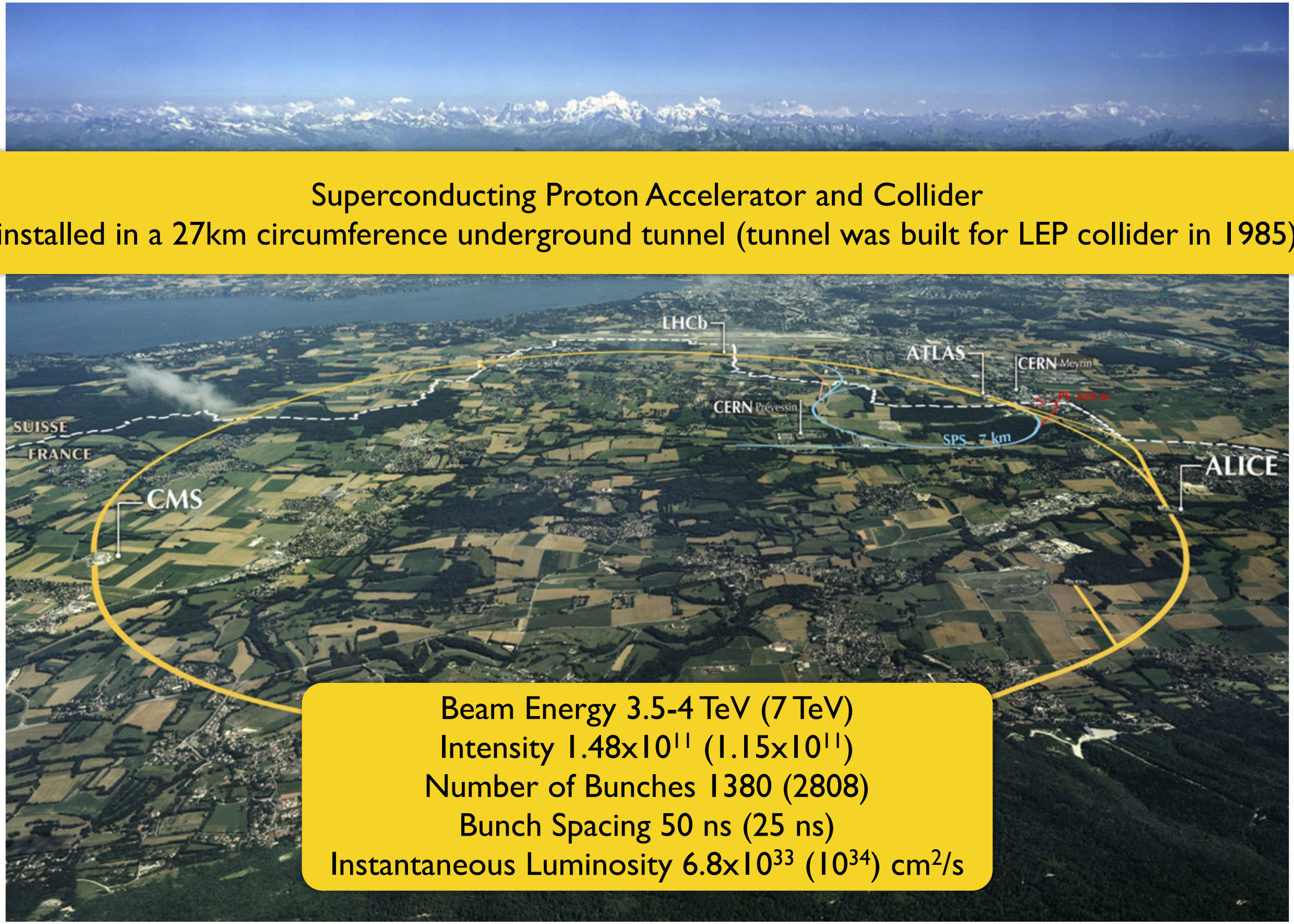
Hunt for SUperSYmmetry at the LHC with the

Zoltan Gecse

a place of mind
THE UNIVERSITY OF BRITISH COLUMBIA

CAP Congress, 2015

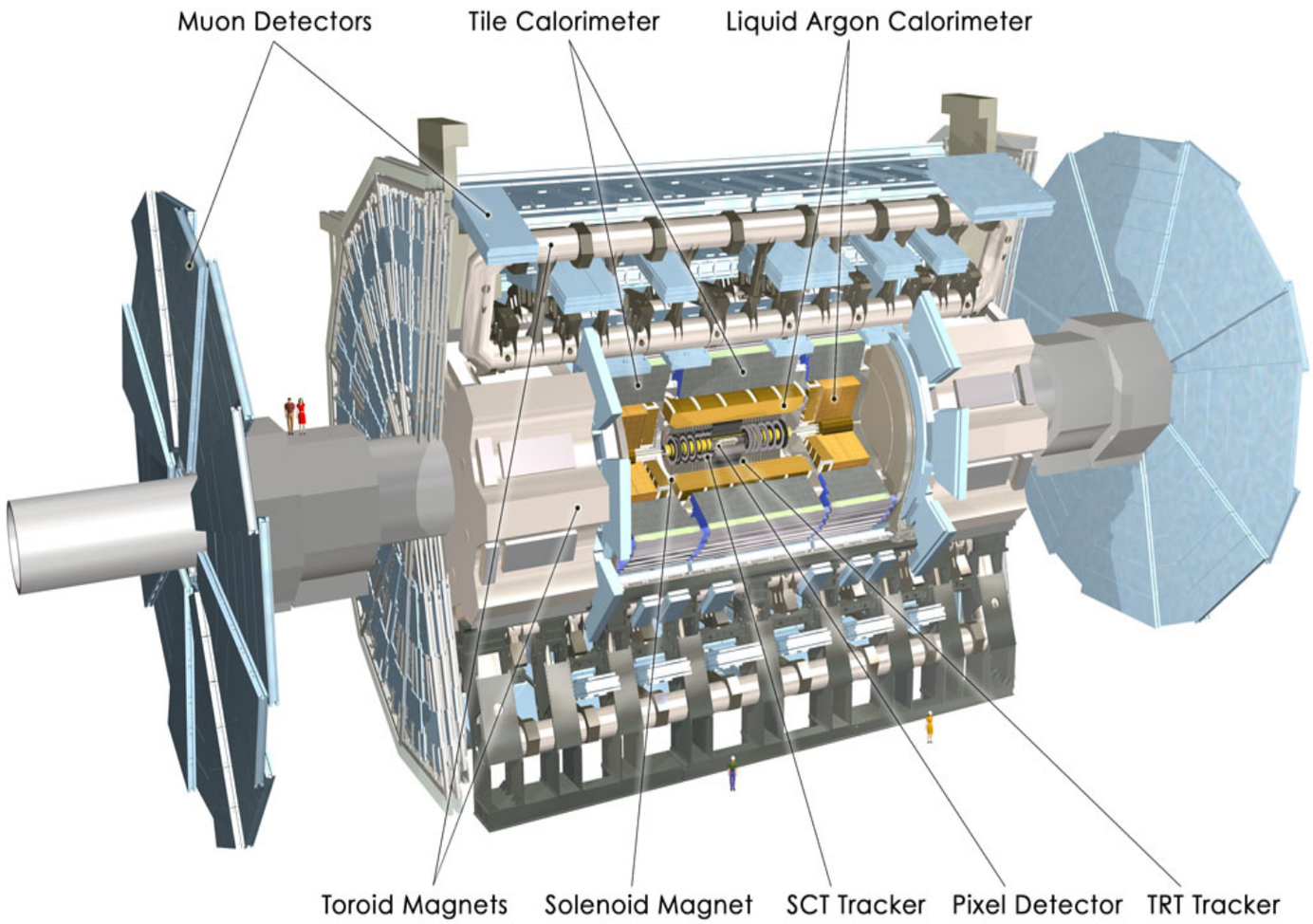
The Large Hadron Collider (LHC)



Superconducting Proton Accelerator and Collider
installed in a 27km circumference underground tunnel (tunnel was built for LEP collider in 1985)

Beam Energy 3.5-4 TeV (7 TeV)
Intensity 1.48×10^{11} (1.15×10^{11})
Number of Bunches 1380 (2808)
Bunch Spacing 50 ns (25 ns)
Instantaneous Luminosity 6.8×10^{33} (10^{34}) cm^2/s

The ATLAS Detector



Muon Spectrometer (|η|<2.7):
σ/p_T ~ 10% (1TeV)

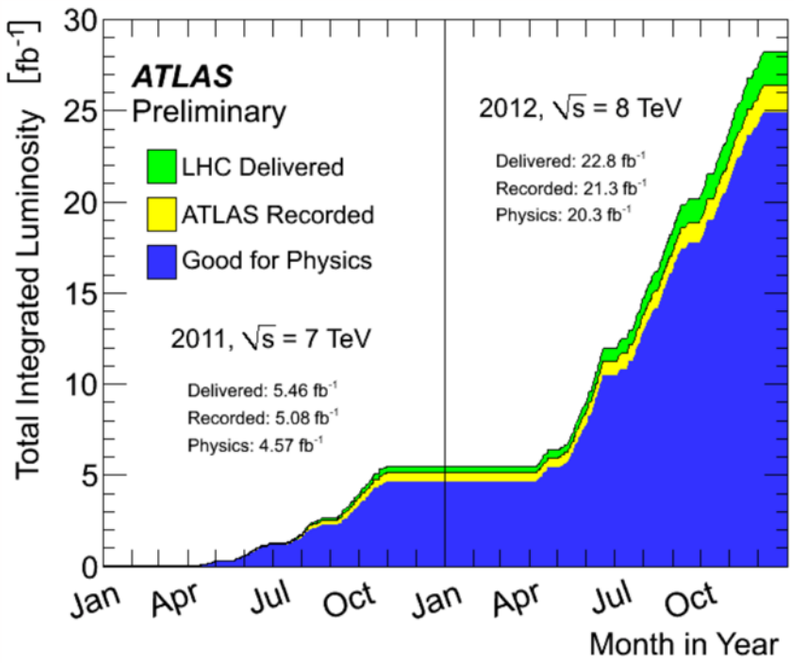
HAD calorimeter (|η|<4.9):
scintillator Tiles (central),
LAr (fwd). σ/E ~ 50%/√E ⊕ 0.03

EM calorimeter (|η|<4.9):
LAr.σ/E ~ 10%/√E

Inner Detector
(|η|<2.5, B=2T):
Si Pixels, Si strips, Transition Radiation (straws)
e/π separation.
σ/p_T ~ 3.8×10^{-4} p_T (GeV) ⊕ 0.015

Three Level Trigger system

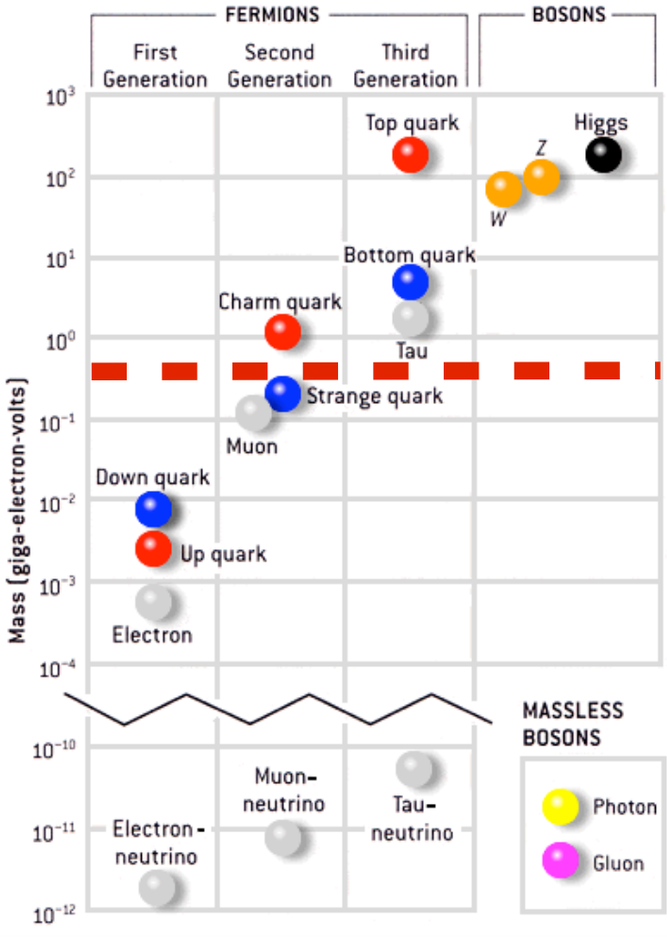
- L1 - hardware: 70 kHz, 2.5 μs latency
- L2 - software: 6.5 kHz, 10 ms latency
- EF - software: 600 Hz, 1-2 s latency



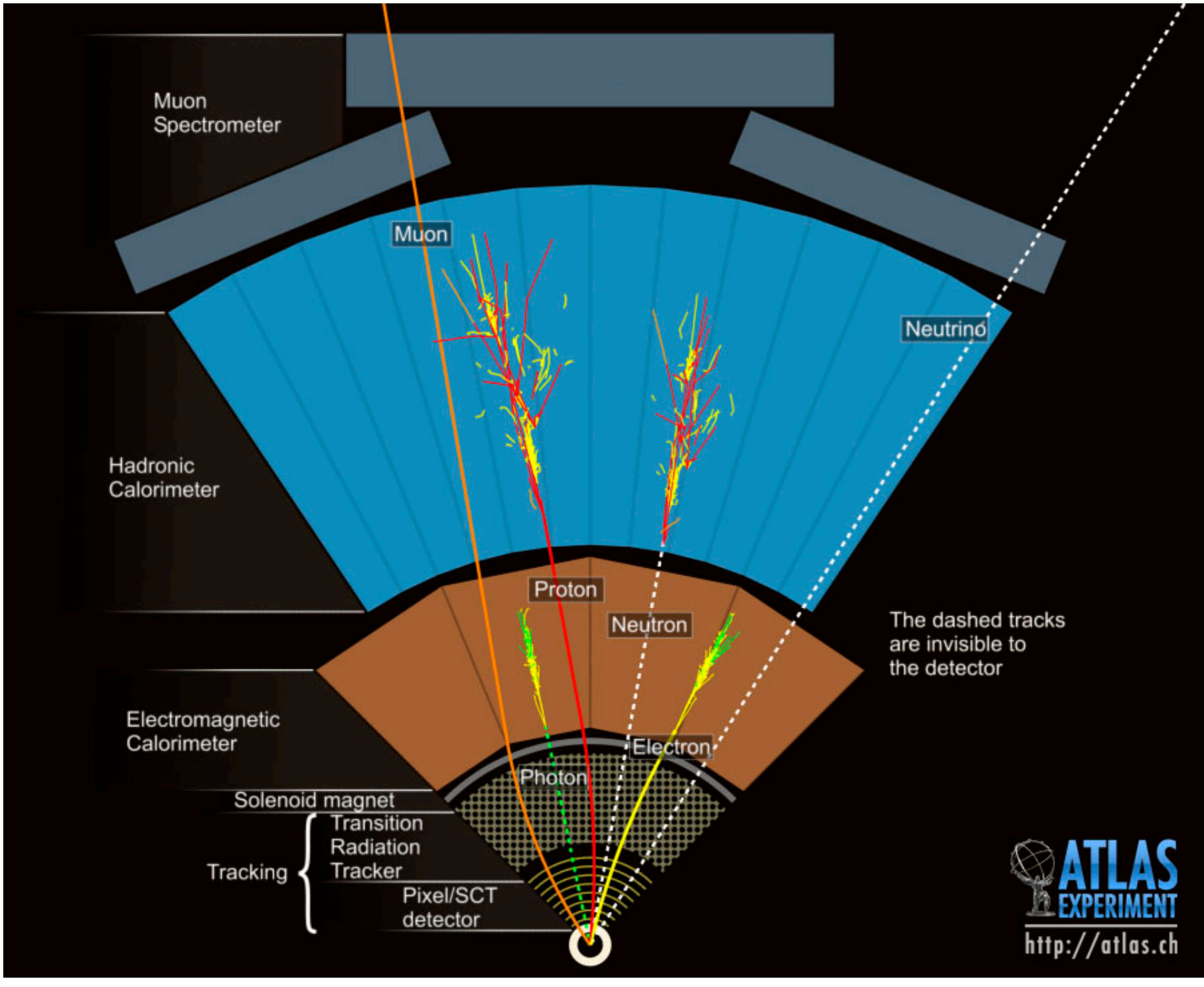
- Excellent performance of the ATLAS detector during Run 1
- Including trigger, data processing, data handling and distributions, reconstruction, simulation

Particle Identification

- Unstable on the detector scale, decay into lighter particles, observed via their daughters

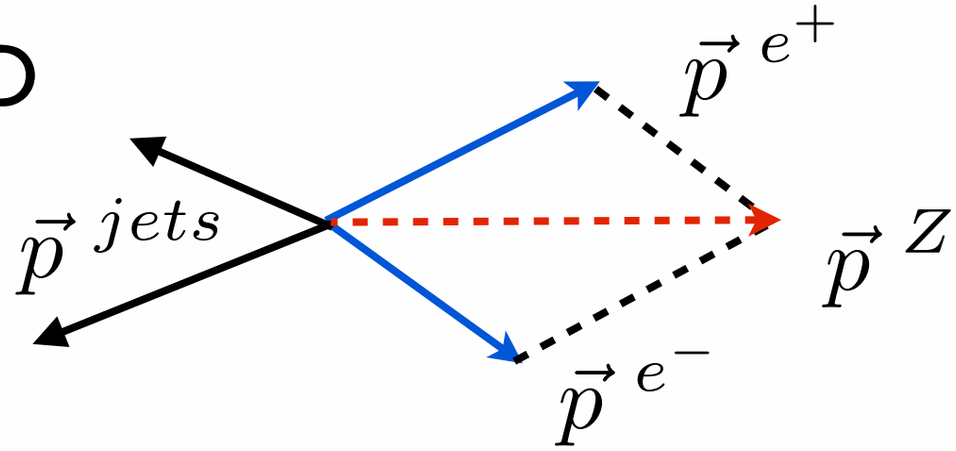


- Stable on the detector scale, observed directly



Invariant Mass, Transverse Mass, Missing Transverse Momentum

3D



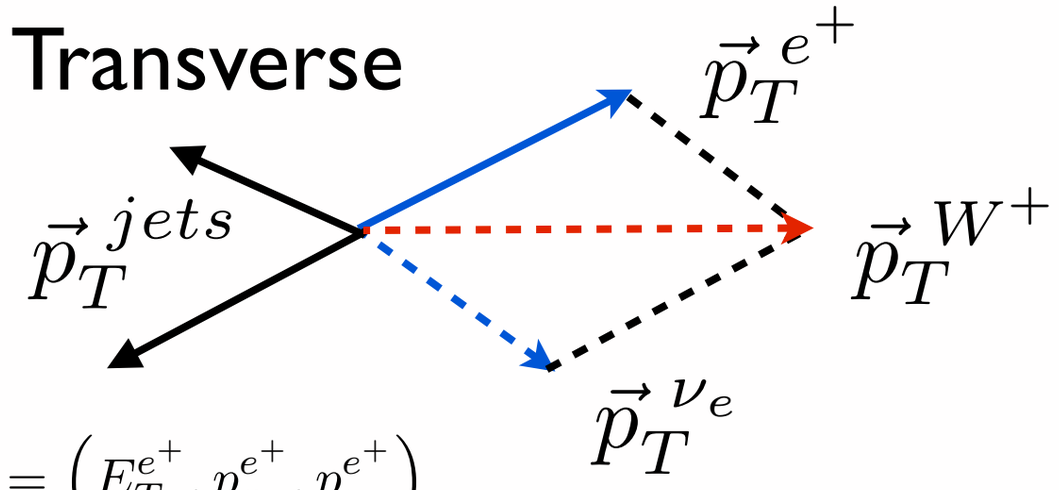
$$p^{e^+} = \left(E^{e^+}, p_x^{e^+}, p_y^{e^+}, p_z^{e^+}\right)$$

$$p^{e^-} = \left(E^{e^-}, p_x^{e^-}, p_y^{e^-}, p_z^{e^-}\right)$$

$$p^Z = p^{e^+} + p^{e^-}$$

$$m^{Z\,2} = E^{Z\,2} - |\vec{p}^{\,Z}|^2$$

2D Transverse



$$p_T^{e^+} = \left(E_T^{e^+}, p_x^{e^+}, p_y^{e^+}\right)$$

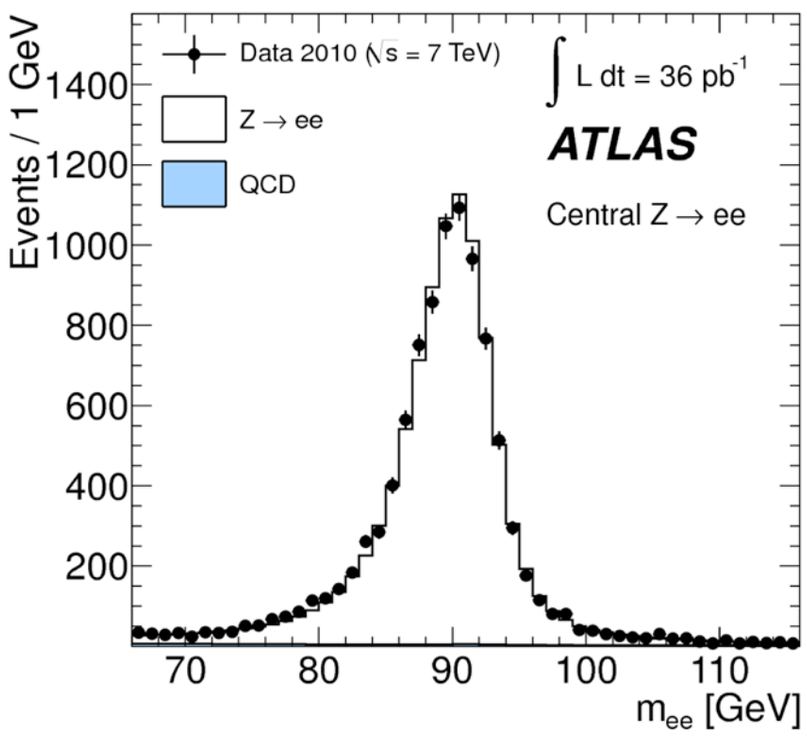
$$p_T^{\nu_e} = \left(E_T^{miss}, p_x^{miss}, p_y^{miss}\right),$$

