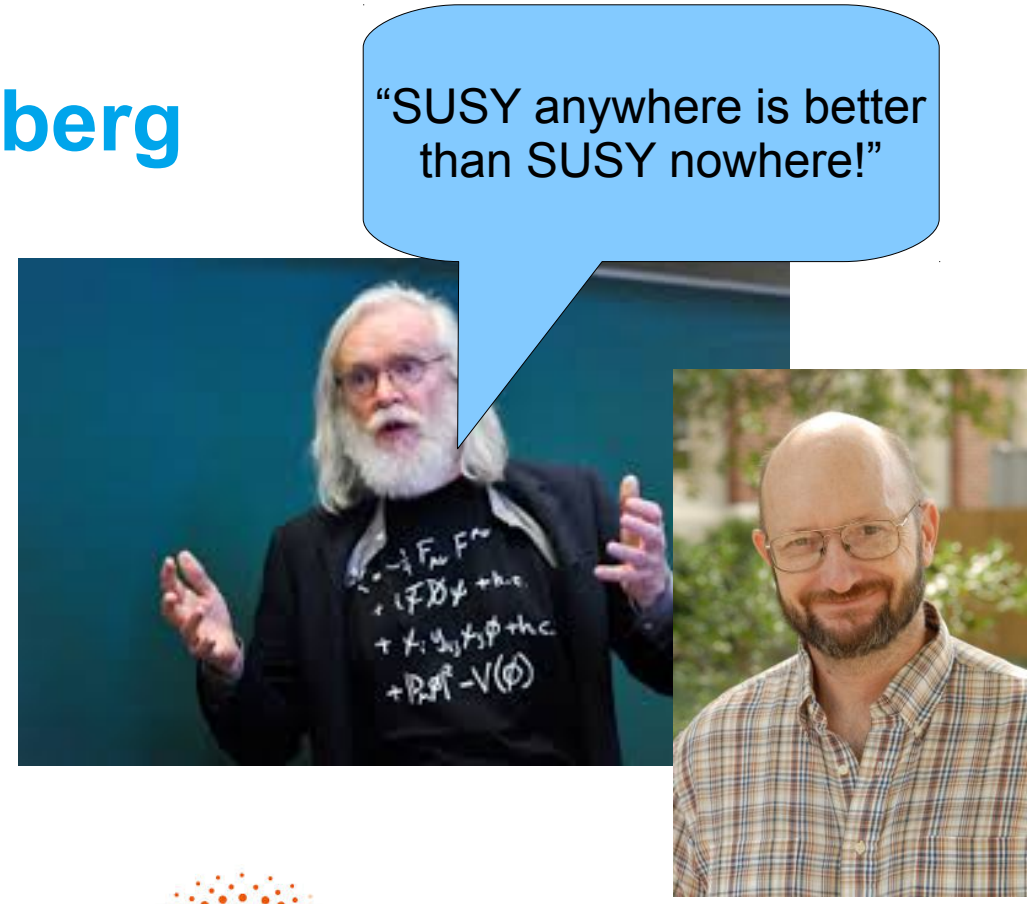
Thoughts about SUSY naturalness.

...and the SUSY WIMP...

Kai Schmidt-Hoberg



Partially based on

1603.09347
1701.03480

HELMHOLTZ ASSOCIATION

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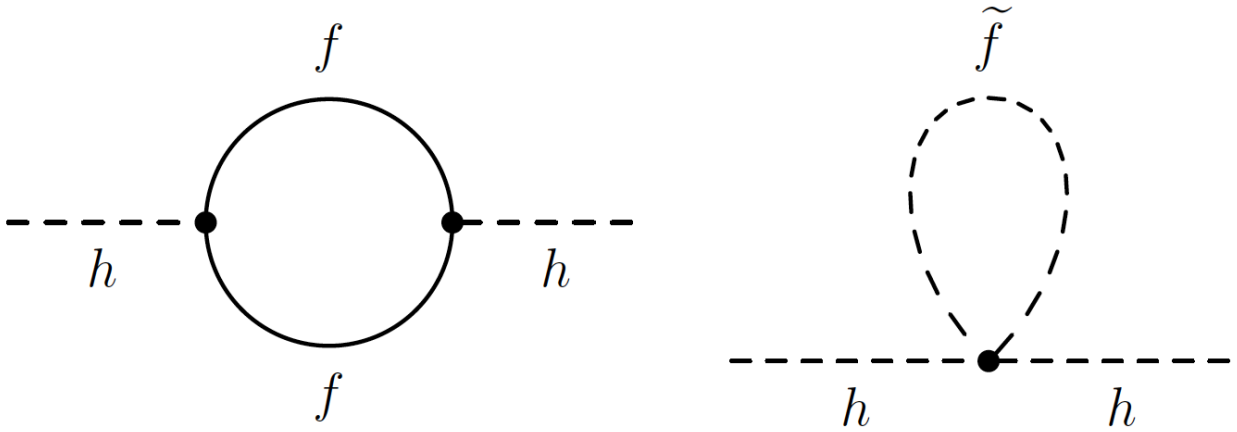
DESY

Why we like(d) SUSY

- Hierarchy problem: stabilizes the weak against the Planck scale



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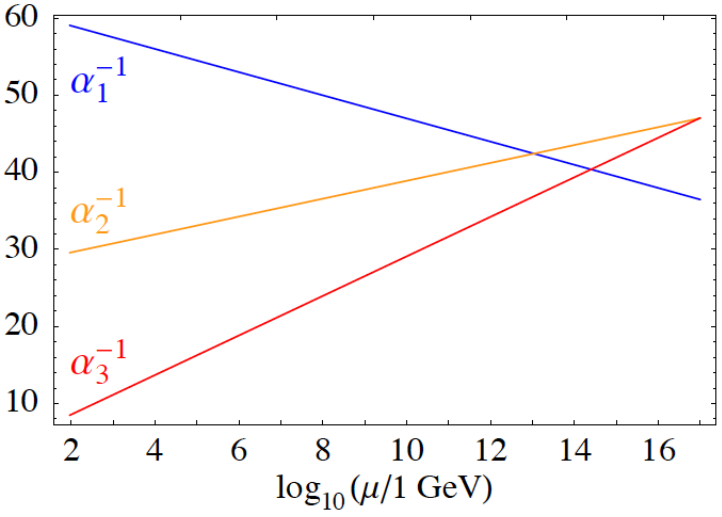

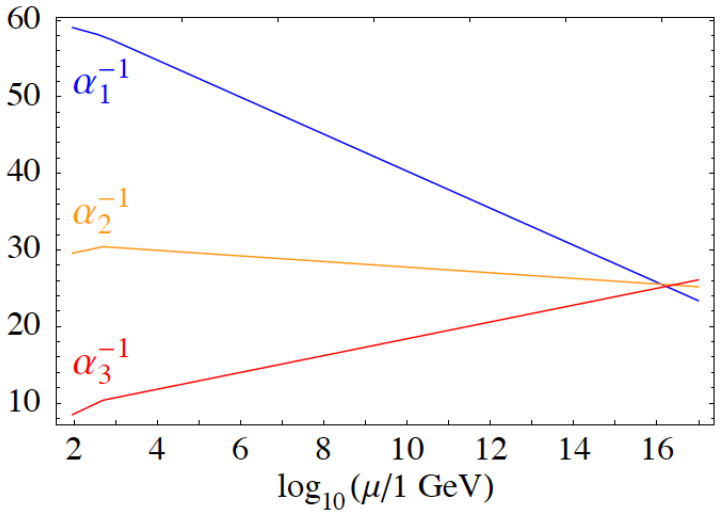

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- A 125 GeV Higgs boson: Additional hint for SUSY?

...somebody still owes me...

