SUSY searches with the ATLAS detector

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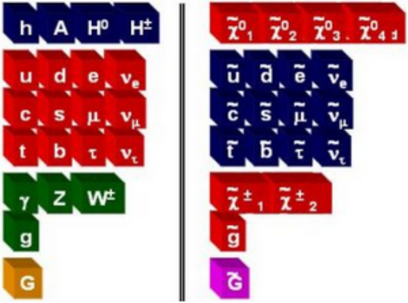
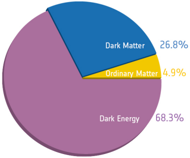
Supersymmetry: symmetry relating fermions and bosons

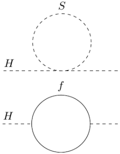
- Only possible extension of Poincare space-time symmetry.
- **M**inimal **S**upersymmetic **S**tandard **M**odel (MSSM): each Standard Model particle receive a supersymmetric partner.
- Extended Higgs sector required.



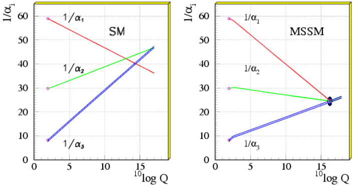
Motivations for Supersymmetry (selection):



Can provide a dark matter candidate.

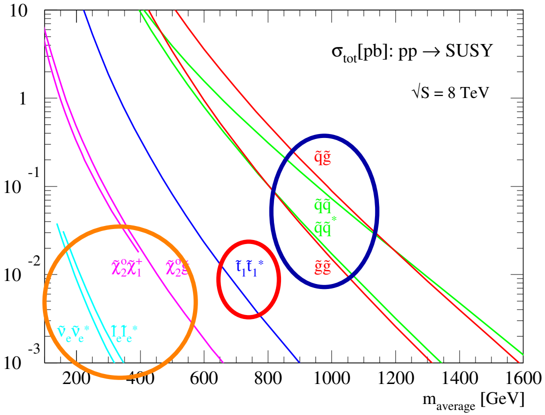


Solves hierarchy problem if masses of SUSY particles not too high.



Unification of gauge couplings

Production of supersymmetric particles at the LHC



[Prospino, `http://www.thphys.uni-heidelberg.de/~plehn/includes/prospino/prospino_lhc8.eps`]

Strong production of quarks (1st and 2nd generation) and gluinos

→ high cross section if masses not too high

→ Expected limits ∼ 1.2 (0.7) TeV for gluinos (squarks)

Strong production of third generation squarks

→ Expected limits up to 0.7 TeV.

Electroweak production of sleptons and eletroweakinos

→ might be most copiously produced at the LHC if squarks and gluinos heavy but electroweakinos light.

→ Expected limits ∼ 0.2 -0.5 TeV

Categorization of SUSY events

R-parity

→ Forbid baryon and lepton number violation by requiring *R*-parity conservation:

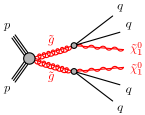
$$R\text{-parity} = (-1)^{3(B-L)+2S} = \begin{cases} +1 & \text{for Standard Model particles} \\ -1 & \text{for SUSY particles} \end{cases}$$

B: baryon number, *L*: lepton number, *S*: spin

→ Distinguish different categories: *R*-parity conserved, *R*-parity violated and long lived scenarios

If *R*-parity conserved:

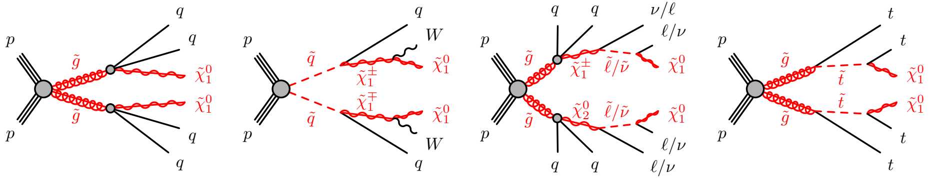
- SUSY particles produced in pairs and decay until lightest supersymmetric particle (LSP) reached.
- LSP stable, only weakly interacting, neutral → dark matter candidate.
- LSP escapes detection → (large) E_T^{miss}.