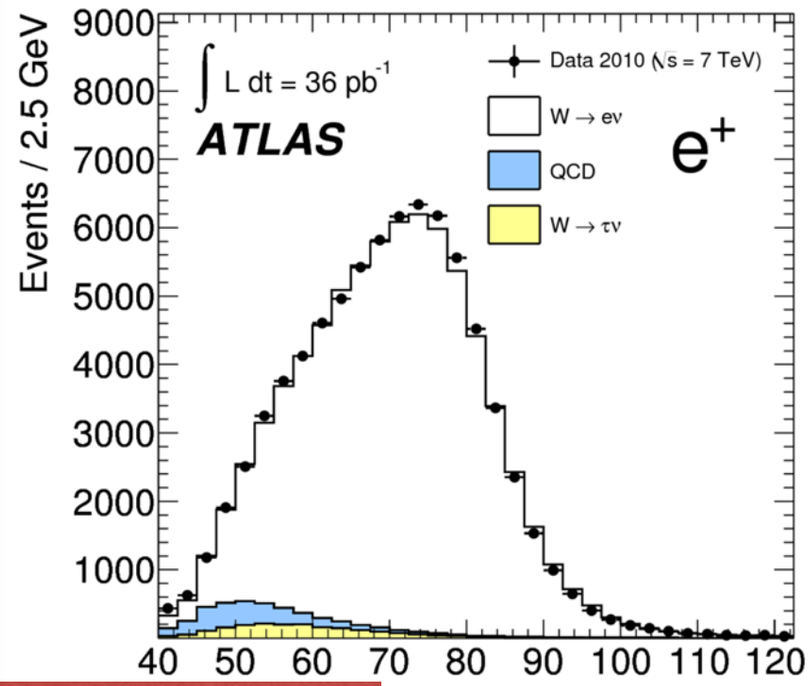
$$\vec{p}_T^{\,miss} = -\sum_i^{visible} \vec{p}_T^{\,i}$$

$$E_T^{miss} = |\vec{p}_T^{\,miss}|$$

$$p_T^{W^+} = p_T^{e^+} + p_T^{\nu_e}$$

$$m_T^{W\,2} = E_T^{W\,2} - |\vec{p}_T^{\,W}|^2, \quad m_T^W \leq m^W$$





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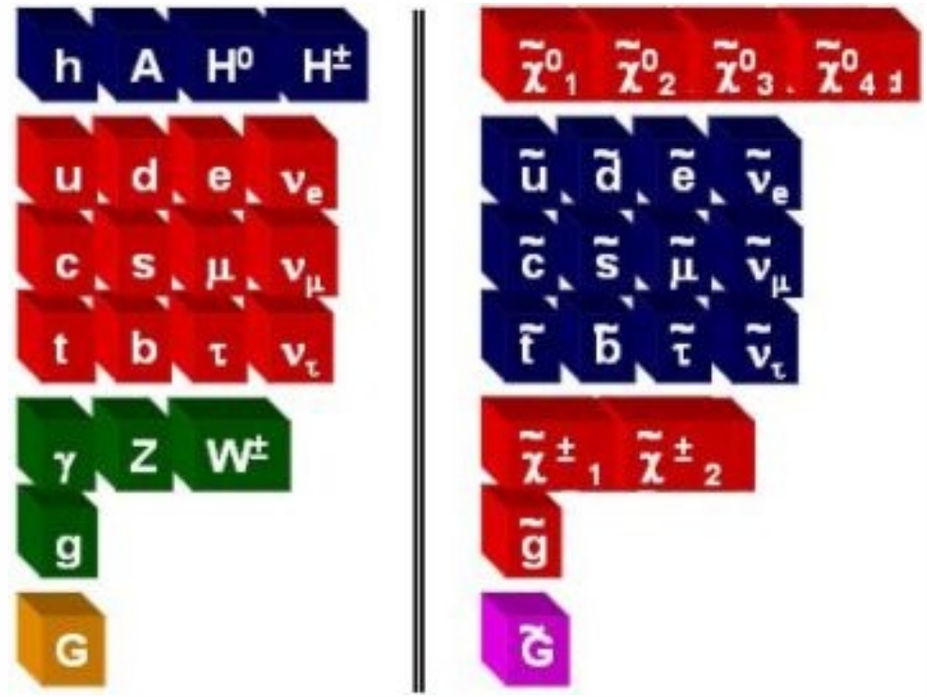
Why SUSY?

- **Theoretically and experimentally motivated**
  - Extends Poincare space-time symmetry
  - Natural grand unified theory
  - Can incorporate gravity
  - Solves hierarchy problem
  - can provide candidate for cold DM (if a new parity, R-parity is conserved)

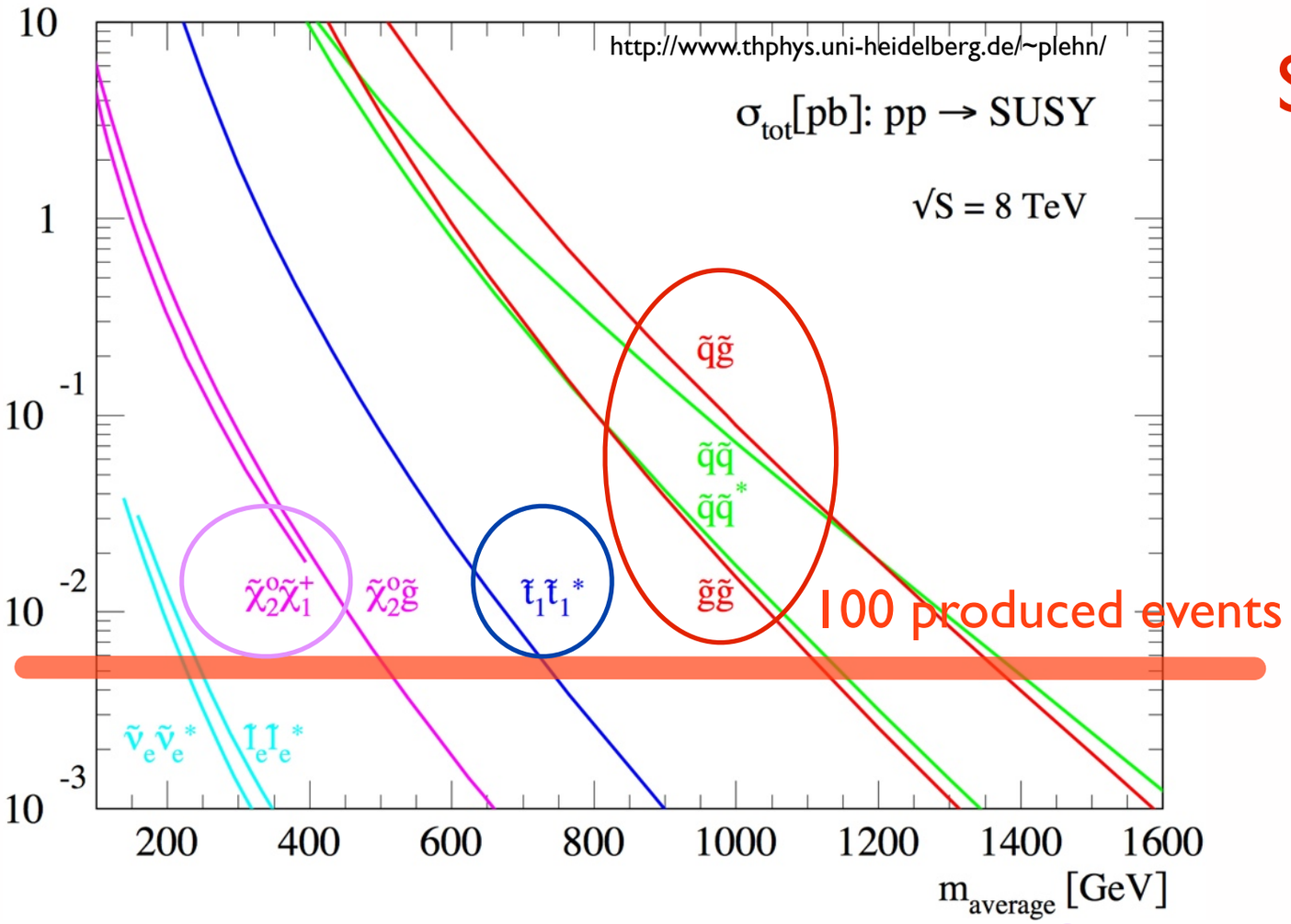


$$P_R = (-1)^{2s+3B+L}$$

- **MSSM developed in the early '80 and starting point for searches ever since**
  - More than 100 soft SUSY breaking parameters

- **Simplified Models:**
  - physical masses of SUSY particles
  - fixed branching fractions, pure states

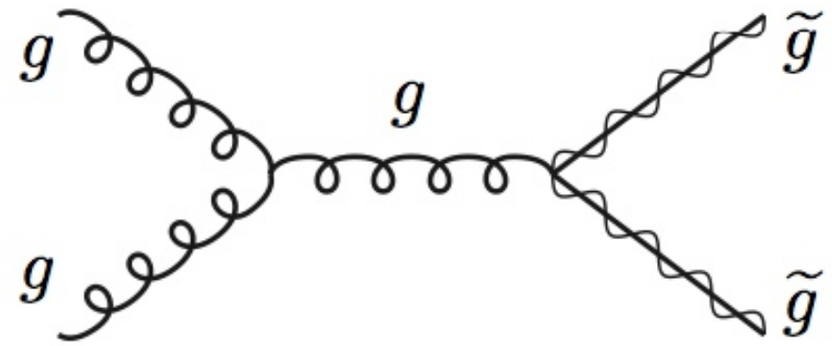
Production of SUSY Particles at the LHC



100 produced events

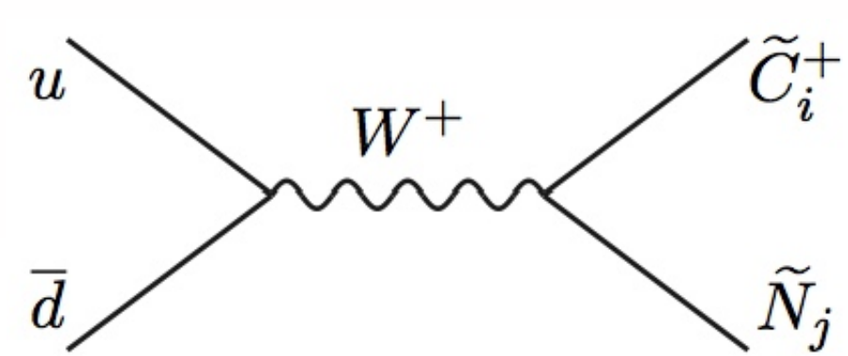
Strong production of gluinos, 1st/2nd generation squarks

expected sensitivity up to ~1.2TeV



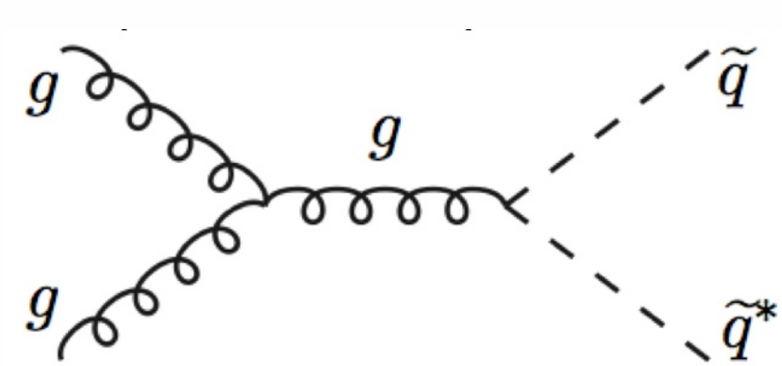
Electro-weak production of electroweakinos and sleptons

expected sensitivity ~0.2-0.5TeV



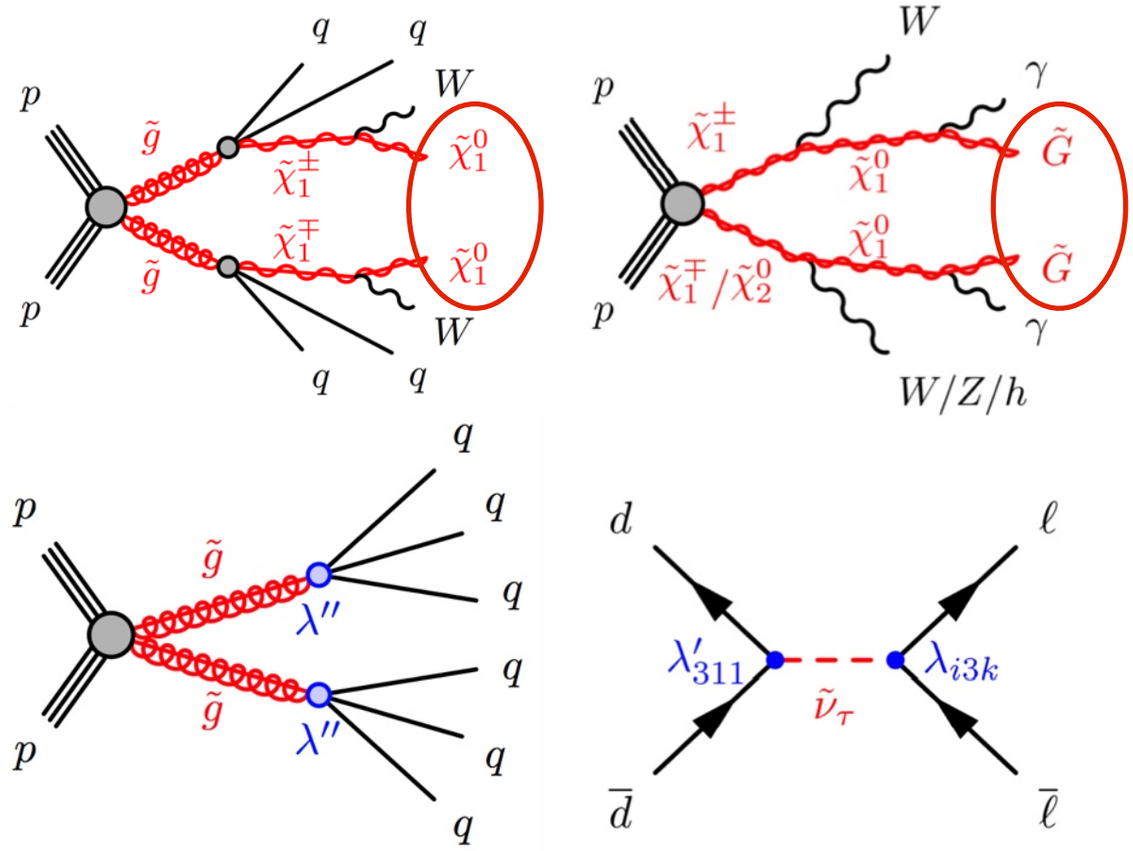
Strong production of 3rd generation squarks

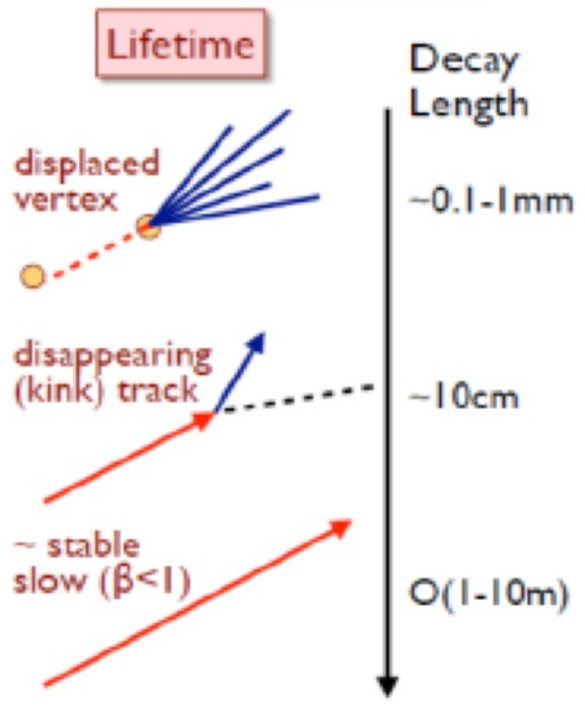
expected sensitivity ~0.7TeV



Phenomenology of SUSY

- **R-parity conserved (RPC)**
  - SUSY particles created in pairs
  - Lightest SUSY particle (LSP) is stable, DM candidate
  - Expect large ETmiss from escaping LSP
- **R-parity violated (RPV)**
  - RPC pair-production, but decaying LSP
  - RPV production of a single SUSY particle
  - Loss of ETmiss, but large object multiplicity and resonances
- **Long Lived (LL) particles (in both RPC and RPV)**
  - Meta-stable gluinos decaying via very heavy virtual squarks
  - Meta-stable due to small phase space available to the decay ("compressed spectra")
  - Meta-stable due to small couplings



