# Where is the new physics at the LHC ?

M. E. Peskin
Sakata100, Nagoya
October, 2011

I am honored to be invited to lecture at the celebration of the 100th birthday of Shoichi Sakata.

My topic will be the current state of searches for new physics beyond the Standard Model at the LHC.

I hope to discuss this topic in the spirit of Sakata, in a sense that I will explain.


Sakata, Ohnuki, and Maki in Nagoya

Morris Low Nagoya 2006

No signs of new physics have turned up yet at the LHC.

Not everyone considers this to be a problem, but many people are impatient.   There are good reasons to be impatient, which I will explain later.

I add that the press is impatient, and eager to say that the theorists have it wrong ...

New York Times (Claudia Dreyfus) interview
with Stephen Hawking

May 9, 2011 (w. public LHC results
from 0.04 fb-1/experiment)

Q. About the Large Hadron Collider, the supercollider in Switzerland, there were such high hopes for it when it was opened. Are you disappointed in it?

A. It is too early to know what the LHC will reveal. It will be two years before it reaches full power. When it does, it will work at energies five times greater than previous particle accelerators.

We can guess at what this will reveal, but our experience has been that when we open up a new range of observations, we often find what we had not expected. That is when physics becomes really exciting, because we are learning something new about the universe.

Why is there an expectation that we will find new physics at the LHC?

Dark Matter:

This is the #1 proof of physics beyond the Standard Model.

In the case of a thermally produced Weakly Interacting Massive Particle, we have the Turner-Scherrer relation

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

Solve this and find:

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

But, there are counterexamples: axion, WIMPzilla for which the TeV scale is not relevant to explain dark matter.

## Electroweak Symmetry Breaking:

In the well-tested Standard Model of weak interactions, the gauge symmetry that is fundamental to the theory prohibits the masses of quark, leptons, and W and Z bosons.

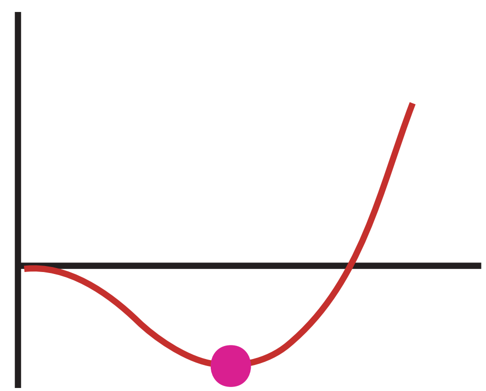
To produce these masses, the gauge symmetry SU(2)XU(1) must be spontaneously broken.

In the minimal form of the Standard Model, we postulate

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

with $\mu^2 < 0$

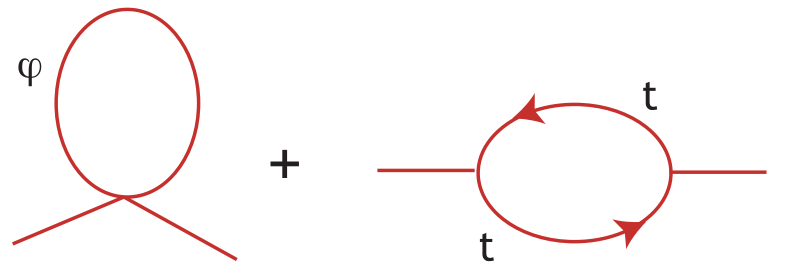
Then indeed $\langle\varphi\rangle = |\mu|/\sqrt{2\lambda} \neq 0$



However, this explanation is not very satisfying. Why is the symmetry broken? The answer is: because $\mu^2 < 0$ .

This deplorable answer is even worse than it seems.

The parameter $\mu^2$ is not computable even in principle in the MSM, because most of the diagrams contributing to $\mu^2$ are quadratically ultraviolet divergent




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

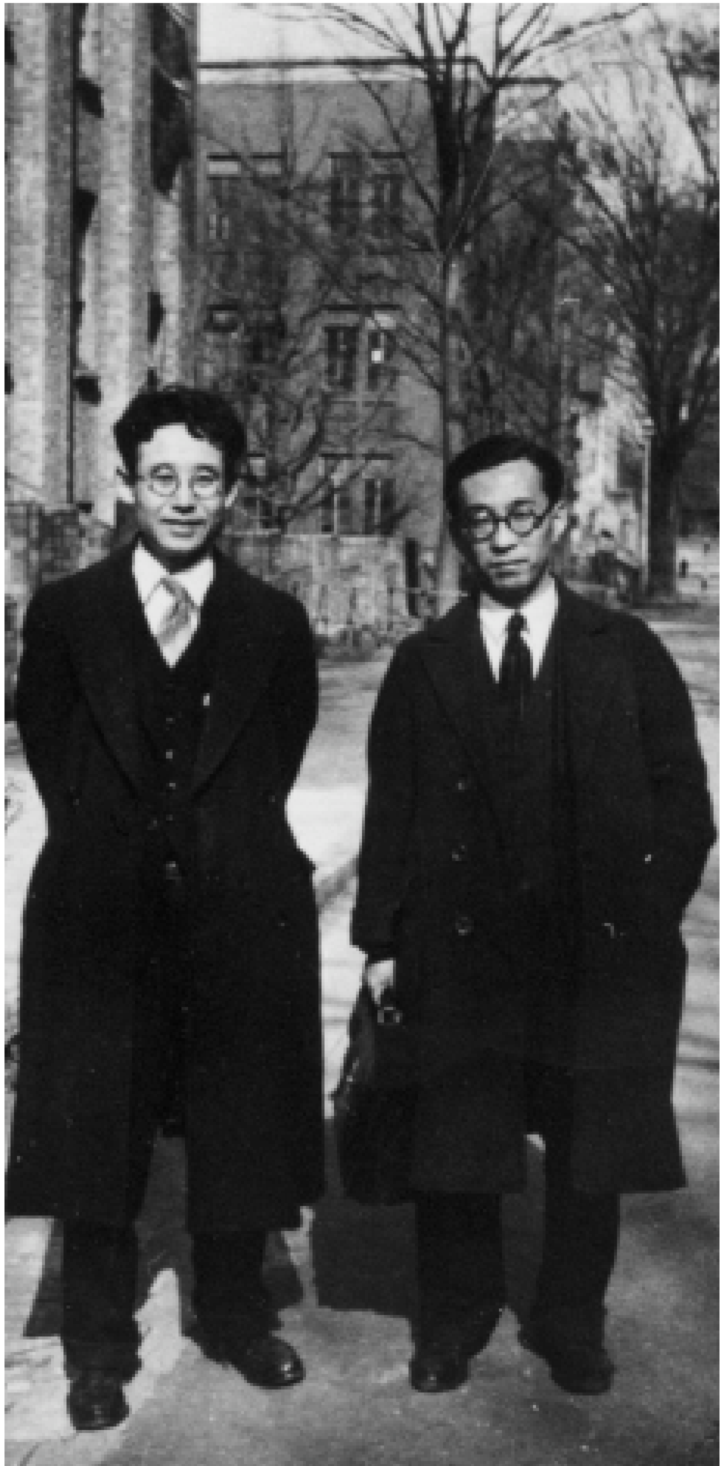
If the cutoff $\Lambda$ is a very high scale, e.g. $\Lambda \sim 10^{16}$ GeV it is very difficult to understand how $m_h$ could be as small as 100 GeV.

This is called the "gauge hierarchy problem".

However, we do not need to invoke haughty principles to realize that there is a problem.

We have the faith that the most important phenomena in Nature should have direct mechanical explanations.

This is the faith that led Sakata to seek a unifying constituent model of hadrons rather than the mystical explanation given by Geoffrey Chew -- much more fashionable at the time -- that the strong interactions were the only possible consistent strong interaction theory.



... the progress in science and the success in practice continuously proves the validity of materialism. In this respect, materialism is no longer a naive point of view, but a scientific view of the world which is supported by all the fruits of modern science. Then we may conclude that any standpoint which denies materialism obstructs the progress of science.

--- Shoichi Sakata (1947)

Sakata and Takatani
Morris Low Nagoya 2006

In this workshop, the term "dynamical symmetry breaking" has so far been reserved for strong-interaction symmetry-breaking mechanisms. I would argue that weak-coupling mechanisms that explain the asymmetric minimum of the Higgs potential also qualify as mechanical or materialist explanations.

In this approach, we postulate an elementary scalar Higgs field (which may still be an effective scalar arising at a higher mass scale). Then we find a set of Feynman diagrams that generate a negative value of $\mu^2$ for this field.

Models of this type lead to a light scalar HIggs boson similar to the Higgs boson of the minimal Standard Model.

Don't worry! It will show up in the 2012 LHC data.

In this approach, the first step is to build the model around a symmetry that sets the Higgs boson mass to zero in the leading order. There are three ways known to do this:

1. $\delta\varphi = \epsilon$ realized if $\varphi$ is a Goldstone boson

2. $\delta\varphi = \epsilon_\mu A^\mu$ combined with gauge symmetry

3. $\delta\varphi = \overline{\epsilon}\psi$ combined with chiral symmetry

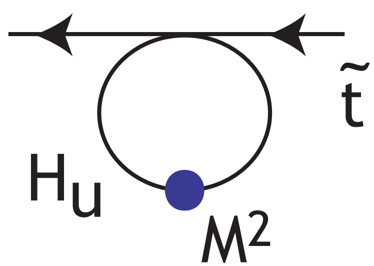
These mechanisms are realized in

little Higgs, gauge-Higgs unification, supersymmetry

In this lecture, I will concentrate on the best-studied case, supersymmetry.

Supersymmetry is often considered to be a mystical approach to physics beyond the Standard Model. The idea that supersymmetry can provide a mechanical solution to the generation of the Higgs potential is due to Dimopoulos, Nilles, Raby, and Susskind.

Following their lead, it was discovered by many authors that diagrams of the form




give a negative contribution to the $\mu^2$ term of the Higgs boson $H_u$ that dominates if the top quark mass is large.

In the simplest models of supersymmetry, all of the quarks, leptons, and gauge bosons have partners of opposite statistics that lie below the 1 TeV mass scale.

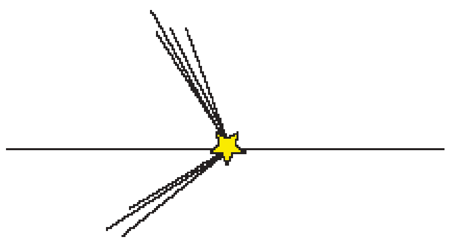
These models give pb cross sections to final states with many jets and missing transverse energy (or other exotic signatures, e.g., stable particles).

This is not a naive expectation, but experiment says that it is wrong.

example from CMS:

2 jets w.

