Recent results from SUSY searches with ATLAS and prospects for the HL-LHC

ANDREA VENTURA
UNIVERSITY OF SALENTO & INFN LECCE

ON BEHALF OF THE
ATLAS COLLABORATION

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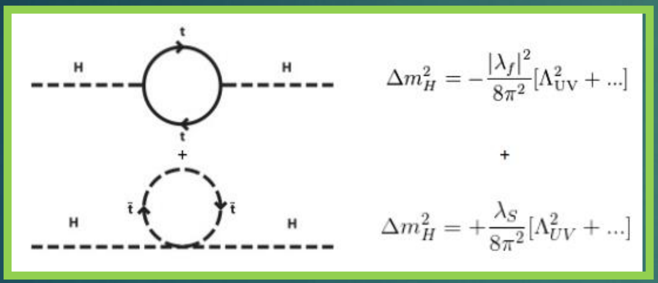
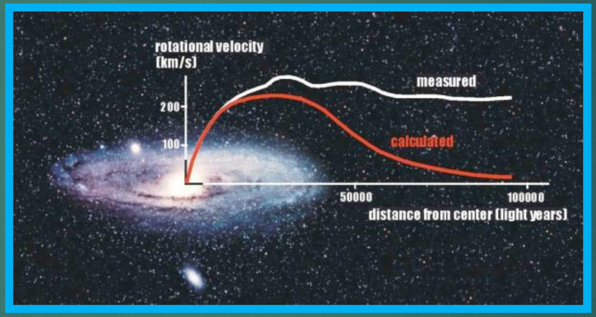
Outline of the talk

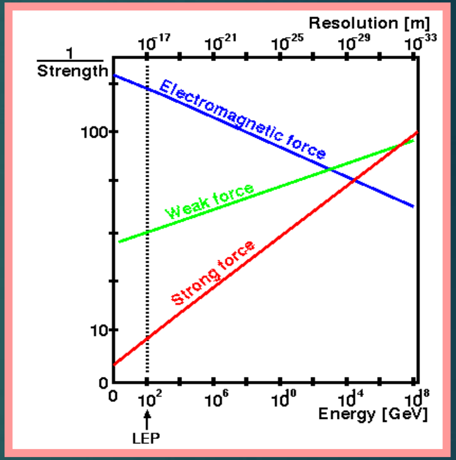
- Why Supersymmetry
- ATLAS at the LHC
  - Upgrades for HL-LHC
- SUSY searches and perspectives for the HL-LHC
  - Gluinos/squarks (1st and 2nd generation)
  - Direct pair production of 3rd generation squarks
  - Electroweak production of gauginos
  - Long-lived particles
- Summary and Conclusions

Why Supersymmetry

- The Standard Model (**SM**) doesn't explain many problems:
  - **Hierarchy problem**: SM needs incredible fine tuning for m_H stability
  - **Dark Matter**: the SM doesn't have a good candidate
  - **Gauge coupling unification**: in the SM there is no unification of coupling constants at high energies



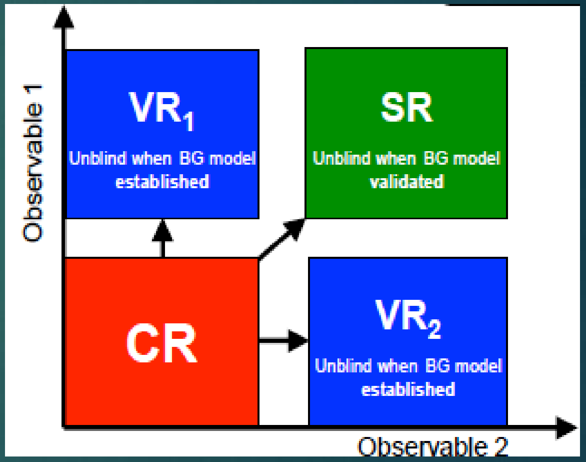




- Supersymmetry (**SUSY**) could actually solve such problems by introducing a «sparticle» for each SM particle, differing by ½ spin unit
- If R-parity is conserved, the **L**ightest **S**USY **P**article (**LSP**) provides a natural Dark Matter candidate. $R : (-1)^{3(B-L)+2s}$

SUSY search strategy

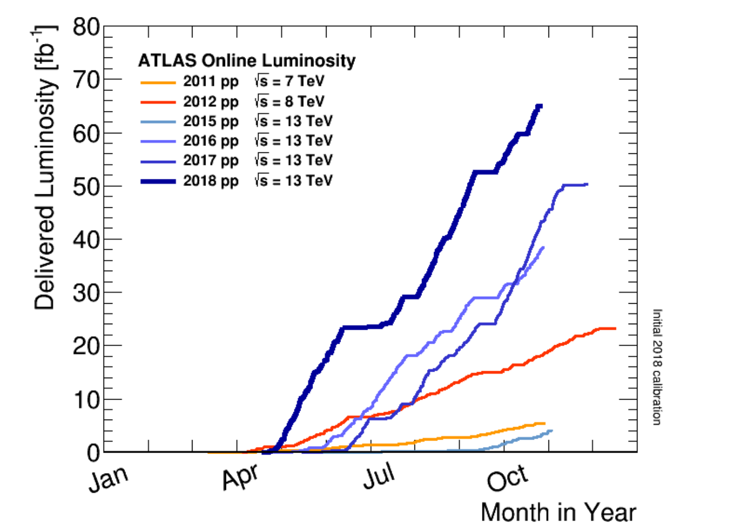
- **Simplified** SUSY models assumed.
- **Event selection** based on sensitive kinematic observables.
- SUSY search is first optimized on Monte Carlo (MC) for:
  - **Discovery** → dedicated analyses in given Signal Regions (**SR**);
  - **Exclusion** → more elaborated methods (MVA, shape-fits).
- Main SM irreducible backgrounds estimated in given process-ehnanced Control Regions (**CR**), with normalization validated in Validation Regions (**VR**).
- Whenever possible, *data-driven* methods used for reducible backgrounds.
- Minor backgrounds estimated with MC.

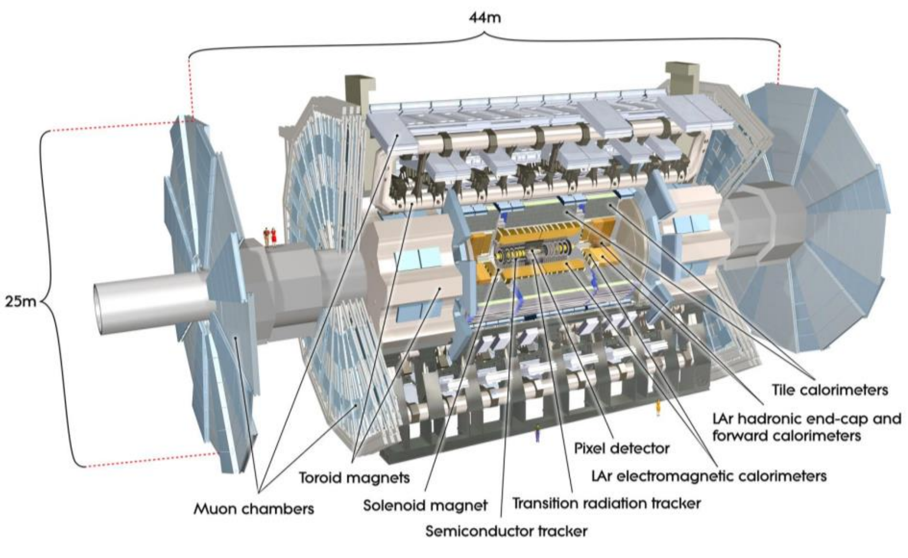


- Final results obtained with a simultaneous **combined fit** of all components in CRs (and SRs for exclusion).