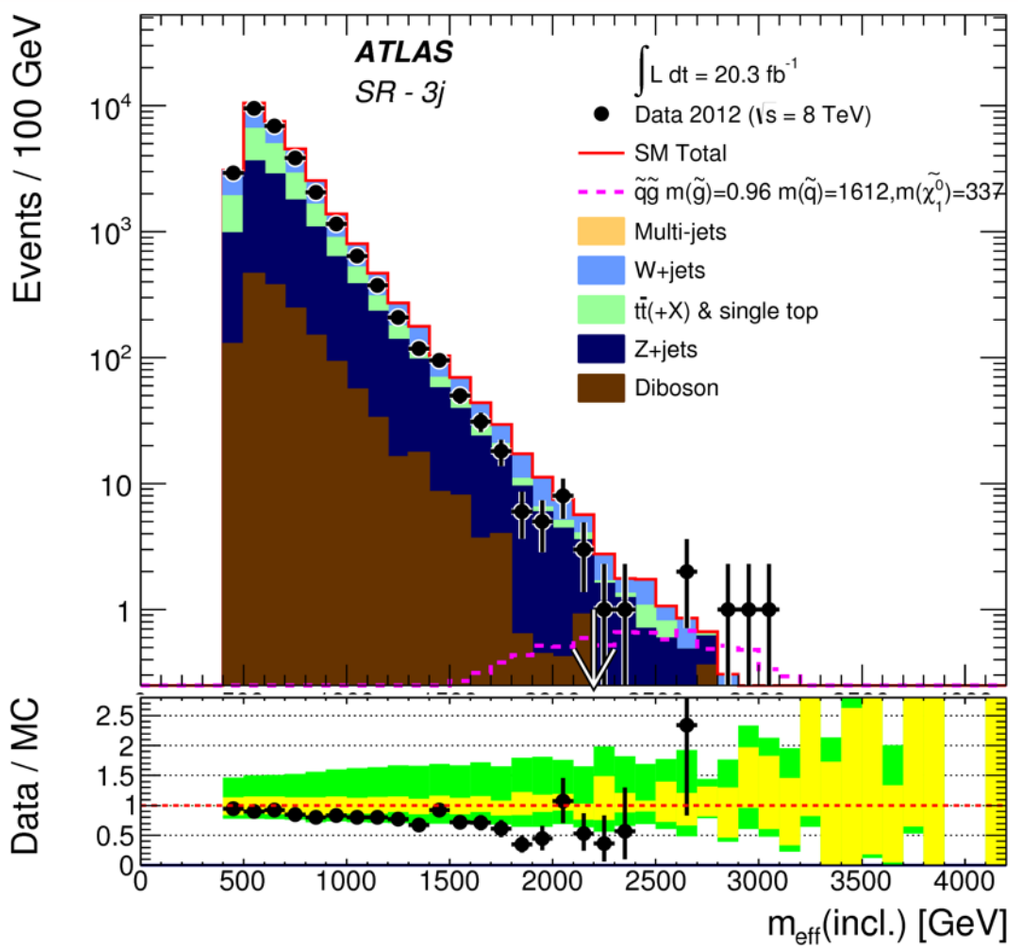


Outline: Selected Results from 2015

- R-parity Conserving SUSY
  - Scenarios with Neutralino 1 as LSP
    - Search for charginos and neutralinos with Higgs bosons
    - Search for scharm and stop with charm tagging
    - Search for gluinos with leptons in the final state
  - Scenarios with Gravitino as LSP
    - Search for gluinos with Z in the final state
- R-parity Violating SUSY
  - Search with multi-jets
  - Search for lepton resonances
- Searches for Metastable and Long Lived SUSY
  - search for particles decaying in the detector

General Analysis Strategy

- **Select Signal Regions using discriminating variables**
  - e.g. SUSY characterized by significant ETmiss mostly from escaping LSPs
  - or large meff = ETmiss + $\sum_{\text{all objects}}$pT proportional to the mass of the heavy SUSY particles produced in the event
- **Analyses are usually based on many signal region (SR) bins**
- **Fake instrumental backgrounds with data-driven methods**
- **Remaining backgrounds from MC, usually normalized in Control Regions (CR) in a simultaneous fit in all CR (and SR for limits)**
- **Signal Regions blind until modeling validated in Validation Regions (VR)**



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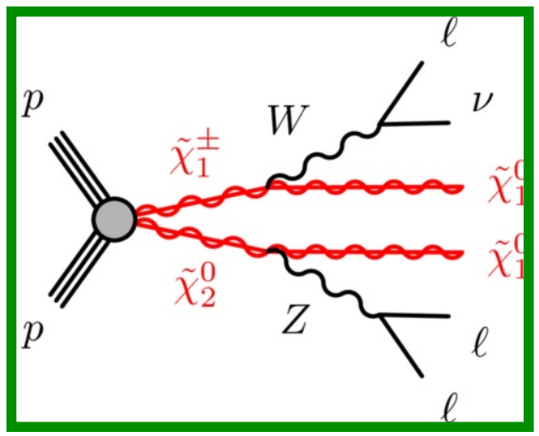
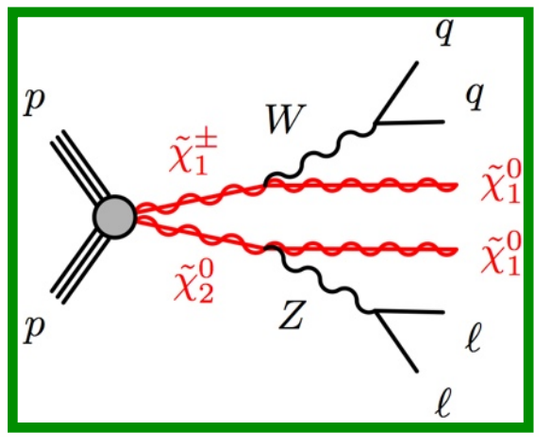
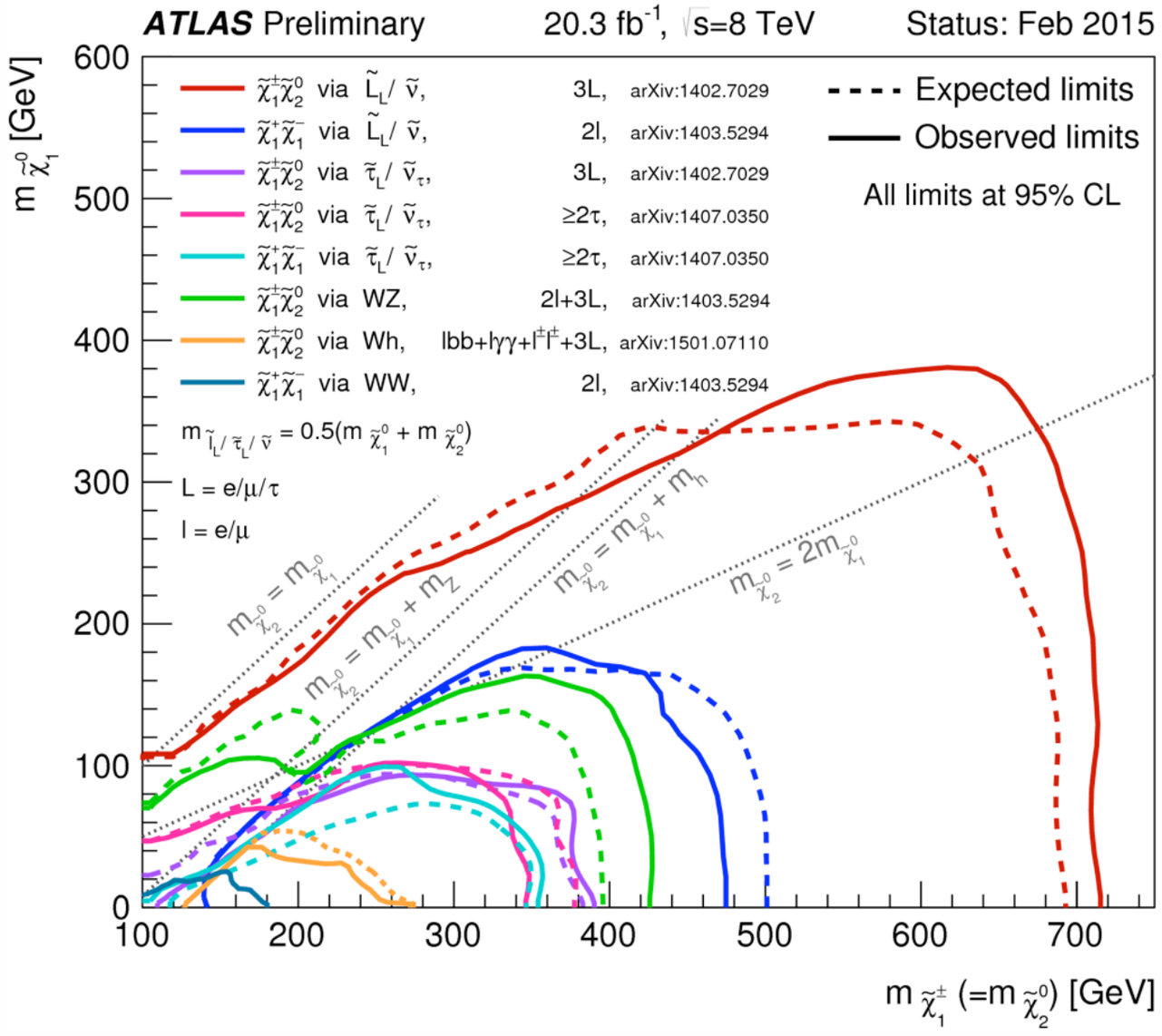
Search for Electroweakinos

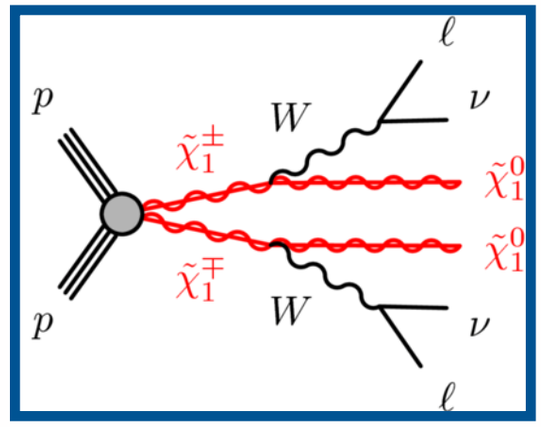
Electroweakinos (charginos, neutralinos) expected to be light from naturalness argument,

high discovery potential! But challenging search due to small EWK cross-section









Electroweakino mass > 400 GeV in models with decay via gauge bosons (heavy sleptons)

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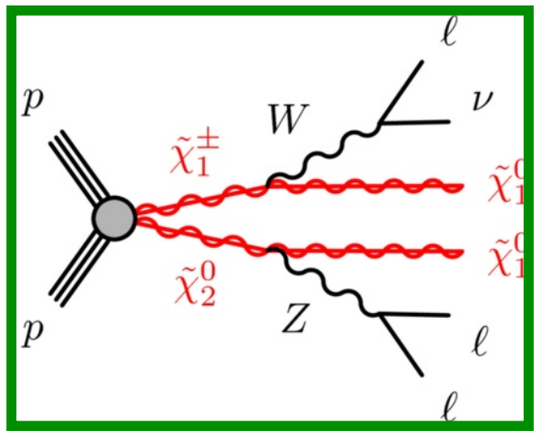
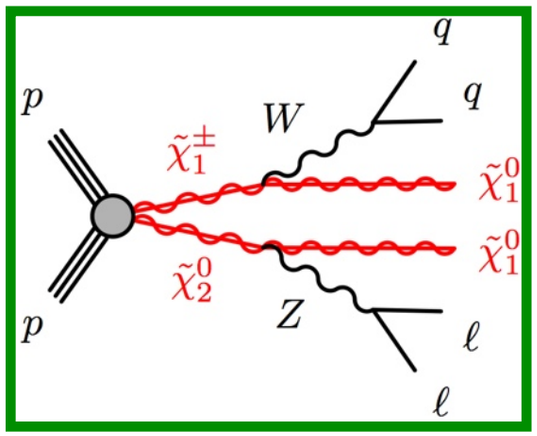
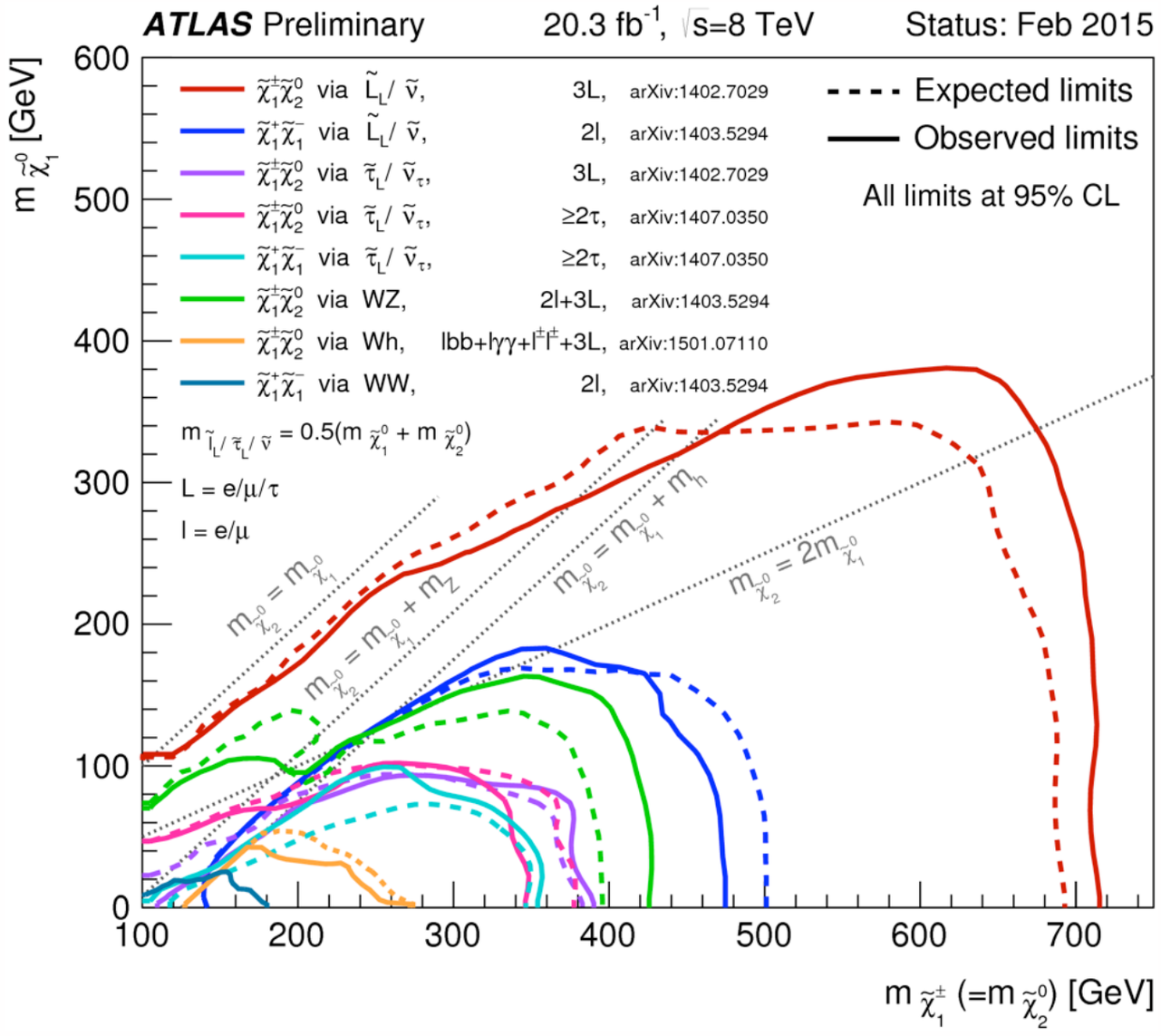
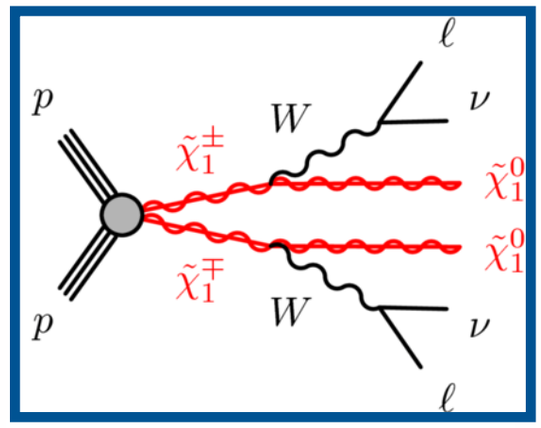
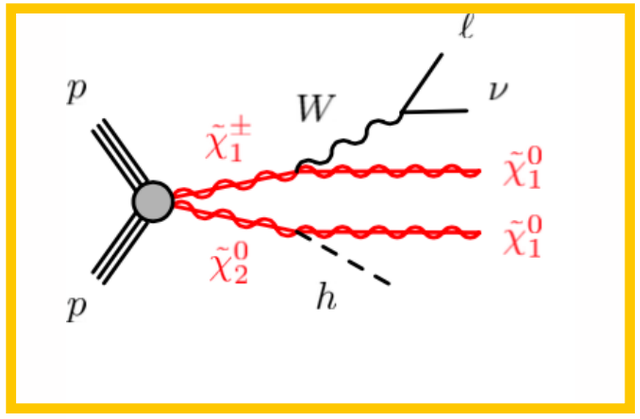








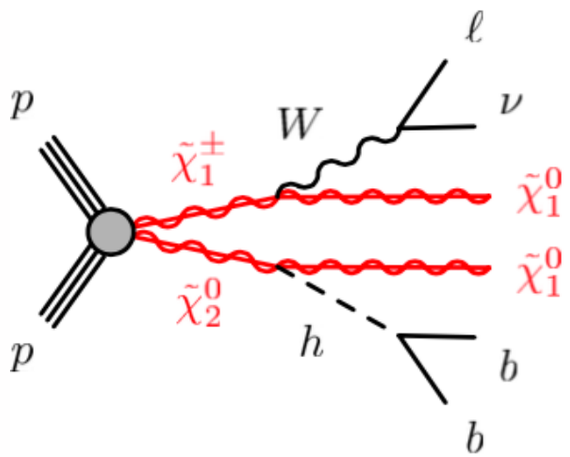


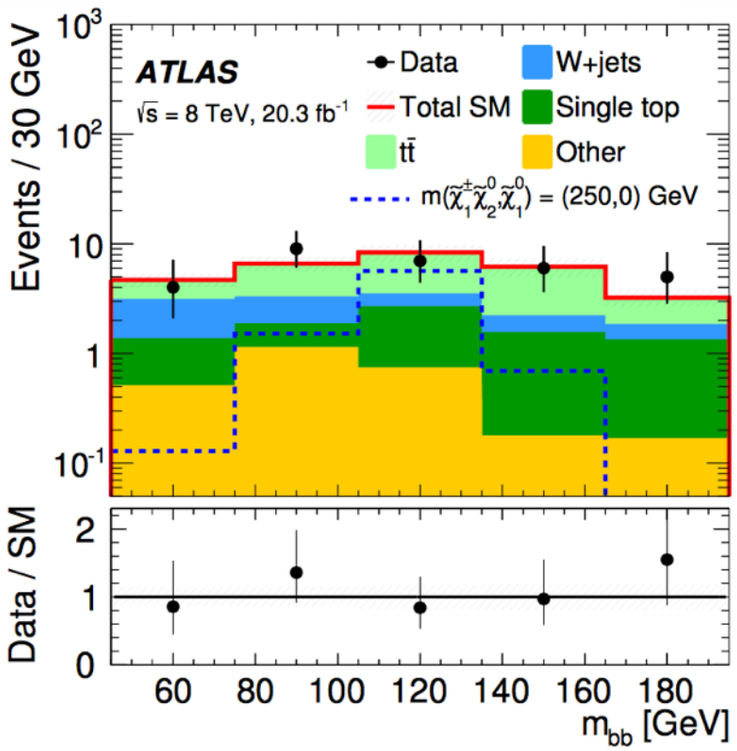
Dedicated search for Higgs in decays

Electroweakino mass > 400 GeV in models with decay via gauge bosons (heavy sleptons)

