Searches for squarks and gluinos in fully hadronic final states with the ATLAS detector

International Conference on High Energy Physics, ICHEP 2016

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Enrico Fermi Institute

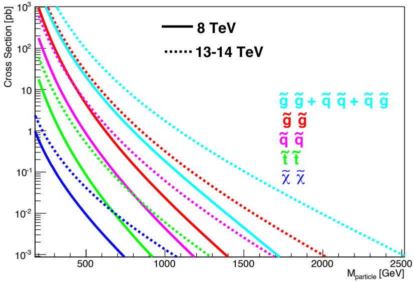
THE UNIVERSITY OF CHICAGO

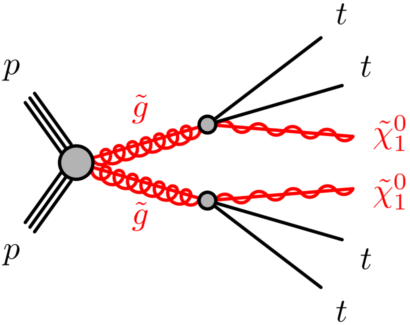
August 4, 2016

Outline

Supersymmetry (SUSY) at $\sqrt{s} = 13$ TeV

More information in arXiv:1411.1427

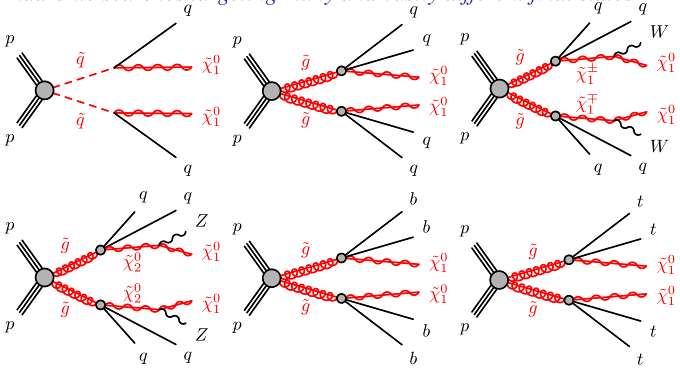




- **Expect large increase of SUSY cross-sections going from 8 $\rightarrow$ 13 TeV**
  - $\sigma(\tilde{g}\tilde{g})$ increases by $\times 30$ for $m(\tilde{g}) = 1.4$ TeV at 13 TeV
  - Very large phase space, e.g. $m(\tilde{g}) - m(\tilde{\chi}_1^0) \gg m(t)$: $\rightarrow$ **boosted top/W, compressed mass spectra, significant variety of final states!**
- **Strong focus on $\tilde{g}$ initiated processes with first Run 2 data, with discovery potential beyond Run 1 limits with >10 fb^{-1} of 13 TeV data**

Supersymmetry (SUSY) at $\sqrt{s} = 13$ TeV

Just a few all-hadronic searches targeting many and vastly different final states



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  - $\sigma(\tilde{g}\tilde{g}) \times 30$ for $m(\tilde{g}) = 1.4$ TeV
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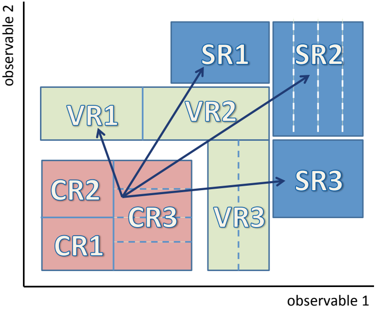
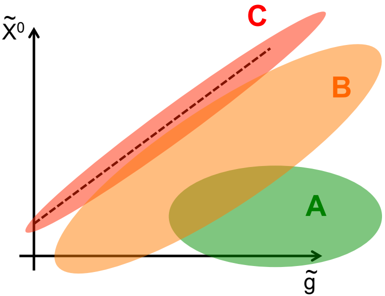
Search strategies for all-hadronic SUSY processes at 13 TeV





- Cut and count analysis strategies are used
- **Signal regions (SR)** $\perp$ to **validation (VR)** & **control regions (CR)**
- SRs typically target **large, intermediate, or small** mass splittings
- Primary backgrounds from MC are normalized in CRs and tested in VRs

Classes of observables used when searching for SUSY

Three primary classes of event selection observables [arXiv:1605.01416] that are sensitive to distinct features of SUSY processes:

- **Missing energy-type:** sensitive to the properties of the invisible states, e.g. how many neutralinos in the event, what is their mass, etc.;
- **Energy scale-type:** sensitive to the overall energy scale of the event, e.g. the mass of the gluino ($m_{\tilde{g}}$);
- **Energy structure-type:** sensitive to the structure of the visible energy, e.g. how many partons are generated in the decay, how that energy is partitioned across the final state objects (*both visible and invisible*);

→ ***Observables that fall into each of these classes are used in the two searches that I will discuss in detail today.***

13 TeV ATLAS searches using >10 fb^{-1} of 2016 data discussed in this talk:

- **Zero-lepton final states with 2-6 jets**: ATLAS-CONF-2016-078
- **Multi-*b* jet final states with 0 and 1 lepton**: ATLAS-CONF-2016-052

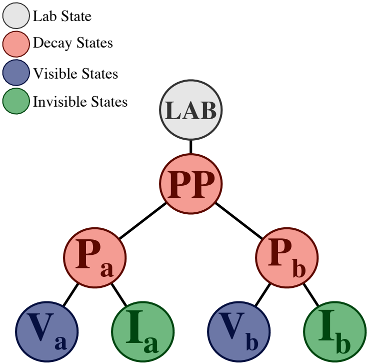
Observables used in these two 13 TeV searches for SUSY

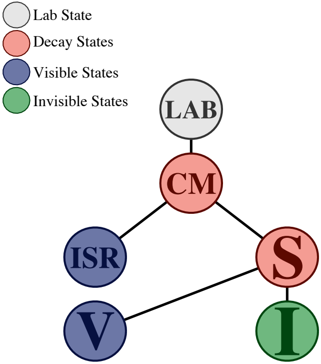
For the 13 TeV ATLAS searches, we utilize each of these classes:

- **Missing energy-type:**
  - **Missing transverse momentum:** $E_{\mathrm{T}}^{\mathrm{miss}}$ and $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$
  - **Missing transverse momentum significance:** $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$
  - **RJigsaw H-scale for 1 visible, 1 invisible state:** $H_{1,1}^{\mathrm{PP}}$ (Similar to $E_{\mathrm{T}}^{\mathrm{miss}}$)
- **Energy scale-type:**
  - **Effective mass:** $M_{\mathrm{eff}} = \sum_{\mathrm{jets}} p_{\mathrm{T}} + \sum_{\mathrm{leptons}} + E_{\mathrm{T}}^{\mathrm{miss}}$ (also considering only first 4 jets)
  - **Scalar sum of visible momenta:** H_{T},
  - **Transverse mass:** $m_{\mathrm{T}} = \sqrt{2p_{\mathrm{T}}^{\ell}E_{\mathrm{T}}^{\mathrm{miss}}(1-\cos(\Delta\phi(\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}},\ell))}$ (b-quarks can also replace the lepton)
  - **RJigsaw H-scale:** $H_{2,1}^{\mathrm{PP}}$, $H_{4,1}^{\mathrm{PP}}$ (Similar to M_{eff})
  - **RJigsaw ISR p_{T} scale:** $|p_{TS}^{\mathrm{ISR}}|$ (sum p_{T} of ISR jets
- **Energy structure-type:**
  - **Jet multiplicity:** N_{jet}, $N_{b-\mathrm{jet}}$
  - **Total jet mass:** $M_{\mathrm{J}}^{\Sigma} = \sum m^{\mathrm{jet}}$ (also considering only first 4 large-radius jets)
  - **Angular distributions:** $\Delta\phi_{\mathrm{min}}^{4j} = \min(|\phi_{\mathrm{any-jet}} - \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}|) > 0.4$ (for all 0ℓ selections)
  - **Aplanarity:** $A = (3/2)\lambda_3$
  - **QCD $E_{\mathrm{T}}^{\mathrm{miss}}$ alignment:** Δ_{QCD} (signed asymmetry between $E_{\mathrm{T}}^{\mathrm{miss}}$ and jet azimuthal directions)

Recursive Jigsaw Reconstruction (RJR) for SUSY at 13 TeV

See the poster by Paul Jackson on RJR techniques and the recent paper (arXiv:1607.08307)





- Decompose events according to **particular decay topology assumption** and partition kinematics to **estimate missing degrees of freedom**
- **"Hemispheres"** defined using thrust axis of event
- Observables are computed by **minimizing hemisphere masses** and assigning missing degrees of freedom with each

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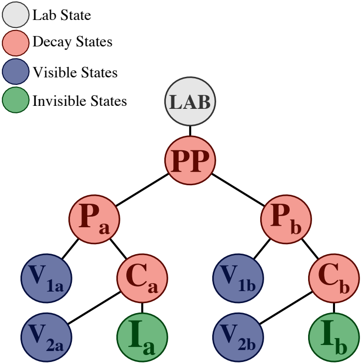

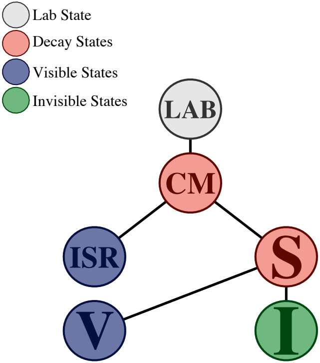

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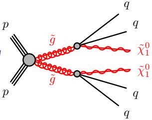
Targeting zero-lepton (0L) final states with 2-6 jets



Just released for ICHEP! ATLAS-CONF-2016-078

- **Two simultaneous strategies: Large M_{eff}** and **Recursive Jigsaw (RJR)**:
  - $M_{\text{eff}} > (0.8 - 2.2)$ TeV, $N_{\text{jet}} > (2-6)$, $E_{\text{T}}^{\text{miss}} > 200, 500$ GeV, $\Delta\phi > (0.2 - 0.4)$
  - $H_{1,1}^{\text{PP}}/H_{4,1}^{\text{PP}} > (0.2 - 0.35)$, $\Delta_{\text{QCD}} > 0$,

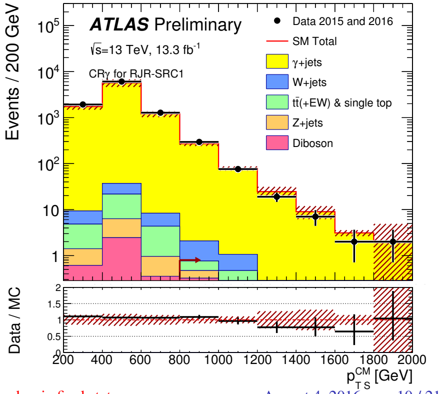
  $\rightarrow$ ***First use of the RJR technique at the LHC!***
- **30 signal regions between the M_{eff} and RJR analyses:**
  - *See backup slides for details!*

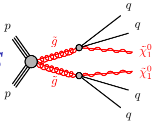
Control regions (CR) establish backgrounds in assoc. signal regions (SR)

- **$Z(\rightarrow \nu\nu)$+jets:** from $\gamma + jets$ in CRγ
- **Multi-jets:** from multijets in CRQ
- **$W(\rightarrow \ell\nu)$+jets:** from W+jets in CRW
- **$t\bar{t}$:** from semileptonic $t\bar{t}$ in CRT

Validation regions (VR) are used to confirm the predictions from the CRs.

[CRγ for RJR analysis]





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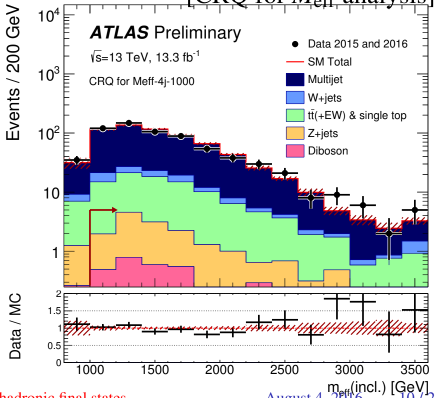
[CRQ for M_{eff} analysis]



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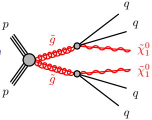

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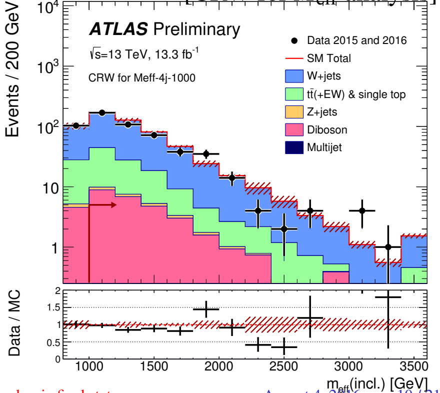
[CRW for M_{eff} analysis]



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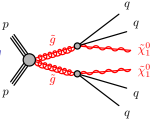

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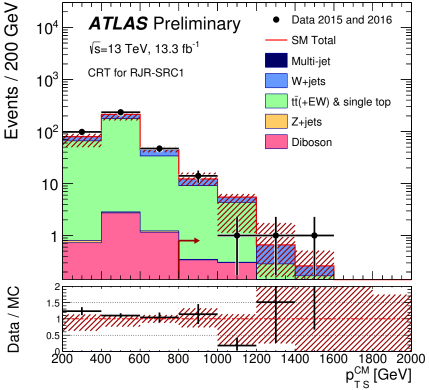
[CRT for RJR analysis]



