Beyond the Standard Model: the Quest Continues

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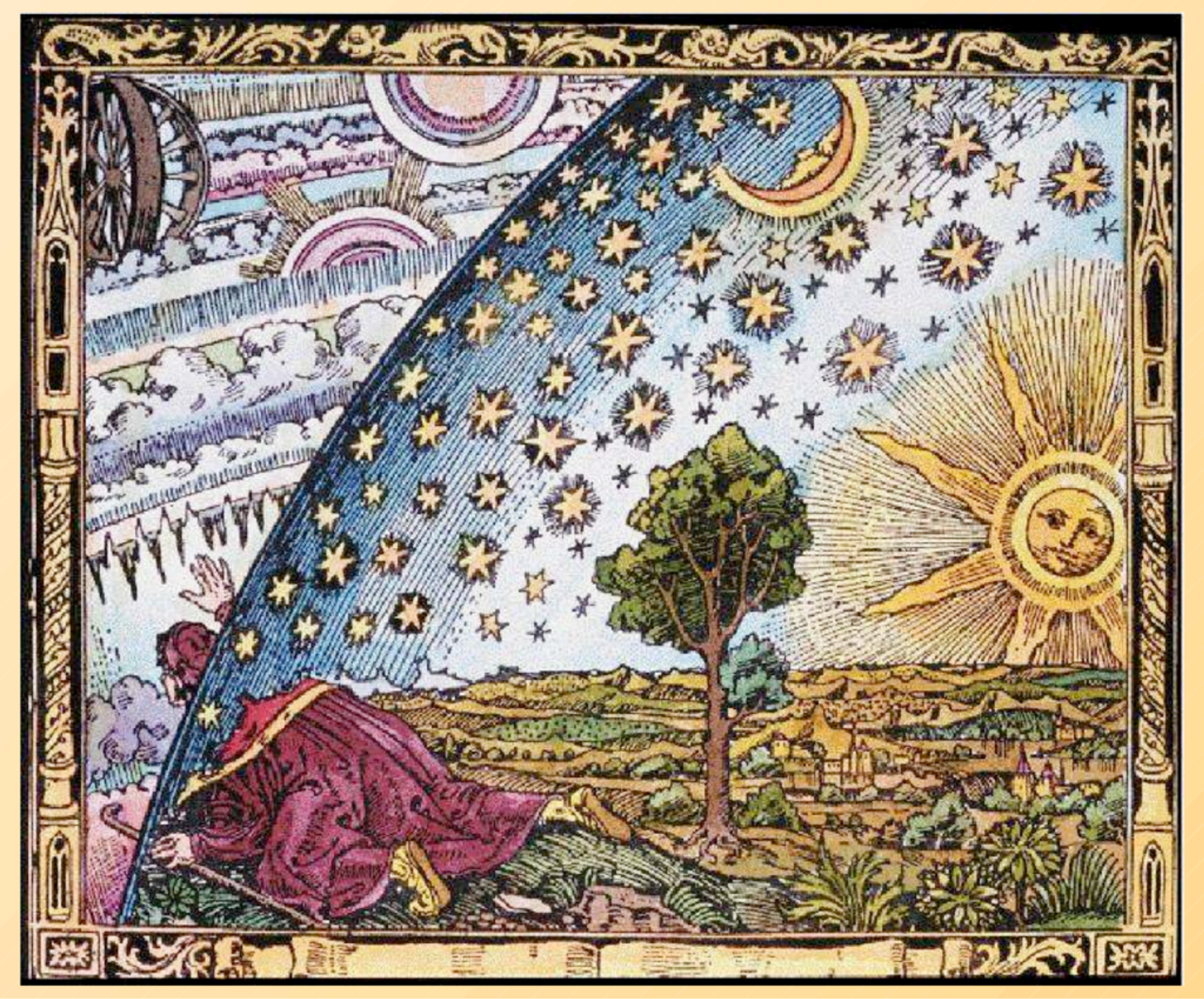
The first MC4BSM was held at Fermilab in 2006.

We looked forward to the LHC first beams -- 2 years away.

We all thought that new physics would leap out at us when the LHC turned on at 14 TeV.

It is not so different today.



We on the theory side have done a large amount of work since 2006.

Experimenters have done even more. They have gathered and analyzed Petabytes of data from the LHC at 7 and 8 TeV.

The major experiments ATLAS and CMS have succeeded in their primary goal of discovering the Higgs boson.

No other new particles have appeared in the data.

Our questions have become more anxious.

Is the Standard Model the end of the story ?

If not, where is the new physics ?

Could the Standard Model be the final answer ?

Some observed phenomena require extensions of the Standard Model

Dark Matter

Cosmic baryon-antibaryon asymmetry

Inflation

Neutrino mass (requires some new dim-5 operators)

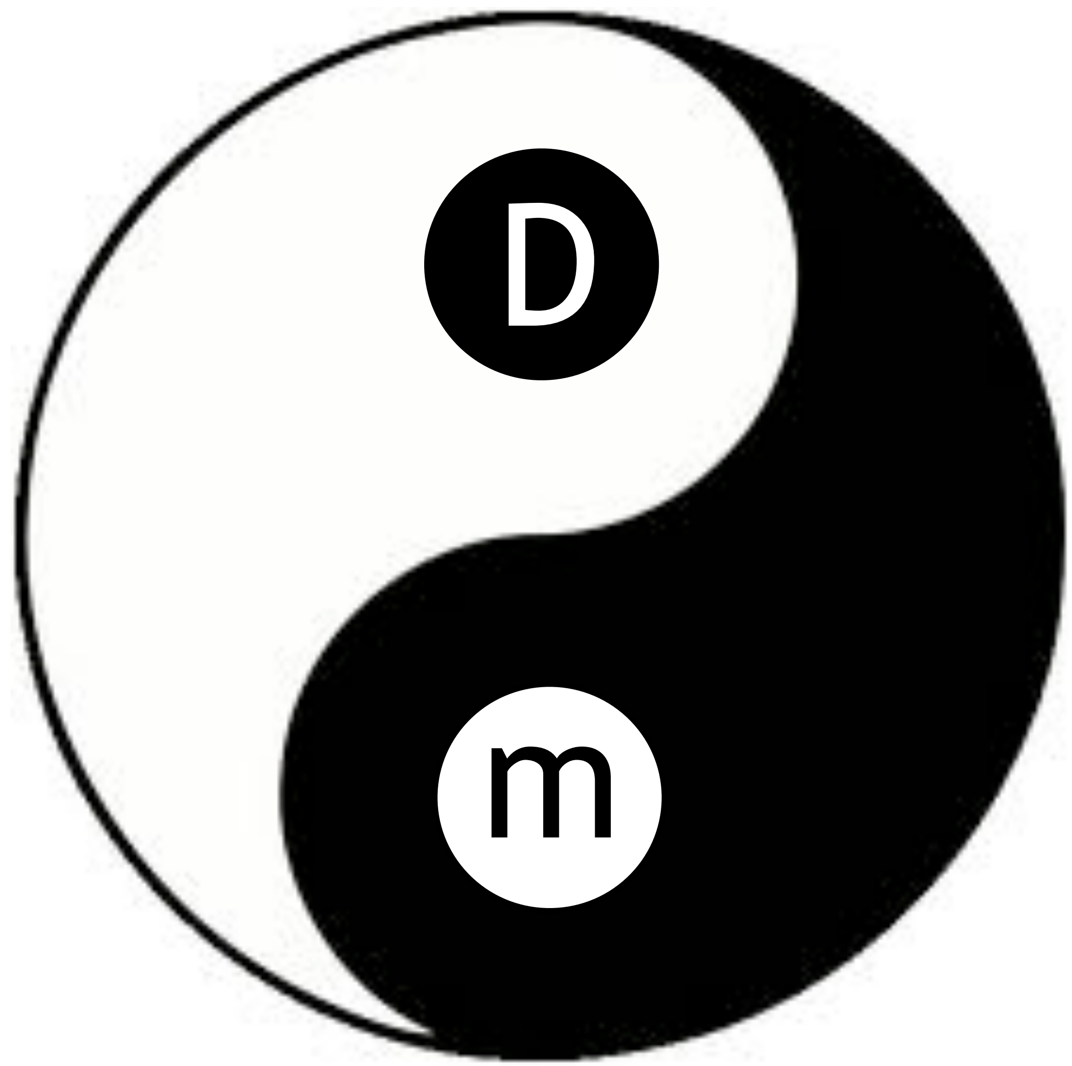
Suggestion of grand unification in fermion quantum numbers

Anomalies in particle physics: muon g-2, top FB asymmetry, ...

but none of these -- except the last -- require new physics at TeV energies

Still, let’s not underestimate our ignorance.

light side / dark side



Okun

light side / dark side

Maxwell's equations

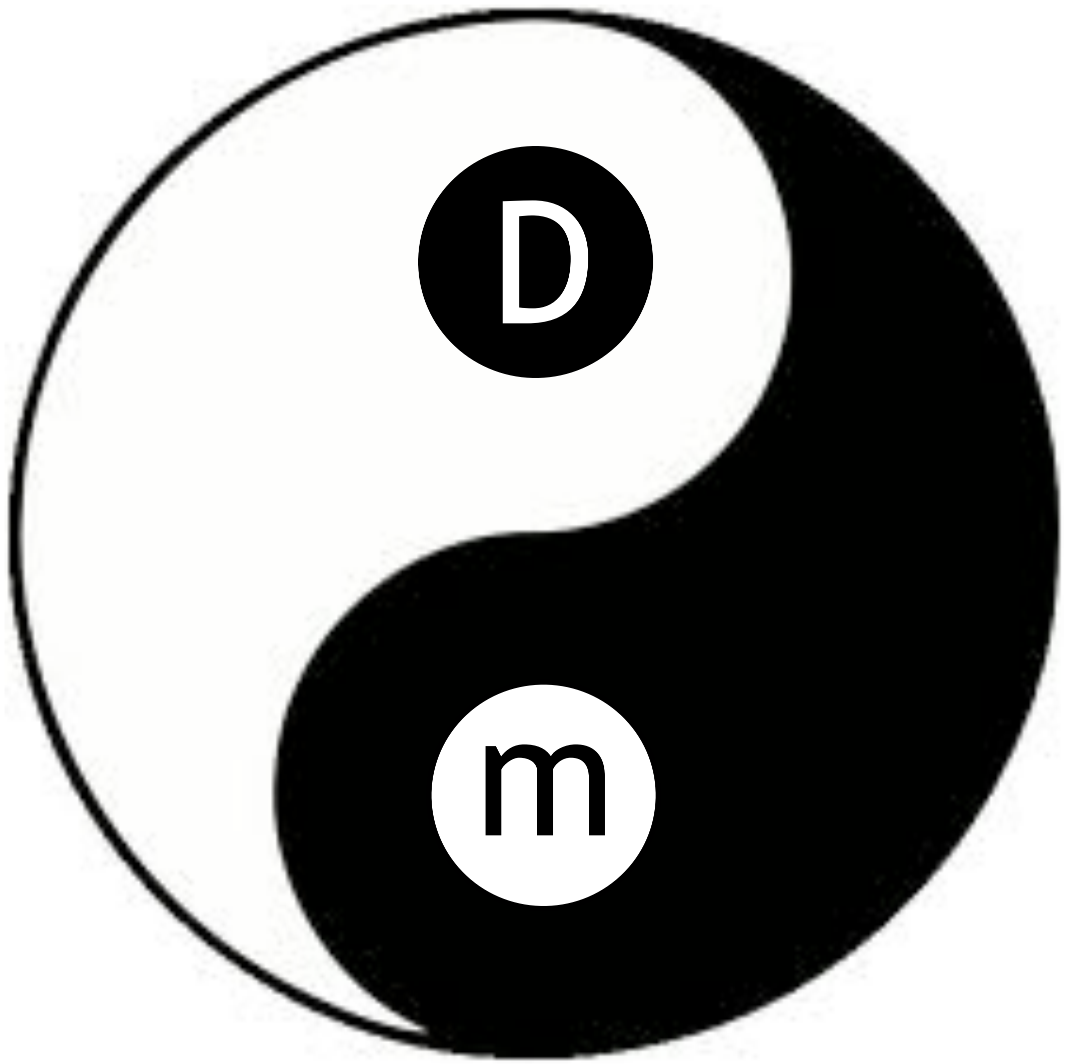
Quantum numbers

Parity violation

W, Z boson

Asymptotic Freedom

Standard Model
all-powerful



W, Z mass

Quark masses and
mixings

CP violation

L, B violation

Dark energy

Standard Model
impotent

Dark Matter ?

Okun

The Light Side is governed by the principle of local gauge invariance.

Given the SM quantum number assignments, there is no further freedom in the couplings of SM particles to the vector bosons of SU(3) x SU(2) x U(1).

Deviations from the SM predictions can occur only at the level of radiative corrections or higher-dimension operators (1% level and below).

