# SUSY Scenarios according to EWSB

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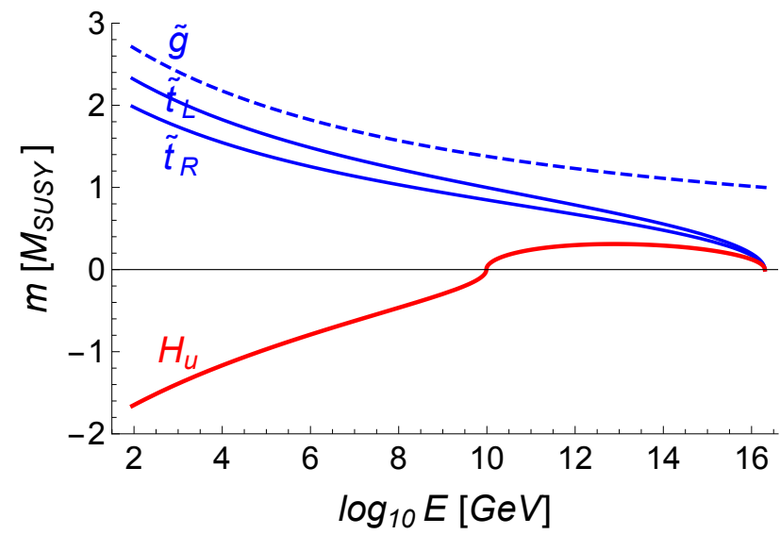
# EWSB in MSSM

EWSB can be achieved radiatively:

$$\frac{1}{2}M_Z^2 \simeq -\mu^2(M_Z) - m_{H_u}^2(M_Z)$$

$\tan\beta >$ **few**




and relates the EW scale to superpartner masses:

$$M_Z^2 \simeq -1.9\mu^2 + 5.9M_3^2 - 1.2m_{H_u}^2 + 1.5m_{\tilde{t}}^2 - 0.8A_tM_3 + 0.2A_t^2 + \ldots$$

MSSM with boundary conditions at GUT scale
$\tan\beta = 10$

**We should find superpartners "soon"!**

# The most common naturalness argument

based on the largest individual contribution to the EW scale; estimated by a variety of probabilistic methods or sensitivity measures, e.g.:

$$\max_i \left| \frac{\partial \ln M_Z^2}{\partial \ln p_i} \right|$$

R. Barbieri and G. Giudice

Requiring no individual contribution is $\gg M_Z^2$:

$$M_Z^2 \simeq -1.9\mu^2 + 5.9M_3^2 - 1.2m_{H_u}^2 + 1.5m_{\tilde{t}}^2 - 0.8A_tM_3 + 0.2A_t^2 + \ldots$$

Expectations:

**gluino, stop, chargino** $\lesssim \mathbf{few} \times \mathbf{100\,GeV}$

# Naturalness seems to contradict limits

- direct limits:

**gluino** $\gtrsim 2\,\mathrm{TeV}$

**stop** $\gtrsim 1\,\mathrm{TeV}$

**chargino** $\gtrsim 1\,\mathrm{TeV}$

**not universal, depend on assumptions!**

- stop masses inferred from the Higgs mass:

$m_{\tilde{t}} \gtrsim 7\,\mathrm{TeV}$ for $X_t/m_{\tilde{t}} \simeq 0$

$m_{\tilde{t}} \gtrsim 3\,\mathrm{TeV}$ for $X_t/m_{\tilde{t}} \simeq -1$

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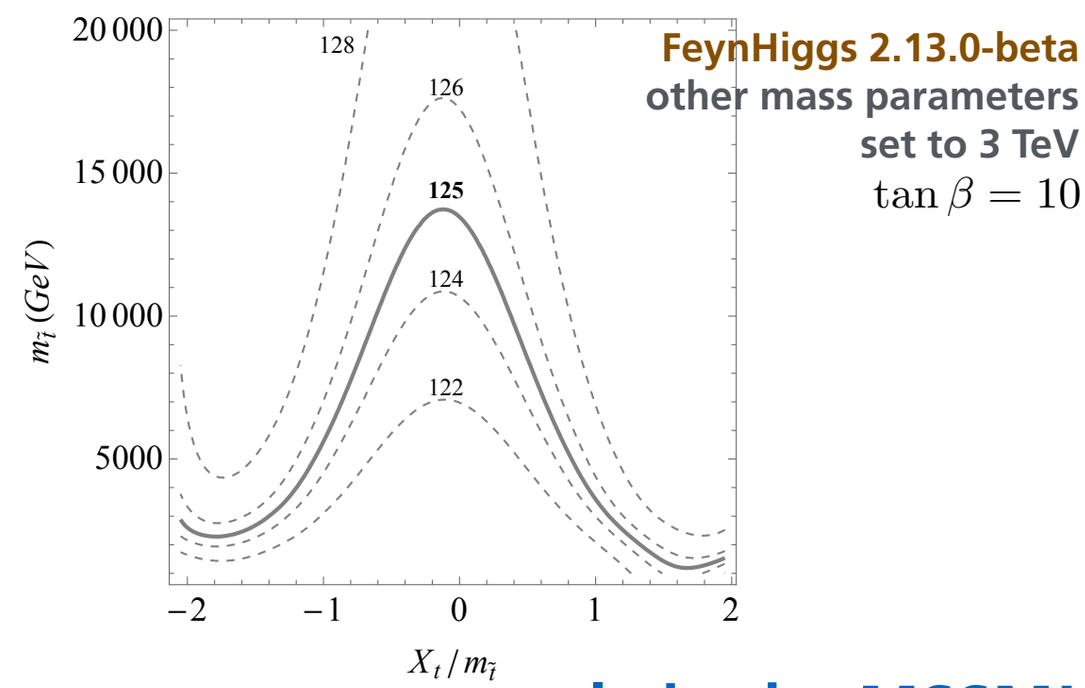


**only in the MSSM!**

# The most common naturalness argument

Limits suggest that the LHS is ~1000 times smaller than some terms on the RHS:

$$M_Z^2 \simeq -1.9\mu^2 + 5.9M_3^2 - 1.2m_{H_u}^2 + 1.5m_{\tilde{t}}^2 - 0.8A_tM_3 + 0.2A_t^2 + \ldots$$

Fine tuning:

In model with parameter A ~ 1 contributing to observable X, in order to get X = 0.001, there has to be something else that cancels the contribution of A very precisely:

X = A - B

e.g.: A = 0.963
B = 0.962

**B has to be tuned to A at ~0.1% level!**

# Outline

- SUSY is tuned or special

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  - Stops are little different — RD, arXiv:1606.09031
  - Gluino is little different — P. Fox, A. Nelson, N. Weiner, hep-ph/0206096
  - The μ term is little different — NMSSM-like models
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- Simple naturalness argument is too strong requirement

  RD, arXiv:1611.03188
  RD and N. McGinnis, arXiv:1705.01910

# SUSY is tuned or special

# SUSY is tuned

accident, anthropic reasoning, bad joke of the creator …

Then the only solid indication for superpartner masses comes from the Higgs mass:

$$m_{\tilde{t}} \gtrsim 7\,\mathrm{TeV} \quad \text{for } X_t/m_{\tilde{t}} \simeq 0$$

