Perturbative Unitarity Constraints on a SUSY Higgs portal

Sonia El Hedri
with
Kassahun Betre, Devin Walker

ERC Workshop, Schloss Waldthausen

November 12, 2014

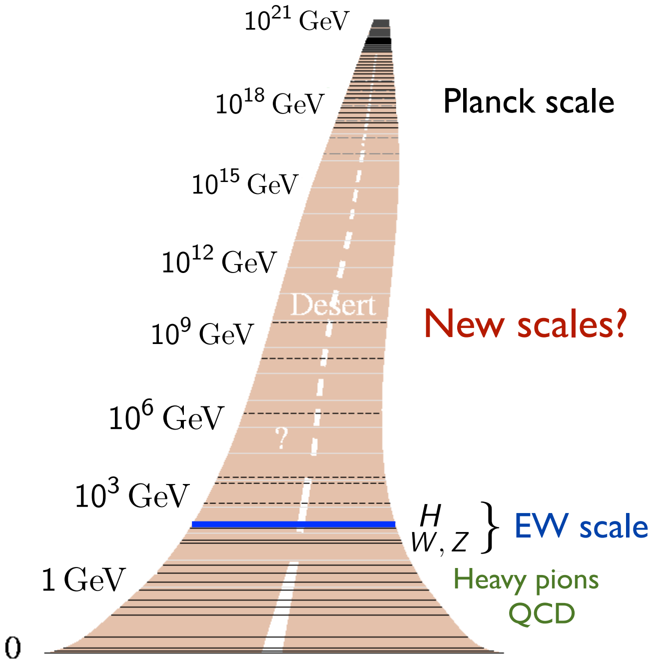
arXiv:1407.0395
arXiv:1410.1534

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Finding New Energy Scales

Application to the NMSSM

Parameter scan and results



10^{21} GeV
10^{18} GeV
Planck scale
10^{15} GeV
10^{12} GeV
Desert
10^{9} GeV
New scales?
10^{6} GeV
?
10^{3} GeV
H
W, Z
EW scale
1 GeV
Heavy pions
QCD
0

Finding new energy scales

How to look for the next energy scale?

- Break down of the theory?

  $\Rightarrow$ SM perturbative up to the GUT scale

  $\Rightarrow$ Electroweak vacuum metastable

  Degrassi, Di Vita, Elias-Miró, Espinosa, Giudice, Isidori, Strumia, [arXiv:1205.6497]

- New observations

  $\Rightarrow$ Evidence for Dark Matter, neutrino masses, ...

  $\Rightarrow$ Unknown/too high energy scale

- Naturalness arguments

  $\Rightarrow$ Upper bounds depend on the fine-tuning

- Other possibilities??

Finding new energy scales

How to look for the next energy scale?

- Break down of the theory?

  $\Rightarrow$ SM perturbative up to the GUT scale

  $\Rightarrow$ Electroweak vacuum metastable

  Degrassi, Di Vita, Elias-Miró, Espinosa, Giudice, Isidori, Strumia, [arXiv:1205.6497]

- Look for new phenomena

  $\Rightarrow$ Evidence for Dark Matter, neutrino masses, ...

  $\Rightarrow$ Unknown/too high energy scales

- Naturalness arguments

  $\Rightarrow$ Avoid fine-tuning of the Higgs mass $\Rightarrow$ Upper bounds depend on the tolerated fine-tuning

- **Perturbative Unitarity**

Unitarity in the Standard Model

- Breaking of perturbative unitarity is a sign for new physics
  - **Light pion effective theory**: unitarity violated around 1.2 GeV

    $\Rightarrow$ Axial and vector resonances at 800 MeV
  - **Fermi theory**: Unitarity violated around 350 GeV

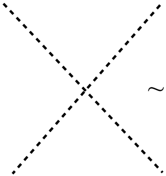
    $\Rightarrow$ W boson at 80 GeV
  - **Electroweak theory**: unitarity violated around 1 TeV

    $\Rightarrow$ Higgs boson at 125 GeV

Effects of unitarity on couplings

$$\mathrm{Re}\mathrm{T}_{ii} < \frac{1}{2}$$

Dimensionless Unitarity

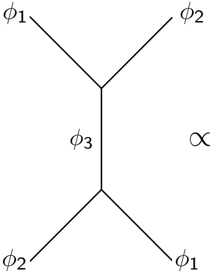


$$\sim \lambda^2$$

Bounds on quartic couplings

Lee, Quigg, Thacker [Phys. Rev. D 16, 1519 (1977)]

Dimensionful Unitarity



$$\propto \frac{A_{123}^2}{s - m_{\phi_3^2}}$$

Bounds on mass ratios

Schuessler, Zeppenfeld [arXiv:0710.5175]

Anchoring the spectrum: Low Energy Observables

- Unitarity constrains BSM theories
  - $\Rightarrow$ Upper bounds on dimensionless couplings
  - $\Rightarrow$ Upper bounds on **ratios** of scales
- Does not prevent decoupling

What if new phenomena are observed?

