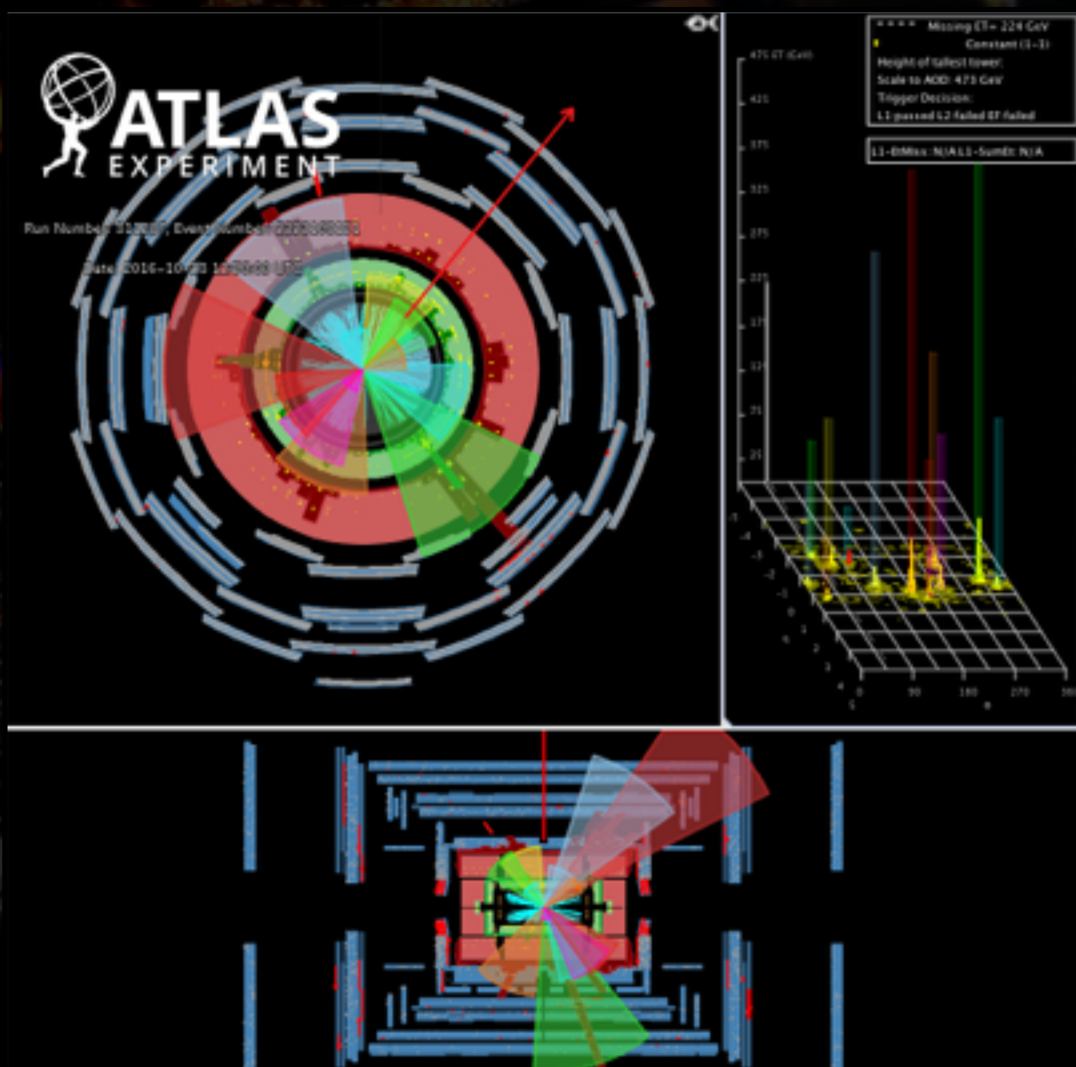
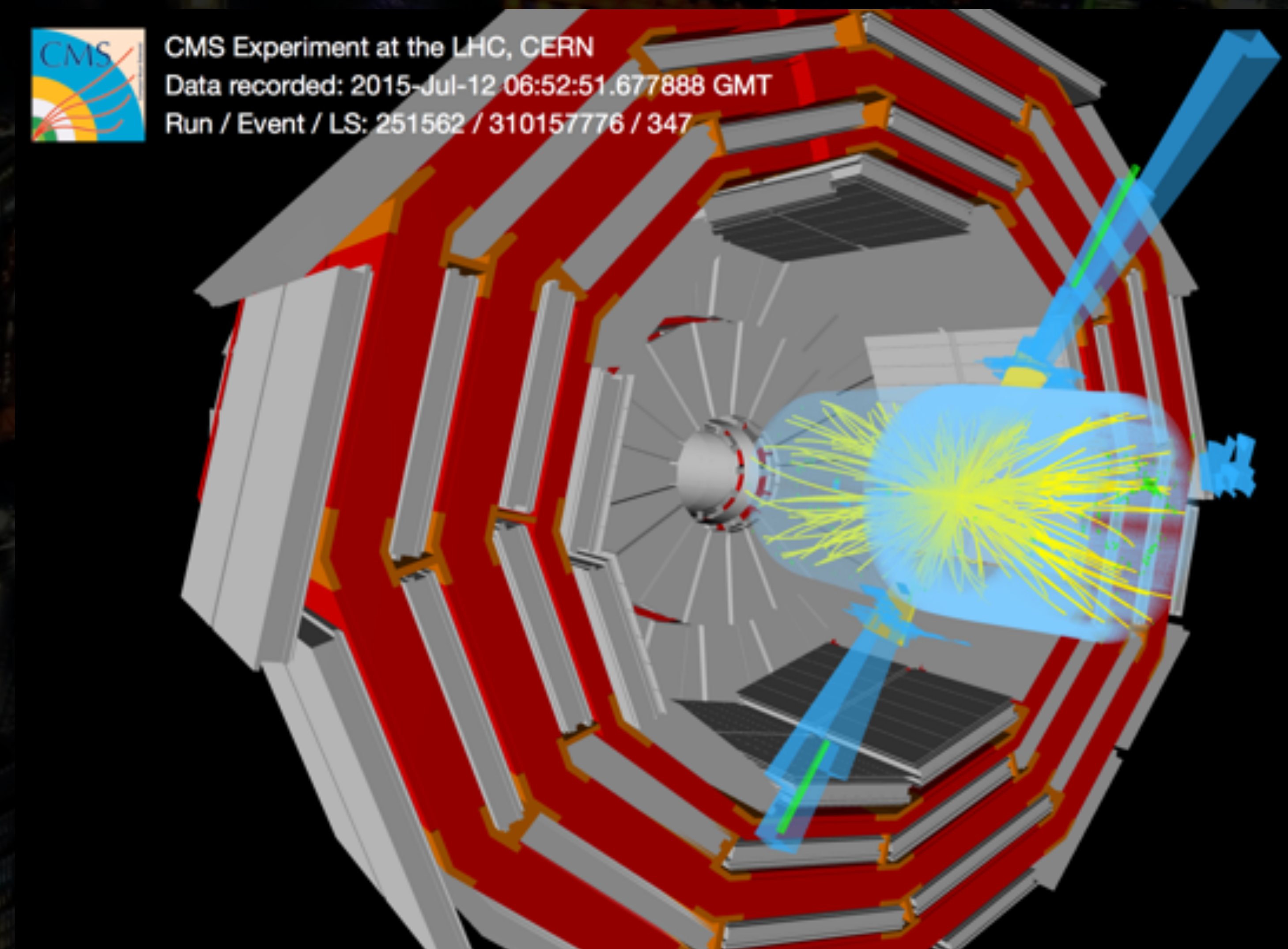
KHOO TENG JIAN
(OBO ATLAS & CMS COLLABORATIONS)

UNIVERSITÉ DE GENÈVE

JET AND ETMISS RECONSTRUCTION IN ATLAS AND CMS





LHCP 2017, 上海

Hadronic observables & elements

Jet reconstruction & calibration

MET reconstruction & performance

Jet substructure & tagging

- Strongly associated with calorimetry, but tracking is progressively more important — will demonstrate.
- *Brief* overview starting from basic elements

JET RECONSTRUCTION

[CMS PAS-PFT-09-001]

Particle Flow candidates

Charged Hadron Subtraction (CHS)

PileUp Per Particle ID (PUPPI)

[CERN-CMS-DP-2015-034]

Jet pruning
z_{cut}=0.1

Soft-drop
z_{cut}=0.1, β=0
(mod. mass-drop)

INPUTS

CONSTITUENT CORRECTIONS

ALGORITHMS

General purpose:
Anti-k_T, R=0.4

W/Z/H/t-tagging:
CMS: anti-k_T, R=0.8
ATLAS: anti-k_T, R=1.0

Low-pT top-tagging:
Cam/Aachen, R=1.5

Variable radius

(SUB)JET CORRECTIONS

Topo-clusters

PF tracks
PF clusters

Origin-correction

Charged Hadron Subtraction (CHS)

Jet trimming
R_{sub}=0.2, f_{cut}=0.05

(forward) Jet Vertex Tagger

[arXiv:1603.02934]

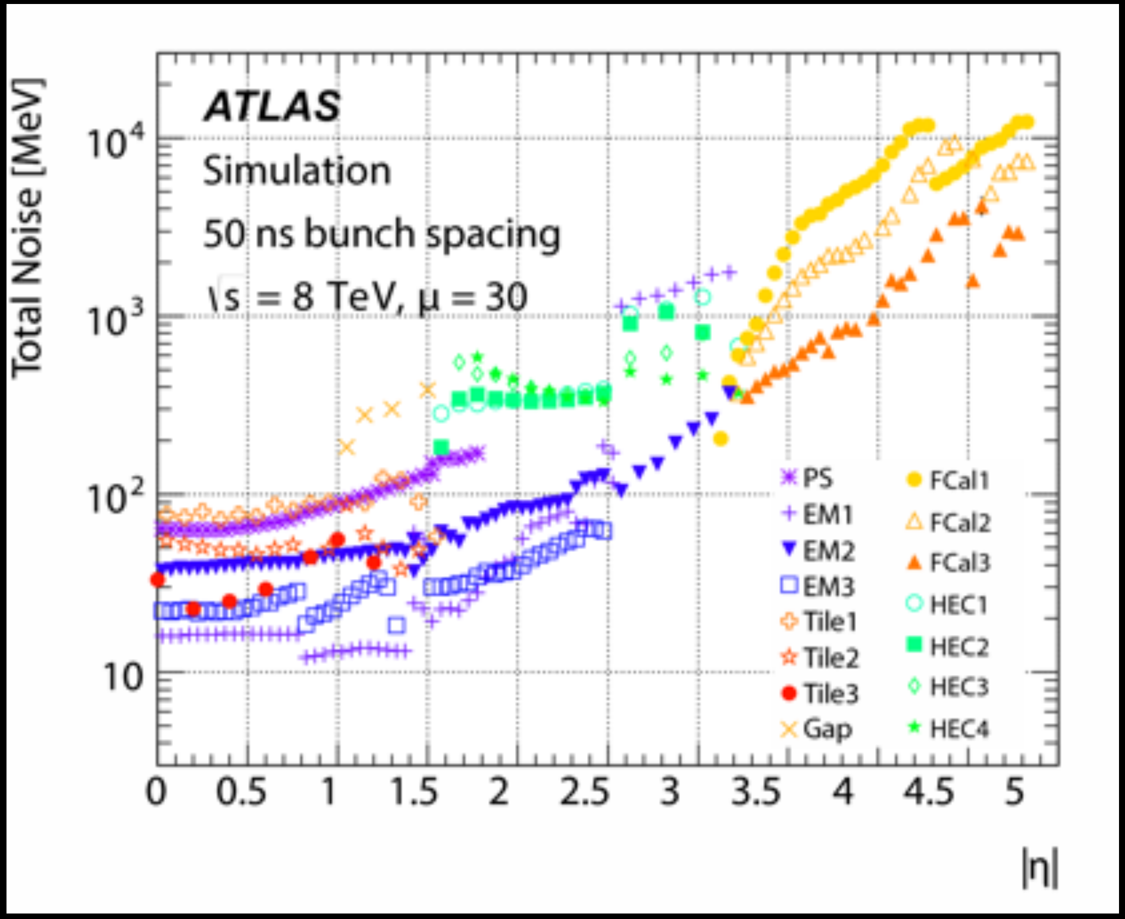
[arXiv: 1703.10485]

[arXiv: 1510.03823]

[JETM-2016-006]

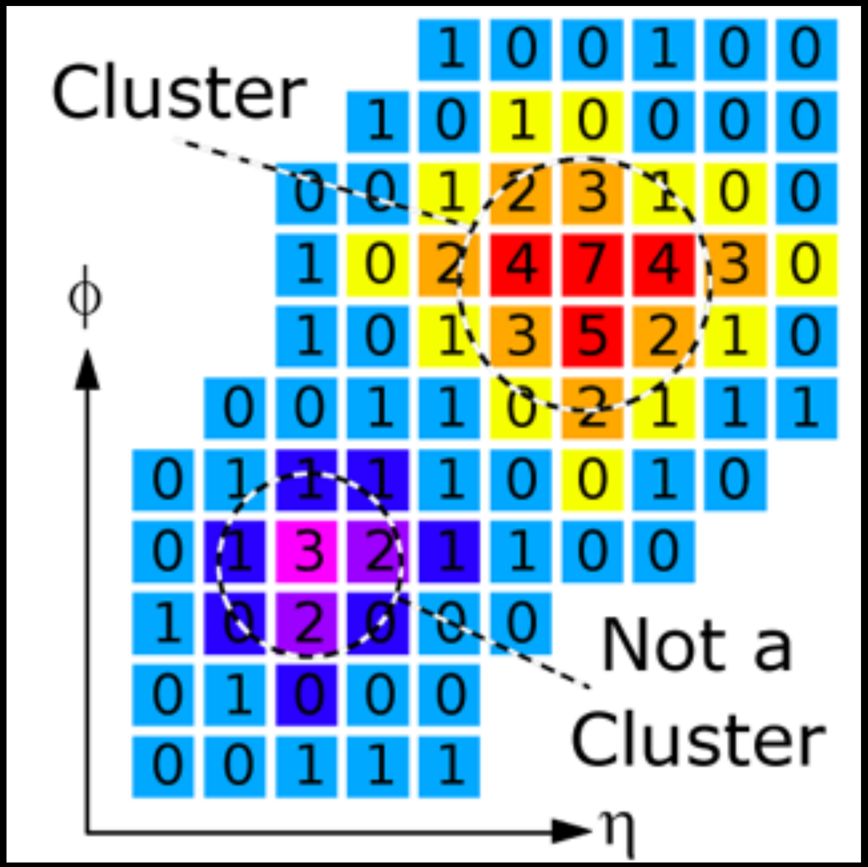
Topological Clustering

ATLAS hadronic reconstruction begins with 3D topological clusters constructed from calorimeter cells.



Cluster seeding & expansion in 3D
(4/2/0 $|\sigma_{noise}|$)

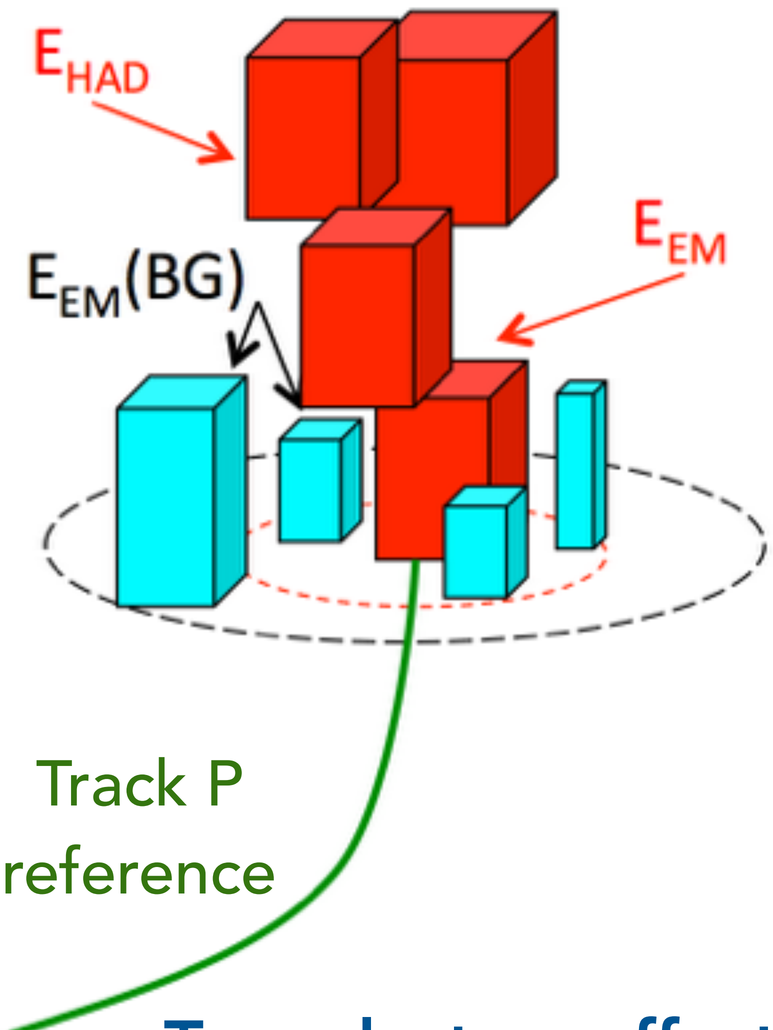
Fig by Jet Goodson



Noise-suppressed and calibrated for pileup-stability and good single-hadron response.

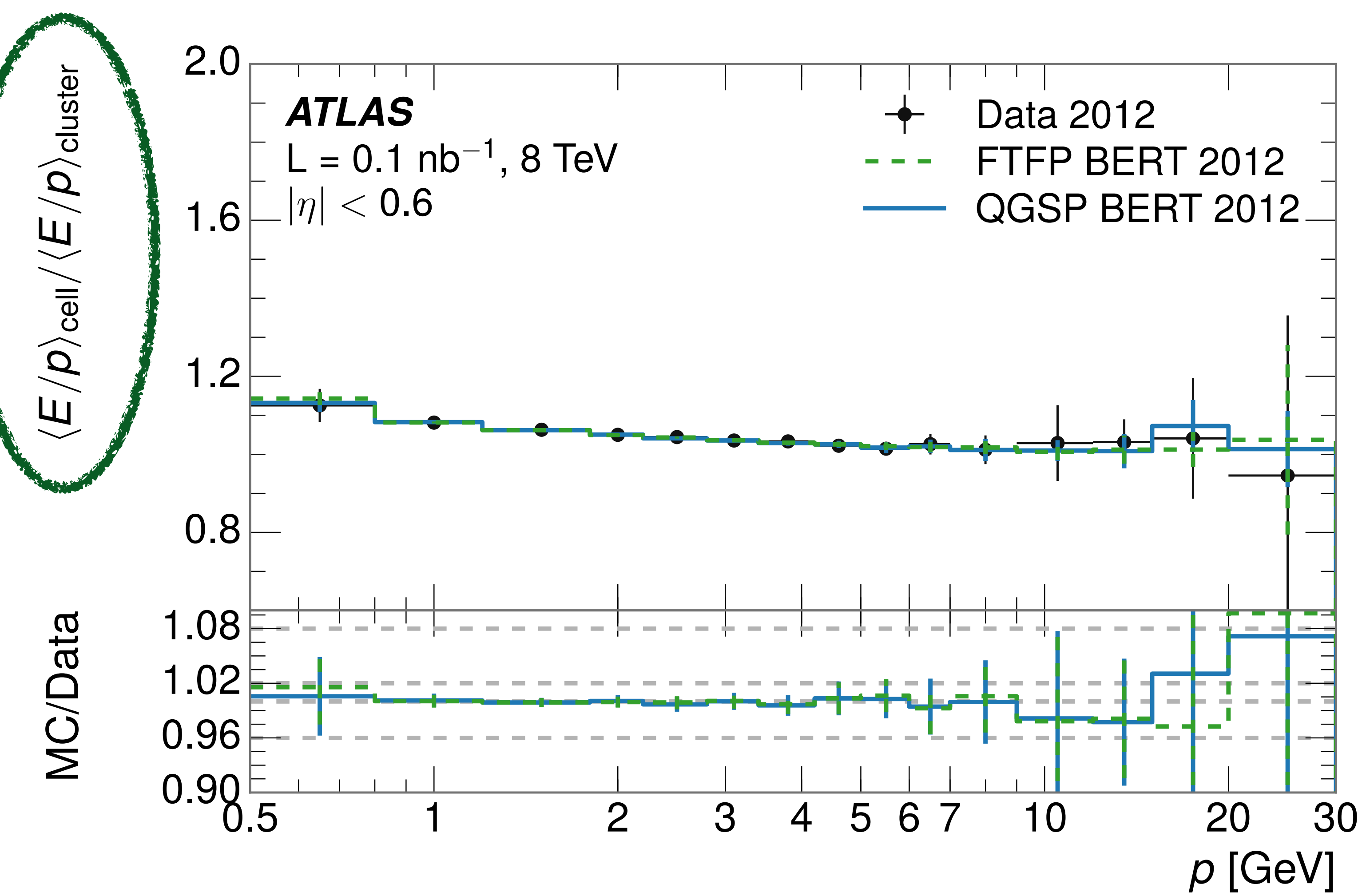
[arXiv:1603.02934]

SINGLE-HADRON RESPONSE & JET COMPOSITION MEASUREMENTS



Isolated charged hadron response measured in data

Full calorimeter R / topo-cluster R



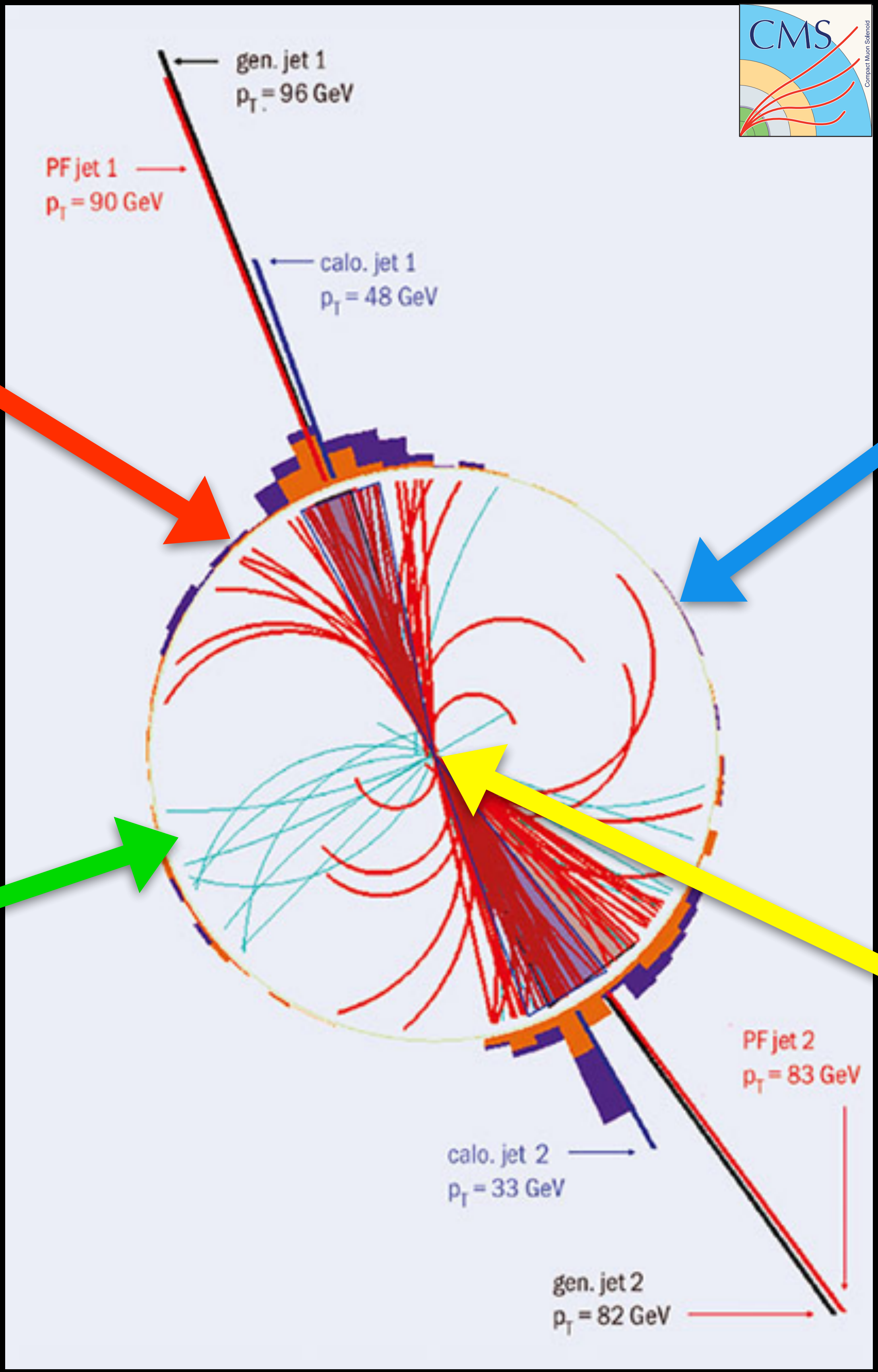
Topoclusters effectively capture shower energy for isolated single particles

AND MANY MORE INTERESTING MEASUREMENTS

[EPJC (2017) 77:26]

Tracks capture jet structure in fine detail

Correct for bending in magnetic field

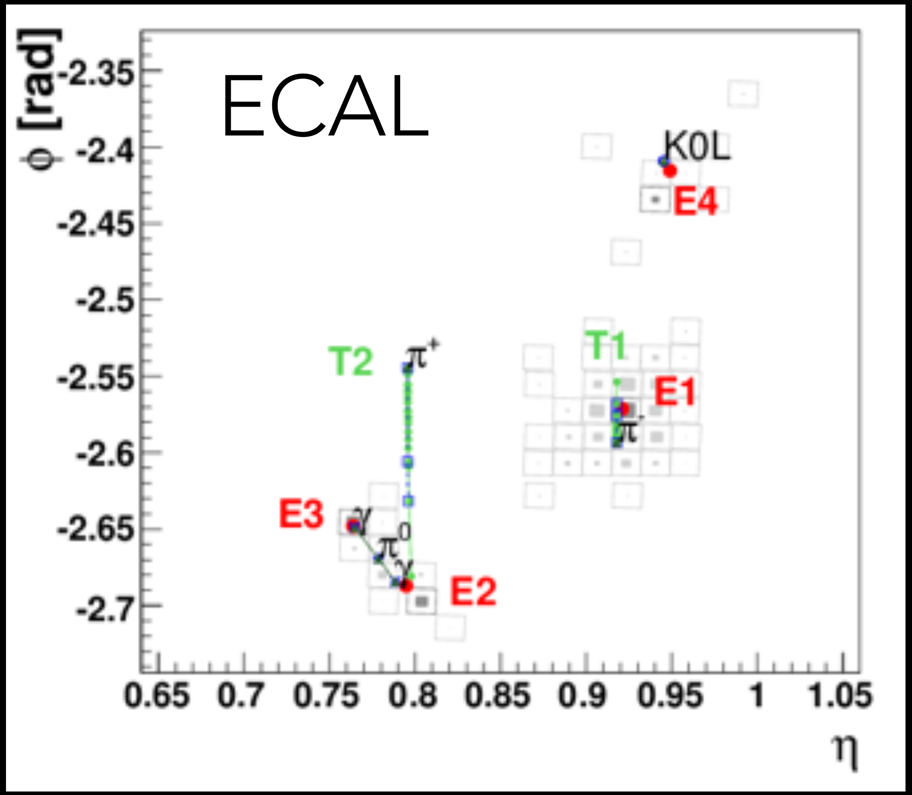


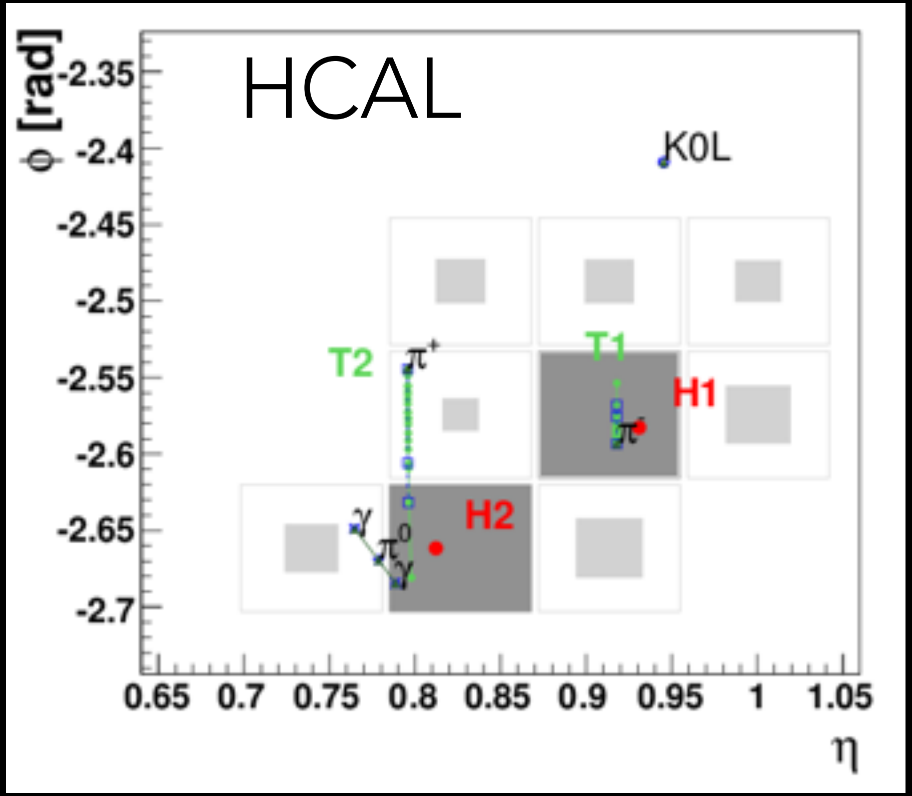
Better particle momentum resolution

Identify origin vertices

Particle flow reconstruction

- Foundation of CMS hadronic reconstruction
- Integrated with **global event reco**
  1. Muons & electron constituents removed
  2. Extrapolated tracks matched to clusters to form charged hadrons
  3. Photon & neutral hadrons created from excess ECAL/HCAL energy
  4. *Dedicated calibrations applied to each particle type*

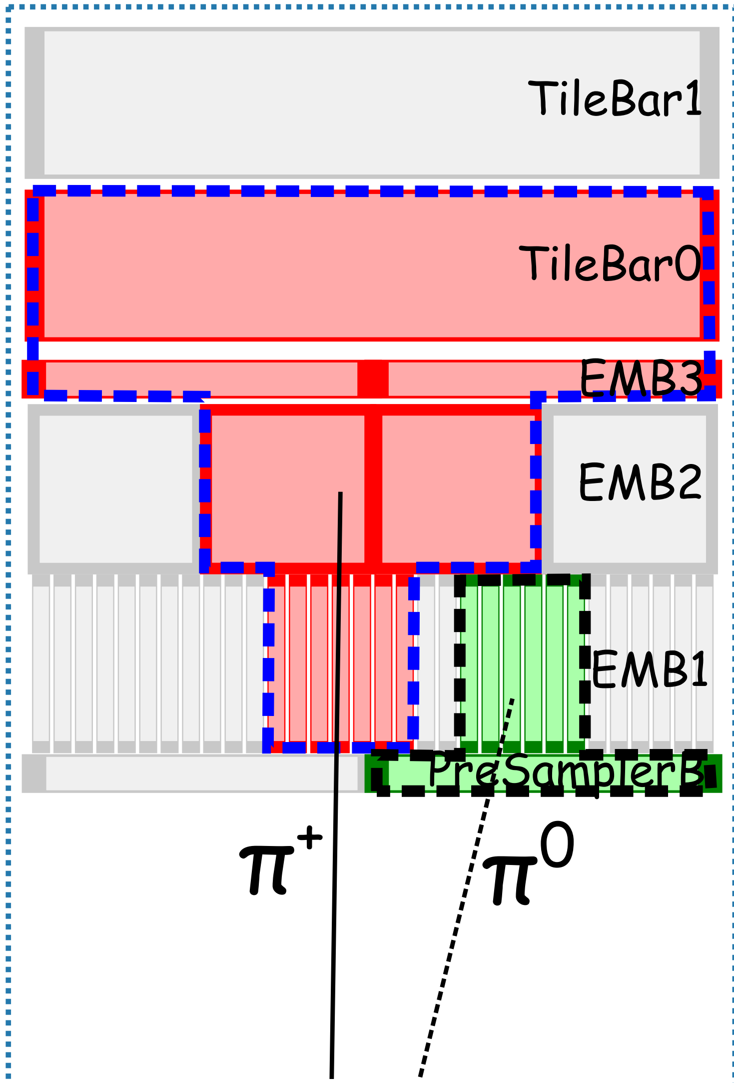




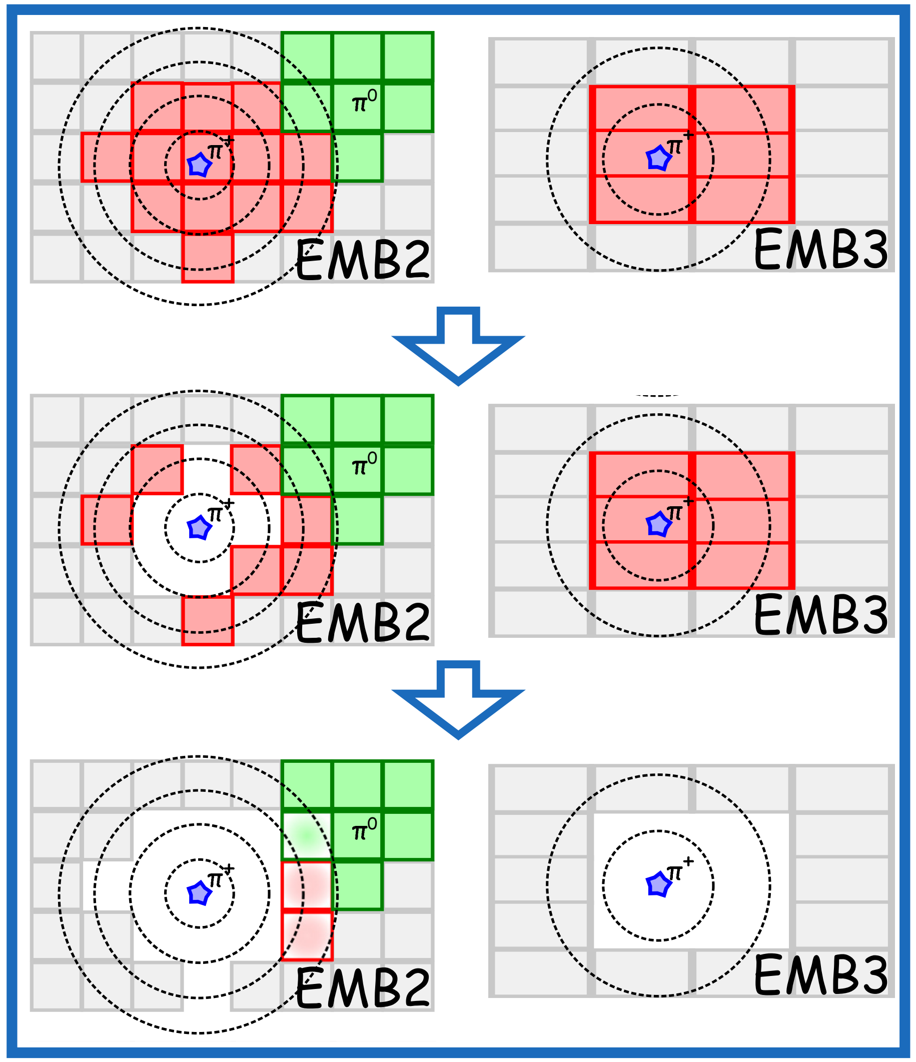
[CMS PAS-PFT-09-001]

PARTICLE FLOW @ ATLAS

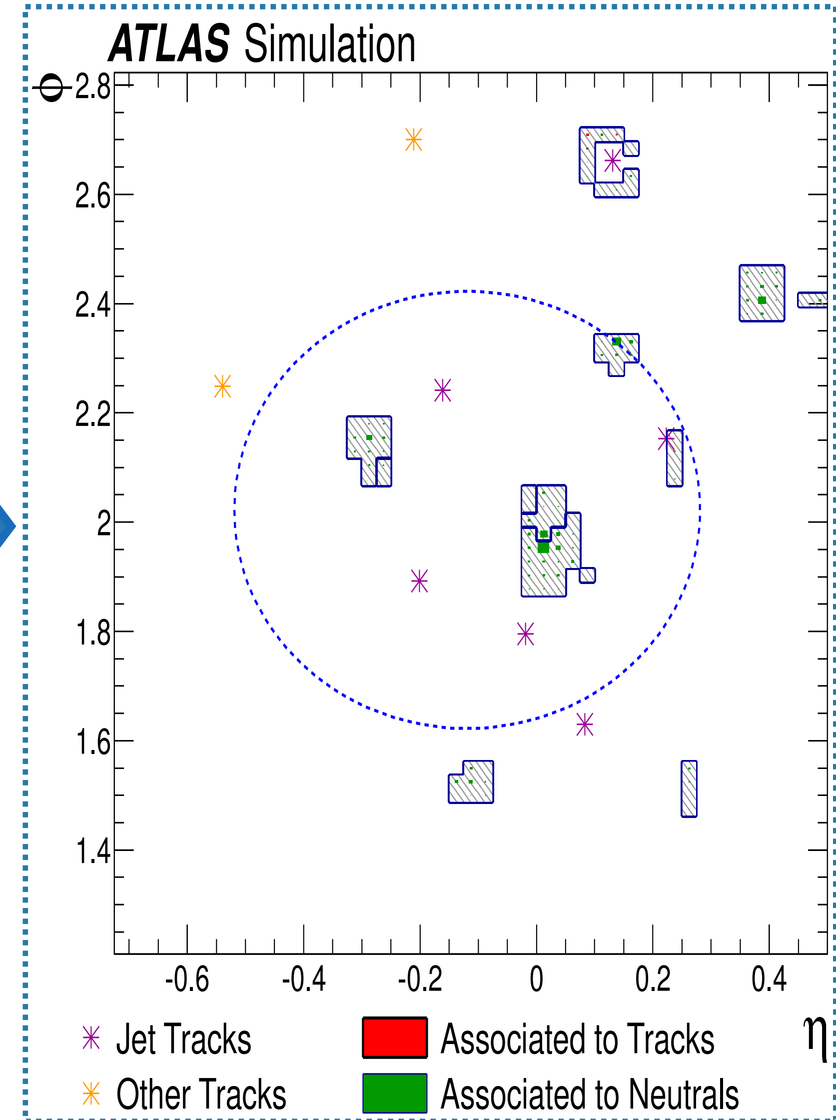
Different approach for longitudinally/laterally segmented calorimeter
Subtract calorimeter energy with parameterised shower shape.



