Constraints on Supersymmetry after Run 1 ALTAS Searches

Anyes Taffard

University of California Irvine

On behalf of the ATLAS Collaboration

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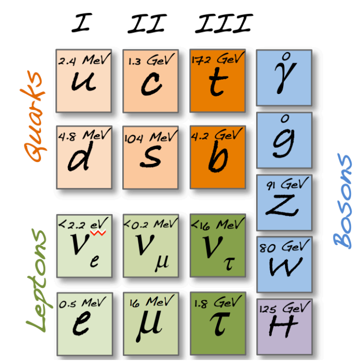
SUperSYmmetry (SUSY) in a Nutshell

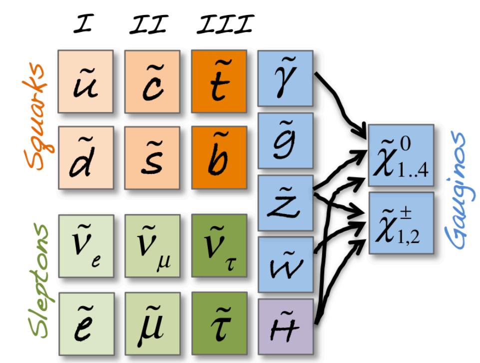
One of the most popular extensions of the Standard Model (SM)

- ✓ SUSY postulates "superpartners" to each SM particles
- ✓ Higgs sector extended to 5 Higgs
- ✓ Charginos: mixture of Wino/charged Higgsinos
- ✓ Neutralinos: mixture of Bino/Wino/neutral Higgsinos



Why is SUSY popular ? It answers many open questions at once:

- ✓ Provides a solution to the hierarchy problem
  - The fermion/boson contributions to the Higgs mass cancel
- ✓ Allows unification of gauge couplings
- ✓ Offers a dark matter (DM) candidate (if R-parity is conserved)



The SUSY experimental challenge:

- ✓ SUSY is very predictive in terms of spins and couplings, but tells us nothing about the masses after symmetry breaking
- ✓ Results: >100 free parameters !
  - All possible mass hierarchies between SUSY particles: 9! models
- ✓ Unknown mass hierarchy determines decay chain and (possibly long) lifetimes

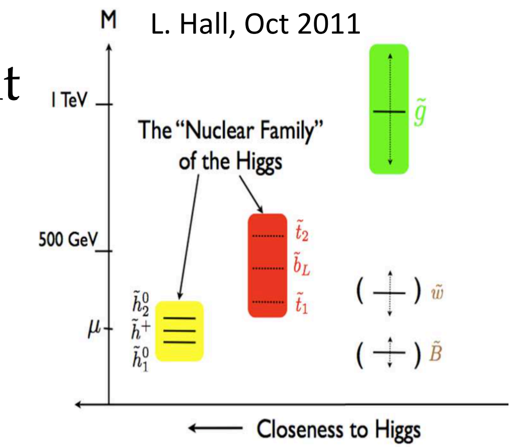
Complete SUSY Models
- mSUGRA, AMSB, GMSB

Phenomenological Models:
- pMSSM (19 parameters), GGM (gravitino)

Simplified Models
- Physical masses of SUSY particles
- Fixed decay chain & branching fractions

Guidance from naturalness

- ✓ Because of sparticles contribution to the Higgs mass, can approximate their upper limits from the requirement of "small" (<10%) fine-tuning of the Higgs mass :
  - Gluino ~ few TeV
  - Stop ~ 1TeV (lowest mass squark)
  - Higgsino ~200-300 GeV

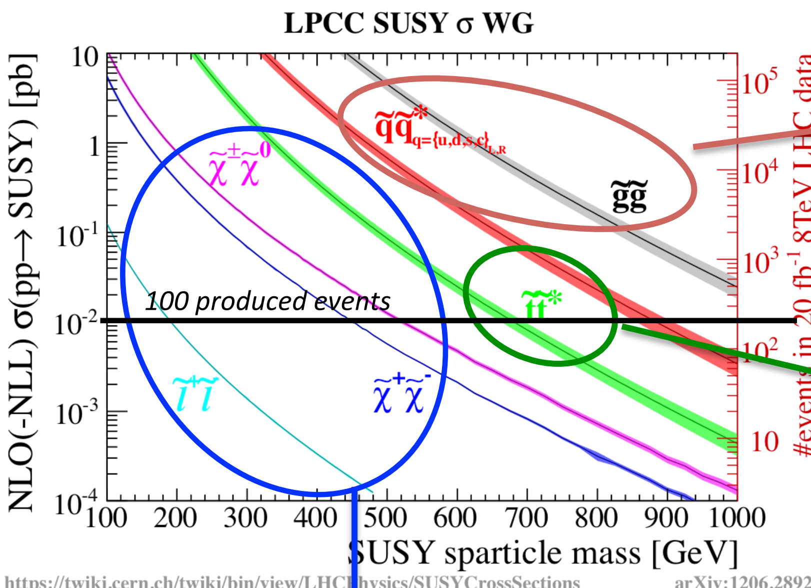


<u>In this talk, will focus on:</u>

R-Partity violation: See Minghui Liu's talk

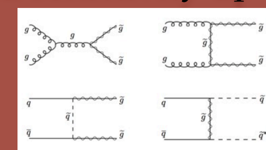
- ✓ R-Parity is conserved (P_R=-1 SUSY particles / +1 SM particles) $P_R=(-1)^{2s+3B+L}$
  - SUSY particles are pair produced at the LHC and the lightest one is stable.
- ✓ Nature of the stable Lightest SUSY particle (LSP) in MSSM:
  - $\tilde{\chi}_1^0$ with M_{LSP}> GeV or $\tilde{G}$ with M_{LSP}<< GeV
- ✓ The value of the $\Delta M = M_{SUSY}$ (highest particle produced at LHC) – M_{LSP}
  - If ΔM > O(100) GeV → open spectra → **high energetic objects**
  - If ΔM < O(100) GeV → **compressed spectra** → very difficult experimentally

Production of SUSY Particles at the LHC



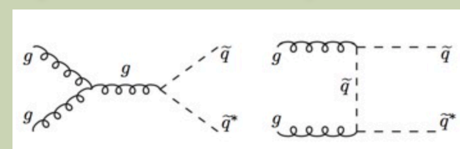
Strong production of gluinos, 1st and 2nd generation squarks

expected sensitivity up to ~1.2 TeV



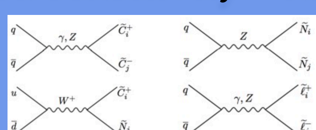
Strong production of 3rd generation squarks

expected sensitivity ~0.7 TeV



Electro-weak production of electroweakinos and sleptons

expected sensitivity ~0.2-0.5 TeV



Stringent constraint on strong production

- ✓ squarks (~850 GeV) gluinos (~1.33 TeV)

May favor electroweak production at the LHC

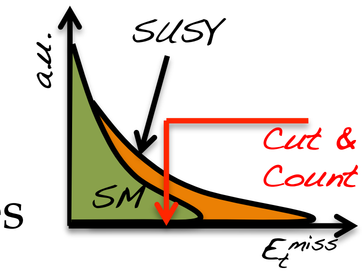
- ✓ Final states with multi-leptons and $E_T$miss

ATLAS SUSY searches focus largely in addressing direct production of gluinos, stops, EW-gauginos with simplified models

Common Analysis Strategies

Some SUSY processes can be SM-like.
SUSY searches rely on accurate modeling of SM backgrounds.

The presented analyses follow a common strategy:



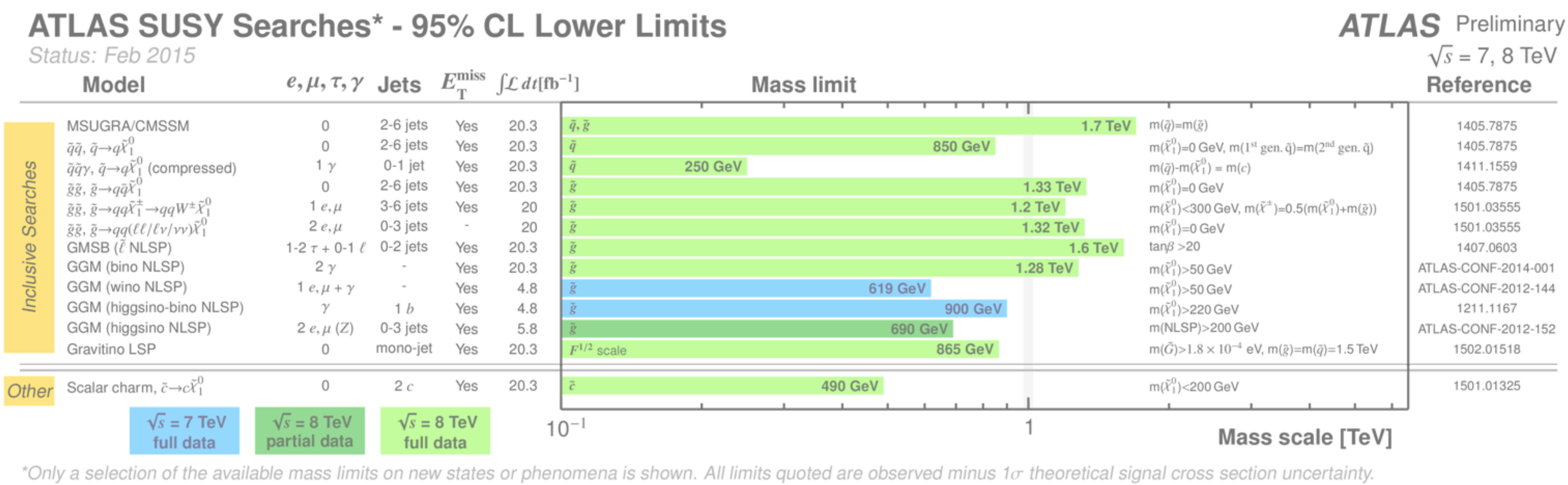
✓ Define **S**ignal **R**egions (SRs) based on signal kinematic features

✓ Estimate the SM processes in the SRs using:
- **Semi-data driven** method for irreducible backgrounds:
  - Define a **C**ontrol **R**egion (CR) for each background
  - Normalized Monte Carlo yield to data in Control Regions (CR)
  - Apply transfer factor to extrapolate background yield from CRs to SRs
- **Data-driven** method for instrumental background (QCD multijet backgrounds)
- **Monte Carlo simulation** only for minor backgrounds.

