Boosted Top : An Experimental Overview

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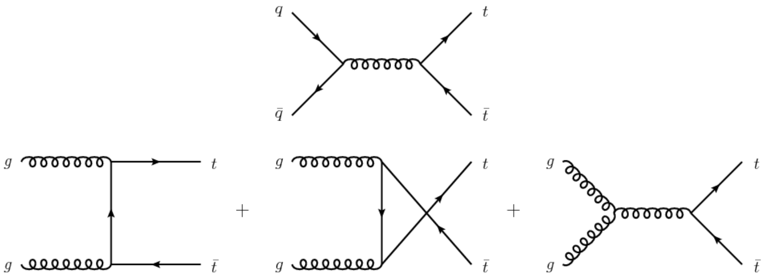
Outline

Outline

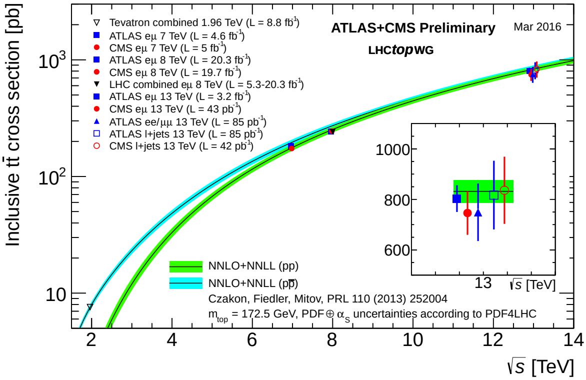
Top Quark Production at LHC



Important Feautures Of Top Quark

- **The heaviest particle in SM with mass 172.5 GeV**
- **With the strongest Yukawa coupling, it is the single most important parameter to determine the shape of the SM effective potential.**
- **Study of top quarks are important to measure its own properties as well as to understand the SM background in new physics search.**

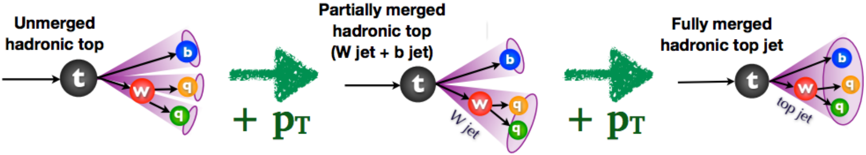
Boosted Top Quarks



- **At current LHC energies we have significant production cross-section of top quark pairs.**
- **Many new physics models predict heavy particles $\sim$ 1 TeV scale.**
  - **Those particles can decay into boosted top quarks.**
  - **Boosted tops are natural probes to BSM physics.**

Boosted Top Reconstruction : Fat Jets

- **If a top quark has a boost $\gamma(E/m)$: its decay products are collimated within an angle $\sim 2/\gamma$.**
- **We need a fat-jet of size parameter $R > 2/\gamma$ to capture all the decay products.**
- **Two popular choices of fat jets: Anti-kT (R = 1.0) and Cambridge-Aachen (R = 1.5).**



- **Given a fat jet, we need to figure out whether its originating from a top quark.**
  $\rightarrow$ Use fat jet properties to construct several Top-Taggers.
- **In general, the following jet substructure variables are used to design Top taggers :**
  - **trimmed jet mass (m_{jet})**
  - **K_t splitting scales ($\sqrt{d_{ij}}$)**
  - **N subjettiness (τ_N)**
  - **shower deconstruction (χ_{SD})**

Jet substructure variables for top-tagger

- **Trimming:** Remove the low p_T constituent $\rightarrow$ reduces the impact of pileup (large-R jets are more likely to be contaminated by PU).
- **k_t splitting scales :** scale of the last recombination steps in the $\mathrm{k_t}$ algorithm. Large R jet constituents are reclustered using $\mathrm{k_t}$ algorithm.

$$\sqrt{d_{ij}} = min(p_{Ti}, p_{Tj}) \times \Delta R_{ij} \,.$$

  - ✔ Sensitive to whether the last recombination steps correspond to the merging of the decay products of massive particles.
  - ✔ For hadronic top case : $\sqrt{d_{12}} \sim m_t/2$ and $\sqrt{d_{23}} \sim m_W/2$

Jet substructure variables for top-tagger

- **N-subjettiness:** τ_N quantify how well jets can be described as containing N or fewer subjets.

$$\tau_N = \frac{1}{d_0} \sum_k p_{Tk} \times \Delta R_k^{min} ,$$

with $d_0 \equiv \sum_k p_{Tk} \times R$.
  - ✔ $\tau_{ij} = \tau_i / \tau_j$.
  - ✔ τ_{32} discriminates 3-prong subjet structures with 2 or 1-prong fat jets.
  - ✔ τ_{21} is used to separate a 2-prong fat jet from 1-prong fat jet.
- **Shower Deconstruction:** ratio of likelihoods that measure the compatibility of the shower with a top quark decay over the same for a background process.

