Search for production of supersymmetric particles in final states with missing transverse momentum and multiple b-jets in 2015–2016 LHC p–p collision data with the ATLAS detector

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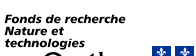


Supersymmetry

- Extension of the Standard Model which associates new particles to each SM particle
- Can solve simultaneously many problems with SM:
  - Hierarchy problem
  - Dark matter
  - Unification of couplings
  - μ $g-2$
  - ...

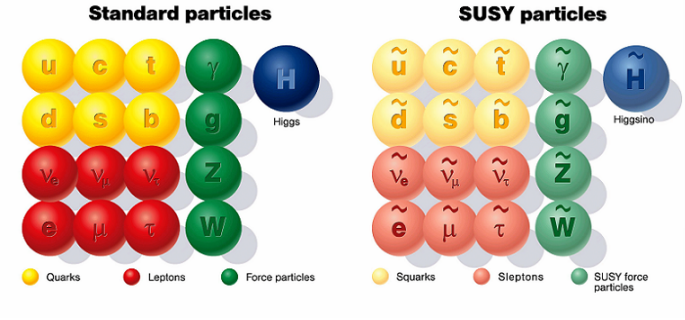
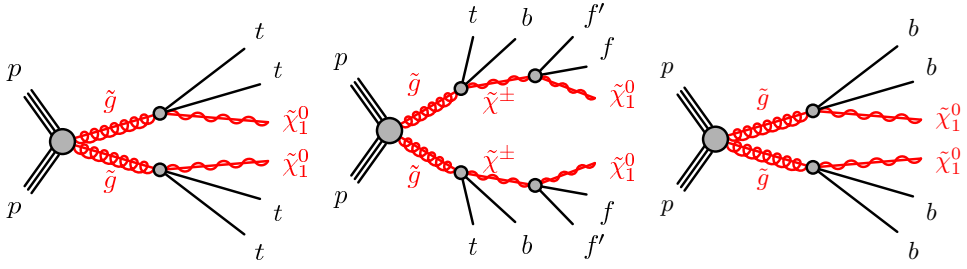


Figure: CERN & IES de SAR

Simplified models

- If SUSY solves hierarchy problem: stop, sbottom, gluino relatively light
  - In such models, lots of third-generation quarks in final states!
- Motivates searches using simplified models of pair-produced gluinos: [1711.01901]
  - Gtt: $\tilde{g} \to t + t + \tilde{\chi}_1^0$
  - Gtb: $\tilde{g} \to t + b + \tilde{\chi}_1^\pm \to f + f' + \tilde{\chi}_1^0$
  - Gbb: $\tilde{g} \to b + b + \tilde{\chi}_1^0$
- Scenarios with different decays for both gluinos also considered
- Two $\tilde{\chi}_1^0$ in all final states $\implies$ high E_T^{miss}



Figures: [1711.01901]

Objects

- Small-radius jets:
  - anti-kT algorithm with radius = 0.4
  - Reconstructs quarks and gluon jets
- *b*-jets
  - Small-radius jets indentified as originating from b-quark by multivariate algorithm
- Large-radius jets
  - Small-radius jets *reclustered* using anti-kT with radius = 0.8
  - Reconstructs boosted top-quarks and *W*-bosons
- Leptons
  - Electrons or muons
- Missing transverse momentum (E_T^{miss})
  - Negative vector sum of momenta of all selected objects
  - "Soft" term computed from tracks from primary vertex but not associated with objects

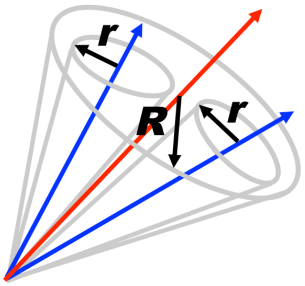
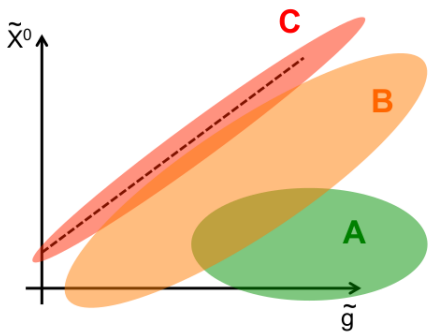


Figure: Ben Nachman

Figure: 2 small-R jets reclustered into a single large-R jet

Search strategy, part I

- Preselection: $E_T^{miss} > 200$ GeV + trigger, ≥ 4 small-radius jets, ≥ 2 b-jets
- Split in $= 0$ and ≥ 1 lepton channels
- Define signal regions by setting thresholds on a few key observables
- Discovery: simple cut-and-count analysis with 10 signal regions
- Exclusion: Simultaneous ("multi-bin") fit of 14 orthogonal signal regions
- Different signal regions target different regimes of $|m_{\tilde{g}} - m_{\tilde{\chi}_1^0}|$:



A → large mass splitting

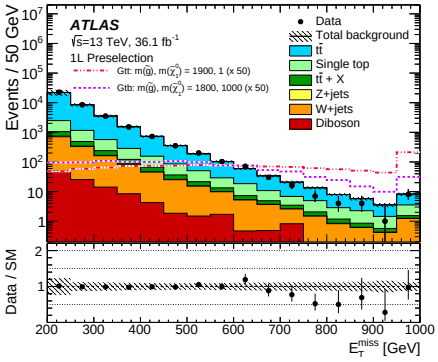
B → intermediate mass splitting

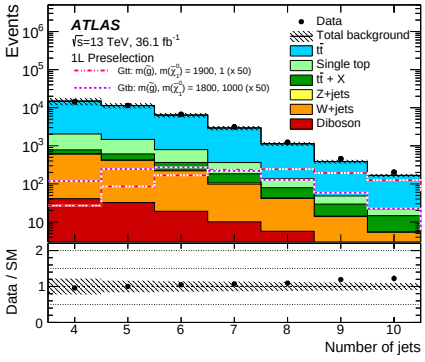
C → small mass splitting

Figure: Chiara Rizzi

Signal regions observables: E_T^{miss}, N_b

- Some of the variables used for signal region definitions





Plots: [1711.01901]

- Typically require $> 250 - 500$ GeV of E_T^{miss}
- Typically require $\geq 6 - 8$ small-R jets!
- b-jet multiplicity also used

Observables: m_{eff}, M_J^{Σ}

- Some of the variables used for signal region definitions
- m_{eff}: "effective mass": sum of p_T of small-radius jets and leptons, and E_T^{miss}
- M_J^{Σ}: sum of masses of the 4 leading large-radius jets

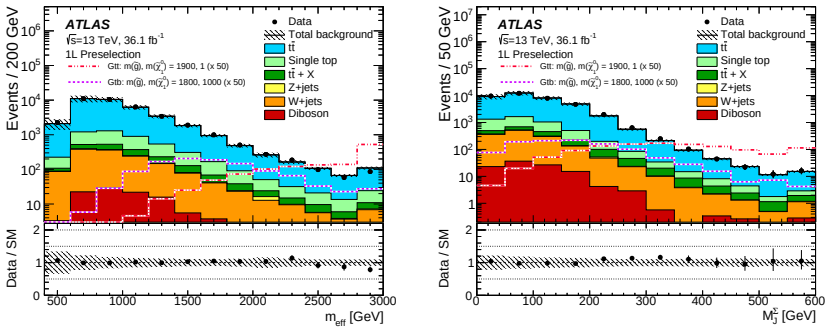


Figure: [1711.01901]

- Typical m_{eff} cut between 1 and 2.8 TeV!
- Typical M_J^{Σ} cut between 100 and 300 GeV

Search strategy, part II

- Summary of variables used:
  - $N_j, N_b, E_T^{miss}, m_{eff}, M_J^{\Sigma}, m_T, m_{T,b}^{min}$
- CR: Background-enriched control regions: Used to fit the background normalization (data over simulation)
- SR: Signal-enriched regions to perform search. Background expectation scaled using control region fit results
- VR: Intermediate validation regions to verify background normalization

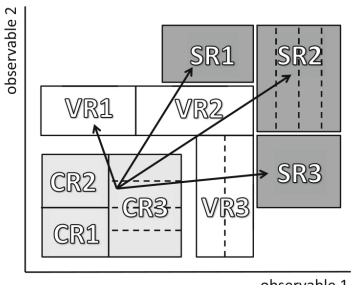


Figure: [1410.1280]

Results

- Cut-and-count analysis: No excess ☹

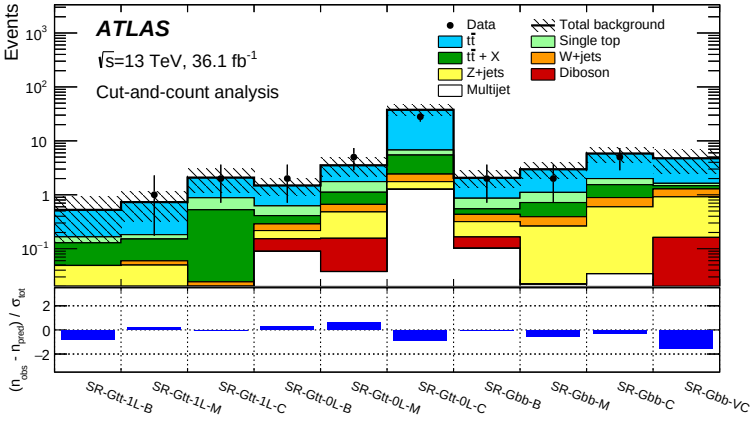
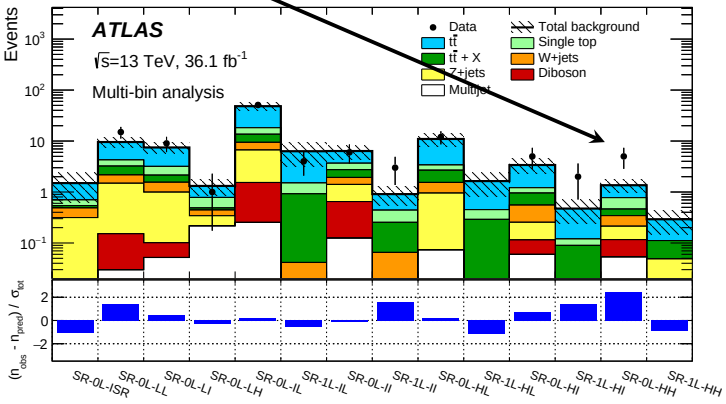


Figure: [1711.01901]