✓ All predictions are validated against data in **V**alidation **R**egions (VRs)

✓ Finally, look at the observed data in the SRs

Strong Production Searches

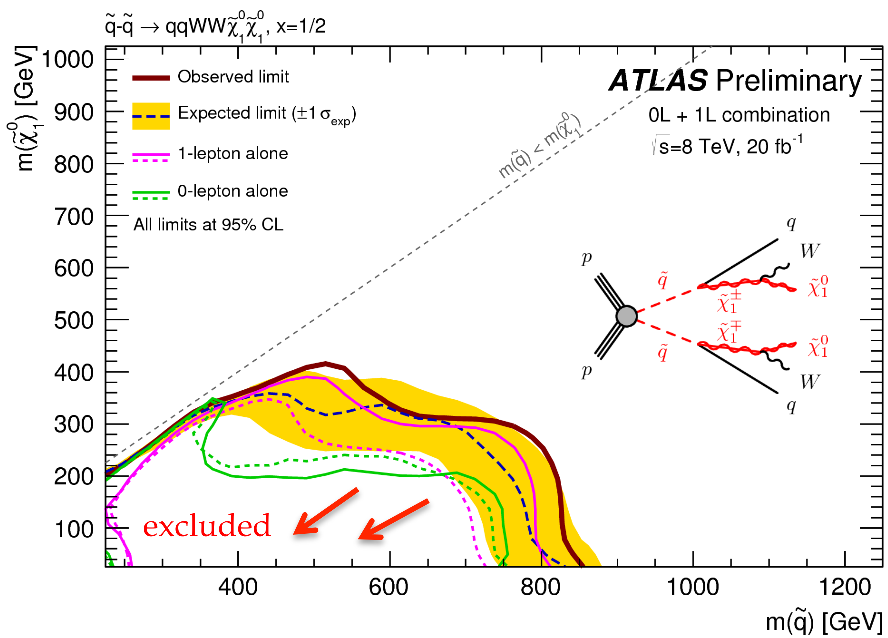


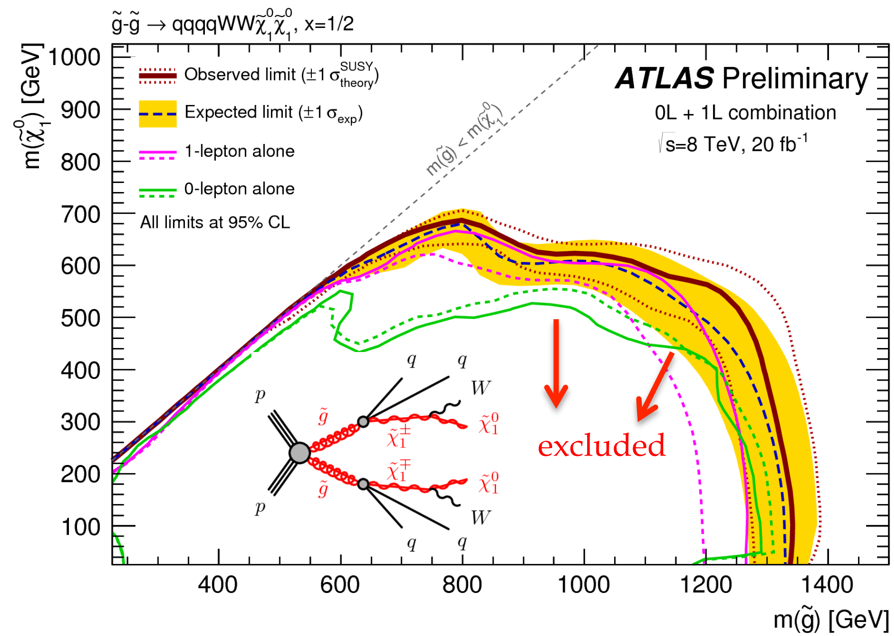
- Inclusive Search
- $\tilde{g} \rightarrow t\bar{t}\,\tilde{\chi}_1^0$
- Scalar charm
- Z+Met

Inclusive Searches

- ✓ Final states with jets, missing transverse momentum (E_T^{miss}) and zero or one isolated lepton (e/μ)
- ✓ Broad search strategy with several SRs to obtain best sensitivity:
  - Lepton veto SRs [arXiv: 1405.7875]
  - Soft lepton SRs
  - Hard leptons SRs

  } [arXiv: 1501.03555]
- ✓ Many Simplified Model interpretations, with single production and decay process.
- ✓ Combinations to strengthen limits (~50 GeV) and test holes in sensitivity.

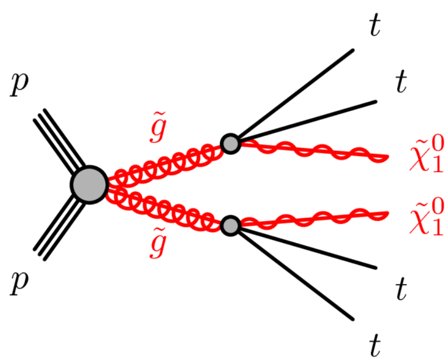


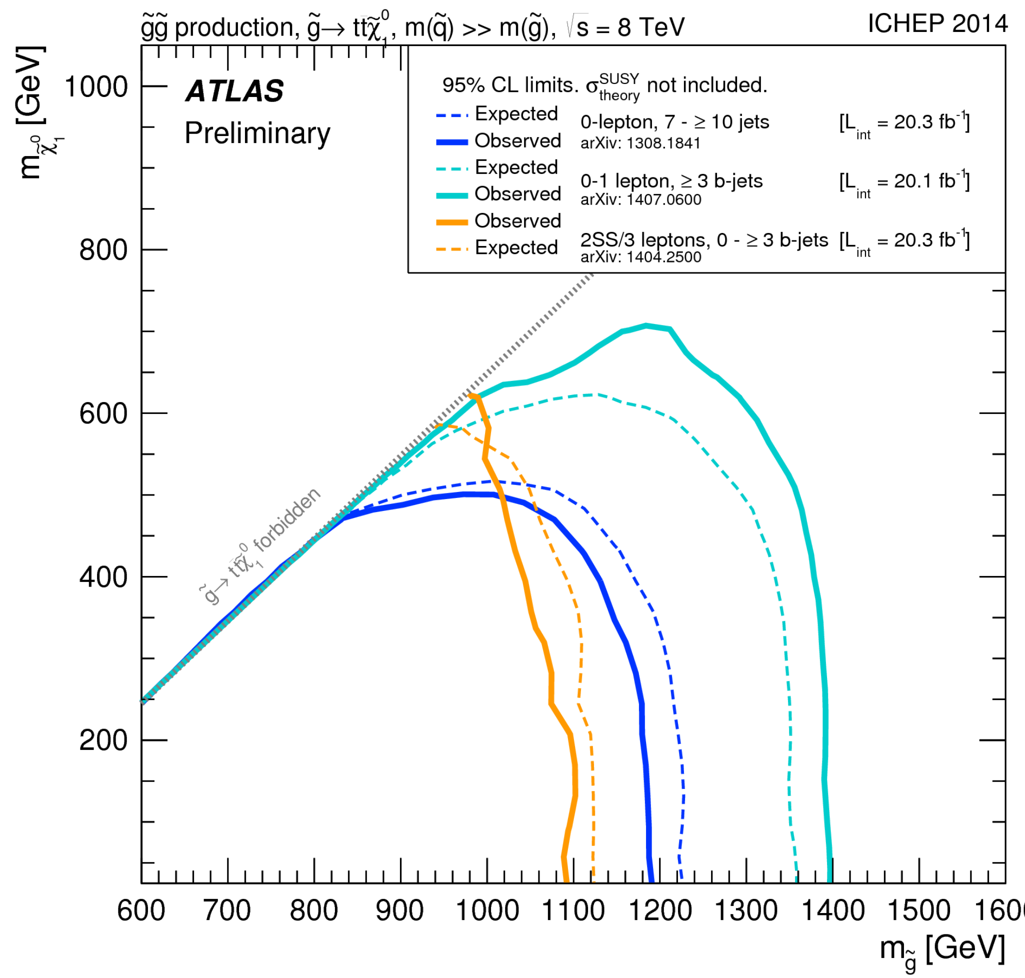


Gluino Searches with top quarks

- ✓ Interpretation for a pair of gluinos decaying promptly via off-shell stop

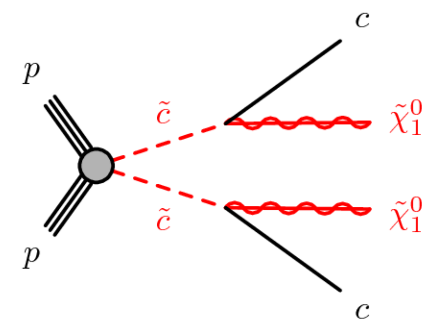
  $\tilde{g} \rightarrow t\bar{t}\,\tilde{\chi}_1^0$



