Bundesministerium
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DFG

FSP 101
ATLAS

# Search for the top quark SUSY partner with the HEPTopTagger in ATLAS

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INTERNATIONAL MAX PLANCK RESEARCH SCHOOL

PT FS FOR PRECISION TESTS OF FUNDAMENTAL SYMMETRIES

# Outline

- Introduction and motivation:

  search for the top supersymmetric partner, *stop*

- Method:

  HEPTopTagger algorithm and performance

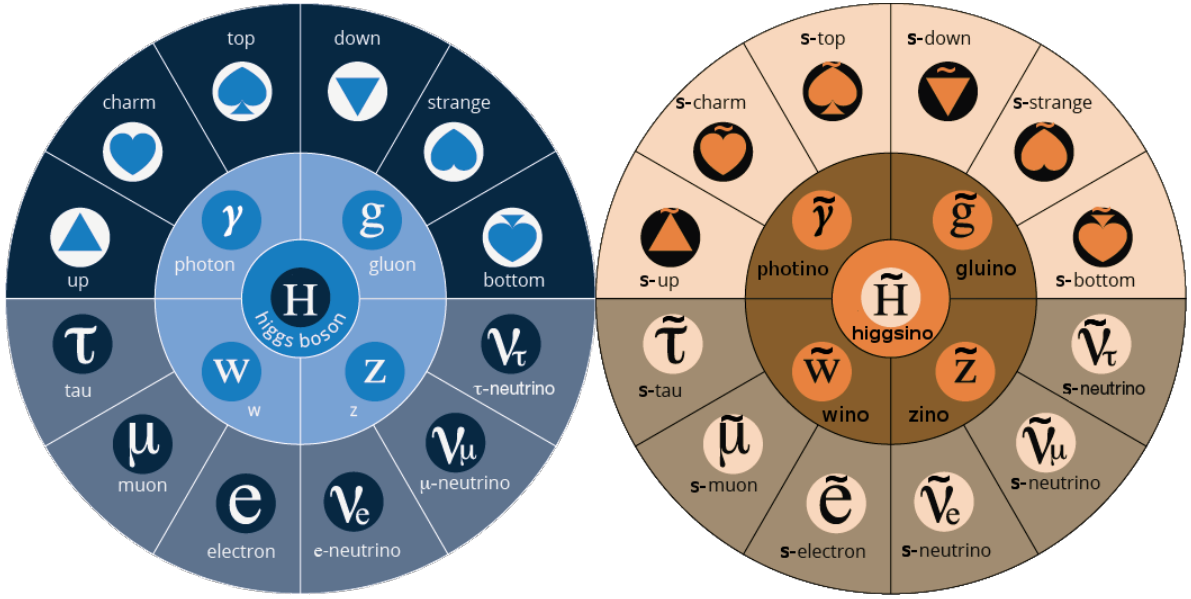
- Analysis:

  stop search with the HEPTopTagger at 8 TeV

- Results:

  exclusion limits

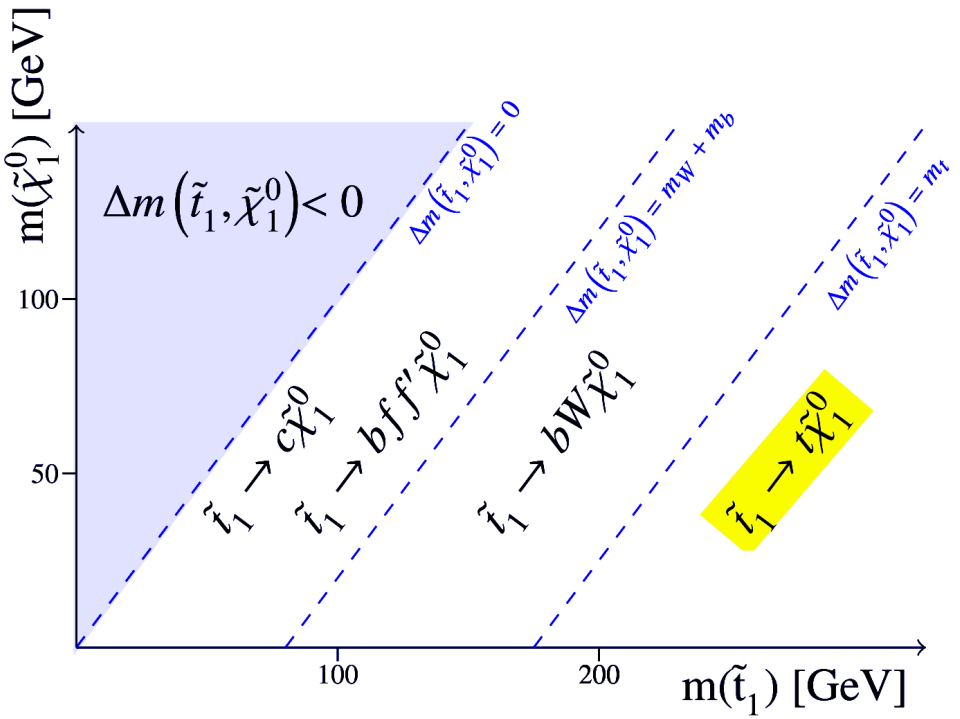
# SUPERSYMMETRY




- Space-time symmetry relating fermions and bosons
- Additional particles could solve the Higgs mass hierarchy problem: **central role of the top SUSY partner** $\tilde{t}$
- **Naturalness** favours light $\tilde{t}$
- Assumption of R-parity conservation:
  - Lightest SUSY Particle (LSP) stable $\to$ DM candidate
  - LSP: neutralino $\tilde{\chi}_1^0$ (mixture of neutral higgsinos and gauginos)

# Stop decay

- signature driven approach with **simplified models**: $(m_{\tilde{t}}, m_{\tilde{\chi}_1^0})$




$$pp \to \tilde{t}\tilde{t}^*(+X) \to t\tilde{\chi}_1^0\, \bar{t}\tilde{\chi}_1^0(+X)$$

# Direct $\tilde{t}$ search in fully hadronic channel

## Fully hadronic channel:

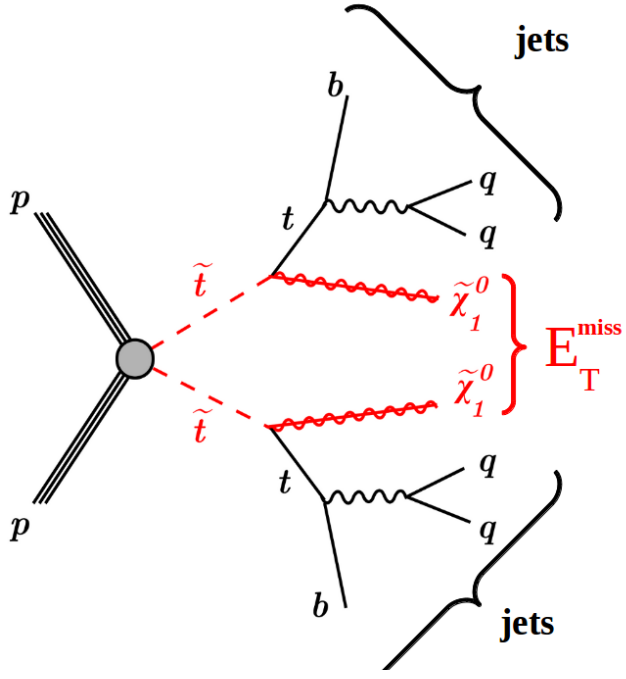
- large branching ratio (BR($t \to qq'b$)=68%)
- $E_{\mathrm{T}}^{\mathrm{miss}}$ only from $\tilde{\chi}_1^0$
- top quark kinematic fully reconstructed

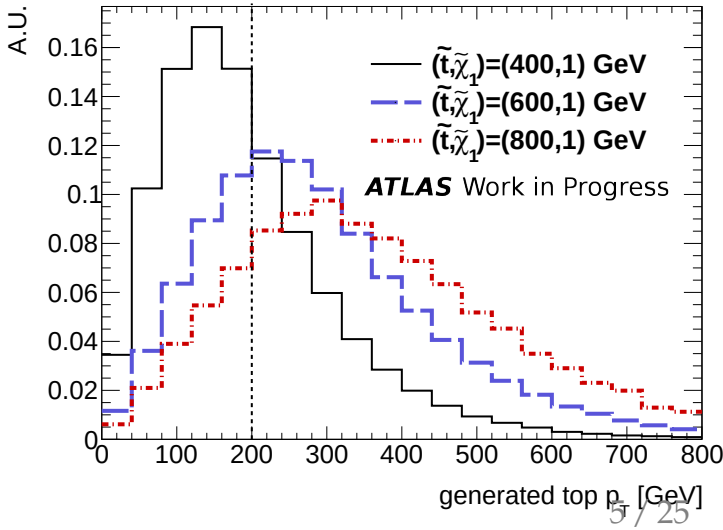
## ATLAS 8 TeV published analysis: (JHEP09(2014)015)

- moderate top $p_{\mathrm{T}}$: resolved techniques
- top quark reconstructed from R=0.4 jets

## $m_{\tilde{t}} \gg m_{\tilde{\chi}_1^0}$

- top quark produced with high $p_{\mathrm{T}}$
- boosted techniques
- top quark reconstruction with **HEPTopTagger**



