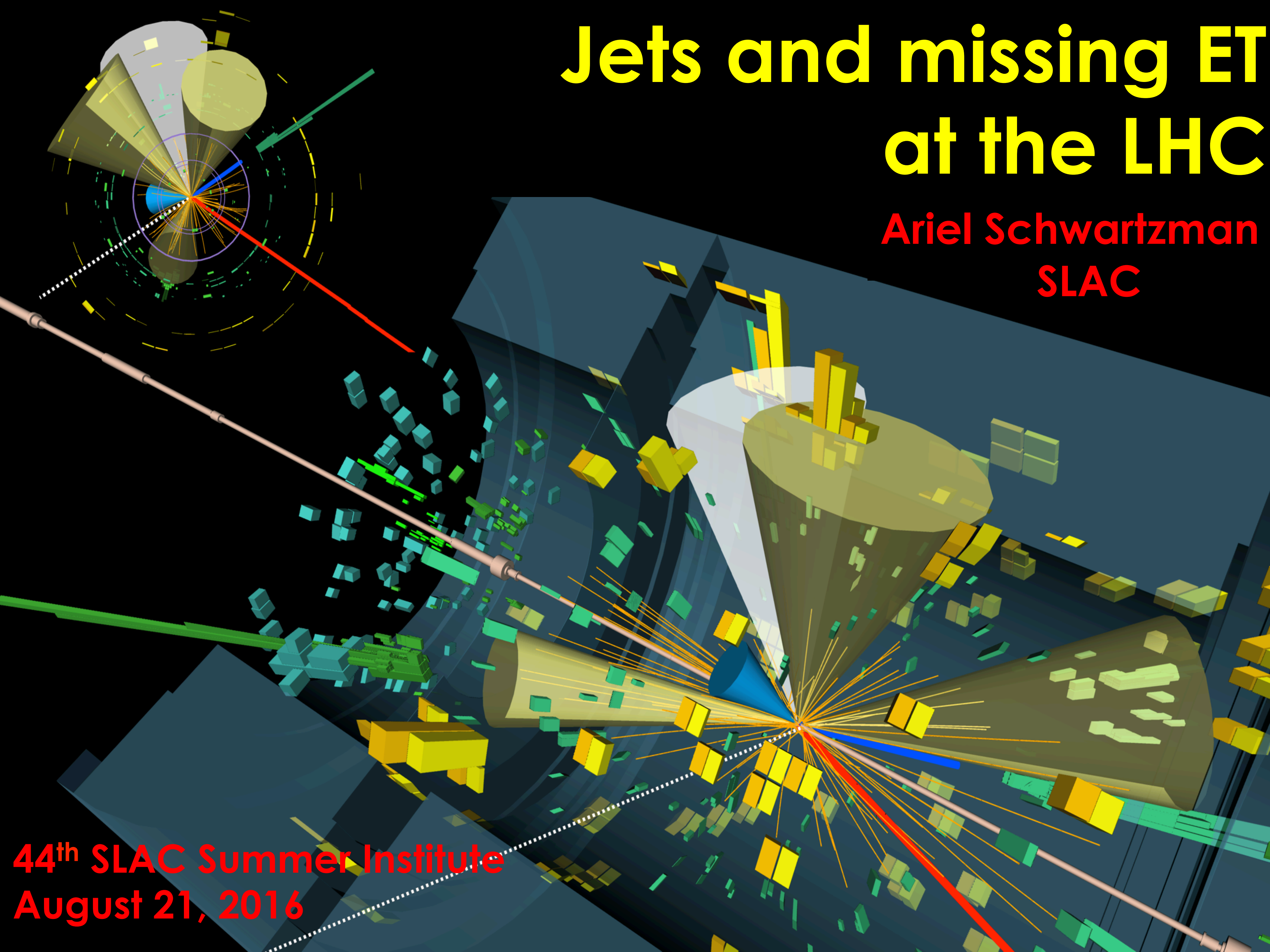
Jets and missing ET at the LHC

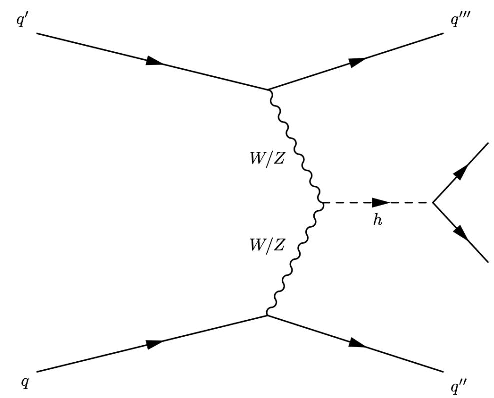
Ariel Schwartzman
SLAC

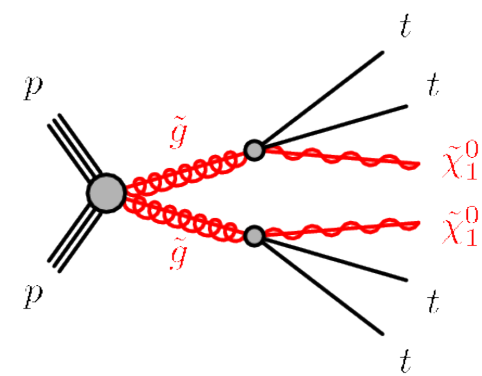


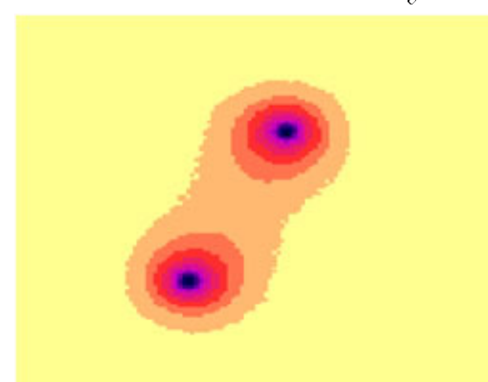
44th SLAC Summer Institute
August 21, 2016

Jets and Missing ET

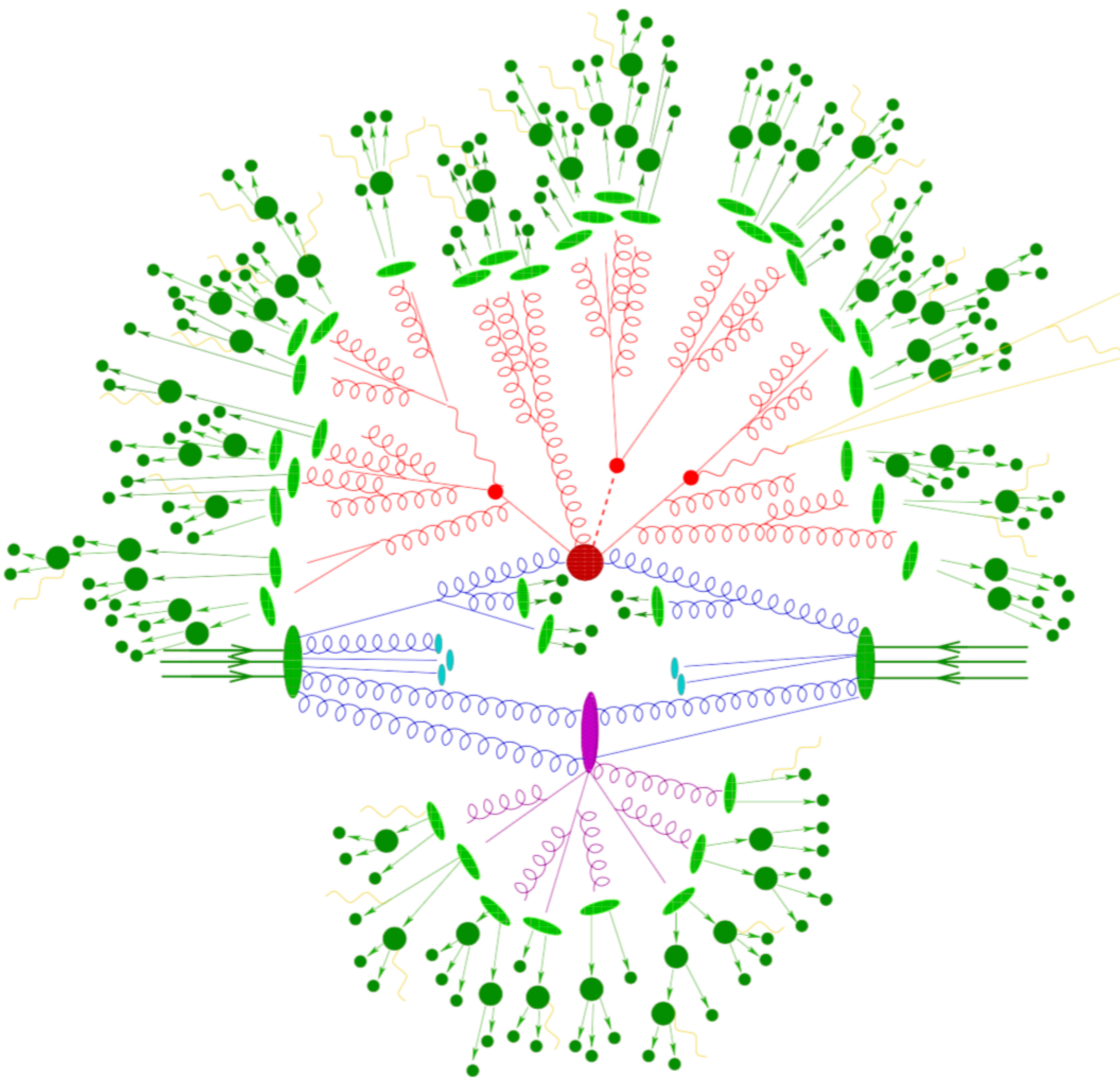
- Jets are one of the most prominent physics signatures at high energy colliders
- Individual jets are proxies for quark and gluons
- Combinations of jets are used to identify heavy electroweak particles (W,Z,H bosons and the top quark)
  - crucial signatures for searches of new phenomena and precision measurements
- Jets have internal structure: quantum properties





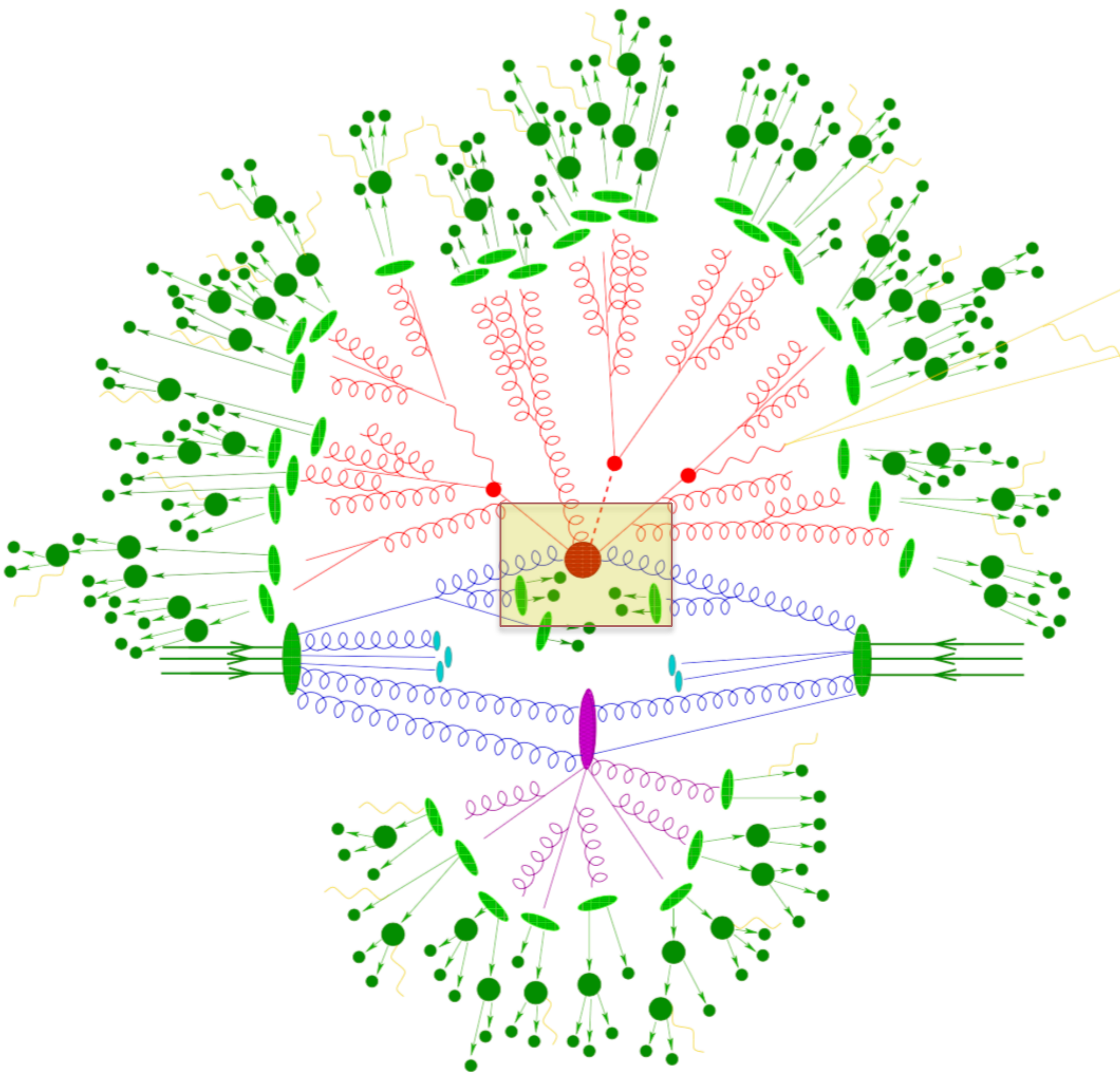


Jets and jet algorithms (I)



- Quark and gluons (partons) produced at short distances (hard process)
- As they propagate they radiate more partons (parton shower)
- Form uncolored hadrons (hadronization)

Jets and jet algorithms (I)



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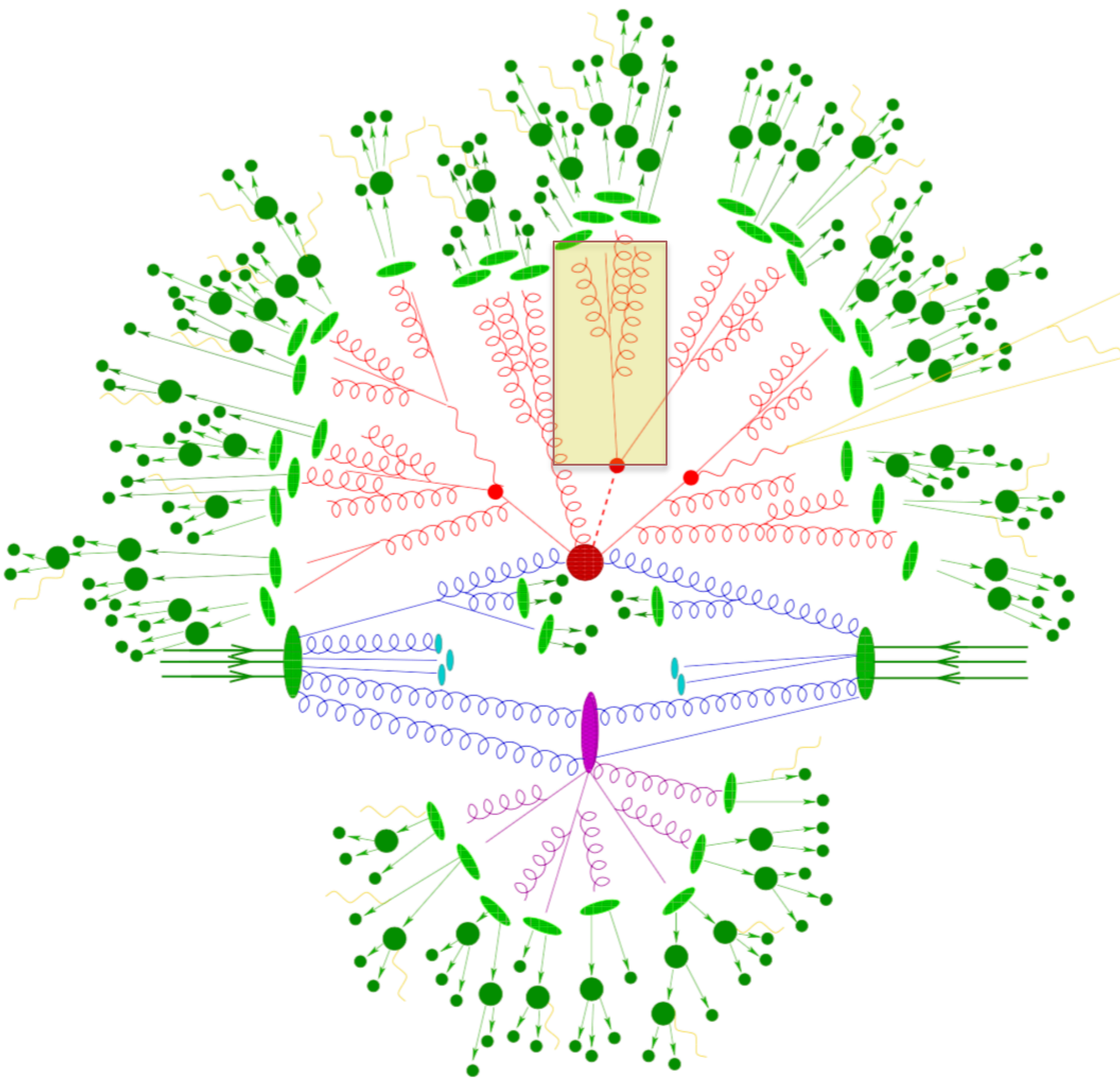

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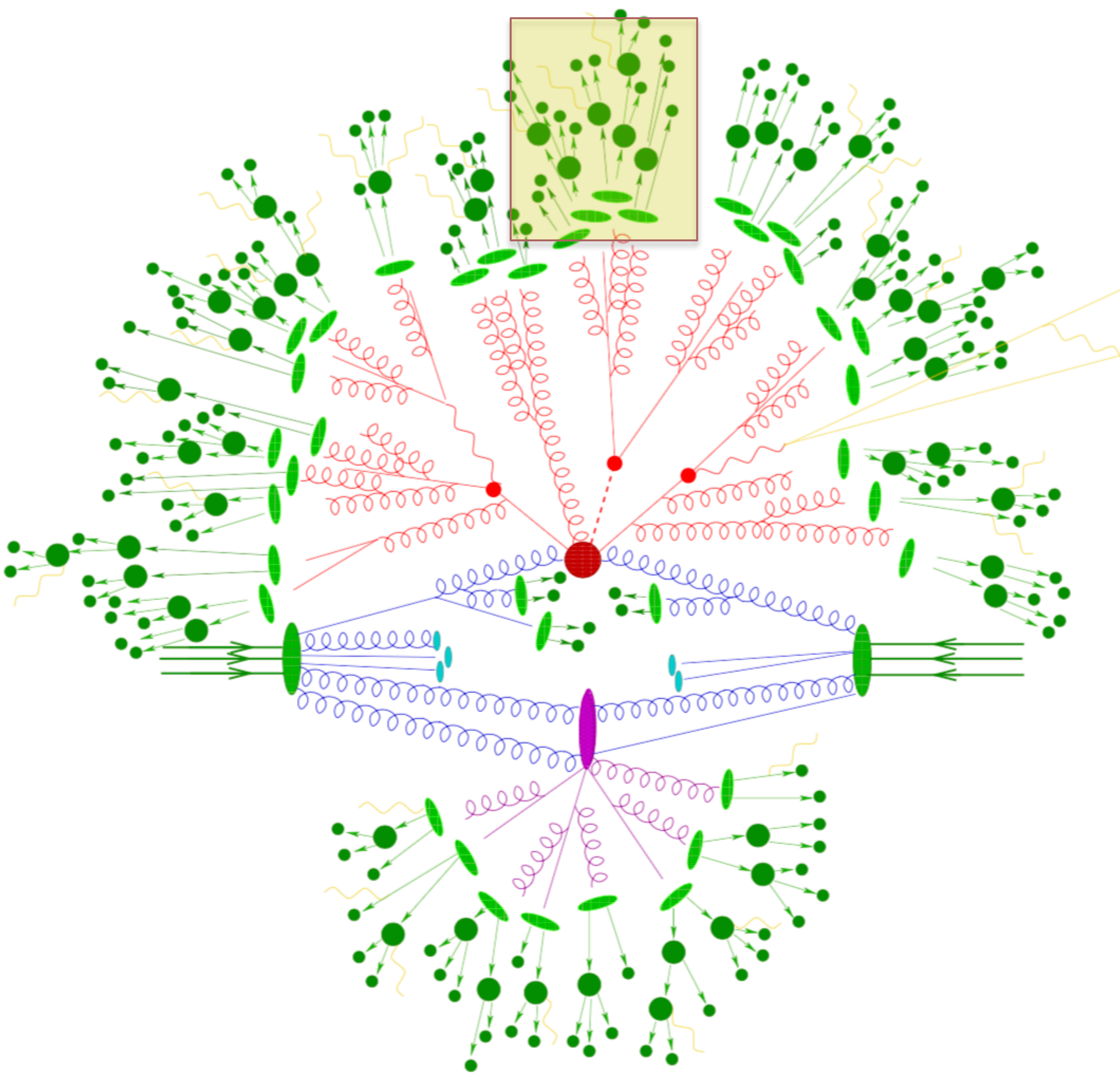

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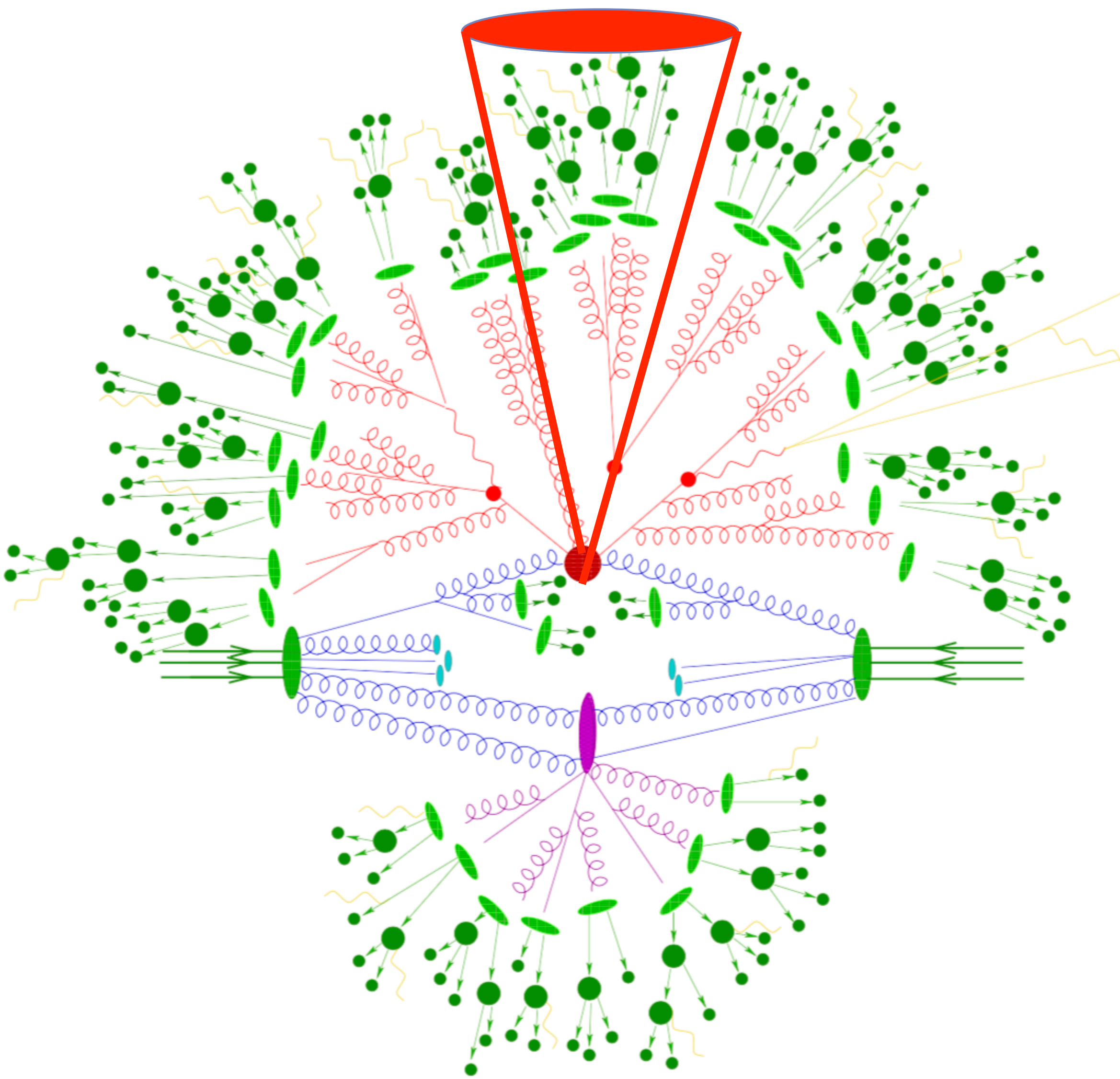

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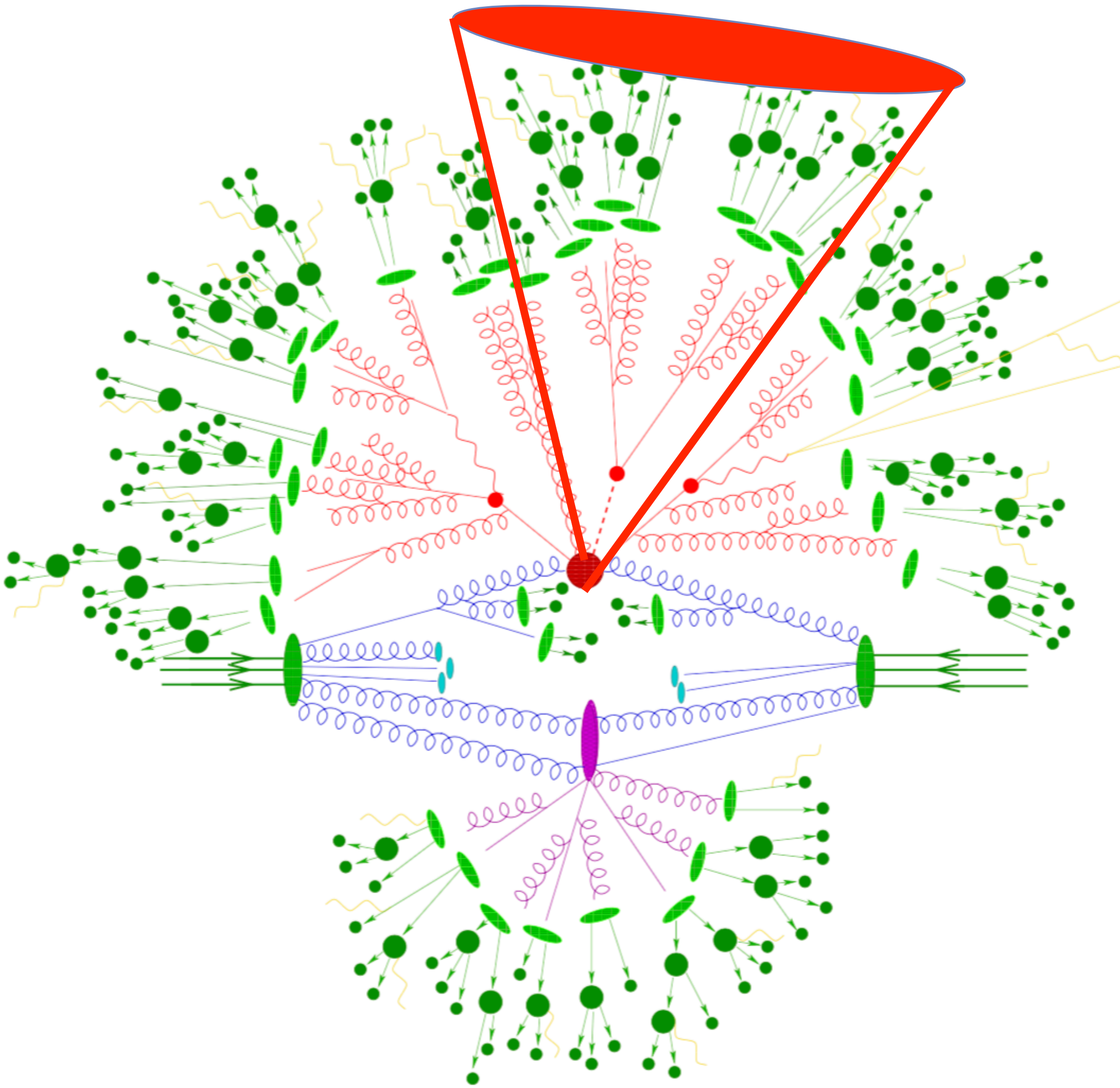
- **Jets: tools to organize the event**

Jets and jet algorithms (I)



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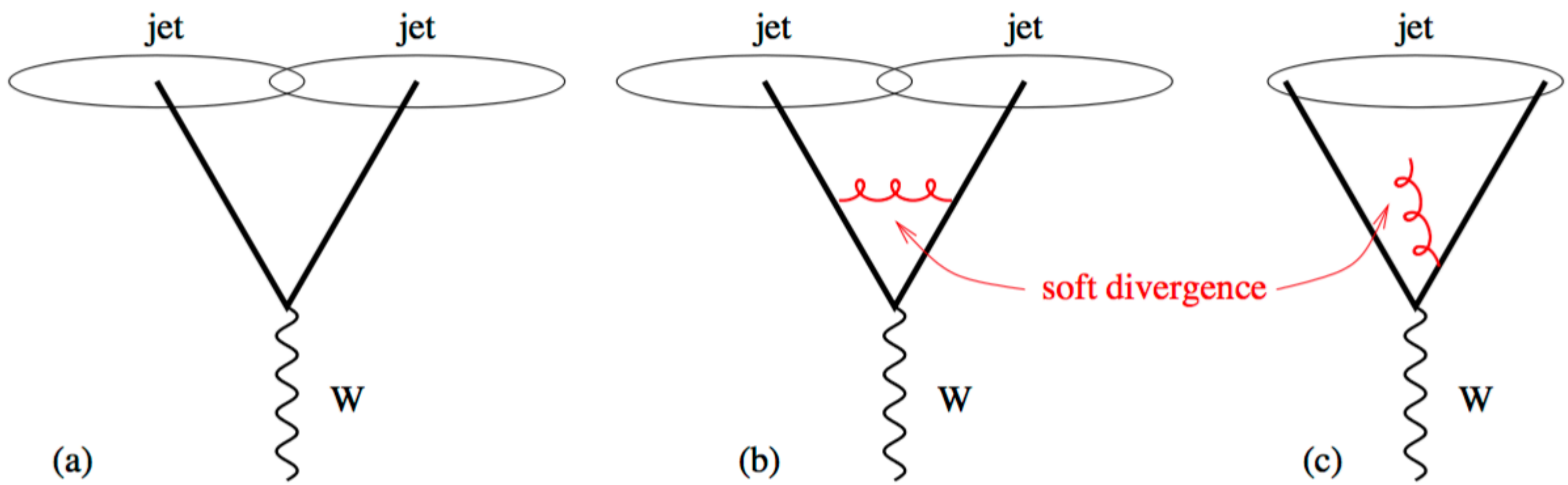
- **Jets: tools to organize the event**

Jets and jet algorithms (II)

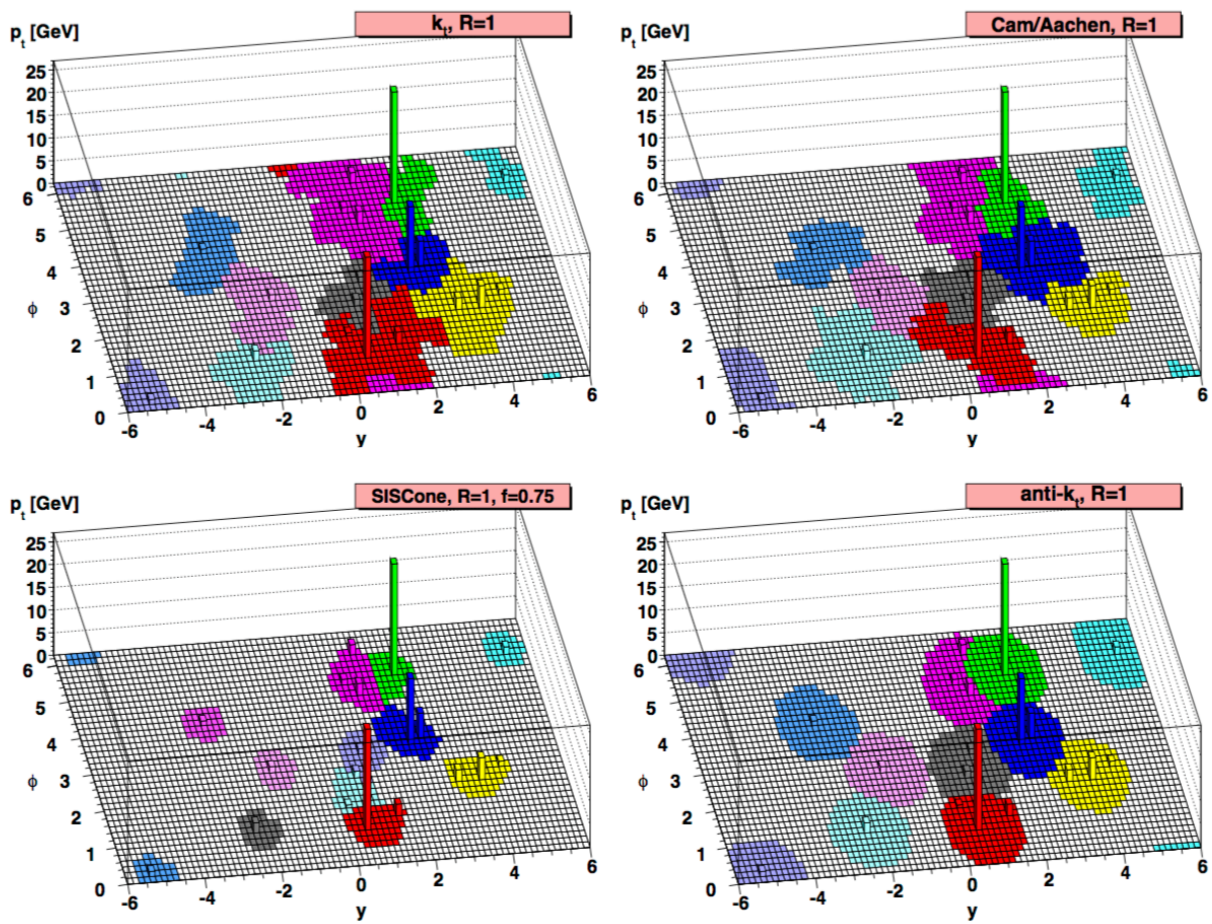
- Jet algorithms: set of rules to group particles together and to assign a momentum to the resulting jet
- Infrared and collinear safe



- LHC uses sequential recombination jet algorithms
  - K_t, C/A, **anti-k_t**

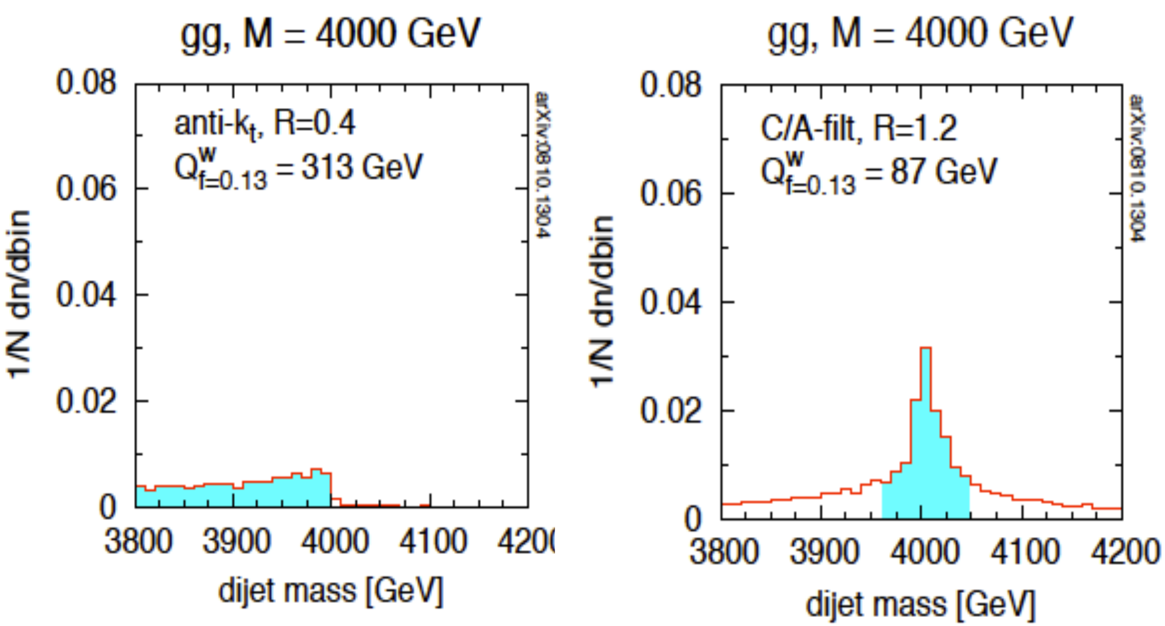
Jets and jet algorithms (III)

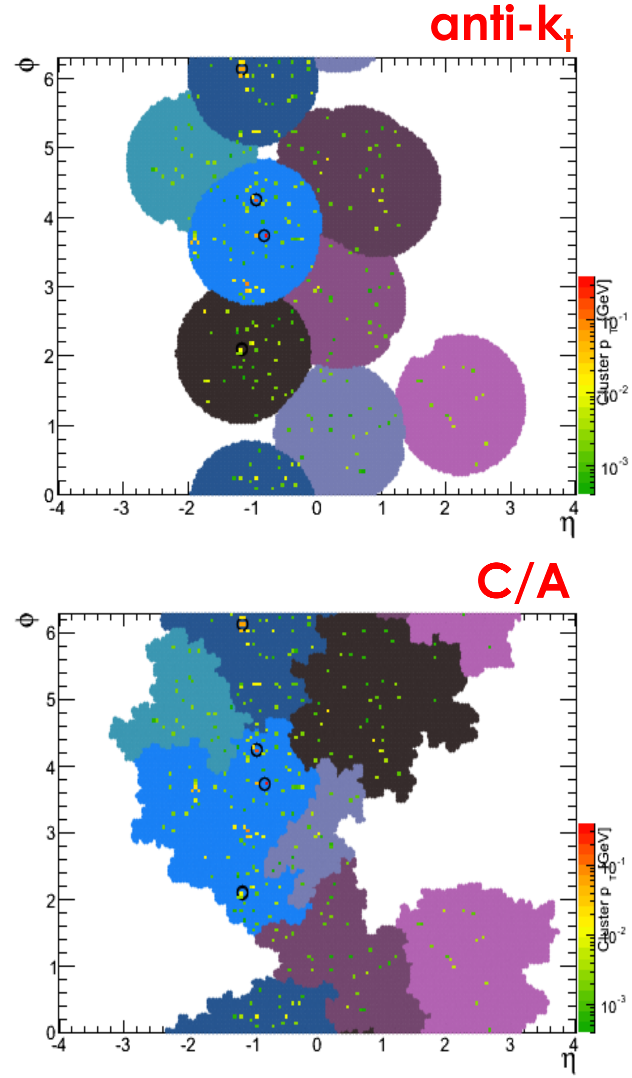
$$d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p}) \frac{\Delta R_{ij}^2}{R^2}, \quad d_{iB} = p_{ti}^{2p}$$



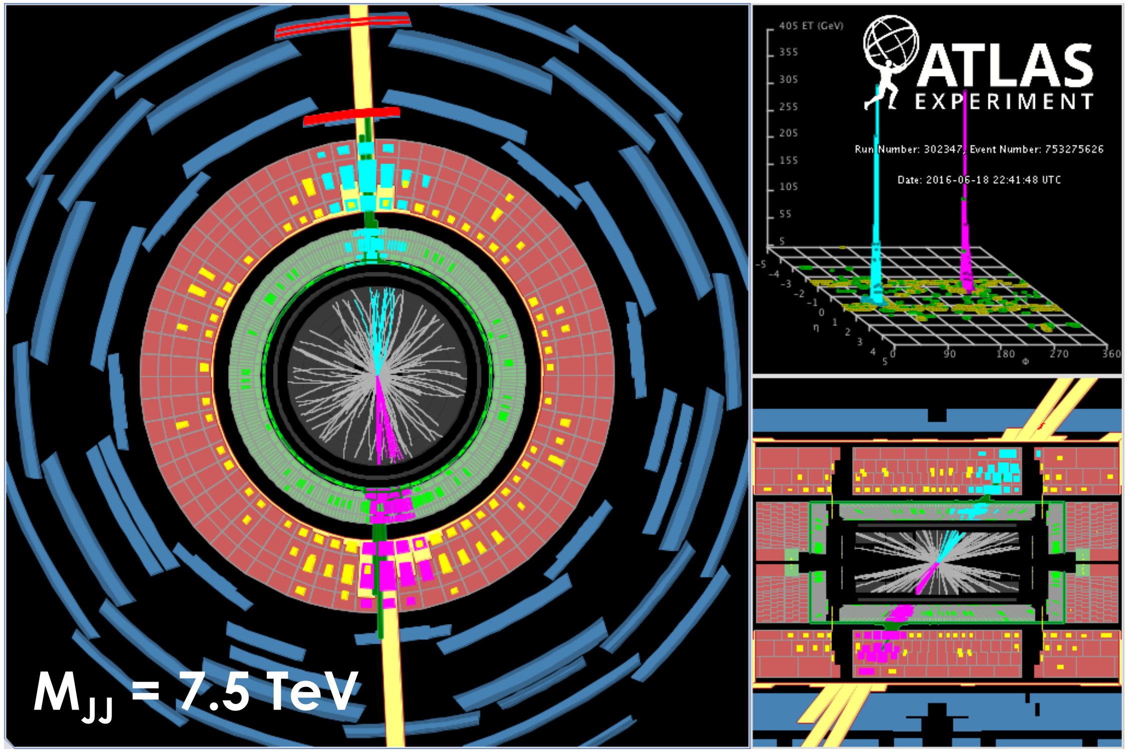
Jets and Missing ET

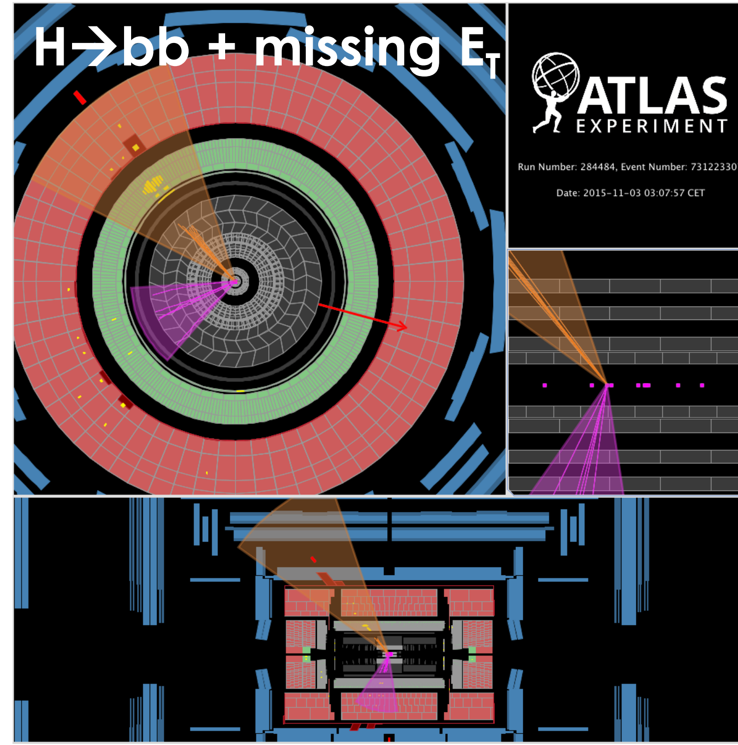
- **Jets are *tools* to organize and interpret events**
- **Multiple interpretation of events**

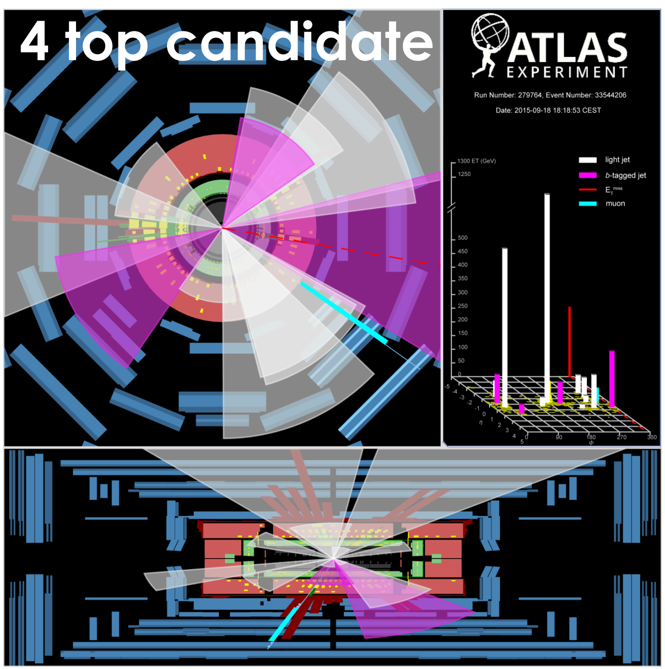


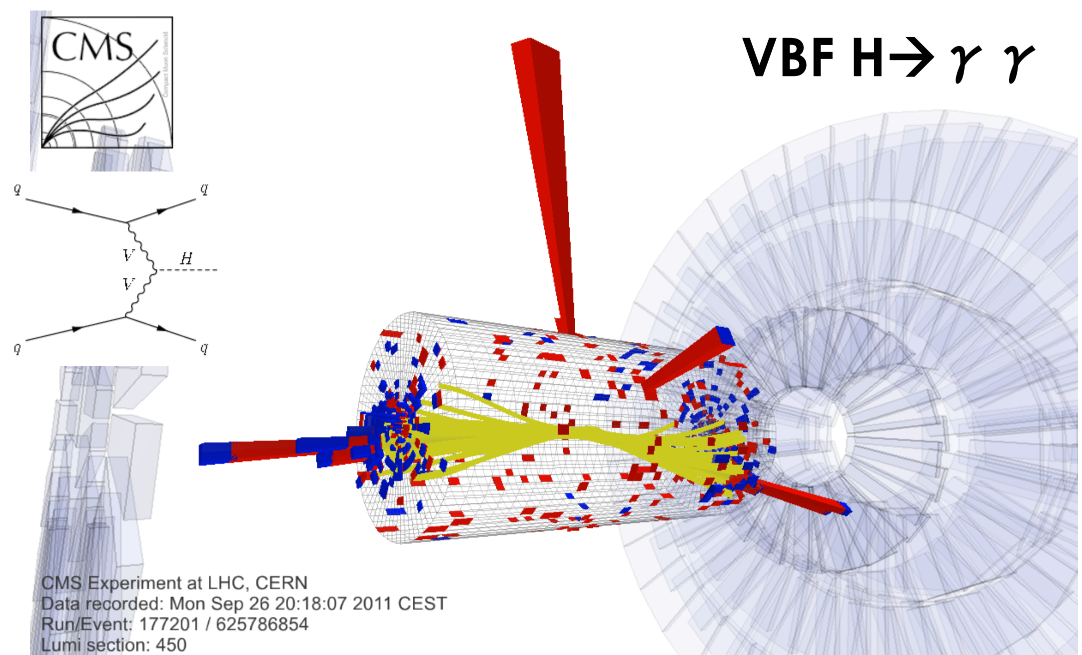


G. Salam


ATLAS
EXPERIMENT
Run Number: 302347, Event Number: 753275626
Date: 2016-06-18 22:41:48 UTC
M_{JJ} = 7.5 TeV

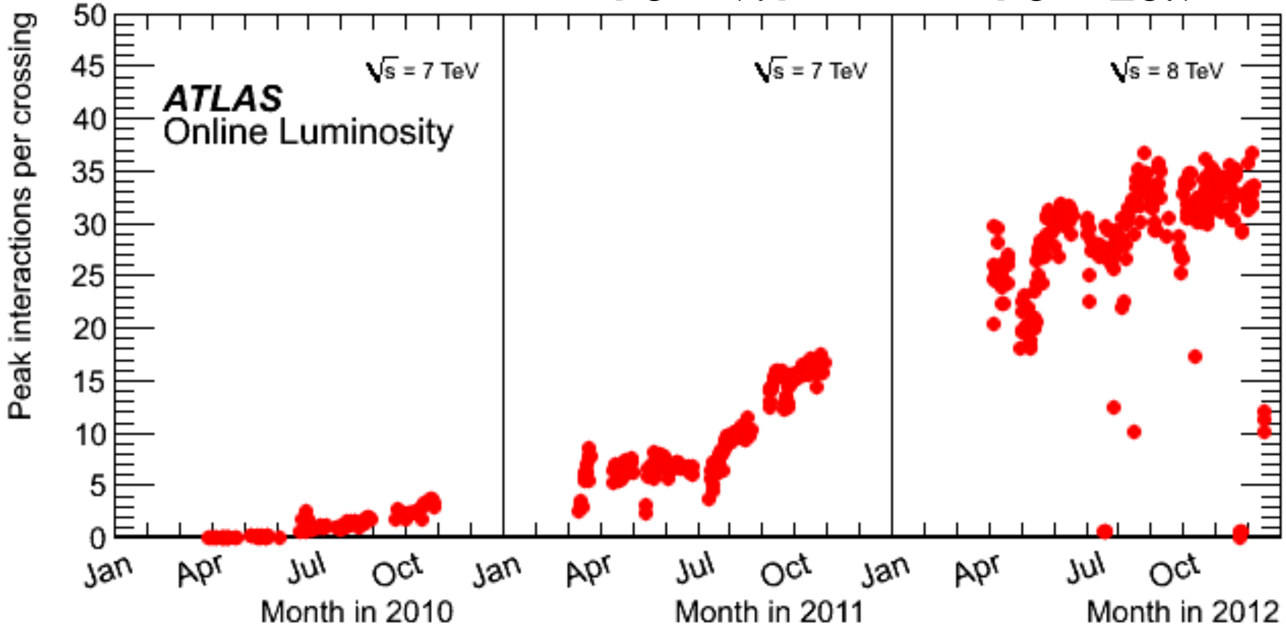

H→bb + missing E_T
ATLAS
EXPERIMENT
Run Number: 284484, Event Number: 731223307
Date: 2015-11-03 03:07:57 CET


4 top candidate
ATLAS
EXPERIMENT
Run Number: 279764, Event Number: 33544206
Date: 2015-09-18 18:18:53 CEST
light jet
b-tagged jet
muon

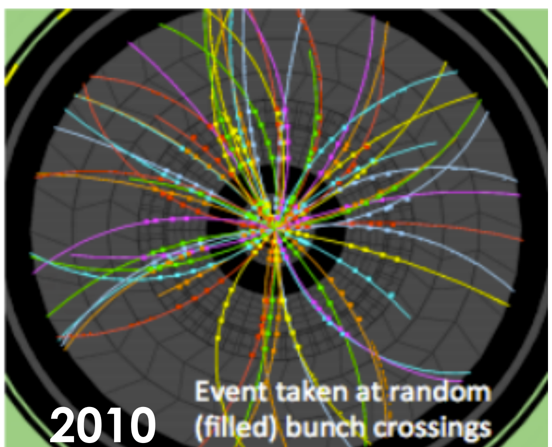

VBF H→γγ
CMS
q
q
V
H
V
q
q
CMS Experiment at LHC, CERN
Data recorded: Mon Sep 26 20:18:07 2011 CEST
Run/Event: 177201 / 625786854
Lumi section: 450

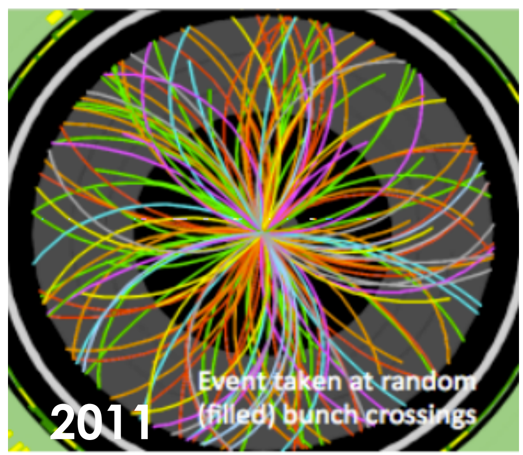
Pile-up in Run 1

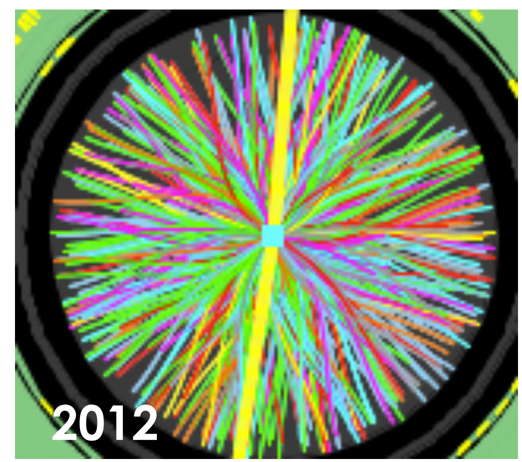
<PU>=9.1 <PU>=20.7



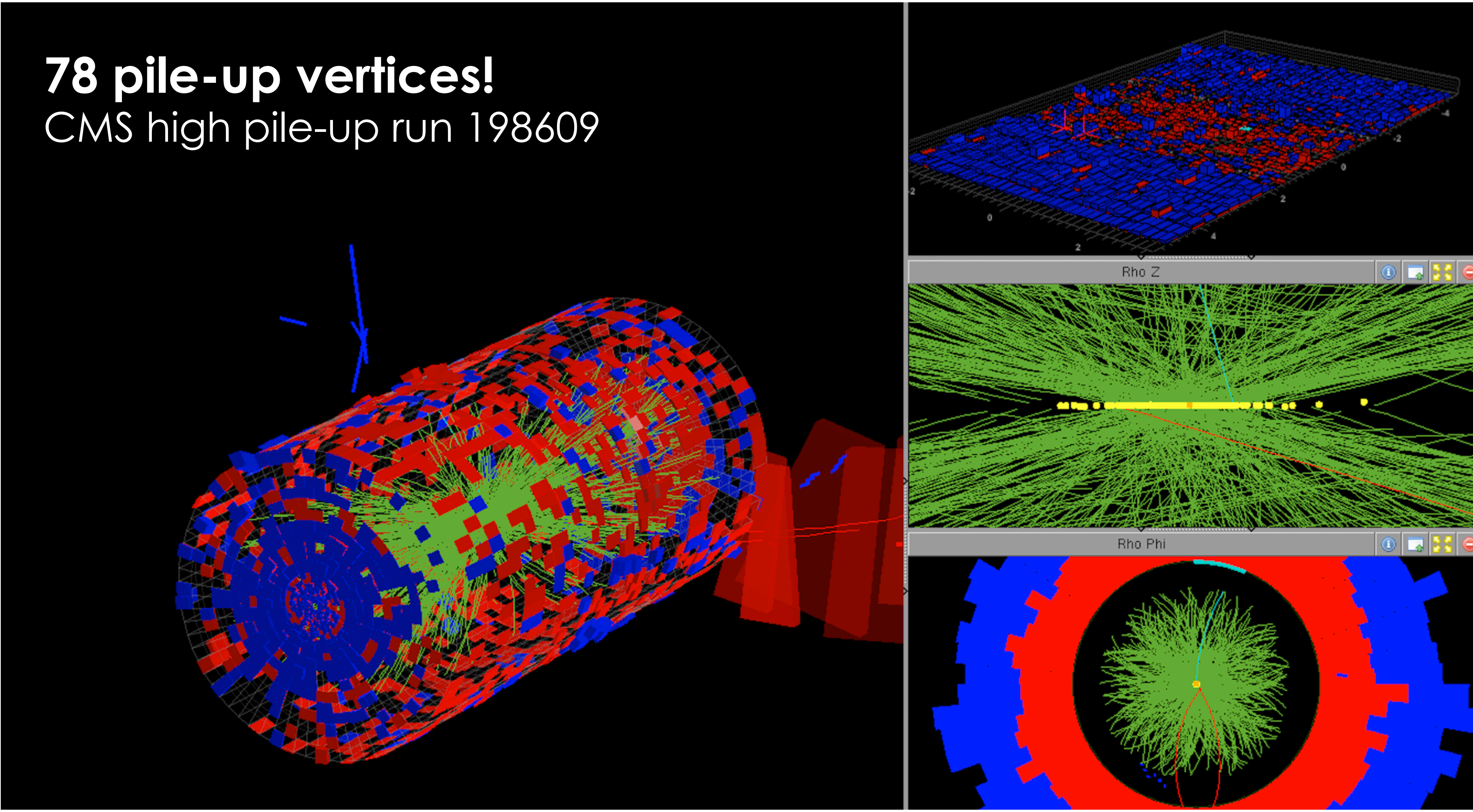
HL-LHC
<PU>~200!



