Recent ATLAS SUSY Results

Ben Hooberman

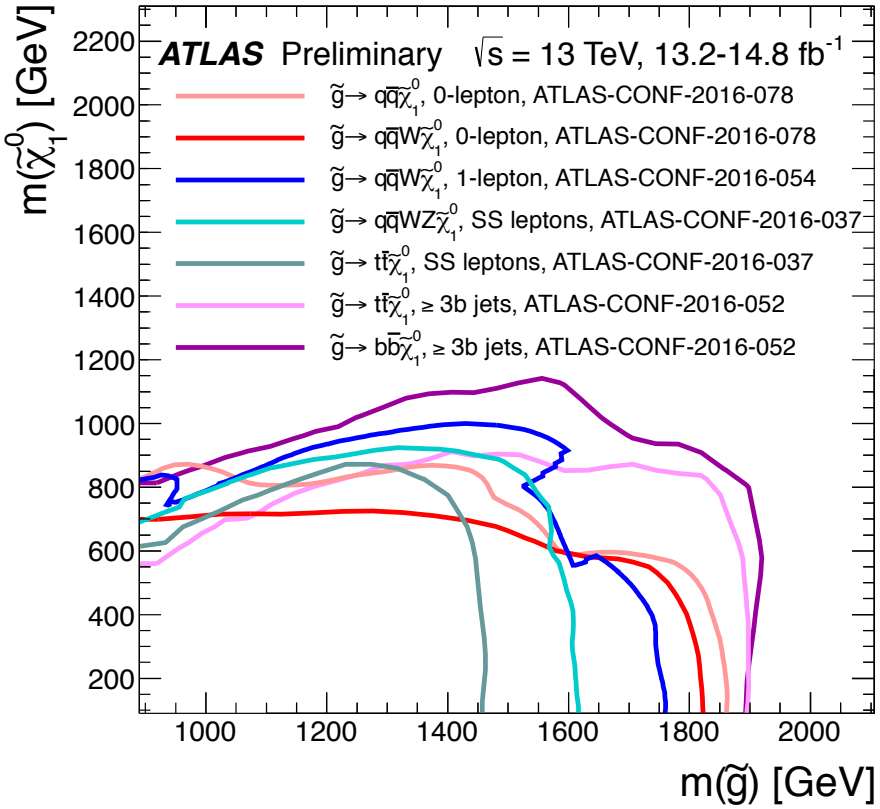
University of Illinois at Urbana-Champaign

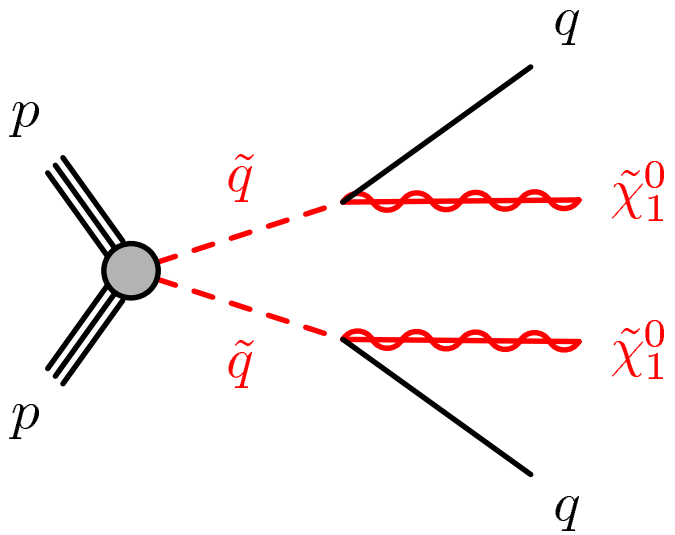
Contents

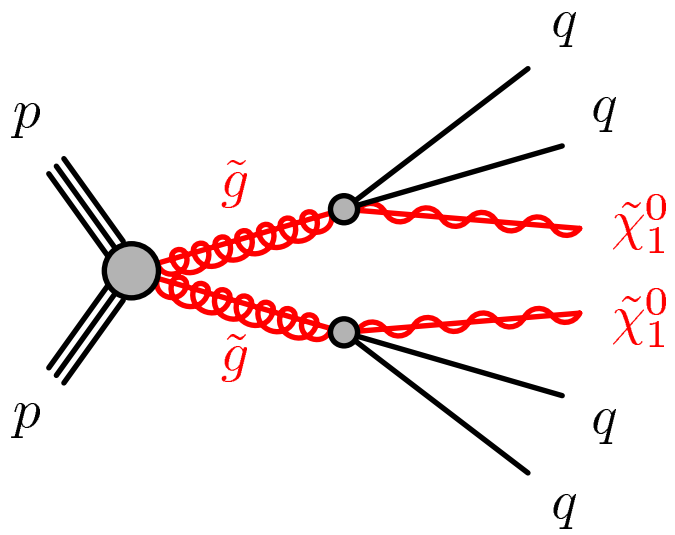
	Search	Final State	Max. Mass Reach	References [1]
strong	**inclusive squarks and gluinos**	0 leptons + 2-6 jets + MET	m_{gluino} ~ 2.0 TeV, m_{squark} ~ 1.6 TeV	ATLAS-CONF-2017-022
strong	**gluinos with t/b**	0/1 lepton + 3-4 b-jets + MET	m_{gluino} ~ 2.0 TeV	ATLAS-CONF-2017-021
3rd gen.	**stops**	0 leptons + b-jets + MET	m_{stop} ~ 950 GeV	ATLAS-CONF-2017-020
3rd gen.	**stops with Z/h**	1/2/3 leptons + b-jets + MET	m_{stop} ~ 870 GeV	ATLAS-CONF-2017-019
3rd gen.	**stop 2×2**	4 jets	m_{stop} ~ 610 GeV	ATLAS-CONF-2017-025
RPV/long-lived	**RPV 1L**	1 lepton + 8-12 jets + no MET	m_{gluino} ~ 2.1 TeV, m_{stop} ~ 1.1 TeV	ATLAS-CONF-2017-013
RPV/long-lived	**Long-lived charginos**	disappearing track+1/4 jets	$m_{chargino}$ ~ 430 GeV	ATLAS-CONF-2017-017
RPV/long-lived	**Long-lived massive particles**	displaced vertex + MET	m_{gluino} ~ 2.2 TeV for lifetimes O(10^{-2})-O(10) ns	ATLAS-CONF-2017-026

- **8 NEW results based on full 2015+2016 data sample**
  - See CERN seminar: M. Backes https://indico.cern.ch/event/580623/ (some material borrowed)
  - [1] Full results at: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
- **Look for the interesting analysis features!**

Part 1: Strong SUSY

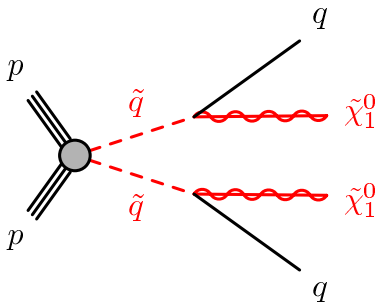


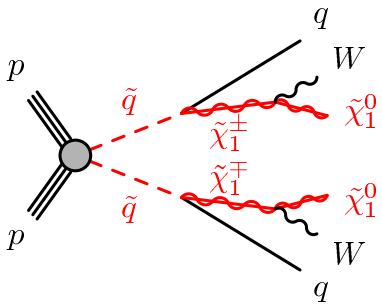


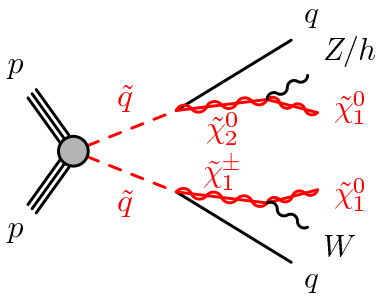


Overview of 0ℓ Search

squarks



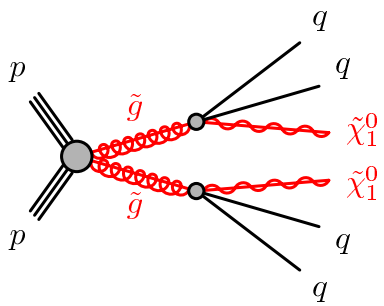


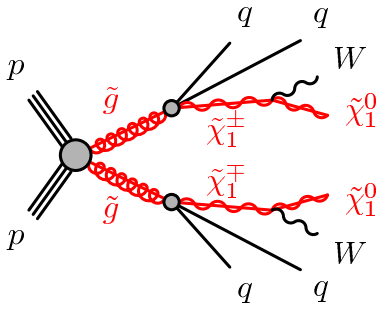


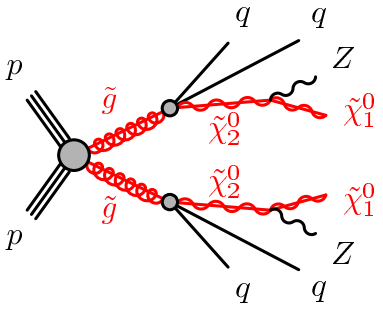
"1-step" decays

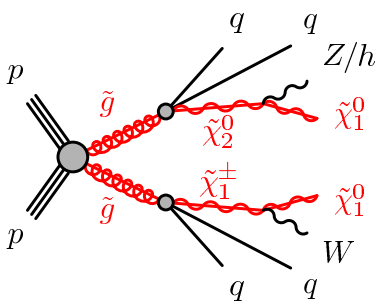
"2-step" decays via W/Z/h

gluinos







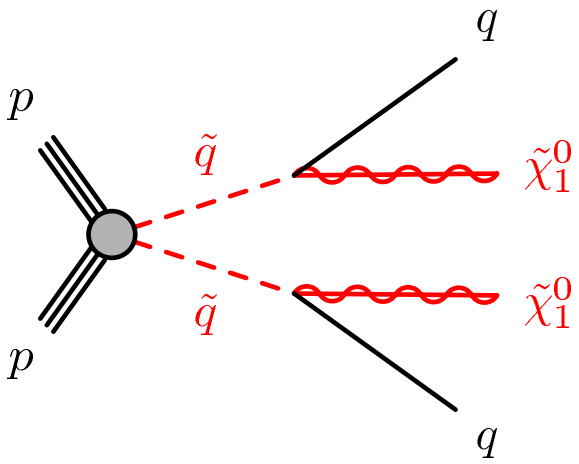


- **Strong SUSY workhorse**: inclusive search for squarks and gluinos
- **Signature**: 0 leptons + 2-6 jets + MET
- **Strategy**: two approaches based on m_{eff} and "RJR" variables (extends sensitivity to compressed SUSY)

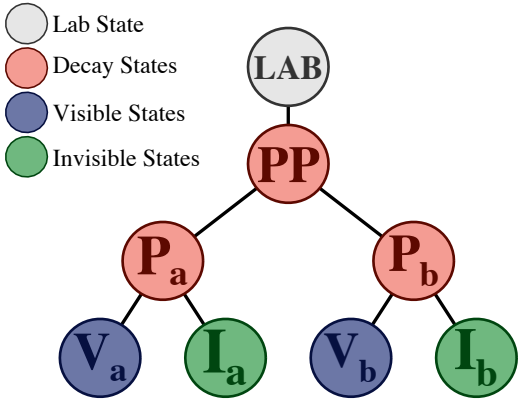
$$m_{\text{eff}} = \sum p_T^{\text{jet}} + E_T^{\text{miss}}$$

Aside: Recursive Jigsaw Reconstruction

target signal process



assumed decay chain



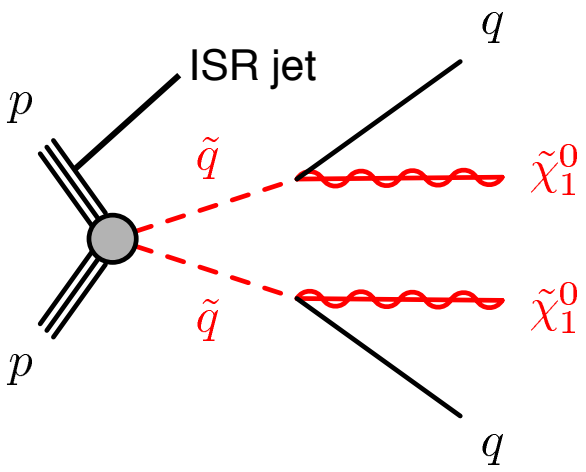
- Razor [1] → Super-Razor [2] → **Recursive Jigsaw Reconstruction (RJR) [3]**
- Novel method for **reconstructing** final states assuming a specific decay chain
- Perform **recursive** series of Lorentz boosts to transform between frames, using **jigsaw** rules to specify unknown degrees of freedom
- Obtain **complete set of useful variables** *diagonalized* with physical observables: angles, energies, masses, etc
- Code from Paul Jackson and Chris Rogan available at http://restframes.com/

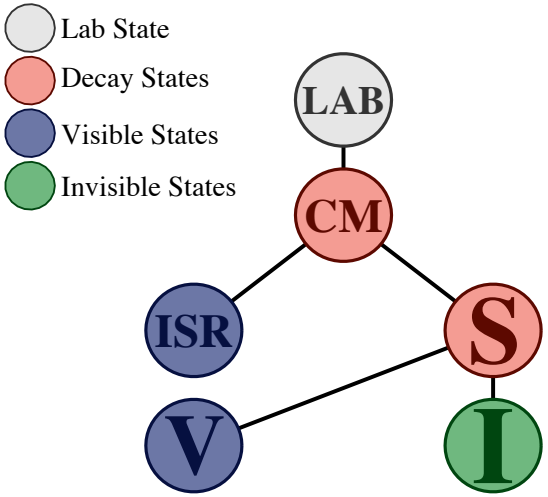
[1] Rogan, "Kinematical variables towards new dynamics at the LHC", arXiv:1006.2727 [hep-ph], CALT-68-2790
[2] Buckley, Lykken, Rogan, Spiropulu, "Super-razor and searches for sleptons and charginos at the LHC," PRD 89 (2014) 055020
[3] Jackson, Rogan, Santoni, "Sparticles in Motion - getting to the line in compressed scenarios with the Recursive Jigsaw Reconstruction," PRD95 (2017) 035031

Aside: RJR for Compressed SUSY

- Need to separate jets from SUSY decays (**V**) from recoil system (**ISR**)
- Apply jigsaw rule based on minimization of masses in estimated CM frame:

$$M_{CM} = \sqrt{M_{ISR} + \left(p_{ISR}^{CM}\right)^2} + \sqrt{M_S + \left(p_S^{CM}\right)^2}$$





Jackson, Rogan, Santoni, PRD95 (2017) 035031

Aside: RJR for Compressed SUSY

- Need to separate jets from SUSY decays (**V**) from recoil system (**ISR**)
- Apply jigsaw rule based on minimization of masses in estimated CM frame:

$$M_{CM} = \sqrt{M_{ISR} + \left(p_{ISR}^{CM}\right)^2} + \sqrt{M_S + \left(p_S^{CM}\right)^2}$$

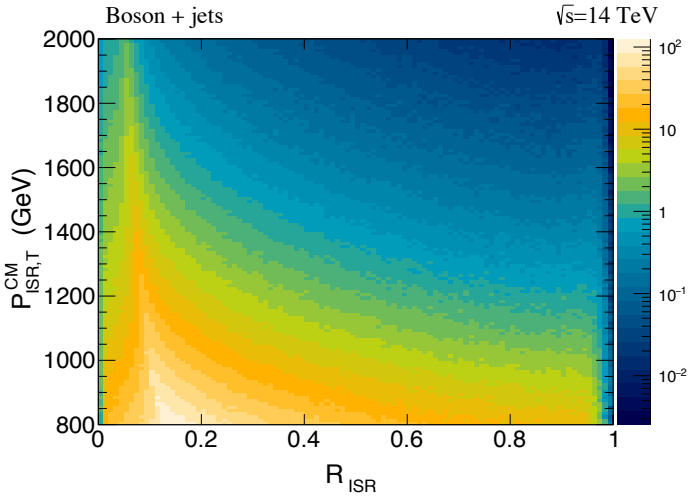
- Reconstruct S vs. B discriminants in CM frame, e.g.:

$$R_{\mathrm{ISR}} \equiv \frac{|\vec{p}_{\mathrm{I},T}^{\,\mathrm{CM}} \cdot \hat{p}_{\mathrm{ISR},T}^{\,\mathrm{CM}}|}{|\vec{p}_{\mathrm{ISR},T}^{\,\mathrm{CM}}|} \sim \frac{E_T^{\mathrm{miss}}}{p_T^{ISR}} \sim \frac{m_{\tilde{\chi}}}{m_{\tilde{q}}}$$

