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# Run II prospects for SUSY/BSM

# The numbers

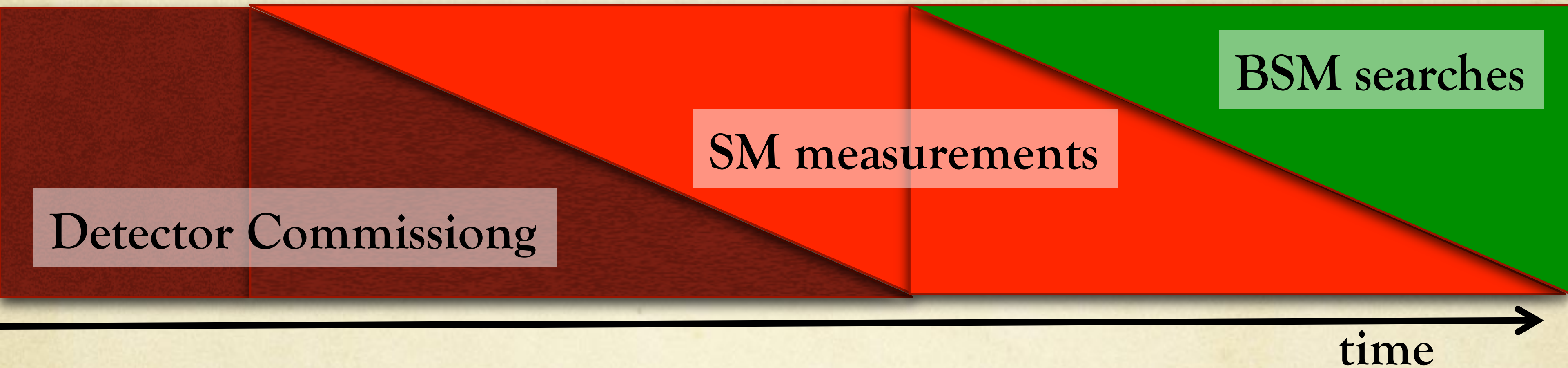
| | Tevatron run II | LHC run I | LHC run II |
|---|---|---|---|
| Collision energy | 1.96 TeV | 7-8 TeV | 13 TeV |
| Luminosity [$10^{32}$ $cm^{-2}$ $s^{-1}$] | 4 | 70 | 160 |
| Int. Lum. [$fb^{-1}$] | 10 | 25 | 120 |
| Collisions per BX | 8 | 21 | 45 |

- **Run II will give a quantum leap in luminosity and collision energy, like the LHC start-up in 2010**
  - The energy increase is smaller and luminosity increase larger
- **Of course we won't have the design luminosity from the first day**
  - The current schedule foresee 1-3 $fb^{-1}$ by early July (mix of 50 and 25 ns operation)

http://lhc-commissioning.web.cern.ch/lhc-commissioning/2015/2015-commissioning-outline.htm

  - Total integrated luminosity in 2015 might be similar to 2012

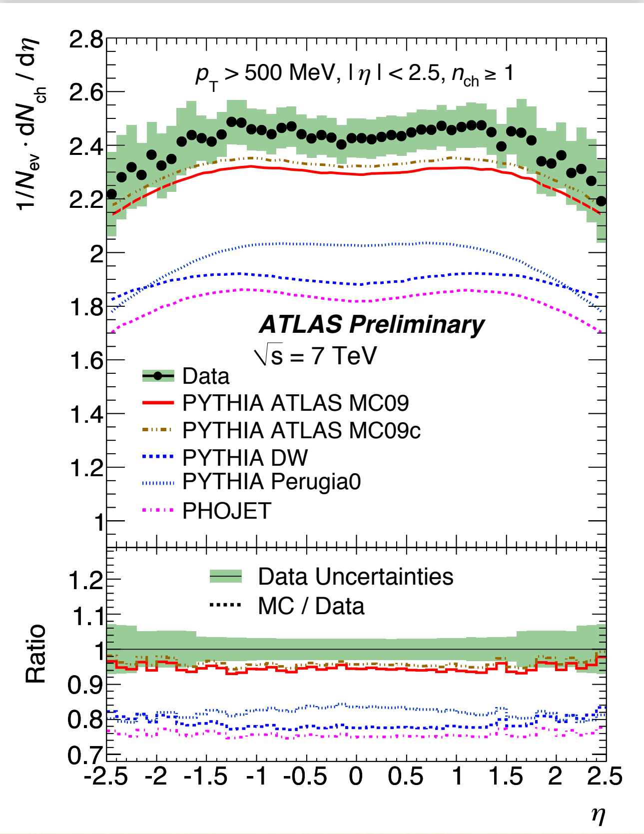
# From first collisions to searches




- Oversimplified diagram ! We will keep improving our detector understanding up to (or beyond) the end of the run for example
- The concept is that BSM searches make use of and rely on previous work on detector commissioning and SM physics measurement
  - Need to re-align tracking detectors, some pieces are new (innermost pixel layer), etc.
  - MC to data corrections for detector performance need to be derived again
  - MC might not describe 13 TeV collisions physics out of the box
- All of this is similar to 2010, though simpler (the detector is not totally new, the collision energy step is smaller, we benefit from the software developed in run I)

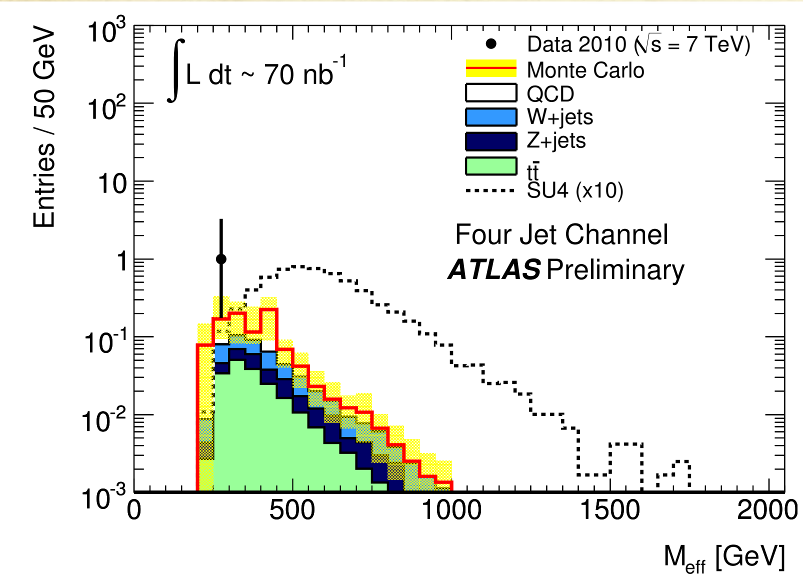
# Let's look back at 2010

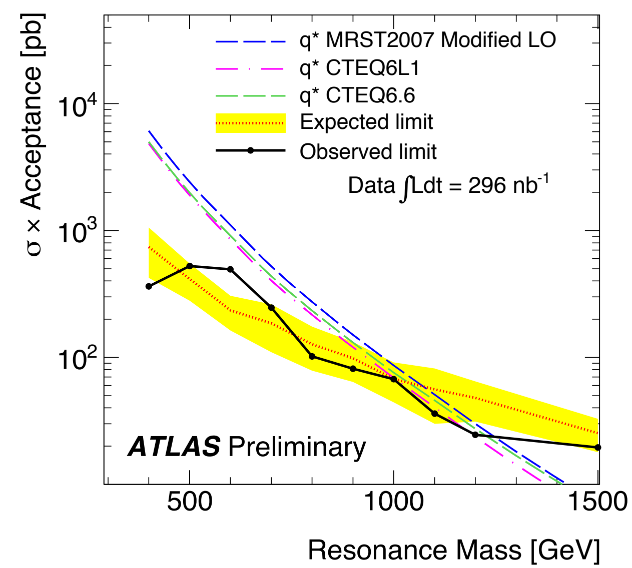
- First 7 TeV collisions were on March 30th
  - But we took advantage of lower energy collisions in 2009 and cosmics data, that was critical for the quick exploitation of high energy collisions which followed
- First preliminary results were:
  - Charge particle multeplicity with in April [6.8 μb-1] and improved Pythia tune by the end of May
  - Underlying event measurement in May [6.8 μb-1]
  - Jet observation in May
  - W, Z, J/ψ observation in June
  - W, Z, J/ψ cross section in July
- And a large number of preliminary results from trigger, luminosity, combined performance groups



