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FOR FUNDAMENTAL PHYSICS

ATLAS EXPERIMENT

Supersymmetry searches in ATLAS

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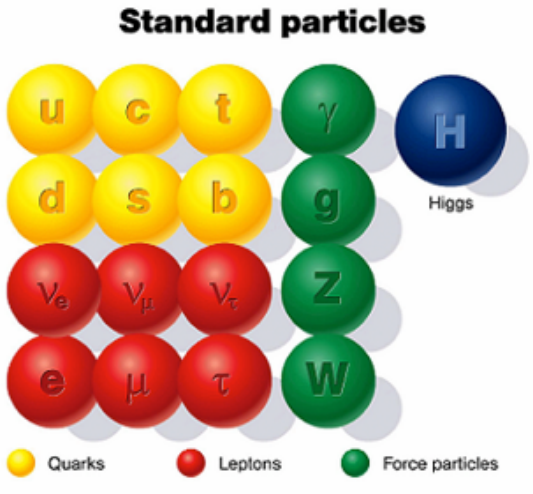
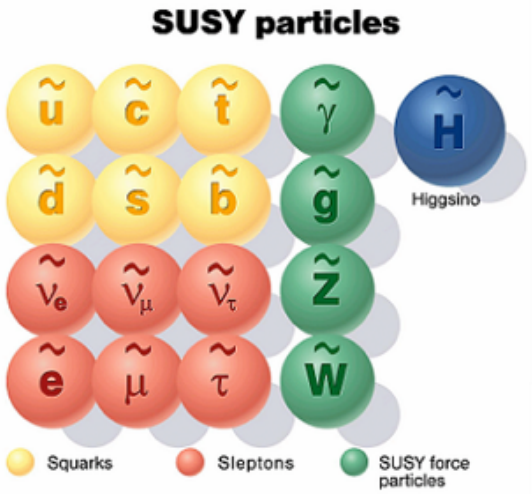
LHEP
UNIVERSITÄT BERN

Supersymmetry and MSSM





$$W^{\pm}\ W^{0}\ B \xrightarrow{mixing} W^{\pm}\ Z\ \gamma$$

$$\tilde{H}_u^0\ \tilde{H}_d^0\ \tilde{W}^0\ \tilde{B}^0 \xrightarrow{mixing} \tilde{\chi}_1^0\ \tilde{\chi}_2^0\ \tilde{\chi}_3^0\ \tilde{\chi}_4^0 \quad \text{neutralinos}$$

$$\tilde{H}_u^+\ \tilde{H}_d^-\ \tilde{W}^+\ \tilde{W}^- \xrightarrow{mixing} \tilde{\chi}_1^{\pm}\ \tilde{\chi}_2^{\pm} \quad \text{charginos}$$

The Standard Model (SM) is a successful description of fundamental interactions

- Has an **high-level of fine-tuning**
- Doesn't provide an explanation for **Dark Matter**
- Doesn't provide an **unification** of QCD and EW coupling constants

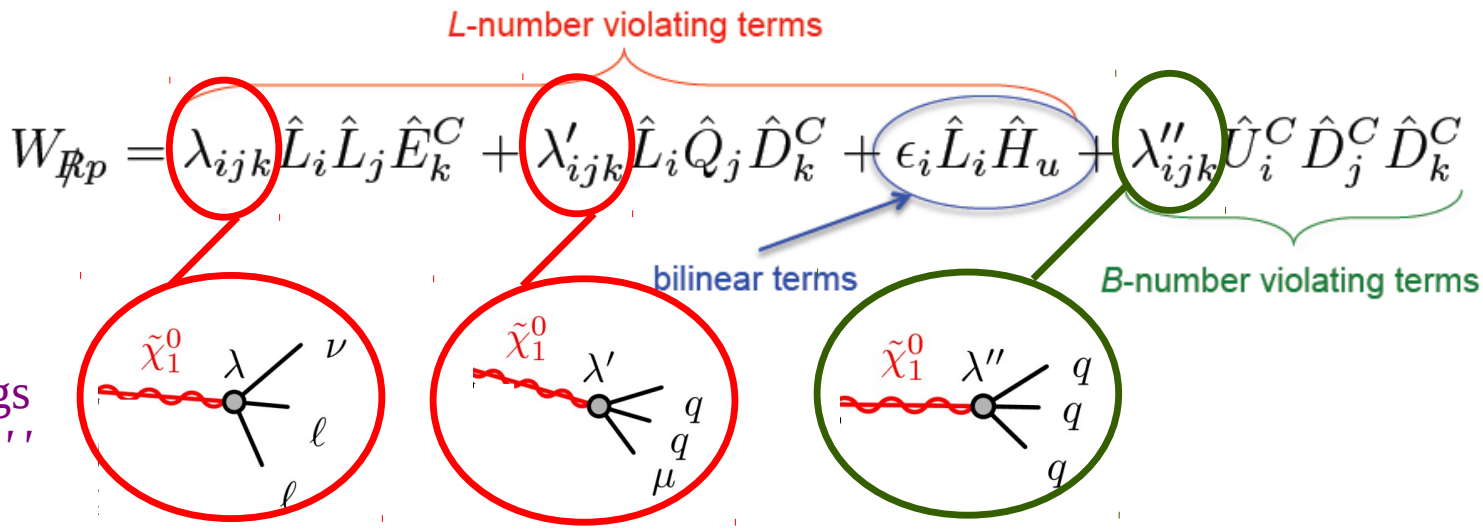
Supersymmetry (SUSY) can extend the SM

- New physics at TeV scale
- SUSY relates each SM particle to another, known as *superpartner*, that differs by half unit of spin.
- SUSY is broken: sparticle masses are function of the breaking terms.

R-Parity

- **R-parity** R = $(-1)^{3B+L+2S}$ is a discrete multiplicative symmetry.
  - **SUSY particles must be produced in pairs**
  - The Lightest Supersymmetric Particle (LSP) is stable (dark matter candidate)

The MSSM potential



- No reason to assume conservation of R-parity
  - Can constrain proton decay with lepton or baryon violating SUSY, but not both
  - LSP decays → no dark matter candidate
  - **non-prompt decays** if λ couplings are small

Natural SUSY

Naturalness provides a useful criterion to address the status of SUSY at the electroweak scale.

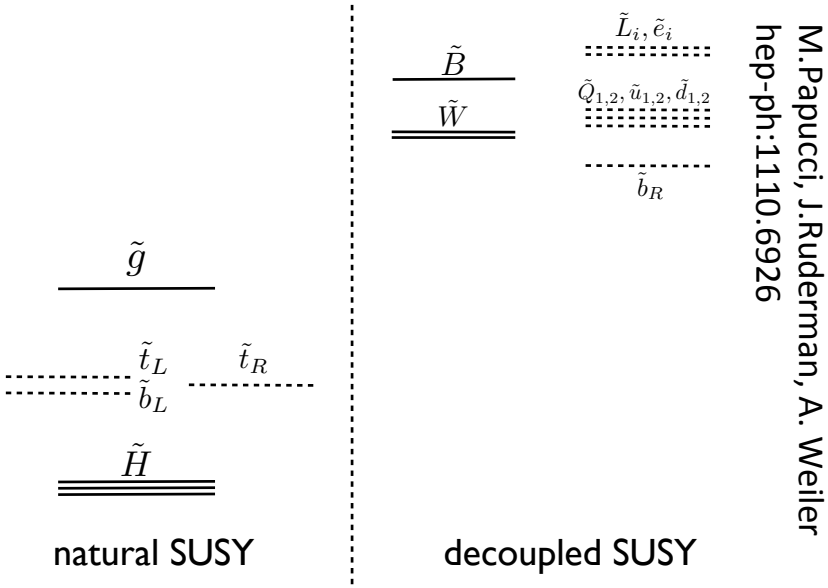
- **The naturalness requirement is summarized by the following relation in the Minimal Supersymmetric Standard Model (MSSM)**

$$-\frac{m_Z^2}{2} = |\mu|^2 + m_H^2$$

If the superpartners are too heavy, contributions to the right-hand side must be tuned against each other to achieve electroweak symmetry breaking at the observed energy scale.

$$\delta m_H^2\Big|_{stop} \cong -\frac{3y_t^2}{8\pi^2}\left(m_{Q_3}^2 + m_{U_3}^2 + |A_t|^2\right)\ln\left(\frac{\Lambda}{TeV}\right)$$

$$\delta m_H^2\Big|_{gluino} \cong -\frac{2y_t^2}{\pi^2}\left(\frac{\alpha_s}{\pi}\right)|M_3|^2 \ln^2\left(\frac{\Lambda}{TeV}\right)$$



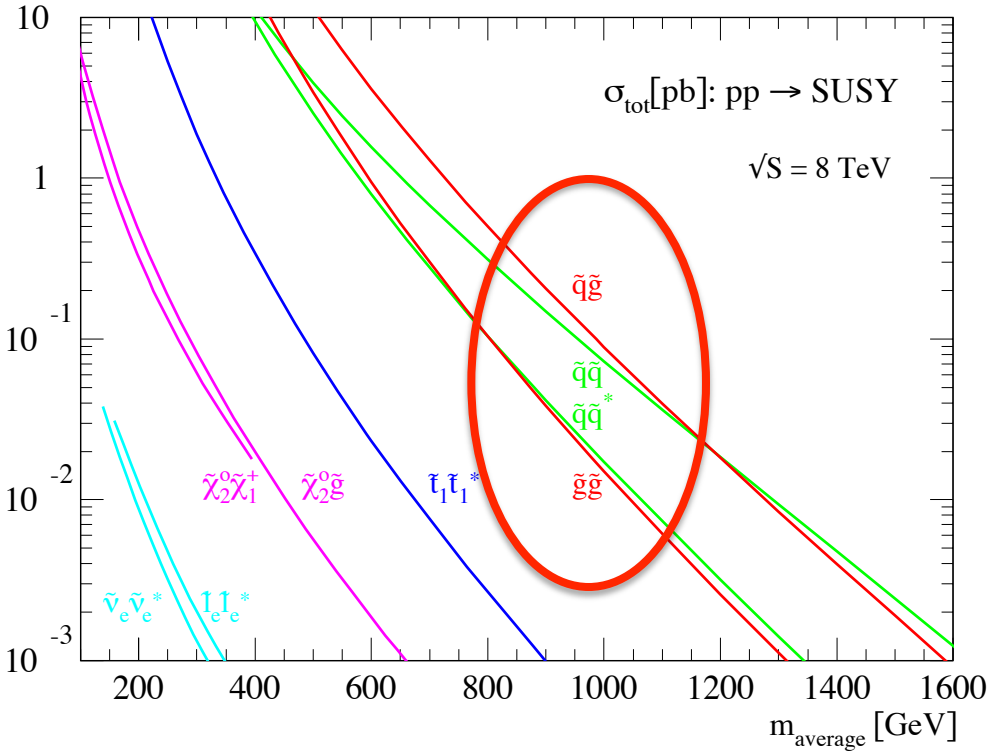
In a natural theory we expect:

- Two *higgsinos*, i.e. one chargino and two neutralinos of a few hundred GeV ($\mu \cong m_Z$ at tree level)
- ***stop* and *sbottoms*** up to several hundred GeV (1-loop radiative corrections)
- *Gluinos* up to a few TeV (2-loop radiative corrections)

Common analysis strategies

The analyses presented in the following slides share a common approach:

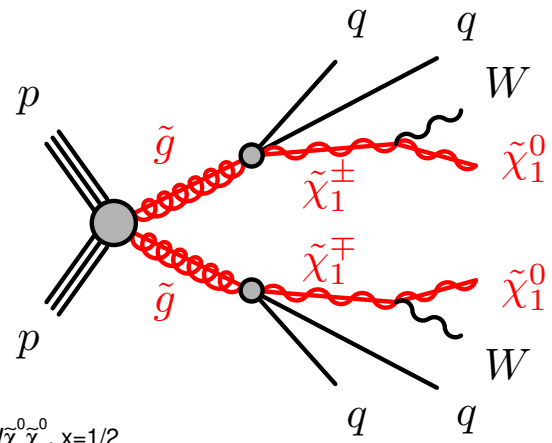
- Define a *Signal Region* (SR) based on signal kinematic features
- Estimate the Standard Model processes in the SR:
  - **Data-driven** reducible backgrounds (QCD multijet backgrounds)
  - **Semi data-driven** major irreducible backgrounds
    - Define a *control region* (CR) for each of the backgrounds
    - Normalise MC yields to data $N(\mathrm{SR}) = (N^{\mathrm{Data}}(\mathrm{CR}) - N_{\mathrm{others}}(\mathrm{CR})) \frac{N^{\mathrm{MC}}(\mathrm{SR})}{N^{\mathrm{MC}}(\mathrm{CR})}$
    - Apply transfer factor from CR to SR
  - Minor backgrounds are taken from **MC simulation** only
- Check background estimation against data in *Validation Regions* (VR)
- Look at the observed data in the SR