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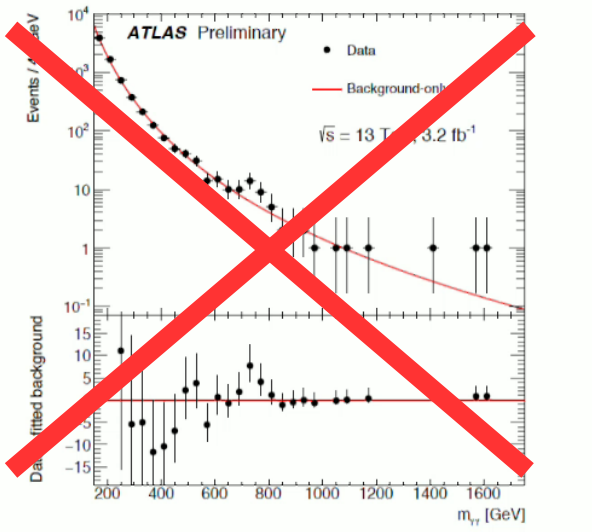
- Gauge coupling unification:
- A 125 GeV Higgs boson: Additional hint for SUSY?
- Also hard to get 750 GeV diphoton excess ;-)



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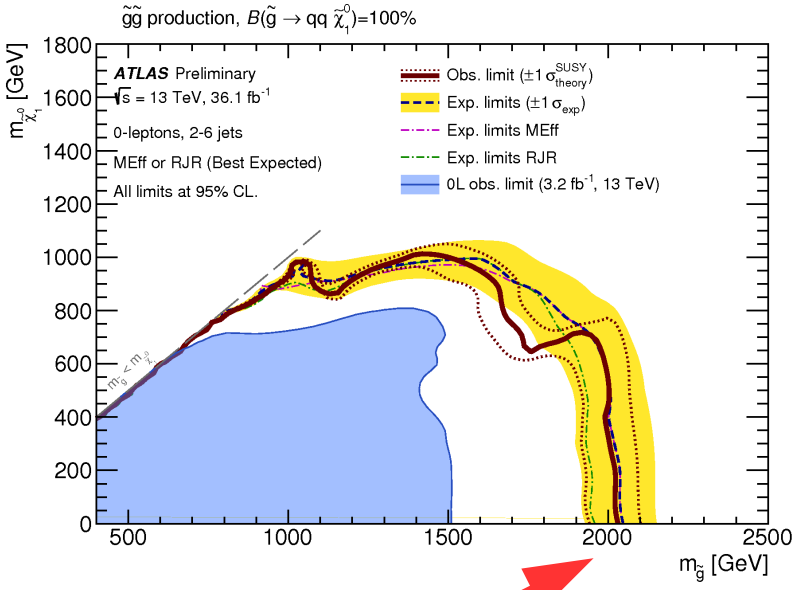
- So why do people get worried?



~ 2 TeV

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NATURALNESS!

DM naturalness in the MSSM

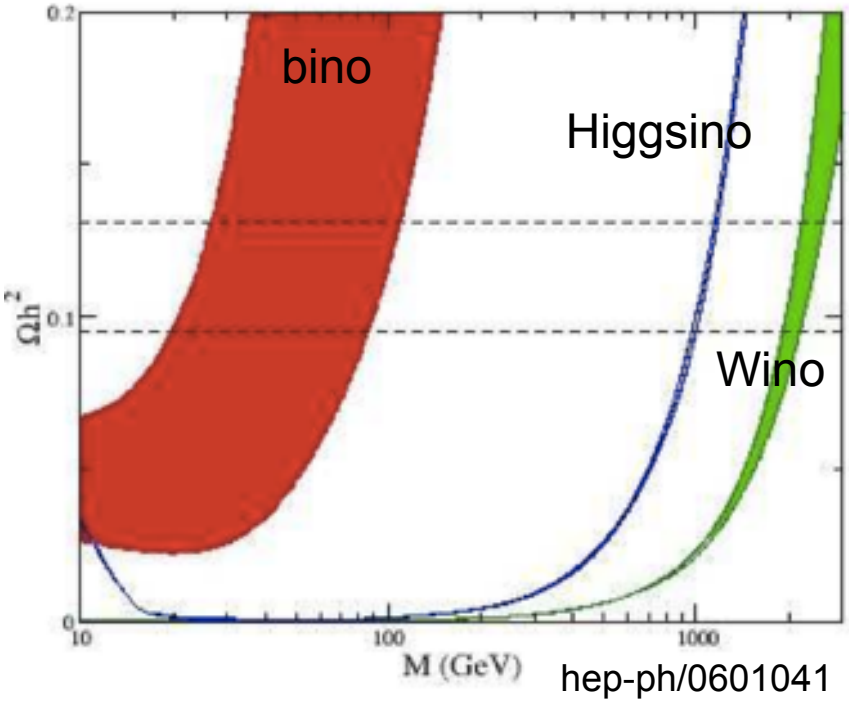
> How naturally can the dark matter relic abundance be achieved?

Often universal gaugino masses assumed at high scale, at low scale M3:M2:M1 ~ 6:2:1 → bino LSP

Bino: Typically need to finely tune relic density via coannihilations or resonances :-(

2-3 TeV Wino challenged by ID
Mariengela Lisanti et al 1307.4082

1 TeV Higgsino looking good :-)



hep-ph/0601041

EW naturalness in the MSSM

- How naturally can we achieve the correct Higgs vev?
- Electroweak vev (or m_Z) determined by SUSY parameters (from minimization condition for scalar potential)

$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - \mu^2 \simeq -m_{H_u}^2 - \mu^2$$

- Cancellation (tuning) needed for large SUSY masses
- How to quantify this?

$$\Delta_p \equiv \frac{\partial \ln v^2}{\partial \ln p} = \frac{p}{v^2}\frac{\partial v^2}{\partial p}$$

'sensitivity measure'

- Large Δ implies large tuning

Caveats of the sensitivity measure

- What fundamental parameters should be included (and what are the fundamental parameters)?
- Also depends on parametrization of fundamental parameters
- At which scale?
- It measures sensitivity rather than 'tuning' – can be different
- The acceptable values Δ depends on taste – no absolute measure

→ While for a given definition it can be calculated precisely, its physical interpretation is somewhat blurred.

The usual story

- What does this tell us about a natural SUSY spectrum?
- μ is a superpotential parameter and hardly runs: $\mu_{EW} \sim \mu_{GUT}$

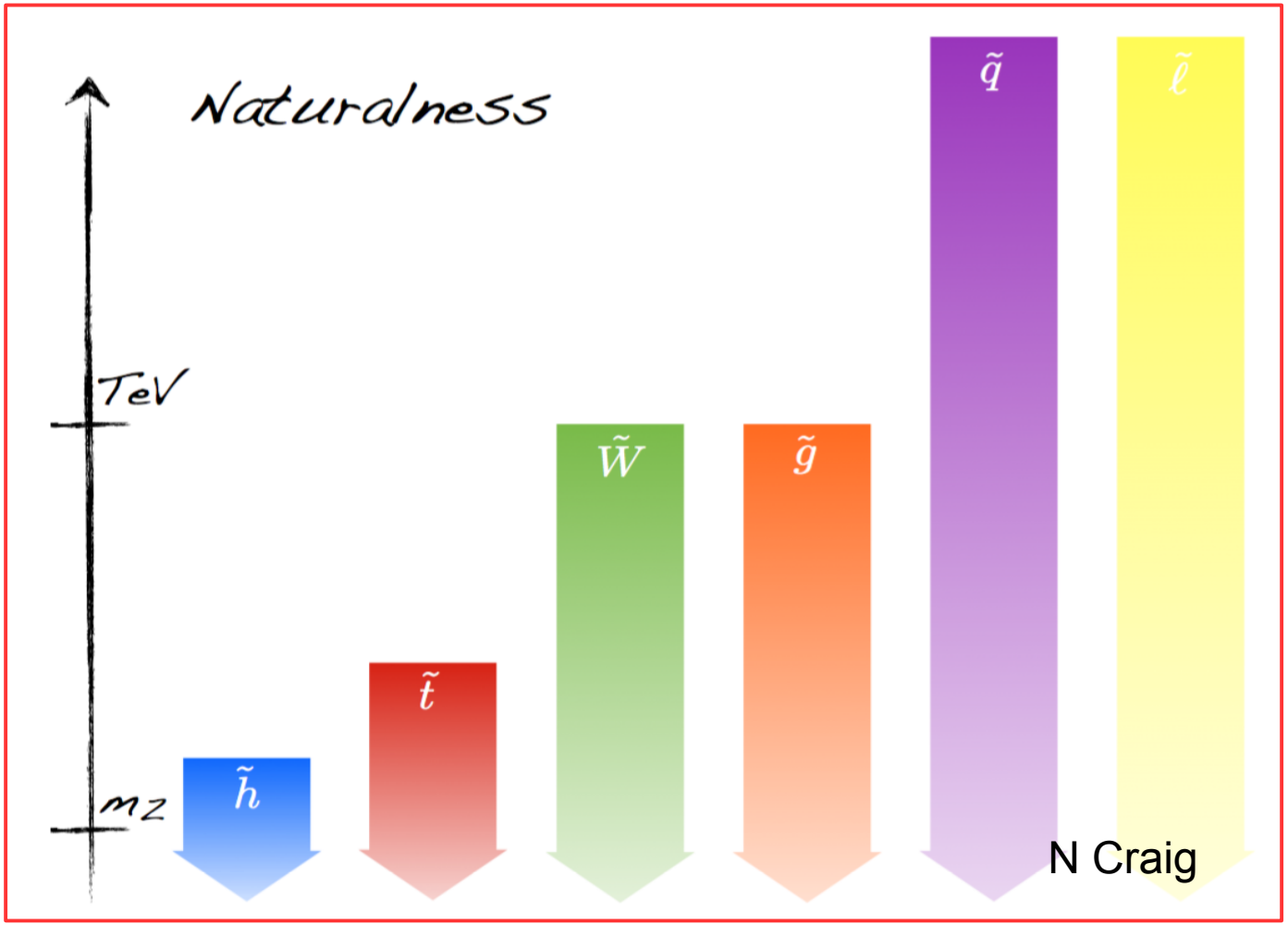
$$\text{Higgsino mass} \sim \mu \sim 1\ \text{TeV} \rightarrow\ \Delta_\mu \sim \frac{2\mu^2}{M_Z^2}\ \sim 250$$

