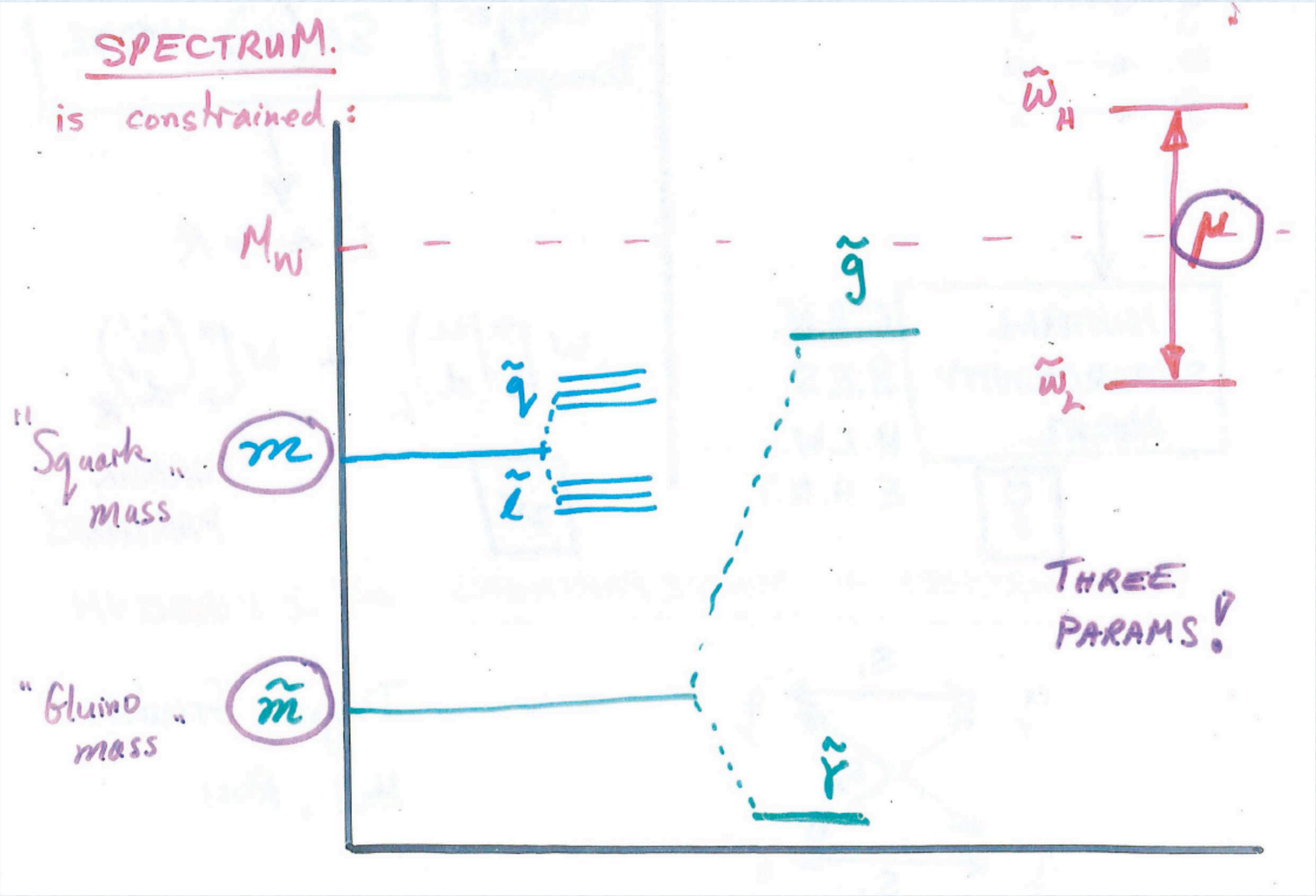
Johns Hopkins 36th Workshop
Galileo Galilei Institute
October 2012

Where is SUSY?

Lawrence Hall
University of California, Berkeley

BERKELEY CENTER FOR THEORETICAL PHYSICS

SUSY Spectrum, 1984



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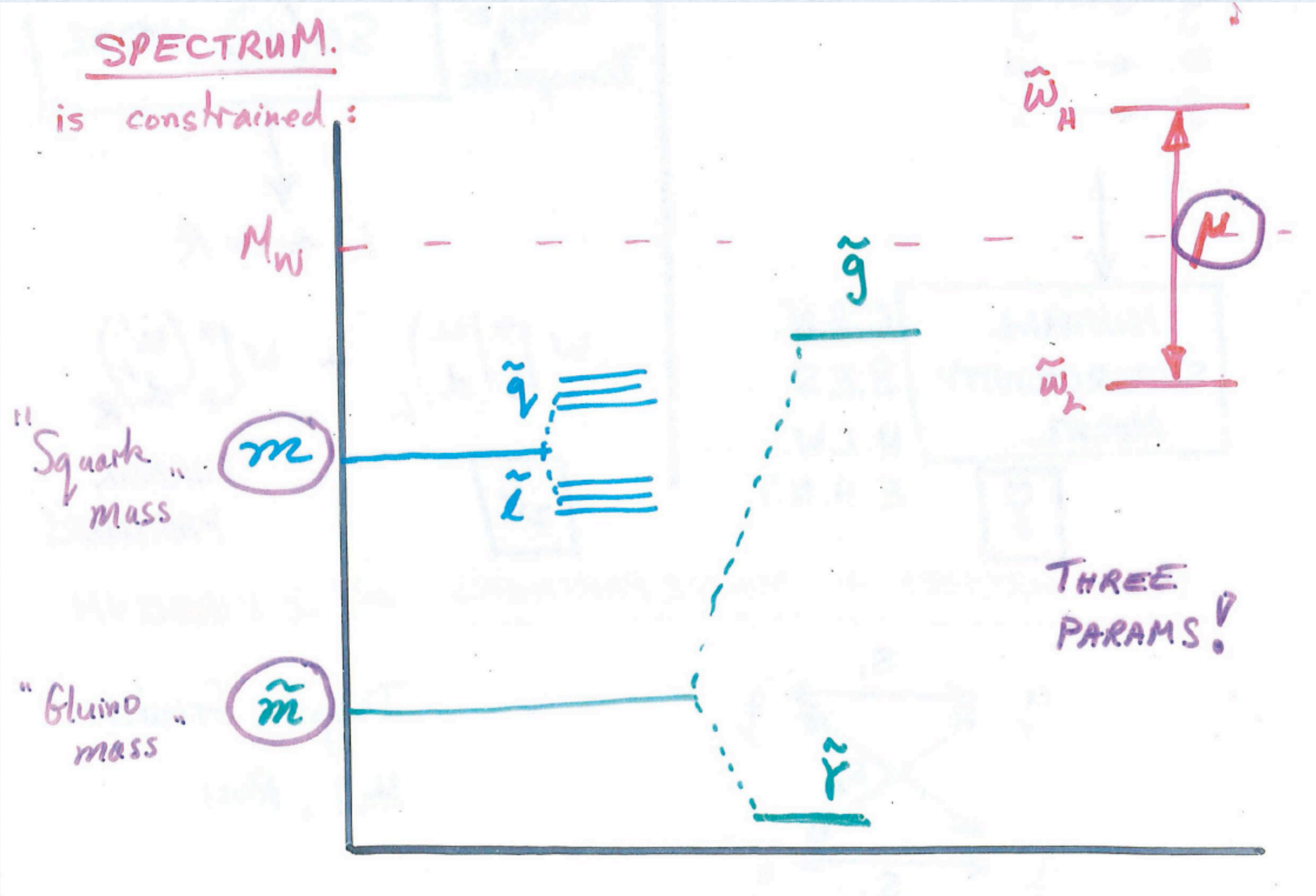
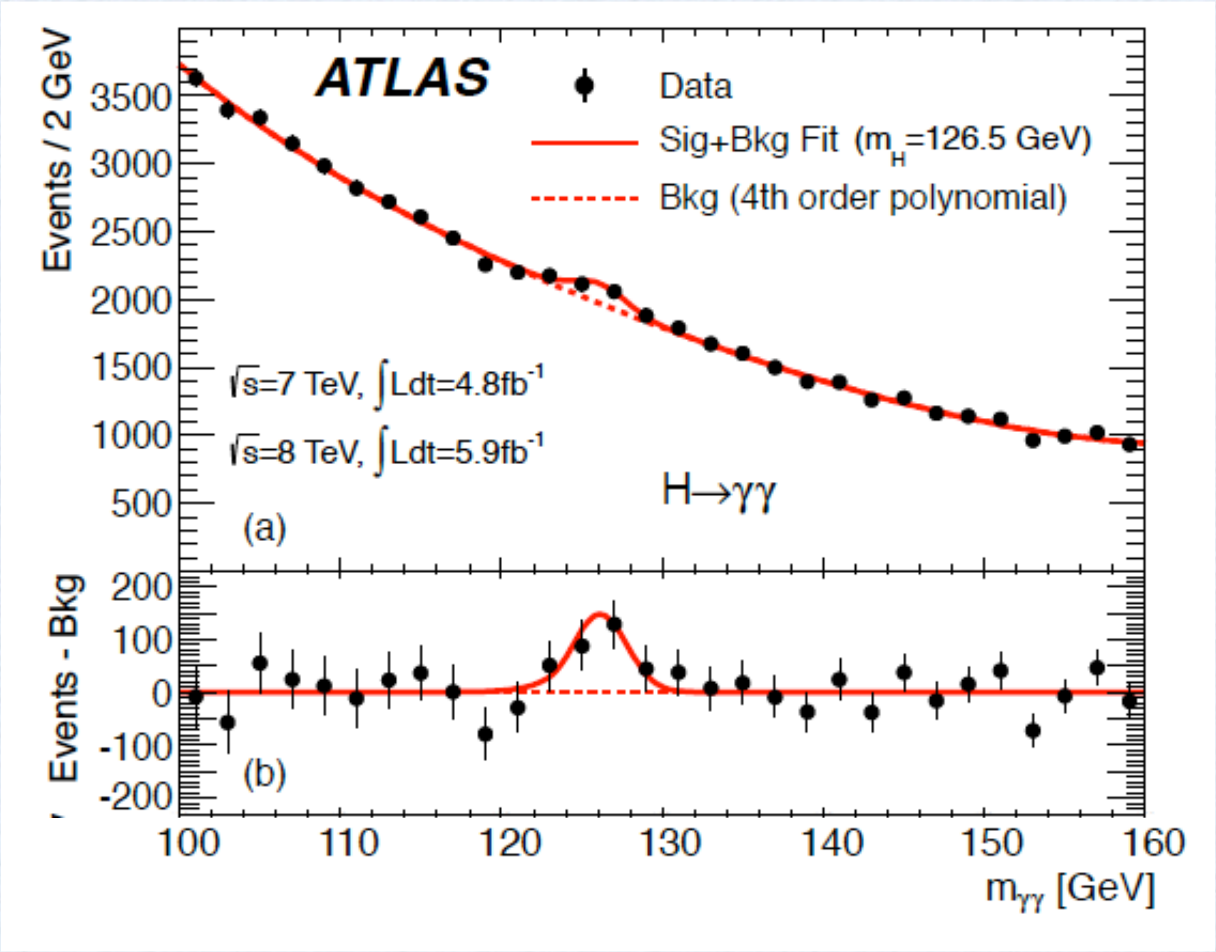
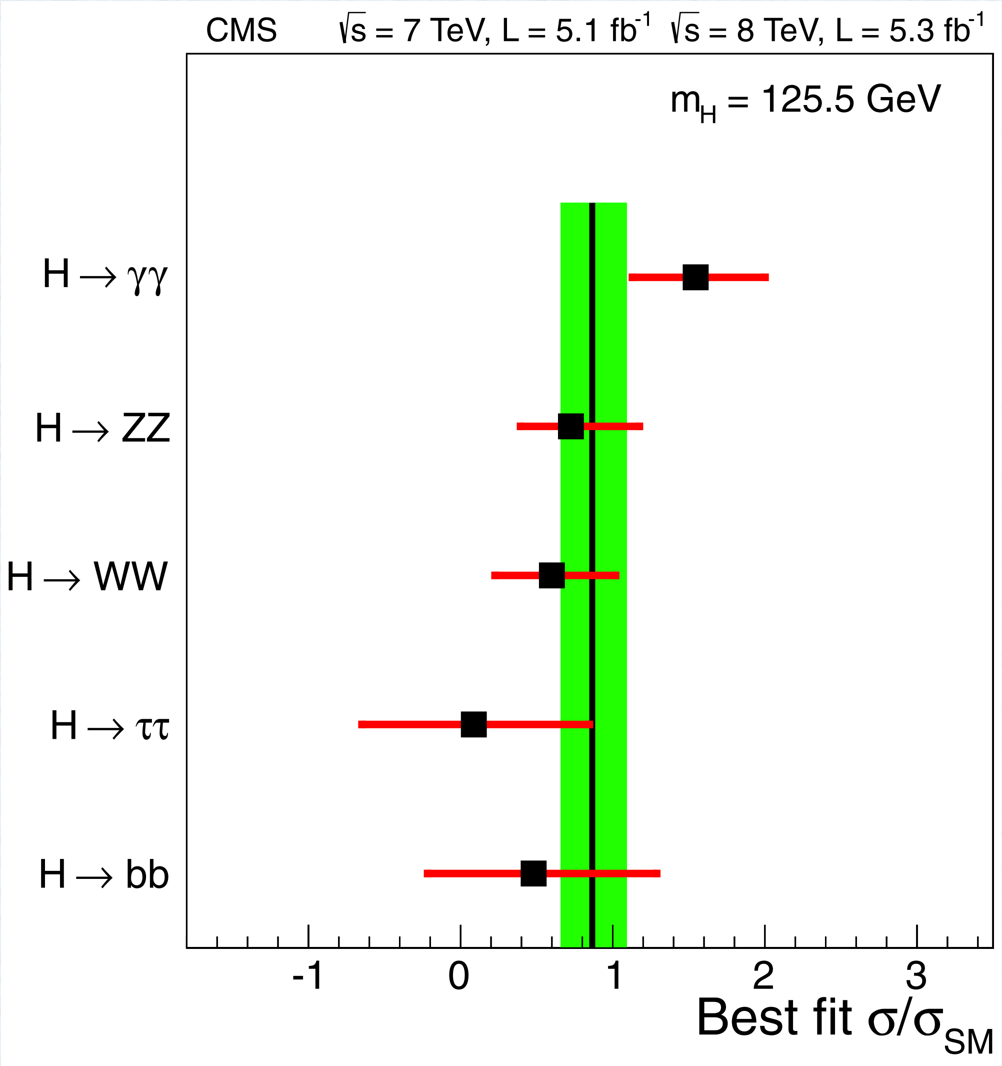


Over 3 decades of susy: seismic shifts!

(I) 2011-
A New Era of Data

A 125 GeV Higgs Boson





Is good news for perturbative Susy

Is SUSY Natural?

Natural

$$\tilde{m} \sim v$$

Unnatural

$$\tilde{m} \gg v$$

Origin of v ?

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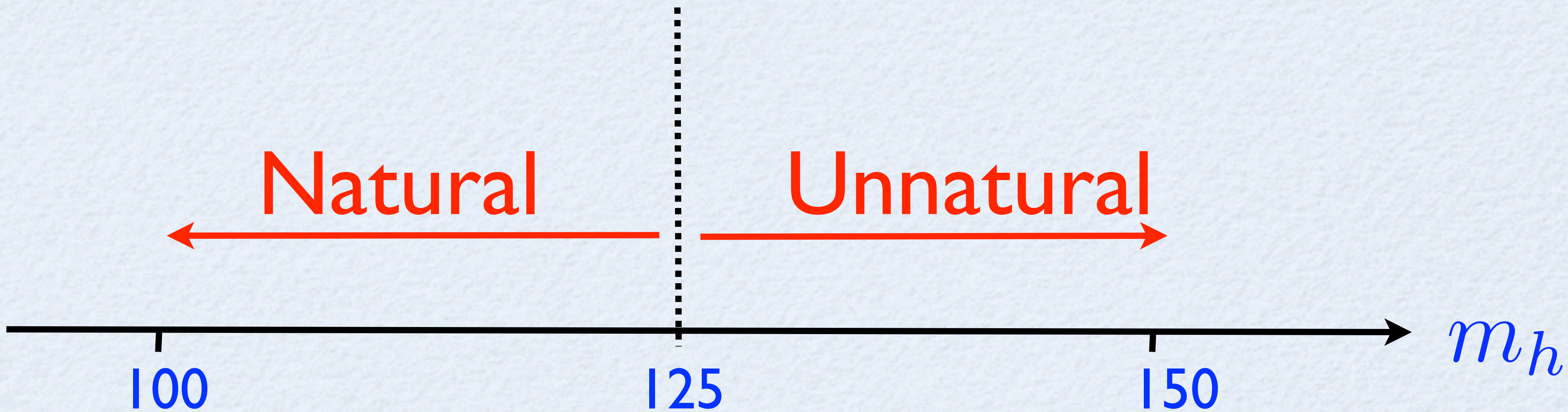


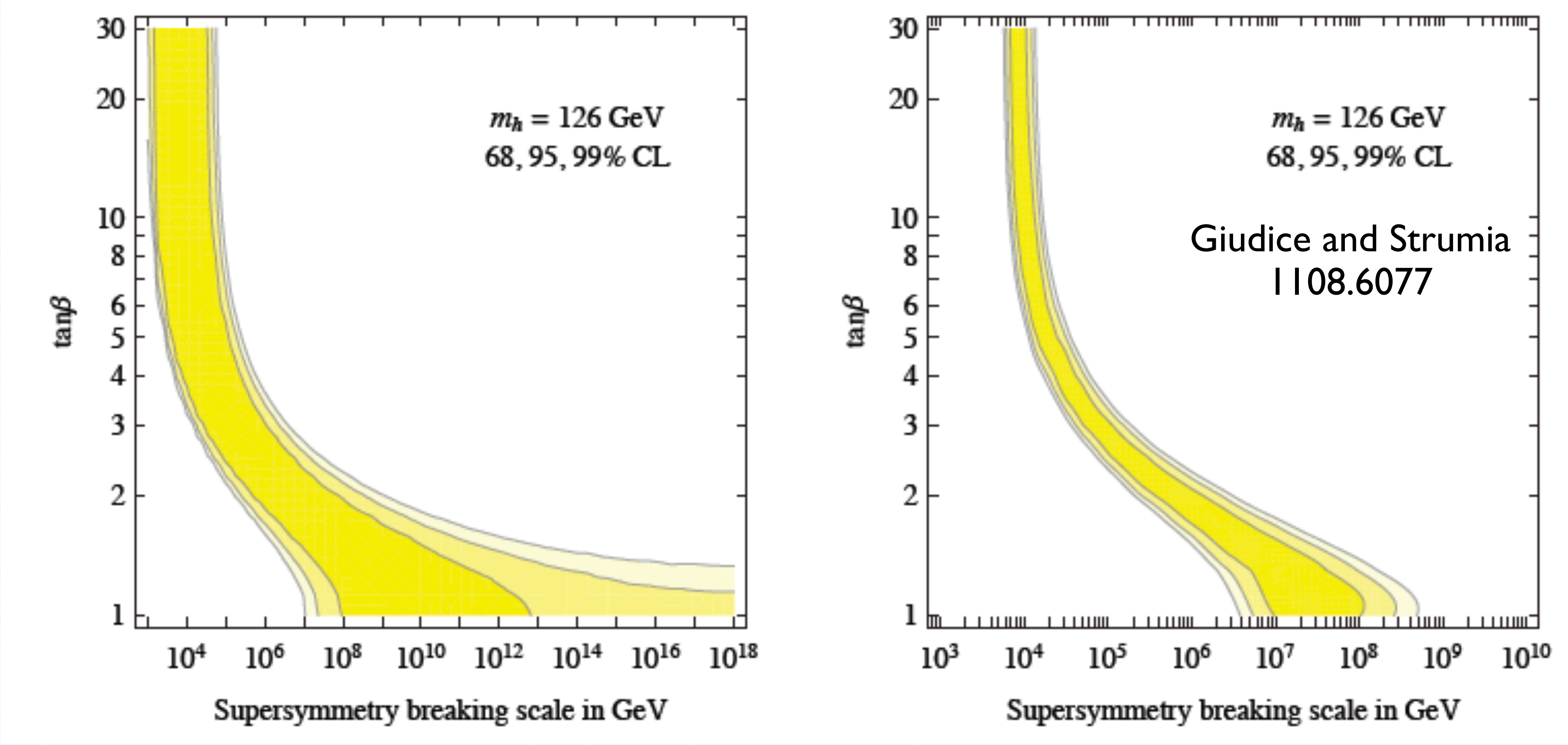
Inconclusive

Large Range of $\tilde{m}$ is Possible in MSSM

A) SM below $\tilde{m}$

B) Split SUSY (Fermionic superparters at 1 TeV)