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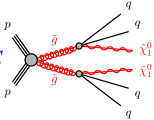

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Control region selection requirements for each region and analysis approach:

CR	SR background	CR process	CR selection (Meff-based)	CR selection (RJR-based)
Meff/RJR-CRγ	$Z(\rightarrow \nu\bar{\nu})$+jets	γ+jets	Isolated photon	Isolated photon
Meff/RJR-CRQ	Multi-jet	Multi-jet	SR with reversed requirements on (i) $\Delta\phi(\text{jet}, \boldsymbol{E}_{\text{T}}^{\text{miss}})_{\text{min}}$ and (ii) $E_{\text{T}}^{\text{miss}}/m_{\text{eff}}(N_{\text{j}})$ or $E_{\text{T}}^{\text{miss}}/\sqrt{H_{\text{T}}}$	$\Delta_{\text{QCD}} < 0$ reversed requirement on $H_{1,1}^{\text{PP}}$ (RJR-S/G) or $R_{\text{ISR}} < 0.5$ (RJR-C)
Meff/RJR-CRW	$W(\rightarrow \ell\nu)$+jets	$W(\rightarrow \ell\nu)$+jets	30 GeV< $m_{\text{T}}(\ell, E_{\text{T}}^{\text{miss}}) < 100$ GeV, b-veto	
Meff/RJR-CRT	$t\bar{t}$(+EW) and single top	$t\bar{t} \rightarrow b\bar{b}qq'\ell\nu$	30 GeV< $m_{\text{T}}(\ell, E_{\text{T}}^{\text{miss}}) < 100$ GeV, b-tag	

Results in 0L final states with 2-6 jets: M_{eff} analysis

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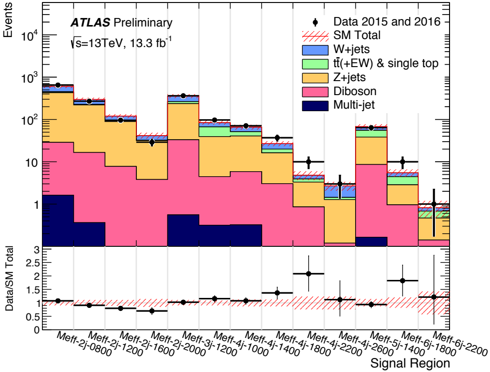
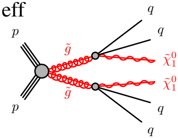
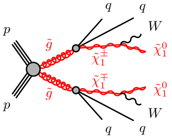
- Observe good agreement in most SRs
- Observe some deviations from the predictions up to approximately 2.5σ for the 4-jet and 6-jet regions with high M_{eff}







Targeted signal	$\tilde{g}\tilde{g},\, \tilde{g} \to q\bar{q}\tilde{\chi}_1^0$	$\tilde{g}\tilde{g},\, \tilde{g} \to q\bar{q}W\tilde{\chi}_1^0$
Requirement	**Meff-4j-2200**	**Meff-6j-1800**
$N_{\text{jet}} \geq$	4	6
E_T^{miss}[GeV] $>$	200	200
$p_T(j_1)$ [GeV] $>$	200	200
$p_T(j_4)$ [GeV] $>$	150	–
$p_T(j_5)$ [GeV] $>$	–	–
$p_T(j_6)$ [GeV] $>$	–	50
$\lvert\eta(j_{1,\ldots,n})\rvert <$	2.0	2.0
$\Delta\phi(\text{jet}_{1-3}, \vec{p}_T^{\text{ miss}})_{\text{min}} >$	0.4	0.4
$\Delta\phi(\text{jet}_{i>3}, \vec{p}_T^{\text{ miss}})_{\text{min}} >$	0.4	0.2
Aplanarity $>$	0.04	0.08
$E_T^{\text{miss}}/M_{\text{eff}}(N_j) >$	0.2	0.15
M_{eff}(incl.) [GeV] $>$	2200	1800

Results in 0L final states with 2-6 jets: RJR analysis

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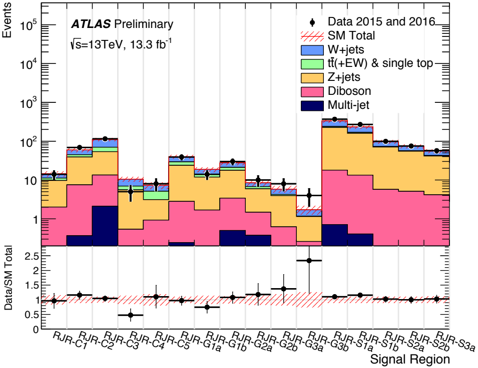
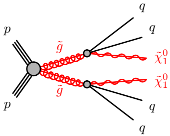
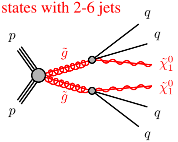
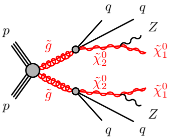
- Observe good agreement in most SRs
- Observe some deviations from the predictions in the gluino-targeted SRs
  - ...not independent with respect to M_{eff} analysis





Targeted signal	$\tilde{g}\tilde{g},\ \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	
Requirement	**RJR-G3a**	**RJR-G3b**
$H_{1,1}^{\rm PP}/H_{4,1}^{\rm PP} \geq$	0.2	
$H_{{\rm T}\,4,1}^{\rm PP}/H_{4,1}^{\rm PP} \geq$	0.65	
$p_{{\rm PP},\,z}^{\rm lab}/\left(p_{{\rm PP},\,z}^{\rm lab} + H_{{\rm T}\,4,1}^{\rm PP}\right) \leq$	0.6	
$\min\left(p_{{\rm j2\,T}\,i}^{\rm PP}/H_{{\rm T}\,2,1\,i}^{\rm PP}\right) \geq$	0.08	
$\max\left(H_{1,\,0}^{\rm Pi}/H_{2,\,0}^{\rm Pi}\right) \leq$	0.98	
$\Delta_{\rm QCD} >$	0	
$H_{1,1}^{\rm PP}$ [GeV] $>$	900	
$H_{{\rm T}\,4,1}^{\rm PP}$ [GeV] $>$	2300	2800





Results in 0L final states with 2-6 jets

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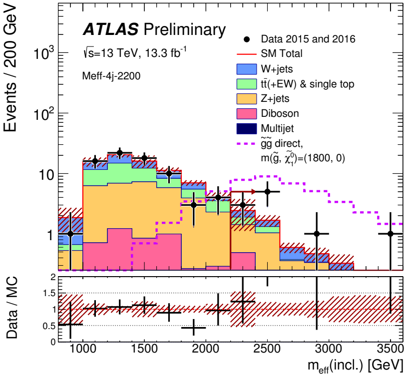
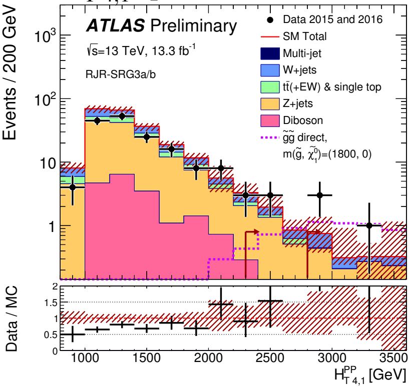
M_{eff} spectrum in **Meff-4j-2200**



