Precision measurements of boosted top at LHC

Jie Yu

Iowa State University

On behalf of the ATLAS and CMS Collaborations

Precision Theory, Quy-Nhon, Vietnam

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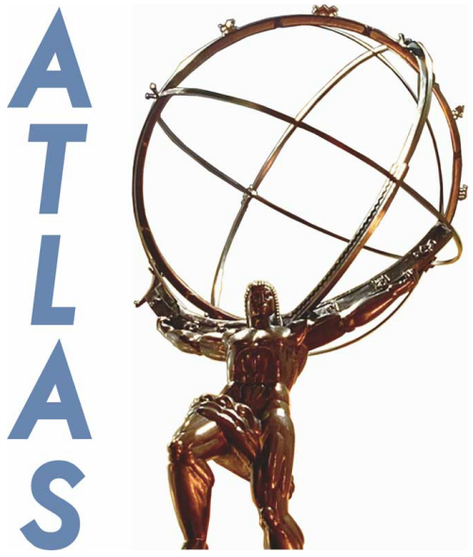
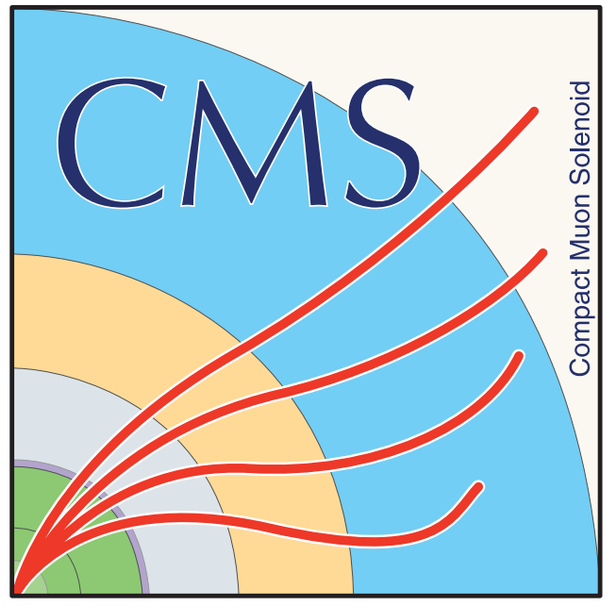
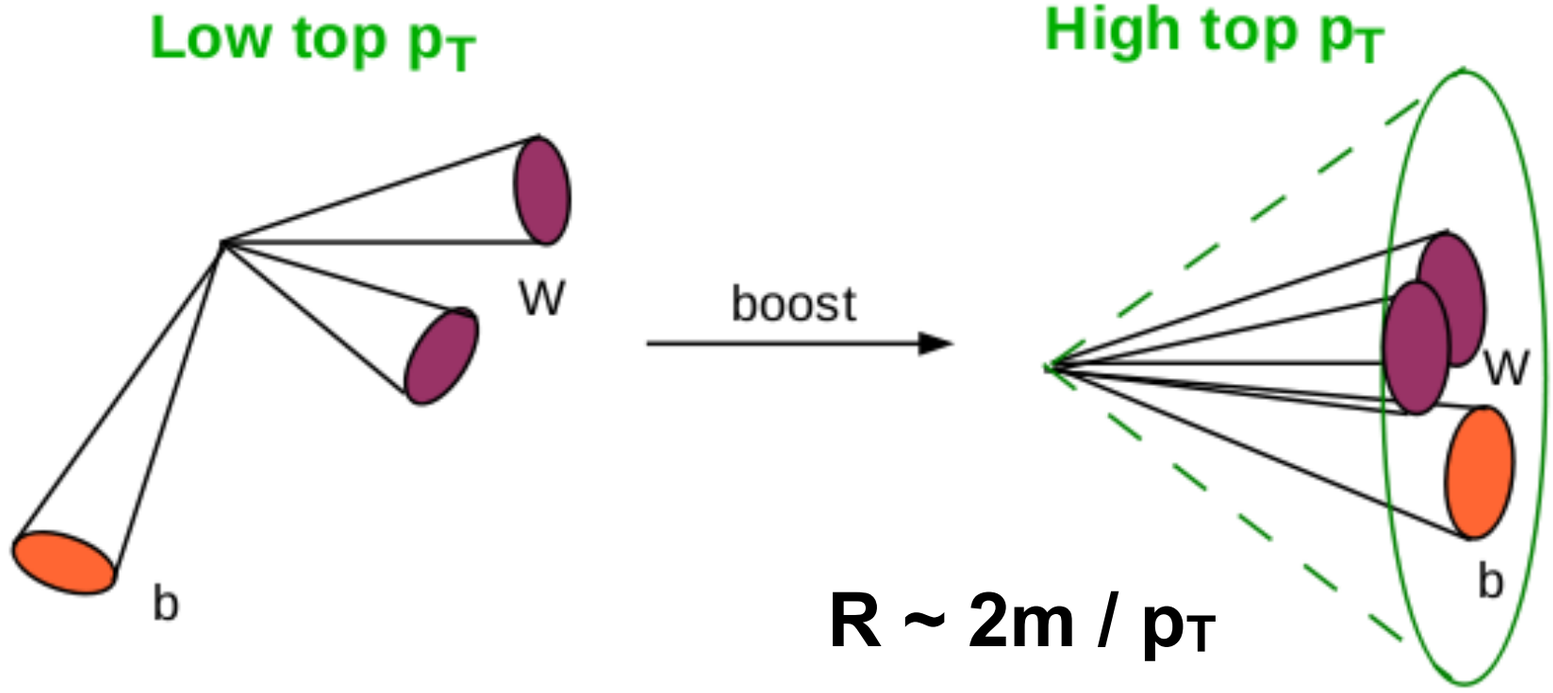




Introduction

- Outline
  - Introduction to Top Tagger
  - Boosted top measurements in CMS and ATLAS

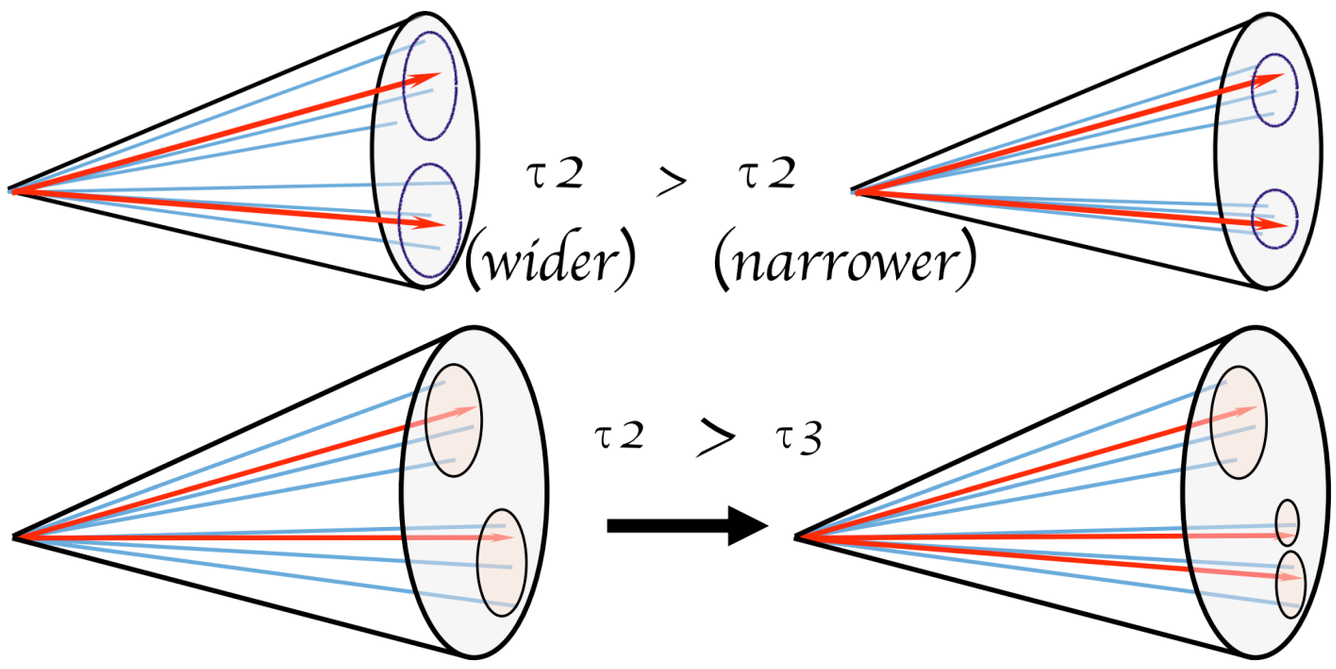


- The necessity of Top Tagger at LHC
  - New Physics (NP): plenty of NP models predict highly boosted top-quarks in the final state.
  - Decay products highly collimated: less efficient in resolving small-R jets.
  - Effective in high pileup: luminosity increases and pileup increases with it.
  - High efficiency vs rejection: a single jet containing all top-decay products has different properties compared to a QCD jet (single dense core).

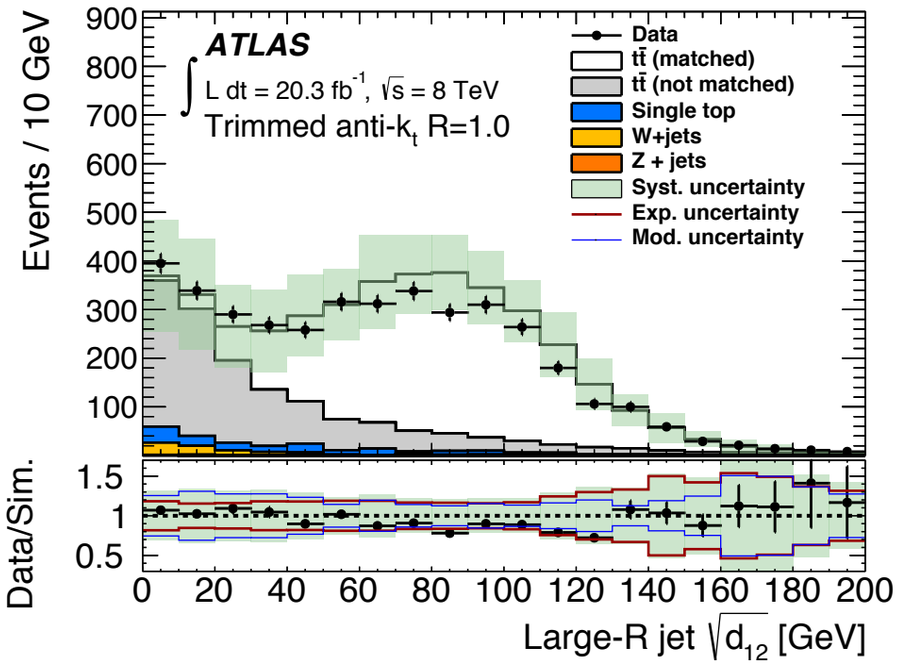
Top Tagger in ATLAS

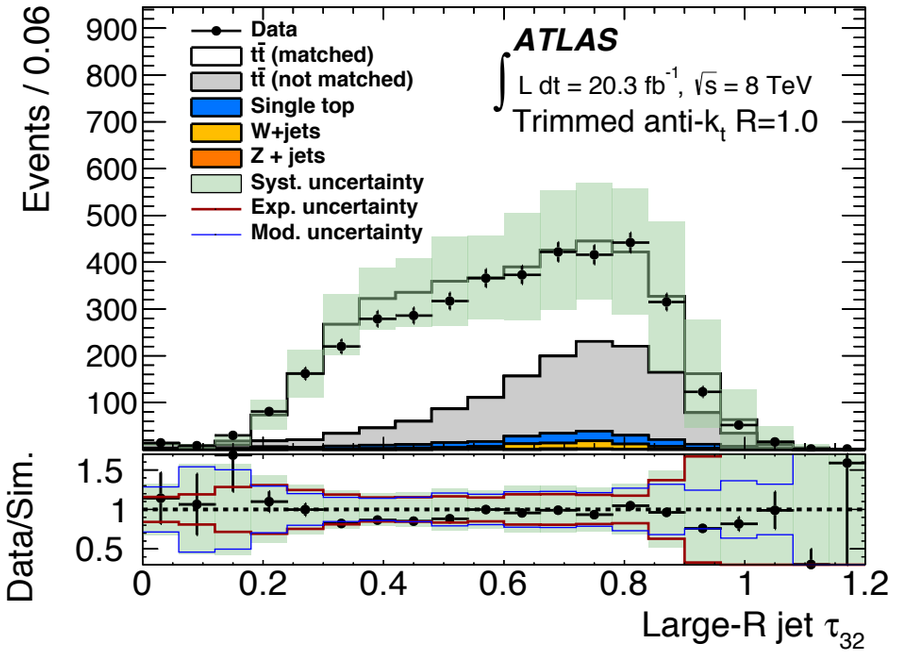
- Large-R jet reconstruction:
  - Anti-kt R=1.0 p_T > 350 GeV |η|<2.0.
  - Groomed and trimmed, sub-jet (kt, R=0.3) of p_T < 5% * p_T^J removed (suppress pileup).
  - Trimmed jet mass corrected to particle top jet using MC.
- Top Tagging: sub-structure variables:
  - **Kt splitting scale** $\sqrt{d_{ij}} = \min(p_{Ti}, p_{Tj}) \times \Delta R_{ij}$,
    $\sqrt{d_{12}} \sim m_{top} / 2$, $\sqrt{d_{23}} \sim m_W / 2$
  - **N-subjetness**, jet shape variable to measure the hypnosis of having N-subjets:

$$\tau_N = \frac{\sum_{i=1}^{n_{\text{constituents}}} p_{T,i} \min\{\Delta R_{1,i}, \Delta R_{2,i}, ..., \Delta R_{N,i}\}}{\sum_{i=1}^{n_{\text{constituents}}} p_{T,i} R}$$



