Supersymmetry from the weak scale to the inflationary scale

Supersymmetry from the weak scale to the inflationary scale

Supersymmetry and CMSSM-like models

Supersymmetry from the weak scale to the inflationary scale

Supersymmetry and CMSSM-like models

Weak scale susy?

Supersymmetry from the weak scale to the inflationary scale

Supersymmetry and CMSSM-like models

Weak scale susy?

High scale susy?

Supersymmetry from the weak scale to the inflationary scale

Supersymmetry and CMSSM-like models

Weak scale susy?

High scale susy?

No susy?(Planck Scale)

SUSY Dark Matter

MSSM and R-Parity → Stable DM candidate

1) Neutralinos

$$\chi_i = \alpha_i \widetilde{B} + \beta_i \widetilde{W} + \gamma_i \widetilde{H}_1 + \delta_i \widetilde{H}_2$$

2) Gravitino

3) Sneutrino

Excluded (unless add L-violating terms)

4) Other:

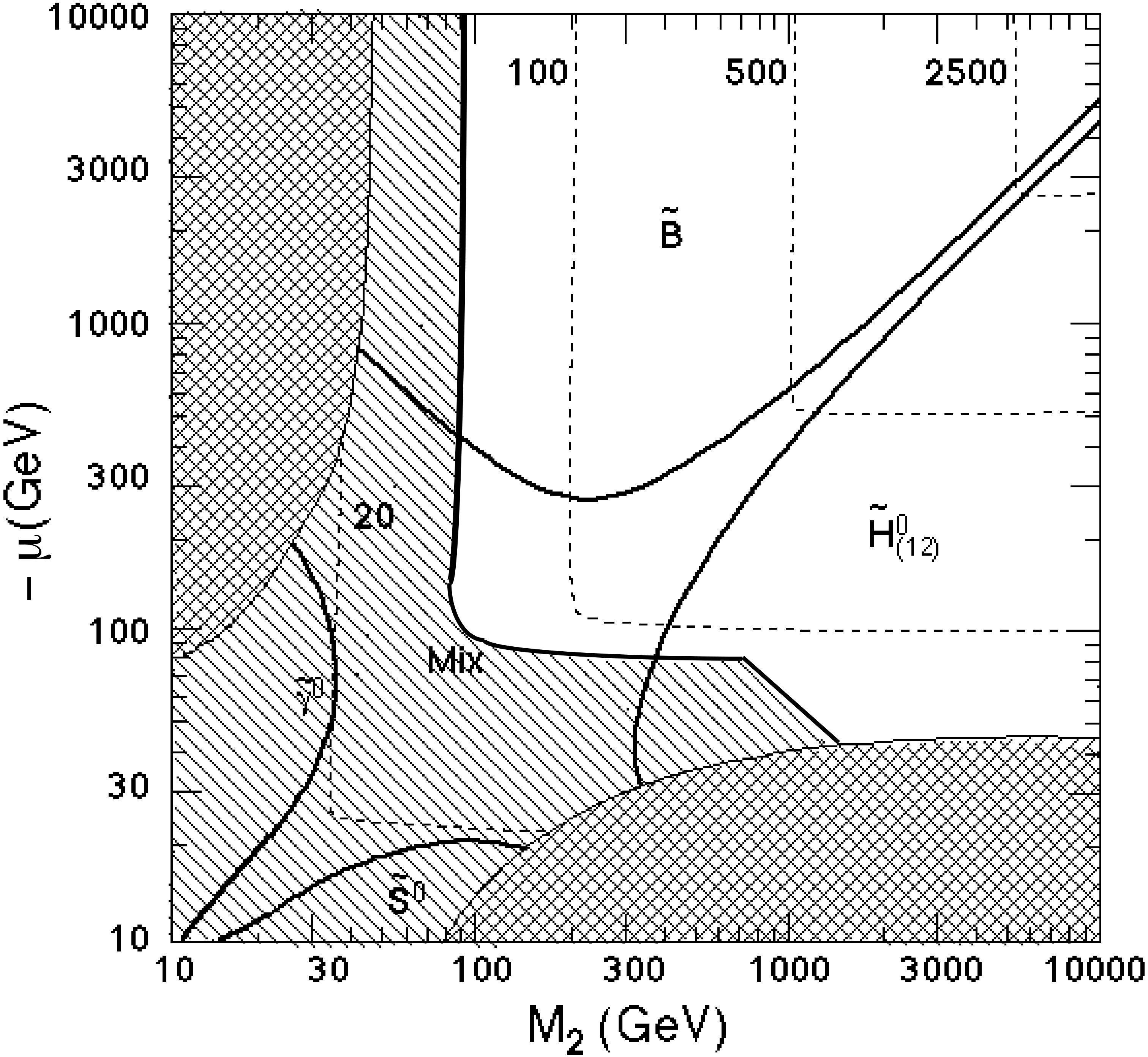
Axinos, etc

Neutralinos

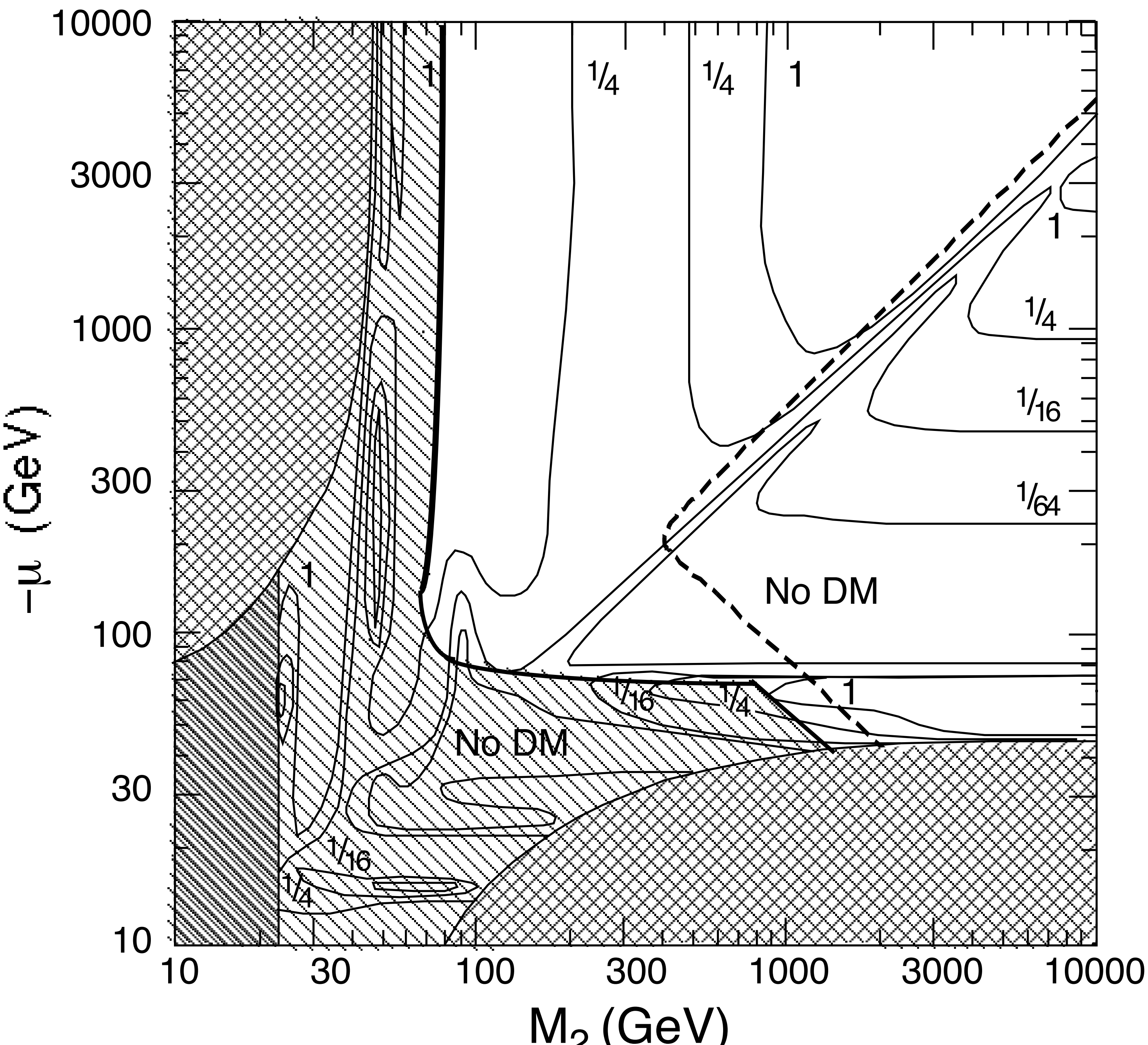
Mass matrix

$$(\tilde{B}, \tilde{W}^3, \tilde{H}_1^0, \tilde{H}_2^0) \begin{pmatrix} M_1 & 0 & \frac{-g_1 v_1}{\sqrt{2}} & \frac{g_1 v_2}{\sqrt{2}} \\ 0 & M_2 & \frac{g_2 v_1}{\sqrt{2}} & \frac{-g_2 v_2}{\sqrt{2}} \\ \frac{-g_1 v_1}{\sqrt{2}} & \frac{g_2 v_1}{\sqrt{2}} & 0 & -\mu \\ \frac{g_1 v_2}{\sqrt{2}} & \frac{-g_2 v_2}{\sqrt{2}} & -\mu & 0 \end{pmatrix} \begin{pmatrix} \tilde{B} \\ \tilde{W}^3 \\ \tilde{H}_1^0 \\ \tilde{H}_2^0 \end{pmatrix}$$

- Depends on $M_{1/2}$, μ, tan β
- Assume $M_1 = M_2 = M_3$ @ GUT scale
- Relic density also depends on m_0 and m_A



10000
3000
1000
300
100
30
10
− μ (GeV)
10
30
100
300
1000
3000
10000
M2 (GeV)
100
500
2500
B̃
20
H̃0(12)
Mix
γ̃0
S̃0



10000
3000
1000
300
100
30
10
10
30
100
300
1000
3000
10000
M2 (GeV)
−μ (GeV)
1
1/4
1/4
1
1
1/4
1/16
1/64
No DM
1
1/16
1/4
1
No DM
1/16
1/4

Constrained Models (CMSSM)

- MSSM with R-Parity (still more than 100 parameters)

Constrained Models (CMSSM)

- MSSM with R-Parity (still more than 100 parameters)

- Gaugino mass Unification

$$
\begin{aligned}
W &= h_u H_2 Q u^c + h_d H_1 Q d^c + h_e H_1 L e^c + \mu H_2 H_1 \\
\mathcal{L}_{\mathrm{soft}} &= -\frac{1}{2} M_\alpha \lambda^\alpha \lambda^\alpha - m_{ij}^2 \phi^{i*} \phi^j \\
&\quad -A_u h_u H_2 Q u^c - A_d h_d H_1 Q d^c - A_e h_e H_1 L e^c - B\mu H_2 H_1 + h.c.
\end{aligned}
$$

Constrained Models (CMSSM)

- MSSM with R-Parity (still more than 100 parameters)

- Gaugino mass Unification
- A-term Unification

$$
\begin{aligned}
W &= h_u H_2 Q u^c + h_d H_1 Q d^c + h_e H_1 L e^c + \mu H_2 H_1 \\
\mathcal{L}_{\text{soft}} &= -\frac{1}{2} M_\alpha \lambda^\alpha \lambda^\alpha - m_{ij}^2 \phi^{i*} \phi^j \\
&\quad - A_u h_u H_2 Q u^c - A_d h_d H_1 Q d^c - A_e h_e H_1 L e^c - B\mu H_2 H_1 + h.c.
\end{aligned}
$$

