Perturbative Unitarity Constraints on the NMSSM SUSY Mass Spectra

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Finding New Energy Scales

- The Standard Model is not a complete theory of the Universe
- Multiple evidences for new physics
- Strong evidence for non-baryonic Dark Matter
- No new particles observed

How can we find the next energy scale?

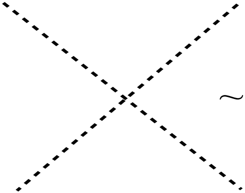
- Naturalness $\Rightarrow$ TeV scale?
- Fine-tuning dependent scale, orders of magnitude variations
- Use other fundamental principles?

Unitarity

- Breaking of perturbative unitarity is a sign for new physics
  - **Fermi theory**: Unitarity violated around 350 GeV
    $\Rightarrow$ W boson at 80 GeV
  - **Light pion effective theory**: unitarity violated around 1.2 GeV
    $\Rightarrow$ Axial and vector resonances at 800 MeV
  - **Electroweak theory**: unitarity violated around 1.2 TeV
    $\Rightarrow$ Higgs boson at 125 GeV
- Can we use unitarity to constrain BSM theories?

Effects of unitarity on couplings

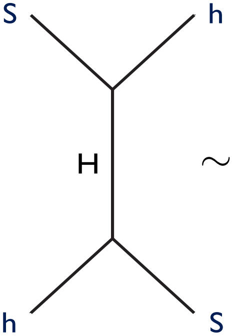
Dimensionless Unitarity



$$\sim \lambda^2$$

Bounds on quartic couplings
Lee, Quigg, Thacker [Phys. Rev. D 16, 1519 (1977)]

Dimensionful Unitarity



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

Bounds on mass ratios
Schuessler, Zeppenfeld [arXiv:0710.5175]

A recipe for constraining new models

- Applies to
  - Models predicting a **Dark Matter candidate**
  - Known production and annihilation mechanisms
- **Dimensionful unitarity**: upper bounds on the mass ratios
  - Contracted spectrum
- **Dimensionless unitarity**: upper bounds on dimensionless couplings
- **Tension with Relic Abundance constraints** for heavy Dark Matter

Unitarity and Relic Abundance set an upper bound on the masses of the new particles!

- Unitarity constraints on the Higgs portal $\Rightarrow$ 10 TeV bounds
  Walker [arXiv:1310.1083]

Application: the NMSSM

- Preliminary study: Focus on the NMSSM Higgs sector
- Assume thermal Dark Matter production/annihilation
- Higgsino/Singlino Dark Matter: SUSY-Higgs portal

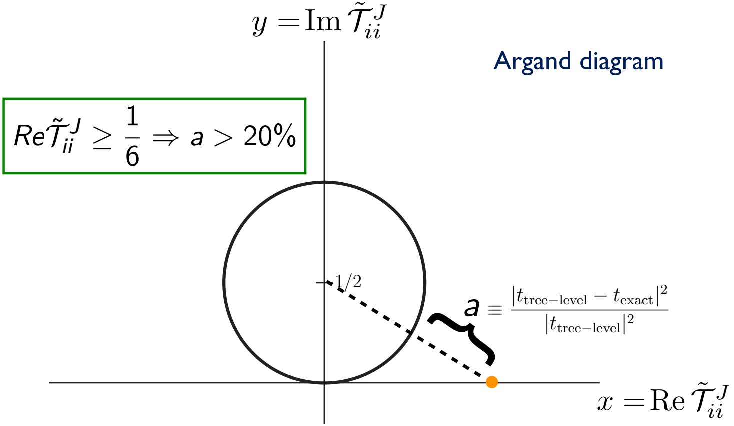
$$\begin{aligned}
\mathcal{W}_{\rm NMSSM} &= -\lambda \hat{S}\hat{H}_u.\hat{H}_d + \frac{1}{3}\kappa \hat{S}^3 \\
V_{\rm soft} &= m_{H_d}^2 H_d^\dagger H_d + m_{H_u}^2 H_u^\dagger H_u + m_S^2 S^\dagger S \\
&\quad - \left(\lambda A_\lambda S H_u H_d - \frac{1}{3}\kappa A_\kappa S^3 + h.c.\right)
\end{aligned}$$

- Six parameters after EWSB

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

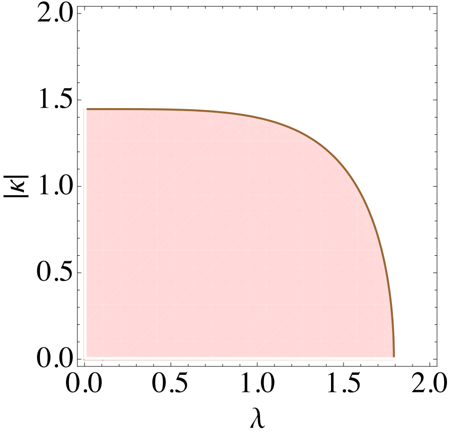
Perturbative Unitarity

Conservative estimate of the minimal amount of loop corrections in a theory



Schuessler and Zeppenfeld [arXiv:07105175, Schuessler thesis (2005)]