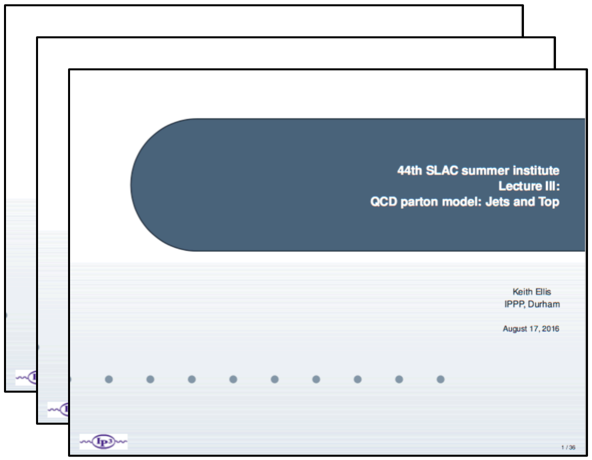


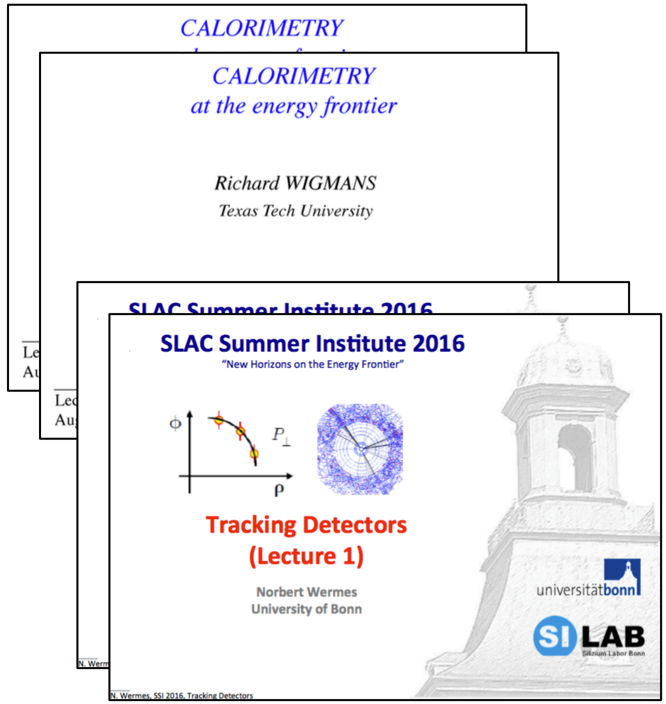


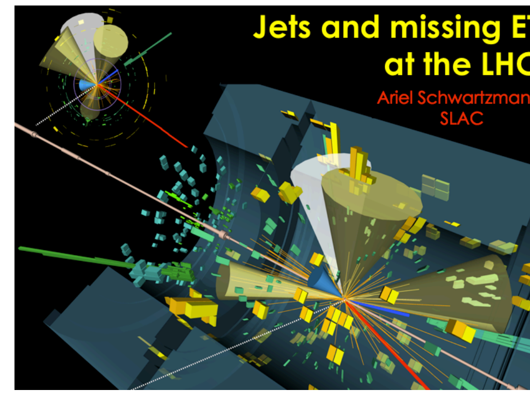
High pile-up

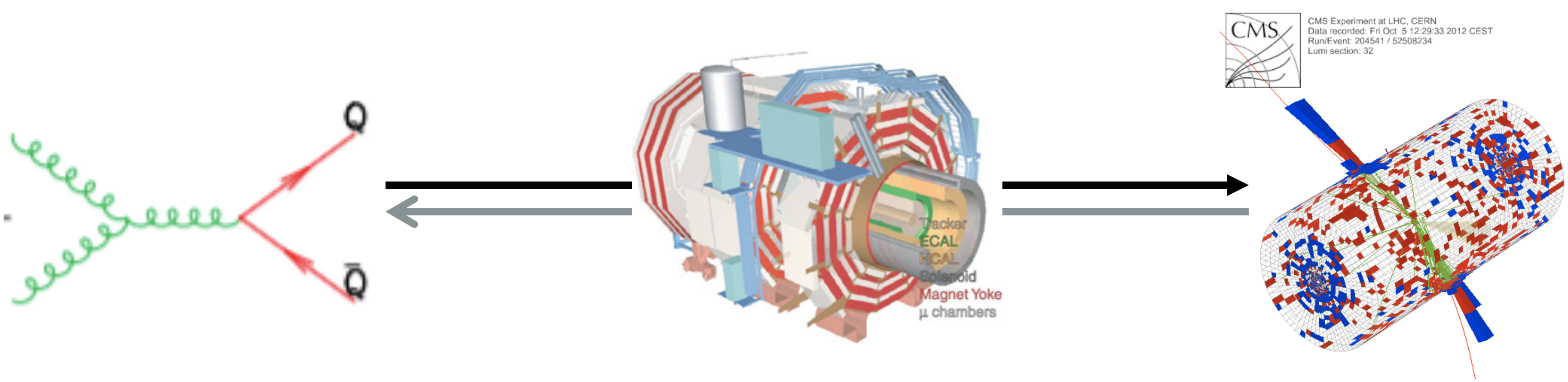


Goal of this talk

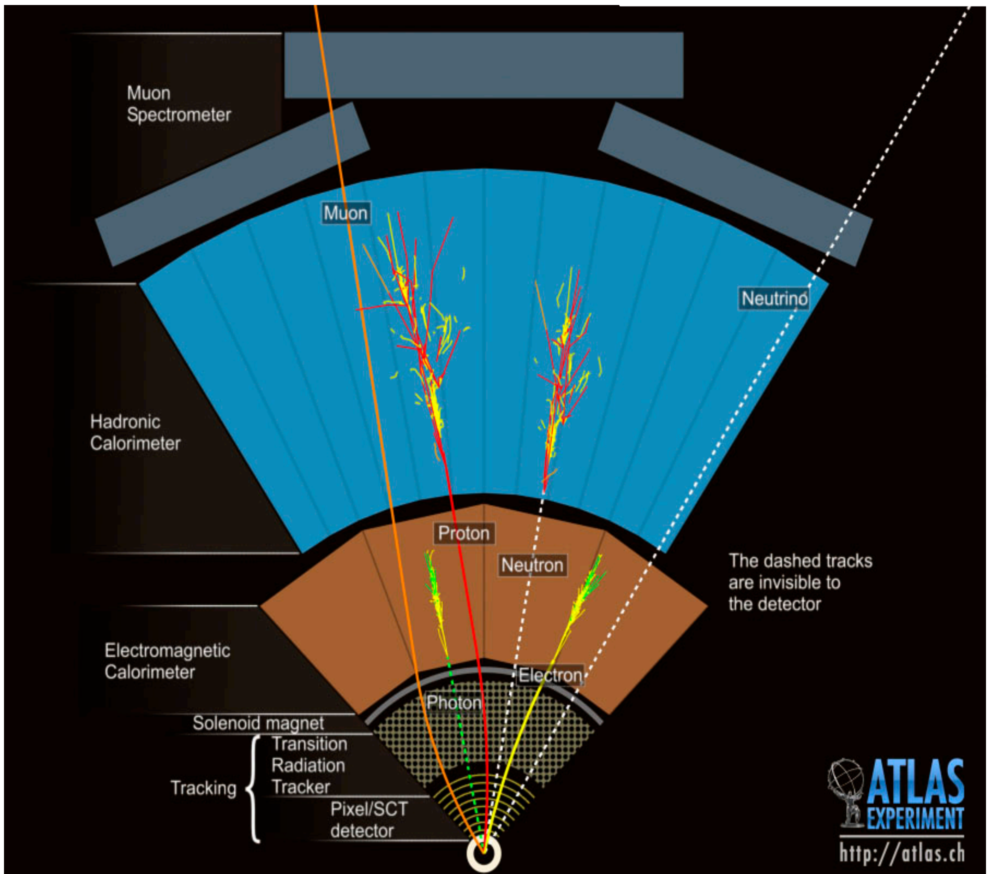


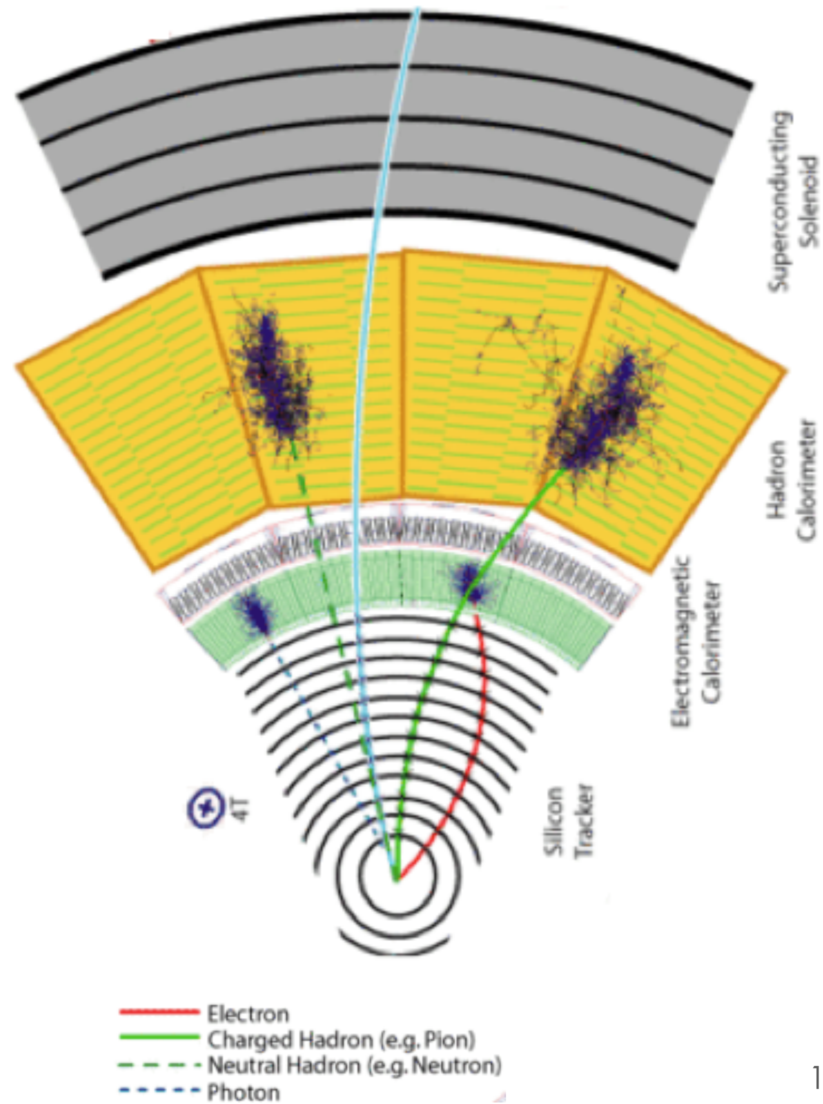






ATLAS and CMS Detectors





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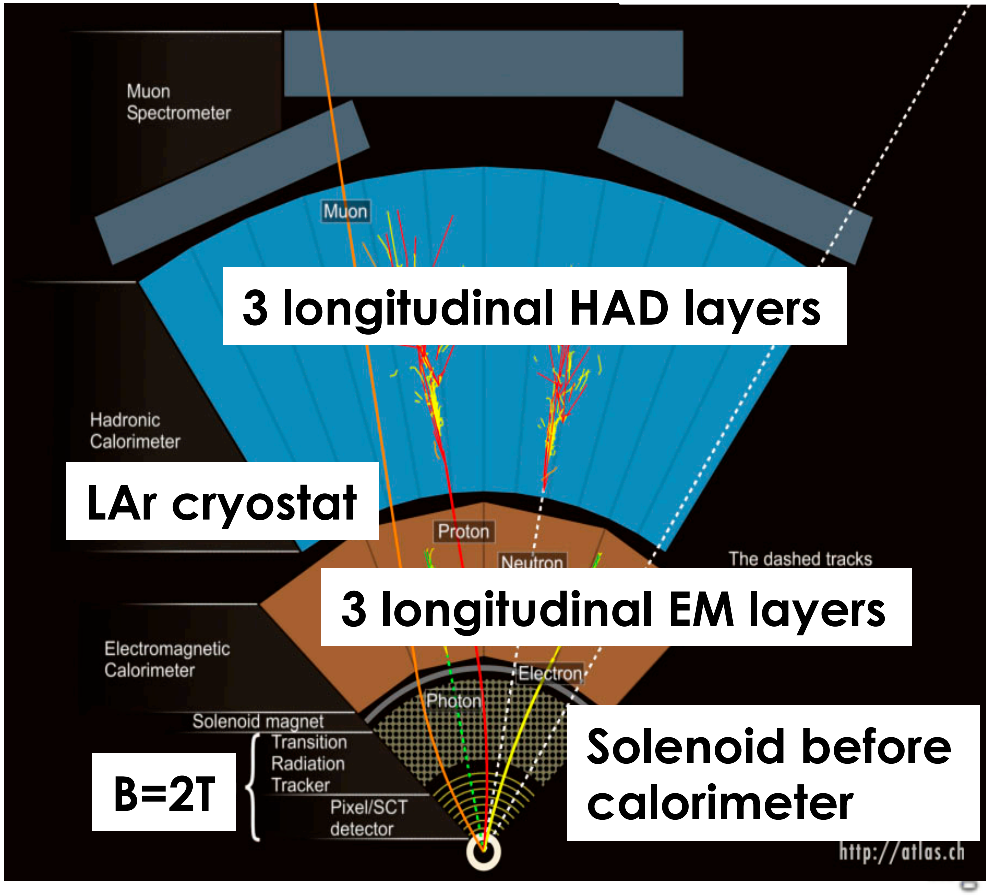

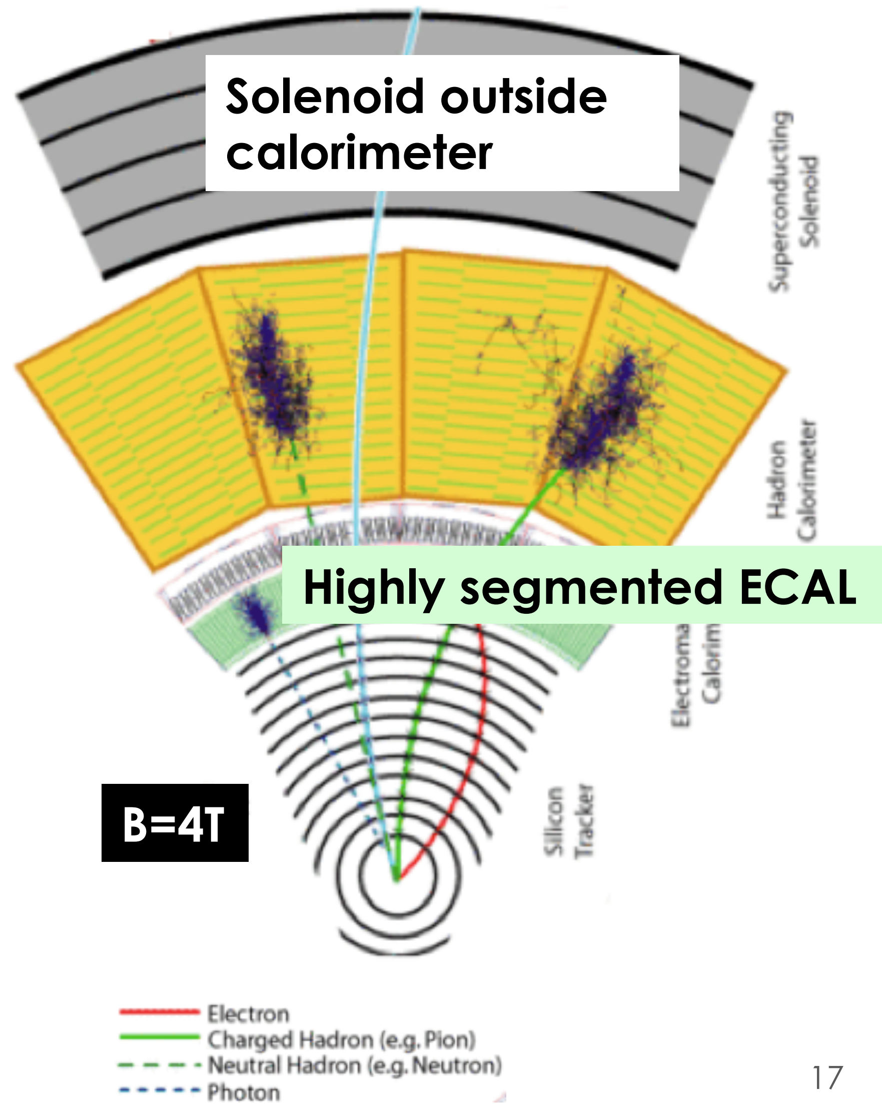

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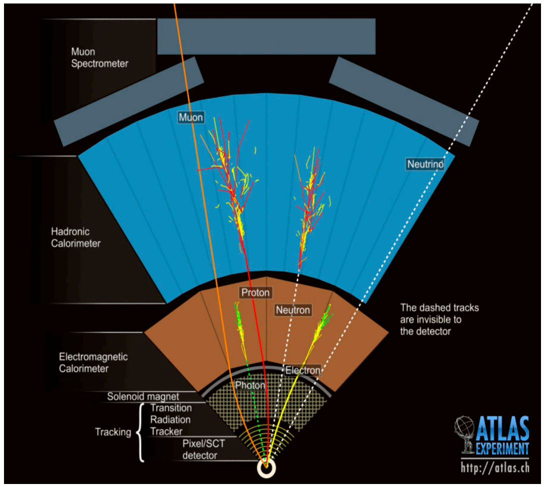
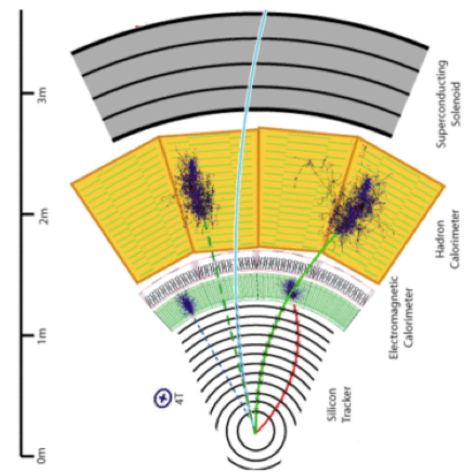




Excellent hadron energy resolution
Longitudinal EM/HAD segmentation
Fine transverse segmentation

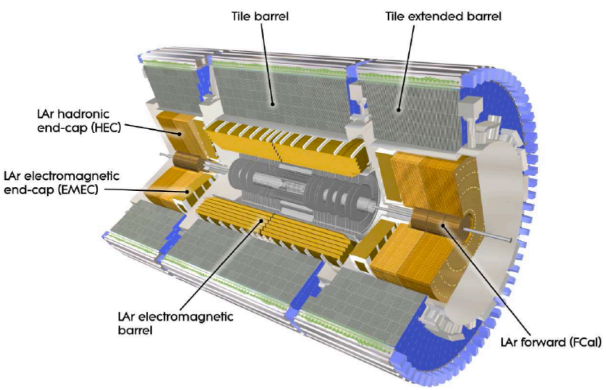
Can use shower shape information and 3-dimensional clustering to identify and calibrate EM/HAD energy depositions → **More handles for calorimeter-based jet reconstruction and calibration**

High magnetic field
Very fine transverse EM granularity

Low p_T tracking
Good separation between photons and pion showers

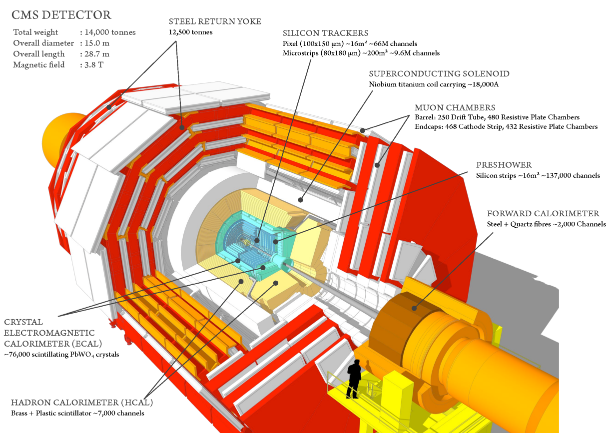
Low p_T charged particles do not reach the calorimeter → **need to integrate tracking with calorimeter information**

Jet reconstruction overview



Calorimeter Topo-clusters → jets → Track corrections

ATLAS



Calorimeter clusters + tracks → Particle flow objects → jets

CMS

Jet reconstruction at ATLAS

- **Topological clustering**
  - Three-dimensional clustering algorithm at the level of individual calorimeter cells

Noise suppression

limit the formation and grow of clusters from electronic and pileup noise

Local calibration

EM/HAD classification and calibration

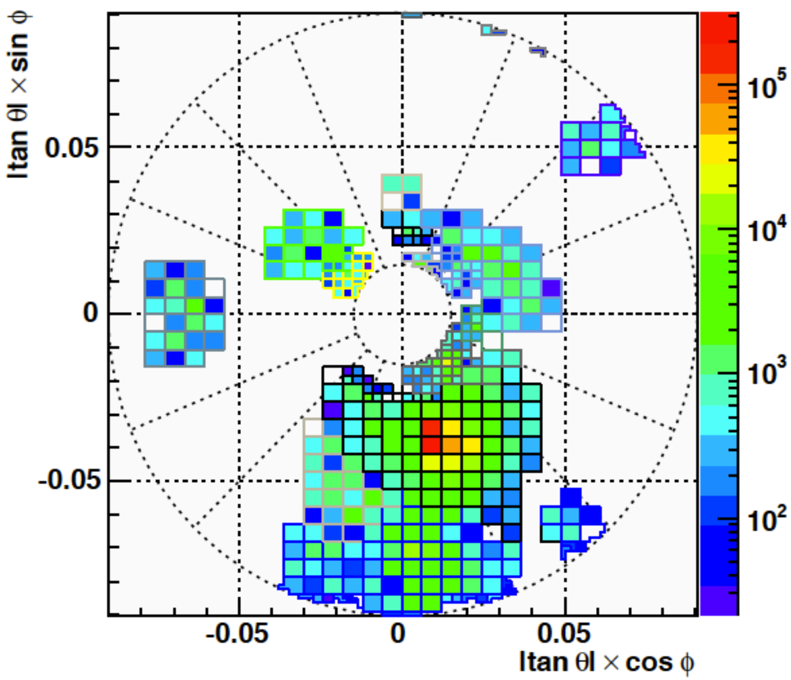
Reduce pile-up contributions before jet finding

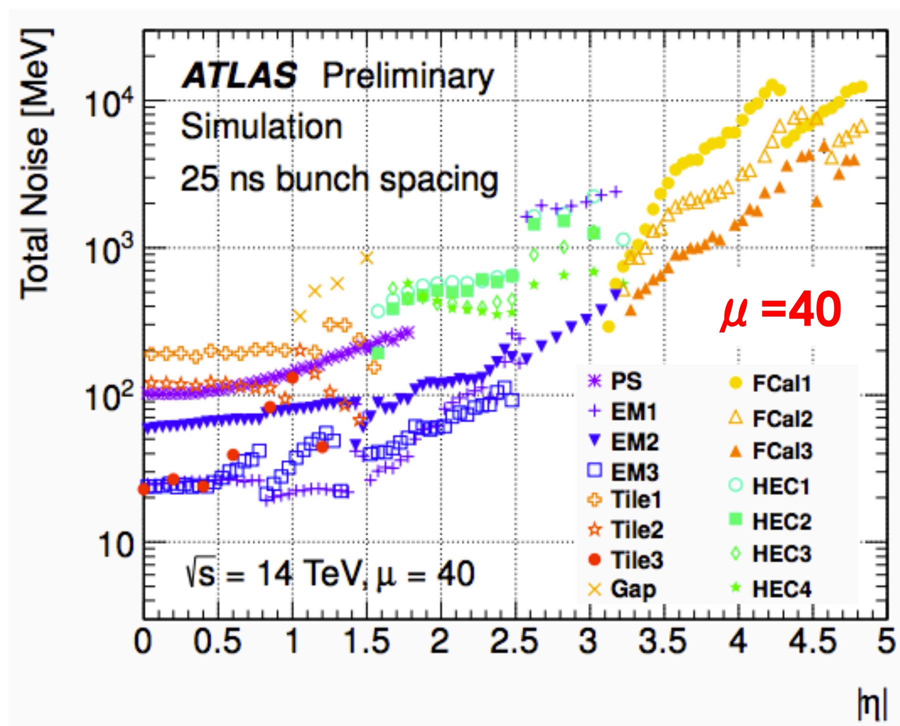
Improves the linearity of the jet energy response and the energy resolution

Jet reconstruction at ATLAS

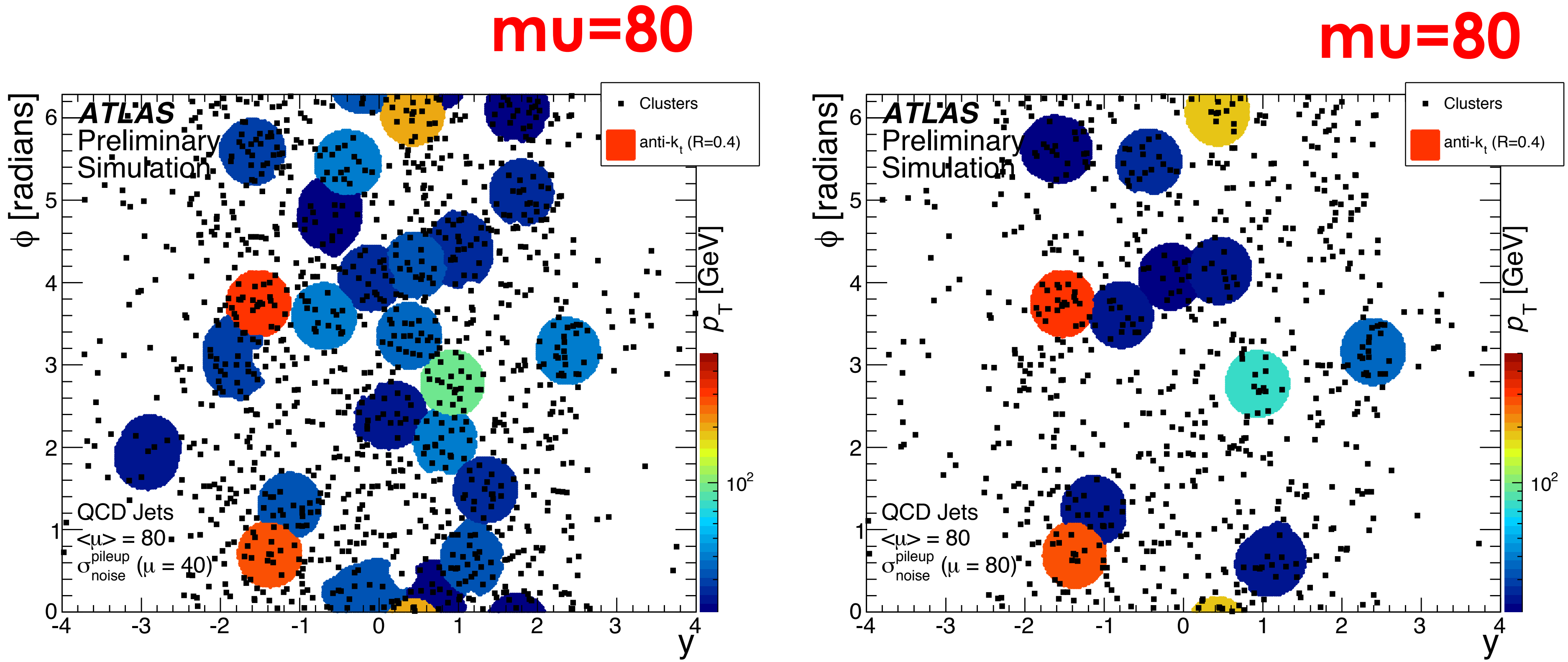
- **Topological clusters:**
  - 3D nearest-neighbor algorithm that clusters calorimeter cells with energy significance ($|E_{cell}| / \sigma$) >**4** for the seed, >**2** for neighbors, and >**0** at the boundary
- **Sigma noise (σ)**: electronic + pileup noise
  - Adjusted with μ for **pileup noise suppression**

2010: $\sigma(\mu=0)$
2011: $\sigma(\mu=8)$
2012: $\sigma(\mu=30)$





Topoclustering pile-up suppression



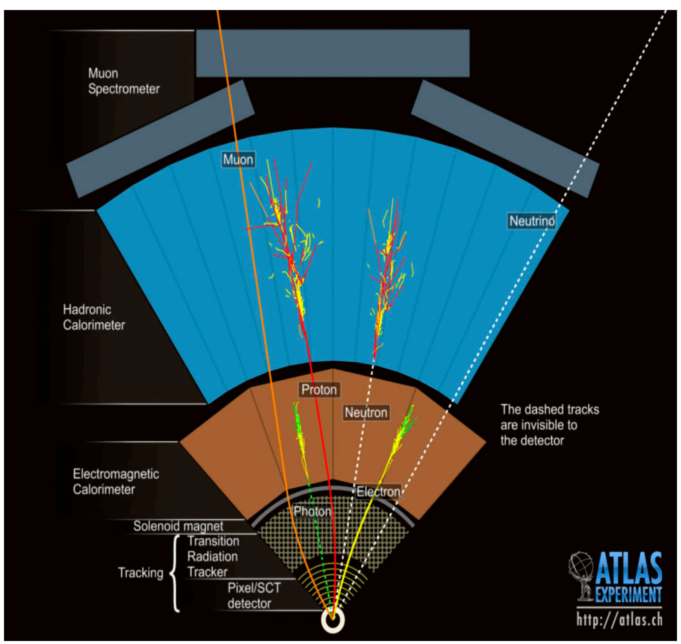
$\sigma_{noise}^{pileup}(\mu = 40)$ → $\sigma_{noise}^{pileup}(\mu = 80)$

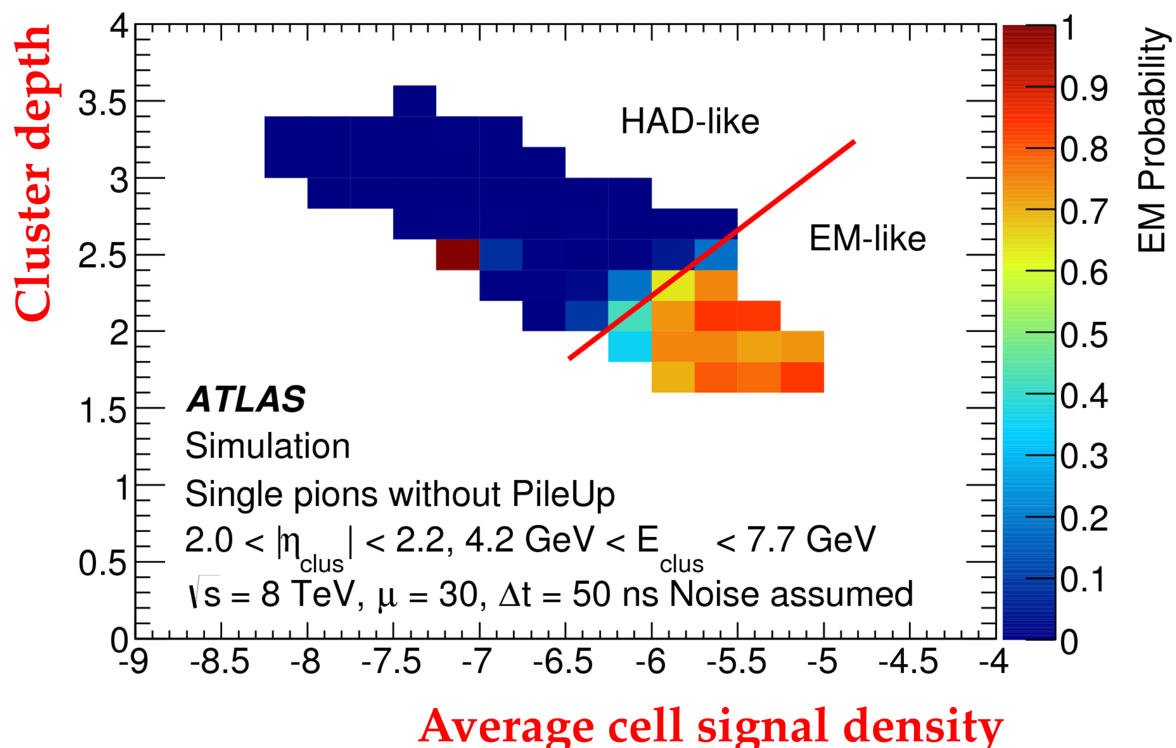
Sigma noise provides particle (cluster) level pile-up suppression

Local cluster calibration

Topo-cluster Formation → **Cluster Classification** → **Calibration** → **Out-of-cluster Corrections** → **Dead Material Corrections**

Use local cluster shape information to classify and calibrate EM/HAD clusters. Calibrations derived using single pion Monte Carlo

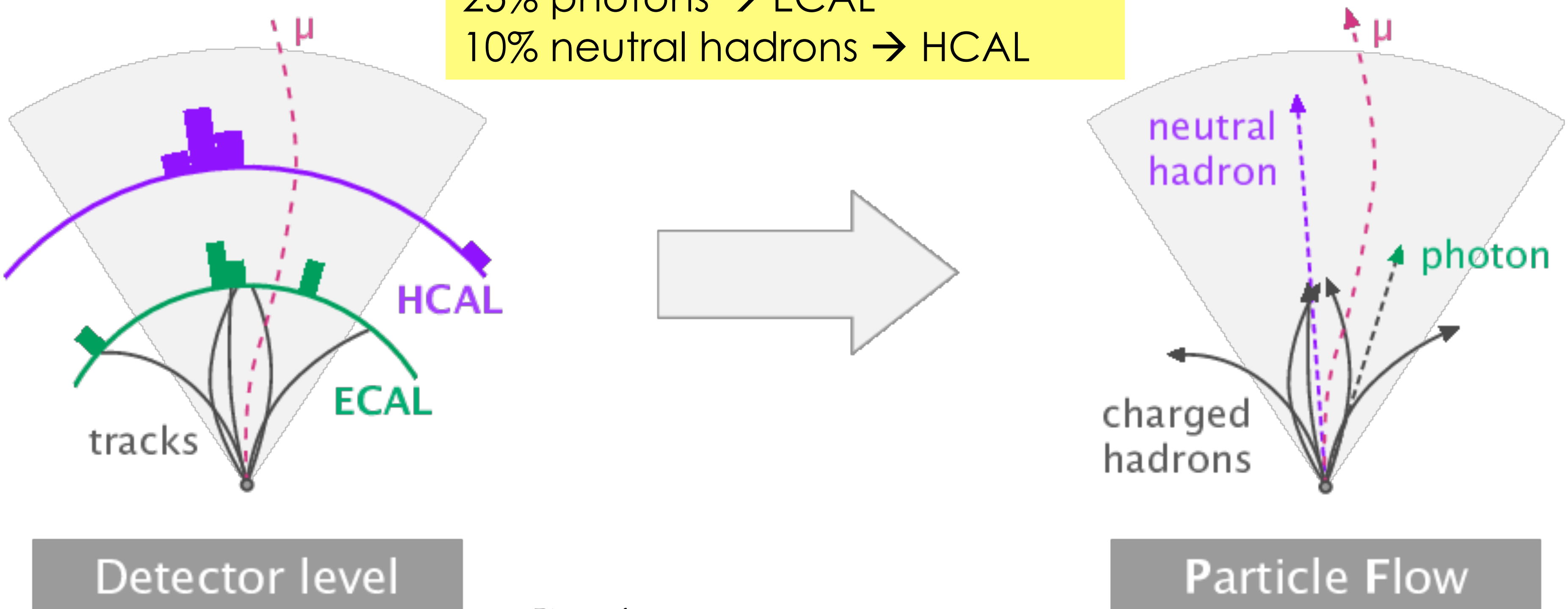




CMS Particle Flow

- **Reconstruct individually each particle combining tracking and calorimeter information:**
  - Relies on high granularity and resolution of ECAL and **high magnetic field** to <u>separate individual showers</u>

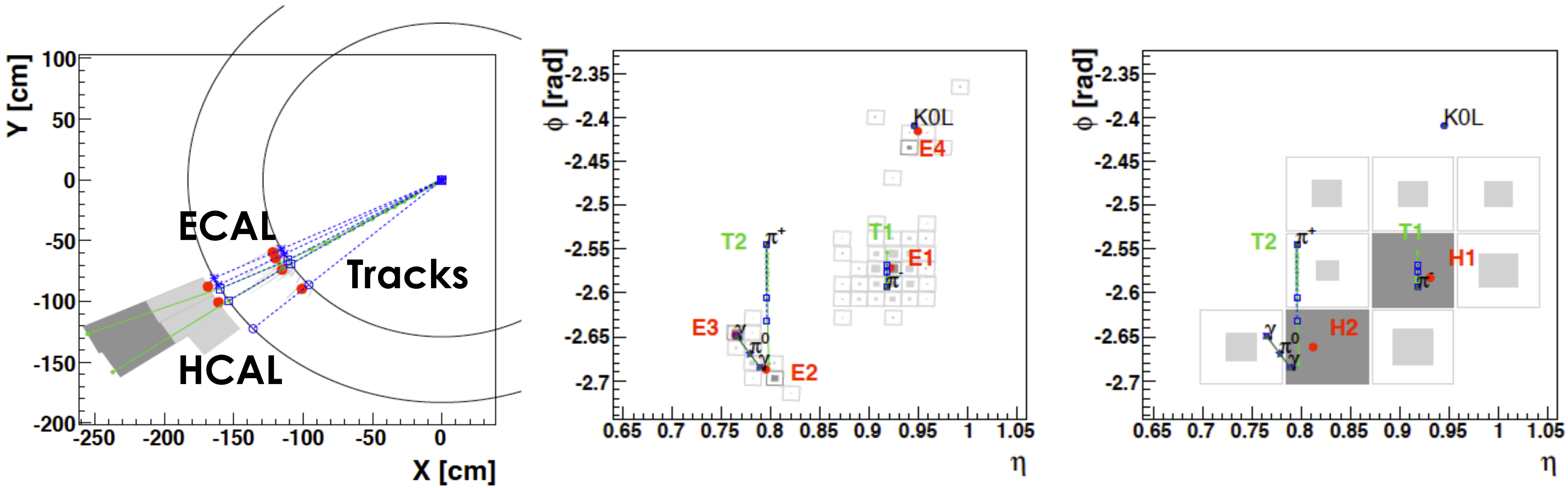
65% charged hadrons → Tracker
25% photons → ECAL
10% neutral hadrons → HCAL



Picture from http://bartosik.pp.ua/hep_sketches/cms_particle_flow

Particle Flow

CMS PAS PFT-09-001

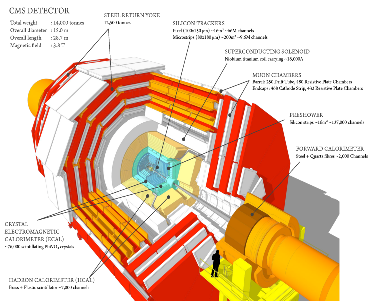


65% charged hadrons → Tracker
25% photons → ECAL
10% neutral hadrons → HCAL

Average (large fluctuations)

- **Performance limited by confusion:** ability to separate individual particle showers)
  - Need High granularity, B field

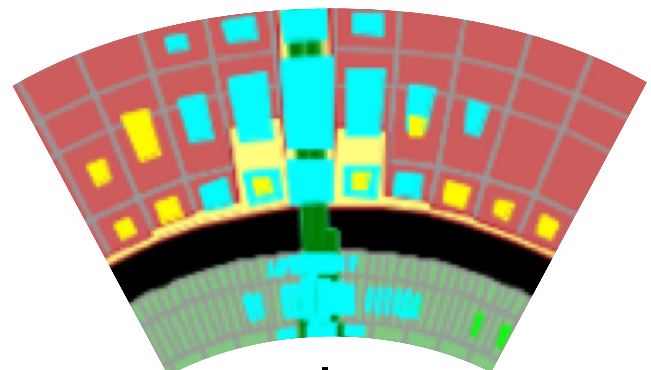
Jet calibration overview



Input signals: Topo-clusters, PFlow objects → **jets** → **Calibration**

Jet energy response:

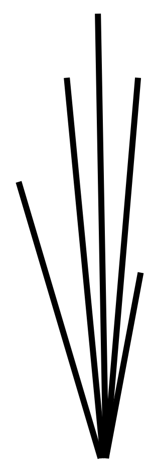
$$R(E,\eta) = \left\langle \frac{E^{reco}}{E^{truth}} \right\rangle$$



Reconstructed jet

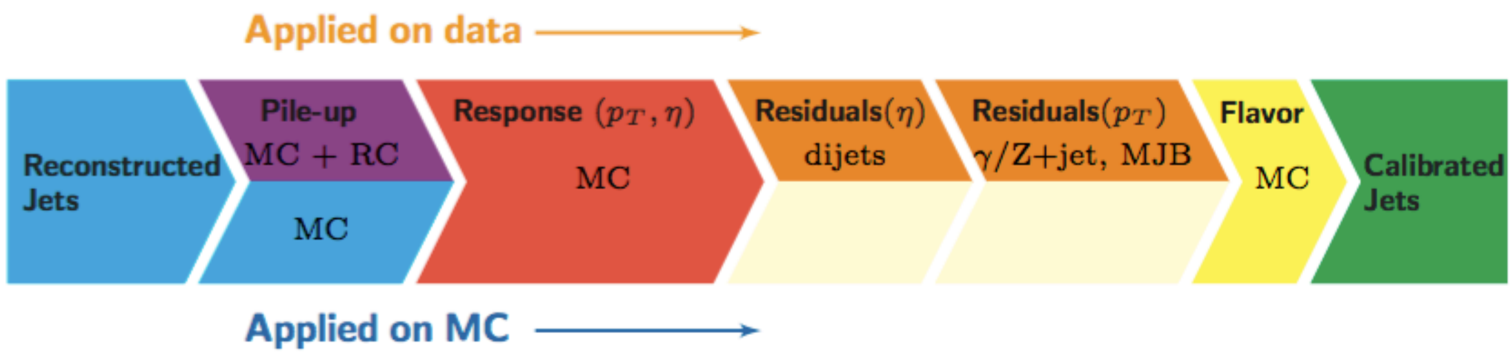
Calibration ↓

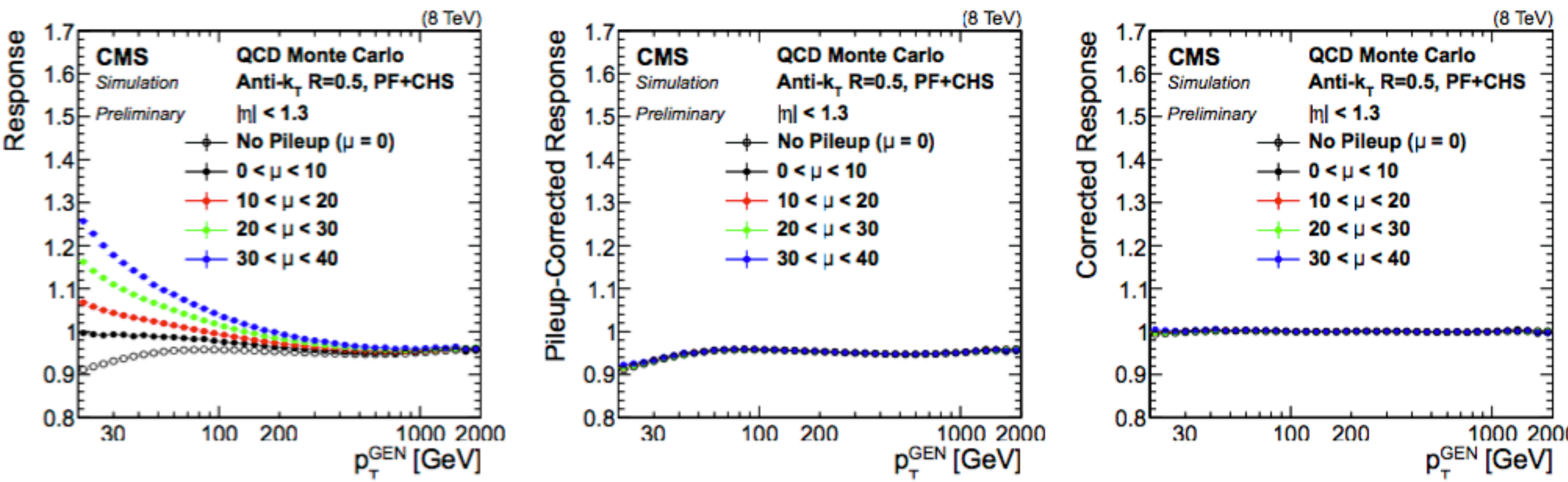
Particle (truth) jet



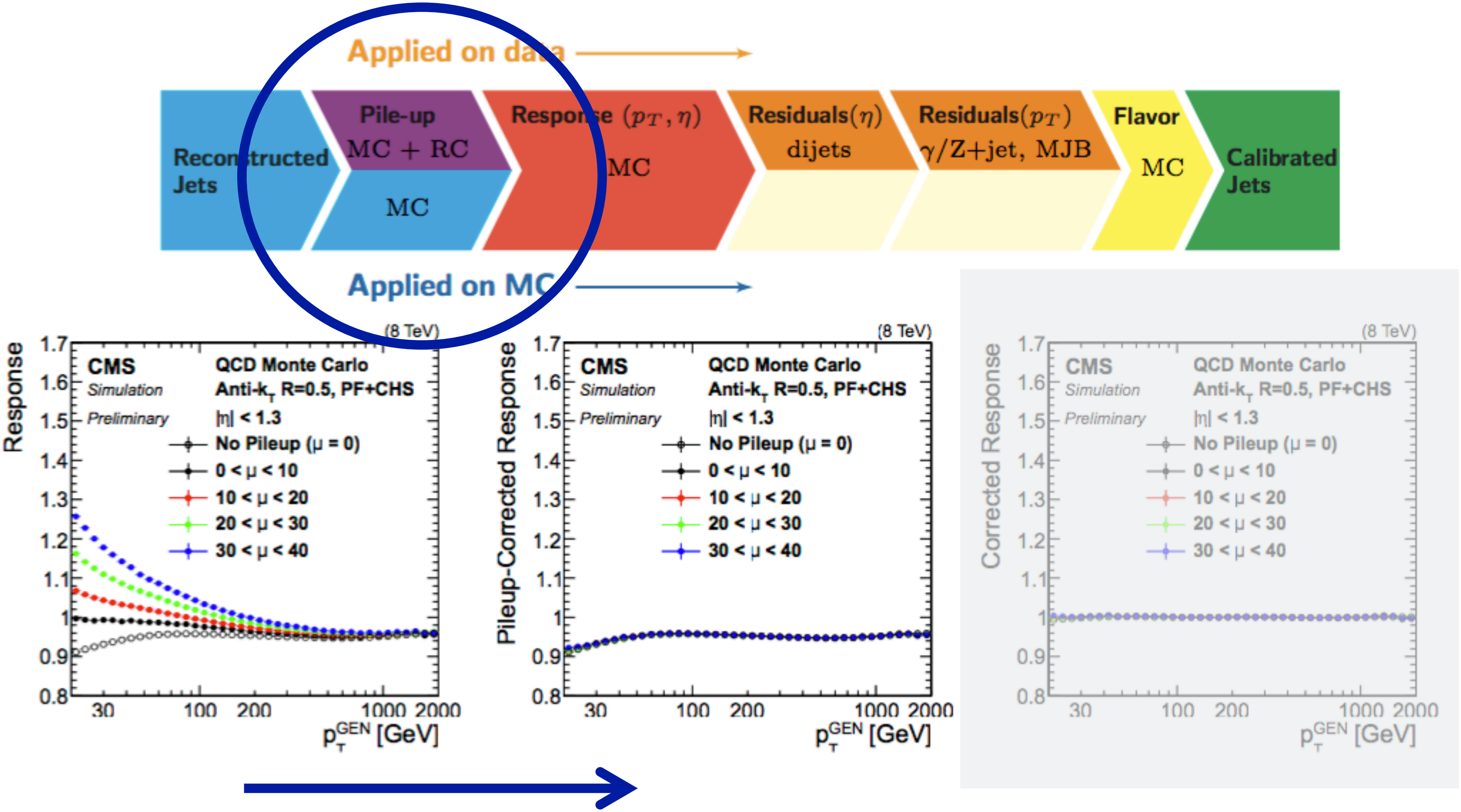
- Calorimeter non-compensation
- Inactive regions of the detector
- Energy deposits below thresholds
- Particles not included in the jets
- Pile-up
- *Data / Monte Carlo scale*