Results

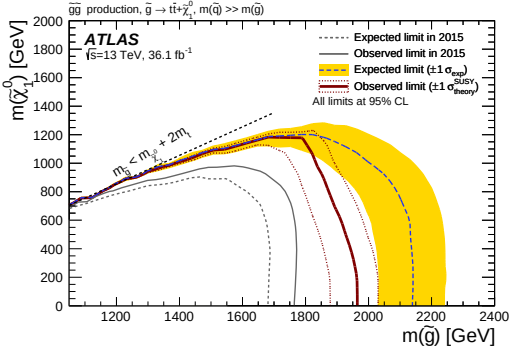
- Multi-bin analysis: used to set limits on various models
- $\approx 2\sigma$ excess in SR-0L-HH, will be cross-checked with 2017 data

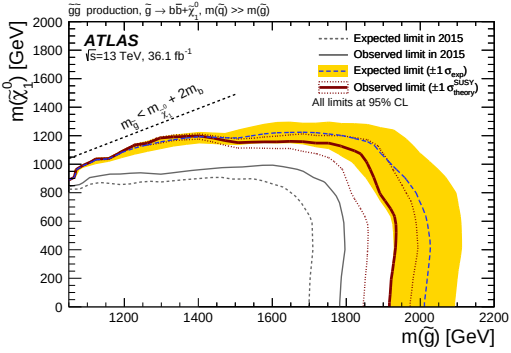


Figures: [1711.01901]

Results

- multi-bin analysis
- $\approx 2\sigma$ excess in one bin lowers the observed limit for model with Br(gluino→tops) = 100%





Figures: [1711.01901]

Left: Br(gluino→tops)=100%

Right: Br(gluino→bottoms)=100%

Results

- Use mixed samples to derive limits as function of gluino branching ratios to tt, bb, and tb
- Probes how limits change when branching ratios are relaxed
- Very useful for theorists ☺
- Hashing indicates excluded side
- Dashed line: expected, Solid line: observed

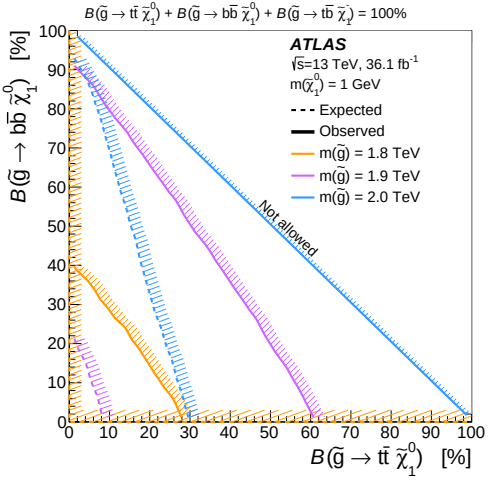
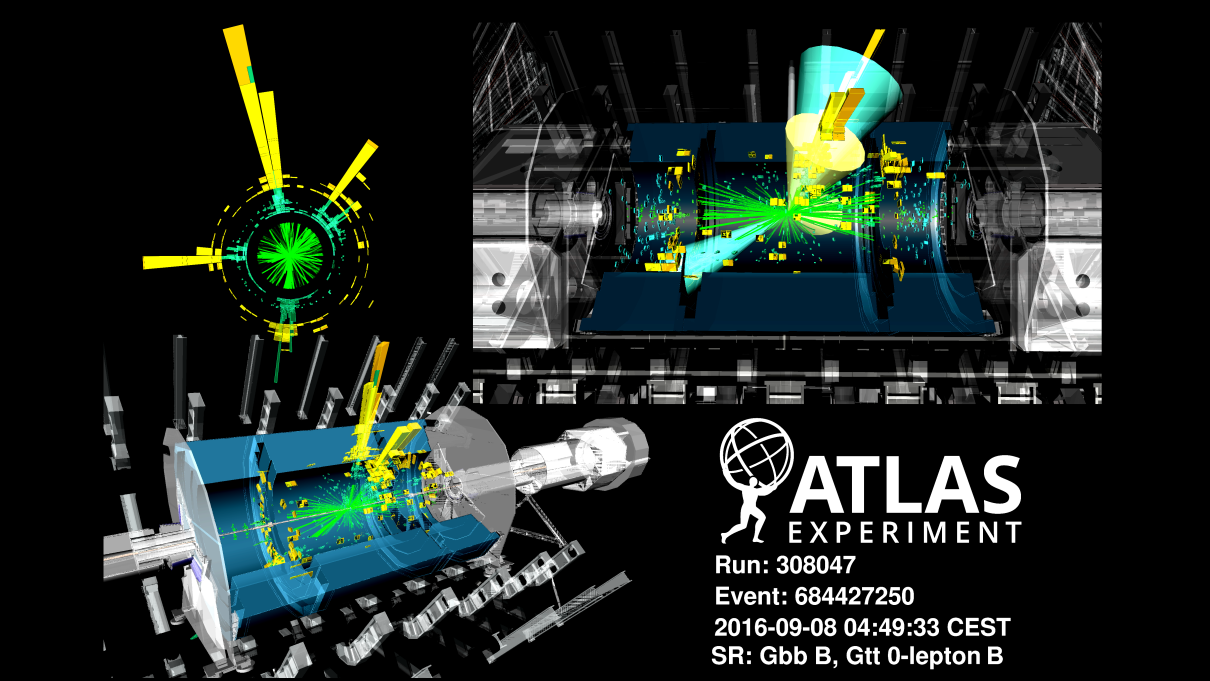
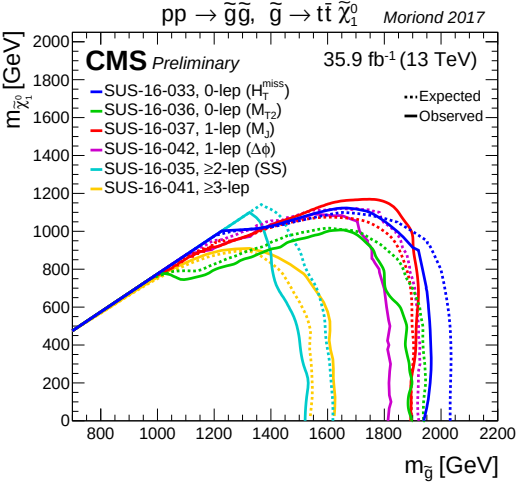