$\tan\beta$

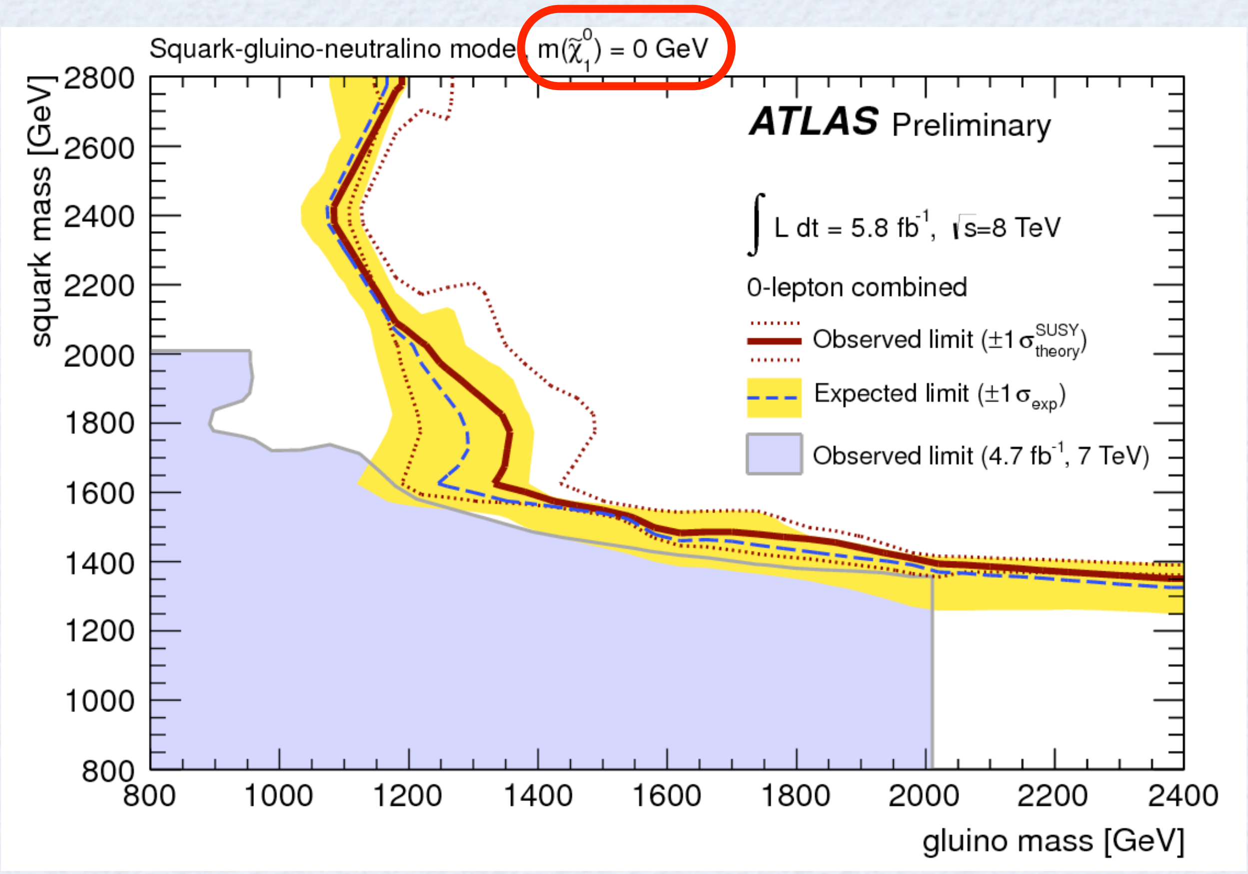


$\tilde{m}$

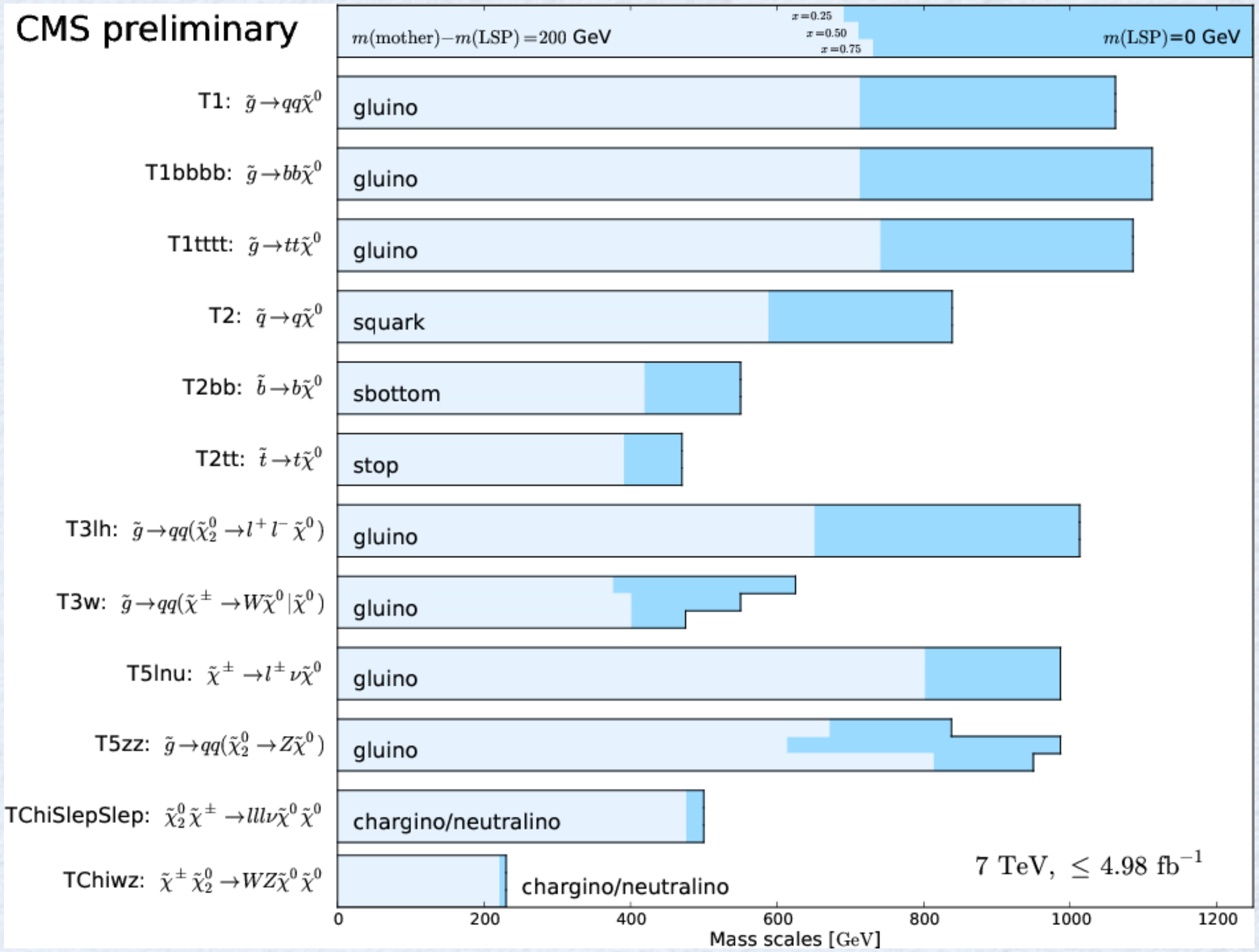
No Superpartners Yet!!

Jets + missing transverse energy
from
squark and gluino production

8/13/12



A compilation of CMS results
from 2011 data



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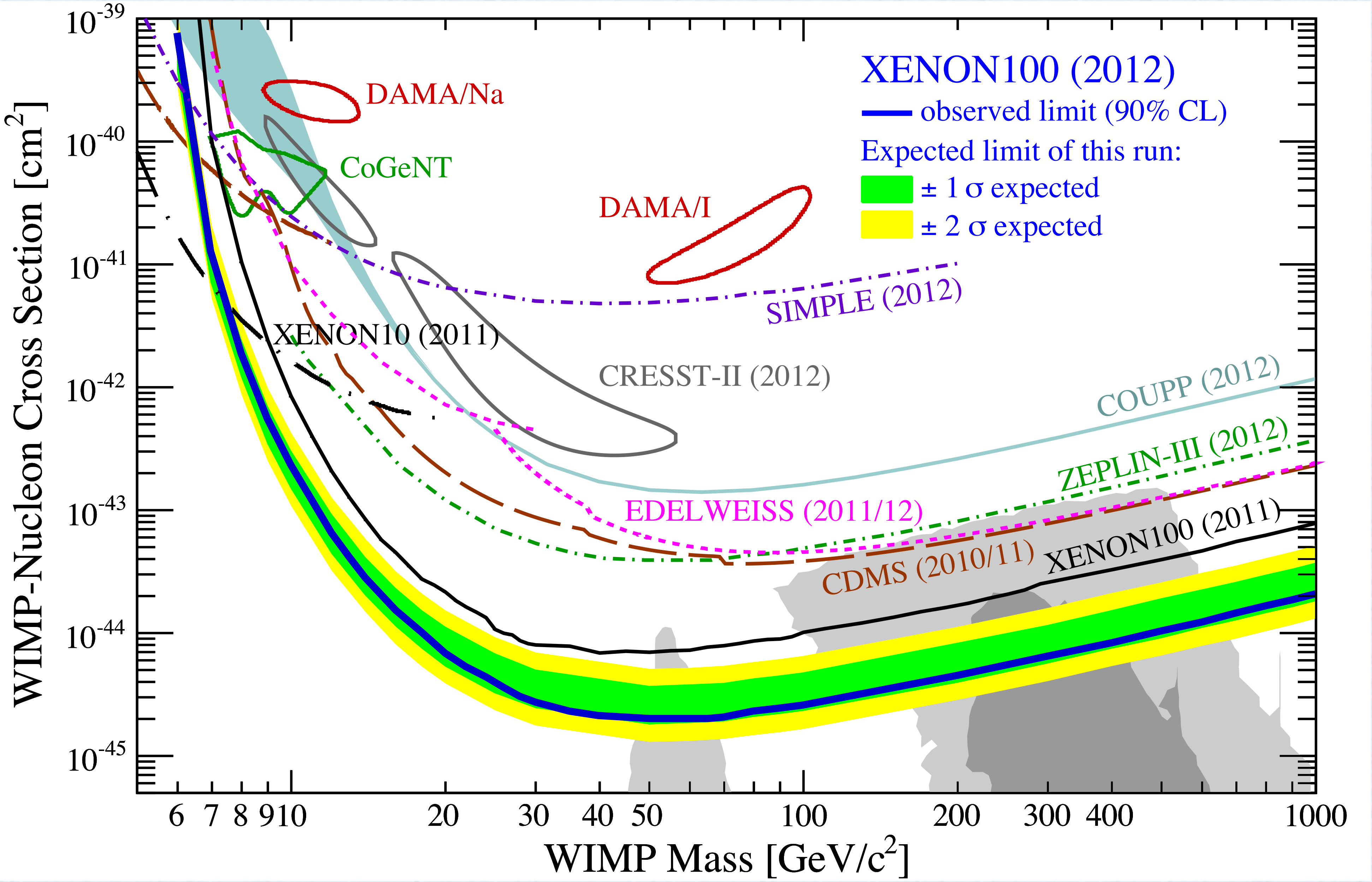
Any superpartners at the TeV scale?

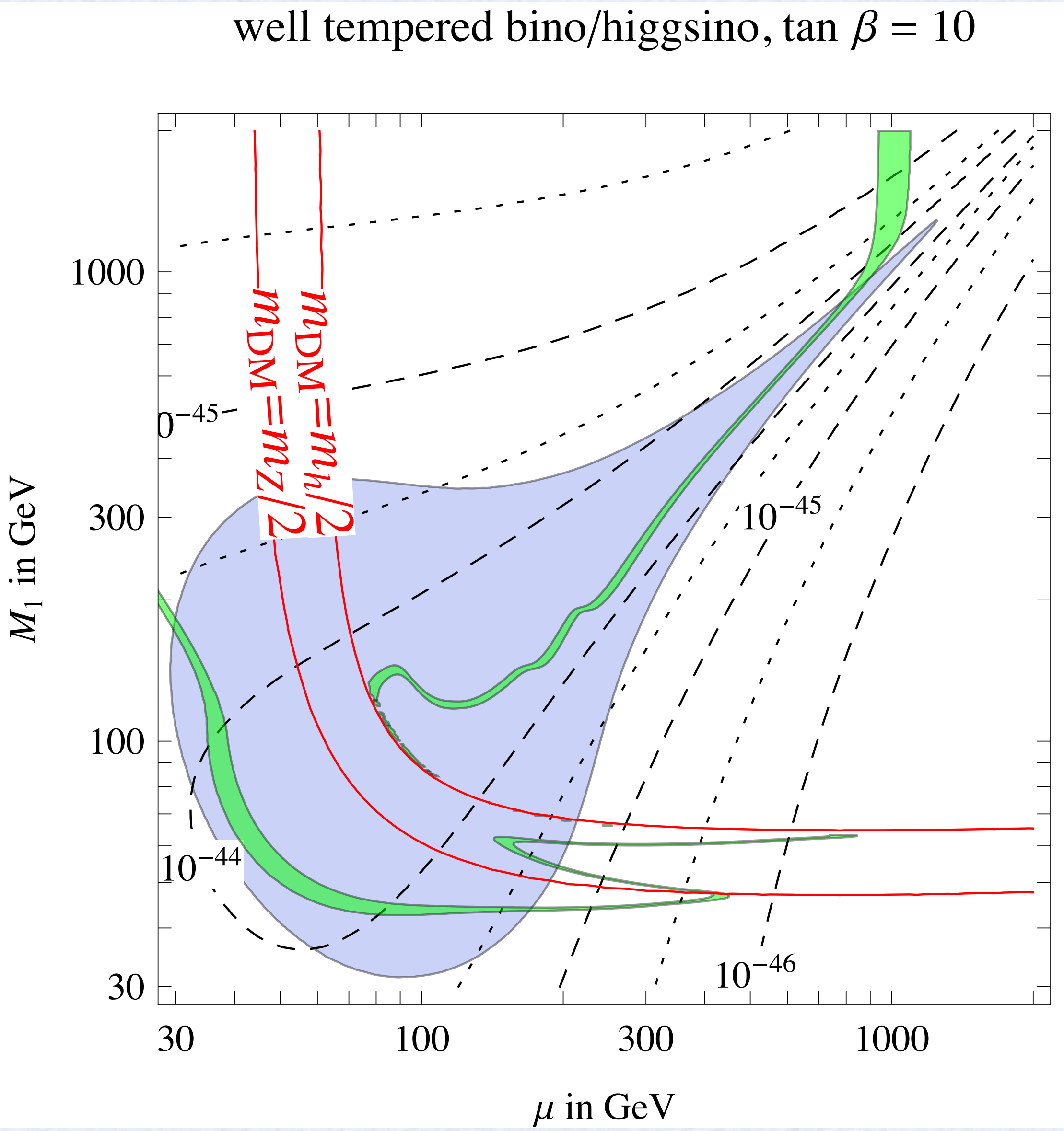
- Dark Matter
- Yukawa unification
- Spread Susy

2012 Result on Direct Detection



Implications for Neutralino DM

$\tilde{b}/\tilde{h}$



"The Well-Tempered Region is excluded"

Farina, Kadastik, Raidal, Pappadopulo, Pata, Strumia 1104.3572 revised Aug 2012

Indirect Detection via Gamma Rays

Fermi LAT
1108.3546

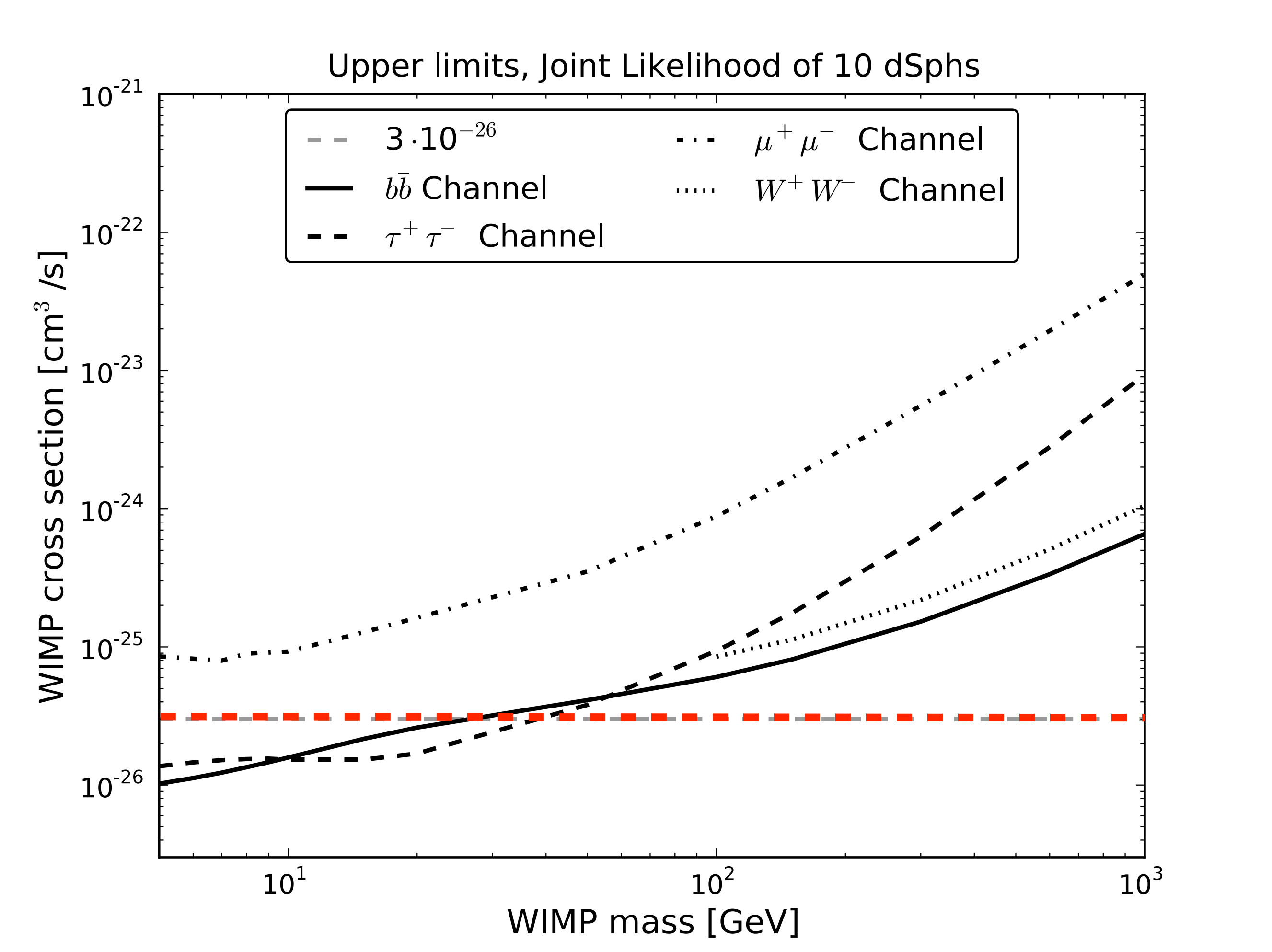


FIG. 2. Derived 95% C.L. upper limits on a WIMP annihilation cross section for the $b\bar{b}$ channel, the $\tau^+\tau^-$ channel, the $\mu^+\mu^-$ channel, and the W^+W^- channel. The most generic cross section ($\sim 3 \cdot 10^{-26}\,\mathrm{cm^3 s^{-1}}$ for a purely s-wave cross section) is plotted as a reference. Uncertainties in the J factor are included.

