupan, Phys. Lett. B 716, 179

Dark Matter Annihilation

- t-channel annihilation:

$$\langle\sigma|v|\rangle \;=\; \frac{\sin^4\theta}{4\pi\,\left(2\,m_\chi^2-m_h^2\right)^2}\sqrt{1-\frac{m_h^2}{m_\chi^2}}\left(m_\chi^2\left(\lambda_{\chi A}^4+6\,\lambda_{\chi A}^2\lambda_{\chi V}^2+\lambda_{\chi V}^4\right)-m_h^2\left(\lambda_{\chi A}^2+\lambda_{\chi V}^2\right)^2\right)+\ldots$$

- s-channel annihilation:

$$\langle\sigma|v|\rangle_{\bar f f} \;=\; \frac{\lambda_{\chi A}^2\sin^2\theta\cos^2\theta}{4\pi}\sum_{f=u,d,c,s,t,b,e,\mu,\tau}\sqrt{1-\frac{m_f^2}{m_\chi^2}}\left(\frac{g\,m_f}{m_W}\right)^2\left(\frac{m_\chi^2-m_f^2}{\left(4\,m_\chi^2-m_h^2\right)^2}\right)+\ldots$$

$$\langle\sigma|v|\rangle_{VV} \;=\; \frac{\lambda_{\chi A}^2\,m_W^2\,\sin^2\theta\cos^2\theta}{8\,\pi}\sum_{V=W,Z}\sqrt{1-\frac{m_V^2}{m_\chi^2}}\left(\frac{g_{Vh}^2}{m_V^4\,\left(4m_\chi^2-m_h^2\right)^2}\right)\left(3\,m_V^4-4m_V^2\,m_\chi^2+4\,m_\chi^4\right)+\ldots$$

$$\langle\sigma|v|\rangle_{hh} \;=\; \frac{\lambda_{h^3}^2\,\lambda_{\chi A}^2\,\sin^2\theta}{2\,\pi}\sqrt{1-\frac{m_h^2}{m_\chi^2}}\frac{9\,u^2}{\left(4\,m_\chi^2-m_h^2\right)^2}+\ldots$$

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More annihilation channels for Model 2

Unitarity Considerations
(Higgs-Gauge Boson Amplitude)

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

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

Unitarity Considerations
(Fermion-fermion Scattering Amplitude)

$$\left(\chi_+ \overline{\chi}_+,\, \chi_- \overline{\chi}_-\right)$$

$$\mathcal{M}^{(0)} \;=\; -\frac{1}{32\pi} \begin{pmatrix} \lambda^* \lambda & -2\,\lambda^2 \\ -2\,\lambda^{*\,2} & \lambda^* \lambda \end{pmatrix}$$

$$\lambda = \lambda_{\chi_V} + i\,\lambda_{\chi_A}$$

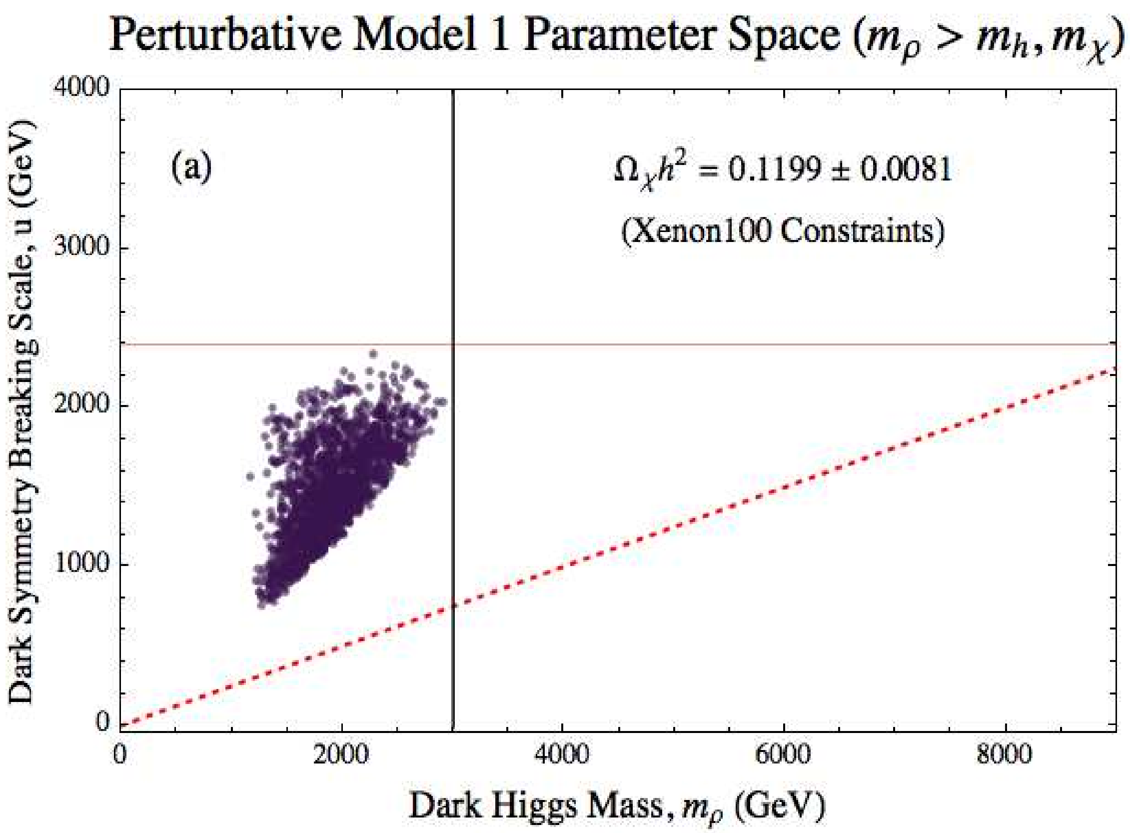
- Require: $|\mathrm{Re}\,\mathcal{M}^{(0)}| \leq \frac{1}{2}$

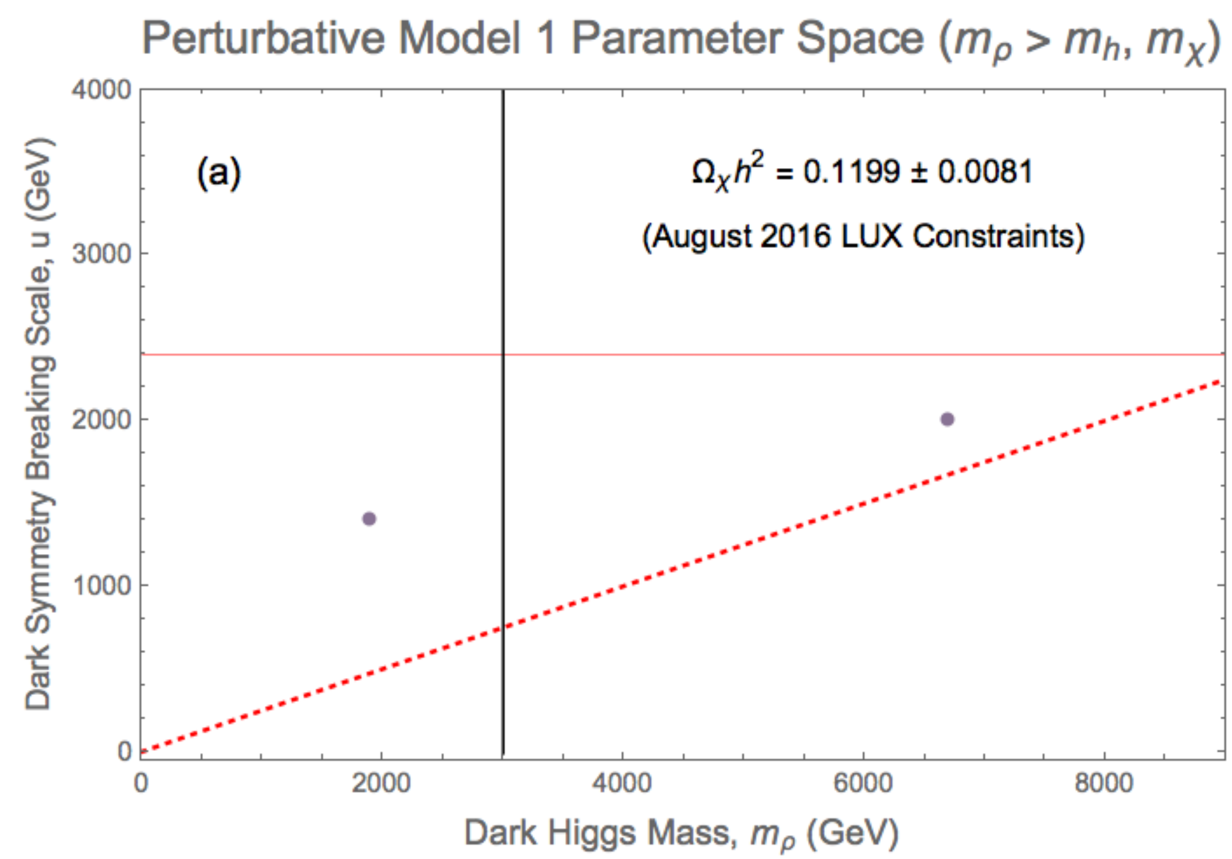
  Equivalent to about a 40% NLO correction over LO

- Parameter scan over the variables.
  (Unitarity, relic abundance, Higgs mass are constraints.)

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

Results





(Walker, 2013)

$$\mathcal{L} = \overline{\chi}\left(\lambda_{\chi V} + i\,\lambda_{\chi A}\gamma_5\right)\Phi\,\chi$$

Model 1: $\lambda_{\chi\,A} = 0,$

Model 2: $\lambda_{\chi\,A}$ and $\lambda_{\chi\,V}$ are non-zero

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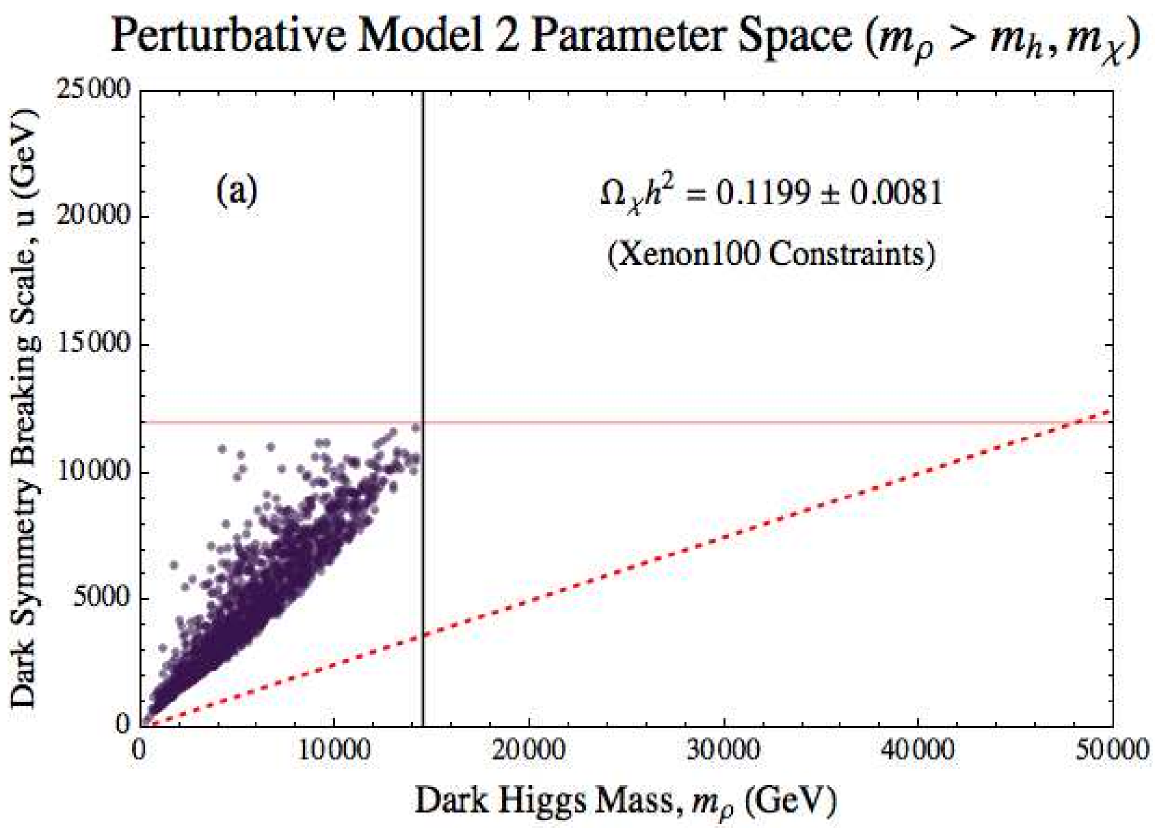

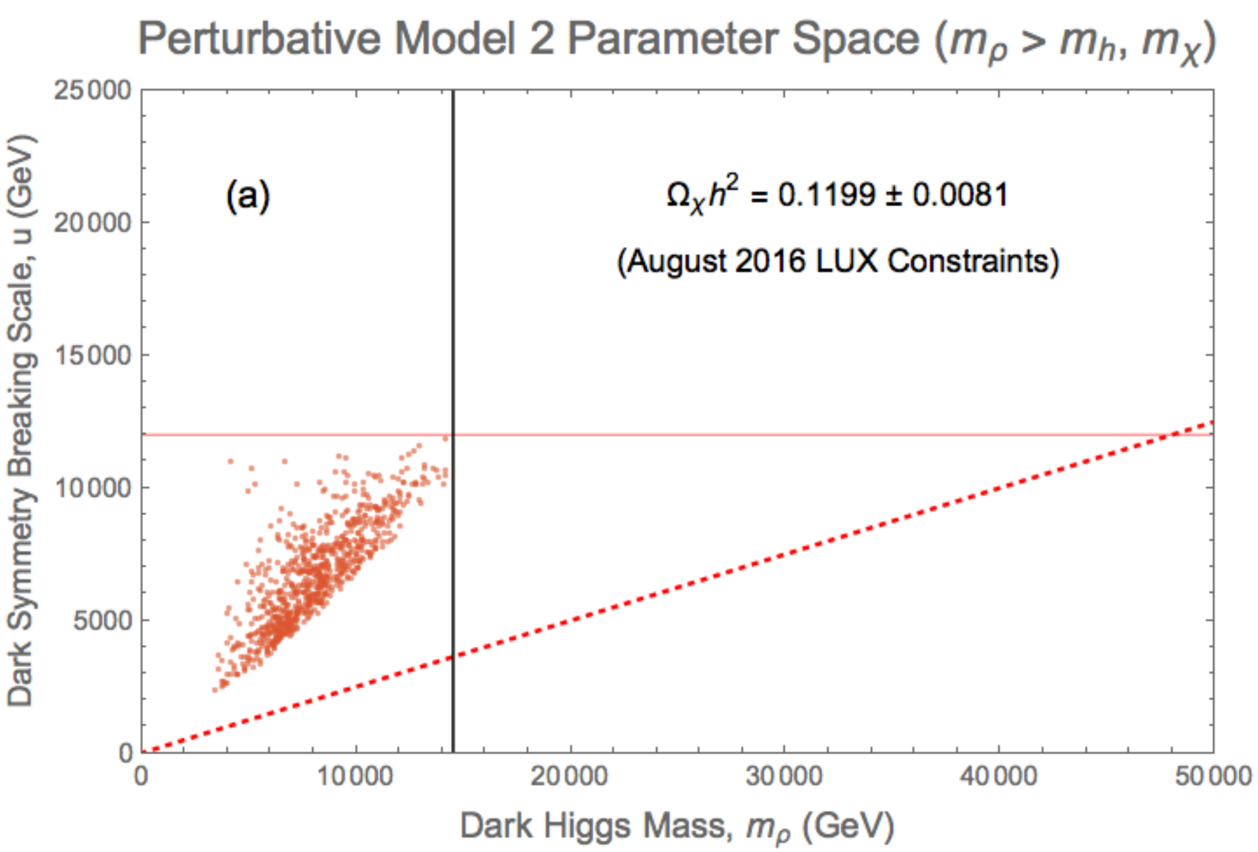

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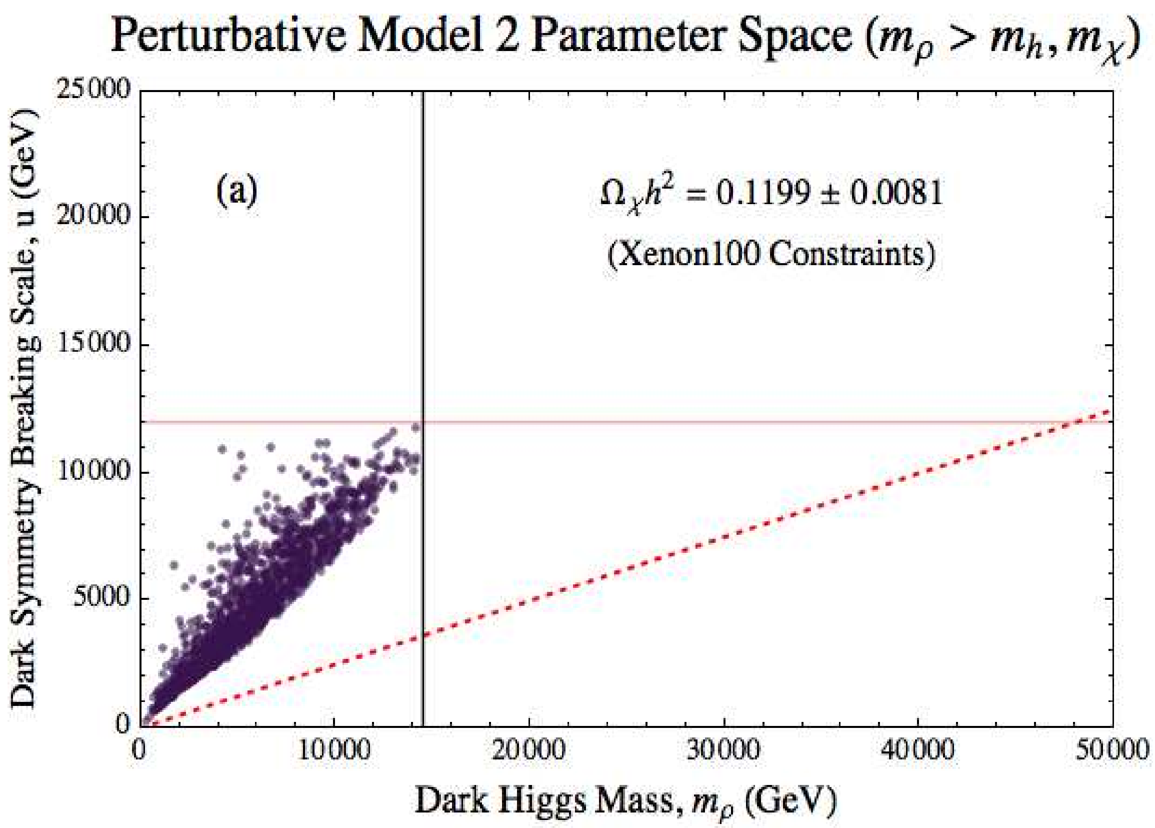
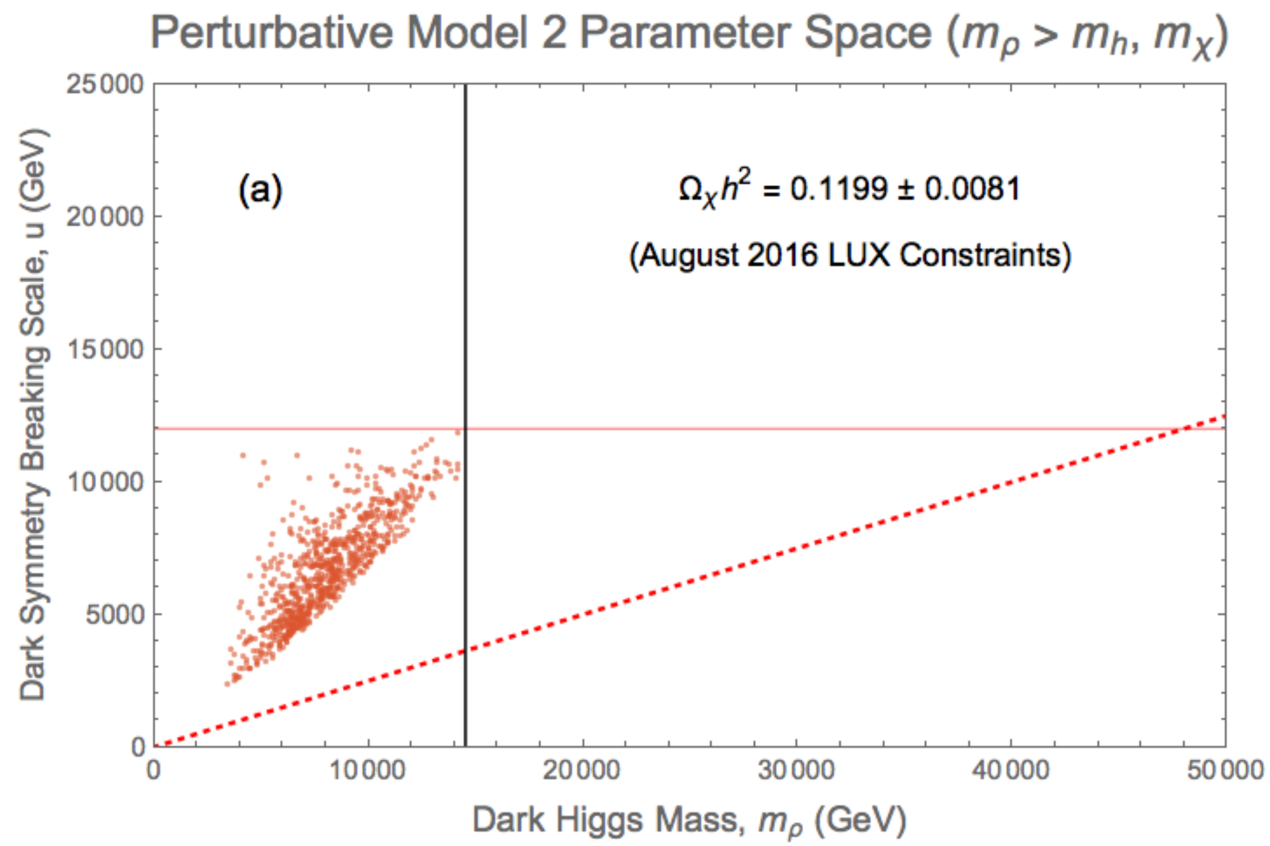
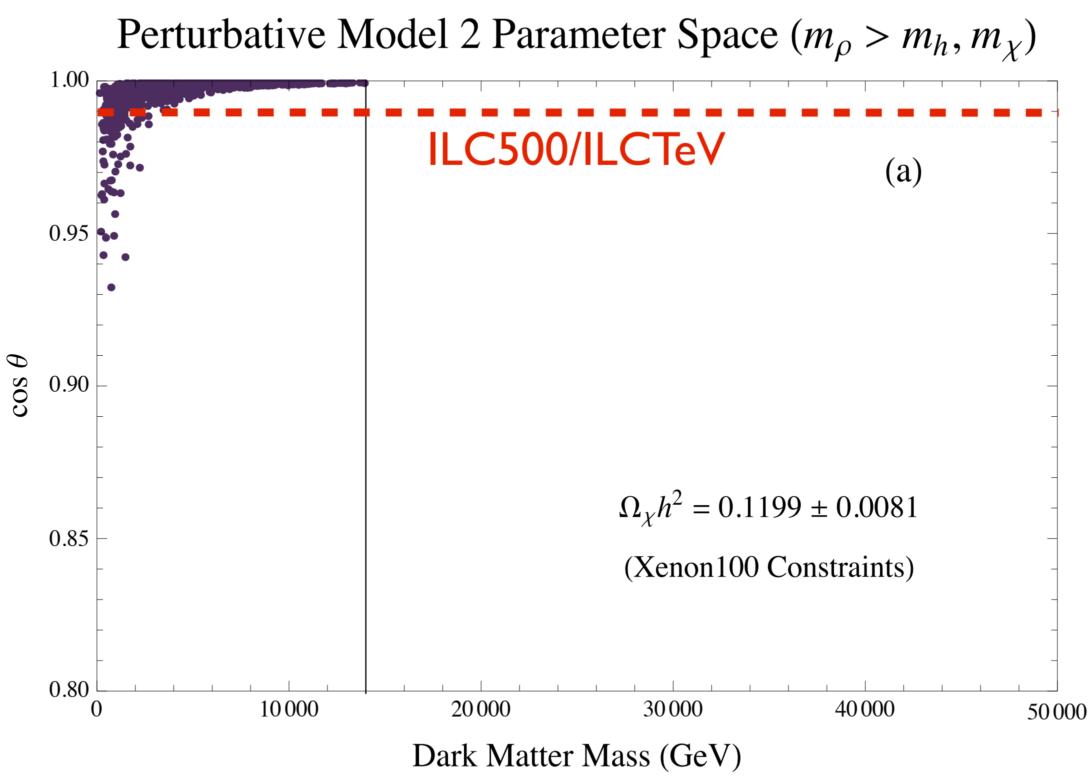


