# Searches for squarks and gluinos in final states involving dark matter candidates with ATLAS

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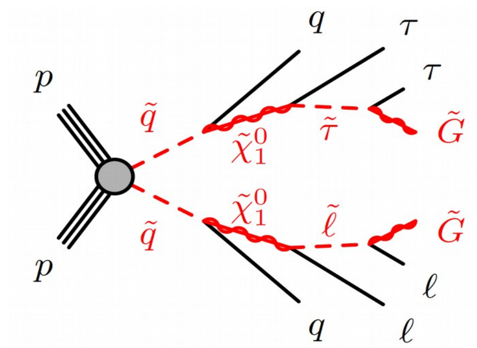
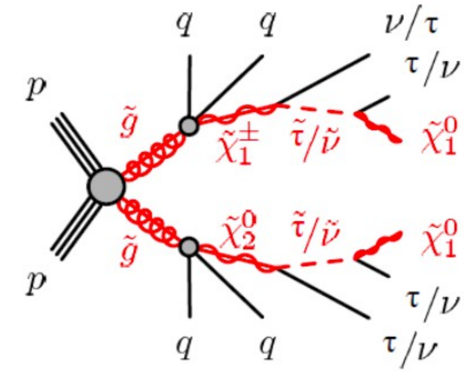
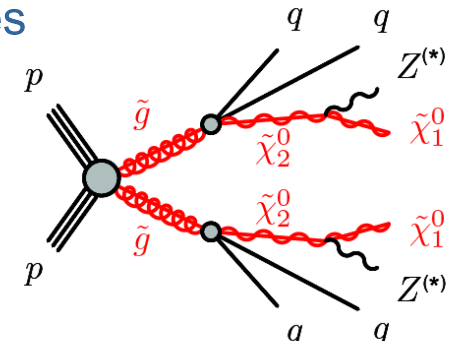
# Outline

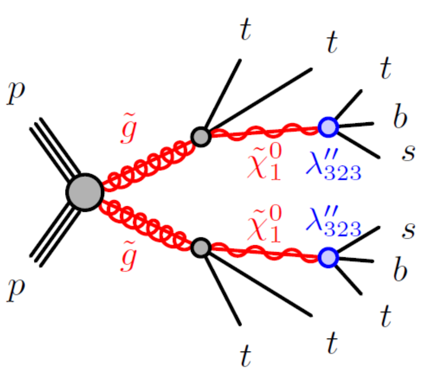


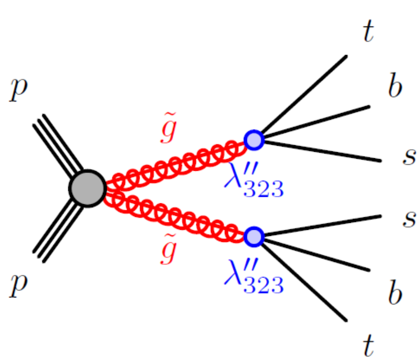



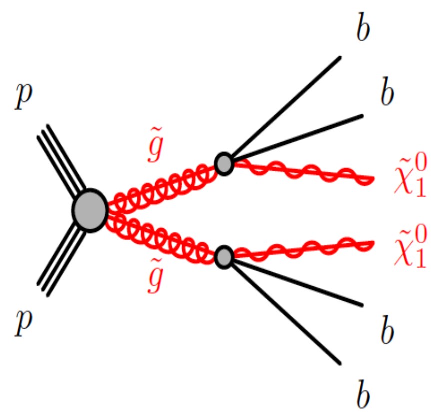

This talk will cover the most recent studies with final states containing jets and missing transverse energy (MET) + X, typical signatures of SUSY strong production channels with the lightest Neutralino and Gravitino as Dark Mater candidates

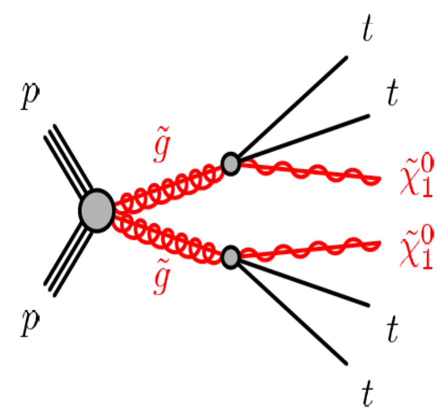



- tau leptons, jets and missing transverse energy (new for ICHEP)
- b-jets and large missing transverse energy
- two opposite-sign leptons, jets and MET (“Z/Edge”)
- RPC to RPV multijet and R-hadrons



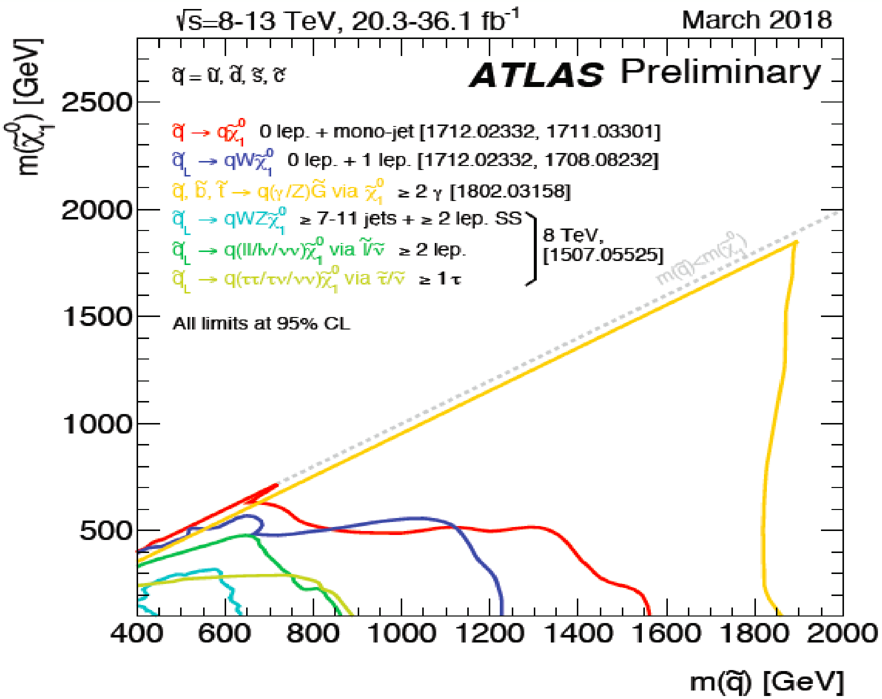



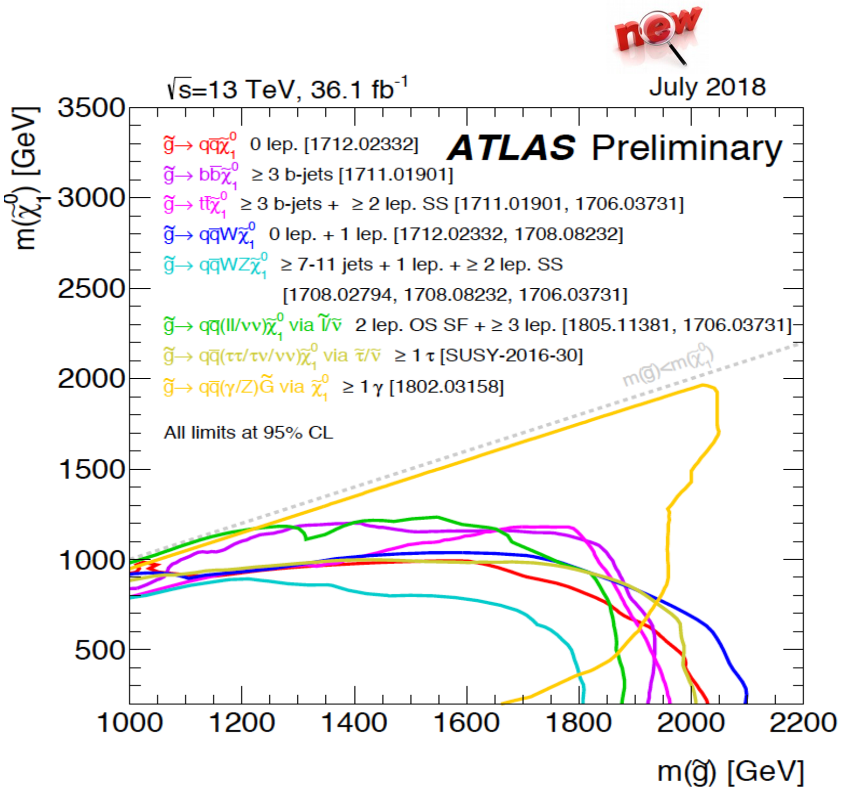



# Squarks and gluino latest limits

Most up-to-date limits for simplified models exploiting the 2015-2016 Run 2 dataset




1.5-2 TeV exclusion for gluinos at low LSP mass. Up to 1.8 TeV for squarks (8-fold degeneracy)

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SUSY/

# Data and selection

Events are required to pass MET trigger with (lowest) thresholds of 70 GeV, 100 GeV and 110 GeV for the 2015, early 2016 and late 2016. High $p_T$ lepton analysis uses single/dilepton triggers.