Track-cluster matching
1:1 or 1:many



Cell-level subtraction
by ring & layer



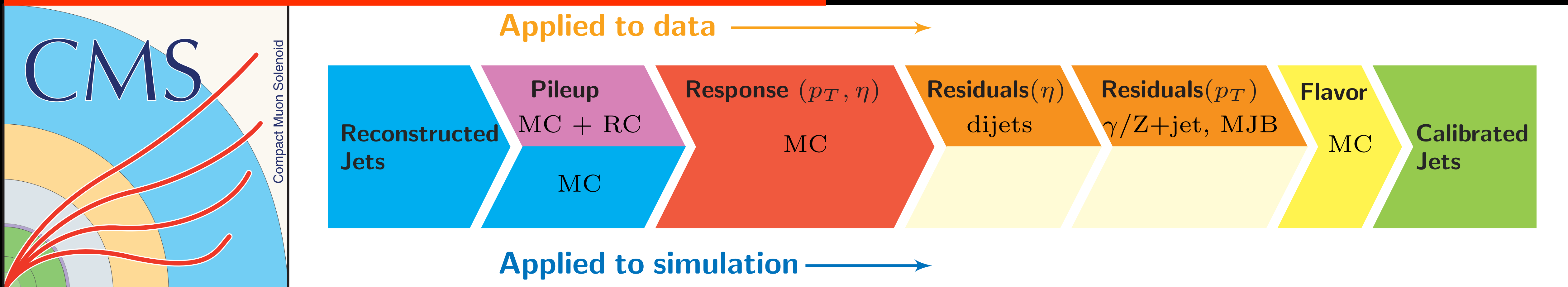
No-pileup illustration
(charged energy selectively removed)

Difficult in high-pT jets! Most gains at low pT.

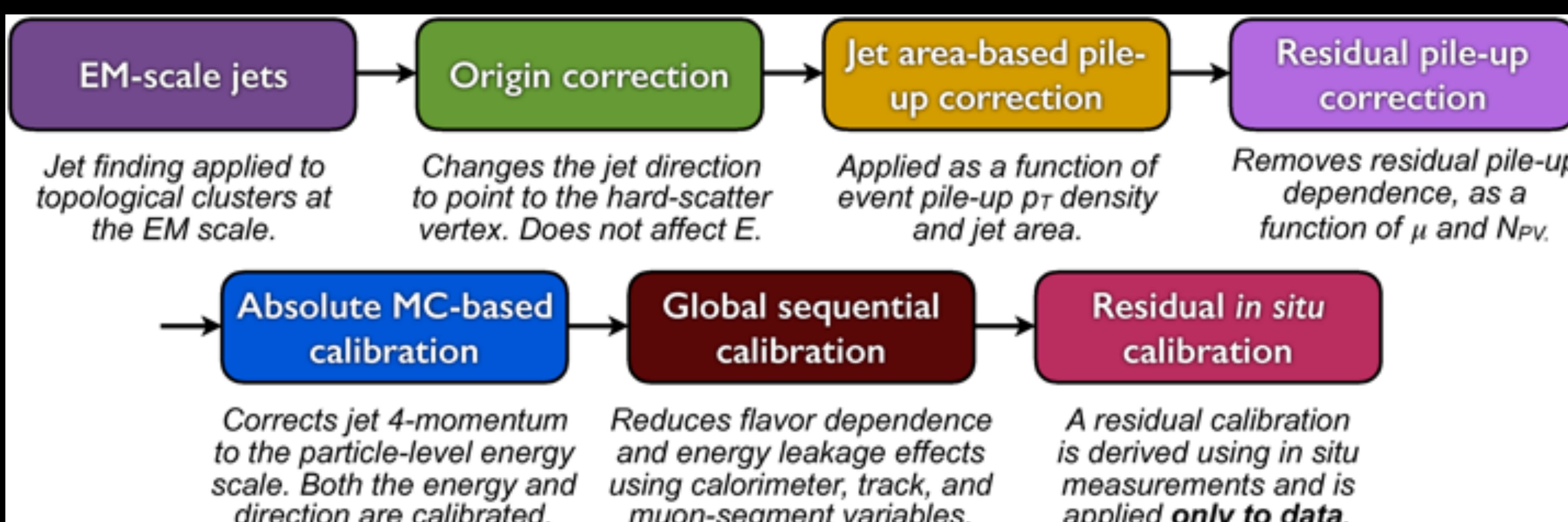
[arXiv: 1703.10485]

Jet Calibration

[JINST 12 (2017) P02014], [CMS DP -2016/020]



Four-vector restored to particle-scale reference four-momentum using similar sequential corrections.

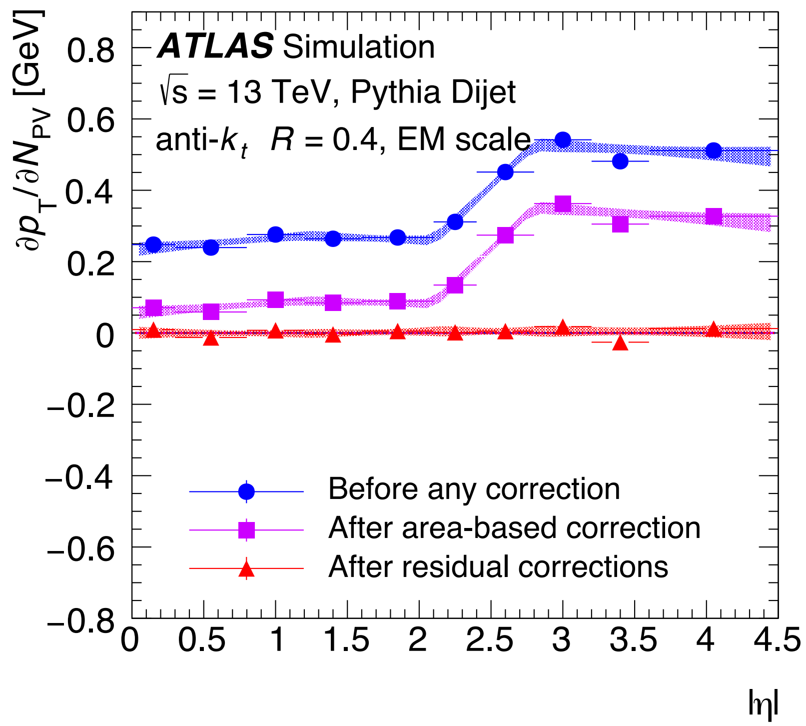


ATLAS EXPERIMENT

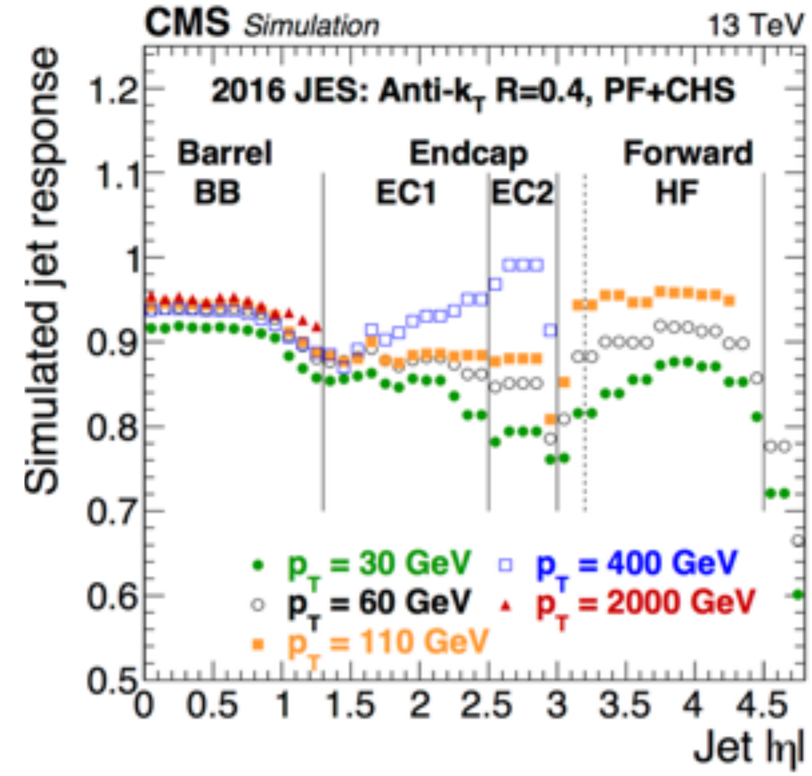
[arXiv: 1703.09665]

JET CALIBRATION STEPS ILLUSTRATED

Pile-up corrections

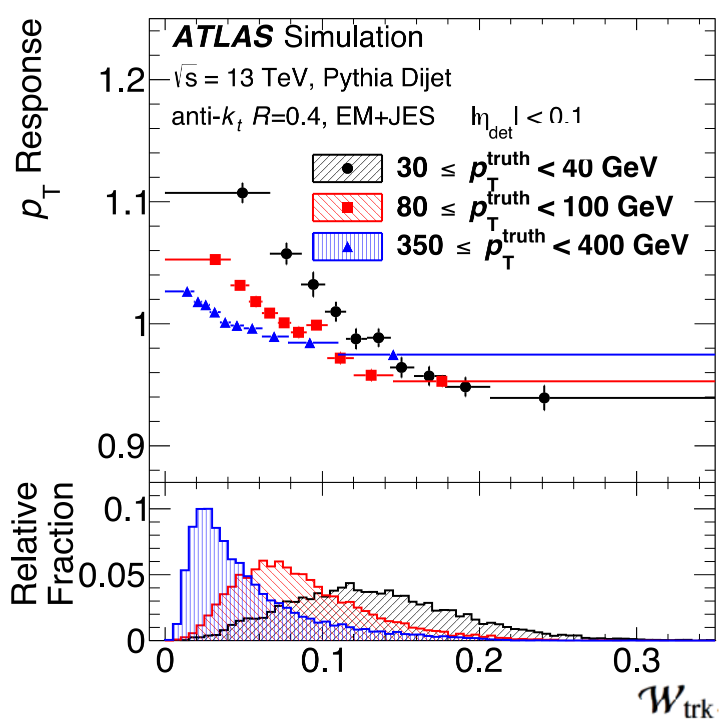


MC-based absolute scale

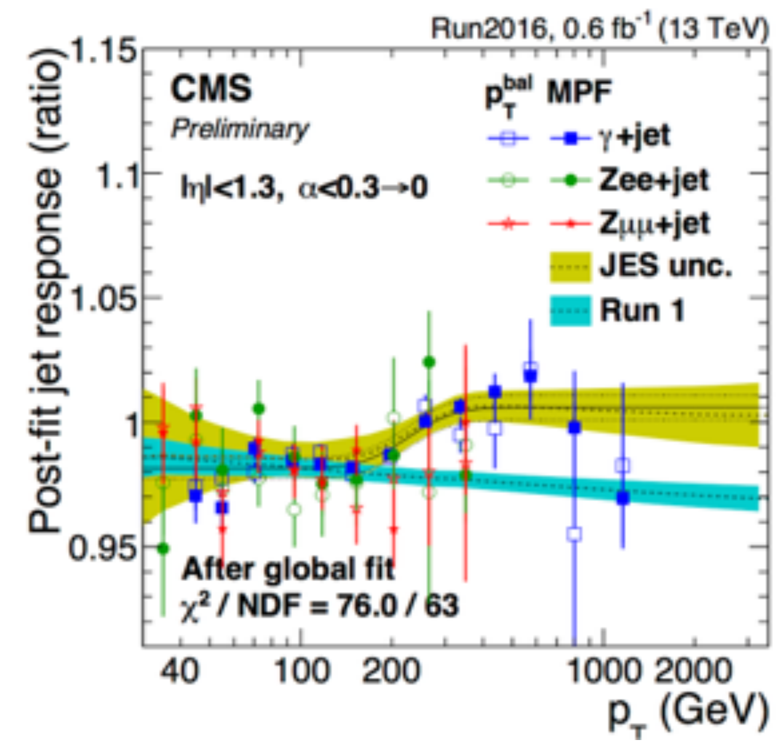


Additional corrections

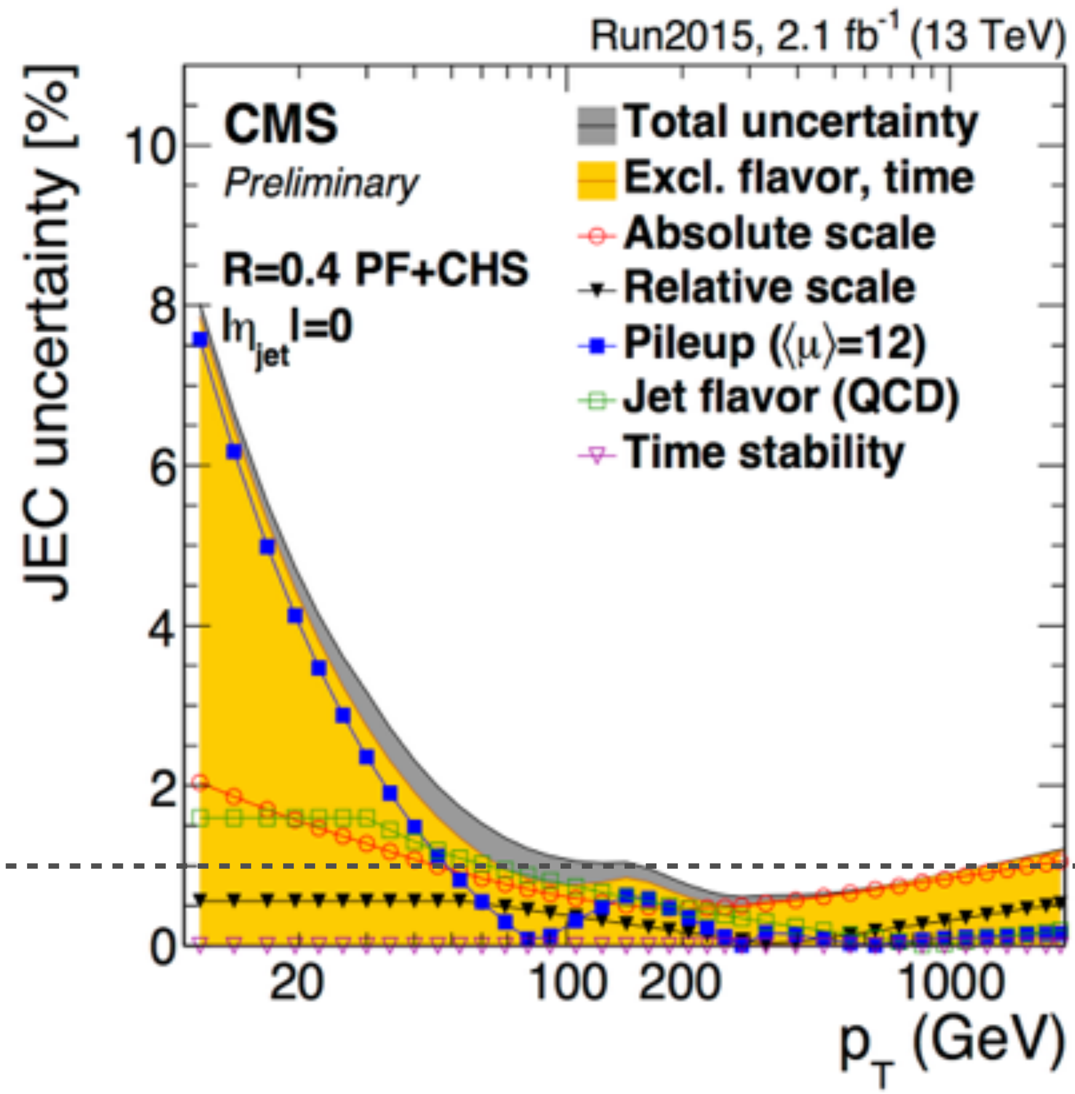
(Flavour/fragmentation/shower depth)

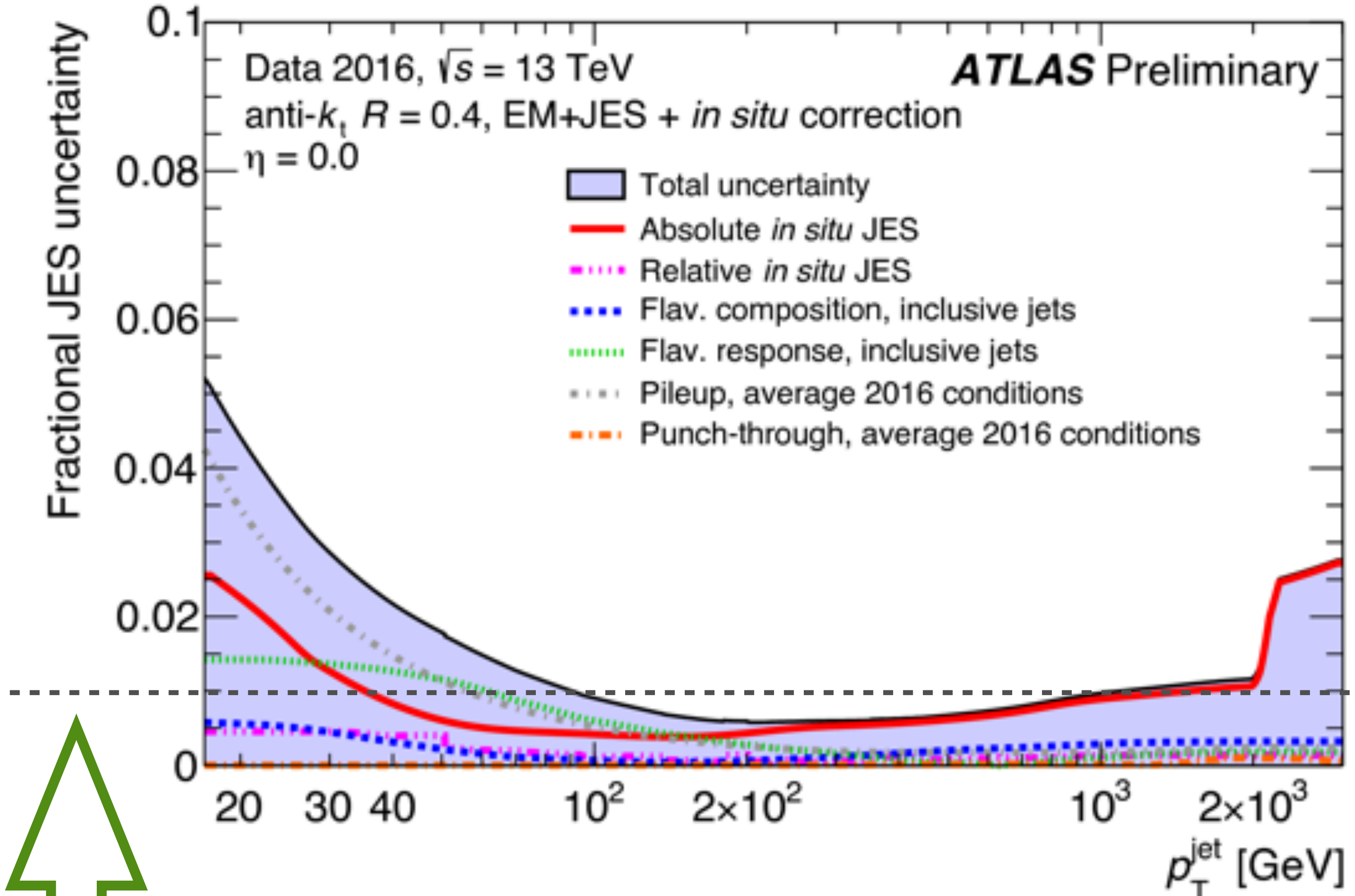


In situ data/MC corrections



Jet Uncertainties



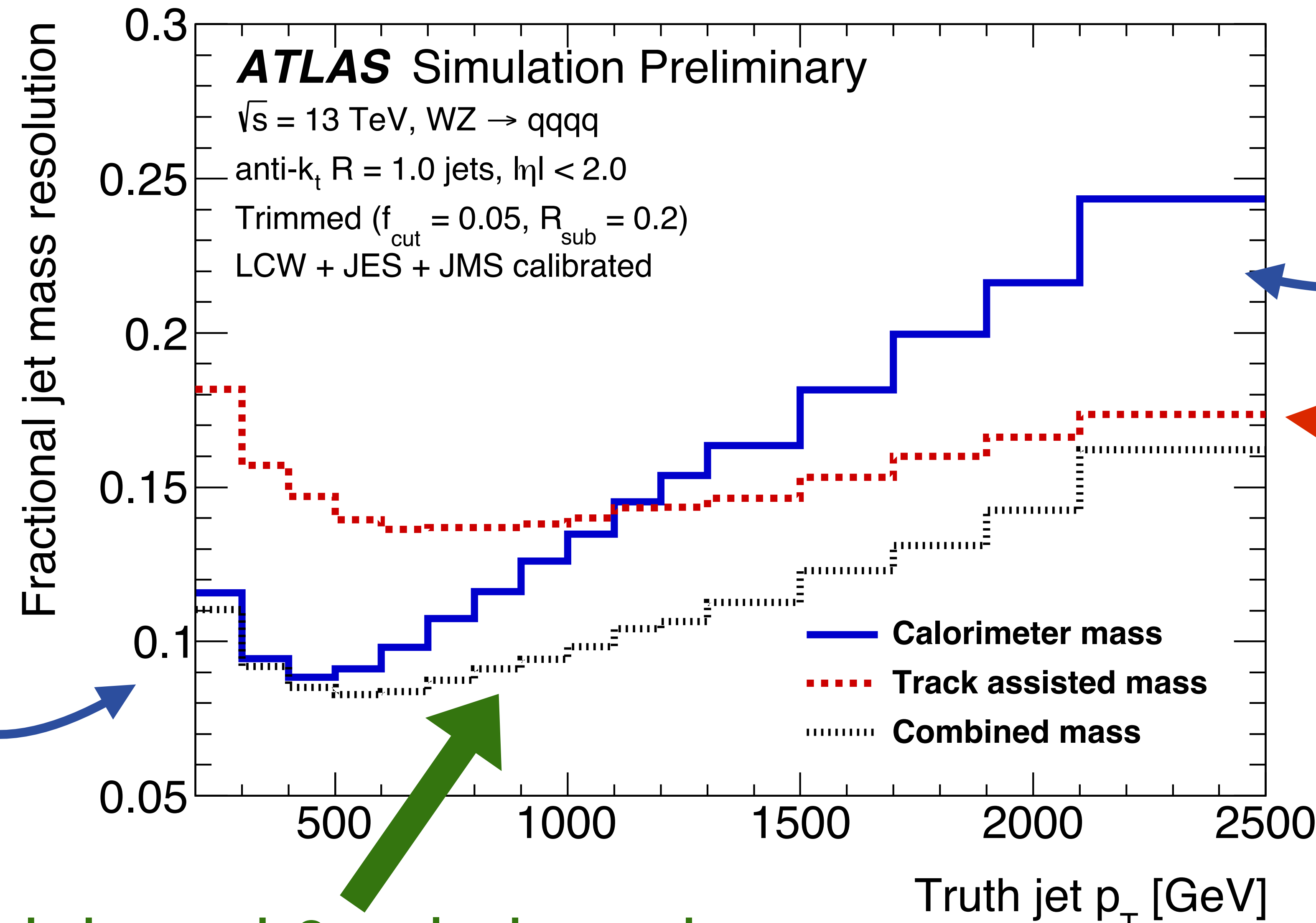


Sub-percent precision reached for O(100 GeV)

JET MASS CALIBRATION

Calo resolves mass well at low pT

Merged clusters at high pT obscure substructure

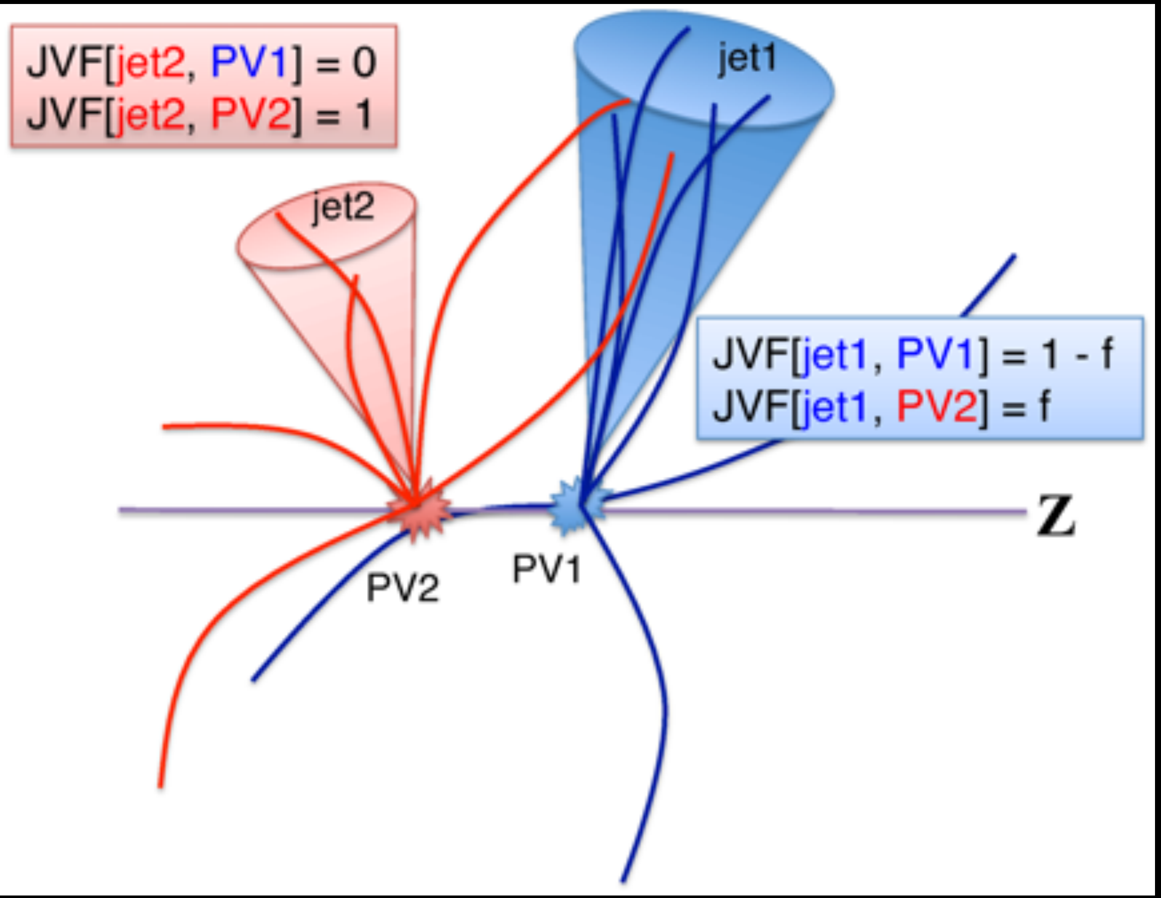


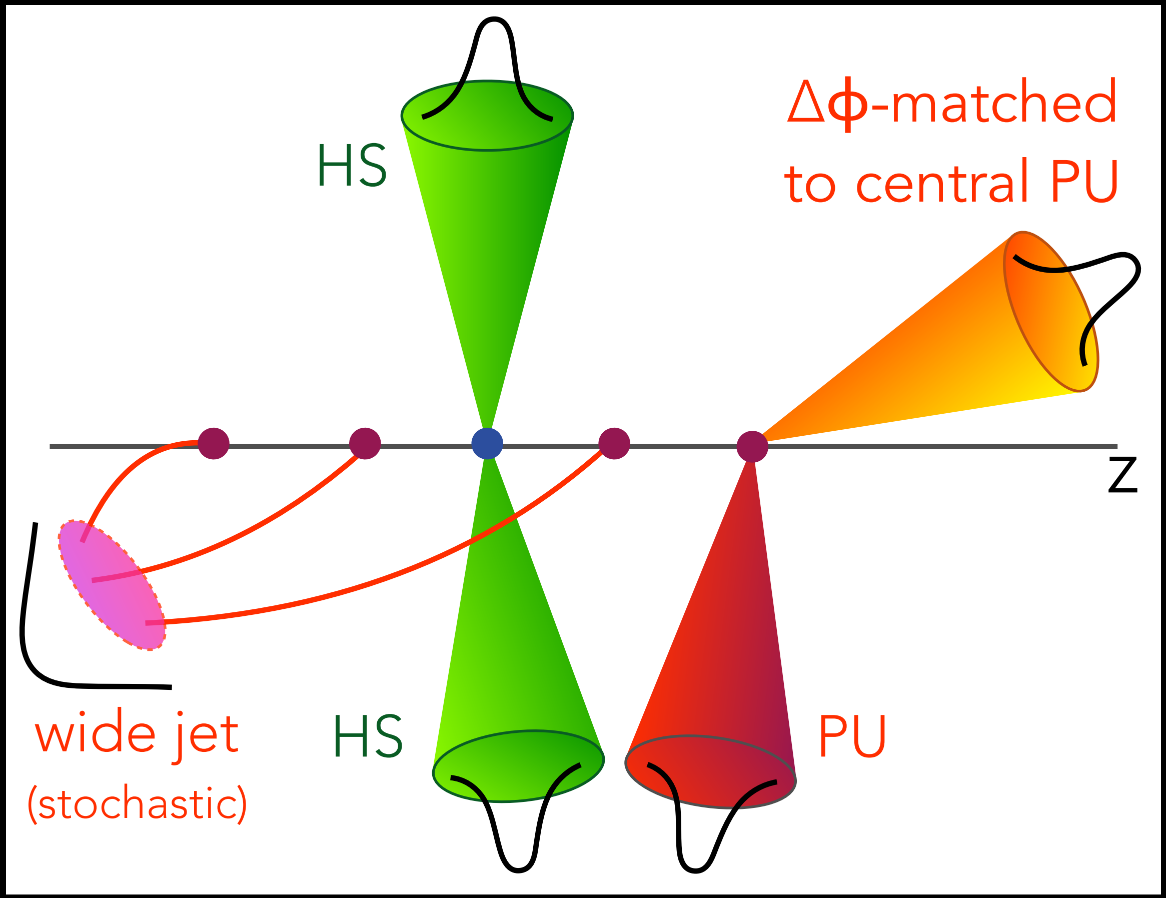
Combine track-based & calo-based with resolution-weighted average for best performance across pT spectrum

Recover with track-jet mass, scaled by pT_{trk} / pT_{calo}

[JETM-2017-002], [ATLAS-CONF-2016-035]

JET-LEVEL PILEUP SUPPRESSION





- Track associations — Identify vertex origin
- Jet width & angular variables:
  - wider spread in PU jet constituents
- Central-forward matching tags PU outside tracker

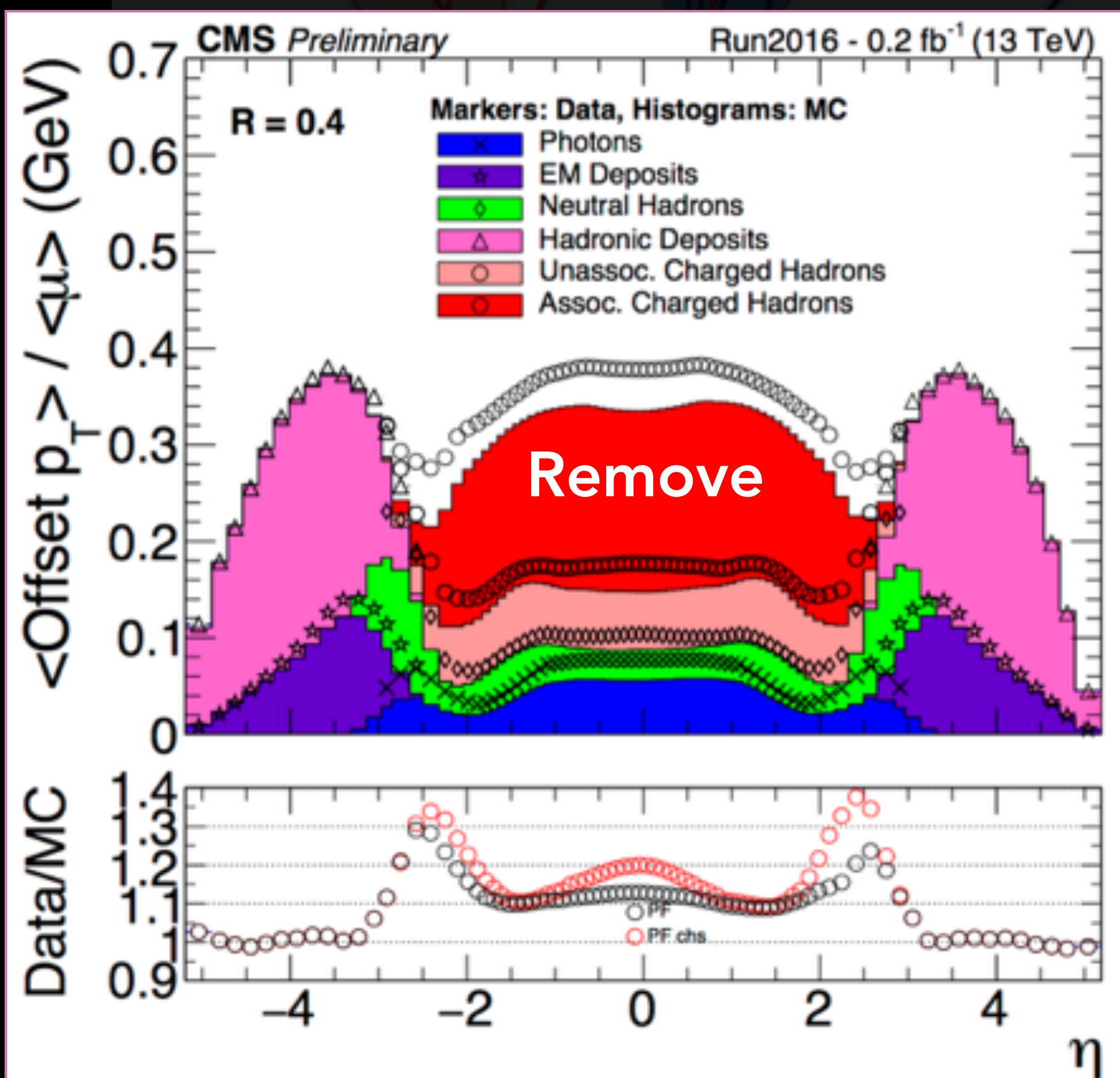
CMS-PAS-JME-16-004

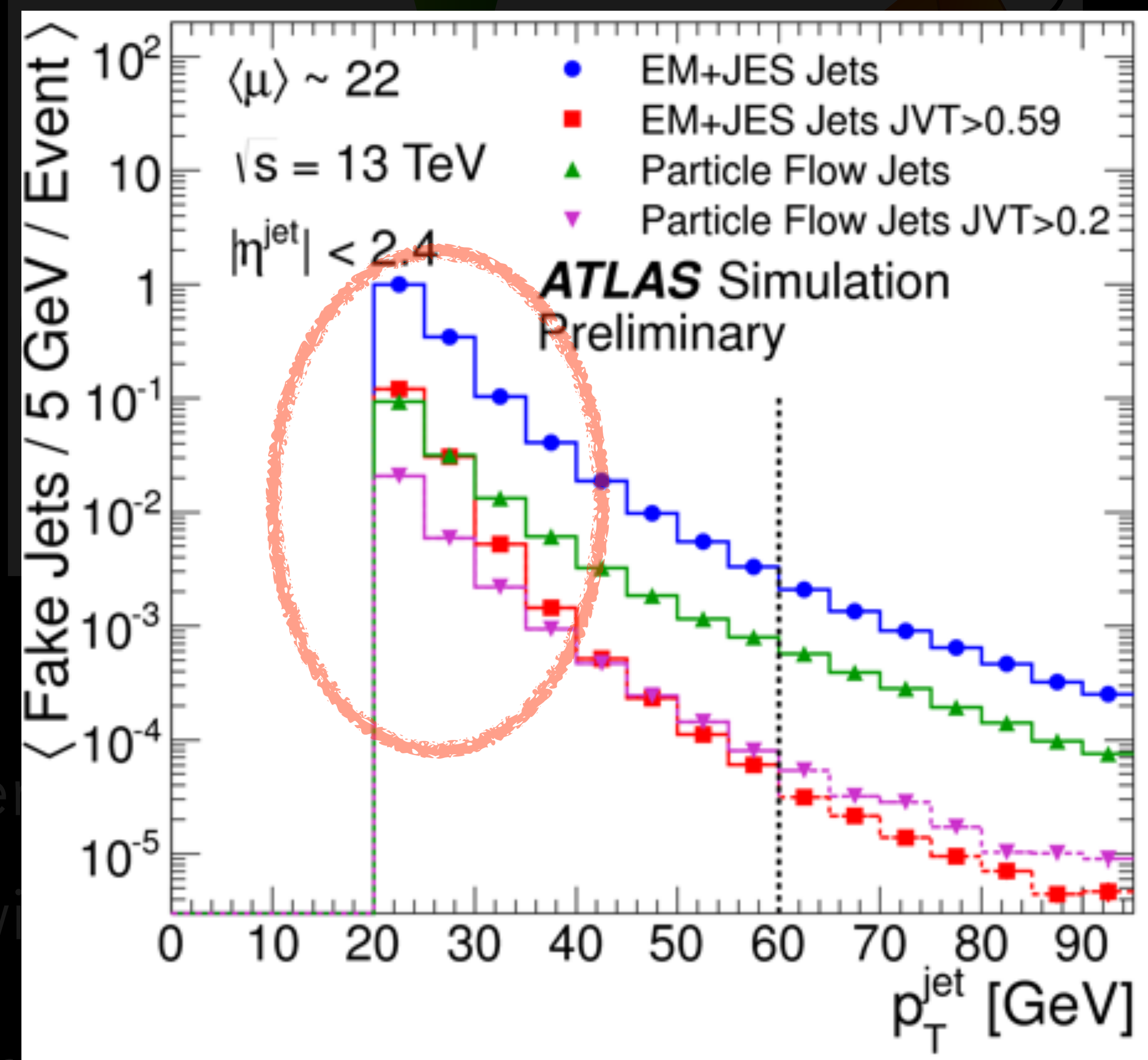
arXiv: 1510.03823, 1705.02211

Crucial for VBF analyses

JET-LEVEL PILEUP SUPPRESSION

Low pT PFlow rejection equal to Calo+JVT, PF+JVT equal/better at pT>40 with higher hard-scatter efficiency