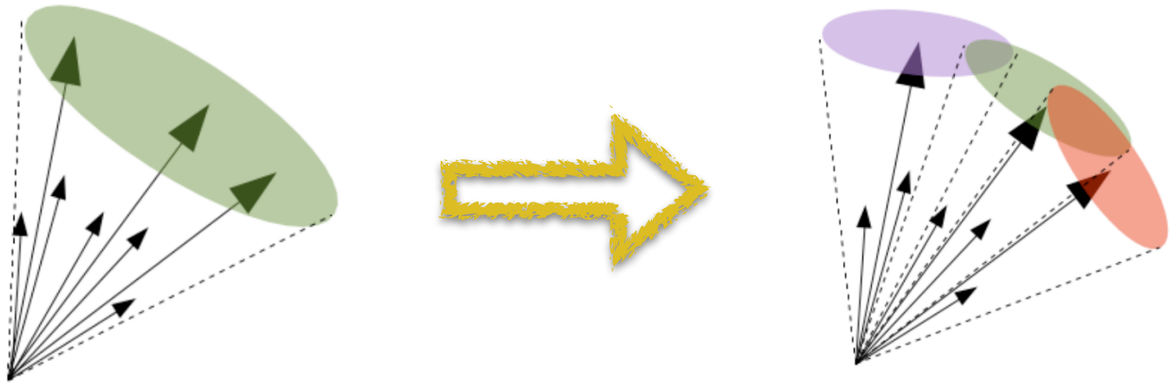
arxiv:1603.03127





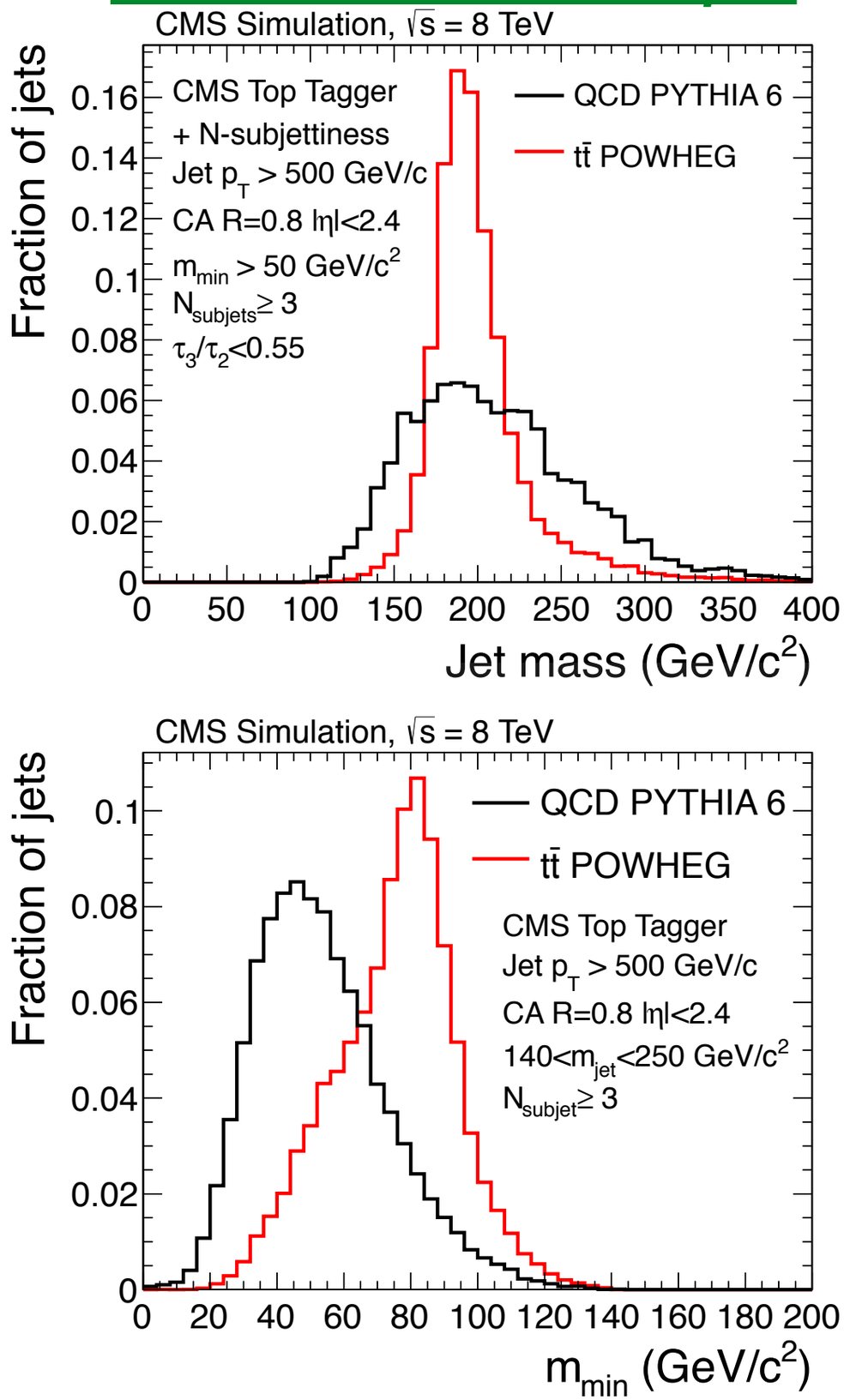
$\tau_{32} = \tau_3/\tau_2$

Top Tagger in CMS



- Large-R jet: C/A with R = 0.8, p_T > 350 GeV.
- CMS Top-Tagging algorithm:
  - Primary decomposition: reversed order pairwise cluster sequence to find **two** subclusters. (If failed, original jet is kept.)
  - Secondary decomposition: decomposition into 3 - 4 subjets.
  - Most discriminant variables constructed (3 leading subjets):
    - Jet mass m_{jet}, etc.
    - Minimum pairwise mass m_{min} = $\min(m_{12},m_{13},m_{23})$
- Other algorithms: N-subjetness, HEP Top Tagger

Link CMS: JME-13-007-pas

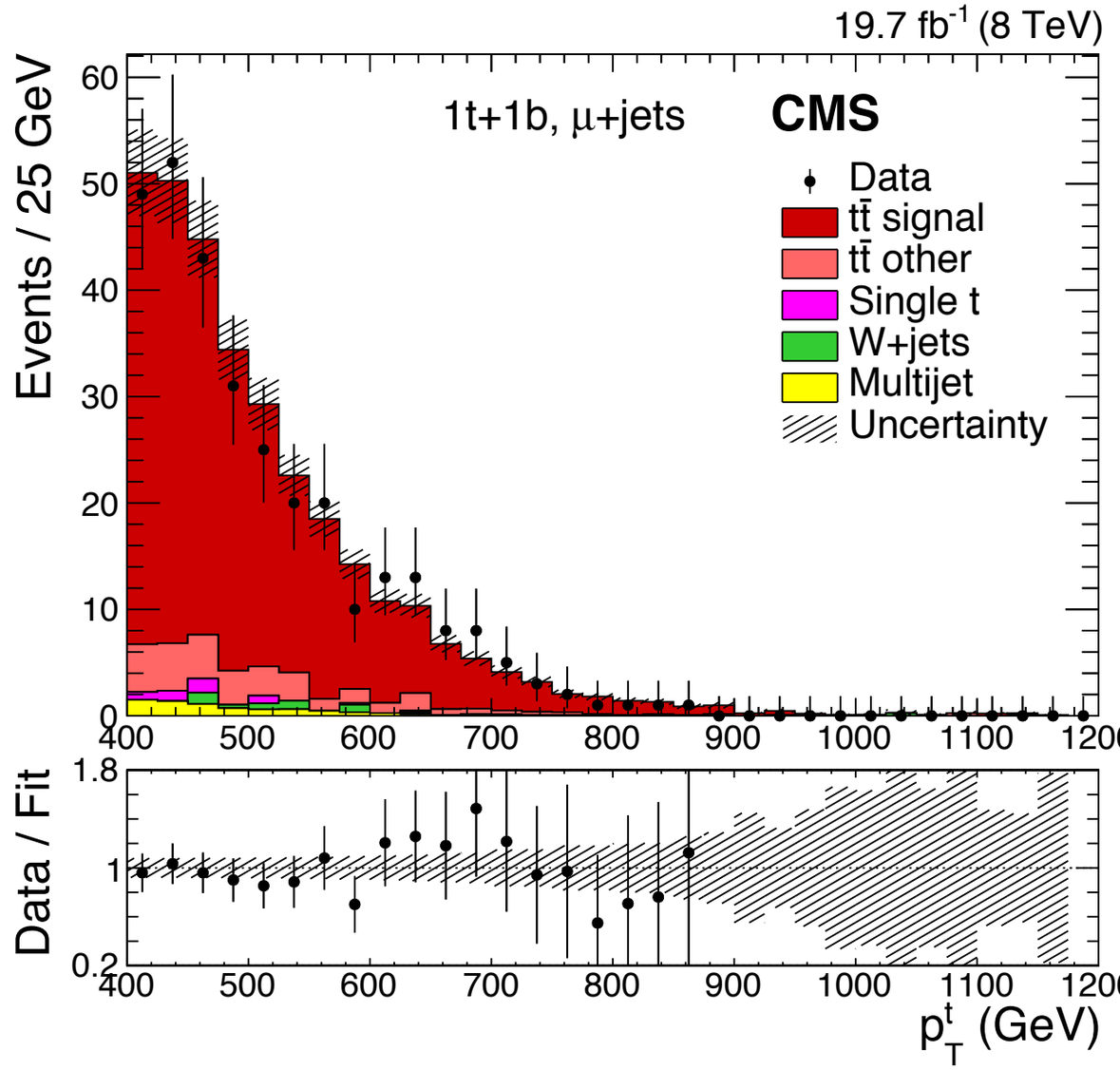


Differential Cross-section Measurements using boosted top

Differential cross section @8TeV in CMS

- Precisely measure differential cross-section of top pair at high pT:
  - Critical test of Standard Model.
  - Monte Carlo generator tuning, precise determination of PDF of the proton.
  - Sensitive to new physics search / background to BSM.

- Event selection **1 lepton + jets**:
  - **Cambridge/Aachen (C/A) large-R jet R=0.8, p_T > 400 GeV**; mass ~ [140, 250] GeV; CMS Top Tagger.
  - Anti-kt small-R jet R=0.5, b-tagging @65%.
- Maximum likelihood fit in (0t, 1t+0b, 1t +1b) exclusive categories.
  - Discriminant variables: lepton |eta| used in (0t, 1t+0b), m_{vtx} used in 1t+1b
  - Background normalizations and experimental uncertainties treated as nuisance parameters.



arxiv:1605.00116

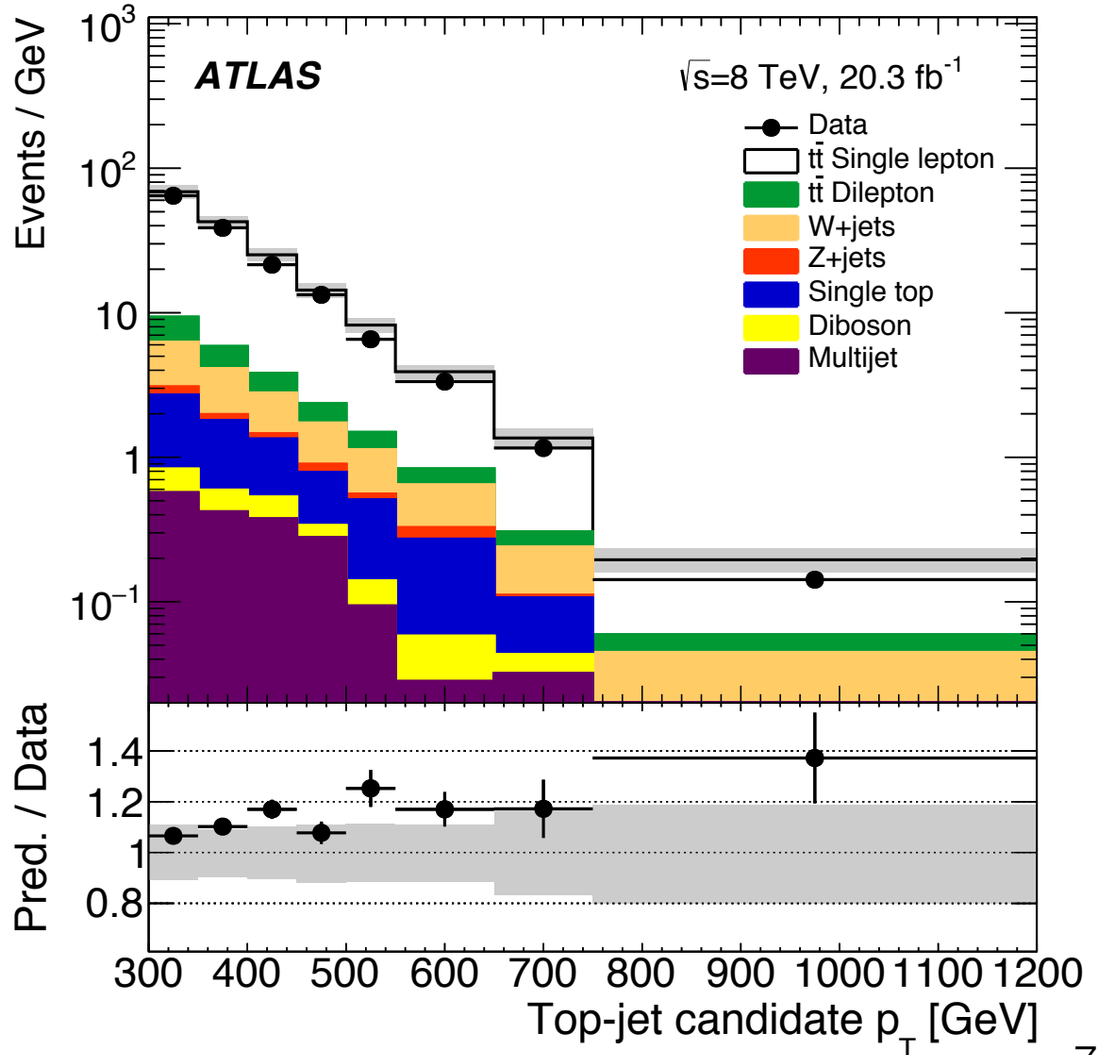
Differential cross section @8TeV in ATLAS

- Event selection **1 lepton + jets**:
  - **Anti-kt R=1.0, trimmed, p_T > 300 GeV**; mass > 100 GeV; $\sqrt{d_{12}}$ > 40 GeV
  - Anti-kt small-R jet R=0.4, b-tagging @70%
- W+jets background estimated with data-driven charge asymmetry method.
  Multi-jets background estimated with Matrix-Method.

