Searches for light squark and gluino production

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On behalf of
ATLAS and CMS

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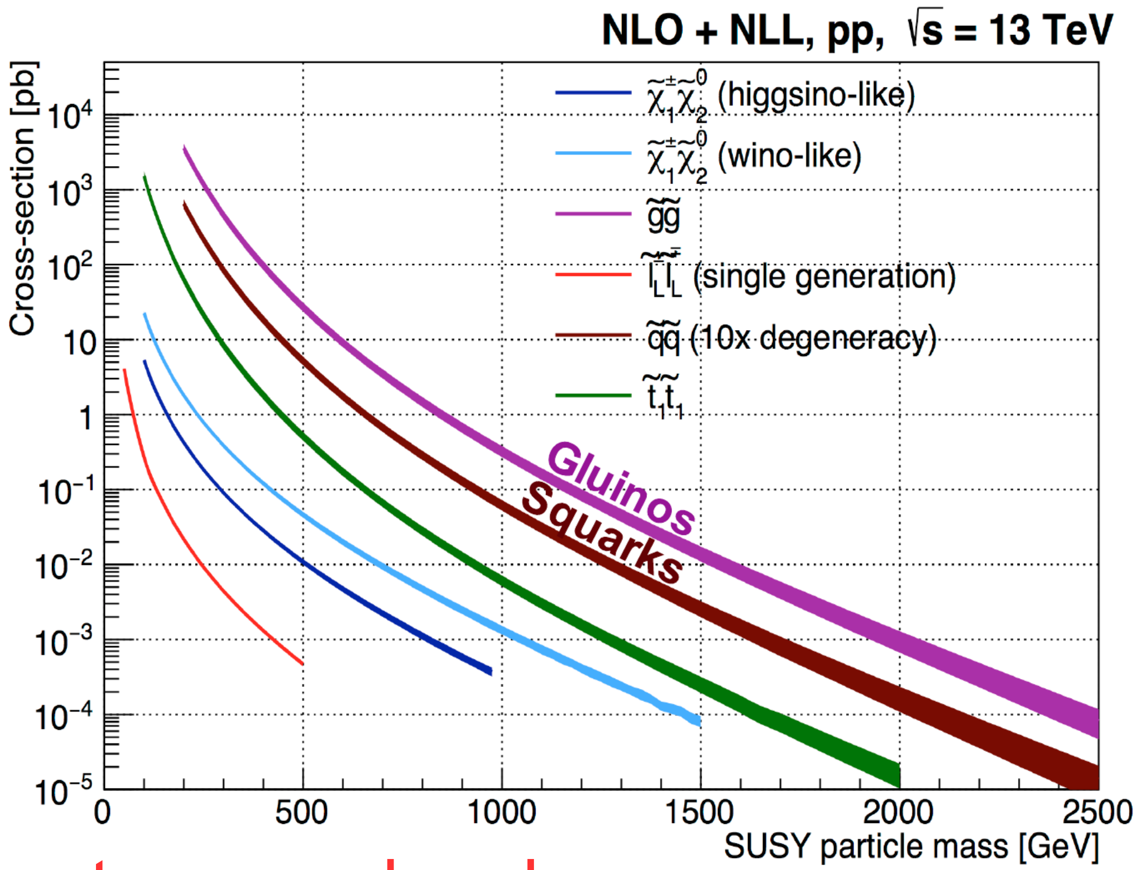
Motivation

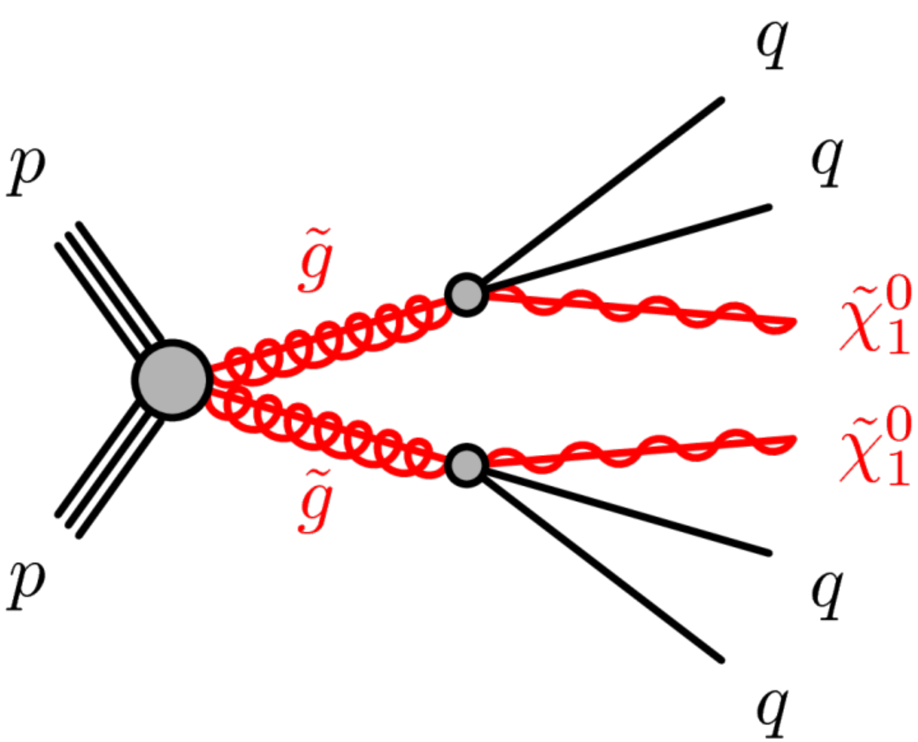
- TeV-scale gluinos are well-motivated by EW fine-tuning problem
- Cross-sections are large for TeV-scale quarks and gluinos
  - Ideal for early Run-2 searches

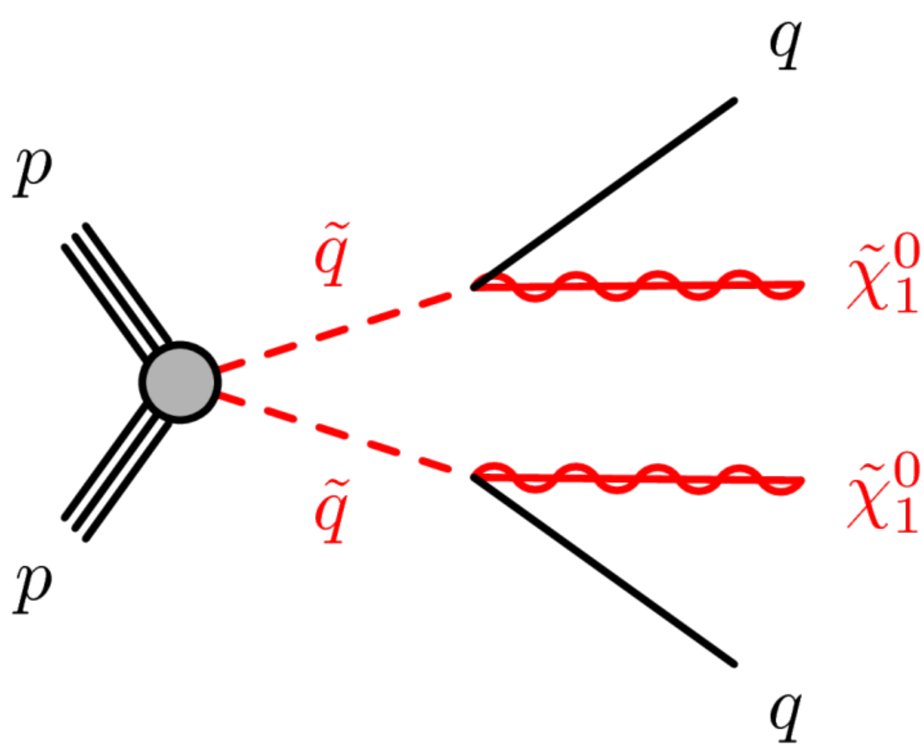


- Unfortunately no significant excess has been seen
  - Can only set limits on potential SUSY signals

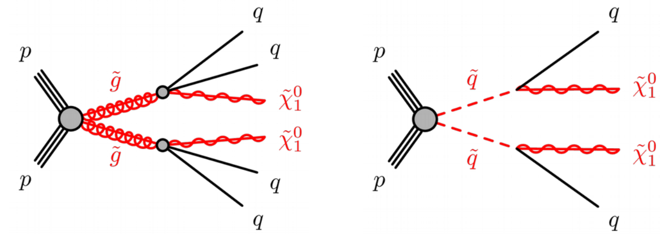
- Will give overview of status after searches in 2016 data
- *This will not be a comprehensive review*
  - I will detail mainly recent results

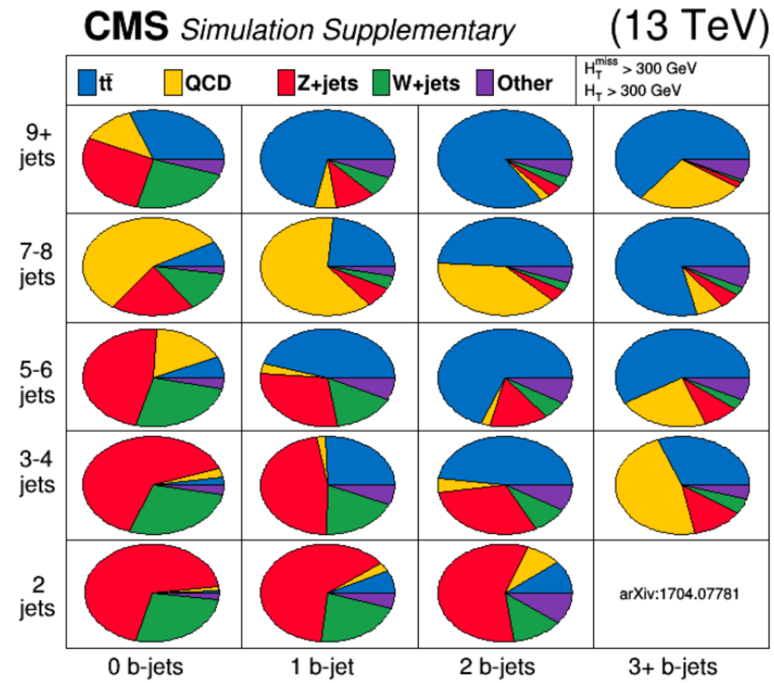
Direct Squark & Gluino Decays





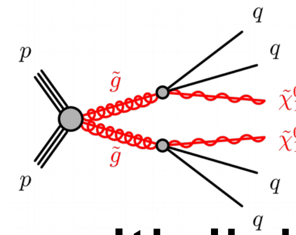
All-hadronic Searches

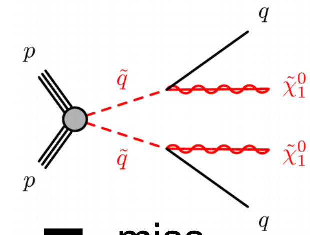




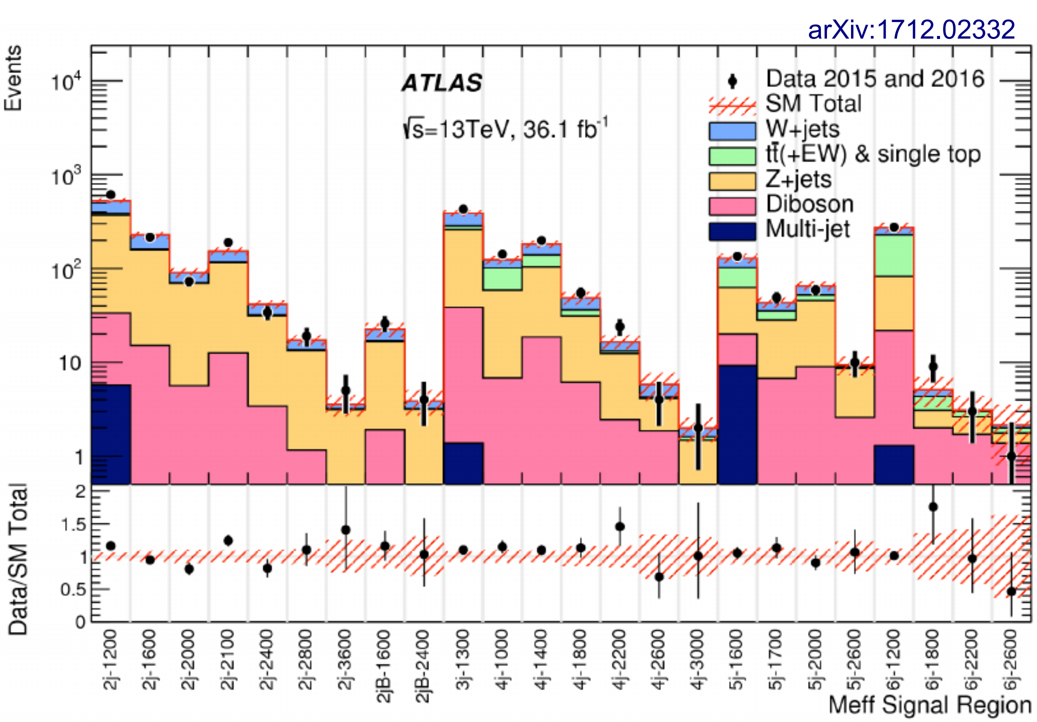
- Signal: jets and missing energy
- Main backgrounds:
  - Multi-jets (QCD)
  - W+jets & $t\bar{t}$ with missed lepton and hadronic taus
  - Irreducible Z(→νν)+jets
- Different kinematic variables are used to separate signal and backgrounds used in all-hadronic ATLAS and CMS searches:
  - M_{eff} – scalar sum of jets and E_{Tmiss}
  - HT_{miss} – vector sum of jets
  - MT_2 – “transverse mass” assuming two invisible part.
  - α_T – di-jet balance $\alpha_T = E_T^{j2} / M_T$
  - Recursive Jigsaw – reconstruction of intermediate rest-frames

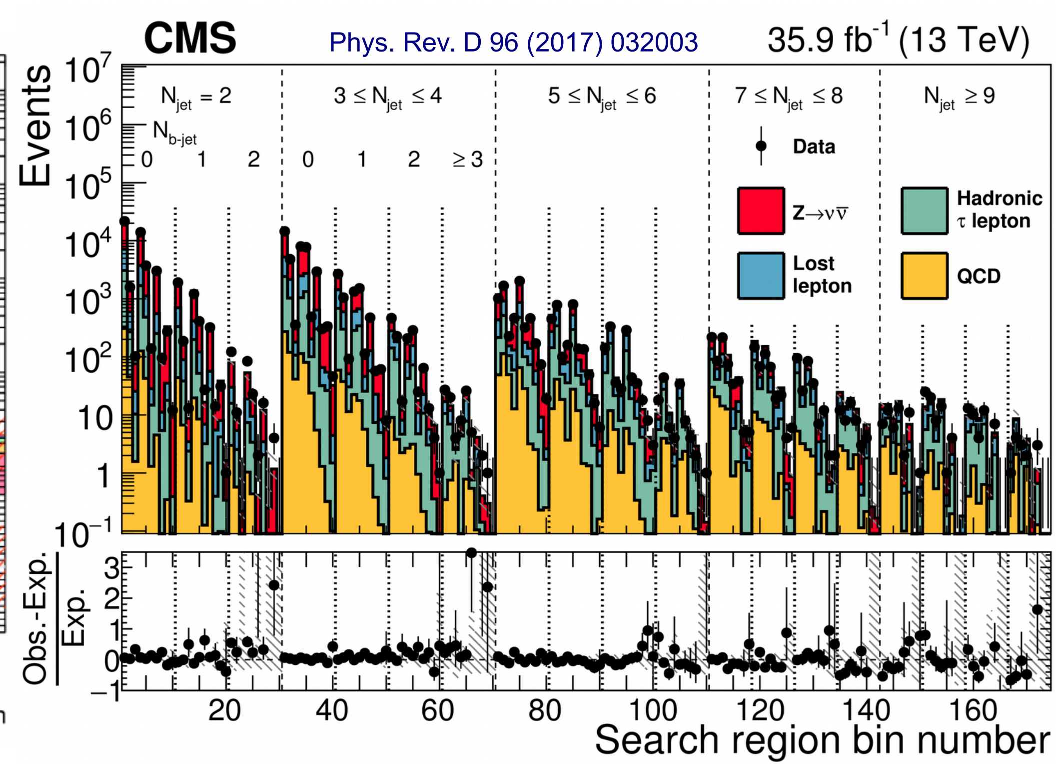
Analysis Results



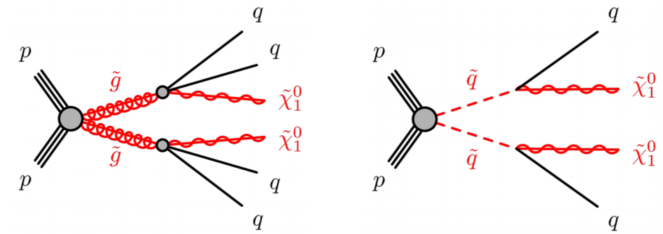


- Data split in multiple bins of (b-)jet multiplicity, E_T^{miss}, and other kinematic variables to maximize sensitivity
- Data-driven background estimates (either fully or simulation scaled using data control regions)
- No significant excess in any all-hadronic search
  - CMS example: one bin at 3.5σ, three >2σ, but out of 174 bins