$$\chi(\{p_i^k\}) = \frac{\sum_{perm} P(\{p_i^k\}|signal)}{\sum_{perm} P(\{p_i^k\}|background)} .$$

  - ✔ Computation of SD is CPU intensive.
  - ✔ If χ is larger than a certain cut value, the large-R jet is tagged as a top jet.
- **HEPTopTagger:** identifies the hard jet substructure and tests it for compatibility with the 3-prong pattern of hadronic top-quark decays.
This tagger was developed to find top quarks with $p_T > 200$ GeV and to achieve a high rejection of background, which is largest for low-p_T large-R jets.

Outline

Atlas Top-Taggers in Run-1

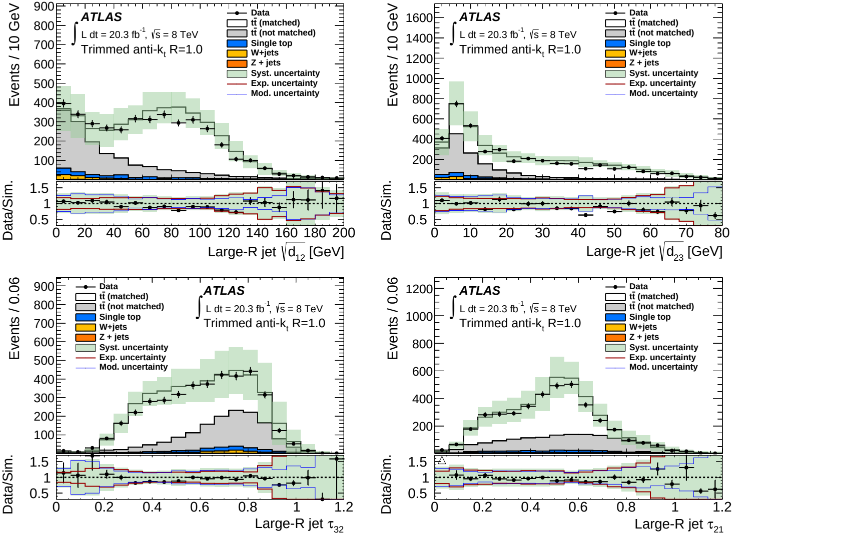
The substructure variables are used to define the top-taggers as following :

Tagger	Top-tagging criterion
Substructure tagger I	$\sqrt{d_{12}} > 40$ GeV
Substructure tagger II	$m > 100$ GeV
Substructure tagger III	$m > 100$ GeV and $\sqrt{d_{12}} > 40$ GeV
Substructure tagger IV	$m > 100$ GeV and $\sqrt{d_{12}} > 40$ GeV and $\sqrt{d_{23}} > 10$ GeV
Substructure tagger V	$m > 100$ GeV and $\sqrt{d_{12}} > 40$ GeV and $\sqrt{d_{23}} > 20$ GeV
W' top tagger	$\sqrt{d_{12}} > 40$ GeV and $0.4 < \tau_{21} < 0.9$ and $\tau_{32} < 0.65$

The large-R jets and their selection criteria as used by different taggers :

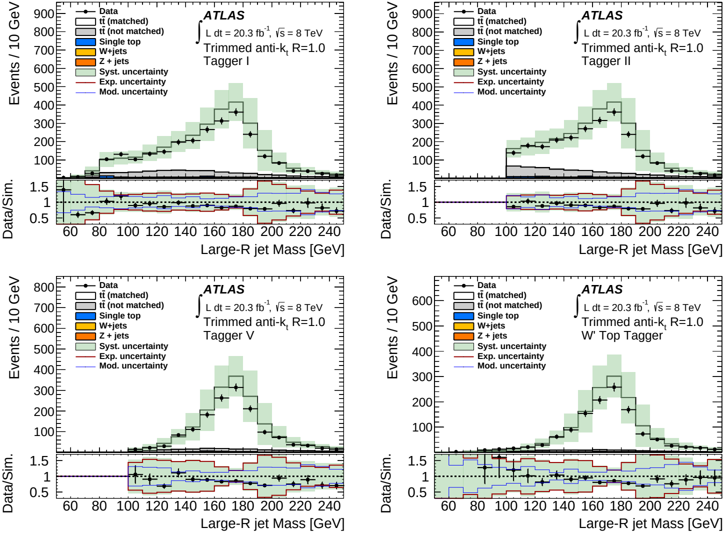
Tagger	Jet algorithm	Grooming	Radius parameter	p_{T} range	$\|\eta\|$ range
Tagger I–V W' top tagger Shower Deconstruction	anti-k_t	trimming ($R_{\mathrm{sub}} = 0.3$, $f_{\mathrm{cut}} = 0.05$)	$R = 1.0$	> 350 GeV	< 2
HEPTopTagger	C/A	none	$R = 1.5$	> 200 GeV	< 2

