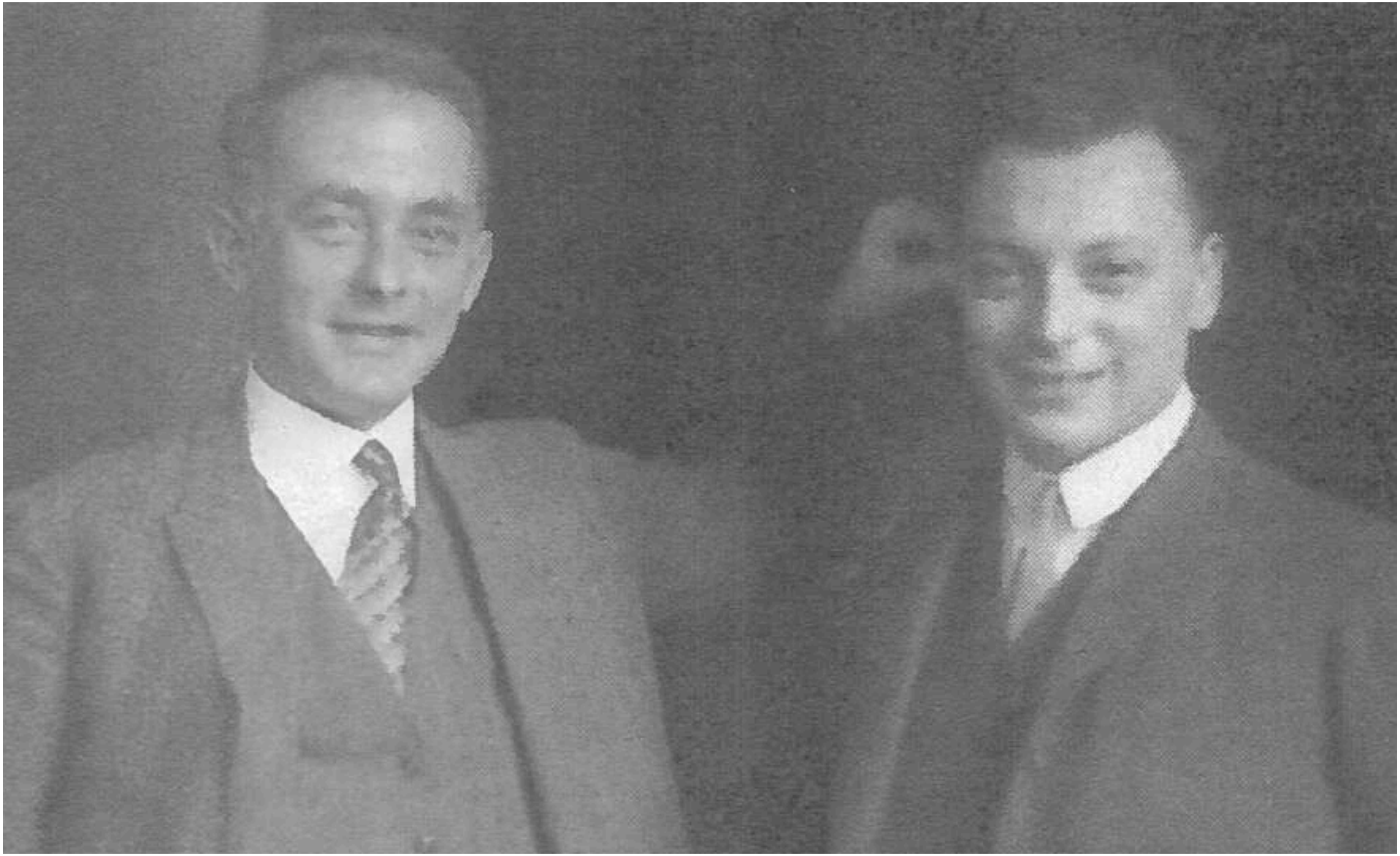
Elusive Particle, Desperate Remedy

thanks to
Devin Walker

M. E. Peskin
W. Pauli Center Opening
April 2013



Max Born and Wolfgang Pauli in Hamburg - 1925
(© CERN; from C. Enz’s biography)

Max Born to Einstein, 1925:

... the report on the "little Pauli" is not complete. I remember that he liked to sleep late, and he missed the lecture at eleven o'clock more than once. We then sent him our maid at half-past-ten to be sure that he was up. Without question, he was a first-rate genius, but my apprehension "such a good assistant I will never have again" was yet unjustified. His successor Heisenberg was as intelligent and more conscientious at that; him, we did not have to waken or otherwise remind him of his duties.

.. an older Pauli, already Professor at ETH, Zürich ..

Nov. 26, 1930: Pauli's divorce from Kate Deppner (soon, Kate Goldfinger)

Dec. 4, 1930: Pauli's letter to Lisa Meitner's conference on radioactivity at Tübingen:

I have hit upon a desperate remedy to save the "exchange law" (1) of statistics and the energy law. This is the possibility that there might exist in nuclei electrically neutral particles ...

Our situation in physics today is perhaps not quite so intractable,

but still we feel some desperation.

We have a coherent picture of physics that explains both the phenomena of the Standard Model and the most important phenomena and regularities outside this model.

But, the needed evidence for this theory has not appeared.

I will describe a solution that involves an new elusive particle, the singlino.

I make no claim to genius or originality. This particle has been studied for many years by Urs Ellwanger, Jack Gunion, Sabine Kraml, and others.

comprehensive review (pre-LHC):

Ellwanger, Hugonie, and Teixeira, arXiv:0910.1785

Standard Model of Particle Physics

symmetry group: SU(3)xSU(2)xU(1)

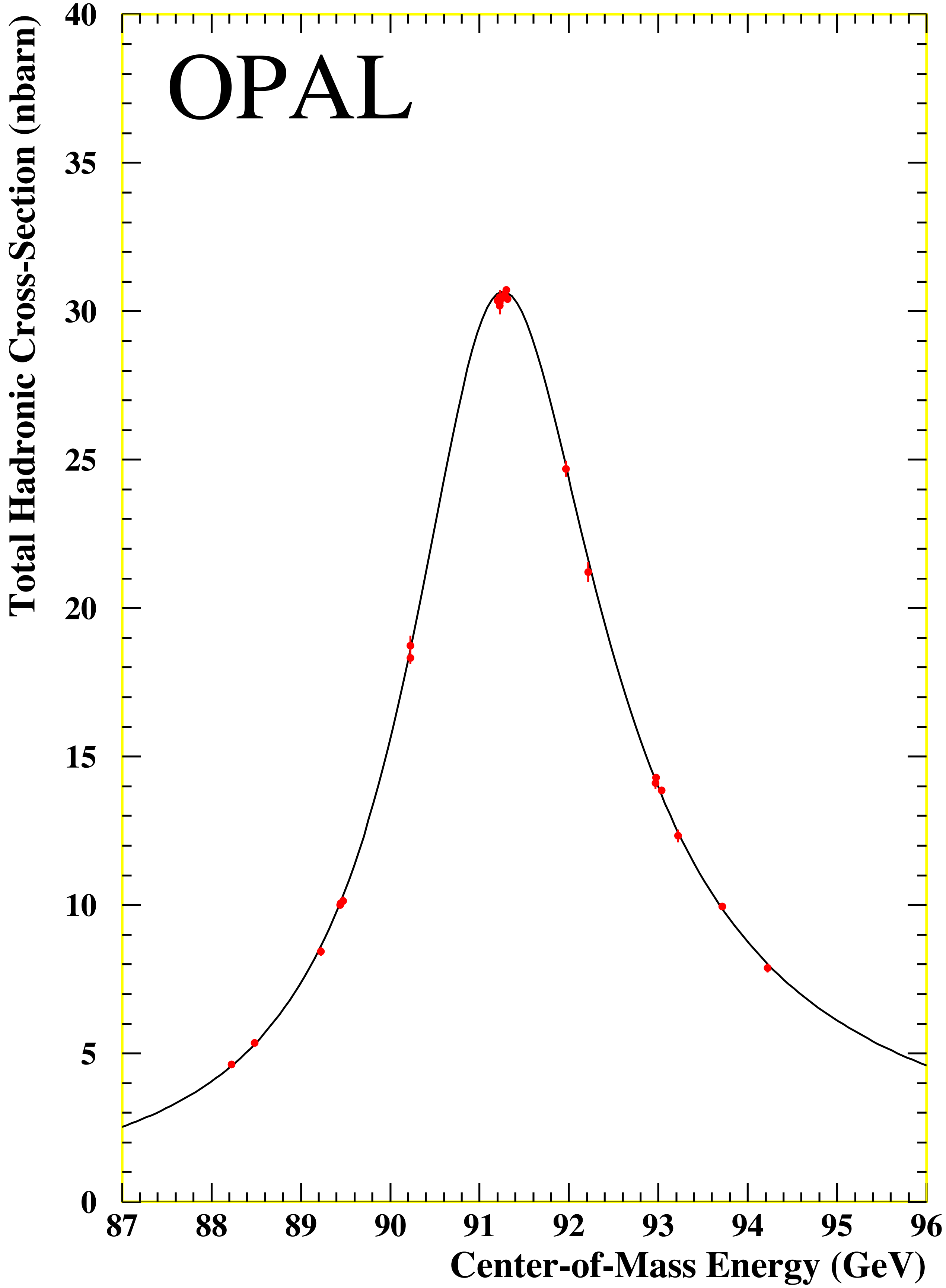
vector bosons: $g \; , \; \gamma \; , \; W^+ \; , \; W^- \; , \; Z^0$

fermions in the representations:

$$I = \frac{1}{2} \; : \; \begin{pmatrix} \nu \\ e \end{pmatrix}_L \; , \; \begin{pmatrix} u \\ d \end{pmatrix}_L \qquad I = 0 \; : \; e^-_R \; , \; u_R \; , \; d_R$$

Z boson charges:

$$Q_Z = I^3 - s_w^2 Q$$


OPAL
Total Hadronic Cross-Section (nbarn)
Center-of-Mass Energy (GeV)
0
5
10
15
20
25
30
35
40
87
88
89
90
91
92
93
94
95
96

but, the model is incomplete:

many different representations ?

the Higgs boson and its potential ?

dark matter ?

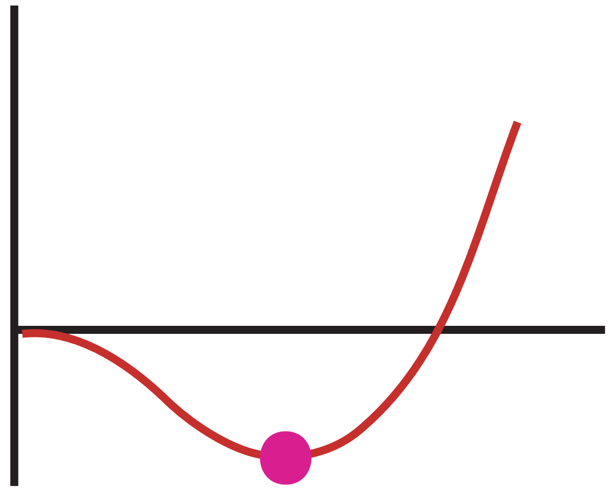
The problem of the Higgs potential has many aspects:

1. need to postulate a scalar field

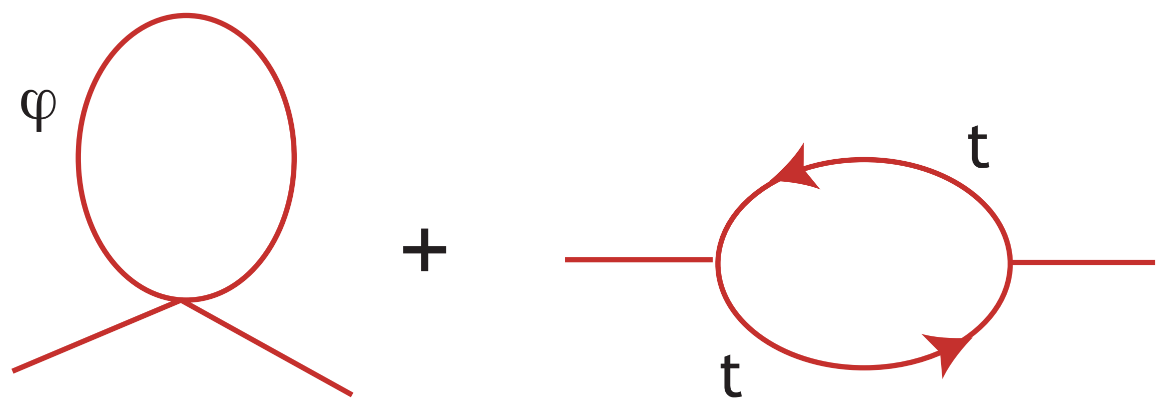
2. no explanation for the scalar potential

$$V(\varphi) = \mu^2 |\varphi|^2 + \lambda |\varphi|^4$$

3. instability with respect to radiative corrections



$$\mu^2 = \mu^2_{\text{bare}} + \frac{\lambda}{8\pi^2}\Lambda^2 - \frac{3y_t^2}{8\pi^2}\Lambda^2 + \cdots$$