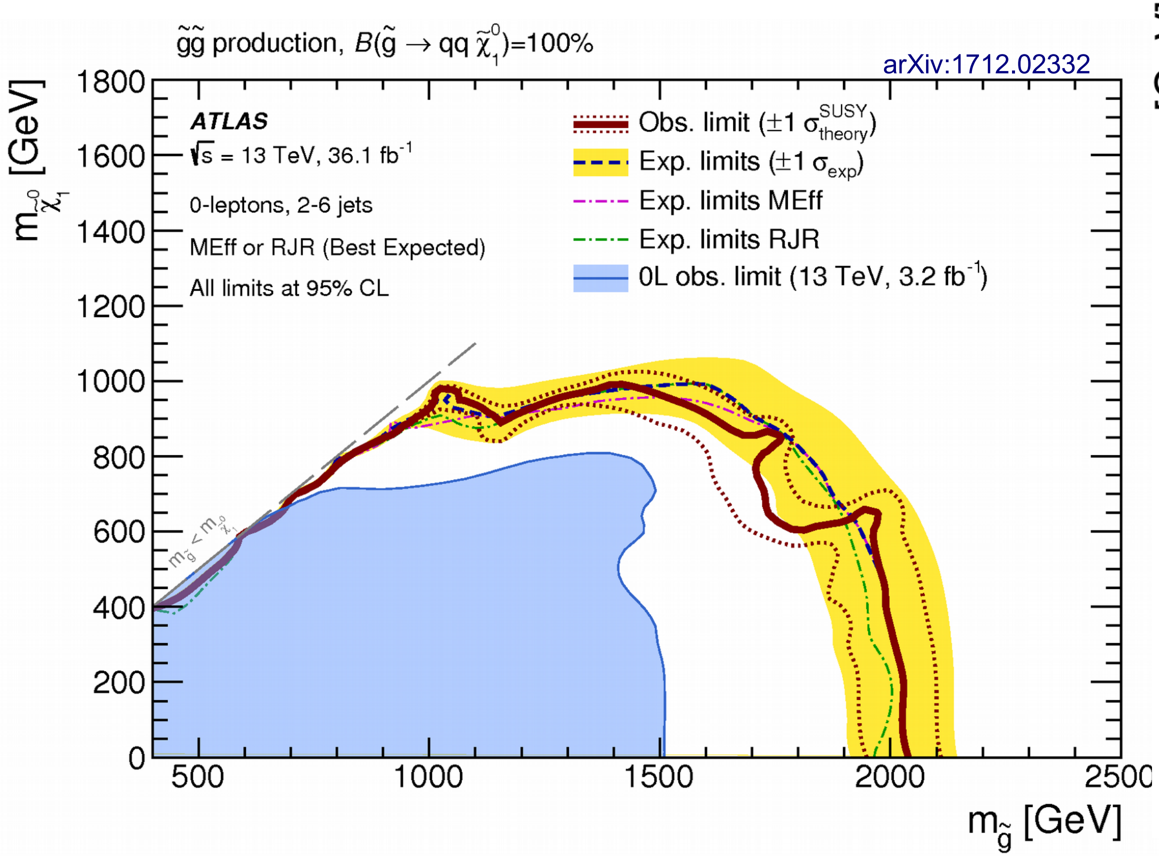


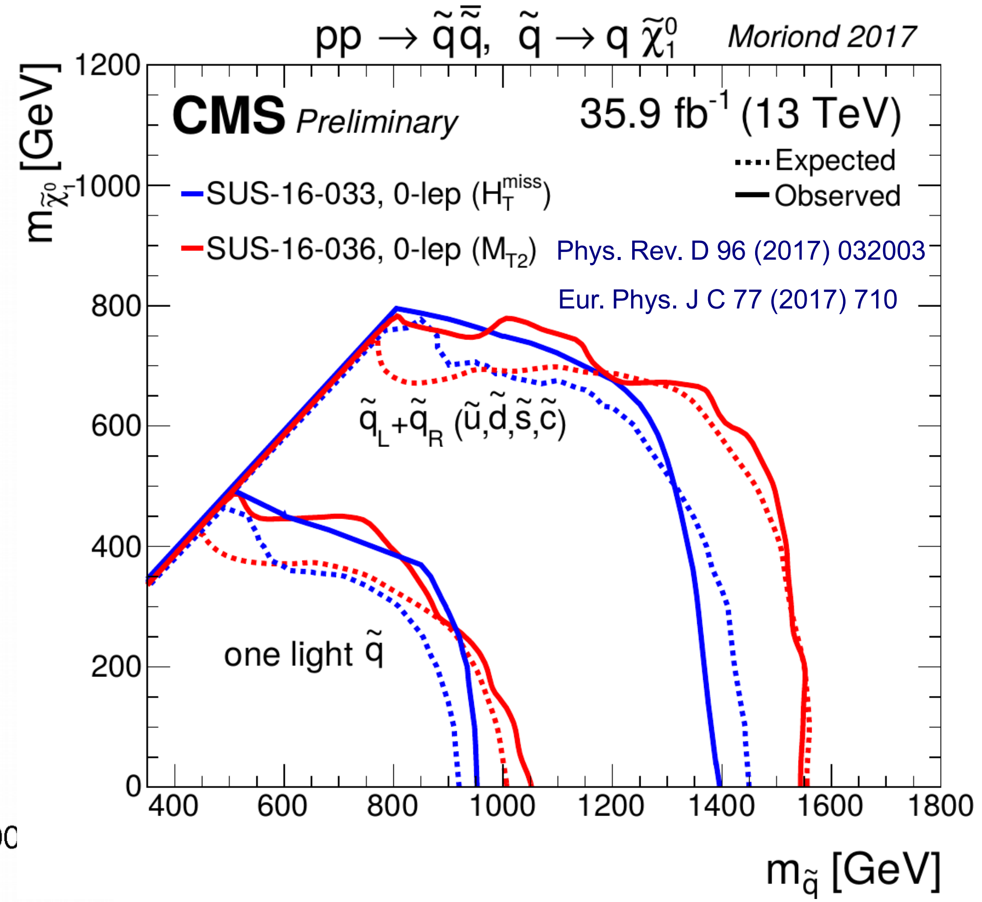


Mass Limits

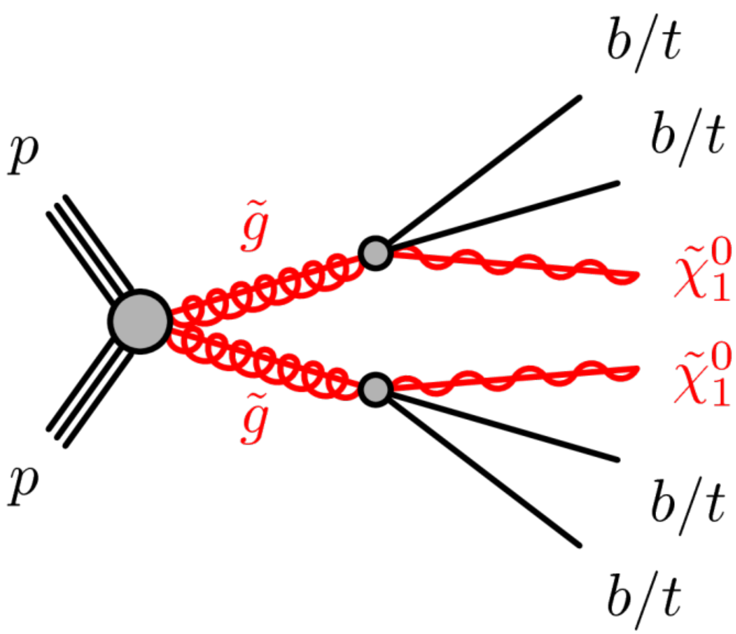


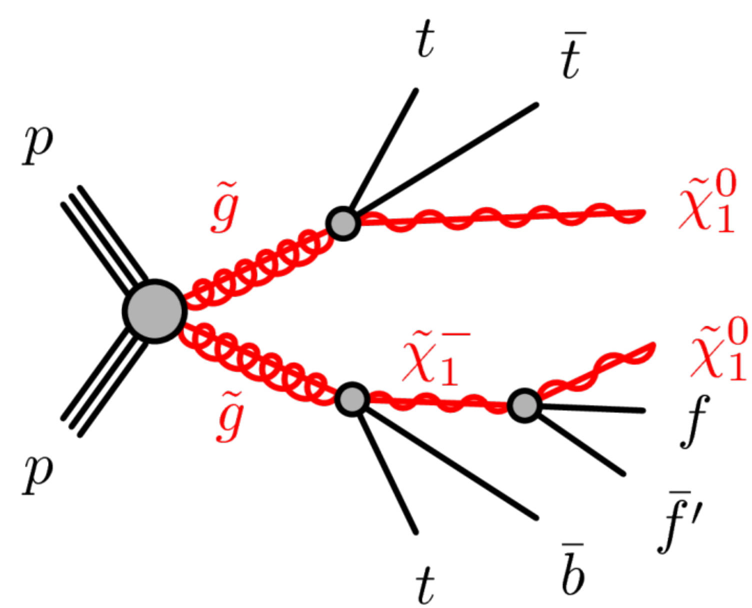
- Set limits on signal cross sections vs masses
- Corresponding sparticle mass limits for *BF=100%*:
  - Squarks: up to 1.55 TeV assuming 8-fold squark degeneracy
  - Gluinos: up to 2.05 TeV with neutralinos up to 1.1 TeV



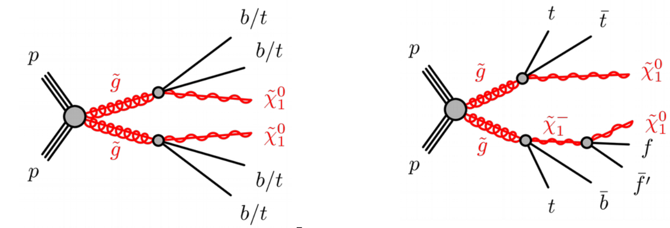


Gluino Decays to 3rd Generation Quarks

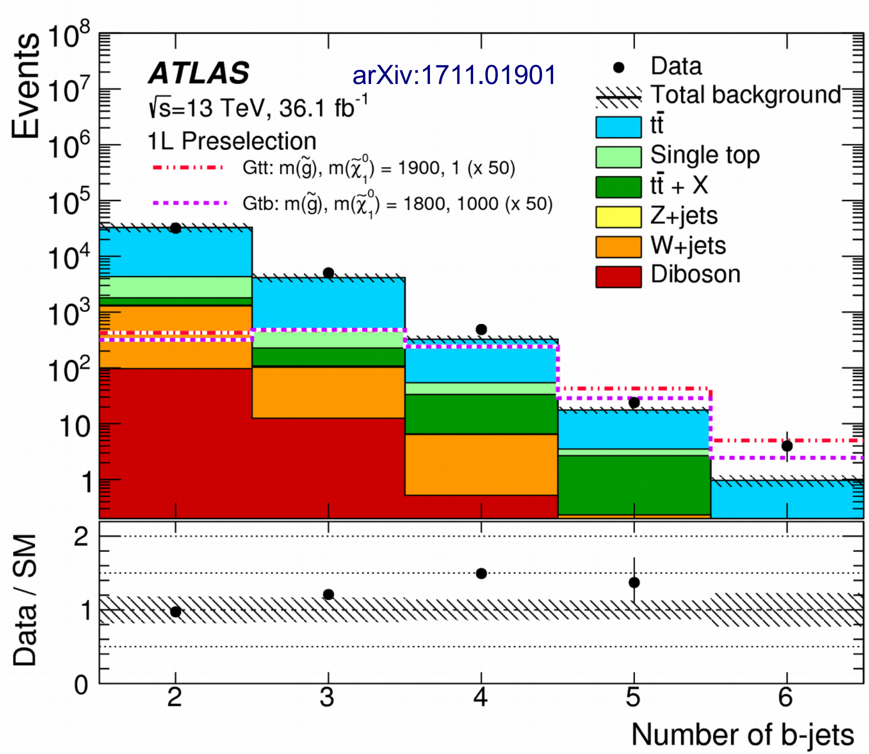


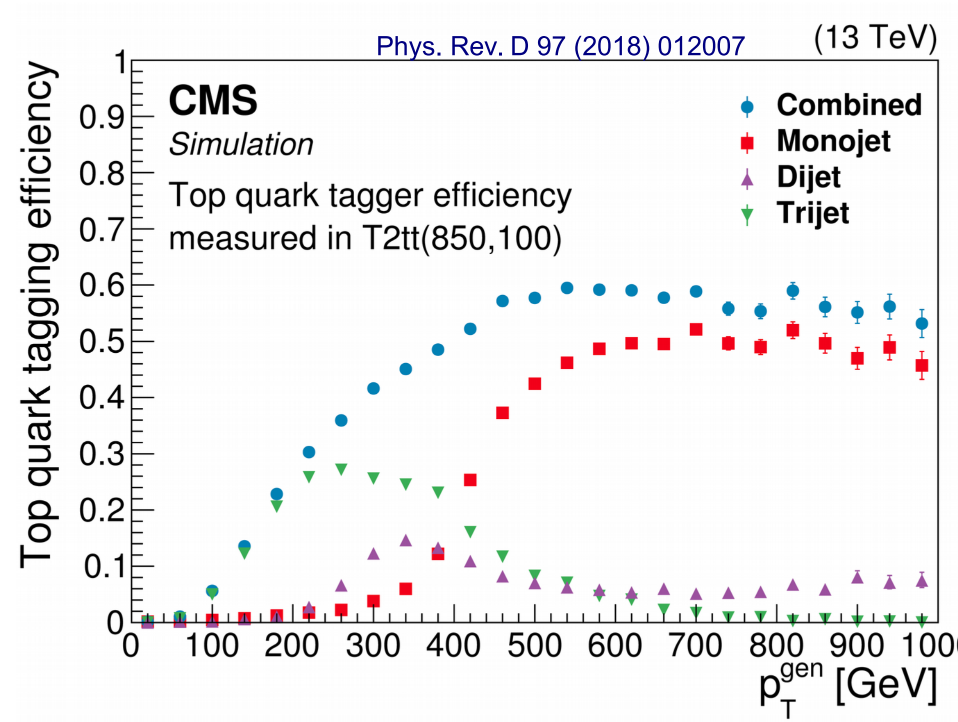


Gluino Searches

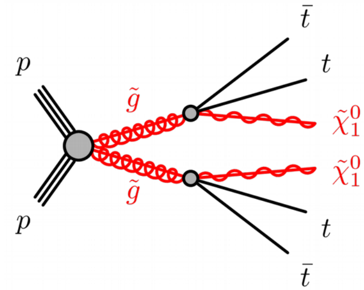


- Natural SUSY favors gluino decays to stop/sbottoms
- Provides rich set of possible final states
  - 4 b-jets and up to 4 top quarks
  - Up to 12 jets or 4 charged leptons
- Inclusive all-hadronic searches have good sensitivity, but additional sensitivity by using leptons and top-tagging

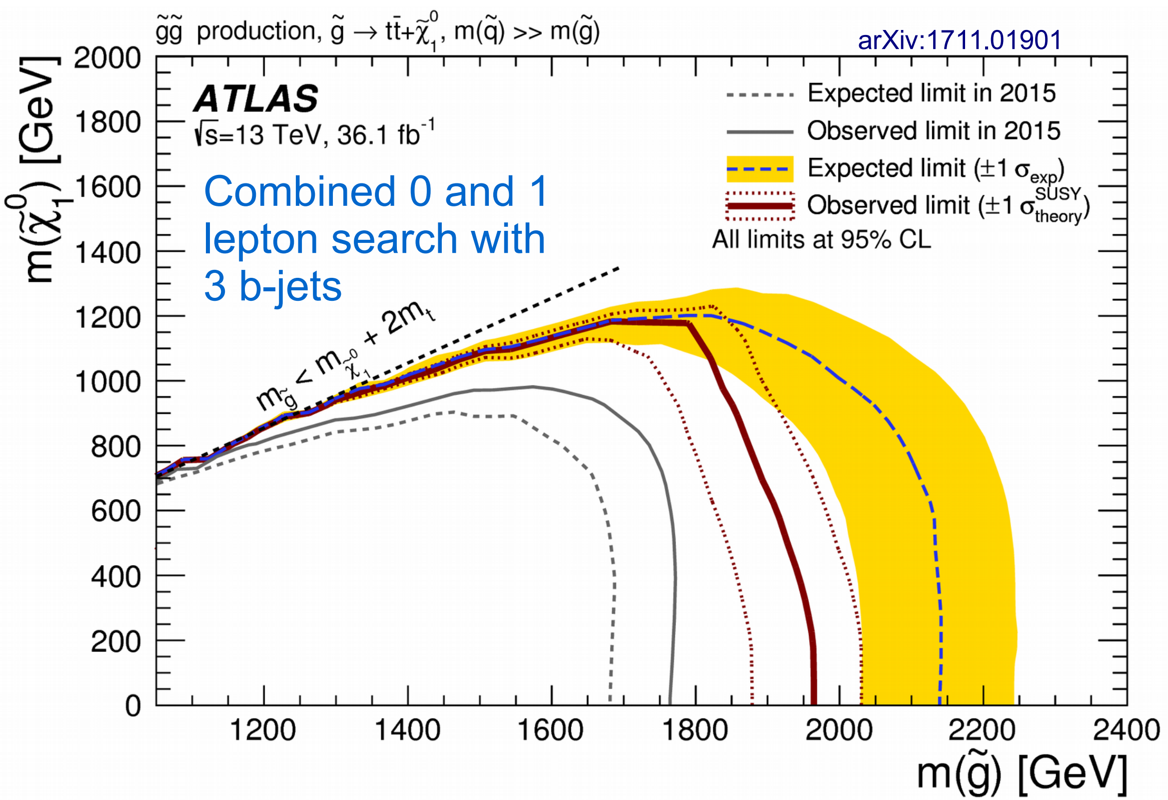


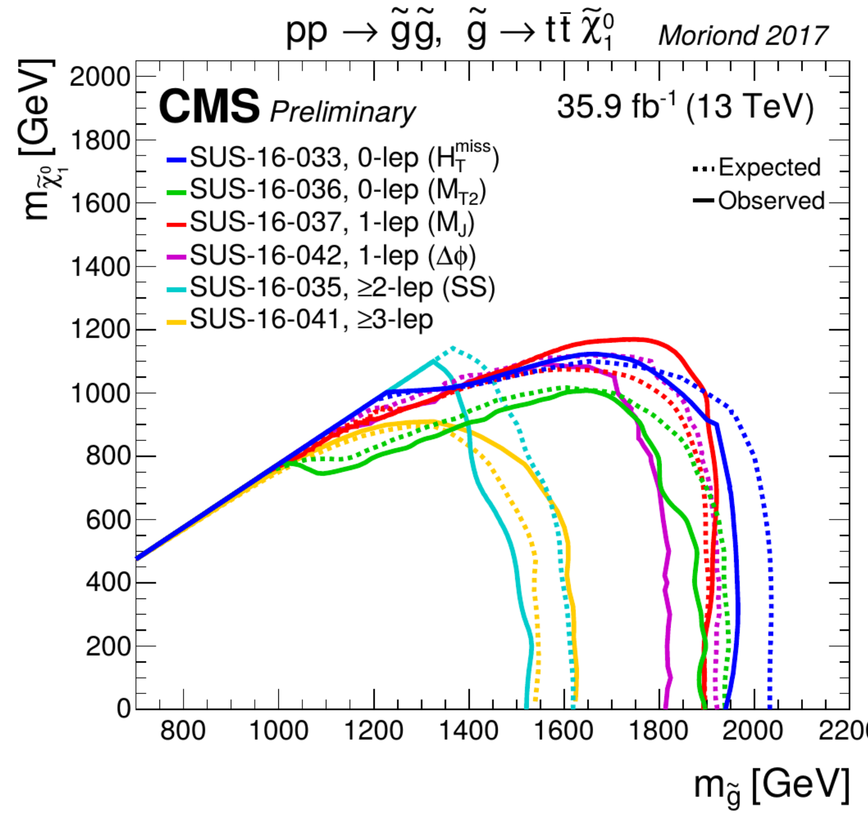


Mass Limits, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$

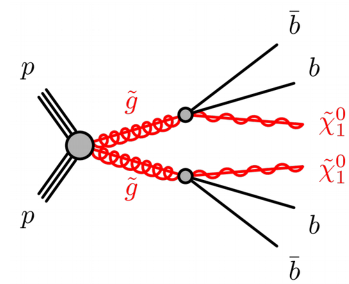


- Good exclusion of heavy gluinos
  - Up to 1.97 TeV for gluinos and neutralinos up to 1.19 TeV
- Worse than expected exclusion in ATLAS result is due to 2.3σ excess in most sensitive bin (out of 14)