- "Natural SUSY requires light Higgsino"
- What about the m_{Hu} part?
- Loop effects introduce a large sensitivity to stop and gluino masses

$$\delta m_{H_u}^2 = -\frac{3y_t^2}{4\pi^2} m_{\tilde{t}}^2 \ln\left(\Lambda/m_{\tilde{t}}\right)$$

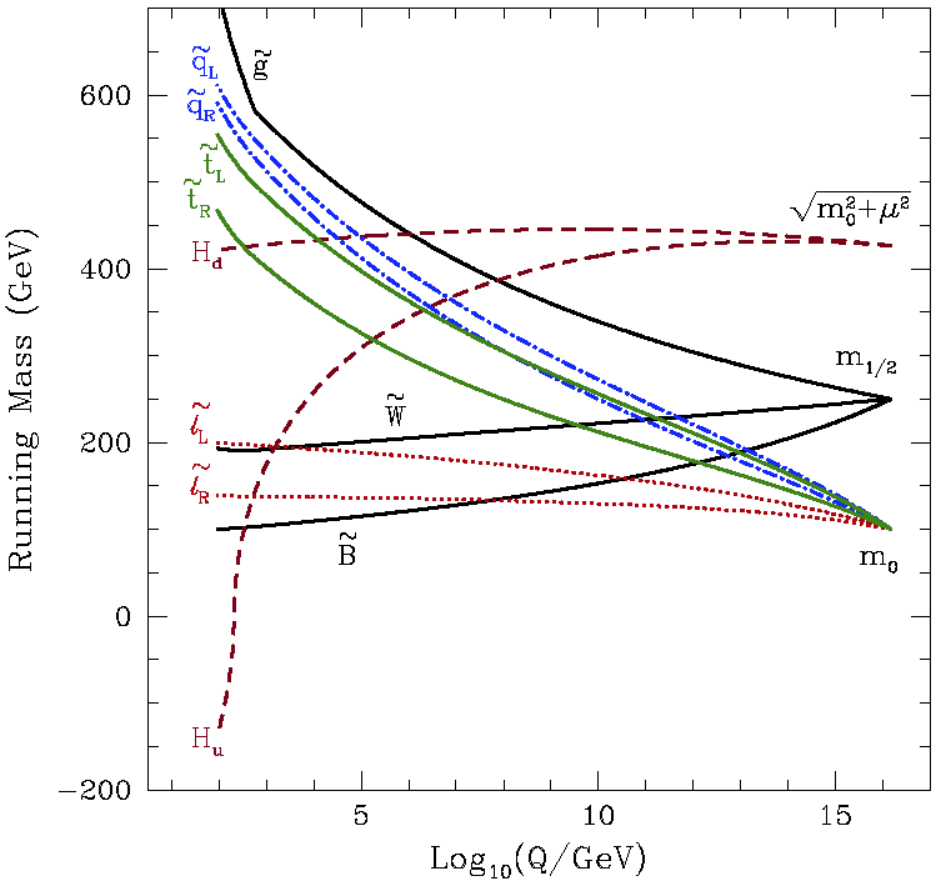
$$\delta m_{\tilde{t}}^2 = \frac{2g_s^2}{3\pi^2} m_{\tilde{g}}^2 \ln\left(\Lambda/m_{\tilde{g}}\right)$$

The 'natural SUSY' spectrum



High scale SUSY

- In many models SUSY breaking at high scale in hidden sector
- Often some universality
- Take into account running to predict SUSY spectrum at the electroweak scale.



EW naturalness in the MSSM – the GUT picture

- Starting from the high scale, all soft terms contribute to m_{Hu} and hence m_Z

$$
\begin{aligned}
m_Z^2 \simeq\ & -2.18\mu^2 + 3.84M_3^2 + 0.32M_3M_2 + 0.047M_1M_3 - 0.42M_2^2 \\
& +0.011M_2M_1 - 0.012M_1^2 - 0.65M_3A_t - 0.15M_2A_t \\
& -0.025M_1A_t + 0.22A_t^2 + 0.004M_3A_b \\
& -1.27m_{H_u}^2 - 0.053m_{H_d}^2 \\
& +0.73m_{Q_3}^2 + 0.57m_{U_3}^2 + 0.049m_{D_3}^2 - 0.052m_{L_3}^2 + 0.053m_{E_3}^2 \\
& +0.051m_{Q_2}^2 - 0.11m_{U_2}^2 + 0.051m_{D_2}^2 - 0.052m_{L_2}^2 + 0.053m_{E_2}^2 \\
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- We don't just want m_{Hu} to be small, but every contribution to it. Assuming no correlations among the terms, need rather light stops and gluinos

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$m_i^2 = m_0^2$

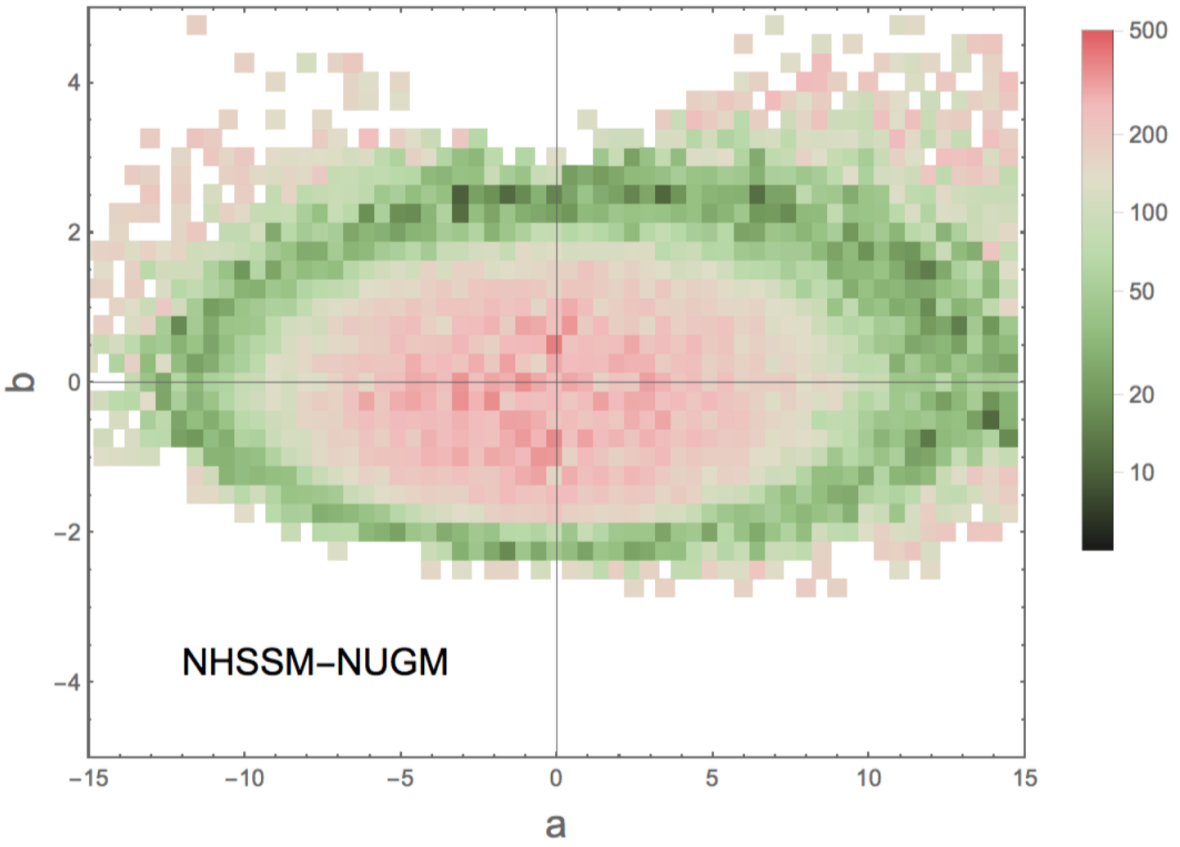
$\sim 0.01\ m_0^2$

- We don't just want m_{Hu} to be small, but every contribution to it. Assuming no correlations among the terms, need rather light stops and gluinos
- But we know correlations should be present…
- Example: the scalar focus point.

