

# Search for supersymmetry with the ATLAS detector in fully hadronic final states

Koichi NAGAI, University of Oxford  
on behalf of ATLAS collaboration  
at Lake Louise Winter Institute 2016



Large Hadron Collider successfully delivered approx.  $4 \text{ fb}^{-1}$  at  $\sqrt{s} = 13 \text{ TeV}$  in 2015.

- Increase of beam energy provided higher sensitivity to massive new particles.

A total of  $3.2 \text{ fb}^{-1}$  of collision data was collected by the ATLAS detector with good detector conditions and data quality.

- ATLAS detector upgrades in the last long shutdown increase sensitivity of analysis:
  - ➔ **Insertable B-Layer** (the inner most layer of Pixel detector, ave. 3 cm from the beam axis)
    - ✓ improved tracking and b-tagging
  - ➔ **ATLAS High Level Trigger system**
    - ✓ larger acceptance, while enhancing rejection
      - ⦿ Improved trigger on missing  $E_T$
      - ⦿ Improved jet energy scale

Supersymmetry (SUSY) is an extension of Standard Model.

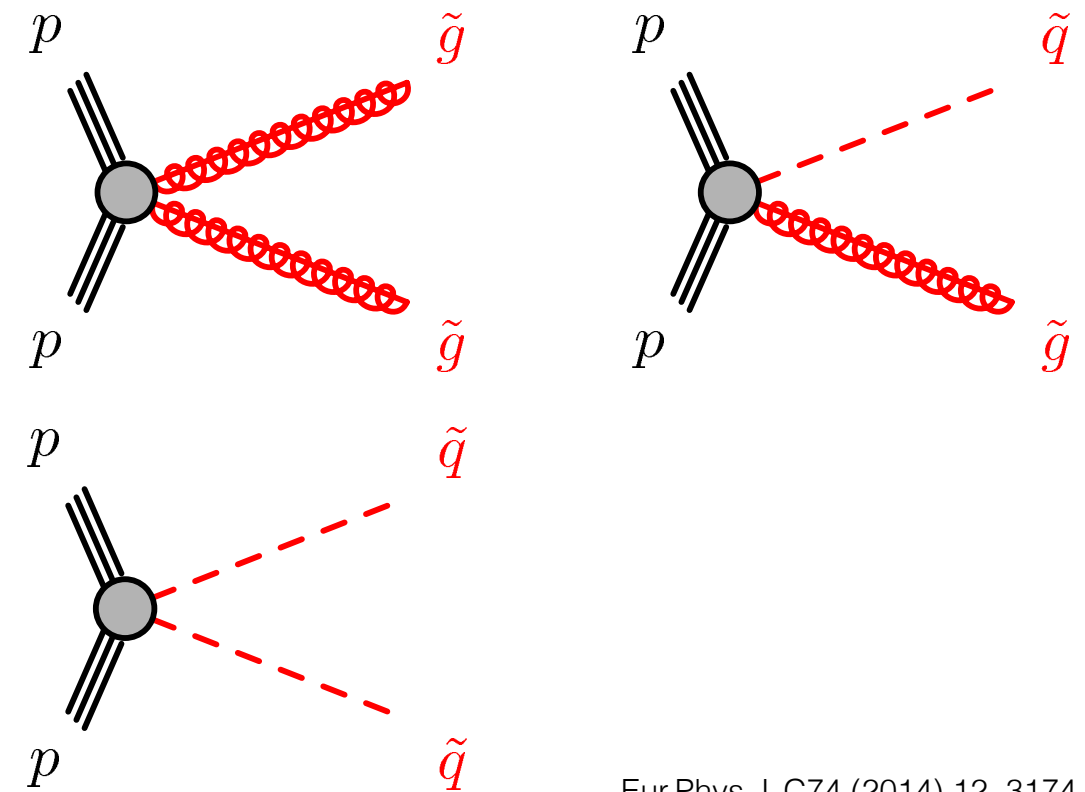
- can provide a solution of hierarchy problem

If R-parity is conserved,

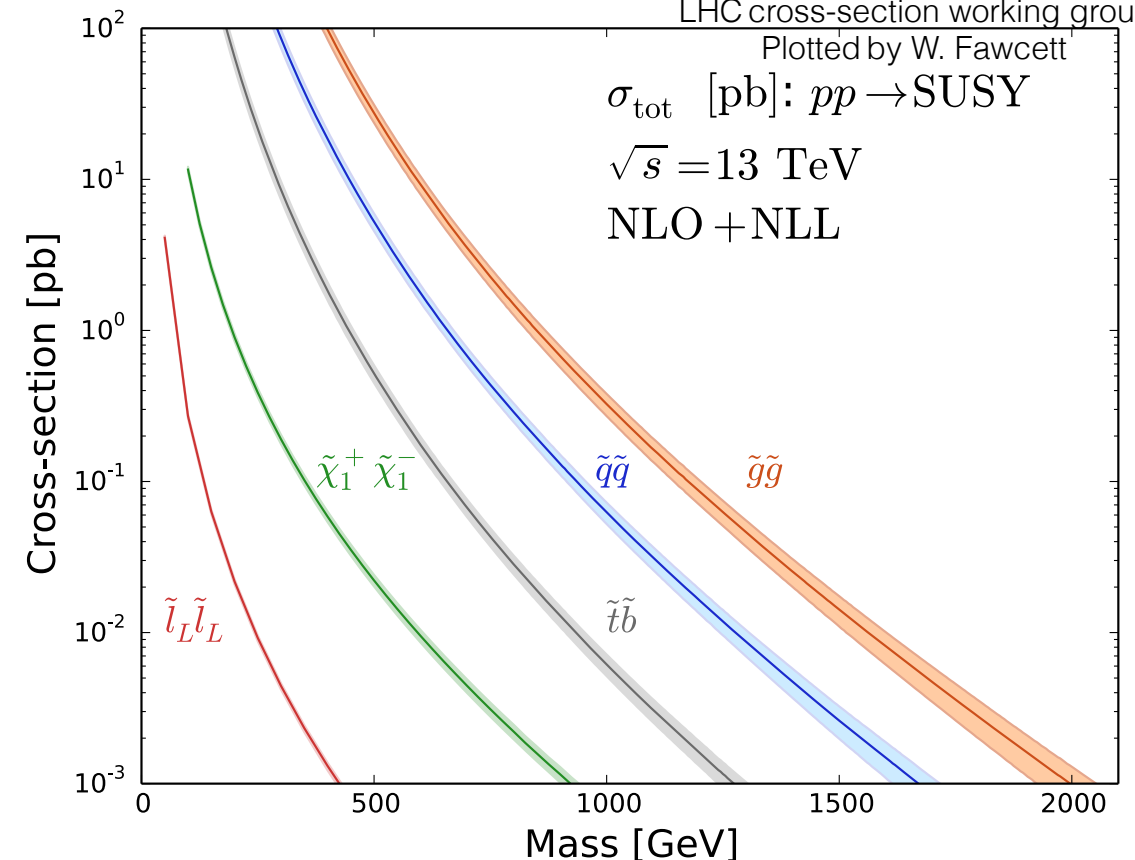
- SUSY particles are produced in pair
- Then decay to SM particles and the lightest SUSY particle (LSP).
- LSP is stable and weakly interacting.
  - ➔ missing transverse momentum:  $E_T^{\text{miss}}$

At LHC, a pair of SUSY particles can be dominantly produced with strong interactions.

- Productions of gluino and squark have a large cross-sections



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LHC cross-section working group



Decays of gluino and squark depend on models.

- There are more than 100 parameters to be tuned even in Minimal Supersymmetric Standard Model (MSSM).

Searches for gluino/squark are guided by

- “Simplified Model”
- particular decay modes.

The selections were constructed for particular sparticle production and decay or expected event signature, according to

- ➔ # of leptons, # of jets, # of b-jets
- ➔ missing transverse momentum:  $E_T^{\text{miss}}$

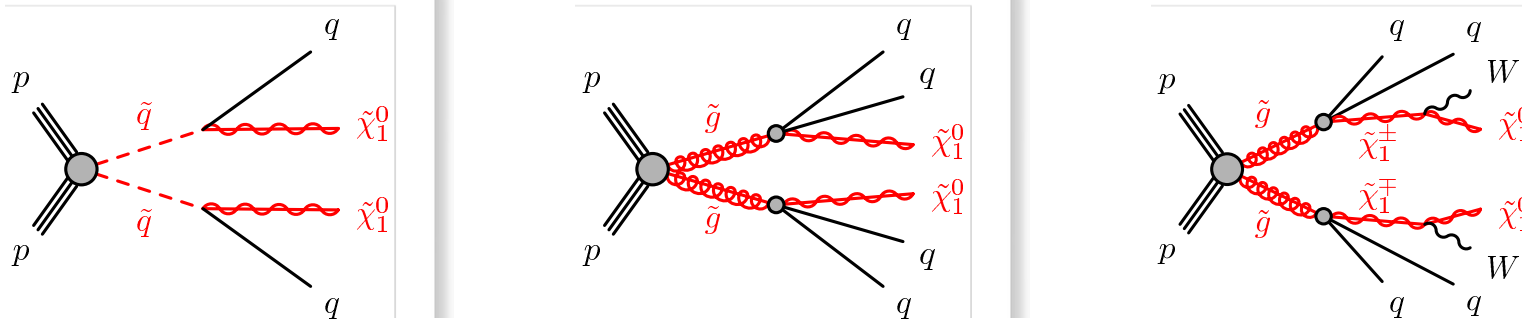
In this talk, we mainly look at results with full hadronic final states (0 lepton).

- ➔ events containing 0 lepton + 2-6 jets +  $E_T^{\text{miss}}$  ( LSP )
- ➔ events containing 0 lepton + 7 to 10 jets +  $E_T^{\text{miss}}$  ( LSP )
- ➔ gluino mediated stop/sbottom production [Gtt/Gbb] +  $E_T^{\text{miss}}$  ( LSP )
- ➔ pair-production of sbottoms: 2 b-jets +  $E_T^{\text{miss}}$  ( LSP )

