PUSHING LIMITS ON GENERIC SQUARKS AND GLUINOS WITH 13 TEV DATA

MORIOND EW 2017

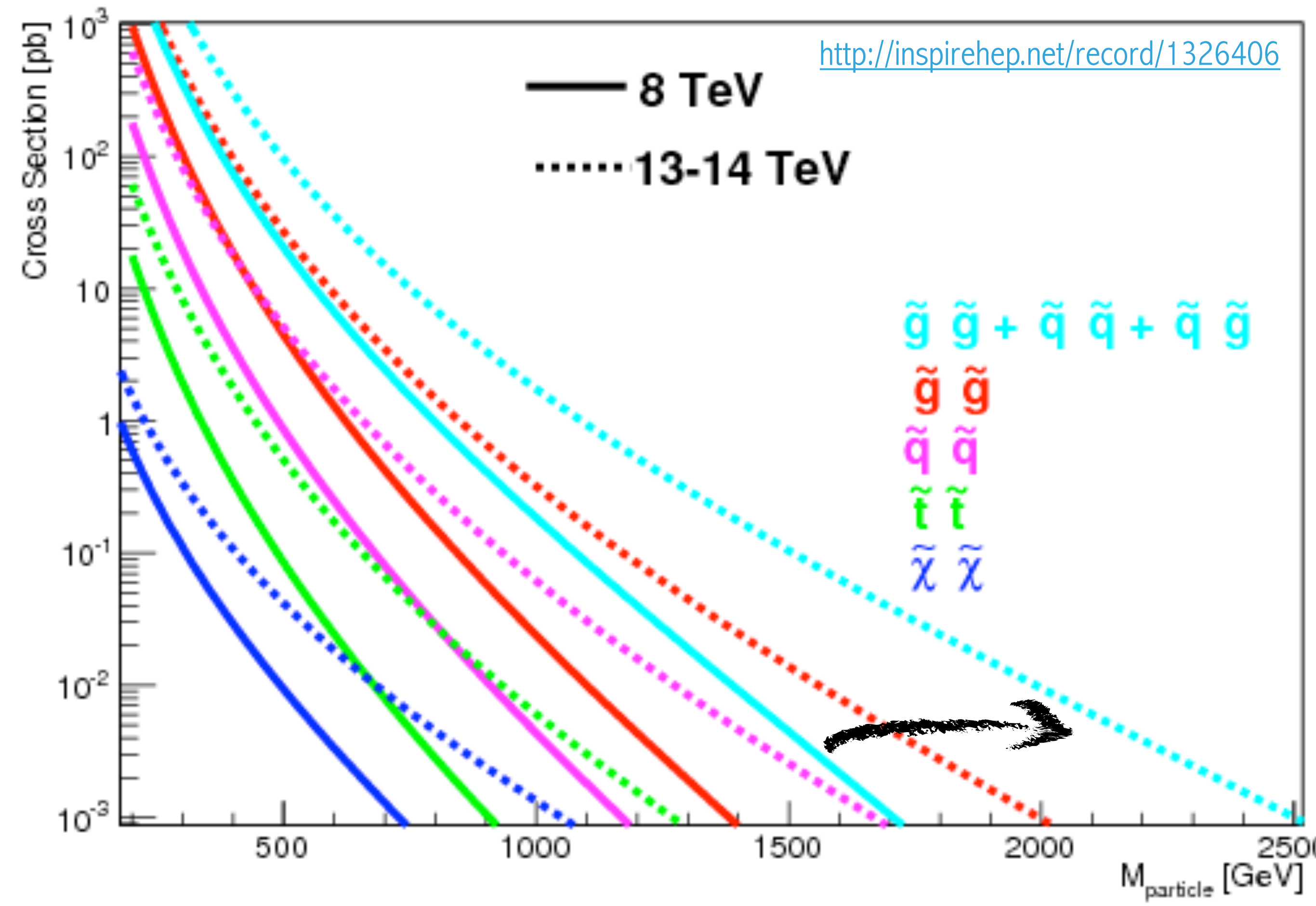
EMMA KUWERTZ (UNIVERSITY OF VICTORIA)
ON BEHALF OF THE ATLAS AND CMS COLLABORATIONS

University of Victoria

SEARCHING FOR SUSY @ 13 TEV

SUSY is a highly favoured extension of the SM, and predicts supersymmetric partners to existing SM particles at high energies, but nothing showed up in the LHC Run 1 dataset.

- Significant increase in squark & gluino production cross-section when increasing from 8 to 13 TeV:
  - Effort at both CMS & ATLAS to exploit this early on in Run 2.
- Nothing conclusive reported from partial dataset available for ICHEP 2016
  - First results from the full 2015+2016 dataset available.



FINAL STATE SIGNATURES

- R-parity conservation (RPC)
  - Missing transverse momentum (MET)
  - Stable LSP → dark matter candidate?
- R-parity violation (RPV)
  - Little/no MET
  - Unstable LSP → multiple final state particles

SUSY SEARCHES AT ATLAS AND CMS

- Both experiments employ similar analysis techniques when performing searches.
  - Select "hard" SUSY-like signatures using MET, jet/lepton transverse momentum (p_T) & multiplicity
  - Exploit more complicated event-level variables to target specific topologies (e.g. recursive jigsaw variables)
  - Many analyses presented today use Δφ(jets,MET) to reject events with "fake" MET due to jet mis-measurement.

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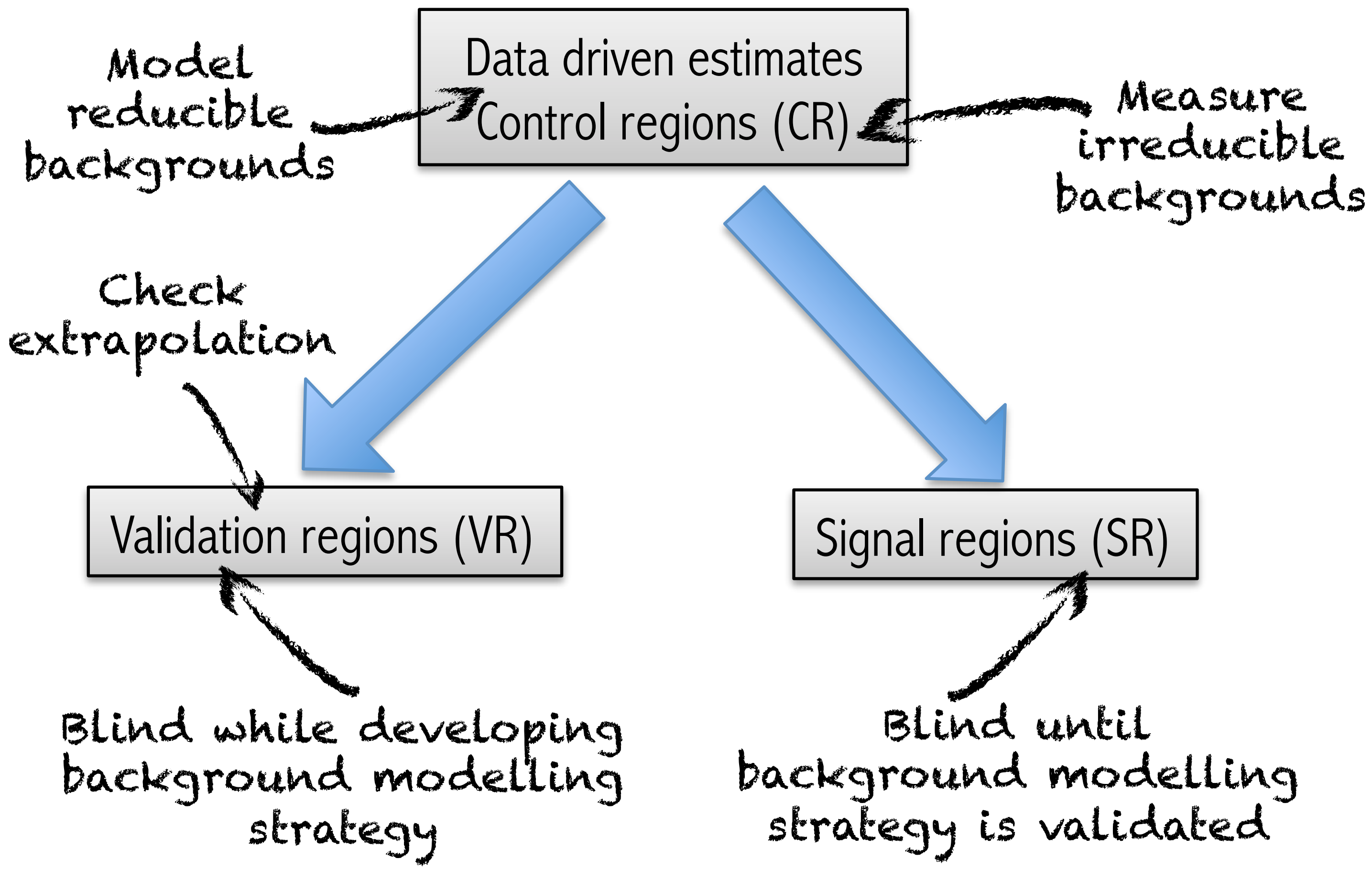
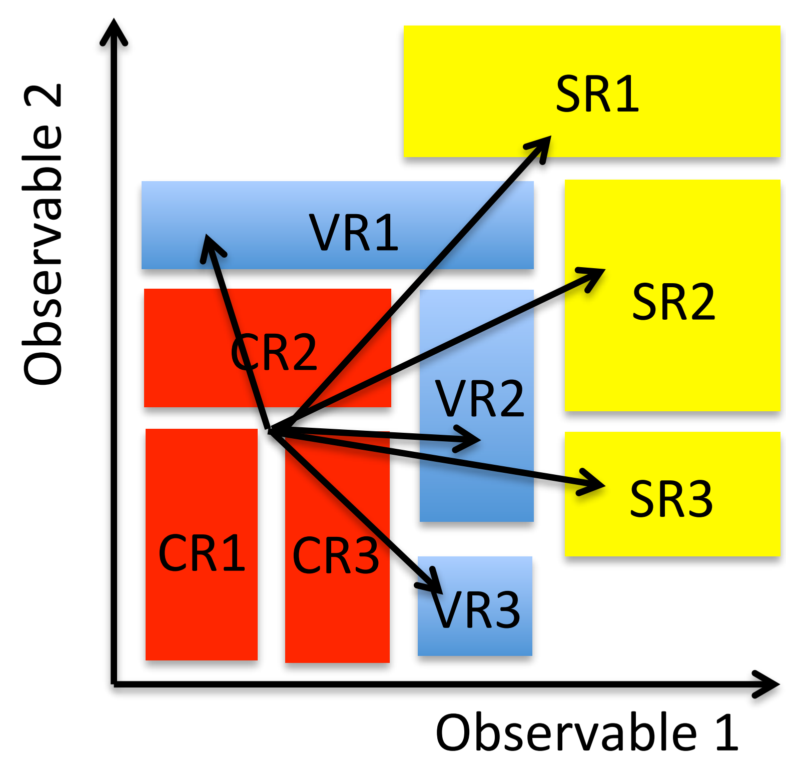




OVERVIEW

Many analyses updated/in progress with the full (2015+)2016 dataset.

NEW RESULTS FOR TODAY

- CMS
  - 0-lepton + MHT + >=2 jets – CMS-PAS-SUS-16-033
  - 0-lepton + M_{T2} + >=1 jets – CMS-PAS-SUS-16-036
  - 1-lepton + >=6 jets – CMS-PAS-SUS-16-037
  - Same-sign 2-lepton – CMS-PAS-SUS-16-035
  - photon + HT (GMSB) – CMS-PAS-SUS-16-047
  - photon + MET (GMSB) – CMS-PAS-SUS-16-046
- ATLAS
  - ≥1-lepton + multijets (RPV) – ATLAS-CONF-2017-013
  - 0-lepton + 2-6 jets – ATLAS-CONF-2017-022
  - 0/1-lepton, ≥3 b-jets – ATLAS-CONF-2017-021

ATLAS results page: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults

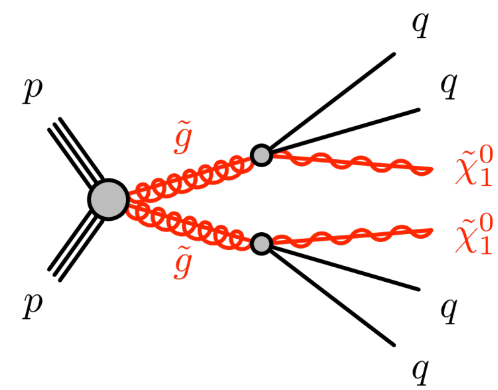
CMS results page: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

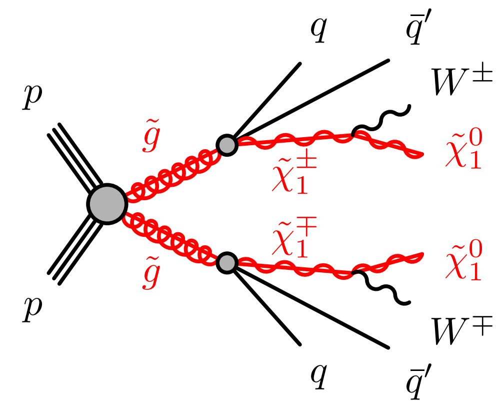
ALL HADRONIC SEARCHES

0L, 2-6 JETS [ATLAS]

M_{EFF} BASED ANALYSIS

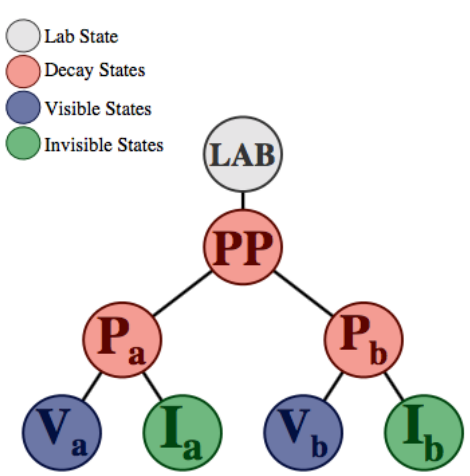
- High $m_{\text{eff}} \equiv \sum_{i=1}^{n} |\mathbf{p}_{\text{T}}^{(i)}| + E_{\text{T}}^{\text{miss}}$ → high masses
- ≥2-5 jet regions → direct squark/gluino decays
- ≥5-6 jet regions → decays via W/Z bosons
- ≥2 large-R jet regions → decays via boosted W/Z bosons

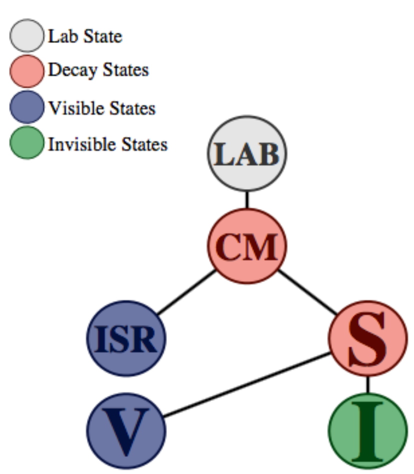




RECURSIVE JIGSAW (RJR) ANALYSIS

- Use the RJR variables [arxiv:1607.08307] to impose specific decay topology assumption





- Partition final state jets into two hemispheres so grouped to minimise the hemisphere masses

0L, 2-6 JETS [ATLAS]

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W+JETS, TTBAR

- Control regions with isolated leptons.
- Use b-tag/veto to separate ttbar/W+jets.

Z→νν

- Control sample with isolated photons.

MULTIJETS

- Data driven approach normalised in multijet control regions.