- **Migration matrixes** are estimated using default MC of Powheg+Pythia to extract the ttbar cross sections.
  - Backgrounds are subtracted from data.

- Fiducial regions defined using particle- and parton-level objects.

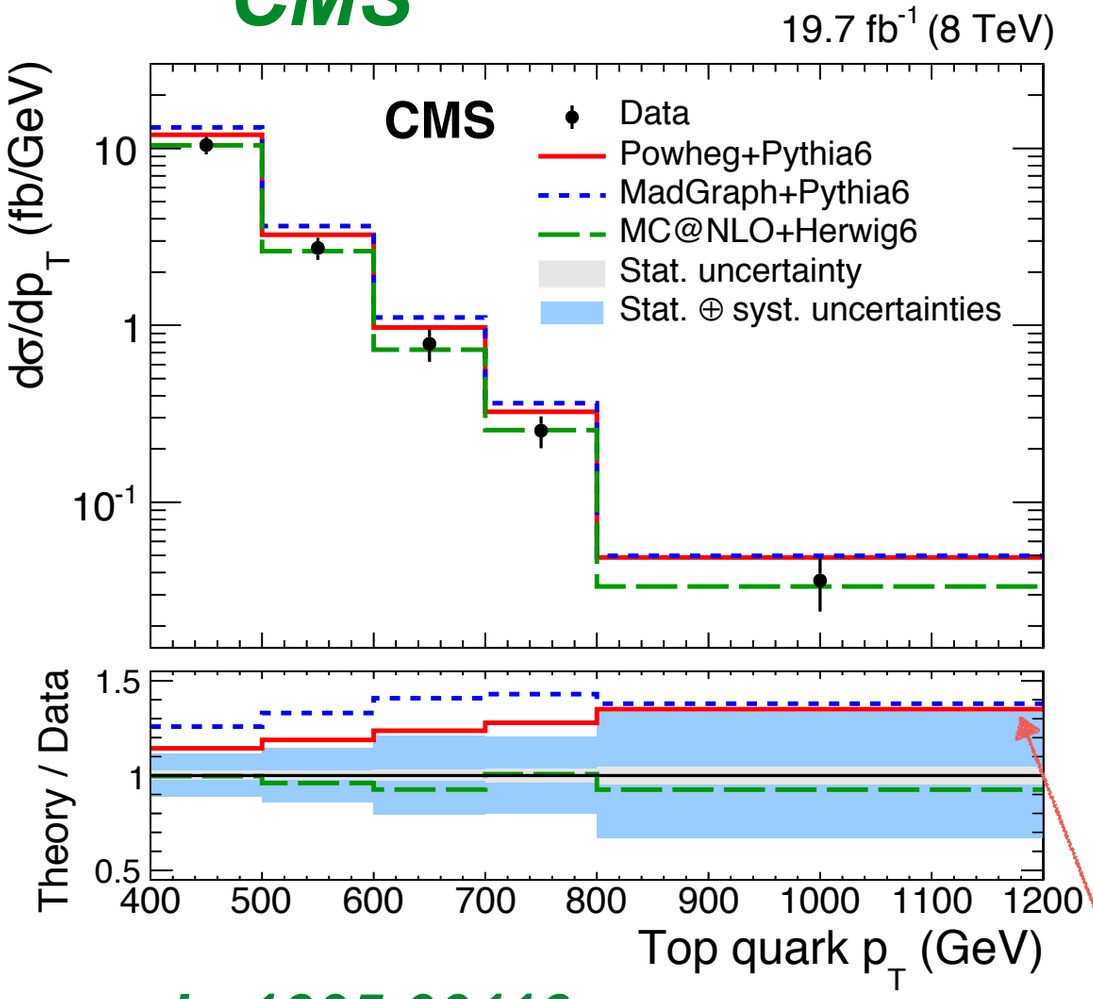
arxiv:1510.03818



Results @8 TeV in ATLAS & CMS

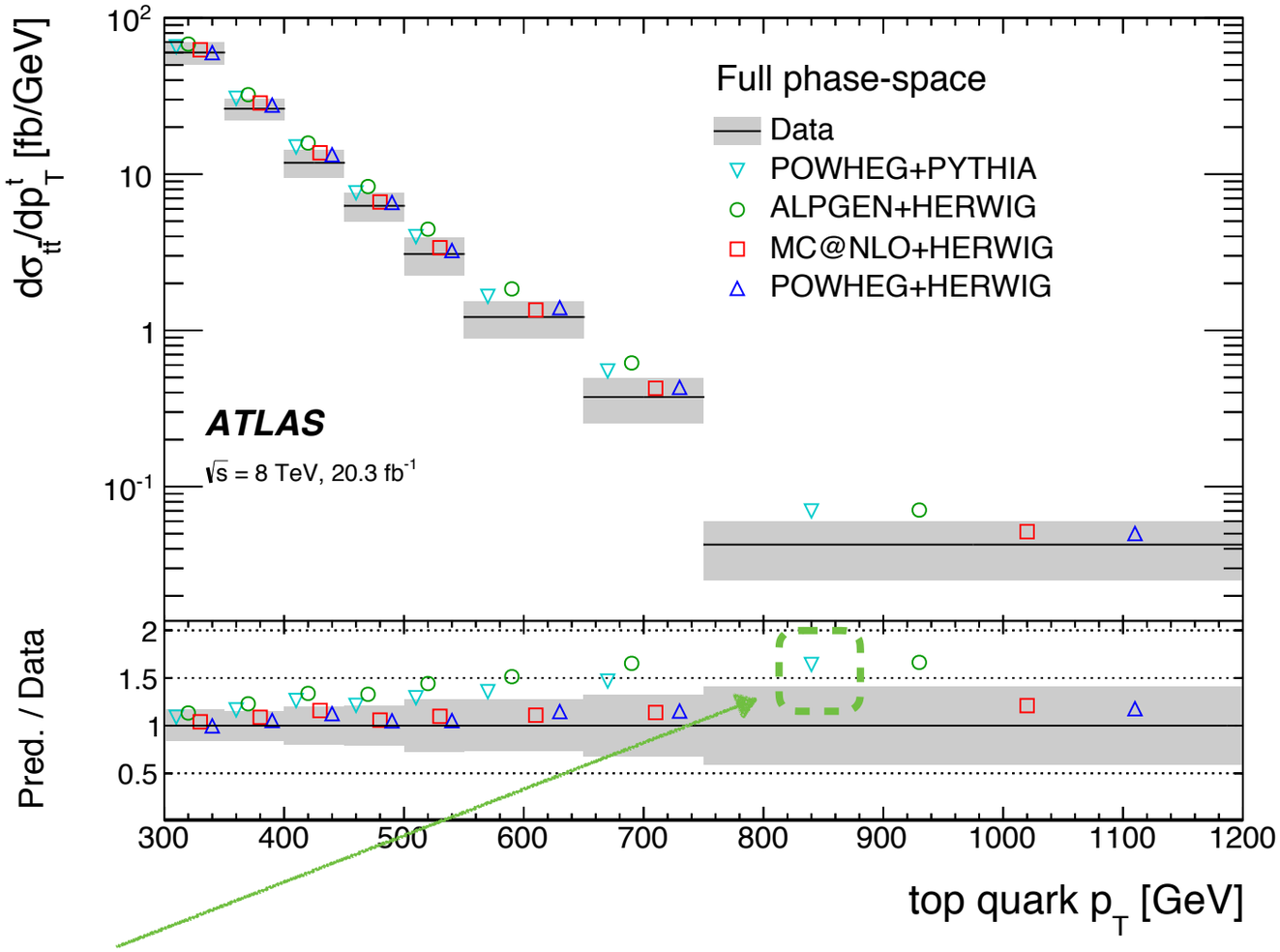
- Differential cross section measured as a function of hadronic top p_T and |η|
- Measured detector level kinematic spectrums are unfolded to particle-level and parton-level.
- A direct comparison can be made using parton level distributions.

CMS



arxiv:1605.00116

ATLAS



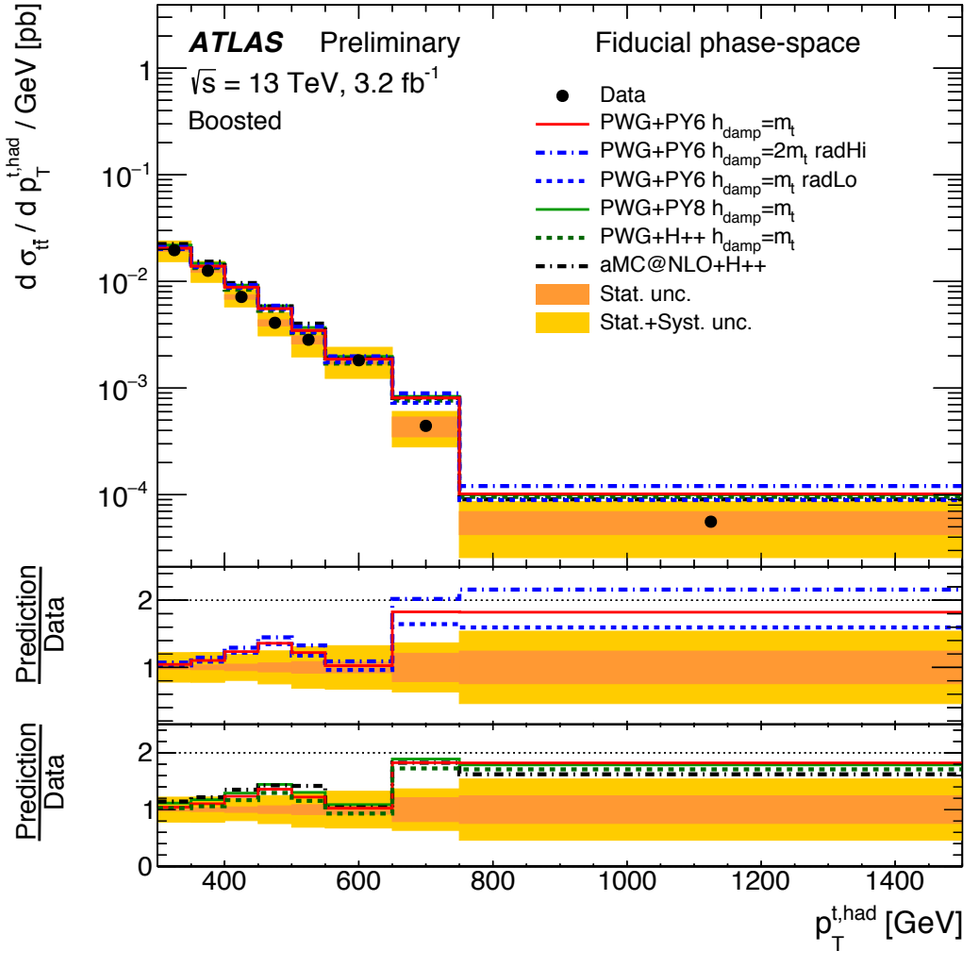
Powheg+Pythia6

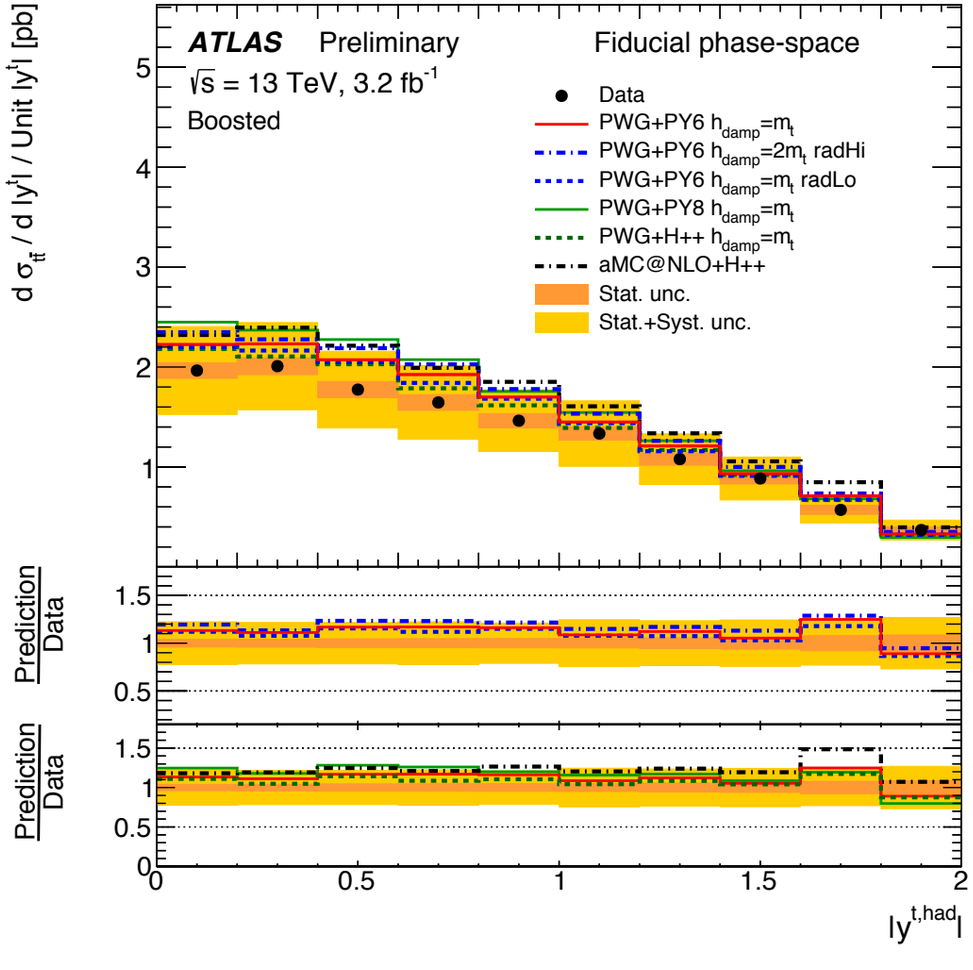
arxiv:1510.03818

Differential cross section (l+jets) @13TeV in ATLAS

- ATLAS updated the measurement using **3.2 fb^{-1} 2015 data at 13TeV**.
- Large-R jet of trimmed anti-kt 1.0, p_T^J in [300, 1500] GeV, m > 50 GeV.
- Differential cross section unfolded to particle level objects for measured observables of $p_T^{t,had}$, $|y^{t,had}|$.
- Higher prediction by Powheg+Pythia6 (**hdamp = m_{top}**) seen also at 8 TeV results.