# Summer 2010: First BSM searches !

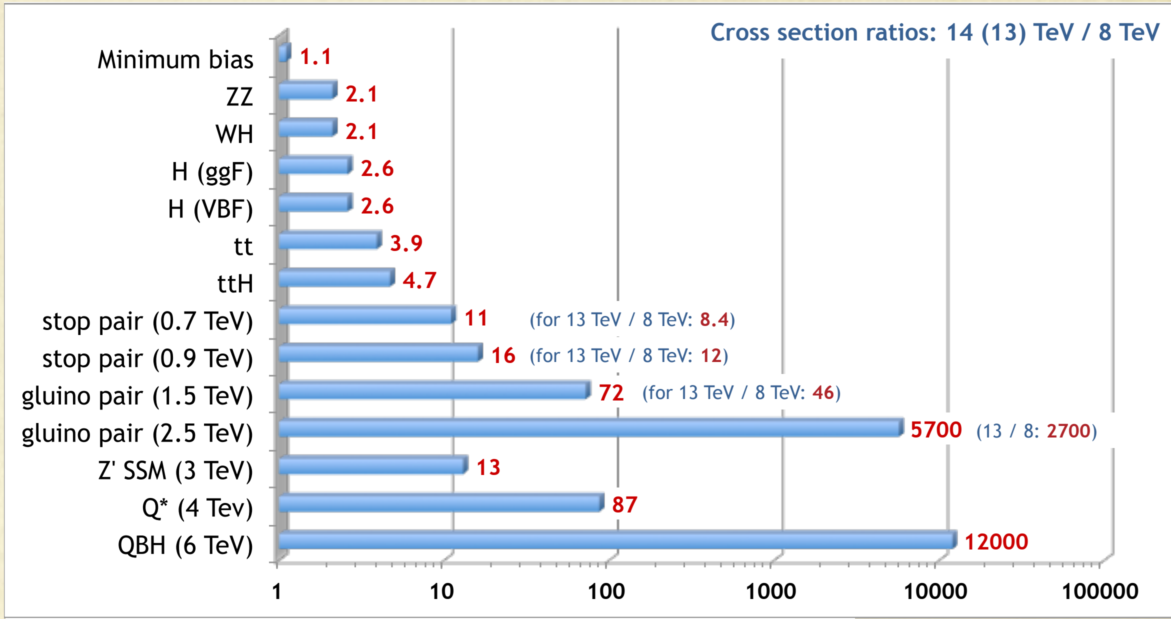
- SUSY 0, 1 lepton + MET + jets [0.07 $pb^{-1}$]
- Dijet resonance, multibody, and W' searches [0.3 $pb^{-1}$]
- The dijets were the first BSM paper submitted by ATLAS in August.
- ➢ For high mass objects we could challenge the Tevatron sensitivity because of the higher energy, despite very low luminosity.
- ➢ They will be the first things where we exceed run I sensitivity in 2015

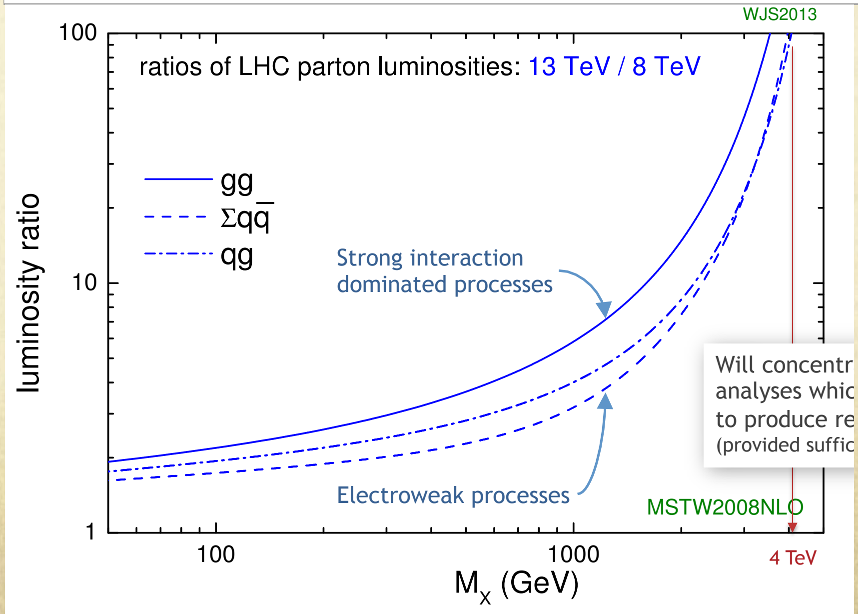


# Cross section ratios

- The gain from collision energy is the largest for heavy and gluon fusion produced objects.
- For each process one can compute the luminosity needed to produce as many signal events as in run I. Caveats:
  - Backgrounds increase too
  - PDF uncertainties get large at large $\sqrt{\hat{s}}$