This is sometimes called the "hierarchy problem", but in fact it is a no-physics-insight problem

A beautiful explanation for the fermion quantum numbers: grand unification in SU(5) or SO(10)

$$SU(3)\ :\ \begin{pmatrix} t^a & \\ & 0 \end{pmatrix}\ ;\quad SU(2)\ :\ \begin{pmatrix} 0 & \\ & \sigma^a/2 \end{pmatrix}\ ;\quad U(1)\ :\ \sqrt{\frac{3}{5}}\begin{pmatrix} -\frac{1}{3}\mathbf{1} & \\ & \frac{1}{2}\mathbf{1} \end{pmatrix}$$

$$\overline{5}\ :\ \begin{pmatrix} \overline{d} \\ \overline{d} \\ \overline{d} \\ e \\ \nu \end{pmatrix}_L\ ;\qquad 10\ :\ \begin{pmatrix} 0 & \overline{u} & \overline{u} & u & d \\ & 0 & \overline{u} & u & d \\ & & 0 & u & d \\ & & & 0 & \overline{e} \\ & & & & 0 \end{pmatrix}_L$$

for example, for u, d : $\quad Y = \frac{1}{2} - \frac{1}{3} = \frac{1}{6}$

for $\overline{u}$: $\quad Y = 2(-\frac{1}{3}) = -\frac{2}{3}$

Grand unification predicts

$$g_s = g = \sqrt{5/3}\, g'$$

a rather poor relation.

This is remedied,

qualitatively but not quantitatively,

by the running of coupling constants.

A context for answering the remaining questions is provided by the postulate of supersymmetry:

$$Q_\alpha \varphi = \psi_\alpha$$
$$Q_\alpha \psi_\beta = (\sigma \cdot \partial)_{\alpha\beta} \varphi$$

The algebra of charges (Wess-Zumino) is

$$\{Q_\alpha, Q^\dagger_\beta\} = 2\sigma^m_{\alpha\beta} \, P_m$$

All particles and fields must be included.

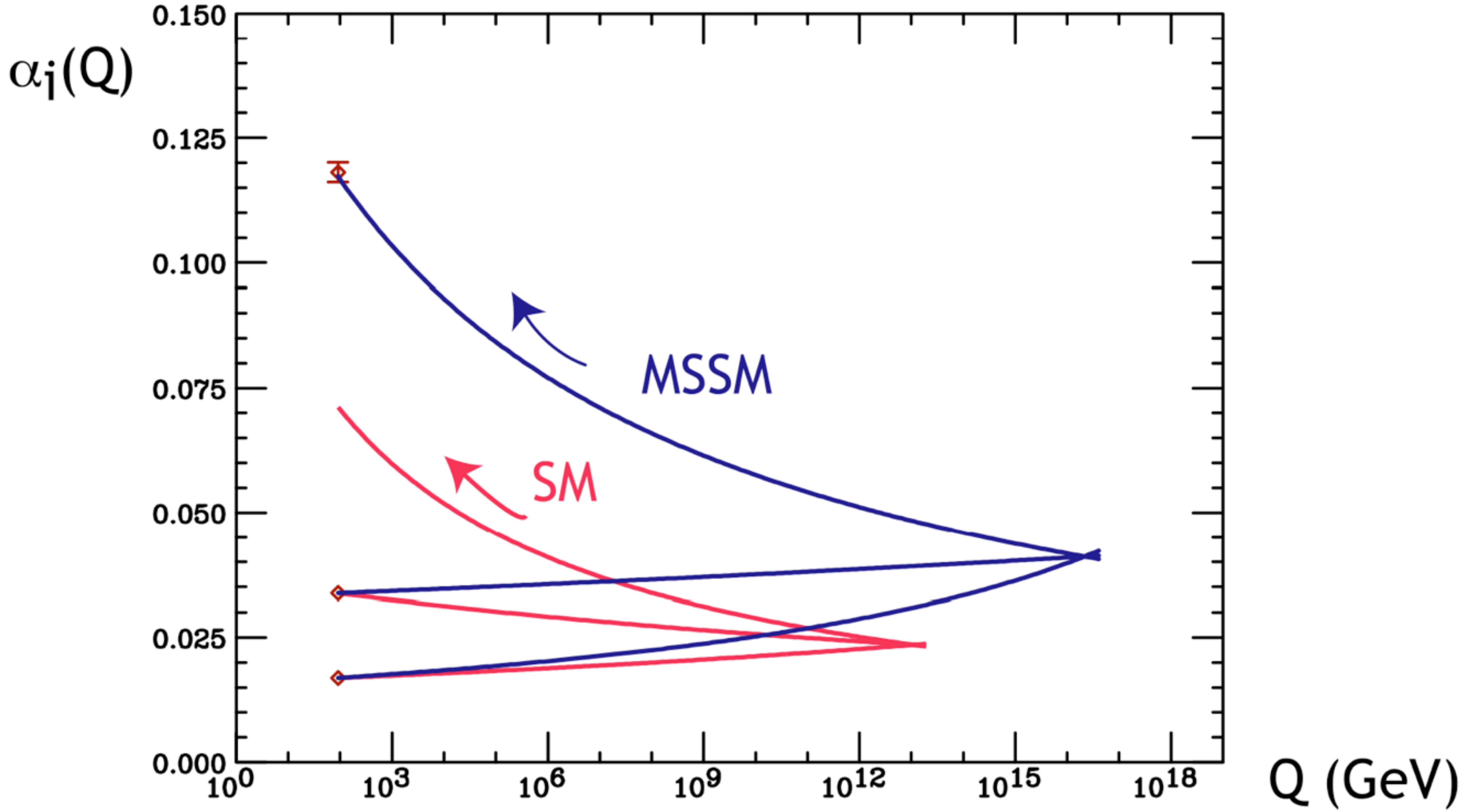
Supersymmetry (SUSY) thus requires a doubling of all particles of the Standard Model:

$$L = \begin{pmatrix} \nu \\ e \end{pmatrix} \qquad \overline{e} \qquad Q = \begin{pmatrix} u \\ d \end{pmatrix} \qquad \overline{u} \qquad \overline{d}$$

requires

$$\widetilde{L} \qquad \widetilde{\overline{e}} \qquad \widetilde{Q} \qquad \widetilde{\overline{u}} \qquad \widetilde{\overline{d}}$$

This can be good thing :



αi(Q)
0.150
0.125
0.100
0.075
0.050
0.025
0.000
MSSM
SM
10^0
10^3
10^6
10^9
10^12
10^15
10^18
Q (GeV)

SUSY leads to a complicated but ultimately appealing story for the Higgs field potential:

1. SUSY gives a raison d'être for the presence of scalar fields

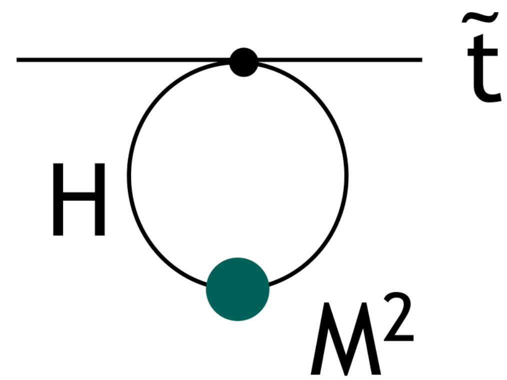
2. SUSY causes all quadratic divergences to cancel

3. It is easy to arrange that, if SUSY is unbroken,

$$\langle \varphi \rangle = 0$$

so the Higgs potential is a secondary consequence of spontaneous SUSY breaking.

4. After spontaneous SUSY breaking, a calculable effect produces $\mu^2 < 0$



$$\frac{dM_t^2}{d\log Q} = \frac{2}{(4\pi)^2} \cdot 1 \cdot y_t^2[M_t^2 + M_{\bar{t}}^2 + M_{Hu}^2 + A_t^2] - \frac{8}{3\pi}\alpha_3 m_3^2 + \cdots$$

$$\frac{dM_{\bar{t}}^2}{d\log Q} = \frac{2}{(4\pi)^2} \cdot 2 \cdot y_t^2[M_t^2 + M_{\bar{t}}^2 + M_{Hu}^2 + A_t^2] - \frac{8}{3\pi}\alpha_3 m_3^2 + \cdots$$

$$\frac{dM_{Hu}^2}{d\log Q} = \frac{2}{(4\pi)^2} \cdot 3 \cdot y_t^2[M_t^2 + M_{\bar{t}}^2 + M_{Hu}^2 + A_t^2] m_3^2 + \cdots$$

SUSY requires two Higgs fields H_u , H_d

Their mass matrix has the form

$$\begin{pmatrix} m_A^2 \sin^2\beta + m_Z^2 \cos^2\beta & -(m_A^2 + m_Z^2)\sin\beta\cos\beta \\ -(m_A^2 + m_Z^2)\sin\beta\cos\beta & m_A^2 \cos^2\beta + m_Z^2 \sin^2\beta \end{pmatrix}$$

where $\tan\beta = \langle H_u\rangle \,/\, \langle H_d\rangle$

The lowest eigenvalue satisfies

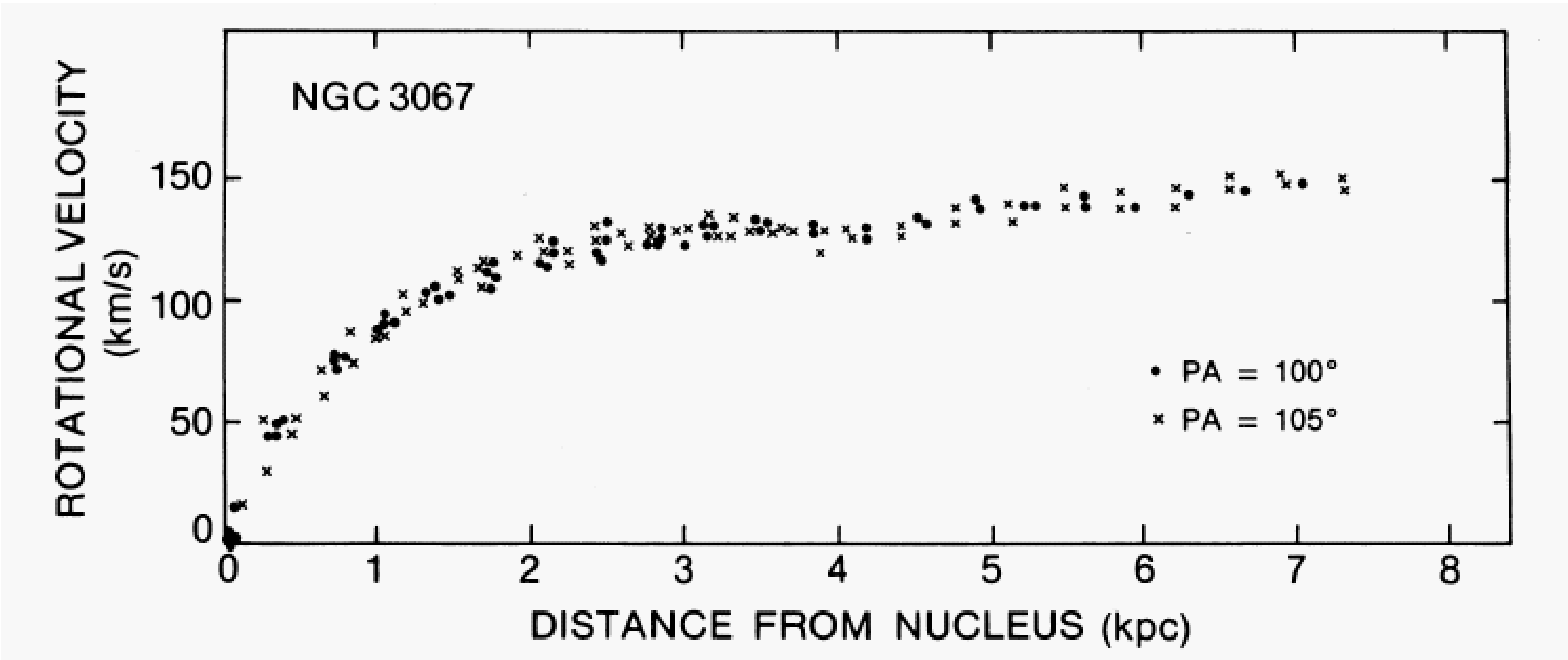
$$m_h^2 \leq m_Z^2 \cos^2 2\beta$$

There is a bonus:

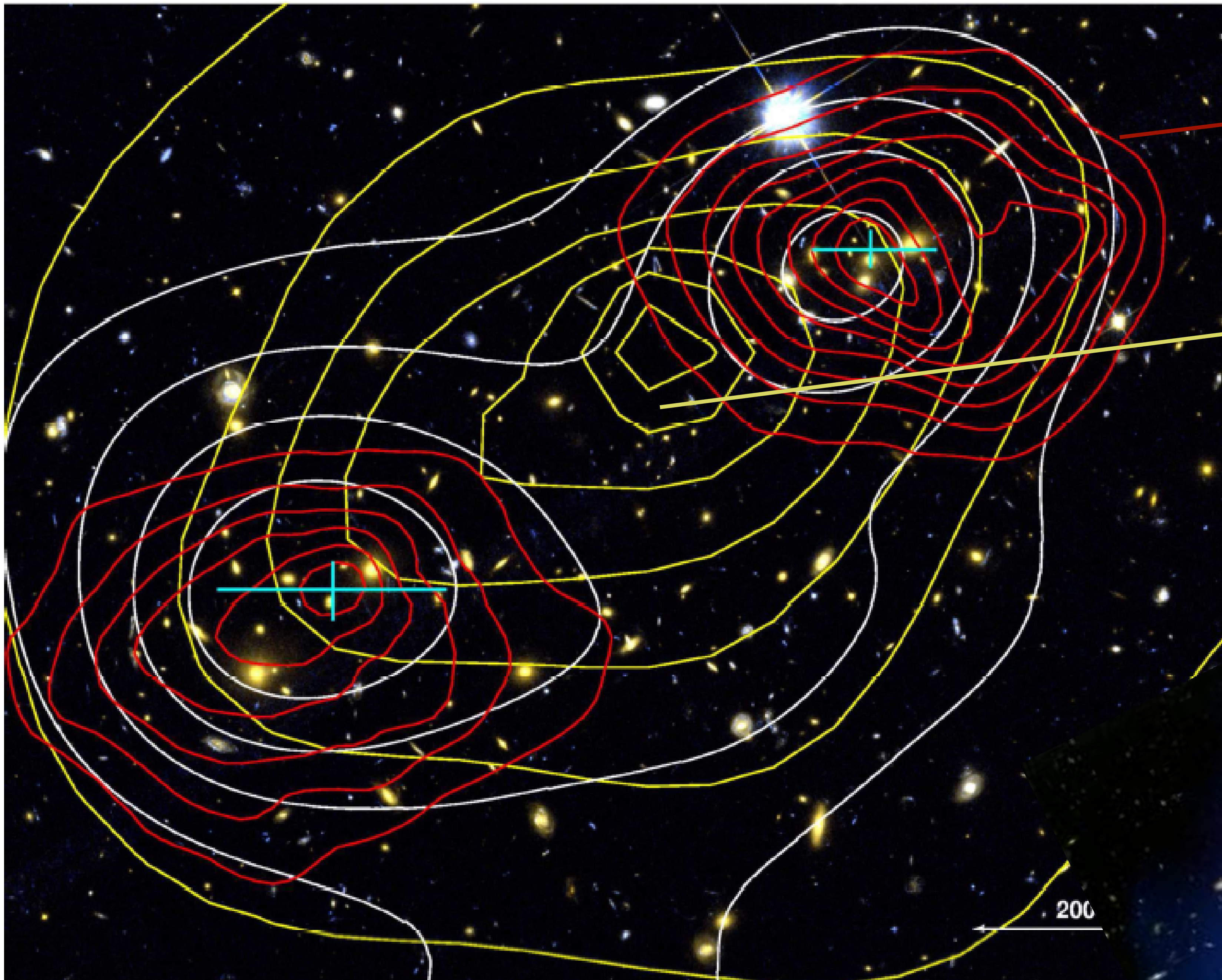
All SUSY-conserving interactions and (almost) all effective interactions generated by SUSY breaking respect the symmetry

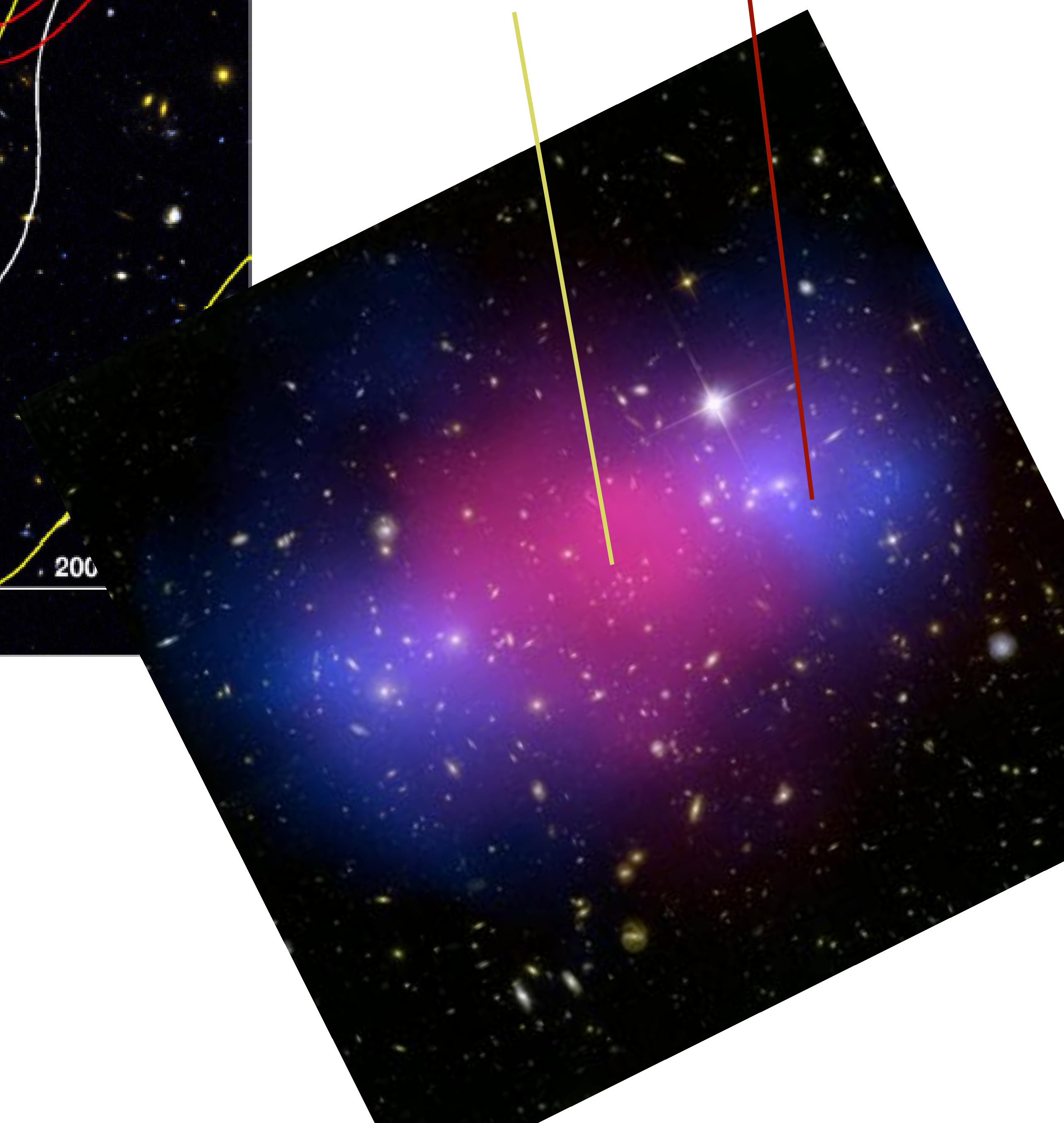
$$R = (-1)^{L+Q+2J}$$

Typically, the lightest SUSY particle absolutely stable.

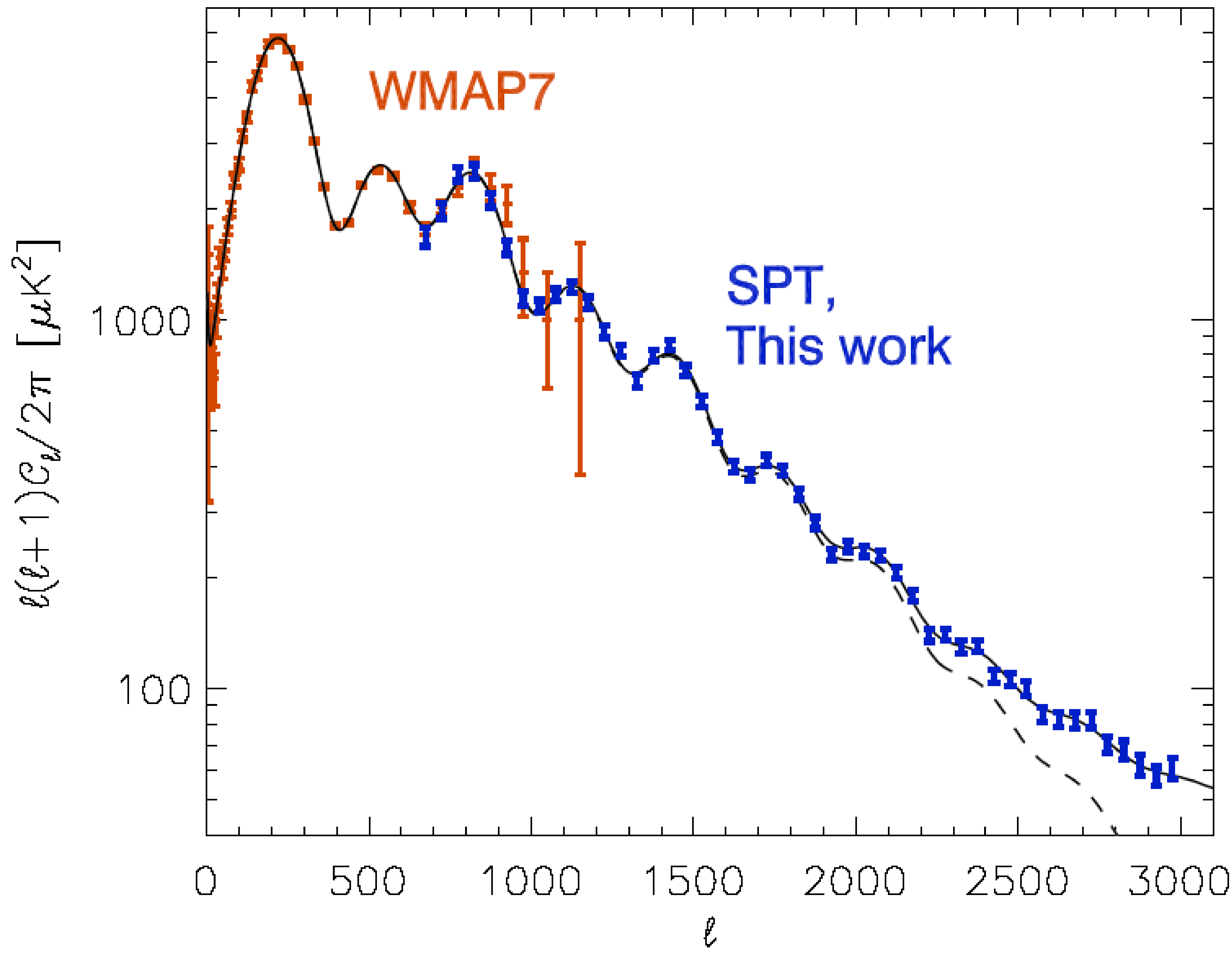


Rubin, Thonnard, Ford





MACS J0025.4-1222 images in X-ray (Chandra) and gravitational lensing



WMAP7
SPT,
This work
1000
100
0
500
1000
1500
2000
2500
3000
ℓ
$\ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$

Consistently between these probes, dark matter makes up about 80% of the mass in the universe.

Dark matter is an insult to particle physicists. It is not present in the Standard Model, and it does not appear at our accelerators.

Thermal WIMP model:

Dark matter is neutral, stable, weakly interacting, and produced thermally in the early universe.

$$\Omega_N = \frac{s_0}{\rho_c}\left(\frac{45}{\pi g_*}\right)^{1/2}\frac{1}{\xi_f m_{\rm Pl}}\frac{1}{\langle\sigma v\rangle}$$

from this equation

$$\langle\sigma v\rangle = 1\ \mathrm{pb}$$

or $\langle\sigma v\rangle = \dfrac{\pi\alpha^2\hbar^2}{2m^2c^2}$ where m = 200 GeV.