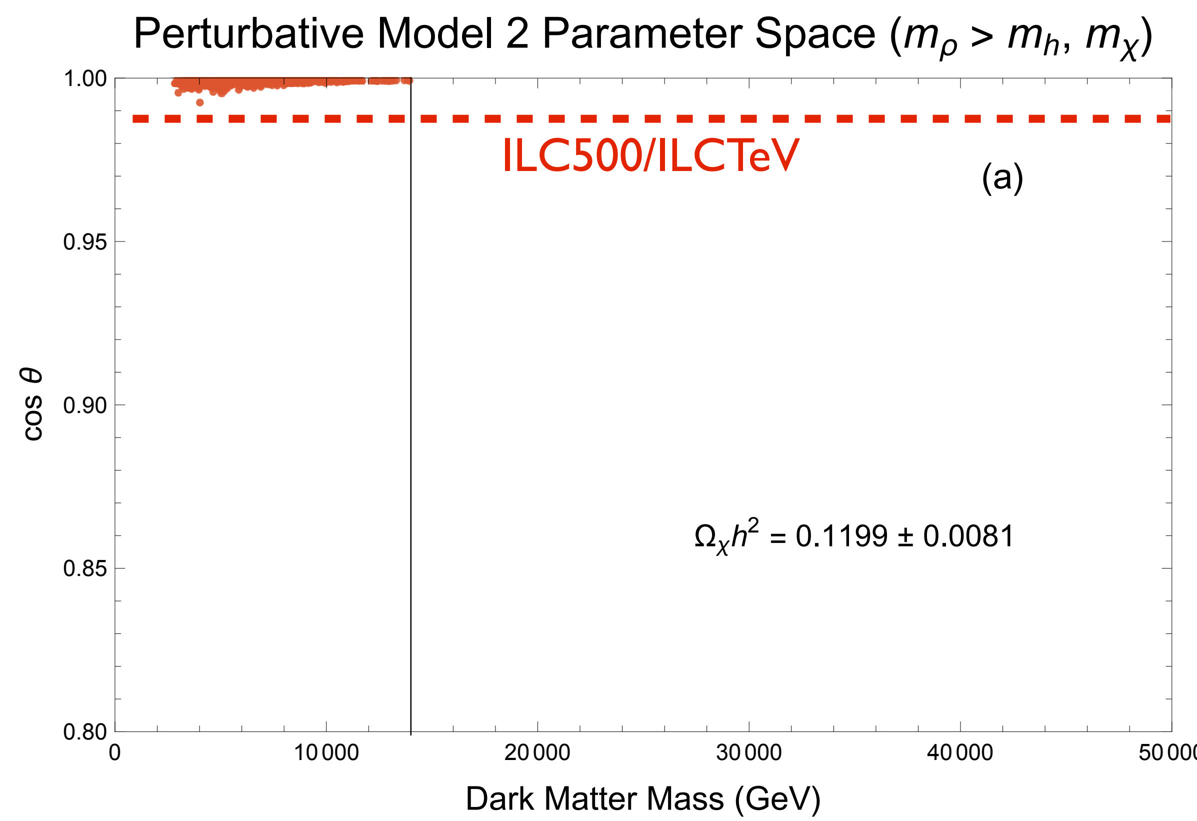


(Walker, 2013)

One ton experiments are sensitive to all of the points

Results

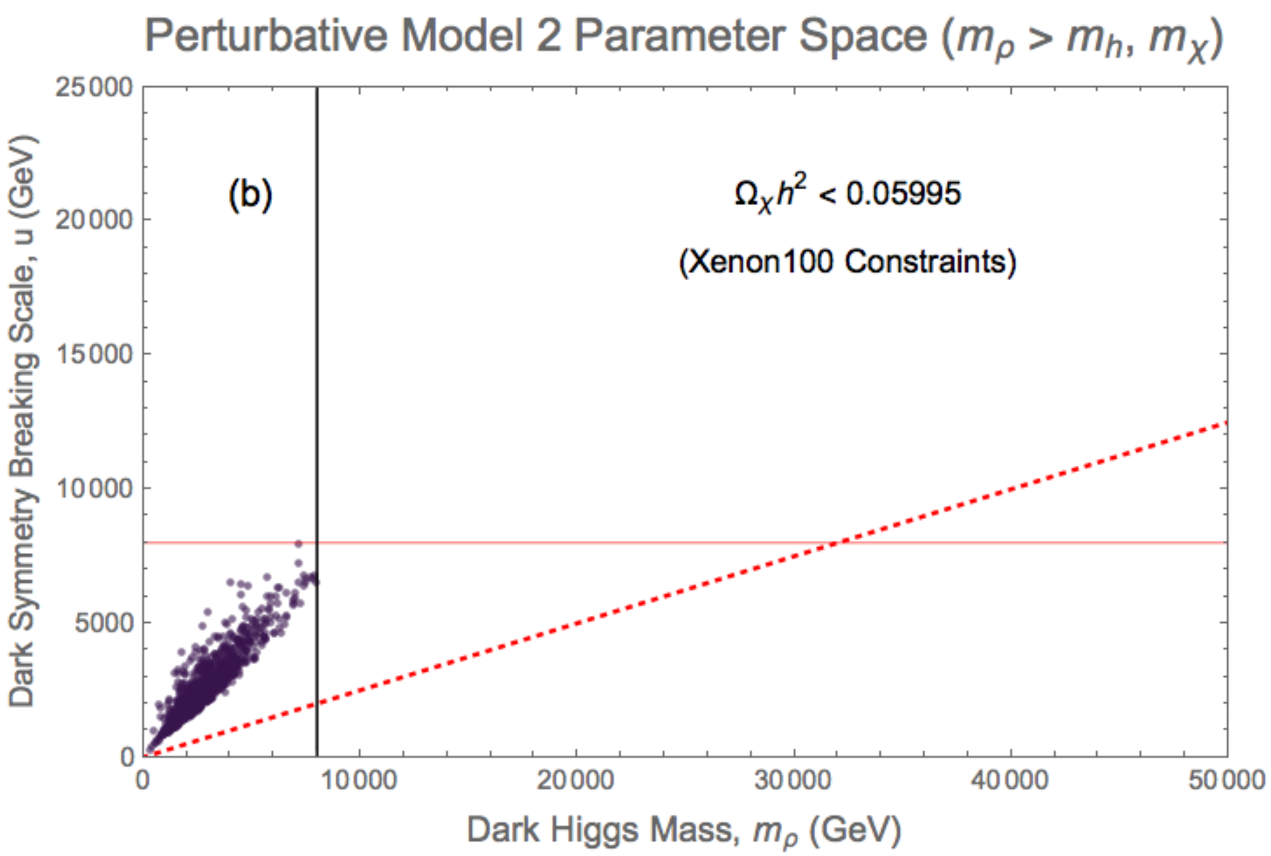


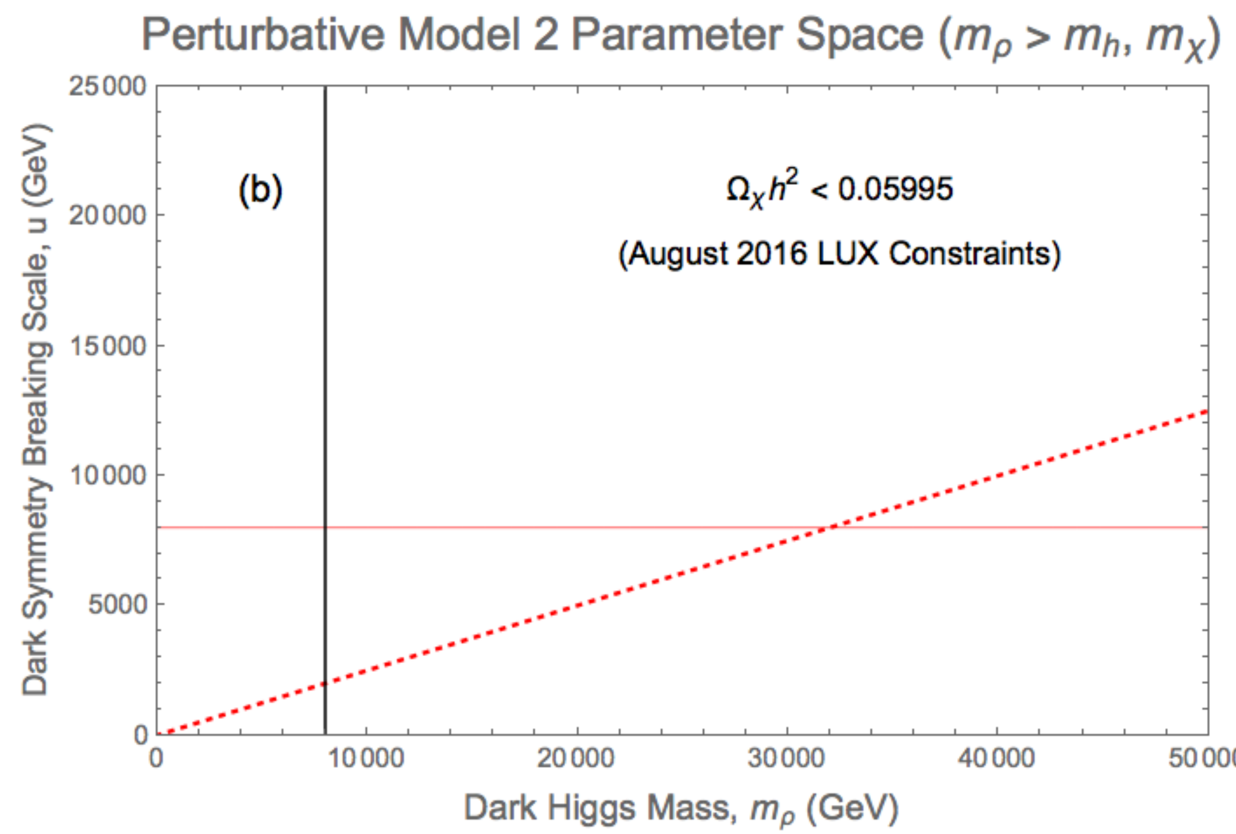


(Walker, 2013)

- DM Bound up to 14 TeV.
- SM Higgs mixing measurements at colliders will not constrain significantly.

Multi-Component DM Results





(Walker, 2013)

- Assume thermal DM is half of the relic abundance.
- Perturbative Higgs portal with thermal DM in multi-component DM universe is highly constrained.

Why Perturbativity Matters

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- Impact on Dark Matter Phenomenology:

  Modifies Direct/Indirect Detection of Dark Matter

  Modifies LHC Production

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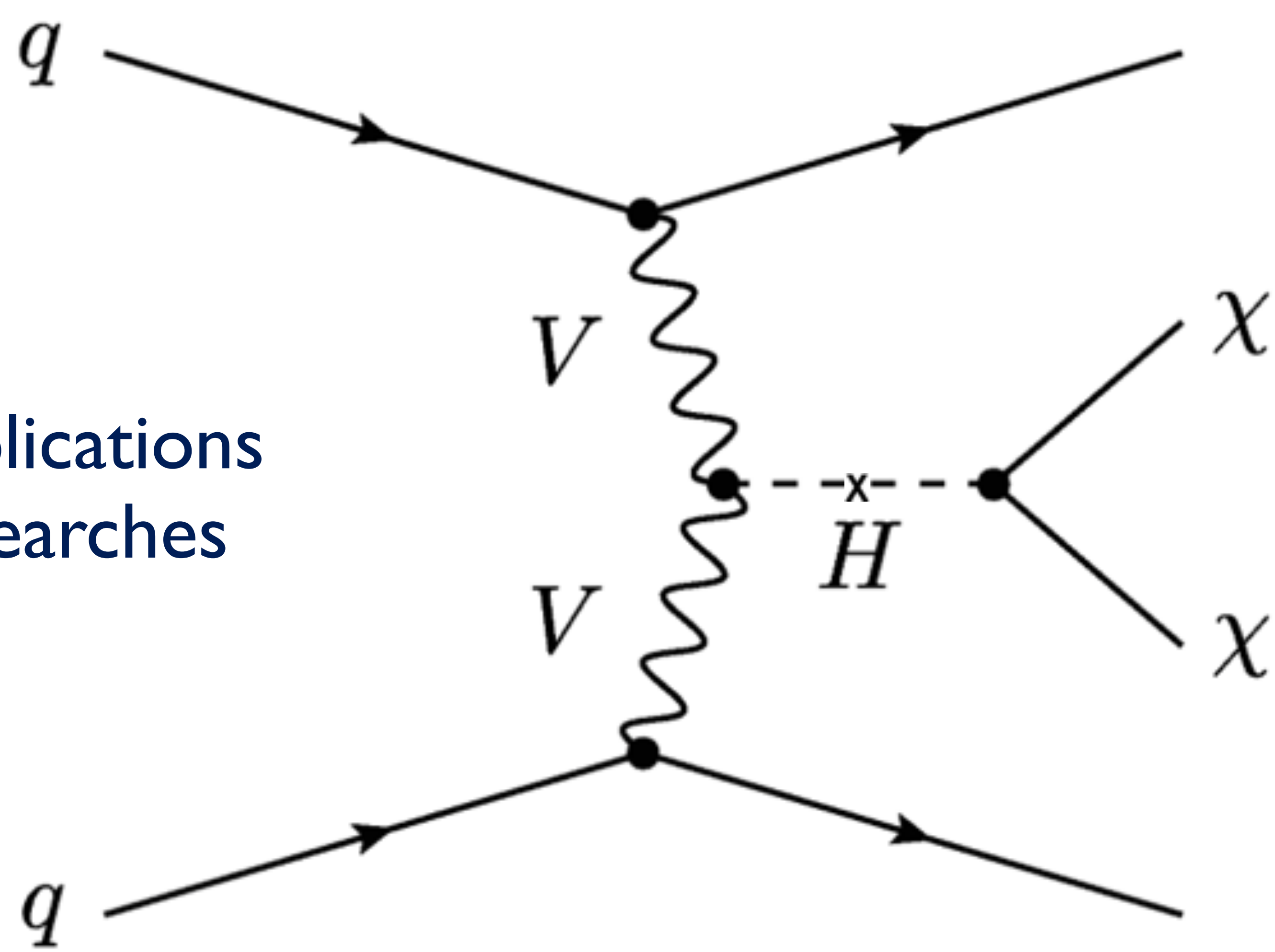
E.g., severe complications for large MET searches



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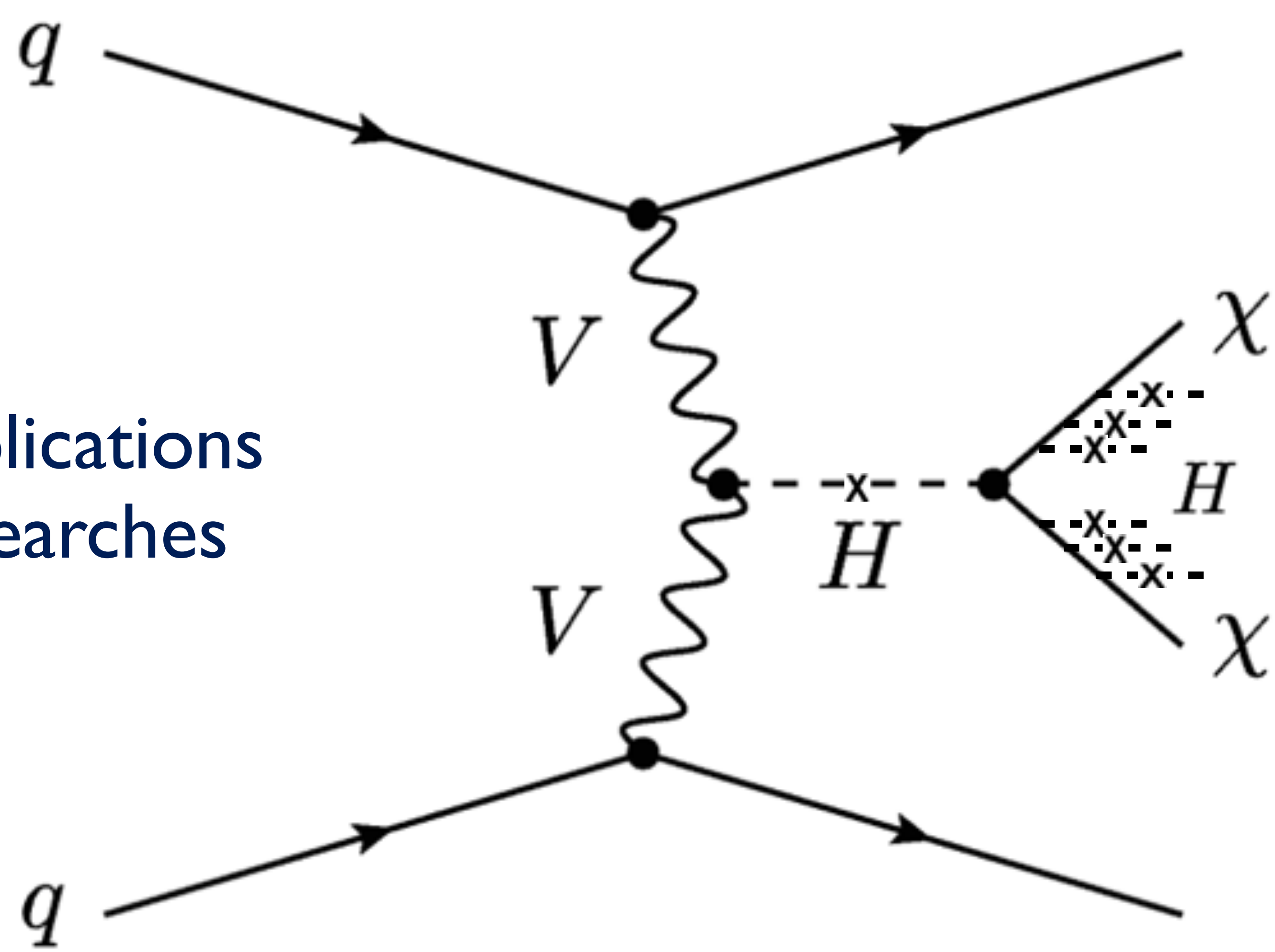