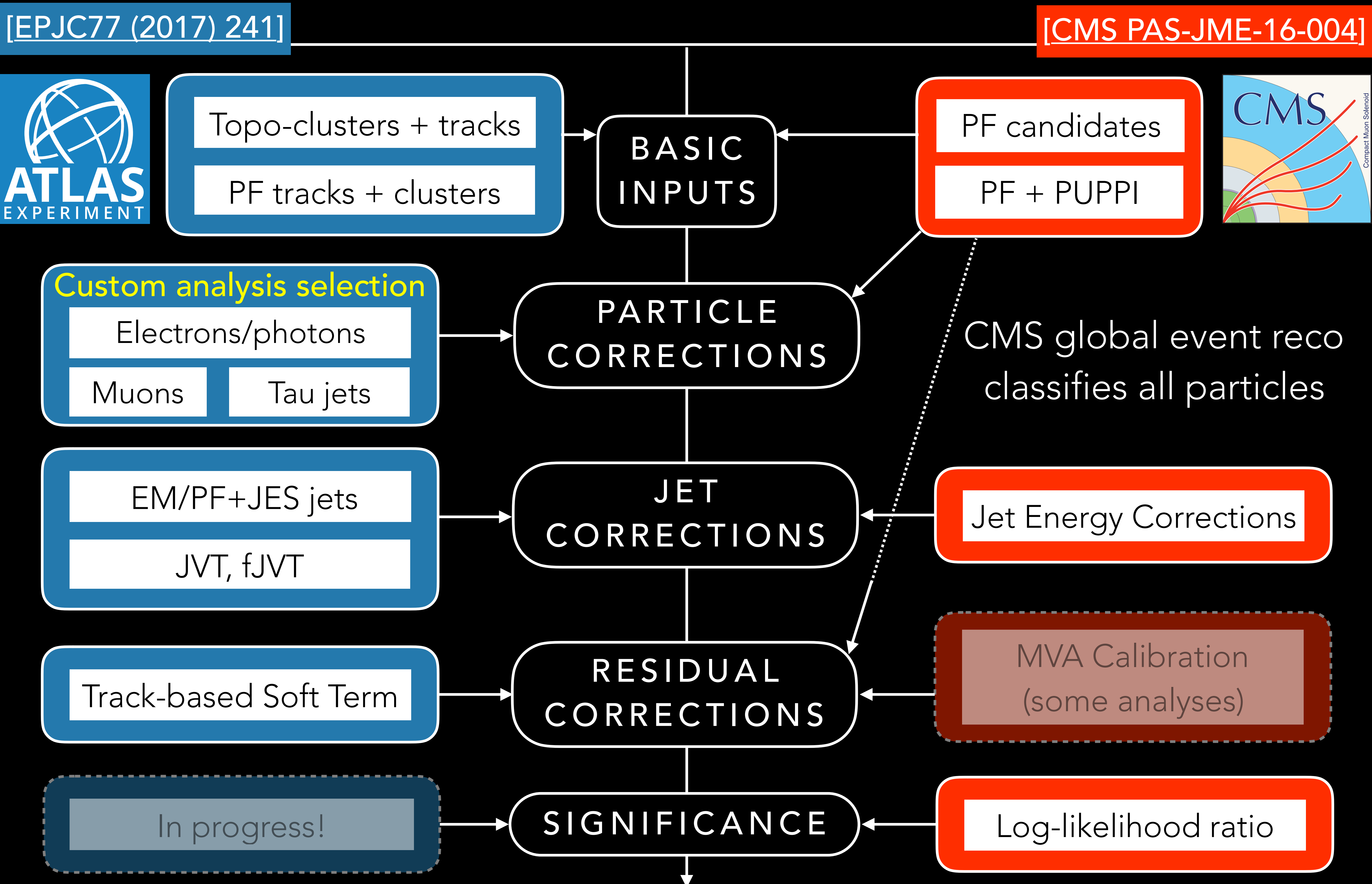
PFlow+CHS reduce pileup at source.

Jet-level cuts still needed, achieve better suppression.

CMS-PAS-JME-16-004

arXiv: 1510.03823, 1705.02211

MISSING TRANSVERSE MOMENTUM

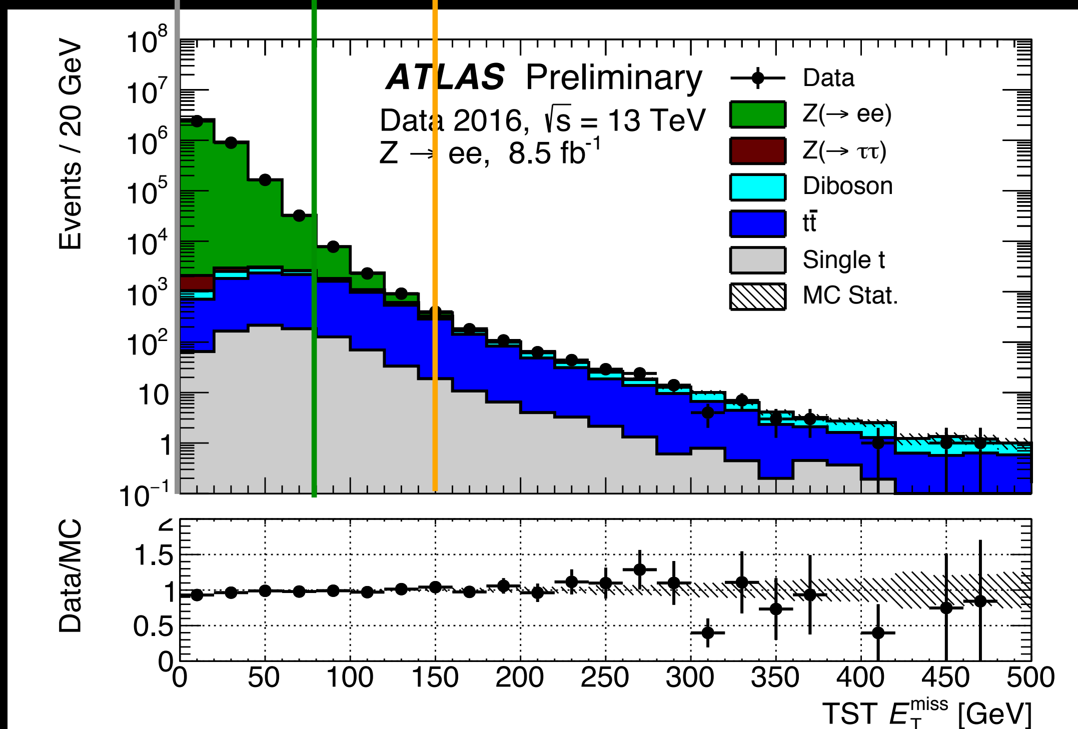


MISSING TRANSVERSE MOMENTUM

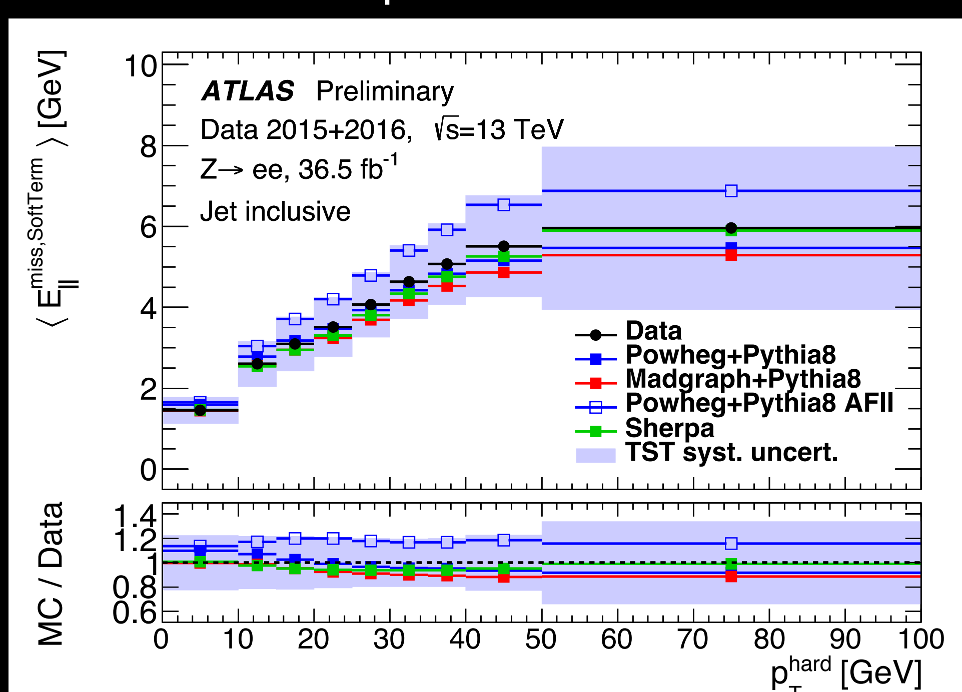
[JETM-2016-008, JETM-2017-001]

[CMS PAS-JME-16-004]

Core Tails True MET

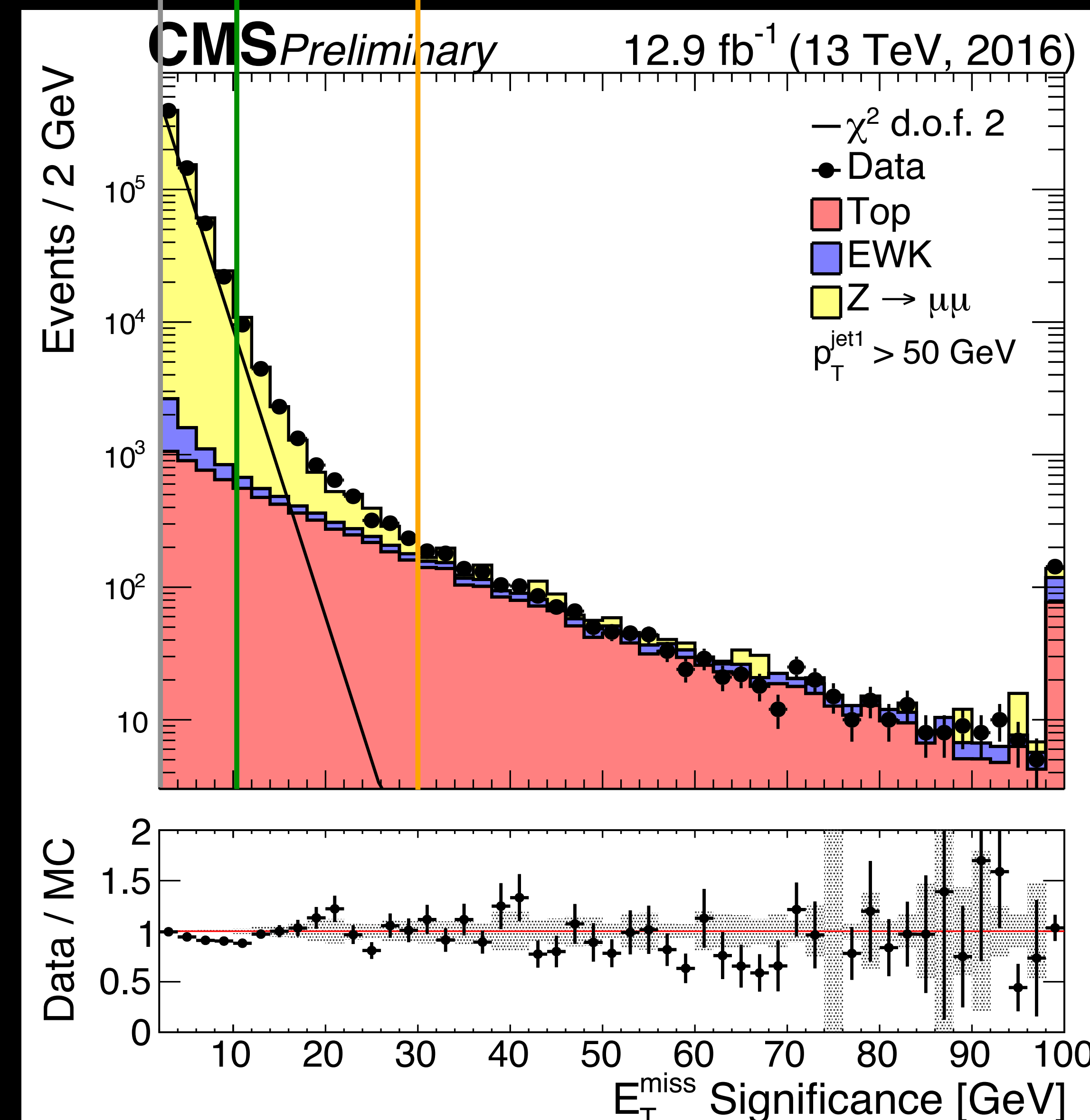


Syst σ from envelope of data/MC differences



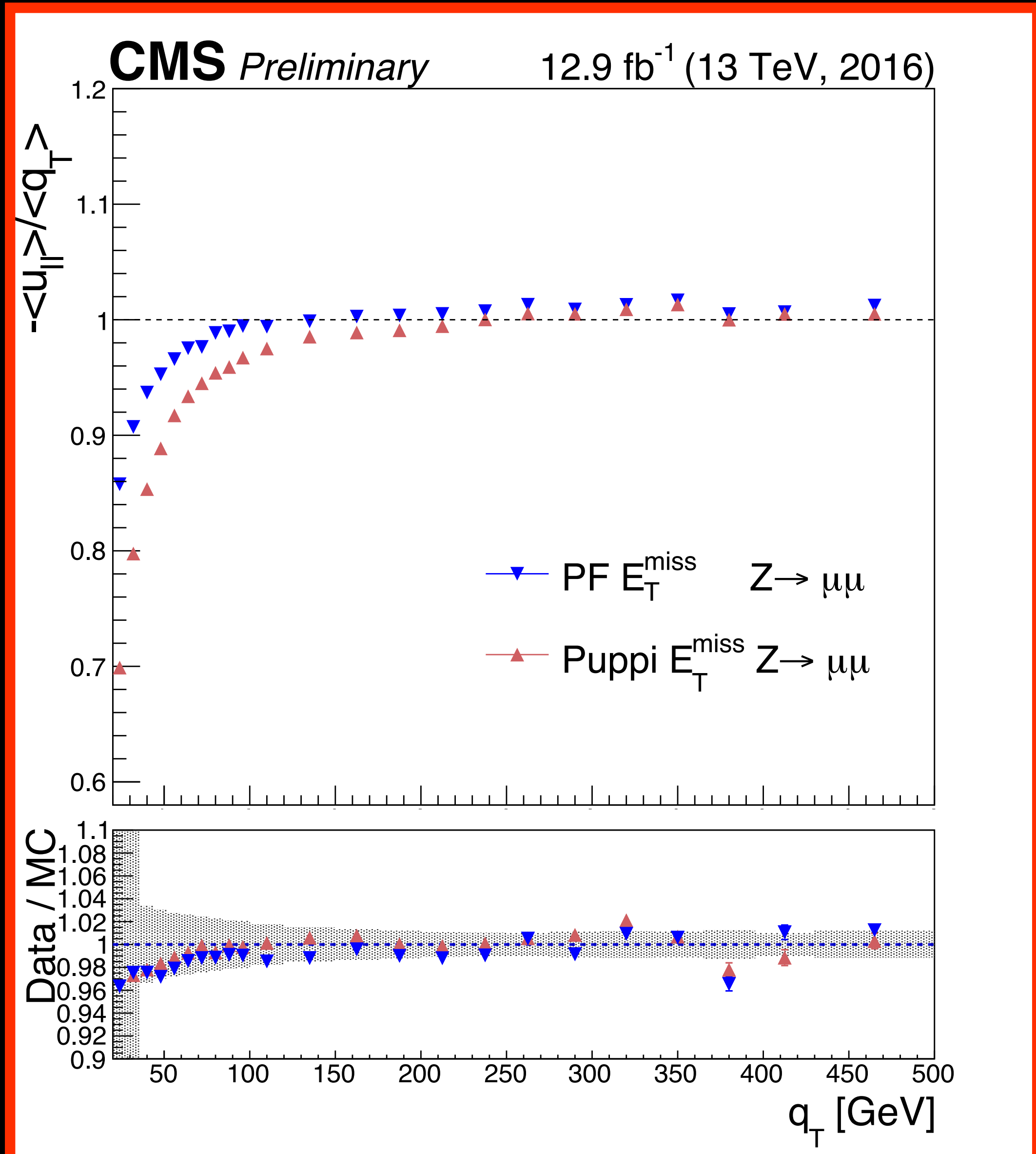
Sherpa 2.2.1 soft modelling improvements crucial

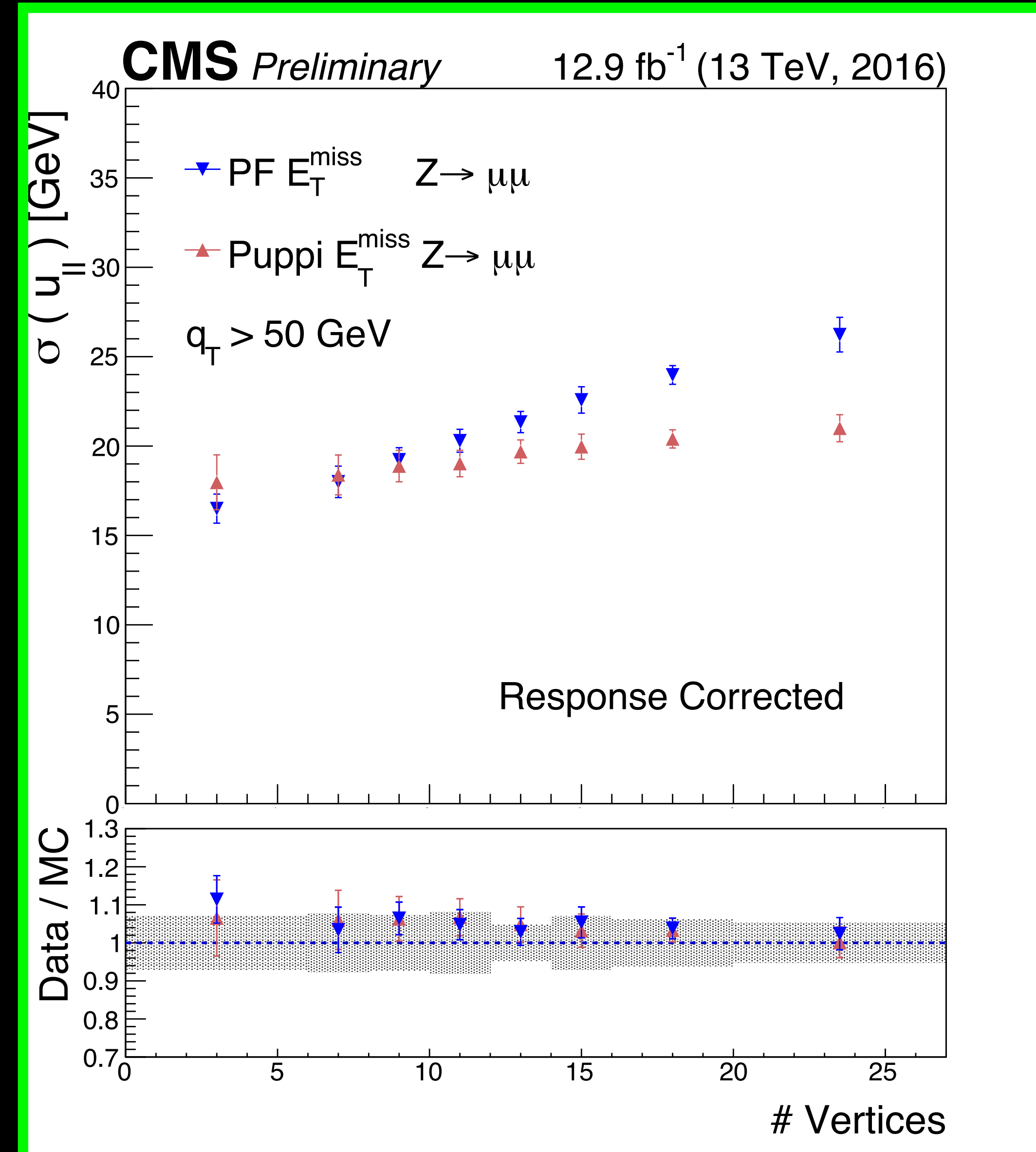
Core Tails True MET



Significance calculation effectively separates real & fake MET

PUPPI filtering improves resolution with pile-up at cost of underestimating hadronic recoil.



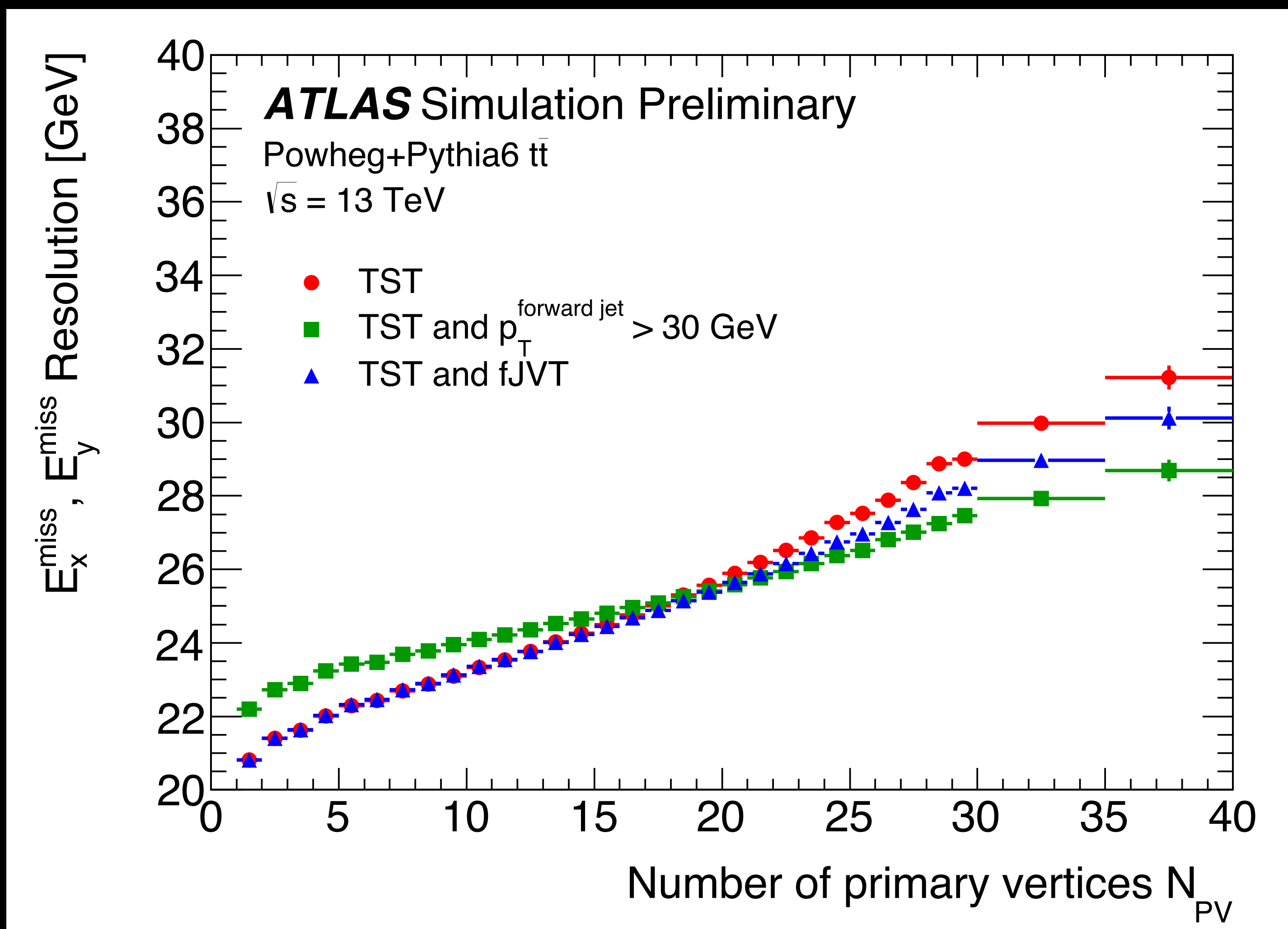


Difficult trade-off between optimising for scale and optimising for resolution. Needs to be driven by physics goals.

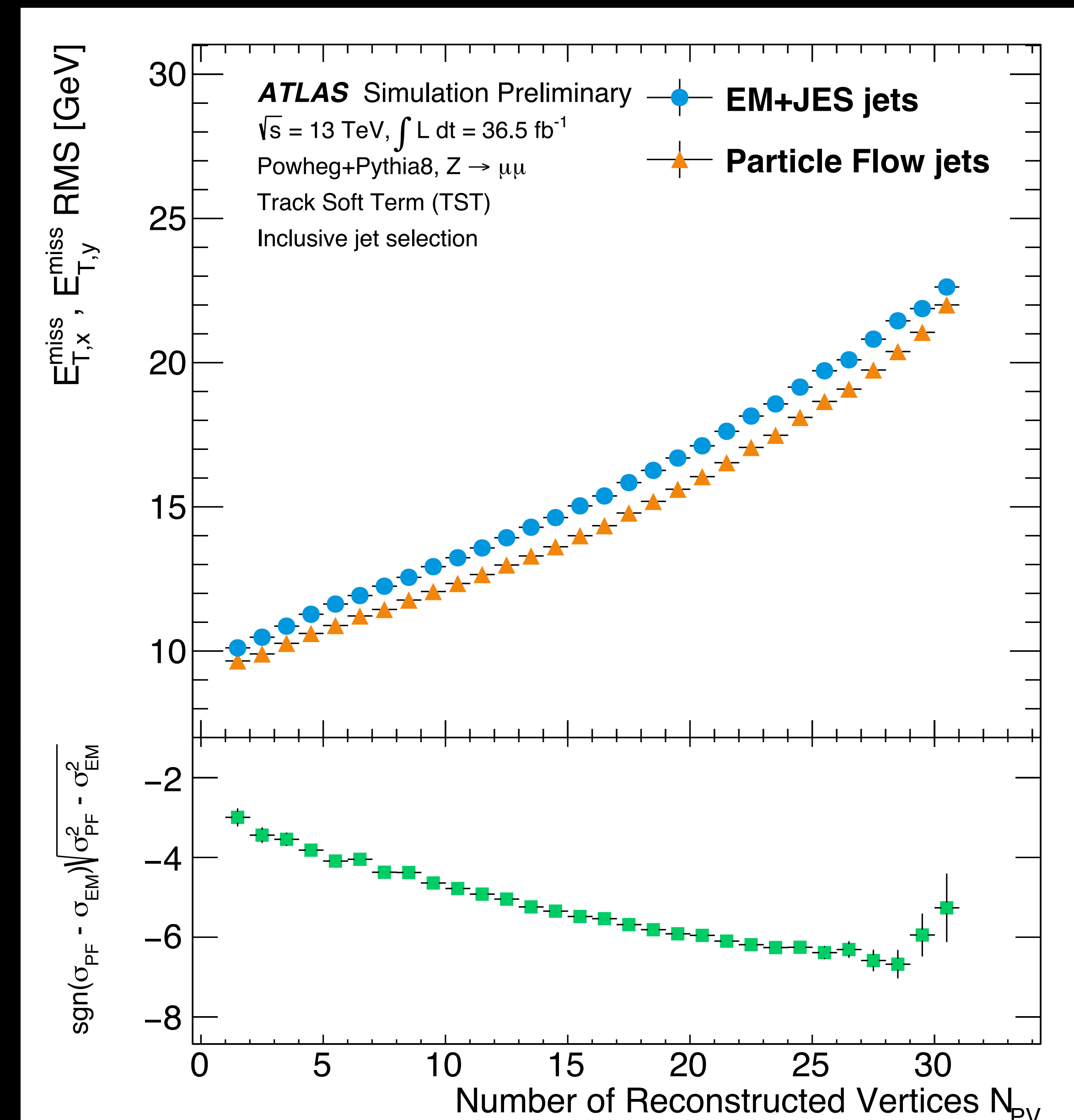
[CMS PAS-JME-16-004]

MISSING TRANSVERSE MOMENTUM

Forward pileup suppression has large impact



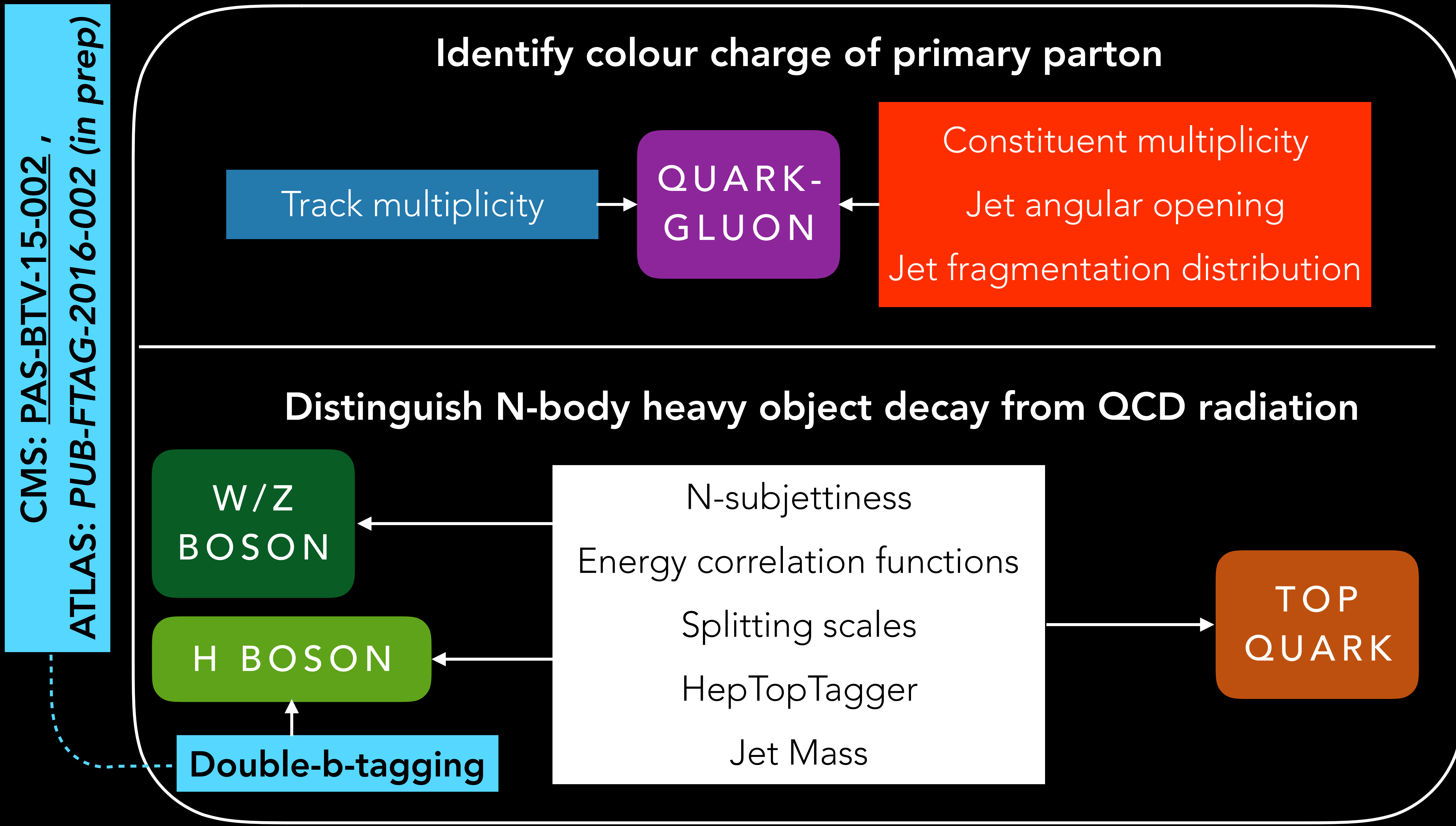
Indiscriminate cuts cause scale defects, need dedicated pileup taggers.