Distribution Of Jet-Substructure Variables



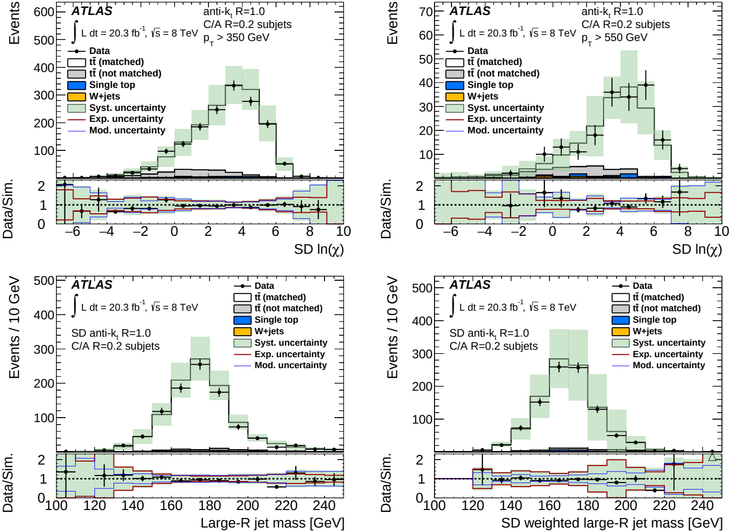
Distributions with leading trimmed anti-kT R = 1.0 jets.

Distribution Of Jet-Mass From Substructure Taggers

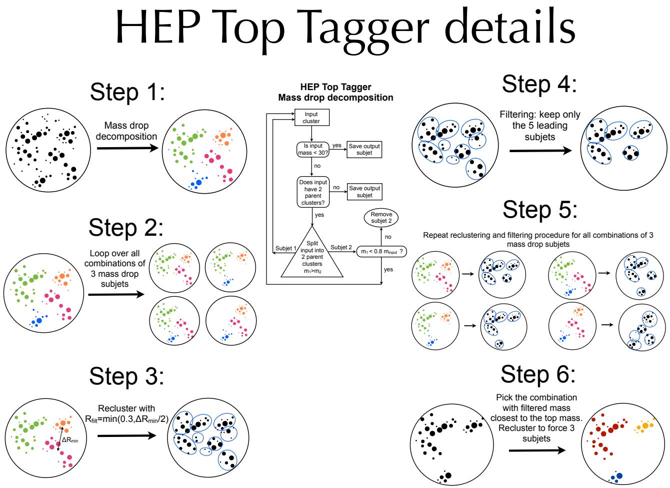


Mass distributions of the leading trimmed anti-kT R = 1.0 jets.

Distribution Of Shower Deconstruction Weight



Distributions of $log(\chi_{SD})$ with leading trimmed anti-kT $R = 1.0$ jets and its effect on jet-mass.



HepTopTagger Description.

HepTopTagger Specification

- **C/A R = 1.5 jets are analysed with the HEPTopTagger algorithm.**
- **It identifies the hard jet substructure and tests it for compatibility with the 3-prong pattern of hadronic top-quark decays.**

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

HepTopTagger Parameters

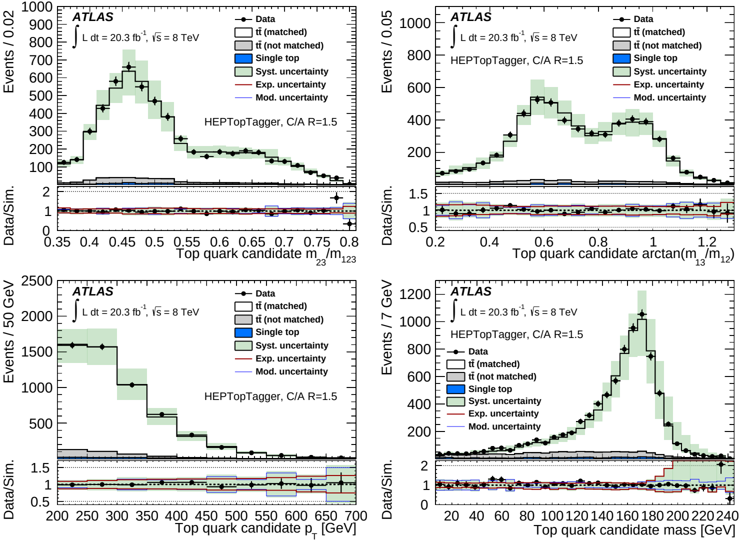
Parameter	Value
m_{min}	100 GeV
$p_{\text{T,min}}$	140 GeV
ΔR_{max}	1.1

HepTopTagger04 Parameters.