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*Petraki and Von Harling, 2014

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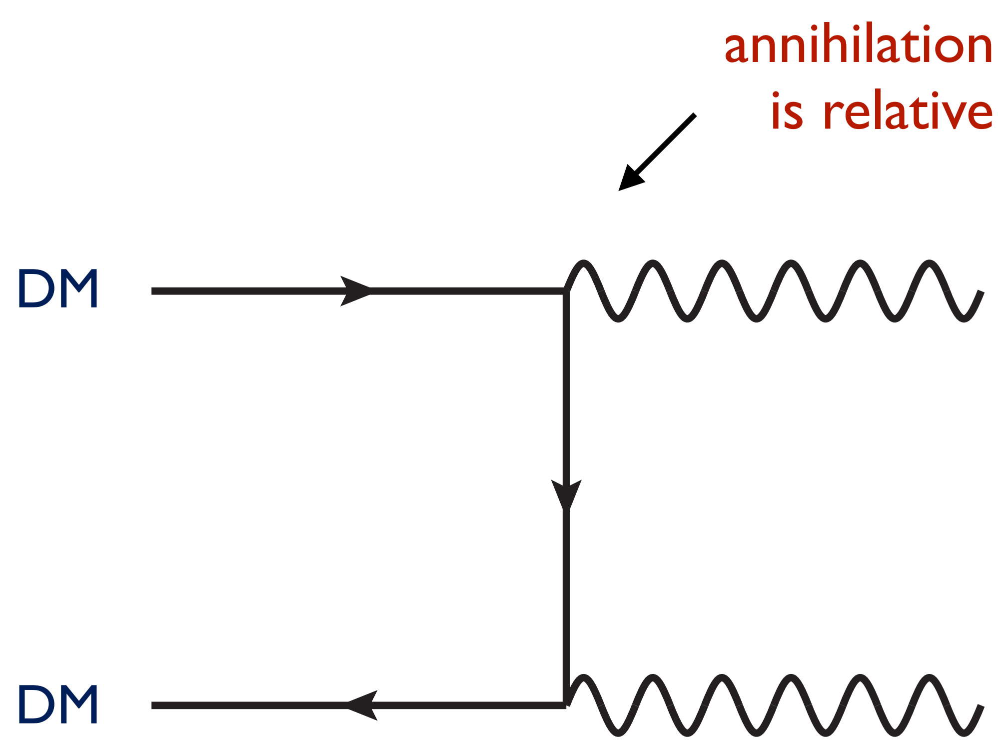

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Why Perturbativity Matters

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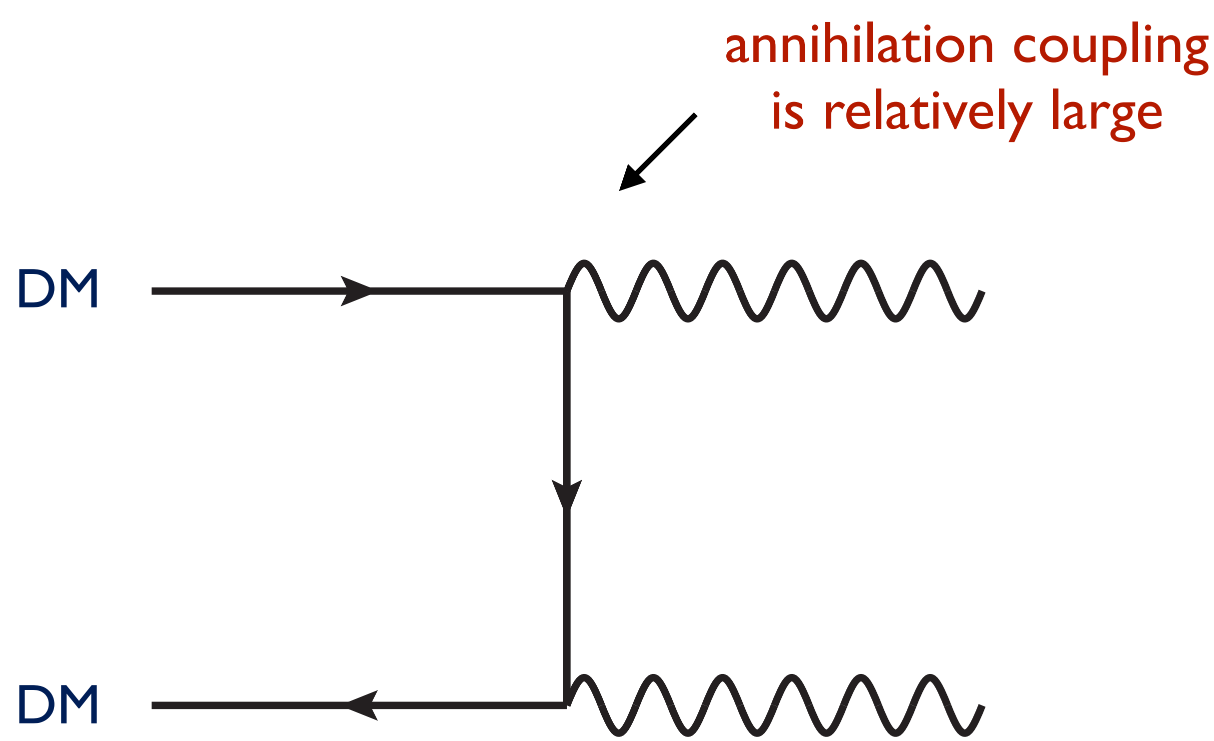
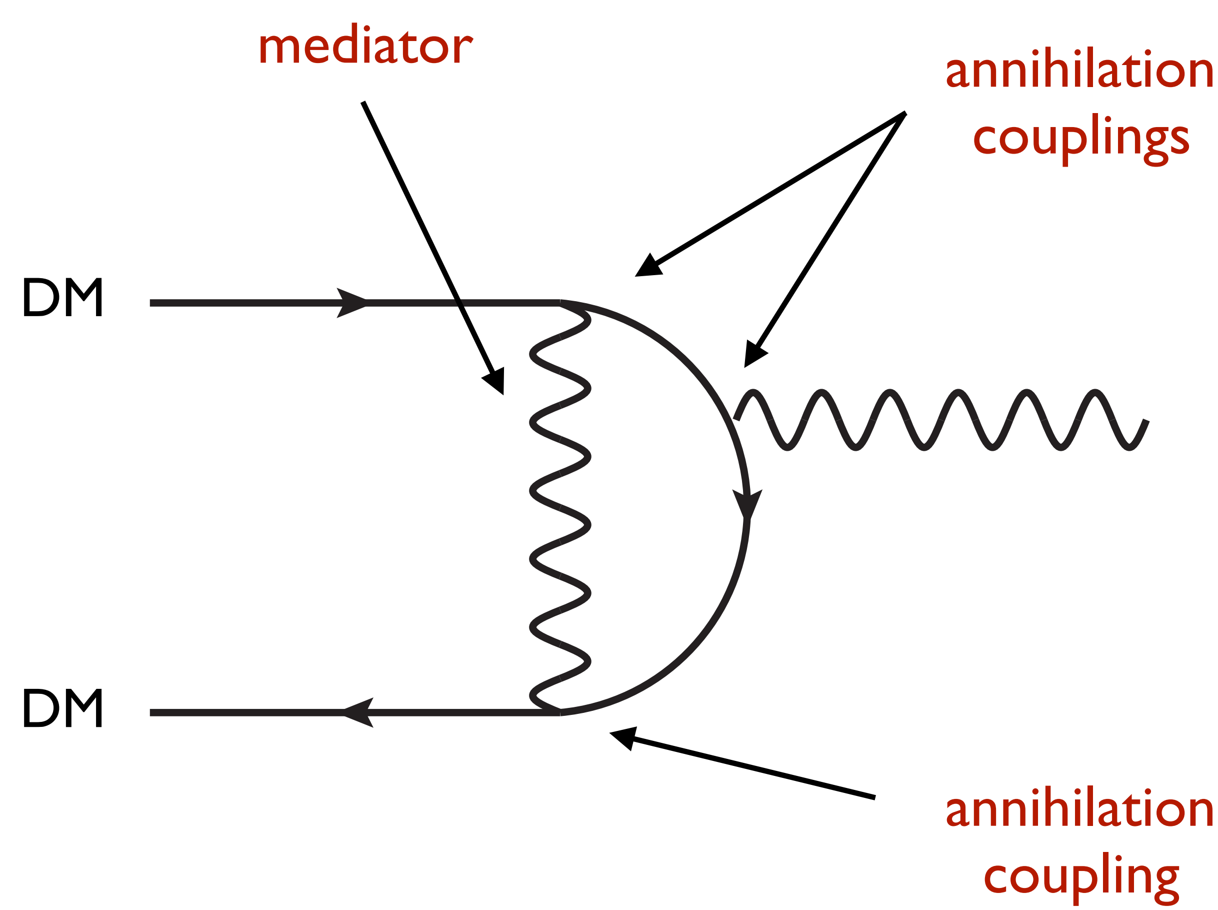
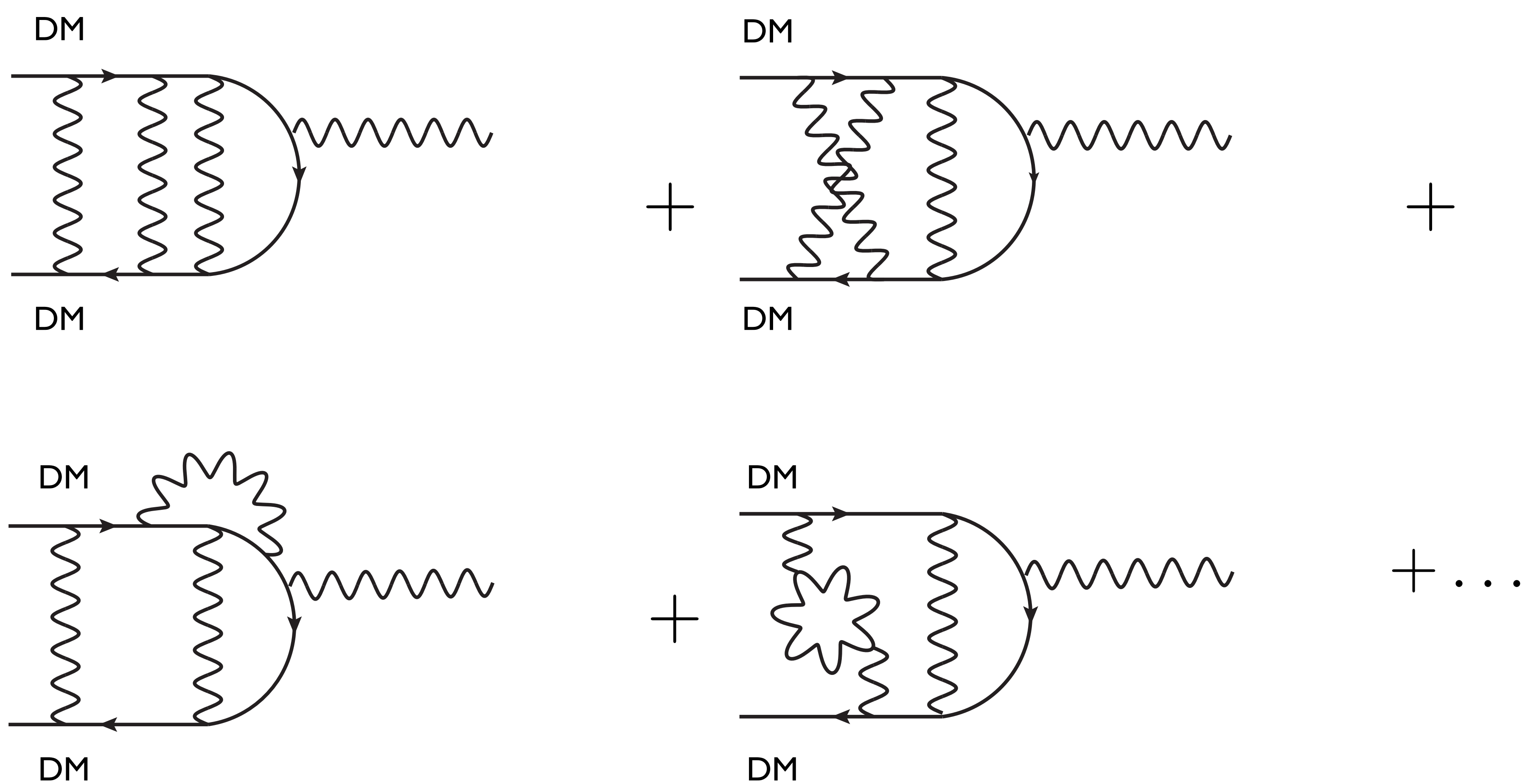




*Petraki and Von Harling, 2014

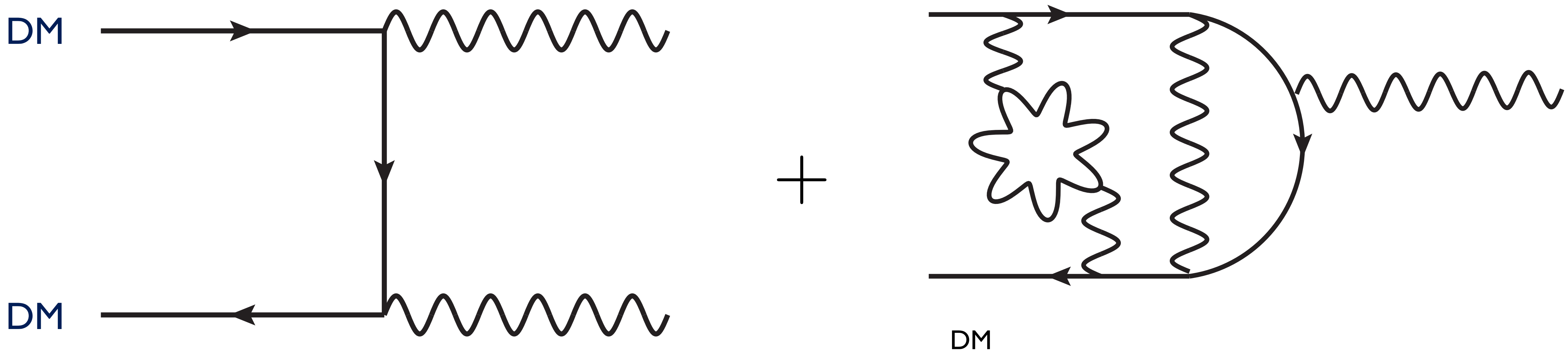
Why Perturbativity Matters

- Perturbative Unitarity gives first estimate for when bound state formation occurs*:



*See also Petraki, Postma and Wiechers, 2015.

Why Perturbativity Matters



Two Dark Matter "Annihilation" Processes. Must account for both when considering CDM properties.

*See Petraki's talk; Petraki and Von Harling, 2014

Conclusions/Other Portals

We presented work that used perturbative unitarity constraints on a simple Higgs portal model.

The upper bounds may help to understand when new physics will appear.

Bounds can be used to constrain thermal dark matter.

Bounding thermal dark matter means one can systematically move forward to understand the nature of dark matter.

A Colored/Charged Portal*

*Cahill-Rowley, El Hedri, Shepherd and Walker, 2015

- Place perturbative unitarity constraints on charged/colored scalars*:

$$V_i = \frac{1}{2} m^2_{\tilde{f}i}\, \tilde{f}_i^* \tilde{f}_i + \left(\lambda_i\, \tilde{f}^*\, \bar{\chi}\, P_i\, f + \mathrm{h.c.} \right)$$

$i = L, R$

$\tilde{f} \equiv \tilde{t}_R$

- Dark Matter sector:

$$\mathcal{L}_\chi = i\bar{\chi}\partial\!\!\!/\chi - m_\chi \bar{\chi}\chi$$

*See also DiFranzo, Nagao, Rajaraman, Tait, 2009

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(Yukawa-type coupling: Weaker constraints than Simone, Giudice, Strumia, 2014.)

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- Place perturbative unitarity constraints on charged/colored scalars*:

$$V_i = \frac{1}{2} m_{\tilde{f} i}^2 \, \tilde{f}_i^* \tilde{f}_i + \left(\lambda_i \, \tilde{f}^* \, \bar{\chi} \, P_i \, f + \mathrm{h.c.} \right) \qquad i = L, R$$

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- Dark Matter sector:

$$\mathcal{L}_\chi = i \bar{\chi} \partial\!\!\!/ \chi - m_\chi \bar{\chi} \chi$$

(Agnostic on the dark matter mass generation mechanism)

*See also DiFranzo, Nagao, Rajaraman, Tait, 2009

Stop Effective Model

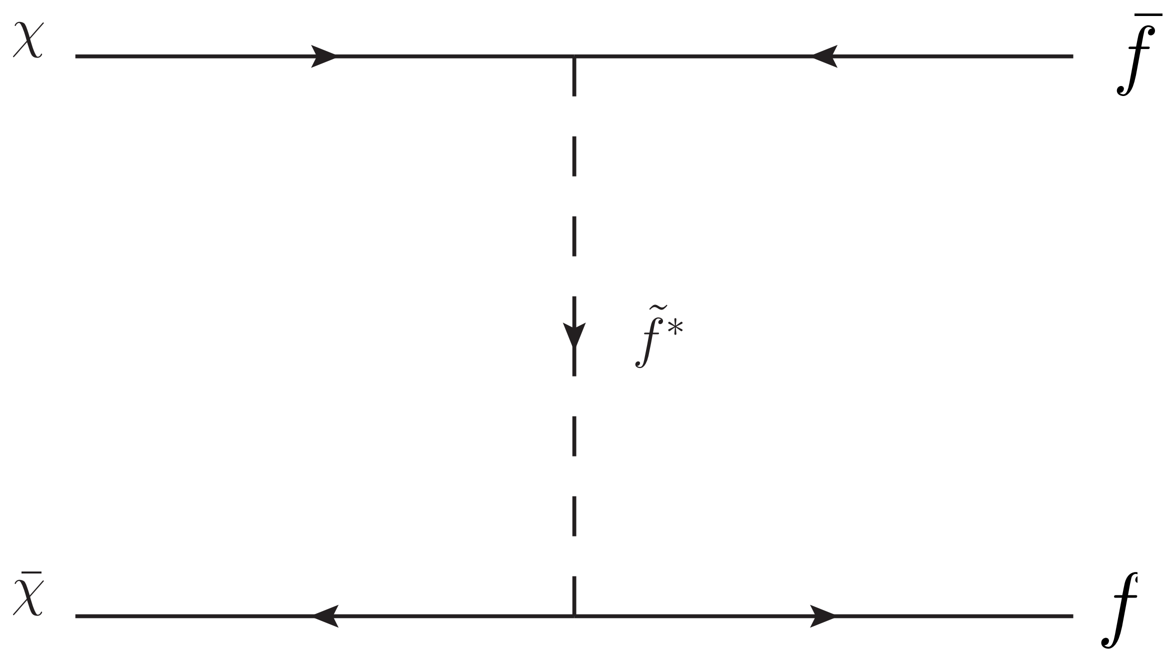
- Only the RH stop lighter than other squark flavors

