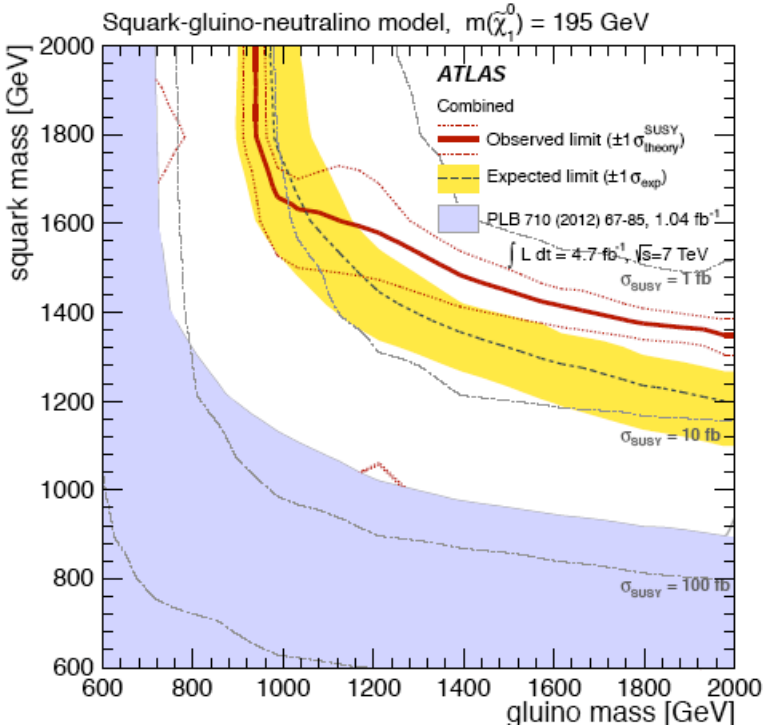
Models of Electroweak Symmetry Breaking in the Harsh Light of LHC



M. E. Peskin
Sept. 2012

Where is the new physics at the LHC ?

LHC has now been running in earnest for 2 years.

ATLAS and CMS have discovered a new boson. This probably means that LHC has succeeded in its primary mission of discovering the Higgs boson.

LHC has seen no signs of new physics beyond the Standard Model.

We must have learned something from this. But what ?

The discovery of the Higgs closes one door and opens another.

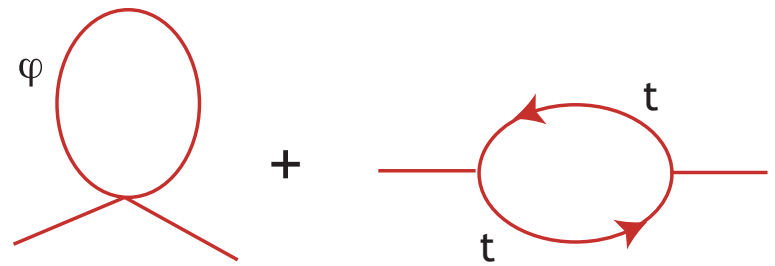
With clarification of the Higgs properties, we will have evidence that SU(2)xU(1) is broken by the vacuum expectation value of a scalar field.

But, still, this scalar field and its interactions are a mystery.

In the Standard Model, we have 3 gauge couplings. This part of the theory is understood perfectly. And, we have 14 couplings and a mass related to the Higgs. This part of the theory is understood not at all.

-- Okun

The Standard Model is no help here. None of the 14 couplings are computable within the Standard Model. The massive parameter μ^2 is additively renormalized. The corrections to μ^2 are quadratically divergent.



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

The criterion for electroweak symmetry breaking is $\mu^2 < 0$. So, it is not possible to predict in this theory whether or not electroweak symmetry will be broken.

We should not be complacent! "It is just the Standard Model" is not an acceptable position.

It is important to add that any theory that includes an extension of the Standard Model

neutrino mass, dark matter, grand unification, string theory

is based on some hypothesis for how electroweak symmetry is broken.

What do models of electroweak symmetry breaking look like ?

Such models should generate the weak interaction symmetry breaking scale

$$v = 246 \text{ GeV}$$

by minimizing the potential for a fundamental or effective Higgs field. So

1. Quadratic divergences in the Higgs mass parameter μ^2 should not appear.

2. A physical mechanism should predict $\mu^2 < 0$.

There are 3 types of models that address these criteria:

1. Models in which EWSB is the result of fermion pair condensation in a TeV energy strong interaction theory

   example: (walking) technicolor

2. Models in which EWSB results from the VEV of a fundamental scalar field.

   example: supersymmetry

3. Models in which EWSB results from a massless composite scalar field

   example: Little Higgs
   example: warped extra dimensions

in #2, #3, $\mu^2 < 0$ can be due to radiative corrections driven by large y_t

I would like to discuss the status of these models in the current LHC era.

1. Technicolor

In technicolor, EWSB does not arise from the vev of a scalar field. No light scalar particle is needed for EWSB.

This is somewhat inconvenient in the face of the discovery of a new boson at 125 GeV.

But, maybe that boson is not the Higgs boson. Walking technicolor provides a candidate, the technidilaton.

The Higgs boson and the dilaton couple differently to W,Z:

Higgs: $$\mathcal{L} = \frac{1}{4} g^2 (v+h)^2 W^+_\mu W^{-\mu}$$

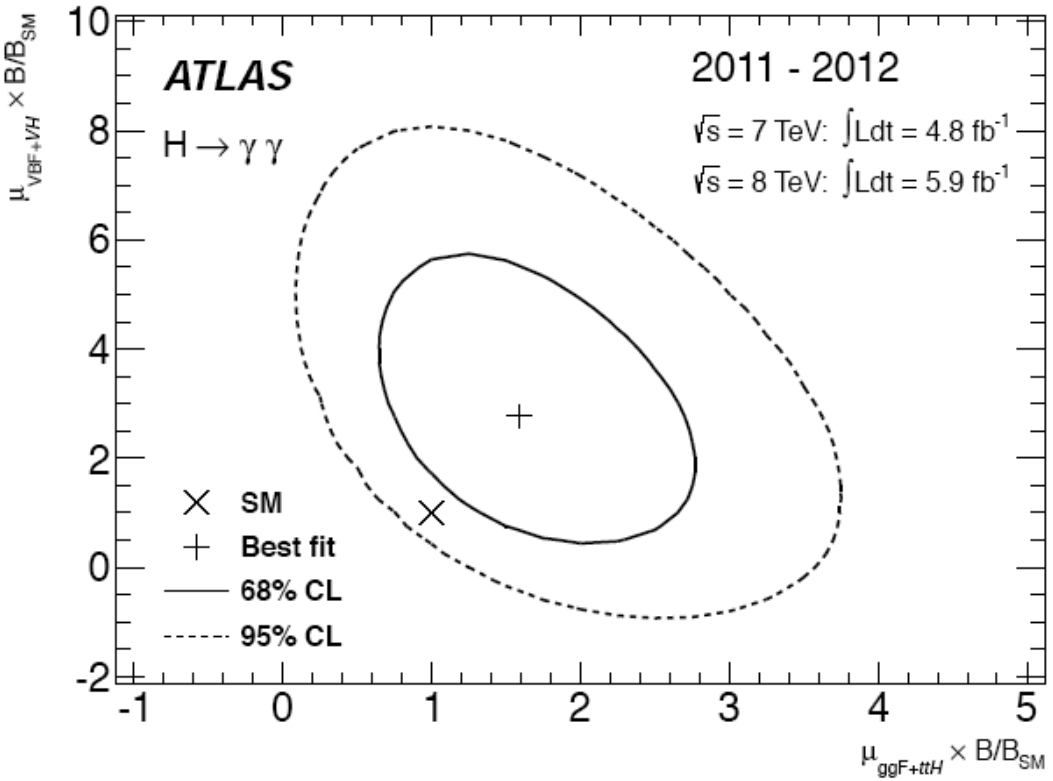
Dilaton: $$\mathcal{L} = \frac{c}{\Lambda} D F^+_{\mu\nu} F^{-\mu\nu}$$

yielding for the dilaton, in the simplest model,

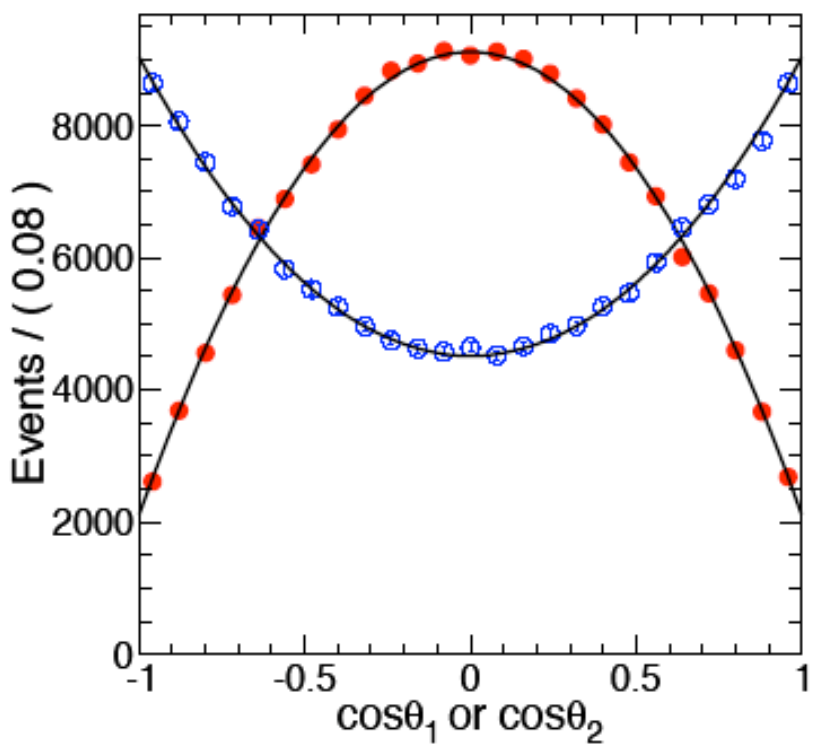
suppressed coupling to WW, ZZ

transverse, not longitudinal Z polarization in $D \to ZZ$

current data favors the Higgs hypothesis:



ATLAS



Gao et al.
CMS MELA analysis

Of course, it is difficult to exclude a model that needs nonperturbative inputs:

1FM with $N_{\rm TC}$	$R_{\gamma\gamma}$	R_{gg}	$R_{WW/ZZ}$	$R_{b\bar{b},c\bar{c},\tau^+\tau^-}$
3	0.11	8.8	0.13	0.53
5	0.64	25	0.16	0.66
7	1.7	48	0.18	0.72
9	3.2	79	0.19	0.75

TABLE V: The TD signatures at $M_\phi = 125$ GeV for the 1FMs, normalized to those of the SM Higgs.

F_ϕ [GeV]	$N_{\rm TC}$	$R_{b\bar{b},\tau^+\tau^-}$	$R_{WW/ZZ}$	$R_{\gamma\gamma}$
700	4	1.3	1.3	1.7
	5	1.3	1.3	3.8
800	4	0.97	0.97	1.3
	5	1.0	1.0	2.9
900	4	0.77	0.77	1.1
	5	0.79	0.79	2.3
1000	4	0.62	0.62	0.85
	5	0.64	0.64	1.9

TABLE VII: The modified TD signatures at 125 GeV taking into account the prescriptions described in the text.

Matsuzaki and Yamawaki, arXiv:1206.6703v3

2. Supersymmetry

27 August 2011 Last updated at 06:41 GMT

7.4K Share

LHC results put supersymmetry theory 'on the spot'

By Pallab Ghosh
Science correspondent, BBC News

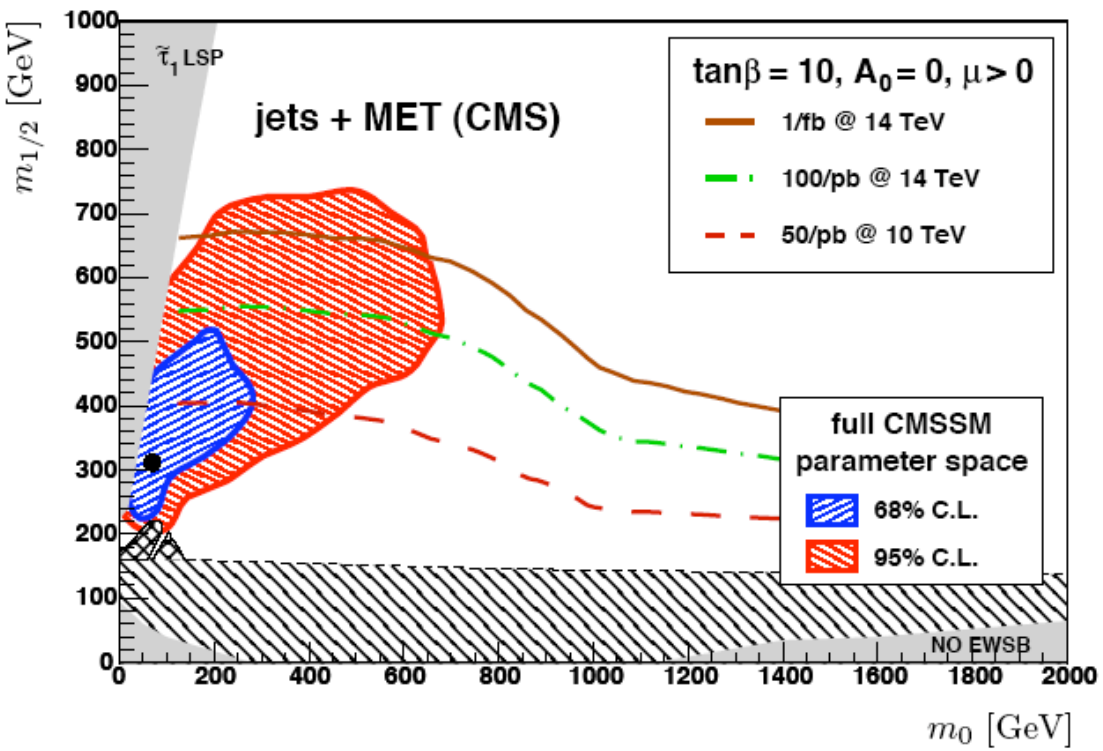
Results from the Large Hadron Collider (LHC) have all but killed the simplest version of an enticing theory of sub-atomic physics.