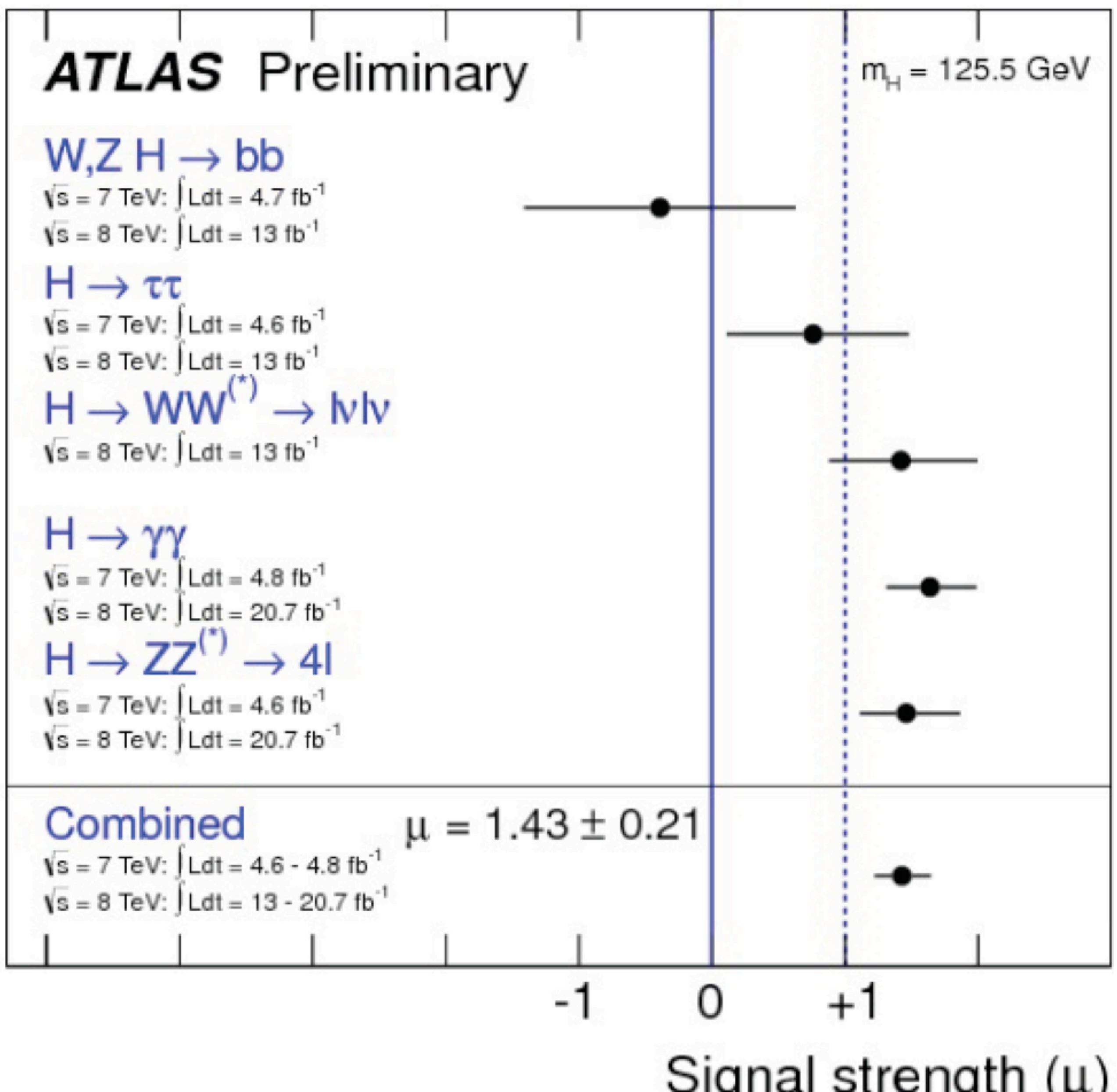
For the Dark Side, the situation is completely different.

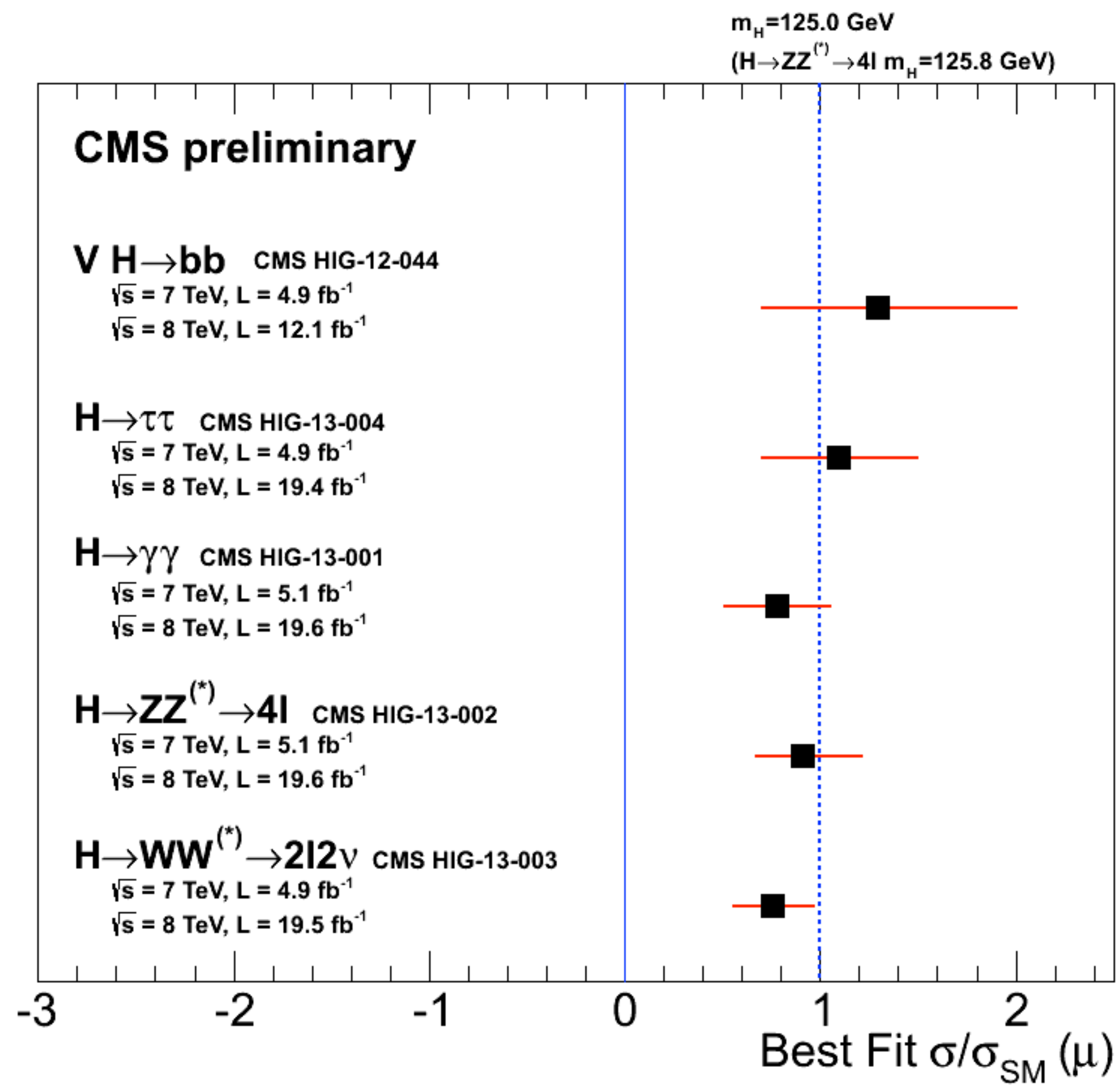
The SM calls for one SU(2) doublet of Higgs fields, with one physical Higgs boson.

However, this is only a guess. That guess is not guided by any fundamental principle.

Finally, after decades of speculation, we have a toehold on the dark side with the discovery of the Higgs boson at 125 GeV.

It is imperative to follow up this discovery by making precision measurements of the couplings of this boson. The current status is





The result seem to point to agreement of the Higgs couplings with the simplest SM predictions.

It is important not to over-interpret this conclusion.

Haber's Decoupling Theorem states

In any model of the Higgs field sector, no matter how complex,

if the lightest Higgs particle has mass m_h much less than the masses M of other new particles,

that lightest Higgs will have the couplings predicted in the SM, up to corrections of order

$$m_h^2/M^2 \quad \text{or} \quad m_t^2/M^2$$

The Dark Side is full of mysteries, but the leading one is this:

Why does the dark side spontaneously break the SM gauge symmetry ?

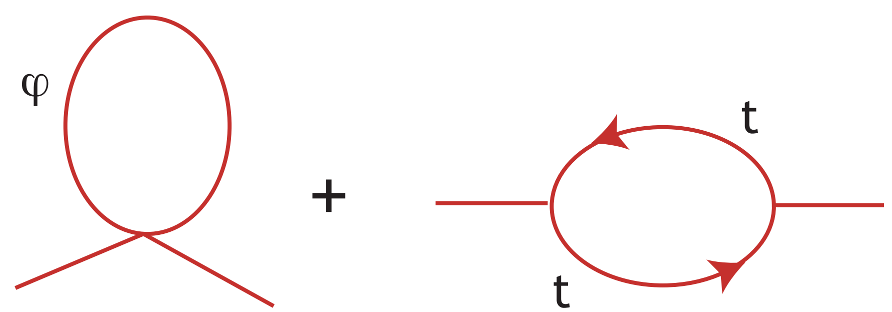
In quantum field theory, the mechanism must be associated with new particles ?   What are these particles, and where are they ?

Any explanation of the other mysteries of the Dark Side requires an answer to this question ?   Hence, this is our problem #1.

It is technically possible that the only field on the Dark Side is the minimal SM Higgs field. Then spontaneous breaking requires that the Higgs mass satisfies

$$\mu^2 < 0$$

The value of μ^2 receives large radiative corrections, so a mechanical explanation for $\mu^2 < 0$ with particles of mass Λ becomes much less plausible as Λ increases.



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

This is often called the "hierarchy" or "naturalness" problem, but really it is a "no-physics-insight" problem. It is the problem that a physical mechanism requires new fields and new particles, and we have not found them yet.

Linde and others have taken the position that the value of μ^2 is an accident of where we live in the multiverse. Then the actual values of μ^2 and the other renormalizable parameters of the SM cannot be predicted from first principles. Their values are the result of historical evolution, perhaps constrained by the anthropic principle.

If you believe that the Standard Model is the end of the story, this is what you are buying. Examine your beliefs carefully !

The alternative is that we have yet not looked hard enough to find new particles beyond the Standard Model.

To build a physics explanation of the symmetry breaking, we need to have a theory in which we can calculate the Higgs boson mass term. There are two alternatives for such a theory:

1. The Higgs boson is a composite of more fundamental constituents. The scale of compositeness should be close to 1 TeV by fine-tuning considerations.

2. The Higgs boson is a fundamental field, in a theory in which a symmetry forbids the Higgs mass term. Small effects that break this symmetry generate a nonzero value of μ^2.

Theories in which the Higgs field is composite but is an effective local scalar field at 1 TeV are included in class #2.

The class #1 includes technicolor models. These models have been in serious trouble for some time, since they generically predict large corrections to precision electroweak observables.

Technicolor models now have a new problem that, generically, they do not contain light spin 0^+ particles. However, they might contain an effective scalar, the dilaton. It is possible that, in some special models, this particle might mimic the properties of the SM Higgs boson.

For theories of class #2, we need an appropriate symmetry. We need to forbid the term

$$\delta\mathcal{L} = -\mu^2 \varphi^\dagger \varphi$$

Only three possibilities are known:

1. Shift symmetry: $\Delta\varphi = \epsilon$
2. Rotation into a gauge boson: $\Delta\varphi = \epsilon^\mu A_\mu$
3. Rotation into a fermion: $\Delta\varphi = \epsilon \cdot \psi$

In option #1, the entire Higgs multiplet are Goldstone bosons of a symmetry broken spontaneously at high energy.

In option #2, the Higgs fields are the 5th component of gauge fields in a model with extra space dimensions.

In option #3, the symmetry is supersymmetry.

All three options have been well studied by theorists. Options #1 and #2 are dual in a precise sense. In all three theories, corrections due to the top quark give $\mu^2 < 0$.

All three options contain new particles with TeV masses that cut off the radiative corrections to the Higgs mass term. These are appropriate partners of the top quark, the Higgs fields, and the W and Z bosons.

So, by the logic so far, these particles must exist.

What is the status ?

27 **August 2011** Last updated at 06:41 GMT

LHC results put supersymmetry theory 'on the spot'

By Pallab Ghosh
Science correspondent, BBC News

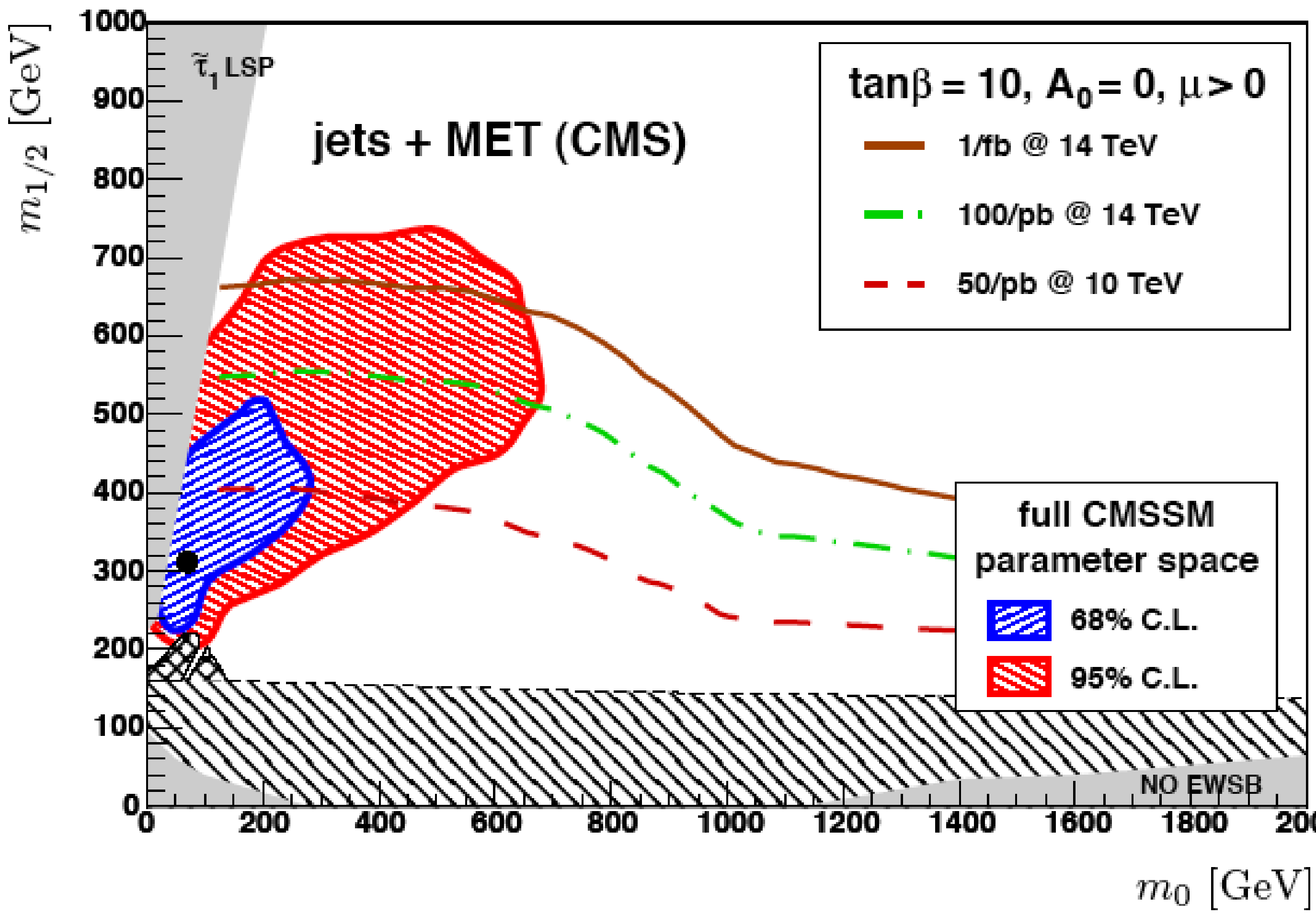
Results from the Large Hadron Collider (LHC) have all but killed the simplest version of an enticing theory of sub-atomic physics.