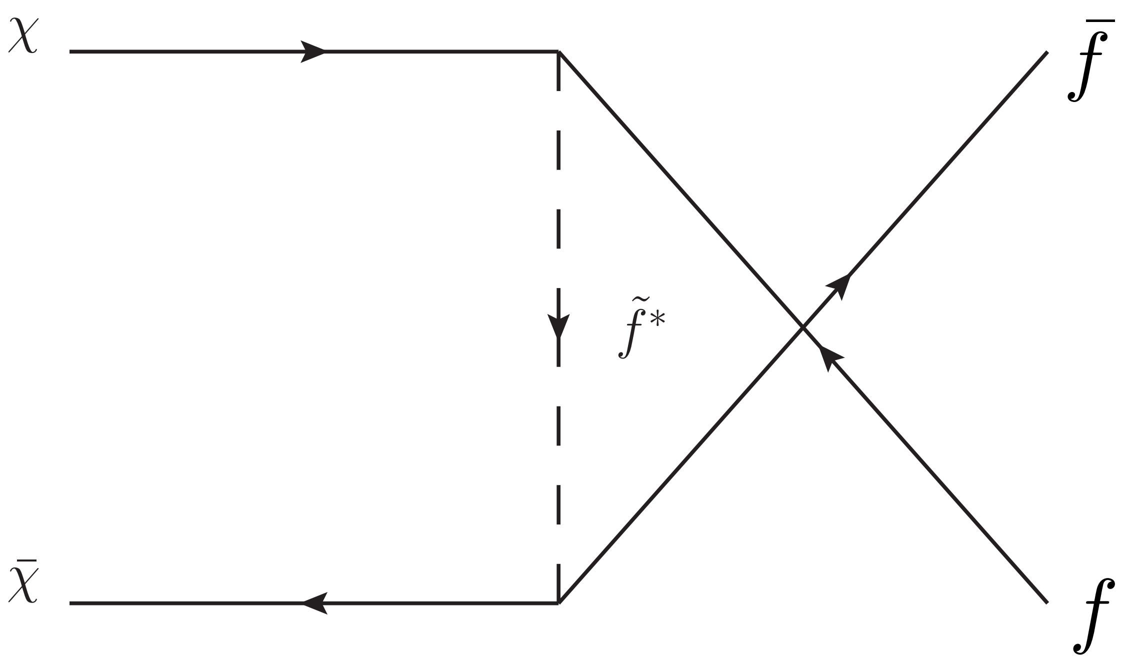
$$\tilde{l} = \begin{pmatrix} \tilde{e} \\ \tilde{\nu}_e \end{pmatrix} \quad \begin{pmatrix} \tilde{e}\mu \\ \tilde{\nu}_\mu \end{pmatrix} \quad \begin{pmatrix} \tilde{\tau} \\ \tilde{\nu}_\tau \end{pmatrix} \qquad \tilde{e}_R = \begin{pmatrix} \tilde{\tau} \\ \tilde{\mu} \\ \tilde{e} \end{pmatrix}$$

(Keep flavor triplets to avoid flavor violation)

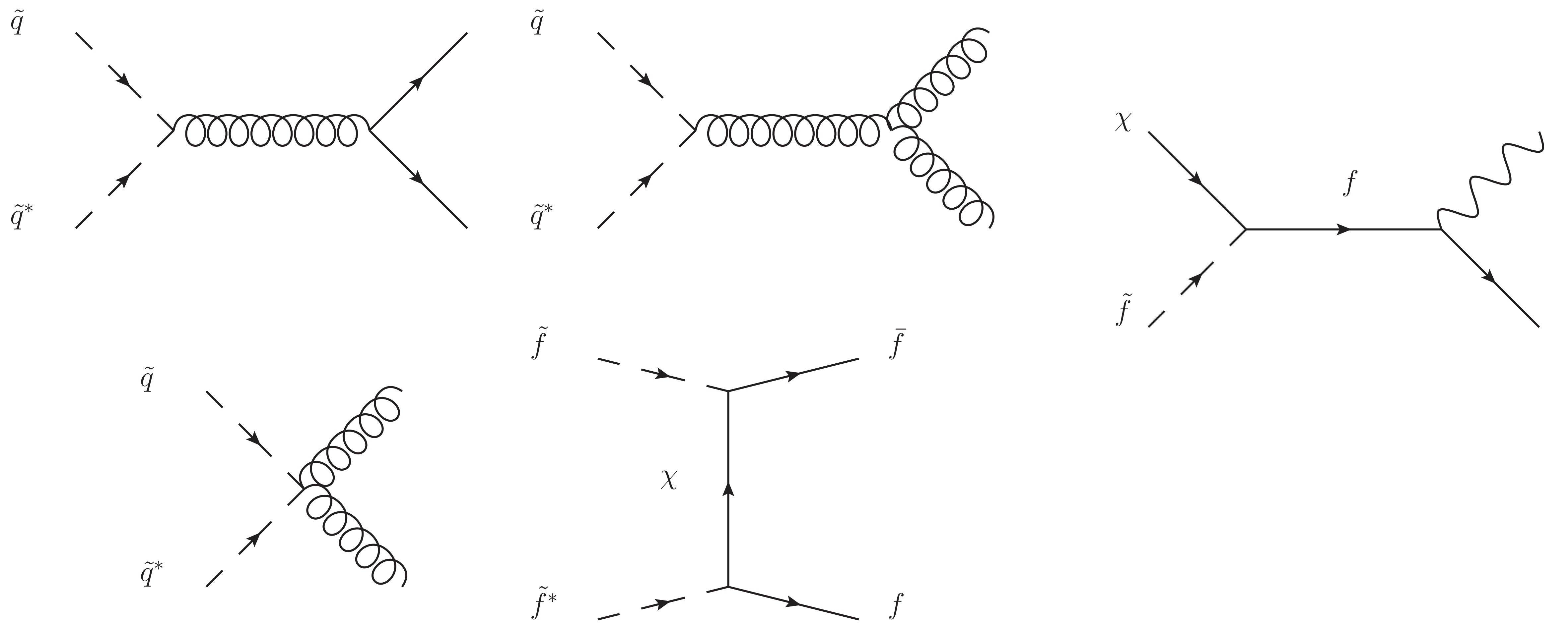
- Free parameters to constrain: $\left\{\lambda, m_{\tilde{f}i}, m_{\chi}\right\}$

- Basic Annihilation Diagrams





- Include co-annihilation in computation of dark matter. Additional diagrams include, e.g:



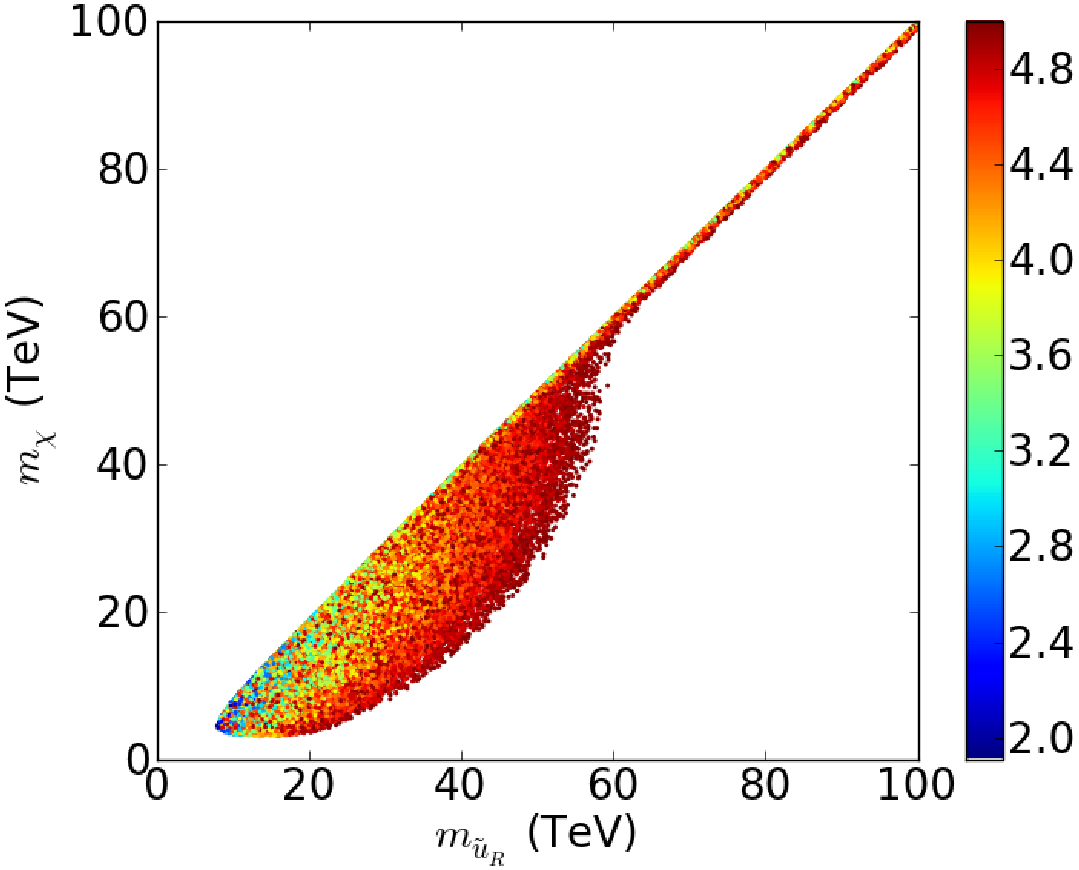
Color Singlet Model

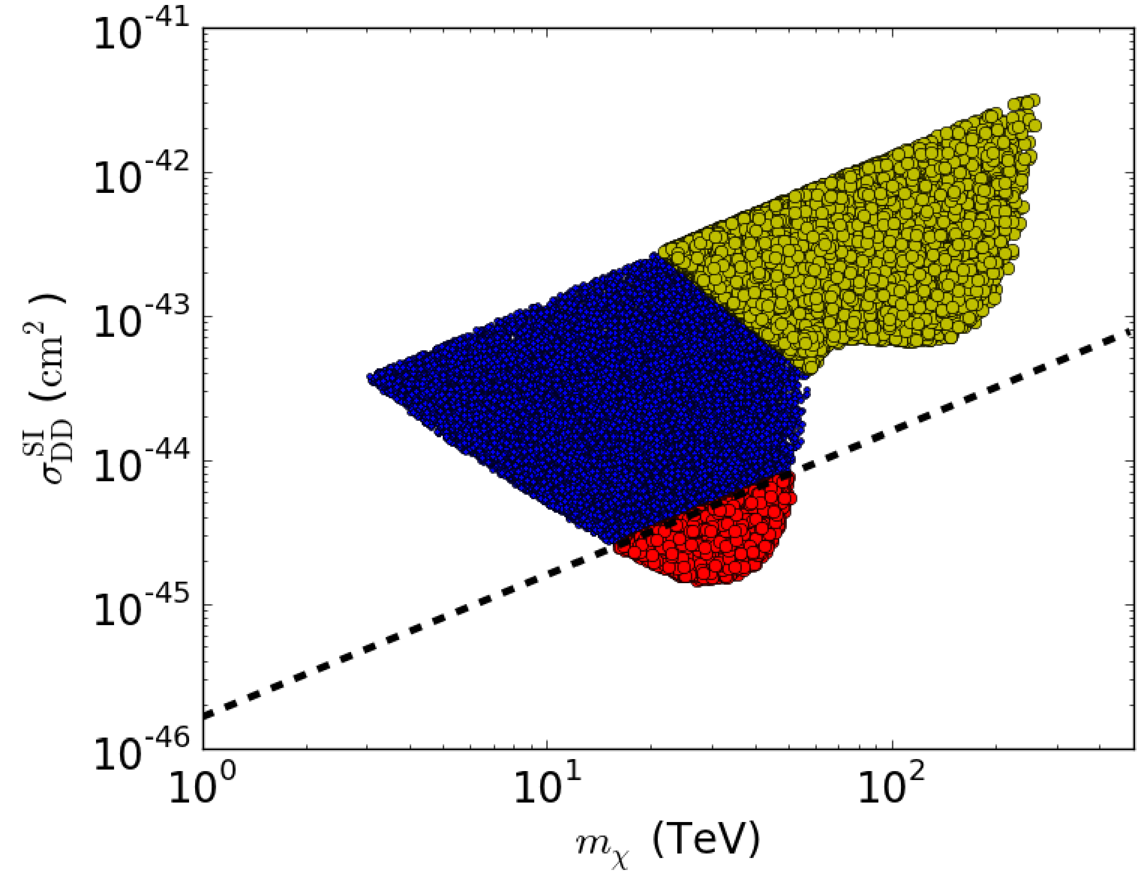
- Mediator quantum numbers: $(1,2)_{-1/2} \quad (1,1)_1$

$$\tilde{l} = \begin{pmatrix} \tilde{e} \\ \tilde{\nu}_e \end{pmatrix} \quad \begin{pmatrix} \tilde{e}\mu \\ \tilde{\nu}_\mu \end{pmatrix} \quad \begin{pmatrix} \tilde{\tau} \\ \tilde{\nu}_\tau \end{pmatrix} \qquad \tilde{e}_R = \begin{pmatrix} \tilde{\tau} \\ \tilde{\mu} \\ \tilde{e} \end{pmatrix}$$

(Keep flavor triplets to avoid flavor violation)

- Some results:





Recap/Conclusions

Extra Slides

A NMSSM (SUSY) Higgs Portal

NMSSM Higgs Sector

- Only basic details and results.

- Superpotential/soft-breaking terms:

$$\mathcal{W}_{\rm NMSSM} = -\lambda \hat{S}\hat{H}_1 \cdot \hat{H}_2 + \frac{1}{3}\kappa \hat{S}^3$$

(scale invariant NMSSM)

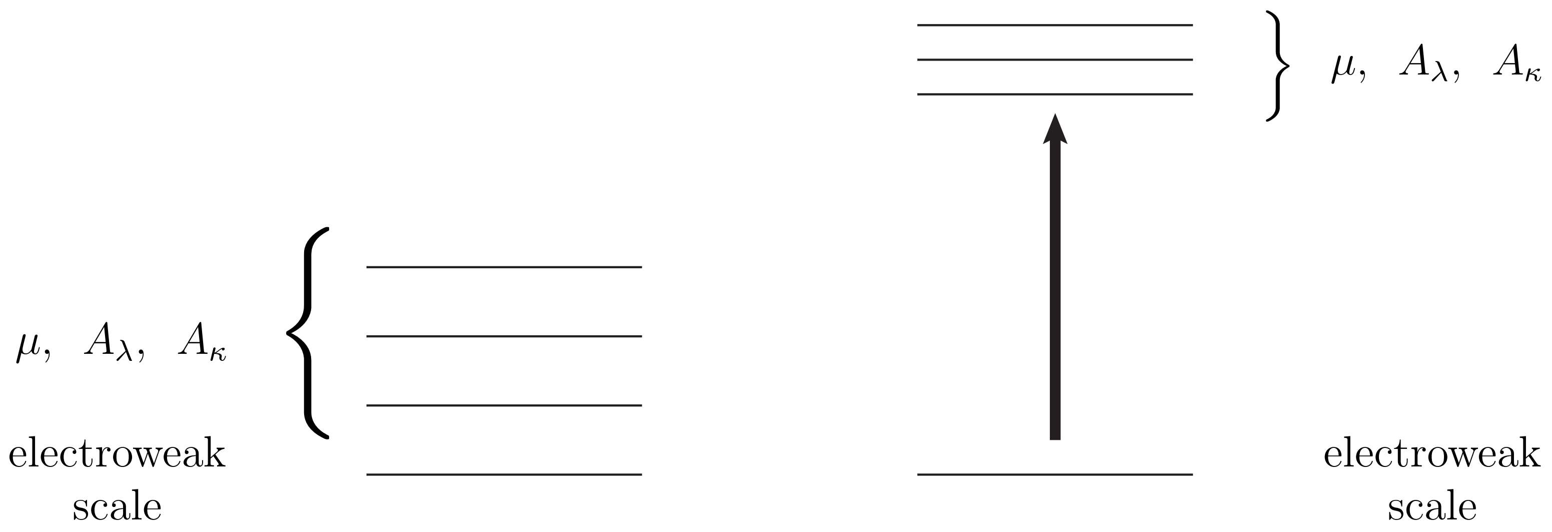
$$V_{\rm soft} = m_{H_1}^2 H_1^\dagger H_1 + m_{H_2}^2 H_2^\dagger H_2 + m_S^2 S^\dagger S - \left(\lambda A_\lambda S H_1 \cdot H_2 - \frac{1}{3}\kappa A_\kappa S^3 + h.c.\right)$$

NMSSM Higgs Sector

- Six free parameters:
  (after requiring the correct electroweak vacuum)

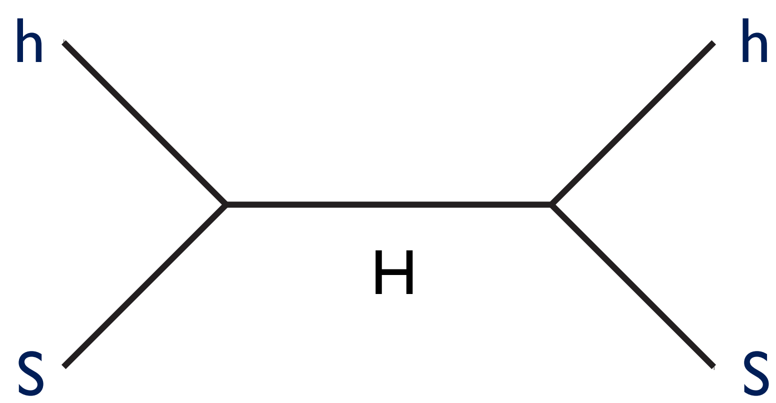
$$\lambda, \quad \kappa, \quad \tan\beta, \quad \mu, \quad A_\lambda, \quad A_\kappa$$

- Generate tension by decoupling NMSSM Higgs sector SUSY breaking scales



NMSSM Higgs Sector

- Perturbative unitarity on dimensionless couplings and ratio of scales.

