Supersymmetry at the LHC

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* ⋆ Weak scale SUSY solves the big hierarchy problem. Low scale physics does not have quadratic sensitivity to high scales if the low scale theory is embedded into a bigger framework with a high mass scale, Λ.

* ⋆ This was one of the reasons why many of us have hoped for a discovery of superpartners as experiments have explored higher and higher scales. DESY, TRISTAN, CERN S$p\bar{p}$S, LEP, Tevatron, LEP2, and now, the LHC.

* ⋆ The upper limit on the SUSY scale suggested by these arguments is soft (more about this later), and people once felt that the 40 TeV SSC was the right machine. We instead have LHC8, and will have LHC14 (or, perhaps, LHC1*, *=2 or 3) next year. The higher LHC luminosity will compensate somewhat for the lower energy.

* ⋆ LHC8, and the ATLAS and CMS experiments, have performed very well, as we all know!

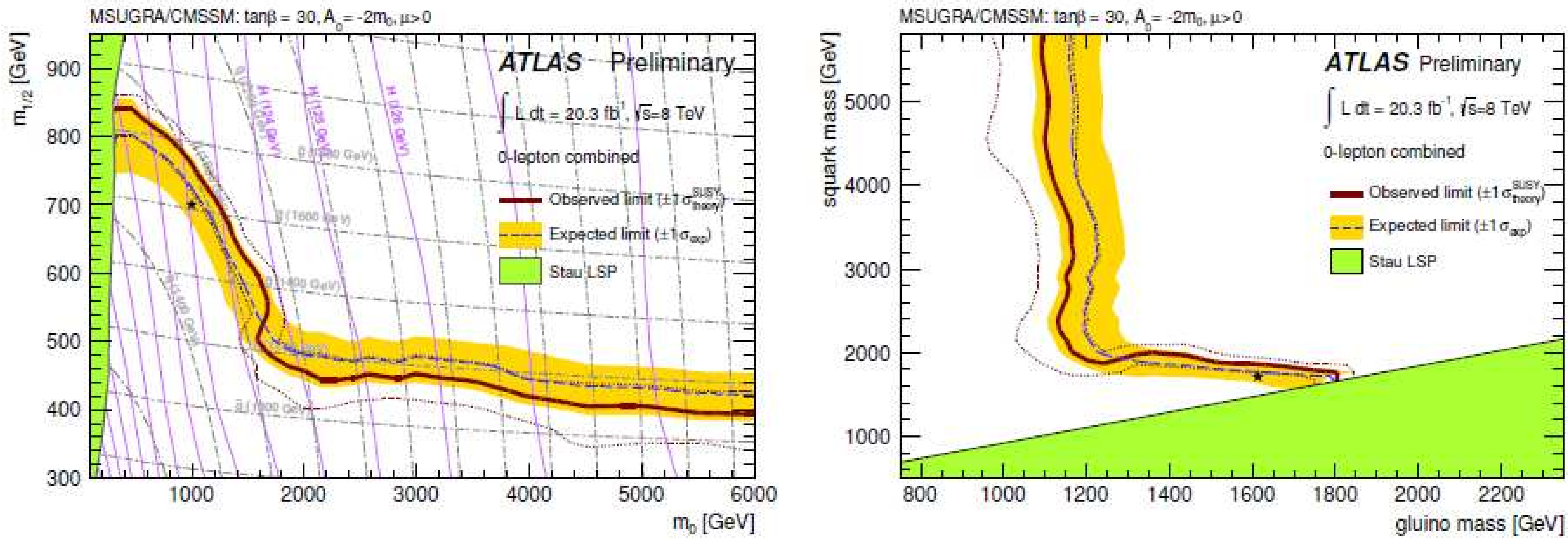
The discovery of a SM-like Higgs boson was a truly spectacular event. This boson is the relic of a novel mechanism suggested in 1964 by which gauge bosons could acquire masses in a gauge-invariant way.

- ⋆ Realization by Peter Higgs that there would be a new, massive spin zero particle that also couples to other particles.
- ⋆ Development of many realistic strategies (by an entire community of theorists) that could reveal the Higgs boson signal over SM backgrounds.
- ⋆ Development of clever and sophisticated techniques by a community of experimentalists to implement and improve on these suggestions. Indeed, experimentalists and theorists worked together on this.
- ⋆ Culmination in the discovery announced in Summer 2012. The process took 48 years!

Our accelerator experiments have become large and sophisticated, and it is very likely that important future discoveries will be the result of a similar process.

