Search for SUSY with missing transverse momentum and multiple b-jets with the ATLAS detector

2020 CAP Conference – Particle Physics Session

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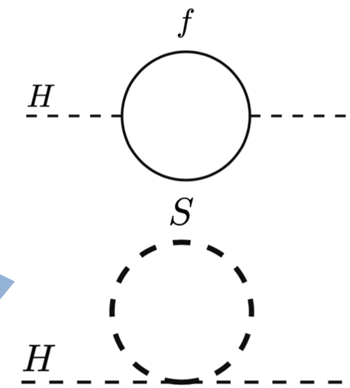
The roadmap

1. Introduction to strong multi-b analysis:
    - Theory of Supersymmetry
    - Simplified Supersymmetric models
    - Objects (including triggers and stable particles) and variables definition
2. Data and background agreement study:
    - using Monte-Carlo samples for backgrounds with the latest recommendation from combined performance groups and full Run2 data (2015-2018)
    - **data-driven** method for multijet (QCD) estimation in 0-Lepton region
    - developed a **reweighting strategy** in 1-Lepton region to fix discrepancy
3. Cut-and-Count approach:
    - **optimizing** all signal regions
    - updating control and validation regions
    - blinded **background-fit results** for 139 fb^{-1} dataset
    - theory systematics for ttbar, singletop and W/Z boson+jets (ongoing)

Theory of Supersymmetry

"Supersymmetry (include all types) is one of the most **loved**, and most **hated**, theories around that works as an extension of our beyond Standard Model." (Zach Marshall)



- It's loved because it has some very nice features:
  - It can explain **dark matter** (Lightest SUSY particles)
  - It has some very suggestive features when it comes to the possibility of unifying the forces (a "grand unified theory")
  - It can explain **hierarchy problem** (NLO to Higgs mass) by introducing top squark

- It's hated , for the most part, because:
  - the full version has **many free parameters** (even large free parameters in minimal Supersymmetric Standard model)
  - also SUSY has been searched for over 35 years and not been seen yet!
  - large mass plane excluded in most SUSY channels

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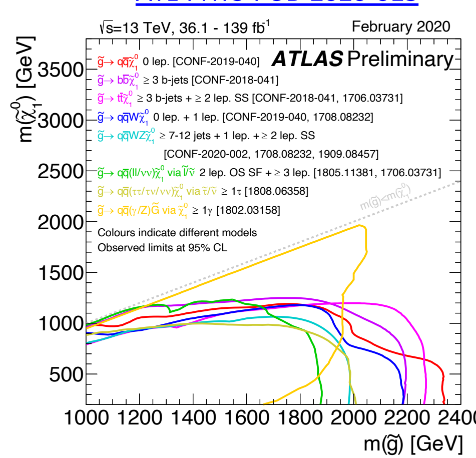
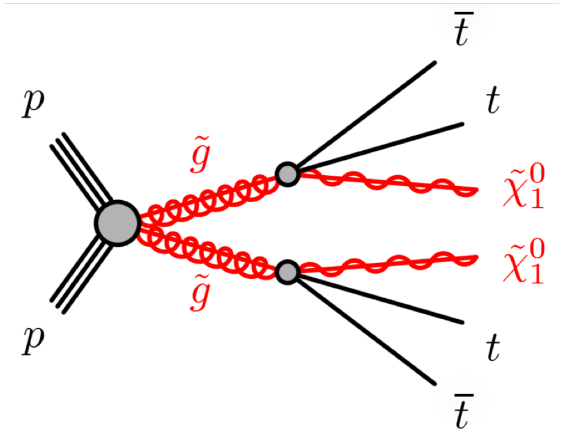
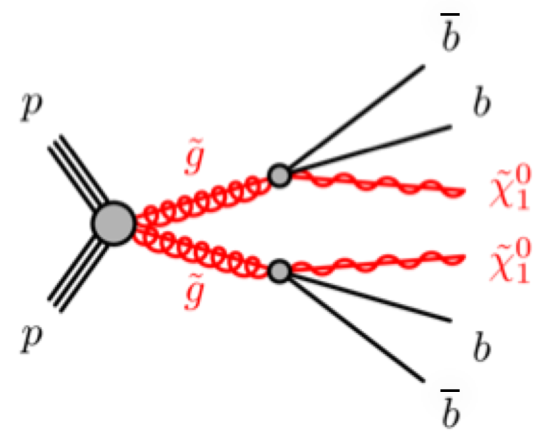


The Simplified Models

Target gluino pair production (strong SUSY) with off-shell top and bottom squarks in their decay products

Gtt





Gbb

channels

- Gtt: 0 lepton (0L), 1 lepton (1L)
- Gbb: 0 lepton (0L), ~~1 lepton (1L)~~

- Potentially high cross-section for gluino pair production
- Assume **100% branching ratio** to corresponding squarks
- Targeting final states with large amount of E_T^{miss} and many b-jets
- Main background is **semi-leptonic $t\bar{t}$** (composition study)

Triggers and Object Definition

Triggers

- E_T^{miss} trigger: large E_T^{miss} is expected in this analysis so unprescaled E_T^{miss} trigger used for different data taking periods.

Electrons/Muons

- Baseline electrons/muons need to satisfy Loose/Medium identification operating point, $p_T > 20$ GeV, and $|\eta| < 2.47$. After overlap removal signal leptons are required to satisfy Tight identification and isolation cuts. Leptons are matched to the primary vertex by having more cuts on transverse and longitudinal impact parameters

Jets

- Baseline jets are reconstructed with topo-clusters as the input for anti-k_T algorithm radius $R = 0.4$ and $p_T > 20$ GeV, $|\eta| < 2.8$. To suppress fake jets from pileup interaction, jets are required to have jet vertex tagger JVT > 0.59. Calibrated jets are then filtered with $p_T > 20$ GeV to form signal jets

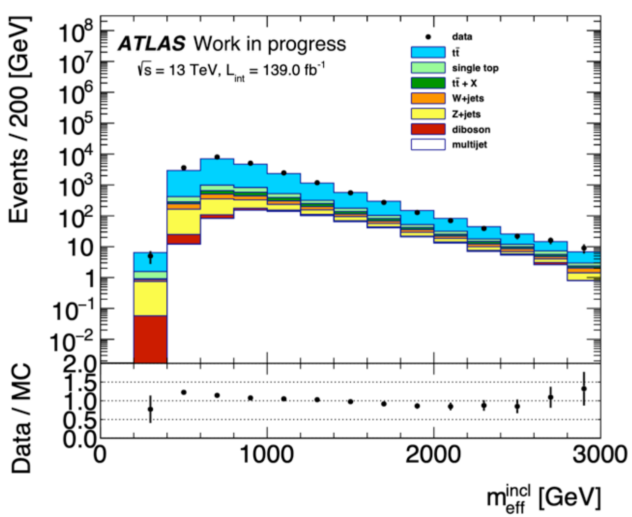
B-Jets

- Jets are considered *b*-tagged based on the output of the MV2c10-tagger algorithm trained by the ttbar samples with 15% c-jet fraction. The rejection factor against c-jets and light jets are 6 and 134 respectively for 77% *b*-tag efficiency

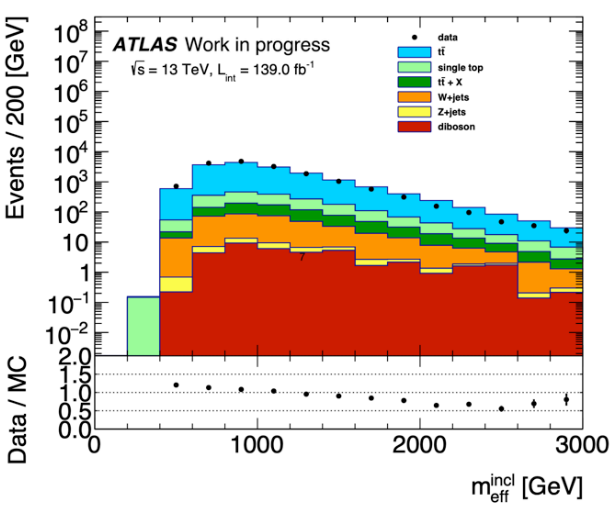
Data-Background Comparison in Preselection

- Preselection cuts in 0-lepton (0L) and 1-lepton (1L) regions:
  - 4 jets with $p_T > 30$ GeV
  - 3 *b*-jets with $p_T > 30$ GeV
  - ≥ 1 signal lepton in 1L region
  - E_T^{miss} trigger with offline $E_T^{miss} > 200$ GeV
  - 0L additionally applies a minimum $\Delta\phi_{min}$(MET,jet) cut to suppress QCD events
- **Slope in 1L region** for p_T related variables (E_T^{miss}, m_{eff}^{incl}) observed. Modeling issue could be the reason for overestimation in 1L region ($m_{eff}^{incl} = \Sigma_{i\leq n} p_T^{jet_i} + \Sigma_{j\leq m} p_T^{lep_j} + E_T^{miss}$)

0Lepton region



1Lepton region



Reweighting in 1Lepton region (I)

- **4 orthogonal control regions** enriched in various processes used as the input to derive reweighting functions for ttbar, singletop and Z/W+jets

selections in 4 dedicated control regions for reweighting ($N_{jet} \geq 4$)

Parameter	Control Region			
	$t\bar{t}$	Single top	W+jets	Z+jets
E_T^{miss}, GeV	≥200	≥200	≥200	≥200
$N^{signal\ lep.}$	=1	=1	=1	=2
N^{b-jets}	=2	=2	=0	=0
$m_{T,min}^{b-jet}$, GeV	≤350	≥350	X	X
M_Z, GeV	X	X	X	$60 \leq M_Z \leq 120$

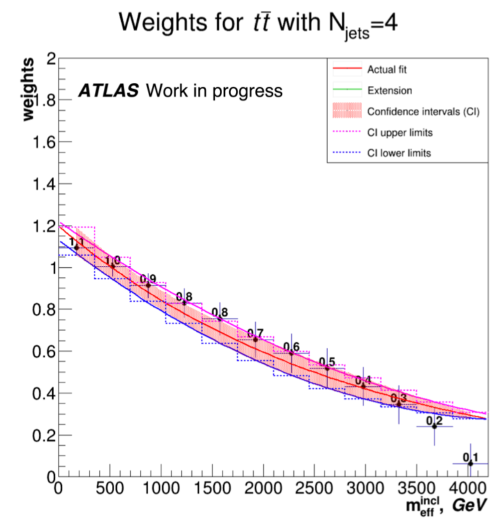
- Derive kinematic correction based on m_{eff}^{incl} to change the background shape closer to data
- Need to solve a system of equations **for each m_{eff}^{incl} bin** (12 bins). Below fraction is $f_{CR}^{sample} = MC_{CR}^{sample} / MC_{CR}^{combined}$. Total number of events before and after reweighting used to derive Scale-Factor useful to keep normalization constant

Math motivation behind these equations in backup

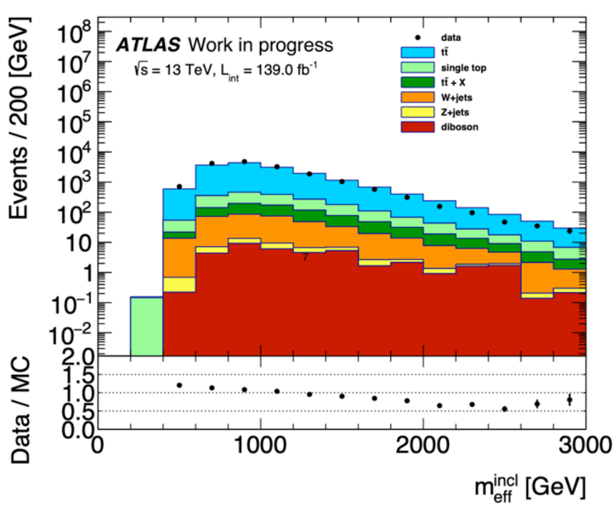
$$\begin{pmatrix} f_1^{t\bar{t}} & f_1^{st} & f_1^{w+jets} & f_1^{z+jets} \\ f_2^{t\bar{t}} & f_2^{st} & f_2^{w+jets} & f_2^{z+jets} \\ f_3^{t\bar{t}} & f_3^{st} & f_3^{w+jets} & f_3^{z+jets} \\ f_4^{t\bar{t}} & f_4^{st} & f_4^{w+jets} & f_4^{z+jets} \end{pmatrix} \begin{pmatrix} w^{t\bar{t}} \\ w^{st} \\ w^{w+jets} \\ w^{z+jets} \end{pmatrix} = \begin{pmatrix} Data_1/MC_1 \\ Data_2/MC_2 \\ Data_3/MC_3 \\ Data_4/MC_4 \end{pmatrix}$$