ATLAS experiment at the LHC

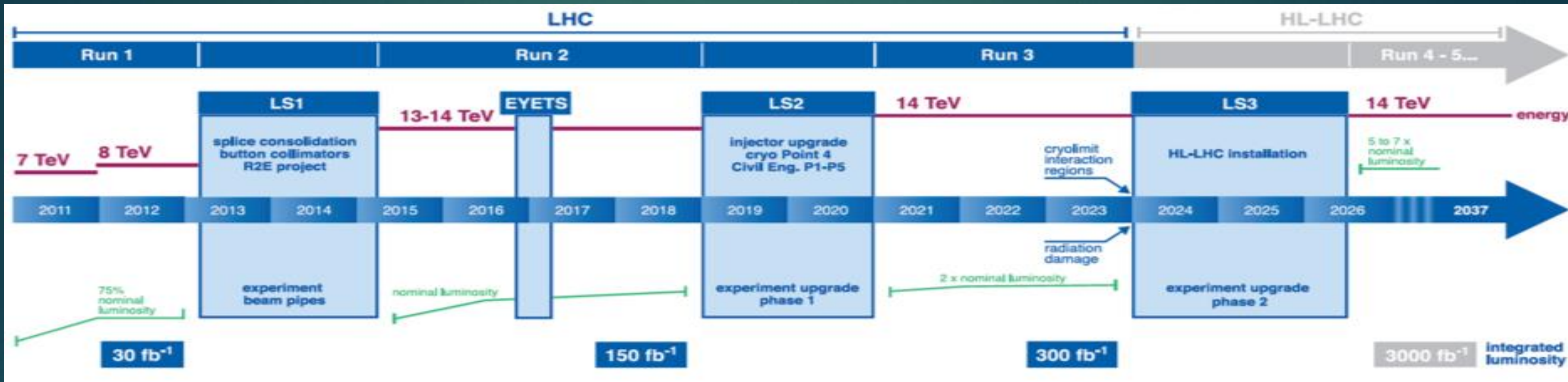
- Delivered luminosity @ 7,8,13 TeV by the LHC (proton–proton collisions):
  - 4.6 & 20.3 fb^{-1} (2011-12) @ 7 & 8 TeV
  - 36.1 fb^{-1} (2015-16) & 44.3 fb^{-1} (2017) @ 13 TeV
  - 60.5 fb^{-1} (2018) @ 13 TeV





- LHC provides the best possible environment to search for new processes in high energy physics

HL-LHC & ATLAS upgrades



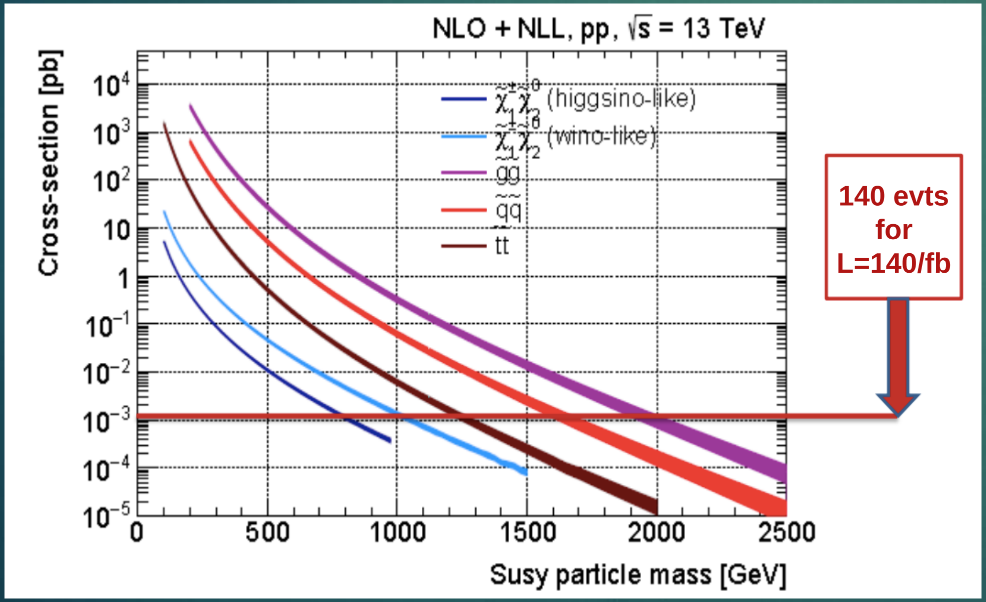
ATLAS-TDR-025

ATL-PHYS-PUB-2016-026

- New conditions at the HL-LHC
  - $\sqrt{s}$ = **14 TeV**, $\mathcal{L} = 7.5 \times 10^{34}$ cm^{-2}s^{-1}, $\langle\mu\rangle = 200$
  - total integrated luminosity **3000 fb^{-1}**
- Requires significant **detector upgrades** in terms of radiation hardness, bandwidth, granularity and η coverage
- New all-silicon Inner Tracker, upgraded read-out electronics for calorimeters, new innermost layer in muon system barrel

ATLAS SUSY search scenarios

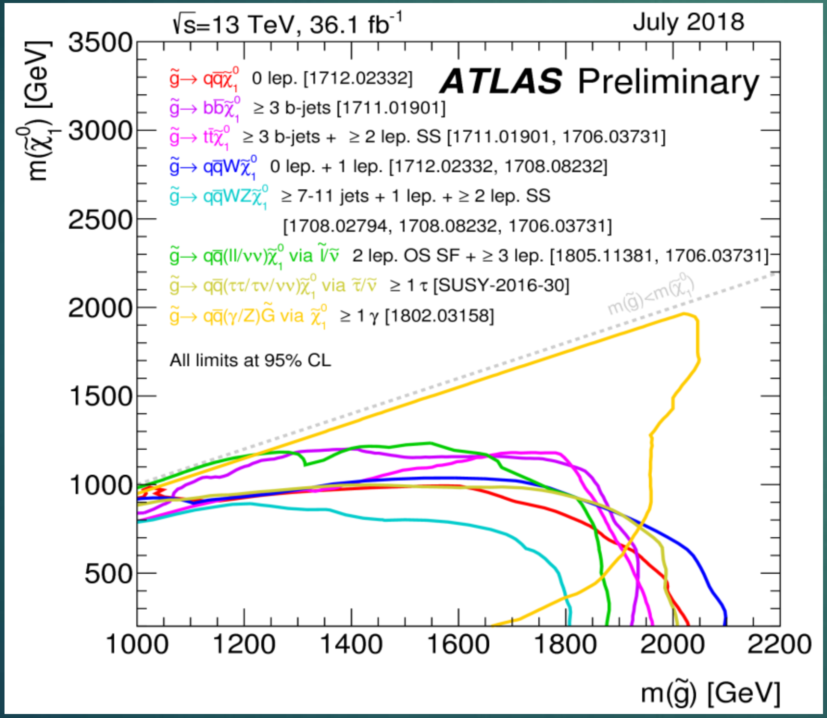
- Different kinds of sparticles are searched at the LHC
  - **Strong production** (gluinos & 1st / 2nd generation squarks)
  - **Stop/sbottom production** (3rd generation squarks)
  - **Electroweak production** (gauginos & sleptons)

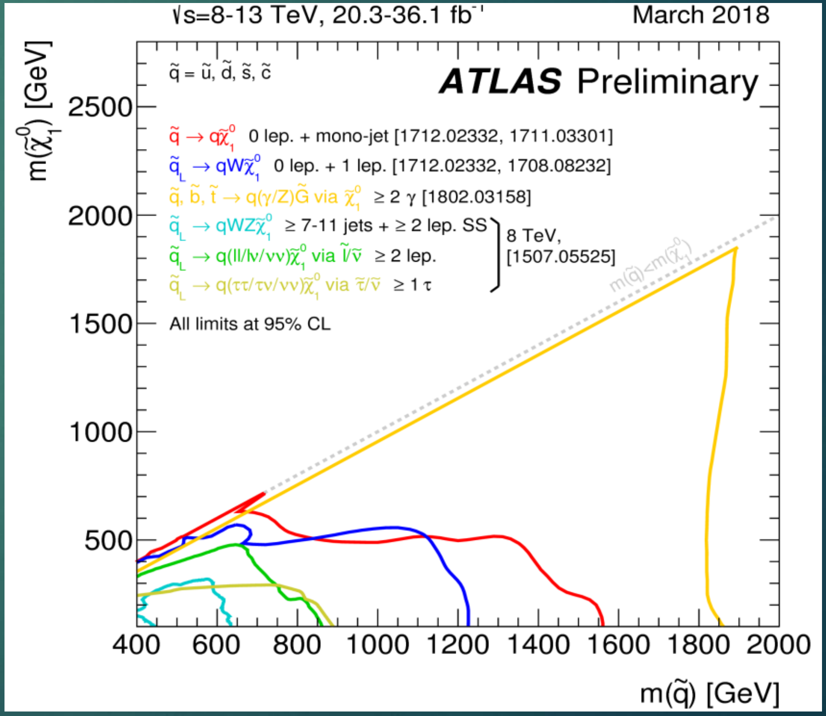


- Cross-sections differ significantly: initial target is strong production, further searches with more integrated luminosity concern 3rd generation squarks and electroweak sparticles production

Strong production searches

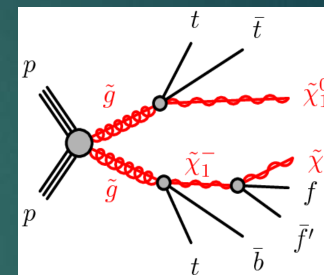
- Many gluino/squark searches with ATLAS aiming at different mass scenarios
  - Gluino masses excluded at 95% C.L. up to more than 2 TeV
  - Squark masses excluded at 95% C.L. up to around 1.8 TeV