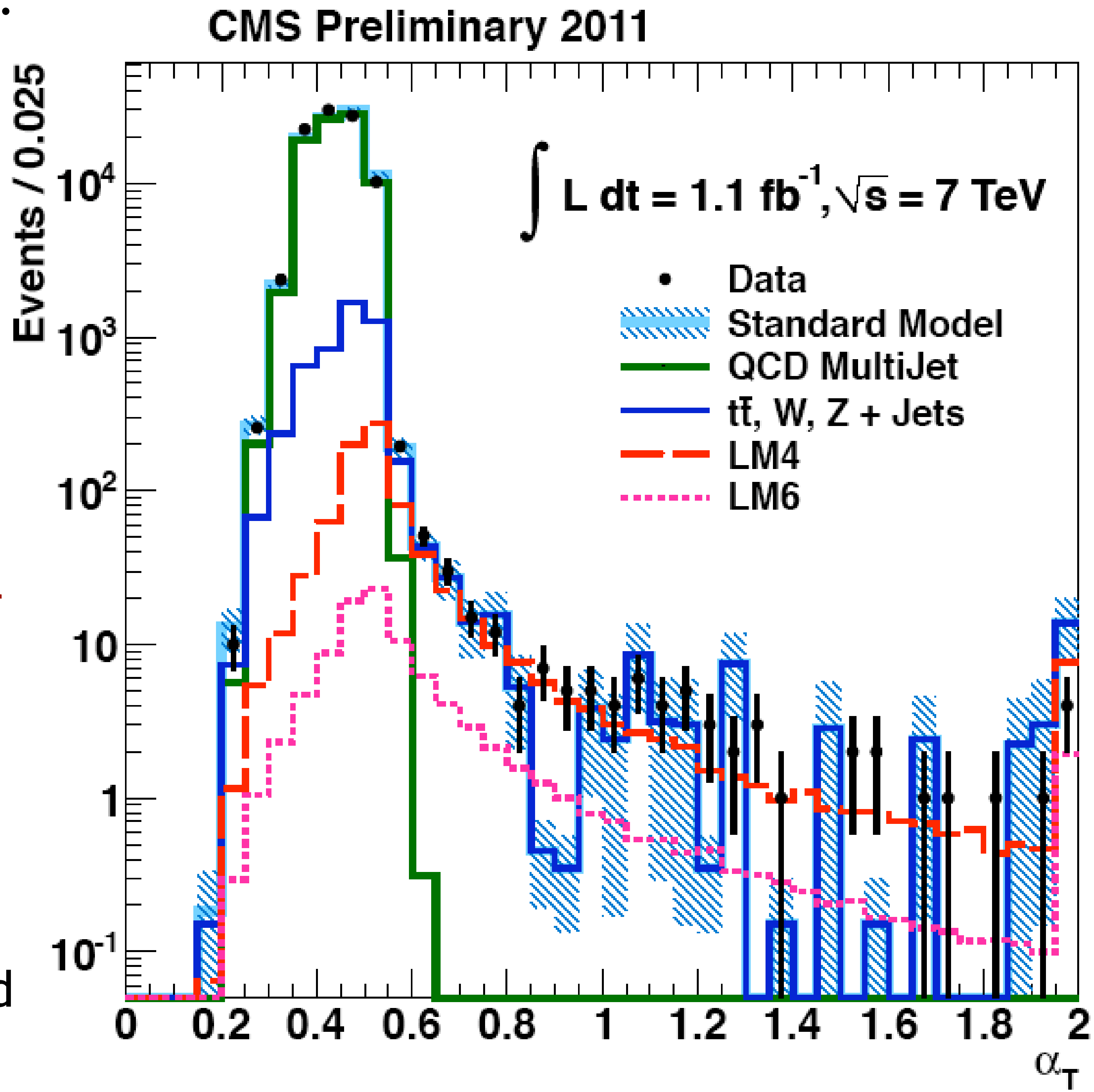
ET > 100 GeV

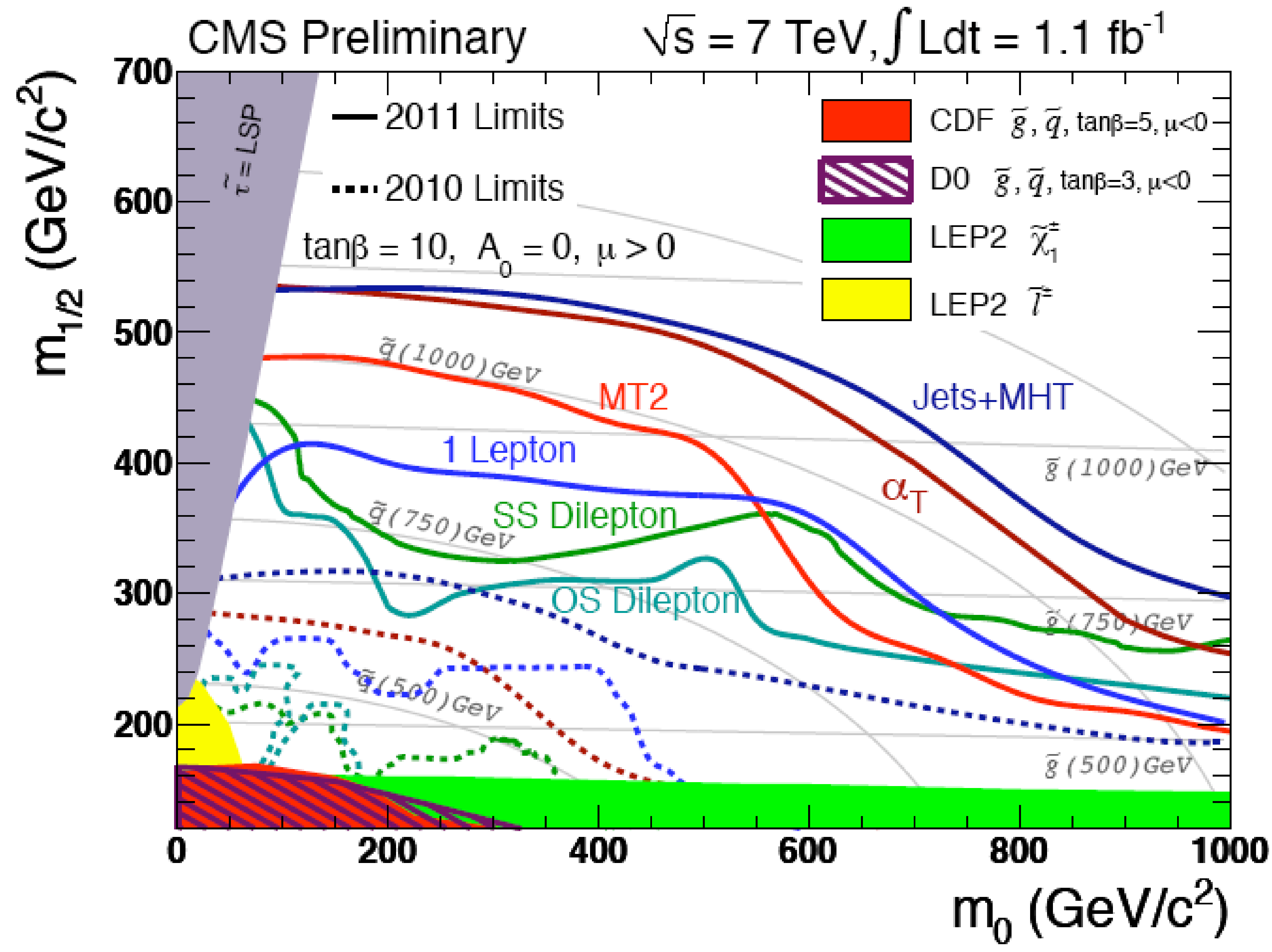


use the "scissors" variable of Randall and Tucker-Smith

$$\alpha_T = \frac{p_{T,2}}{m_T(12)}$$

to remove events with missing ET from mis-measured jets.

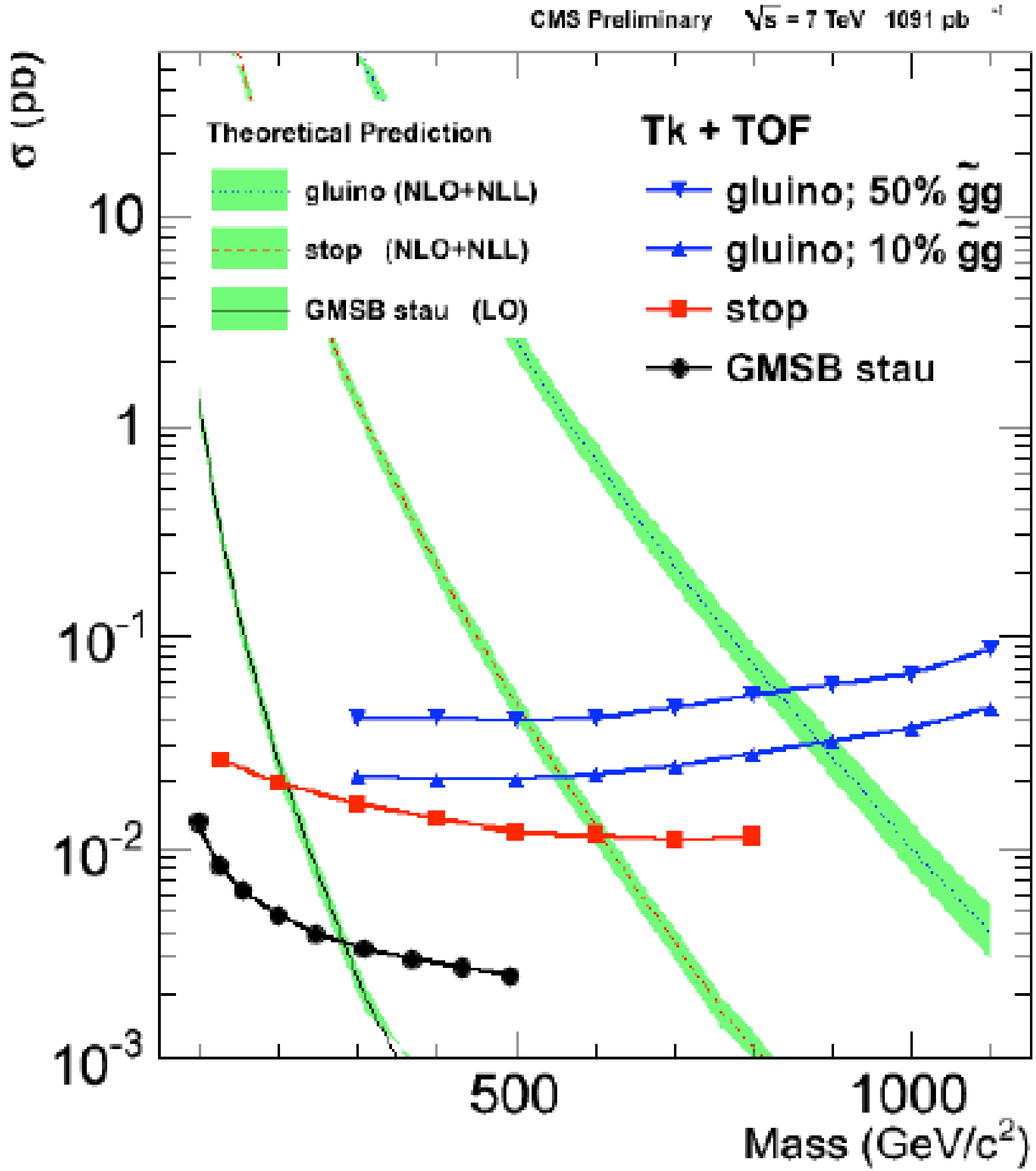



CMS Preliminary
$\sqrt{s}$ = 7 TeV, $\int$ Ldt = 1.1 fb$^{-1}$
$m_{1/2}$ (GeV/c$^2$)
$m_0$ (GeV/c$^2$)
$\tilde{\tau}$ = LSP
2011 Limits
2010 Limits
tanβ = 10, $A_0$ = 0, μ > 0
CDF $\tilde{g}, \tilde{q}$, tanβ=5, μ<0
D0 $\tilde{g}, \tilde{q}$, tanβ=3, μ<0
LEP2 $\tilde{\chi}_1^{\pm}$
LEP2 $\tilde{l}^{\pm}$
Jets+MHT
MT2
$\alpha_T$
1 Lepton
SS Dilepton
OS Dilepton
$\tilde{q}$(1000)GeV
$\tilde{q}$(750)GeV
$\tilde{q}$(500)GeV
$\tilde{g}$ (1000)GeV
$\tilde{g}$ (750)GeV
$\tilde{g}$ (500)GeV
0
200
400
600
800
1000
200
300
400
500
600
700

Notice that the experiments exclude the point where squarks and gluons have equal masses even as large as 1.2 TeV -- with the assumption that the neutralinos and charginos are much lighter.