Reweighting in 1Lepton region (II)

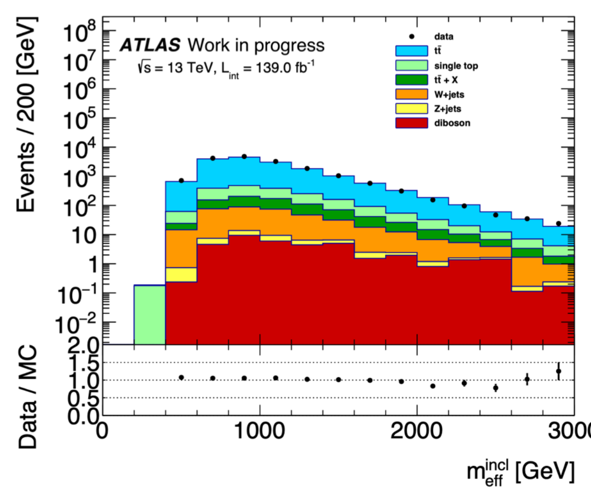
- To get better shape for [N(jets)] distribution, reweighting functions derived separately in N_{jets}=4,5,6, ≥7 slices
- Right plot shows ttbar reweighting function in m_{eff}^{incl} bin for N_{jets}=4. The same produced for N_{jets}=5,6, ≥7
- Final **reweighting functions** ([backup]) used to normalize background samples (event-by-event)



Preselection (before reweighting)



Preselection (after reweighting)



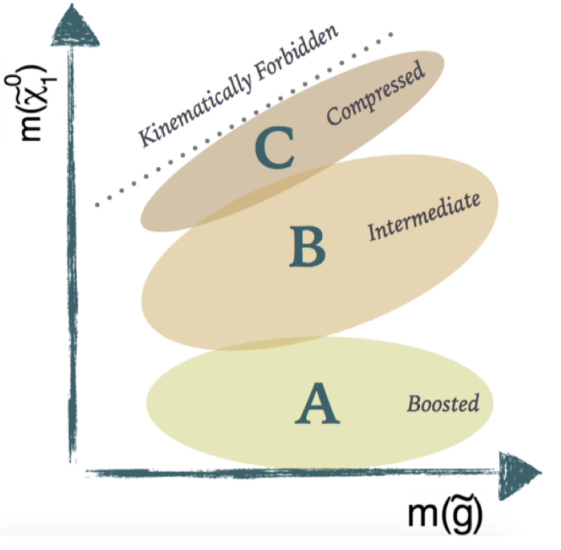
Cut-and-count Analysis

- Define signal regions target a different region of signal grid parametrized by the **mass splitting** between gluino and neutralino
  - **partially-overlapping** single-bin signal regions
  - optimized to maximize the SUSY discovery power

- Signal region definition: **Maximize significance** (next slide)

- Control region definition:
  1. have enough (>100) reweighted Background events
  2. minimize signal contamination (<1%).
  3. have the same signal region background composition
  4. make it orthogonal to signal region

- Validation region definition:
  1. kinematically close to signal region
  2. orthogonal to signal and control region
  3. >10 Bkgd events and small signal contamination (<10%)
  4. have the same signal region background composition

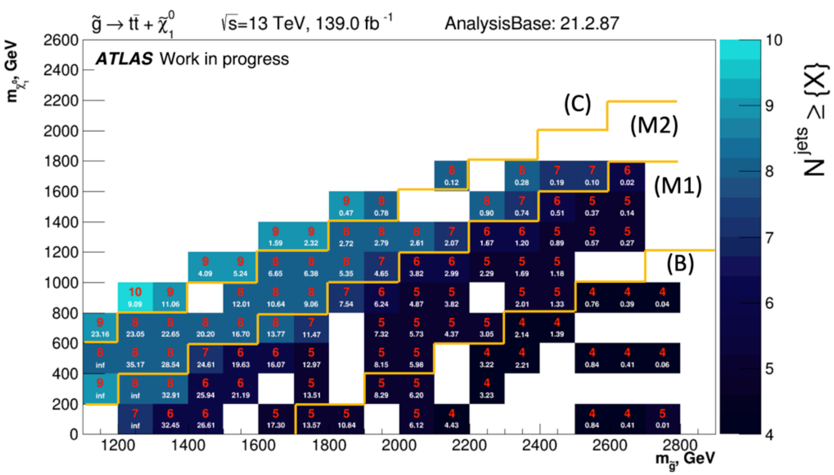


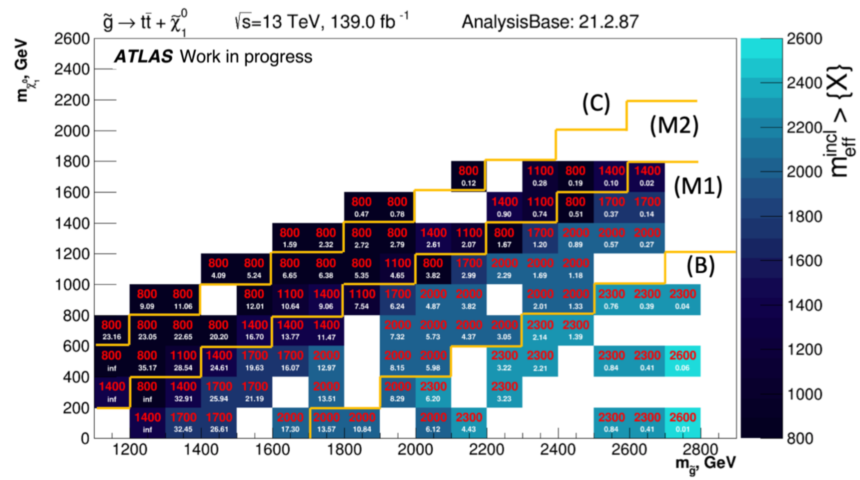
Signal region optimization (I)

- The strategy is to perform a signal grid scan over the selected variables to optimize with the maximum significance (python package developed for this goal)
- First step is to define **supercut** (table below) which includes start, stop and step size for different variables. Some variables are fixed like p_T^{jet} and $N^{b\text{-jet}}$
- The optimization package **loops through signal mass points** and use supercut to derive sig/bkg yields for more than 10.000 selections
- **Significance** derived by built-in Root[1,2] function for each selection and the maximum significance represent the optimal selection

Gtt 1-lepton								
Parameters:	N_{jet}	$N^{\text{b-jet}}$	p_T^{jet}	E_T^{miss}	$m_{\text{eff}}^{\text{incl}}$	m_T	$m_{T,\text{min}}^{b\text{-jets}}$	$M_J^{\Sigma,4}$
Min value:	4	3	30	200	800	100	0	0
Max value:	10	X	X	600	3200	200	120	300
Step:	1	X	X	100	300	50	40	100

Signal region optimization (II)

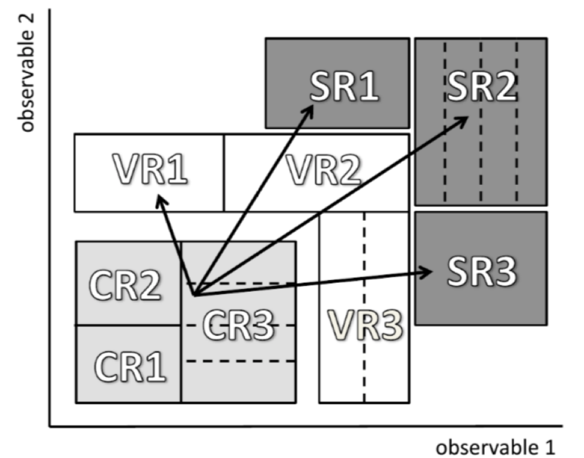




- Plots show the **optimal significance** (in white) possible with the best selected variable in red (number of jets and m_{eff}^{incl}) at each mass point
- 4 kinematic regions can be defined based on gluino-neutralino mass splitting:
  - **Boosted**: $\Delta m \geq 1700$ GeV
  - **Moderate** (1): $1000 \leq \Delta m \leq 1700$ GeV
  - **Moderate** (2): $400 \leq \Delta m \leq 1000$ GeV
  - **Compressed**: $\Delta m \leq 400$ GeV

Fit Strategy + Systematic Uncertainties

- Standard semi-data-driven approach using control regions to normalize largest background:
  - **data-driven norm** for ttbar, shape from MC
  - data-driven QCD estimation for 0-lepton channel
  - all other backgrounds estimation from MC
  - validate this approach using validation regions

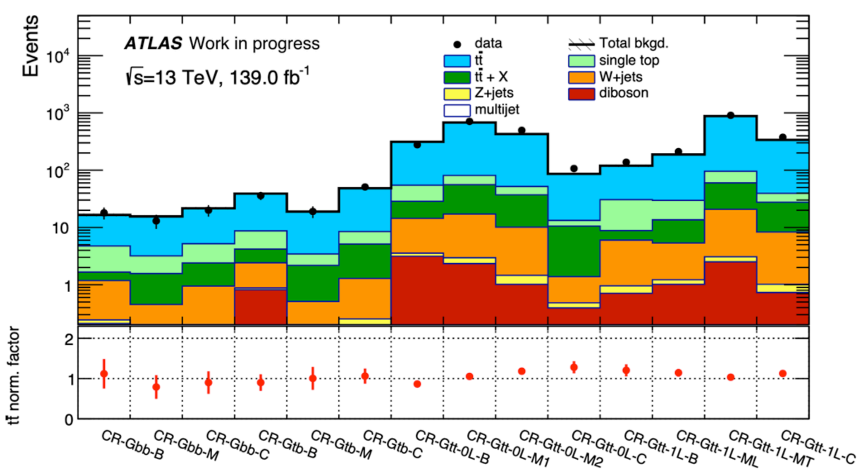


- Systematic uncertainties included in the Fit:
  - **systematics on objects**: jet energy scale JES (is scaled up and down by 1σ uncertainty), jet energy resolution JER (extra p_T smearing term added to jets for possible underestimation energy resolution), uncertainty on b-tagging efficiency
  - **theory** uncertainties (**not included yet**): systematic comparisons with alternatively-produced samples
    - radiation, parton shower and hadronization, Matrix element generator
    - combine in quadrature for each region

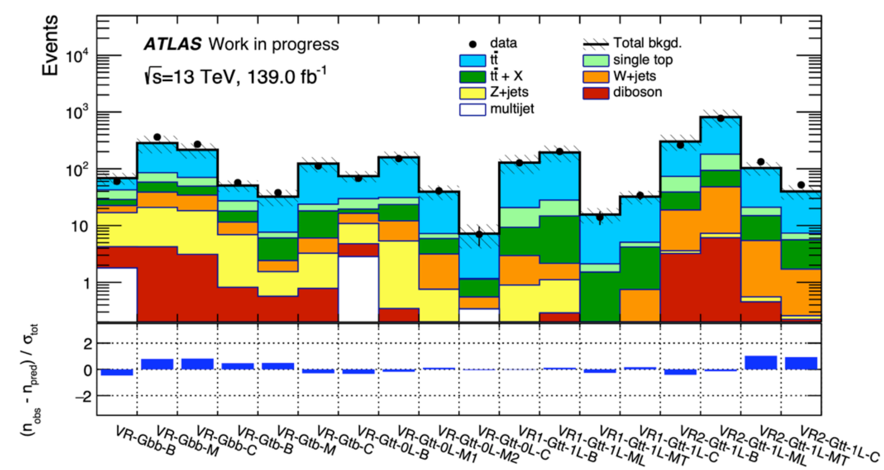
Background-only fit

- background-only-fit results for 139 fb^{-1} data in control (left) and validation (right) regions. No large excess observed in all validation regions
- Background-only-fit: only the control region is used to constrain the fit parameters
- Dominant background is ttbar. Subdominant in 0L are $Z(\rightarrow \nu\nu)$+jets and $W(\rightarrow \nu l)$+jets and in 1L are single-top and top-EW events
- Next step is to **add theory systematic into fit**, and make Data/MC sanity checks

