Inclusive searches for squarks and gluinos with the ATLAS detector

Boosting the sensitivity with the **full 2015/2016 13 TeV dataset**

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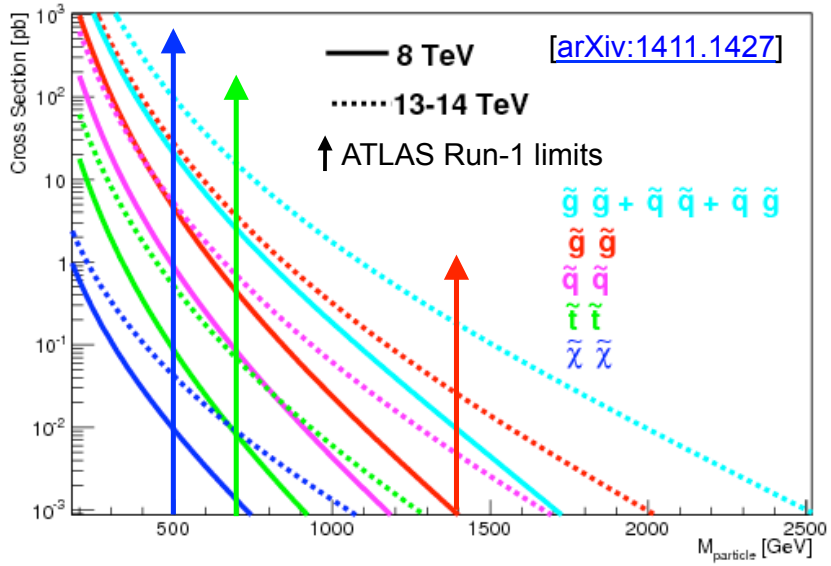
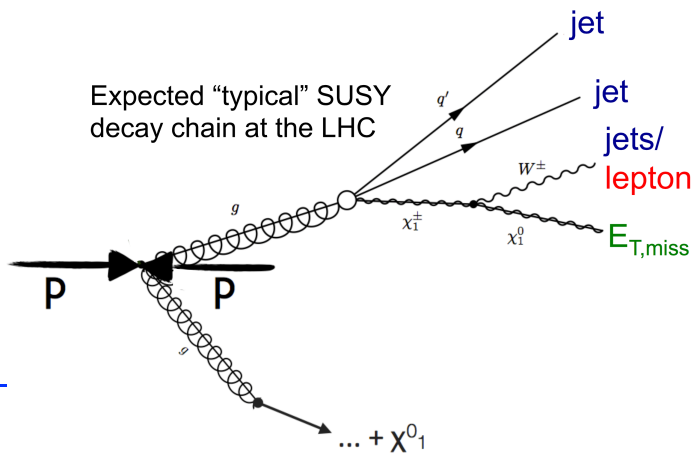
Introduction

- If **gluinos** and **squarks** (1st and 2nd generation) exist at LHC-accessible energies and R-parity is conserved:
  - Pair-production with large cross-sections compared to 3rd generation squarks and electro-weak production
  - Direct or cascade decays to the stable lightest SUSY particle (LSP).
- Experimental signature of inclusive searches (depending on mass spectra):
  - Significant missing transverse momentum (E_T^{miss})
  - Multiple high-p_T jets
  - Other objects, e.g. leptons
- Extensive LHC search program did not lead to any significant signs of SUSY
- This presentation covers **5 searches** using the **full 2015 + 2016 ATLAS dataset** @ 13 TeV (~36 fb^{-1}) in the following final states:
  - 0-ℓ + 2-6 jets + $E_{T,miss}$: ATLAS-CONF-2017-022
  - 0-ℓ + 7-11 jets + $E_{T,miss}$: arXiv:1708.02794
  - 0/1-ℓ + 3-4 b-jets + $E_{T,miss}$: ATLAS-CONF-2017-021
  - 2-ℓ (same-sign) or 3-ℓ + jets + $E_{T,miss}$: arXiv:1706.03731
  - 1-ℓ + jets + $E_{T,miss}$: arXiv:1708.08232





Blueprint of Inclusive SUSY searches

① Build signal regions (**SR**s) based on requirements on signal / background discriminating variables to target specific SUSY event topologies. Optimised for discovery & exclusion.

② Determine Standard Model background in the SRs:

Irreducible Backgrounds

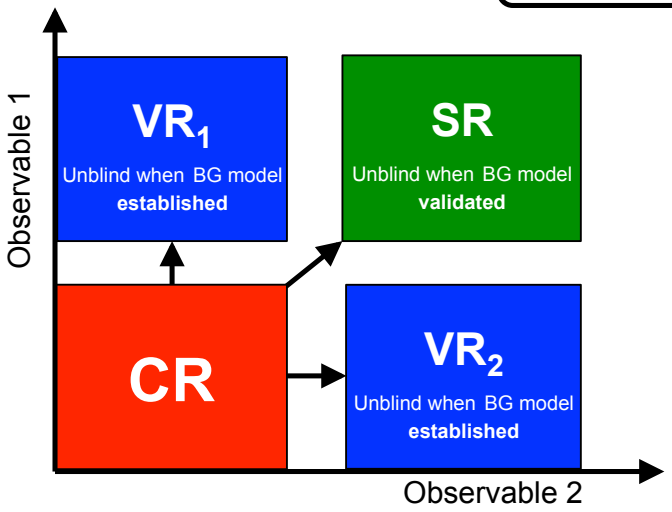
- Dominant processes:
  - MC normalised to data in process-enhanced control regions (**CR**s)
  - Extrapolation to validation regions (**VR**s) & **SR**s
- Subdominant processes: Pure MC predictions

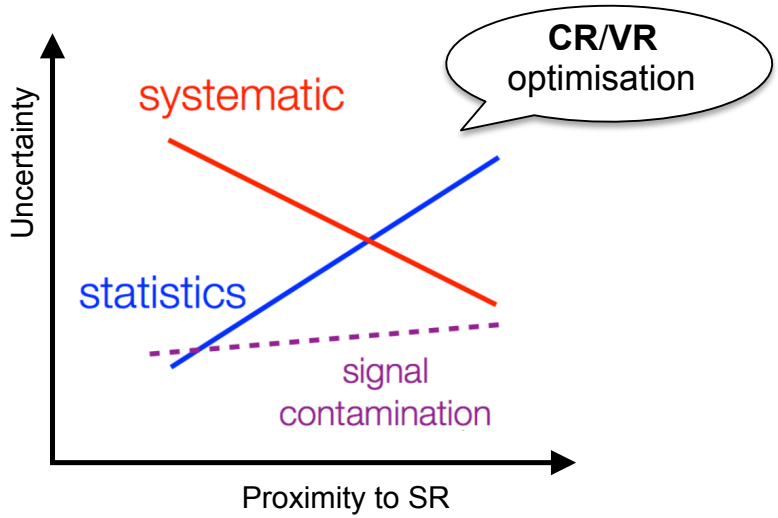
Reducible Backgrounds

- Fake $E_{T,miss}$, fake leptons backgrounds: Pure data-driven estimates
- Validation in **VR**s

Combined Fit

- Simultaneous fit of all components in **CR**s (and **SR**s for exclusion)





Inclusive 0-ℓ Search: Overview

- Final state: **2-6 Jets + E_{Tmiss} (no leptons!)**

$\mathbf{H_T} = \Sigma p_T^{jet}$,
$\mathbf{m_{eff}} = H_T + E_{T,miss}$

m_{eff}-based Analysis Stream

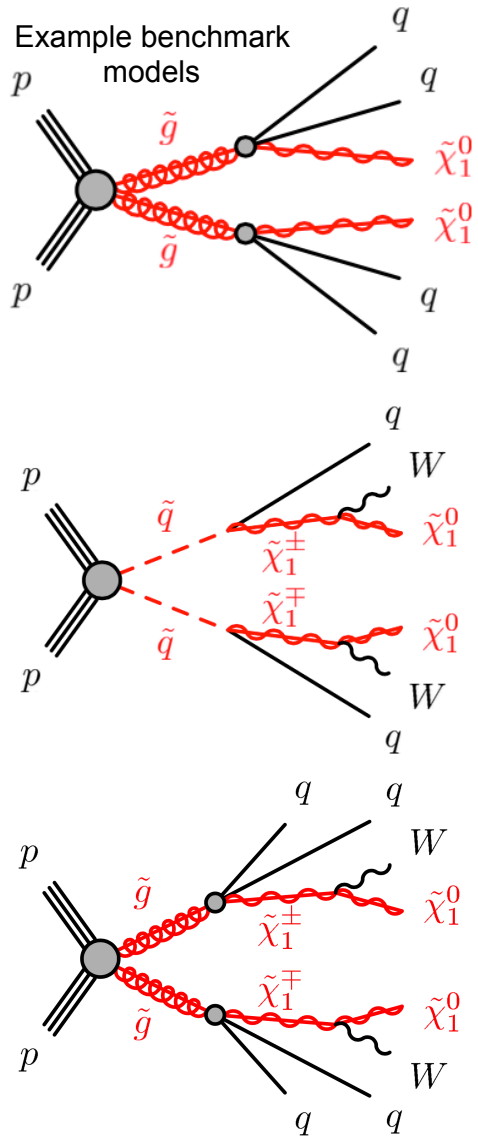
- **24 inclusive SRs** using the *effective mass* as final discriminant:
  - ≥2/3 jet regions → **direct** squark decays
  - ≥4/5 jet regions → **direct** gluino decays
  - ≥5/6 jet regions → gluino/squark decays **via χ±** with W bosons
  - ≥2 **large-R** jets → gluino/squark decays with **boosted** W bosons
  - → Scans **of m_{eff}, $E_{T,miss}/m_{eff}$ or $E_{T,miss}/\sqrt{H_T}$** to cover variety of mass spectra