I will discuss the $(m_0, m_{1/2})$ parameter space in a moment.

Constraints on gauge-mediated SUSY in which the lightest Standard Model SUSY partner decays to the gravitino -- with the favored mode of stau NLSP -- are even stronger.


CMS Preliminary $\sqrt{s}$ = 7 TeV 1091 pb$^{-1}$
σ (pb)
Theoretical Prediction
gluino (NLO+NLL)
stop (NLO+NLL)
GMSB stau (LO)
Tk + TOF
gluino; 50% $\tilde{g}g$
gluino; 10% $\tilde{g}g$
stop
GMSB stau
10
1
$10^{-1}$
$10^{-2}$
$10^{-3}$
500
1000
Mass (GeV/$c^2$)

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: $m_1$, $m_2$, $m_3$, $\mu$
- 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: $A_\tau$, $A_b$, $A_t$

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

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

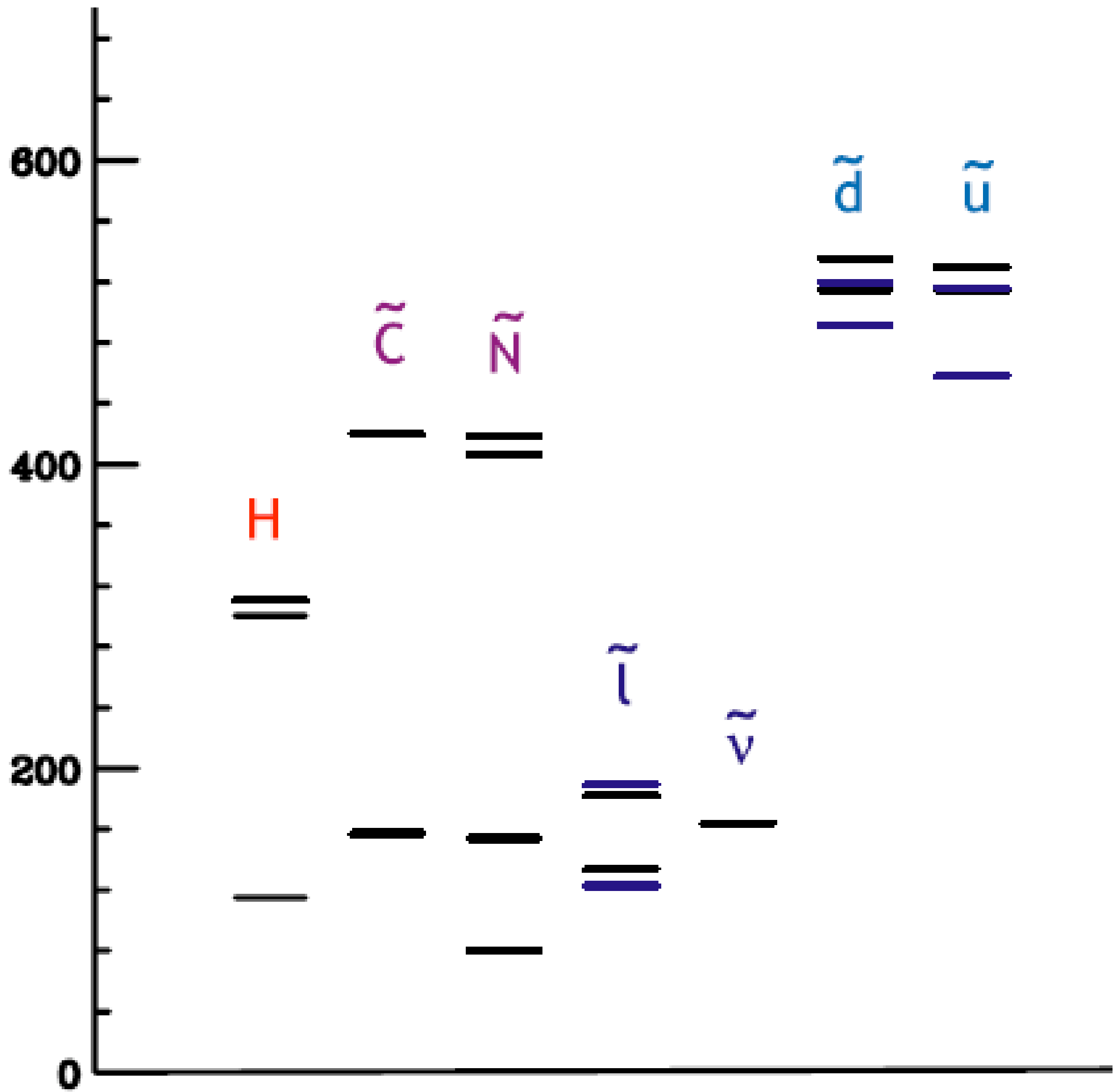
In this space, $\mu$ is an output parameter. We solve for $\mu$ using the relation for the Higgs v.e.v or the Z boson mass

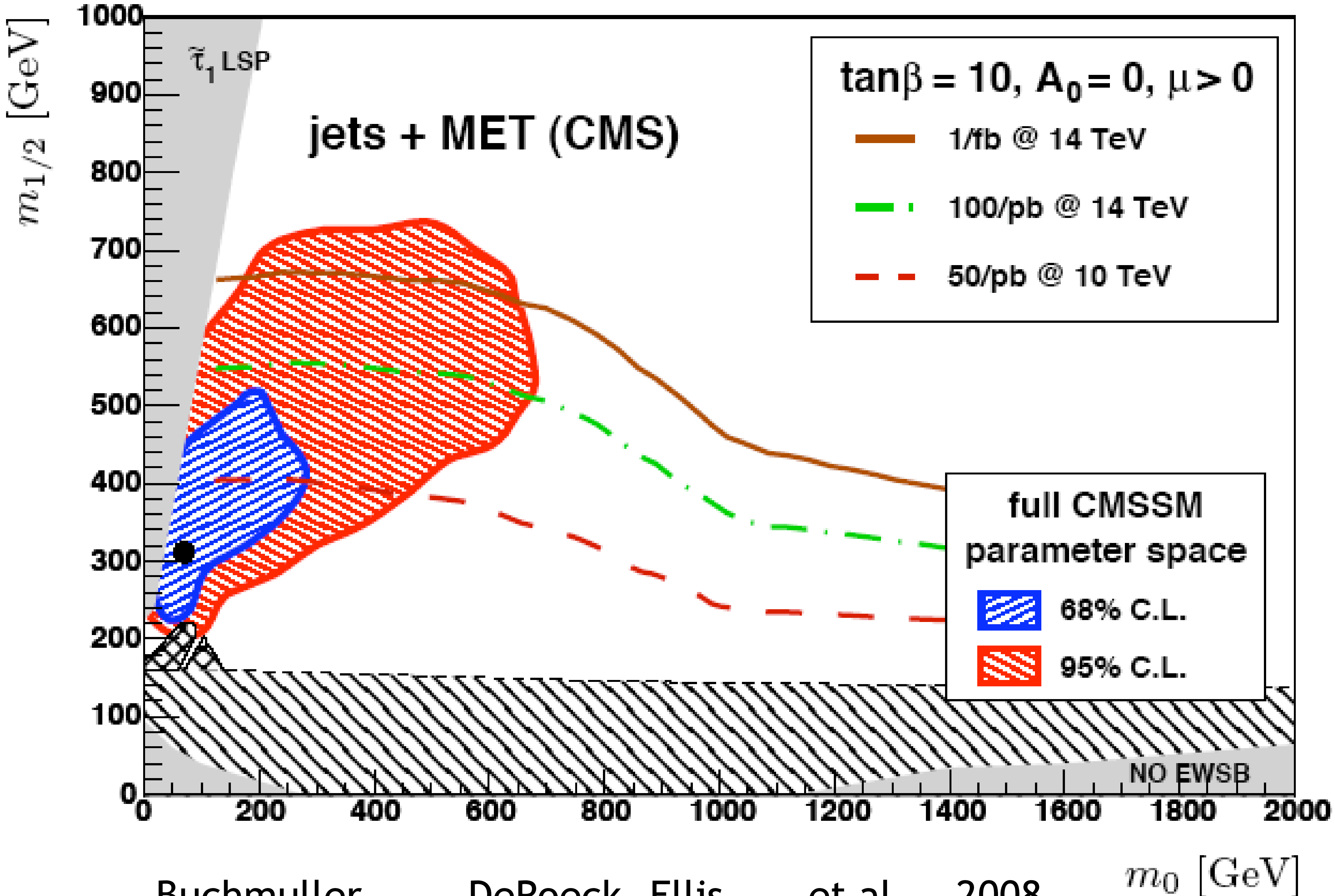
$$m_Z^2 = 2\,\frac{M_{Hd}^2 - \tan^2\beta M_{Hu}^2}{\tan^2\beta - 1} - 2\mu^2$$

The result is that $\mu$ is typically somewhat larger than $m_0$ .