Control regions



Validation regions

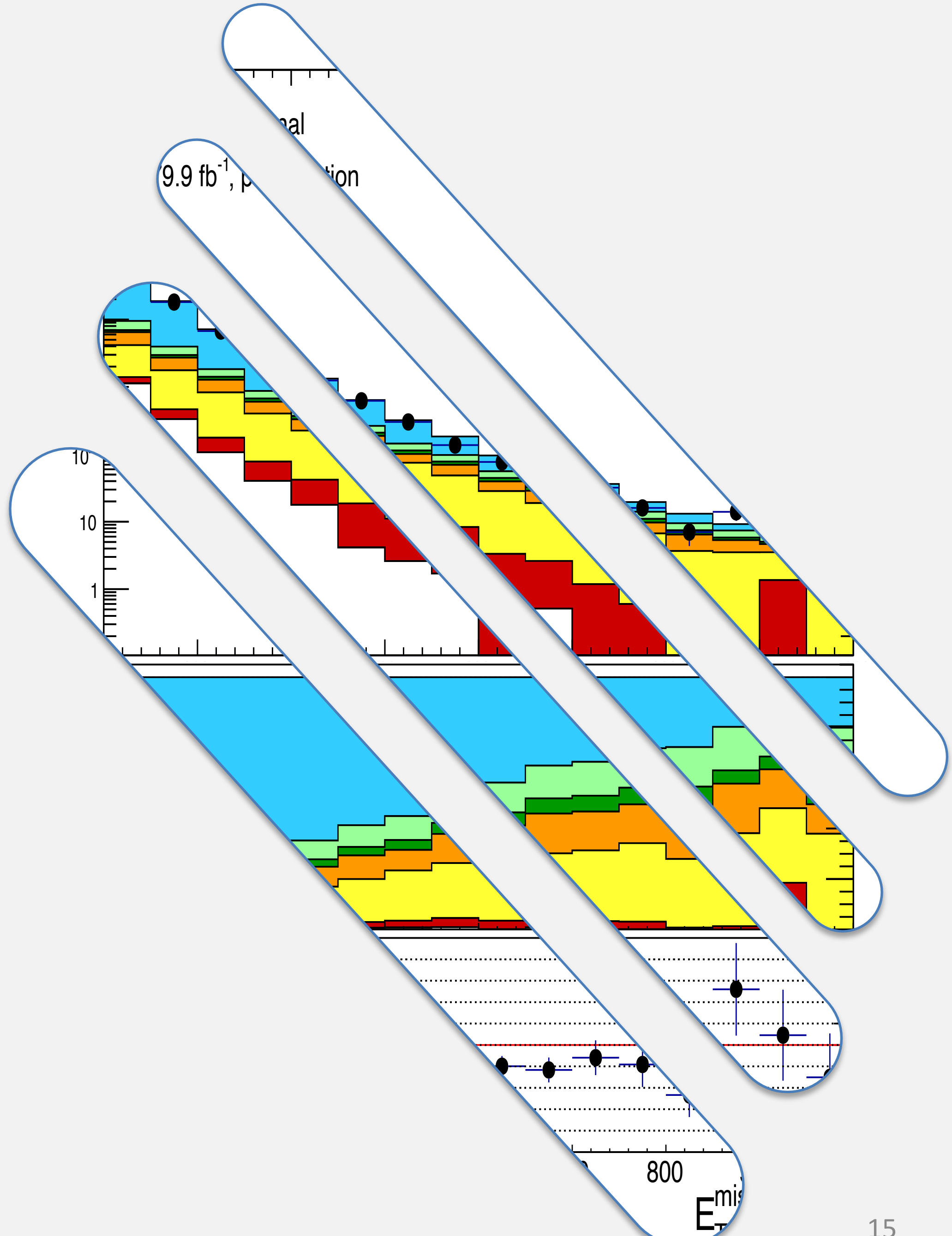


Summary & Next Steps

- In general strong multi-b analysis is in good shape:
  - QCD estimation and 2D re-weighting strategy finalized. Good agreement at preselection level
  - all regions (Control-Validation-Signal) are updated now for 139 fb^{-1} analysis with maximum significance
  - derived background-only fit results in all regions (no huge excess observed)
  - theory systematic for ttbar and singletop are evaluated

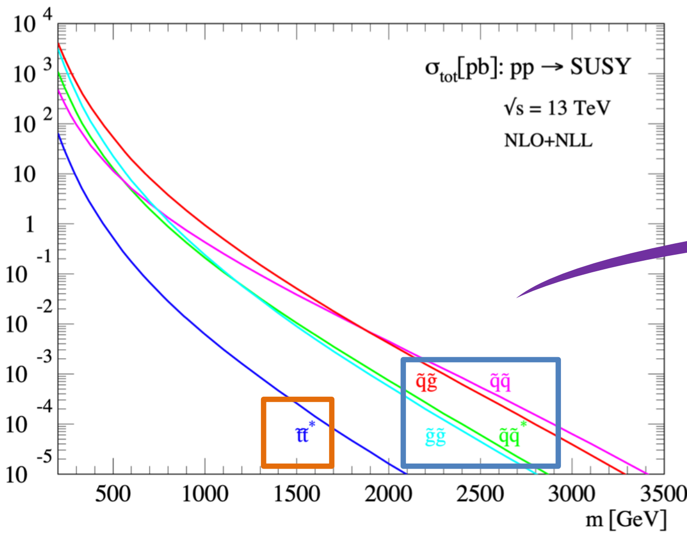
- Next steps toward the unblinding:
  - need to derive theory systematic for other backgrounds like W/Z+jets
  - Fit results should be updated by including all systematics. Then we are good to go for unblinding the analysis and extrapolate data into signal regions
  - After unblinding, performing model dependent-exclusion fit would be the last step

Backup



Supersymmetry with ATLAS

arXiv: 1407.5066[hep-ph]



Classify SUSY searches based on:

- Production cross-section (strong)
- Final states after decays (strong)
- Decay chain (3rd gen + EW)
- Lifetime (long-lived)
- R-parity conserving/violating (RPV - RPC)

- Simplified models
- LSP: $\tilde{\chi}_1^0$ or $\tilde{G}$ or …
- Frequently main backgrounds: $t\bar{t}$ & single top, W+jets, Z+jets, and multijets
- Discriminating variables: p_T of objects, number of leptons, number of jets, scalar sum of p_T (e.g. m_{eff}^{incl}), m_T, m_{T2}

List of Multi b-jets MC Samples

- The samples are from the MC16a and MC16d production campaign of ATLAS-PMG

	Process	Generator + fragmentation/hadronization	Tune	PDF set	Cross-section order
	Gbb/Gtb/Gtt	MadGraph5_aMC@NLO-2.2.2 + Pythia v8.186	A14	CTEQ6L1	NLO+NLL
New	$t\bar{t}$	Powheg-Box v2 + Pythia-8.230	A14	NNPDF3.0	NNLO+NNLL [47]
	Single top	Powheg-Box v1 or v2 + Pythia-6.428 or -8.230	PERUGIA2012	CT10	NNLO+NNLL [48–50]
	$t\bar{t}W/t\bar{t}Z$	MadGraph5_aMC@NLO-2.2.2 + Pythia-8.186	A14	NNPDF2.3	NLO [51]
	4-tops	MadGraph-2.2.2 + Pythia-8.186	A14	NNPDF2.3	NLO [51]
	$t\bar{t}h$	MadGraph5_aMC@NLO-2.2.1 + Herwig++-2.7.1	UEEE5	CT10	NLO [52]
	Dibosons WW, WZ, ZZ	Sherpa-2.2.1	Default	NNPDF3.0	NLO
New	W/Z**+jets**	Sherpa-2.2.1	Default	NNPDF3.0	NNLO [53]

Triggers + Object Definition

Triggers

- E_T^{miss} trigger:

2015 HLT_xe70
2016 HLT_xe90_mht_L1XE50, HLT_xe100_mht_L1XE5, HLT_xe110_mht_L1XE50
2017 HLT_xe110_pufit_L1XE55
2018 HLT_xe110_pufit_xe65_L1XE55

Electrons

- baseline $\rightarrow p_T > 20$ GeV , $|\eta| < 2.47$, LooseLHBlayer
- signal $\rightarrow$ MediumLLH, $\left|\frac{d_0}{\sigma(d_0)}\right| < 5$, LooseTrackOnly isolation, $|Z_0 \sin\theta| < 0.5$

Muons

- baseline $\rightarrow p_T > 20$ GeV , $|\eta| < 2.5$, Medium
- signal $\rightarrow \left|\frac{d_0}{\sigma(d_0)}\right| < 3$, LooseTrackOnly isolation, $|Z_0 \sin\theta| < 0.5$ mm

Jets

- baseline $\rightarrow p_T > 20$ GeV , **anti-k$_T$** jets (R=0.4), Calibrated: EM+JES+GSC $|\eta| < 2.8$, JVT cut for $p_T < 50$ GeV (Medium WP)
- signal $\rightarrow p_T > 30$ GeV
- b-tagging: **MV2c10-tagger** algorithm trained by ttbar sample with 15% c-jets, OP= 77% (FixedCutBEff_77)

MET

- Track-based soft term **(TST)** definition with Tight WP

➢ baseline object-definition in SUSYTools

➢ our SUSYTools config-file here

Definition of Key Variables

$\Delta\phi_{\min}^{4j}$ to suppress multijets in which E_T^{miss} is aligned with one jet:

$$\Delta\phi_{\min}^{4j} = \min(|\phi_1 - \phi_{E_T^{miss}}|, \dots, |\phi_4 - \phi_{E_T^{miss}}|)$$

Inclusive effective mass, to select highly energetic events:

$$m_{eff}^{incl} = \Sigma_{i \le n}\, p_T^{j_i} + \Sigma_{j \le m}\, p_T^{lep_j} + E_T^{miss}$$

m_T to remove semileptonic $t\bar{t}$ and W+jets events (region ≥ 1 lepton) :

$$m_T = \sqrt{2 p_T^l E_T^{miss} (1 - \cos\Delta\phi(\vec{p}_T^{miss}, \vec{p}_T^{l}))}$$

$m_{T,min}^{b-jets}$ min transverse mass between E_T^{miss} and three leading b-jets:

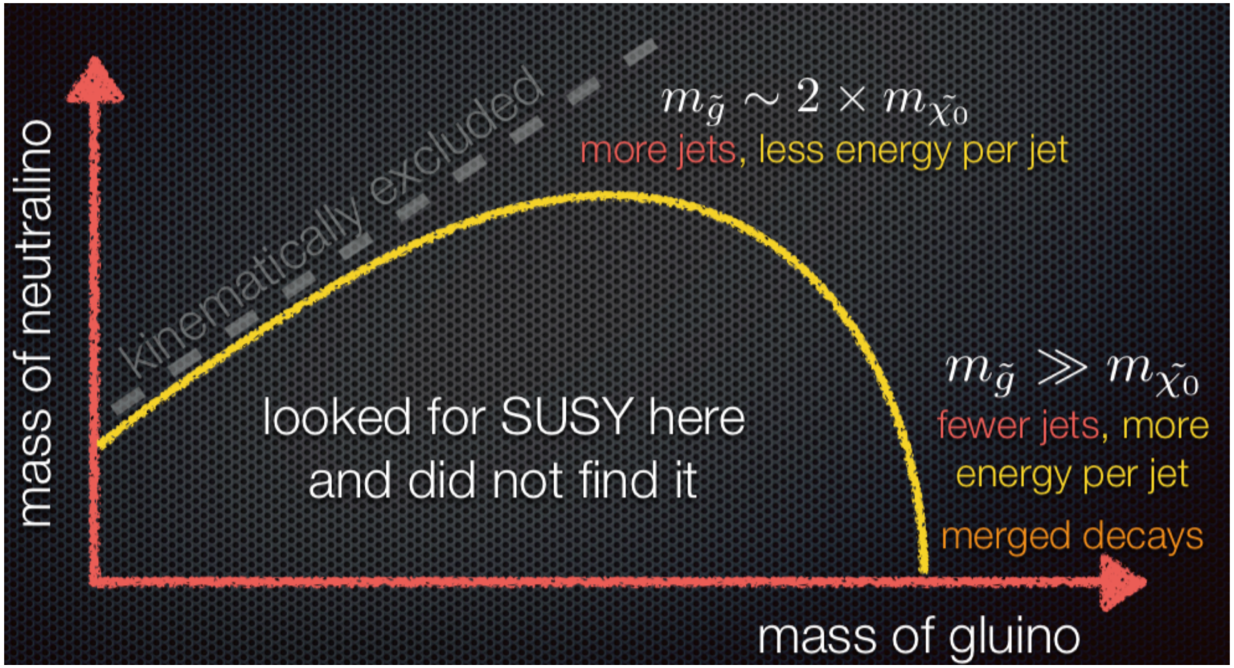
$$m_{T,min}^{b-jets} = \min_{i \le 3}(\sqrt{2 p_T^{b-jet_i} E_T^{miss} \left(1 - \cos\Delta\phi\left(\vec{p}_T^{miss}, \vec{p}_T^{b-jet_i}\right)\right)})$$