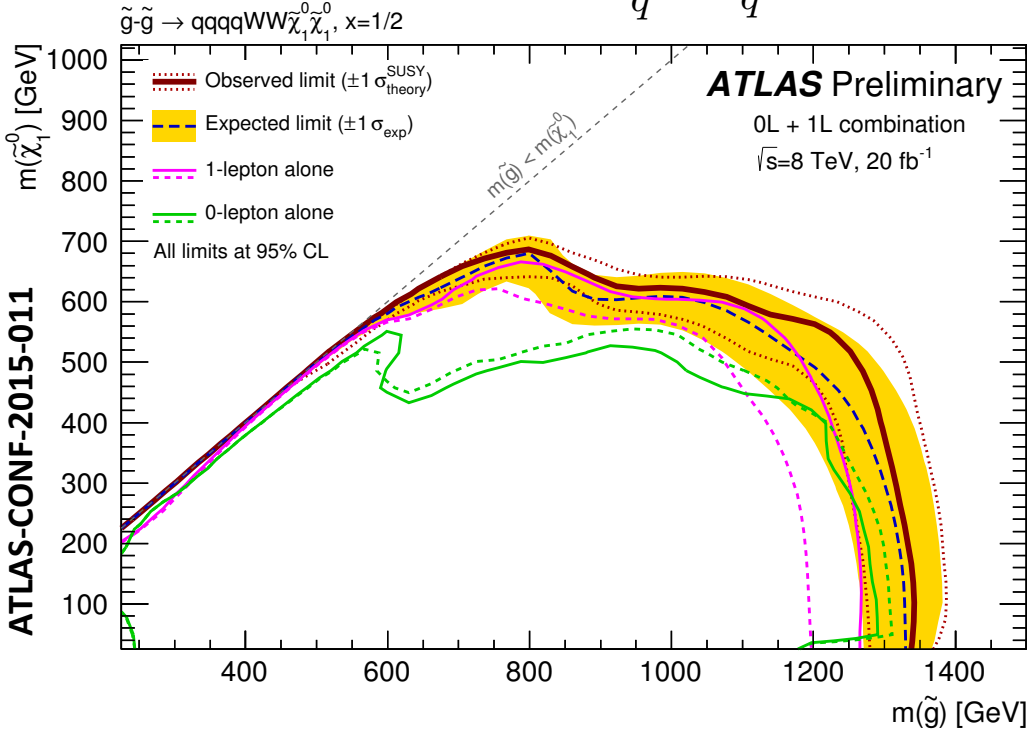


INCLUSIVE STRONG PRODUCTION SEARCHES

- 0L + 1L combinations
- Inclusive searches (Gtt)
- Z+MET excess
- Direct scharm pairs
- RPV multi-jets
- Prospects

Inclusive searches





Comprehensive search strategy: several complementary SRs to get the best sensitivity:

- a lepton veto
- soft lepton
- hard lepton

Many simplified models interpretations, with a single production and decay process.

Combinations to strengthen limits and test holes in sensitivity

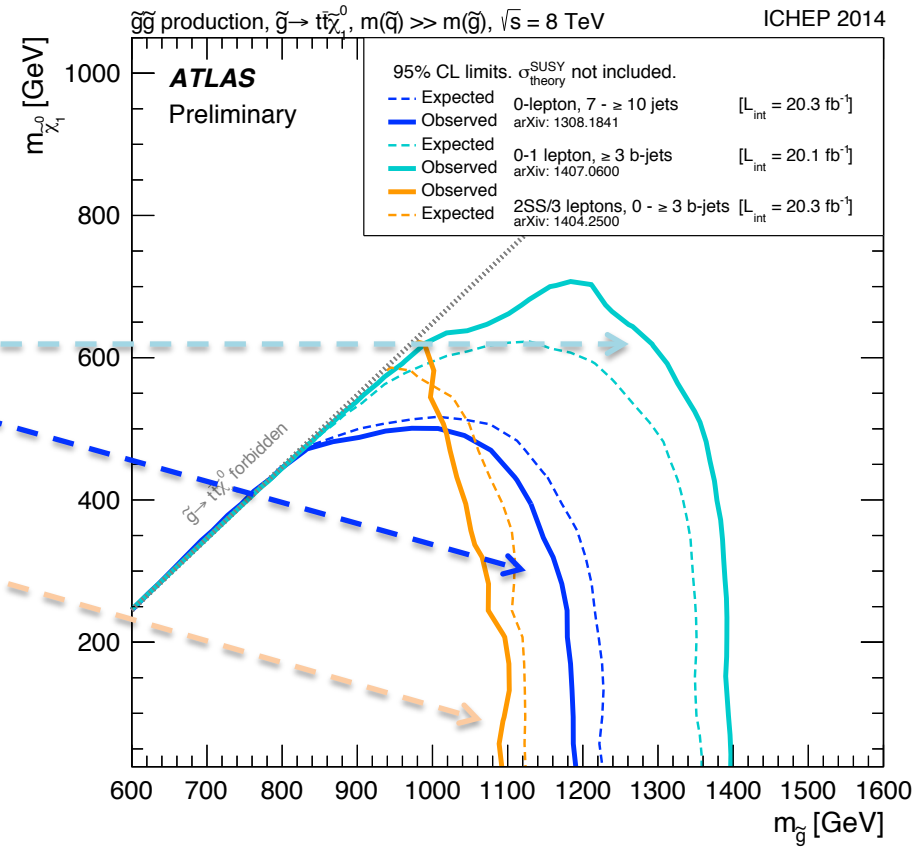
- Up to 100 GeV improvements

Gluino searches with top quarks

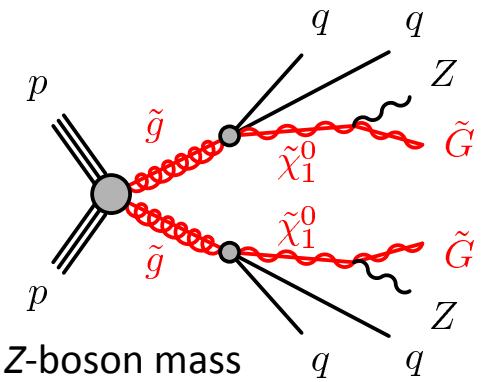
Gtt interpretation: a pair of gluinos decays promptly via off-shell stop to four top quarks and two lightest neutralinos (LSP)

Comprehensive search strategy:

- 0L, 7-10 jets
- 0-1L, ≥3 b-jets
- 2L SS/3L
  - **low-background** from SM: can also target low E_T^{miss} scenarios, like RPV, and compressed spectra.
    - Same-sign: two highest p_T leptons have same charge, with p_T >20,15 GeV, no other lepton with p_T > 15 GeV.
    - 3 lepton: three (or more) leptons with p_T > 20,15,15 GeV

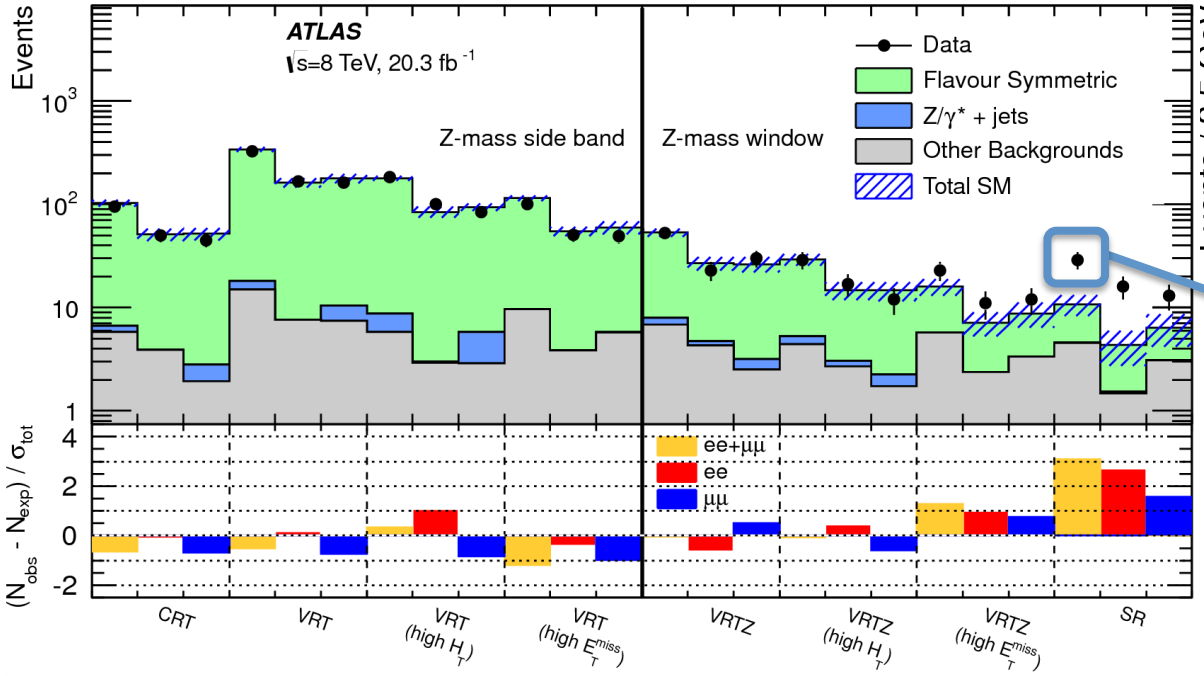


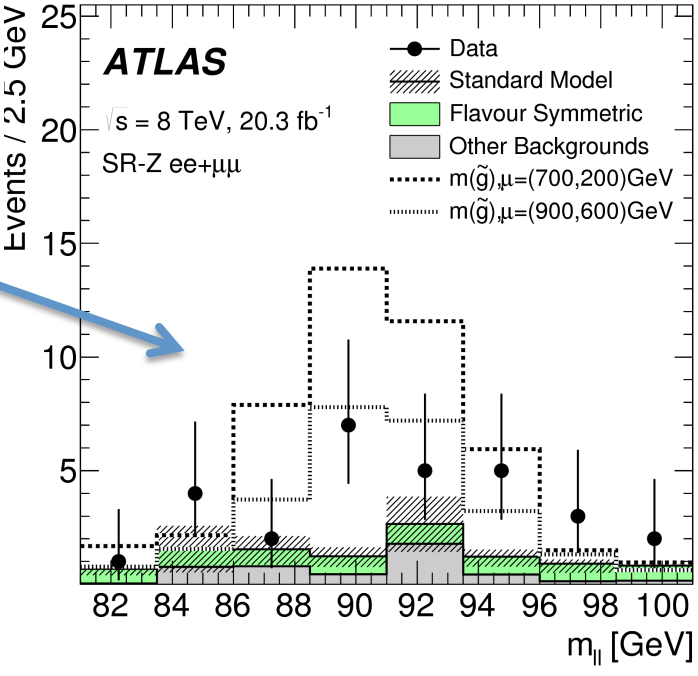
Z+MET



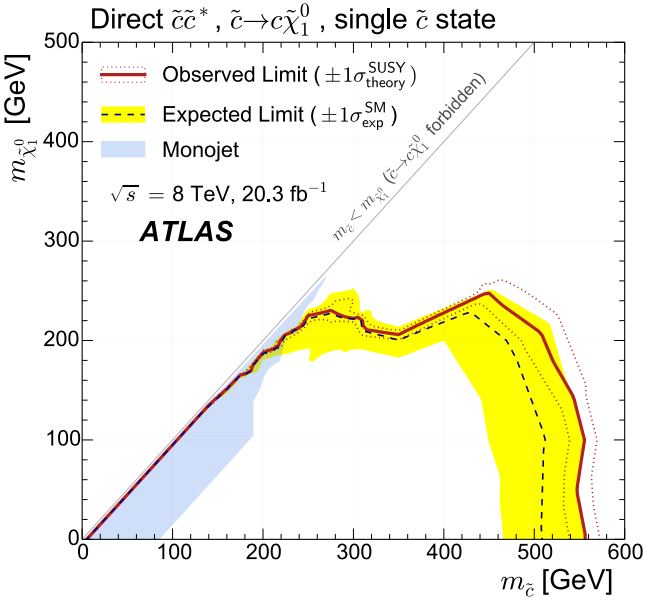
- Search for decays of squarks and gluinos with *Z* bosons in the final state
  - a peak in the dilepton invariant mass distribution around the *Z*-boson mass
- Data-driven background estimates for all major backgrounds
- Several regions / methods for **cross-checks**
  - 1.7σ excess in μμ, 3.0σ excess in ee

arXiv: 1503.03290





Direct scharm pairs



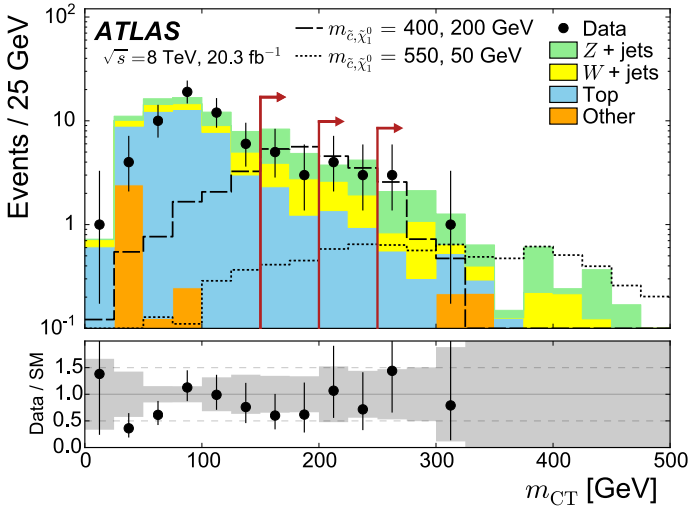
Large E_T^{miss} and at least two jets, where the two leading jets are each tagged as originating from c-quarks.