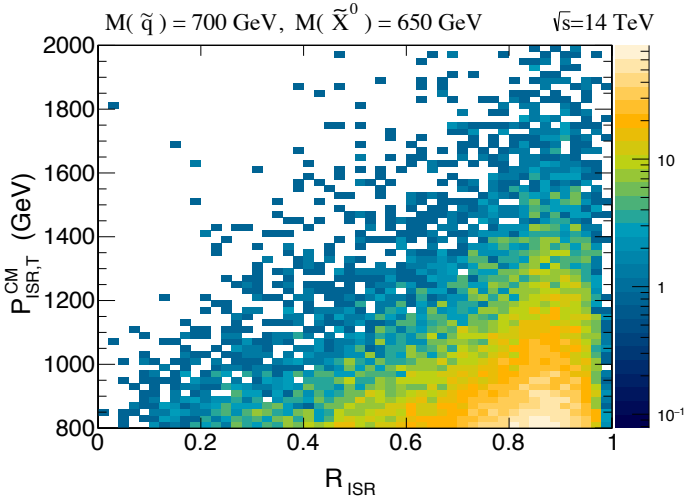
$p_{\mathrm{ISR},T}^{\mathrm{CM}}$ = vector sum p_T of ISR jets

- Exploit different correlations for S vs. B

background (V+jets)



signal (squark → q LSP)



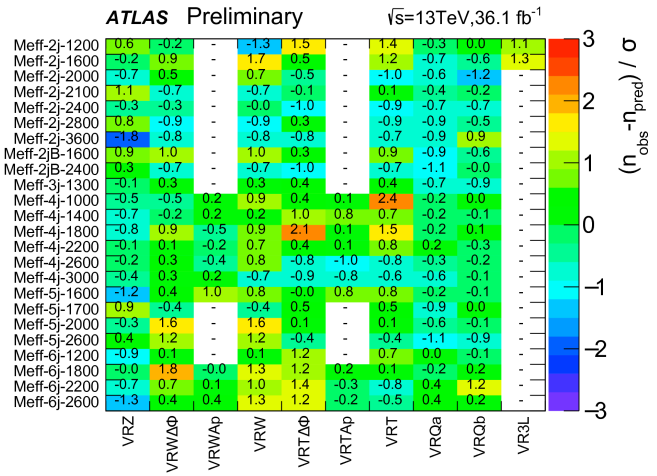
Jackson, Rogan, Santoni, PRD95 (2017) 035031

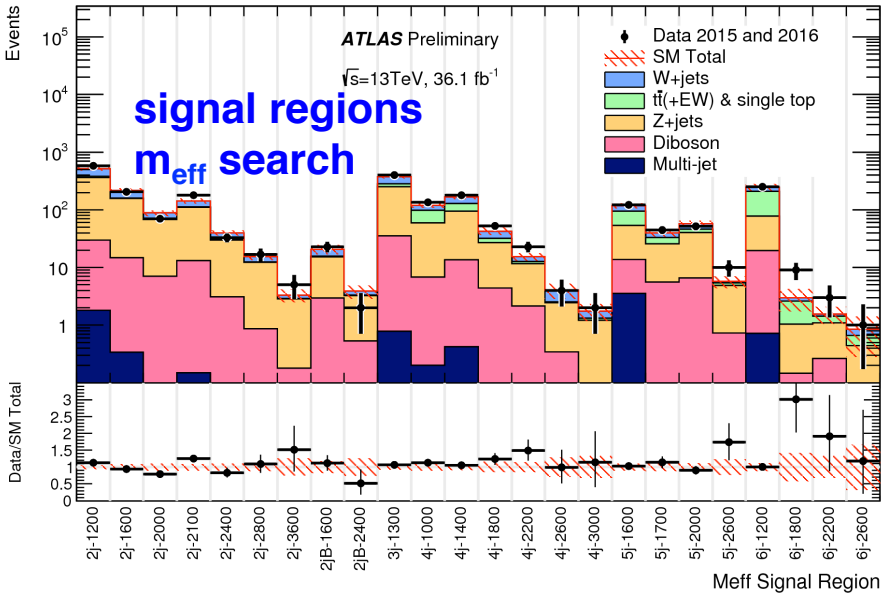
inclusive 0L
CONF-2017-022

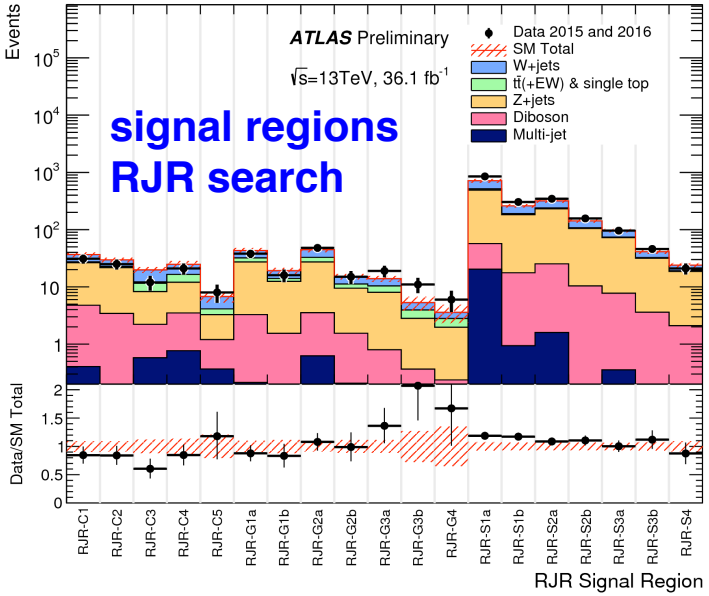
Results

- Background estimates validated in **validations regions** for the major background processes
- **Data is broadly consistent with SM**
  - Max excess 2.2σ out of 43 overlapping regions (in RJR-S1a targeting gluino → q q N1)

validation regions

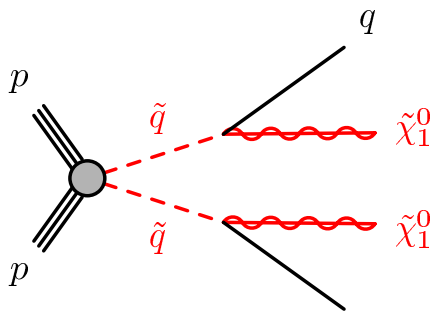


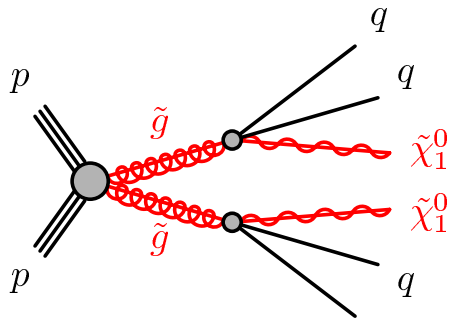


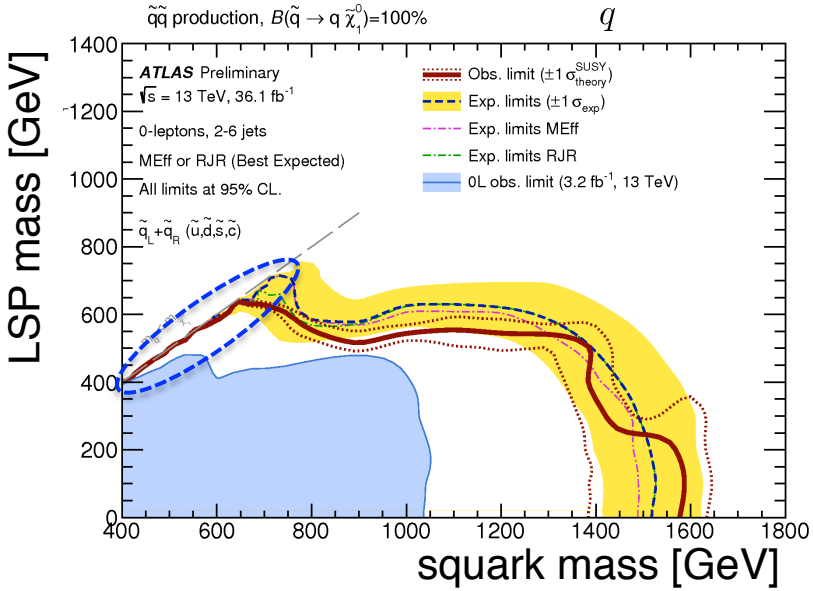


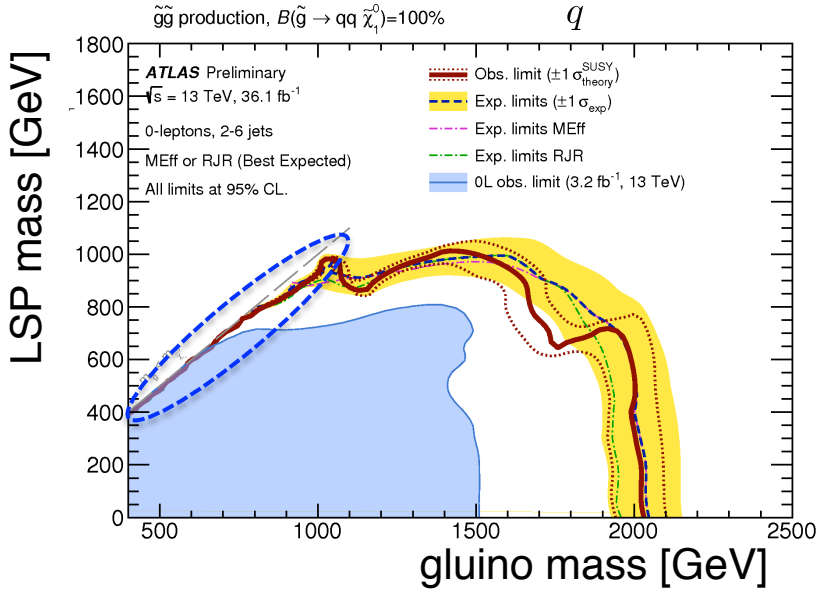
inclusive 0L
CONF-2017-022

Interpretations



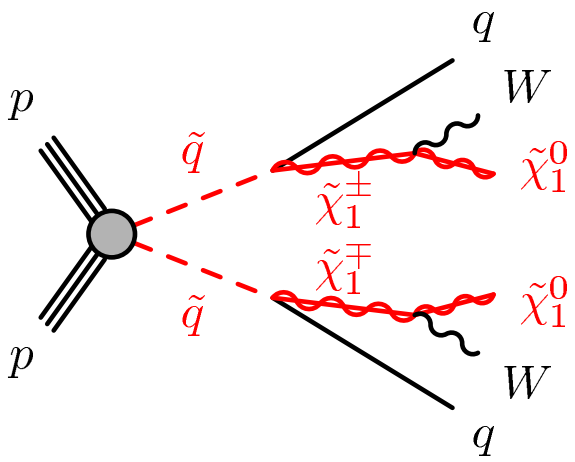


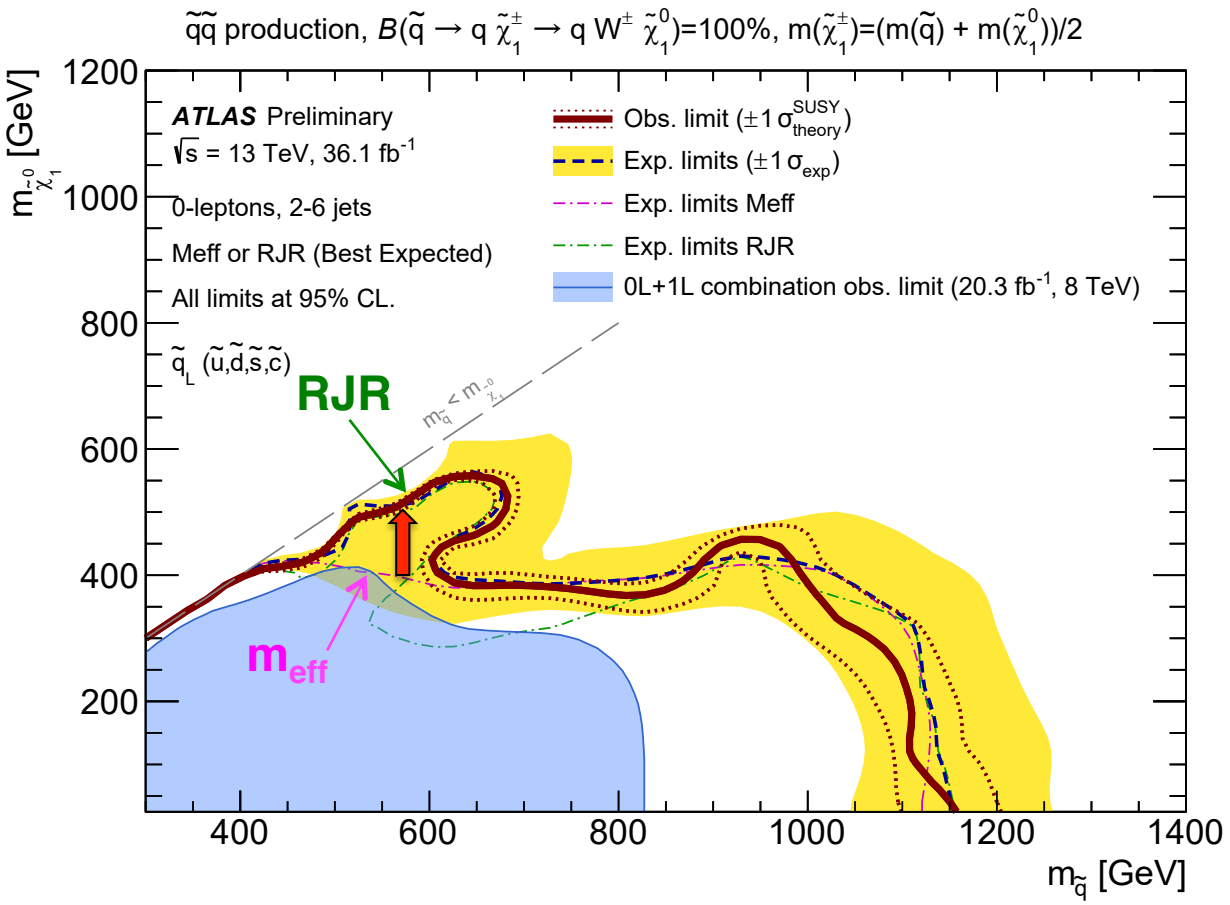




- **Probe up to 1.6 TeV squarks and 2.0 TeV gluinos**
- RJR method enhances sensitivity to compressed region, nearly down to **ΔM = m(squark/gluino) – M(LSP) = 0 GeV**

Interpretations

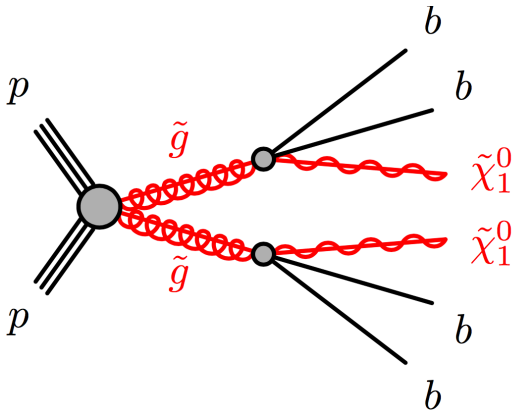




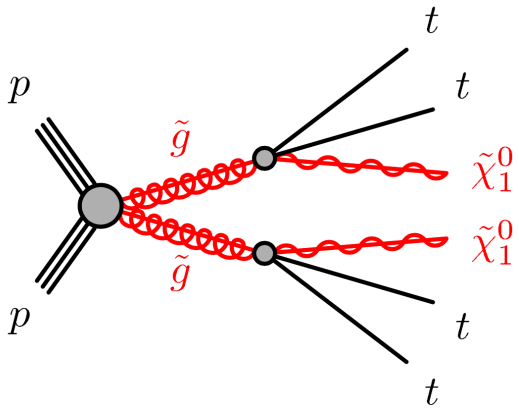
- RJR approach extends sensitivity by ~200 GeV in mass of $\tilde{\chi}_1^0$