$M_J^{\Sigma,4}$ sum of the mass of re-clustered jets (higher for Gtt signal):

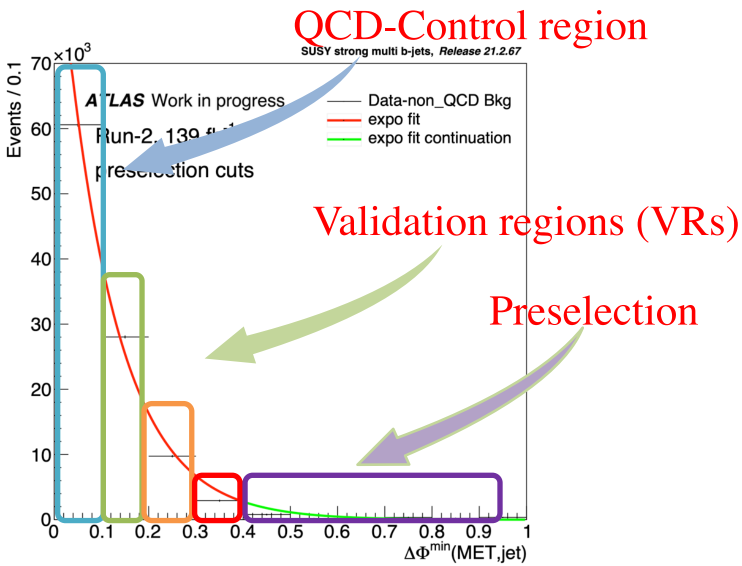
$$M_J^{\Sigma,4} = \Sigma_{i \le 4} m_{J,i}$$

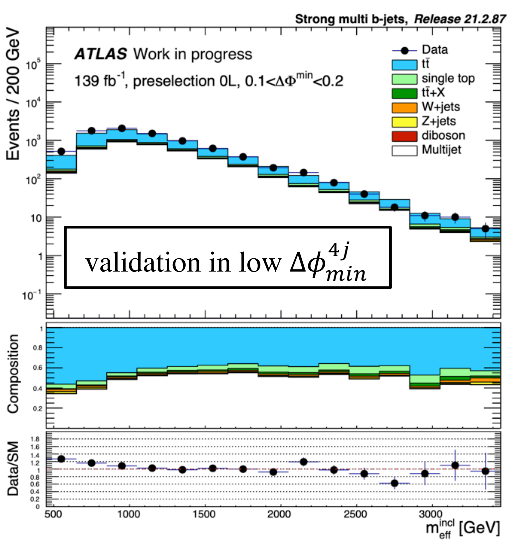
Parameterizing the Model

- **Boosted** region with large mass splitting between gluino and neutralino ($\Delta m \gtrsim 1.7$ TeV) possibly leading to **highly boosted objects** in final state.
  - Jets at high Lorentz boost (merged decays – close together and less reconstructed)
  - Lower number of jets is expected due to merging
- **Compact** region ($\Delta m \lesssim 400$ GeV) targeting events with more jet multiplicity and less energy per jet.



QCD data-driven estimation in 0L

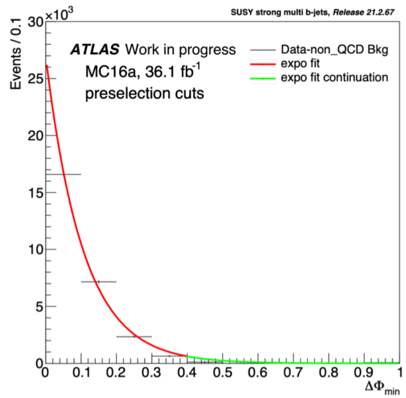


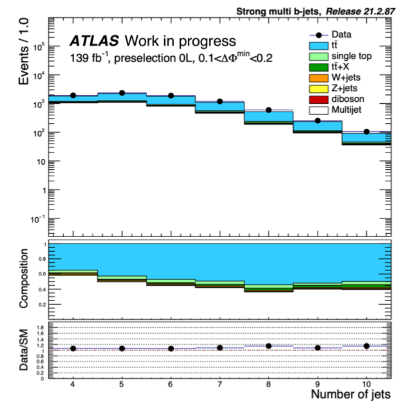


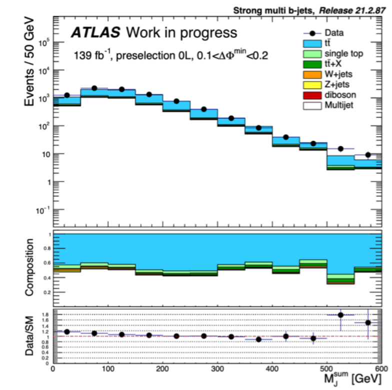
- In each 0L region, consider an equivalent selection with $\Delta\phi_{min}^{4j}$ modified from > 0.4 to < 0.1
- QCD in modified region = data - MC
- Scale by $\Delta\phi_{min}^{4j}$ norm to derive QCD prediction in the actual analysis region
- $\Delta\phi_{min}^{4j}$ norm derived with an **exponential fit to data-MC distribution** of $\Delta\phi_{min}^{4j}$ at preselection
- Validated in 0.1< $\Delta\phi_{min}^{4j}$ <0.2 where QCD is dominant. More validation plots in backup

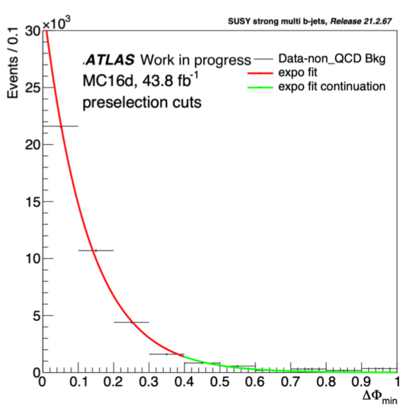
QCD Validation Plots

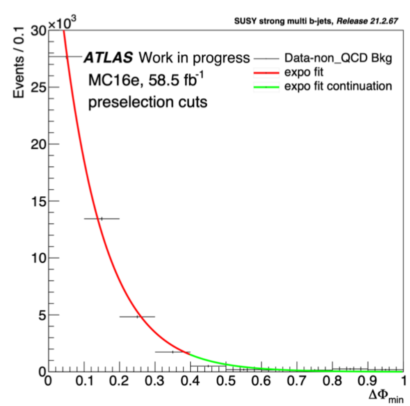
- Exponential fit for different data taking years (left) MC16a-d-e and more validation plots in low $\Delta\phi^{4j}_{min}$ slice (right):

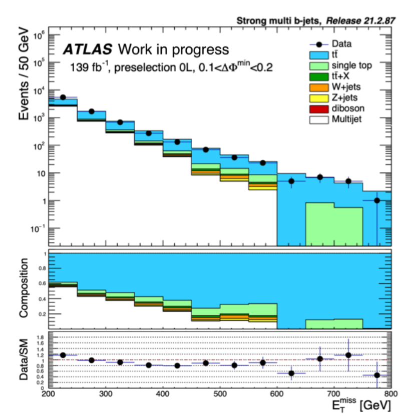


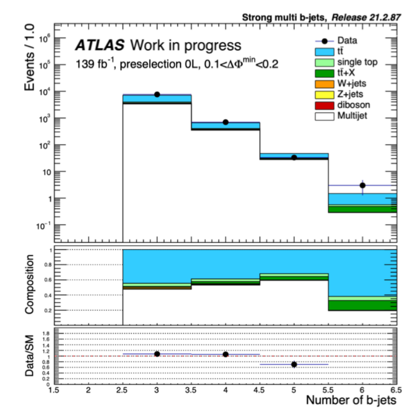








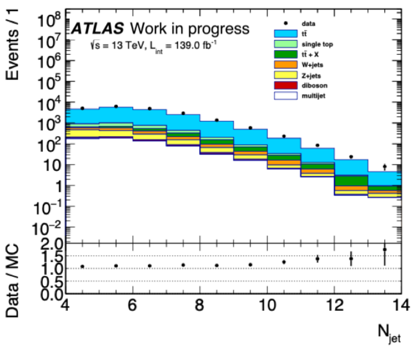


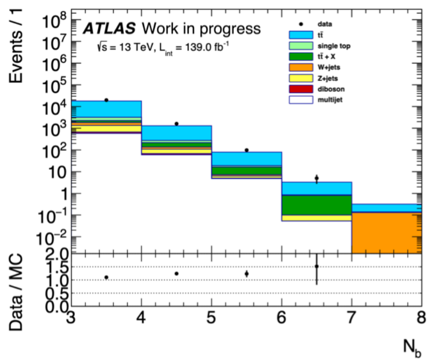


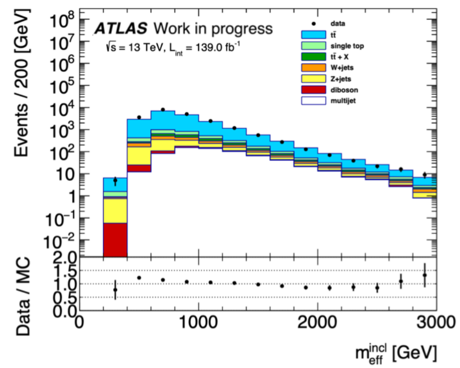
Data-MC Comparison at Preseletion

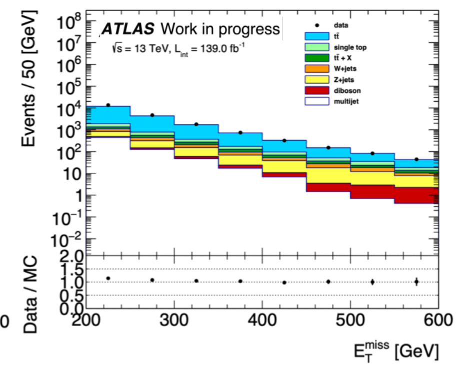
- Preselection: E_T^{miss} trigger, $E_T^{miss} > 200$ GeV, $N_{jet} \geq 4$, $N_{bjet} \geq 3$, if 0L $\Delta\phi_{min}^{4j} > 0.4$
- All 1Lepton region plots are after reweighting

0L

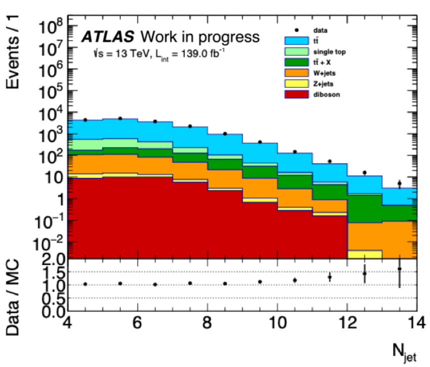


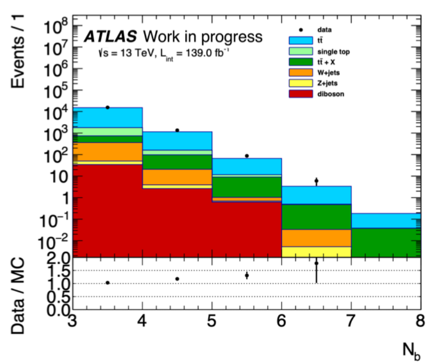


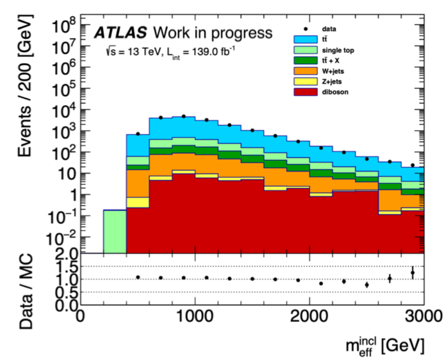


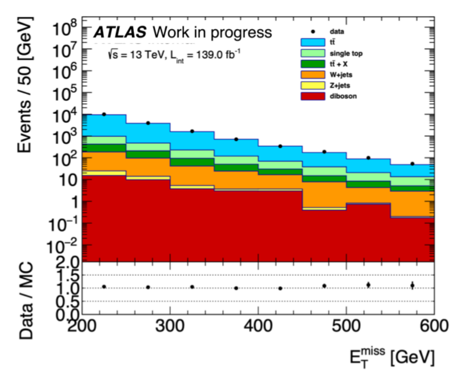


1L









Re-weighting Strategy

- The goal is after reweighting events, data and MC would be the same in each bin of m_{eff}^{incl} . Four equations with 4 unknown parameters (weights) in each bin of m_{eff}^{incl}:

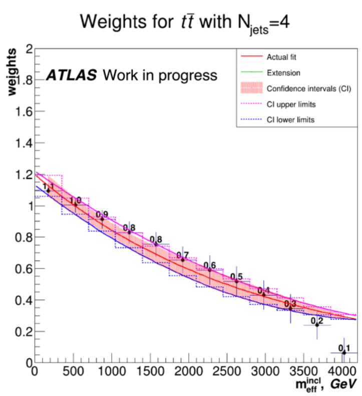
$$w_{t\bar{t}}N_1^{t\bar{t}} + w_{st}N_1^{st} + w_{wj}N_1^{wj} + w_{zj}N_1^{zj} = d_1$$
$$w_{t\bar{t}}N_2^{t\bar{t}} + w_{st}N_2^{st} + w_{wj}N_2^{wj} + w_{zj}N_2^{zj} = d_2$$
$$w_{t\bar{t}}N_3^{t\bar{t}} + w_{st}N_3^{st} + w_{wj}N_3^{wj} + w_{zj}N_3^{zj} = d_3$$
$$w_{t\bar{t}}N_4^{t\bar{t}} + w_{st}N_4^{st} + w_{wj}N_4^{wj} + w_{zj}N_4^{zj} = d_4$$

Divide both side by total MC_i in that bin (f)

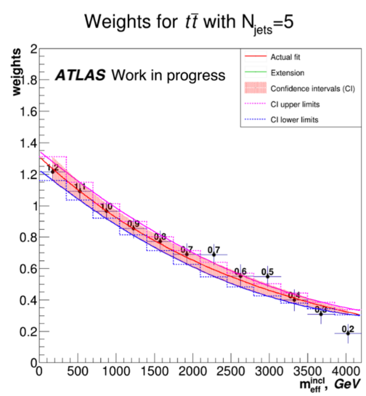
$$w_{t\bar{t}}f_1^{t\bar{t}} + w_{st}f_1^{st} + w_{wj}f_1^{wj} + w_{zj}f_1^{zj} = R_1 = d_1/mc_1$$
$$w_{t\bar{t}}f_2^{t\bar{t}} + w_{st}f_2^{st} + w_{wj}f_2^{wj} + w_{zj}f_2^{zj} = R_2 = d_2/mc_2$$
$$w_{t\bar{t}}f_3^{t\bar{t}} + w_{st}f_3^{st} + w_{wj}f_3^{wj} + w_{zj}f_3^{zj} = R_3 = d_3/mc_3$$
$$w_{t\bar{t}}f_4^{t\bar{t}} + w_{st}f_4^{st} + w_{wj}f_4^{wj} + w_{zj}f_4^{zj} = R_4 = d_4/mc_4$$

Re-weighting Functions

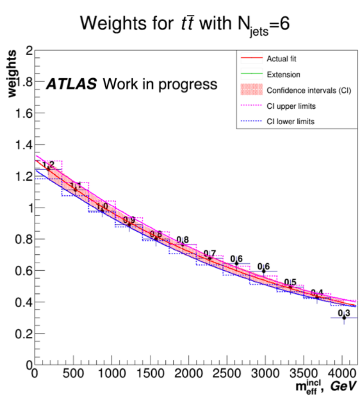
- Re-weighting functions for ttbar and W+jets in different N(jets) slices:



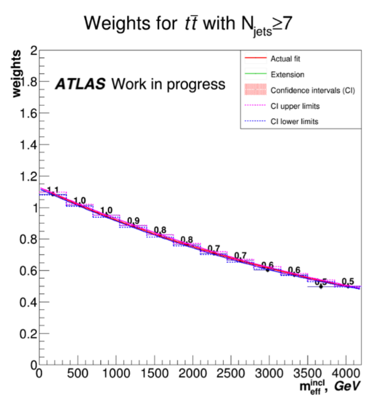
(a)



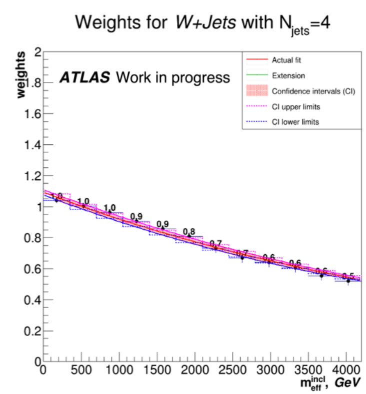
(b)



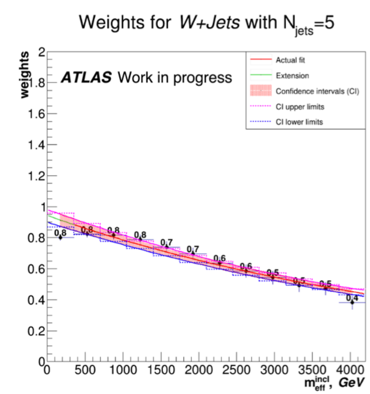
(c)



(d)



(a)



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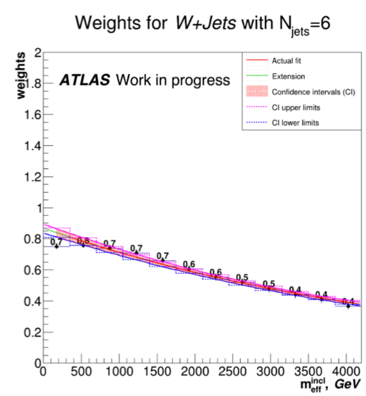
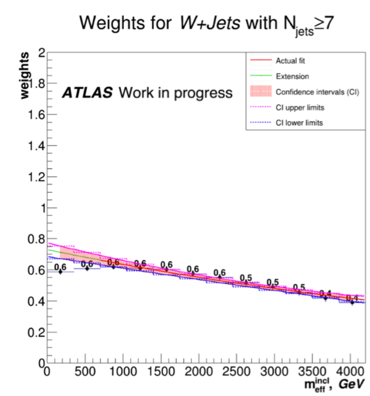


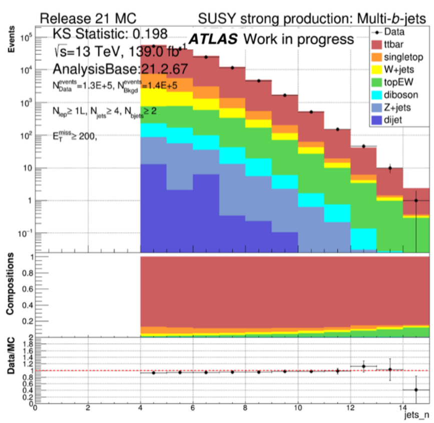
(c)



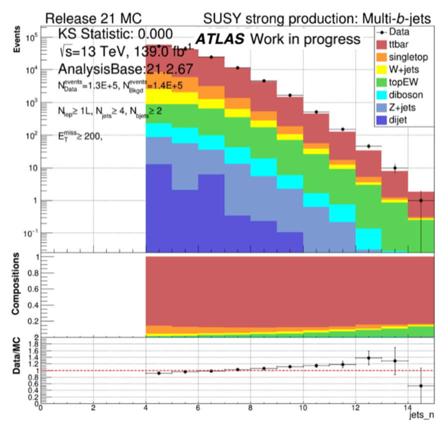
(d)

Re-weighting affects N_{jets}

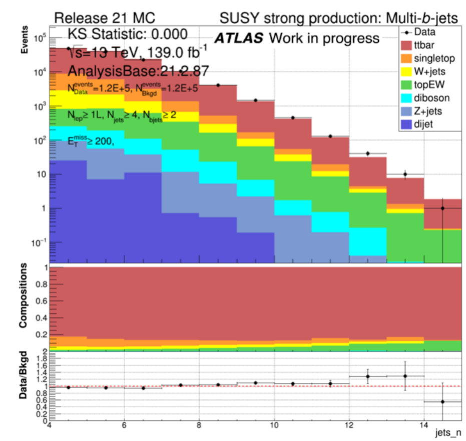
before RW



after 1D RW



after 2D RW



- N(jets) distribution before 1D meff reweighting (left) and after 1D meff reweighting (middle) and after 2D meff-N (jets) reweighting (right).
- Fix N(jets) and make reweighing within one bin of the distribution

Systematic Variations in Re-weighting

- Uncertainties on $Data_i$ and $Bkgd_i$ are known, thus on $Data_i/Bkgd_i$ too.
- To get uncertainties on weights, run pseudo-experiments:
  - Set $func = p_0 * exp\left(-\frac{1}{2}\left(\frac{x-p_1}{p_2}\right)^2\right)$ with
    - $p_1 = mean$ i.e. $Data_i/Bkgd_i$
    - $p_2 = \sigma$ i.e. uncertainty on $Data_i/Bkgd_i$
    - And $p_0 = 1/(2\pi\sigma)$.
  - Solve matrix equation with $Data_i/Bkgd_i = func \rightarrow GetRandom()$ N times.
  - Fit resulting arrays of weights value (N values for each w^i) with gaussian.
  - And extract corresponding $p_1 = mean$ and $p_2 = \sigma$ for weights.

- Solved 12 matrices (for each bin in m_{eff}^{incl} [0,4200]). Plot the results and fit with an Expo.

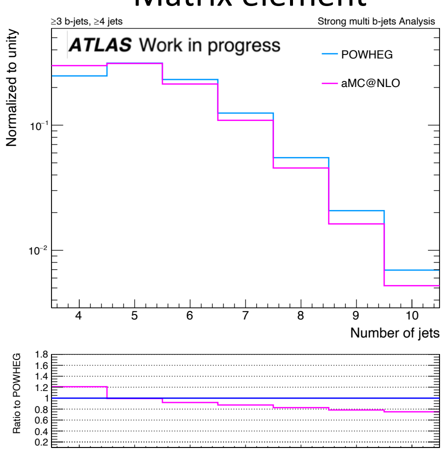
Plan for Theory systematics

- SUSY recipe for modeling uncertainties, closely following Physics Modeling Group's recommendations. modeling uncertainties can be evaluated at TRUTH or Reconstruction level:

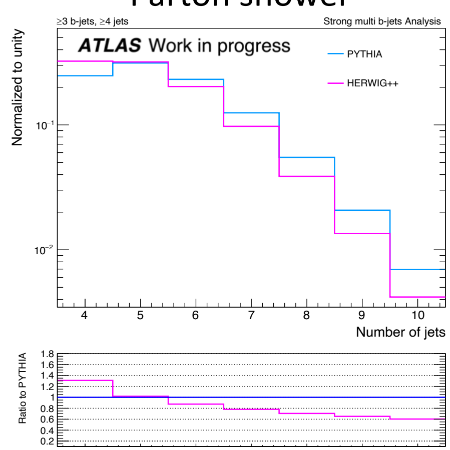
Hard-scatter	Compare Powheg+Pythia8 versus aMcAtNlo+Pythia8 (TRUTH samples)
Parton showering + Hadronization	Compare Powheg+Pythia8 versus Powheg+Herwig7 (TRUTH samples)
Radiation High/Low	Use internal weights of nominal samples. Weights include variation in renormalization/factorization scales (α_R, α_F) and tune parameters
Interference	Quantum interference between LO ttbar and NLO singletop (Wt channel). Dedicated *WWbb* samples are generated to evaluate this systematic