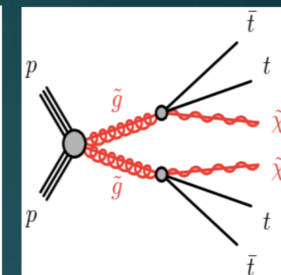


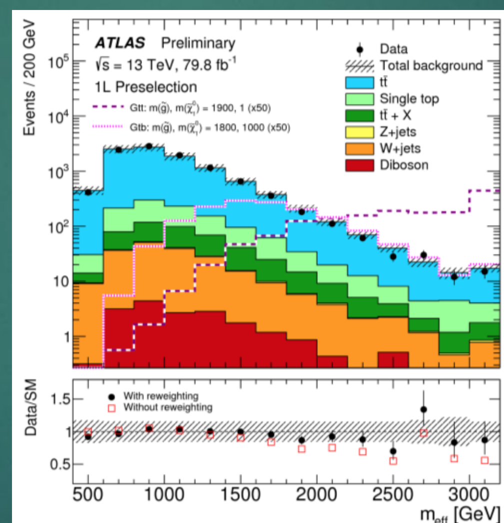


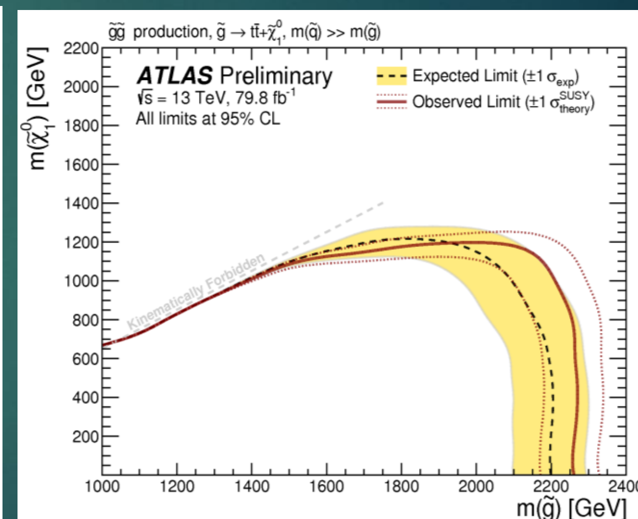
Search for gluinos with multi-b

- Gluino pair production with many b-jets and 0/1 leptons
  - Mass difference $\Delta m(\tilde{\chi}_1^{\pm},\tilde{\chi}_1^{0})$ fixed to 2 GeV
- Main background: ttbar in association with light/heavy flavor jets
- Inclusive cut&count multi-bin analysis:
  - Different SRs based on # of jets and on # of b-jets
  - E_T^{miss} > 300 GeV up to 600 GeV
  - High m_{eff}
  - 0 or 1 lepton







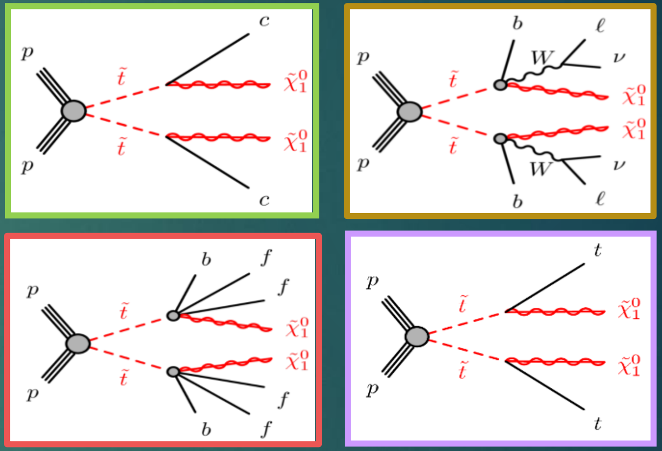


- Gluino masses excluded up to 2.2 TeV

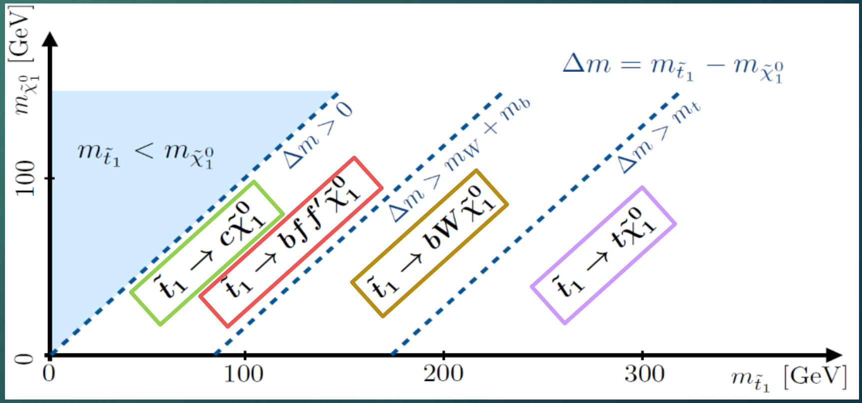
ATLAS-CONF-2018-041

Strongly produced 3rd gen. squarks

- Many sophisticated analyses aim at **bottom** and **top** squarks
  - Fundamental theoretical role (m_H radiative corrections, natural SUSY)

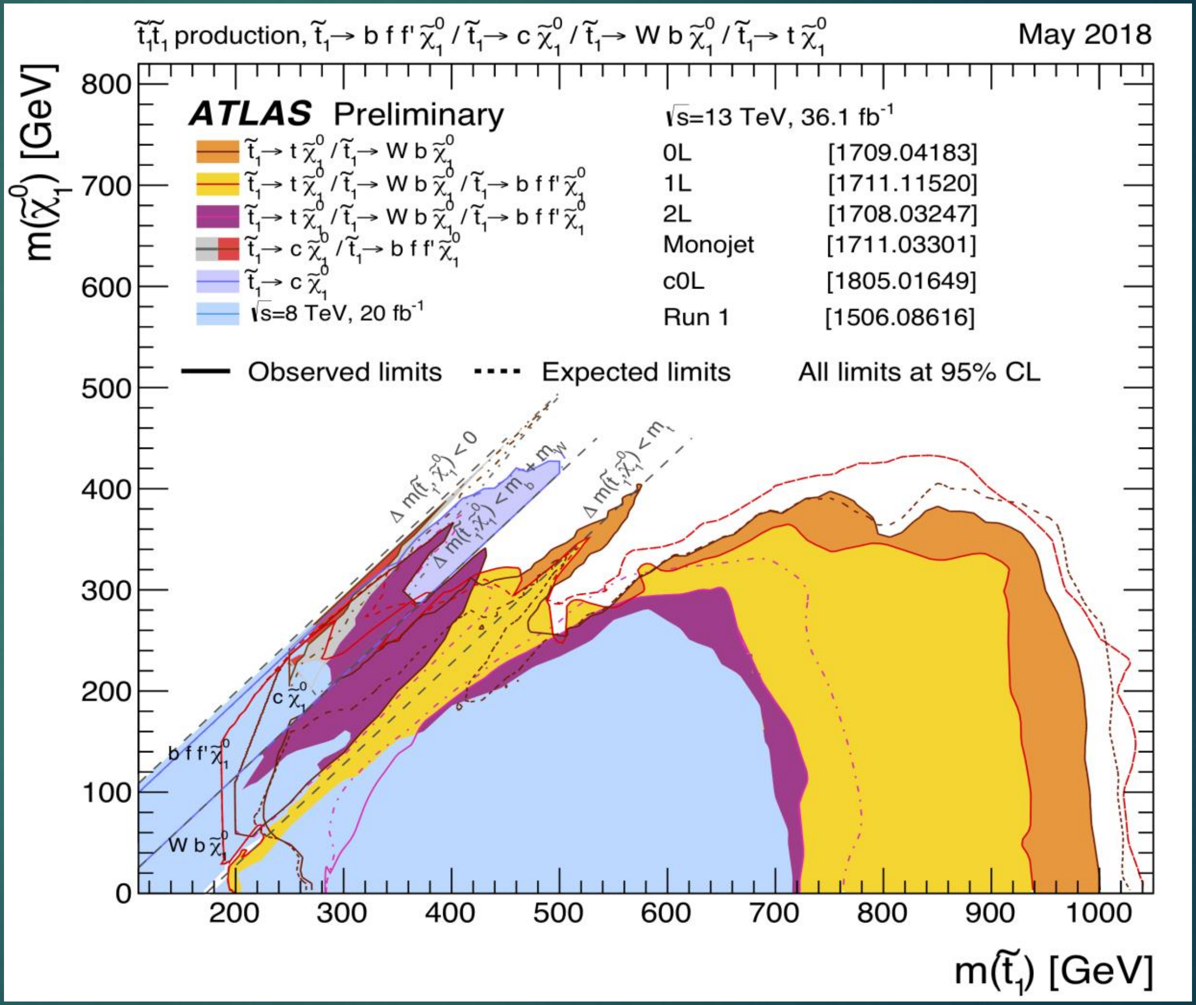


- Stop pair production is a possibility to be investigated in case gluino pair production is not observed
  - Much lower cross-section at any mass scale compared to $\tilde{g}\tilde{g}$.
- Due to the large top mass, stop decay phenomenology can be complex: 2-, 3-, 4-body
  - Final states: $0\ell/1\ell/2\ell$ + b-jets + E_T^{miss}
- Most difficult regions are those in the transition regions with $\Delta m(\tilde{t},\tilde{\chi}_1^0)=m_t$ and with $\Delta m(\tilde{t},\tilde{\chi}_1^0)=m_W$