Typical objects selection:

- Electrons: Medium selection criteria and isolated, $p_T$ > ~10 GeV, η<2.47
- Photons: tight selection criteria and isolated, $p_T$ > ~25 GeV, η<2.37
- Muons: Medium selection criteria and isolated, $p_T$ > ~10 GeV, η<2.5
- Jets: anti-*kt* , $p_T$ > ~30 GeV, η<2.5. b-jets with a selection that provides 77% efficiency for tagging
- MET calculation includes baseline objects (e/μ/j/γ) and track soft term

$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell} E_{\mathrm{T}}^{\mathrm{miss}} \{1 - \cos[\Delta\phi(\vec{p}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\ell})]\}}$$

→ Reduce the ttbar and W+jets background events in which a W boson decays leptonically

$$H_{\mathrm{T}} = \sum_{\mathrm{visible}} |p_{\mathrm{T}}|$$

→ Signal models with large visible activity

$$m_{\mathrm{eff}} = H_{\mathrm{T}} + E_{\mathrm{T}}^{\mathrm{miss}}$$

→ Signal models with large hadronic activity together with large MET

$$M_J^{\Sigma,4} = \sum_{i \le 4} m_{J,i}$$

→ The presence of numerous boosted and semi-boosted object in the signal events leads to the formation of high-pT, massive jets

$$m_{\mathrm{T2}}^{\tau\tau} = \sqrt{\min_{\vec{p}_{\mathrm{T}}^{\,a} + \vec{p}_{\mathrm{T}}^{\,b} = \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}} \left(\max\left[m_{\mathrm{T}}^2(\tau_1, \vec{p}_{\mathrm{T}}^{\,a}), m_{\mathrm{T}}^2(\tau_2, \vec{p}_{\mathrm{T}}^{\,b})\right]\right)}$$

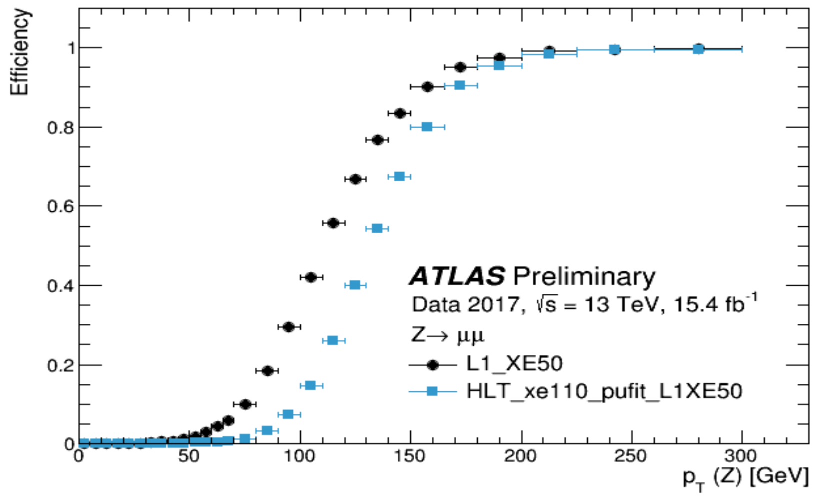
→ High values for rejecting ttbar background

$$\Delta\phi(\mathrm{jet}_{12}, \boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}})$$

→ Remove events with MET arising from jet mismeasurements

# Performance highlights

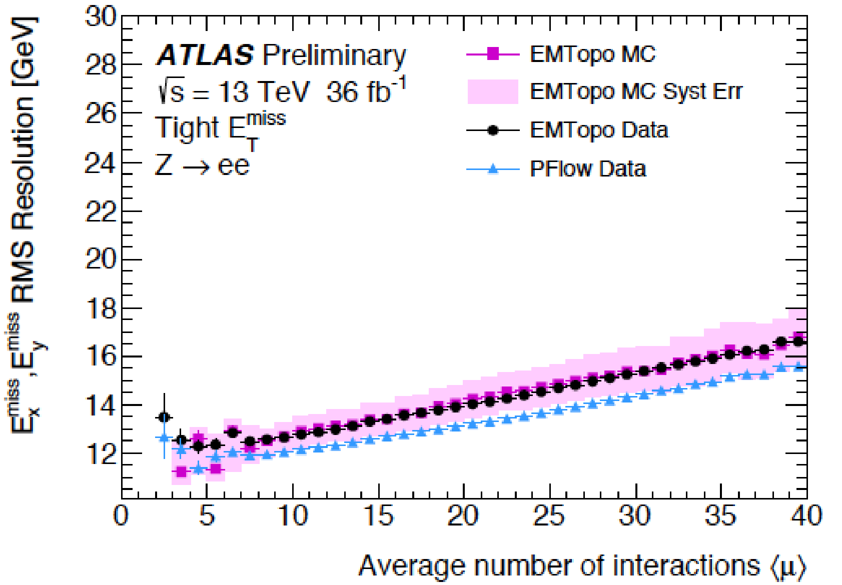
Missing transverse momentum: measure it and trigger on it are key issues for many SUSY searches



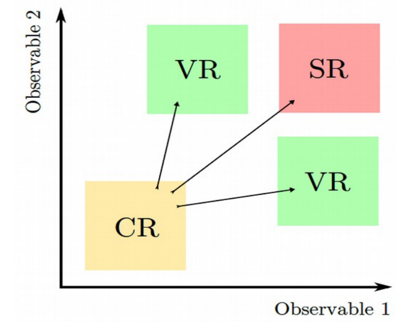

(Z boson is used as a proxy for the missing transverse momentum)

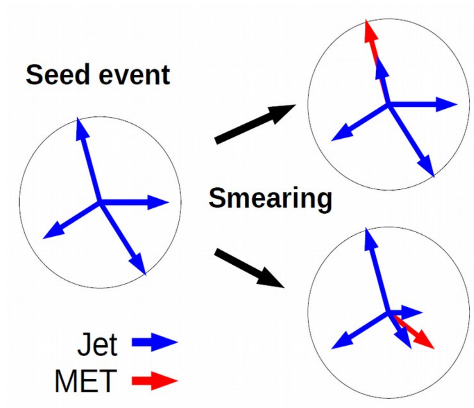
- Trigger is fully efficient for offline selection greater than ~200 GeV.
- The increased number of hadronic interactions makes these triggers sensitive to the increase in instantaneous luminosity.

- Various strategies are used to suppress effects arising from pileup in the reconstruction and calibration algorithms.
- Good agreement between data and MC.