(II) Natural SUSY

1. MSSM ??

2. Adding a singlet

Fine-Tuning in the MSSM: 2012

$$m_h^2 = M_Z^2 \cos^2 2\beta + \delta_t^2$$

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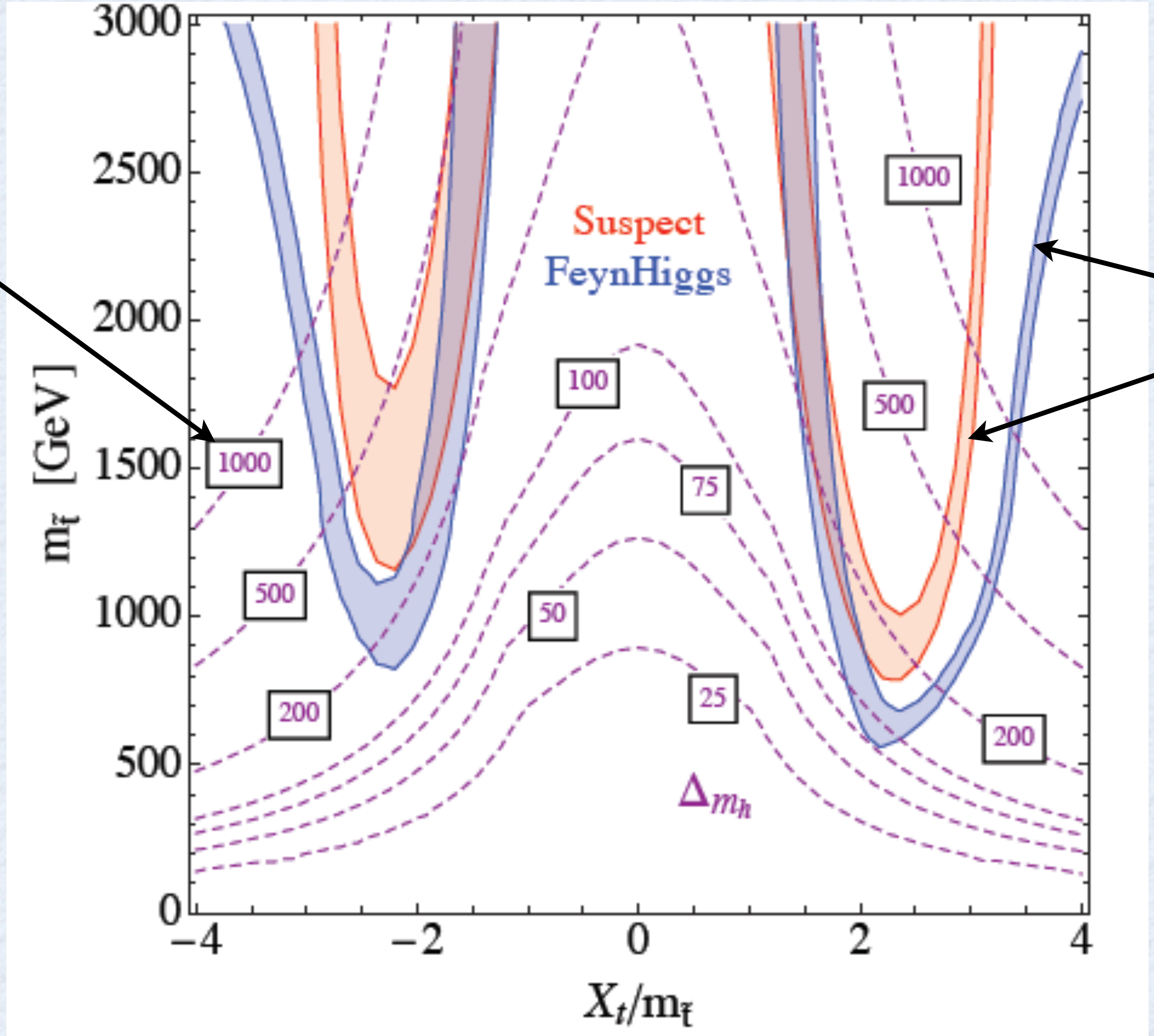
$$m_h^2 = M_Z^2 \cos^2 2\beta + \delta_t^2$$

$$\Delta = \frac{\partial \ln m_h}{\partial \ln p}$$



$m_h = 124 - 126$ GeV

Minimize Δ

$\tan\beta > 10$

$m_{Q_3} = m_{U_3} = m_{\tilde{t}}$

messenger scale of 10 TeV

David Pinner, Josh Ruderman, LJH 1112.2703

$\Delta > 100$ The MSSM is fine-tuned

Adding a Singlet: $\lambda S H_u H_d$

$$m_h^2 = M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \delta_t^2$$

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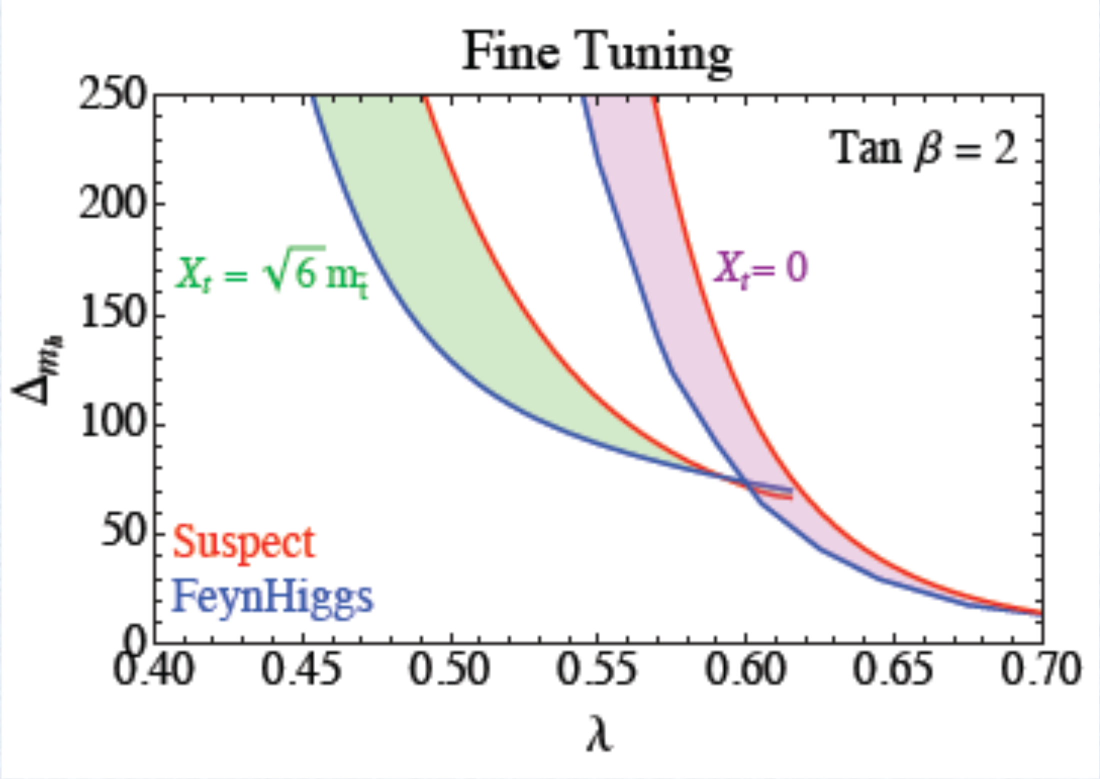
$\lambda < 0.7$



David Pinner, Josh Ruderman, LJH 1112.2703

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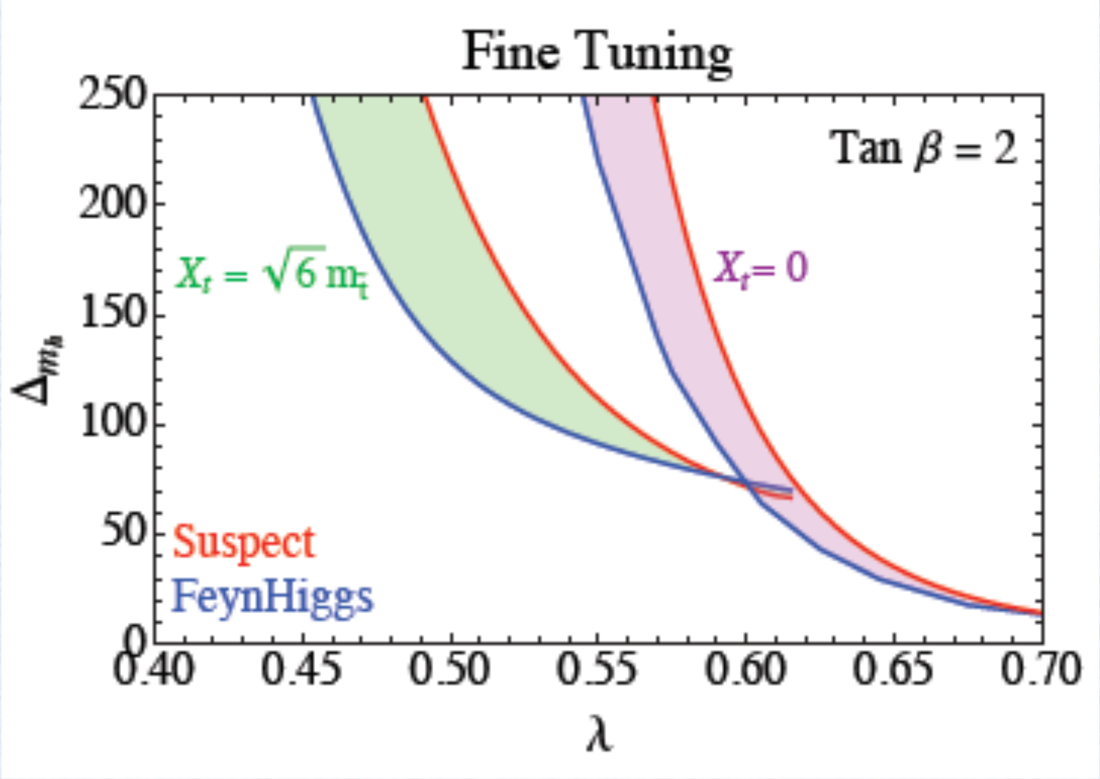


David Pinner, Josh Ruderman, LJH 1112.2703

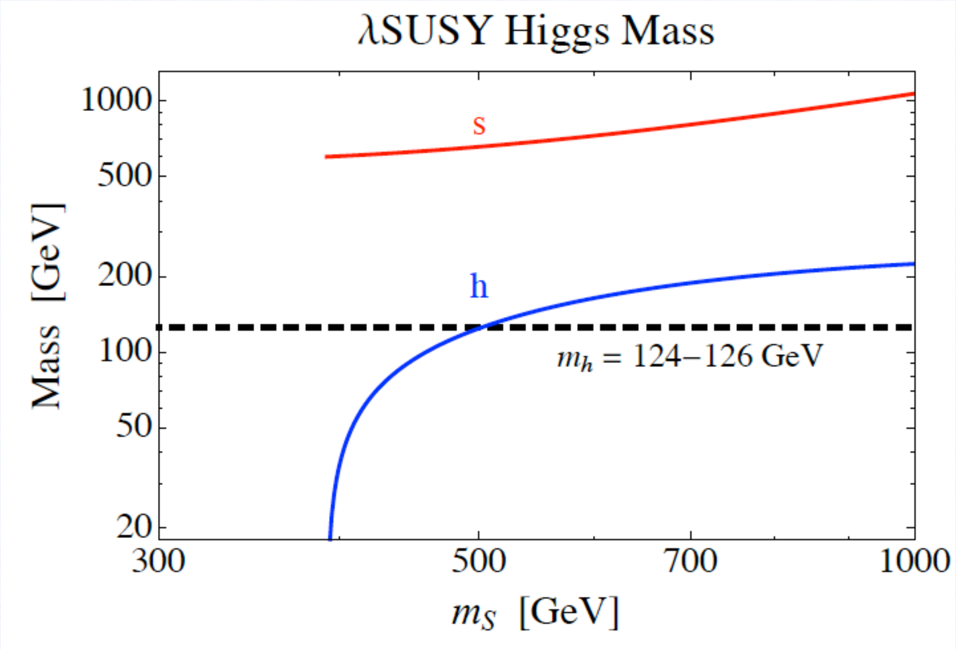
Why not go to larger λ?

To very large λ? ⟶ Natural theory with heavy Higgs

Adding a Singlet: $\lambda S H_u H_d$

David Pinner, Josh Ruderman, LJH   1112.2703

$$1 < \lambda < 2$$



Adding a Singlet: $\lambda \, S H_u H_d$

David Pinner, Josh Ruderman, LJH 1112.2703

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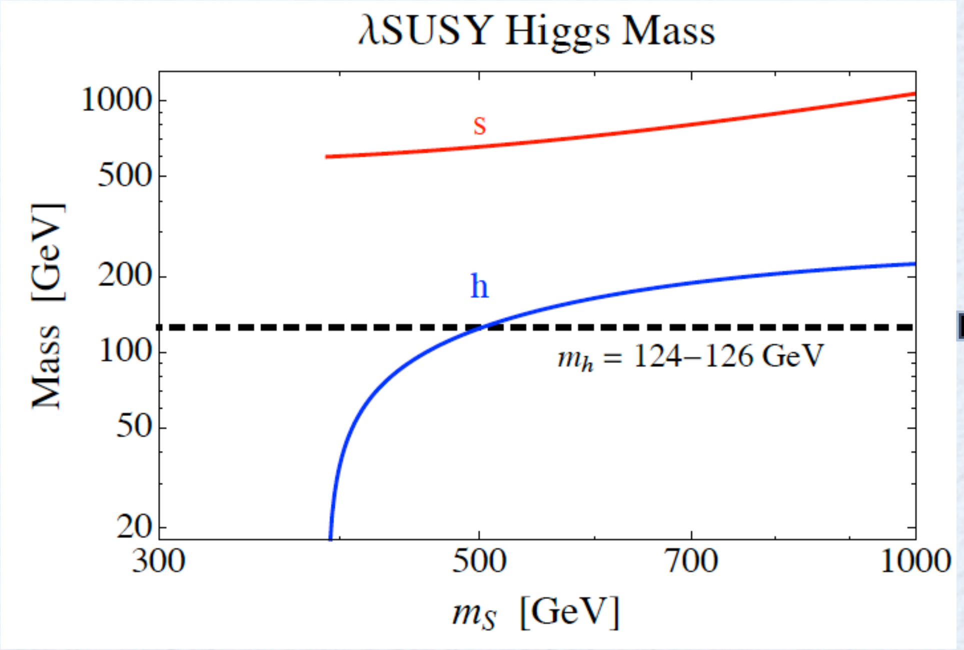
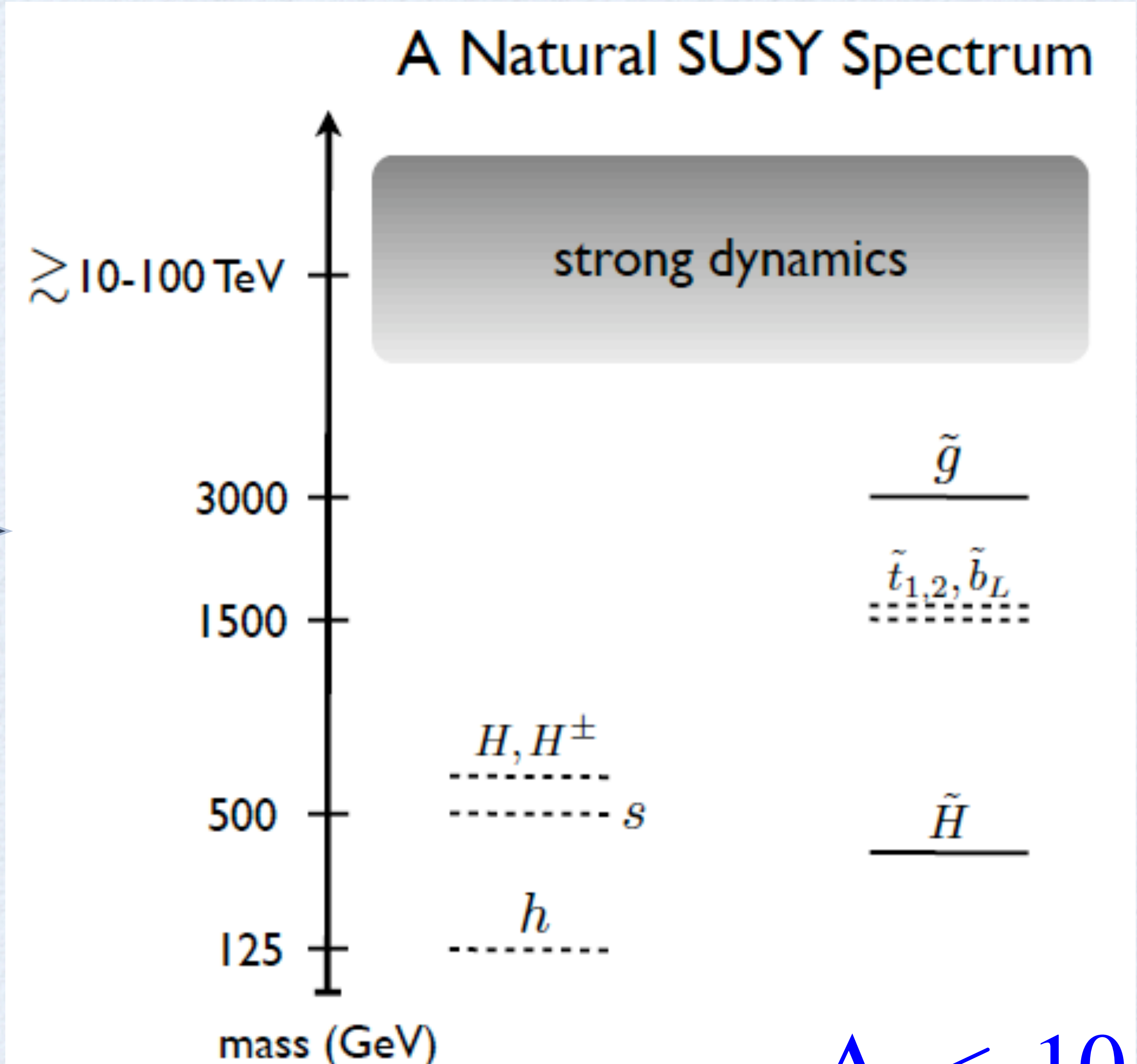