Jet calibration overview



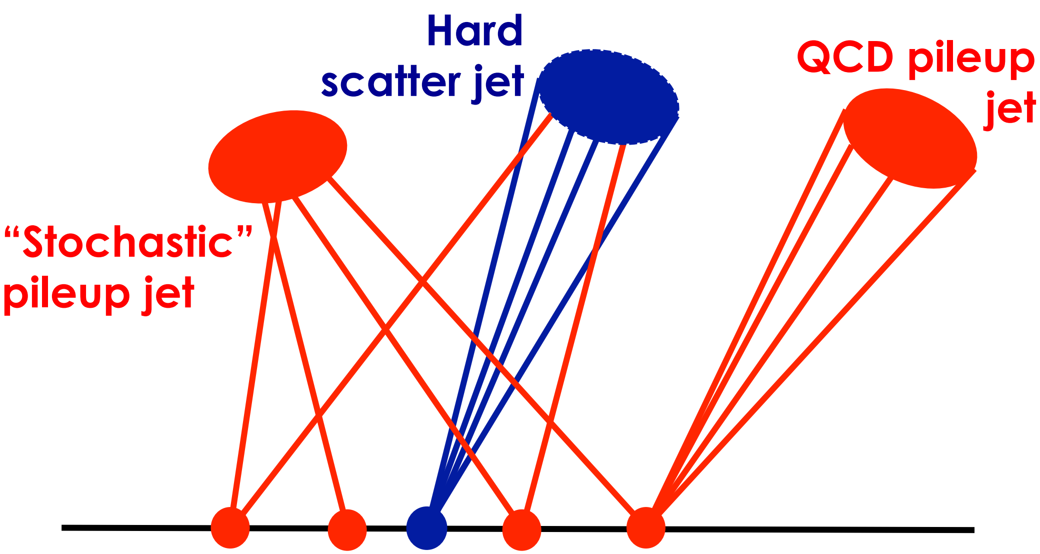


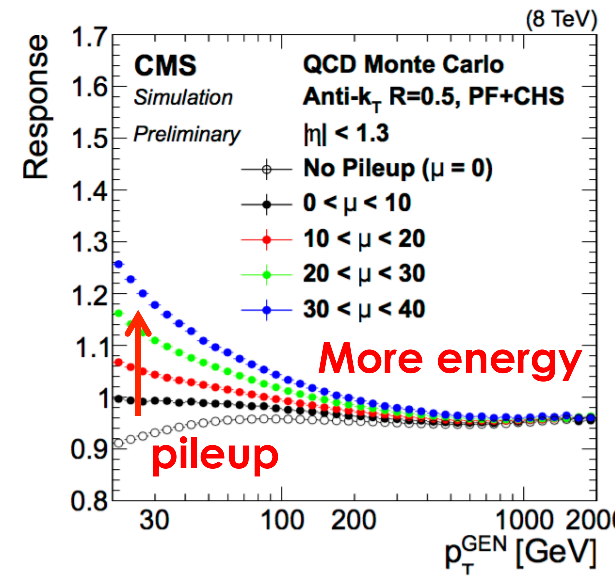
Jet calibration overview



The challenge of pile-up

One the most difficult challenges at the LHC

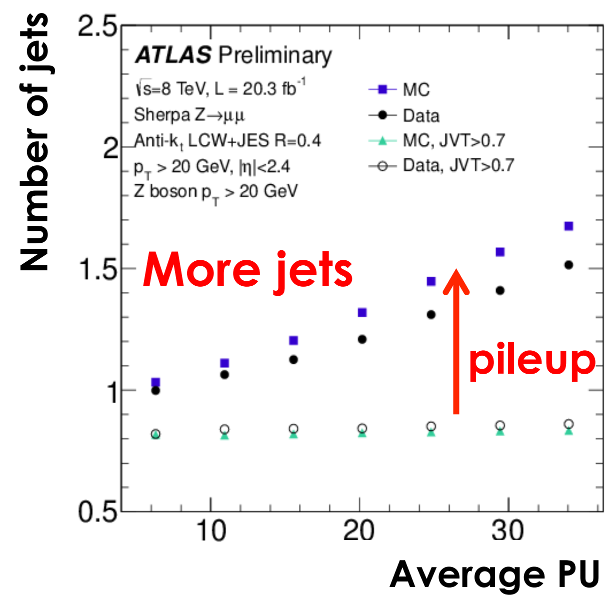




Additional energy (offset)

Fluctuations:

- Reduce accuracy of the jet energy and mass determination
- Additional fake pileup jets



Pileup mitigation: four key ideas

Constituent level pile-up suppression

Topo-clustering(ATLAS
Charged Hadron Subtraction
and PUPPI (CMS)

Area-Median Subtraction

$$p_T^{jet,corr} = p_T^{jet} - \rho \times A_T^{jet}$$

Jet-Vertex Tagging

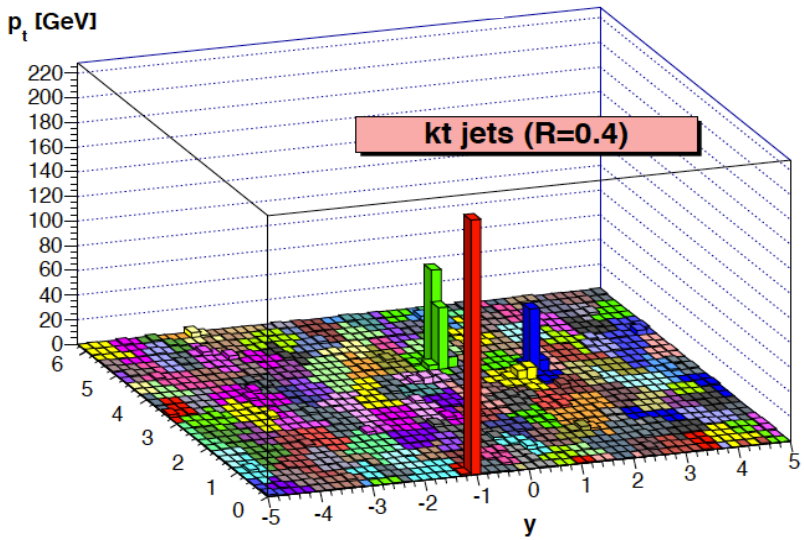
Use of tracking information to
reject jets from pileup

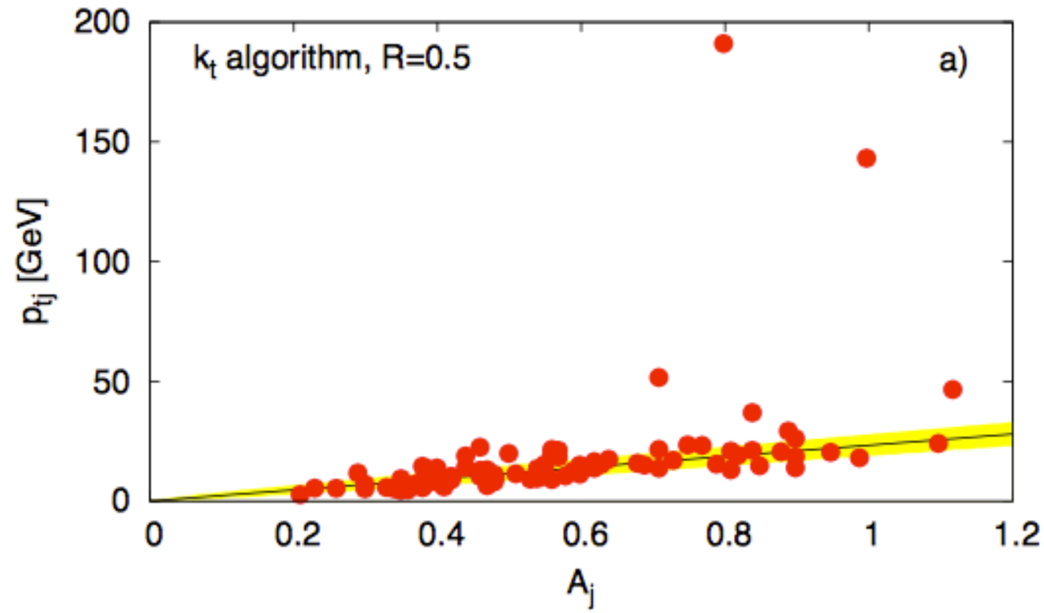
Grooming

Reduce local
fluctuations of pileup
(Large-R jets)

Pileup subtraction (I)

arXiv:0707.1378 [hep-ph]



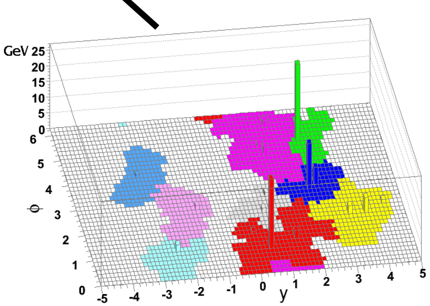


$$p_T^{jet,corr} = p_T^{jet} - \rho \times A_T^{jet}$$

Event-by-event estimate of diffuse noise

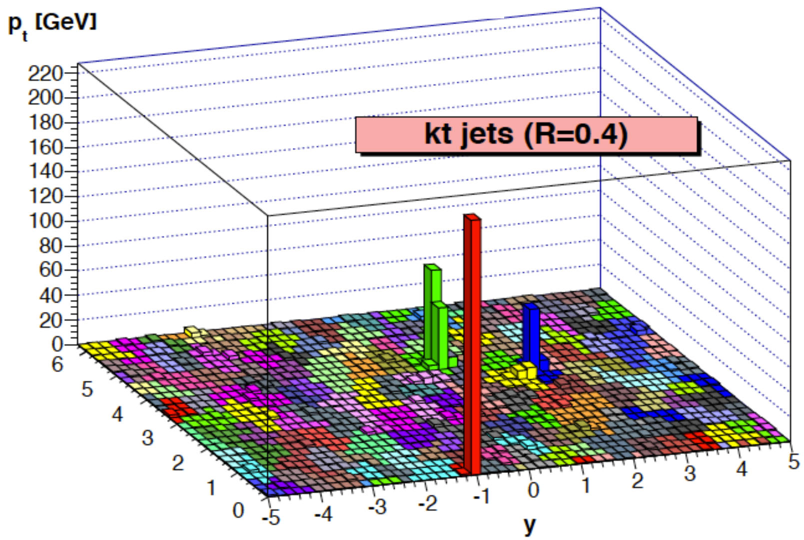
$$\rho = median\left[\left\{\frac{p_{Tj}}{A_j}\right\}\right]$$

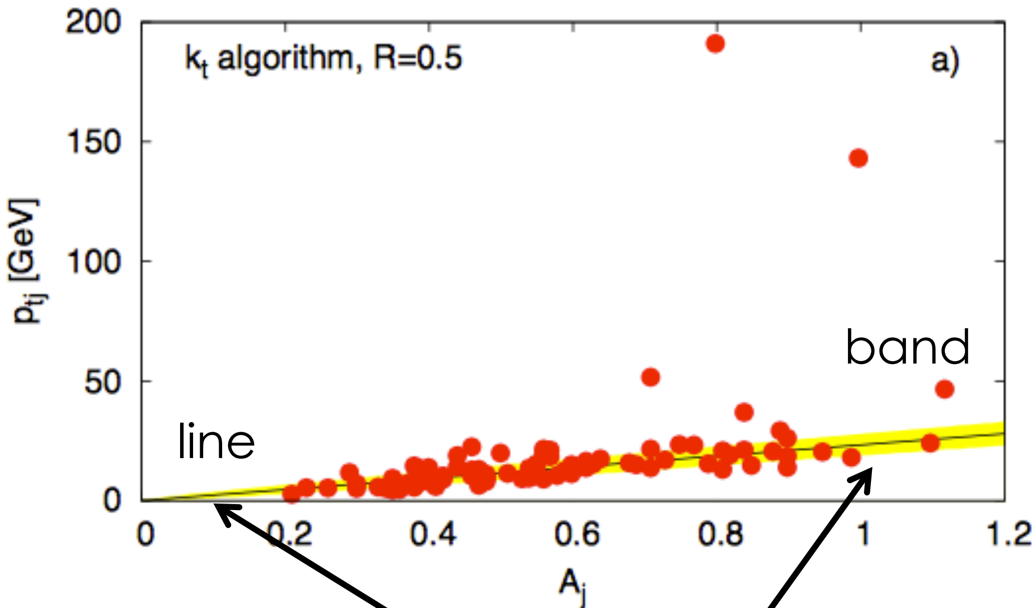
Jet Area: susceptibility to diffuse noise contamination



Pileup subtraction (II)

arXiv:0707.1378 [hep-ph]





$$\Delta p_T = \rho A \pm \sigma_\rho \sqrt{A}$$

Geometrical contamination

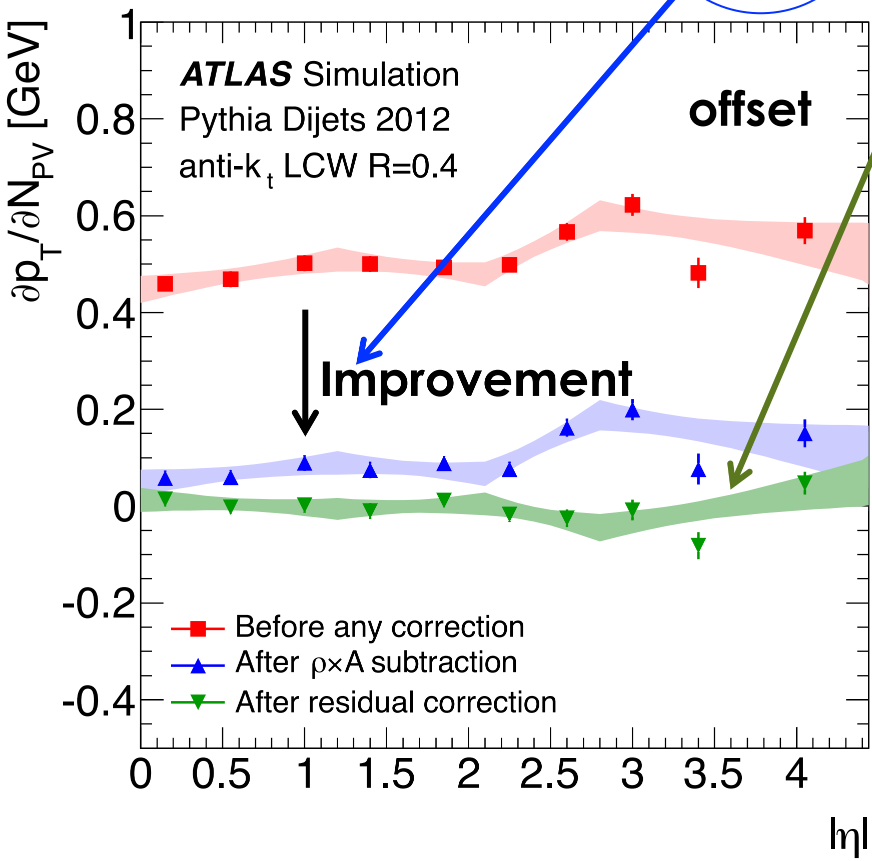
Fluctuations in the noise from point to point in the event

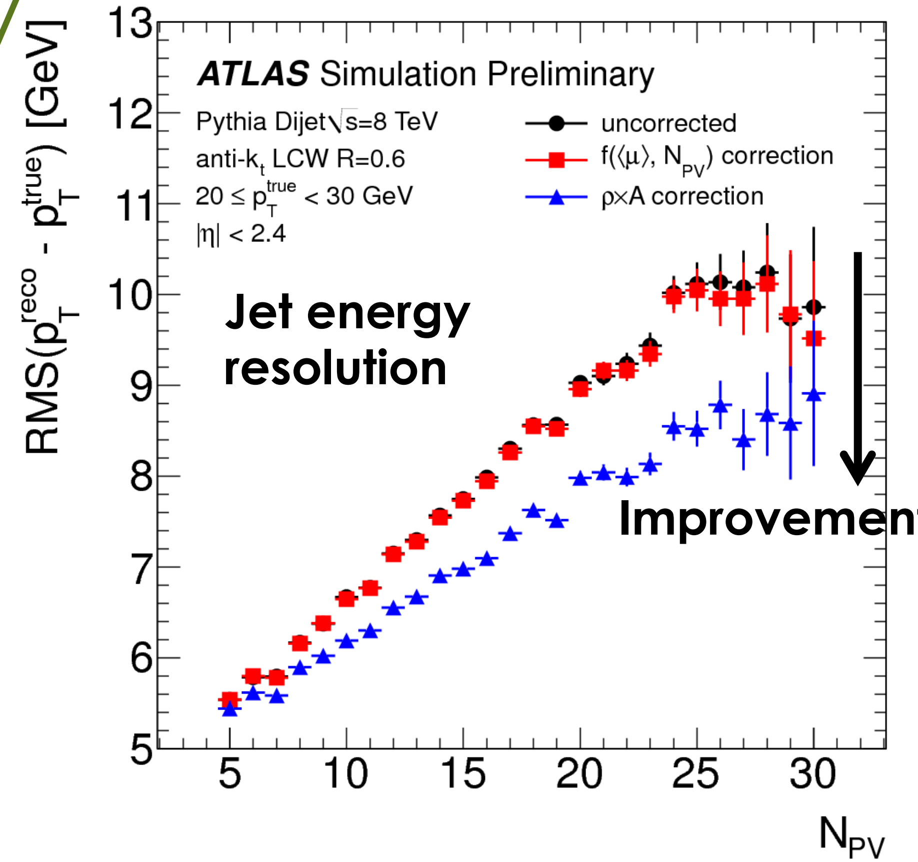
$$p_T^{jet,corr} = p_T^{jet} - \rho \times A_T^{jet}$$

Pileup subtraction

Residual correction

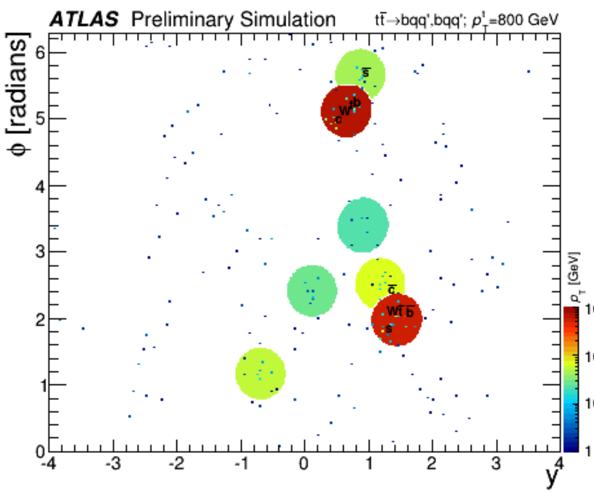
$$p_{\mathrm{T}}^{\mathrm{corr}} = p_{\mathrm{T}} - \rho A_{\mathrm{T}} - \alpha(N_{\mathrm{PV}} - 1) - \beta\langle\mu\rangle$$

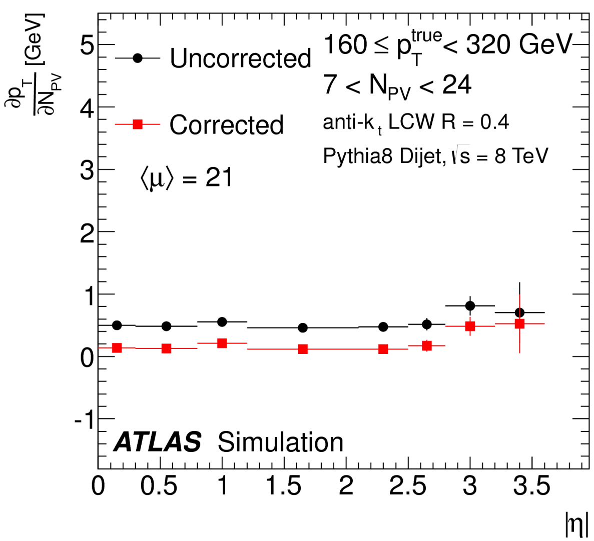




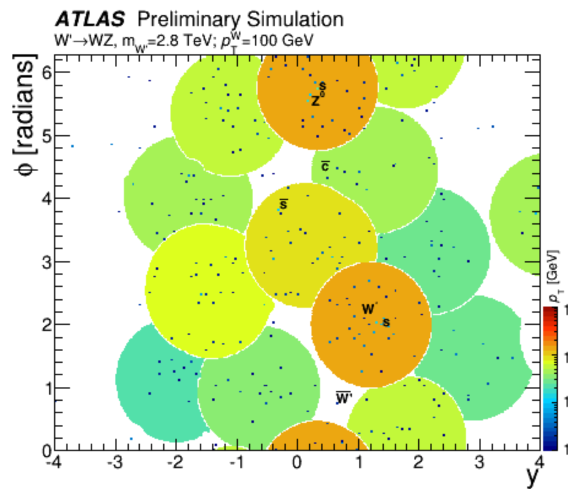
- Significant improvement of the jet p_T resolution
- **10-20% reduction in jet-by-jet pileup fluctuations**

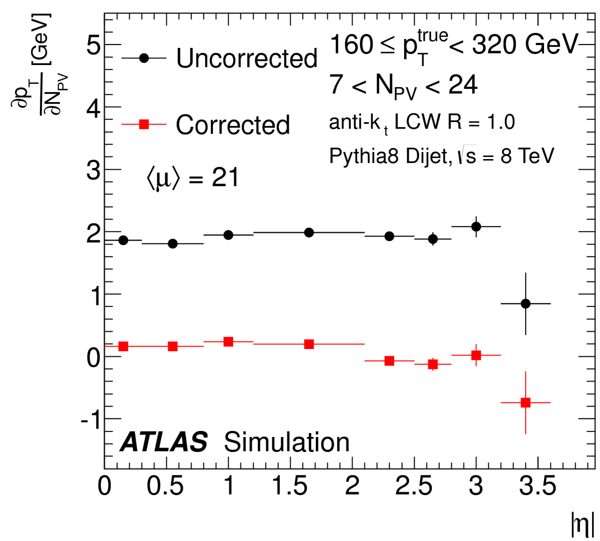
anti-k_t R=0.4



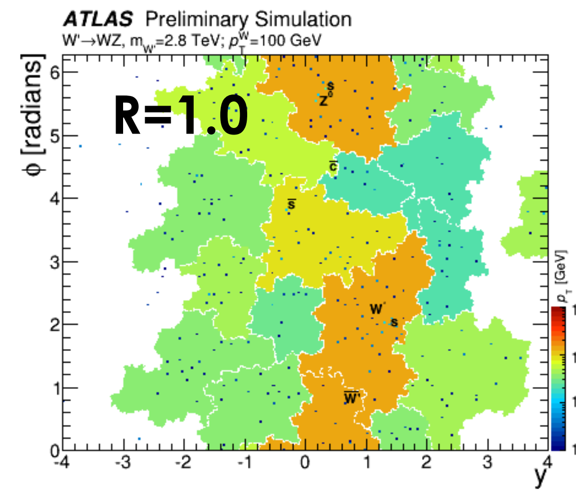


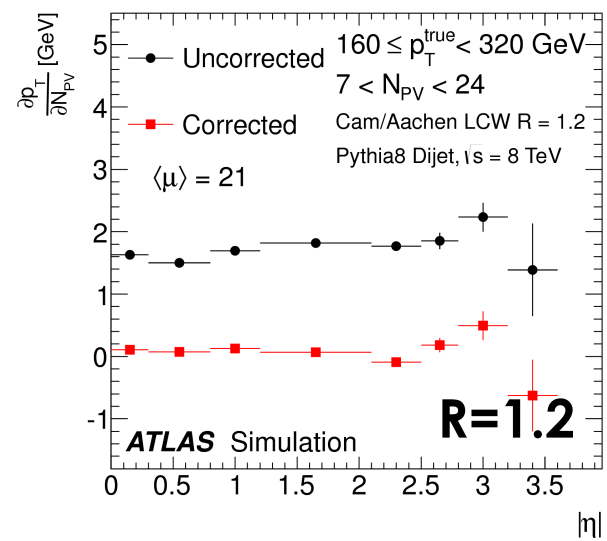
anti-k_t R=1.0



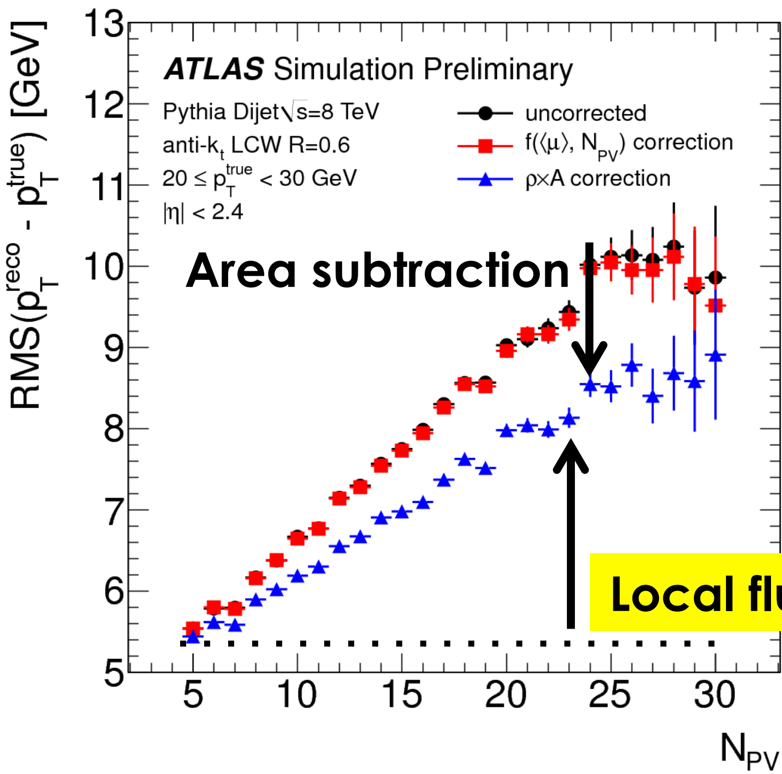


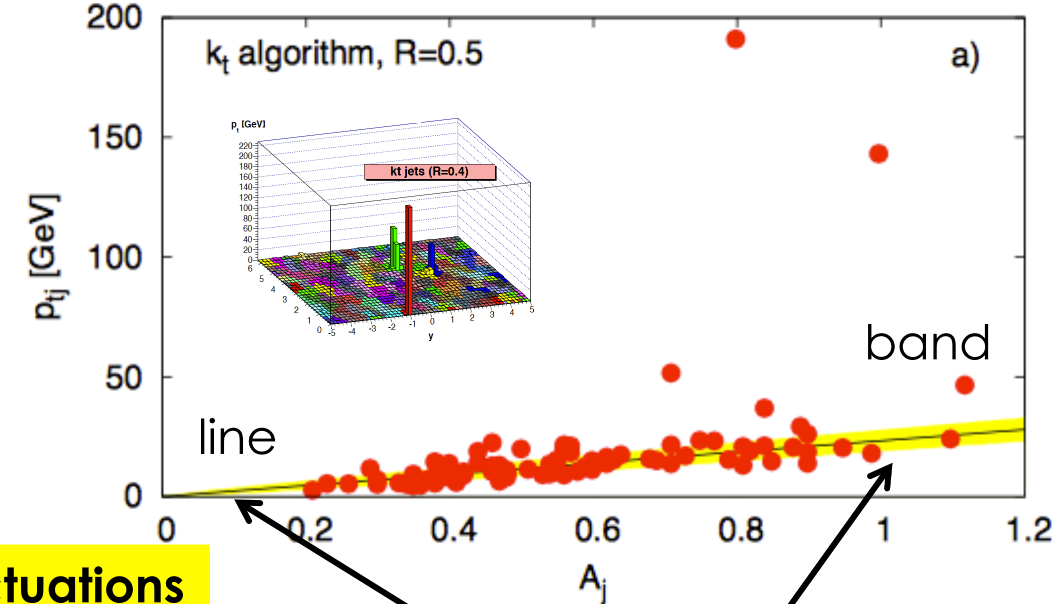
C/A large-R





Local pile-up fluctuations





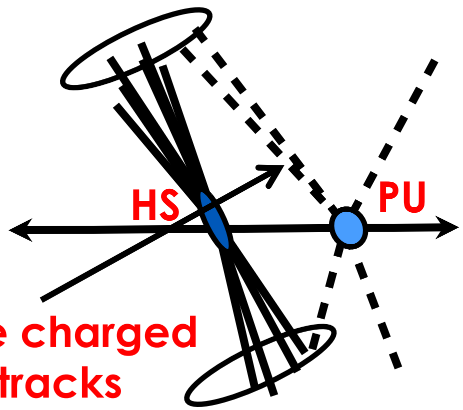
$$\Delta p_T = \rho A \pm \sigma_\rho \sqrt{A}$$

Geometrical contamination

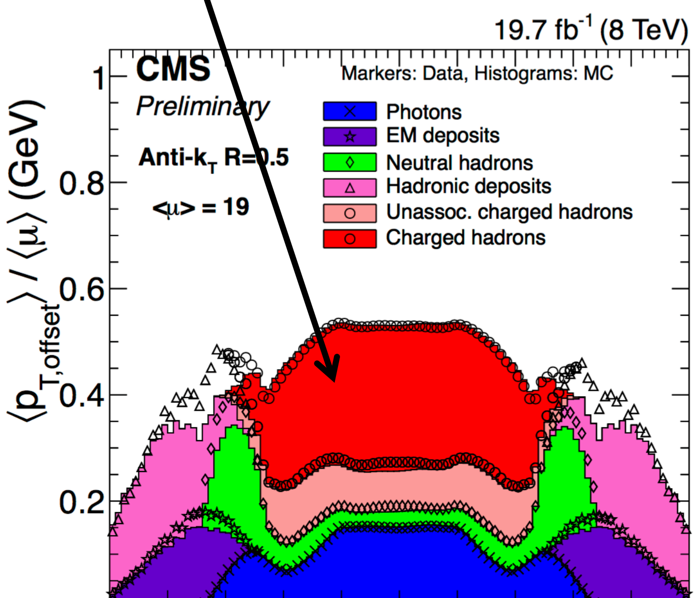
Fluctuations in the noise from point to point in the event: **local fluctuations**

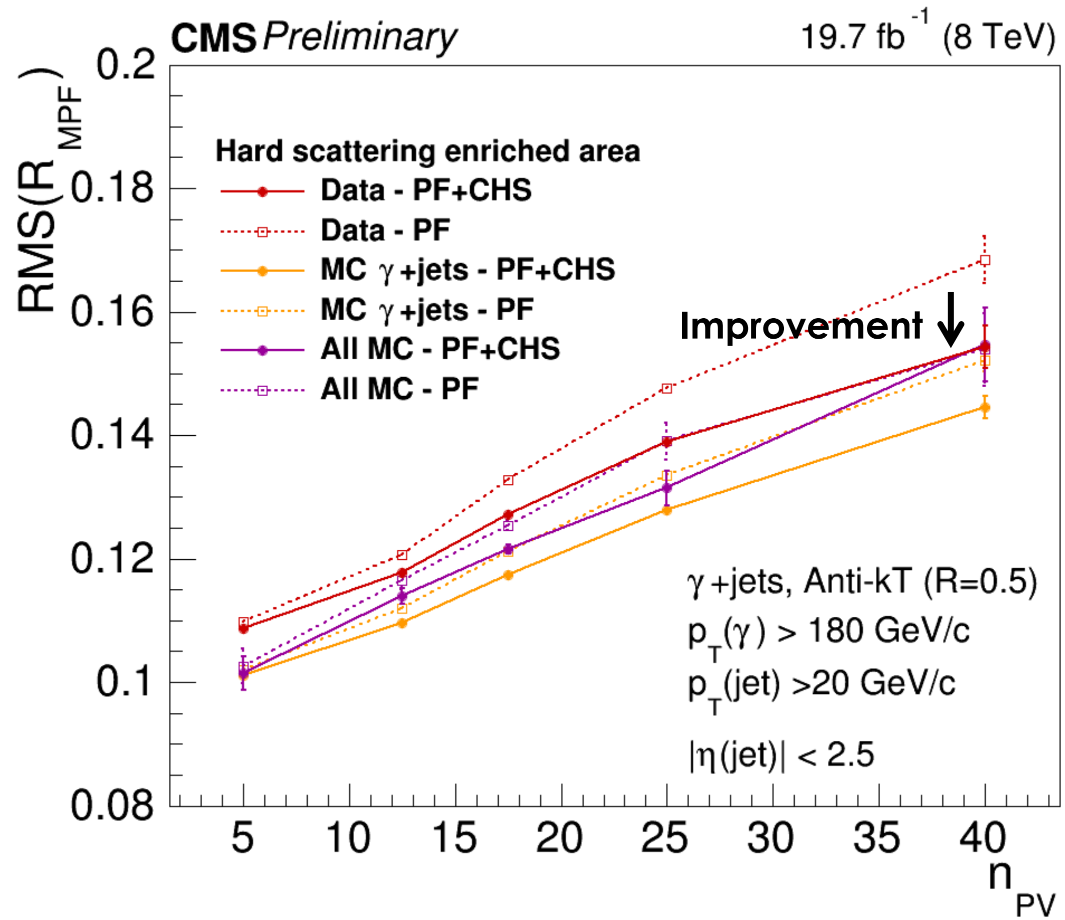
$$p_T^{jet,corr} = p_T^{jet} - \rho \times A_T^{jet}$$

CMS Charged Hadron Subtraction



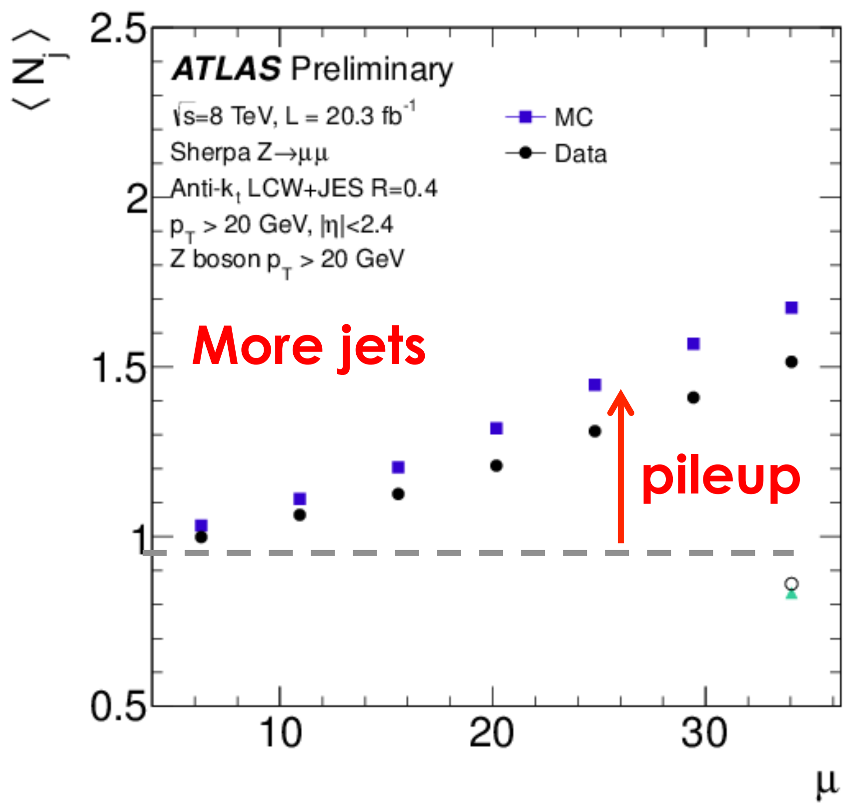
Remove charged pile-up tracks

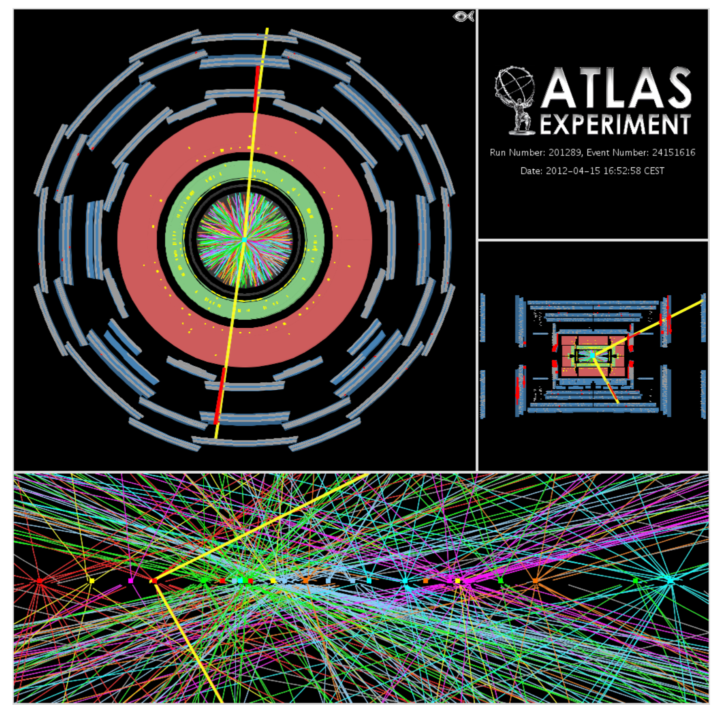




Rejecting jets from pileup

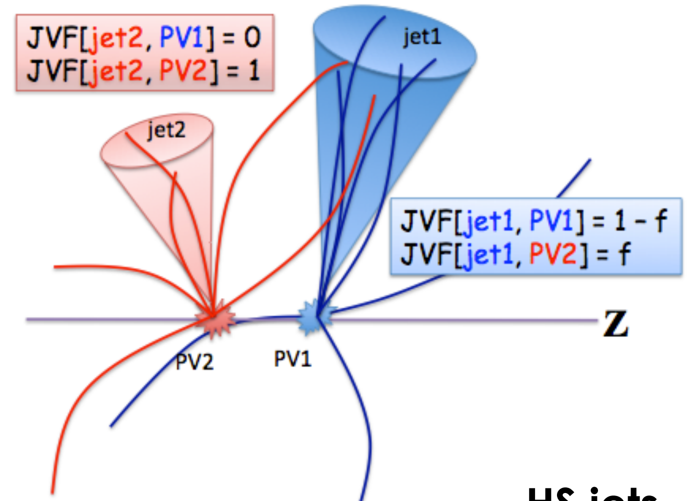
- **Pileup can create pileup jets:**
  - QCD jets originating from a pileup vertex
  - Random combination of particles from multiple pileup interactions ("stochastic pileup jets")



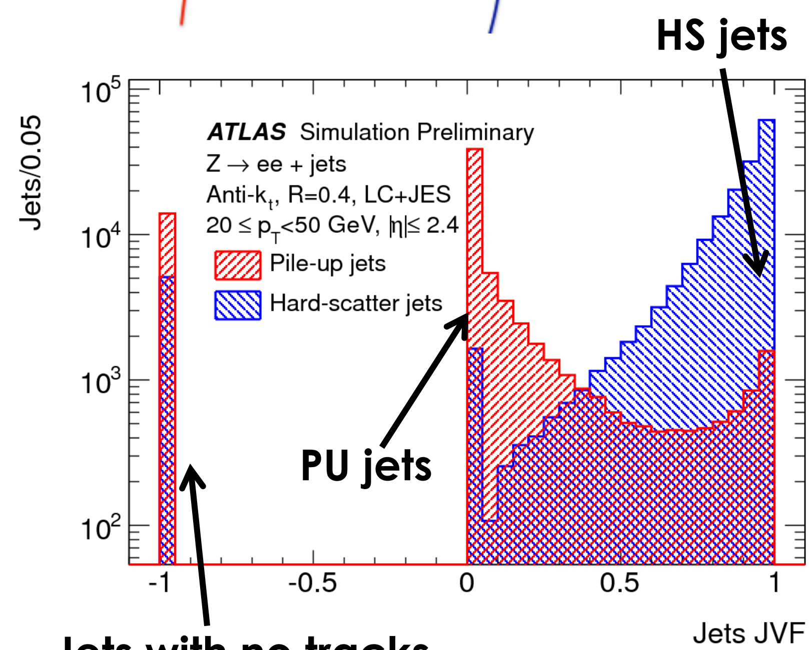


Jet Vertex Tagging / JetID

- **Jet vertex fraction algorithm (JVF)**
  - Tag and reject pileup jets using tracking and vertexing information

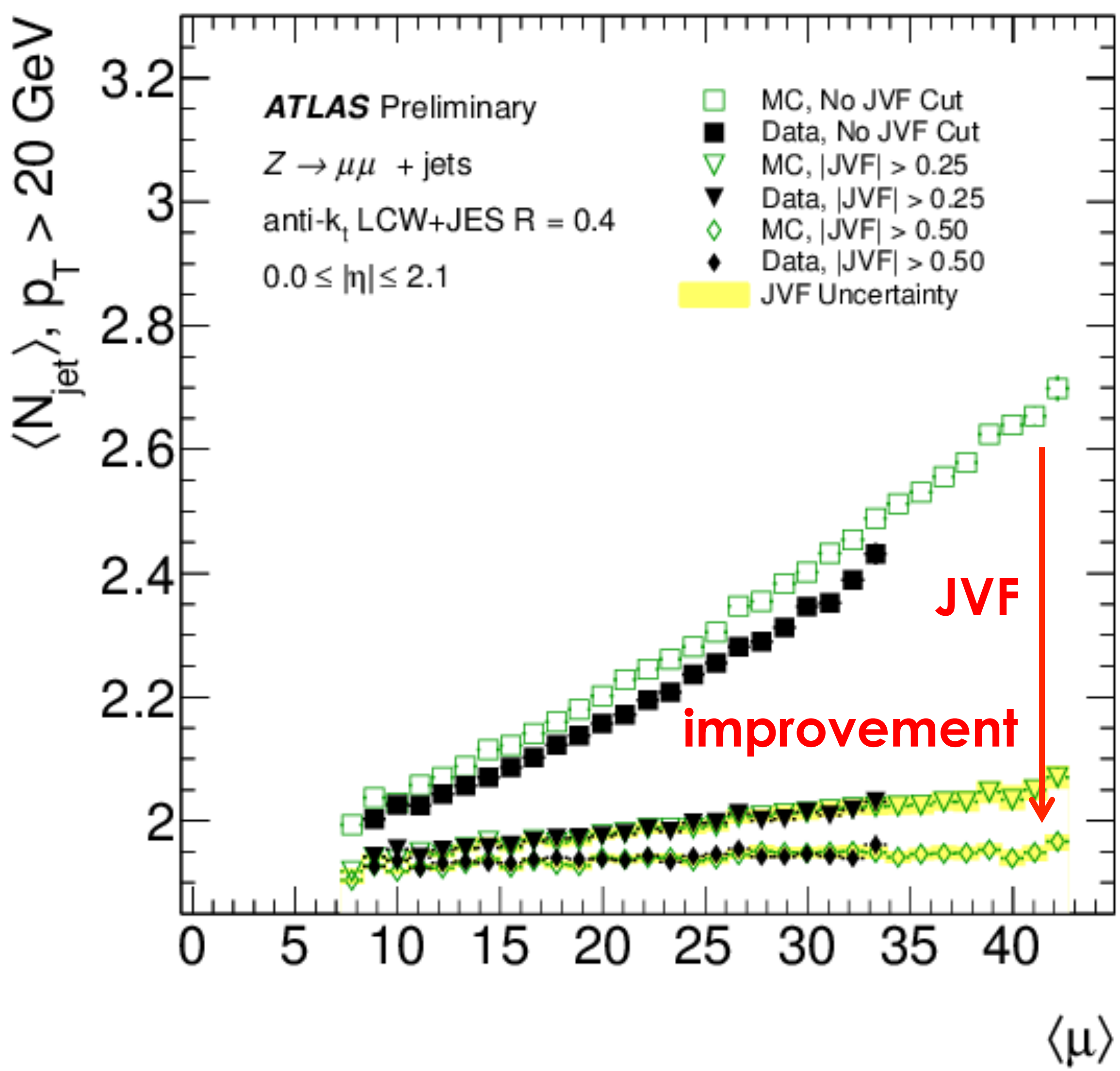


$$JVF = \frac{\Sigma p_T^{trk}(PV_0)}{\Sigma p_T^{trk}(PV_0) + \Sigma p_T^{trk}(PU_n)}$$



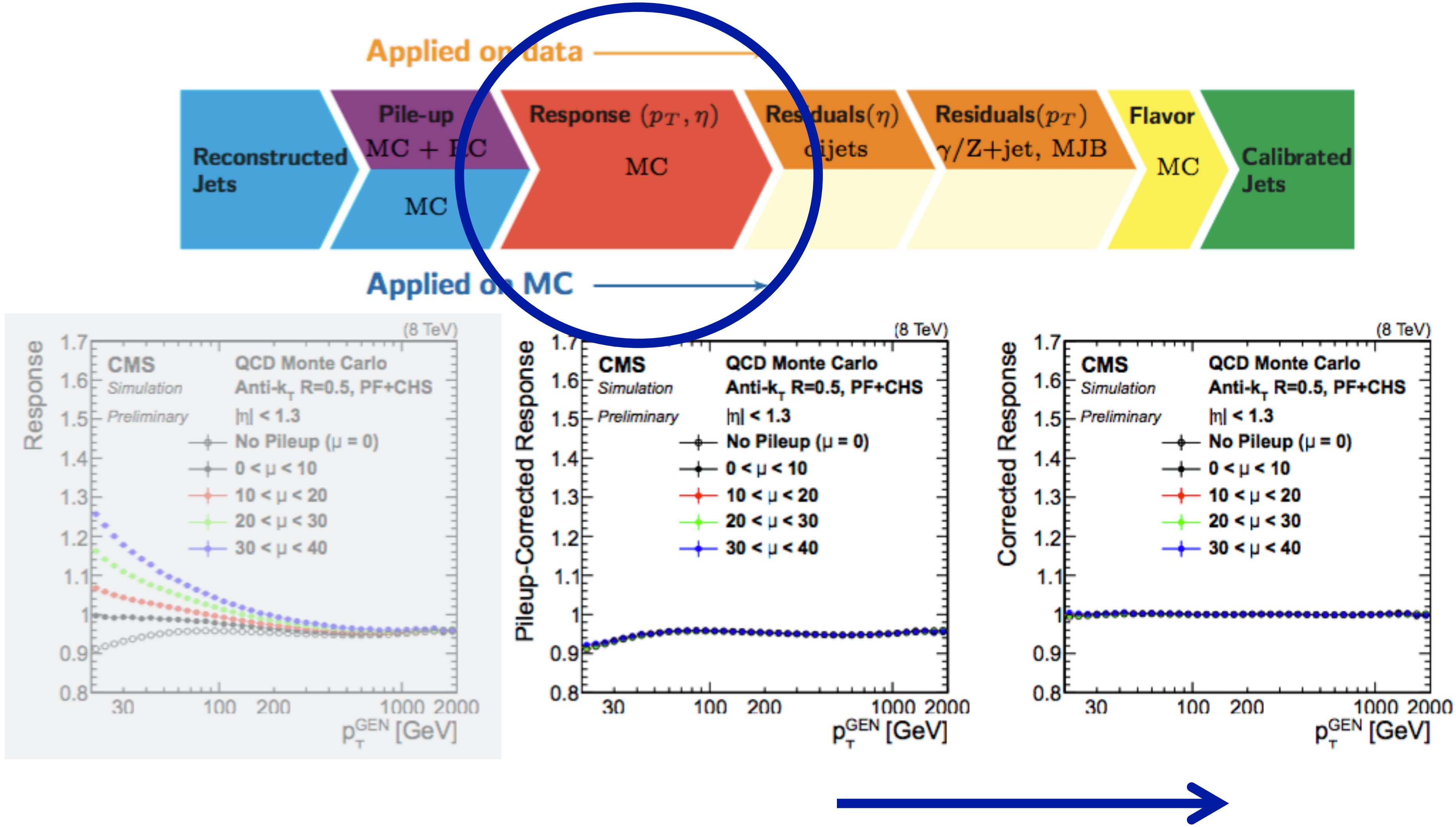
ATLAS-CONF-2013-083
CMS PU Jet ID: CMS PAS JME-13-005