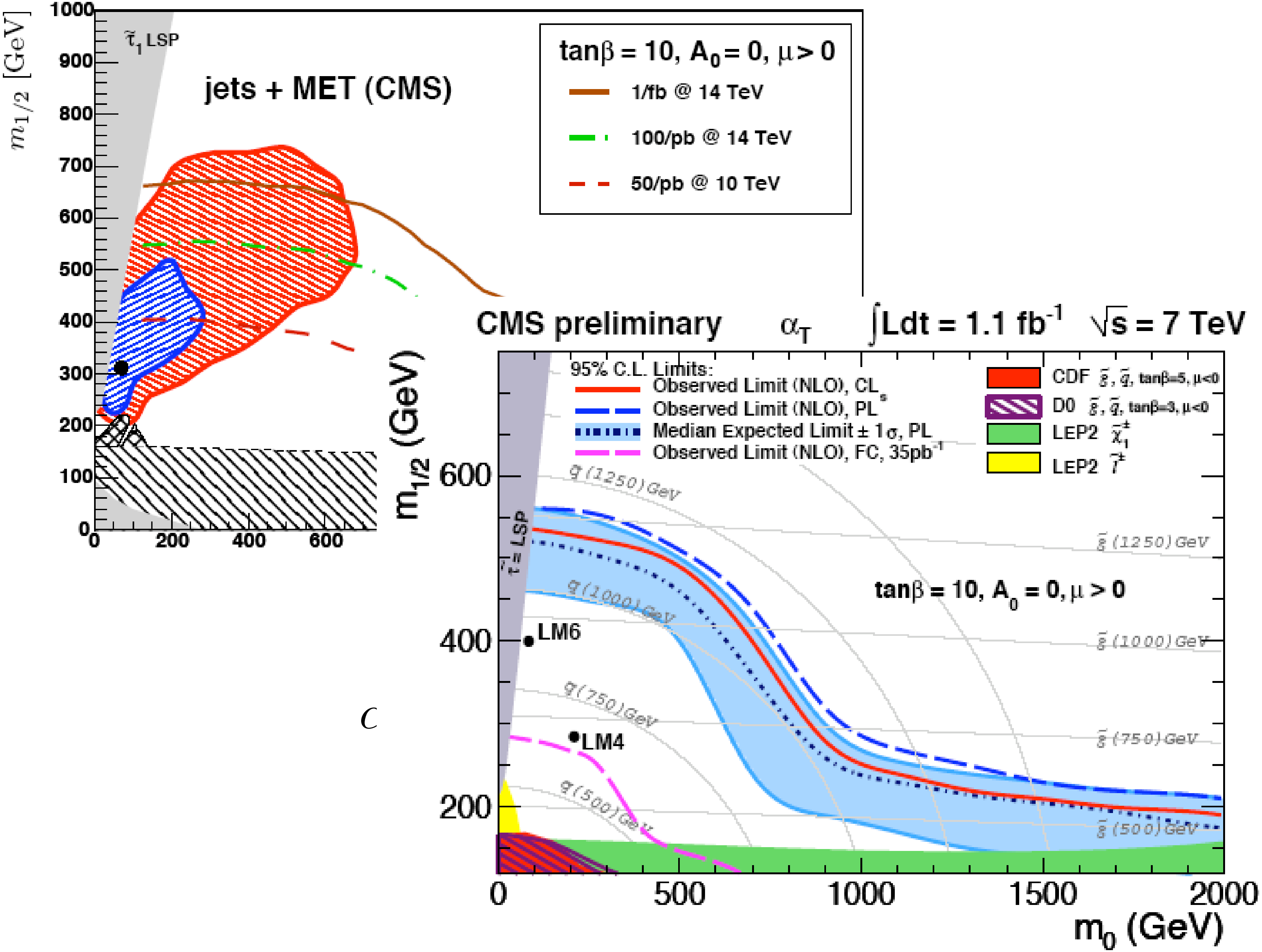
The MSUGRA space ties together constraints on the Higgs boson mass, the muon (g-2), $b \to s\gamma$ , dark matter, etc. The framework is very restrictive. Fitting tensions in low-energy observables with the Standard Model, it was possible to predict, before the LHC, the preferred parameter region of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

a typical MSUGRA spectrum






Buchmuller, ... , DeRoeck, Ellis ..., et al. 2008



jets + MET (CMS)
$\tan\beta = 10$, $A_0 = 0$, $\mu > 0$
1/fb @ 14 TeV
100/pb @ 14 TeV
50/pb @ 10 TeV
$\tilde{\tau}_1$ LSP
$m_{1/2}$ [GeV]
CMS preliminary
$\alpha_T$
$\int L dt = 1.1\ fb^{-1}$ $\sqrt{s} = 7$ TeV
95% C.L. Limits:
Observed Limit (NLO), $CL_s$
Observed Limit (NLO), $PL$
Median Expected Limit ± 1σ, PL
Observed Limit (NLO), FC, $35pb^{-1}$
CDF $\tilde{g}, \tilde{q}$, $\tan\beta=5, \mu<0$
D0 $\tilde{g}, \tilde{q}$, $\tan\beta=3, \mu<0$
LEP2 $\tilde{\chi}_1^{\pm}$
LEP2 $\tilde{l}^{\pm}$
$\tan\beta = 10$, $A_0 = 0$, $\mu > 0$
$\tilde{\tau}$ = LSP
LM6
LM4
$m_{1/2}$ (GeV)
$m_0$ (GeV)
C

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. Where should we look next ?

For fundamental purposes (e.g. connection to string theory and quantum gravity), we need SUSY only at $10^{18}$ GeV.

For the connection to grand unification, we need SUSY only at 10 TeV.

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 $\mu$ .

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

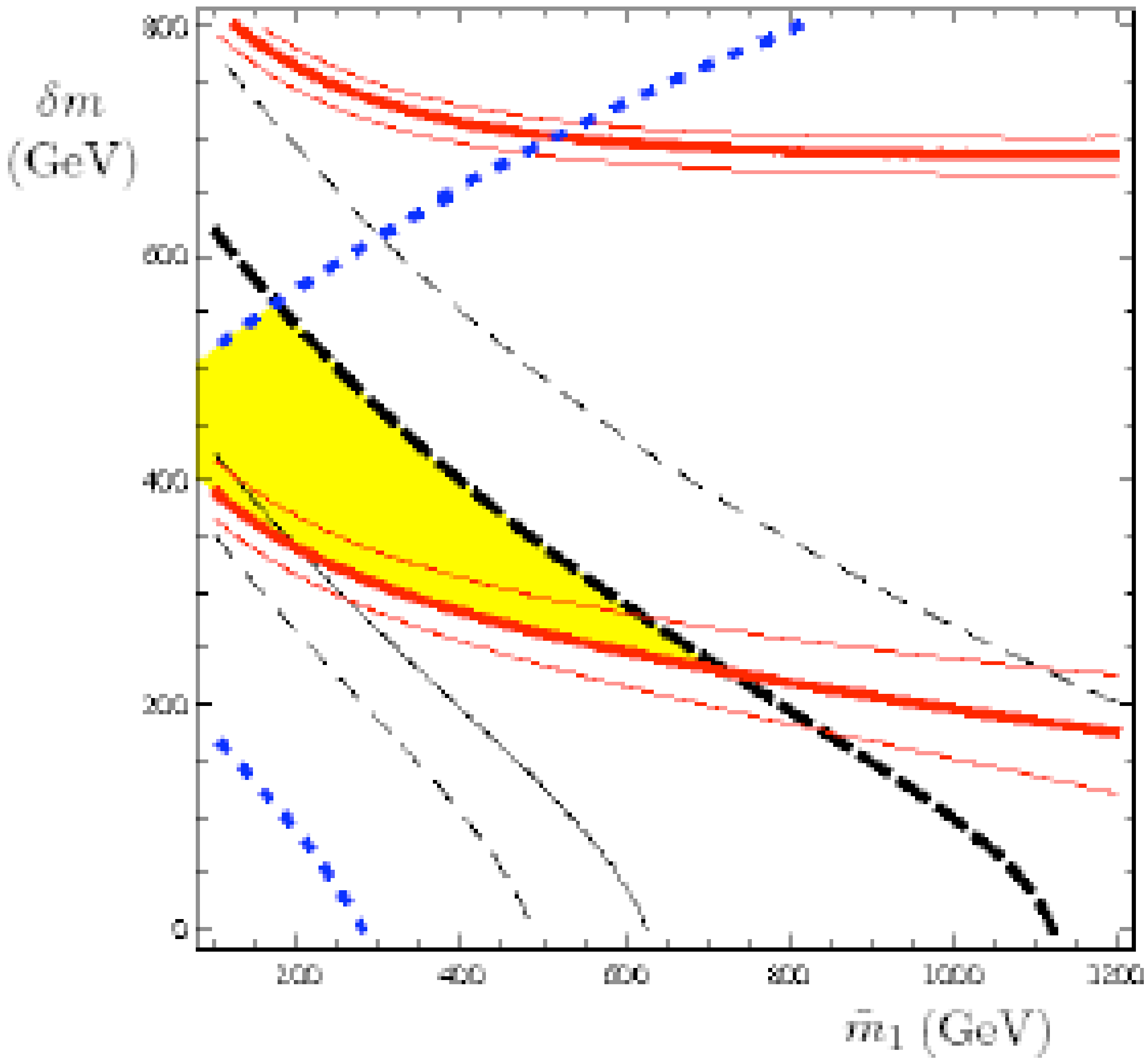
with only 3rd-generation sfermions, gauginos, Higgsino light.
There are many variations on this theme:

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)

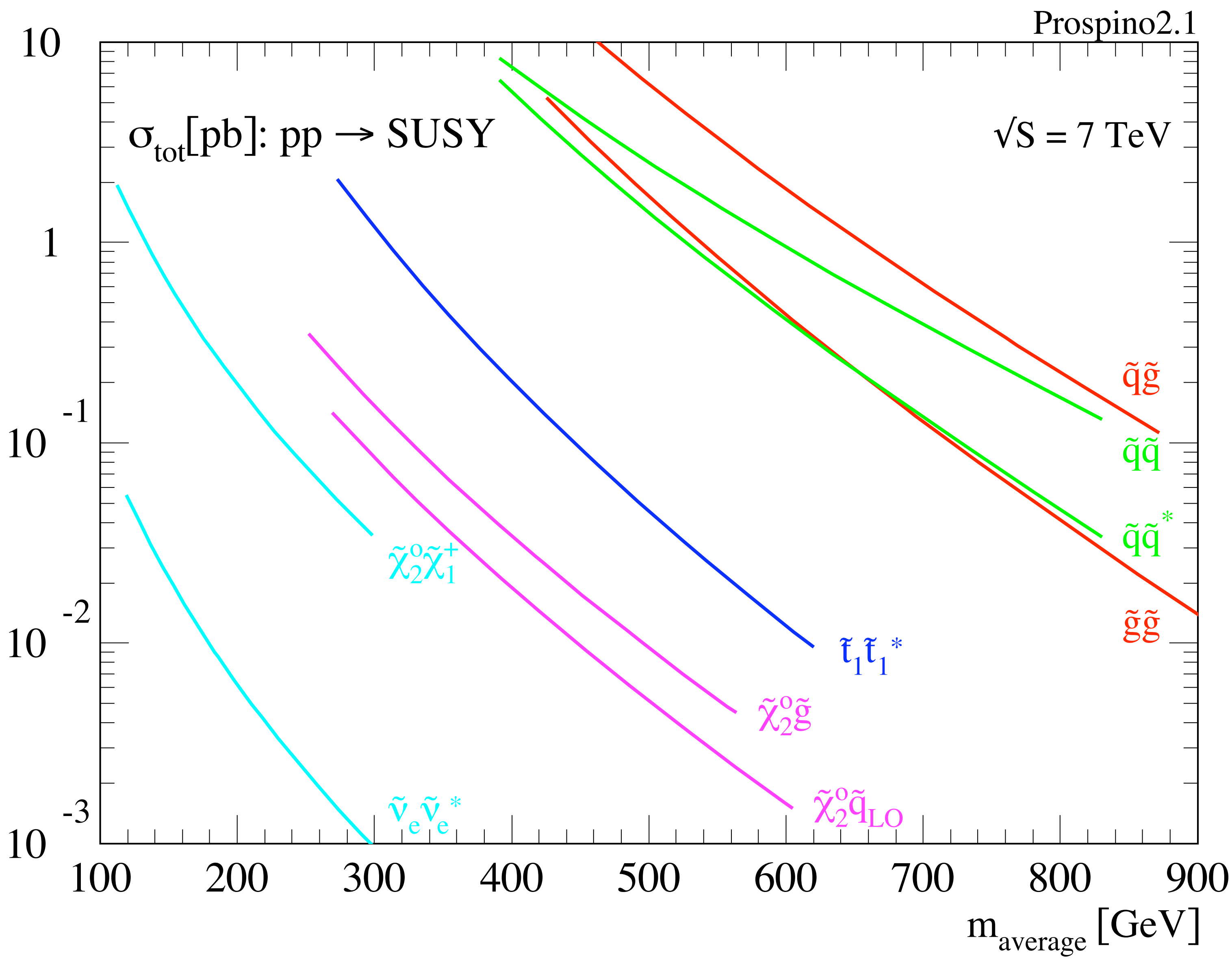
Hidden SUSY    Baer, Barger, Huang
(only Higgsinos below 1 TeV)