not orthogonal but complementary

Recursive Jigsaw Analysis Stream

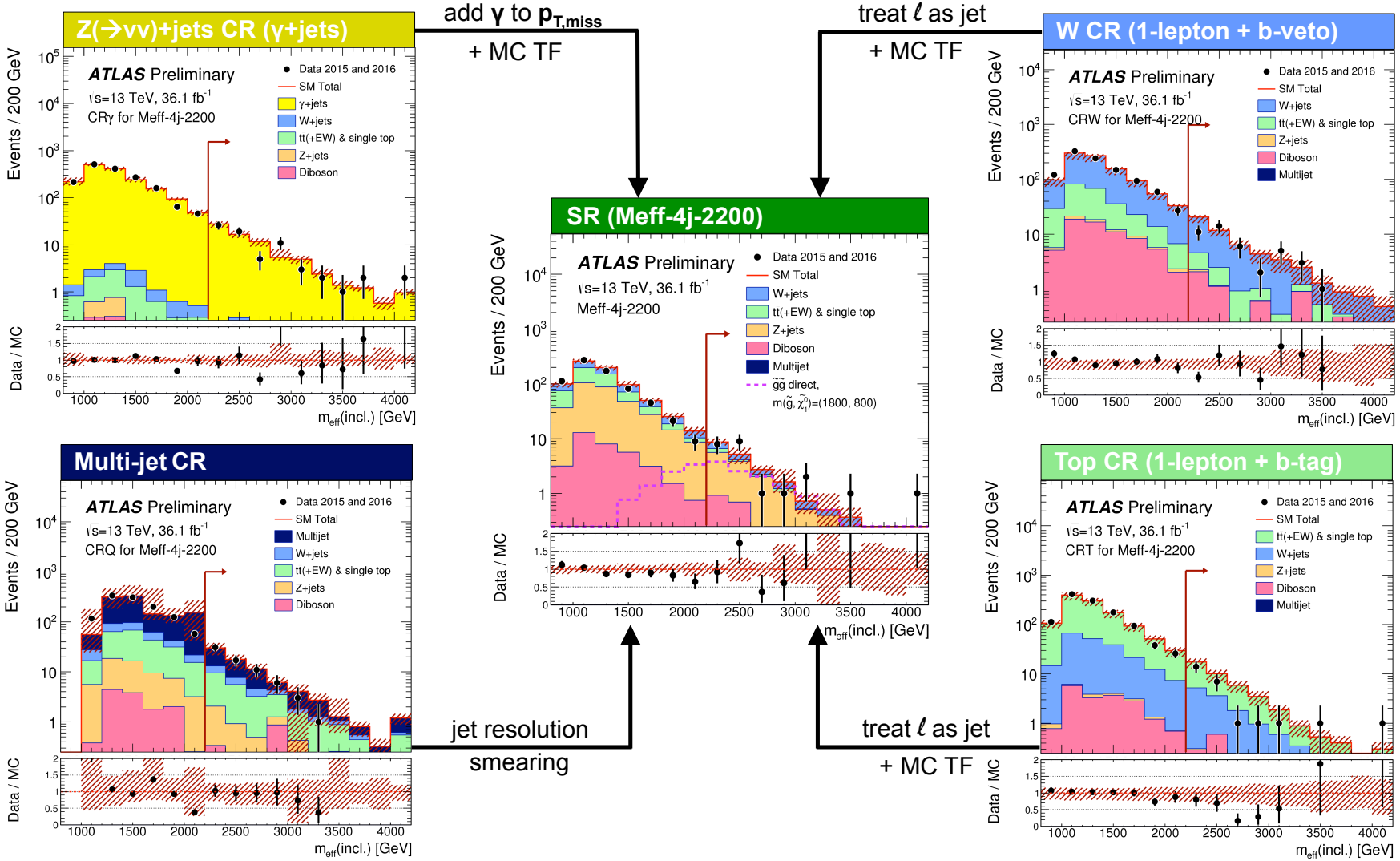
- **19 inclusive SRs** based on the *recursive jigsaw* reconstruction technique:
  - Impose specific decay hypothesis on event and assign four-momenta to invisible states.
  - Compute kinematic variables in the frames of the intermediate hypothesized particles

Example benchmark models



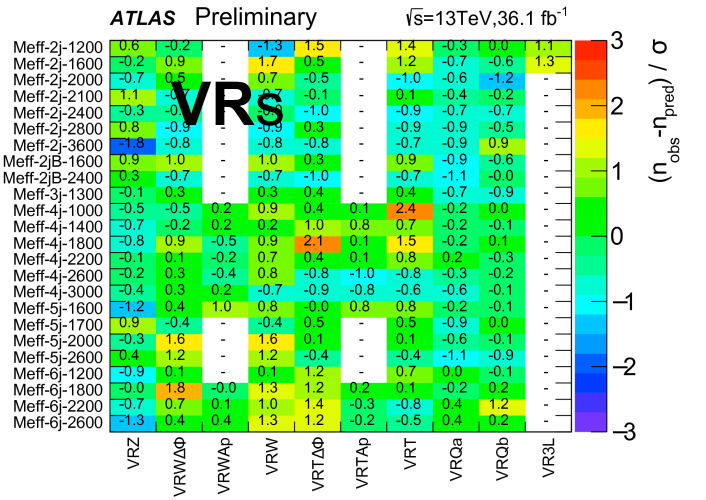
Inclusive 0-ℓ Search: Backgrounds

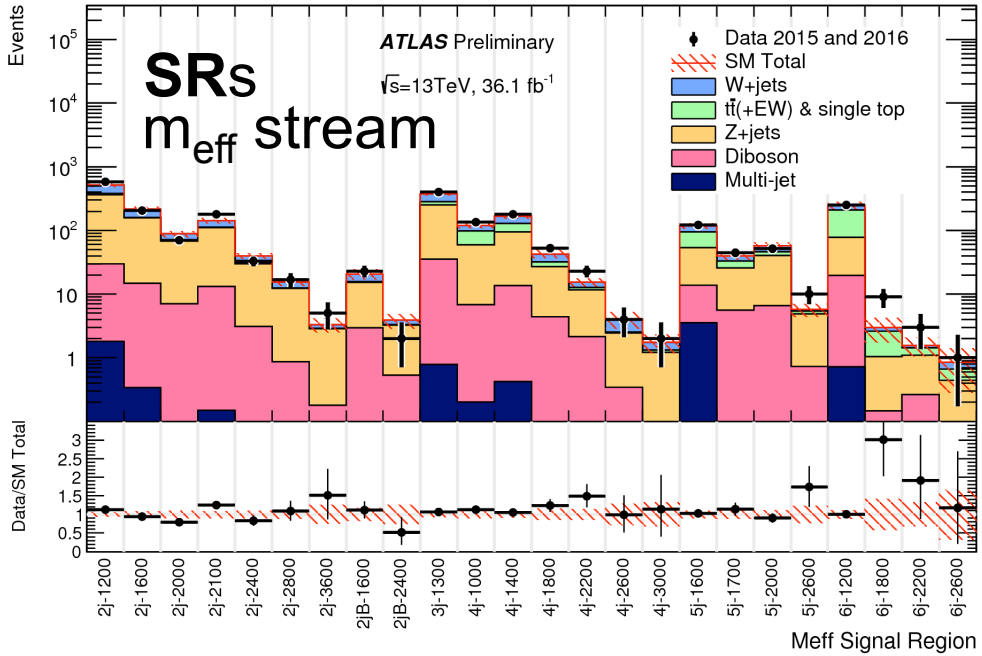
- Dominant backgrounds estimated in 4 CRs for each SR → extrapolation to VRs/SRs with transfer factors (TFs)

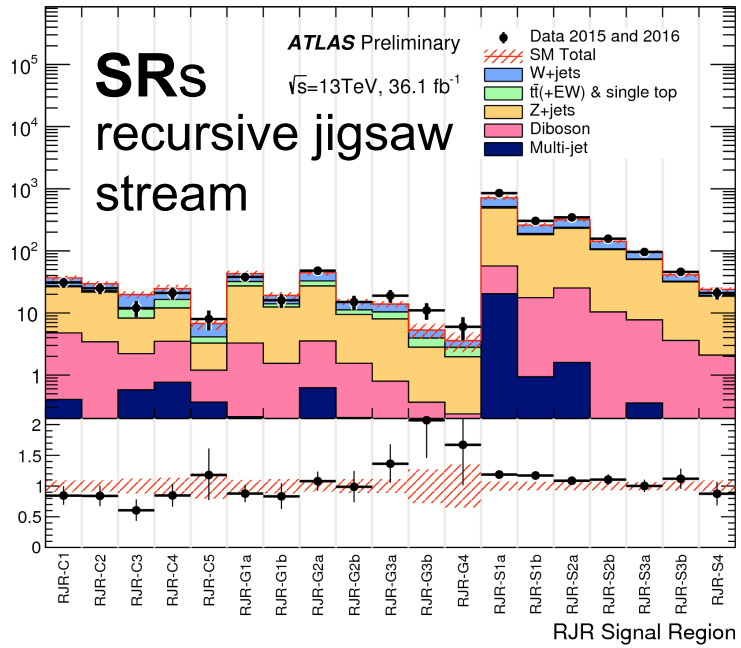


Inclusive 0-ℓ Search: Results

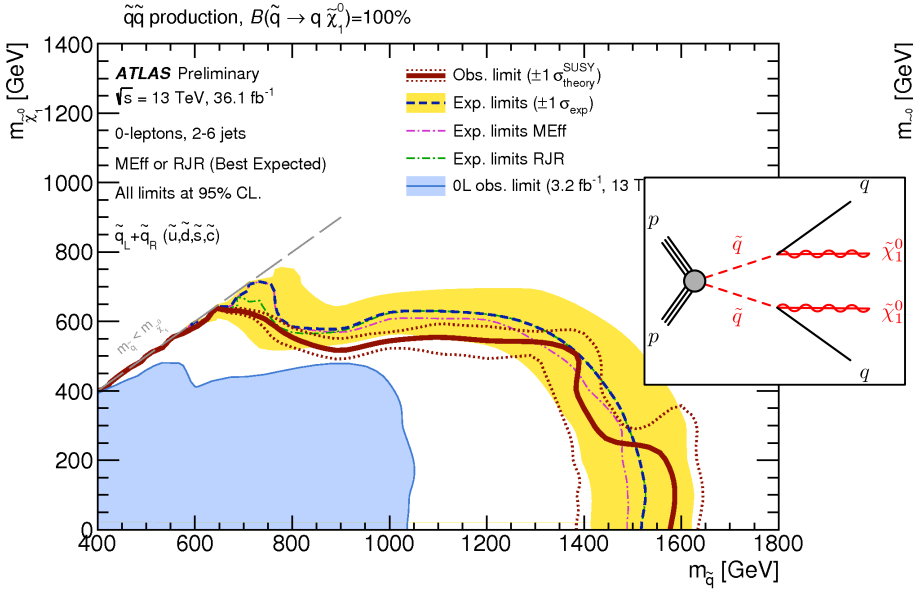
- Background estimates validated in **large amount of validations regions** for the major background processes
- **No significant deviations** from the Standard Model expectation in both streams