In SUSY, the spin 1/2 partners of γ, Z^0, H_u, H_d are WIMPs.

It is a wonderful story.

If only reality were not so harsh.

1. Failure to discover the Higgs boson at LEP

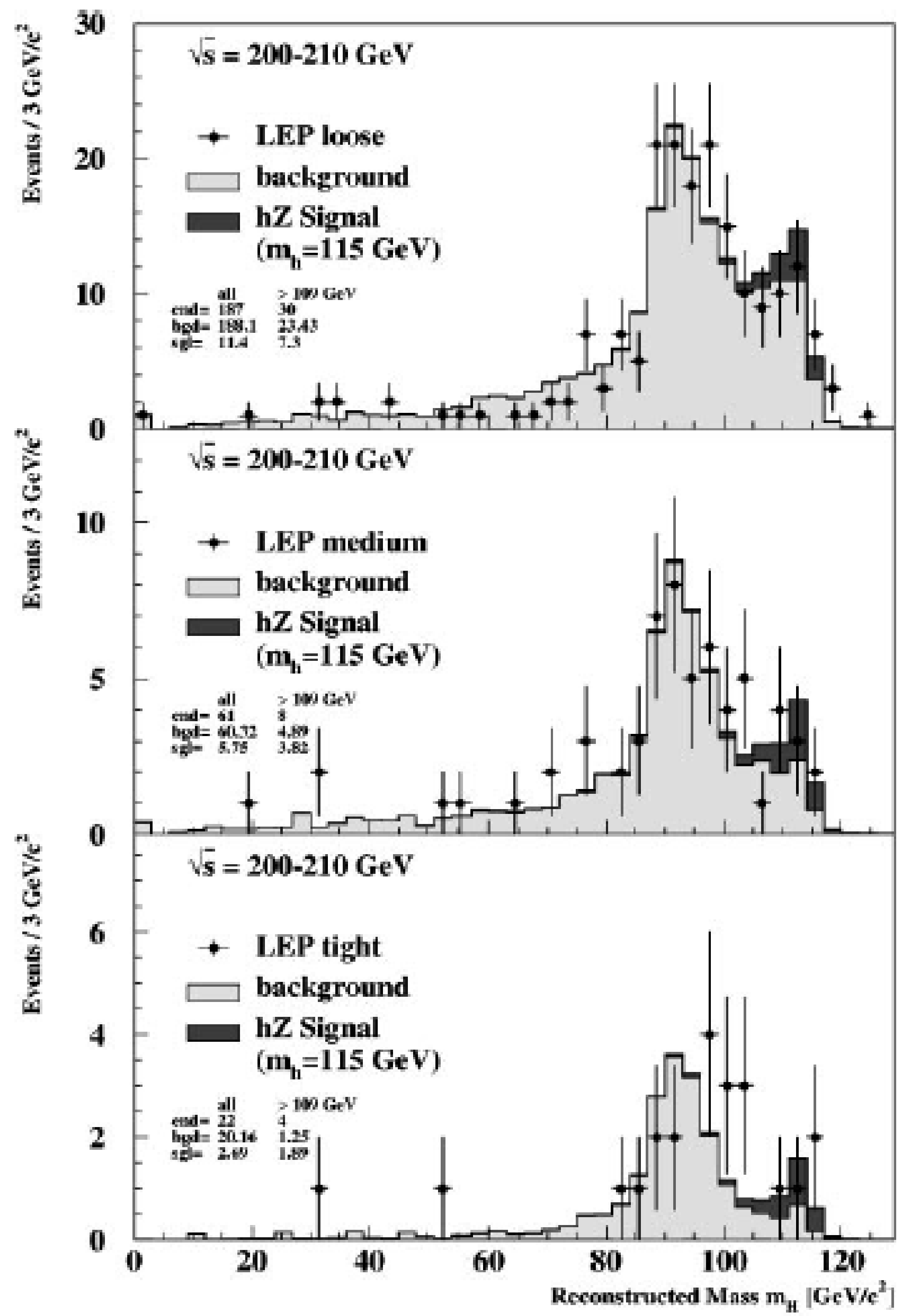
I told you that

$$m_h^2 \leq m_Z^2 \cos^2 2\beta$$

The LHC experiments have now discovered the Higgs boson at

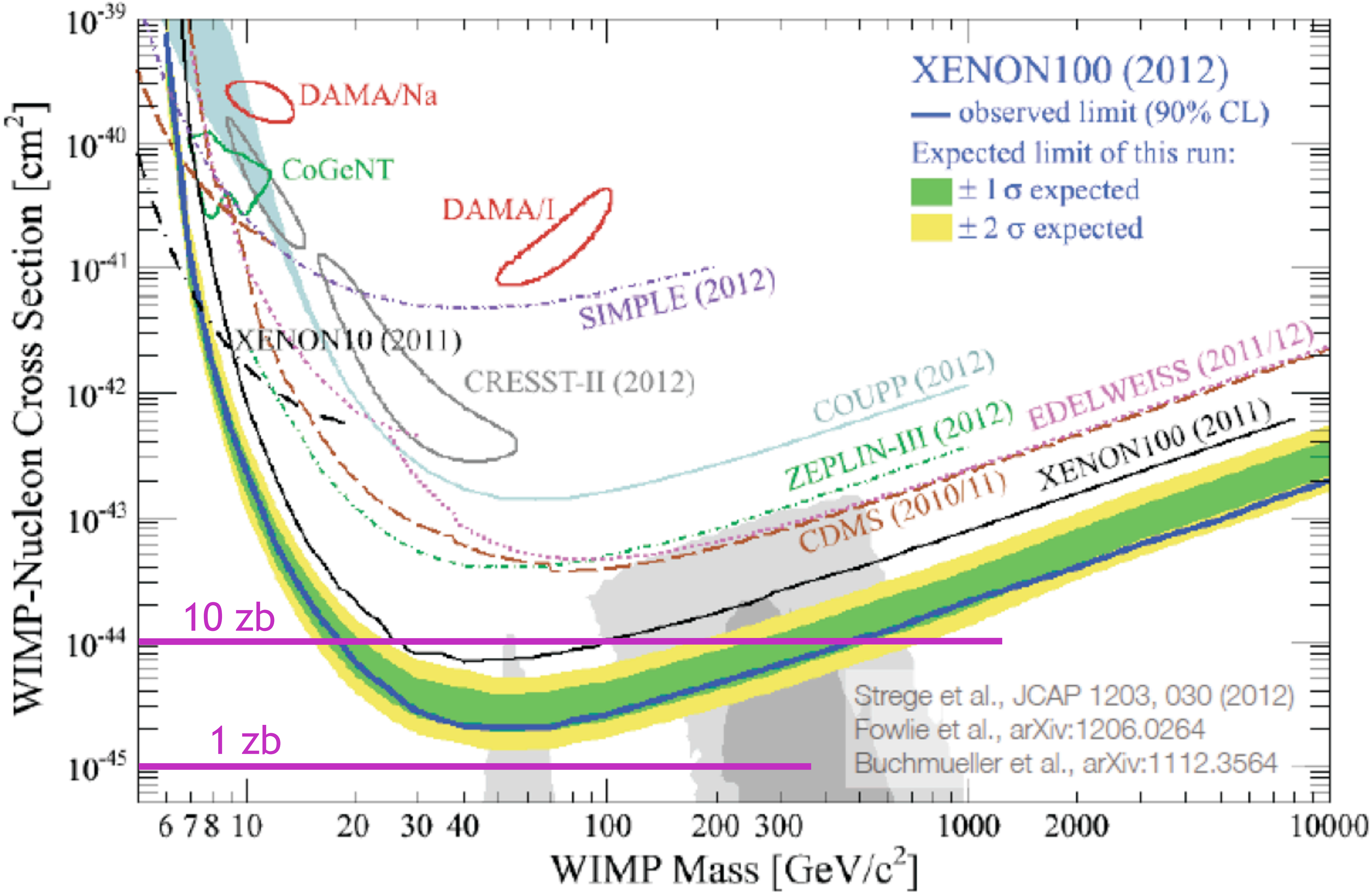
$$m_h = 125 \text{ GeV}$$

but this value does not satisfy the inequality.



Kado and Tully

2. Failure to discover dark matter in direct detection experiments



Mao, Strigari, Wechsler, Wu, Han, arXiv:1210.2721:

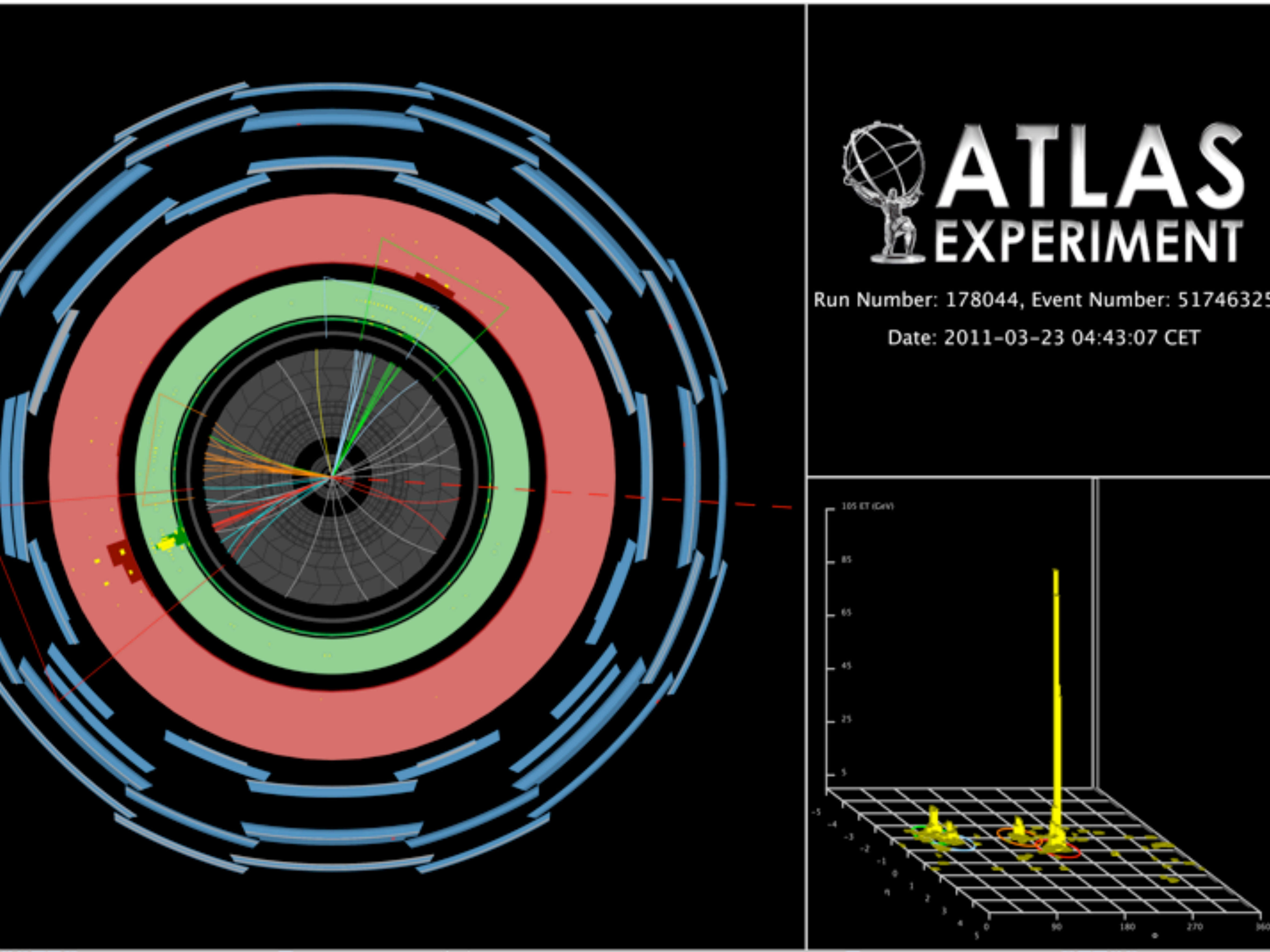
The conventional assumptions about the dark matter halo of the galaxy give limits about a factor 2 too strong.