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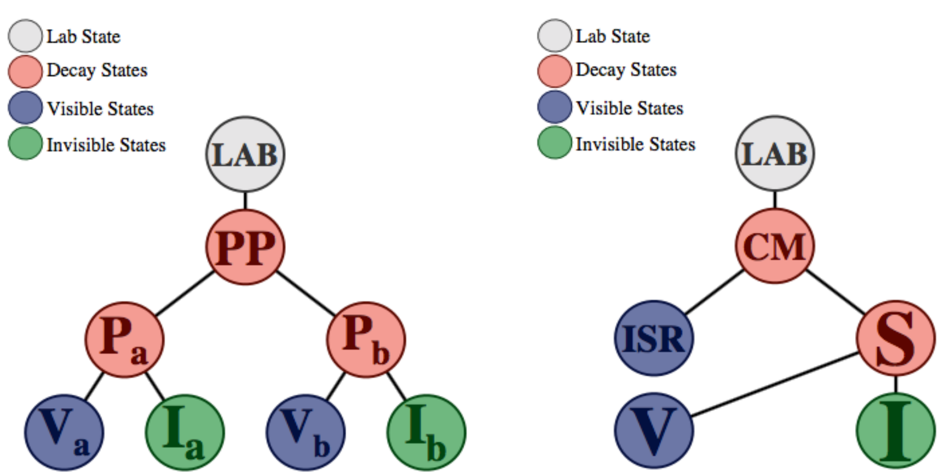

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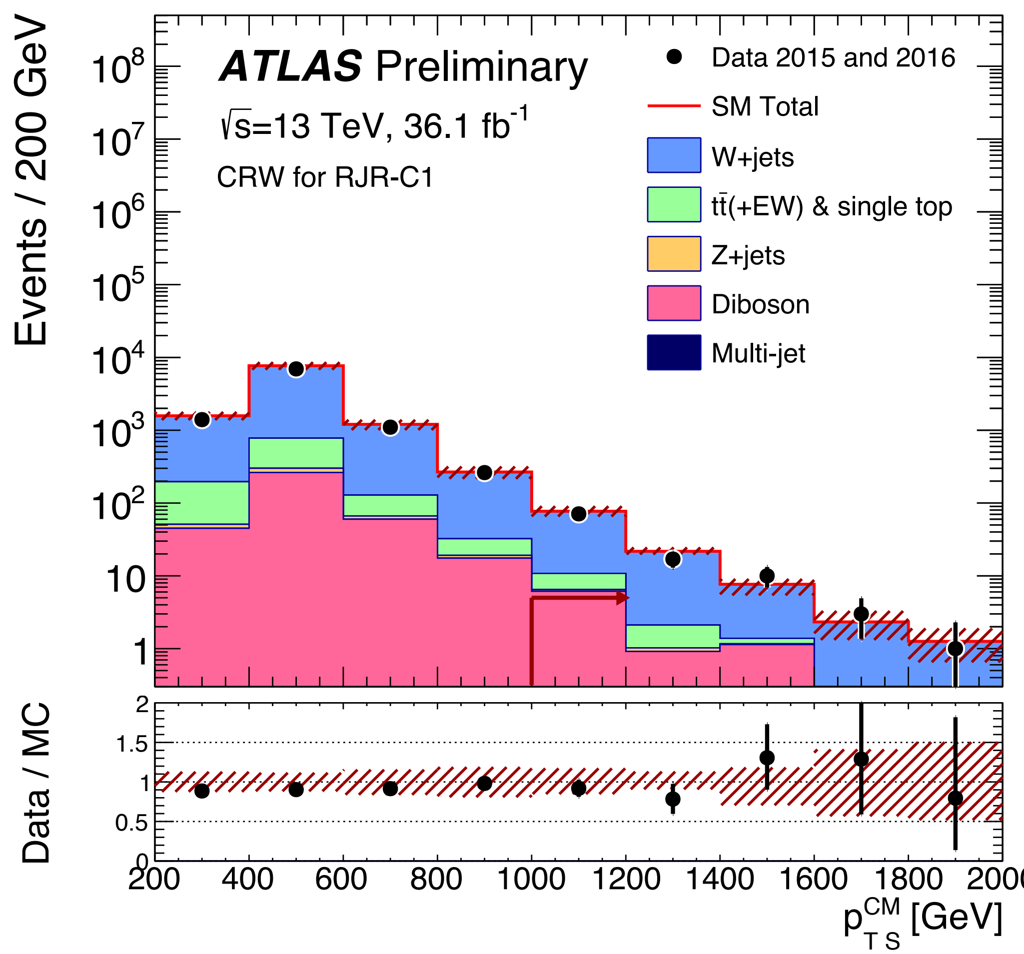

0L+JETS [CMS]

H_T-MHT BASED ANALYSIS

- Targets direct stop/sbottom production and (in)direct squark/gluino decays.
- 174 search regions in total:
  - 5 exclusive N_{jet} bins,
  - 4 exclusive N_{bjet} bins,
  - 10 exclusive intervals in H_T - MHT plane.

M_{T2} BASED ANALYSIS

- Many search regions with events classified according to N_{jet}, H_T and N_{bjet} and binned in MT2
- Cluster final state jets to form two "pseudo-jets" and calculate M_{T2} as

$$M_{T2} = \min_{\vec{p}_T^{\,\text{miss}\,X(1)} + \vec{p}_T^{\,\text{miss}\,X(2)} = \vec{p}_T^{\,\text{miss}}} \left[\max\left(M_T^{(1)}, M_T^{(2)} \right) \right]$$

- Multijet background confined to low M_{T2}

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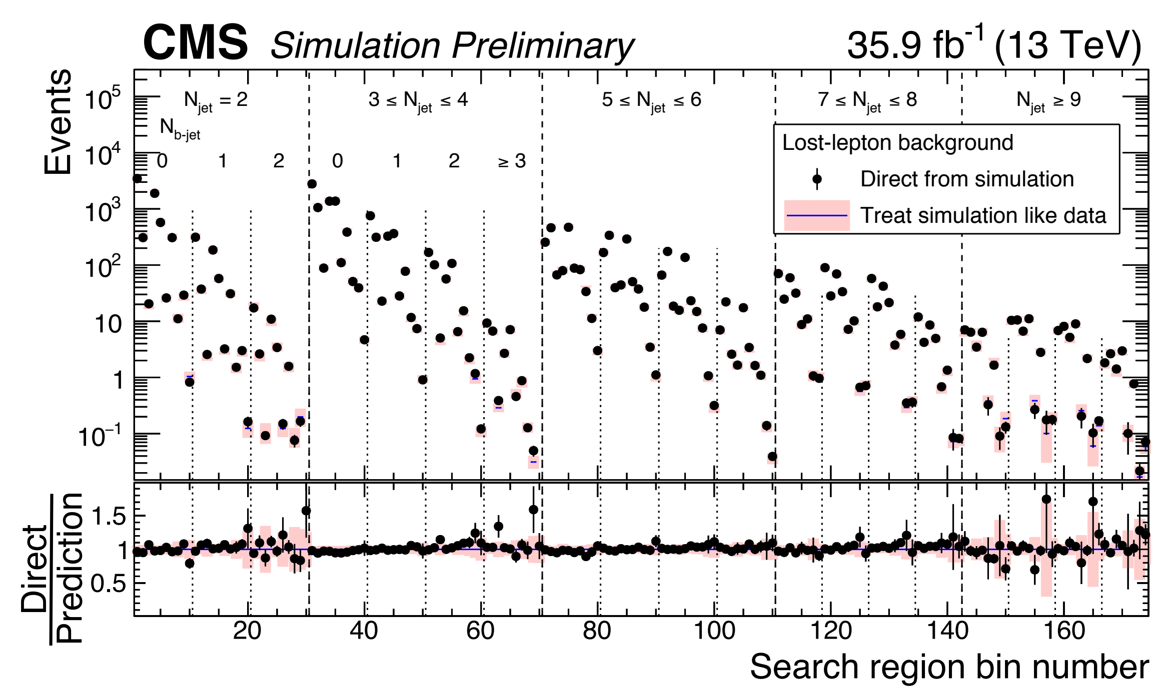
W+JETS, **TTBAR**
- Isolated e/μ regions
  → probability to miss the lepton
- Isolated muon regions
  → smear to expected τ_h p_T distribution.

Z→νν
- Isolated photon regions / use Z→ll to emulate Z→νν.

Multijets
- Invert Δφ(jets,MET) cut
  → extrapolation as a function of H_T, MHT and N_{jet}

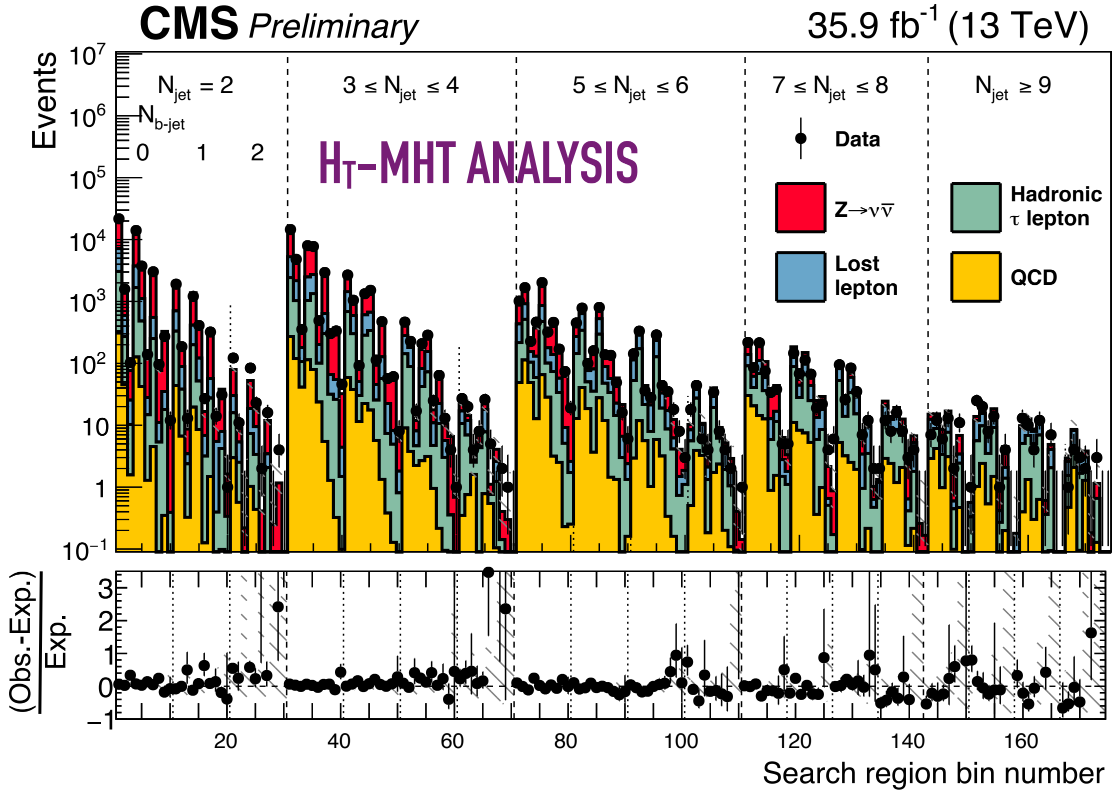
validation of ttbar/W+jets "lost lepton" background estimate

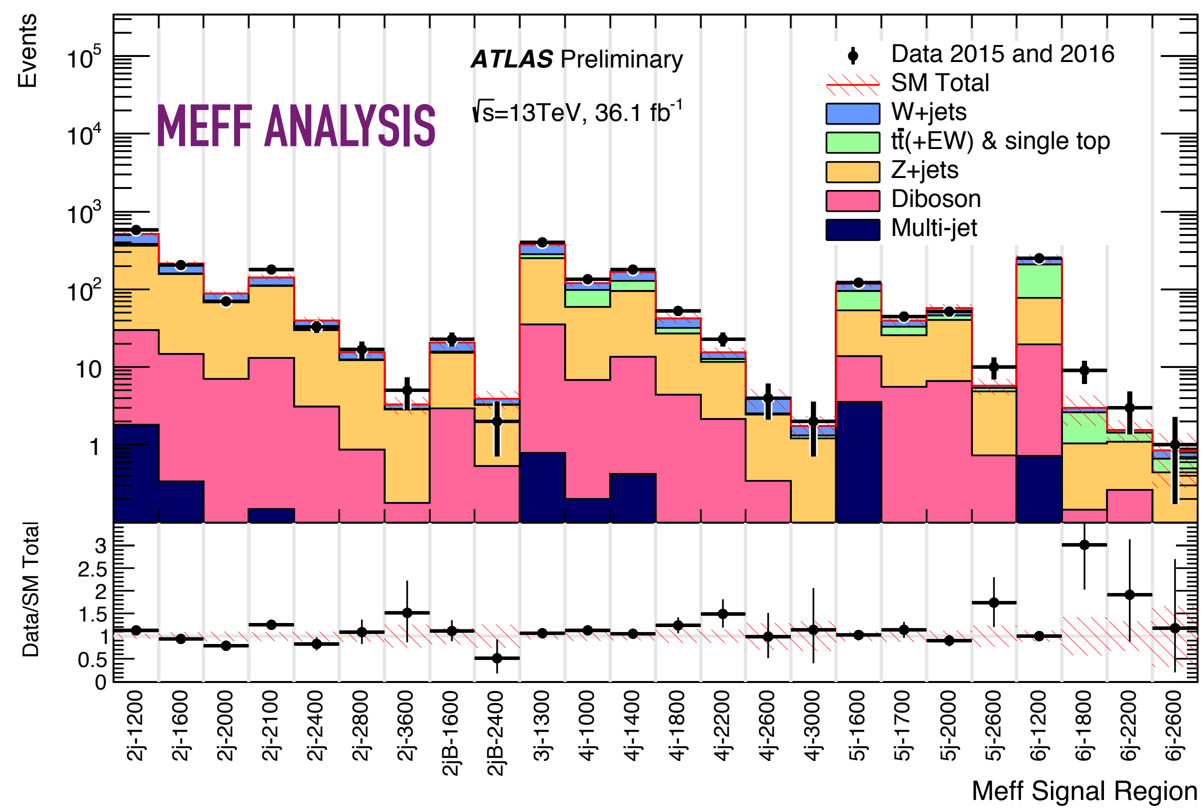


Background estimates validated using MC-closure tests.

0L+JETS [ATLAS/CMS]

No significant deviation from the Standard Model expectation is observed.