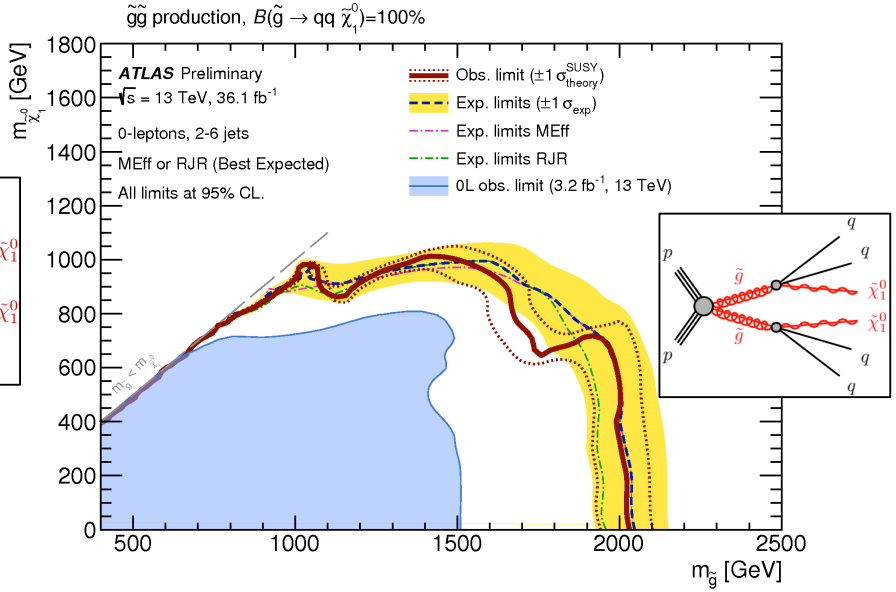


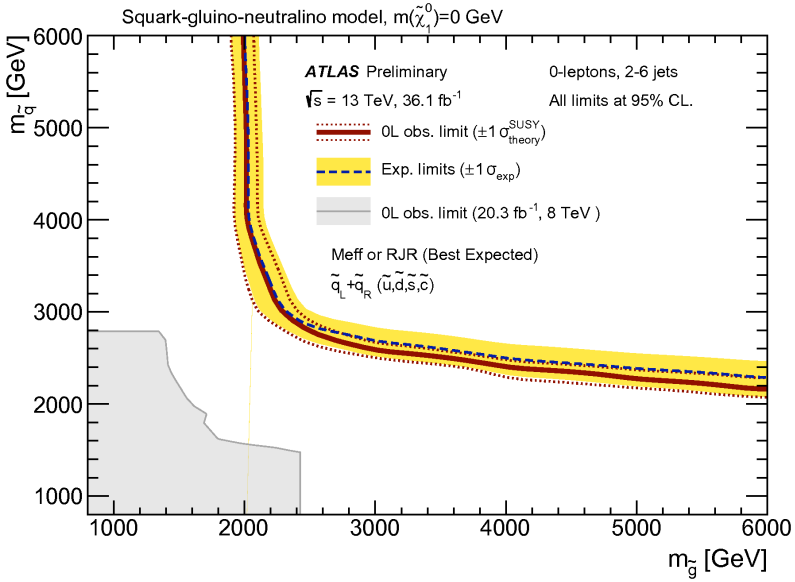


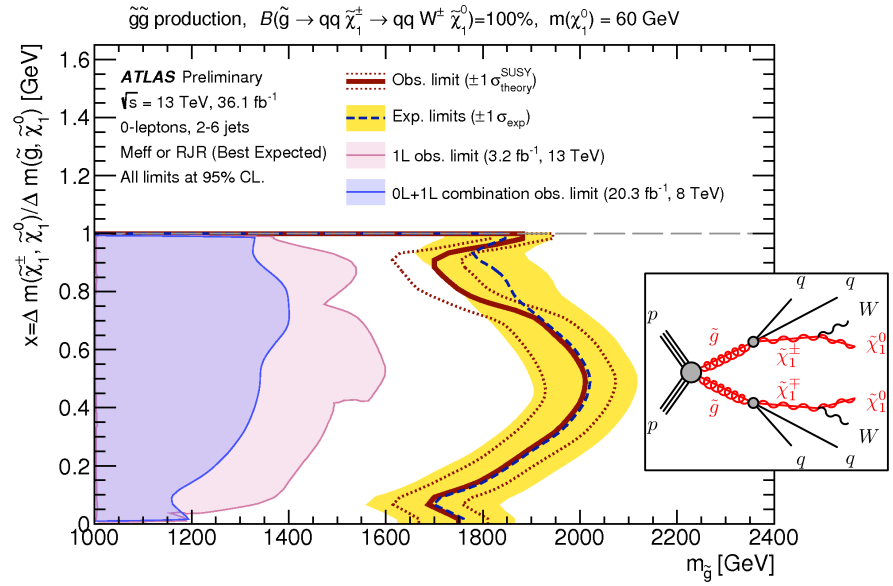


Inclusive 0-ℓ Search: Interpretations

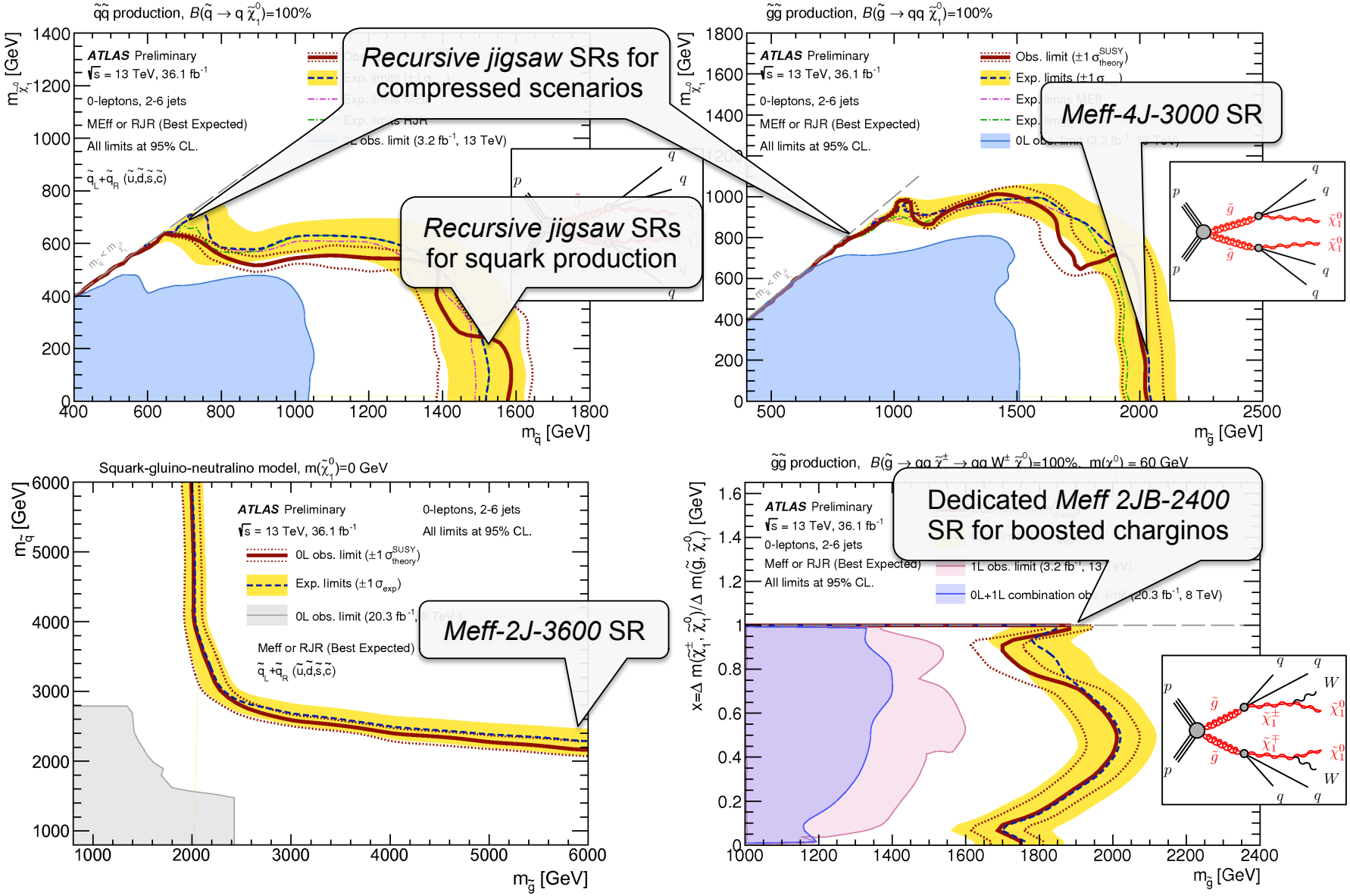








Inclusive 0-ℓ Search: Interpretations



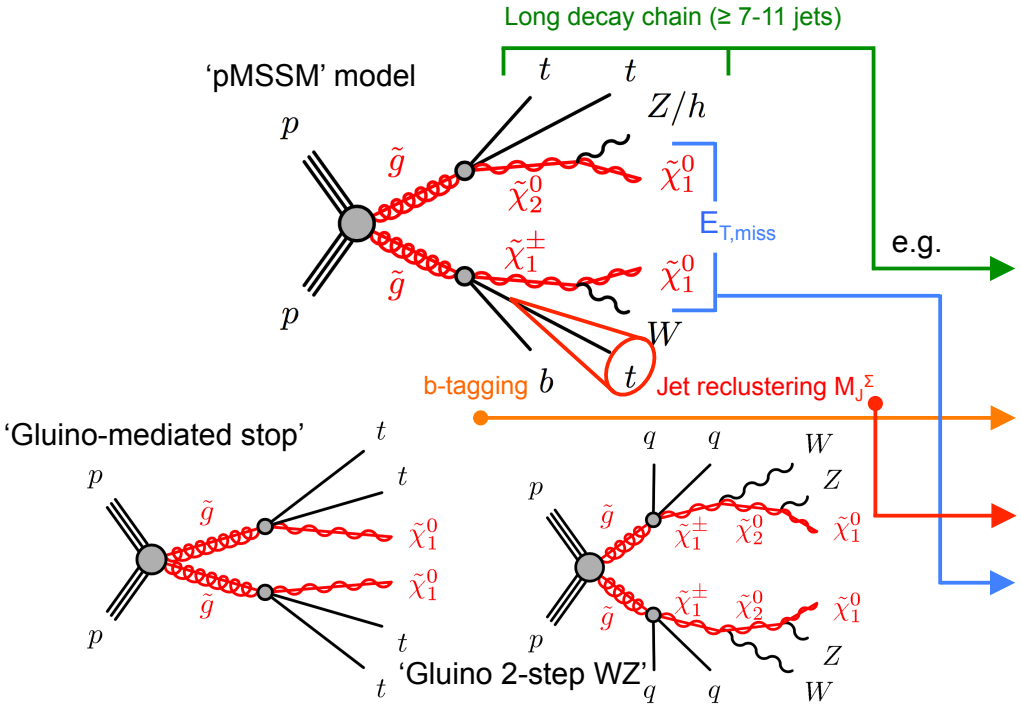
0-ℓ + multi-jets: Analysis Strategy

- Target final state: **0-lepton + ≥ 7-11 + low / moderate $E_{T,miss}$**
- Key feature: Use of $E_{T,miss}$ significance (instead of $E_{T,miss}$) as discriminating variable:

$$E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}\text{, where: } H_{\mathrm{T}} = \sum_{j} p_{\mathrm{T},j}^{\mathrm{jet}}$$

→ Analysis also sensitive to scenarios with lower $E_{T,miss}$ (including RPV models)

- Benchmark scenarios for inclusive gluino & squark production (RPC):

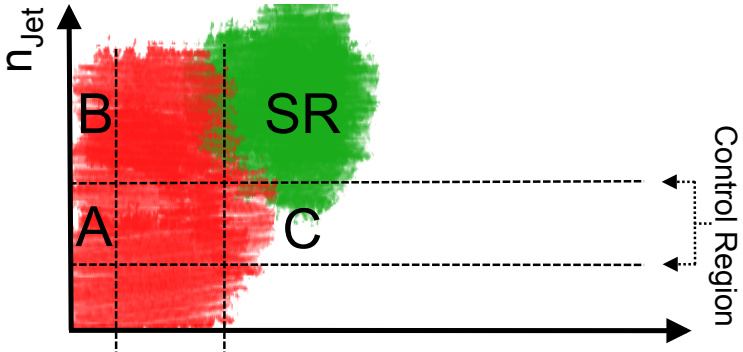


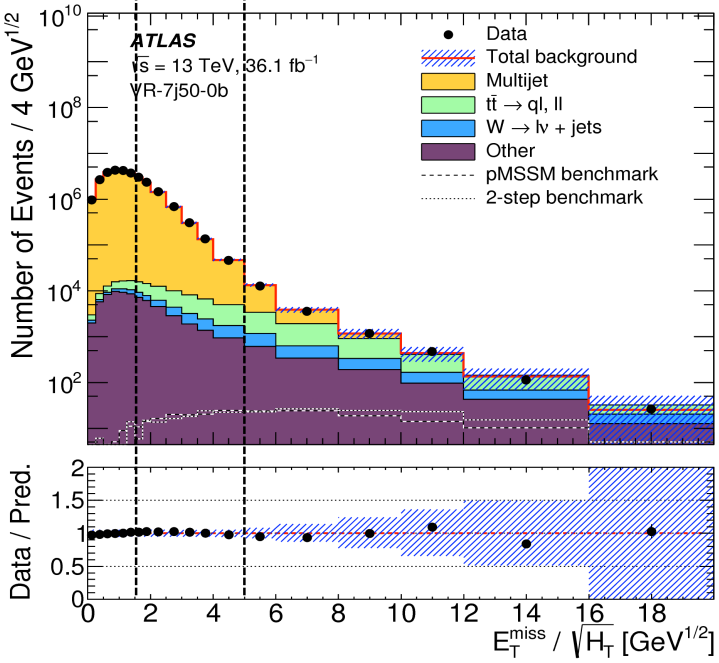
Two analysis streams (27 inclusive regions):