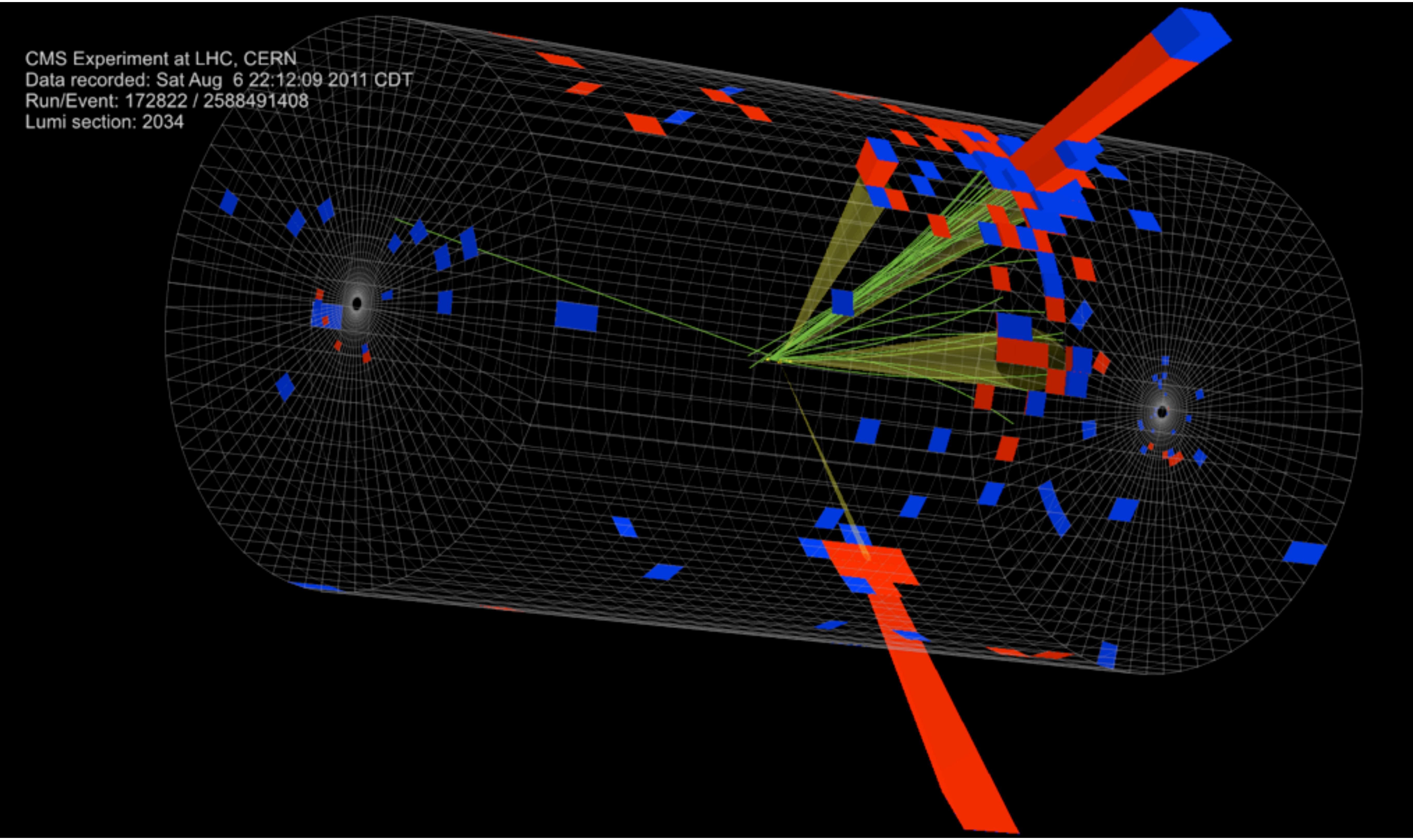
The next generation of experiments will in any event improve the sensitivity by orders of magnitude.

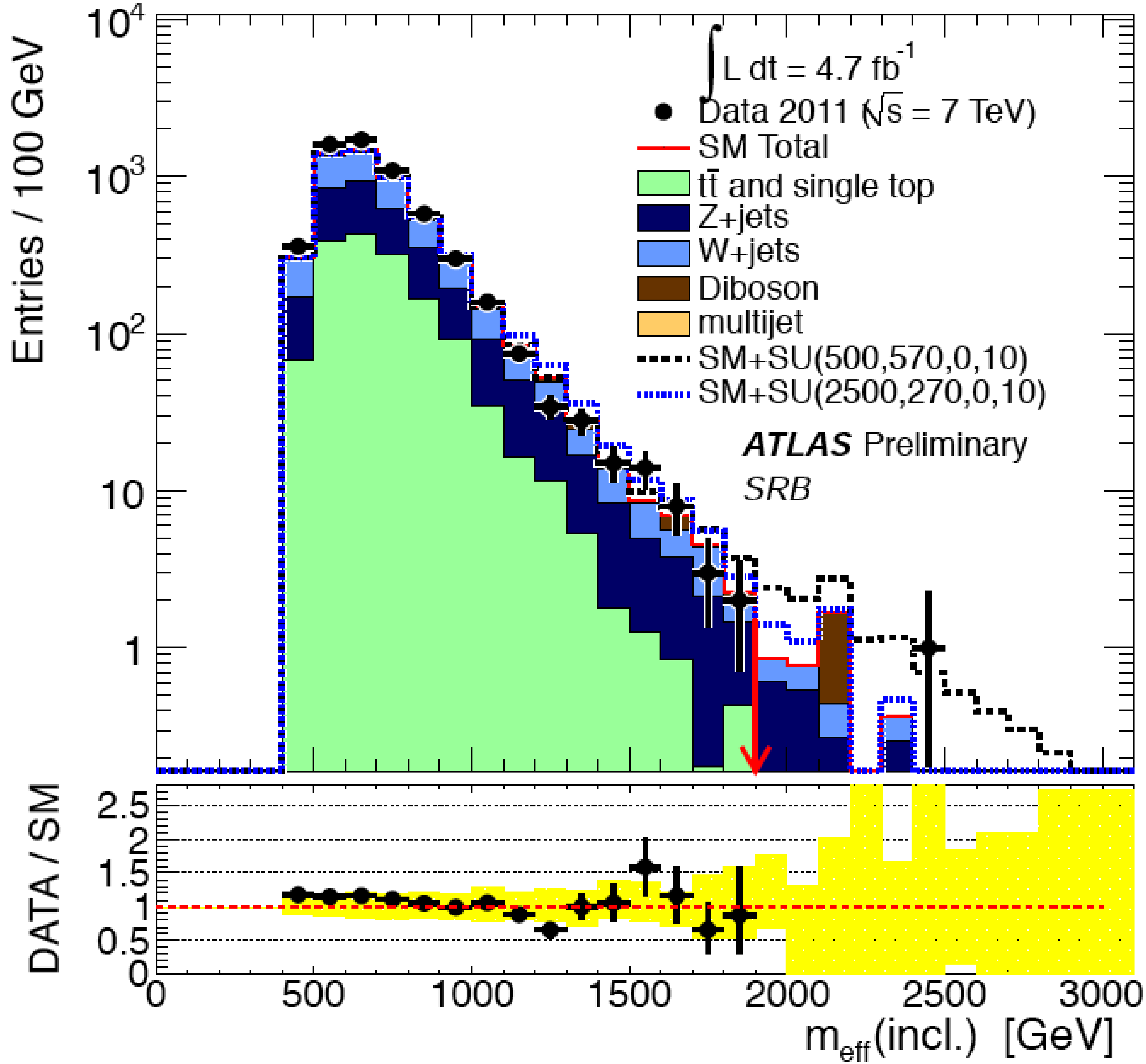
3. Failure to discover events with jets + missing ET at the LHC

If the lightest SUSY particle is neutral, stable, and weakly interacting, it should carry off unobserved momentum from high-energy collisions.

In fact, events with SUSY production should result in two unobserved particles.

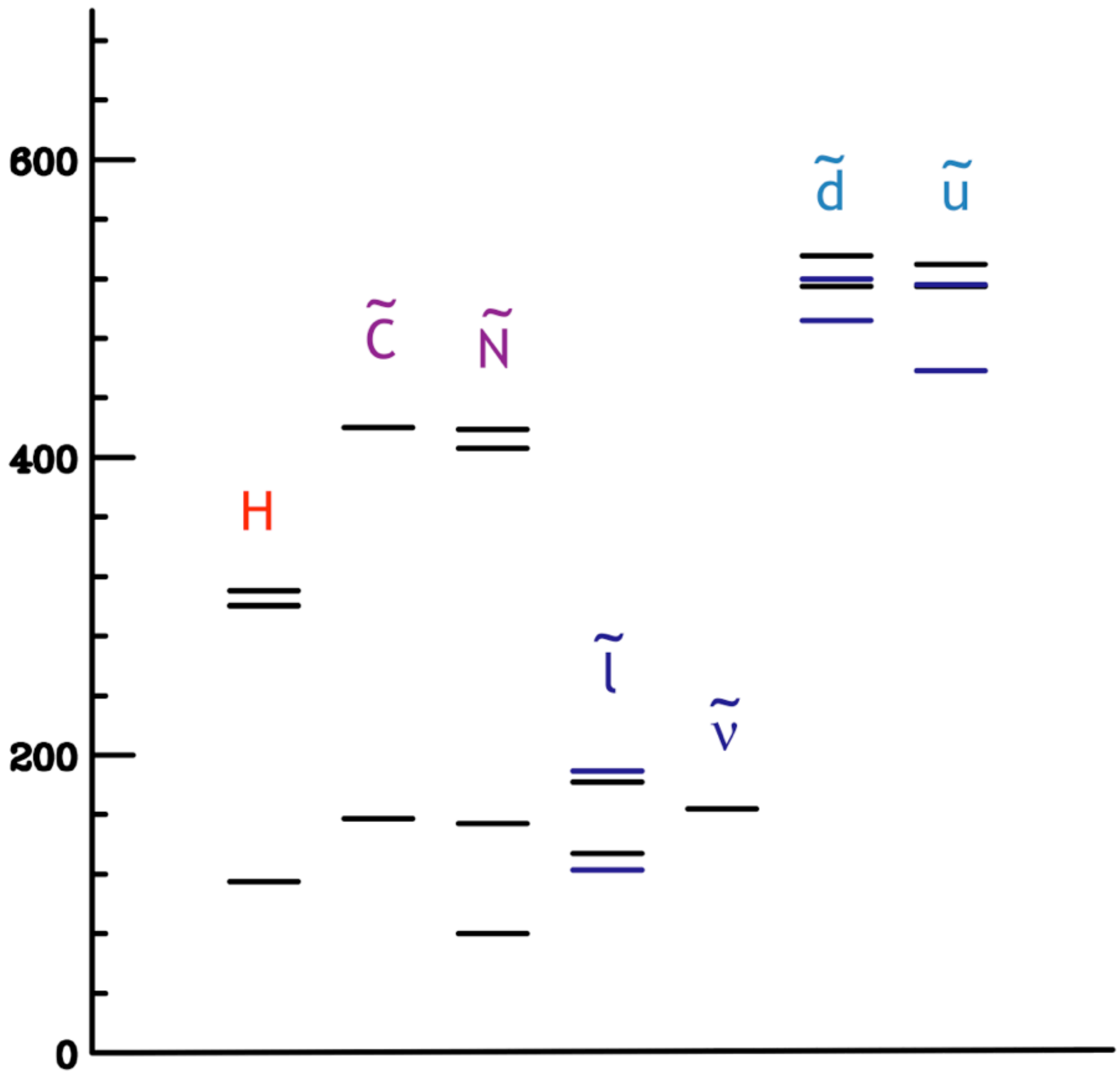

ATLAS
EXPERIMENT
Run Number: 178044, Event Number: 51746325
Date: 2011-03-23 04:43:07 CET
105 ET (GeV)
85
65
45
25
5
0
90
180
270


CMS Experiment at LHC, CERN
Data recorded: Sat Aug 6 22:12:09 2011 CDT
Run/Event: 172822 / 2588491408
Lumi section: 2034