Topological search

Dedicated search

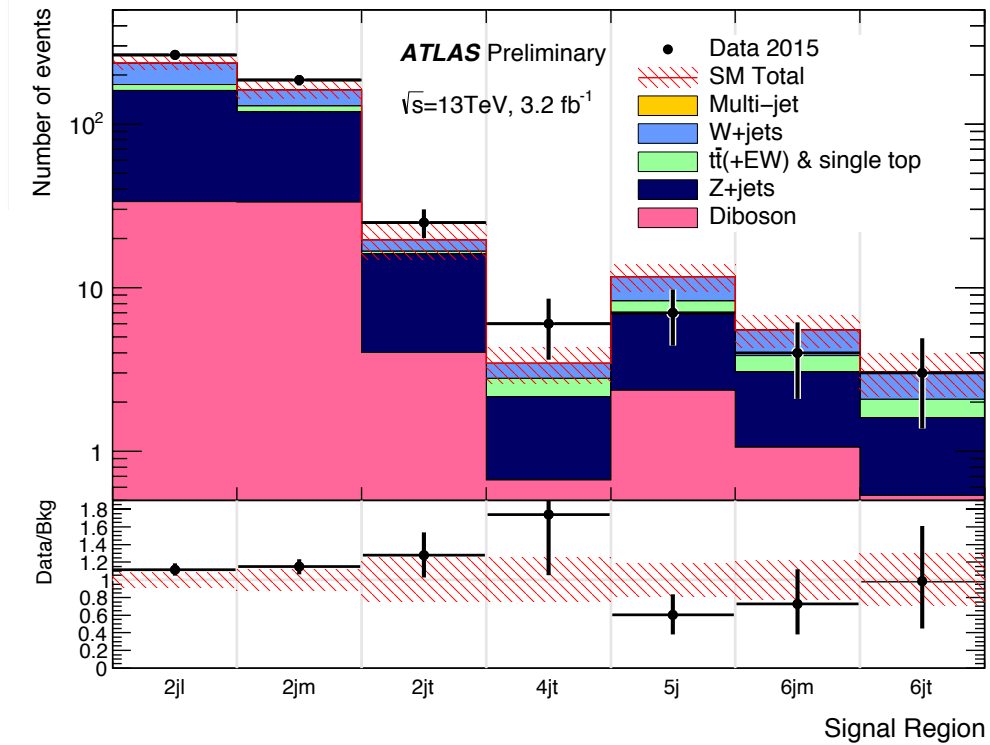
# 0 lepton 2-6 jets



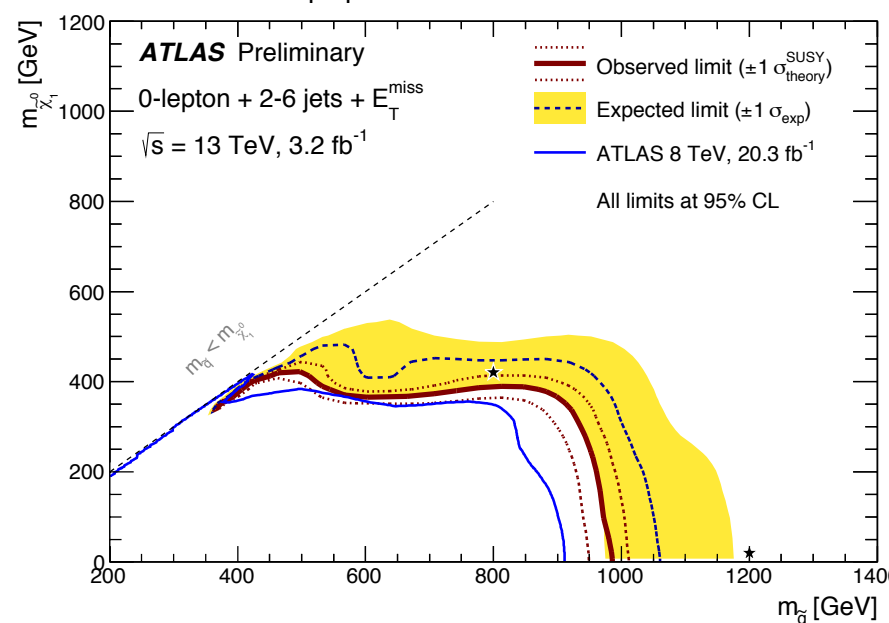
<https://cds.cern.ch/record/2114828>

The final state with “0 lepton + 2-6 jets” is expected by large number of R-parity conserving SUSY models.

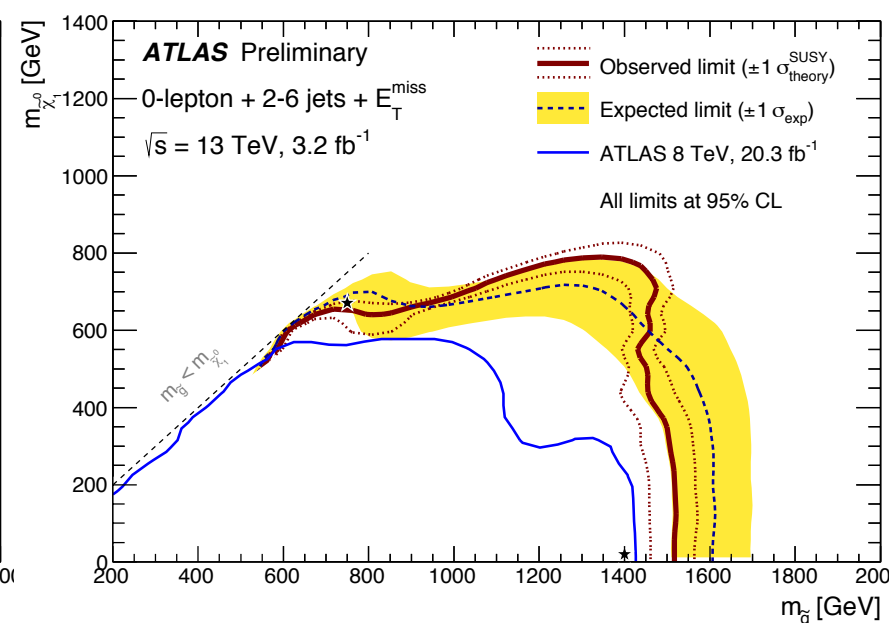
- Total of 7 Signal Regions are constructed mainly according to number of jets.
- Expected SM BGs: Z+jets, W+jets, top quark pairs, single top quarks, the multi-jet production.
- Simulated BGs were normalised by using dedicated CRs.
- No excess was found with all SRs.



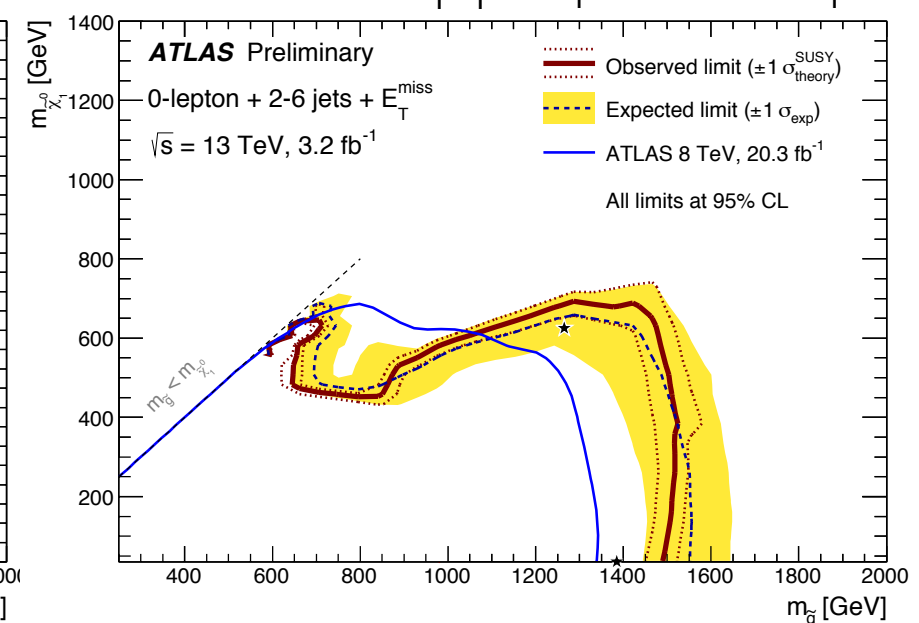
$$\tilde{q}-\tilde{q} \rightarrow qq\tilde{\chi}_1^0\tilde{\chi}_1^0$$



$$\tilde{g}-\tilde{g} \rightarrow qqqq\tilde{\chi}_1^0\tilde{\chi}_1^0$$



$$\tilde{g}-\tilde{g} \rightarrow qqqqWW\tilde{\chi}_1^0\tilde{\chi}_1^0 \quad m(\tilde{\chi}_1^\pm) = (m(\tilde{g}) + m(\tilde{\chi}_1^0))/2$$





The motivation of “0 lepton + 7-10 jets” topology search at Run 2 is

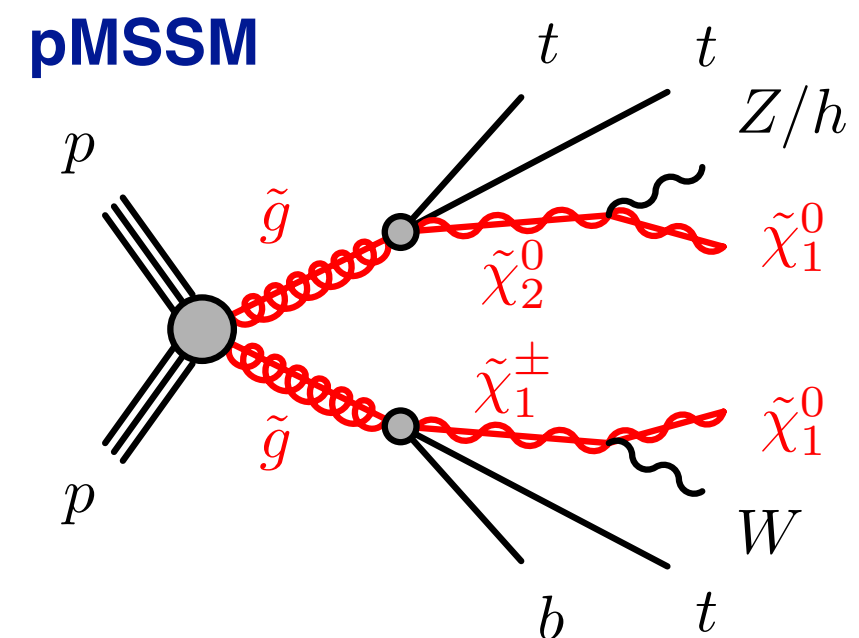
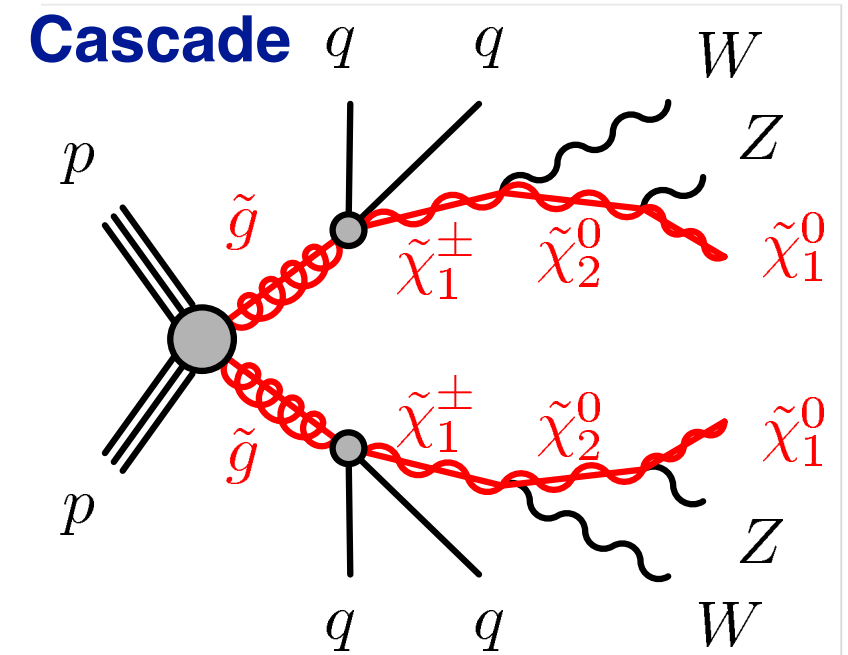
- cascade decay of SUSY particle which can produce high jet multiplicity.
- some slices in phenomenological MSSM (19 parameters) which are searchable only with this topology.