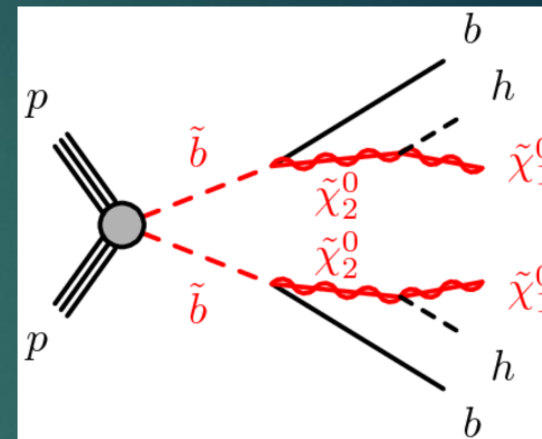
Searches for top squarks

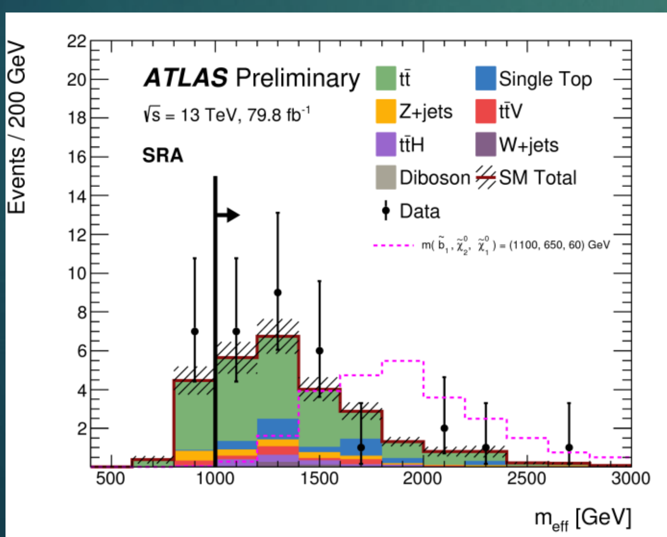
- In the most favourable scenarios stop masses reach exceeds 1 TeV
  - Weaker limits in models / parameter space with compressed mass spectra
  - Few gaps are still left to investigate for top squark decays

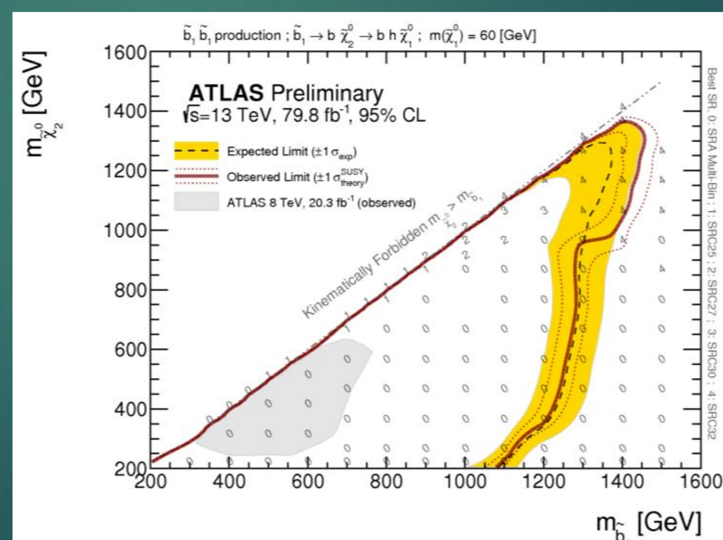


Searches for bottom squarks

- Searches performed with L = 80 fb^{-1}
- Signature with at least **3 b-tag jets**
- Signal regions for both boosted and compressed topologies
- Dominant backgrounds: $t\bar{t}$ and $Zb\bar{b}$
- Main uncertainties: theoretical and modeling of backgrounds(11%-22%)





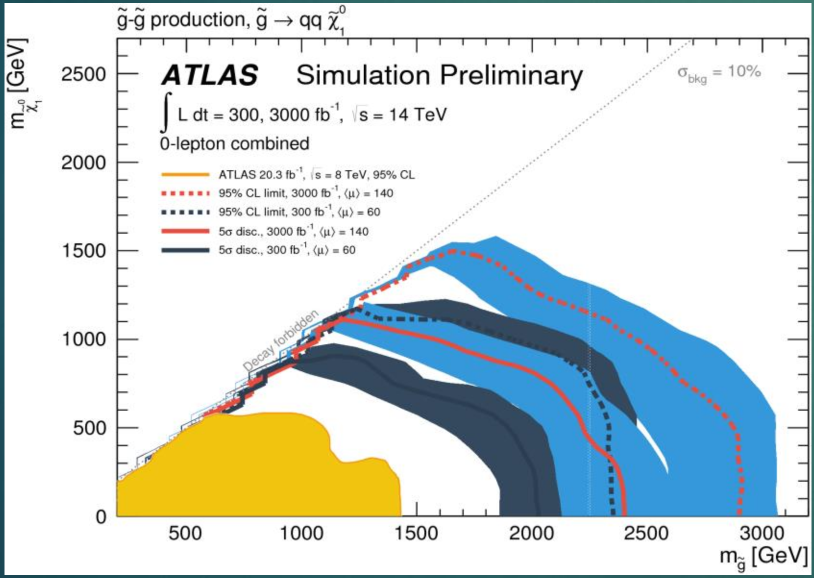


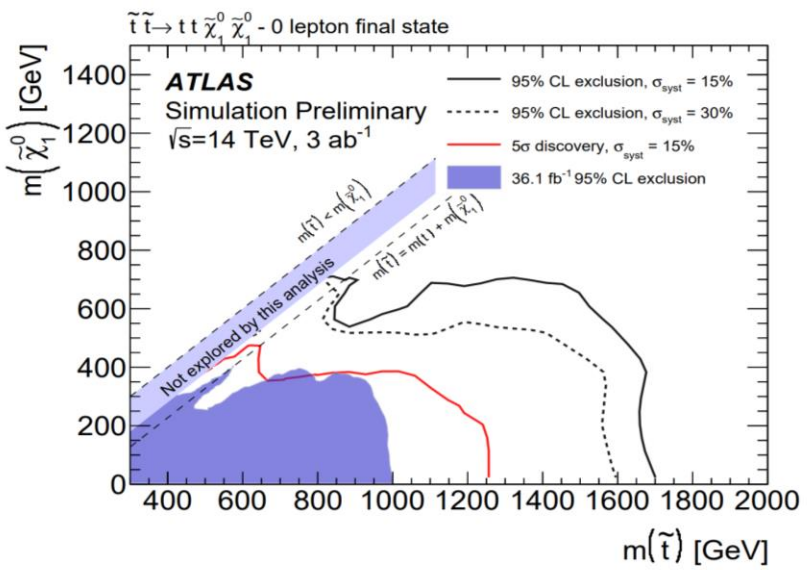
- Bottom-squarks with mass up to 1.4 TeV are excluded at 95% C.L.

ATLAS-CONF-2018-040

Gluino & squark searches at HL-LHC

- All the **detector upgrades** and the **increased luminosity** of the HL-LHC will allow unprecedented sensitivity in SUSY searches
  - SUSY analysis approach for the HL-LHC based on truth-level events + smearing of ATLAS detector (full simulation)
- Strong sparticle pair production discovery/exclusion limits can be significantly extended with integrated luminosity up to **3000 fb^{-1}**