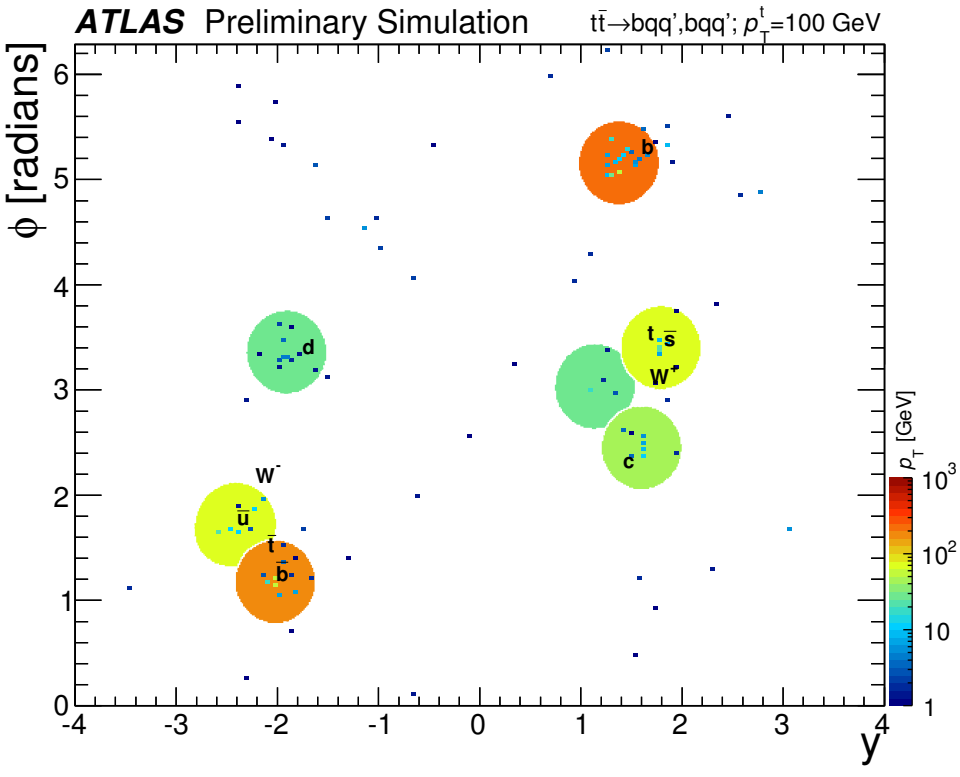



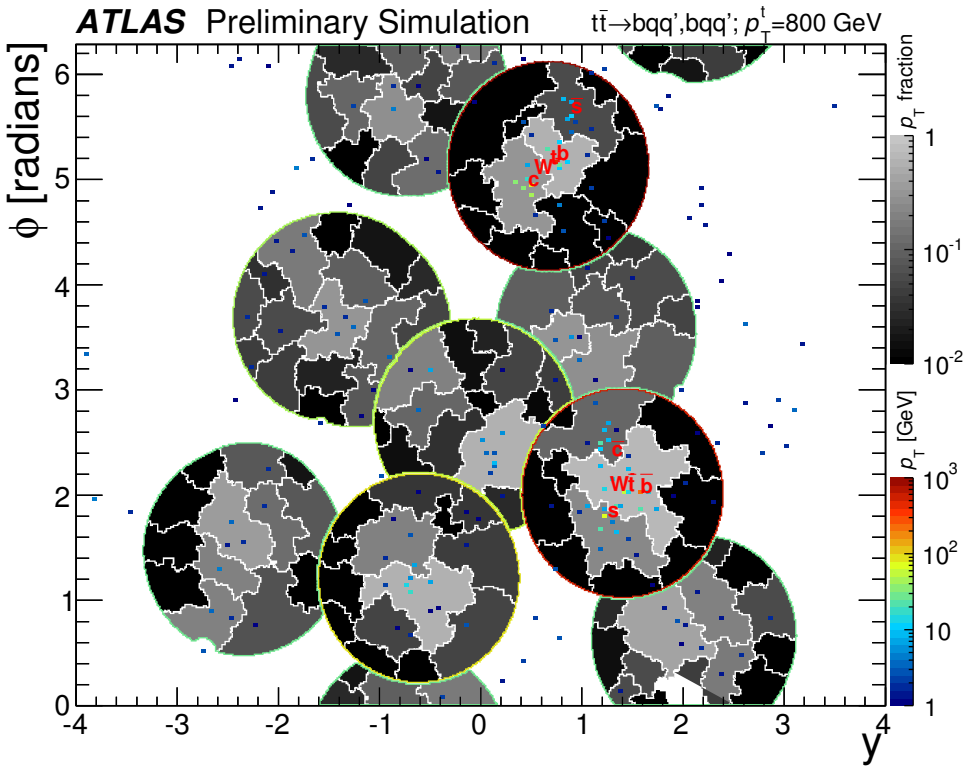
# HEPTopTagger algorithm and performance

# Tagging Boosted Top Quarks (twiki)
## Resolved vs Boosted Regime

- $\Delta R \sim \frac{2m}{p_T}$ $(\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2})$
- high $p_T$ top quark: decay products in a single large-$R$ jet

**low $p_T$ tops, resolved decay products** **high $p_T$ tops, collimated decay products**



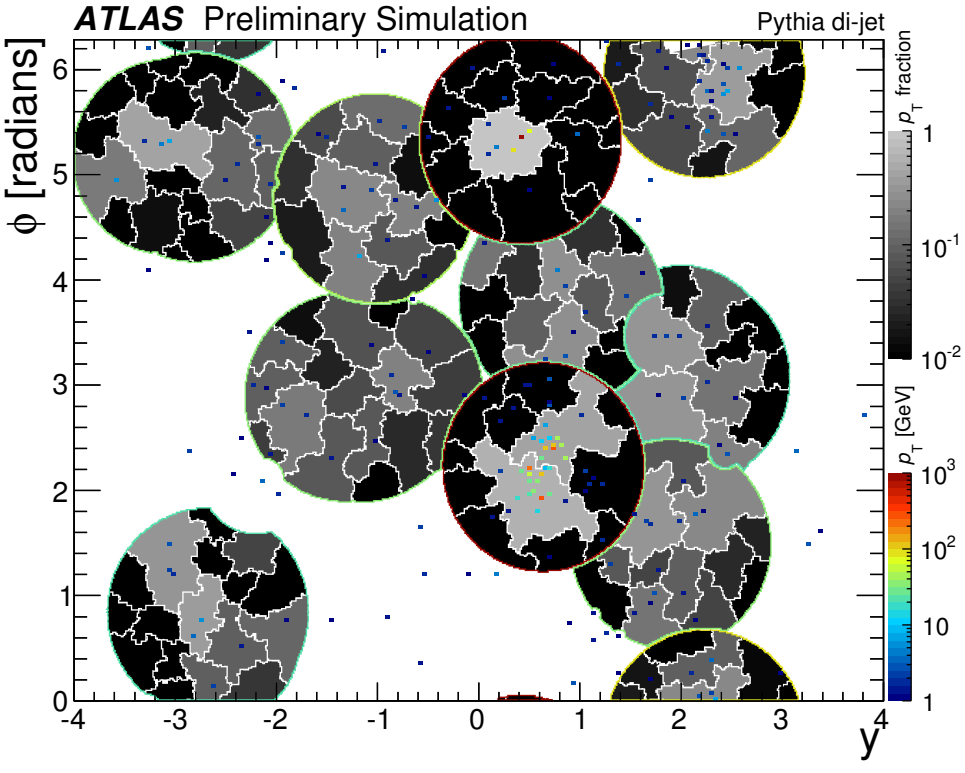



# Tagging Boosted Top Quarks (twiki)

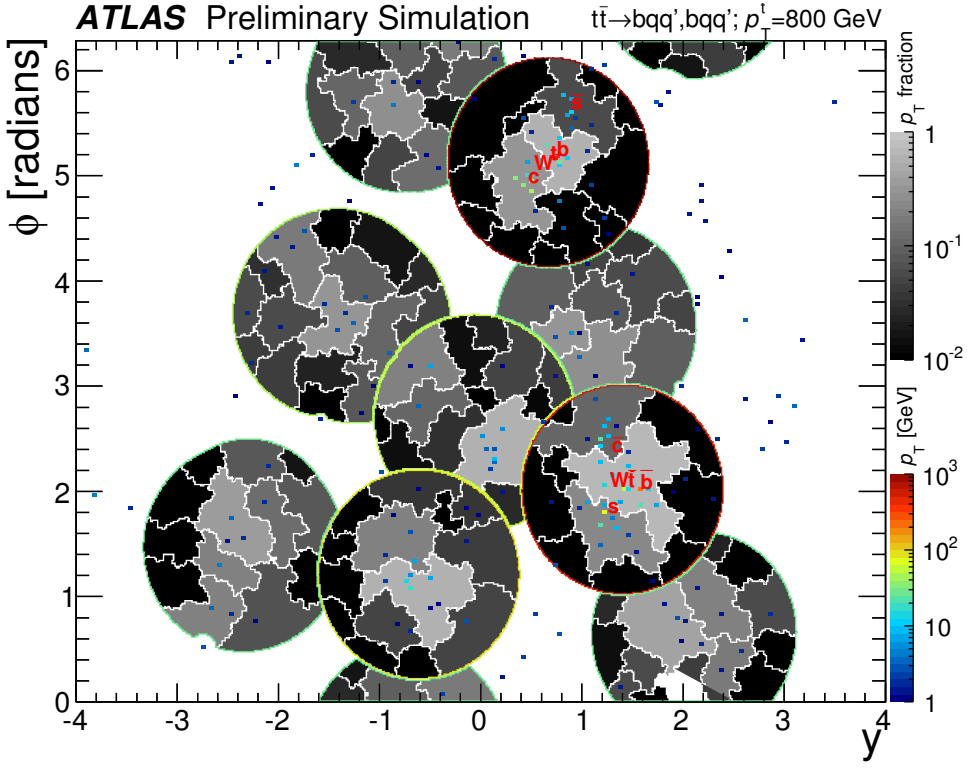
## Multi-jet vs top quark substructures

- looking into substructure to discriminate top quark vs bkg
- reduction of pileup → better reconstruction of top kinematic

**multi-jet background**




**top quark decay**



# HEPTopTagger

(Plehn, Salam, Spannowsky, Takeuchi, Zerwas: JHEP 1010 (2010) 078 & JHEP08 (2012) 091)