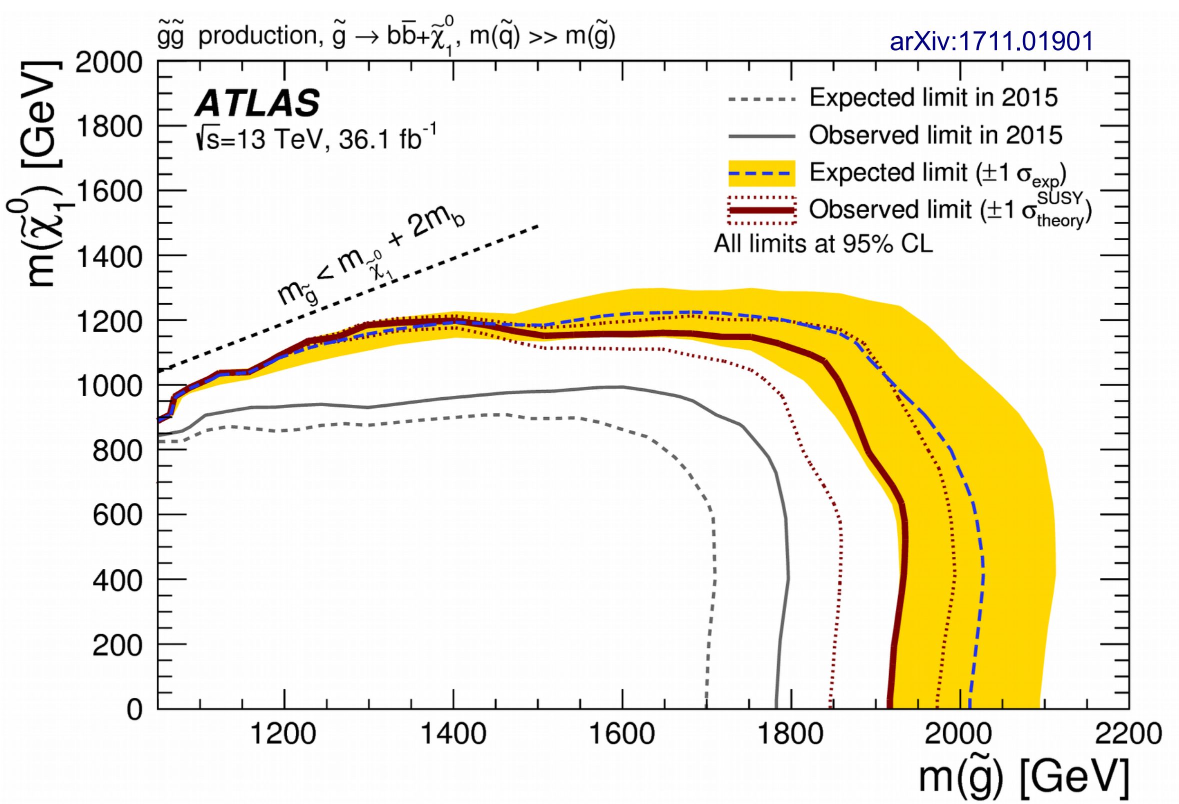


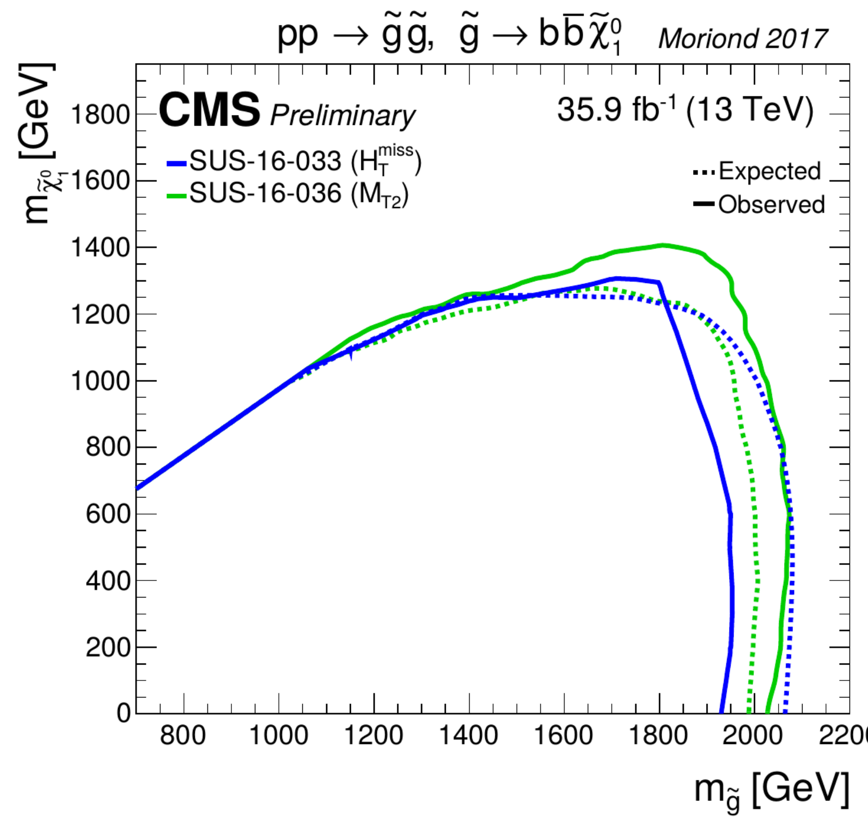


Mass Limits, $\tilde{g} \rightarrow b\bar{b}\tilde{\chi}_1^0$

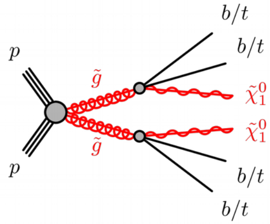


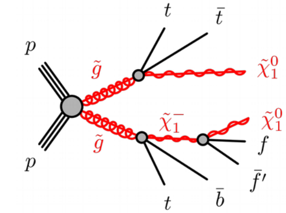
- Exclusion in 4b final state just as good
  - Gluinos excluded up to 2.05 TeV for 100% BF



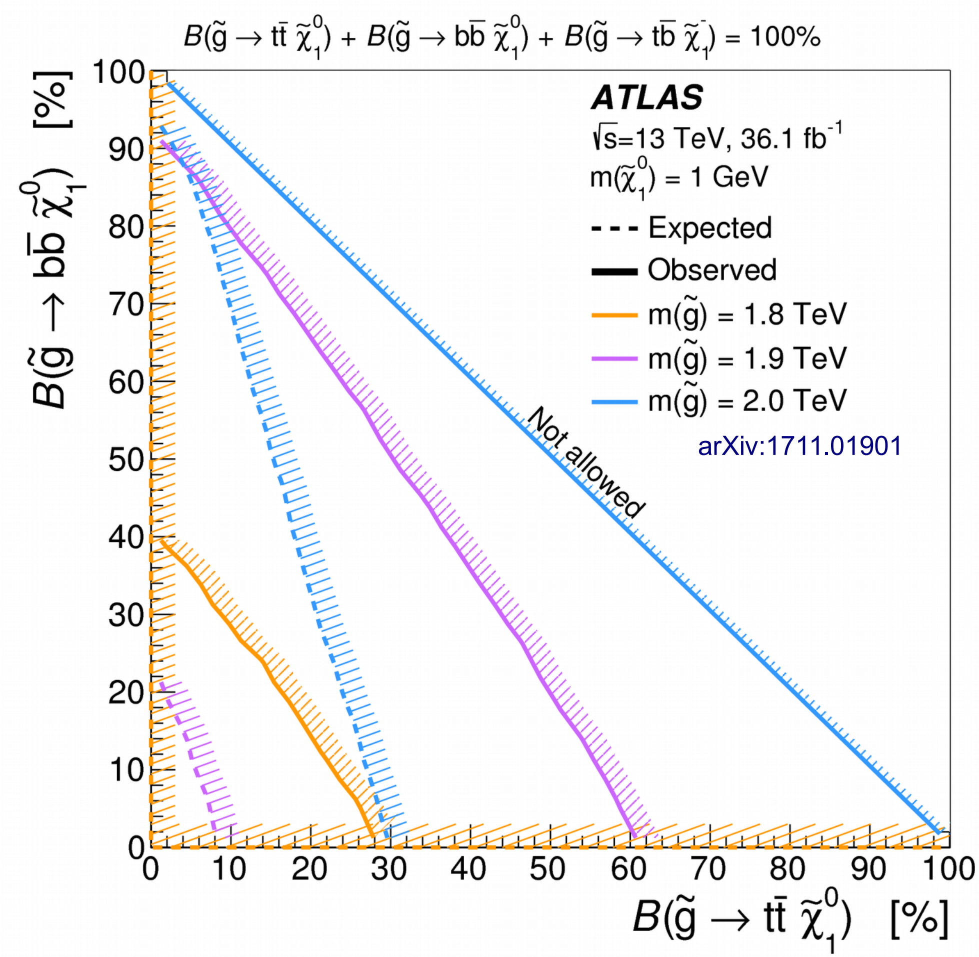


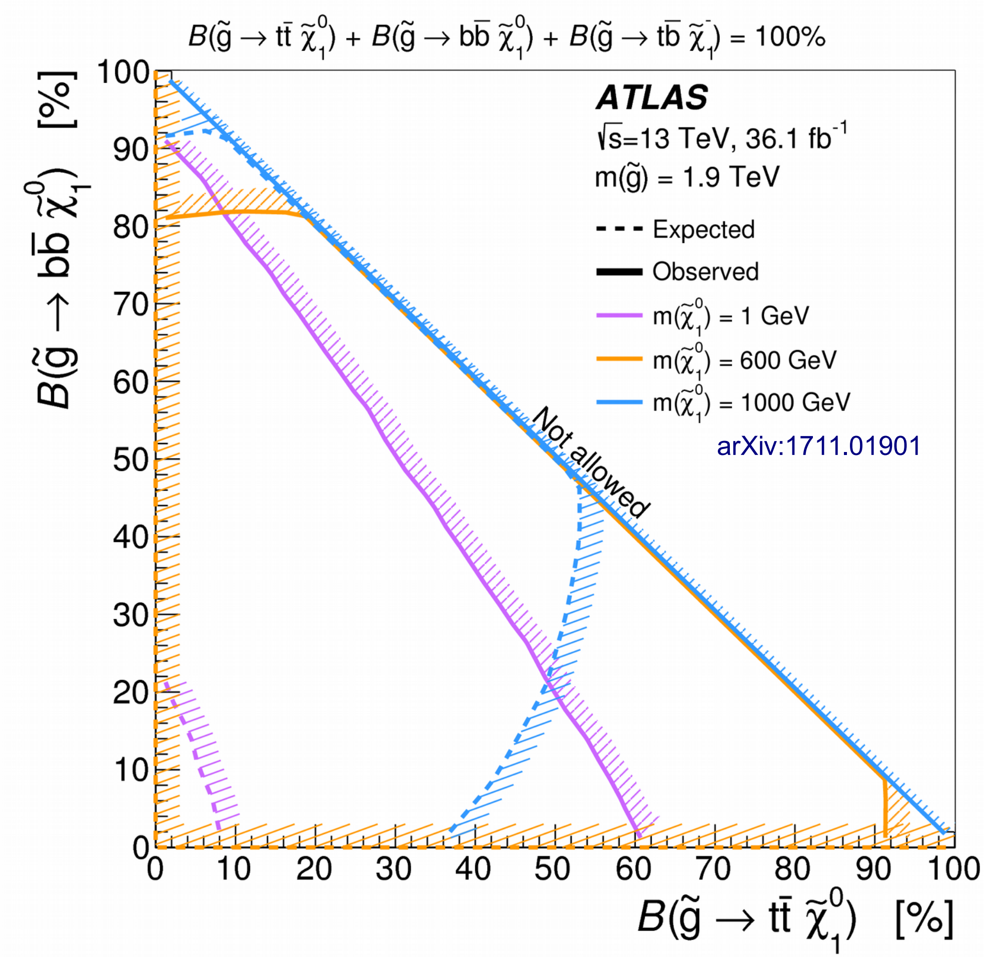
Mixed Gluino Decays



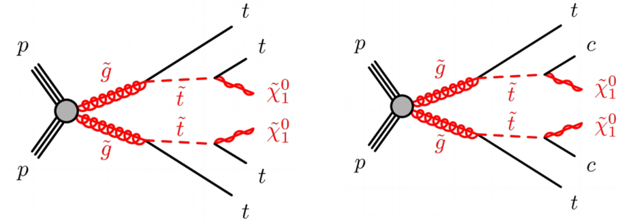


- Limits weaken if a mixture of gluinos decays is allowed, particularly $\tilde{g}\to t\bar{b}\tilde{\chi}_1^-$
- If $\tilde{g}\to t\bar{b}\tilde{\chi}_1^-$ dominant, ATLAS limit is below 1.8 TeV even for very light neutralino