Link: ATLAS-CONF-2016-040





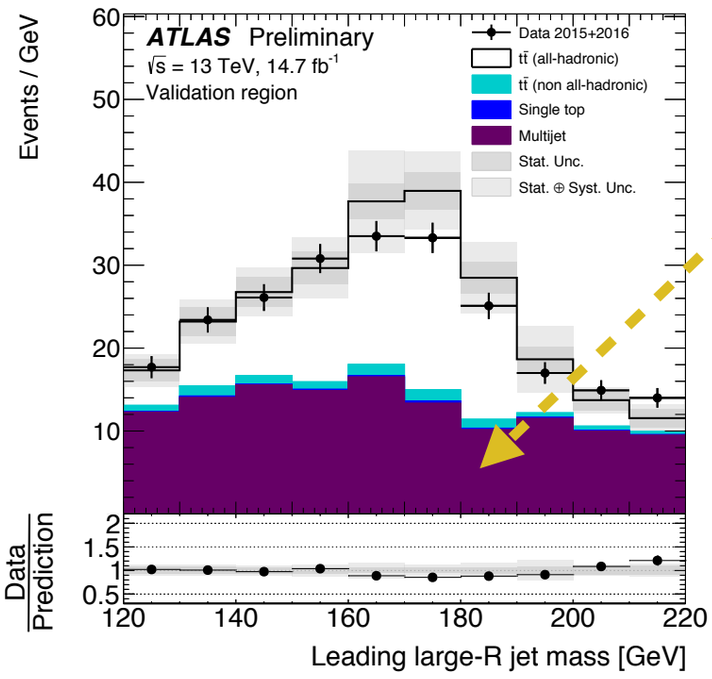
Differential cross section (full-had) @13TeV in ATLAS

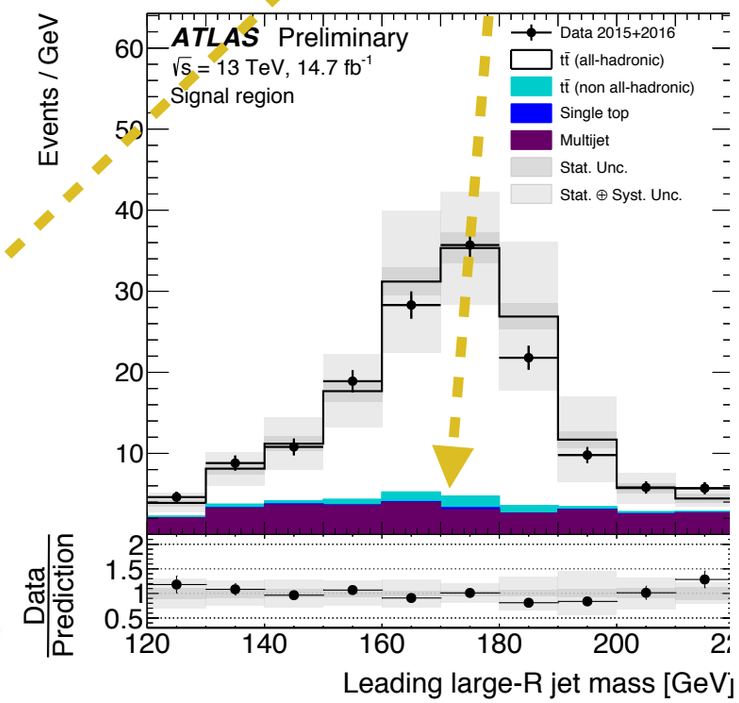
- Measurement in **full hadronic** final state using **14.7 fb^{-1} 2015 and 2016 data at 13TeV**.
- Two large-R jet with **p_T^1 > 500 GeV** and **p_T^2 > 350 GeV**; mass in [122.5, 222.5] GeV;
- Top tagging @50% (flat in pT) with a rejection of 17 (@500 GeV) and 10 (@1TeV) to light flavor / gluon jet.
- At least two small-R jet (used for b-tagging).

$$S_{bg} = \frac{1}{2}\left(\frac{G}{A} + \frac{H}{B}\right) \times C$$

- **QCD** measured with data.
- Validated in **region-F**.

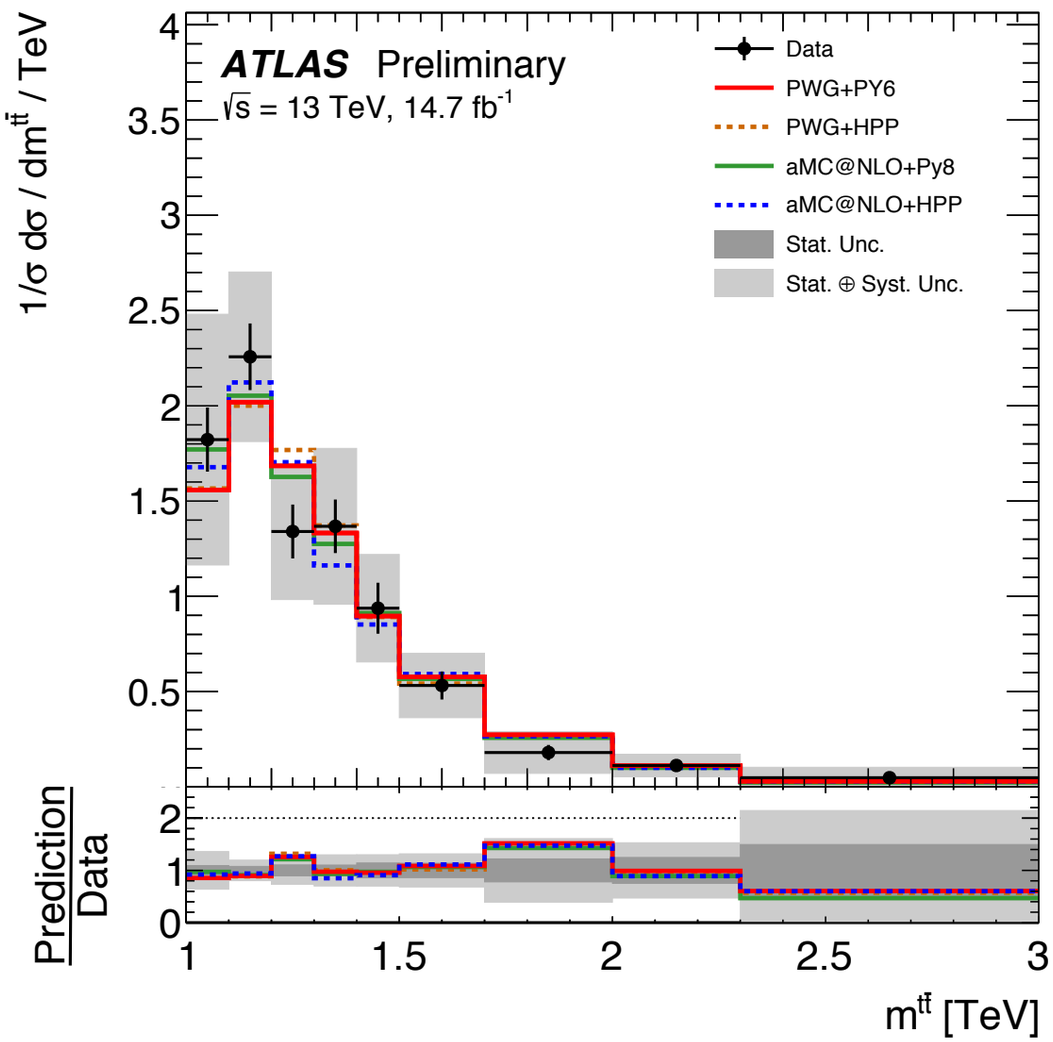
	0 t	1 t	2 t
0 b	A	D	G
1 b	B	E	H
2 b	C	F	S





NEW!

Link: ATLAS-CONF-2016-100

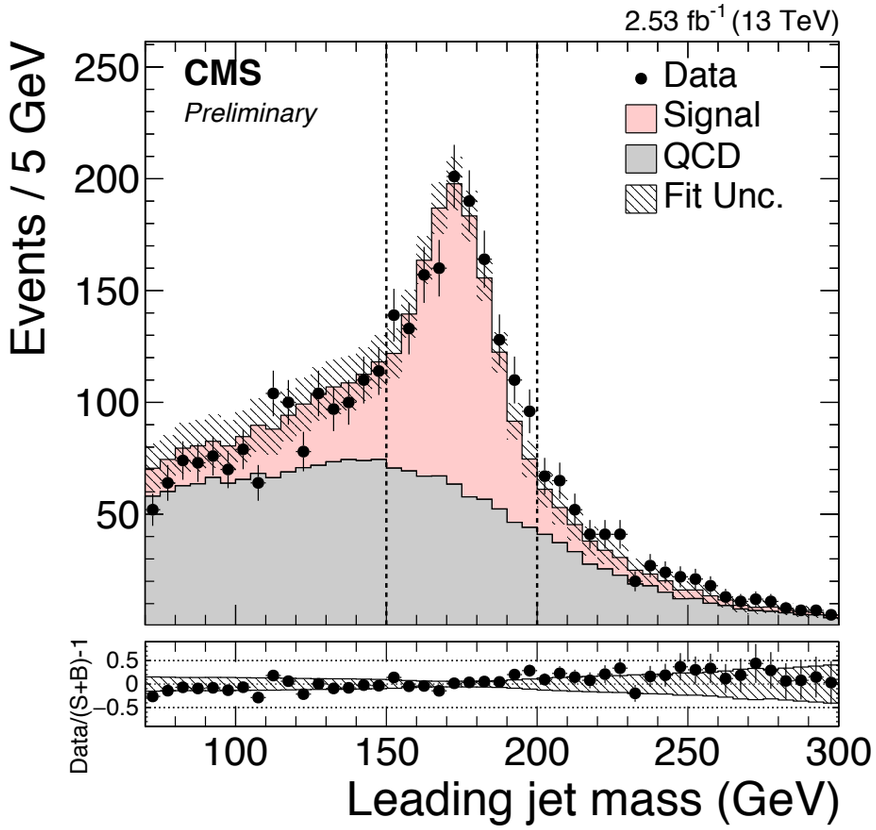


Inclusive & differential cross section (full-had) @13TeV in CMS

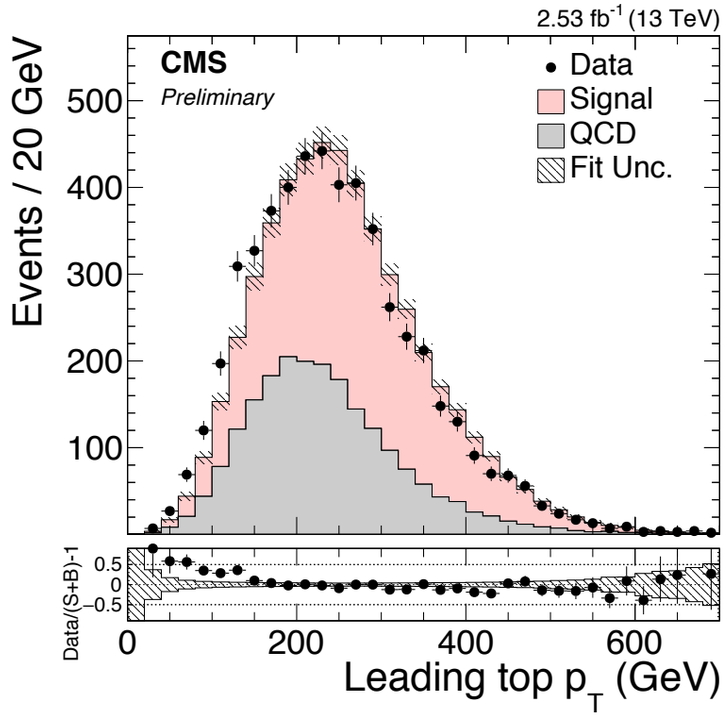
- Measurement in **full hadronic** final state using **2.53 fb^{-1} 2015 data at 13TeV**.
- $\mathcal{F}$ is a fisher discriminant constructed with τ_{32} and τ_{21}.
- m_{SD} is the soft-drop mass of the large-R jet.

Boosted
lepton veto
AK8 jets
$p_T > 200\,\text{GeV}$, $\lvert\eta\rvert < 2.4$, $m_{SD} > 50\,\text{GeV}$
$N_{jets} \geq 2$
$p_T^{(1)} > 450\,\text{GeV}$
both jets should contain one b-tagged subjet
$\mathcal{F} > 0$
$150 < m_{SD}^{(1)} < 200\,\text{GeV}$

- Fitting **leading large-R jet m_{SD}** templates from signal and QCD background.
- QCD template obtained from data and corrected with simulation.



