Review: SUSY and Extra Dimensions

BSM: need, expectations for its scale and lessons from early LHC.

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1. State of play in HEP
2. Experimental reasons and Theoretical motivations for going beyond the SM (BSM).
3. Two ways of being BSM:SUSY and Extra Dimensions
4. **What does the current information (Tevatron and LHC) tell us?**

The field of High Energy Physics (HEP) had been in a strange situation.

The usual road through which Science progresses:

Existing Theory and Unexplained Phenomena $\Rightarrow$ New Theoretical developments $\Rightarrow$ Predictions $\Rightarrow$ Testing in Experiments.

State in HEP for the past decade or so

Existing Theory **No Unexplained Phenomena!**, demands made by the Community on the properties of a theory $\Rightarrow$ New Theoretical Developments $\Rightarrow$ Predictions $\Rightarrow$ Testing in Experiments.

We have strong theoretical reasons to believe that there is new physics at $\sim$ TeV scale, Dont have *any strong* experimental evidence indicating its need.

The track record of particle physicists is pretty good so far and theoretical developments based on demands of aesthetics alone have been fruitful at getting at the root of fundamental questions.

BUT

The gap between theory and experiment had never been so large!

When we say we expect new physics at the TeV scale are we theorists sure of prefactor before the TeV. How big or small can it be?.

Hope: TeV energy colliders : Large Hardon Collider (LHC) would help unravel the mystery. Data from LHC have started coming, time of reckoning has arrived!

Generalities:

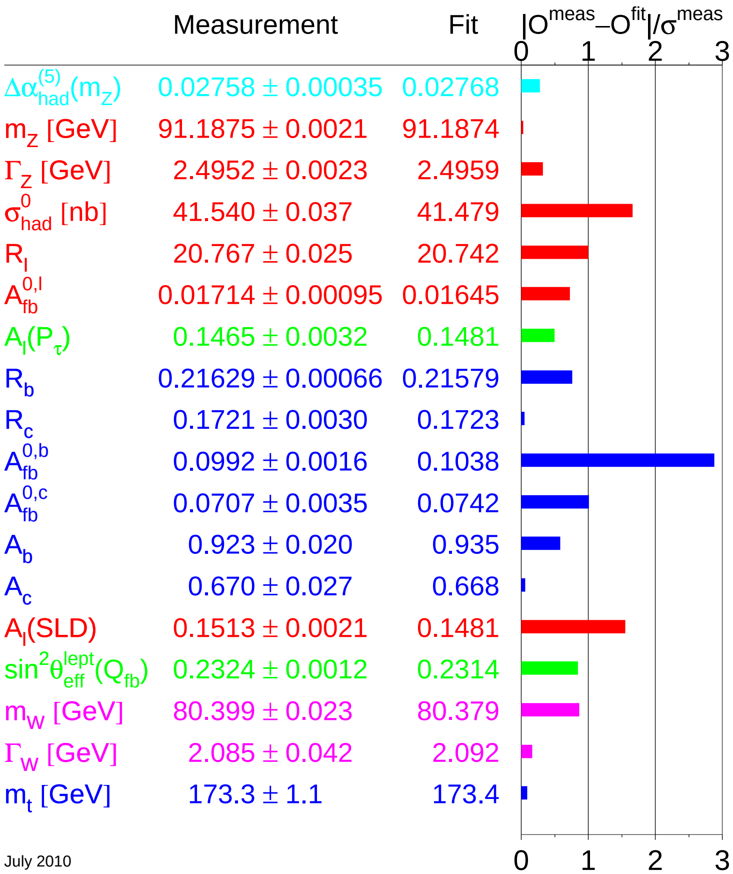
The SM Lagrangian consists of 'proved' gauge sector and **yet to be proved scalar** sector:

$$\begin{aligned}\mathcal{L} = & - \frac{1}{4} F^a_{\mu\nu} F^{a\,\mu\nu} + i\bar{\psi}\, \not{D}\psi \\ & + \psi^T \lambda \psi h + h.c. \\ & + |D_\mu h|^2 - V(h)\end{aligned}$$

Gauge sector in good shape.

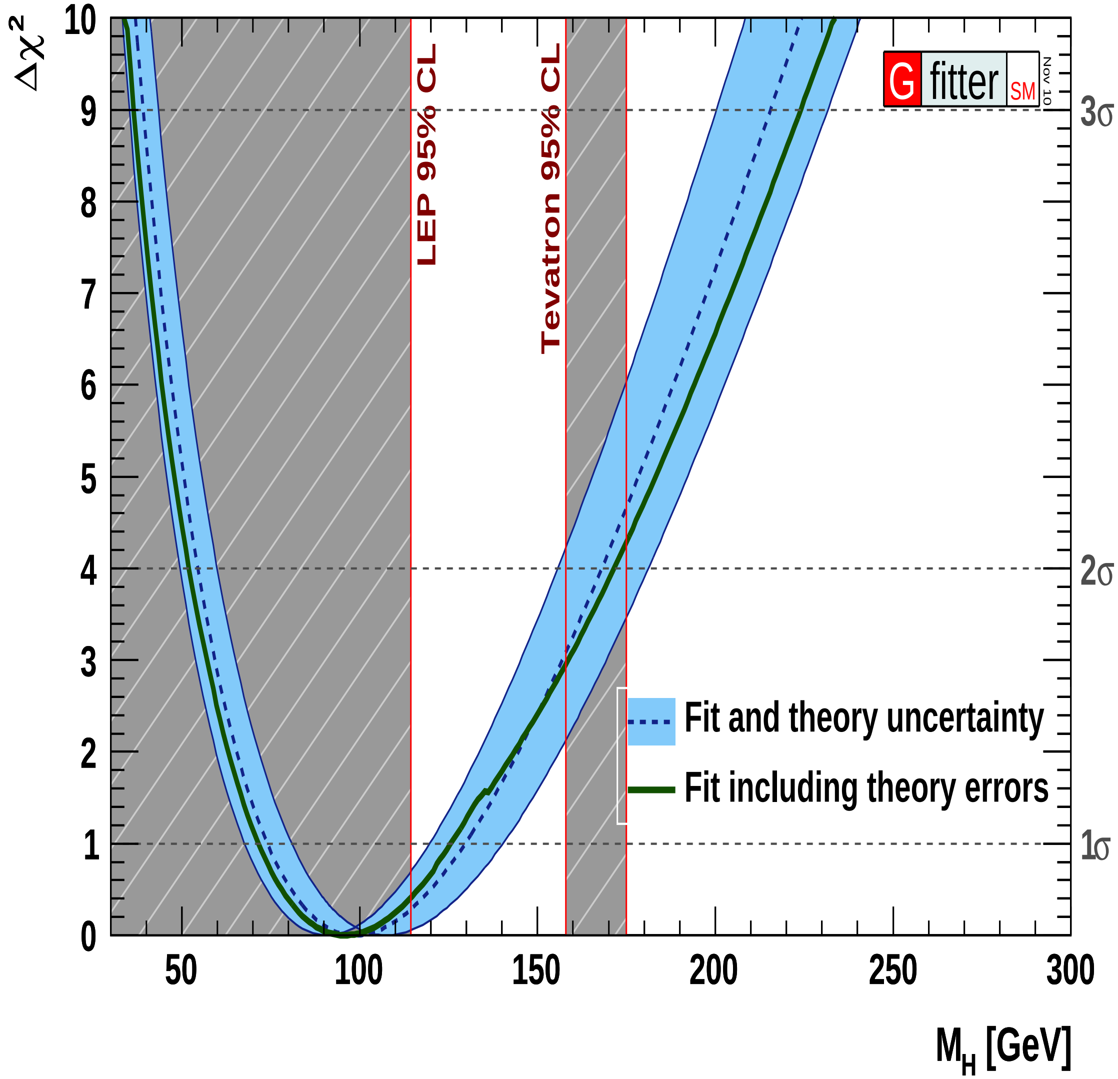
The beginning of the spell of the gauge principle cast by QED is made much stronger with Non Abelian Gauge Field Theories with Spontaneous Symmetry Breaking and without symmetry breaking

But no direct evidence yet exists for the last piece of the Gauge Paradigm : the scalar sector! What is the experimental information on it?