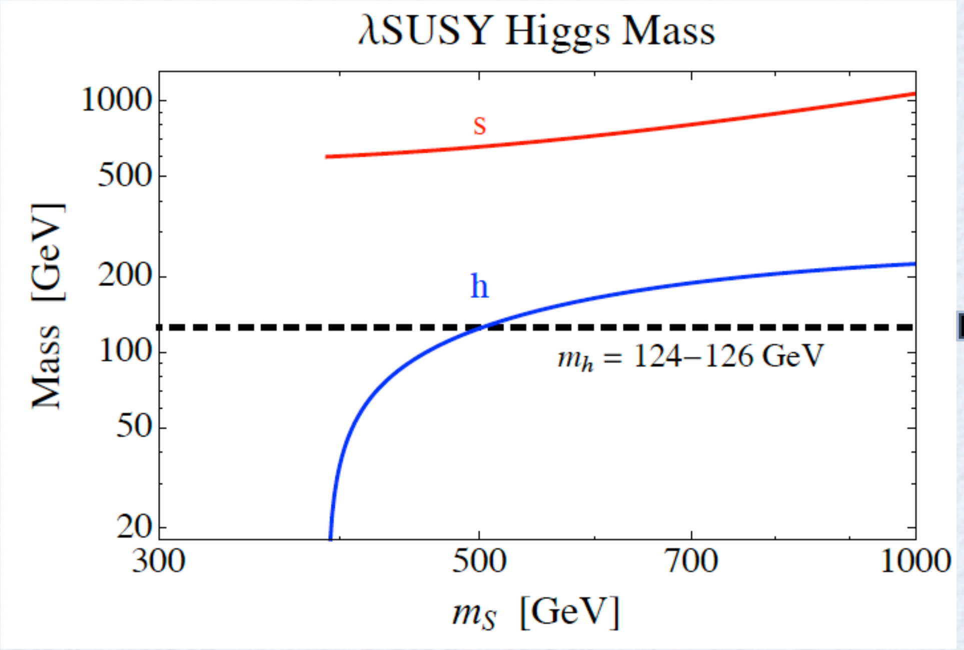


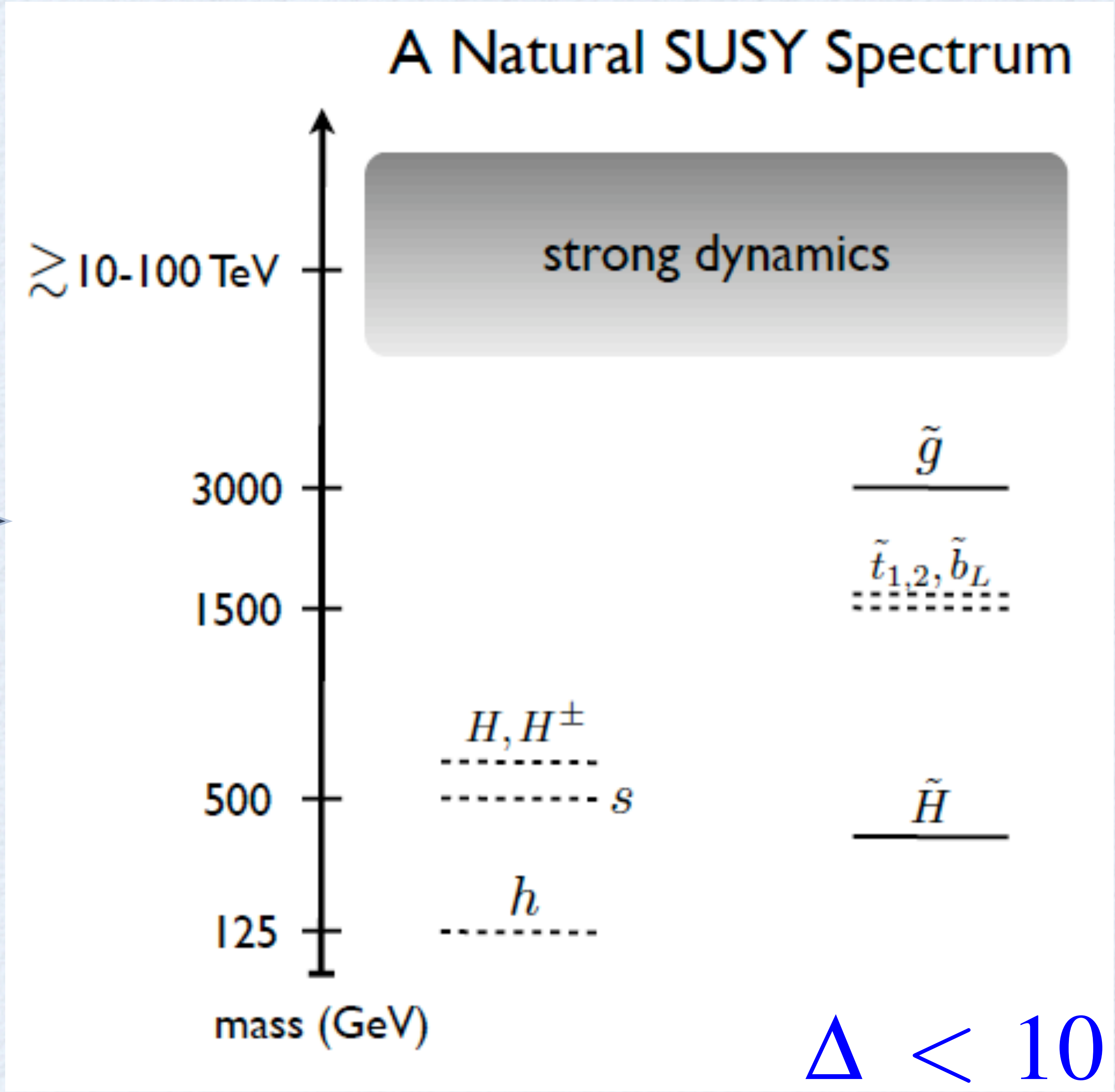
$\Delta < 10$

Adding a Singlet: $\lambda S H_u H_d$

David Pinner, Josh Ruderman, LJH 1112.2703

$1 < \lambda < 2$





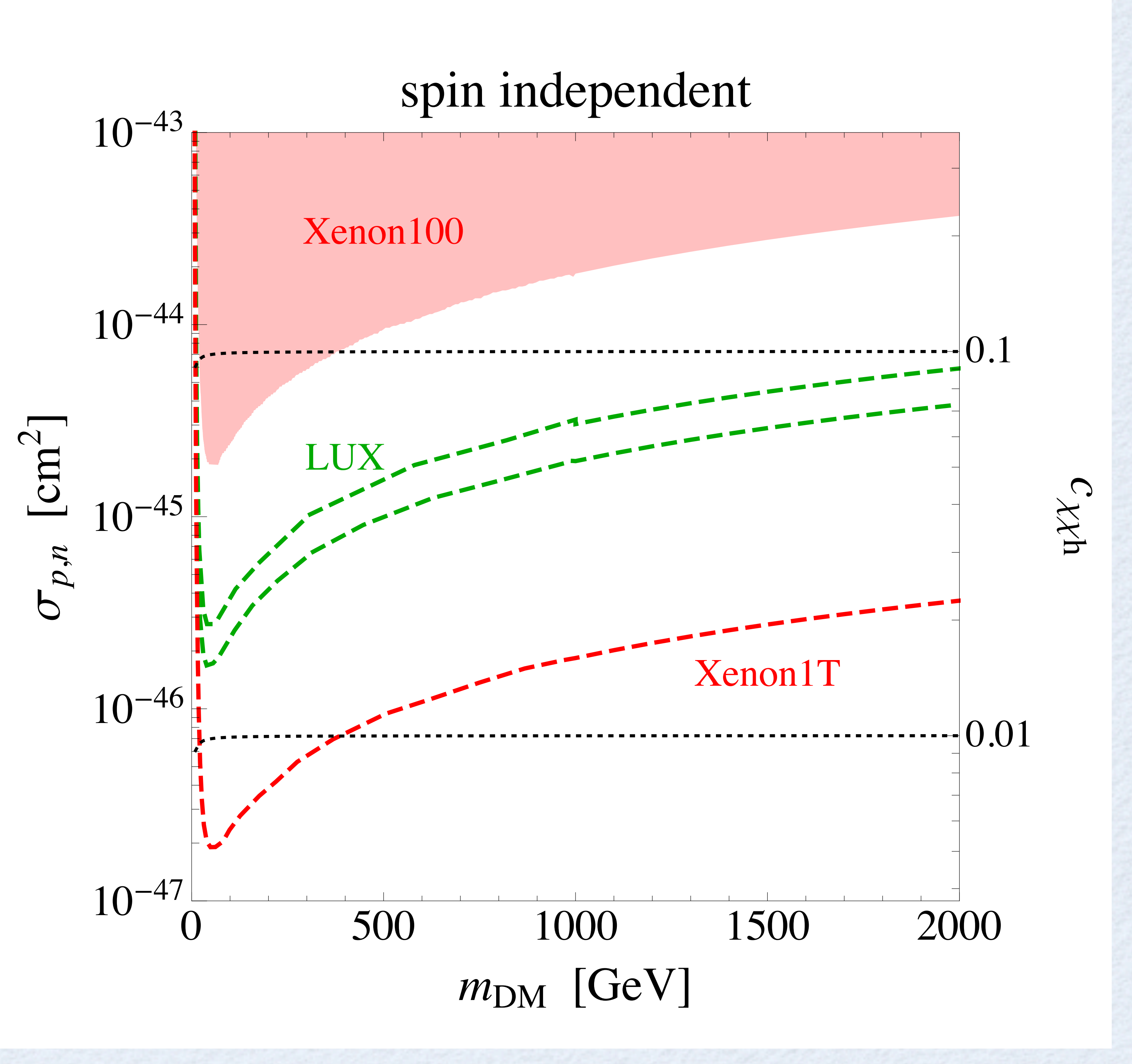
Explains why we haven't seen superpartners yet

(III) TeV Susy

- Dark Matter
- Coupling Unification
- Spread Susy

Direct Detection of Dark Matter

Exciting times ahead:



Cliff Cheung, David Pinner, Josh Ruderman, LJH 1210...

TeV Scale from Cosmological Abundance

- R parity
- $\tilde{m} < T_R$
- LSP is a SM superpartner
- No dilution

$$\tilde{m} \sim \mathrm{TeV}$$

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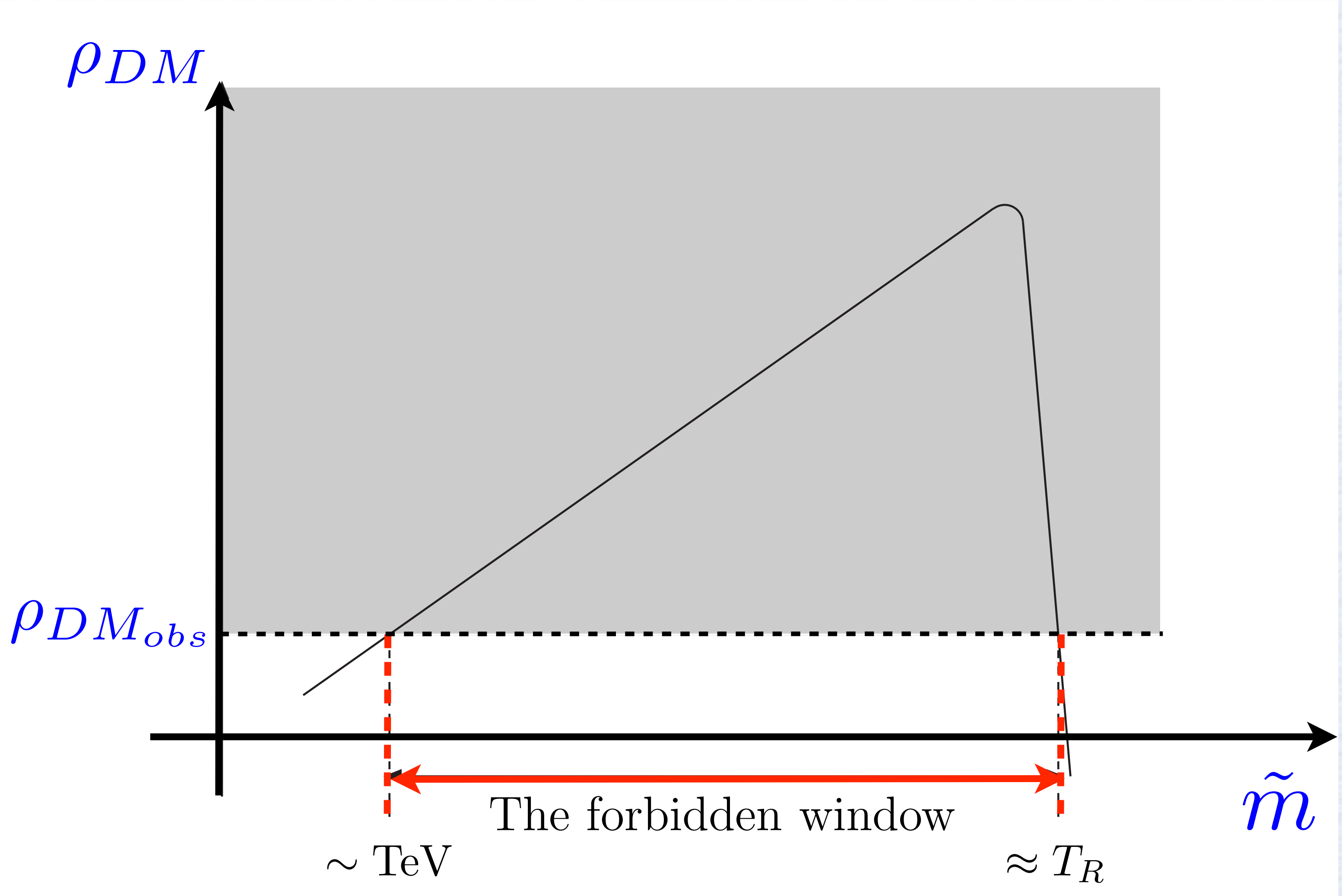
$\Rightarrow$ $\tilde{m} \sim \text{TeV}$

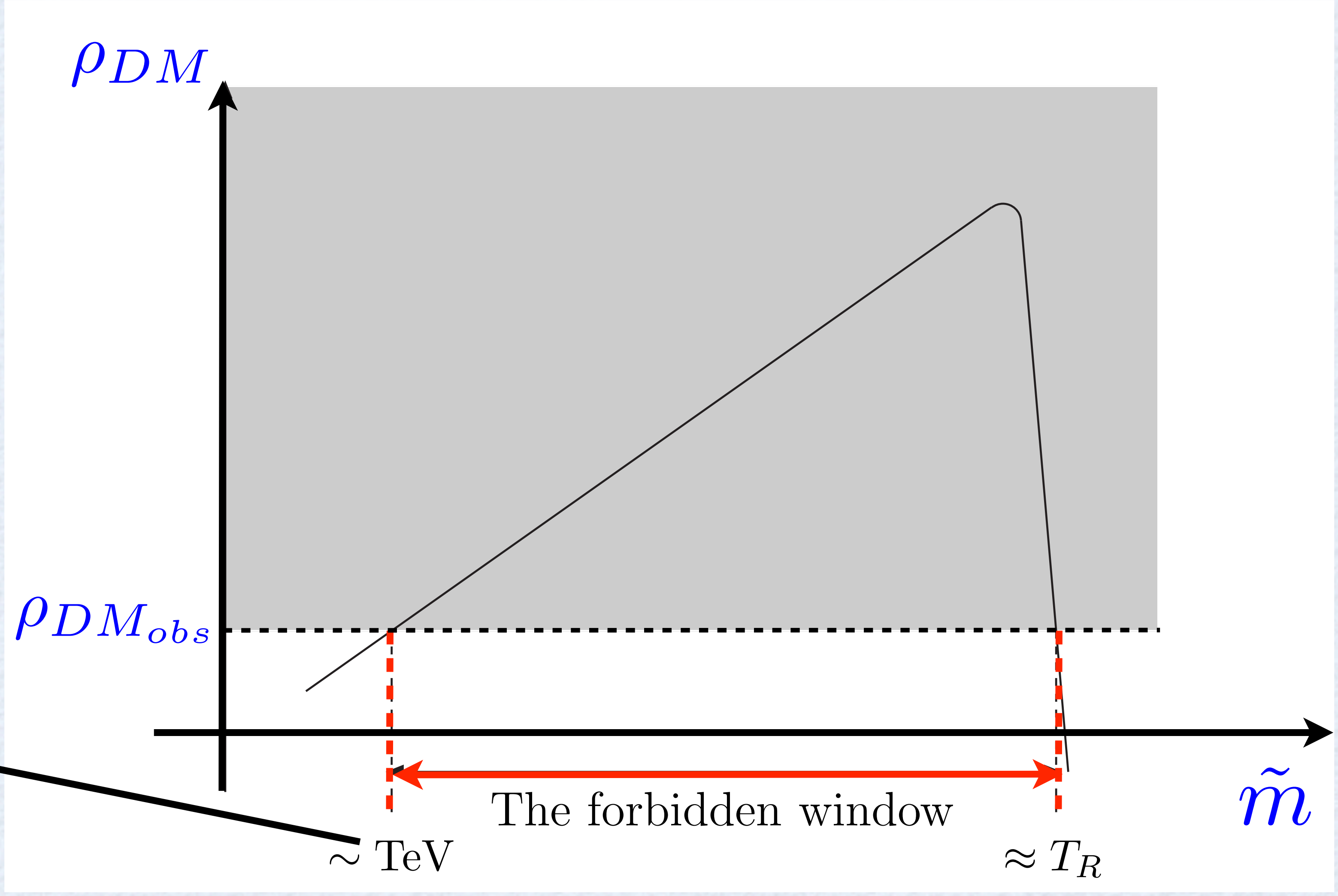


TeV Scale from Cosmological Abundance

- R parity
- $\tilde{m} < T_R$
- LSP is a SM superpartner
- No dilution

$$\tilde{m} \sim \text{TeV}$$

$$\tilde{m} \sim \alpha \sqrt{T_{eq} M_{Pl}}$$



Current Limits on Bino/Higgsino DM

Parameter space

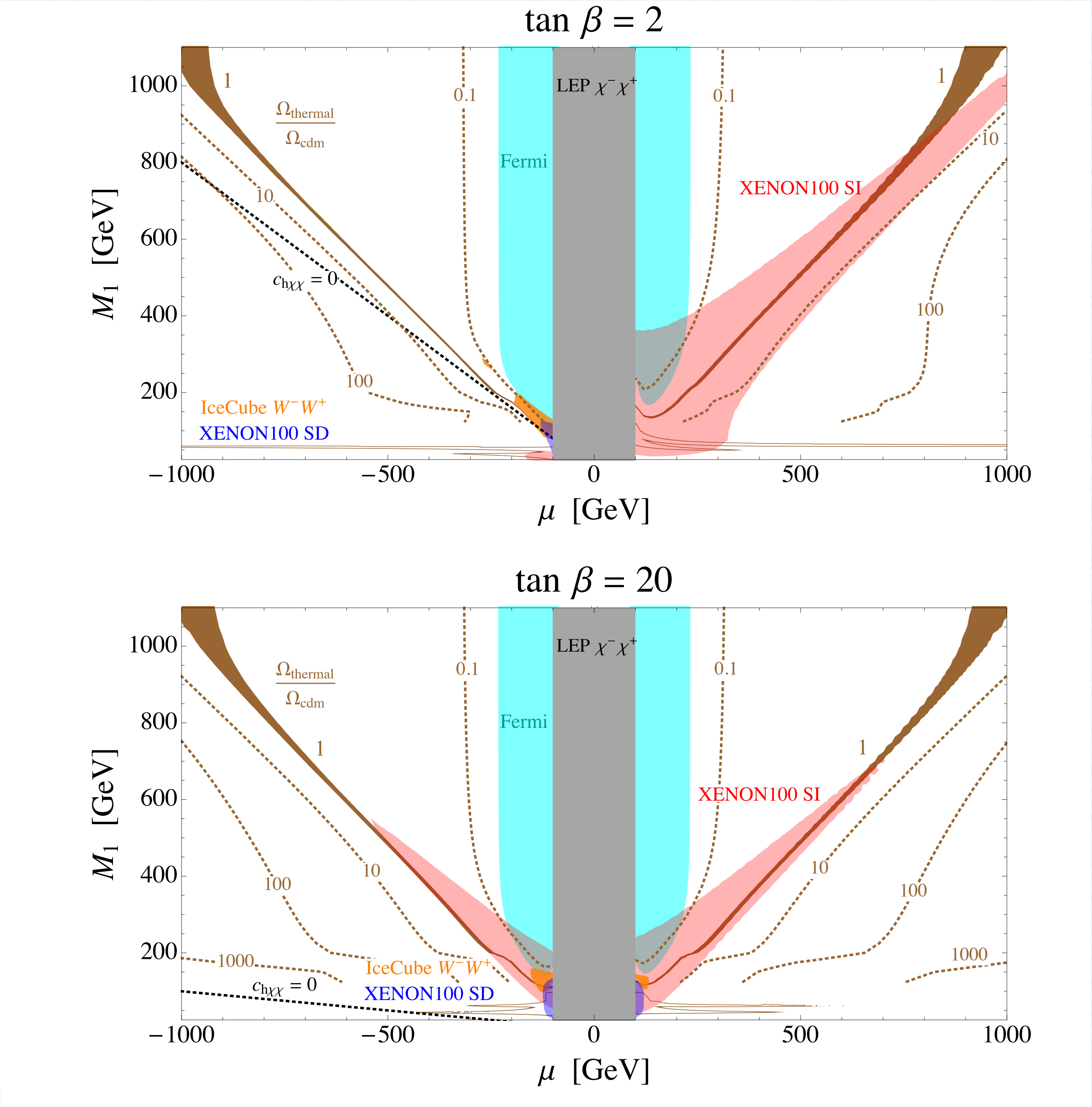
$(M_1, \mu, \tan\beta)$

Assume

$\Omega_{LSP} = \Omega_{obs}$

"Blind Spot"

$c_{h\chi\chi} \quad \propto \quad M_1 + \mu \sin 2\beta$



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Future Probes of Bino/Higgsino DM

Parameter space

$$(M_1, \mu, \tan\beta)$$

Assume

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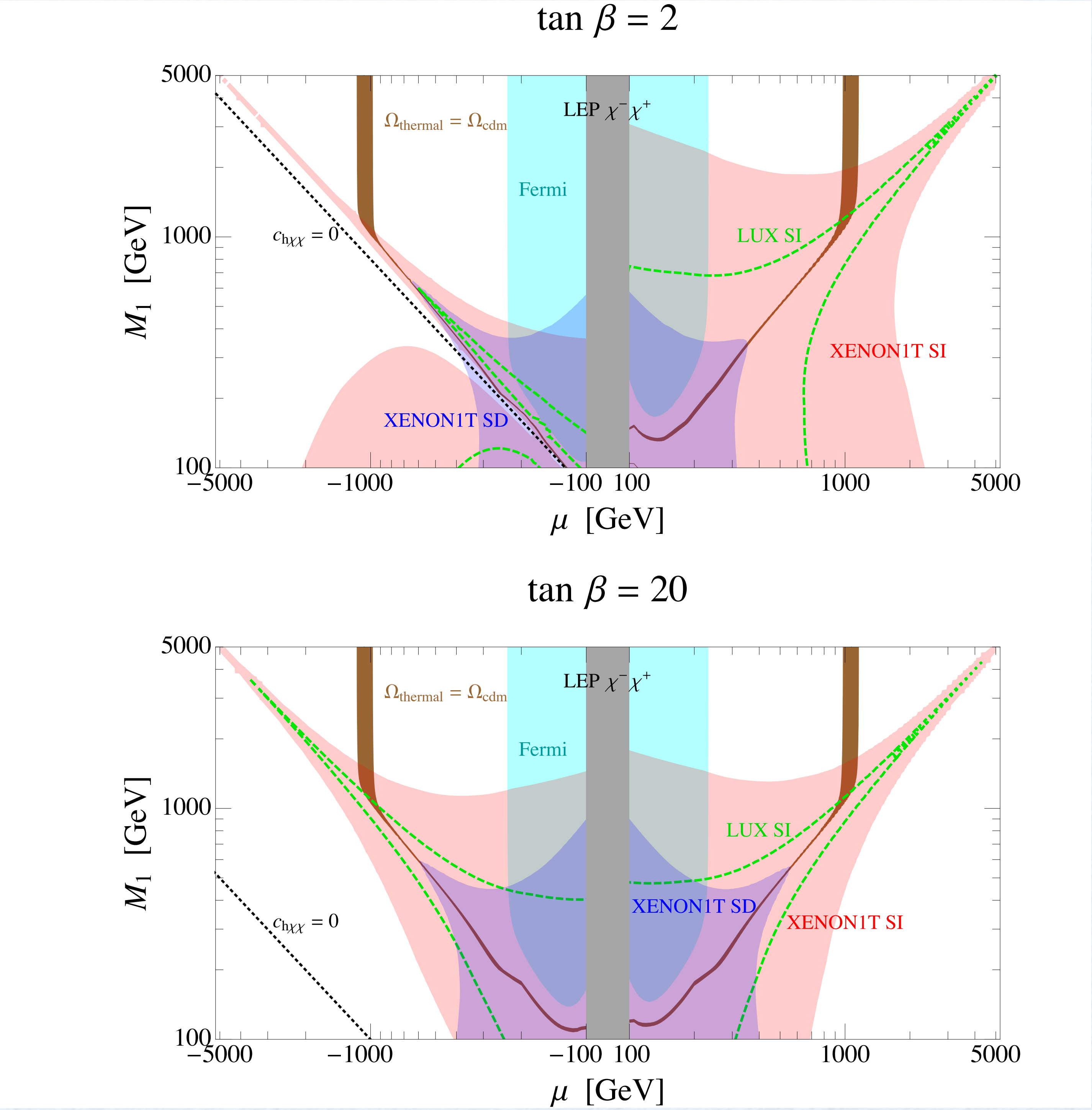

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Bino/Higgsino DM from Freeze-out