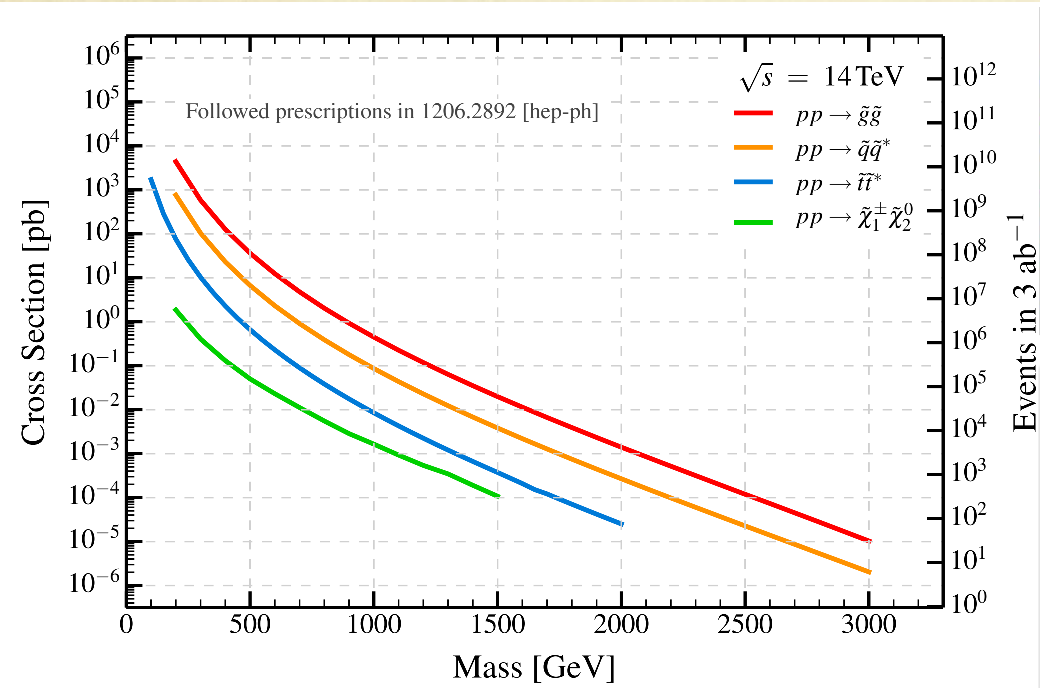



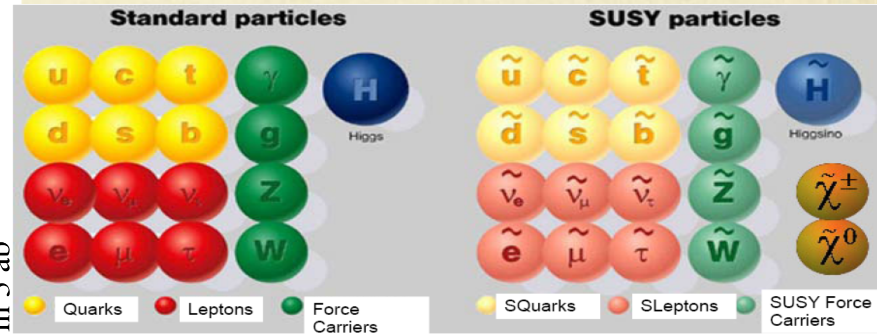
# SM measurements

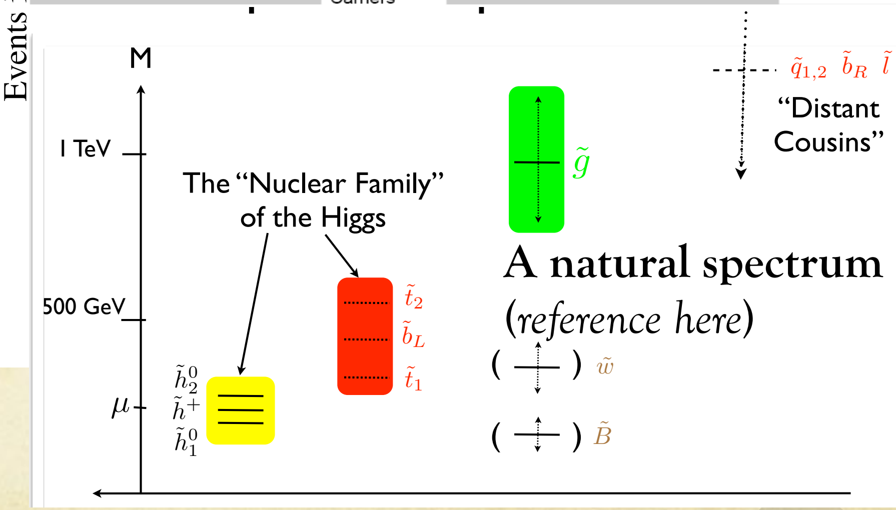
- These are critical for the understanding of backgrounds for searches
- But they are also a possible window on new physiscs of their own, expecially if the NP is not something we expect and have designed a dedicated search for
- Inclusive and differential cross sections, cross section ratios (13/8 TeV), rare/ forbidden decays, should all be pursued
- With higher energy and luminosity, new processes become accessible (ttZ, ttW, tttt, tri-bosons, ...)
- Higgs measurements are of course a window on New Physics
- Ignoring all that, I will move on searches for direct production of SUSY and exotic new states.

# Supersymmetry

- ➢ Lots of SUSY particles, each of them an opportunity for discovery.
- ➢ For simplicity/timing, focus here on the particles expected to be light if SUSY is to solve the hierarchy problem: neutralinos/charginos, stop, gluinos




1) Squark and gluino production searches
2) Third generation squark searches
3) Electroweak production
4) Long lived particle, RPV, etc.

# Gluino production

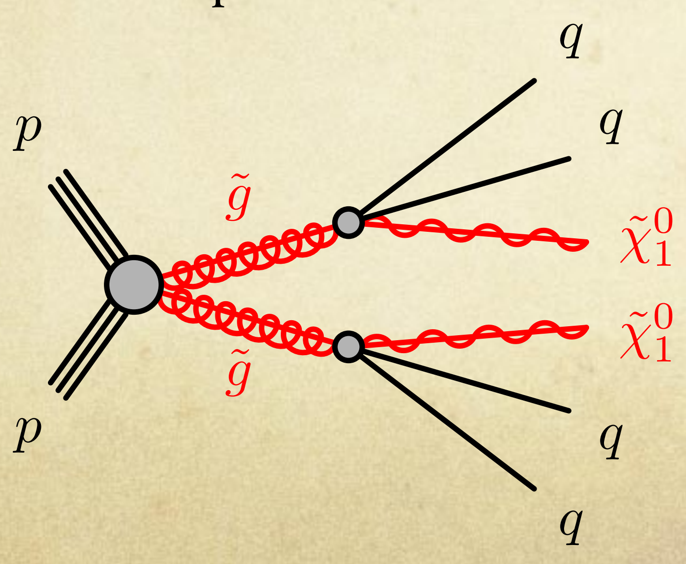
- Gluino contributes to the Higgs mass at 2-loop. Gluino mass $M_3$ as a function of fine-tuning $\Delta$ :

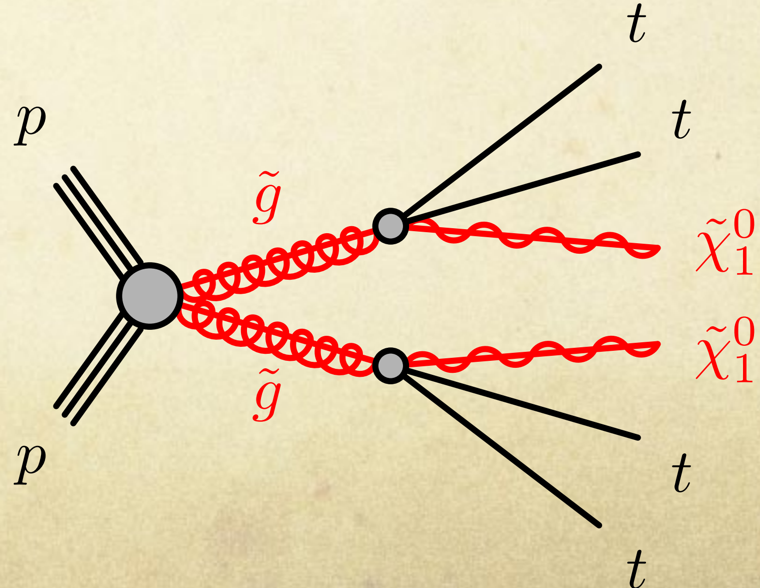
$$M_3 \lesssim 900 \text{ GeV} \sin\beta \; L_\Lambda^2 \left(\frac{m_h}{125 \text{ GeV}}\right) \sqrt{\frac{\Delta}{5}}$$

(Han et al., arXiv:1308.5307v1)

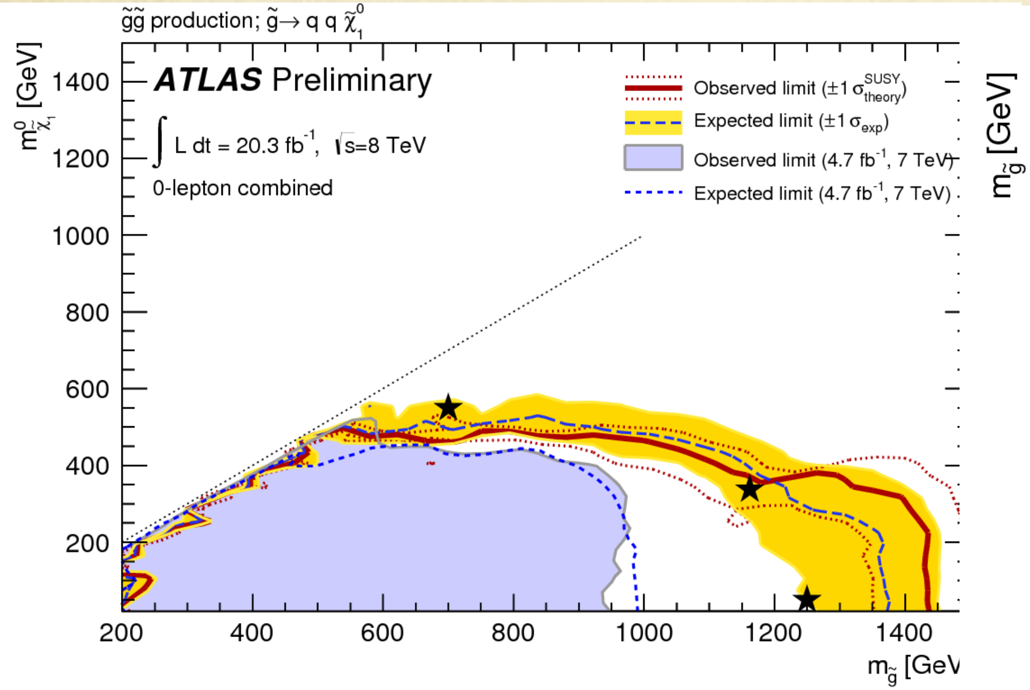
Gluino should be lighter than 900 (4000) GeV if one allows a fine tuning of 20% (1%)