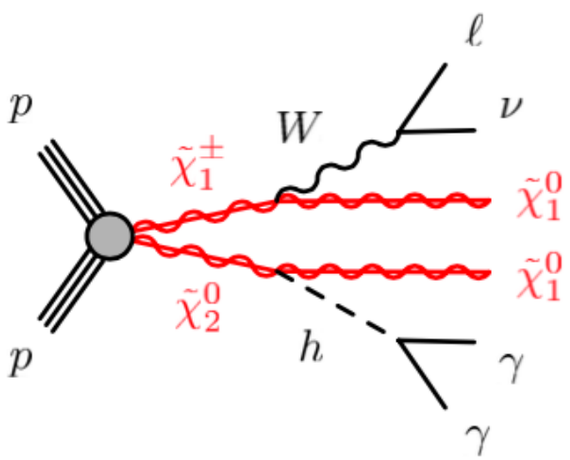
The Higgs boson as a probe for SUSY

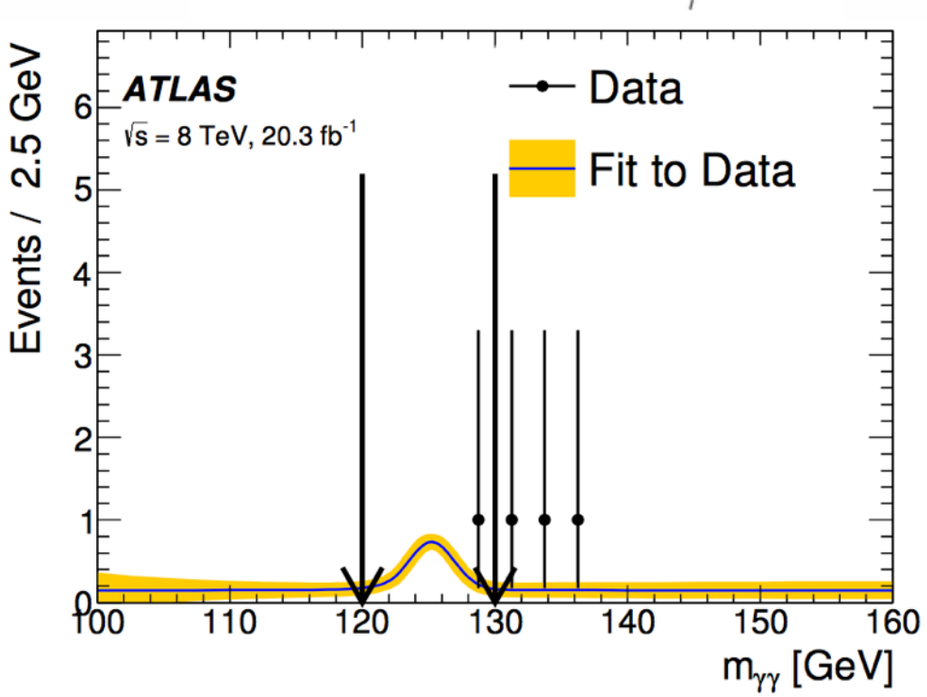
- Search in events with 1 lepton & 2 b
  - selection on di-jet invariant mass distribution



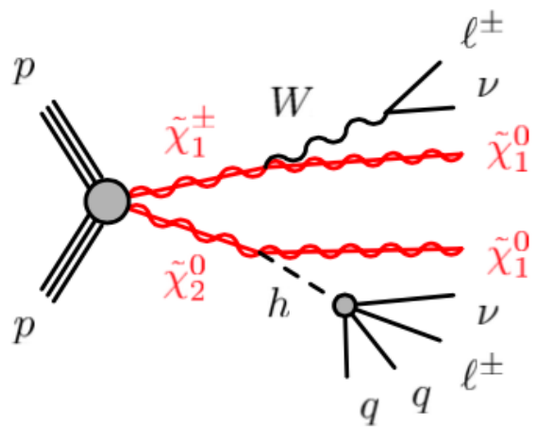


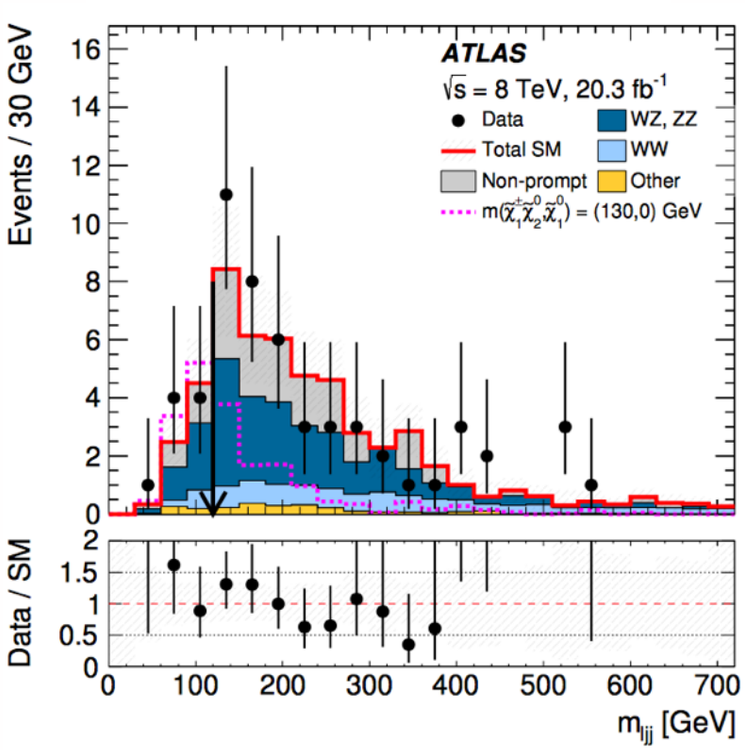
- Search in events with 1 lepton & 2 photons
  - unbinned fit to the diphoton mass distribution





- Search in events with 2 same sign leptons
  - exploit partially reconstructed mass in mljj





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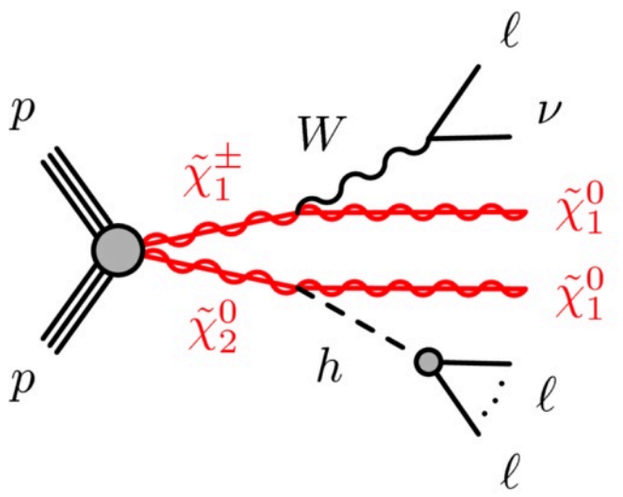
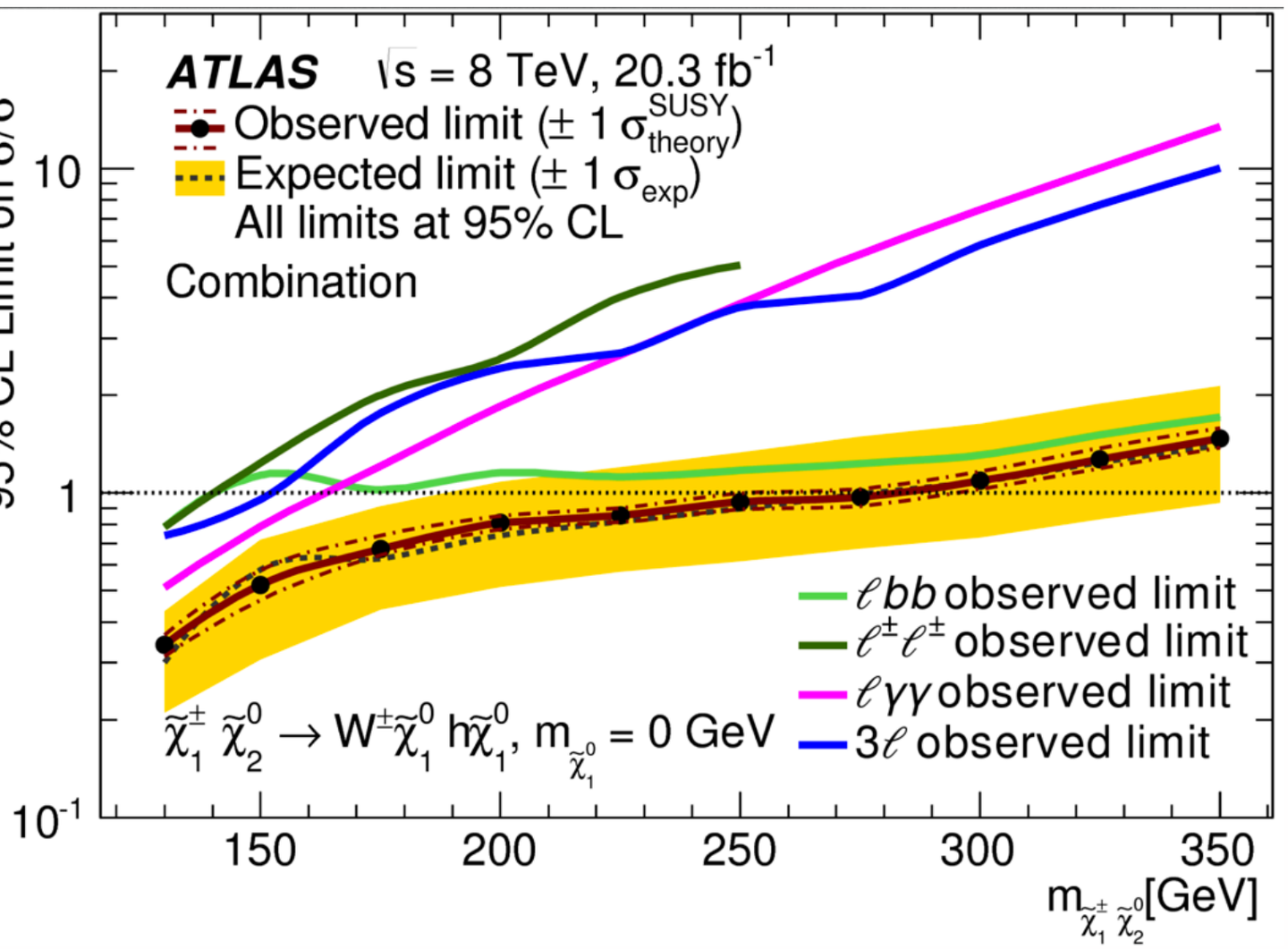
Higgs Bosons as Probes for EWK SUSY



Combining 3 channels
+ 3L search



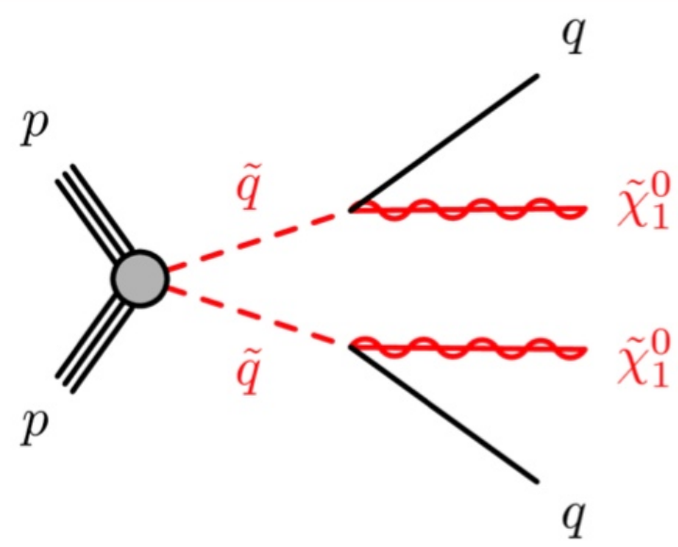
- For chargino mass < 170 GeV all channels contribute
- For chargino mass > 170 1L+bb channel dominates

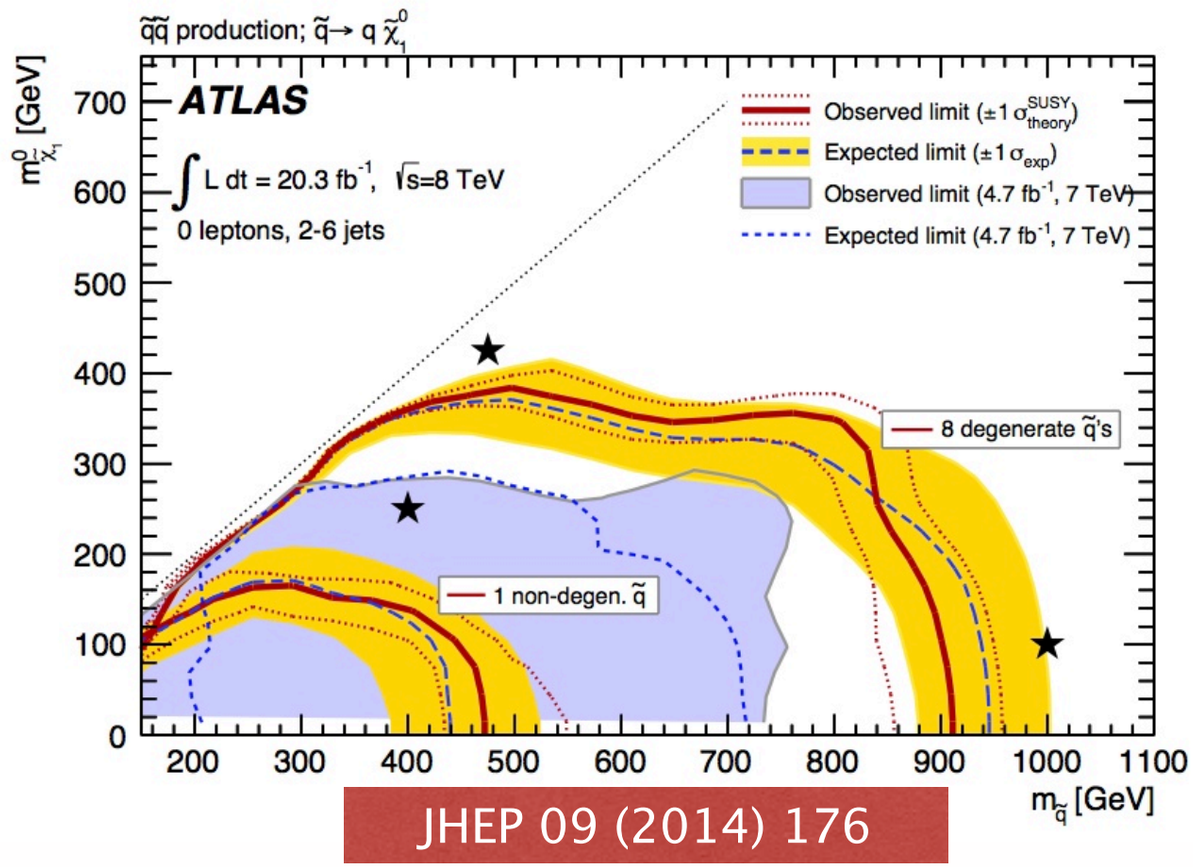
Electroweakino mass > 250 GeV , for massless LSP
in models with higgs in decay

Eur. Phys. J. C (2015) 75:208

Search for Squarks (including charm squark)

- Search for squarks based on events with no leptons, large missing transverse momentum
  - based on the assumption that all flavors (except the 3rd generation) are mass degenerate





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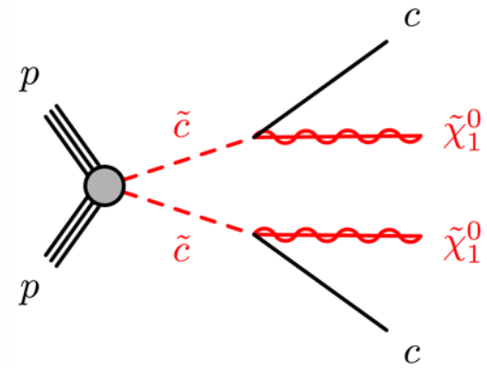
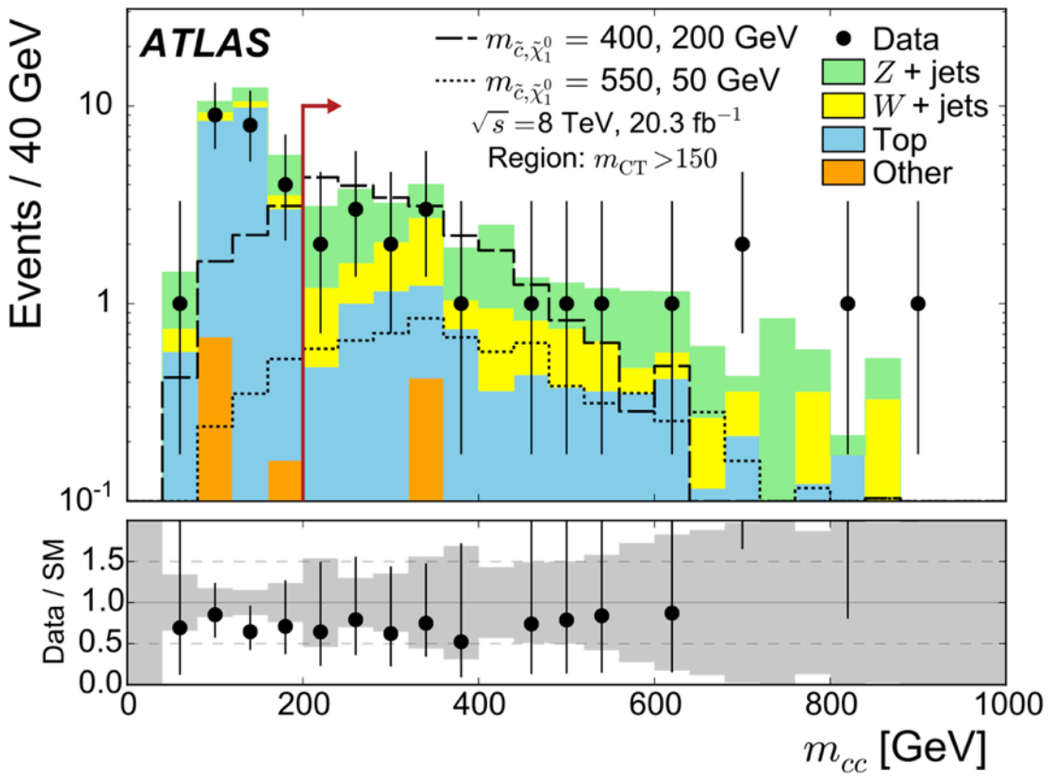
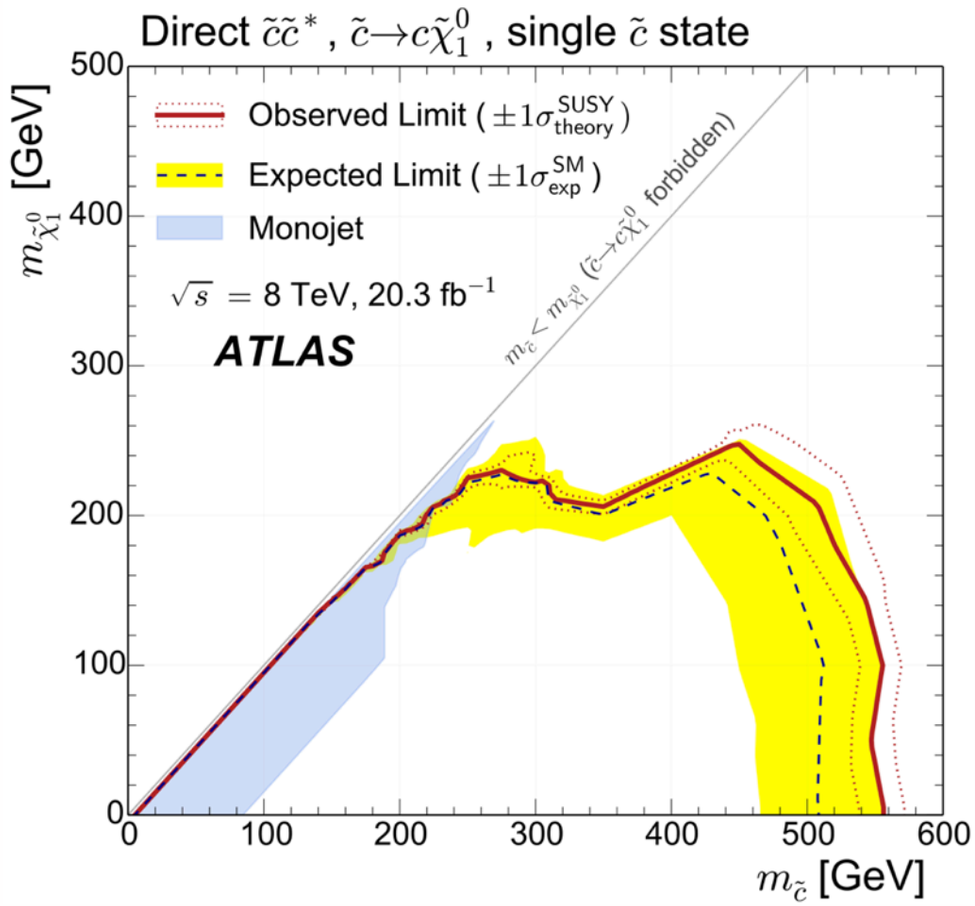
- But non-degenerate light flavor squarks are well motivated! (arXiv:1212.3328)
- Flavor dependent search is critical for discovery and to probe the flavor structure of the underlying theory