Generator comparison

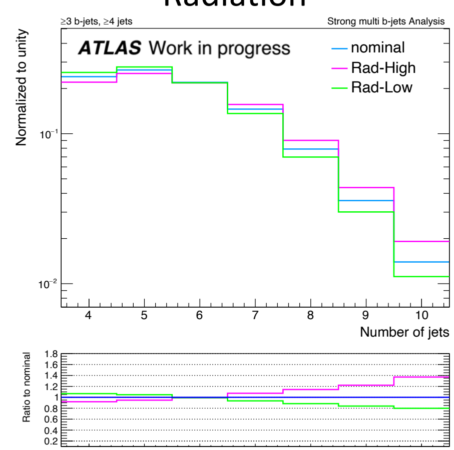
Matrix element



Parton shower



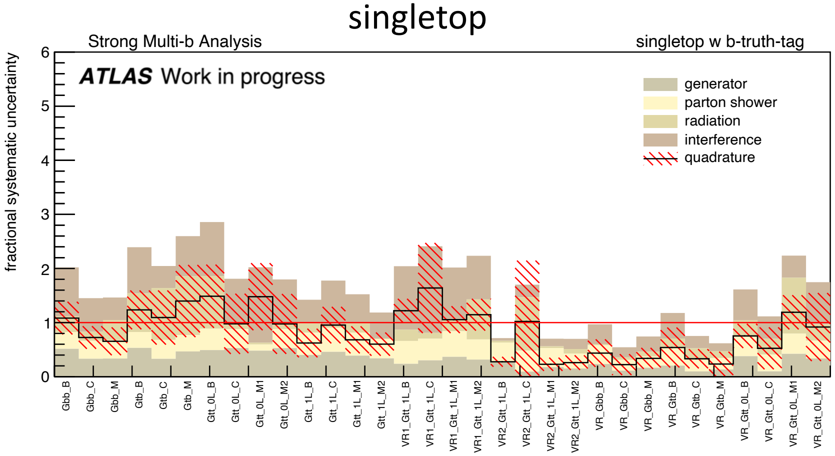
Radiation



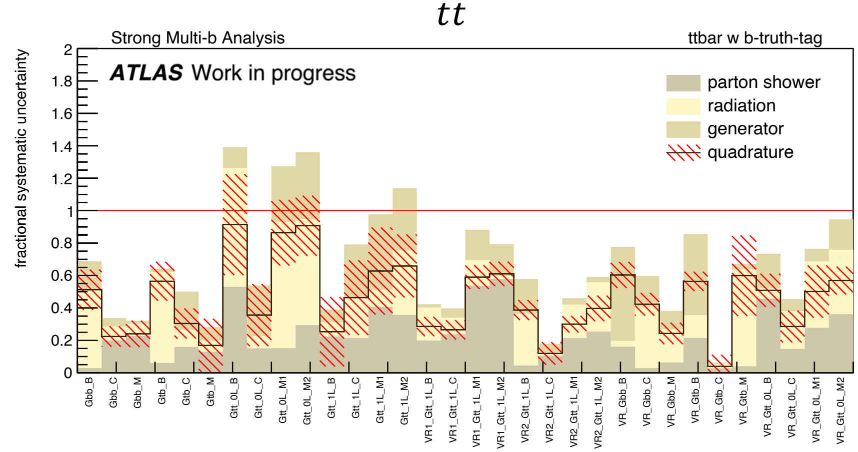
Theory systematics for ttbar and singletop

- Each component of the uncertainty is shown as stacked and the sum in **quadrature** is overlaid in black. The statistical uncertainty of the quadrature is shaded red
- With truth *b*-tagging, there is no more cut on $N_{b\text{-jets}}$, instead all events are kept weighted. The weight is the probability that, out of all selected jets in the event, a certain number pass the *b*-tagging identification
- truth *b*-tagging leads to reduced uncertainties in most regions. The statistical uncertainty (shaded) is also smaller with TRF, which means more accurate prediction of the uncertainty is expected
- Using the same method to evaluate theory systematic for singletop. **Having less statistics** in systematic samples makes it more challenging (need to relax some of the cuts to gain stats)

singletop



$t\bar{t}$



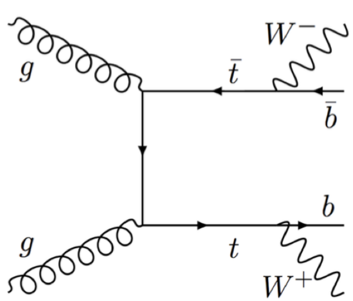
singletop modeling uncertainties (I)

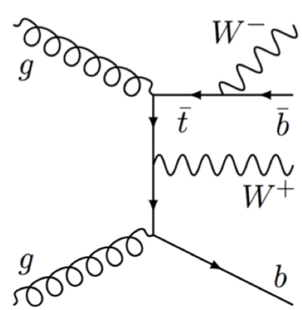
For the singletop background, the following variations can be considered:

Hard-scatter	Compare Powheg+Pythia8 versus aMcAtNlo+Pythia8
Parton showering	Compare Powheg+Pythia8 versus Powheg+Herwig7
Radiation UP/Down	Use internal weights of nominal samples (like ttbar)
Wt interference	DR-vs-DS comparison may not be ideal. Instead, dedicated interference samples (LO WWbb) can be used (twiki)

- Three possible singletop production channels are: s-chan, t-chan, and Wt chan. The **LO ttbar** (double resonance) diagram and **NLO singletop** diagram (single resonance) can have same final state particles which causes interference.

double resonance
LO ttbar



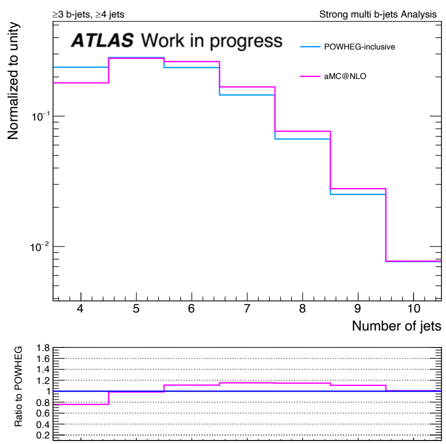


single resonance
NLO singletop

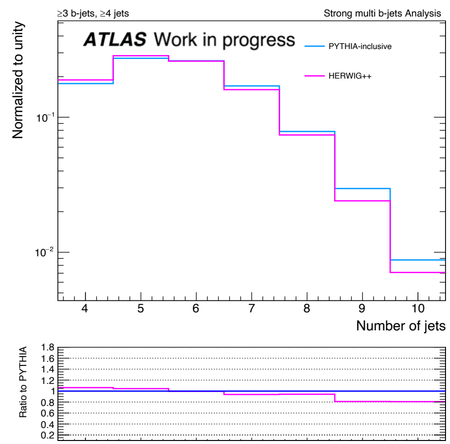
singletop modeling uncertainties (II)

- For interreference: 1 - (sum - double-resonant) / single-resonant (=1 - (WWbb - ttbar) / Wtb)

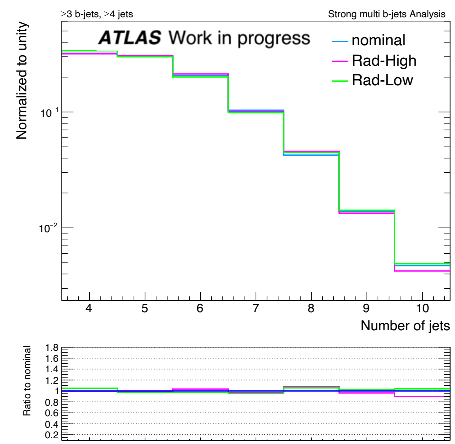
Matrix element



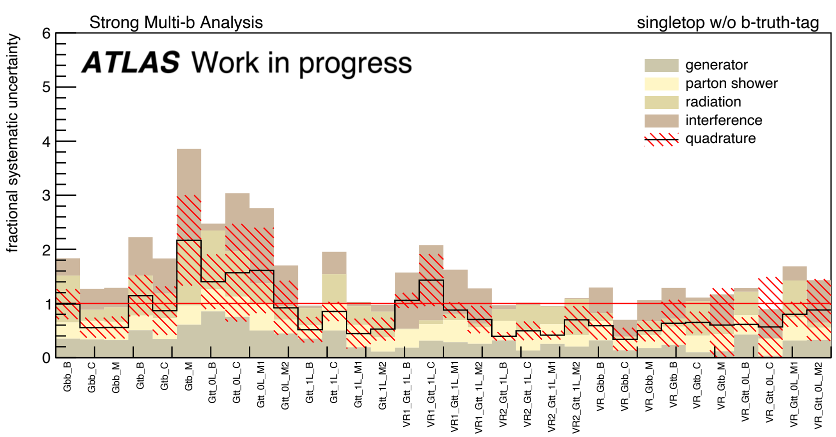
Parton shower



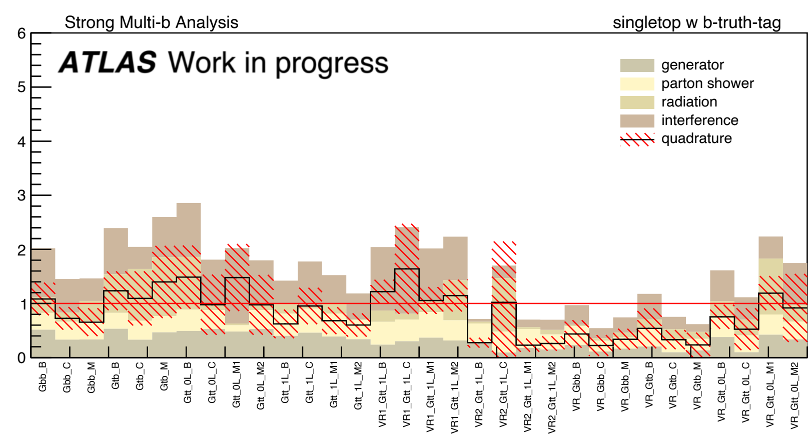
Radiation



w/o TRF



w TRF



Radiation systematic

- In this update **Radiation** uncertainty has been added:

1. **2-sided radiation systematic:** $\frac{|TF_{up} - TF_{down}|}{|TF_{up} + TF_{down}|} * 2$

2. **PMG weights:** CutBookKeeper contains all the pmg weight and we can use ->getWeight(weight_name) to retrieve the weight value

```
const xAOD::CutBookkeeperContainer* completeCBC(nullptr);
ANA_CHECK(m_event->retrieveMetaInput(completeCBC, "CutBookkeepers"));
for (const auto& cbk: *completeCBC) {
     std::string name_meta = cbk->name();
     std::cout << ”weight Name: " << name_meta << std::endl;
  }
```

3. **Input ttbar SUSY10:** all campaigns of DAOD_SUSY10 ttbar samples used for radiation
4. **Extension to NN:** if NN variables are defined in Treemaker.cxx we can easily make the plots for NN regions. Otherwise we can start making NN variables in bigTuple

Gtt 1Lepton Regions

Table 4: Definitions of the Gtt 1-lepton SRs, CRs and VRs of the cut-and-count analysis. All kinematic variables are expressed in GeV except $\Delta\phi^{4j}_{min}$, which is in radians. The jet p_T requirement is also applied to b-tagged jets.

Gtt 1-lepton

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

Targeted kinematics	Type	N_{jet}	E_T^{miss}	m_{eff}^{incl}	m_T	$m_{T,min}^{b-jets}$	$M_J^{\Sigma,4}$
Region B (Boosted, Large Δm)	SR	≥ 4	≥ 600	≥ 2300	≥ 150	≥ 120	≥ 200
	CR	$= 4$	≥ 200	≥ 1500	< 150	–	–
	VR-m_T	≥ 4	≥ 200	≥ 1500	≥ 150	< 120	–
	VR-$m_{T,min}^{b-jets}$	> 4	≥ 200	≥ 1200	< 150	≥ 120	< 200
Region M (Moderate-1 Δm)	SR	≥ 5	≥ 600	≥ 2000	≥ 200	≥ 120	≥ 200
	CR	$= 5$	≥ 200	≥ 1200	< 200	–	–
	VR-m_T	≥ 5	≥ 200	≥ 1200	≥ 200	< 120	< 200
	VR-$m_{T,min}^{b-jets}$	> 5	≥ 200	≥ 1000	< 200	≥ 120	≥ 100
Region M (Moderate-2 Δm)	SR	≥ 8	≥ 500	≥ 1100	≥ 200	≥ 120	≥ 100
	CR	$= 8$	≥ 200	≥ 800	< 200	–	–
	VR-m_T	≥ 8	≥ 200	≥ 800	≥ 200	< 120	< 100
	VR-$m_{T,min}^{b-jets}$	> 8	≥ 200	≥ 800	< 200	≥ 120	≥ 100
Region C (Compressed, small Δm)	SR	≥ 9	≥ 300	≥ 800	≥ 150	≥ 120	–
	CR	$= 9$	≥ 200	≥ 800	< 150	–	–
	VR-m_T	≥ 9	≥ 200	≥ 800	≥ 150	< 120	–
	VR-$m_{T,min}^{b-jets}$	> 9	≥ 200	≥ 800	< 150	≥ 120	–

tighter cuts (like m_{eff}) for boosted region

reverse cut on m_T for orthogonality

validates background in high m_T region

validates background in high $m^b_{T,min}$ region

Gtt 0Lepton Regions

Table 3: Definitions of the Gtt 0-lepton SRs, CRs and VRs of the cut-and-count analysis. All kinematic variables are expressed in GeV except $\Delta\phi^{4j}_{\text{min}}$, which is in radians. The jet p_T requirement is also applied to b-tagged jets.