JVF pileup jet suppression



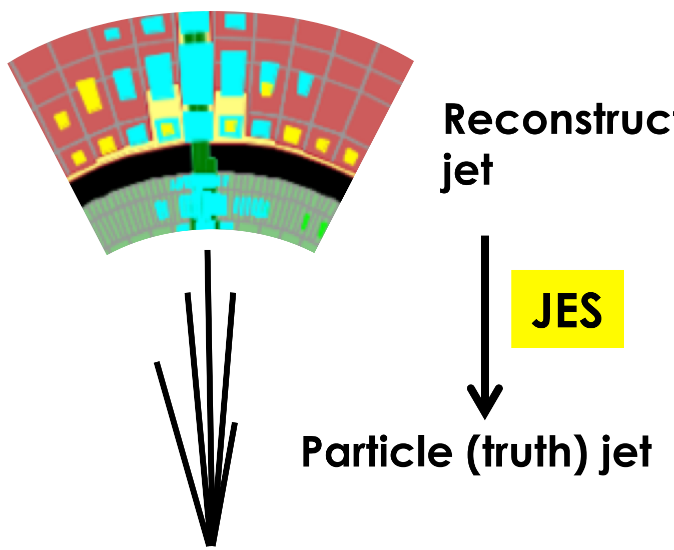
- JVF restores the N_{jet} distribution as a function of pileup
- Improves the data/MC agreement

Jet calibration overview

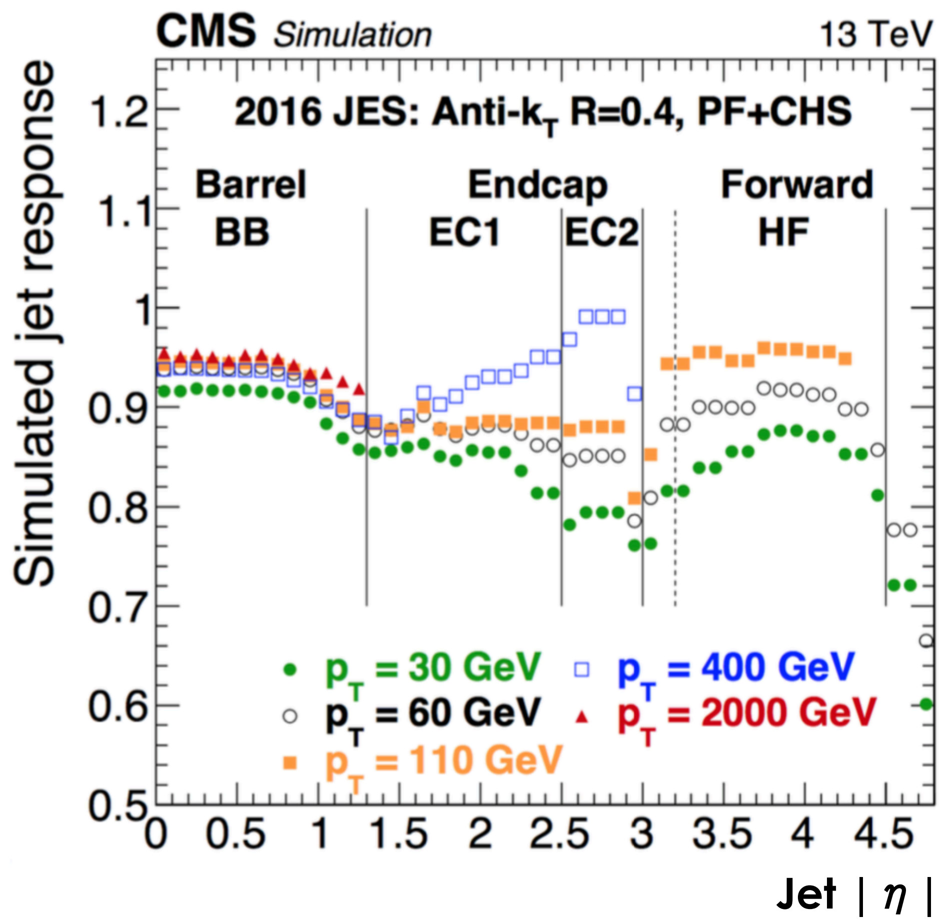


Jet energy scale correction

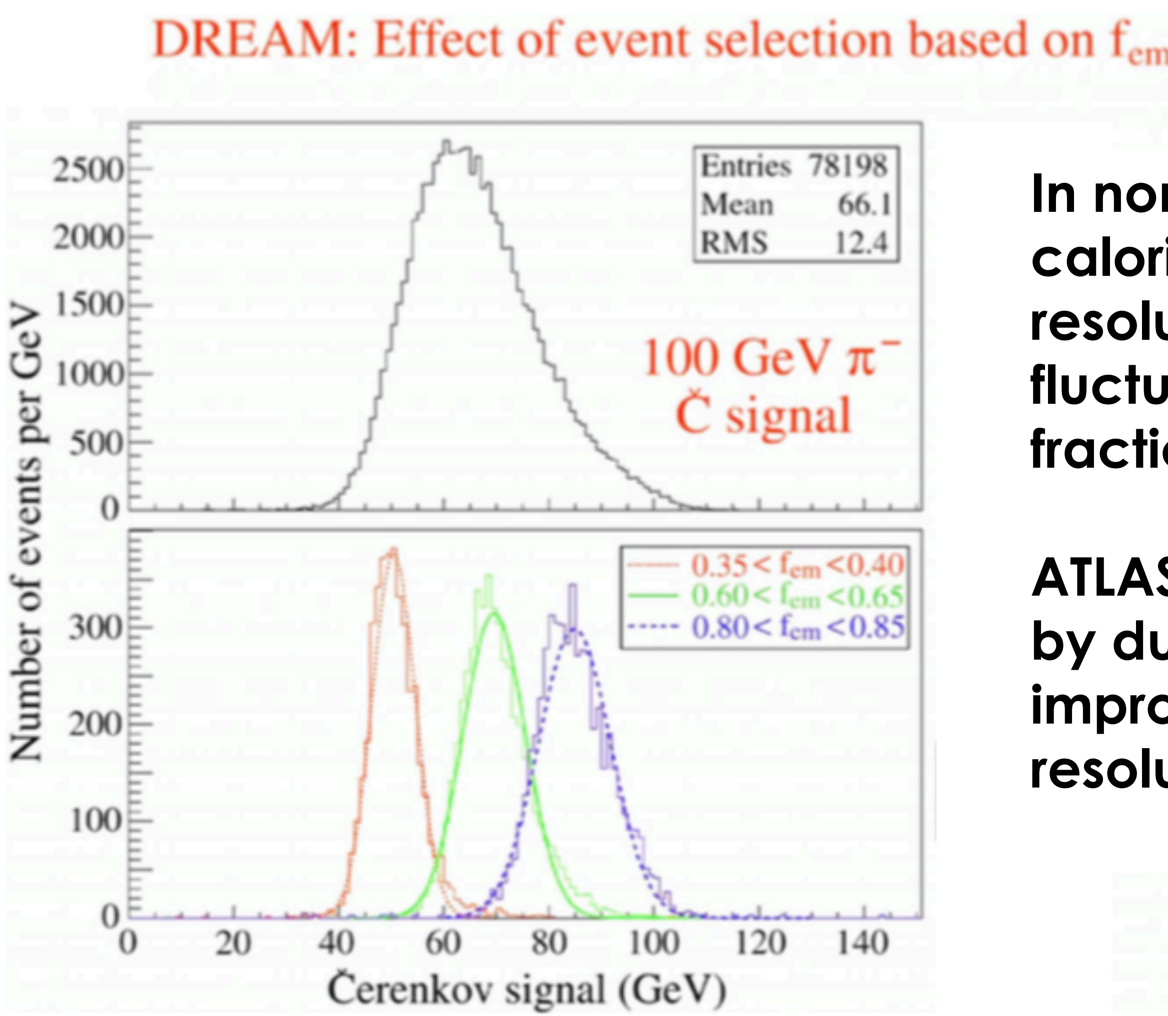
- Multiplicative factor (JES) derived as a function of jet p_T (E) and η in di-jet Monte Carlo events: *JES = 1 / R(E, η)*



$$R(E,\eta) = \left\langle \frac{E^{reco}}{E^{truth}} \right\rangle$$



Reducing fluctuations (I)

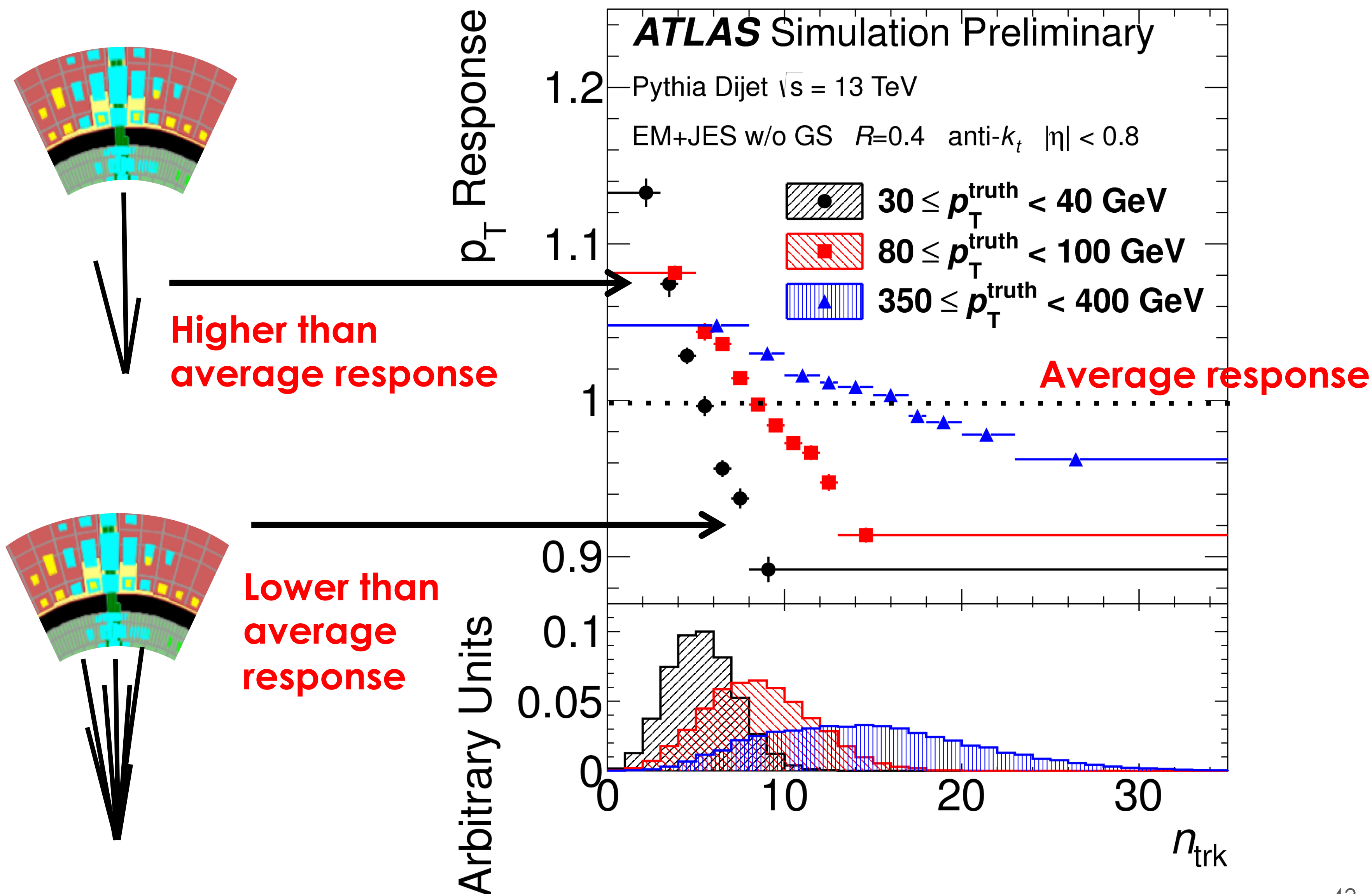


In non-compensating (e/h>1) calorimeters, the energy resolution is driven by the large fluctuations in the EM shower fraction

ATLAS uses a method *inspired* by dual-readout calorimetry to improve the jet energy resolution

Slide from R. Wigmans lecture 1

Reducing fluctuations (II)



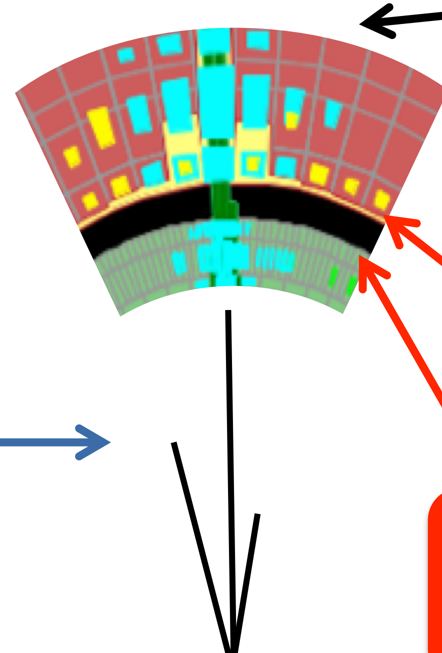
Global Sequential Calibration

- Use jet-by-jet information to correct the response of ***each jet individually*** **after the average JES correction**
  - Reduce fluctuations in the jet energy response due to detector effects
  - Reduce the difference in response between quark and gluon initiated jets

Muon variables

Number of muon segments

Sensitive to leakage



Calorimeter variables

Tile layer 0 energy fraction

EM layer 3 energy fraction

Sensitive to LAr cryostat energy loss

Tracking variables

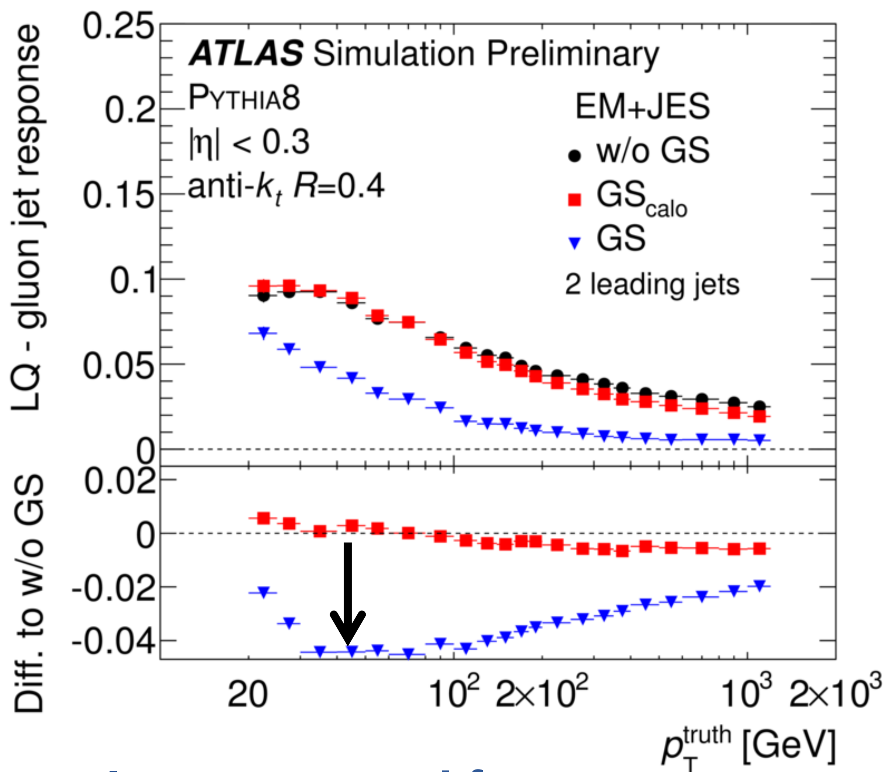
Number of tracks

Jet (track) width

Sensitive to quark/gluon differences

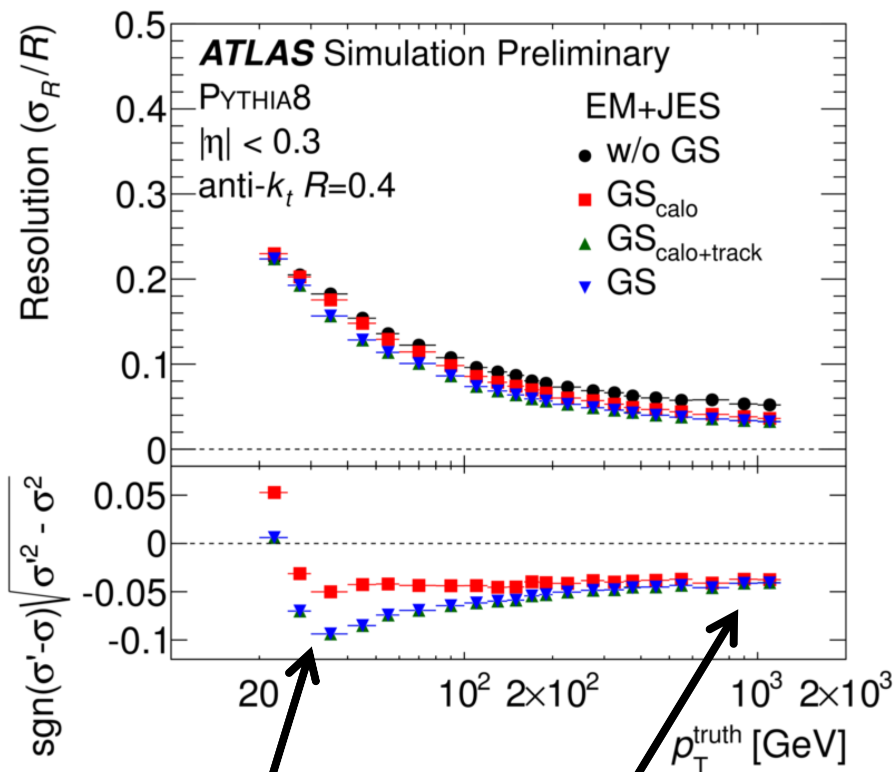
Global Sequential Calibration

Quark/Gluon response difference



Improvement from tracking variables

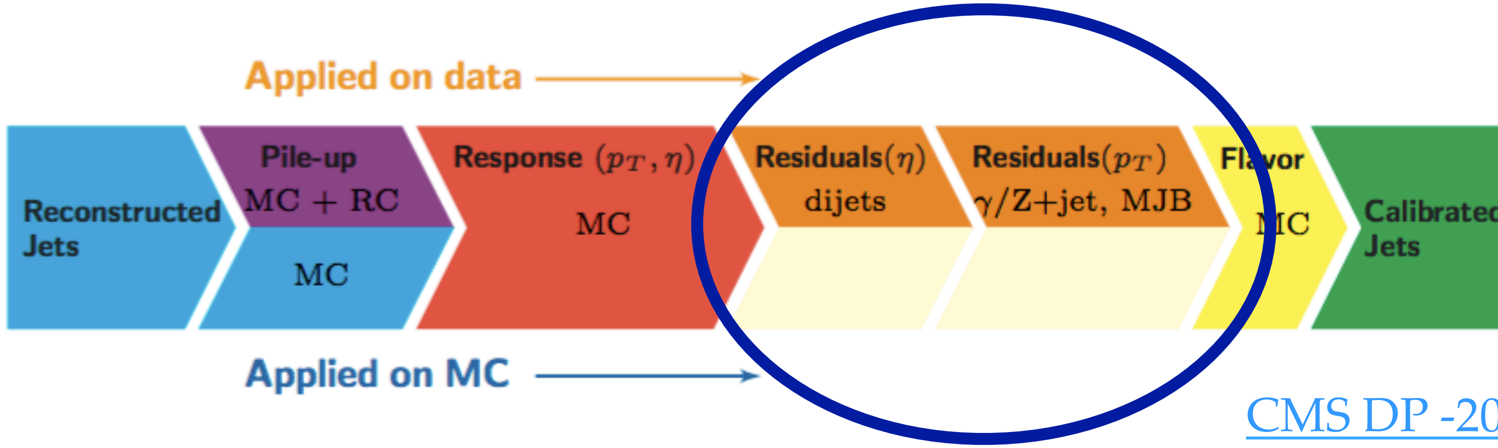
Jet energy resolution



Improvement from tracking variables at low p_T

Improvement from calorimeter variables at high p_T

Jet calibration overview



CMS DP -2016/020
JETM-2016-002

Residual *in situ* jet energy scale correction:

- Brings the energy response of jets in data and MC to agreement, reducing a major source of systematic uncertainty

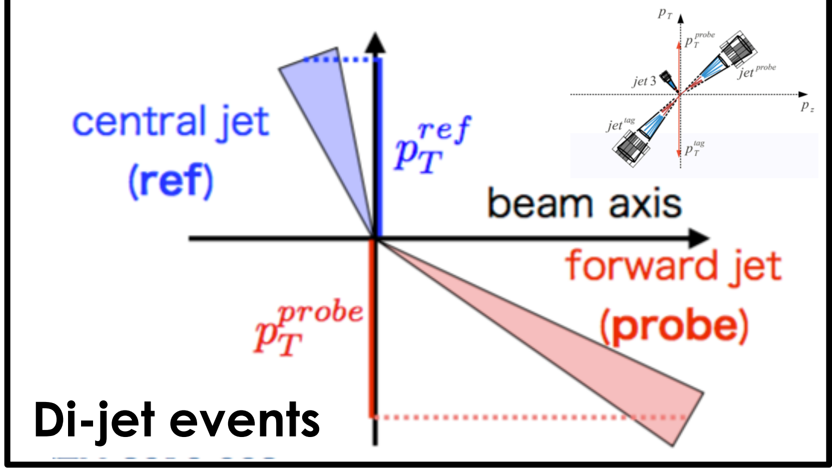
$$JES^{in\,situ} = \frac{\left\langle p_T^{jet} / p_T^{ref} \right\rangle_{MC}}{\left\langle p_T^{jet} / p_T^{ref} \right\rangle_{DATA}}$$

Reference objects:
Z, γ, jets

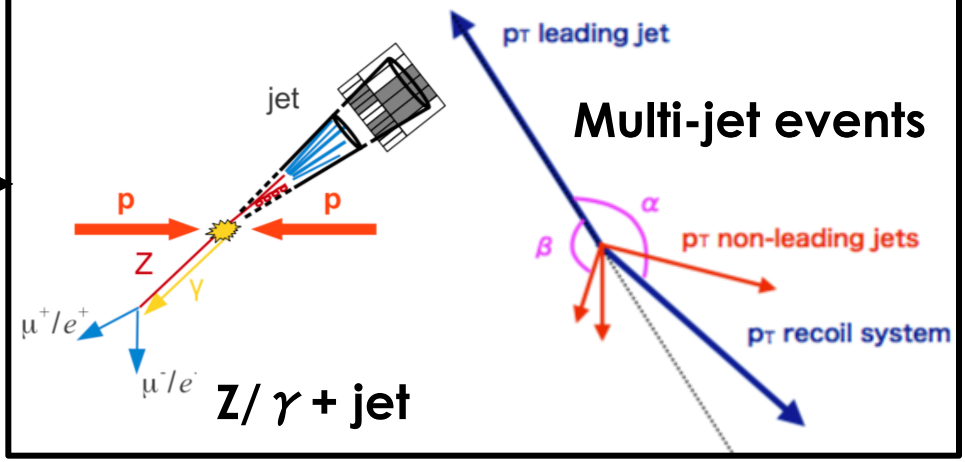
- Jet energy scale uncertainty determined by the **uncertainty on the measurement of the jet response in data**

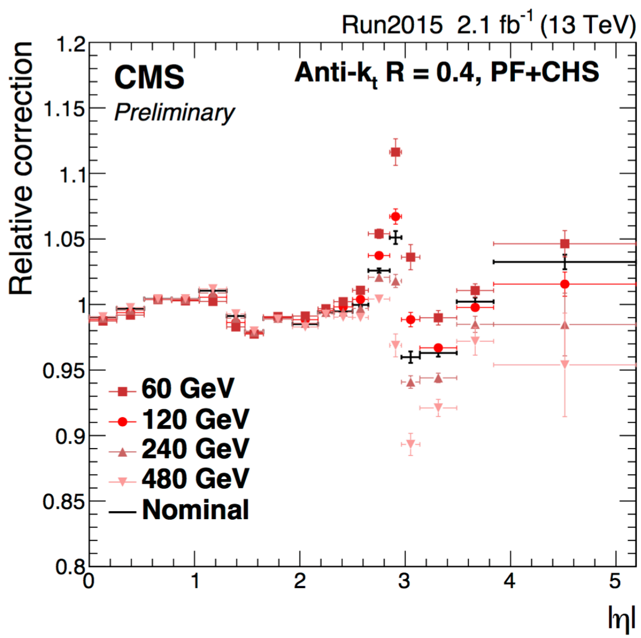
In situ jet energy calibration

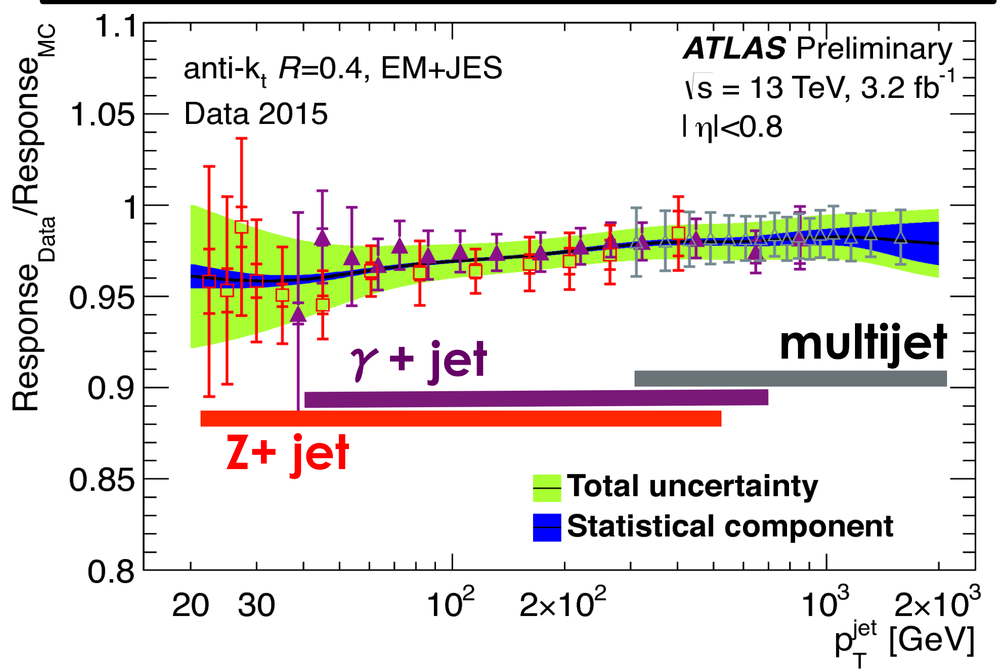
Relative η inter-calibration



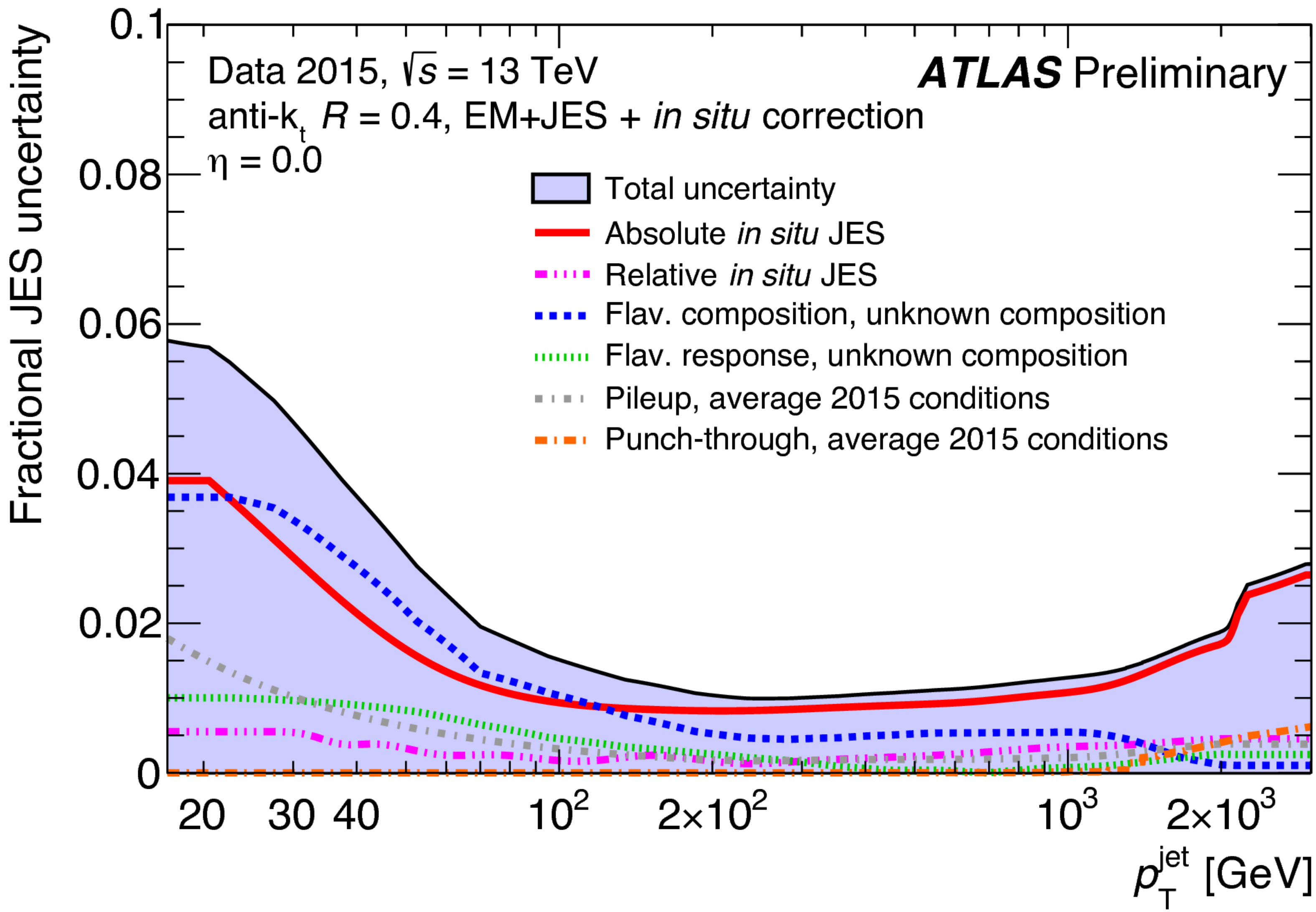
Absolute p_T calibration







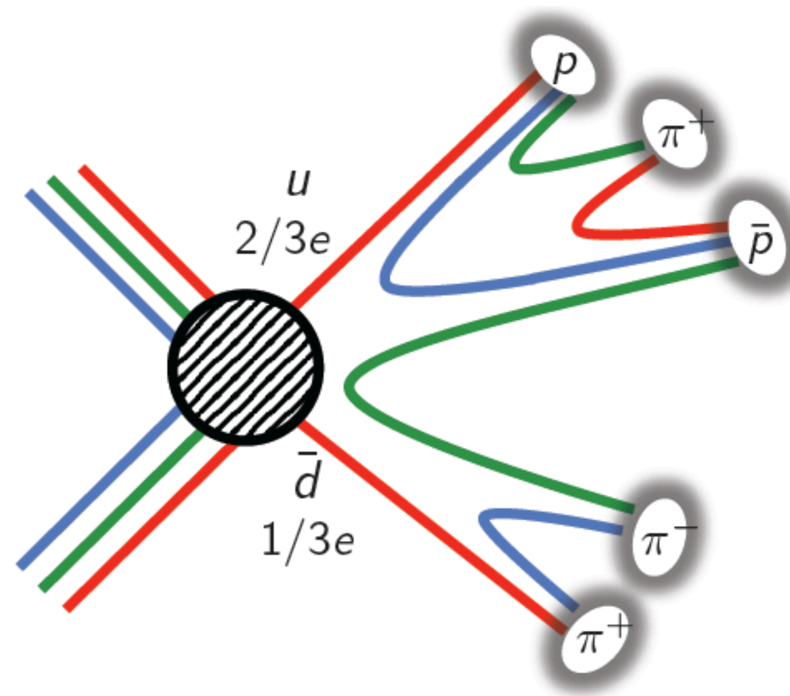
Systematic uncertainties



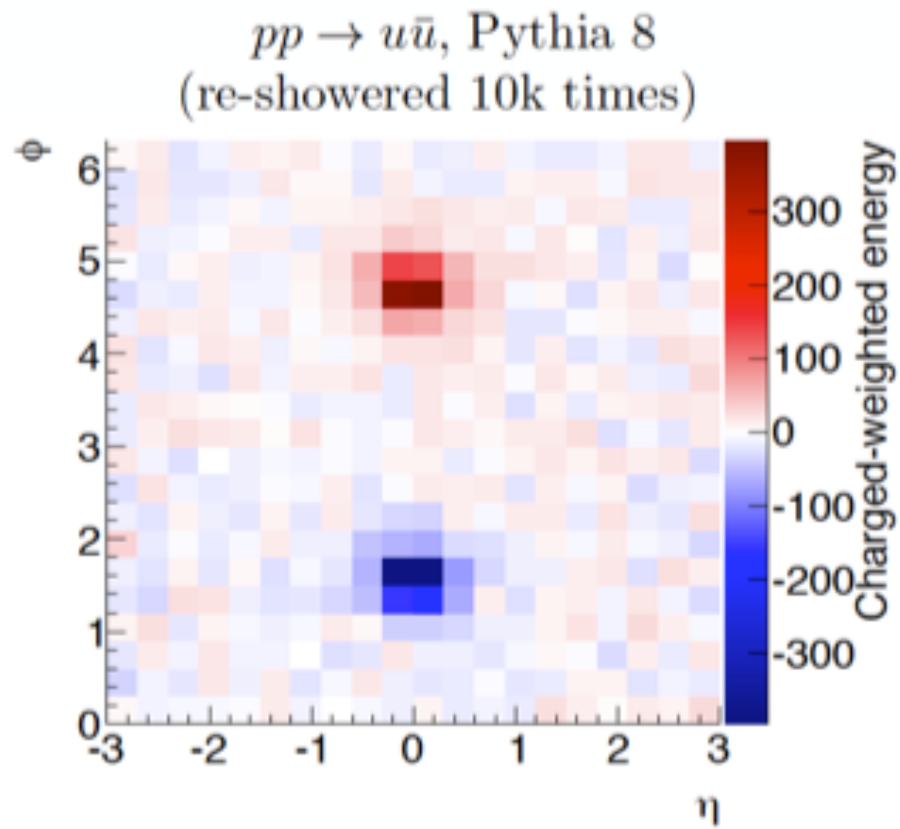
Jet quantum properties

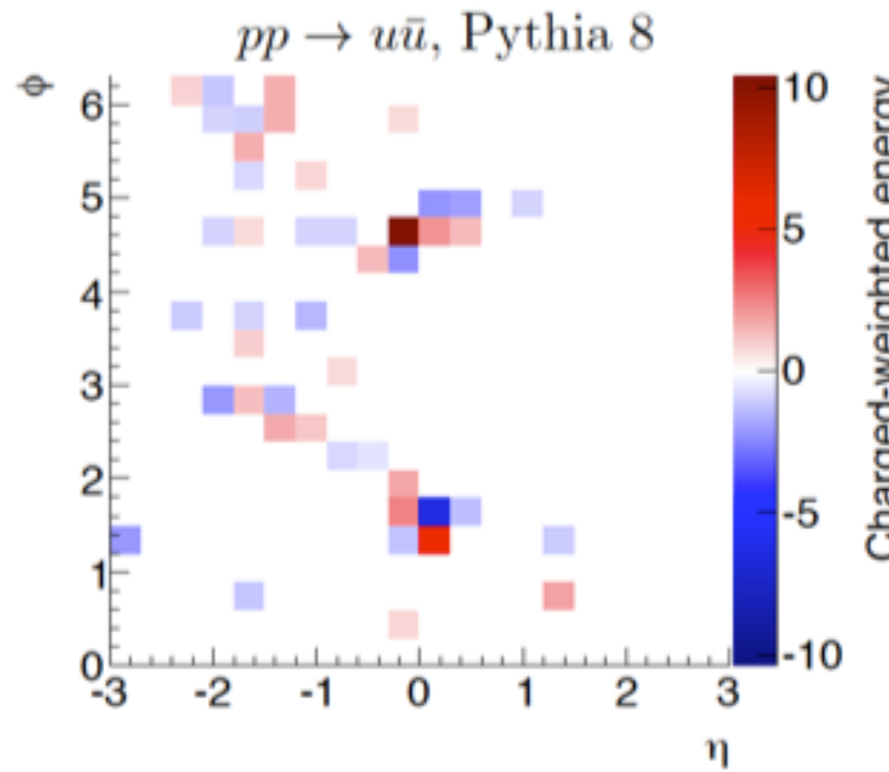
- Exploit the internal jet (and event) substructure to measure jet quantum properties:
  - o **Electric charge**
  - o Color charge
    - **Quark vs. gluons**
    - **Color connections between jets**

- Tools to enhance precision measurements (Higgs, VBF final states) and to characterize new physics



Jet charge (I)



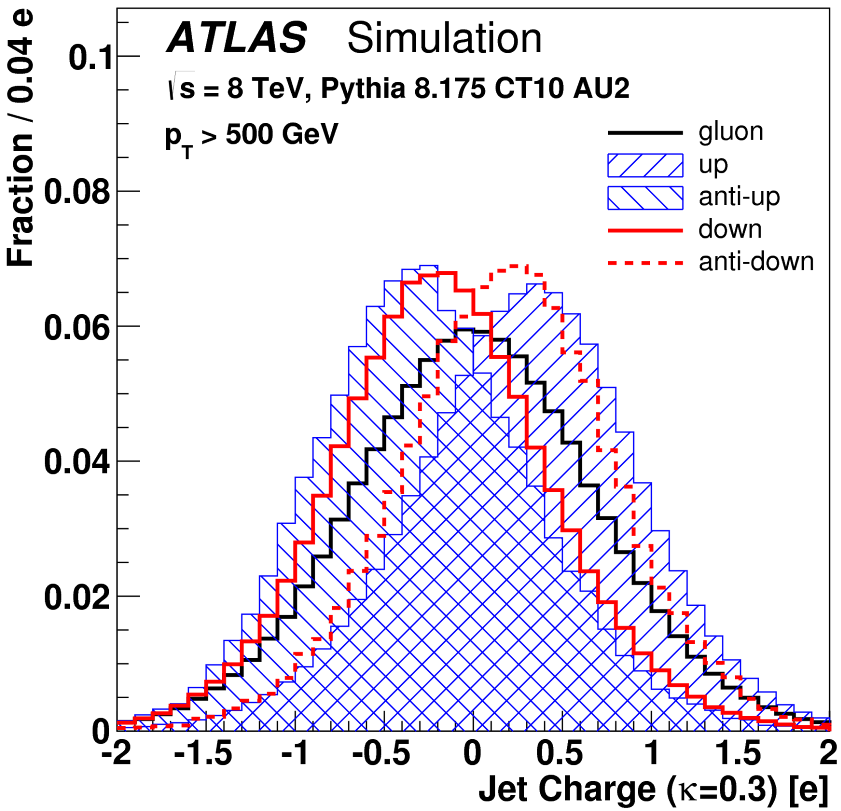


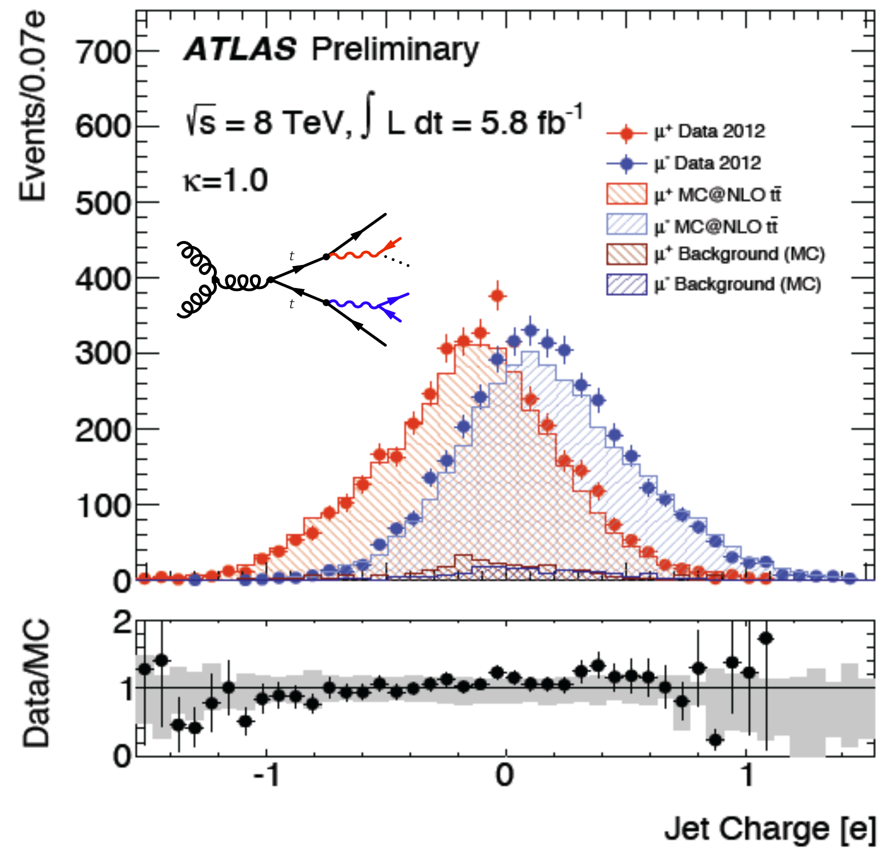
Weighted sum over track charges is an experimental handle on the electric charge of jets (Field, Feynman, 1978)

$$Q_j = \frac{1}{(p_{T_j})^\kappa} \sum_{i \in tracks} q_i \times (p_T^i)^\kappa$$

Jet charge (II)

ATLAS-CONF-2013-086
CMS PAS SMP-15-003

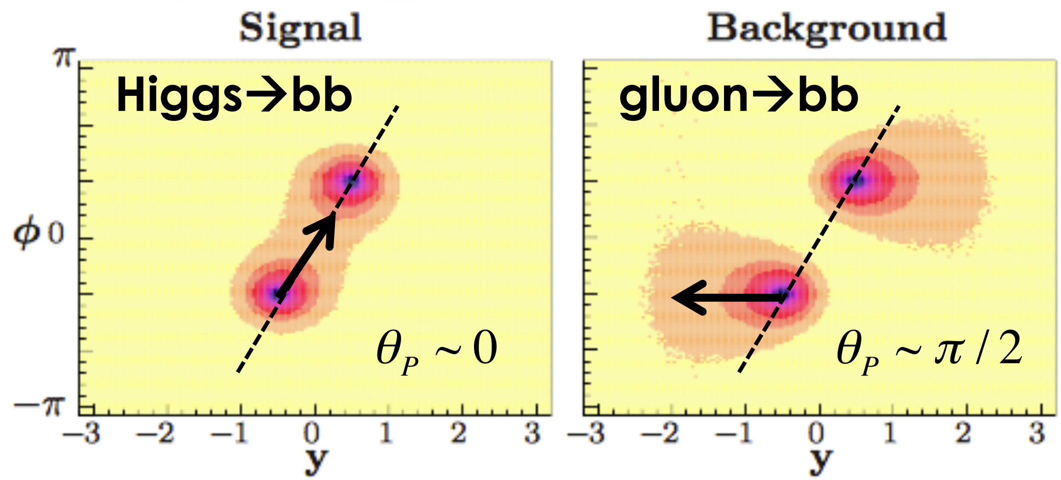




$$Q_j = \frac{1}{(p_{T_j})^{\kappa}} \sum_{i \in tracks} q_i \times (p_T^i)^{\kappa}$$

Color flow: jet pull (I)

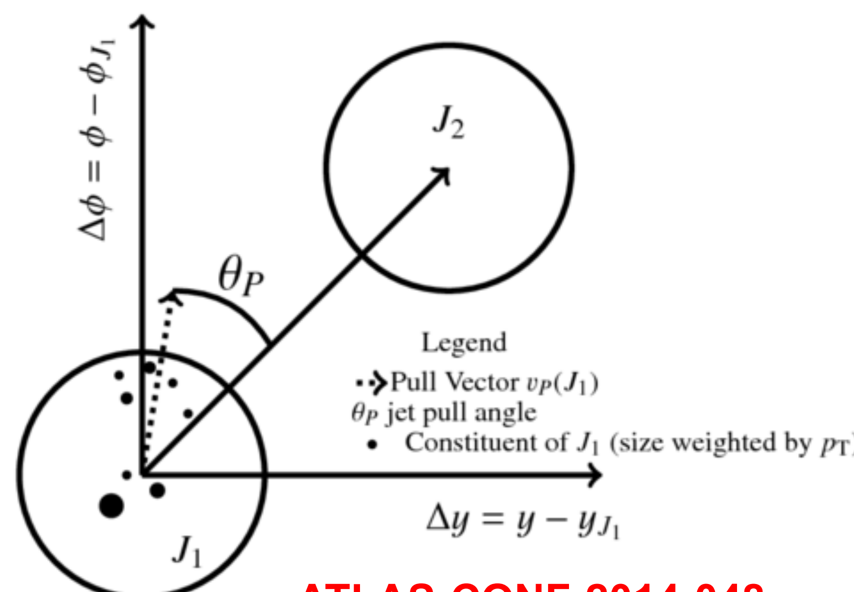
- **Observable designed to be sensitive to the color connections between the hard-scatter partons initiating the jets**
  - Multiple physics applications (QCD, Higgs, new particle searches…)



Jet Superstructure (Schwartz and Gallicchio) arXiv:1001.5027

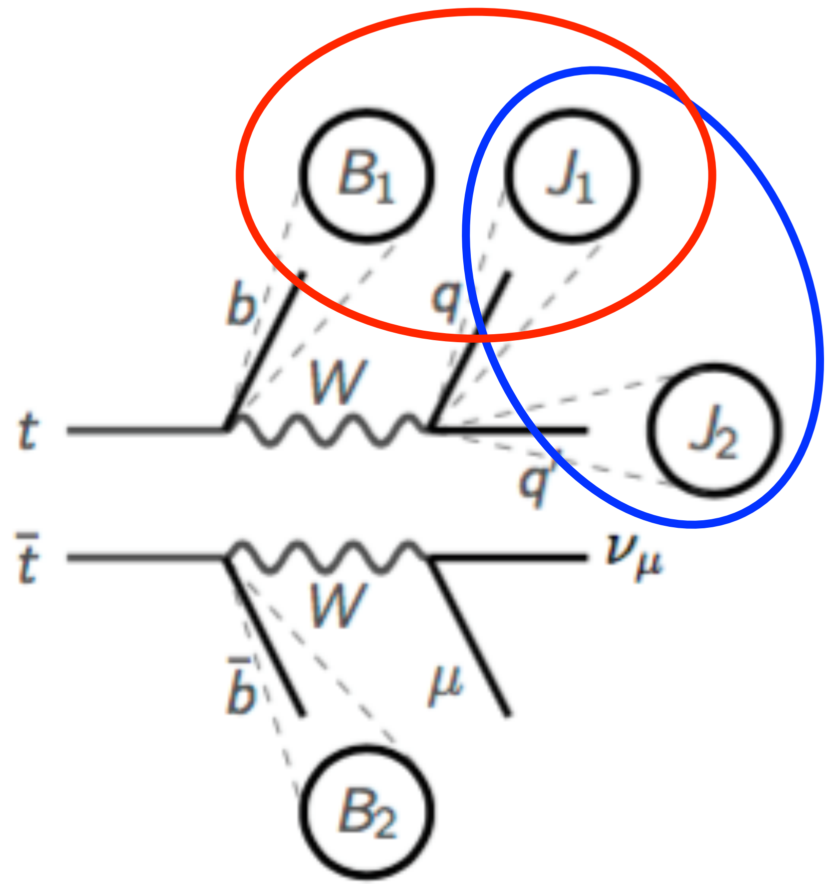
Jet Pull Vector $\sum_{i \in J} \frac{p_T^i |r_i|}{p_T^J} \vec{r}_i$

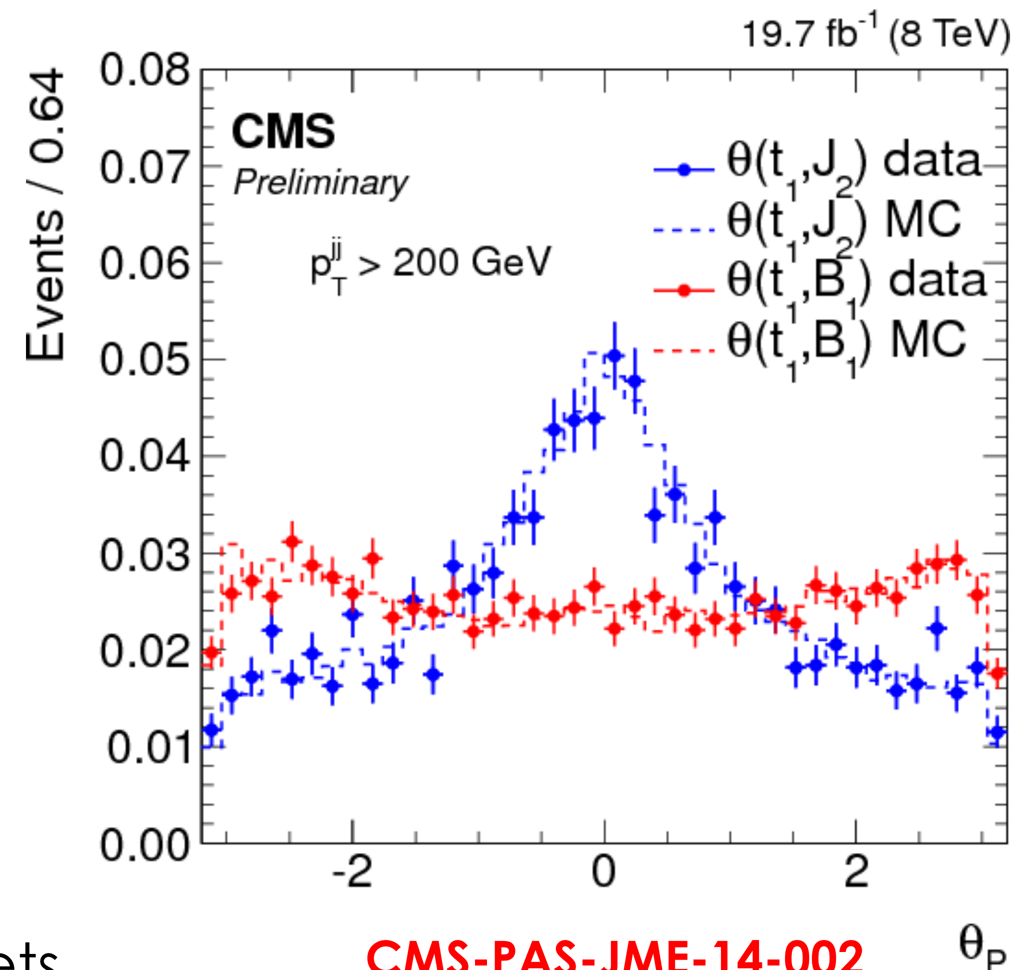
θ_p**(J1,J2) =** angle between J_1 pull vector and the vector connecting J_1 and J_2



ATLAS-CONF-2014-048

Color flow: jet pull (II)





