# ATLAS SUSY Results with $\geq 3$ $b$-jets

*USLUA 2016 LBNL*

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November 4, 2016

# Naturalness with SUSY

With the discovery of a 125 GeV Higgs, BSM physics is very well motivated!

Searches for (supersymmetric) top-partners are critical!

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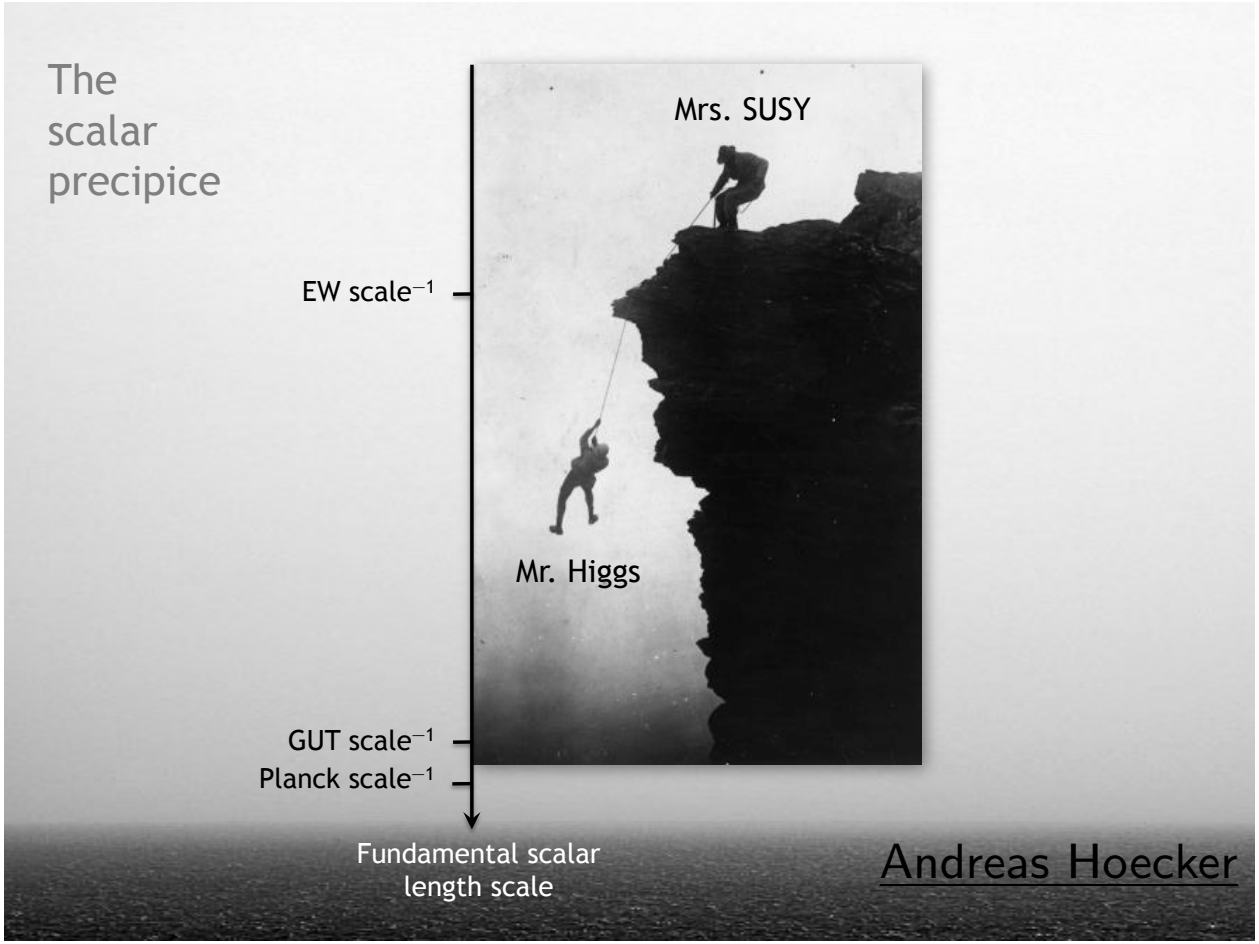


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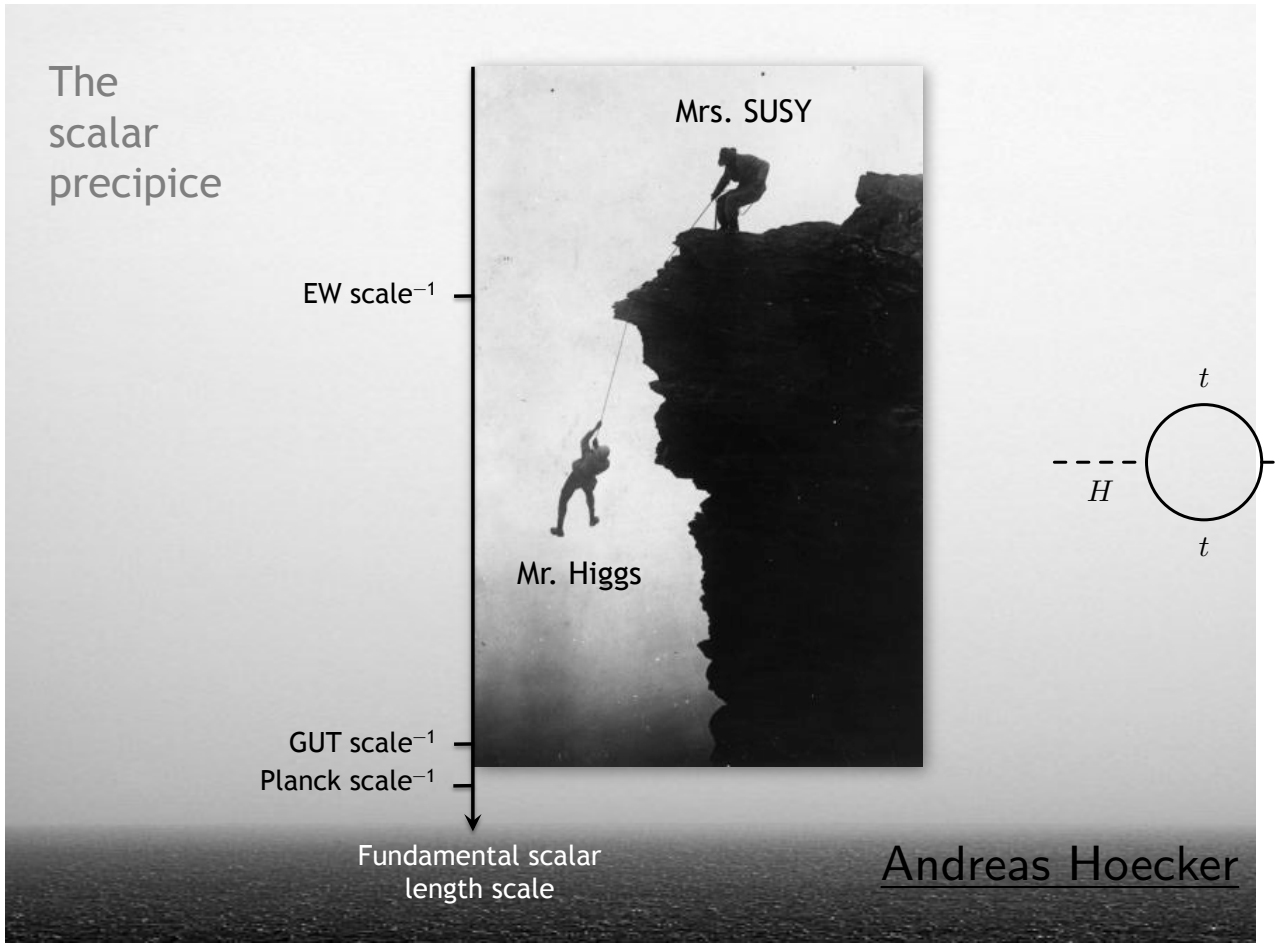