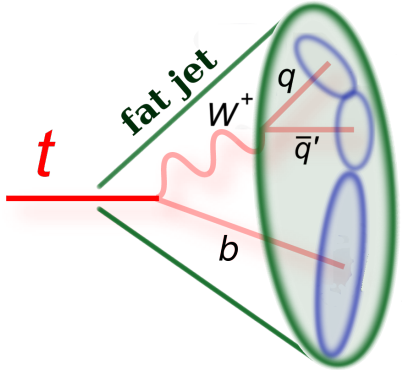
**Fat jet R=1.5**

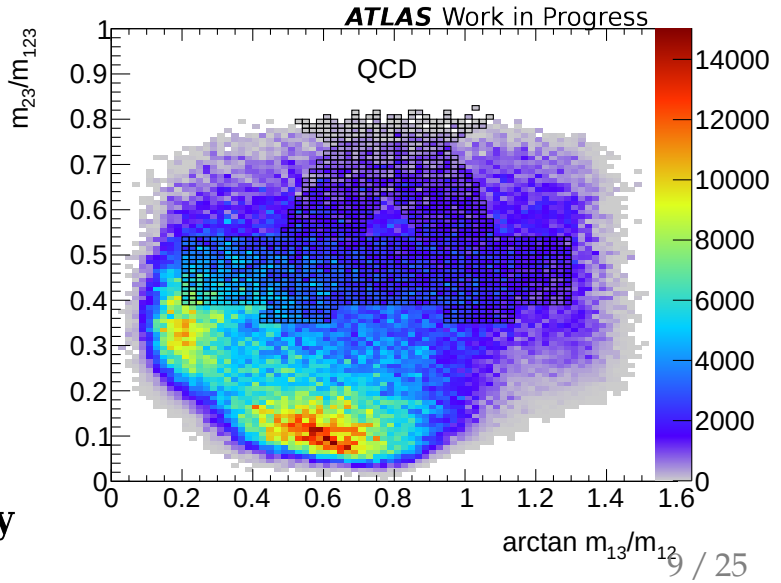
**HEPTopTagger**

- **Hard subjet selection**
- **Filtering**
- **Top decay compatibility**

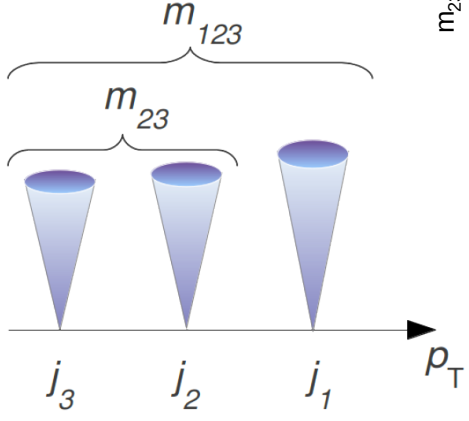
**Top candidate 4-vector**
**$p_T$>200 GeV**

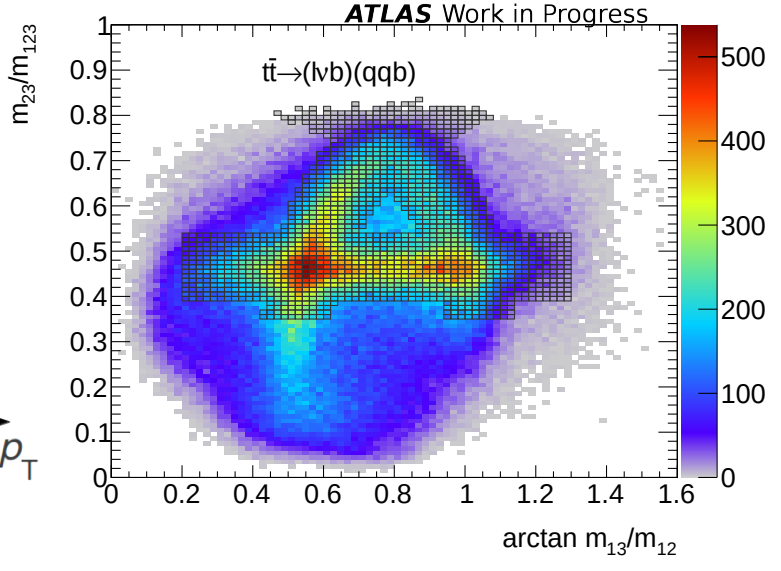
| | |
|---|---|
| $m_{\text{cut}}$ | 50 GeV |
| $R_{\text{filt}}^{\text{max}}$ | 0.25 |
| $N_{\text{filt}}$ | 5 |
| $f_W$ | 15% |



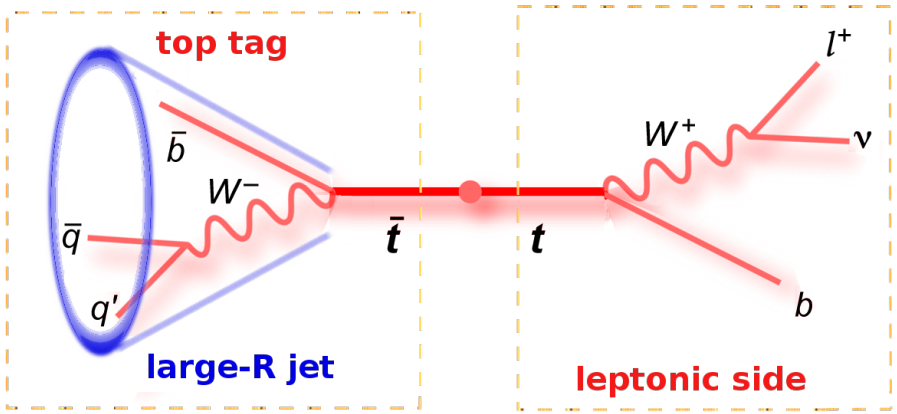


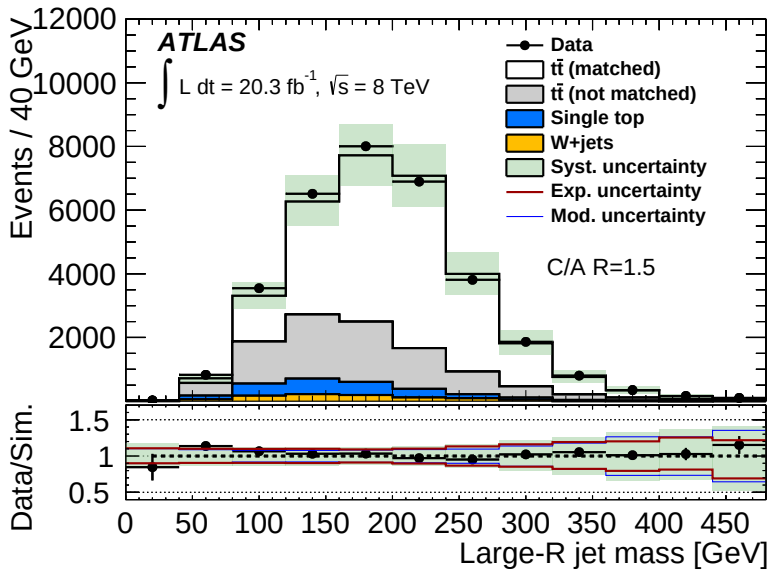
# Identification of high $p_T$ top quarks at $\sqrt{s} = 8$ TeV

arXiv:1603.03127

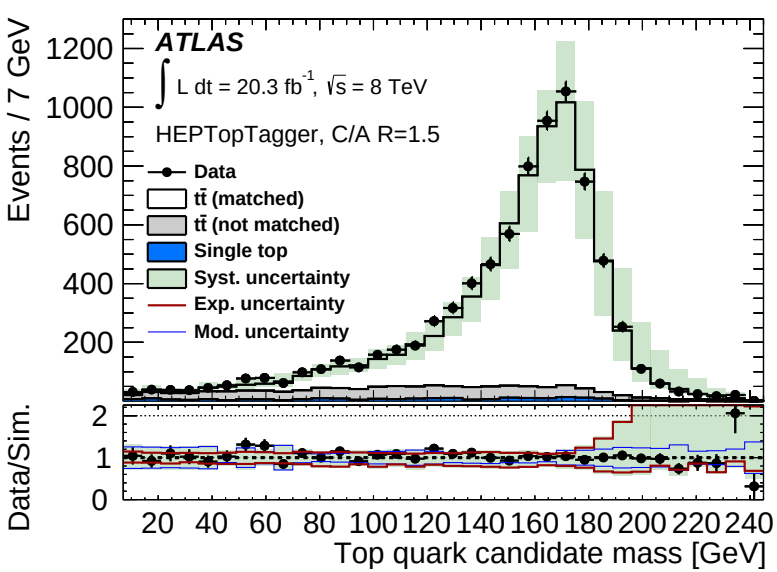



- $1\,\ell = e, \mu$
- $N_{b\text{-jets}} \geq 2$
- $E_T^{miss} > 20\,\text{GeV}$
- $E_T^{miss} + m_T^W > 60\,\text{GeV}$
- fat jet $p_T > 200\,\text{GeV}$