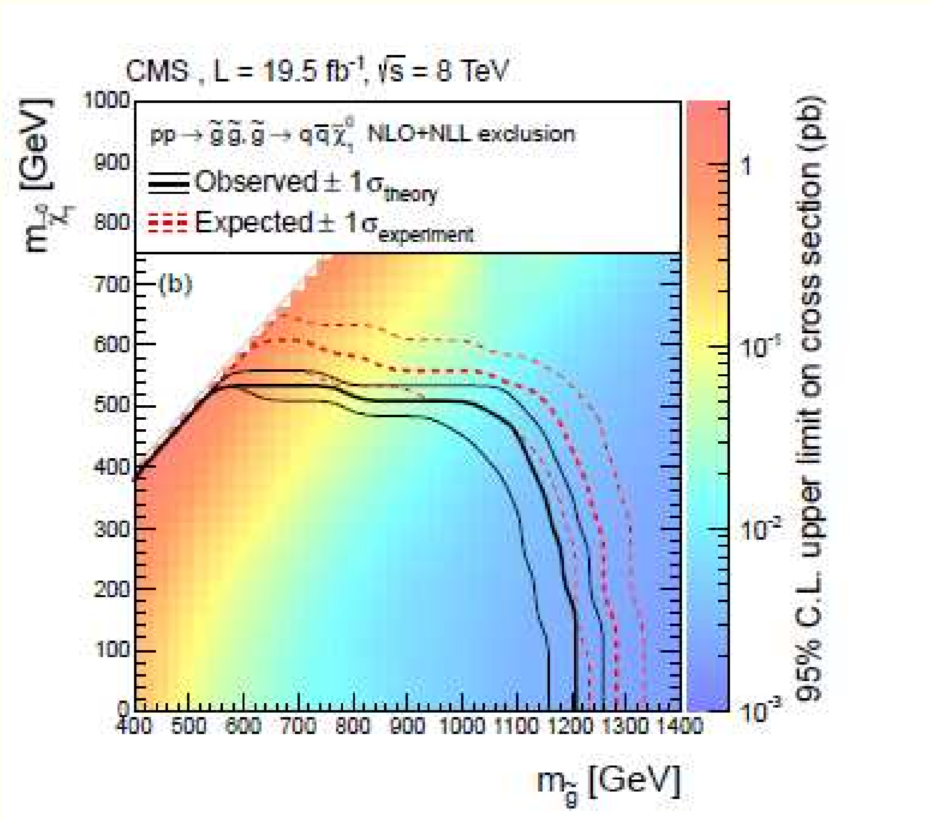
- ⋆ Where we are today
- ⋆ Simplified model analyses
- ⋆ Comments on operator analyses
- ⋆ Remarks on naturalness
- ⋆ High luminosity LHC
- ⋆ The End

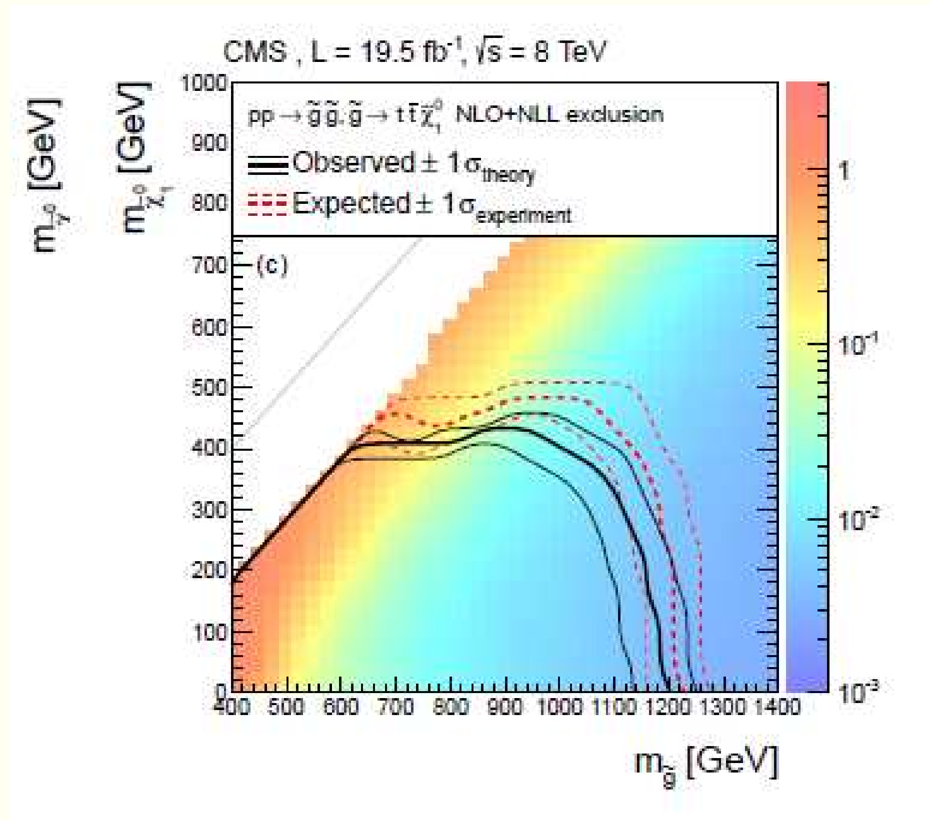
The ATLAS and CMS experiments have made many searches for SUSY.