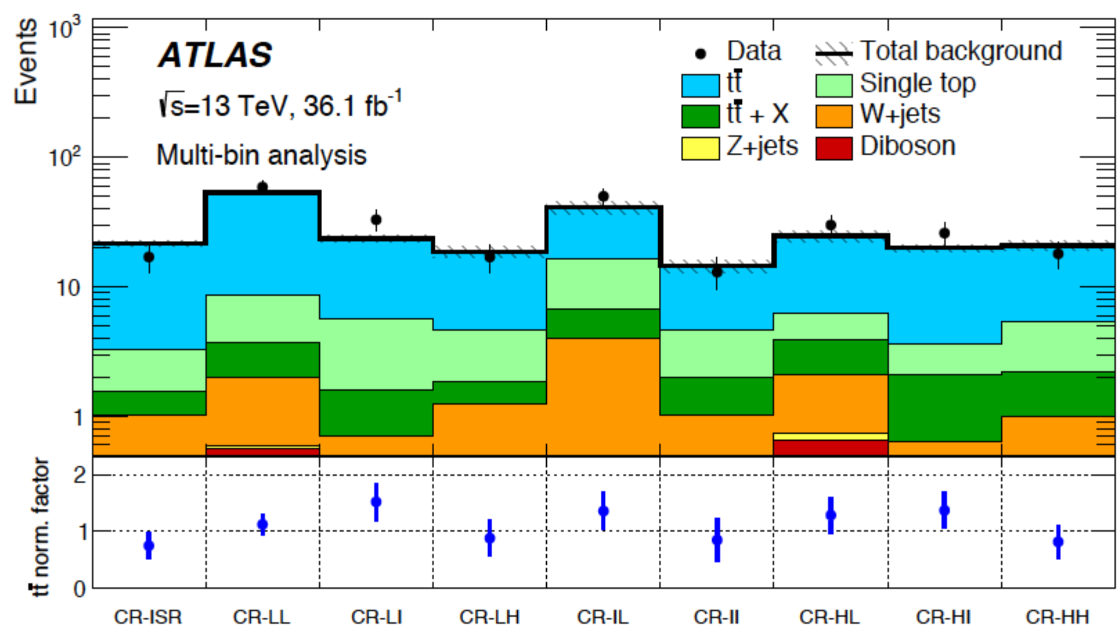
# Main backgrounds estimation




Taus in final state: ttbar, W/Z+jets and QCD-Multijet
- Control Regions to obtain scaling factors.
- Multi-jet background estimated from data by a Jet energy smearing technique.

Multi-b signatures: Dominant background is ttbar
- Normalize this background using Control Regions (take all other backgrounds from MC)



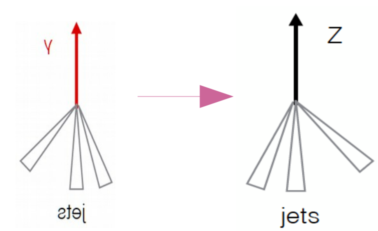
# Main backgrounds estimation

Opposite sign leptons in final state: Dominated by ttbar, but also includes WW, Wt, and Z(ττ)

High-pT search:
Flavour-Symmetric (FS) background based on the ratio of ee, μμ and eμ (different-flavour DF) dileptonic events. Expected to be 1:1:2 from the two leptons originate from the independent W → lν decays

$$N^{\text{est}} = \frac{f_{\text{SR}}}{2} \cdot \left[ \sum_{i}^{N_{e\mu}^{\text{data}}} \left( k_e(p_{\text{T}}^{i,\mu}, \eta^{i,\mu}) + k_\mu(p_{\text{T}}^{i,e}, \eta^{i,e}) \right) \cdot \alpha(p_{\text{T}}^{i,\ell_1}, \eta^{i,\ell_1}) - \sum_{i}^{N_{e\mu}^{\text{MC}}} \left( k_e(p_{\text{T}}^{i,\mu}, \eta^{i,\mu}) + k_\mu(p_{\text{T}}^{i,e}, \eta^{i,e}) \right) \cdot \alpha(p_{\text{T}}^{i,\ell_1}, \eta^{i,\ell_1}) \right]$$

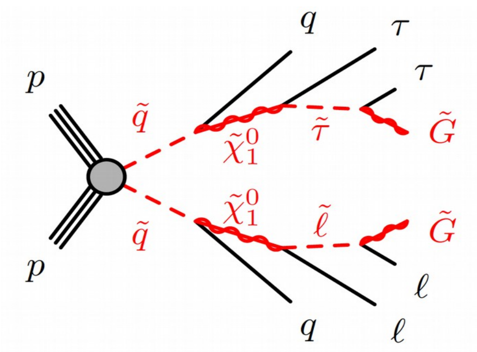
- Normalized γ+jets data events to model Z+jets events in SR



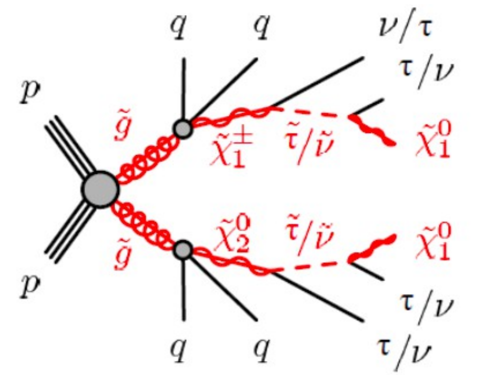

Low-pT search:
- DF samples to normalise the dominant top-quark (ttbar and Wt) with the shape taken from MC simulation.

- Fake or misidentified leptons estimated using a data-driven matrix method → $N_{\text{pass}}^{\text{fake}} = \frac{N_{\text{fail}} - (1/\epsilon^{\text{real}} - 1) \times N_{\text{pass}}}{1/\epsilon^{\text{fake}} - 1/\epsilon^{\text{real}}}$

# Tau leptons search strategy

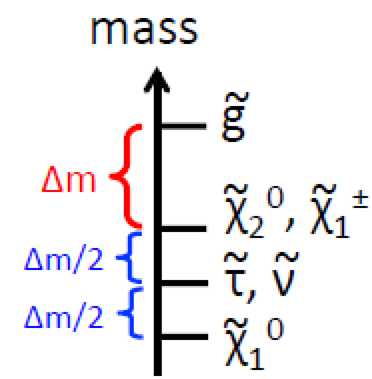



Signatures of minimal gauge-mediated supersymmetry breaking (GMSB) and simplified model are probed




- One Tau channel
  - Low/medium gluino mass regime
- DiTau channel
  - High gluino mass regime

| Subject of selection | $1\tau$ SRs Compressed | Medium-Mass |
|---|---|---|
| Tau leptons | $p_T^\tau < 45$ GeV | $p_T^\tau > 45$ GeV |
| Event kinematics | $E_T^{miss} > 400$ GeV | |
| | $m_T^\tau > 80$ GeV | $m_T^\tau > 250$ GeV |
| | — | $H_T > 1000$ GeV |