- Study jet pull in data using jets from hadronic W's in ttbar events

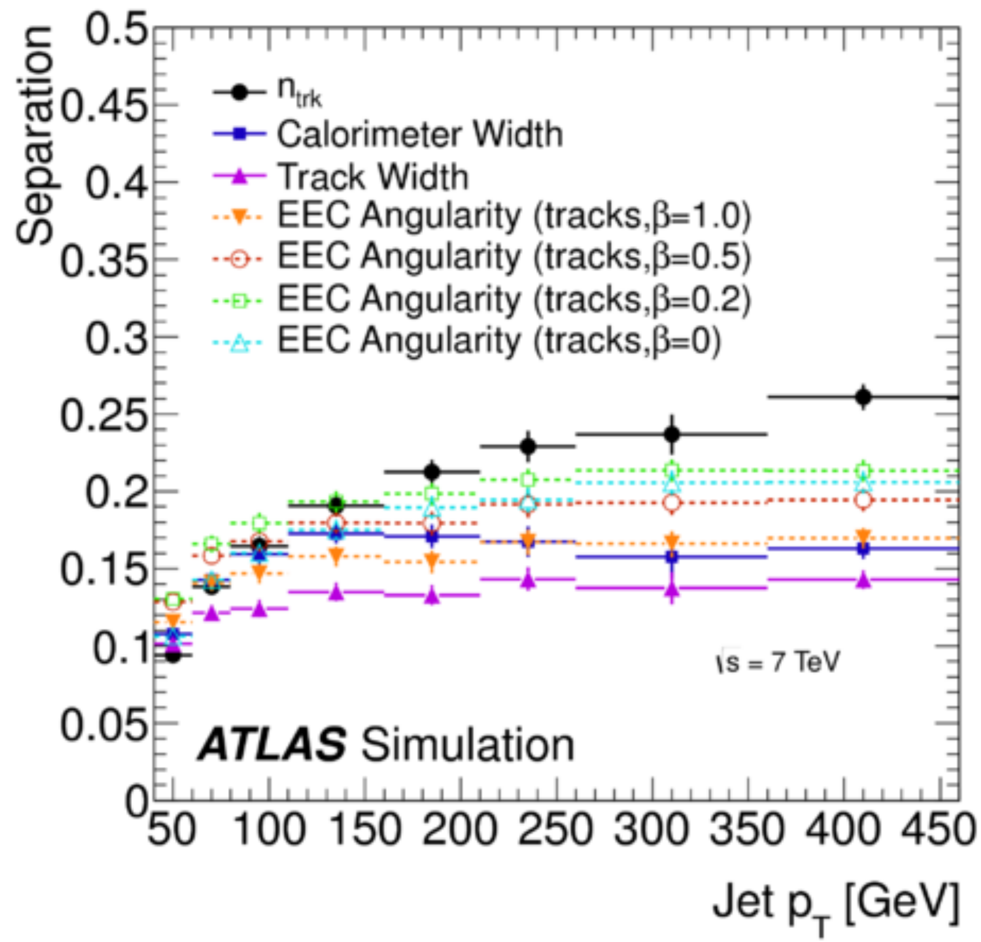
CMS-PAS-JME-14-002
ATLAS-CONF-2014-048

Quark-gluon jet tagging

- Distinguish quark from gluon initiated jets using jet properties that result from the **different color charge between quark (C_F=4/3) and gluon (C_A=3)** partons

$$\frac{\langle N_g \rangle}{\langle N_q \rangle} = \frac{C_A}{C_F} = \frac{9}{4}$$

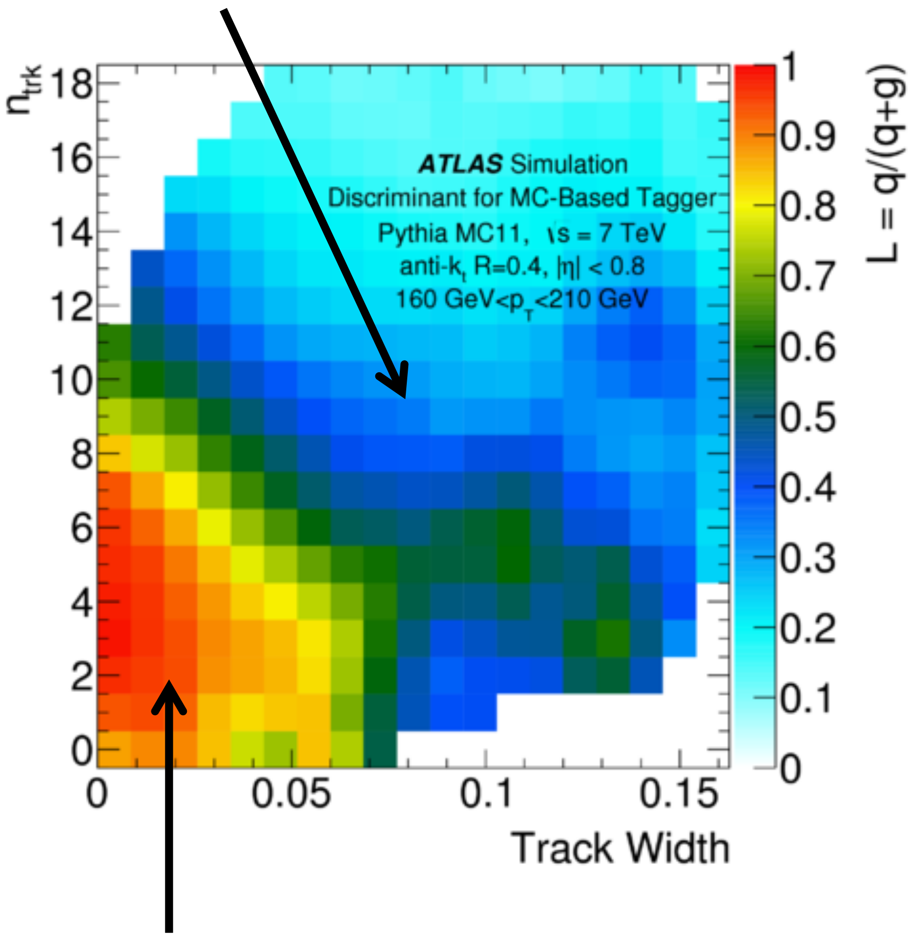
- Gluons are expected to have more particles, be wider, and have a softer particle spectrum



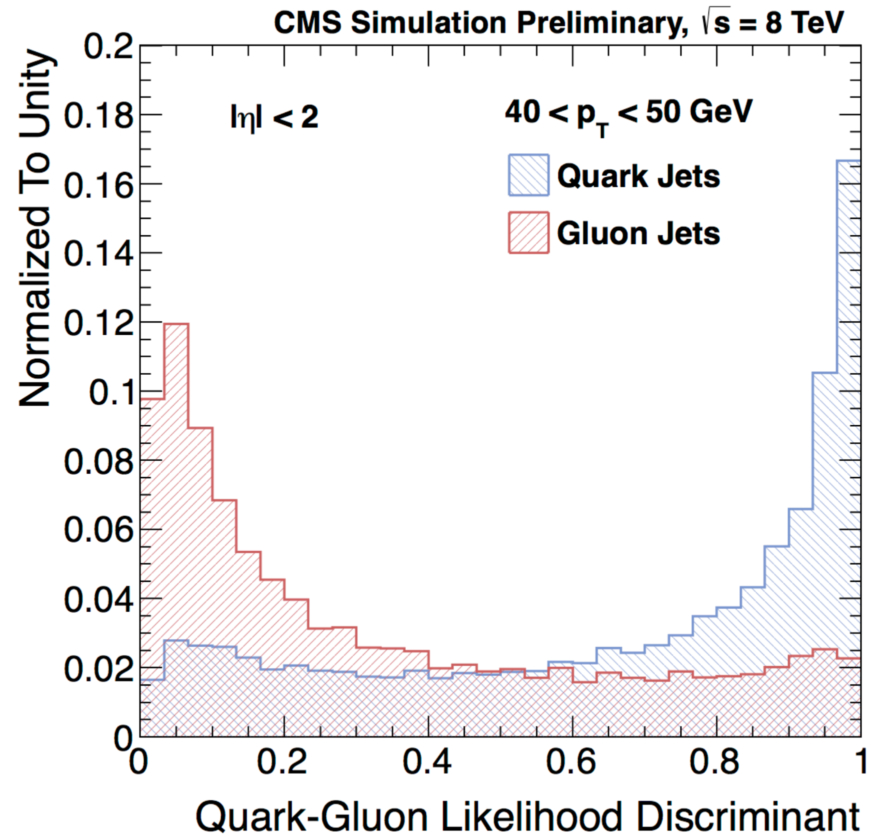
Eur. Phys. J. C (2014) 74: 3023
CMS-PAS-JME-13-002

Quark-gluon jet tagging

Gluon-like

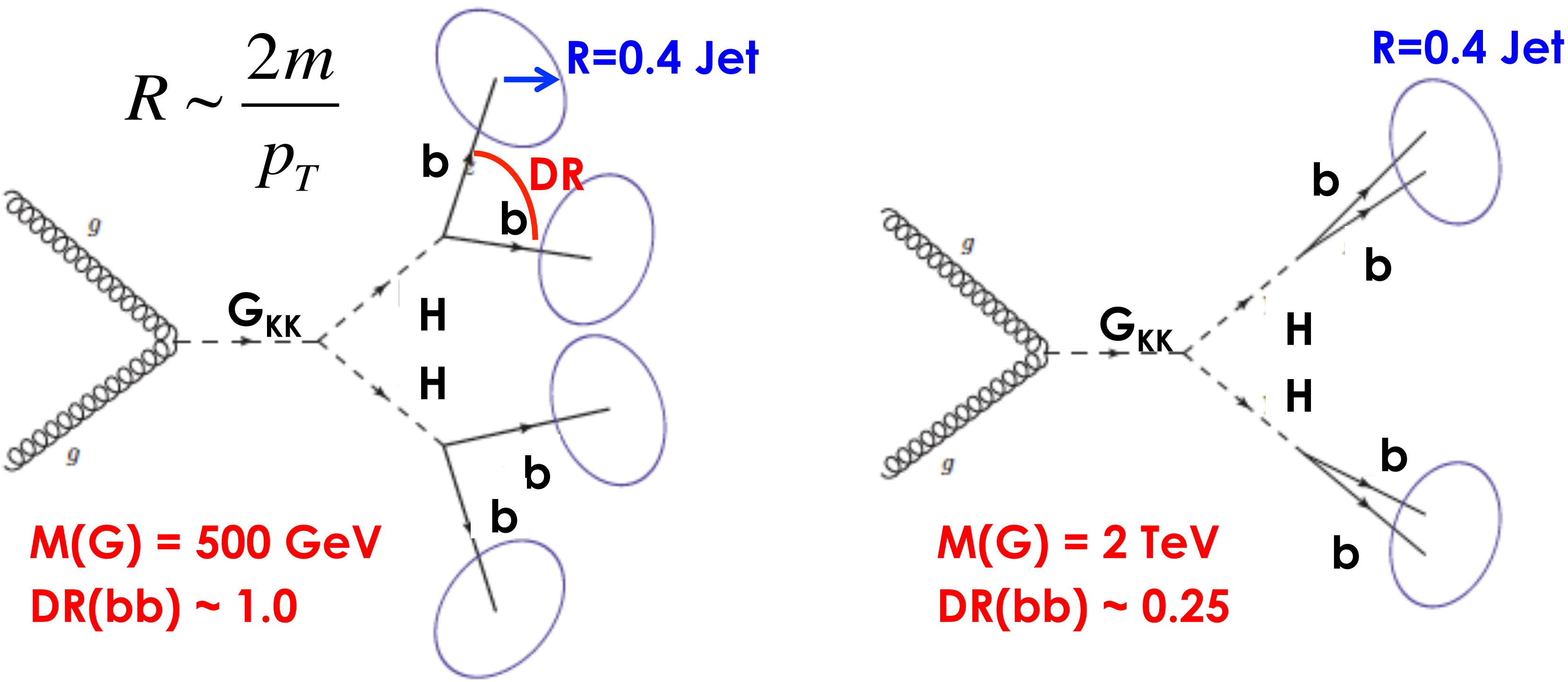


Quark-like



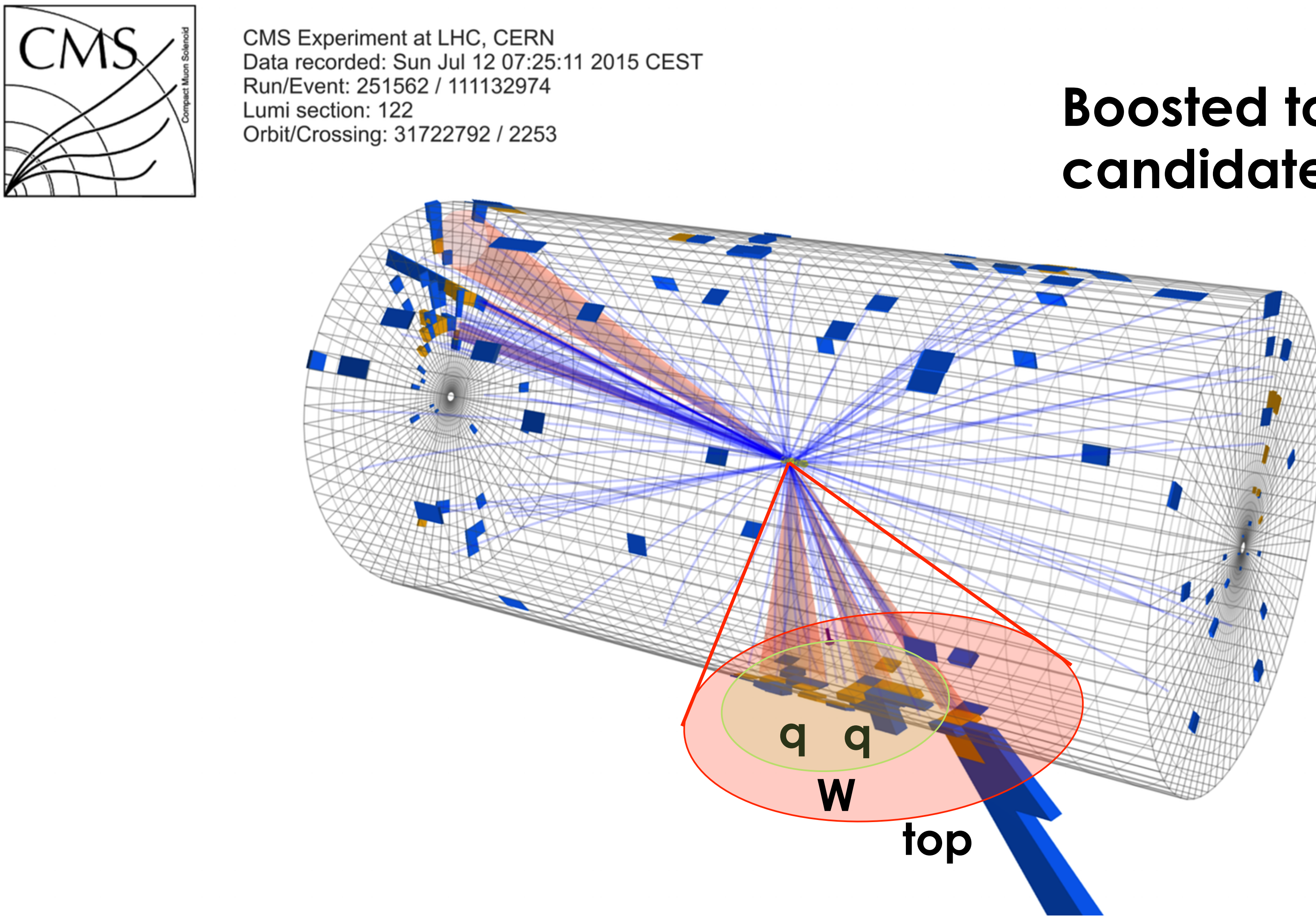
Boosted EW objects

Due to the large hierarchy of scales at the LHC ($\sqrt{s} >> M_{EW}$), heavy electroweak particles can be highly boosted



Boosted regime: EW decay products are collimated and merged within a single jet

Boosted top pair candidate event



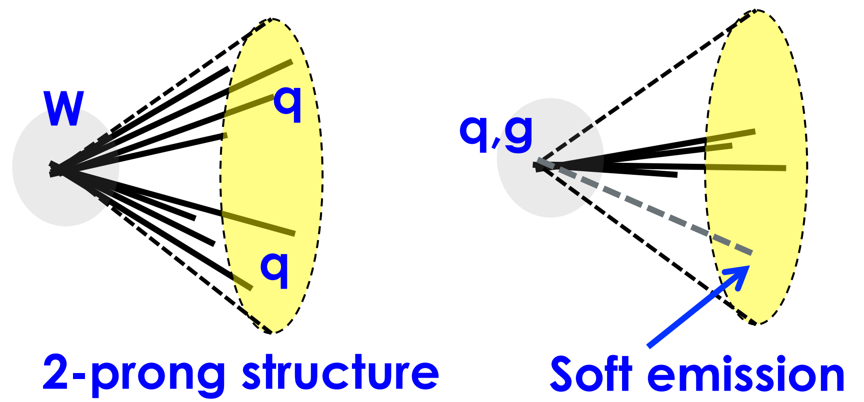
Jet substructure

Use large radius jets + internal jet structure:

Large-R jets from the decay of a massive particle have different characteristics than jets originating from quarks and gluons (soft divergences in QCD)

See K. Ellis' lecture 3

Single large-R jet



- **Jet mass**
- **N-prong structure**
- **Radiation pattern**

- **Two main challenges:**
  - **Very large QCD background**
  - **High pileup**
    - Contamination proportional to the area of the jet:
      - x6 increase from *R=0.4* to *R=1.0*

Jet substructure

Two major ideas:

Tagging

Identify the internal structure of jets

Reduce QCD background

Grooming

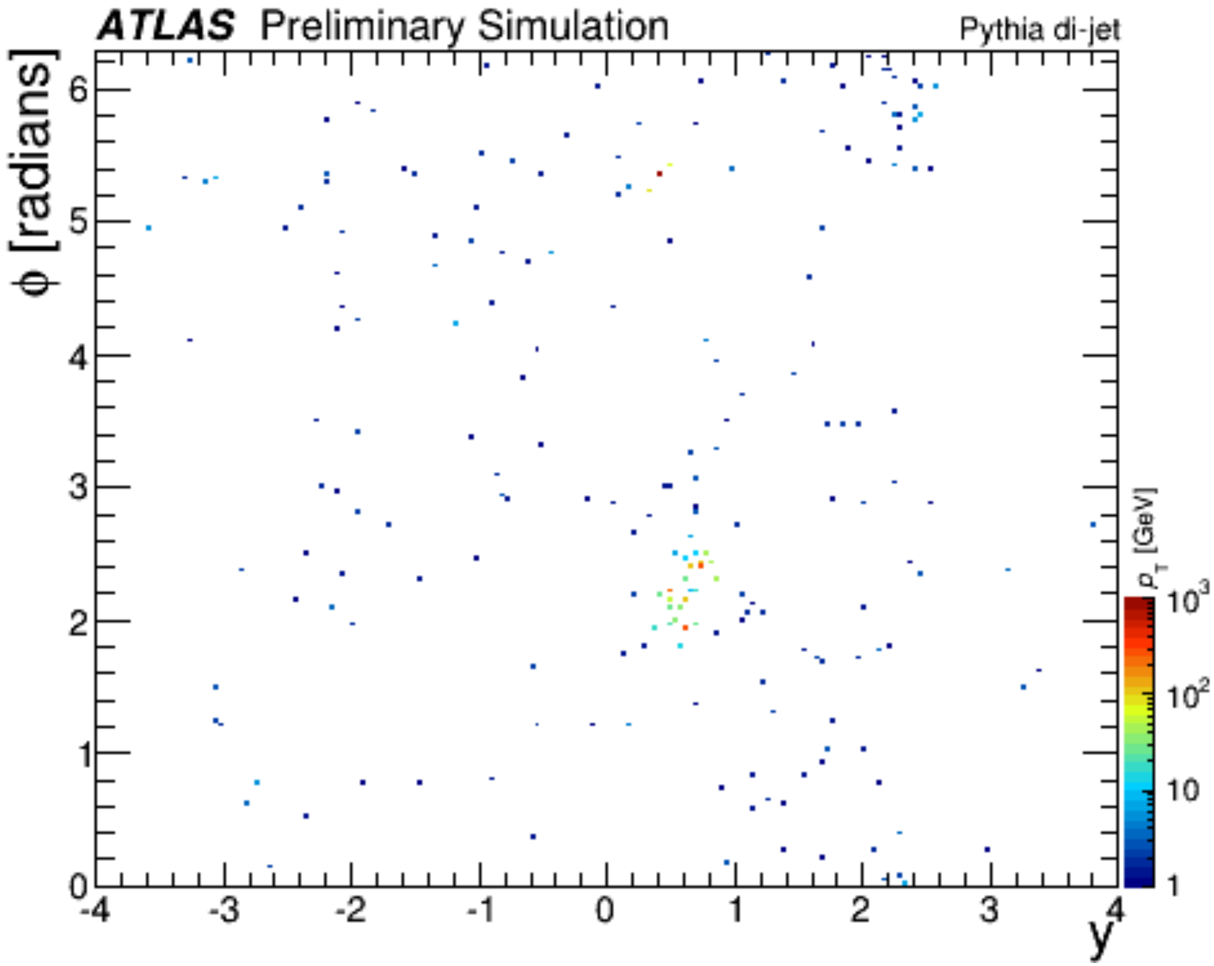
Reduce contamination from pile-up

Improve the signal mass resolution

Many techniques!

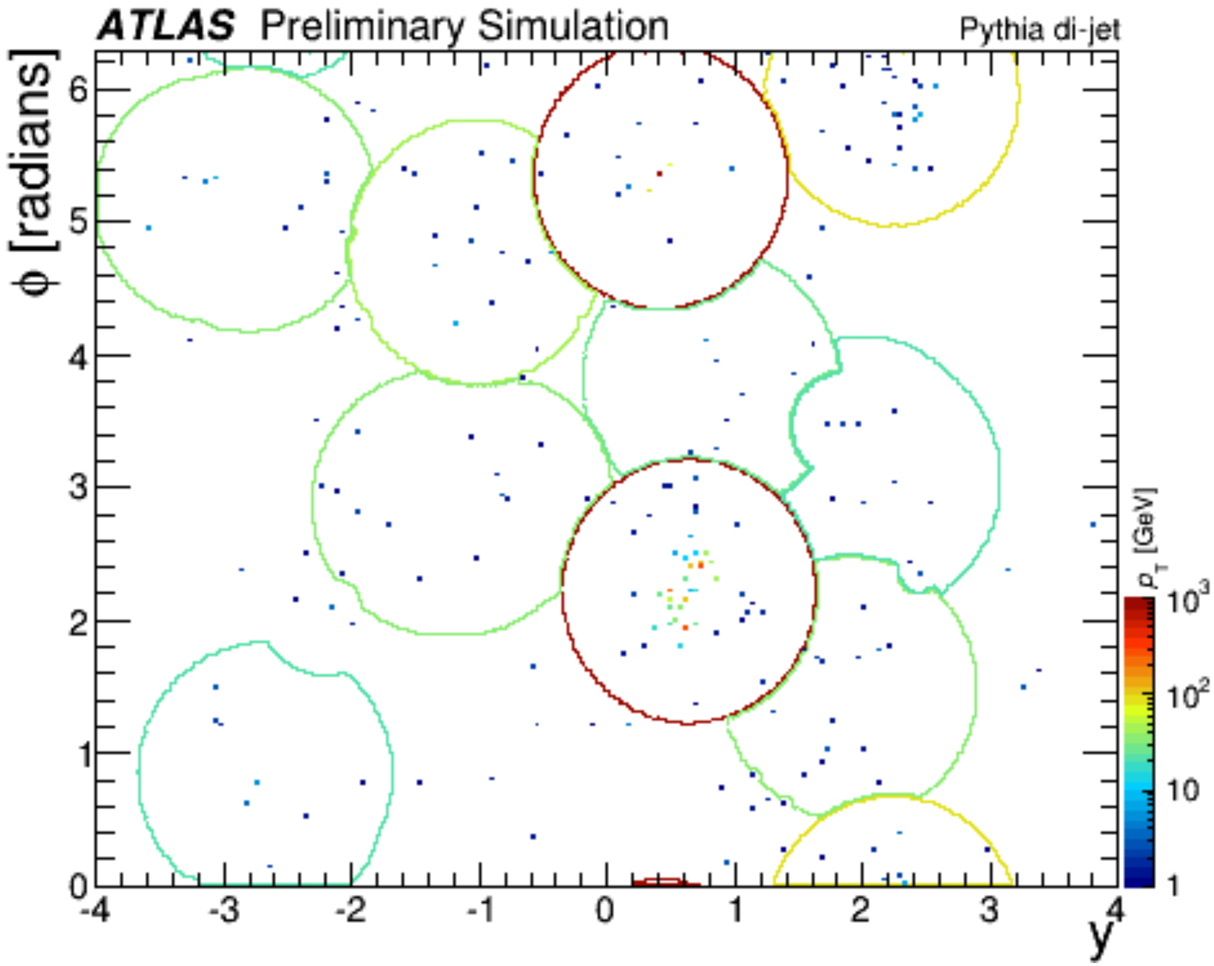
- trimming, filtering, pruning, mass drop, soft drop, HEPTopTagger, Shower Deconstruction, N-subjettiness, planar flow, energy correlations, template method, jet images,…

Jet trimming (1/4)



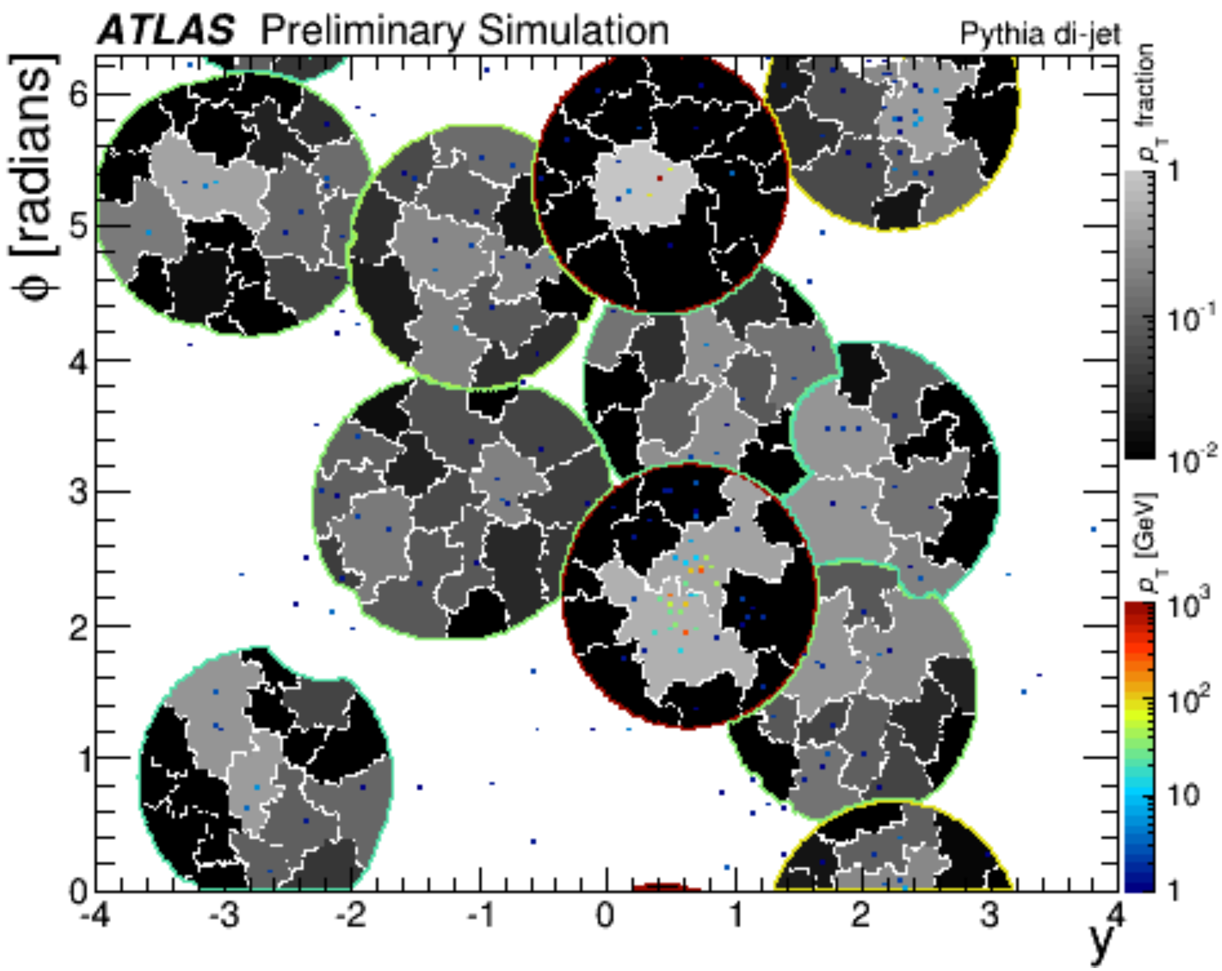
Pythia di-jet event (QCD background)

Jet trimming (2/4)



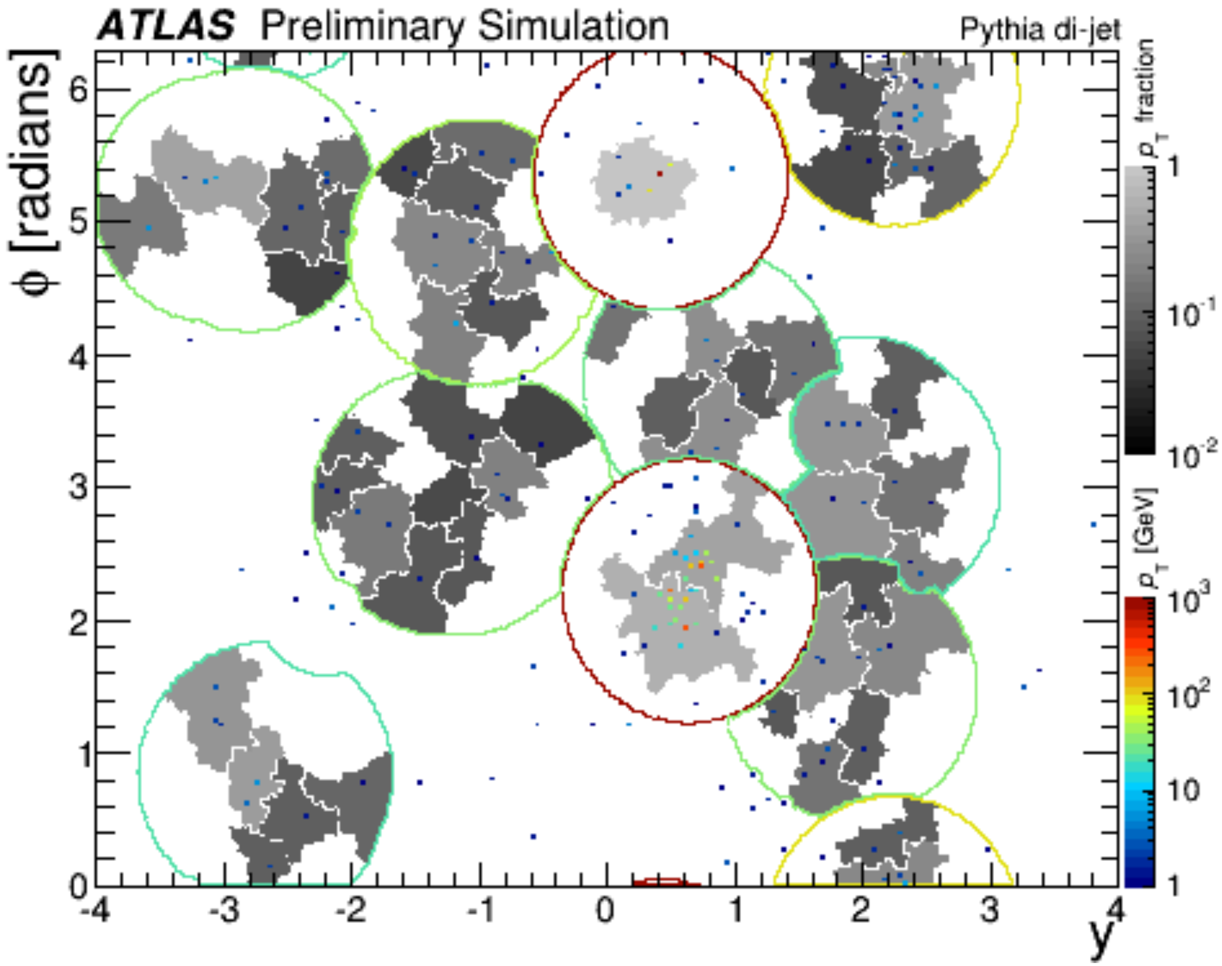
Anti-k_t (R=1.0) jet built from topo-clusters (p_T>20 GeV)

Jet trimming (3/4)



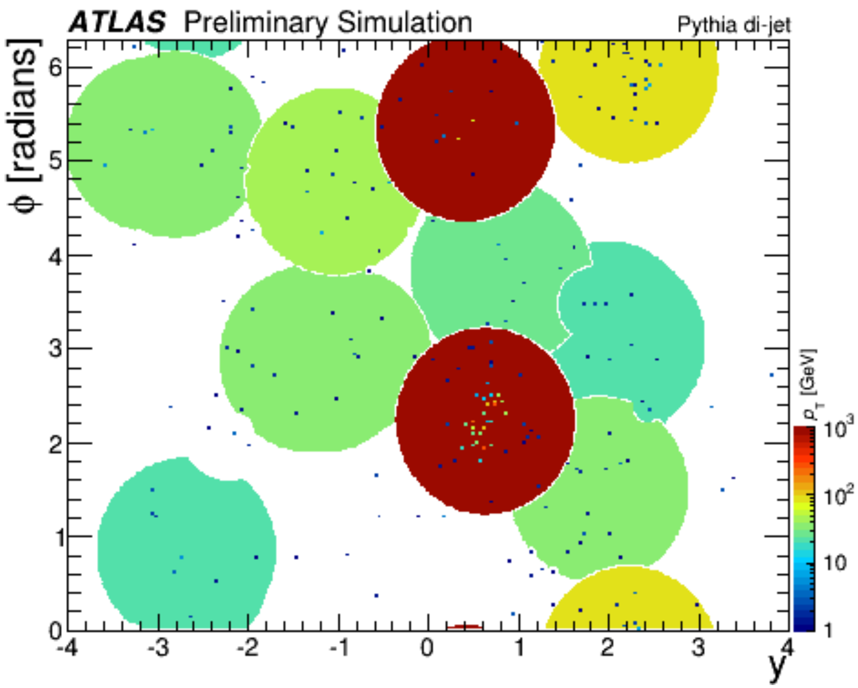
Re-cluster jet constituents with the k_t R=0.3 jet algorithm: **subjets**

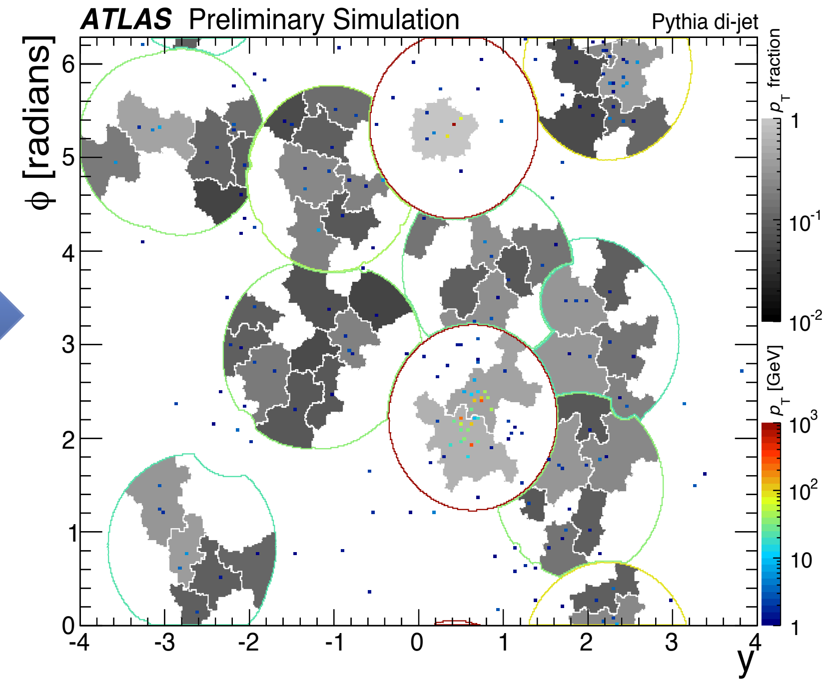
Jet trimming (4/4)



Remove soft subjets if $p_T^{subjet} < f_{cut} . p_T^{jet}$

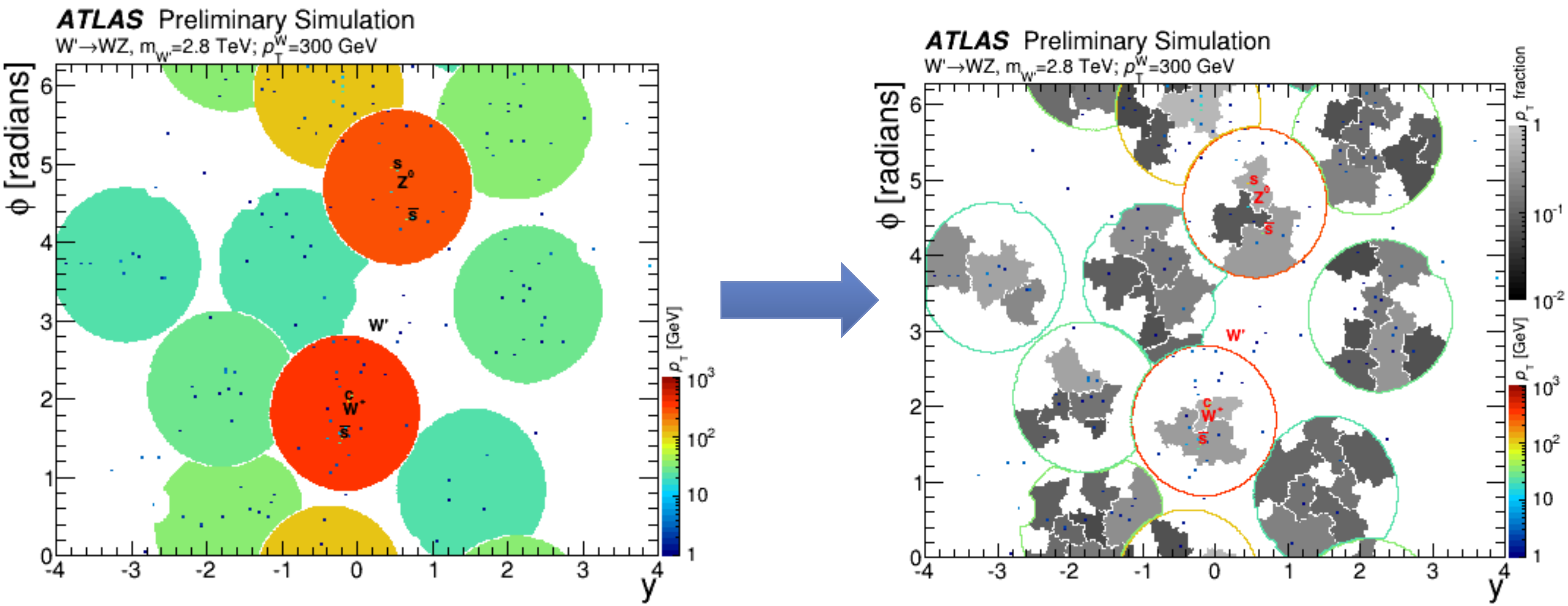
Jet trimming (QCD)





Grooming effectively reduces the area of jet, reducing the jet sensitivity to pileup fluctuations

Jet trimming (W/Z)

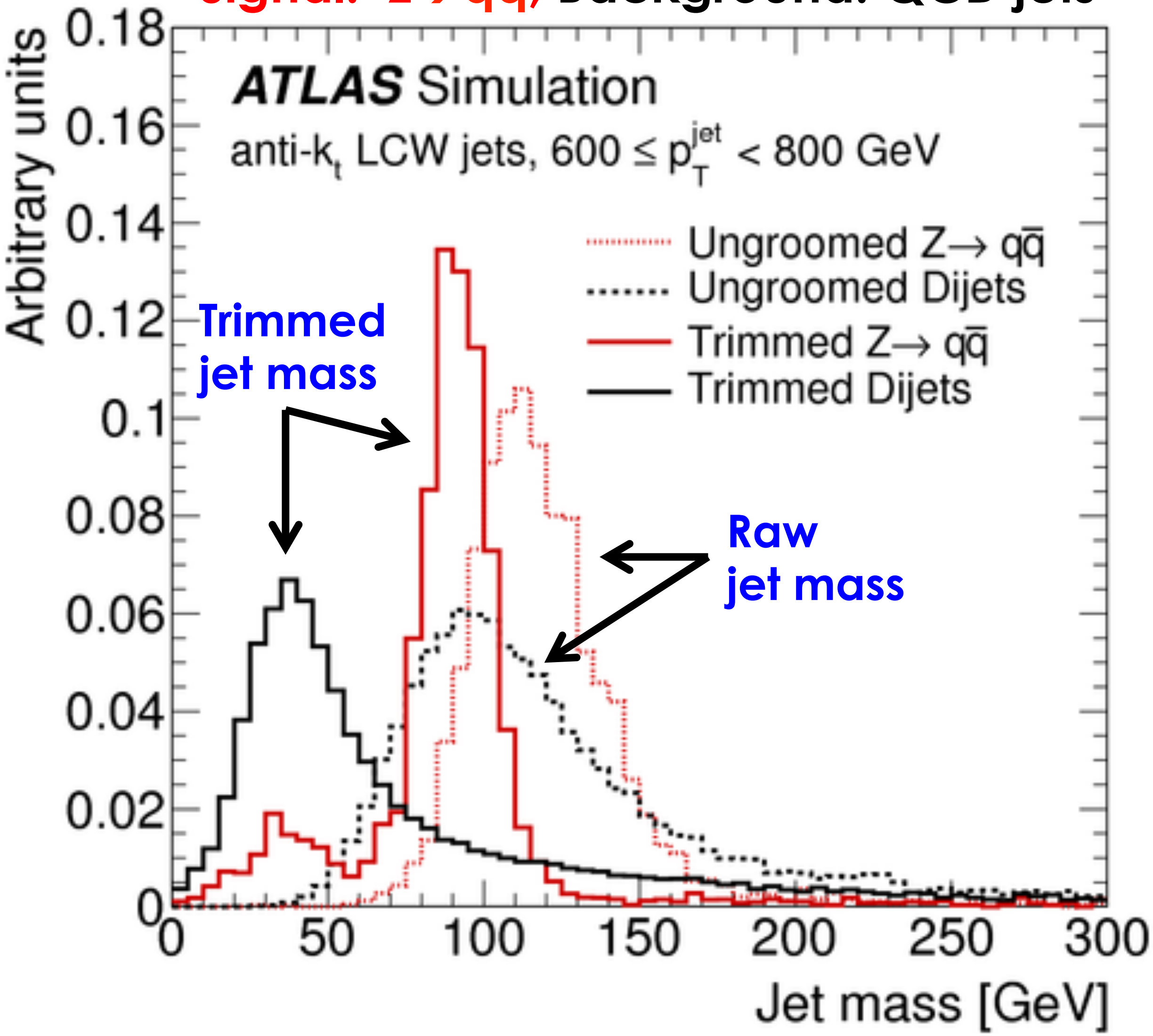


Grooming retains the hard n-prong structure of boosted electroweak objects

Trimming performance

JHEP09 (2013) 076

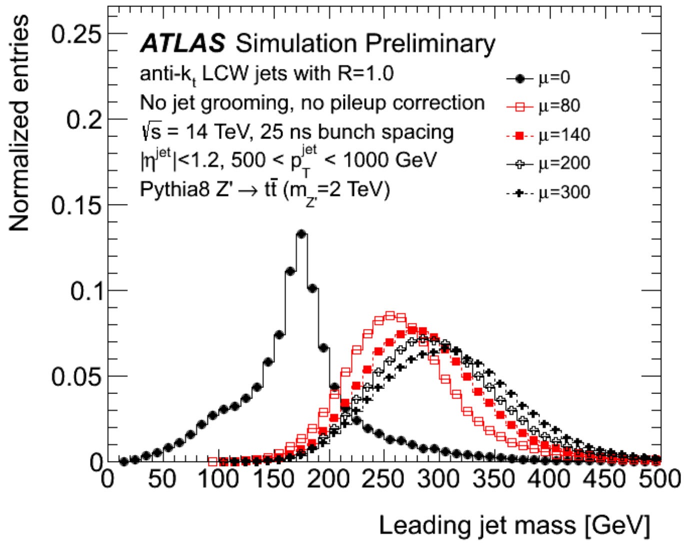
Signal: Z→qq, Background: QCD jets



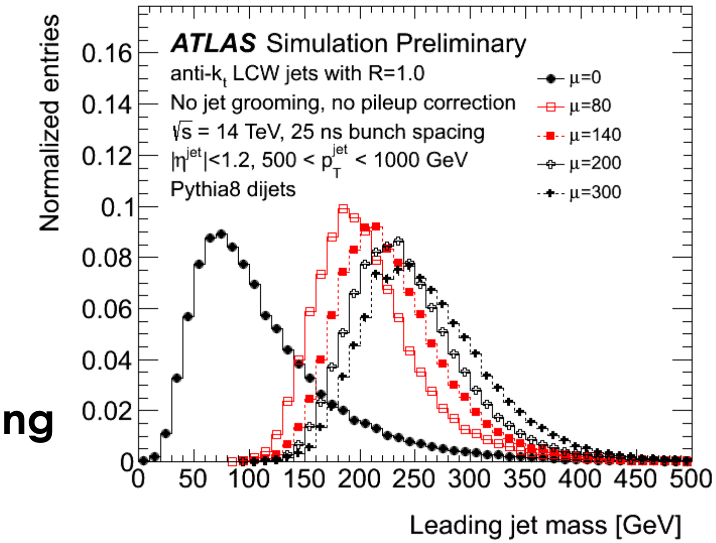
- **Improved mass resolution** (sharpens the mass peak)
- **Reduced QCD background** (improved S/B)