These give “natural” models of the Higgs potential and are barely constrained by the current LHC SUSY limits.



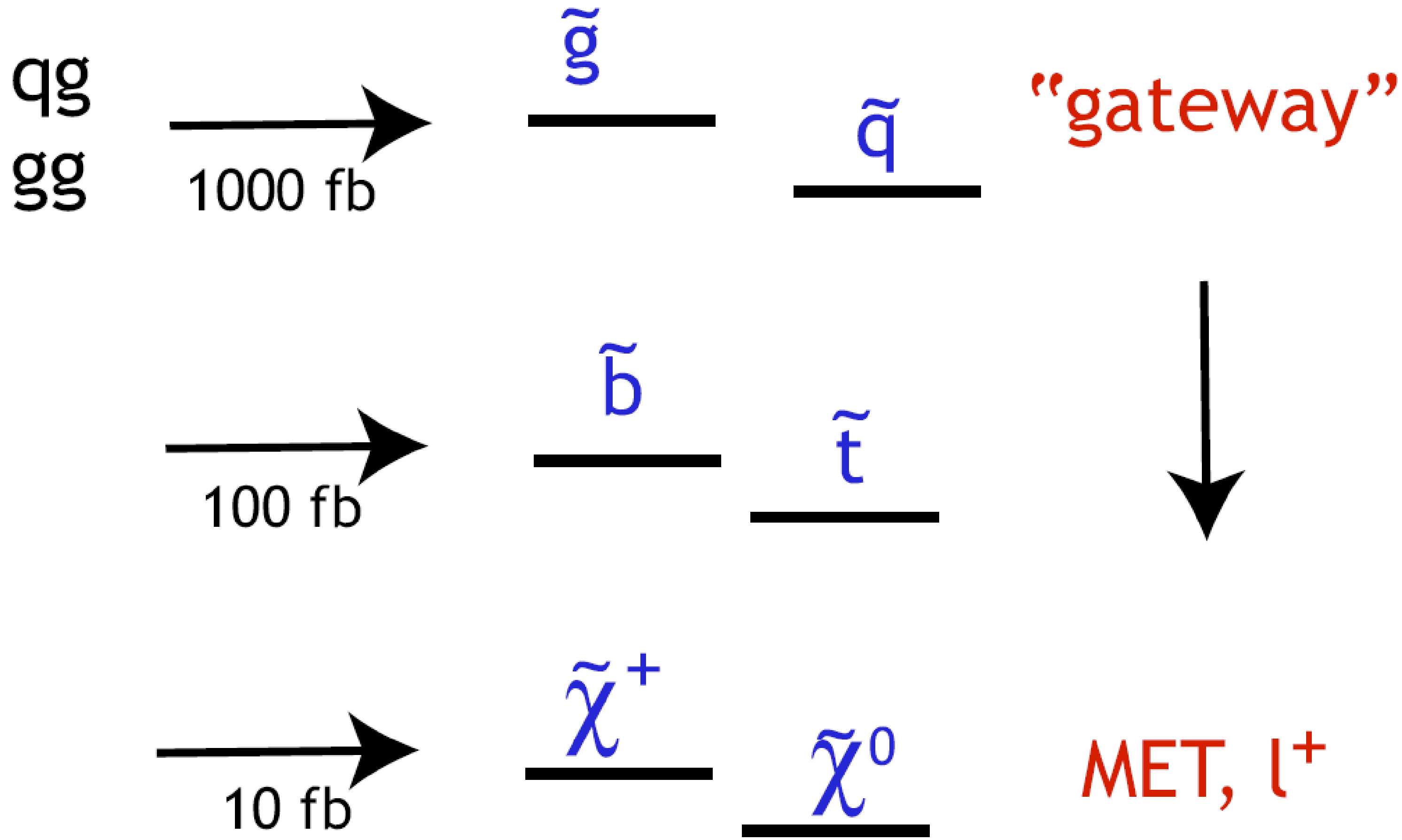

Perelstein-Spethmann: region of the $(m(\tilde{t},1), m(\tilde{t},2))$ plane prefered by naturalness constraints.

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:

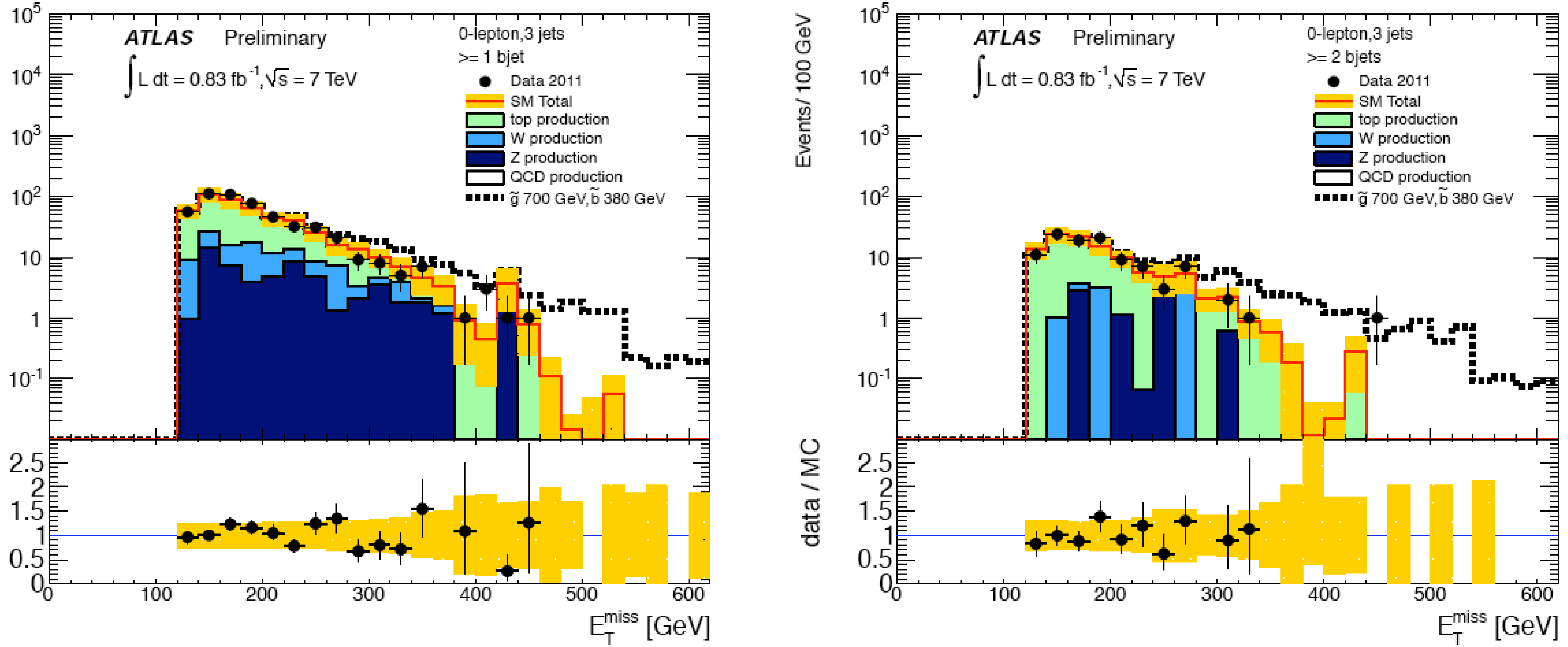



The exotic and characteristic signatures of SUSY are at the bottom. The gateway channel is at the top. If a channel is not allowed energetically, we must defer to the next one.

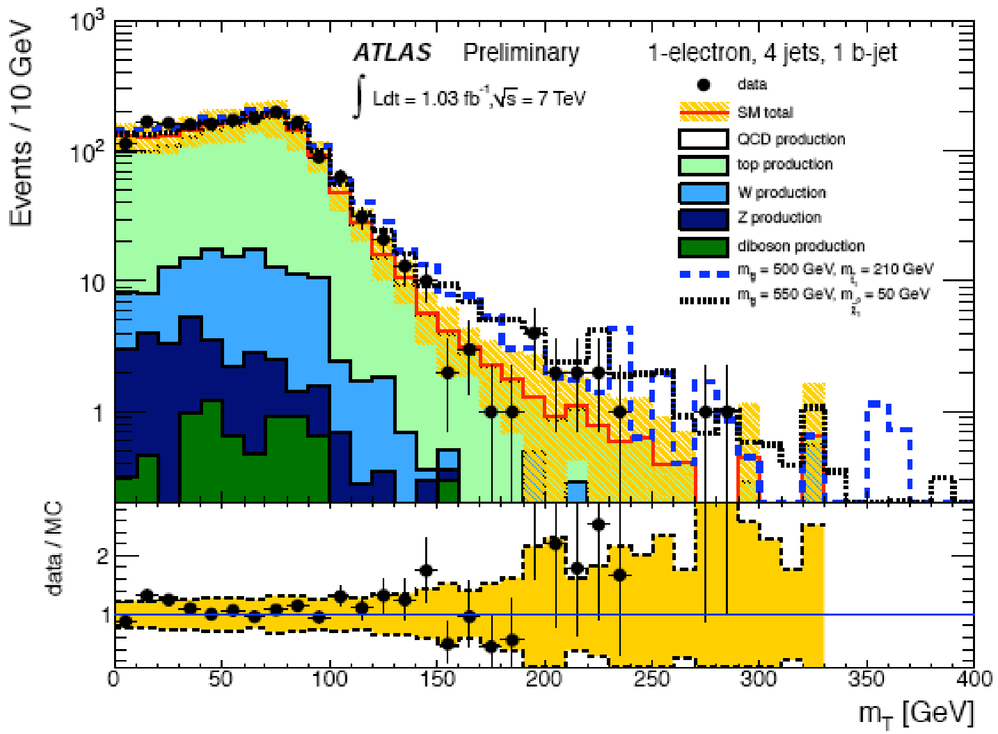
In the region of phase space that we are considering, whether $m(\tilde{t}) < m(\tilde{g})$ or $m(\tilde{t}) > m(\tilde{g})$, the dominant decays of the gluino are to final states with b-quark jets. Searches for this signature are more sensitive than generic searches.