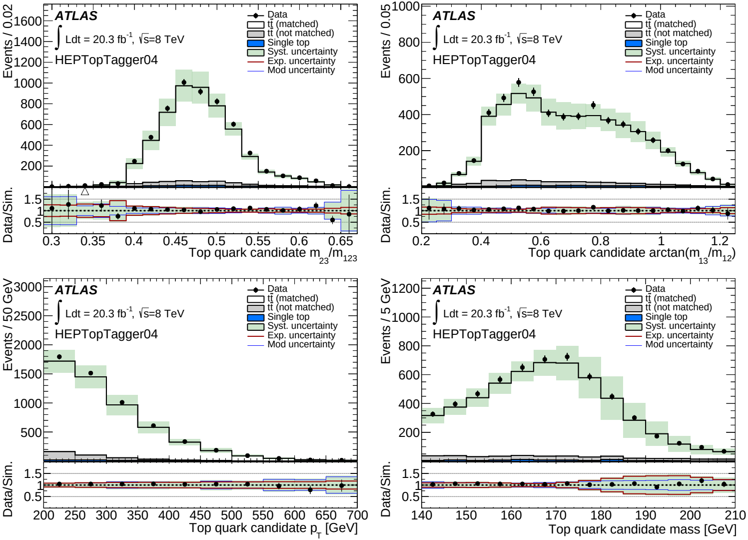
The large-R jet is considered to be tagged if :

- **The top-quark-candidate mass is between 140 and 210 GeV.**
- **The top-quark-candidate pT is larger than 200 GeV.**

Distribution Of Variables From HepTopTagger

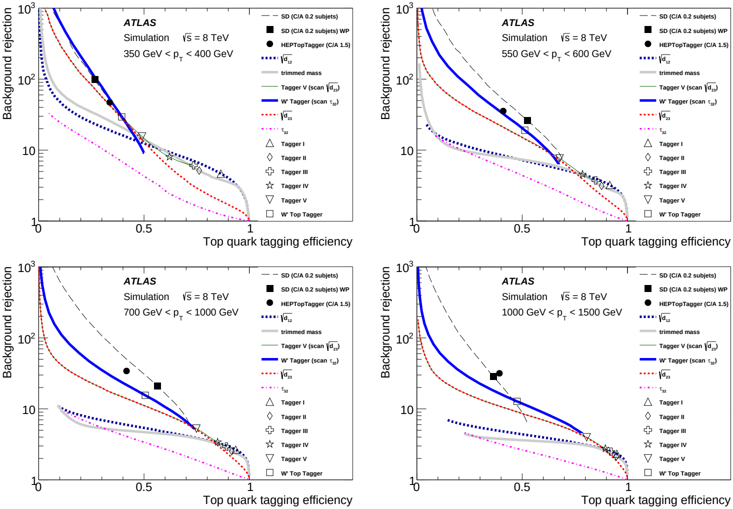


Distributions with leading trimmed C/A R = 1.5 jets.



Distributions with leading trimmed C/A R = 1.5 jets.