Limit of 1200 GeV on gluino mass, independent of $m_{\tilde{q}}$, 1800 GeV, if $m_{\tilde{q}} = m_{\tilde{g}}$ within mSUGRA.

Similar gluino limits from CMS with very different assumptions. Reasonable as we'd expect the answer to mostly depend on the gluino cross section, an not so much on decay patterns.





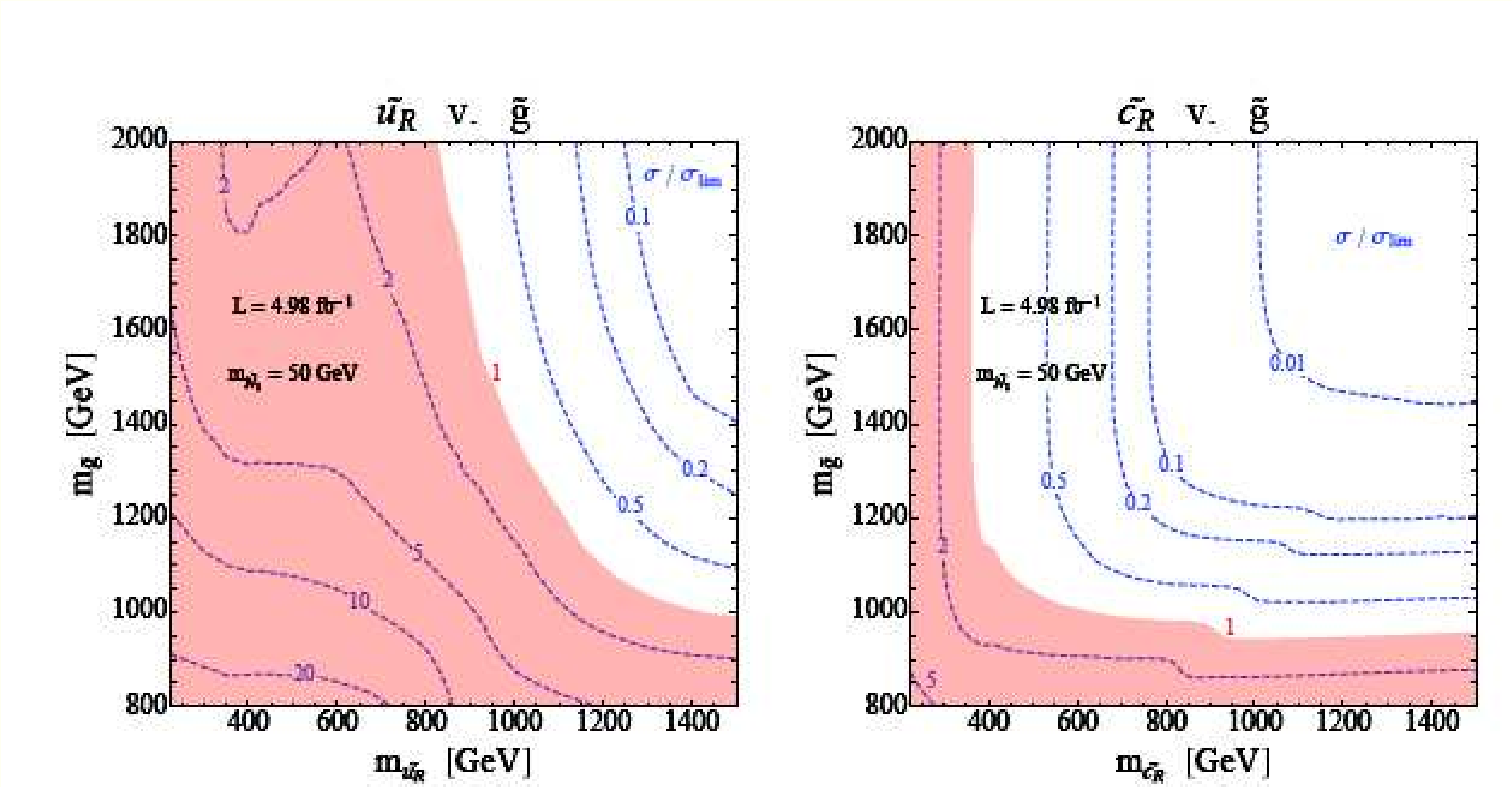
The mSUGRA squark limit for $m_{\tilde{q}} = m_{\tilde{g}}$ is really a limit on first generation squarks, as these are the guys that can be produced by "valence quark" collisions.