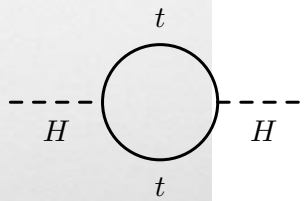


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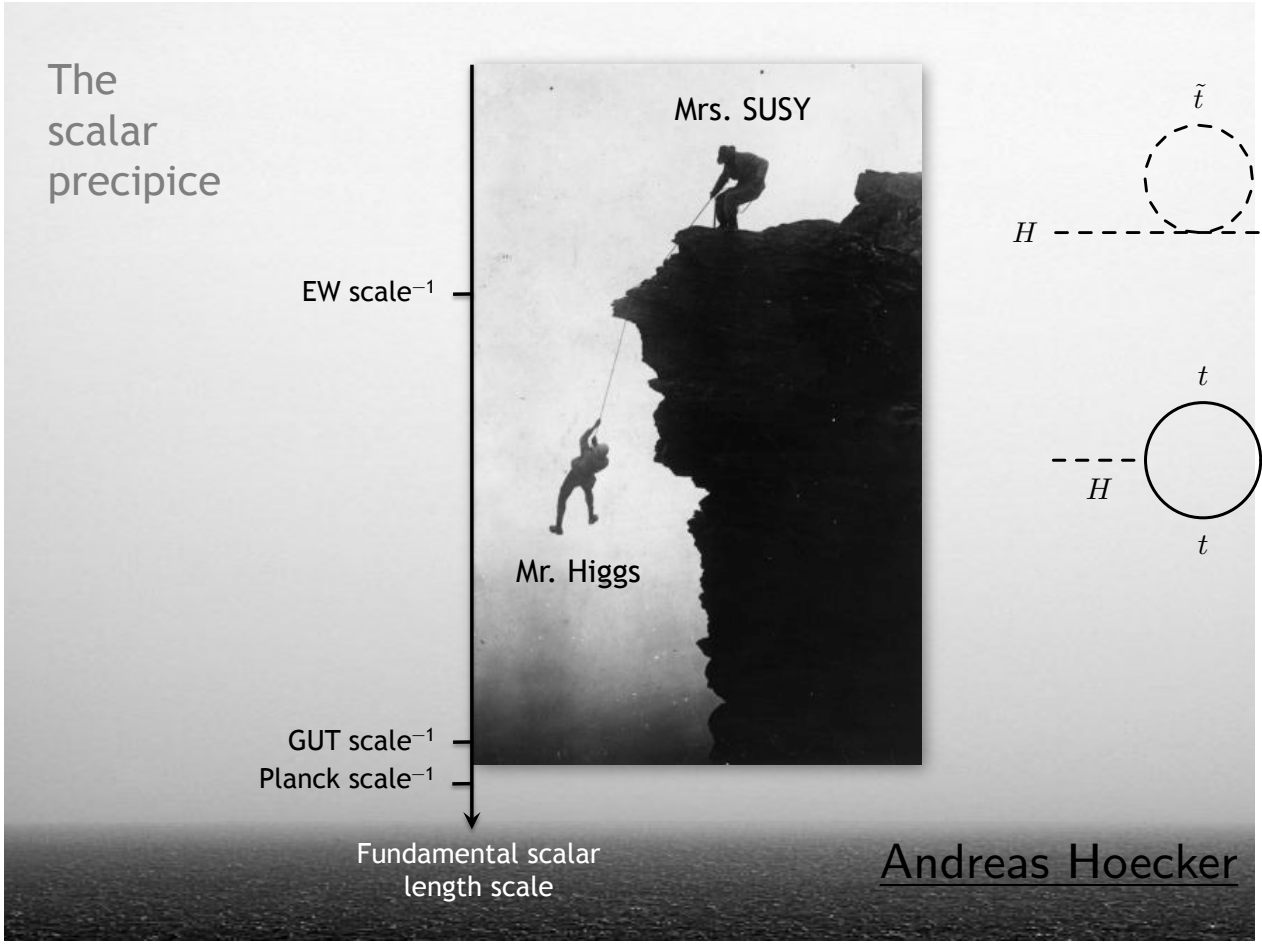


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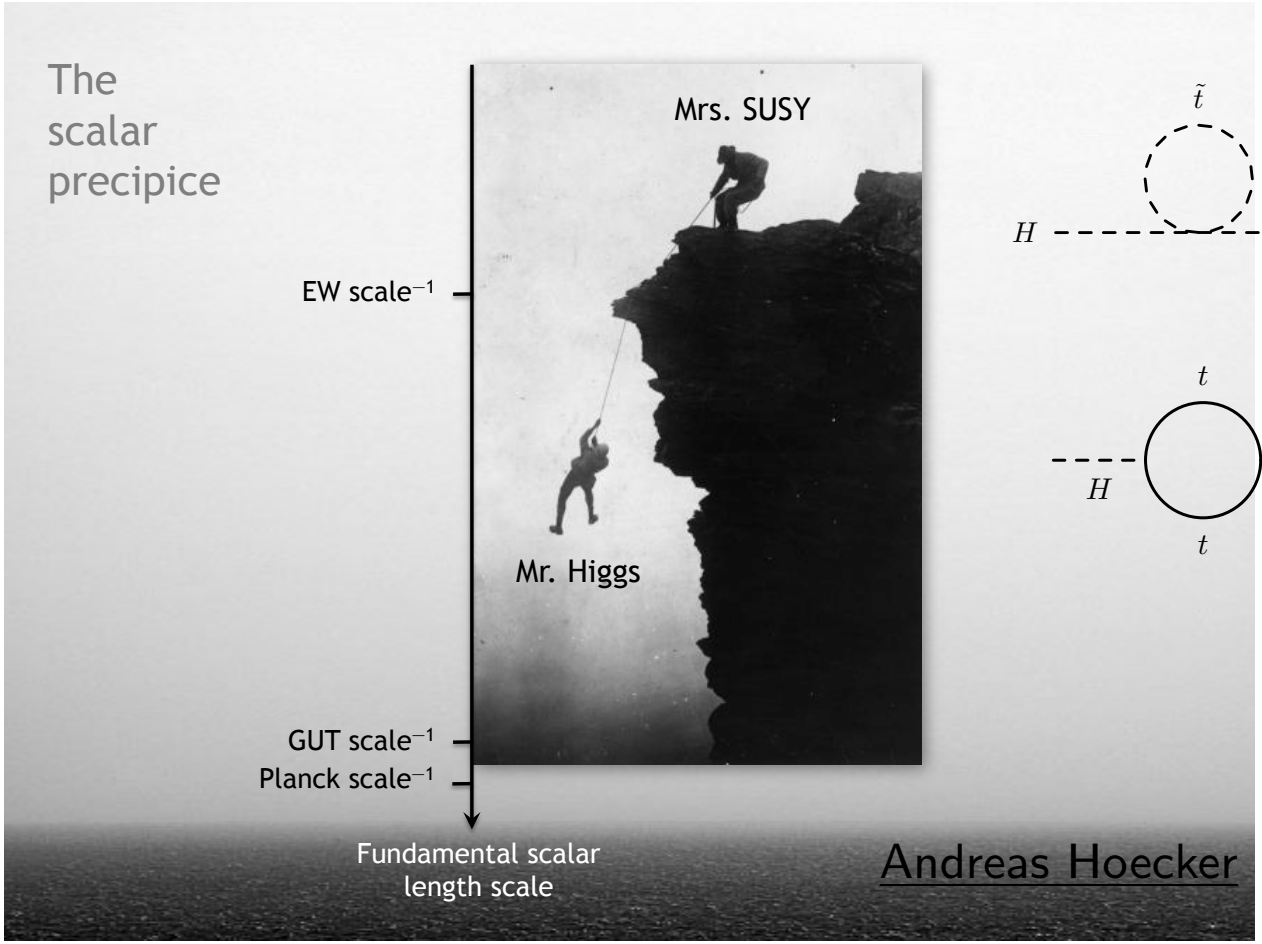


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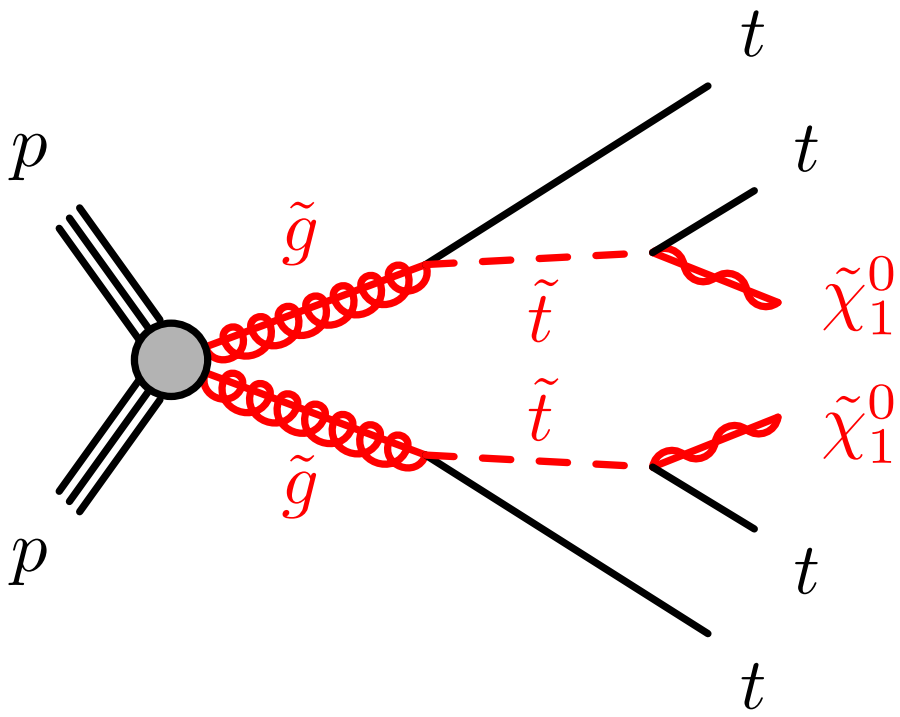
# Natural SUSY Signatures