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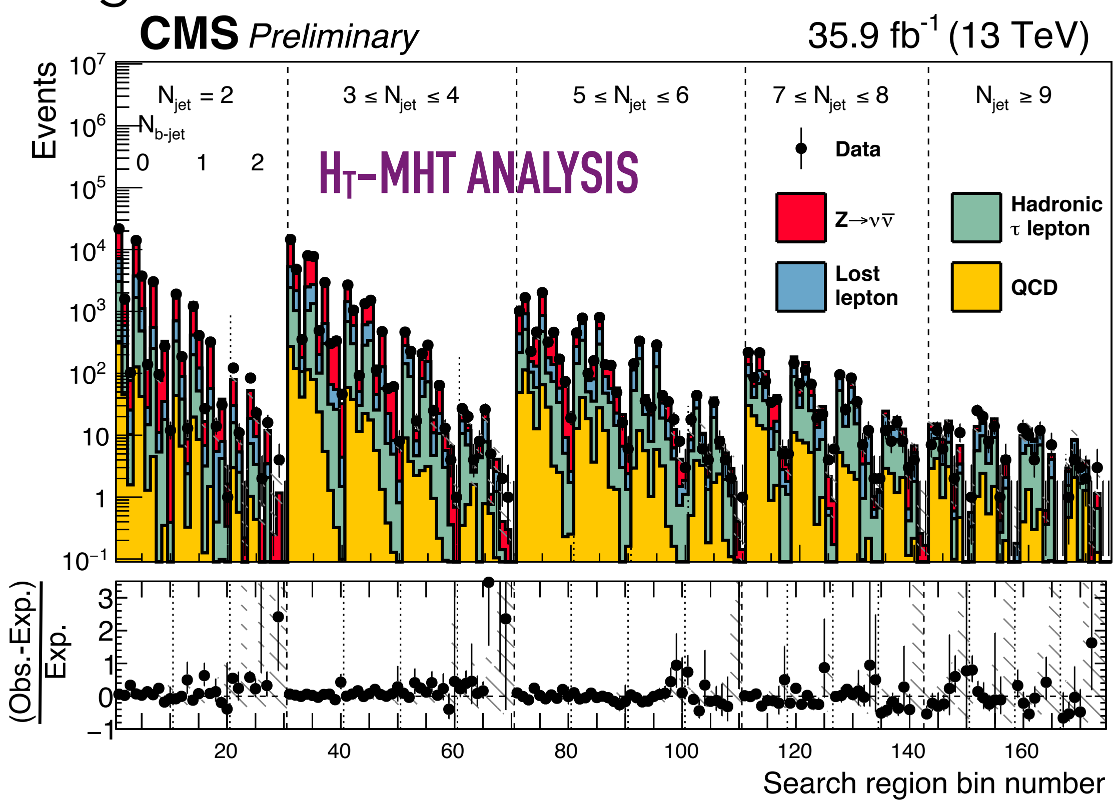
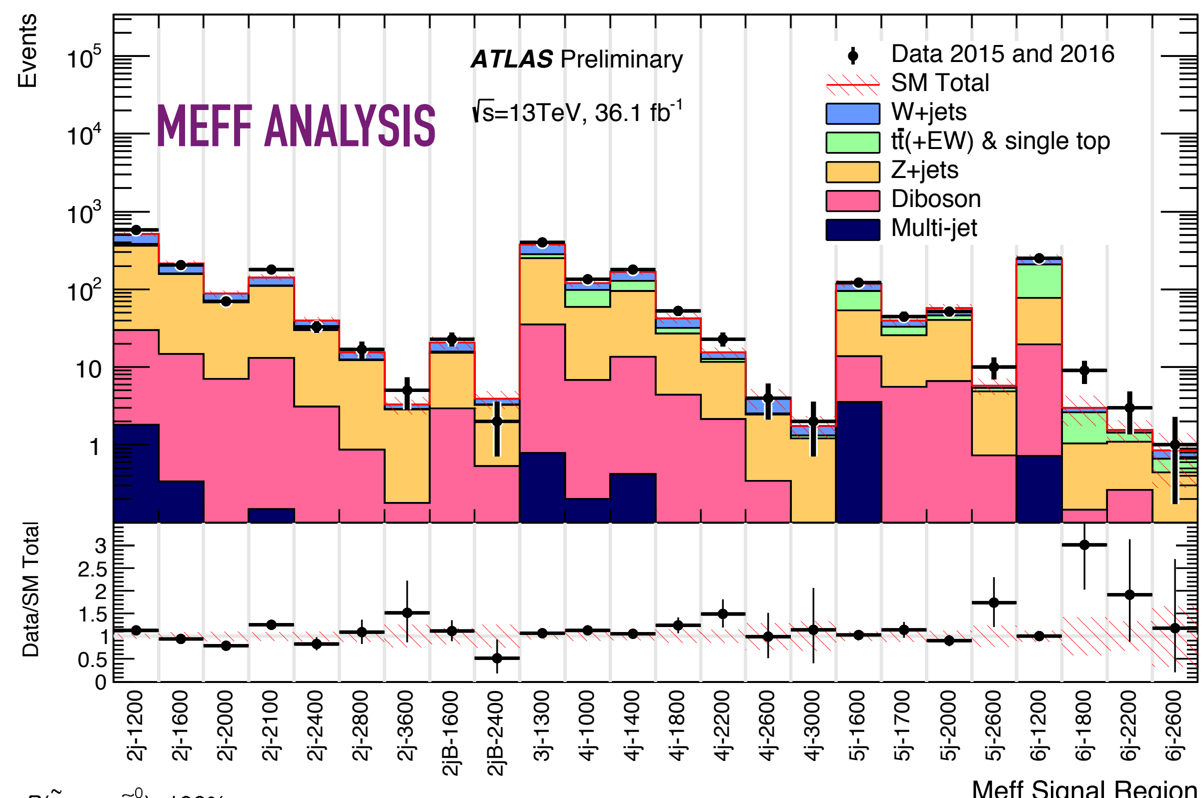
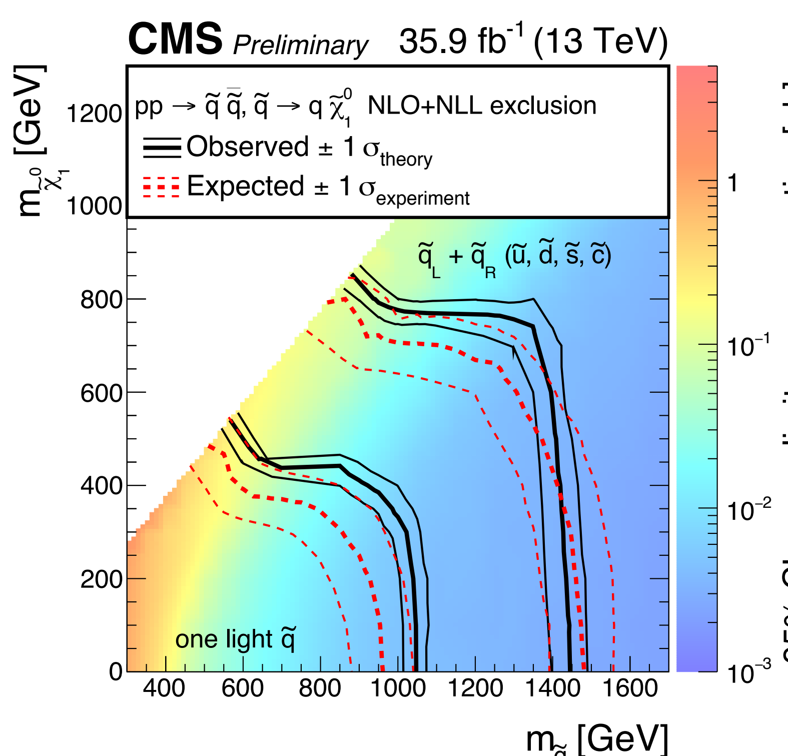
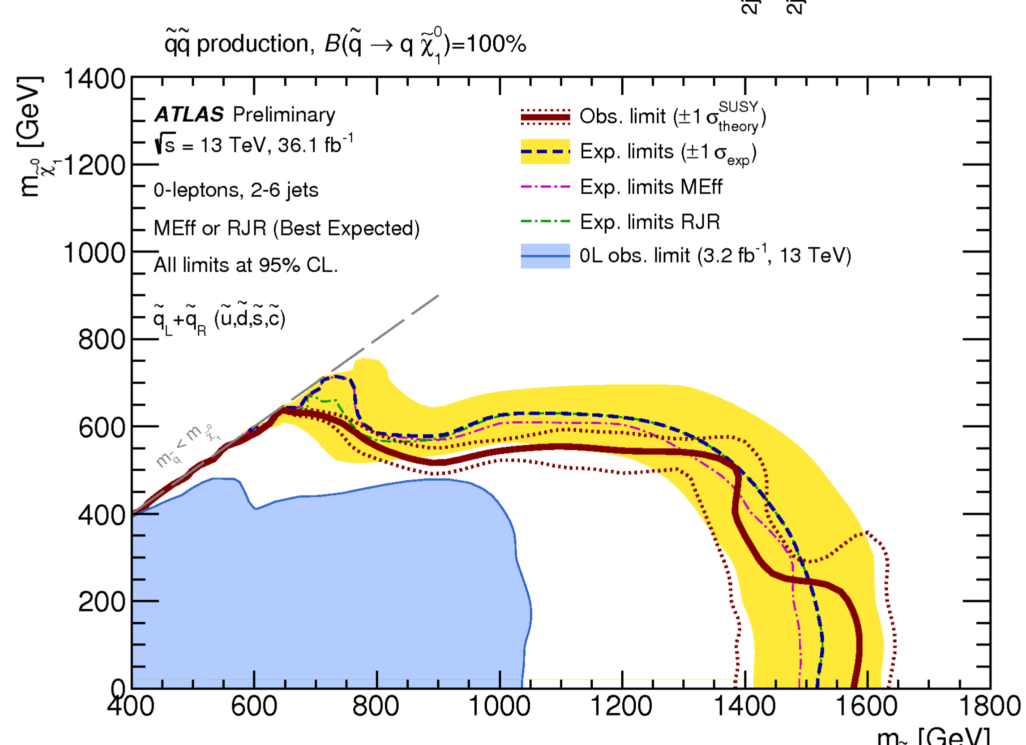








"Best expected" M_{eff}/RJR combination for squark/gluino direct decays.

Exclude squark masses up to ~1.6 TeV, LSP masses up to ~850 GeV.

ATLAS EXPERIMENT

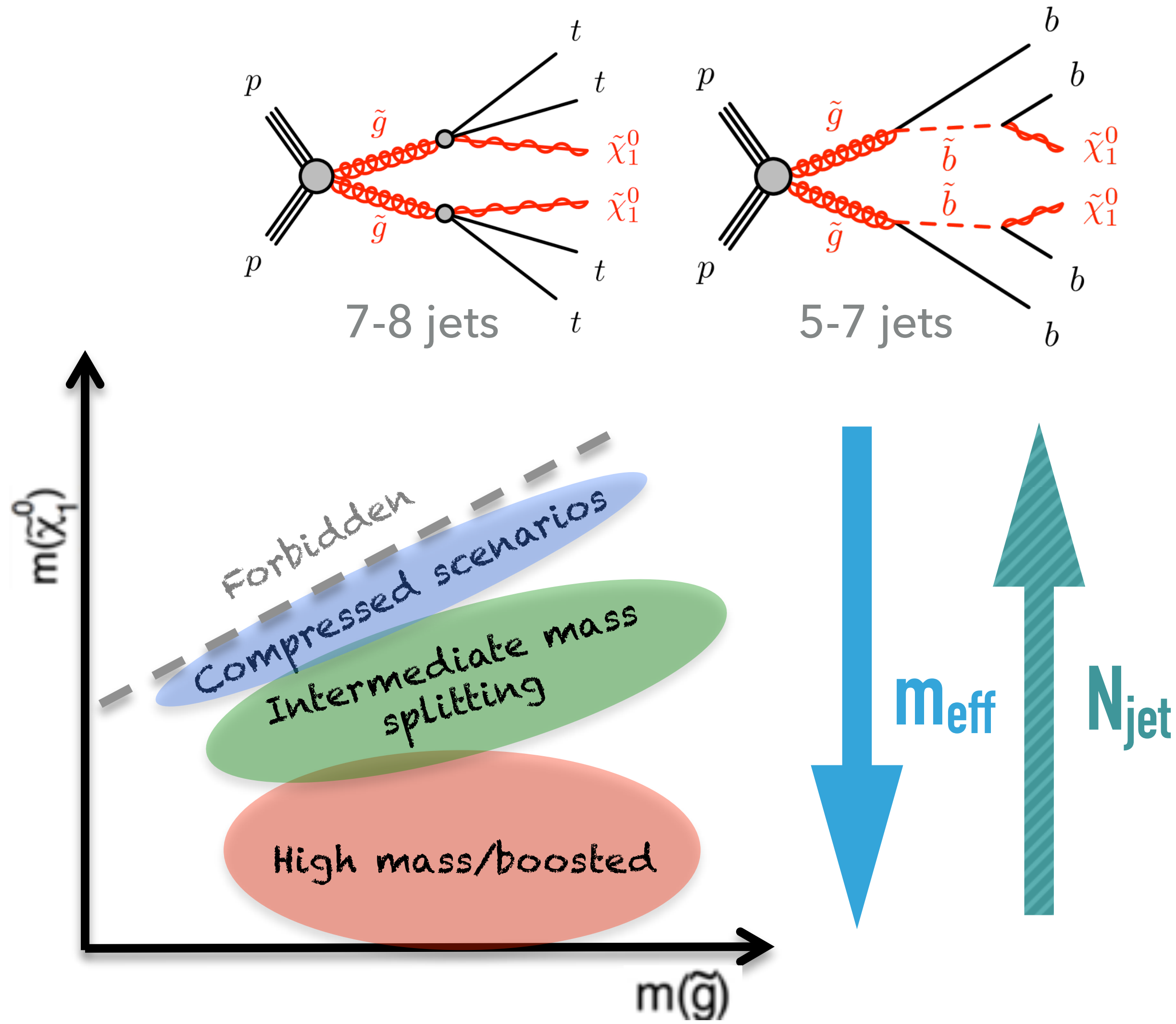
University of Victoria

LEPTONS + JETS

0/1L, ≥3 B-JETS [ATLAS]

Analysis targeting gluino mediated stop/sbottom production

- 10 "discovery" SRs make use of (b-)jet multiplicity, total jet mass (M_J), m_{eff}, m_T and MET
- Further "exclusion" SRs binned in m_{eff} and jet multiplicity
    - High MET, m_{eff}, M_J → large mass splitting/boosted decays
    - Hard leading jet for very small mass splittings
    - Moderate to high jet multiplicity for Gbb/Gtt



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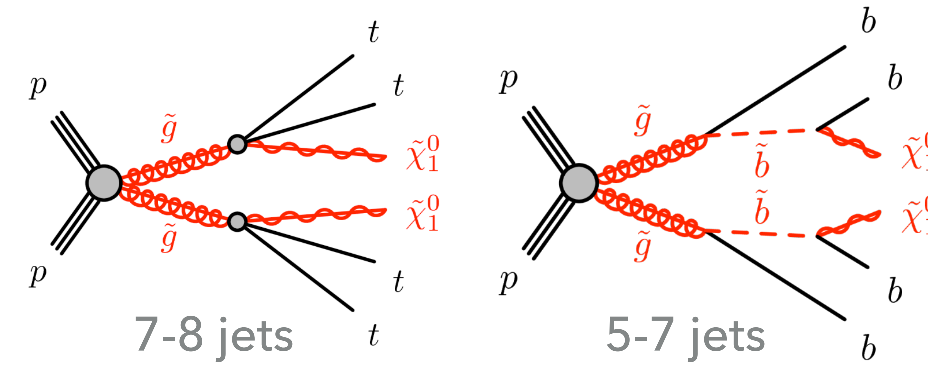
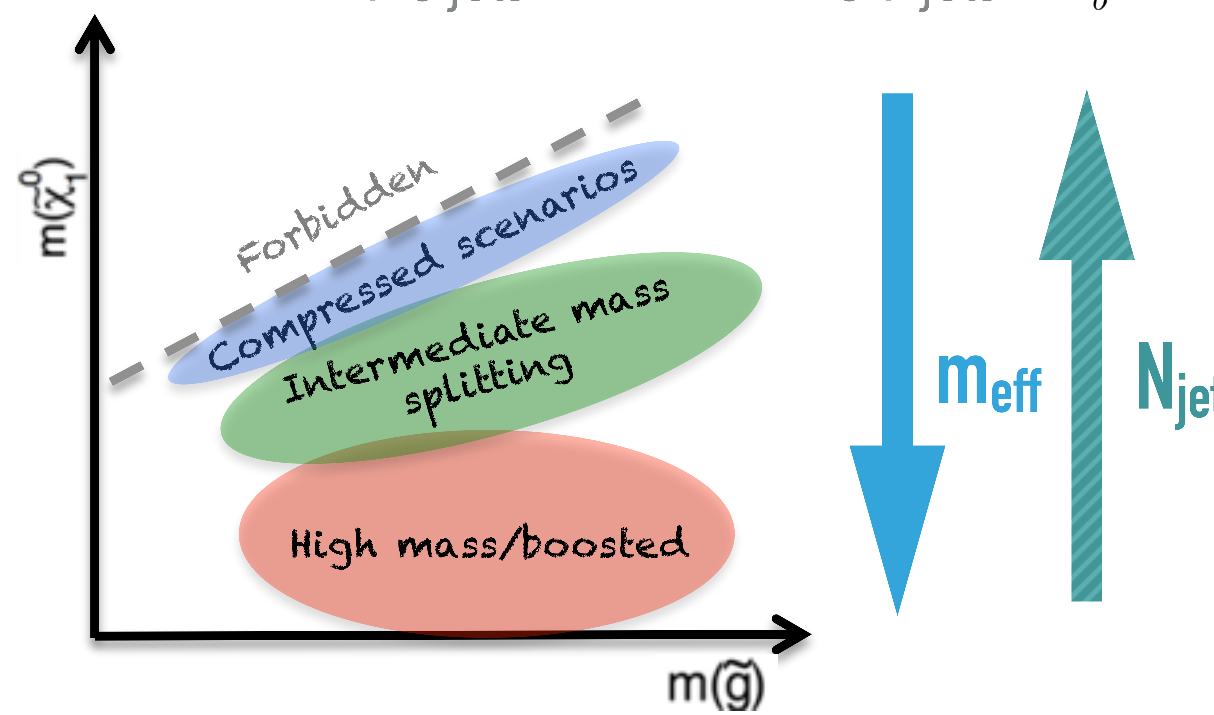
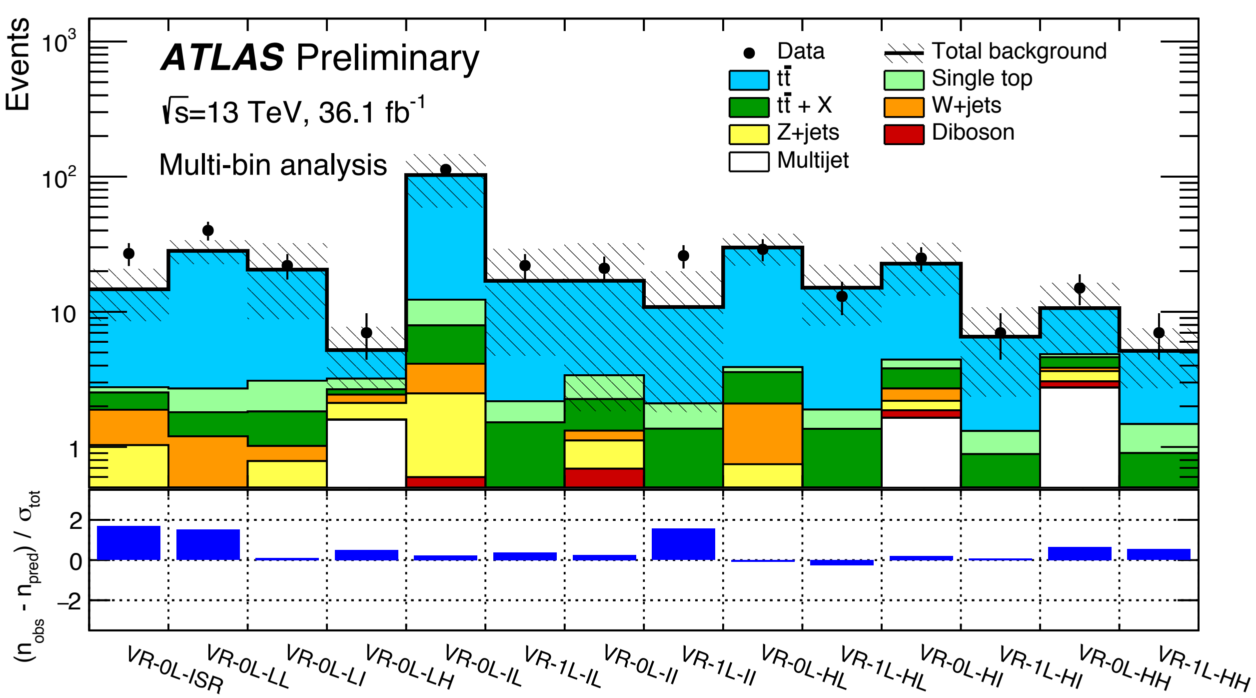