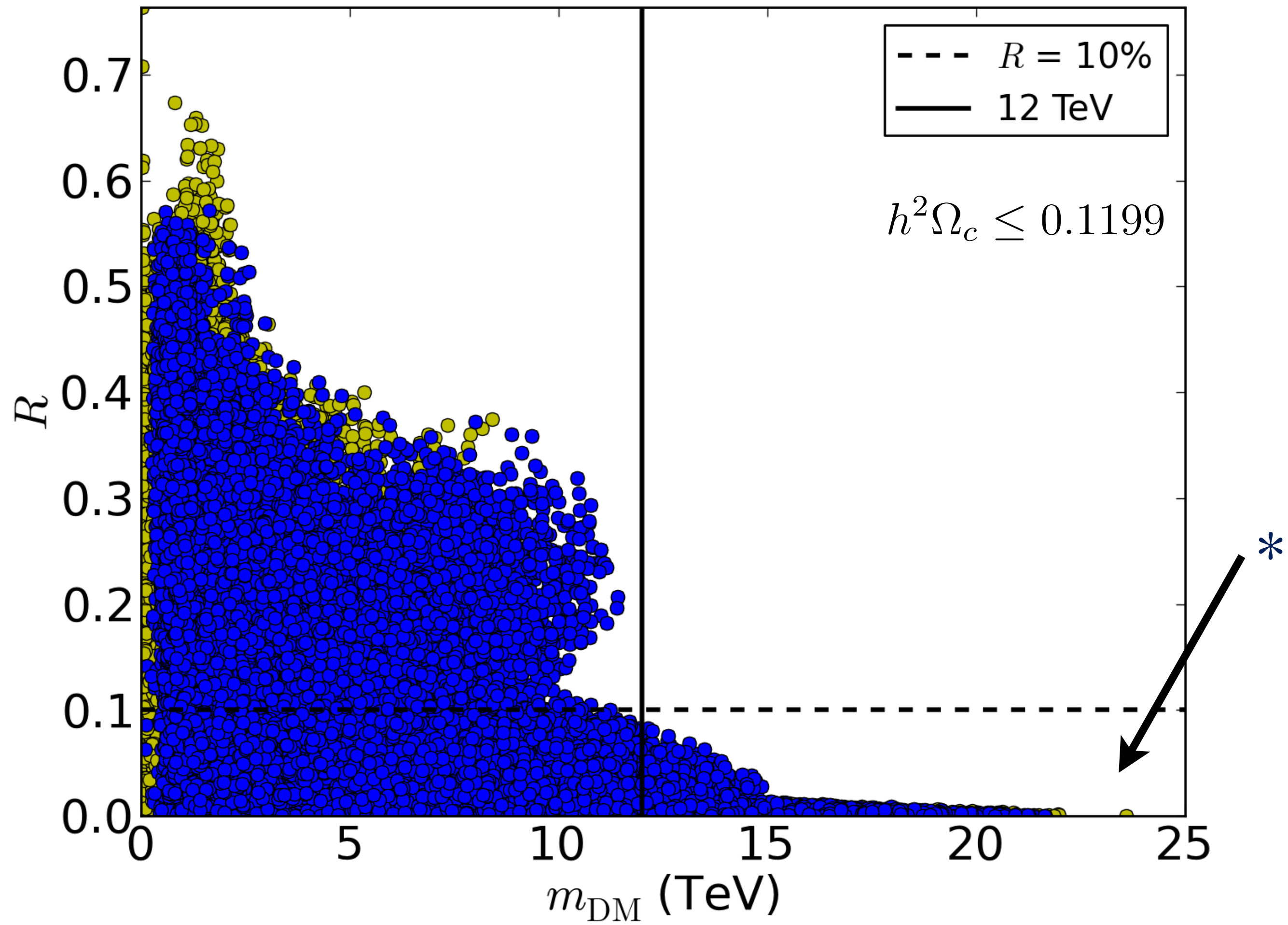


$$\mathcal{M} \sim \frac{A_\lambda^2}{s - m_H^2}$$

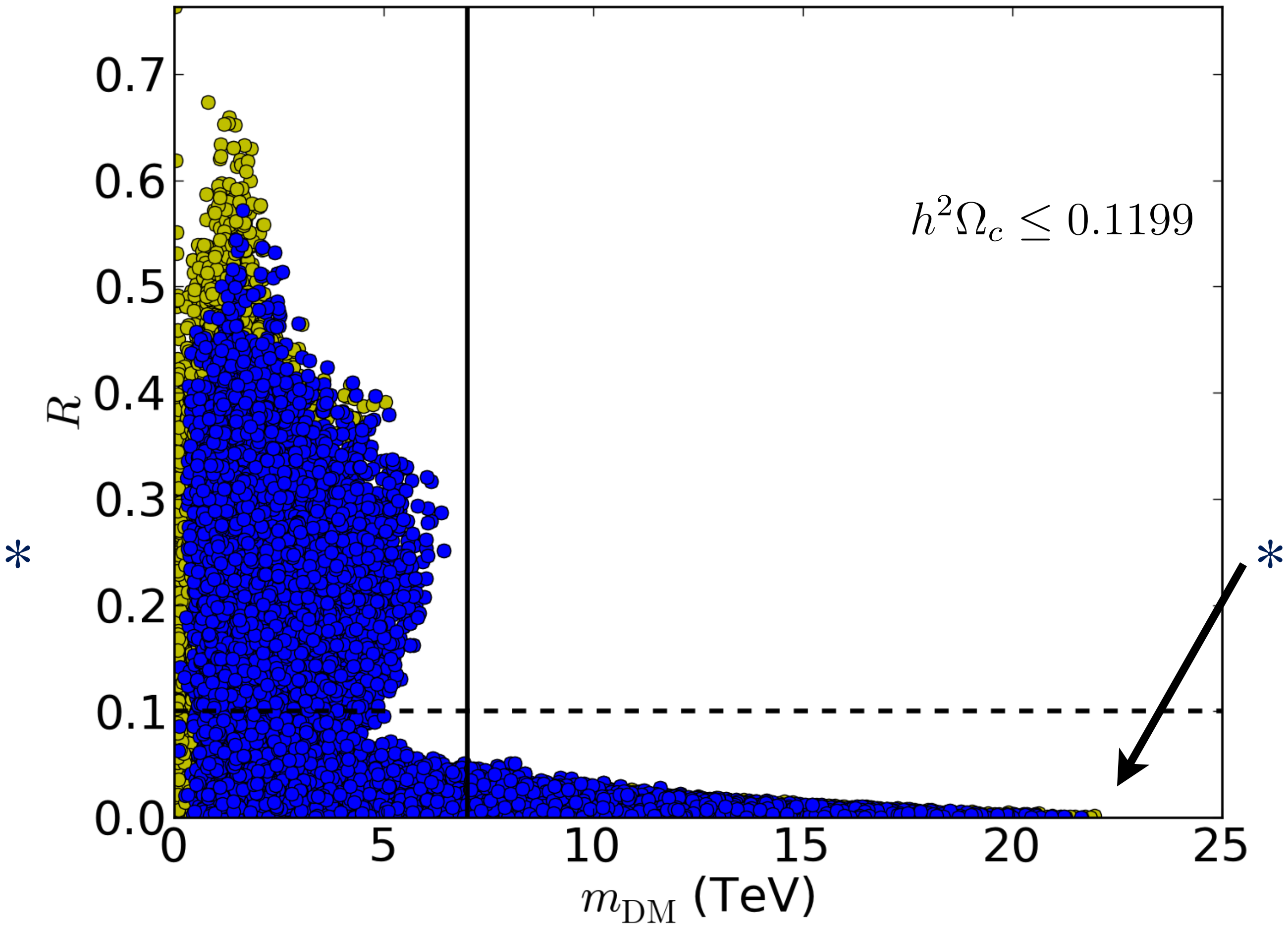
Select a conservative value of s, where the amplitude can be relatively large but far away from resonances.

$$\sqrt{s_{\rm max}} = \sqrt{5} m_{\rm heavy}$$

Gold - Xenon 1T projected exclusion



Dark Matter Mass constraints for 41% correction



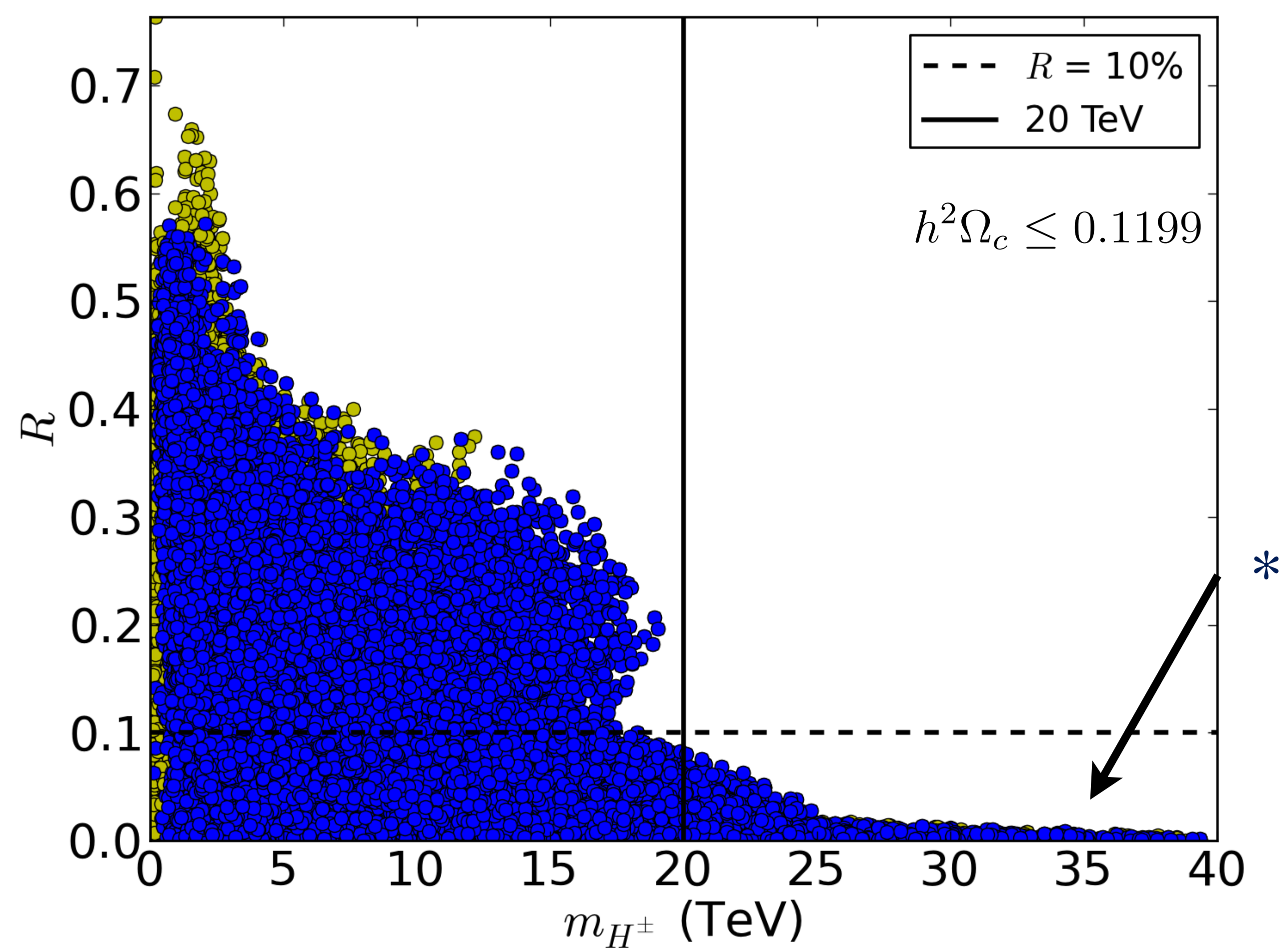
Dark Matter Mass constraints for 20% correction

funnel regime*

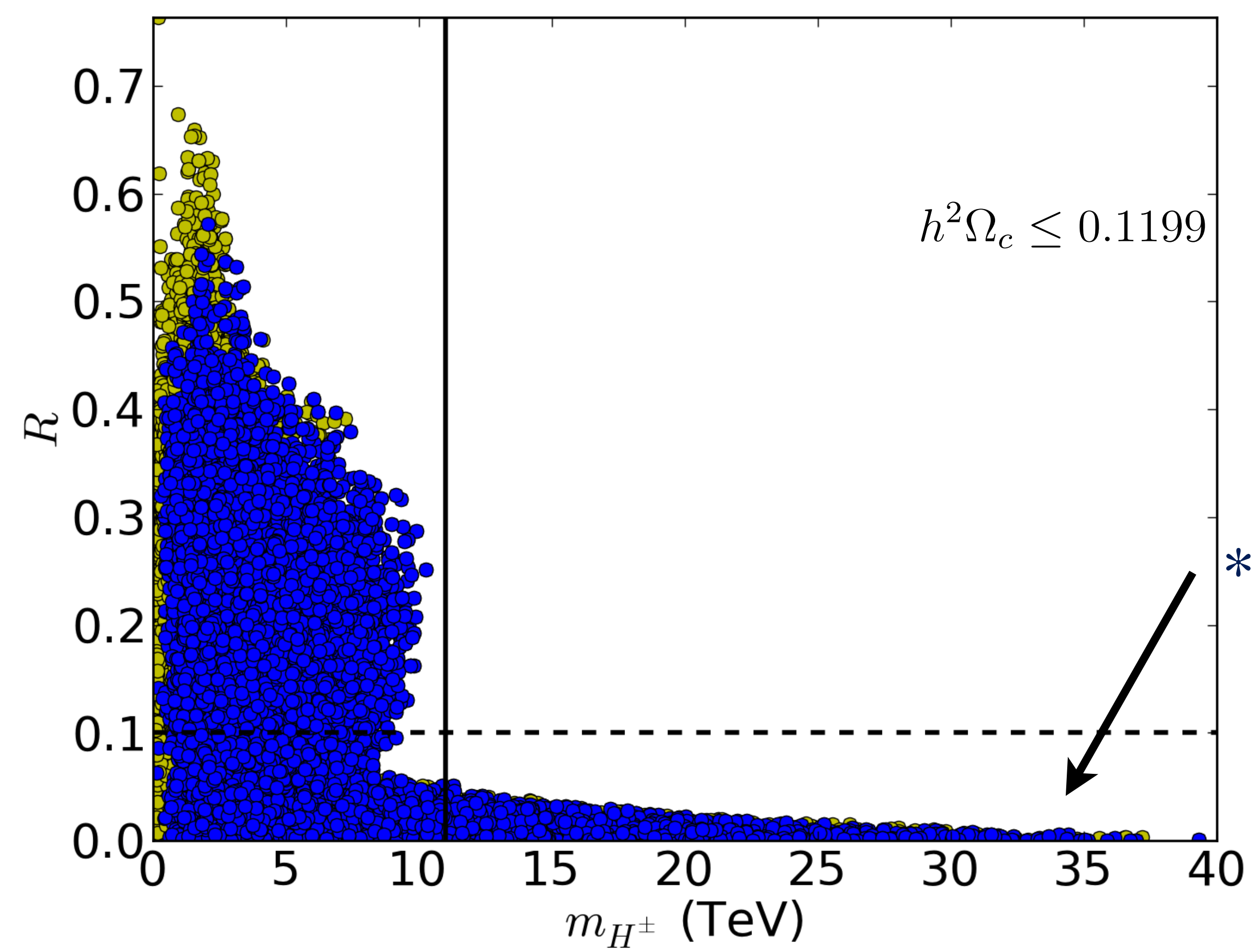
Resonant annihilation fine-tuning parameter:

$$R = \min_{\rm i} \left| 2\, m_{\rm DM} - m_{H_i} \right| / m_{H_i}$$

Gold - Xenon 1T projected exclusion



Charged Higgs Mass constraints for 41% correction



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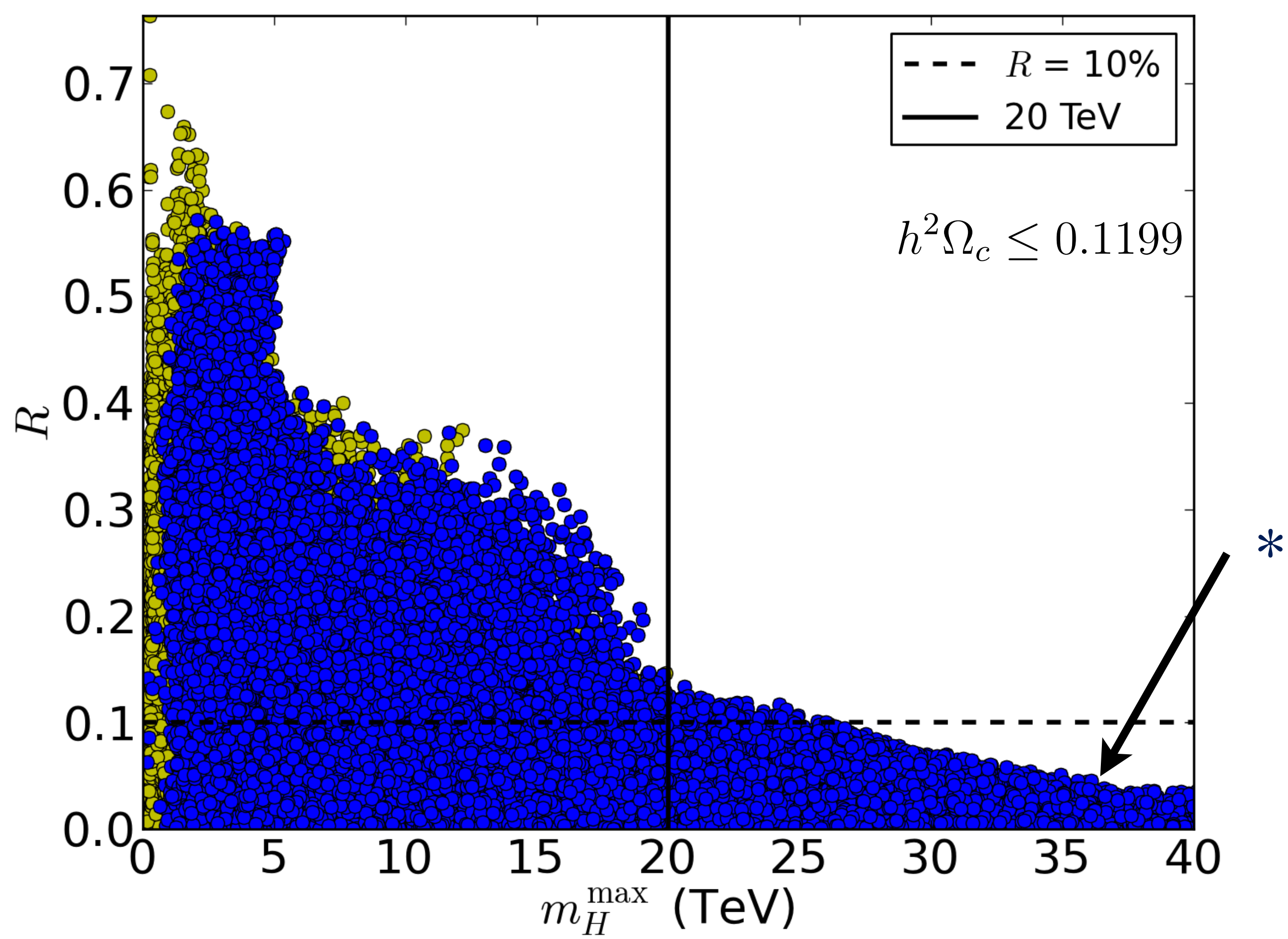
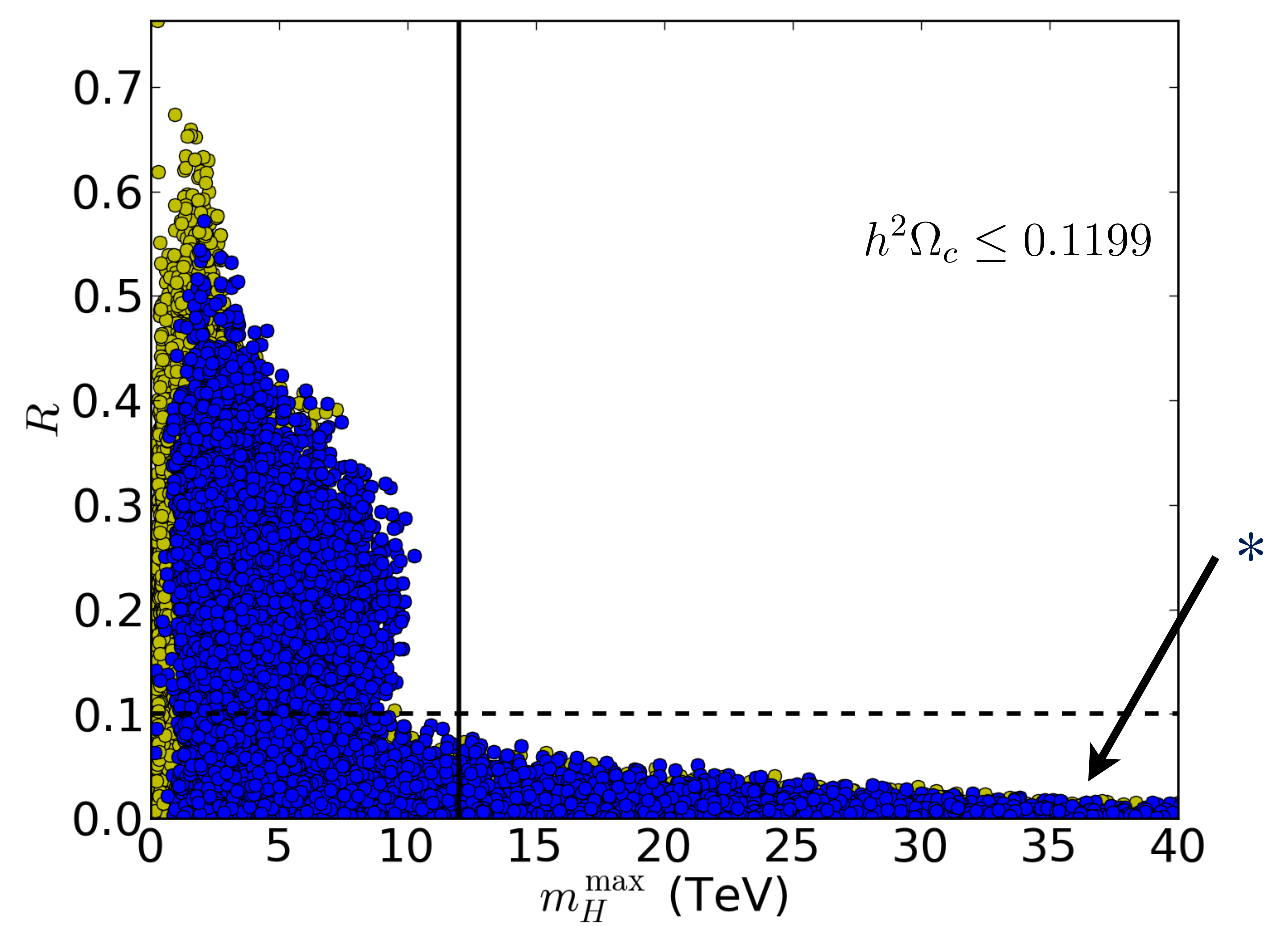