ATLAS search strategy

Prompt					Long-Lived
R-Parity-Conserving			R-Parity Violation		
Strong 1st, 2nd gen. squarks, gluinos	3rd gen. stop, sbottom	Weak EWK-inos, sleptons	RPC prod. RPV decays	RPV prod. RPV decays	Various ranges of lifetime

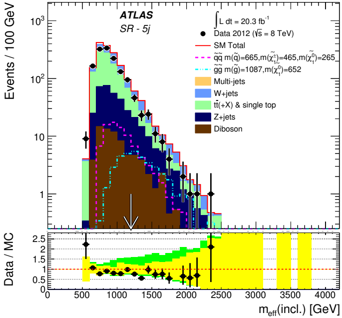
[https://indico.cern.ch/event/352689/material/slides/0.pdf]



⇒ Final states with (many) jets, possibly leptons and a (more or less) high E_T^{miss}

Analyses (selection):

- 0-lepton + 2-6 jets [`JHEP 09 (2014) 176`]
- 0 or 1-lepton + 3 b-jets [`JHEP 10 (2014) 024`]
- 2 same-sign leptons/3-leptons [`JHEP 06 (2014) 035`]
- 1 or 2 soft or hard lepton(s) + jets (to be published soon, `https://indico.cern.ch/event/352689/`)
- ...



[`JHEP 09 (2014) 176`]

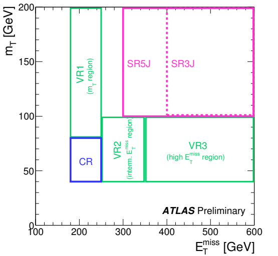
All searches use the full 2012 statistics of $\sim$ 20 fb^{-1} collected by the ATLAS detector in *pp* collisions at 8 TeV.

Searches in final states with one or two leptons

https://indico.cern.ch/event/352689/

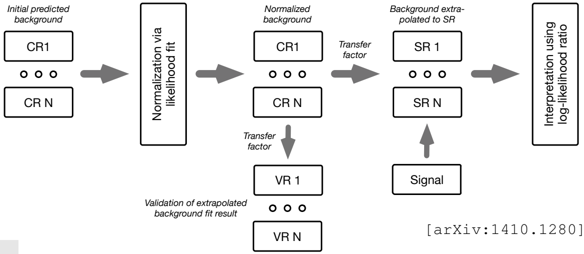
Four different analyses, requiring 1 or 2 electrons or muons:

- A 'soft' lepton ($6/7 < p_T(e/\mu) < 25$ GeV)
  $\rightarrow$ compressed scenarios
- A 'hard' lepton ($p_T > 25$ GeV)
  $\rightarrow$ medium to large mass splittings
- Two hard leptons
  $\rightarrow$ longer decay chains
- Two soft muons
  $\rightarrow$ specialized to minimal Universal Extra Dimensions



Signal discriminated wrt background by requirements on jet multiplicity, m_T, E_T^{miss}, m_{eff}

(Example from the soft 1-lepton analysis)



[arXiv:1410.1280]

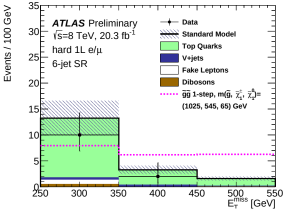
Major backgrounds ($t\bar{t}$, W+jets, Z+jets) estimated by:

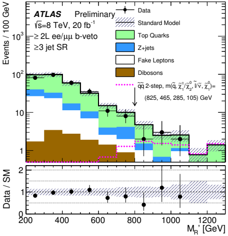
- Defining control regions dominated by backgrounds to be estimated.
- Fit background model simultaneously to data in all control regions.
- Extrapolation to validation and signal regions.