Improvements seen with PFlow

[JETM-2017-001], [JETM-2017-007]

JET & BOOSTED-OBJECT TAGGING



CMS PAS JME-16-003

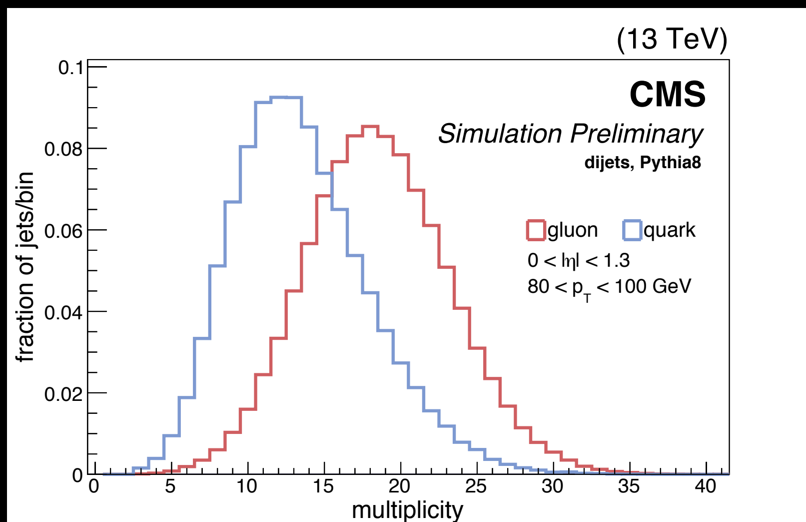
JETM-2017-004, JETM-2017-005
PUB in preparation

CMS PAS JME-16-003

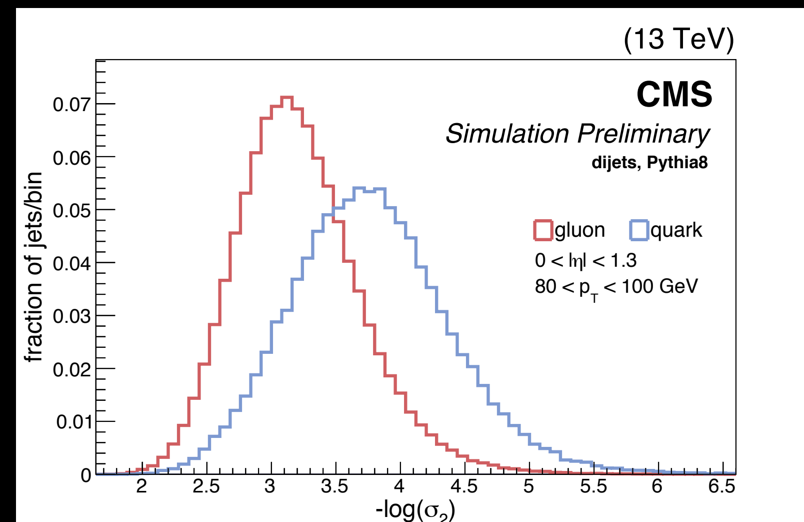
QUARK-GLUON TAGGING

See also: B.Nachman (15/5), ATL-PHYS-PUB-2017-009

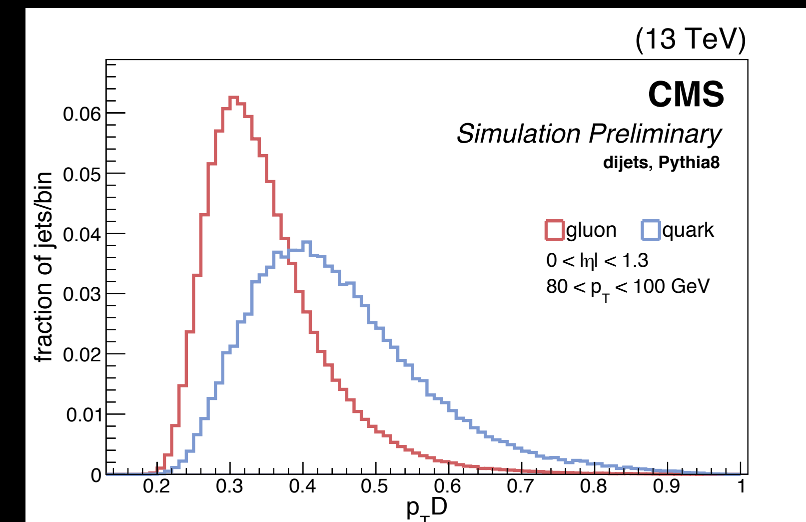
Constituent multiplicity

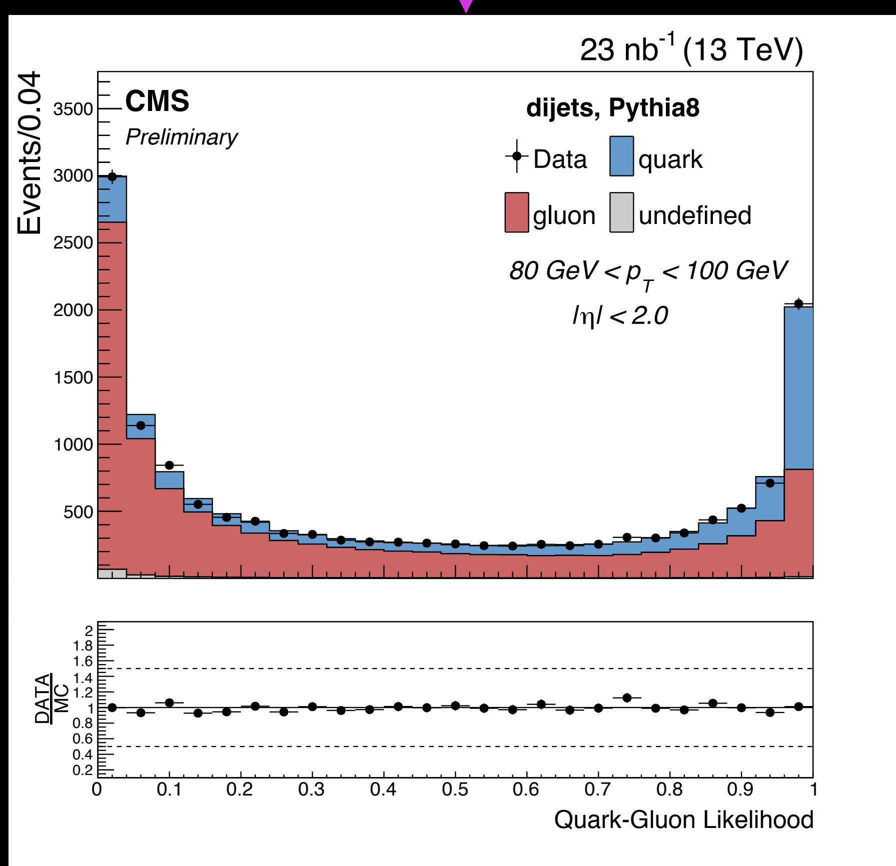


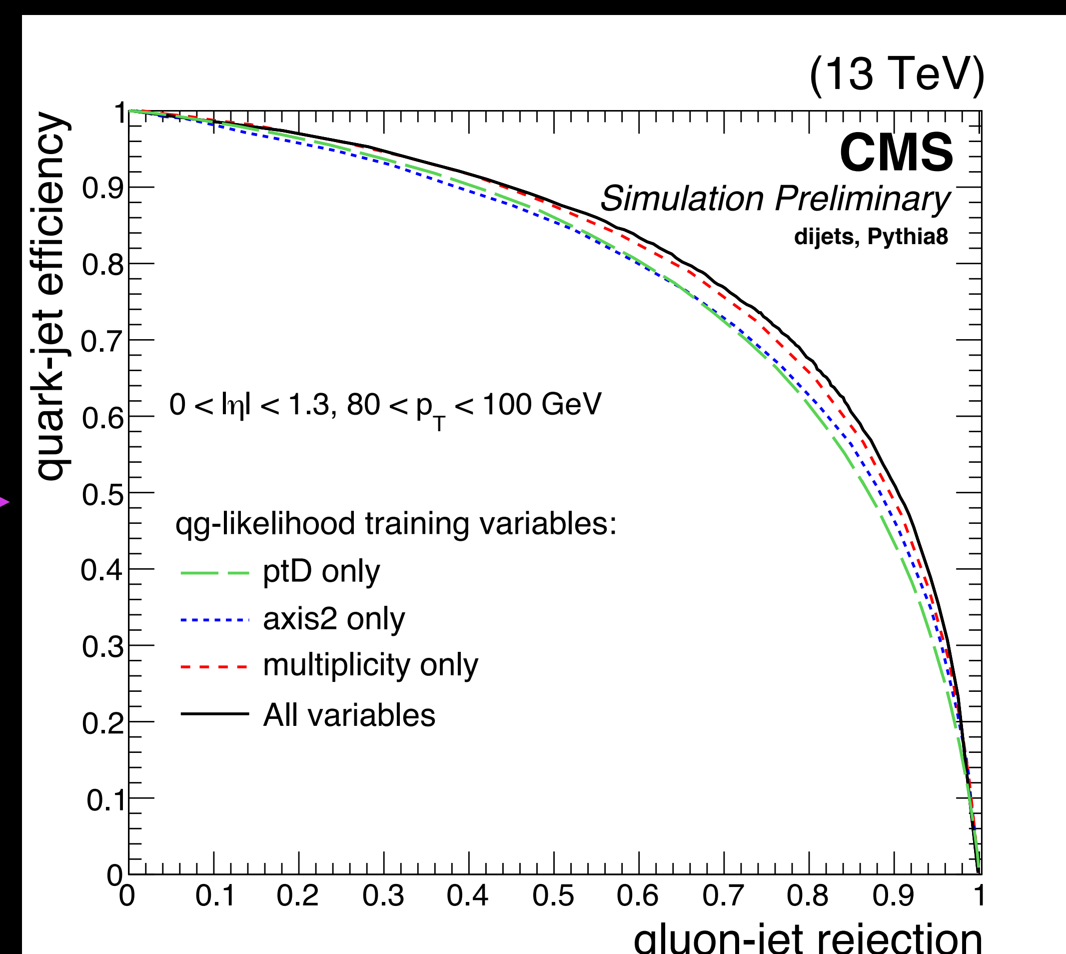
Jet opening angle



Fragmentation distribution



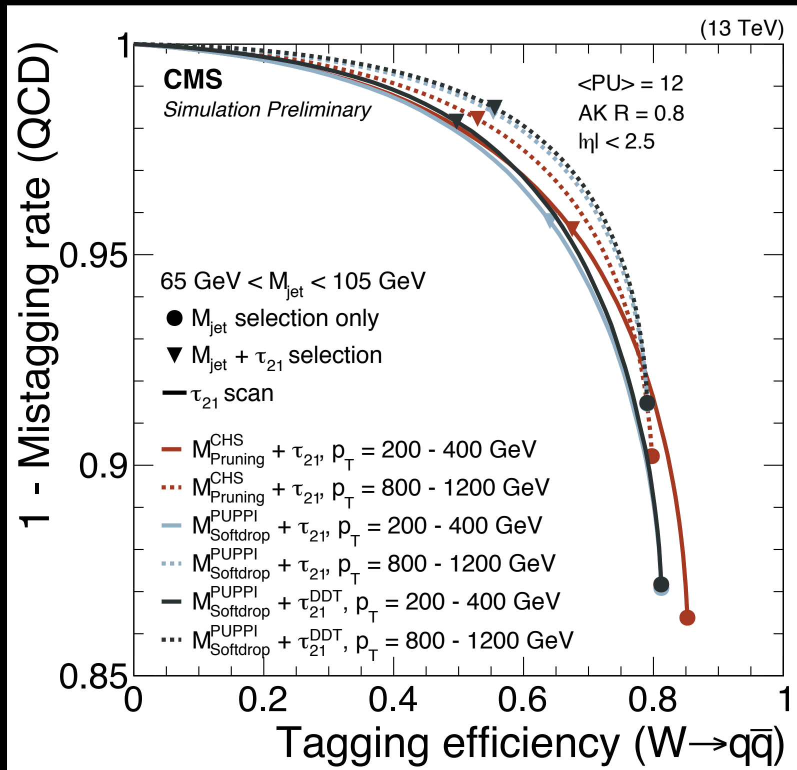




Likelihood capitalises on broader, higher-multiplicity gluon-jet radiation pattern

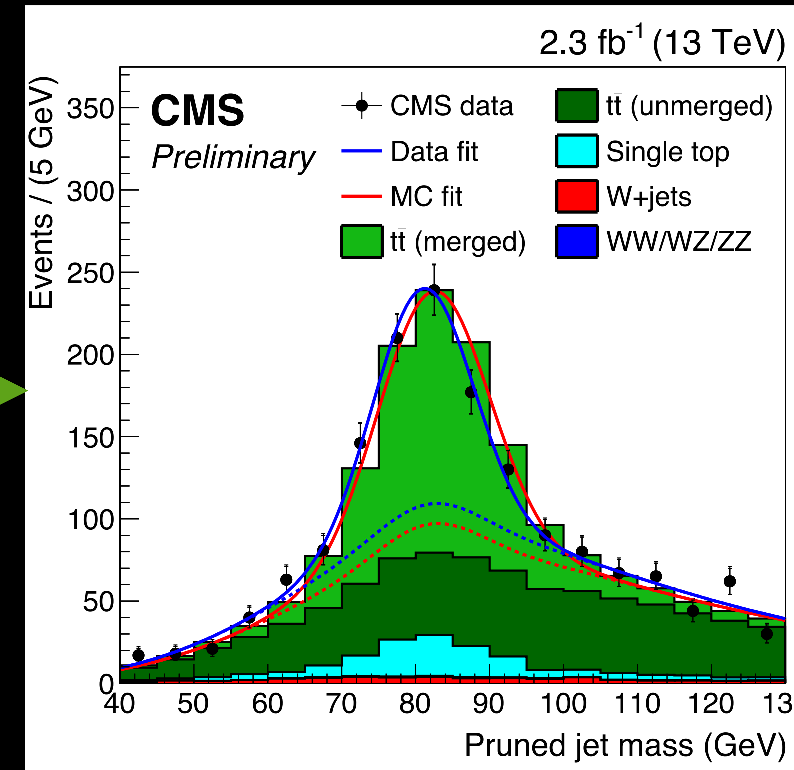
CMS PAS JME-16-003

W BOSON TAGGING



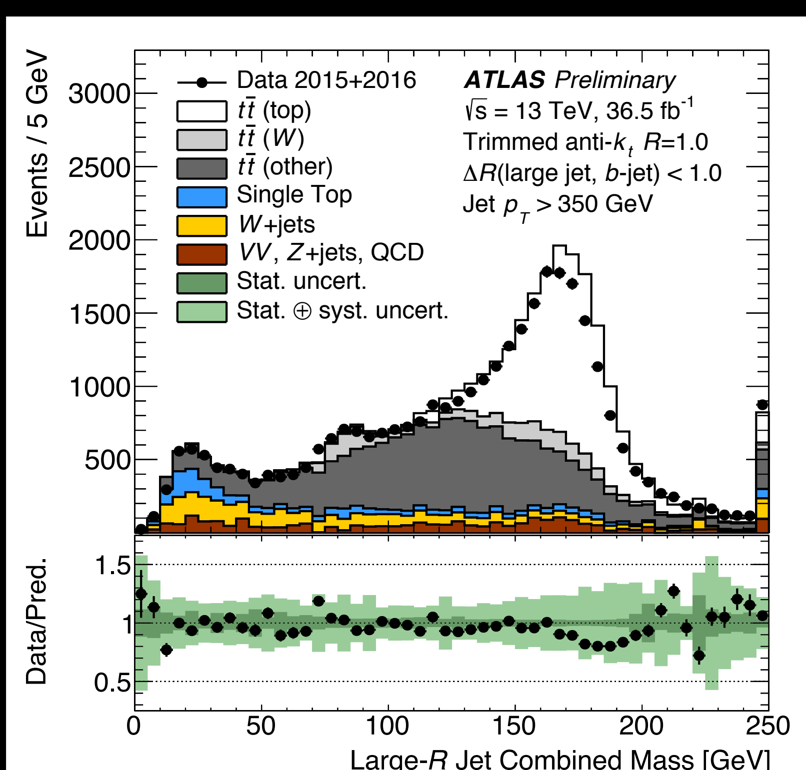
Various strategies studied for PU suppression & substructure refinement.

DDT "Decorrelated Taggers" [arXiv: 1603.00027] reduce pT-dependence of substructure selection.



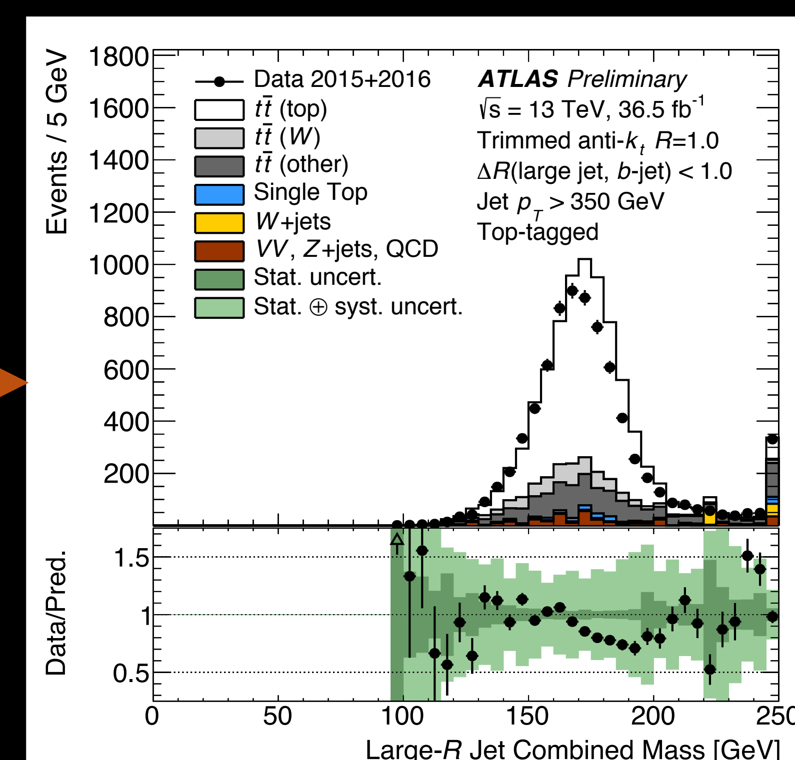
TOP QUARK TAGGING

ATLAS EXPERIMENT JETM-2017-004, JETM-2017-005



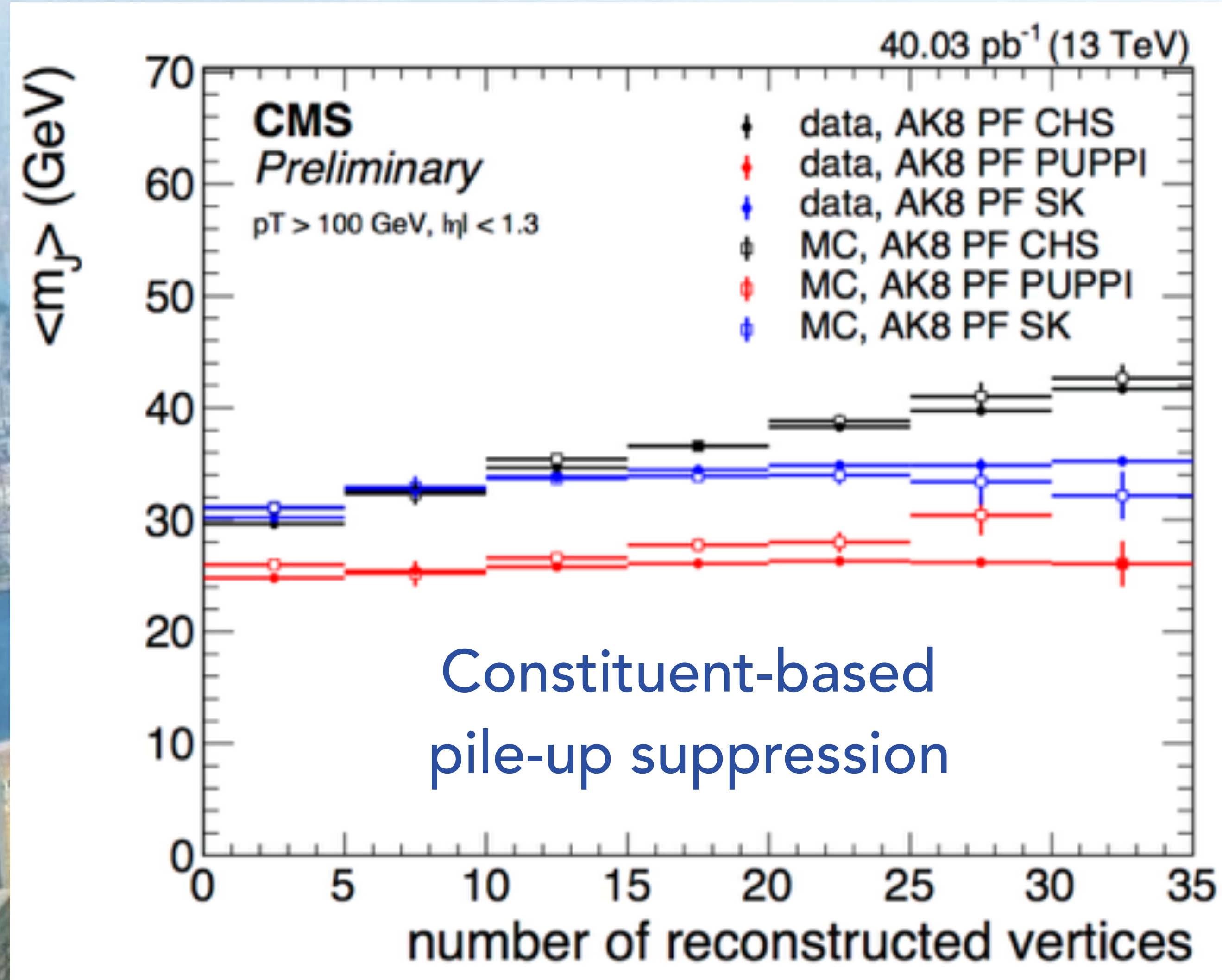
New tagger optimisation strategy: focus on fully-contained top jets.

Flat-pT training ensures good performance in wide kinematic range.

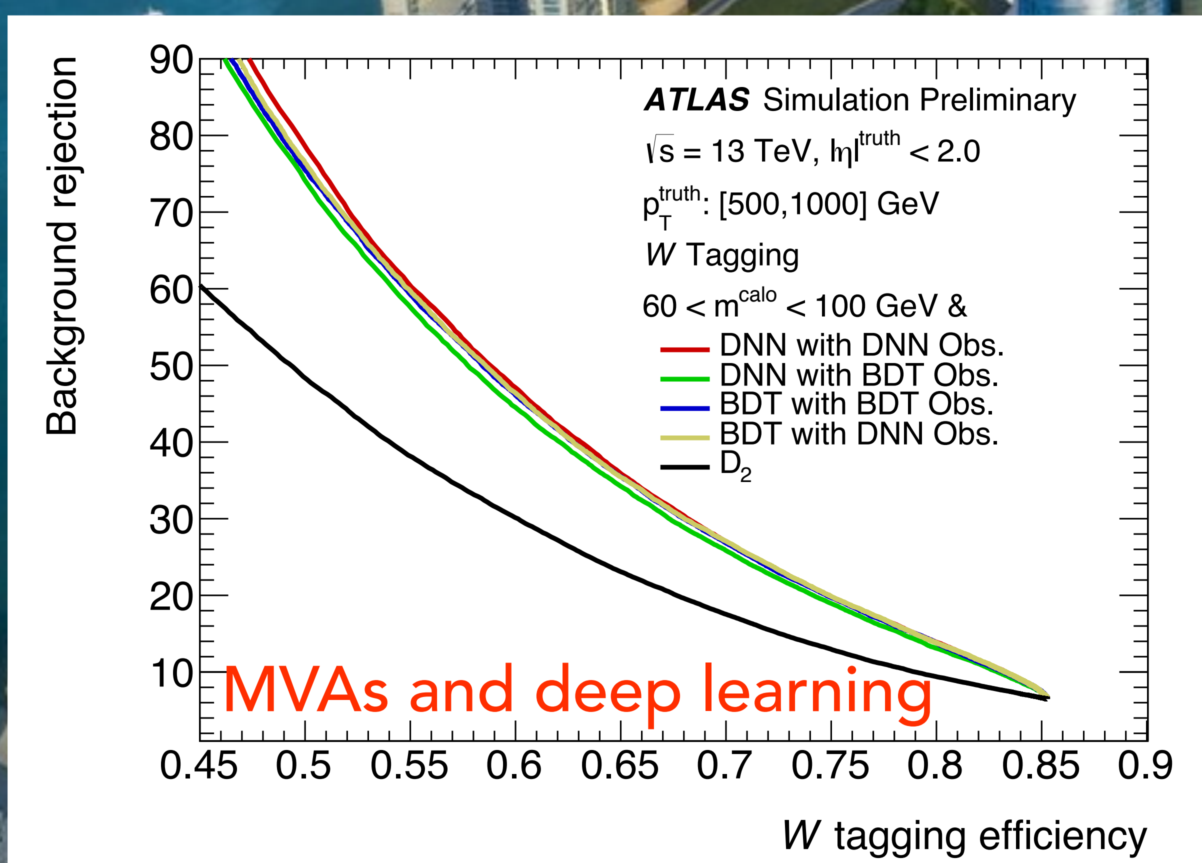


A Taste of Things to Come

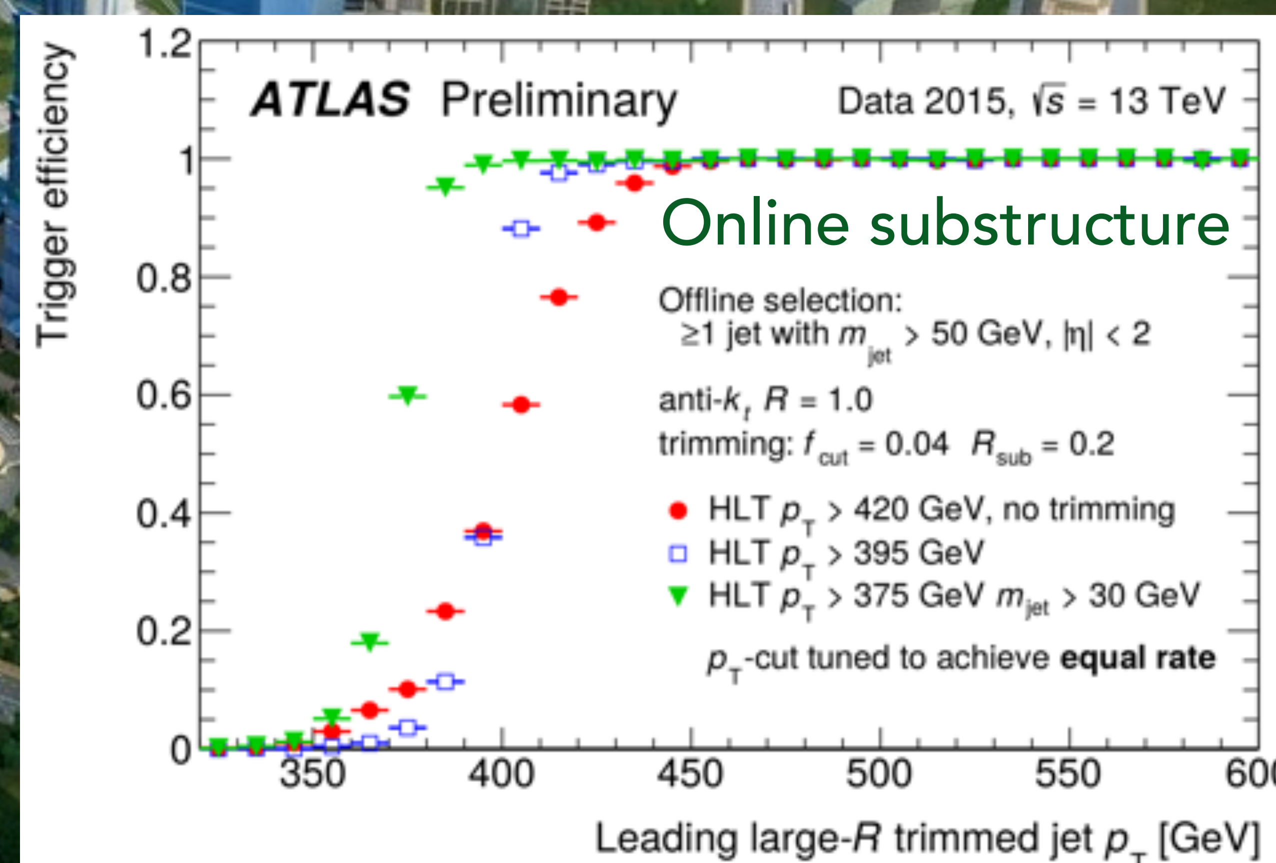
- Run 3 & HL-LHC
  - Software challenges: high-throughput & trigger reconstruction
  - Physics challenges: pileup, pileup, pileup!
- ATLAS:
  - PFlow in analysis: multijet SUSY, ZH, ttH…?
  - Jet substructure & advanced calibration in triggers
- CMS:
  - Advanced trigger-level pile-up suppression
  - Deep-learning jet applications



Constituent-based pile-up suppression



MVAs and deep learning



Online substructure

© Gensler / CTBUH

THE JETS ARE OUT THERE!

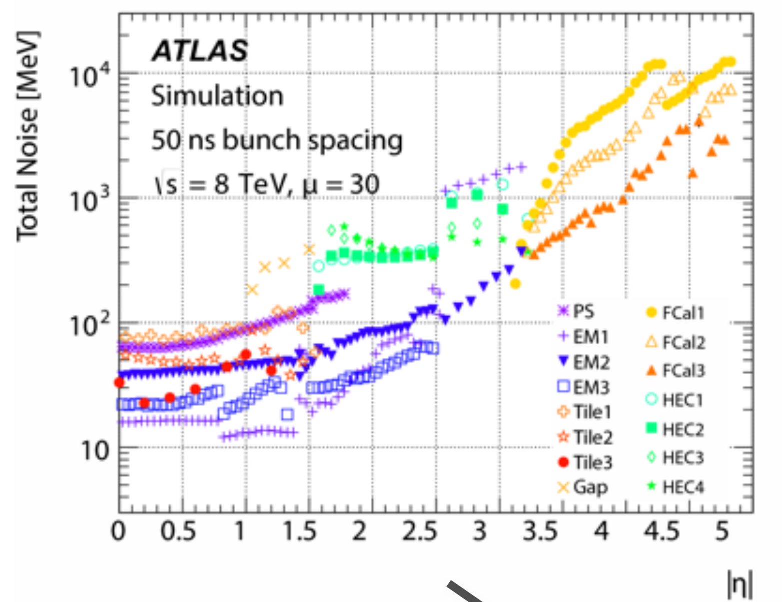
BACKUPS

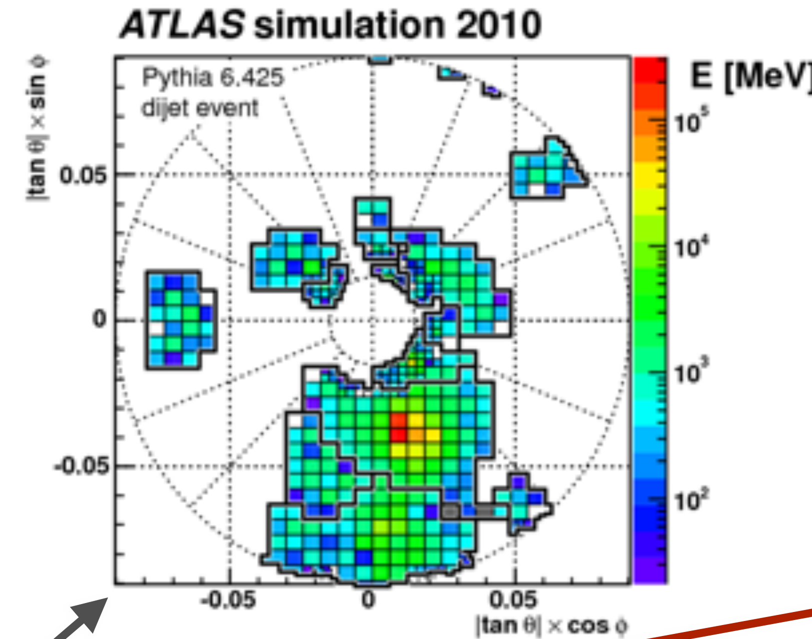

Penggunaan **Jet Backup**
untuk Restore Konten
Website
CloudHost
Image: Knowledge Base 2016 - idcloudhost.com

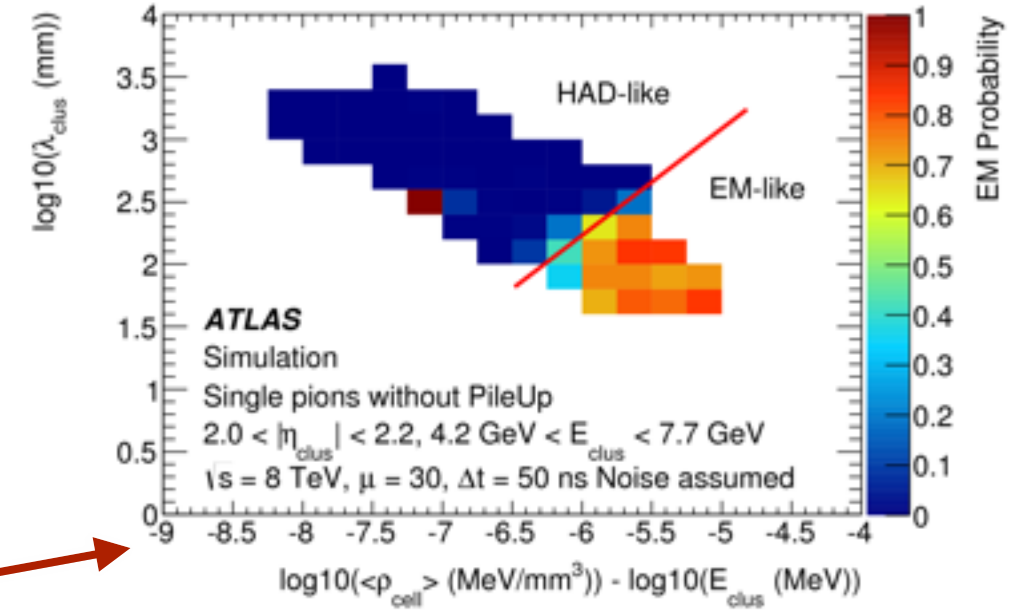
JET INPUTS

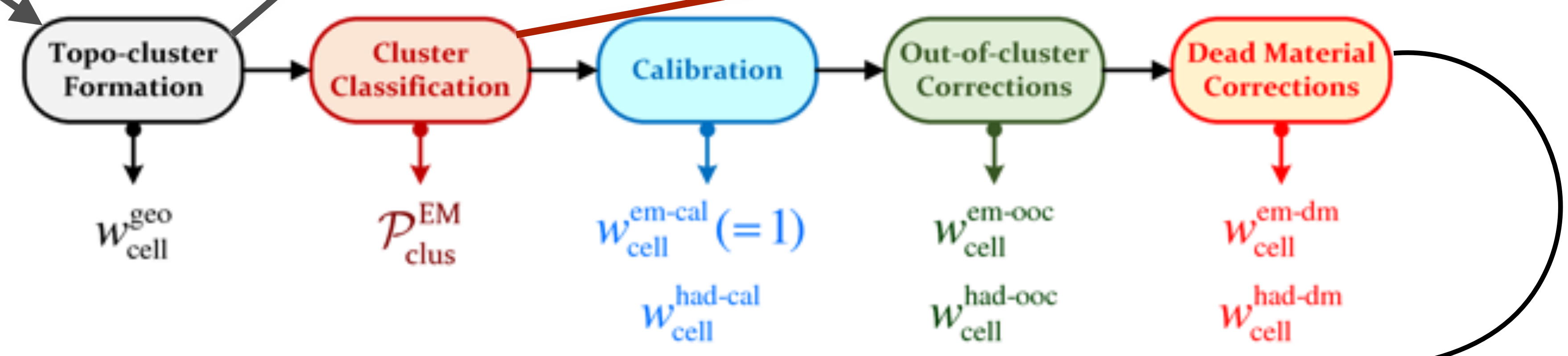
[arXiv:1603.02934]