Assume

$$\Omega^{FO}_{LSP} = \Omega_{obs}$$

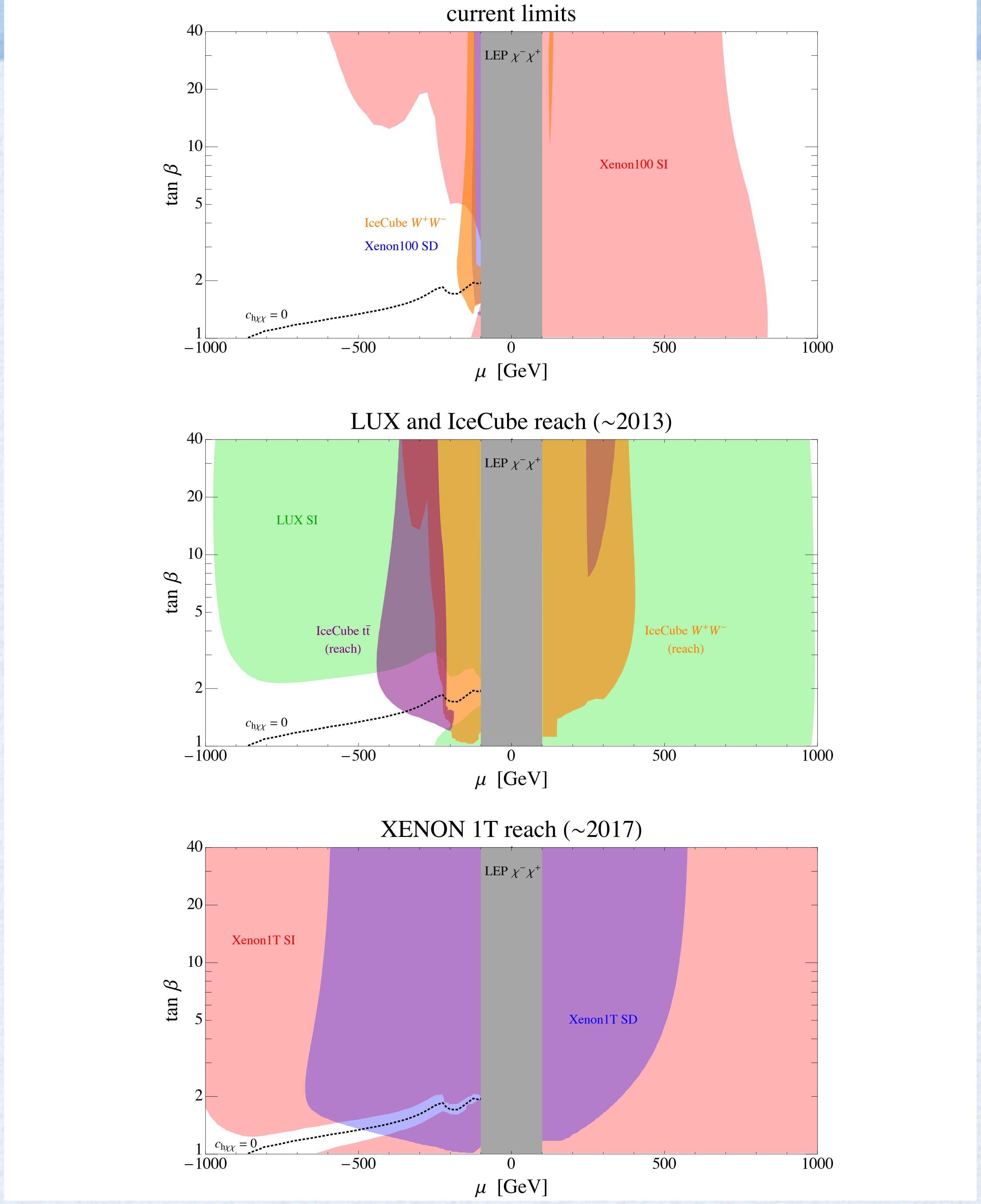
Parameter space

$$(M_1, \mu, \tan\beta) \rightarrow (\mu, \tan\beta)$$

"Blind Spot"

$$c_{h\chi\chi} \quad \propto \quad M_1 + \mu \sin 2\beta$$

Cliff Cheung, David Pinner, Josh Ruderman, LJH
1210...



LSP Dark Matter Summary

- Cosmological abundance of LSP provides independent argument for $\tilde{m} \sim \mathrm{TeV}$

- For freeze-out (bino/Higgsino and bino/wino)

  Current experiments

  have removed about half the space

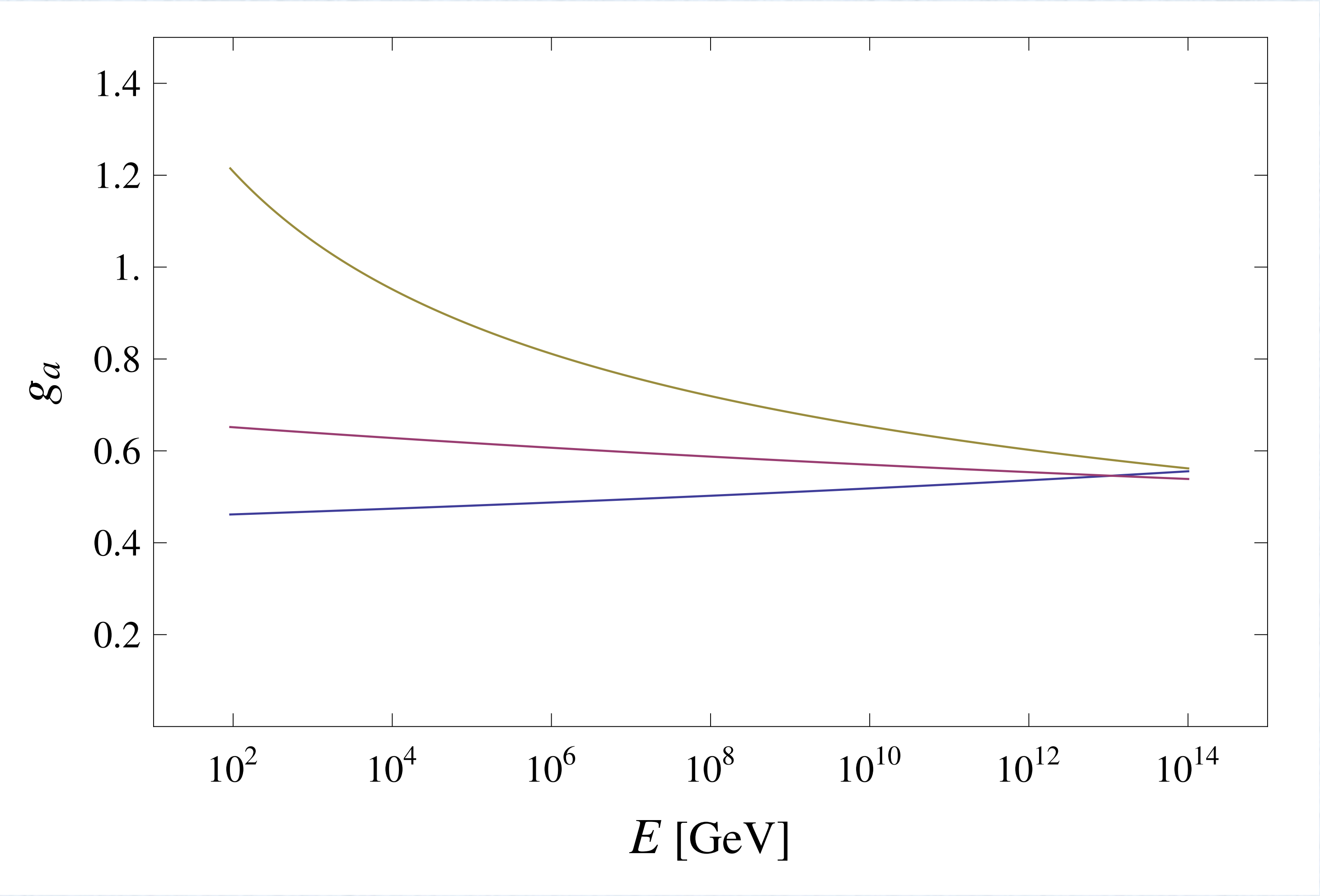
  LUX and Xenon1T

  will explore most of the space

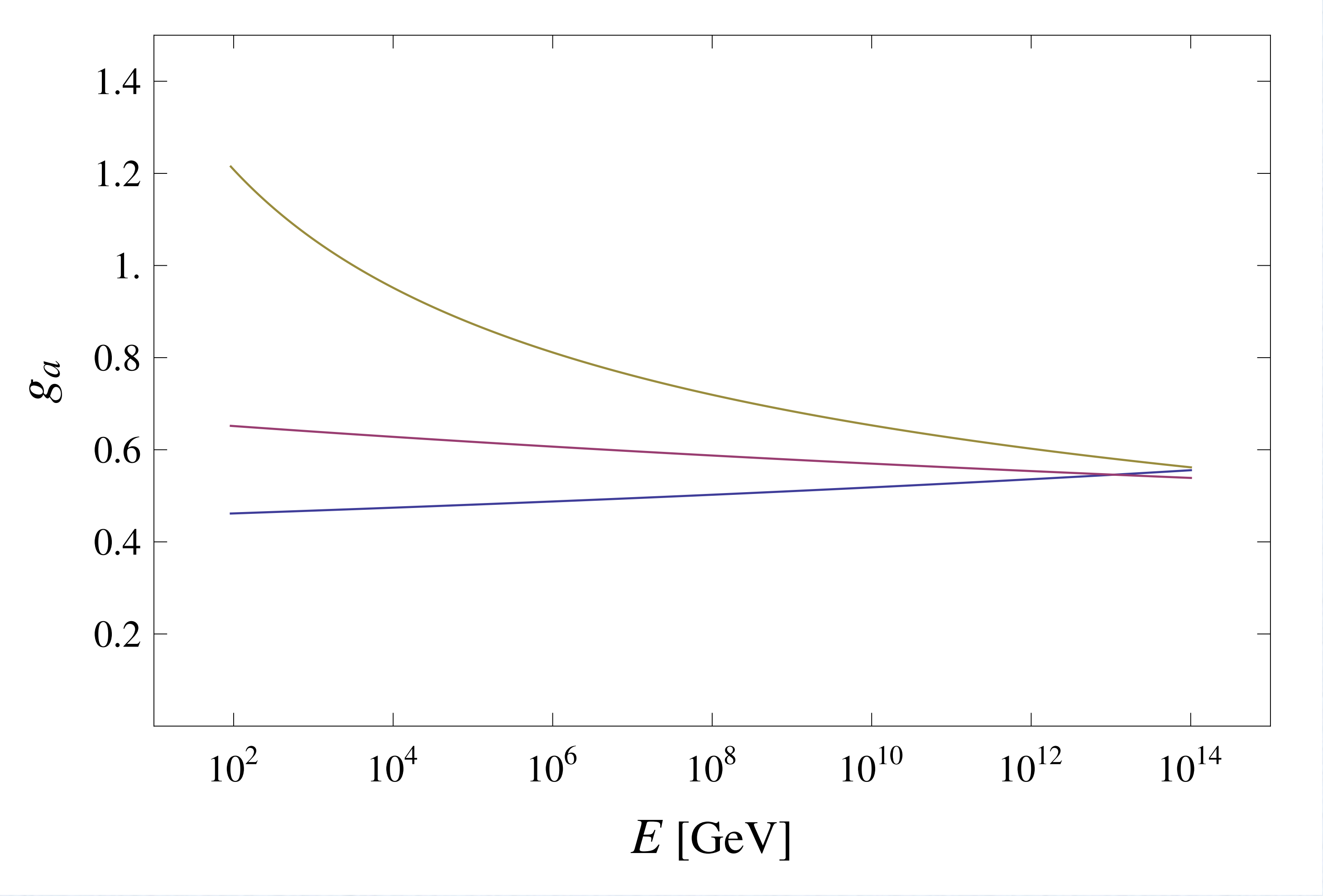
(III) TeV Susy

- Dark Matter
- → Coupling Unification
- Spread Susy

Gauge Coupling Unification



Gauge Coupling Unification



occurs in the Standard Model!

Weak scale susy improves the precision:

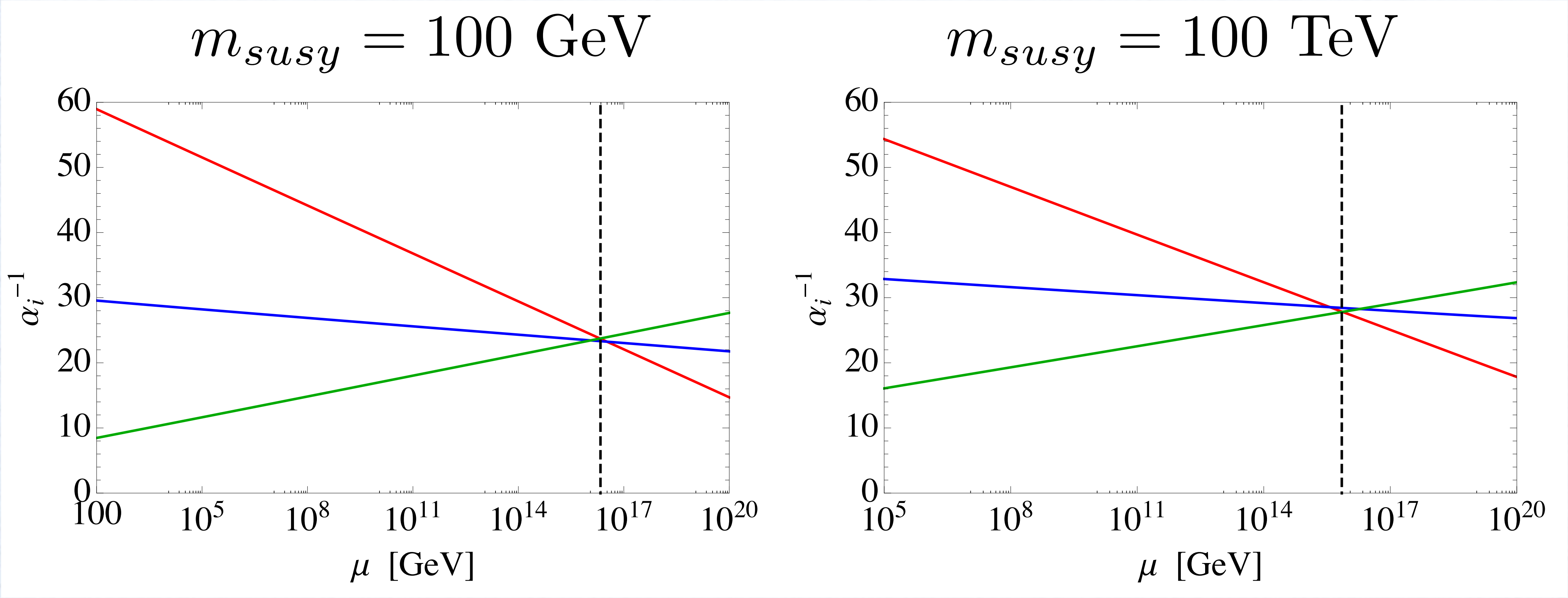
$$\epsilon_g = 0.12 \quad \rightarrow \quad \epsilon_g = 0.014$$

Gauge Coupling Unification

Weak scale susy improves the precision:

$$\epsilon_g = 0.12 \quad \rightarrow \quad \epsilon_g = 0.014$$

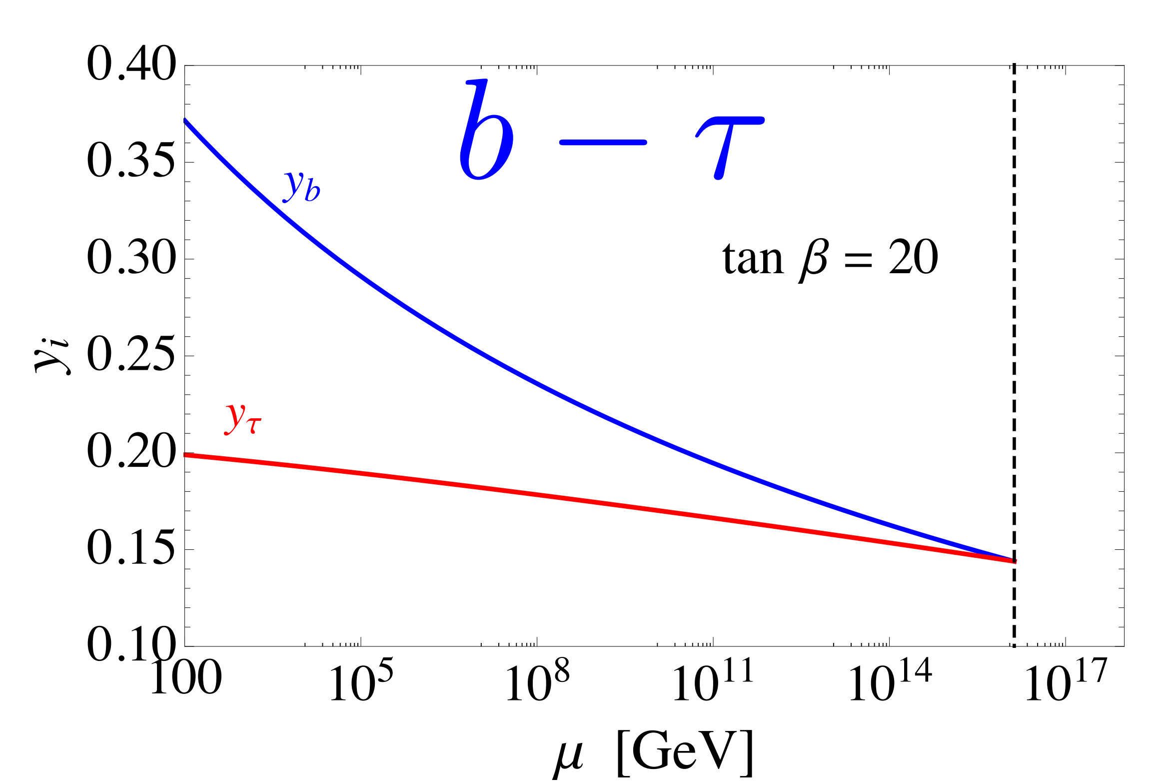
But does not usefully constrain the superparticle masses

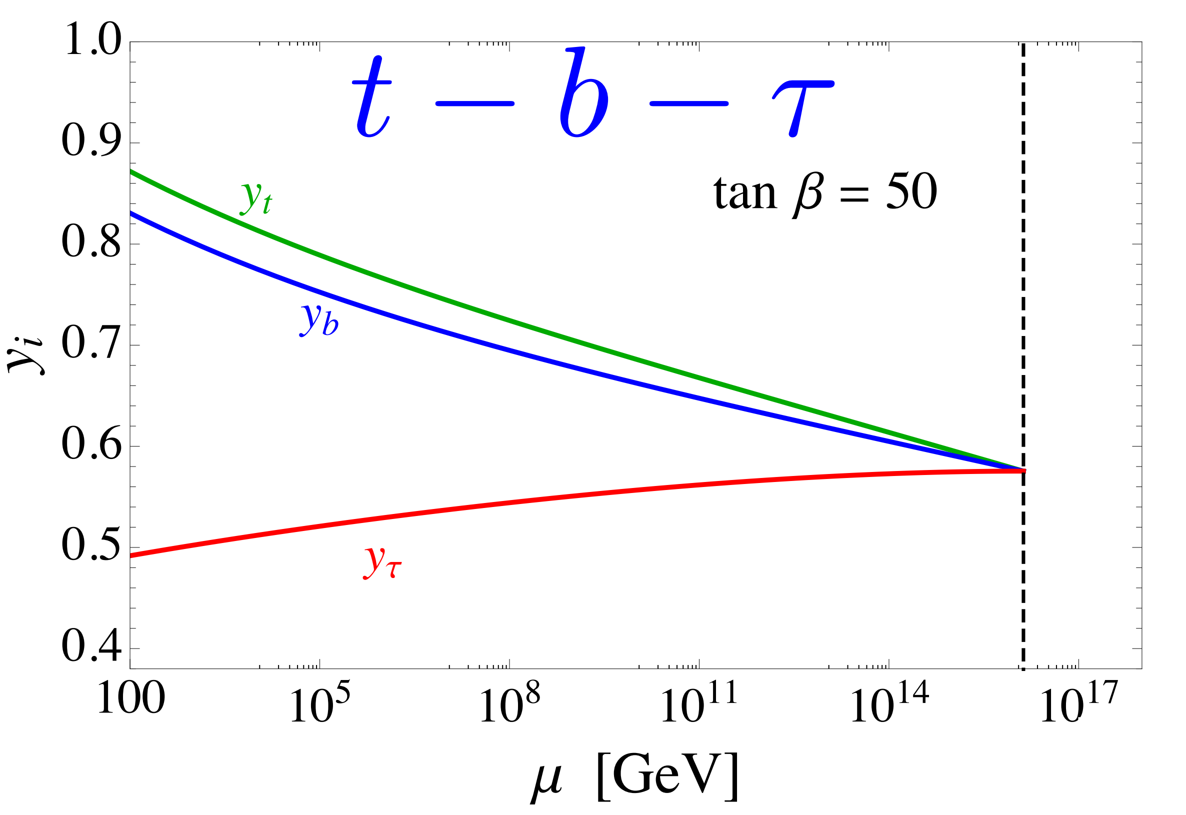


$$\epsilon_g = 0.014 \quad \rightarrow \quad \epsilon_g = 0.017$$

Logarithmic evolution!