Top quark mass with 300 PU

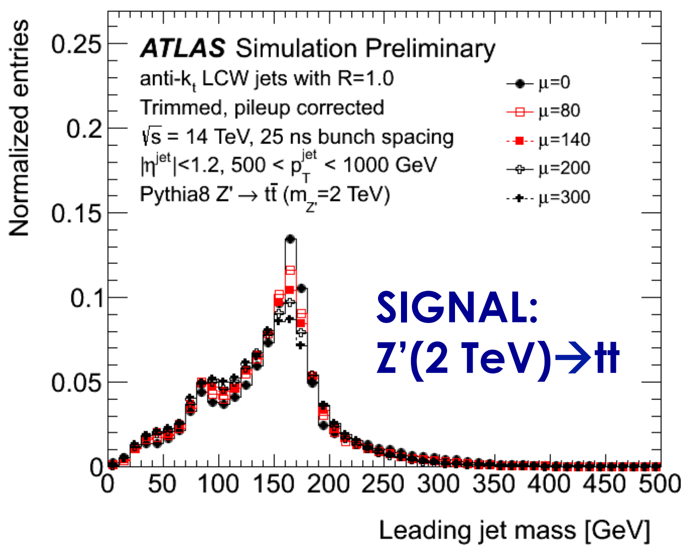
SIGNAL: Z'(2 TeV)→tt

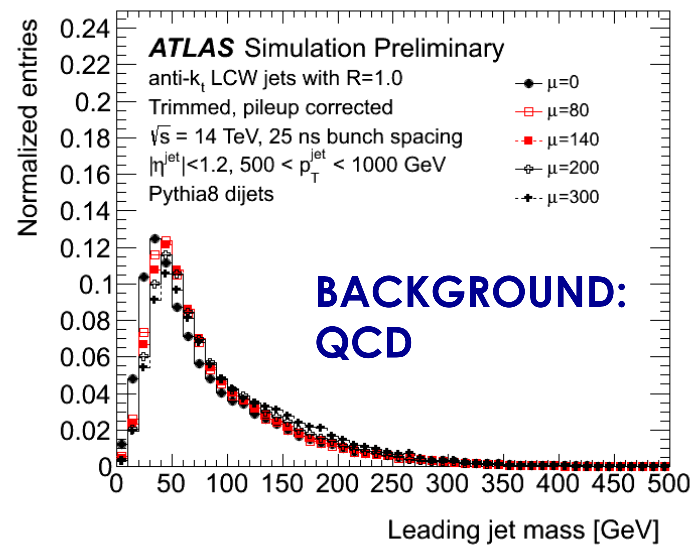


BACKGROUND: QCD



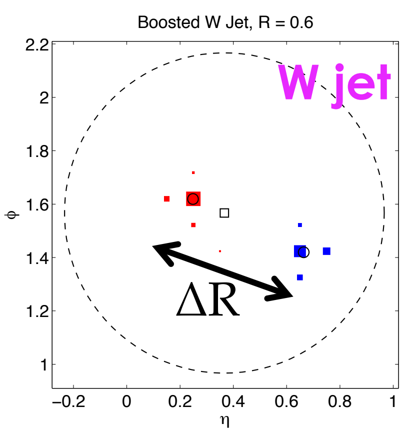
grooming

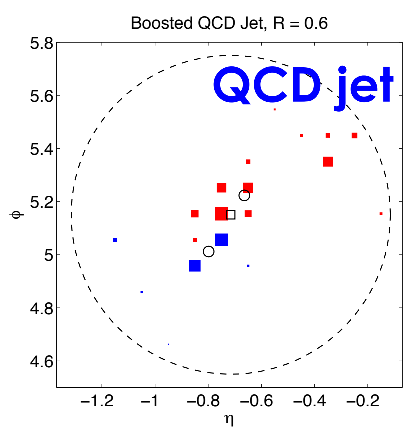


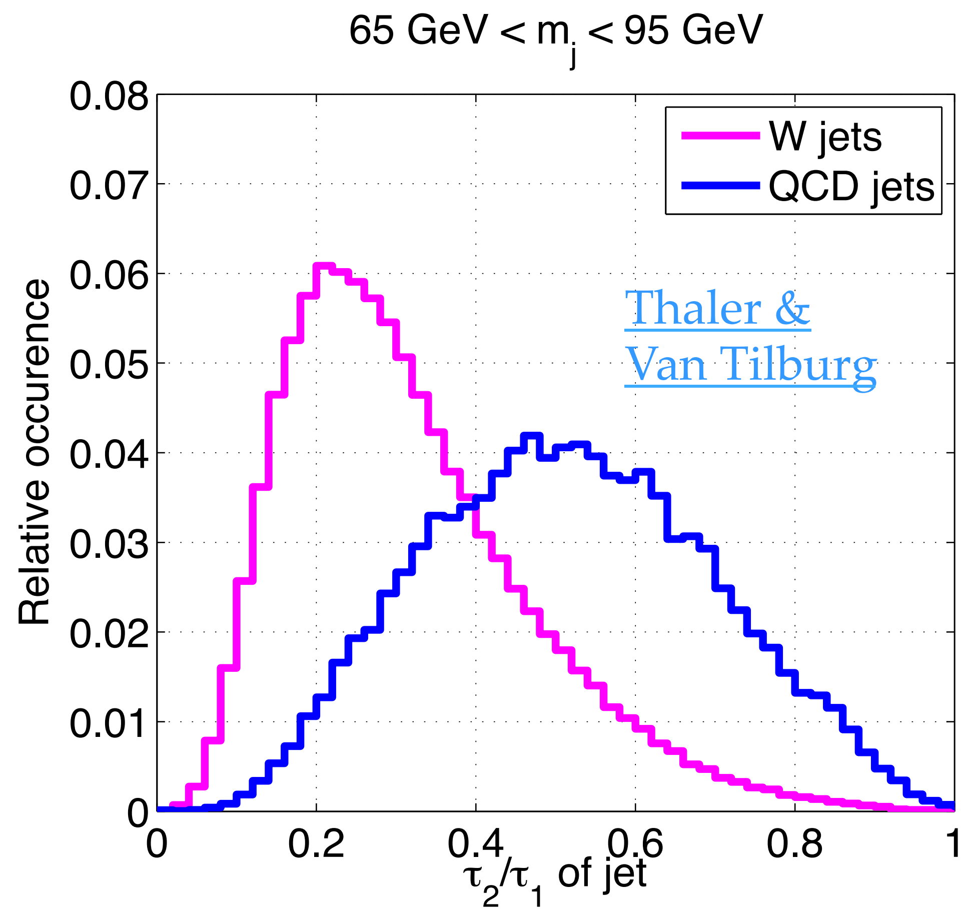


W jet tagging

- **n-subjettiness:**
  - Measures the n-prong structure of jets

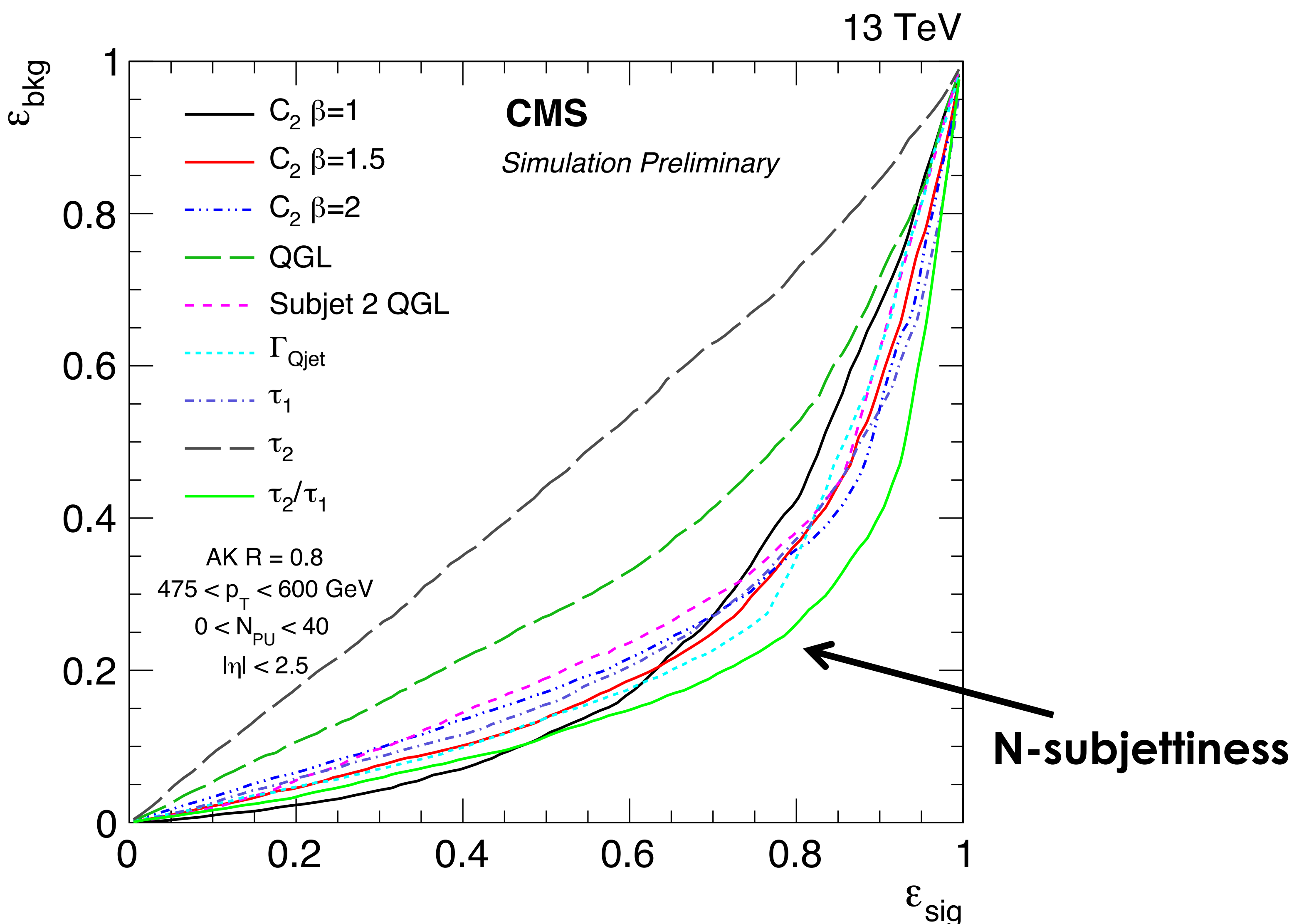






$$\tau_N = \frac{1}{d_0}\sum p_{T,k} \min\{\Delta R_{k,axis-1},\dots,\Delta R_{k,axis-n}\}$$

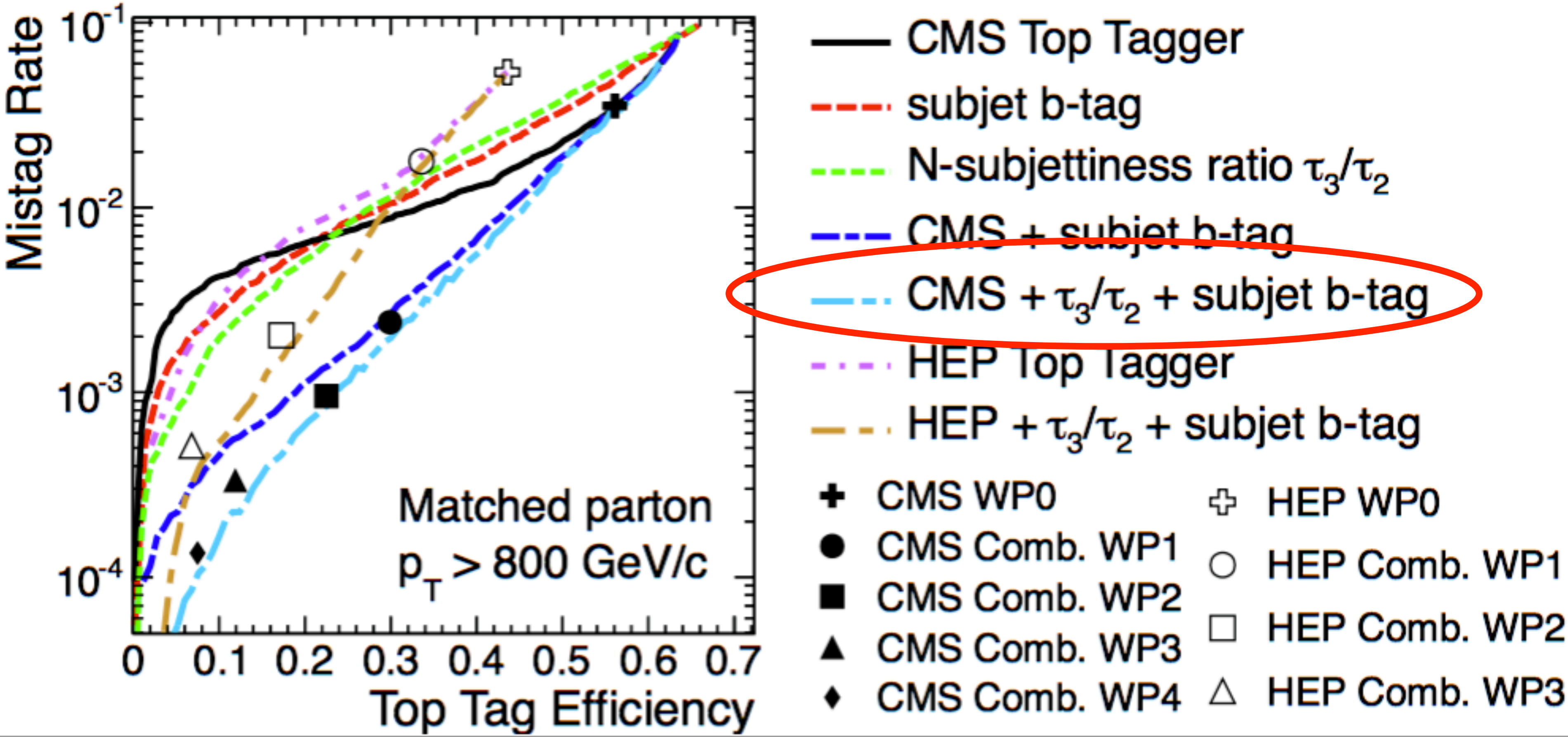
W jet tagging



CMS-PAS-JME-14-002

Top tagging (Run 1)

C/A R=0.8 jets

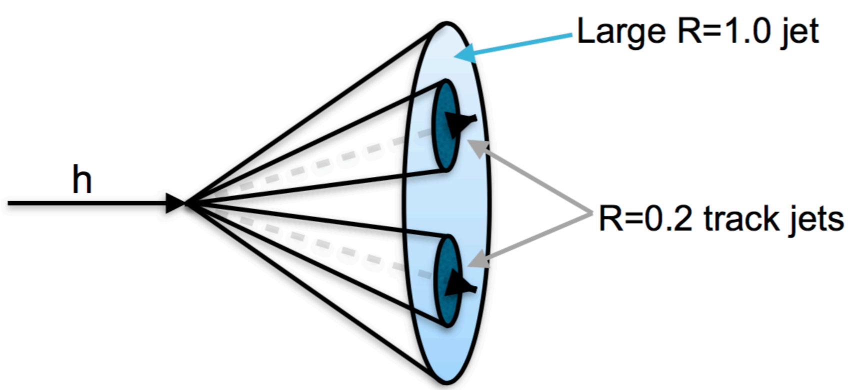


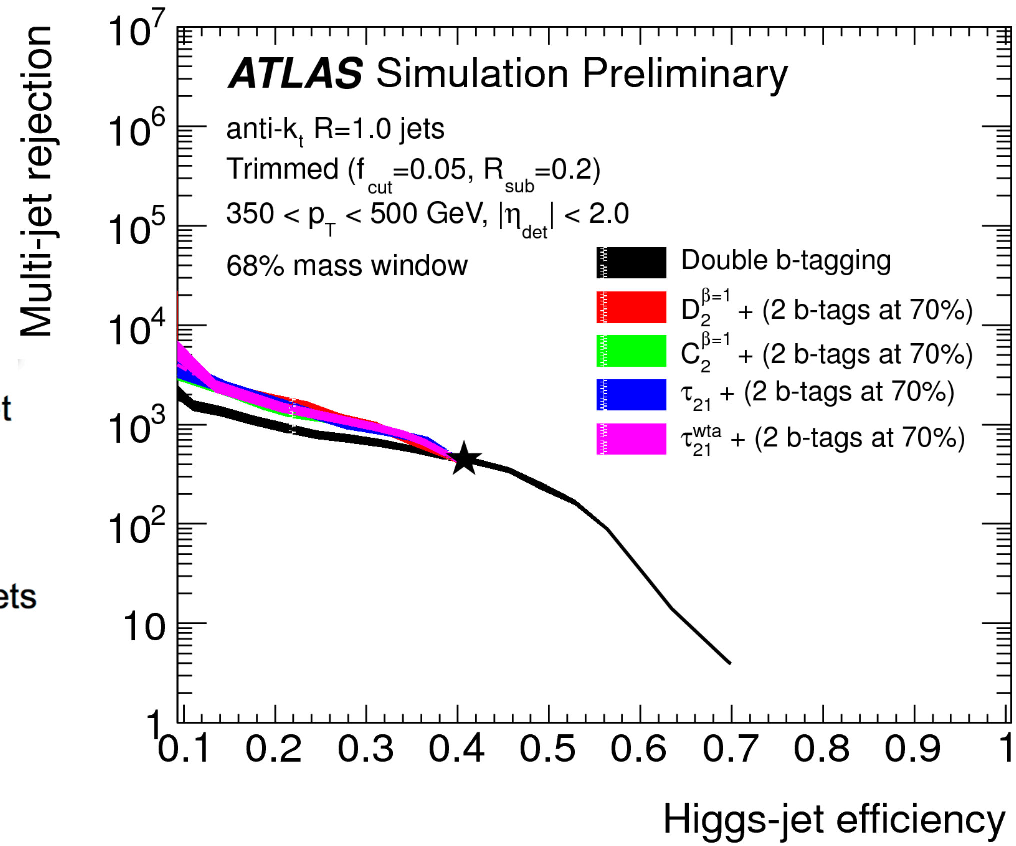
CMS-PAS-JME-15-002

Higgs tagging

- Use small-R (R=0.2) track-jets to resolve b-hadrons at small angular distances
- Associate b-tagged track-jets to un-groomed large-R jets

- Double b-tagging provides most of the discrimination power





ATLAS-PHYS-PUB-2015-035

Very high p_T jets

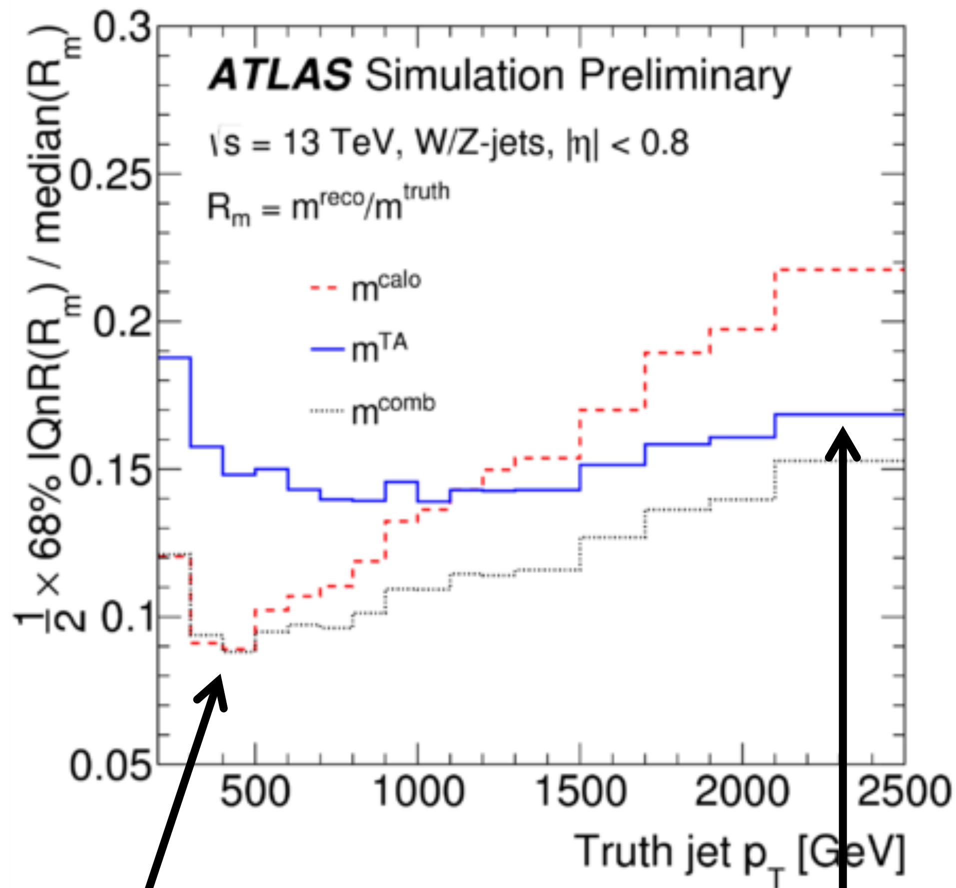
- At very high boost, the decay products of EW objects can merge into single cells

- **Track-assisted mass:**

$$m = m^{track} \times \left[\frac{p_T^{calo}}{p_T^{track}} \right]$$

Measure substructure with tracks

Measure p_T with calorimeter



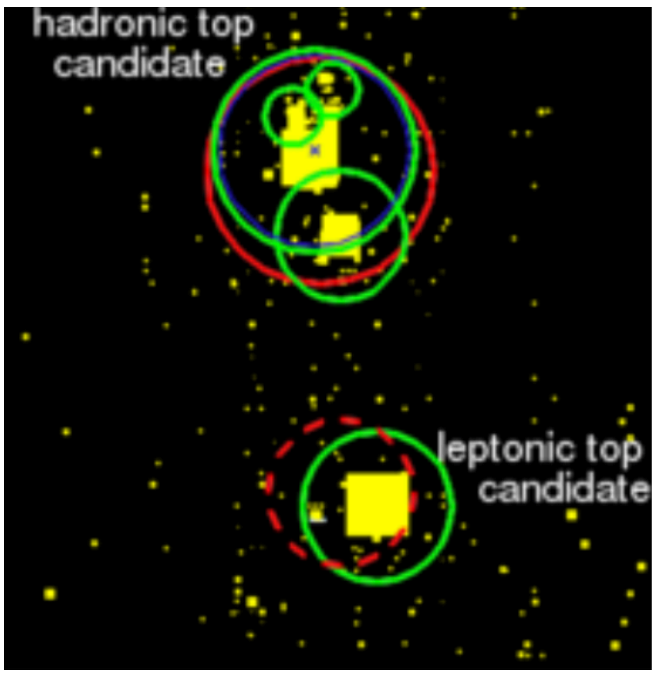
Low p_T: Calorimeter better

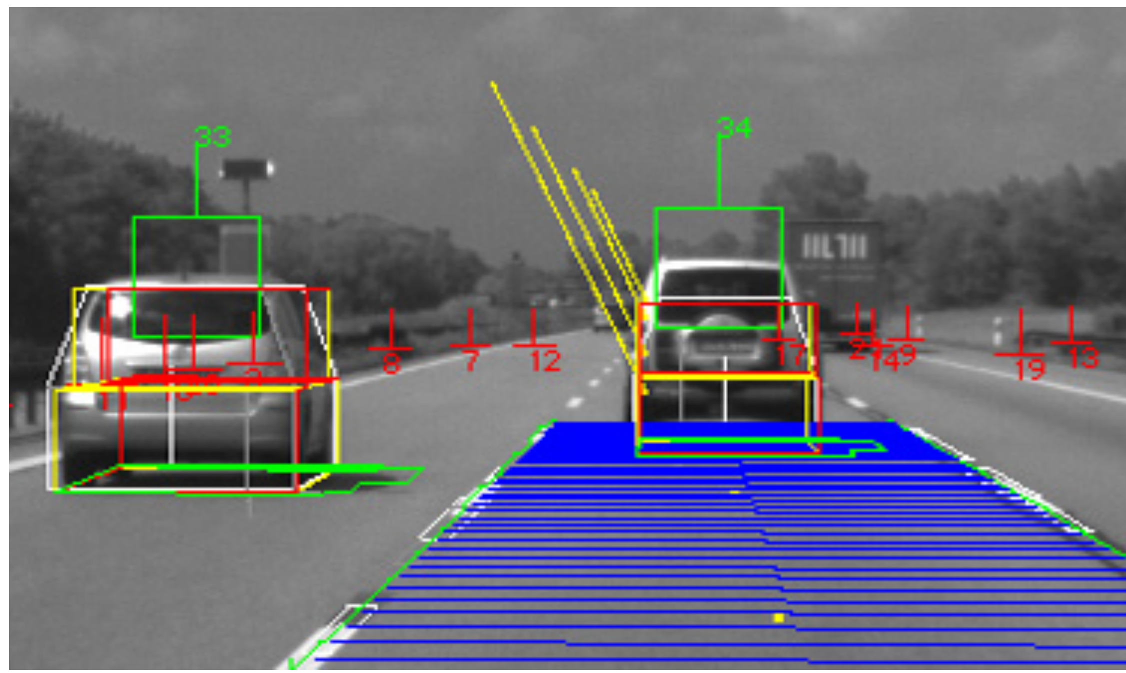
High p_T: TA-mass better

ATLAS-CONF-2016-035

Jets and machine learning

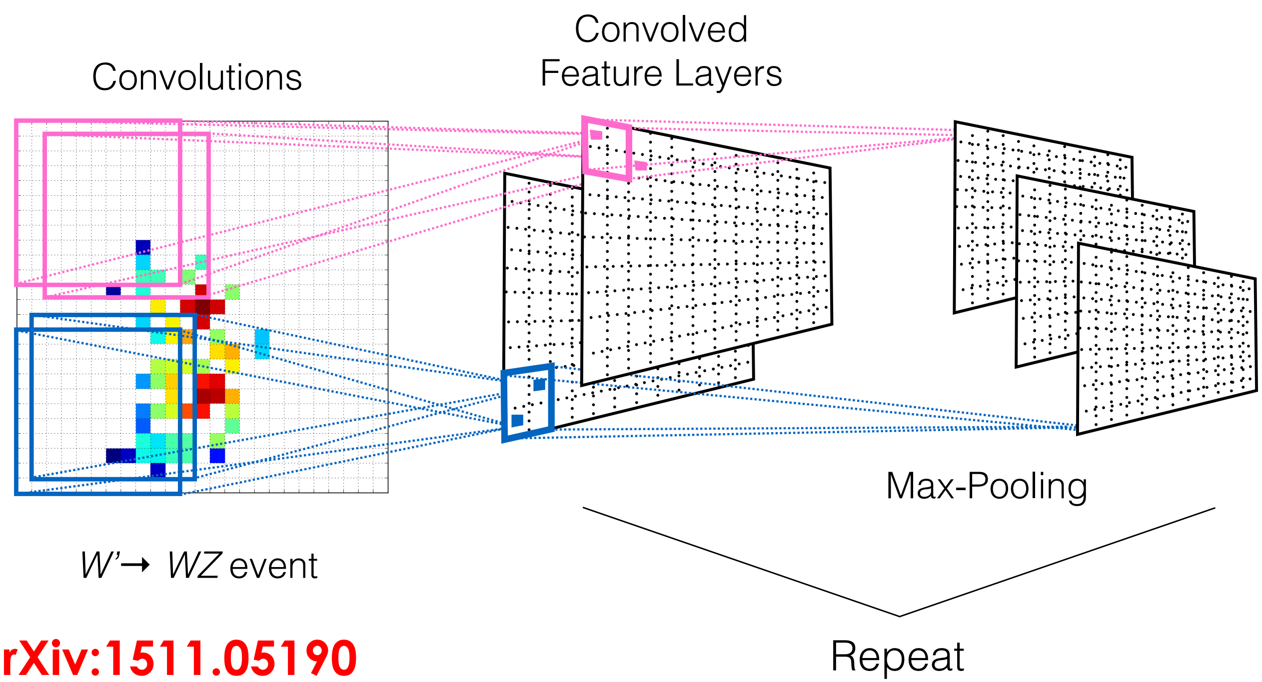
- **Jet tagging as a computer vision problem**
- Utilize state-of-the art image processing/classification to analyze jets in new ways

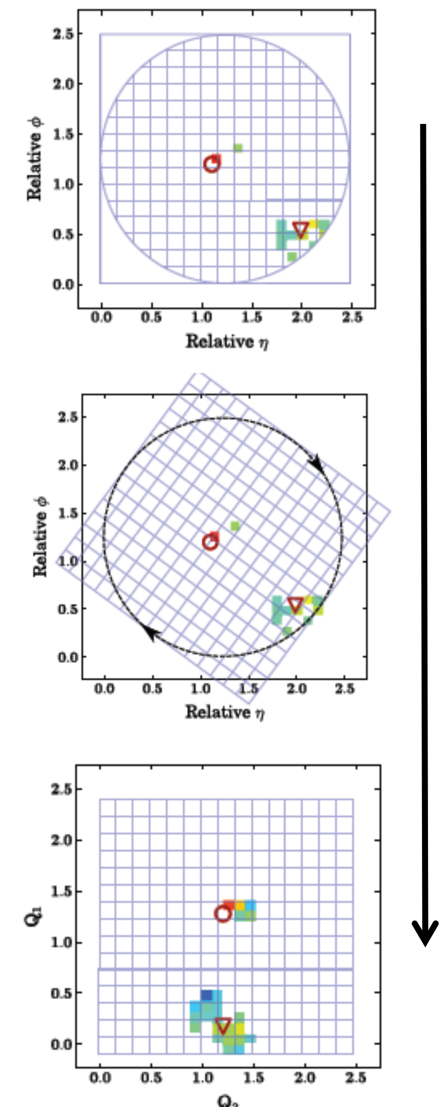




Deep learning W tagging

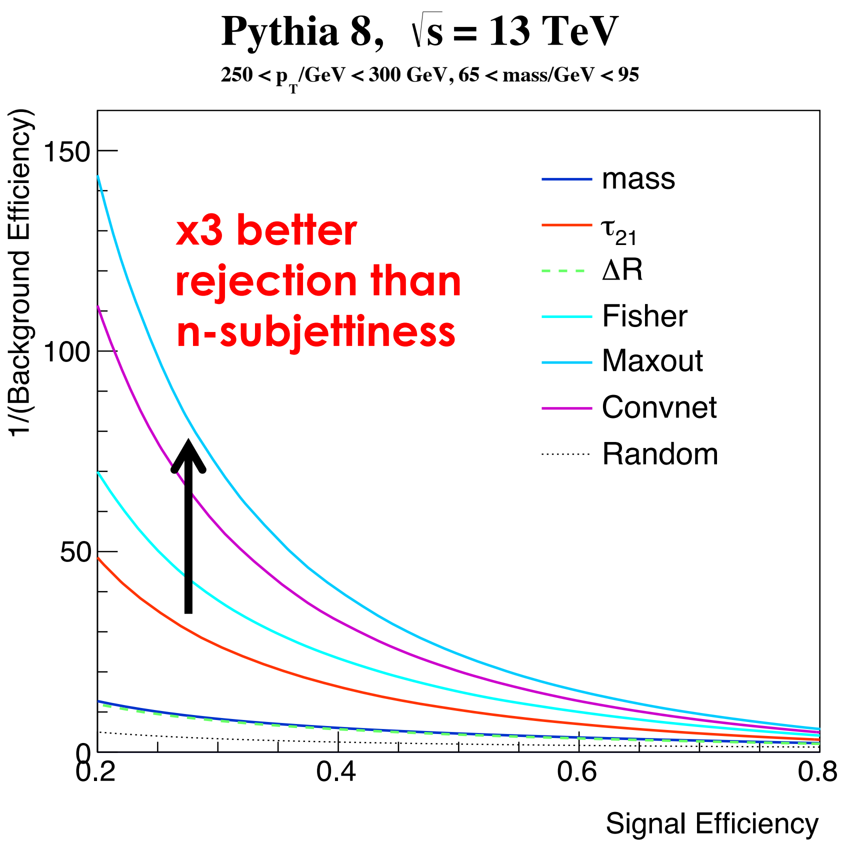
- **New data representation: the jet-image**
  - Calorimeter towers → **pixels in a camera**
- Use all available calorimeter information
- Enable the use of cutting-edge computer vision image classification algorithms (deep neural networks)

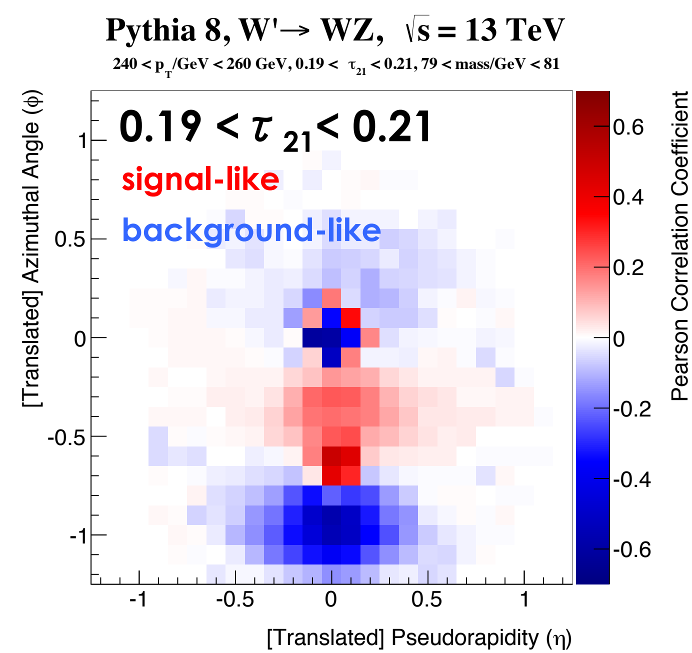




arXiv:1511.05190

Deep learning W tagging





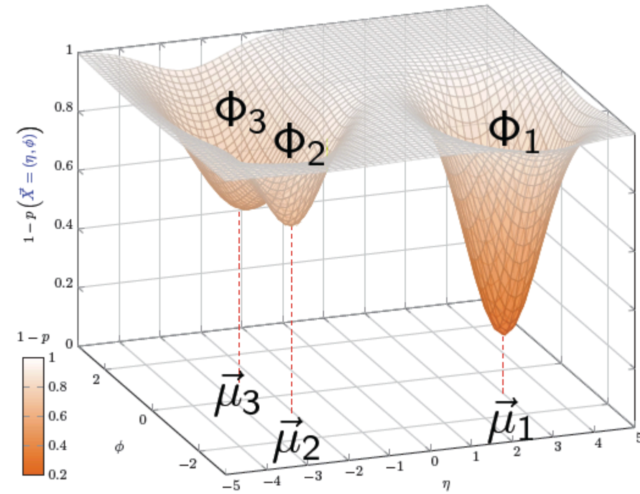
Deep correlation jet-image: Pearson Correlation coefficient of pixels intensity with the network output: how discriminating information is contained within the network

- **Large performance gains beyond jet substructure observables**
- **Visualization of the discriminant adds a new capability** to understand the physics within jets

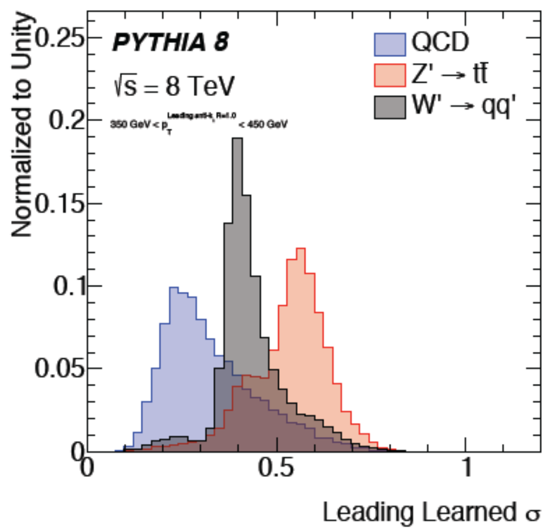
Fuzzy jets

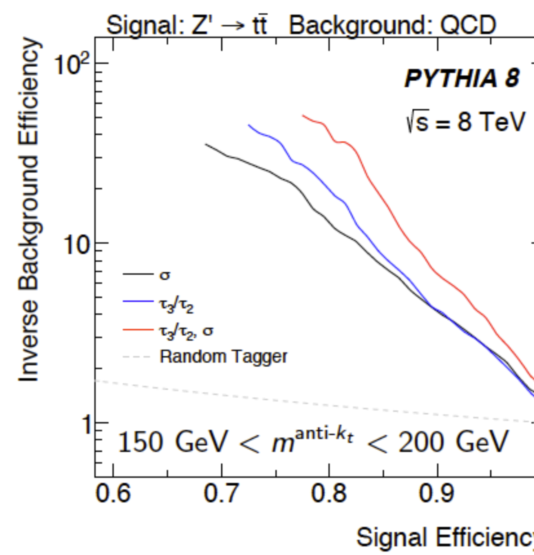
arXiv:1509.02216

- **View jet clustering as an *unsupervised learning* task**
- For state-of-the-art clustering, every clustered object belongs to exactly one jet
- **Fuzzy jets: incorporate probabilistic membership, in order to learn new features of the jet structure**



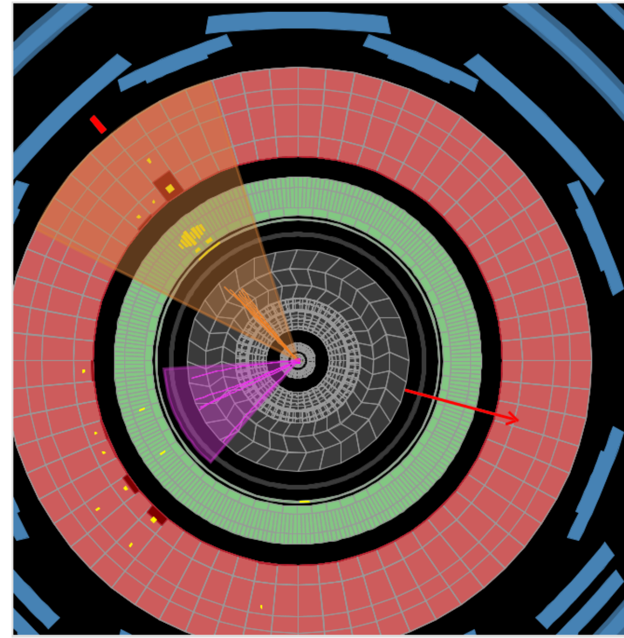
- **Modified Gaussian Mixture Model (IRC safe)**
- Algorithm learns the jet shape
- **Improved top tagging performance**





Missing ET

- One of the most important observables in searches for new physics (SUSY, dark matter) and precision measurements (H, W, top)
- **Transverse momentum imbalance of the event**
  - Relies on the reconstruction (<u>and calibration</u>) of all high p_T objects in the event, as well as the "un-clustered energy"
  - **<u>Pile-up is a major challenge</u>**



$$E_{x(y)}^{miss} = E_{x(y)}^{HARD} + E_{x(y)}^{SOFT}$$

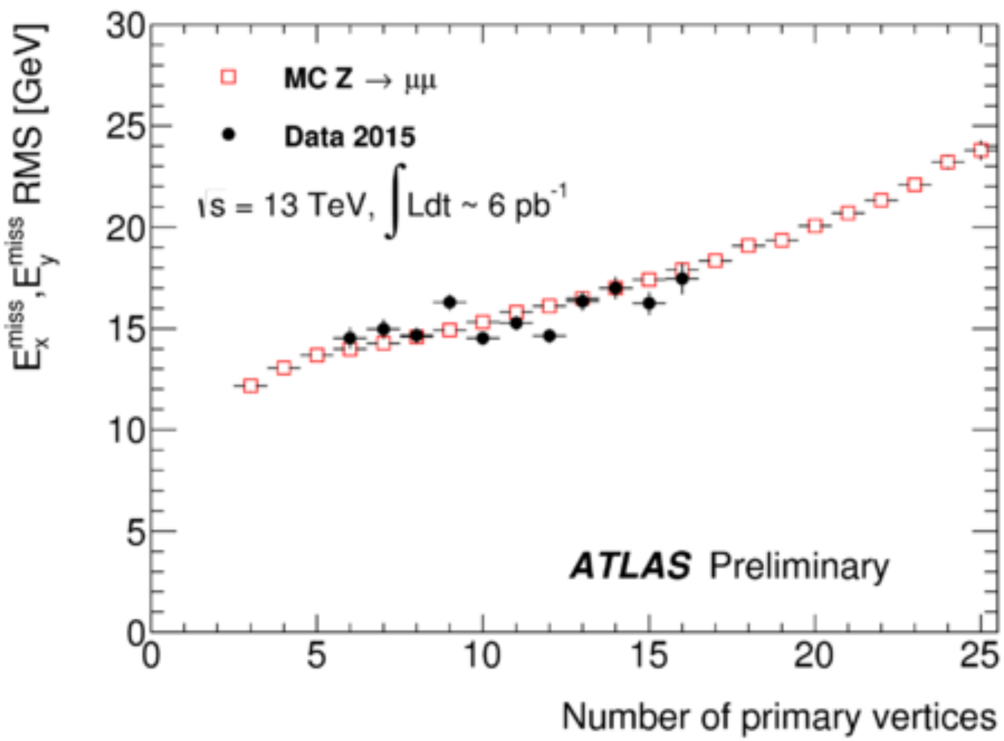
Jets, e, μ , τ "unclustered" E_T

Track Soft Term (ATLAS)
PV-tracks outside hard objects

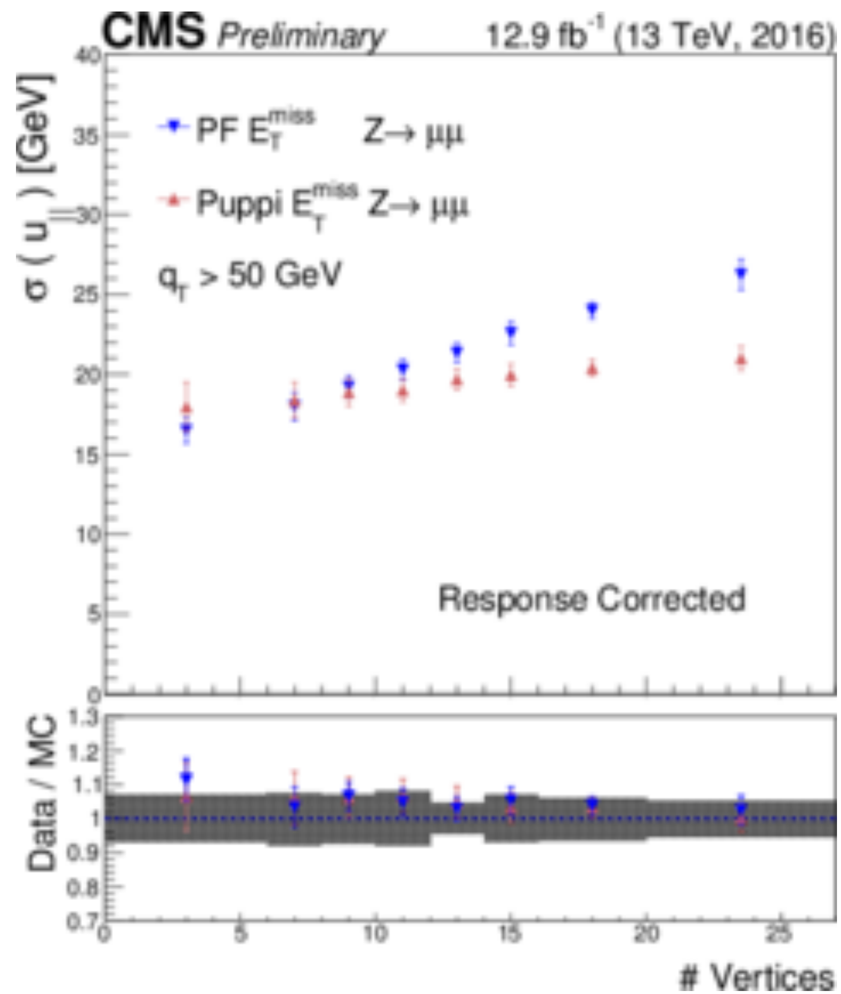
PUPPI (CMS)
Scale the 4-momentum of pflow objects based on a local pile-up probability

Missing ET Performance

- Measured in *Z+jet* events



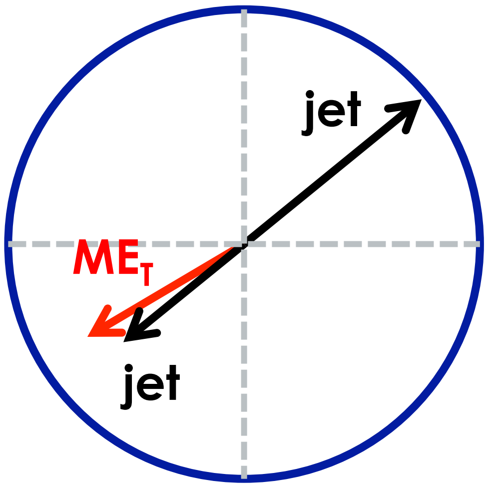
ATLAS-PHYS-PUB-2015-027



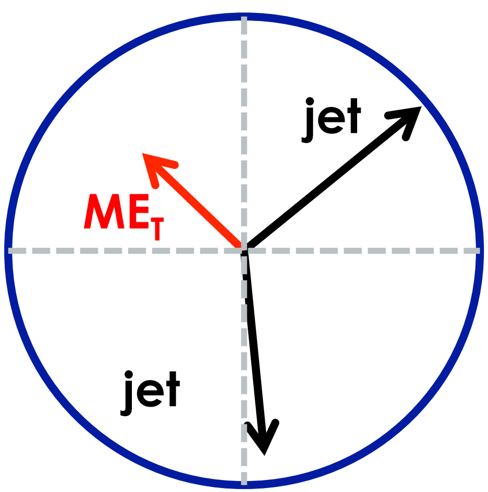
CMS-PAS-JME-16-004

Missing ET Significance

CMS-PAS-JME-16-004



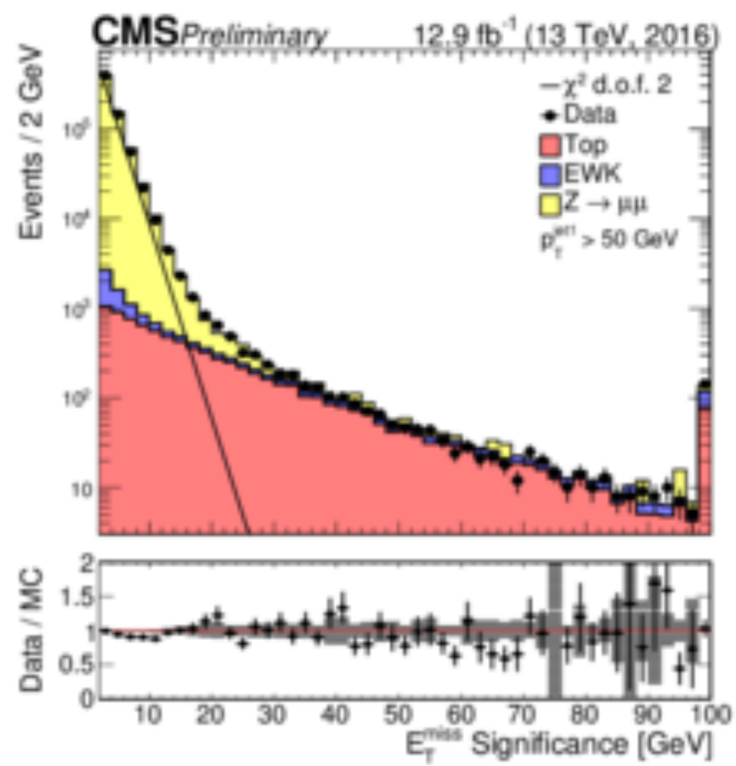
Low ME_T significance



High ME_T significance

- Estimate the probability distribution for ME_T due to resolution fluctuations *event-by-event*

$$S = 2\ln\left(\frac{L(\varepsilon = ME_T)}{L(\varepsilon = 0)}\right)$$

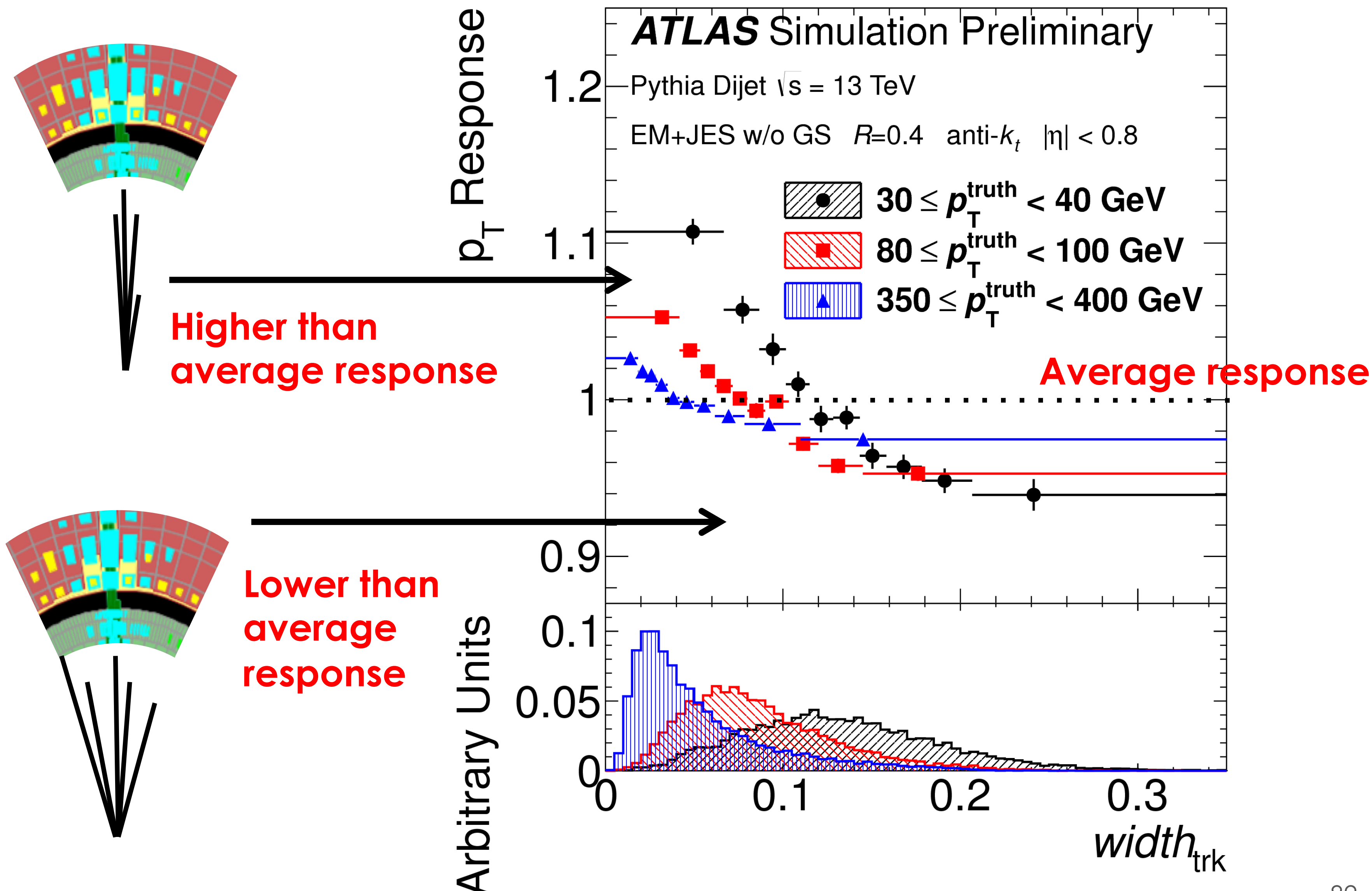


Summary

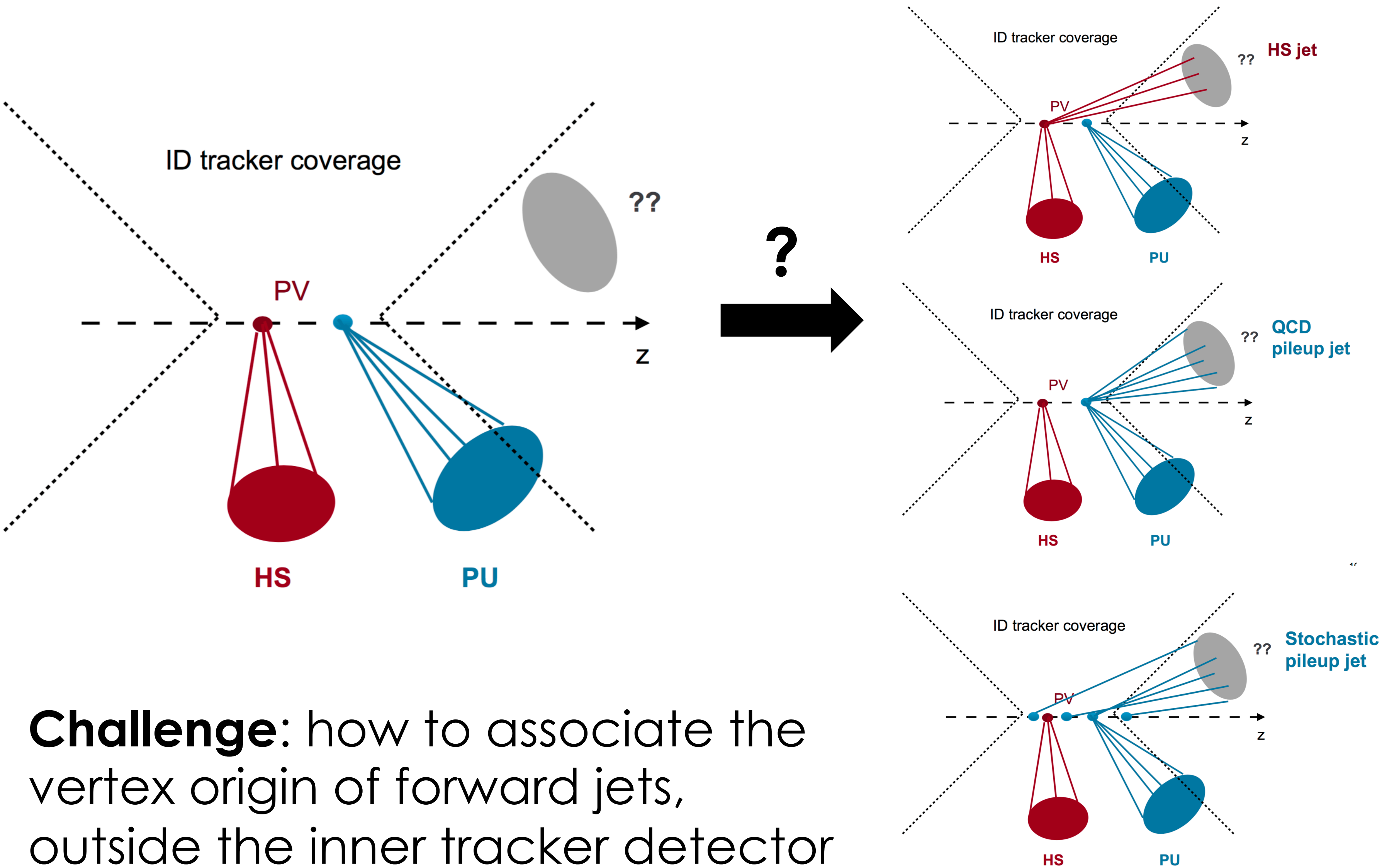
- **Jets and missing ET are key signatures for the analysis of LHC data**
  - Quark, gluons, heavy electroweak particles
  - Quantum properties
- **ATLAS and CMS developed sophisticated techniques for the reconstruction and calibration of jets combining calorimeter and tracking information**
  - Different approaches motivated by the different detector strengths and capabilities
- **Many different jet algorithms and jet substructure techniques have enabled a rich toolkit for the analysis and interpretation of events at the energy frontier**

Backup

Reducing fluctuations (III)