Bitten the dust

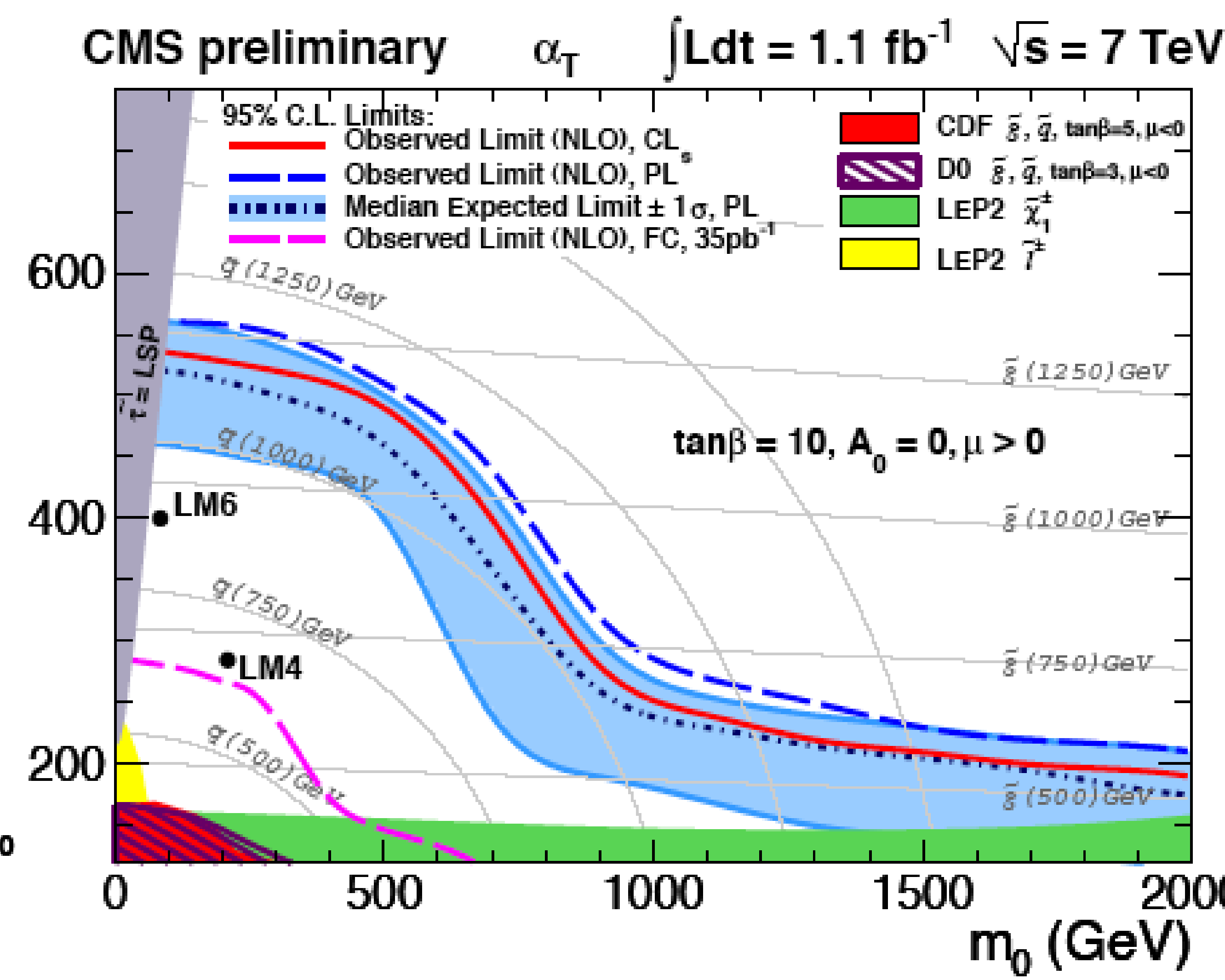
This failure to find indirect evidence of supersymmetry, coupled with the fact that two of the collider's other main experiments have not yet detected supersymmetic particles, means that the simplest version of the theory has in effect bitten the dust.

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.

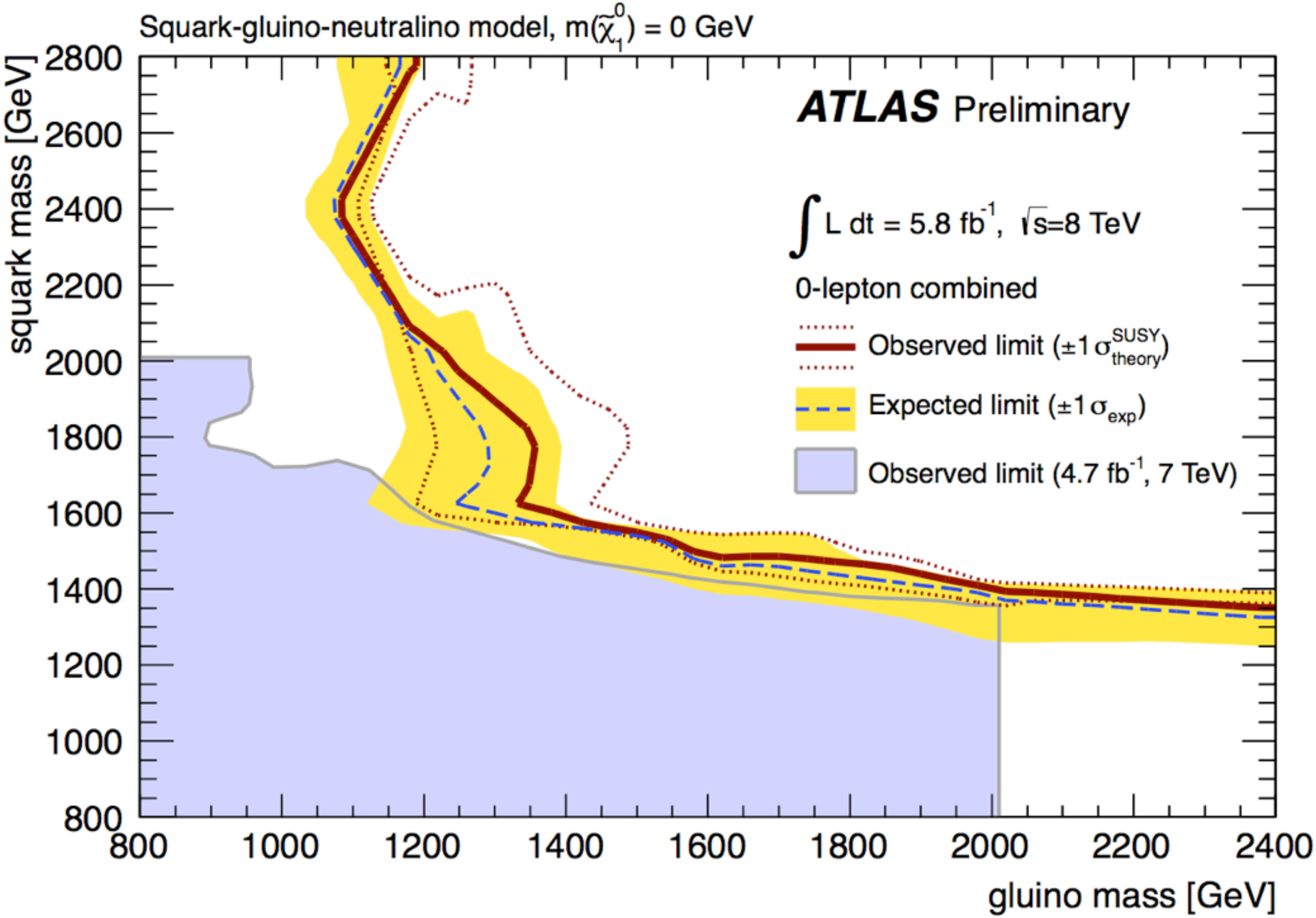
Buchmuller, ... , DeRoeck, Ellis ...
2008



CMS LP11 α_T analysis



from my Lepton-Photon 2011 talk



Squark-gluino-neutralino model, $m(\tilde{\chi}_1^0)$ = 0 GeV
ATLAS Preliminary
$\int L\,dt$ = 5.8 fb^{-1}, $\sqrt{s}$=8 TeV
0-lepton combined
Observed limit ($\pm 1\,\sigma^{SUSY}_{theory}$)
Expected limit ($\pm 1\,\sigma_{exp}$)
Observed limit (4.7 fb^{-1}, 7 TeV)
squark mass [GeV]
gluino mass [GeV]
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
800
1000
1200
1400
1600
1800
2000
2200
2400

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: $m^2(L_i)$, $m^2(\bar{e}_i)$, $i = 1, 2, 3$
- squark masses: $m^2(Q_i)$, $m^2(\bar{u}_i)$, $m^2(\bar{d}_i)$, $i = 1, 2, 3$
- 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.

Most of this region of parameter space is now excluded.

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.

What is the alternative ?

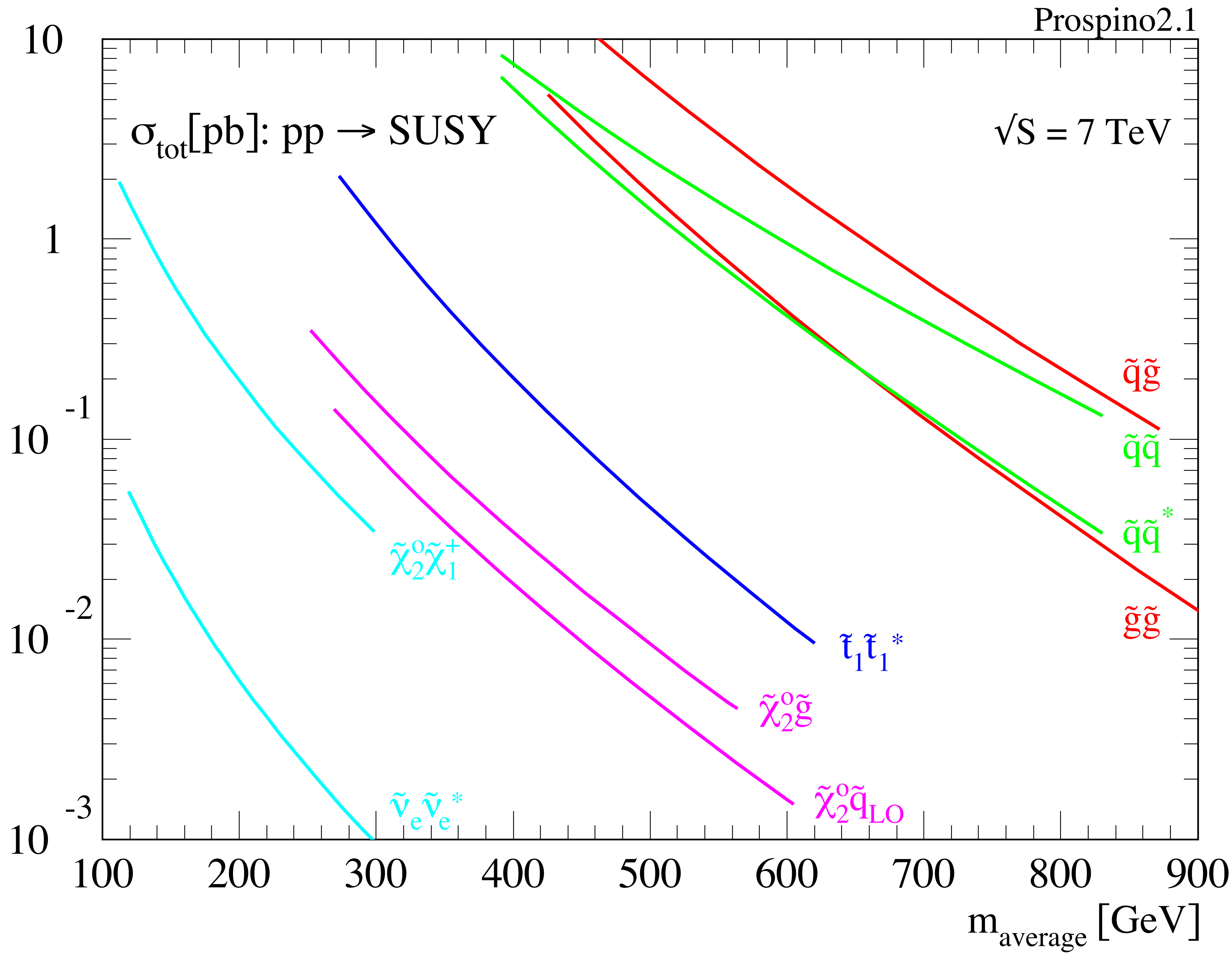
Go back to the formula

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

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 to obtain the negative Higgs mass-squared. The gluino mass enters more indirectly, through its effect on the top squark mass.

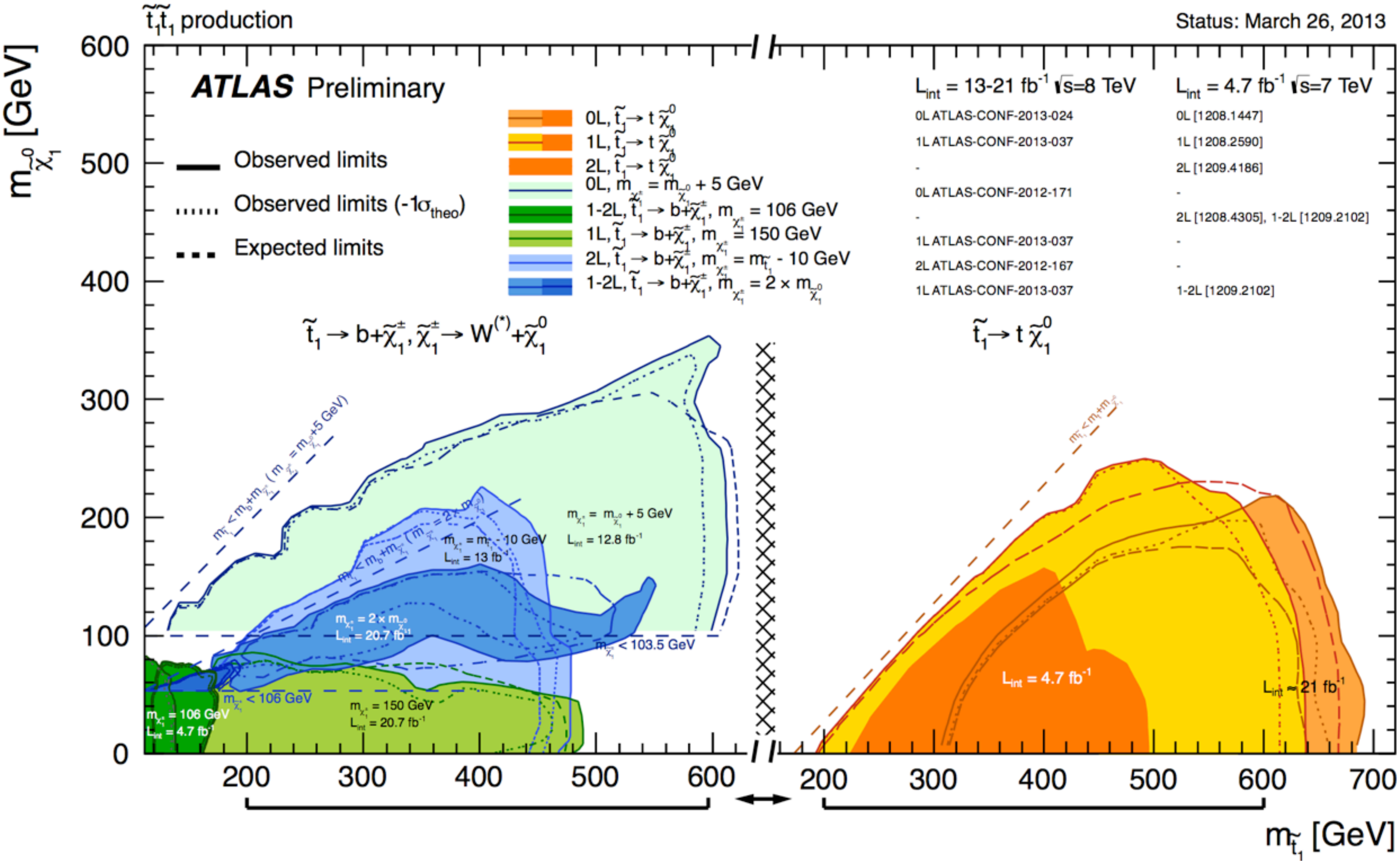
The 1st and 2nd generation squarks enter hardly at all.