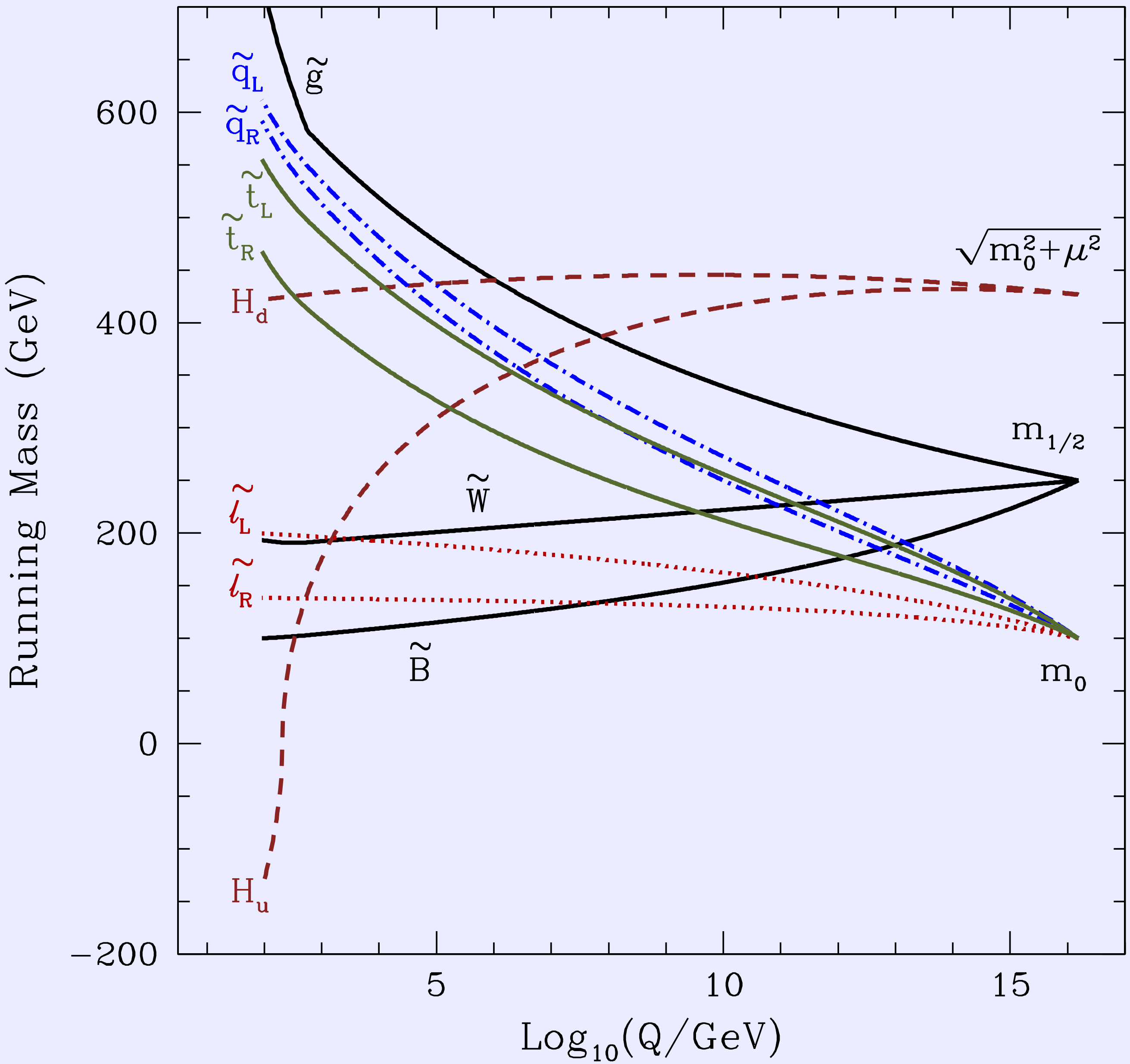
Constrained Models (CMSSM)

- MSSM with R-Parity (still more than 100 parameters)

- Gaugino mass Unification
- A-term Unification
- Scalar mass unification

$$
\begin{aligned}
W &= h_u H_2 Q u^c + h_d H_1 Q d^c + h_e H_1 L e^c + \mu H_2 H_1 \\
\mathcal{L}_{\rm soft} &= -\frac{1}{2} M_\alpha \lambda^\alpha \lambda^\alpha - m_{ij}^2 \phi^{i*} \phi^j \\
&\quad - A_u h_u H_2 Q u^c - A_d h_d H_1 Q d^c - A_e h_e H_1 L e^c - B\mu H_2 H_1 + h.c.
\end{aligned}
$$

CMSSM Spectra



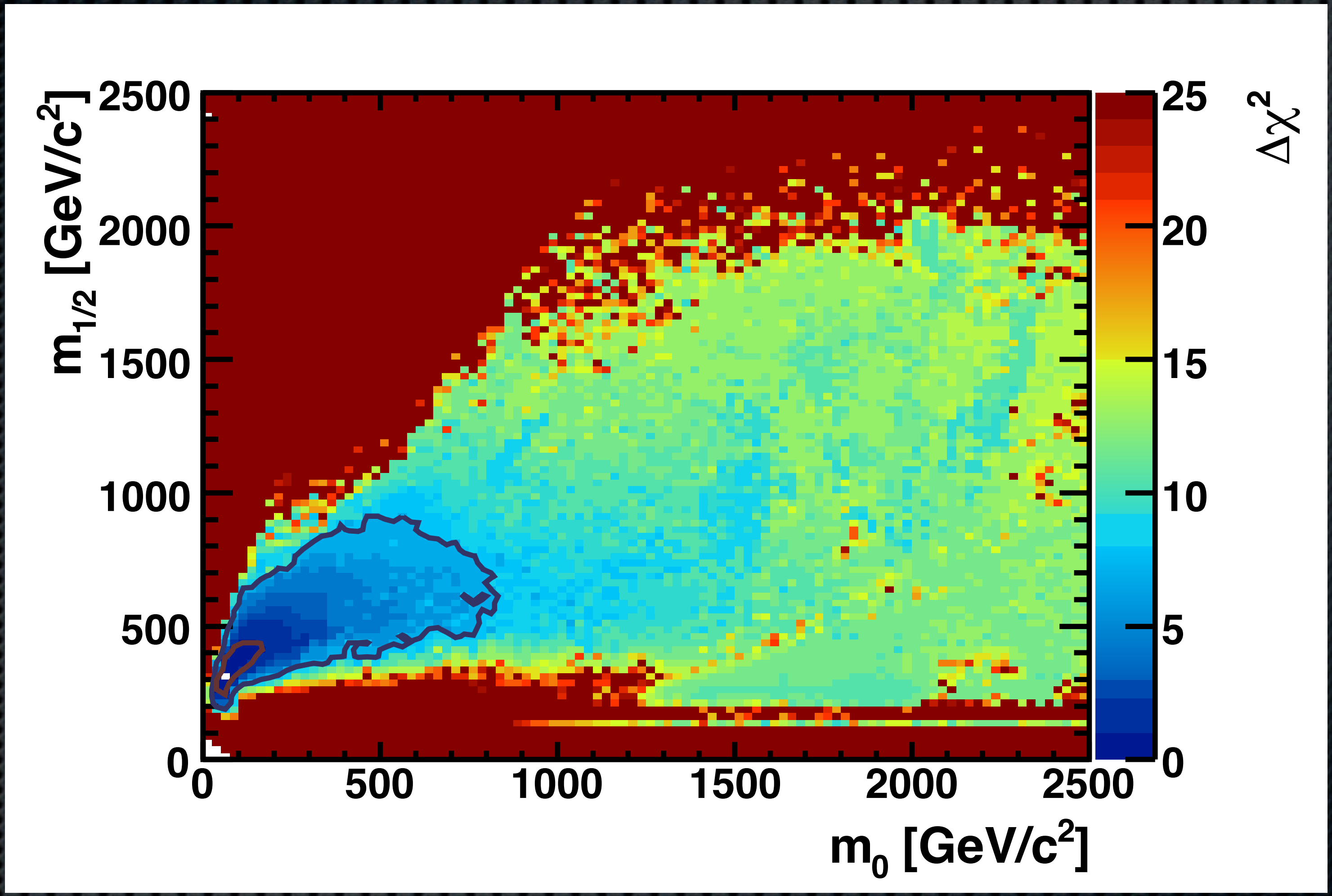
Unification to rich spectrum
+
EWSB

Falk

What happened to weak scale SUSY

Mastercode

2009

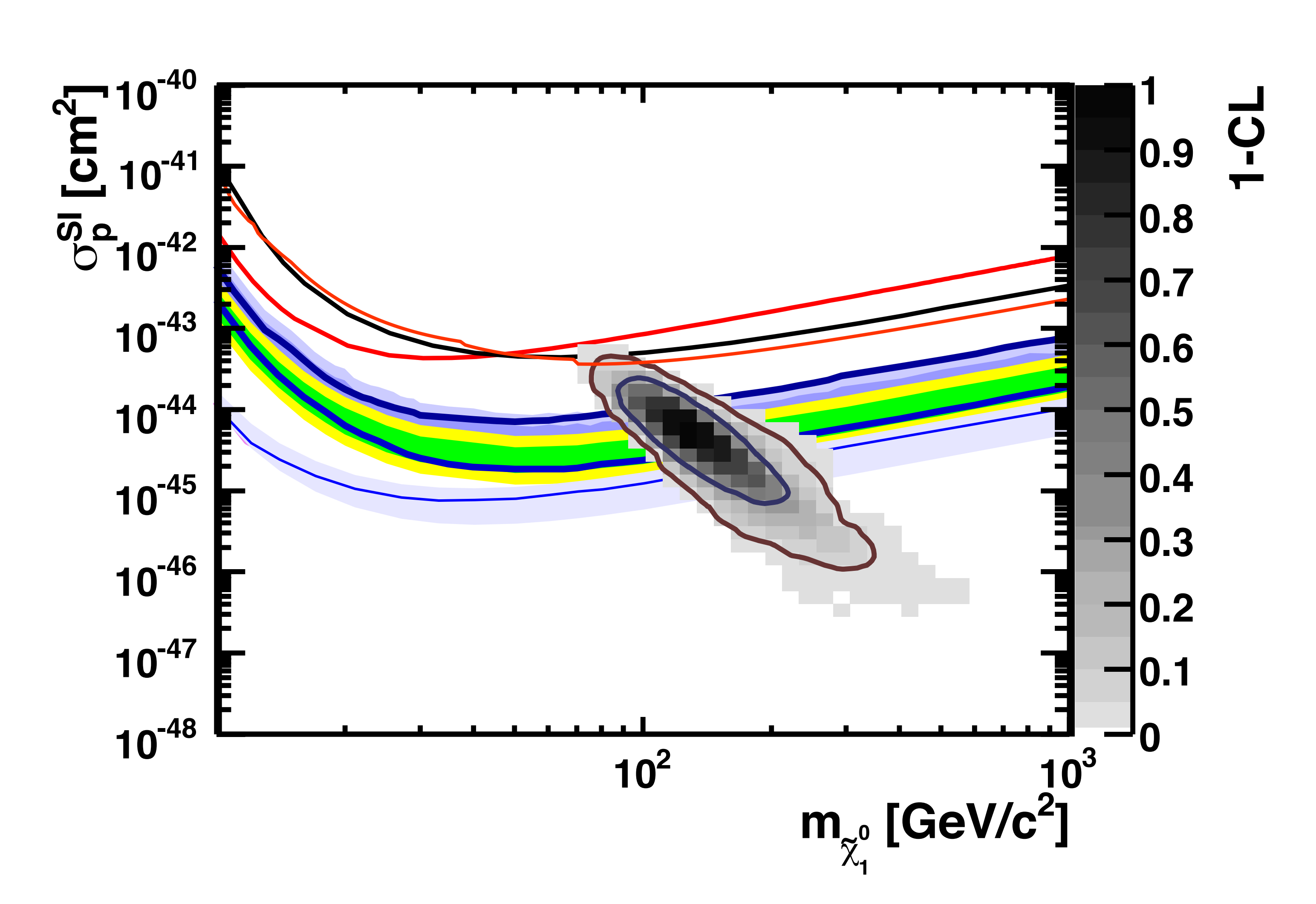


- CMSSM

Buchmueller, Cavanaugh, De Roeck, Ellis, Flacher, Heinemeyer, Isidori, Olive, Ronga, Weiglein