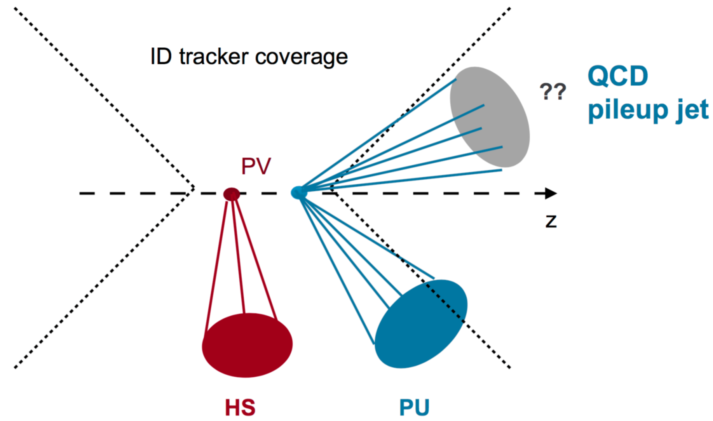
Forward pile-up jets

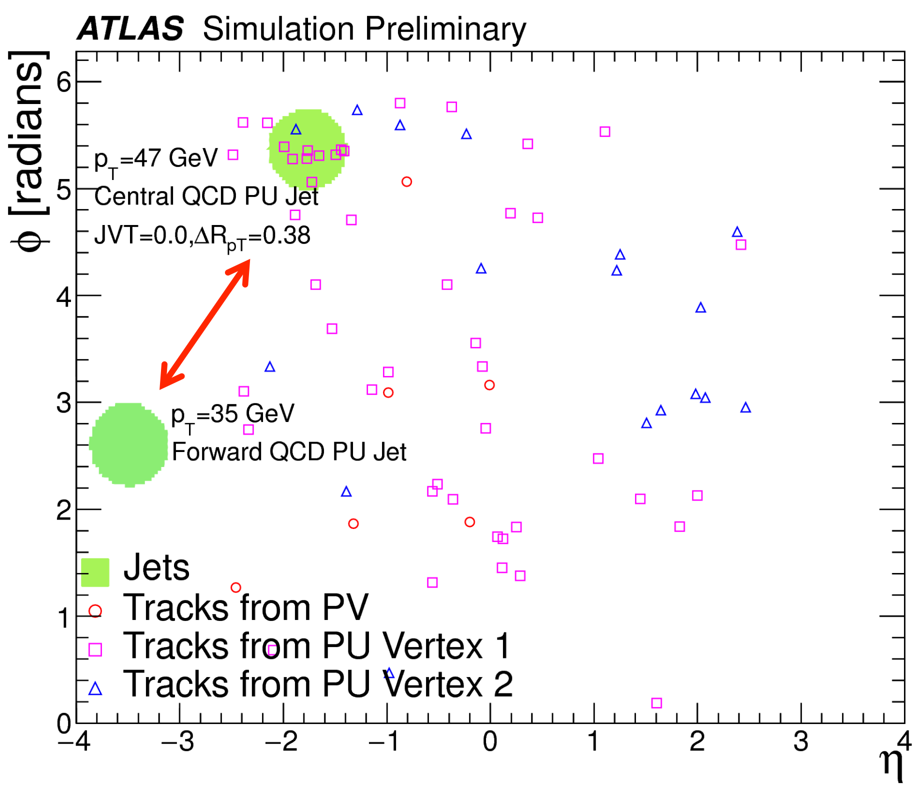


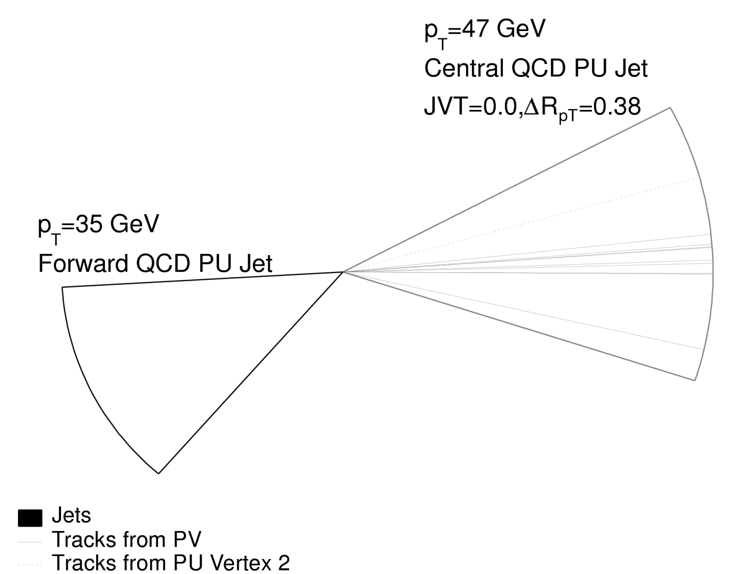
- **Challenge**: how to associate the vertex origin of forward jets, outside the inner tracker detector

Forward pile-up jet tagging

- **Use tracks in the central region to indirectly tag forward pileup jets:** Exploit angular correlations of *QCD* jets produced in pile-up interactions

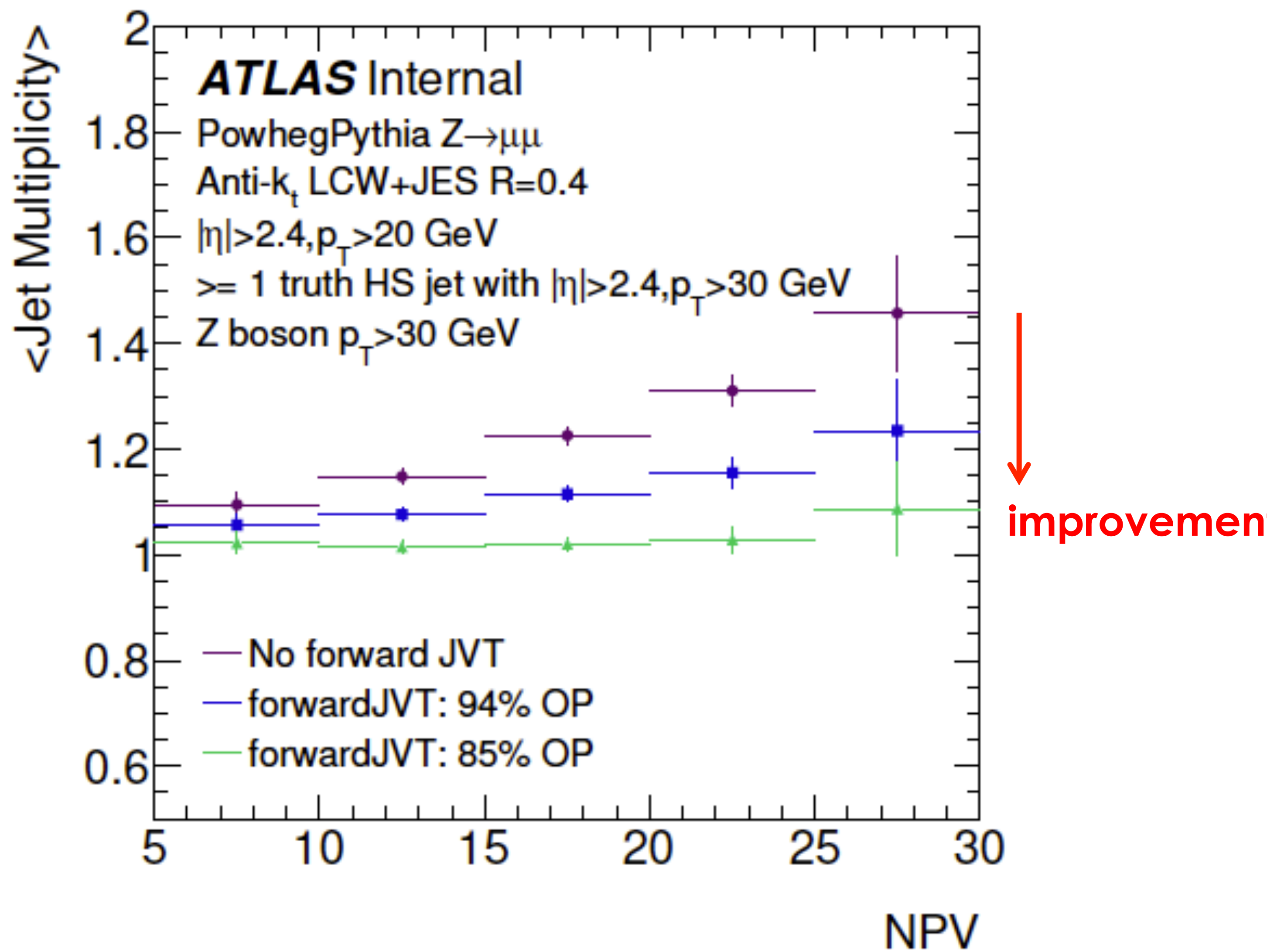






Back-to-back QCD pile-up in the central region

Forward pile-up jet tagging

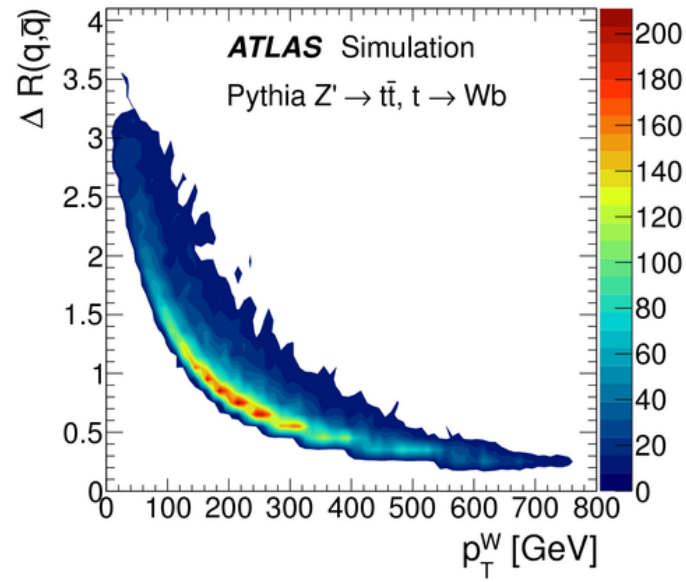


ATLAS-PHYS-PUB-2015-034

Expanding the use of jets

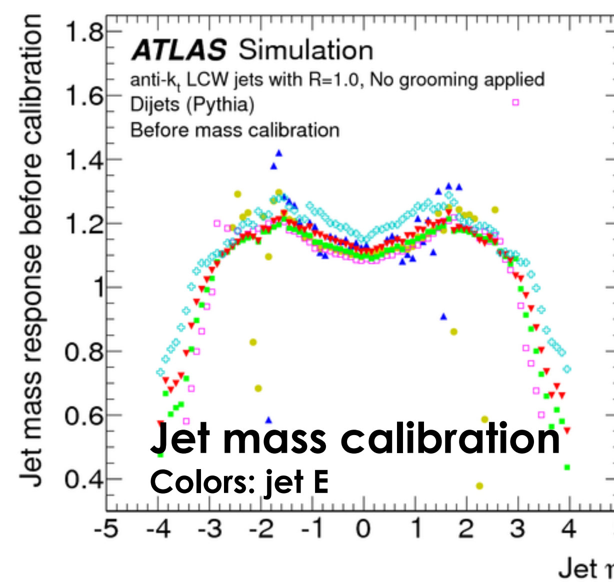
Many motivations to use jets with different R parameters

- Angular size of jets produced by a massive particle scales as $2m/p_T$
- Pileup contamination scales as R^2



<u>Major experimental limitation</u>:

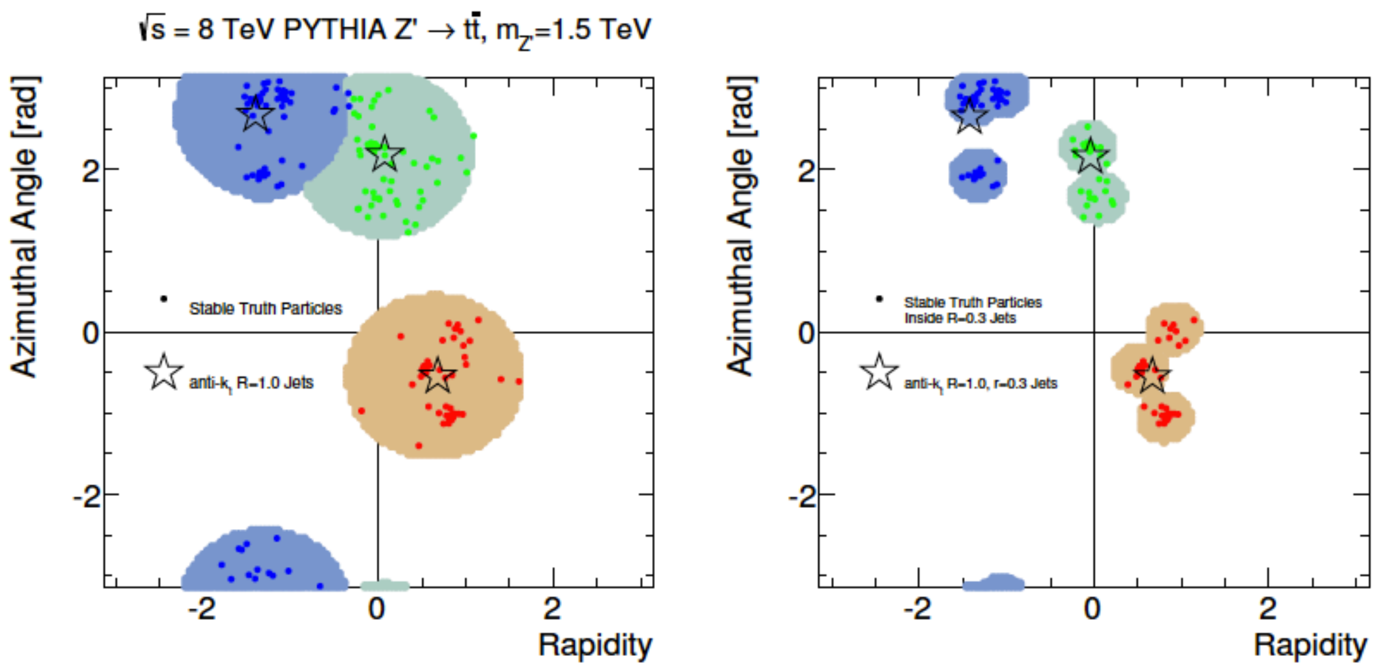
- jet calibrations and uncertainties need to be derived for every jet collection



Jet re-clustering

JHEP 02 (2015) 075

- **Build jets from jets**
- **Introduce a new angular scale r < R at which jets are calibrated**
- **Cluster radius r jets into radius R jets**
    - Large-R jet calibrations (and uncertainties!) propagate from r to R

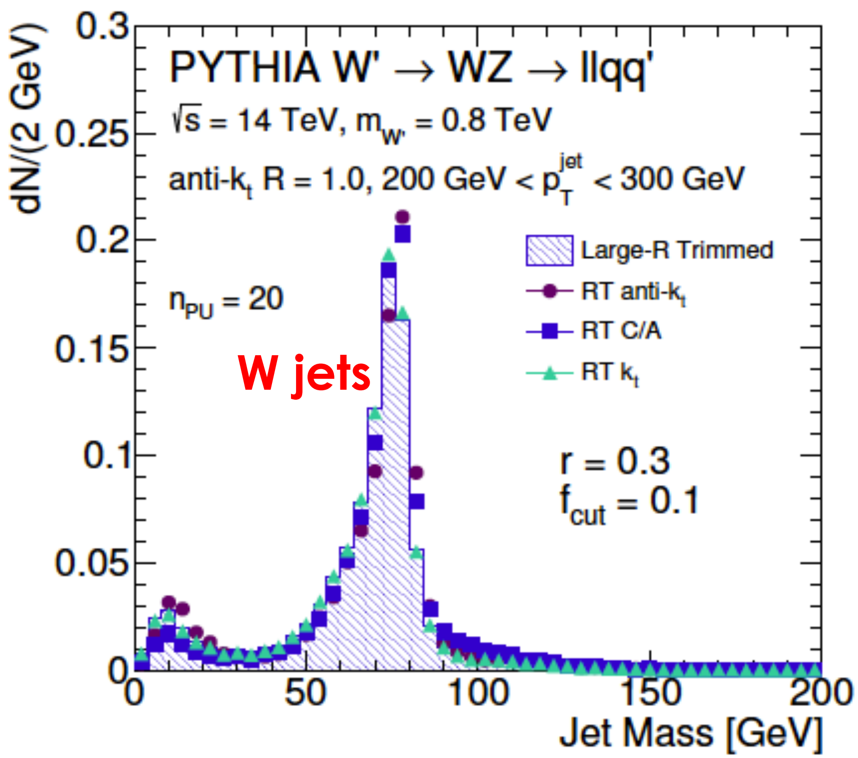


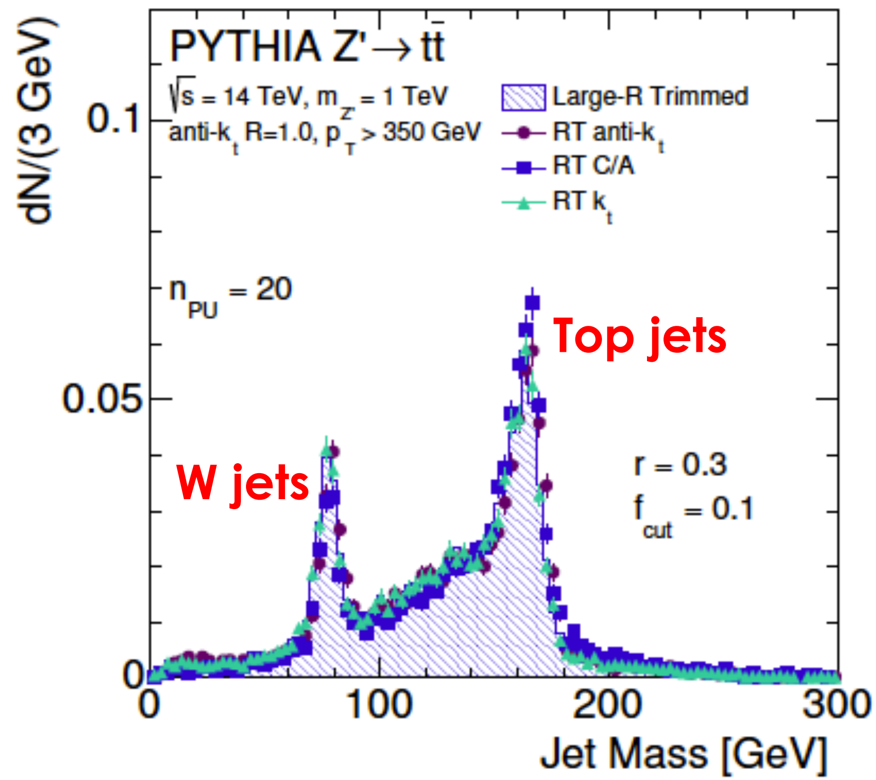
- **Allows for unprecedented flexibility to optimize the R jet parameter in the context of specific physics analyses**
    - Improve the discovery potential to new physics

Reclustered grooming

- Discard small radius r jets *i* re-clustered into large-R jet *J* if:

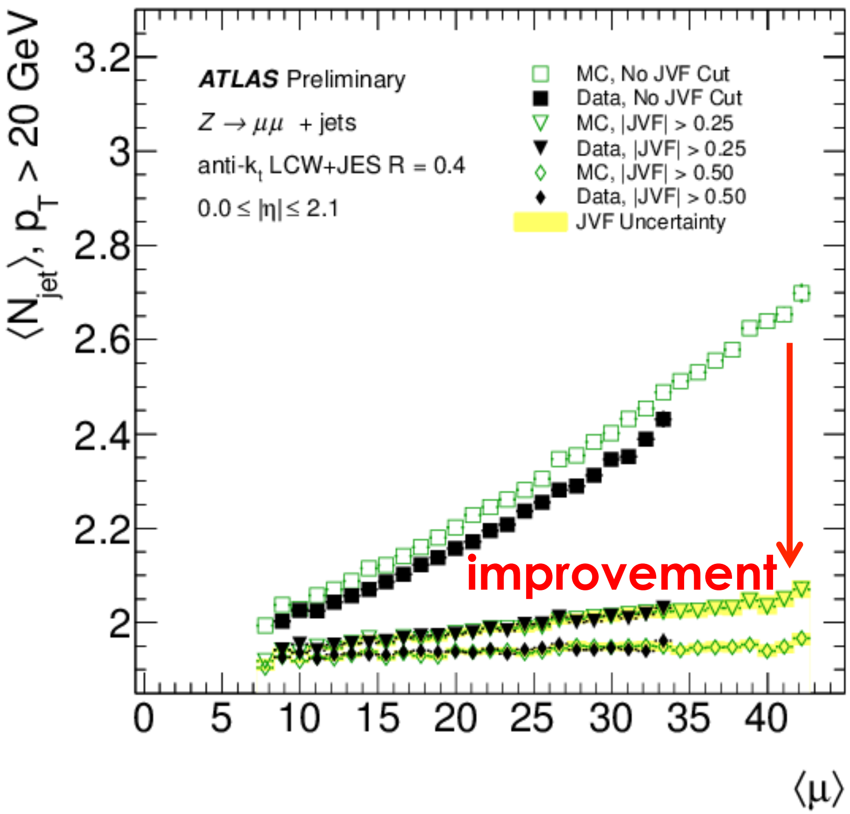
$$p_{T,i} < f_{cut} . p_T^J$$

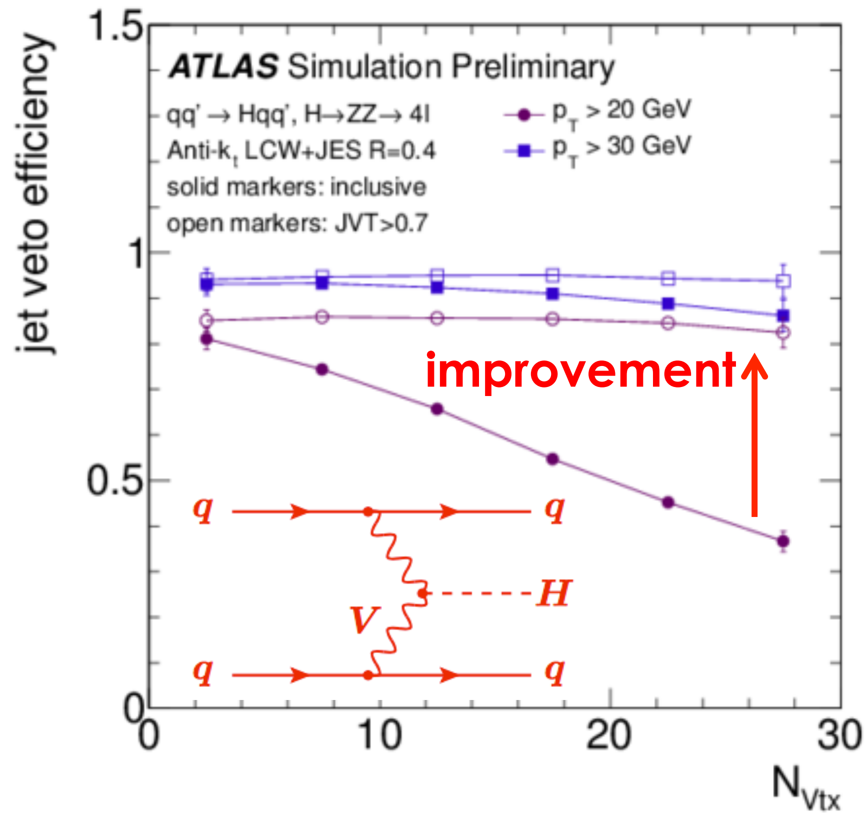




- Enables a natural transition between large-R and small-R jets

JVF pileup jet suppression





- JVF restores the N_{jet} distribution as a function of pileup
- Improves the data/MC agreement
- JVF makes the jet veto efficiency stable with pileup without the need to raise the jet p_T threshold

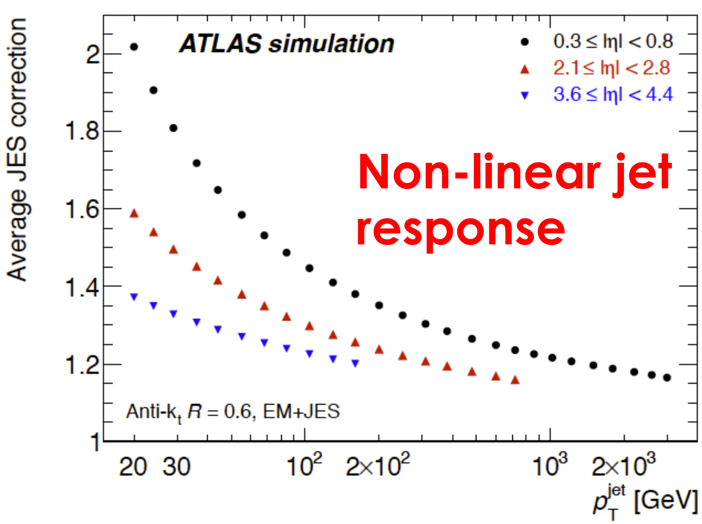
Jet calibration overview

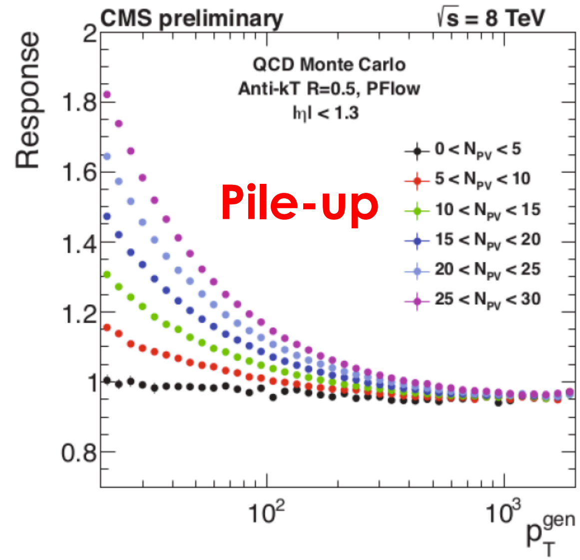
- **Two main goals:**

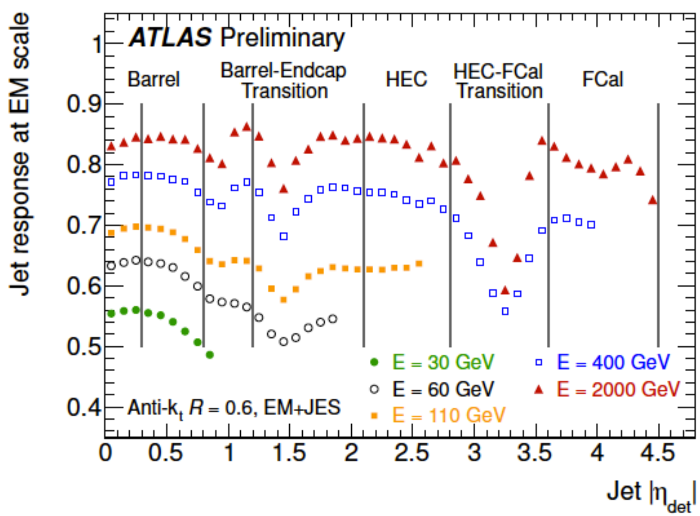
  1. **Reduce fluctuations (improve resolution)**
     - Event-by-event pileup subtraction
     - Jet-by-jet corrections

  2. **Reduce data/MC differences (improve uncertainty)**
     - Jet energy calibration determined from data (in-situ)
     - Jet-by-jet techniques to reduce effects not well modeled
       - Pile-up jets: Jet Vertex Fraction
       - Flavor dependence of the response: Global Sequential Calibration

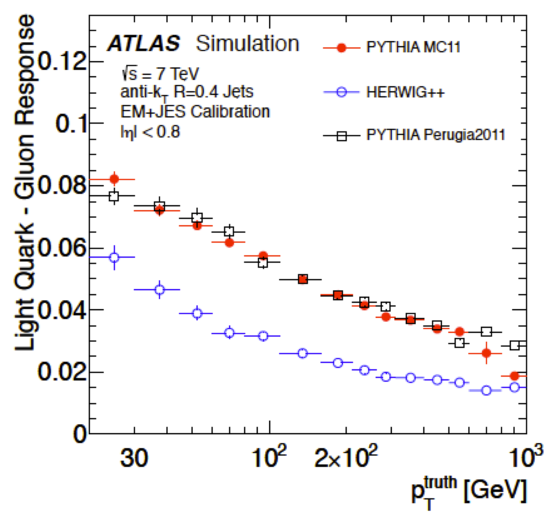
Experimental challenges







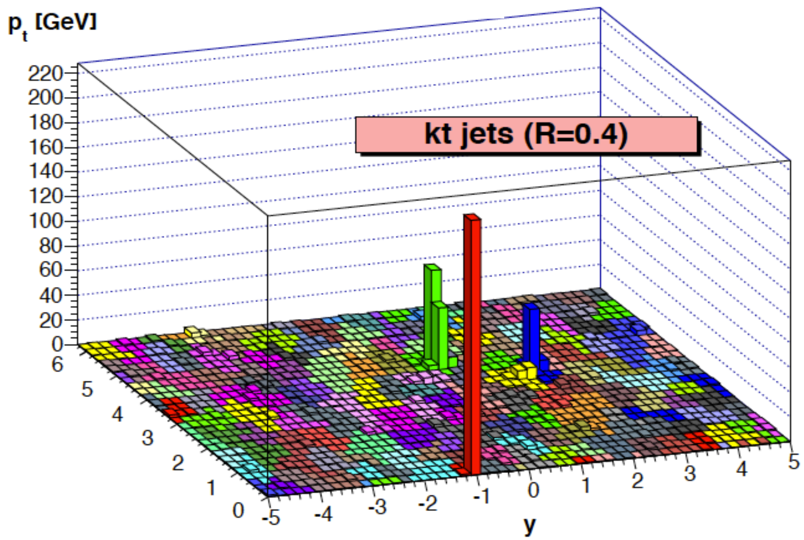
Eta-dependent response

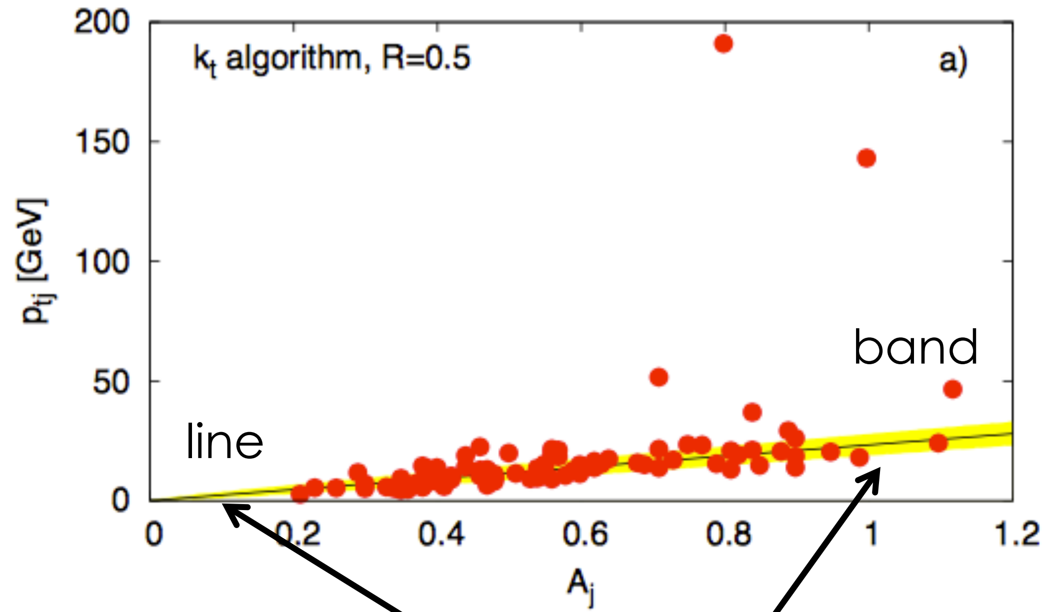


Flavor dependence

Pileup subtraction

arXiv:0707.1378 [hep-ph]





Determine the median p_T density (ρ) per unit of area ***of each event***, and the jet area (***A***)

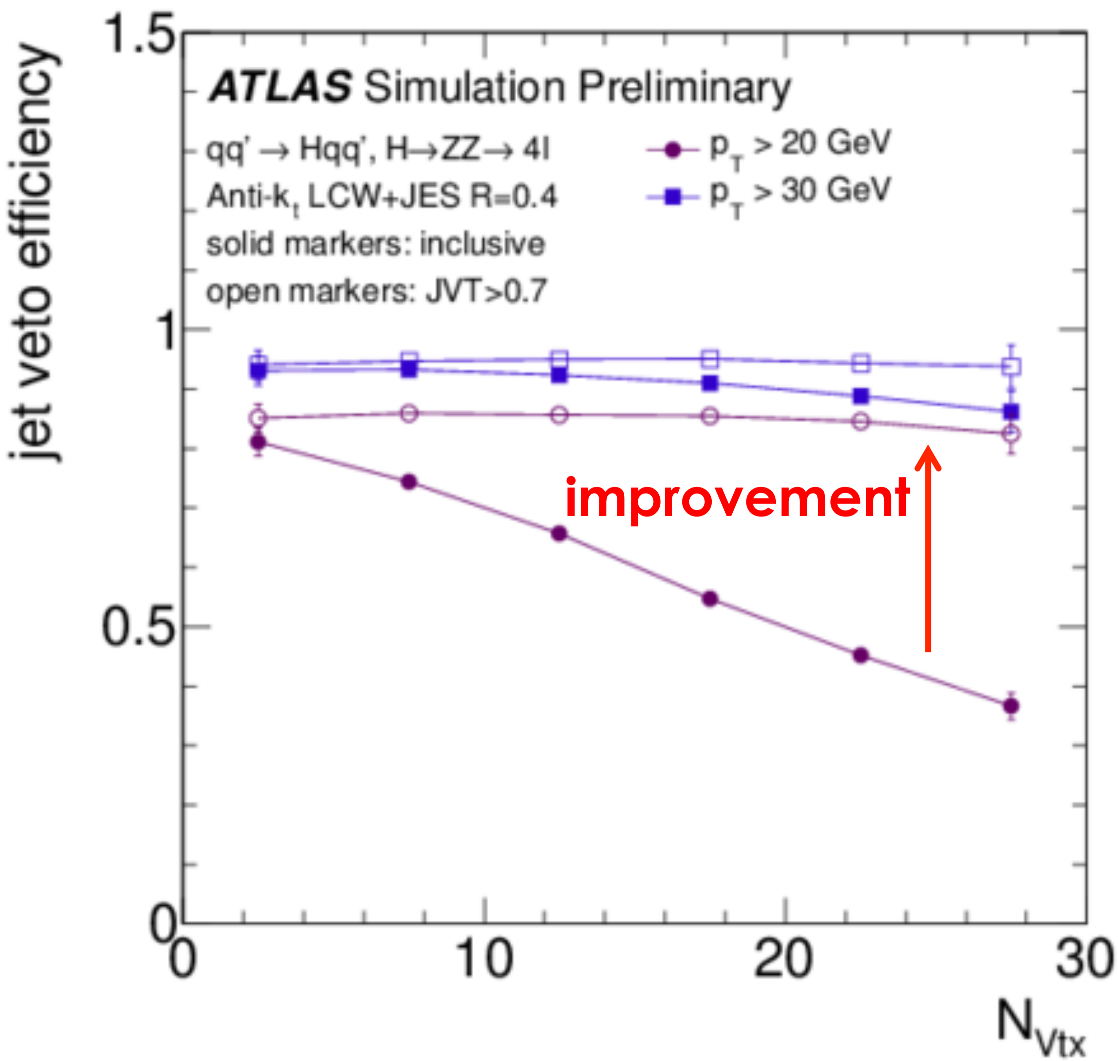
$$\Delta p_T = \rho A \pm \sigma_\rho \sqrt{A}$$

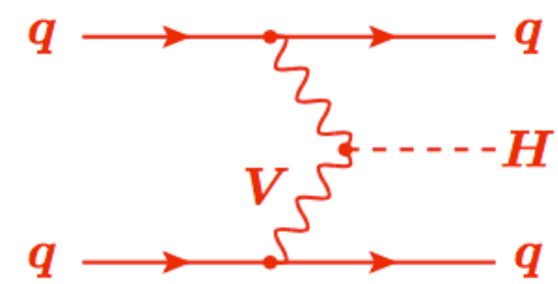
Geometrical contamination

Fluctuations in the noise from point to point in the event

$$p_T^{jet,corr} = p_T^{jet} - \rho \times A_T^{jet}$$

VBF Higgs→ZZ→*llll*

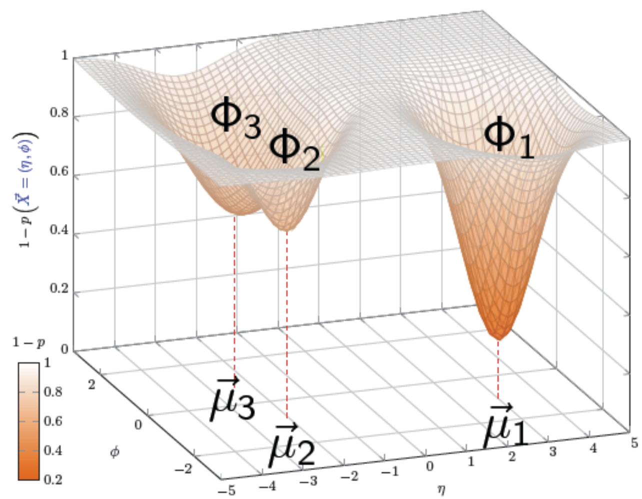


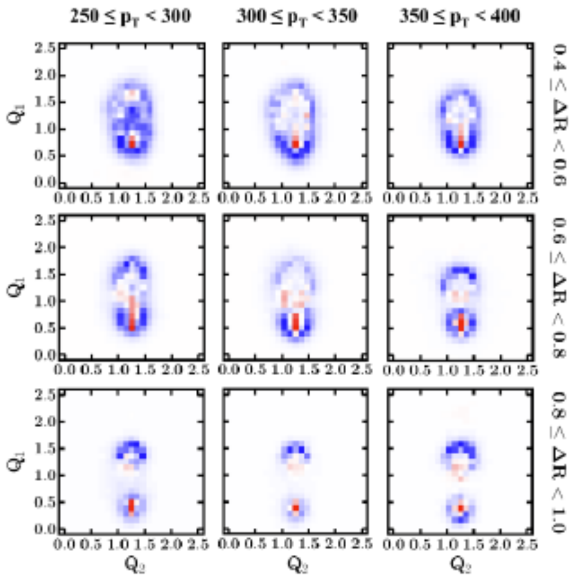


- **JVF makes the jet veto efficiency stable with pileup without the need to raise the jet p_T threshold**

ATLAS-CONF-2014-018

Pattern recognition and machine learning in jet physics





Computer vision: jet images

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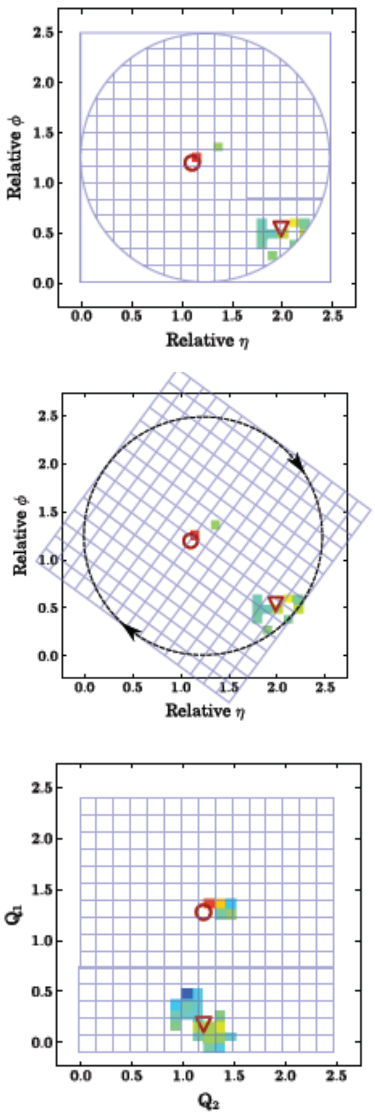
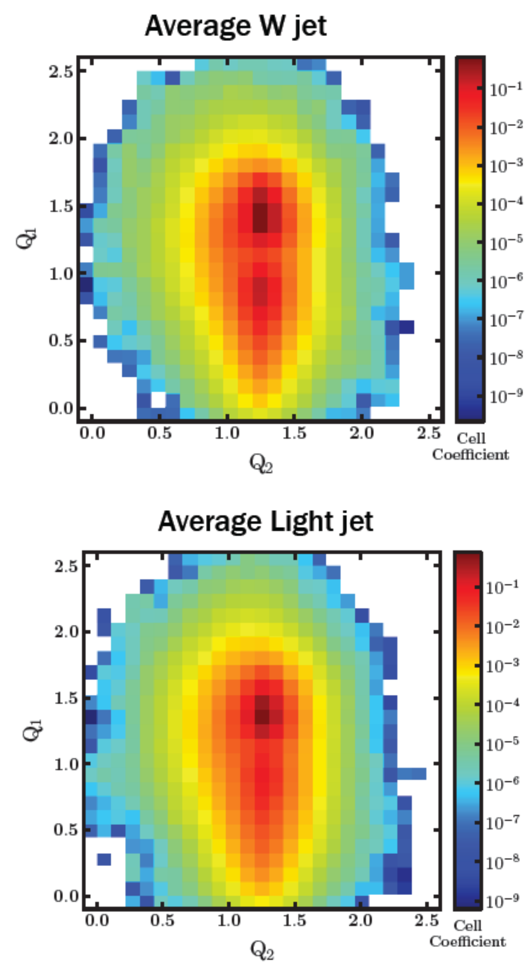
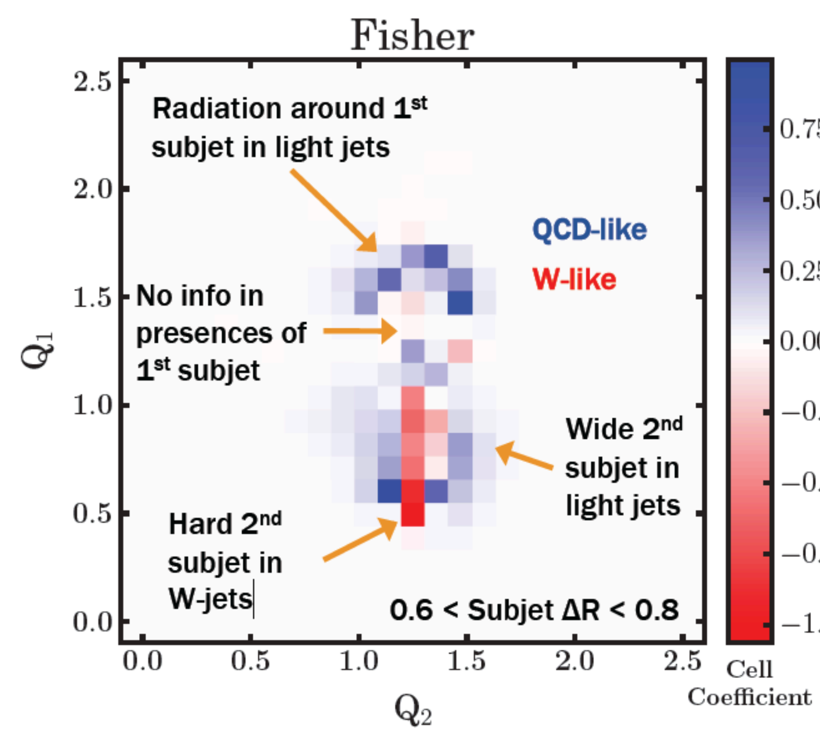
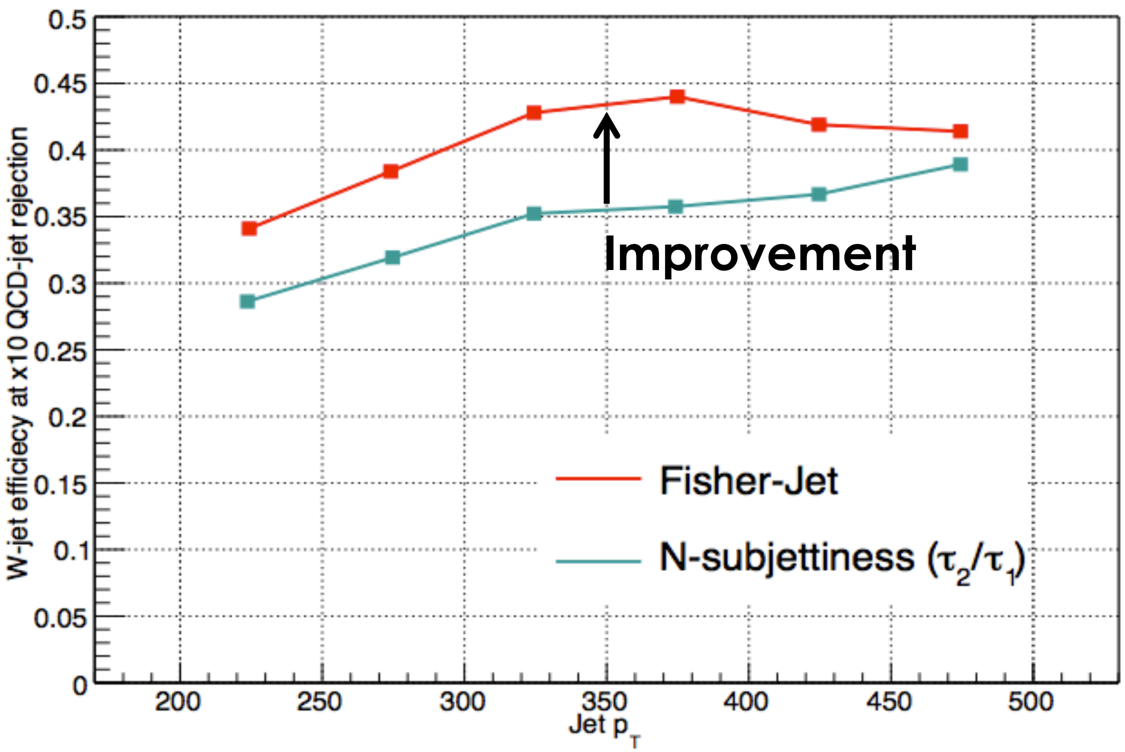


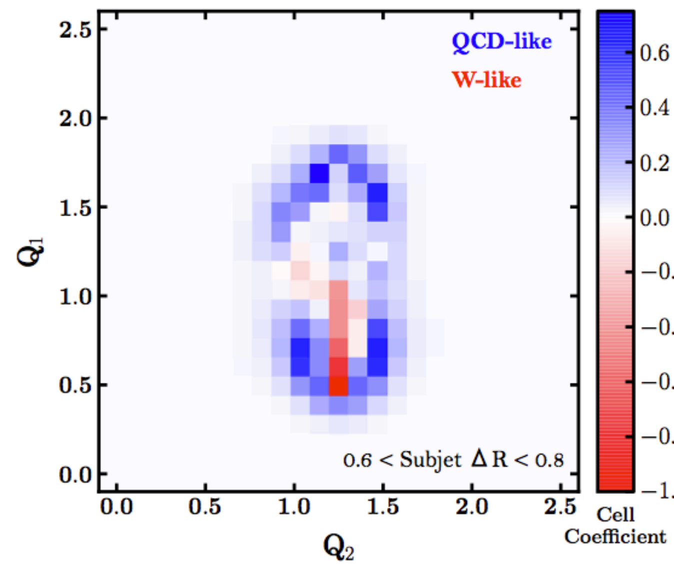




Fisher discriminant

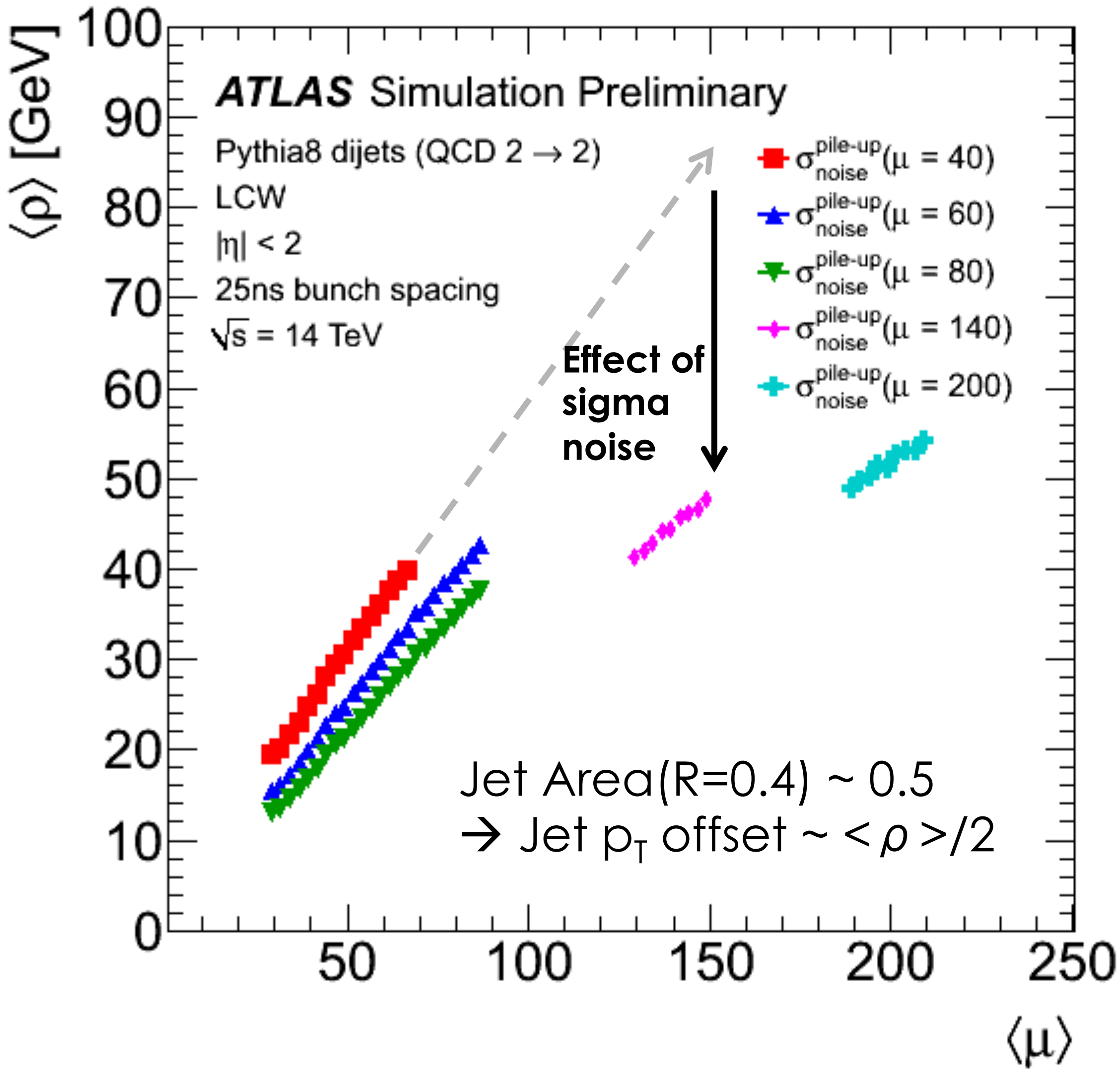
Jet-image W tagging





- Connection between jets and images enabled the use of computer vision algorithms to jet tagging for the first time
- **Improved performance with respect to state-of-the art methods**
- **Visualization of the discriminant adds a new capability to understand the physics within jets and design more powerful jet tagging methods**