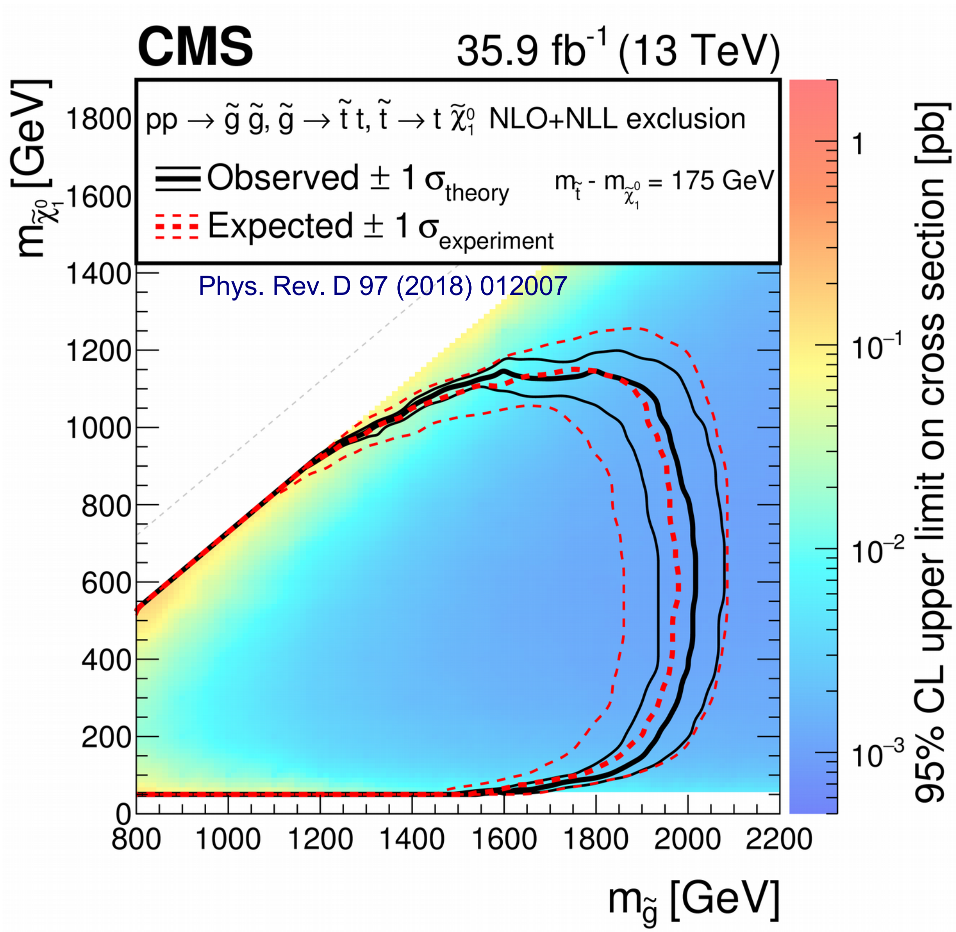


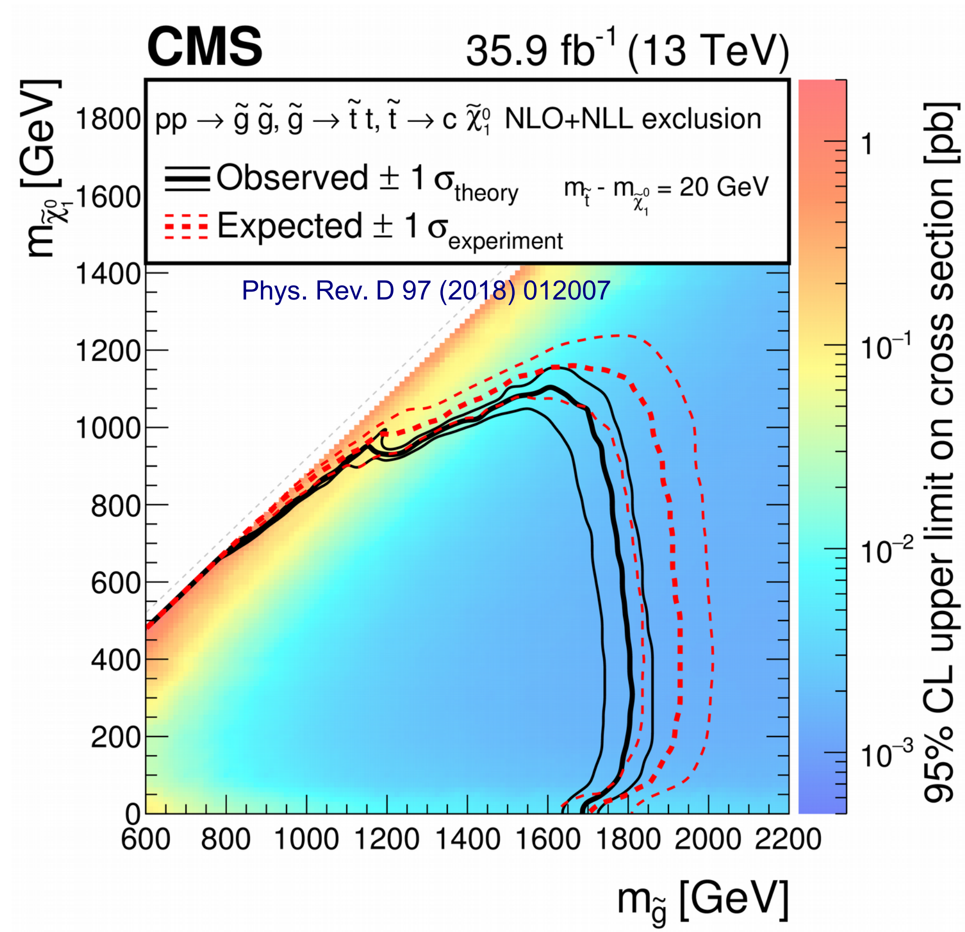


Gluino Decays with Compressed Stops

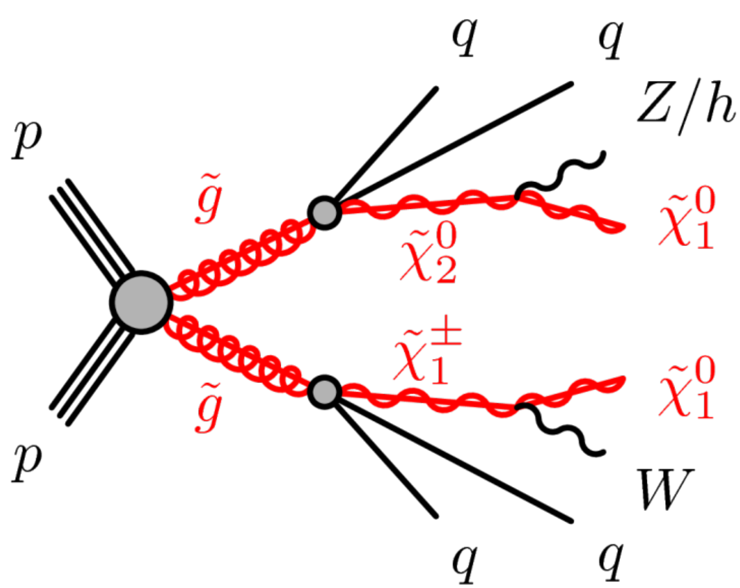


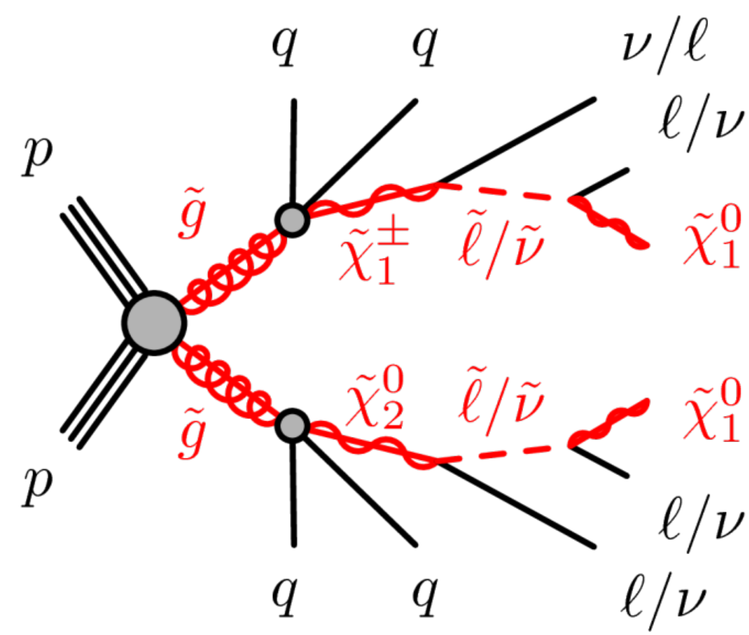
- Gluino decays through real stop generally excluded at same level as through virtual stop
- Exception: $m(\tilde{t}_1) \sim m(\tilde{\chi}_1^0)$
  - Can have gluinos below 1.8 TeV with light neutralino



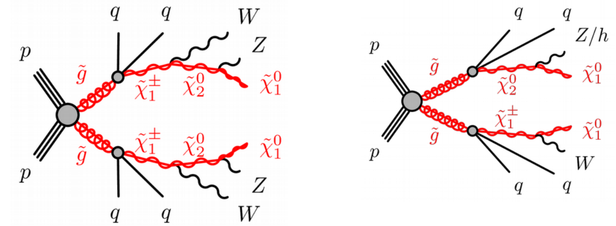


Multi-step Decays

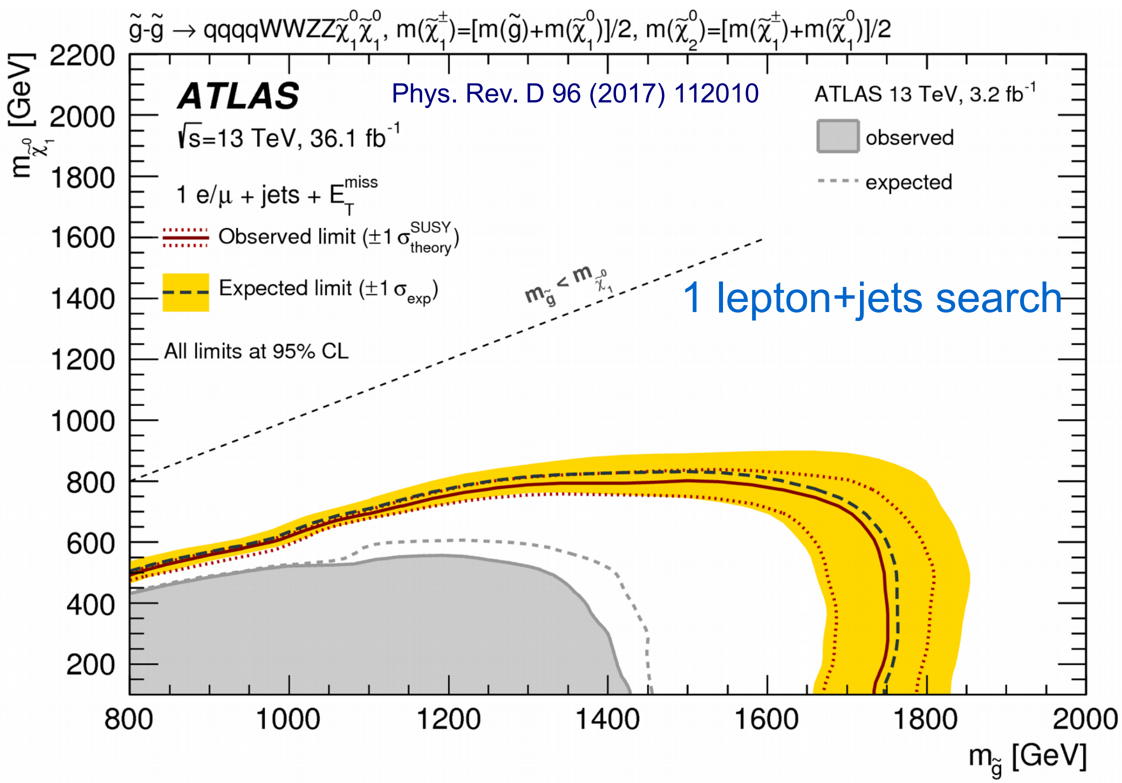


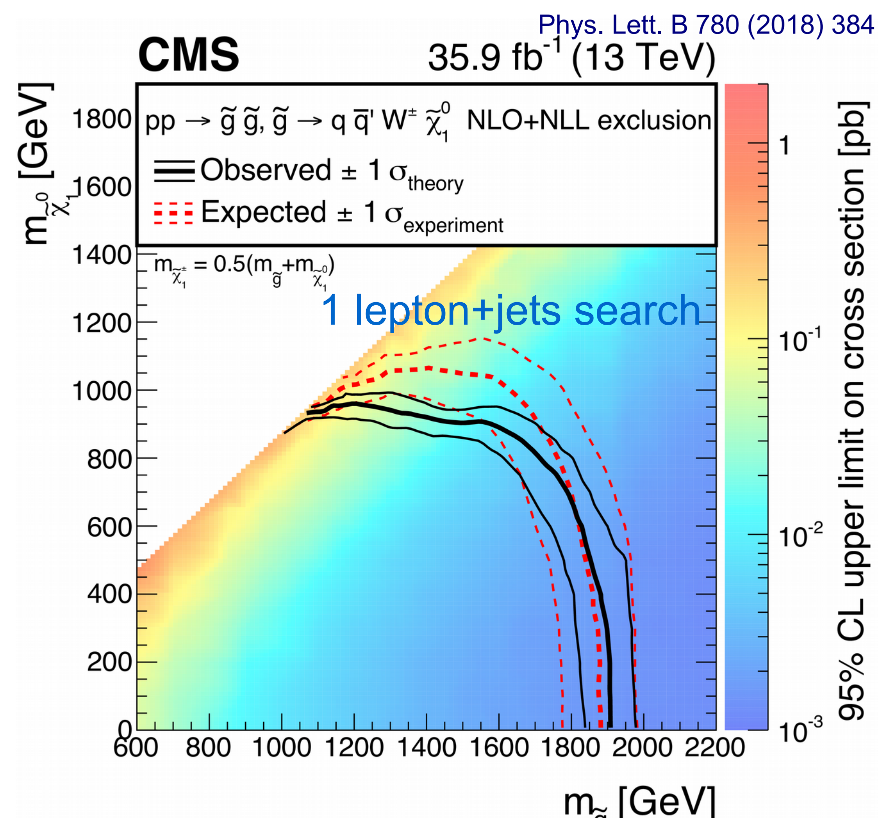


Multi-step Decays

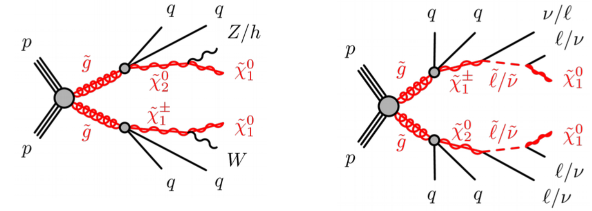


- Can introduce additional sparticles in decay chain
  - Lower E_{Tmiss}, but higher jet and lepton multiplicity
- Inclusive 0 and 1-lepton searches still sensitive
- Sensitivity depends on intermediate sparticle masses
  - Gluino limits 1.7-2.0 TeV for intermediate decays to W/Z when the neutralino is light (*assuming 100% BF*)

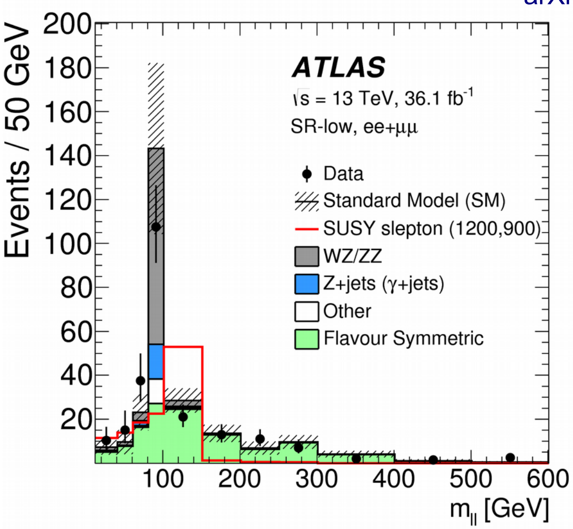


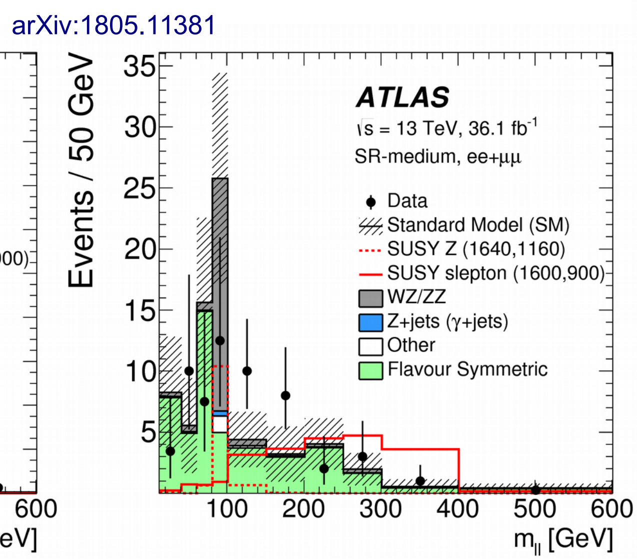


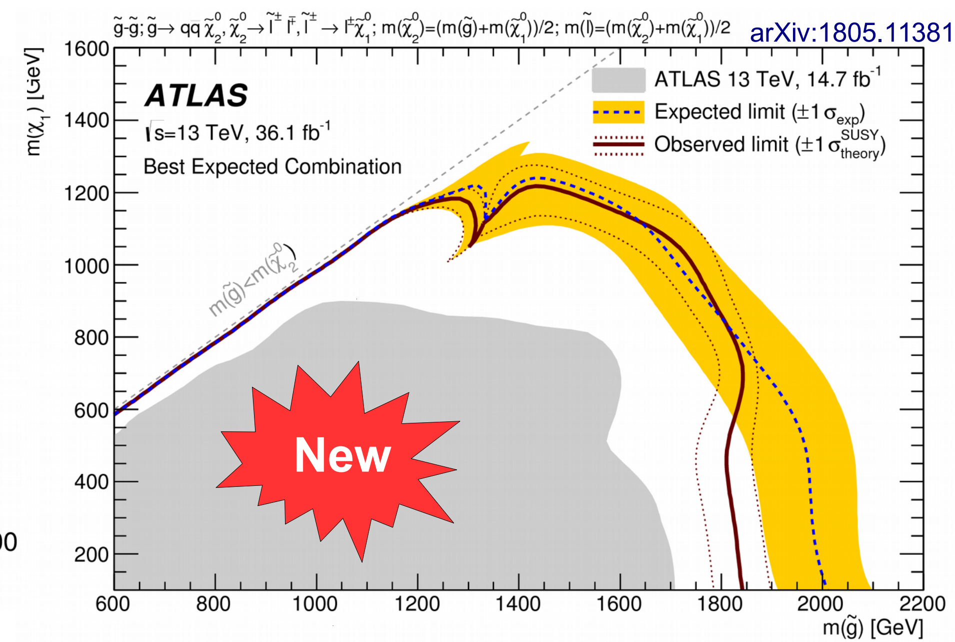
Di-lepton Edge Search



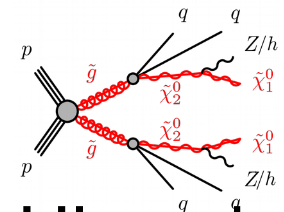
- New ATLAS opposite-charge, same-flavor di-ℓ search
- Targets strong decays through $Z^{(*)}$ or sleptons
  - Searches for triangular edge or Z-peak in m(ℓℓ) spectrum
  - Opposite flavor pairs used for dominant backgrounds
- New low-p_T di-lepton selection for compressed region
  - $p_T(\ell)$>7 GeV and m(ℓℓ)>4 GeV
- Excludes gluinos up to 1.85 TeV for slepton decays and sensitive down to mass splittings of 20 GeV