Overview of multi-b Search

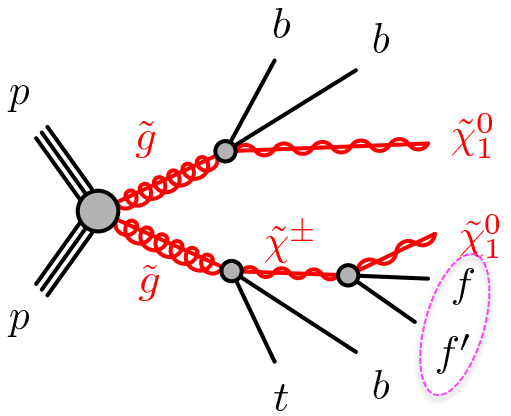
gluino decays via bottom
0-lepton channel



gluino decays via top
0/1-lepton channel



mixed decays to top/bottom (including g → t b C1)
0-lepton channel

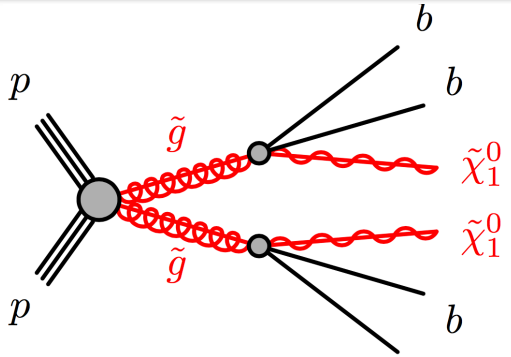


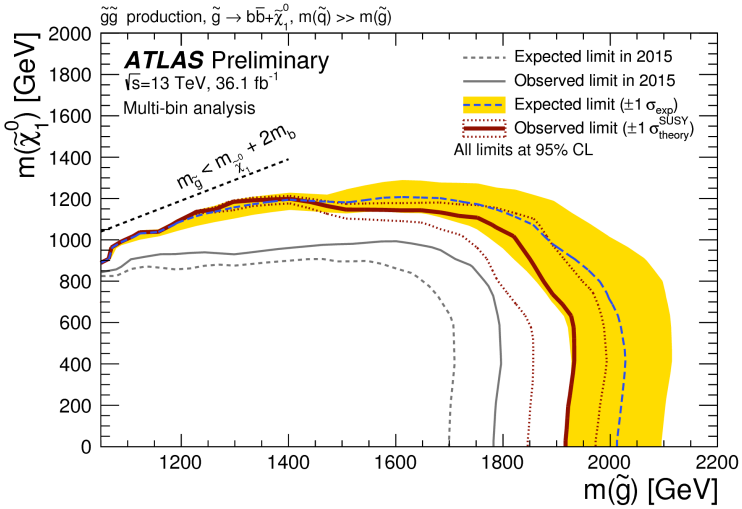
soft → undetected

- **Strong SUSY with heavy flavor**: target gluino decays via 3rd gen. squarks
  - Also target models with mixed decays $\tilde{g}\tilde{g} \to (t\bar{t}\,\tilde{\chi}_1^0)(b\bar{b}\,\tilde{\chi}_1^0)$ and $\tilde{g} \to t\bar{b}\,\tilde{\chi}_1^-$
- **Signature**: 0/1 leptons + ≥3 b-jets + MET
- **Strategy**: two approaches → **cut-and-count** overlapping regions for discovery, **multi-bin** exclusive regions for exclusions

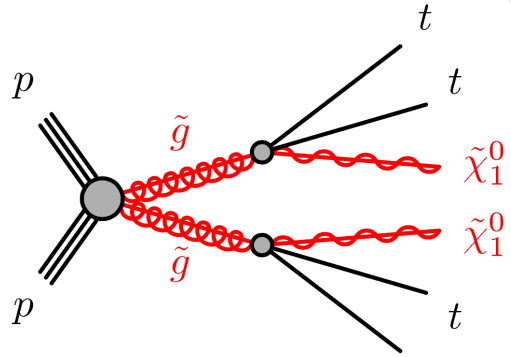
b-jet+MET
CONF-2017-021

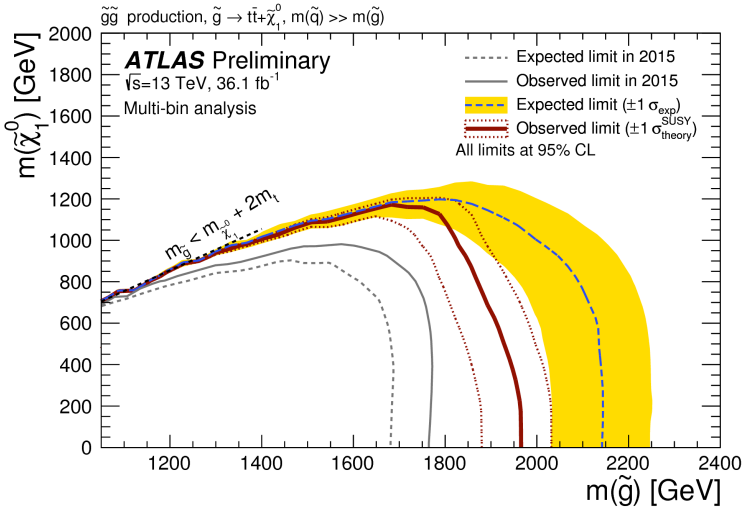
Interpretations





Probe gluinos up to 1.9 TeV, and down to
Δm = m(gluino)-m(LSP) ~ 100 GeV

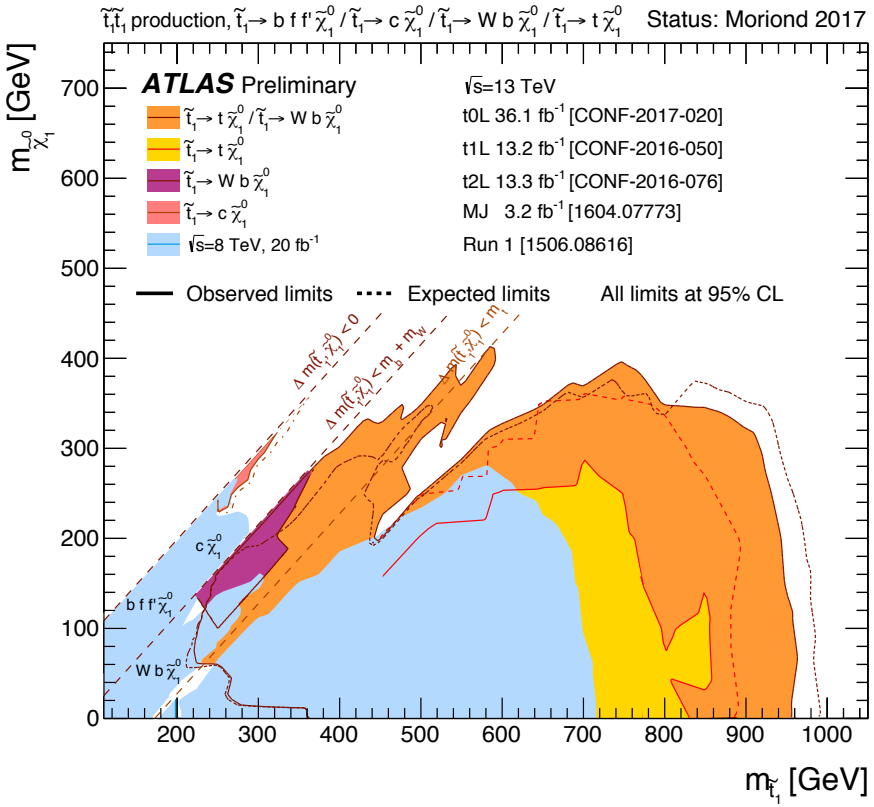


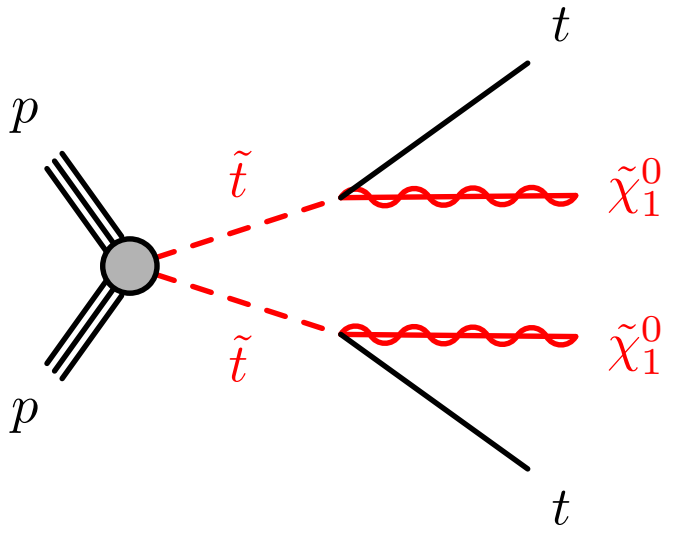


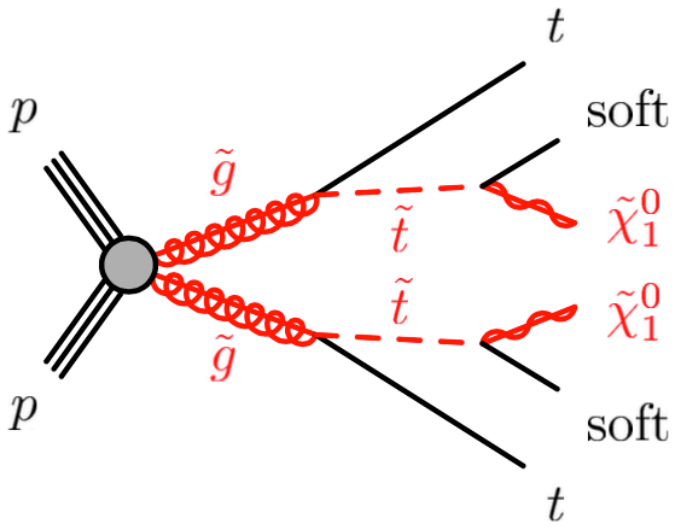
Probe gluinos up to 1.95 TeV, and down to
Δm = m(gluino)-m(LSP) ~ 2 m_{top}

- Also consider variable BF for $\tilde{g} \to t\bar{t}\,\tilde{\chi}_1^0 \,/\, b\bar{b}\,\tilde{\chi}_1^0 \,/\, t\bar{b}\,\tilde{\chi}_1^-$
  - **For ligh $\tilde{\chi}_1^0$, exclude m_{gluino} < 1.5 regardless of BF**

Part 2: 3rd Generation SUSY

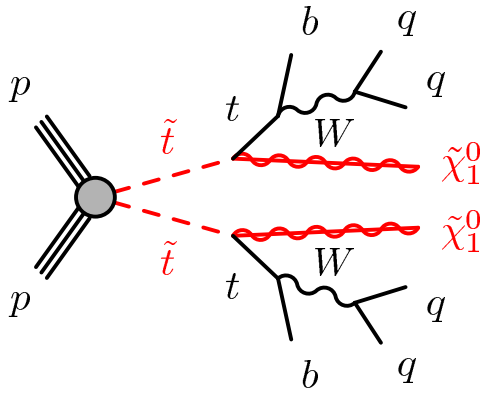


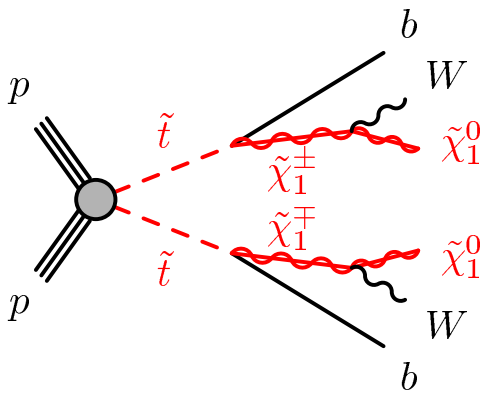


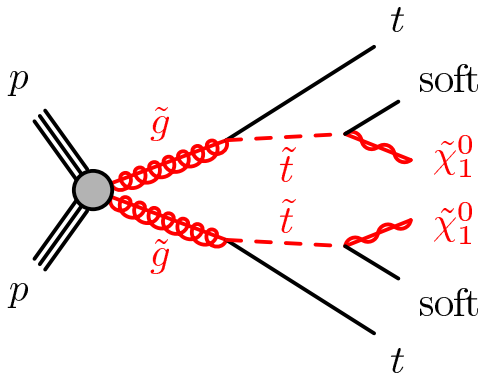


Overview of 0ℓ Search

- Search for **top squark pairs** in all-hadronic final state
- **Signature**: ≥4 jets + ≥1 b-jet + MET
- **Strategy**: 5 sets of signal regions (SR), exploit boosted top/W reconstruction







SRA: large Δm = $m_{stop} - m_{LSP}$,
2top / top+W / 1top

SRD: $t \rightarrow b\tilde{\chi}_1^+$
≥5 jets, 2 b-jets

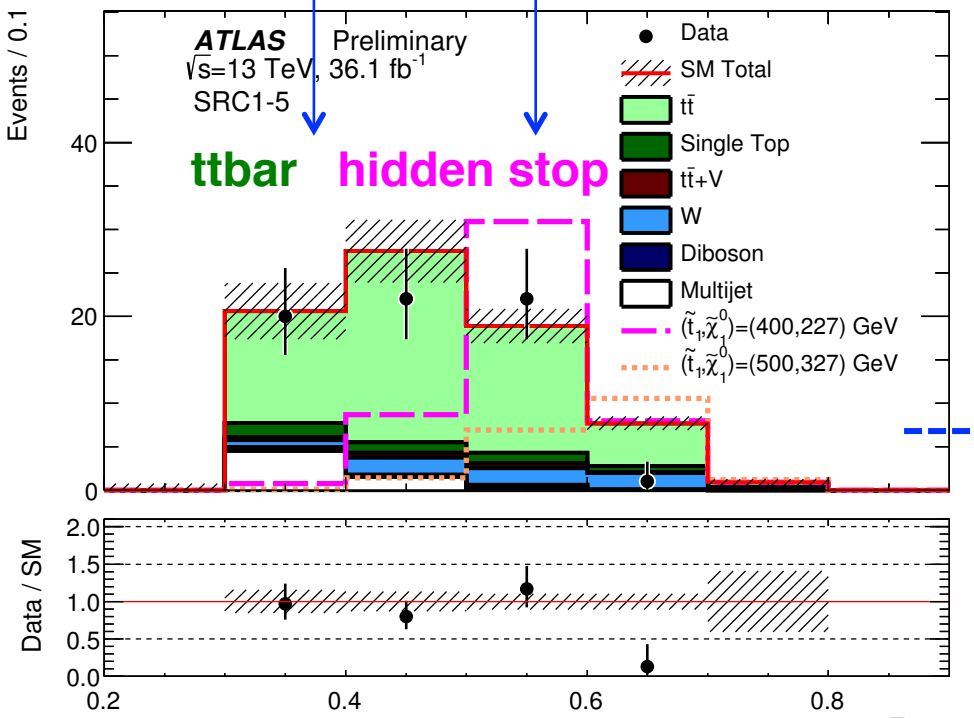
SRE: very small Δm
2top

SRB: intermediate Δm,
2top / top+W / 1top

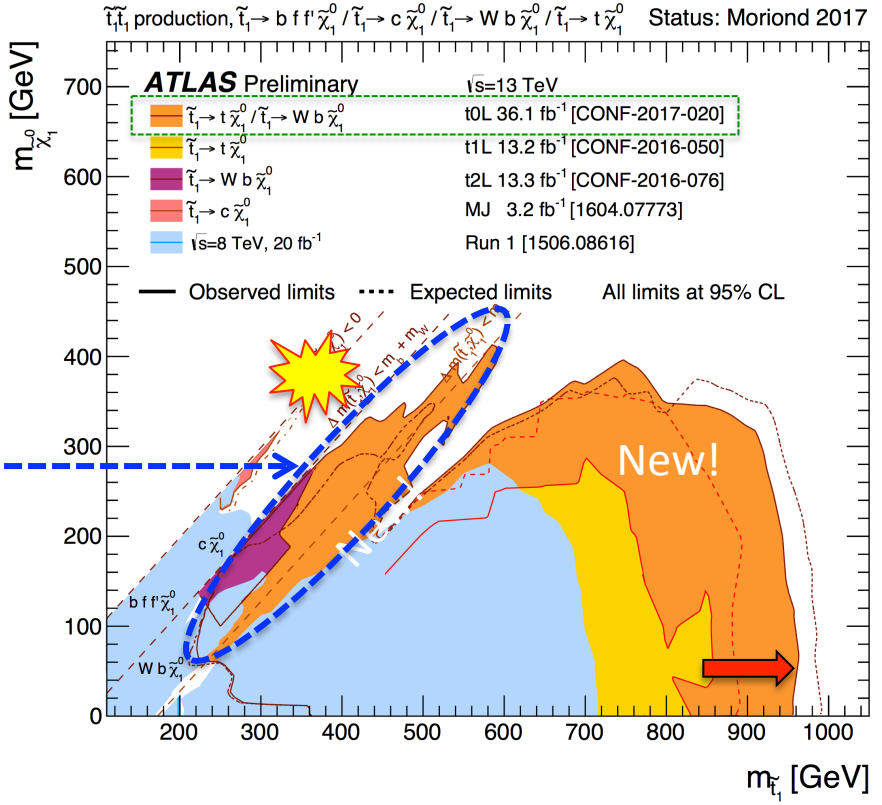
SRC: "hidden stops" $m_{stop} \sim m_{top} + m_{LSP}$,
select events with ISR, use RJR to enhance sensitivity