Bitten the dust

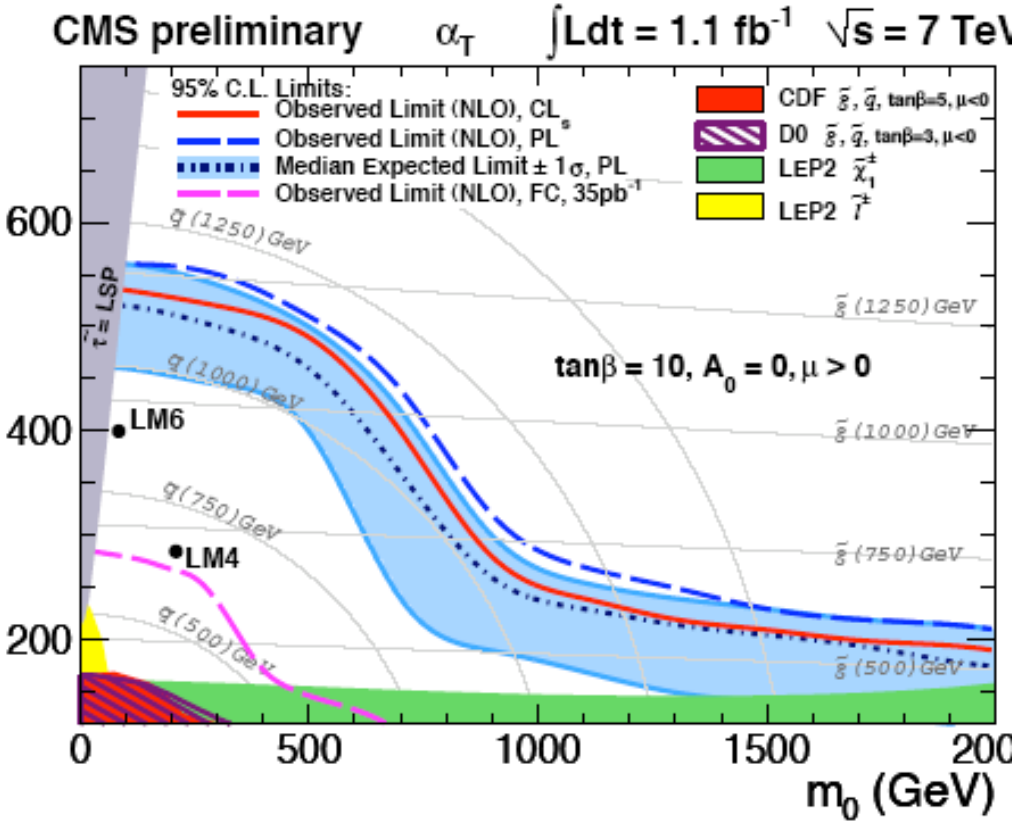
This failure to find indirect evidence of supersymmetry, coupled with the fact that two of the collider's other main experiments have not yet detected supersymmetic particles, means that the simplest version of the theory has in effect bitten the dust.

Before the start of LHC, I expected early discovery of supersymmetry in the jets+MET signature. Many other theorists also had this belief. But, it was not correct.

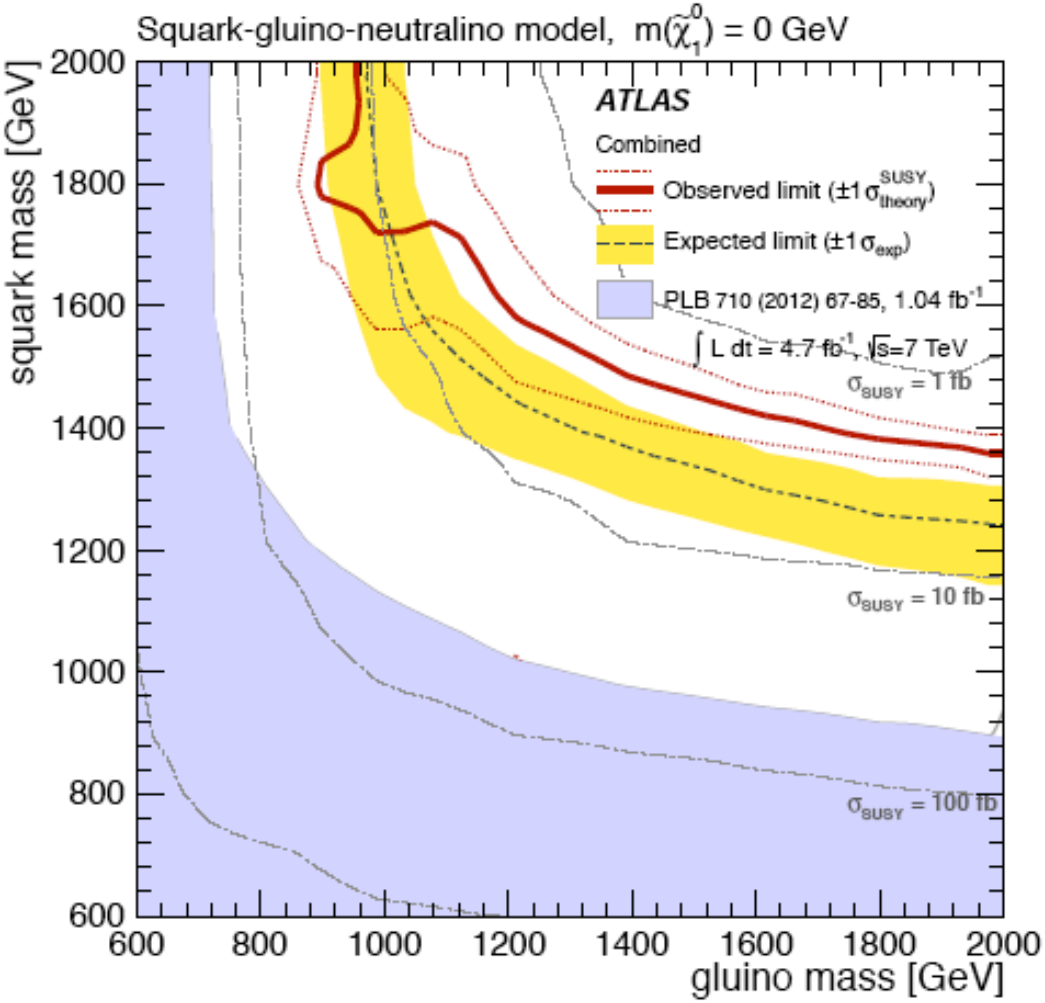
Buchmuller, ... , DeRoeck, Ellis ... 2008

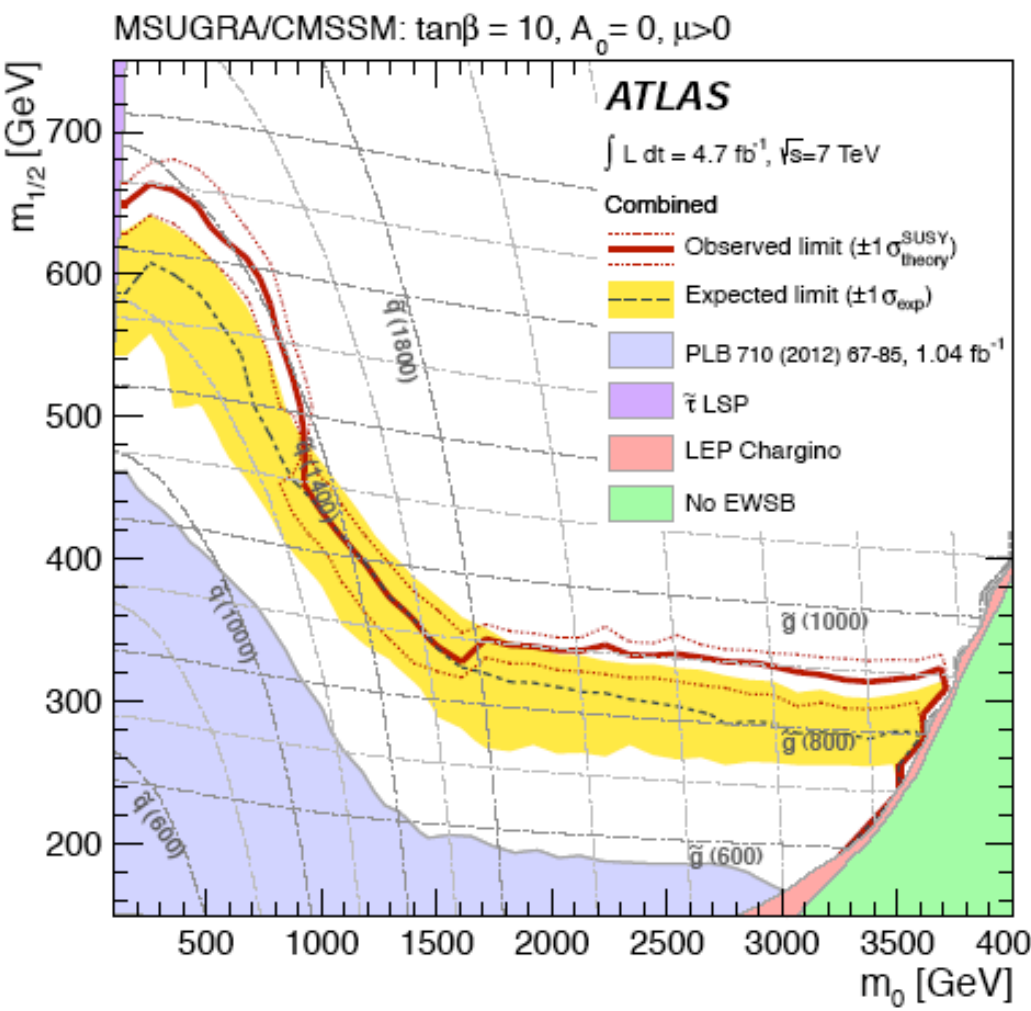


CMS LP11 α_T analysis



from my Lepton-Photon 2011 talk





ATLAS full 2011 data set

Many discussions of the consequences of SUSY are given using the parameter space of a restricted model called MSUGRA or cMSSM.

The phenomenological description of SUSY breaking requires 105 parameters for a full description. Many of these are strongly constrained (as flavor or CP-violating). However, there is a set of 24 parameters that are relatively unconstrained:

- gaugino and Higgsino masses: m_1, m_2, m_3, μ
- slepton masses: $m^2(L_i)$, $m^2(\overline{e}_i)$, $i = 1, 2, 3$
- squark masses: $m^2(Q_i)$, $m^2(\overline{u}_i)$, $m^2(\overline{d}_i)$, $i = 1, 2, 3$
- Higgs potential terms: m_A, $\tan\beta$
- A terms: A_τ, A_b, A_t

The set with 1st and 2nd generation parameters equal is also considered; this is called the pMSSM.

Most studies of the phenomenology of SUSY simplify this further, assuming complete unification of all scalar masses, all gaugino masses, and all A terms. The resulting MSUGRA parameter space is

$$(m_0, m_{1/2}, \tan\beta, A, \mathrm{sign}(\mu))$$

In this space, μ is an output parameter. We solve for μ using the relation for the Higgs v.e.v or the Z boson mass

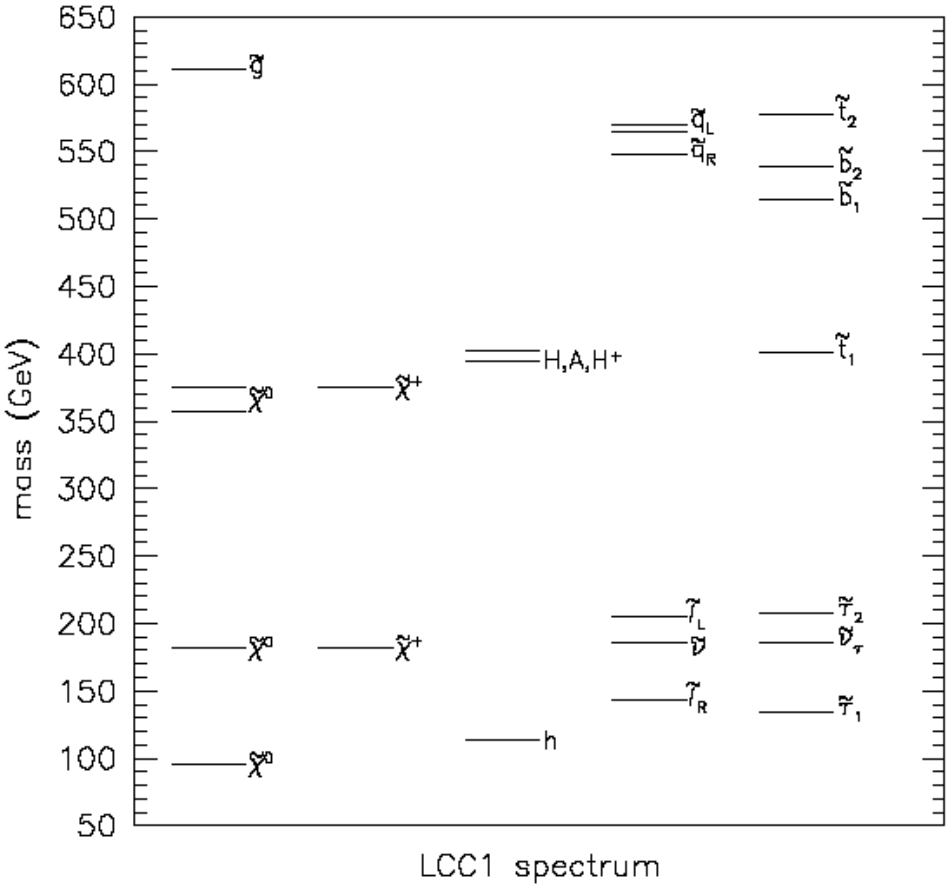
$$m_Z^2 = 2\,\frac{M_{Hd}^2 - \tan^2\beta M_{Hu}^2}{\tan^2\beta - 1} - 2\mu^2$$

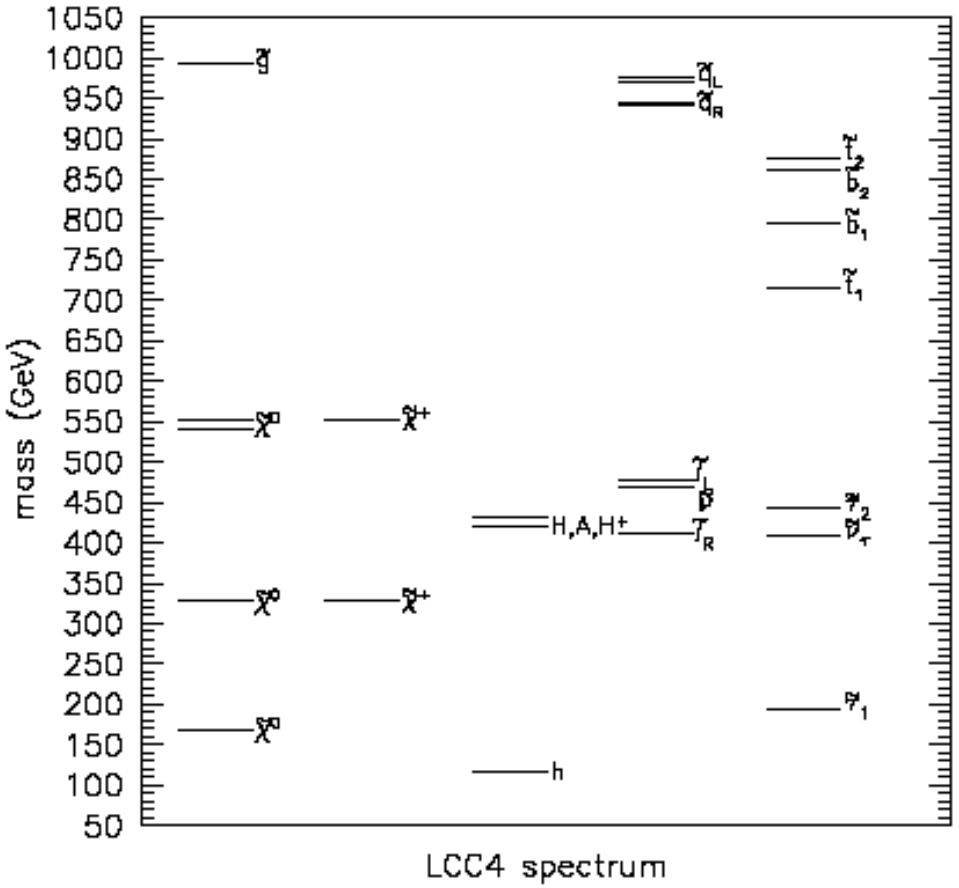
The result is that μ is typically somewhat larger than m_0 .