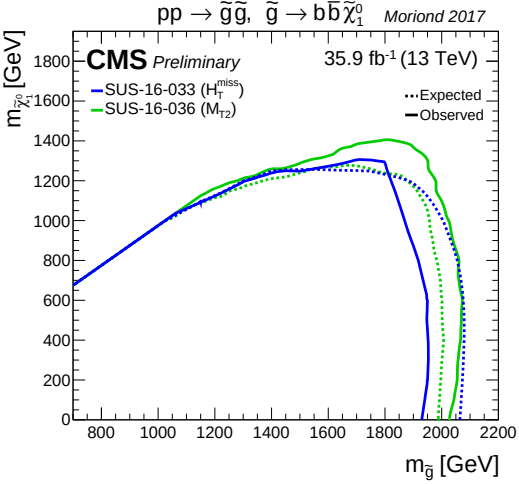
Figure: [1711.01901]


ATLAS
EXPERIMENT
Run: 308047
Event: 684427250
2016-09-08 04:49:33 CEST
SR: Gbb B, Gtt 0-lepton B

BACKUP

CMS results


pp → g̃g̃, g̃ → tt̄ χ̃⁰₁
Moriond 2017
CMS Preliminary
35.9 fb-1 (13 TeV)
SUS-16-033, 0-lep (H_T^miss)
SUS-16-036, 0-lep (M_T2)
SUS-16-037, 1-lep (M_J)
SUS-16-042, 1-lep (Δφ)
SUS-16-035, ≥2-lep (SS)
SUS-16-041, ≥3-lep
Expected
Observed
m_χ̃⁰₁ [GeV]
m_g̃ [GeV]


pp → g̃g̃, g̃ → bb̄ χ̃⁰₁
Moriond 2017
CMS Preliminary
35.9 fb-1 (13 TeV)
SUS-16-033 (H_T^miss)
SUS-16-036 (M_T2)
Expected
Observed
m_χ̃⁰₁ [GeV]
m_g̃ [GeV]

Samples

Process	Event Generator + fragmentation/hadronisation	Tune	PDF set	Cross-section order
SUSY signal	MadGraph5_aMC@NLO v2.2.2 + Pythia v8.186	A14	NNPDF2.3	NLO+NLL [56,57,58,59,60,61]
$t\bar{t}$	Powheg-Box v2 + Pythia v6.428	PERUGIA2012	CT10	NNLO+NNLL [63]
Single top	Powheg-Box v1 or v2 + Pythia v6.428	PERUGIA2012	CT10	NNLO+NNLL [64,65,66]
$t\bar{t}W/t\bar{t}Z$**/4-tops**	MadGraph5_aMC@NLO v2.2.2 + Pythia v8.186	A14	NNPDF2.3	NLO [67]
$t\bar{t}H$	MadGraph5_aMC@NLO v2.2.1 + Herwig++ v2.7.1	UEEE5	CT10	NLO [68]
Diboson WW, WZ, ZZ	Sherpa v2.1.1	Default	CT10	NLO [46]
W/Z**+jets**	Sherpa v2.2.0	Default	NNPDF3.0	NNLO [69]

Table: [1711.01901]

Objects (in-depth)

- Small-Radius jets
  - Anti-kT algorithm with radius parameter $= 0.4$
  - Calibrated to particle-level with data and simulation-extracted jet energy scale
  - Jets from non-collision sources or detector noise rejected
  - MVA used to reject pile-up jets
  - Candidate jets: $p_T > 20$ GeV, $|\eta| < 2.8$
  - After overlap-removal with leptons: $p_T > 30$ GeV
- Large-Radius jets
  - Small-radius jets *reclustered* using anti-kT with radius $= 0.8$ (after overlap removal)
  - "Trimming": subjets with pT fraction $< 10\%$ of re-clustered jet removed
  - $p_T > 100$ GeV, $|\eta| < 2.0$
- b-jets
  - b-tagging working point: 77% efficiency
  - Rejection: c: 6, τ: 22, light quarks/gluons: 134
  - MVA using information about impact parameter of matched tracks, presence of displaced secondary vertices and reconstructed flight paths of b and c quarks within the jets
  - [1512.01094]
  - ATL-PHYS-PUB-2016-012

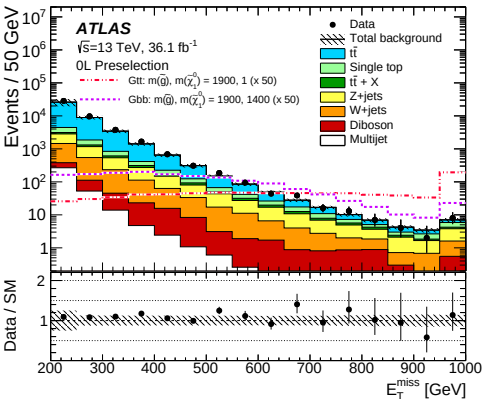
Objects (in-depth)