Results & Interpretation

strong separation



$$R_{\mathrm{ISR}} \equiv \frac{E_{\mathrm{T}}^{\mathrm{miss}}}{p_{\mathrm{T}}^{\mathrm{ISR}}} \sim \frac{m_{\tilde{\chi}_1^0}}{m_{\tilde{t}}}.$$

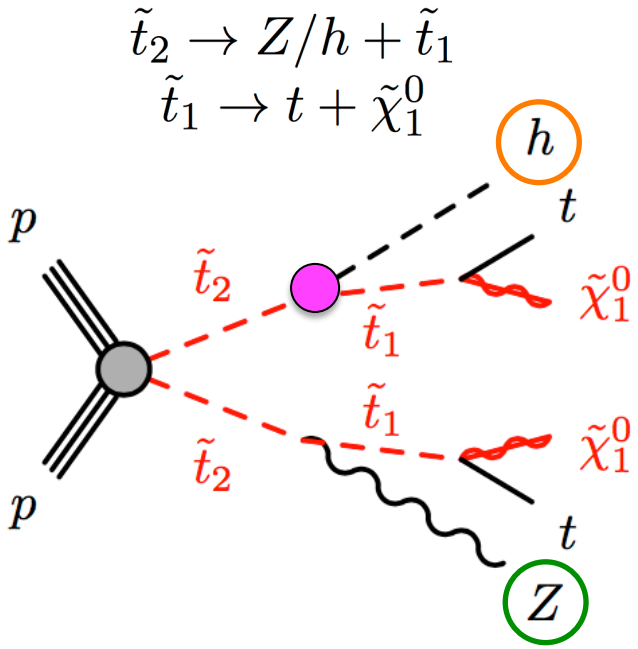


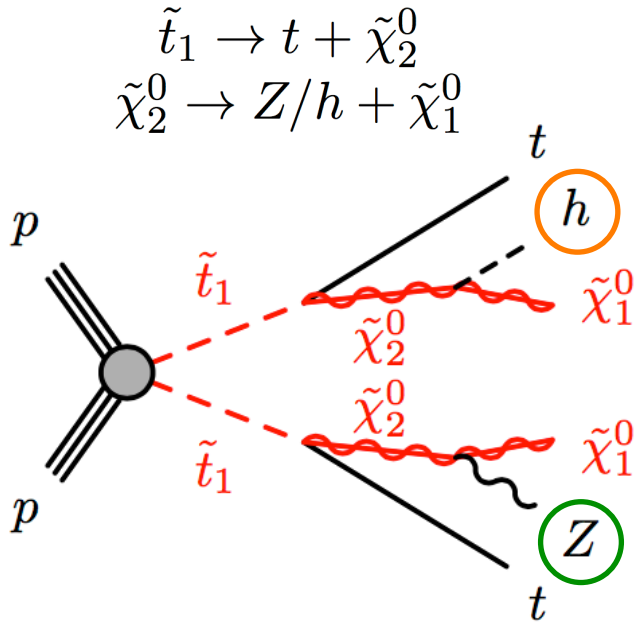
enhanced sensitivity to hidden stops

exclude m_{stop} 235-590 GeV

mass reach up to 950 GeV

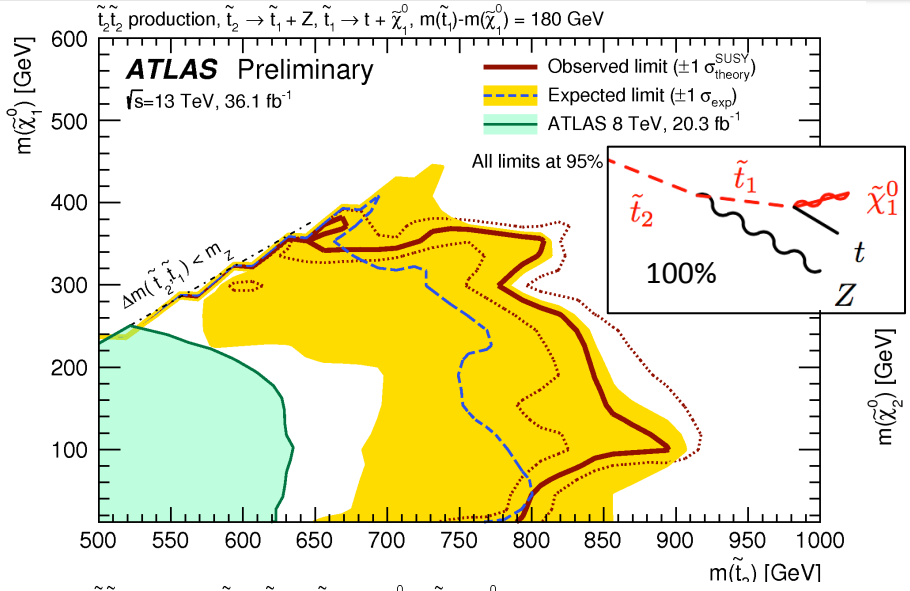
Stop with Z/h Overview

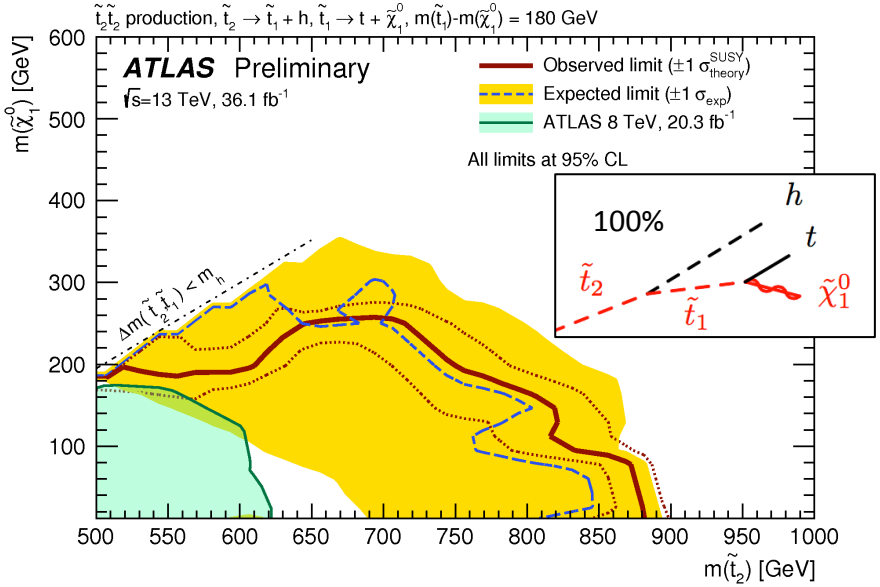


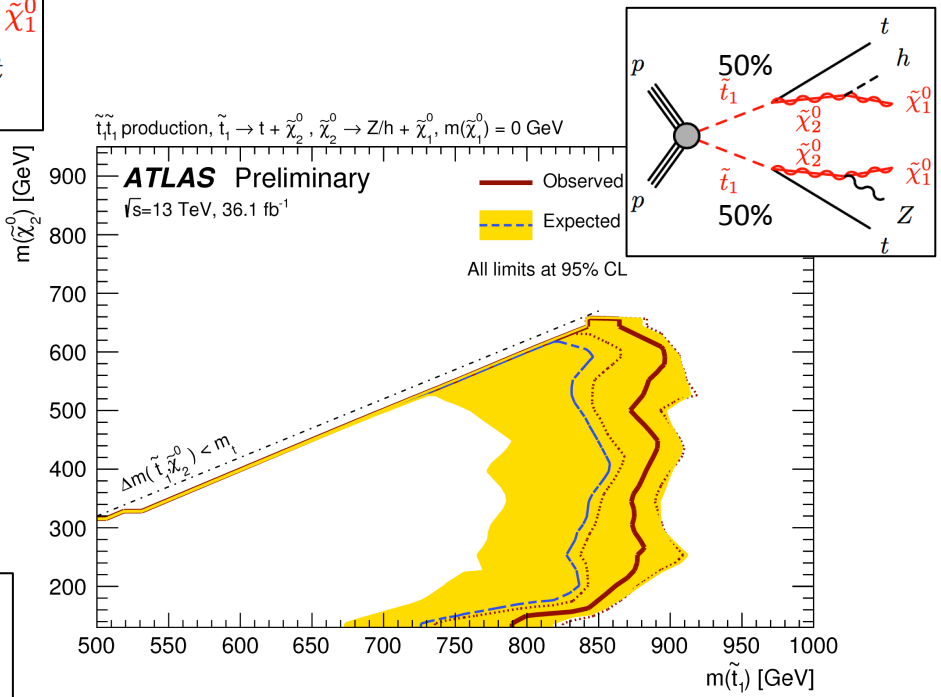


- Extend search to target **stops with Z/h bosons in decay chain**
- **Signature**: 1/2/3 leptons + jets + MET
- **Strategy**: two approaches targeting decays via Z or h:
  - **Target Z→ℓ⁺ℓ⁻:** search in events with 3ℓ+b
  - **Target h→bb:** search in events with 1/2 ℓ+4b and reconstruct h→bb candidate
    → probe **stop-higgs coupling** that is key for solution to hierarchy problem