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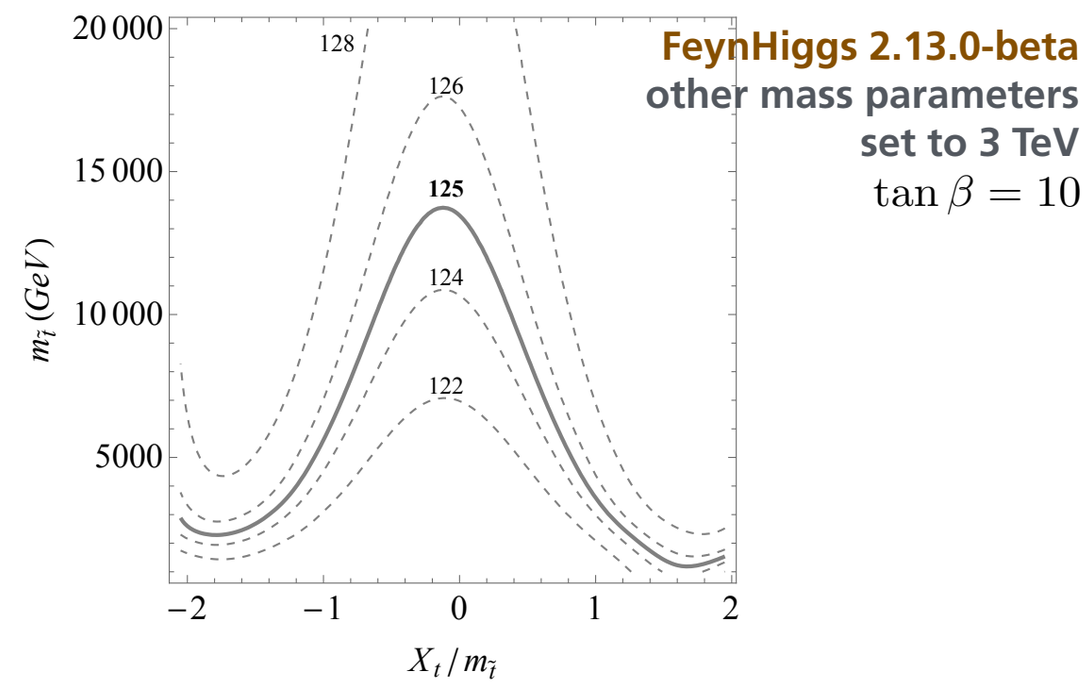



**Experiments only started touching the suggested range!**

# SUSY breaking scenario is special

- (Extremely) Low mediation scale

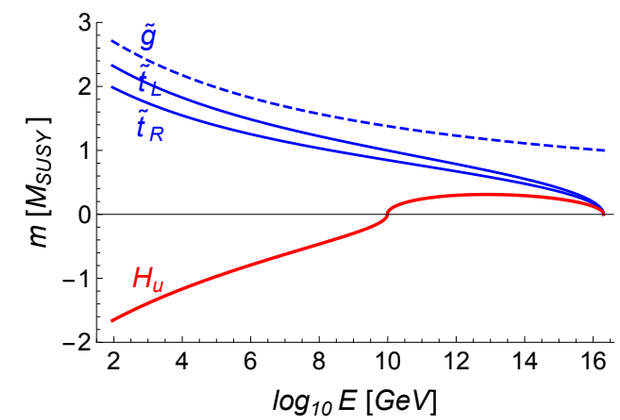
$$M_Z^2 \simeq -1.9\mu^2 + 5.9M_3^2 - 1.2m_{H_u}^2 + 1.5m_{\tilde{t}}^2 - 0.8A_tM_3 + 0.2A_t^2 + \ldots$$

$\mathbf{f}(\lambda_\mathbf{t}, \alpha_\mathbf{3}, \mathbf{\Lambda})$

**coefficients go to 0 as the mediation scale decreases**

**gluino and stop can even decouple from EWSB**

**but, in that limit, understanding of EWSB is gone!**



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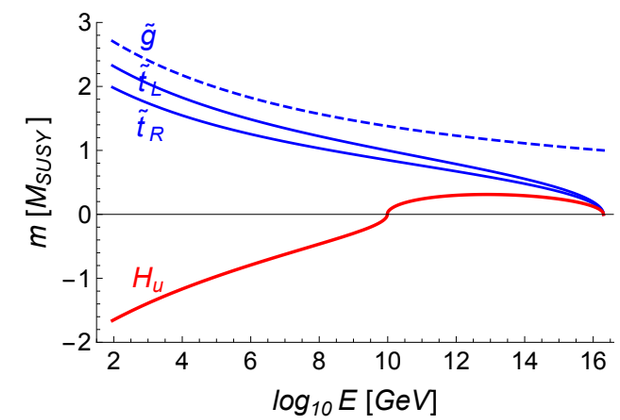


- Relations - model leads to automatic cancellations

$$M_Z^2 \simeq -1.9\mu^2 + 5.9M_3^2 - 1.2m_{H_u}^2 + 1.5m_{\tilde{t}}^2 - 0.8A_tM_3 + 0.2A_t^2 + \ldots$$

**e.g. focus point:** $\mathbf{0.3\ m_0^2}$ **and many others**

**Seems like a coincidence since coefficients are** $\mathbf{f}(\lambda_\mathbf{t}, \alpha_\mathbf{3}, \mathbf{\Lambda})$ **!**

# SUSY is light but we haven't seen it yet

Possible reasons:

- degenerate/compressed spectra
- unsearched for (or harder to search for) decay modes
- complicated or too many decay modes

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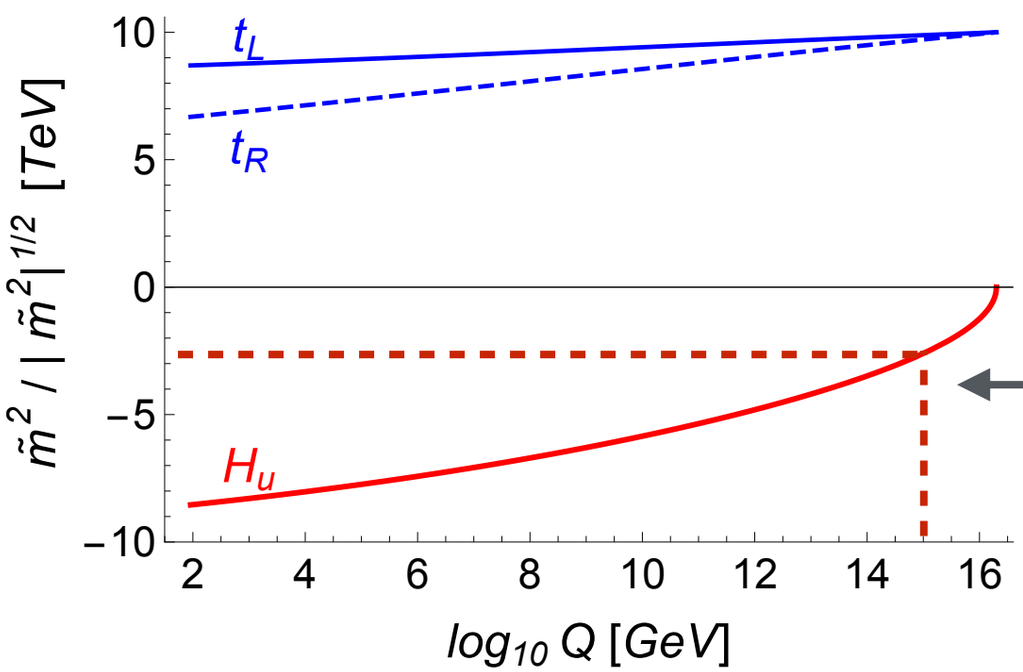
**Requires extra mechanism to increase the Higgs mass.**