Link: CMS-Top-16-013



$$B_{\text{signal}}^{\text{data}}(x) = \left[\frac{B_{\text{signal}}(x)}{B_{\text{control}}(x)}\right]_{\text{MC}} \cdot B_{\text{control}}^{\text{data}}(x)$$

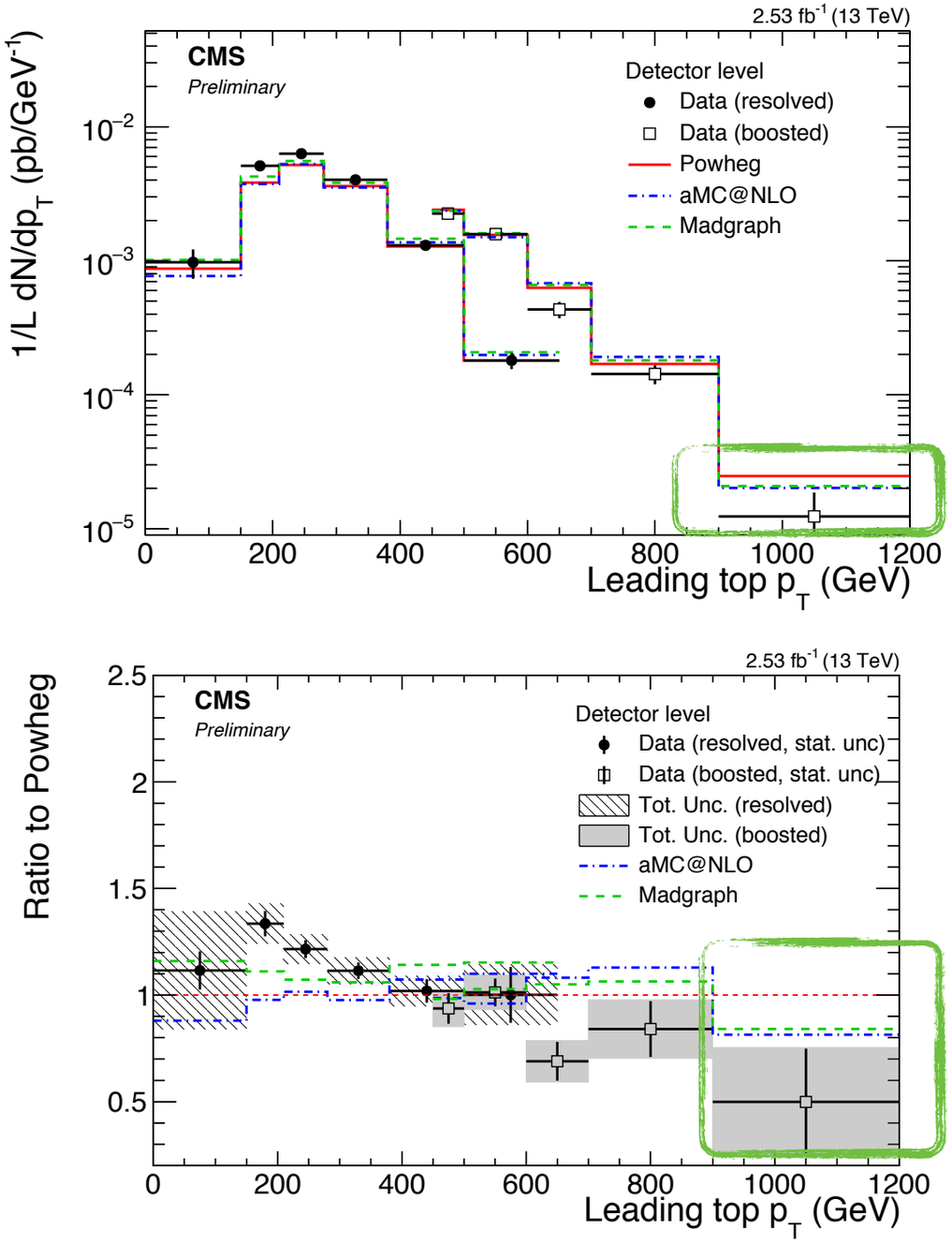
$\mathcal{X}$ = **leading m_{jet} (fitting discriminant)**

- Post-fit leading jet pT distribution can be a validation of the fit.

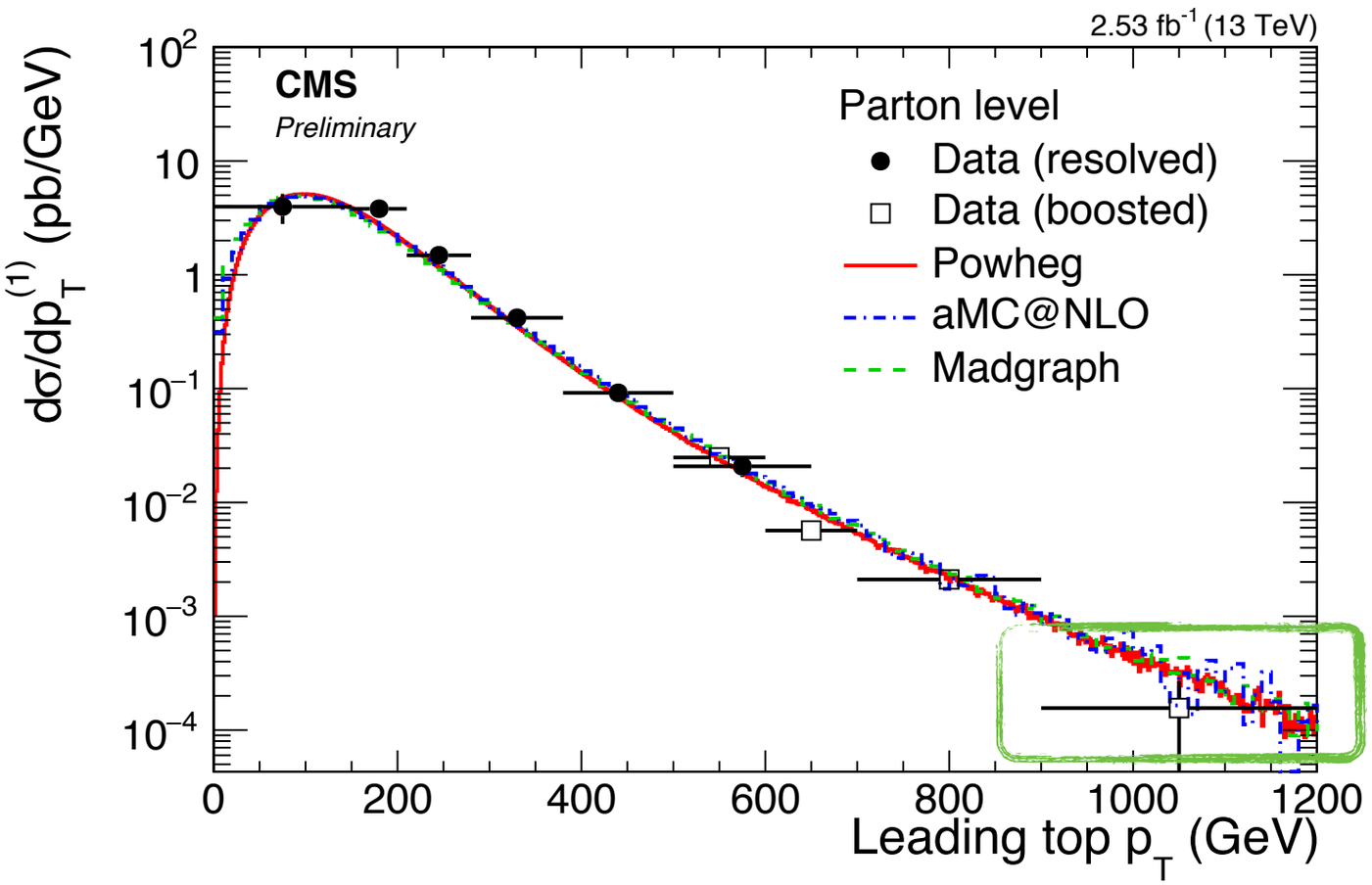
Inclusive & differential cross section (full-had) @13TeV in CMS

- Inclusive cross section at 13TeV: $\sigma_{t\bar{t}} = 727 \pm 46(\text{stat})^{+115}_{-112}(\text{syst}) \pm 20(\text{lumi})\ \text{pb}.$
- Slightly lower than that in theory: $\sigma^{\text{th}}_{t\bar{t}} = 832^{+20}_{-29}\ (\text{scale}) \pm 35\ (\text{PDF} + \alpha_s)\ \text{pb}$

Link: CMS-Top-16-013



Detector level differential cross section.



Parton level differential cross section.

- Powheg+Pythia over estimates the cross section at high top p_T.

Other Measurements using boosted top

Jet Mass Distribution @8TeV in CMS

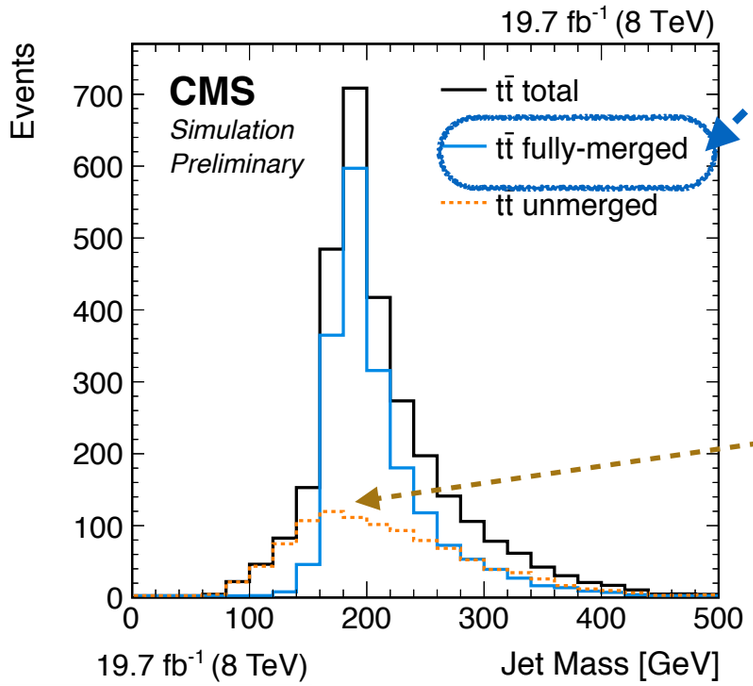
- A detailed understanding of jet substructure variable, especially **jet mass m_{jet}** is crucial for LHC analyses in boosted topologies.

Link: CMS-Top-15-015

- The location of m_{jet} distribution is sensitive to **top quark mass m_{top}**.
- Event selection in l+jets: **C/A jet R=1.2**, p_T > 400 GeV.

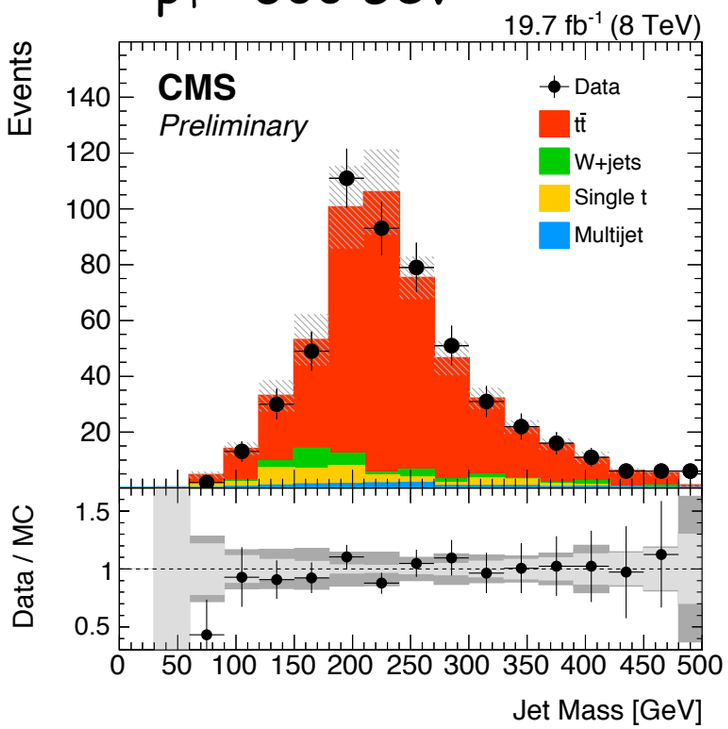
Leptons	$p_T^{\ell} > 45\,\text{GeV}$	$\lvert\eta^{\ell}\rvert < 2.5$
CA12 jets	$p_{T,1} > 400\,\text{GeV}$ $p_{T,2} > 150\,\text{GeV}$ $p_{T,\text{veto}} > 150\,\text{GeV}$	$\lvert\eta\rvert < 2.5$
Event	$\Delta R(\ell, \text{jet2}) < 1.2$ $m(\text{jet1}) > m(\text{jet2} + \ell)$	