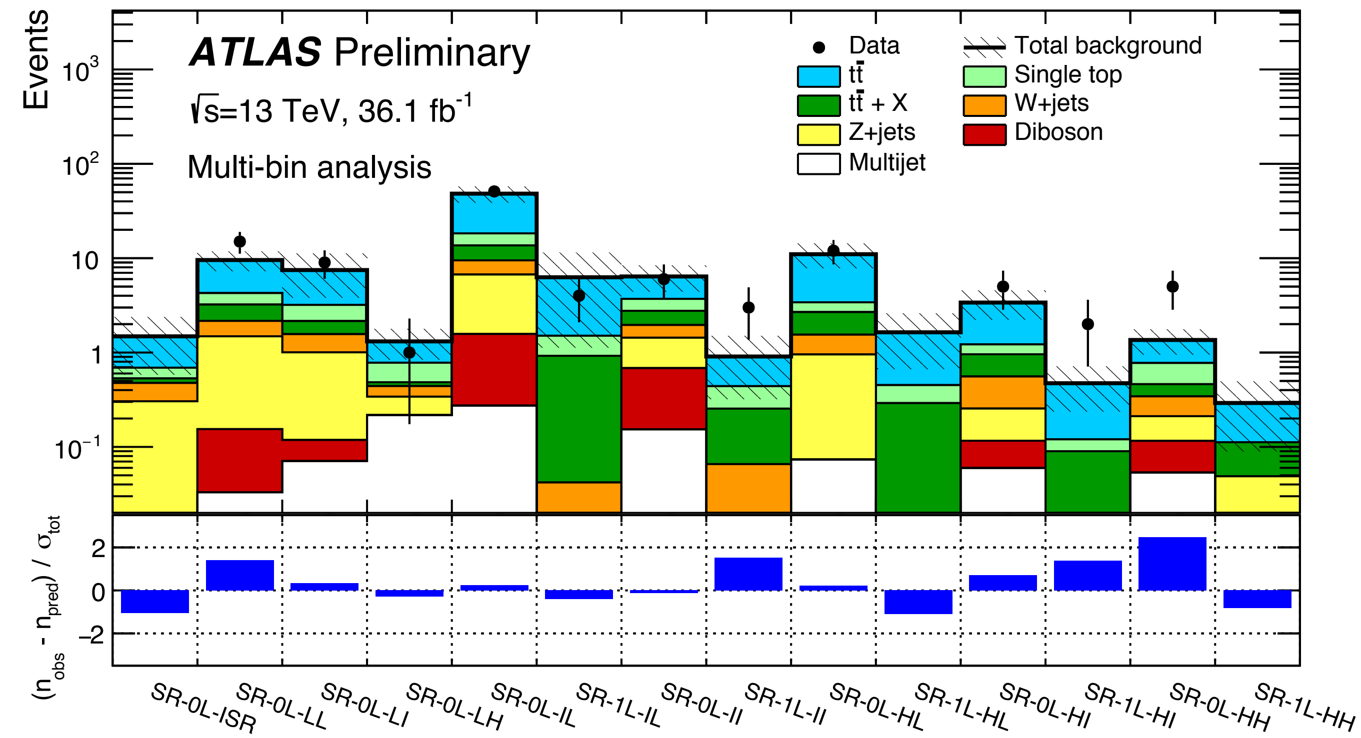


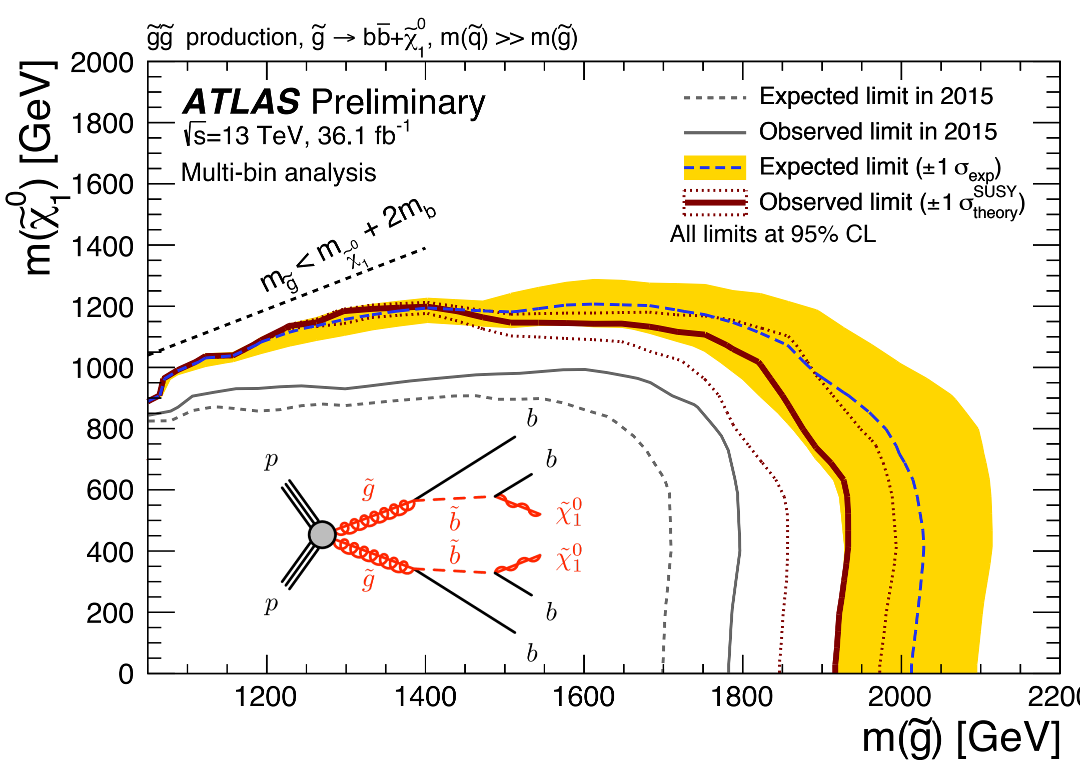


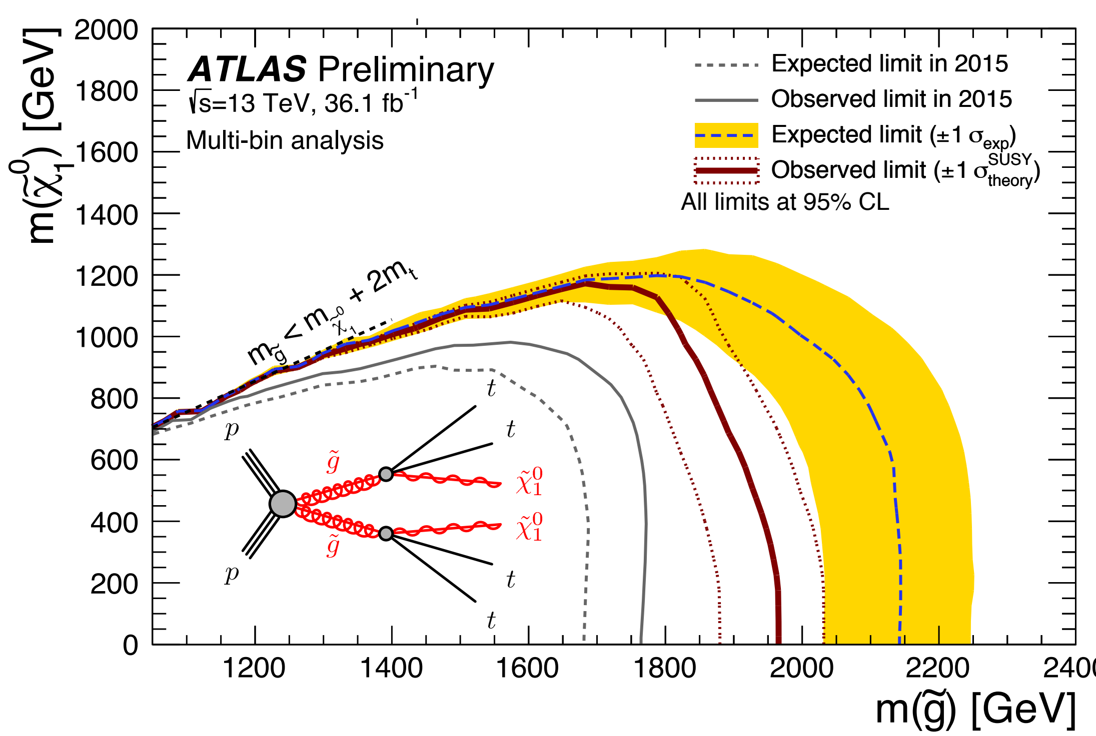
- Dominant background from ttbar
    - 1-lepton control regions used to normalise ttbar MC (invert m_T cut in 1L SRs)
    - CRs are orthogonal → simultaneous fit to all regions for exclusion

0/1L, ≥3 B-JETS [ATLAS]

Results consistent with the SM expectation



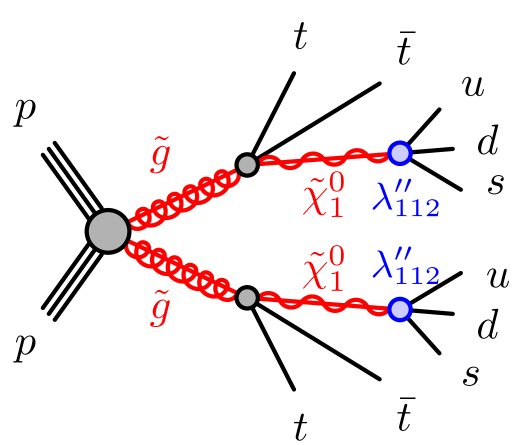




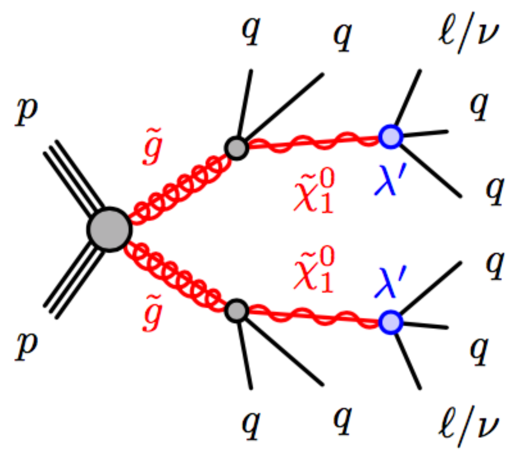
RPV ≥1L+MULTIJETS [ATLAS]

R-**P**arity **V**iolating SUSY search → signatures with little or no MET and many (b-tagged) jets.

RPV model with virtual stops → sensitivity using b-tagged jets



Gluino decay via light flavour quarks → sensitivity with 0 b-tagged jets



- Select events with ≥5 jets with p_T>[40,60,80] GeV
- Events categorised according to N_{jet} and N_{bjet}
- Events with [5,6,7] jets and 0 b-tags further categorised:
  - ≥2 leptons within $81<m_{ll}$/GeV<101
  - positive charge leading lepton (Z-veto)
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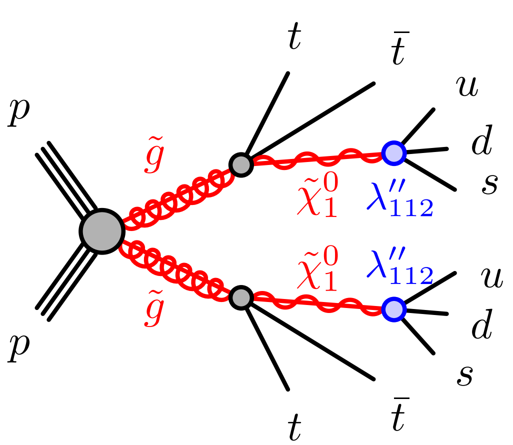

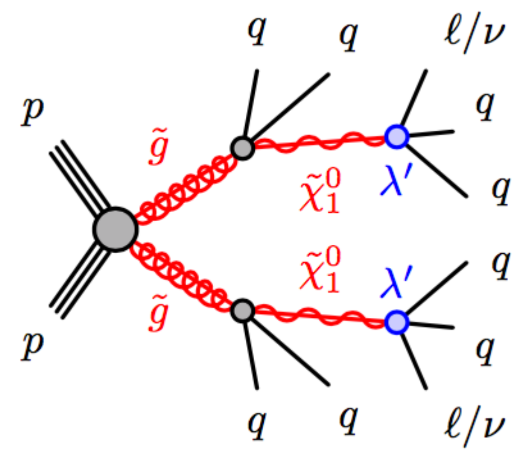

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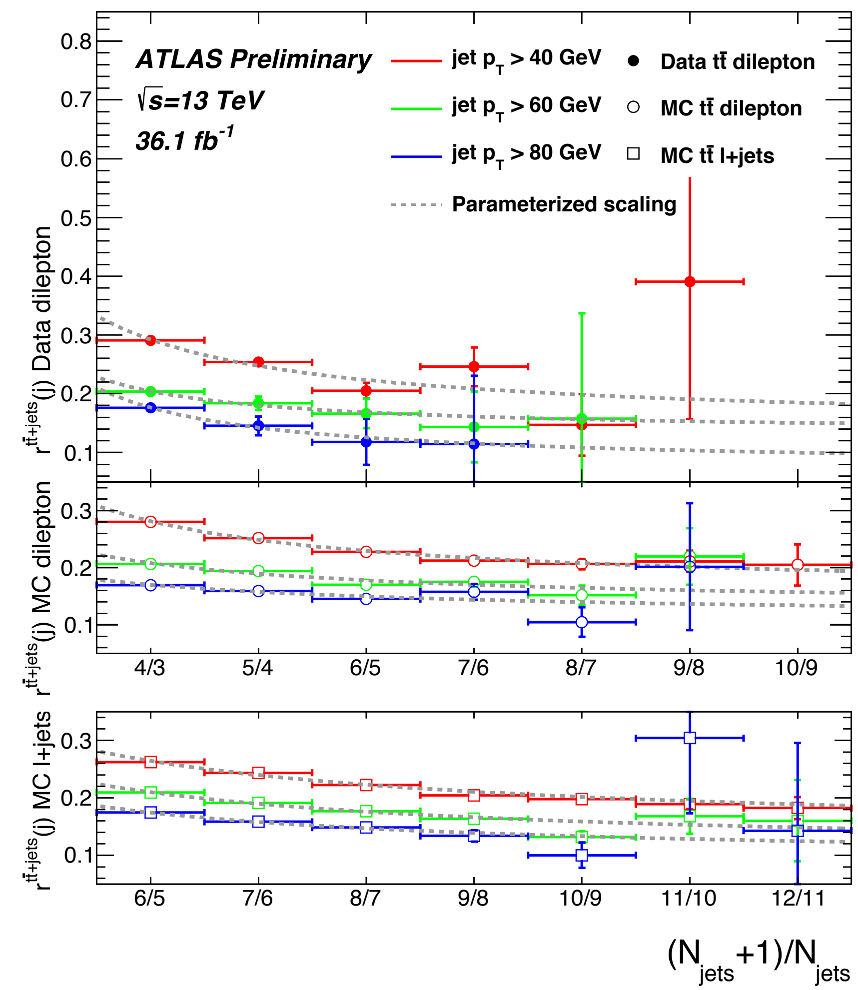
W+JETS

- dominant in low b-jet multiplicity regions.
- normalise in each N_{jet} bin using scaling law that assumes almost constant probability for a single additional jet emission.

TTBAR

- dominant in high b-jet multiplicity regions
- use N_{bjet} distribution in 5-jet region & parameterise evolution in N_{jet} using probability to get additional b-tags



ATLAS EXPERIMENT

University of Victoria

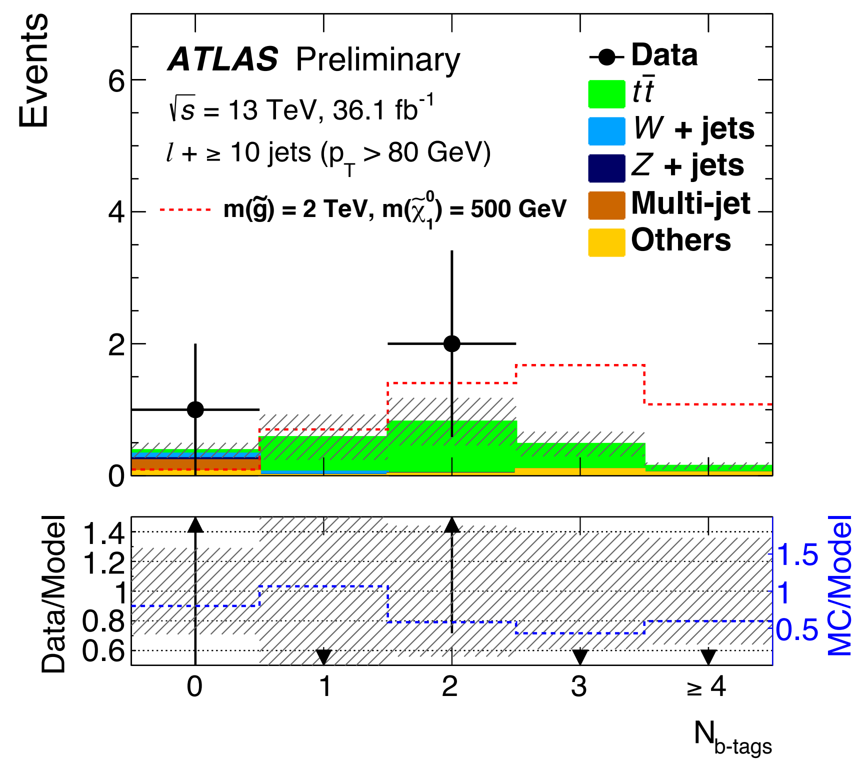
RPV ≥1L+MULTIJETS [ATLAS]

Results show good agreement with SM expectation.