The background rejection vs the tagging efficiency

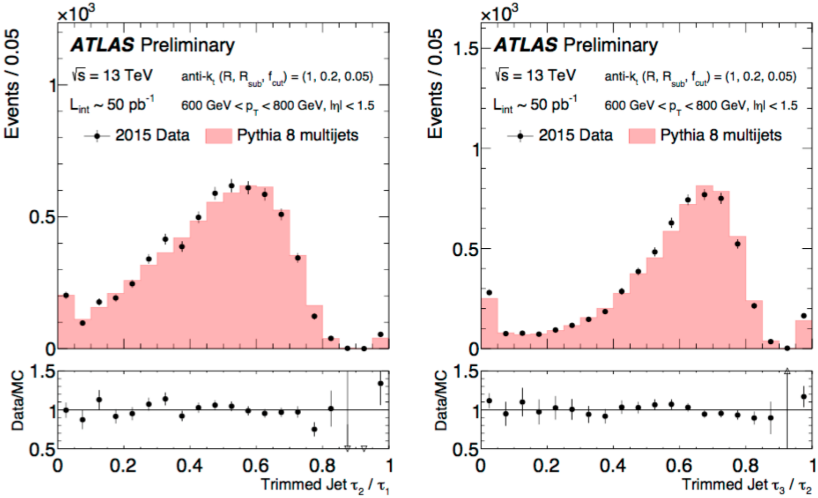


The background rejection as a function of the tagging efficiency

Uncertainties In Top-Tagger Efficiencies

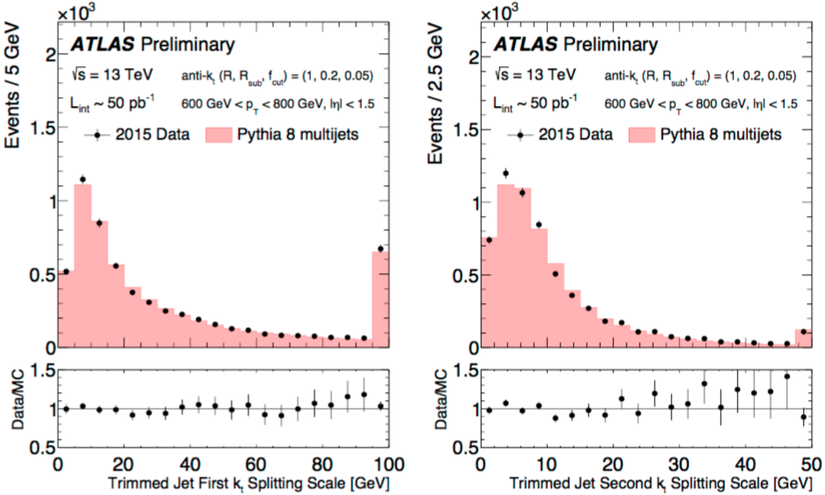
Source	Relative uncertainty of top-tagging efficiency (%)							
	Tagger I	Tagger II	Tagger III	Tagger IV	Tagger V	W′ Tagger	Shower Deconstruction	HEPTop-Tagger
Large-R jet energy scale	4.4	4.5	4.8	5.3	5.8	6.0	6.7	2.9
Large-R jet energy resolution	<0.1	0.1	0.1	0.2	0.2	0.3	0.8	1.5
Luminosity	1.0	1.0	1.1	1.2	1.3	1.4	1.5	1.3
b-tagging efficiency	2.7	2.6	2.9	3.1	3.5	3.7	3.9	3.5
Lepton reconstruction efficiency	0.5	0.5	0.5	0.6	0.7	0.8	0.8	2.0
$t\bar{t}$ cross section	1.9	1.8	1.9	2.1	2.4	2.6	2.6	2.0
$t\bar{t}$ ISR/FSR	1.4	1.3	1.4	0.5	1.6	1.6	2.2	3.2
$t\bar{t}$ generator	10	9.2	11	12	15	16	18	6.7
$t\bar{t}$ parton shower	4.8	4.1	4.6	4.8	4.6	5.1	5.1	1.7
$t\bar{t}$ PDF uncertainty	4.4	3.8	4.5	4.2	5.2	6.8	8.3	2.2
$t\bar{t}$ renormalization scale	0.8	0.8	0.8	0.9	1.0	1.1	1.0	0.6
Trimmed large-R jet mass scale	-	1.5	0.8	0.6	0.2	-	-	-
Trimmed large-R jet mass resolution	-	0.1	0.1	0.1	<0.1	-	-	-
$\sqrt{d_{12}}$	1.2	-	0.6	0.5	0.4	0.5	-	-
$\sqrt{d_{23}}$	-	-	-	0.7	1.1	-	-	-
τ_{21}	-	-	-	-	-	0.6	-	-
τ_{32}	-	-	-	-	-	1.4	-	-
Subjet energy scale	-	-	-	-	-	-	0.5	1.1
Subjet energy resolution	-	-	-	-	-	-	0.4	0.7
Total	13	12	14	15	18	20	22	9.9

N-subjettiness at 13 TeV



The early 13 TeV data is showing good consistency with expected values.

N-subjettiness at 13 TeV



The early 13 TeV data is showing good consistency with expected values.

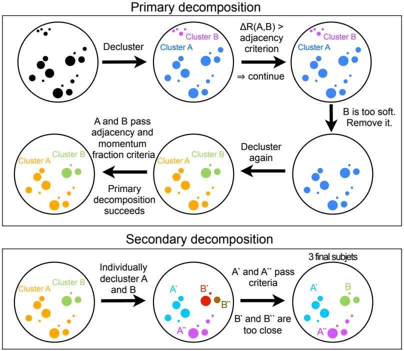
Outline

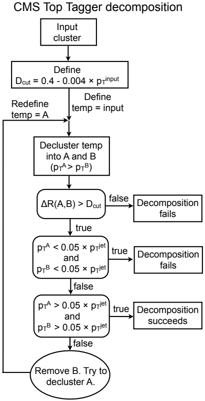
CMS Top-Tagger Algorithm

The CMS top-taggers are based on following variables :

- **Jet mass** m_{jet}
- **Number of Subjets** $N_{subjets}$ **: The number of subjets found by the top-tagging algorithm.**
- **Minimum pairwise mass** m_{min} **:** $m_{min} = Min[m_{12}, m_{23}, m_{12}]$.
- **Jets are selected with** $p_T > 350$ **GeV and** m_{min} **close to** W **mass.**