Yukawa Coupling Unification

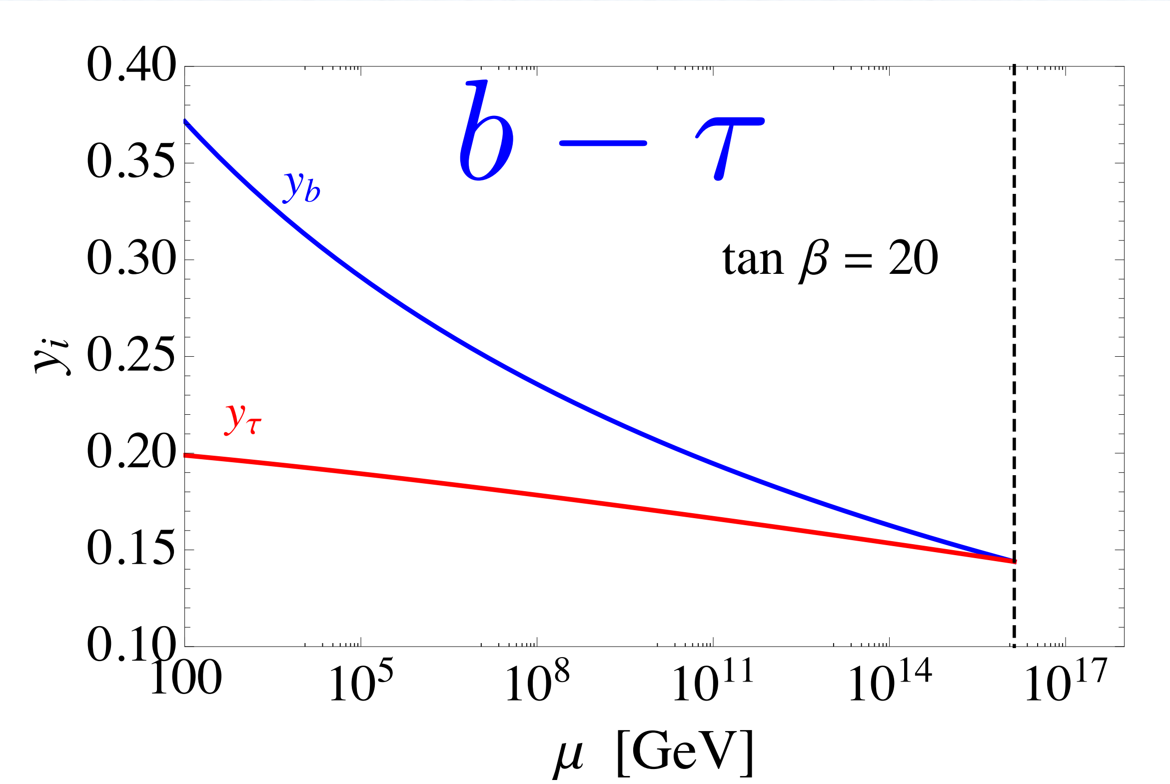


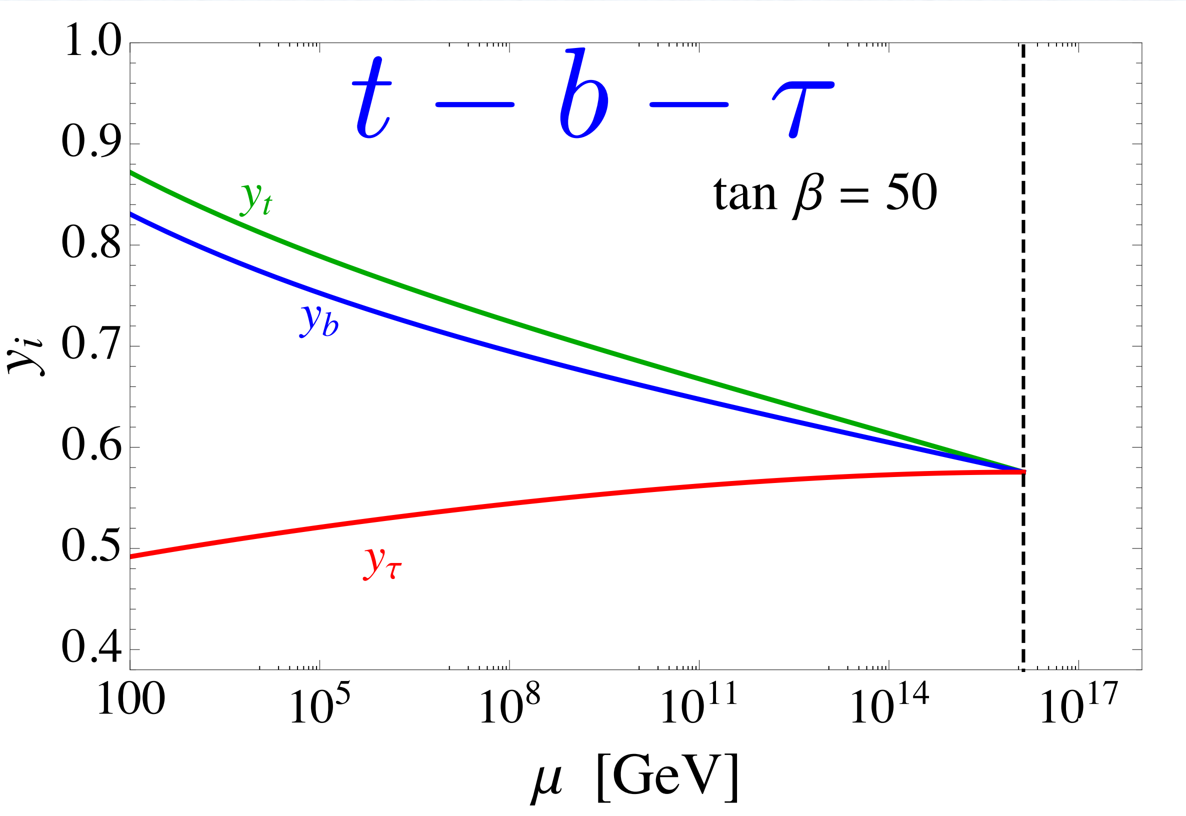


Once again, weak scale susy improves the precision

$$\epsilon_g = 0.60 \quad \rightarrow \quad \delta_b^{fin} = 0.12$$

Yukawa Coupling Unification





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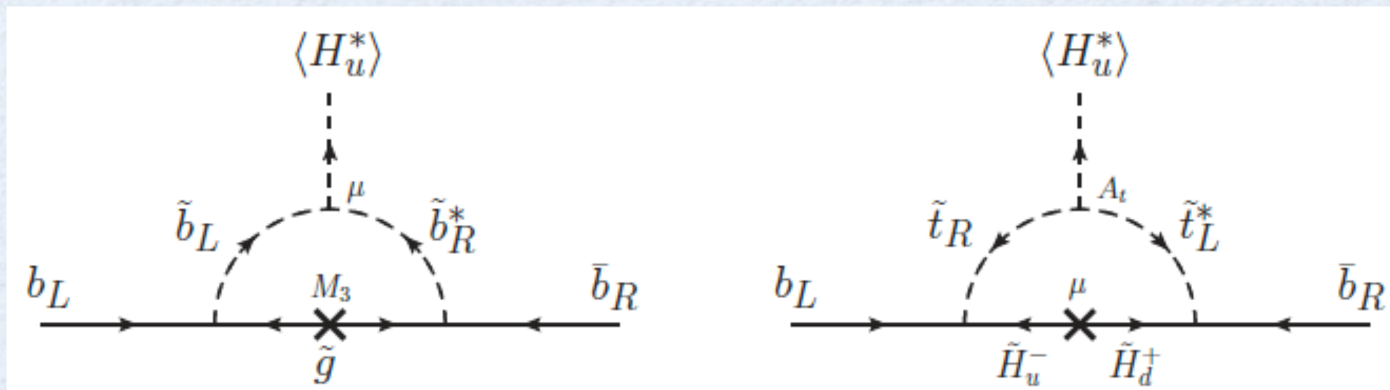
Yukawas span 6 decades: **Is b/τ a hint?**

Constraining $\tilde{m}$

Gilly Elor, David Pinner, Josh Ruderman, LJH 1206.5301

δ_b^{fin}



$$\delta_b^{fin} = -\frac{g_3^2}{12\pi^2}\frac{\mu M_3}{m_{\tilde{b}}^2}\tan\beta - \frac{y_t^2}{32\pi^2}\frac{\mu A_t}{m_{\tilde{t}}^2}\tan\beta$$

$$\delta_b^{fin} \propto \frac{\mu}{m_{\tilde{q}}}\tan\beta$$

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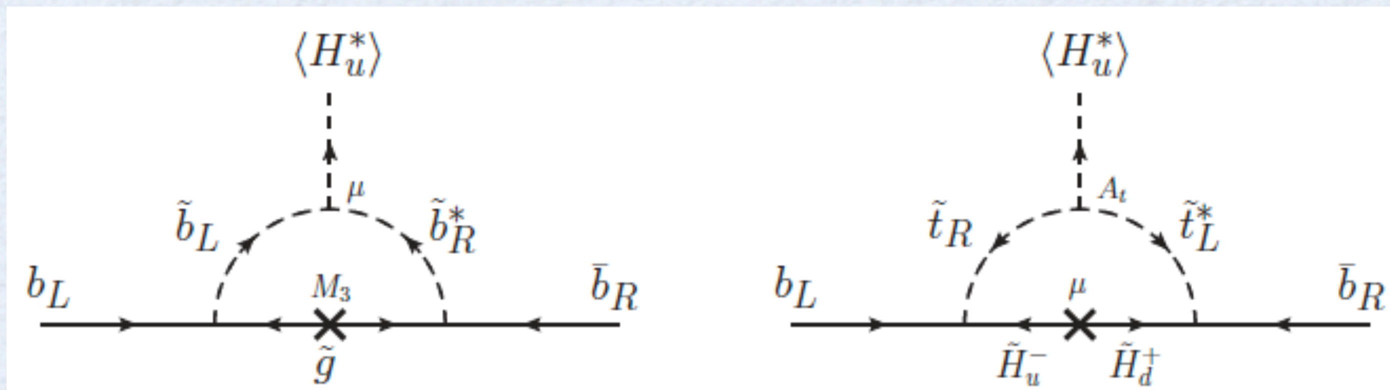

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$$\delta_b^{fin} \propto \frac{\mu}{m_{\tilde{q}}}\tan\beta$$

Need large $\tan\beta$

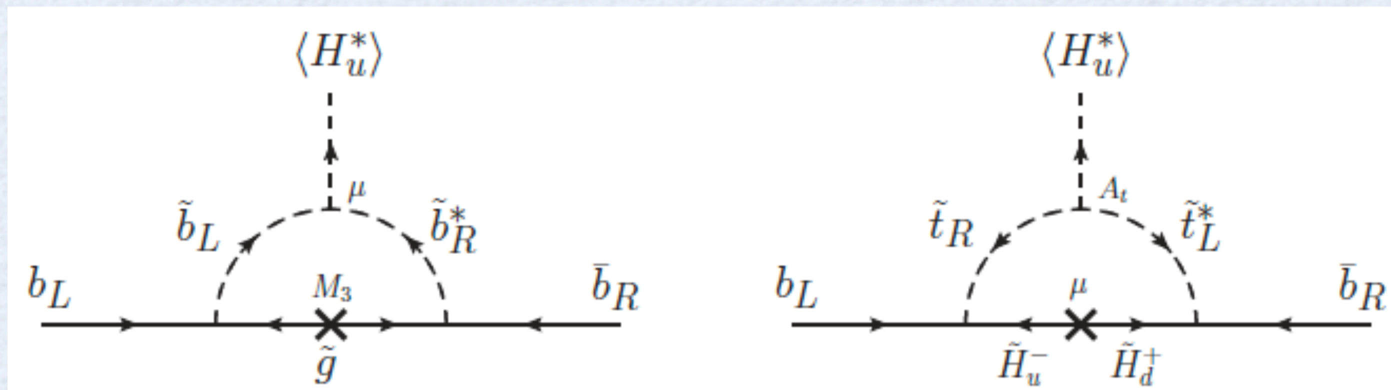
bino/Higgsino LSP dark matter → Cannot decouple squarks

Power law behavior!

Constraining $\tilde{m}$

Gilly Elor, David Pinner, Josh Ruderman, LJH 1206.5301

δ_b^{fin}



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$$\delta_b^{fin} \propto \frac{\mu}{m_{\tilde{q}}} \tan\beta$$

Need large $\tan\beta$

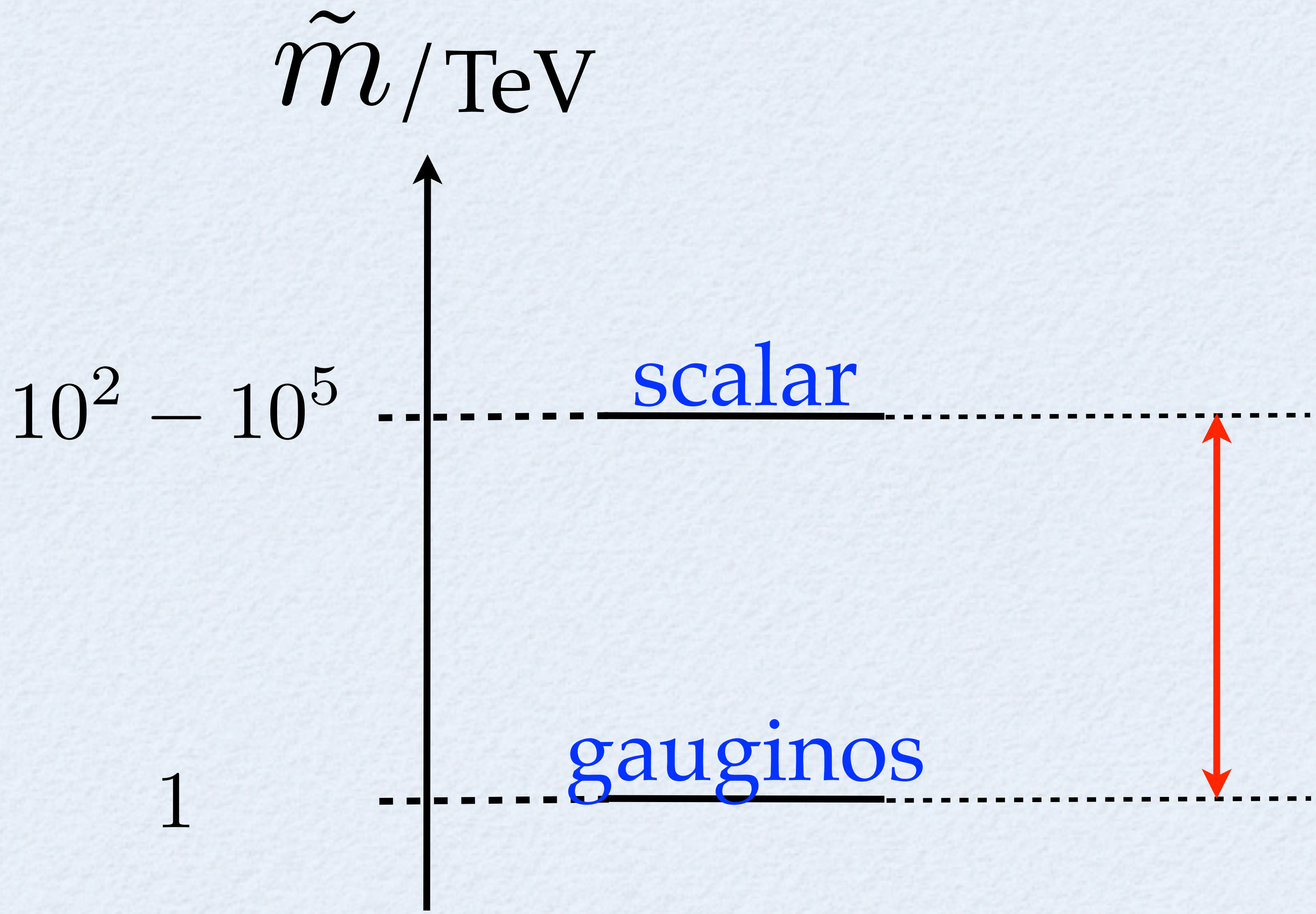
bino/Higgsino LSP dark matter → Cannot decouple squarks → $m_{\tilde{q}} < 10 \text{ TeV} \frac{\tan\beta}{50}$

Power law behavior!