- All the current experiments have tested the perturbative predictions of the Standard Model (SM) to an **unprecedented** accuracy.
- **May be holds also some clues of Physics beyond the SM**

see http://lepewwg.web.cern.ch



What does it mean for the Higgs? If all the current information is put together the Higgs mass should be less than 150 GeV. (**indirect experimental limit!**)

Lessons:

- The EW precision data like a light higgs.

- ANY discussion of alternate scenarios of symmetry breaking MUST always pass the **precision** test.

Last decade great progress in the flavour sector:

The correctness of CKM picture, ν oscillations...

SM needs to be augmented by

$$\mathcal{L}' = \frac{1}{M} L_i \lambda^{\nu}_{ij} L_j h^2 \text{ and/or } L_i \lambda^{\nu}_{ij} N_j h + h.c. \tag{1}$$

Neutrinos are special in that they are neutral and many new physics ideas have implications for neutrino mass generation which can *in principle* be different from other fermions. (Beyond standard model..)

1] Neutrinos have nonzero masses *and* the fermion masses have a huge hierarchy

SM has bearing on on issues cosmological and needs BSM physics as well.

2]. The contents of our periodic table seem to account for ONLY 4% of the matter in the Universe! Astrophysical evidence pretty convincing.

Dark Matter: exptal information indicates a BSM particle Dark Energy: ???Many many ideas..

3] **A** *qualitative* **explanation of the** $B\!-\!\bar{B}$ **asymmetry in the Universe, in terms of** *known* **CP violation in the SM,** *measured in laboratory*, **is possible.**

A quantitative explanation indicates need of Physics beyond the SM.

Then there are esthetic/theoretical reasons motivated by the experimental information on the Higgs mass!

The fact that SM works so well means

1) a Higgs OR a look alike must exist and data tell us it must be light!

2) We should also understand why it is light!! Loop corrections will always push it to the maximum mass in the theory.

This is one reason for expecting physics beyond the Standard Model!!

The hierarchy problem:

The EW theory has been tested at 1-loop level. The Higgs mass which is a free parameter in the SM, receives large quantum corrections and the mass will approach the cutoff scale of the theory.

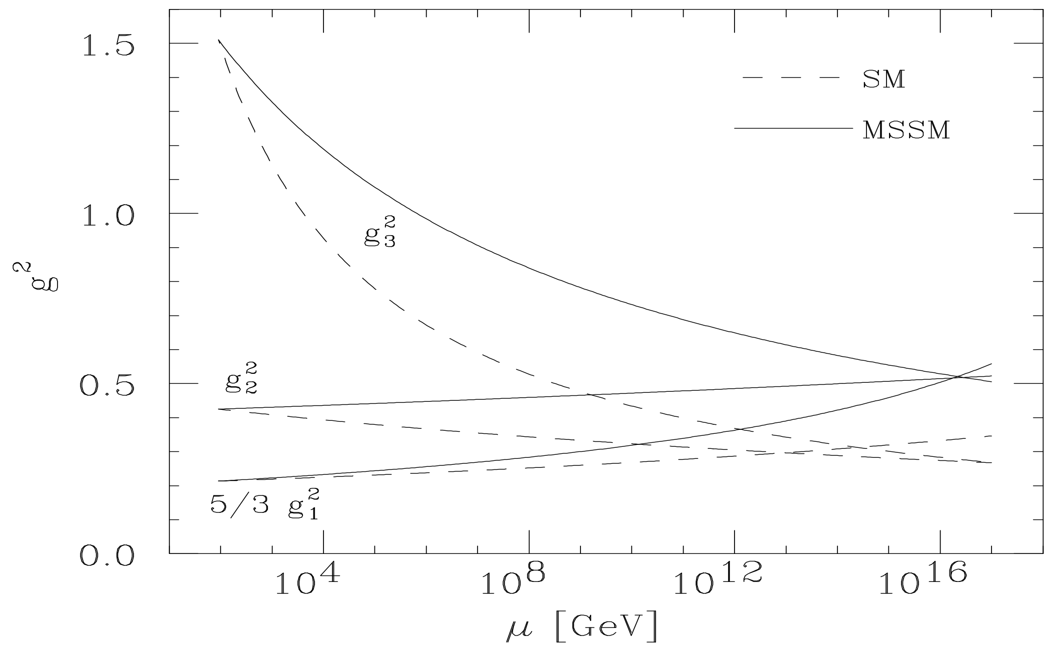
If, $m_{\mathsf{h}}^2 = m_{\mathsf{bare}}^2 + \delta m_{\mathsf{h}}^2$ the top loop (e.g.) gives

$$\delta m^2_{\mathsf{h}|\mathsf{top}} \sim -\frac{3G_{\mathsf{F}}}{2\sqrt{2}\pi^2} m_t^2 \Lambda^2 \sim -(0.2\Lambda)^2.$$

The light higgs is 'natural' then only if $\Lambda \sim$ TeV.

A little more 'experimentally' motivated hint for BSM?:

- Do strengths of all the interactions unify at some high energy?
- with Supersymmetry (still to be discussed) there is some evidence that they might.
- Models to explain observed mass patterns, all like unified models.



Is that the whole truth? Is this a time for a paradigm shift?

Are Quantum Field Theories sort of a 'low energy' paradigm?. Can we combine gravity somewhere in the picture? Are 'String' theories the language to use once you want to include gravitation.

Jury is more than out on this point!

- Dark Matter makes up 23% of the Universe.!
- Direct evidence for the nonzero ν masses
- Quantitative explnation of the Baryon Asymmetry in the Universe!

- **Instability of the EW scale under radiative corrections.**
- Need to get a basic understanding of the flavour Issue
- Unification of couplings
- Inclusion of Gravity in the picture?

We know at present two ways to keep the Higgs 'naturally' light:

1] Introduce a symmetry:

Supersymmetry : cancel the large top loop contribution by contributions from scalars. There exist host of new particles which we should see at the colliders, *around* TeV scale.

OR

Little Higgs models: The Higgs mass is small because its mass is protected as it is a pseudo goldstone boson. There exist many additional fermions, gauge bosons in the theory at the TeV scale.

2] The cutoff is lowered to TeV:composite models and brane-worlds. Brane Worlds postulate behaviour of the space and time different from what we understand, such as additional compactified dimensions! new developments: String theories have begun to make some statements about such models!

3]Higgsless models?

Little Higgs or Higgsless models in genreal have problem passing the acid test of LEP precision measurements. Issues of ultraviolet completions seem to reintroduce a high scale (much above a TeV scale) Supersymmetry.

1)Introduce a symmetry: supersymmetry

Theoretically extremely elegant and attractive: Spacetime symmetry, finite ultraviolet behaviour.