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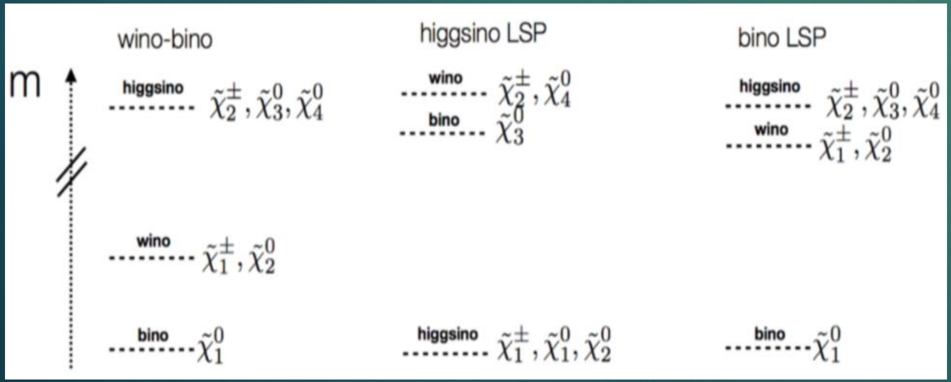
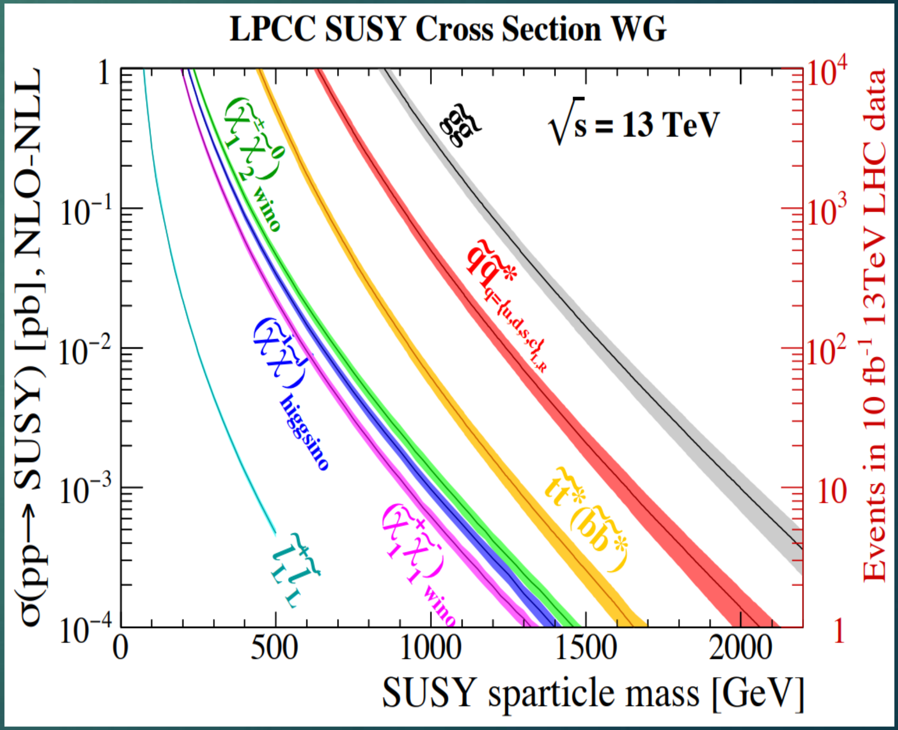
ATL-PHYS-PUB-2018-021

Electroweak production

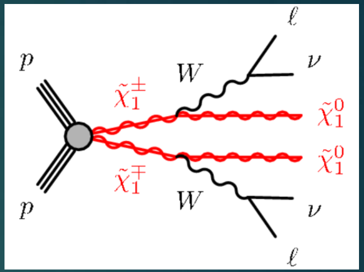
- SUSY can be produced via **EW** interaction, through direct production of charginos, neutralinos, sleptons
  - Lower cross-sections but promising discovery channel if colored sparticles have mass above 3-4 TeV
  - Less jet activity, large E_T^{miss} and clean signatures with leptons
  - Different possible LSP scenarios: $\mathcal{O}$(100 MeV) mass splitting when the LSP is pure Higgsino

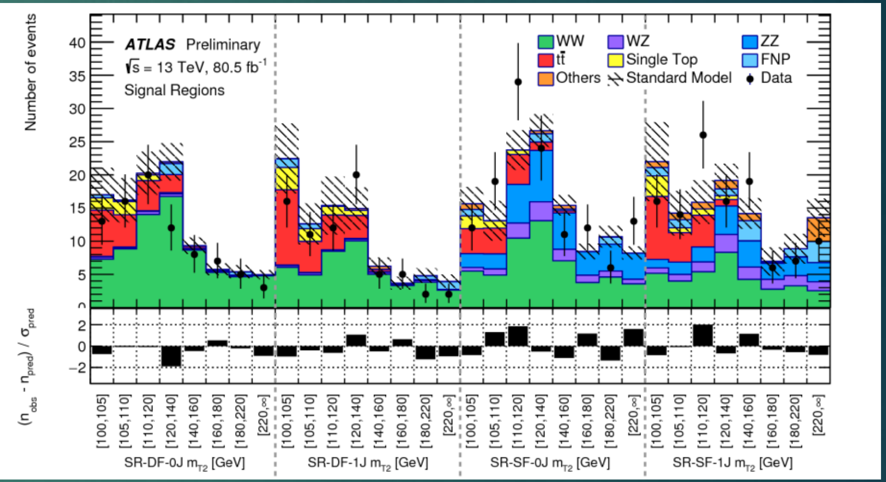




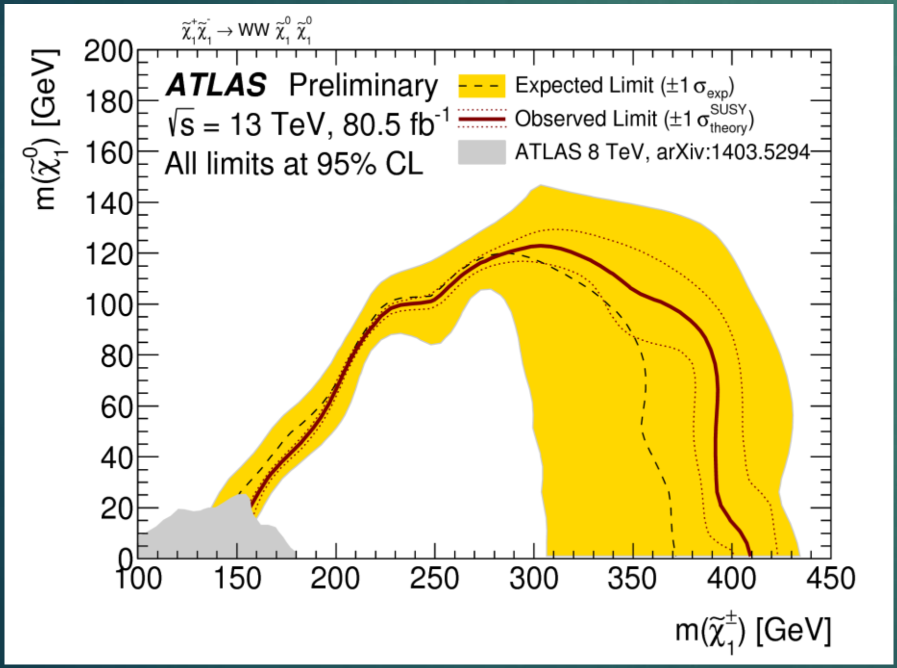
Chargino pair production via WW

- Target process: $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp} \rightarrow WW\tilde{\chi}_1^0\tilde{\chi}_1^0$
- Define SRs at large E_T^{miss} significance ($\mathcal{S}$) using new object-based definition (ATLAS-CONF-2018-038)





Different Flavour ($e^+\mu^-,\mu^+e^-$) Same Flavour ($e^+e^-,\mu^+\mu^-$)

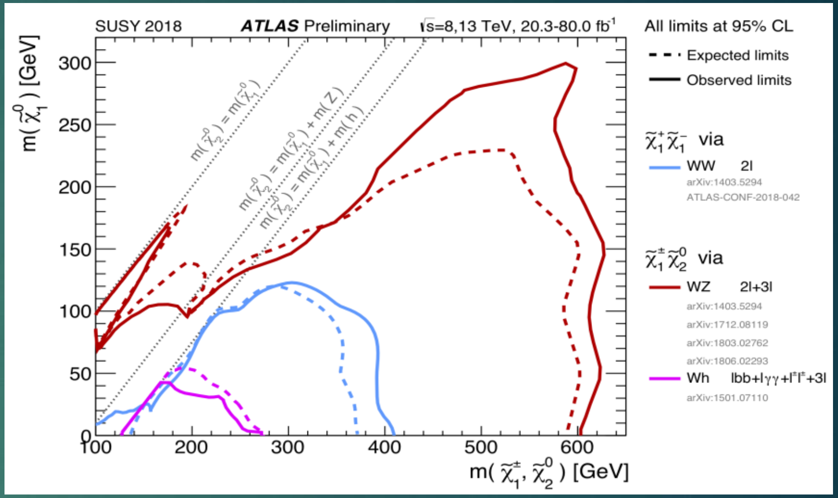


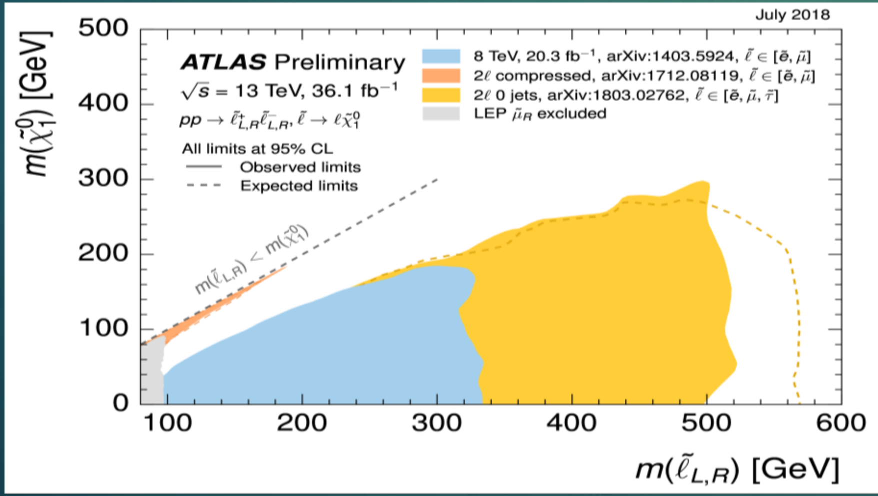
- Shape fits in $\boldsymbol{m_{T2}}$ (*stransverse mass*) and jet multiplicity significantly improves sensitivity