## Before HEPTopTagger

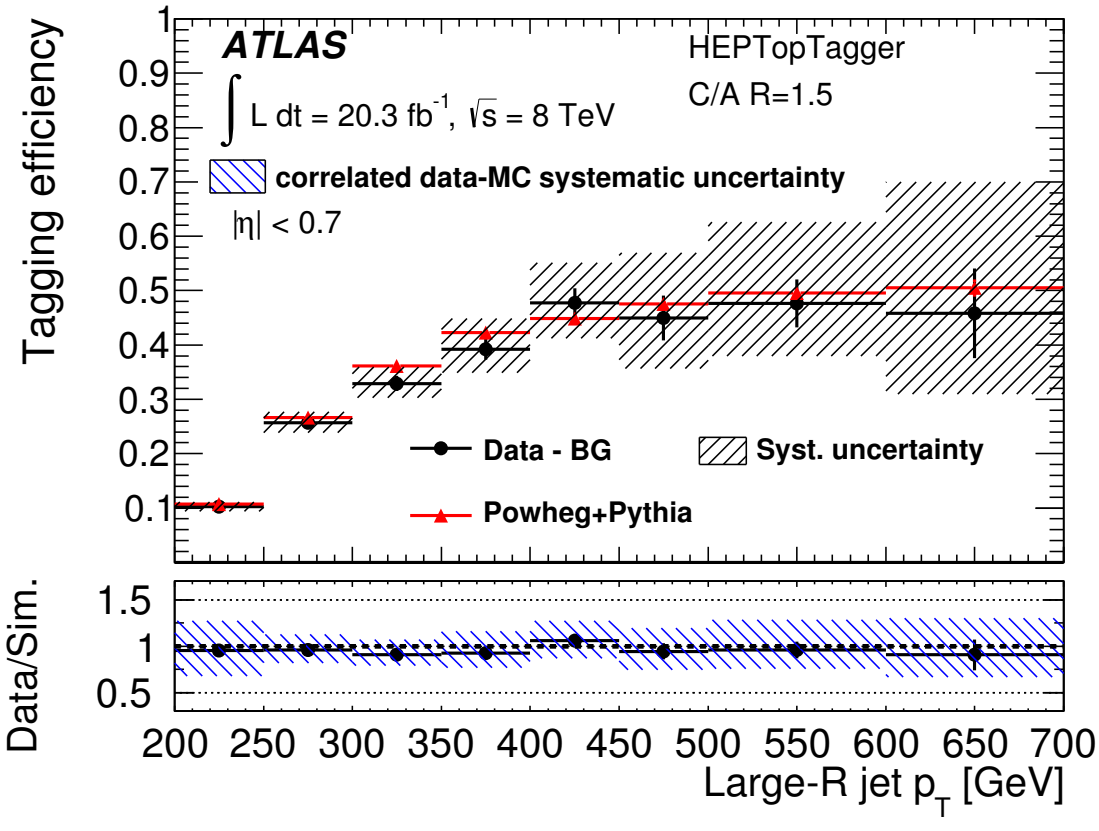



## After HEPTopTagger



# HEPTopTagger efficiency measurement

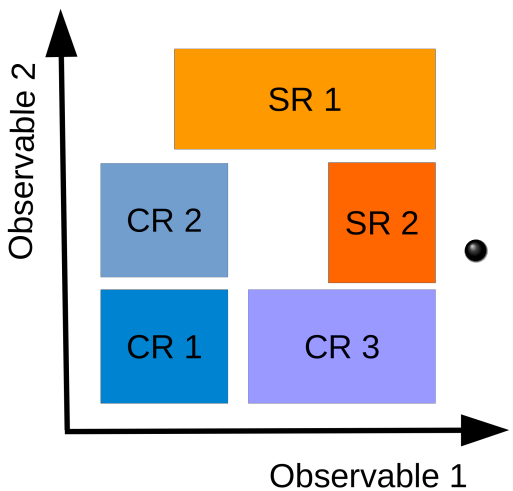
$$f_{\text{data},i} = \left( \frac{N^{\text{tag}}_{\text{data}} - N^{\text{tag}}_{t\bar{t}\,\text{not matched}} - N^{\text{tag}}_{\text{non-}t\bar{t}}}{N_{\text{data}} - N_{t\bar{t}\,\text{not matched}} - N_{\text{non-}t\bar{t}}} \right)_i \quad \text{vs} \quad f_{\text{MC},i} = \left( \frac{N^{\text{tag}}_{\text{MC}}}{N_{\text{MC}}} \right)_i$$



# Direct stop search with the HEPTopTagger

## Analysis Strategy and Background Estimation in SUSY Searches

- **Signal Region** (SR): extreme region of phase space
- More precise bkg estimation $\rightarrow$ better sensitivity
  - **data-driven methods**:
    - shape and normalization extracted from data
    - large cross section processes like multi-jet
  - **semi data-driven approach**:
    - shape from simulation
    - normalization from **Control Regions** (CR) with high bkg purity and low signal contamination
    - SM processes with large cross sections $t\bar{t}$, $V$+jets
- **pure simulation**:
  - low cross section SM processes like $VV$, $t\bar{t}V$



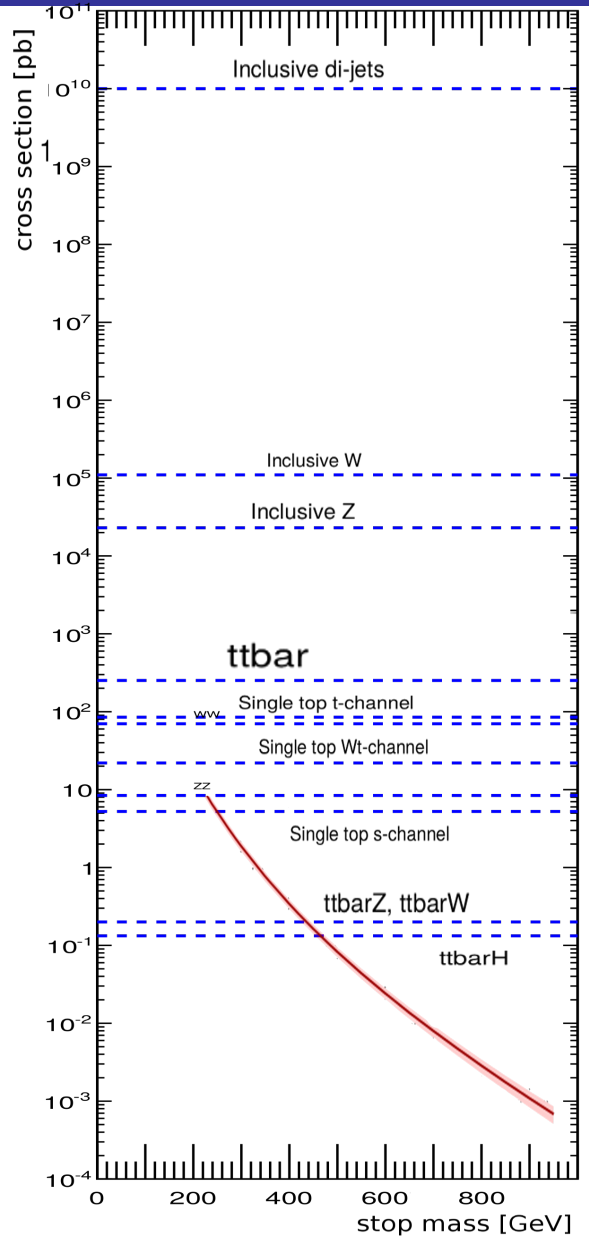
# Analysis Strategy with the HEPTopTagger

## Standard Model background:

- multi-jets
- $t\bar{t}$, single top, $t\bar{t}V$
- W+jets, Z+jets, VV

## Baseline Selection

- electron and muon veto
- $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger, $E_{\mathrm{T}}^{\mathrm{miss}} > 150\,\mathrm{GeV}$



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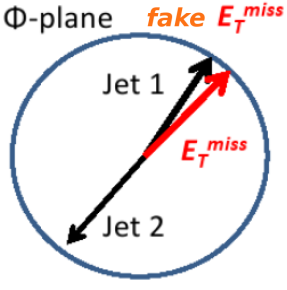
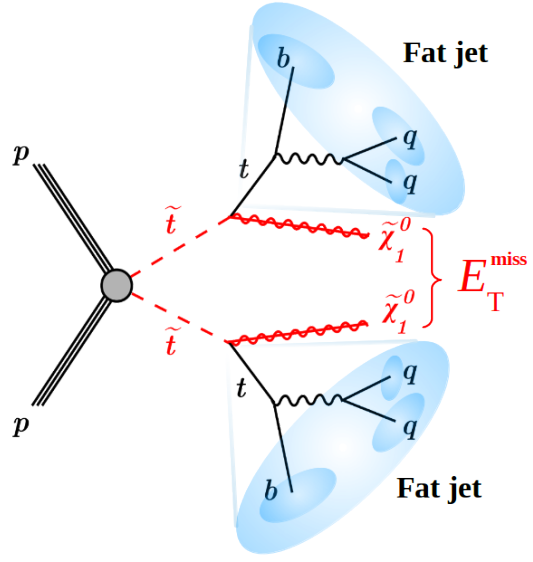
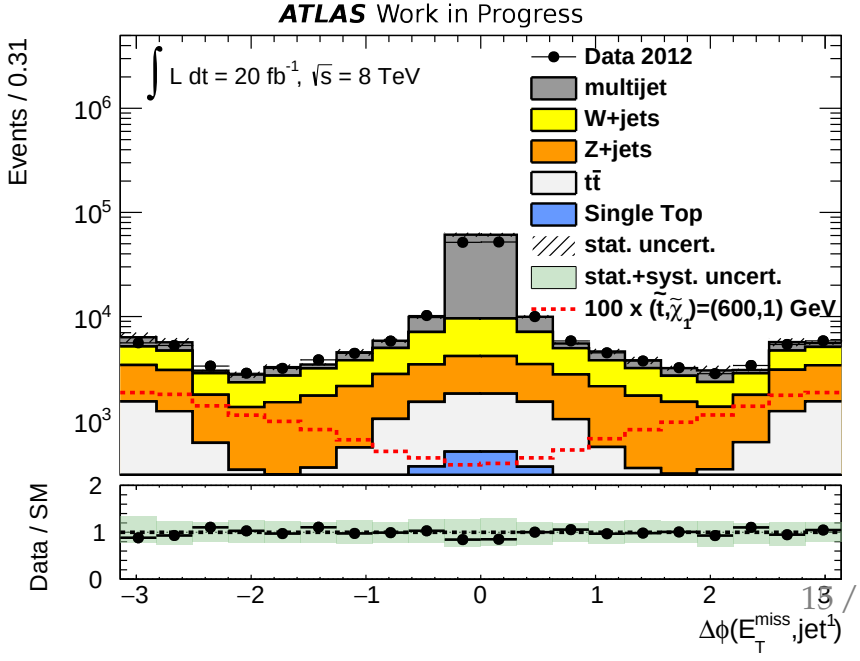
- $|\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, j_{R=0.4}^{0,1,2})| > \pi/5$