- Look for pair-production of gluinos
  - Highest cross-section SUSY particles: production gateway to third-generation partners!
- Gluinos cascade decay to top quarks and neutralino
  - Non-interacting LSP appears as missing energy in the detector

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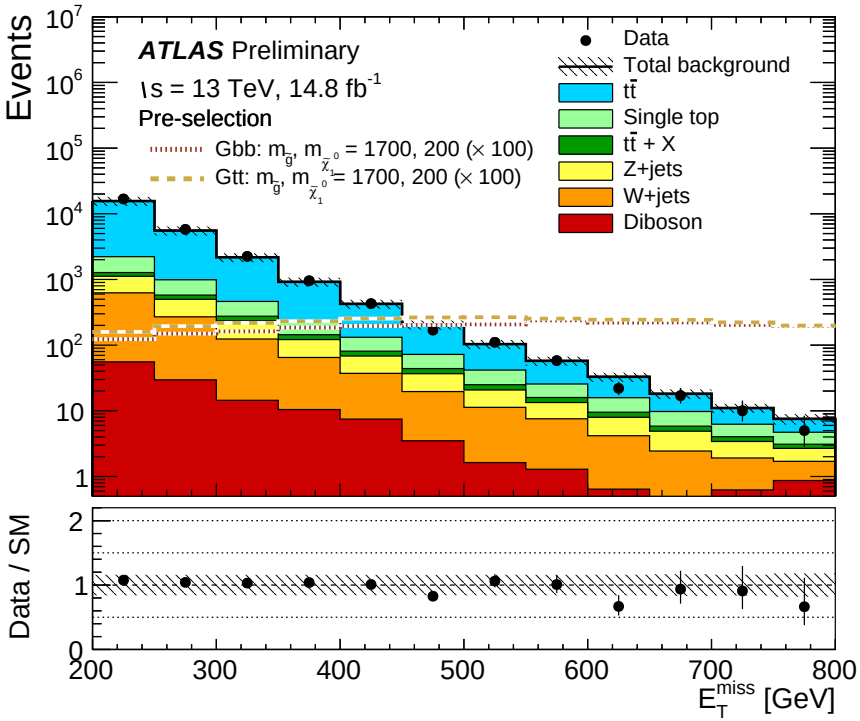
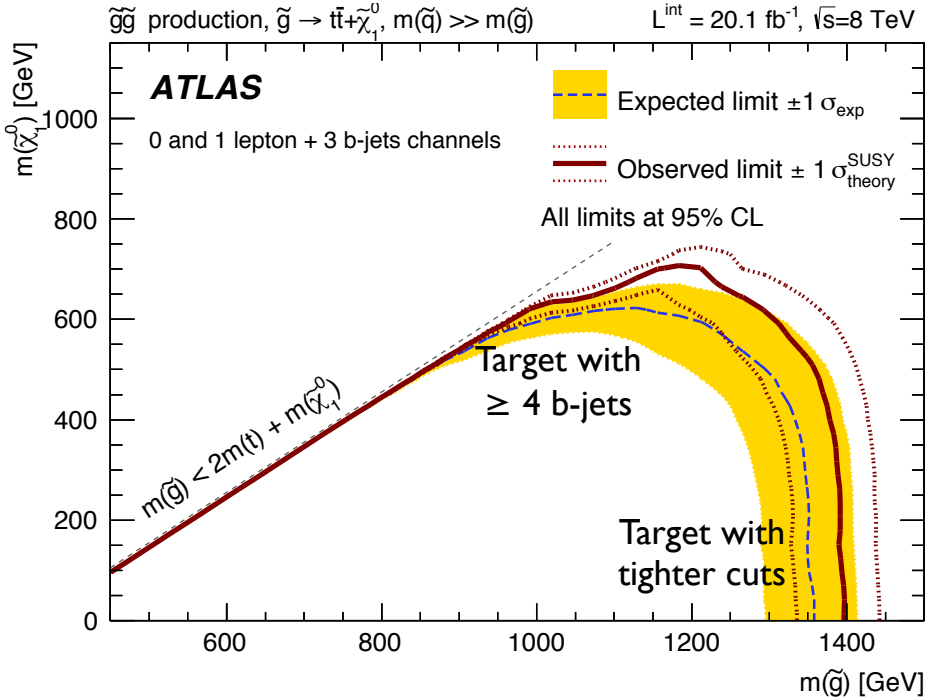
# Some Features of Signal Regions

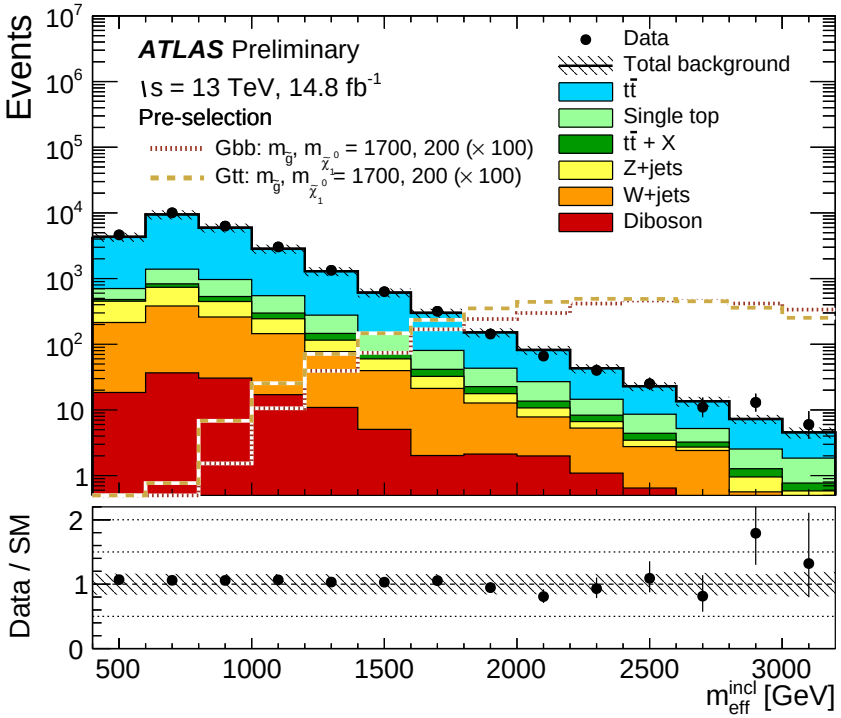


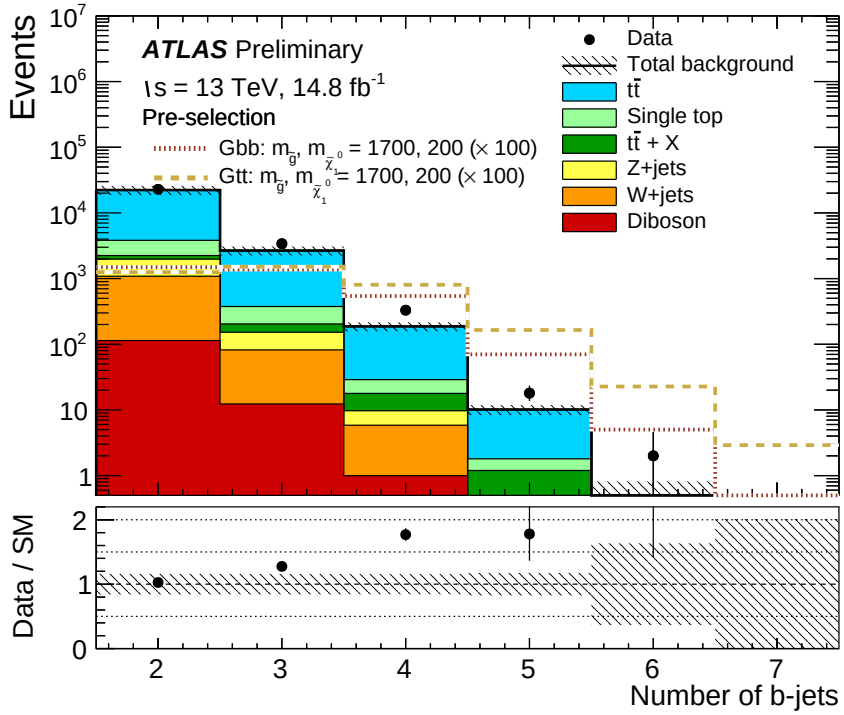




- Trigger on $E_T^{miss} > 200$ GeV
- NB: $t\bar{t}$ is dominant background
  - Normalized in $1\ell$ data; all other backgrounds from MC

- Look for *spectacular* signatures with high $m_{eff} = H_T + E_T^{miss}$, many jets, many $b$-jets
- Define multiple (single-bin) signal regions to target low and high mass-splitting