Stop with Z/h Interpretation

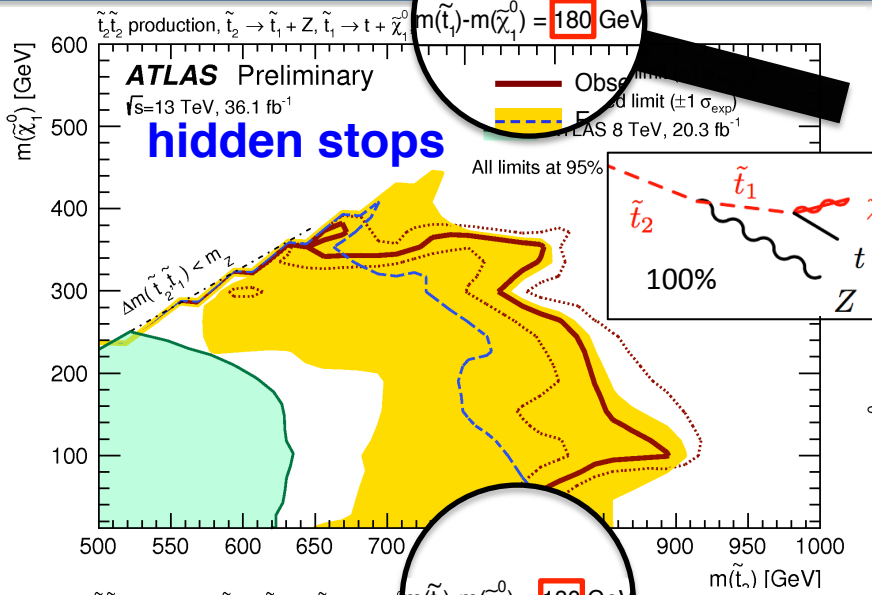


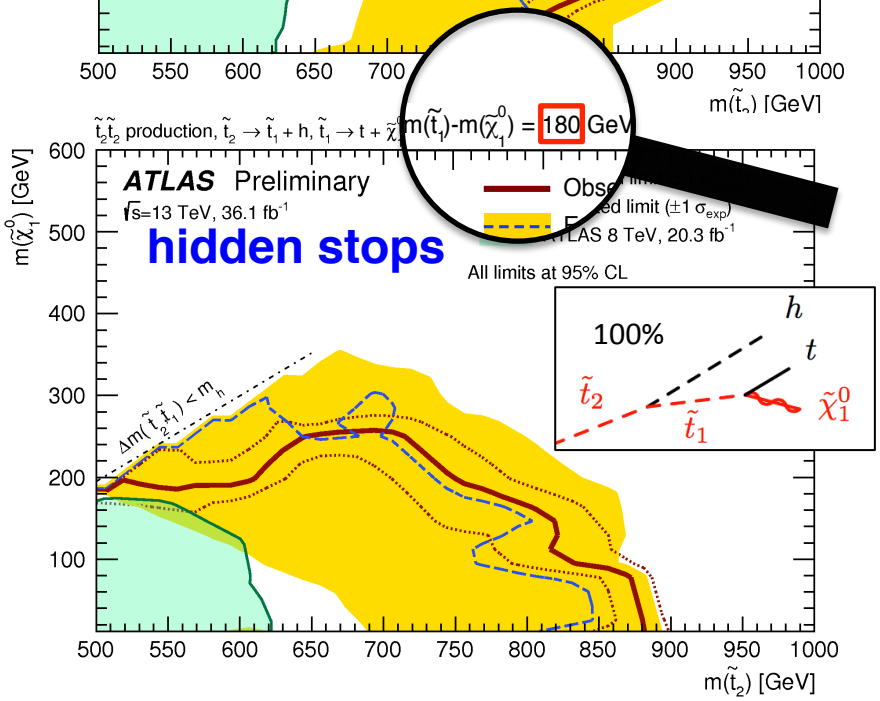


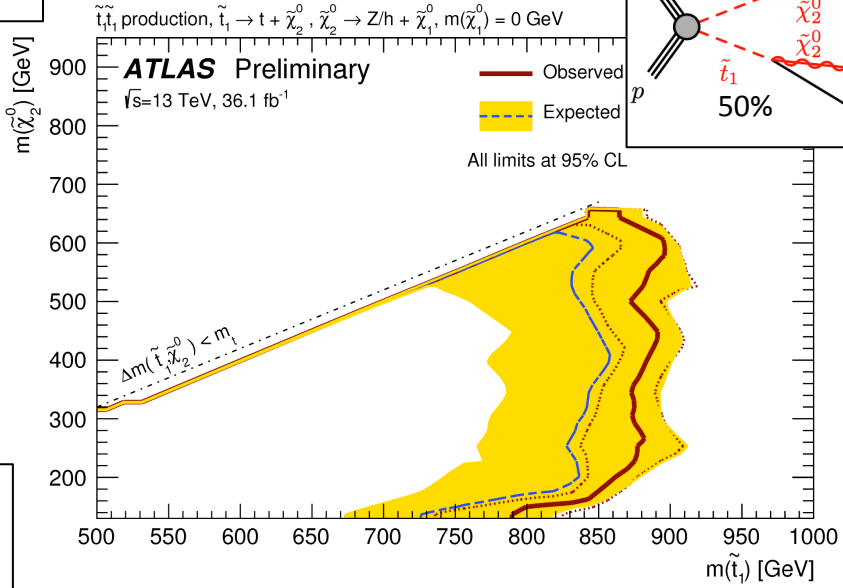


stop with Z/h
CONF-2017-019

Stop with Z/h Interpretation

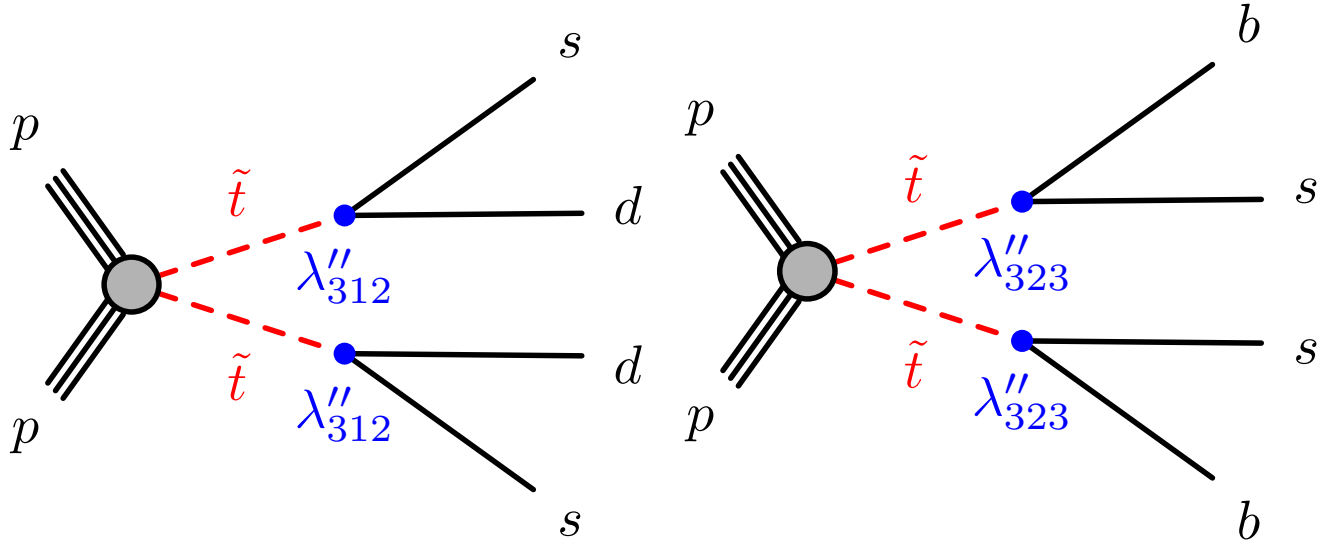






Overview of stop 2×2 Search

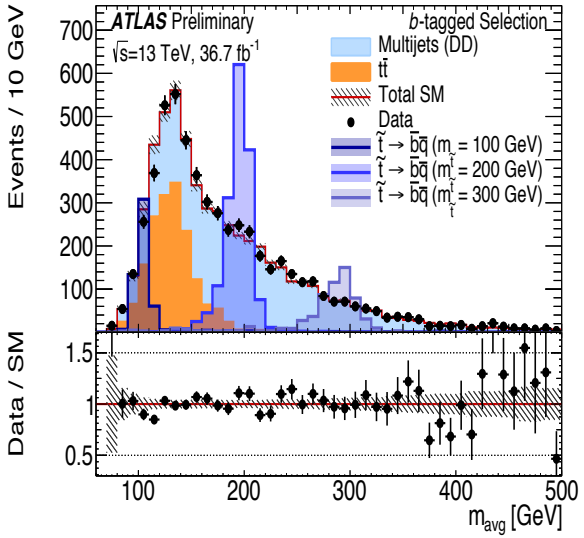
$$\mathcal{W}_{\mathrm{RPV}} = \kappa_i L_i H_u + \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i \bar{Q}_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k,$$

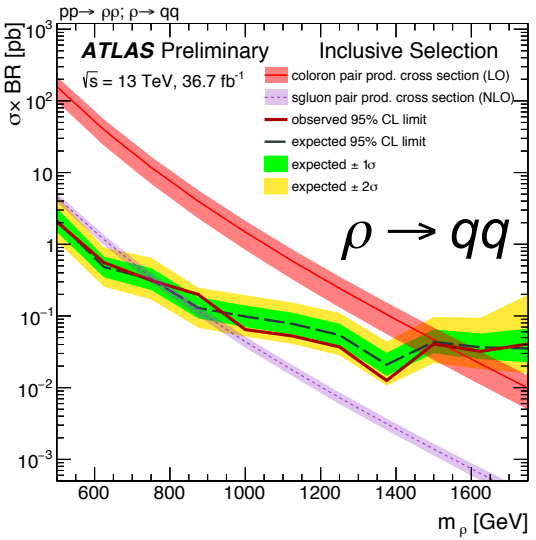


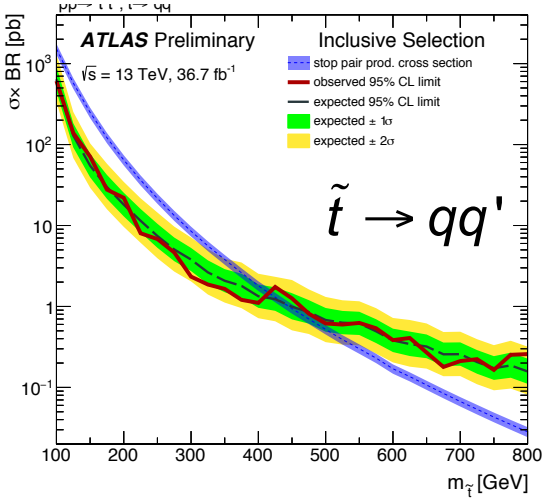
- **RPV stops**: stops could be light but elude detection in MET-based searches if they decay via RPV operators, e.g. stop ⟶ j j
- **Signature**: 4 jets with 2 resonances, inclusive or ≥2 b-jets
- **Strategy**: select events with ≥4 p_T > 120 GeV jets, pair leading 4 jets into 2 di-jets by minimizing $\Delta R_{\mathrm{min}} = \sum_{i=1,2} |\Delta R_i - 1|$

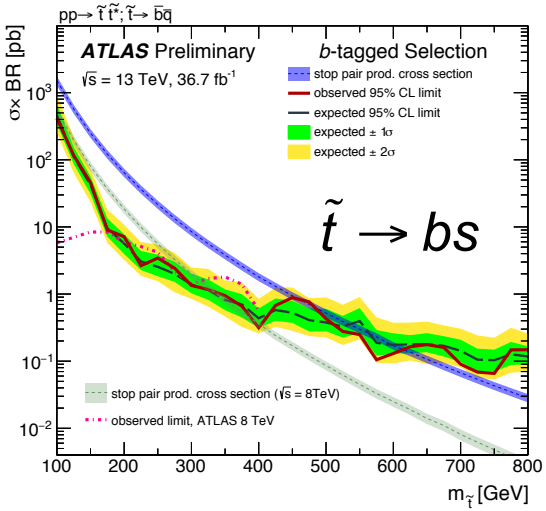
Overview of stop 2×2 Search

- No evidence of resonances in average di-jet mass
- Probe up to $m_{stop} \sim 410$ GeV
- Probe up to $m_{stop} \sim 610$ GeV for HF-enriched decays
- Probe color octet scalar gluons up to $m_g \sim 800$ GeV

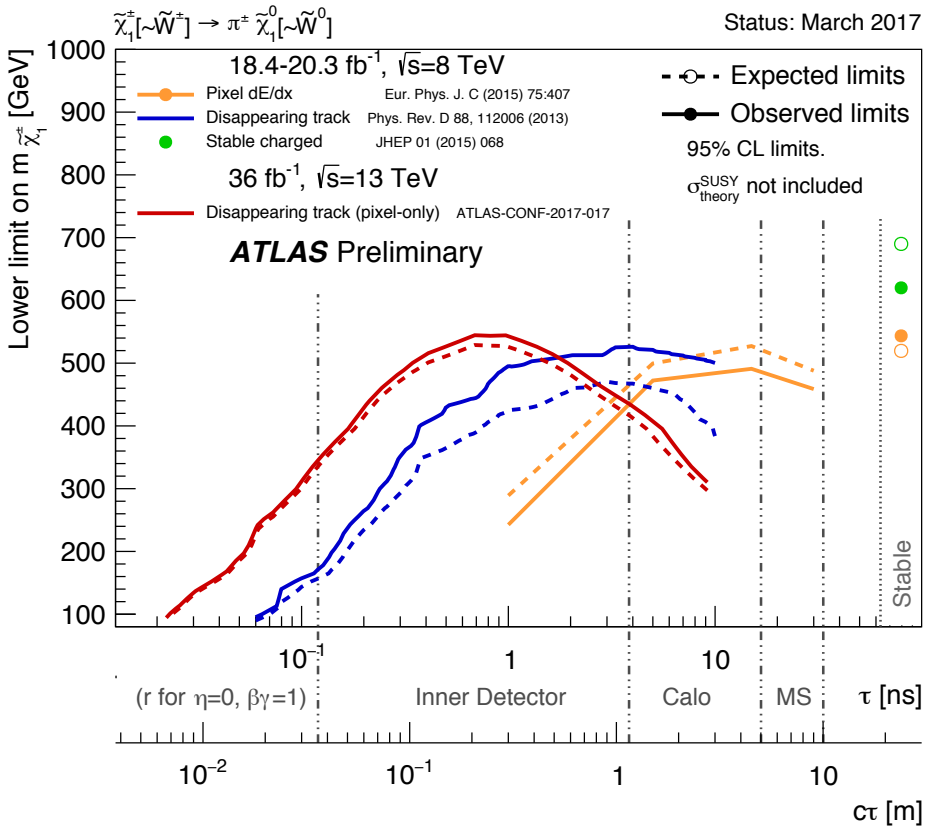


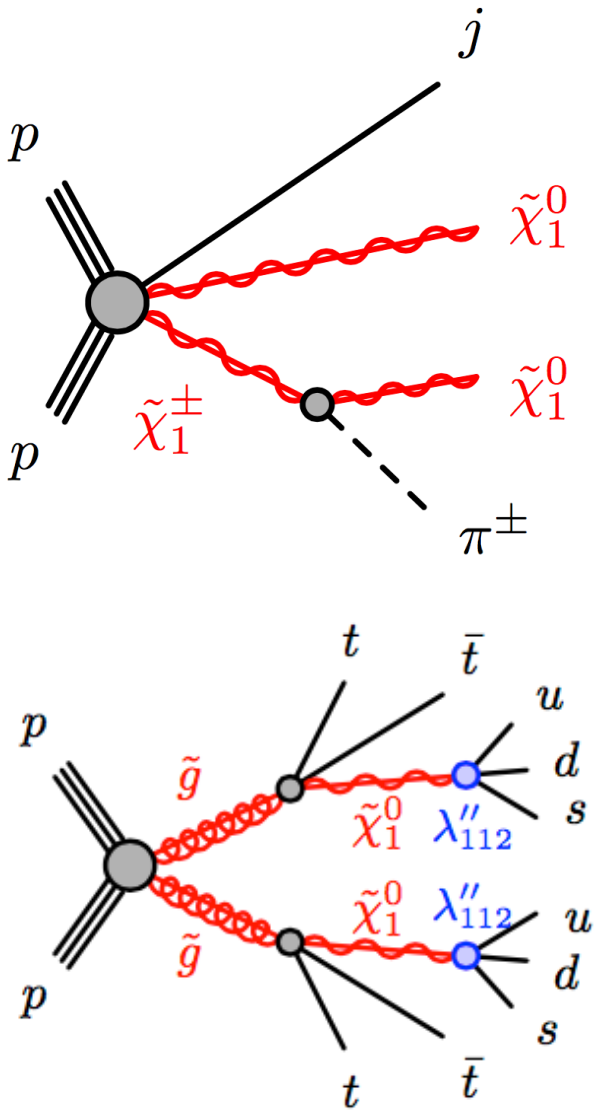




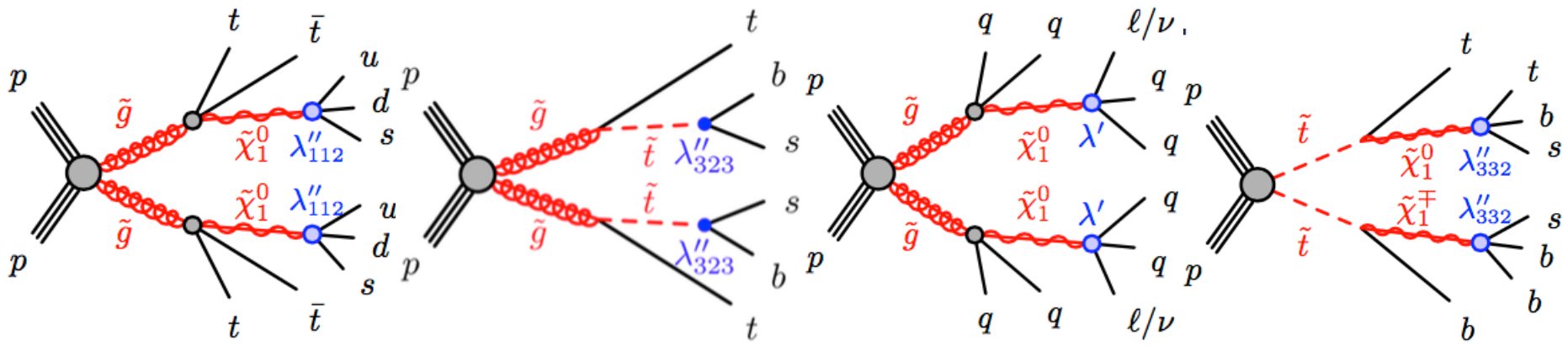


Part 3: RPV/Long-lived SUSY





Overview of RPV 1ℓ Search



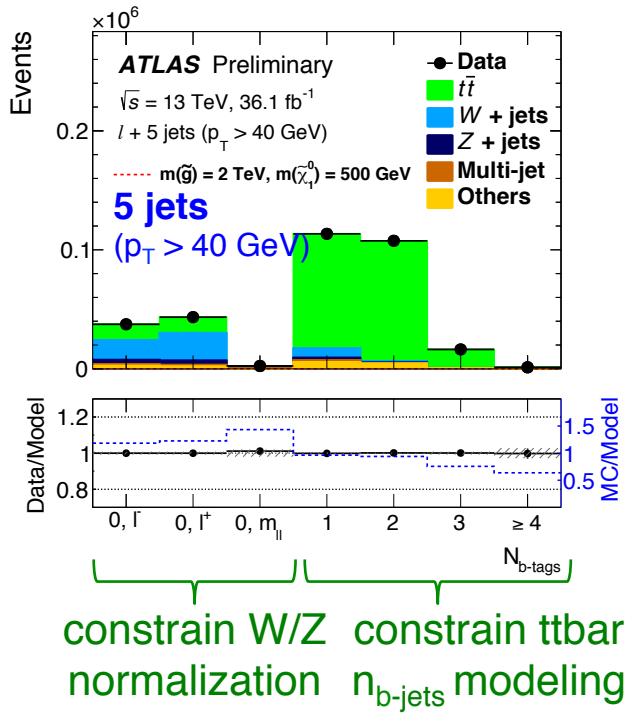
- **RPV SUSY**: strong production with LSP decays to jets/leptons
- **Signature**: high multiplicity events with 1 lepton, ≥8 jets, no MET
  - Final state actively asked for by theory community, e.g. [1]
- **Strategy**: 3 search channels with jet p_T > 40/60/80 GeV thresholds, results categorized by 0/1/2/3/≥4 b-jets

[1] Evans, Kats, Shih, Strassler, "Toward Full LHC Coverage of Natural Supersymmetry," JHEP 1407 (2014) 101