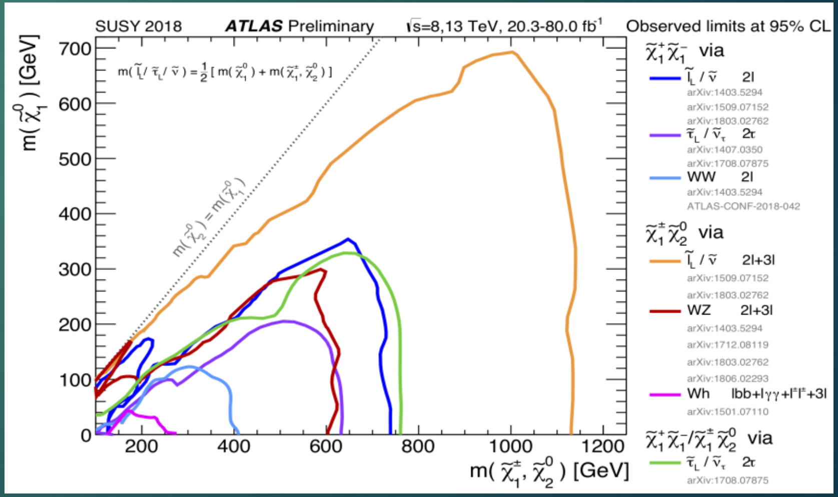
ATLAS-CONF-2018-042

EW production summary

- For gaugino decays via W/Z/h bosons the sensitivity is up to ~600 GeV (limits with up to 80 fb^{-1})
- For gaugino decays via sleptons the sensitivity exceeds 1.1 TeV
- For direct slepton production the sensitivity goes beyond 500 GeV (with 36 fb^{-1})



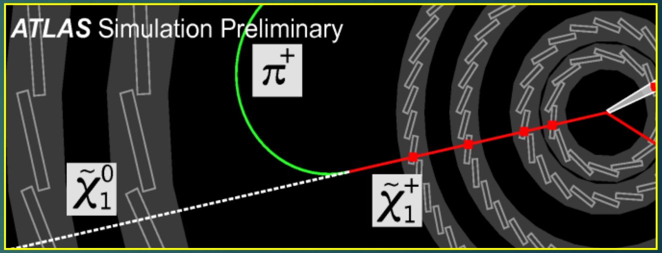




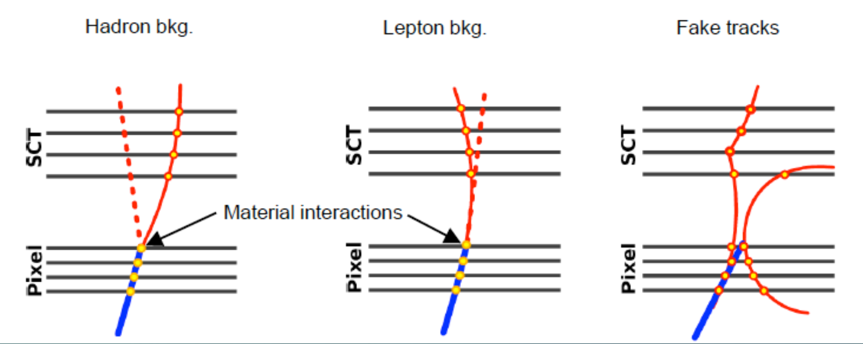
LLP searches: disappearing tracks

JHEP 06 (2018) 022

- SUSY scenarios can foresee **long-lived particles** (LLPs)
- Events with large E_T^{miss}, high p_T jets and a short track:
  $\tilde{\chi}_1^\pm$ NLSP almost degenerate with $\tilde{\chi}_1^0$ LSP: $\tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 \pi^+$ *(soft)* $\Rightarrow$ not reconstructed π^+ disappearing track in ID
- Small $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \Rightarrow$ long-lived charginos

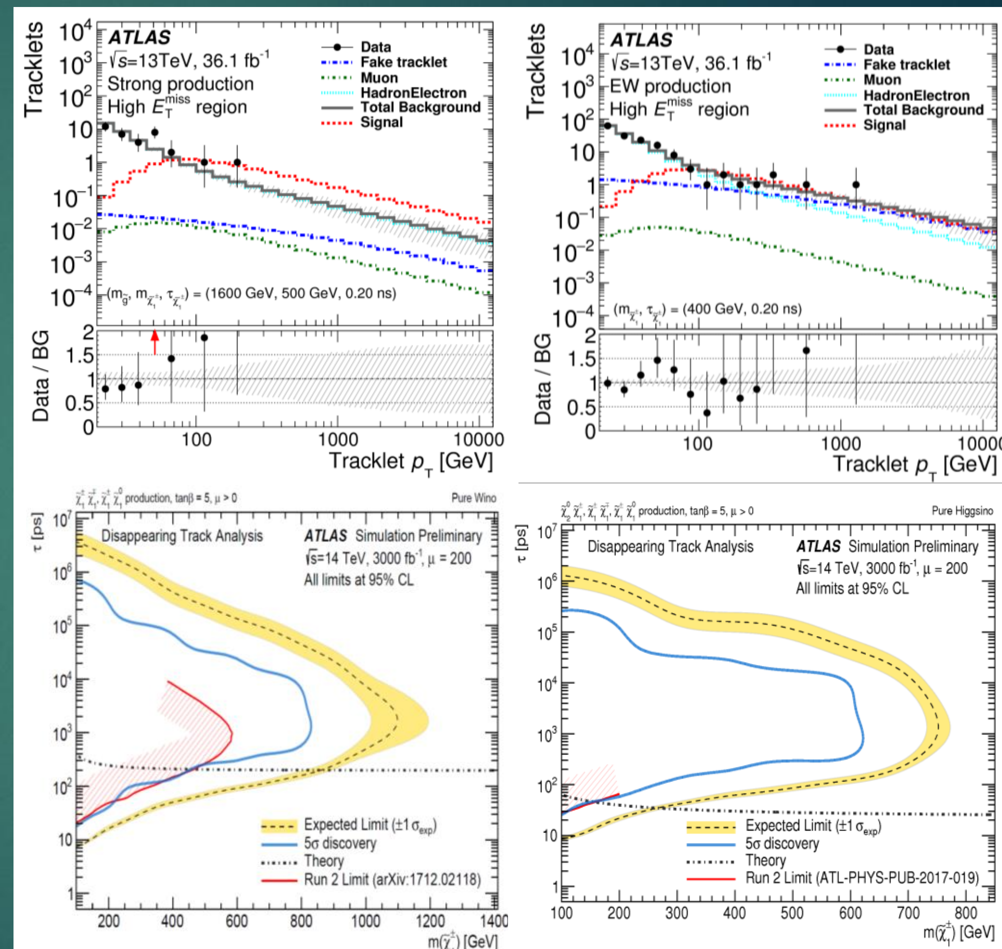


- Sensitivity to tracklets (shorter lifetimes) improved in Run 2 with insertion of **IBL**
- Selection based on MET trigger, lepton veto, 1 high-p_T jet and 1 isolated pixel tracklet
- Background estimate performed with data-driven templates
- Likelihood fit to pixel tracklets p_T spectrum in different regions