The MSUGRA space ties together constraints on the Higgs boson mass, the muon (g-2), $b \to s\gamma$, dark matter, etc. The framework is very restrictive. Fitting tensions in low-energy observables with the Standard Model, it was possible to predict, before the LHC, the preferred parameter region of the model.

That region is now excluded !

Here are two illustrative mSUGRA spectra:





Baltz et al.

So, if we believe that SUSY gives the explanation for electroweak symmetry breaking by the Higgs boson, this is not the right place to look for it. Maybe this is not surprising, given the simplicity and lack of motivation of the MSUGRA assumptions.

Thinking more generally, the reason that we need SUSY below 1 TeV is to naturally generate the Higgs potential that gives

$$\langle \varphi \rangle = \frac{1}{\sqrt{2}} (246 \text{ GeV})$$

What constraints does this last requirement put on SUSY masses ?

Go back to the formula

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

This is an interesting formulae, relating the Z mass at 91 GeV to a set of masses that are potentially much larger. But, a large cancellation in this formula is unnatural. This specifically puts a limit on the parameter μ .

The top squark mass is constrained indirectly, since top squark loops renormalize M_{Hu}^2. This effect is necessary, as we have seen, to obtain the negative Higgs mass-squared. The gluino mass enters more indirectly, through its effect on the top squark mass.

The 1st and 2nd generation squarks enter hardly at all.

In 1996, Cohen, Kaplan, and Nelson proposed the

more minimal supersymmetric model

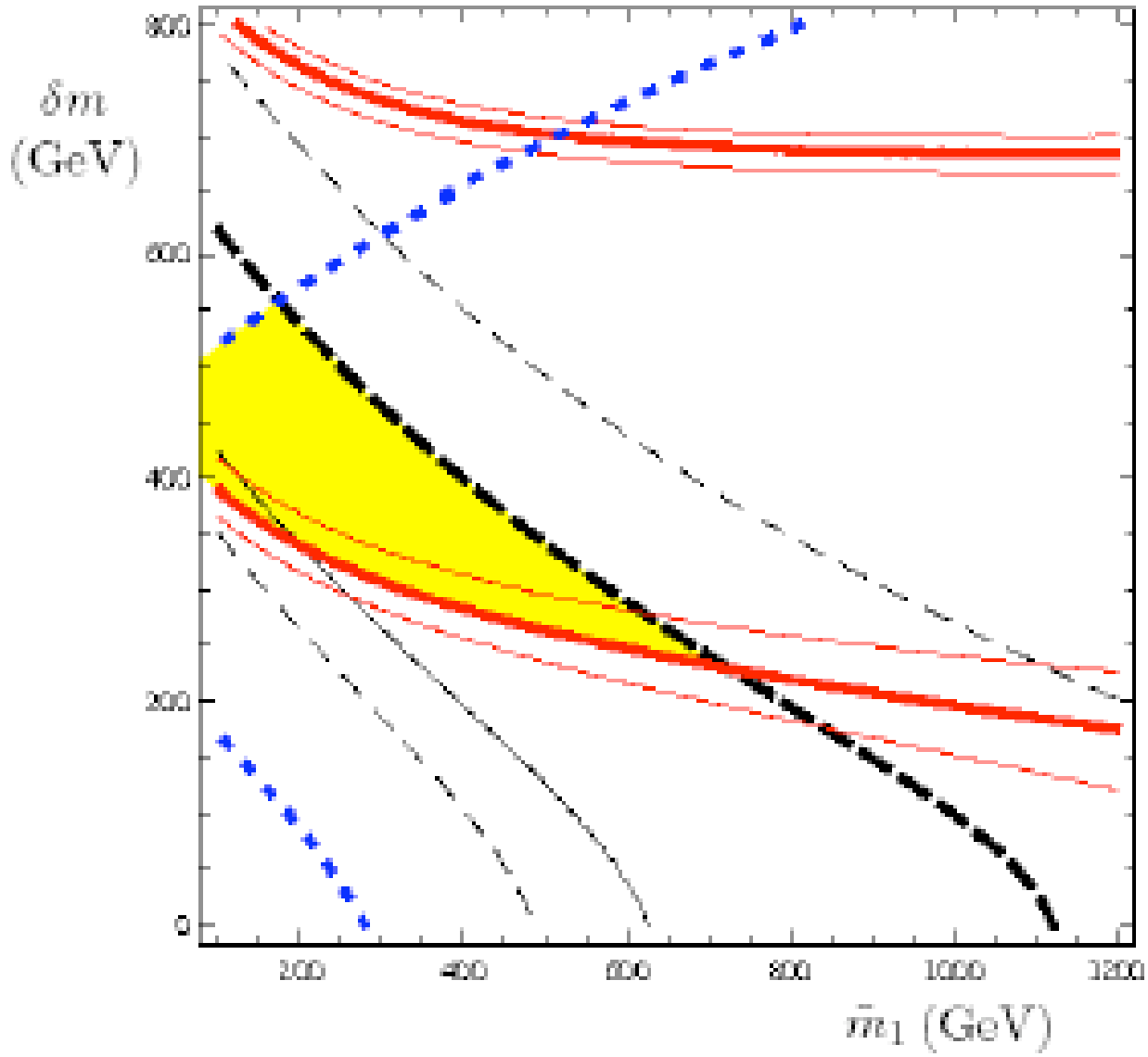
with only 3rd-generation sfermions, gauginos, Higgsino light.
There are many variations on this theme:

Focus Point Region Feng Matchev Moroi
(solution of MSUGRA constraints w. all squarks at ~ 3 TeV)

Golden Region Perelstein Spethmann
(only Higginos and stops below 1 TeV)

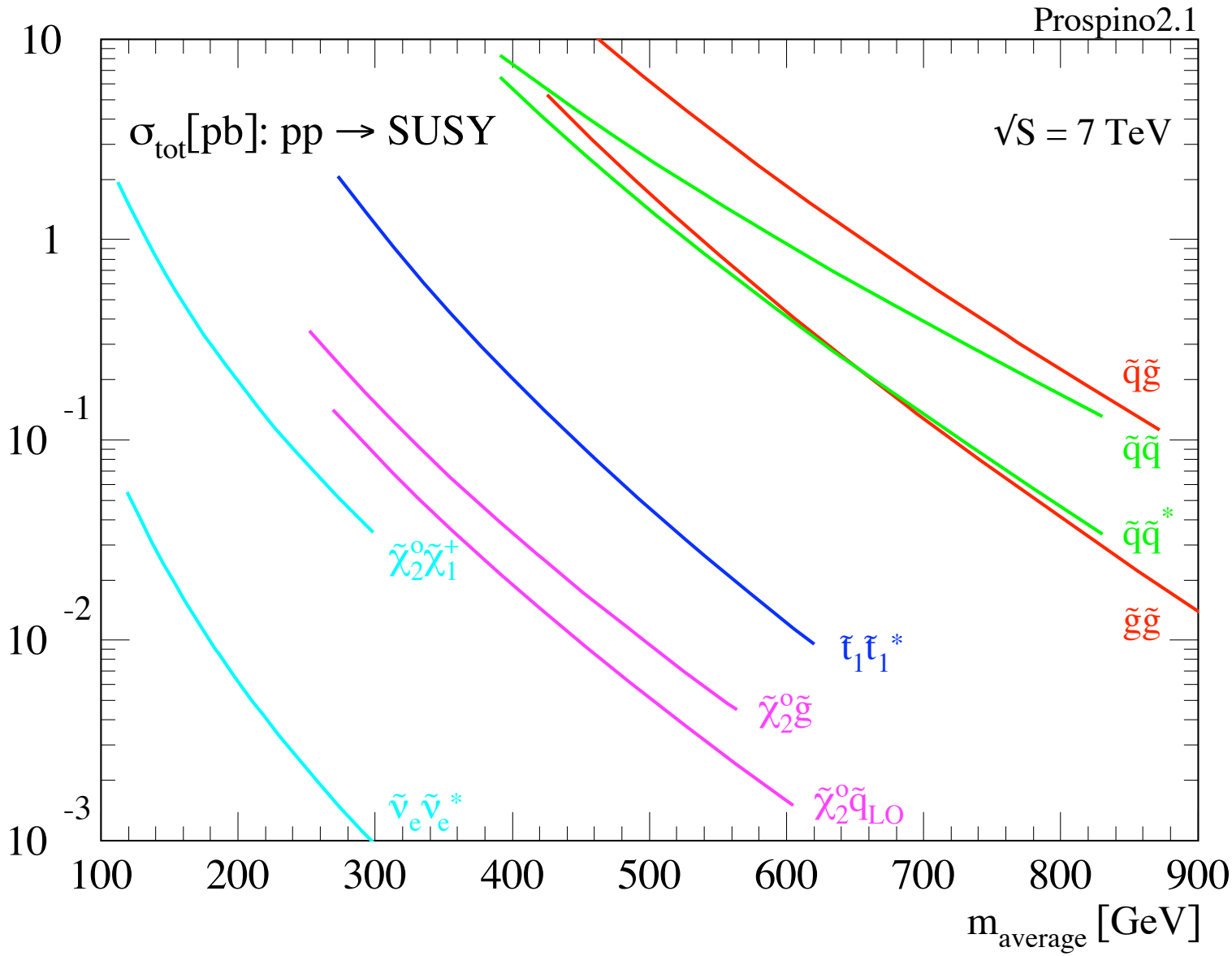
Hidden SUSY Baer, Barger, Huang
(only Higgsinos below 1 TeV)

These give "natural" models of the Higgs potential and are much more weakly constrained by the current LHC SUSY limits.



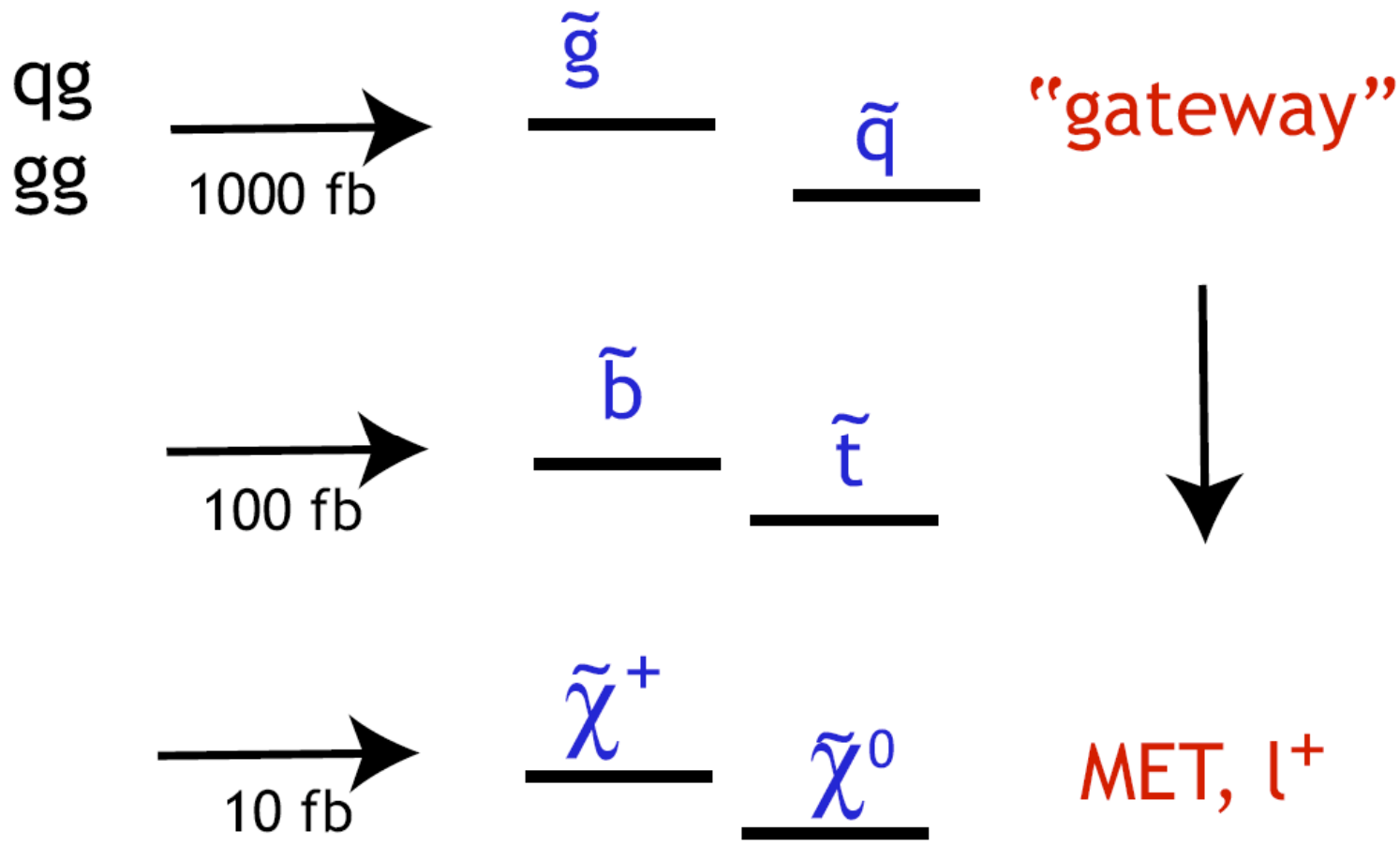
Perelstein-Spethmann: region of the $(m(\tilde{t},1), m(\tilde{t},2))$ plane prefered by naturalness constraints.