# Stops are little different

# Lowering the mediation scale?

**~2 TeV gluino does not result in more than 10% tuning in EWSB as far as the mediation scale is below ~1000 TeV**

**However, ~10 TeV stops, suggested by the Higgs mass, feed to $\tilde{m}^2_{H_u}$ very fast:**

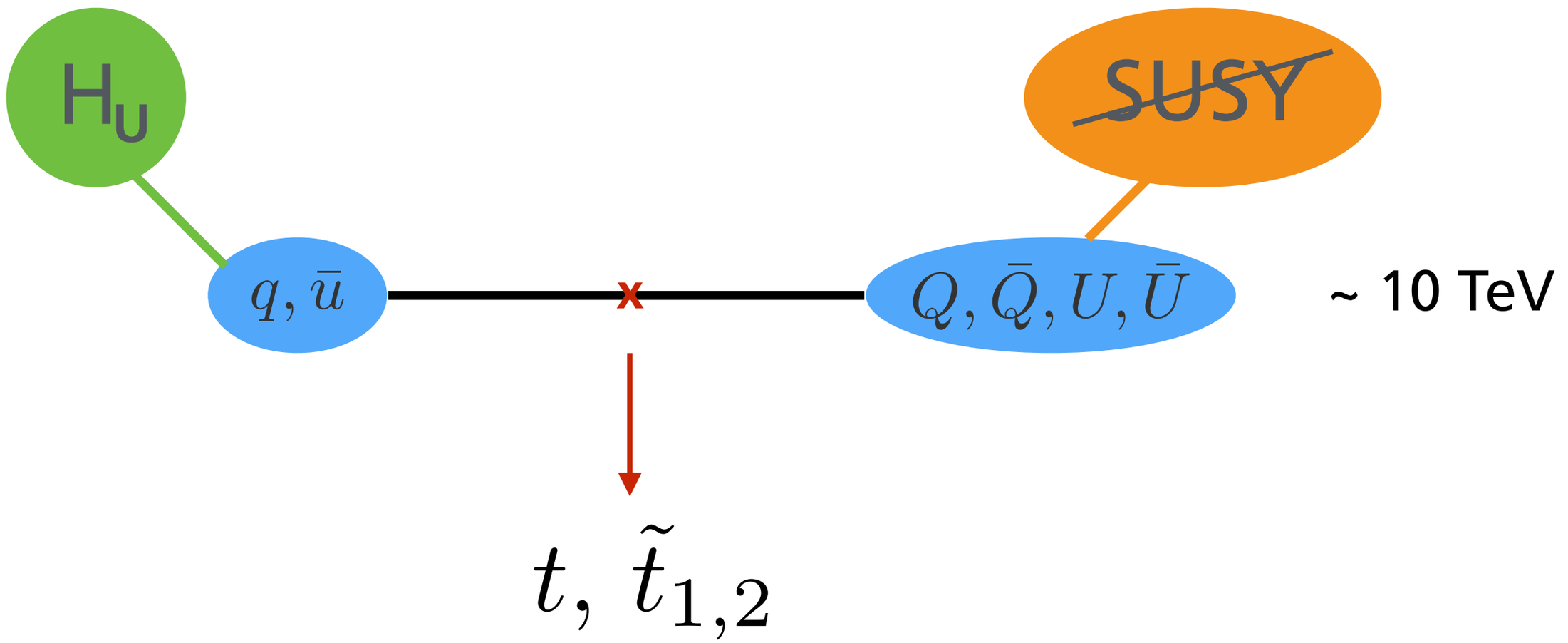



**just 1 decade of RG running results in ~3 TeV contribution to $\tilde{m}^2_{H_u}$ indicating ~0.1% tuning**

# “Instant” stop masses

**In models with vector like families, stop can be a mixture of a state that couples to the Higgs but doesn’t have large soft mass and a state with large soft mass that doesn’t couple to the Higgs:**

RD, arXiv:1606.09031




**stops get large soft masses without ever contributing in RG evolution**

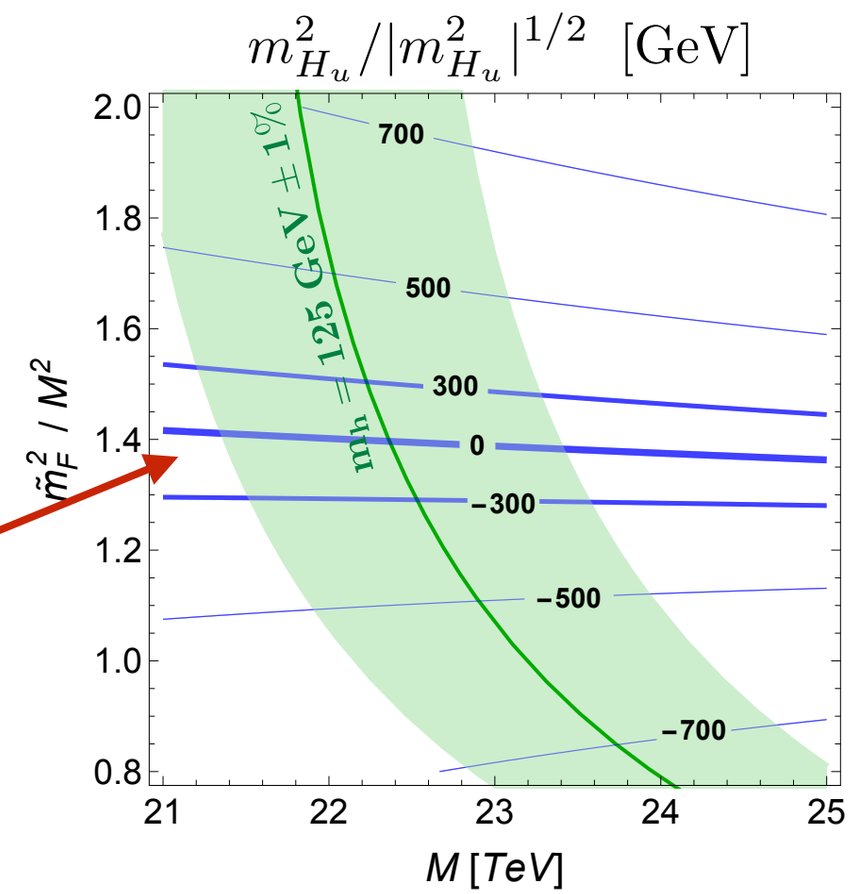
# Threshold corrections and 2 loop effects

Assuming universal vectorlike and soft masses, there are just two parameters that determine stop masses (and thus the Higgs mass).