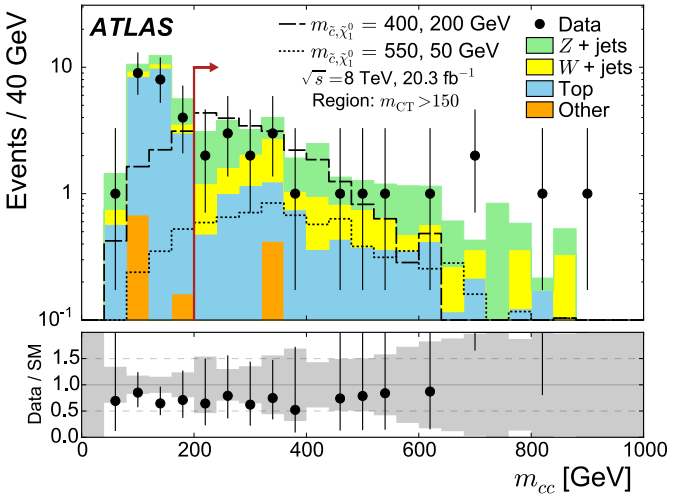
c-jet tagging efficiency calibrated in inclusive jet events over a range of p_T using jets from collision data containing D* mesons.

- c-tagging efficiency of 19% (13%, 0.5%) is achieved for c-jets (b-jets, light-flavour or gluon jets) in ttbar events.

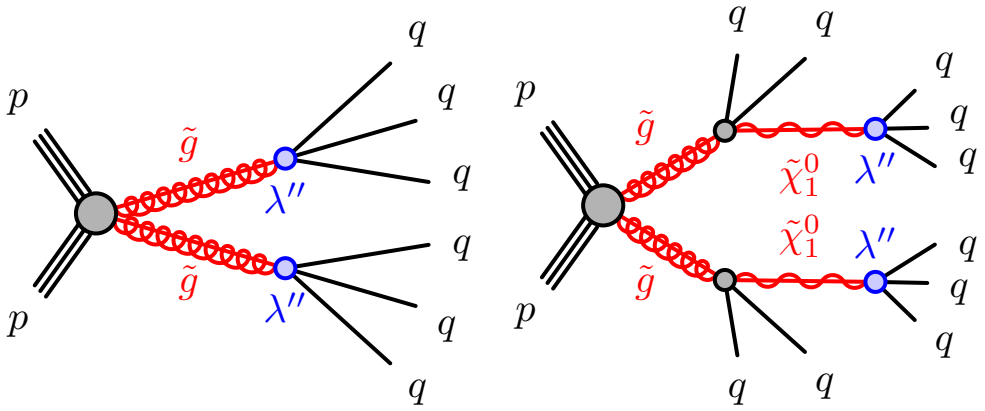
Final selections on m_{CT} and m_{cc}

arXiv: 1501.01325



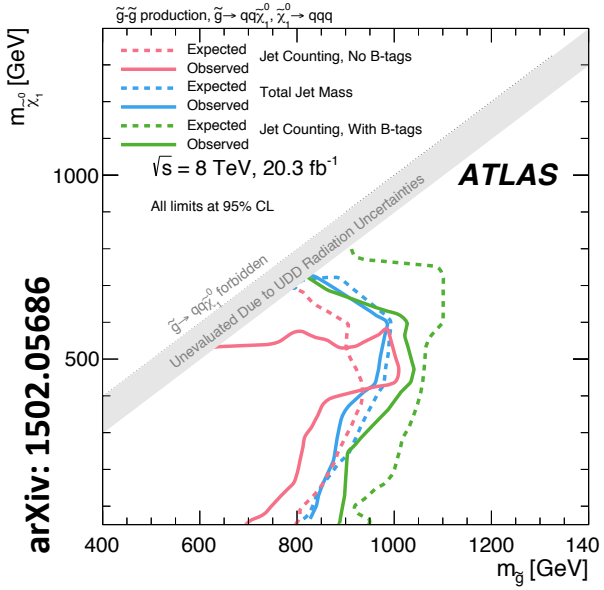


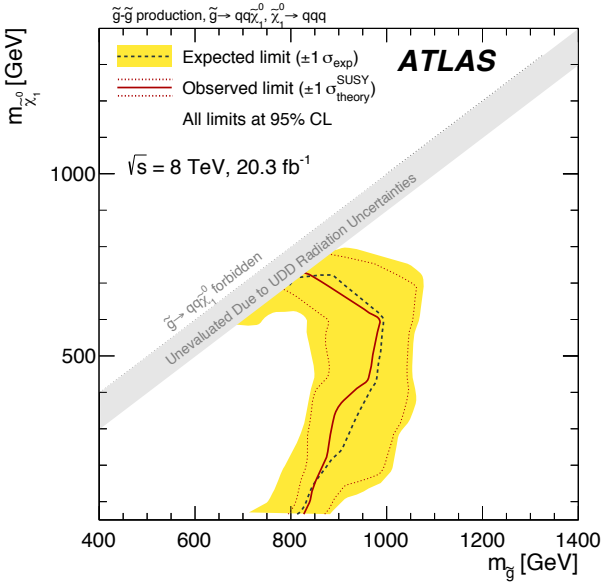
RPV multi-jet



Two search strategies

- **Jet counting** analysis
  - Look for and excess of events with 6 or more jets (0-2 b-jets)



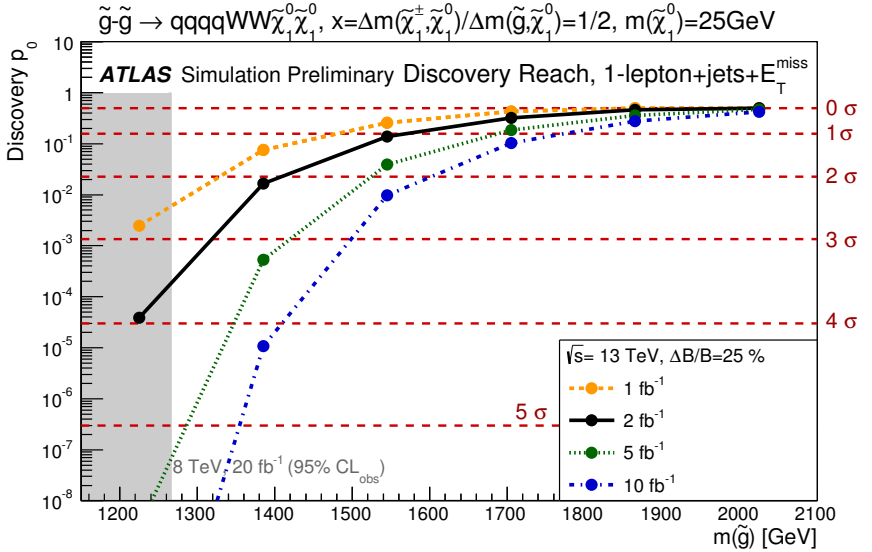


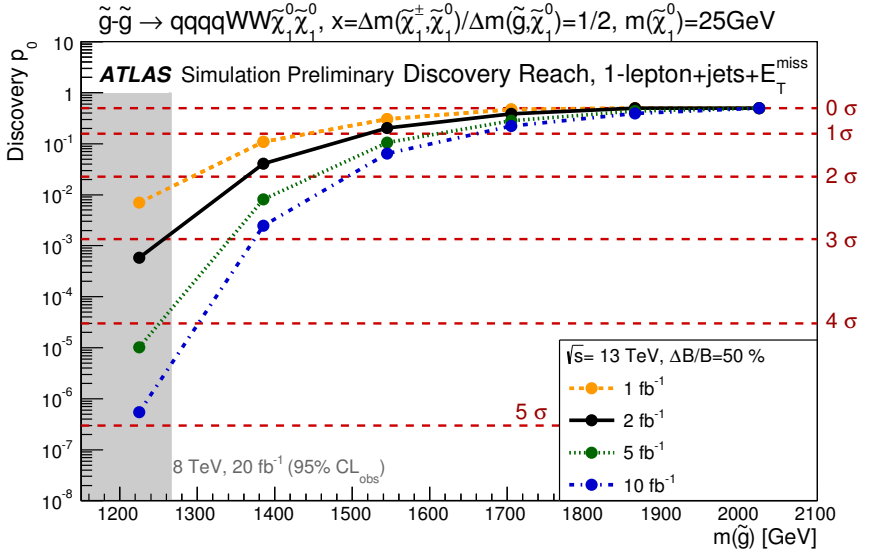
- **Total jet mass** analysis
  - Scalar sum of masses of the four leading large-R jets

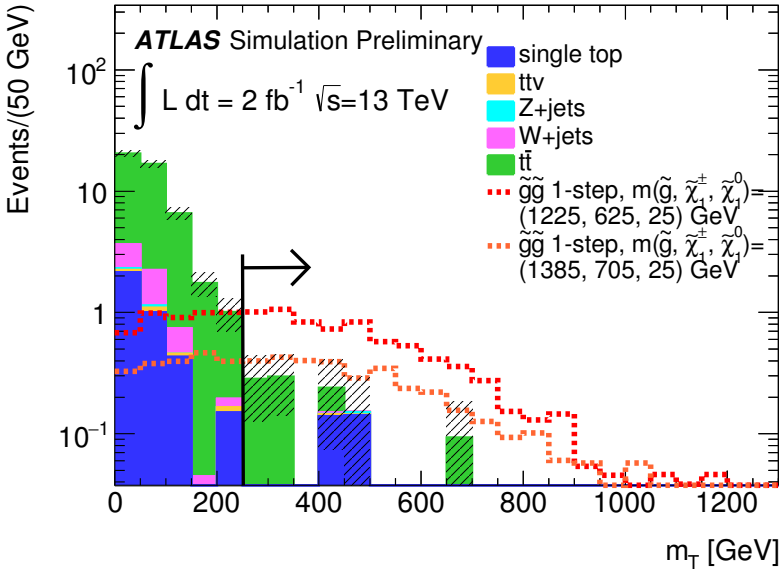
No excesses observed

Prospects

- Getting ready for 13TeV data
- First collisions will come **soon!**
- Simple selections
  - 3σ evidence with 2-10 fb^{-1}, even with poor systematics assessment