Elastic scaterring cross-section

Mastercode 2009



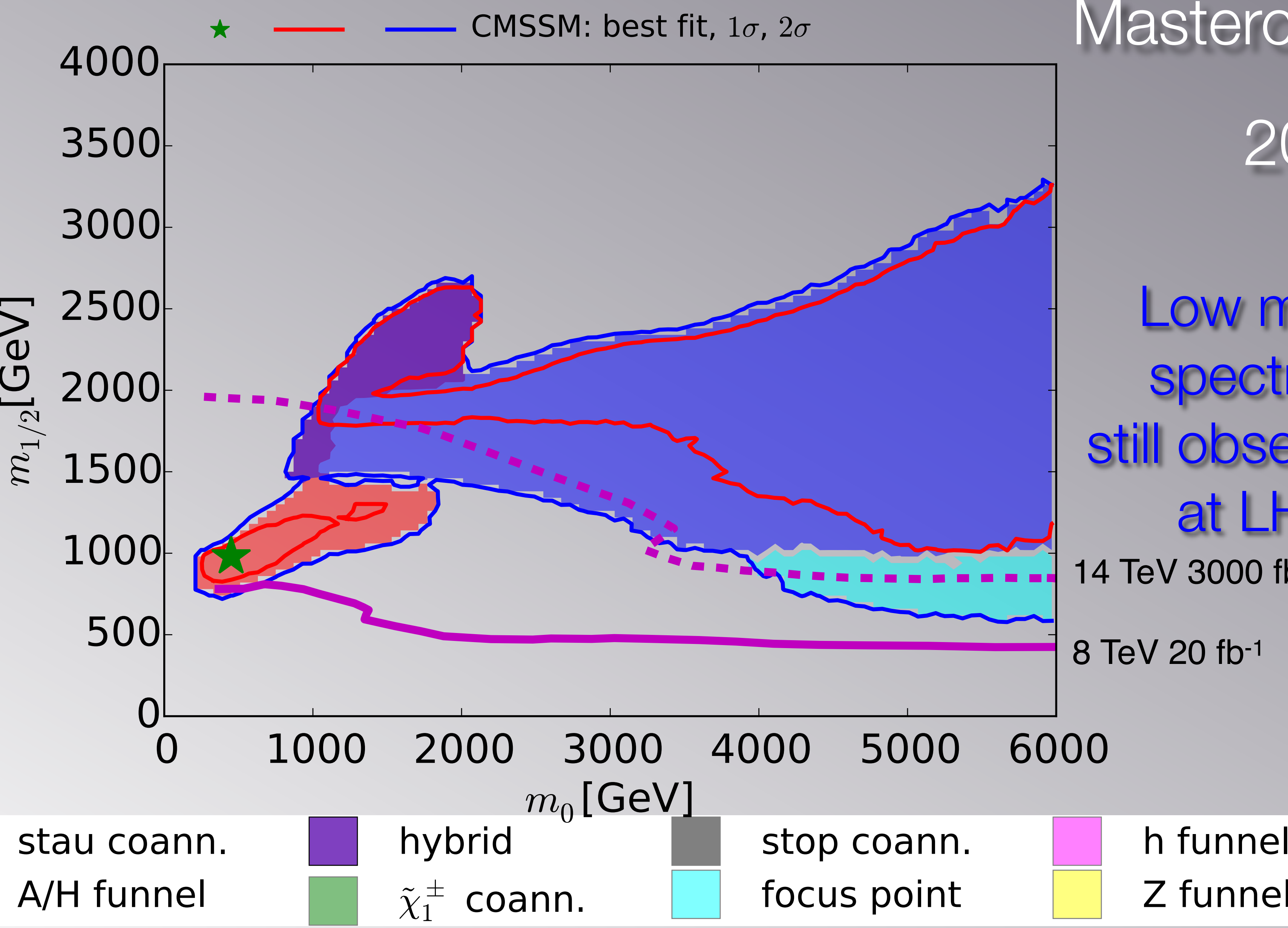
Buchmueller, Cavanaugh, De Roeck, Ellis, Flacher, Heinemeyer, Isidori, Olive, Ronga, Weiglein

- CMSSM

LHC Happened

Mastercode

2015



Low mass spectrum still observable at LHC

14 TeV 3000 fb^{-1}

8 TeV 20 fb^{-1}

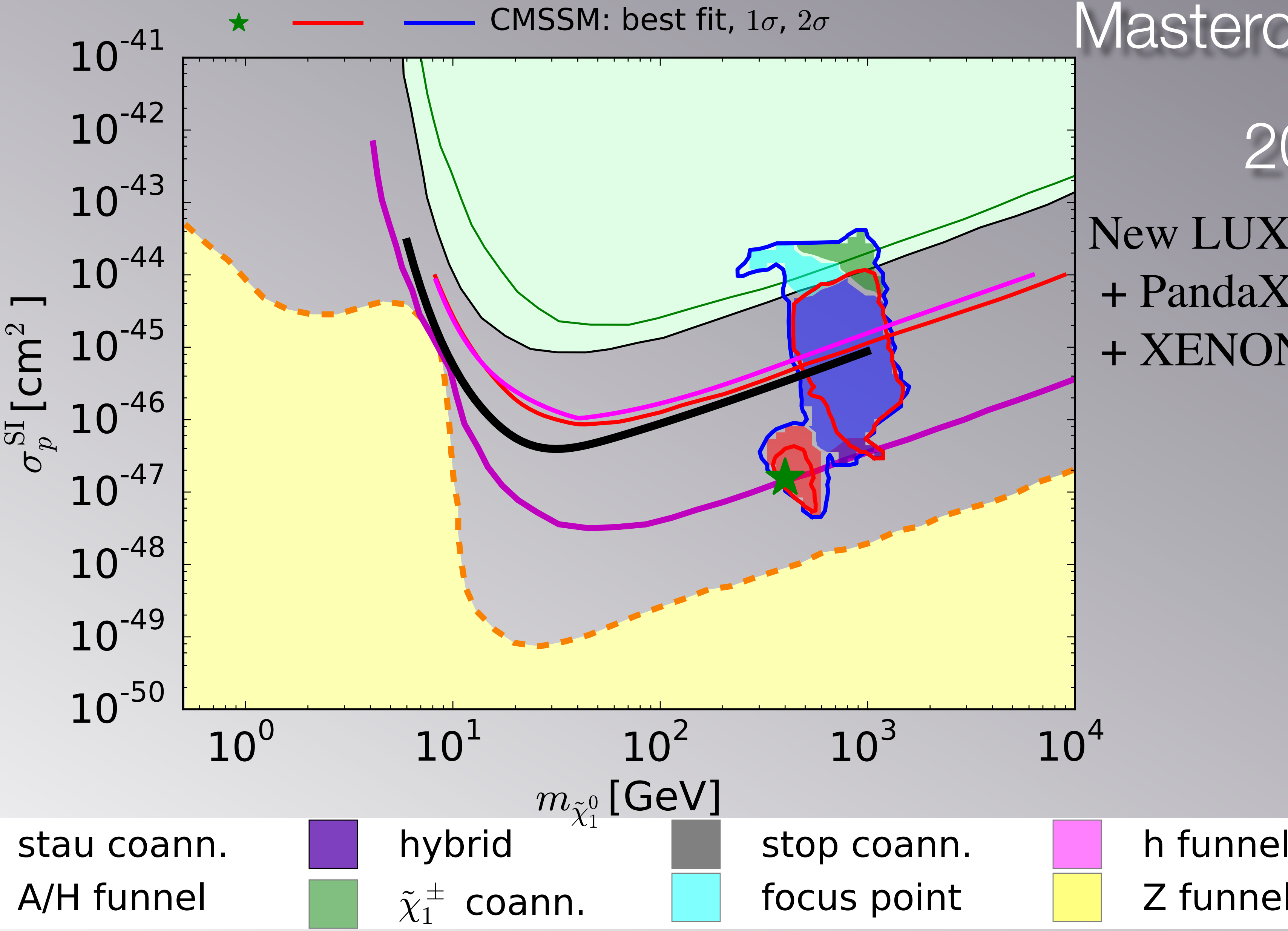
- CMSSM

Bagnaschi, Buchmueller, Cavanaugh, Citron, De Roeck, Dolan, Ellis, Flacher, Heinemeyer, Isidori, Malik, Martinez Santos, Olive, Sakurai, de Vries, Weiglein

Elastic scaterring cross-section

Mastercode

2015



New LUX bound
+ PandaX
+ XENON1t

- CMSSM

Bagnaschi, Buchmueller, Cavanaugh, Citron, De Roeck, Dolan, Ellis, Flacher, Heinemeyer, Isidori, Malik, Martinez Santos, Olive, Sakurai, de Vries, Weiglein

Hadronic matrix elements

The scalar cross section

$$\sigma_3 = \frac{4m_r^2}{\pi}\left[Zf_p + (A-Z)f_n\right]^2$$

where

$$\frac{f_N}{m_N} = \sum_q f_{T_q}^N \frac{\alpha_{3q}}{m_q}$$

and

$$m_p f_{Tq}^{(p)} \equiv \langle p|m_q \bar{q}q|p\rangle \equiv m_q B_q$$

integrating out the heavy quarks

$$\frac{f_p}{m_p} = \sum_{q=u,d,s} f_{Tq}^{(p)} \frac{\alpha_{3q}}{m_q} + \frac{2}{27} f_{TG}^{(p)} \sum_{c,b,t} \frac{\alpha_{3q}}{m_q}$$

$$f_{T_G}^N = 1 - \sum_{q=u,d,s} f_{T_q}^N .$$

Hadronic matrix elements

$$\Sigma_{\pi N} = \frac{1}{2}(m_u + m_d)\left(B_u^p + B_d^p\right)$$

$$\sigma_0 = \frac{1}{2}(m_u + m_d)\left(B_u^p + B_d^p - 2B_s^p\right) \quad \mathbf{= 36 \pm 7\ MeV}$$

$$z \equiv \frac{B_u^p - B_s^p}{B_d^p - B_s^p} = \frac{m_{\Xi^0} + m_{\Xi^-} - m_p - m_n}{m_{\Sigma^+} + m_{\Sigma^-} - m_p - m_n} = 1.49$$

Hadronic matrix elements

$$\Sigma_{\pi N} \;=\; \frac{1}{2}(m_u + m_d)\left(B_u^p + B_d^p\right)$$

$$\sigma_0 \;=\; \frac{1}{2}(m_u + m_d)\left(B_u^p + B_d^p - 2B_s^p\right) \quad = 36 \pm 7 \text{ MeV}$$

$$z \;\equiv\; \frac{B_u^p - B_s^p}{B_d^p - B_s^p} \;=\; \frac{m_{\Xi^0} + m_{\Xi^-} - m_p - m_n}{m_{\Sigma^+} + m_{\Sigma^-} - m_p - m_n} \;=\; 1.49$$

$$\sigma_s = m_s B_s^p = \frac{m_s}{m_u + m_d}\left(\Sigma_{\pi N} - \sigma_0\right)$$