$H_{T\,4,1}^{\mathrm{PP}}$ spectrum in **RJR-G3a**



- Observe slight excesses in signal regions designed to be sensitive to gluino production with hadronic final state bosons

Final limits in 0L final states with 2-6 jets

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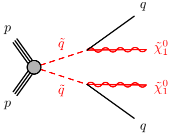

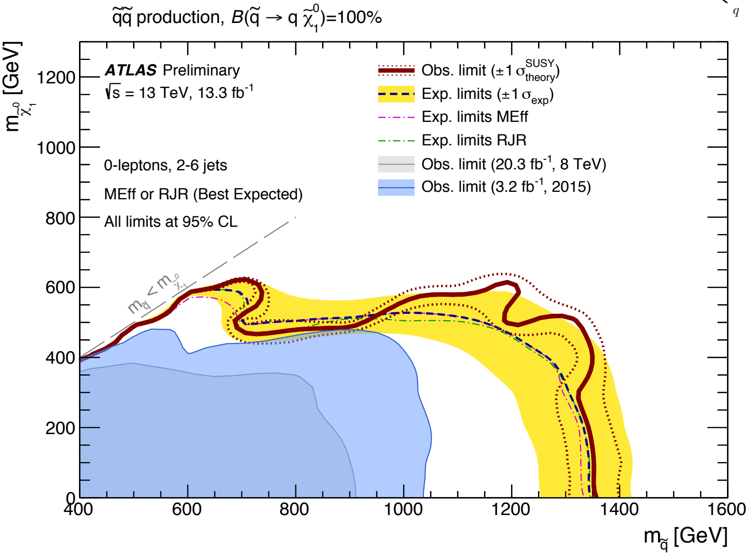

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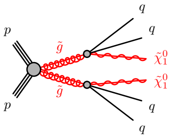

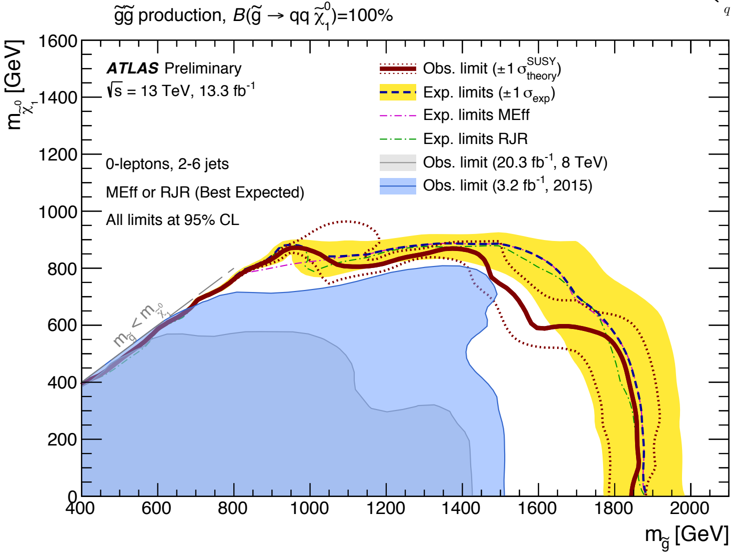

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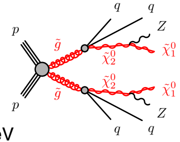

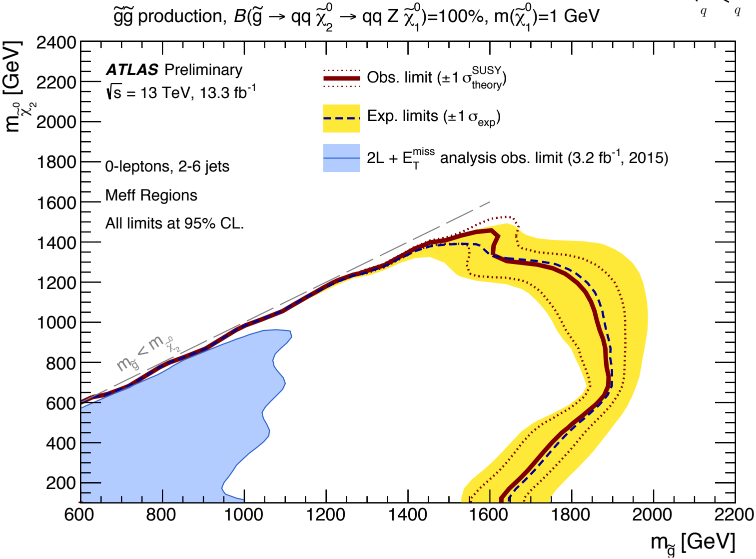

Search for multi-b jet final states with 4 b's, 0 leptons (Gbb)

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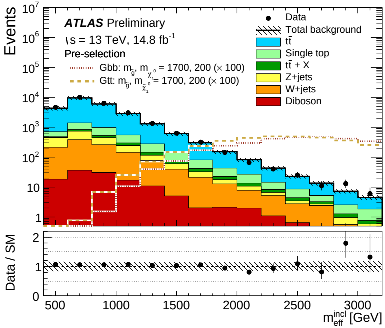

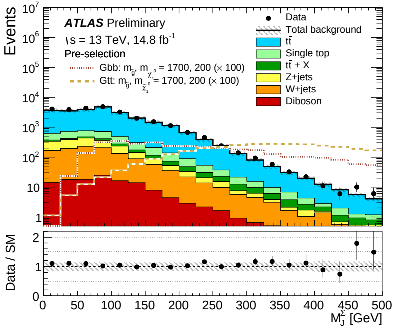

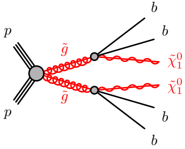

	Variable	Signal region	Control region	Validation region
Region A (Large mass splitting)	p_T^{jet}	> 70	> 70	> 70
	$N_{b\text{-jets}}$	≥ 3	≥ 3	≥ 3
	E_T^{miss}	> 450	> 350	> 450
	m_{eff}^{4j}	> 1900	> 1750	< 1900

(+ additional selections on m_T and leptons)

Search for multi-b jet final states with 4 tops, 0 leptons (Gtt)

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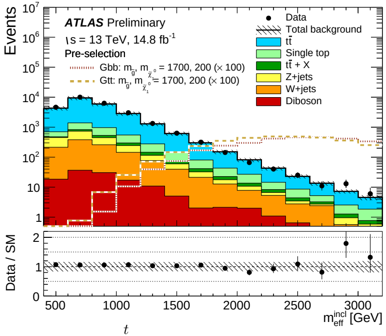