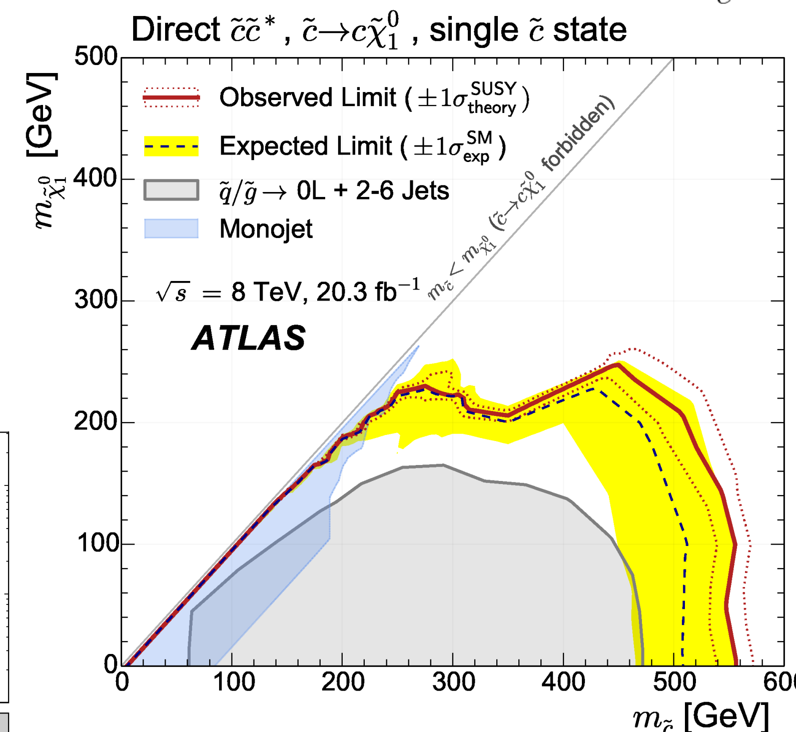


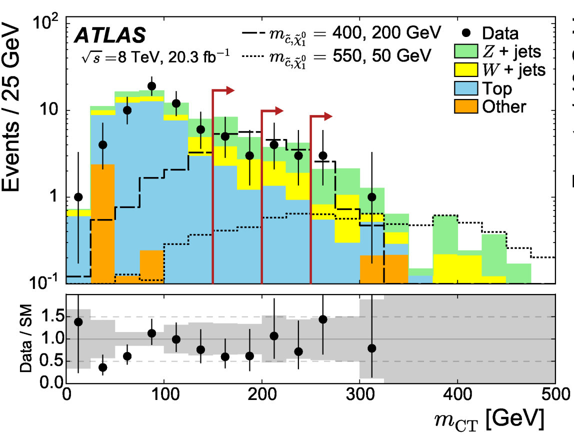
- ✓ Broad search strategy:
  - 0L + 7-10 jets [arXiv: 1308.1841]
  - 0-1L + ≥ 3 b-jets [arXiv: 1407.0600]
  - 2L same sign/3L [arXiv: 1404.2500]
    - Benefit from low SM backgrounds
    - Can also target low E_T^{miss} scenarios such as RPV or compress spectra

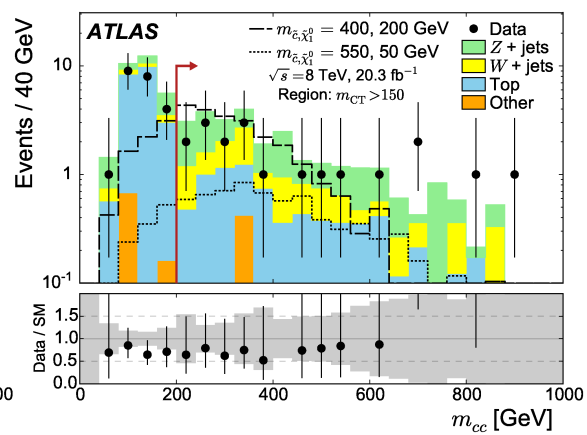
Direct Scalar Charm



- ✓ Final state with large E_T^{miss} and at least two jets, with the two leading tagged as originating from c-quarks.
- ✓ c-jet tagging efficiency as a function of jet p_T, is calibrated from data in inclusive jets events containing D^* mesons.
  - Tagging efficiency of 19% (13%, 0.5%) is achieved for c-jets (b-jets, light-flavor/gluon jets)
- ✓ Final SR selection based on:
  - Contransverse mass m_{CT} $m_{CT} = \sqrt{\left(E_T^{v_1} + E_T^{v_2}\right) - \left|\mathbf{p}_T^{v_1} - \mathbf{p}_T^{v_2}\right|^2}$
    - Reduces ttbar with mis-tagged b's as c-jet
  - Invariant mass of the two c-tagged jets: m_{cc}
    - Reduces Z+jets, with c from gluon splitting







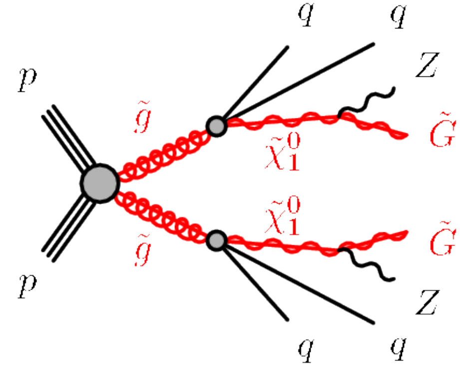
100 GeV gain compared to 0L

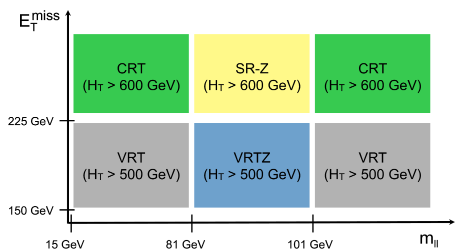
arXiv: 1503.03290

Squarks/gluinos Search with Z final state

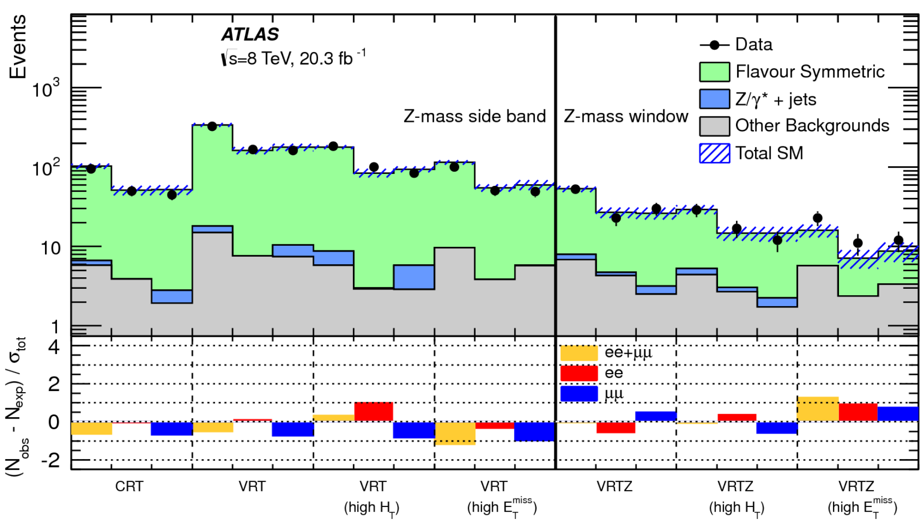
$$H_T = \sum_i p_T^{jet,i} + p_T^{lepton,1} + p_T^{lepton,2}$$

- ✓ Final state with Z, ≥2 jets and large E_T^{miss} and H_T
- ✓ Data driven estimates for all major backgrounds
  - Flavor symmetric background (eg tt, WW) estimated from eμ CR
  - Several regions and alternative background estimate methods used for cross-checks
- ✓ Observed 3.0σ (1.7σ) over fluctuation in ee (μμ) channels