Topo-cluster formation & calibration

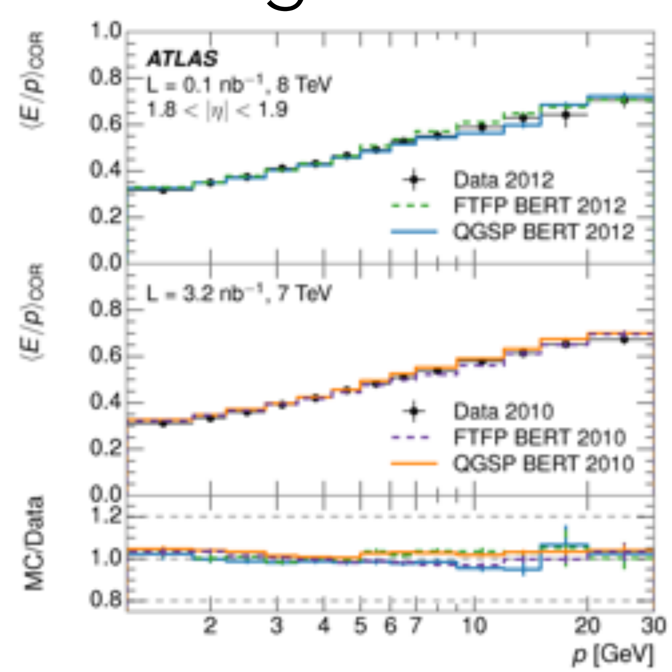


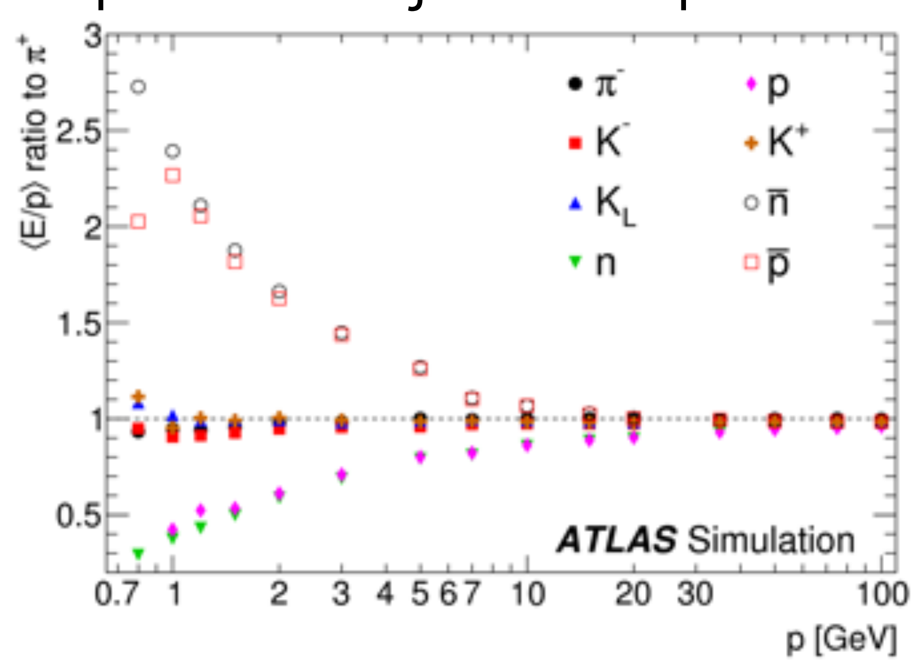


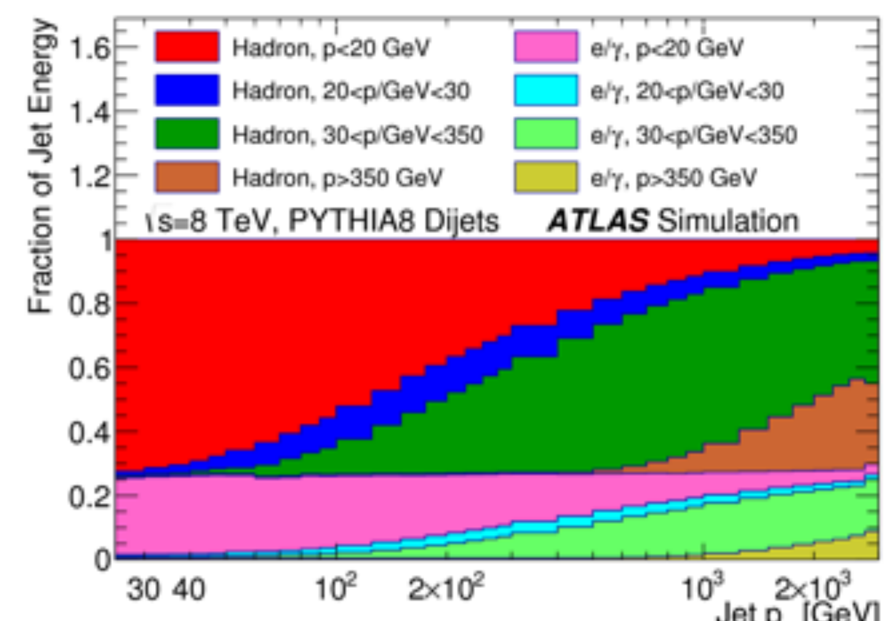




Single-hadron response & jet composition measurements

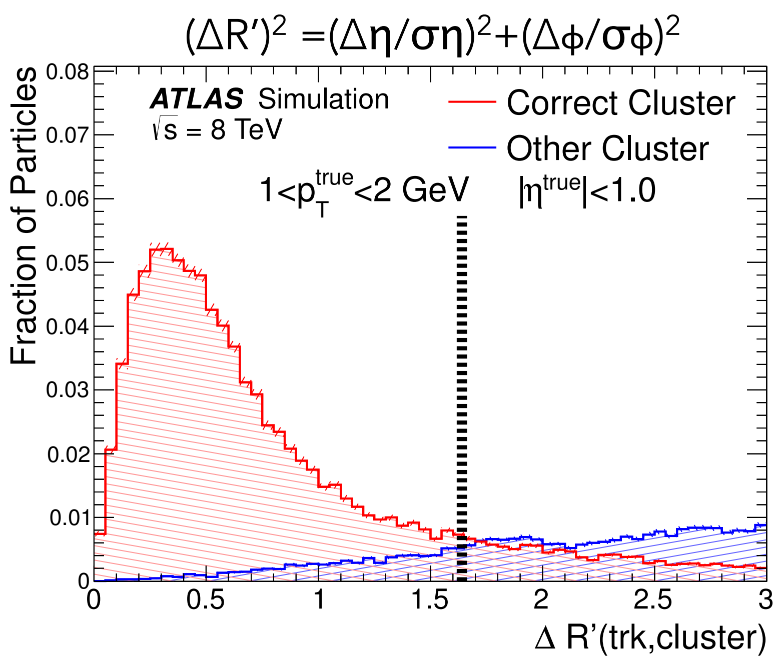




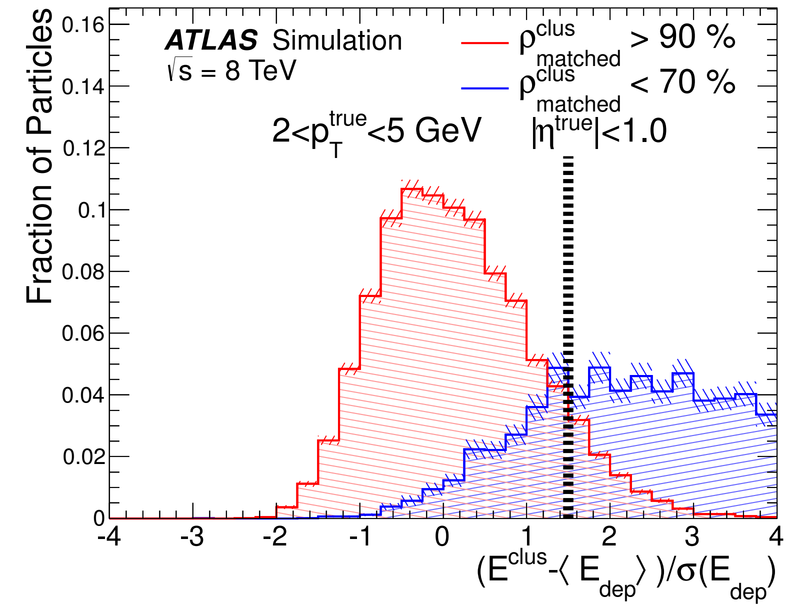


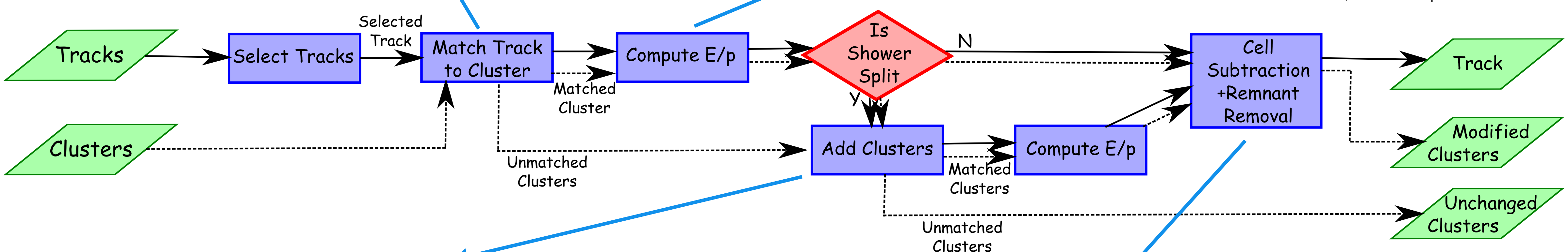
[EPJC (2017) 77:26]

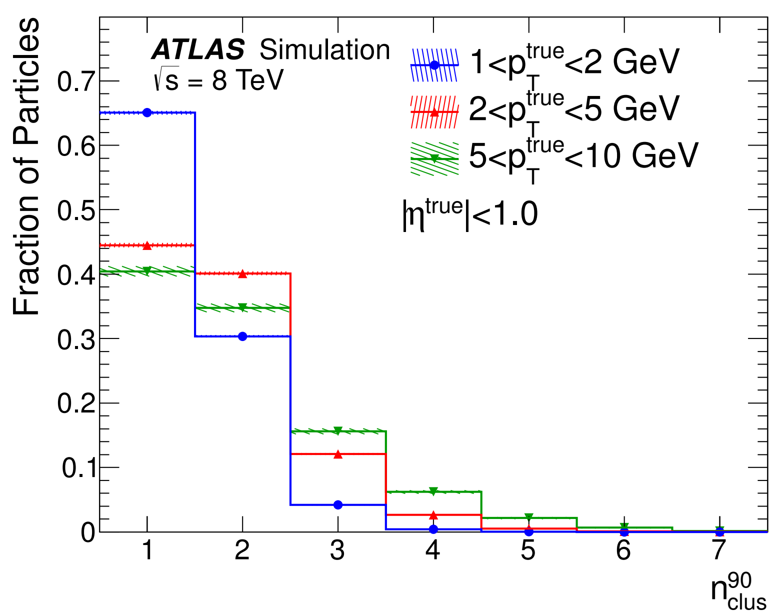
Particle flow @ ATLAS

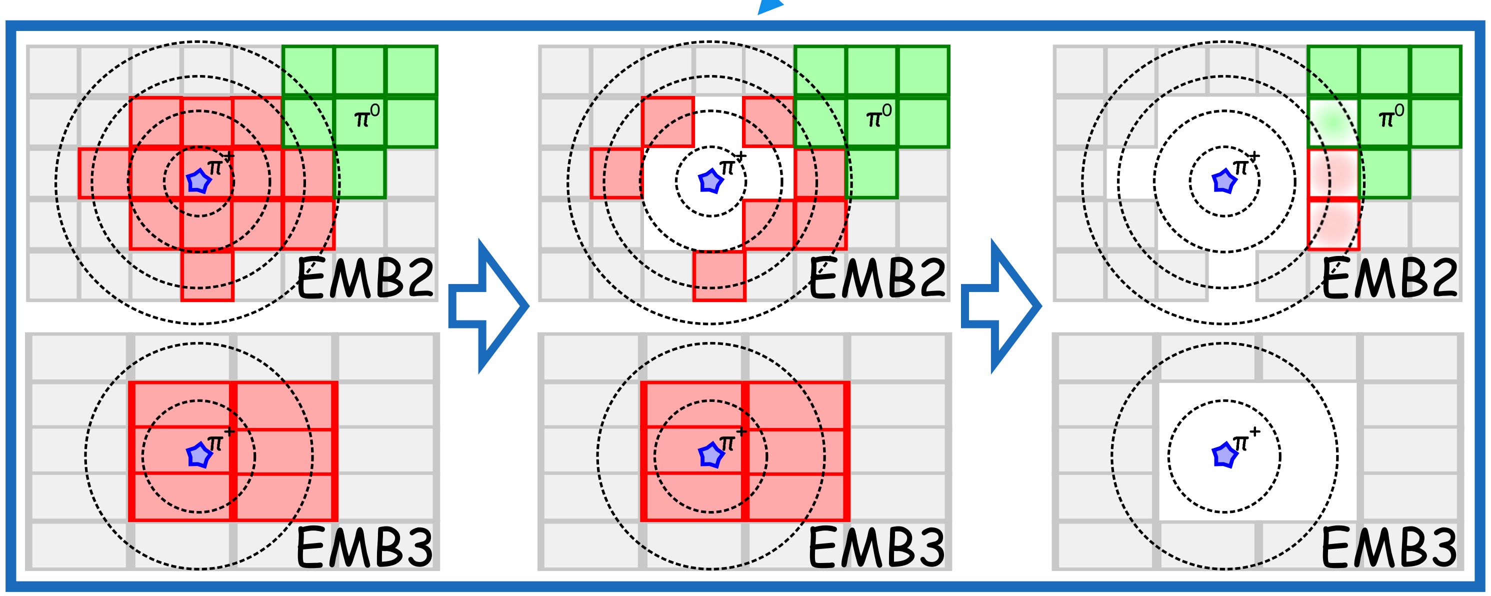


Optimised during LS1 to accurately subtract calorimeter energy, prevent double-counting wrt tracker momentum measurement.



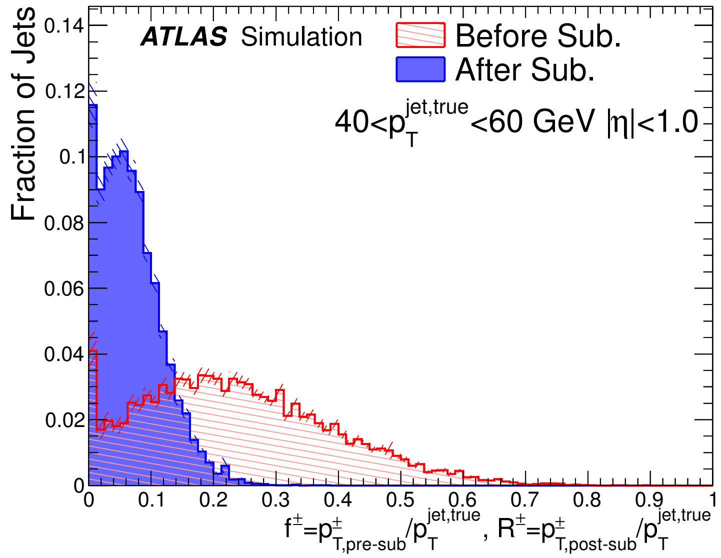


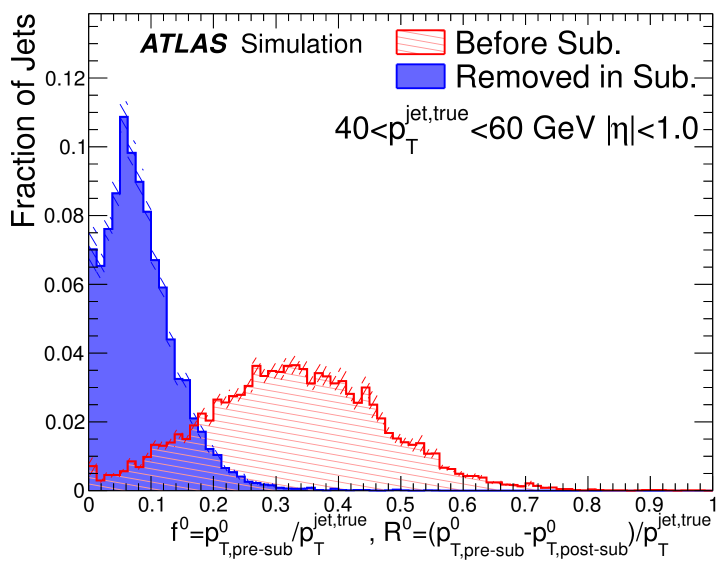


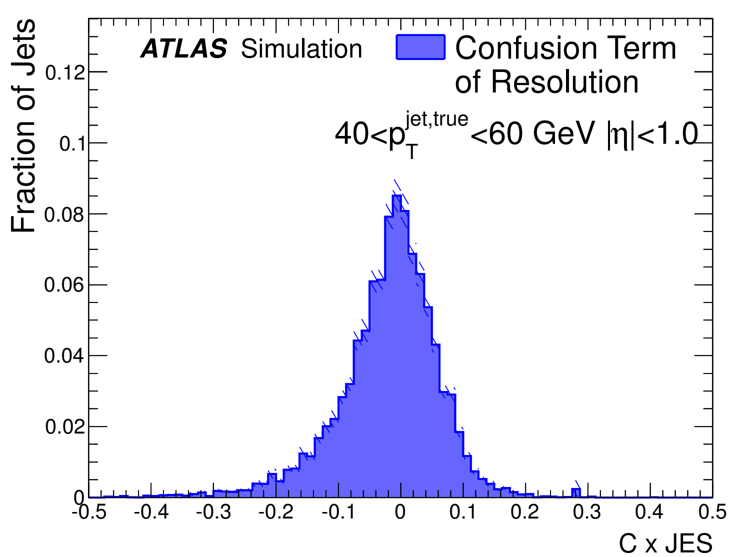


[arXiv: 1703.10485]

PARTICLE FLOW @ ATLAS

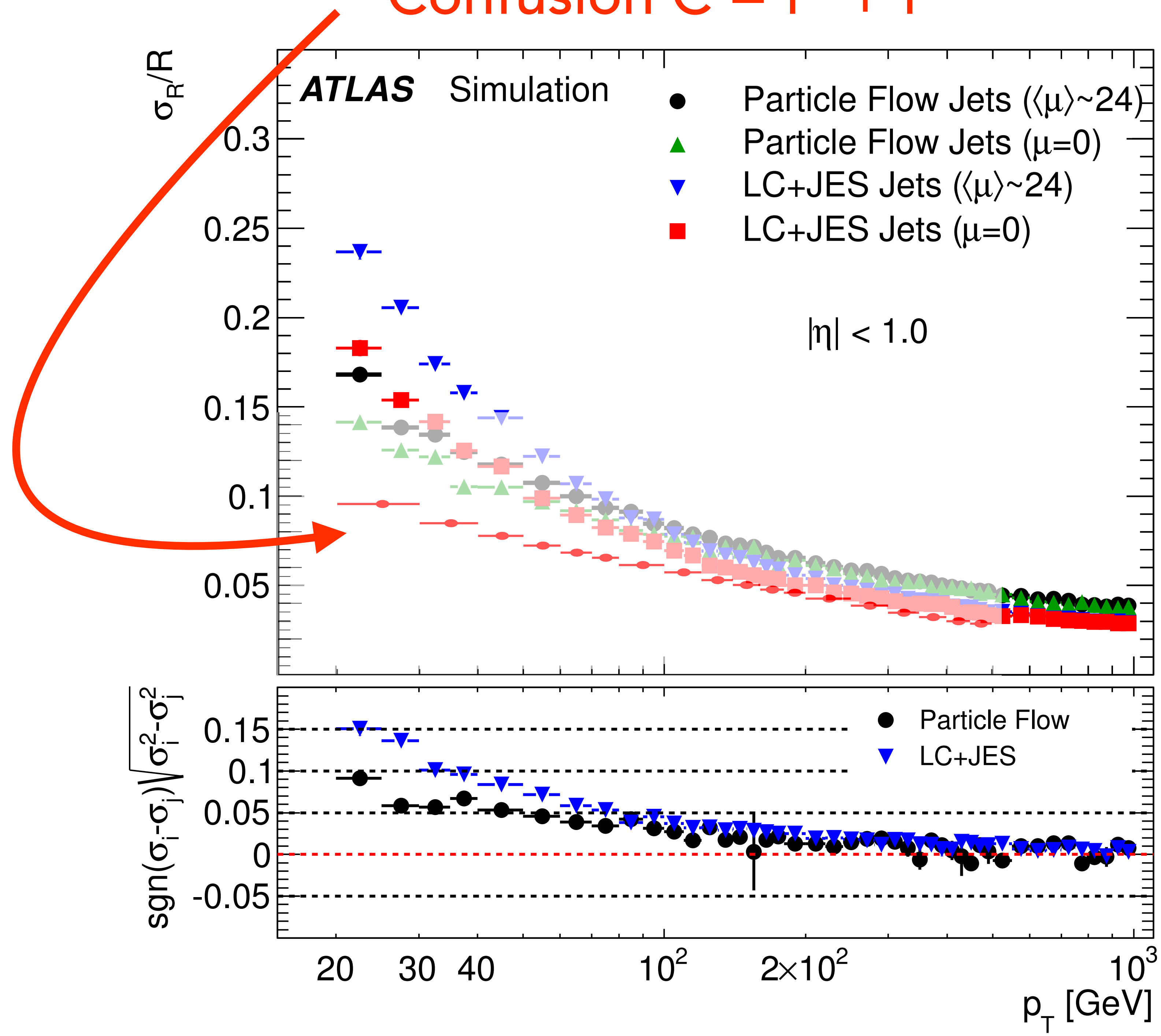






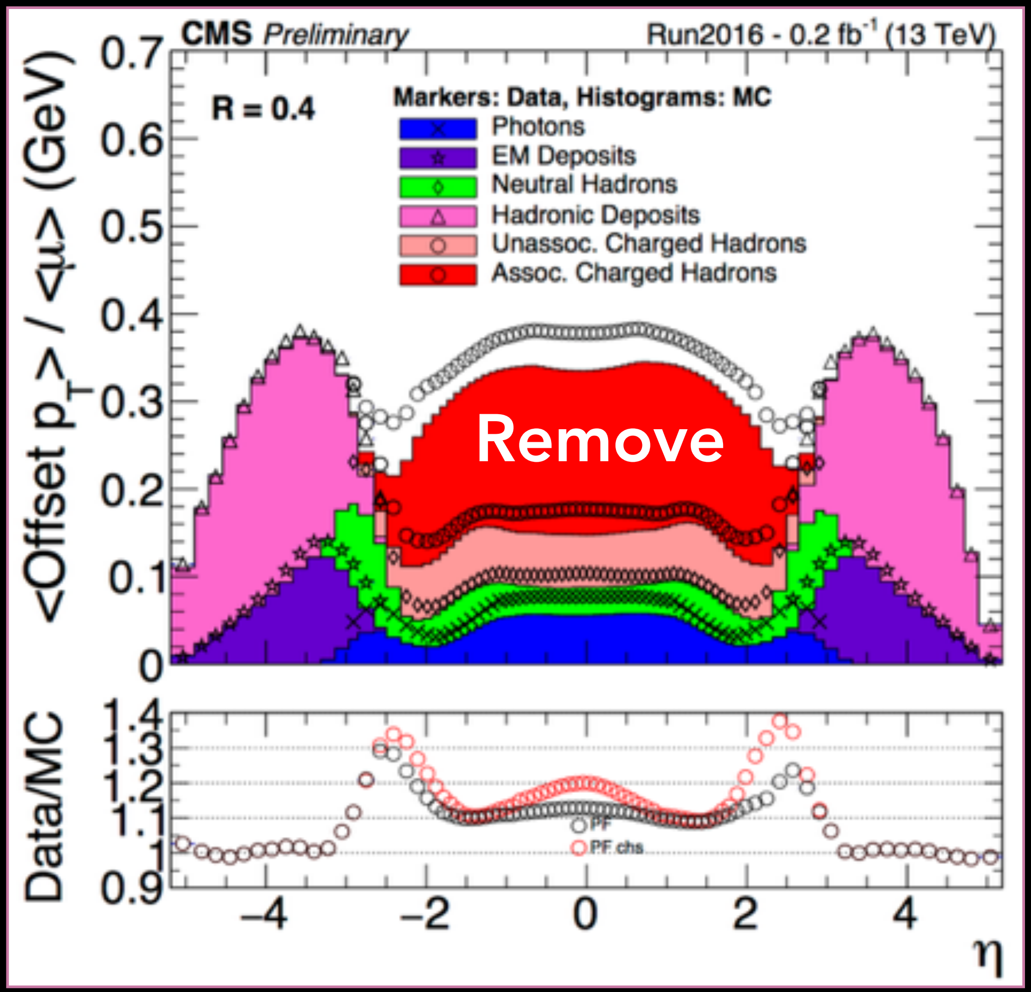
With truth info, checked impact of subtraction mistakes on resolution.

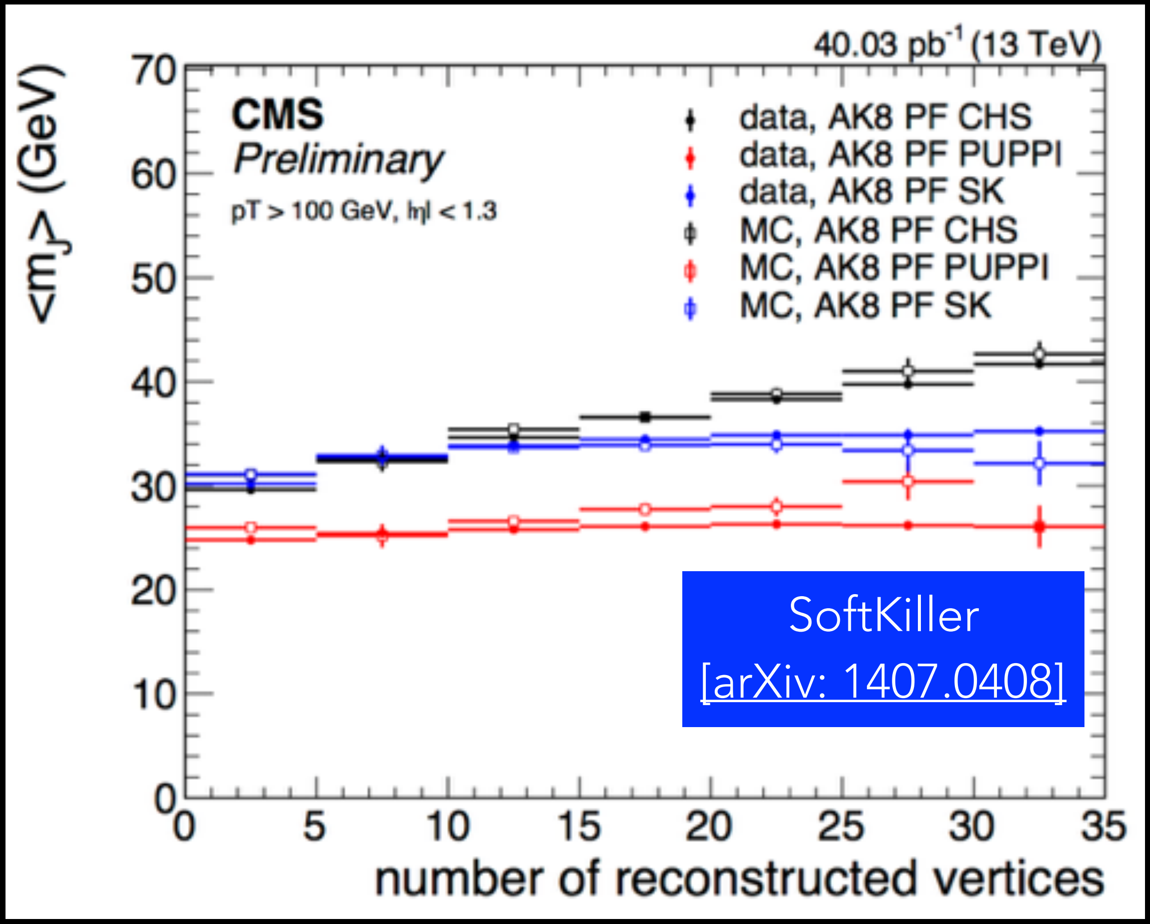
Confusion $C = f^{\pm} + f^0$



[arXiv: 1703.10485]

CONSTITUENT PILEUP SUPPRESSION





Charged Hadron Subtraction (used with PFlow):

- Associate tracks to origin vertices
- PF charged hadrons from pileup vertices discarded before jet-finding.

PileUp-Per-Particle-Identification [arxiv: 1407.6013]:

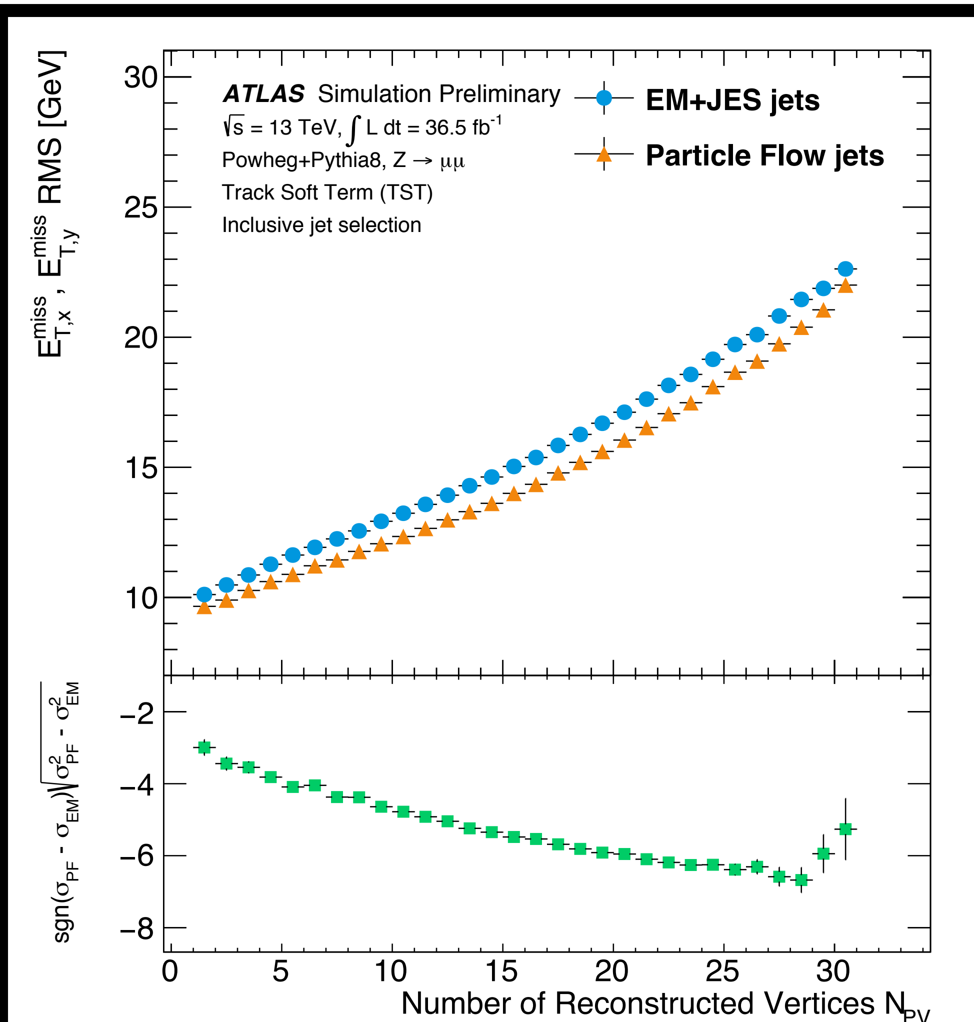
- Weight particles by pileup probability
  - Central region: prefer high local pT density of PV charged particles
  - Forward region: prefer high local pT density of particles

See also: JETM-2016-012 (HL-LHC)

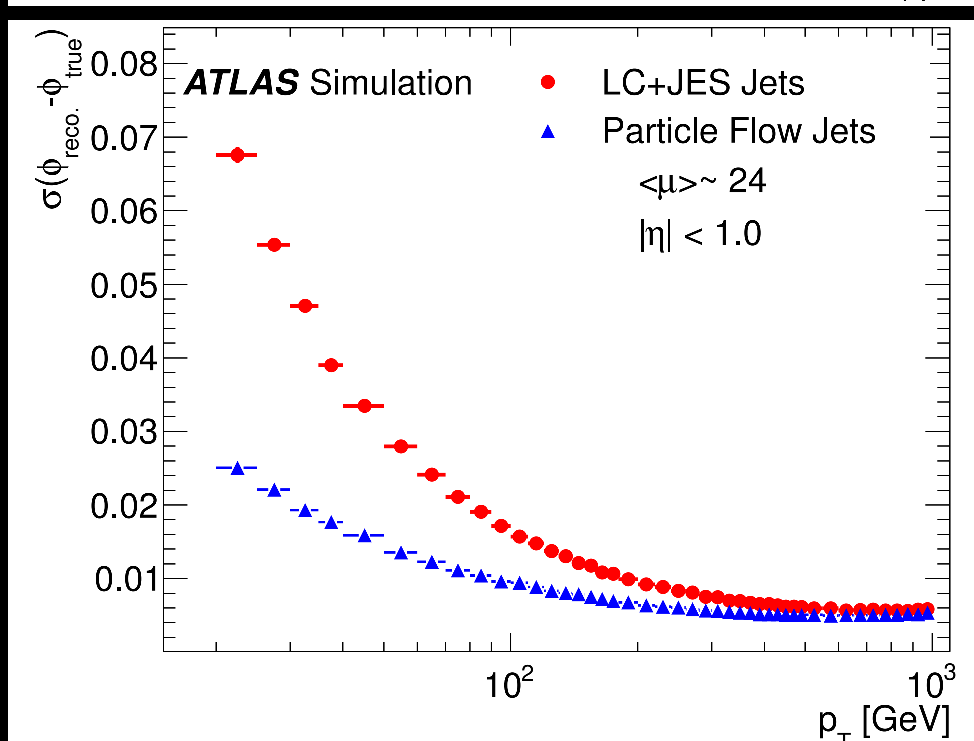
WHY PFLOW? (THE EMPIRICAL ANSWER)

[arXiv: 1703.10485], [JETM-2017-006], [PLACEHOLDER]