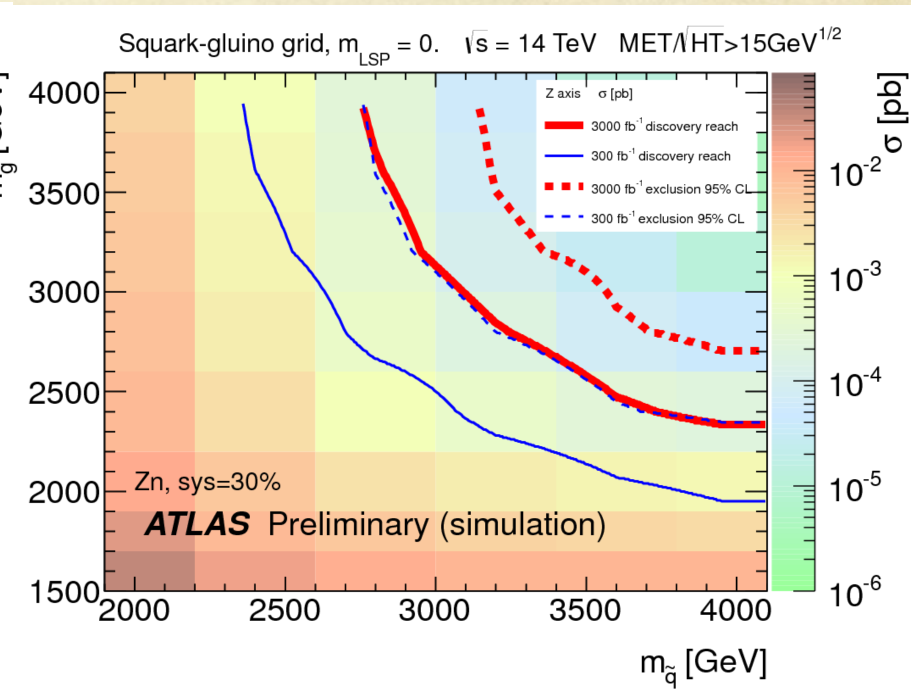
- Easiest case is a gluino decaying directly to a massless neutralino and two quarks



# Gluino sensitivity




- Left: current (preliminary) limits.
  1400 GeV limit in easiest case, degraded to 550 GeV if gluino and lightest neutralino close in mass
- Right: ultimate (LHC upgrade studies) sensitivity
  Discovery (exclusion) sensitivity with 300 $fb^{-1}$ up to 1950 (2350) GeV for easy case
- Early run II searches: a1400 GeV gluino gives 20 events in 20 fb-1 at 8 TeV or in **0.7 fb-1 at 13 TeV**

# Gluino questions

- For decays in b or top quarks: high pt b-tagging performance and boosted (W and top) reconstructions become more and more important as we push up in mass. Work needed there !
- Can we improve the compressed mass spectrum sensitivity ?
- Are we failing to see low mass colored particles, which we will never see because of trigger and because we focus our searches on high mass stuff only ?
  - For gluino it seems limits are robust (see also Evans et al., arXiv: 1310.5758) but a single squark state (whose cross section is 8 times smaller) might still be quite light.

Note these questions can apply to many other BSM candidates

# Scalar top searches

- The stop contributes to the Higgs mass at 1-loop. Average (of the two states) stop mass as a function of fine tuning is:

$$\sqrt{m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2 + A_t^2} \lesssim 600\ \text{GeV} \sin\beta\ L_\Lambda \left(\frac{m_h}{125\ \text{GeV}}\right)\sqrt{\frac{\Delta}{5}}$$

Lightest stop must be lighter than 600(2700) GeV if 20% (1%) fine tuning is allowed.

- Currently big activity on this from Italian institutes

- Several decay chains possible, might be several open decays in competition

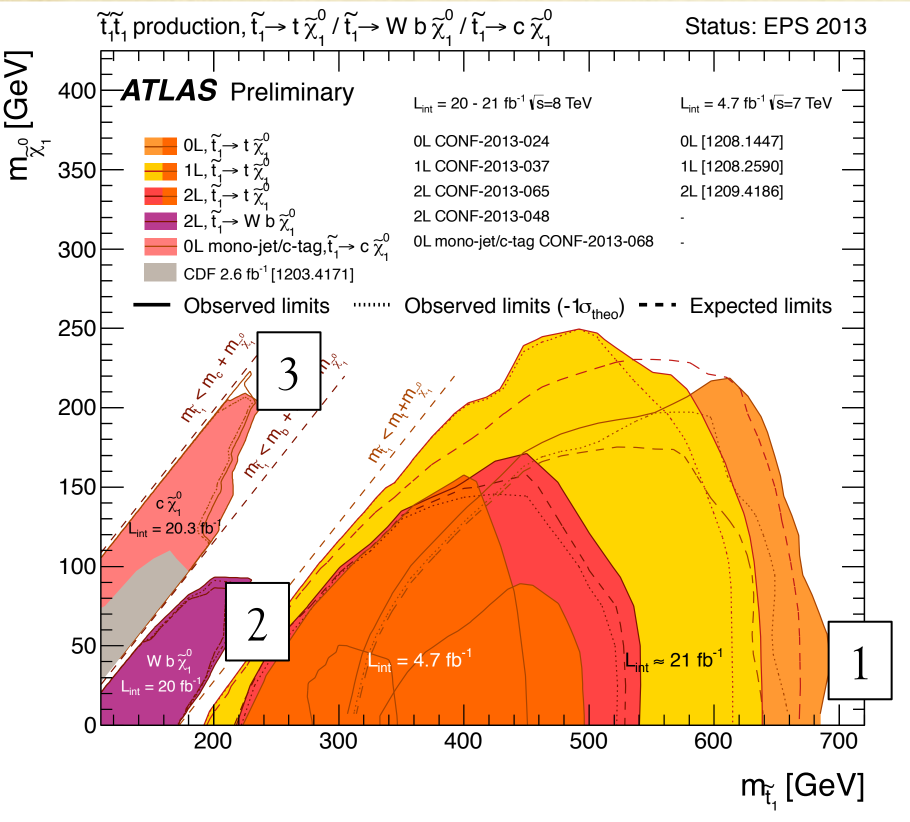
$\tilde{t} \rightarrow t\tilde{\chi}_1^0$ } Well studied

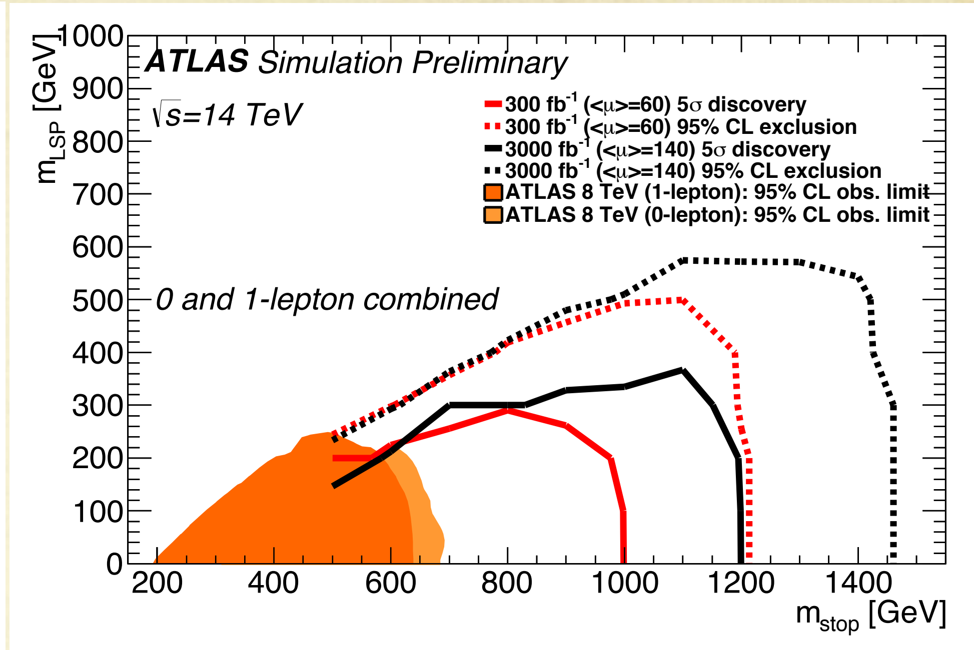
$\tilde{t} \rightarrow b\tilde{\chi}_1^+$ }

$\tilde{t} \rightarrow c\tilde{\chi}_1^0$ Loop decay (if others closed kinematically)

$\tilde{t} \rightarrow t\tilde{\chi}_4^0 \rightarrow tH\tilde{\chi}_2^0 \rightarrow tHff'\tilde{\chi}_1^0$

# Stop sensitivity




**Here the case in which the $\chi^0_1$ is the only SUSY particle in which the stop can decay is shown.**

1) **Heavy stop, lightest neutralino.**

Current limit 680 GeV. For this value, Run II will produce more stops than run I after 3 fb$^{-1}$.