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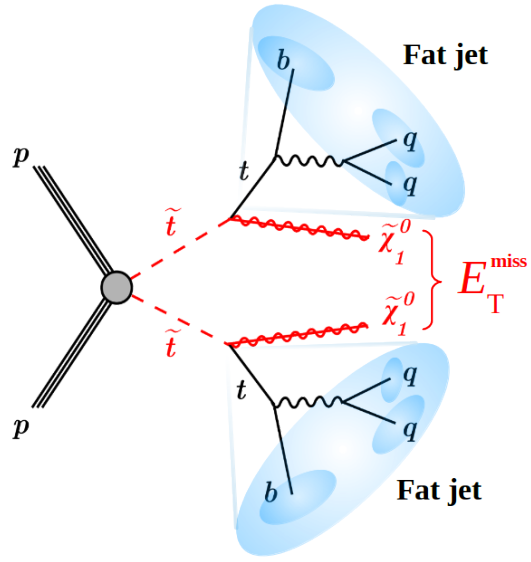
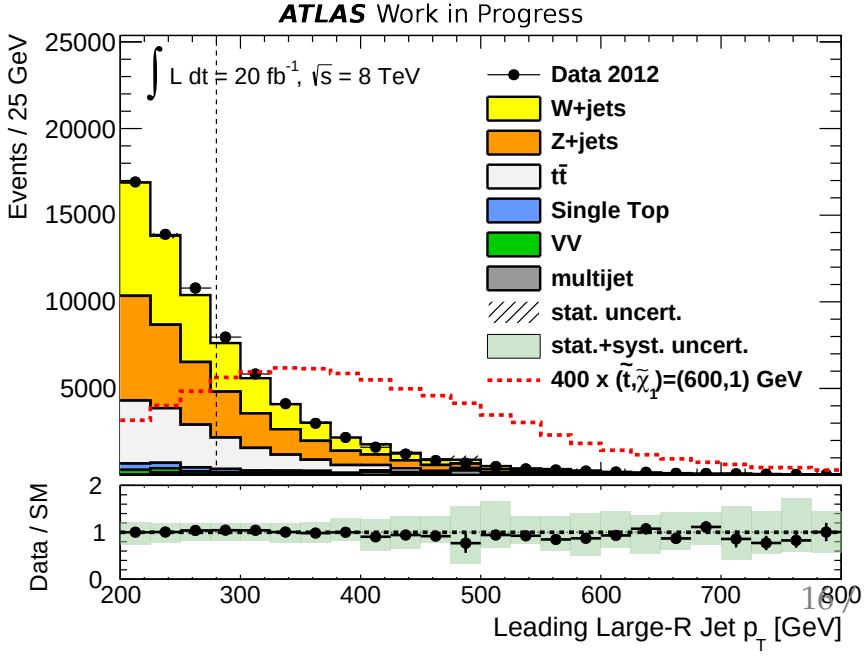
- $|\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, j_{R=0.4}^{0,1,2})| > \pi/5$
- large-$R$ jet $p_{\mathrm{T}} > 280\,\mathrm{GeV}$



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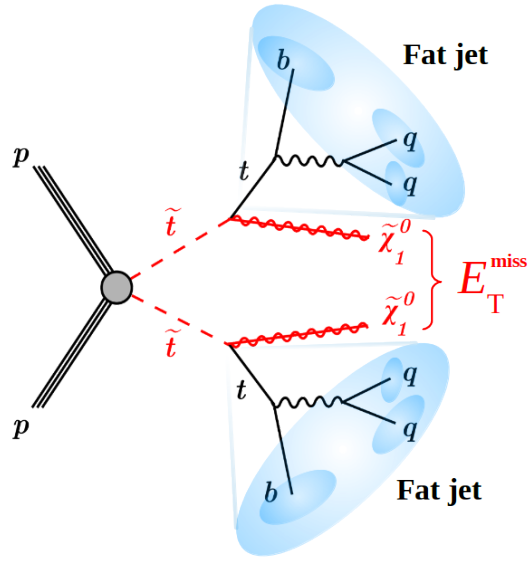
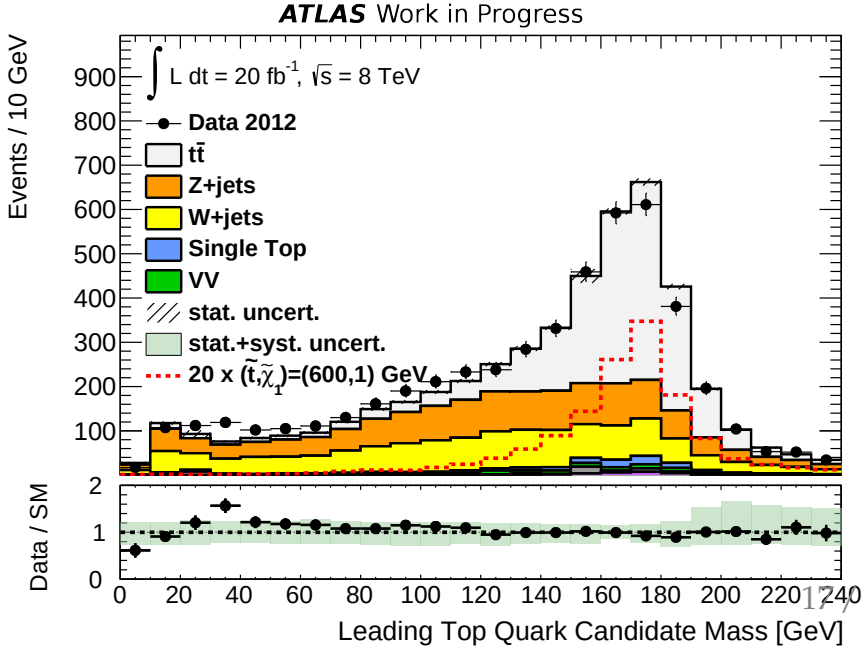
- $|\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, j_{R=0.4}^{0,1,2})| > \pi/5$
- large-$R$ jet $p_{\mathrm{T}} > 280\,\mathrm{GeV}$
- tagged by the HEPTopTagger

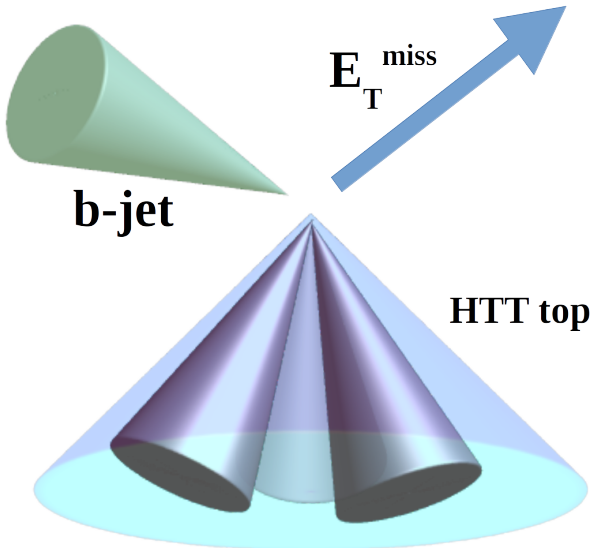


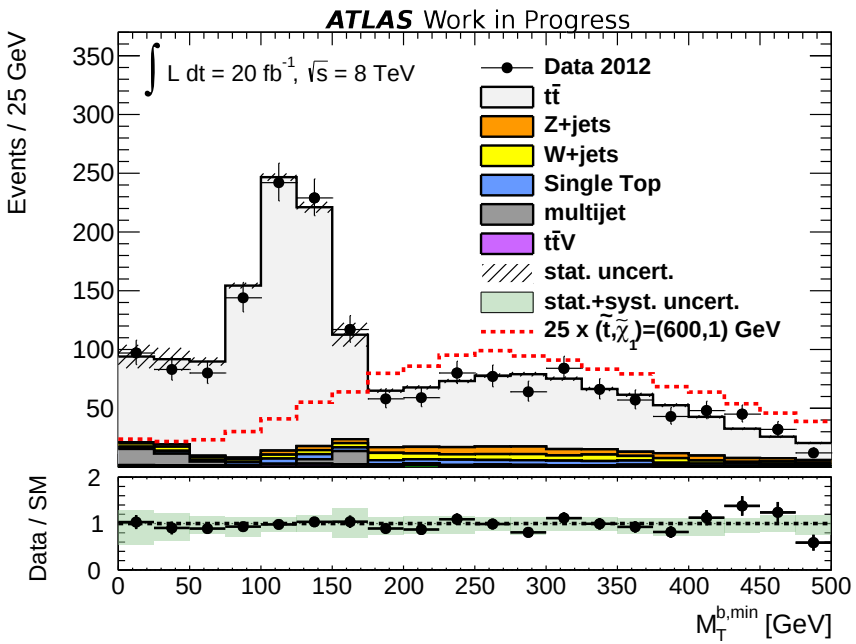



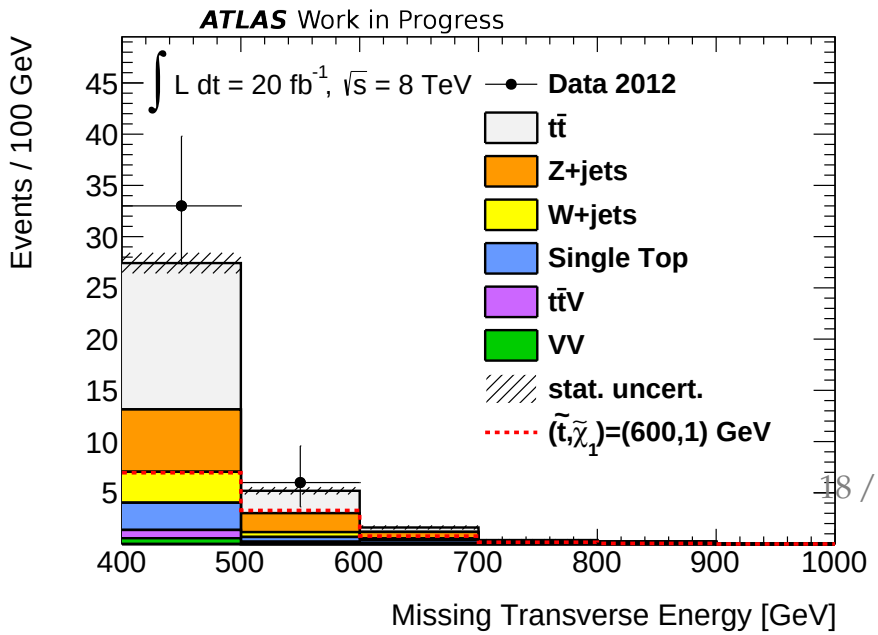
# 1. Signal region: 1 large-$R$ jet with a top candidate