- Couple unitarity to low energy observables

Unitarity and Dark Matter

- Dark Matter is one of the only evidences of new physics beyond the SM
- Unknown mass, **known relic density**
- Only gravitational couplings observed

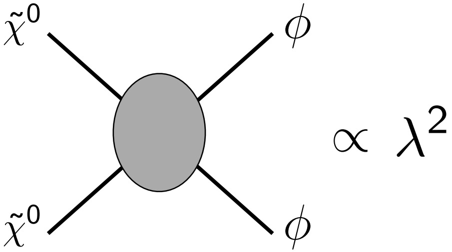
Thermal Dark Matter

- Dark Matter relic density is obtained through annihilation to lighter particles
- Dark Matter **cannot** decouple from the light sector
- Relic Density known as a function of DM couplings

Thermal Dark Matter

Heavy dark matter requires large couplings

⇒ Unitarity violation at large mass



- Existing Unitarity Bound : 120 TeV for $\lambda = 4\pi$ Griest and Kamionkowski, 1990
- Much tighter bounds for specific theories!

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]

The NMSSM Higgs sector

- Focus on NMSSM Higgs Sector

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

- Winos, Binos and Sfermions decoupled
- Six parameters after EWSB

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

NMSSM spectrum: Decoupling limit

- One light Higgs, $m_h = 125\,\mathrm{GeV}$
- Heavy Higgs masses depending on

$$\mu^2,\ A_\lambda\mu \text{ and } A_\kappa\mu$$

- Higgsino/Singlino Dark Matter

$$m_{\mathrm{DM}} \sim \mu$$

- DM annihilation governed by λ and/or κ

Upper Bounds on the NMSSM

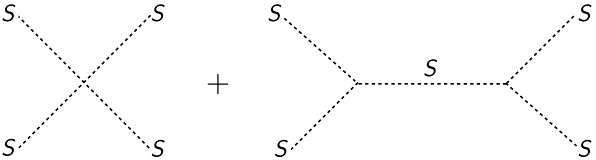
- Tree-level study

$$m_Z^2 \cos^2 2\beta + \lambda v^2 \sin^2 2\beta \geq (125\,\mathrm{GeV})^2$$

$$\lambda \geq 0.7$$

- Using unitarity + Relic abundance measurements
- We want to obtain
  - $\Rightarrow$ Upper bounds on λ, κ
  - $\Rightarrow$ Upper bounds on $A_{\lambda,\kappa}/\mu$
  - $\Rightarrow$ Upper bound on μ

NMSSM and Unitarity



$$\propto \kappa^2 + \frac{\kappa^2 A_\kappa^2}{s - m_S^2}$$

- Lee-Quigg-Thacker type bounds on λ and κ

If $s \sim 5m_S^2$

$$\mathcal{A} \propto \kappa^2 + \mathcal{O}\left(\frac{\kappa^2 A_\kappa}{\mu}\right)$$