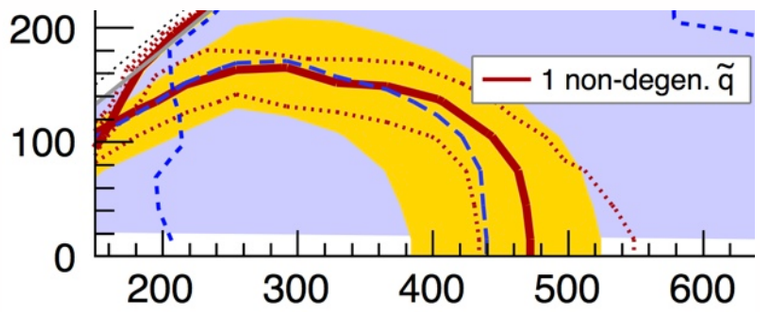
Search for Charm Squark

- **New search for charm squark at LHC!**
- **Signal and background discrimination based on c-tagging**
  - Neural Network dedicated to c-jet identification based on impact parameter and secondary vertex information









Limit on charm squark mass ~ 540 GeV, significantly improved w.r.t squark search

Phys. Rev. Lett. 114, 161801 (2015)

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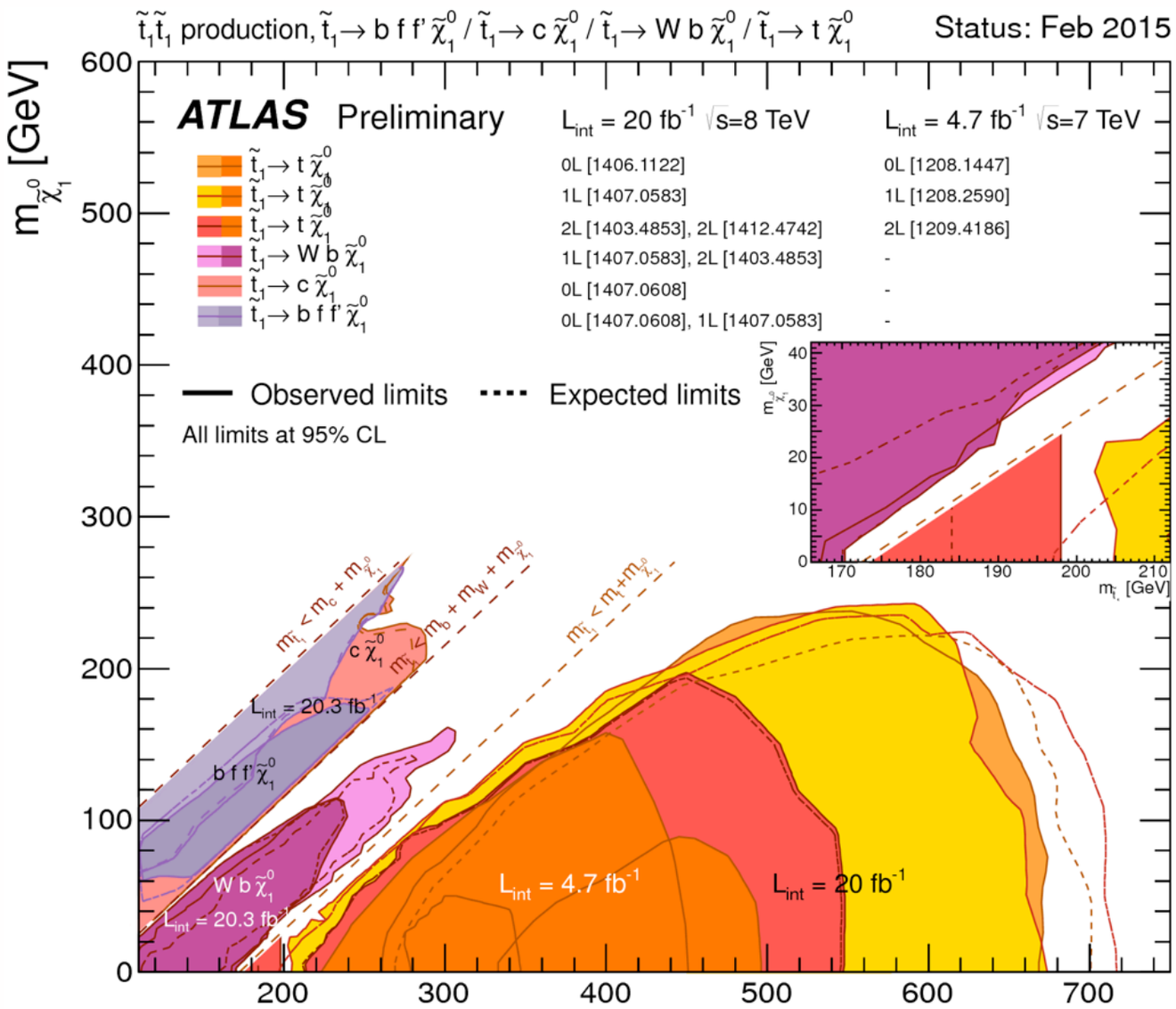
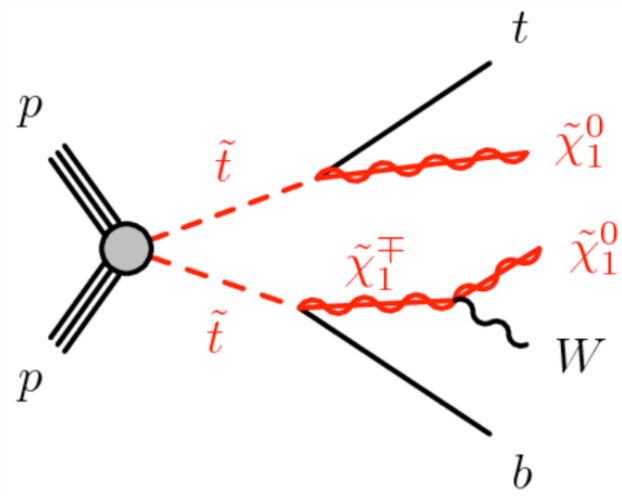
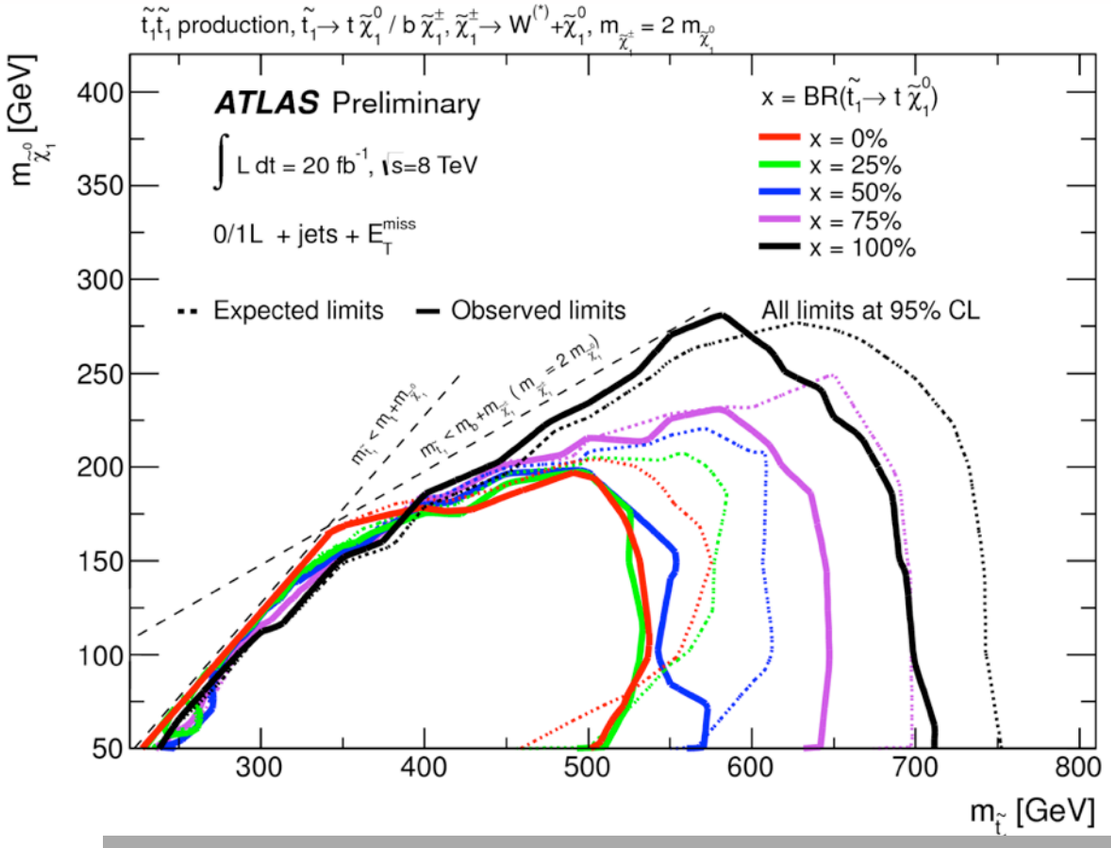
Summary of Searches for Stop

- Dedicated search for stops, in final states with no leptons, leptons, multiple leptons and jets, missing transverse energy, ...
  - numerous SRs to maximize our sensitivity



(Searches for stops decaying via charginos not shown)





Sensitivity highly depends on the BR due to competing decay modes

ATLAS-CONF-2015-010

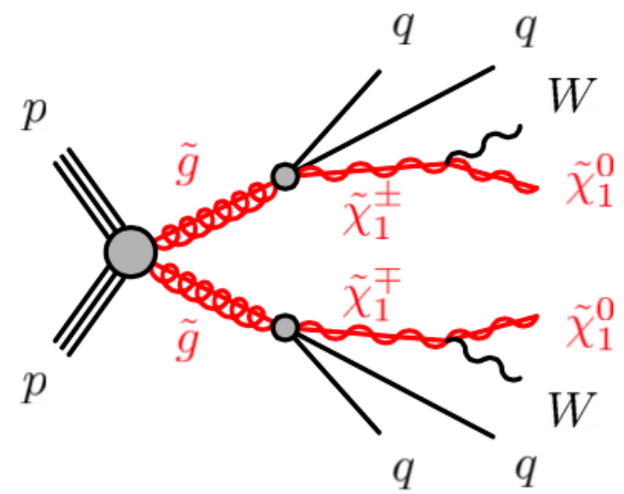
Searches for Gluinos decaying via Charginos and Sleptons

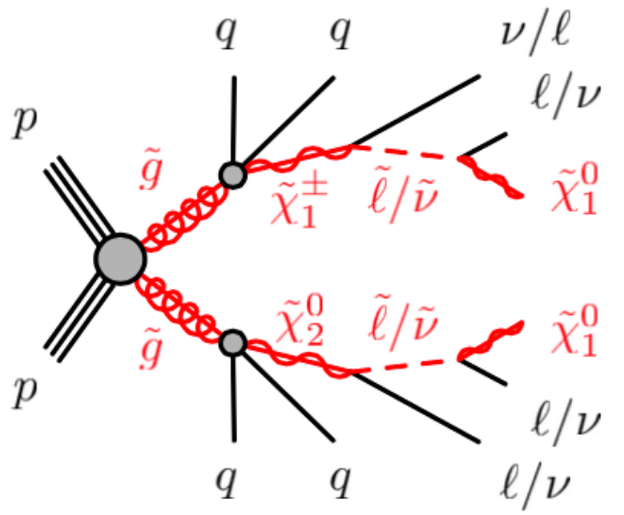
- Gluinos can undergo long decay chain through charginos and sleptons leading to final states with leptons

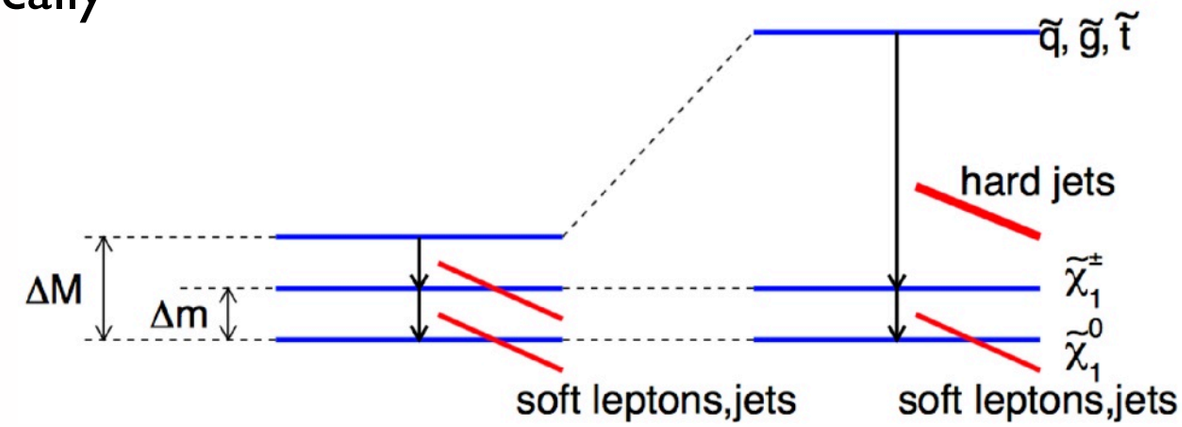
- Four searches targeting
  - compressed scenarios using low pT leptons
  - scenarios with medium to large mass splittings with high pT leptons

- Signal to background discrimination based on
  - number of jets, ETmiss, Meff, number of jets,...

- Non-overlapping signal regions are statistically combined







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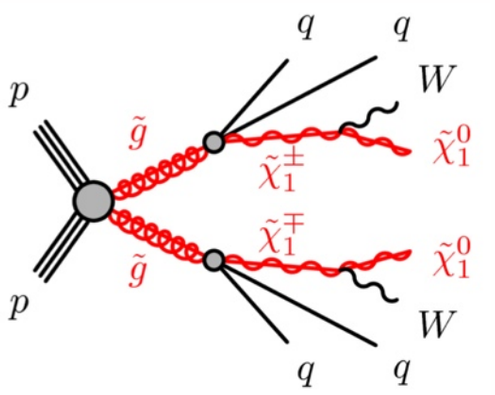
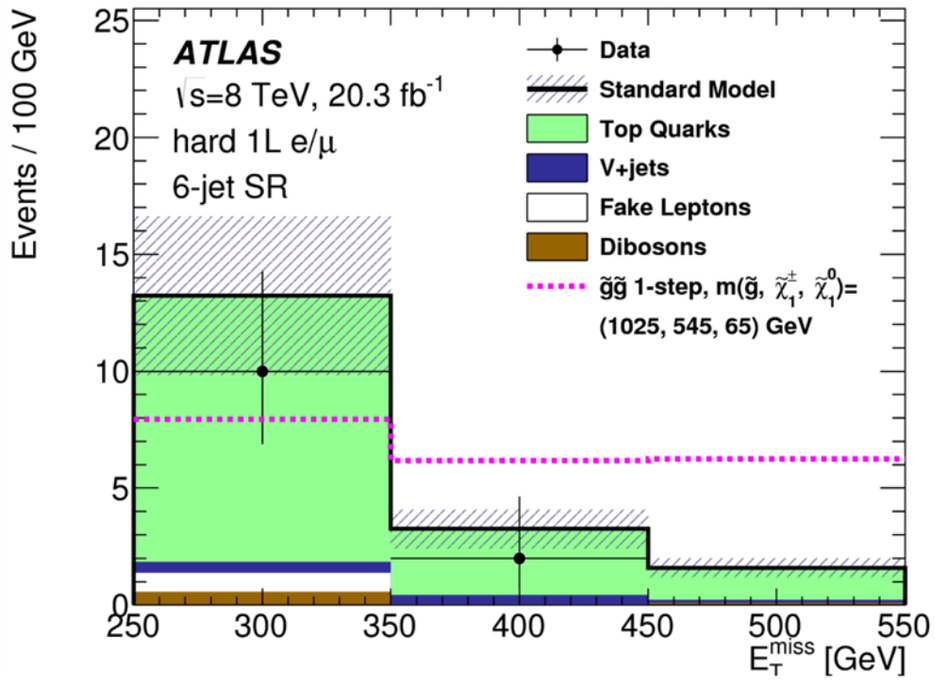
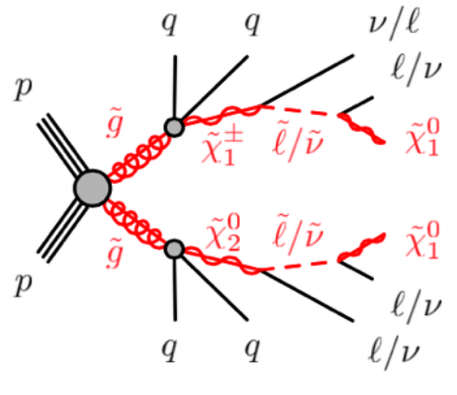
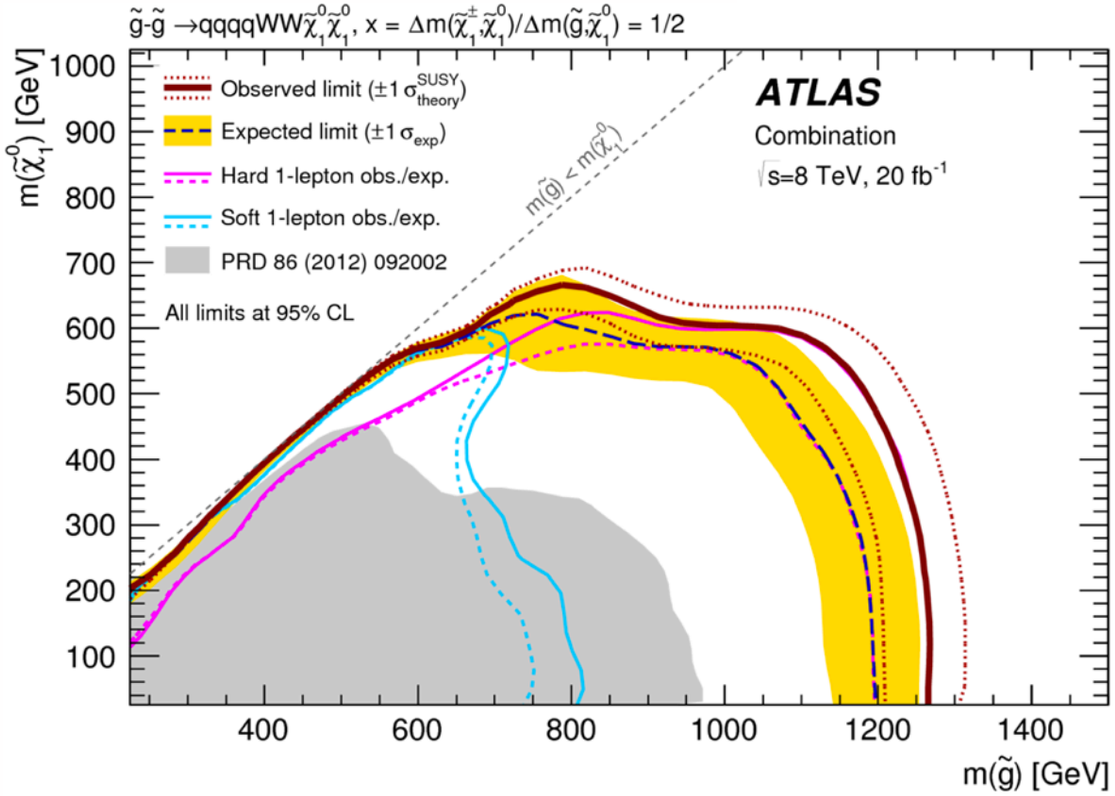
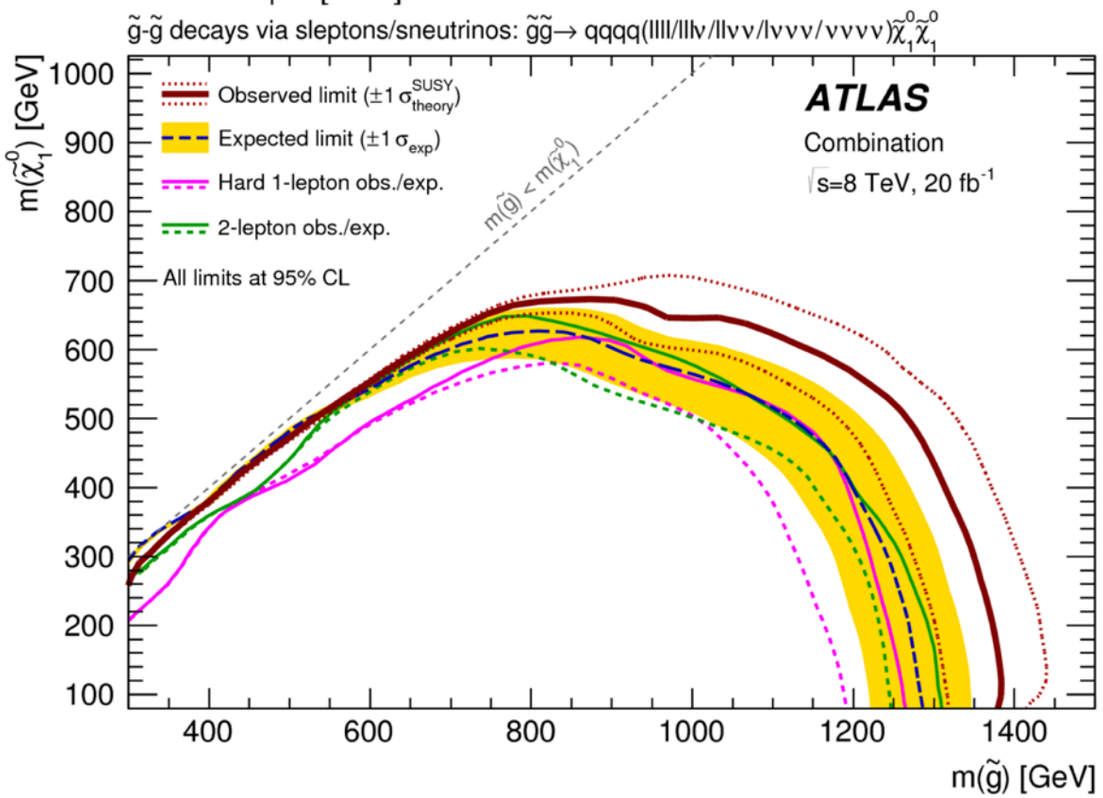
Searches for Gluinos decaying via Charginos and Sleptons