The final state is characterised with

- moderate  $E_T^{\text{miss}}$
- large jet multiplicity

Selection is constructed with 15 Signal Regions

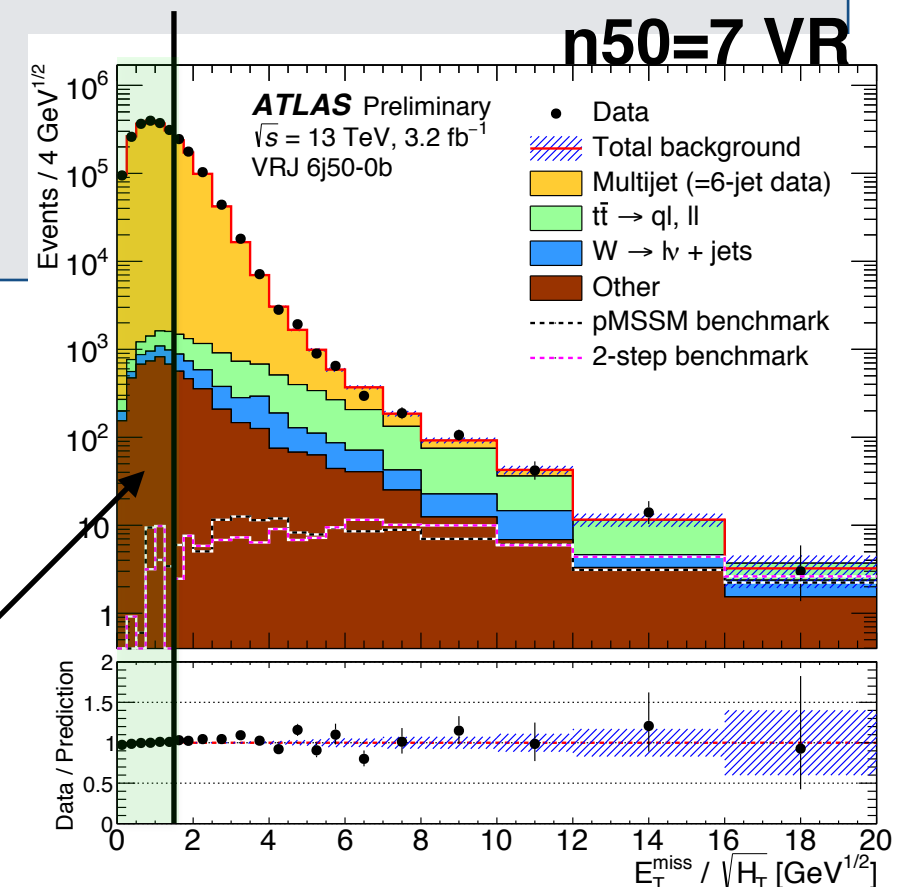
- defined by jet  $p_T$  and jet multiplicity, and then by # of b-jets to obtain further sensitivities.
- Veto event with  $e^\pm$  and  $\mu^\pm$
- Signal is selected with MET significance  $E_T^{\text{miss}} / \sqrt{H_T} \geq 4\text{GeV}^{1/2}$



	“multi-jet”	“leptonic”
Processes	<b><math>t\bar{t}</math> (hadronic decay)</b> <b>QCD processes</b>	<b><math>t\bar{t}</math> (leptonic decay)</b> <b>W+jets</b> Z+jets, $t\bar{t}+X$ , single top, diboson
Estimation method	<b>Data-driven</b> <ul style="list-style-type: none"> <li>Exploit invariance of MET significance <math>E_T^{\text{miss}}/\sqrt{H_T}</math> vs. jet multiplicity.</li> <li>A template of <math>E_T^{\text{miss}}/\sqrt{H_T}</math> distribution is extracted at low jet multiplicity</li> </ul>	<b>Monte Carlo</b> <ul style="list-style-type: none"> <li>Normalised to data in dedicated 1-lepton control regions</li> </ul>

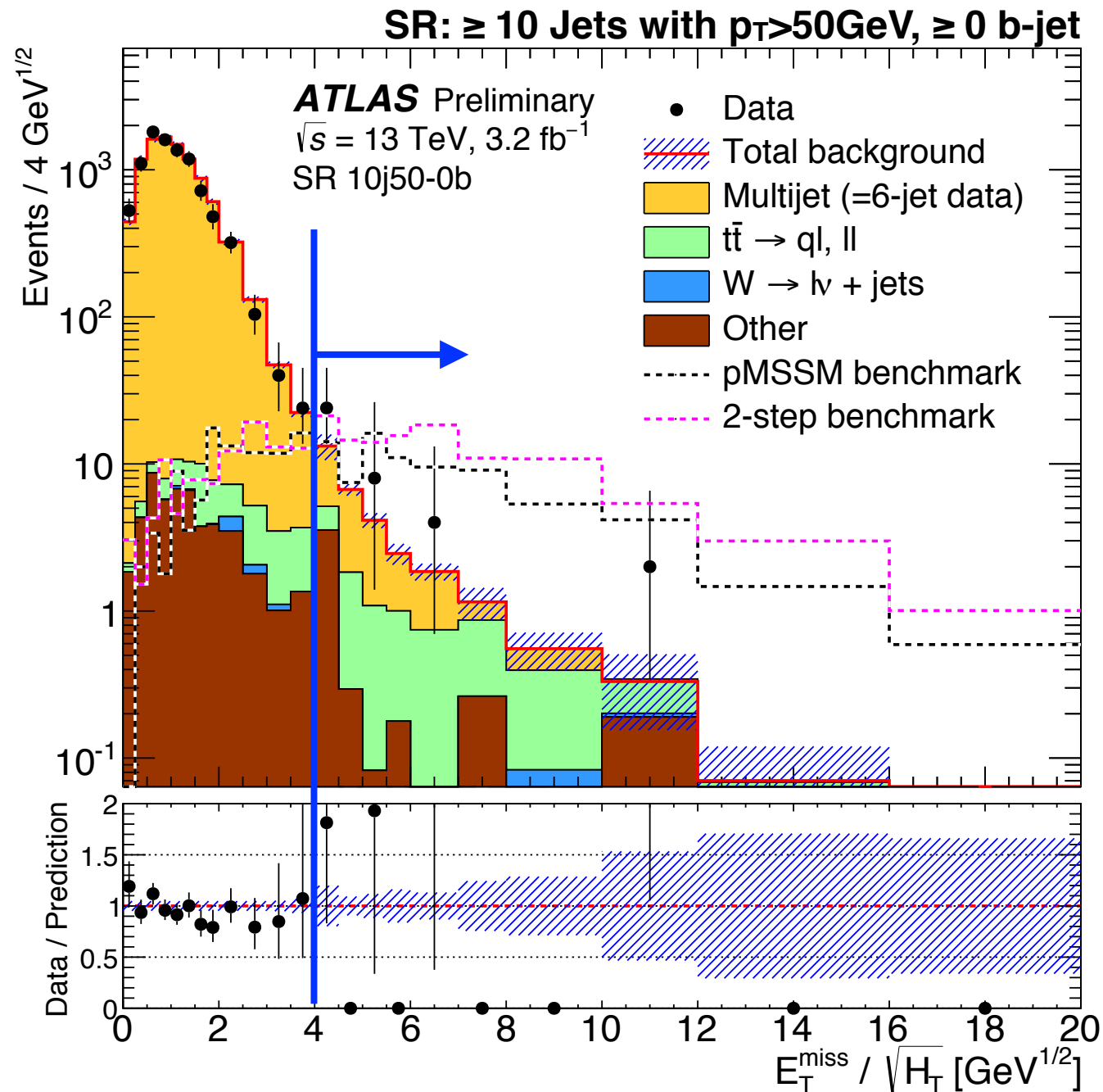
In VRs

Area	METsig [GeV <sup>1/2</sup> ]
Control	< 1.5



Over all systematic uncertainty varied from 12% to 45%.

- the theoretical uncertainties on the  $t\bar{t}$  backgrounds are typically the most significant sources



In SRs

Area	METsig [GeV <sup>1/2</sup> ]
Control	< 1.5
Validation	1.5 - 3.5
Signal	> 4.0



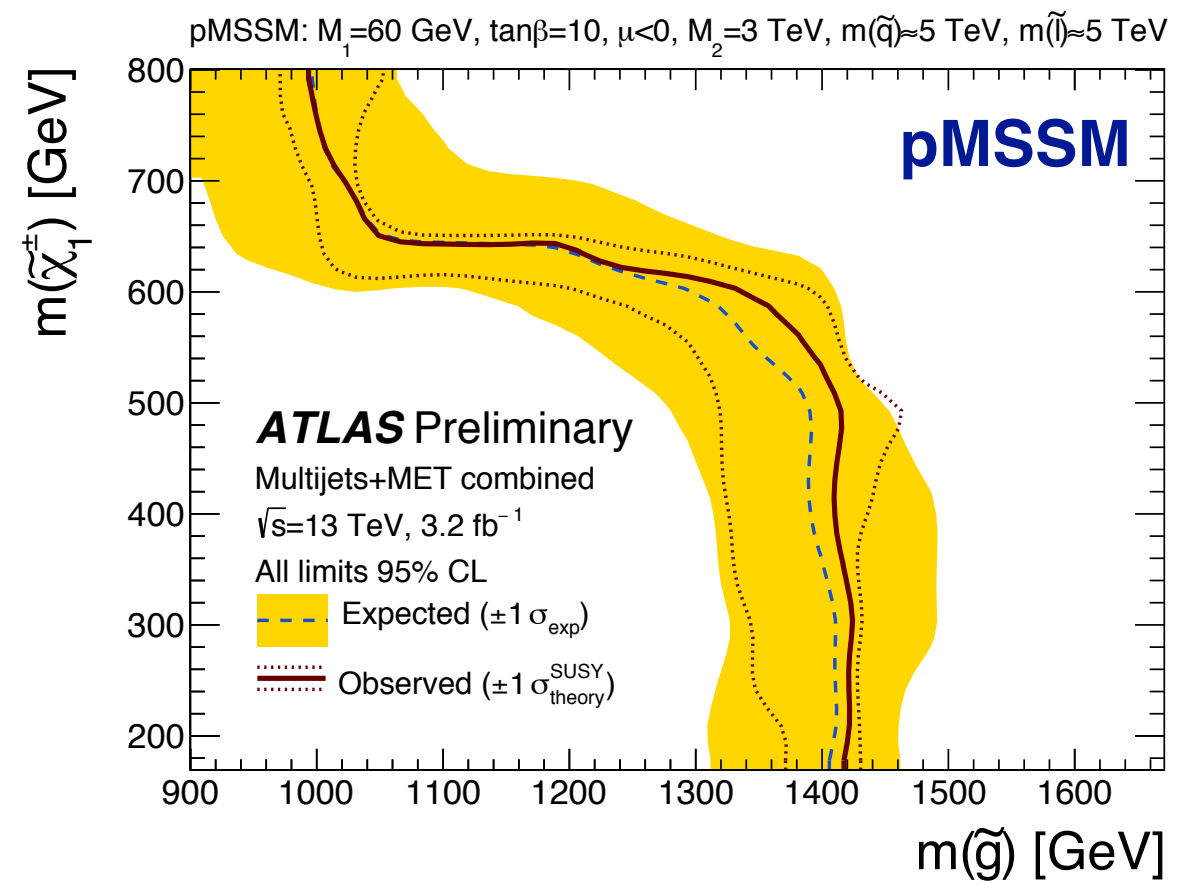
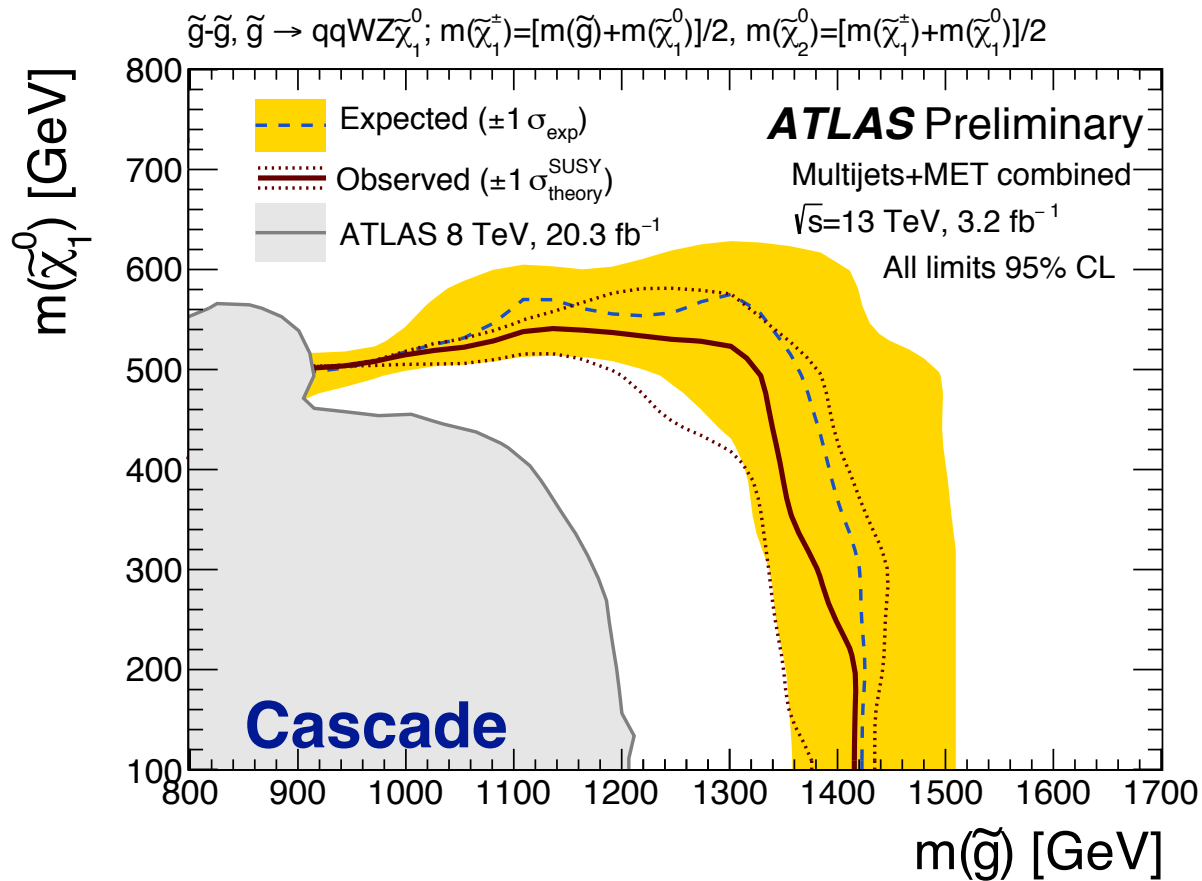
Over all systematic uncertainty varied from 12% to 45%.