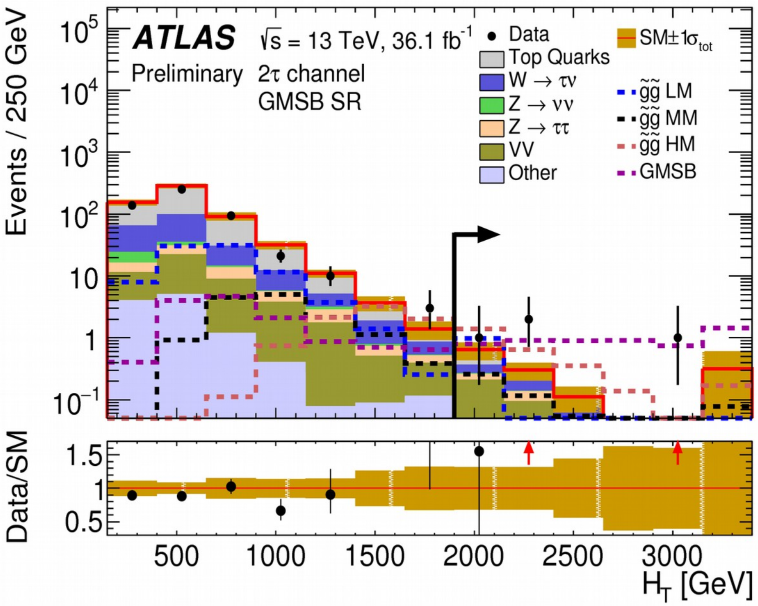


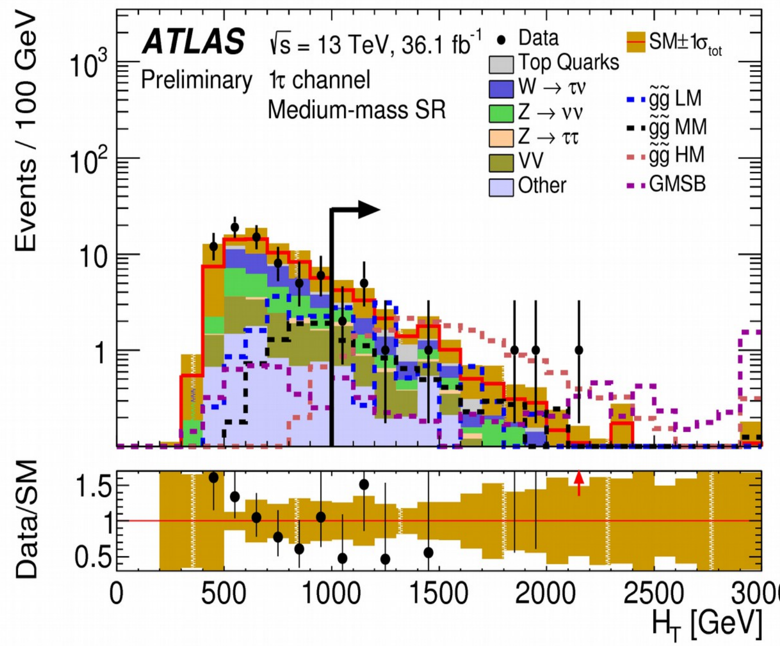

| Subject of selection | $2\tau$ SRs Compressed | High-Mass | Multibin | GMSB |
|---|---|---|---|---|
| Event kinematics | $m_{T2}^{\tau\tau} > 70$ GeV | $m_T^{\tau_1} + m_T^{\tau_2} > 350$ GeV | $m_T^{\tau_1} + m_T^{\tau_2} > 150$ GeV | $m_T^{\tau_1} + m_T^{\tau_2} > 150$ GeV |
| | $H_T < 1100$ GeV | $H_T > 1100$ GeV | $H_T > 800$ GeV | $H_T > 1900$ GeV |
| | $m_T^{sum} > 1600$ GeV | — | $N_{jet} \geq 3$ | — |
| | | | 7 bins in $m_T^{\tau_1} + m_T^{\tau_2}$ | |

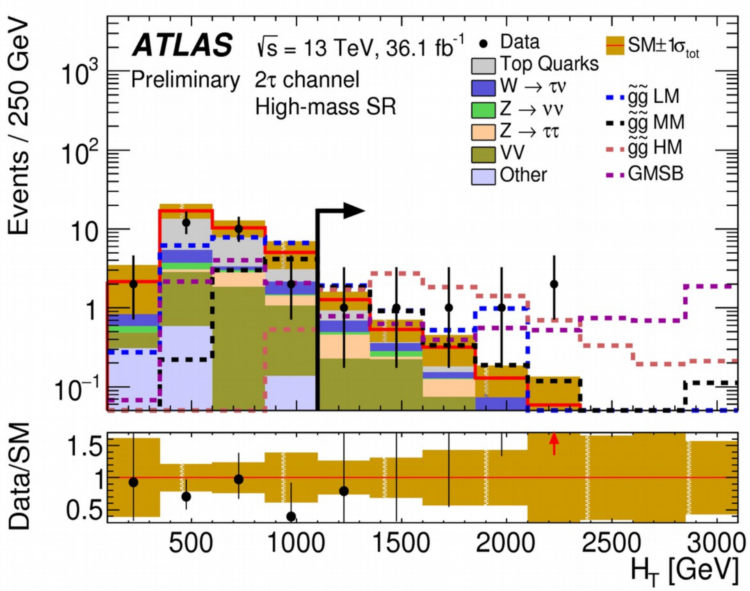
Orthogonal signal regions for combination

SUSY-2016-30

# Tau leptons results



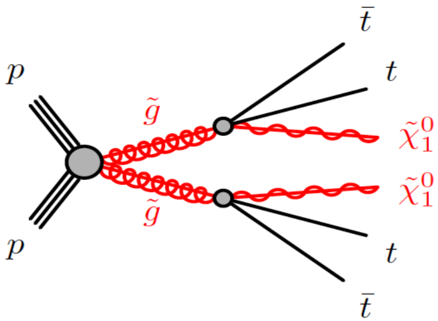



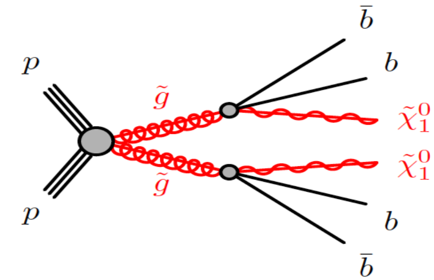

Apart from an excess of 1.8 standard deviations in the GMSB and the High-Mass SR of the 2 channel, no significant deviation of data from the SM prediction is observed.

$$H_T = \sum_{\text{visible}} |p_T|$$

# Multi b jets search strategy

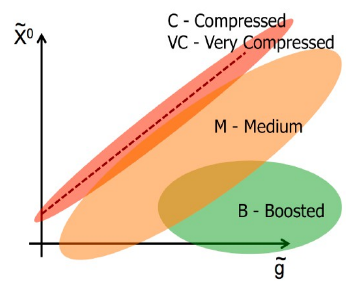



Gluinos decaying via third generation off-shel squarks to the lightest neutralino




Two signal region strategies:

1) cut-and-count analysis, using partially overlapping single-bin SRs, optimised to maximise the expected discovery power for benchmark signal models.

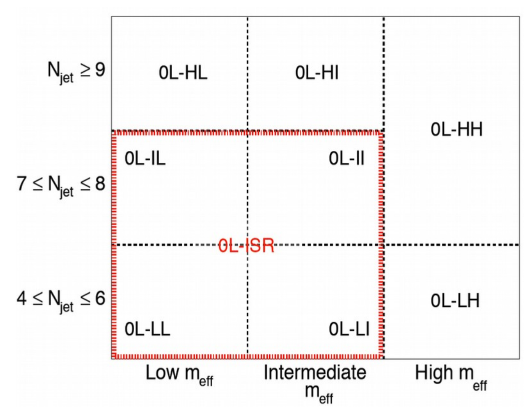



**Gtt 1-lepton**

Criteria common to all regions: $\geq 1$ signal lepton, $p_T^{jet} > 30$ GeV, $N_{b\text{-jets}} \geq 3$