Contributions to $\tilde{m}^2_{H_u}$ :

- threshold corrections

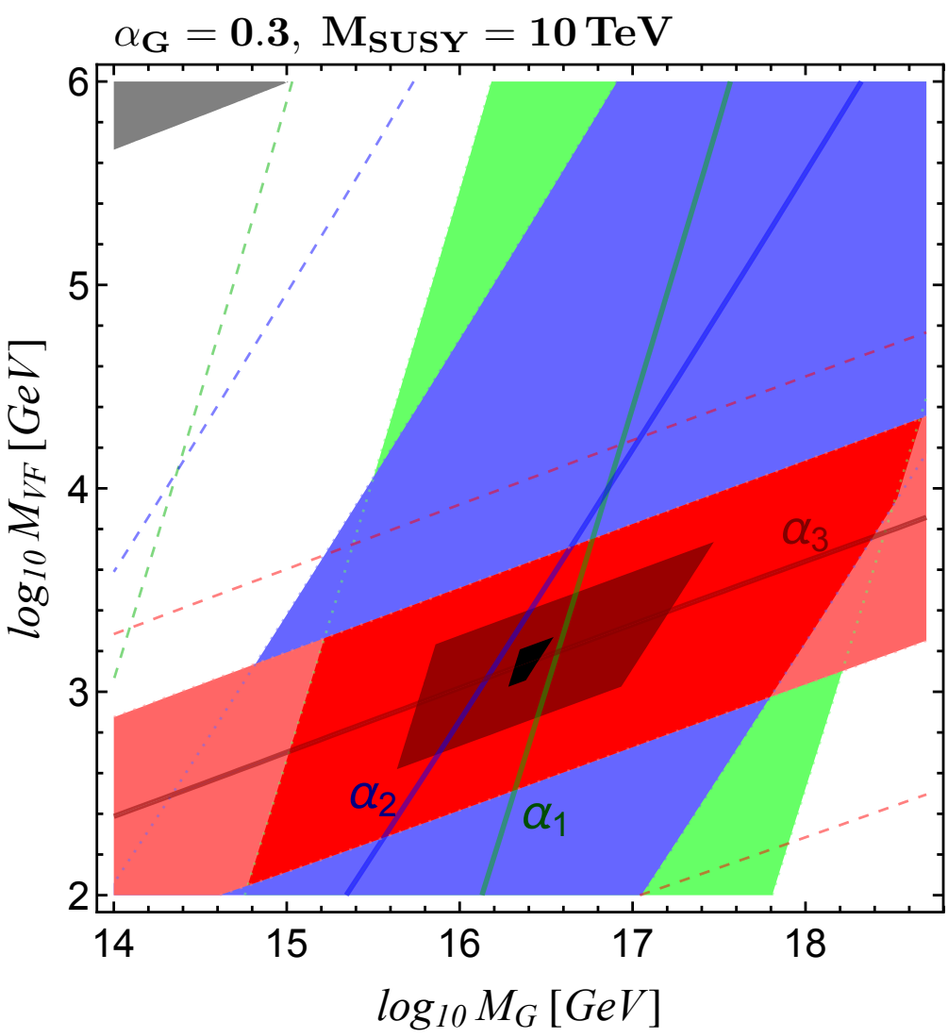
  **~20% range of soft mass squared results in < 300 GeV correction**



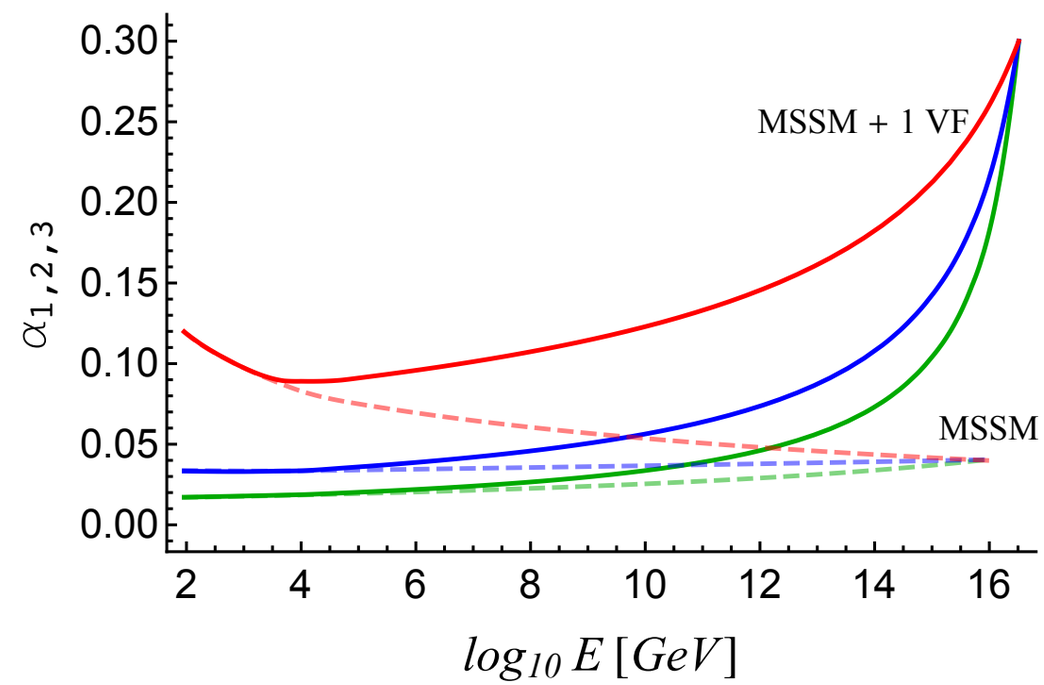

- two loop effects (gluino and gauge contributions from scalars), small for low mediation scale

# MSSM + 1 complete vectorlike family

Relative strength of gauge interactions can be understood from the particle content:




RD and N. McGinnis, to appear



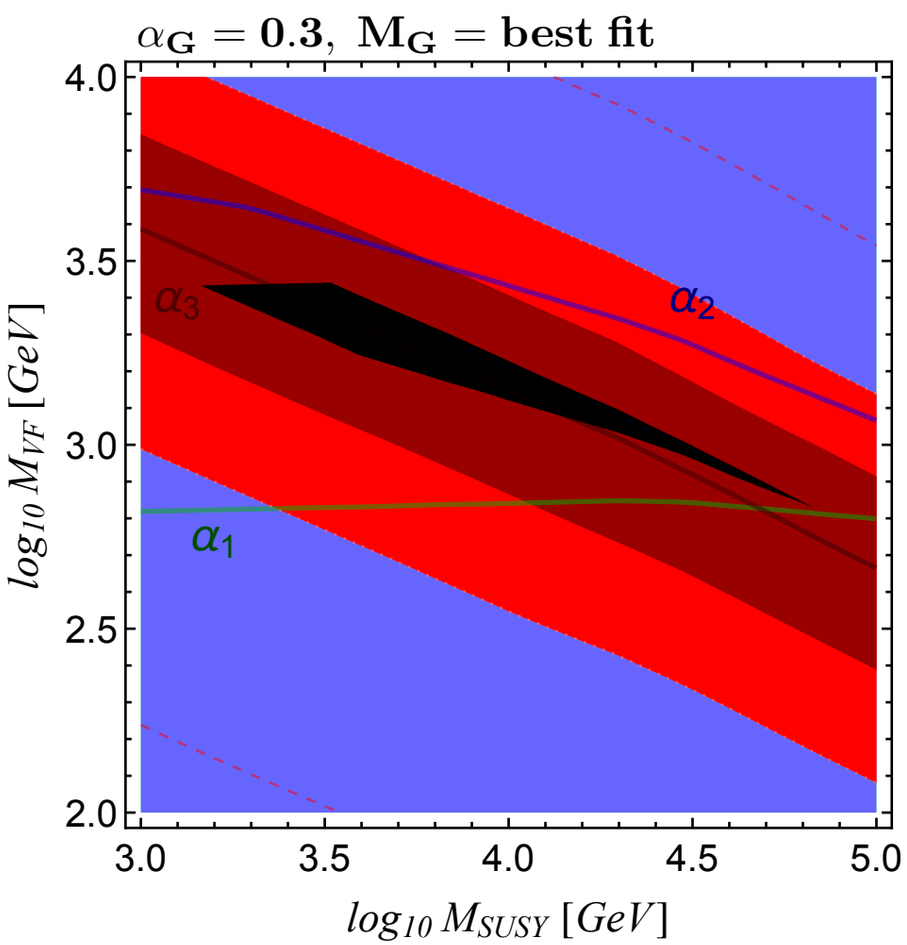

**All three gauge couplings within:**

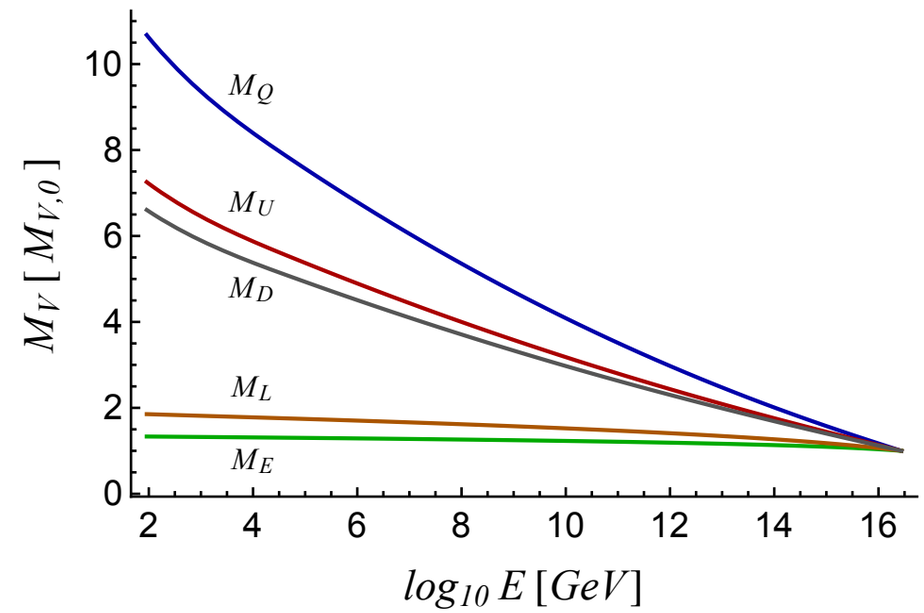
- **1.5%**
- **5%**
- **10%**

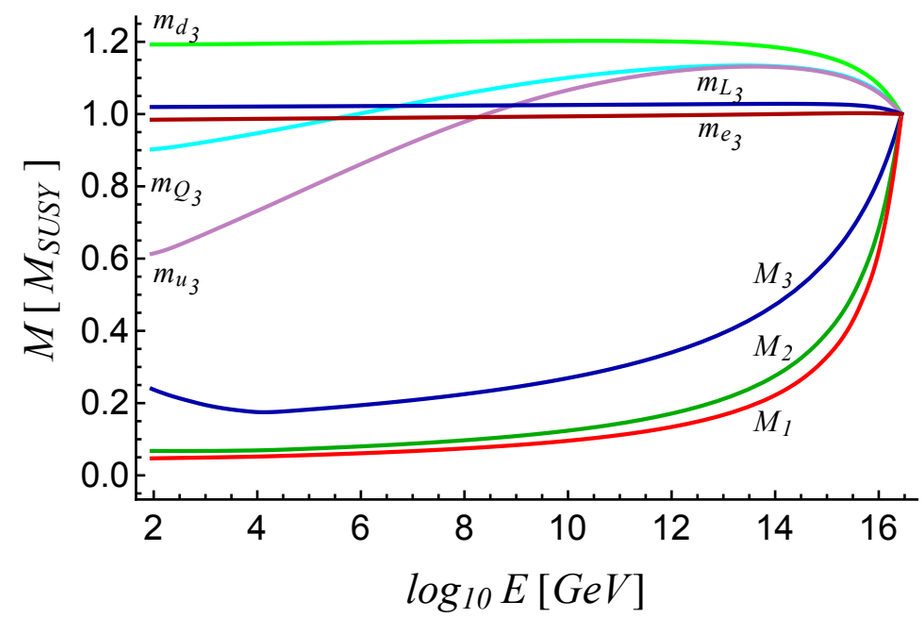
**from the measured values.**

# MSSM + 1 complete vectorlike family

## Preferred spectrum:




**Independently points to ~10 TeV scale.**

# Naturalness argument based on the largest contribution is too strong requirement

# Little hierarchy from complexity

In a model with more parameters contributing to X:

$$X = A - B - c - d$$

in order to get X = 0.001 for randomly chosen A ~ 1, no parameter needs to be carefully chosen, e.g.:

A = 0.963

B = 0.9
c = 0.06
d = 0.002

**only the first digit of all parameters need to be adjusted no matter what the following digits are**

**what is a tuned outcome in a model with 2 parameters may be a completely ordinary outcome in a more complex model**

RD, arXiv:1611.03188

# Minimally specified CMSSM

Assume model parameters of the same order

$$\mathbf{M_{1/2},\ m_0,\ \mu,\ -A_0\ \simeq\ M_{SUSY}}$$

and vary them in ± 50% range keeping only one digit specifying the departure from $\mathbf{M_{SUSY}}$, e.g.:

$$\begin{aligned} \mathbf{M_{1/2}} &= \mathbf{0.6\,M_{SUSY}} \\ \mathbf{m_0} &= \mathbf{1.1\,M_{SUSY}} \\ \mu &= \mathbf{1.4\,M_{SUSY}} \\ \mathbf{-A_0} &= \mathbf{0.9\,M_{SUSY}} \\ &\vdots \end{aligned}$$

$$\begin{aligned} \mathbf{M_{1/2}} &= \mathbf{0.9\,M_{SUSY}} \\ \mathbf{m_0} &= \mathbf{1.2\,M_{SUSY}} \\ \mu &= \mathbf{0.6\,M_{SUSY}} \\ \mathbf{-A_0} &= \mathbf{0.8\,M_{SUSY}} \\ &\vdots \end{aligned}$$

$$\begin{aligned} \mathbf{M_{1/2}} &= \mathbf{0.5\,M_{SUSY}} \\ \mathbf{m_0} &= \mathbf{1.1\,M_{SUSY}} \\ \mu &= \mathbf{1.5\,M_{SUSY}} \\ \mathbf{-A_0} &= \mathbf{0.8\,M_{SUSY}} \\ &\vdots \end{aligned}$$