Prospino: Beenacker, Plehn, Spira et al.

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.



t̃1t̃1 production
Status: March 26, 2013
ATLAS Preliminary
Observed limits
Observed limits (-1σtheo)
Expected limits
0L, t̃1→ t χ̃01
1L, t̃1→ t χ̃01
2L, t̃1→ t χ̃01
0L, mχ̃±1 = mχ̃01 + 5 GeV
1-2L, t̃1 → b+χ̃±1, mχ̃±1 = 106 GeV
1L, t̃1 → b+χ̃±1, mχ̃±1 = 150 GeV
2L, t̃1 → b+χ̃±1, mχ̃±1 = mt̃1 - 10 GeV
1-2L, t̃1 → b+χ̃±1, mχ̃±1 = 2 × mχ̃01
Lint = 13-21 fb-1 √s=8 TeV
0L ATLAS-CONF-2013-024
1L ATLAS-CONF-2013-037
0L ATLAS-CONF-2012-171
1L ATLAS-CONF-2013-037
2L ATLAS-CONF-2012-167
1L ATLAS-CONF-2013-037
Lint = 4.7 fb-1 √s=7 TeV
0L [1208.1447]
1L [1208.2590]
2L [1209.4186]
2L [1208.4305], 1-2L [1209.2102]
1-2L [1209.2102]
t̃1 → b+χ̃±1, χ̃±1 → W(*)+χ̃01
t̃1→ t χ̃01
mχ̃±1 = mχ̃01 + 5 GeV
Lint = 12.8 fb-1
mχ̃±1 = mt̃1 - 10 GeV
Lint = 13 fb-1
mχ̃±1 = 2 × mχ̃01
Lint = 20.7 fb-1
mχ̃±1 < 103.5 GeV
mχ̃±1 < 106 GeV
mχ̃±1 = 106 GeV
Lint = 4.7 fb-1
mχ̃±1 = 150 GeV
Lint = 20.7 fb-1
Lint = 4.7 fb-1
Lint = 21 fb-1
mχ̃01 [GeV]
mt̃1 [GeV]
0
100
200
300
400
500
600
700

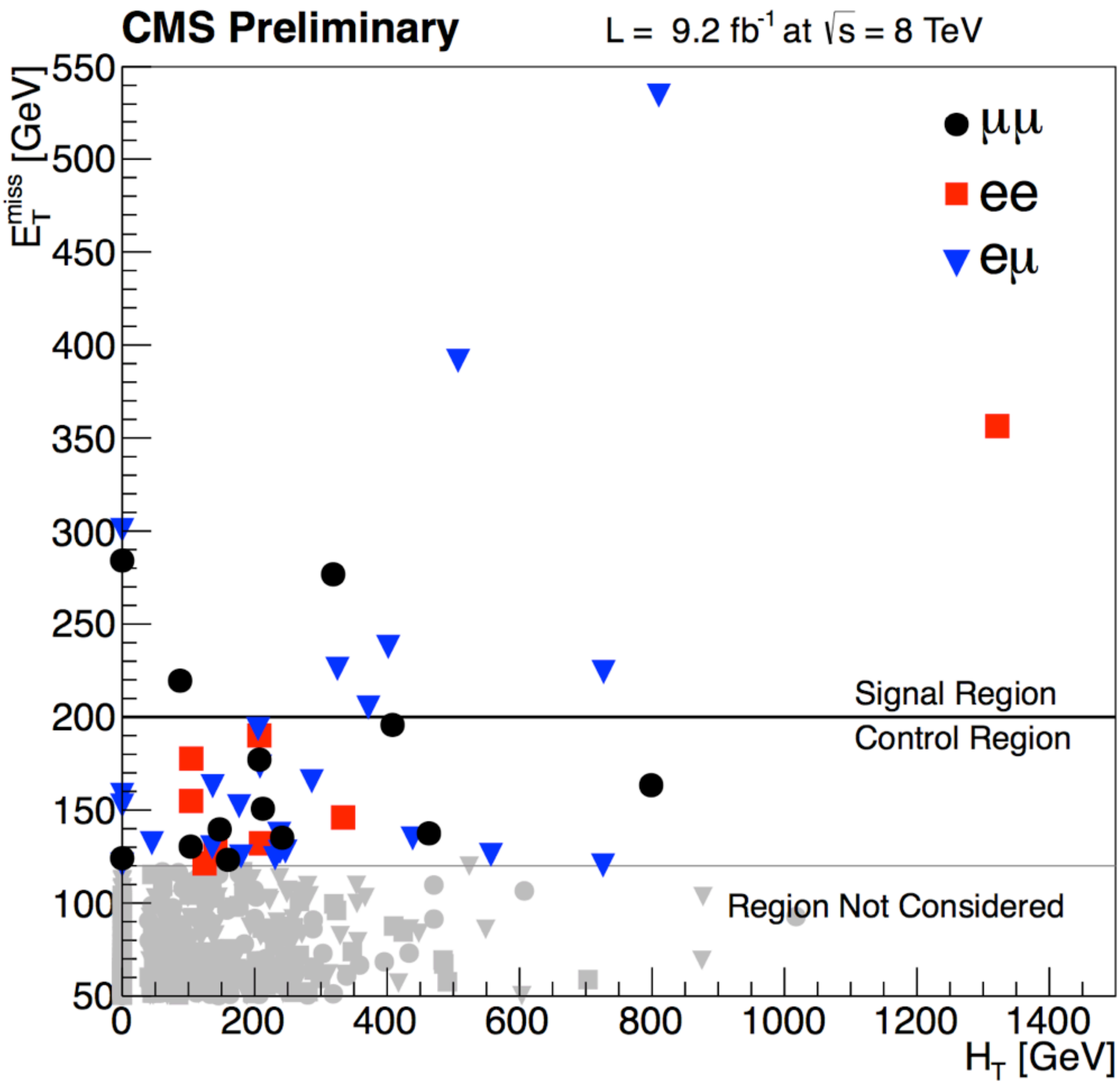
Another feature that makes searches for MET difficult is the possibility of small mass differences, “compressed spectrum”.

Searches for MET typically require large values

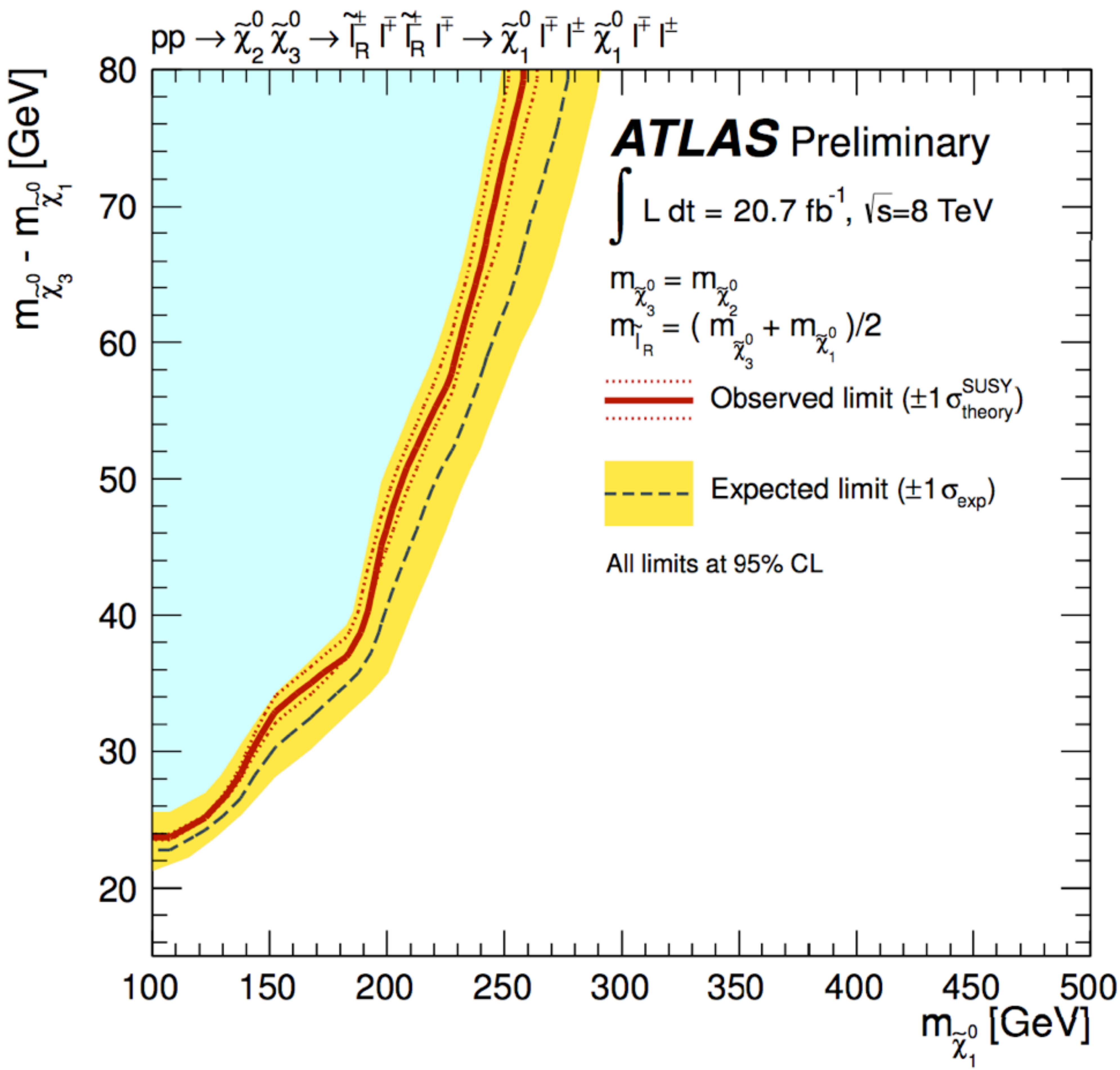
$$\not{E}_T > 130 \text{ GeV}$$

and also the presence of hard jets or leptons.   Small mass gaps in the spectrum frustrate these requirements.

These difficulties are seen most clearly in the search for charginos and neutralinos through multilepton events.

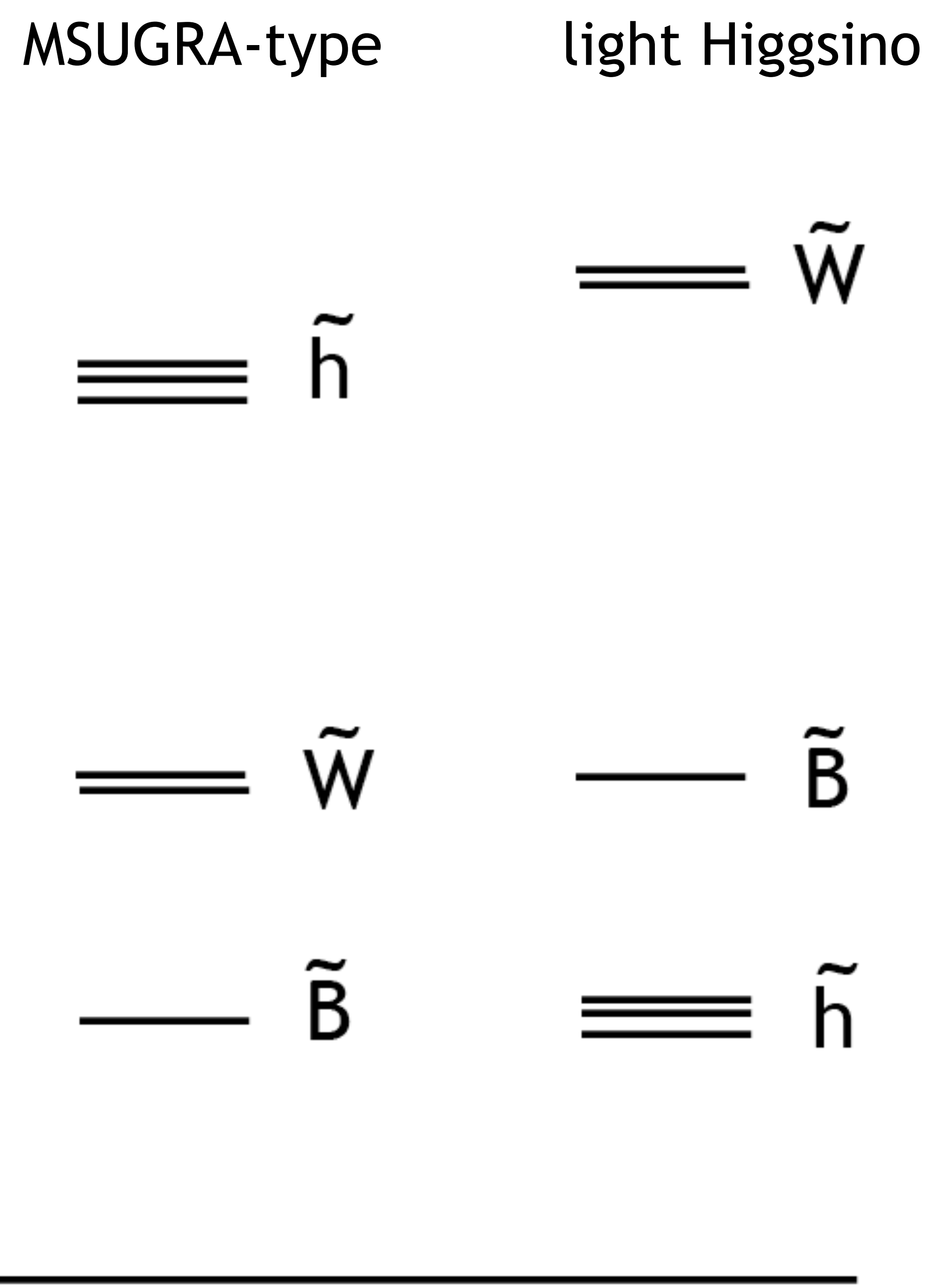


CMS like-sign dilepton + MET analysis



$pp \to \tilde{\chi}_2^0 \tilde{\chi}_3^0 \to \tilde{l}_R^{\pm} l^{\mp} \tilde{l}_R^{\pm} l^{\mp} \to \tilde{\chi}_1^0 l^{\mp} l^{\pm} \tilde{\chi}_1^0 l^{\mp} l^{\pm}$
ATLAS Preliminary
$\int L\,dt = 20.7\ fb^{-1}$, $\sqrt{s}$=8 TeV
$m_{\tilde{\chi}_3^0} = m_{\tilde{\chi}_2^0}$
$m_{\tilde{l}_R} = (m_{\tilde{\chi}_3^0} + m_{\tilde{\chi}_1^0})/2$
Observed limit ($\pm 1\,\sigma_{theory}^{SUSY}$)
Expected limit ($\pm 1\,\sigma_{exp}$)
All limits at 95% CL
$m_{\tilde{\chi}_3^0} - m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{\chi}_1^0}$ [GeV]
20
30
40
50
60
70
80
100
150
200
250
300
350
400
450
500