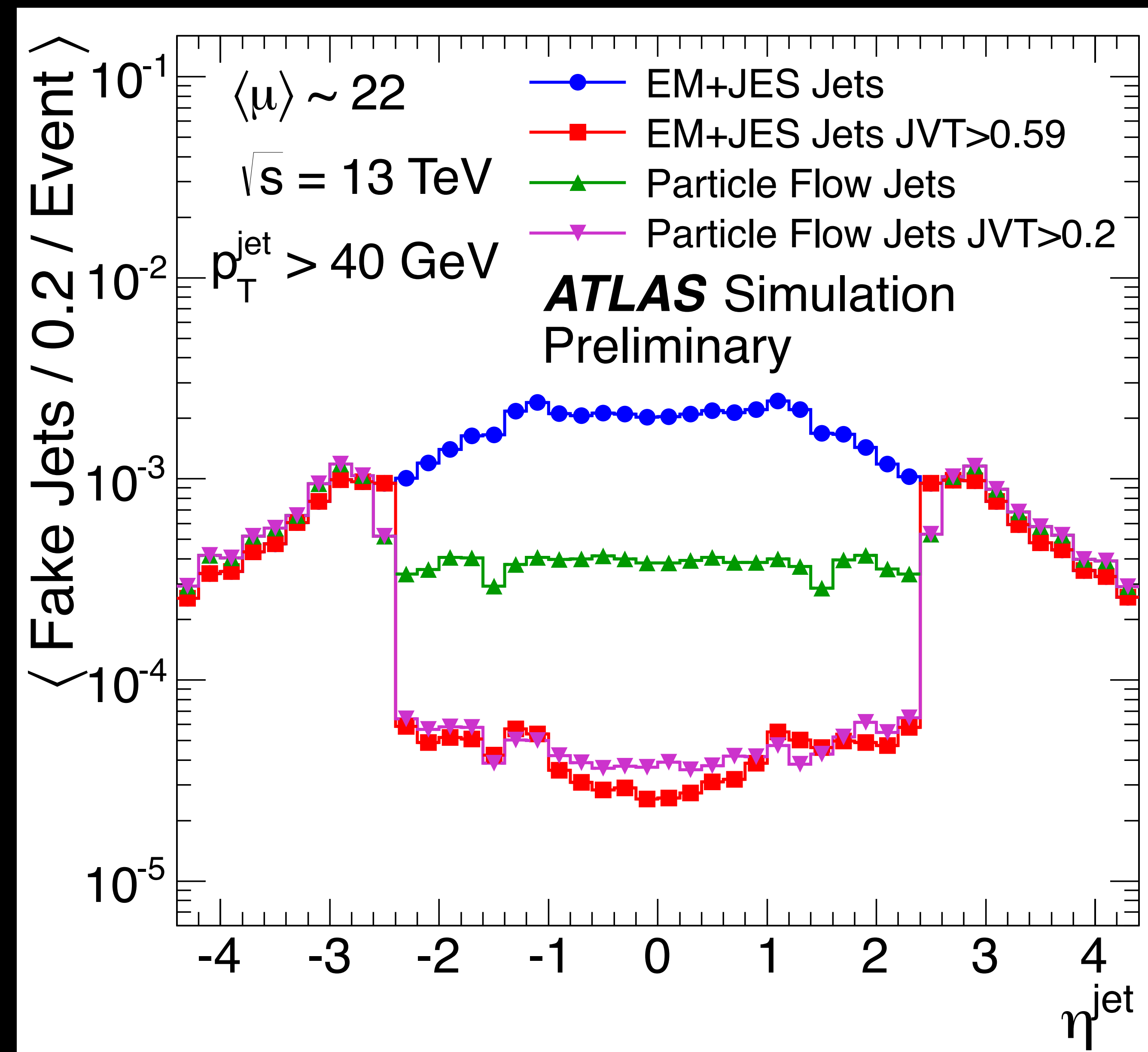
MET resolution



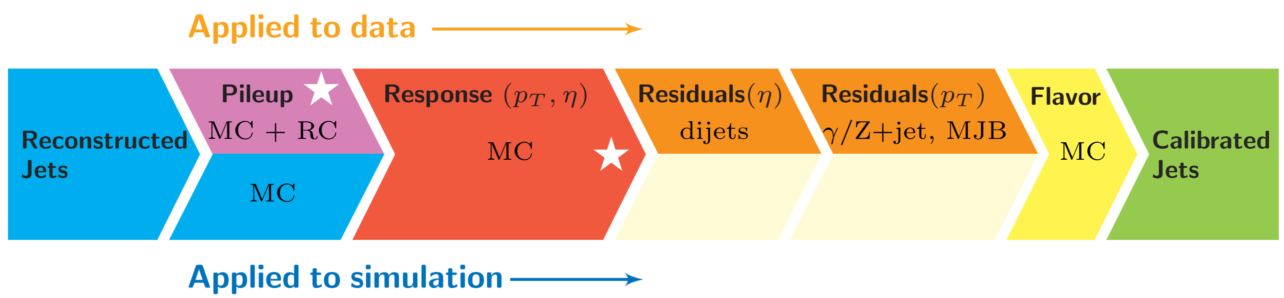
Angular resolution

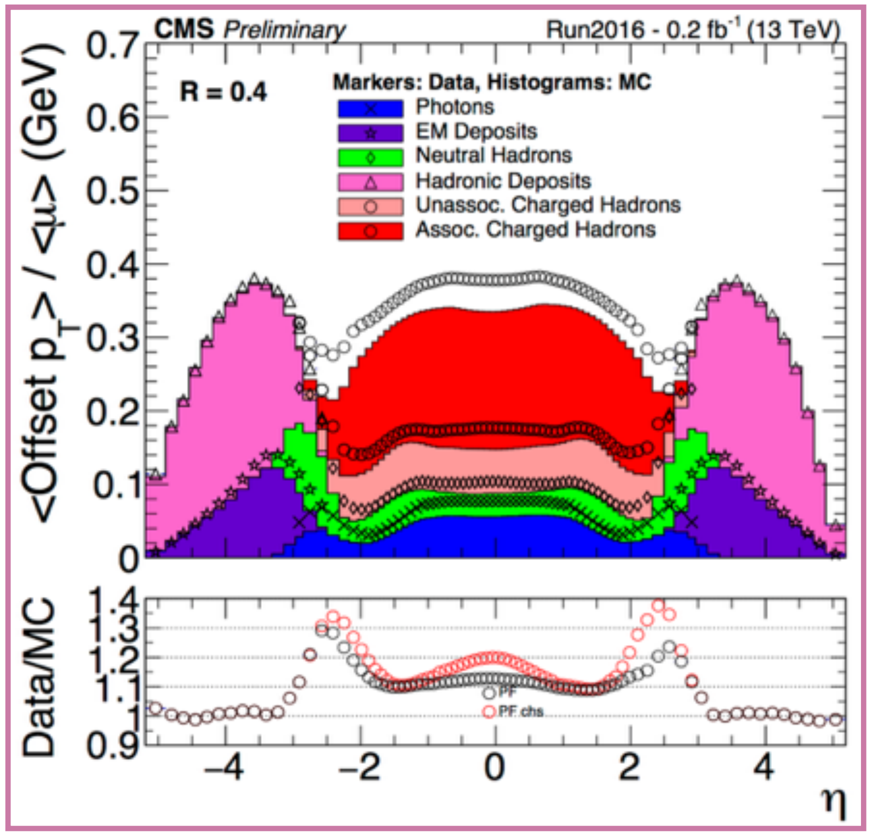


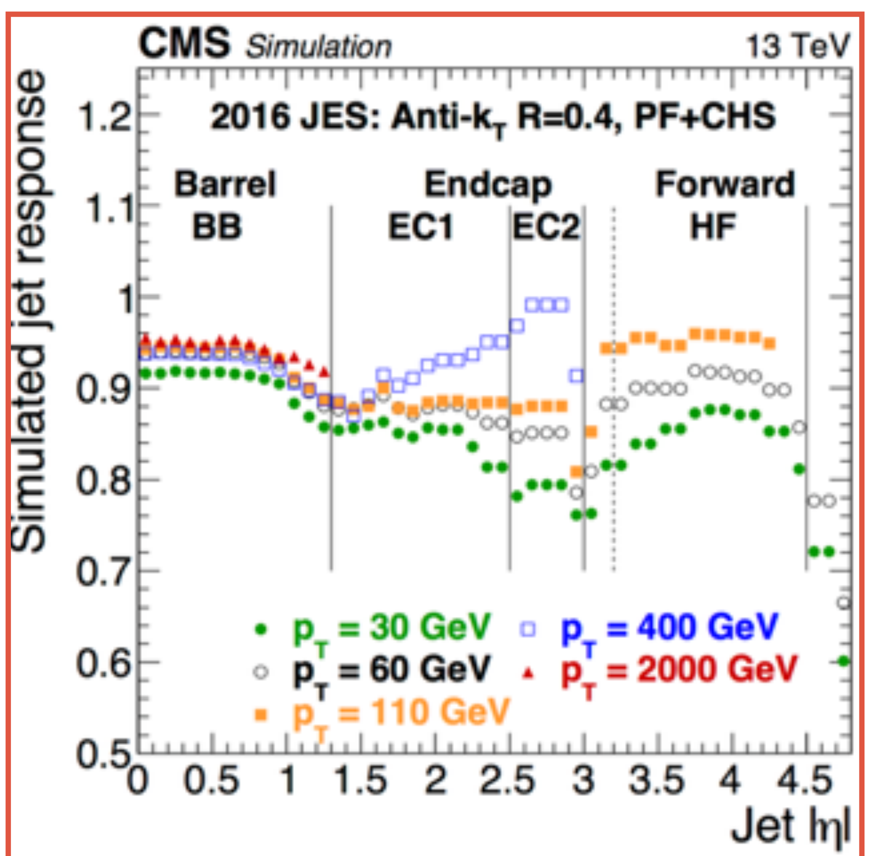
Pileup reduction

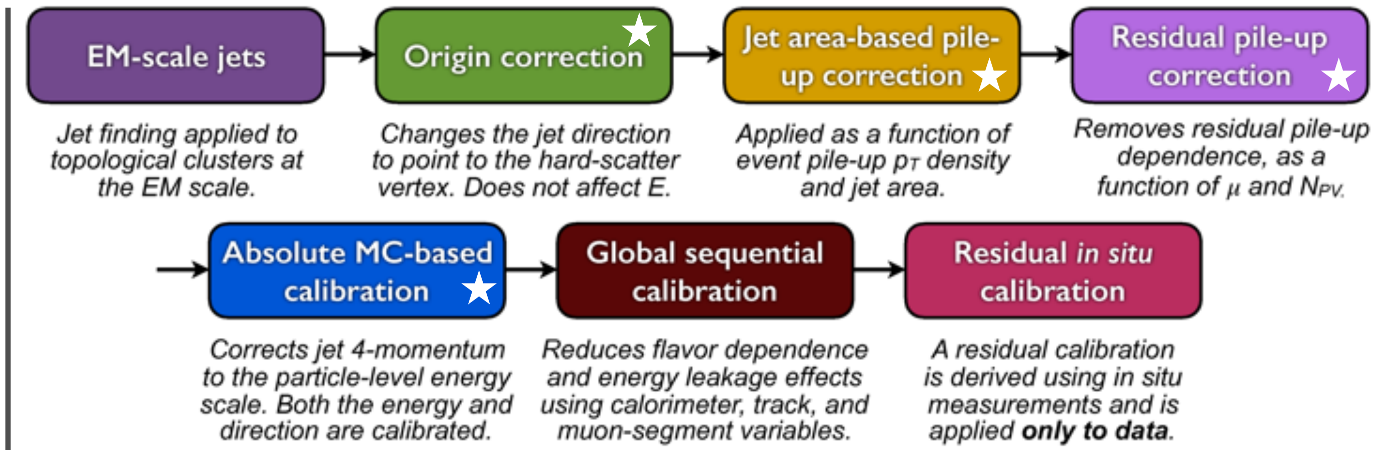


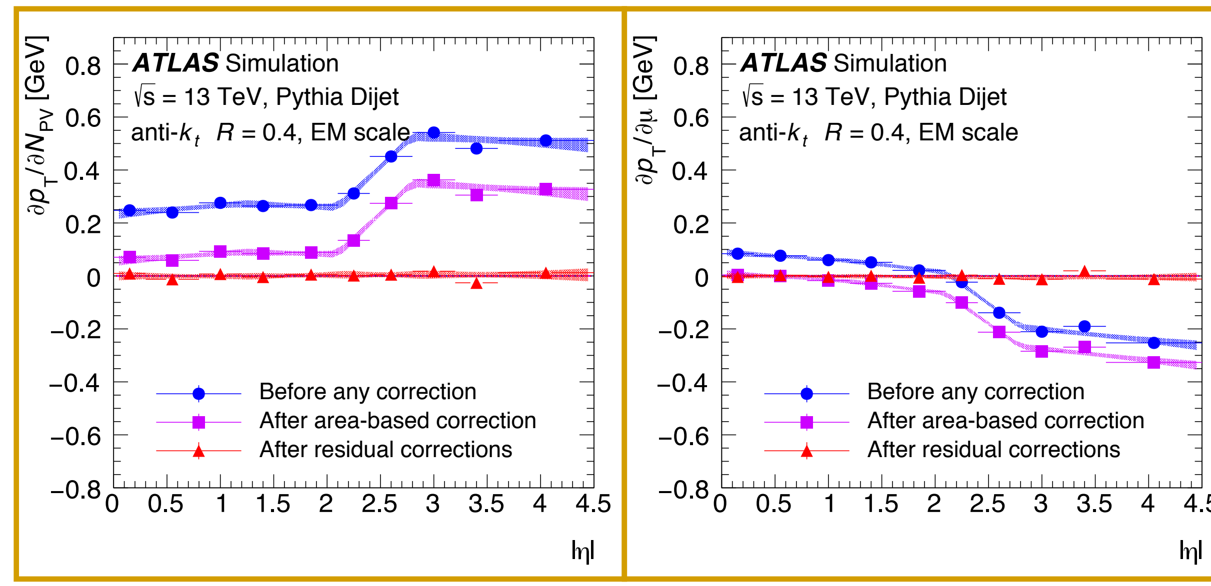
JET CALIBRATION

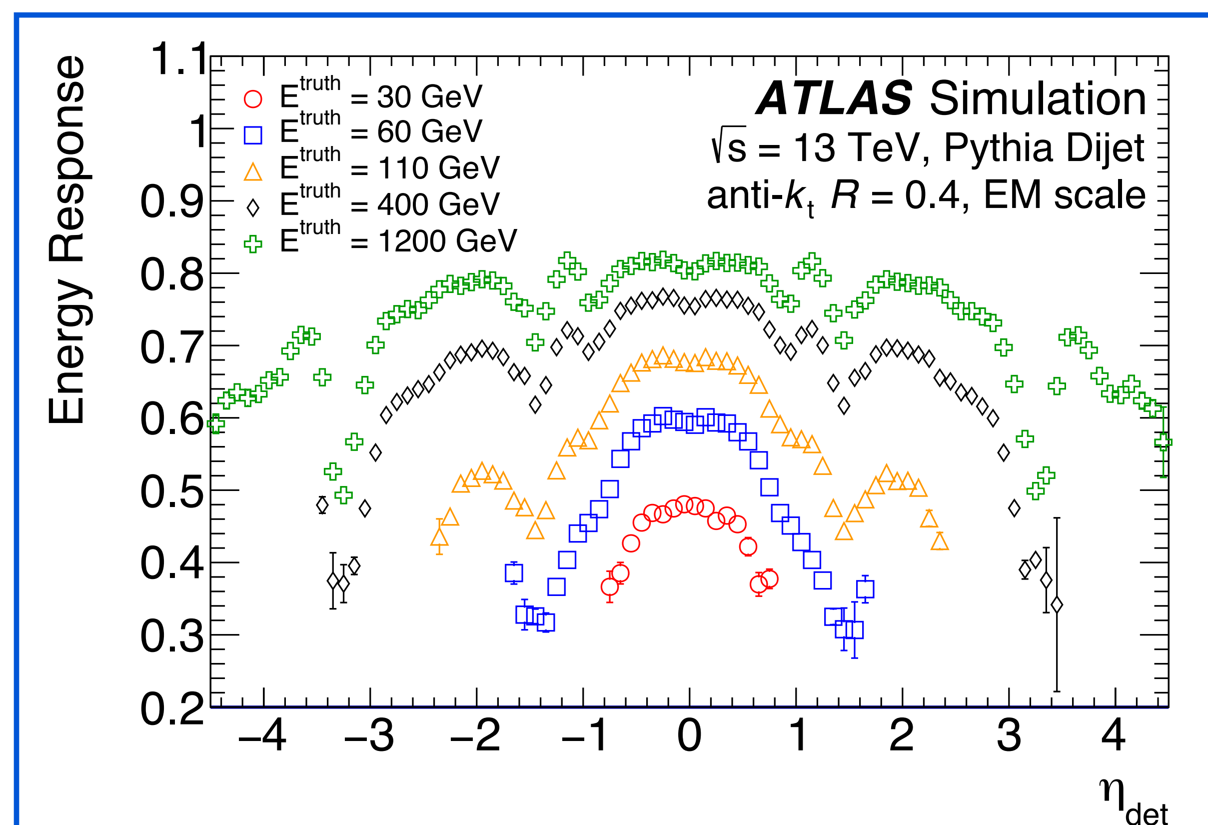

Applied to data
Reconstructed Jets
Pileup
MC + RC
MC
Response (p_T, η)
MC
Residuals(η)
dijets
Residuals(p_T)
γ/Z+jet, MJB
Flavor
MC
Calibrated Jets
Applied to simulation

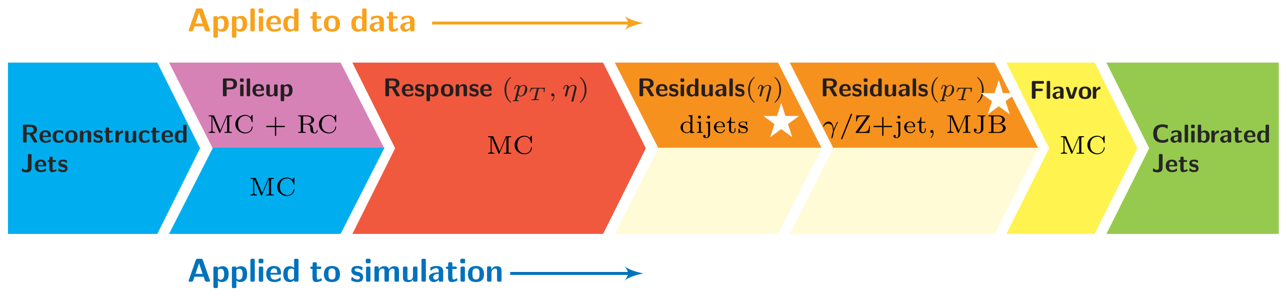

CMS Preliminary
Run2016 - 0.2 fb^{-1} (13 TeV)
R = 0.4
Markers: Data, Histograms: MC
Photons
EM Deposits
Neutral Hadrons
Hadronic Deposits
Unassoc. Charged Hadrons
Assoc. Charged Hadrons
$\langle$Offset $p_T\rangle$ / $\langle\mu\rangle$ (GeV)
Data/MC
PF
PF chs
η

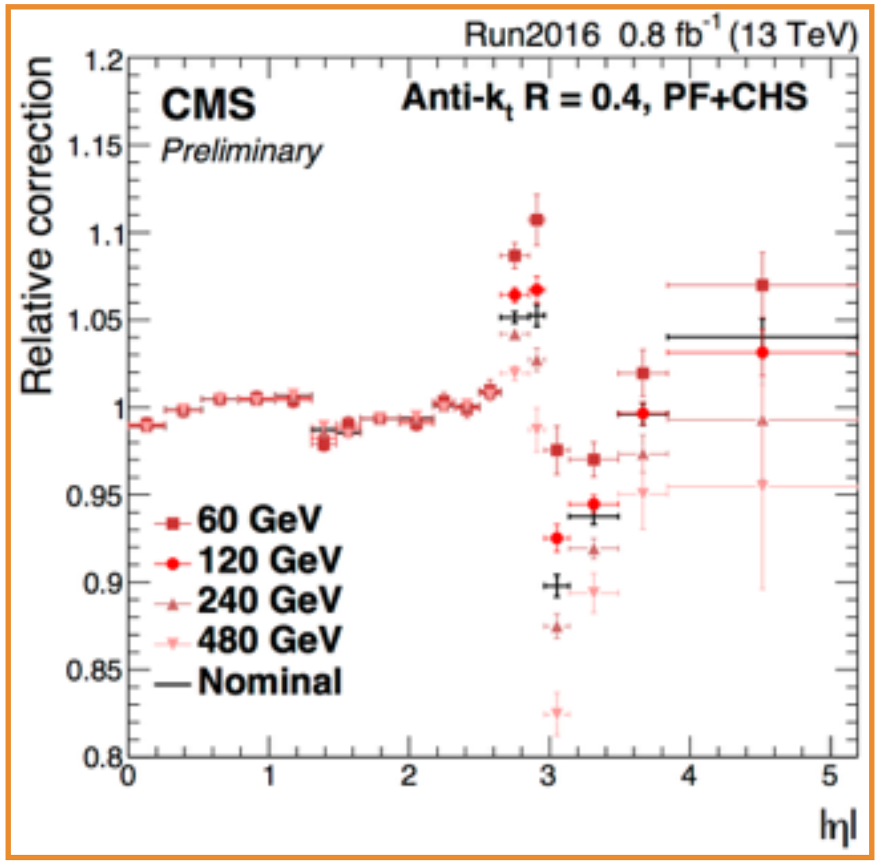

CMS Simulation
13 TeV
2016 JES: Anti-k$_T$ R=0.4, PF+CHS
Barrel
BB
Endcap
EC1
EC2
Forward
HF
Simulated jet response
p_T = 30 GeV
p_T = 60 GeV
p_T = 110 GeV
p_T = 400 GeV
p_T = 2000 GeV
Jet |η|

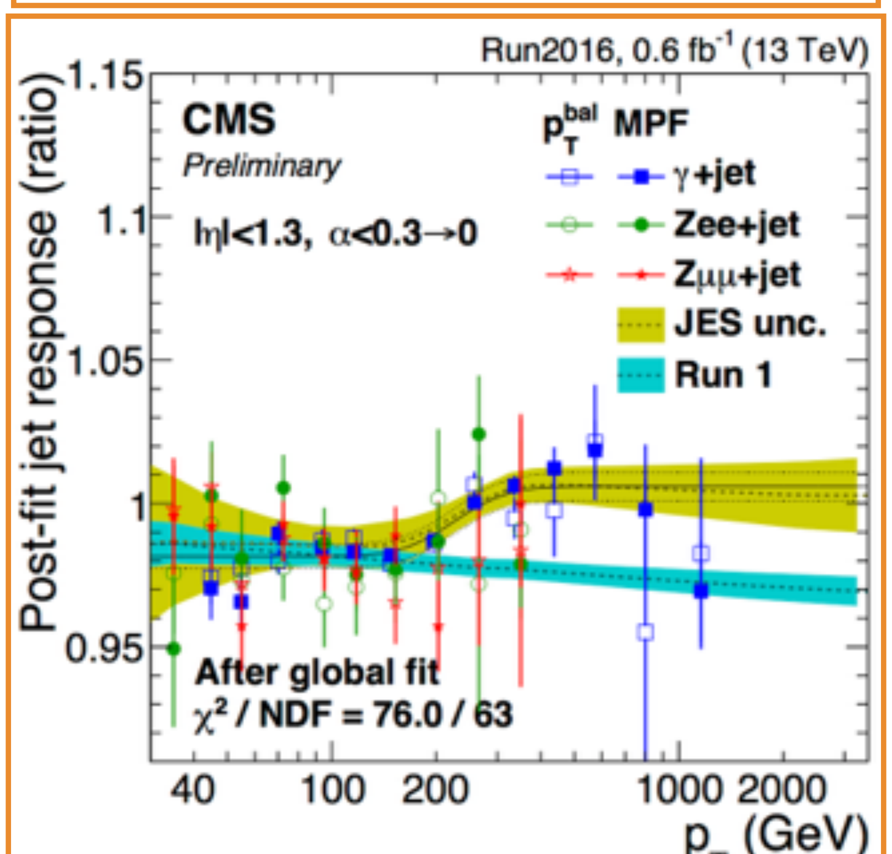

EM-scale jets
Jet finding applied to topological clusters at the EM scale.
Origin correction
Changes the jet direction to point to the hard-scatter vertex. Does not affect E.
Jet area-based pile-up correction
Applied as a function of event pile-up p_T density and jet area.
Residual pile-up correction
Removes residual pile-up dependence, as a function of μ and N_{PV}.
Absolute MC-based calibration
Corrects jet 4-momentum to the particle-level energy scale. Both the energy and direction are calibrated.
Global sequential calibration
Reduces flavor dependence and energy leakage effects using calorimeter, track, and muon-segment variables.
Residual in situ calibration
A residual calibration is derived using in situ measurements and is applied only to data.

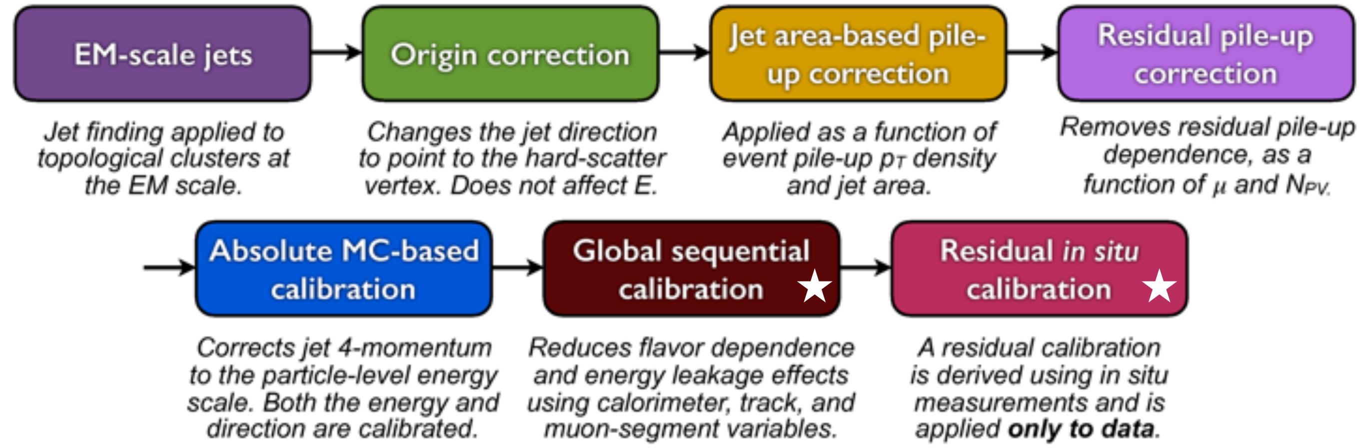

ATLAS Simulation
$\sqrt{s}$ = 13 TeV, Pythia Dijet
anti-k_t R = 0.4, EM scale
$\partial p_T/\partial N_{PV}$ [GeV]
$\partial p_T/\partial\mu$ [GeV]
Before any correction
After area-based correction
After residual corrections
|η|


ATLAS Simulation
$\sqrt{s}$ = 13 TeV, Pythia Dijet
anti-k_t R = 0.4, EM scale
E^{truth} = 30 GeV
E^{truth} = 60 GeV
E^{truth} = 110 GeV
E^{truth} = 400 GeV
E^{truth} = 1200 GeV
Energy Response
η_{det}


Applied to data
Reconstructed Jets
Pileup
MC + RC
MC
Response (p_T, η)
MC
Residuals(η)
dijets
Residuals(p_T)
γ/Z+jet, MJB
Flavor
MC
Calibrated Jets
Applied to simulation


Run2016 0.8 fb^{-1} (13 TeV)
CMS
Preliminary
Anti-k$_t$ R = 0.4, PF+CHS
Relative correction
60 GeV
120 GeV
240 GeV
480 GeV
Nominal
|η|


Run2016, 0.6 fb^{-1} (13 TeV)
CMS
Preliminary
|η|<1.3, α<0.3→0
p_T^{bal} MPF
γ+jet
Zee+jet
Zμμ+jet
JES unc.
Run 1
After global fit
χ^2 / NDF = 76.0 / 63
Post-fit jet jet response (ratio)
p_T (GeV)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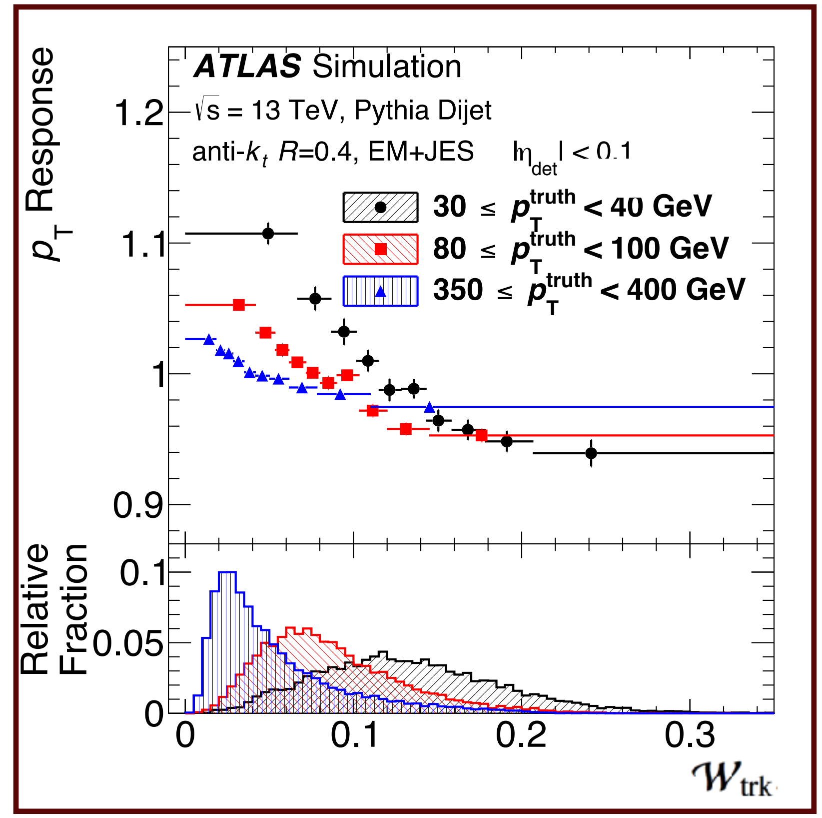
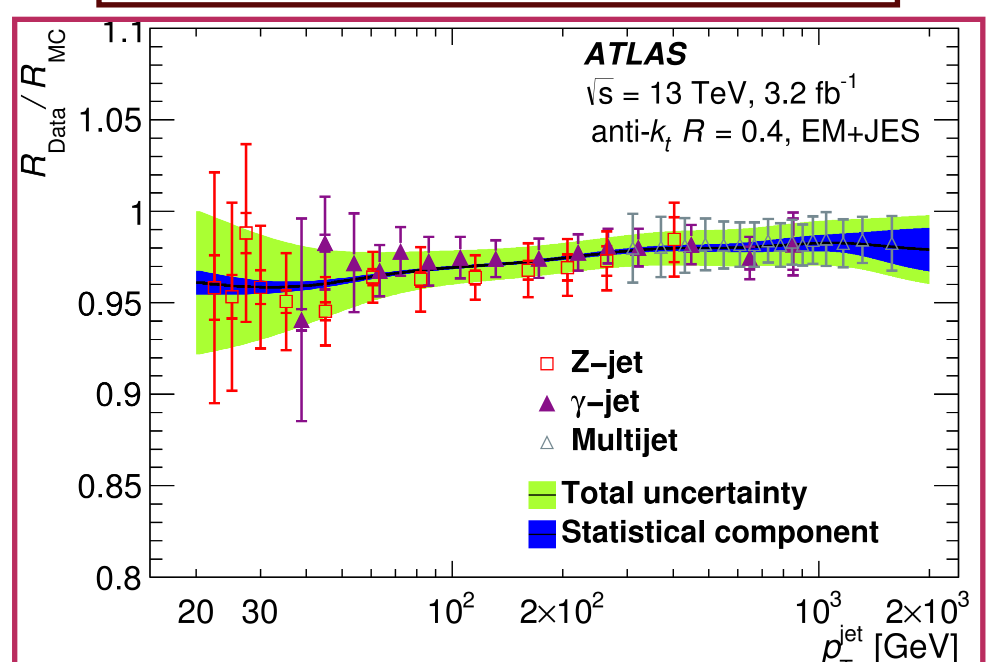
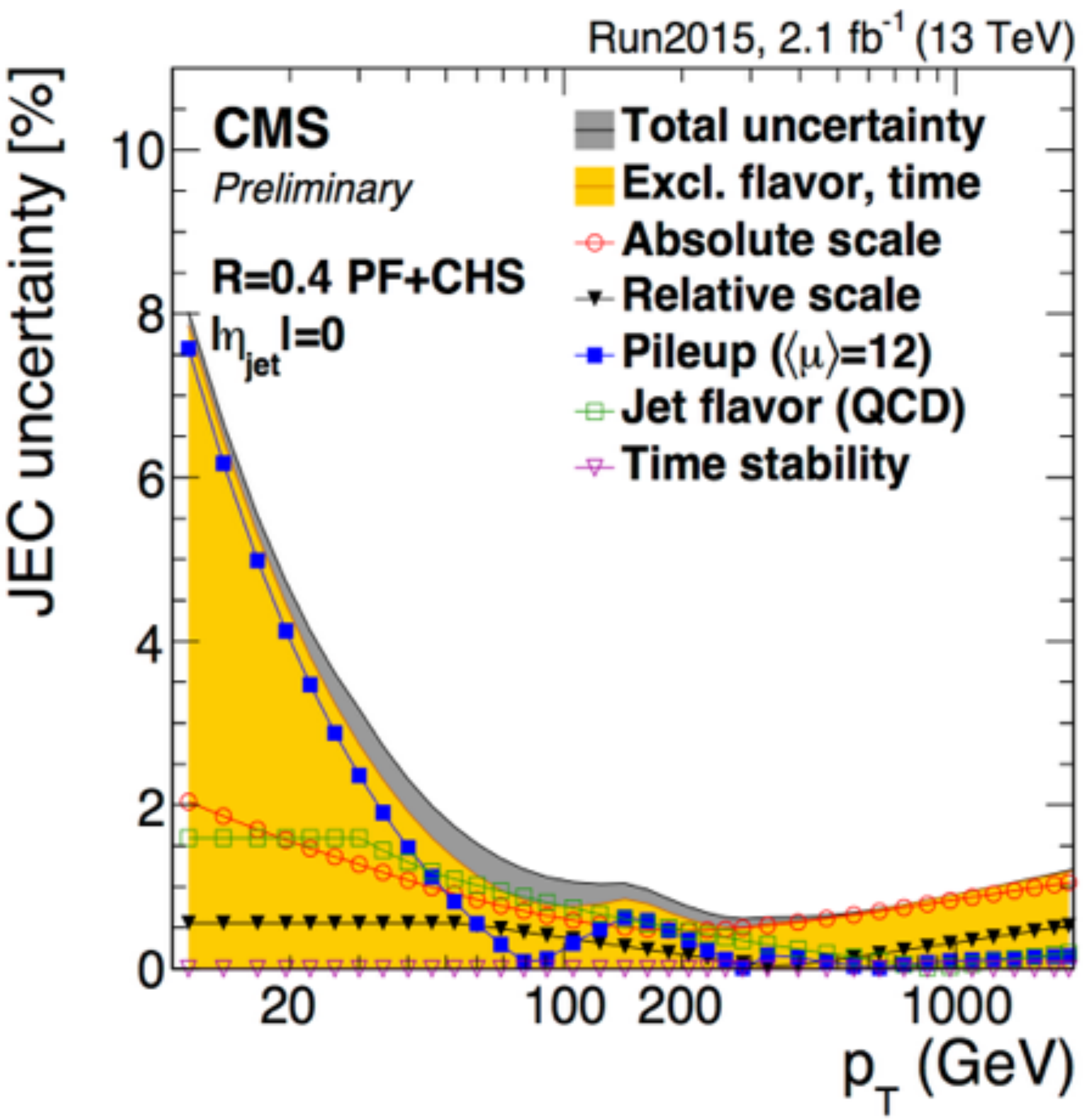
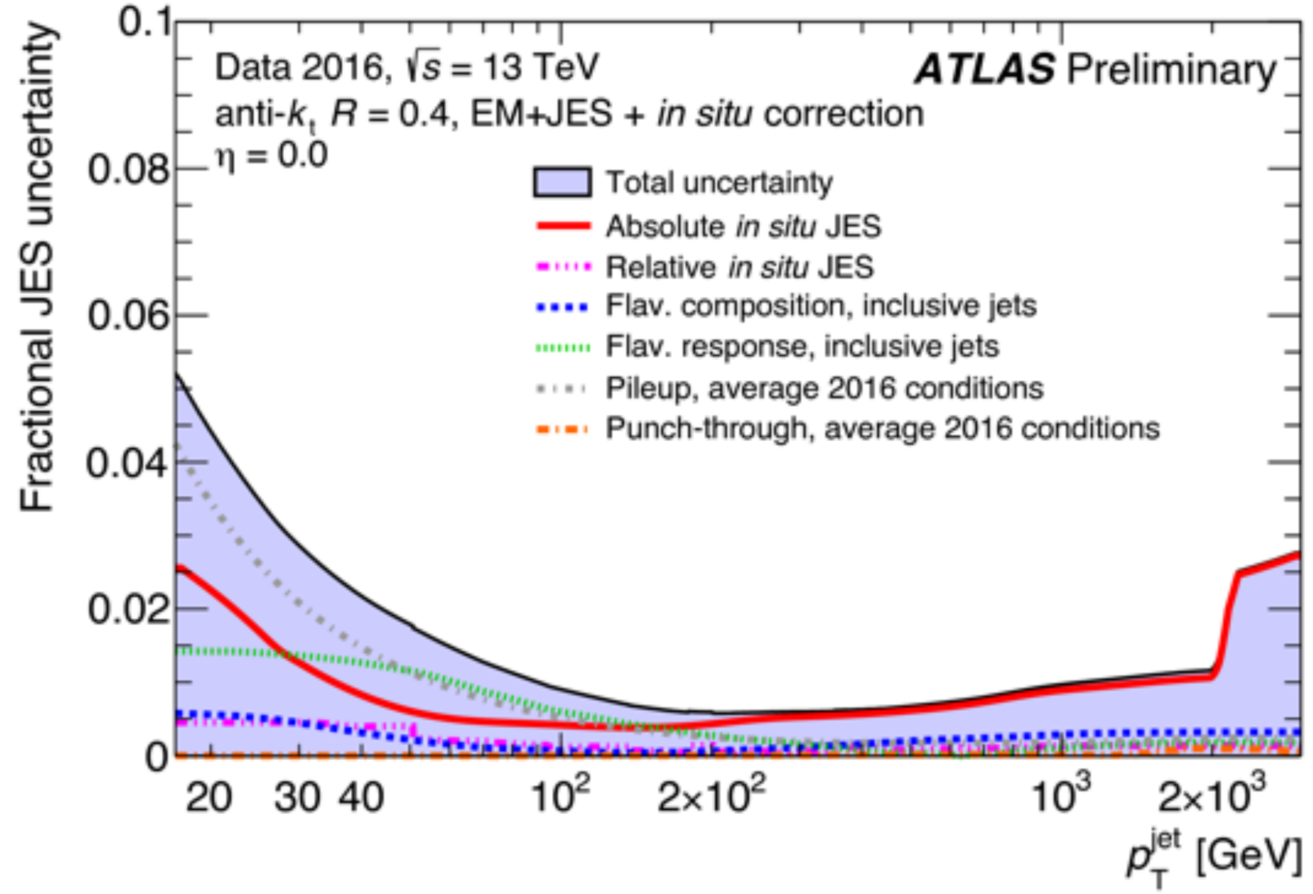
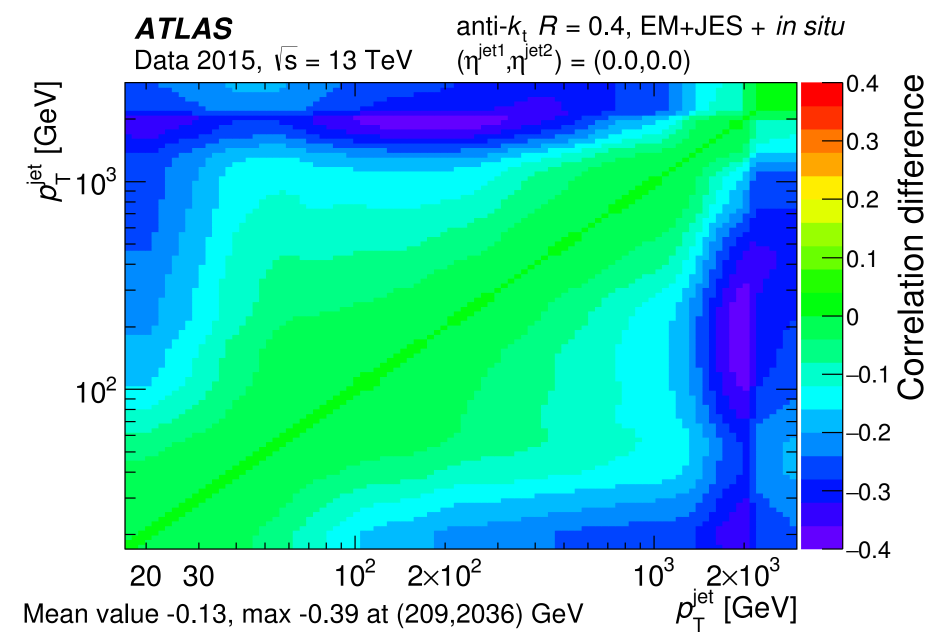