This has interesting implications if we consider the size of SUSY pair production cross sections at 7 TeV.



Prospino: Beenacker, Plehn, Spira et al.

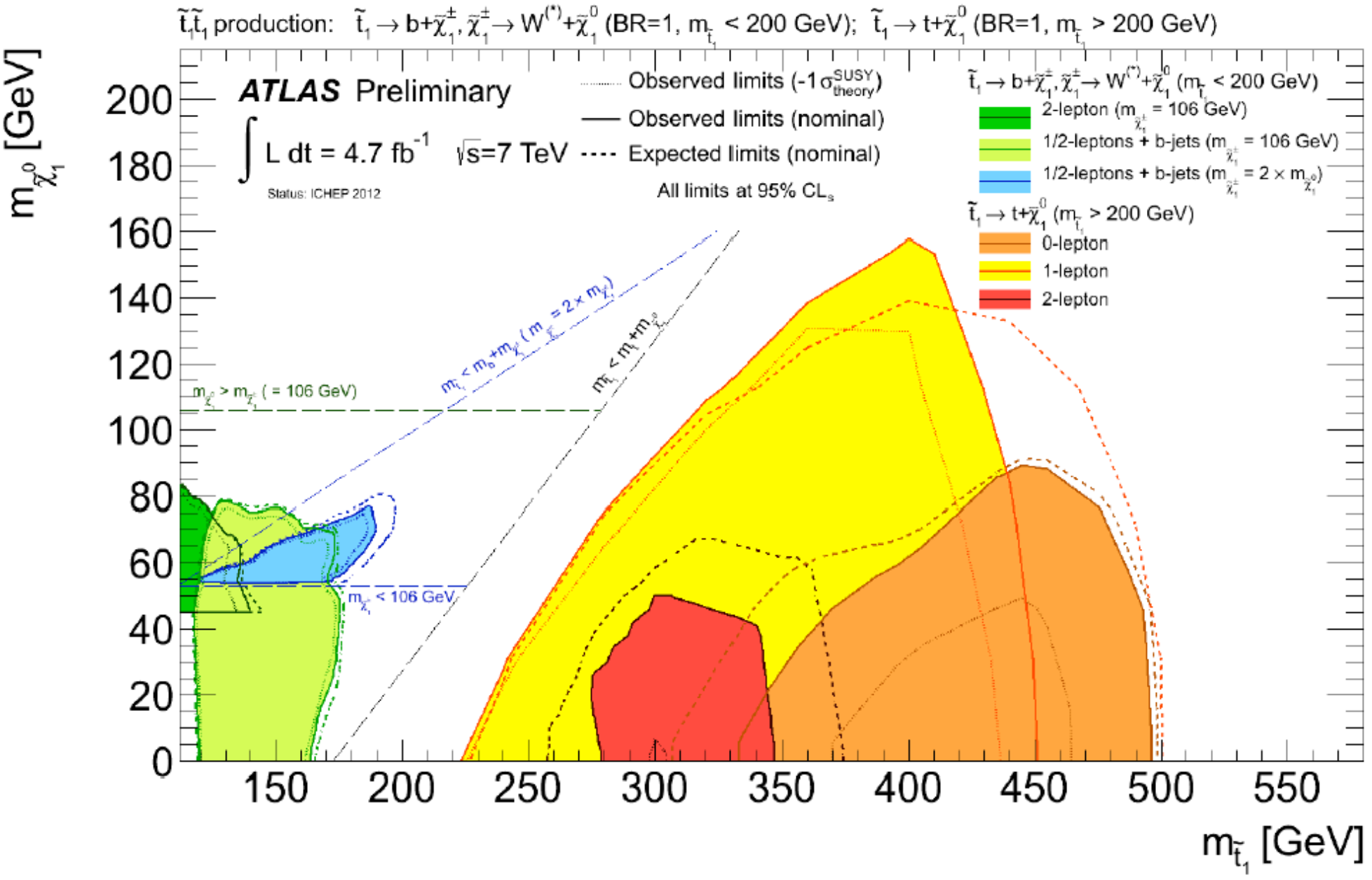
Here is a useful caricature of SUSY phenomenology at hadron colliders:



The exotic and characteristic signatures of SUSY are at the bottom. The gateway channel is at the top. If a channel is not allowed energetically, we must defer to the next one.

It is only recently that the LHC experiments have begun to be sensitive to SUSY reactions with direct stop or sbottom production. These are the only searches the restrict the stop and sbottom masses for gluino masses above 1 TeV.

Especially for stop, these are difficult searches, with complex final states in which the MET signature is much diluted.

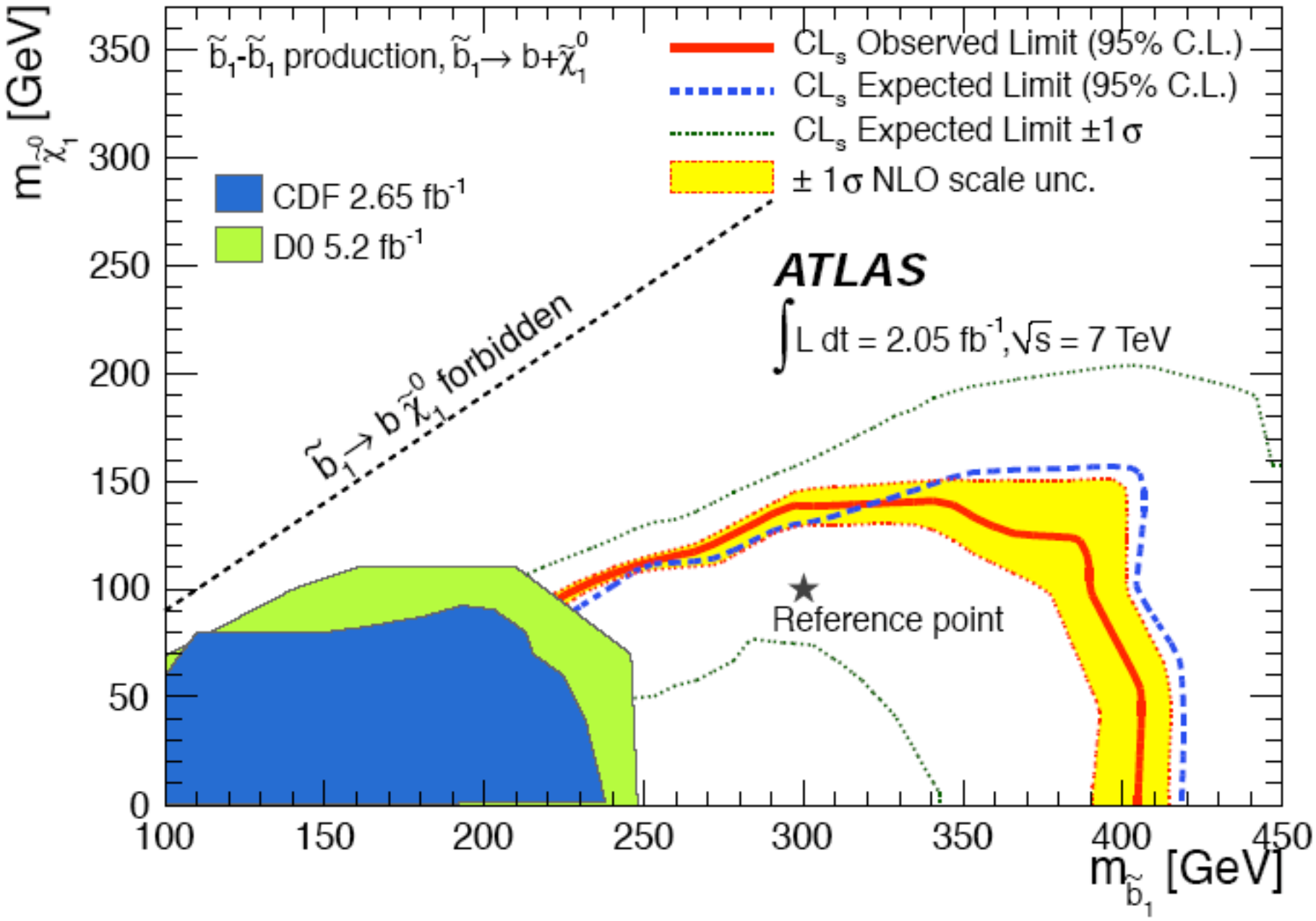

$\tilde{t}_1\tilde{t}_1$ production: $\tilde{t}_1 \to b+\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^{\pm} \to W^{(*)}+\tilde{\chi}_1^0$ (BR=1, $m_{\tilde{t}_1} < 200$ GeV); $\tilde{t}_1 \to t+\tilde{\chi}_1^0$ (BR=1, $m_{\tilde{t}_1} > 200$ GeV)
ATLAS Preliminary
$\int L\,dt = 4.7\ fb^{-1}$ $\sqrt{s}$=7 TeV
Status: ICHEP 2012
Observed limits ($-1\sigma^{SUSY}_{theory}$)
Observed limits (nominal)
Expected limits (nominal)
All limits at 95% CL_s
$\tilde{t}_1 \to b+\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^{\pm} \to W^{(*)}+\tilde{\chi}_1^0$ ($m_{\tilde{t}_1} < 200$ GeV)
2-lepton ($m_{\tilde{\chi}_1^{\pm}}$ = 106 GeV)
1/2-leptons + b-jets ($m_{\tilde{\chi}_1^{\pm}}$ = 106 GeV)
1/2-leptons + b-jets ($m_{\tilde{\chi}_1^{\pm}} = 2 \times m_{\tilde{\chi}_1^0}$)
$\tilde{t}_1 \to t+\tilde{\chi}_1^0$ ($m_{\tilde{t}_1} > 200$ GeV)
0-lepton
1-lepton
2-lepton
$m_{\tilde{\chi}_1^0} > m_{\tilde{\chi}_1^{\pm}}$ (= 106 GeV)
$m_{\tilde{t}_1} < m_b + m_{\tilde{\chi}_1^{\pm}}$ ($m_{\tilde{\chi}_1^{\pm}} = 2 \times m_{\tilde{\chi}_1^0}$)
$m_{\tilde{t}_1} < m_t + m_{\tilde{\chi}_1^0}$
$m_{\tilde{\chi}_1^0} < 106$ GeV
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{t}_1}$ [GeV]
0
20
40
60
80
100
120
140
160
180
200
150
200
250
300
350
400
450
500
550

Since it is not unlikely that $m(\widetilde{\chi}^0) > 100\ \mathrm{GeV}$, this is still a weak exclusion.

There is a gap for $m(\widetilde{t}) \approx m_t$. Filling this gap requires a precision study top quark pair production.

Another blind spot is very light stop, with $\widetilde{t} \to c\widetilde{\chi}^0$.

It is possible to search more powerfully for sbottom, with $\widetilde{b} \to b\widetilde{\chi}^0$. The $\widetilde{b}_L$ and $\widetilde{t}_L$ massses are split only by stop mixing, renormalization from the Higgs couplings, and effects of order m_Z^2. Unfortunately, it is quite possible that $m(\widetilde{t}_L) \gg m(\widetilde{t}_R)$.


$\tilde{b}_1$-$\tilde{b}_1$ production, $\tilde{b}_1 \rightarrow b+\tilde{\chi}_1^0$
CL$_s$ Observed Limit (95% C.L.)
CL$_s$ Expected Limit (95% C.L.)
CL$_s$ Expected Limit ±1σ
± 1σ NLO scale unc.
CDF 2.65 fb^{-1}
D0 5.2 fb^{-1}
ATLAS
∫L dt = 2.05 fb^{-1}, √s = 7 TeV
$\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$ forbidden
Reference point
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{b}_1}$ [GeV]
0
50
100
150
200
250
300
350
100
150
200
250
300
350
400
450

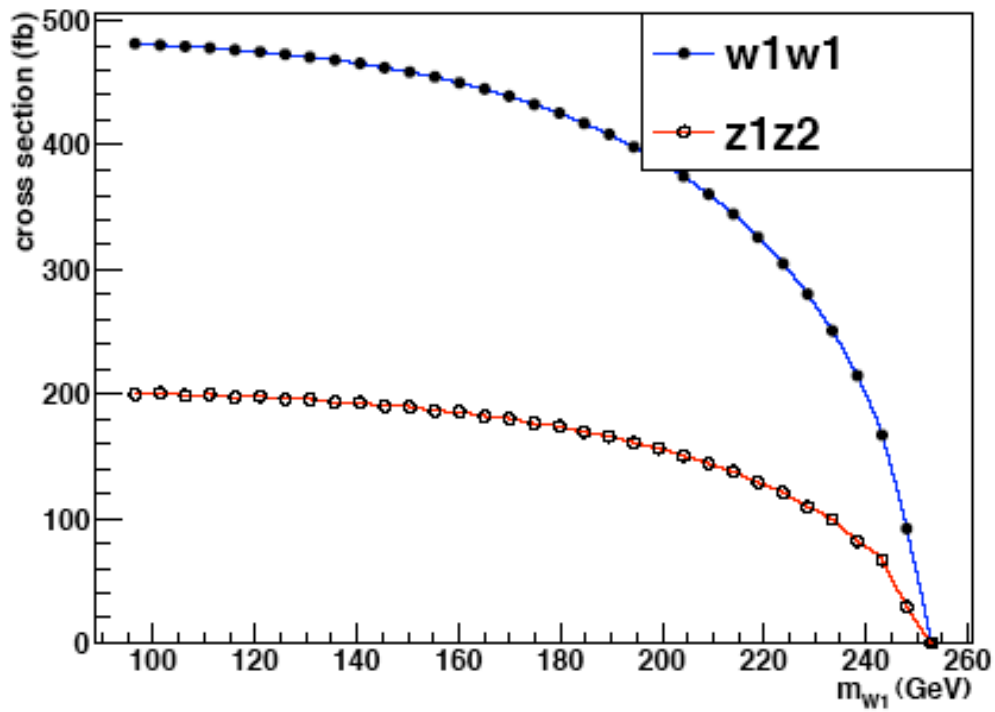
Applying the naturalness citerion in the most extreme way, we could consider that the only light SUSY particles are Higgsinos.