Stated differently,

$$\sigma(uu \to \tilde{u}\tilde{u}) \gg \sigma(gg \to \tilde{c}\bar{\tilde{c}}) \;\; \text{or} \;\; \sigma(u\bar{u}/d\bar{d} \to \tilde{c}\bar{\tilde{c}}).$$

This is an effect of the parton distribution functions.

Of course, something has to fix FCNCs if there are big intergeneration mass splittings for squarks with the same quantum numbers.

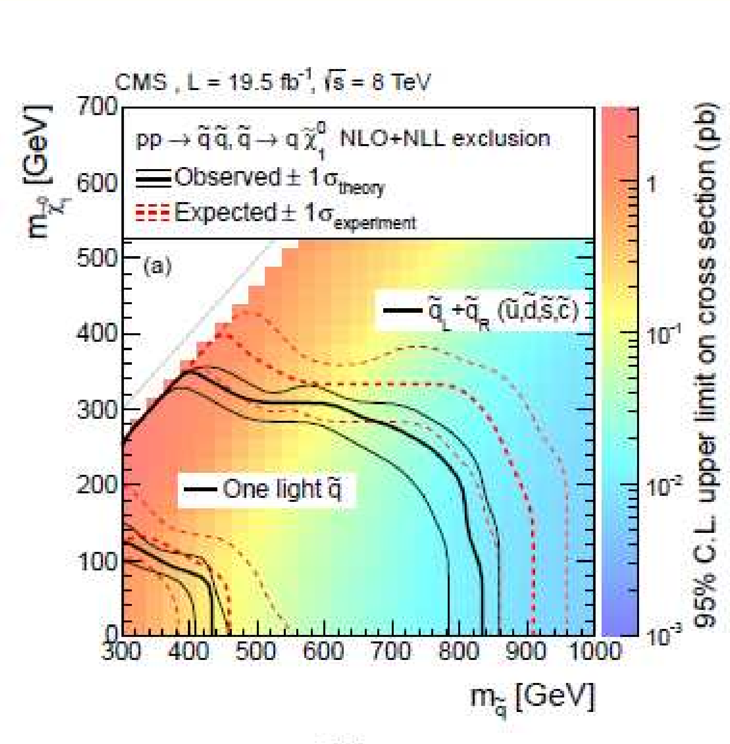


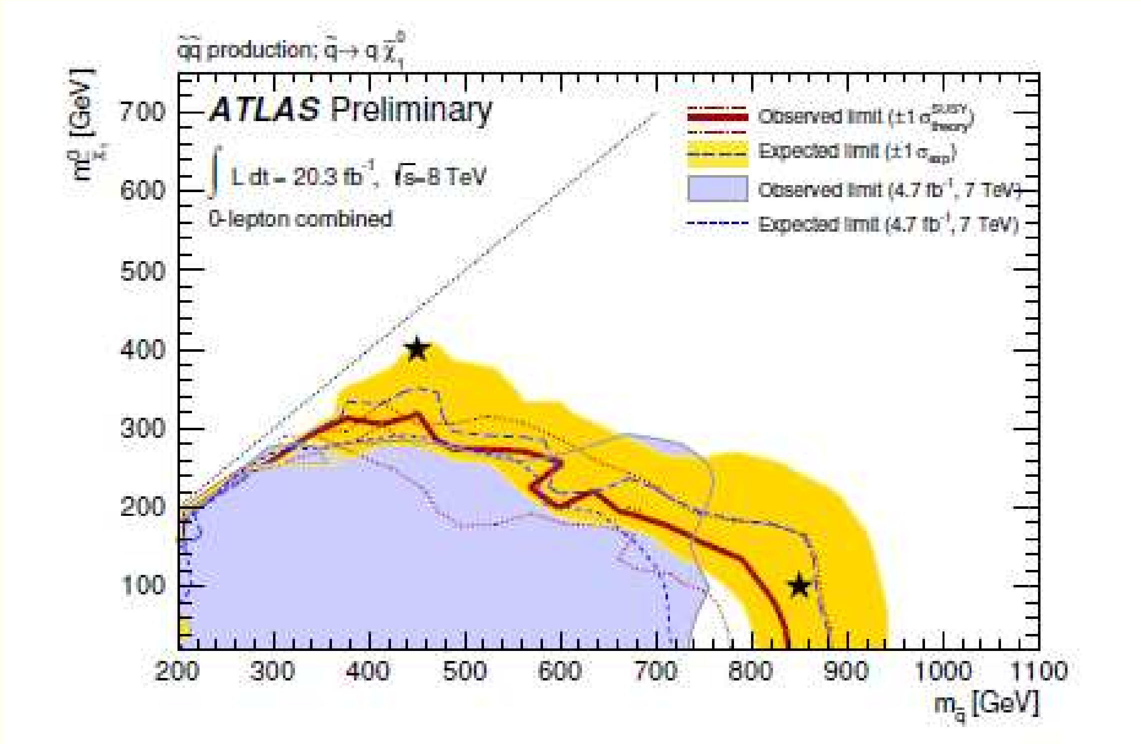
R. Mahlbubani *et al.* PRL (2013) 151804.