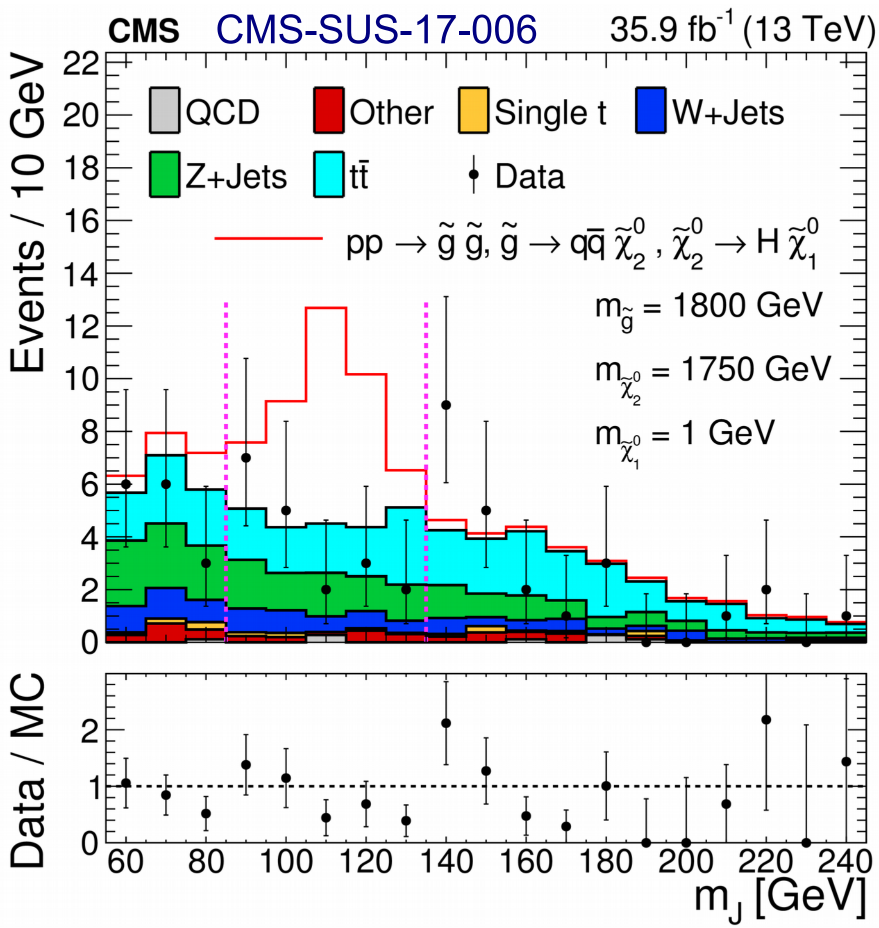


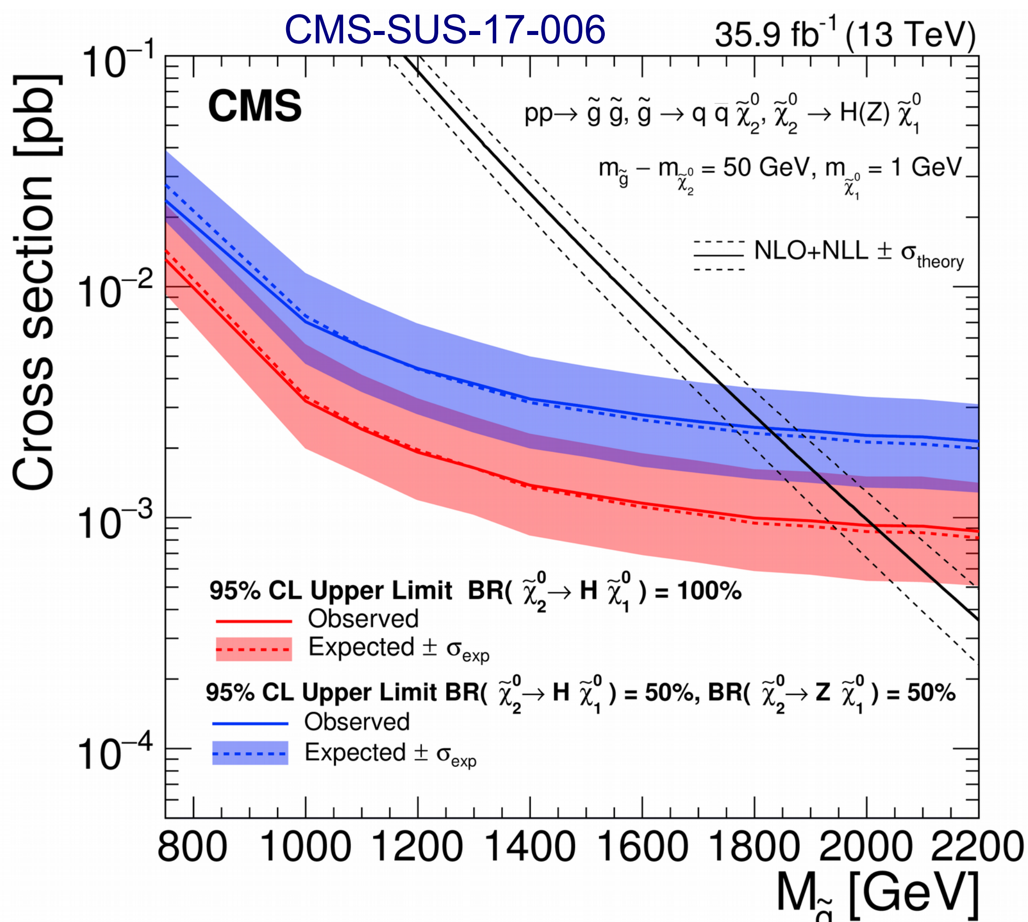


Decays with Higgs

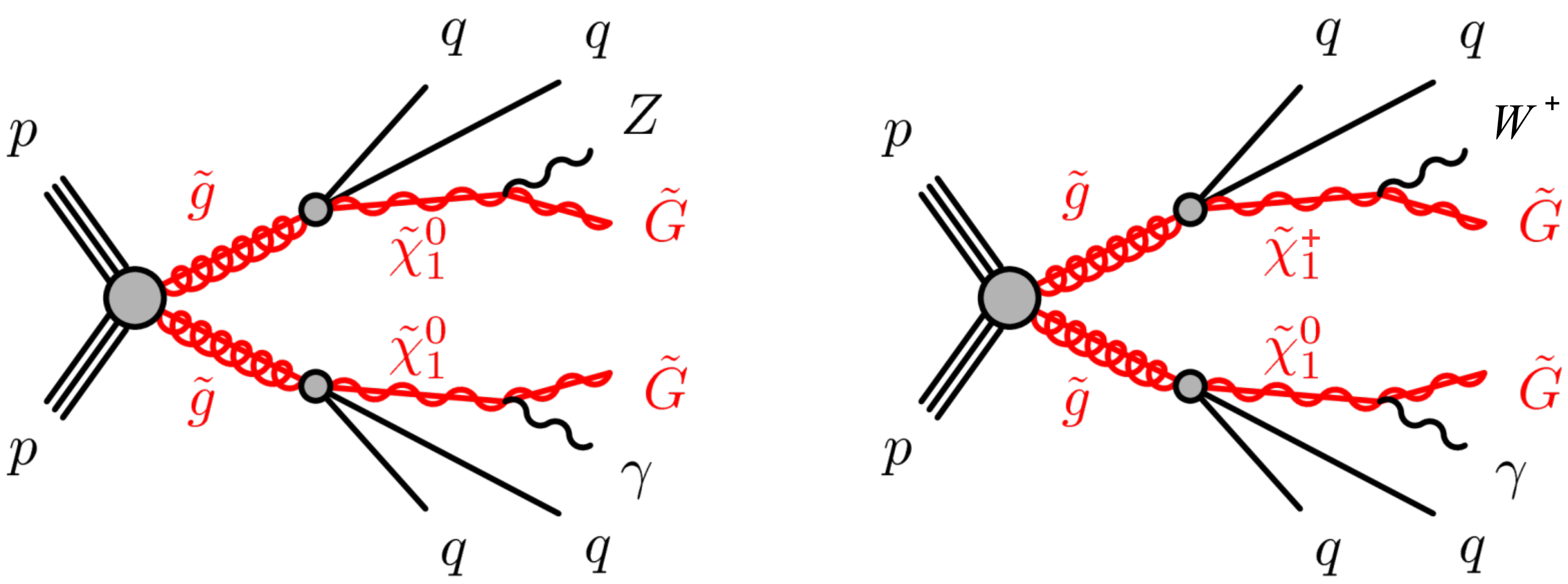


- Dedicated CMS search for decays with Higgs boson
- 1-2 large radius jets with double b-tag and large E_{Tmiss}
  - Backgrounds estimated from 0-tag and mass sidebands
- For models with energetic Higgs production, gluino mass limits between 1.8 and 2 TeV depending on BF

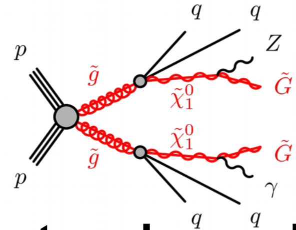


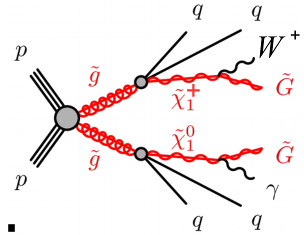


Decays with Photons

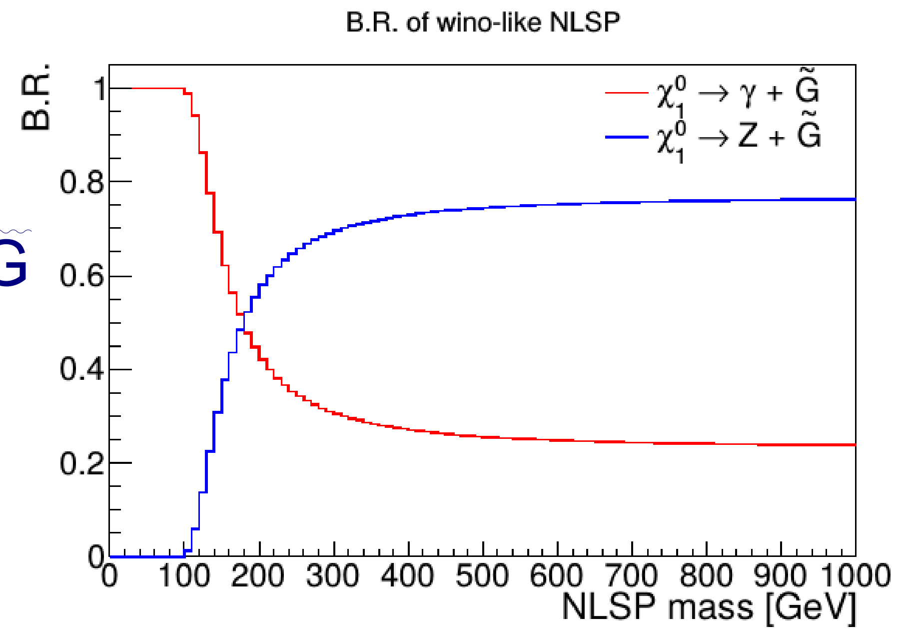


Decays to Photon(s)



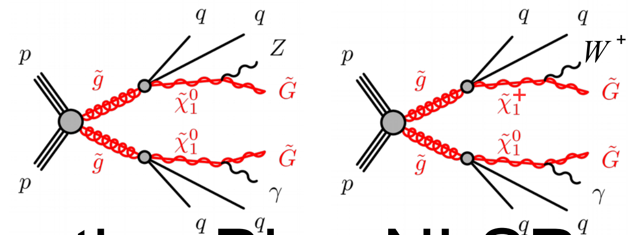


- With gauge-mediated supersymmetry breaking, Gravitino, $\tilde{G}$, becomes stable LSP with mass<<1 GeV
- $\tilde{\chi}_1^0$ becomes NLSP
- Decay depends on NLSP type
  - Bino-like: mostly $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$
  - Wino-like: mix of $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$ & $\tilde{\chi}_1^0 \rightarrow Z\tilde{G}$
  - Higgsino-bino mixture will give mix of $\tilde{\chi}_1 \rightarrow \gamma\tilde{G}$, $\tilde{\chi}_1 \rightarrow Z\tilde{G}$ & $\tilde{\chi}_1 \rightarrow h\tilde{G}$, depending on model parameters

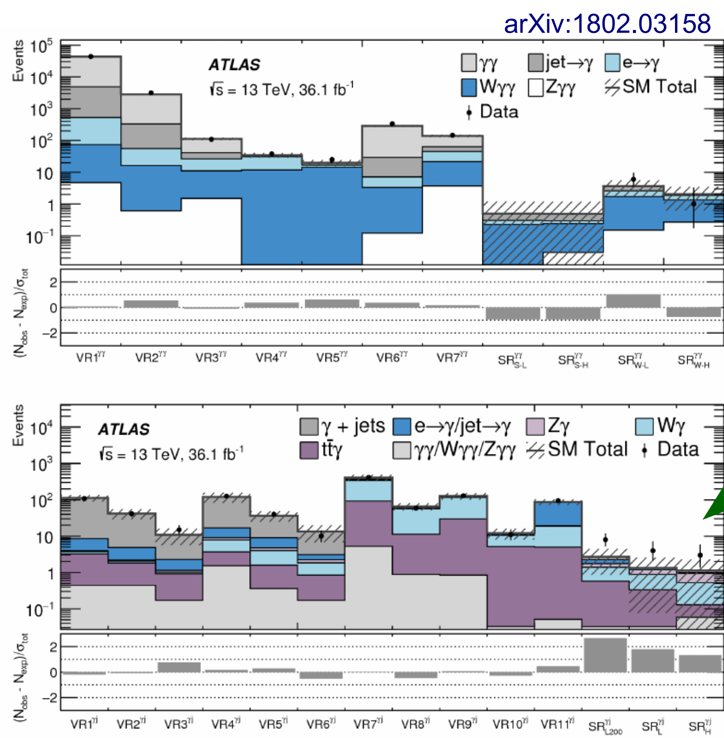


- Focus here on photonic decay mode

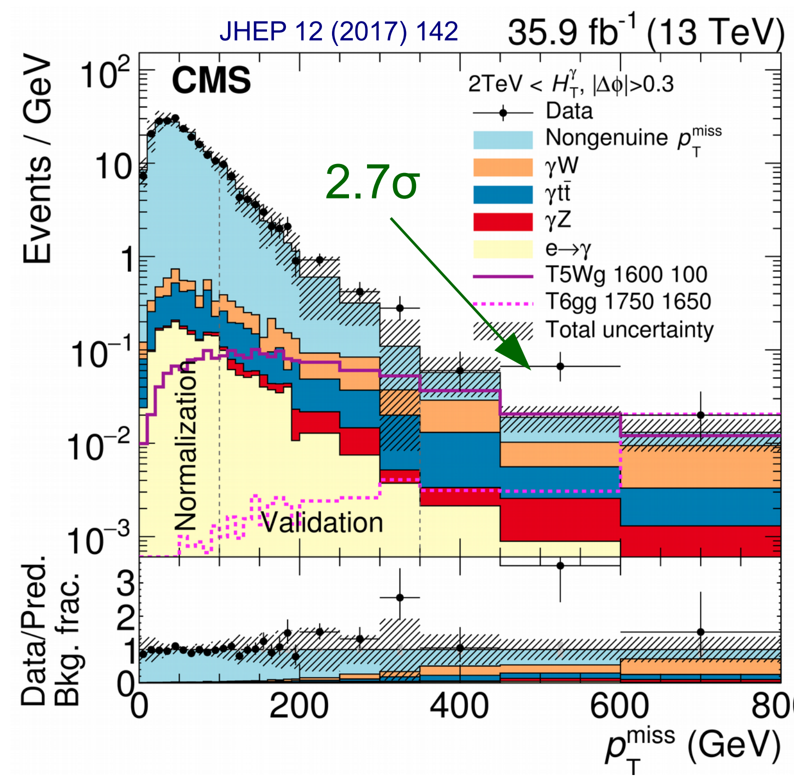
Photon Searches



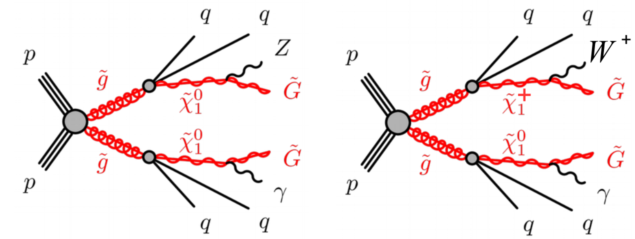
- ATLAS 2-photon+E_{Tmiss} search targeting Bino NLSP
  - 2x75 GeV photons and large $H_T = p_T^{\gamma} + \sum_{jets} p_T$
- ATLAS 1-photon+jets for Higgsino-Bino mixture NLSP
  - 3-5 jets and large $M_{eff} = H_T + E_{Tmiss}$
- CMS 1-photon+jets search targeting strong production
  - Six bins in E_{Tmiss} and H_T