This is a sector $\widetilde{\chi}_1^0$, $\widetilde{\chi}_2^0$, $\widetilde{\chi}_1^\pm$

below 200 GeV, with mass splittings of order 10 GeV. It is very difficult for LHC to observe these particles.

At the ILC, the cross sections are large. Observation is not trivial, but Baer, Barger, Huang, arXiv:1107.5581 give a straightfoward set of cuts.

The cross sections are strongly dependent on beam polarization, allowing a test of the Higgsino/chargino mixture.



The Higgsino is not a good dark matter candidate, having too large an annihilation cross section to WW, ZZ.

However, we might need to go to the NMSSM to raise the Higgs mass to 125 GeV. Then a singlino LSP below the Higgsino can be a good dark matter candidate, with

$$\sigma(\widetilde{S}\widetilde{S} \to W^+W^-) \sim \lambda^4 \sigma(\widetilde{H}\widetilde{H} \to W^+W^-)$$

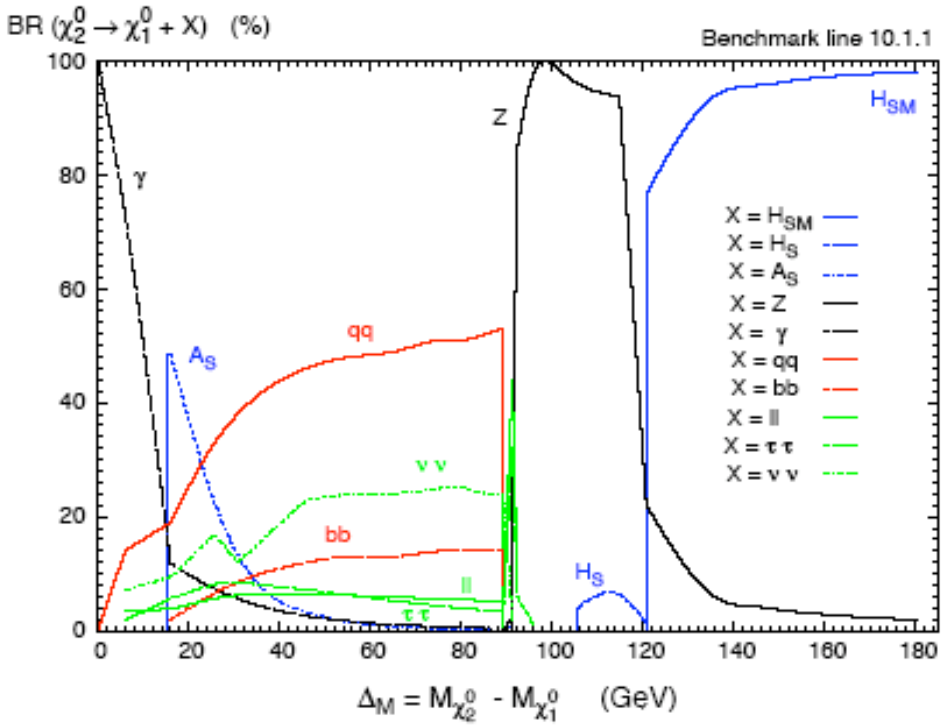
The Higgsino decays to the singlino with

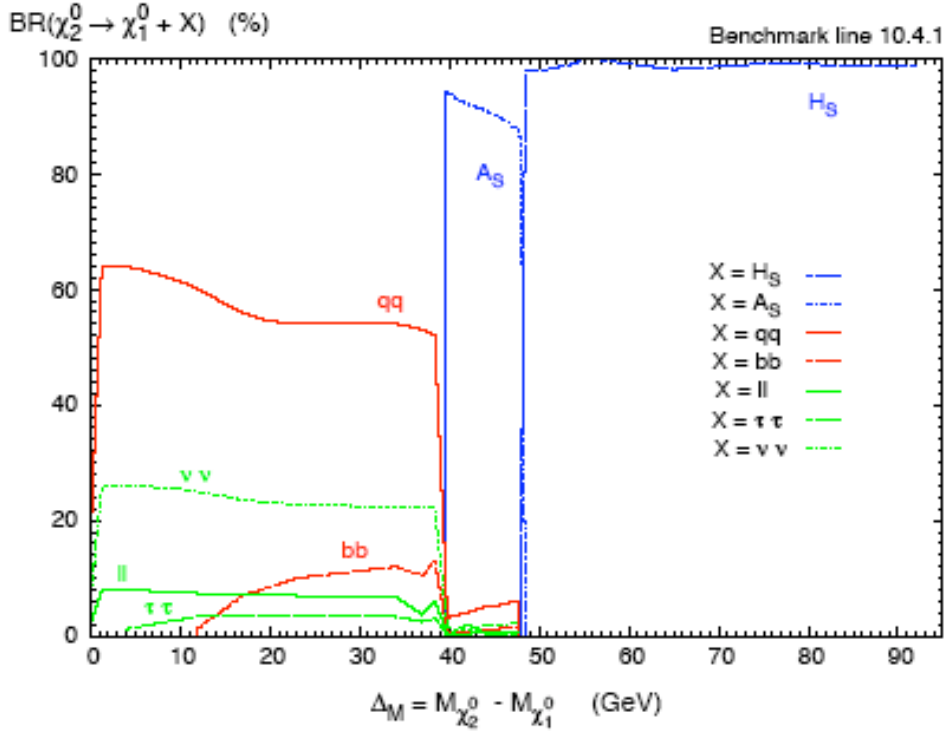
$$\Gamma(\widetilde{H}) \sim \lambda^2 \cdot \mathrm{GeV}$$

At the ILC, this width can be measured down to tens of MeV in a threshold scan.

λ can also be determined at the ILC using precision measurements of the 5 neutralino mass eigenvalues.

The Higgsino has a rich pattern of decay modes, none of which pass LHC triggers.





Das, Ellwanger, Teixeira, arXiv:1202.5244

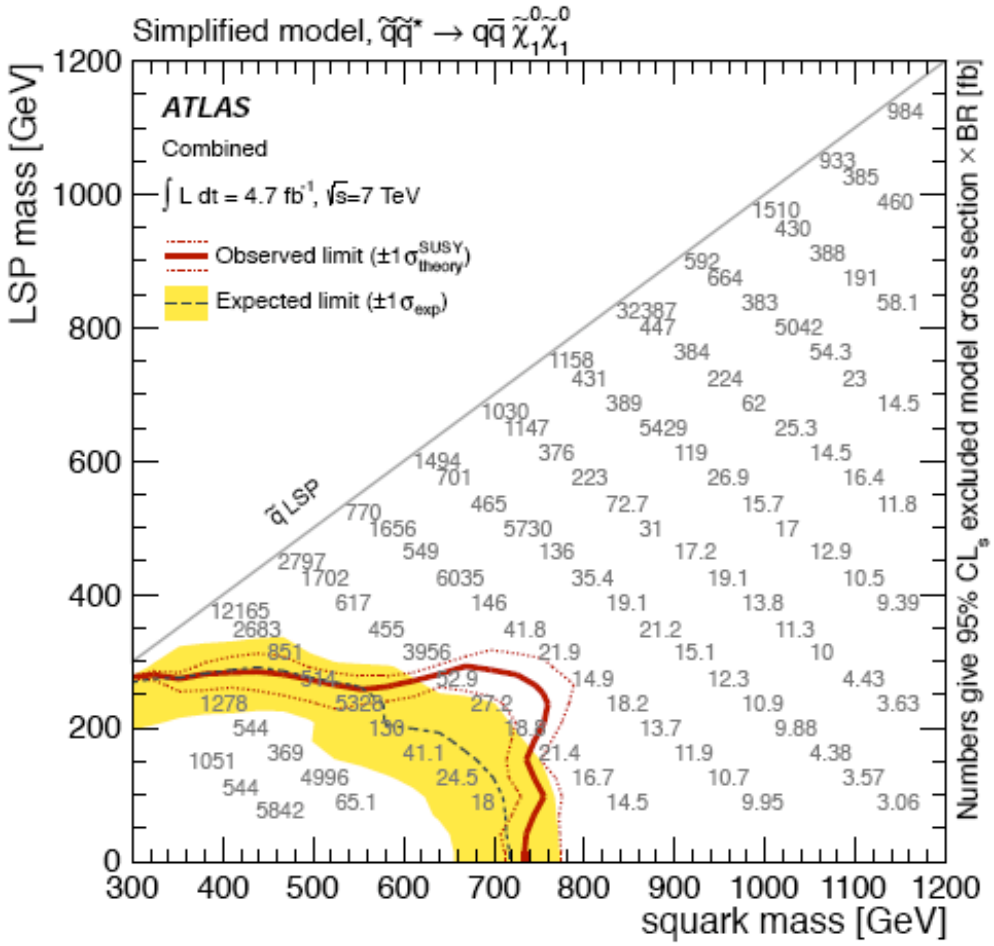
There are many more special mechanism that can operate to allow supersymmetry to evade the LHC exclusions. It is important to note that the strongest generic SUSY exclusions -- the CMS α_T and razor analyses -- are mainly sensitive to final states of the form:

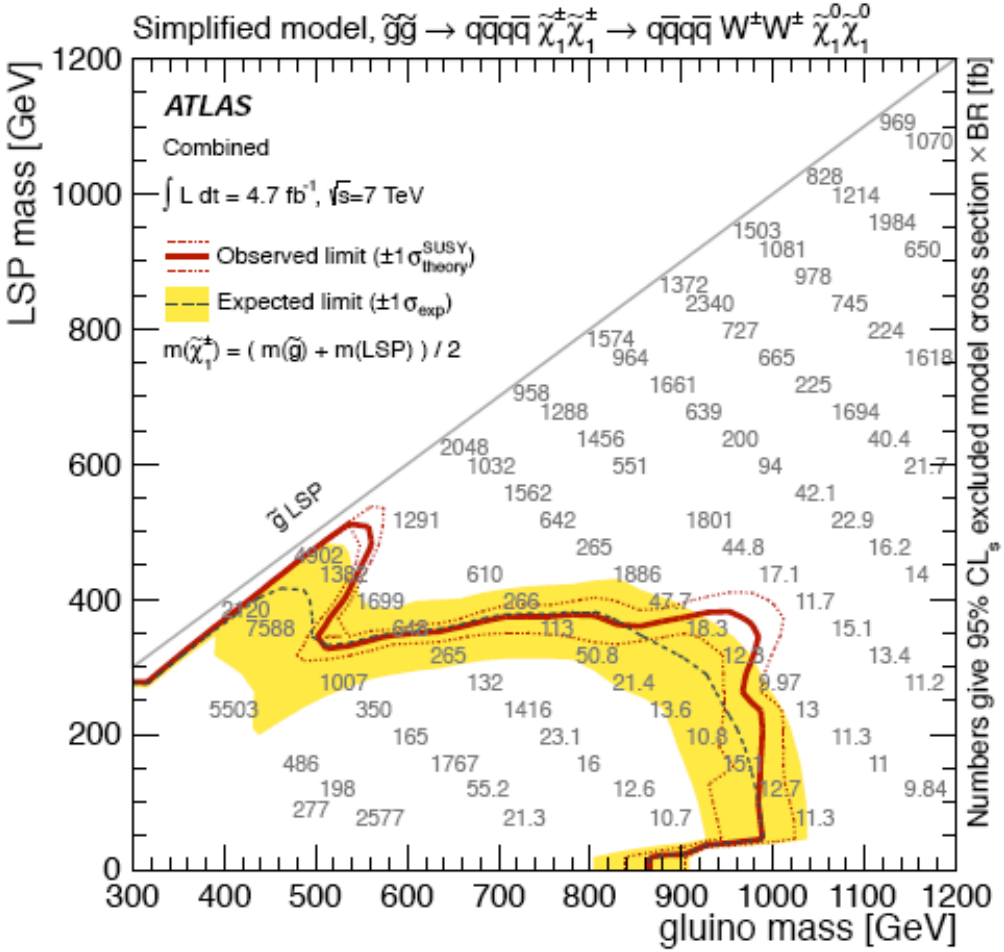
2 hard jets + MET

If these are removed by some mechanism, for example,

$m(\widetilde{q}_L) \ll m(\widetilde{q}_R), m(\widetilde{g})$
multiple degenerate weakinos
compressed spectrum
singlino LSP

we could still even have a large squark sector below 600 GeV.


Simplified model, $\tilde{q}\bar{\tilde{q}}^{*} \rightarrow q\bar{q}\,\tilde{\chi}_1^0\tilde{\chi}_1^0$
ATLAS
Combined
$\int L\,dt = 4.7\ fb^{-1}$, $\sqrt{s}=7$ TeV
Observed limit ($\pm 1\,\sigma^{SUSY}_{theory}$)
Expected limit ($\pm 1\,\sigma_{exp}$)
$\tilde{q}$ LSP
LSP mass [GeV]
squark mass [GeV]
Numbers give 95% CL_s excluded model cross section × BR [fb]


Simplified model, $\tilde{g}\tilde{g} \rightarrow q\bar{q}q\bar{q}\,\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\pm} \rightarrow q\bar{q}q\bar{q}\,W^{\pm}W^{\pm}\,\tilde{\chi}_1^0\tilde{\chi}_1^0$
ATLAS
Combined
$\int L\,dt = 4.7\ fb^{-1}$, $\sqrt{s}=7$ TeV
Observed limit ($\pm 1\,\sigma^{SUSY}_{theory}$)
Expected limit ($\pm 1\,\sigma_{exp}$)
$m(\tilde{\chi}_1^{\pm}) = (\,m(\tilde{g}) + m(\mathrm{LSP})\,) / 2$
$\tilde{g}$ LSP
LSP mass [GeV]
gluino mass [GeV]
Numbers give 95% CL_s excluded model cross section × BR [fb]

I am often asked whether the LHC data excludes the capability of the ILC to study supersymmetry.