- the theoretical uncertainties on the  $t\bar{t}$  backgrounds are typically the most significant sources

No excess was observed in any SRs.

Results are interpreted with a cascade decay model and a slice of pMSSM.

- The SRs with the best expected limit are used for the calculation at each signal point



Masses of stop and sbottom are expected to be light to solve the hierarchy problem.

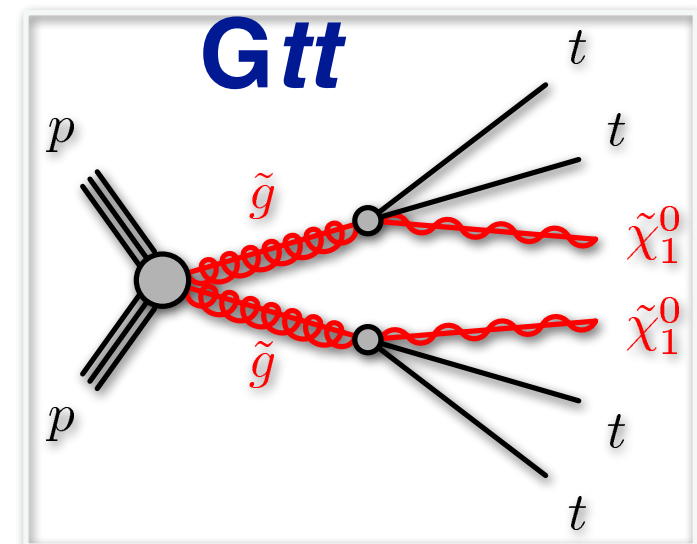
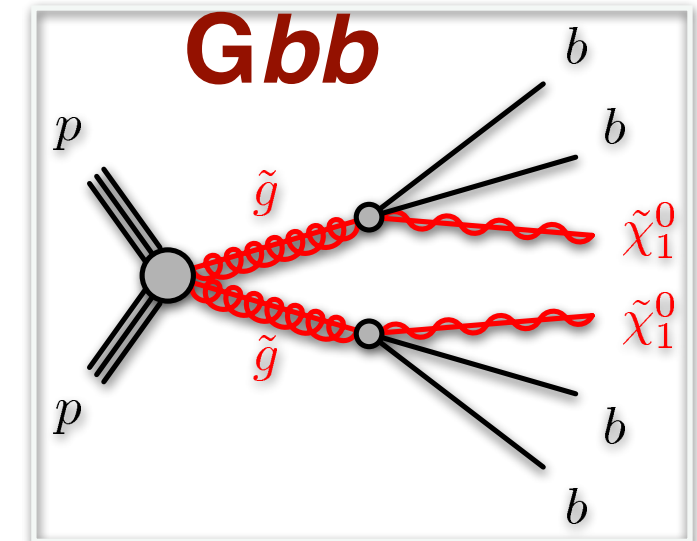
A search for gluino mediated stop ( **$G_{tt}$** )/sbottom ( **$G_{bb}$** ) productions was performed.

Signal regions are built by considering event signatures:

- Several energetic jets (up to 12)
- High number of b-jets
  - ✓ at least three jets are expected to be identified as b-jets
- Large missing momentum
- mass difference between gluino and LSP

For  **$G_{tt}$** , followings are also considered

- Massive large-R jet due to boosted top
  - ➔ top-tagged large-R jet ( $R=1.0$ )
- Potentially isolated  $e^\pm$  or  $\mu^\pm$  from  $W$  in top decay



# Gtt/Gbb: Background

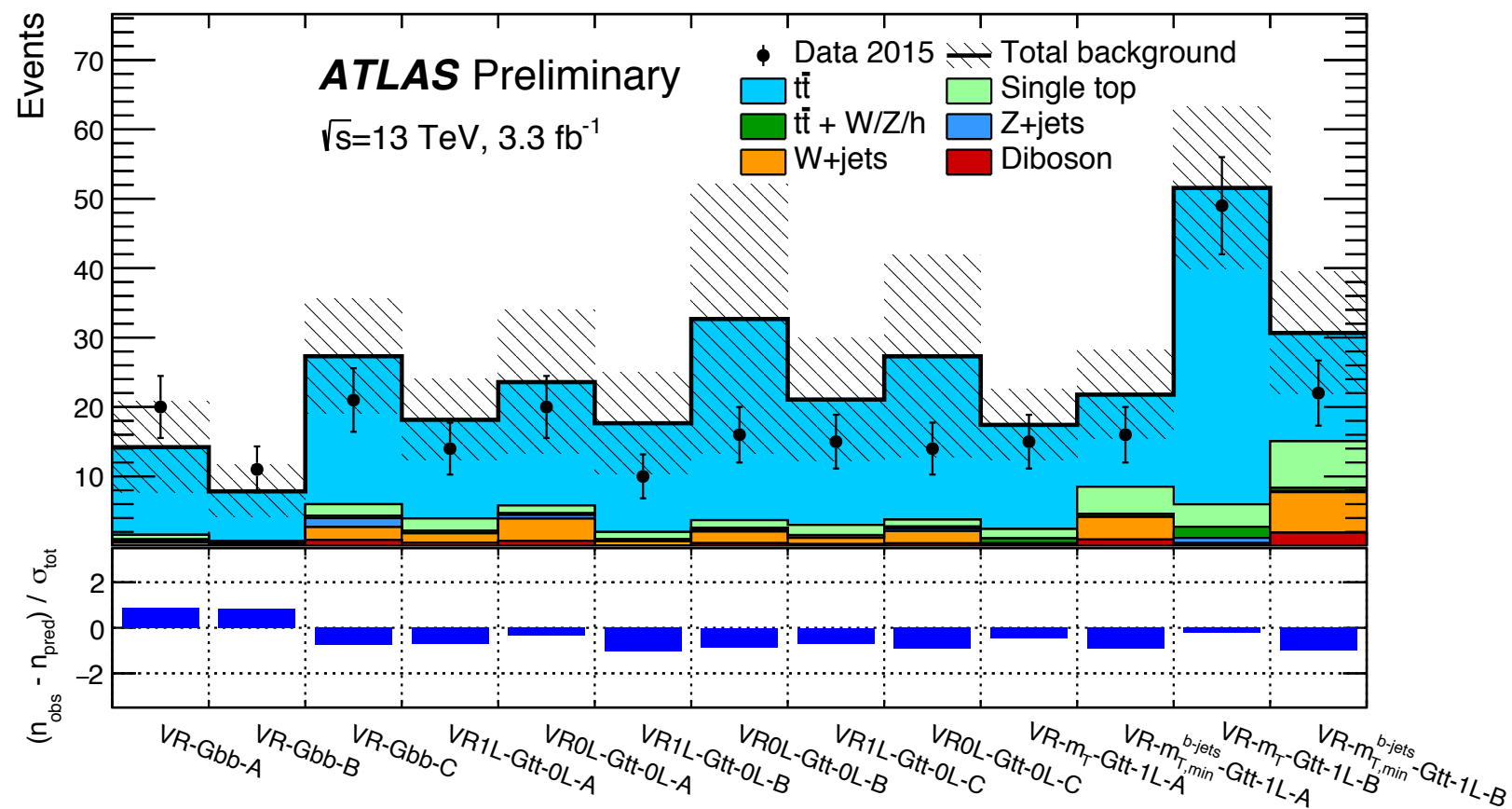
$t\bar{t}$  production is the dominant SM background

- normalised in dedicated 1-lepton control regions.

Other BGs (Z+jet, W+jet, single top, di-boson &  $t\bar{t}+W/Z/h$ ) are normalised by the best available calculated cross-sections.

- ➔ Multi jet BG is negligible for all SR.

The obtained normalisation was validated with dedicated VRs

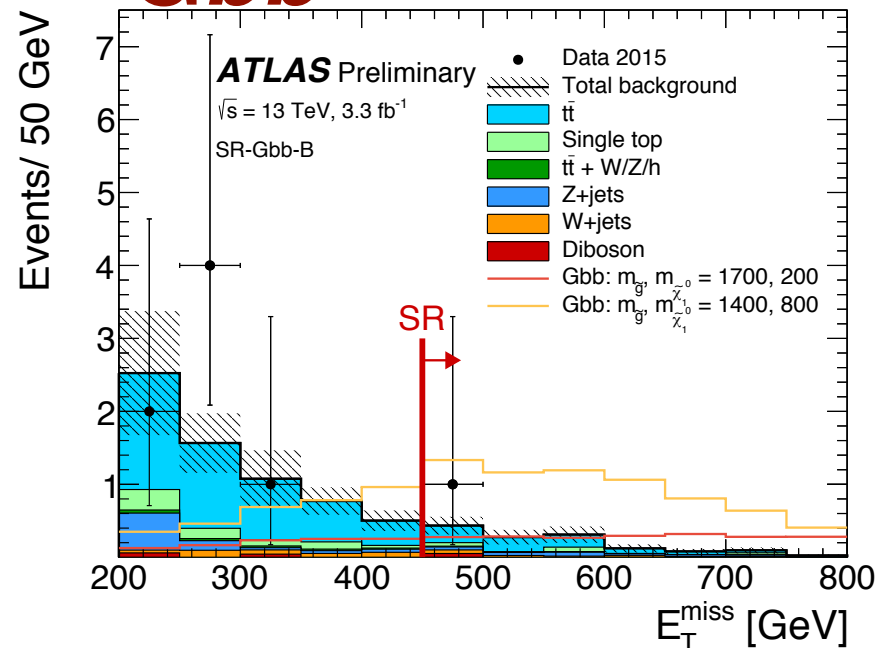


Data has a good agreement with expected BG.