This problem bites us particularly hard if the lightest states of the supersymmetry spectrum are the partners of Higgs bosons.   The Higgsinos are naturally almost degenerate, with mass splittings of 10 GeV or less.



At 14 TeV, it might be possible to prove the presence of a light Higgsino sector at the LHC by an excess of events with

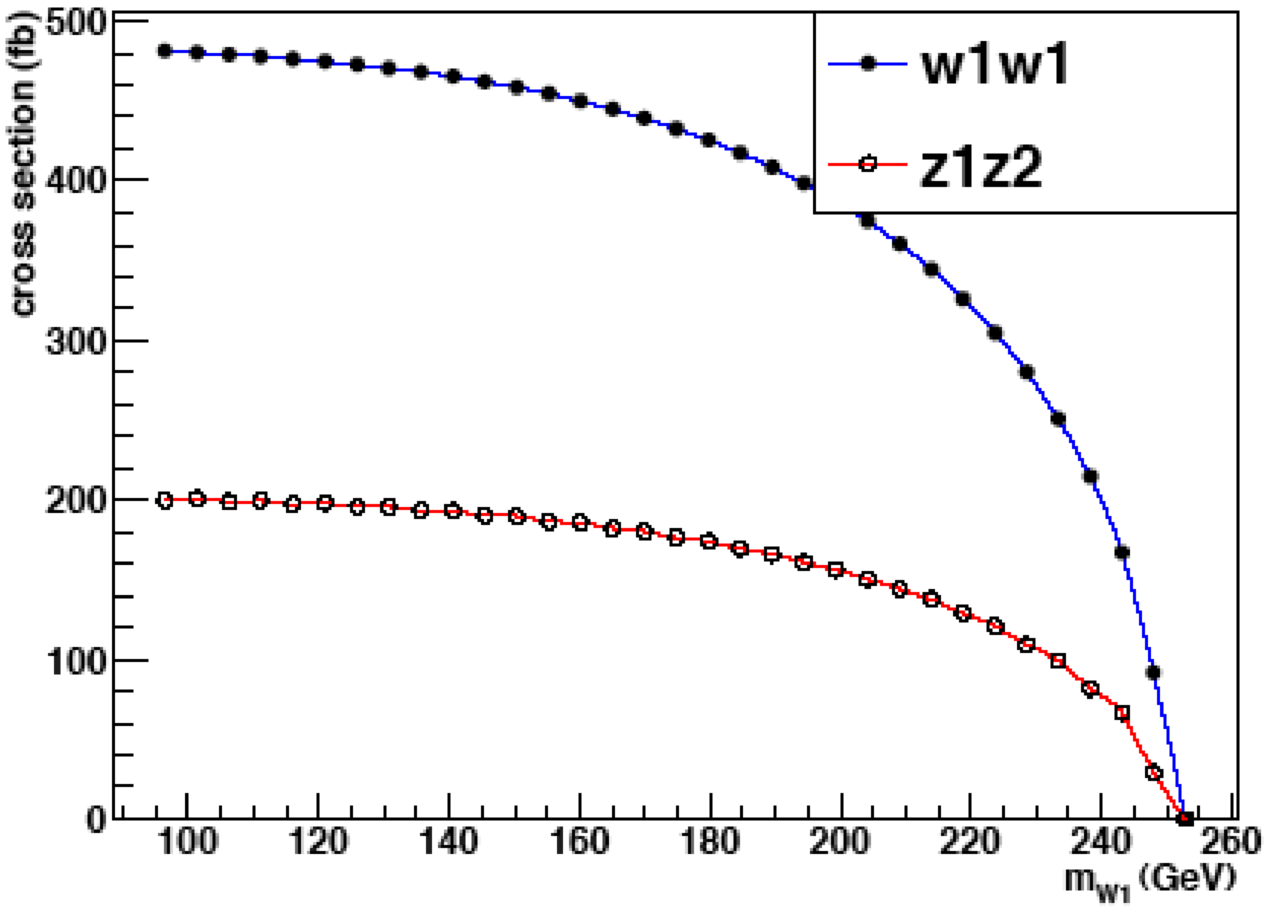
$$pp \to \mathrm{ISR\ jets} + \mathrm{missing}$$

It will still be very difficult to probe the nature of these states.

It is important to recognize that, if we build a next-generation e+e- collider (ILC), motivated as a Higgs boson factory, we can study this sector in detail.

In this scenario, the ILC will also be a Higgsino factory. Detection of the Higgsinos is not trivial, but Baer, Barger, Huang, have presented a straightfoward set of cuts.

The cross sections are strongly dependent on beam polarization, allowing measurement of the quantum numbers and the Higgsino/chargino mixing angles.



Typical supersymmetry models implement a symmetry called R-parity that makes the lightest supersymmetric particle stable.

This gives the possibility of a link between supersymmetry and dark matter.

Recall the requirement for a thermal relic to give the correct dark matter abundance:

$$\langle \sigma v \rangle = 1 \text{ pb} = \frac{\pi}{2} \frac{\alpha^2}{(200 \text{ GeV})^2}$$

It seems that SUSY gives us exactly what we want, but the true situation is more subtle.

Bino dark matter has helicity suppressed annihilation, leading to a cross section that is a factor of 10 too small.

Higgsino dark matter has open annihilation to WW, ZZ, leading to a cross section that is a factor of 10 too large.

Only special regions of the parameter space give the correct annihilation rate.

For bino dark matter, we need to enhance the annihilation rate by adding other annihilation mechanisms:

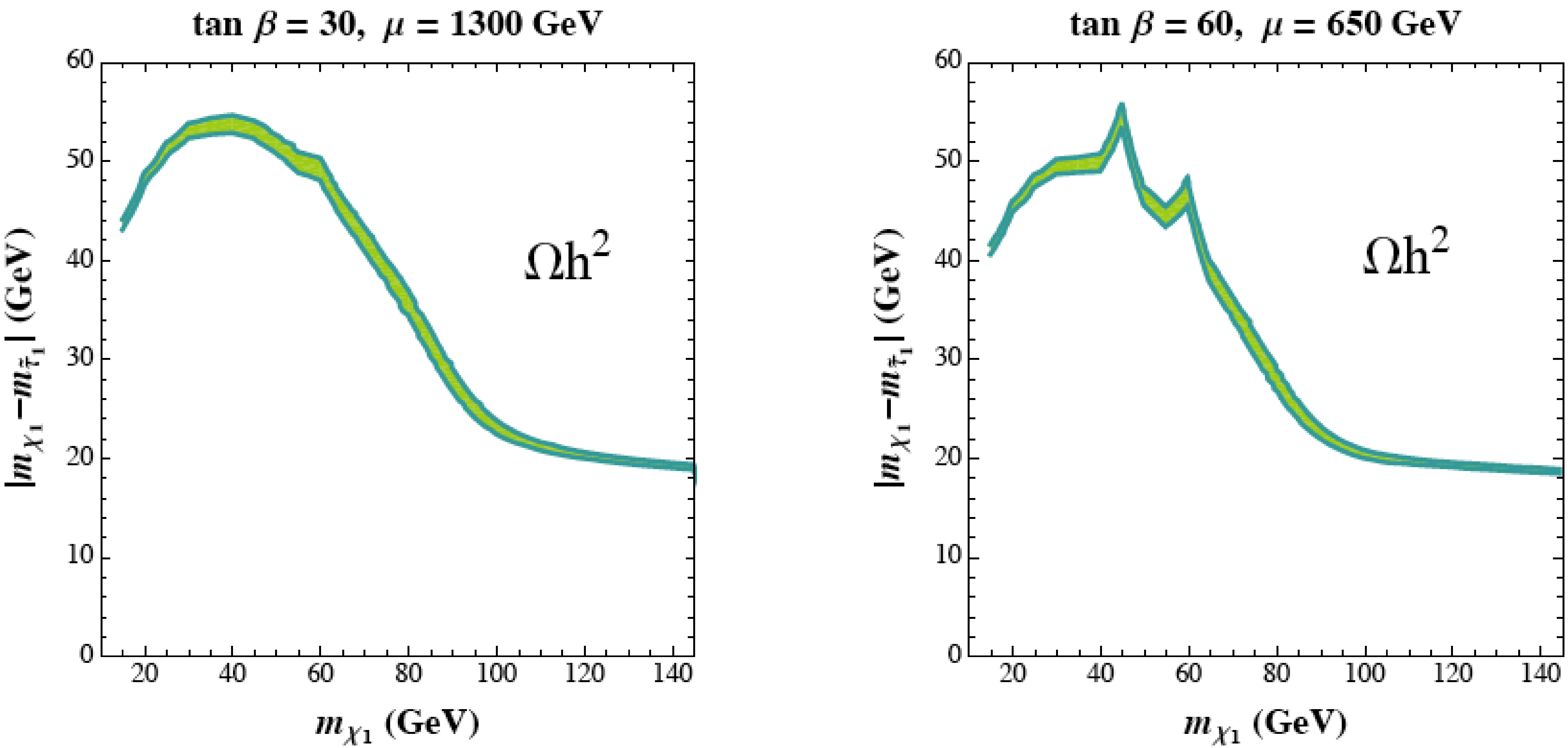
resonant annihilation through the heavy Higgs boson A^0

co-annihilation with $\widetilde{\tau}$, $\widetilde{W}$, $\widetilde{t}$.

mixing with Higgsino ("well-tempered")

The co-annihilation scenarios, in particular, require compressed spectra, with the heavier species often within 10 GeV of the LSP.

Carena, Gori, Shah, Wagner, Wang



The possibility of SUSY dark matter brings with it the dream that we can measure the properties of SUSY particles well enough to predict the dark matter annihilation cross section, and thus the thermal relic abundance, from microscopic data.

This dream is still alive.

The alternative to SUSY models are models in which the Higgs fields are Goldstone bosons. Typically, the symmetry-breaking would come from dynamics at 10 TeV.

In the dual picture, the Higgs doublet field is the 5th component of a gauge field in higher dimensions, with compactification at the multi-TeV scale.

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 $(\widetilde{H}, \widetilde{W}, \widetilde{t})$.

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

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

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.

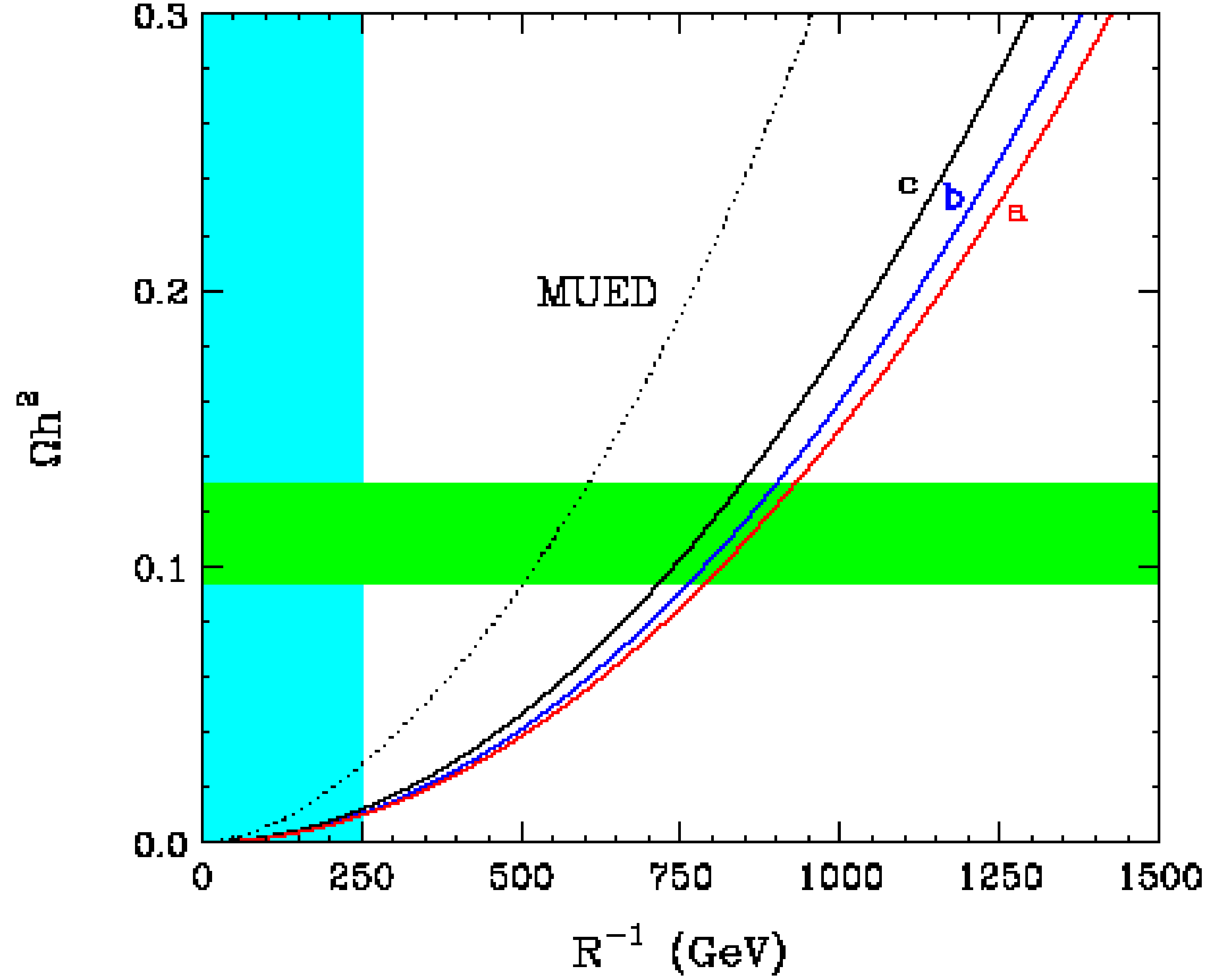
The new fermions are vectorlike singlet T or doublet (T,B).