ATLAS Simulation
√s = 13 TeV, Pythia Dijet
anti-k_t R=0.4, EM+JES |η$_{det}$| < 0.1
30 ≤ p_T^{truth} < 40 GeV
80 ≤ p_T^{truth} < 100 GeV
350 ≤ p_T^{truth} < 400 GeV
p_T Response
Relative Fraction
$\mathcal{W}_{trk}$


ATLAS
√s = 13 TeV, 3.2 fb^{-1}
anti-k_t R = 0.4, EM+JES
Z–jet
γ–jet
Multijet
Total uncertainty
Statistical component
R_{Data} / R_{MC}
p_T^{jet} [GeV]

JET UNCERTAINTIES

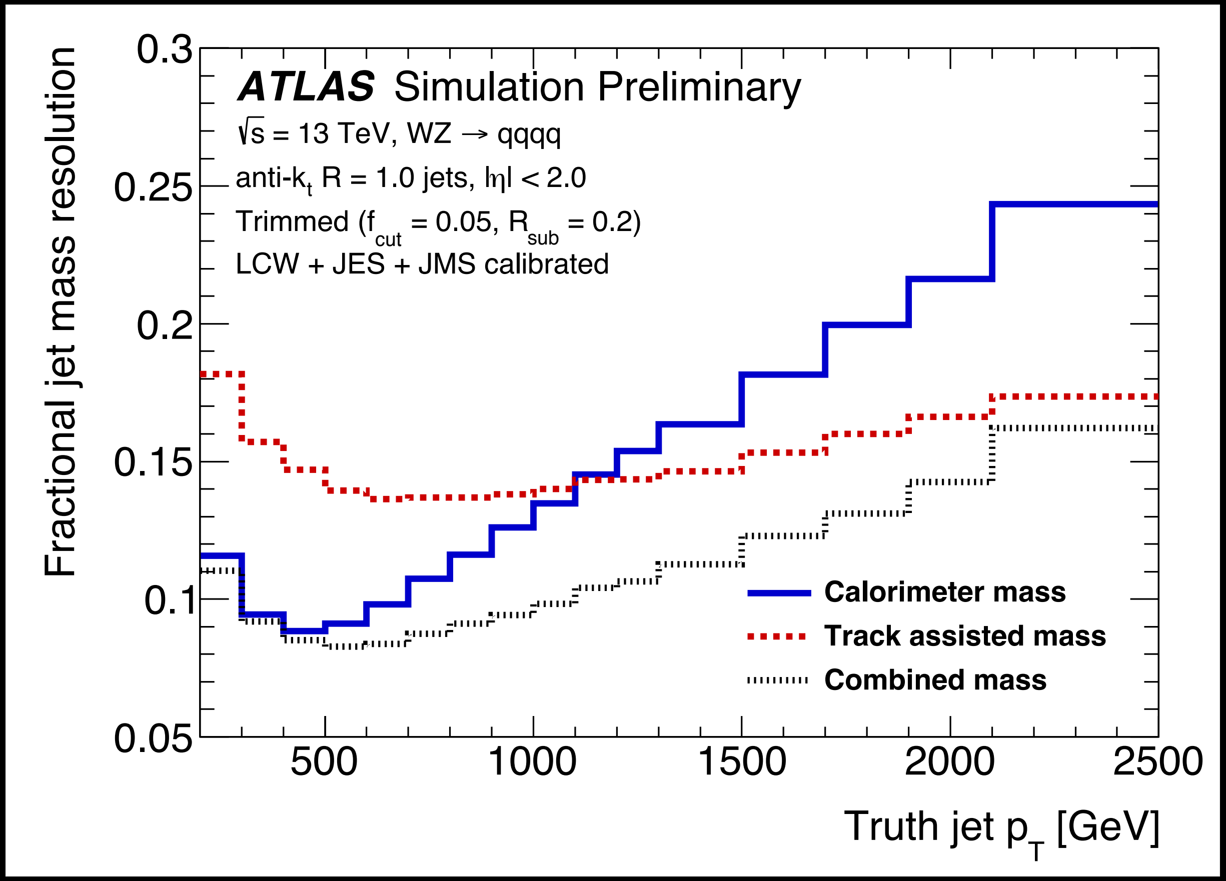


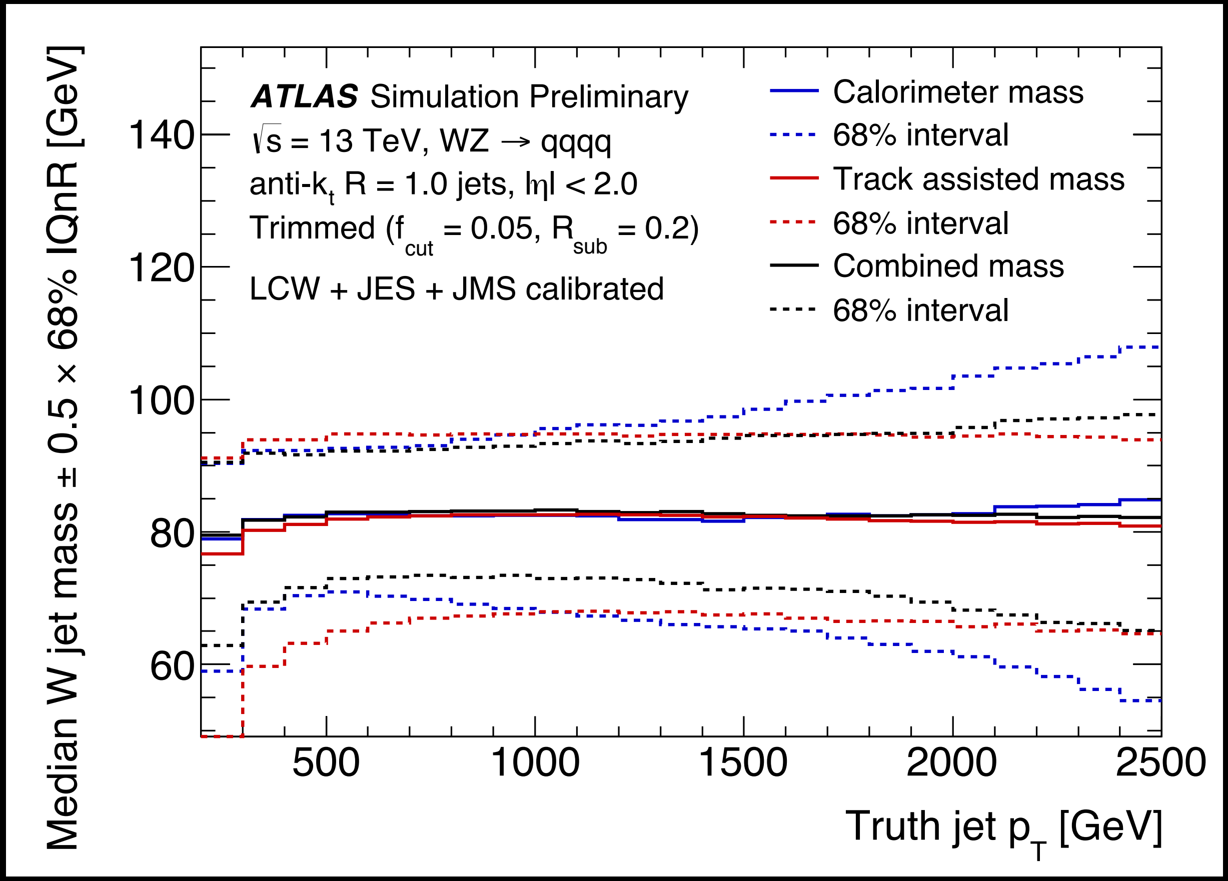




Uncertainty correlation losses from nuisance parameter reduction for simple analyses

JET MASS CALIBRATION

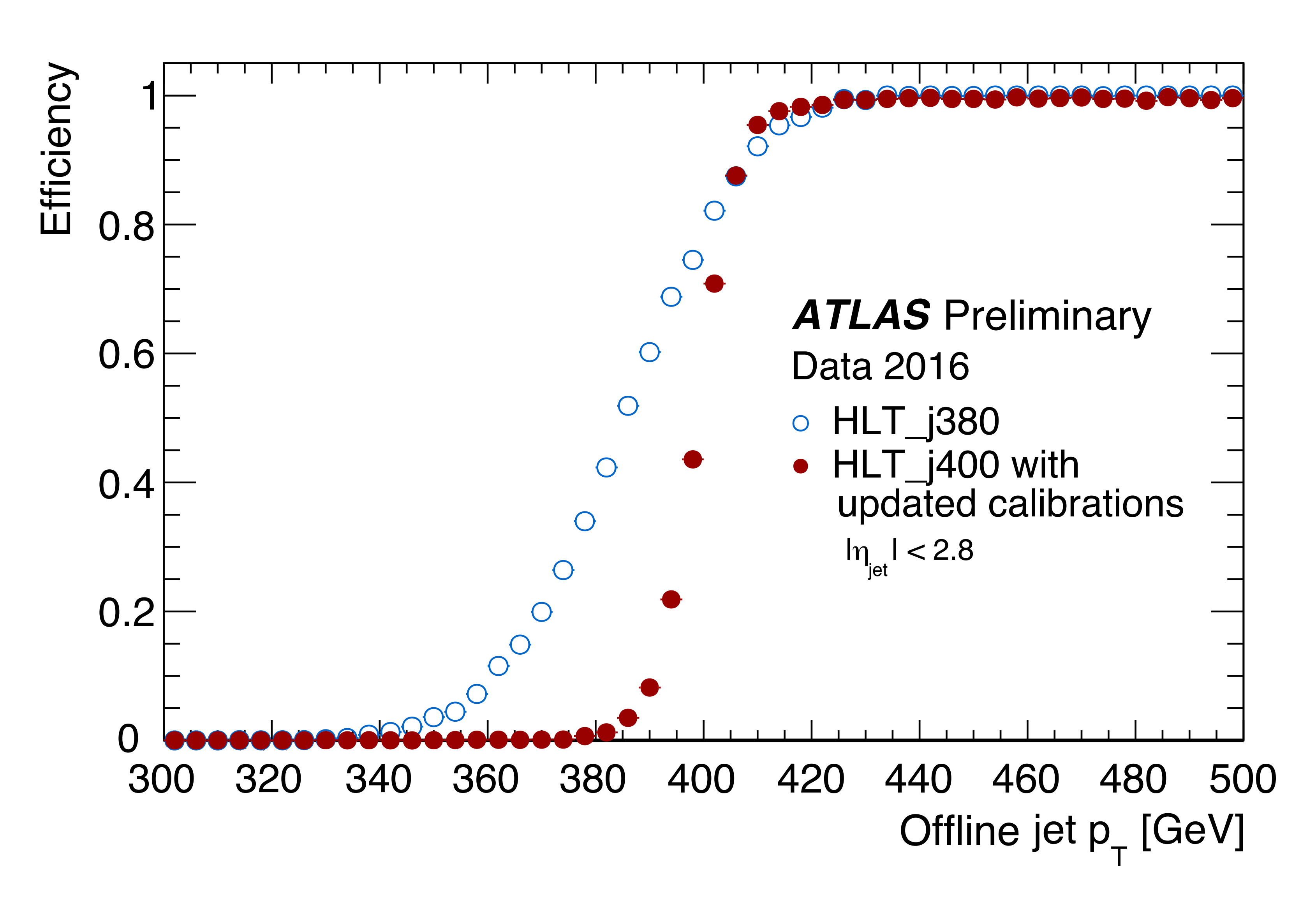




- Detector response shapes jet mass as well as energy.
- At high pT, cluster merging obscures substructure, but can still be resolved with tracks but response suffers from lack of neutral information.
- Correct track-jet mass as $m_{trk} * pT_{trk} / pT_{calo}$ [ATLAS-CONF-2016-035], combine with calo mass using resolution-weighted average.

[JETM-2017-002]

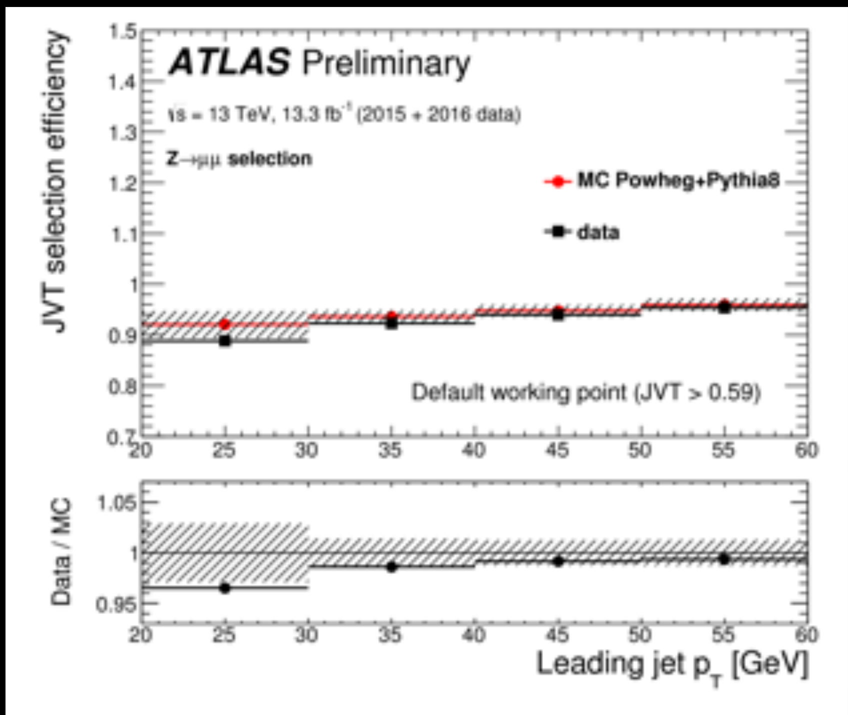
TRIGGER JET CALIBRATION

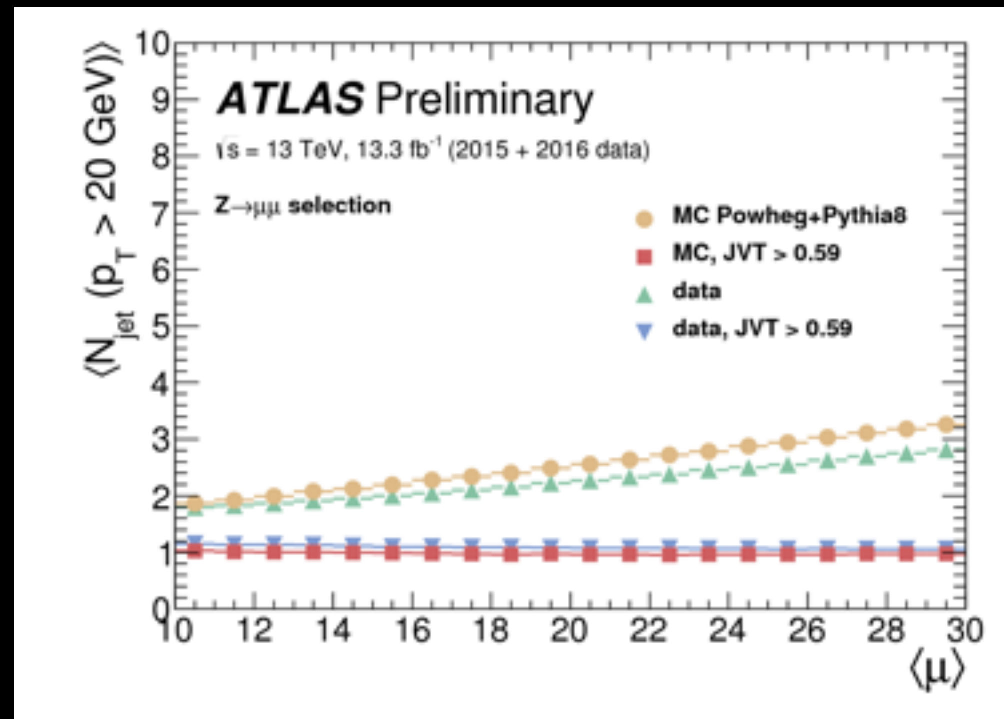


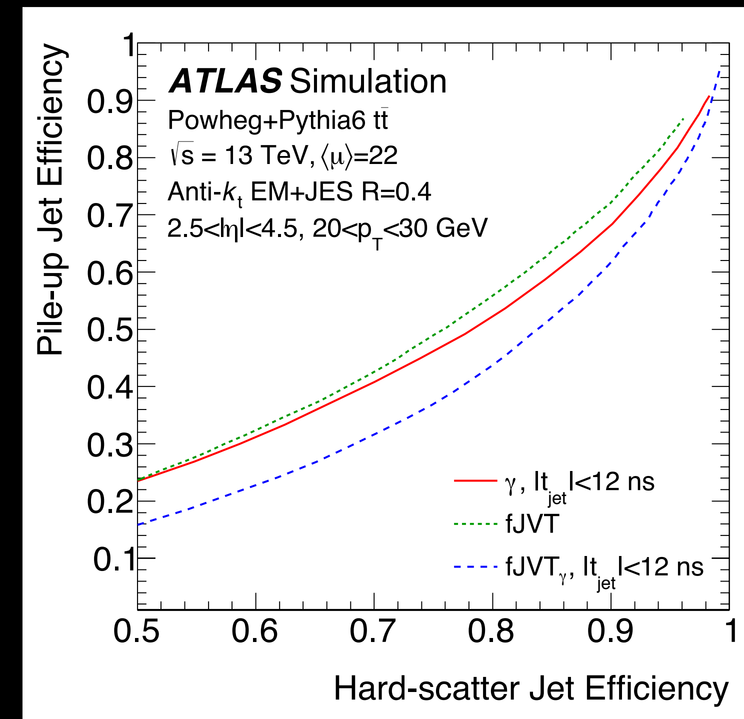
- Track-based Global Sequential Calibration vastly improves resolution, sharpening turn-on.

PILEUP SUPPRESSION

JET-LEVEL PILEUP SUPPRESSION







Jet Vertex Tagger [arXiv: 1510.03823]:

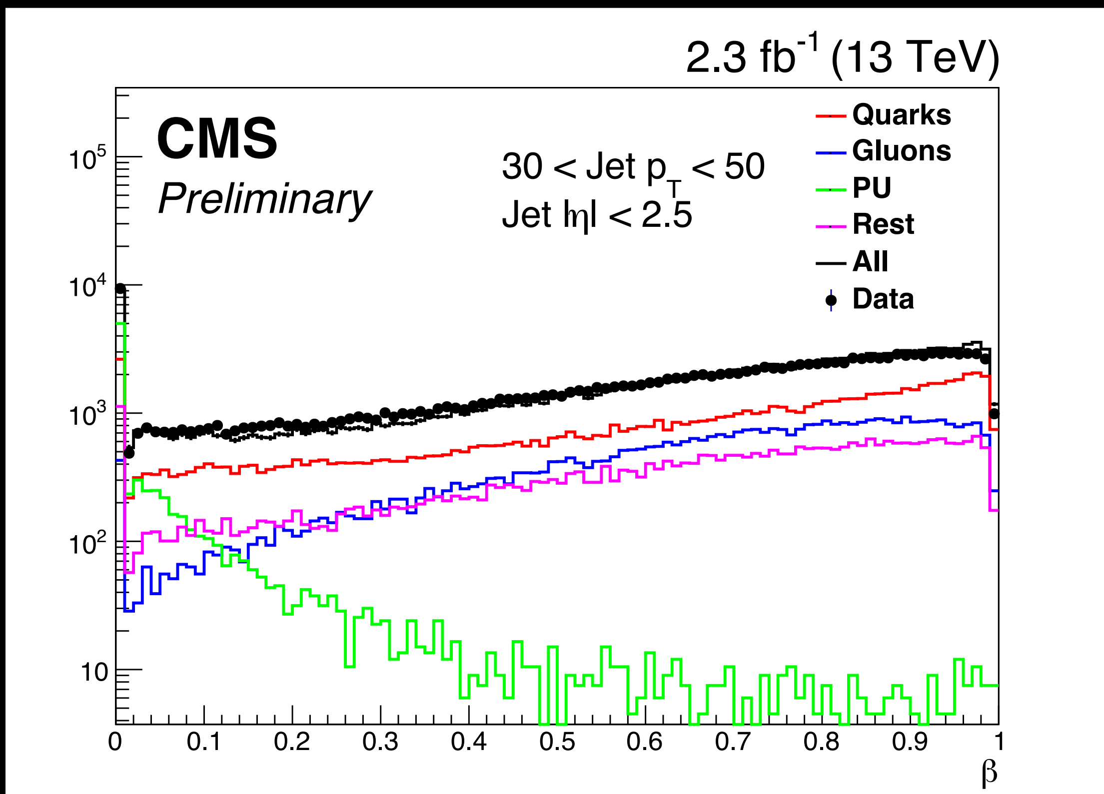
- Identify jets with large fraction of track pT from pileup vertices
- Additional discrimination from track-calorimeter pT correlation

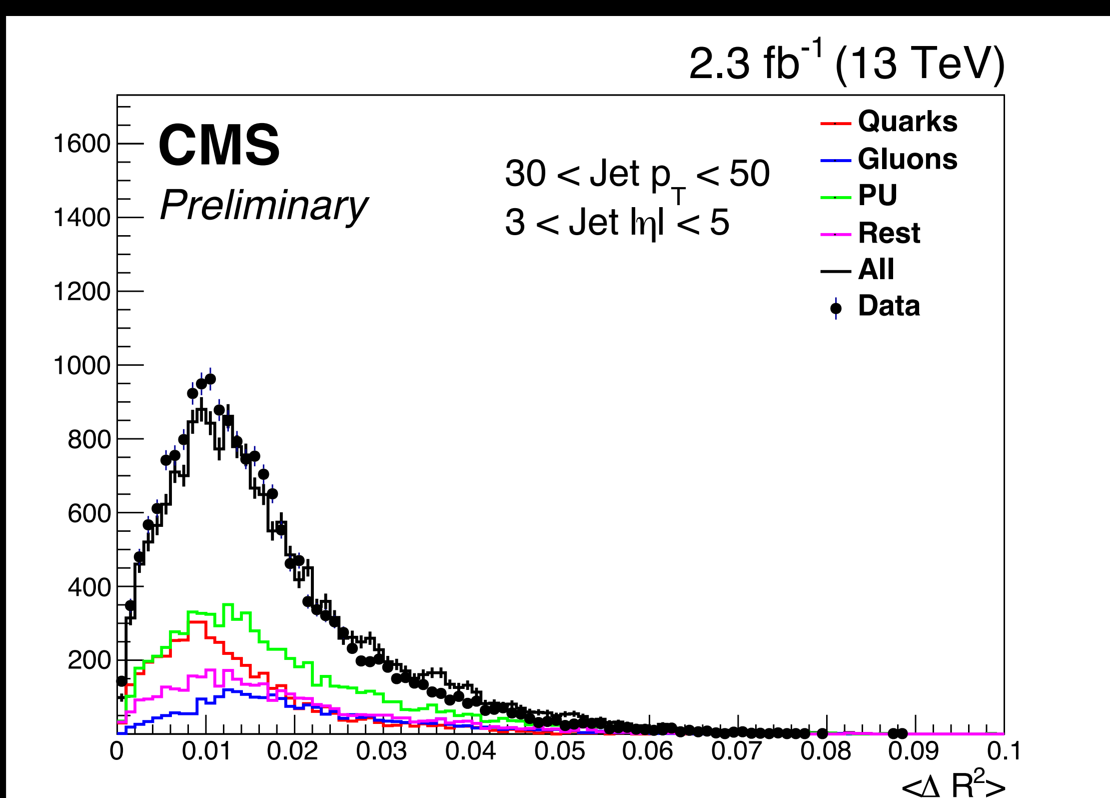
forward JVT [arXiv:1705.02211]:

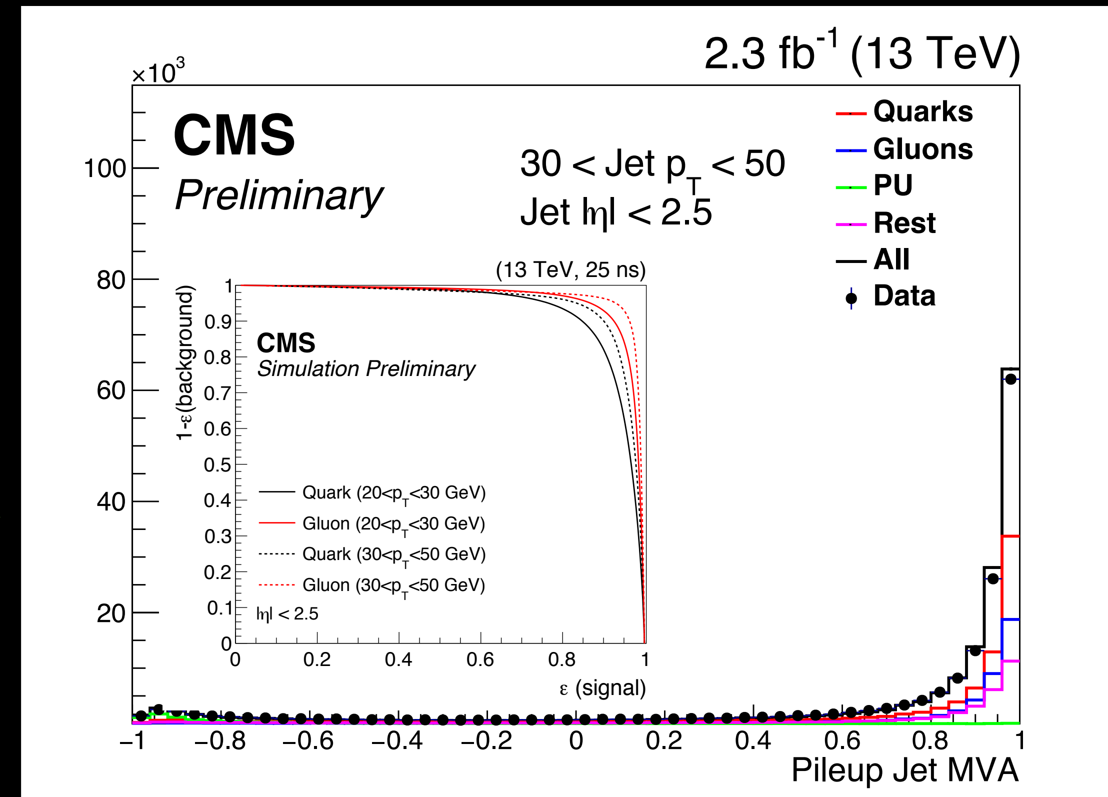
- Jet shape (width) discriminates stochastic & QCD-like jets
- Central pileup jets used to tag forward dijet partners

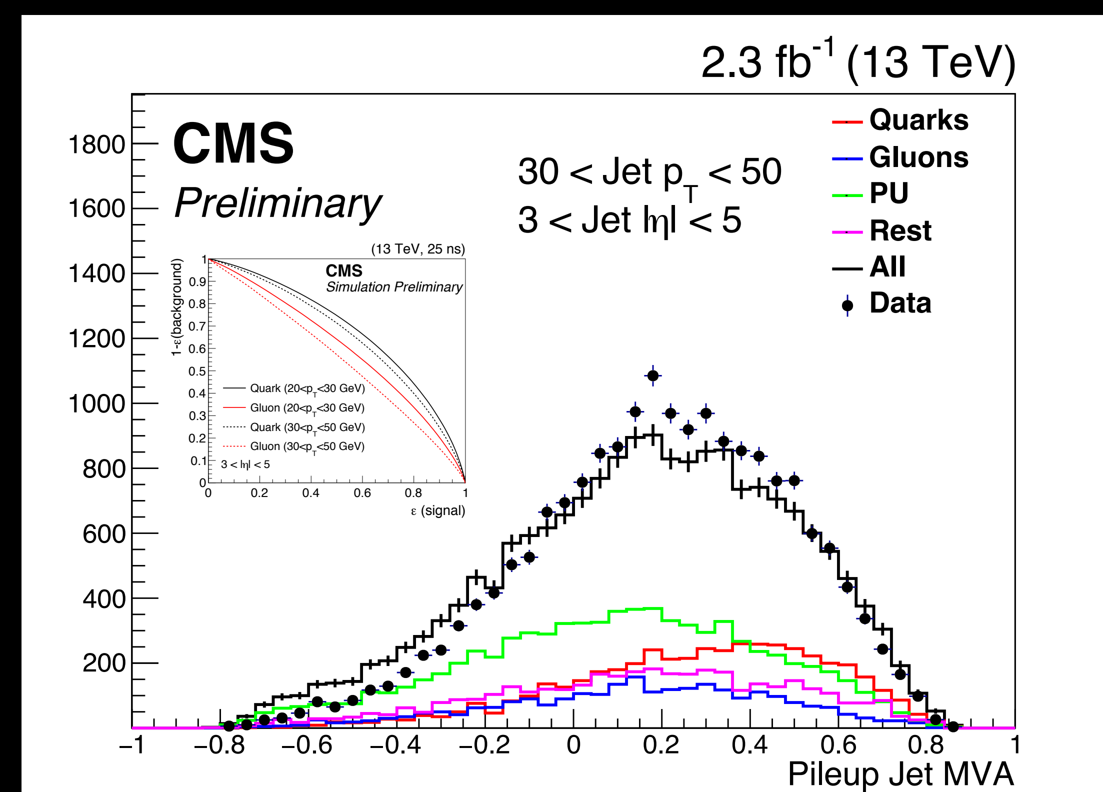
Jet-level PileUp Suppression

Tracking available in central region





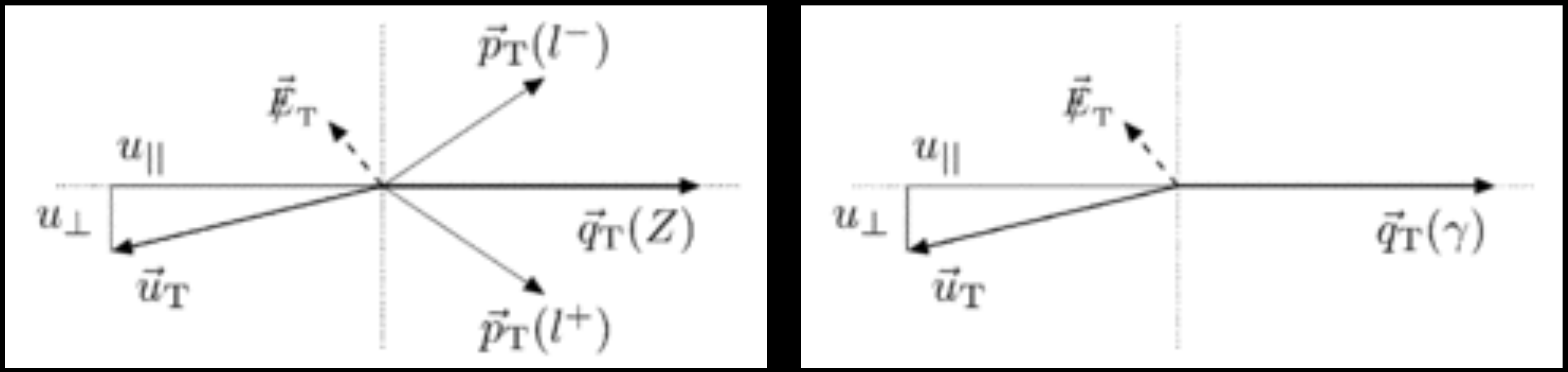




Forward tagging uses width

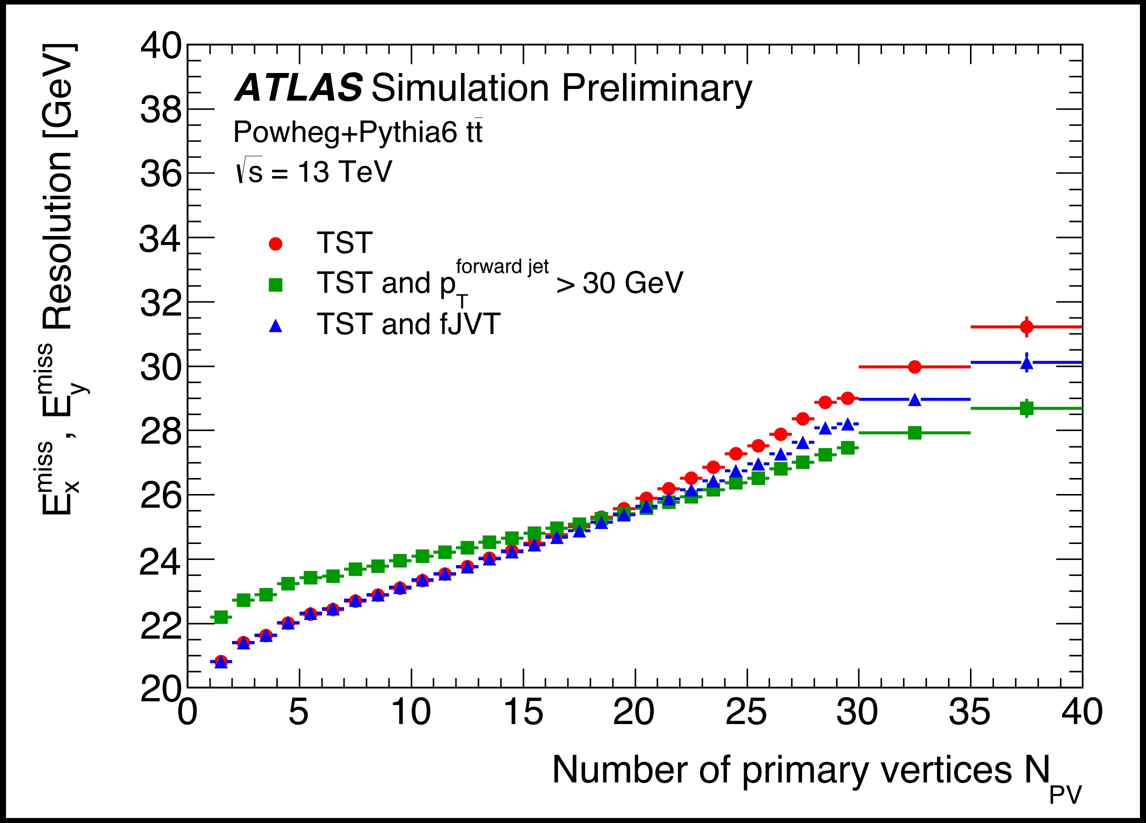
MISSING TRANSVERSE MOMENTUM

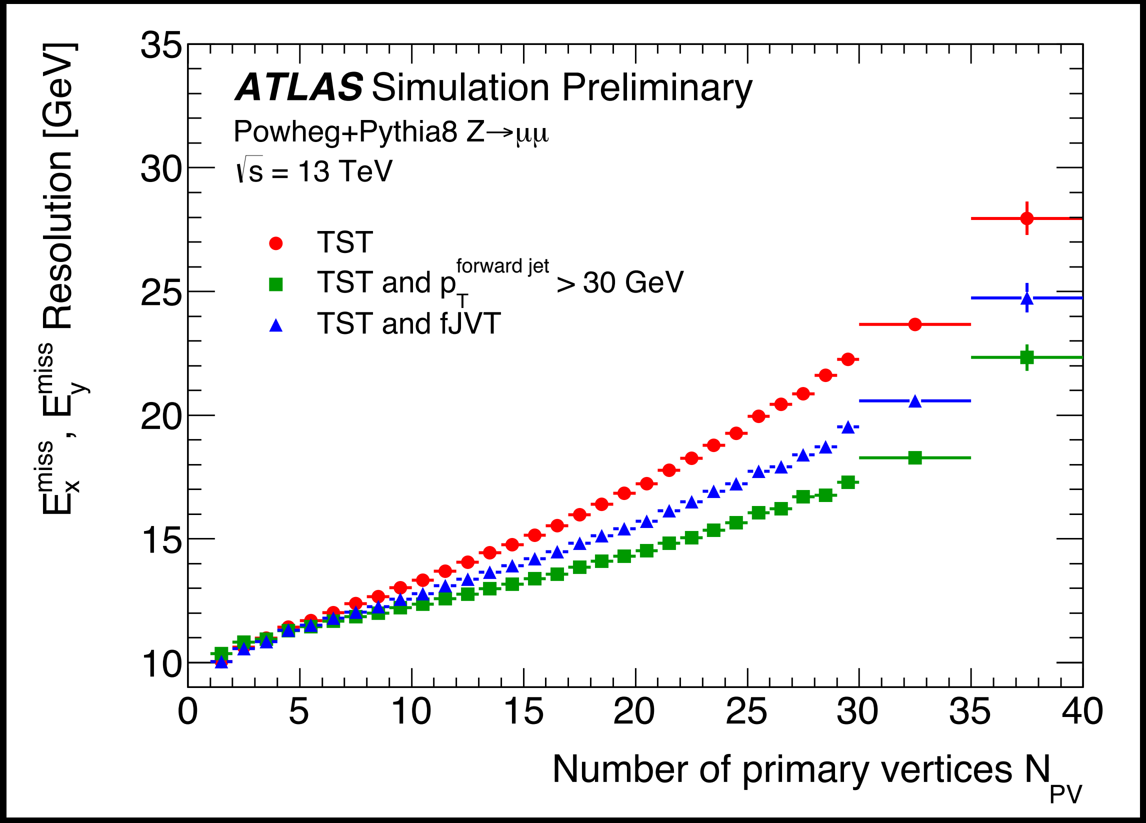
PERFORMANCE ASSESSMENT

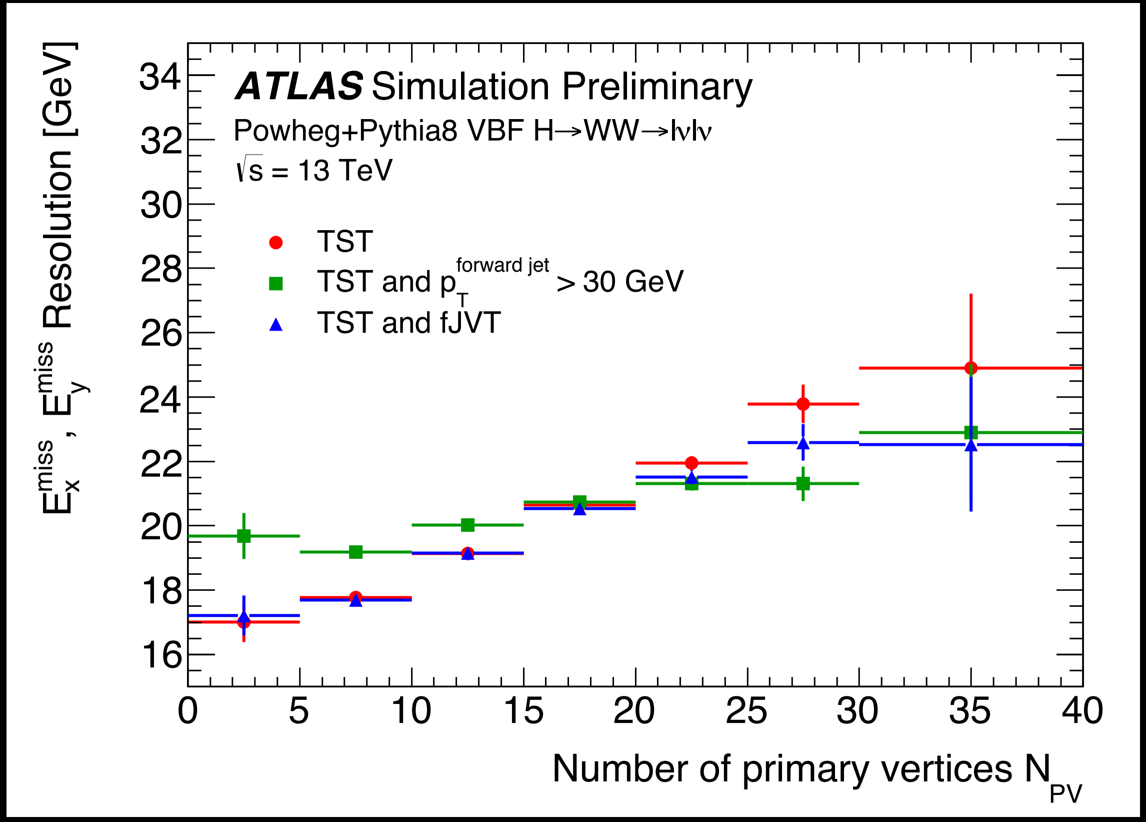


- Use projections parallel and perpendicular to the reference object (Z or photon) to isolate scale defect & resolution effects