- All heavy particle masses are of order μ or less

Perturbative Unitarity

Constrains a given scattering matrix

$$S = 1 + iT$$

Optical theorem

$$S^\dagger S = I \Rightarrow \frac{1}{2}(T - T^\dagger) = |T_{ii}^2|$$

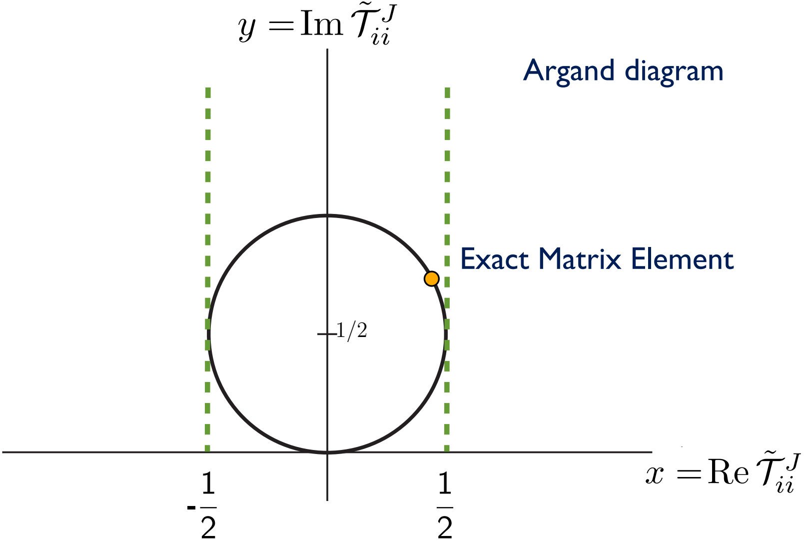
Use Partial Wave Decomposition

$$\tilde{T}_{ij}^J = \frac{\lambda_i^{1/4}\lambda_f^{1/4}}{32\pi s}\int_{-1}^{1} T_{ij} P_J(\cos\theta) d\cos\theta$$

We find

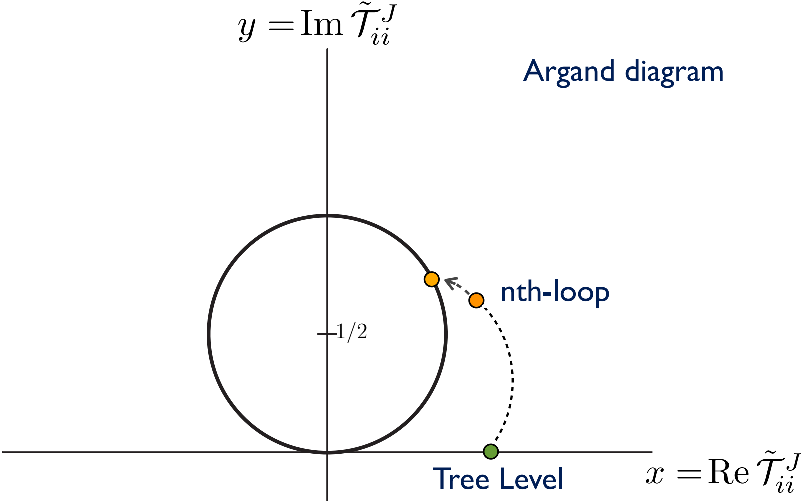
$$\mathrm{Im}\,\tilde{T}_{ii} = |\tilde{T}_{ii}|^2 \Rightarrow |\mathrm{Re}\,\tilde{T}_{ii}| < \frac{1}{2}$$

Perturbative Unitarity: a Geometric view



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

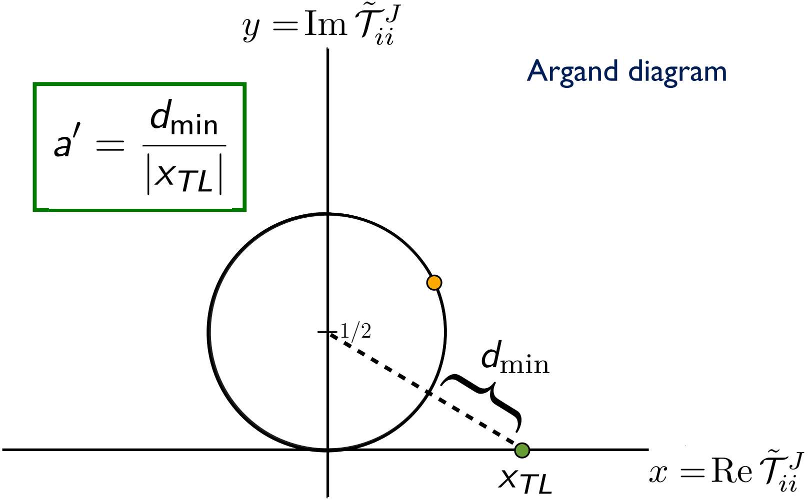
Perturbative Unitarity: a Geometric view