Example: CMS Top Tagger decomposition





CMS Combined Top-Taggers

Working point	m_{jet} selection	m_{min} selection	subjet b-tag WP	τ_3/τ_2 selection
CMS Tagger WP0	140-250 (GeV/c^2)	$>$ 50 (GeV/c^2)	none	none
CMS Combined WP1	140-250 (GeV/c^2)	$>$ 50 (GeV/c^2)	CSV-loose	$<$ 0.7
CMS Combined WP2	140-250 (GeV/c^2)	$>$ 50 (GeV/c^2)	CSV-loose	$<$ 0.6
CMS Combined WP3	140-250 (GeV/c^2)	$>$ 50 (GeV/c^2)	CSV-medium	$<$ 0.55
CMS Combined WP4	140-250 (GeV/c^2)	$>$ 65 (GeV/c^2)	CSV-medium	$<$ 0.4

CMS taggers with different working points.

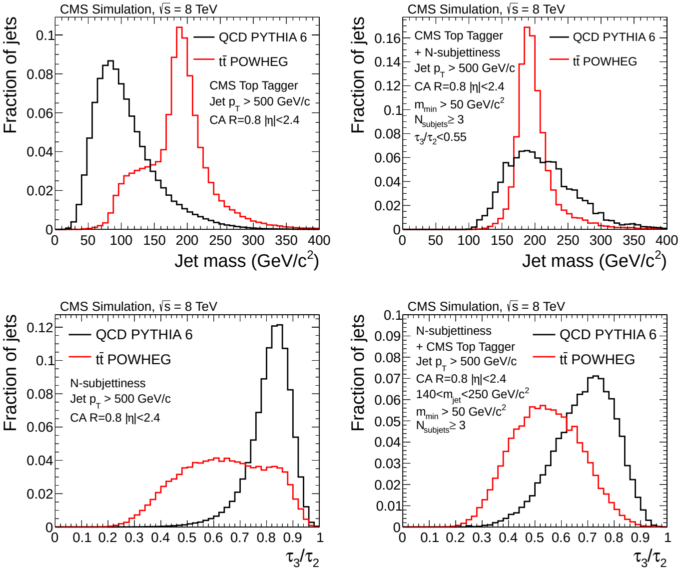
Working point	m_{123} selection	f_W selection	subjet b-tag WP	τ_3/τ_2 selection
HEP WP0	140-250 (GeV/c^2)	0.495	none	none
HEP Combined WP1	140-250 (GeV/c^2)	0.495	CSV-loose	none
HEP Combined WP2	140-250 (GeV/c^2)	0.15	CSV-medium	none
HEP Combined WP3	140-250 (GeV/c^2)	0.15	CSV-medium	$<$ 0.63

HEPTopTagger with different working points.

Tagging selection	Efficiency (%) vs. N_{vtx} slope	Mistag rate (%) vs. N_{vtx} slope
CMS Tagger WP0	-0.031 $\pm$ 0.034	0.095 $\pm$ 0.006
$\tau_3/\tau_2 < 0.55$ (R=0.8)	-0.429 $\pm$ 0.031	-0.031 $\pm$ 0.001
Subjet b-tag CSV-medium	-0.049 $\pm$ 0.033	0.006 $\pm$ 0.002
CMS Combined Tagger WP3	-0.213 $\pm$ 0.024	-0.002 $\pm$ 0.0002
HEP Tagger WP2	-0.180 $\pm$ 0.028	-0.010 $\pm$ 0.006
HEP Combined Tagger WP3	-0.463 $\pm$ 0.0236	-0.001 $\pm$ 0.002

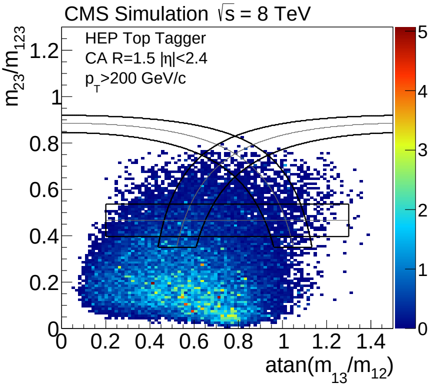
Sensitivity of the taggers w.r.t pileup.

CMS Combined Taggers Performance

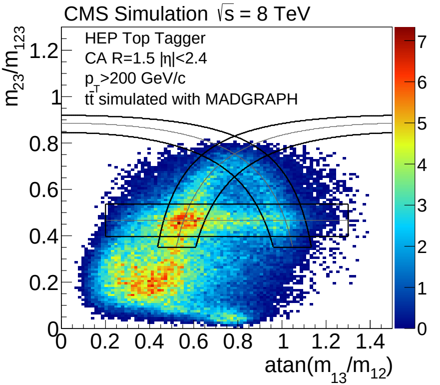


Performance of CMS combined taggers.