FORWARD PILEUP-SUPPRESSION

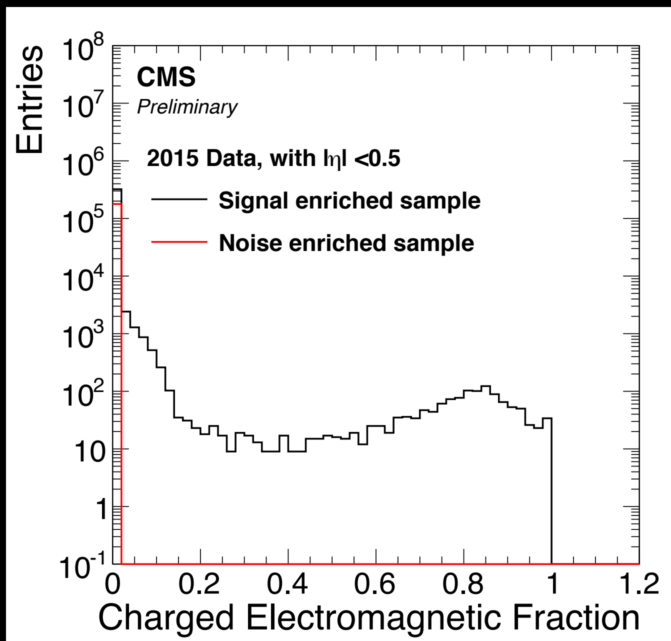


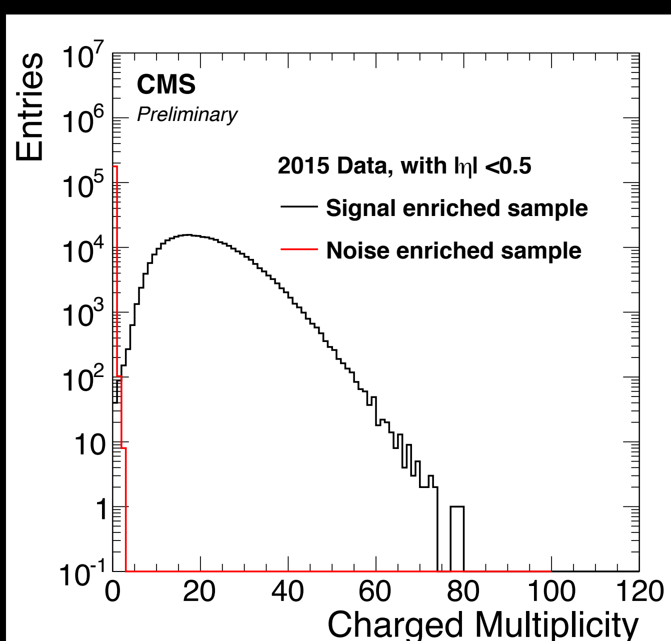


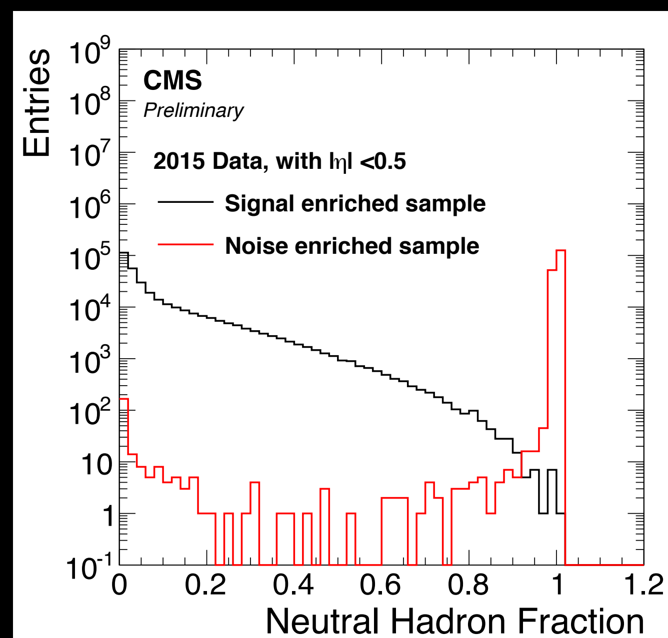


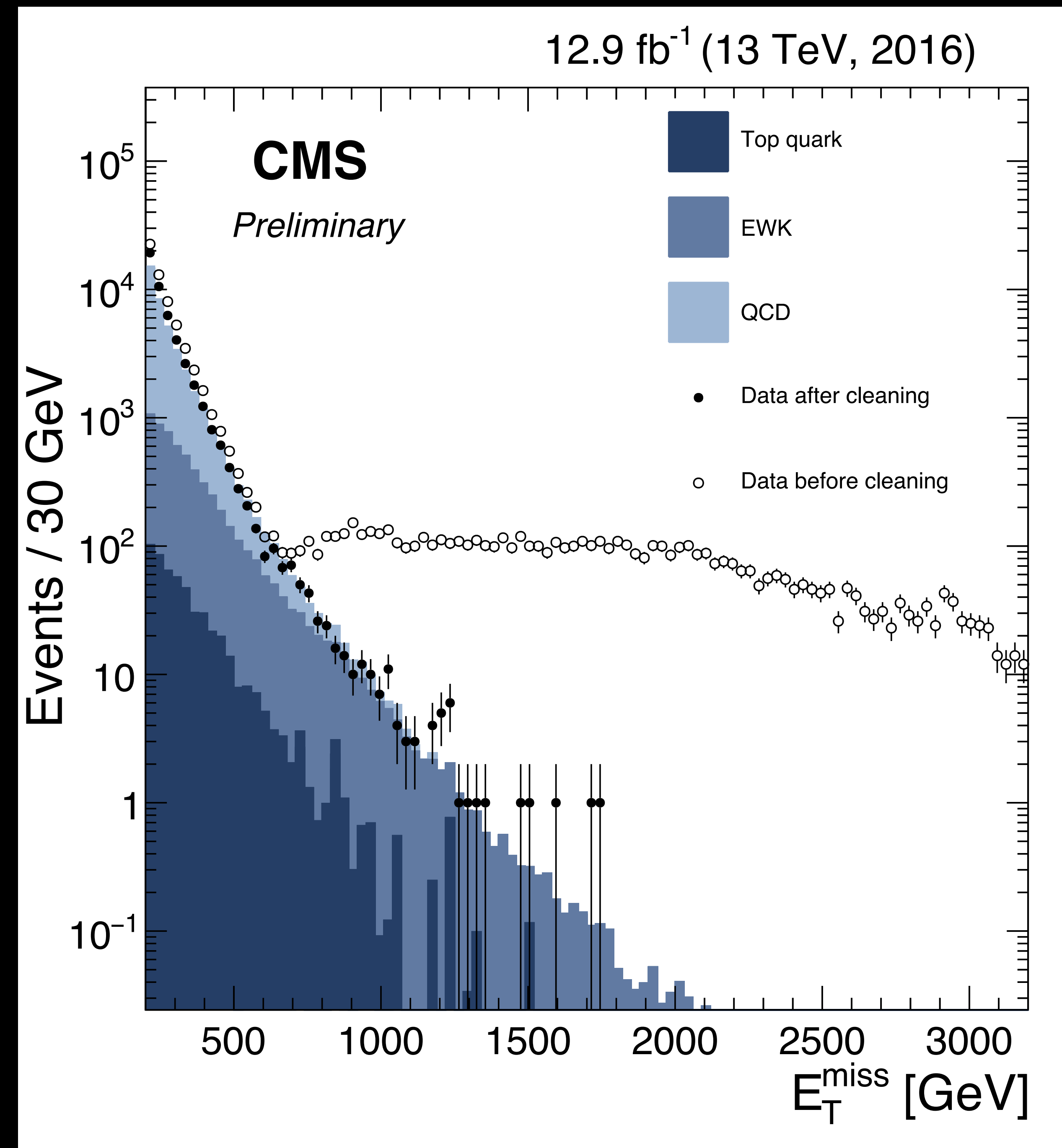
- Simply raising pt threshold is effective in Z+jets, due to low intrinsic forward activity.
- VBF & ttbar, with more jets, require dedicated fJVT cut.

Event cleaning









Impossible to do MET without removing detector defects!

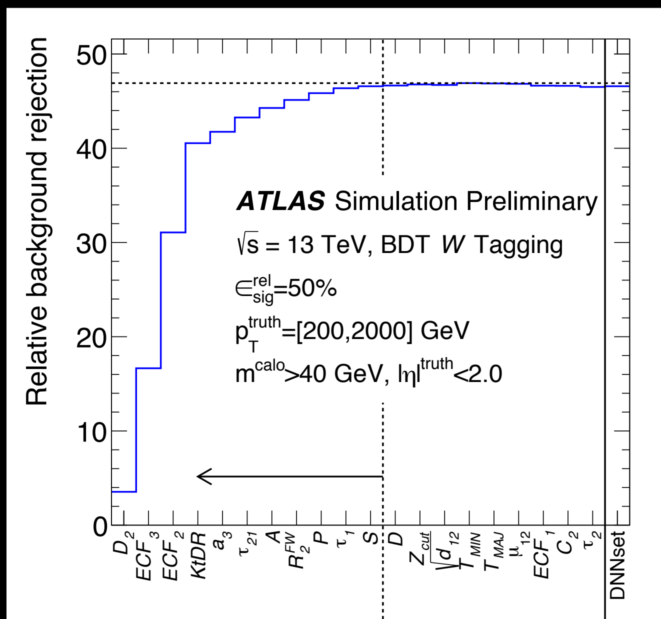
JET TAGGING

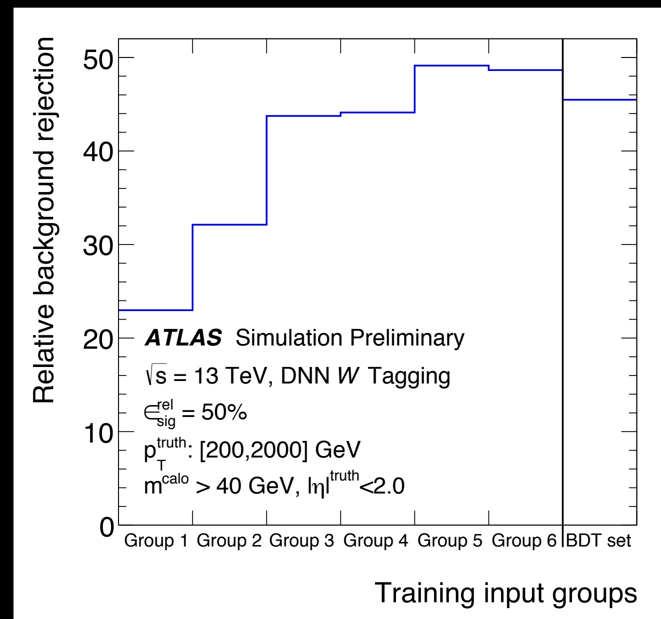
ATL-PHYS-PUB-2017-004

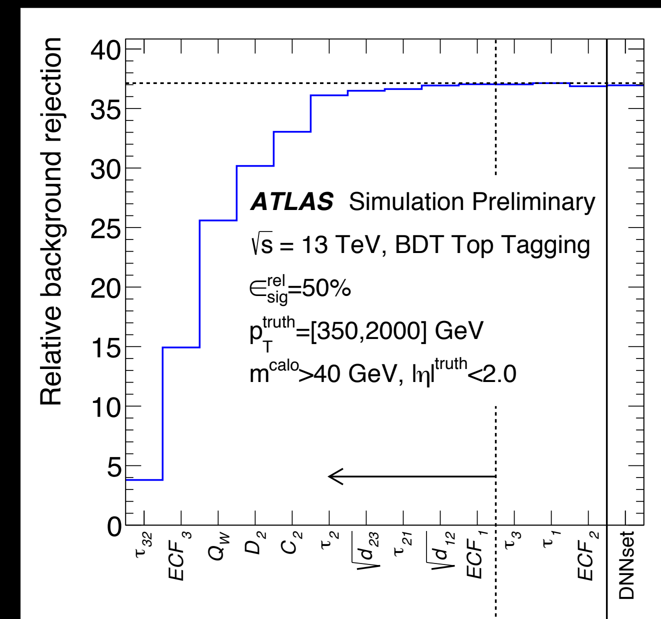
MACHINE LEARNING

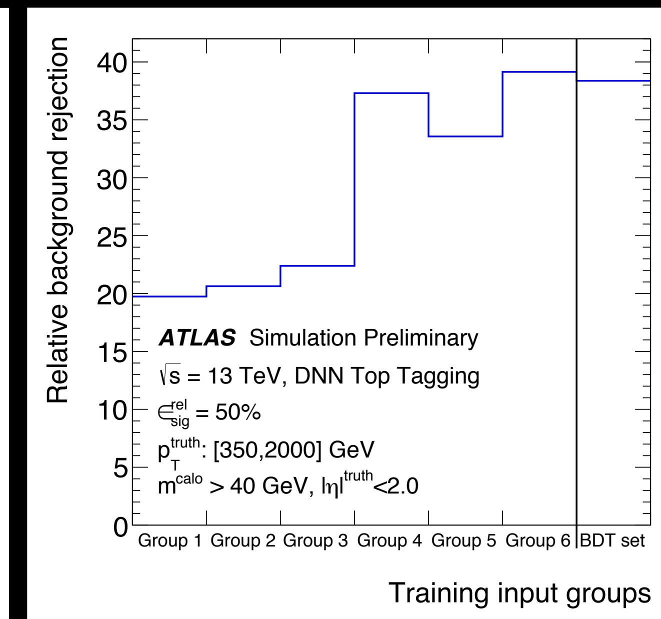
W BOSON TAGGING

TOP QUARK TAGGING







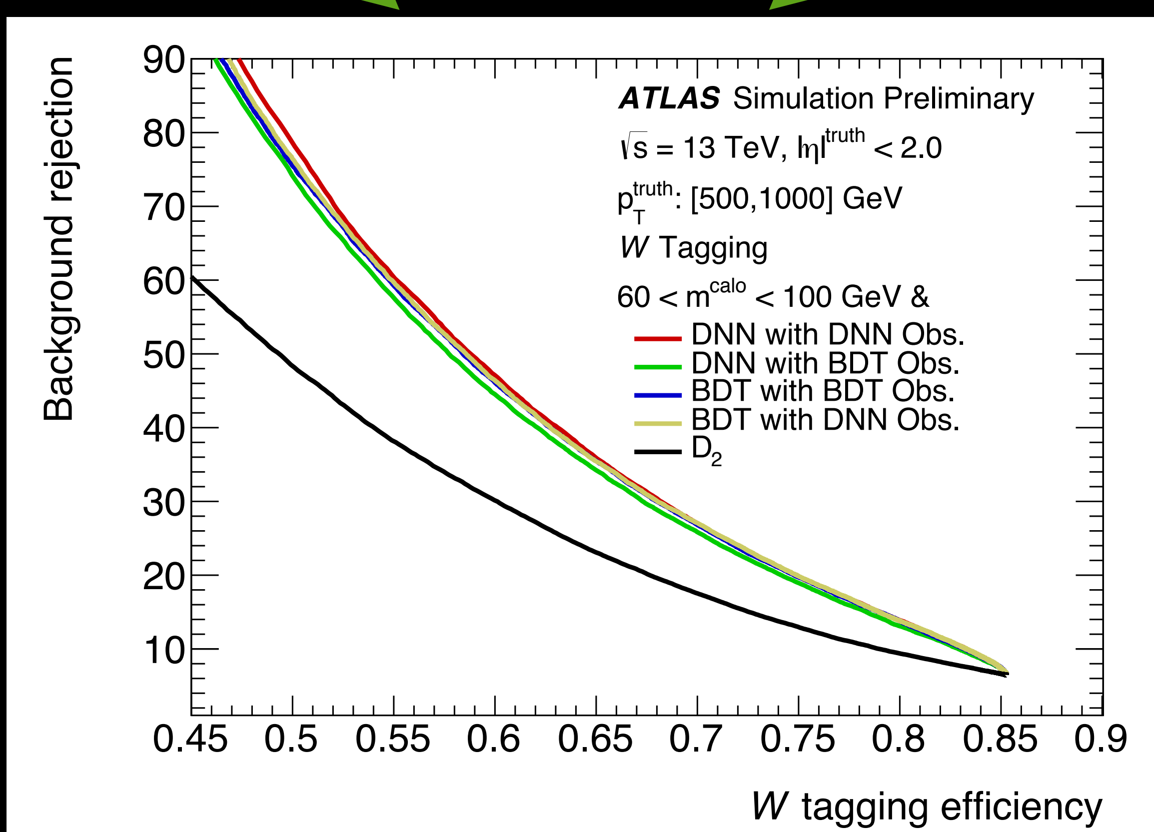


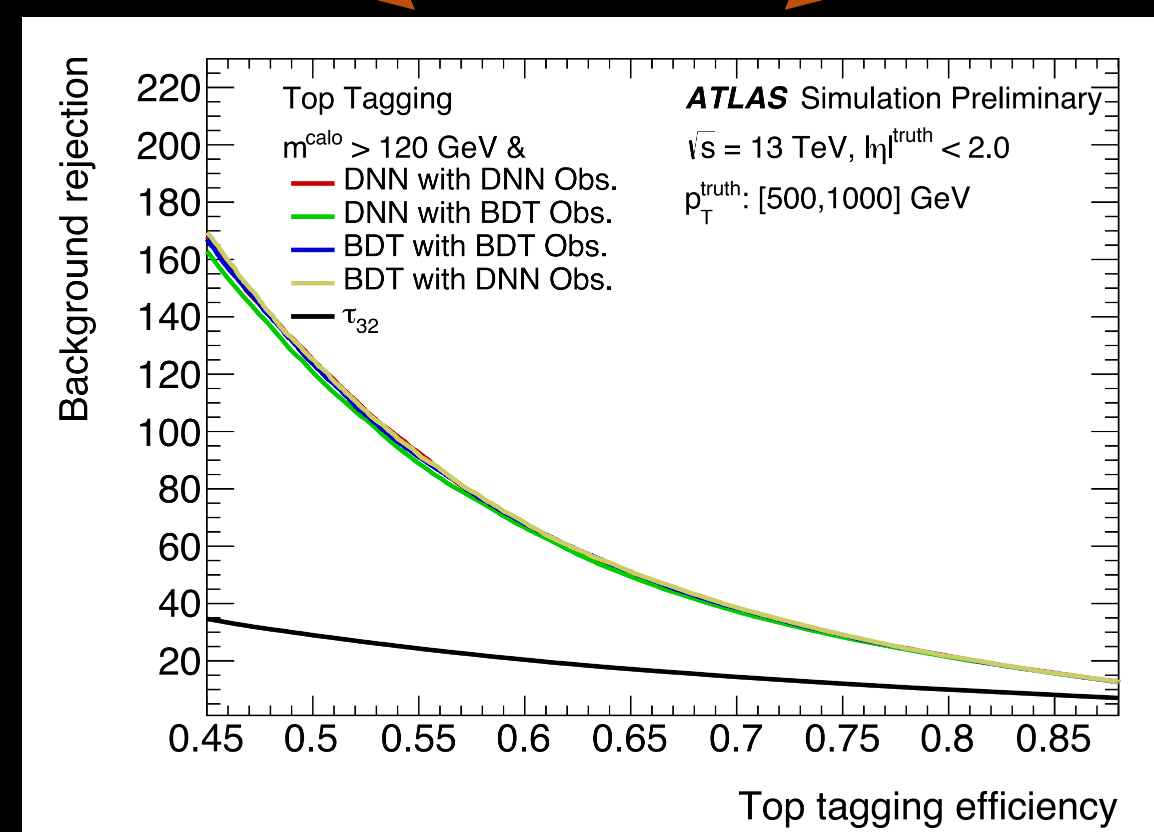
BDT

DNN

BDT

DNN





ATL-PHYS-PUB-2017-004

MACHINE LEARNING

W BOSON TAGGING

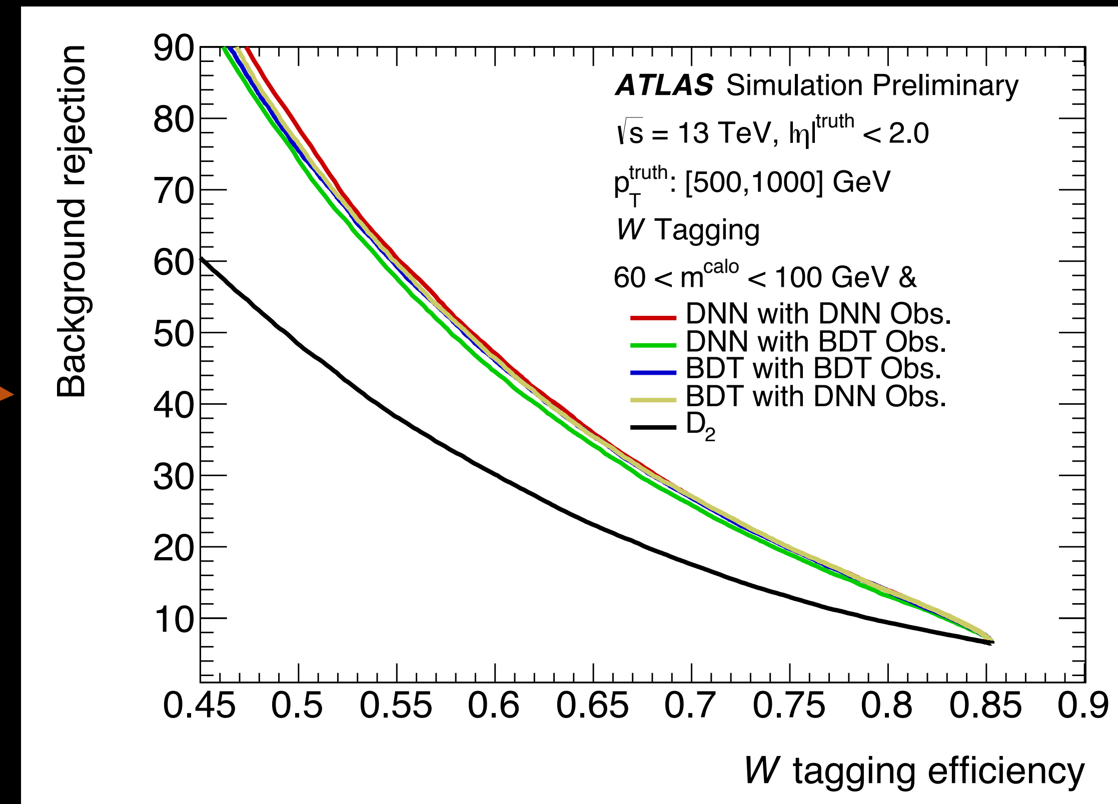
TOP QUARK TAGGING

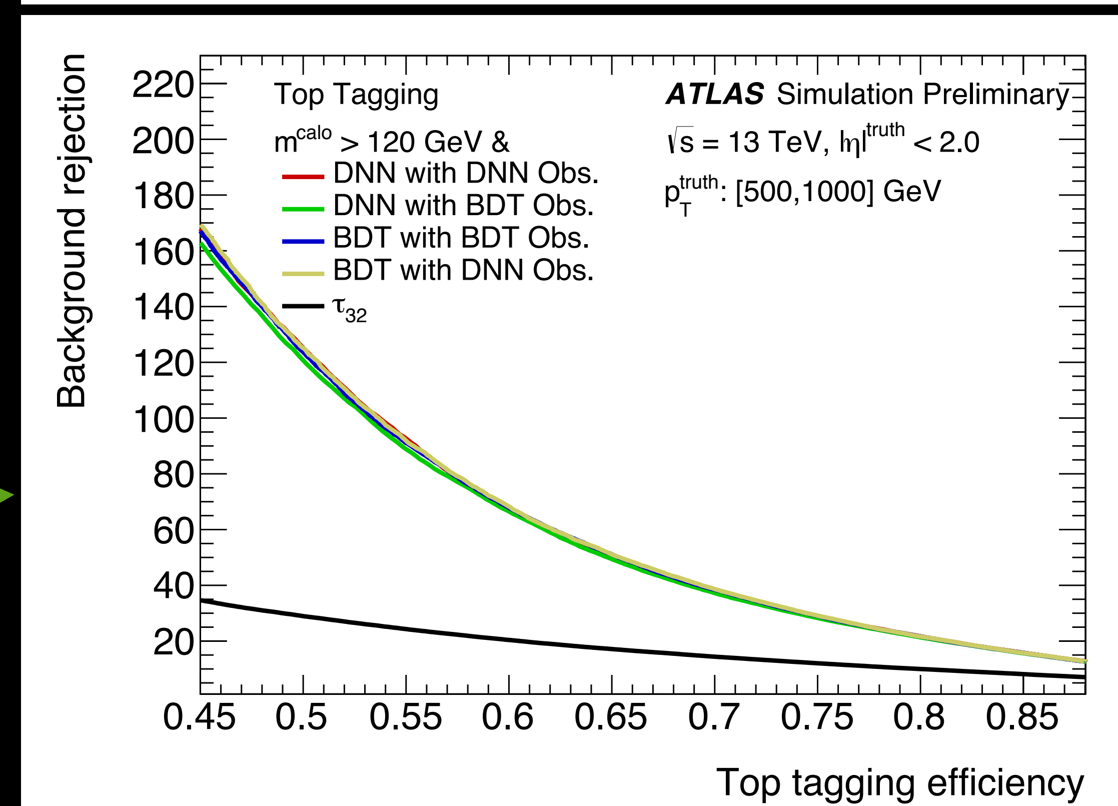
Optimised minimal input ensemble performing well for each ML alg.
Calo substructure only.
Implicit pt/mass dependence.

	W-Boson Tagging		Top-Quark Tagging	
Observable	BDT	DNN	BDT	DNN
ECF_1		∘	∘	∘
ECF_2	∘	∘		∘
ECF_3	∘	∘	∘	∘
C_2		∘	∘	∘
D_2	∘	∘	∘	∘
τ_1	∘	∘		∘
τ_2		∘	∘	∘
τ_3				∘
τ_{21}	∘	∘	∘	∘
τ_{32}			∘	∘
R_2^{FW}	∘	∘		
S	∘	∘		
$\mathcal{P}$	∘	∘		
$\mathcal{D}$		∘		
a_3	∘	∘		
A	∘	∘		
T_{MIN}				
T_{MAJ}				
Z_{CUT}		∘		
μ_{12}		∘		
$\sqrt{d_{12}}$		∘	∘	∘
$\sqrt{d_{23}}$			∘	∘
$KtDR$	∘	∘		
Q_w			∘	∘

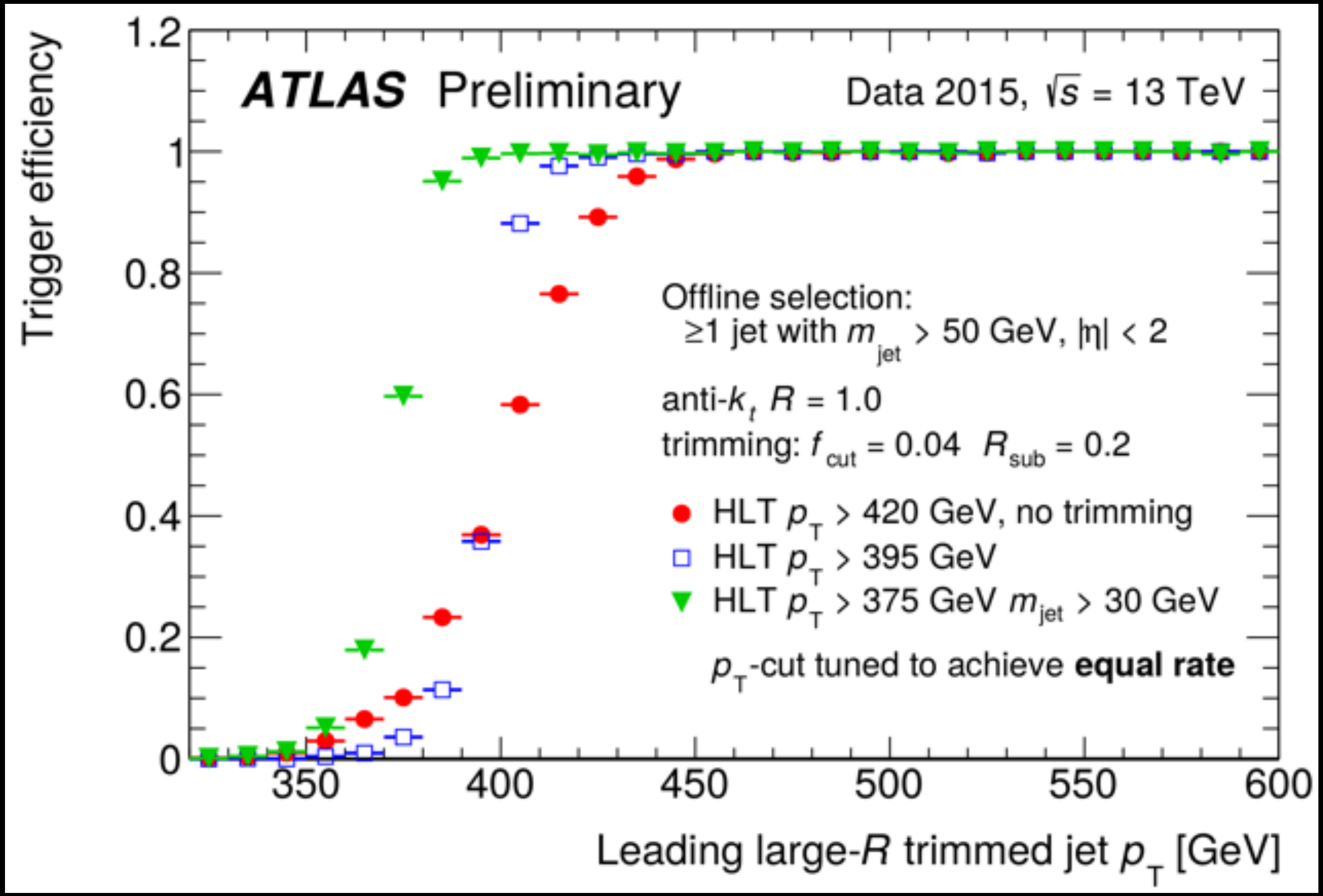
BDT

DNN





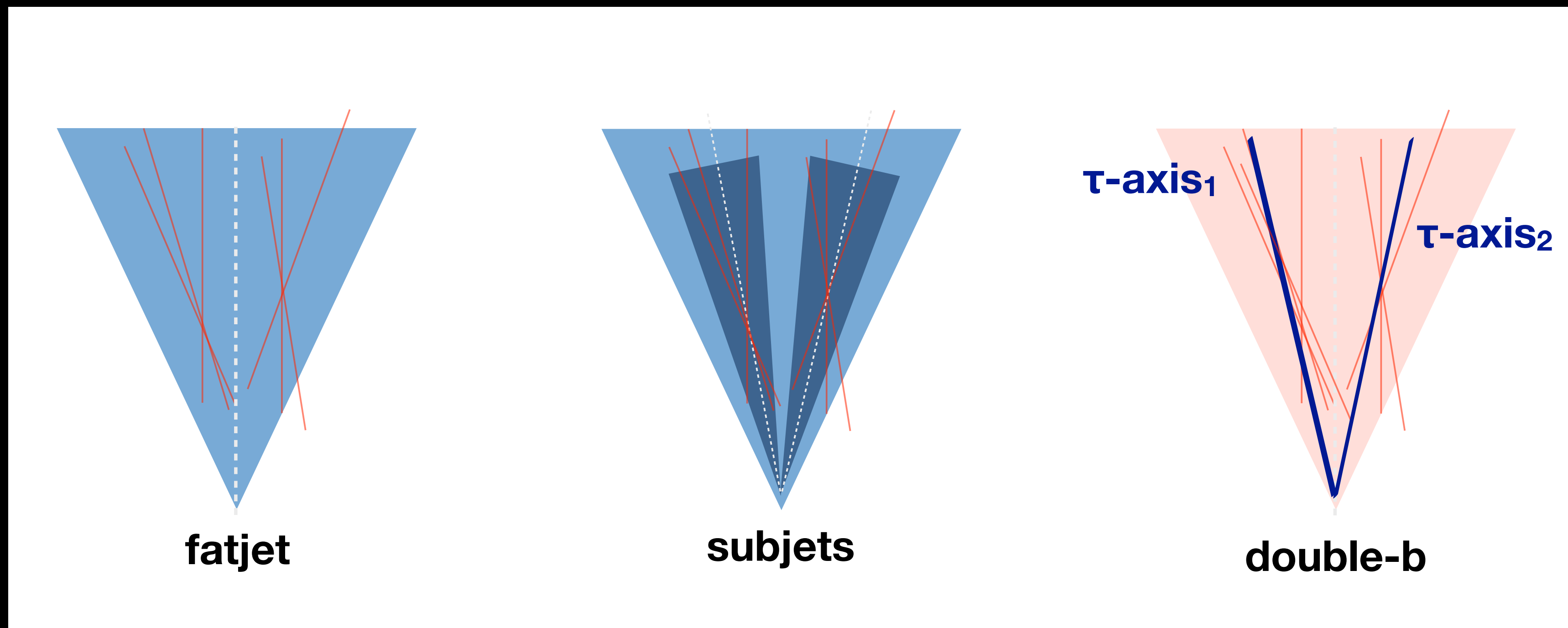
JET SUBSTRUCTURE TRIGGERS



- Selection on jet mass with trimming cuts background, allowing drastic lowering of threshold.

H BOSON TAGGING

DOUBLE B-TAGGING



N-subjettiness axes used as proxy for jet axes for b-tagging.