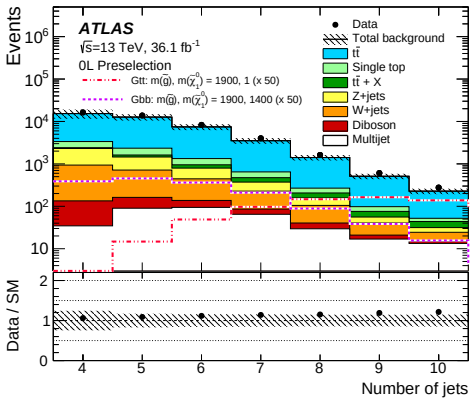
- Electrons
  - Energy clusters in electromagnetic calorimeter matched to inner detector tracks
  - $p_T > 20$ GeV, $|\eta < 2.47|$
  - Set of "loose" quality criteria
  - [1407.5063]
  - ATLAS-CONF-2016-024
- Muons
  - Muon spectrometer tracks matched to inner detector tracks
  - $p_T > 20$ GeV, $|\eta < 2.5|$
  - Set of "medium" quality criteria
  - [1603.05598]

Overlap removal

1. Electron closer than $\Delta R = 0.01$ from muon removed
   - Suppress contribution from muon bremsstrahlung
2. Discard non-b-tagged jets closer than $\Delta R = 0.2$ from electron
   - Suppress contribution from showering of prompt electrons
3. Discard electrons with $E_T < 50$ GeV closer than $\Delta R = 0.4$ from jet.
   If $E_T > 50$ GeV, threshold is $\Delta R = min(0.4, 0.04 + 10GeV/E_T)$
   - Supress contribution from electrons produced in hadron decay chain

Observables: E_T^{miss}, N_b

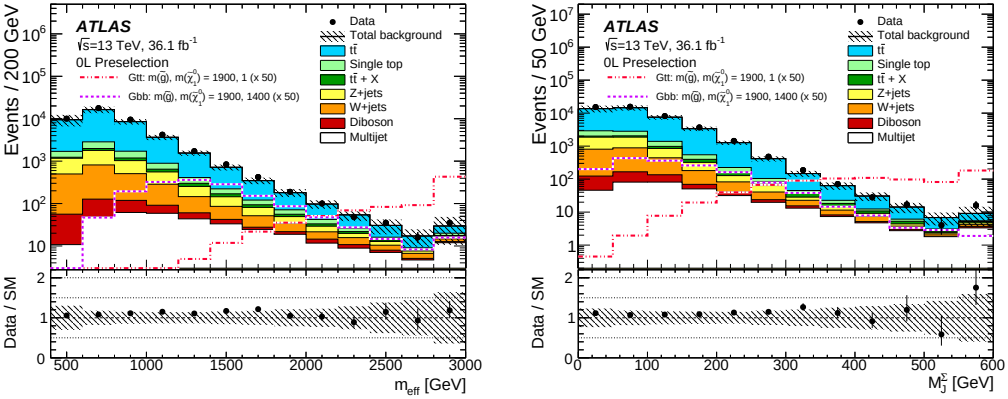




Figures: [1711.01901]

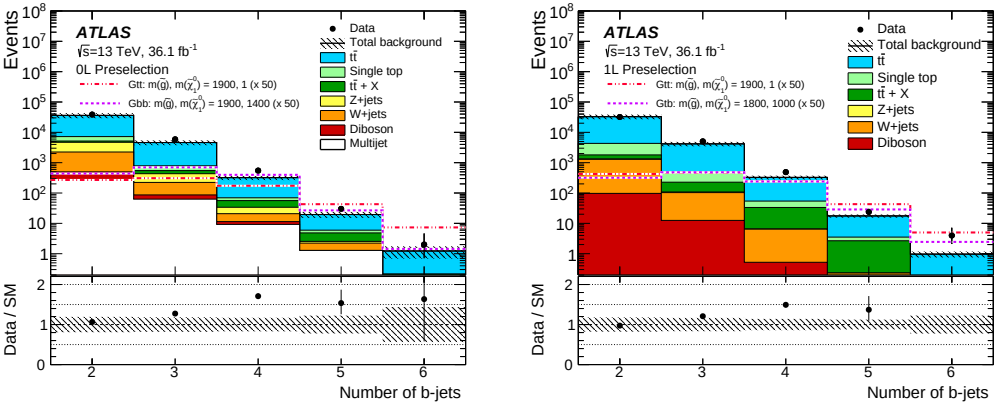
Observables: m_{eff}, M_J^{Σ}

- m_{eff}: "effective mass": sum of p_T of small-radius jets and leptons, and E_T^{miss}
- M_j^{Σ}: sum of masses of the 4 leading large-radius jets



Figures: [1711.01901]

Observables: N_j



Figures: [1711.01901]