Topoclustering pileup suppression



- Linear behavior of rho up to high mu for fixed sigma noise values
- Higher pileup sigma noise values lead to partial suppression of pileup
- **Optimization of topoclustering sigma noise is key to reconstruct jets at high luminosity**

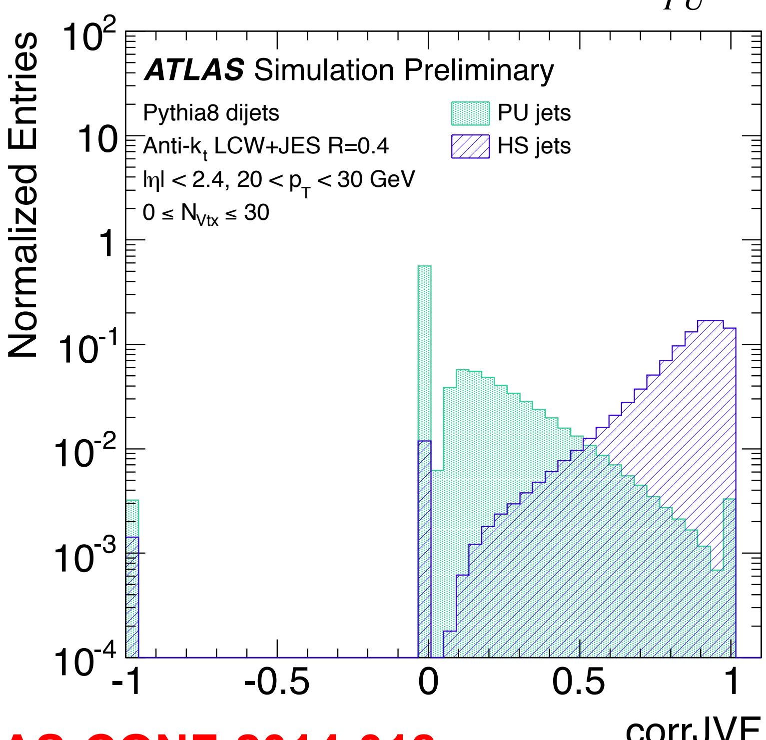
New jet-vertex tagging variables

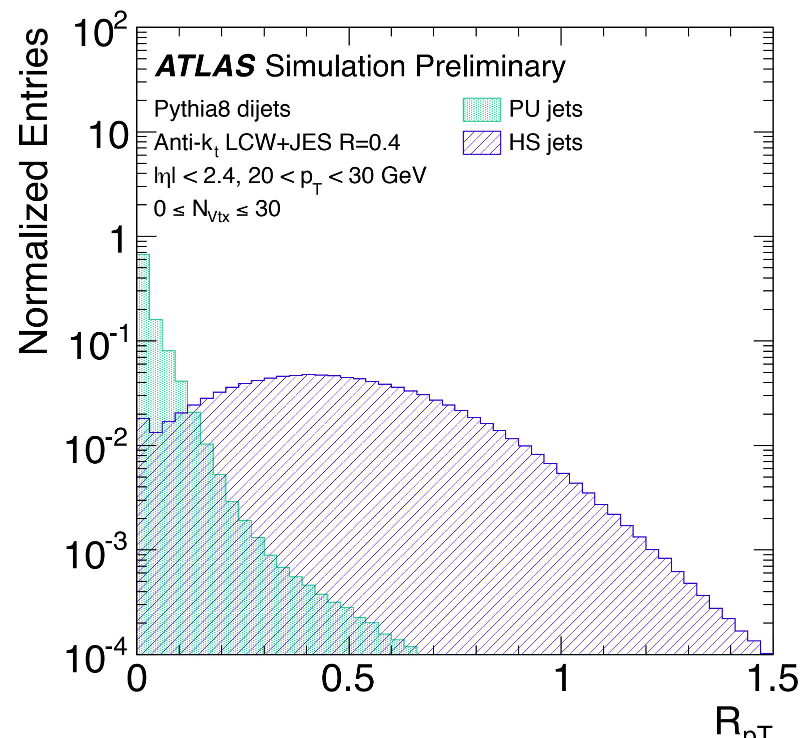
- Correct JVF for its pileup dependence:

$$CorrJVF = \frac{\Sigma p_T^{trk}(PV_0)}{\Sigma p_T^{trk}(PV_0) + \frac{\Sigma p_T^{trk}(PU_n)}{k\, n_{PU}^{trk}}}$$

- Use pileup-corrected observables:

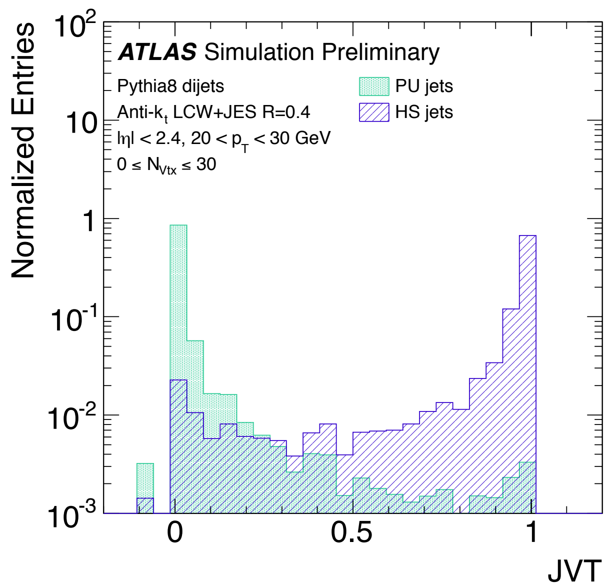
$$R_{pT} = \frac{\Sigma p_T^{trk}(PV_0)}{p_T^{jet}}$$

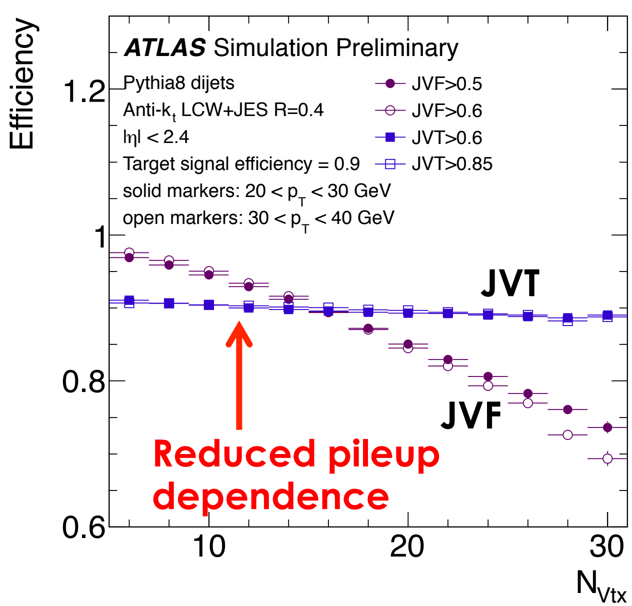


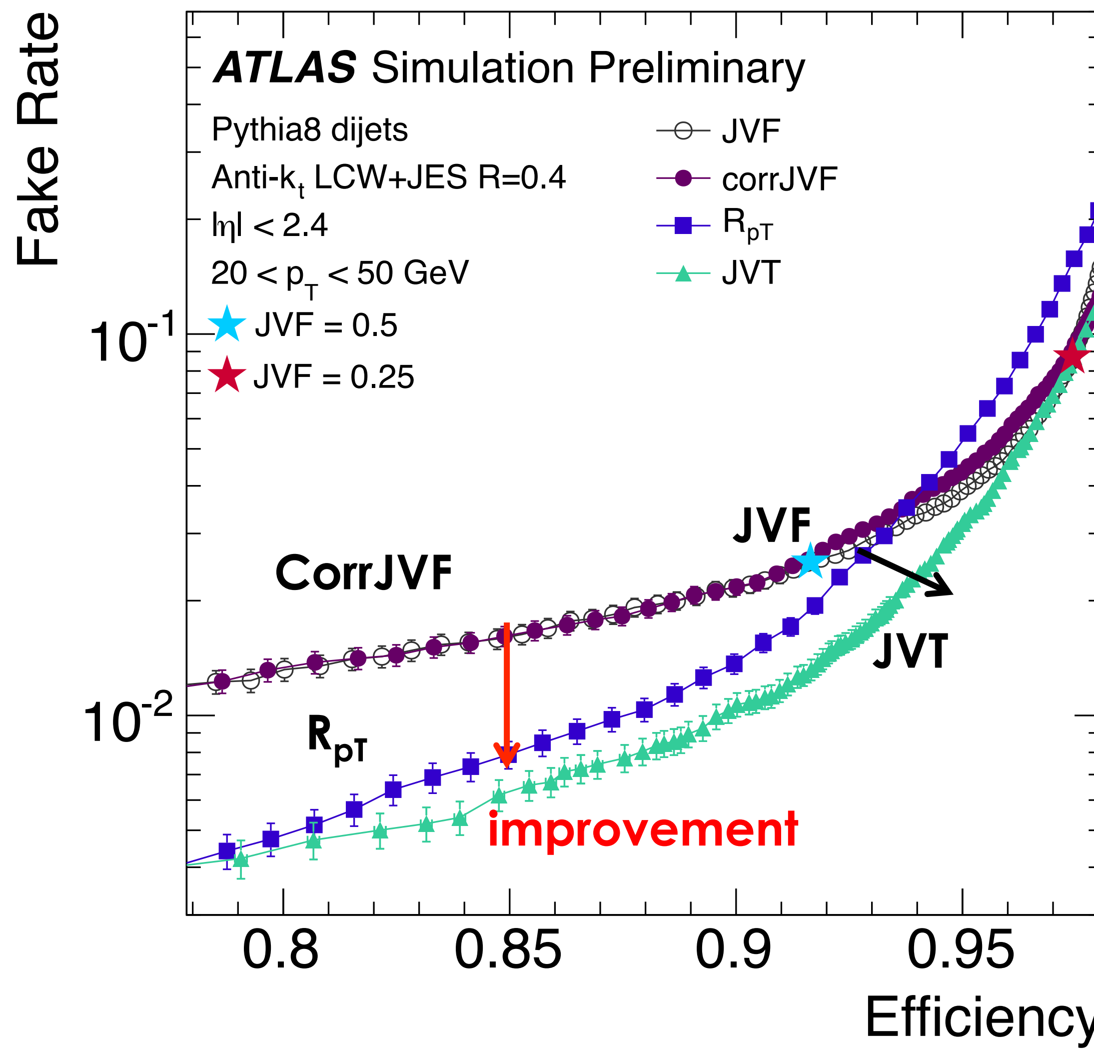


ATLAS-CONF-2014-018

Jet Vertex Tagger (JVT)







New ATLAS pileup suppression algorithm for Run 2

High multiplicity searches using jet mass

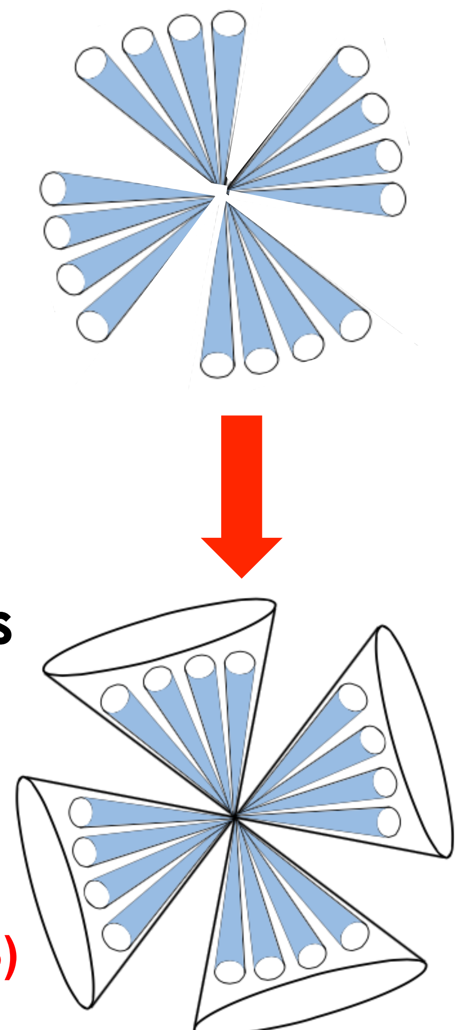
- Search for events with four large-R jets and use the total-jet-mass event-level observable to separate signal from background:

$$M_J^{\Sigma} = \sum_{\substack{p_T > 100\,GeV \\ |\eta| < 2.5}}^{4} m^{jet}$$

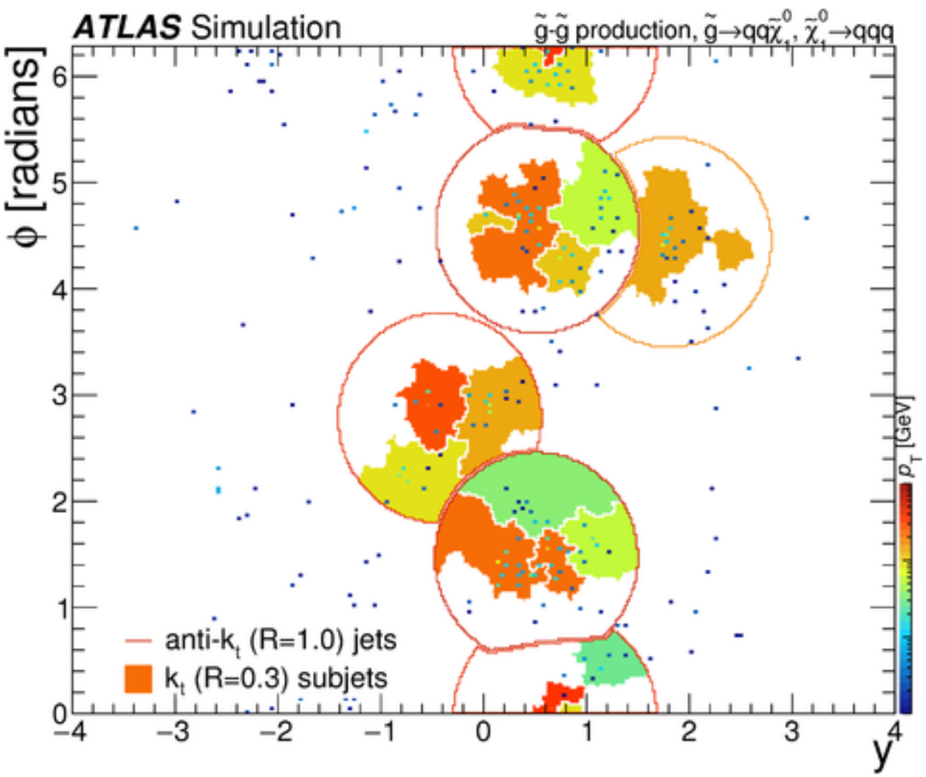
- **Large-R jets in high multiplicity events have a multi-prong structure from the accidental merging of partons resulting in large jet masses**
  - Jet masses do not correspond to a parent's particle's mass

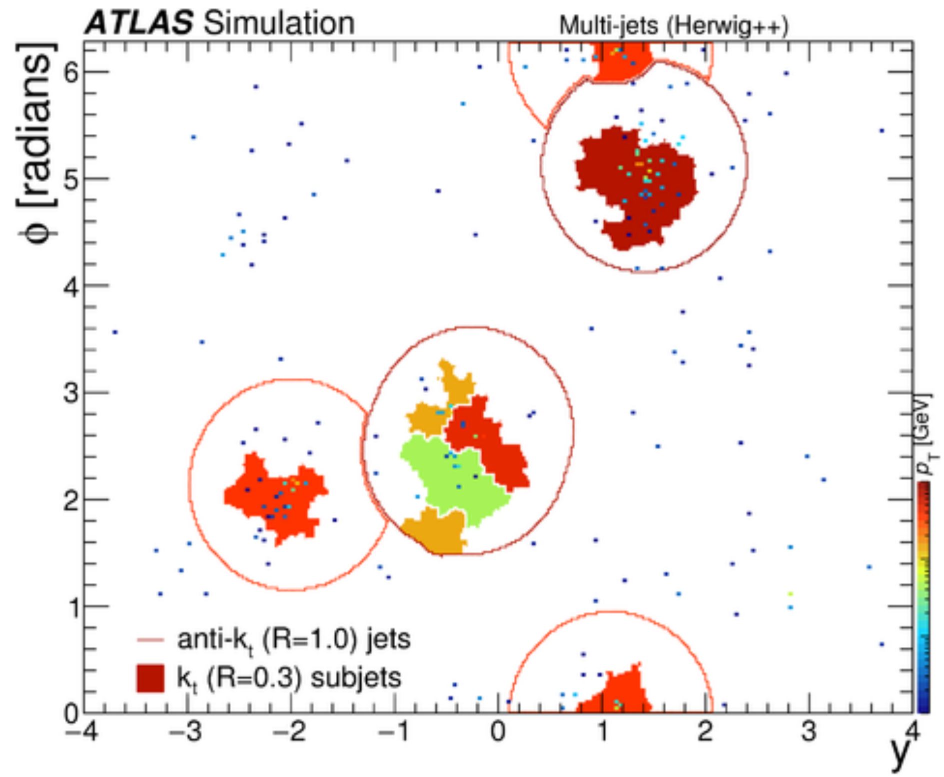
- Two assumptions:
  - **Jet rich environment**
  - **Large-R Jet masses uncorrelated**

A. Hook, E. Izaguirre, J. Wacker, et. al. (arXiv:1202.0558)



Total-jet-mass





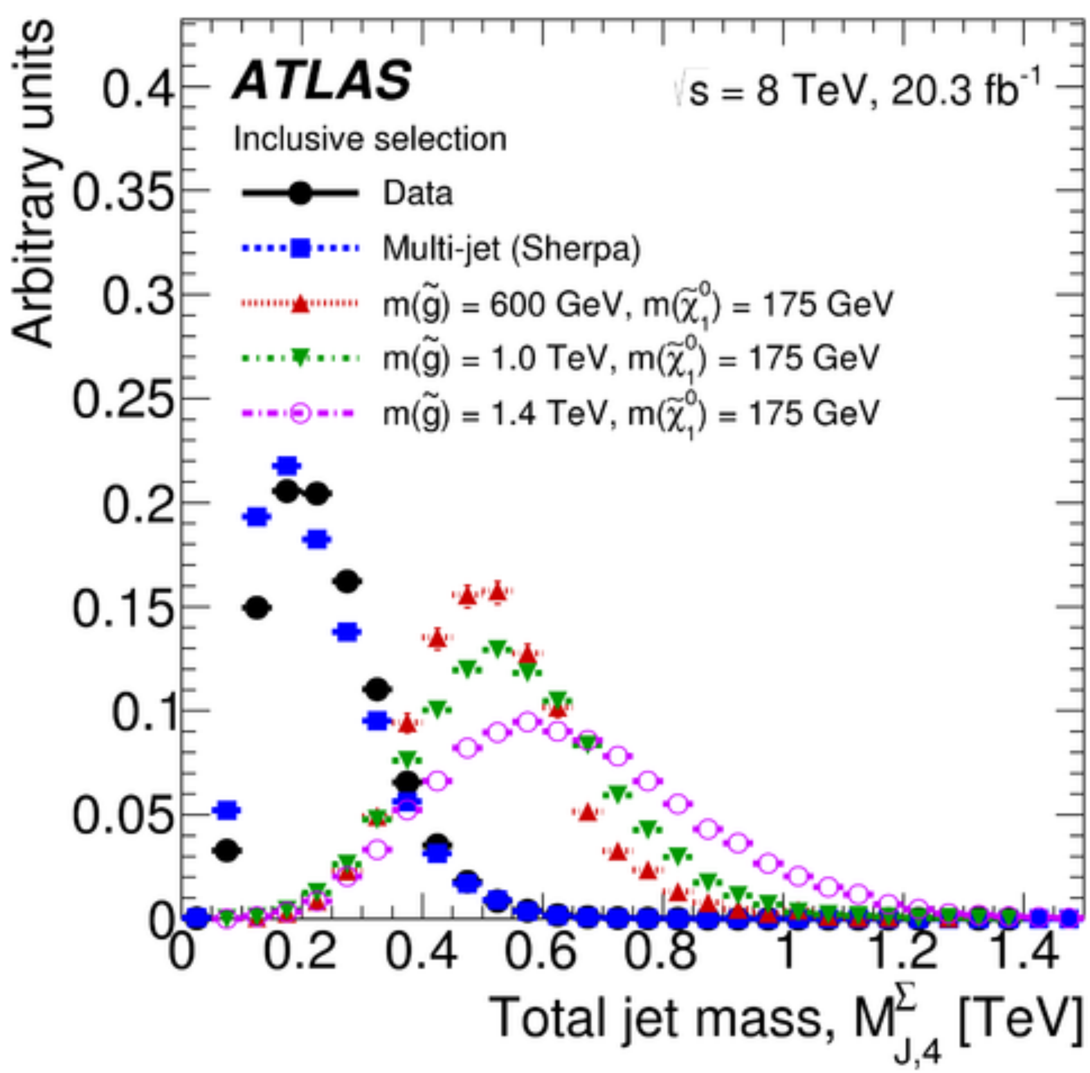
Signal event (gluino mass = 1 TeV)

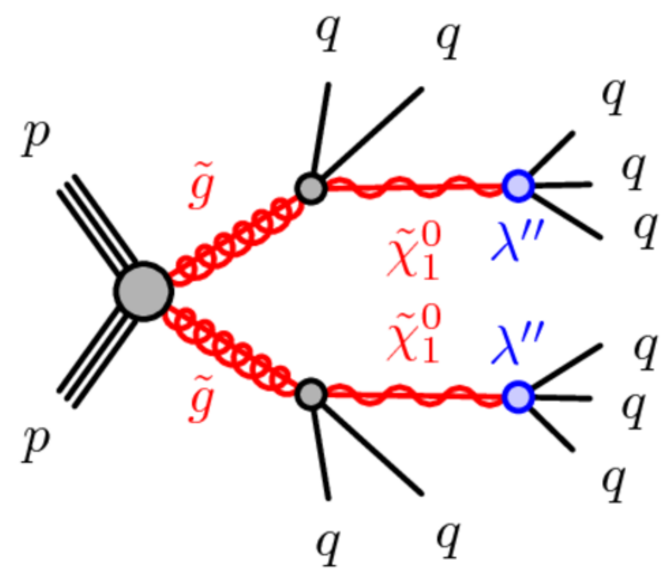
Background event

$$M_J^{\Sigma} = 705\,\mathrm{GeV}$$

$$M_J^{\Sigma} = 260\,\mathrm{GeV}$$

Total-jet-mass





Total jet mass sensitive to gluino mass and mass splitting:

$$m_{\tilde{g}} - m_{\tilde{\chi}^0_1}$$

Jet calibration

Jet energy scale

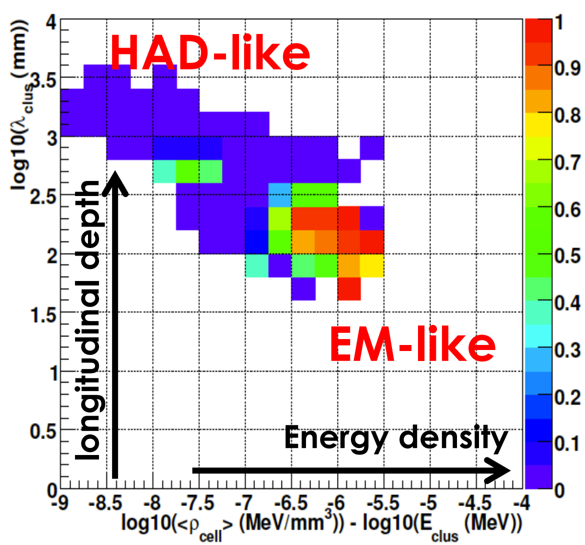
inputs

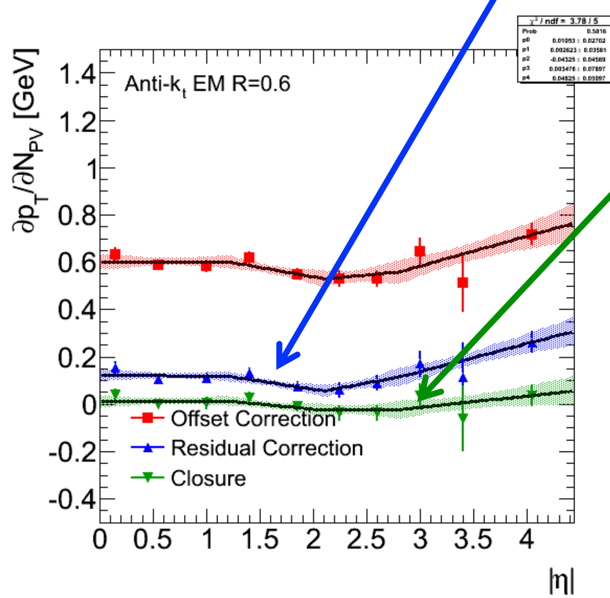
Topo-clusters (pileup noise threshold) → Local cluster weighting (LCW) → Event-by-event pileup subtraction → Residual offset (out-of-time, occupancy) → Jet Energy Scale

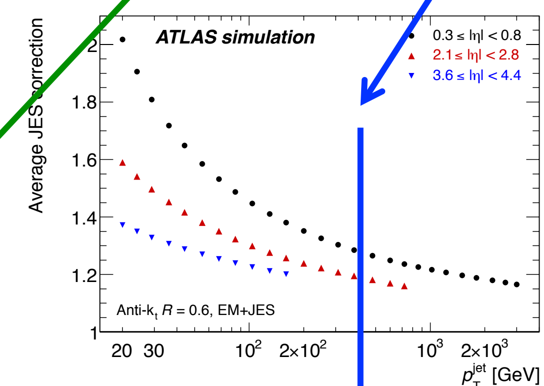
Pileup noise:
σ(μ)

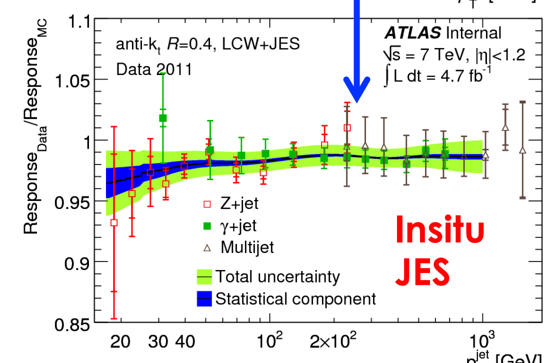
EM/HAD classification

$$p_T^{calib} = \left(p_T - \rho A - \alpha(N_{PV} - 1) - \beta\langle\mu\rangle\right) \times JES$$



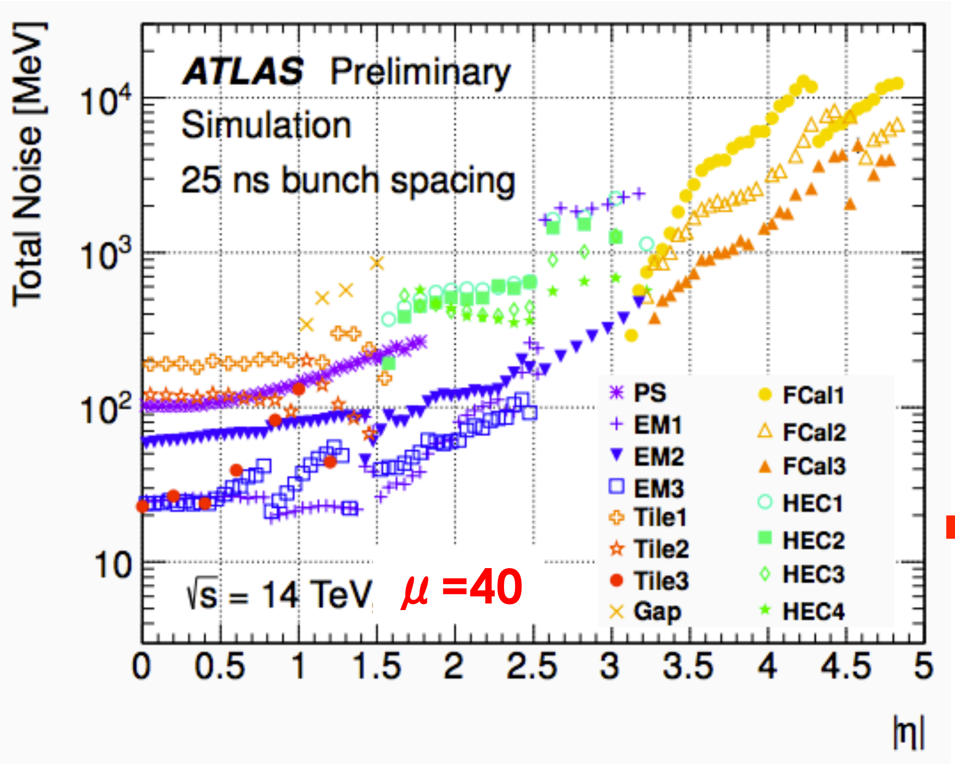


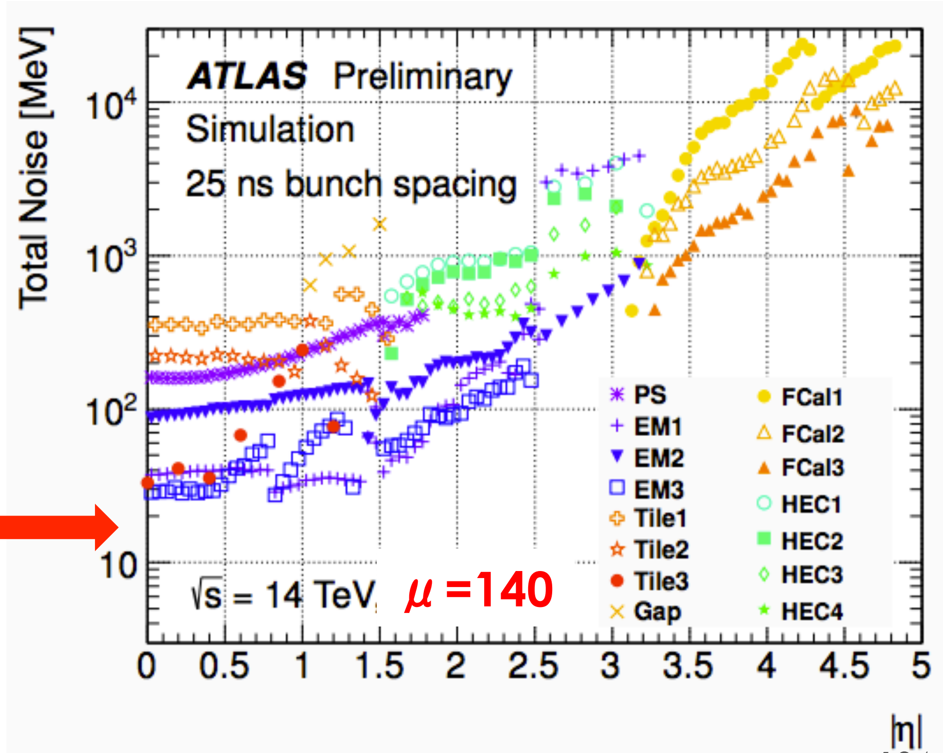




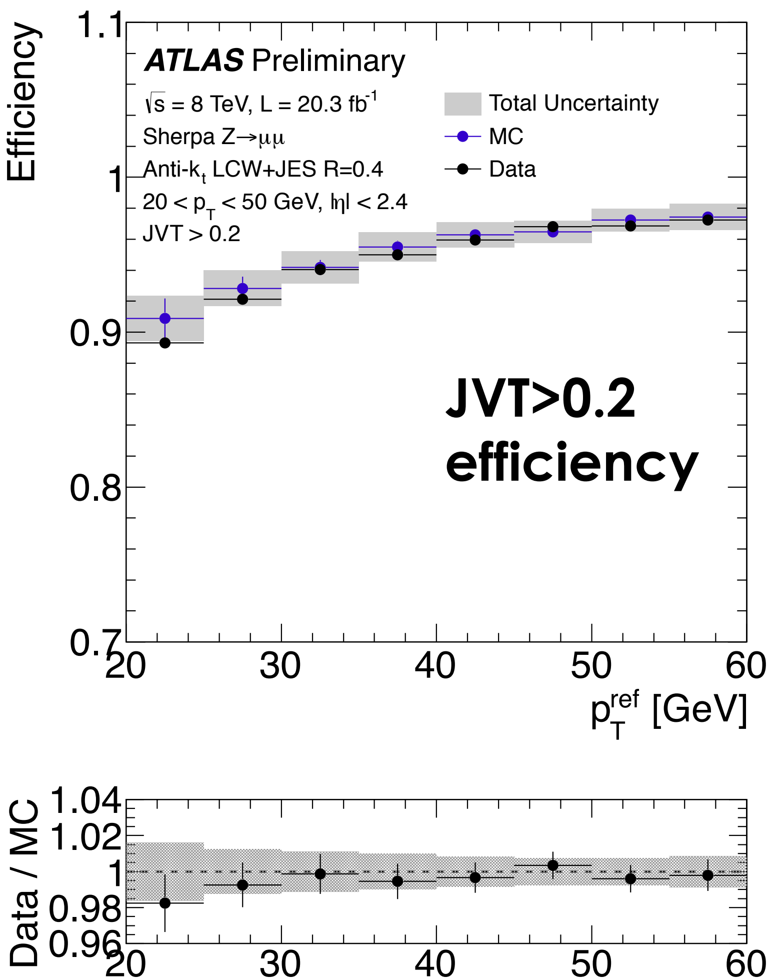
Topo-clustering at high luminosity

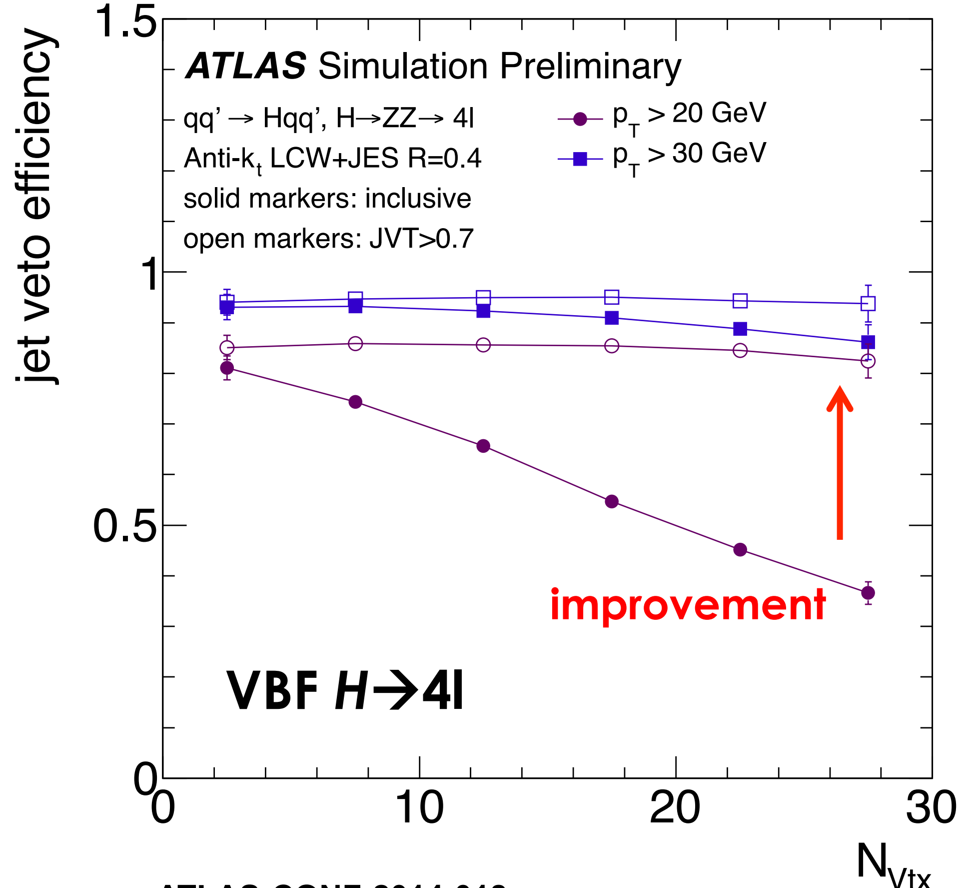
- **Adjust σ pileup noise for each μ configuration**
- **Optimization of local calibration for EM/HAD cluster classification for each pileup noise value**
  - Derived from single pion simulation with μ =0 and σ (μ >0)





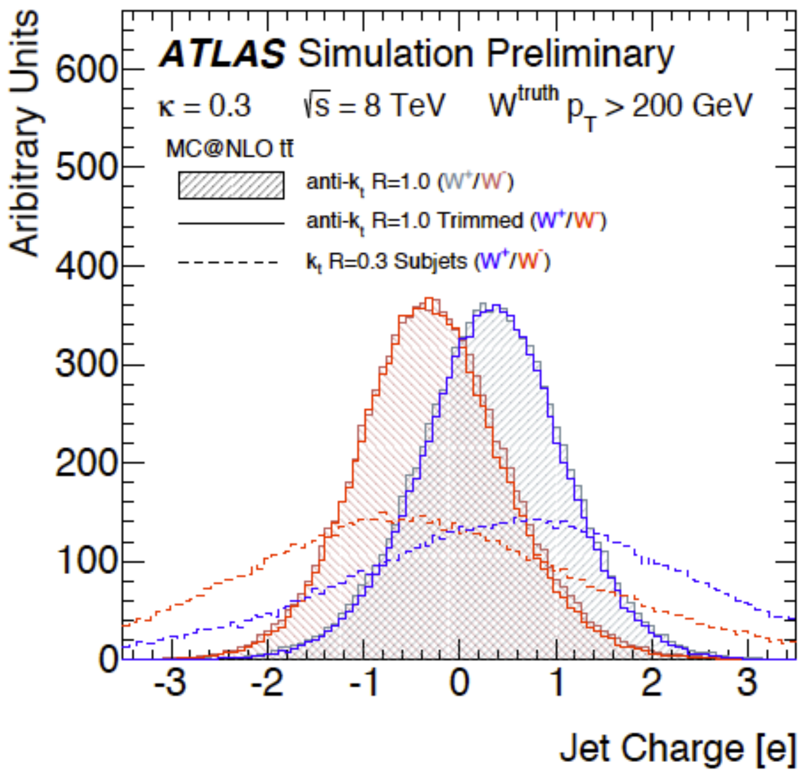
Jet Vertex Tagging performance



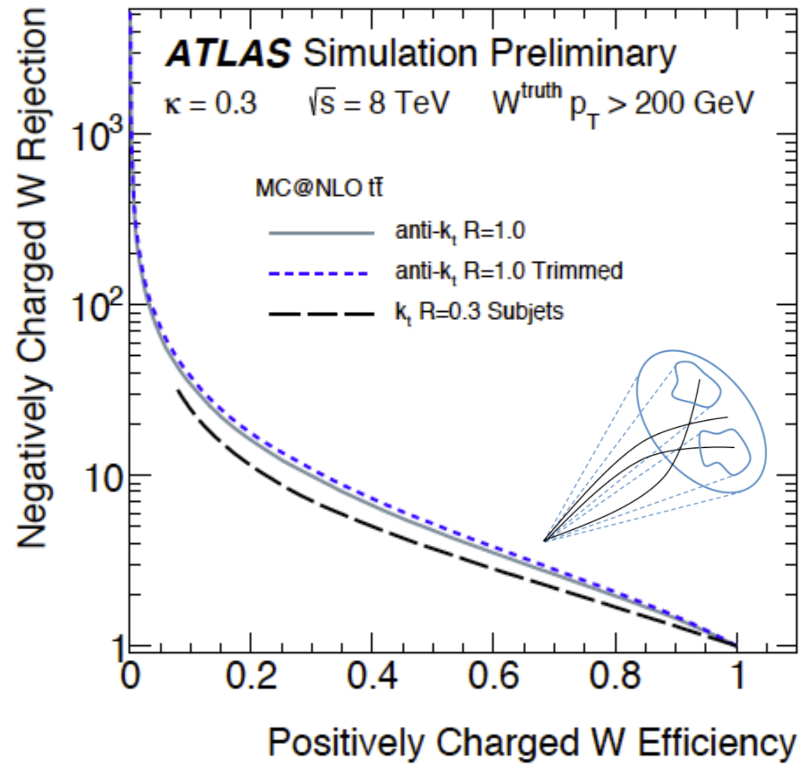


ATLAS-CONF-2014-018

Jet charge in boosted W jets



ATLAS-CONF-2013-086



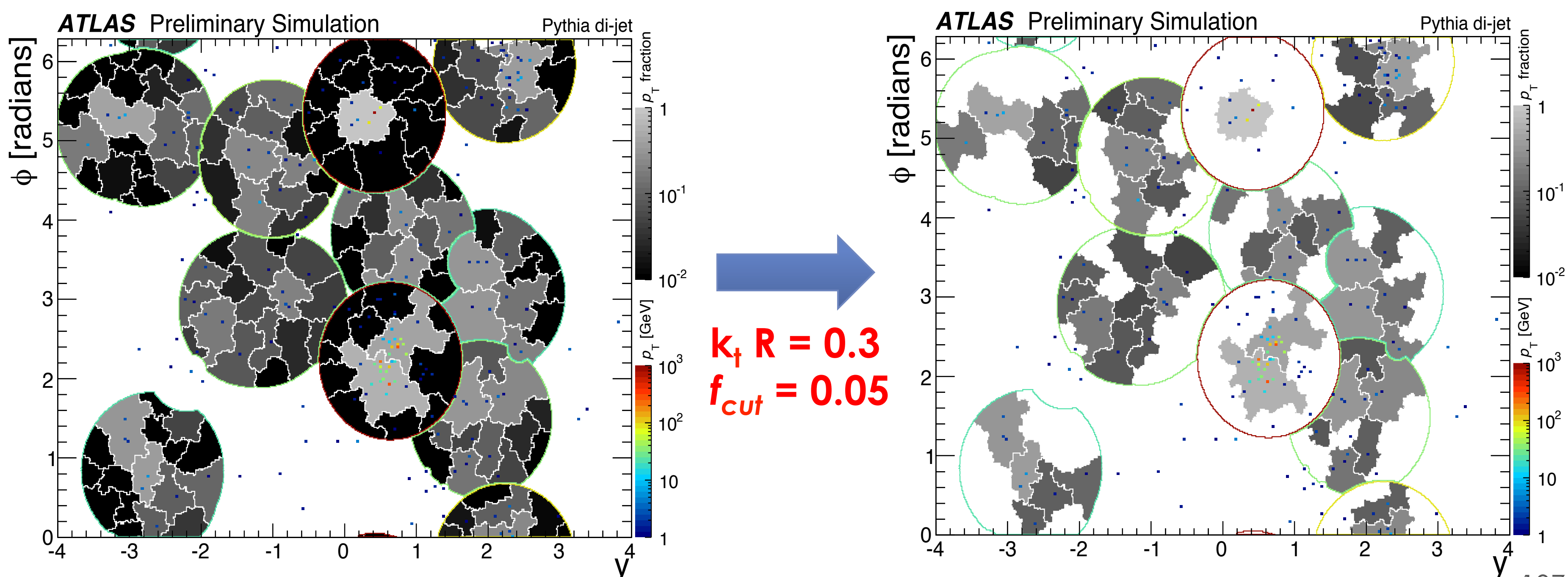
- **Different ways to define jet charge in a boosted W jet**
  - Using the sum of leading subjet charges leads to worse separation
- **Optimal definition makes use of all associated tracks**
  - Grooming has not impact

Jet trimming

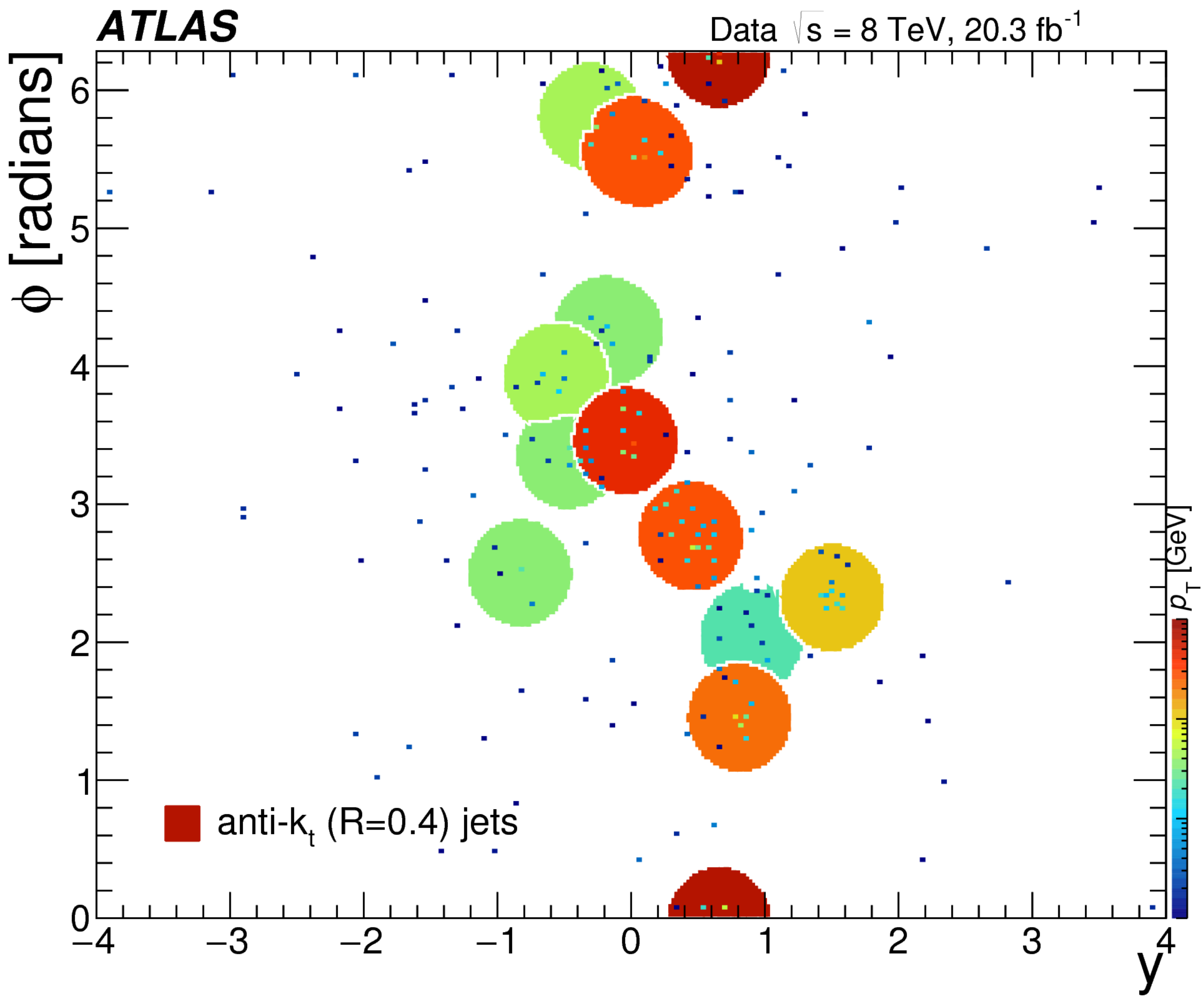
- Jet contamination from pileup, underlying event, and initial state radiation is softer than hard-scatter partons and final state radiation:
  - **Remove soft components of the jet**
  - **Reduce the area of the jet**

1. **Recluster jet constituents into k_t subjets with small R**
2. **Discard subjets with:**

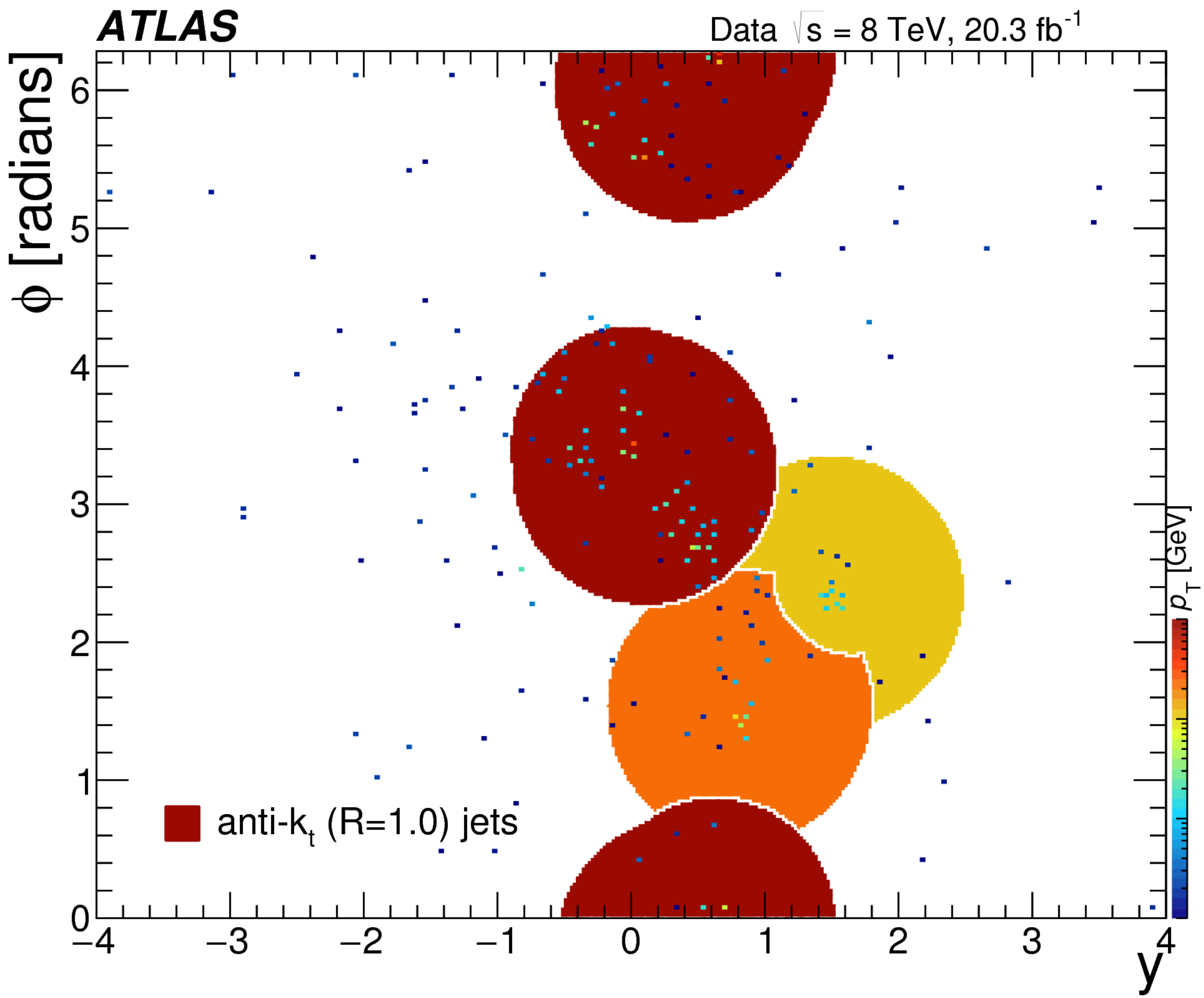
$$p_T < f_{cut} \cdot p_T^{jet}$$



Multijet event (R=0.4)



Multijet event (R=1.0)



Multijet event (Trimming)