Discovery (exclusion) sensitivity with 300 fb$^{-1}$ up to 1000(1200) GeV.

2) **Stealth stop (mstop-m$\chi^0_1$ ≈ mtop)**

Signal is top-like. Not tackled yet (but a number of ideas exist in the literature)

3) **Compressed mass spectrum (mstop-m$\chi^0_1$ small)**

Current exclusion 200 GeV, and working in progress to improve it

# Ideas/things to study

- **High stop/sbottom mass:** boosted top reconstruction, high pt b tagging should become critical (first work being done on run I data already)
- **Stealth stop** with light $\chi^0_1$: use precision measurement of cross section, spin effects (in production and decay) and top polarization to disentangle from top ? Heavier $\chi^0_1$: use boosted/VBF production (boost is transferred to $\chi^0_1$) to disentangle from top ?
- **Complex decays:** how can we improve the analysis strategies (largely developed for simplified decay modes) for a mixture of several long decay chains ?
- **Ideas from CMS**: their run I analysis strategies very different from ours, can we learn something from those ?
- **New signatures and MSSM coverage** : any decay modes not considered so far ? how to evaluate coverage in theory space ?
- **New analysis strategies:** (mostly suggestions from theory papers)
- **Background rejection/estimates:** ttZ from tt$\gamma$, isolated track/tau vetos, ...
- **Run II conditions:** pileup effects, JVF/lepton iso cuts, etmiss definition, trigger to use, ...
- **Interpretations:** which signal grids to generate ?
- **Low mass holes:** Which areas below 500 GeV are still unexcluded ? How we cover those ?

# Gaugino direct production

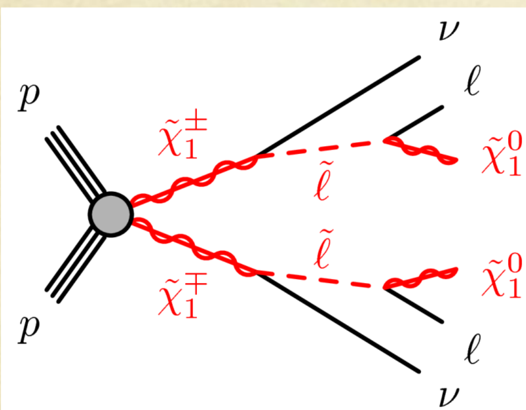
- The lightest neutralino is likely the lightest supersymmetric particles and the Dark Matter candidate – light gauginos are well motivated

- The Higgsino mass parameter is also the Higgs mass parameter, should be small:

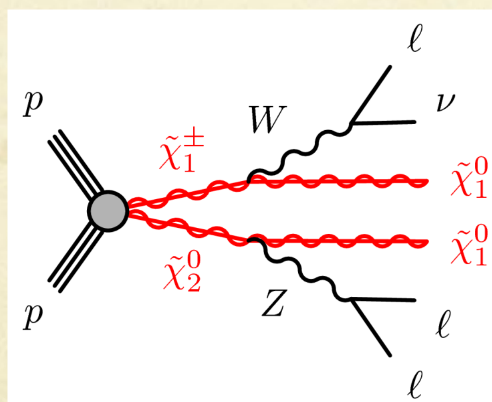
$$\mu \lesssim 200 \text{ GeV} \left(\frac{m_h}{125 \text{ GeV}}\right) \sqrt{\frac{\Delta}{5}}$$

Lightest neutralino must be lighter than 200(900) GeV if 20% (1%) fine tuning is allowed.

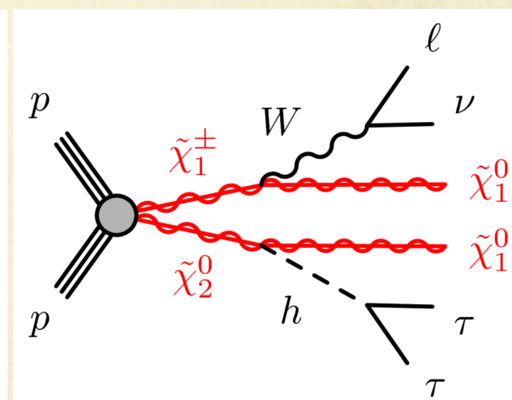
- Run I searches have focused on $\chi^{\pm}_1 \chi^0_2$ and $\chi^{\pm}_1\chi^{\pm}_1$ production with the




Intermediate mass sleptons
Leptonic BR 100%, easy !



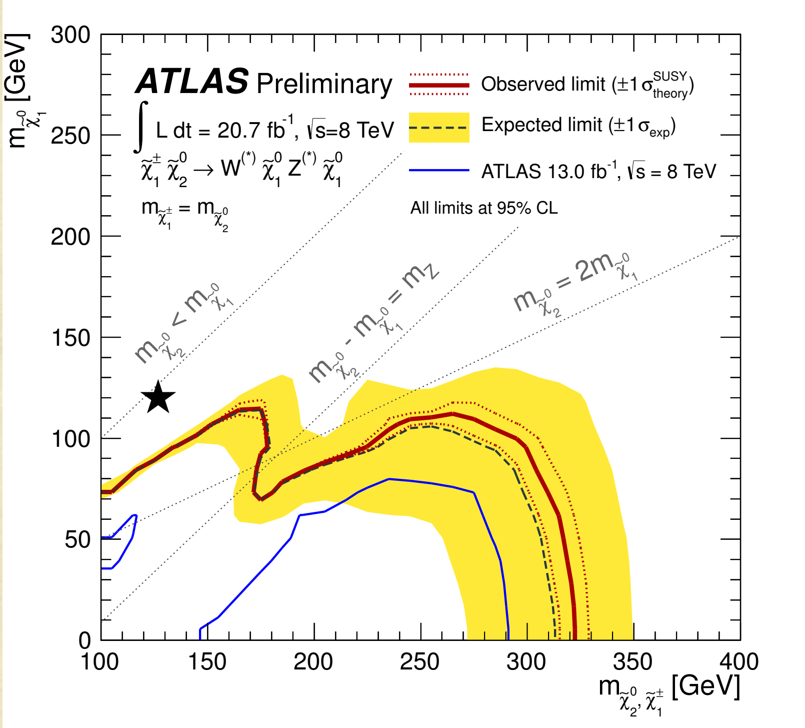

$\tilde{\chi}_2^0\tilde{\chi}_1^{\pm} \rightarrow \tilde{\chi}_1^0 Z \tilde{\chi}_1^0 W$