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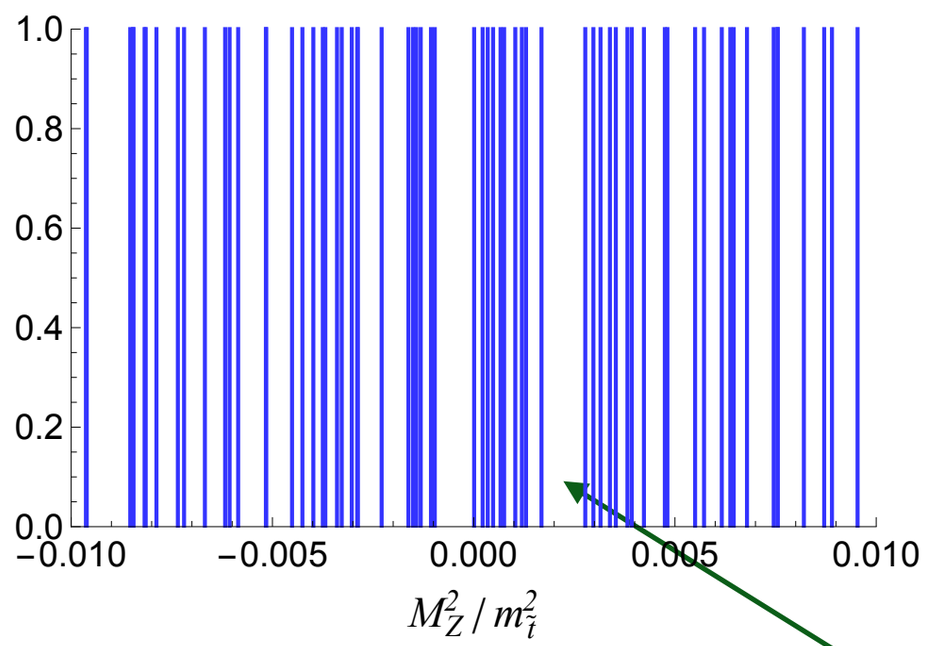
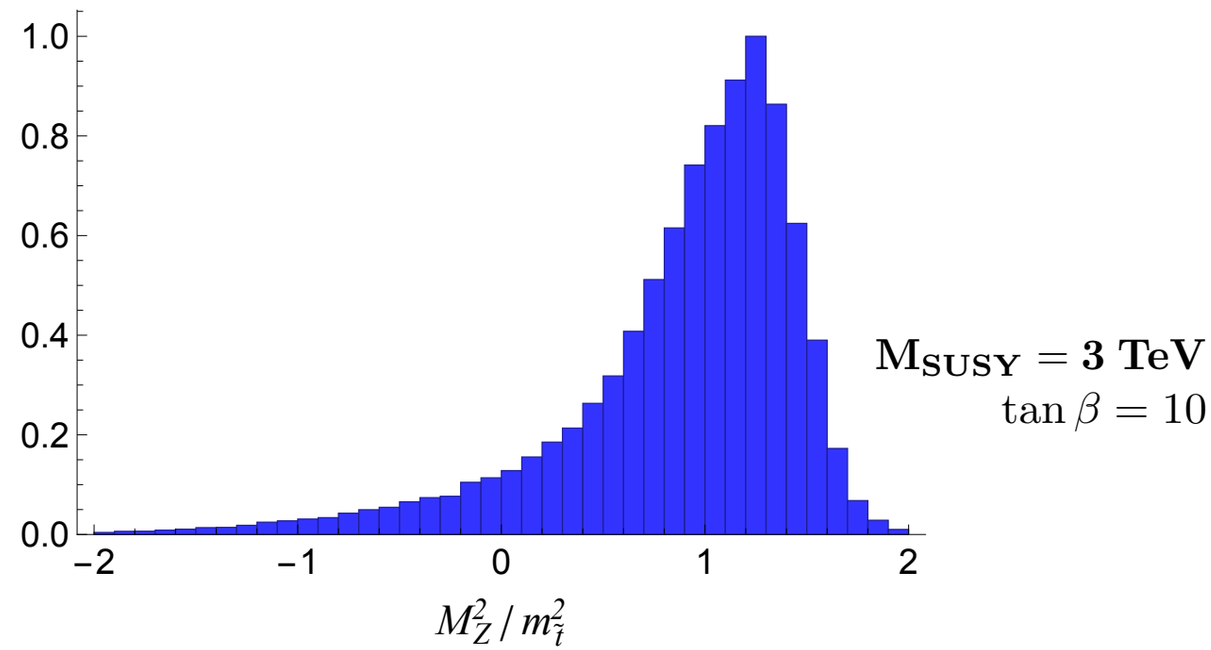
## Maximal hierarchy from minimally specified inputs:

RD and N. McGinnis, arXiv:1705.01910




**the largest gaps ~0.001 (fairly uniform away from edges of the distribution)**

**The smallest outcome that does not depend on specifying parameters with more than 1 digit is indicated by the largest gap found in the distribution. Outcomes smaller than the largest gap are accidental.**

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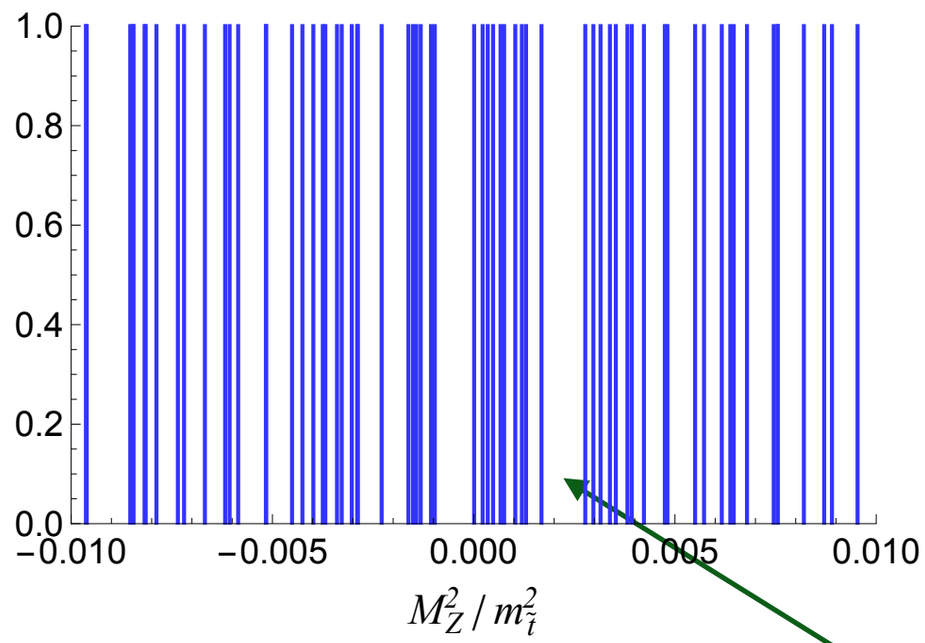