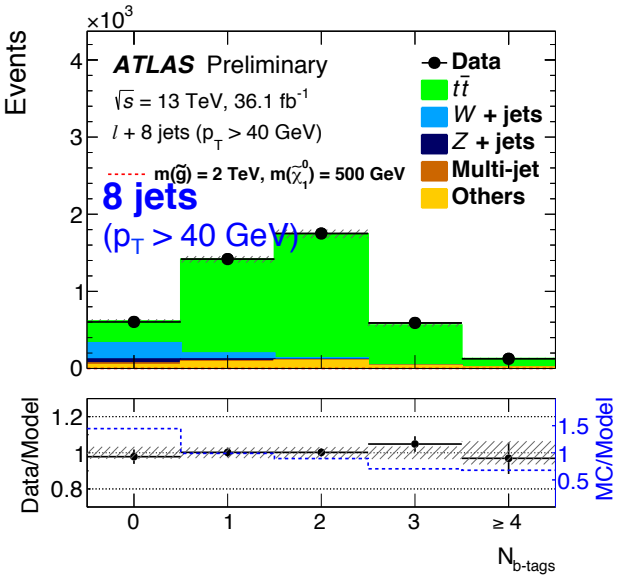
RPV 1L
CONF-2017-013

Example Results

control / validation regions

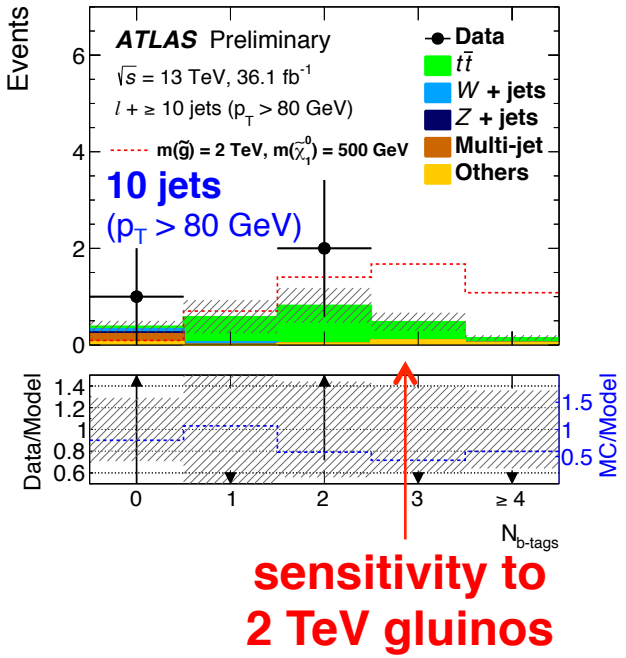


constrain W/Z normalization



constrain ttbar $n_{b\text{-jets}}$ modeling

signal regions

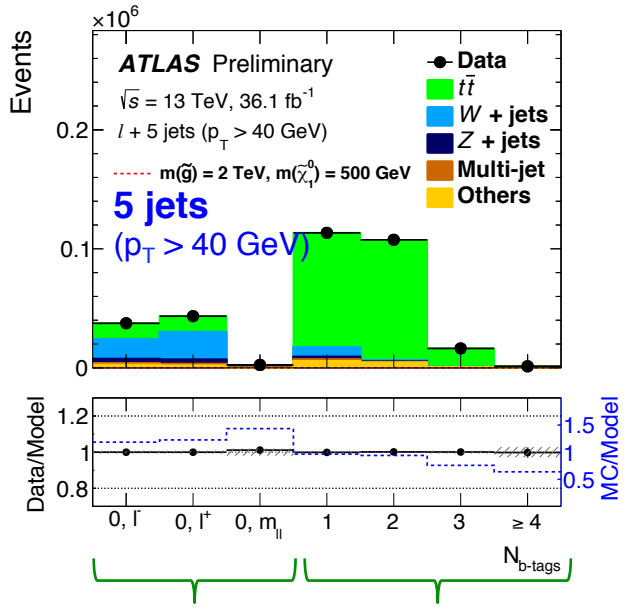


sensitivity to 2 TeV gluinos

- MC over-estimates data with 0 b-jets (W+jets mismodeling) and under-estimates at high b-jets (tt+HF mismodeling)
- Background model extrapolates normalizations and shapes from low → high jet multiplicities
- **Data is broadly consistent with background model**

Example Results

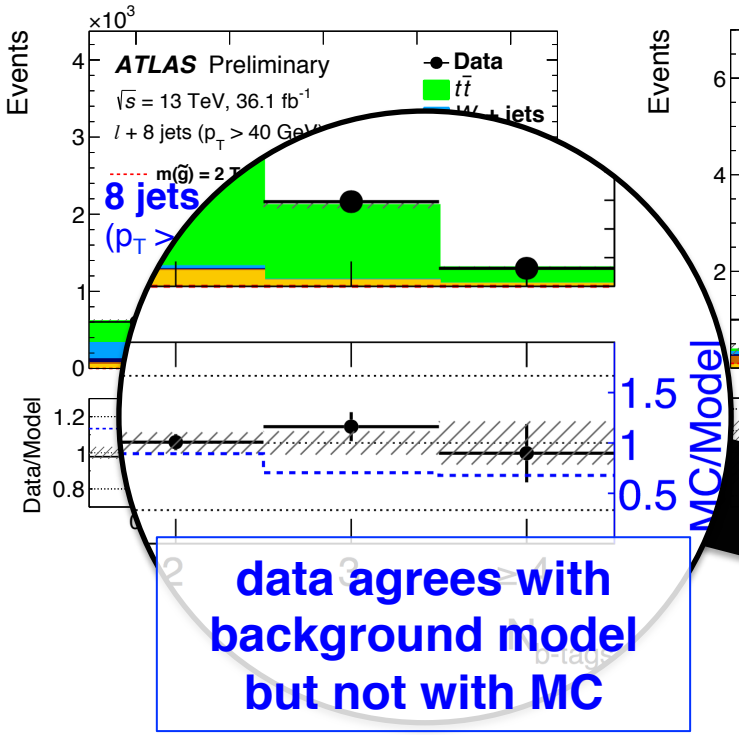
control / validation regions

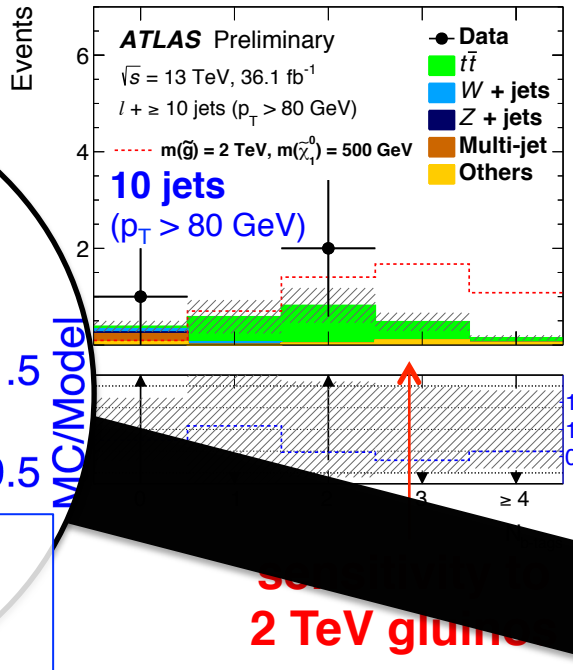


constrain W/Z normalization

constrain ttbar $n_{b\text{-jets}}$ modeling

signal regions





data agrees with background model but not with MC

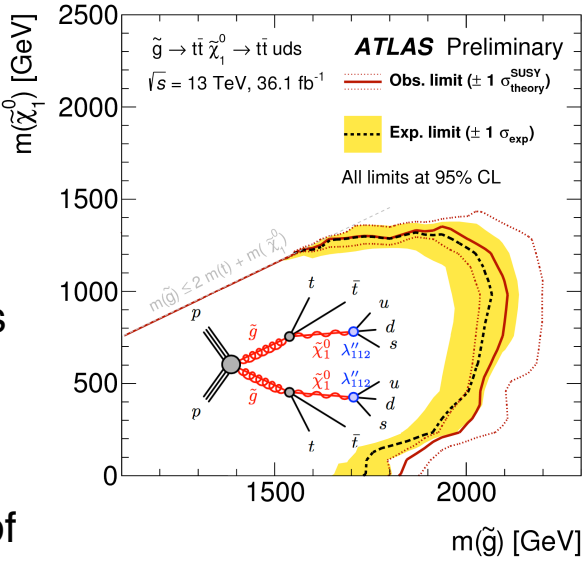
2 TeV gluino

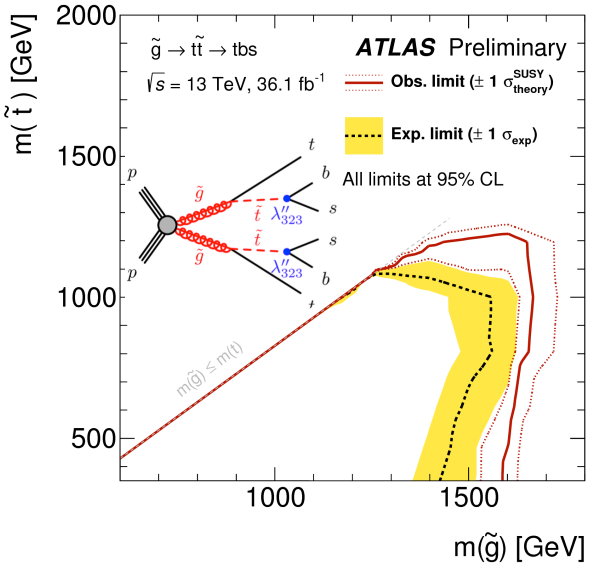
- MC over-estimates data with 0 b-jets (W+jets mismodeling) and under-estimates at high b-jets (tt+HF mismodeling)
- Background model extrapolates normalizations and shapes from low → high jet multiplicities
- **Data is broadly consistent with background model**

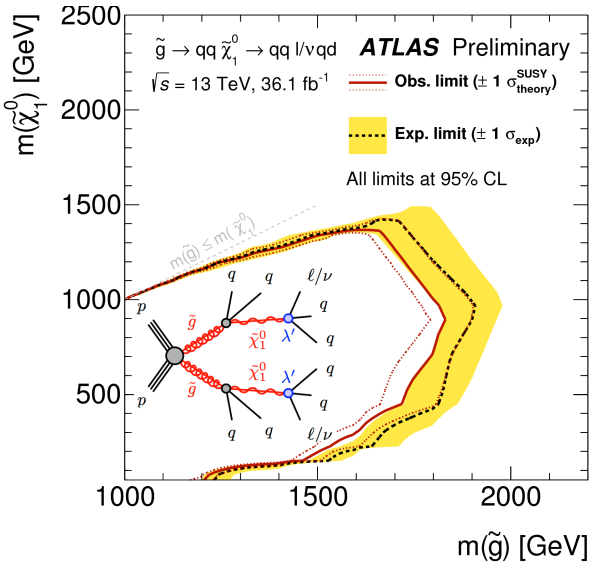
RPV 1L
CONF-2017-013

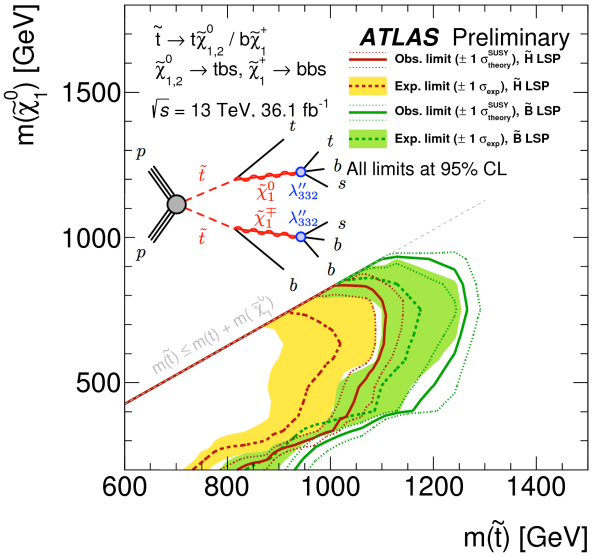
Interpretations

- Limits on 4 RPV SUSY models
  - Probe up to m_{gluino} ~ 2.1
  - Probe up to m_{stop} ~1.1 TeV
- Limit on SM 4-top production of 6.5× SM (9.1 expected)





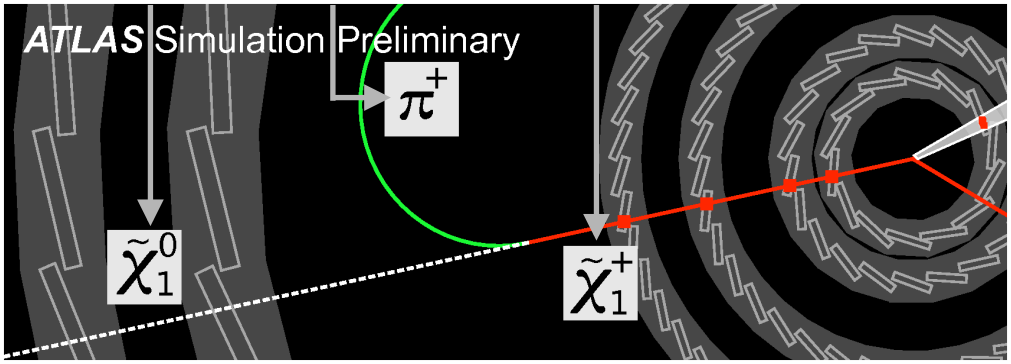


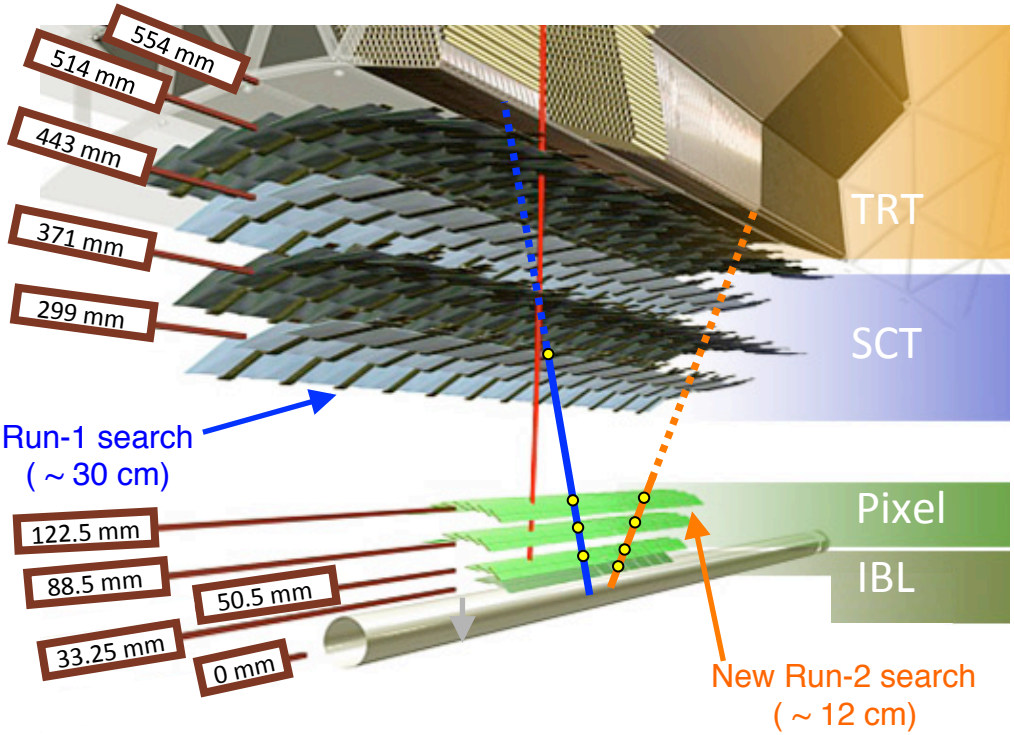


Overview of Disappearing Track Search

- For pure wino-like $\tilde{\chi}_1^{\pm}$ / $\tilde{\chi}_1^0$ (e.g. in AMSB)
  - $\Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0) \sim 160$ MeV
  - $\tilde{\chi}_1^{\pm}$ **long-lived:** $\tau \sim 0.2$ ns
  - **Sizable decay length:** $c\tau \sim 6$ cm
- Chargino decays into ultra-soft pion and neutralino → **disappearing track + MET**
- Run-1 search was sensitive to disappearing tracks with **decay lengths starting from 30 cm ~ 1 ns**
- **Pixel-only tracklets** with new insertable pixel B-layer (IBL) extends sensitivity to shorter decay lengths (12 cm ~ 0.4 ns) **for first time**