(III) TeV Susy

- Dark Matter
- Coupling Unification
- Spread Susy

A Mildly Split Spectrum



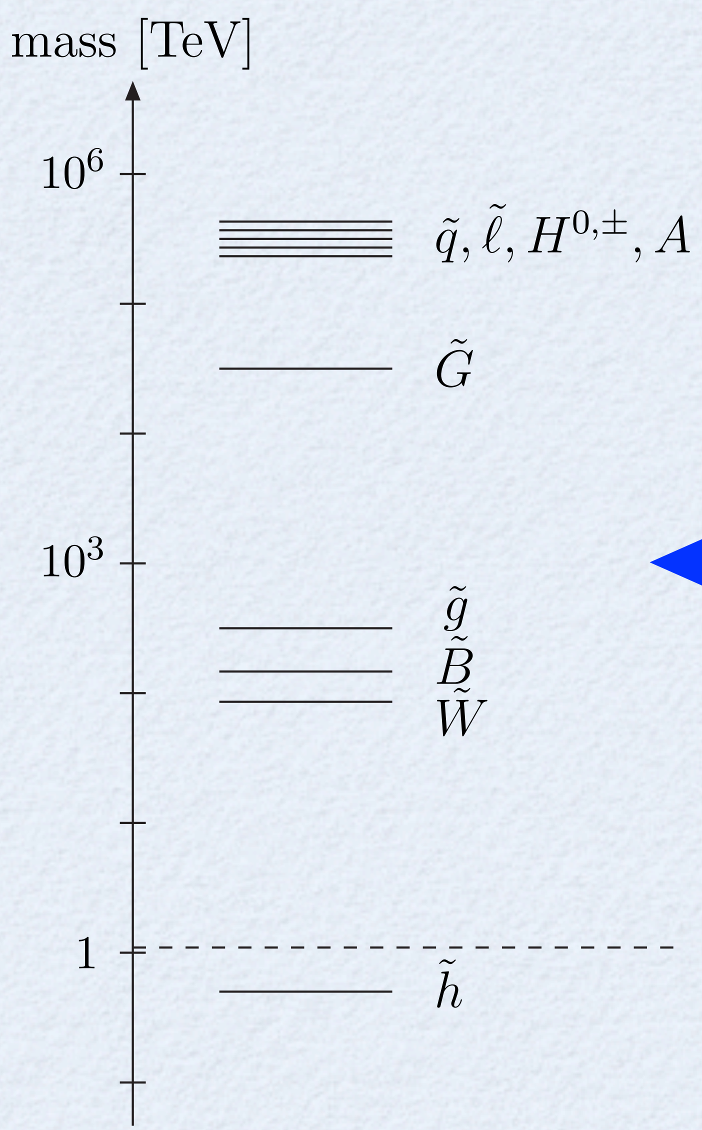
Spread SUSY

1. 1-loop gaugino masses from Anomaly Mediation

2. $\frac{M_{Fund}}{M_{Pl}} \sim 1 - 10^{-2}$

Two Versions

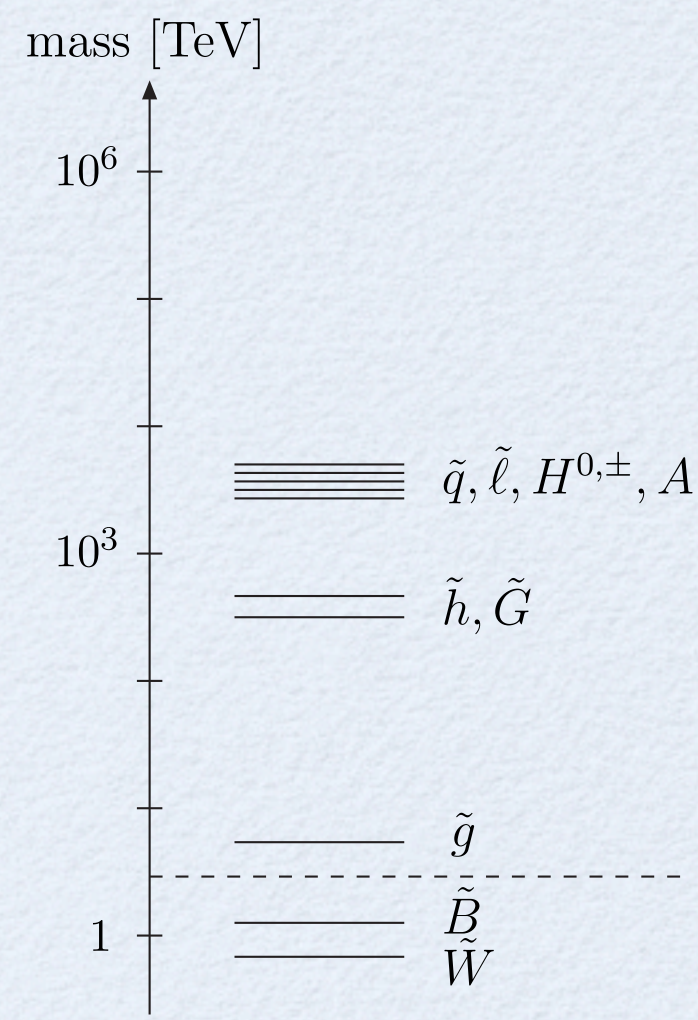
Higgsino LSP



Different origins for μ

Yasunori Nomura, LJH 1111.4519

Wino LSP

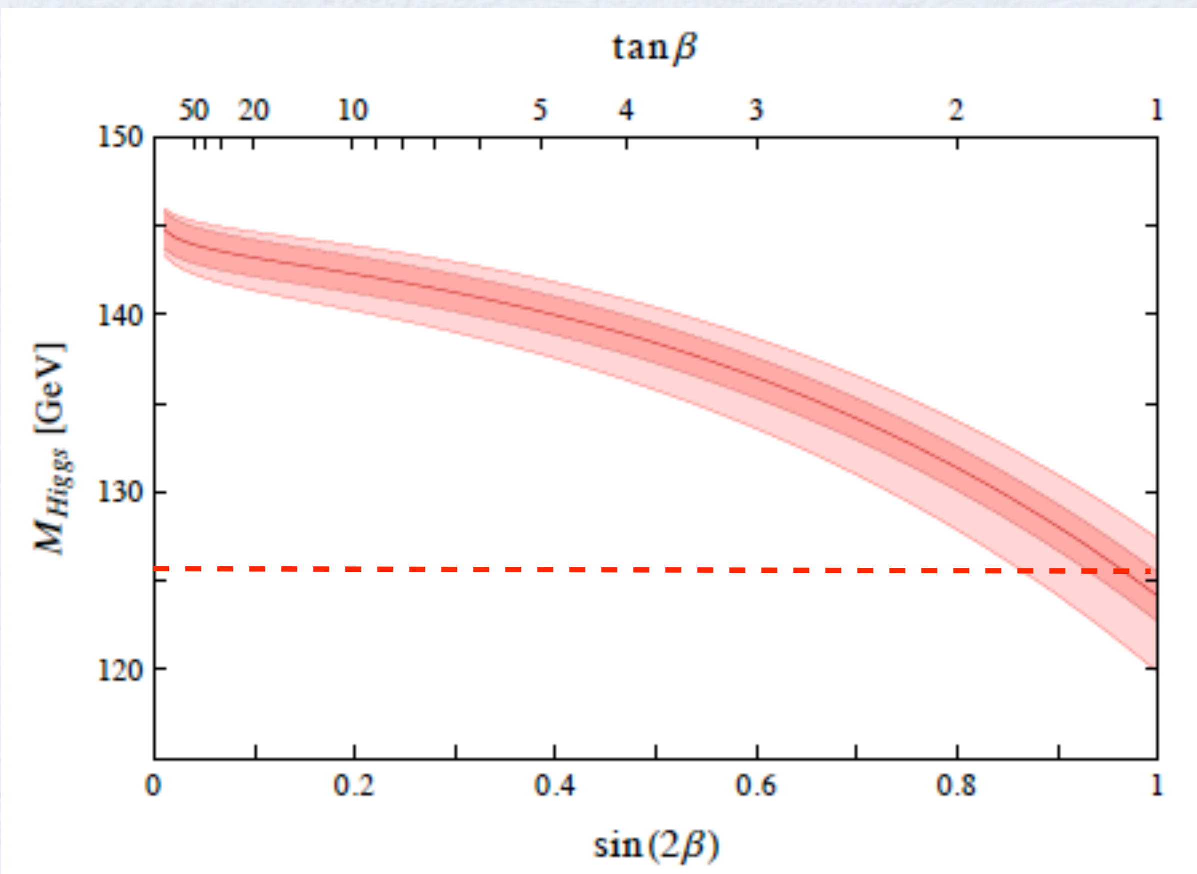


Giudice, Luty, Murayama, Rattazzi
hep-ph/9810442

Wells hep-ph/0411041
Arkani-Hamed, Delgado,
Giudice ph/0601041

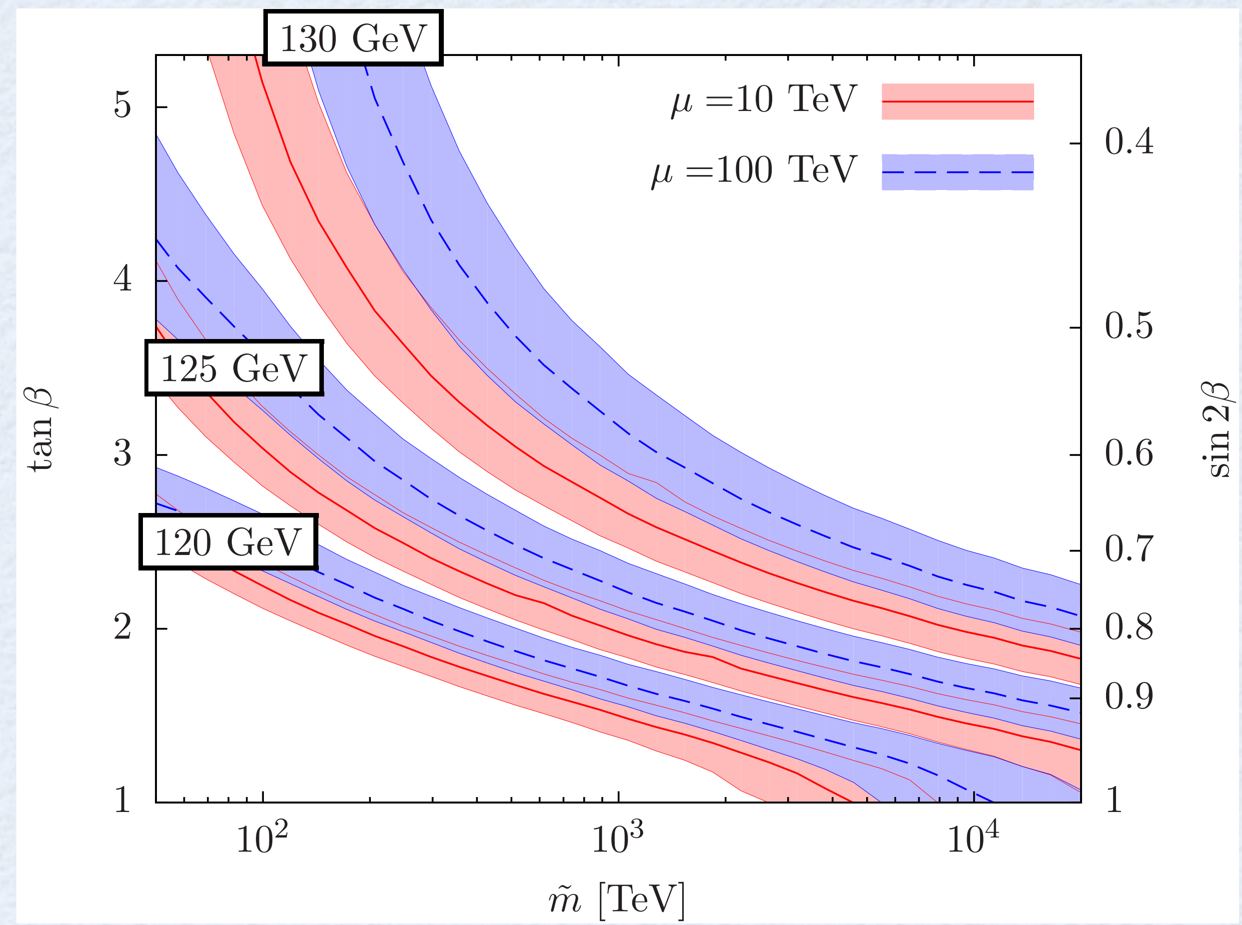
Higgs Mass in Spread SUSY

Higgsino LSP



Yasunori Nomura, LJH 1111.4519

Wino LSP

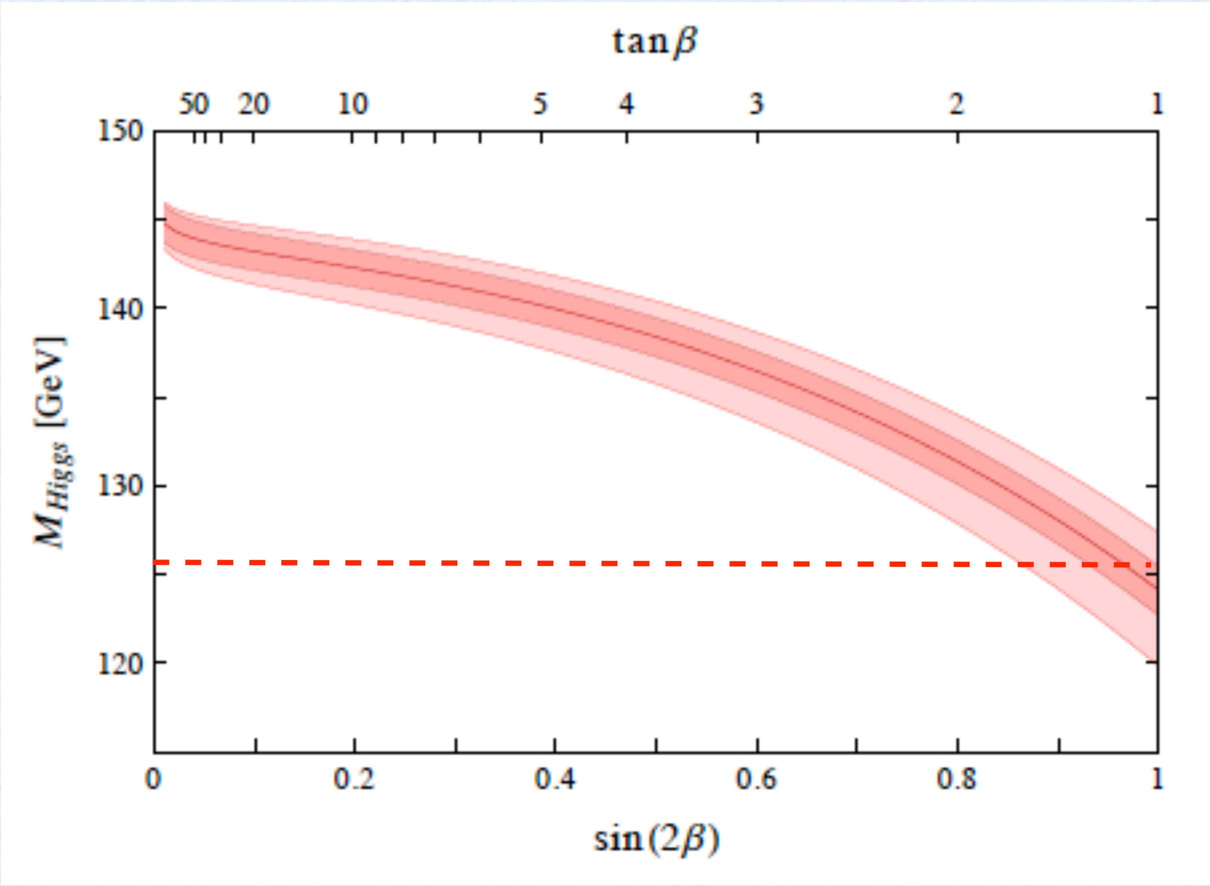


Yasunori Nomura, Satoshi Shirai, LJH 1210.2395

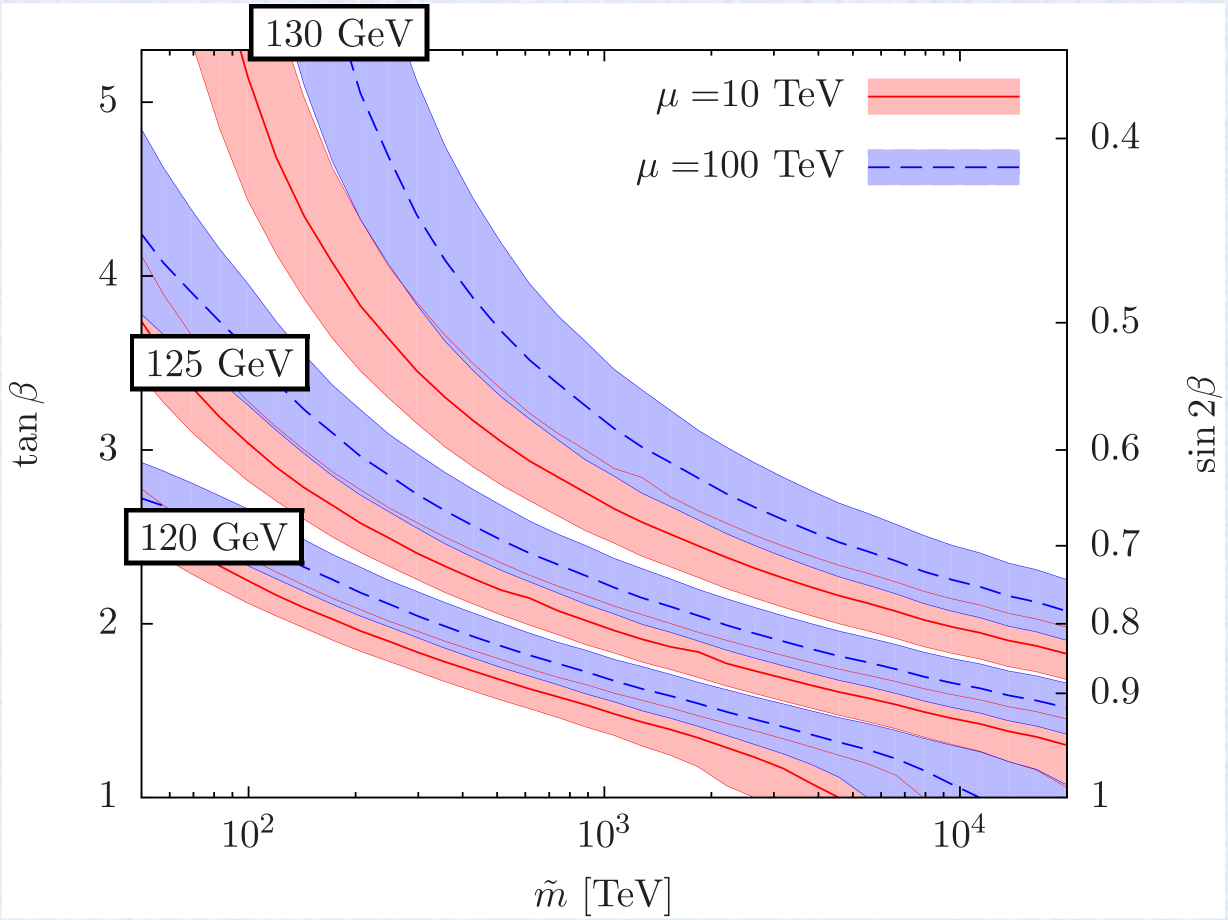
$$\delta m_t = 1\,\mathrm{GeV}$$

Higgs Mass in Spread SUSY

Higgsino LSP



Wino LSP



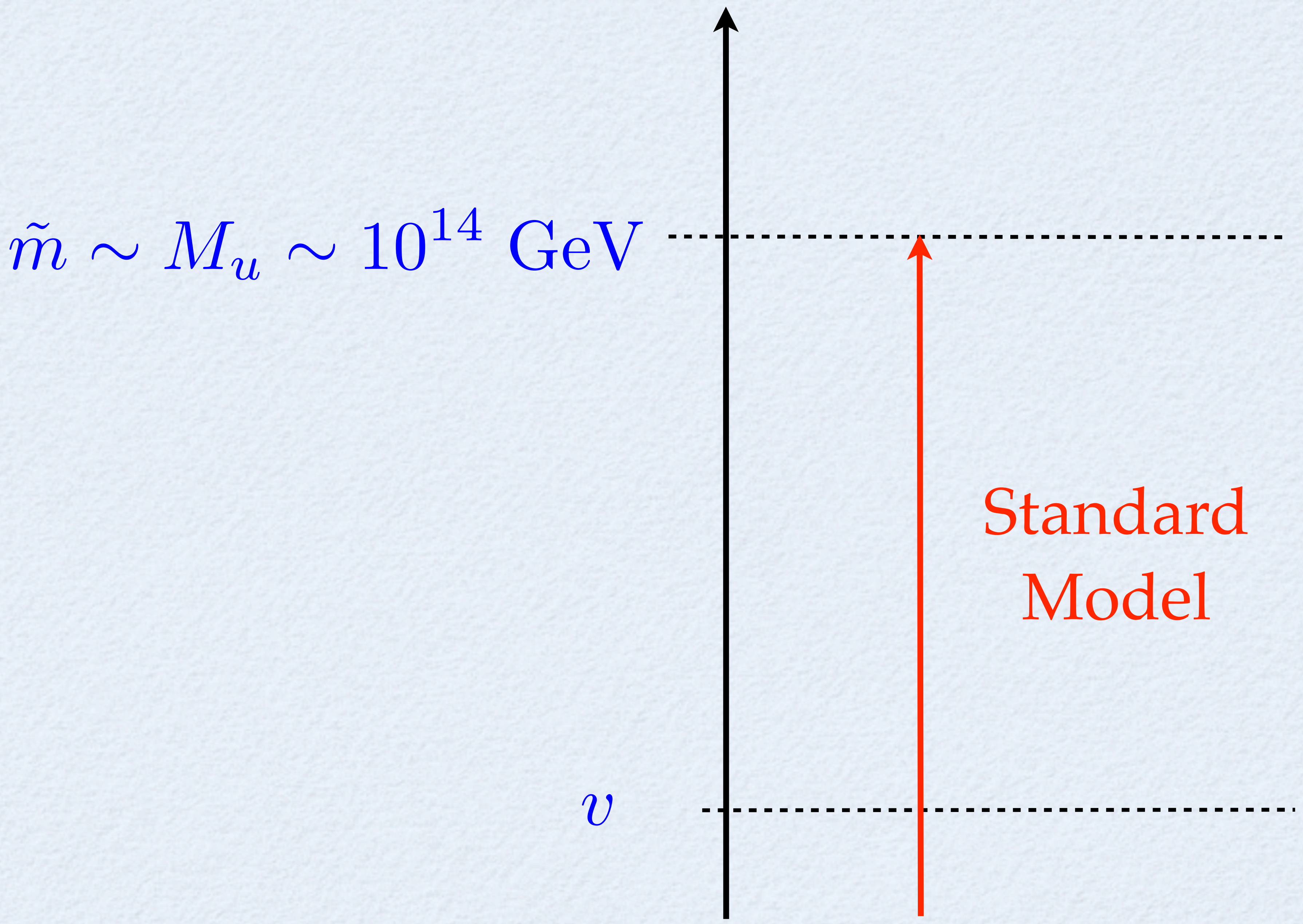
$$\delta m_t = 1\,\mathrm{GeV}$$

Yasunori Nomura, LJH 1111.4519

Yasunori Nomura, Satoshi Shirai, LJH 1210.2395

LHC gluino signal

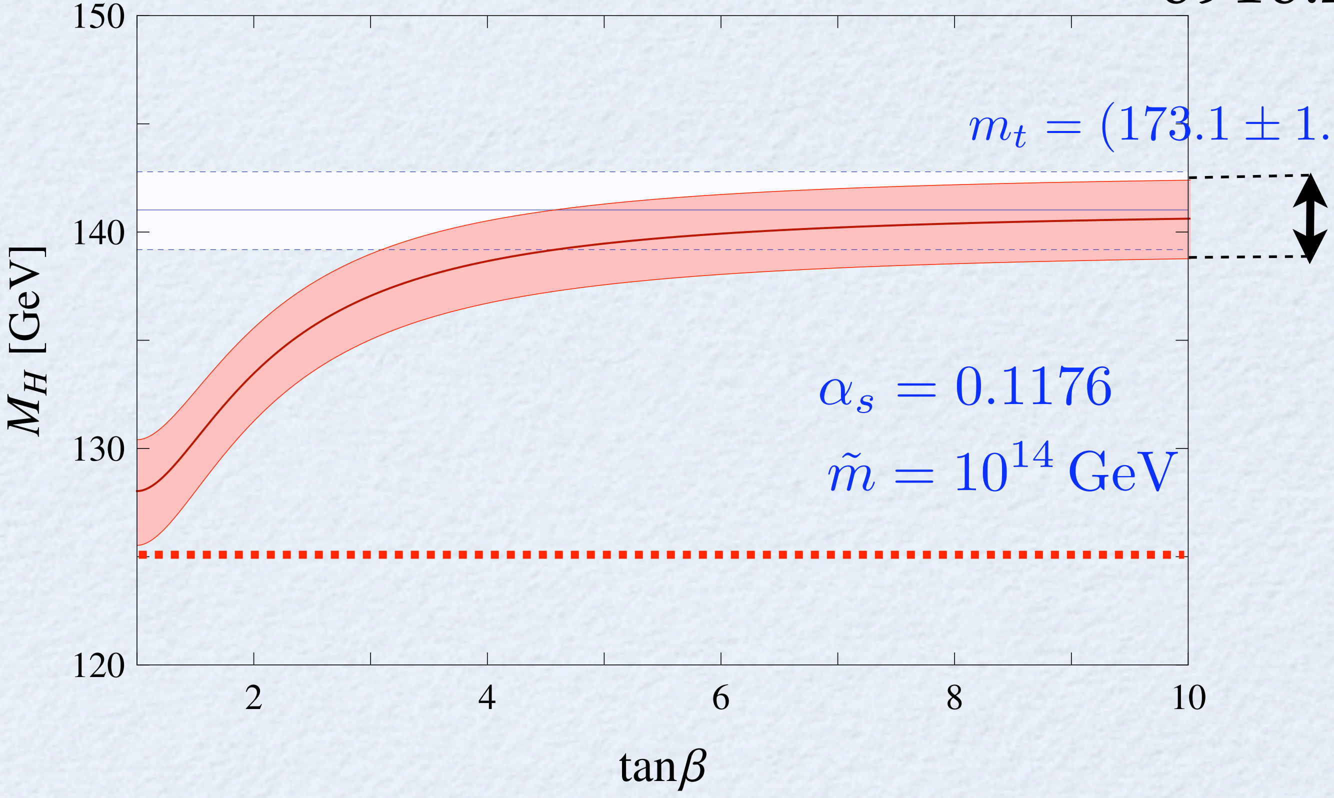
(IV) High Scale Susy



Higgs Mass

$$\lambda(\tilde{m}) = \frac{g^2(\tilde{m}) + g'^2(\tilde{m})}{8} \cos^2 2\beta$$