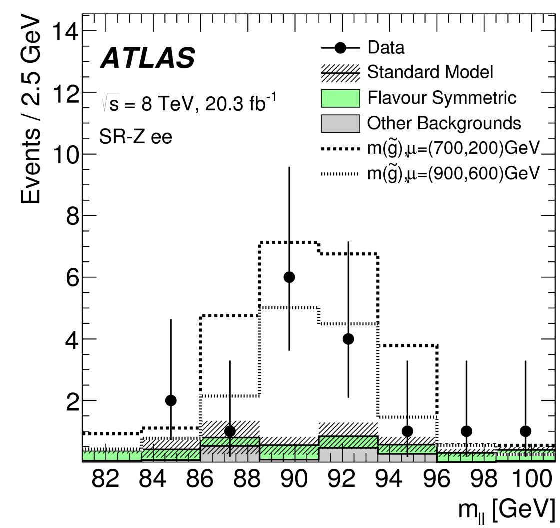




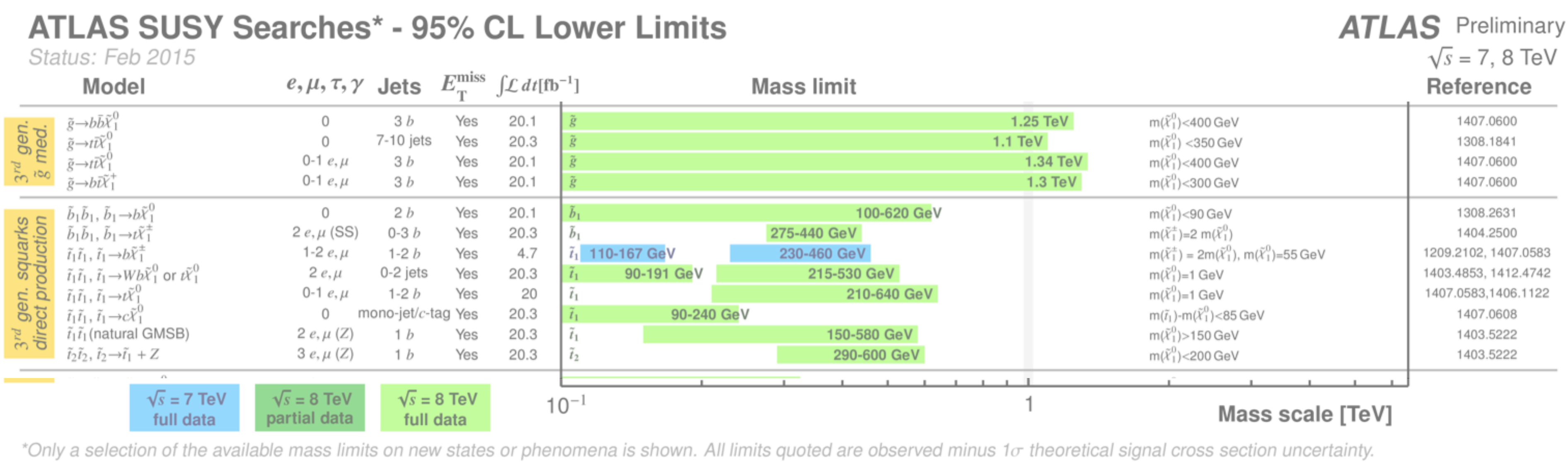
Good agreement in VRs



Over fluctuation in SR



Third Generation Squark Searches



- ➢ Overview
- ➢ Stop search combination
- ➢ Stealth stops

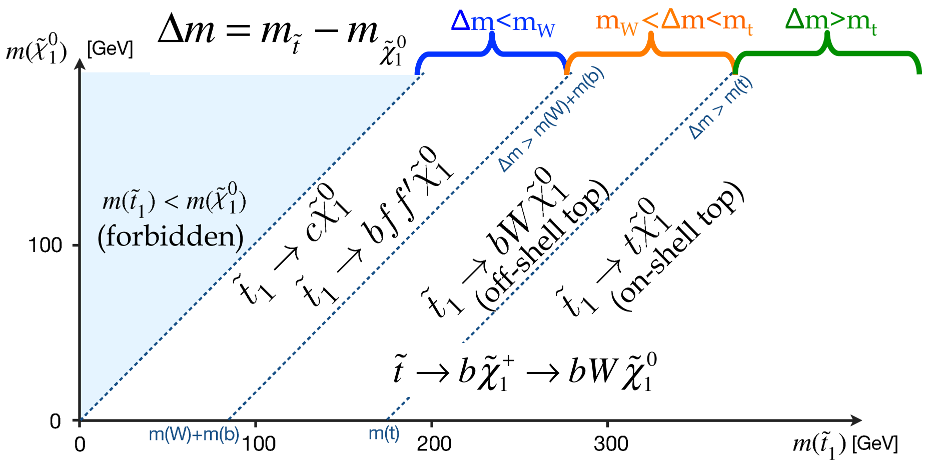
See Alexandre Aubin's talk

Stop Searches Overview

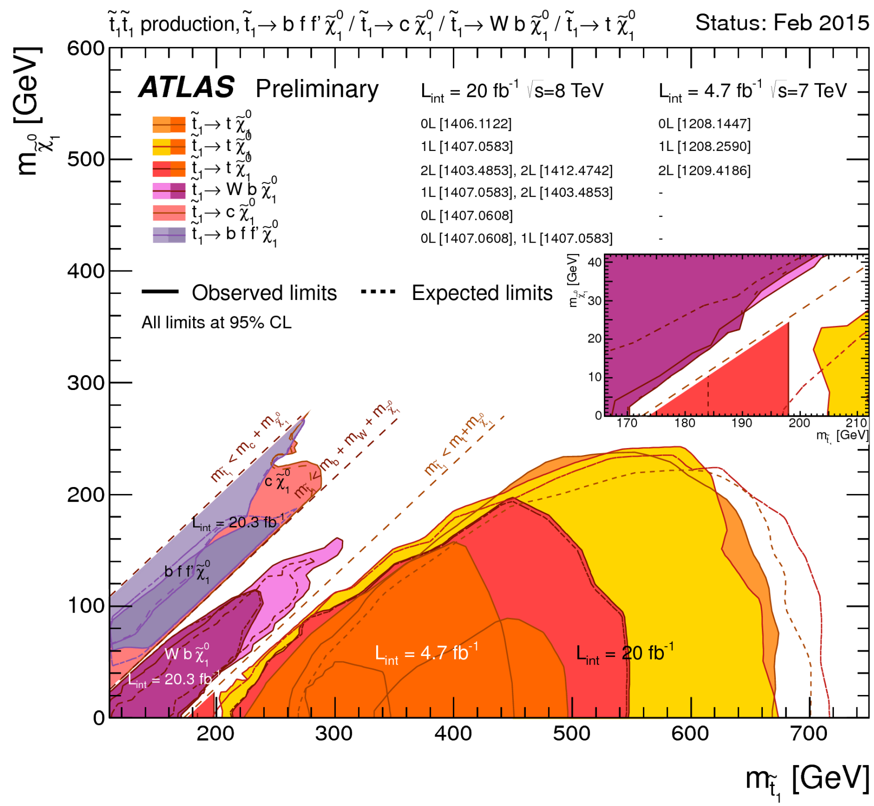
✓ Complicated search due to heavy quark masses

✓ Decays depends strongly on mass hierarchy of sparticles

- Required dedicated SRs



- If $\Delta m > m_{top}$
  - Decay to on-shell top quarks ($t \rightarrow Wb$).
- If $\Delta m < m_W$ (compress region)
  - No phase space left to produce massive bottom/top quarks or high p_T objects. Decay can include "soft" charm quark.
- If $m_W < \Delta m < m_{top}$:
  - Can have W's, charginos etc… (depending on mass of sparticles).