Gtt cut-and-count SR/VR/CR

Gtt 1-lepton

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

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

Gtt 0-lepton

Criteria common to all regions: $p_{\mathrm{T}}^{\mathrm{jet}} > 30$ GeV

Targeted kinematics	Type	N_{lepton}	$N_{b\text{-jets}}$	N_{jet}	$\Delta\phi_{\mathrm{min}}^{4\mathrm{j}}$	m_{T}	$m_{\mathrm{T,min}}^{b\text{-jets}}$	$E_{\mathrm{T}}^{\mathrm{miss}}$	$m_{\mathrm{eff}}^{\mathrm{incl}}$	M_J^{Σ}
Region B (Boosted, Large Δm)	SR	$= 0$	≥ 3	≥ 7	> 0.4	–	> 60	> 350	> 2600	> 300
	CR	$= 1$	≥ 3	≥ 6	–	< 150	–	> 275	> 1800	> 300
	VR	$= 0$	≥ 3	≥ 6	> 0.4	–	–	> 250	> 2000	< 300
Region M (Moderate Δm)	SR	$= 0$	≥ 3	≥ 7	> 0.4	–	> 120	> 500	> 1800	> 200
	CR	$= 1$	≥ 3	≥ 6	–	< 150	–	> 400	> 1700	> 200
	VR	$= 0$	≥ 3	≥ 6	> 0.4	–	–	> 450	> 1400	< 200
Region C (Compressed, moderate Δm)	SR	$= 0$	≥ 4	≥ 8	> 0.4	–	> 120	> 250	> 1000	> 100
	CR	$= 1$	≥ 4	≥ 7	–	< 150	–	> 250	> 1000	> 100
	VR	$= 0$	≥ 4	≥ 7	> 0.4	–	–	> 250	> 1000	< 100

Tables: [1711.01901]

Observables: m_T, $m_{T,min}^{b-jets}$

- m_T: "transverse mass": Attempt to measure W mass using leading lepton and E_T^{miss} in $\geq$1-lepton events
- $m_{T,min}^{b-jets}$: inspired by m_T but use b-jets instead of lepton.
  - Starting with the 3 leading b-jets, use the b-jet leading to minimal m_T^{b-jets}

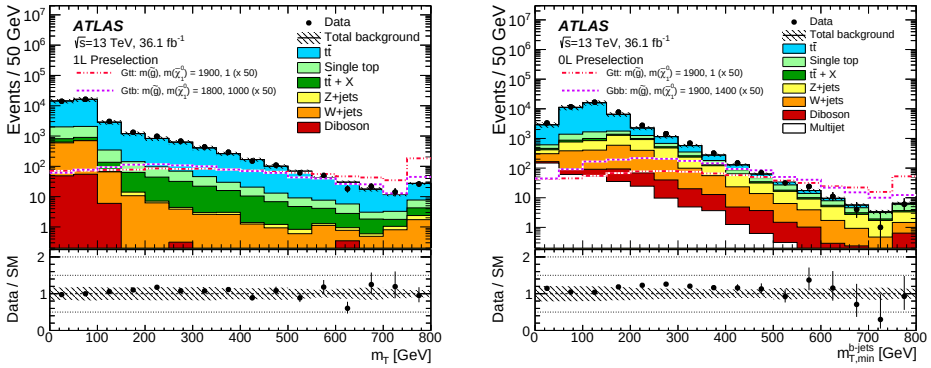


Figure: [1711.01901]

Gbb cut-and-count SR/VR/CR

Gbb

Criteria common to all regions: $N_{\text{jet}} \geq 4$, $p_{\text{T}}^{\text{jet}} > 30$ GeV

Targeted kinematics	Type	N_{lepton}	$N_{b\text{-jets}}$	$\Delta\phi_{\text{min}}^{\text{4j}}$	m_{T}	$m_{\text{T,min}}^{b\text{-jets}}$	$E_{\text{T}}^{\text{miss}}$	m_{eff}	Others
Region B (Boosted, Large Δm)	SR	$= 0$	≥ 3	> 0.4	–	–	> 400	> 2800	–
	CR	$= 1$	≥ 3	–	< 150	–	> 400	> 2500	–
	VR	$= 0$	≥ 3	> 0.4	–	–	> 350	1900–2800	–
Region M (Moderate Δm)	SR	$= 0$	≥ 4	> 0.4	–	> 90	> 450	> 1600	–
	CR	$= 1$	≥ 4	–	< 150	–	> 300	> 1600	–
	VR	$= 0$	≥ 4	> 0.4	–	> 100	250–450	1600–1900	–
Region C (Compressed, small Δm)	SR	$= 0$	≥ 4	> 0.4	–	> 155	> 450	–	–
	CR	$= 1$	≥ 4	–	< 150	–	> 375	–	–
	VR	$= 0$	≥ 4	> 0.4	–	> 125	350–450	–	–
Region VC (Very Compressed, very small Δm)	SR	$= 0$	≥ 3	> 0.4	–	> 100	> 600	–	$p_{\text{T}}^{\text{j}_1} > 400$, $\text{j}_1 \neq b$, $\Delta\phi^{\text{j}_1} > 2.5$
	CR	$= 1$	≥ 3	–	< 150	–	> 600	–	
	VR	$= 0$	≥ 3	> 0.4	–	> 100	225–600	–	

Table: [1711.01901]

multi-bin high-N_j SR/VR/CR

High-N_{jet} regions

Criteria common to all regions: $N_{b\text{-jets}} \geq 3$, $p_{\text{T}}^{\text{jet}} > 30$ GeV