Searches in final states with one or two leptons

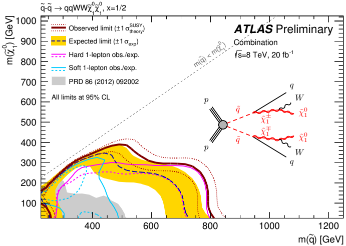
https://indico.cern.ch/event/352689/

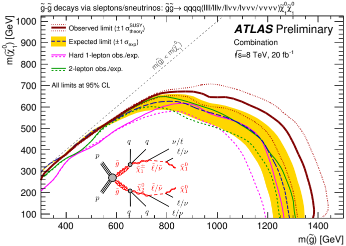
Results in agreement with Standard Model expectations.





Results interpreted in multiple supersymmetric models (both simplified and phenomenological).





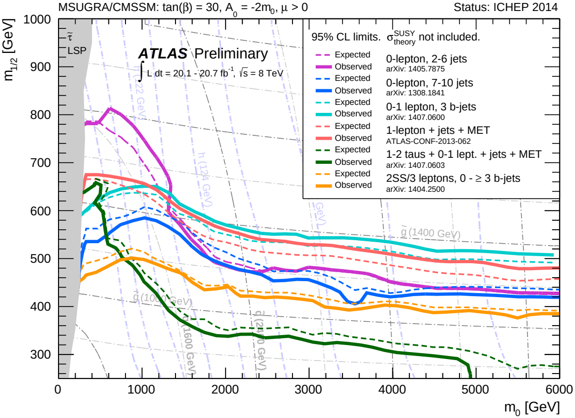
Signal regions/analyses statistically combined to increase sensitivity.

Gluino masses $\gtrsim$ 1.2 TeV/squark masses $\gtrsim$ 700 GeV excluded for massless LSP, independently of the specific model.

Interpretations in cMSSM/MSUGRA

Interpretations also provided in full phenomenological models, e.g. in cMSSM/MSUGRA (4 parameters plus 1 sign):

- m_0 (unified scalar mass at M_{GUT})
- $m_{1/2}$ (unified gaugino mass at M_{GUT})
- $\tan\beta$
- A_0 (unified tri-linear coupling at M_{GUT})
- sign of μ



Gluino masses below 1.3 TeV excluded for all m_0 values.

→ Analyses nicely complementary.

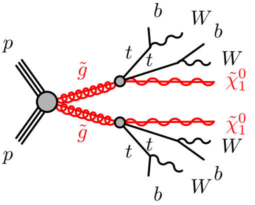
Gluino mediated stop quark production

In 'natural' SUSY models: stop masses to be below $\sim$ 1 TeV and gluino masses below $\sim$ 2-3 TeV.

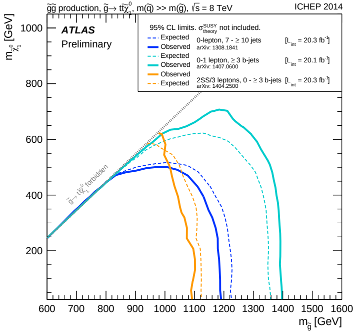
(If stops and gluinos heavier, significant fine-tuning required and SUSY cannot provide a full solution to the hierarchy problem.)

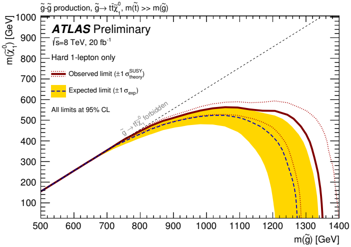
$\rightarrow$ Search for direct and gluino-mediated stop production.

Gluino-mediated stop production: Busy final state with four top quarks and E_T^{miss}



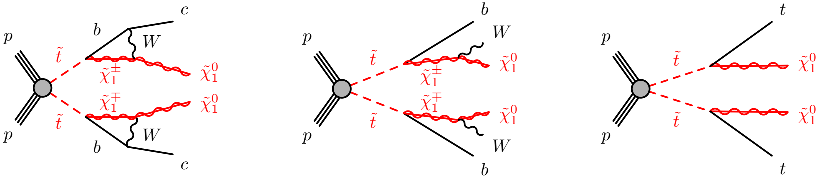
- $\rightarrow$ Four b-jets in the final state.
- $\rightarrow$ Analyses requiring b-jets particularly sensitive - as the analysis (in turquoise) requiring 3 b-jets in final states with 0 or 1 lepton.