MET + pion (very soft) + disappearing track

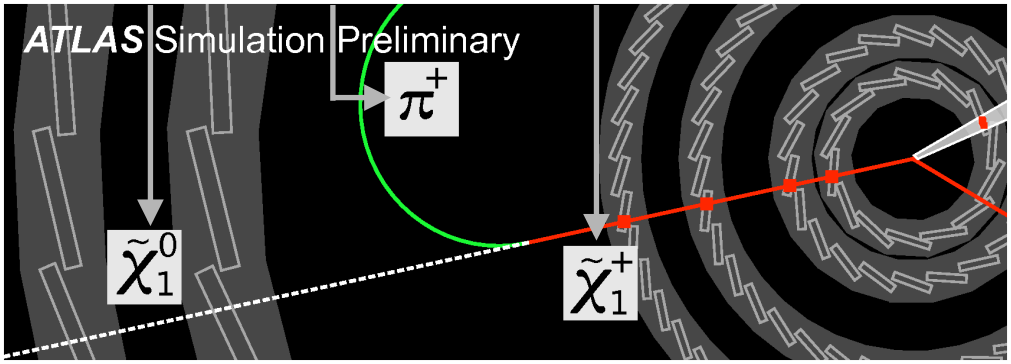


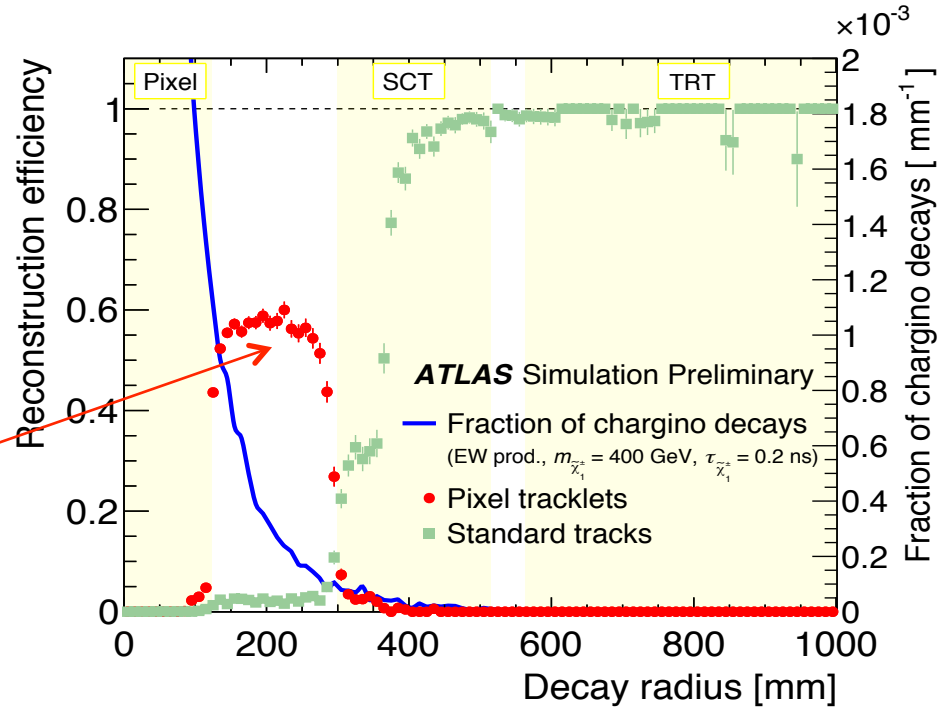


Overview of Disappearing Track Search

- For pure wino-like $\tilde{\chi}_1^{\pm}$ / $\tilde{\chi}_1^0$ (e.g. in AMSB)
  - $\Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0) \sim 160$ MeV
  - $\tilde{\chi}_1^{\pm}$ **long-lived:** $\tau \sim 0.2$ ns
  - **Sizable decay length:** $c\tau \sim 6$ cm
- Chargino decays into ultra-soft pion and neutralino → **disappearing track + MET**
- Run-1 search was sensitive to disappearing tracks with **decay lengths starting from 30 cm ~ 1 ns**
- **Pixel-only tracklets** with new insertable pixel B-layer (IBL) extends sensitivity to shorter decay lengths (12 cm ~ 0.4 ns) **for first time**

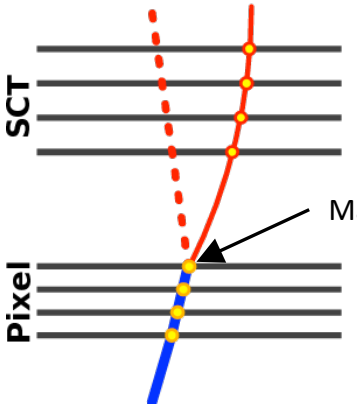
MET + pion (very soft) + disappearing track



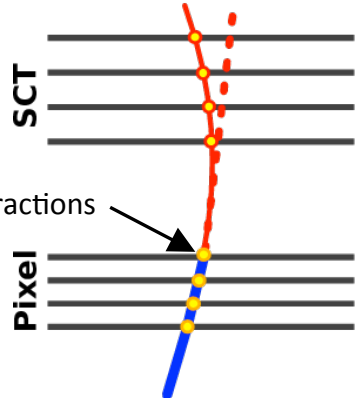


Backgrounds vs. Signal

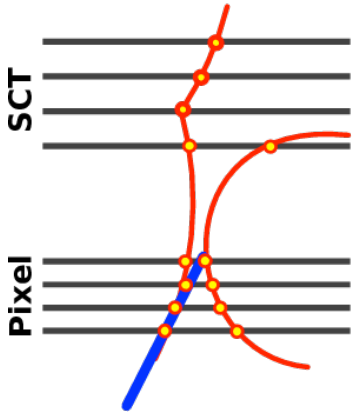
Hadrons
nuclear interaction



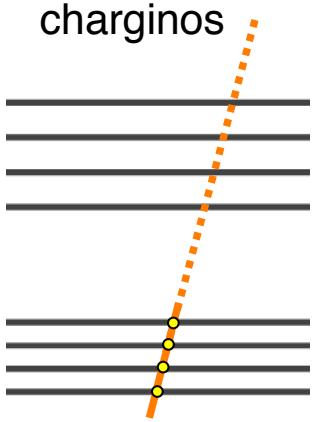
Leptons
hard brem



Fakes
combinatorics



Signal
charginos

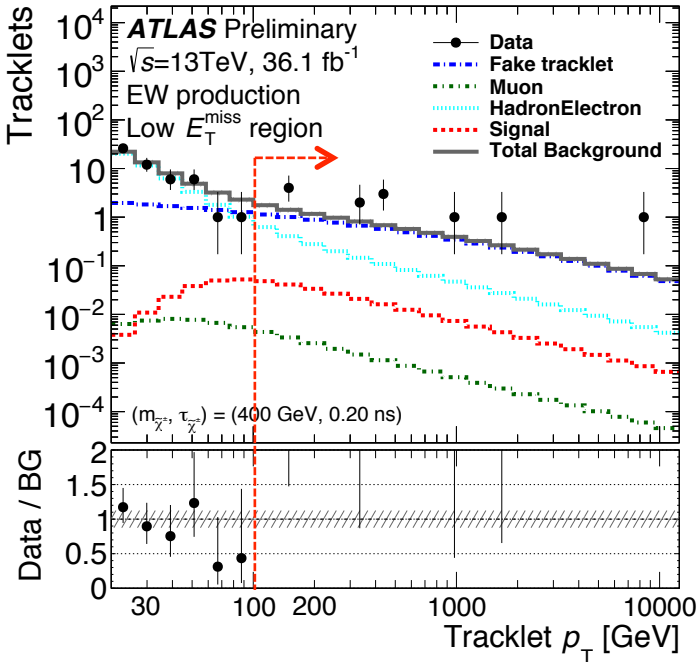


Simultaneous **fit of tracklet p_T** distribution using **templates** for the 3 backgrounds (+ signal)

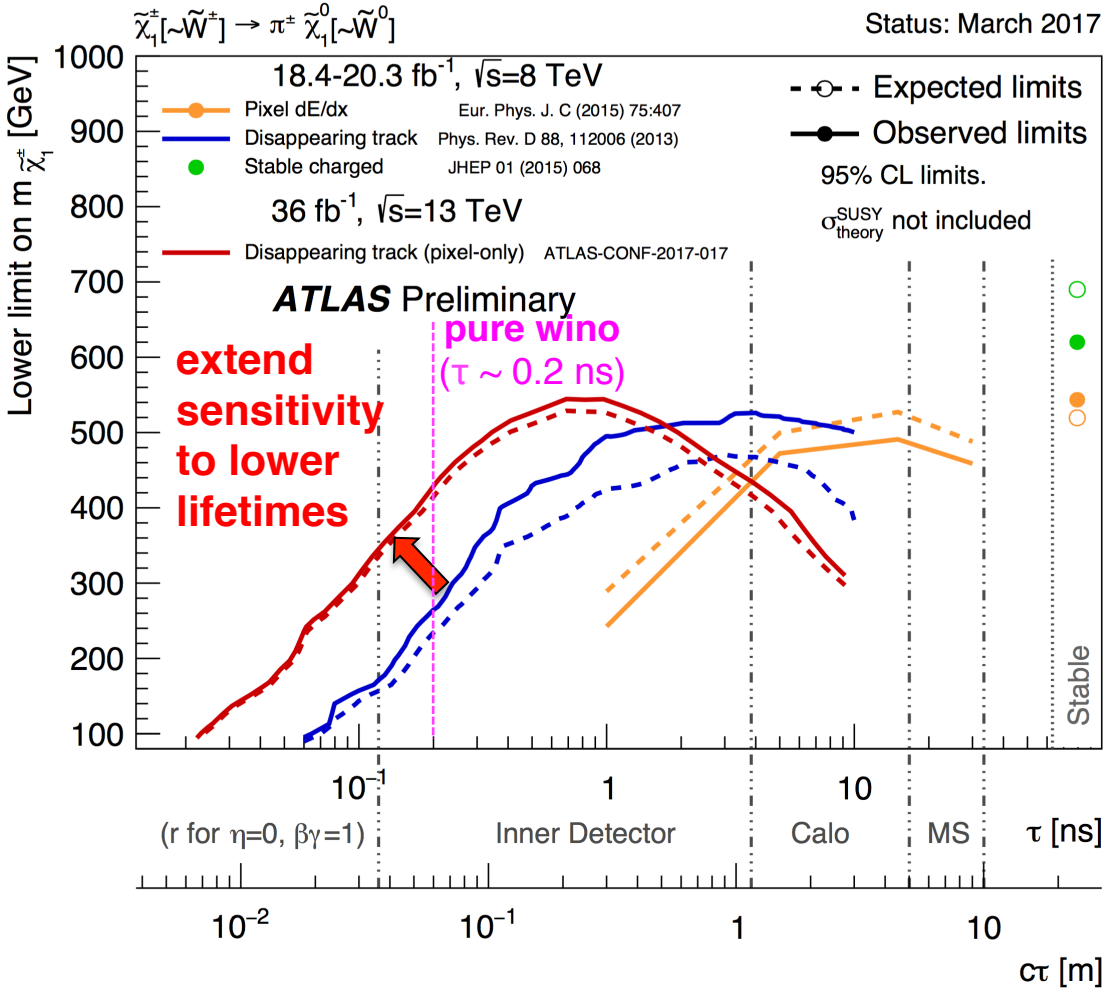
Results & Interpretation

9 observed

6.1 +/- 0.6 expected

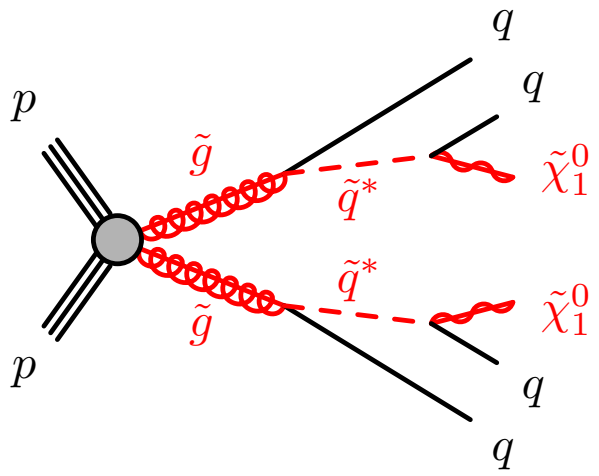


electroweak category
high MET



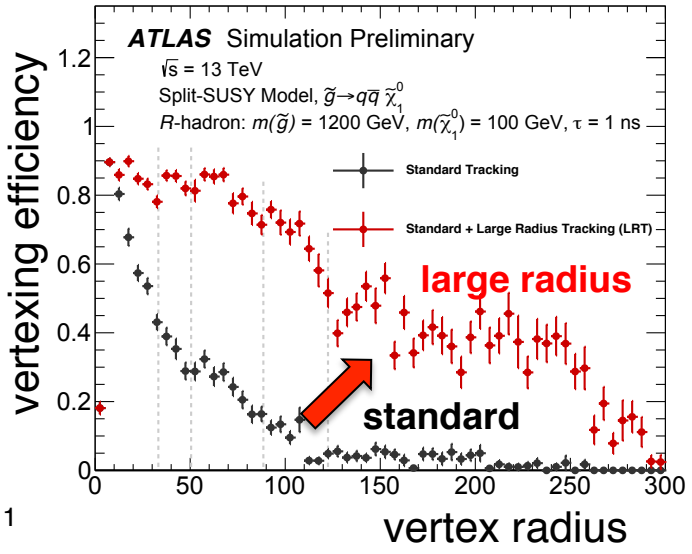
Overview of Displaced Vertex Search

- **Search for long-lived particles from:**
  - Gluino decays with very massive quarks (e.g. split SUSY [1,2])
  - Hidden valley models [3]
  - RPV SUSY [4,5]



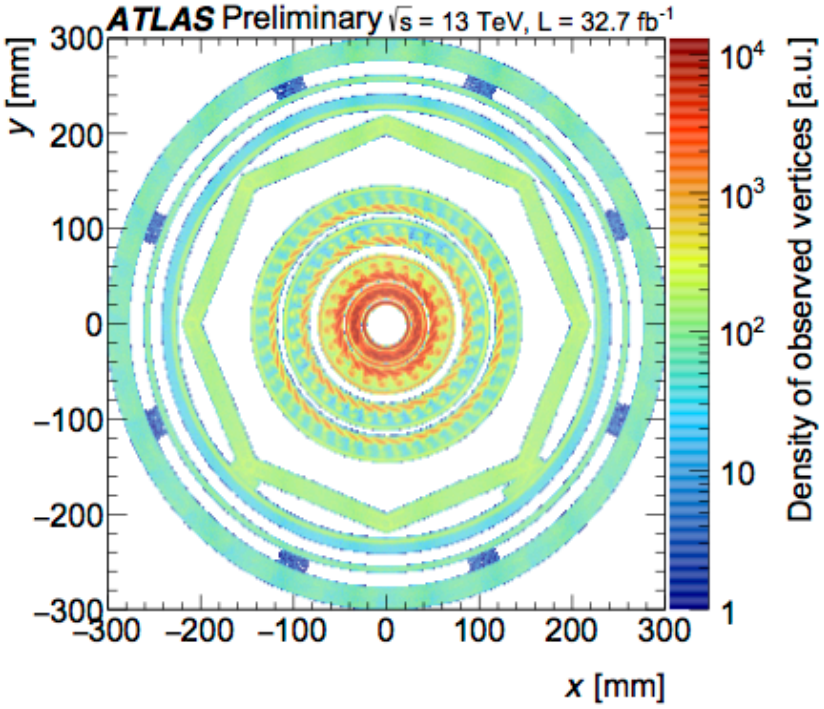
- **Signature:**
  - Displaced vertex (R ~ 1-100 mm) with high track multiplicity (≥5) and mass (>10 GeV) + MET

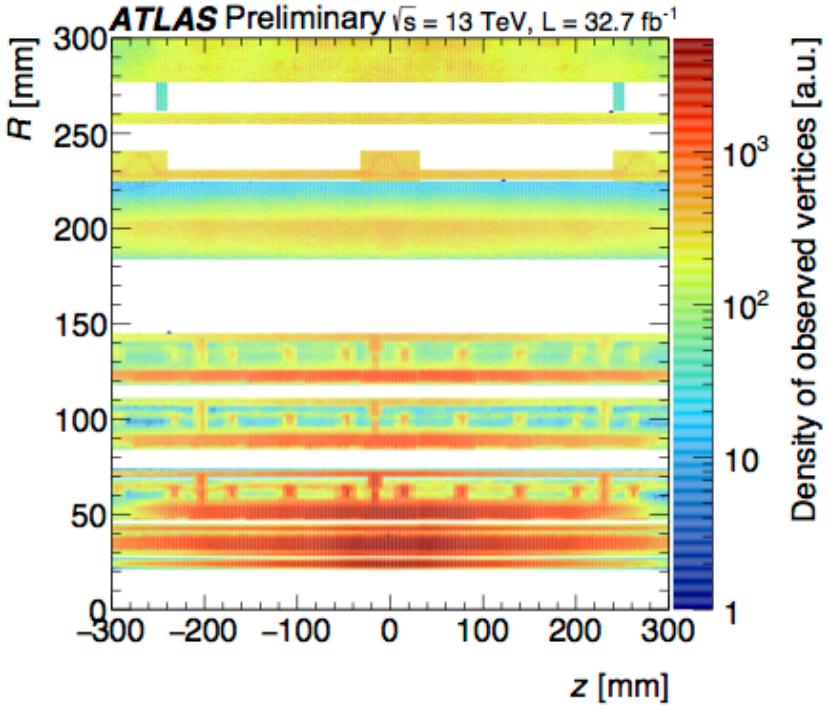
- **Strategy (specialized algorithms):**
  - **Tracking:** 2nd pass ***"Large Radius Tracking"***
  - **Vertexing:** find 2-track vertex seeds, merge, discard poorly associated tracks, require R < 30 cm and |z| < 30 cm



[1] Arkani-Hamed and Dimopolous, JHEP 06 (2005) 073
[2] Guidice and Romanino, Nucl. Phys. B 699 (2004) 65
[3] Strassler and Zurek, PLB 651 (2007) 374
[4] Barbieri et al., Phys. Rept. 420 (2005) 1
[5] Allanach et al., PRD75 (2007) 035002