We see a significantly lower limit on charm squarks vis-a-vis up squarks.

Be careful about interpreting the meaning of various bounds.

LHC experiments have also analysed their data under the assumption that gluinos are very heavy. (This situation does not arise in high scale models because renormalization effects from gluino loops increase the squark mass.)





CMS ATLAS

Collider data do not say squarks are as heavy as we might naively think. (As $m_{\tilde{g}} \to \infty$, the valence quark effect that we mentioned above disappears.)

Many experimental analyses done in "simplified models"

Often touted as model-independent analyses. Because of the underlying assumptions, these analyses make it simple to present results as nice plots, but I think many complications remain hidden.

- ⋆ Focus is on one process and decay chain that gives a particular final state. Often many processes contribute to the same final state. Proponents say, the bounds abstracted are conservative. May be true in the absence of a signal, but in the more interesting case where there is a signal, SMA may be misleading.

- ⋆ Proponents say by combining SMA from different production mechanisms in a weighted manner, more complicated cases can be studied. True, but possibilities may proliferate fast. Moroever, in real situations, signals from, say, leptonic decays of squarks could migrate to the non-leptonic channel. These would be missed if only one branch included.

- ⋆ I think SMAs often use a constant matrix element for 3-body decays. This can be dangerous *e.g.* for $\widetilde{Z}_2 \to \widetilde{Z}_1 \ell\bar{\ell}$ decays when there are cuts on the lepton p_Ts.

- ⋆ If there is a signal for a process where there is significant contamination from another SUSY process (*e.g.* gluino contamination to the stop signal), interpreting the results with SMA could completely mislead. Model analyses would necessarily lead to simultaneous signals in many channels.
- ⋆ For heavy sparticle decays, we know from the $SU(3) \times SU(2) \times U(1)$ symmetry, that cascade decays are a rule rather than an exception. Hard to incorporate in SMA, as the number of chains is very large.

Perhaps, I am being unfair here, but in my view SMAs are of limited value.

In my opinion, a more useful presentation of data would be cross sections for particular event topologies for many selected cuts, together with corresponding backgrounds from SM processes. (In fairness the many tutti-frutti plots in SMA papers do include some of this information.)

I admit that making such cross section plots is not as glamorous as excluding a gluino below 1.2 TeV or an extra-dimension larger than XX cm, but it would allow everyone to cleanly test their own pet model(s).