Criterion	Heavy-flavour channel		Jet mass channel
Jet $\lvert\eta\rvert$	< 2.0		
Jet p_{T}	> 50 GeV	> 80 GeV	> 50 GeV
N_{jet}	$\geq 8, 9, 10, 11$	$\geq 7, 8, 9$	$\geq 8, 9, 10$
Lepton veto	No preselected e or μ after overlap removal		
b-jet selection	$p_{\mathrm{T}} > 50$ GeV and $\lvert\eta\rvert < 2.0$		
Large-R-jet selection	$p_{\mathrm{T}} > 100$ GeV and $\lvert\eta\rvert < 1.5$		
$N_{b\text{-tag}}$	$\geq 0, 1, 2$		≥ 0
M_{J}^{Σ} (*)	≥ 0		$\geq 340, 500$ GeV
$E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$	$> 5\ \mathrm{GeV}^{1/2}$		

(*) $M_{\mathrm{J}}^{\Sigma} = \sum_{j} m_j^{R=1.0}$

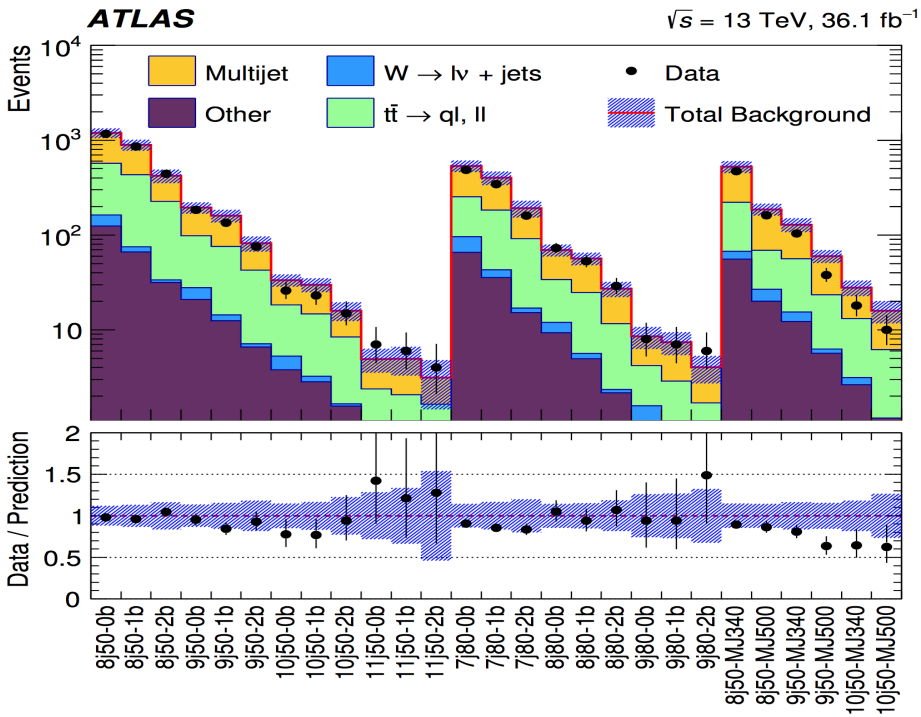
0-ℓ + multi-jets: Backgrounds & Results



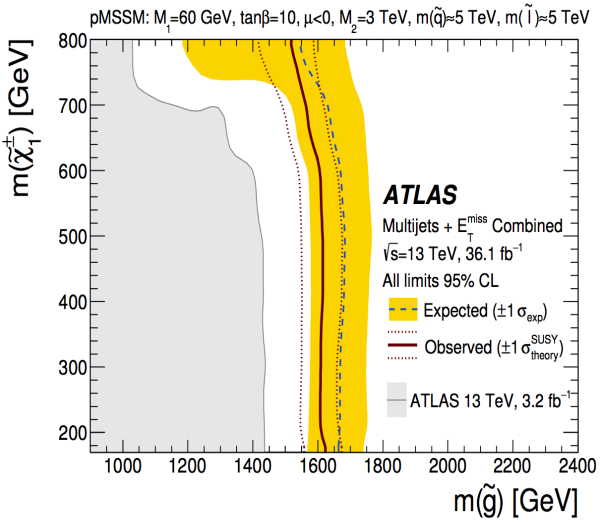


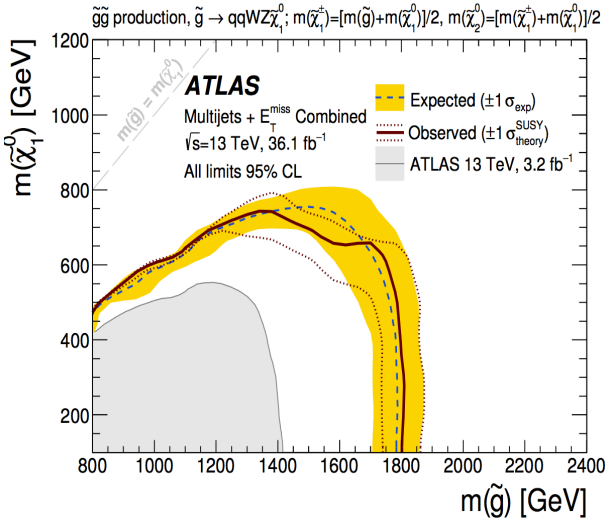
- Data-driven method for dominant multi-jet background (including fully hadronic tt):
  - $E_{T,miss}$ / $\sqrt{H_T}$ template extracted from data @ lower N_{jet} & normalised @ low $E_{T,miss}$ / $\sqrt{H_T}$ in SR
- Leptonic backgrounds (tt, V+jets, single-top, diboson):
  - 1-ℓ control regions (tt / W+jets) & simulation (others)

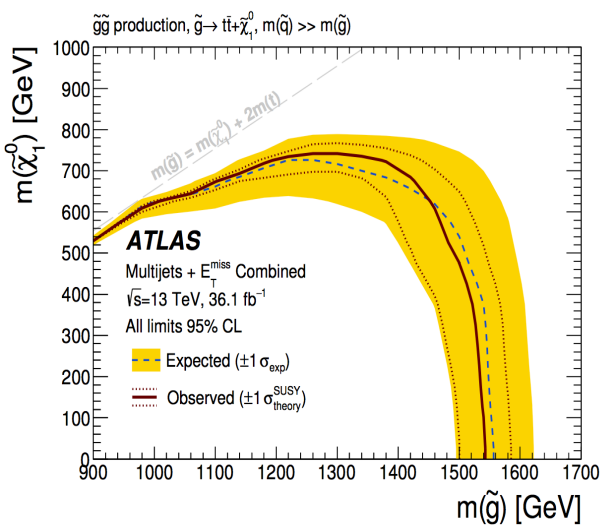
→ **No significant deviations** from the Standard Model expectation in both streams

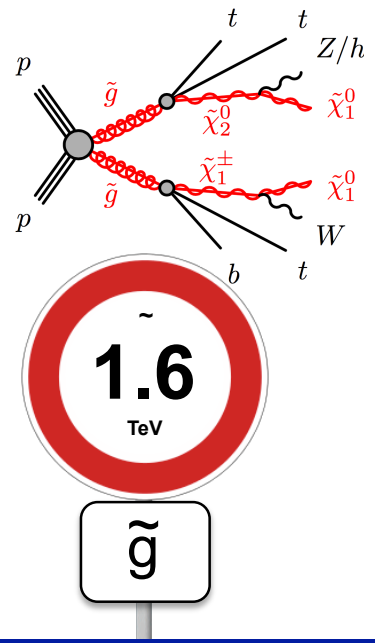


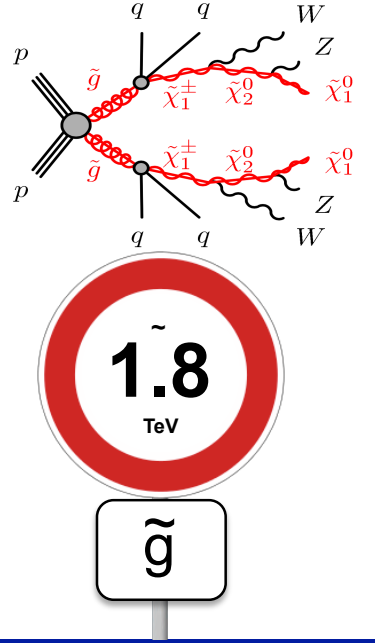
0-ℓ + multi-jets: Interpretation

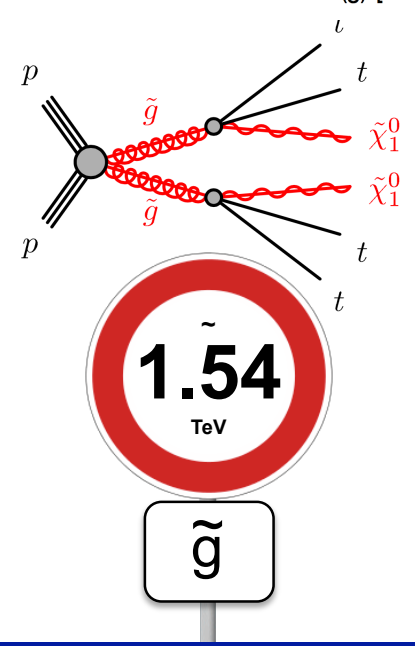










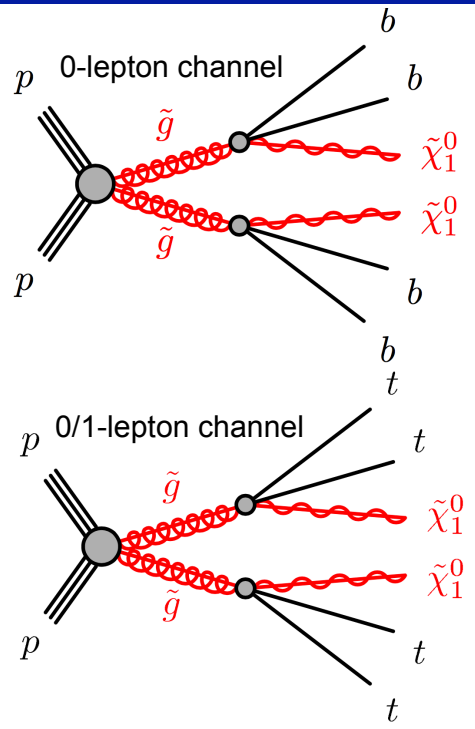


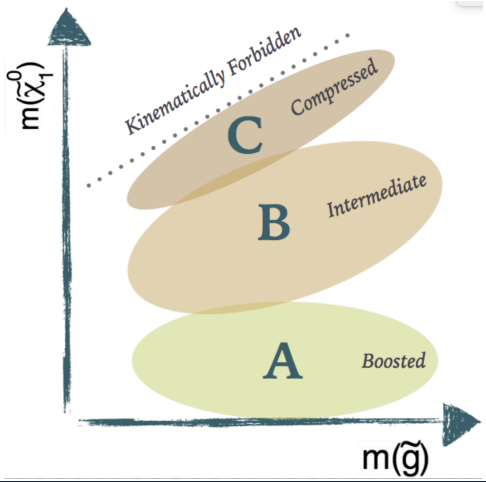
Multi b-jet Search: Overview

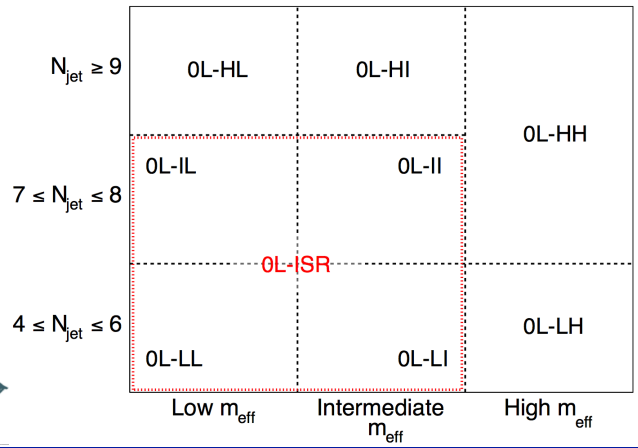
- Defining feature: **≥ 3 b-jets + 0/1 lepton + $E_{T,miss}$** final state
- Main benchmarks are gluino-mediated stop/sbottom production