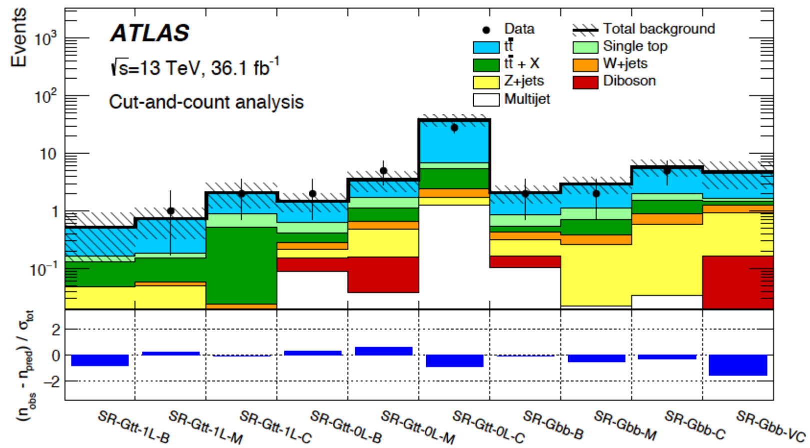
| Targeted kinematics | Type | $N_{jet}$ | $m_T$ | $m_{T,min}^{b\text{-jets}}$ | $E_T^{miss}$ | $m_{eff}^{incl}$ | $M_J^{\Sigma}$ |
|---|---|---|---|---|---|---|---|
| Region B (Boosted, Large $\Delta m$) | SR | $\geq 5$ | $> 150$ | $> 120$ | $> 500$ | $> 2200$ | $> 200$ |
| | CR | $= 5$ | $< 150$ | – | $> 300$ | $> 1700$ | $> 150$ |
| | VR-$m_T$ | $\geq 5$ | $> 150$ | – | $> 300$ | $> 1600$ | $< 200$ |
| | VR-$m_{T,min}^{b\text{-jets}}$ | $> 5$ | $< 150$ | $> 120$ | $> 400$ | $> 1400$ | $> 200$ |
| Region M (Moderate $\Delta m$) | SR | $\geq 6$ | $> 150$ | $> 160$ | $> 450$ | $> 1800$ | $> 200$ |
| | CR | $= 6$ | $< 150$ | – | $> 400$ | $> 1500$ | $> 100$ |
| | VR-$m_T$ | $\geq 6$ | $> 200$ | – | $> 250$ | $> 1200$ | $< 100$ |
| | VR-$m_{T,min}^{b\text{-jets}}$ | $> 6$ | $< 150$ | $> 140$ | $> 350$ | $> 1200$ | $> 150$ |
| Region C (Compressed, small $\Delta m$) | SR | $\geq 7$ | $> 150$ | $> 160$ | $> 350$ | $> 1000$ | – |
| | CR | $= 7$ | $< 150$ | – | $> 350$ | $> 1000$ | – |
| | VR-$m_T$ | $\geq 7$ | $> 150$ | $< 160$ | $> 300$ | $> 1000$ | – |
| | VR-$m_{T,min}^{b\text{-jets}}$ | $> 7$ | $< 150$ | $> 160$ | $> 300$ | $> 1000$ | – |

2) A multi-bin analysis, using a set of non-overlapping SRs and CRs that are combined to strengthen the exclusion limits on the targeted signal benchmarks.

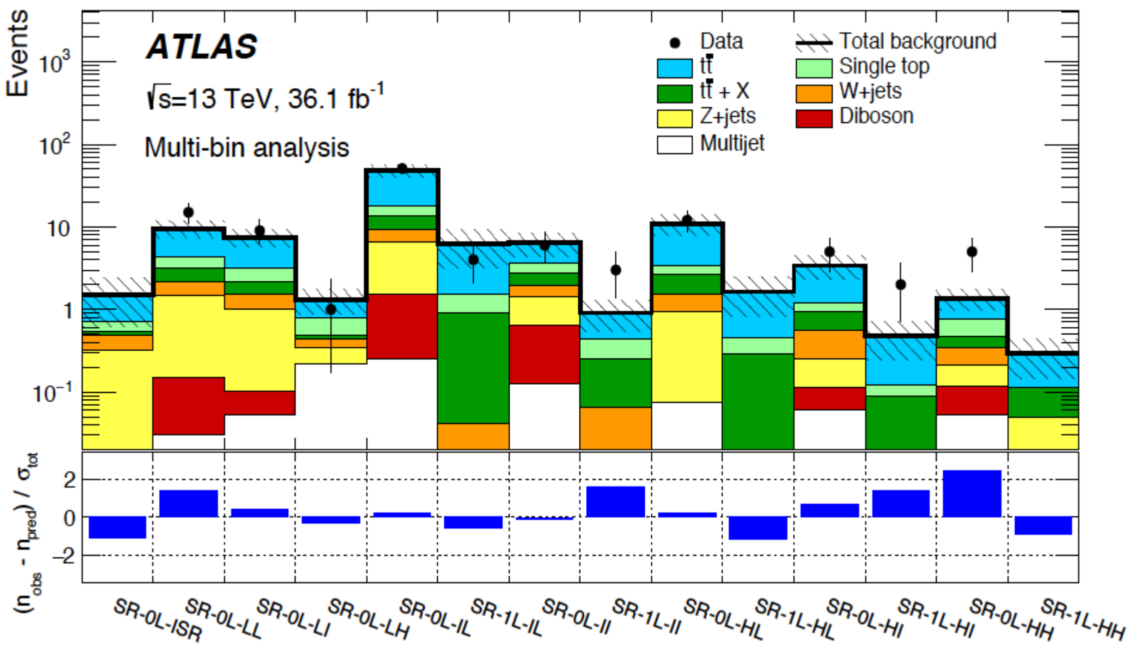



$$m_{eff} = H_T + E_T^{miss}$$

# Multi b jets results

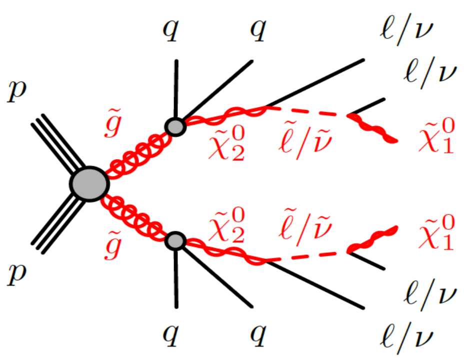



All search regions dominated by ttbar + heavy flavour events.

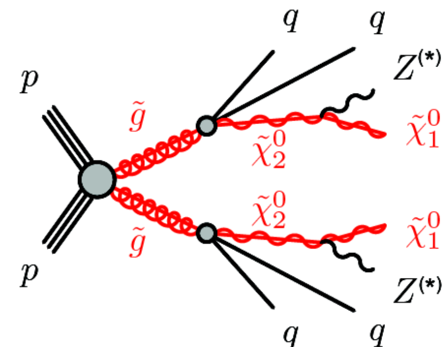



Most significant deviation (~2.5σ local) from expectation in multi-bin SR-0L-HH (High meff and Δm)

Exclusion stream uses meff and jet multiplicity information to perform a multi-bin fit



# Opposite sign dilepton search strategy



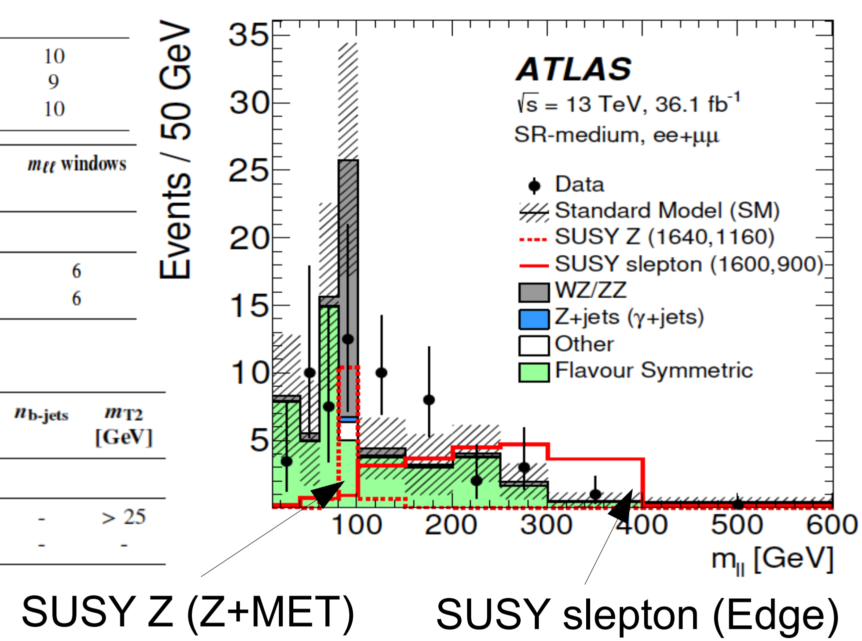
Previous Run II Paper to follow up Run I excess that was not confirmed. Now optimized for 13 TeV and larger dataset size