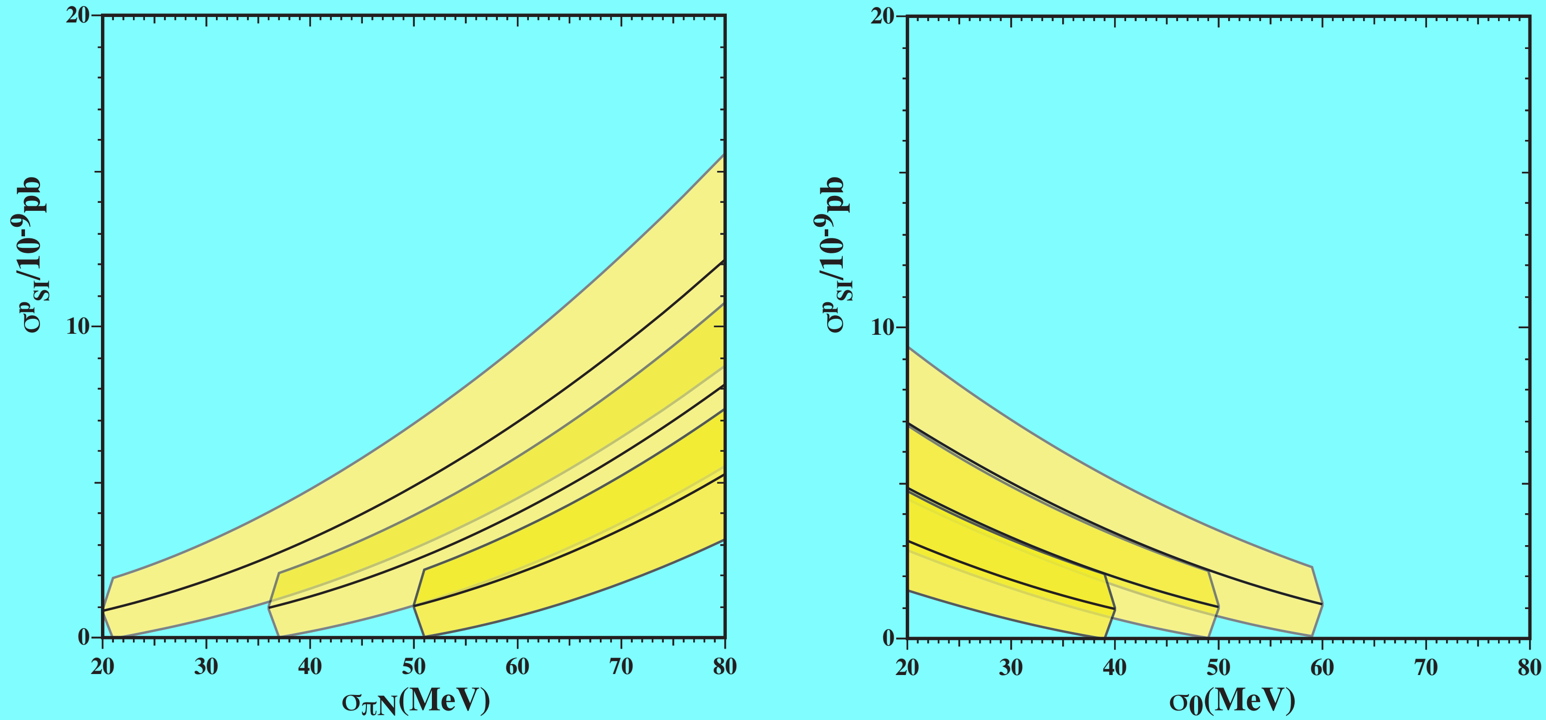


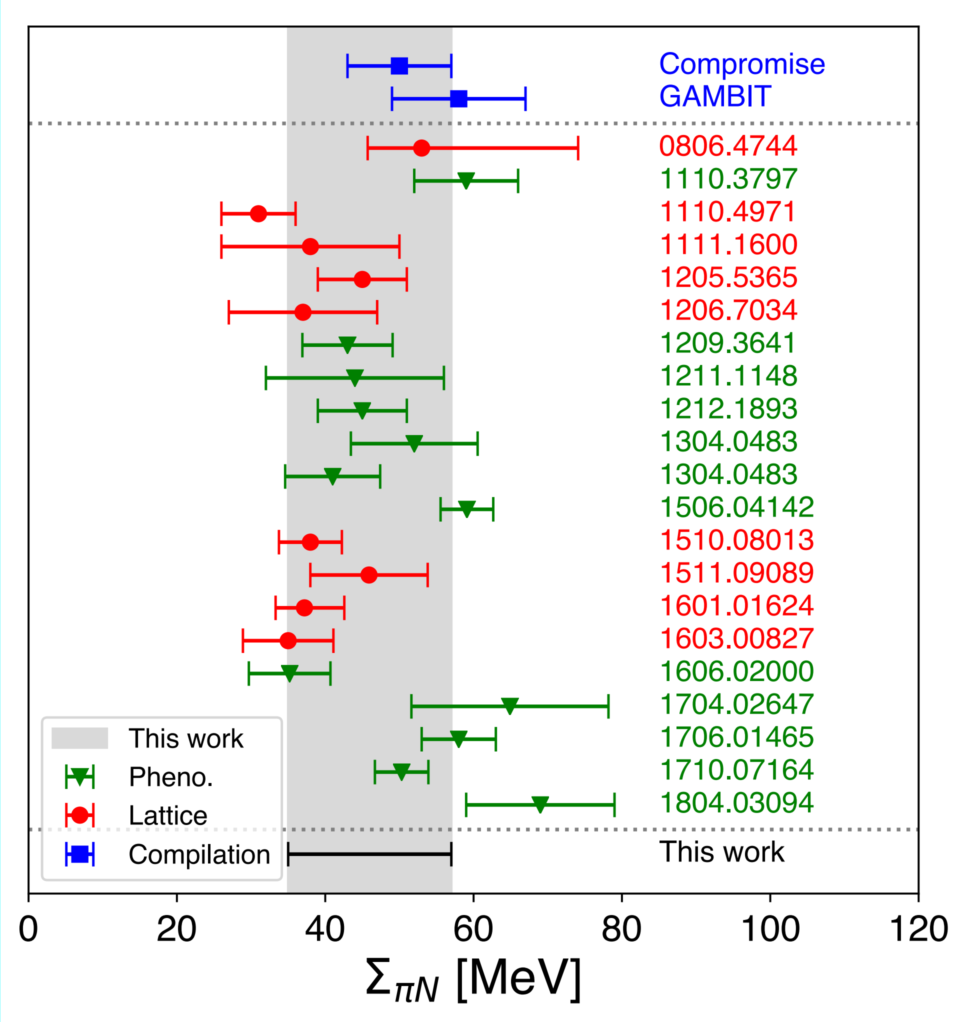
Figure 1: *Left:* σ^p_{SI} *vs* $\Sigma_{\pi N}$ *for* $\sigma_0 = 20, 36, 50$ *MeV. Right:* σ^p_{SI} *vs* σ_0 *for* $\Sigma_{\pi N} = 40, 50, 60$ *MeV. The color bands show the 1-*σ *uncertainty in the elastic cross section calculated using the three-flavour expression (5).*

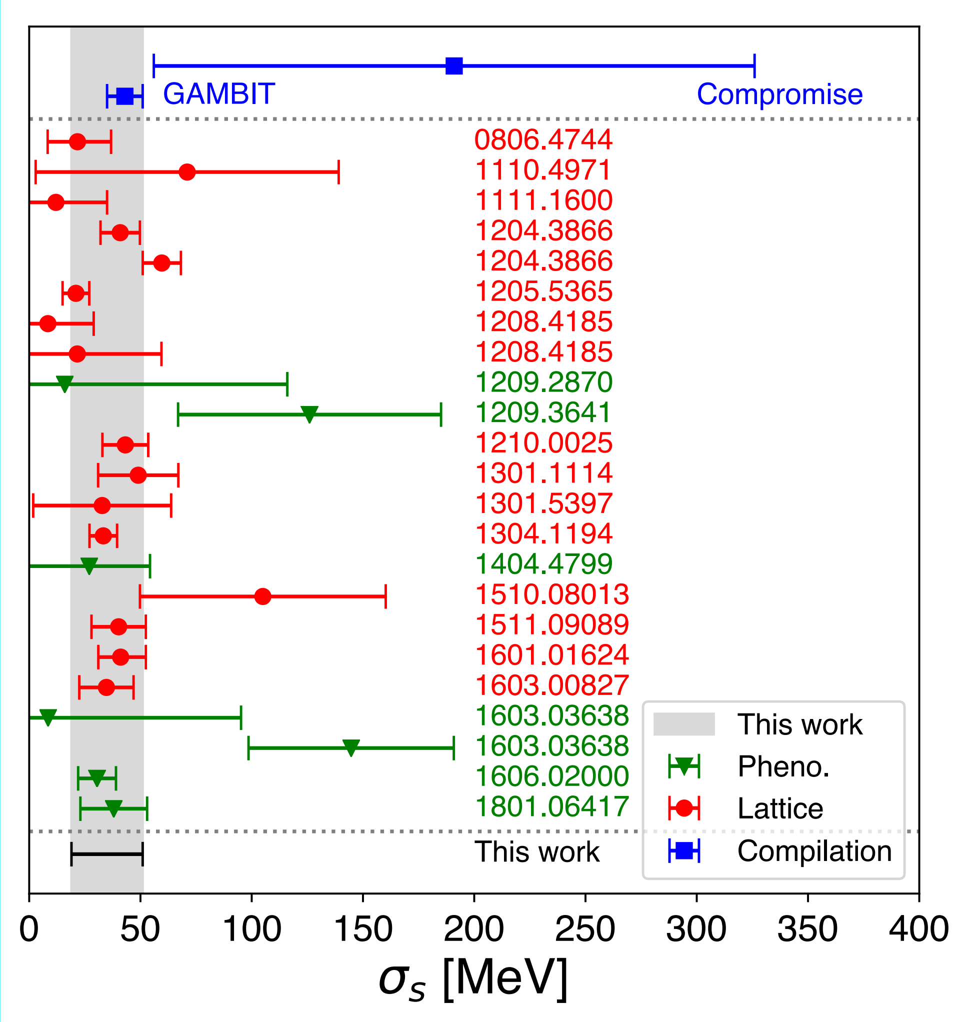
e.g. $\Sigma_{\pi N} = 50 \pm 7$ MeV $\sigma_0 = 36 \pm 7$ MeV $\Rightarrow \sigma_p^{SI} = (2.5 \pm 1.5) \times 10^{-9}$ pb

for $m_{1/2} = 3$ TeV, $m_0 = 8.2$ TeV, $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$ $m_\chi = 1.1$ TeV

Ellis, Nagata, Olive

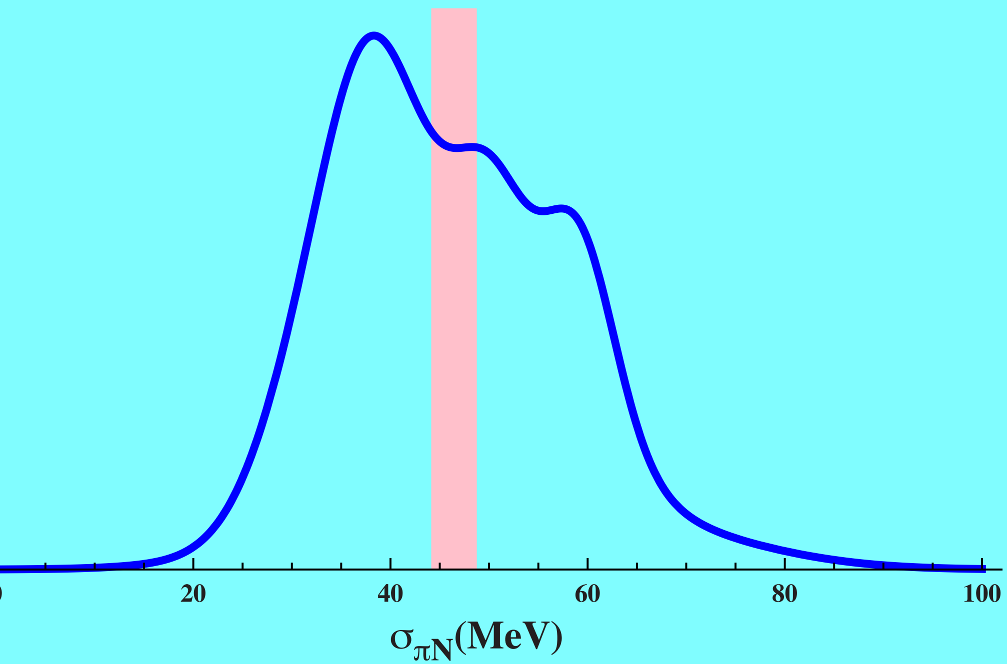
Lattice Data





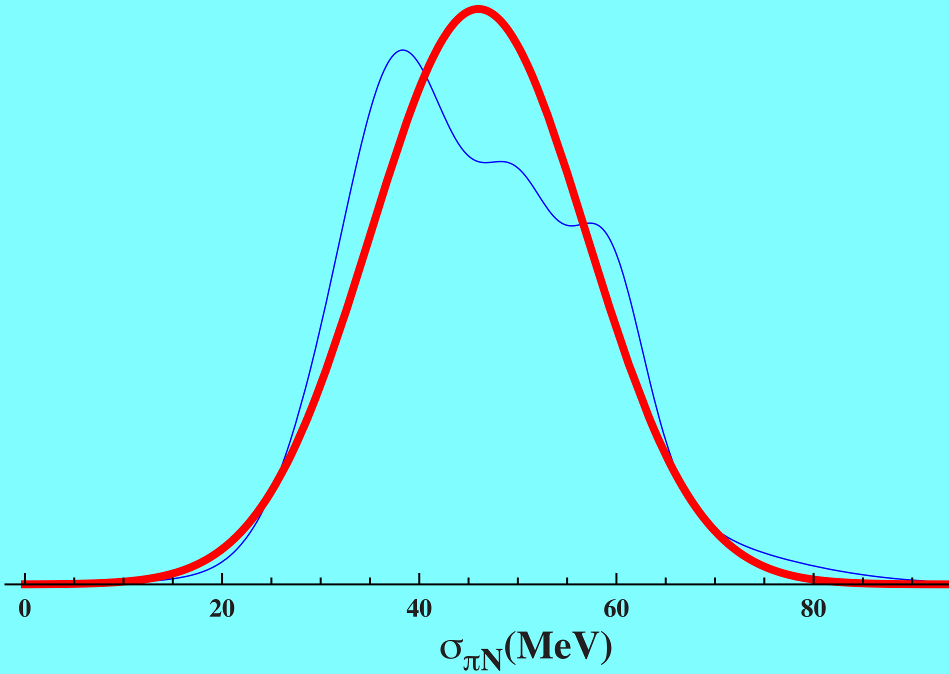
Ellis, Nagata, Olive

‘Ideogram’