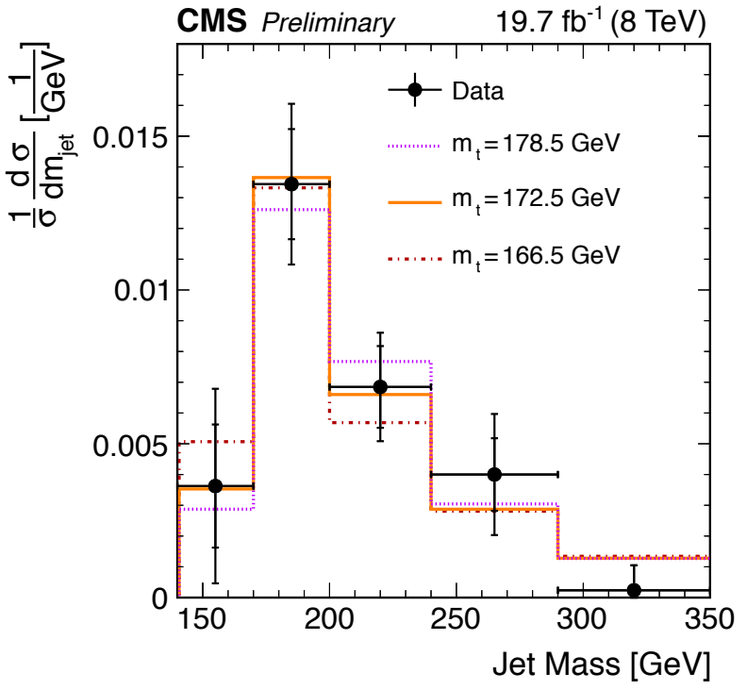
Table. Fiducial region definition using particle objects



- ΔR between leading particle-level jet to each parton from top decay < 1.2
- 35% of events not fully-merged in Powheg+Pythia

p_T > 500 GeV



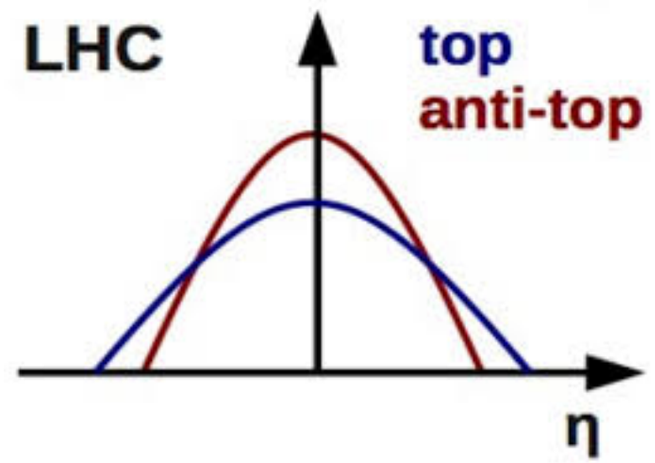


- Total cross section m_{jet} in [140, 350] GeV: **103.5 ± 18.2 fb**.
- Top mass is extracted from m_{jet}: **m_{top} = 171.8 ± 9.5 GeV**.

Charge asymmetry @8TeV in ATLAS

- Production of qqbar -> ttbar at NLO gives non-zero charge asymmetry from interferences between diagrams.

arxiv:1512.06092

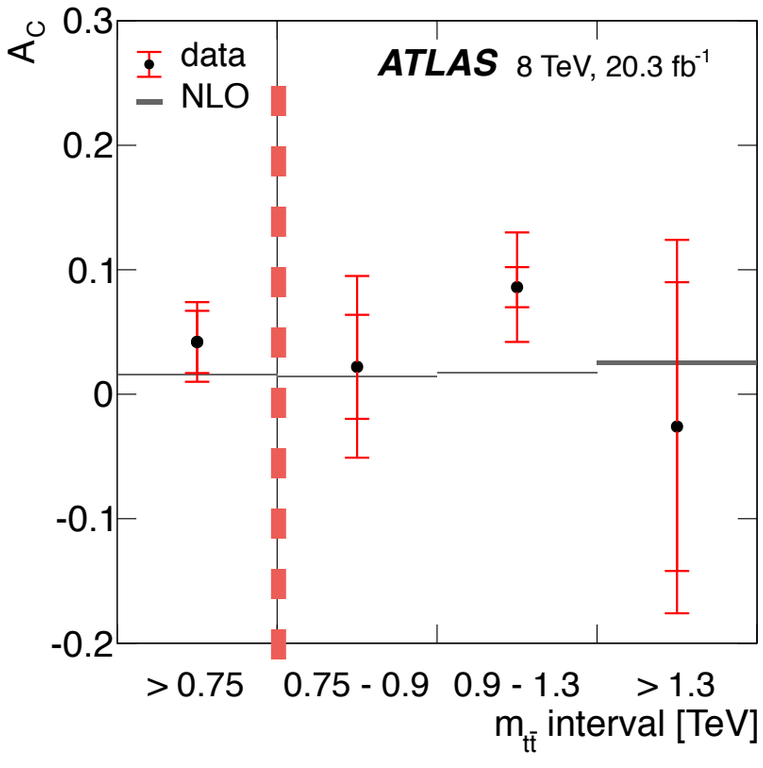


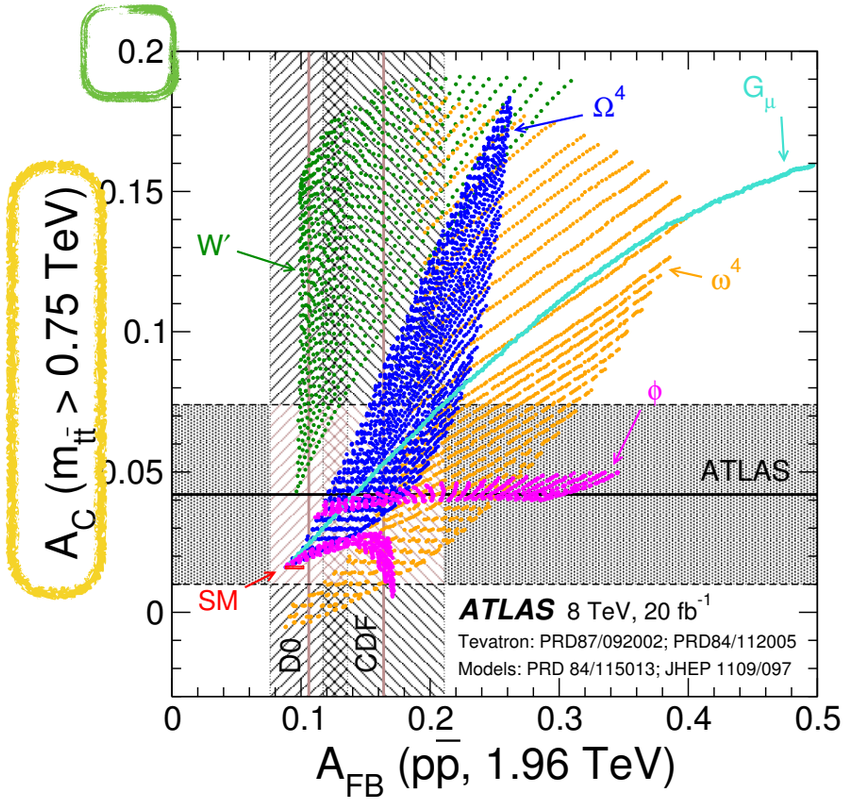
- Asymmetry from qqbar initial state (15%) diluted by gluon-initiated (85%) state productions => **~1% (SM).**
  - At high m_{ttbar}, asymmetry is larger.
  - Deviation from SM —> indication of BSM.

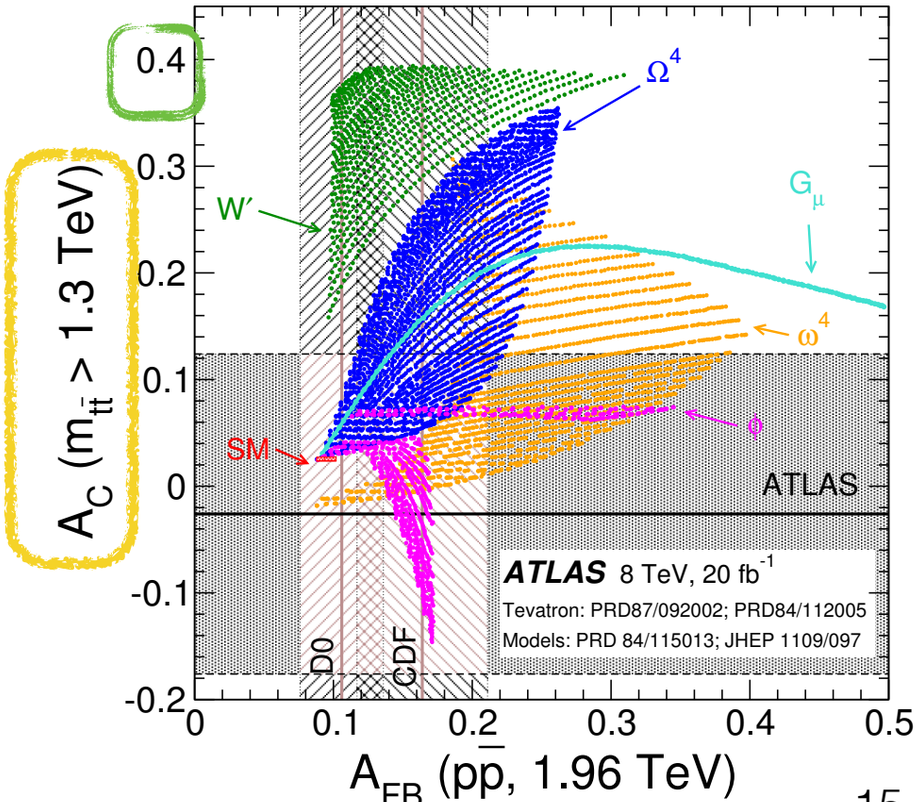
$$A_C^{t\bar{t}} = \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)}$$

$$\Delta|y| = |y^{t}| - |y^{tbar}|$$

- ttbar —> l+jets: **trimmed anti-kt large-R jet R=1.0**, $|\eta| < 2.0$, $p_T > 300$ GeV.







Summary

- Several algorithms of boosted top reconstruction and identification have been developed in ATLAS and CMS using Run-I data @7 & 8TeV.
  - Taggers make use of the substructure variables.
  - Optimized for various physics analyses in SM measurements.
  - Also have been widely used in BSM searches.

- Physics analyses benefit from the Top Tagging algorithms to improve sensitivity at high p_T of top.

- Measurements at 7 & 8TeV in Run-I and at 13TeV in Run-II from ATLAS and CMS collaborations are presented.

- Looking forward to more exiting results at 13TeV in Run-II using more data.