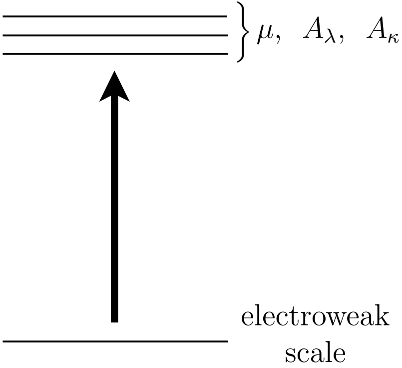
Dimensionless unitarity in the NMSSM



For large s, only quartic couplings remain

$$\lim_{s\to\infty}|Re\mathcal{T}_{ij}| < \frac{1}{6} \Rightarrow \lambda, \kappa \lesssim 2$$

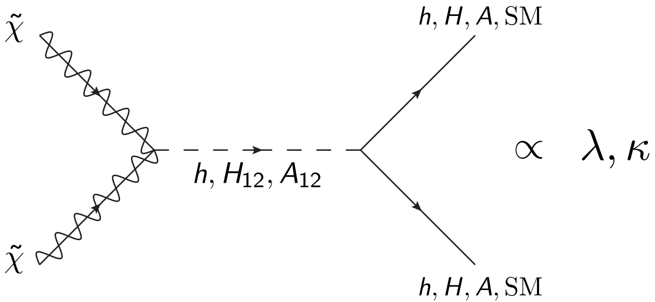
Dimensionful Unitarity in the NMSSM



- m_H, m_A, m_χ depend on A_λ, A_κ, μ
- Apply unitarity a la Zeppenfeld to constrain ratios
- Energy-dependent scattering amplitudes

  $\Rightarrow$ Scan over s

Relic density anchors the heavy spectrum



- λ and κ increase with the DM mass
- Maximal mass when λ or κ hits the unitarity bound

Finding upper bounds: procedure

- Uniform scan over 6 parameters with the 125 GeV Higgs mass constraint

$$\lambda, |\kappa| < 4, \quad |A_i|, |\mu| < 40\,\text{TeV}$$

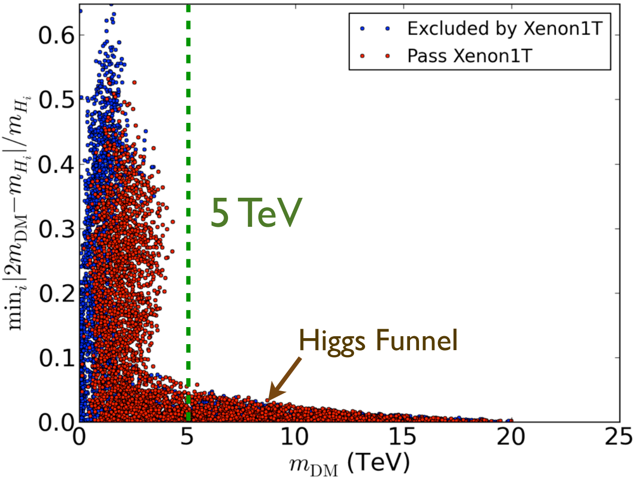
- Apply vacuum constraints
  Kanehata, Kobayashi, Konishi, Seto, Shimomura [arXiv:1103.5109]
- Unitarity: allow for at most 20% loop corrections to tree-level amplitudes

$$|Re\mathcal{T}_{ij}| \leq \frac{1}{6}$$

- Compute relic density using MicrOmegas and NMSSMTools

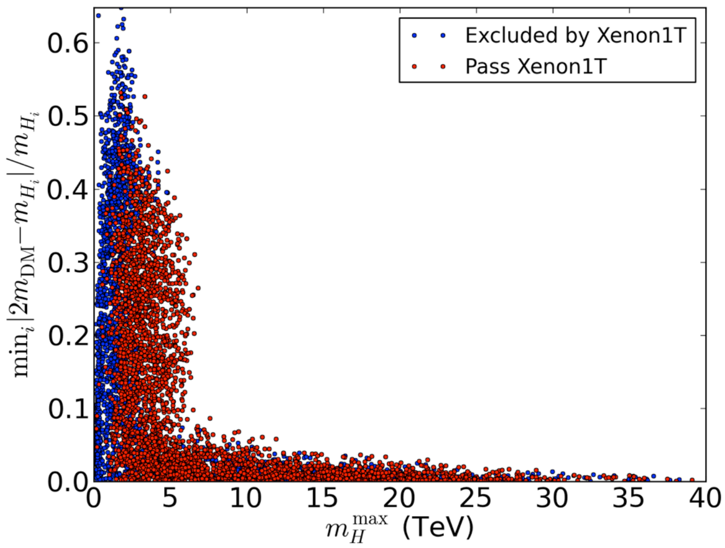
$$\Omega h^2 < 0.1199 \text{ (Planck measurement)}$$