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 is a candidate for the dark matter WIMP.

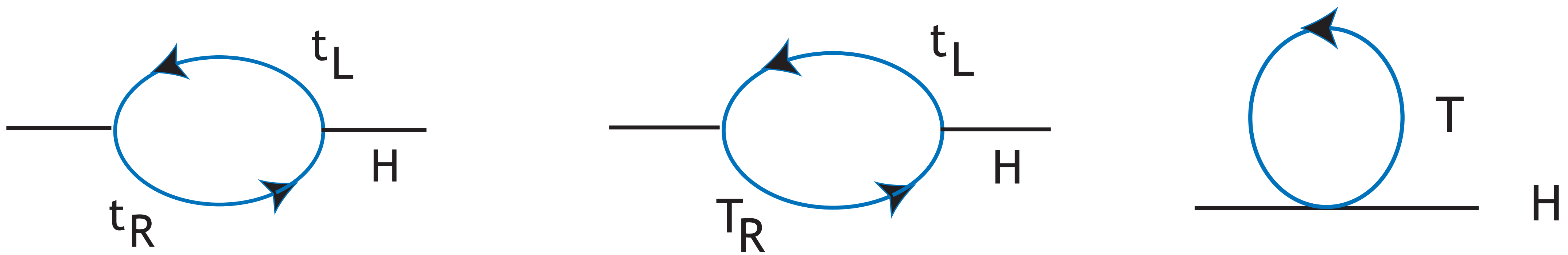
There is no strong naturalness argument that this particle should be light. Relic density calculations prefer larger values, 500 - 1000 GeV.



Kong-Matchev

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

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



$$m_h^2 = -3\frac{\lambda_T^2 m_T^2}{8\pi^2}\log\frac{(10\ \mathrm{TeV})}{m_T^2}$$

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

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

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

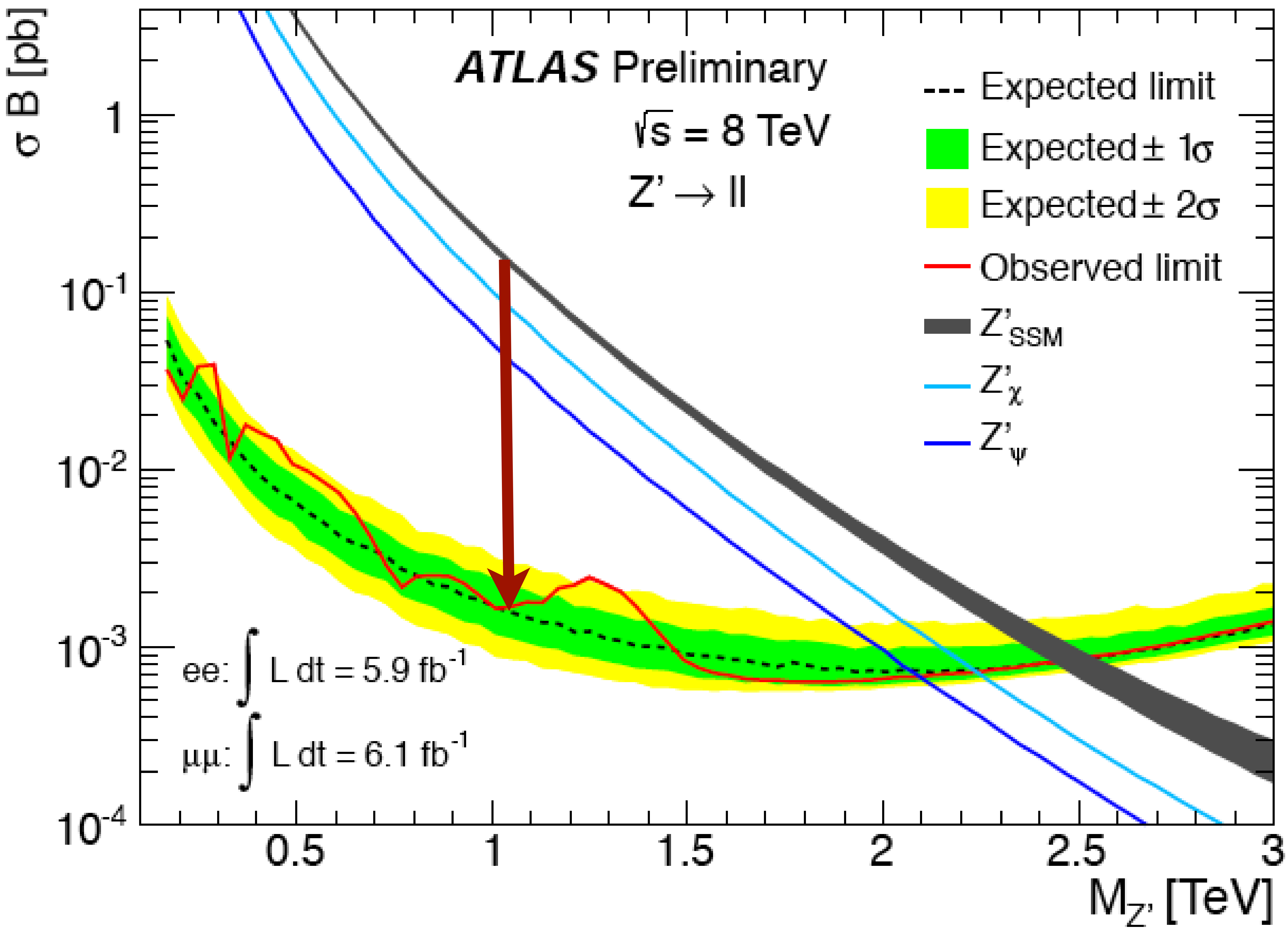
The partners of W, Z have suppressed couplings to light fermions. The coupling of the first excitations can even be 0, if a KK symmetry is present to give dark matter. Cross sections for the second KK excitation are suppressed by wave function overlap in the extra dimensions.

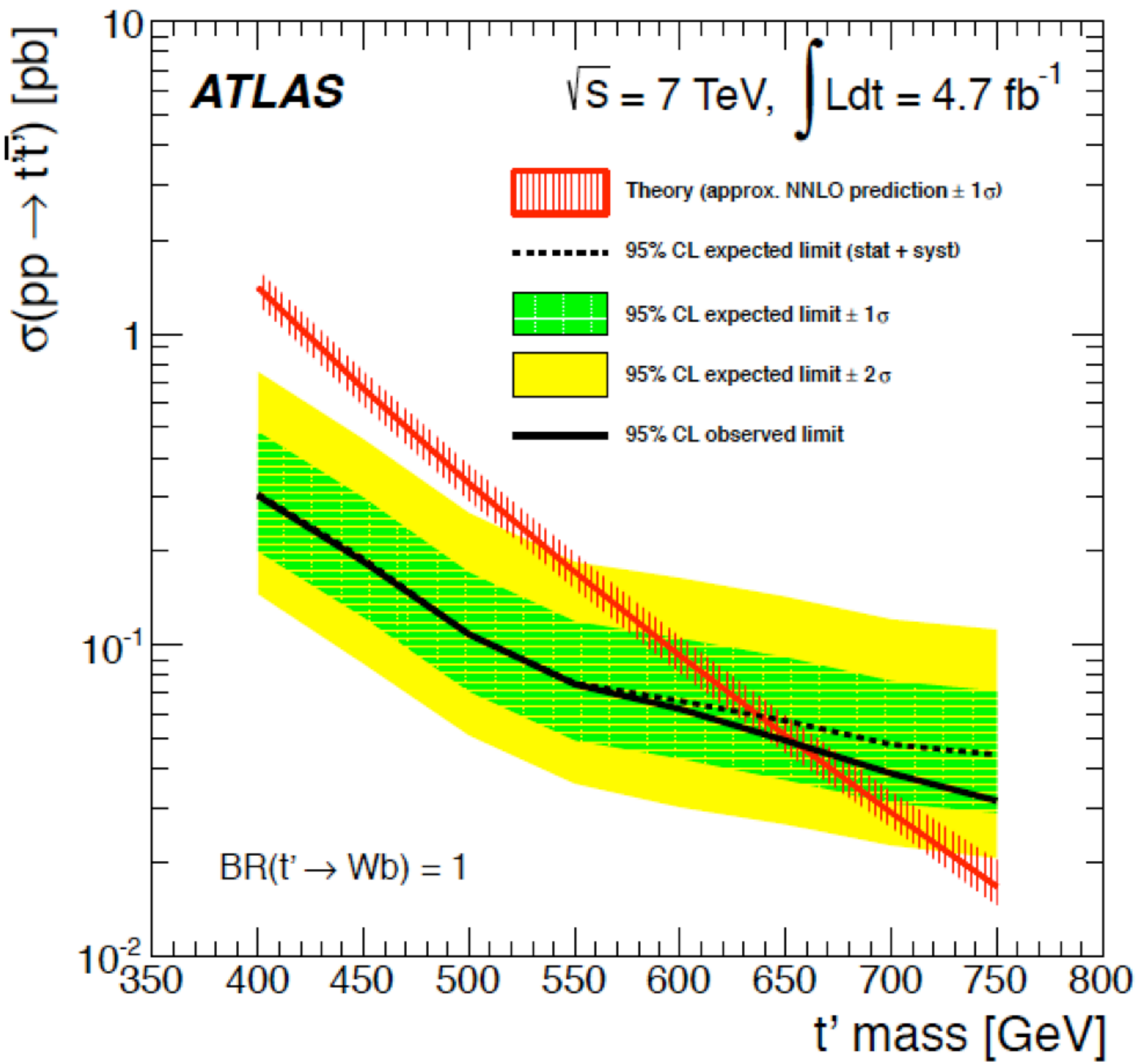
This has unexpected consequences for the search for W and Z partners.

It is relevant and even important to search for resonances in Drell-Yan with cross sections only a few percent of the cross section for a sequential W or Z.

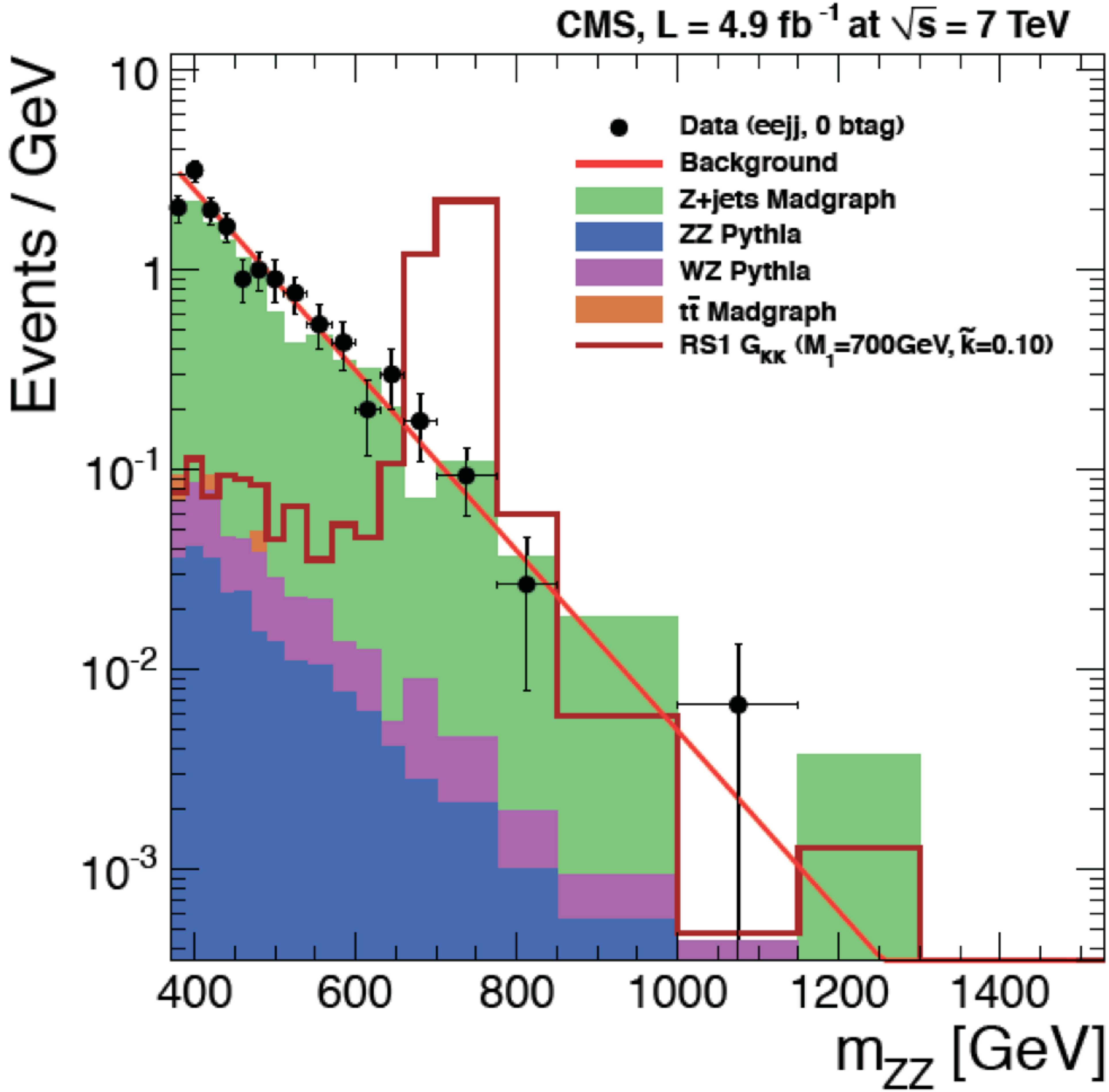
Fermion mass ration such as m_μ / m_e may be explained by wavefunction overlap of the leptons and Higgs bosons. Then, we expect different couplings of the heavy W or Z to different leptons.