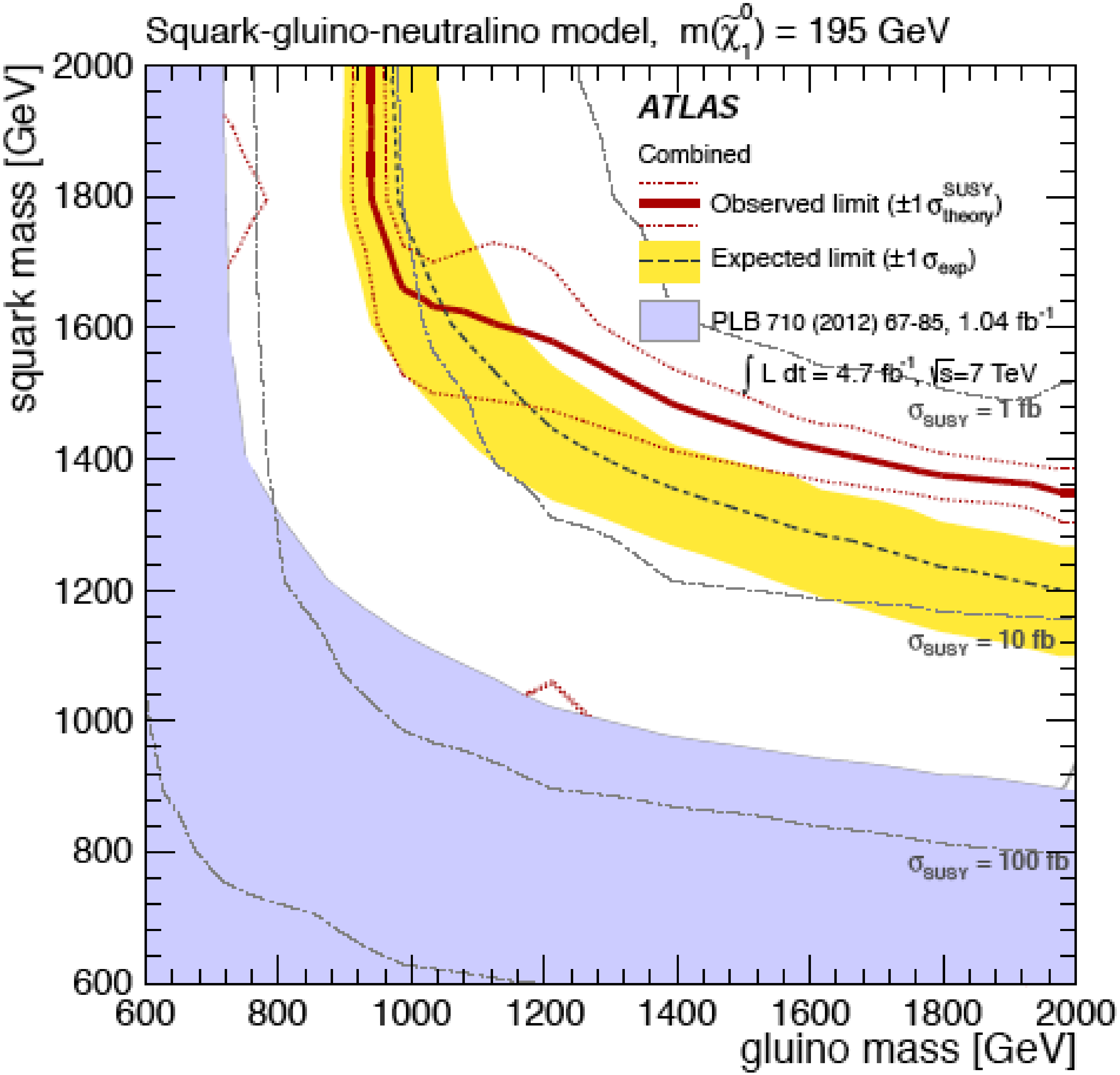


$\int L\,dt = 4.7\ fb^{-1}$
Data 2011 ($\sqrt{s}$ = 7 TeV)
SM Total
$t\bar{t}$ and single top
Z+jets
W+jets
Diboson
multijet
SM+SU(500,570,0,10)
SM+SU(2500,270,0,10)
ATLAS Preliminary
SRB
Entries / 100 GeV
DATA / SM
m_{eff}(incl.) [GeV]

a typical pre-2010 SUSY spectrum:



in the context of such models:



Where must the SUSY partners be ?

argument from "naturalness":

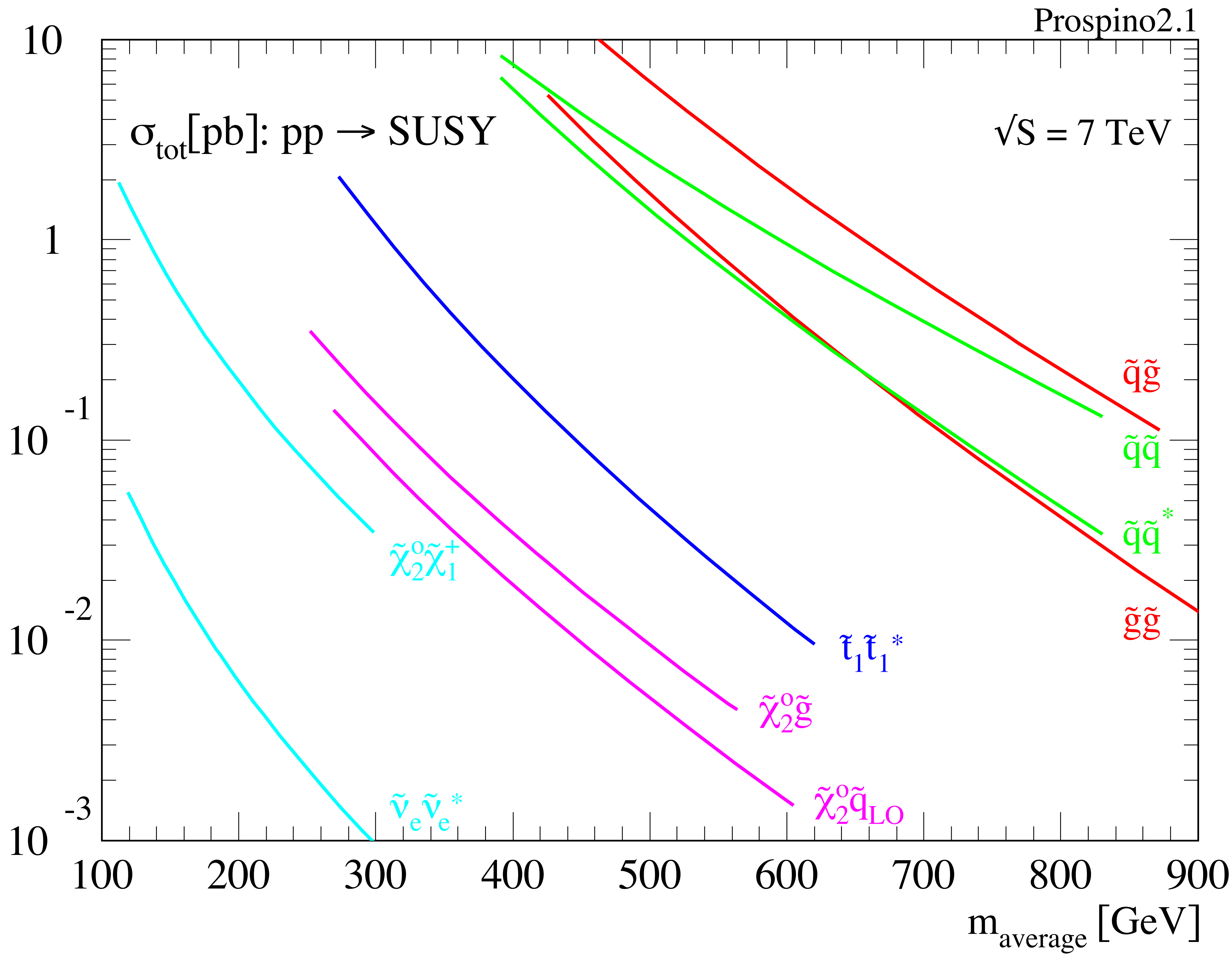
$$m_Z^2 = 2\,\frac{M_{Hd}^2 - \tan^2\beta M_{Hu}^2}{\tan^2\beta - 1} - 2\mu^2$$

μ appears directly : $m(\widetilde{h}) < 200\ \mathrm{GeV}$

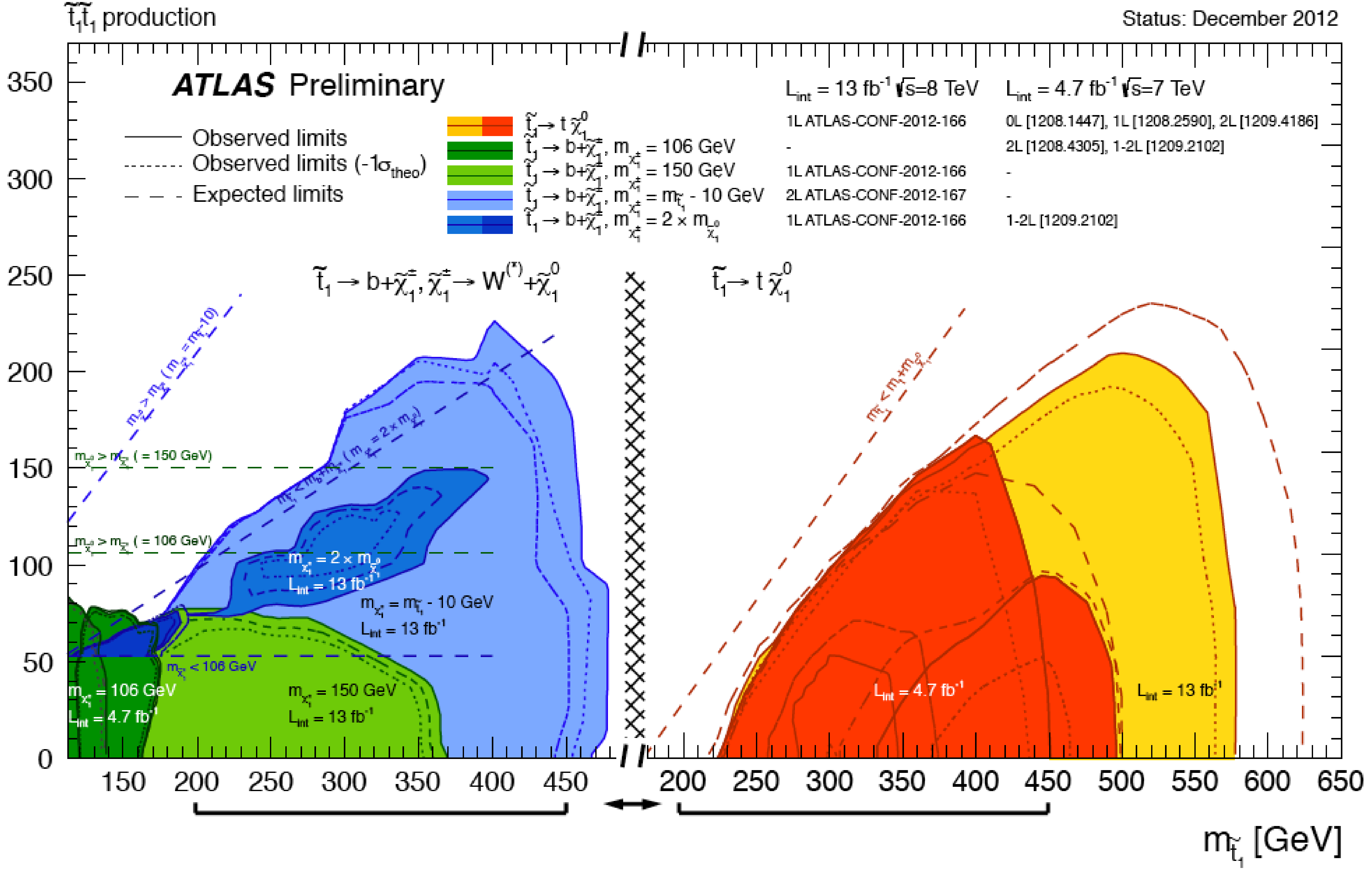
$\widetilde{t}$ renormalizes $m(\widetilde{H}_u)$: $m(\widetilde{t}) < 1000\ \mathrm{GeV}$

$\widetilde{g}$ renormalizes $m(\widetilde{t})$: $m(\widetilde{g}) < 3000\ \mathrm{GeV}$

Other SUSY masses can be much higher.