High-$p_T$ lepton search addresses non-compressed cases where kinematic edge near the Z peak and above. Low-$p_T$ lepton search addresses small Δm between two lightest neutralinos

| High-$p_T$ regions | $E_T^{miss}$ [GeV] | $H_T$ [GeV] | $n_{jets}$ | $m_{\ell\ell}$ [GeV] | $m_{T2}$ [GeV] | SF/DF | $n_{b\text{-jets}}$ | $\Delta\phi(\text{jet}_{12}, p_T^{miss})$ | $m_{\ell\ell}$ windows |
|---|---|---|---|---|---|---|---|---|---|
| Signal regions | | | | | | | | | |
| SR-low | > 250 | > 200 | ≥ 2 | > 12 | > 70 | SF | – | > 0.4 | 10 |
| SR-medium | > 400 | > 400 | ≥ 2 | > 12 | > 25 | SF | – | > 0.4 | 9 |
| SR-high | > 200 | > 1200 | ≥ 2 | > 12 | – | SF | – | > 0.4 | 10 |

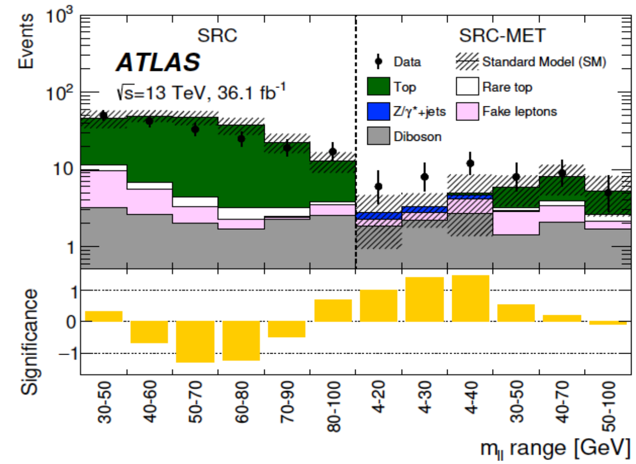
| Low-$p_T$ regions | $E_T^{miss}$ [GeV] | $p_T^{\ell\ell}$ [GeV] | $n_{jets}$ | $n_{b\text{-jets}}$ | $m_{\ell\ell}$ [GeV] | SF/DF | OS/SS | $\Delta\phi(\text{jet}_{12}, p_T^{miss})$ | $m_T$ [GeV] | $m_{\ell\ell}$ windows |
|---|---|---|---|---|---|---|---|---|---|---|
| Signal regions | | | | | | | | | | |
| SRC | > 250 | < 20 | ≥ 2 | – | > 30 | SF | OS | > 0.4 | – | 6 |
| SRC-MET | > 500 | < 75 | ≥ 2 | – | > 4, ∉ [8.4, 11] | SF | OS | > 0.4 | – | 6 |

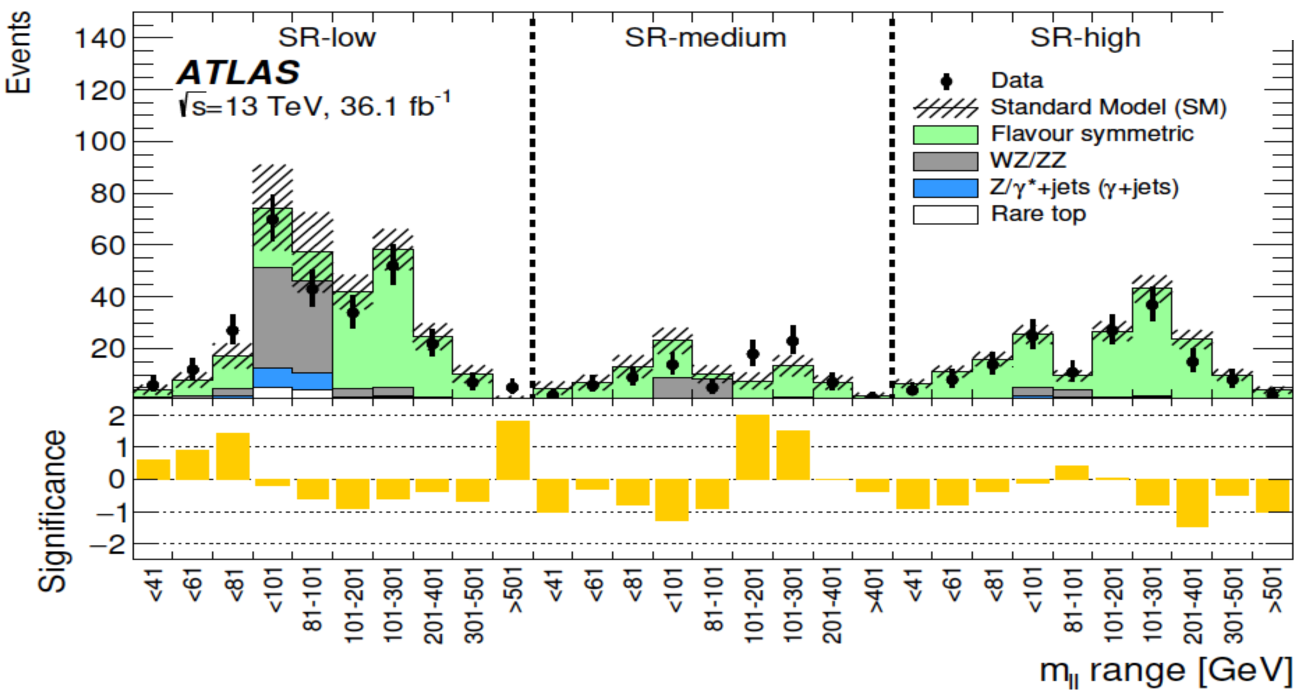
| On-shell Z regions | $E_T^{miss}$ [GeV] | $H_T$ [GeV] | $n_{jets}$ | $m_{\ell\ell}$ [GeV] | SF/DF | $\Delta\phi(\text{jet}_{12}, p_T^{miss})$ | $n_{b\text{-jets}}$ | $m_{T2}$ [GeV] |
|---|---|---|---|---|---|---|---|---|
| Signal region | | | | | | | | |
| SRZ-soft | > 400 | > 400 | ≥ 2 | $81 < m_{\ell\ell} < 101$ | SF | > 0.4 | - | > 25 |
| SRZ-hard | > 200 | > 1200 | ≥ 2 | $81 < m_{\ell\ell} < 101$ | SF | > 0.4 | - | - |



# Opposite sign dilepton results

Since the edge analysis searches for a kinematic endpoint in the dilepton invariant mass distribution, a binned $m_{ll}$ shape fit is performed in the edge SRs to enhance sensitivity to an edge-like feature.