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

Perturbativity breakdown

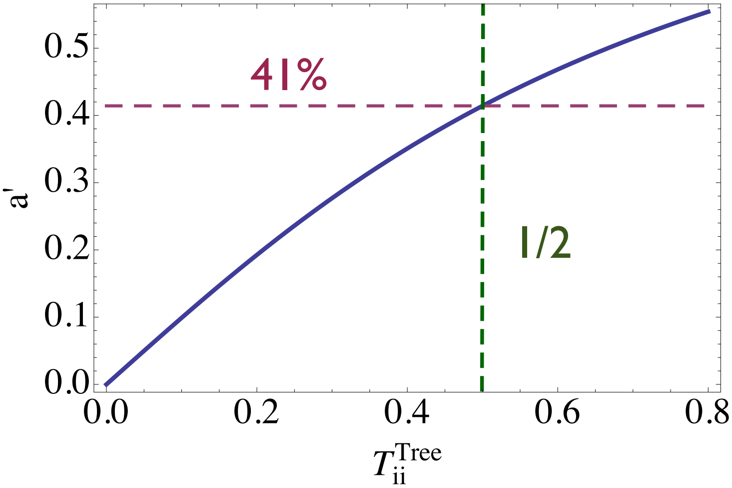
$$a' = \frac{d_{\text{min}}}{|x_{TL}|}$$



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

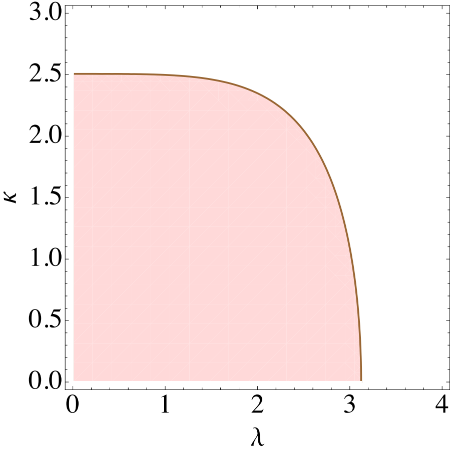
Perturbativity breakdown

- Conservative estimate of loop corrections



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

Constraints on dimensionless couplings

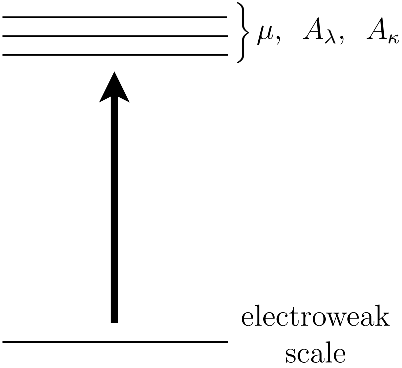


For large s, only quartic couplings remain

$$\lim_{s\to\infty} |Re\,\tilde{\mathcal{T}}_{ii}| < \frac{1}{2}$$

$$\lambda, \kappa \lesssim 3$$

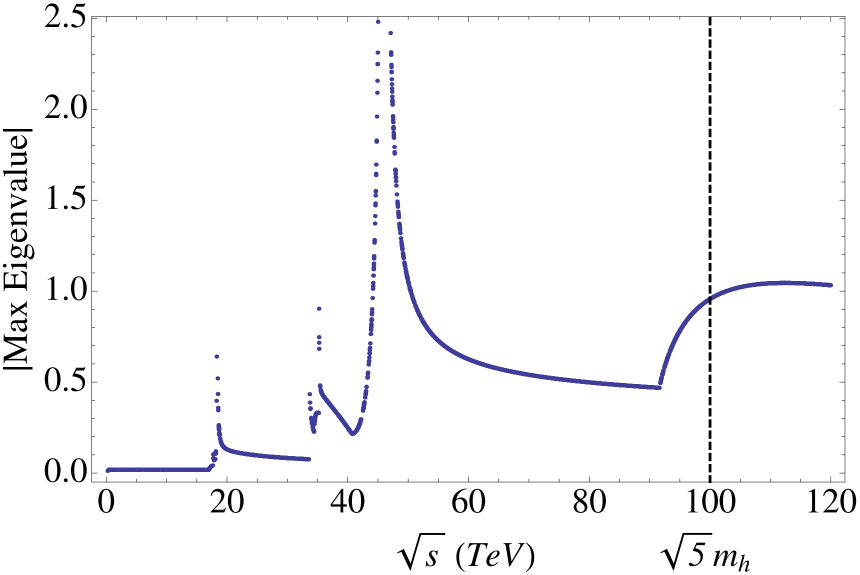
Unitarity and SUSY breaking scales



- m_H, m_A, m_χ depend on A_λ, A_κ, μ
- Trilinear couplings
  $\Rightarrow$ vanish at high energy
- Energy-dependent scattering amplitudes