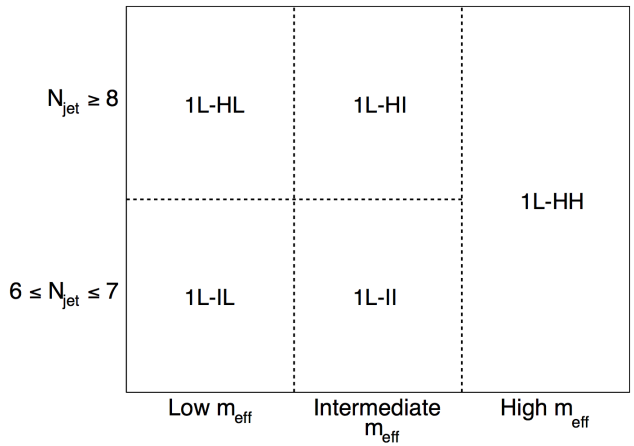
① 10 Inclusive signal regions optimised for discovery:
  - Selection: ≥ 3-8 jets using $N_{b\text{-tag}}$, m_{eff}, m_T, $E_{T,miss}$, $\Sigma m_{large\text{-}R\ jets}$ to target compressed, intermediate, & large mass splittings

② Binned orthogonal signal regions optimised for exclusion:
  - Selection: Ranging from low to high (m_{eff} & N_{jet}) to cover broad range of mass spectra
  - Combined fit over all bins to enhance exclusion power



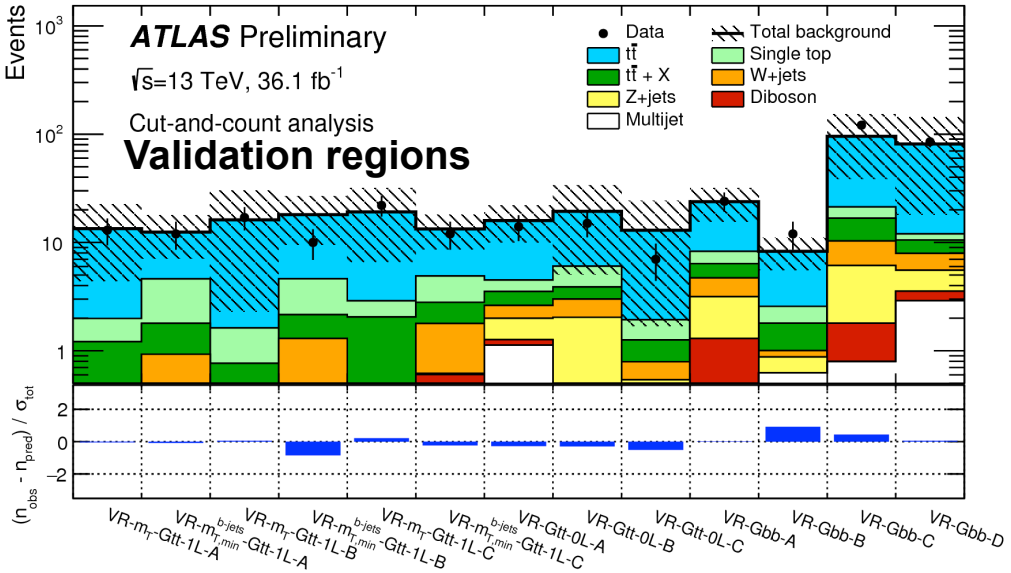


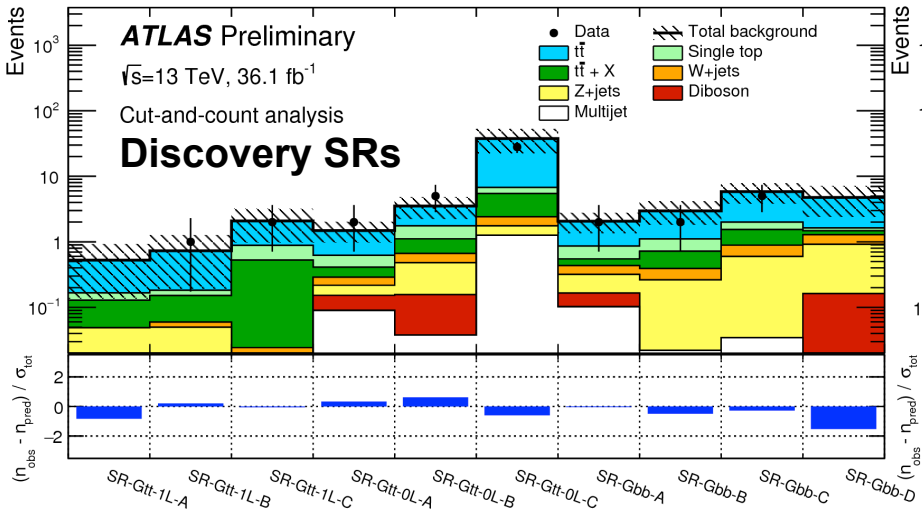


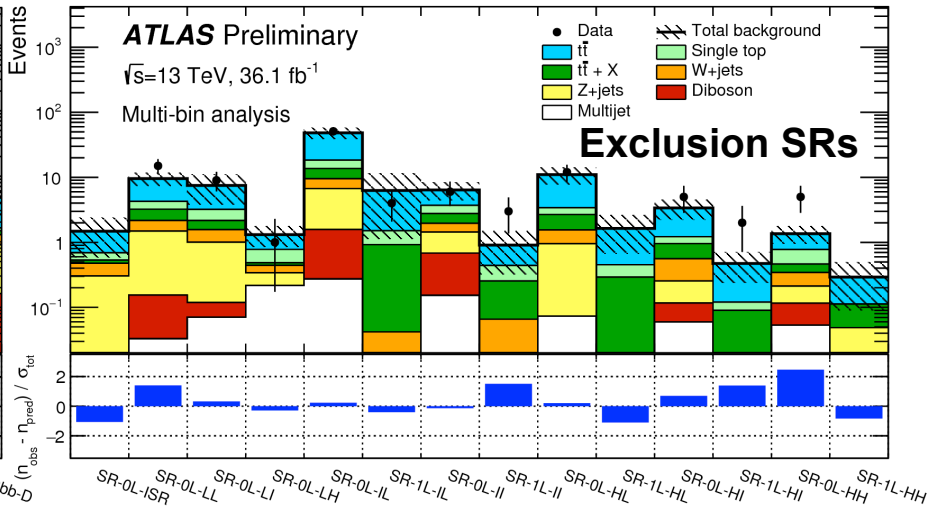


Multi b-jet Search: Backgrounds & Results

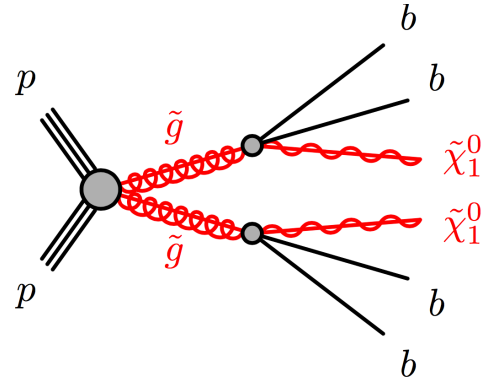
- Major background tt+jets estimated with 1-lepton control regions, other backgrounds from simulation
- Generally **good agreement** between data and prediction in discovery and exclusion signal regions
- Small deviation in 0-lepton high-mass signal region ~ 2σ