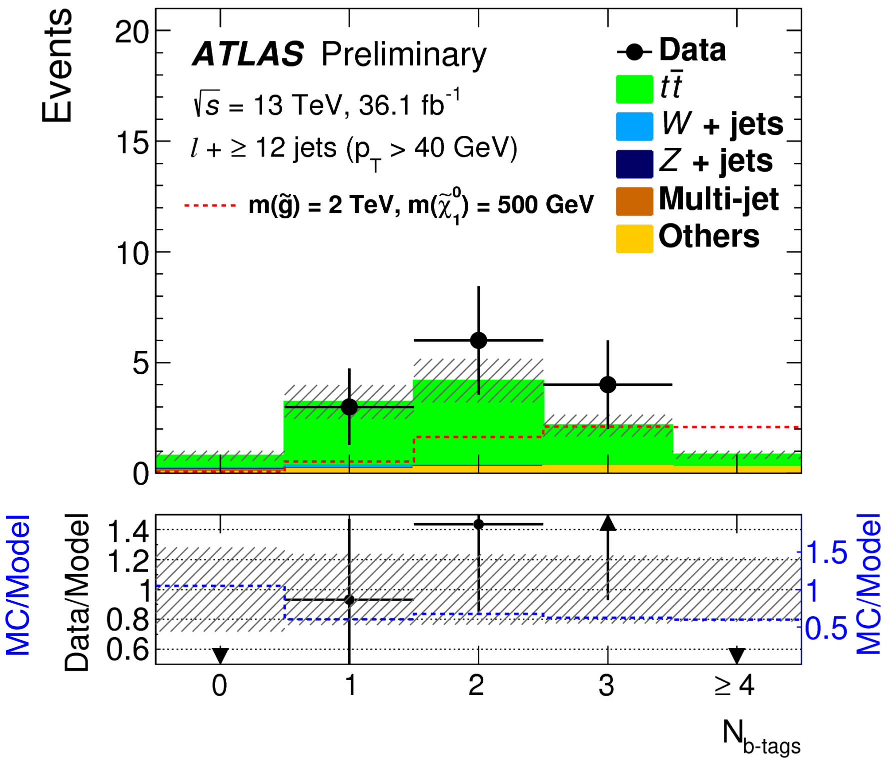
Limits set on several simplified models:

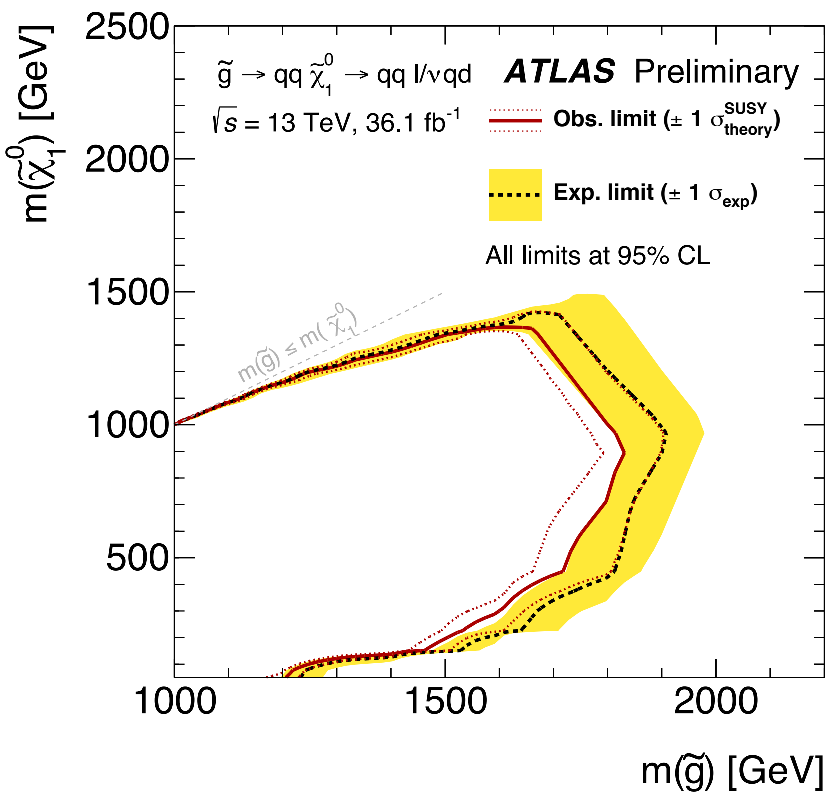
- Best sensitivity from p_T>80 GeV regions for gluino production
- Best sensitivity from p_T>60 GeV for top squark production (see Andreas's talk this afternoon).

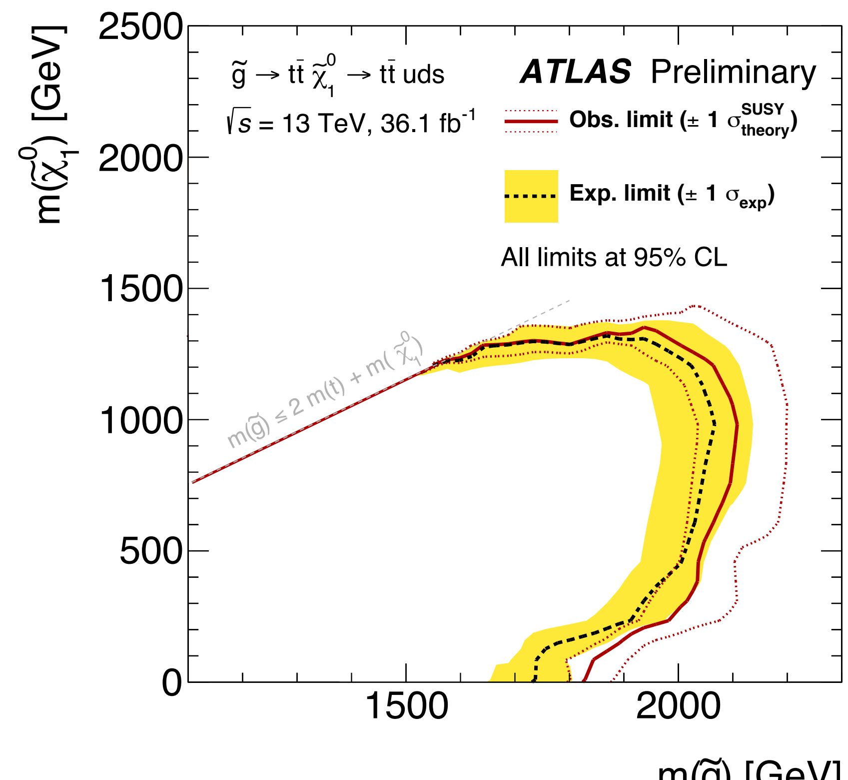
10 jet regions with p_T>80 GeV



12 jet regions with p_T>40 GeV



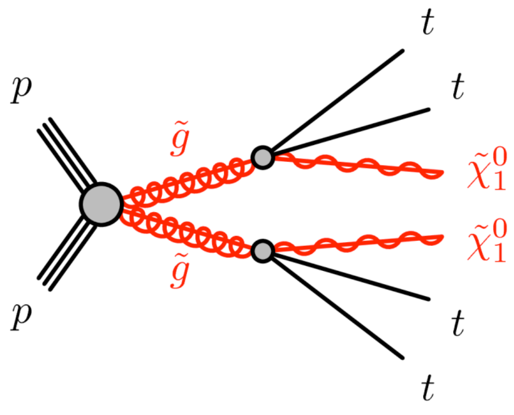




1L, ≥6 JETS [CMS]

18 SRs orthogonal in N_{jet}, MET, N_{bjet}, M_J and M_T

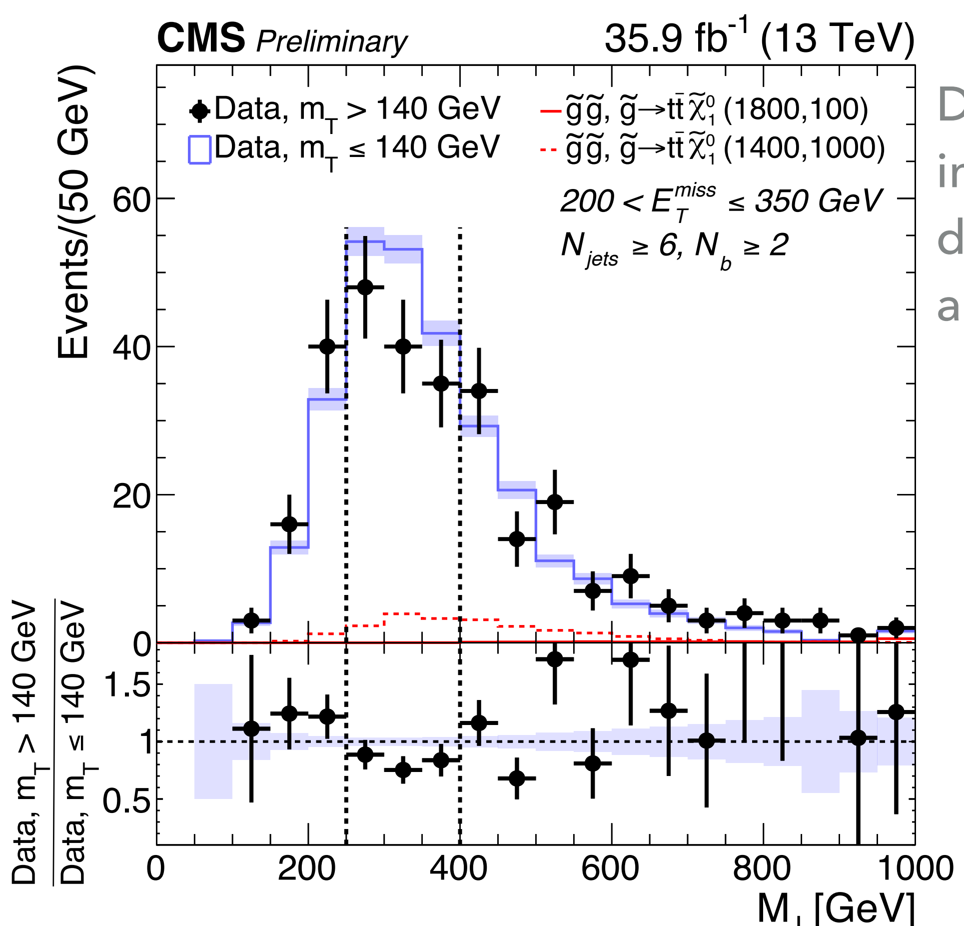
- b-tag selection sensitive to gluino mediated stop model
- Recluster R=0.4 jets into large R jets to target boosted bosons



W+JETS
- Negligible due to M_T cuts.

TTBAR
- Extrapolate M_J distribution from low M_T to high M_T

MULTIJETS
- Negligible in the SRs



Demonstrate invariance of M_J distribution for low and high M_T

$$M_J = \sum_{J_i=\text{large-}R\text{ jets}} m(J_i)$$

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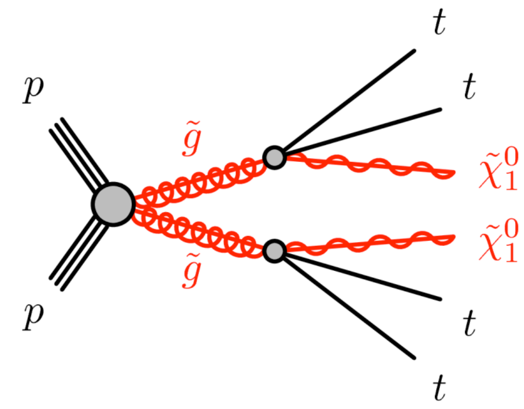

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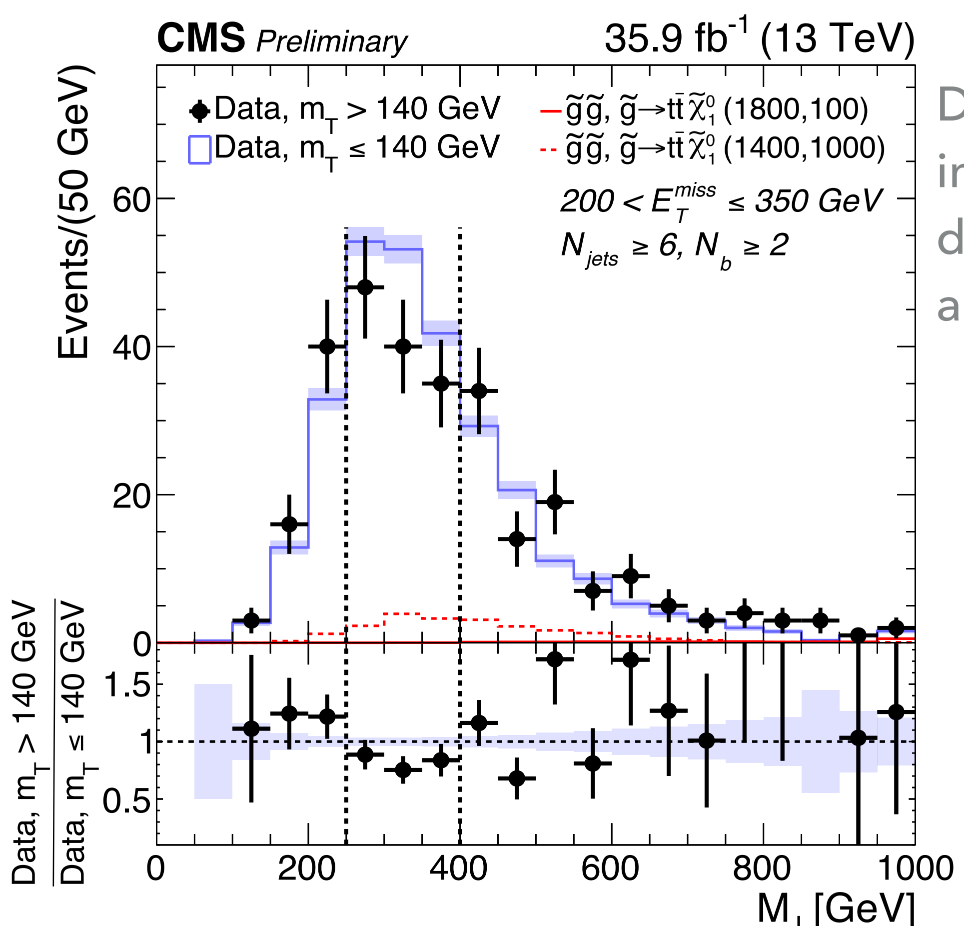
No significant excess with respect to the SM expectation



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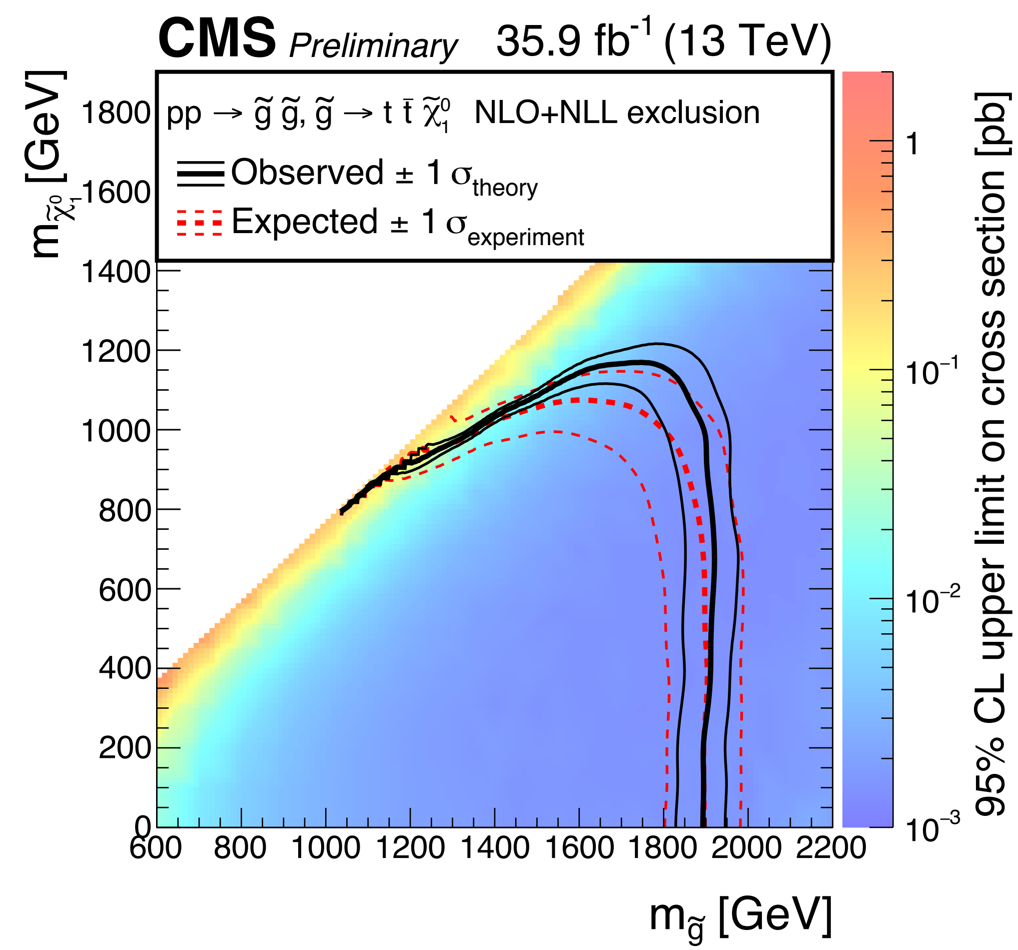
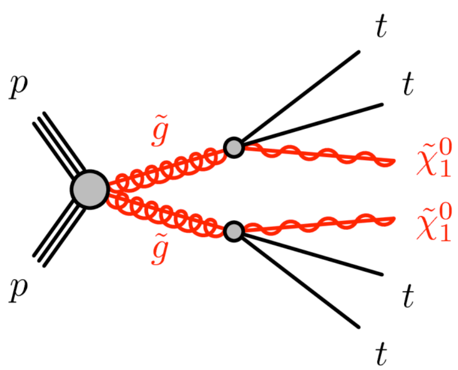
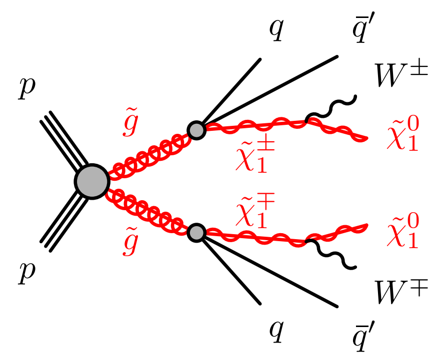


Exclude gluino masses up to 1.9 TeV.