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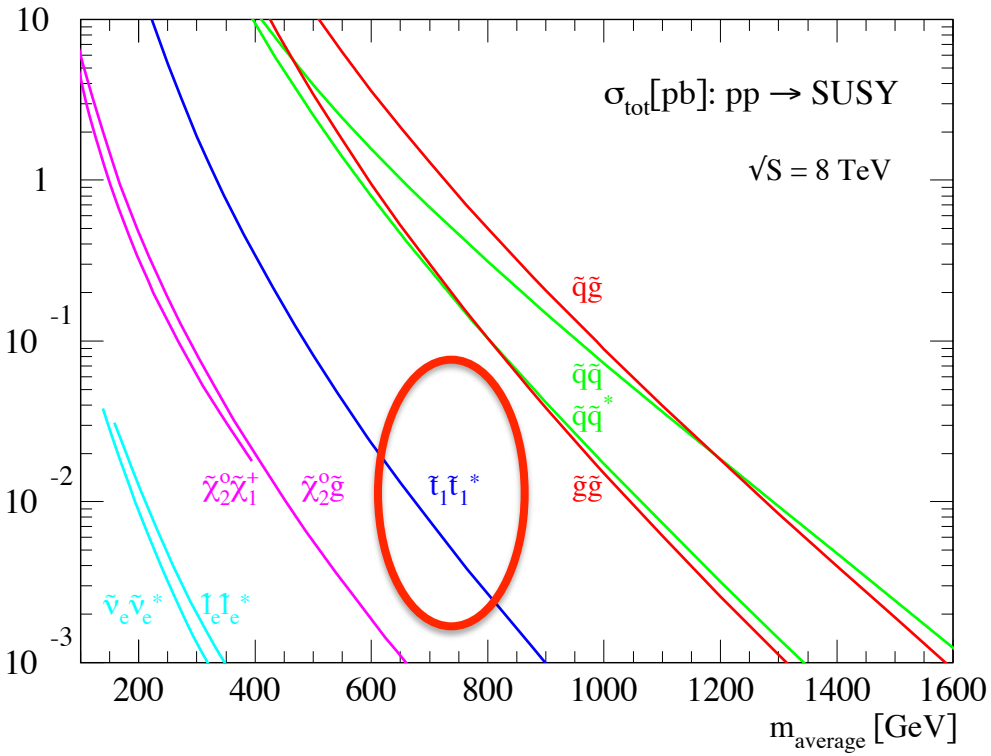
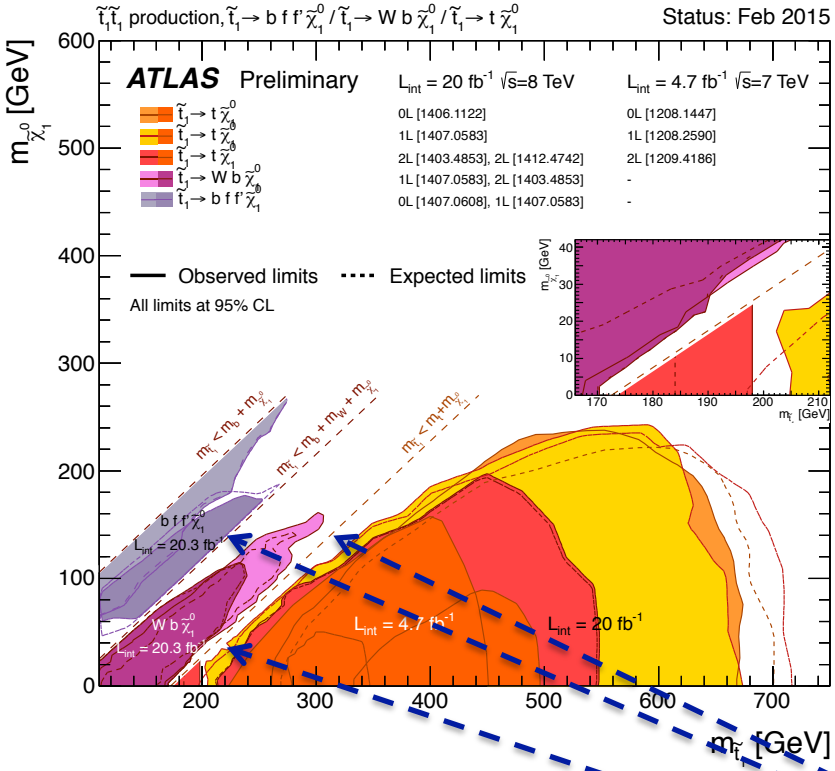
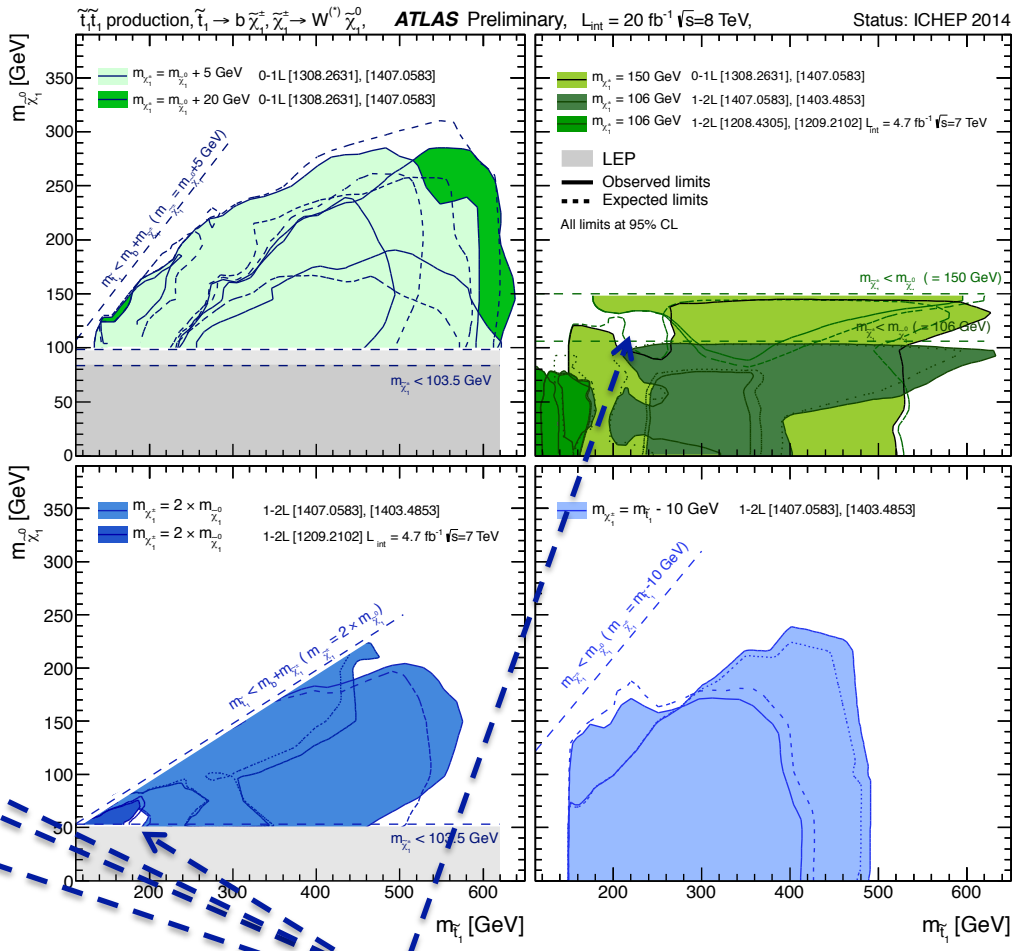


THIRD GENERATION SQUARK SEARCHES

- Stop summaries
- 0L + 1L combinations
- Tricky corners
- RPV stop
- Prospects

Summary of stop searches

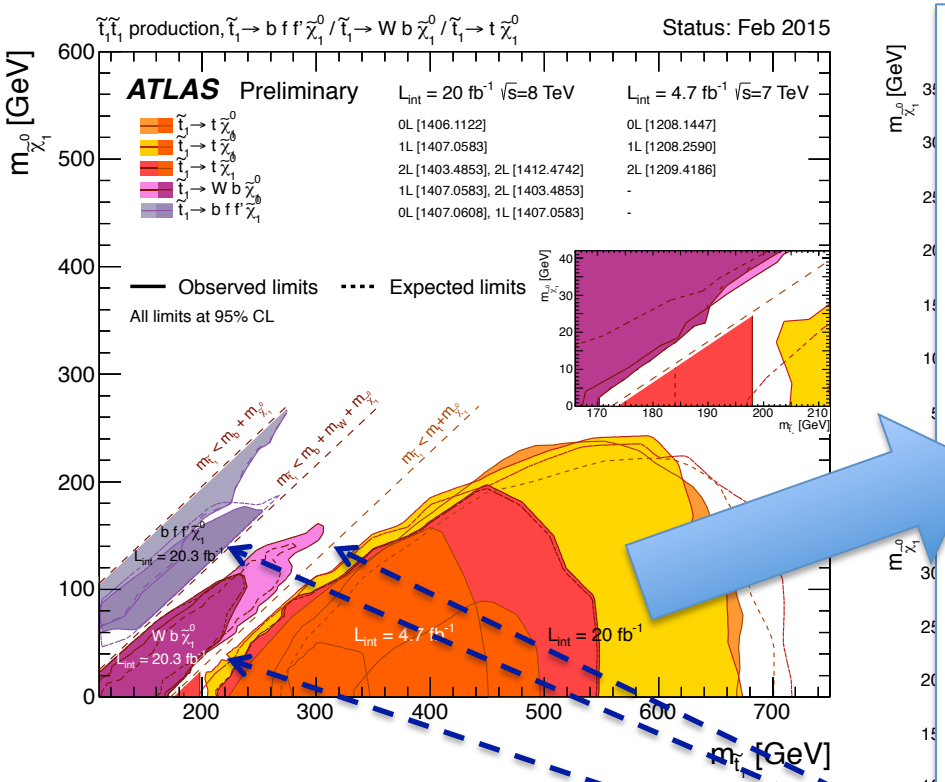




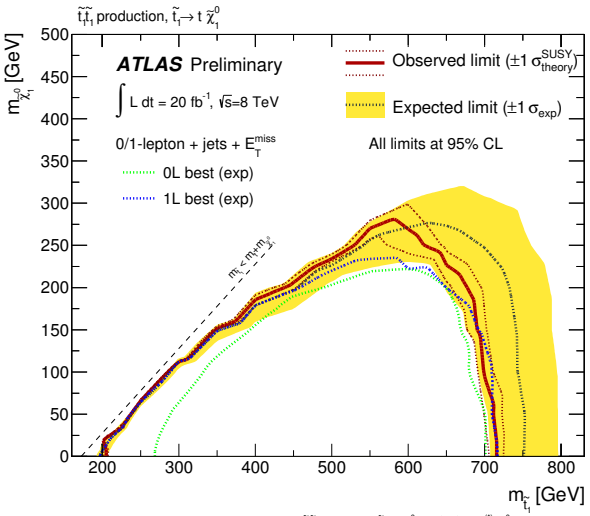
Comprehensive search program

- 0L, 1L, 2L, mono-jet searches
- Some difficult low-mass models still unexcluded

0L + 1L combination

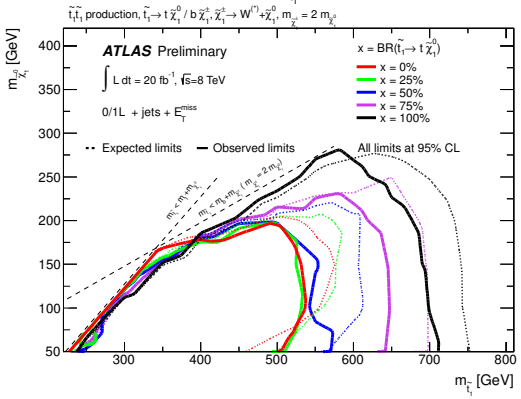


Combinations to strengthen limits and test holes in sensitivity (0L + 1L) for stop → t+N1

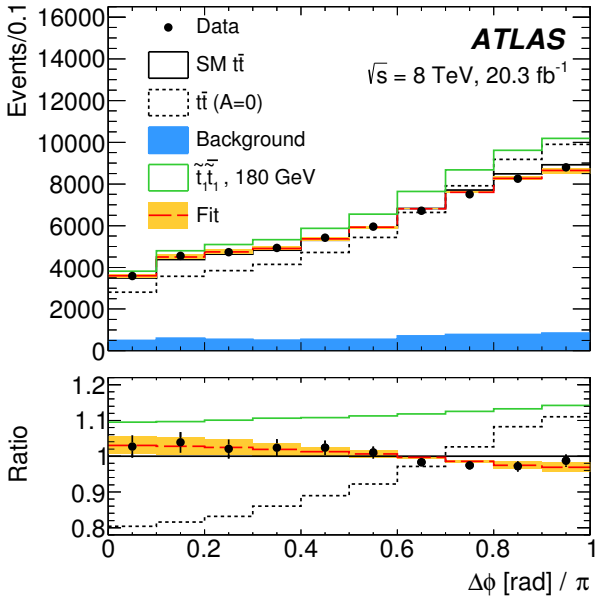


ATLAS-CONF-2015-010

Sensitivity as a function of the branching ratio to competing models (bC1) also studied in combination.