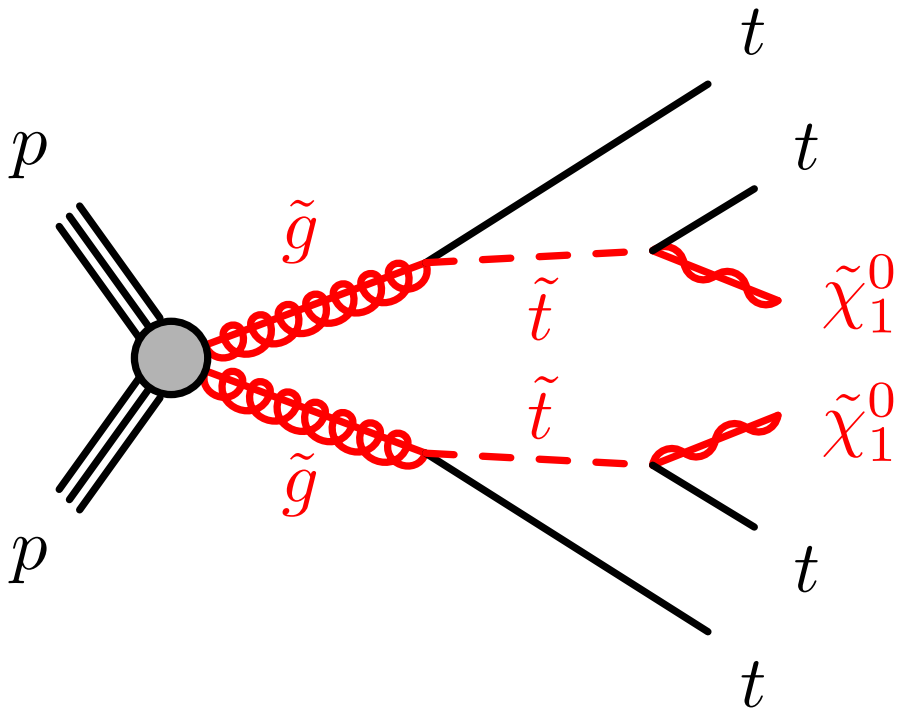
# Signal Discrimination




- $m_{eff}$ provides huge discrimination between signal and background
  - Especially in high mass-splitting regions,great background rejection
- $b$-tagging clearly provides significant power as well
  - Especially important in low mass-splitting regions, where signatures have low visible energy

# Using Event (Sub)Structure

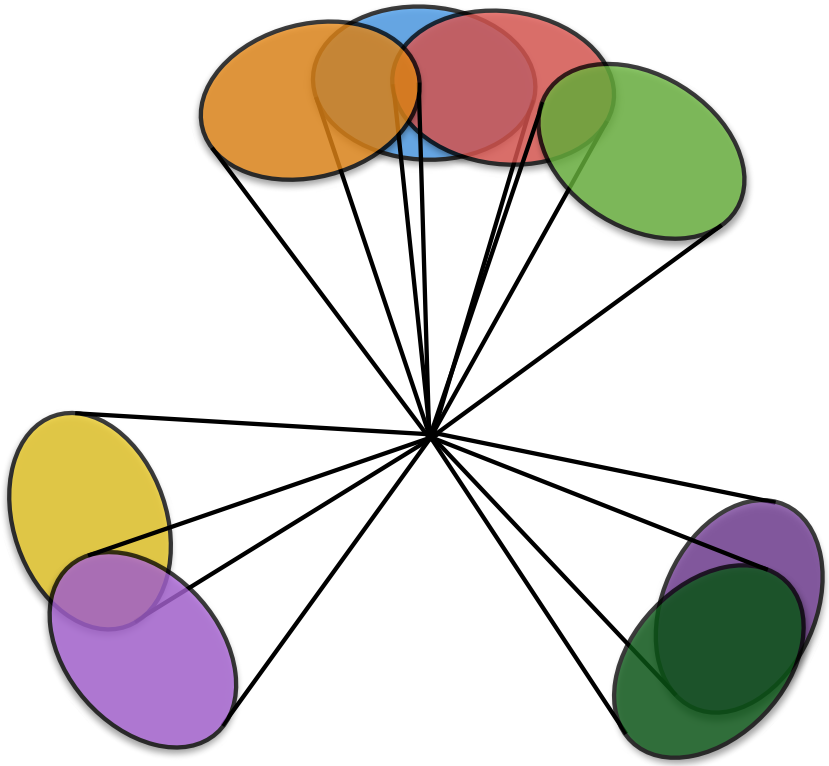



- Gluino-stop signal has *huge number of jets* in the final state: 10 in $1\ell$, 12 in $0\ell$ channels!
- These jets won't be isotropically distributed: $\tilde{g}$ will likely be produced at rest, but $t$ will have significant $p_T$
  - Depends on $m_{\tilde{g}} - m_{\tilde{\chi}_1^0}$: high difference, more phase-space for large momentum

$\rightarrow$ Jets will likely be grouped!

- How can we use this information?
  - NB: With so many jets in the final state, jets from *other* $t$ can start to overlap as well!

# Accidental Substructure



- High multiplicity leads to **significant "accidental" overlaps**

→ We can use **large jets** to capture these overlaps: jets have **mass**

- We can use this structure to search for new physics!

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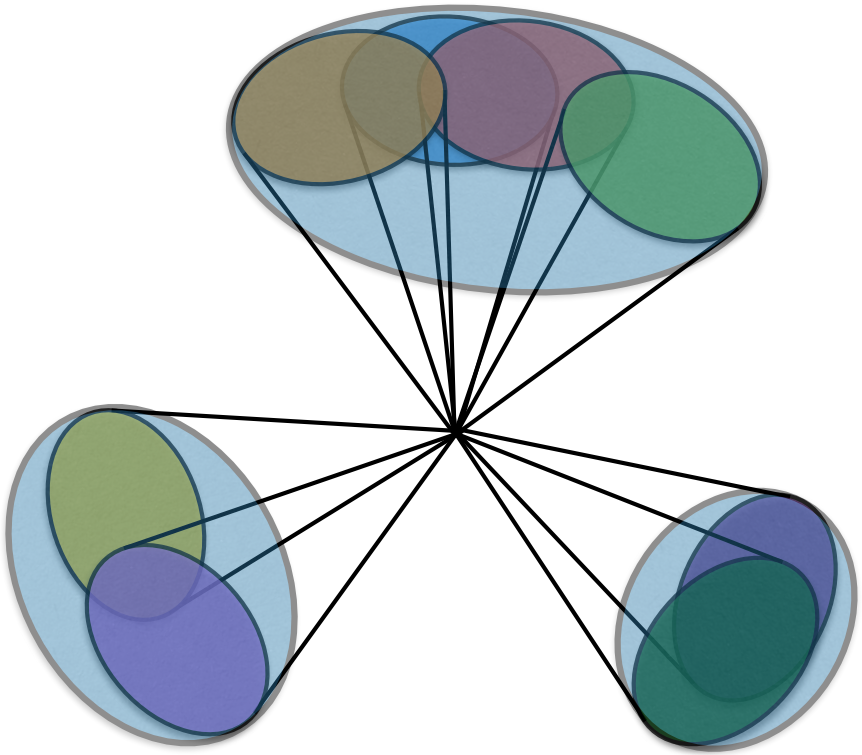

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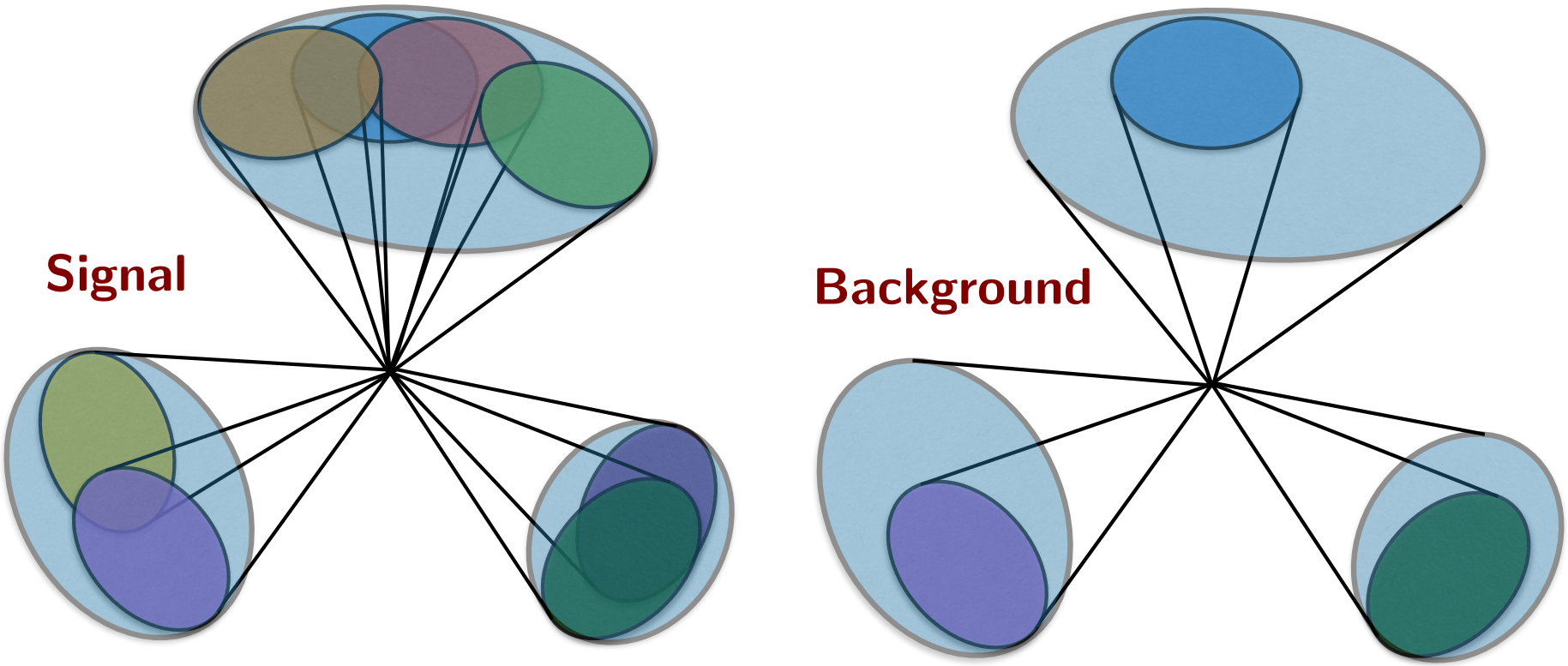