One cannot answer this question by giving specific model points, since these might be cherry-picked. Instead, I prefer a sociological argument:

1. No theorist who believed in SUSY before 2009 has renounced SUSY in the light of the LHC exclusions.

2. Model builders are still building models with 200 GeV charginos.

Blum, D'Agnolo, and Fan, arXiv:1206.5303

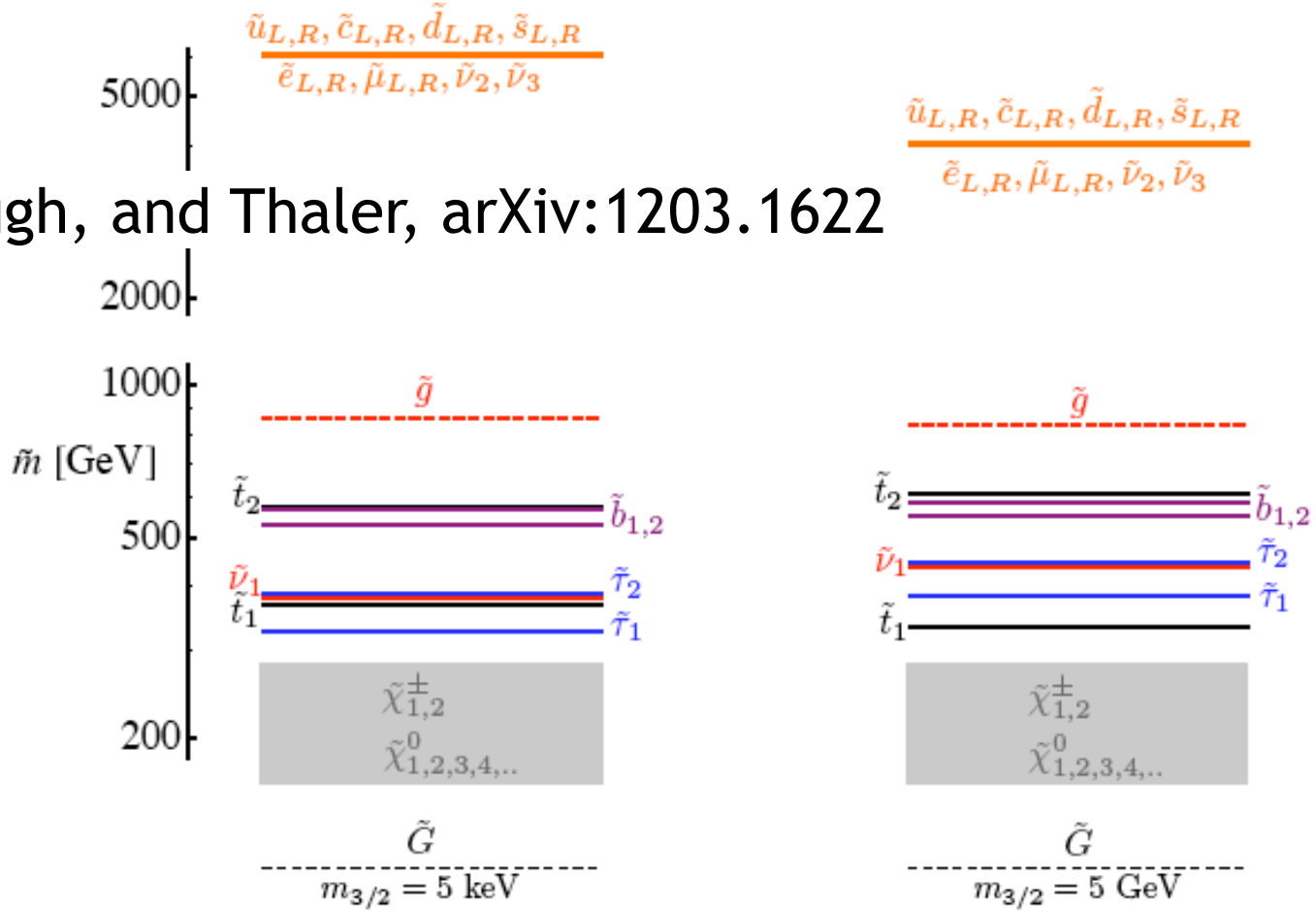
Naturalness dictates that at least one chargino must be light, $m_{\tilde{\chi}^\pm} \lesssim 200$ GeV. Hence, the chargino contribution to r_γ may be expected to become relevant [73–75]. What limits the effect to be modest is the direct bound, that we take to be $m_{\tilde{\chi}^\pm} > 94\,\text{GeV}$ [76]. Imposing this bound, we compute

Cohen, Hook, Torroba, arXiv:1204.1337

v	M_3	M_2	M_1
350 TeV	2.5 TeV	1.0 TeV	530 GeV
$\widetilde{m}_3^2$	$\widetilde{m}_{1,2}^2$	$\widetilde{m}_{H_u}^2$	$\widetilde{m}_{H_d}^2$
$(1.2\text{ TeV})^2$	$(5\text{ TeV})^2$	$-(220\text{ GeV})^2$	$(300\text{ GeV})^2$
μ	b_μ	M_A	$\tan\beta$
220 GeV	- 0.030 GeV^2	135 GeV	4.2

Table 3: An example set of consistent parameters with the solution to the μ problem given in Eq. (24). We have assumed gaugino mass unification and to good approximation $\widetilde{m}_{Q_i}^2 = \widetilde{m}_{u_i}^2 =$

Craig, McCullough, and Thaler, arXiv:1203.1622



Randall and Reece, arXiv:1206.6540

We are now in a position to try to put everything together. In terms of the low-energy effective theory, one set of numbers that gives a good solution in the tree-level potential: $\lambda = 1.1$, $f = (100\ \text{GeV})^2$, $T = 1.8 \times 10^6\ \text{GeV}^3$, $A_\lambda = 200$ GeV, $m^2_{H_u} = -(70\ \text{GeV})^2$, $m^2_{H_d} = (120\ \text{GeV})^2$, $m^2_S = (100\ \text{GeV})^2$. This leads to $\tan\beta = 1.7$, a 121 GeV mostly-up-type Higgs, and Higgses at 214 and 252 GeV that are mixtures of mostly S and H_d. The effective μ-term $\lambda\langle S\rangle = -148$ GeV.

So, SUSY can hide from the LHC exclusions -- but only up to a point.

Top squarks are needed to generate EWSB by radiative corrections. The gluino mass radiative corrects the top square masses. It is very difficult to keep EWSB natural if these particles move to multi-TeV masses.

Thus, I expect that $(\widetilde{t}_L, \widetilde{b}_L, \widetilde{t}_R, \widetilde{g})$ are below 2 TeV and in the range of the 14 TeV LHC experiments.

When LHC eventually reaches the threshold for gluino pair production, the generic jet+MET observables will begin to work and SUSY will be discovered unambiguously.

In such models, the LHC can explore the heavy SUSY states, but it is very difficult for LHC to characterize the light states, including the dark matter particle. Lepton collider measurements, probably even below 500 GeV, are needed for this.

3. Models with composite Higgs

In Little Higgs models, the Higgs field is a Goldstone boson associated with a symmetry breaking at 10 TeV.

In Gauge-Higgs unification models, the Higgs doublet field is the 5th component of a gauge field in higher dimensions.

In both cases, the effective theory at 1 TeV contains a effective scalar doublet whose mass receives no quadratically divergent corrections.

Thus, the radiative corrections from W, Z, t must be cancelled by corrections due to new particles. In SUSY, these are $(\widetilde{\chi}, \widetilde{t})$.

In composite Higgs models, we find new states (W', Z', T) with the same statistics as W, Z, t.

This already raises an issue:

In the Standard Model, all masses are of the form

$$m \sim \lambda v \quad \text{where} \quad v = 246 \ \ \mathrm{GeV}$$

and λ is a perturbative coupling. This limits masses to be below about 500 GeV.

If we want (W', Z', T) to be heavier, the main part of their masses cannot come from electroweak symmetry breaking.

So these cannot be simple sequential W, Z or 4th generation t.

This affects the search strategies and the quoted limits on these particles.

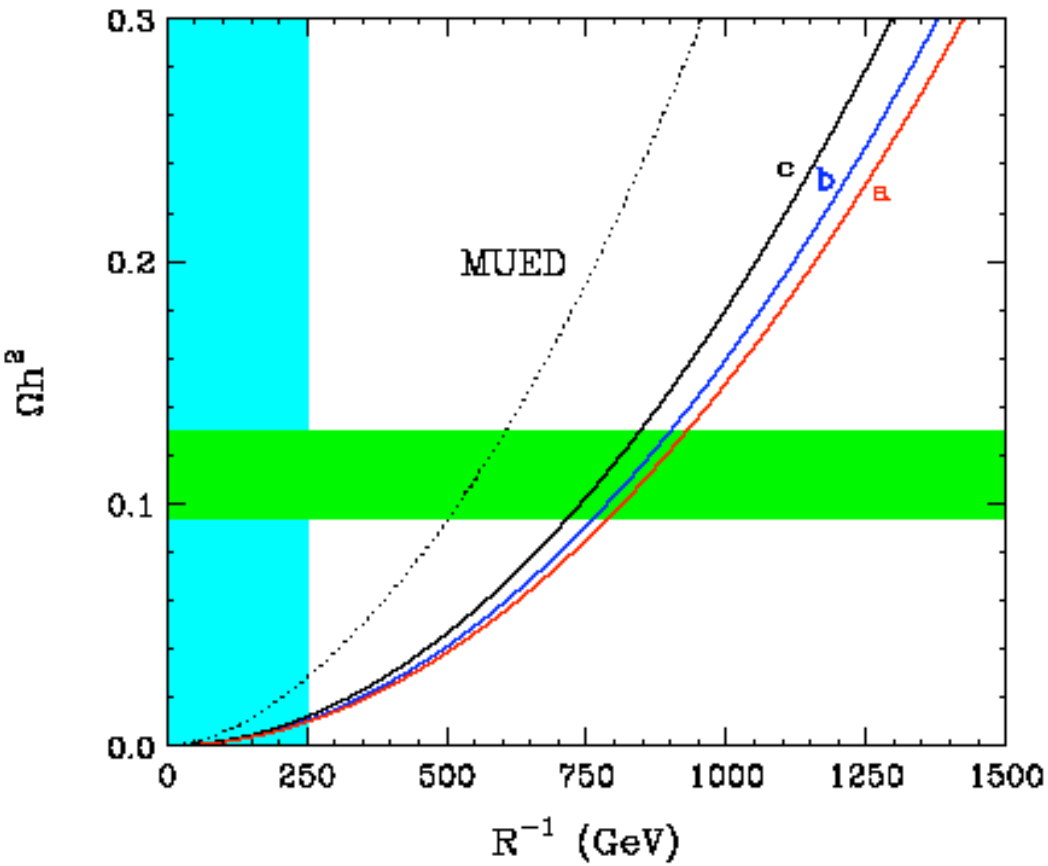
The new fermions are vectorlike singlet T or doublet (T,B).

The new gauge bosons are most easily visualized as higher dimensonal Kaluza Klein excitations of the W, Z.

The original theories of this type put the masses of these particles in the multi-TeV range.

The lightest vector partner of γ/Z^0 is a candidate for the dark matter WIMP.

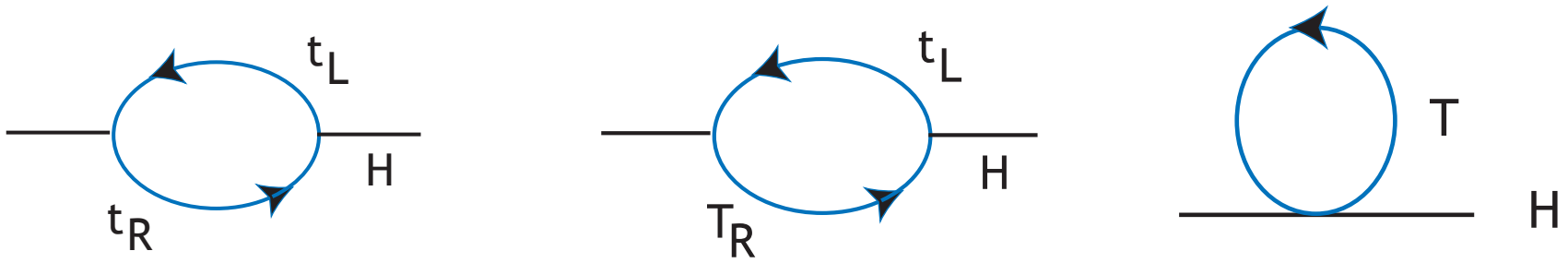
There is no strong naturalness argument that this particle should be light. Relic density calculations prefer larger values, 500 - 1000 GeV.



Kong-Matchev

Again, there are mechanisms for generating a negative Higgs μ^2 term making use of the large value of the top quark mass.

For example, in Little Higgs (SU(3)/SU(2)xU(1))



$$m_H^2 = -3\frac{\lambda_1^2\lambda_2^2 f^2}{8\pi^2}\log\frac{M^2}{m_T^2} = -3\frac{\lambda_T^2 m_T^2}{8\pi^2}\log\frac{M^2}{m_T^2}$$

In gauge-Higgs unification, there is a similar computation making use of the Hosotani mechanism.

The partners of W, Z, and t are hardly constrained by current LHC experiments.

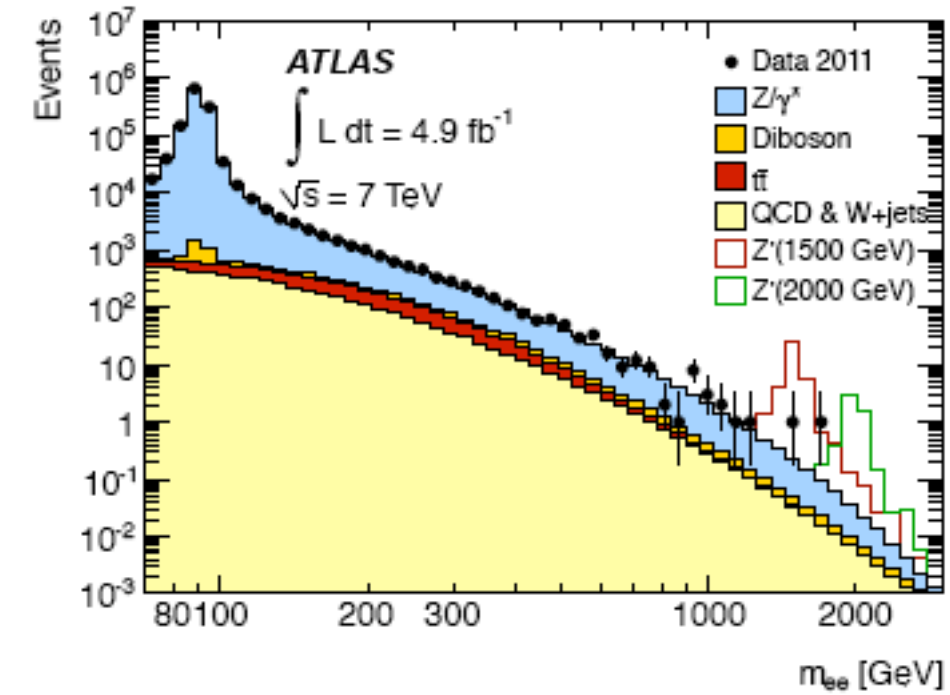
The partner of t is not a sequential 4th generation quark. It is a vectorlike quark, with a decay pattern

