Run 1 legacy performance: Jets / ETMiss / Tau

Toshi SUMIDA (ATLAS, Kyoto-U), Tai SAKUMA (CMS, U-Bristol)

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Rencontres du Vietnam
- Physics at LHC and beyond

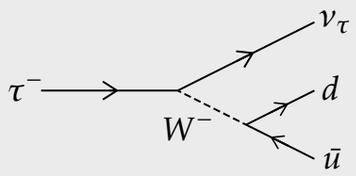
https://indico.cern.ch/event/300048/contribution/10

Introduction

Jets, MET, taus at hadron colliders

Taus

- decay *hadronically* at 65% into one or three charged hadrons, up to two neutral hadrons, and a neutrino
- reconstructed from decay products



MET (Missing E_T, Missing transverse momentum)

- the momentum imbalance of all visible particles in the plane transverse to the beam axis
- the total transverse momentum carried away by invisible particles

Jets

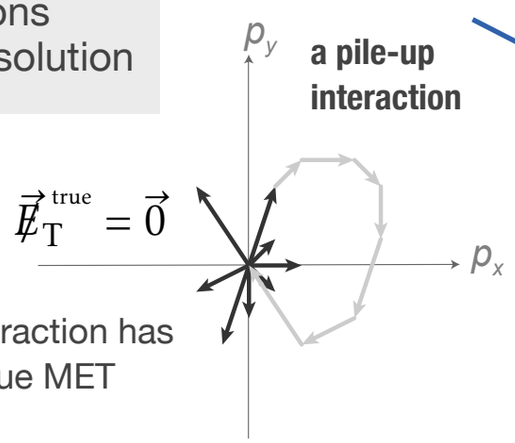
- collimated cluster of stable particles, primarily hadrons originating from quarks or gluons
- defined by jet-clustering algorithms, e.g., anti-kT, Cambridge-Aachen
- corrected for detector effects (jet energy corrections (JEC), or scale (JES))
- can be tagged to indicate potential origins, e.g., b/c-quarks, boosted-W/Z bosons, boosted-top quarks, boosted-Higgs bosons

Introduction

Jets, MET, taus in events with pile-up interactions

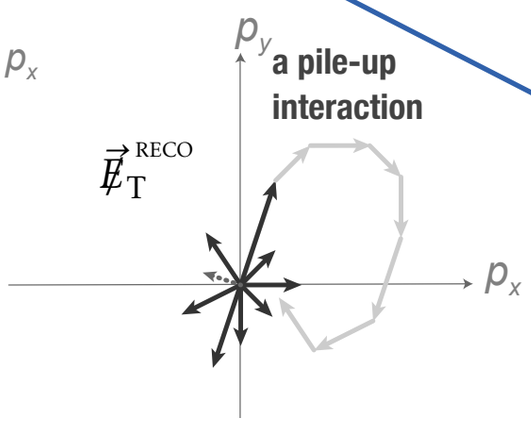
MET in pile-up

- pile-up interactions degrade MET resolution



A pile-up interaction has nearly zero true MET

If we perfectly measured all visible particles, pile-up interactions would not change MET