It is not correct in general to assume lepton universality.


ATLAS Preliminary
√s = 8 TeV
Z' → ll
Expected limit
Expected ± 1σ
Expected ± 2σ
Observed limit
Z'SSM
Z'χ
Z'ψ
ee: ∫ L dt = 5.9 fb-1
μμ: ∫ L dt = 6.1 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

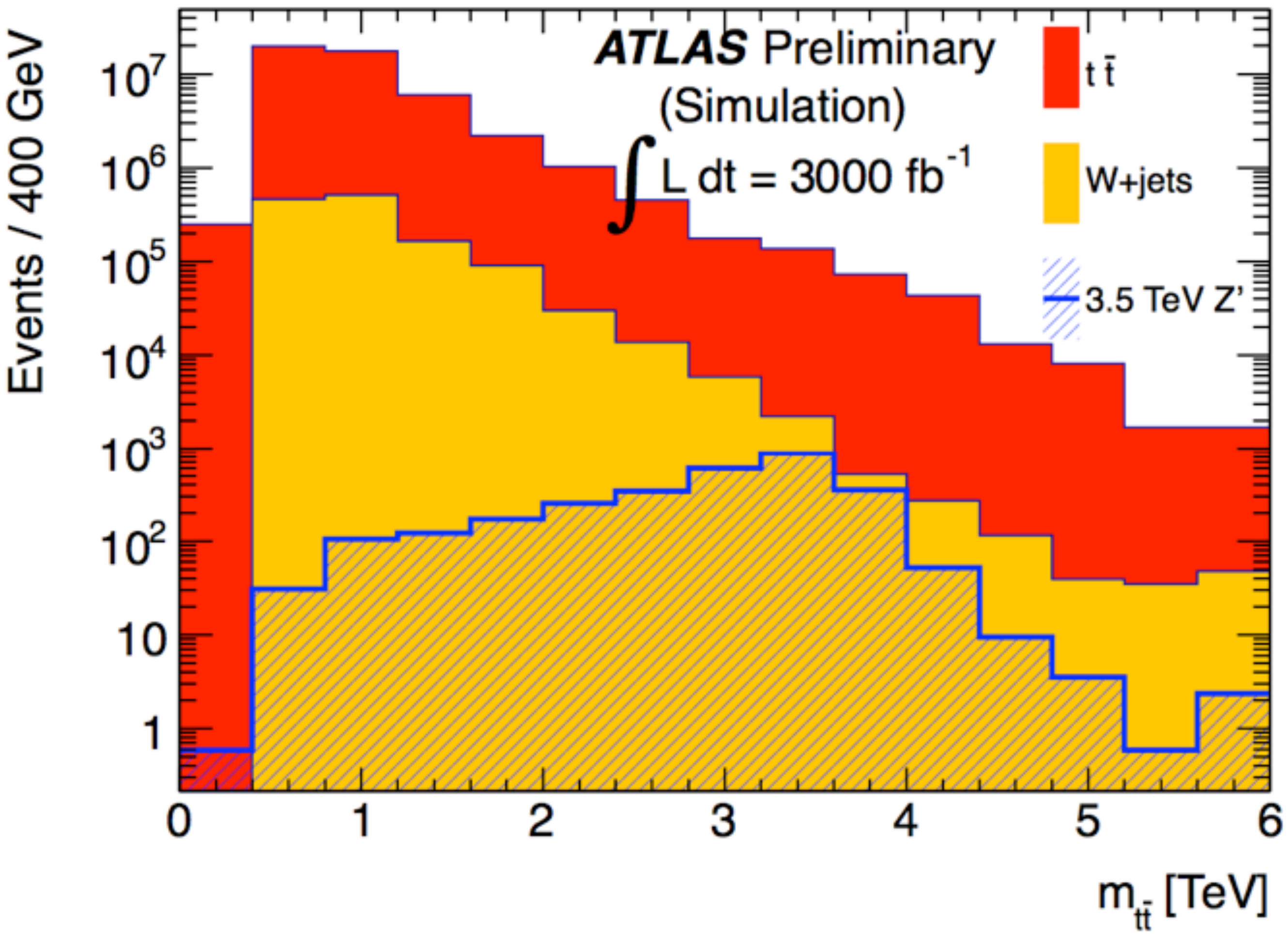


ATLAS
$\sqrt{s}$ = 7 TeV, $\int$Ldt = 4.7 fb^{-1}
Theory (approx. NNLO prediction ± 1σ)
95% CL expected limit (stat + syst)
95% CL expected limit ± 1σ
95% CL expected limit ± 2σ
95% CL observed limit
BR(t' → Wb) = 1
σ(pp → t't̄') [pb]
t' mass [GeV]
10
1
10^{-1}
10^{-2}
350
400
450
500
550
600
650
700
750
800

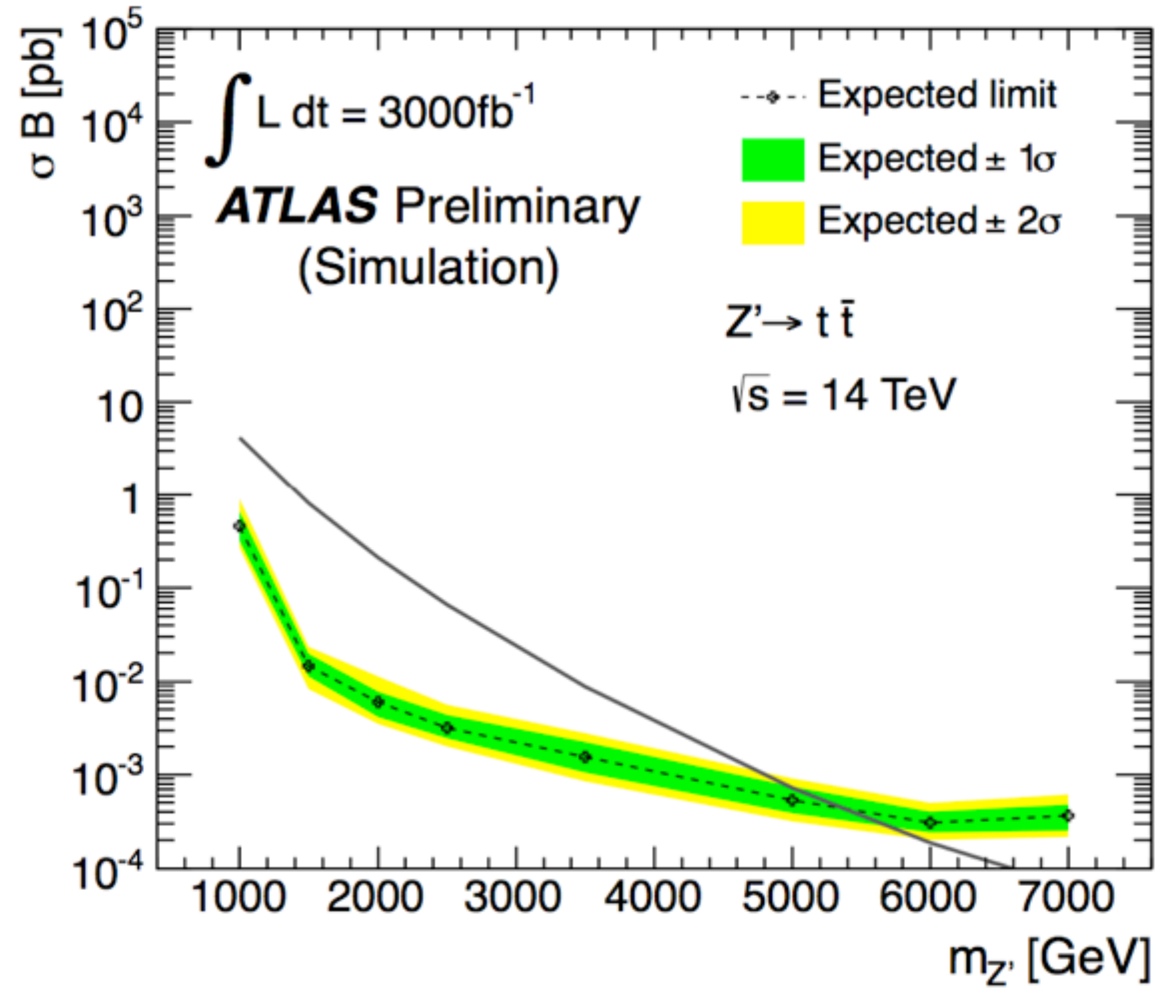


CMS, L = 4.9 fb^-1 at √s = 7 TeV
Events / GeV
10
1
10^-1
10^-2
10^-3
Data (eejj, 0 btag)
Background
Z+jets Madgraph
ZZ Pythia
WZ Pythia
tt̄ Madgraph
RS1 G_KK (M_1=700GeV, k̃=0.10)
400
600
800
1000
1200
1400
m_ZZ [GeV]

Reconstructed ttbar mass spectrum



Expected KKgluon mass limit



model	$300\ \mathrm{fb}^{-1}$	$1000\ \mathrm{fb}^{-1}$	$3000\ \mathrm{fb}^{-1}$
g_{KK}	4.3 (4.0)	5.6 (4.9)	6.7 (5.6)
$Z'_{\mathrm{Topcolour}}$	3.3 (1.8)	4.5 (2.6)	5.5 (3.2)

Polland - Kotwall

Though these searches are interesting, they are not yet accessing the multi-TeV region where the new particles are expected.

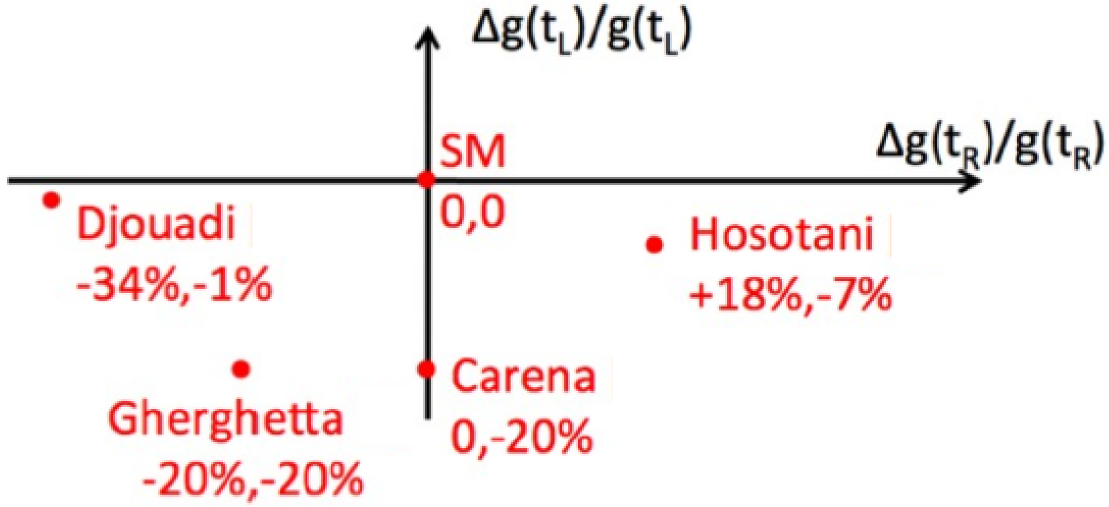
That will have to wait for the 14 TeV LHC.

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.

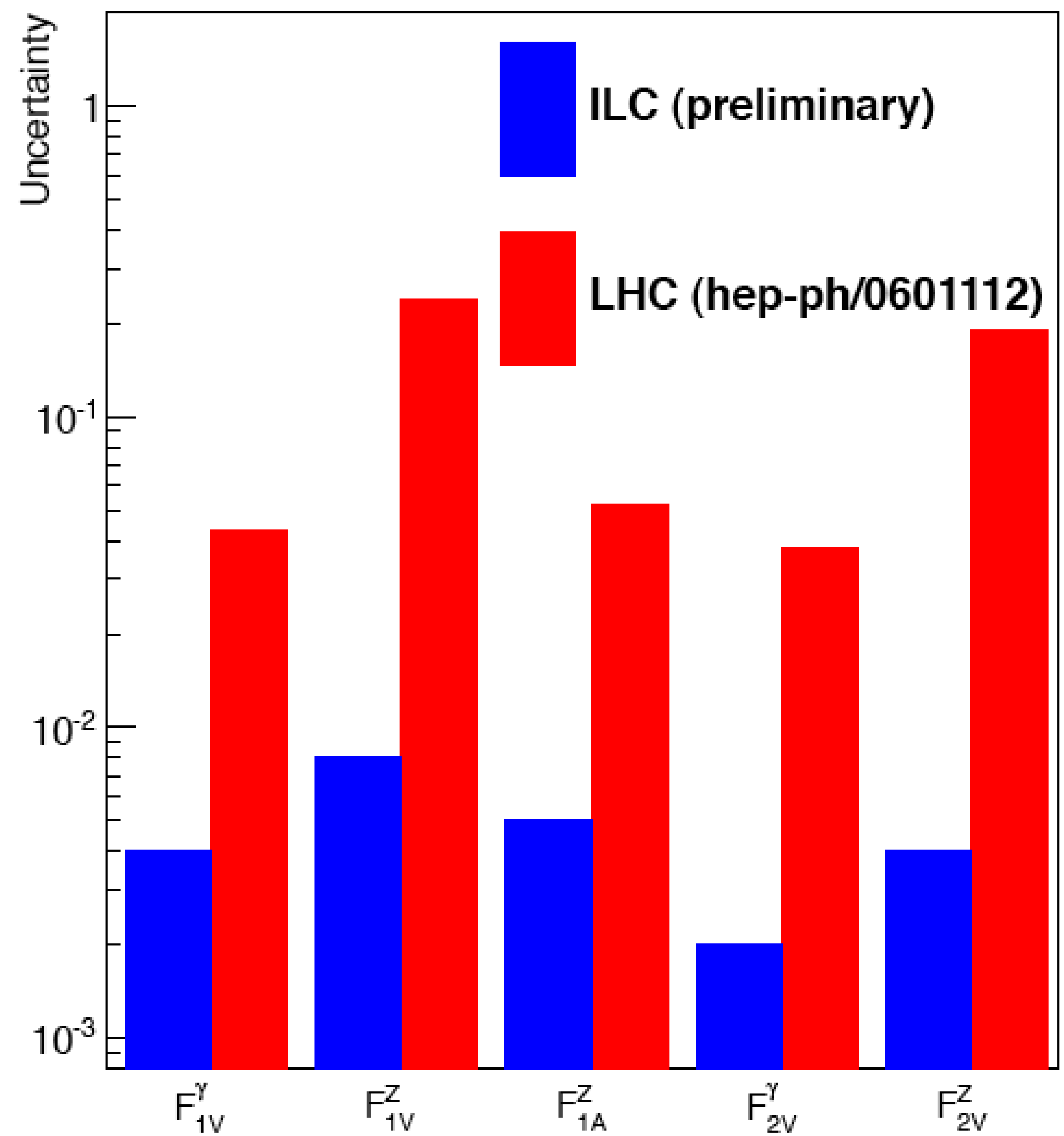
Composite Higgs particles and associated structure must modify the couplings of Higgs, W, Z, and top. The gives anomalies that are detectable in precision experiments. We already know the energy scale needed for those experiments. It is 350-400 GeV.