Effective Operator Analyses: A Caution

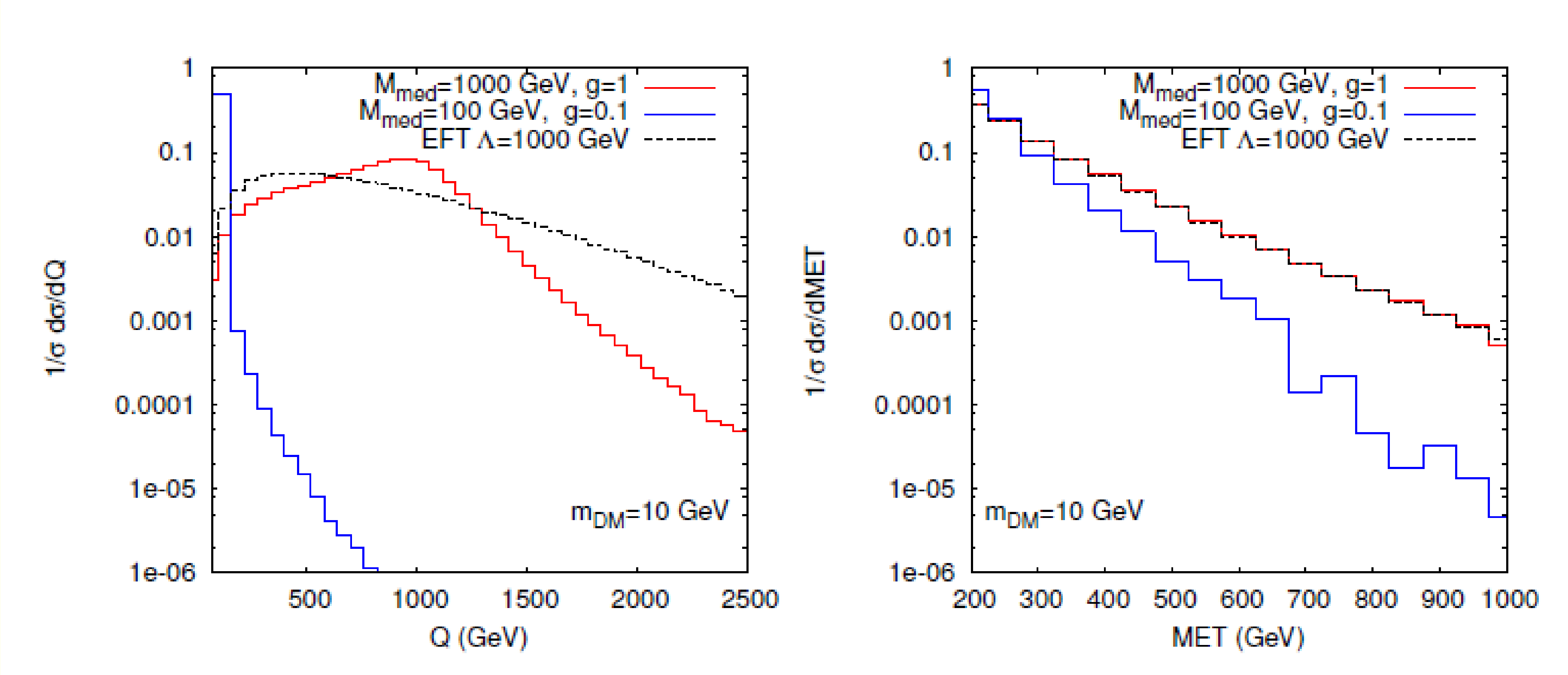
Effective Lagrangians have provided a powerful tool for analyses of processes where the UV physics is not completely known.

This tool has been used, but also abused, in many DM analyses.

The idea is that if, in any amplitude, the propagator mass is large compared to the momentum scale, the propagator becomes independent of kinematics of the reaction, and the process can be envisioned as arising from a contact interaction.

But this approximation breaks down very badly if the s or t or u, whichever is appropriate, becomes comparable to or exceeds the squared mass in the propagator. Obvious remark, but.....

The scale of s, t and u is set by the selection cuts when DM mass squared is small compared to these.



Buchmueller, Dolan, McCabe, arXiv:1308.6799

The right frame shows the $\not{E}_T$ distribution for monojet events from DM pair production. For a hard $\not{E}_T$ cut needed to kill the background, the contact approximation grossly overestimates the signal even when the DM is very light.

Make sure effective operator analysis is applicable to a particular situation before using it.

SUSY AND NATURALNESS

Remember that naturalness of the Higgs boson was the important motivation for introducing weak scale SUSY

However, many authors have suggested that because we have not already discovered superpartners means SUSY is not fulfilling the promise to solve the fine-tuning problem.

★ REMINDER – SUSY solves the big hierarchy problem. Low scale physics does not have quadratic sensitivity to high scales if the low scale theory is embedded into a bigger framework with a high mass scale, Λ.

★ All talk about naturalness of weak scale SUSY models and associated fine-tuning has, at most, to do with logarithmic sensitivity to Λ.

Much discussion of fine-tuning has revolved around the well-known (loop-corrected) minimization condition (written in terms of the parameters of the weak-scale theory),

$$\frac{M_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2,$$

and requiring that there are no large cancellations on the RHS.[a]

$$\Delta_{\rm EW} = max\left(\frac{m_{H_u}^2}{\frac{1}{2}M_Z^2}\frac{\tan^2\beta}{\tan^2\beta-1}, \frac{\Sigma_u^u}{\frac{1}{2}M_Z^2}\frac{tan^2\beta}{\tan^2\beta-1}, \cdots\right)$$

.