## Selection

- 1 large-$R$ jet
- 1 HEPTopTagger candidate
- $N_{b\text{-jets}} \geq 1$
- $m_{\mathrm{T}}^{\mathrm{b,min}} \geq 175\,\mathrm{GeV}$
- $E_{\mathrm{T}}^{\mathrm{miss}} \geq 400\,\mathrm{GeV}$



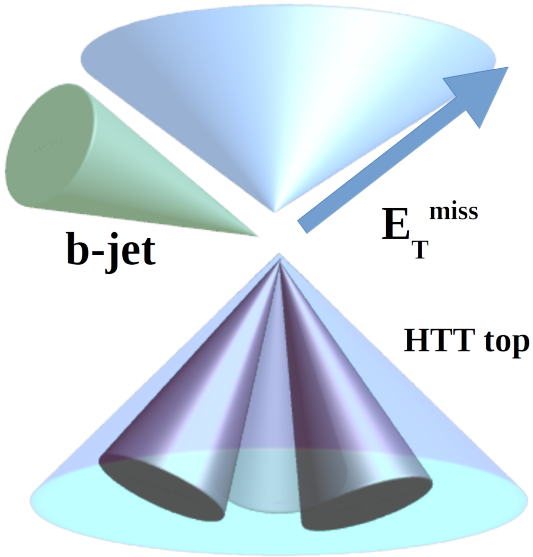



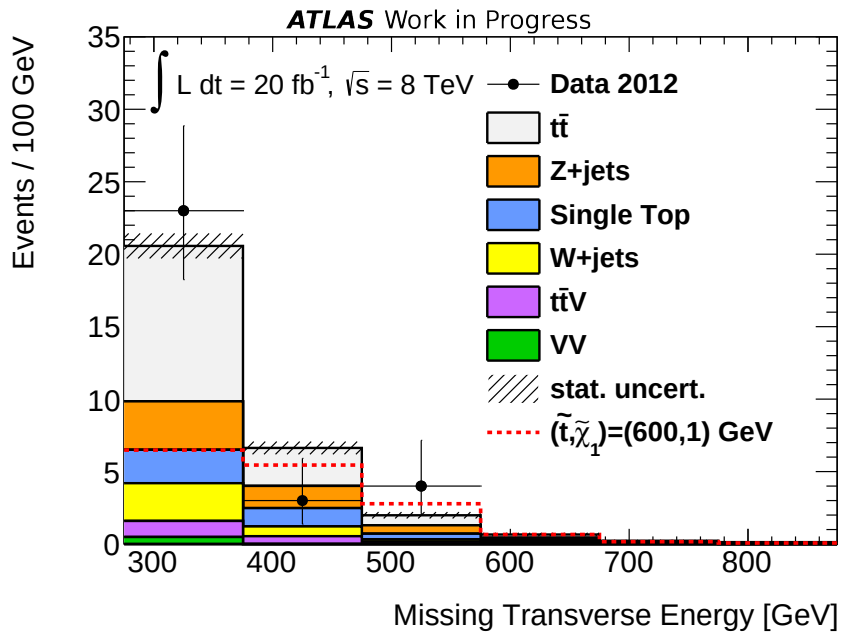



# 2. Signal region: 2 large-$R$ jets, one tagged

## Selection

- 2 large-$R$ jets
- 1 HEPTopTagger candidate
- $N_{b\text{-jets}} \geq 1$
- $m_{\mathrm{T}}^{\mathrm{b,min}} \geq 175\,\mathrm{GeV}$
- $E_{\mathrm{T}}^{\mathrm{miss}} \geq 275\,\mathrm{GeV}$

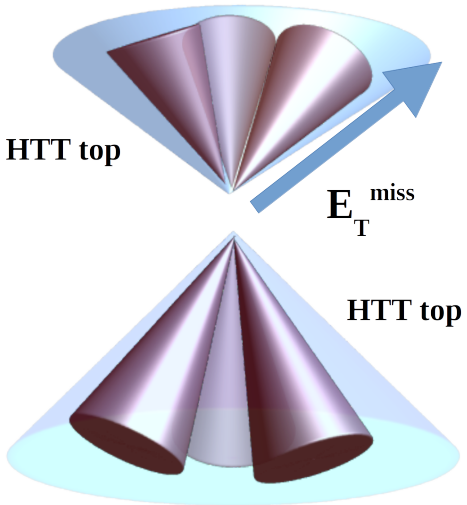


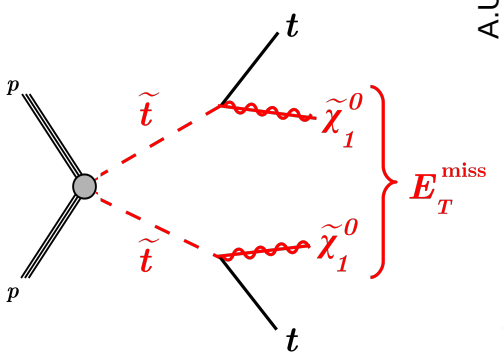
# 3. Signal region: 2 top candidates

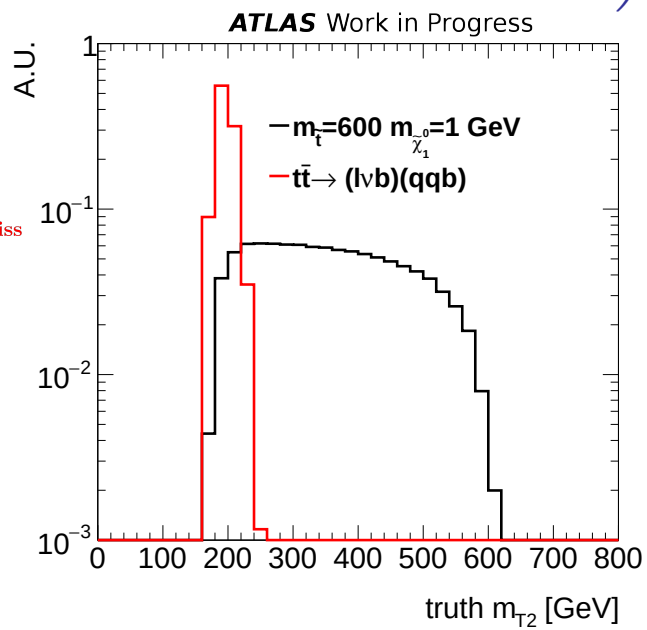
## Selection

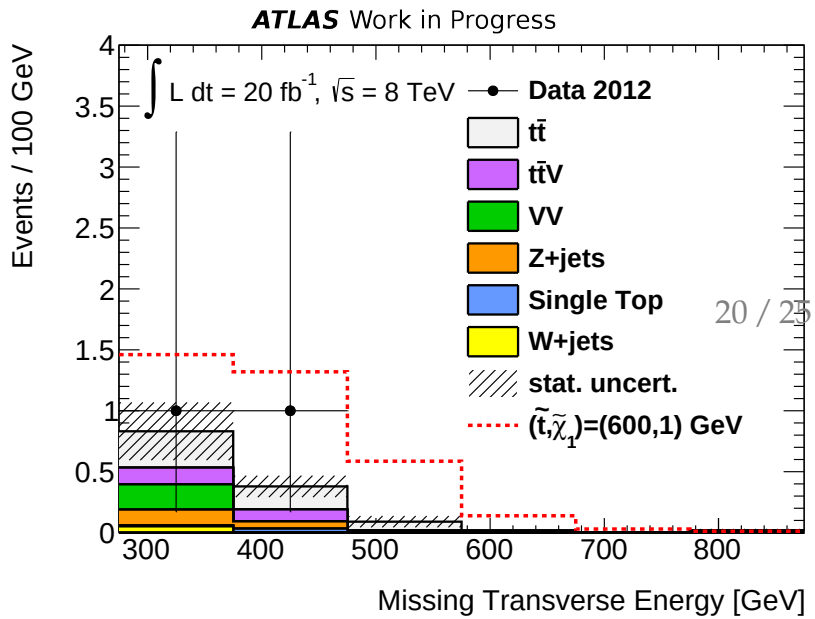
- 2 large-$R$ jets
- 2 HEPTopTagger candidates
- $m_{\mathrm{T2}} > 300\,\mathrm{GeV}$
- $E_{\mathrm{T}}^{\mathrm{miss}} \geq 275\,\mathrm{GeV}$




$$m_{T2}^2 = \min_{\vec{p}_T^{\,\chi_a} + \vec{p}_T^{\,\chi_b}} \left( \max \left( M_{\mathrm{T}}^2(\vec{p}_T^{\,t}, \vec{p}_T^{\,\chi_a}), M_{\mathrm{T}}^2(\vec{p}_T^{\,t}, \vec{p}_T^{\,\chi_b}) \right) \right)$$