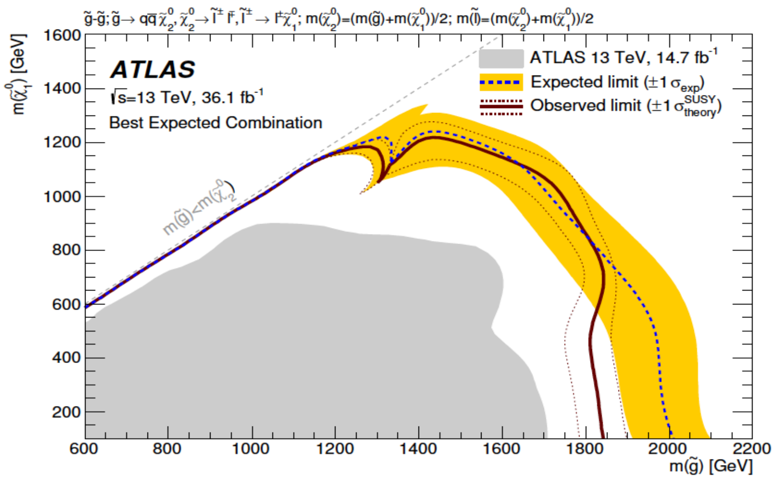




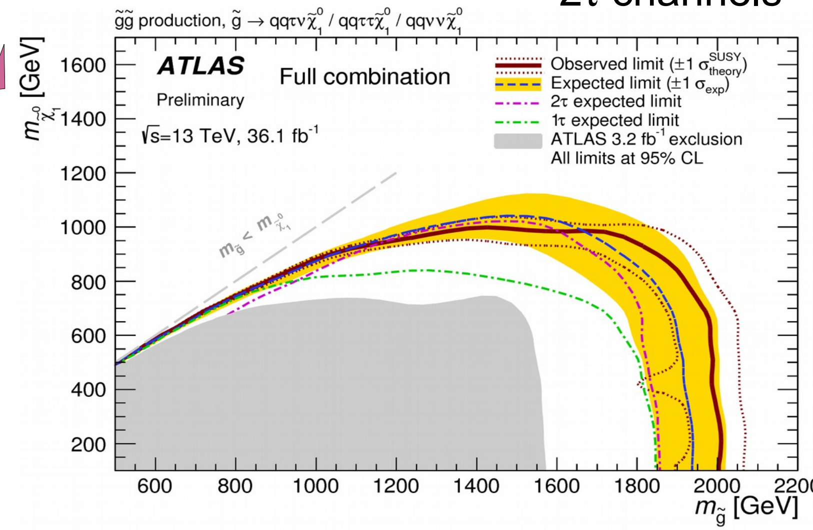
Models without light sleptons are targeted by windows $m_{ll} < 81$ GeV for $m_{\chi} < m_Z$, and window with $81 < m_{ll} < 101$ GeV for $m_{\chi} > m_Z$.

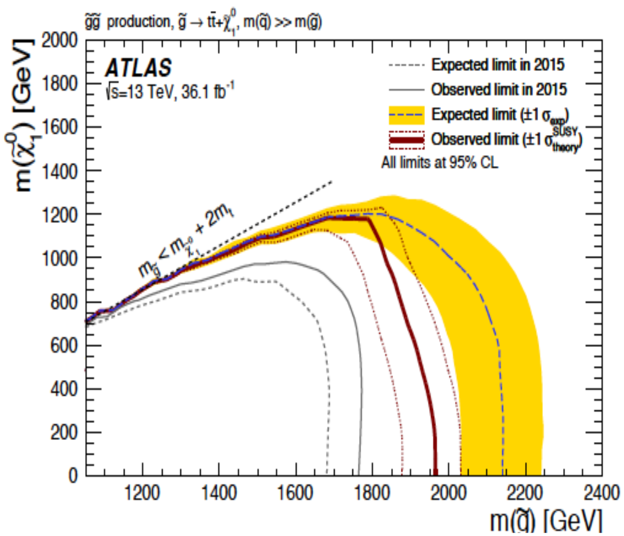
# Exclusion limits

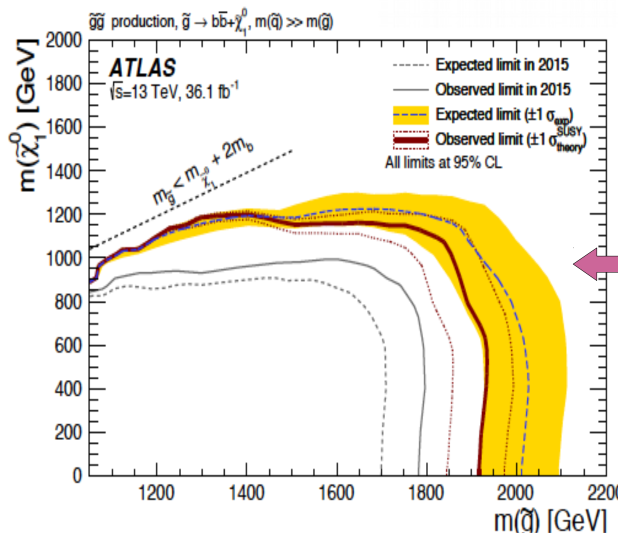
Significant improvements in sensitivity over previous results




Limits for the combination of the 1τ and 2τ channels



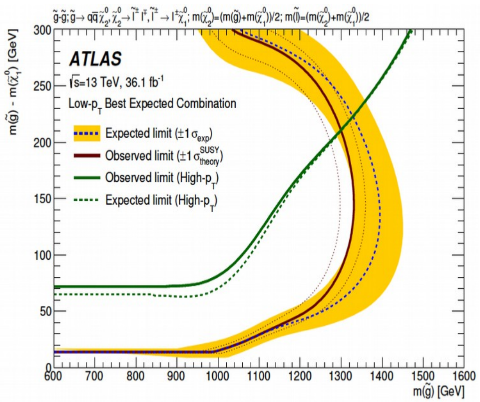



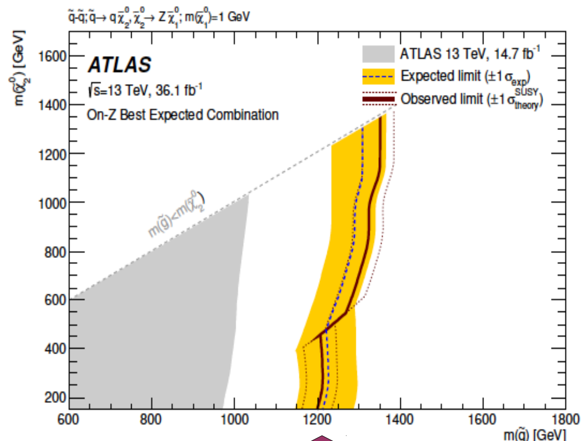

All the regions of the multi-bin analysis are statistically combined to set model-dependent upper limits.

Observed constraints on gluino masses reach 1.9 - 2 TeV for simplified models at low neutralino masses