Backup

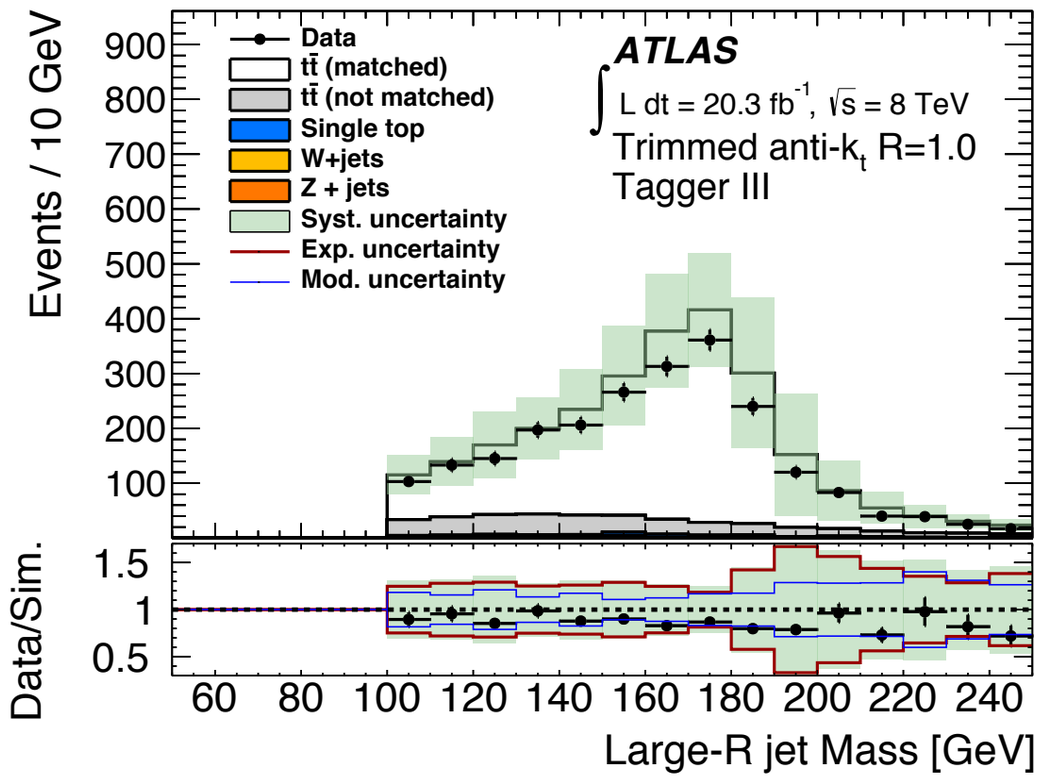
Top Tagger in ATLAS

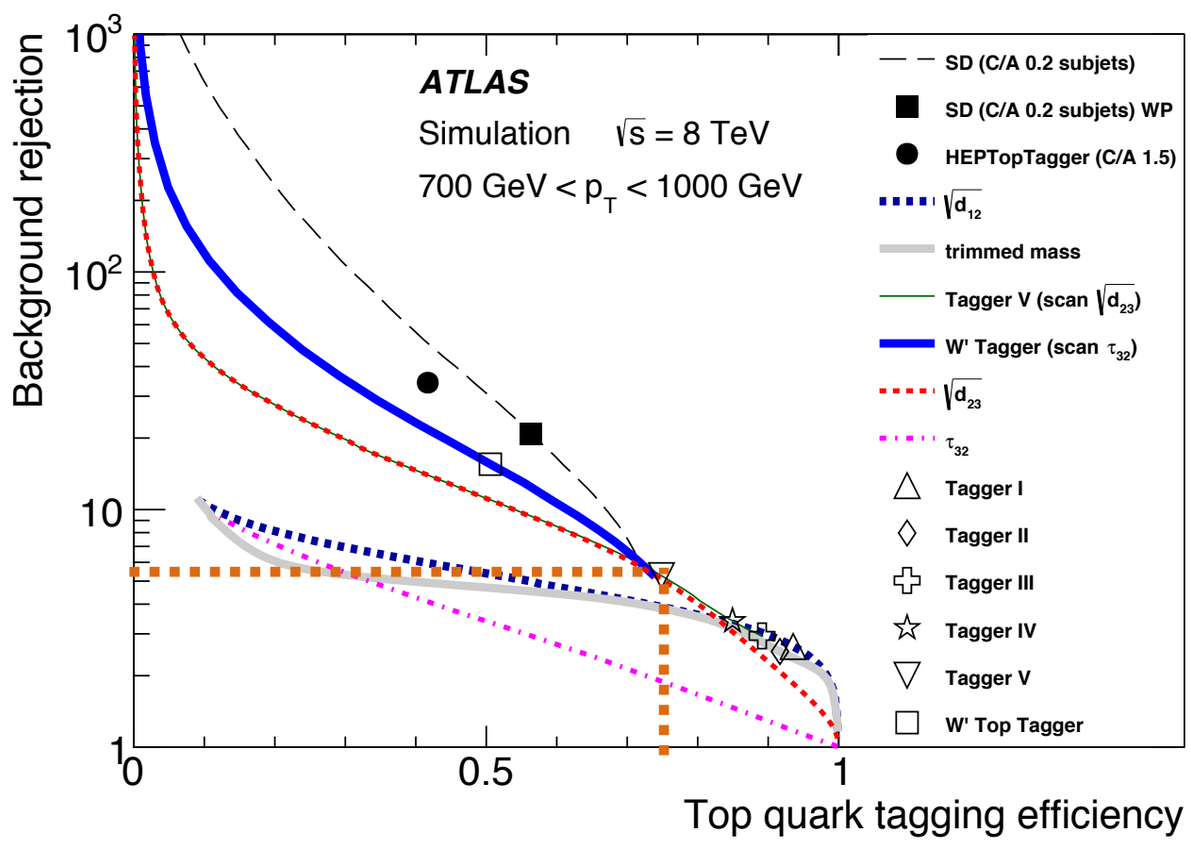
Tagger	Top-tagging criterion
Substructure tagger I	$\sqrt{d_{12}} > 40$ GeV
Substructure tagger II	$m > 100$ GeV
Substructure tagger III	$m > 100$ GeV and $\sqrt{d_{12}} > 40$ GeV
Substructure tagger IV	$m > 100$ GeV and $\sqrt{d_{12}} > 40$ GeV and $\sqrt{d_{23}} > 10$ GeV
Substructure tagger V	$m >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

- Cuts optimized for specific analysis, e.g.: tagger III is for a search of ttbar resonance in single-lepton channel.

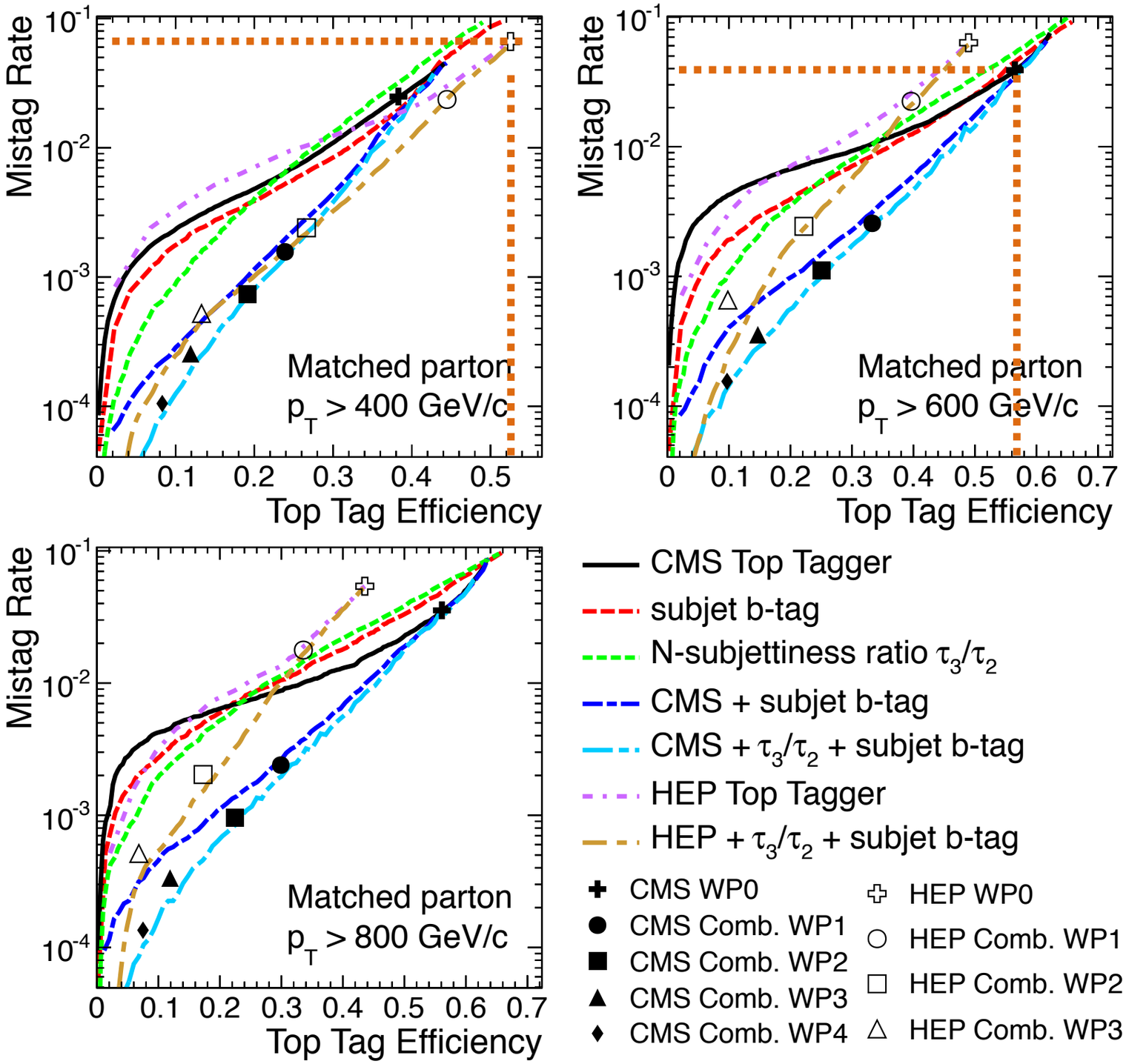
- Shower Decomposition (SD): likelihood for scenario of hadronic originated and background originated large-R jet.
- HepTOPTagger: test the compatibility of the substructure with the 3-prong patten.

arxiv:1603.03127



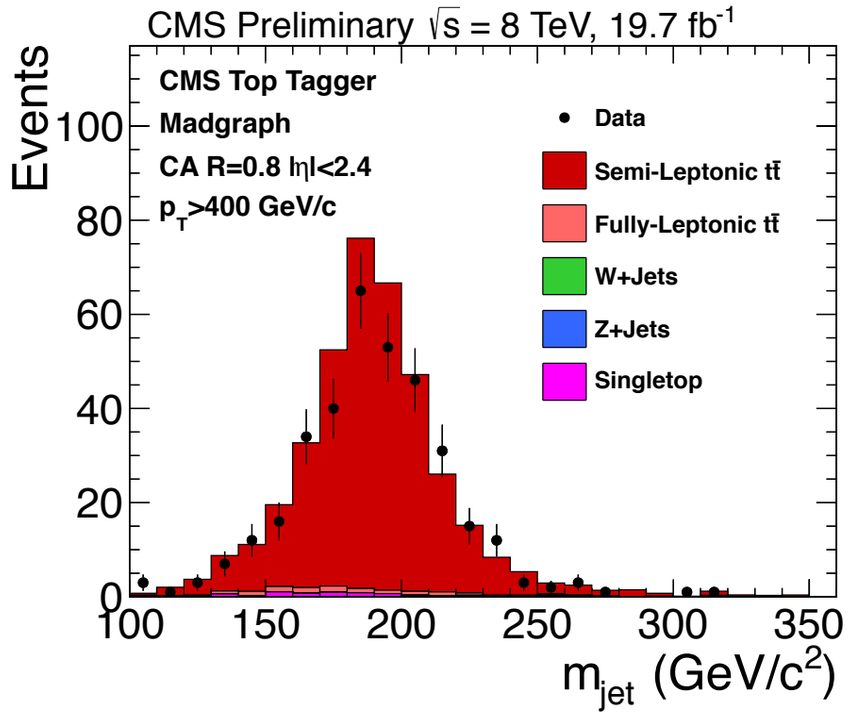


Top Tagger in CMS



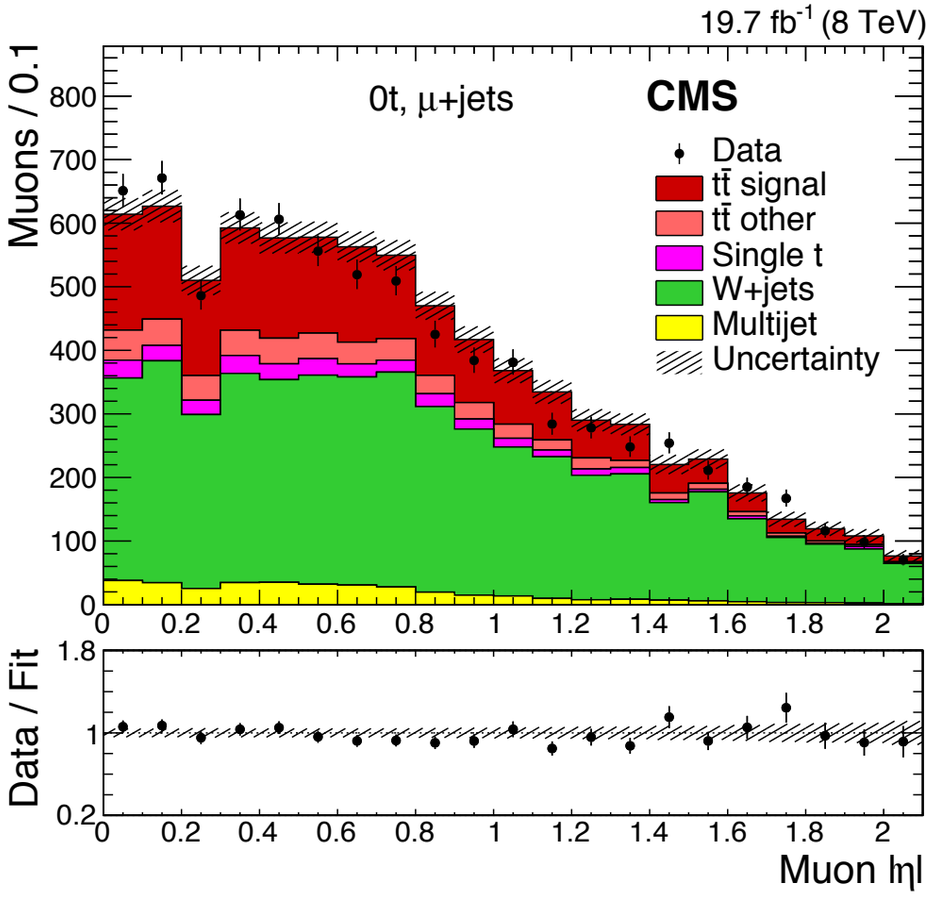
Link CMS: JME-13-007-pas

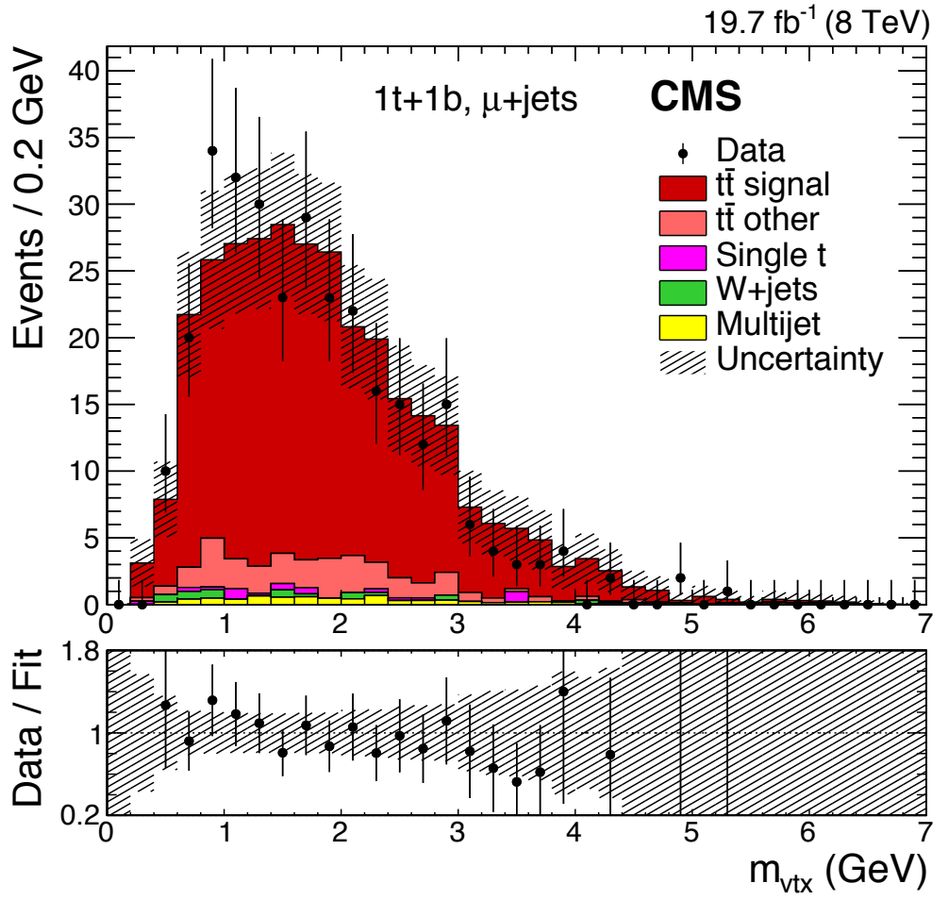
- Combined Tagger working points defined by varying cuts on m_{min}, subjet b-tagging and $\tau_{32}=\tau_3/\tau_2$.
- The tagging efficiency is calibrated using ttbar data.