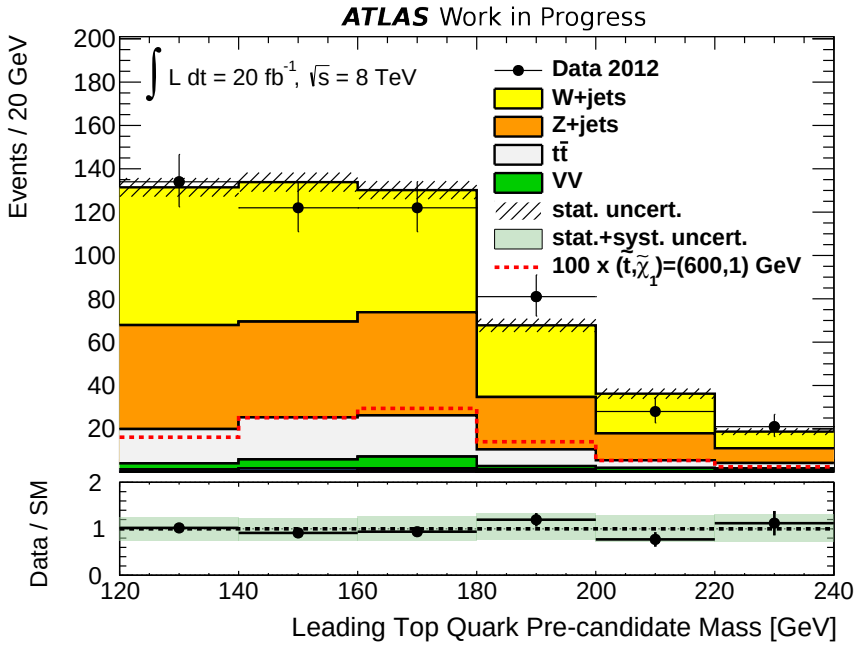


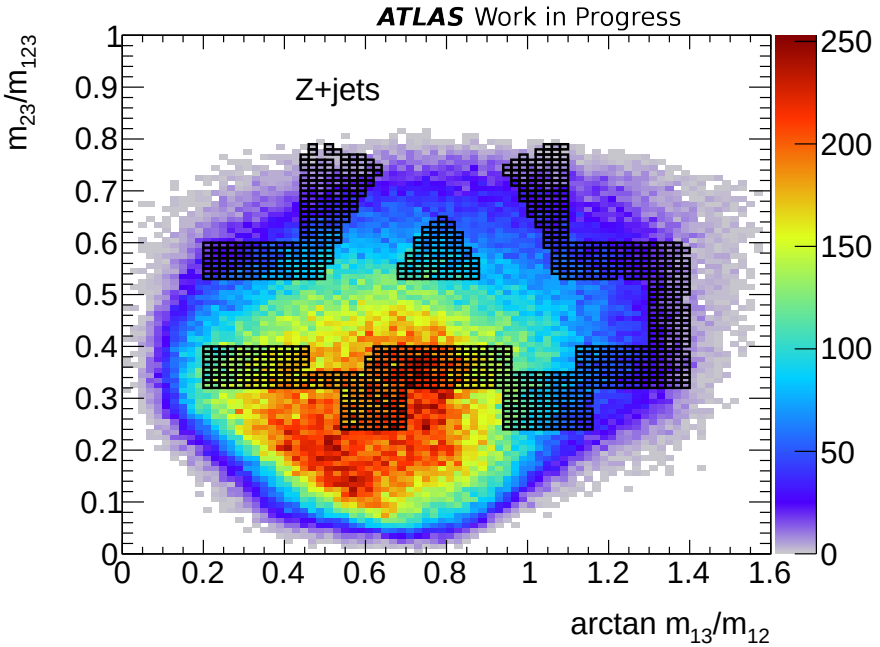



# Control regions (CR)

**V+jets** low $E_{\mathrm{T}}^{\mathrm{miss}}$, $N_{b\text{-jets}} = 0$, "inverted" top candidate

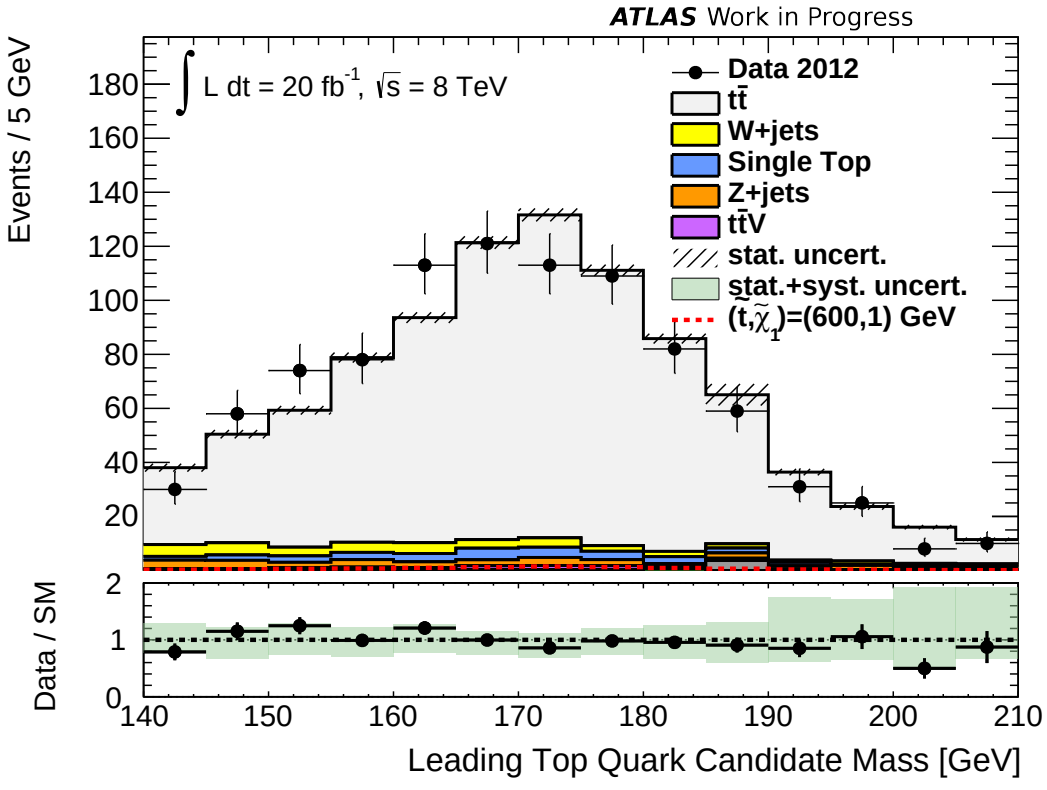


# Control regions (CR)

**V+jets** low $E_{\mathrm{T}}^{\mathrm{miss}}$, $N_{b\text{-jets}} = 0$, "inverted" top candidate

**$t\bar{t}$** low $E_{\mathrm{T}}^{\mathrm{miss}}$, $N_{b\text{-jets}} \geq 1$, low $m_{\mathrm{T}}^{\mathrm{b,min}}$



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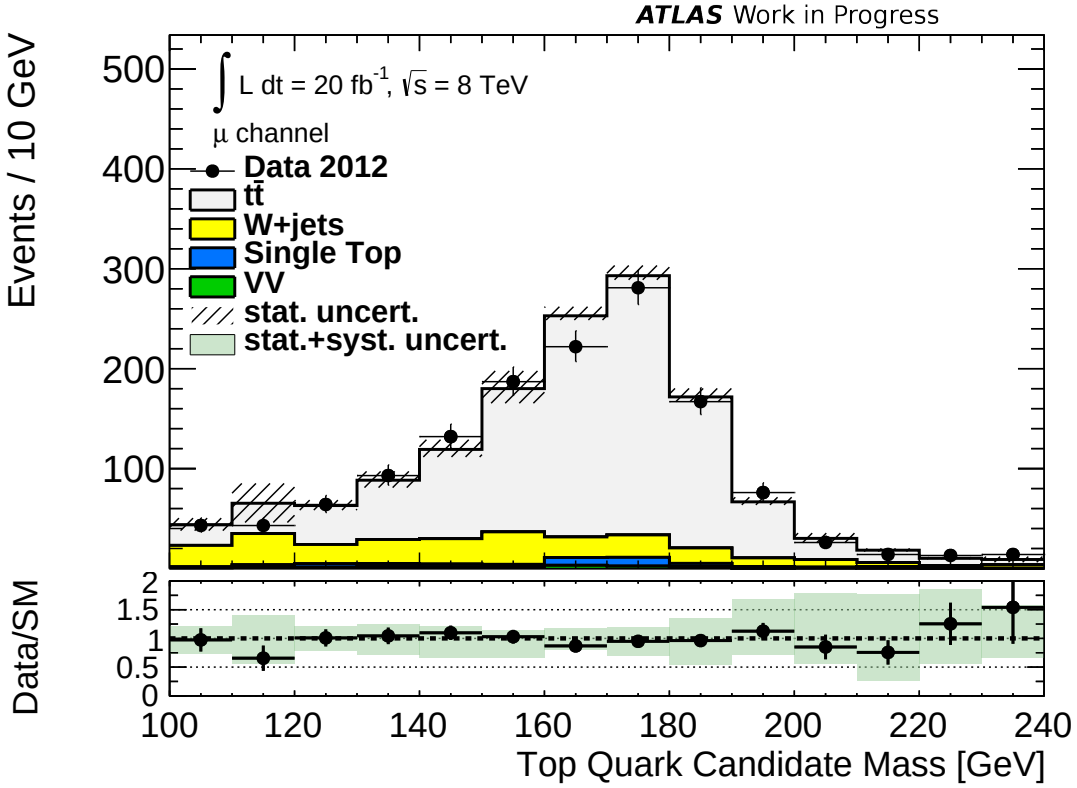
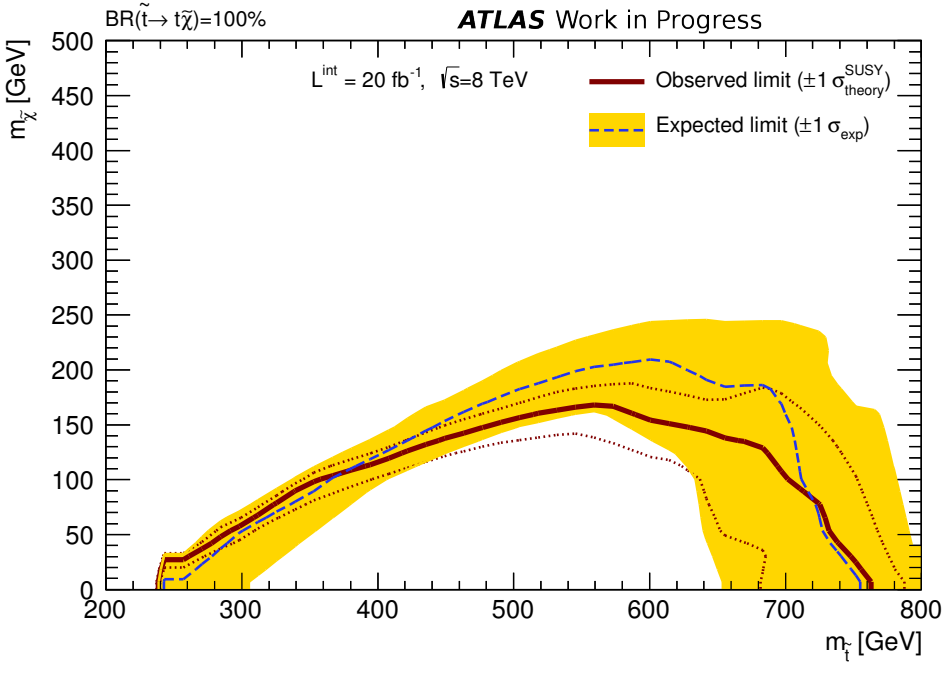
**$t\bar{t}$** low $E_{\mathrm{T}}^{\mathrm{miss}}$, $N_{b\text{-jets}} \geq 1$, low $m_{\mathrm{T}}^{\mathrm{b,min}}$