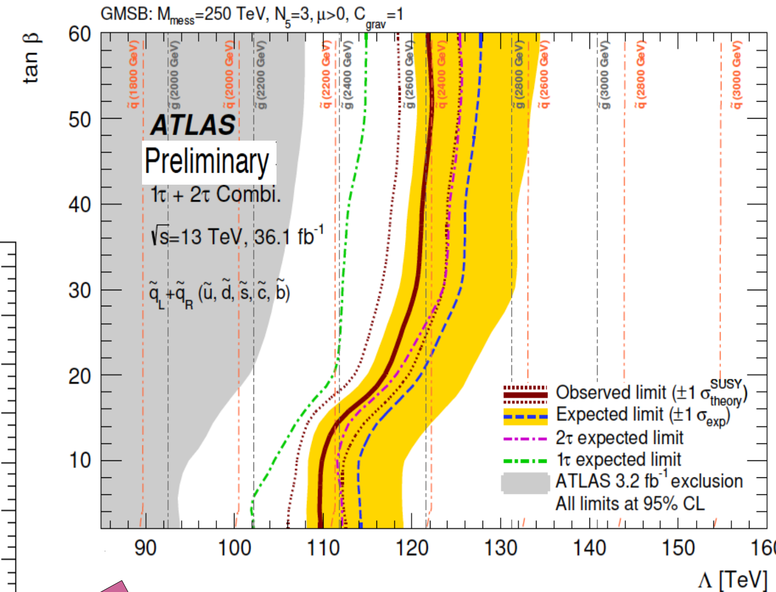
# Complementary interpretations

Zoomed results in the compress region for OS 2L

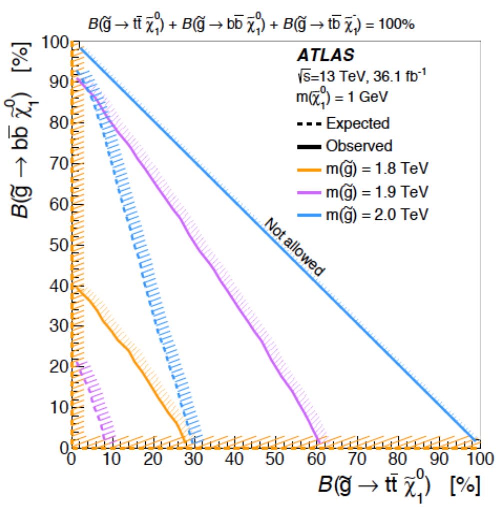


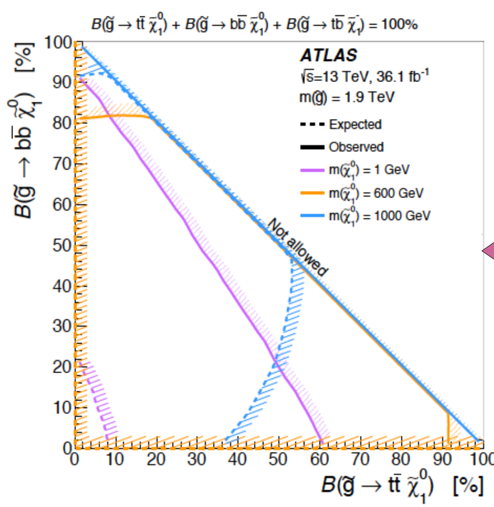




Constrains on squarks mass up to 1.3 TeV




GGM parameters limits for the combination of the 1τ and 2τ channels



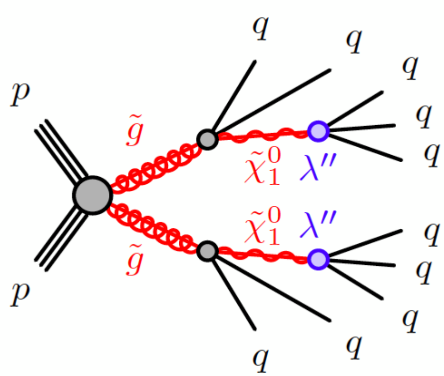

Limits also interpreted in a less simplified model as a function of the gluino BR to ttN1 / bbN1 / tbN1

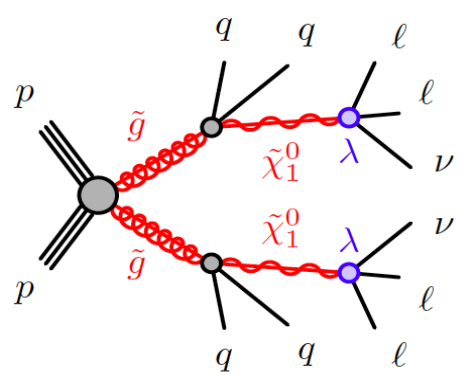
# Reinterpretation of searches: RPC meets RPV

$$\mathcal{W}_{\mathrm{RPV}} = \frac{\lambda_{ijk}}{2} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \frac{\lambda''_{ijk}}{2} \bar{U}_i \bar{D}_j \bar{D}_k + \kappa_i L_i H_u$$

General R-parity-violating (RPV) superpotential in MSSM

- If RPV SUSY particles may cascade to LSP which then decays to SM particles
- κ, λ, λ' all give rise to final states with some amount of MET from neutrinos
- λ'' gives rise to multijet final states



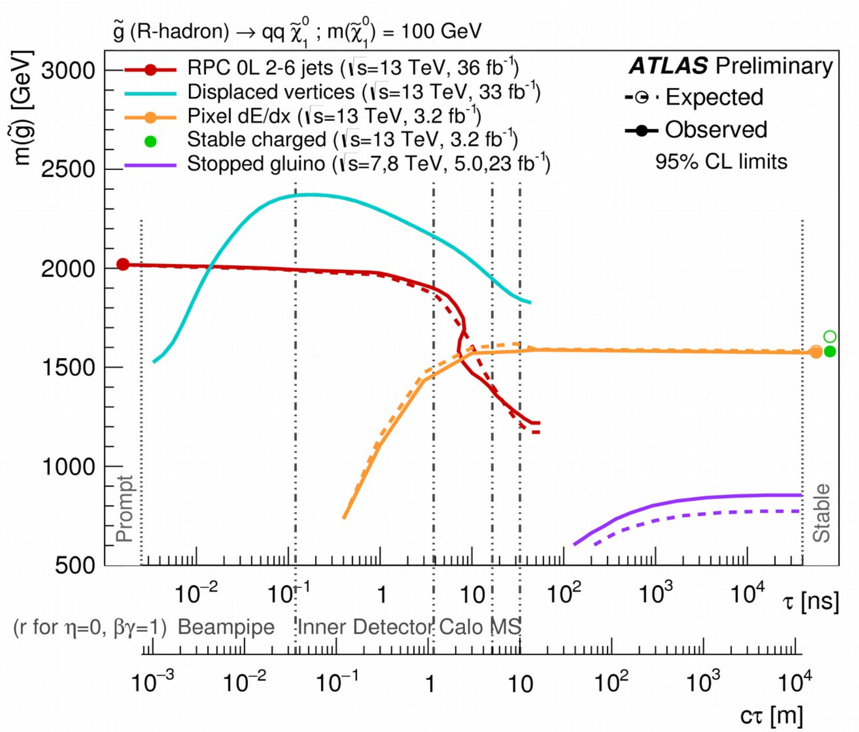



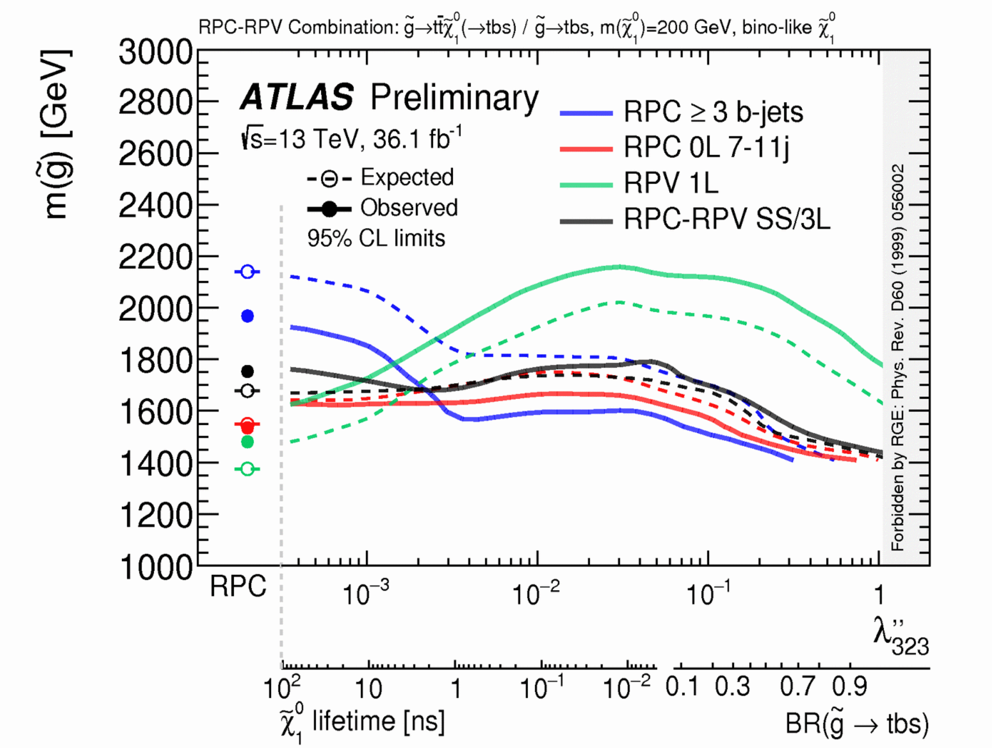

Most RPV searches focus on maximal violation of R-parity. Reinterpretation of searches for SUSY in models with variable RPV coupling strength and long-lived R-hadrons

Hadronic final states with non-zero baryon-number-violating RPV λ'' couplings assumed, while lepton-number-violating couplings, λ, λ' are set to zero.

# RPC meets RPV results

The LSP lifetime depends on the strength of the coupling. Scaling the coupling allows to search for SUSY final states in different regimes




gluino mass up to ~ 2 TeV can be excluded

# Conclusions

- No evidence for any SUSY physics yet
  - gluino masses in simplified models reaching the natural 2 TeV limit
- Up to now searches in ideal models based on simple BR assumption and straightforward parameter values
  - unexplored phase space for gluino masses below 2 TeV in more complicated scenarios
- In 2017 and 2018 more data is to be added (~150 $fb^{-1}$)
  - many unconventional signatures and models to be explored
  - not only accumulate luminosity but improvements in performances and new analysis strategies and technics

# Backup slides