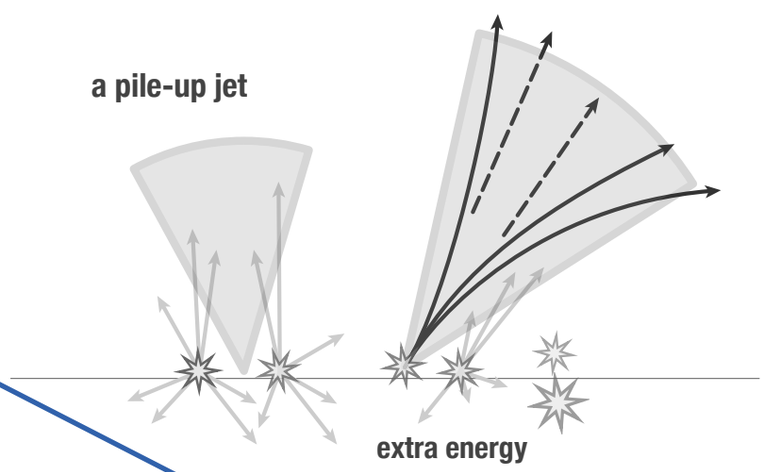


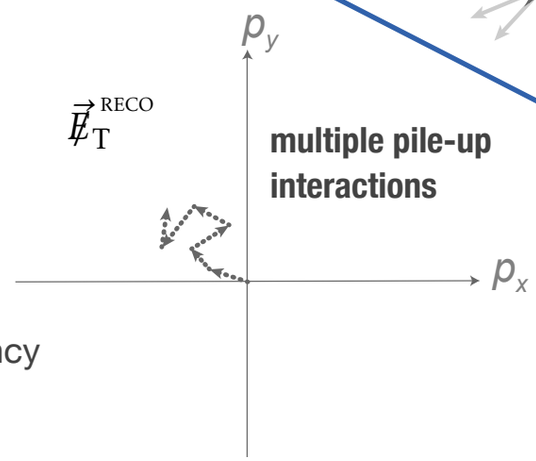
As we don't perfectly measure all visible particles, a pile-up interaction has non-zero reconstructed MET

e.g., resolution, response, efficiency

Jets in pile-up

- particles produced in pile-up interactions add extra energy to jets
- some jets are entirely made of pile-up particles (***pile-up jets***)





Reconstructed MET in pile-up interactions is a random walk on the px - py plane

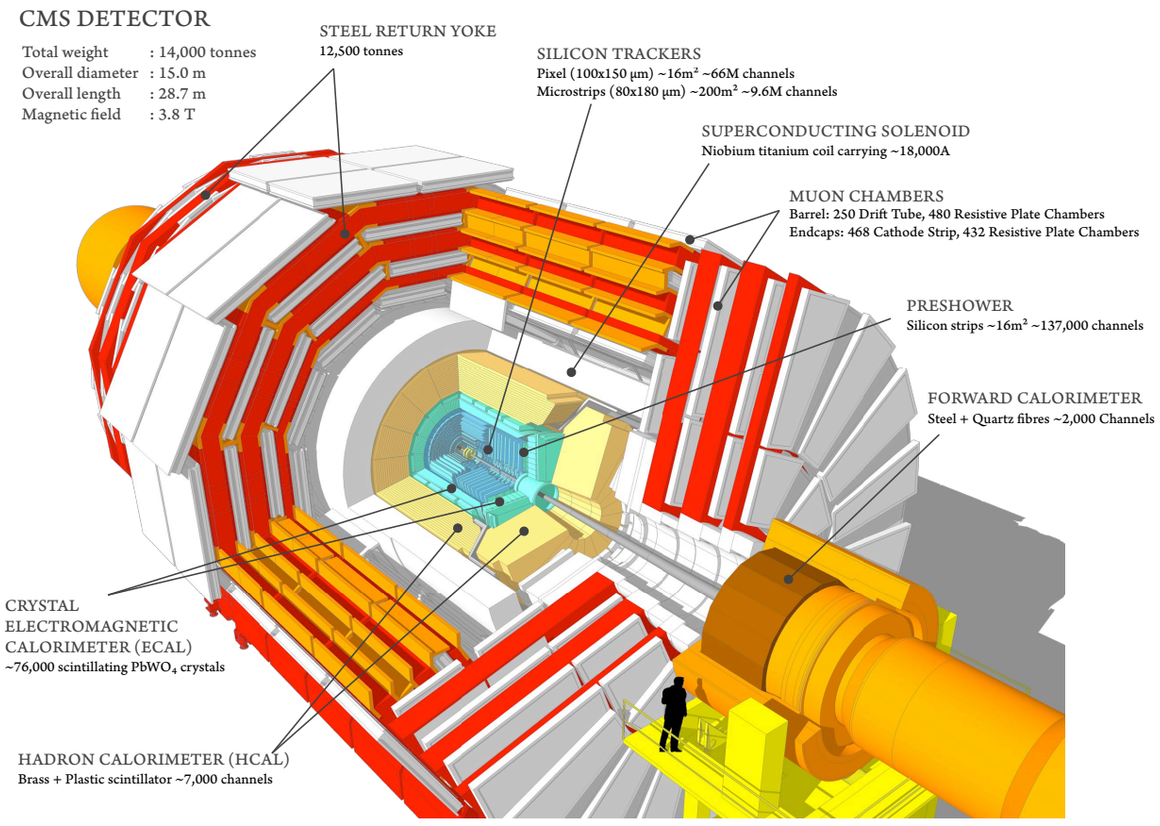
The more pile-up interactions, the larger the reconstructed MET is likely to be, degrading the MET resolution