The gaugino focus point

- Assume fixed ratios of gaugino masses
- Possible also in GUTs Horton, Ross, 0908.0857

$$M_1 = a \cdot m_{1/2}$$
$$M_2 = b \cdot m_{1/2}$$
$$M_3 = m_{1/2}$$



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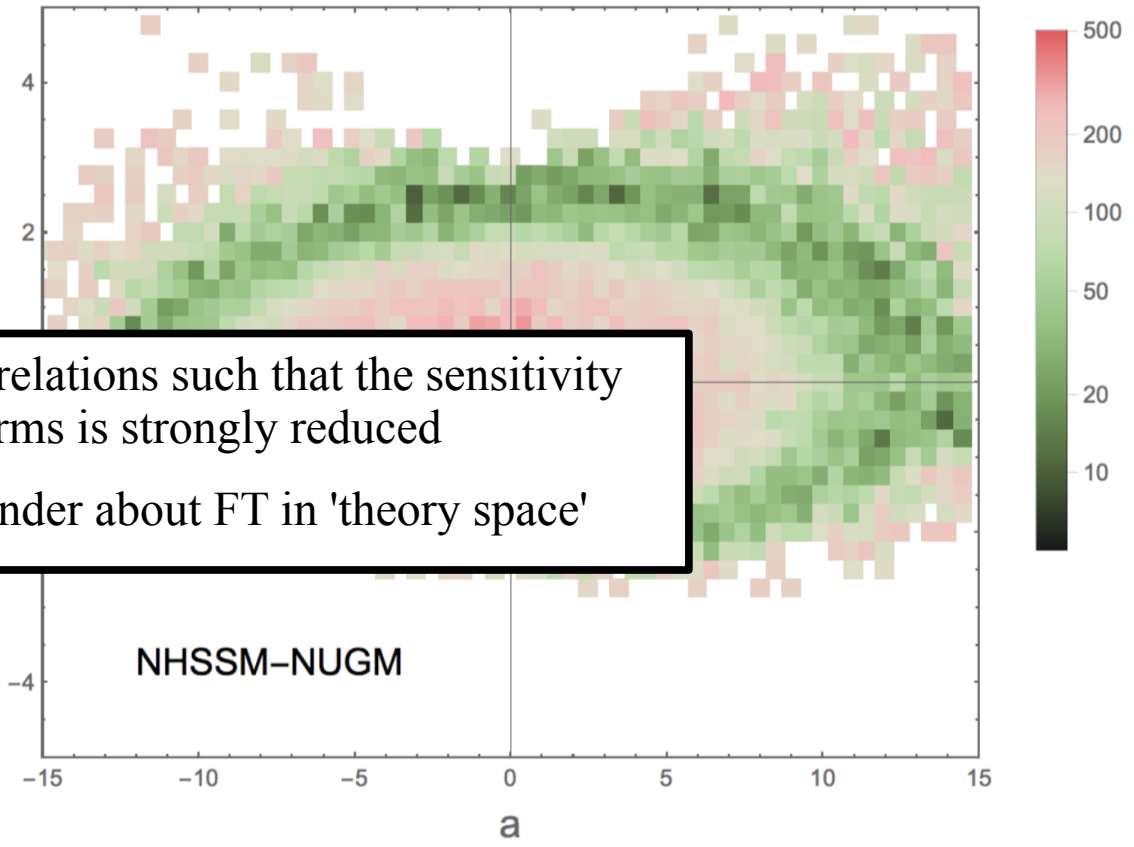

- Can find correlations such that the sensitivity to the soft terms is strongly reduced
- You may wonder about FT in 'theory space'

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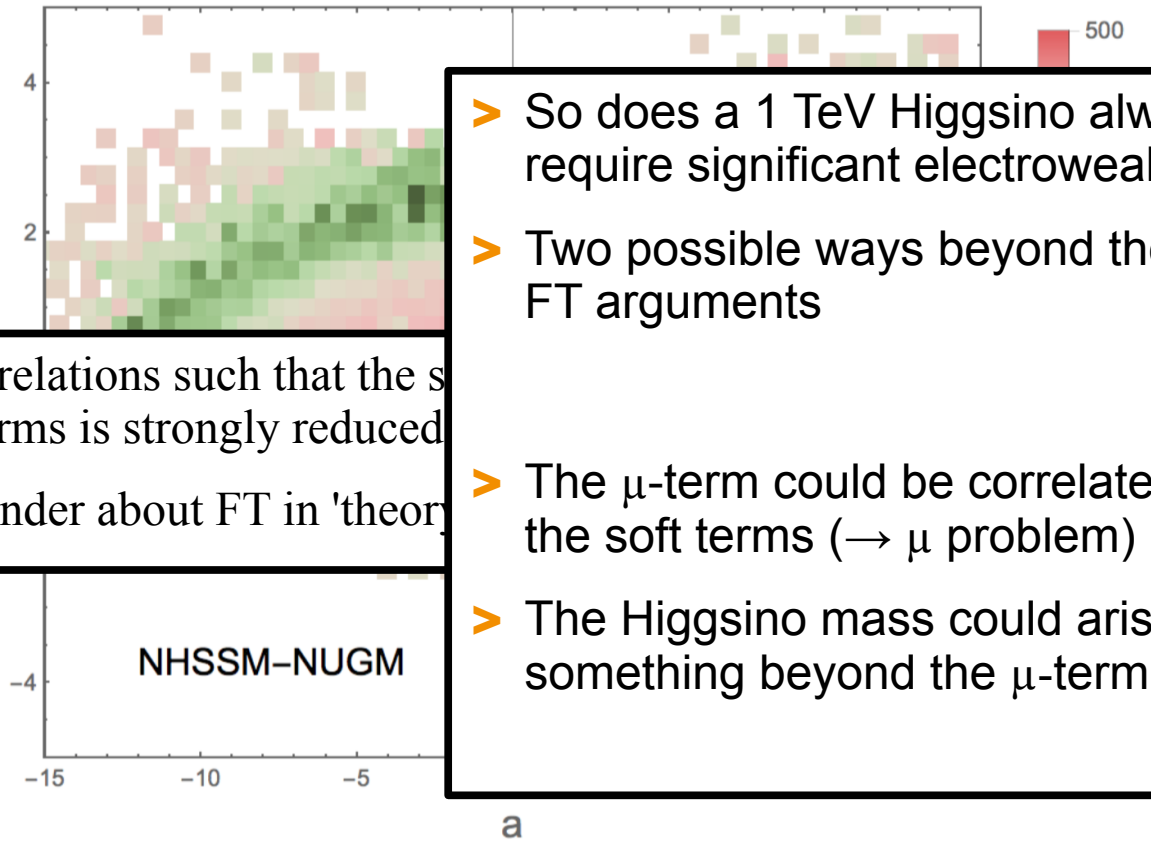


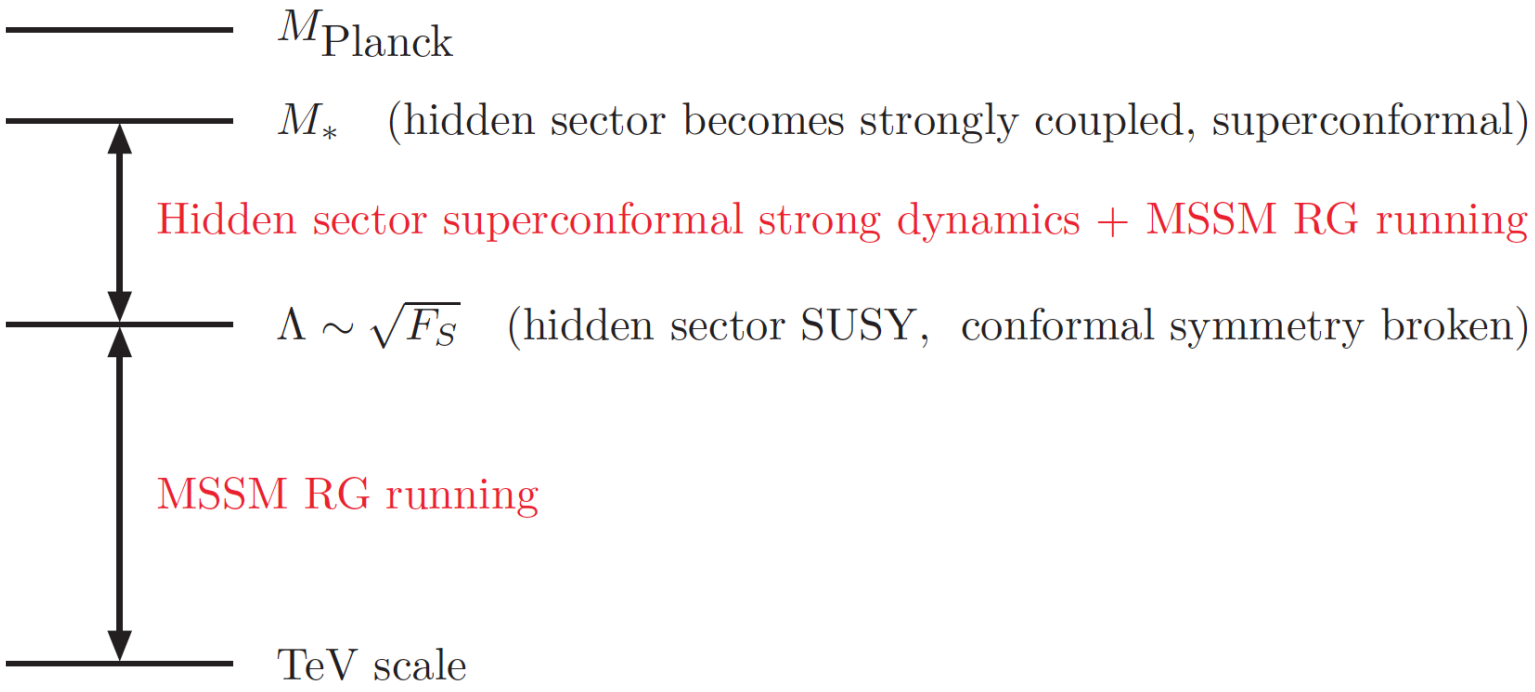
- Can find correlations such that the s
  to the soft terms is strongly reduced
- You may wonder about FT in 'theor