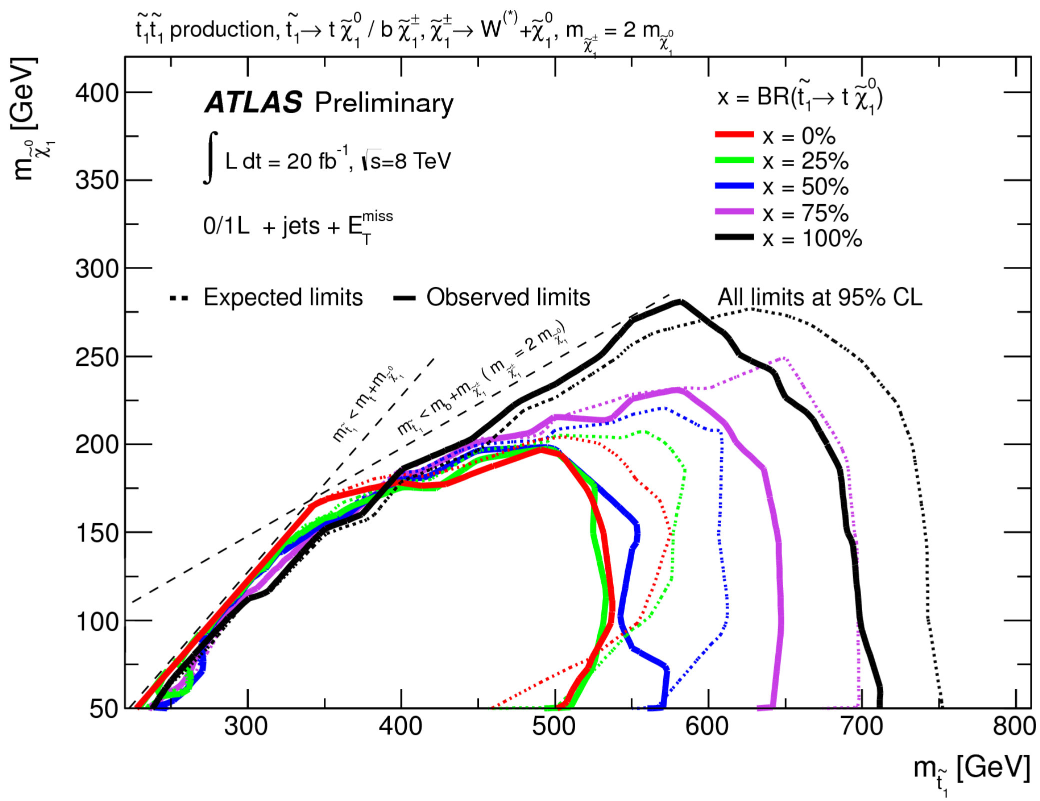


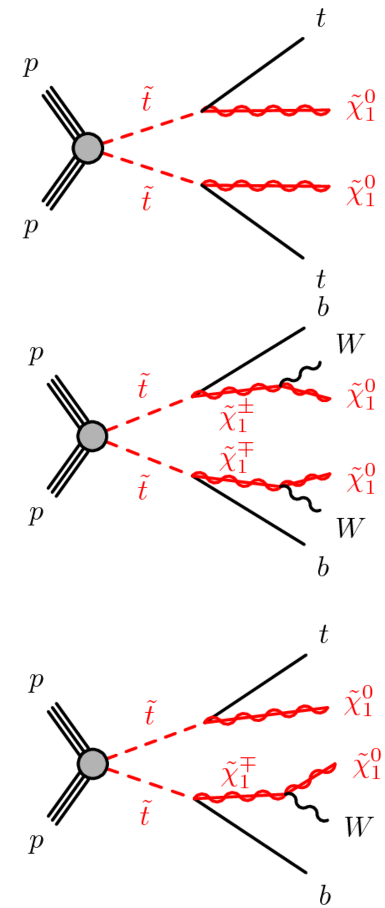
Broad search strategy:

- 0L, 1L, 2L, mono-jets searches
- Challenging low-mass models still not excluded

Stop Searches Combination

- ✓ Search for light scalar top motivated by naturalness argument.
- ✓ Statistical combination of 0L and 1L search channels for $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ or $\tilde{t} \rightarrow b\tilde{\chi}_1^\pm$
  - Improve expected limit by ~50 GeV in stop mass at low LSP mass.
- ✓ Exclusion limits set for different branching ratios x for $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ and (1-x) for $\tilde{t} \rightarrow b\tilde{\chi}_1^\pm$



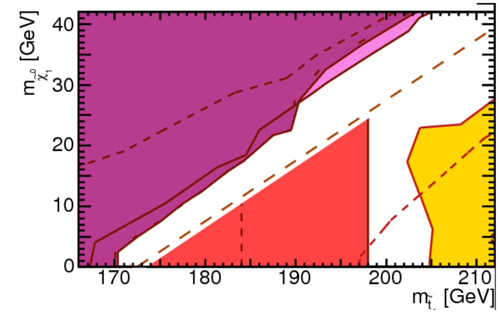


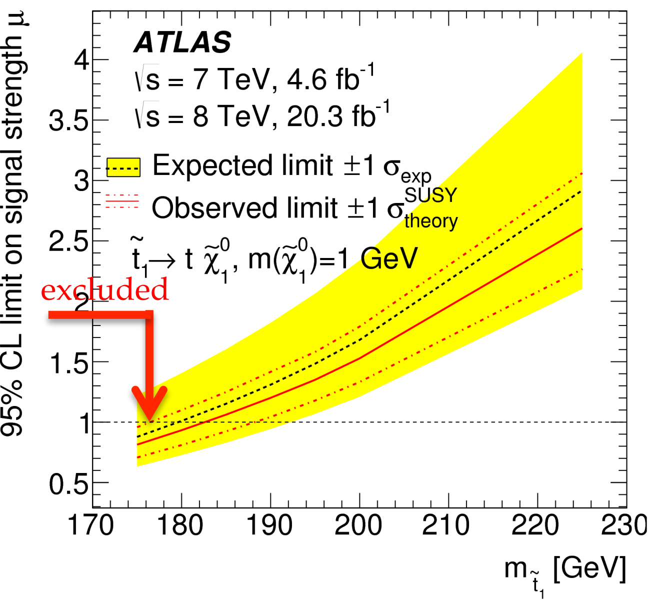
arXiv: 1412.4742
arXiv: 1406.5375

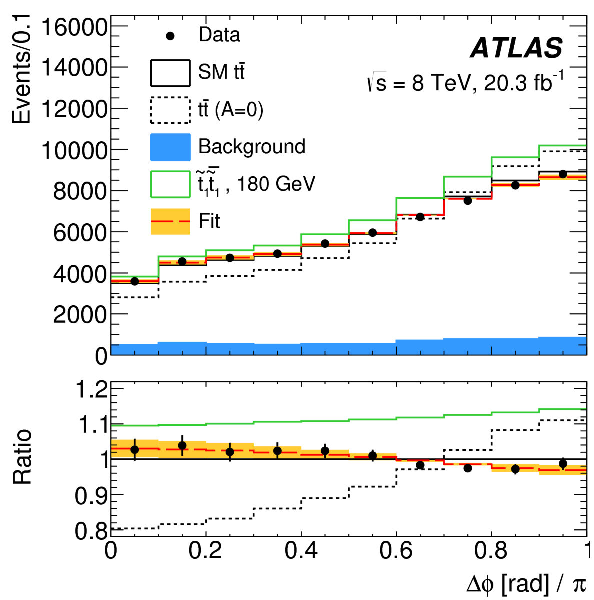
Stealth stops

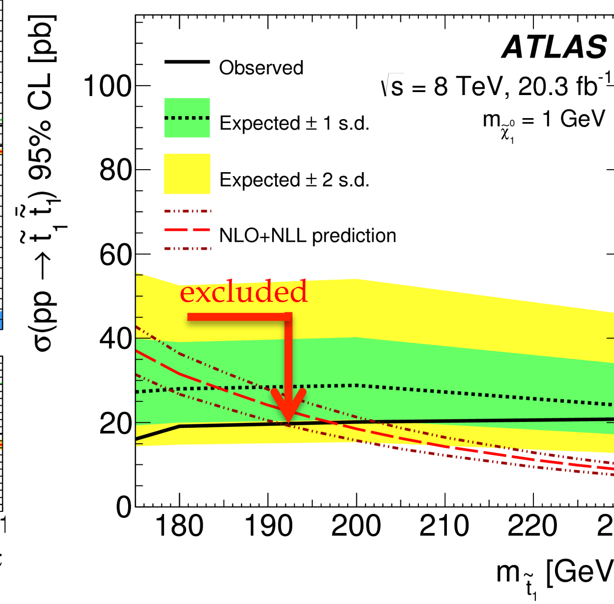
- ✓ Stop quarks with mass just slightly above the top mass, are very difficult to find
  - Theory uncertainty on ttbar theory cross section is comparable to stop cross section at this mass
  - Stop-antistop could mimic top pair production $\tilde{t}\tilde{\bar{t}} \rightarrow t\bar{t}\,\tilde{\chi}_1^0\,\tilde{\chi}_1^0$
- ✓ Use ttbar dilepton candidates (90% pure) to constraint "stealthy stop"
  - Re-interpret ttbar cross section measurement to place limit on top squarks
  - Measure angle between leptons (related to ttbar spin correlation) and test consistency between SM and SM + very light top squark