[a] Realizable in NUHM2, where the choice of A_0 that makes Σ_u^u small, simultaneously raises the Higgs boson mass.

Δ_{EW} knows nothing about the high scale physics, or the logs that we mentioned above. To see these, write

$m^2_{H_u,H_d} = m^2_{H_u,H_d}(\Lambda) + \delta m^2_{H_u,H_d}$, etc.

The logs are sitting in the $\delta m^2_\bullet$ terms.

Define Δ_{HS} analogously to Δ_{EW}.

Δ_{HS} is a sensible measure of fine-tuning in that it knows about the high scale origins via the logs. If there are large cancellations between $m^2_\bullet(\Lambda)$ and $\delta m^2_\bullet(\Lambda)$, the theory is regarded as fine-tuned.

However, Δ_{HS} knows nothing about the correlations between various parameters that are present if the weak scale theory is derived from a high scale theory with fewer parameters.

Clearly, the inclusion of the correlations make an important difference as they allow some cancellations between $m^2_\bullet(\Lambda)$ and the $\delta m^2_\bullet$ without associated fine-tuning.

Correlations most easily incorporated in the traditional Barbieri-Guidice measure $\Delta_{\rm BG} \equiv \frac{\frac{dM_Z^2}{M_Z^2}}{\frac{da_i}{a_i}}$ (a_i are the independent parameters of the model), first introduced by EENZ.

$$\Delta_{\rm HS} > \Delta_{\rm BG} > \Delta_{\rm EW}.$$

Sufficient correlations among model parameters may lead to large cancellations, and concomitantly small values of $\Delta_{\rm BG}$.

$\Delta_{\rm HS}$ and $\Delta_{\rm BG}$ are strongly correlated except when effects of parameter correlations are important.

If $\Delta_{\rm BG}$ is the right measure because it knows about the large logs and about correlations amongst parameters, why should I care about $\Delta_{\rm EW}$?

The utility of $\Delta_{\rm EW}$

- ⋆ $\Delta_{\rm EW}$ is essentially determined by the SUSY spectrum.
- ⋆ If $\Delta_{\rm EW}$ is large, the underlying theory that leads to the spectrum will be fine-tuned. A small $\Delta_{\rm EW}$ does not imply the theory is not fine-tuned, but leaves open the possibility of finding a meta-theory theory with approriate correlations between parameters that is not fine-tuned.
- ⋆ $\Delta_{\rm EW}$ is, therefore, not a fine-tuning measure, but measures minimum fine-tuning needed for any given spectrum.
- ⋆ Low $\Delta_{\rm EW} \Longrightarrow$ low $|\mu|$, but squarks (including stops) may be much heavier.
- ⋆ Many aspects of the phenomenology depend just on the spectrum, so this can be investigated even without knowledge of the underlying high scale theory that leads to low fine-tuning.

We think low $|\mu|$ more basic to fine-tuning considerations than light stops. This feature is consistent with, but hidden, in many analyses of fine-tuning.