LLP searches: disappearing tracks

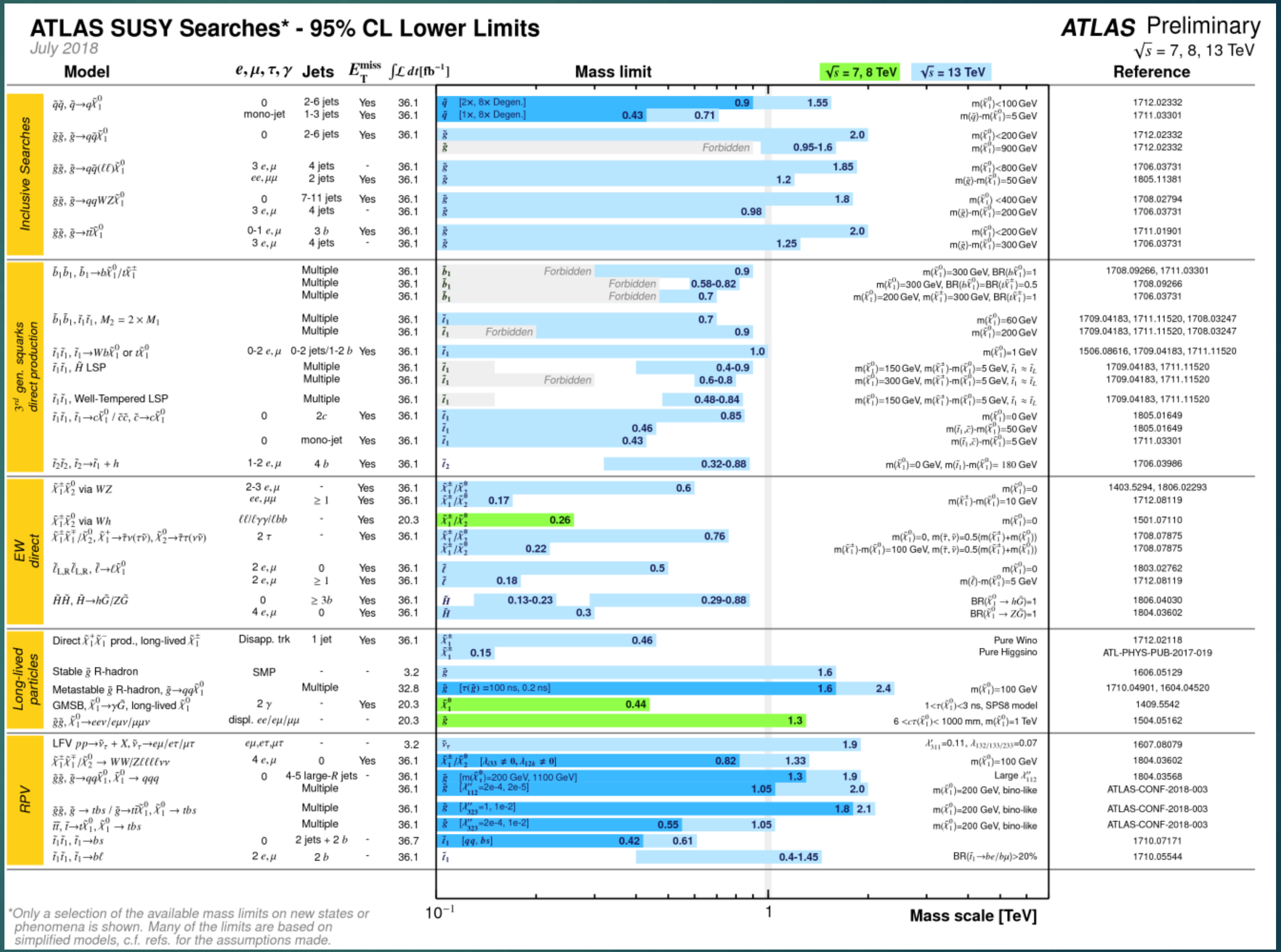
- Two different signatures are studied (for strong and EW productions)
- No significant excess is found above SM prediction for 36.1 fb^{-1}
  - Strong production excludes up to 1.8 TeV for lifetimes under 1.1 ns
  - Pure wino $\tilde{\chi}_1^0$ exclude chargino masses up 460 GeV (for pure higgsino $\tilde{\chi}_1^0$, up to 152 GeV)
  - At the HL-LHC (3 ab^{-1}) wino-like $\tilde{\chi}_1^0$ exclusion goes up to 850 GeV chargino masses (for higgsino-like, ~250 GeV)



JHEP 06 (2018) 022 , ATL-PHYS-PUB-2018-031

Summary of all SUSY results

- Broad spectrum of SUSY searches carried out at 7, 8 and 13 TeV
- No evidence for SUSY until now
- Excluded mass ranges: gluino > 2 TeV, stop > 1 TeV, EW > 500 GeV



- Moving toward increased luminosity/energy with more sophisticated techniques

Conclusions

- Most recent **ATLAS** analyses have been shown here, based on up to ~80 fb^{-1} (2015+2016+2017)
- Many **SUSY** searches have been carried out (and many more will come with new data collected in 2018)
- After 8 years of LHC, still no hints of SUSY at the LHC have been observed so far, but there are lots of phase space still left to be explored in Run 2 and in Run 3
- Hopefully the **High Luminosity LHC** will provide better constraints (or discovery) in ATLAS SUSY searches
- Only a small representative selection of recent results of ATLAS SUSY searches has been presented here; the full updated list of results is available at the link:
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults

Backup slides

SUSY terminology

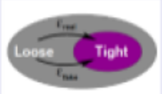
- **Natural SUSY**: With light SUSY (accessible at the LHC), SUSY can solve the hierarchy problem and keep the Higgs mass light. As SUSY particles get heavy, the second-order (log) corrections get larger, and the cancelation that protects the Higgs mass is not as satisfying. Natural SUSY is the name given to SUSY that has particles that are light enough (this is a matter of taste) to satisfactorily solve the hierarchy problem without large log corrections.
- **SUSY Higgses**: SUSY includes two doublets, giving rise to five Standard Model-sector Higgs bosons (h, H, A, H±). The Higgs found at the LHC with a mass of 125 GeV is generally identified as the h in this characterization.

Fake leptons background

Matrix method

- Fake leptonic background estimation
  - Measure real and fake efficiencies in QCD-CRs
  - Apply Matrix Method to get contribution in SR

$$\text{QCD BG} = \frac{1}{1/\epsilon_{\text{fake}} - 1/\epsilon_{\text{real}}} \cdot N_{\text{fail}} - \frac{1/\epsilon_{\text{real}} - 1}{1/\epsilon_{\text{fake}} - 1/\epsilon_{\text{real}}} \cdot N_{\text{pass}}$$



N_{pass}: Events passing the signal selection cuts (*tight*)

N_{fail}: Events satisfying relaxed lepton isolation criteria but not passing the signal selection cuts (*loose-but-not-tight*)

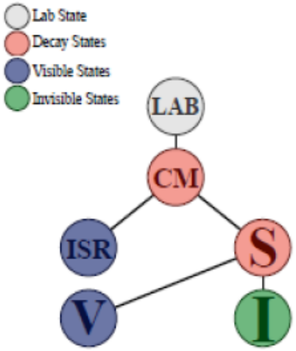
ϵ_{real}: Probability that a loose non-QCD event passes also the tight selection cuts

ϵ_{fake}: Probability that a loose QCD event passes also the tight selection cuts

Measure: ε, f, N_T, N_L

A recursive jigsaw reconstruction (RJR) technique

- Divide each event into an ISR and sparticle (S) hemisphere
- S → invisible (I) + visible (V) decay of stops
- Objects are grouped; maximizing the pT of S and ISR over all object assignment choices



Discriminating variables

complexity

- Reconstructed object multiplicities, momenta, energies, e.g. $N_{jet/b\text{-}tag/\ell/\gamma}$, p_T, $E_{T,miss}$, …
- Scale variables, e.g. $m_{eff} = \Sigma p_T + E_{T,miss}$,
- Angular variables, e.g. **min $\Delta\Phi$**(jet, $E_{T,miss}$), …
- Mass variables, e.g. $m_{\ell\ell}$, $m_T^{b/\ell/j}$, $\Sigma m_{fat\text{-}jet}$, …
- Event shape variables, e.g. **Aplanarity**, …
- Hypothesis-based event variables e.g. m_{T2}, …

⋮

- More complex methods, e.g. new **recursive jigsaw reconstruction** [arxiv:1607.08307], …

- More and more complex variables are exploited to extract signal from background.

$$m_{\mathrm{T}}(\mathbf{p}_{\mathrm{T}}, \mathbf{q}_{\mathrm{T}}) = \sqrt{2(p_{\mathrm{T}}q_{\mathrm{T}} - \mathbf{p}_{\mathrm{T}} \cdot \mathbf{q}_{\mathrm{T}})}$$