Targeted kinematics	Type	N_{lepton}	$\Delta\phi_{\text{min}}^{4j}$	m_{T}	N_{jet}	$m_{\text{T,min}}^{b\text{-jets}}$	M_J^{Σ}	$E_{\text{T}}^{\text{miss}}$	m_{eff}
High-m_{eff} (HH) (Large Δm)	SR-0L	$= 0$	> 0.4	–	≥ 7	> 100	> 200	> 400	> 2500
	SR-1L	≥ 1	–	> 150	≥ 6	> 120	> 200	> 500	> 2300
	CR	≥ 1	–	< 150	≥ 6	> 60	> 150	> 300	> 2100
	VR-0L	$= 0$	> 0.4	–	≥ 7	< 100 if $E_{\text{T}}^{\text{miss}} > 300$	–	< 300 if $m_{\text{T,min}}^{b\text{-jets}} > 100$	> 2100
	VR-1L	≥ 1	–	> 150	≥ 6	< 140 if $m_{\text{eff}} > 2300$	–	< 500	> 2100
Intermediate-m_{eff} (HI) (Intermediate Δm)	SR-0L	$= 0$	> 0.4	–	≥ 9	> 140	> 150	> 300	$[1800, 2500]$
	SR-1L	≥ 1	–	> 150	≥ 8	> 140	> 150	> 300	$[1800, 2300]$
	CR	≥ 1	–	< 150	≥ 8	> 60	> 150	> 200	$[1700, 2100]$
	VR-0L	$= 0$	> 0.4	–	≥ 9	< 140 if $E_{\text{T}}^{\text{miss}} > 300$	–	< 300 if $m_{\text{T,min}}^{b\text{-jets}} > 140$	$[1650, 2100]$
	VR-1L	≥ 1	–	> 150	≥ 8	< 140 if $E_{\text{T}}^{\text{miss}} > 300$	–	< 300 if $m_{\text{T,min}}^{b\text{-jets}} > 140$	$[1600, 2100]$
Low-m_{eff} (HL) (Small Δm)	SR-0L	$= 0$	> 0.4	–	≥ 9	> 140	–	> 300	$[900, 1800]$
	SR-1L	≥ 1	–	> 150	≥ 8	> 140	–	> 300	$[900, 1800]$
	CR	≥ 1	–	< 150	≥ 8	> 130	–	> 250	$[900, 1700]$
	VR-0L	$= 0$	> 0.4	–	≥ 9	< 140	–	> 300	$[900, 1650]$
	VR-1L	≥ 1	–	> 150	≥ 8	< 140	–	> 225	$[900, 1650]$

Table: [1711.01901]

multi-bin intermediate-N_j SR/VR/CR

Intermediate-N_{jet} regions

Criteria common to all regions: $N_{b\text{-jets}} \geq 3$, $p_{\text{T}}^{\text{jet}} > 30$ GeV

Targeted kinematics	Type	N_{lepton}	$\Delta\phi_{\text{min}}^{4\text{j}}$	m_{T}	N_{jet}	$\text{j}_1 = b$ or $\Delta\phi^{\text{j}1} \leq 2.9$	$m_{\text{T,min}}^{b\text{-jets}}$	M_J^{Σ}	$E_{\text{T}}^{\text{miss}}$	m_{eff}
Intermediate-m_{eff} (II) (Intermediate Δm)	SR-0L	$= 0$	> 0.4	–	$[7, 8]$	✓	> 140	> 150	> 300	$[1600, 2500]$
	SR-1L	≥ 1	–	> 150	$[6, 7]$	–	> 140	> 150	> 300	$[1600, 2300]$
	CR	≥ 1	–	< 150	$[6, 7]$	✓	> 110	> 150	> 200	$[1600, 2100]$
	VR-0L	$= 0$	> 0.4	–	$[7, 8]$	✓	< 140	–	> 300	$[1450, 2000]$
	VR-1L	≥ 1	–	> 150	$[6, 7]$	–	< 140	–	> 225	$[1450, 2000]$
Low-m_{eff} (IL) (Low Δm)	SR-0L	$= 0$	> 0.4	–	$[7, 8]$	✓	> 140	–	> 300	$[800, 1600]$
	SR-1L	≥ 1	–	> 150	$[6, 7]$	–	> 140	–	> 300	$[800, 1600]$
	CR	≥ 1	–	< 150	$[6, 7]$	✓	> 130	–	> 300	$[800, 1600]$
	VR-0L	$= 0$	> 0.4	–	$[7, 8]$	✓	< 140	–	> 300	$[800, 1450]$
	VR-1L	≥ 1	–	> 150	$[6, 7]$	–	< 140	–	> 300	$[800, 1450]$

Table: [1711.01901]

multi-bin low-N_j SR/VR/CR

Low-N_{jet} regions

Criteria common to all regions: $N_{b\text{-jets}} \geq 3$, $p_{\text{T}}^{\text{jet}} > 30$ GeV

Targeted kinematics	Type	N_{lepton}	$\Delta\phi_{\text{min}}^{4\text{j}}$	m_{T}	N_{jet}	$\text{j}_1 = b$ or $\Delta\phi^{\text{j}_1} \leq 2.9$	$p_{\text{T}}^{\text{j}_4}$	$m_{\text{T,min}}^{b\text{-jets}}$	$E_{\text{T}}^{\text{miss}}$	m_{eff}
High-m_{eff} (LH) (Large Δm)	SR	$= 0$	> 0.4	–	$[4, 6]$	–	> 90	–	> 300	> 2400
	CR	≥ 1	–	< 150	$[4, 5]$	–	-	–	> 200	> 2100
	VR	$= 0$	> 0.4	–	$[4, 6]$	–	> 90 if $E_{\text{T}}^{\text{miss}} < 300$	–	> 200	$[2000, 2400]$
Intermediate-m_{eff} (LI) (Intermediate Δm)	SR	$= 0$	> 0.4	–	$[4, 6]$	✓	> 90	> 140	> 350	$[1400, 2400]$
	CR	≥ 1	–	< 150	$[4, 5]$	✓	> 70	–	> 300	$[1400, 2000]$
	VR	$= 0$	> 0.4	–	$[4, 6]$	✓	> 90	< 140	> 300	$[1250, 1800]$
Low-m_{eff} (LL) (Low Δm)	SR	$= 0$	> 0.4	–	$[4, 6]$	✓	> 90	> 140	> 350	$[800, 1400]$
	CR	≥ 1	–	< 150	$[4, 5]$	✓	> 70	–	> 300	$[800, 1400]$
	VR	$= 0$	> 0.4	–	$[4, 6]$	✓	> 90	< 140	> 300	$[800, 1250]$