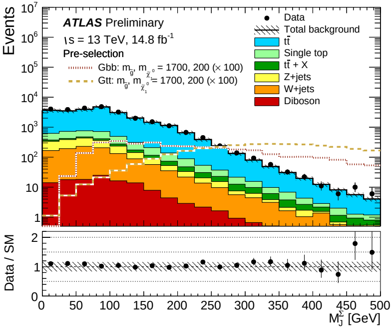

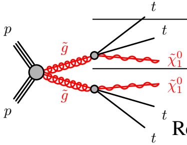

Region A
(Large mass splitting)

Variable	Signal region	Control region	VR1L	VR0L
E_T^{miss}	> 400	> 250	> 200	> 300
m_{eff}^{incl}	> 2000	> 1750	> 1750	> 1300
M_J^{Σ}	> 200	> 200	> 200	< 200

(+ additional selections on m_T, $m_T^{b-\text{jets}}$, N_{jet}, and leptons)

Yields in all signal regions: 4b, 4 top 0L (& 1L)

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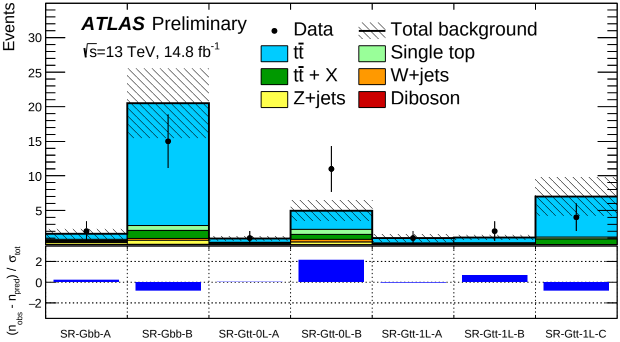
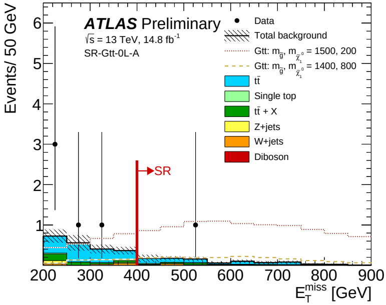
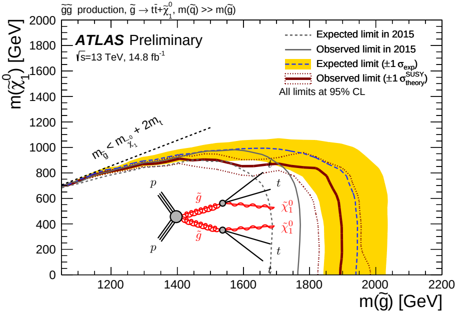


- No significant excess is found above the predicted background.
- The background is dominated by $t\bar{t}$ events in all signal regions.
- The subdominant contributions in the Gbb and Gtt 0-lepton signal regions are $Z(\rightarrow \nu\nu)$+jets and $W(\rightarrow \ell\nu)$+jets events

Results for the zero-lepton channel of gluino-mediated $\tilde{t}/\tilde{b}$

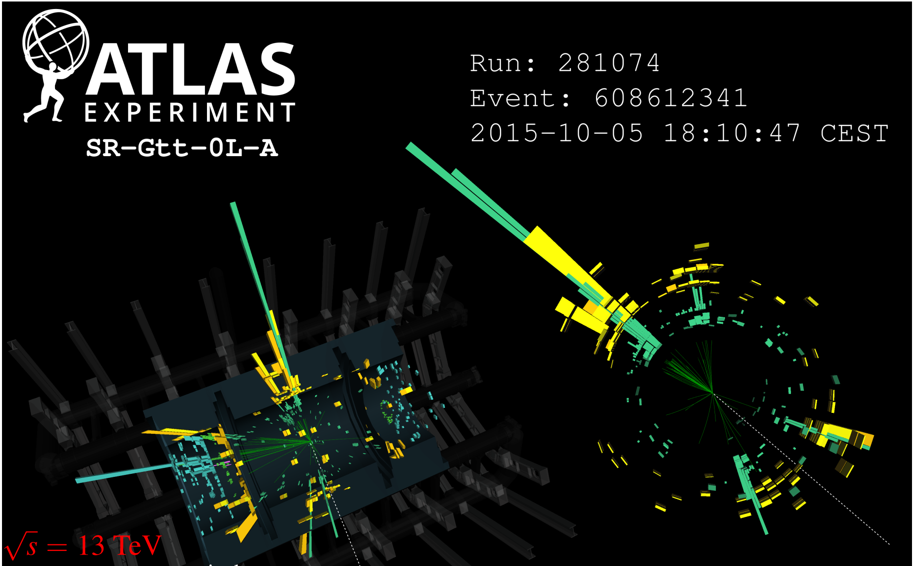
2015 paper released in May 2016 arXiv:1605.09318 (accepted in PRD)





- For each mass point, the combination of signal regions that leads to the best expected exclusion is chosen
- Exclude gluino masses up to $m_{\tilde{g}} \approx 1.85$ TeV
- Significant improvement compared Run 1! → **450 GeV increase in sensitivity!**

Large effective mass and boosted top-quark candidate event



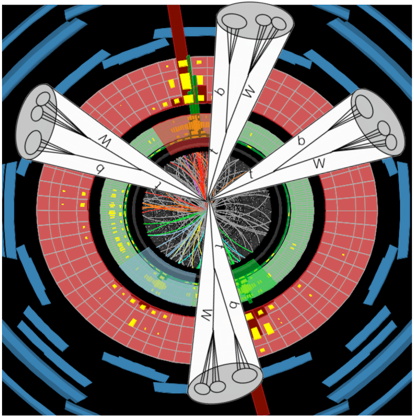
Effective mass, $m_{\mathrm{eff}}^{\mathrm{incl}} = 1800$ GeV. 3 b-tagged jets, 1 boosted top-candidate.

Outline

ATLAS has a robust and broad effort devoted to searching for SUSY in fully hadronic final states, using new techniques, novel approaches to final state reconstruction, and a holistic perspective on using various classes of observables for these searches.

Summary and conclusions

- Completed the flagship **jets+$E_{\mathrm{T}}^{\mathrm{miss}}$** search with the first 2016 data and significantly extended the Run 1 and 2015 sensitivity
- Implemented novel **recursive jigsaw reconstruction** technique for partitioning final state kinematics and constructing a **dynamic and discriminating basis of event-level observables**
- Completed the dedicated search for 4 b and 4 top SUSY processes using the **total jet mass observable**, and extended limits significantly



2016?

Thank you!