How is the stabilisation brought about?

The sparticle loops cancel the large self energy corrections and keep the higgs mass 'naturally' small.

Eqally important: As we saw the data seem to *like* a light Higgs.

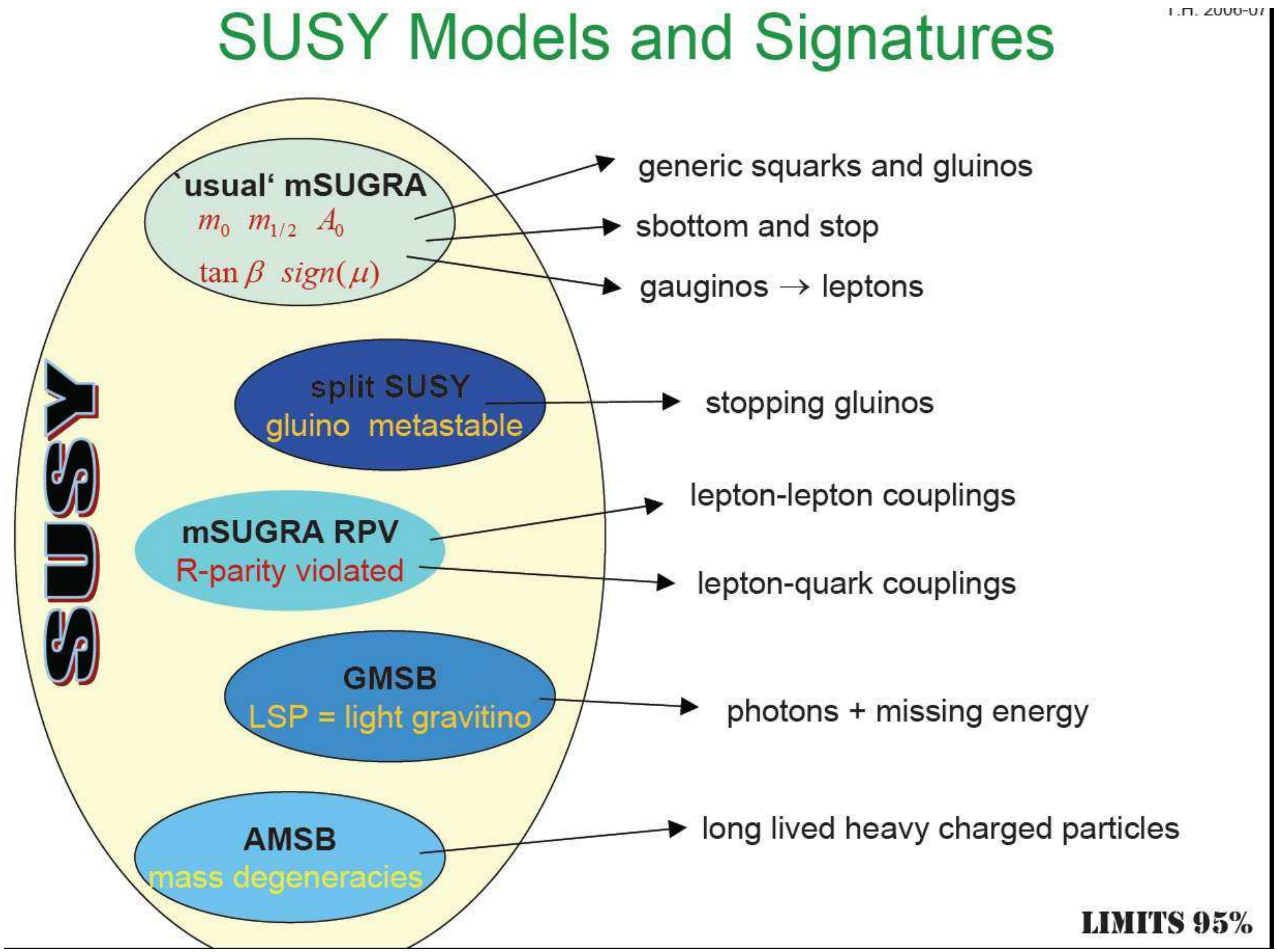
But the Higgs is not 'soo' naturally light unless sparticle masses are small.

A ready made DM candidate in case of R-parity conservation.

Search for SUSY is the case of experiments chasing a beautiful theoretical idea.

It is *clearly* broken. ALL the experiments have so far only given NEGATIVE results, giving LOWER limits on sparticle masses.

The symmetry is beautiful, the ideas of how to break it are mostly not!


SUSY Models and Signatures
SUSY
`usual' mSUGRA
m_0 $m_{1/2}$ A_0
$\tan\beta$ $sign(\mu)$
generic squarks and gluinos
sbottom and stop
gauginos → leptons
split SUSY
gluino metastable
stopping gluinos
mSUGRA RPV
R-parity violated
lepton-lepton couplings
lepton-quark couplings
GMSB
LSP = light gravitino
photons + missing energy
AMSB
mass degeneracies
long lived heavy charged particles
LIMITS 95%

NON-obseration of direct SUSY signal anywhere so far is not only discouraging, but also points to a problem called 'small hierarchy problem'.

The LEP Higgs mass limit implies rather heavy supersymmetric partner of the top $\sim$ TeV, if $A = 0$ which is not 'natural'. Light stop admitted with large A_t.

More generally, in SUSY models the EW symmetry breaking is radiatively induced. This means a relationship between M_Z and other SUSY parameters, masses. With sparticles as heavy as required to satisfy the LEP Higgs mass limit, a fine tuning of a percent or more is required to satisfy this relation. **Naturalness may be lost! (Guidice, Rattazi 06)** Non minimal (NMSSM) cures this problem to a large extent.

Are we being fussy?

Keeps the Higgs light! But sparticle should not be too heavy. What is 'too heavy'? When should we be worried?

Predictive: Higgs mass limits, quite robust with respect to SUSY breaking parameters.

WIMP miracle happens easily. Ready made DM candidate. But in CMSSM again it is now under great scrutiny. Good point: predictive in a given model.

Baryogenesis works. Requires NMSSM and/or additional CP violation.

Can address ν masses, but requires R-parity violaton.

Flavour physics: SUSY has no neat solution. B physics measurements put it under strain in fact.

Local supersymmetry : Supergravity contains automatically Einstein Gravity.

String theory requires Supersymmetry, BUT REMEMBER NOT TEV scale Supersymmetry.

Question:

1)Should we be worried now with the newer exclusions from CMS/ATLAS?

Is it still 'natural' ? In T. Huxley's words will SUSY be a great tragedy of science: 'A beautiful theory slain by an ugly fact?'

2) Synergy between the DM experiments and LHC experiments?

3) What are the chances of SUSY detection given the current CMS/ATLAS results?

I will present examples of such studies a little later.

Some general features of Xtra dimensional theories (idea began with Kaluza and Klein)

• Observed world has 3 space time dimensions, embedded in a higher D-dimensional spacetime, $D = 3 + \delta + 1$.

• Additional space dimensions will modify Newtonian Gravity at short distances. Experimental constraints on the *absence* of such deviation constrains the 'size' of the extra dimensions, which must be compactified.

• These theories will always have a graviton (spin 2 particle) as well as tower of Kaluza Klein (KK) excitations of which the normal SM particles are the zero modes.