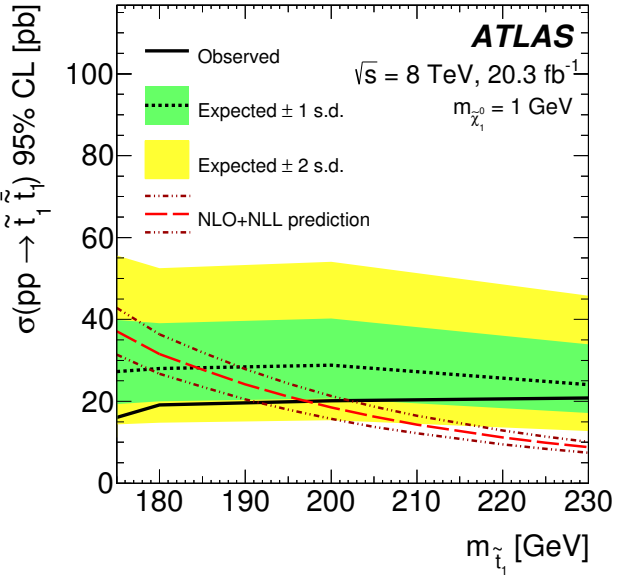


Tricky corners

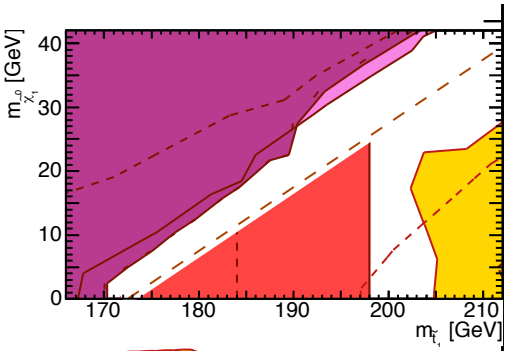


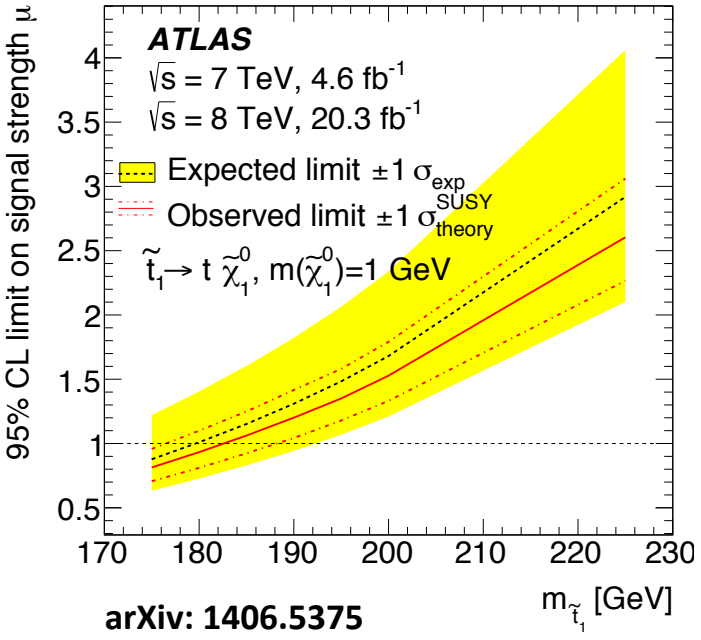
arXiv: 1412.4742

- Stop squarks **just above the top mass** are *very* difficult to find
  - Pure (90%) sample of dileptonic top events, look at **spin correlations**
- Test the **angle between the charged leptons** for consistency with SM, and for SM plus a very light top squark, we can exclude $m_{top} < m_{stop} < 191$ GeV



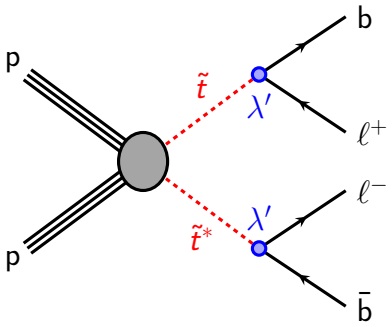
The ttbar **cross-section measurement** was **re-interpreted** to place limits on top squarks





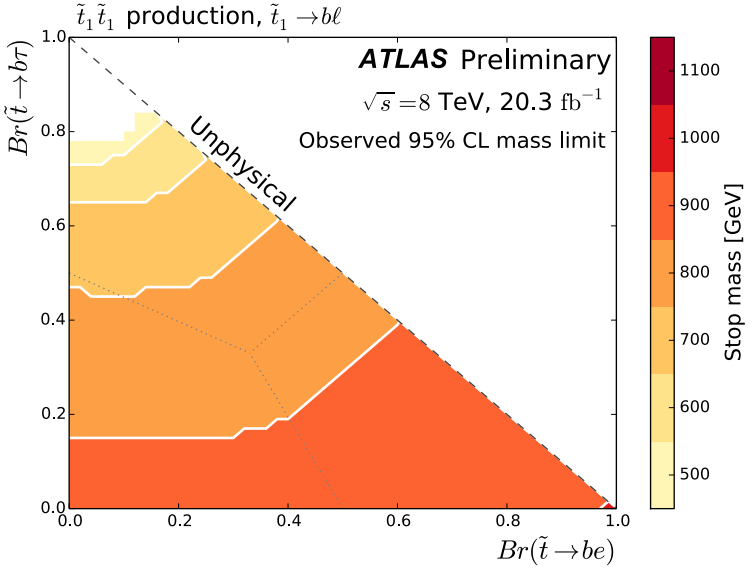
arXiv: 1406.5375

RPV top squarks



- 2 OS leptons (e,μ)
- 2 b-jets

Search for 2 b-l resonances with similar mass.



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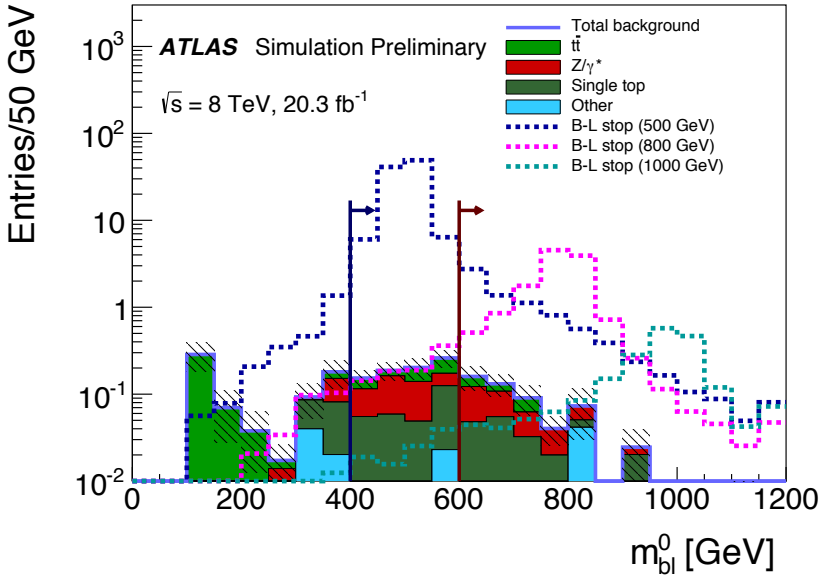
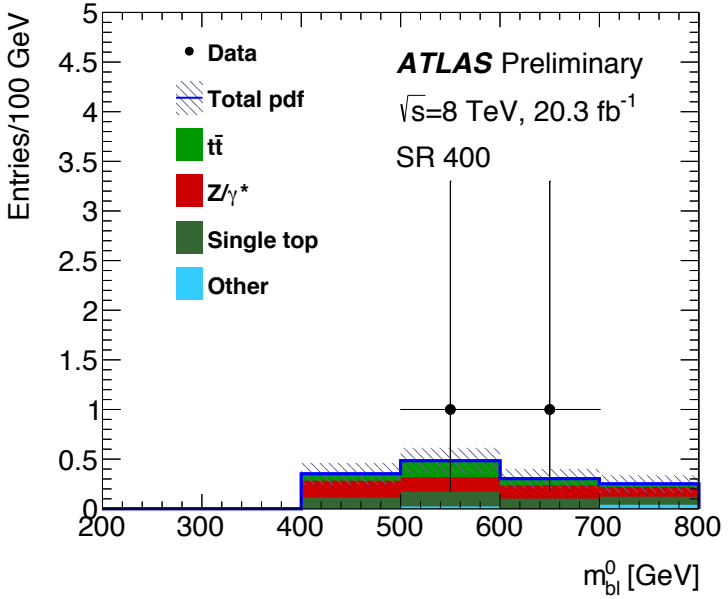
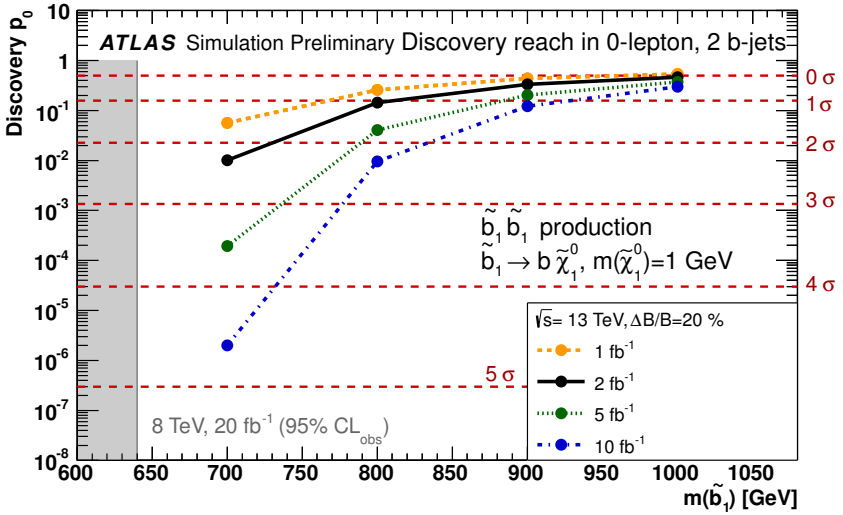
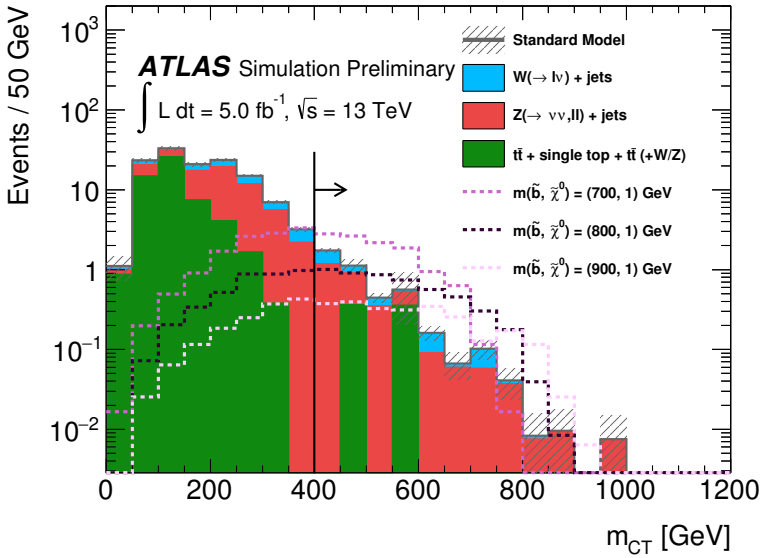


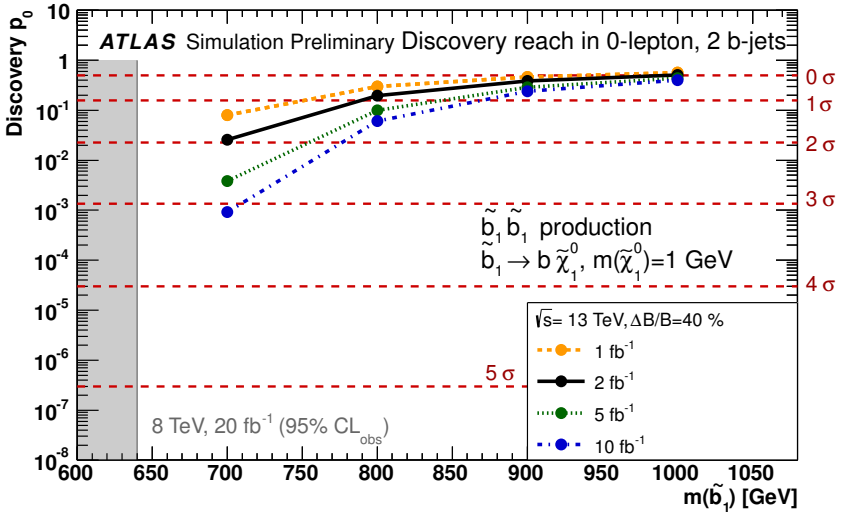


Prospects

- **3σ evidence** of third generation squarks with 2-10 fb^{-1} **possible** in the 2015 dataset
- Best early sensitivity above run I limits coming from m_{CT} based sbottom searches