SAME SIGN 2L [CMS]

Exploit low SM background expectation in same-sign final state





- 3 exclusive selections based on lepton p_T
  - $[10,10]<p_T/\text{GeV}<[25,25]$
  - $p_T(1)>25$ GeV, $10<p_T(2)/\text{GeV}<25$
  - $p_T>[25,25]$ GeV

  (first two: off-shell bosons/ compressed region)
- Events categorised into exclusive bins using H_T, N_{jet}, M_T, MET, lepton charge and N_{bjet}
  - 51 search regions in total

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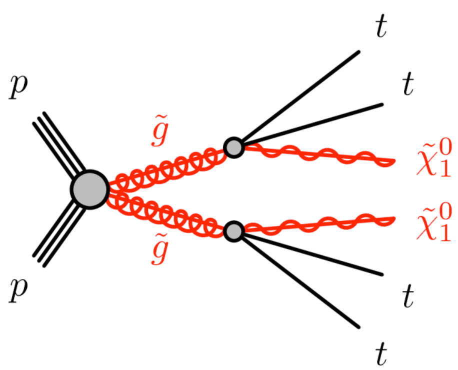

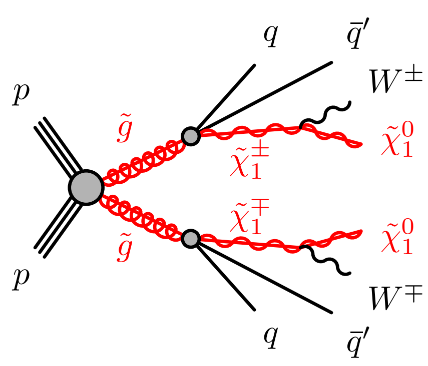

NON-PROMPT LEPTONS
- ttbar, W+jets
- Tight-to-loose ratio based on data control samples

REAL SS BACKGROUND
- ttbar+W, WZ
- MC simulation with control regions

CHARGE MIS-ID
- Opposite-sign control sample reweighted according to charge-flip probability

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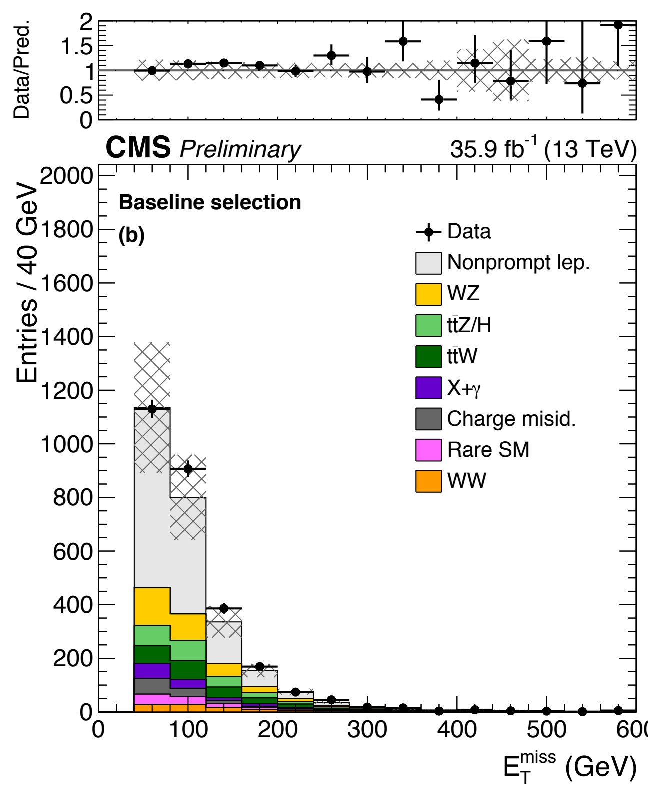
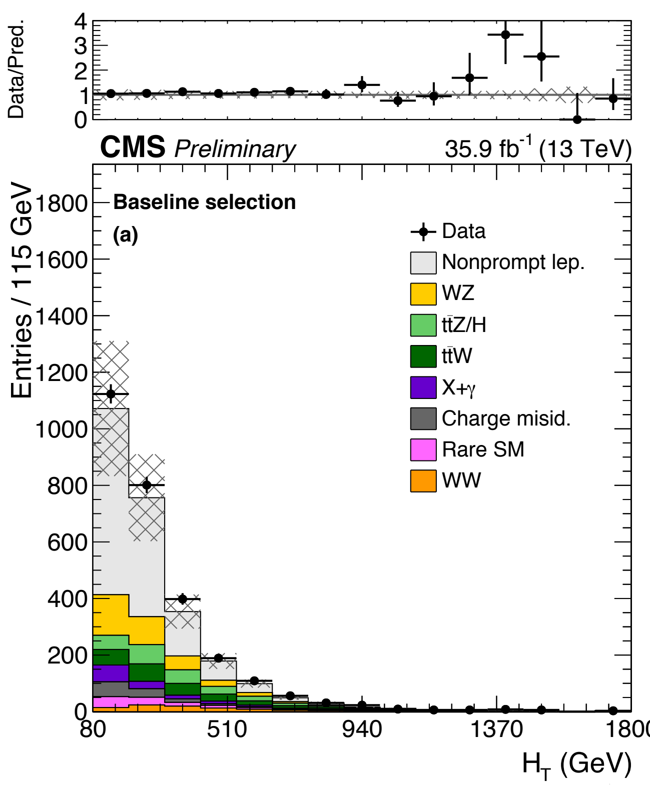
Validate modelling of analysis variables at pre-selection

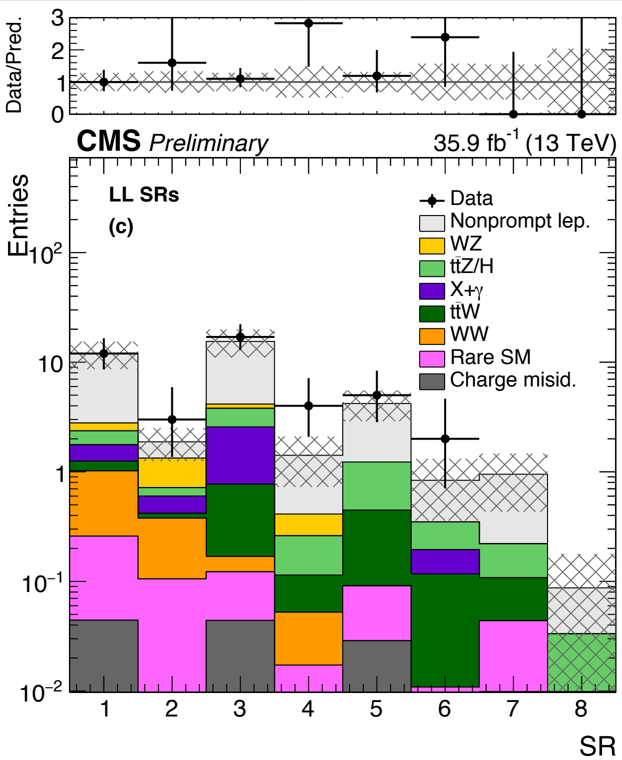




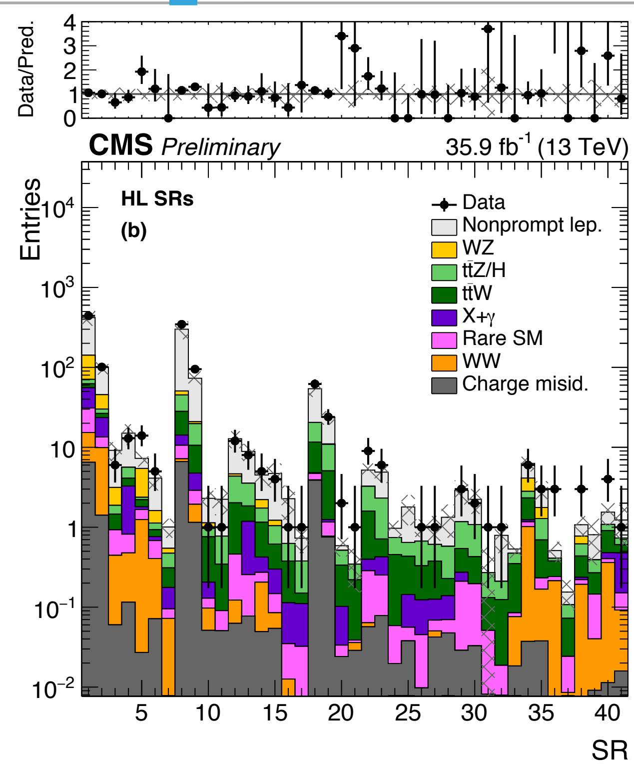
ATLAS EXPERIMENT

University of Victoria

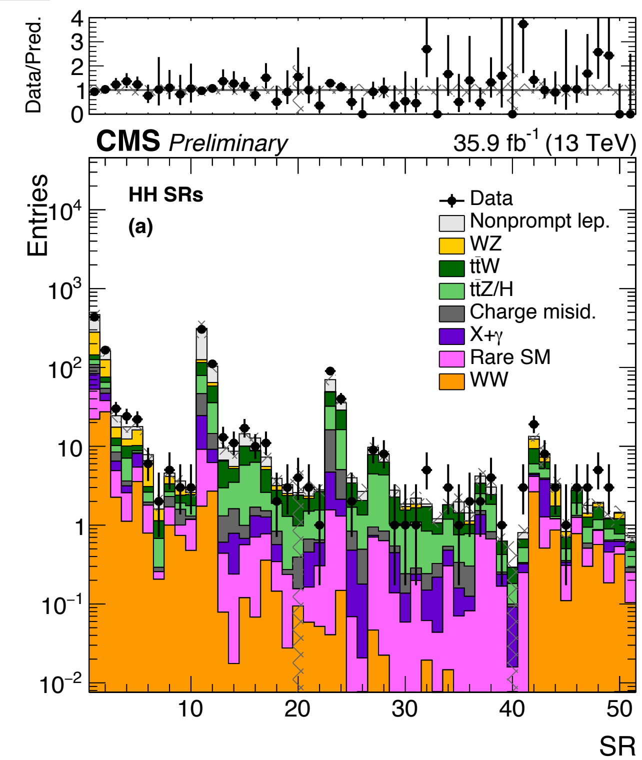
SAME SIGN 2L [CMS]



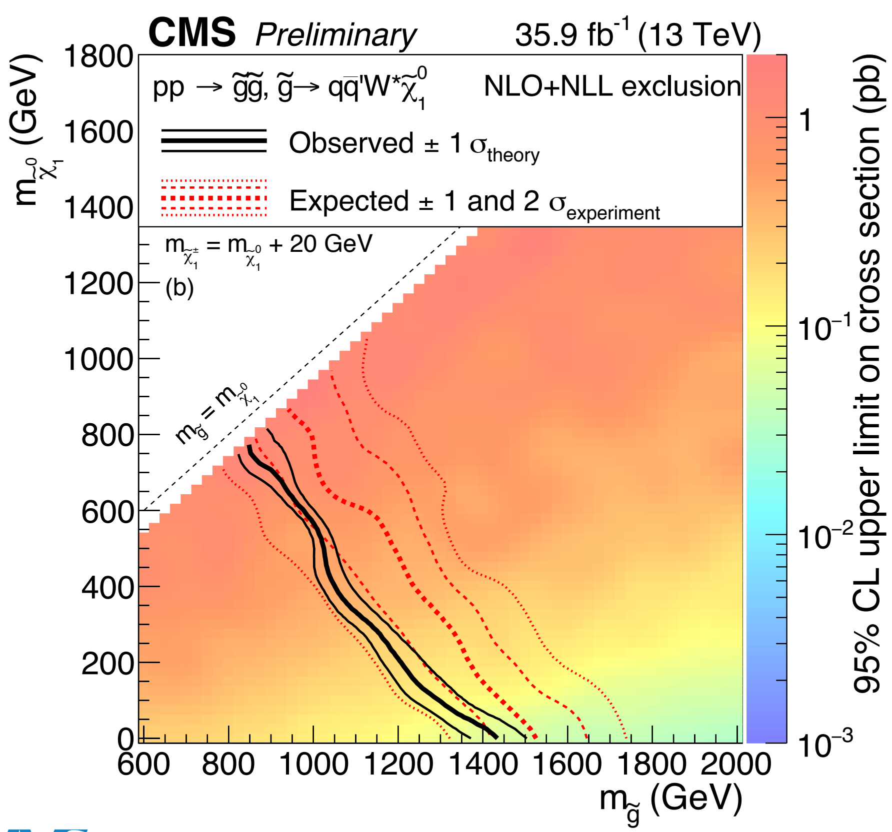
Results for [10,10]<p_T/GeV<[25,25] SRs

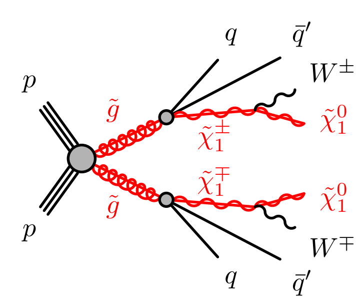


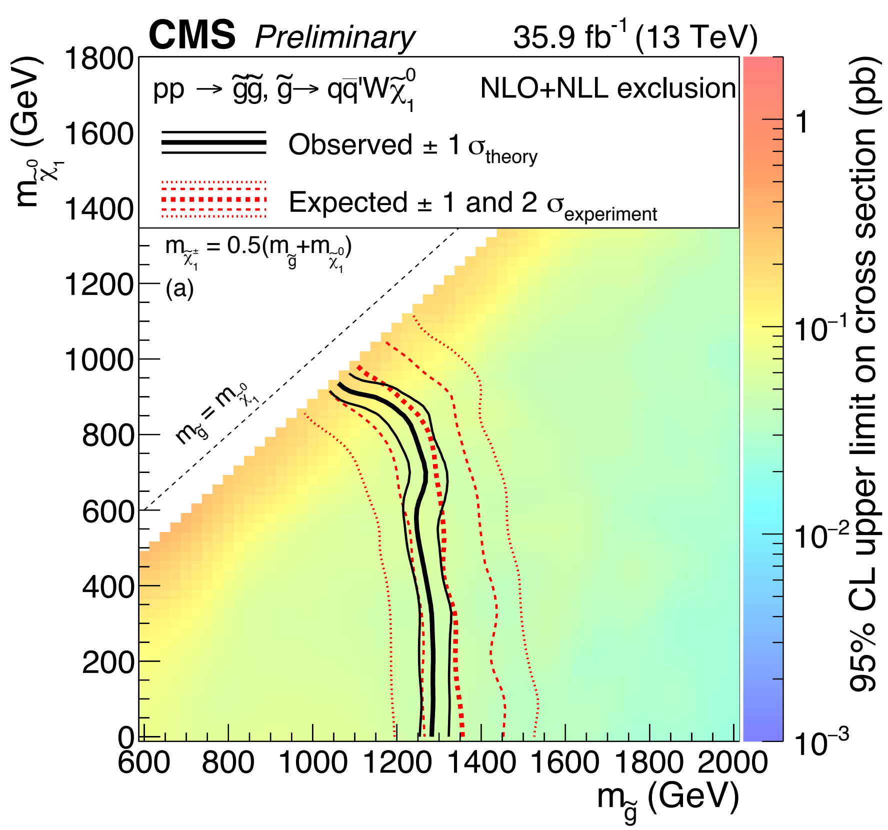
Results for $p_T(1)$>25 GeV, 10<$p_T(2)$/GeV<25 SRs