    Can exclude $m_{top} < m_{stop} < 191\ GeV$

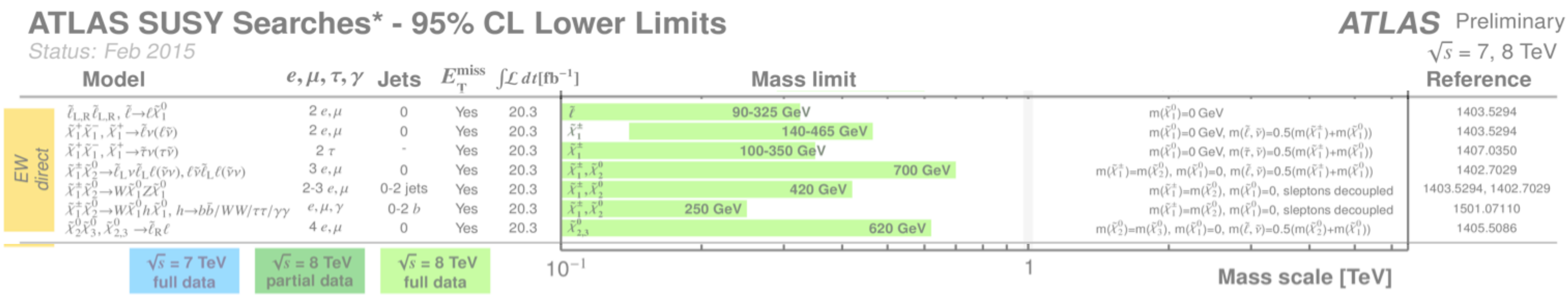




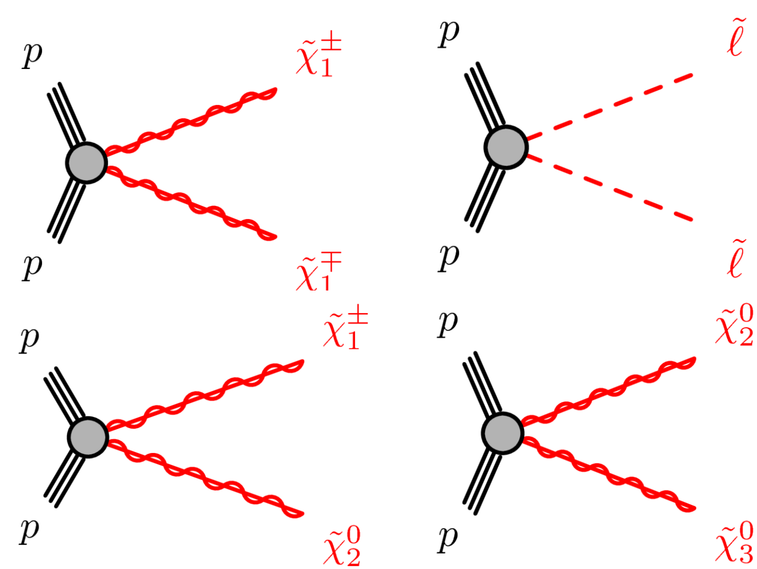




Electroweak Searches



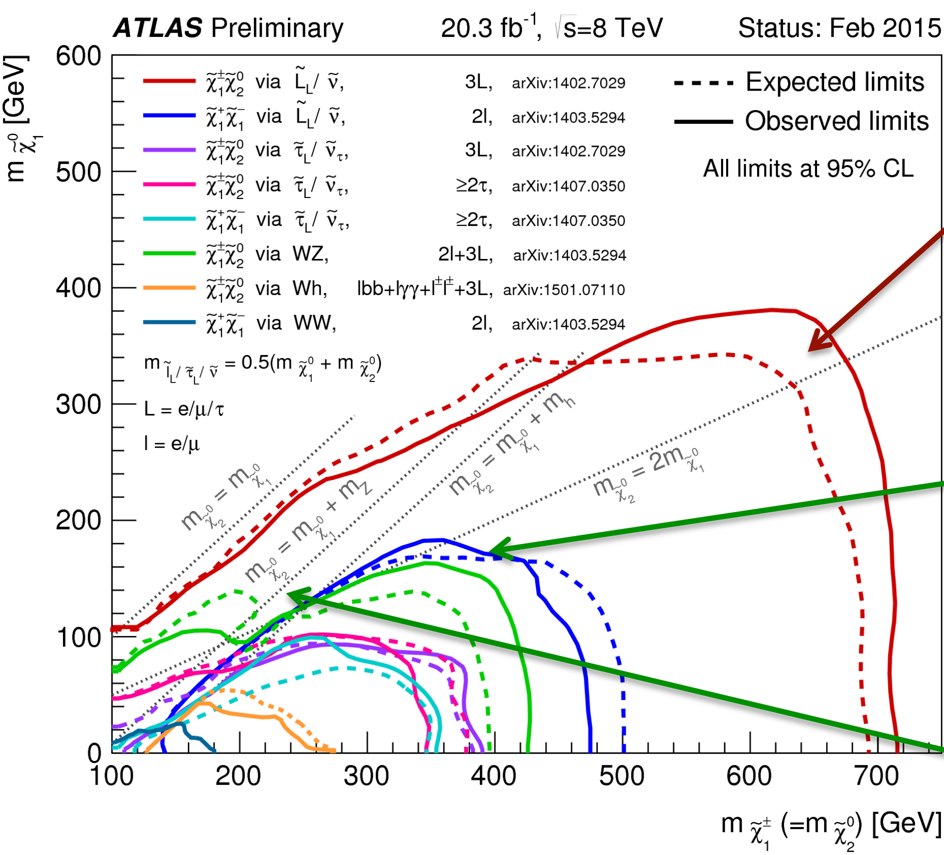
- ➢ Electroweak Summary
- ➢ Searches with Higgs



See Alexandre Aubin's talk

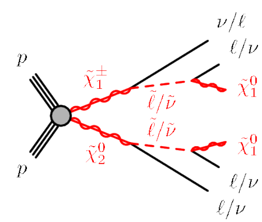
Electroweak SUSY Summary

- ✓ Very clean multi-lepton (e, μ, τ) signatures with low jet activity
  - Low cross-section balanced by smaller and relatively well understood SM backgrounds
- ✓ Many different final states to consider. Broad search strategy.

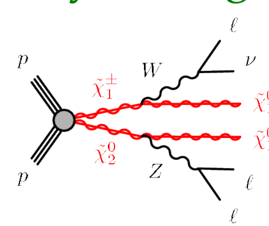


Limit strength vary widely depending on the model assumptions

- Decay through intermediary sleptons



- Decay through SM vector bosons



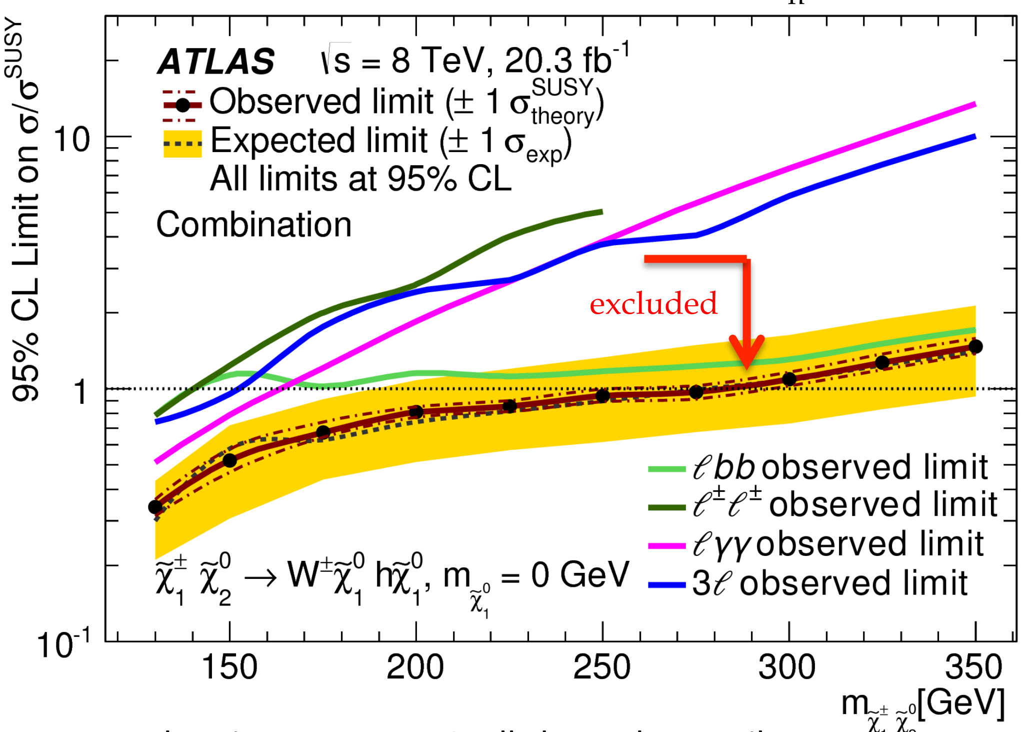
Compress spectra region can be challenging

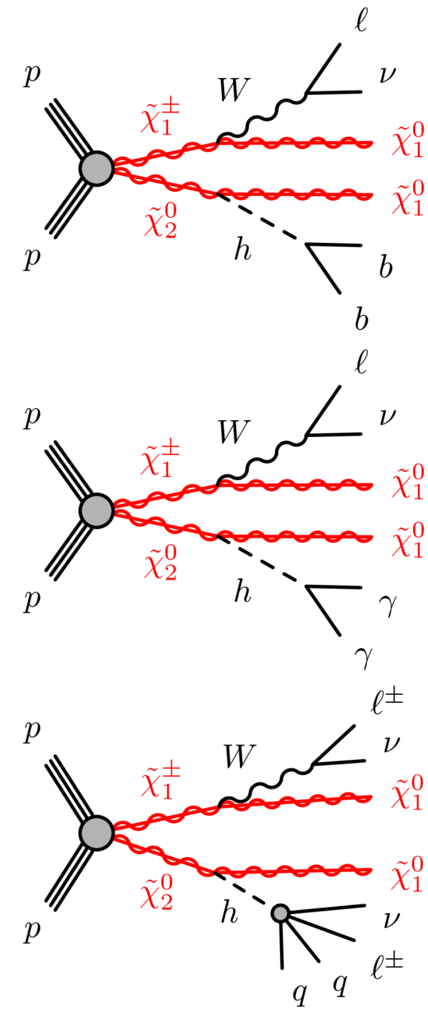
arXiv: 1501.07110

Chargino, neutralino decaying to Higgs

- ✓ If the electroweakinos (C_1, N_2) are Wino-like, mostly Higgs in decay
- ✓ Three channels analyzed and statistically combined with 3L
  - 1L bb (W→lν, h→bb)
  - 1L γγ (W→lν, h→γγ)
  - 2L SS (W→lν, h→WW)