  $\Rightarrow$ Scan over s

General Optimal s



Unitarity: Summary

- Upper bounds on λ and κ

$$\lambda, \kappa \lesssim 3$$

- Optimal bounds for

$$s \sim 5m_H^2$$

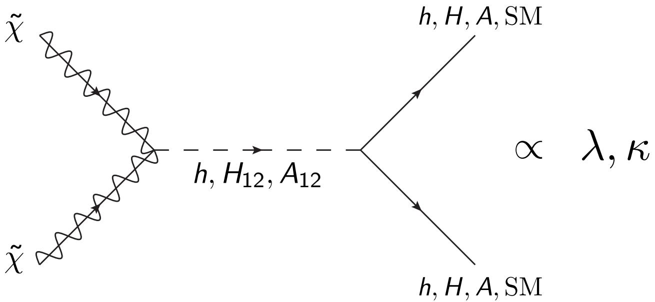
- Upper bounds on ratios of scales

$$\frac{A_\lambda}{\mu} \text{ and } \frac{A_\kappa}{\mu} \sim \mathcal{O}(1)$$

- μ is the only scale left unconstrained $\Rightarrow$ Need to constrain the DM mass!

Relic density

Relic density anchors the heavy spectrum



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

Loopholes in Fine-Tuned Regions

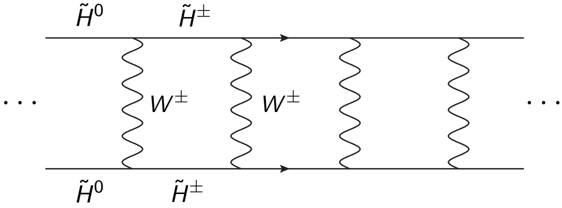
- Higgs funnels: s-channel resonances when

$$R = \min_i \frac{|2m_\chi - m_{H_i}|}{m_{H_i}} \lesssim 0.1$$

- t-channel resonances: not in our model but can exist if

$$m_{\chi^0} \sim m_W + m_{\chi^\pm}$$

- Sommerfeld enhanced regions: for low Higgsino-Chargino splitting



Finding upper bounds: procedure

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

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

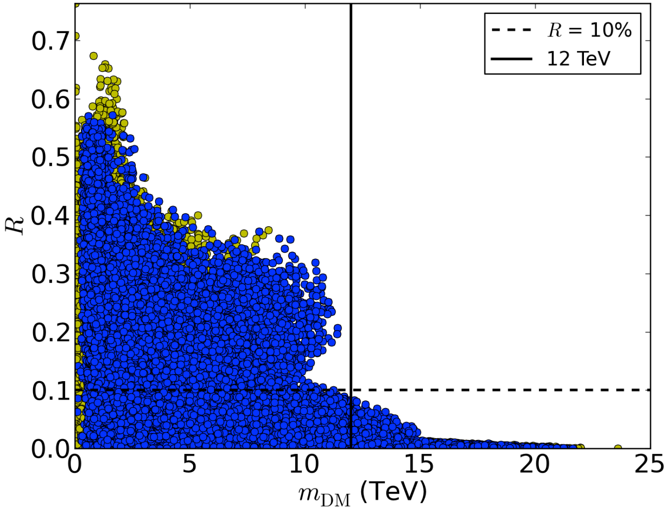
- Apply vacuum constraints
  Kanehata, Kobayashi, Konishi, Seto, Shimomura [arXiv:1103.5109]
- Unitarity: allow for at most 40% loop corrections to tree-level amplitudes

$$|Re\mathcal{T}_{ij}| \leq \frac{1}{2}$$

- Compute relic density using MicrOmegas and NMSSMTools

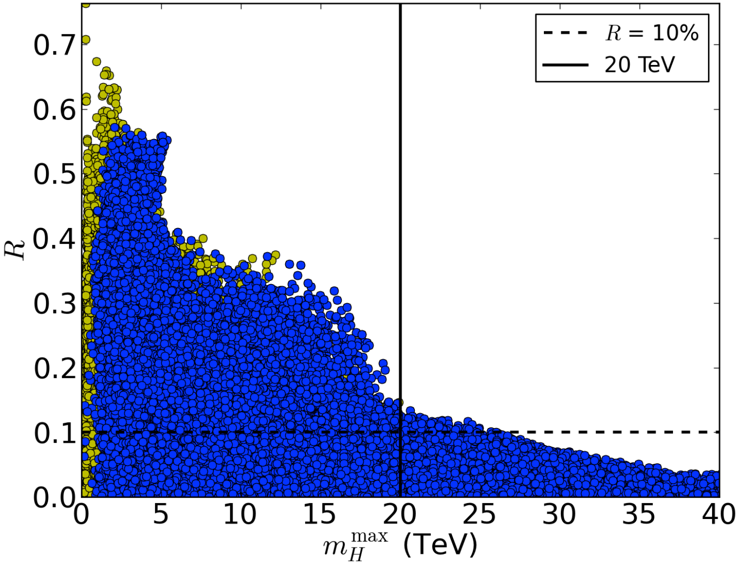
$$\Omega h^2 < 0.1199 + 0.0081 \text{ (Planck measurement)}$$