- So does a 1 TeV Higgsino always require significant electroweak tuning?
- Two possible ways beyond the naive FT arguments
- The μ-term could be correlated with the soft terms (→ μ problem)
- The Higgsino mass could arise from something beyond the μ-term

A further correlation

- The μ-term could be correlated with the soft terms

S Martin, 1712.05806
Perez, Roy, Schmaltz, 0811.3206



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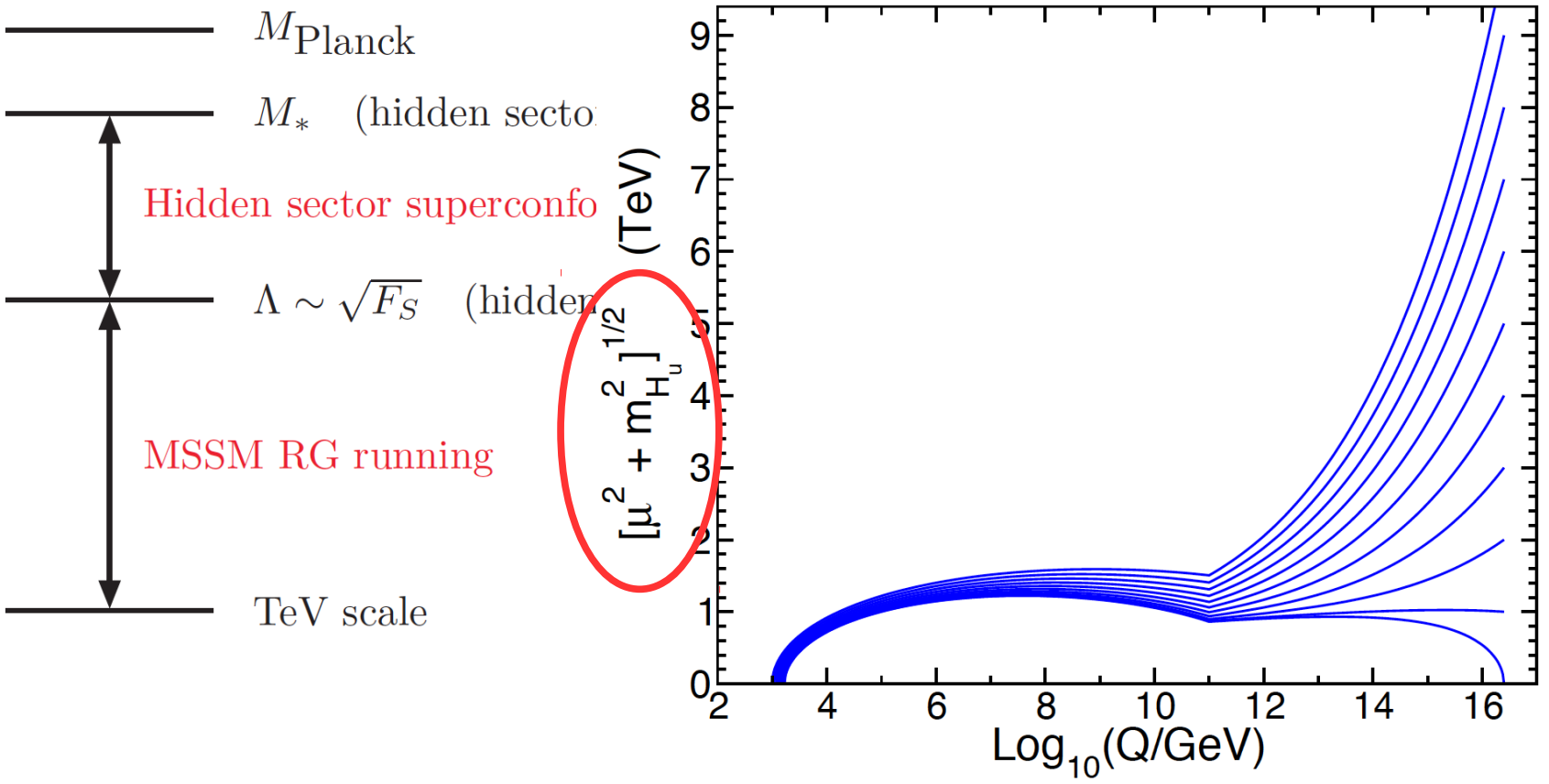


A new contribution to the Higgsino mass

- Non-standard SUSY breaking terms (in the classification of S Martin: 'maybe-soft')

$$\mathcal{L}_{NH} = \mu' \tilde{h}_d \tilde{h}_u + T'_{u,ij} h^*_d \tilde{u}^*_{R,i} \tilde{q}_j + T'_{d,ij} h^*_u \tilde{d}^*_{R,i} \tilde{q}_j + T'_{e,ij} h^*_u \tilde{e}^*_{R,i} \tilde{l}_j + \text{h.c.}$$

Girardello, Grisaru (1982)

- μ' contributes to the Higgsino mass ($m_h \sim \mu + \mu'$) but does not enter the scalar potential

- Now putting everything together...

Embedding this into a model

- Studied different MSSM variants with GUT boundary conditions

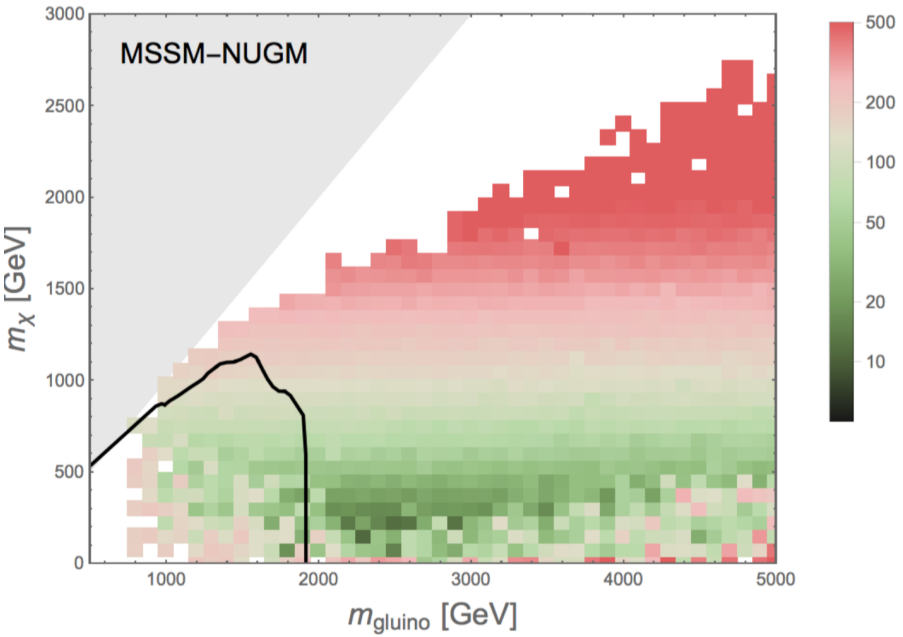
	$m_{h_u}^2$	$m_{h_d}^2$	M_1	M_2	M_3	μ'	A_0'
CMSSM	m_0^2	m_0^2	$m_{1/2}$	$m_{1/2}$	$m_{1/2}$	-	-
MSSM-NUHM	$m_{h_u}^2$	$m_{h_d}^2$	$m_{1/2}$	$m_{1/2}$	$m_{1/2}$	-	-
MSSM-NUGM	m_0^2	m_0^2	$a \cdot m_{1/2}$	$b \cdot m_{1/2}$	$m_{1/2}$	-	-
CNHSSM	m_0^2	m_0^2	$m_{1/2}$	$m_{1/2}$	$m_{1/2}$	μ'	A_0'
NHSSM-NUHM	$m_{h_u}^2$	$m_{h_d}^2$	$m_{1/2}$	$m_{1/2}$	$m_{1/2}$	μ'	A_0'
NHSSM-NUGM	m_0^2	m_0^2	$a \cdot m_{1/2}$	$b \cdot m_{1/2}$	$m_{1/2}$	μ'	A_0'