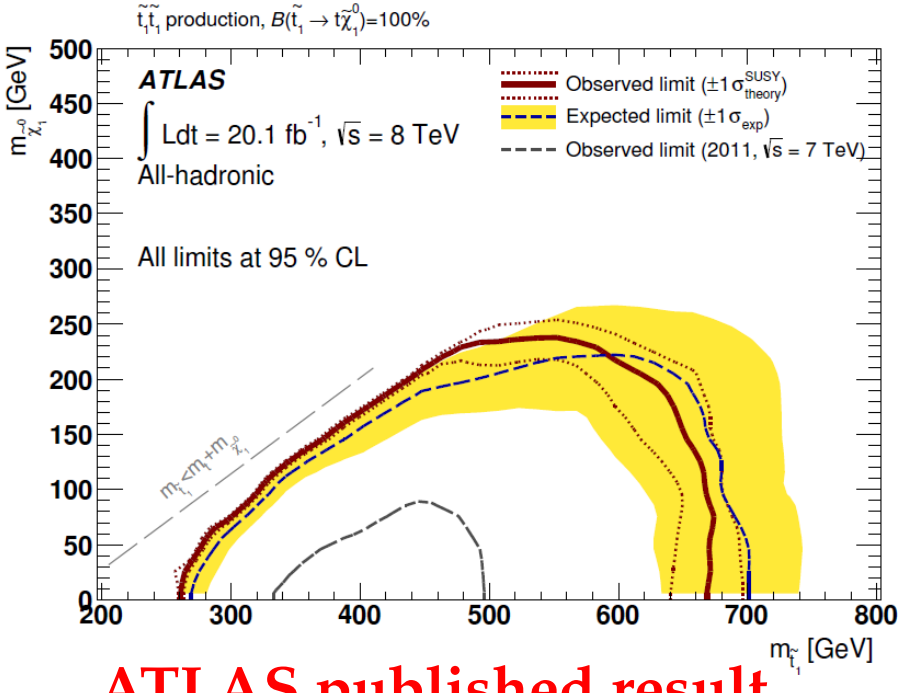
**$\mu$+jets** low $E_{\mathrm{T}}^{\mathrm{miss}}$, 1 muon



# Results

- No significant excess observed
- 95% C.L. exclusion limits computed for each point in the 2D $(m_{\tilde{t}}, m_{\tilde{\chi}_1^0})$ parameter space



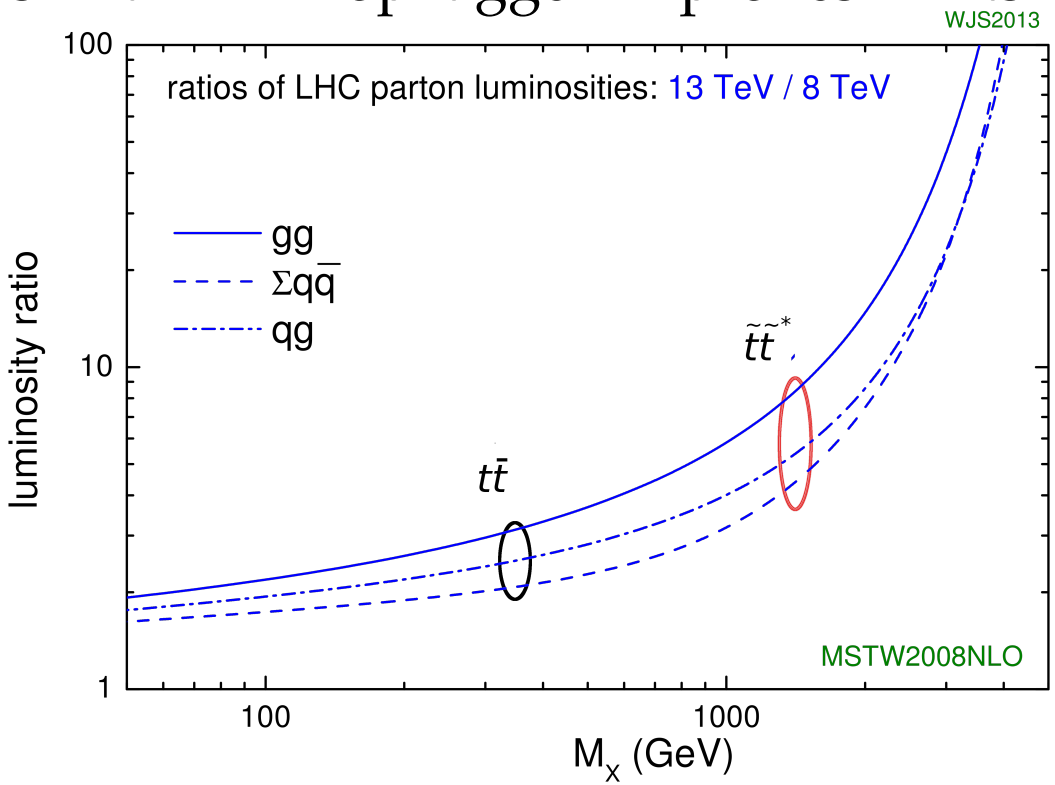




**ATLAS published result**

**Limit improvement for $m_{\tilde{t}} \gg m_{\tilde{\chi}_1^0}$**

# Conclusions and Outlook

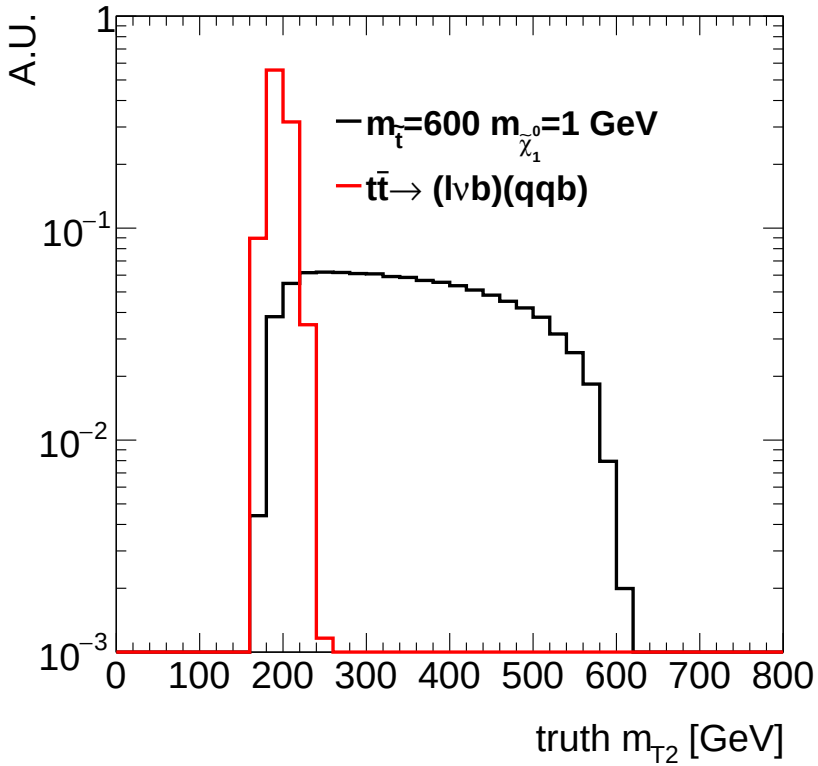
- search for stop pair production in fully hadronic channel
- analysis with HEPTopTagger improves limits



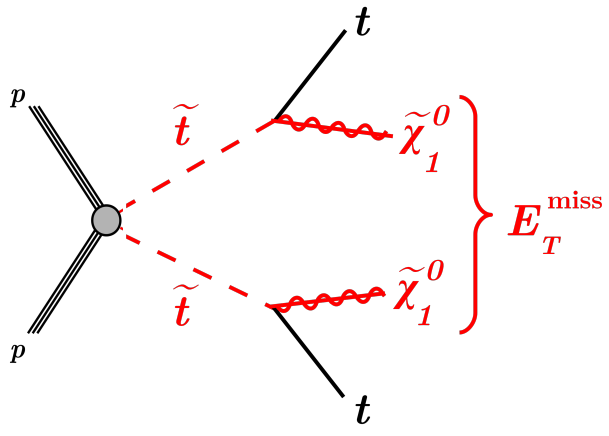

- at 13 TeV enhancement of signal cross section wrt bkg
- larger $m_{\tilde{t}}$ investigated $\rightarrow$ top quarks more boosted
- HEPTopTagger signal regions could be implemented orthogonally wrt to resolved ones

# $m_{T2}$, stransverse mass

(PHYS. LETT. B 463 99 (1999), J. PHYS. G 29 2343 (2003), JHEP 0812:063,2008)




- large discrimination power
- $m_{T2}^{\max}$ corresponds to $m_{\tilde{t}}$




By analogy with W transverse mass: $m_{\tilde{t}} \geq M_{\mathrm{T}}^{\tilde{t}}(\vec{p}_{T,t}, \vec{p}_{T,\chi})$

scanning over $\vec{p}_T^{\,\chi_a}, \vec{p}_T^{\,\chi_b}$ with: $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}} = \vec{p}_T^{\,\chi_a} + \vec{p}_T^{\,\chi_b}$

$$m_{T2}^2 = \min_{\vec{p}_T^{\,\chi_a} + \vec{p}_T^{\,\chi_b}} \left( \max \left( M_{\mathrm{T}}^2(\vec{p}_T^{\,t}, \vec{p}_T^{\,\chi_a}), M_{\mathrm{T}}^2(\vec{p}_T^{\,t}, \vec{p}_T^{\,\chi_b}) \right) \right)$$

$$\mathbf{m}_{\tilde{\mathbf{t}}}^2 \geq \mathbf{m}_{\mathbf{T2}}^2$$

**HEPTopTagger**