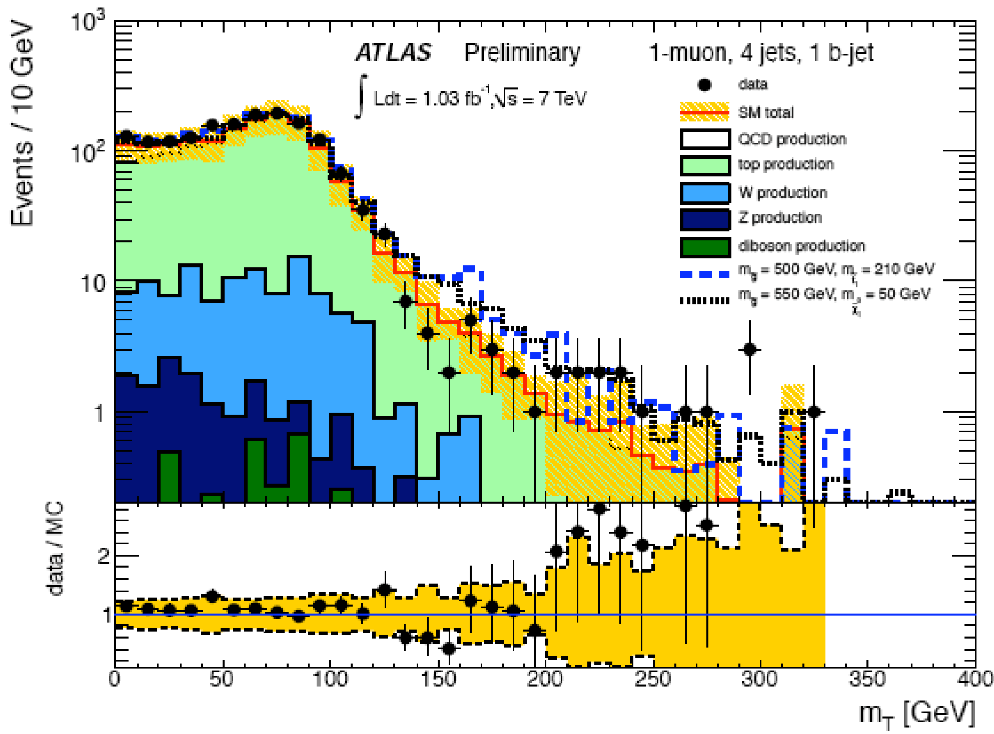
Howver, especially in models with gluino decay to stop, the final states contain less missing ET and softer jets.

# ATLAS search for b-jets + MET

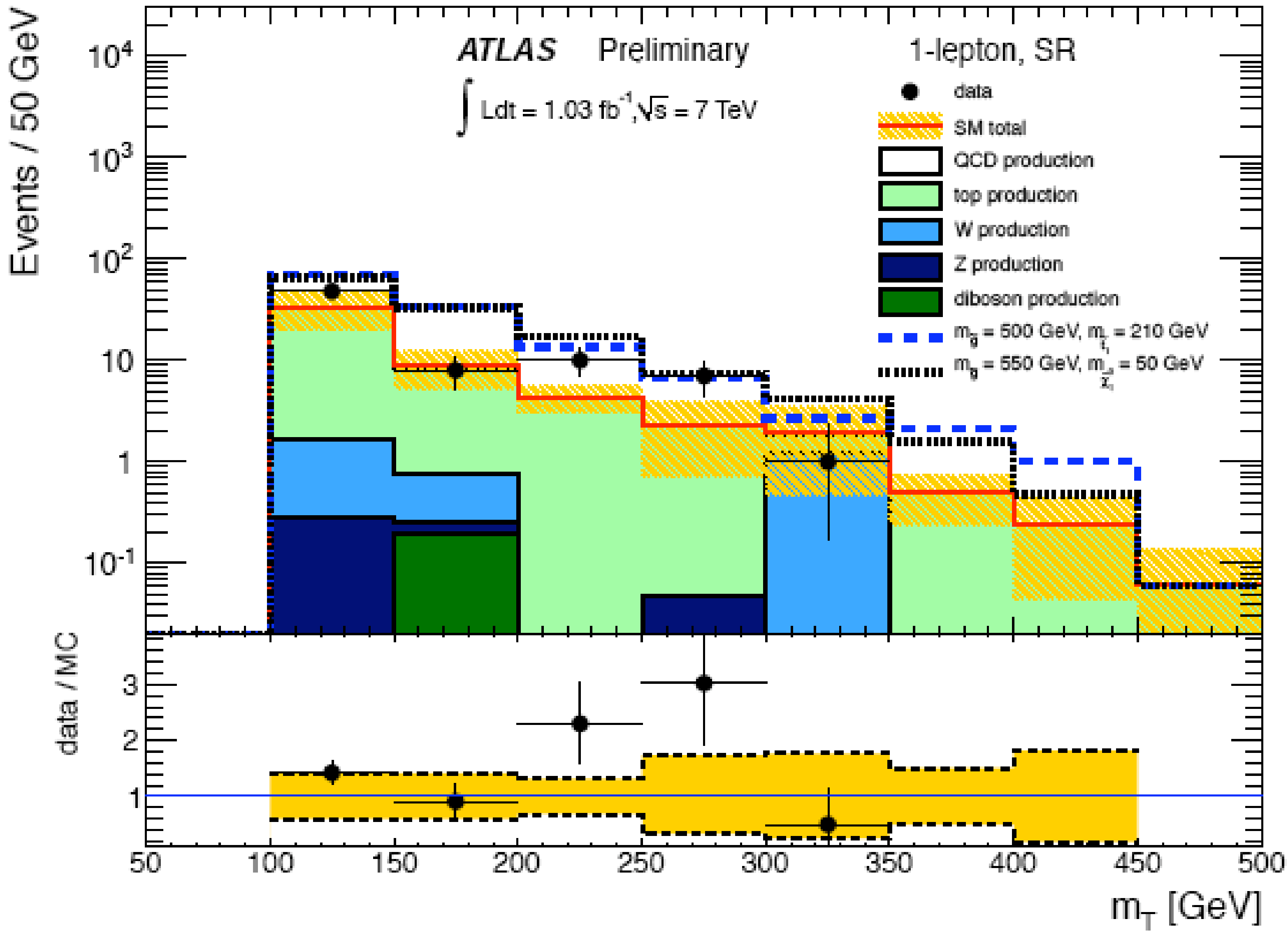


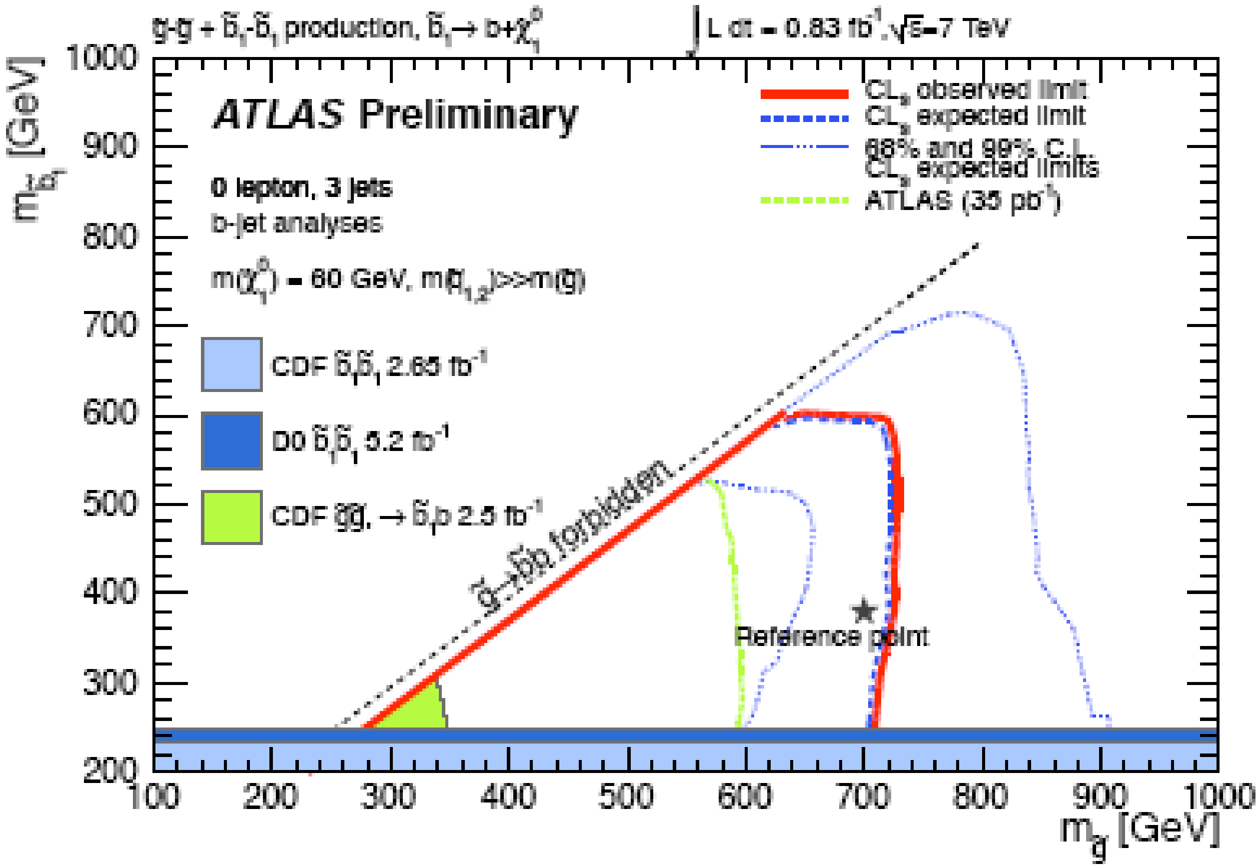
# ATLAS search for b-jets + lepton + MET