Gluino mass > 1.2TeV for massless N1, independently of decay modes

1501.03555

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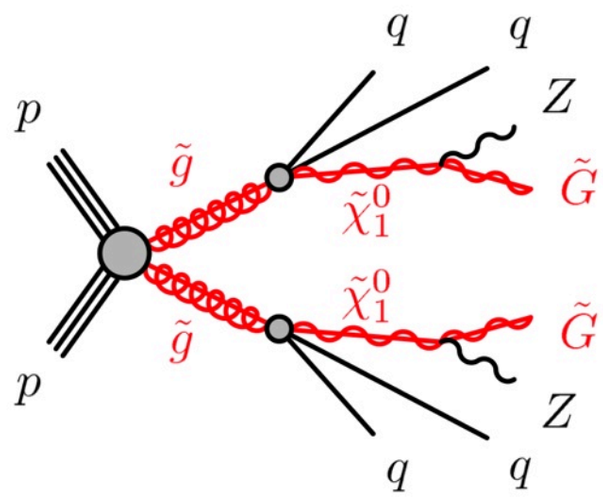
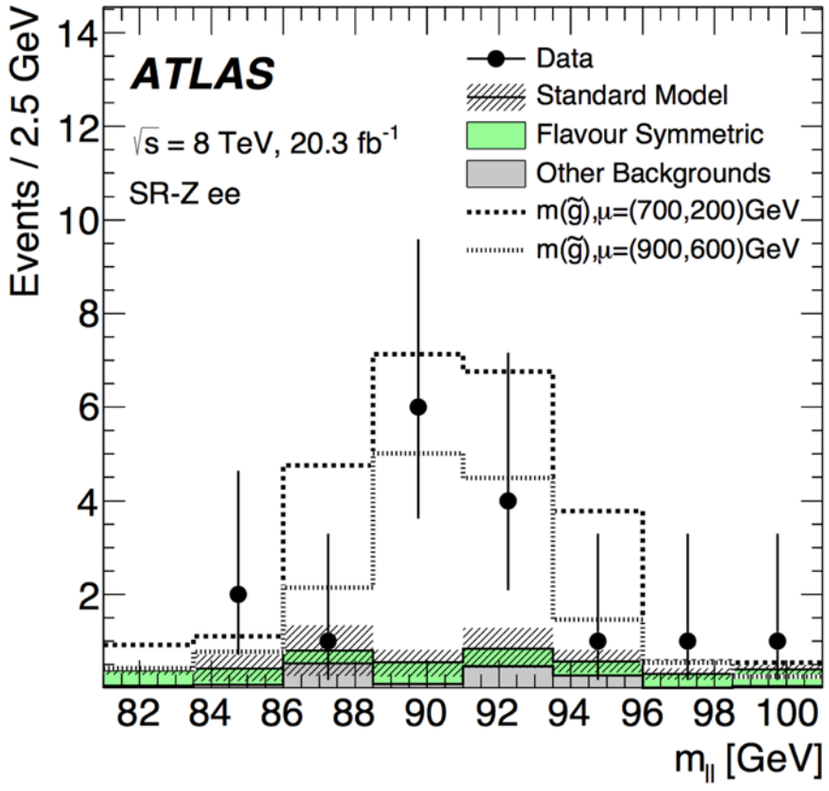
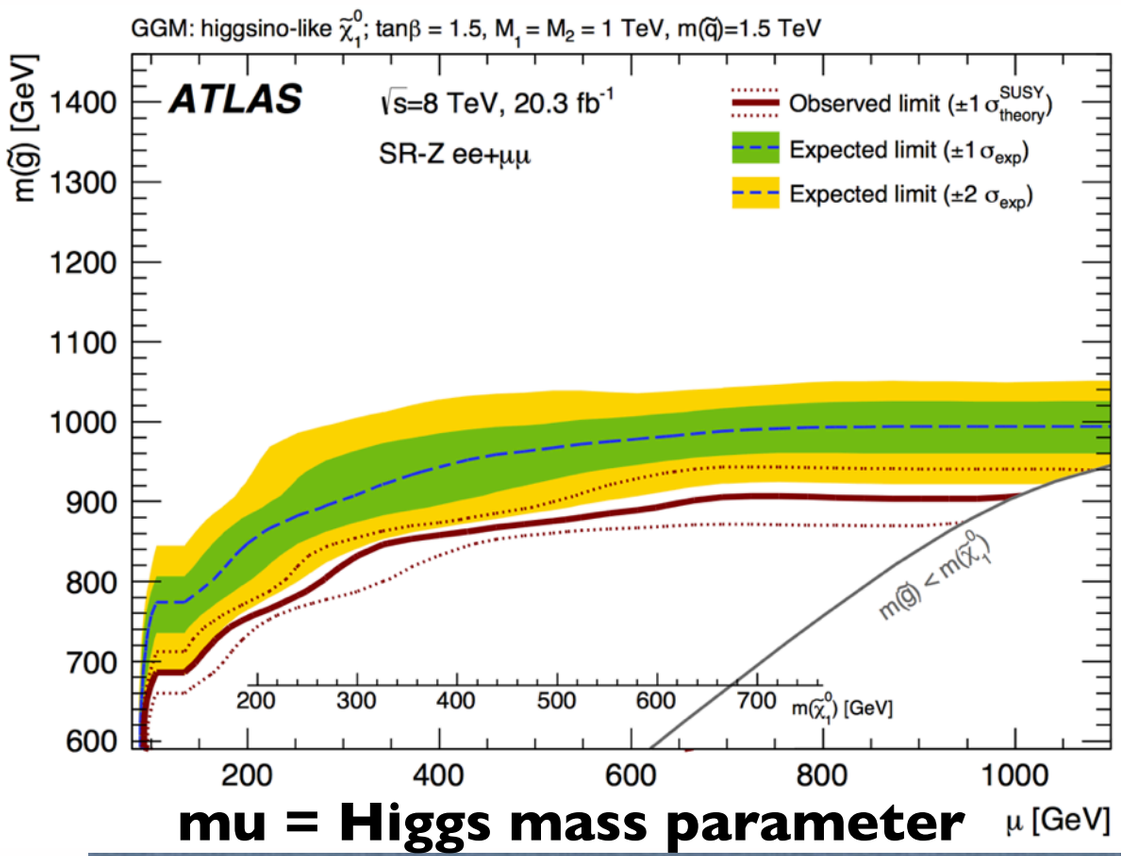
Search for Gluinos with Gravitino LSPs in the decay

- In Gauge Mediated SUSY the phenomenology is driven by the nature of the NLSP
  - The NLSP is the neutralino 1 (N1) while the gravitino is the LSP
- The N1 can decays into Z and gravitino
- Signal region with Zs
- Observe 3 (1.7) sigma over-fluctuation in electron (muon) channel







mu = Higgs mass parameter

Gluino mass > 0.9 TeV

arXiv:1503.03290

Brief Introduction to R-parity violating SUSY

- R-parity conservation is imposed to prevent proton decays
- However, R-parity can be violated without causing the proton to decay if either the baryon or the lepton number is conserved
- Phenomenology of R-parity violating SUSY is driven by the Lambda couplings

MSSM potential

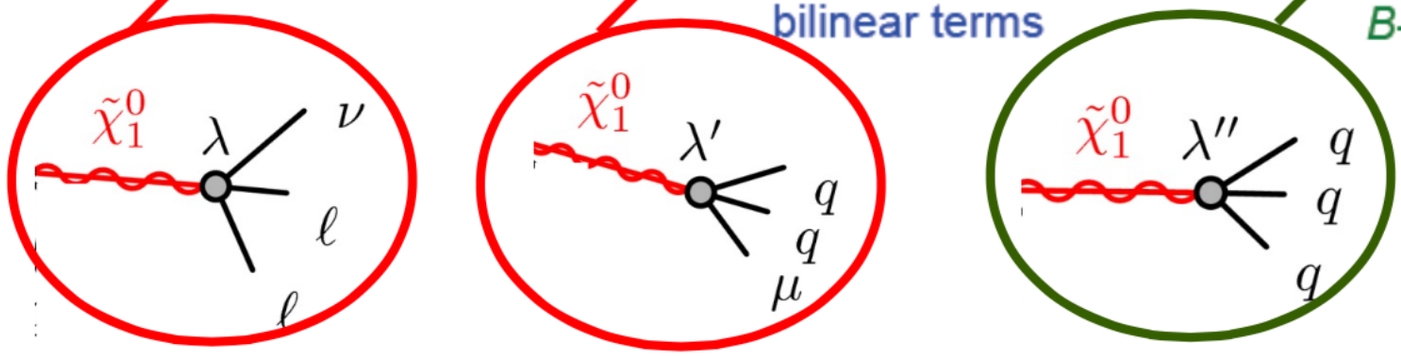
$$W_{\not R p} = \lambda_{ijk}\hat{L}_i\hat{L}_j\hat{E}^C_k + \lambda'_{ijk}\hat{L}_i\hat{Q}_j\hat{D}^C_k + \epsilon_i\hat{L}_i\hat{H}_u + \lambda''_{ijk}\hat{U}^C_i\hat{D}^C_j\hat{D}^C_k$$

L-number violating terms

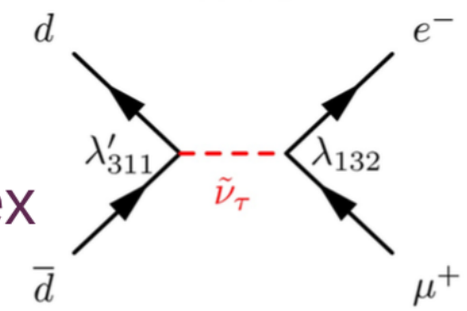
bilinear terms

B-number violating terms

RPV couplings $\lambda, \lambda', \lambda''$



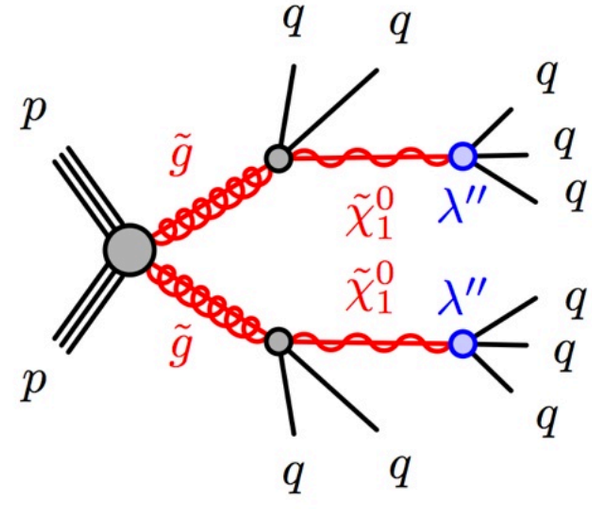
RPV can be at the production vertex and/or at decay vertices

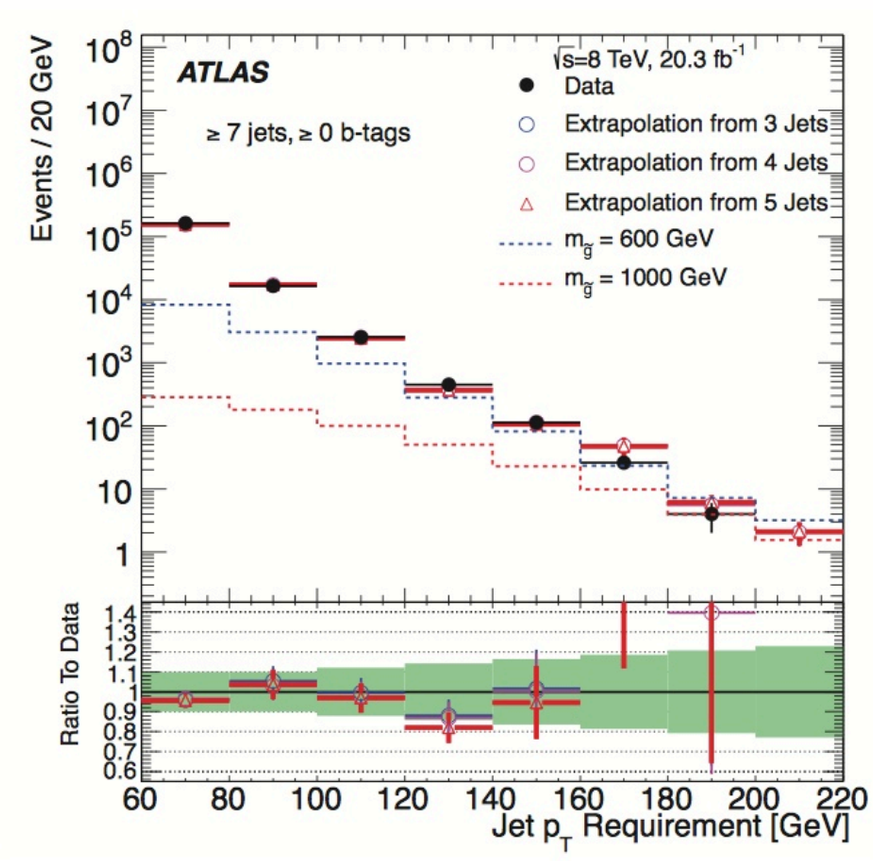


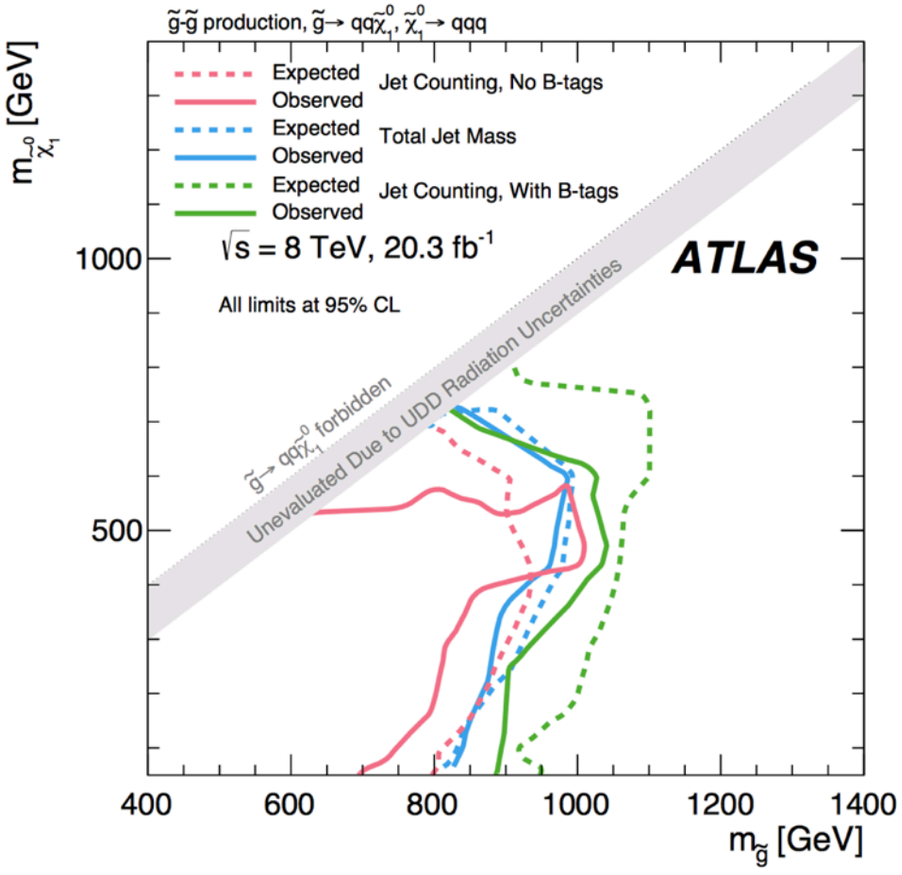
Search for SUSY with RPV-decays: MultiJet Final States (II)

- Single coupling dominance, assume only $\frac{1}{2}\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k$ non zero (UDD scenarios)
- Two dedicated searches
  - "Jet-counting", classifying events depending on the number of b-tagged jets
  - "Total Jet Mass", using a template method based on the topological MJ, agnostic to the flavor

$$M_{\mathrm{J}}^{\Sigma} = \sum_{\substack{p_{\mathrm{T}}>100\ \mathrm{GeV} \\ |\eta|\leq 2.5}}^{4} m^{\mathrm{jet}}$$