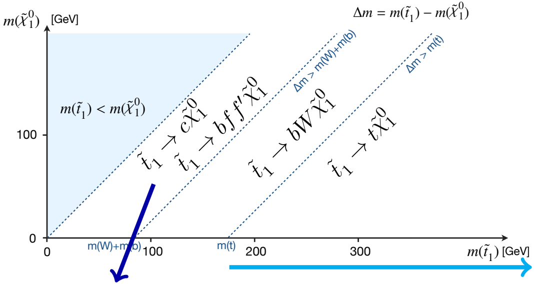




$m_{\tilde{t}} > m_{\tilde{g}}$: Gluino masses up to 1.4 TeV excluded (depending on the LSP mass).

Searches for direct stop production





Often long and complicated decay chains.

Usually final states with many b-jets

<u>Compressed scenarios:</u>

→ mono-jet searches

→ soft lepton analyses

<u>Can exploit final states with 0- 2 leptons</u>

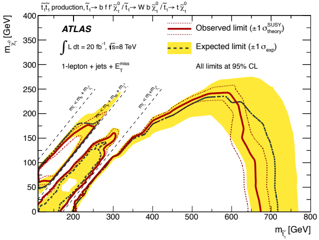
- Usage of complex discriminating variables
- e.g. exploit boosted topology to reject top background

Two examples for stop searches

Search for stops in final states with 1 lepton + 3-4 jets + E_T^{miss}

JHEP11(2014)118

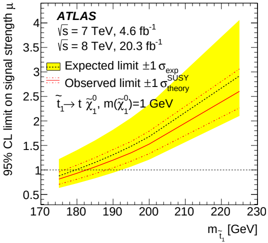
- 15 signal regions covering many topologies: direct stop to LSP decay, 3- and 4-body decays,...
- Using a large collection of dedicated variables, including soft leptons and boosted jets.
- Sensitivity to stop masses up to 650 GeV.



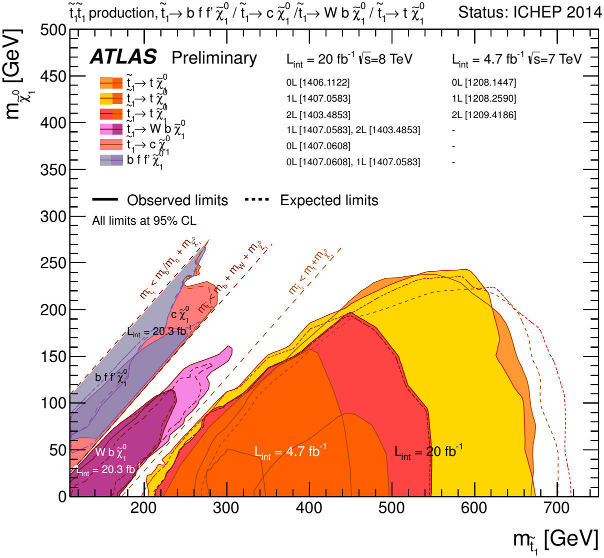
Constraints from precision measurements of the ttbar cross section on light stops

Eur.Phys.J.C74 (2014) 3109

- Most searches have no sensitivity to stop masses close to the top mass.
- Can access this region through precision measurement of the $t\bar{t}$ cross section.
- Exclude stop masses below 180 GeV.



Summary on stop searches



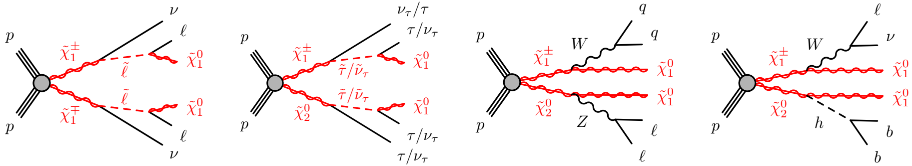
Various analyses to cover gaps at top (and *W*) mass (difficult to access):

- $t\bar{t}$ cross section measurements.
- Search for $\tilde{t}_2$ with Z in final state. $\rightarrow$ `Eur.Phys.J.C (2014) 74:2883`
- Measurement of spin correlation in $t\bar{t}$ events. $\rightarrow$ `ATLAS-CONF-2014-056`

$\rightarrow$ Searches sensitive up to stop masses of $\sim$ 700 GeV

Searches for directly produced electroweakinos

→ Direct chargino/neutralino/slepton production can dominate at the LHC if squarks/gluinos much heavier.