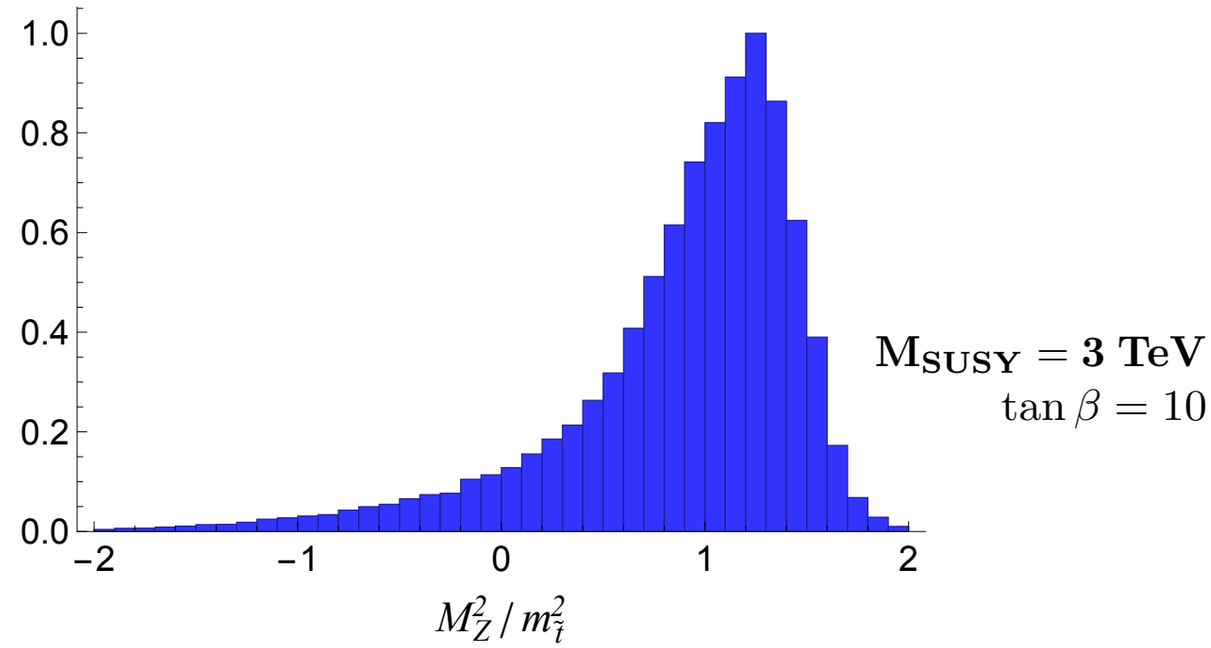


**the largest gaps ~0.001** (fairly uniform away from edges of the distribution)

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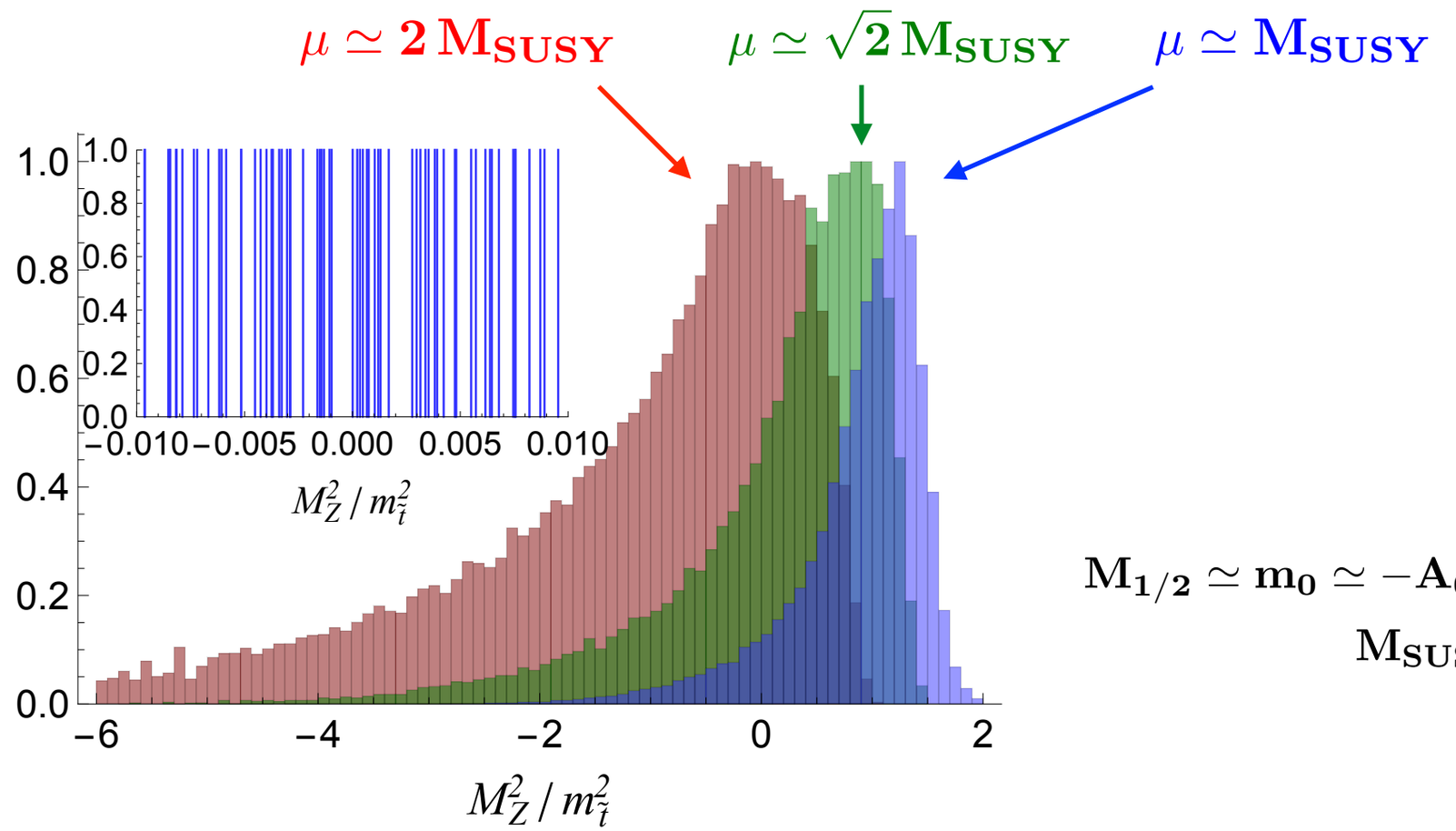
$$m_{\tilde{t}} \simeq 30\, M_Z$$

**is an ordinary outcome from minimally specified parameters**

# Minimally specified CMSSM

For different central values of parameters, the peak of the distribution changes




$\mathrm{M_{1/2} \simeq m_0 \simeq -A_0 \simeq M_{SUSY}}$

$\mathrm{M_{SUSY} = 3\ TeV}$

$\tan\beta = 10$

but the maximal gap size remains almost the same.