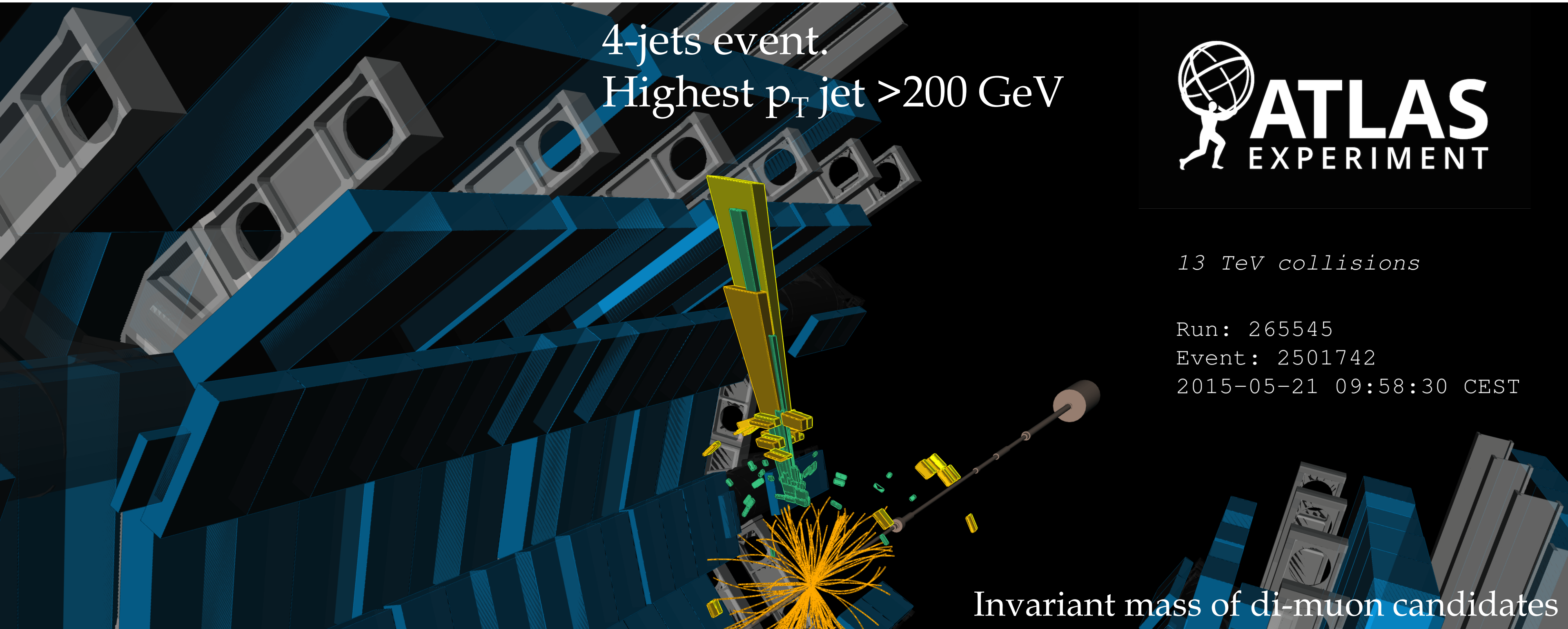
m_h=125 GeV



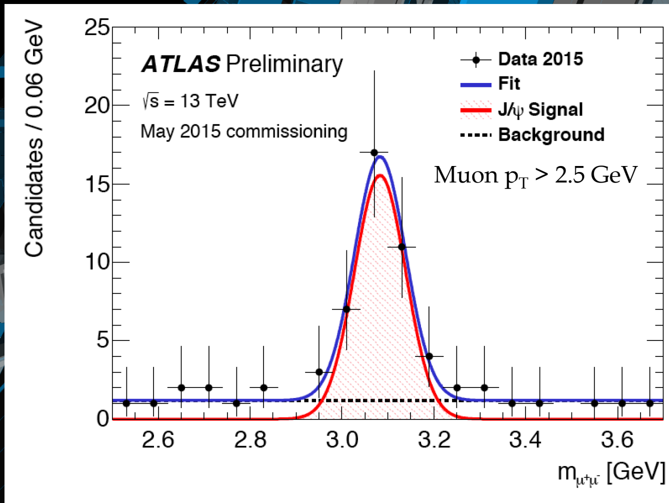


For charginos mass <170, all channels contribute
For charginos mass>170, 1L+bb channel dominates

Run 2 Prospects

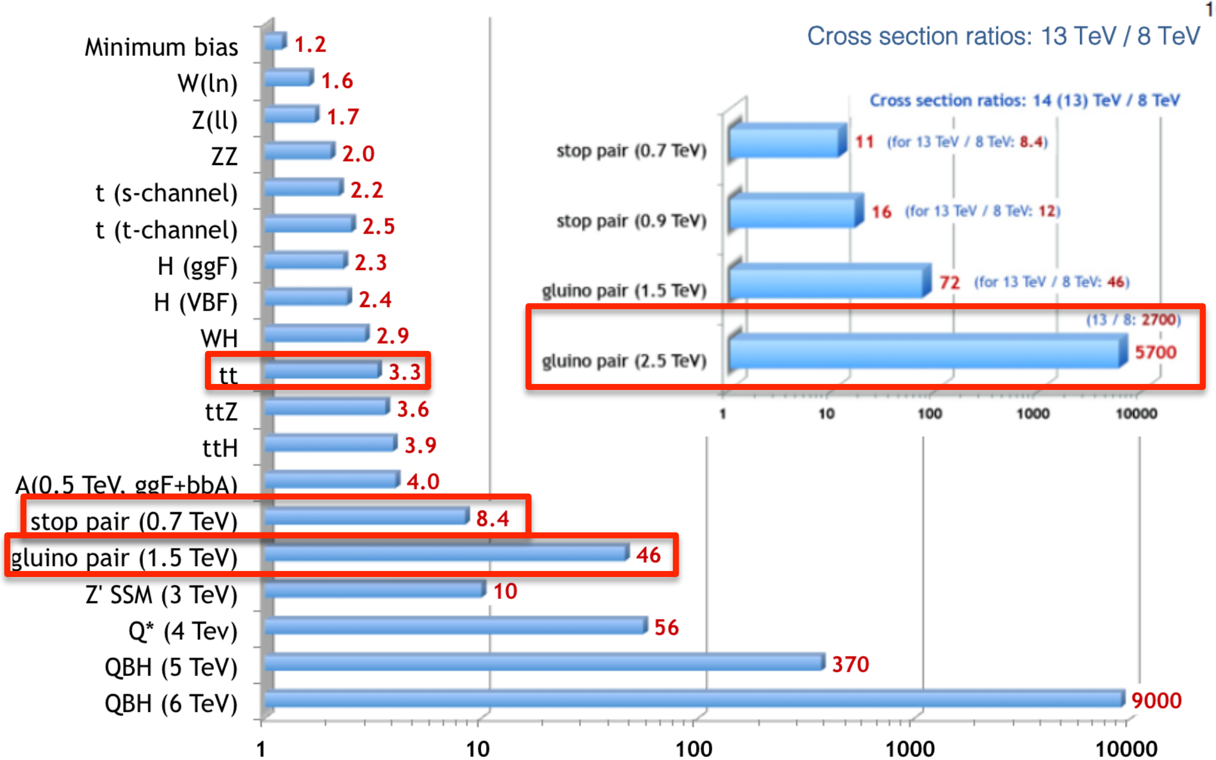


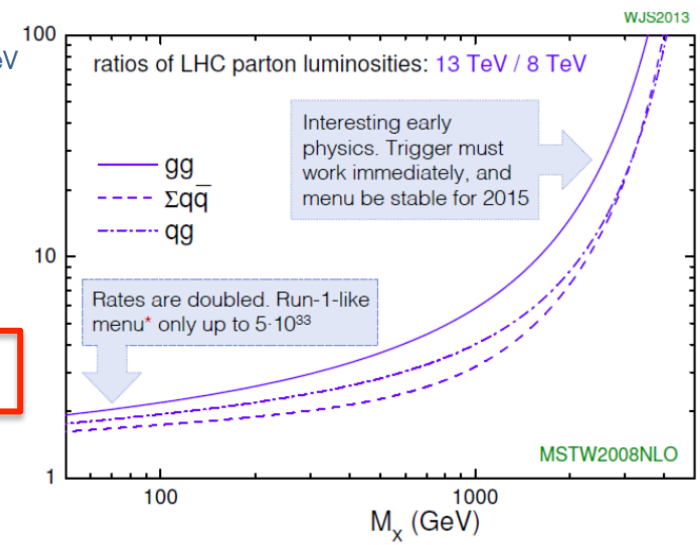
Invariant mass of di-muon candidates



Near future

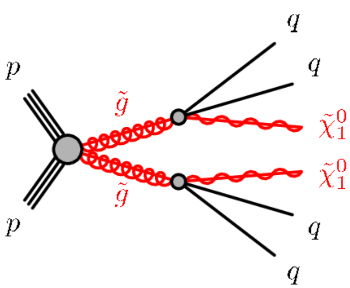
- ✓ Significant preparation for Run 2 in progress
- ✓ 13TeV Collisions starting THIS WEEK !!!
- ✓ Excited to finally lay hands on 13 TeV data
  - Reach for strongly produced SUSY is expected to increase significantly in Run-2
  - New heavy state could be discovered relatively quickly !
  - The HL-LHC will allow to ultimately probe the TeV scale and Natural SUSY