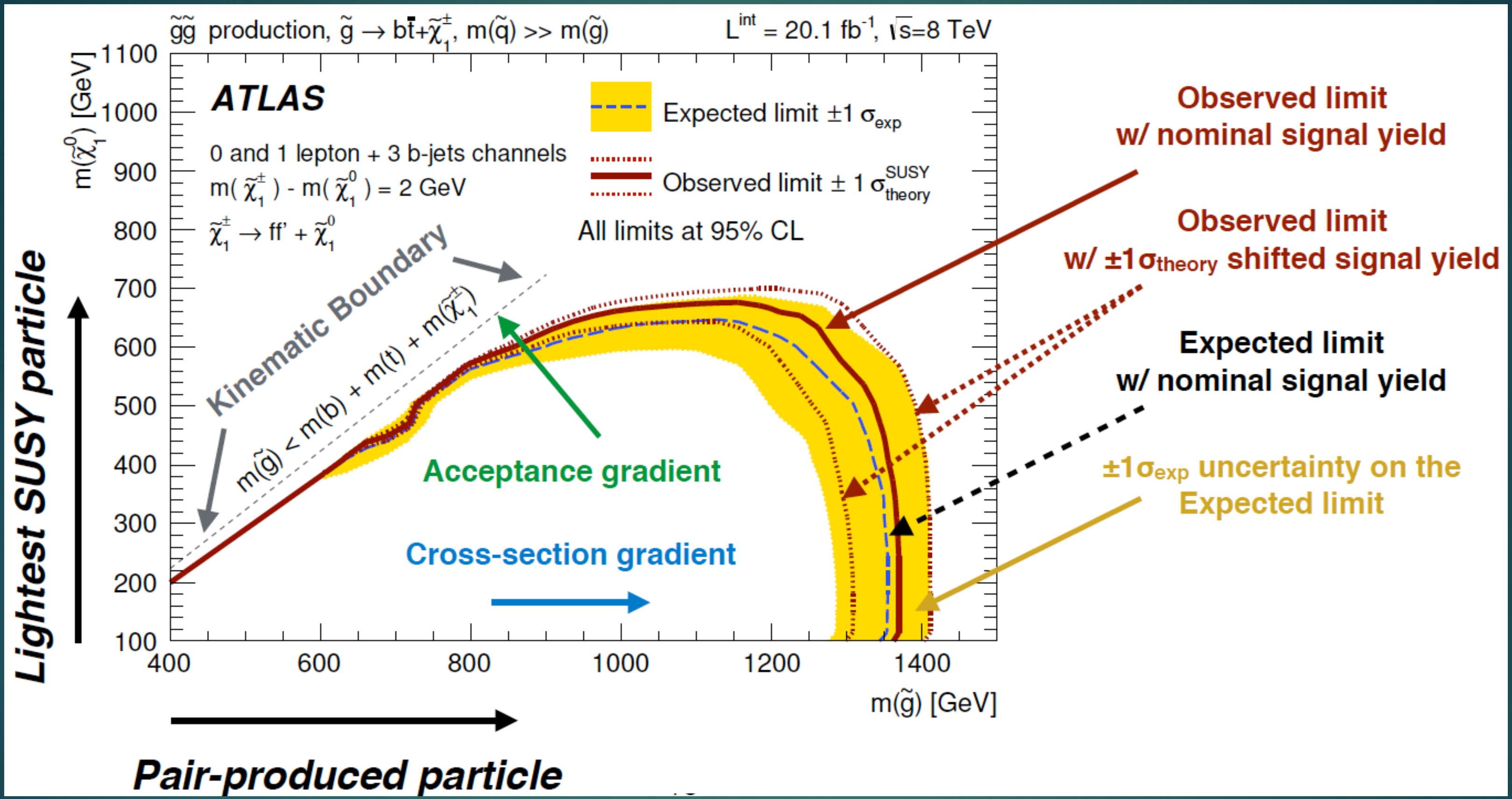
$$m_{\mathrm{T2}} = \min_{\mathbf{q}_{\mathrm{T}}} \left[\max\left(m_{\mathrm{T}}(\mathbf{p}_{\mathrm{T}}^{\ell 1}, \mathbf{q}_{\mathrm{T}}), m_{\mathrm{T}}(\mathbf{p}_{\mathrm{T}}^{\ell 2}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}} - \mathbf{q}_{\mathrm{T}})\right)\right]$$

$$E_T^{miss} = -\sum_{i\in ev.} p_T^i \qquad m_{eff} = \sum_i p_T^i + E_T^{miss}$$

$$m_{\mathrm{T2}} = \min_{\mathbf{q}_{\mathrm{T}}} \left[\max\left(m_{\mathrm{T}}(\mathbf{p}_{\mathrm{T}}^{\ell 1}, \mathbf{q}_{\mathrm{T}}), m_{\mathrm{T}}(\mathbf{p}_{\mathrm{T}}^{\ell 2}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}} - \mathbf{q}_{\mathrm{T}})\right)\right]$$

$$m_{\mathrm{T}}(\mathbf{p}_{\mathrm{T}}, \mathbf{q}_{\mathrm{T}}) = \sqrt{2(p_{\mathrm{T}}q_{\mathrm{T}} - \mathbf{p}_{\mathrm{T}} \cdot \mathbf{q}_{\mathrm{T}})}$$

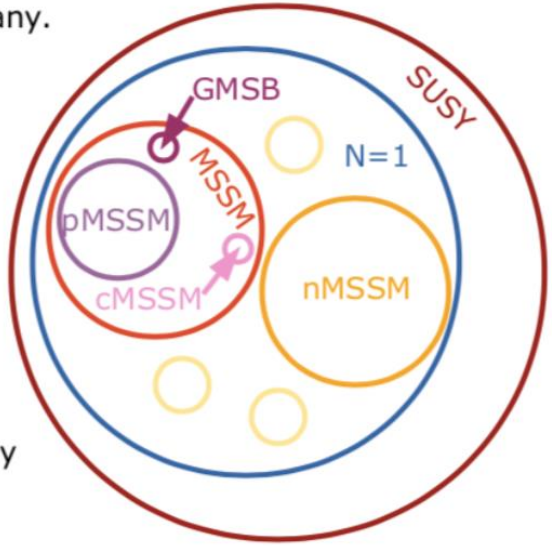
Interpretation of results



- Results are usually shown in bi-dimensional slices of SUSY particle masses or dedicated observables
- Typically limits are computed at 95% confidence level (C.L.)

Which SUSY?

- SUSY is not one model, rather infinitely many.
- MSSM
  - Minimal new particle content.
  - No assumption on SUSY breaking → 120 additional free parameters.
- pMSSM
  - Reduce MSSM to 19 free parameters by imposing phenomenological and experimental constrains.
- cMSSM
  - Reduce MSSM to 5 free parameters by assuming universality at GUT scale.
- GMSB/AMSB
  - Reduce MSSM to 5 free parameters by assuming SUSY breaking mechanism.
- NMSSM
  - Extend MSSM by adding an additional singlet chiral superfield.
- Simplified Models
  - Masses of non-relevant SUSY particles are put very large.
  - 100% BR to single final state.

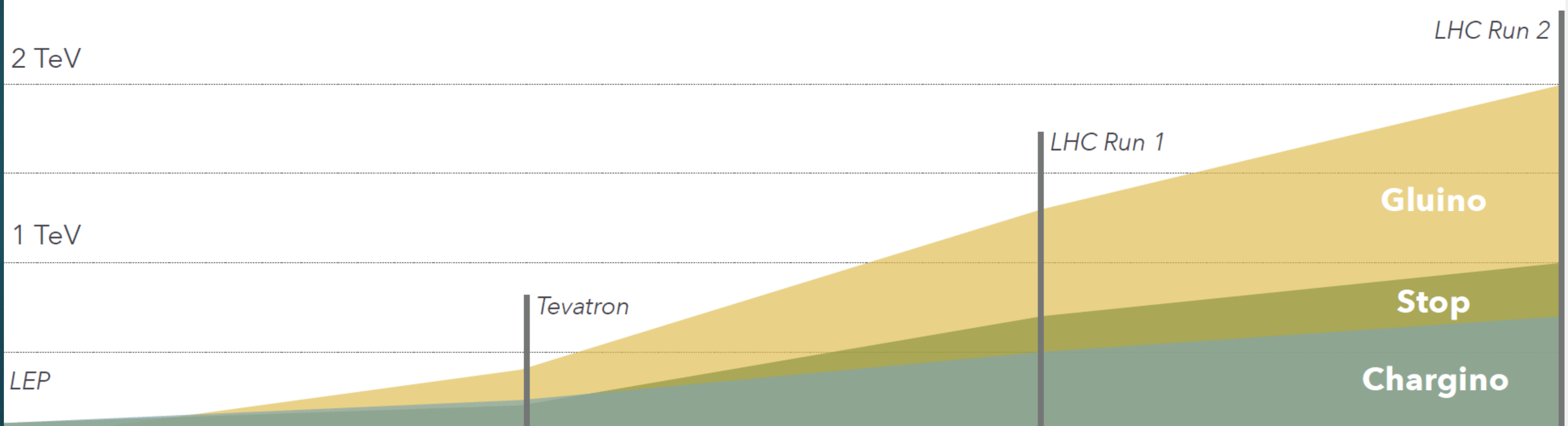


- From «SUSY Searches at ATLAS and CMS» - Marija Vranjes Milosavljevic - PPC 2018

Where we stand

- Various collider experiments searching for SUSY the past ~20 years.
- Null search results constrain — *under very specific assumptions* — the mass scale of the SUSY particles.
- ATLAS (and CMS) used the first LHC data to search for naive SUSY decay chains.

Today: complex and challenging analyses recently published.



- From «Recent Results From SUSY Searches With ATLAS» - E. Kourlitis - HEPMAD 2018