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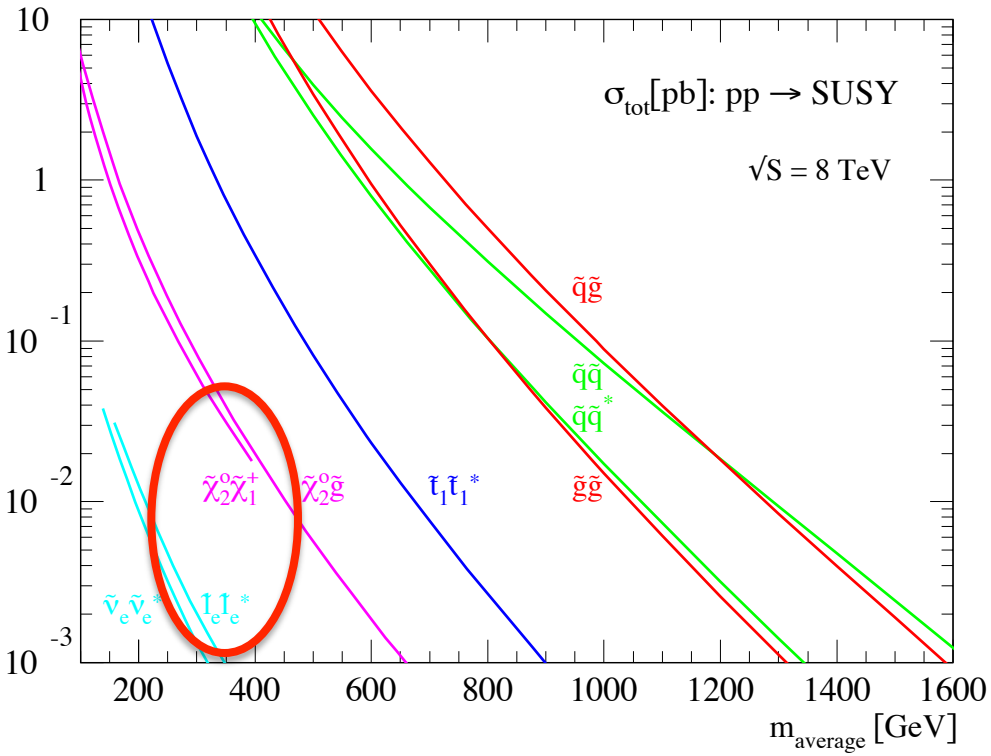
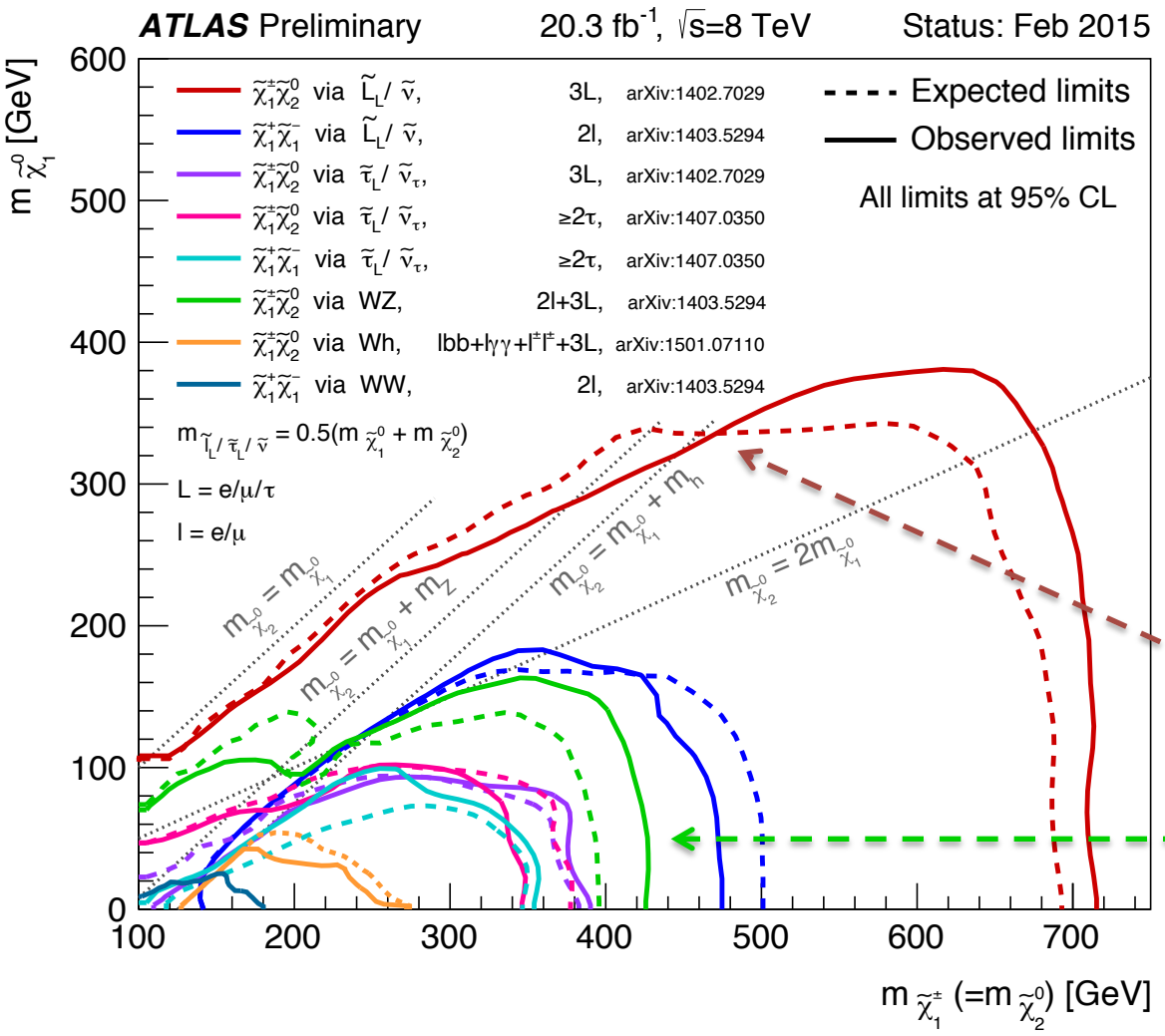


ELECTROWEAK SEARCHES

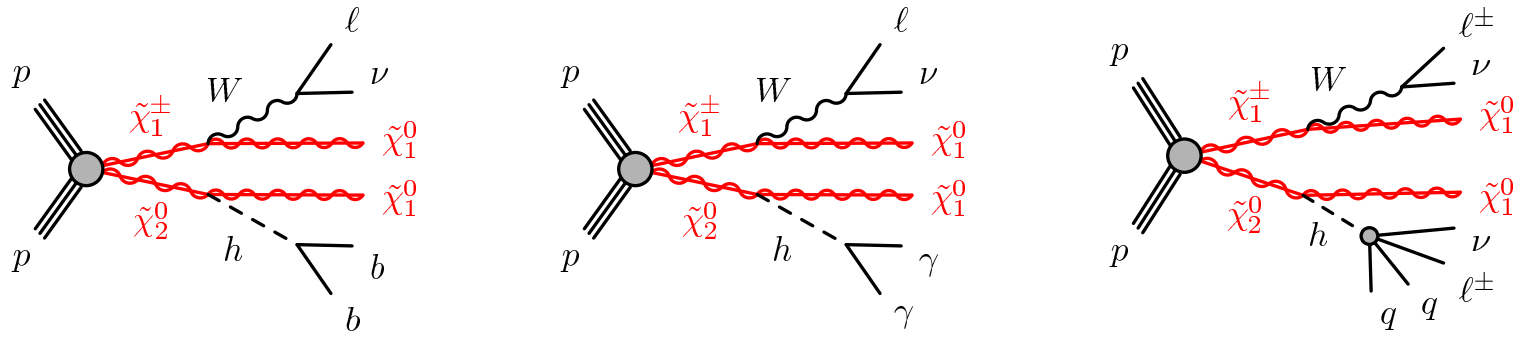
- EWK summary
- C1,N2 decays via Higgs bosons

EWK summary

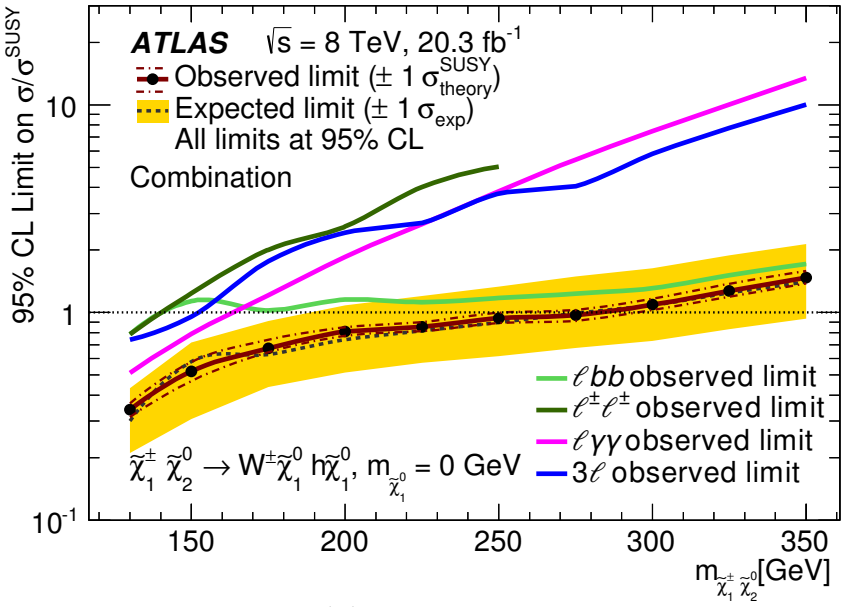


- **Very clean multi-lepton signatures.**
  - Low hadronic activity.
- Many different final states.
- Set limits vary wildly depending on the model assumptions
  - Decay through sleptons
  - Decay through SM vector bosons

Chargino, neutralino pairs decays to the 125 GeV Higgs boson



arXiv: 1501.07110



(d) Combination

C1, N2 pairs decaying via SM-like Higgs boson.

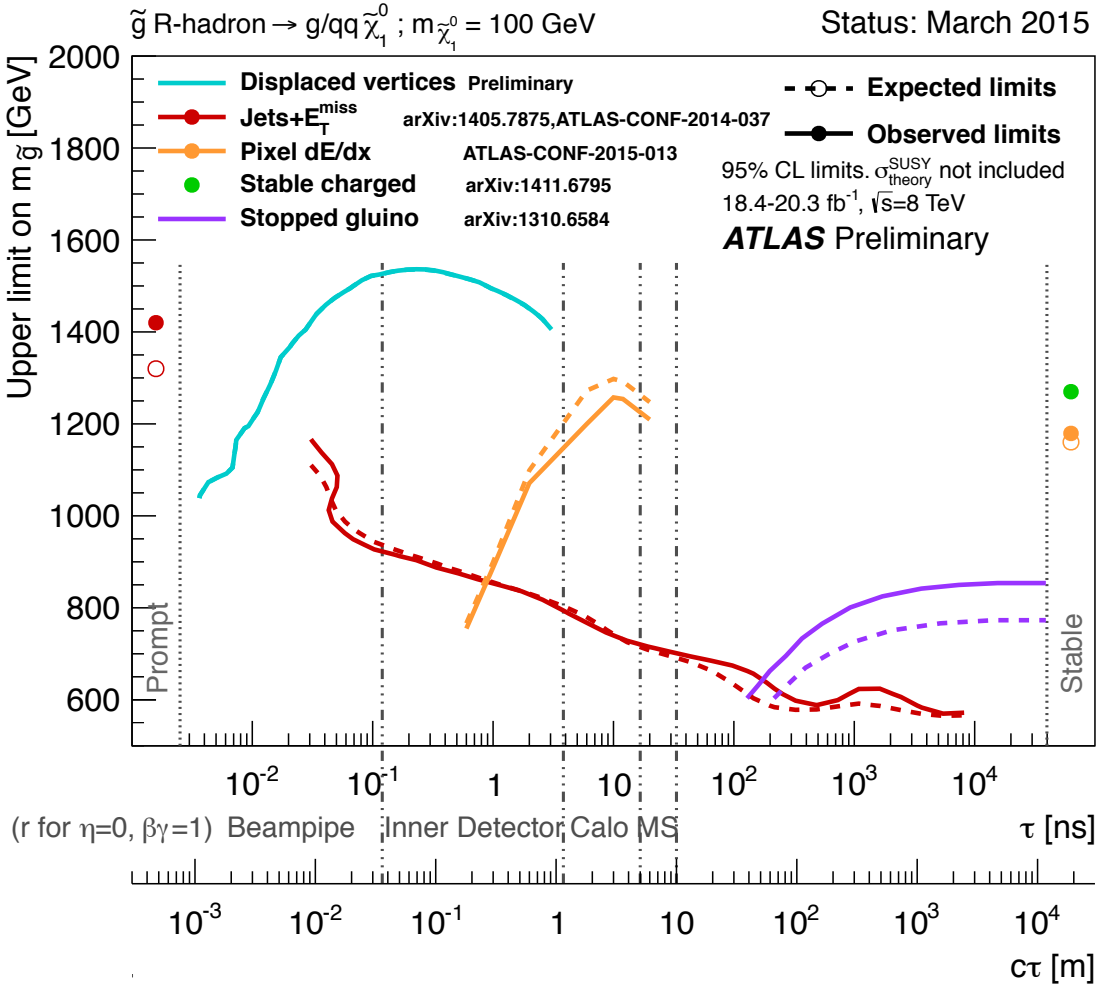
Three channels analyzed and combined:

- 1L bb (W→lν, h→bb)
- 1L γγ (W→lν, h→γγ)
- 2L SS (W→lν, h→WW)