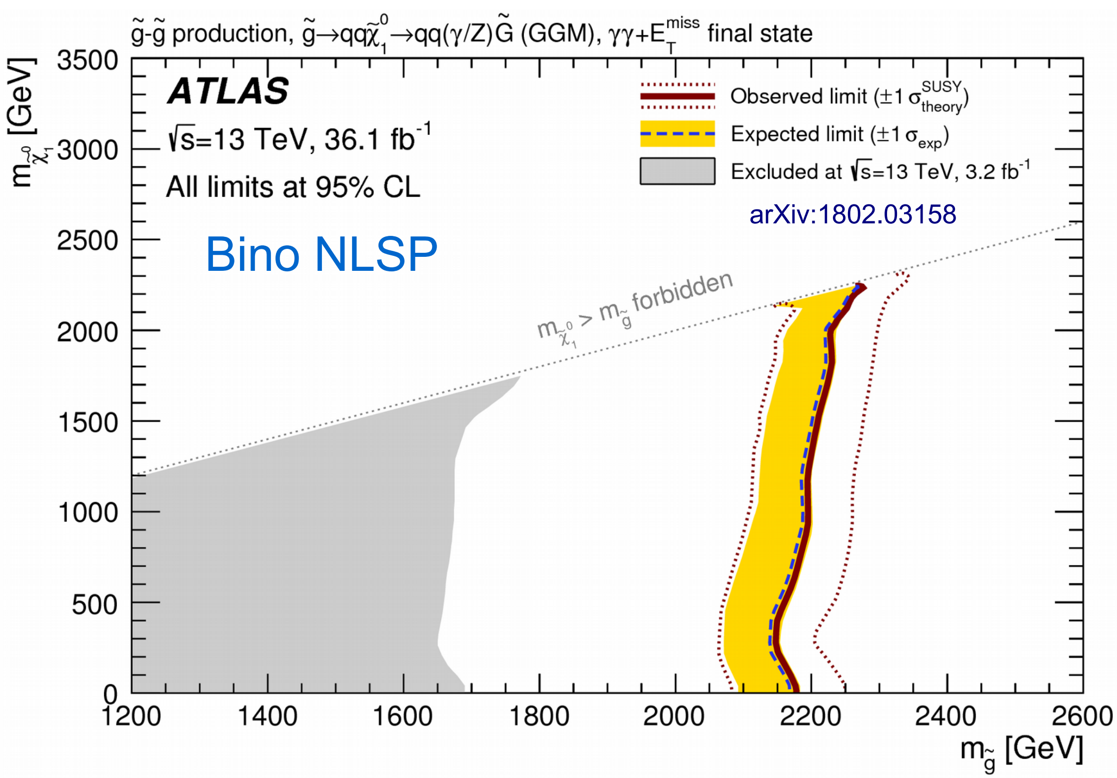
1.2-2.4σ, SRs not orthogonal

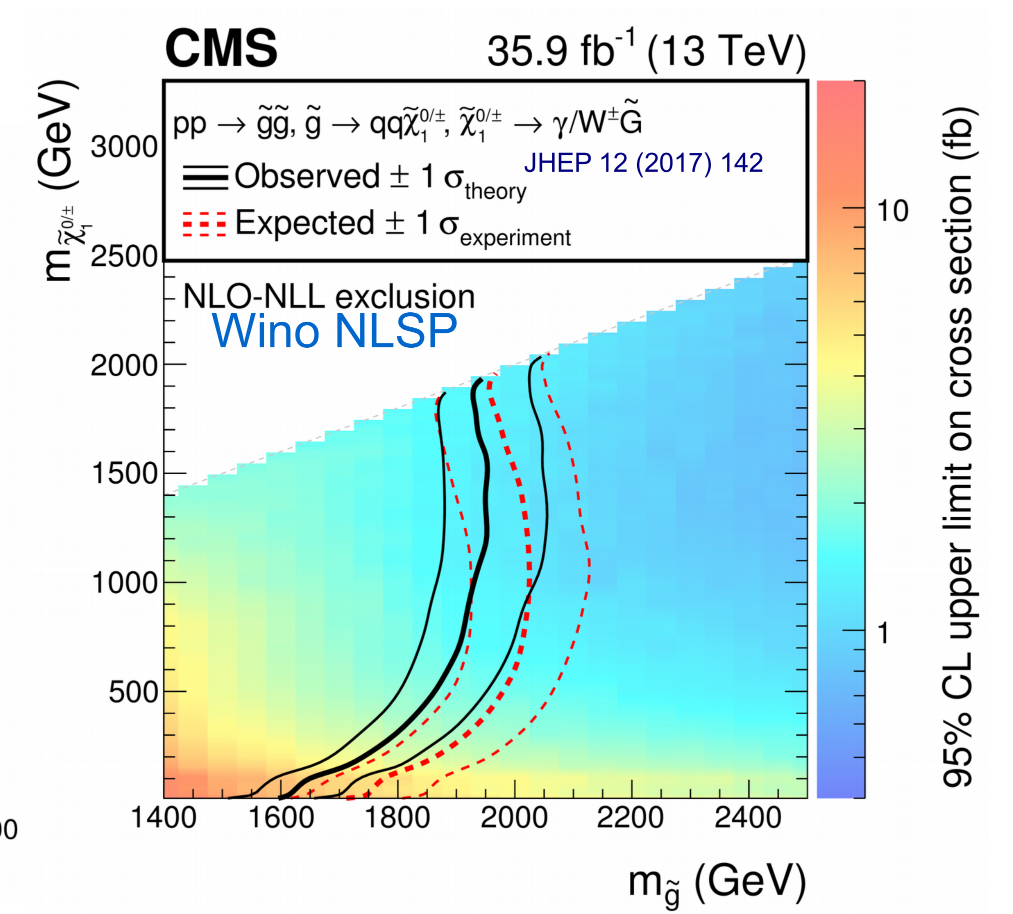


Limits on Gluinos

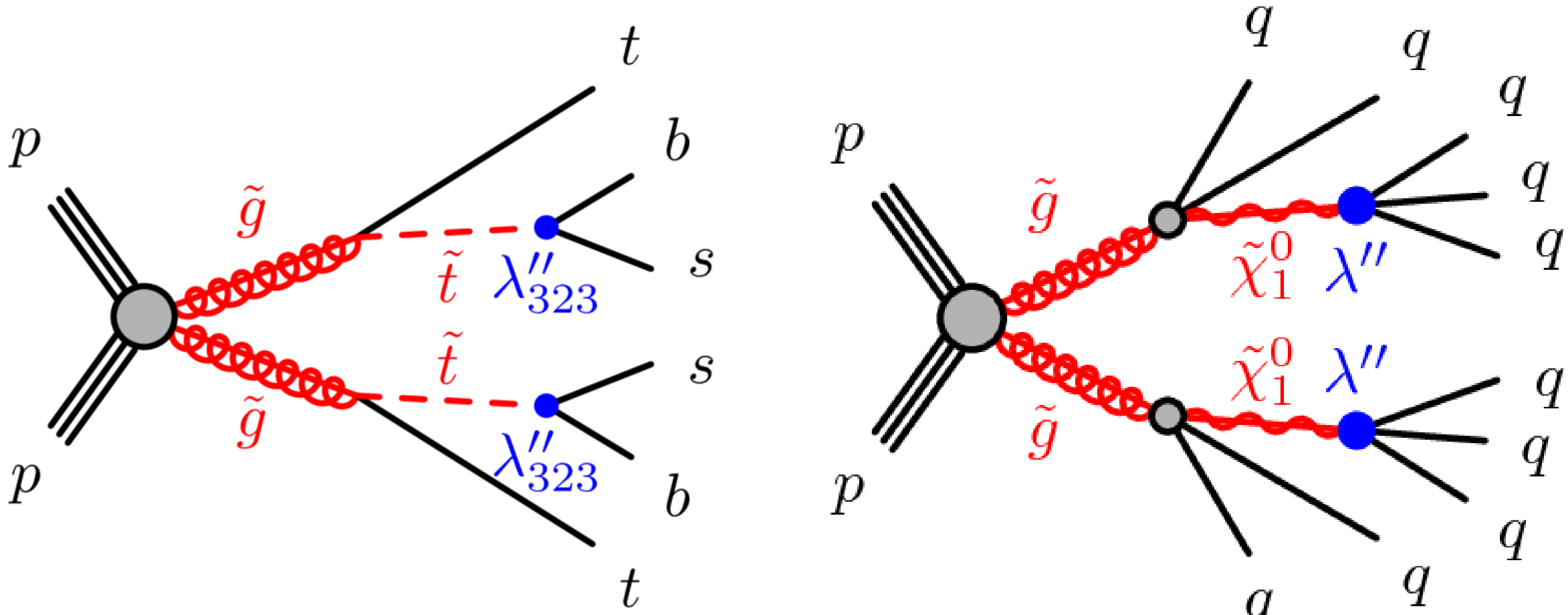


- Bino NLSP with mostly di-photon final state excluded for gluinos <2.15 TeV
- Wino NLSP and considered Bino-Higgsino NLSP excluded up to ~2 TeV for heavy NLSP, while for light NLSP, gluinos could be as light as 1.6 TeV





RPV Decays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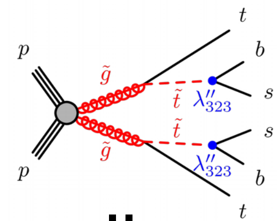
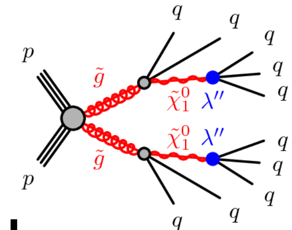
R-Parity Violation





- LSP is not stable if R-parity violation allowed
- RPV component of MSSM superpotential:

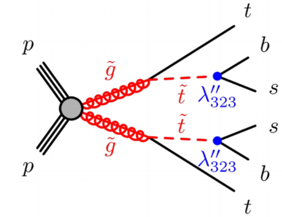
$$W_{\mathrm{RPV}} = \frac{1}{2}\lambda_{ijk}L_iL_j\bar{E}_k + \lambda'_{ijk}L_iQ_j\bar{D}_k + \frac{1}{2}\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k + \kappa_i L_i H_2$$

  - i,j and k are quark/lepton generations,
  - λ''_{ijk} is strength of the baryon-number violating terms giving rise to “UDD scenarios”

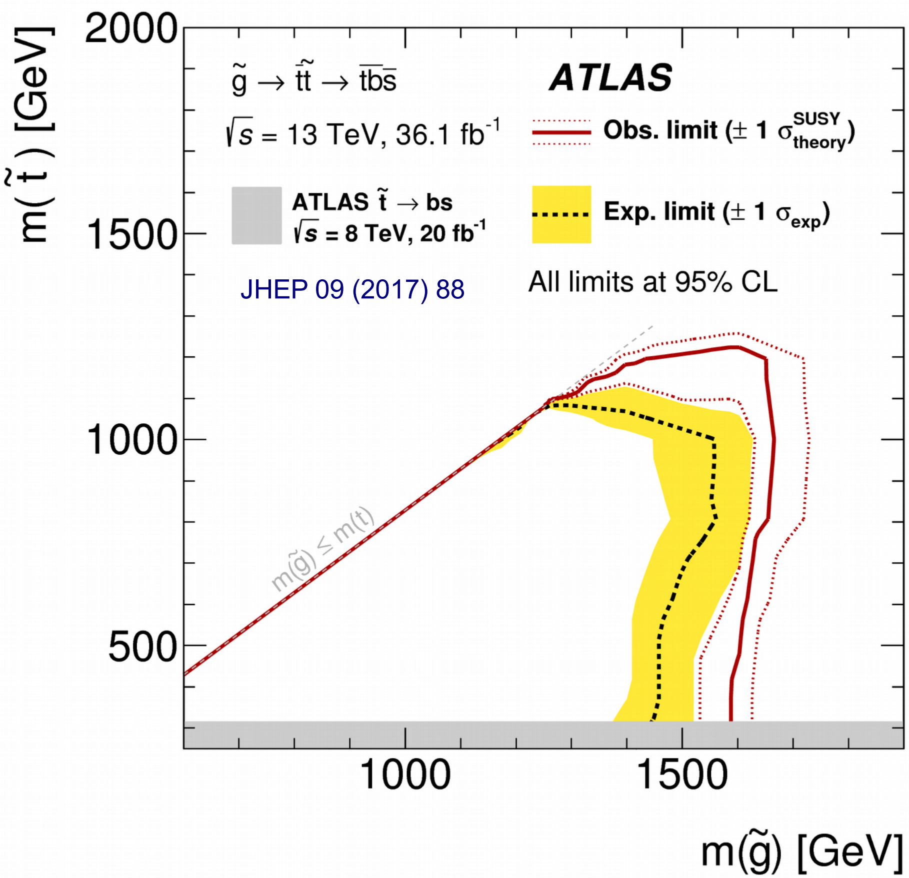
- If λ'' is small, LSP is long-lived
  - If very long-lived, it decays outside detectors → same as RPC
  - If inside the experiments → next talk
- For large λ'', LSP decays promptly
  - At maximal values even non-LSPs can decay promptly

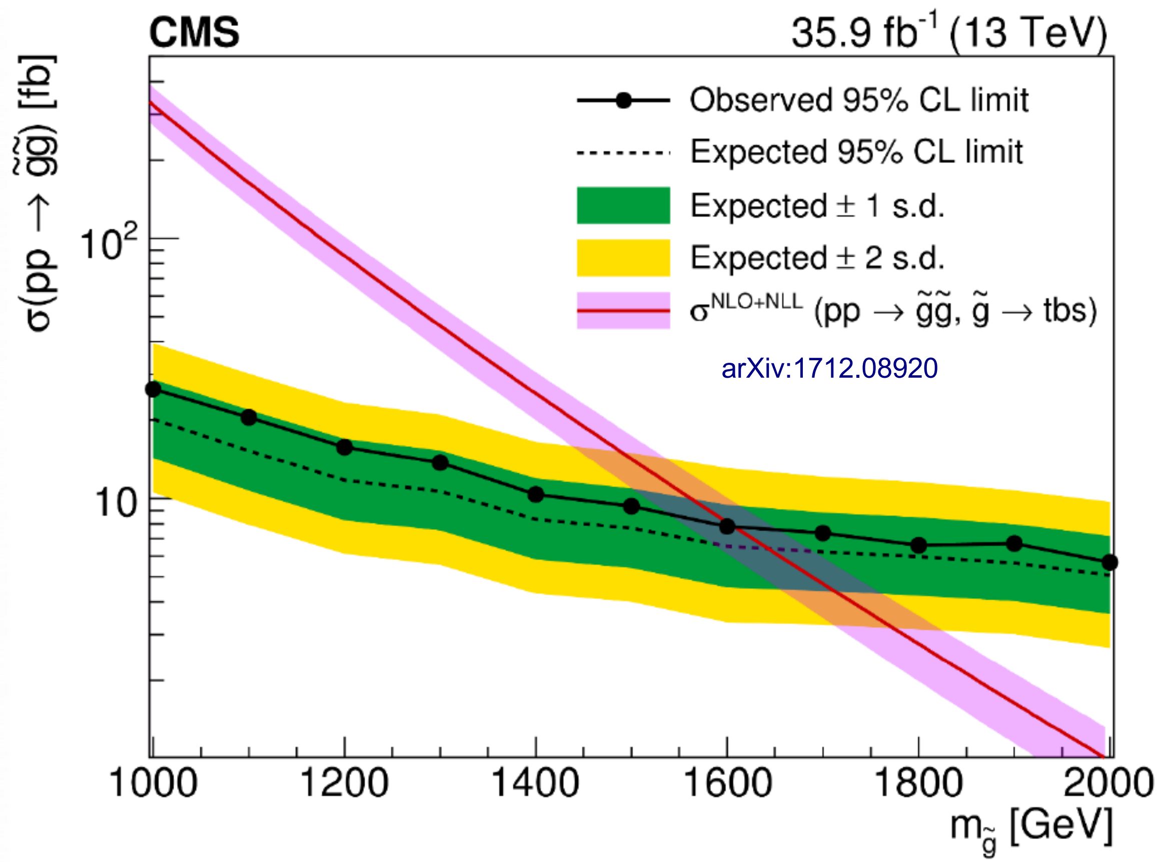
- Needs dedicated searches without E_{Tmiss} requirement

Gluino to *tbs* decays

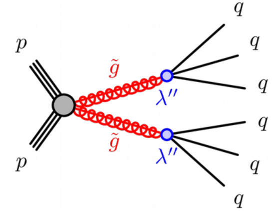
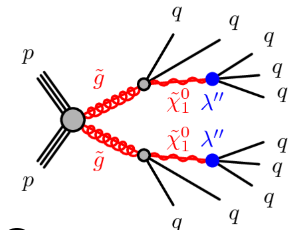


- In MFV SUSY, RPV coupling to 3rd gen quarks largest
  - Gluino can decay to tbs through (virtual) stop
- Best limits from 1-lepton+many jets+bjet searches
  - Data-driven background estimates due to high jet multiplicity
- Both ATLAS and CMS set gluino limits at ~1.6 TeV





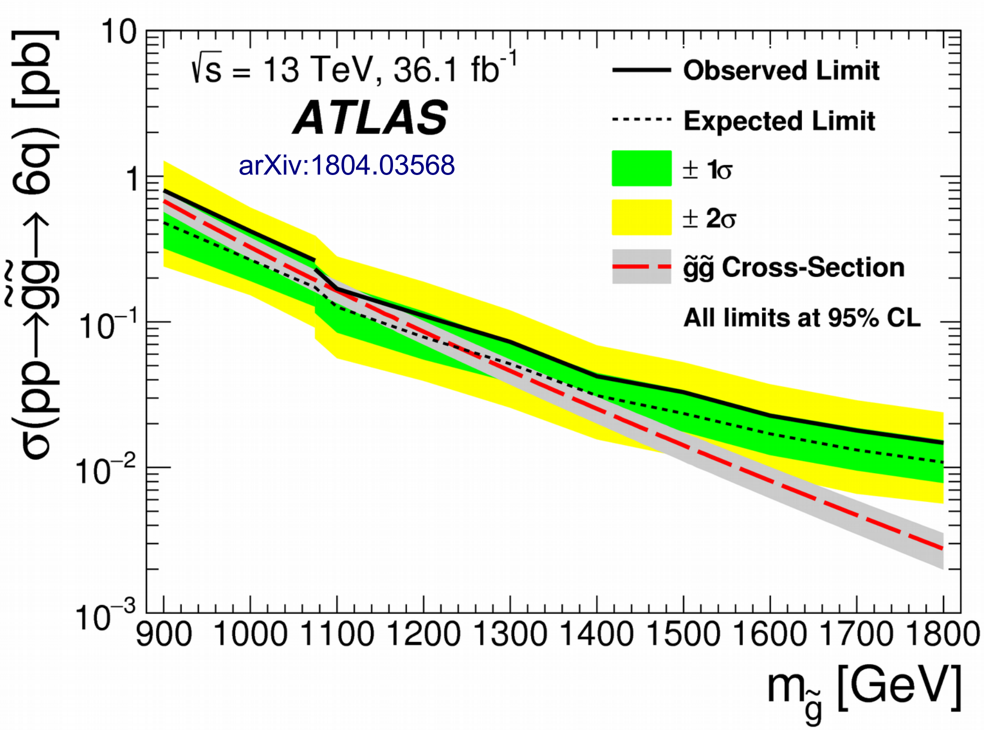
Generic UDD Search

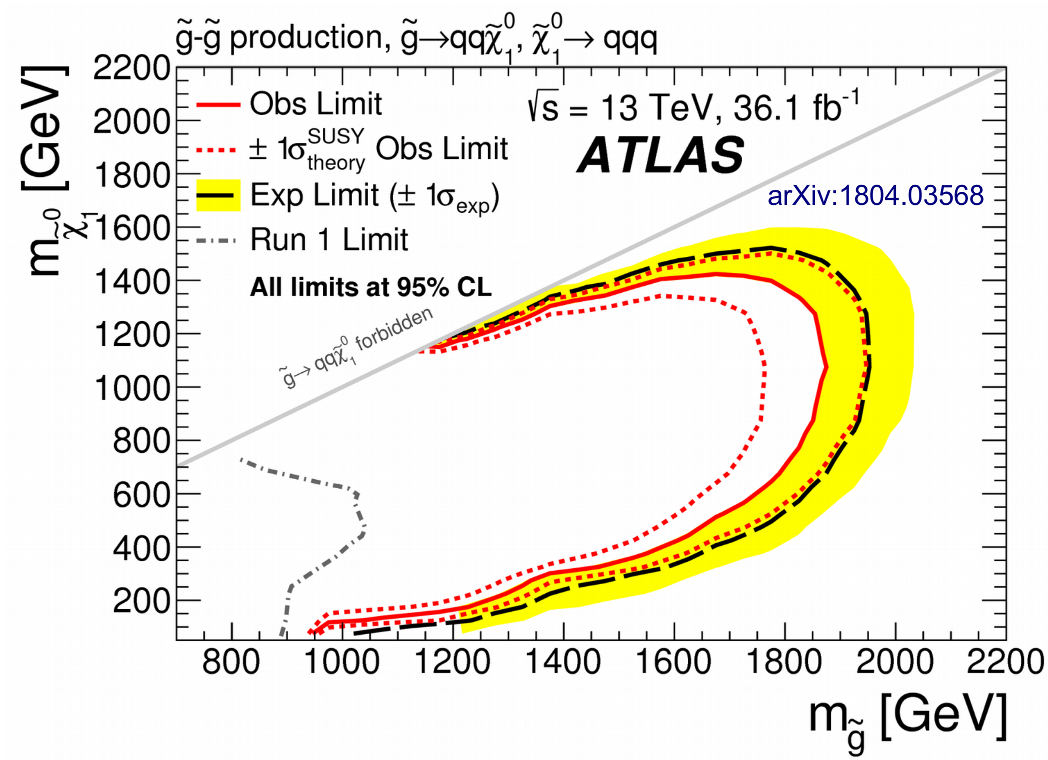



- Weaker limits if RPV coupling not mostly to 3rd gen
- ATLAS targeted search using R=1 anti-kt fat jets and b-tagging

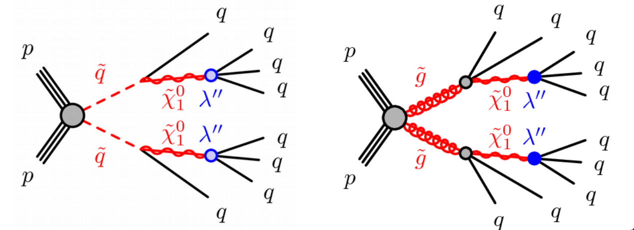
$$M_J^{\Sigma} = \sum_{\substack{p_T > 200\,\mathrm{GeV} \\ |\eta| \leq 2.0 \\ j=1-4}} m_{\mathrm{jet}}^{j}$$

  - Use $\Delta\eta_{12}=|\eta(j_1)-\eta(j_1)|$ and M_J^{Σ} to discriminate and estimate bkgd
- Assumes RPV coupling the same for all generations
  - Cannot exclude gluino below 1 TeV for either decays through $\tilde{\chi}_1^0$ or direct RPV decay of gluino to three quarks!