$$\Sigma_{\pi N} = 46.1 \pm 2.2 \text{ MeV}$$

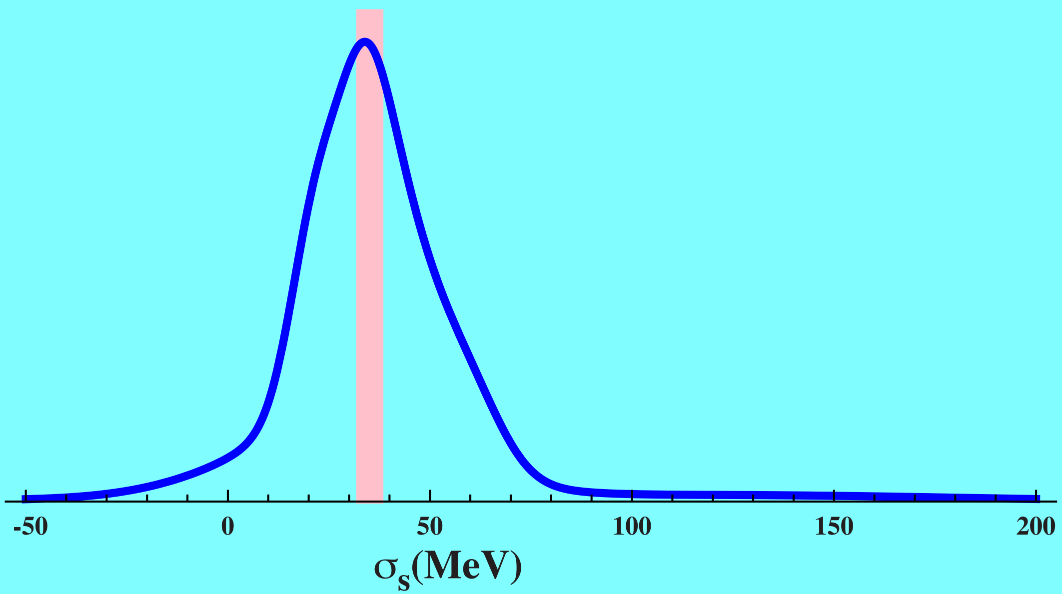
Gaussian approx



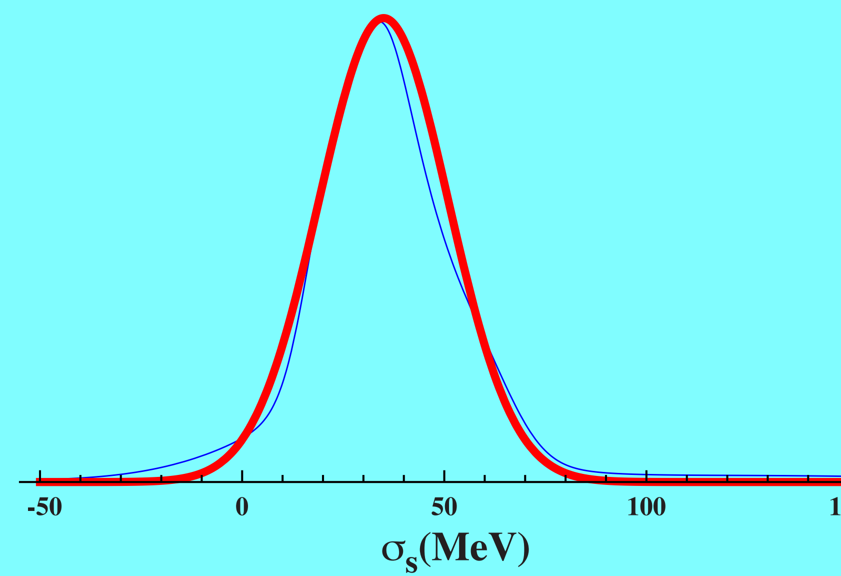
$$\Sigma_{\pi N} = 46 \pm 11 \text{ MeV}$$

Ellis, Nagata, Olive

‘Ideogram’



Gaussian approx



$$\sigma_s \quad = \quad 35.2 \pm 3.1 \text{ MeV}$$

$$\sigma_s \quad = \quad 35 \pm 16 \text{ MeV}$$

$$\sigma^p_{SI} = (1.25 \pm 0.13) \times 10^{-9} \text{ pb}$$

Ellis, Nagata, Olive

1-loop improved calculations for σ_{cbt}

$$\sigma_c = \frac{2}{27}\left(-0.3 + 1.48 f^p_{T_G}\right) m_p = 73.4 \pm 1.9 \text{ MeV}$$

$$\sigma_b = \frac{2}{27}\left(-0.16 + 1.23 f^N_{T_G}\right) M_N \qquad \sigma_b = 67.3 \pm 1.6 \text{ MeV}$$

$$\sigma_t = \frac{2}{27}\left(-0.05 + 1.07 f^N_{T_G}\right) M_N \qquad \sigma_t = 64.7 \pm 1.4 \text{ MeV}$$

$\sigma_p^{SI} = (1.38 \pm 0.17) \times 10^{-9}$ pb

Ellis, Nagata, Olive

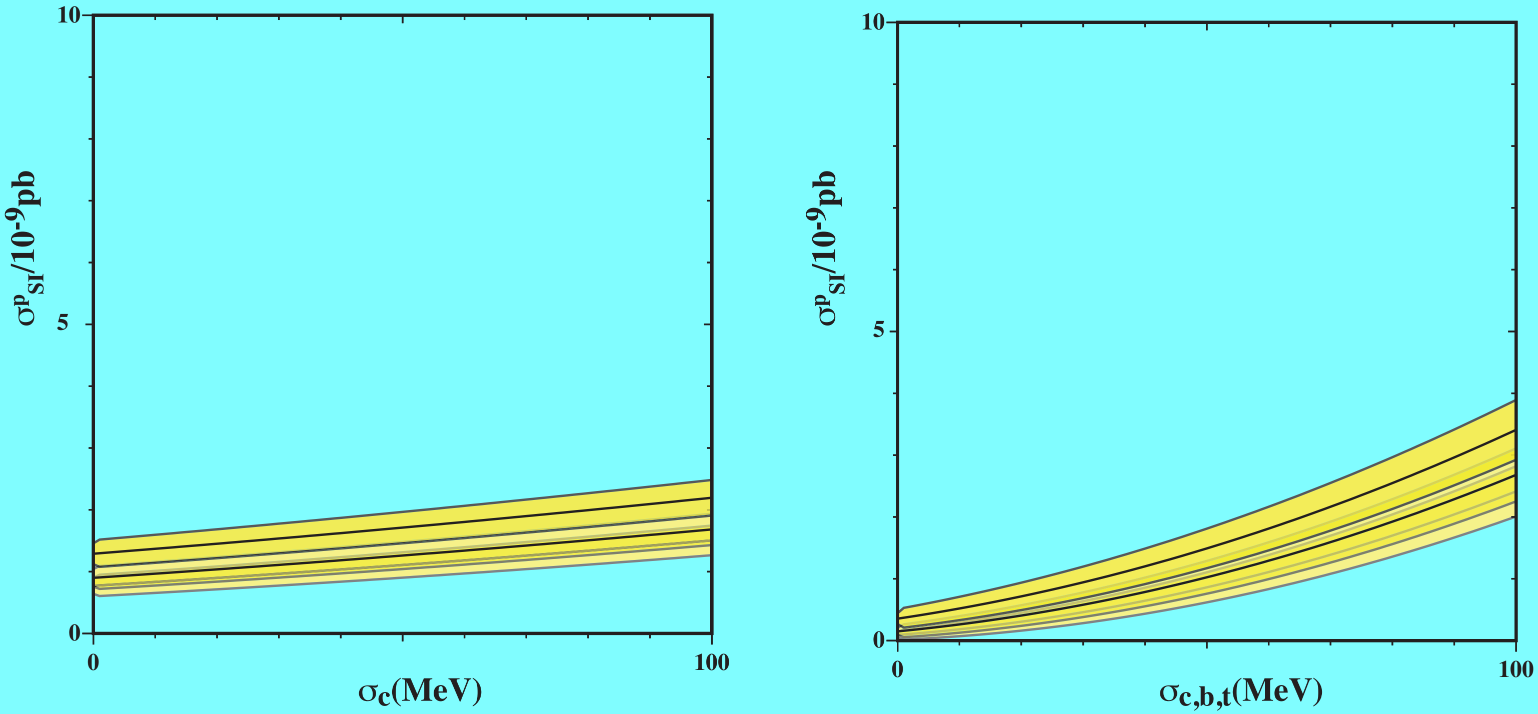


Figure 10: *Left:* σ^p_{SI} *vs* σ_c *for fixed* $\Sigma_{\pi N} = 46$ *MeV and* $\sigma_s = 30, 50, 100$ *MeV. Right:* σ^p_{SI} *vs* $\sigma_c = \sigma_b = \sigma_t$ *for fixed* $\Sigma_{\pi N} = 46$ *MeV and* $\sigma_s = 30, 50, 100$ *MeV.*