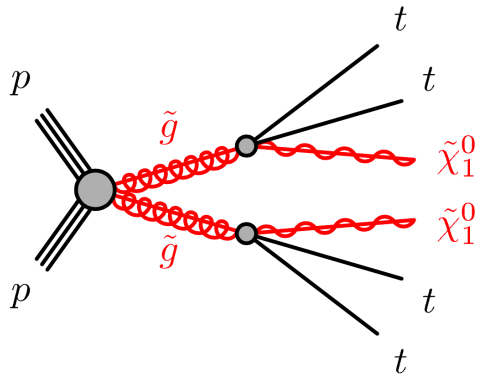


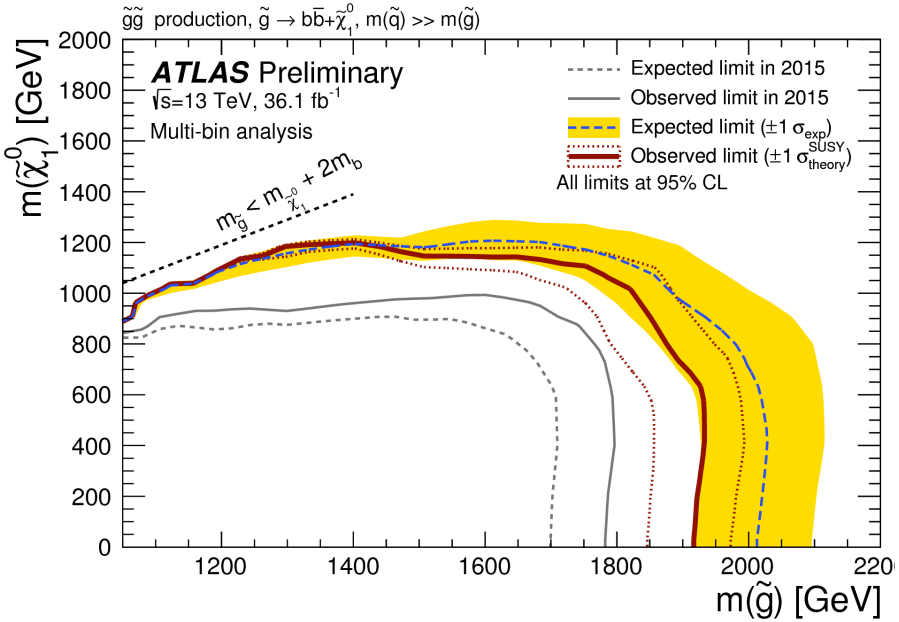


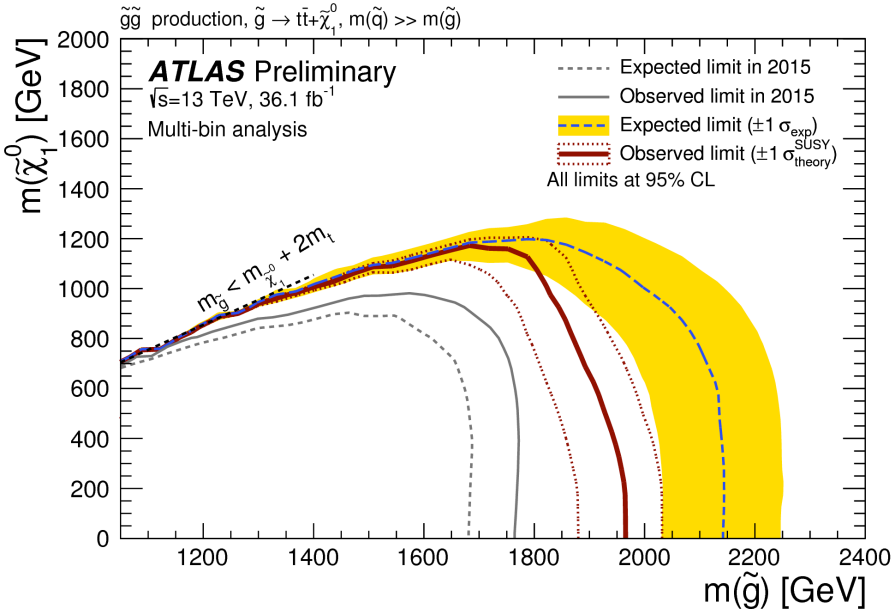


Multi b-jet Search: Interpretation







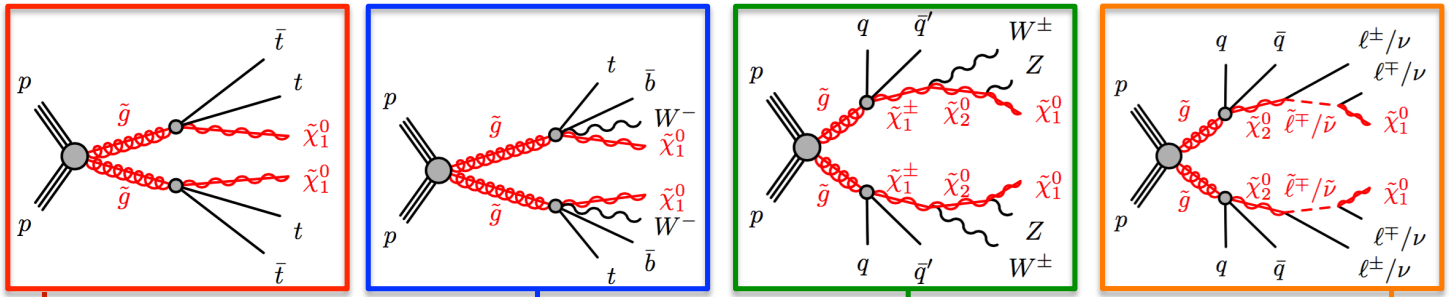


→ Sensitivity extended in g→bb+$\tilde{\chi}^0$ analysis extended by ~100 GeV w.r.t. 14.8 fb^{-1} analysis – observed **beyond 1.9 TeV**

→ Sensitivity extended in g→tt+$\tilde{\chi}^0$ analysis extended by ~200 GeV w.r.t. 14.8 fb^{-1} analysis – observed limit **beyond 1.95 TeV**

2-ℓ (same-sign) / 3-ℓ Search

- Target final state**: 2 same-sign leptons** ($e^{\pm}e^{\pm}$, $e^{\pm}\mu^{\pm}$, $\mu^{\pm}\mu^{\pm}$) or **three leptons** (e/μ without flavour / charge selection)
- Key feature: SM backgrounds in same-sign final states small while rich SUSY / BSM phenomenology
  → Can apply much looser kinematic requirements in this channel to discriminate signal from background
  → Sensitive to large number of models (including e.g. compressed / RPV models)
- Benchmark scenarios for inclusive gluino & squark production (RPC):



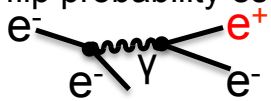
→ Ten inclusive signal regions to target the various scenarios:

Signal region	$N_{\text{leptons}}^{\text{signal}}$	$N_{b\text{-jets}}$	N_{jets}	$p_{\text{T}}^{\text{jet}}$ [GeV]	$E_{\text{T}}^{\text{miss}}$ [GeV]	m_{eff} [GeV]	$E_{\text{T}}^{\text{miss}}/m_{\text{eff}}$	Other
Rpc2L2bS	≥ 2SS	≥ 2	≥ 6	> 25	> 200	> 600	> 0.25	–
Rpc2L2bH	≥ 2SS	≥ 2	≥ 6	> 25	–	> 1800	> 0.15	–
Rpc2Lsoft1b	≥ 2SS	≥ 1	≥ 6	> 25	> 100	–	> 0.3	20,10 < $p_{\text{T}}^{\ell_1}, p_{\text{T}}^{\ell_2}$ < 100 GeV
Rpc2Lsoft2b	≥ 2SS	≥ 2	≥ 6	> 25	> 200	> 600	> 0.25	20,10 < $p_{\text{T}}^{\ell_1}, p_{\text{T}}^{\ell_2}$ < 100 GeV
Rpc2L0bS	≥ 2SS	= 0	≥ 6	> 25	> 150	–	> 0.25	–
Rpc2L0bH	≥ 2SS	= 0	≥ 6	> 40	> 250	> 900	–	–
Rpc3L0bS	≥ 3	= 0	≥ 4	> 40	> 200	> 600	–	–
Rpc3L0bH	≥ 3	= 0	≥ 4	> 40	> 200	> 1600	–	–
Rpc3L1bS	≥ 3	≥ 1	≥ 4	> 40	> 200	> 600	–	
Rpc3L1bH	≥ 3	≥ 1	≥ 4	> 40	> 200	> 1600	–	

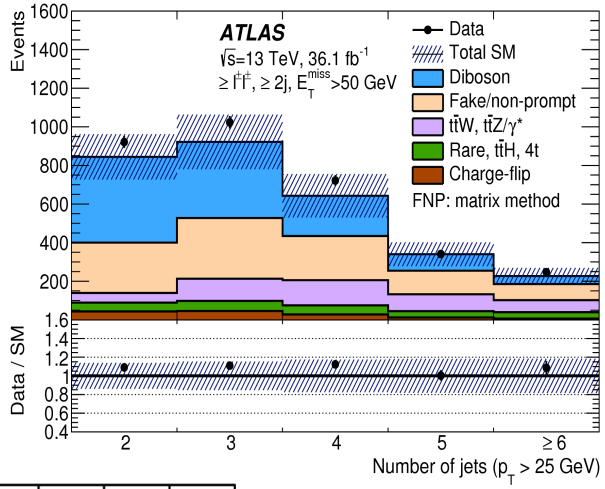
No specific target model – generalisation of Rpc3L0b to ≥ 1 b-jet final states

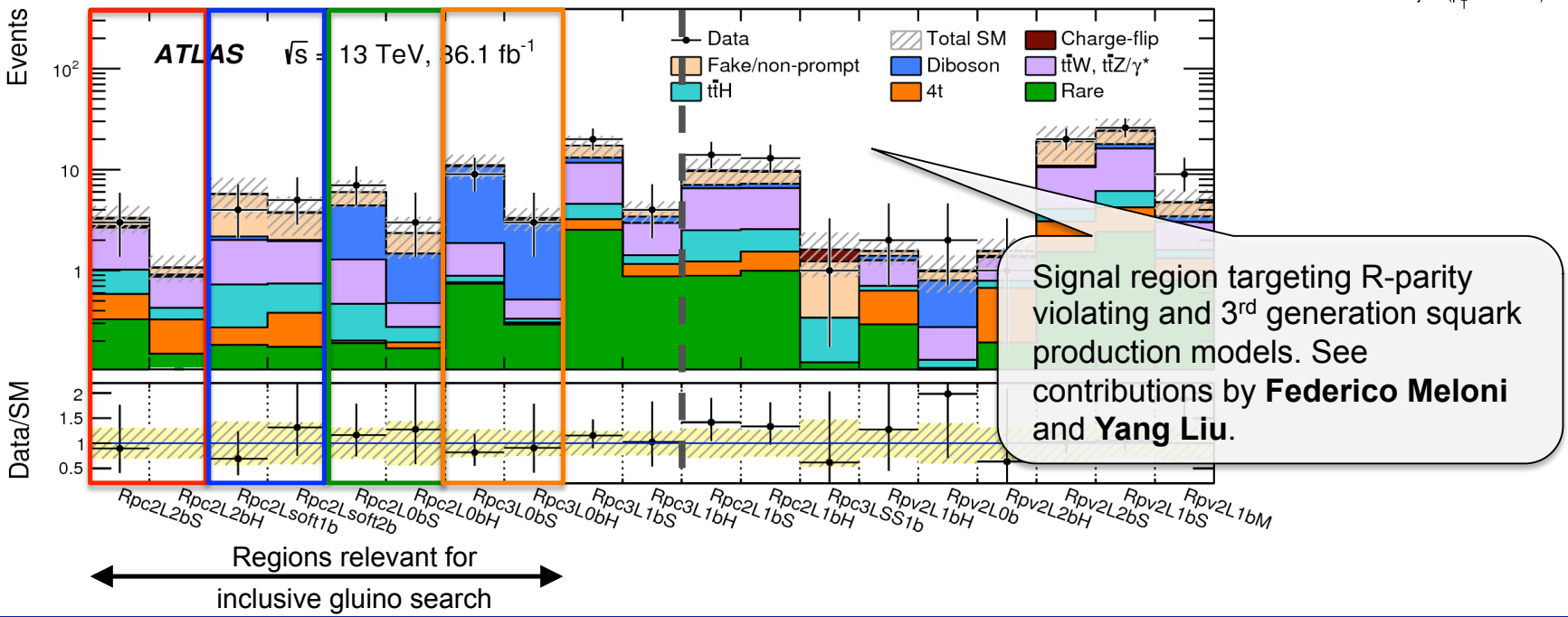
2-ℓ (SS) / 3-ℓ: Backgrounds & Results

- Dominant background: **Rare processes with prompt leptons** (mainly tt+V & diboson): Simulation + validation regions
- **Fake and non-prompt leptons (FNP):** 2 data-driven methods (loose-tight matrix-method & normalisation of FNP contributions in data control regions)
- **Electron charge mis-measurement** (dominated by hard bremsstrahlung conversion): Charge flip probability estimated from Z → ee events



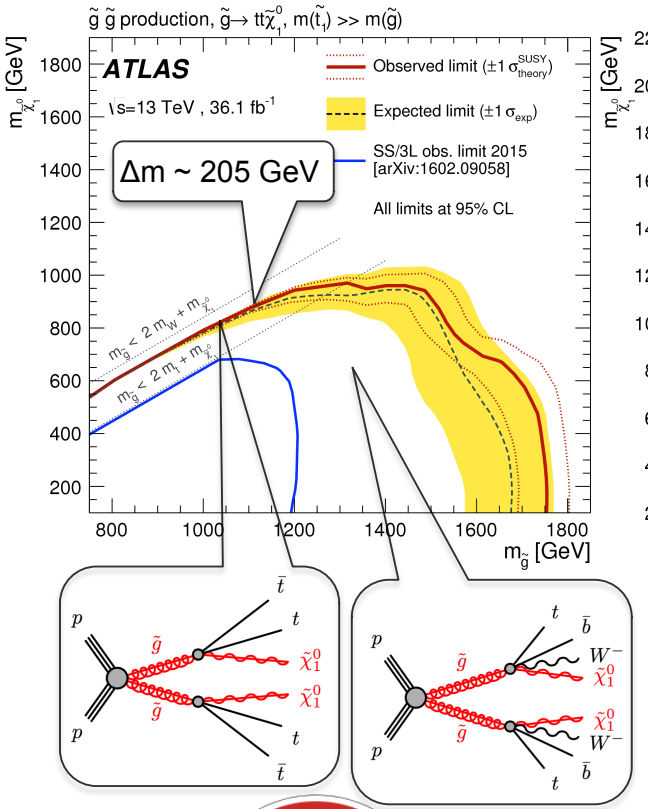
- Results: **No significant deviations** from the Standard Model:

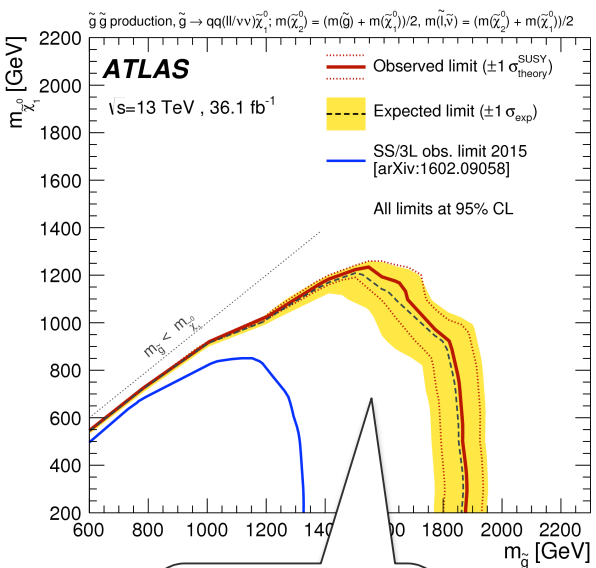


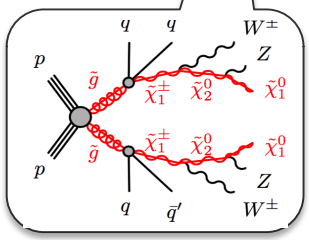


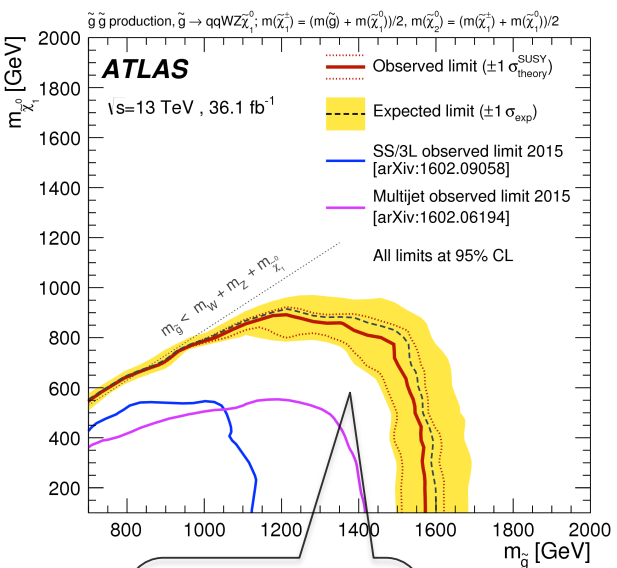
Signal region targeting R-parity violating and 3rd generation squark production models. See contributions by **Federico Meloni** and **Yang Liu**.

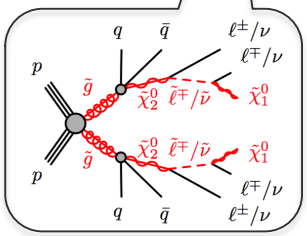
2-ℓ (SS) / 3-ℓ: Interpretation







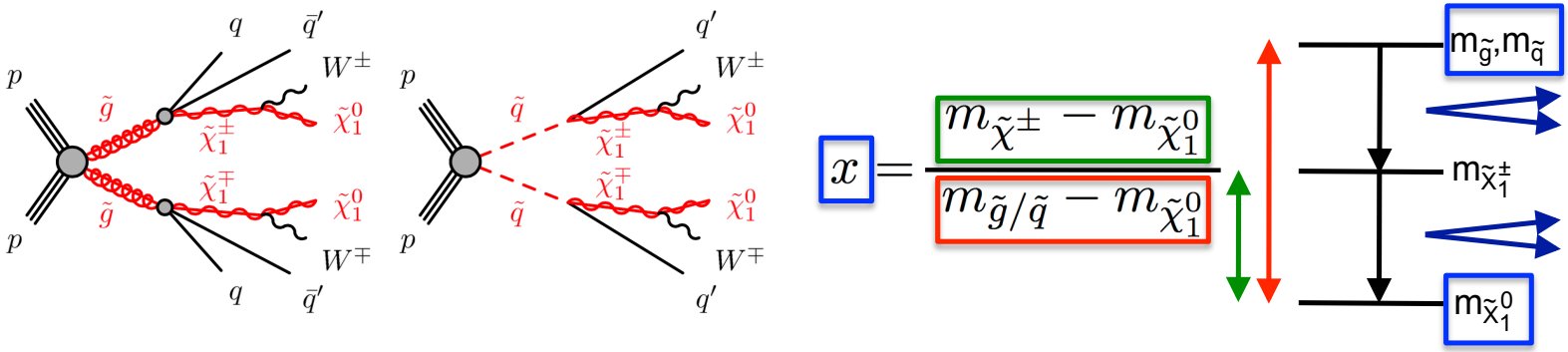




1-ℓ + jets + E_T^{miss} Search: Signal Regions

- Target final state: **1 lepton (soft/hard) + jets + E_T^{miss}**
- Two analysis streams

  (1) "2-6 jet stream": Targeting simplified models with gluino/squark production and 1-step decay via chargino to LSP



→ **Two model planes** to probe optimal slices of parameter space with x = ½ or variable x

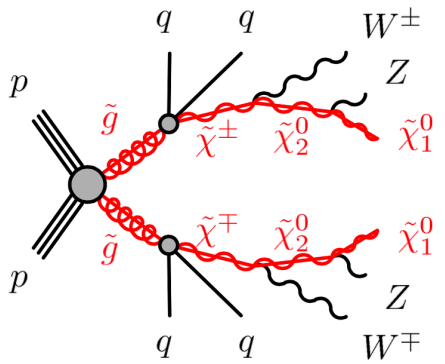
SR	2J	4J high-x	4J low-x	6J
N_ℓ	= 1	= 1	= 1	= 1
p_T^ℓ [GeV]	> 7(6) for $e(\mu)$ and < min(5 · N_{jet}, 35)	> 35	> 35	> 35
N_{jet}	≥ 2	4–5	4–5	≥ 6
E_T^{miss} [GeV]	> 430	> 300	> 250	> 350
m_T [GeV]	> 100	> 450	150–450	> 175
Aplanarity	–	> 0.01	> 0.05	> 0.06
E_T^{miss}/m_{eff}	> 0.25	> 0.25	–	–
N_{b-jet} (excl)	= 0 for b-veto, ≥ 1 for b-tag			
m_{eff} [GeV] (excl)	3 bins ∈ [700,1900] + [> 1900]	2 bins ∈ [1000,2000] + [> 2000]	2 bins ∈ [1300,2000] + [> 2000]	3 bins ∈ [700,2300] + [> 2300]
m_{eff} [GeV] (disc)	> 1100	> 1500	> 1650(1300) for gluino (squark)	> 2300(1233) for gluino (squark)

- **4 exclusive signal regions** targeting different mass splittings
- Includes **soft-lepton** 2J region to target compressed scenarios
- For discovery: Tight cuts on m_{eff}
- For exclusion: Further binning in m_{eff} and N_{b-jet} to (28 regions in total) to maximise sensitivity to a wide range of models

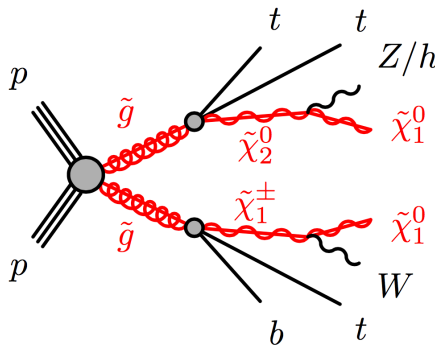
1-ℓ + jets + E_T^{miss} Search: Signal Regions

- Target final state: **1 lepton (soft/hard) + jets + E_T^{miss}**
- Two analysis streams

(2) "9 jet stream": Targeting models with higher jet multiplicities:



"2-step W/Z"



"0-lepton + multi-jets pMSSM slice"

example decay chain

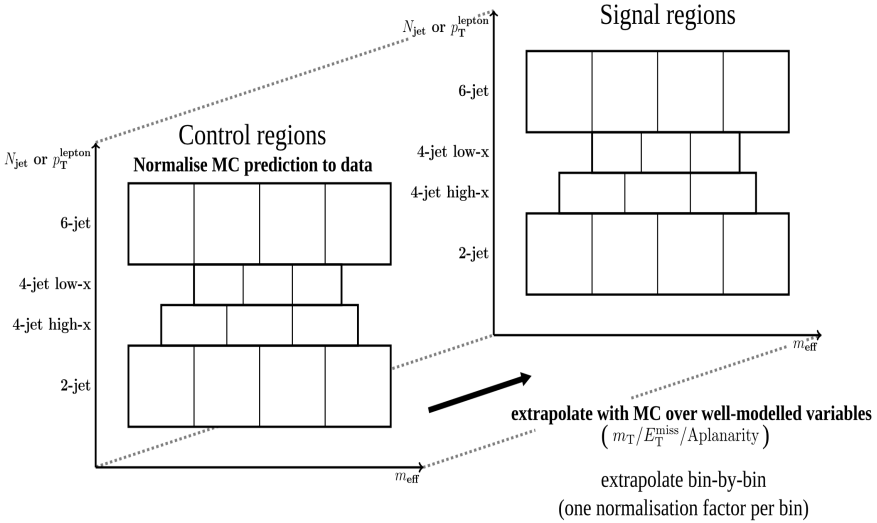
SR	9J
N_ℓ	= 1
p_T^ℓ [GeV]	> 35
N_{jet}	≥ 9
E_T^{miss} [GeV]	> 200
m_T [GeV]	> 175
Aplanarity	> 0.07
$E_T^{miss}/\sqrt{H_T}$ [GeV$^{1/2}$]	≥ 8
m_{eff} [GeV] (excl)	[1000, 1500], [>1500]
m_{eff} [GeV] (disc)	> 1500

- **Dedicated 9-jet signal region**
- For discovery: Tight cut on m_{eff}
- For exclusion: Binning in m_{eff} to maximise sensitivity

1-ℓ + jets + E_T^{miss} Search: Backgrounds

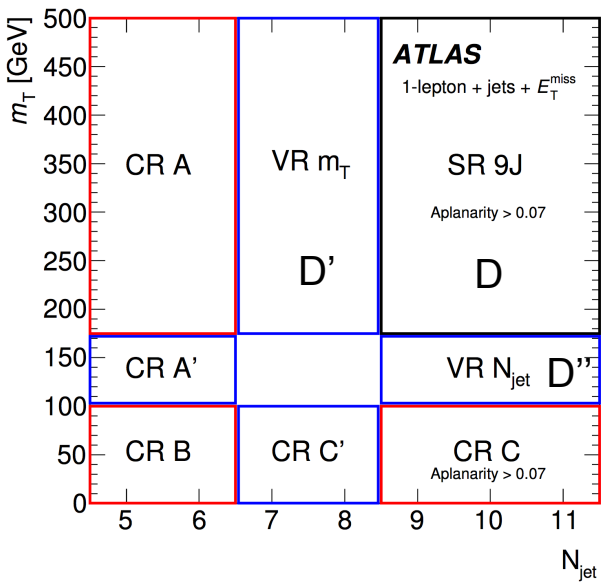
2-6 jet stream:

- Dominant **top & W+jets** backgrounds:
  - Dedicated control regions **in each m_{eff} bin** + extrapolation to **validation** and signal regions
- Other Backgrounds: Z+jets, tt+V, di-boson
  - From simulation