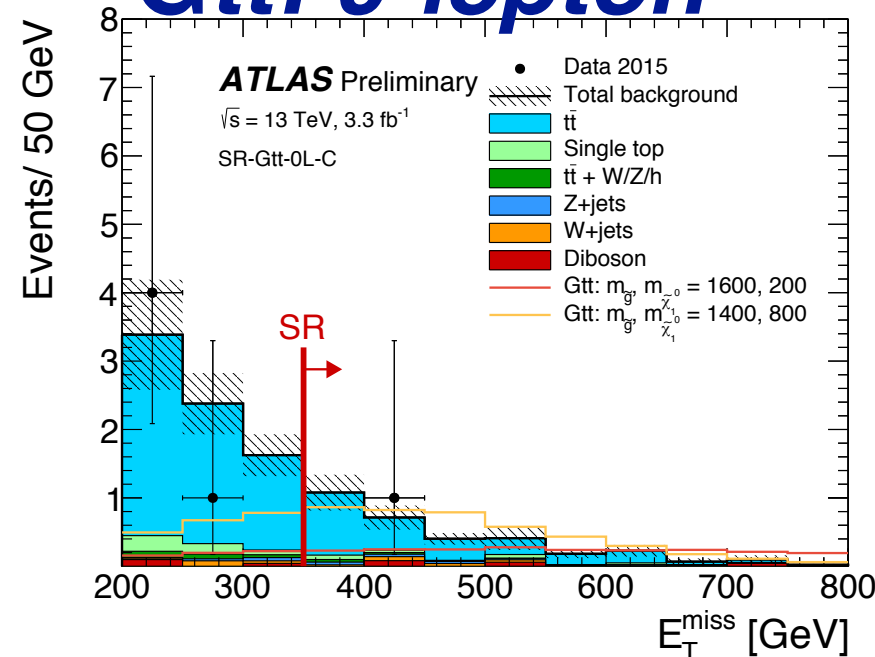
Sensitivity is improved by using

- top-tagged large-R jets
- lepton isolation adapted to top decay
- the minimum transverse mass between  $E_T^{\text{miss}}$  and any of three b-jets

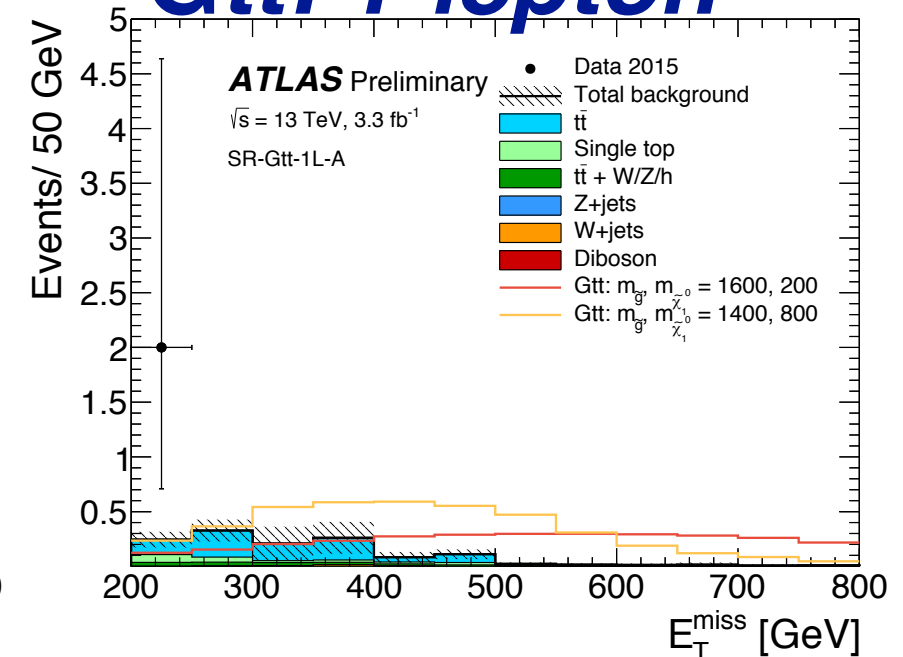
## Gbb



## Gtt: 0-lepton



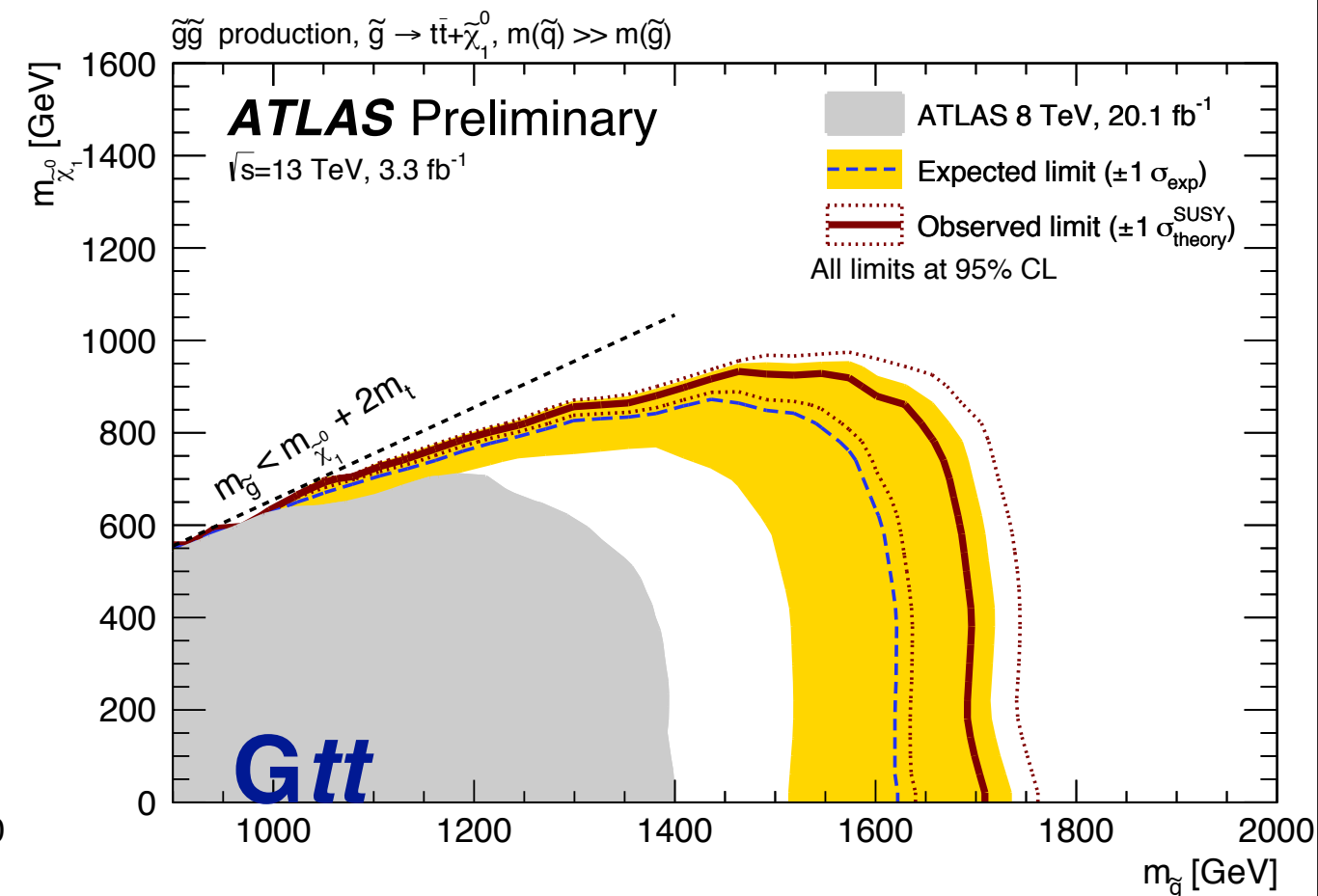
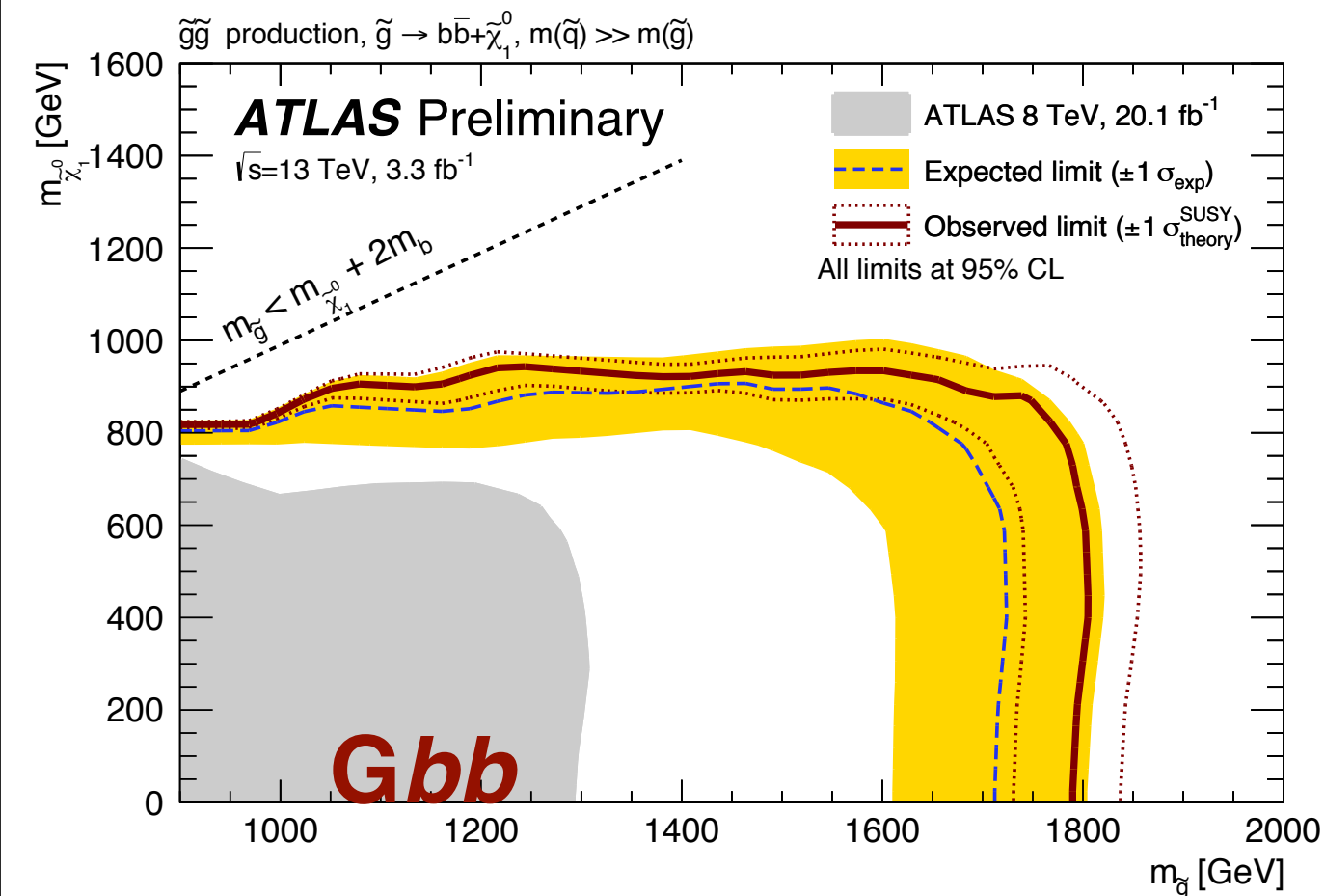
## Gtt: 1-lepton



Data has a good agreement with expected BG.