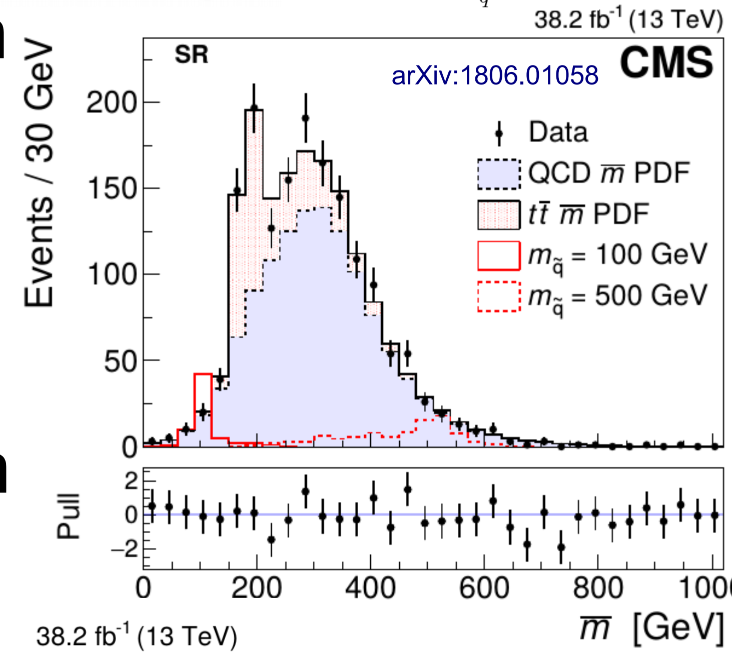


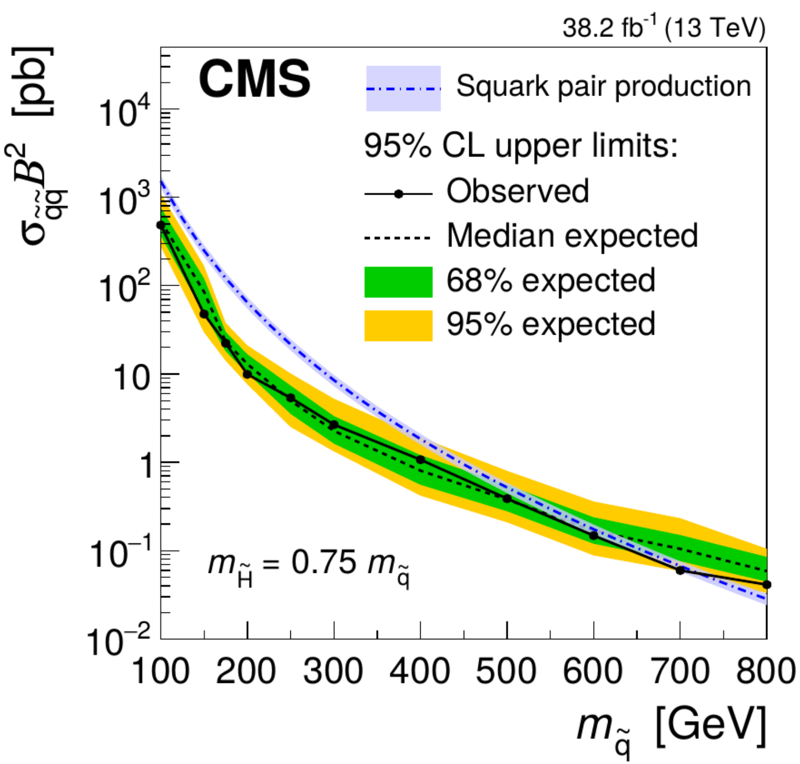


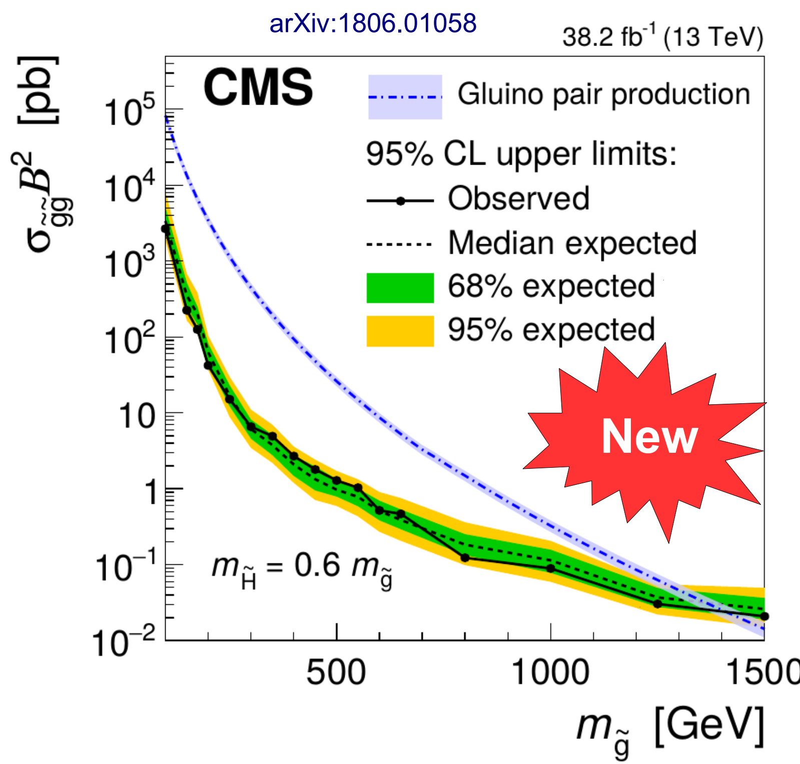
Generic UDD Search



- CMS uses di-fat jet (R=1.2) search to target 4-5 quark decays
- Suppresses QCD and top pair background by n-subjettiness and fat jet mass asymmetry
- QCD background uses data-driven templates





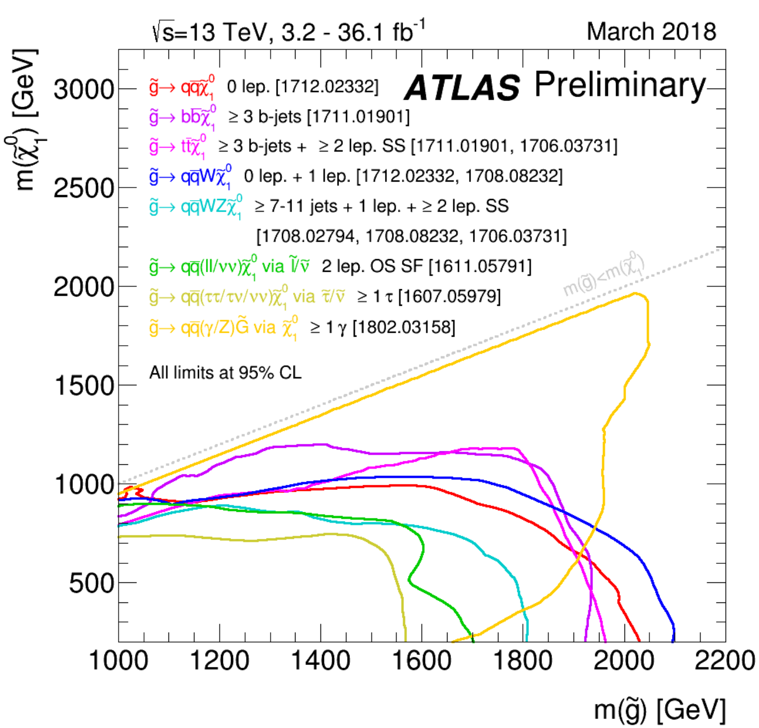


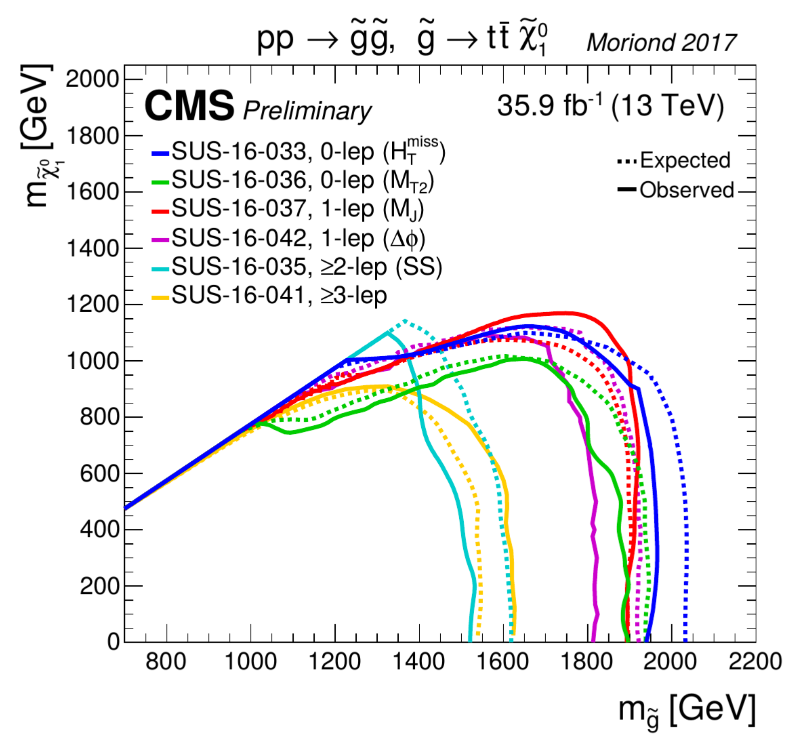
Excludes $\tilde{q}$ and $\tilde{g}$ down to 100 GeV (the LEP limit)
Limit mass to 720 GeV (one $\tilde{q}$) and 1.41 TeV ($\tilde{g}$)

Summary

Summary

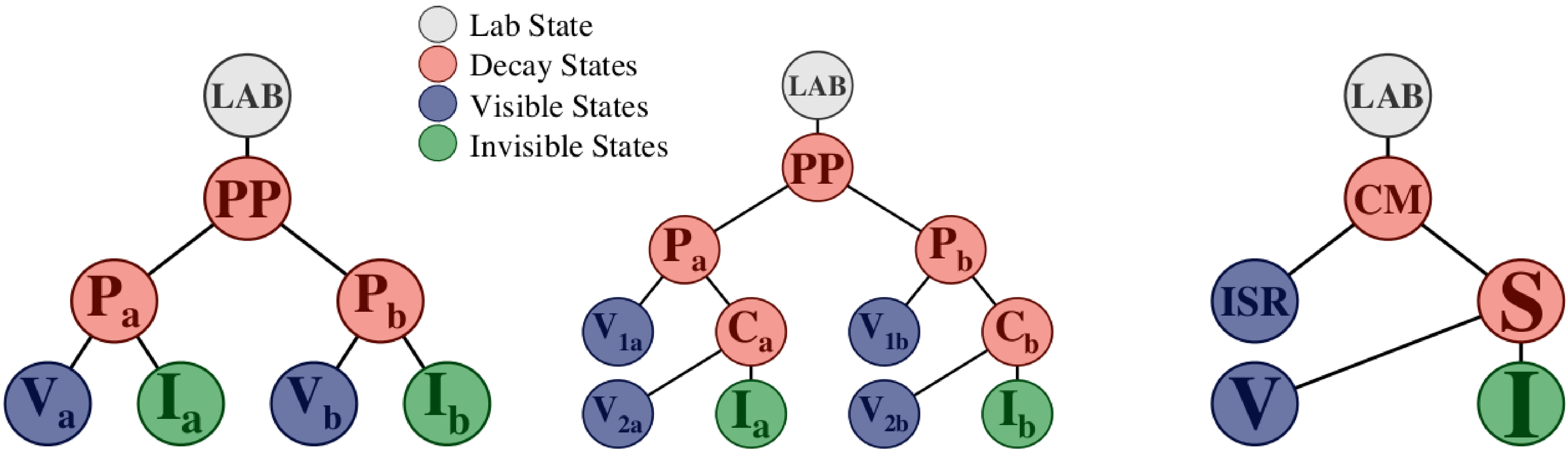
- Extensive search for squarks of gluinos in ATLAS&CMS
  - Wide range of possible decay signatures considered
- Typically set gluino mass limits 1.8-2.0 TeV
  - Weaker limits for mixtures of decays
  - Much weaker for RPV decays (could be as light as 1 TeV)
- Squark mass limits typically 1.5-1.8 TeV
  - Assumes degenerate light-flavour squarks and R-parity conserved
  - Otherwise can be below 1 TeV





Backup

Kinematic Variables



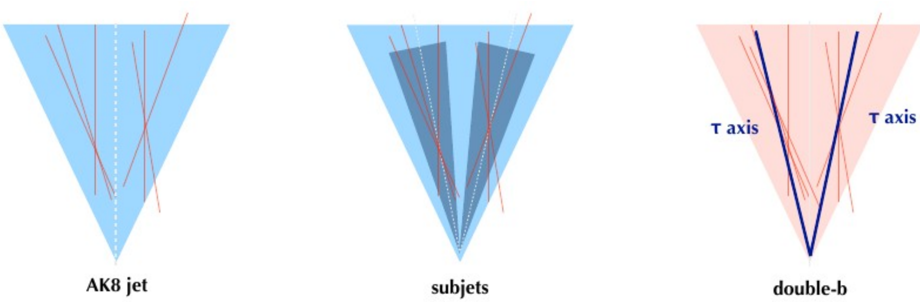
$$M_{\mathrm{T2}} = \min_{\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}X(1)} + \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}X(2)} = \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}} \left[\max\left(M_{\mathrm{T}}^{(1)}, M_{\mathrm{T}}^{(2)} \right) \right]$$

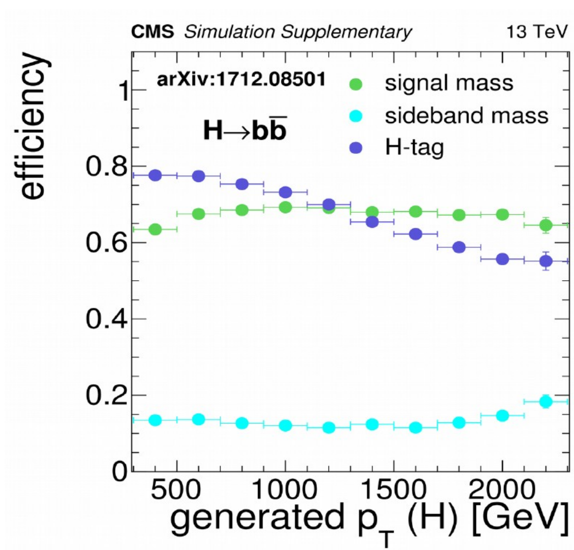
$$\alpha_T = \frac{E_T^{j_2}}{M_T} \underset{m\to 0}{=} \sqrt{\frac{E_{T,2}}{2E_{T,1}(1-\cos\phi)}} \to \frac{H_T - \Delta H_T}{2\sqrt{H_T^2 - \not{H}_T^2}}$$

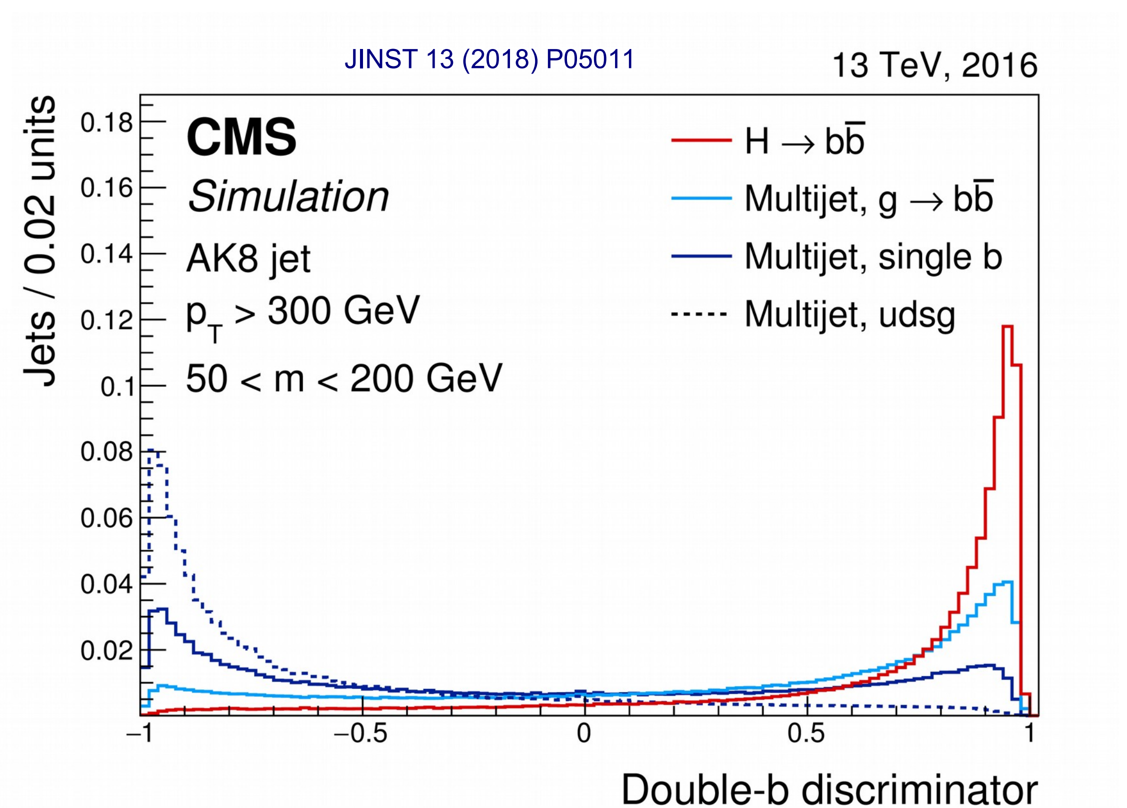
$$\not{H}_T = |\sum_{i\in \mathrm{jet}} \vec{p}_T^{\,j_i}|$$

Double b-tagging

- Dedicated BDT trained for b-tagging highly boosted H→bb fat jets
- Finds subjets in anti-kt 0.8 jet to resolve decay chain with two separate b-hadrons
  - Calculate b-tagging sensitive variables with respect to subjet axis
- Includes correlations between subjet variables



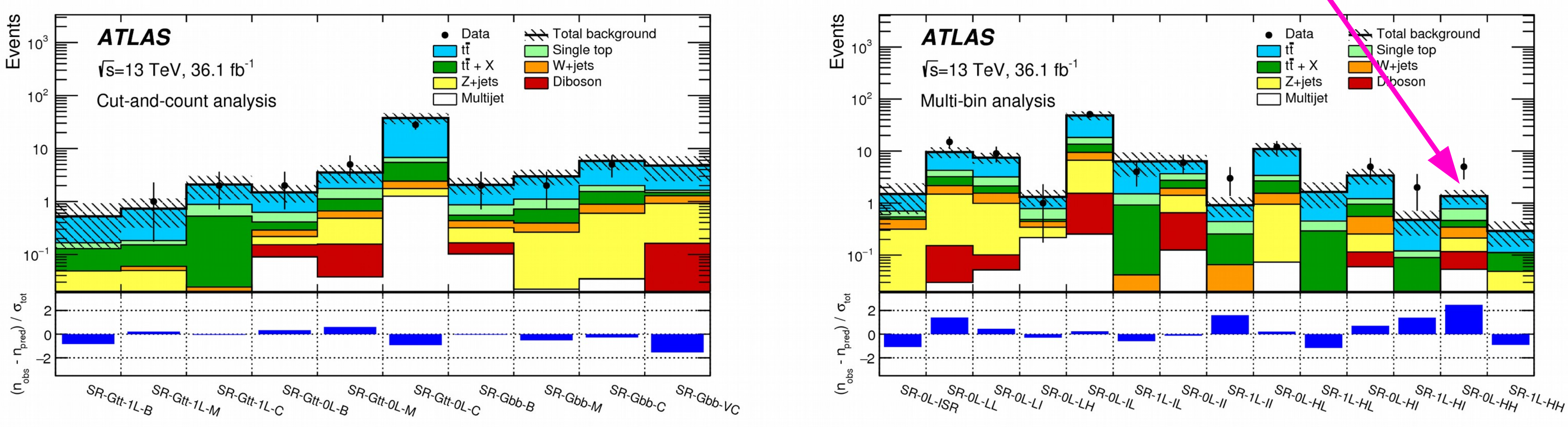




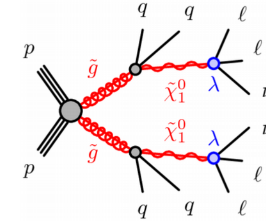
Multi-b Analysis Excess

- Small excess in 0-lepton signal region with high m_{eff} (>2500 GeV) and N_{jets}>6
  - No excess in corresponding 1-lepton SR