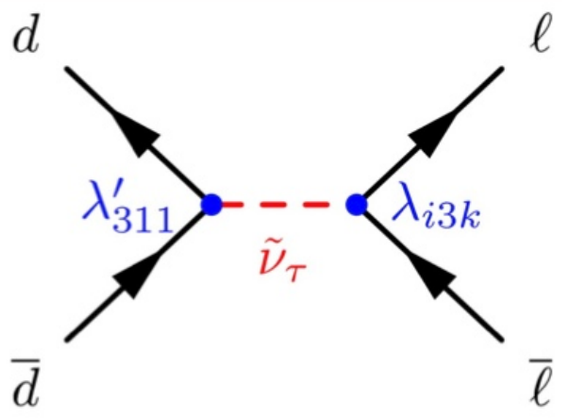




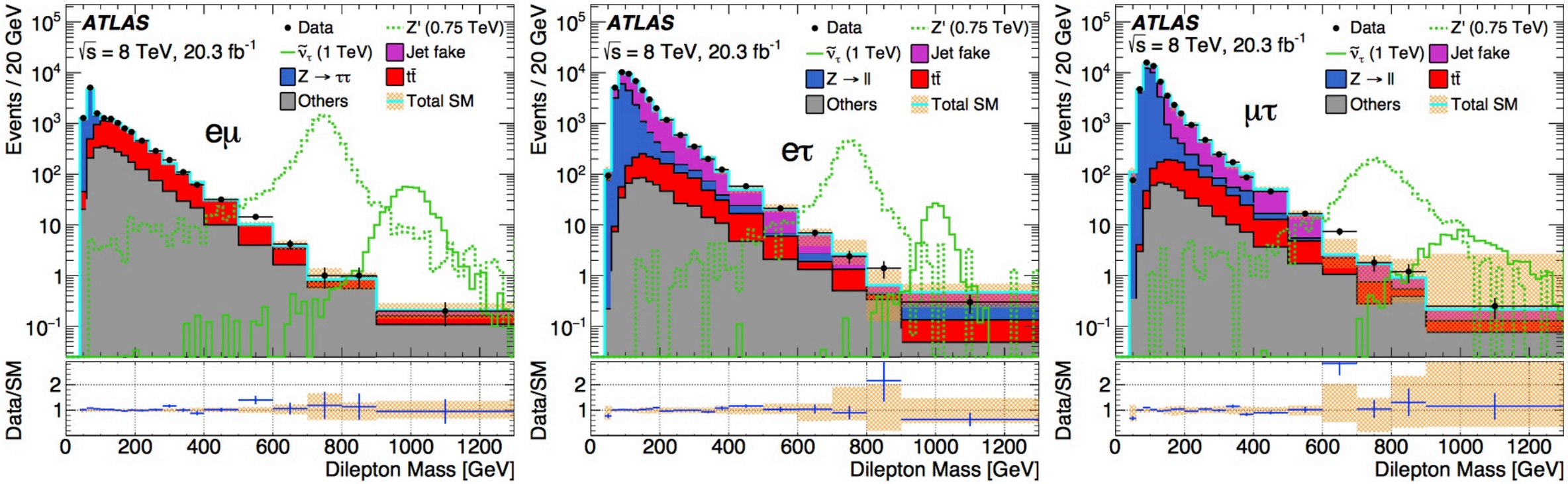
arXiv:1502.05686

R-parity Violation at Production and Decay

$$W_{\not R_p} = \frac{1}{2}\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \frac{1}{2}\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k + \kappa_i L_i H_2,$$



- Assuming RPV production and decays of stau neutrinos
- Excess searched for in mass ranges compatibles with signal resolution

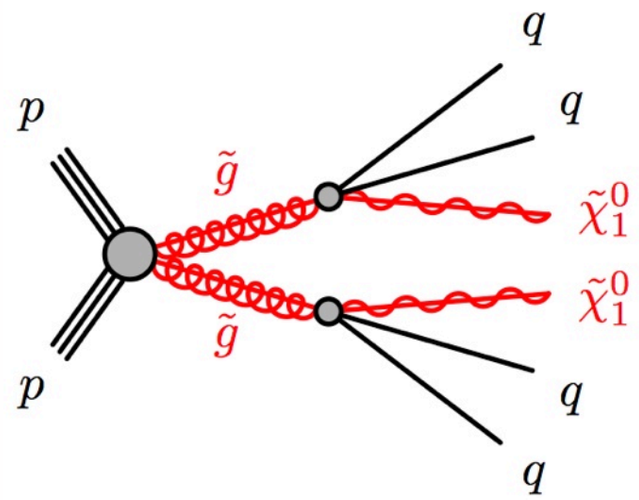


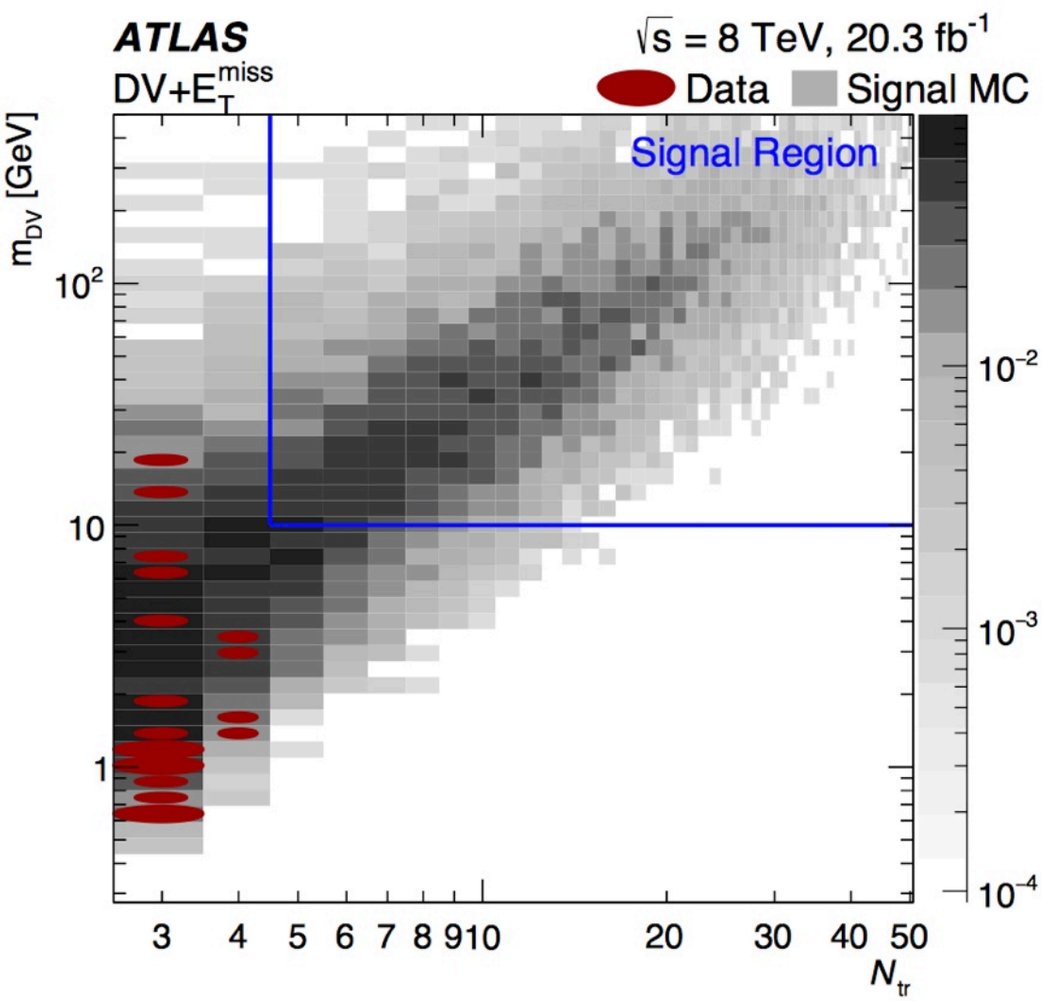
Sensitivity to tau sneutrinos in the range 1.7-2.0 TeV

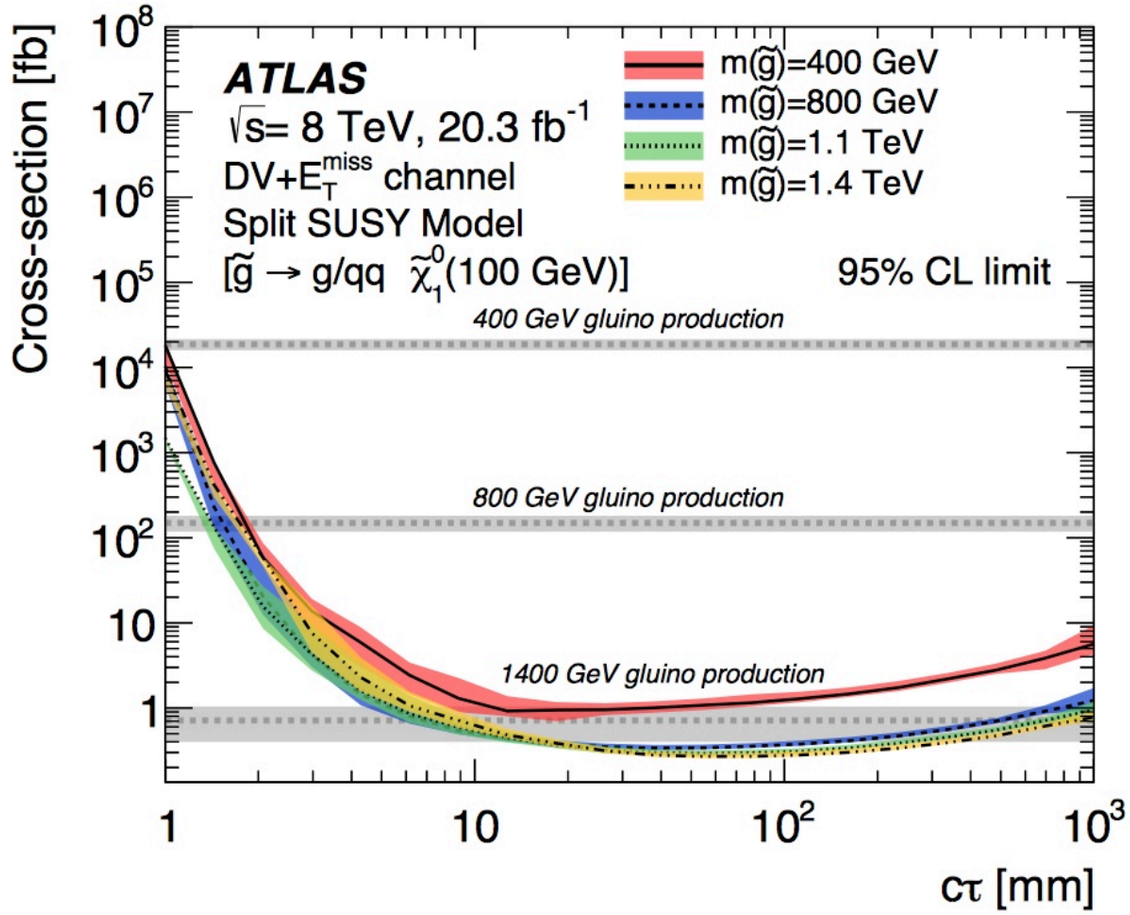
arXiv:1503.04430

Search for Meta-stable Sparticles with Displaced Vertices

- Search for at least one long-lived particle decaying at a significant distance from its production point (Split-SUSY, R-hadrons)
  - Using events with a displaced vertex containing either two leptons or five or more charged particles
  - Vertices are veto-ed in regions of high density material

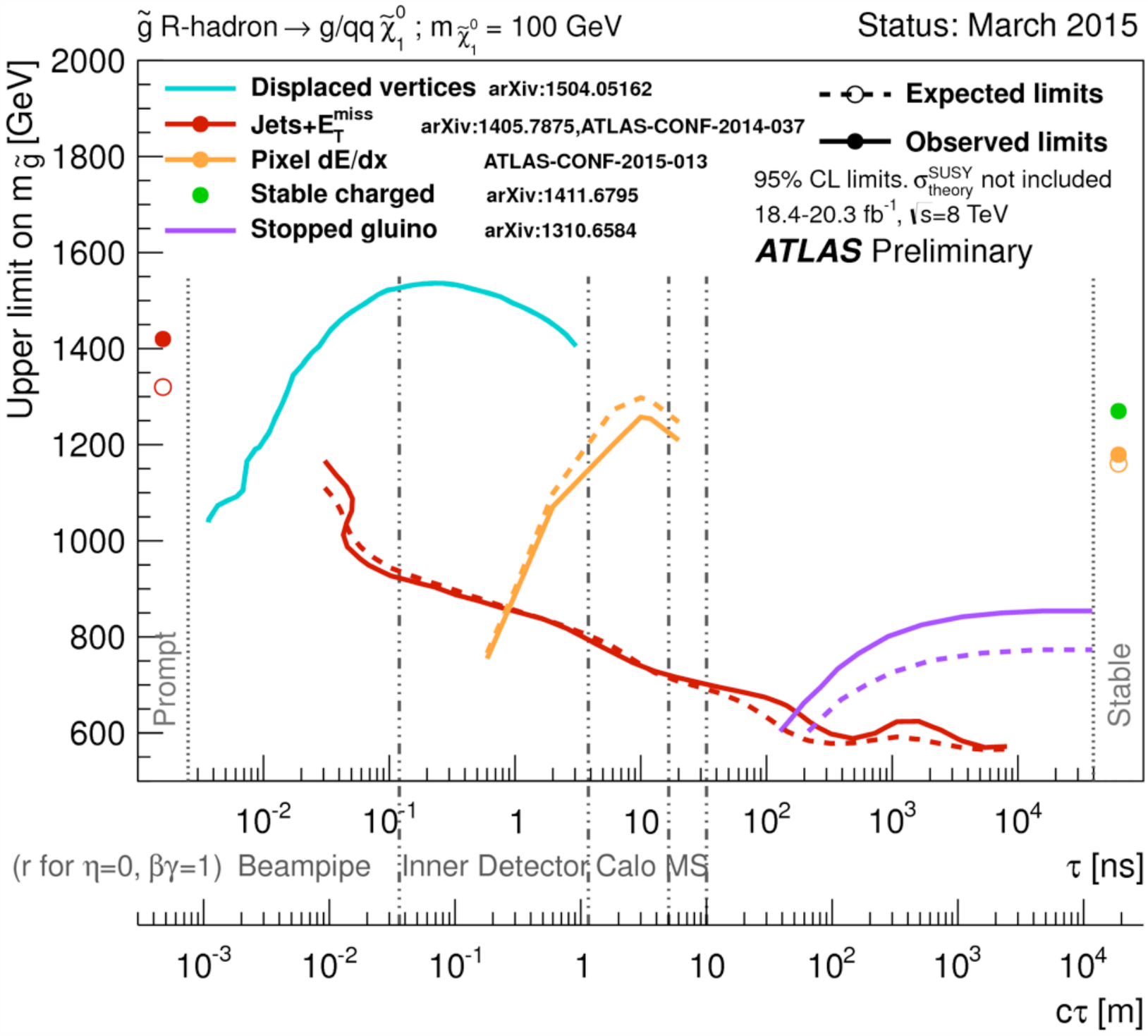




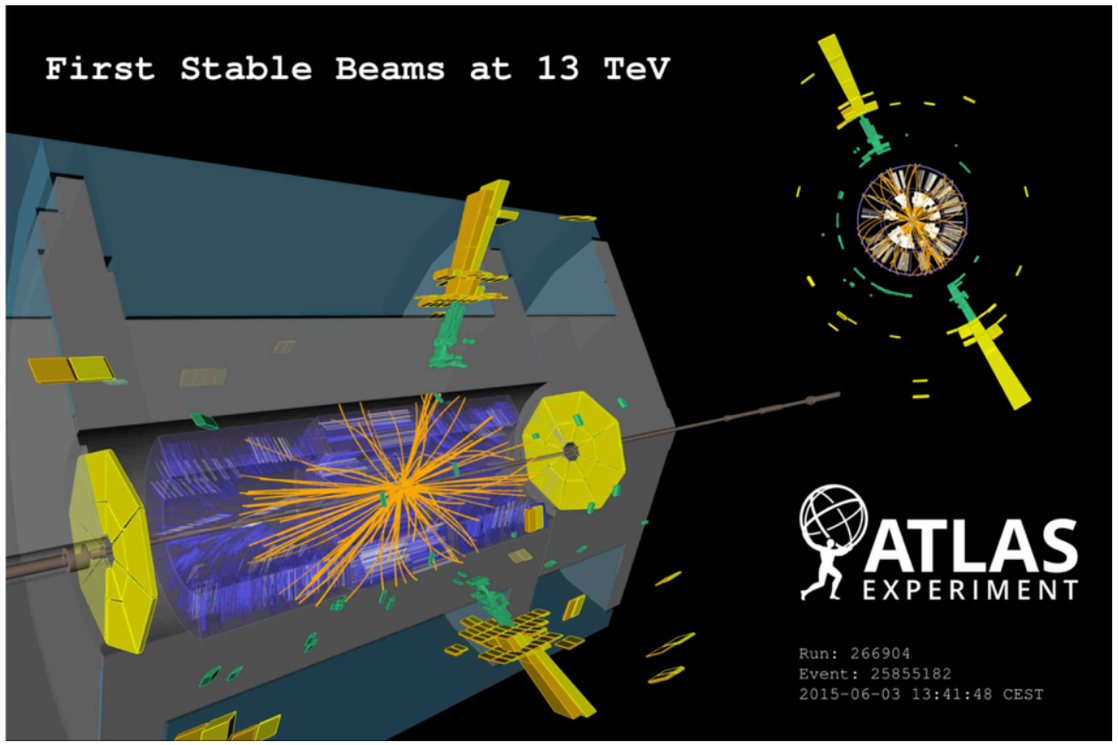


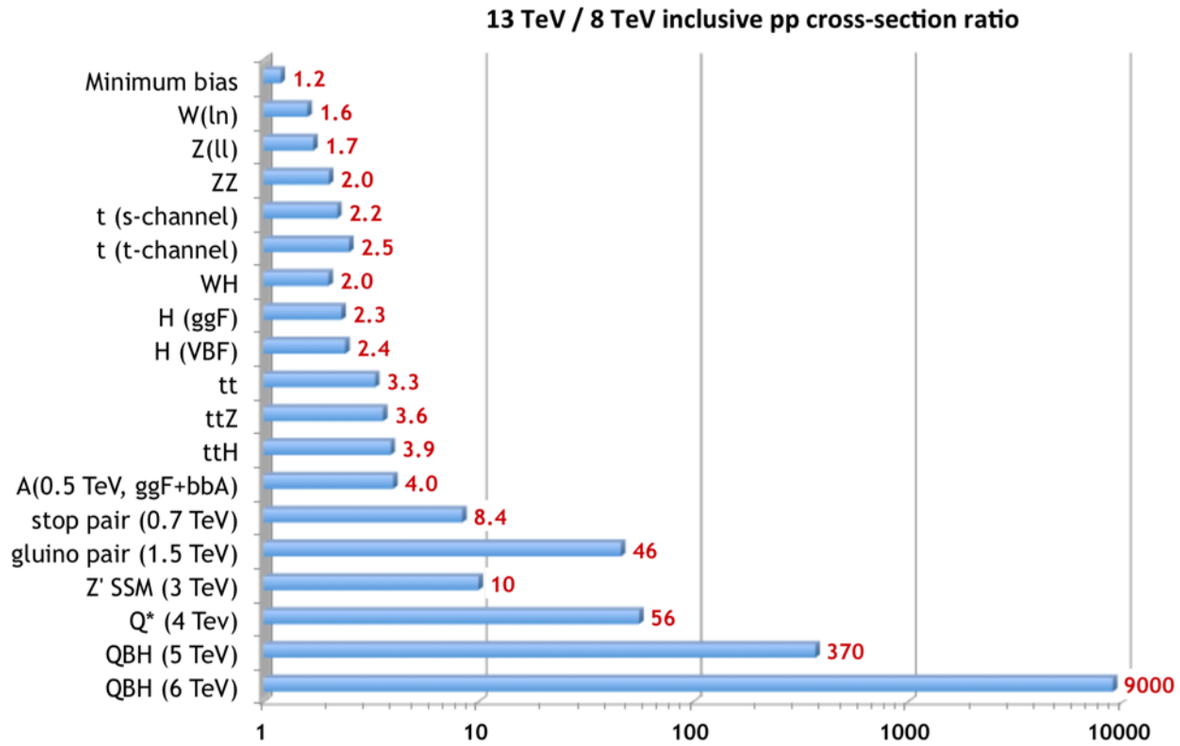
arXiv:1504.05162

Overview of searches for metastable and long lived SUSY

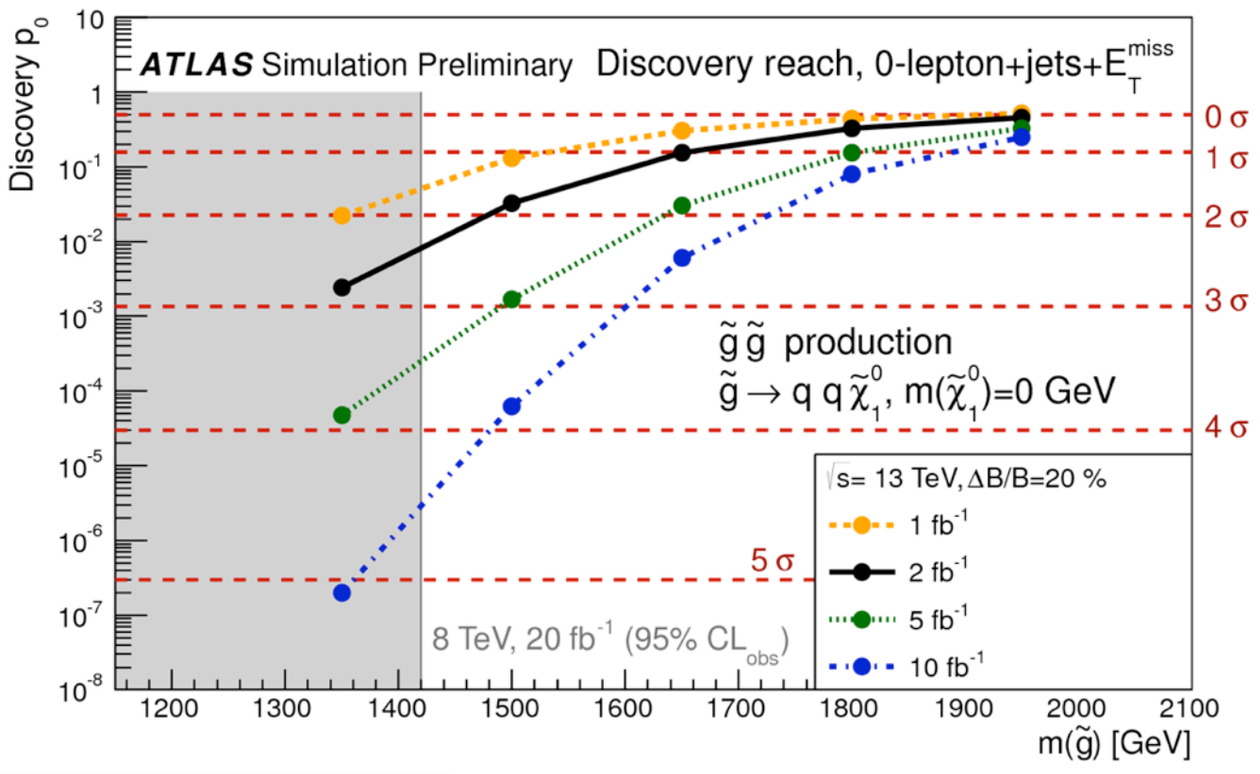


Run 2 at the LHC just started!