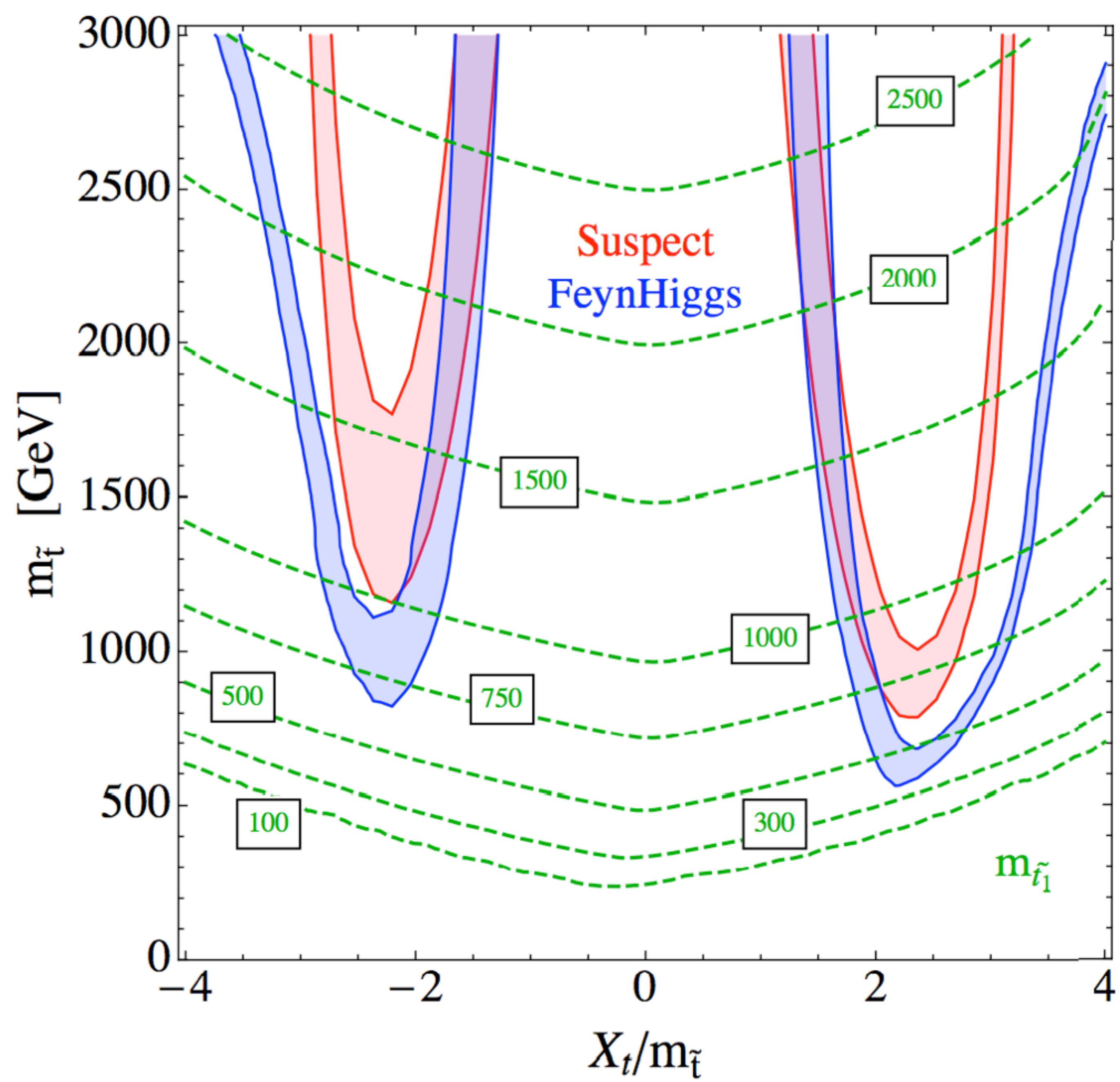
Prospino: Beenacker, Plehn, Spira et al.



$\tilde{t}_1\tilde{t}_1$ production
Status: December 2012
ATLAS Preliminary
Observed limits
Observed limits ($-1\sigma_{theo}$)
Expected limits
$\tilde{t}_1 \to t\,\tilde{\chi}_1^0$
$\tilde{t}_1 \to b+\tilde{\chi}_1^\pm$, $m_{\tilde{\chi}_1^\pm}$ = 106 GeV
$\tilde{t}_1 \to b+\tilde{\chi}_1^\pm$, $m_{\tilde{\chi}_1^\pm}$ = 150 GeV
$\tilde{t}_1 \to b+\tilde{\chi}_1^\pm$, $m_{\tilde{\chi}_1^\pm} = m_{\tilde{t}_1}$ - 10 GeV
$\tilde{t}_1 \to b+\tilde{\chi}_1^\pm$, $m_{\tilde{\chi}_1^\pm} = 2 \times m_{\tilde{\chi}_1^0}$
L_{int} = 13 fb^{-1} $\sqrt{s}$=8 TeV
L_{int} = 4.7 fb^{-1} $\sqrt{s}$=7 TeV
1L ATLAS-CONF-2012-166
0L [1208.1447], 1L [1208.2590], 2L [1209.4186]
2L [1208.4305], 1-2L [1209.2102]
1L ATLAS-CONF-2012-166
2L ATLAS-CONF-2012-167
1L ATLAS-CONF-2012-166
1-2L [1209.2102]
$\tilde{t}_1 \to b+\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \to W^{(*)}+\tilde{\chi}_1^0$
$\tilde{t}_1 \to t\,\tilde{\chi}_1^0$
$m_{\tilde{\chi}_1^\pm} = 2 \times m_{\tilde{\chi}_1^0}$
L_{int} = 13 fb^{-1}
$m_{\tilde{\chi}_1^\pm} = m_{\tilde{t}_1}$ - 10 GeV
L_{int} = 13 fb^{-1}
$m_{\tilde{\chi}_1^\pm}$ < 106 GeV
$m_{\tilde{\chi}_1^\pm}$ = 106 GeV
L_{int} = 4.7 fb^{-1}
$m_{\tilde{\chi}_1^\pm}$ = 150 GeV
L_{int} = 13 fb^{-1}
$m_{\tilde{\chi}_1^0} > m_{\tilde{\chi}_1^\pm}$ (= 150 GeV)
$m_{\tilde{\chi}_1^0} > m_{\tilde{\chi}_1^\pm}$ (= 106 GeV)
L_{int} = 4.7 fb^{-1}
L_{int} = 13 fb^{-1}
$m_{\tilde{t}_1} < m_t + m_{\tilde{\chi}_1^0}$
$m_{\tilde{t}_1}$ [GeV]
0
50
100
150
200
250
300
350
150
200
250
300
350
400
450
200
250
300
350
400
450
500
550
600
650

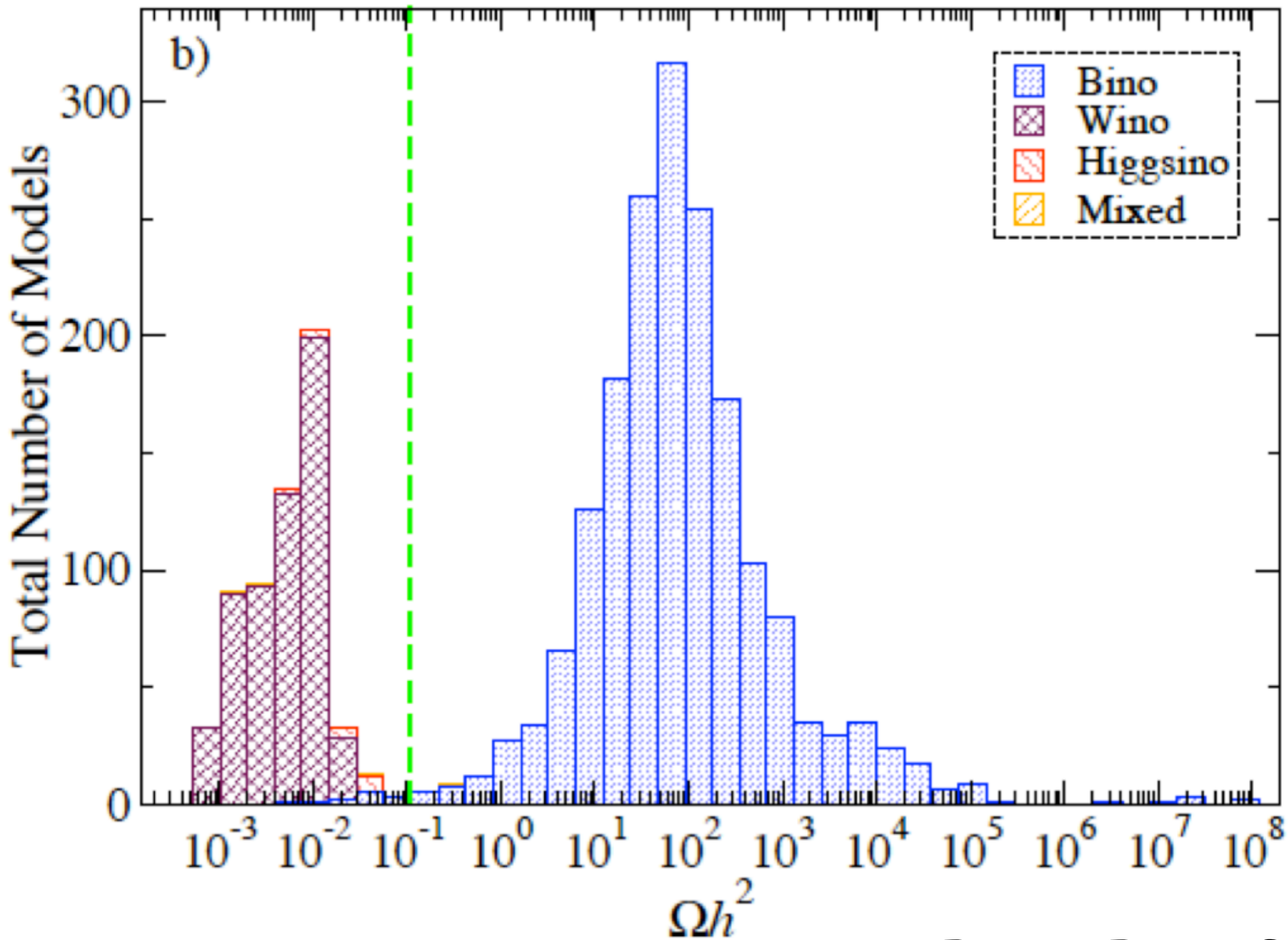
However, we must also consider the problem of the Higgs mass:

$$m_h^2 \approx m_Z^2 \cos^2 2\beta + \frac{3}{(4\pi)^2}\frac{m_t^4}{v^2}\left[\ln\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12 m_{\tilde{t}}^2}\right)\right]$$



Hall, Pinner, Ruderman

Finally, though SUSY in principle leads to a good candidate for WIMP dark matter, in practice it is not so simple:



Baer, Box, Summy

In particular, a light Higgsino consistent with the current limits is not a good dark matter candidate.

Its annihilation rate via

$$\widetilde{h}\widetilde{h} \to W^+W^-, Z^0Z^0$$

is about 10 times the required value.

(A Higgsino of 1 TeV can explain the dark matter.)

So, why not entertain the idea of the singlino ?

Add a SM singlet SUSY multiplet. This has both scalar and fermionic components.

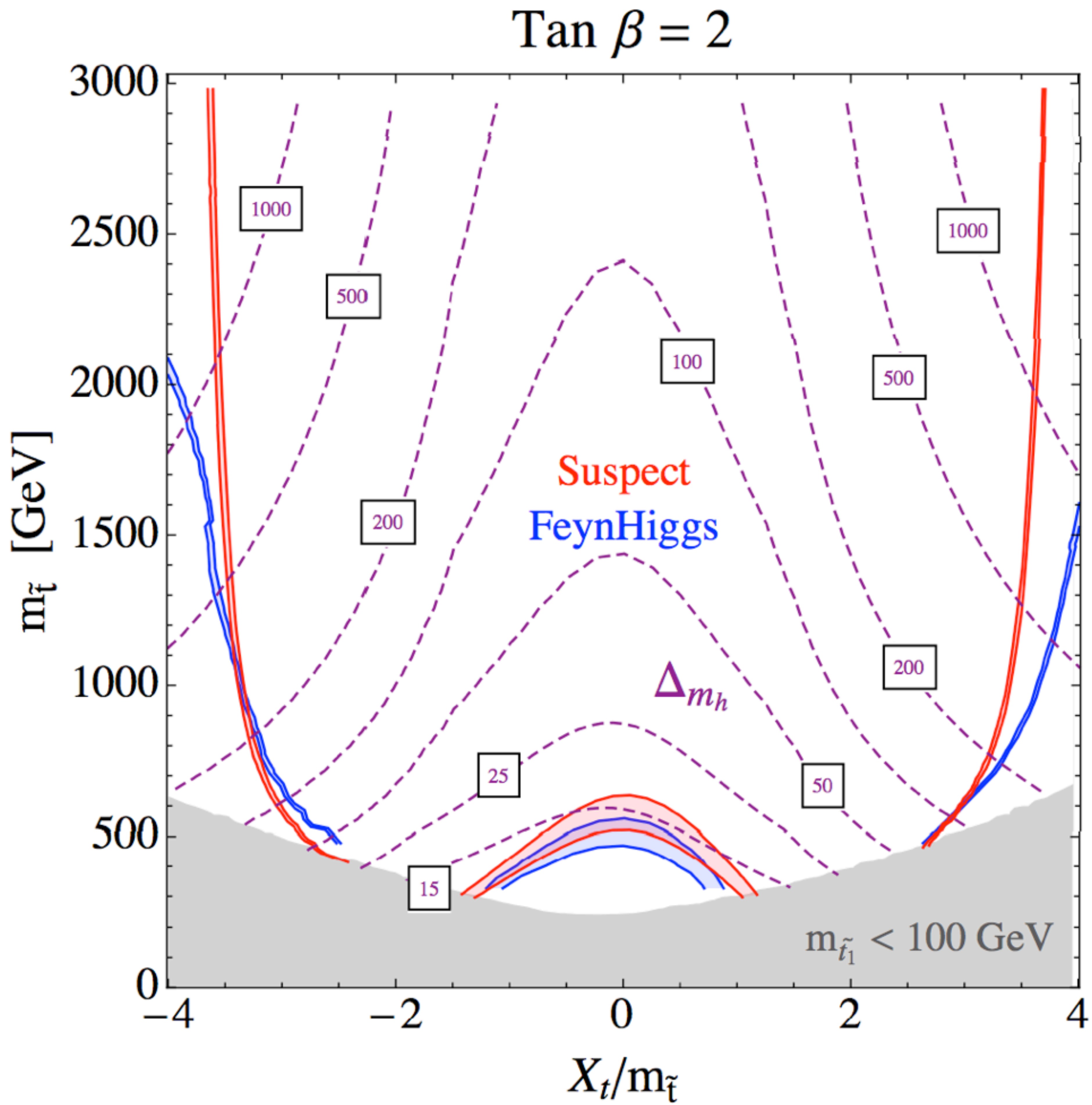
$$W = \mu H_u \cdot H_d \quad \rightarrow \quad W = \lambda S H_u \cdot H_d + \frac{1}{3}\kappa S^3$$