Ellis, Nagata, Olive

Weak (?) scale supersymmetric dark matter

Weak (?) scale supersymmetric dark matter

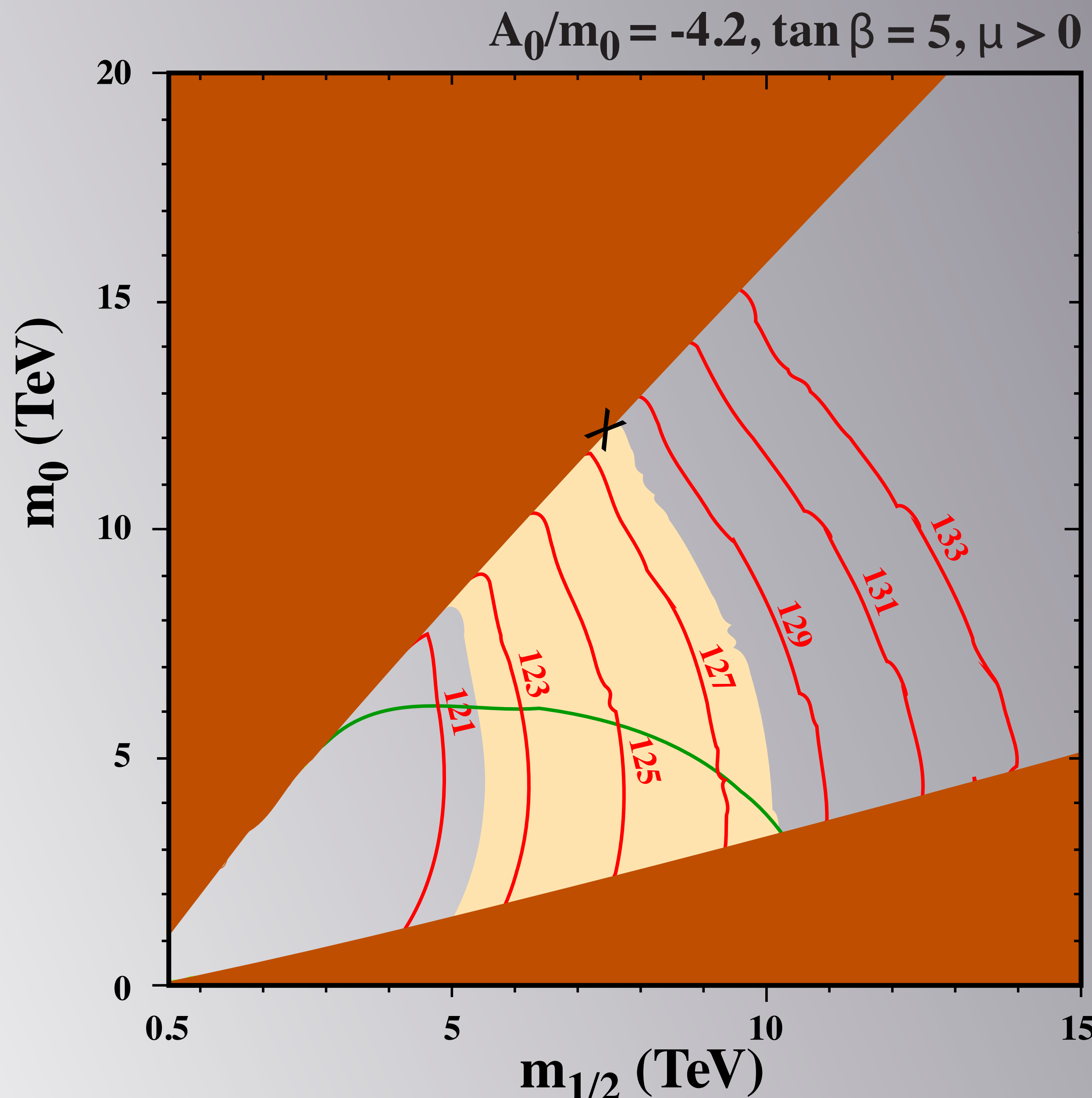
Viable regions of parameter space with dark matter is found along strips:

Weak (?) scale supersymmetric dark matter

Viable regions of parameter space with dark matter is found along strips:

- Stau-coannhilation Strip
  - extends only out to ~1 TeV
- Stop-coannihilation Strip
- Higgs Funnel
- Focus Point

Stop strip

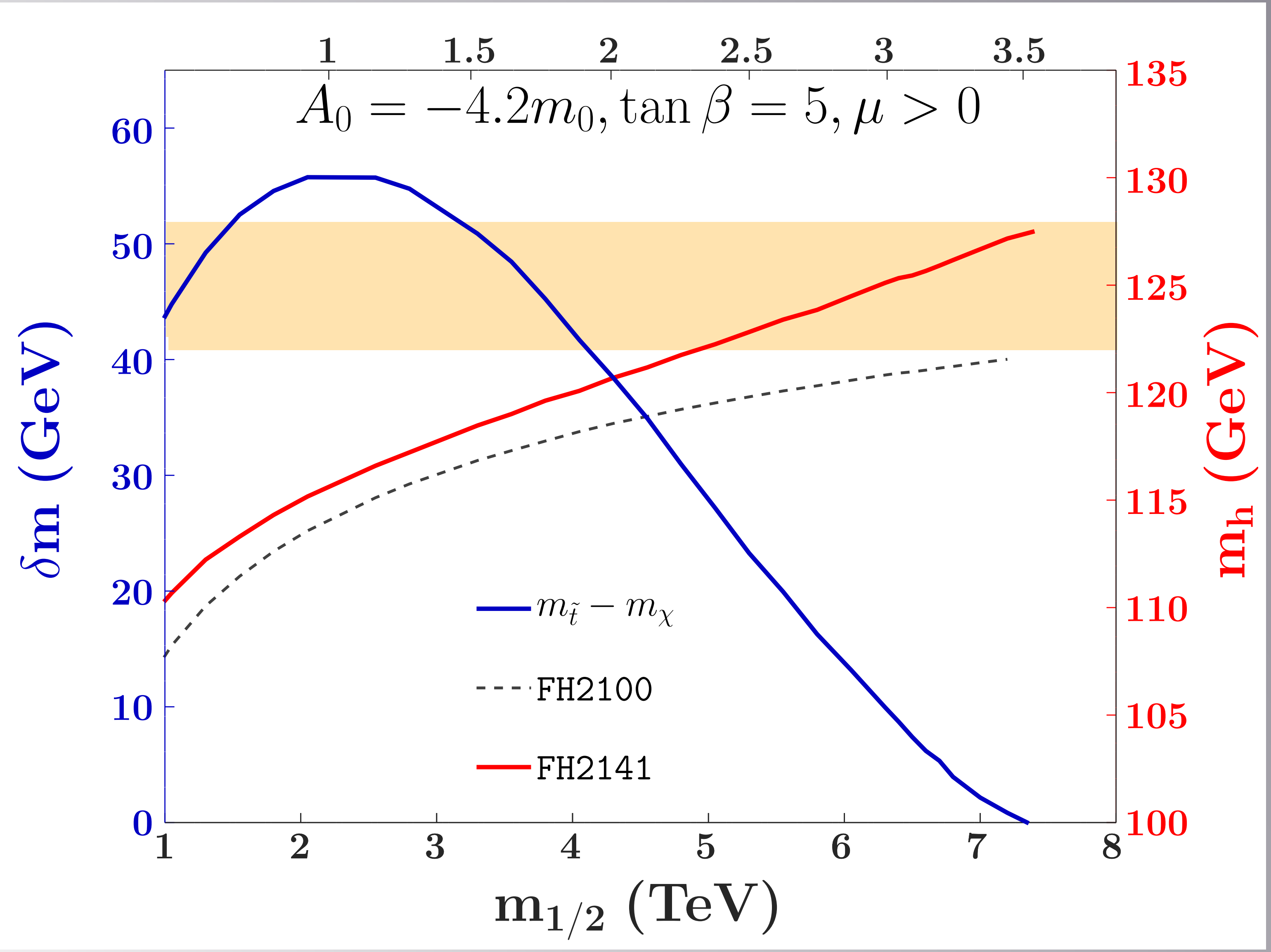


Ellis, Evans, Luo, Nagata, Olive, Sandick

Ellis, Evans, Luo, Olive, Zheng

Bagnaschi et al.

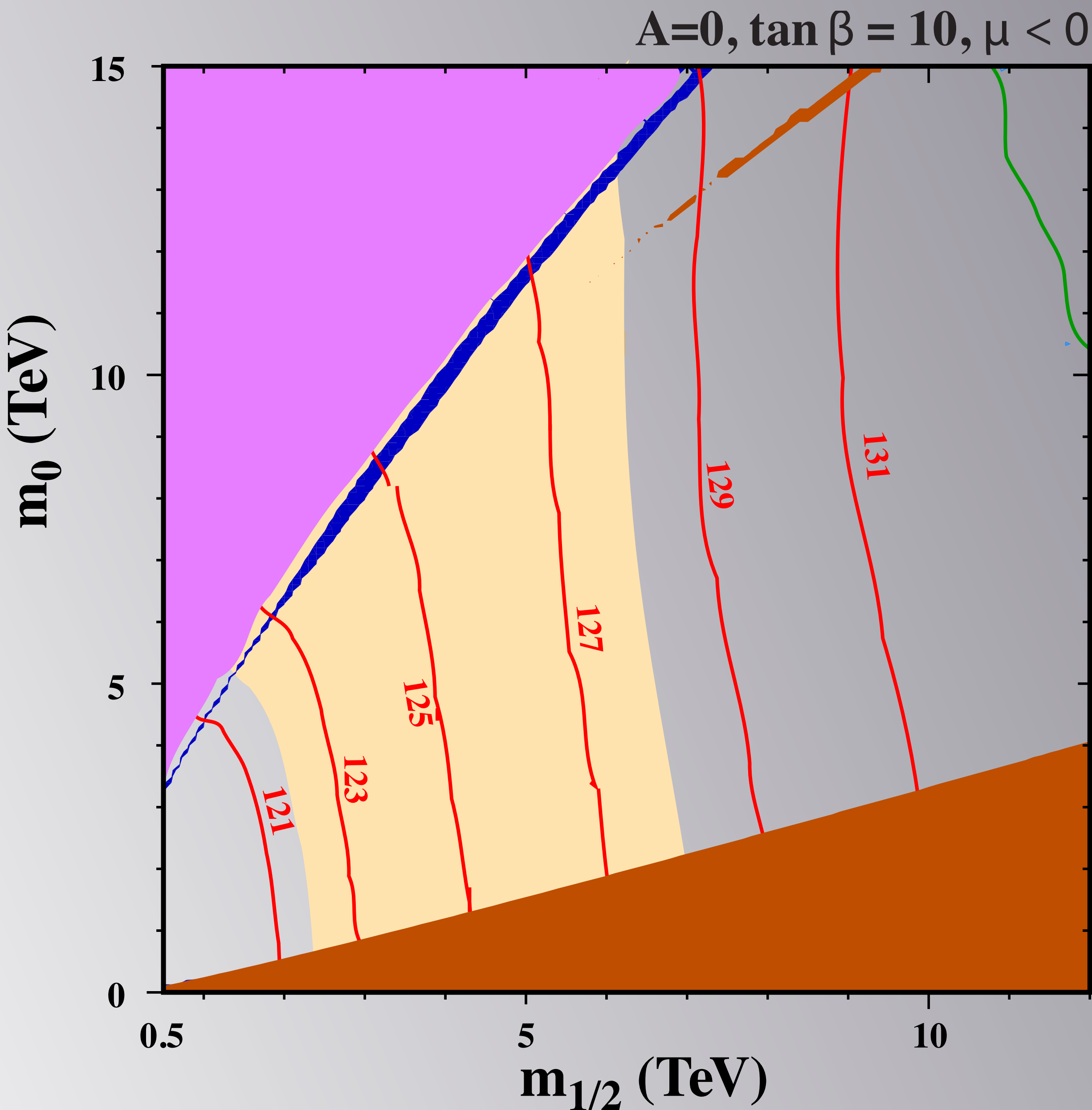
Stop strip



Ellis, Evans, Luo, Olive, Zheng

Bagnaschi et al.

Focus Point



Ellis, Evans, Luo, Nagata, Olive, Sandick

Ellis, Evans, Mustafayev, Nagata, Olive

Bagnaschi et al.