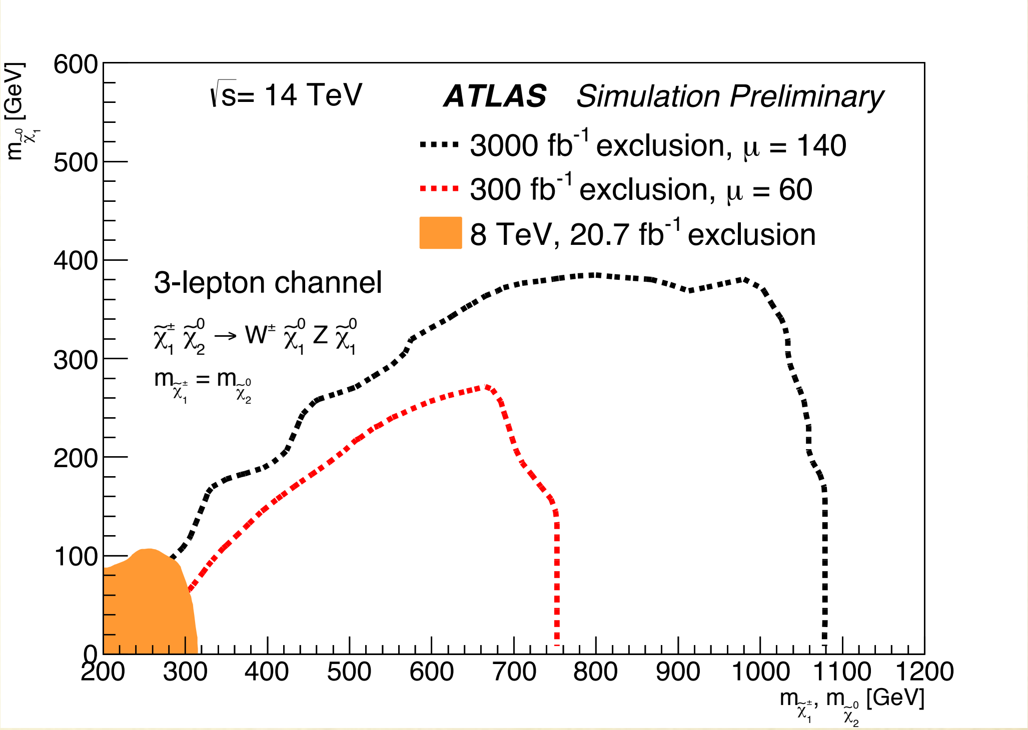



$\tilde{\chi}_2^0\tilde{\chi}_1^{\pm} \rightarrow \tilde{\chi}_1^0 h \tilde{\chi}_1^0 W$

Hardest, several channels depending on Higgs decay, like WH production but with extra MET

# Gaugino sensitivity



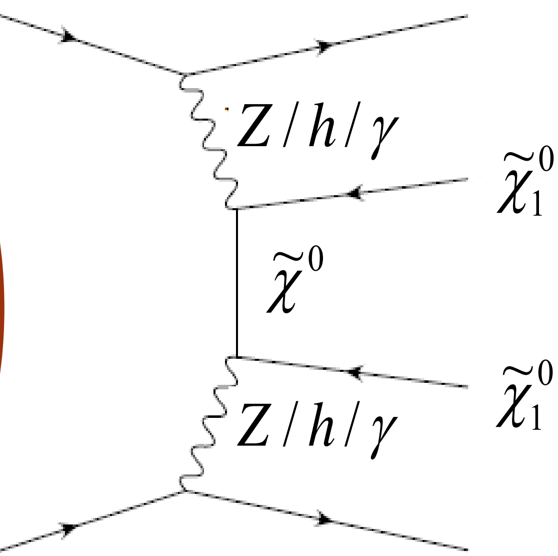

- Current limit is 320 GeV for the decay trough W and Z.

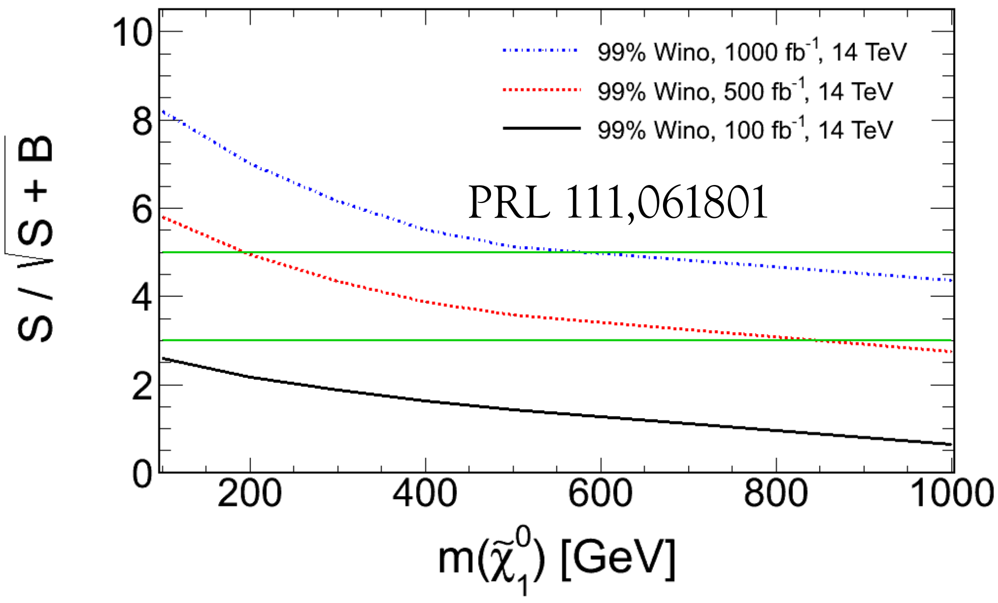
For this mass cross section increases by only a factor of 4 with from run I to run II.

- Need luminosity, but with 300 $fb^{-1}$ can hope for sensitivity up to 700 GeV
- Run I sensitivity to Higgs decay currently marginal (but some channels, and channel combination, not done yet), run II sensitivity will be much better.
- If higgsino are much lighter than Wino and Zino, we have only a triplet of mass degenerate states ($\chi^0_1$, $\chi^0_2$, $\chi^{\pm}_1$) and no sensitivity ★

# Gaugino items for discussion

- Searches here are still mostly 1-bin cut and count. What about a shape analysis to disentangle $\chi^+\chi^- \to W^+\chi^0 W^-\chi^0$ from SM WW ?
- Many of this searches have jet vetos, multiple isolated leptons, moderate missing energy. Pileup effects ?
- Theory papers suggest we can use VBF production to see $N^0_1$ with run II statistics (like for invisible Higgs). No ATLAS studies yet. **Urgent: study how to trigger these events !**



# Long lived particles

- Many models foresee long-lived particles from reduced couplings, decay via an heavy virtual mediator, or small mass differences.
  - Charged or strongly interacting "stable" particles : can use time of flight and ionization. Energy increase will allow to probe ≈1.5 higher mass scales.
  - Charged particle decaying to invisible/soft products: disappearing ID track
  - Neutral particle decaying in the detector: dispaced vertices, trackless jets, …
    - Of special interest: H => XX => 4SM with neutral X
  - Boosted light particle decays: collimated "lepton jets" (LL or not)

ATLAS (and CMS) off to good start but lots, lots, lots left to do

- D-stable particle searches have pretty good coverage
- D-metastable particle searches have far to go
  - Many lifetimes (very long, short-to-medium)
  - Many final states (more to do with lepton pairs, tau pairs, jet pairs)
  - Many mass scales (get down to Higgs!)
- Need more systematic coverage of simple lepton jets
  - Prompt and displaced, ee and $\mu\mu$, in pairs and singly, large and small mass

From M. Strassler talk at LLP workshop

- These searches typically requires non-standard trigger and object reconstruction techniques and very good understanding of detector.