• Gravity propagates into the bulk always, such that the strength of gravity on the 3-brane that is our world is the usual small value. Different Xtra dimesional models differ in the behaviour in the additional δ dimensions called the 'bulk'.

a How many extra dimensions?

b What is the size of the Xtra dimensions? What is the 'size' of the bulk? ('large' extra dimesions, TeV^{-1} dimensions)

c What is the geometry of the additional dimensions? (warped or otherwise?) (Randall Sundrum and many variations thereof)

d Which particles propagate into the bulk?

e Symmetries that the KK spectrum has (Universal Extra Dimension: UED)

f Interesting flavour physics model building possible in RS picture.

• Extra dimensions are an exciting idea. Very interesting that it is compatible with the data. Provide an intimate link with structure of spacetime and technical problems in particle physics

• None of the models is completely free from fine-tuning. RS the best and hence the template of almost all the ED phenomenology these days.

• There is no way to determine the number of the extra dimensions. We do not understand dynamically why some of the dimensions are compact

• Phenomenology is highly model- dependent: only spin-2 graviton is unique, if it (the spin) can be determined.

• Predictions for collider signals in some cases depend on the Ultra-violet completion of the theories. Counterpart of uncertainties about

SUSY breaking (to some extent). In general less predictive than SUSY.

- EWPT not always easy.
- KK parity gives DM candidate.
- Does not address the different reasons for BSM as well as SUSY.

Currently we only have limits on sparticle masses (for given SUSY breaking scenarios) or on the scale Λ of the extra dimensional theories.

Interesting question: in spite of these -ve results do SUSY and ED have anything to say about either of the recent Tevatron anomalies have.

I]

Tevatron has reported A_{FB} in $t\bar{t}$ production at a level of few σ:

Do either SUSY and/or ED have possible explanations?

i) RS KK gluons can perhaps do it..but do not quite find it easy to get the large asymmetry at the same time keeping $t\bar{t}$ spectrum unchanged!

(Djouadi, Moreau, Richard,Singh 0906.0604, Masip, Santiago et al: 1105.3333)

ii) R-parity violating SUSY: 0912.1447

iii) Light stop: Isidori et al: 1103.0016

II] Wjj bump at 3.2σ level:

An explanation in terms of an unmixed radion with $\Lambda \sim 1.5$ TeV.

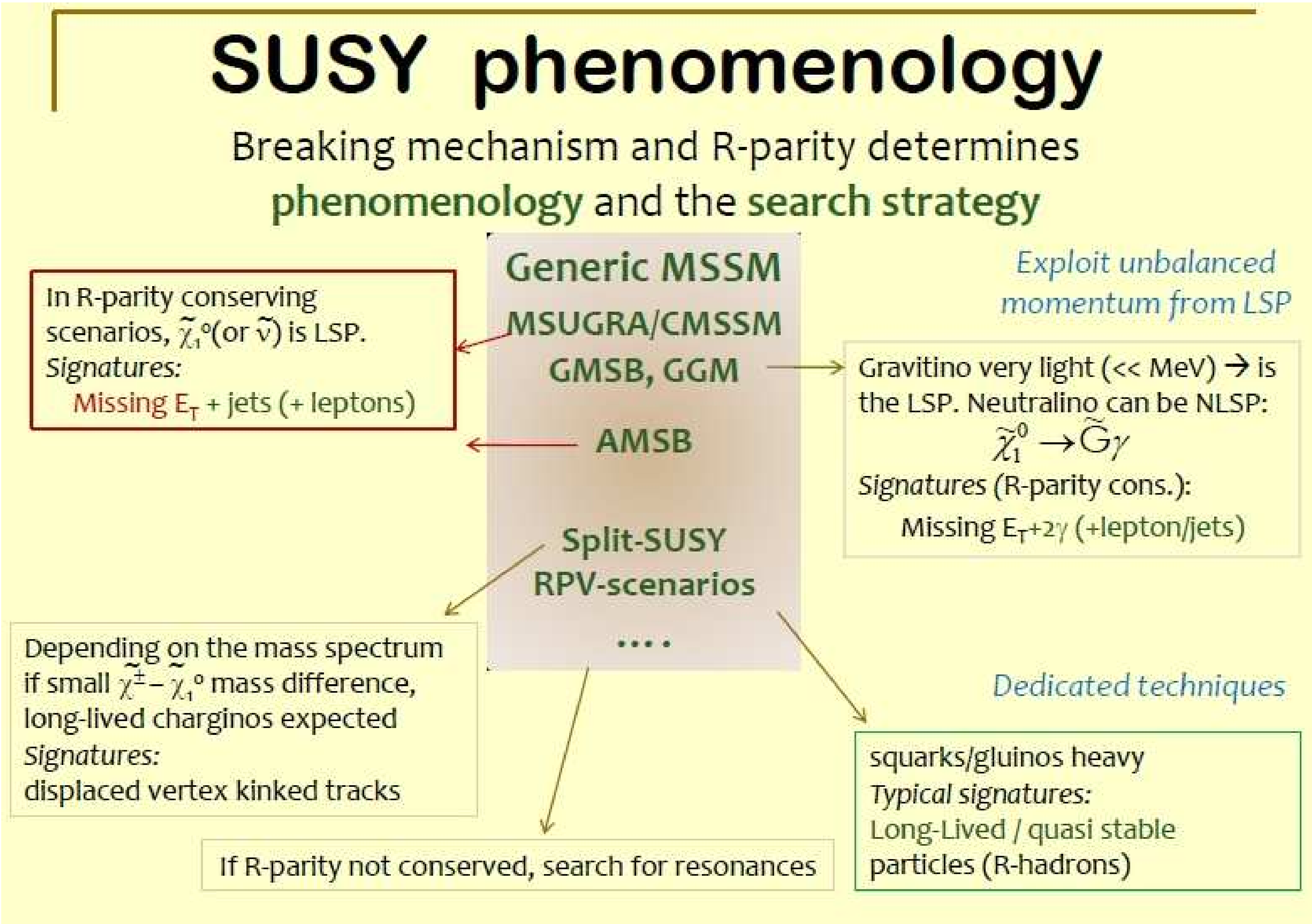
B. Bhattacharjee and S. Raychaudhuri, arXiv: 1104.4749v2

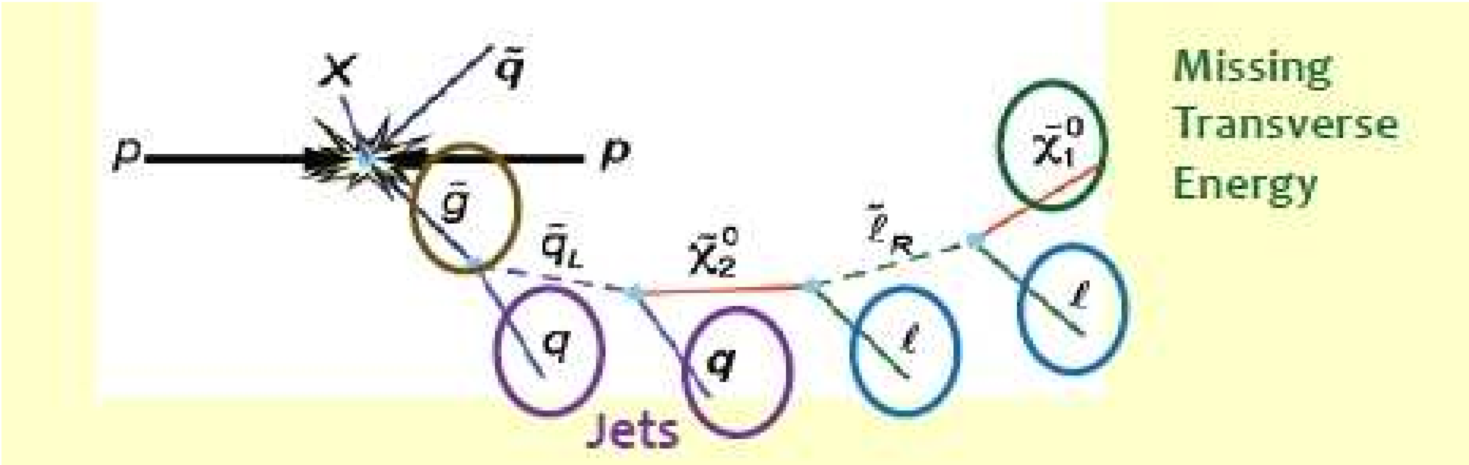
Gravitons produced in a collision can fly off into the extra dimensions, carrying energy-momentum, which would seem to disappear from the brane. (missing energy-momentum signatures).