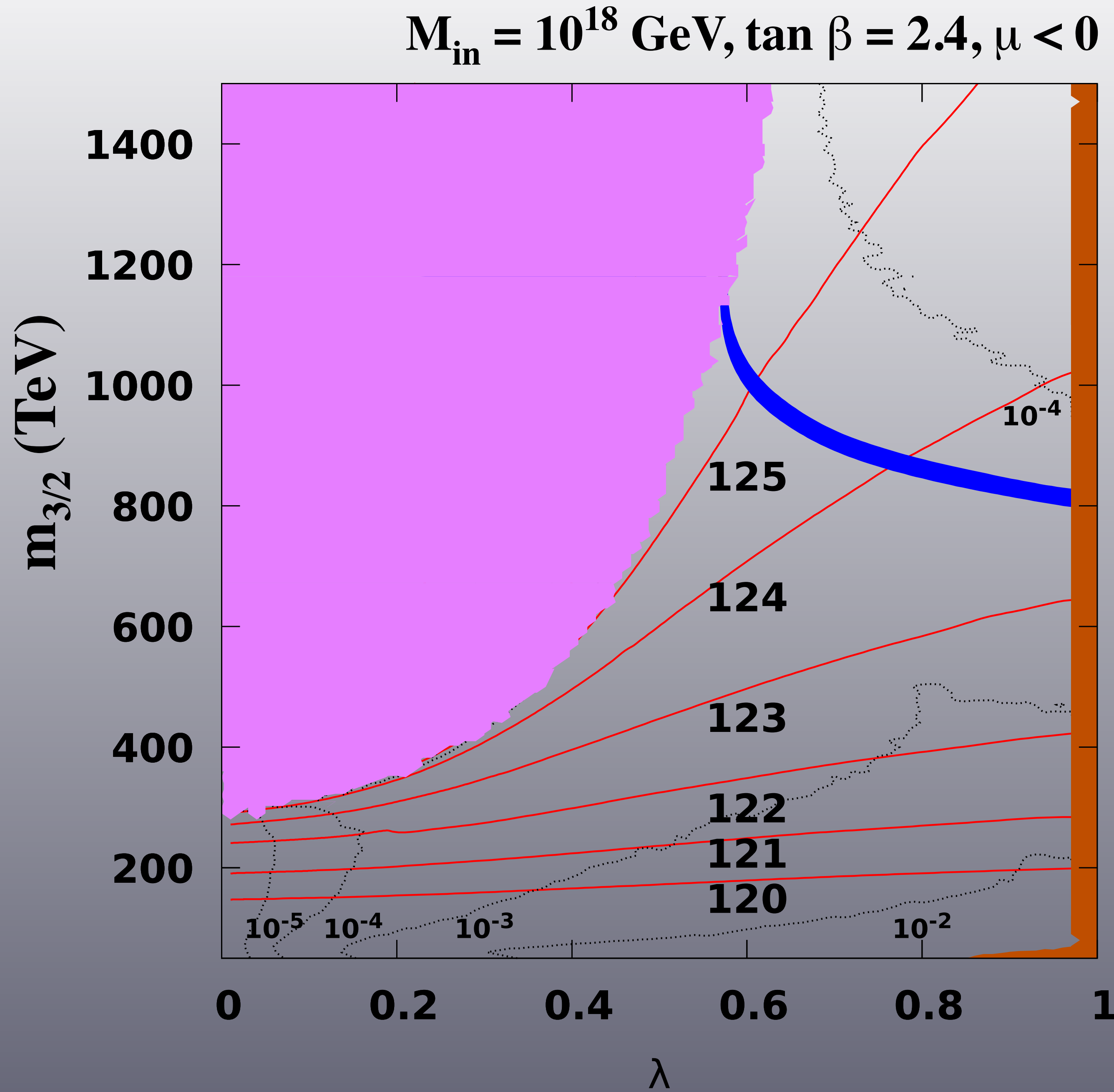
DM density/Higgs mass saturate for $m_{SUSY} \sim O(10)$ TeV

Other Possibilities
(with PeV scales)

More Constrained (fewer parameters)

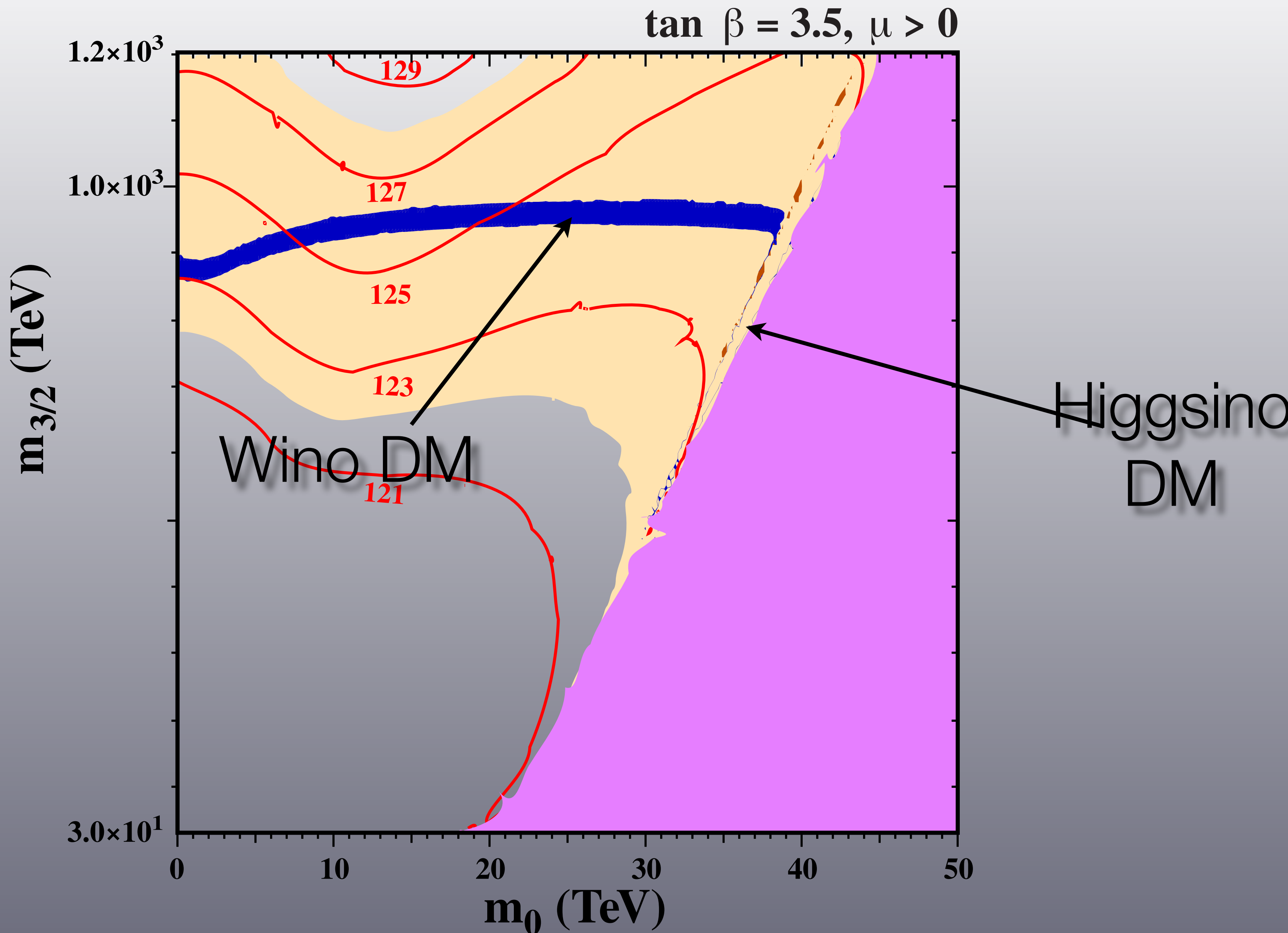
- Pure Gravity Mediation
  - 2 parameter model with very large scalar masses
  - $m_0 = m_{3/2}$, $\tan\beta$
- mAMSB
  - similar to PGM, but allows $m_0 \neq m_{3/2}$