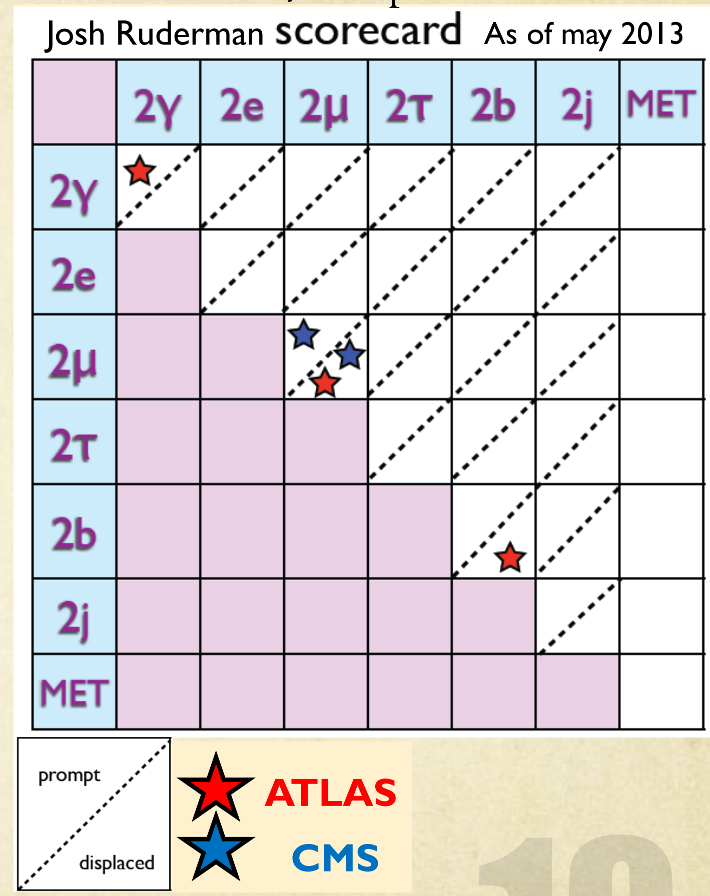
| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Long-lived particles | Direct $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ prod., long-lived $\tilde{\chi}_1^{\pm}$ | 0 | 1 jet | Yes | 4.7 | $\tilde{\chi}_1^{\pm}$ 220 GeV | $1 < \tau(\tilde{\chi}_1^{\pm}) < 10$ ns | 1210.2852 |
| | Stable $\tilde{g}$, R-hadrons | 0-2 e, $\mu$ | 0 | Yes | 4.7 | $\tilde{g}$ 985 GeV | | 1211.1597 |
| | GMSB, stable $\tilde{\tau}$, low $\beta$ | 2 e, $\mu$ | 0 | Yes | 4.7 | $\tilde{\tau}$ 300 GeV | $5 < \tan\beta < 20$ | 1211.1597 |
| | GMSB, $\tilde{\chi}_1^0 \to \gamma G$, long-lived $\tilde{\chi}_1^0$ | 2 $\gamma$ | 0 | Yes | 4.7 | $\tilde{\chi}_1^0$ 230 GeV | $0.4 < \tau(\tilde{\chi}_1^0) < 2$ ns | 1304.6310 |
| | $\tilde{\chi}_1^0 \to qq\mu$ (RPV) | 1 e, $\mu$ | 0 | Yes | 4.4 | $\tilde{q}$ 700 GeV | 1 mm $< c\tau <$ 1 m, $\tilde{g}$ decoupled | 1210.7451 |

# Long lived particles

Some challenges:

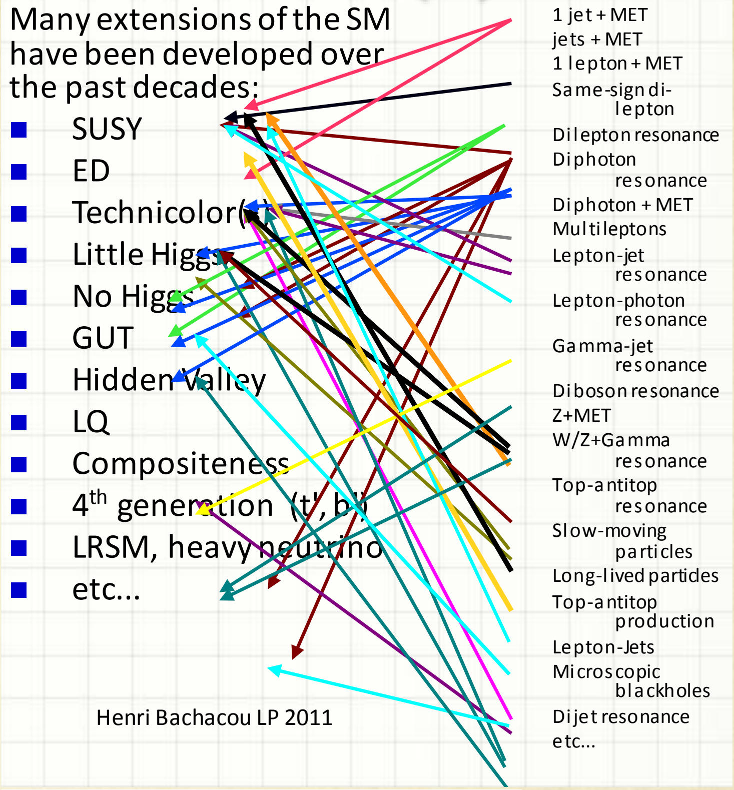
- The dedicated trigger for LLP particles are critical to get the signal – work needed to cope with trigger changes in run II.
- Effect of run 2 conditions on the detector response (also, efficient access of detector level information within the run 2 analysis model)
- Cover the broad spectrum of signatures !
- Exp-theory communication: how to apply the results of an analysis on models different from the one in the original publication, given the reliance of the analysis on detector responde details ?

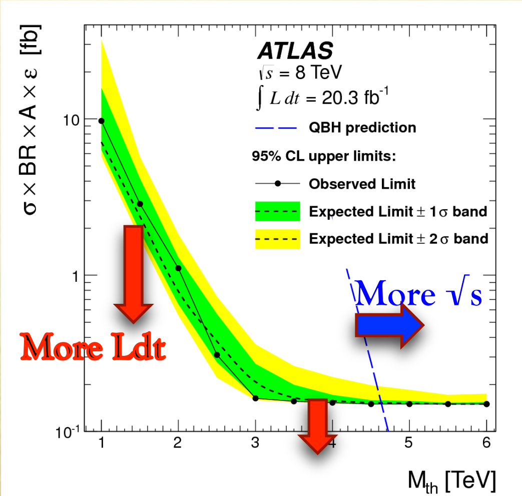
H => XX => 4 SM particles



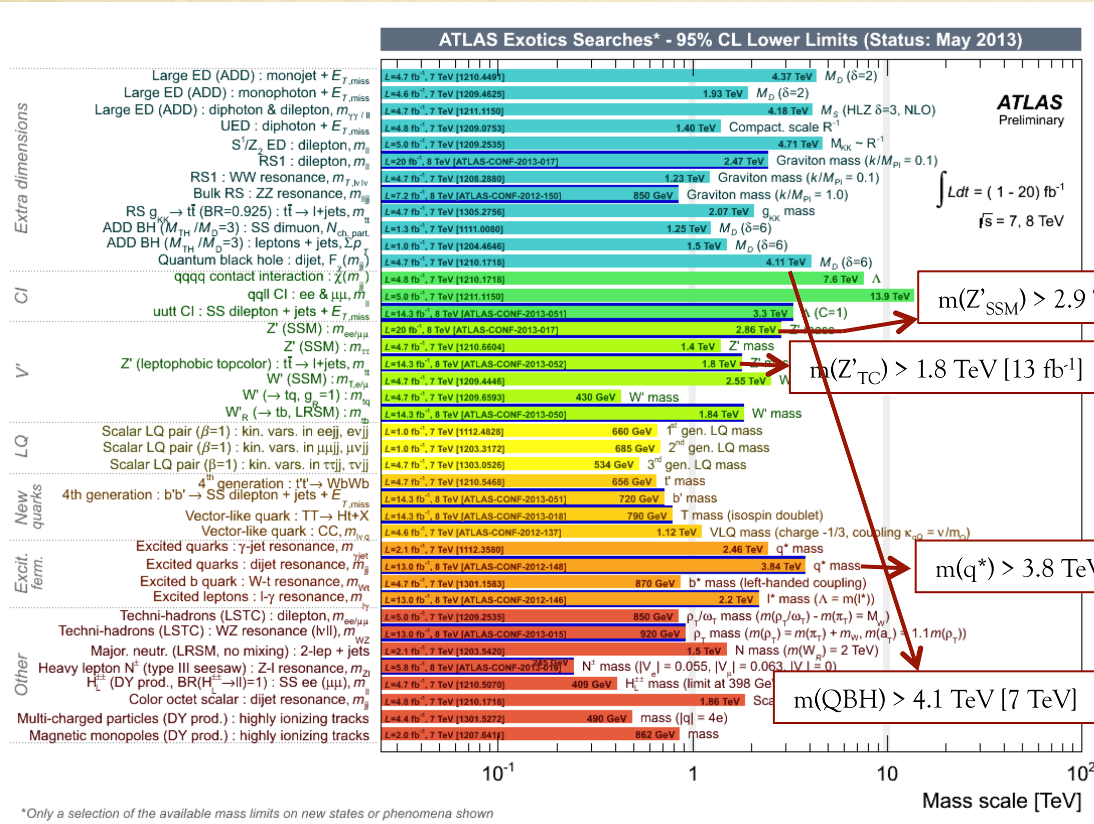
# Exotics, general considerations

- The approach of non-SUSY searches is in general signature driven.
  - Specific models are used for interpretation and guidance, but each signature can arise in several possible models, and in principle we would like to check any possible signature ("leave no stone unturned") should NP be different from what we expect (not unlikely..)
  - XY resonances, X,Y=e,μ,γ,jets,W,Z,top,H
  - X+MET, X as above
  - High multiplicity and high pt final states
- Mass reach increases 8 => 13 TeV
- Coupling reach will benefit from luminosity
  - Provided we can efficiently trigger at low mass !