Virtual graviton exchanges can look like neutral current interactions.

UED signatures can be similar to SUSY cascade decays. These also have a DM candidate. Spin of the DM candidate here will be zero.

RS Models: Higgs phenomenology can be affected by a possible presence of a scalar Radion. The scalar should be light. Heavy Gravitons/KK gluons resonances possible.


SUSY phenomenology
Breaking mechanism and R-parity determines
phenomenology and the search strategy
Generic MSSM
MSUGRA/CMSSM
GMSB, GGM
AMSB
Split-SUSY
RPV-scenarios
....
In R-parity conserving scenarios, $\tilde{\chi}_1^0$(or $\tilde{\nu}$) is LSP.
Signatures:
Missing E_T + jets (+ leptons)
Exploit unbalanced momentum from LSP
Gravitino very light (<< MeV) → is the LSP. Neutralino can be NLSP:
$\tilde{\chi}_1^0 \to \tilde{G}\gamma$
Signatures (R-parity cons.):
Missing E_T+2γ (+lepton/jets)
Depending on the mass spectrum if small $\tilde{\chi}^{\pm} - \tilde{\chi}_1^0$ mass difference, long-lived charginos expected
Signatures:
displaced vertex kinked tracks
If R-parity not conserved, search for resonances
Dedicated techniques
squarks/gluinos heavy
Typical signatures:
Long-Lived / quasi stable particles (R-hadrons)



A lot of work over the past decades done by theorists on

1)How to compute the expected particle spectra for a given SUSY breaking scenario

2) How to compute expected cross-sections for sparticle production

3)What are 'tell tale' final states and signatures for different SUSY models.

That needs to be used once the experimentalists tell us if they have seen any events above the background.

With the low luminosity available currently the SUSY searches are sensitive to the strongly interacting sparticles: gluinos and squarks.

ATLAS has seen even less events than the expected background, but consistent with it. Limits more stringent than expected. This also means: limits to evolve only somewhat slowly with increased statistics.

CMS has seen perhaps a very slight excess in one analysis. Nothing to get excited about but to keep eyes glued to the space.

Experimentalists have interpreted the results in terms of parameter space in the so called CMSSM: where the large number of MSSM parameters (105) to only 5.

At Tevatron 95% c.l. and 99% c.l. exclusions not too different. Not clear the same can not be said of the current (at least) ATLAS limits.

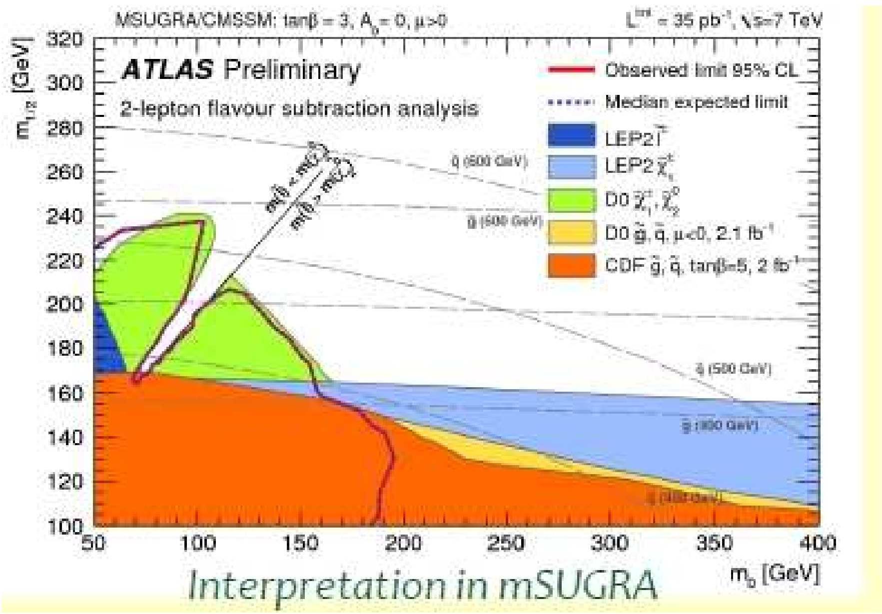
A summary: http://thp.uni-bonn.de/groups/drees/book.html

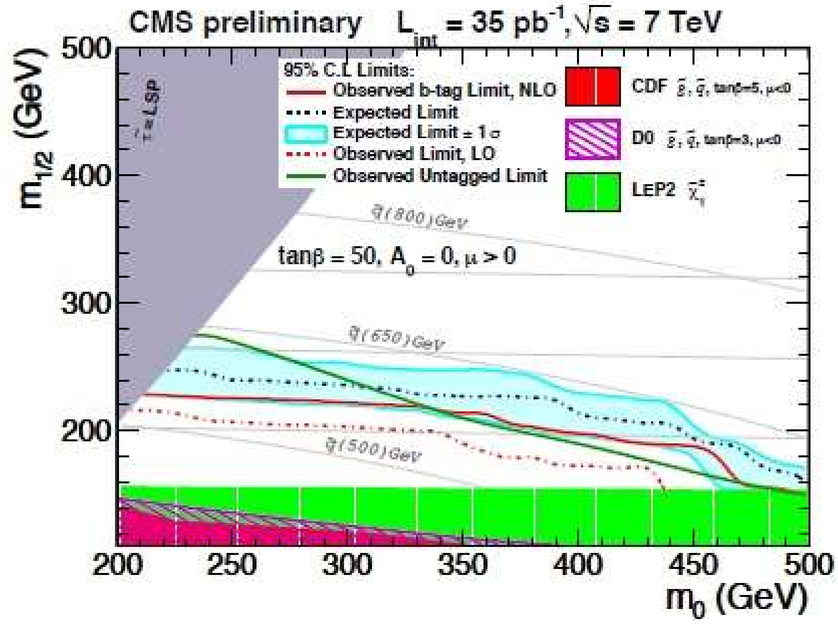
Theorists have

i) Analysed the effect of these data for the best fit to a variety of all the other data such as $(g-2)_\mu, B \to s\gamma$, requiring that SUSY gives the right amount of DM and analysed what region gives the best fit for guiding the next round of searches which are going on now (Ben Allacnach and collaborators, arXiv: 1102.3149v4, 1103.0969v3)

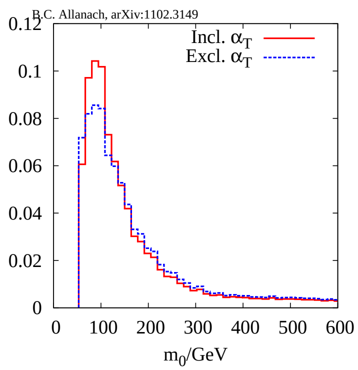
ii)interpret results in terms of a more relaxed set of parameter space than CMSSM and see whether the exclusions are still valid, J. Hewett, T. Rizzo and collaborators, SLAC-PUB-14382. They have done the exercise only for the ATALS TDR results. But now they can perhaps redo their analysis for the actual limits (PMSSM?)