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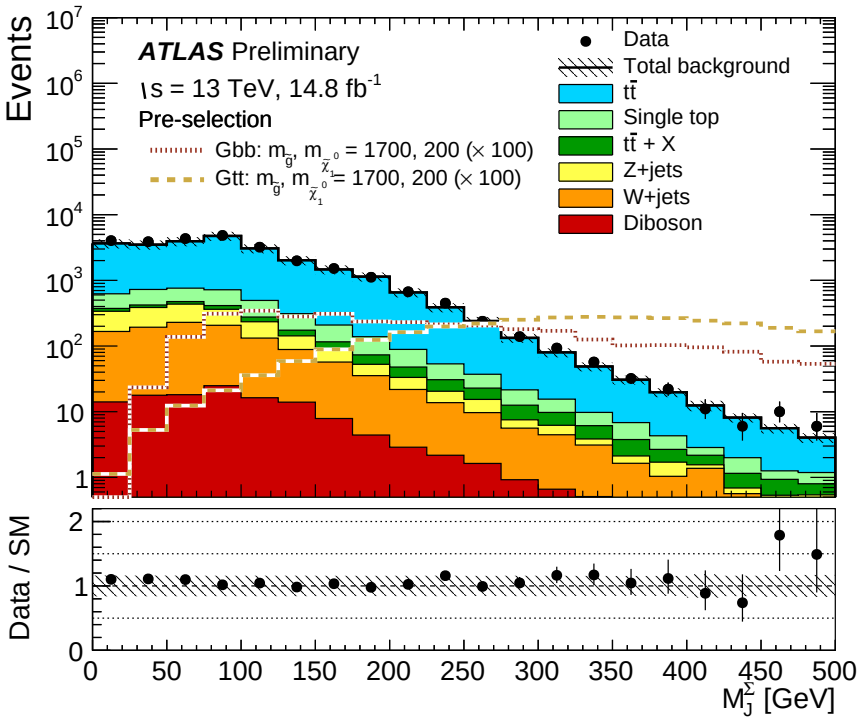
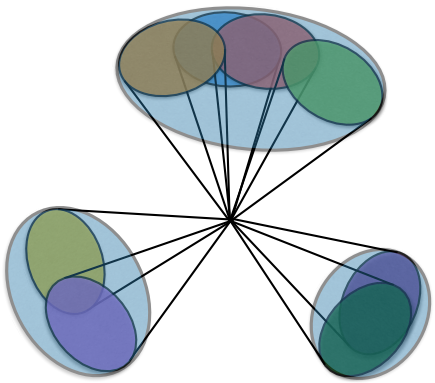
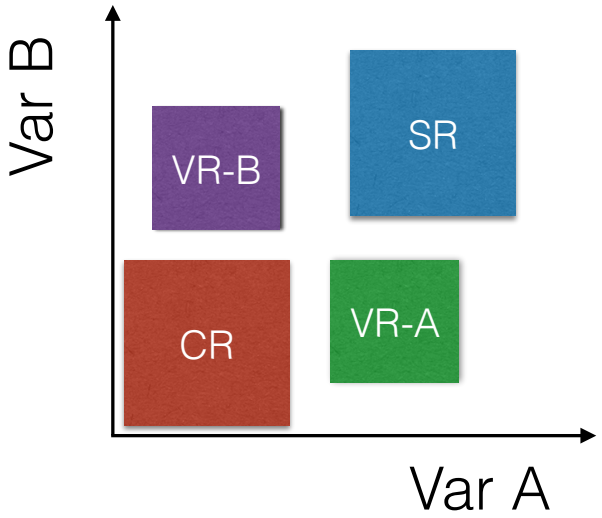
# Total Jet Mass

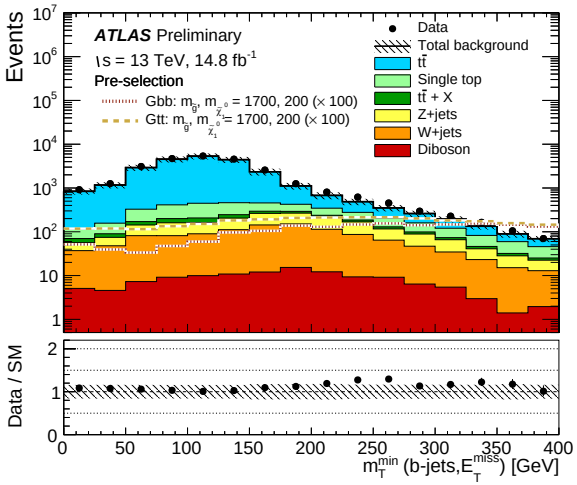


- Identify large-$R$ jets with *re-clustering* approach
  - Run a clustering algorithm on already-reconstructed jets, but with large size ($R = 0.8$)
  - Naturally groups jets close to each other
- Form $M_J^{\Sigma}$ from sum of leading 4 large-$R$ jet masses
  - In signal, many tops overlap, *add mass* to jets, though not necessarily forming clean 'top jets'
  - Both 0L and 1L regions use this very effectively!