Heaviest CP Even Higgs Mass constraints for 41% correction



Heaviest CP Even Higgs Mass constraints for 20% correction

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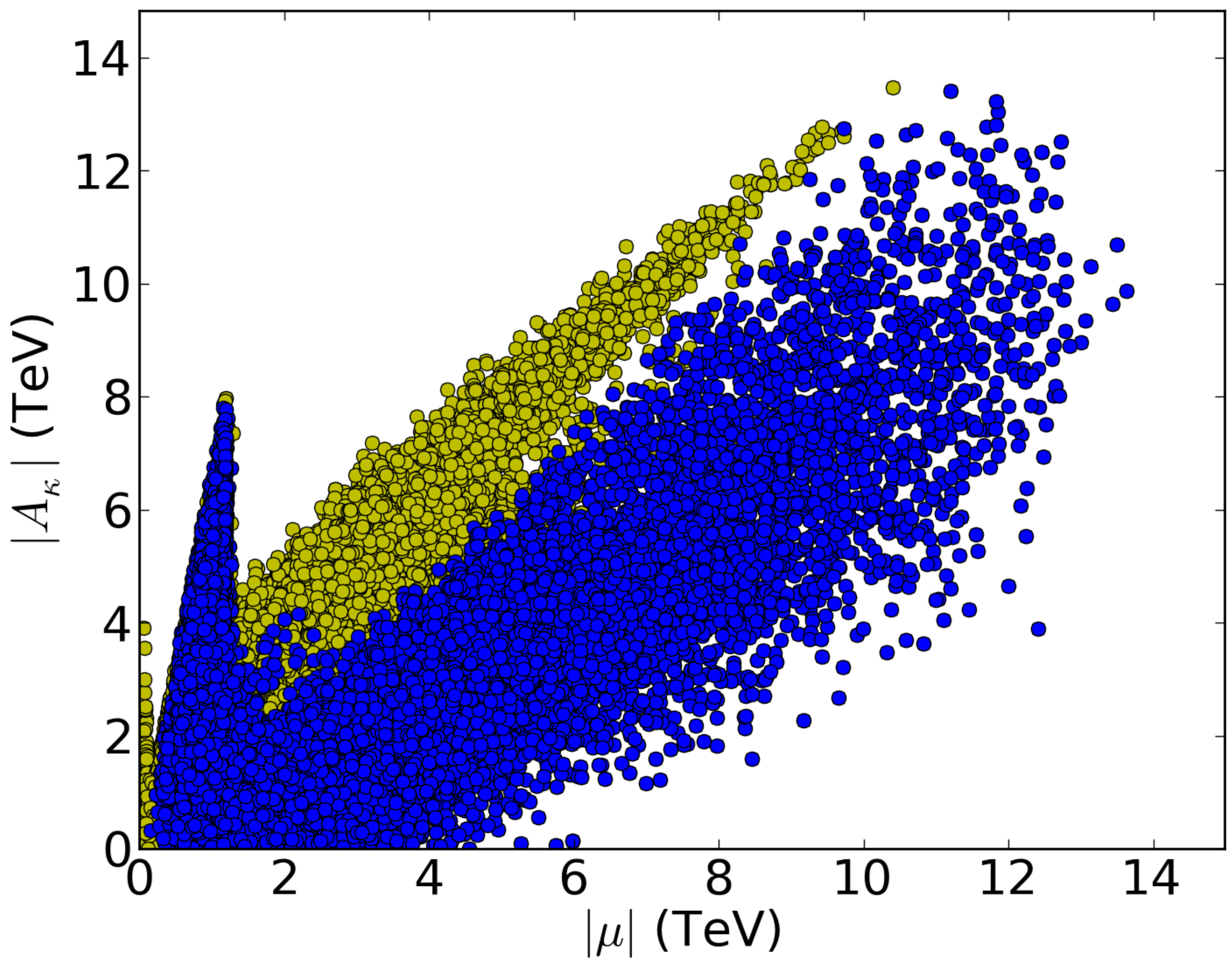
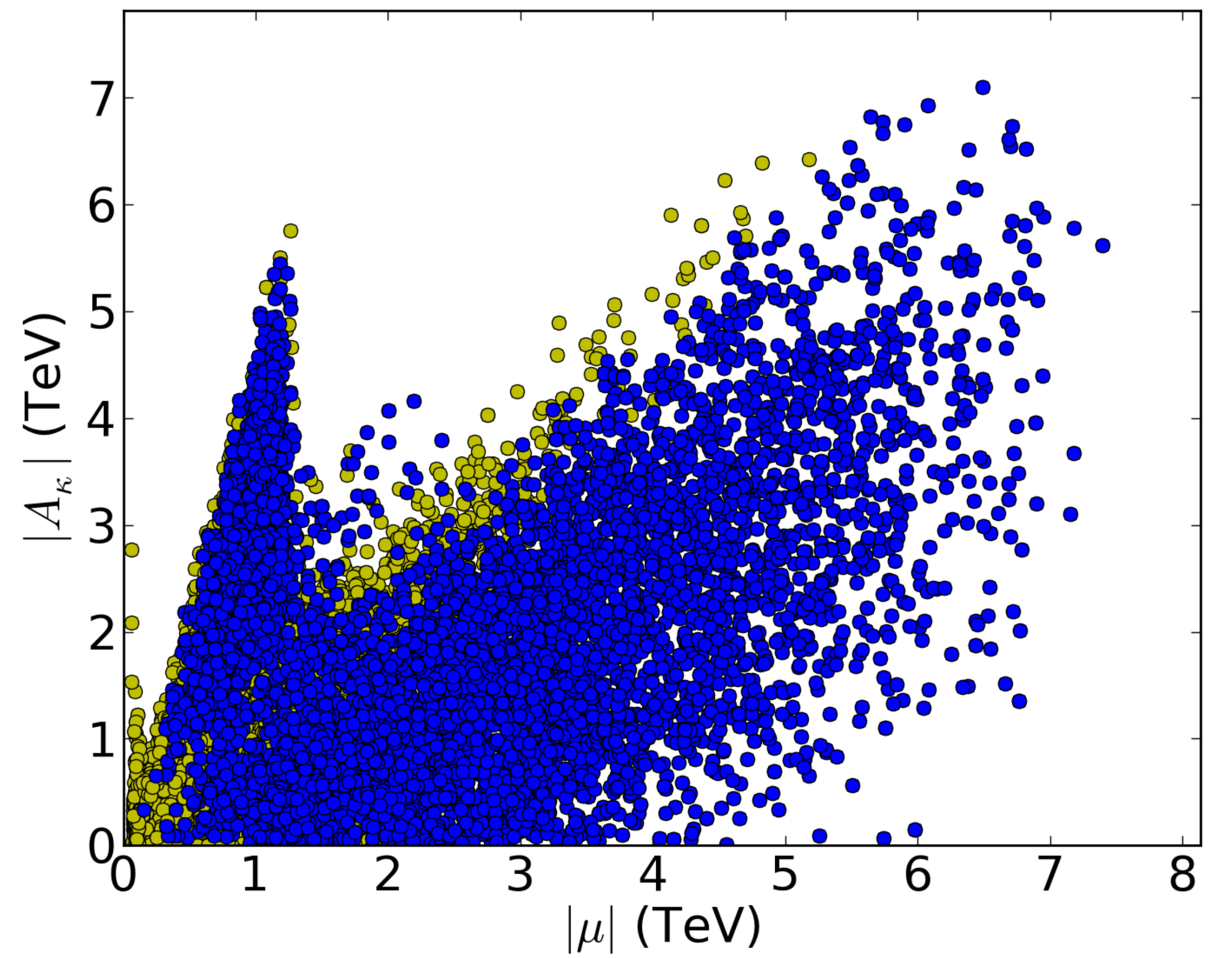
Gold - Xenon 1T projected exclusion

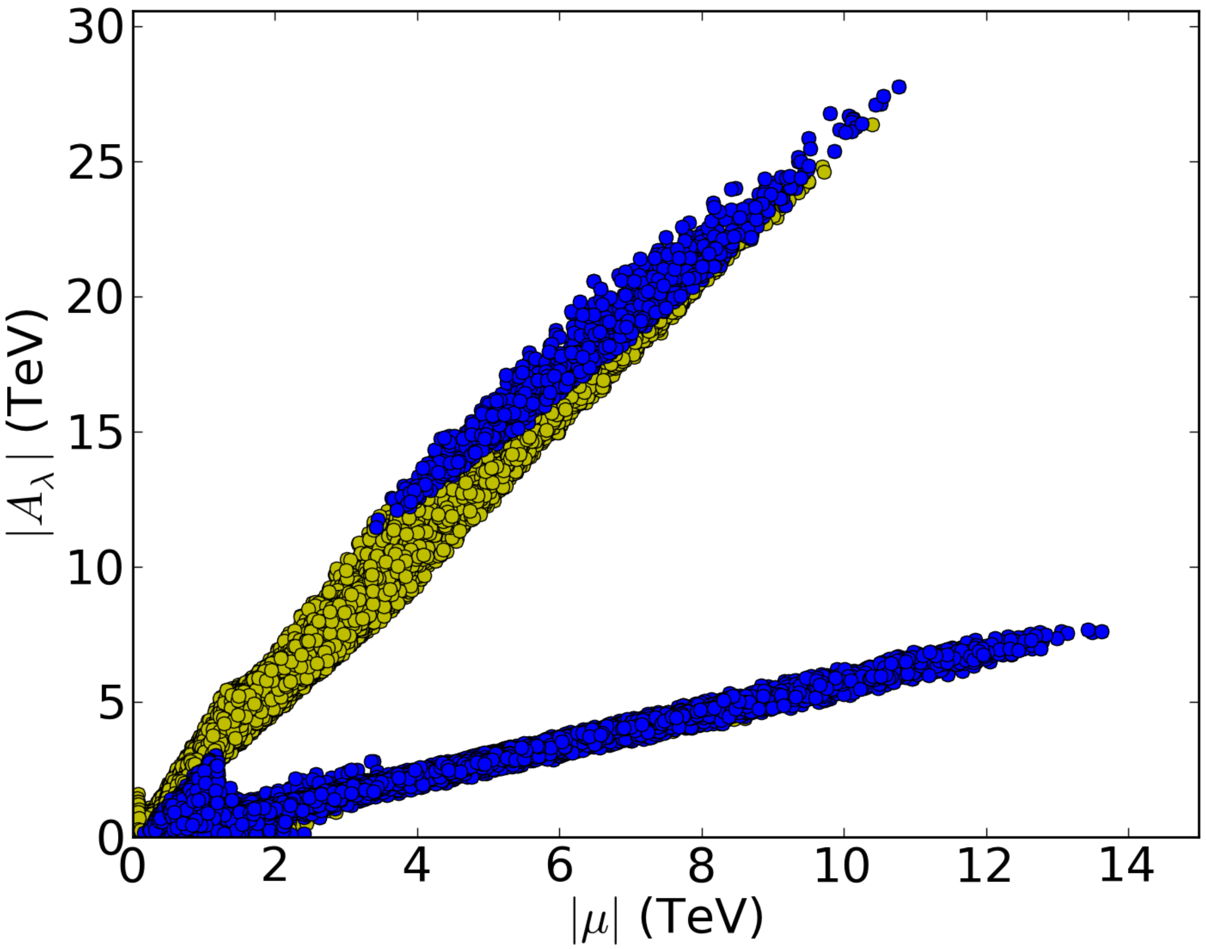


$|A_\kappa|$ versus $|\mu|$ for 41% correction for non-resonant points

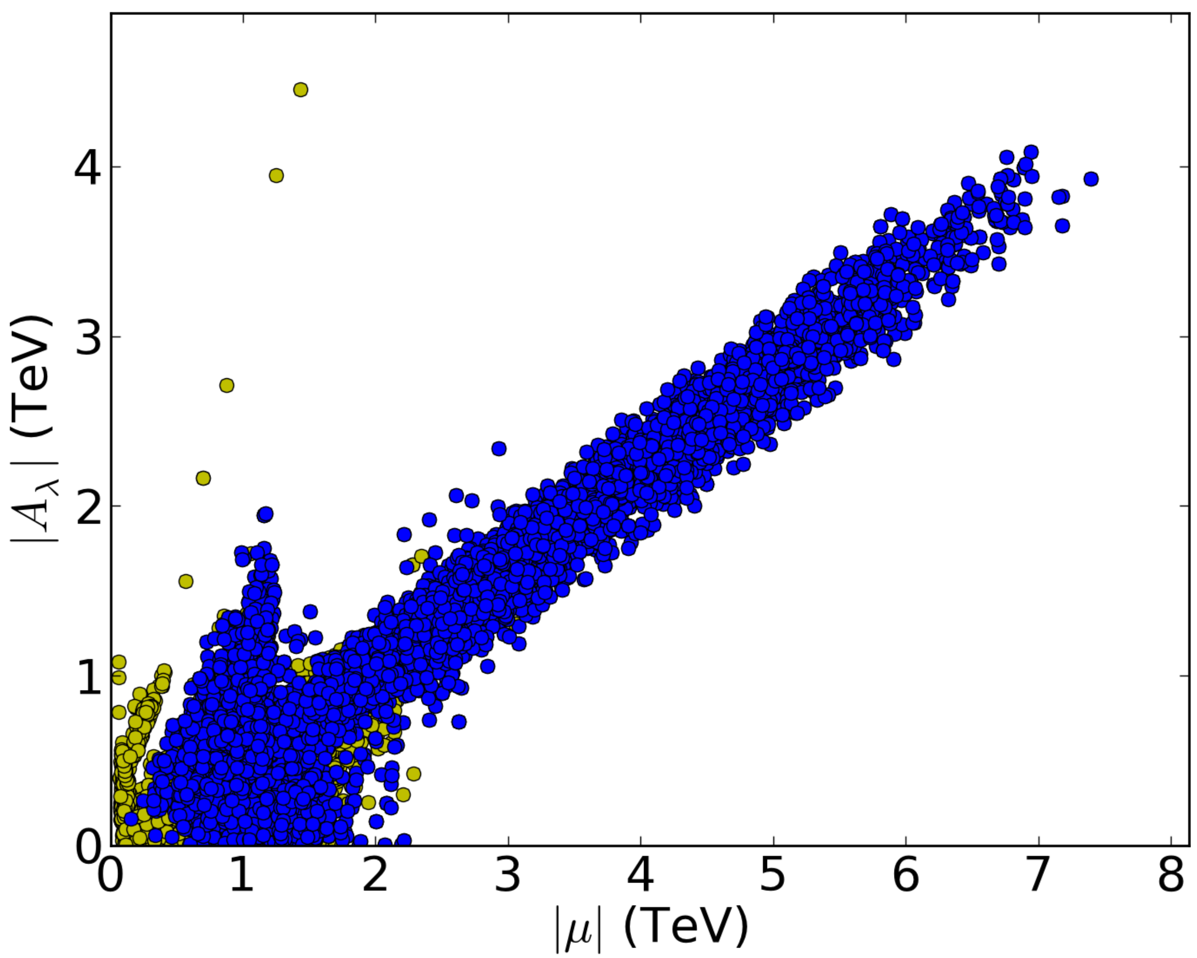


$|A_\kappa|$ versus $|\mu|$ for 20% correction for non-resonant points

Gold - Xenon 1T projected exclusion



$|A_\lambda|$ versus $|\mu|$ for 41% correction for non-resonant points



$|A_\lambda|$ versus $|\mu|$ for 20% correction for non-resonant points

Important implications for SUSY baryogenesis scenarios

A Dark Photon/Higgs Portal

- Place perturbative unitarity constraints not only on dark photons as well as Higgses.
- Gauge sector:

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}\hat{B}_{\mu\nu}\hat{B}^{\mu\nu} - \frac{1}{4}\hat{Z'}_{\mu\nu}\hat{Z'}^{\mu\nu} - \frac{\sin\delta}{2}\hat{B}_{\mu\nu}\hat{Z'}^{\mu\nu}$$

- Dark Matter sector:

$$\mathcal{L}_{\text{DM}} = \bar{\chi}_L \not{D}_\mu \chi_L + \bar{\chi}_R \not{D}_\mu \chi_R - \lambda_\chi \bar{\chi}_L \Phi \chi_R + h.c.$$

- Higgs sector:

$$\mathcal{L}_{\text{Higgs}} = |D_\mu H|^2 + |D_\mu \Phi|^2 - V(H,\Phi)$$

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

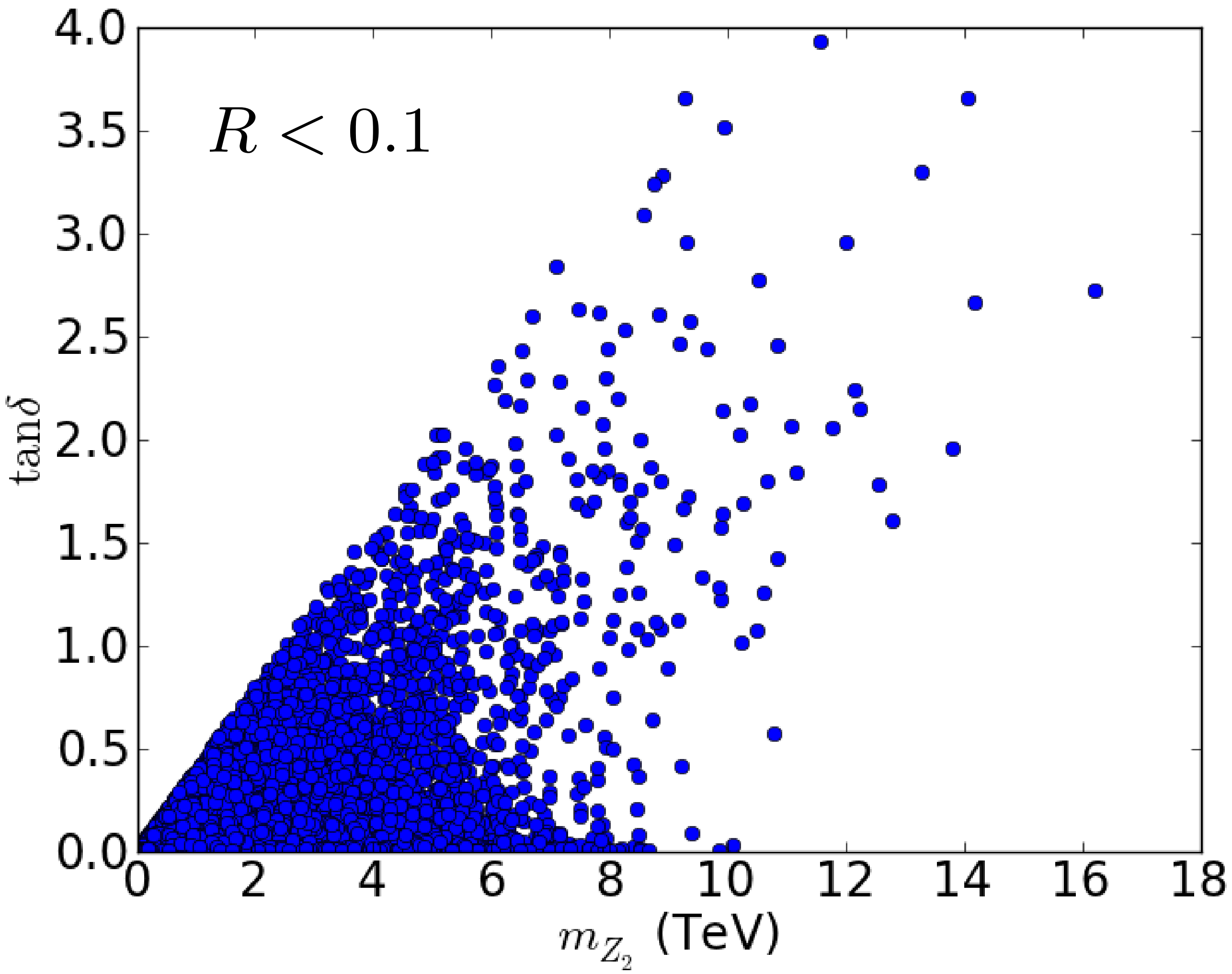
- Free parameters:

$$\{\lambda_1, \lambda_2, \lambda_3, \delta, g', \lambda_\chi, u\}$$

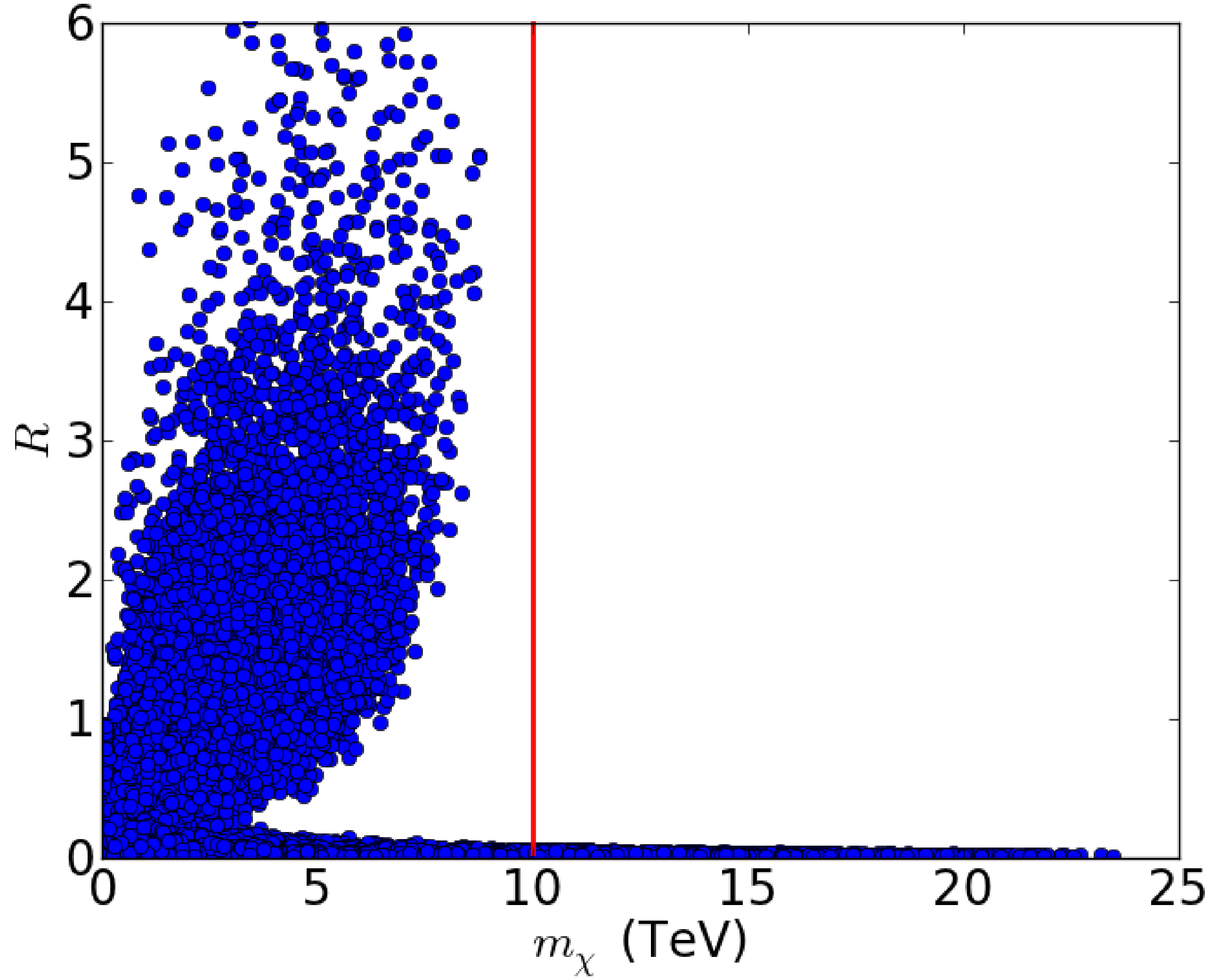
- Unitarity constraint are analogous to the constraints applied to the non-SUSY Higgs case.