Hall, Nomura
0910.2235



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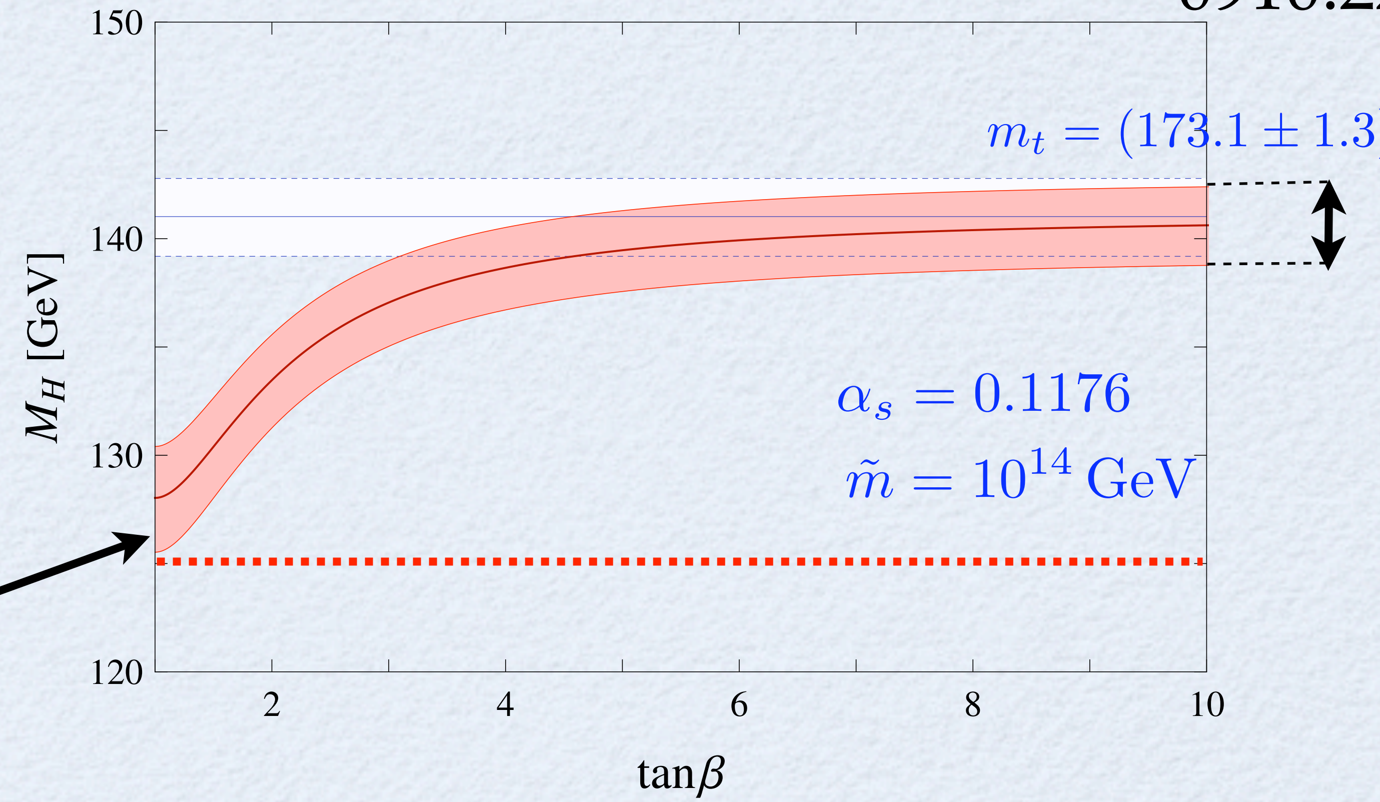
Hall, Nomura
0910.2235



Uncertainties from

NNLO (1205.6497)

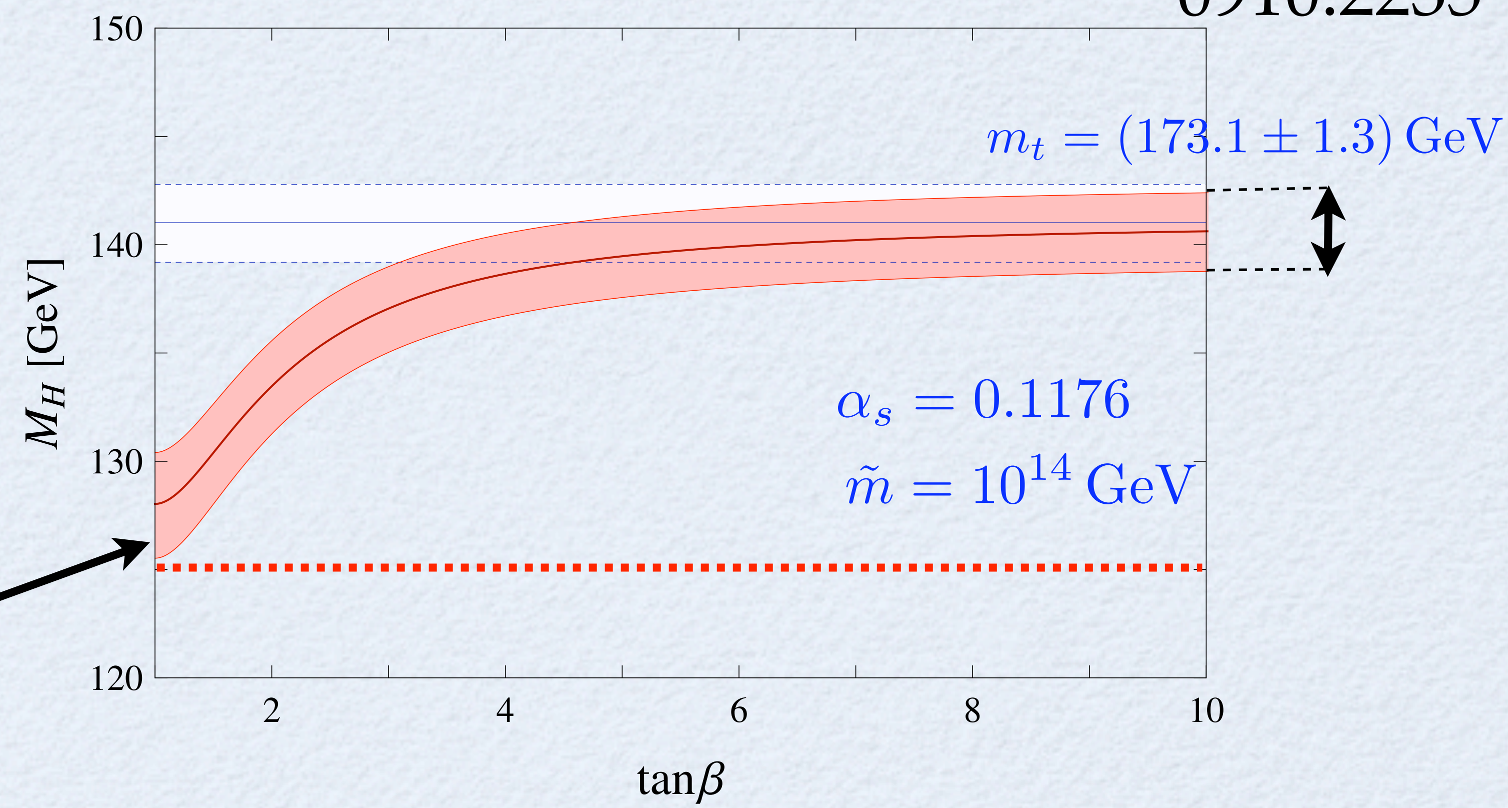
α_s, m_t from experiment (1207.0980)

unified thresholds (not stops)

Higgs Mass

$$\lambda(\tilde{m}) = \frac{g^2(\tilde{m}) + g'^2(\tilde{m})}{8} \cos^2 2\beta$$

Hall, Nomura
0910.2235



Uncertainties from

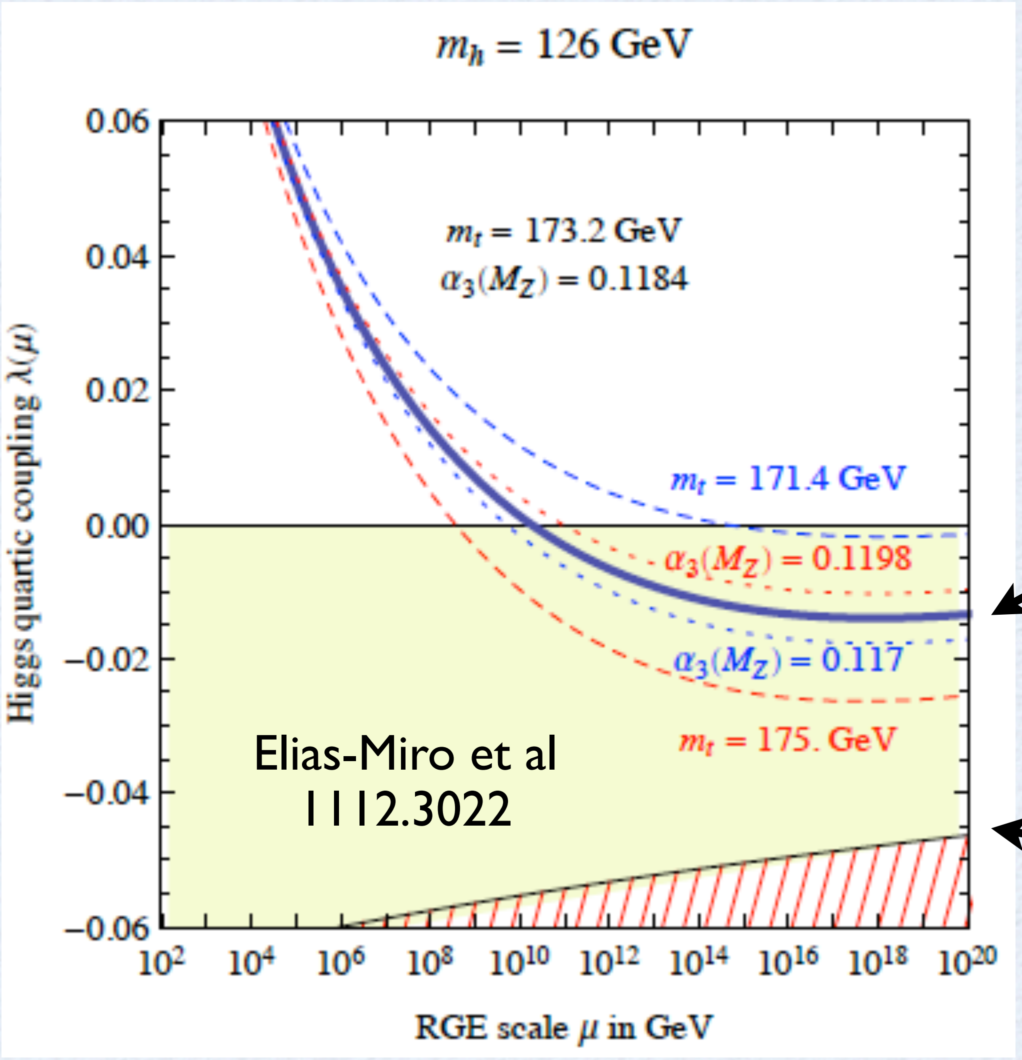
NNLO (1205.6497)

α_s, m_t from experiment (1207.0980)

unified thresholds (not stops)

An Alarming Possibility!!

SM Quartic Trajectory



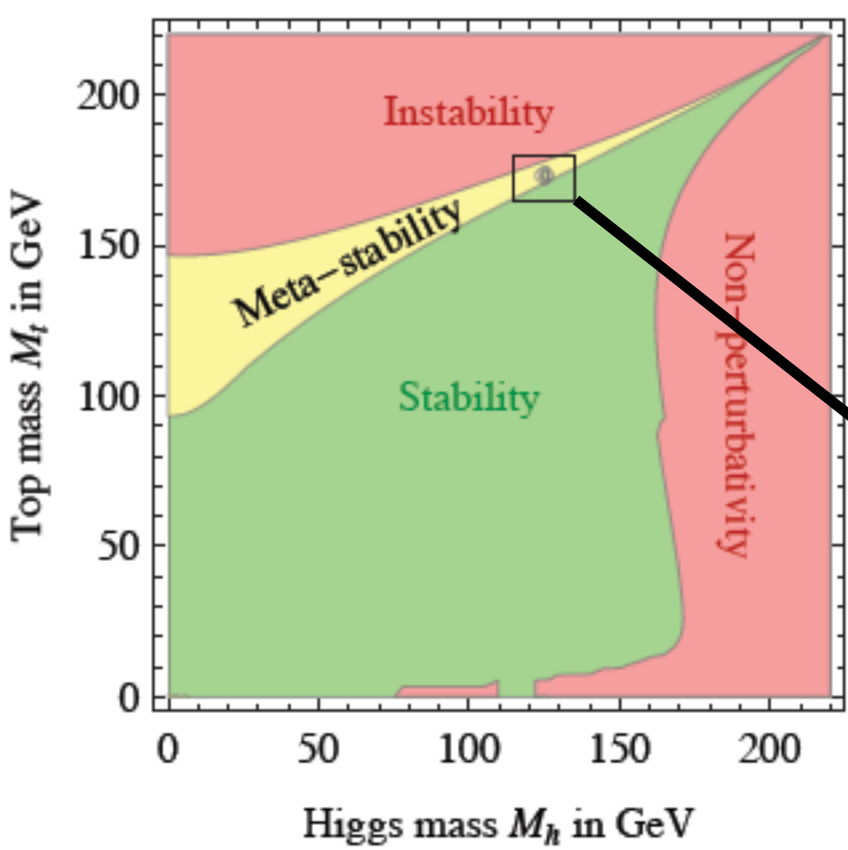
Close to zero

Close to catastrophic vacuum tunneling

Hall, Salem, Watari hep-ph/0608121

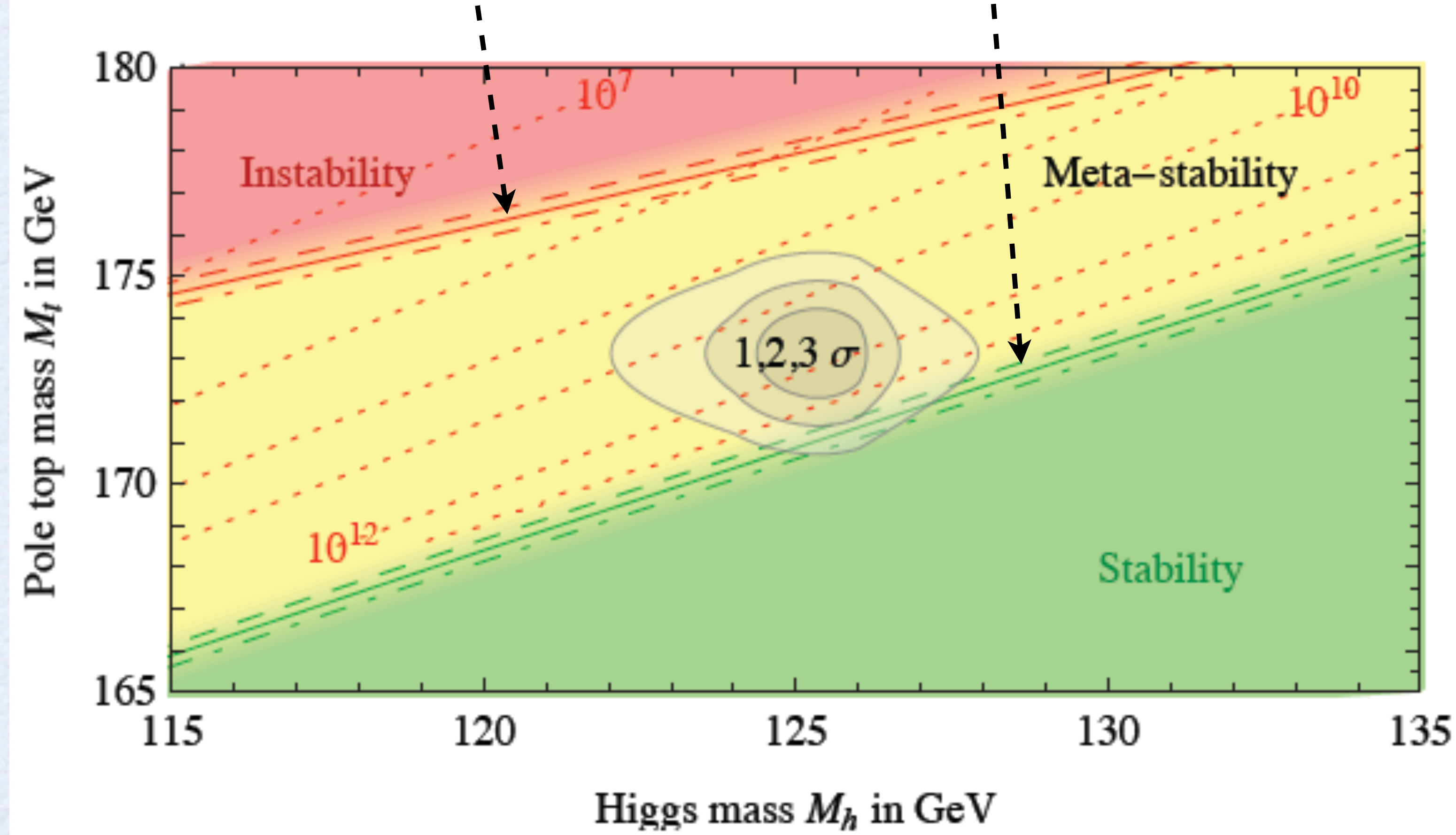
Standard Model Phase Diagram

Degrassi et al 1205.6497



Catastrophic vacuum tunneling boundary

$\lambda(M_{Pl}) = 0$



Status of SUSY in 2012

MSSM

- Fine tuning is worse than 1 in a 100

Natural Susy

- R parity violation
- Adding S helps
- ...

TeV-scale Susy

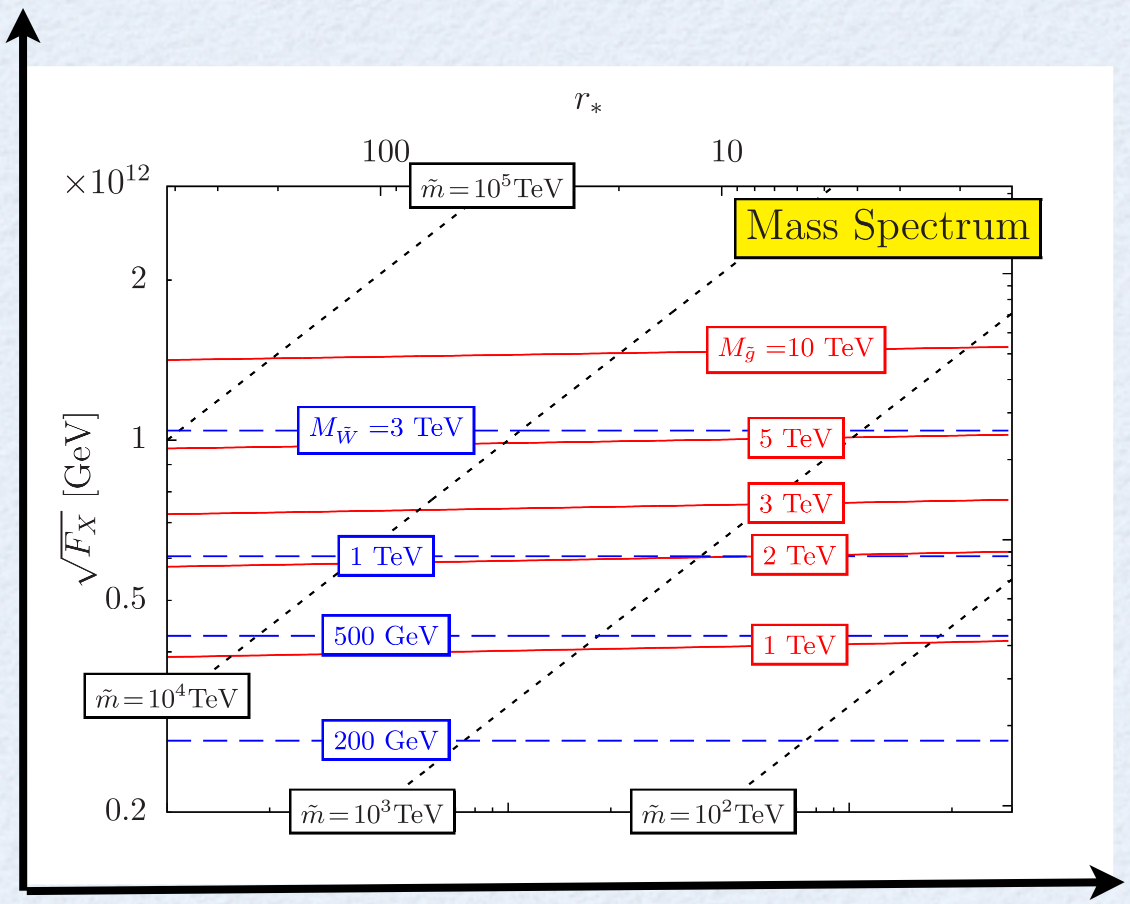
- Dark Matter
- b/τ suggests SUSY at 1-10 TeV
- Moderately Split Spectra like 125 GeV Higgs

High Scale SUSY

- A worry!

Predicted Signals of Spread SUSY

Susy Breaking Scale



Fundamental Scale

(Fixed Higgsino mass)