Taus in pile-up

- pile-up interactions make taus less isolated from other particles

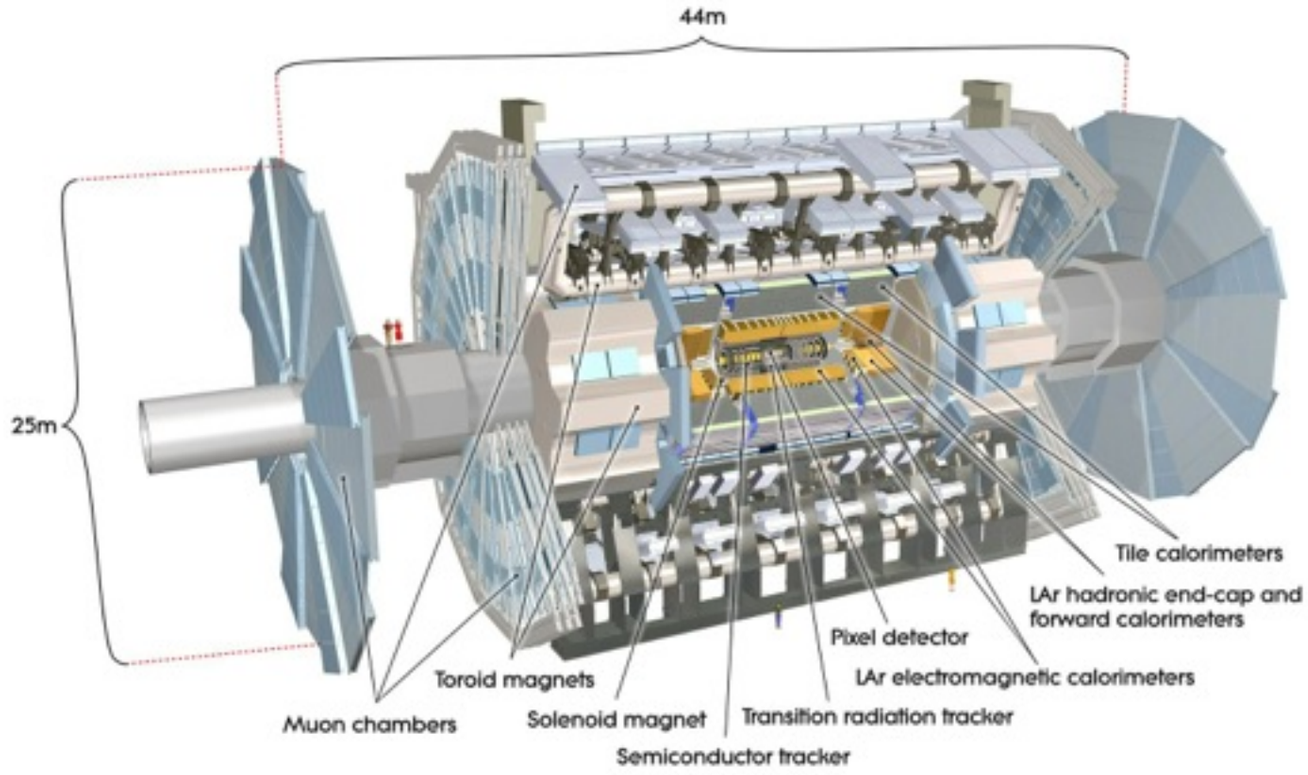
Introduction

The CMS detector



CMS Document 11514