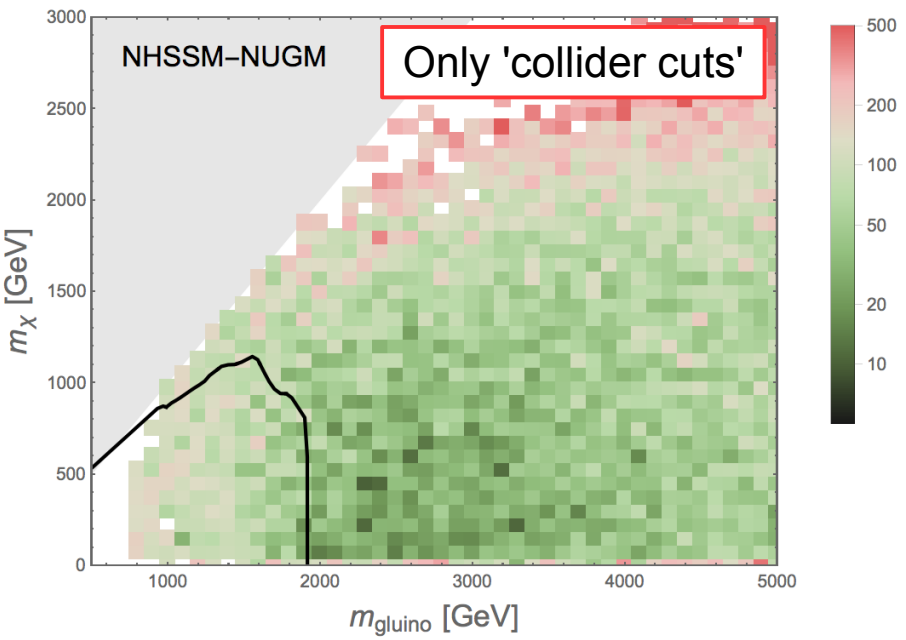
1701.03480

Results non-universal gaugino masses

- Region of small FT can be well beyond LHC reach

$\mu'=0$





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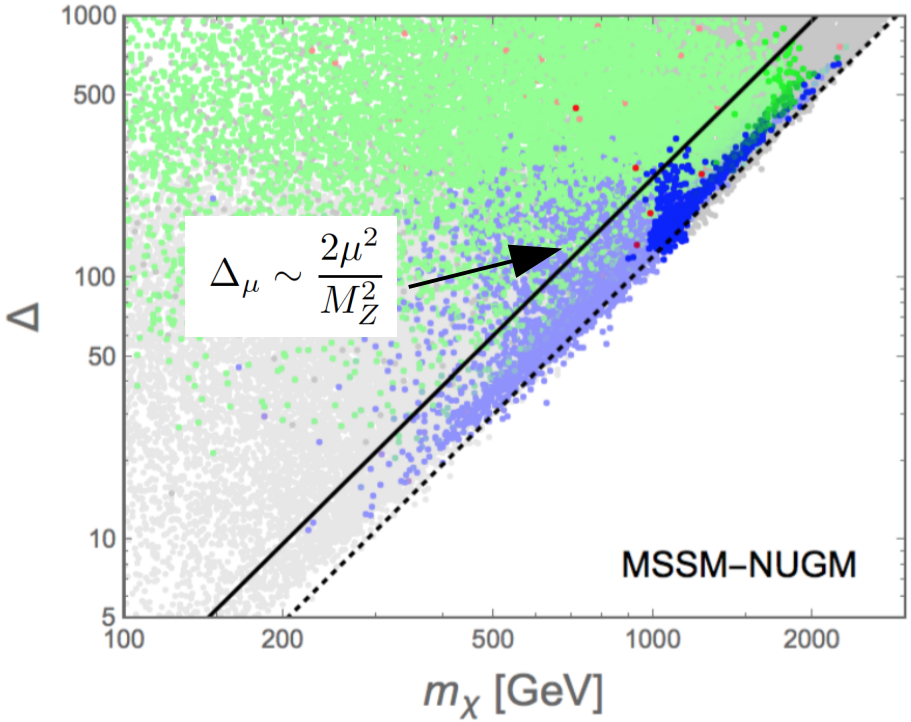
- Allowing for DM underabundance FT can be as small as 10.