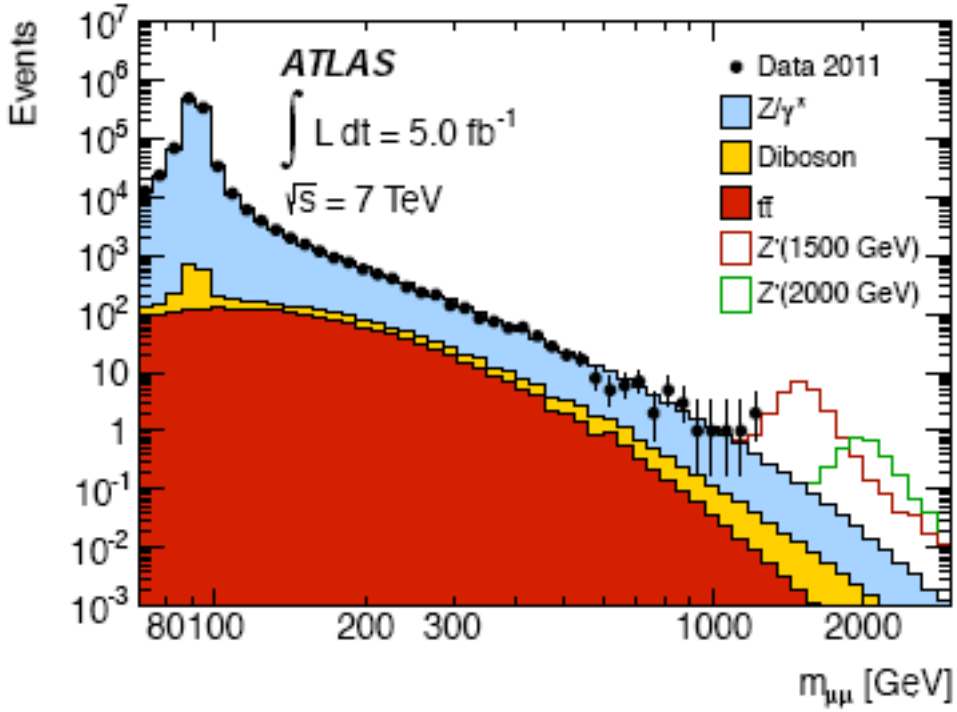
$$T \to bW^+,\ tZ^0,\ th^0 \qquad 2:1:1$$

The upper bound on the mass of the 4th generation quark does not apply. Typical mass values are 1-3 TeV.

The partners of W, Z have suppressed coupling to light fermions (possibly even 0, but symmetry). Their Drell-Yan production cross sections are typically not more than a few percent of the cross sections for sequential W, Z.

Begin with the example of searches in Drell-Yan.





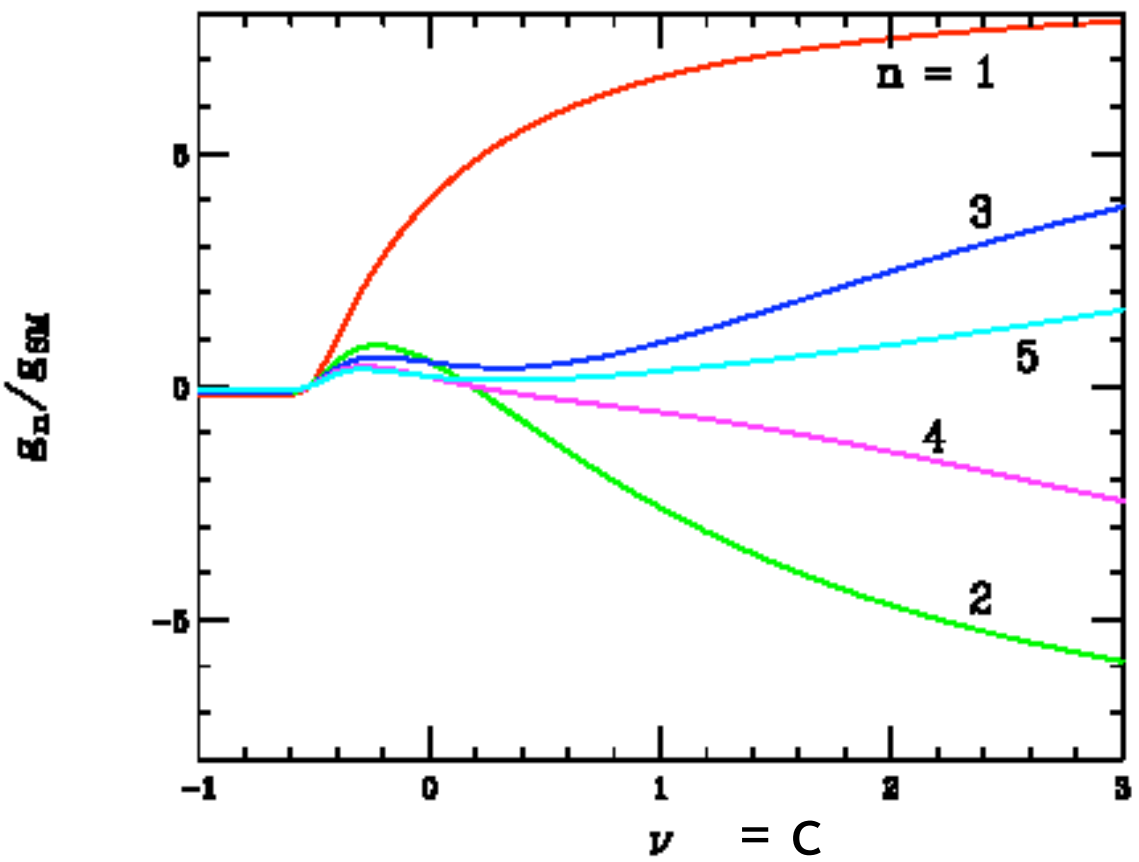
How do we interpret these results?

We are interested in the production of excited or KK W and Z bosons from initial $q\bar{q}$ pairs through vector and axial currents. The main question is the strength of the coupling.

For KK W and Z, this is a geometrical question, having to do with the form of the wavefunctions and their overlap.

Here is the answer in a particular Randall-Sundrum model studied by Davoudiasl, Hewett, and Rizzo

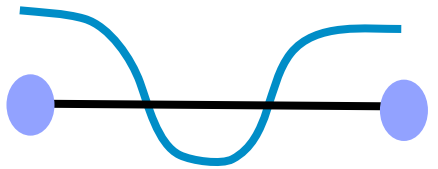
Large enhancements are possible, but, for searches, we are particularly concerned about suppressions.



The situation is particularly clear in the case of a flat extra dimension. Light quarks and leptons have wavefunctions that are flat in the extra dimension. But KK states with n > 0 have nontrivial wavefunctions. In the simplest case, these wavefunctions are orthogonal to the constant mode. A parity symmetry $x^5 \to -x^5$ can enforce absolute orthogonality.

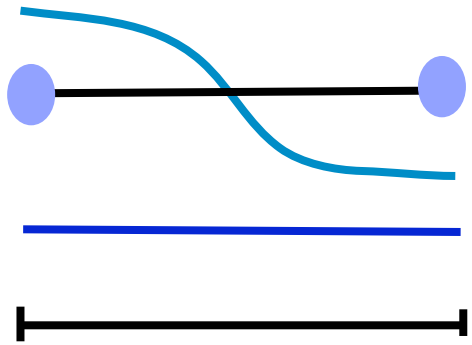
However, even with a parity symmetry, the suppression of the coupling to a level-2 resonance not absolute. Radiative corrections generate some boundary terms, e.g.,

$$\int_{\partial M} d^3x \ (F_{\mu\nu})^2$$



These permit the 0+0 -> 2 transitions with suppressed stregth,

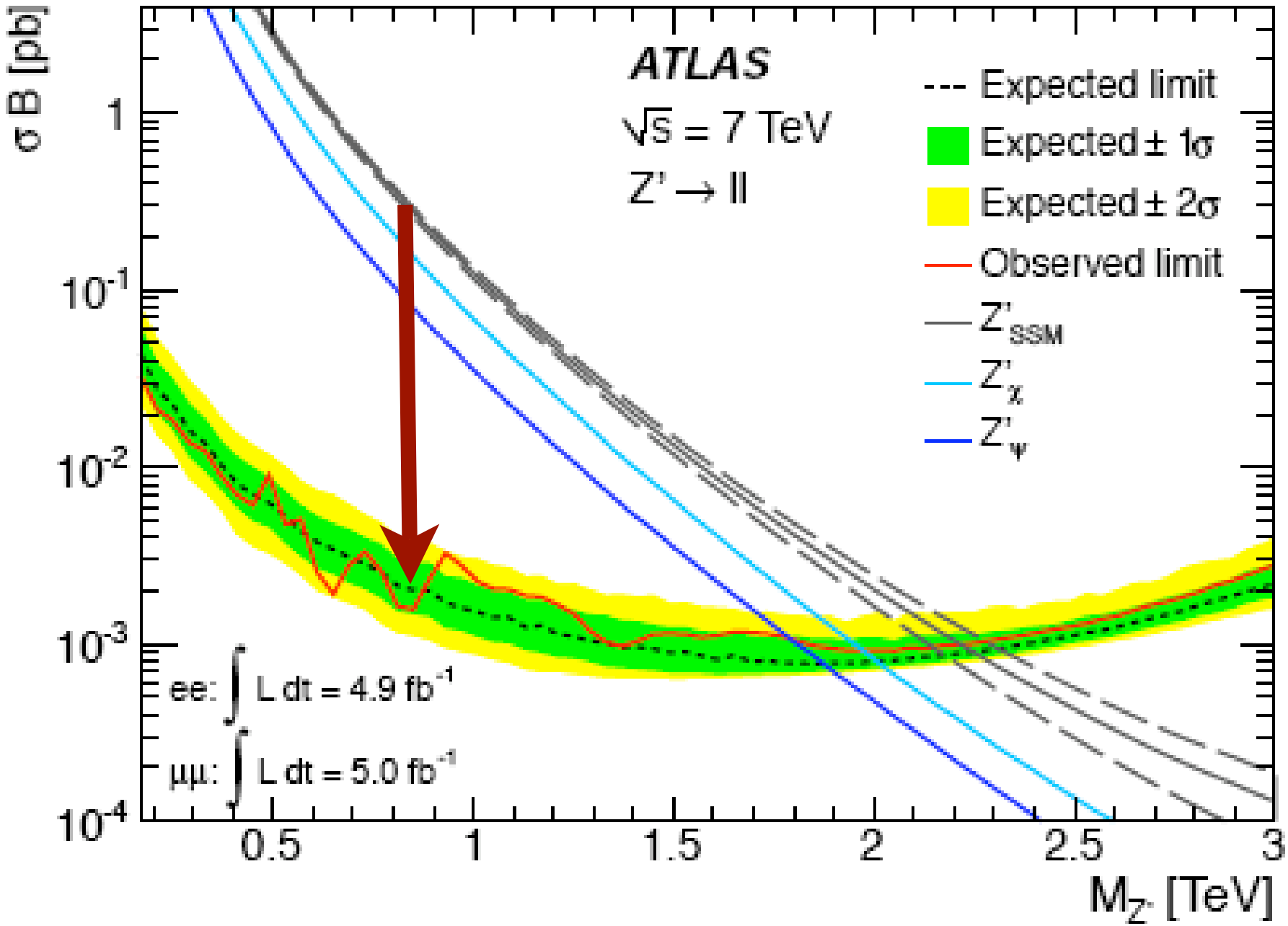
$$\mathcal{O}(\epsilon g) \quad \epsilon \sim 0.1 - 0.3$$



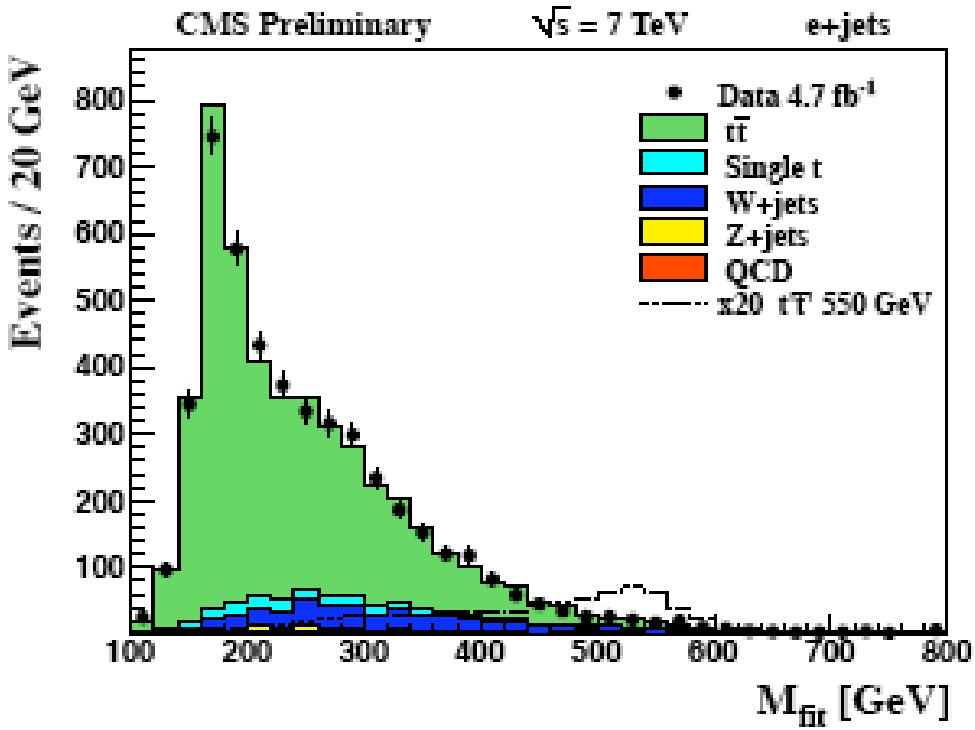
The coupling parameter ϵ comes squared in the production rate, and it is squared again if are searching a dilepton or light quark final state, e.g. $u\bar{d} \to W' \to \ell\nu$.