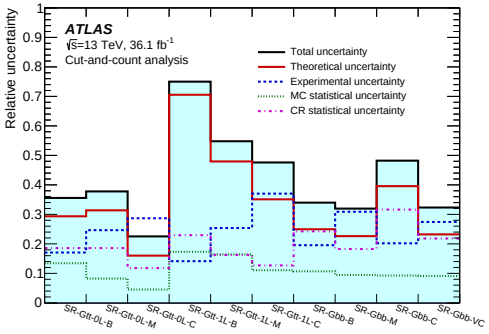
ISR regions

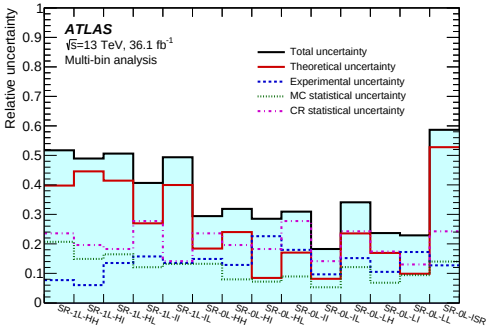
Criteria common to all regions: $N_{b\text{-jets}} \geq 3$, $\Delta\phi^{\text{j}_1} > 2.9$, $p_{\text{T}}^{\text{j}_1} > 400$ GeV, $p_{\text{T}}^{\text{jet}} > 30$ GeV, $\text{j}_1 \neq b$

Type	N_{lepton}	$\Delta\phi_{\text{min}}^{4\text{j}}$	m_{T}	N_{jet}	$m_{\text{T,min}}^{b\text{-jets}}$	$E_{\text{T}}^{\text{miss}}$	m_{eff}
SR	$= 0$	> 0.4	–	$[4, 8]$	> 100	> 600	< 2200
CR	≥ 1	–	< 150	$[4, 7]$	–	> 400	< 2000
VR	$= 0$	> 0.4	–	$[4, 8]$	> 100	> 250	< 2000

Tables: [1711.01901]

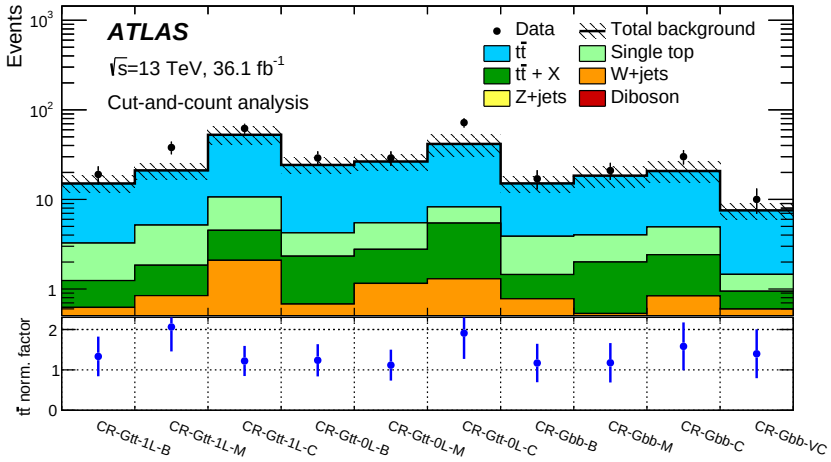
Systematic uncertainties





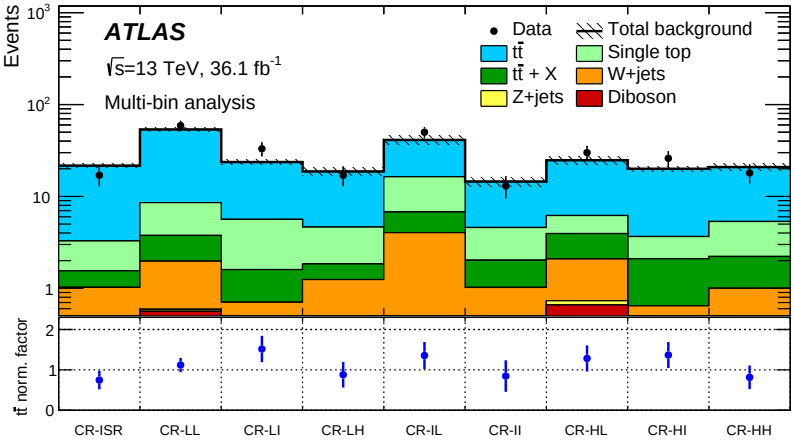
Figures: [1711.01901]

Pre-fit yields in CR: cut-and-count



Figures: [1711.01901]

Pre-fit yields in CR: multi-bin



Figures: [1711.01901]