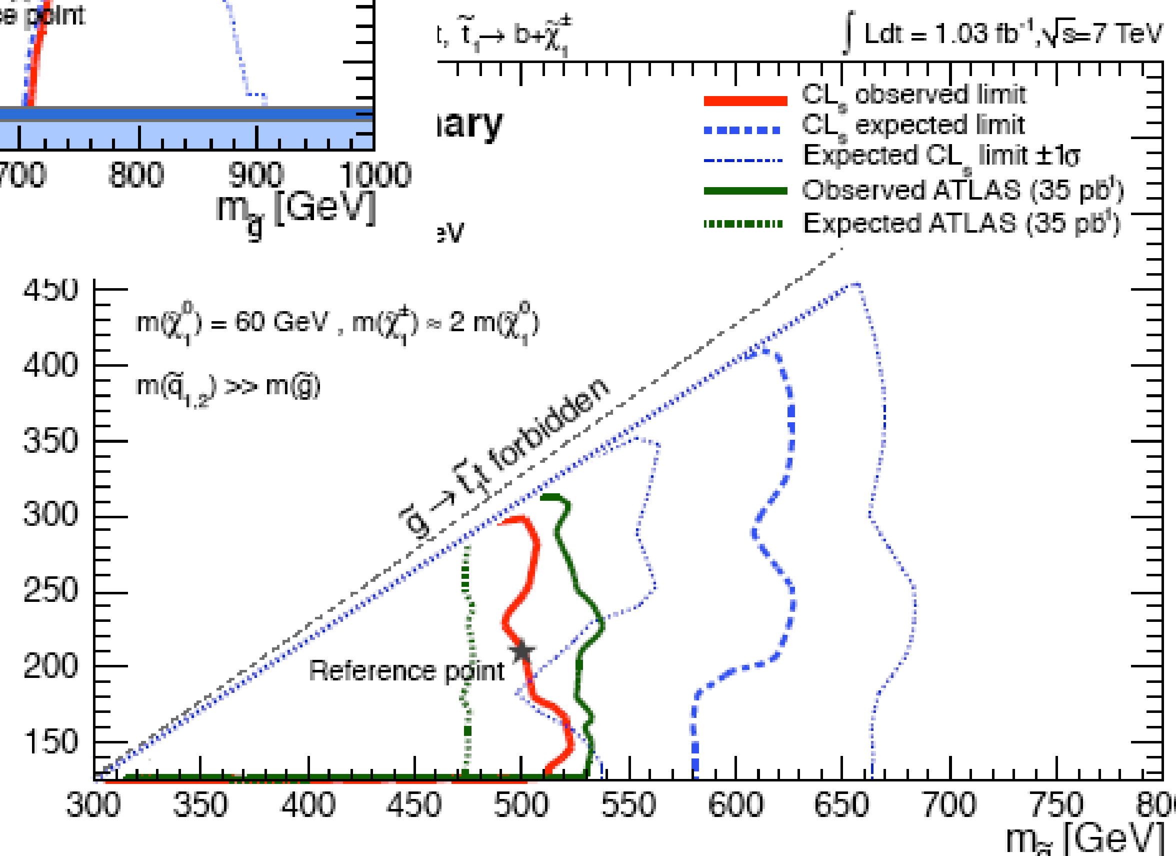



# ATLAS search for b-jets + lepton + MET






$$\tilde{g} \rightarrow \tilde{t} + t$$




$$\tilde{g} \rightarrow \tilde{b} + b$$

Thus, gluinos at 1 TeV and lighter $\tilde{b}$ or $\tilde{t}$ is very much allowed by the current LHC result.

The vertical cutoffs on the previous plots show that we are not yet sensitive to direct $\tilde{b}$ or $\tilde{t}$ pair production. This sensitivity is coming soon when data samples of 5-10 fb-1 are analyzed.

It is also possible that only the charginos and neutralinos are kinematically allowed at 7 TeV. Then SUSY can still appear in processes such as $q\bar{q} \to \tilde{\chi}^0\tilde{\chi}^+ \to \ell^+\ell^-\ell'^+ + \mathrm{MET}$ . These can probably also be found in 10 fb-1 of data if $m(\tilde{\chi}^+) < 200~\mathrm{GeV}$.

Trileptons are signatures of many models, both with weak- and strong-coupling Higgs dynamics. If only this signature is seen, it will be complex (but fun!) to sort out their origin.

A corollary:

Even assuming that SUSY is the explanation of dark matter and the WIMP is the lightest neutralino, current data gives no useful information on lower bounds to the WIMP mass.

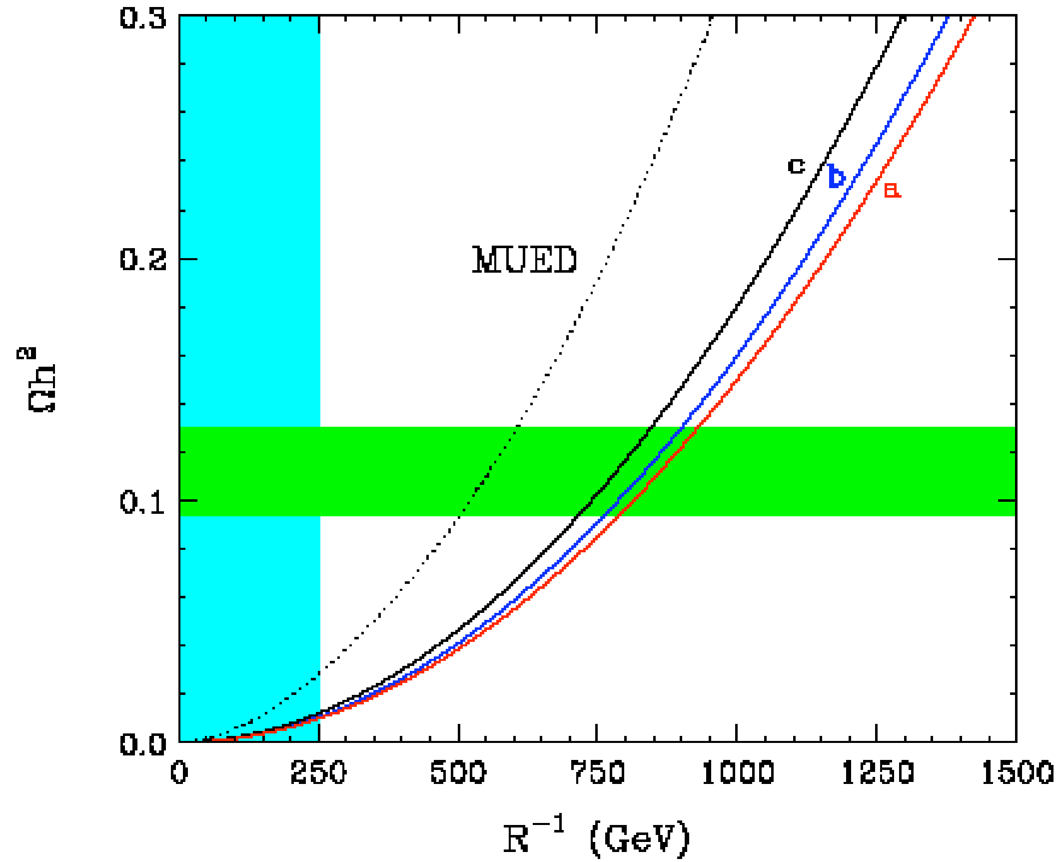
On the other hand, the 2012 data set should give interesting direct constraints.

There is a complementary story to be told for Little Higgs, Gauge-Higgs Unification, and Randall-Sundrum theories.

In these theories, we must have new particles which, in the limit of highest symmetry, cancel the contributions of W, Z, and top to the Higgs self-energy. These now have the same statistics as the original particles.

The lightest vector partner of $\gamma/Z^0$ is again a candidate for the dark matter WIMP.

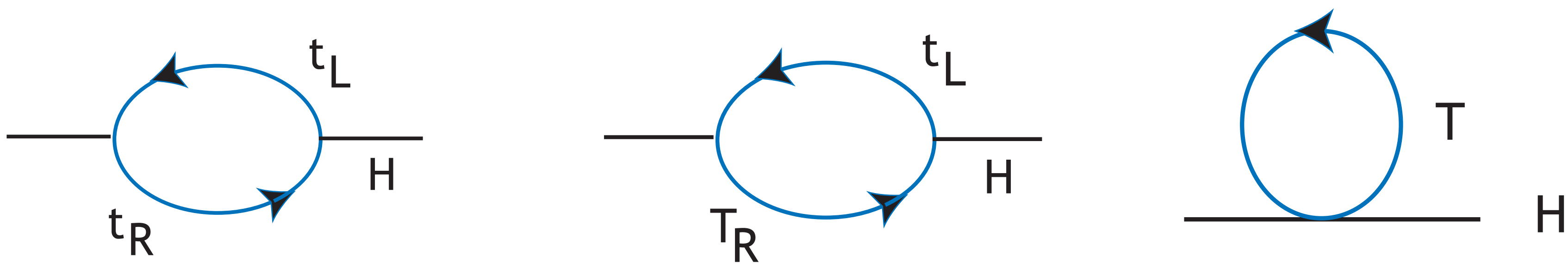
There is no strong naturalness argument that this particle should be light. Relic density calculations prefer larger values, 500 - 1000 GeV.




Kong-Matchev

Again, there are mechanisms for generating a negative Higgs $\mu^2$ 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.

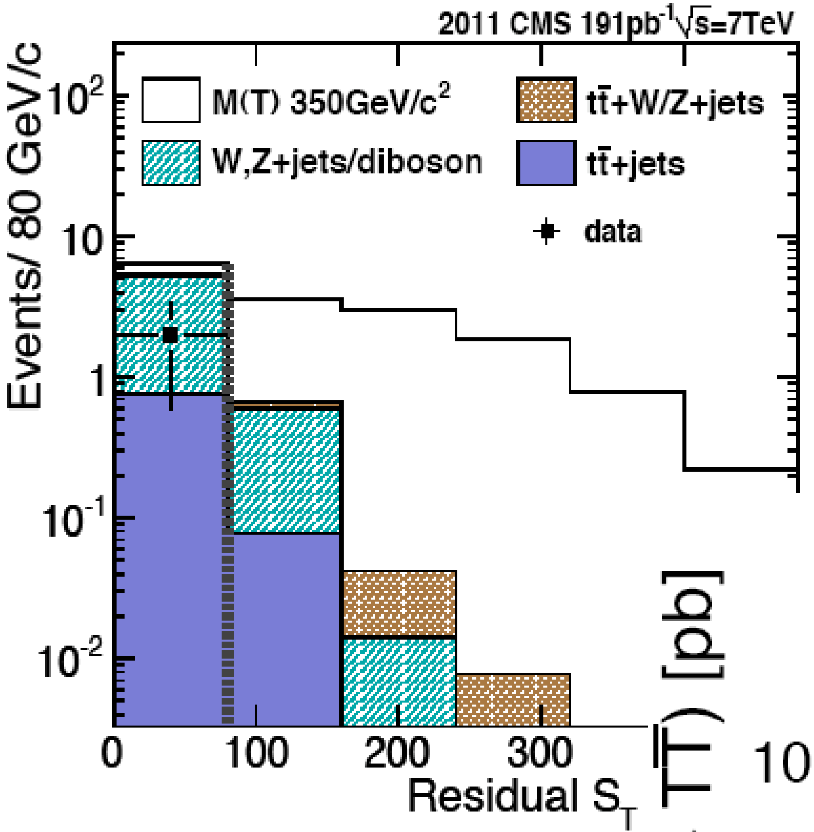
The partners of W, Z, and t are hardly constrained by current LHC experiments.