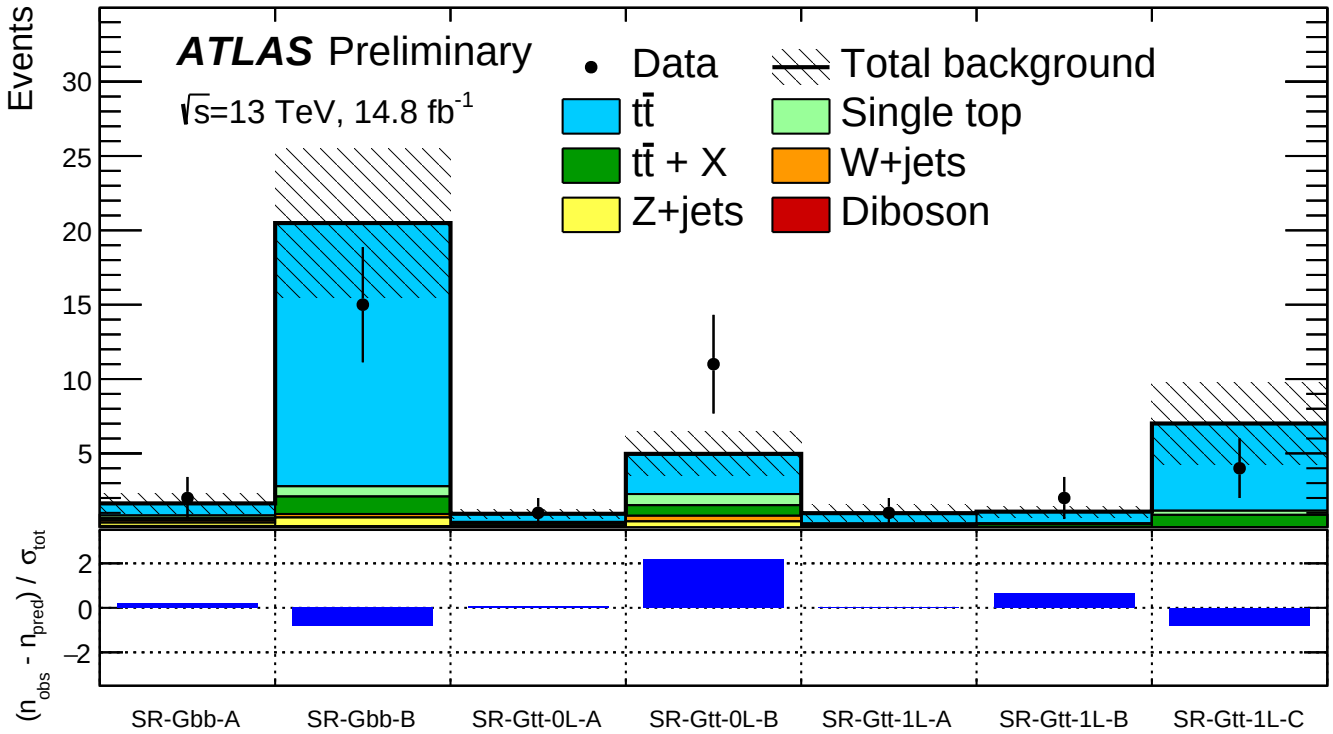
# Background Estimation



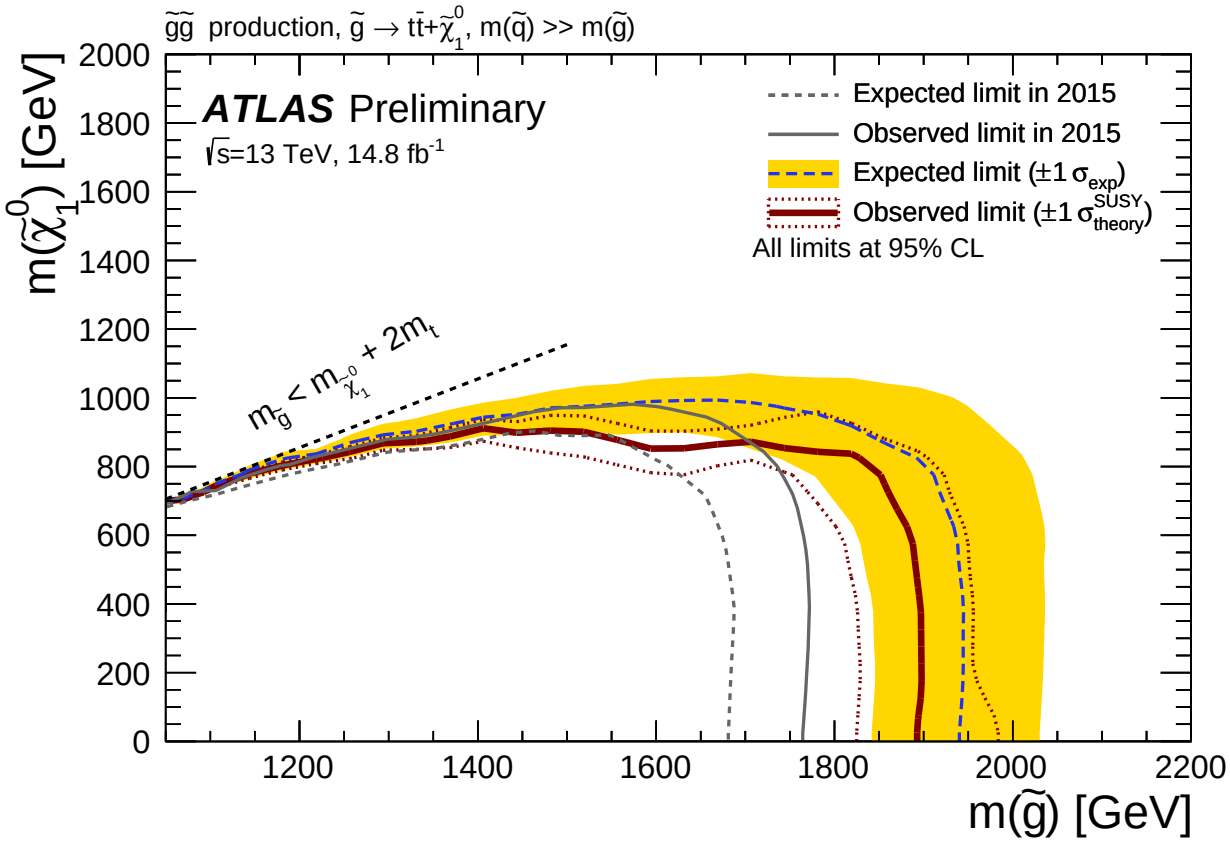

- Normalize this background *using data* using $1\ell$ + low $m_T$ control region
  1. Compare data and MC in this region: derive normalization factor for background
     - Critical to ensure that $t\bar{t}$ + heavy flavor fraction is consistent in CR's and SR!
  2. Validate each inverted cut with validation region
- Other backgrounds taken directly from MC: usually $< 15\%$

# Results: Signal Region Yields




- Signal region predictions both agree well with observation
  - Slight excess in one 0L signal region with moderate $m_{eff}^{incl}$ and $M_J^{\Sigma}$

# Limits




- Limits expand significantly earlier Run 2 sensitivity
- Statistical combination of 0L and 1L analyses provides $\approx$ 100 GeV gain in $\tilde{t}$ models
  - All signal/control/validation regions designed to be independent to allow for straightforward combination

# Conclusions

- $\sqrt{s} = 13$ TeV is here, but SUSY is not (yet!)
- First searches optimized for discovery have not yet observed any significant deviation from the SM
  - Already being used by theorists to probe naturalness in SUSY! (1610.08059 and others)
- Run 2 has just begun, though: 2016 promises 3x the data, and even more coming in 2017!
  - $\approx$40 fb$^{-1}$ available for Moriond, in just a few months
  - $\tilde{g}$ sensitivity will likely extend to 2 TeV and beyond
- New techniques and signal models coming in new results: lots of room left to optimize and explore
  - SUSY could still be right around (one of many) corners!