**Prediction for maximal hierarchy is very robust.**

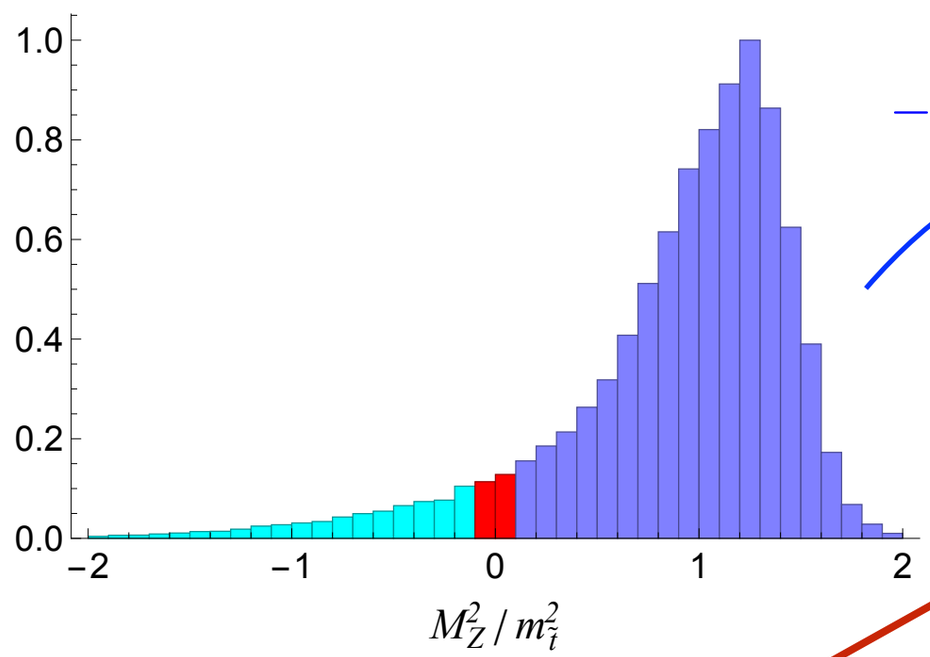
# Pigeons at Saint Marco

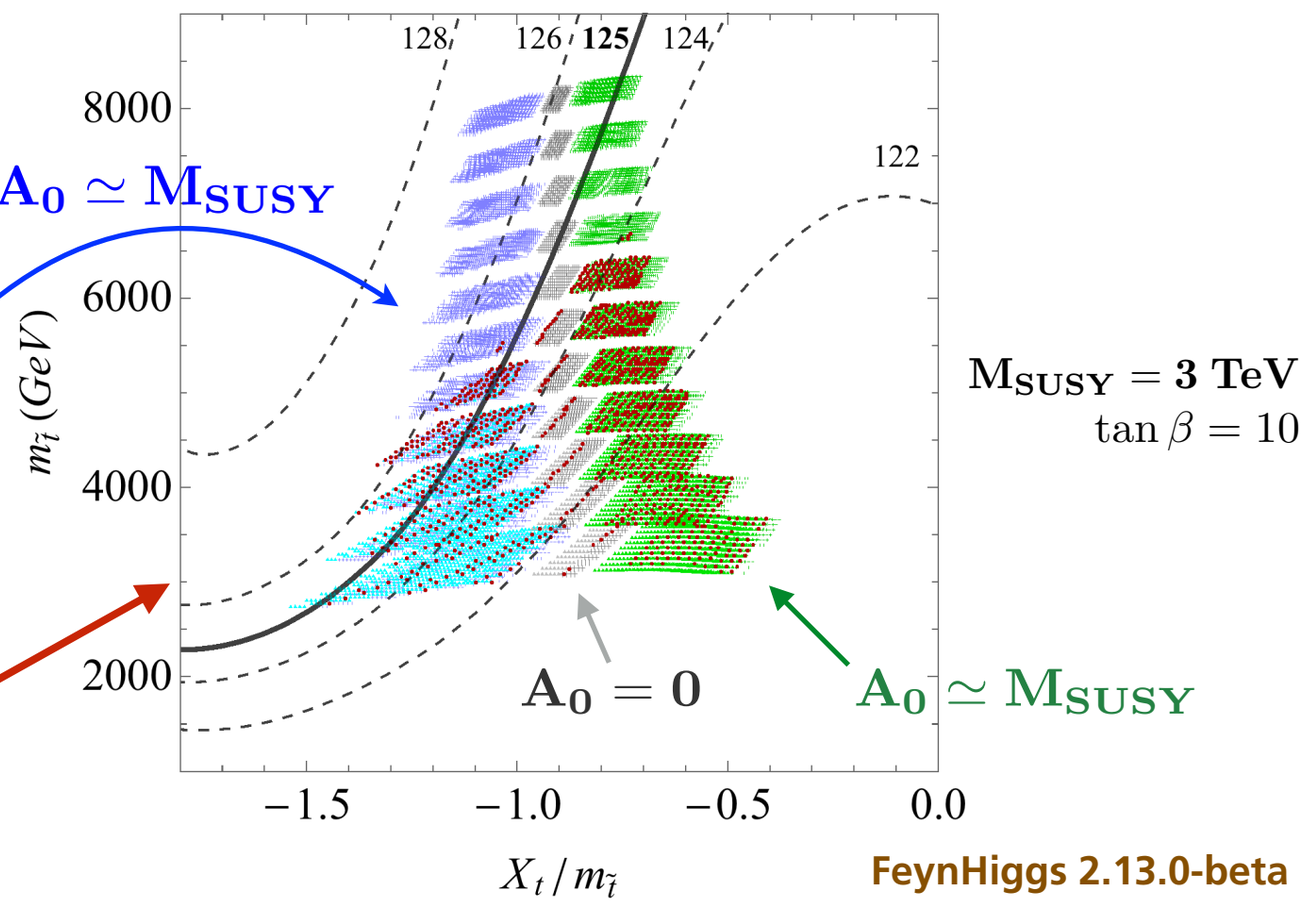
Position of each pigeon in a given time is incredibly tuned,

**but finding a pigeon within 1 meter from you is completely ordinary since they come in 1m intervals.**

# Minimally specified CMSSM

## Higgs boson mass from minimally specified inputs:




$m_{\tilde{t}} \lesssim 30\, M_Z$

**Only scenarios with negative A-terms can have sufficiently heavy stops to explain the Higgs boson mass**

# Conclusions

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The current puzzling situation provides a great opportunity in model building and also in experiment.

Theorists can justify and make anything natural in some sense, but only experiment can make something natural by definition:

**Natural = existing in or produced by nature**

**Merriam-Webster dictionary**