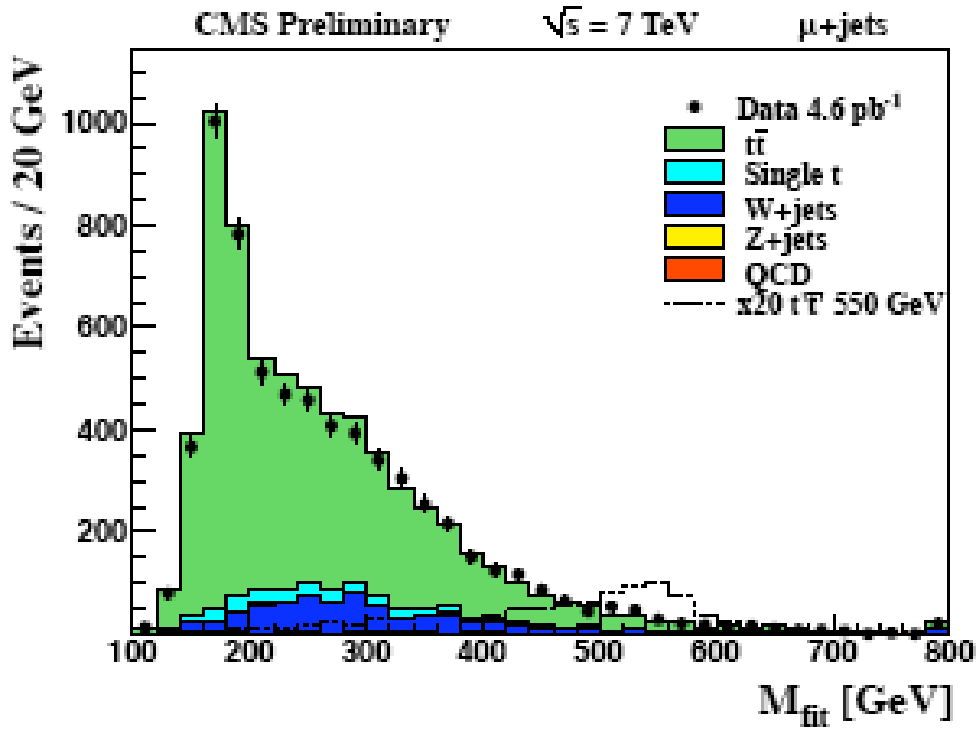
Thus, it is relevant and even important to search for resonances in Drell-Yan with sensitivity $10^{-2} - 10^{-3}$ of the cross section for a sequential W or Z.

If m_μ/m_e is explained, as in RS theory, by wavefunction overlaps of the leptons and Higgs bosons, we expect different couplings of the heavy W or Z to $\mu \; vs. \; e$. Thus, it is not correct in general to assume μ/e universality.

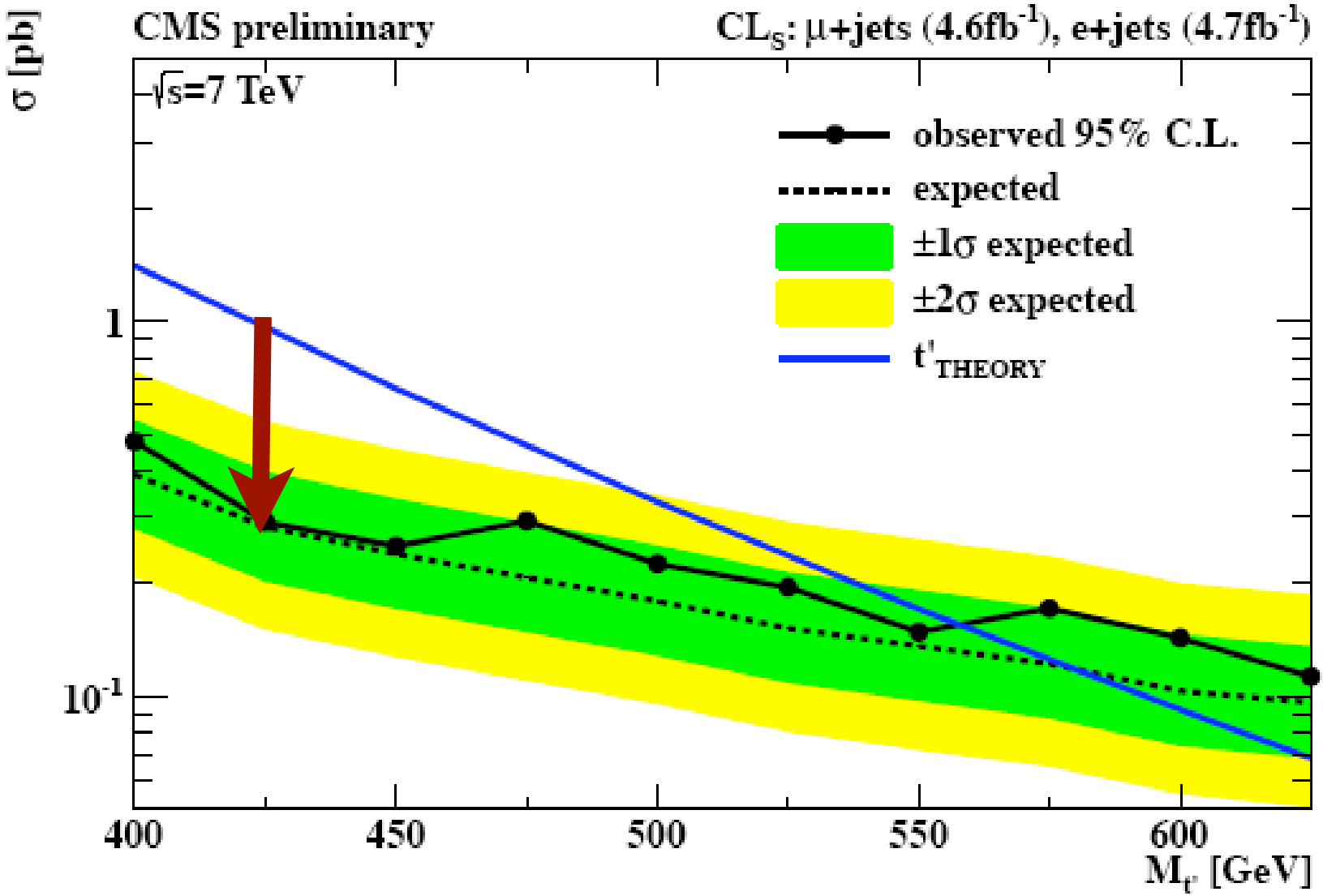

ATLAS
√s = 7 TeV
Z' → ll
Expected limit
Expected ± 1σ
Expected ± 2σ
Observed limit
Z'SSM
Z'χ
Z'ψ
ee: ∫ L dt = 4.9 fb-1
μμ: ∫ L dt = 5.0 fb-1
σ B [pb]
MZ' [TeV]
1
10-1
10-2
10-3
10-4
0.5
1
1.5
2
2.5
3

Similarly, consider a search for T in $T \rightarrow bW^+$:





This is a 50% branching fraction of the T, so we must derate the limit from a search that assumes 100% branching fraction.



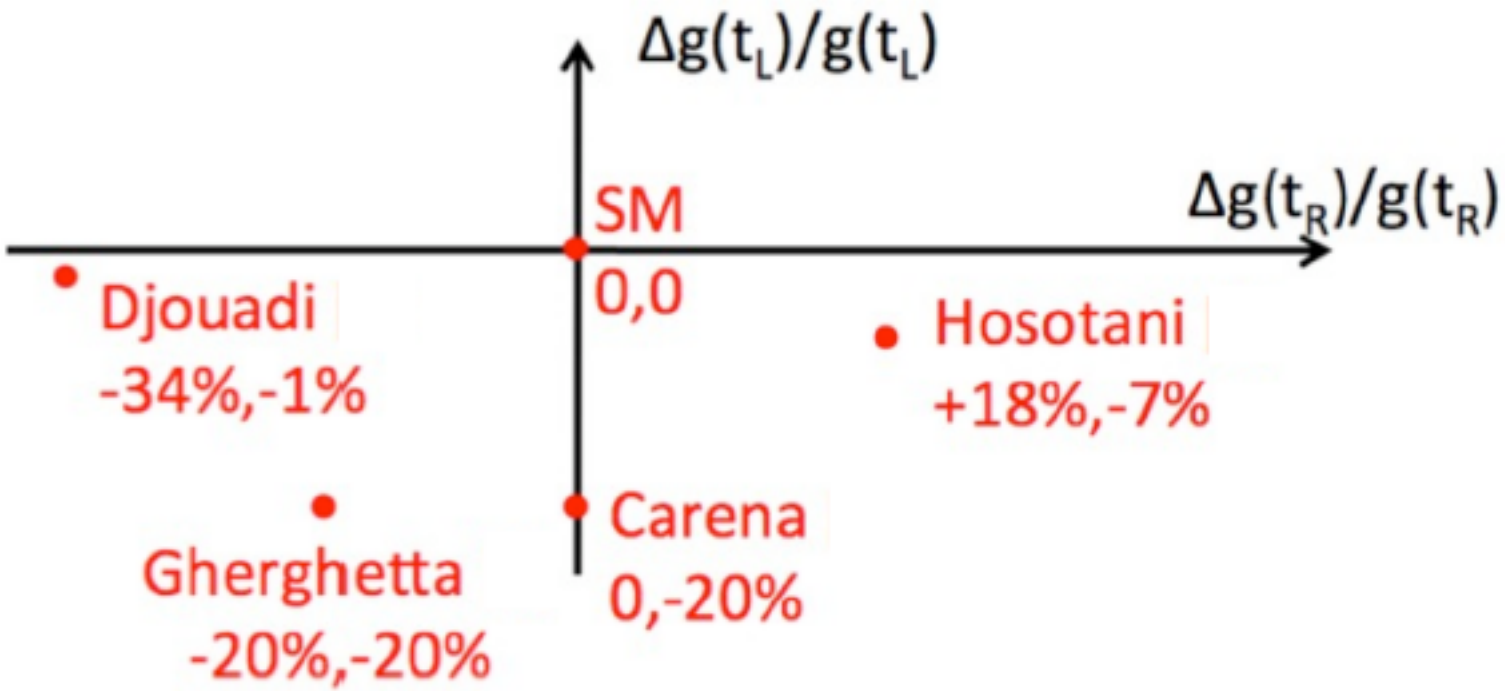
Though these searches are interesting, they are not accessing the multi-TeV region where the new particles are expected. This will have to wait for the 14 TeV LHC.

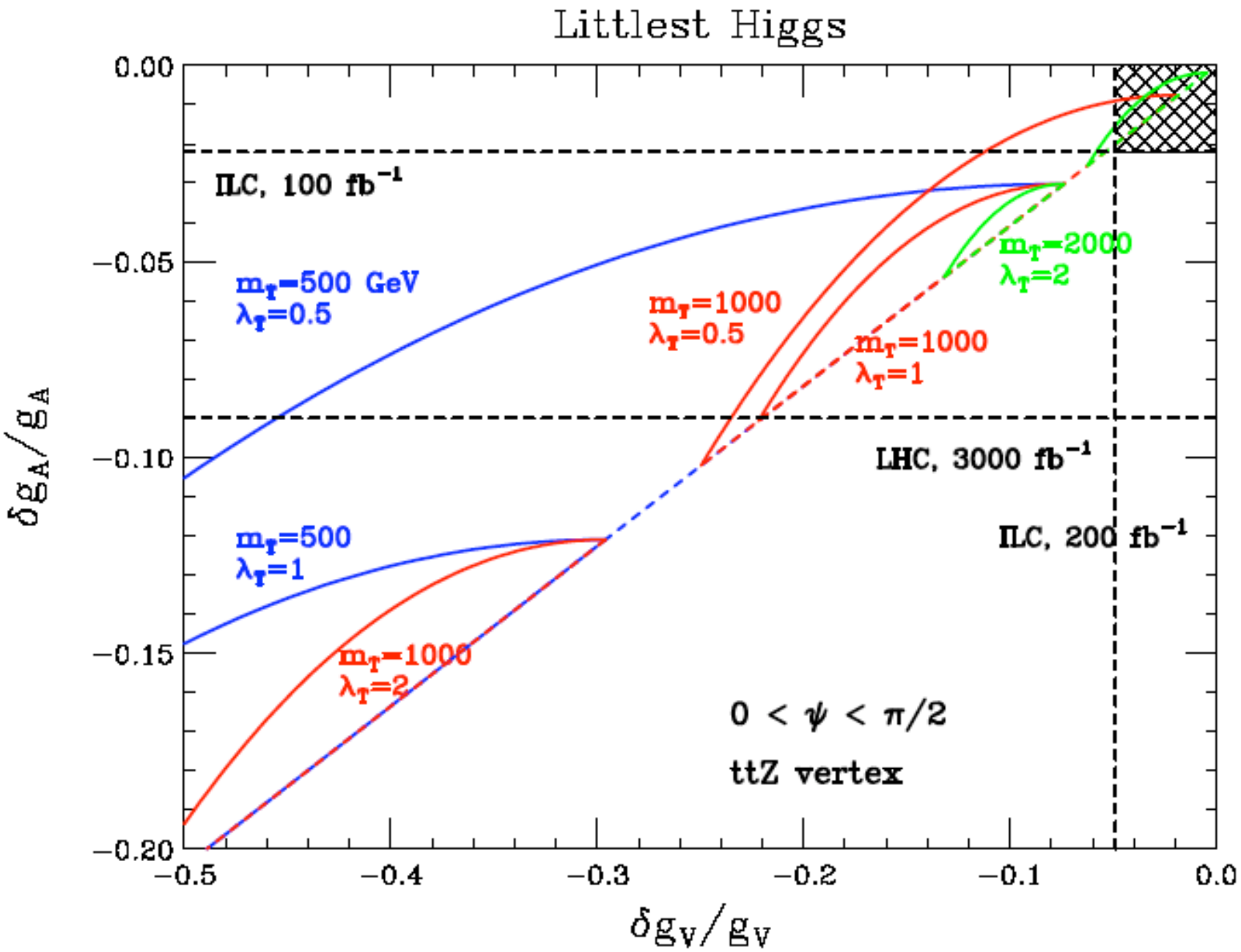
Although the new particles in these models are at very high masses, they do have an imprint at lower energies. And, this is an important part of their characterization in experiments.

Composite Higgs particles and associated structure must modify the couplings of Higgs, W, Z, and top. The gives anomalies that are detectable in precision experiments. We already know the energy scale needed for those experiments. It is 350-400 GeV.

If there is no supersymmetry but instead composite Higgs, this is an important task for the ILC.

Composite Higgs models predict a wide range of values for the couplings of the Z boson to the top. Here is an example of predictions from Randall-Sundrum extra-dimensional models:





Berger, Petriello, Perelstein

Conclusions:

The origin of electroweak symmetry breaking remains a question. This must be solved at the TeV energy scale. Many models have been excluded at the LHC, but many other interesting possibilities remain.

The energy reach of the LHC will increase by a factor 4 in its design phase and another factor 2 in its high-luminosity phase.

Don't give up on the LHC !

The models that are still relevant have important experimental tests in e+e- annihilation below 500 GeV.

Don't give up on the ILC !

"Keep the faith .." This is the only path to a deeper understanding of elementary particle physics.