PGM



Evans, Nagata, Olive

mAMSB

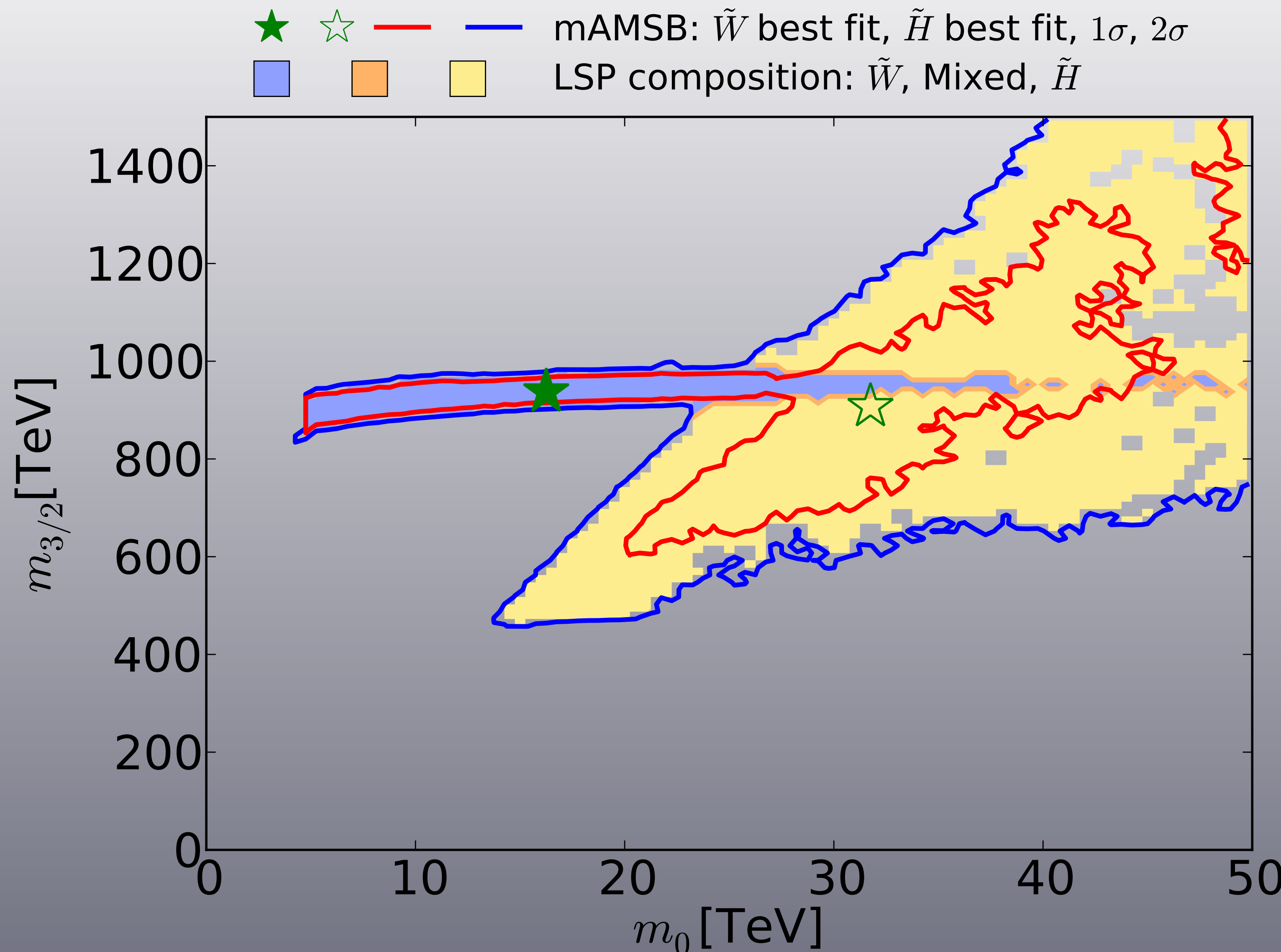


Scalar masses: $m_0 \neq m_{3/2}$

Mastercode 2016

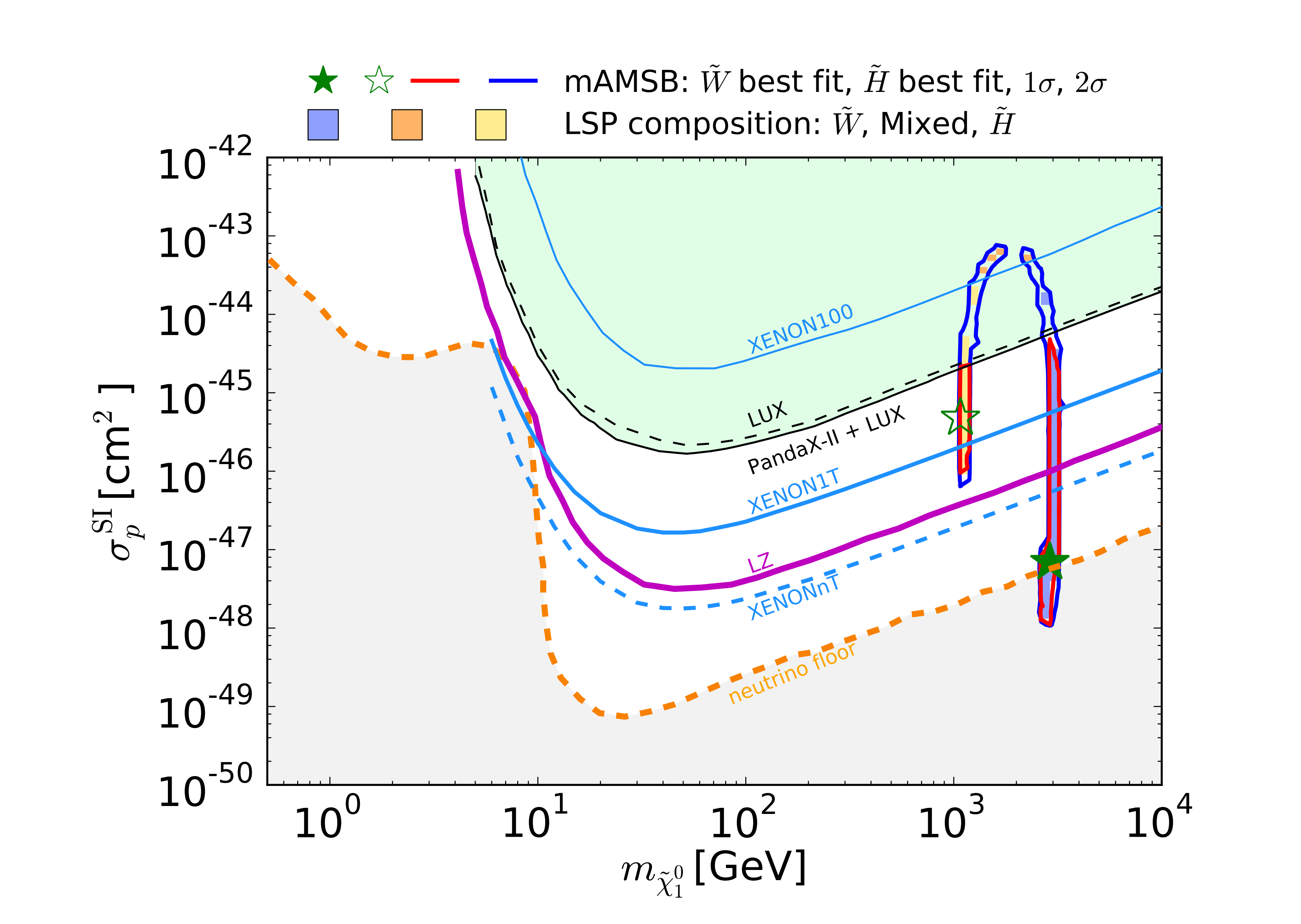
Bagnaschi et al.

Mastercode 2017 mAMSB



Bagnaschi, Borsato, Buchmueller, Cavanaugh, Chobanova, Citron, Costa, De Roeck, Dolan, Ellis, Flacher, Heinemeyer, Isidori, Lucio, Luo, Martinez Santos, Olive, Riochards,Sakurai, Weiglein

mAMSB



Mastercode 2017

Bagnaschi, Borsato, Buchmueller, Cavanaugh, Chobanova, Citron, Costa, De Roeck, Dolan, Ellis, Flacher, Heinemeyer, Isidori, Lucio, Luo, Martinez Santos, Olive, Riochards,Sakurai, Weiglein

Even Larger Mass Scales

What if the entire SUSY matter spectrum were very large

with only the gravitino remaining "light"

Benakli, Chen, Dudas, Mambrini
Dudas, Mambrini, Olive

- 1 parameter model: $m_{3/2}$

Gravitino Mass Limits

For $m_{3/2} \sim$ 10-1000 GeV

Gravitino decays to the LSP/NLSP decays to the gravitino:

Lifetimes 100-10^8 s $\Rightarrow$ BBN limits

$$\Gamma_{\rm decay} \simeq \frac{C^2}{16\pi} \frac{m_\chi^5}{m_{3/2}^2 M_P^2}$$

NLSP $\rightarrow$ gravitino + γ

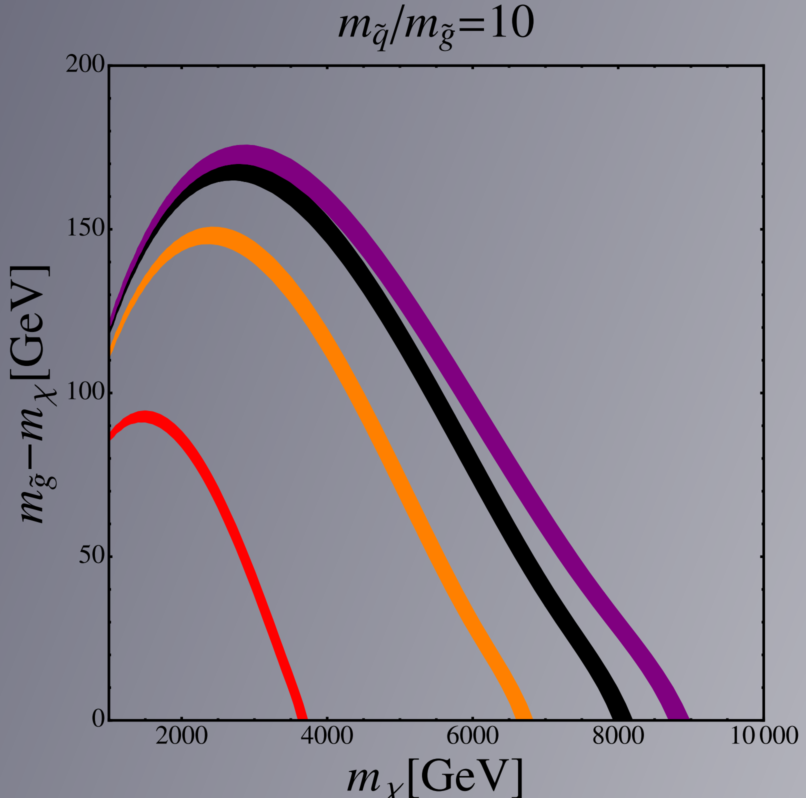
$\tau_\chi \lesssim 100$ s $\Rightarrow m_\chi > 300$ GeV $(m_{3/2}/\text{GeV})^{2/5}$

Gravitino Mass Limits

$\tau_\chi \lesssim 100 \text{ s} \Rightarrow m_\chi > 300 \text{ GeV } (m_{3/2}/\text{GeV})^{2/5}$

Relic Density: $\Omega_{3/2}h^2 = \frac{m_{3/2}}{m_\chi}\Omega_\chi h^2$ or $\Omega_\chi h^2 \lesssim 0.12\frac{m_\chi}{m_{3/2}}$

Gluino coannihilation



Ellis, Luo, Olive

$m_\chi < 8 \text{ TeV} \Rightarrow m_{3/2} < 4 \text{ TeV}$

heavier gravitino → heavier neutralino
→ $\Omega_\chi h^2$ too large → $\Omega_{3/2}h^2$ too large

Gravitino Mass Limits

$m_{3/2} < 4$ TeV unless(!) the susy spectrum lies above the inflationary scale.

For $M_{susy} \sim F^{1/2} > m_{infl} \sim 3 \times 10^{13}$ GeV

$$m_{3/2} = \frac{F}{\sqrt{3}M_P} > \frac{m_\phi^2}{\sqrt{3}M_P} \simeq 0.2 \text{ EeV}$$

Gravitino Production

Standard Picture:

gluon + gluon $\longrightarrow$ gluino + gravitino

$$\langle \sigma v \rangle \sim \frac{1}{M_P^2}\left(1 + \frac{m_{\tilde{g}}^2}{3m_{3/2}^2}\right)$$

$$\Gamma \sim T^3 \frac{m_{\tilde{g}}^2}{M_P^2 m_{3/2}^2}$$

$m_{\tilde{g}} > m_{3/2}$

$$\frac{n_{3/2}}{n_\gamma} \sim \frac{\Gamma}{H} \sim T \frac{m_{\tilde{g}}^2}{M_P m_{3/2}^2}$$

Gravitino Production

Standard Picture:

gluon + gluon → gluino + gravitino

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$m_{\tilde{g}} > m_{3/2}$

Not possible if $m_{\tilde{g}} > m_\phi$

Gravitino Production

$$m_{\tilde{g}} > m_\phi \qquad m_{3/2} = \frac{F}{\sqrt{3}M_P} > \frac{m_\phi^2}{\sqrt{3}M_P} \simeq 0.2 \text{ EeV}$$

gluon + gluon → gravitino + gravitino

$$\langle \sigma v \rangle \sim \frac{T^6}{M_P^4 m_{3/2}^4}$$

$$\Gamma \sim \frac{T^9}{M_P^4 m_{3/2}^4} \qquad \frac{n_{3/2}}{n_\gamma} \sim \frac{\Gamma}{H} \sim \frac{T^7}{M_P^3 m_{3/2}^4}$$

$$\Omega_{3/2} h^2 \simeq 0.11 \left(\frac{0.1 \text{ EeV}}{m_{3/2}} \right)^3 \left(\frac{T_{RH}}{2.0 \times 10^{10} \text{ GeV}} \right)^7$$

Detection?

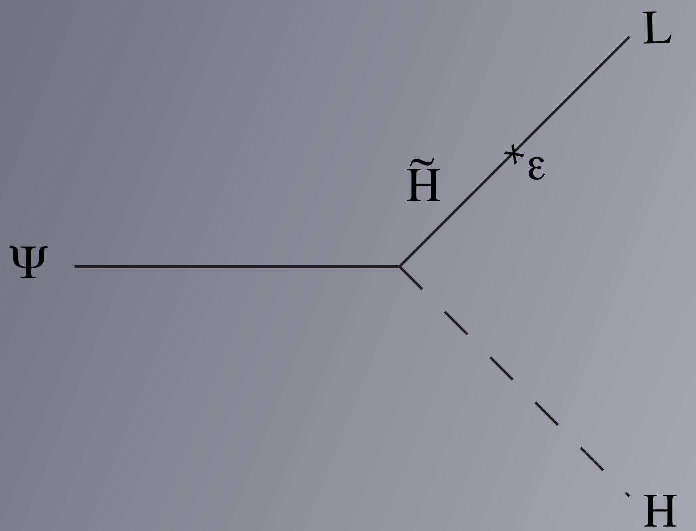
Dudas, Gherghetta, Kaneta, Mambrini, Olive

Signatures of decay with R-parity violation

$$W_{\rm RPV} = \mu' L H_u.$$

Normally, $\mu' < 2 \times 10^{-5}\mathrm{GeV}$ from L-violating interactions

High Scale Susy: $\mu' < 2 \times 10^{-7} \left(\dfrac{\mu \tilde{m}^{1/2}}{\mathrm{GeV}^{3/2}} \right) \; \mathrm{GeV}$



$$\Gamma_{\rm tot} \simeq \frac{\epsilon^2 c_\beta^2 m_{3/2}^3}{16\pi M_P^2} \qquad \epsilon = \mu'/\mu$$

$$\tau_{3/2} \simeq 10^{28} \left(\frac{0.44 \times 10^{-20}}{\epsilon c_\beta} \right)^2 \left(\frac{1 \ \mathrm{EeV}}{m_{3/2}} \right)^3 \mathrm{s}.$$

Even Larger Mass Scales

Planck Scale SUSY $\equiv$ no susy at low energy

Even Larger Mass Scales

Planck Scale SUSY $\equiv$ no susy at low energy

SO(10) GUT?

Even Larger Mass Scales

Planck Scale SUSY $\equiv$ no susy at low energy

SO(10) GUT?

- Hierarchy Problem - No
- Gauge Coupling Unification
- Stabilization of the Electroweak Vacuum
- Radiative Electroweak Symmetry Breaking
- Dark Matter -Yes
- Neutrino masses…

Summary

- LHC susy and Higgs searches have pushed CMSSM-like models to “corners” or strips
- However, still viable and more so beyond the CMSSM
- But maybe the susy spectrum is very heavy
- Is Susy at the multi-TeV or PeV or EeV scale?
- Perhaps sparticles were never part of the thermal background, yet the gravitino may still be the dark matter!
- Can we learn more from a UV completion?
- Signatures at the EeV scale?