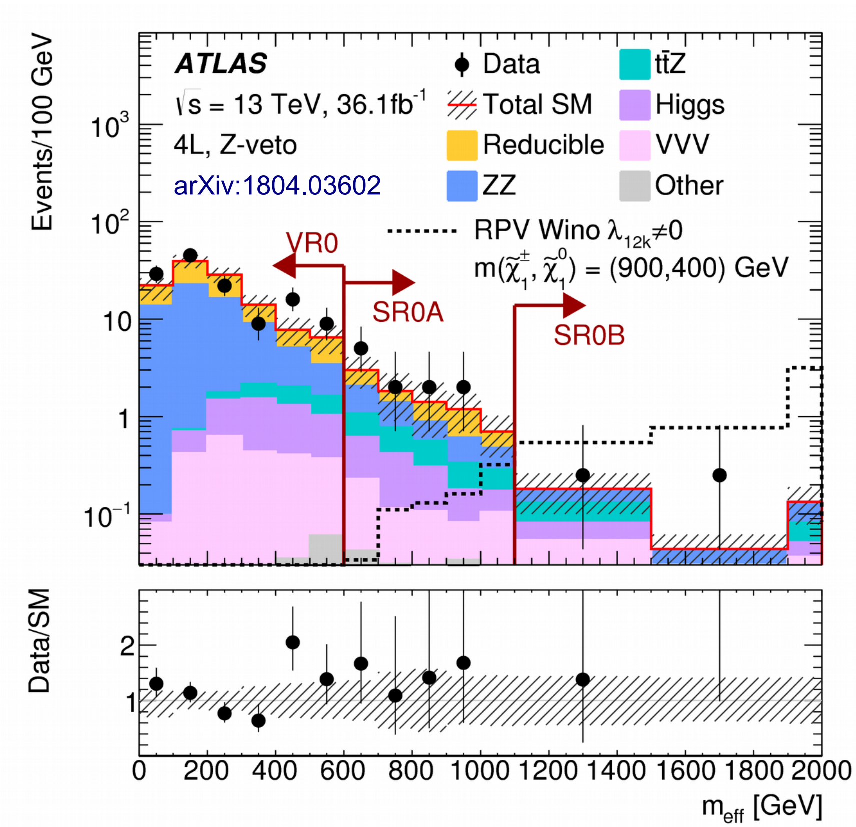
5 obs / ~1.5 exp, 2.3σ local

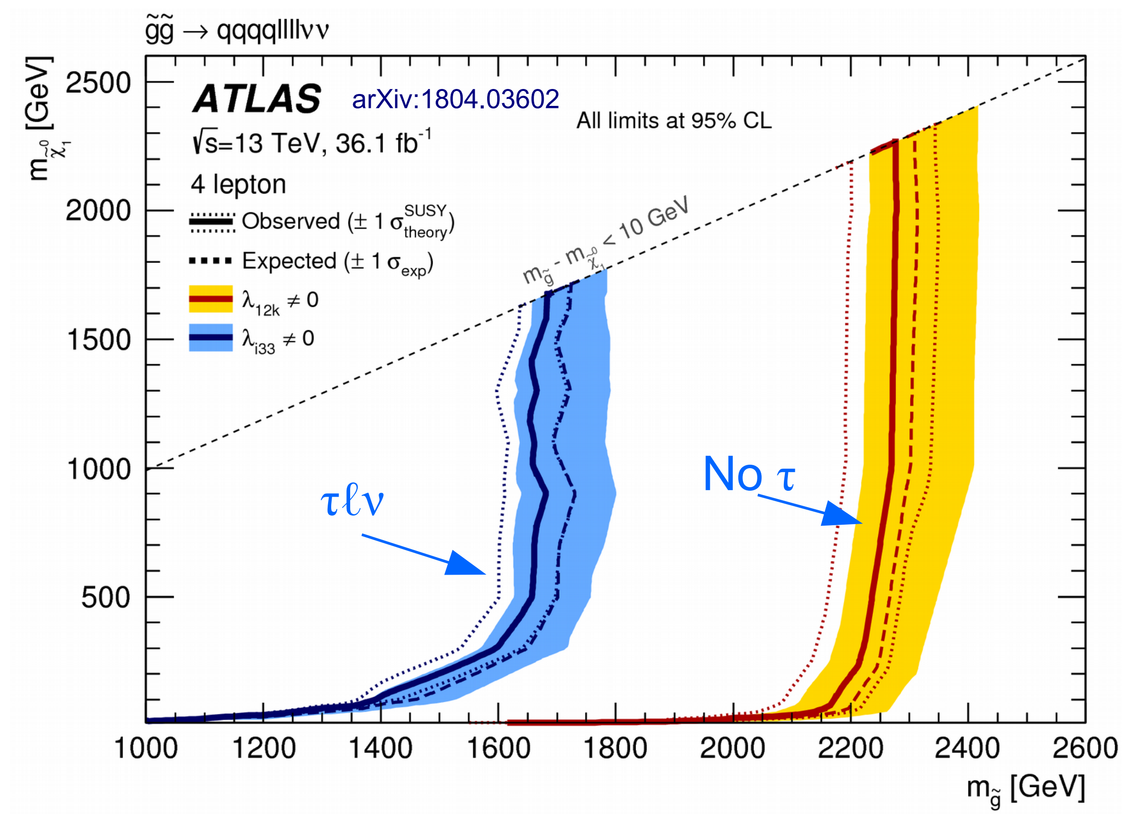


LLE Scenarios

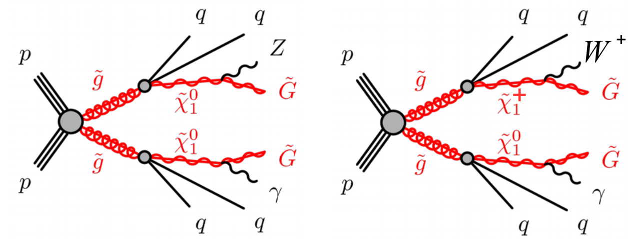


- Lepton-number violating RPV also considered
  - In simplest scenario have $\tilde{\chi}_1^0 \rightarrow \gamma \ell \ell' \nu$
- Strong sensitivity from ATLAS 4-lepton (e,μ,τ) search
  - 4 isolation leptons (0-2τ_{had}) and large $m_{eff} = \sum_\ell p_T + \sum_{jets} p_T + E_{Tmiss}$
- Depending on RPV coupling to τ and $\tilde{\chi}_1^0$ mass, gluino mass limit between 1.4 and 2.2 TeV

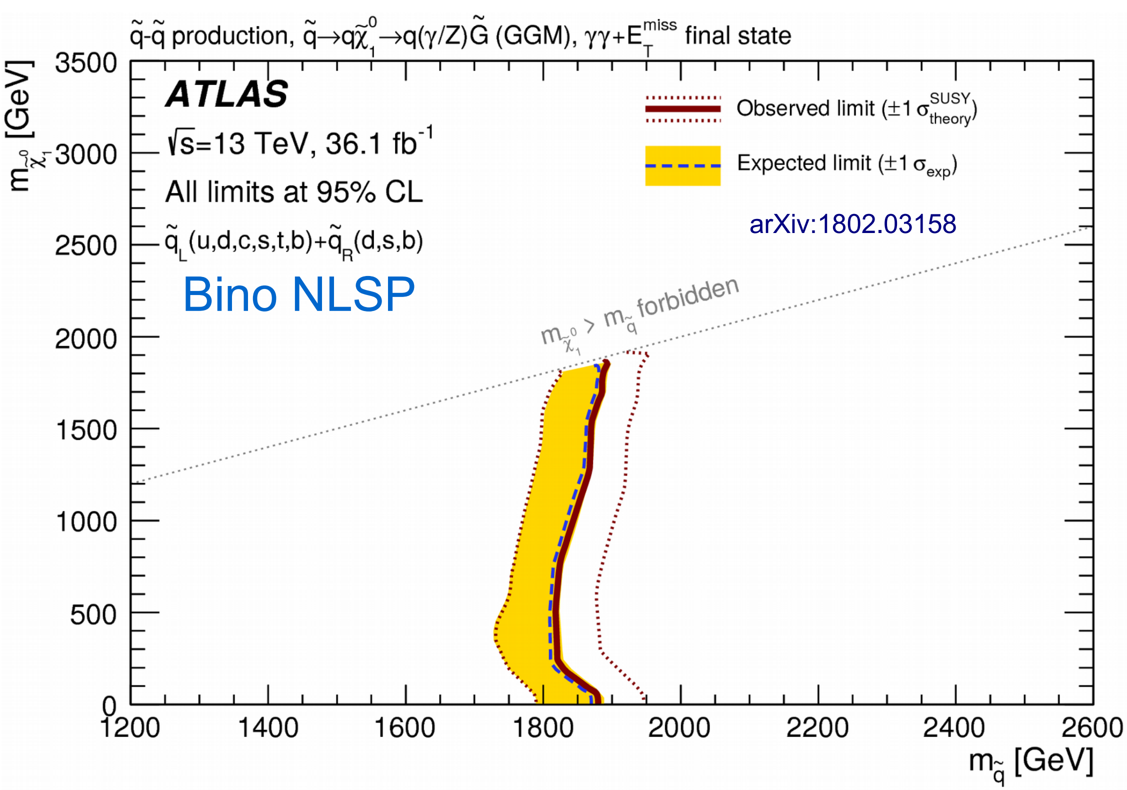


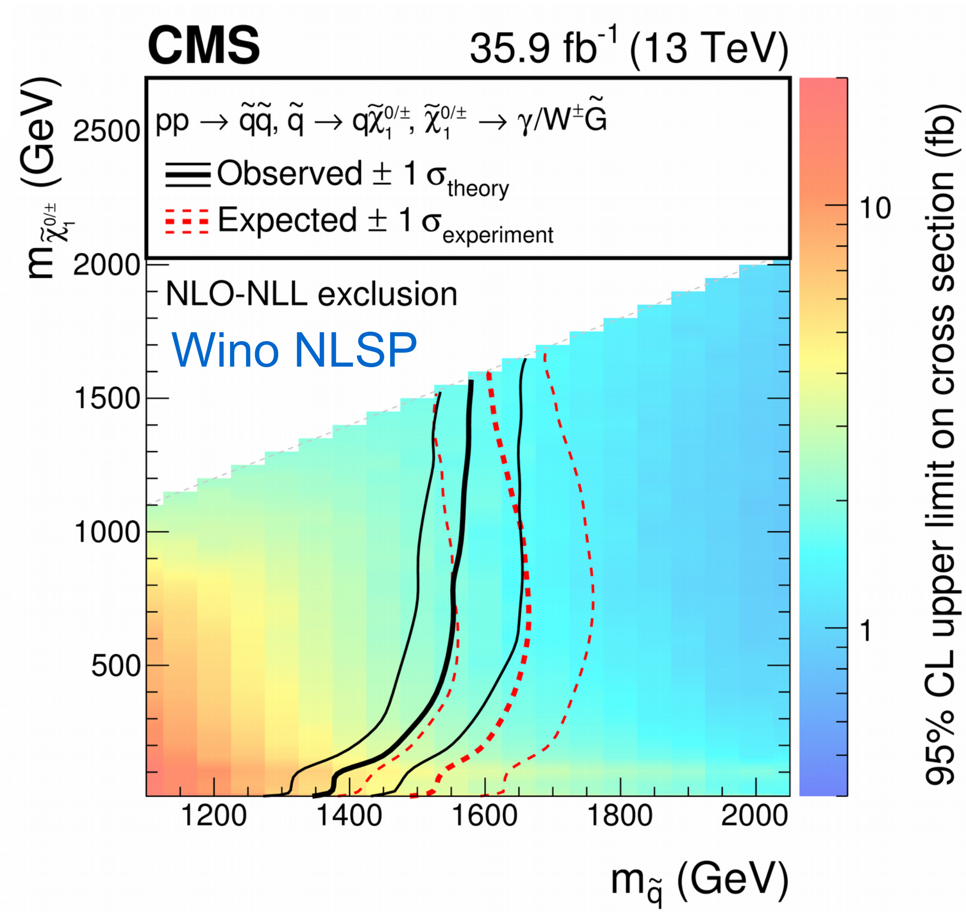


Limits on Squarks



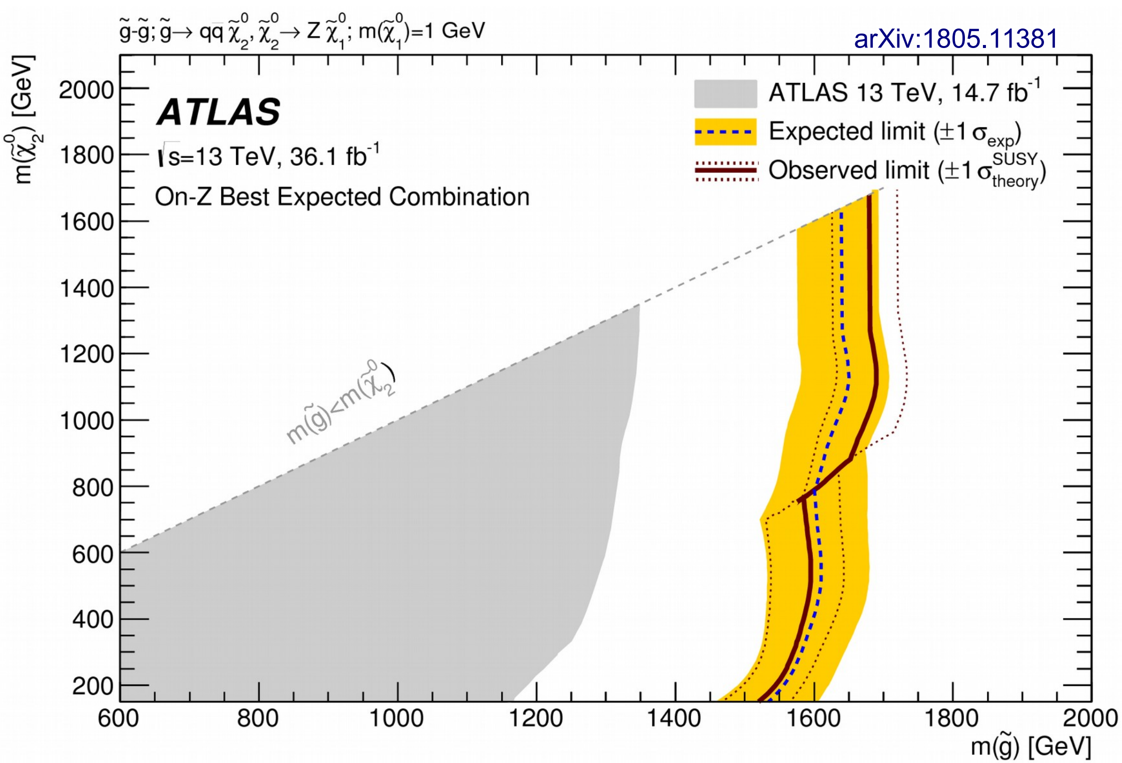
- Again strong limits for Bino NLSP $m(\tilde{q})>1.8$ TeV using ATLAS 2-photon analysis
- For Wino NLSP mass limit can be below 1.4 TeV for light NLSP





Gravitino through Z

- Search for on-shell Z set
  limits on GMSB models with decays through Z
  - For 100% BF to Z exclude models with gluino below 1.5 TeV
  - Inclusive jet+E_{TMiss} set limits at 1.8 TeV for light neutralino



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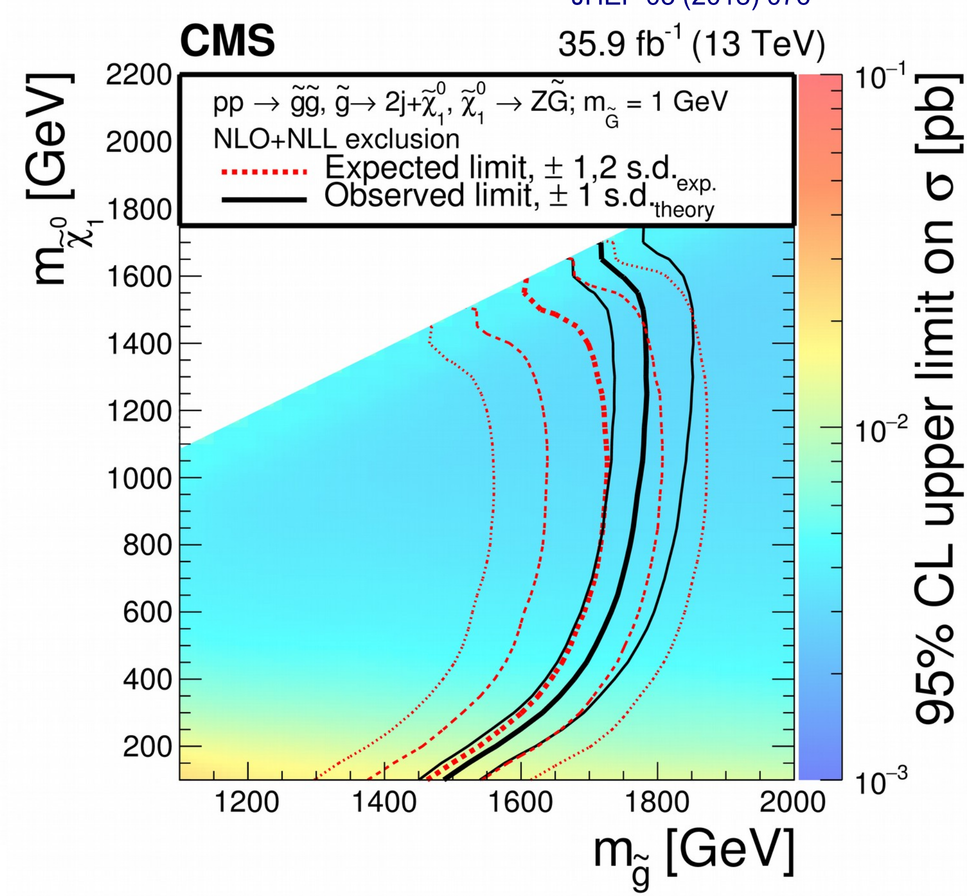

Generality of Limits

- At end of Run-1 did extensive comparison of simplified model limits and exclusion in pMSSM-19 scan
  - Weaker limits, but not excessively so
  - However, no RPV or GMSB type models in scan