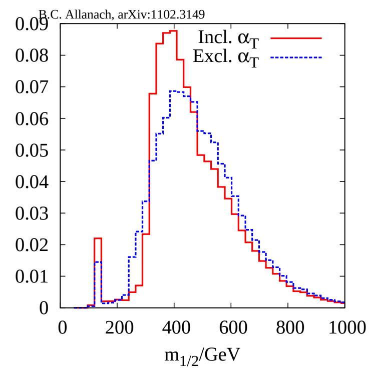
iii) See how much worse the fine tuning problem has become Strumia: 1101.2195v1

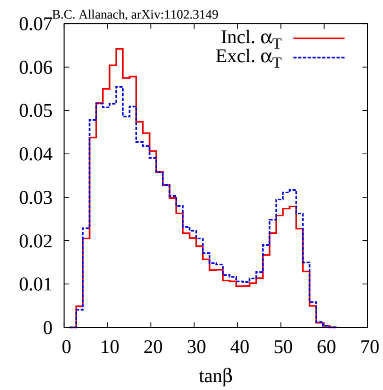




ATLAS CMS data interpreted in CMSSM





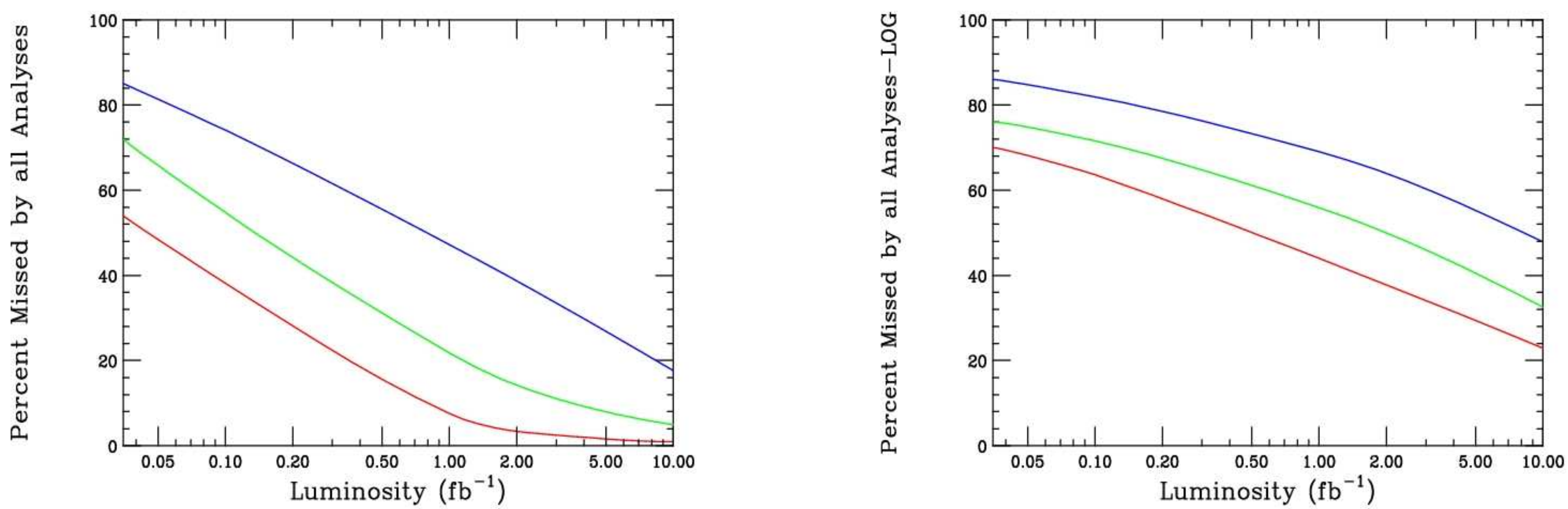


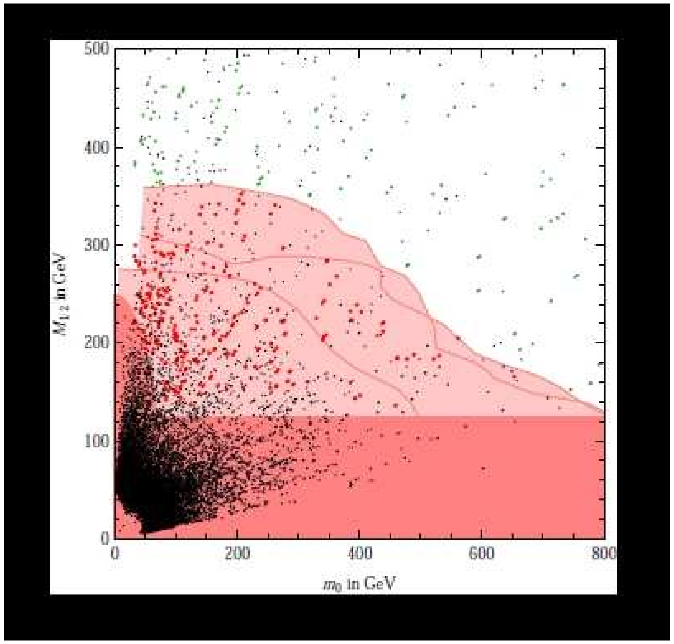
Red: Including new data, Blue: without the new data.

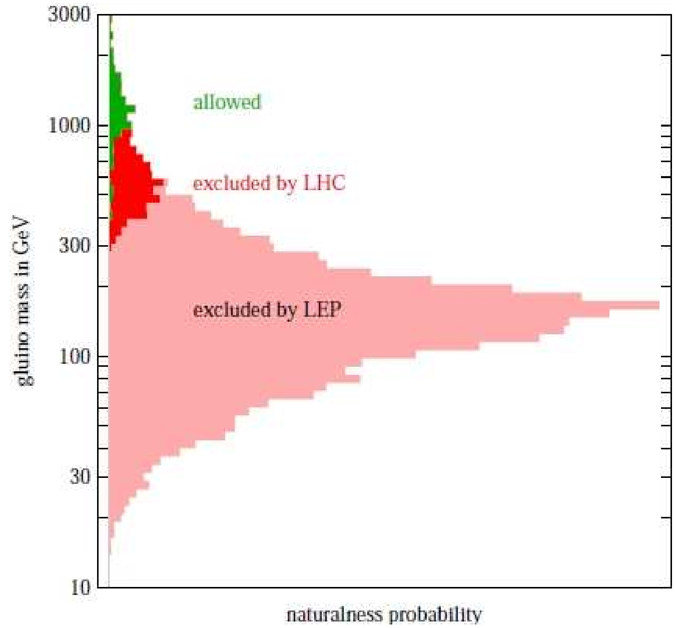
The changes also come from the SUSY Higgs searches which do not favour the large $\tan\beta$ values. This interplay indicates the correlation of new physics searches in different channels (Allanach: 1102.3149).