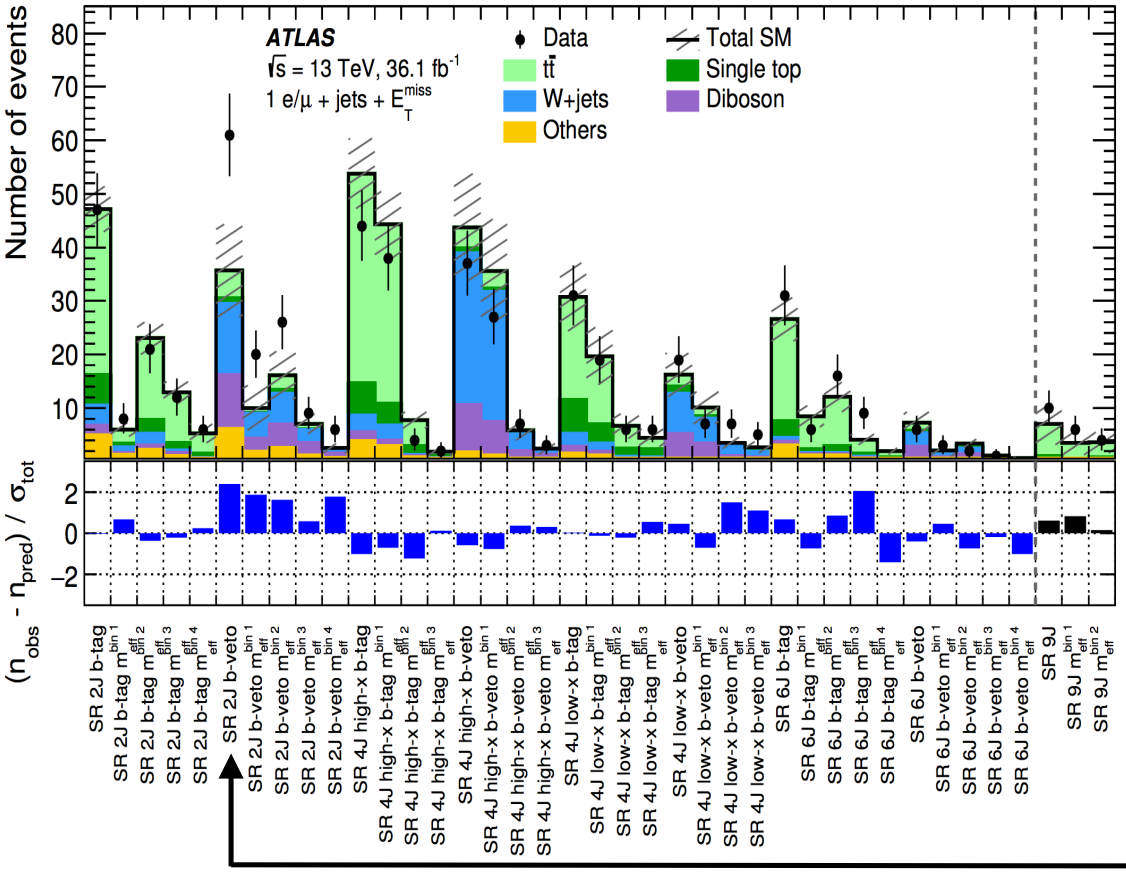
9 jet stream:

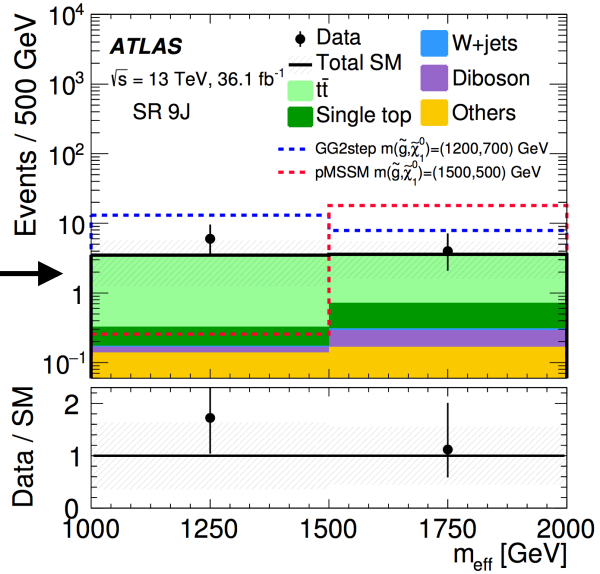
- Dominant **top & W+jets** background:
  - "ABCD" method based on invariance of transverse mass with jet multiplicity (~valid for tight cuts on m_{eff})
  - Simulation-based closure parameter to correct for residual correlations
  - Validation using ABC'D' and A'BCD'' setups
- Other Backgrounds: Z+jets, tt+V, di-boson
  - From simulation

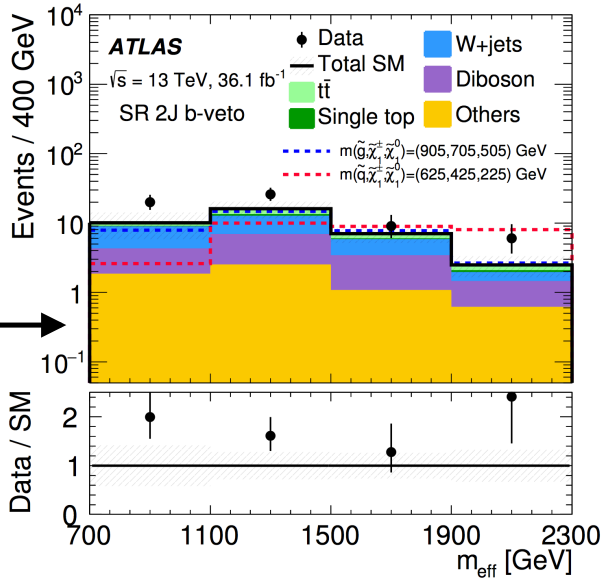


1-ℓ + jets + E_T^{miss} Search: Results

→ **No significant deviation** from the Standard Model expectation (largest deviation just above 2 sigma)

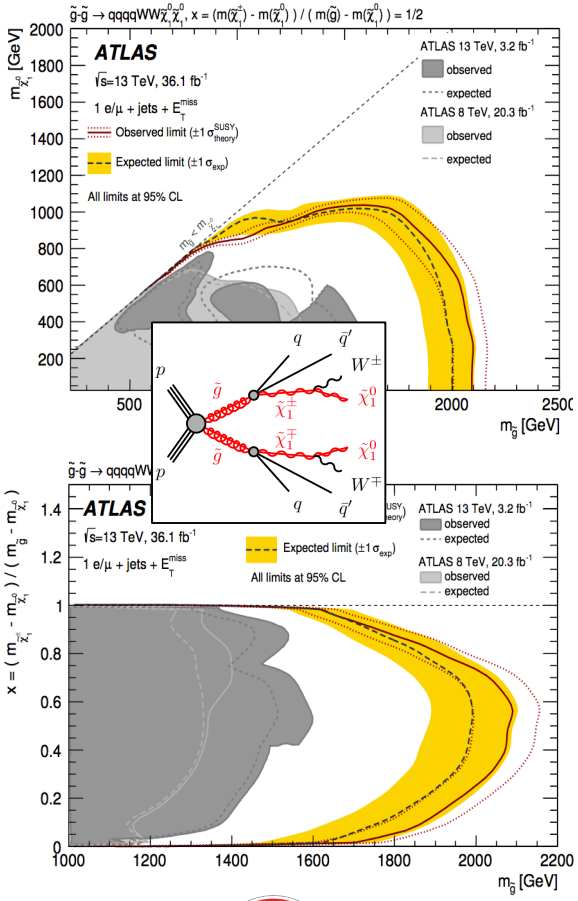


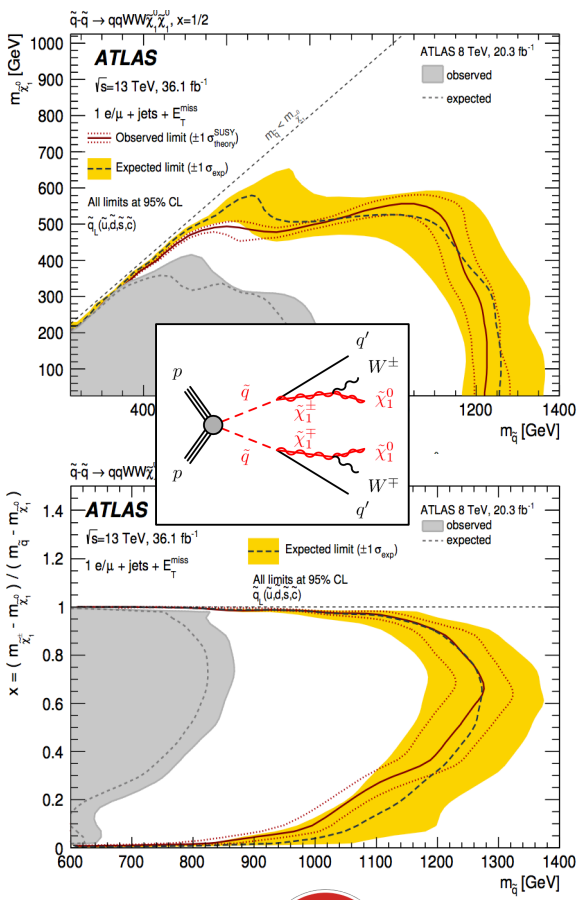


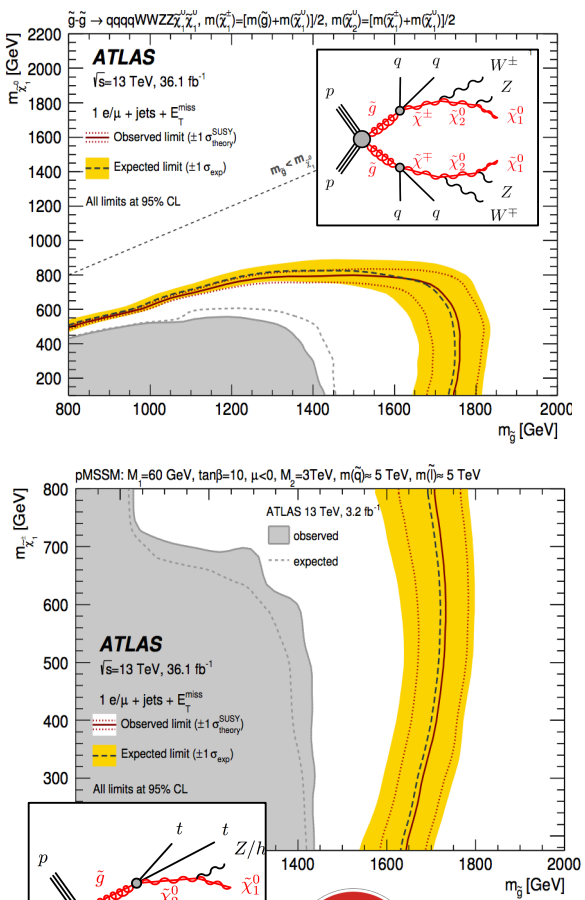


1-ℓ + jets + E_T^{miss} Search: Interpretation

Full statistical combination of 2-6 jet stream exclusion regions







2.1 TeV $\tilde{g}$

1.2 TeV $\tilde{q}$

1.75 TeV $\tilde{g}$

9 jet stream

Summary & Outlook

- Presented 5 new inclusive ATLAS searches for gluinos and squarks using the full **2015 + 2016 dataset of 36.1 fb^{-1} at 13 TeV**:
  - 0-ℓ + 2-6 jets + $E_{T,miss}$: ATLAS-CONF-2017-022
  - 0-ℓ + 7-11 jets + $E_{T,miss}$: arXiv:1708.02794
  - 1-ℓ + jets + $E_{T,miss}$: arXiv:1708.08232
  - 2-ℓ (same-sign) or 3-ℓ + jets + $E_{T,miss}$: arXiv:1706.03731
  - 0/1-ℓ + 3-4 b-jets + $E_{T,miss}$: ATLAS-CONF-2017-021

- **No significant deviations** from SM

- **Significant boost in sensitivity** excluding gluino masses in some scenarios beyond 2 TeV!

- See also contributions by **Federico Meloni** and **Yang Liu** for interpretations od these searches in R-parity violating and 3rd generation squark production models