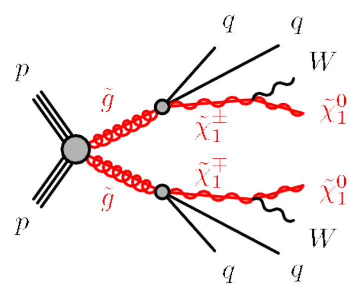


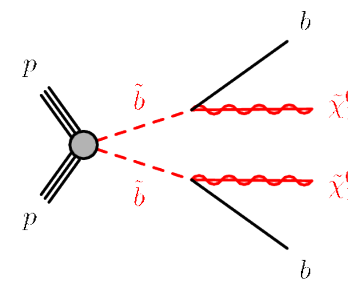


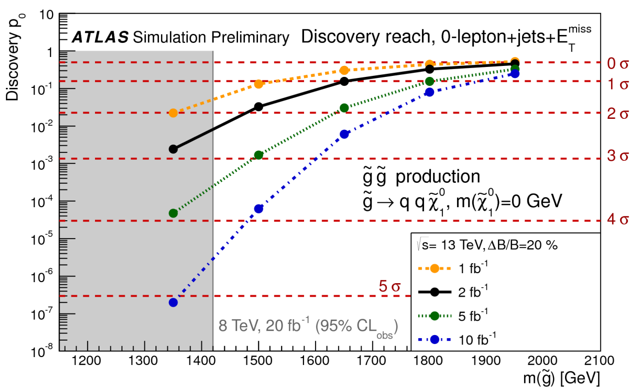
Early Run-2 Prospects

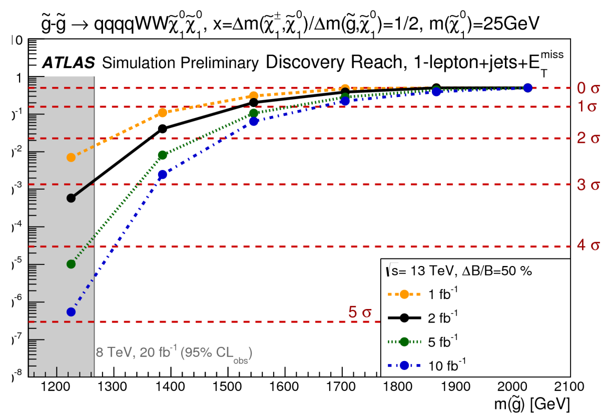
- ✓ How much data is needed at 13TeV for the discovery potential to surpass the 8TeV limit ?
  - Potential of 3σ evidence with 2-10fb^{-1}, even with poor systematics
- ✓ The early months of the 2015 run should be exciting !

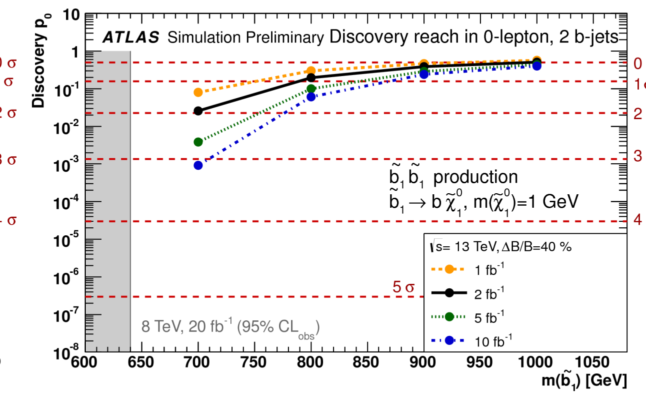












Summary And Outlook

- ✓ Comprehensive set of SUSY searches performed with ATLAS Run-1 data yielded many results.
- ✓ No significant excess above SM expectations is observed in any searches
  - Strong exclusion for m_{LSP}~0 GeV for color and electroweak sectors
- ✓ 95% CL exclusion limits are set for various phenomenological models
- ✓ Parameter space favored by naturalness argument narrowing
  - Compress spectra region remains challenging

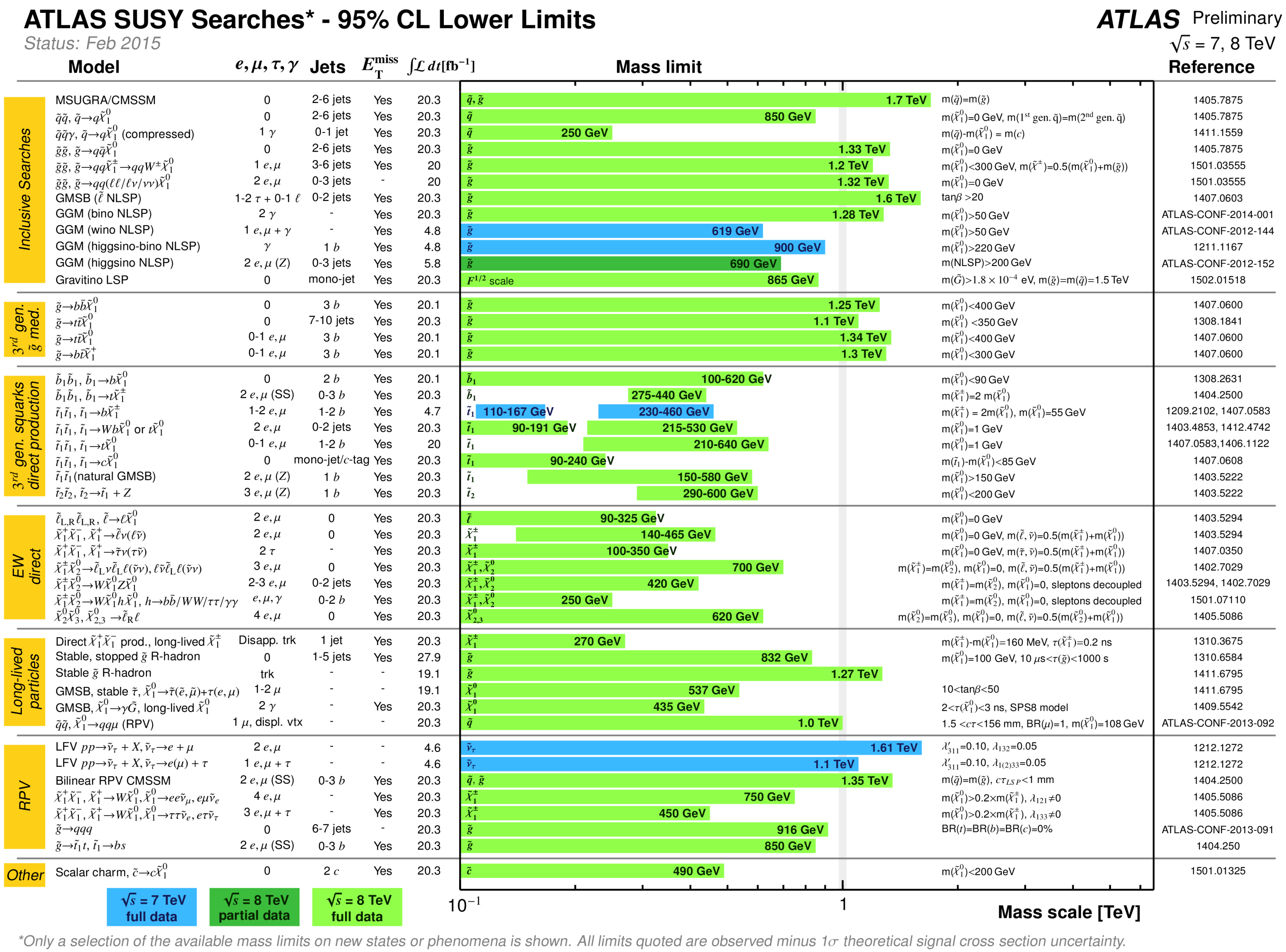
Run-2 is starting !

- ✓ Increase in SUSY cross section due to higher center of mass energy, once again opens the door to discovery.
  - – Largest increase in energy for many years to come
- ✓ Looking forward to run-2 dataset
  - *and hopefully not having to make exclusion plots anymore !*

- ✓ If have to be guided by "natural SUSY", have a long way to go… and it will take time.

Summary of ATLAS Run-1 SUSY Searches

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults



In canonical scenarios, sensitivity achieved up to ~1.3 TeV gluinos, ~700 GeV stop, and ~400 GeV EWK-inos

BACKUPS

Charm Tagger Performance