The ATLAS detector



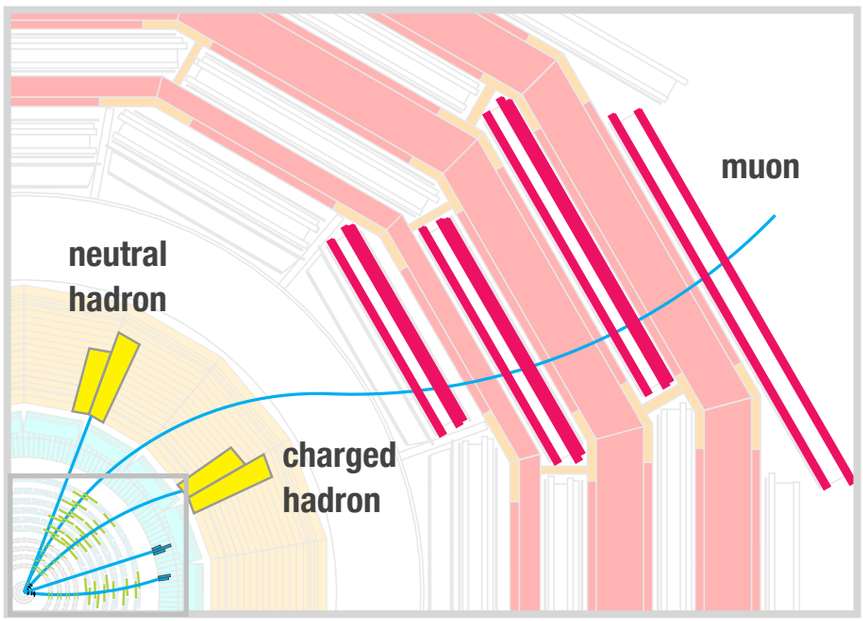
CERN-GE-0803012

Jet/ETMiss/Tau in **CMS**

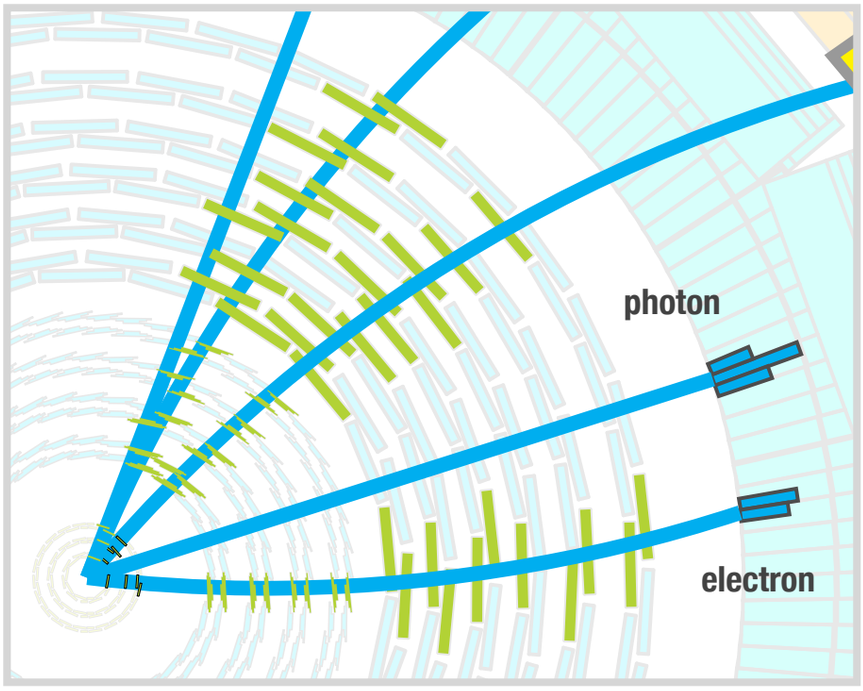
CMS : Jets, MET, taus with Particle Flow candidates