ONLY for the CMSSM.

Hewett et al: pMSSM, Phenomenological MSSM, reduce the 105 parameters to about 19 parameters. (CP conserving and RP conserving). Scan the parameter space and see how much will be covered by using results on ATLAS reach for mSUGRA(CMSSM). Red,green, blue: 100, 50, 20 percent background systematics.







In CMSSM:

$$M_Z^2 \simeq 0.2 m_0^2 + 0.7 M_3^2 - 2\mu^2$$

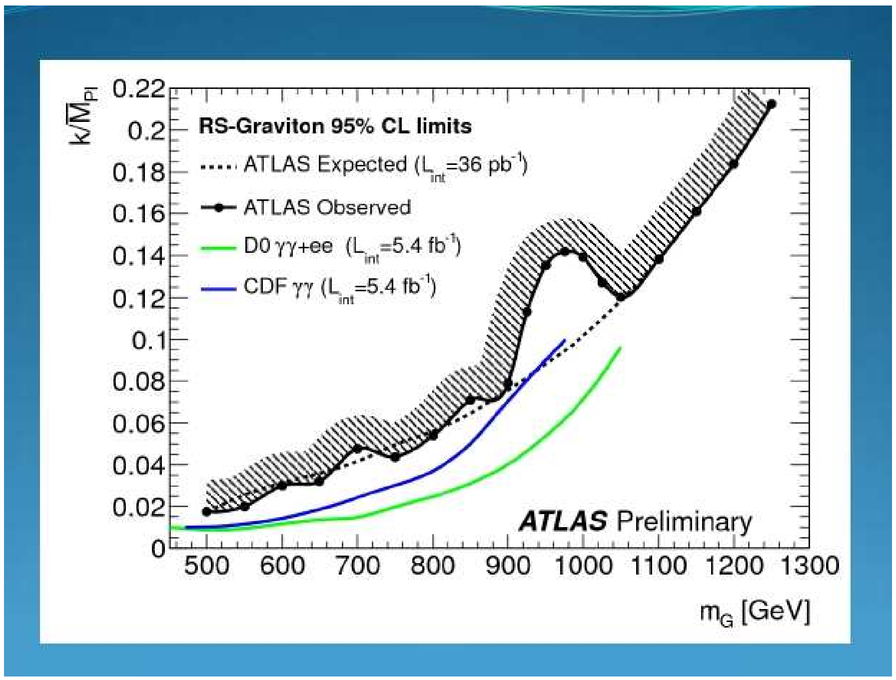
One can define fine tuning measures depending on the level of cancellation required to get the correct mass M_Z.

For CMSSM for $M_3 > 650$ GeV it is about 1 part in 35.

Green points correspond to allowed regions accroding to fine tuning criterion.

Plotted in the second graph is the naturalness probability. In the allowed regions fine tuning is about one part in 100.

In RS models one has resonances which would decay into $\gamma\gamma$ and/or $\mu^+\mu^-$. Already surpassing Tevatron constraints.



Implications for, for example, $t\bar{t}$ physics.

Here one has a effective low energy theory and one can make predictions using semiclasscial approximations.

These contribute to the two jet, dimuon and diphoton cross-sections due to tree level or loop graviton exchange and give rise to higher dimensional operators. Experimentalists prefer first to use dimuon and diphoton. jj final state would be the best channel from the point of view of rates.

There are two types of operators:

Dimension 8: $\mathcal{L}_{int} = c_{\mathcal{T}}\mathcal{T} = \frac{4}{M_T^4}\left(T_{\mu\nu}T^{\mu\nu} - \frac{T_\mu^\mu T_\nu^\nu}{\delta+2}\right)$

$T_{\mu\nu}$ is the SM energy momentum tensor.

Dimension 6: $\mathcal{L}_{int} = C_6 \Upsilon = C_6 \Sigma_f (\bar{f}\gamma_\mu\gamma_5 f)\Sigma_f(\bar{f}\gamma^\mu\gamma^5 f)$

C_6 depends on D-dimensional Planck mass M_D and cutoff parameter Λ in a nontrivial way.

The conversion of the limits on observed signals to parameter M_T which parameterises the large extra dimension really does depend on the ultraviolet completion. Dijets at large invariant mass and large rapidity separations are less suceptible to issues of ultraviolet completion.

Giudice et al do this in arXiv: 1101.4919

For dimension 8 operartor:

For one extra dimension: LHC bounds are comparable to the earlier bounds

For higher number of extra dimensions LHC due to larger energy is already probing new regions of the parameter space for these theories.

Caveats: jj data. Uncertainties in theoretical predictions and experimental analyses?

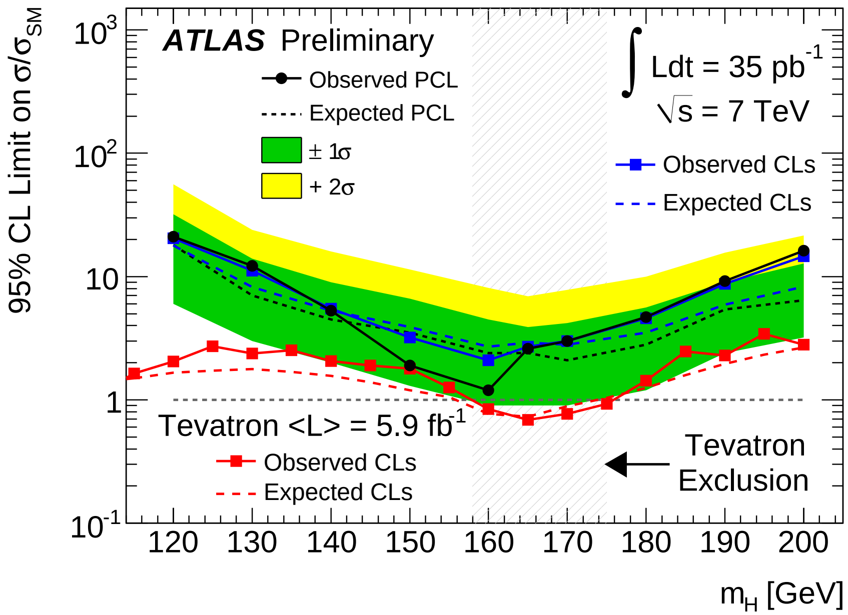
Again watch the space is the message.

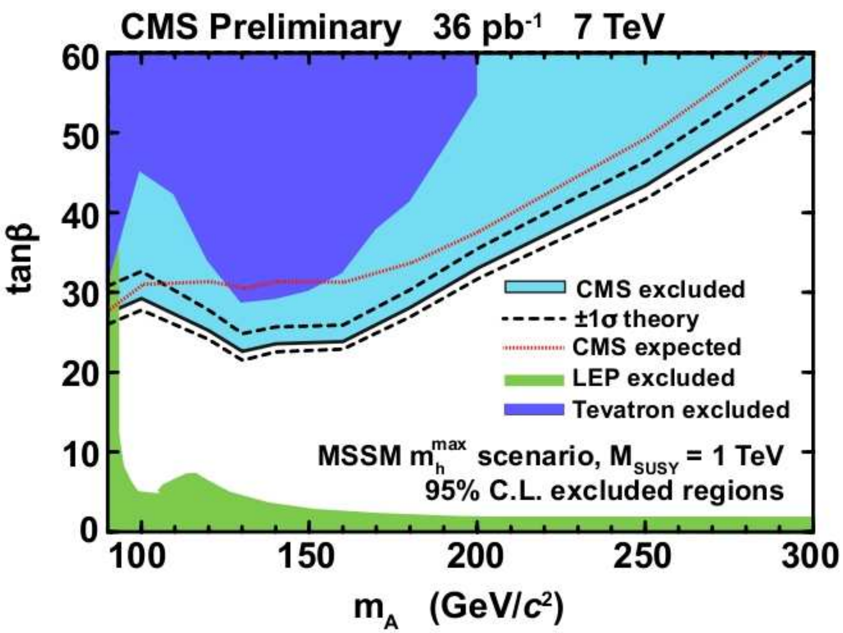
In spite of the small luminosity the LHC is already capable of making statements in new parameter space of BSM models.