Clean signatures with: leptons (including taus), *W*/*Z* bosons and Higgs bosons + $E_{\mathrm{T}}^{\mathrm{miss}}$, low jet multiplicity

E.g. searches in:

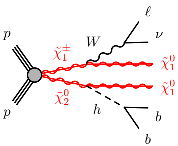
- 3 leptons (e,μ,τ) + $E_{\mathrm{T}}^{\mathrm{miss}}$ [JHEP 04 (2014)169]
- 2 leptons (e,μ) + $E_{\mathrm{T}}^{\mathrm{miss}}$ [JHEP 05 (2014) 071]
- 2 taus + $E_{\mathrm{T}}^{\mathrm{miss}}$ [JHEP 10 (2014) 096]
- 4 leptons + $E_{\mathrm{T}}^{\mathrm{miss}}$ [Phys.Rev.D.90, 052001]

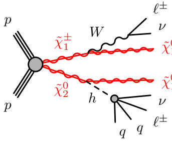
Searches for electroweak SUSY with a Higgs boson

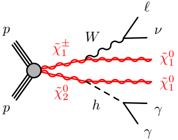
[ATLAS-CONF-2014-062]

Searches in 3 different channels:

- 1-lepton + 2 b-jets
- 2 same-sign leptons
- 1-lepton + 2 photons



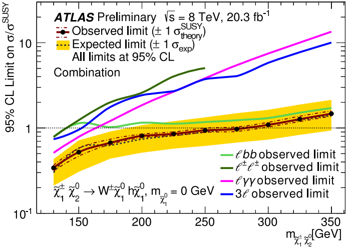


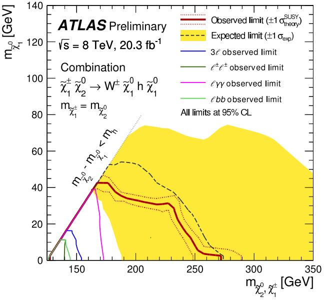


Discriminating variables:

- E_T^{miss}, m_T, m_{CT}, m_{bb}
- $E_T^{miss,rel}$, m_{eff}, maximal m_T, m_{lj}, m_{ljj}
- E_T^{miss}, $m_T(W\gamma_i)$, $\Delta\phi(W, h)$

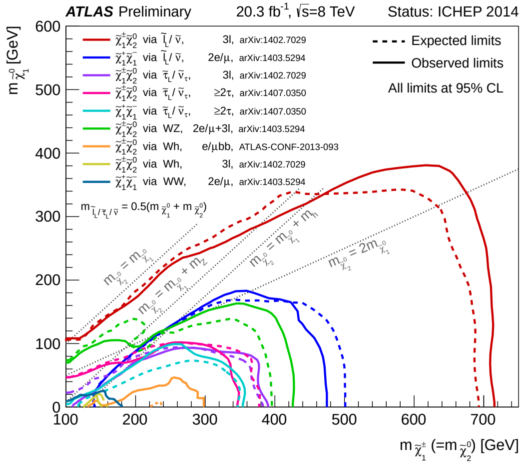
Combining the three searches + 3-lepton search:





Limits up to 250 GeV on the electroweakino mass for massless LSP

Status of searches for electroweakinos



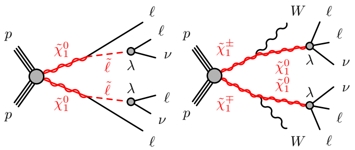
(Be aware that in this plot many different simplified models are shown together.)

- If decays are mediated by sleptons: limits up to 720 GeV.
- If via *WZ*: limits up to $\sim$ 450 GeV.
- Little or now sensitivity to compressed scenarios.