- Some results:

All the points that survive the EWPT, unitarity, and relic density cuts.

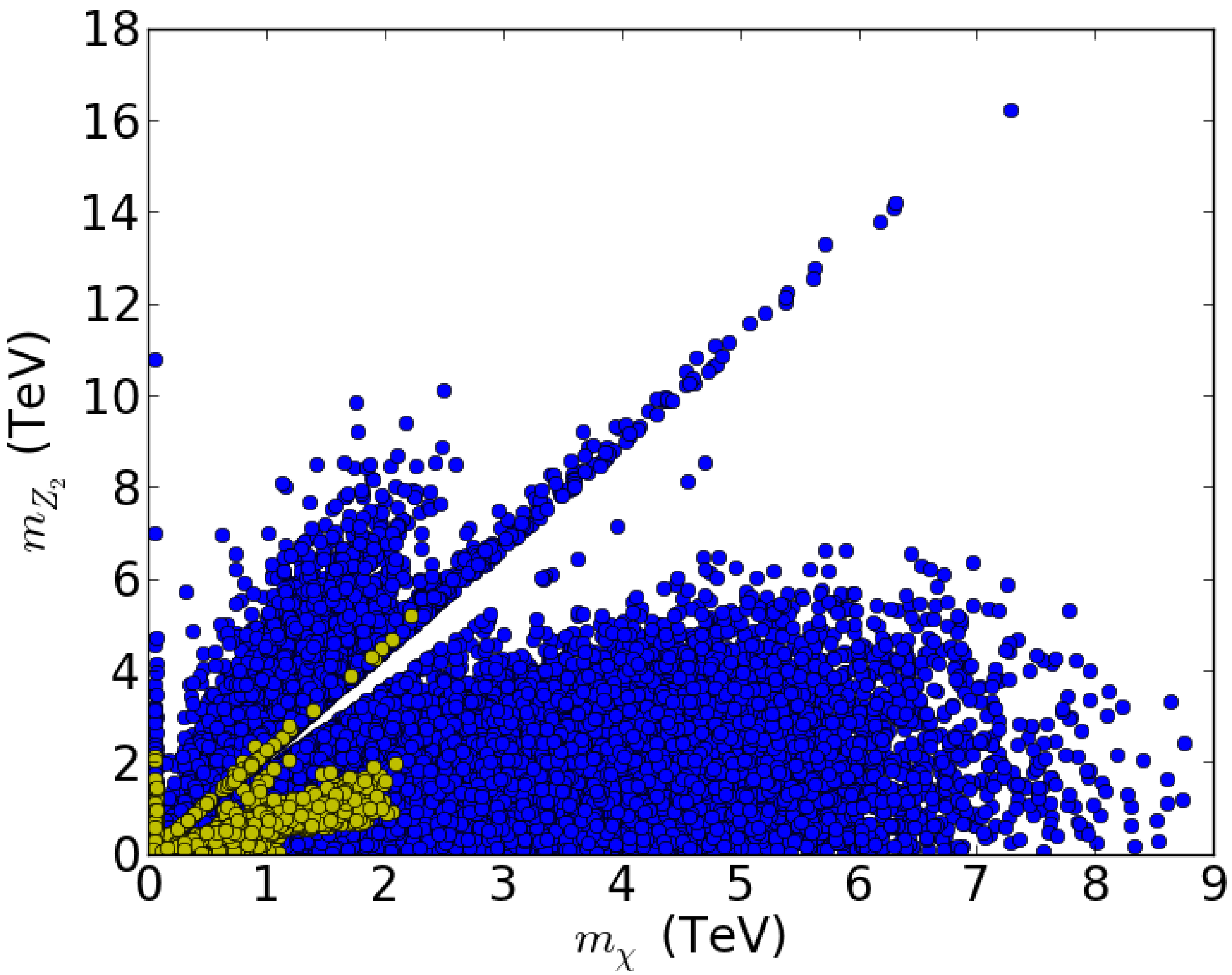


Dark Matter annihilates to Higgses and dark photons



$$R = \min\left(\left|\frac{2m_\chi - m_{H_2}}{m_{H_2}}\right|, \left|\frac{2m_\chi - m_{Z_2}}{m_{Z_2}}\right|\right)$$

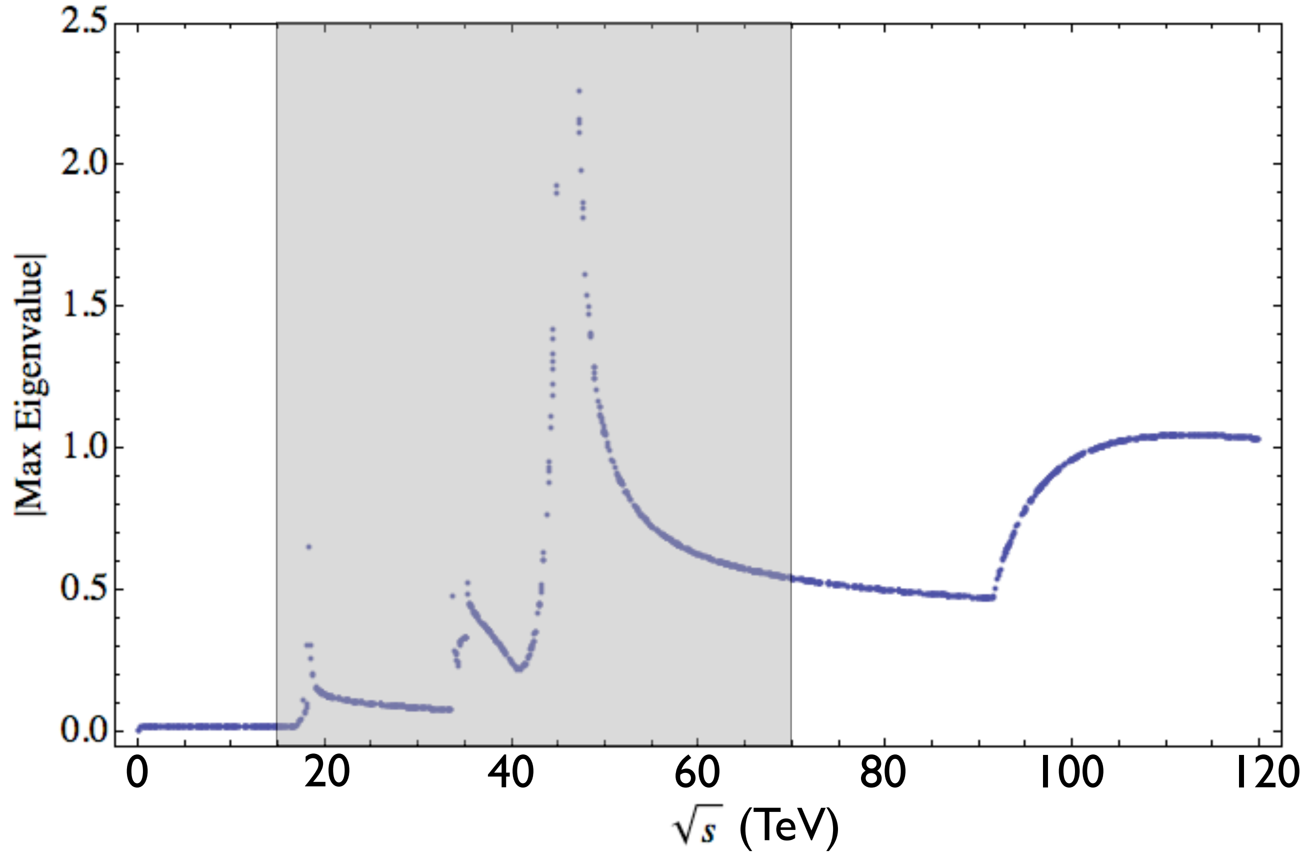
The points that survive the EWPT, unitarity and relic density cuts for R > 0.1. The region around $m_{Z2} \sim 2m\chi$ that is sharply cut corresponds to the removed funnel region (R < 0.1).



The mixed Higgs-gauge points are shown in blue while the "pure gauge" are shown in yellow.

Other NMSSM Backup Slides

NMSSM Arguments



- Example parameter point during the scan:

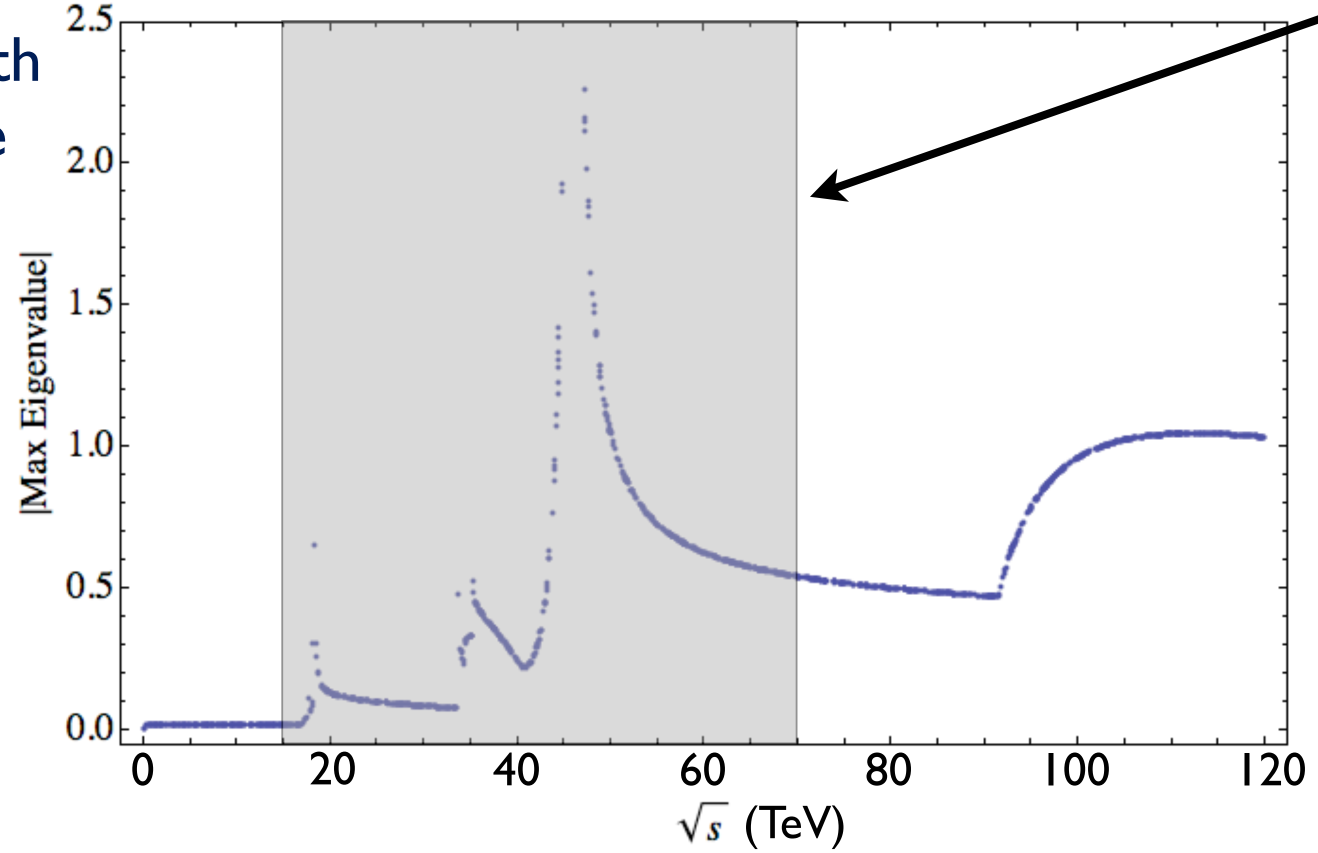
  $\lambda = 0.8396$, $\kappa = 2.3410$, $A_\lambda = -6814.50$ GeV, $A_\kappa = -4364.70$ GeV, $\beta = 0.868950$, $\mu = 8415.30$ GeV.

  The mass of the heaviest scalar particle is 45.83 TeV.

NMSSM Arguments

Max eigenvalue of zeroth partial wave amplitude (next slide)

Gray region not taken into account



- Only consider points where: $\sqrt{s_{\max}} = \sqrt{5}m_{\text{heavy}}$

NMSSM Arguments

- Review:

Unitarity of the S-matrix requires

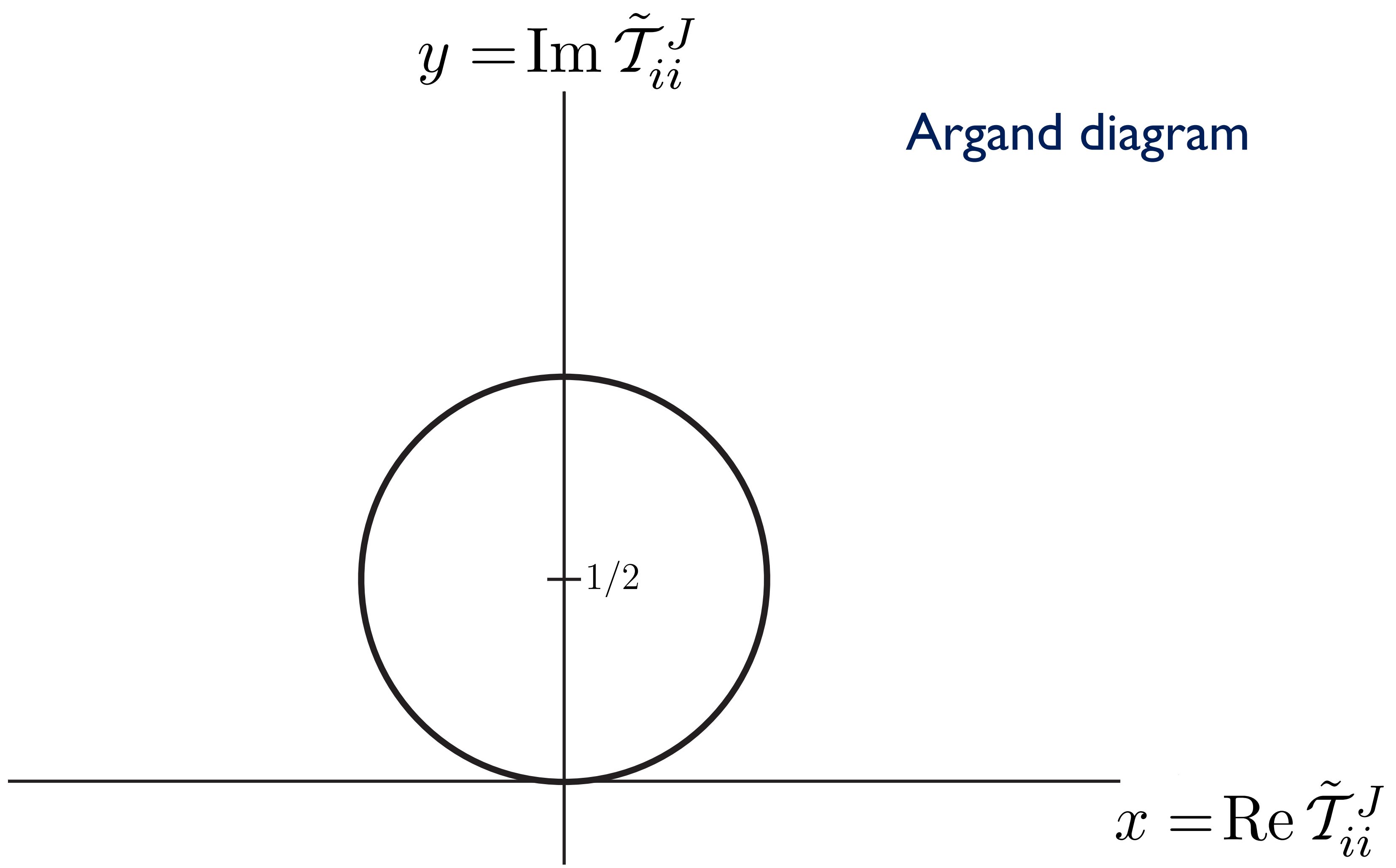
$$-\,\mathrm{i}\left(T - T^{\dagger}\right) = T^{\dagger}T \qquad\qquad \frac{1}{2\mathrm{i}}\left(\mathcal{T}^{J}_{fi} - \mathcal{T}^{J*}_{if}\right) \cong \sum_{h} \mathcal{T}^{J*}_{hf}\,\mathcal{T}^{J}_{hi}$$

where

$$\mathcal{T}^{J}_{fi} = \frac{1}{2}\,\frac{\lambda_f^{1/4}\lambda_i^{1/4}}{16\pi\, s}\int_{-1}^{1} \mathrm{d}\cos\theta\, \hat{\mathcal{T}}_{fi}(\sqrt{s}, \cos\theta)\, P_J(\cos\theta)$$

NMSSM Arguments

- Our approach:

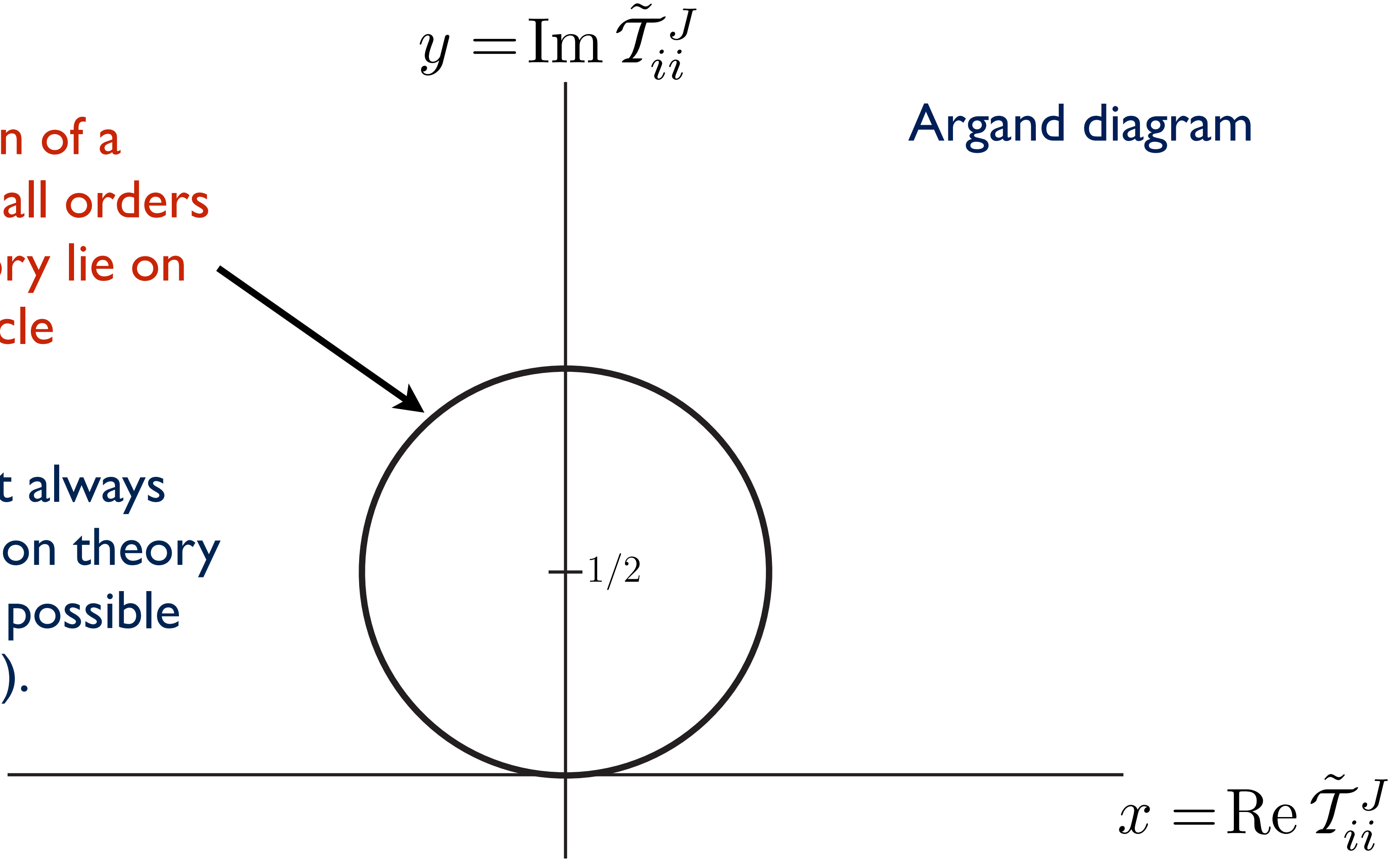


NMSSM Arguments

- Our approach:

Exact computation of a scattering process to all orders of perturbation theory lie on the Argand circle

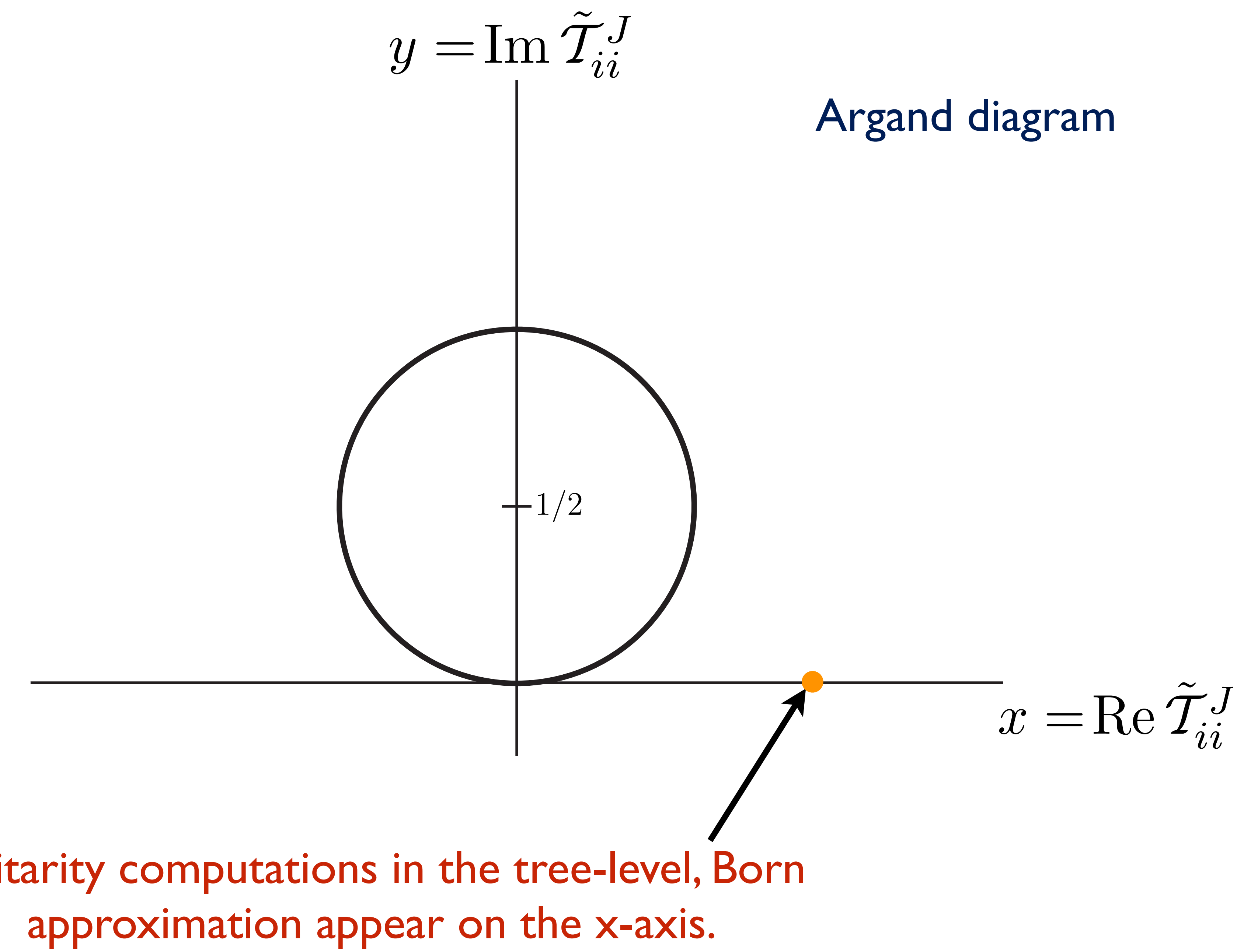
However, we almost always compute in perturbation theory to the lowest order possible (off the circle).



Argand diagram

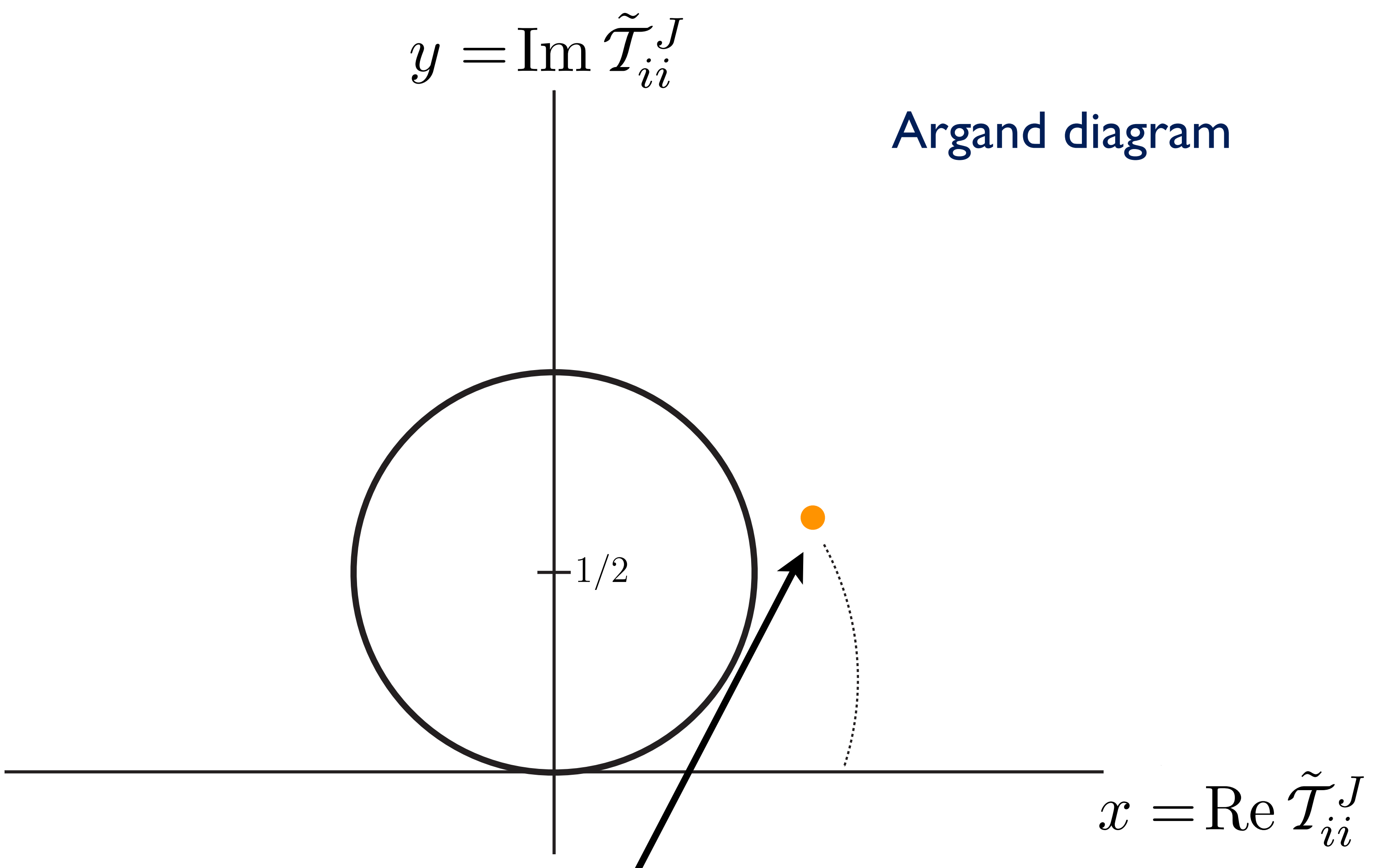
NMSSM Arguments

- Our approach:



NMSSM Arguments

- Our approach:

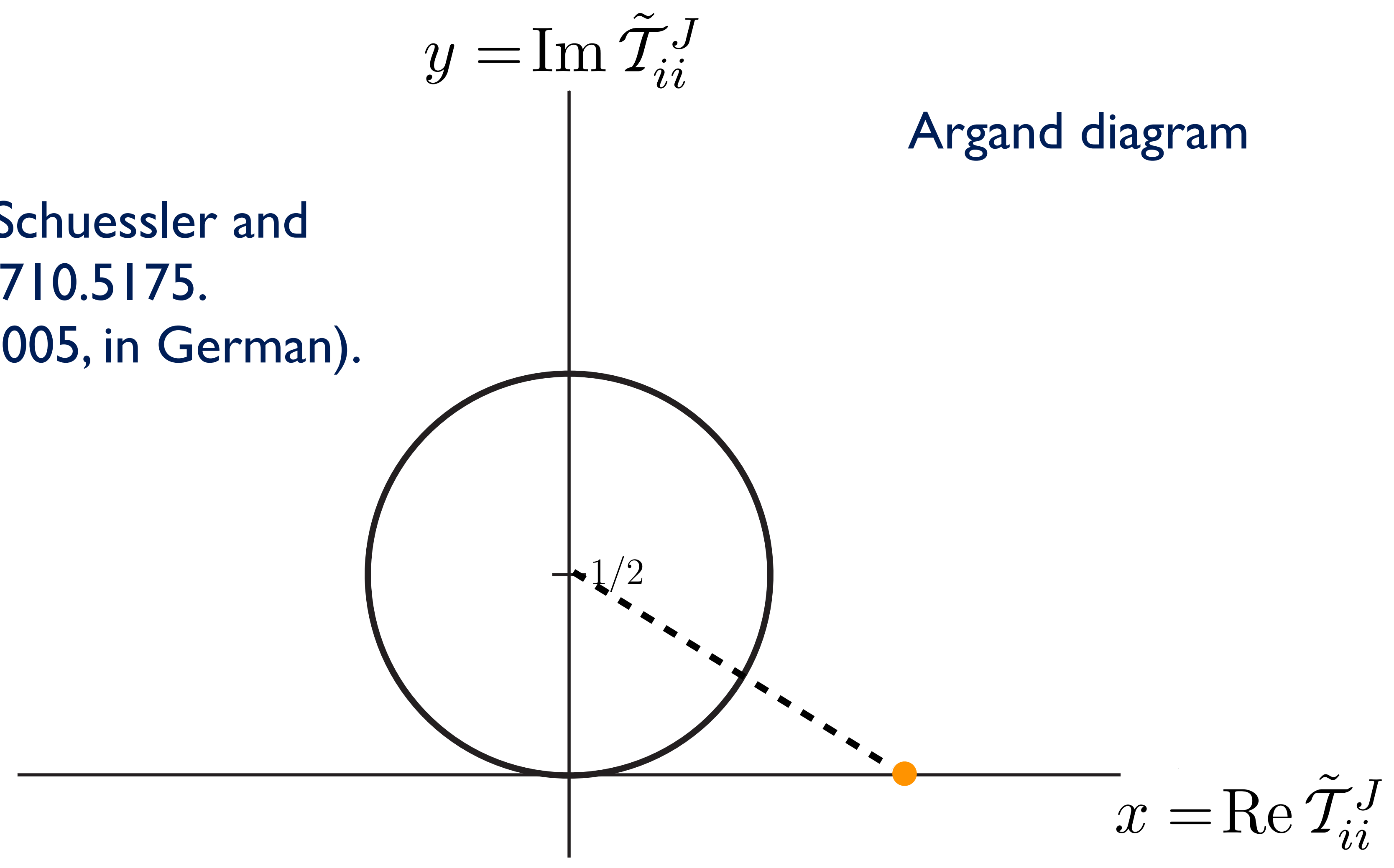


Higher-order corrections move "toward" to the Argand circle. However, a circuitous route is possible* depending on the size of the correction.

*See Aydemir, Anber and Donoghue, arXiv:1203.5153, for a similar analysis of chiral perturbation theory.

NMSSM Arguments

- Our approach:



Argand diagram

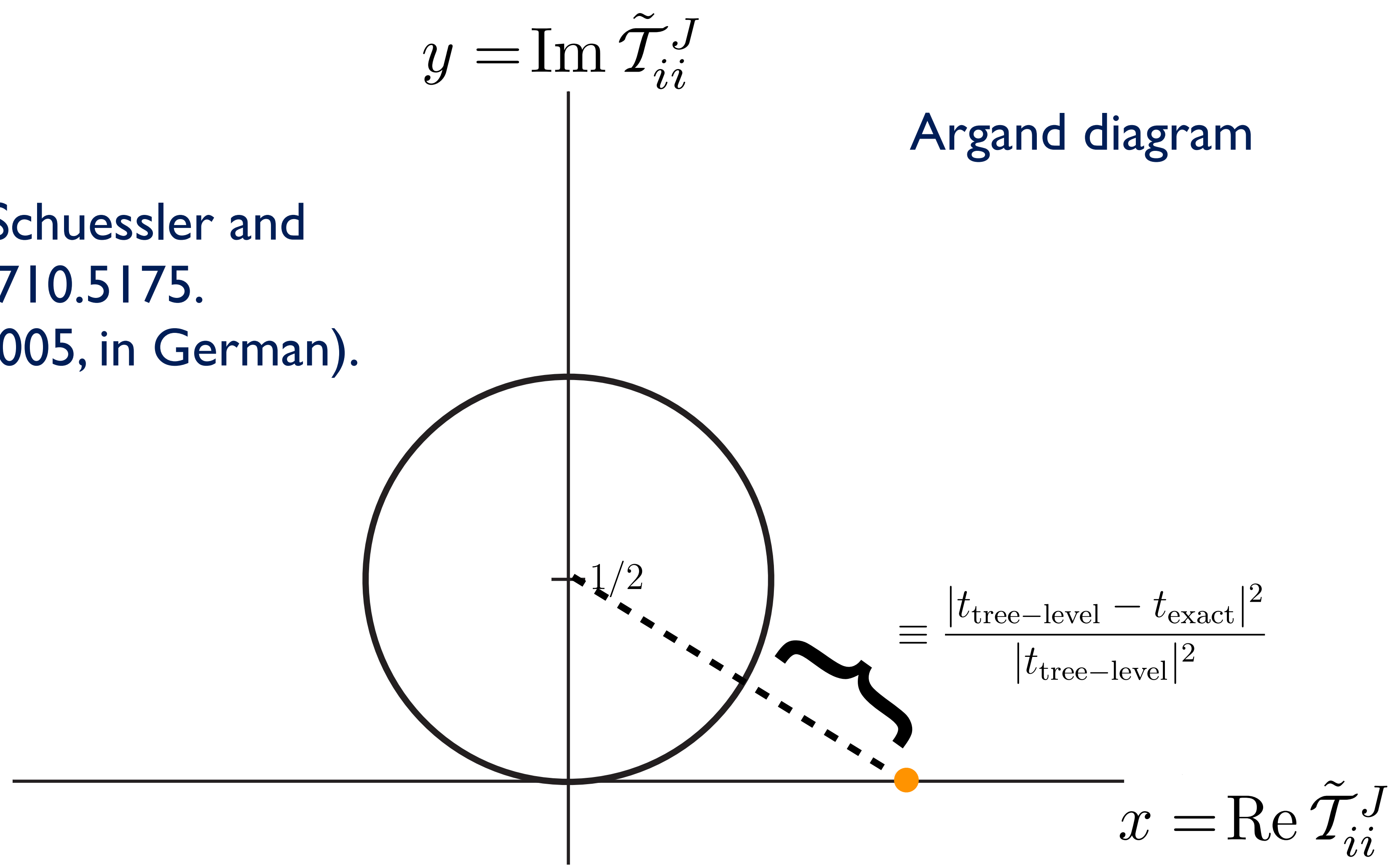
*Methodology from Schuessler and Zeppenfeld, arXiv:0710.5175. Schuessler thesis (2005, in German).

To conservatively estimate the perturbative corrections, take the tree-level computation and draw a straight line to the nearest point* on the circle.

NMSSM Arguments

- Our approach:

*Methodology from Schuessler and Zeppenfeld, arXiv:0710.5175. Schuessler thesis (2005, in German).



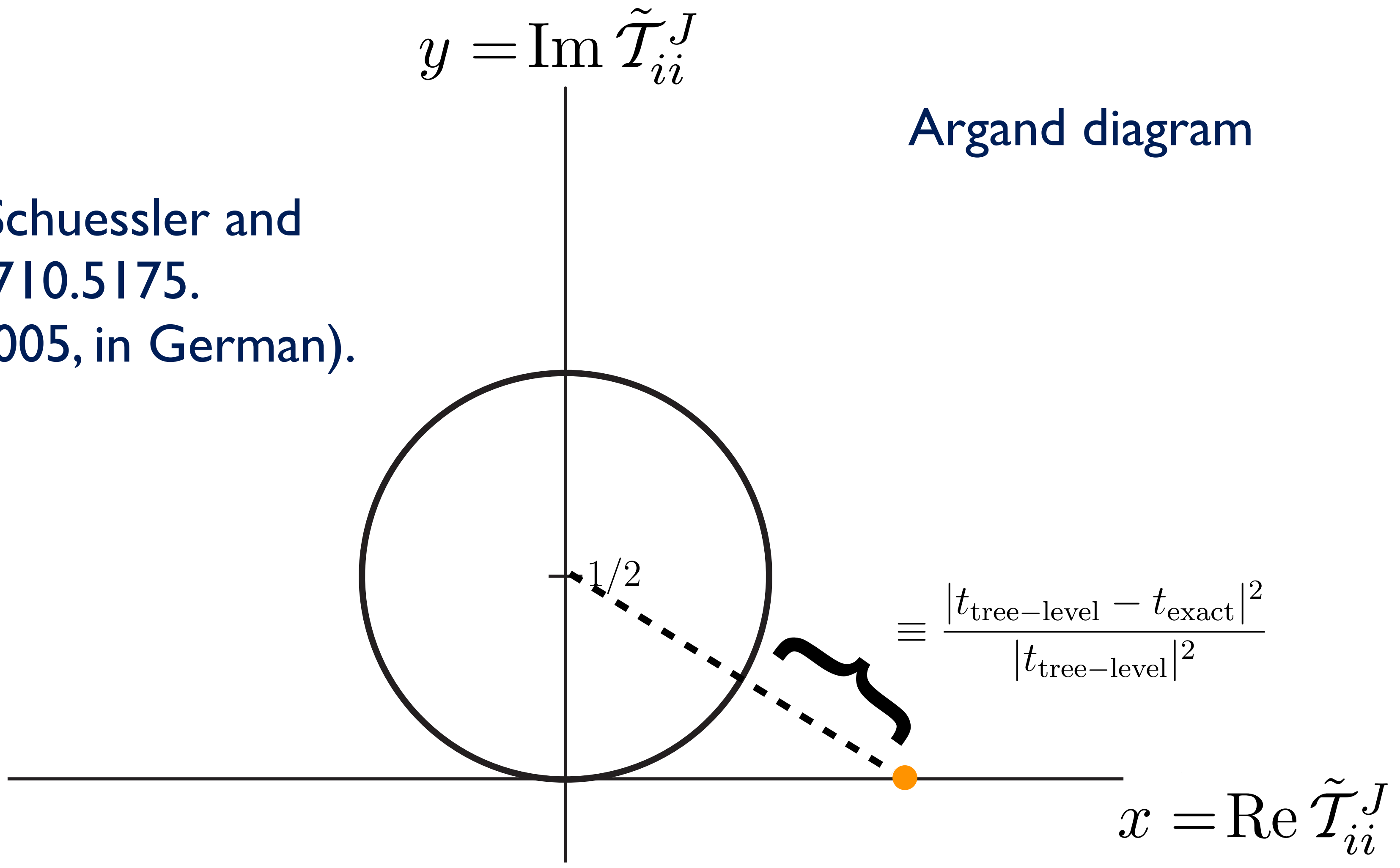
This distance corresponds to the minimum perturbative correction needed to correct the tree-level amplitude*.

NMSSM Arguments

- Our approach:

*Methodology from Schuessler and Zeppenfeld, arXiv:0710.5175. Schuessler thesis (2005, in German).

Argand diagram



We scan over $\sqrt{s}$ to give the maximum value of tree-level amplitude. For our bounds we only allow points in the parameter space that correspond to less than a 41% correction* to the amplitude. We also show 20% corrections in the slides.

NMSSM Perturbative Corrections

- Tree-level unitarity constraints are not enough to get an accurate scale of new physics.*
- In addition require the next order correction not to generate a 41% correction larger than the tree-level correction**. (no Landau poles)
- More (fuller explanation) on this in the next section.

*See Aydemir, Anber and Donoghue, arXiv:1203.5153, for a similar conclusion using chiral perturbation theory.

**See Barbieri, Hall and Rychkov, arXiv:0603188.