For TeV scale Supersymmetry the year 2011 will be critical. The small hierarchy problem (that is a fine tuning to about a one part in 10-100 for the Higgs mass) might be getting accentuated.

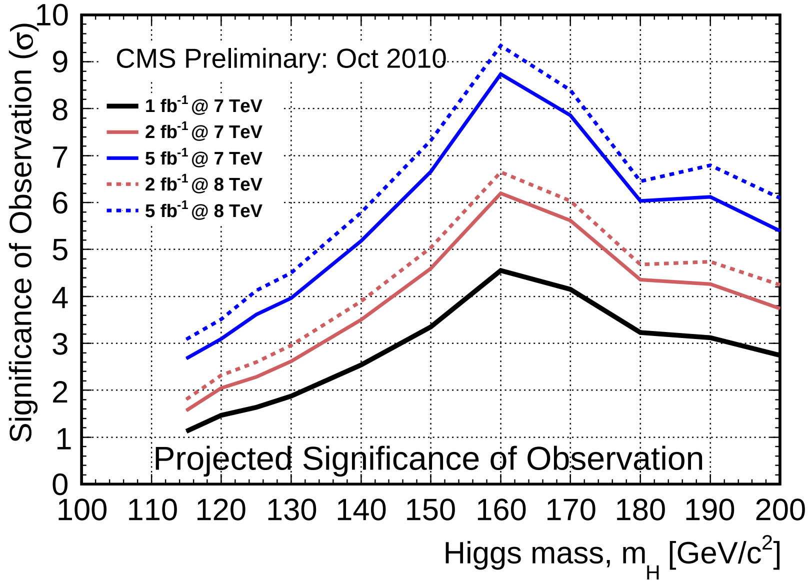
For theories with extra dimension new paramter regions begin to be explored.

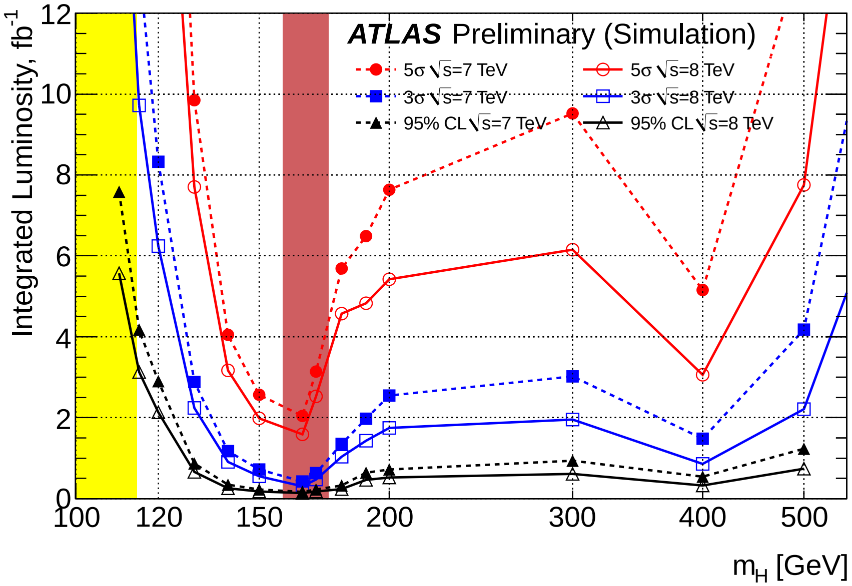
Is there BSM? LHC will tell.Not just from direct searches BUT also from Higgs sector!





LHC experiments will be competitive soon. Constraint on tan β–m_A from Higgs searches.

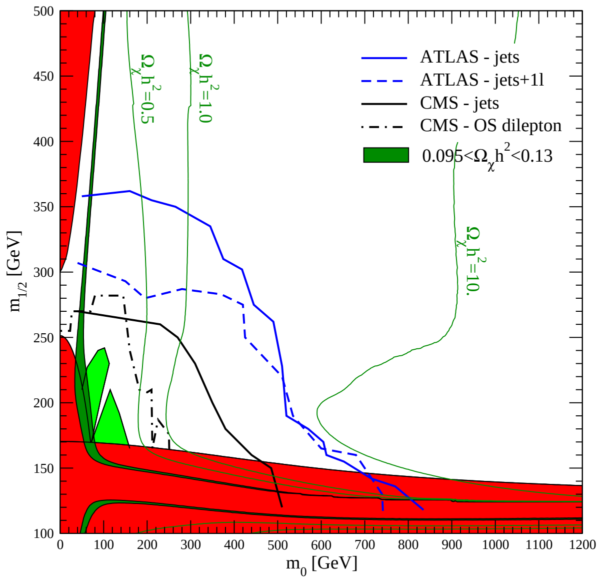


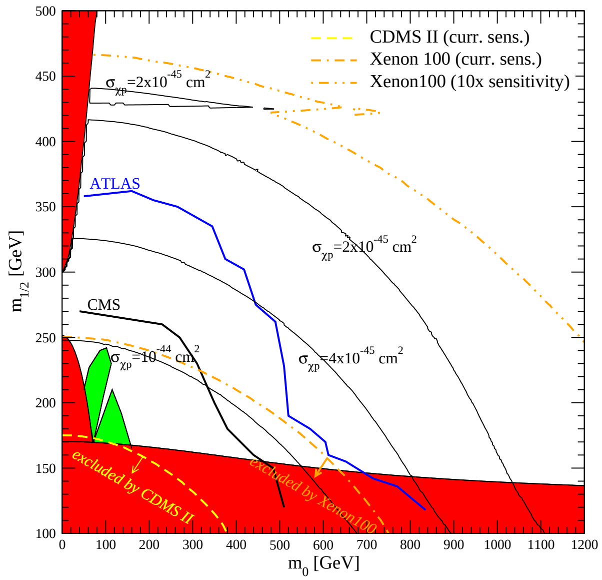


The mass of the Higgs when we see it should already help us a lot in guiding us, as much as the direct searches if not more!

Many extensions of the SM, SUSY for example, has a neutral, stable particle with all the properties needed for it to be an ideal candidate for the dark matter.

The suggested solutions to cosmological questions can be tested in HEP experiments and Physics Beyond the SM can be constrained by Cosmological connections.





Profumo: 1105.5162

1) 2011-2012 is the crucial year for SUSY. Not just direct searches but Higgs physics (just its mass), results from LHCB as well as direct/indirect DM detection from XENON, CoGent putting SUSY under a scanner.

2)Extra dimensions: ideas interesting..but not predicitve enough to be pushed to wall. In principle these ideas do not necessarily address the different observational facts which indicate BSM.

3]We should be infact not surprised if we are completely wrong and none of the ideas are right!