CMS HepTopTagger Performance



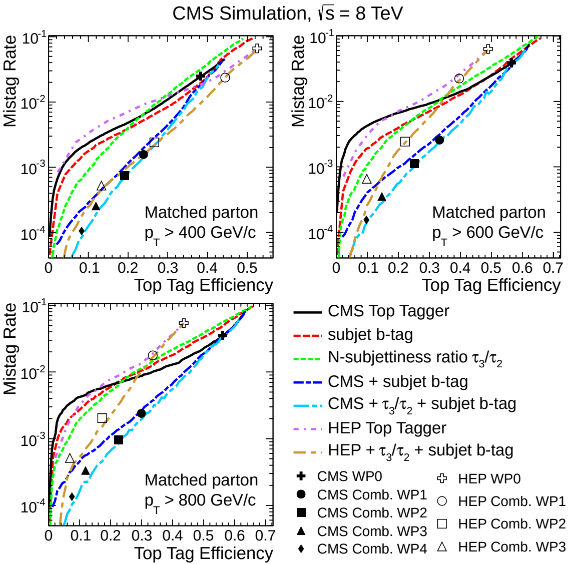
Background Sample



Signal Sample

The background sample consists of cross section weighted boson+jets, diboson, single-top, tt all-hadronic, and tt leptonic production

Mistag Rate vs Tagging Efficiency



- **Mistag rate vs top-jet tagging efficiency as measured from QCD PYTHIA 6 Monte Carlo and POWHEG** *tt* **Monte Carlo.**
- **Jets are selected with a mass cut** $140 < m_{jet} <$ 250 **GeV.**

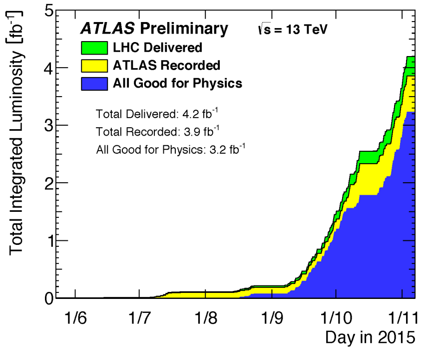
Outline

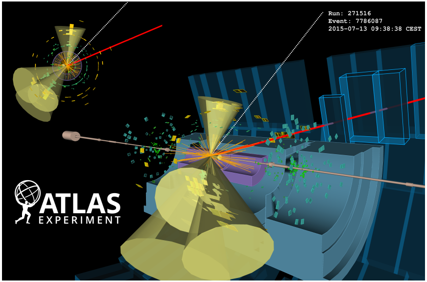
Summary

- **With Run-1 data, comparison of different top-tagger (built from substructure variables, SD and HepTopTagger) performances were studied.**
- **Efficiency and rejection rates are studied for different p_T region**
  - ✔ **The regular taggers are studied in the p_T range 350 to 1500 GeV**
  - ✔ **HepTopTagger is studied in the region 200 $<$ p_T $<$ 350 GeV.**
  - ✔ **In 350 $< p_T <$ 1000 GeV range, SD tagger gives the best background rejection rate.**
  - ✔ **A rejection of $\approx$ 15 to 20 at an efficiency of $\approx 50\%$ can be achieved with the W' top tagger over the range 450 $< p_T <$ 1000 GeV.**
  - ✔ **For 1000 $< p_T <$ 1500 GeV, of all the top-tagging methods studied, the HEPTopTagger offers the best rejection ($\approx$ 30) at an efficiency of $\approx 40\%$.**
  - ✔ **Among all the uncertainty sources, large R JES, $t\bar{t}$ parton-shower and $t\bar{t}$ PDF uncertainty has largest contribution to the top-tagger efficiencies.**
- **Several top tagging algorithms and jet observables are studied in both data and simulation, including the CMS Top Tagger, HEP Top Tagger, and N-subjettiness.**
  - ✔ **The HEP Combined Tagger performs best for low p_T ($p_T <$ 400 GeV) selections.**
  - ✔ **The CMS Combined Tagger performs best for high p_T ($p_T >$ 400 GeV) selections.**