**Thank you for your attention!**

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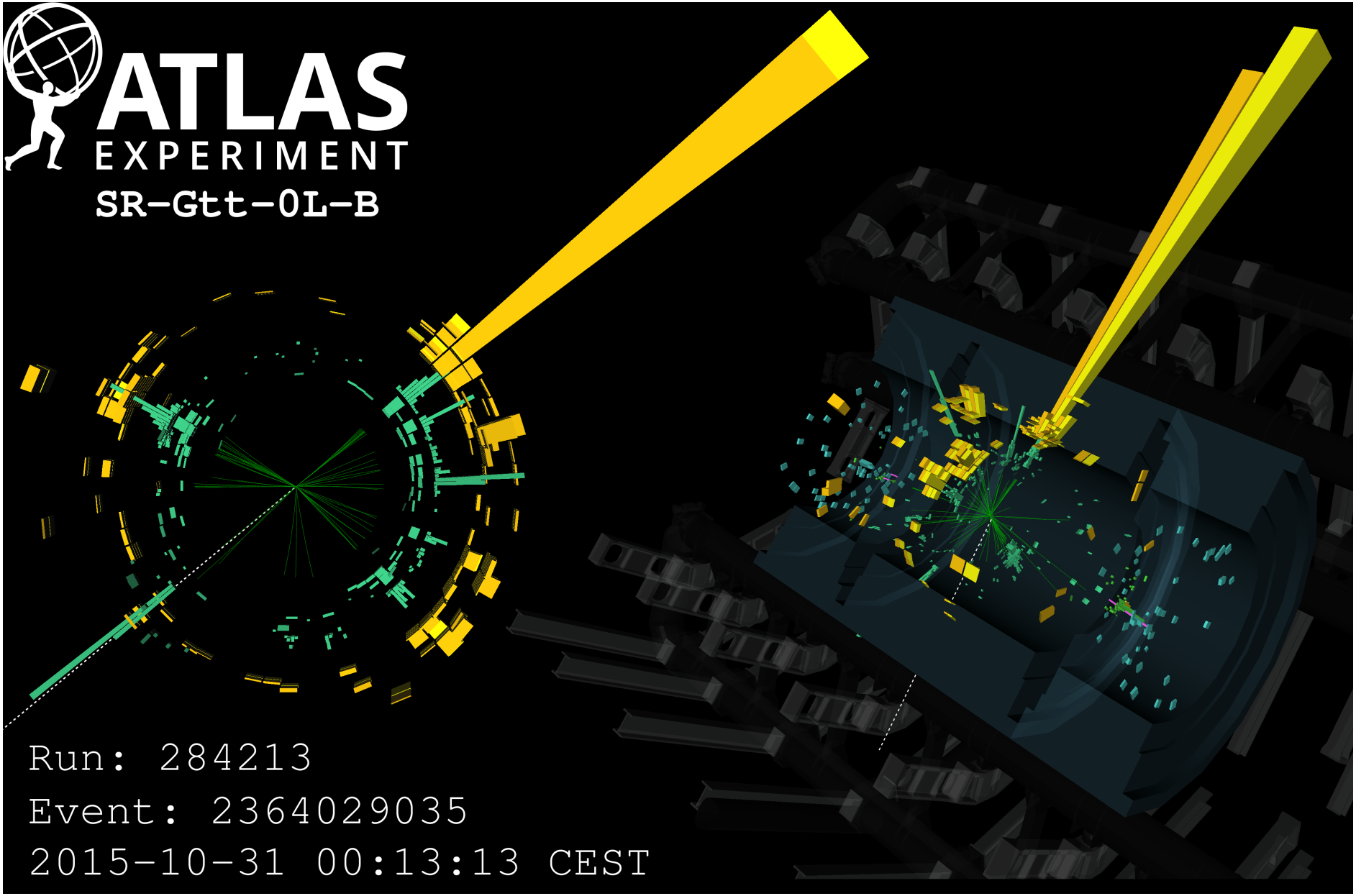
ATLAS
EXPERIMENT
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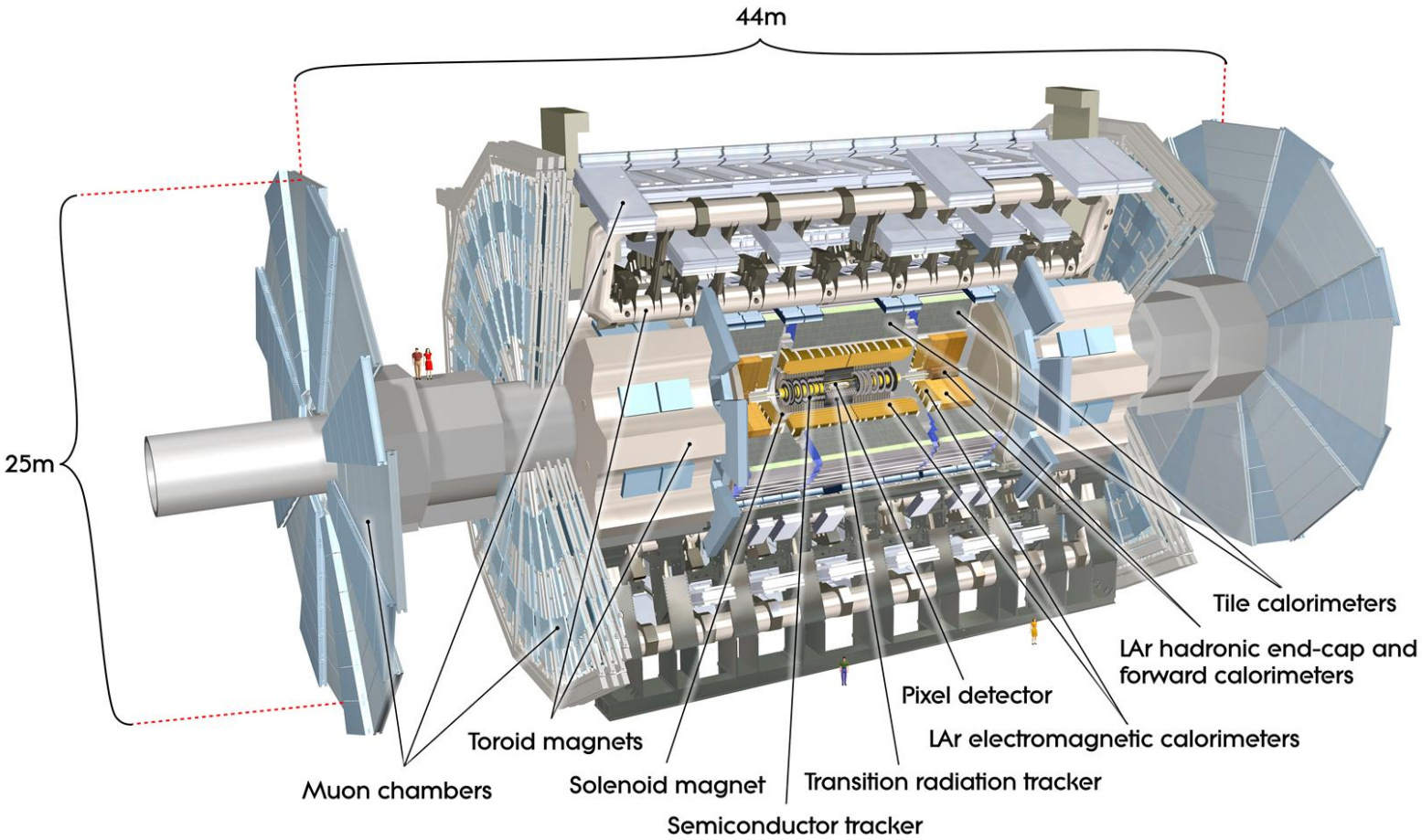
Run: 284213
Event: 2364029035
2015-10-31 00:13:13 CEST

# Backup

# The ATLAS Detector



# Multi-$b$: 0L $\tilde{t}$ SR Definitions

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

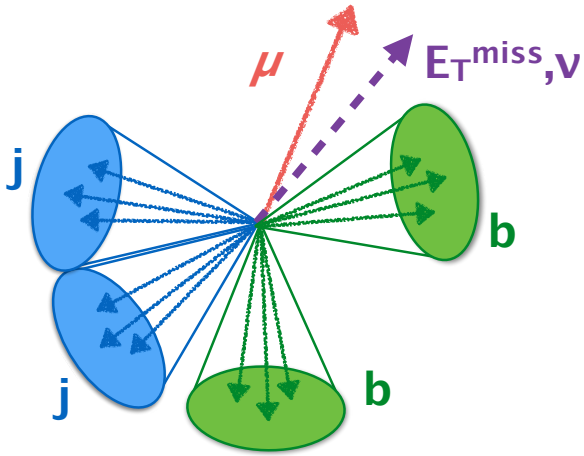
# Multi-$b$: 1L $\tilde{t}$ SR Definitions

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

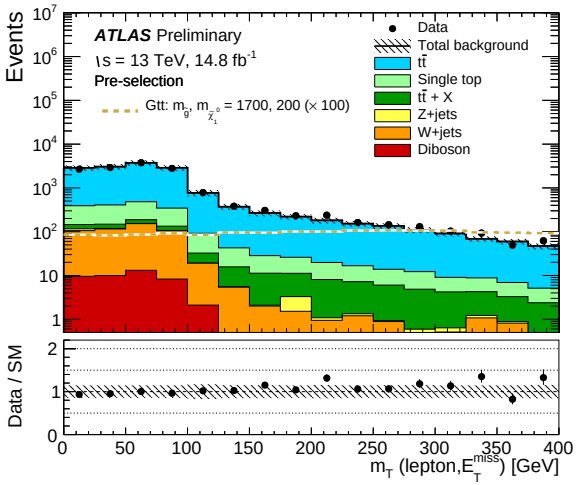
# Multi-$b$: $\tilde{b}$ SR Definitions

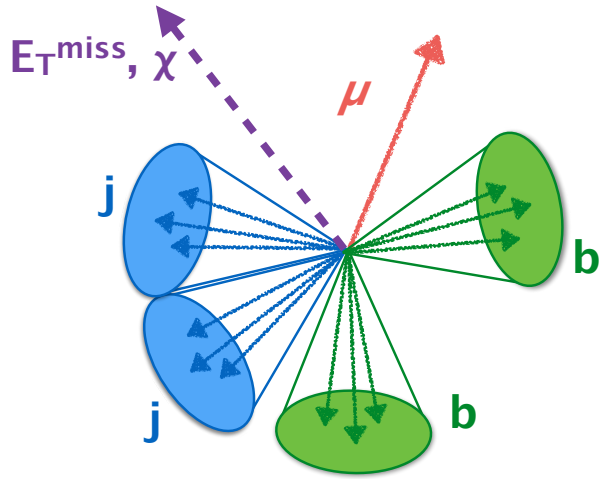
| Criterion common to all Gbb regions: $N^{\text{jet}} \geq 4$ | | | | |
|---|---|---|---|---|
| | Variable | Signal region | Control region | Validation region |
| Criteria common to all regions of the same type | $N^{\text{Candidate Lepton}}$ | $= 0$ | – | $= 0$ |
| | $N^{\text{Signal Lepton}}$ | –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