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

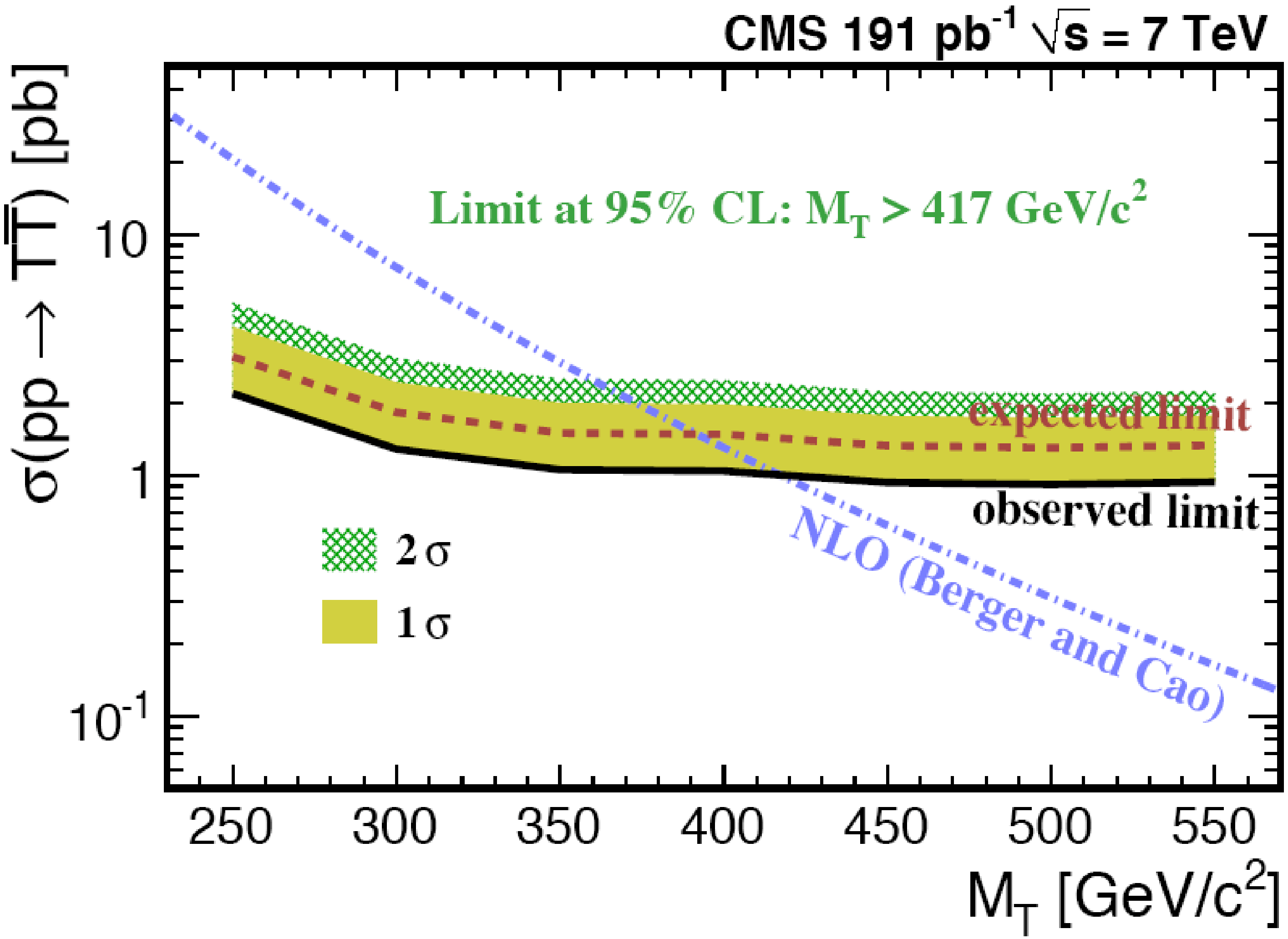
$$T \to bW^+,\ tZ^0,\ th^0 \qquad 2:1:1$$

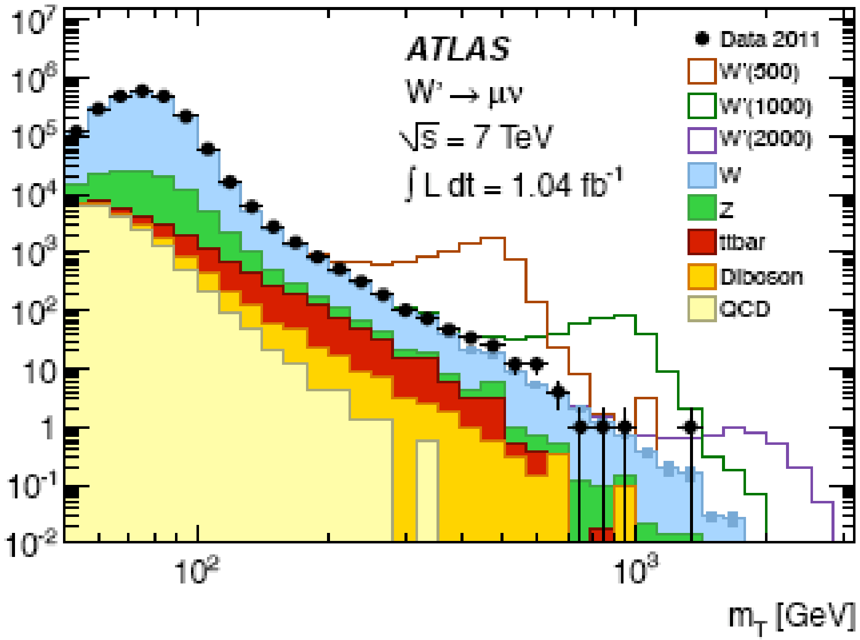
The upper bound on the mass of the 4th generation quark does not apply, and typically a mass of order 1 TeV is needed.

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.



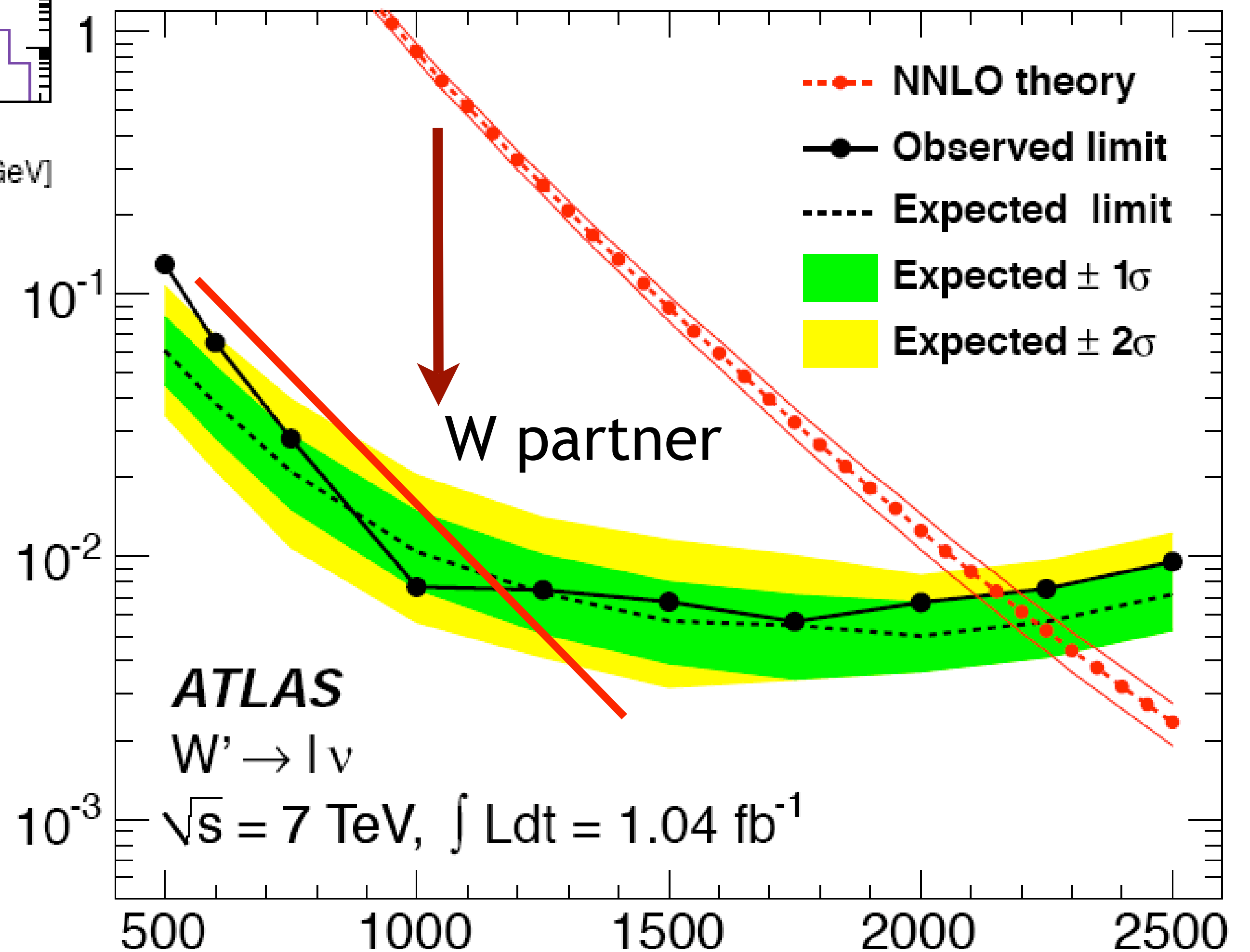

current limits on
$T \to tZ^0$






current limits on W’

sequential W



My conclusion:

Current LHC searches for new particles, using luminosity samples of 1-2 fb-1, do not put strong constraints on models of electroweak symmetry breaking (except for some unlucky special cases such as the MSUGRA region of supersymmetry).

This situation will change dramatically when we have samples of 15-20 fb-1, as expected by the end of 2012. If electroweak symmetry breaking is explained mechanically by a weak-coupling model, we should expect the discovery of new particles.

This discovery and the discovery of the Higgs boson will validate the weak-coupling approach to electroweak symmetry breaking and, hopefully, also to WIMP dark matter.

Many models have been proposed. One will be chosen. Expect confusion, controversy, and exciting times.

For the students, one more remark:

The three giants of Japanese theoretical physics are gone.

Who will be the next one ?

The discoveries of the next few years will give you the opportunity to fill this role.

Three giants of Japanese theoretical physics

Morris Low Nagoya 2006