LONG LIVED PARTICLE SEARCHES

- LLP summary
- Displaced vertices
- dE/dx

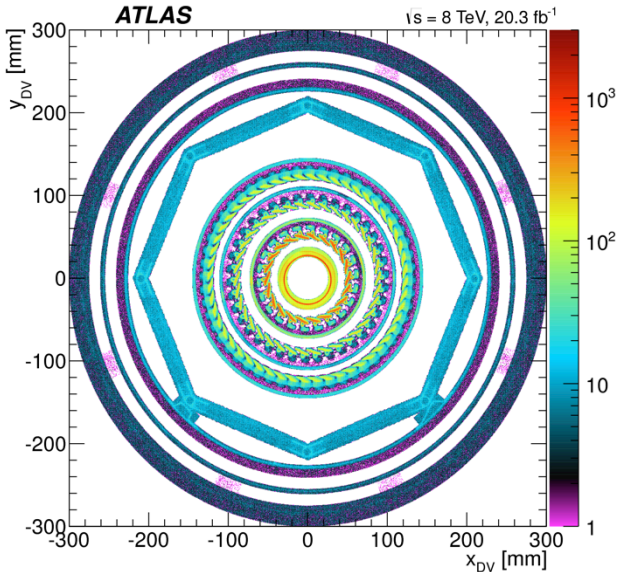
LLP summary

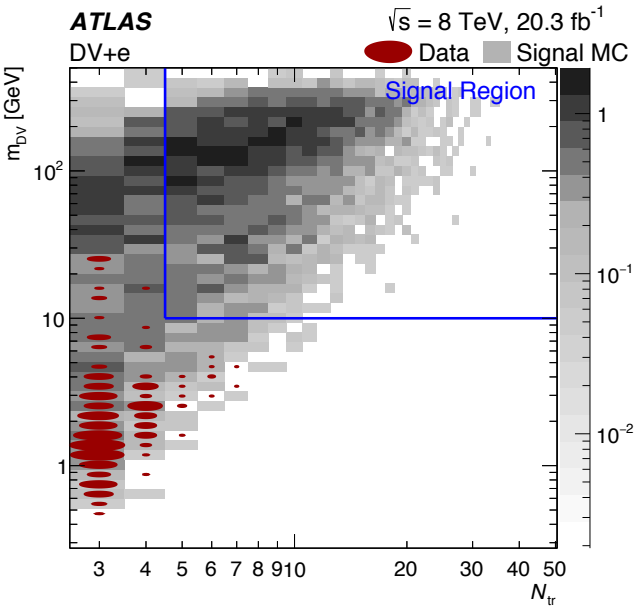


Long-lived SUSY particles can arise from:

- Heavy mediator sparticles (Split SUSY)
- Mass degeneracy
- Weak couplings
- Small RPV λ couplings

Displaced vertices

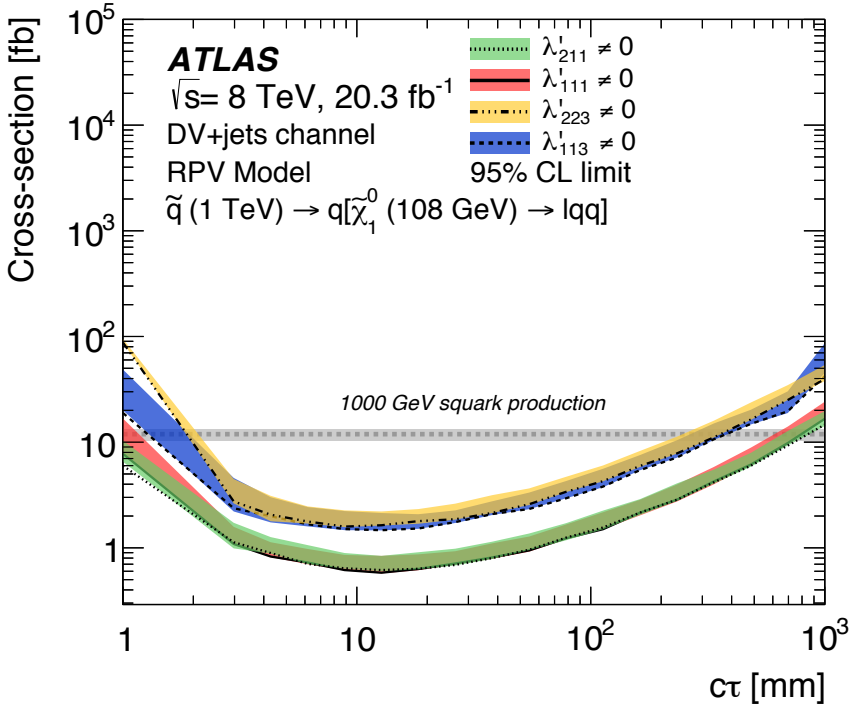




arXiv: 1504.05162

Search for displaced vertex (DV) in the inner detector: r < 30 cm, z < 30 cm.

- Veto vertices near detector material
- No events observed in any signal region.

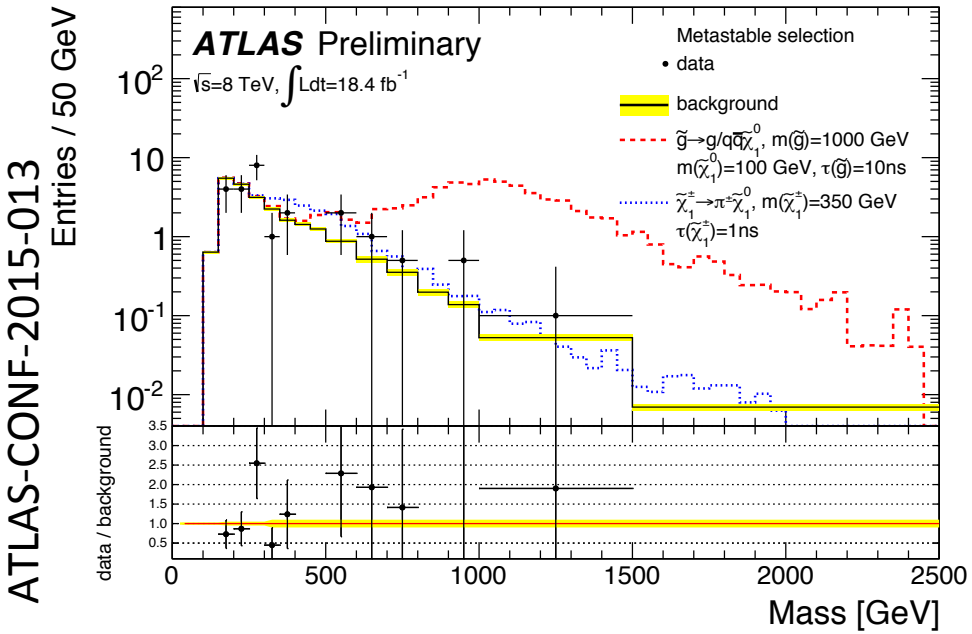


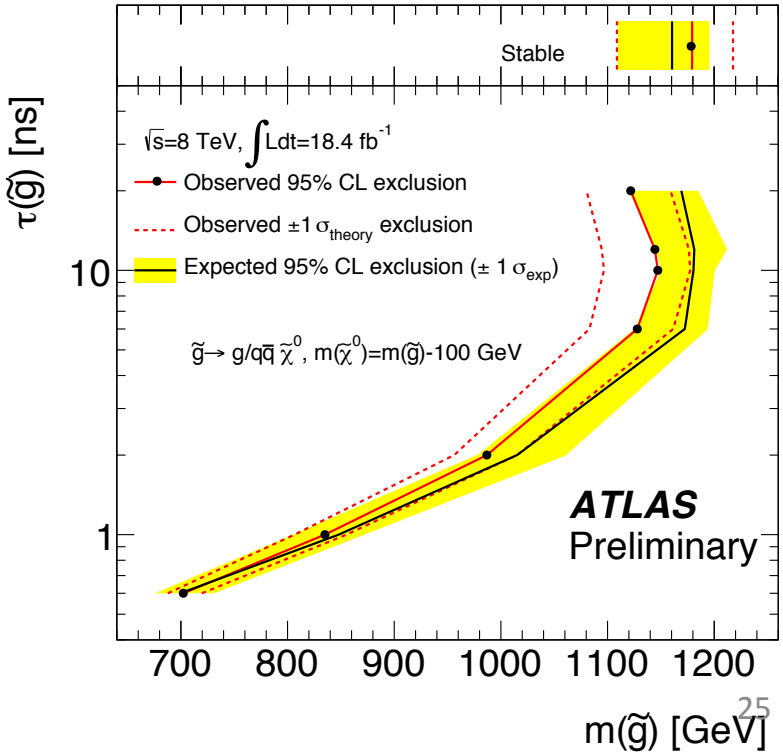
Heavy stable charged particles

Identify low-β particles by:

- large dE/dx from pixel tracker
- Track must extend to r > 45 cm.
  - *Stable*: veto muon from W (m_T<130 GeV).
  - *Metastable*: veto any muon.

- First limits on charged R-hadrons with 1-10 ns lifetime
- Stable charginos < 549 GeV are excluded





Conclusions and Outlook

The analysis of the 2012 data of ATLAS has yielded lots of results:

- 95% CL exclusion limits are set within various phenomenological assumptions
- the parameter space given by the naturalness argument is being filled up

Even if the results have been found consistent with Standard Model expectations, the search continues:

- Stay tuned for more results on 8 TeV data
- The gain in cross section due to the higher center of mass energy in run II will once again open the door to a discovery
- Largest increase in energy for many years to come

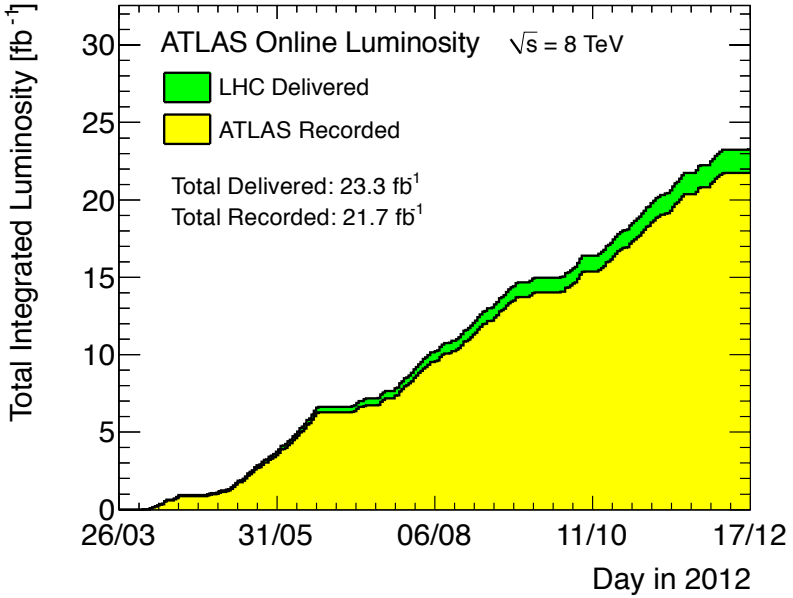
- **The early fb^{-1} of the 2015 run will be very exciting!**

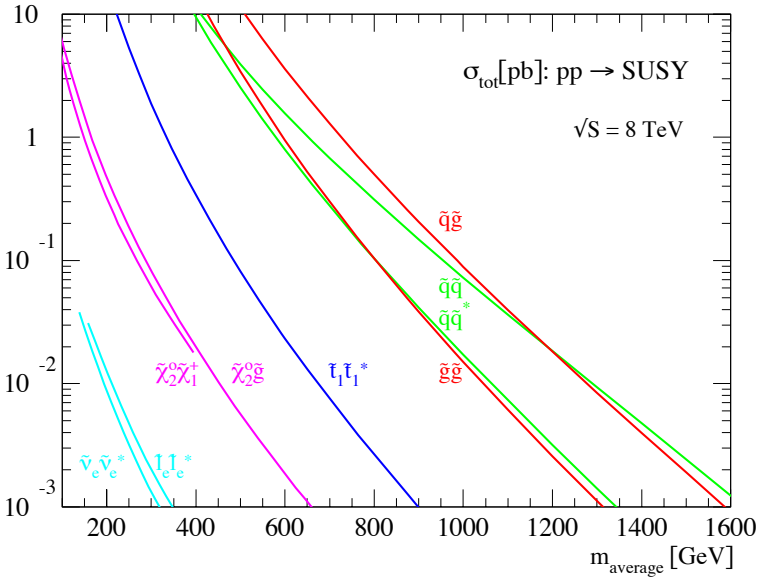
THANKS FOR YOUR ATTENTION!

Collected data and process sensitivity

The results shown in the following are based up to 20.3 fb^{-1} of data, collected between March and December 2012.