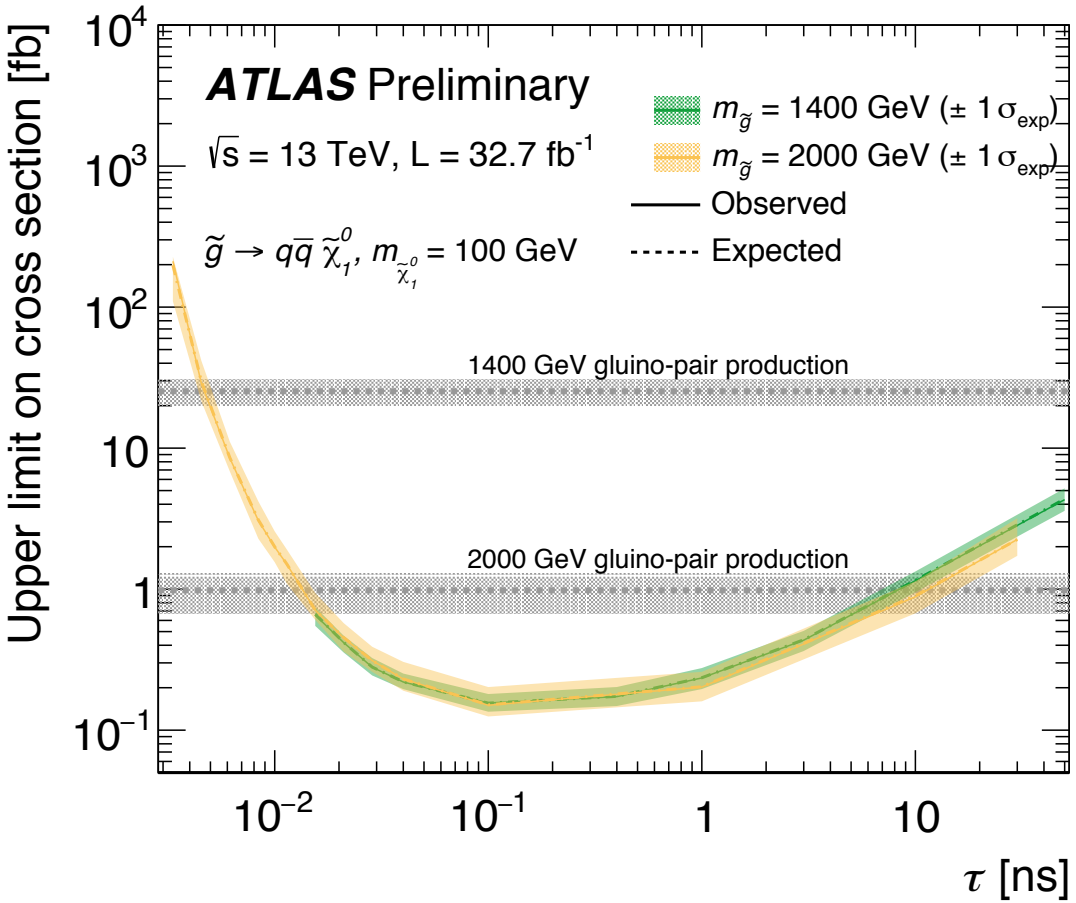
Material Mapping





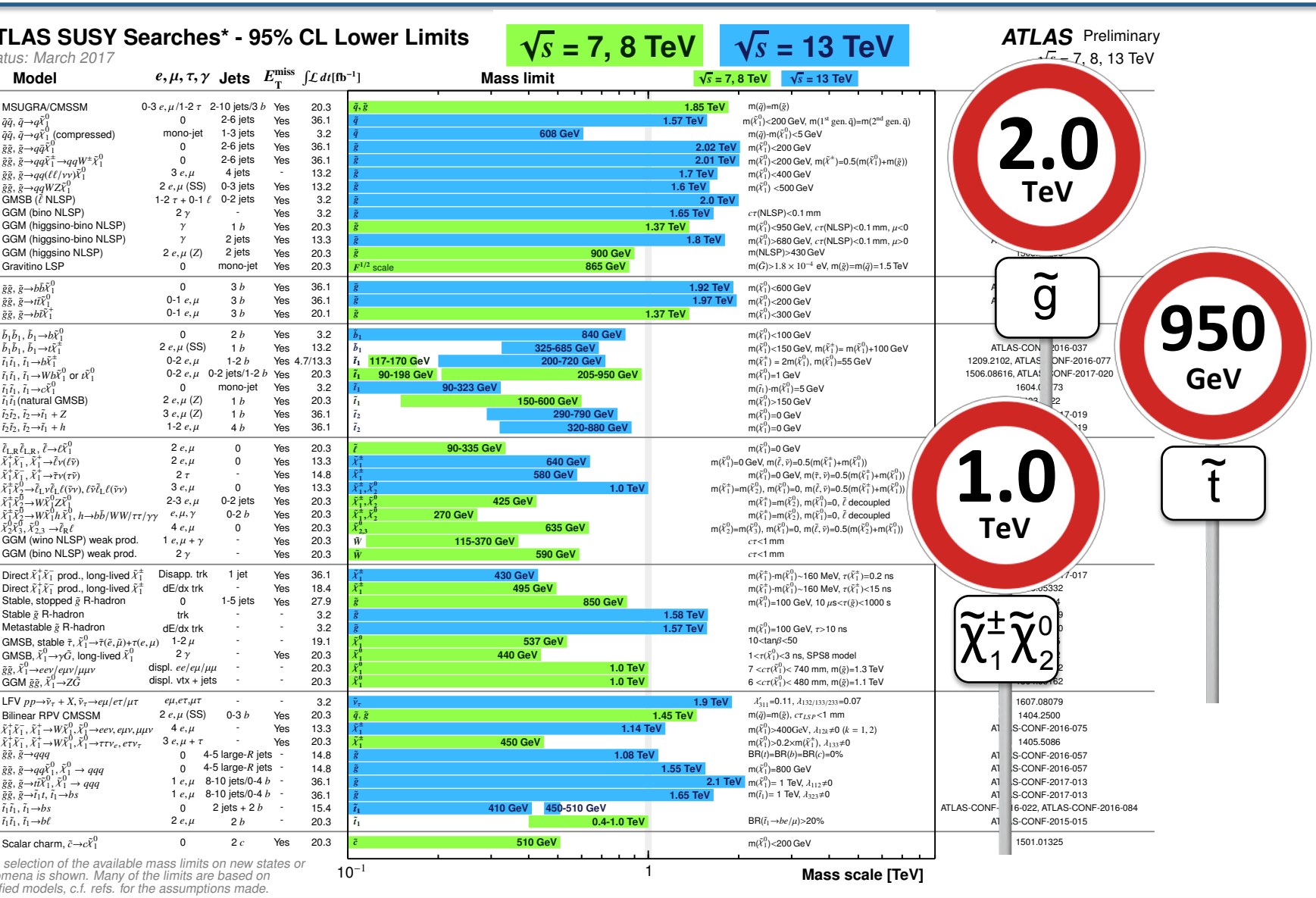
- Map material using displaced vertices in min bias data
- Veto vertices in material regions ⟶ strong suppression of material interactions with 42% reduction in fiducial volume

Results and Interpretation



- **0 events observed vs. 0.02 ± 0.02 expected**
- Exclude long-lived gluinos up to 2.2 TeV with $\tau \sim O(10^{-2})$-$O(10)$ ns

ATLAS SUSY Searches as of March 2017



RPV long-lived EW 3rd gen. strong

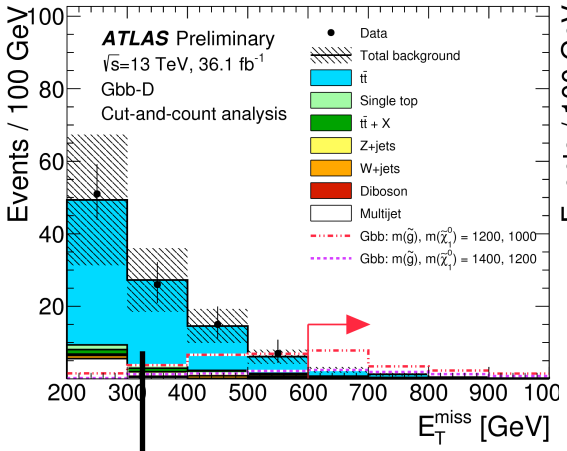
Summary & Outlook

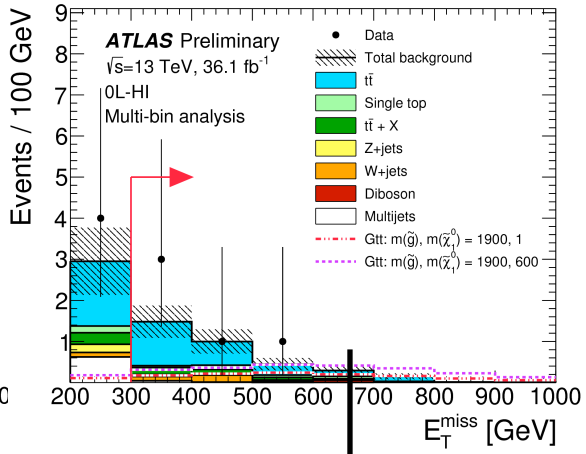
- Huge thanks to LHC team for fantastic performance in 2016
- 8 NEW results based on full 2015+2016 36.1 fb^{-1} 13 TeV data
  - **Strong:** inclusive squark/gluino search + multi-b search
  - **3rd generation:** stop 0ℓ + cascade decays with Z/h + RPV 2×2
  - **RPV/long-lived:** 1ℓ+multi-jet + disappearing track + displaced vertex
- **May interesting new directions:**
  - RJR techniques for compressed SUSY, including hidden stops
  - Targeting mixed decays in addition to BF=100% simplified models
  - Addition of pixel-only tracks to extend long-lived searches to lower cτ
  - Non-standard reconstruction algorithms for displaced tracks/vertices

Backup Material

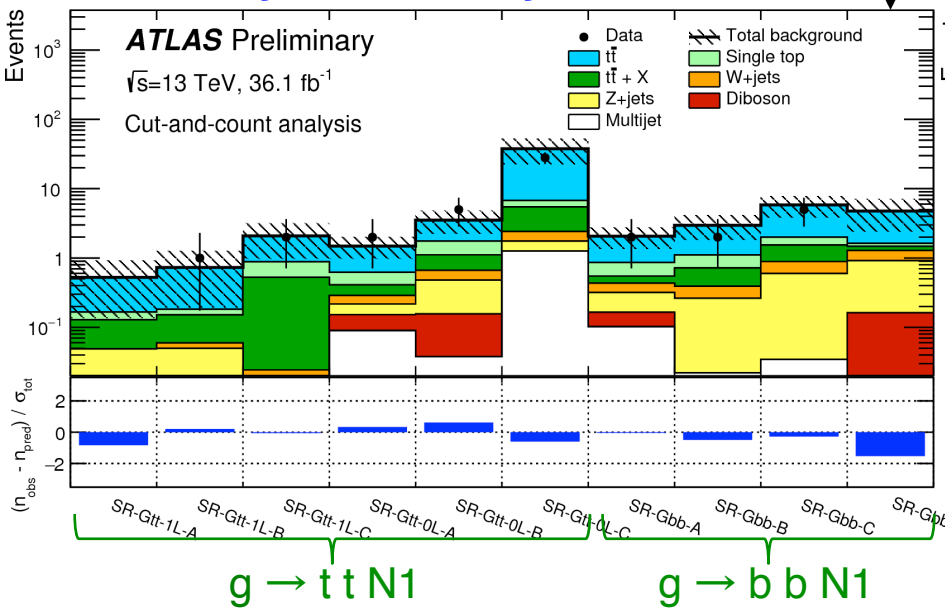
b-jets+MET Results

- **Data is consistent with SM**
- Max excess 2σ in SR-0L-HH



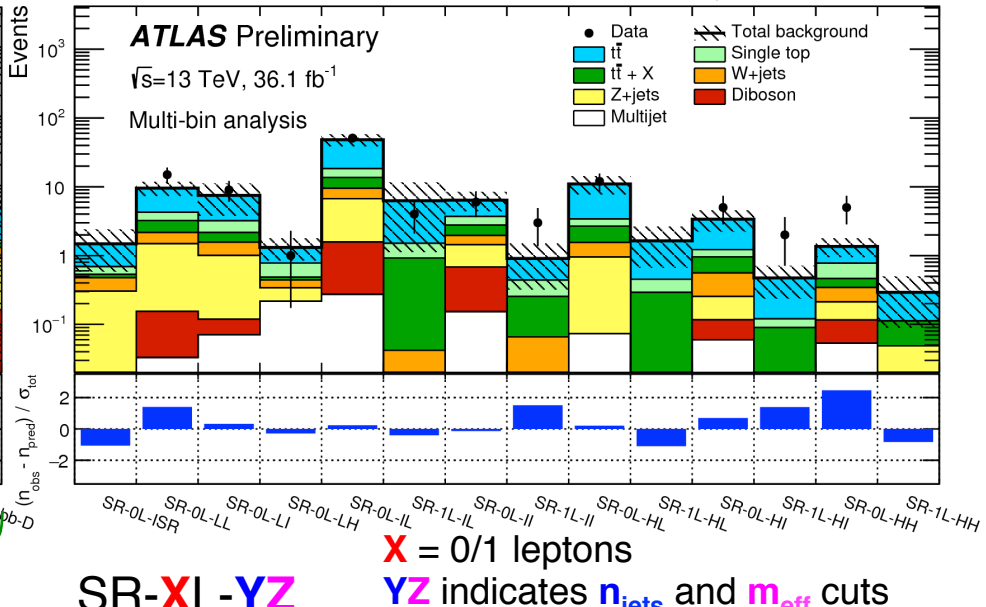


Summary of discovery SRs



g → t t N1 g → b b N1

Summary of exclusion SRs

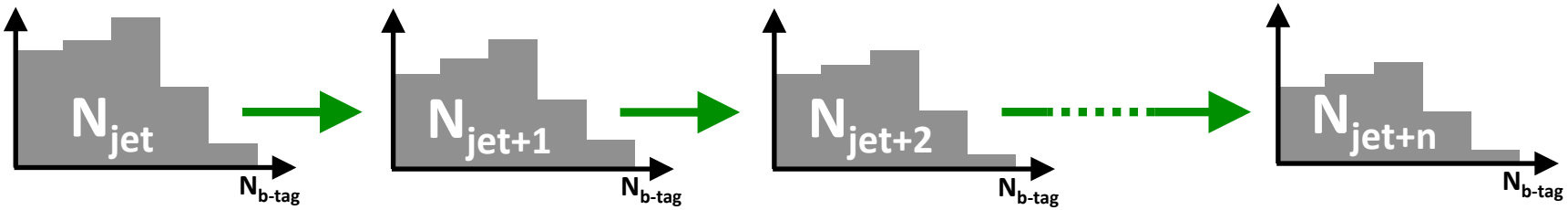


SR-**X**L-**YZ**

X = 0/1 leptons
YZ indicates n_{jets} and m_{eff} cuts (low/intermediate/high)

RPV 1ℓ Search: Backgrounds

- Dominant backgrounds: **tt+jets** @ high $N_{b\text{-jet}}$ and **V+jets** @ low $N_{b\text{-jet}}$ → data-driven estimate
- Basic concept: **Parameterised extrapolation** of $N_{b\text{-tag}}$ spectrum from medium to high N_{jet}



$N_{b\text{-tag}}$	tt+jets	V+jets
Shape	• Initial shape from **5-jet** selection + evolution to higher N_{jet} parameterised with fixed probabilities of additional jets to be b-jets	• From MC for each N_{jet} slice
Normalisation	• N_{jet}-evolution predicted with parameterised model based on combination of **staircase** and (extended) **Poisson scaling** of N_{jet} ratios $\mathbf{r_j = N_{j+1}/N_j}$ with scaling parameters $\mathbf{c_i}$ $$r_j = c_0 + c_1/(j + c_2)$$	

- Other backgrounds: **multi-jets** (data-driven matrix-method estimate), **diboson / single-top / tt+X** (from simulation - mostly < 10%)

→ **Simultaneous fit** of shape & normalisation in all considered bins:

- **Discovery setup**: **Only $N_{b\text{-tag}}$ ==0, ≥3 bins** considered as SRs. Orthogonal bins with small signal contamination used to constrain background model.
- **Exclusion setup**: **All N_{jet} / $N_{b\text{-tag}}$ bins** used to constrain model.