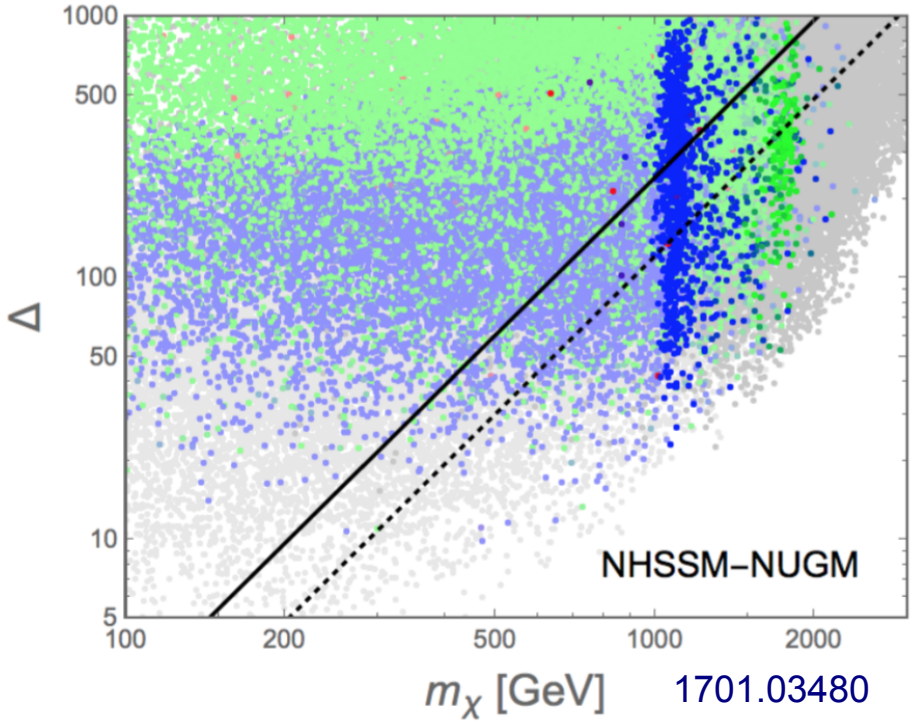
Results non-universal gaugino masses

- A 1 TeV Higgsino can be quite natural

$\mu'=0$

bino
Higgsino
Wino





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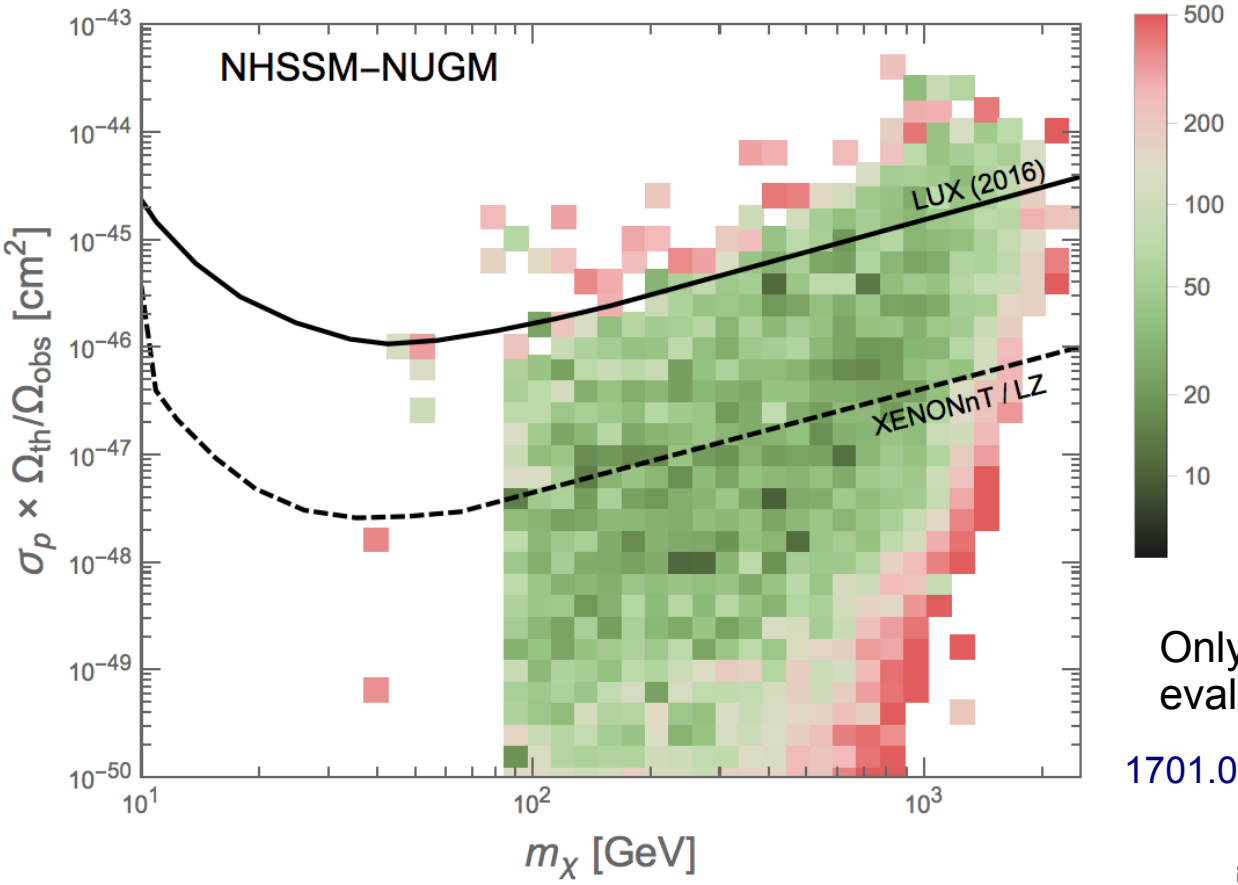
Prospects for direct detection

- Prospects for direct detection
- No lower bound on relic abundance (and rescaled) – other DM component



Only tree-level evaluation

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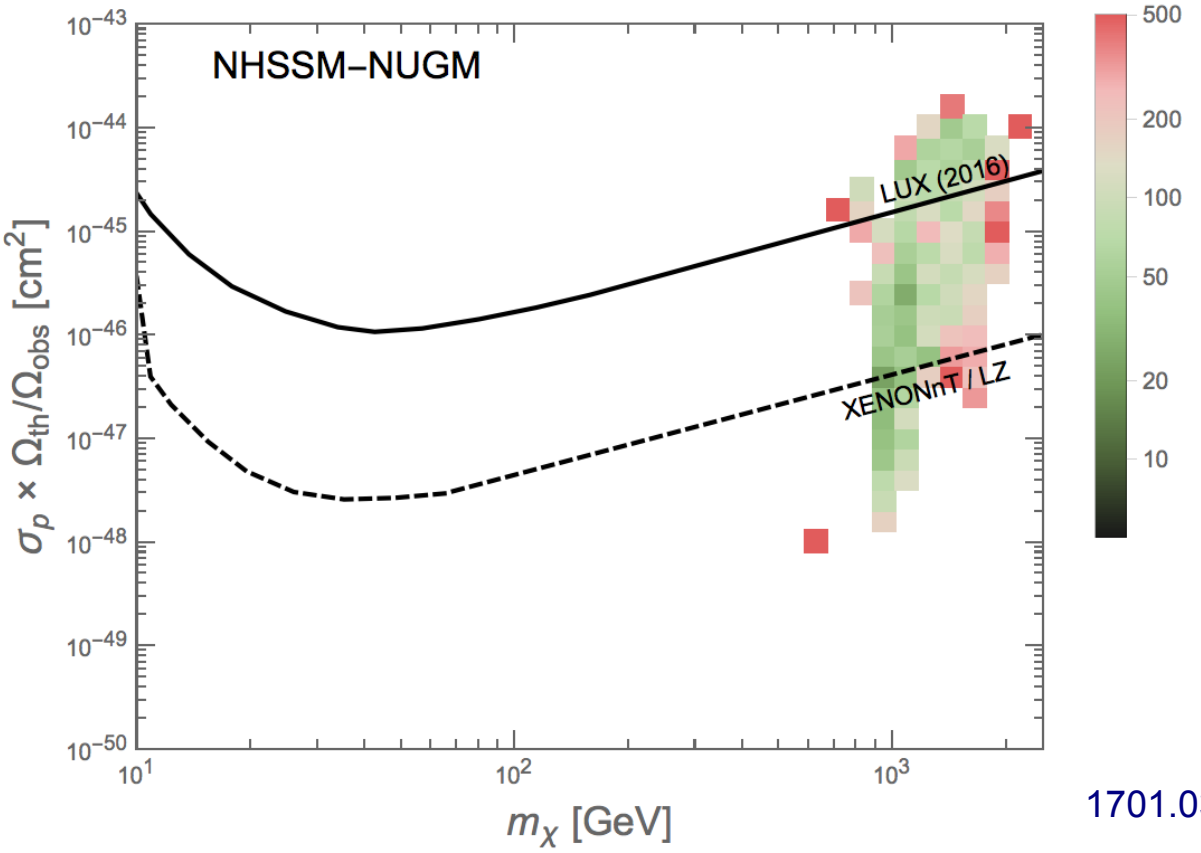
Prospects for direct detection

- Prospects for direct detection
- Correct (thermal) relic abundance



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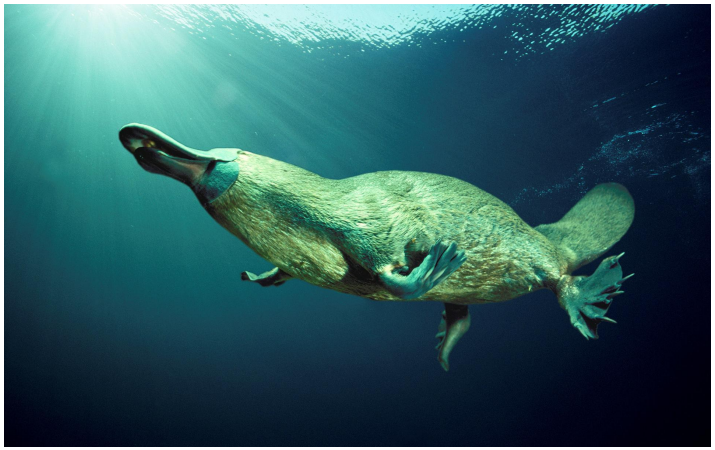
Summary

- What looks unnatural from an IR perspective **might** still look natural from the UV
- Extra Higgsino mass contribution μ' or correlation with soft terms allow natural thermal higgsino
- To do: build a UV model



- 'natural' SUSY could well be beyond the LHC reach
- Good chances at direct detection experiments to find it

Summary

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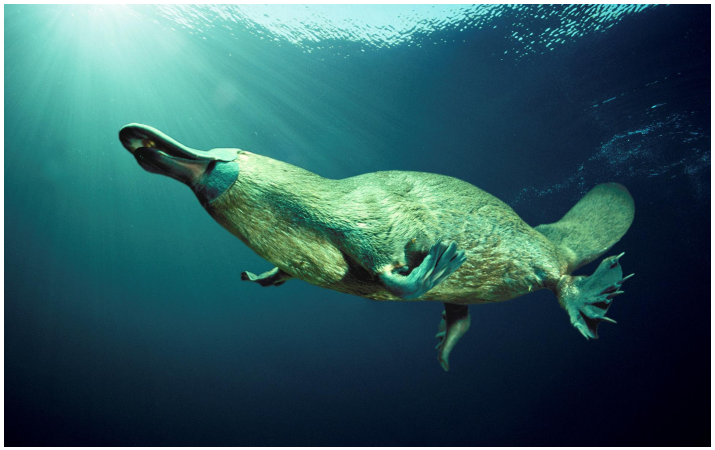
Thank you!