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:



F. Richard



What are the most important gaps in our technology that need to be filled by new simulation tools ?

1. Precise treatment of ISR.

ISR remains a difficulty for event simulation. It can be handled by

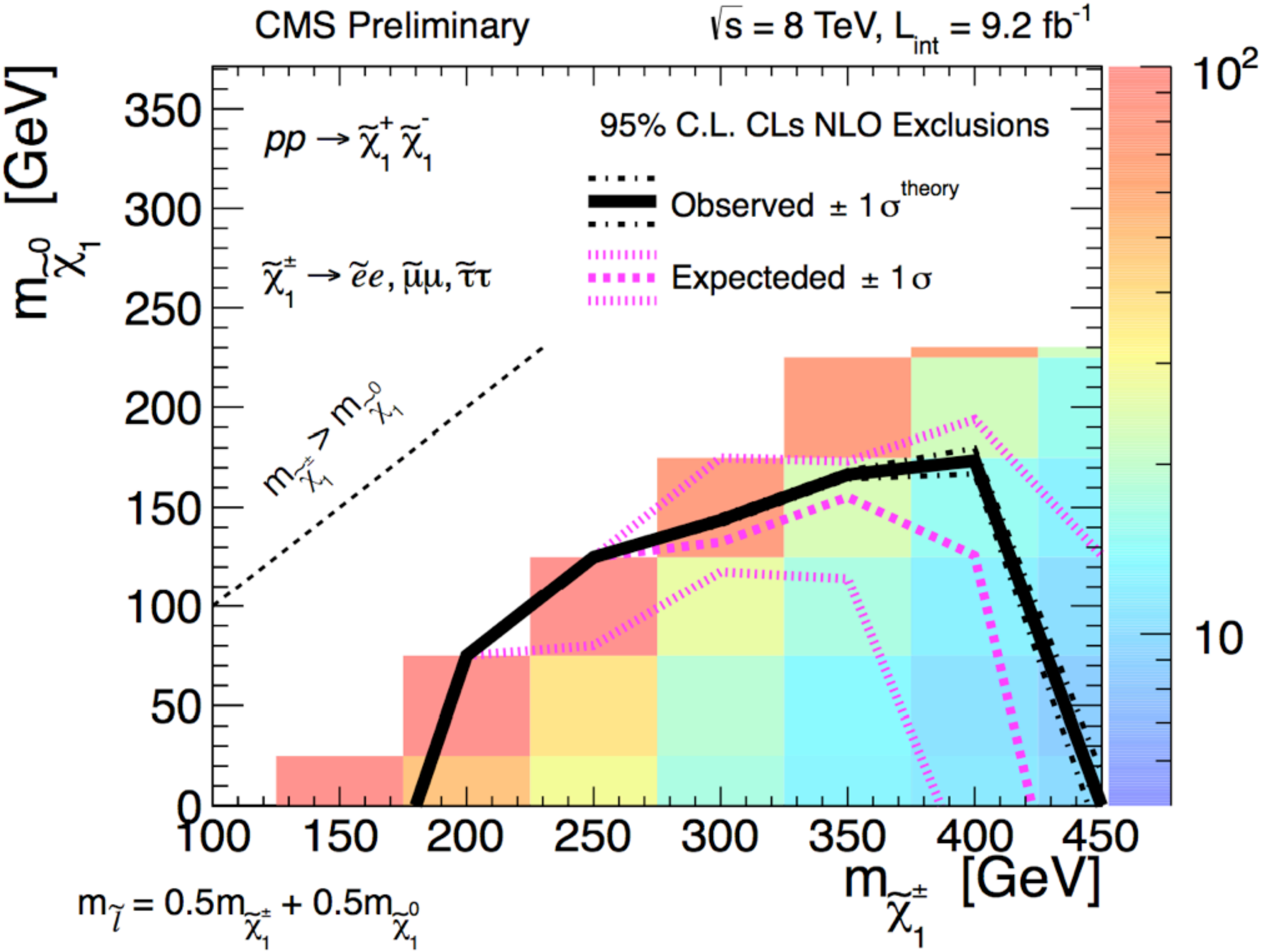
pure parton shower treatment (PYTHIA)

LO matching (Madgraph)

Explicit NLO (or resummed) QCD

These treatments give quite different answers and affect quoted search limits.

Many BSM targets have little energy deposition and depend on ISR for their LHC signals, so we need a standard treatment, which should also be as correct as possible.


CMS Preliminary
$\sqrt{s}$ = 8 TeV, L_{int} = 9.2 fb^{-1}
$pp \to \tilde{\chi}_1^+ \tilde{\chi}_1^-$
$\tilde{\chi}_1^\pm \to \tilde{e}e, \tilde{\mu}\mu, \tilde{\tau}\tau$
$m_{\tilde{\chi}_1^\pm} > m_{\tilde{\chi}_1^0}$
95% C.L. CLs NLO Exclusions
Observed $\pm 1\sigma^{theory}$
Expecteded $\pm 1\sigma$
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{\chi}_1^\pm}$ [GeV]
$m_{\tilde{l}} = 0.5m_{\tilde{\chi}_1^\pm} + 0.5m_{\tilde{\chi}_1^0}$
0
50
100
150
200
250
300
350
100
150
200
250
300
350
400
450
10
10^2

2. Approach to the limit of compressed spectra

As mass gaps decrease, the decay patterns of BSM particles change

new decay modes appear (3 body vs 2 body)

particles can become long-lived

finite width effects are important and affect rates

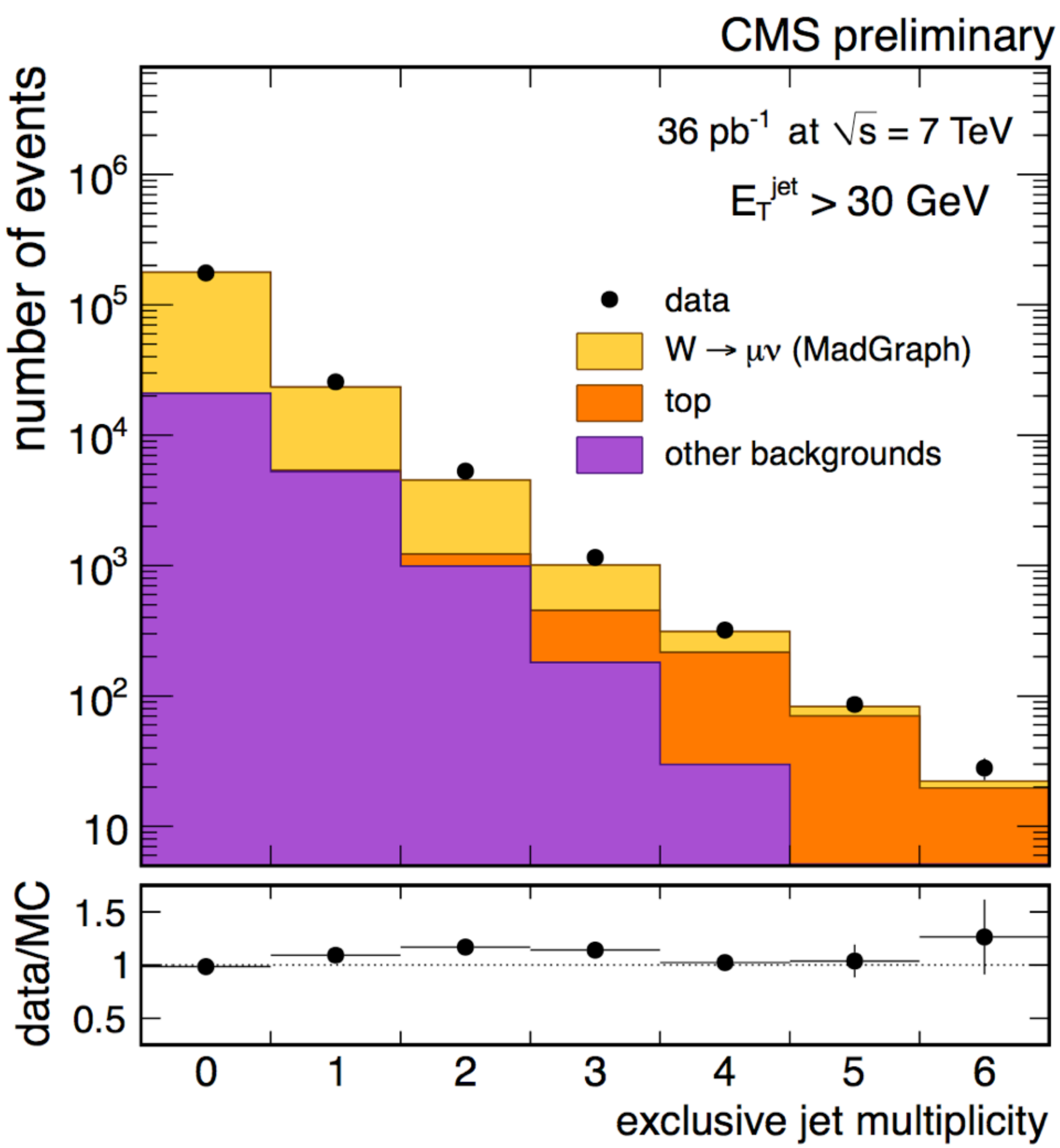
Each situation must be dealt with on a case-by-case basis.

But we should make a toolkit that gives standard solutions to these problems.

3. $t\bar{t}$ + jets

At high jet multiplicity, all background distributions are dominated by $t\bar{t}$ + jets. This effect becomes more important at 14 TeV.

Today, we have control of W + multijets at NLO, but for top + multijets, beyond 2 jet, there is still much to do.



4. Systematic treatment of Composite Higgs

I find it odd that

Supersymmetry and Composite Higgs are parallel roads to BSM physics with comparable a priori weight

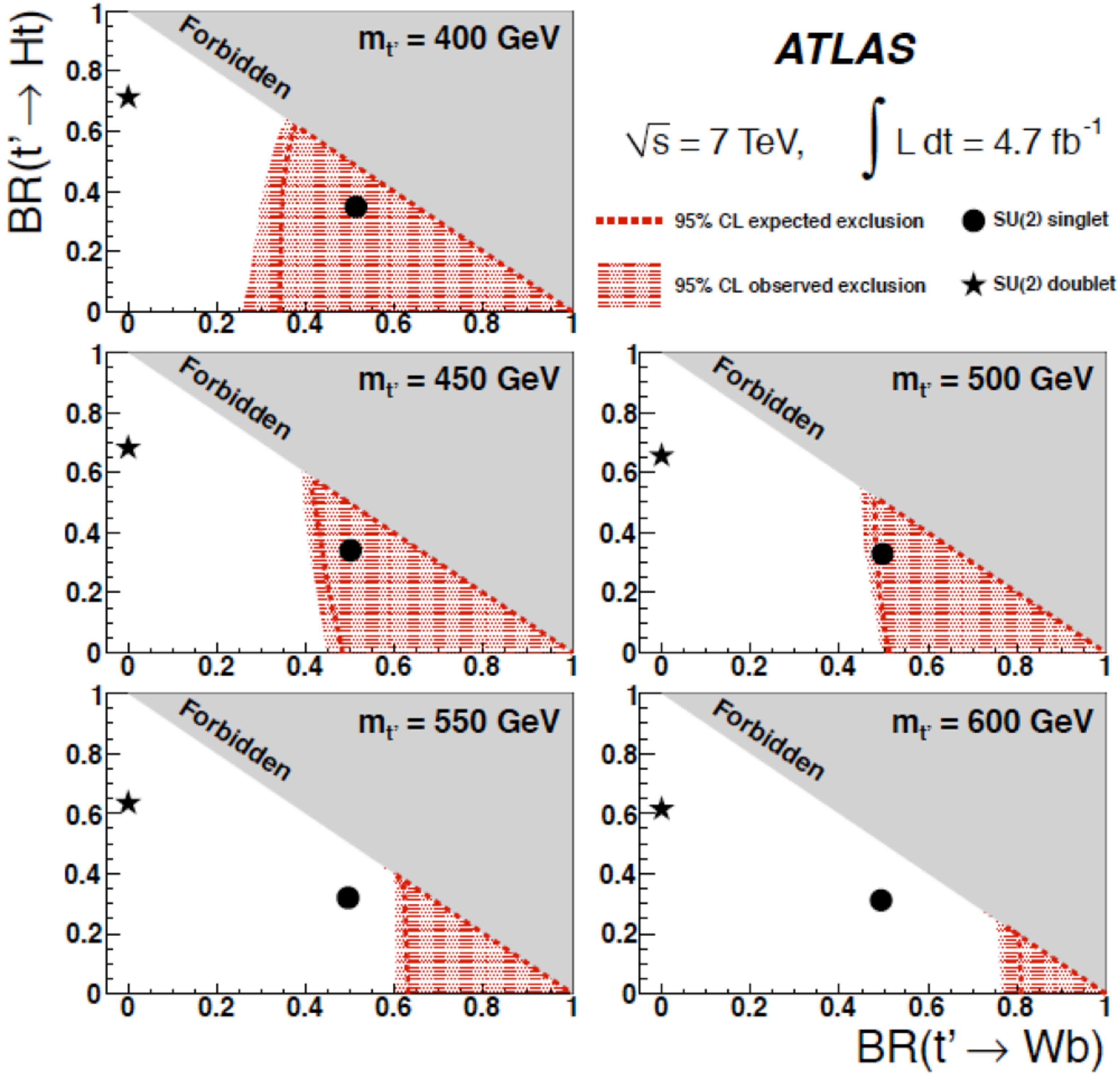
LHC experiments constrain Supersymmetry fairly strongly but are just beginning to probe Composite Higgs models

and yet

detailed toolkits exist for Supersymmetry but not yet for Randall-Sundrum and Little Higgs models

in each LHC experiment, Supersymmetry has a dedicated group, while Composite Higgs models are relegated to “Exotics”

There are signs of people taking the Composite Higgs models more seriously as complete models rather than just as sources of signatures.   But, we need much more.



The BSM physics is out there.

Keep the faith ! There is much, much more territory to explore.