Gtt 0-lepton

Criteria common to all regions: $p_T^{\text{jet}} > 30$ GeV

Targeted kinematics	Type	N_{lepton}	N_{jet}	$\text{N}^{\text{b-jet}}$	E_T^{miss}	$\Delta\phi^{4j}_{\text{min}}$	$\text{m}_{\text{eff}}^{\text{incl}}$	m_T	$\text{m}_{\text{T,min}}^{b\text{-jets}}$	$M_J^{\Sigma,4}$
Region B (Boosted, Large Δm)	SR	$= 0$	≥ 5	≥ 3	≥ 600	≥ 0.4	≥ 2900	–	≥ 120	≥ 300
	CR	$= 1$	≥ 4	≥ 3	≥ 200	–	≥ 2000	< 200	–	≥ 150
	VR	$= 0$	≥ 5	≥ 3	≥ 250	≥ 0.4	≥ 2000	–	–	< 300
Region M (Moderate-1 Δm)	SR	$= 0$	≥ 9	≥ 3	≥ 600	≥ 0.4	≥ 1700	–	≥ 120	≥ 300
	CR	$= 1$	≥ 8	≥ 3	≥ 200	–	≥ 1100	< 150	–	≥ 150
	VR	$= 0$	≥ 9	≥ 3	≥ 300	≥ 0.4	≥ 1400	–	–	< 300
Region M (Moderate-2 Δm)	SR	$= 0$	≥ 10	≥ 3	≥ 500	≥ 0.4	≥ 1100	–	≥ 120	≥ 200
	CR	$= 1$	≥ 9	≥ 3	≥ 200	–	≥ 800	< 150	–	≥ 100
	VR	$= 0$	≥ 10	≥ 3	≥ 300	≥ 0.4	≥ 800	–	–	< 200
Region C (Compressed, moderate Δm)	SR	$= 0$	≥ 10	≥ 4	≥ 400	≥ 0.4	≥ 800	–	≥ 180	≥ 100
	CR	$= 1$	≥ 9	≥ 4	≥ 200	–	≥ 800	< 150	–	≥ 100
	VR	$= 0$	≥ 10	≥ 4	≥ 200	≥ 0.4	≥ 800	–	–	< 100

Gbb Regions

Table 5: Definitions of the Gbb SRs, CRs and VRs of the cut-and-count analysis. All kinematic variables are expressed in GeV except $\Delta\phi^{4j}_{\mathrm{min}}$, which is in radians. The jet p_{T} requirement is also applied to b-tagged jets.

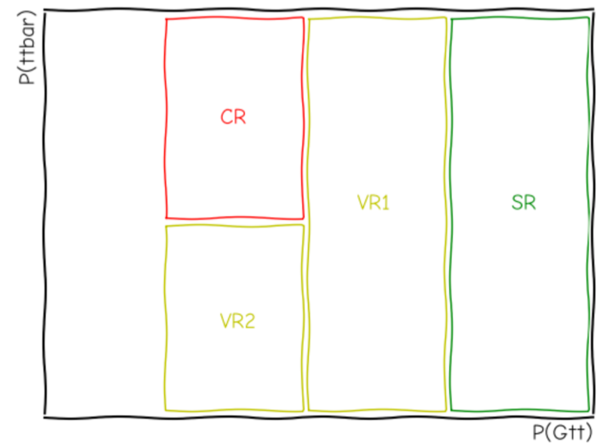
Gbb

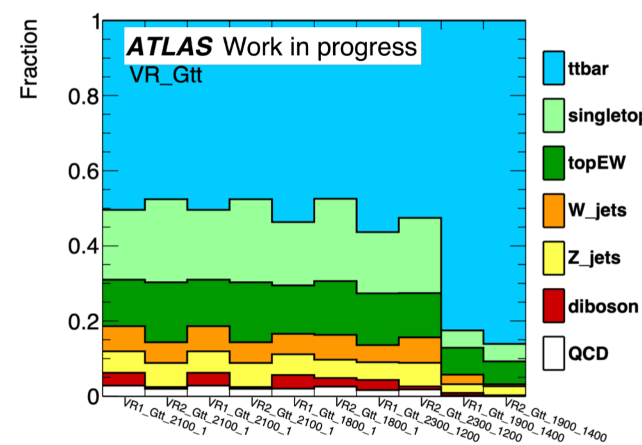
Criteria common to all regions: $N_{\mathrm{jet}} > 3$, $\mathrm{N}^{\mathrm{b-jet}} > 2$, $\Delta\phi^{4j}_{\mathrm{min}} > 0.4$

Targeted kinematics	Type	N_{lepton}	$p_{\mathrm{T}}{}^{\mathrm{jet}}$	$\mathrm{m}_{\mathrm{eff}}^{\mathrm{incl}}$	$E_{\mathrm{T}}^{\mathrm{miss}}$	$\mathrm{m}_{\mathrm{T,min}}^{b\mathrm{-jets}}$	mt
Region B (Boosted, Large Δm)	SR	$= 0$	> 65	> 2600	> 550	> 130	
	CR	$= 1$	> 65	> 2600	> 550		< 200
	VR	$= 0$	> 65	< 2400	> 550	> 130	
Region M (Moderate Δm)	SR	$= 0$	> 20	> 2000	> 550	> 130	
	CR	$= 1$	> 20	> 2000	> 400		< 250
	VR	$= 0$	> 20	> 1600	< 500	> 80	
Region C (Compressed, moderate Δm)	SR	$= 0$	> 20	> 1600	> 550	> 130	
	CR	$= 1$	> 20	> 1600	> 450		< 200
	VR	$= 0$	> 20	> 1500	< 450	> 130	

Neural Network Analysis

- NN is trained to distinguish Gtt and Gbb events from the Standard Model background
- NN **inputs**: so many objects 4-vectors like (p_T, η, ϕ, m) for 10 leading small-R, 4 large-R jets and 4 leptons
- NN is trained to **output** 8 probabilities: prob(Gtt, Gbb, ttbar, singletop, topEW, W/Z jets, diboson)
- Two VRs and one CR are defined for each SR with different slices on Prob(Gtt) and Prob(ttbar)
- For Gtt: additional cuts on m_{eff}, M_J^{sum} in CR/VR. These selections are added to keep kinematics similar in CR/VR and SR
- Pre-fit **composition plot** for Gtt VRs show high ttbar fraction. The same compostion is valid for Gtt-CRs
- Backup includes example of NN-output Data/MC plots. In general good agreement has been observed





NN Gtt Regions

Region	P(Gtt)	log10 P($t\bar{t}$)	m_{eff}	$M_J^{\Sigma,4}$
SR-Gtt-2100-1	$\geq$ 0.9998	-	-	-
VR1-Gtt-2100-1	$\in$ (0.85, 0.9998(	-	$\geq$ 1800	-
VR2-Gtt-2100-1	$\in$ (0.7, 0.85(	<-0.9	$\geq$ 1200	-
CR-Gtt-2100-1	$\in$ (0.7, 0.85(	$\geq$-0.9	$\geq$ 1200	-
SR-Gtt-1800-1	$\geq$ 0.9997	-	-	-
VR1-Gtt-1800-1	$\in$ (0.85, 0.9997(	-	$\geq$ 1600	-
VR2-Gtt-1800-1	$\in$ (0.76, 0.85(	<-1.0	$\geq$ 1200	-
CR-Gtt-1800-1	$\in$ (0.76, 0.85(	$\geq$-1.0	$\geq$ 1200	-
SR-Gtt-2300-1200	$\geq$ 0.9997	-	-	-
VR1-Gtt-2300-1200	$\in$ (0.81, 0.9997(	-	$\geq$ 1500	-
VR2-Gtt-2300-1200	$\in$ (0.74, 0.81(	<-1.0	$\geq$ 1200	-
CR-Gtt-2300-1200	$\in$ (0.74, 0.81(	$\geq$-1.0	$\geq$ 1200	-
SR-Gtt-1900-1400	$\geq$ 0.9996	-	-	-
VR1-Gtt-1900-1400	$\in$ (0.89, 0.9996(	-	$\geq$ 600	< 500
VR2-Gtt-1900-1400	$\in$ (0.87, 0.89(	<-1.6	$\geq$ 600	< 500
CR-Gtt-1900-1400	$\in$ (0.87, 0.89(	$\geq$-1.6	$\geq$ 600	< 500

Table 9: Gtt region definitions for the NN analysis

high P(Gtt) cut for signal regions

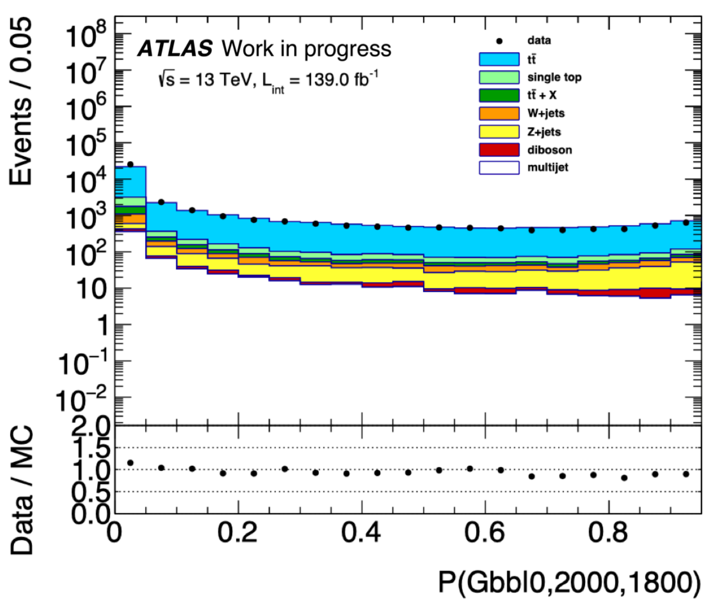
high/low P(ttbar) cut in CRs/VRs for orthogonality

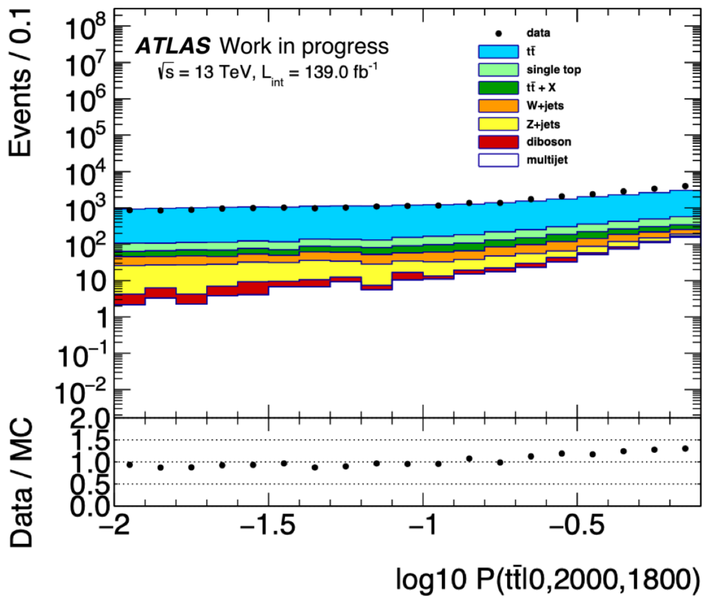
different P(Gtt) slices for SRs and VRs

cuts on m_{eff}, M_J^{sum} in CRs/VRs to keep kinematics similar to SR

NN-output Data/MC Comparison

- However, what really matters is agreement in the NN outputs





- $\approx$ good agreement

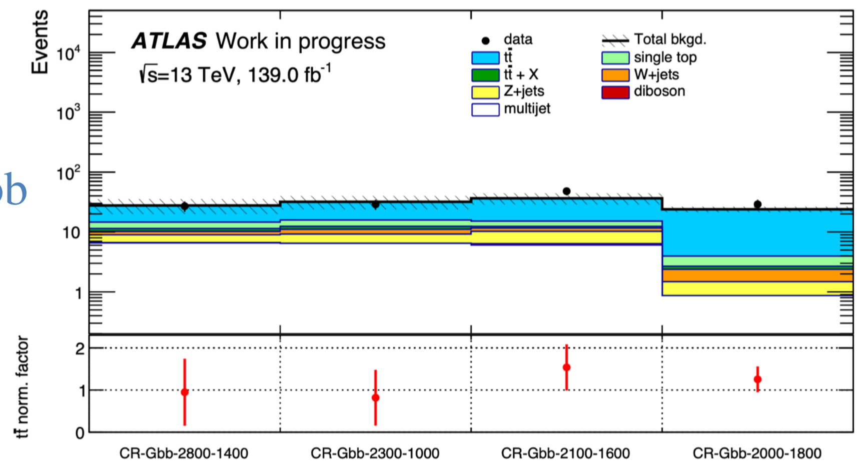
- Discrepancy at higher P(ttbar)
  - SR is high P(signal) $\rightarrow$ low P(ttbar)
  - If problem near SR: CR will take care of it