Then a vacuum expectation value of S at the TeV scale gives

$$\mu = \lambda \langle S \rangle$$

There is a new term in the Higgs potential, so that

$$m_h^2 \leq m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta$$



$\lambda = 0.7$

Hall, Pinner, Ruderman

Now there are 5 neutral SUSY fermions.   Their mass matrix is

$$\begin{pmatrix} M_1 & 0 & -c_\beta s_w m_Z & s_\beta s_w m_Z & 0 \\ 0 & M_2 & c_\beta c_w m_Z & -s_\beta c_w m_Z & 0 \\ -c_\beta s_w m_Z & c_\beta c_w m_Z & 0 & -\mu & -s_\beta (v/v_S)\mu \\ s_\beta s_w m_Z & -s_\beta c_w m_Z & -\mu & 0 & -c_\beta (v/v_S)\mu \\ 0 & 0 & -s_\beta (v/v_s)\mu & -c_\beta (v/v_s)\mu & m_S \end{pmatrix}$$

In the relevant limit

M_1, M_2 are large; with gaugino unification:

$$M_1 \approx m(\widetilde{g})/8 \quad M_2 \approx m(\widetilde{g})/4$$

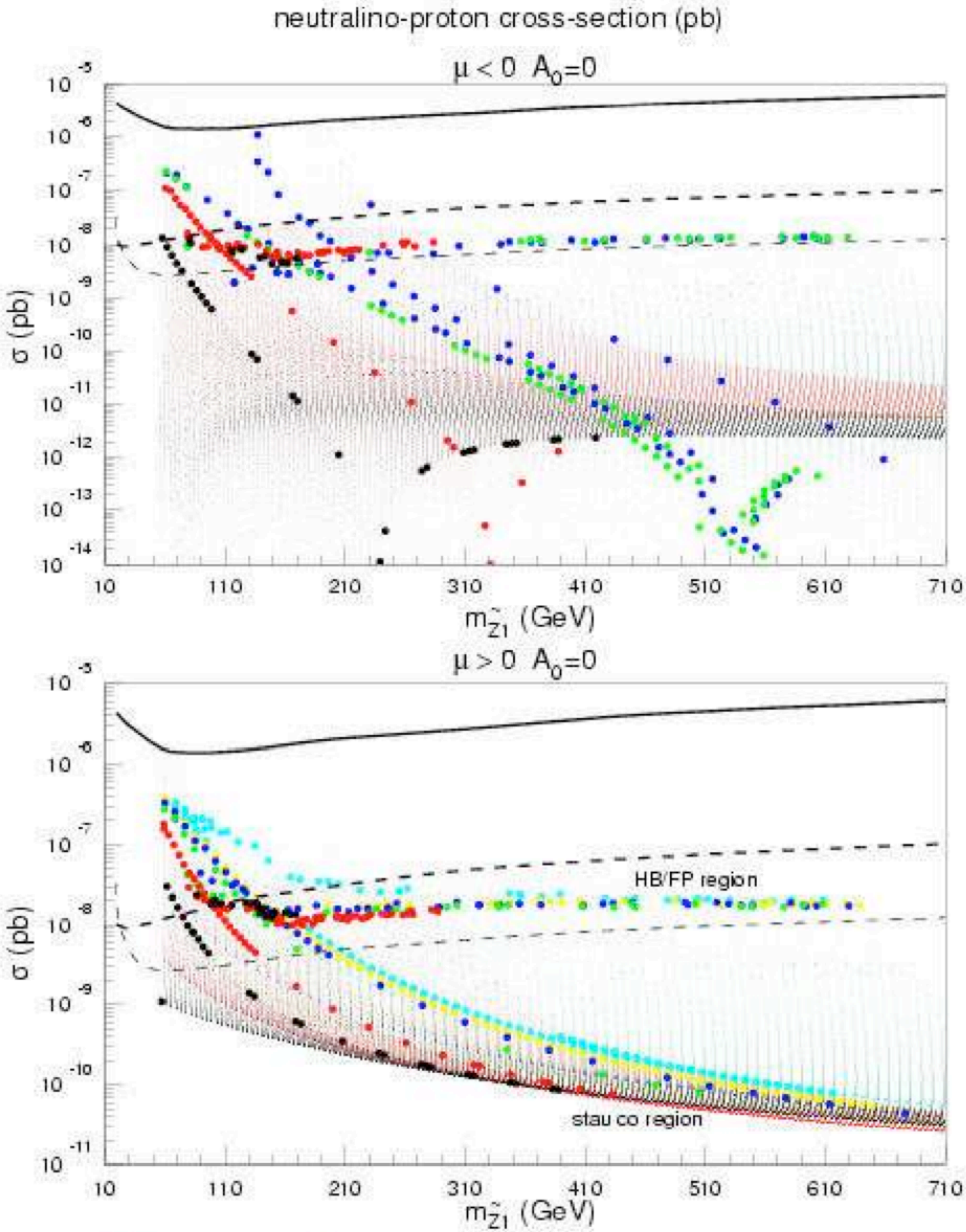
(v/v_s) is small; perhaps $\theta_1, \theta_2 \sim \dfrac{v}{v_s} \sim 0.3$

This choice of the mixing angles θ_1, θ_2 makes the singlino a good dark matter candidate. The annihilation modes are

$$\widetilde{S}\widetilde{S} \to W^+W^-, ZZ$$

through mixing with the Higgsino.

The dark matter phenomenology is similar to that of "well-tempered dark matter" (bino-Higgsino mixing).



Baer, Balacz, Belyaev, and O'Farrill

Finally, SUSY with a singlino is stealthier than typical minimal SUSY models.

A light Higgsino sector is almost impossible to find directly at the LHC. Maybe it can be seen in

$$pp \to \mathrm{ISR\ jets} + (invisible)$$

The presence of a singlino makes this slightly easier, but still difficult. The dominant decays are

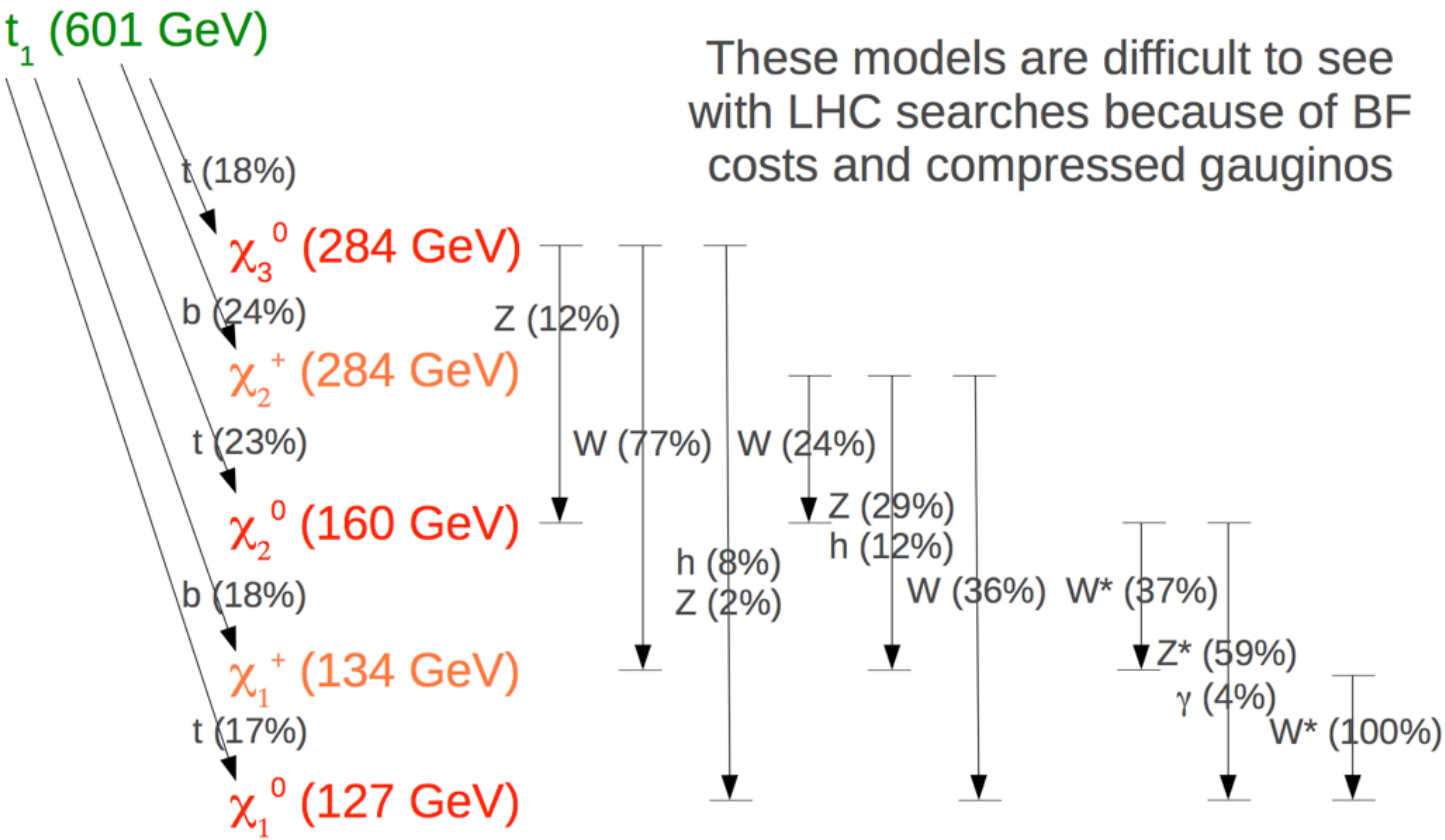
$$\widetilde{h}^+ \to W^{+*}\widetilde{S}\ , \widetilde{h}^0_{1,2} \to Z^*\widetilde{S}$$

The SUSY top partners decay via

$$\widetilde{t} \to t\widetilde{h}, b\widetilde{h}^+$$

with the complex Higgsino decays added to this chain.

Sample spectrum



These models are difficult to see with LHC searches because of BF costs and compressed gauginos

Cahill-Rowley, Hewett, Hoeche, Ismail, Rizzo

In this scenario, the ILC would be a Higgsino factory.

Using beam polarization and precision calorimetry, we could separately study the decays of h_1^0, h_2^0 to $q\overline{q}\widetilde{S}, \quad \ell^+\ell^-\widetilde{S}$.

This would provide the data to predict the cosmic relic abundance of $\widetilde{S}$.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Pauli to Ehrenfest, 1928:

Unfortunately, Oppenheimer has a very bad quality: he approaches me with a fairly absolute faith in authority and considers all I say ... as the last and definitive truth. I know very well with him how the need for foreign authorities comes about. Let them solve his problems so that he need not do it himself. (This connection is of course not consciously clear to him but is only latently with him in the unconscious.) But how I have to wean him from it I do not know.

(signed:) die Geissel Gottes