Sensitivity is improved by using

- top-tagged large-R jets
- lepton isolation adapted to top decay
- the minimum transverse mass between  $E_T^{\text{miss}}$  and any of three b-jets
- Results are interpreted with the simplified model and exclusion limits are set at 95 % CL.



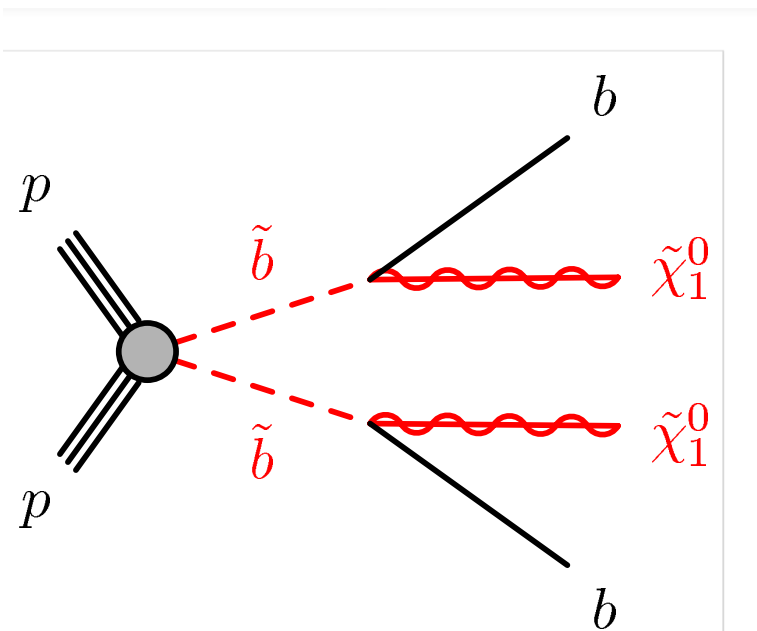


The final state is characterised as

- $E_T^{\text{miss}}$  and 2 b-jets

Two main SRs are designed for large (SRA) and small (SRB)  $\Delta\text{mass}$  between sbottom and LSP.

- SRB aims to detect final state for compressed models tagged by a ISR jet.
- SRA is further divided into three by contranverse mass  $m_{\text{CT}}^2(\mathbf{v}_1, \mathbf{v}_2) = [\mathbf{E}_T(\mathbf{v}_1) + \mathbf{E}_T(\mathbf{v}_2)]^2 - [\mathbf{p}_T(\mathbf{v}_1) - \mathbf{p}_T(\mathbf{v}_2)]^2$   
 $V_1$  and  $V_2$  are b-jets (Main discriminating variable)



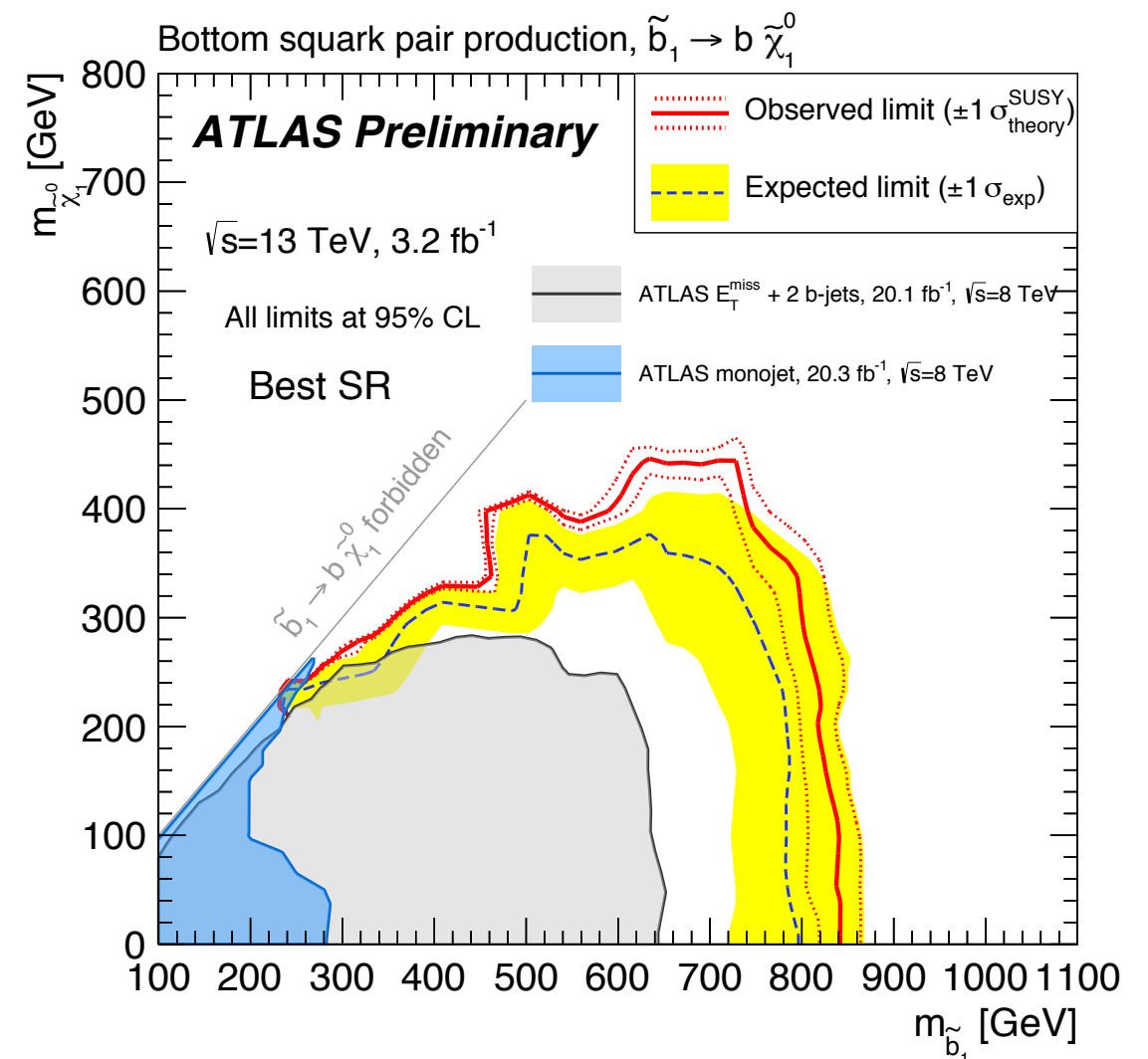
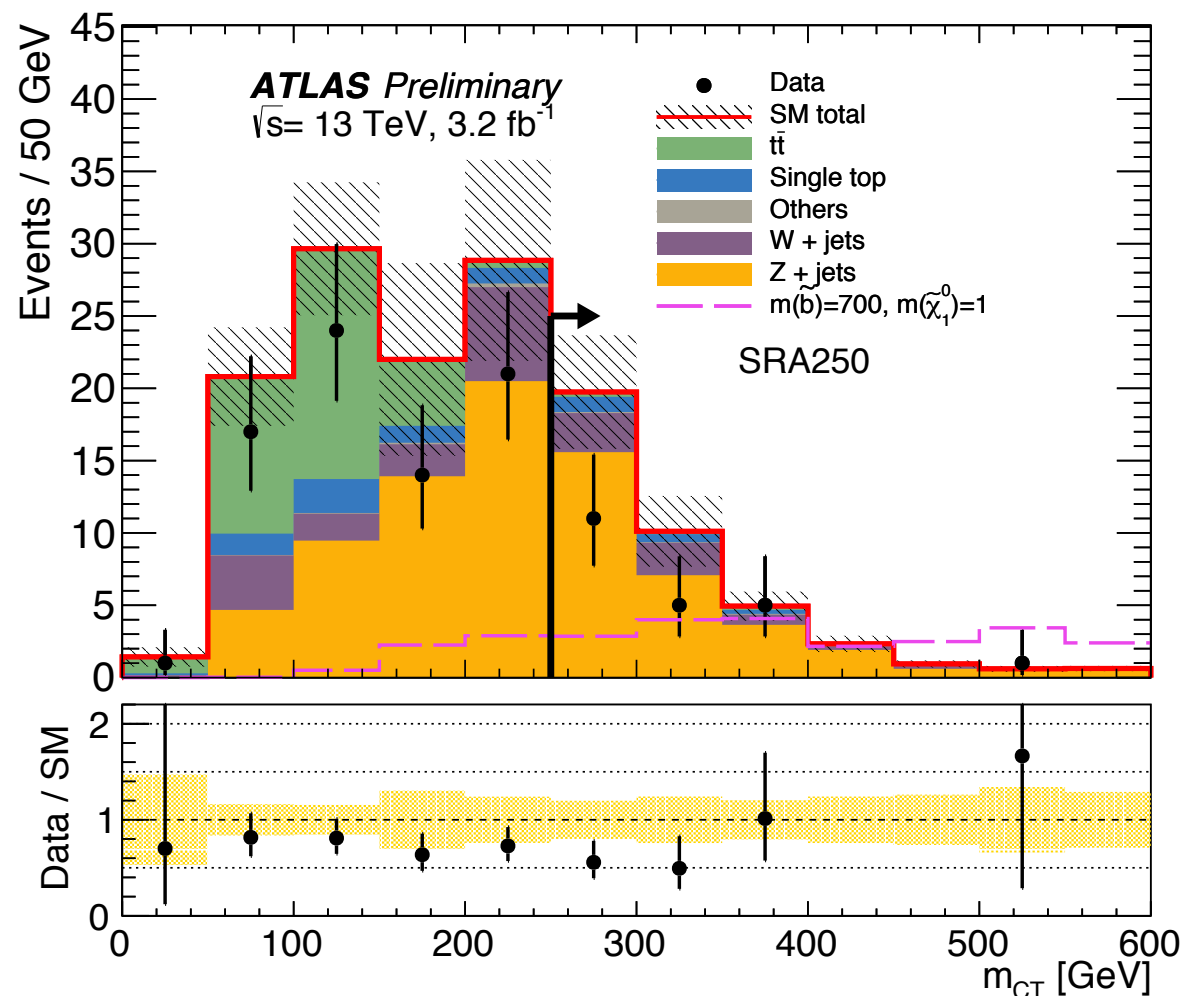
	$\Delta\text{mass}$	Signature	Dominant SM background
SRA	large	high $p_T$ 2 b-jets, large $E_T^{\text{miss}}$	Z + heavy flavour W + heavy flavour top pair single top
SRB	small	1 high $p_T$ non-b-jet, 2 b-jets, large $E_T^{\text{miss}}$	top pair Z + heavy flavour

Backgrounds are estimated by MonteCarlo simulation.

- Dominant BGs are normalised in dedicated CRs with 1- or 2- leptons
  - ➔ CRs are constructed to enhance a particular BG keeping kinematically similar and orthogonal to SRs

No excess was observed.

Results are interpreted into mass plane between LSP and sbottom



LHC performed a nice startup of RUN 2 in 2015 and expanded largely the reach to discover new particles.

Searches for pair production of gluinos and squarks are performed with good quality data of an integrated luminosity of  $3.2 \text{ fb}^{-1}$  recorded by the ATLAS detector.

None of them has shown the evidence of SUSY yet. The exclusion limits were significantly expanded.

This year LHC will deliver significantly increased amount of data and provide further opportunity to discover SUSY.