Results for p_T>[25,25] GeV SRs

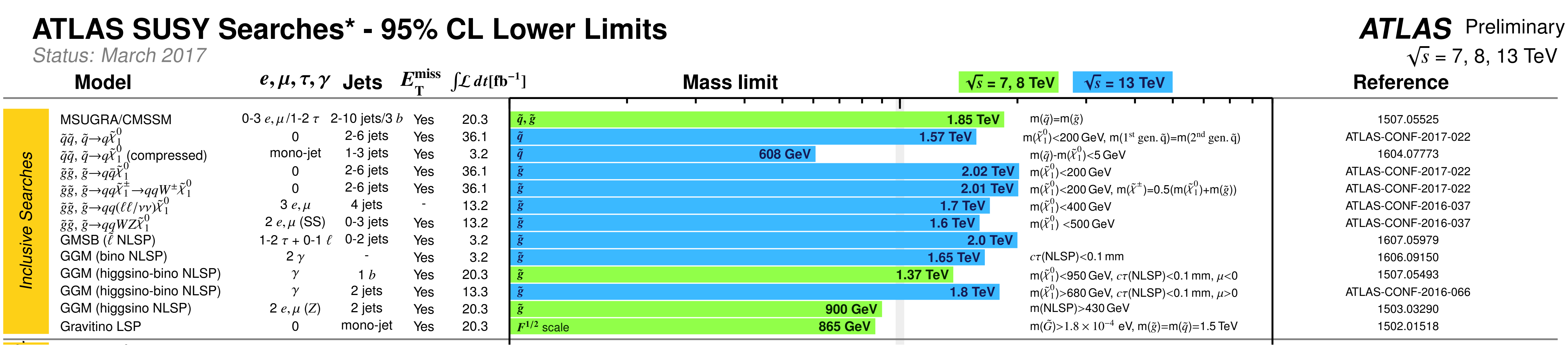






SUMMARY

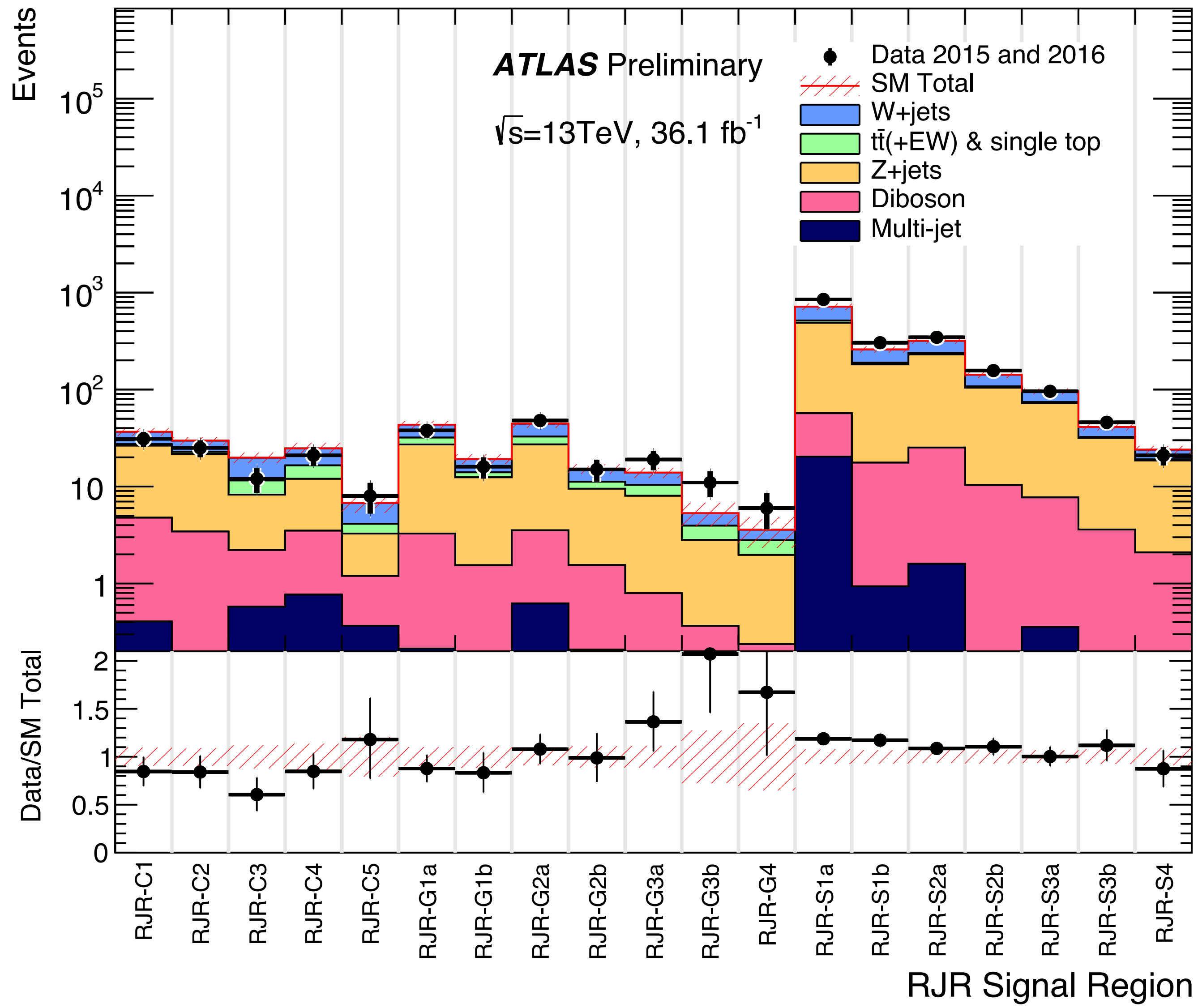
- The LHC was very productive during 2016, providing a large sample of 13 TeV data for the experiments.
- First SUSY searches to take advantage of increased dataset size at 13 TeV are those focusing on strong production of squarks and gluinos.
  - No excesses to get excited about in the newest results so far, pushing the existing limits on squarks and gluinos.
- Many more new results from 2016 still to come, and we're looking forward to taking a much larger 13 TeV dataset beginning this year.



BACKUP SLIDES

0L, 2-6 JETS [ATLAS]

RECURSIVE JIGSAW (RJR) ANALYSIS



Largest deviation ~2 sigma in SR1a.

RECURSIVE JIGSAW VARIABLES (I)

$H_{1,1}^{\mathrm{PP}}$ scale variable similar to MET.

$H_{\mathrm{T}\,2,1}^{\mathrm{PP}}$ transverse scale variable similar to effective mass, Meff, for squark pair-production signals with 2-jet final states.

$H_{1,1}^{\mathrm{PP}}/H_{2,1}^{\mathrm{PP}}$ provides additional information in testing the balance of the information provided by the two scale cuts, where here the denominator is no longer solely transverse. This provides an excellent handle against unbalanced events where the large scale is dominated by a particular object pT or by high MET.

$p_{\mathrm{z}}^{\mathrm{lab}}/(p_{\mathrm{z}}^{\mathrm{lab}} + H_{\mathrm{T}\,2,1}^{\mathrm{PP}})$ 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.

$p_{\mathrm{Tj2}}^{\mathrm{PP}}/H_{\mathrm{T}\,2,1}^{\mathrm{PP}}$ represents the fraction of the overall scale variable that is due to the second highest pT jet (in the PP frame) in the event.

$H_{\mathrm{T}\,4,1}^{\mathrm{PP}}$ analogous to the transverse scale variable described above but more appropriate for four jet final states expected from gluino pair-production.

$H_{1,1}^{\mathrm{PP}}/H_{4,1}^{\mathrm{PP}}$ analogous to the ratio described above for the squark search, but for gluino production.

$H_{\mathrm{T}\,4,1}^{\mathrm{PP}}/H_{4,1}^{\mathrm{PP}}$ a measure of the fraction of momentum that lies in the transverse plain.

$\min_i\,(p_{\mathrm{Tj2i}}^{\mathrm{PP}}/H_{\mathrm{T}\,2,1i}^{\mathrm{PP}})$ represents the fraction of the hemisphere's overall scale due to the second highest pT jet (in the PP frame) in each hemisphere. The minimum value between the two hemispheres is used, corresponding to the index i.

RECURSIVE JIGSAW VARIABLES (II)

$\max_i\,(H_{1,0}^{\mathrm{P_i}}/H_{2,0}^{\mathrm{P_i}})$ testing the balance of solely the jet's momentum in a given hemisphere's approximate particle rest frame (Pi, index i indicating each hemisphere) allows an additional handle against a small but otherwise signal-like set of vector boson with associated jets background events.

$R_{\mathrm{ISR}} \equiv \vec{p}_{\mathrm{I}}^{\,\mathrm{CM}} \cdot \hat{p}_{\mathrm{TS}}^{\,\mathrm{CM}} / p_{\mathrm{TS}}^{\,\mathrm{CM}}$ this is the fraction of the boost of the S system that is carried by it's invisible system I. As the PT of the ISR is increased it becomes more difficult for backgrounds to possess a large value in this ratio - a feature exhibited by compressed signals.

M_{TS} the transverse mass of the system

$N_{\mathrm{jet}}^{\mathrm{V}}$ number of jets assigned to the visible system (V) and not associated with the ISR system.

$\Delta\phi_{\mathrm{ISR,I}}$ This is the opening angle between the ISR system and the invisible system in the lab frame.

$|p_{\mathrm{TS}}^{\mathrm{CM}}|$ the magnitude of the vector-summed transverse momenta of all S-associated jets and MET evaluated in the CM frame.

0/1L, ≥3 B-JETS [ATLAS]

Gtt REGIONS

	Variable	Signal	Control	Validation: 1L	Validation: 0L
Criteria common to all regions of the same type	$N^{\text{Signal Lepton}}$	= 0	= 1	= 1	= 0
	p_T^{jet}	> 30	> 30	> 30	> 30
	$\Delta\phi_{\text{min}}^{4j}$	> 0.4	–	–	> 0.4
	m_T	–	< 150	< 150	–
Region A (Large mass splitting)	$m_{T,\text{min}}^{b-\text{jets}}$	> 60	–	> 60	–
	$N^{b-\text{tag}}$	≥ 3	≥ 3	≥ 3	≥ 3
	N^{jet}	≥ 7	≥ 6	≥ 6	≥ 6
	E_T^{miss}	> 350	> 275	> 300	> 250
	$m_{\text{eff}}^{\text{incl}}$	> 2600	> 1800	> 1800	> 2000
	M_J^{Σ}	> 300	> 300	< 300	< 300
Region B (Moderate mass splitting)	$m_{T,\text{min}}^{b-\text{jets}}$	> 120	–	> 80	–
	$N^{b-\text{tag}}$	≥ 3	≥ 3	≥ 3	≥ 3
	N^{jet}	≥ 7	≥ 6	≥ 6	≥ 6
	E_T^{miss}	> 500	> 400	> 450	> 450
	$m_{\text{eff}}^{\text{incl}}$	> 1800	> 1700	> 1400	> 1400
	M_J^{Σ}	> 200	> 200	< 200	< 200
Region C (Small mass splitting)	$m_{T,\text{min}}^{b-\text{jets}}$	> 120	–	> 80	–
	$N^{b-\text{tag}}$	≥ 4	≥ 4	≥ 4	≥ 4
	N^{jet}	≥ 8	≥ 7	≥ 7	≥ 7
	E_T^{miss}	> 250	> 250	> 225	> 250
	$m_{\text{eff}}^{\text{incl}}$	> 1000	> 1000	> 850	> 1000
	M_J^{Σ}	> 100	> 100	< 100	< 100

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

	Variable	Signal region	Control region	VR-m_T	VR-$m_{T,\text{min}}^{b-\text{jets}}$
Region A (Large mass splitting)	N^{jet}	≥ 5	== 5	≥ 5	> 5
	m_T	> 150	< 150	> 150	< 150
	$m_{T,\text{min}}^{b-\text{jets}}$	> 120	–	–	> 120
	E_T^{miss}	> 500	> 300	> 300	> 400
	$m_{\text{eff}}^{\text{incl}}$	> 2200	> 1700	> 1600	> 1400
	$M_J^{\Sigma,4}$	> 200	> 150	< 200	> 200
Region B (Moderate mass splitting)	N^{jet}	≥ 6	== 6	≥ 6	> 6
	m_T	> 150	< 150	> 200	< 150
	$m_{T,\text{min}}^{b-\text{jets}}$	> 160	–	–	> 140
	E_T^{miss}	> 450	> 400	> 250	> 350
	$m_{\text{eff}}^{\text{incl}}$	> 1800	> 1500	> 1200	> 1200
	$M_J^{\Sigma,4}$	> 200	> 100	< 100	> 150
Region C (Small mass splitting)	N^{jet}	≥ 7	== 7	≥ 7	> 7
	m_T	> 150	< 150	> 150	< 150
	$m_{T,\text{min}}^{b-\text{jets}}$	> 160	–	< 160	> 160
	E_T^{miss}	> 350	> 350	> 300	> 300
	$m_{\text{eff}}^{\text{incl}}$	> 1000	> 1000	> 1000	> 1000
	$M_J^{\Sigma,4}$	–	< 200	–	–

0/1L, ≥3 B-JETS [ATLAS]

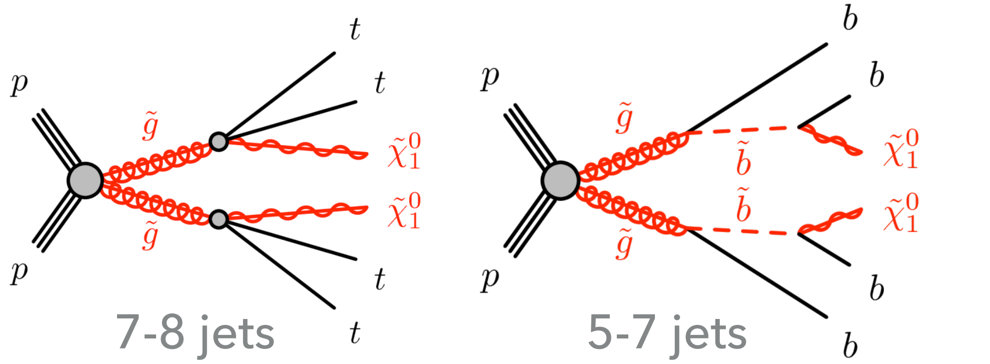
Gbb REGIONS

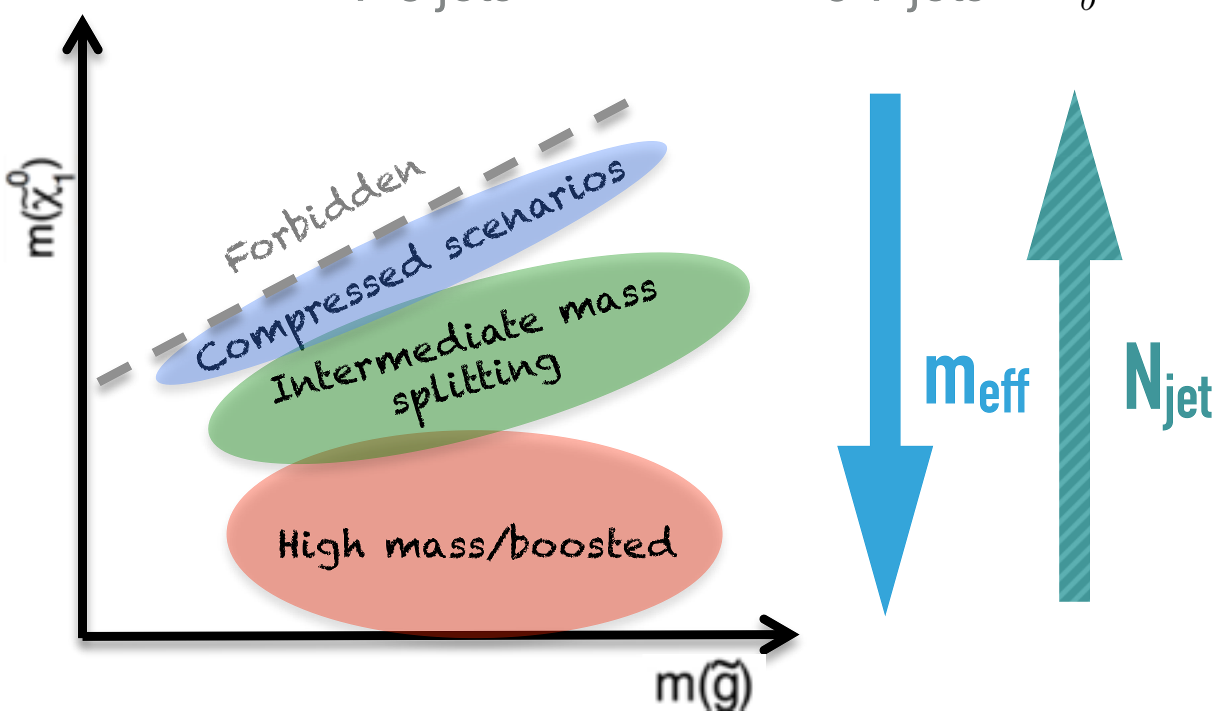
	Variable	Signal region	Control region	Validation region
Criteria common to all regions of the same type	$N^{\text{Signal Lepton}}$	0	= 1	0
	$\Delta\phi^{4j}_{\text{min}}$	> 0.4	–	> 0.4
	m_T	–	< 150	–
	p_T^{jet}	> 30	> 30	> 30
	N_{jet}	≥ 4	≥ 4	≥ 4
Region A (Large mass splitting)	$N_{\text{b-jet}}$	≥ 3	≥ 3	≥ 3
	E_T^{miss}	> 400	> 400	> 350
	m_{eff}	> 2800	> 2500	< 2800 & > 1900
Region B (Small mass splitting)	$N_{\text{b-jet}}$	≥ 4	≥ 4	≥ 4
	E_T^{miss}	> 450	> 375	< 450 & > 350
	$m_{\text{T,min}}^{b-\text{jets}}$	> 155	-	> 125
Region C (Very small mass splitting)	$N_{\text{b-jet}}$	≥ 3	≥ 3	≥ 3
	E_T^{miss}	> 600	> 600	< 600& > 225
	$m_{\text{T,min}}^{b-\text{jets}}$	> 100	-	> 100
	$p_T^{j,1}$	> 400	> 400	> 400
	$j1 \neq b$	(y)	(y)	(y)
	$\Delta\phi(j1, E_T^{\text{miss}})$	> 2.5	> 2.5	> 2.5
Region D (Moderate mass splitting)	$N_{\text{b-jet}}$	≥ 4	≥ 4	≥ 4
	E_T^{miss}	> 450	> 300	< 450& > 250
	$m_{\text{T,min}}^{b-\text{jets}}$	> 90	-	> 100
	m_{eff}	> 1600	> 1600	> 1600 & > 1900