Outline

4. *Backup slides and additional information*
   - Luminosity summary plots for 2016 *pp* data taking
   - Reminder of the ATLAS reconstruction procedure
   - Recursive Jigsaw Reconstruction Observables
   - Signal region definitions for 0L final states with 2-6 jets
   - Signal region definitions multi-*b* jet final states with 0 leptons

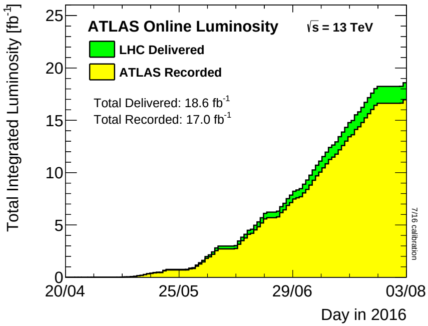
Additional Material

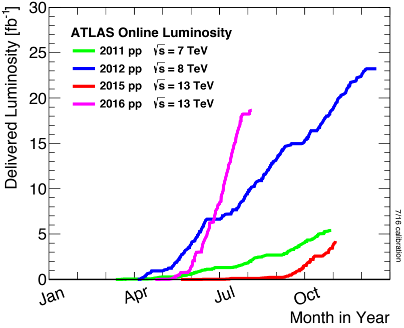
Outline

4 *Backup slides and additional information*

- Luminosity summary plots for 2016 *pp* data taking
- Reminder of the ATLAS reconstruction procedure
- Recursive Jigsaw Reconstruction Observables
- Signal region definitions for 0L final states with 2-6 jets
- Signal region definitions multi-*b* jet final states with 0 leptons

Luminosity summary plots for 2016 pp data taking





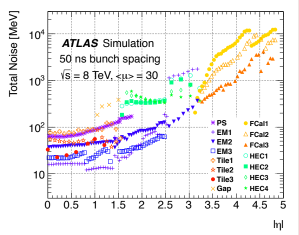
- Public luminosity results for Run 2
- Results related to ATLAS luminosity measurements in Run 2 are given.

Quick reminder of the foundations of jet reconstruction

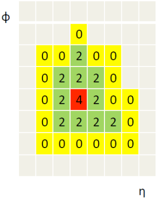
1. Measure calorimeter noise (arXiv:1510.03823)
2. Build a seeded nearest-neighbor cluster using the noise estimates (including pile-up) to define a **significance (E/σ)**
3. Obtain a set of 3D topo-clusters (potentially also calibrated to the hadronic scale)
4. Use as input to calorimeter-based jet reconstruction

Of course, can also use tracks, truth particles!

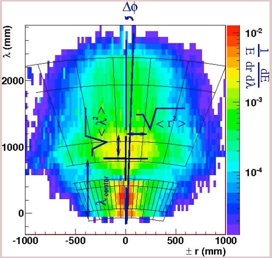
1. Calorimeter noise (σ)



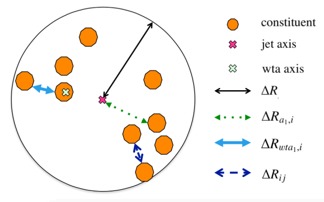
2. Build seeded cluster (# of E/σ)



3. Obtain 3D topo-clusters



4. Use as input for calo-jet reconstruction (fig from arXiv:1510.05821)



Recursive Jigsaw Reconstruction Observables (I)

To select signal events in models with squark-pair production, the following variables are used:

- $H_{1,1}^{\mathrm{PP}} \rightarrow$ scale variable, similar to $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$.
- $H_{\mathrm{T}\,2,1}^{\mathrm{PP}} \rightarrow$ transverse scale variable, similar to effective mass, M_{eff} for squark-pair production signals with two-jet final states.
- $H_{1,1}^{\mathrm{PP}}/H_{2,1}^{\mathrm{PP}} \rightarrow$ provides additional information in testing the balance of the information provided by the two scale cuts, where in the denominator the $H_{2,1}^{\mathrm{PP}}$ is no longer solely transverse. This provides a handle against imbalanced events where the large scale is dominated by a particular object p_{T} or by high $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$.
- $p_{z}^{\mathrm{lab}}/(p_{z}^{\mathrm{lab}} + H_{\mathrm{T}\,2,1}^{\mathrm{PP}}) \rightarrow$ compares the z-momentum of the lab frame to the overall transverse scale variable considered. This variable tests for significant boost in the z direction.
- $p_{\mathrm{Tj2}}^{\mathrm{PP}}/H_{\mathrm{T}\,2,1}^{\mathrm{PP}} \rightarrow$ represents the fraction of the overall scale variable that is due to the second highest p_{T} jet (in the *PP* frame) in the event.

Recursive Jigsaw Reconstruction Observables (II)

For signal topologies with higher jet multiplicities, there is the option to exploit the internal structure of the hemispheres by using a decay tree with an additional decay. For gluino-pair production, the variables used by this search are:

- $H^{\mathrm{PP}}_{\mathrm{T}\,4,1}$ → analogous to the transverse scale variable $H^{\mathrm{PP}}_{\mathrm{T}\,2,1}$ for the squark search but more appropriate for four-jet final states expected from gluino-pair production.
- $H^{\mathrm{PP}}_{1,1}/H^{\mathrm{PP}}_{4,1}$ → analogous to $H^{\mathrm{PP}}_{1,1}/H^{\mathrm{PP}}_{2,1}$ for the squark search.
- $H^{\mathrm{PP}}_{\mathrm{T}\,4,1}/H^{\mathrm{PP}}_{4,1}$ → a measure of the fraction of the momentum that lies in the transverse plane.
- $p^{\mathrm{lab}}_{\mathrm{z}}/(p^{\mathrm{lab}}_{\mathrm{z}} + H^{\mathrm{PP}}_{\mathrm{T}\,4,1})$ → analogous to $p^{\mathrm{lab}}_{\mathrm{z}}/(p^{\mathrm{lab}}_{\mathrm{z}} + H^{\mathrm{PP}}_{\mathrm{T}\,2,1})$ above.
- min $(p^{\mathrm{PP}}_{\mathrm{Tj2i}}/H^{\mathrm{PP}}_{\mathrm{T}\,2,1\mathrm{i}})$ → represents the fraction of a hemisphere's overall scale due to the second highest p_{T} jet (in the *PP* frame) in each hemisphere. The minimum value between the two hemispheres is used.
- max $(H^{\mathrm{P_i}}_{1,0}/H^{\mathrm{P_i}}_{2,0})$ → testing balance of solely the jets momentum in a given hemisphere allows an additional handle against a small but pernicious subset of events.
- $|\frac{2}{3}\Delta\phi^{\mathrm{PP}}_{\mathrm{V,P}} - \frac{1}{3}\cos\theta_{\mathrm{P}}|$ → constructed from the difference between the azimuthal angle between the *V* and *P* frames, evaluated in the *PP* frame and the polar angle of that parent particle. The difference between these two angular properties highlights events where the missing transverse momentum is imbalanced between hemispheres (e.g. semileptonic $t\bar{t}$ decays where the lepton is reconstructed as a jet). This variable exploits the fact that signal events tend to be more "spherical" to efficiently suppress these pernicious background sources.