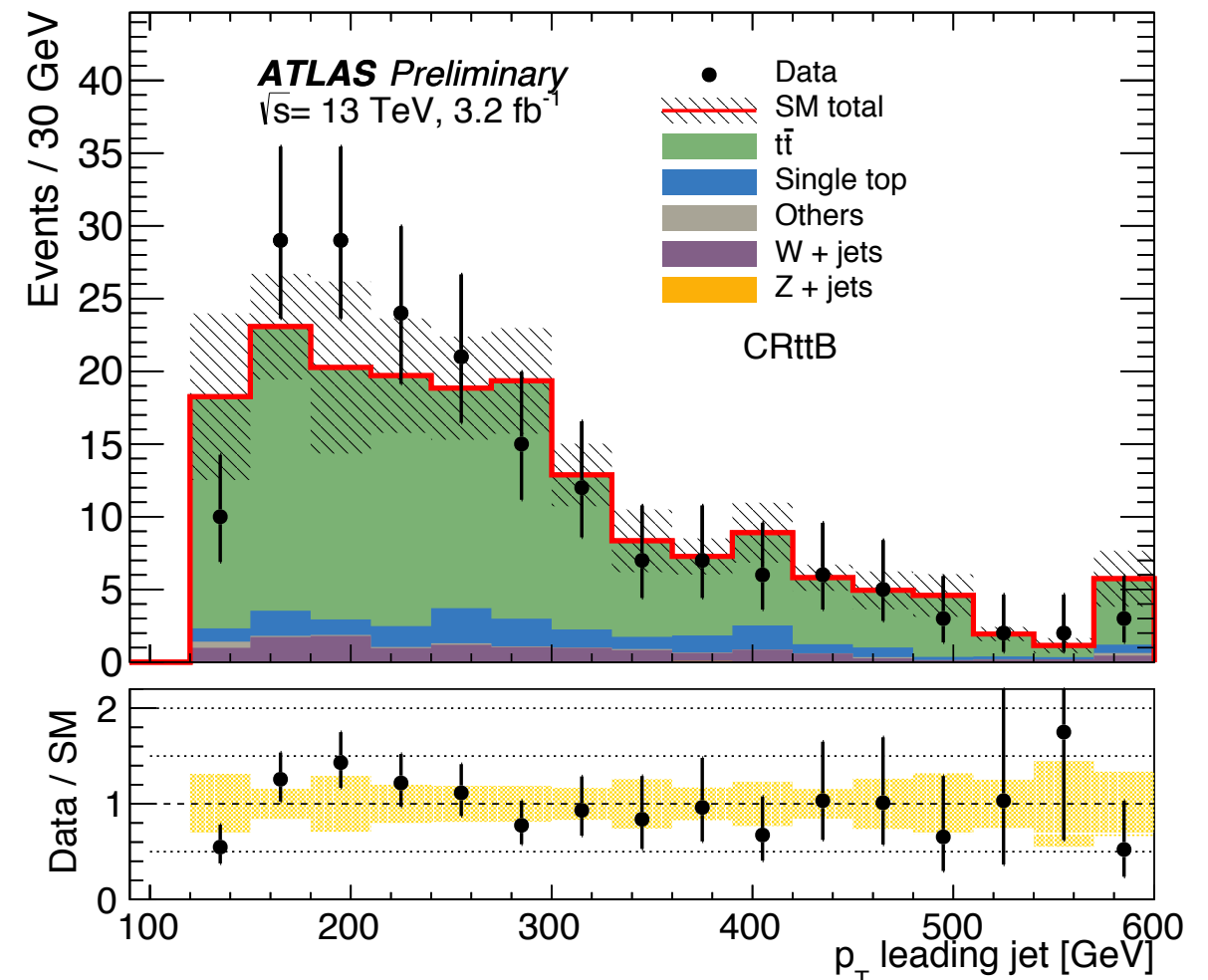
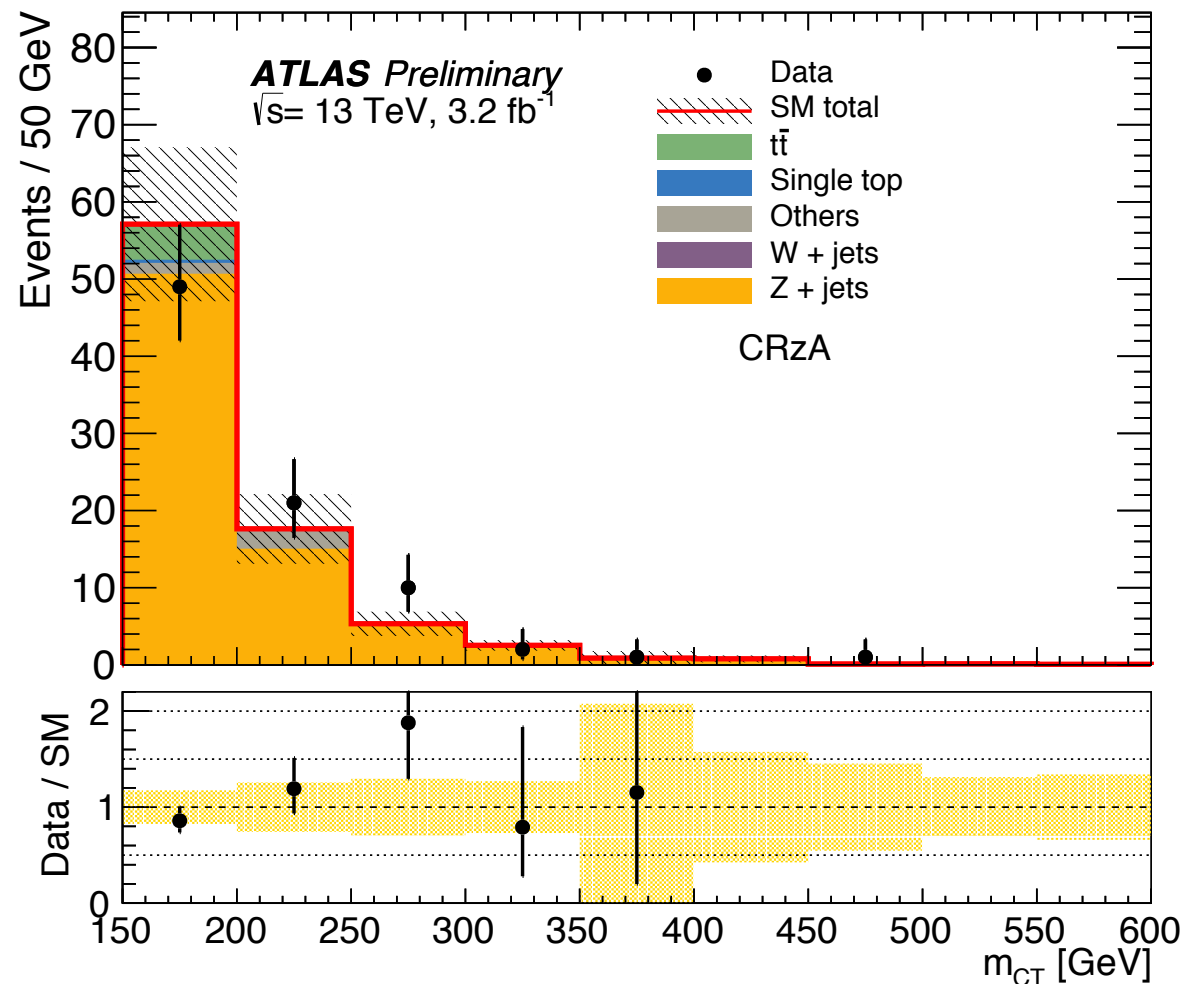
# Backup



# Bottom squark: Background

Backgrounds are estimated by MonteCarlo simulation.

- Dominant BGs are normalised in dedicated CRs with 1- or 2- leptons
  - ➔ CRs are constructed to enhance a particular BG keeping kinematically similar and orthogonal to SRs





# OL7-10jets: Selection Criteria

## Total of 15 Signal regions

- Veto event with  $e^\pm$  and  $\mu^\pm$
- Two Jet  $p_T$  categories are divided by #of jets and #of b-jets to obtain further sensitivities.
- Signal is selected with  $E_T^{\text{miss}} / \sqrt{H_T} \geq 4\text{GeV}^{1/2}$

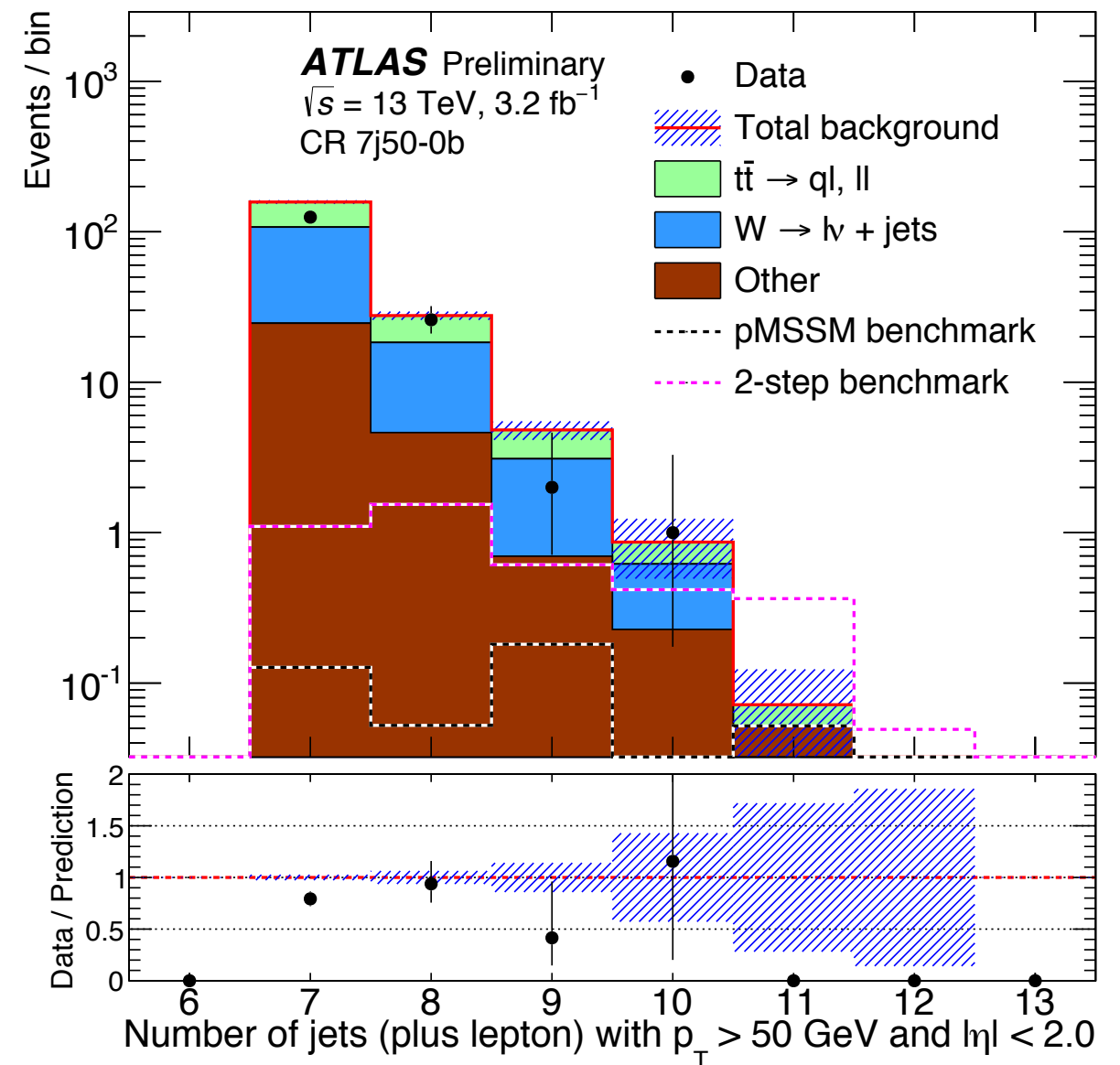
$E_T^{\text{miss}}$  = Negative vector sum of  $p_T$  of all selected and calibrated jet ( $p_T > 20 \text{ GeV}$  &  $|\eta| < 4.5$ ),  $e^\pm$ ,  $\mu^\pm$  and  $\gamma$