Only events satisfying good data quality cuts (i.e. collisions with all detectors in satisfactory working conditions) are considered for the analysis





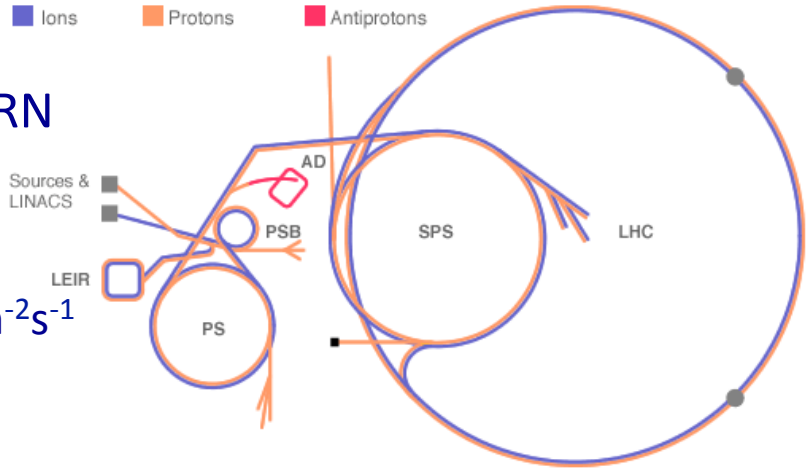
Considering the available integrated luminosity

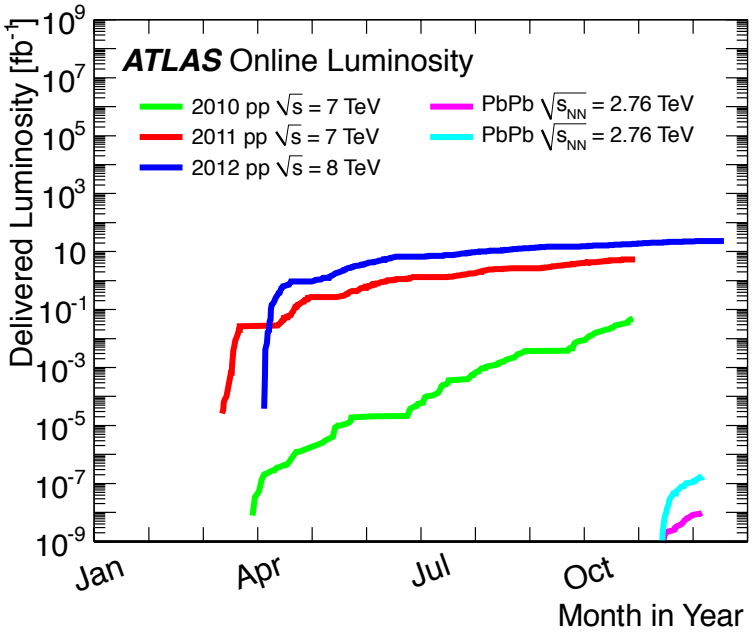
- *squarks* and *gluinos* up to 1.5 TeV
- Direct *top squarks* up to 700 GeV
- *charginos* and *neutralinos* up to 400 GeV
- *sleptons* up to 150 GeV

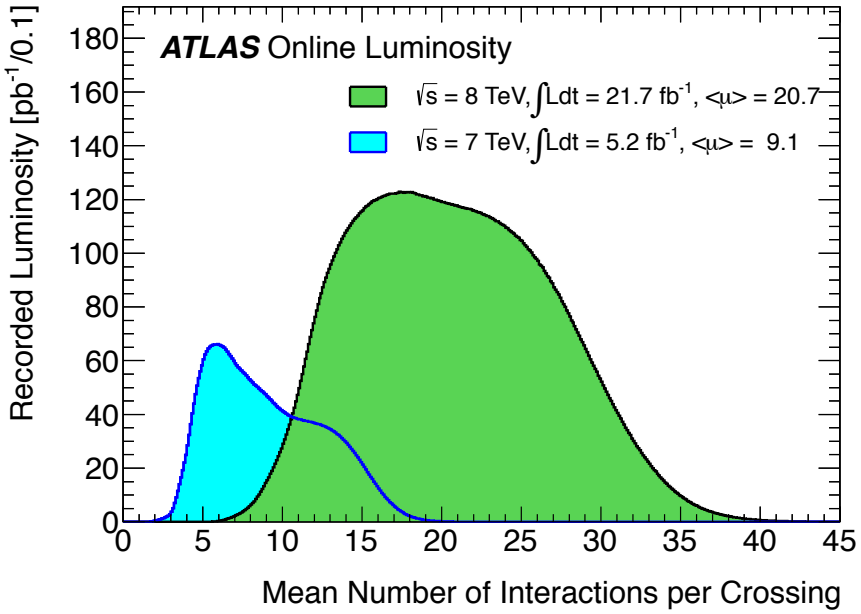
The Large Hadron Collider

LHC is a proton-proton collider situated at CERN

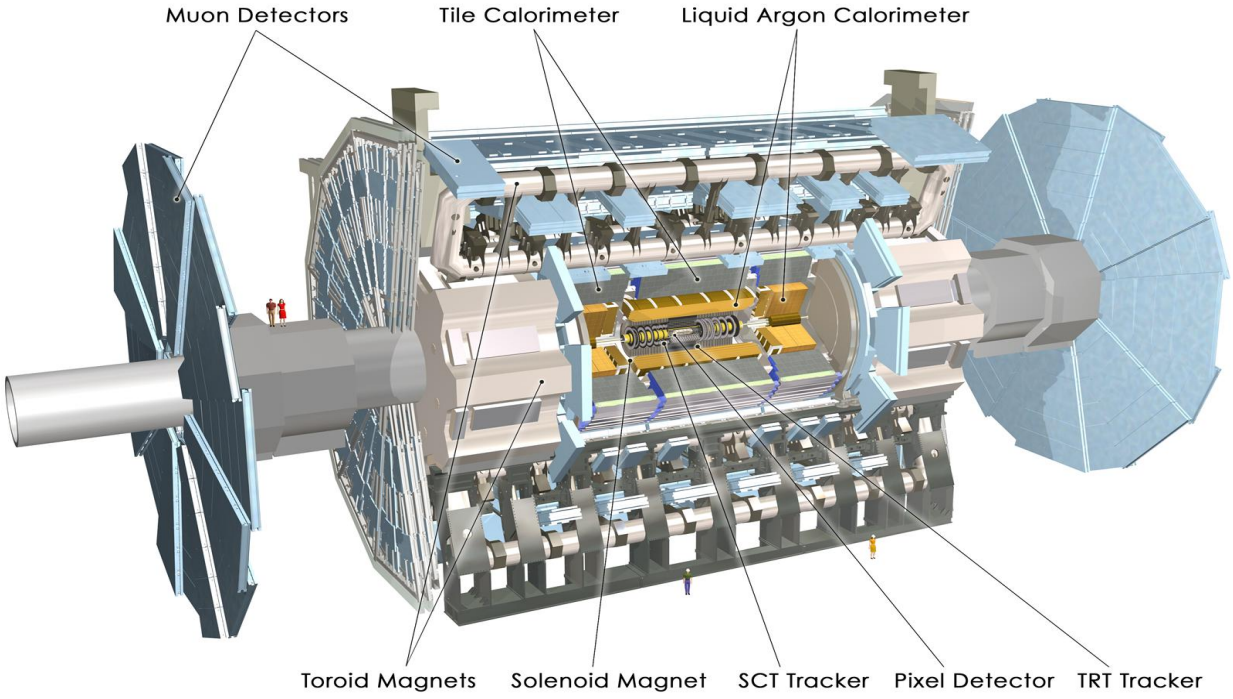
- Collisions at √s = 7 TeV (2010-2011)
- Collisions at √s = 8 TeV (2012)
- High instantaneous luminosities $L = 8 \times 10^{33}\ cm^{-2}s^{-1}$
- More than 25 fb^{-1} of data delivered before LS1







A Toroidal Lhc ApparatuS



ATLAS is a multi-purpose detector composed by:

- **Inner Detector**
  - Track reconstruction for charged particles
  - Primary and secondary vertex reconstruction
- **Calorimeters**
  - Measurement of electron, γ and jet energies
  - Hermeticity for E_T^{miss} reconstruction
- **Muon spectrometer**
  - Muon identification and reconstruction

Common background estimation strategies

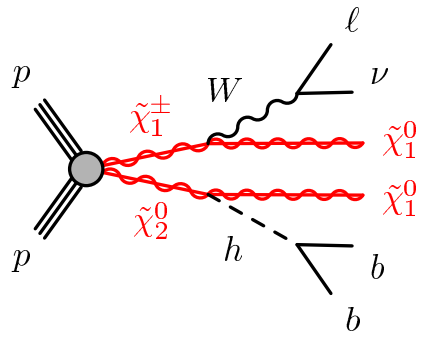
The analyses presented here share some common techniques to estimate the backgrounds:

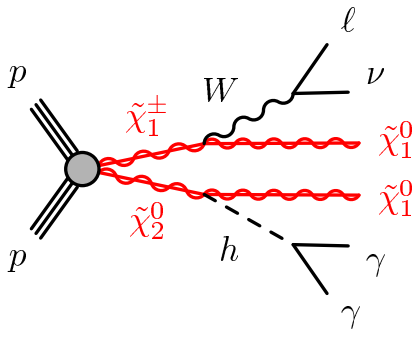
- QCD multijet backgrounds (data-driven)
  - *Hadronic searches*: Estimated smearing a sample of jets from a control region (CR) with a function taken from a simulated dijet sample
  - *Leptonic searches*: Fake rate measured in a CR with relaxed lepton identification criteria and used to estimate the rate in the signal region (SR)
- Major backgrounds (semi data-driven)
  - Define a control region for each of the backgrounds kinematically close to signal region
  - Normalise MC yields to data
  - Apply transfer factor from CR to SR subtracting other backgrounds in the region

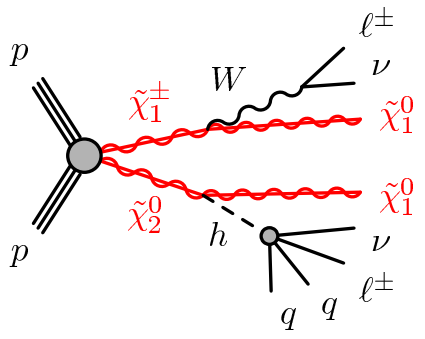
$$N(\mathrm{SR}) = (N^{\mathrm{Data}}(\mathrm{CR}) - N_{\mathrm{others}}(\mathrm{CR}))\,\frac{N^{\mathrm{MC}}(\mathrm{SR})}{N^{\mathrm{MC}}(\mathrm{CR})}$$

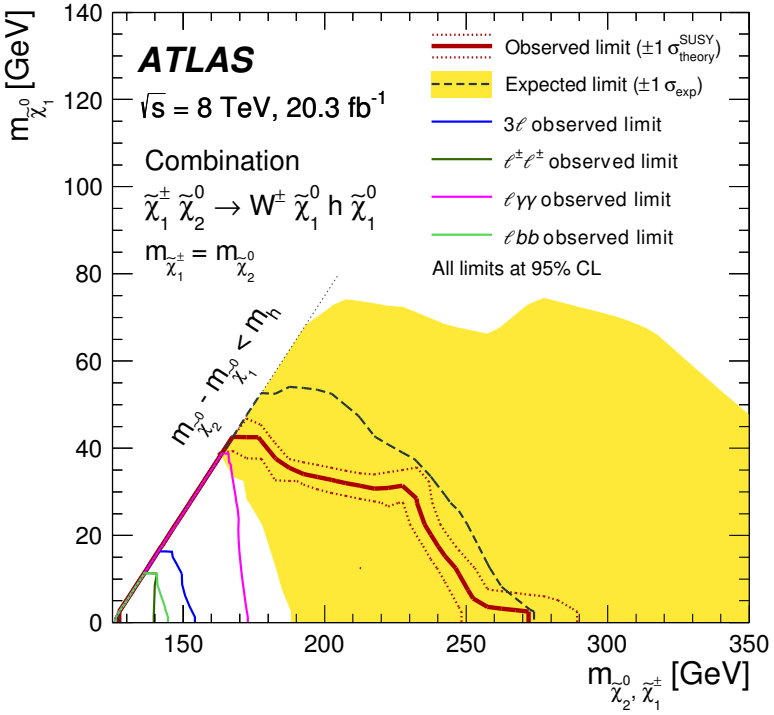
- Minor backgrounds are taken from MC simulation only

Chargino, neutralino pairs decays to the 125 GeV Higgs boson

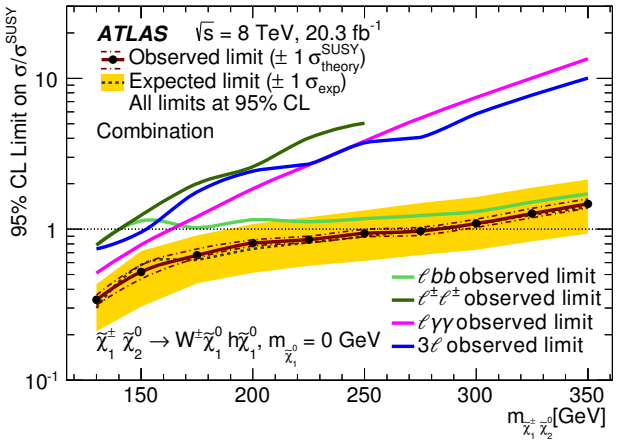








1L bb



(d) Combination