R-parity violating Supersymmetry

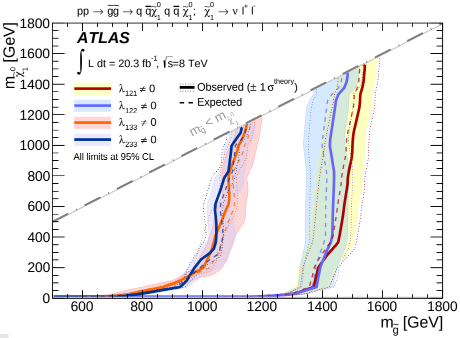
If *R*-parity violated:

- Condition: either lepton or baryon number conserved.
- LSP can decay (thus no dark matter candidate).
- No large E_T^{miss} as signature, but usually high object multiplicities.



4-leptons

Phys.Rev.D. 90, 052001 (2014)

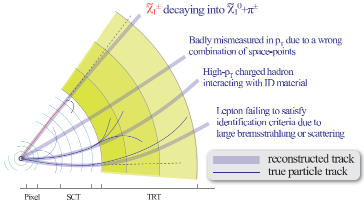


- Analysis requiring 4 leptons, Z-veto and high m_{eff}.
- Backgrounds depending on τ-multiplicity in final state:
  - Irreducible for 0 τ: *ZZ*, *VVV*, $t\bar{t}Z$, Higgs
  - Reducible for 1-2 τ: *Z*+jets, $t\bar{t}$, *WZ*
- Limits reaching up to $\sim$ 1.4 TeV in the gluino mass $\rightarrow$ comparable to RPC searches.

Searches for long-lived particles

Long-lived particles appear in different cases, e.g.:

- Small RPV couplings.
- RPC: compressed scenarios.
- RPC: meta-stable and long-lived gluinos due to heavy squarks.
- RPC: long-lived sleptons/neutralinos due to small coupling to gravitino.



[Phys.Rev.D 88, 112006 (2013)]

Result in distinctive signatures depending on lifetime:

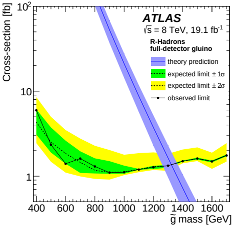
- Displaced vertices, disappearing or kinked tracks.
- Leptons/photons not pointing to the primary vertex.
- Delayed decays of massive particles, ...

Heavy long-lived particles [arXiv:1411.6795]

- Predicted by Split SUSY, GMSB, LeptoSUSY etc.
- Long-lived sleptons, gluinos, squarks and charginos in the final state.
- Significantly slower than light.

$\rightarrow$ $m = p/\beta\gamma$ used as discriminating variable.

- Main background: high p_T mismeasured muons.



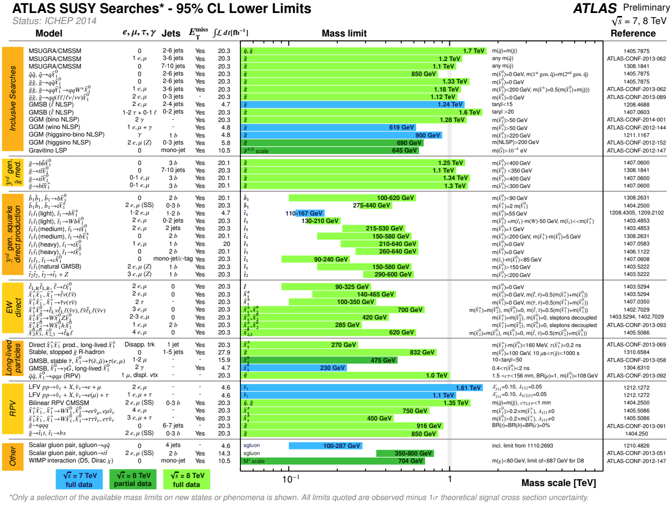
Summary

Limits on:

- Gluinos: $\sim$ 1.2 - 1.3 TeV
- First two generation squarks: $\sim$ 800 GeV
- Stops: $\sim$ 700 GeV
- Electroweakinos: $\sim$ 400 - 700 GeV.