Backup

LHC Luminosity Collection



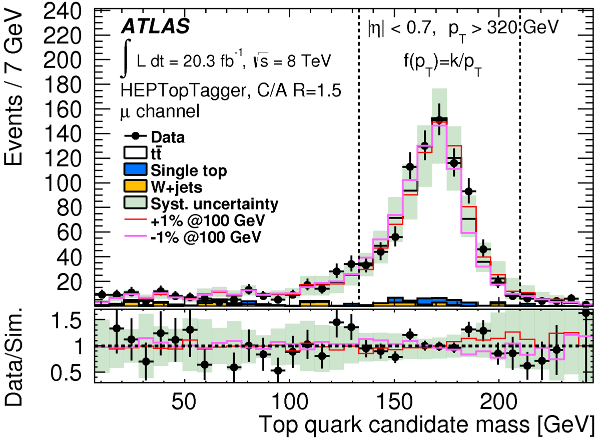


Luminosity for 2015 Data

A boosted $t\bar{t}$ event

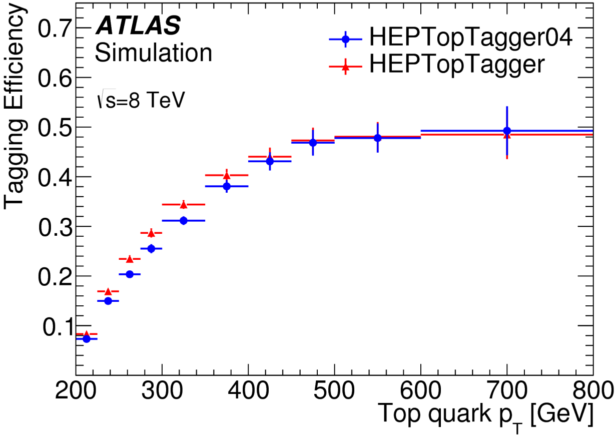
With more data in 2016, we will have a better sensitivity to new physics search in boosted $t\bar{t}$ events.

HepTopTagger top candidate mass



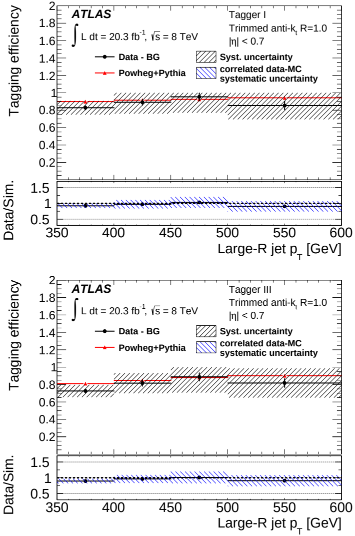
HepTopTagger top candidate mass from μ + jet.

HepTopTagger efficiency



HepTopTagger efficiency vs p_T.

Measured tagging efficiency



Measured tagging efficiency

HepTopTagger W-mass selection

HEP Top Tagger - W mass selection

Bi-dimensional distribution based on the ratio of subjet pairwise masses

$$R^2_{\min}(1+(\frac{m_{12}}{m_{13}})^2) < 1-(\frac{m_{23}}{m_{123}})^2 < R^2_{\max}(1+(\frac{m_{12}}{m_{13}})^2)$$

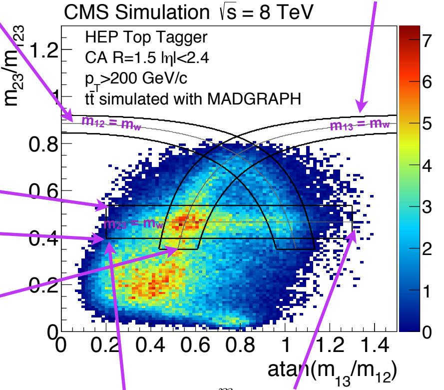
$$R^2_{\min}(1+(\frac{m_{13}}{m_{12}})^2) < 1-(\frac{m_{23}}{m_{123}})^2 < R^2_{\max}(1+(\frac{m_{13}}{m_{12}})^2)$$

$$R_{\min} < \frac{m_{23}}{m_{123}} < R_{\max}$$

$$R_{\max} = (1+f_W) \times m_W/m_t$$

$$R_{\min} = (1-f_W) \times m_W/m_t$$

$$\frac{m_{23}}{m_{123}} > 0.35$$



$$0.2 < \arctan\frac{m_{13}}{m_{12}} < 1.3$$

Jet Grooming

Jet Trimming:

- Recluster the constituents using some jet algorithm (the original reference specifies k_T), and resolve on a fixed small angular scale R_0.
- Keep each subjet i that passes a p_T threshhold : $p_{T,i} > f\Lambda_{hard}$, for a cutoff parameter f_{cut} and a hard momentum scale Λ_{hard}.
- The final trimmed jet is the sum of the retained subjets.

Jet Pruning:

- Given a jet J, recluster its constituents with C-A, and then sequentially unwind the cluster sequence.
- At each splitting $P \to ij$, check whether the splitting is both soft,

$$z = \frac{Min(p_{T,i}, p_{T,j})}{p_{T,P}} < z_{cut} \, ,$$

and at wide angle $\Delta R_{ij} > D_{cut}$. If so, then drop the softer of i, j, and continue unwinding the harder.
- Stop when you find a sufficiently hard (or collinear) splitting.