Results: Dark Matter



- Fine Tuning Factor $R = \min_i \frac{|2m_{\mathrm{DM}} - m_{H_i}|}{m_{H_i}}$

Results: Higgs sector

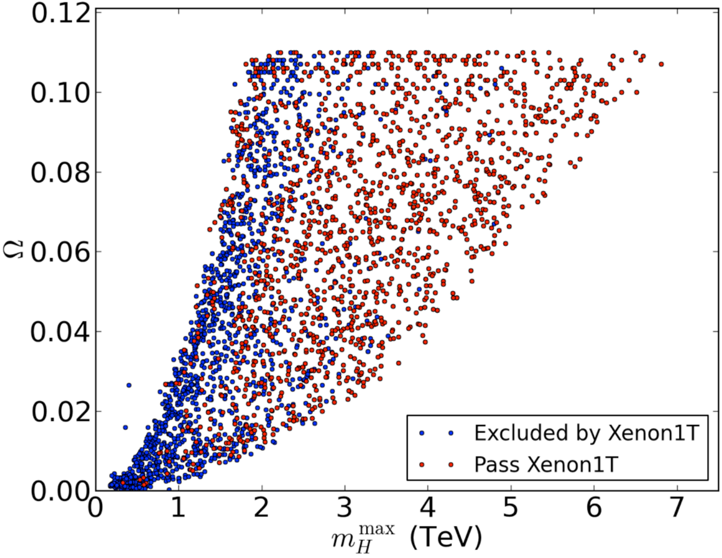


Summary

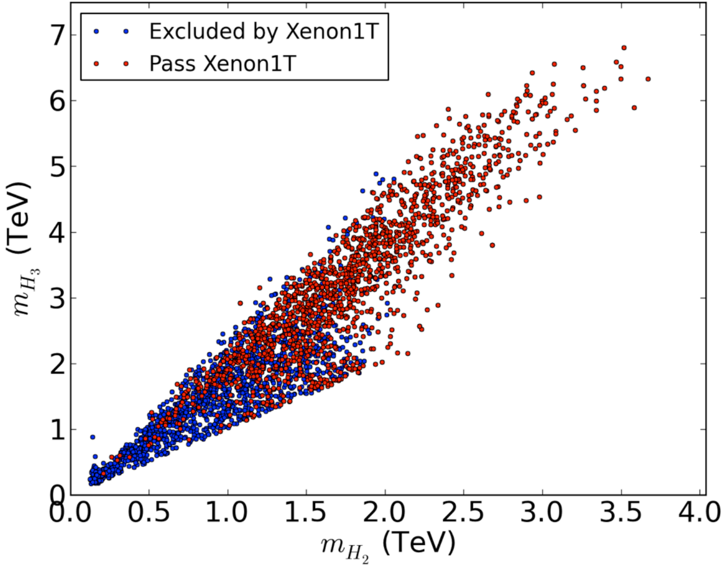
- Need to find new energy scales for future experiments
- Unitarity reliably indicates when new physics will appear
- Unitarity + Thermal Dark Matter hypothesis can give upper bounds on models of new physics
- 5 TeV bounds on DM mass in the NMSSM
- New Higgs fields below 10 TeV: a case for a 100 TeV collider?

Results: Relic Density

Outside Higgs funnel ($R > 10\%$)



Outside Higgs funnel ($R > 10\%$)



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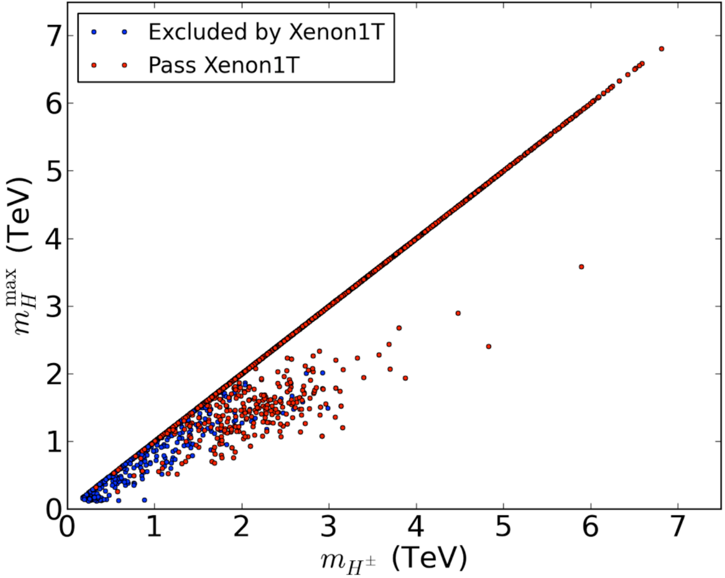

Outside Higgs funnel ($R > 10\%$)