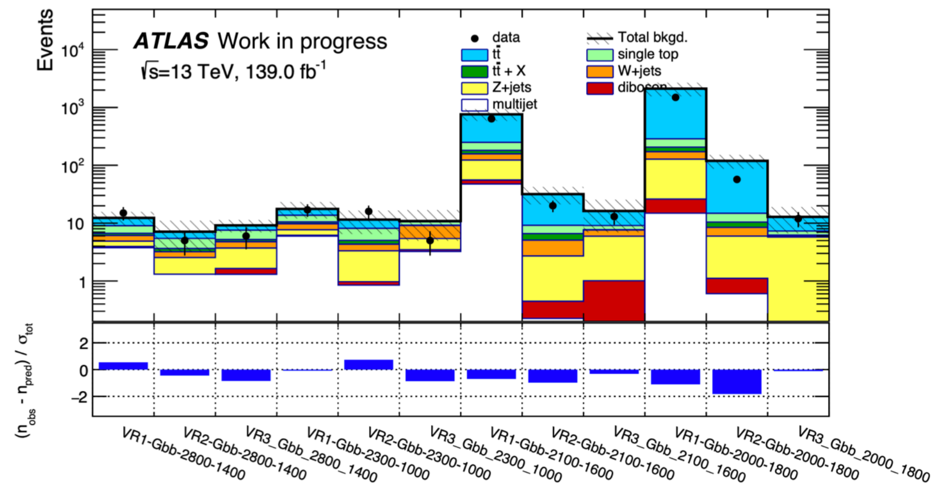
Background-only fit in NN

CRs

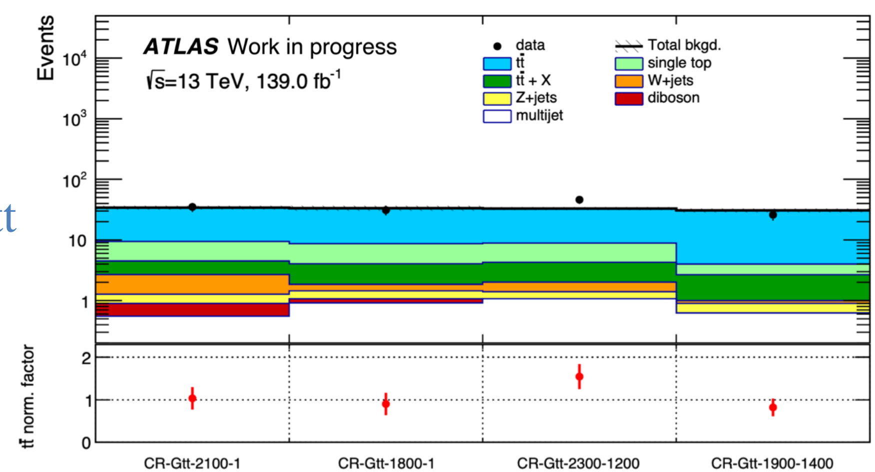
VRs

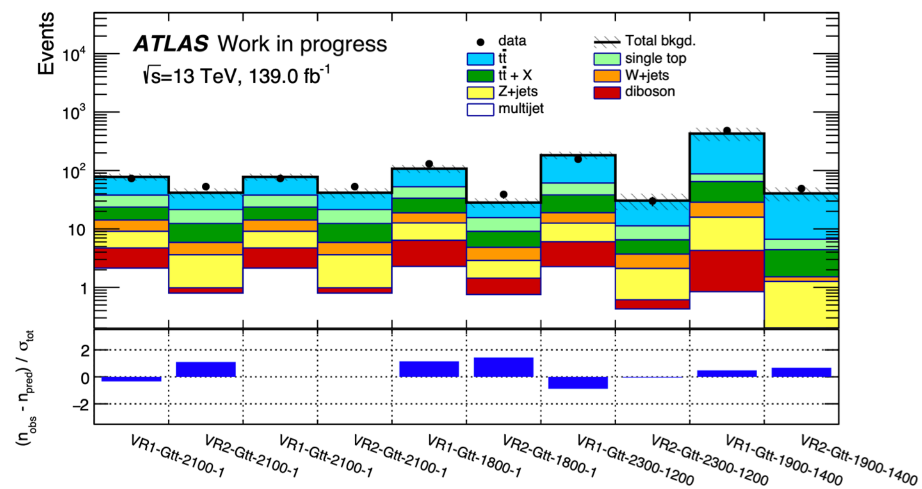
Gbb





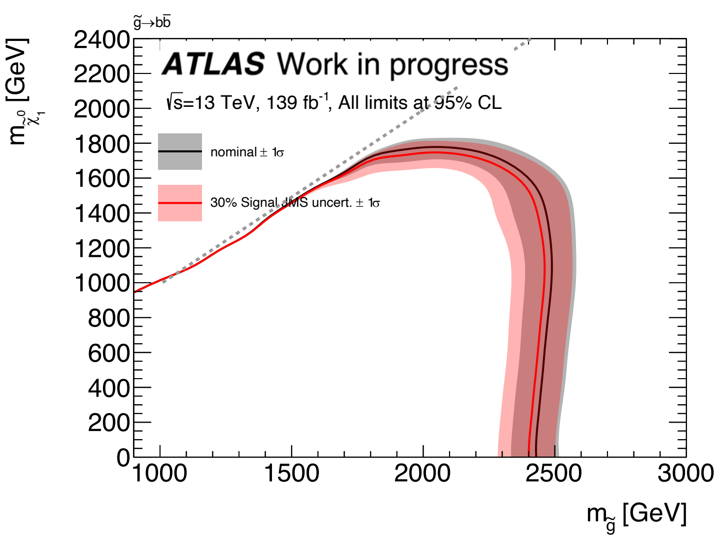
Gtt

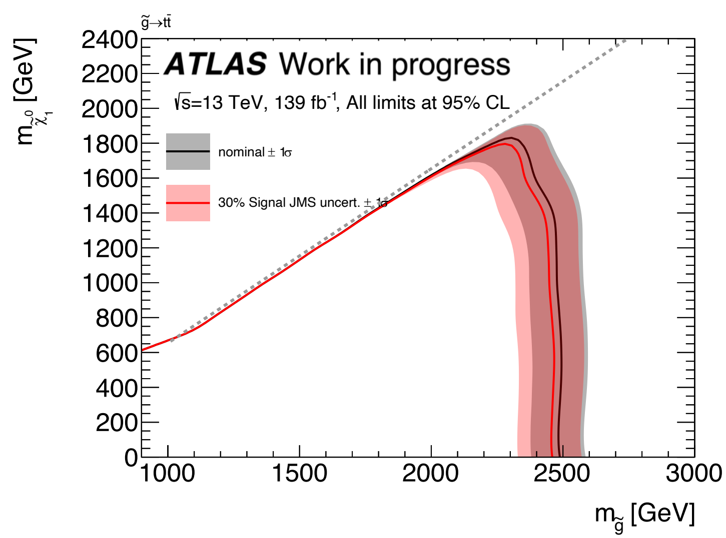




Jet Mass Scale Calibration Evaluation

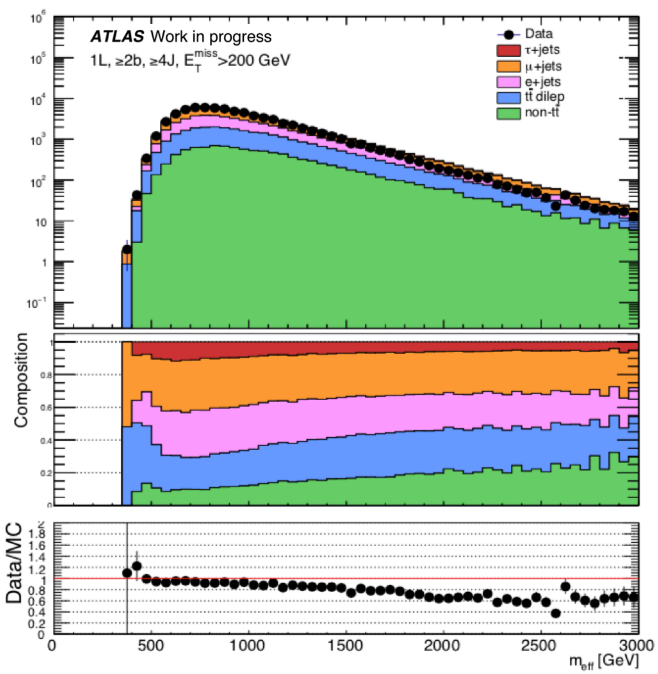
- JMS calibration **is applied to all FullSim** (background samples) and Data samples, but not AF2 which for us is all our signals
- Two Gtt points (2400,1 and 1800,400) requested in FullSim to assess the impact
- Using event-by-event weights to asses the effect on the signal yield is is the vicinity of 30%
- We have added a 30% preliminary syst. uncert to the signal yields and re-draw exclusion plots. Two plots below showing the effect on our limits for Gtt and Gbb
- Simply swapping the samples pushes the effect to the near 40%; we are currently discussing if this term should be included instead

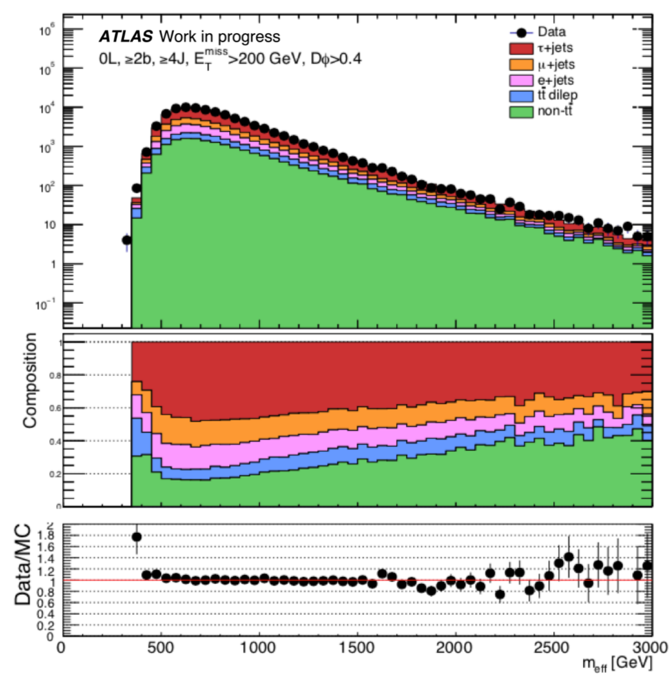




$t\bar{t}$ Composition Study

- Look at the truth composition of $t\bar{t}$ background based on its decay products:
  - 1L (left): dominated by semi-leptonic $t\bar{t}$ events
  - 0L (right): more than 60% of $t\bar{t}$ comes from tau+jets decays, very small fraction of dilepton





Model–dependent Limits (79 fb^{-1})

- Run hypothesis test over all grid points to set exclusion limits on various signal models.
- All the regions of multi-bin analysis are statistically combined to set model dependent upper limit on Gtt and Gbb.
- Gluinos with masses below 2.2 TeV are excluded at 95% CL for neutralino lower than 800 GeV.
- Best exclusion limits on the LSP mass are approximately 1.3/1.2 TeV, reached for gluino mass 1.8/2.1 TeV for Gbb/Gtt .

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