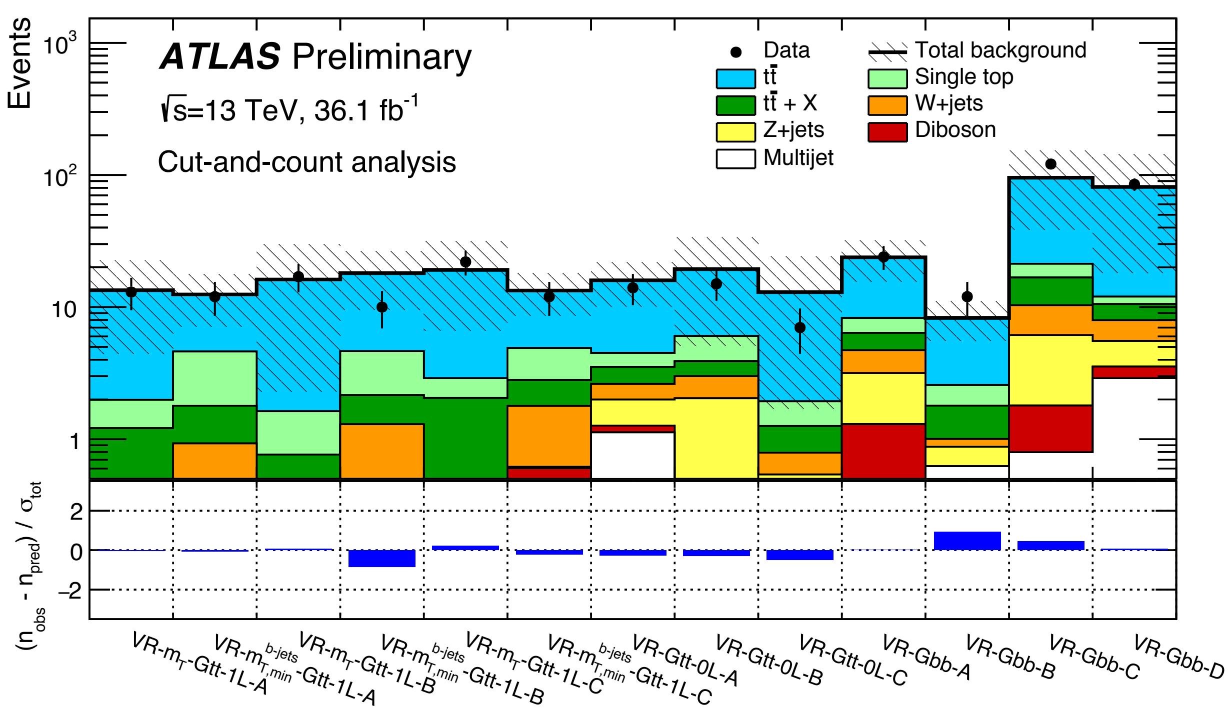
0/1L, ≥3 B-JETS [ATLAS]

Analysis targeting gluino mediated stop/sbottom production

- 10 "discovery" SRs make use of (b-)jet multiplicity, total jet mass (M_J), m_{eff}, m_T and MET
- Further "exclusion" SRs binned in m_{eff} and jet multiplicity
    - High MET, m_{eff}, M_J → large mass splitting/boosted decays
    - Hard leading jet for very small mass splittings
    - Moderate to high jet multiplicity for Gbb/Gtt



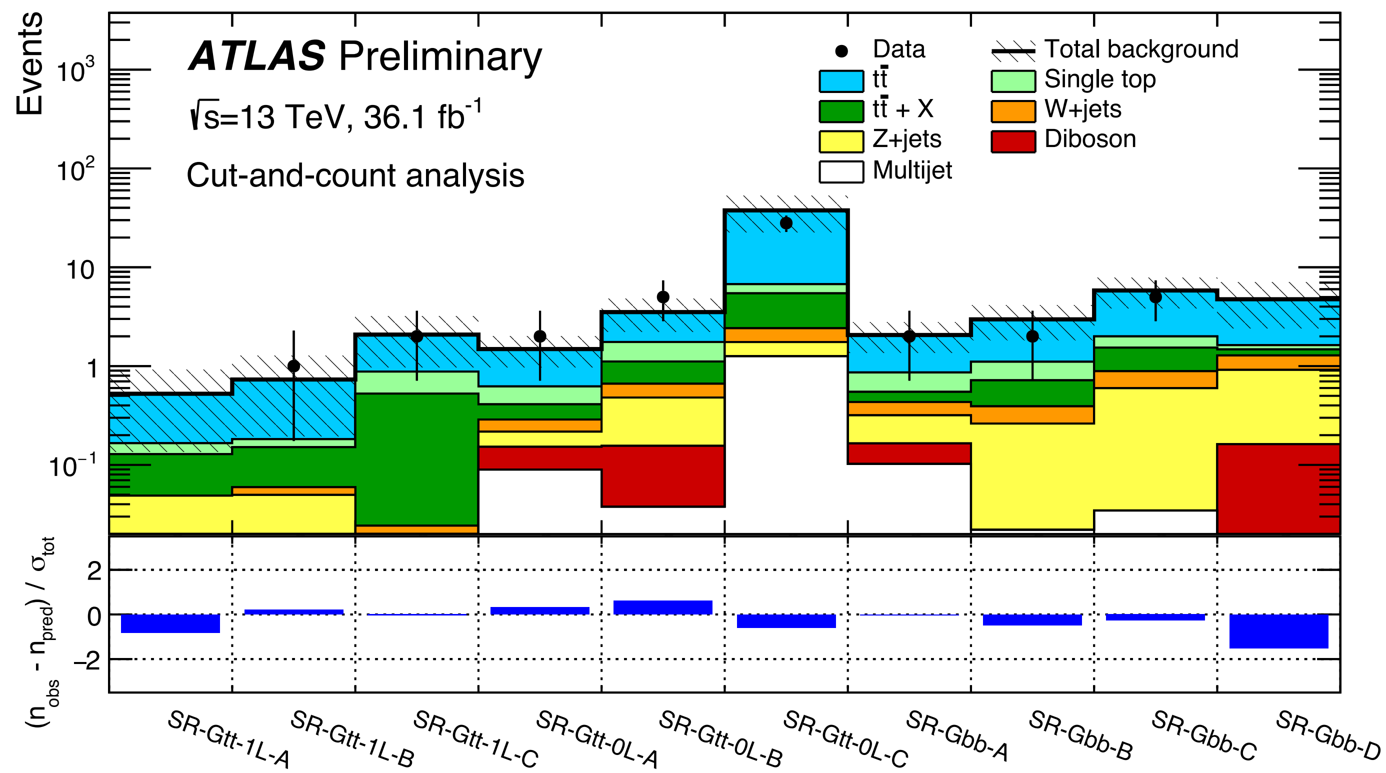




- Dominant background from ttbar
    - 1-lepton control regions used to normalise ttbar MC (invert m_T cut in 1L SRs)
    - CRs are orthogonal → simultaneous fit to all regions for exclusion

0/1L, ≥3 B-JETS [ATLAS]

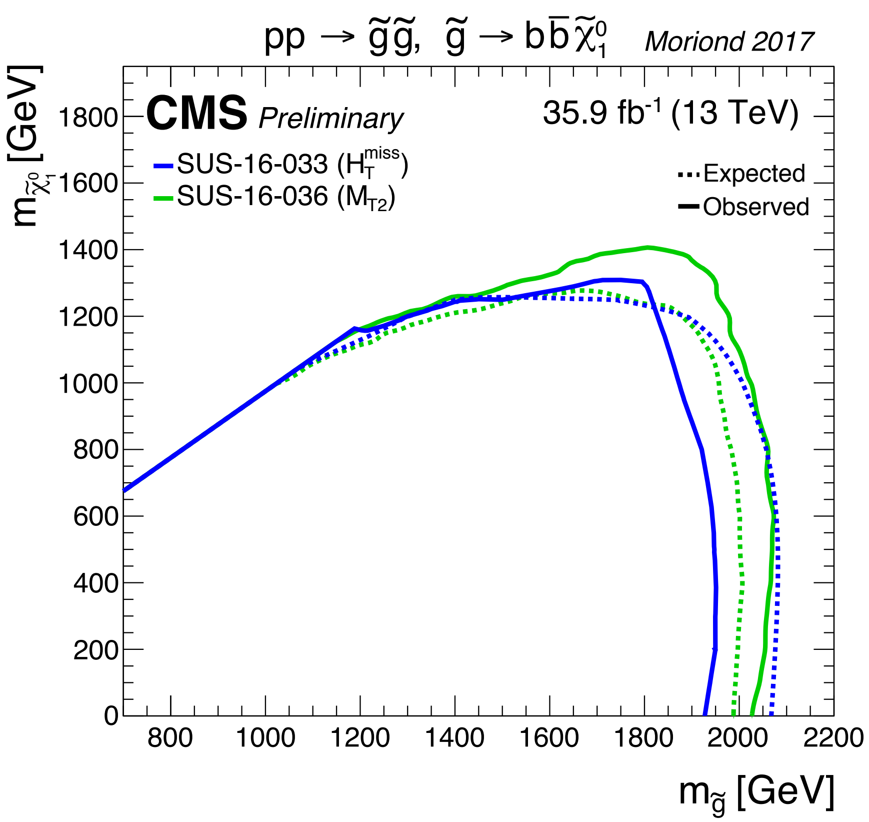
Results consistent with the SM expectation in "discovery" SRs

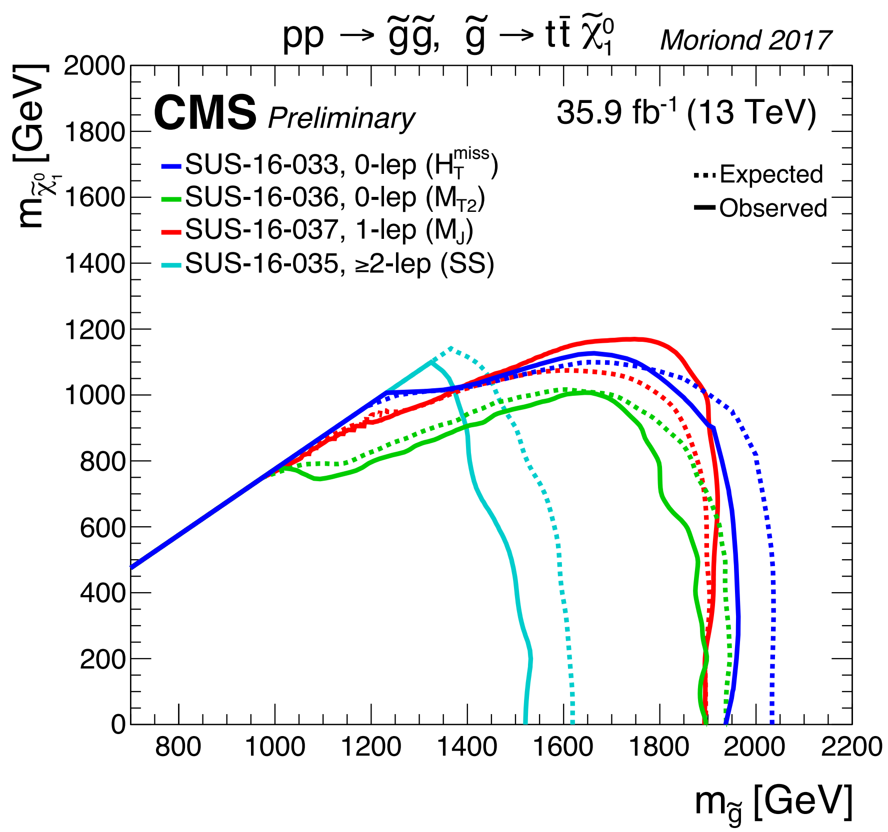


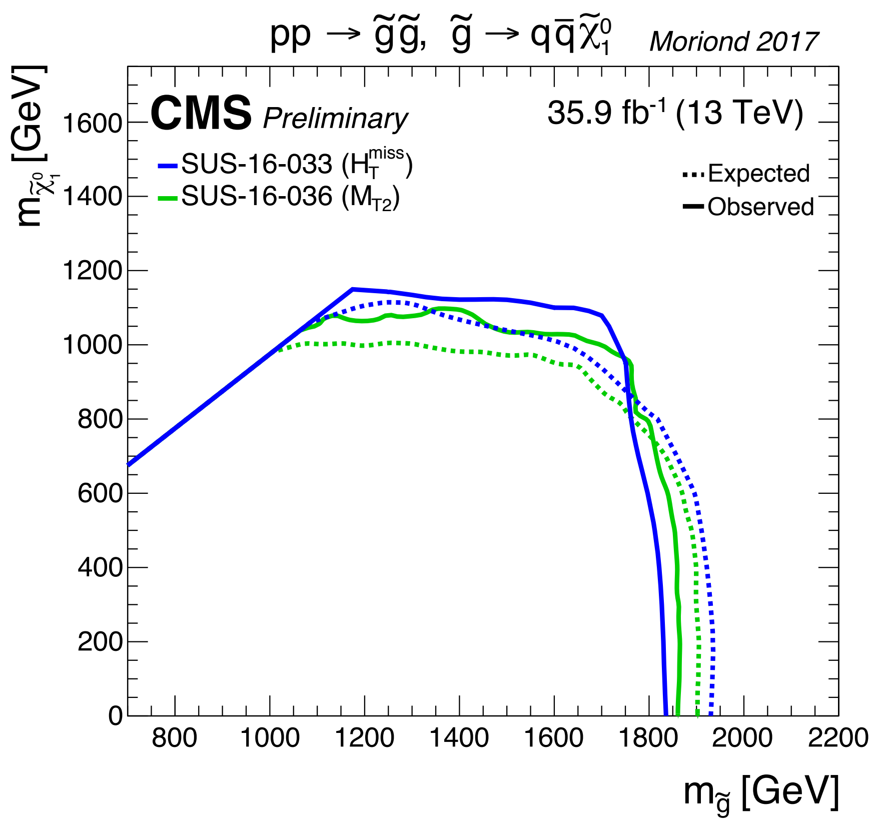
Signal channel	p_0 (Z)	σ_{vis}[fb]	S^{95}_{obs}	S^{95}_{exp}
SR-Gtt-1L-A	0.50 (0.00)	0.08	3.0	$3.1^{+0.9}_{-0.1}$
SR-Gtt-1L-B	0.34 (0.41)	0.11	3.9	$3.6^{+1.2}_{-0.5}$
SR-Gtt-1L-C	0.50 (0.00)	0.14	4.9	$4.8^{+1.8}_{-1.0}$
SR-Gtt-0L-A	0.32 (0.47)	0.13	4.8	$4.1^{+1.7}_{-0.7}$
SR-Gtt-0L-B	0.25 (0.68)	0.21	7.4	$5.9^{+2.2}_{-1.4}$
SR-Gtt-0L-C	0.50 (0.00)	0.55	20.0	$20.0^{+0.0}_{-2.1}$
SR-Gbb-A	0.50 (0.00)	0.13	4.6	$4.5^{+1.7}_{-0.9}$
SR-Gbb-B	0.50 (0.00)	0.13	4.5	$5.0^{+2.1}_{-1.1}$
SR-Gbb-C	0.50 (0.00)	0.18	6.6	$6.9^{+2.8}_{-1.5}$
SR-Gbb-D	0.50 (0.00)	0.09	3.1	$4.4^{+2.0}_{-1.1}$

Model independent upper limits on visible cross-section set by considering each SR individually.

CMS SUMMARY PLOTS







DISCRIMINATING VARIABLES

$$\mathrm{m}_{\mathrm{eff}}^{\mathrm{incl}} = \sum_{i \leq n} p_{\mathrm{T}}{}^{j_i} + \sum_{j \leq m} p_{\mathrm{T}}{}^{\ell_j} + E_{\mathrm{T}}^{\mathrm{miss}}$$

$$\mathrm{m}_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}} E_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos \Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{lepton}))}$$

$$\mathrm{m}_{\mathrm{T,min}}^{b\mathrm{-jets}} = \mathrm{min}_{i \leq 3} \sqrt{(E_{\mathrm{T}}^{\mathrm{miss}} + p_T^{j_i})^2 - (E_{\mathrm{T}}^{\mathrm{miss}}{}_x + p_x^{j_i})^2 - (E_{\mathrm{T}}^{\mathrm{miss}}{}_y + p_y^{j_i})^2}$$

$$M_J^{\Sigma,4} = \sum_{i \leq 4} m_{J,i}$$

Boosted top quarks in signal yield high pT, massive jets (~R=0.8), the MJ variable sensitive to this large-angle clustering of constituents.