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Extra stuff

MSSM

- Field content fixed: theory specified by superpotential and soft terms

technically natural but still tuned
μ-problem

$$\mathcal{W} = \mu H_u H_d + \kappa_i L_i H_u$$
$$+ Y_e^{ij} H_d L_i E_j^c + Y_d^{ij} H_d Q_i D_j^c + Y_u^{ij} H_u Q_i U_j^c$$
$$+ \lambda_{ijk}^{(0)} L_i L_j E_k^c + \lambda_{ijk}^{(1)} L_i Q_j D_k^c + \lambda_{ijk}^{(2)} U_i^c D_j^c D_k^c$$
$$+ \kappa_{ij}^{(0)} H_u L_i H_u L_j + \kappa_{ijk\ell}^{(1)} Q_i Q_j Q_k L_\ell + \kappa_{ijk\ell}^{(2)} U_i^c U_j^c D_k^c E_\ell^c$$

$$L_{SB} = -\frac{1}{2}\sum_a M_a \bar{\lambda}_a \lambda_a - \sum_i m_{\tilde{\Phi}_i}^2 |\tilde{\Phi}_i|^2 +$$
$$T_u H_u \tilde{Q} \tilde{u} + T_d H_d \tilde{Q} \tilde{d} + T_e H_d \tilde{L} \tilde{e} + B_\mu H_u H_d$$

- Many new parameters (>100) but likely not independent

The LSP – a DM candidate.

- Neutralinos are mixtures of bino, Wino and Higgsinos
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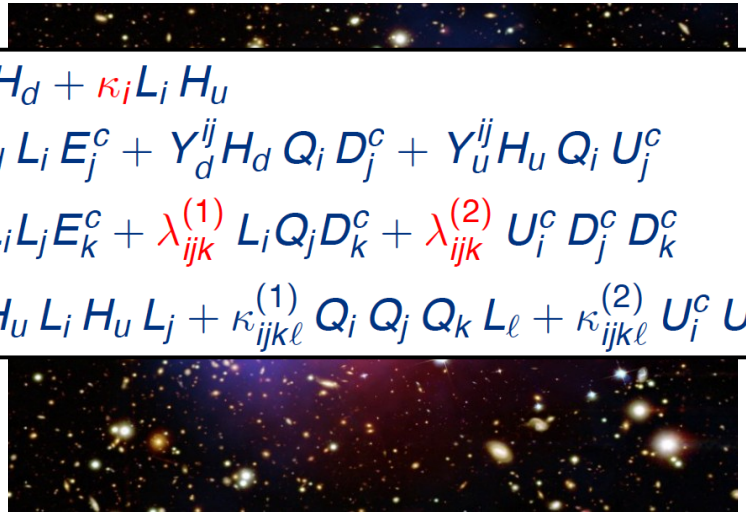
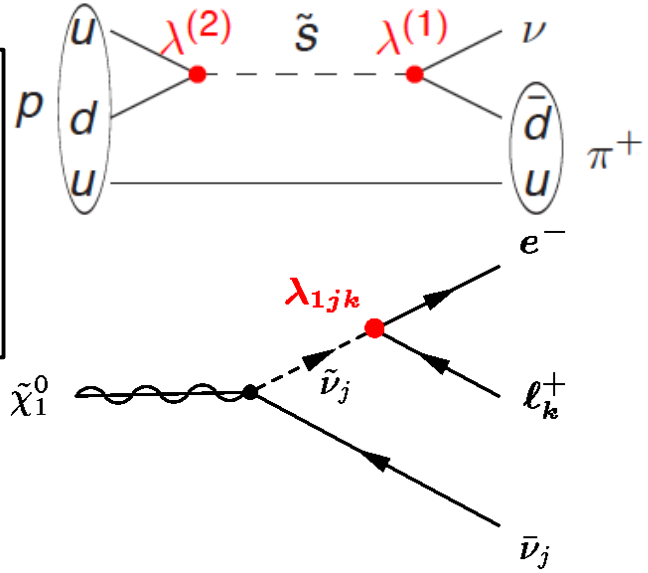


$$
\begin{aligned}
\mathcal{W} \;=\; & \mu\, H_u\, H_d + \kappa_i L_i\, H_u \\
& + Y_e^{ij} H_d\, L_i\, E_j^c + Y_d^{ij} H_d\, Q_i\, D_j^c + Y_u^{ij} H_u\, Q_i\, U_j^c \\
& + \lambda_{ijk}^{(0)}\, L_i L_j E_k^c + \lambda_{ijk}^{(1)}\, L_i Q_j D_k^c + \lambda_{ijk}^{(2)}\, U_i^c\, D_j^c\, D_k^c \\
& + \kappa_{ij}^{(0)}\, H_u\, L_i\, H_u\, L_j + \kappa_{ijk\ell}^{(1)}\, Q_i\, Q_j\, Q_k\, L_\ell + \kappa_{ijk\ell}^{(2)}\, U_i^c\, U_j^c\, D_k^c\, E_\ell^c
\end{aligned}
$$



- With only SUSY and gauge invariance: extra terms leading to proton and dark matter decay → need additional symmetry.
- Standard assumption: R-parity conservation (good enough for dark matter – not good enough for the proton, need a better symmetry such as Z_4^R)

Comment on loop corrections

- So far assumed tree-level relation for EWSB condition

$$\left.\frac{\partial V^{(L)}}{\partial v_u}\right|_{\tan\beta\to\infty} \equiv 0 = (m_{h_u}^2 + \mu^2 + \tfrac{1}{8}(g_1^2+g_2^2)v^2)v + \Sigma_u$$

How to parametrise Σ_u?

1. $\Sigma_u \equiv v\Sigma_{uu}$

$$\rightarrow \qquad \frac{1}{2}M_Z^2 = -|\mu|^2 - m_{H_u}^2 + \Sigma_{uu}$$

no change in FT; **only valid if Σ_{uu} is independent of v!**

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2. $\Sigma_u \equiv \Sigma_1 v + \Sigma_2 v^2 + \Sigma_3 v^3$

$$\rightarrow \qquad \Delta_\mu = \frac{8\mu^2}{(g_1^2+g_2^2+8\Sigma_3)v^2 + 4\Sigma_2 v}$$

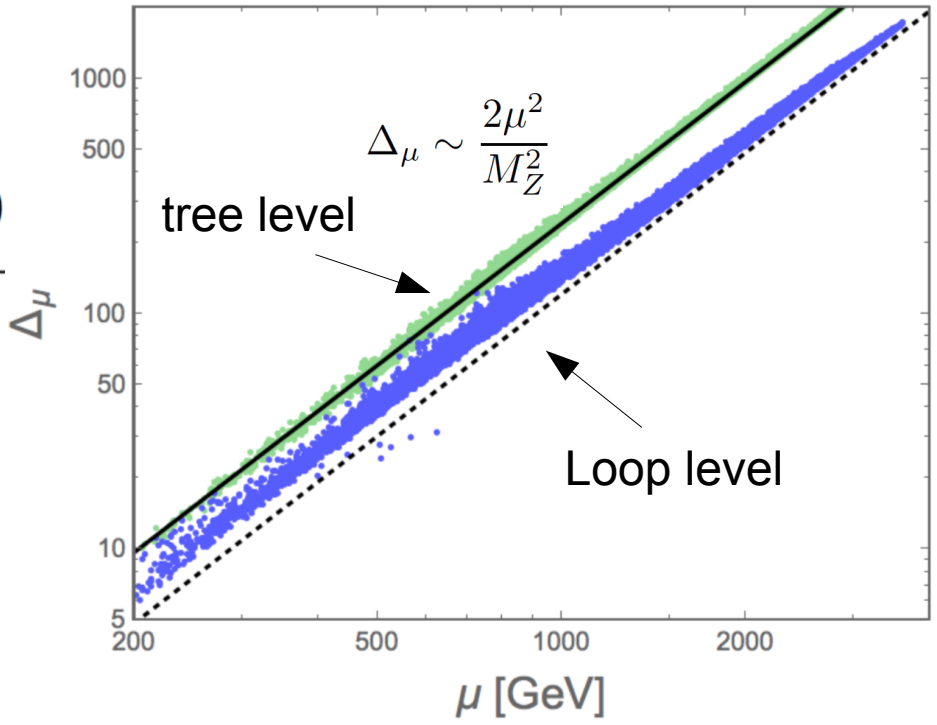
Comment on loop corrections

- Result for leading stop correction

$$\Sigma_1 = -\frac{3 m_{\tilde{t}}^2 Y_t^2 \left(-2\log\left(\frac{2m_{\tilde{t}}^2 + v^2 Y_t^2}{Q^2}\right) + 2 + \log(4)\right)}{32\pi^2}$$

$$\Sigma_2 = 0$$

$$\Sigma_3 = \frac{3 Y_t^4 \left(\log\left(\frac{2m_{\tilde{t}}^2 + v^2 Y_t^2}{Q^2}\right) - \log\left(\frac{v^2 Y_t^2}{Q^2}\right)\right)}{32\pi^2}$$



$$r^{FT} \equiv \frac{\Delta_\mu^{\text{Loop}}}{\Delta_\mu^{\text{Tree}}} \simeq \left(1 + \frac{3}{4\pi^2}\frac{Y_t^4}{g_1^2 + g_2^2}\log\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right)\right)^{-1} \simeq \frac{1}{2}$$

- Reduction of about ½ when including loop corrections