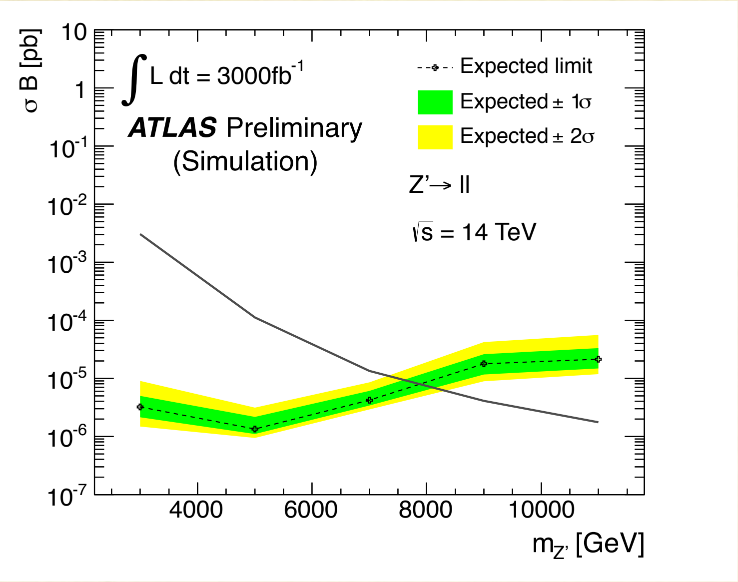
# Exotics, examples

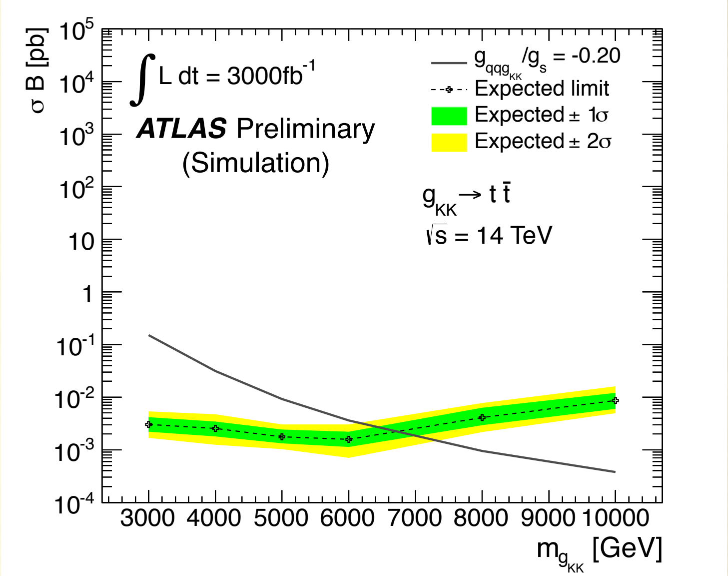



| New state | Mass (TeV) | Cross-section ratio: 13/8 | Cross-section ratio: 14/8 |
|---|---|---|---|
| **Z' (SSM)** | **3** | **9.4** | **13** |
| | 4 | 7.2 | 11 |
| **Z' (TC →*tt*)** | **2** | **6.3** | **7.8** |
| ***q**** **(dijet search)** | **4** | **56** | **87** |
| | 5 | 150 | 270 |
| | 6 | 160 | 320 |
| **QBH** (dijet search) | 4 | 70 | 105 |
| | 5 | 400 | 700 |
| | 6 | 6000 | 12000 |

All good candidates for an early discovery

# Exotics (LHC upgrade studies)




| model | 300 fb$^{-1}$ | 1000 fb$^{-1}$ | 3000 fb$^{-1}$ | |
|---|---|---|---|---|
| $g_{KK}$ | 4.3 (4.0) | 5.6 (4.9) | 6.7 (5.6) | 2.1 |
| $Z'_{\text{topcolor}}$ | 3.3 (1.8) | 4.5 (2.6) | 5.5 (3.2) | 1.8 |

| model | 300 fb$^{-1}$ | 1000 fb$^{-1}$ | 3000 fb$^{-1}$ | |
|---|---|---|---|---|
| $Z'_{SSM} \to ee$ | 6.5 | 7.2 | 7.8 | 2.9 |
| $Z'_{SSM} \to \mu\mu$ | 6.4 | 7.1 | 7.6 | |

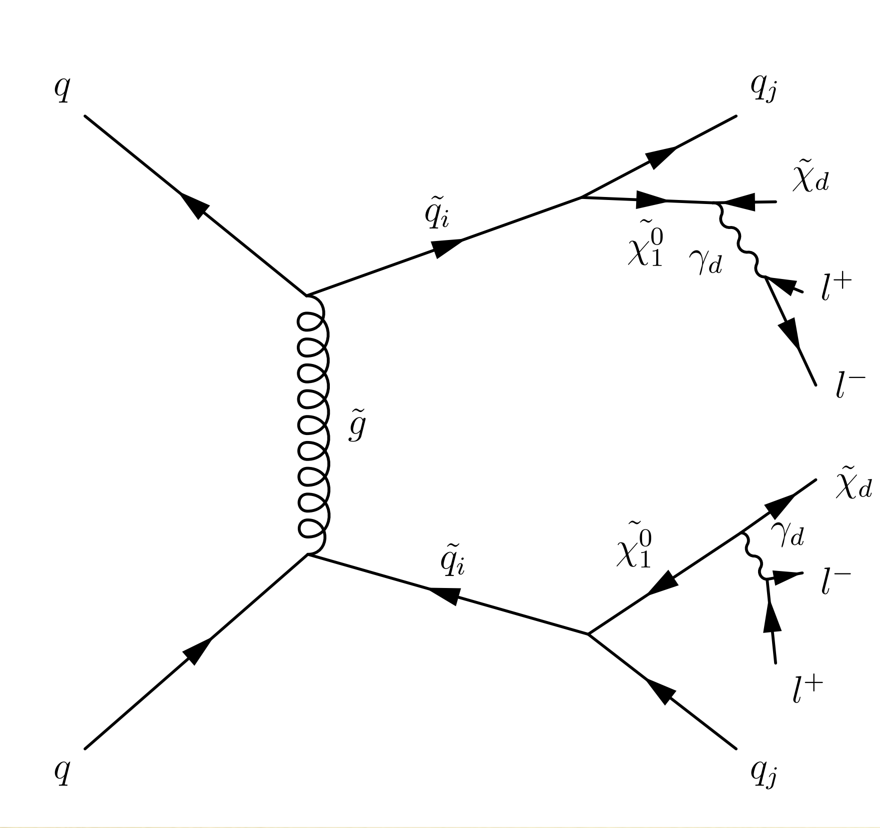
Expected limits

Current limits

# Conclusions

- The aim of searches is discovery !
  - Most important, look for everything. Here I just gave some examples of interesting topics
- We will start breaking new ground with few $fb^{-1}$ – to exploit that, need fast re-commissioning and background understanding. Can we do as well as in 2010 ?
- Ultimately run II will improve mass and coupling reach.
  - The latter should not be forgotten – new physics might show up at relatively low mass. Efficient trigger is a challenge there.
- Not just repeat run I analysis
  - New regime (higher masses, higher pileup). Use run I experience to improve masses.
- Some work to do already now
  - Cosmics, combined performance, background studies to be ready for new physics as early as possible
  - Some processes will give sensitivity early, need analysis code in place
  - Migration to new analysis model
  - Trigger has to be ready before data taking start – make sure we do not miss anything interesting

# Backup



$q$
$q_j$
$\tilde{\chi}_d$
$\tilde{q}_i$
$\tilde{\chi}_1^0$
$\gamma_d$
$l^+$
$l^-$
$\tilde{g}$
$\tilde{\chi}_d$
$\tilde{\chi}_1^0$
$\gamma_d$
$\tilde{q}_i$
$l^-$
$l^+$
$q$
$q_j$


Lepton jets