Results: Dark Matter



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

Results: Higgs sector



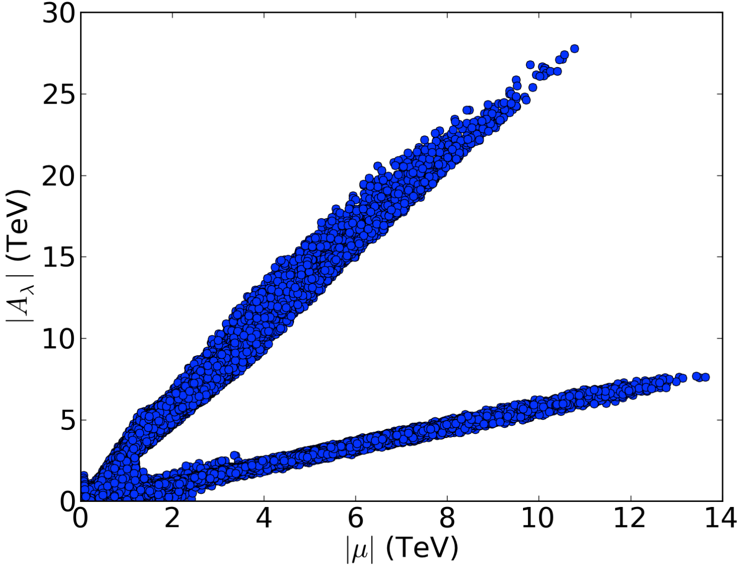
Summary

- 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
- 12 TeV bounds on DM mass in the NMSSM
- All masses are of order the Dark Matter mass or less
- New Higgs fields below 20 TeV

Backup

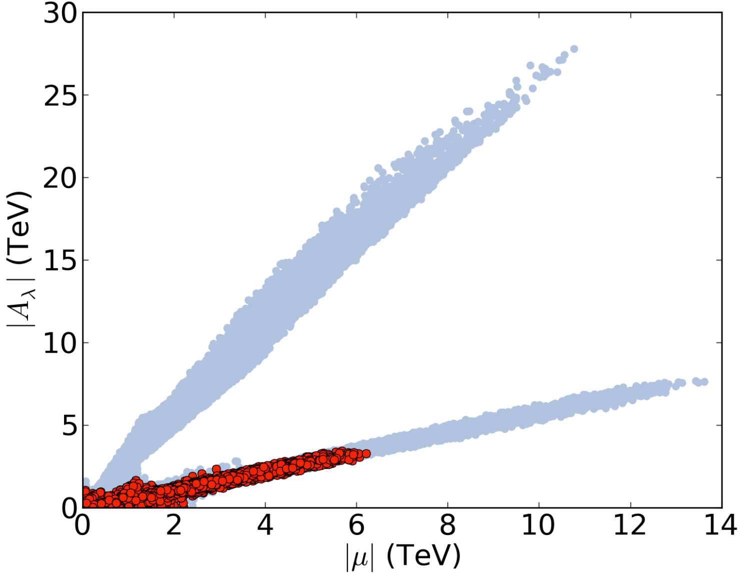
Ratios of SUSY Breaking Scales: tighter unitarity bounds

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



Ratios of SUSY Breaking Scales

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



Vacuum constraints

- NMSSM has unrealistic vacua

  Kanehata, Kobayashi, Konishi, Seto, Shimomura [arXiv:1103.5109]

  - $|H_u| = |H_d| \neq 0$, $|S| \neq 0$
  - $|H|_{u,d} = 0$ or $|S| = 0$

- Require that the EW breaking vacua is the deepest

$$\langle H_u^0 \rangle = \frac{\sqrt{2} m_Z}{g} \sin\beta \quad \langle H_d^0 \rangle = \frac{\sqrt{2} m_Z}{g} \cos\beta \quad \langle S \rangle = \frac{\mu}{\lambda}$$

- Require no CP violation in the Higgs sector