Recursive Jigsaw Reconstruction Observables (III)

Assuming a distinct ISR boost, the model decay tree for ISR yields a slightly different set of variables:

- $|p_{\text{TS}}^{\text{ISR}}| \rightarrow$ the magnitude of the vector-summed transverse momenta of all ISR-associated jets evaluated in the CM frame.
- $R_{\text{ISR}} \equiv \vec{p}_{\text{I}}^{\text{ CM}} \cdot \hat{p}_{\text{TS}}^{\text{ CM}} / p_{\text{TS}}^{\text{ CM}} \rightarrow$ serves as a proxy for $m_{\chi}/m_{\mathfrak{p}}$. $\rightarrow$ This is the fraction of the boost of the S system that is carried by its invisible system I. As the $|p_{\text{TS}}^{\text{ISR}}|$ is increased it becomes increasingly hard for backgrounds to possess a large value in this ratio - a feature exhibited by compressed signals.
- $M_{\text{TS}} \rightarrow$ the transverse mass of the S system.
- $N_{\text{jet}}^{\text{V}} \rightarrow$ number of jets assigned to the visible system (V) and not associated with the ISR system.
- $\Delta\phi_{\text{ISR,I}} \rightarrow$ This is the opening angle between the ISR system and the invisible system in the lab frame.

Signal region definitions for $M_{\rm eff}$ search

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Targeted signal	$\tilde{q}\tilde{q}, \tilde{q} \to q\tilde{\chi}_1^0$				
Requirement	Signal Region				
	Meff-2j-800	**Meff-2j-1200**	**Meff-2j-1600**	**Meff-2j-2000**	**Meff-3j-1200**
$E_T^{\rm miss}$ [GeV] >	250				
$p_T(j_1)$ [GeV] >	200	250			600
$p_T(j_2)$ [GeV] >	200	250			50
$p_T(j_3)$ [GeV] >	–				50
$\lvert\eta(j_{1,2})\rvert$ <	0.8	1.2			–
$\Delta\phi(\text{jet}_{1,2,(3)}, \boldsymbol{E}_T^{\rm miss})_{\rm min}$ >	0.8				0.4
$\Delta\phi(\text{jet}_{i>3}, \boldsymbol{E}_T^{\rm miss})_{\rm min}$ >	0.4				0.2
$E_T^{\rm miss}/\sqrt{H_T}$ [GeV$^{1/2}$] >	14	16	18	20	16
$m_{\rm eff}$(incl.) [GeV] >	800	1200	1600	2000	1200

Targeted signal	$\tilde{g}\tilde{g}, \tilde{g} \to q\bar{q}W\tilde{\chi}_1^0$	
Requirement	Signal Region	
	Meff-6j-1800	**Meff-6j-2200**
$E_T^{\rm miss}$ [GeV] >	250	
$p_T(j_1)$ [GeV] >	200	
$p_T(j_6)$ [GeV] >	50	100
$\lvert\eta(j_{1,\ldots,6})\rvert$ <	2.0	–
$\Delta\phi(\text{jet}_{1,2,(3)}, \boldsymbol{E}_T^{\rm miss})_{\rm min}$ >	0.4	
$\Delta\phi(\text{jet}_{i>3}, \boldsymbol{E}_T^{\rm miss})_{\rm min}$ >	0.2	
Aplanarity >	0.08	
$E_T^{\rm miss}/m_{\rm eff}(N_{\rm j})$ >	0.2	0.15
$m_{\rm eff}$(incl.) [GeV] >	1800	2200

Targeted signal	$\tilde{g}\tilde{g}, \tilde{g} \to q\bar{q}\tilde{\chi}_1^0$					
Requirement	Signal Region					
	Meff-4j-1000	**Meff-4j-1400**	**Meff-4j-1800**	**Meff-4j-2200**	**Meff-4j-2600**	**Meff-5j-1400**
$E_T^{\rm miss}$ [GeV] >	250					
$p_T(j_1)$ [GeV] >	200					500
$p_T(j_4)$ [GeV] >	100			150		50
$p_T(j_5)$ [GeV] >	–					50
$\lvert\eta(j_{1,2,3,4})\rvert$ <	1.2	2.0			–	
$\Delta\phi(\text{jet}_{1,2,(3)}, \boldsymbol{E}_T^{\rm miss})_{\rm min}$ >	0.4					
$\Delta\phi(\text{jet}_{i>3}, \boldsymbol{E}_T^{\rm miss})_{\rm min}$ >	0.4					0.2
Aplanarity >	0.04					–
$E_T^{\rm miss}/m_{\rm eff}(N_{\rm j})$ >	0.25		0.2			0.3
$m_{\rm eff}$(incl.) [GeV] >	1000	1400	1800	2200	2600	1400

Signal region definitions for Recursive Jigsaw search

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Targeted signal	$\tilde{q}\tilde{q}$, $\tilde{q} \to q\tilde{\chi}_1^0$		
Requirement	Signal Region		
	RJR-S1	**RJR-S2**	**RJR-S3**
$H_{1,1}^{\mathrm{PP}}/H_{2,1}^{\mathrm{PP}} \geq$	0.6	0.55	0.5
$H_{1,1}^{\mathrm{PP}}/H_{2,1}^{\mathrm{PP}} \leq$	0.95	0.96	0.98
$p_{\mathrm{PP,\,z}}^{\mathrm{lab}}/\left(p_{\mathrm{PP,\,z}}^{\mathrm{lab}} + H_{\mathrm{T}\ 2,1}^{\mathrm{PP}}\right) \leq$	0.5	0.55	0.6
$p_{\mathrm{j2,\,T}}^{\mathrm{PP}}/H_{\mathrm{T}\ 2,1}^{\mathrm{PP}} \geq$	0.16	0.15	0.13
$\Delta_{\mathrm{QCD}} >$	0.001		

	RJR-S1a	**RJR-S1b**	**RJR-S2a**	**RJR-S2b**	**RJR-S3a**	**RJR-S3b**
$H_{\mathrm{T}\ 2,1}^{\mathrm{PP}}$ [GeV] >	1000	1200	1400	1600	1800	2000
$H_{1,1}^{\mathrm{PP}}$ [GeV] >	1000		1400		1600	