$H_T$  = Scalar sum of  $p_T$  of jets ( $p_T > 40 \text{ GeV}$  &  $|\eta| < 2.8$ )

	Jet $p_T$	# of jets	# of b-jets	$E_T^{\text{miss}} / \sqrt{H_T}$
n50	> 50	$\geq 8$	$\geq 0$	$\geq 4\text{GeV}^{1/2}$
			$\geq 1$	
			$\geq 2$	
		$\geq 9$	$\geq 0$	
			$\geq 1$	
			$\geq 2$	
	$\geq 10$	$\geq 0$		
		$\geq 1$		
		$\geq 2$		
> 80	$\geq 7$	$\geq 0$		
		$\geq 1$		
		$\geq 2$		
	$\geq 8$	$\geq 0$		
		$\geq 1$		
		$\geq 2$		

## “Leptonic” BG estimation

- Each category of jet multiplicity has 2 CRs:
  - ➔ for no b-jet
  - ➔ for exactly 1 b-jet
- CRs requires 1 lepton.
- The lepton is casted as a jet.
- For example, SR with 8 jets  $p_T > 50$  (8j50) has two CRs:
  - ➔ selecting 7 jets + 1 lepton  
 $\checkmark$  7j50-0b and 7j50-1b
- Then a simultaneous BG only fit with 2 CRs is performed to determine normalisations.
  - ➔ normalisation of  $t\bar{t}$  and  $W +$  jets are allowed to float

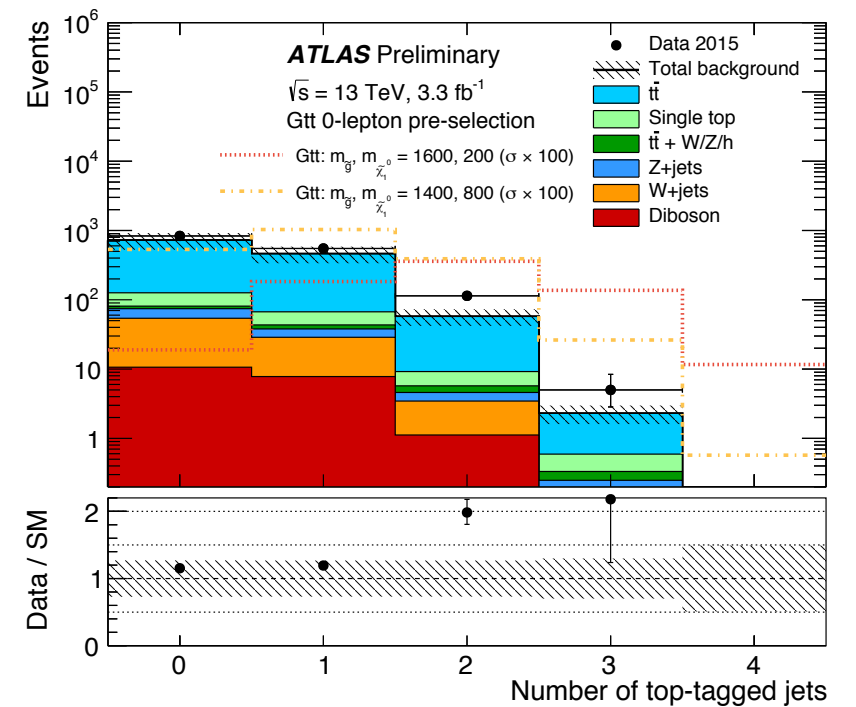
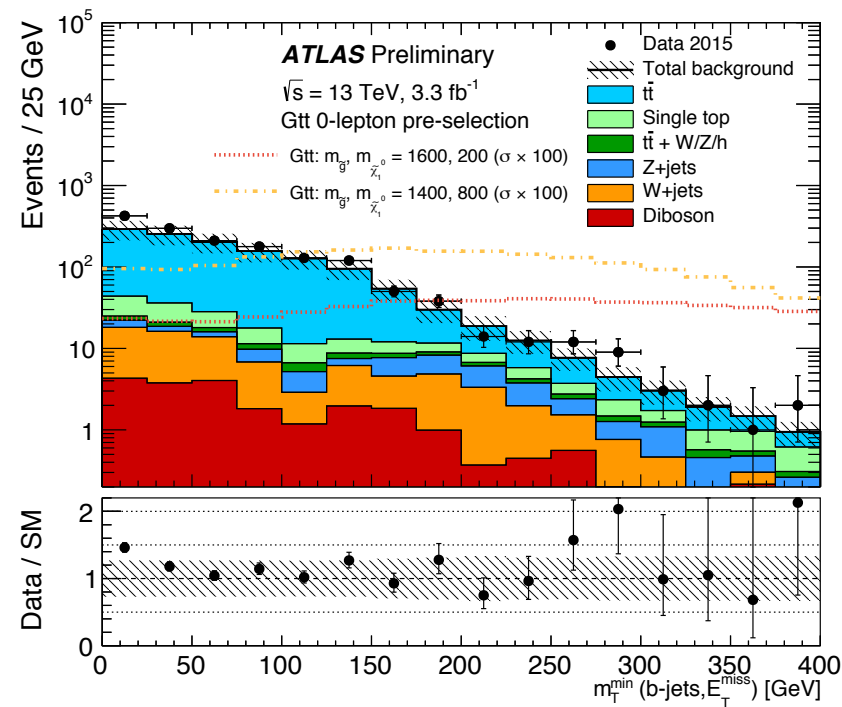
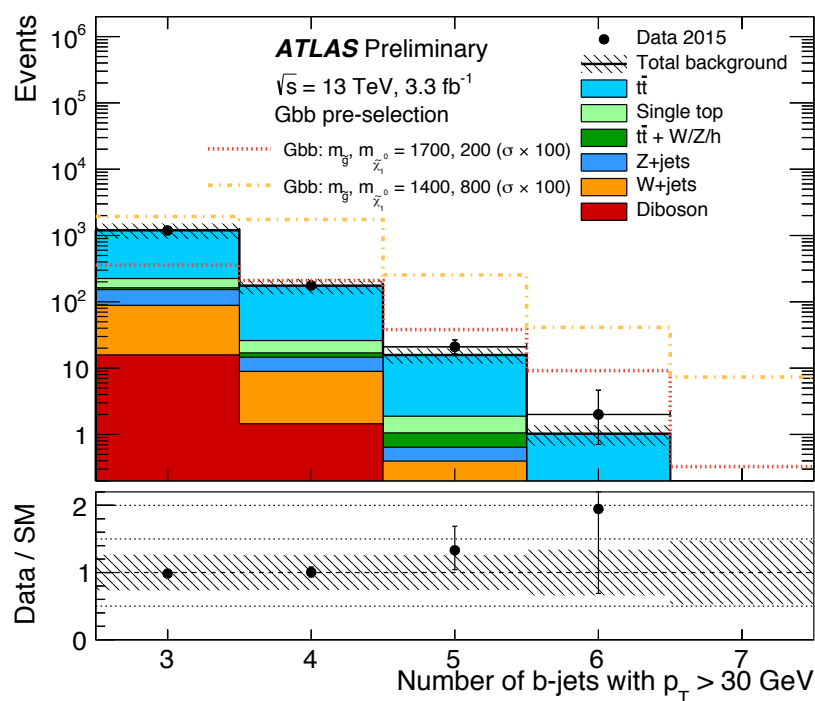


Signal regions for both Gbb and Gtt are defined to select the characteristic final states

- Mass difference between gluino and LSP are taken into account.

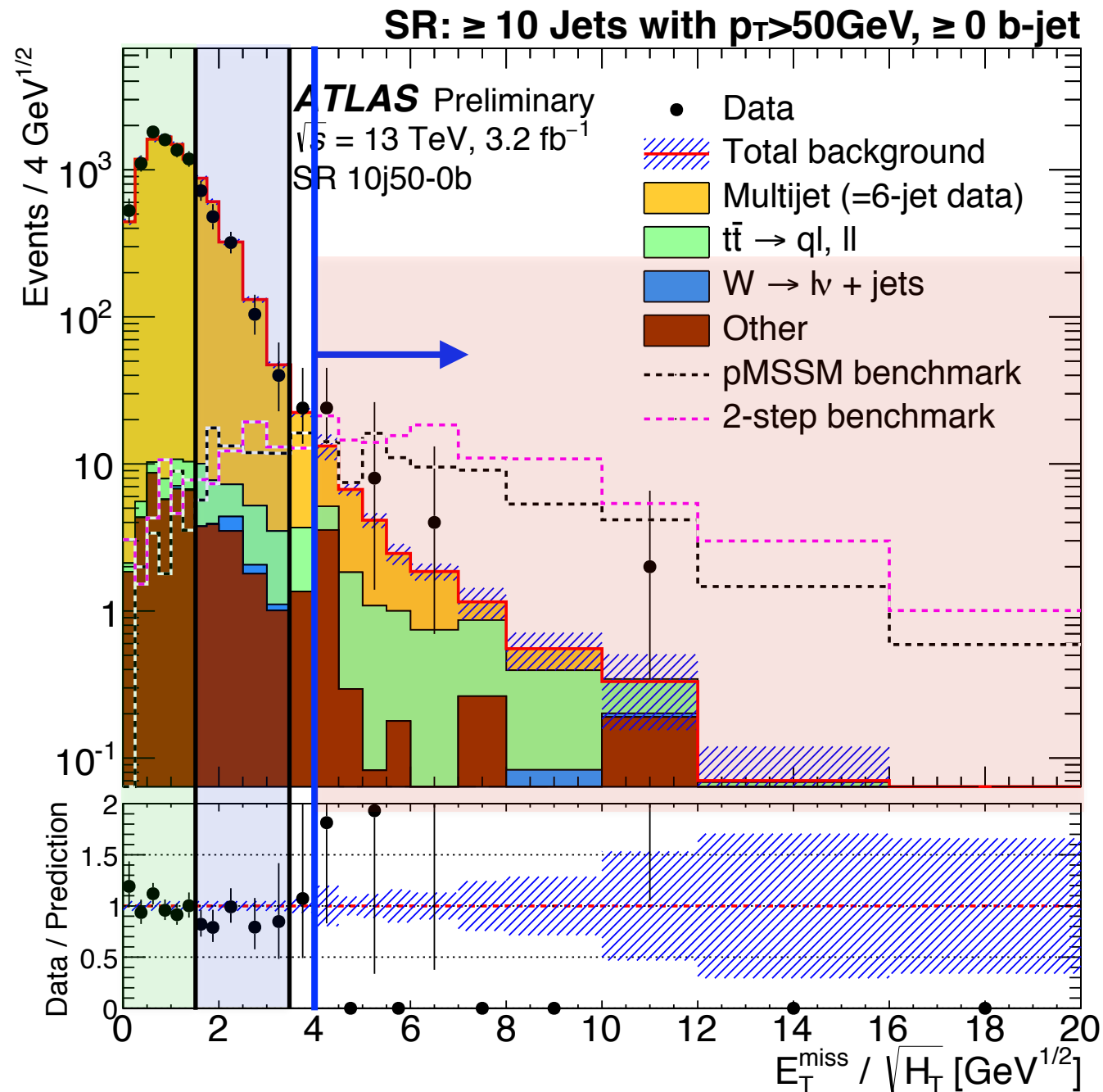
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  - ➔ separate SRs with 1 lepton



Over all systematic uncertainty varied from 12% to 45%.

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In SRs

Area	METSig [GeV <sup>1/2</sup> ]
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Validation	1.5 - 3.5
Signal	> 4.0