Fitting procedure (cross section, CMS)

- Maximum likelihood fit in (0t, 1t+0b, 1t+1b) exclusive categories.
  - Signal and all background yields determined by fit.
  - Discriminant variables: lepton |eta| used in (0t, 1t+0b), m_{vtx} used in 1t+1b
  - Background normalizations and experimental uncertainties treated as nuisance parameters.
  - Signal modeling uncertainties are evaluated separately.



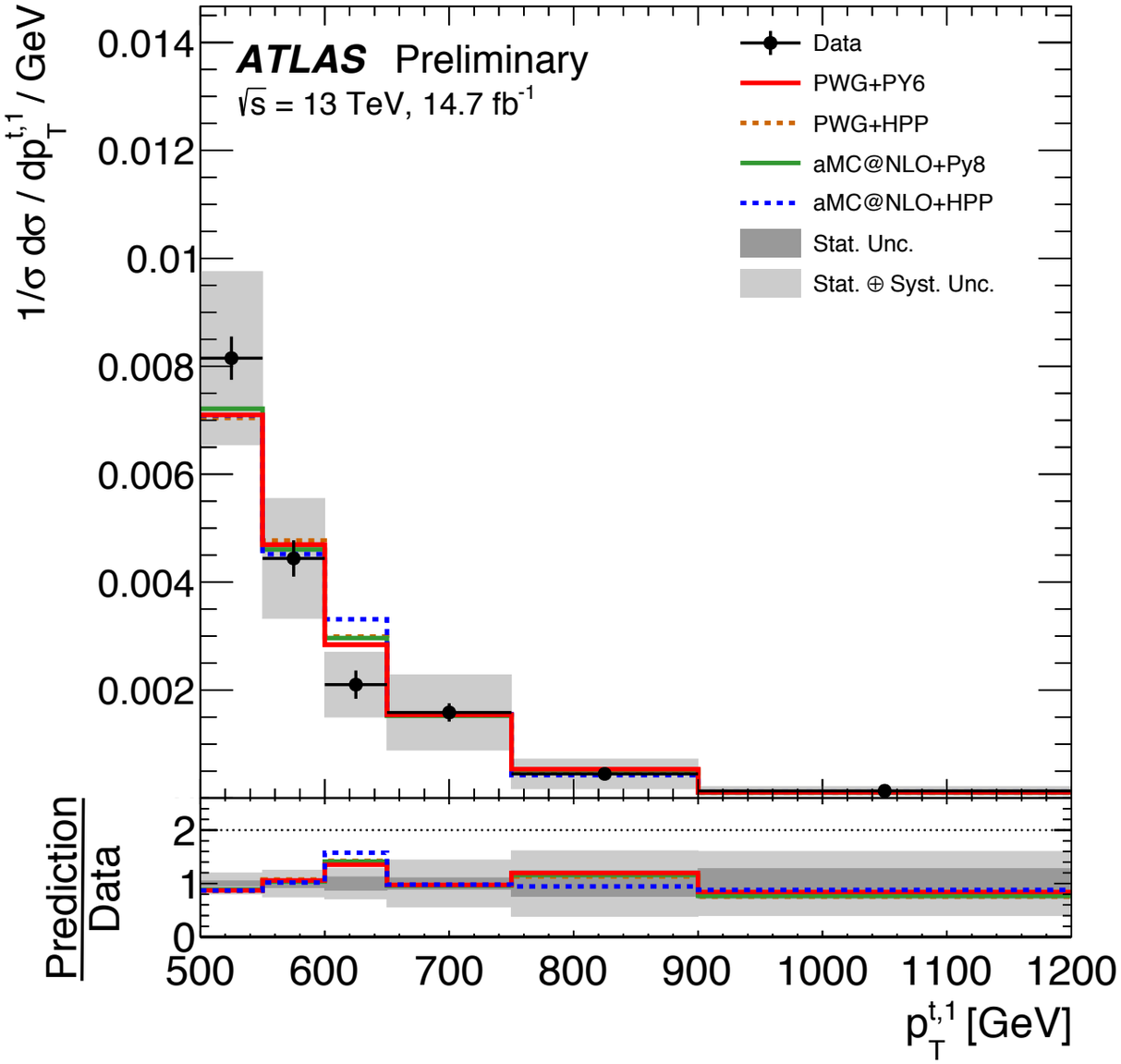


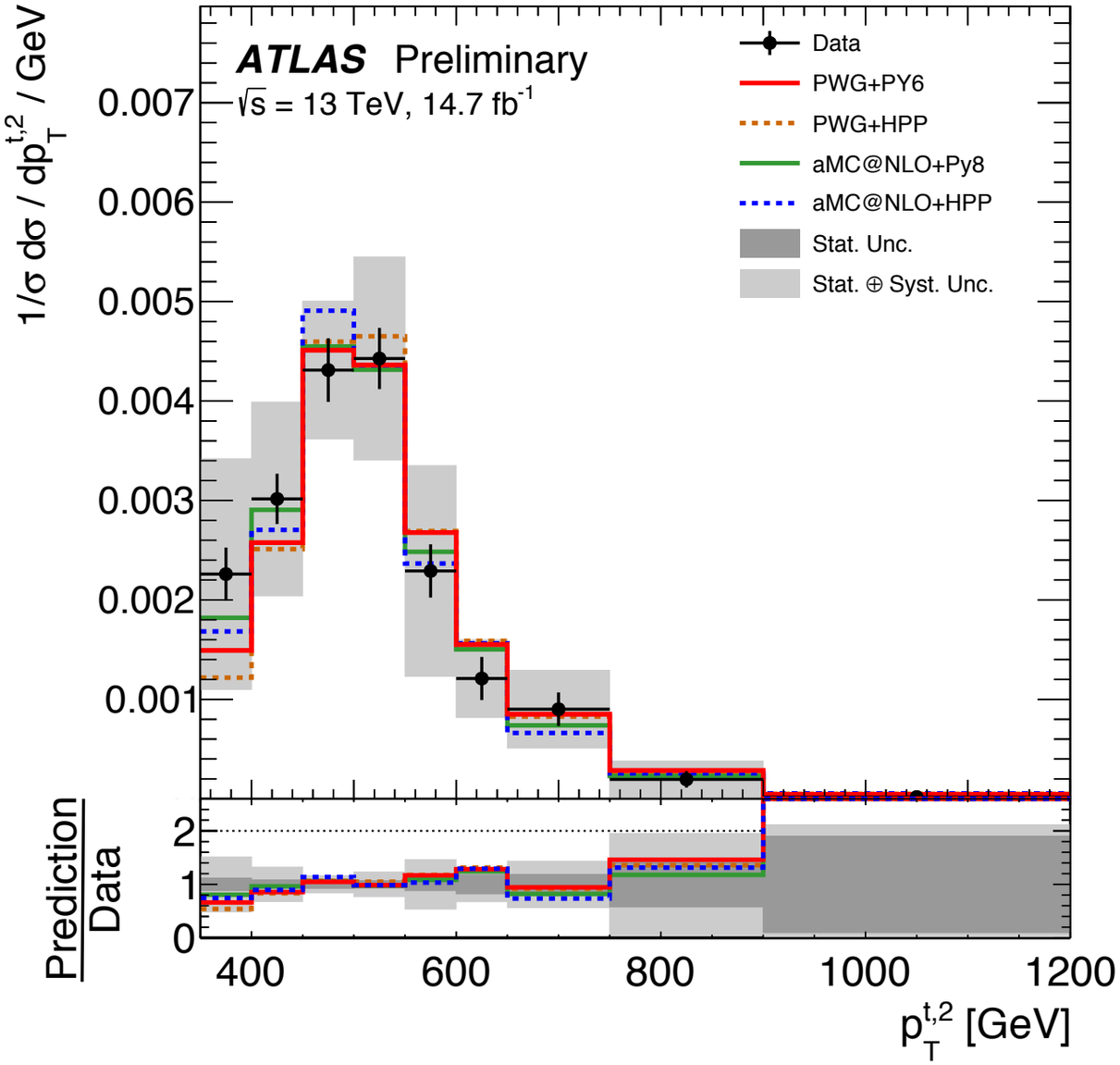
Differential cross section (full-had) @13TeV in ATLAS

NEW!

- Measurement in full hadronic final state using 14.7 fb^{-1} 2015 and 2016 data at 13TeV.
- Differential measurements with more variables.

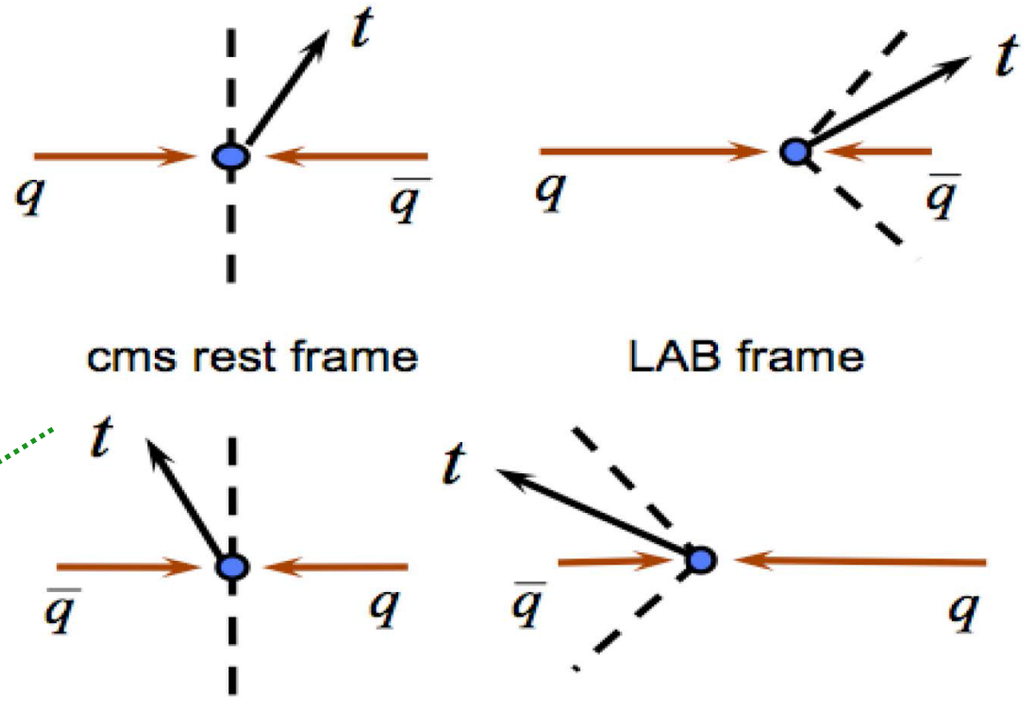
Link: ATLAS-CONF-2016-100

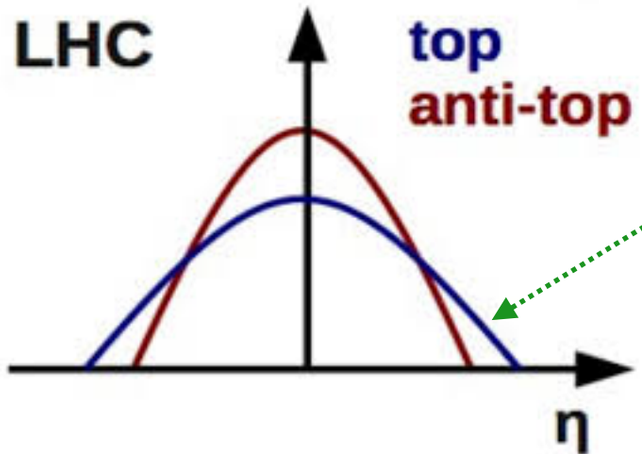


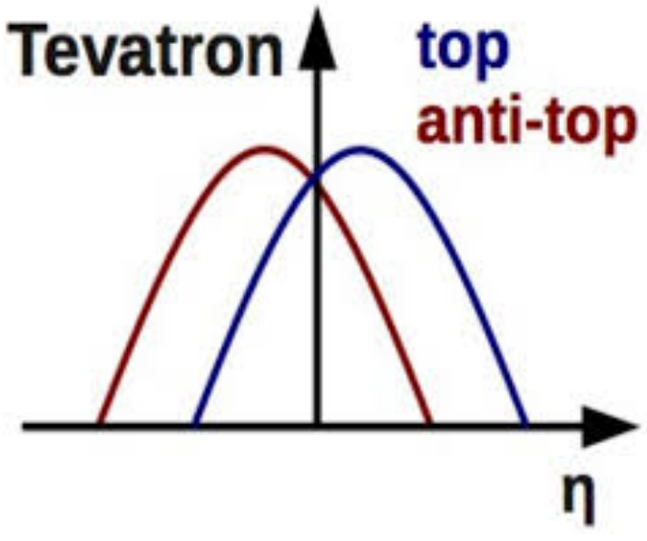


Introduction to charge asymmetry

- Top quark pair production at NLO gives non-zero charge asymmetry from interferences between diagrams.
  - Difference in the average momentum of the valence quark and sea anti-quark, qqbar -> ttbar.







- Asymmetry from qqbar initial state (15%) diluted by gluon-initiated (85%) state productions => **~1% (SM).**
  - At high m_{ttbar}, asymmetry is larger.
  - Deviation from SM —> indication of BSM.

$$A_C^{t\bar{t}} = \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)}$$

$$\Delta|y| = |y^{t}| - |y^{tbar}|$$