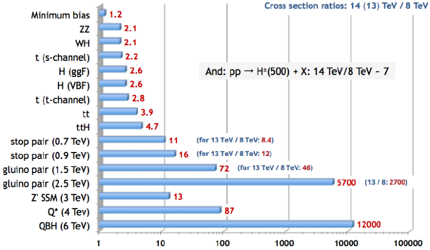
... in the most extreme cases only!

Limits much weaker in certain scenarios: Compressed models,...



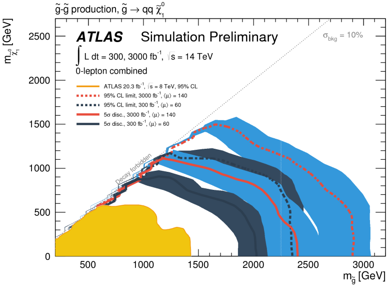
Expectations for Run 2 and the HL-LHC

Extrapolations to 13/14 TeV



→ Expect to be sensitive to yet unexplored SUSY territory with few fb^{-1}!

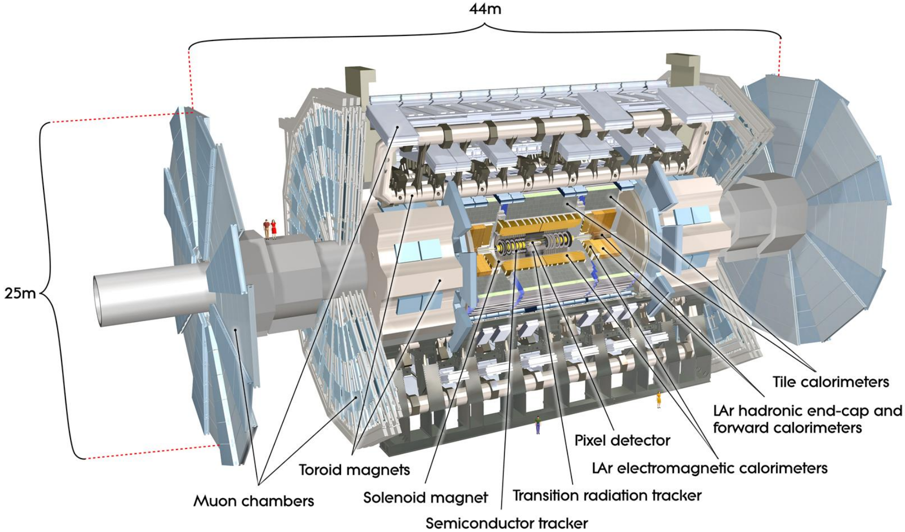
HL-LHC [ATL-PHYS-PUB-2014-010]



→ Discovery reach up to 2.5-3 TeV

Looking forward to Run 2!

Backup

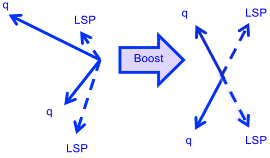

44m
25m
Tile calorimeters
LAr hadronic end-cap and
forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker

Also exploit the longitudinal information of an event.

- Both sparticles are pair-produced, the initial heavy sparticles are assumed here to have the same masses or to be at the same mass scale

$\rightarrow$ Both decay chains are symmetric if going into the frame where the initial heavy sparticle is at rest

$\rightarrow$ Can group all visible particles of one decay chain into a mega-jet; both mega-jets should have the same energy



Variables to benefit from this configuration:

- **Characteristic mass of the event:**
  $M'_R = \sqrt{(j_{1.E} + j_{2,E})^2 - (j_{1,L} + j_{2,L})^2}$
  (E: energy, L: longitudinal component, j_1 and j_2: four-vectors of the two mega-jets)
- **Transverse information of the event:**
  $M_T^R = \sqrt{\frac{|\vec{E}_T^{miss}|(|\vec{j}_{1,T}|+|\vec{j}_{2,T}|)+\vec{E}_T^{miss}\cdot(\vec{j}_{1,T}+\vec{j}_{2,T})}{2}}$
- **Razor:**
  $R = \frac{M_T^R}{M'_R}$