# More Variables: Transverse Mass $m_T$




$\ell$ and $E_T^{miss}$ aligned: background like



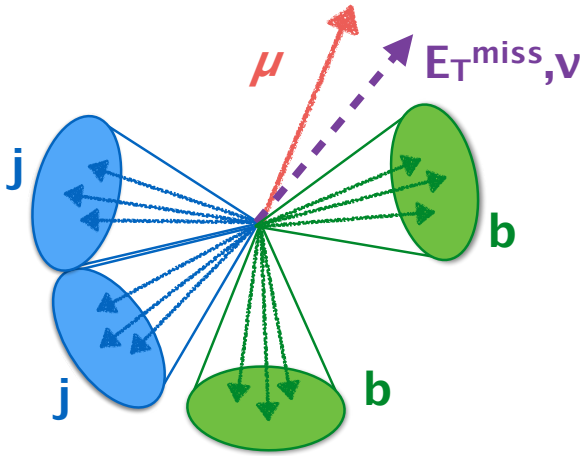




$\ell$ and $E_T^{miss}$ unaligned: signal like

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

- Provides excellent discrimination in $1\ell$ events

# More Variables: Minimum Tranverse $b$-jet Mass $m_T^{b,min}$

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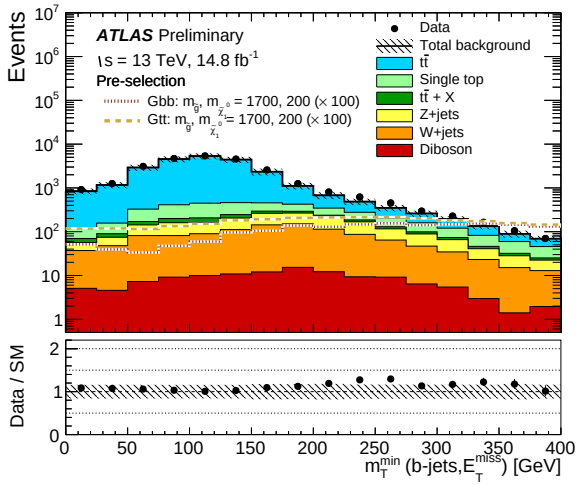
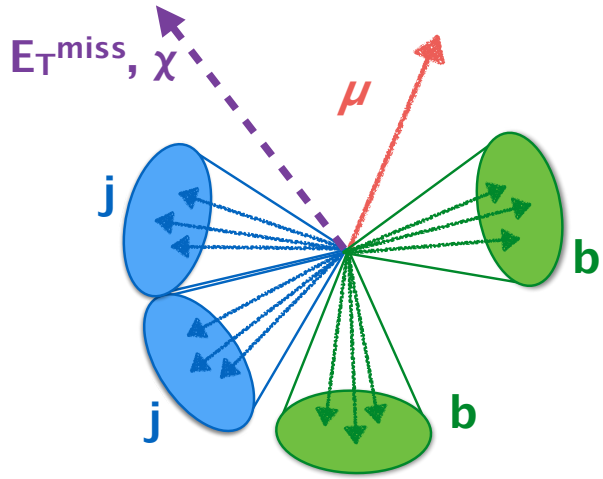


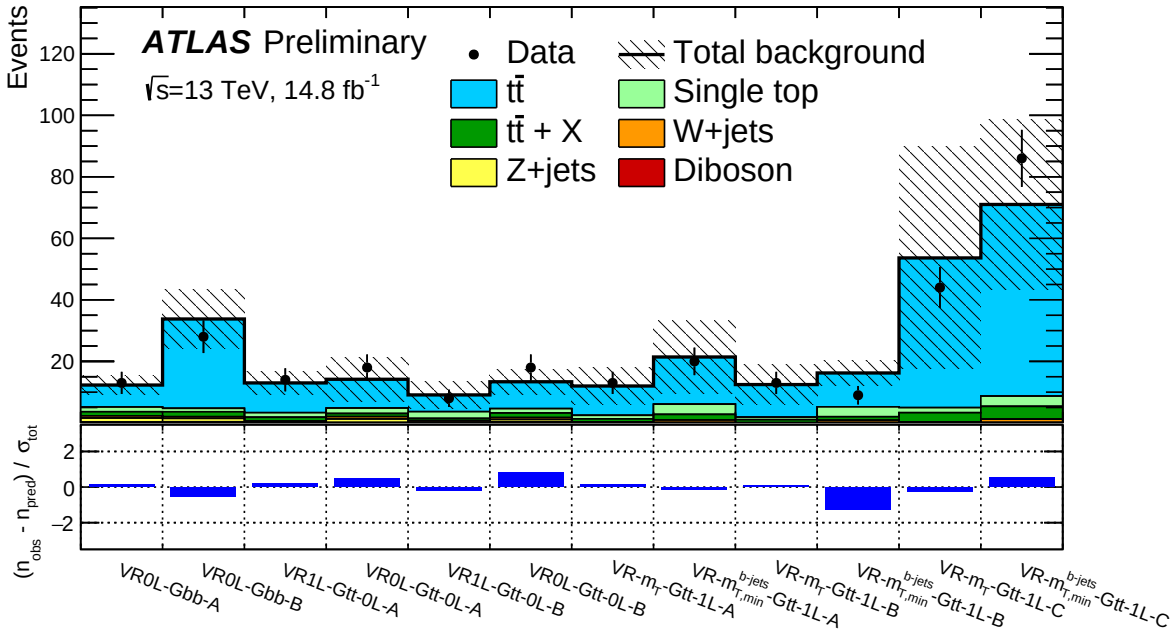




$b$ and $E_T^{miss}$ unaligned: signal like

$$m_T^{b,min} = \min_{i\leq 3}\sqrt{(E_T^{miss} + p_T^{j_i})^2 - (E_x^{miss} + p_x^{j_i})^2 - (E_y^{miss} + p_y^{j_i})^2}$$

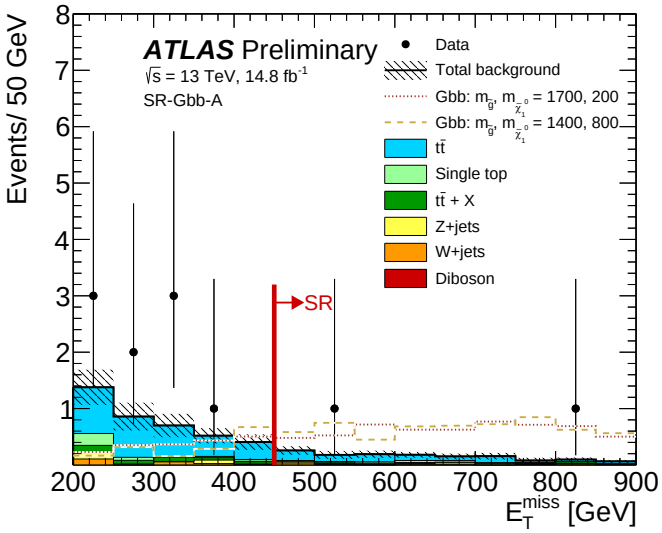
- Provides excellent discrimination in both $0\ell$ and $1\ell$ channels

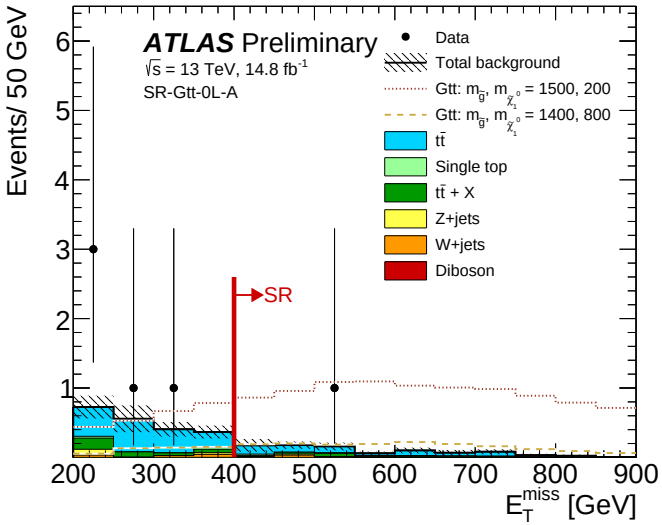
# Validation Regions

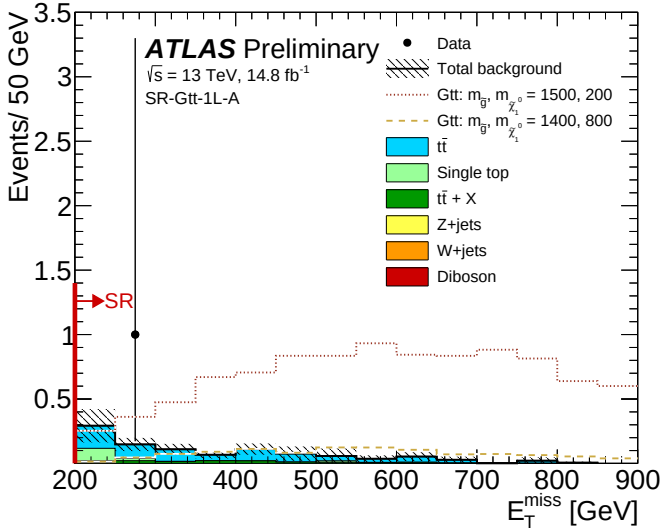



- Validation regions defined for all extrapolations in CR's
  - $0\ell$ CR's, high $m_T$ CR's, etc.
  - Usually use one other orthogonal variable to keep signal contamination low: $M_J^{\Sigma}$, for example
- Good agreement seen for all validation regions: no apparent mismodelings!

# Results in Signal Regions




- Examples of $\tilde{b}$ and 0/1L $\tilde{t}$ regions here
- No signs of significant excesses over SM expectation