- Uncharted territories, probing a new energy frontier!
- Spectacular increase of cross-section (especially for gluon produced heavy particles)
- Evidence for gluinos up to 1.6TeV may be possible by the end of the year!

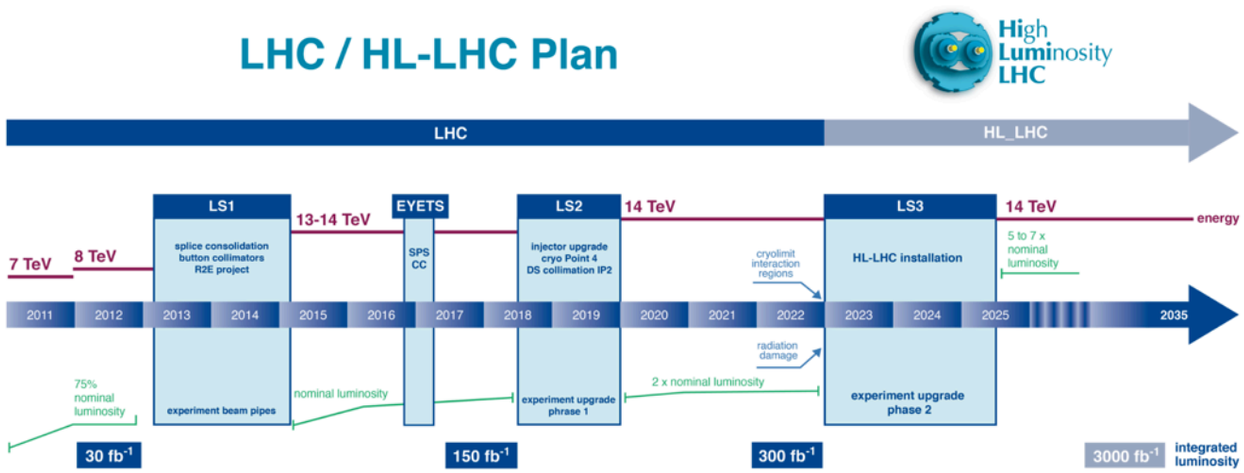


ATL-PHYS-PUB-2015-005

Summary and Outlook

- ATLAS developed a vast program including searches for strongly- and weakly-produced *sparticles* under the assumption of both R-parity conservation (and R-parity violation)
  - scenarios with prompt, metastable, and long lived *sparticles* are explored
- In canonical scenarios, sensitivity is achieved to ~1.2 TeV gluinos, ~700 GeV stops, and of ~400 GeV EWK-inos
- Probed TeV scale for RPV and Long Lived SUSY
  - significant improvement of sensitivity to compressed and challenging scenarios thanks to innovative experimental techniques

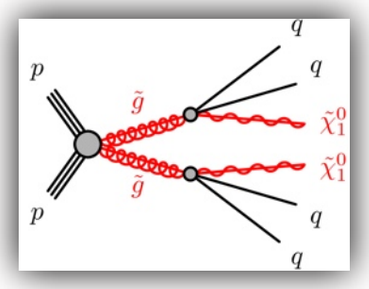
- **Run just started at 13 TeV !**
- **The reach for strongly produced SUSY is expected to increase significantly at Run 2**
- **Discoveries possible in 2015 !**

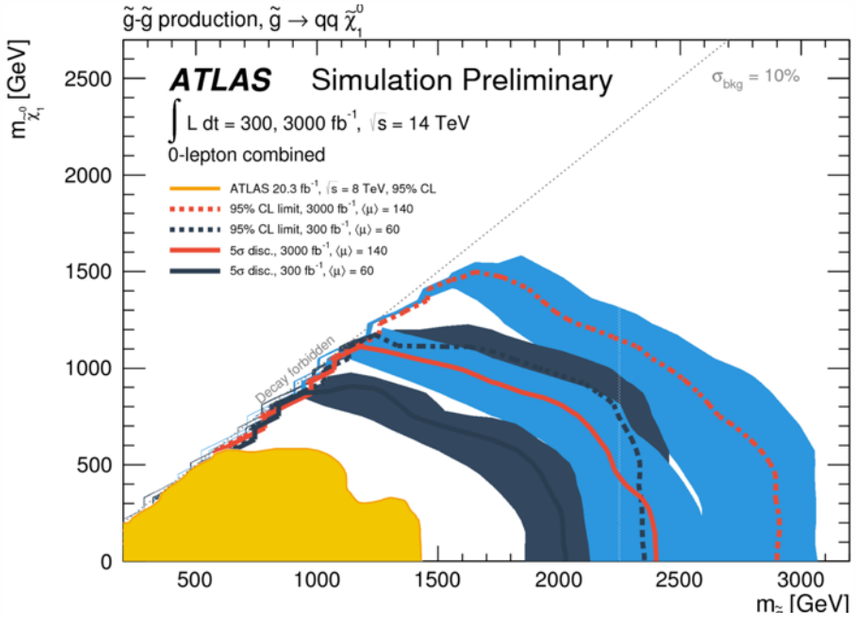


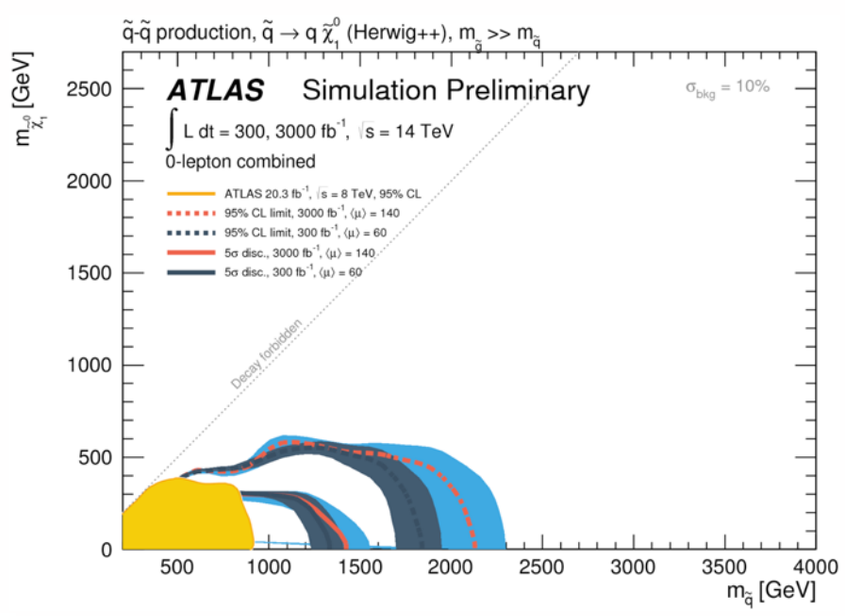
Additional Material

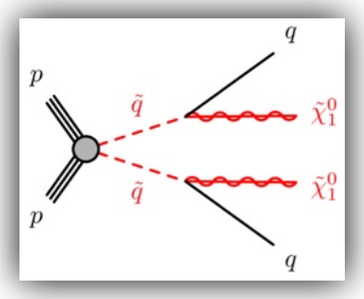
SUSY at Run 3 and HL-LHC

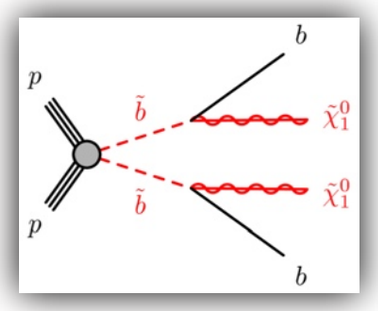
- 14 TeV allows to probe heavier SUSY and 300/3000 fb^{-1} crucial for EWK processes

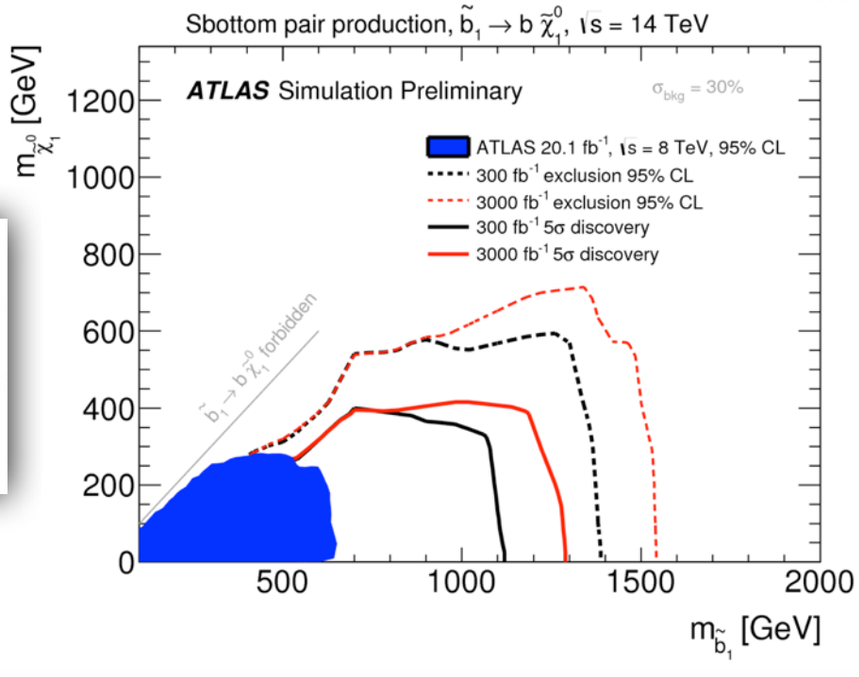


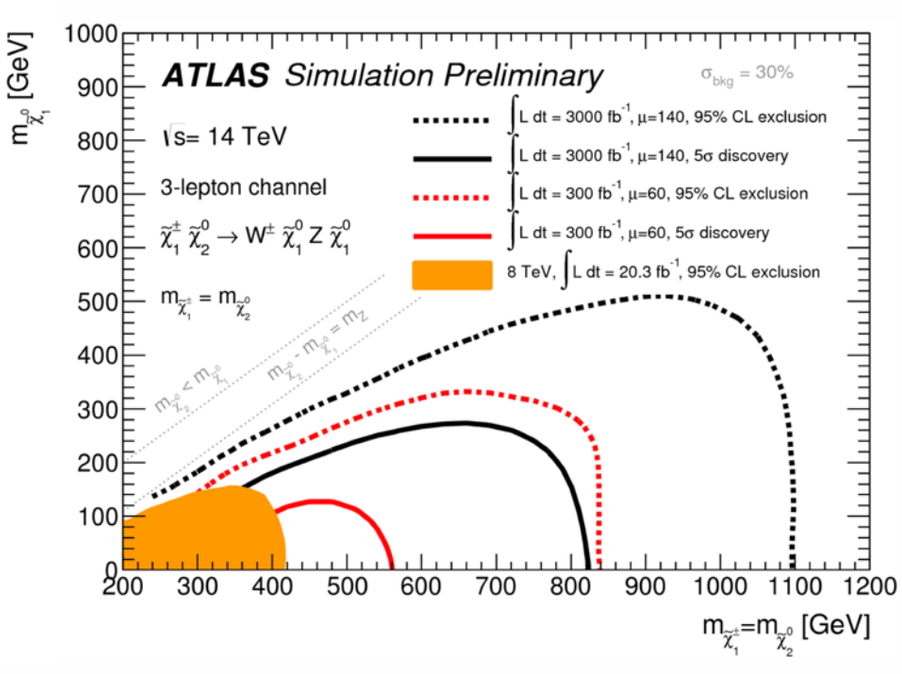


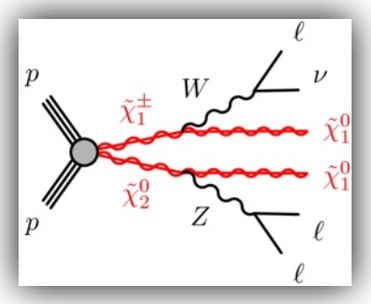










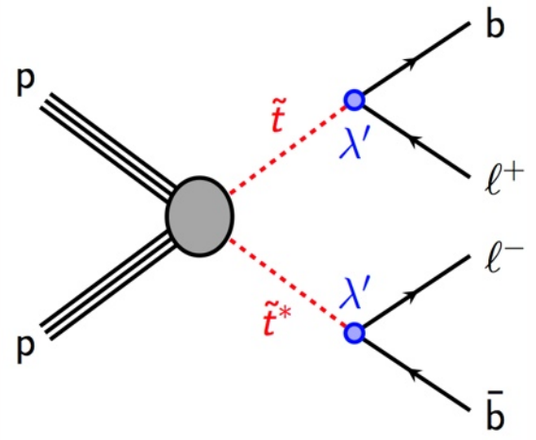


Discovery potential up to 2.5 TeV gluinos, 1.3 TeV squarks/sbottom
800 GeV Electroweakinos, covering 'natural range'

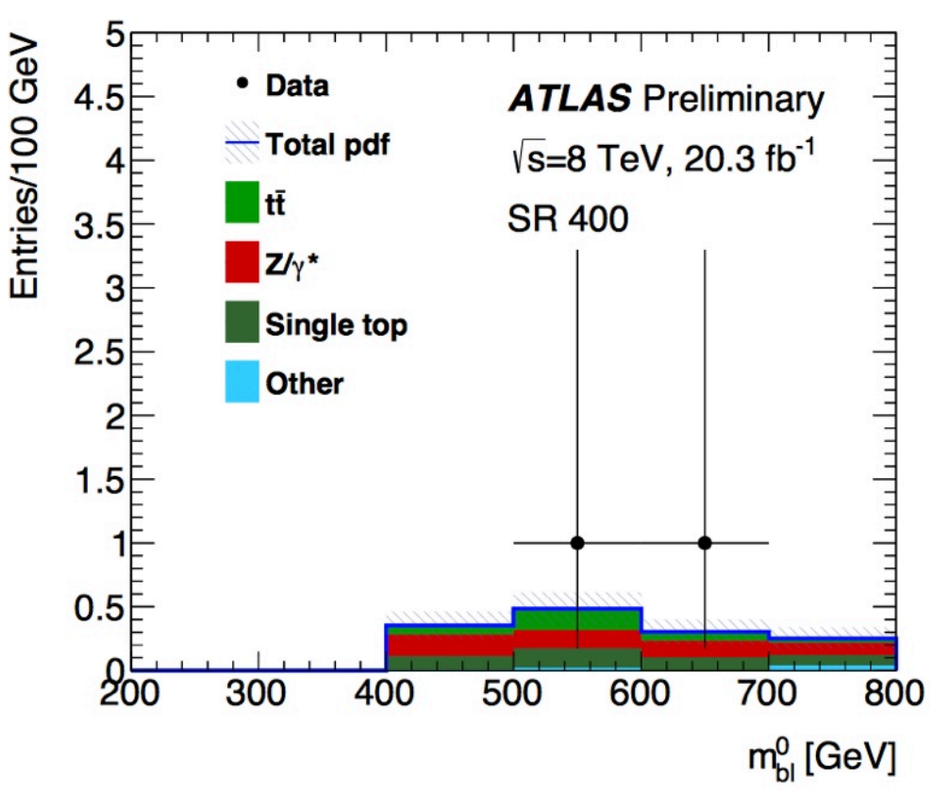
ATL-PHYS-PUB-2014-010

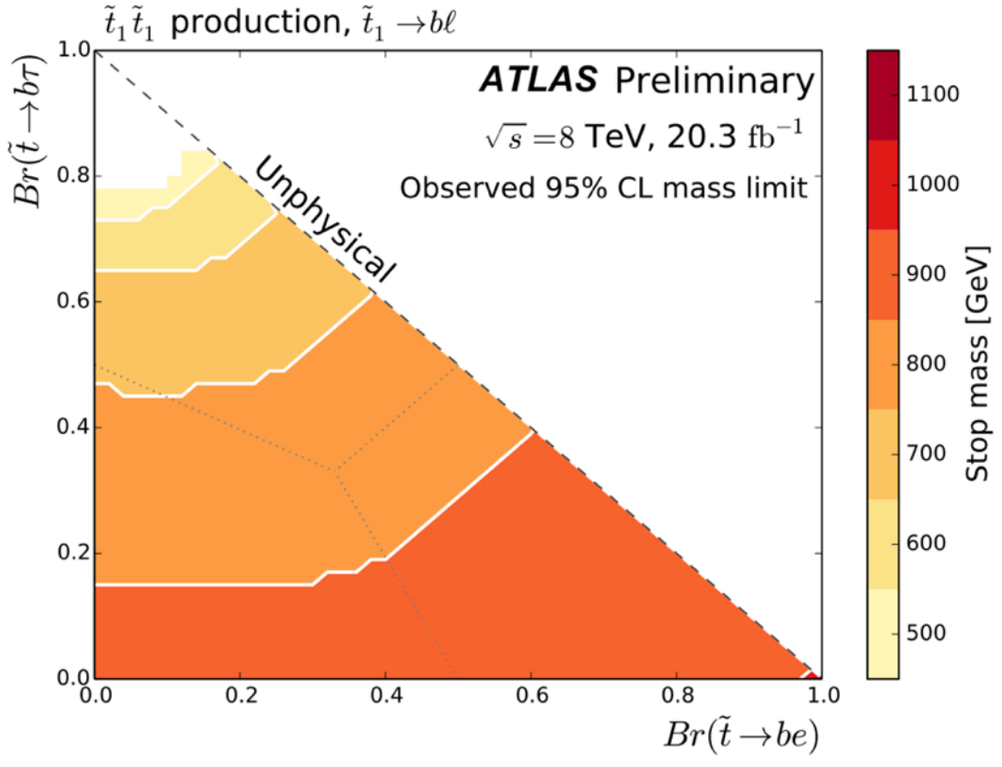
Light Stops decaying via RPV couplings

- If gluinos are heavy, pair production of stop may dominate the SUSY production at LHC
- Search for RPV decay via lambda' couplings
  - final states with 2 leptons and 2 b-jets
  - 2 SRs based on ETmiss, HT, mlb, mlb asymmetry and Etmiss_significance



$$m_{b\ell}\ \text{asymmetry} = \frac{m^0_{b\ell} - m^1_{b\ell}}{m^0_{b\ell} + m^1_{b\ell}}$$





ATLAS-CONF-2015-015