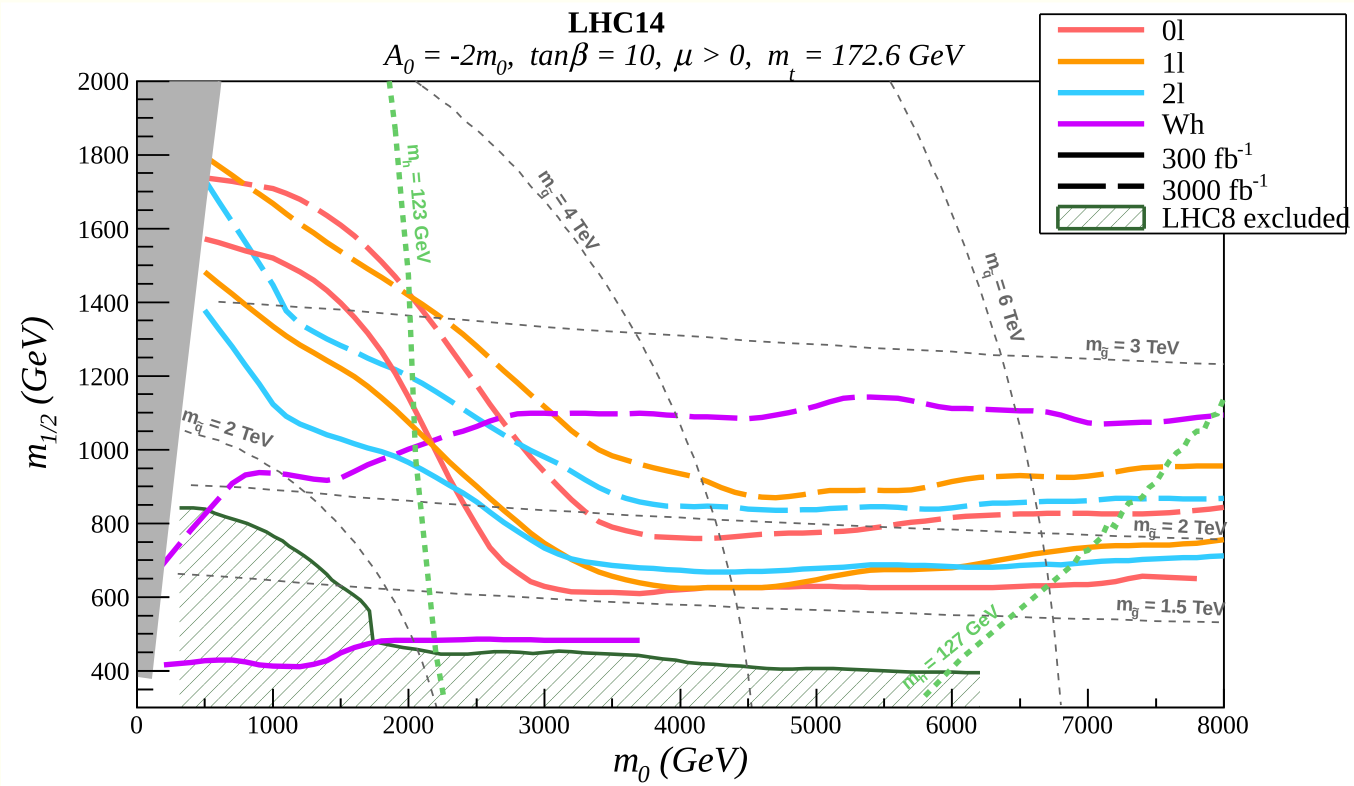
Very generally, if μ is the dominant contribution to the higgsino mass, light higgsinos are a necessary feature of models with low fine-tuning.

Interesting new phenomenology at LHC14, possibly including same sign dileptons from $W^{\pm}W^{\pm}+ \not{E}_T$ events without jets, and $4\ell+ \not{E}_T$ events. However, detection not guaranteed at LHC14, as other superpartners (including stops) may be beyond LHC14 reach.

Light higgsinos of natural SUSY can definitively be tested at ILC600.

See talk by A. Mustafayev in this session.

HIGH LUMINOSITY LHC



New purple channel $pp \to \widetilde{W}_1 \widetilde{Z}_2 X \to W(\to \ell\nu)\widetilde{Z}_1 h(\to b\bar{b})\widetilde{Z}_1 X$

Baer, Barger, Lessa, XT, arXiv:1306.5343

With a high integrated luminosity, novel signals from EW-ino production may beat the reach via strong gluino production even without enhanced leptonic decays.

Final remarks

- ⋆ Obituaries of SUSY are premature. LHC has run at just over half its design energy, and accumulated about 10% of expected integrated luminosity. Much remains to be explored.
- ⋆ SUSY resolves the big hierarchy problem, and there is still the potential for a model with no worse than few percent fine-tuning.
- ⋆ Small $|\mu|$ is a fundamental and necessary (but not sufficient) criterion for low fine-tuning. Associated light higgsinos with novel LHC14 signals, and definitive searches at ILC.
- ⋆ Light higgsino scenarios cannot saturate the total CDM; nonetheless there is enough higgsino DM fraction that will reveal itself in direct and indirect DM searches. Baer, Barger, Mickelson, PLB 726 (2013) 330; Mickelson talk
- ⋆ New strategies at high luminosity LHC.

Data-wise, this is a great time for the field. LHC, DM, and other "from the sky" facilities. Particle physics and cosmology united as never before.

Rather than the negative stuff we see in some blogs, we could argue that we are on track, even at the LHC!

Higgs proposal in 1964 $\longrightarrow$ Discovery in 2012

Space-time SUSY proposal in 1971-72 (Golfand-Likthtman; Volkov-Akulov) $\longrightarrow$ Projected discovery in 2019-20

EAGERLY AWAITING LHC14 DATA.