Targeted signal	compressed spectra in $\tilde{q}\tilde{q}$ ($\tilde{q} \to q\tilde{\chi}_1^0$); $\tilde{g}\tilde{g}$ ($\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$)				
Requirement	Signal Region				
	RJR-C1	**RJR-C2**	**RJR-C3**	**RJR-C4**	**RJR-C5**
$R_{\mathrm{ISR}} \geq$	0.9	0.85	0.8	0.75	0.70
$\Delta\phi_{\mathrm{ISR,\,I}} \geq$	3.1	3.07	2.95	2.95	2.95
$\Delta\phi(\mathrm{jet}_{1,2}, \boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}})_{\mathrm{min}} >$	-	-	-	0.4	0.4
M_{TS} [GeV] $\geq$	100	100	200	500	500
$p_{\mathrm{TS}}^{\mathrm{CM}}$ [GeV] $\geq$	800	800	600	600	600
$N_{\mathrm{jet}}^{\mathrm{V}} \geq$	1	1	2	2	3

Targeted signal	$\tilde{g}\tilde{g}$, $\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$		
Requirement	Signal Region		
	RJR-G1	**RJR-G2**	**RJR-G3**
$H_{1,1}^{\mathrm{PP}}/H_{4,1}^{\mathrm{PP}} \geq$	0.35	0.25	0.2
$H_{\mathrm{T}\ 4,1}^{\mathrm{PP}}/H_{4,1}^{\mathrm{PP}} \geq$	0.8	0.75	0.65
$p_{\mathrm{PP,\,z}}^{\mathrm{lab}}/\left(p_{\mathrm{PP,\,z}}^{\mathrm{lab}} + H_{\mathrm{T}\ 4,1}^{\mathrm{PP}}\right) \leq$	0.5	0.55	0.6
$\min\left(p_{\mathrm{j2\ T\ i}}^{\mathrm{PP}}/H_{\mathrm{T}\ 2,1\ \mathrm{i}}^{\mathrm{PP}}\right) \geq$	0.12	0.1	0.08
$\max\left(H_{1,\,0}^{\mathrm{Pi}}/H_{2,\,0}^{\mathrm{Pi}}\right) \leq$	0.95	0.97	0.98
$\lvert\frac{2}{3}\Delta\phi_{\mathrm{V,P}}^{\mathrm{PP}} - \frac{1}{3}\cos\theta_{\mathrm{p}}\rvert \leq$	0.5	–	
$\Delta_{\mathrm{QCD}} >$	0		

	RJR-G1a	**RJR-G1b**	**RJR-G2a**	**RJR-G2b**	**RJR-G3a**	**RJR-G3b**
$H_{\mathrm{T}\ 4,1}^{\mathrm{PP}}$ [GeV] >	1000	1200	1500	1900	2300	2800
$H_{1,1}^{\mathrm{PP}}$ [GeV] >	600		800		900	

Signal regions for multi-b jet final states with 0L

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Criterion common to all Gbb regions: $N^{\text{jet}} \geq 4$				
	Variable	Signal region	Control region	Validation region
Criteria common to all regions of the same type	$N^{\text{Candidate Lepton}}$	= 0	–	= 0
	$N^{\text{Signal Lepton}}$	–	= 1	–
	$\Delta\phi^{4j}_{\text{min}}$	> 0.4	–	> 0.4
	m_{T}	–	< 150	–
Region A (Large mass splitting)	$p_{\text{T}}^{\text{jet}}$	> 70	> 70	> 70
	$N_{b\text{-jets}}$	≥ 3	≥ 3	≥ 3
	$E_{\text{T}}^{\text{miss}}$	> 450	> 350	> 450
	m^{4j}_{eff}	> 1900	> 1750	< 1900
Region B (Small mass splitting)	$p_{\text{T}}^{\text{jet}}$	> 30	> 30	> 30
	$N_{b\text{-jets}}$	≥ 4	≥ 4	≥ 4
	$E_{\text{T}}^{\text{miss}}$	> 300	> 300	> 275
	m^{4j}_{eff}	> 1000	> 1000	< 1000

Signal regions for multi-b jet final states with 0L

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Criteria common to all Gtt 0-lepton regions: $p_T^{jet} > 30$ GeV, $N_{b\text{-jets}} \geq 3$					
	Variable	Signal region	Control region	VR1L	VR0L
Criteria common to all regions of the same type	$N^{\text{Signal Lepton}}$	$= 0$	$= 1$	$= 1$	$= 0$
	$\Delta\phi_{\text{min}}^{4j}$	> 0.4	–	–	> 0.4
	$m_{T,\text{min}}^{b\text{-jets}}$	> 80	–	> 80	> 80
	m_T	–	< 150	< 150	–
Region A (Large mass splitting)	N^{jet}	≥ 8	≥ 7	≥ 7	≥ 6
	E_T^{miss}	> 400	> 250	> 200	> 300
	$m_{\text{eff}}^{\text{incl}}$	> 2000	> 1750	> 1750	> 1300
	M_J^{Σ}	> 200	> 200	> 200	< 200
Region B (Small mass splitting)	N^{jet}	≥ 8	≥ 7	≥ 7	≥ 7
	E_T^{miss}	> 400	> 400	> 325	$\in (300, 400)$
	$m_{\text{eff}}^{\text{incl}}$	> 1250	> 1250	> 1250	> 1200

Signal regions for multi-b jet final states with 0L

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Criteria common to all Gtt 1-lepton regions: ≥ 1 signal lepton, $p_T^{jet} > 30$ GeV					
	Variable	Signal region	Control region	VR-m_T	VR-$m_{T,min}^{b\text{-jets}}$
Region A (Large mass splitting)	N^{jet}	≥ 6	$= 6$	≥ 5	≥ 6
	$N_{b\text{-jets}}$	≥ 3	≥ 3	≥ 3	≥ 3
	m_T	> 200	< 200	> 200	< 200
	$m_{T,min}^{b\text{-jets}}$	> 120	–	–	> 120
	E_T^{miss}	> 200	> 200	> 200	> 200
	m_{eff}^{incl}	> 2000	> 1500	> 1350	> 1500
	M_J^{Σ}	> 200	> 200	< 200	> 200
Region B (Moderate mass splitting)	N^{jet}	≥ 6	$= 6$	≥ 5	≥ 6
	$N_{b\text{-jets}}$	≥ 3	≥ 3	≥ 3	≥ 3
	m_T	> 200	< 200	> 200	< 200
	$m_{T,min}^{b\text{-jets}}$	> 120	–	–	> 120
	E_T^{miss}	> 350	> 300	> 250	> 300
	m_{eff}^{incl}	> 1500	> 1250	> 1100	> 1500
	M_J^{Σ}	> 150	> 150	< 150	> 150
Region C (Small mass splitting)	N^{jet}	≥ 6	$= 6$	≥ 6	≥ 6
	$N_{b\text{-jets}}$	≥ 4	≥ 4	≥ 3	≥ 4
	m_T	> 150	< 150	> 150	< 150
	$m_{T,min}^{b\text{-jets}}$	> 80	–	< 80	> 80
	E_T^{miss}	> 200	> 200	> 200	> 200
	m_{eff}^{incl}	> 500	> 500	> 500	> 500