- Effective mass: $m_{\text{eff}}^{\text{incl}} = \sum p_{\text{T}}^{\text{jet}} + p_{\text{T}}^{\text{lepton}} + E_{\text{T}}^{\text{miss}}$
- Transverse mass:
  $m_{\text{T}} = \sqrt{2 \cdot E_{\text{T}}^{\text{miss}} \cdot p_{\text{T}}(\text{lepton}) \cdot (1 - \cos\Delta\phi(\vec{E}_{\text{T}}^{\text{miss}}, \vec{p}_{\text{T}}(\text{lepton})))}$
- Cotransverse mass: $m_{CT} = \sqrt{(E_T^{b_1} + E_T^{b_2})^2 - (\vec{p}_T^{b_1} - \vec{p}_T^{b_2})^2}$
- $E_T^{\text{miss,rel}} = \begin{cases} E_T^{\text{miss}} & \Delta\phi > \pi/2 \\ E_T^{\text{miss}} \sin\Delta\phi & \Delta\phi < \pi/2 \end{cases}$

Gauge Mediated SUSY Breaking

$\rightarrow$ Further possibility to break SUSY.

GMSB:

- Breaking of SUSY via messenger interactions.
- SM flavor symmetry naturally protected.
- Gravitino lightest supersymmetric particle.
- Detector signature determined by nature of NLSP (can be $\tilde{\chi}_1^0$, $\tilde{\tau}$, $\tilde{l}_R$)
- NLSP decays to LSP ($\tilde{G}$) and the SM superpartner of the NLSP.
- Parameters for minimal GMSB: Λ (SUSY breaking scale),N_5 (# messenger fields), tan β, sign of μ, C_{grav} (G mass scale factor), M_{mes}.

General Gauge Mediation (GGM):

- No specific SUSY mass hierarchy for (un)colored states $\rightarrow$ any MSSM sparticle can be the NLSP.
- Nature of neutralino depends on M_1, M_2, μ and tan β.

Natural Gauge Mediation:

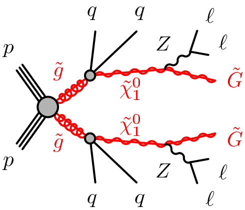
- All sparticles not related to fine-tuning of Higgs sector decoupled.
- Stop and gluino only light colored sparticles.

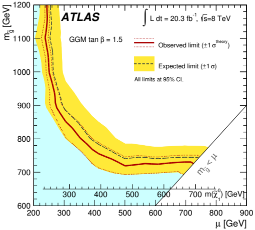
[See also: M.Tripiana, SUSY13, `http://cds.cern.ch/record/1596518/files/ATL-PHYS-SLIDE-2013-496.pdf`]

Selected results in GGM models

4-leptons [Phys.Rev.D. 90, 052001 (2014)]

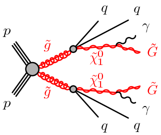
The RPV 4-lepton analysis also interprets in GGM models.

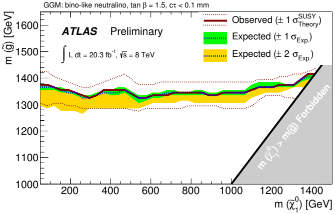




Diphoton+E_T^{miss} [ATLAS−CONF−2014−001]

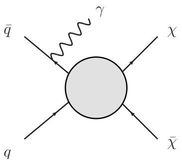
- Analysis specifically designed for GGM models.
- Event selection based on high E_T^{miss}, m_{eff} or H_T, and by cutting on minimal angles ϕ between photons/jets and E_T^{miss}.





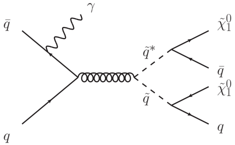
Monophoton

[arXiv:1411.1559]



Events with only a mono-photon appear in various scenarios:

- Large extra spatial dimensions.
- Direct production of weakly interacting massive particles through interaction with quarks via a heavy mediator.
- Very compressed SUSY scenarios, e.g. with pair-wise produced squarks and direct decay to LSPs. (Masses of squarks and LSPs then very close.)



Interpretations