CMS-PAS-PFT-09-001

- Particle Flow (PF) algorithm
  - the primary reconstruction algorithm in CMS
  - uses all CMS detector subsystems
  - reconstructs four momenta of all visible stable particles (PF candidates)
  - identifies each particle as muon, electron, charged hadron, photon, or neutral hadron



- Jets, MET, taus
  - reconstructed as composite objects of PF candidates



particle flow candidates $\mu^{\pm}$, $e^{\pm}$, $h^{\pm}$, γ, h^{0}

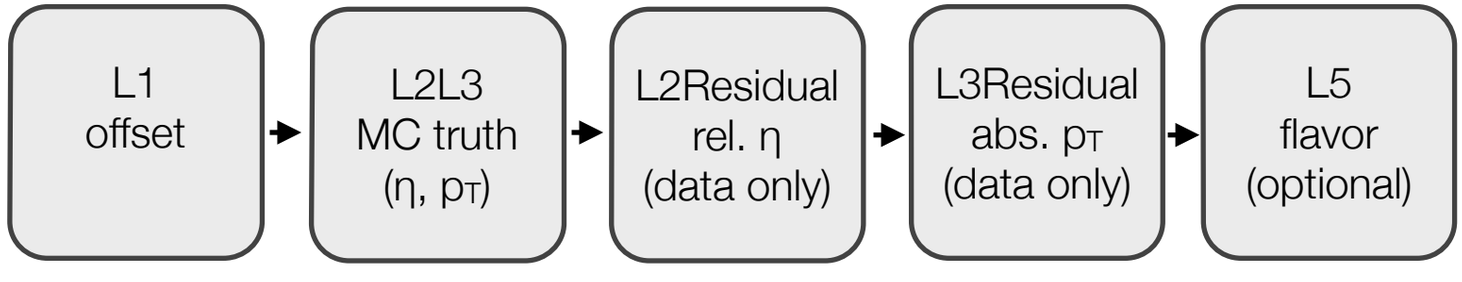
CMS : Jets

Jet Energy Corrections

The 4-momenta of jets are initially reconstructed as the vector sums of the 4-momenta of constituent particles (E-scheme)

$$p_\mu^{\text{raw}} = \left(\sum_{i \in \text{jet}} E^i, \sum_{i \in \text{jet}} p_x^i, \sum_{i \in \text{jet}} p_y^i, \sum_{i \in \text{jet}} p_z^i \right)$$

Then, a series of factorized corrections are applied



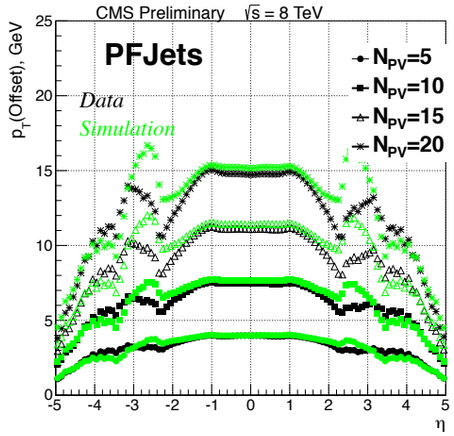
Each correction is a scaling factor. And so is the total correction

$$p_\mu^{\text{cor}} = C p_\mu^{\text{raw}}$$

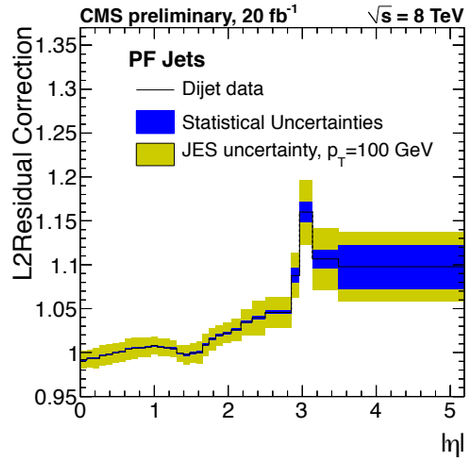
The primary corrections for the detector response are derived from MC. MC is used as it well describes data. The residual corrections are for small differences between data and MC.

CMS-DP-2013-033

L1



L2Residual

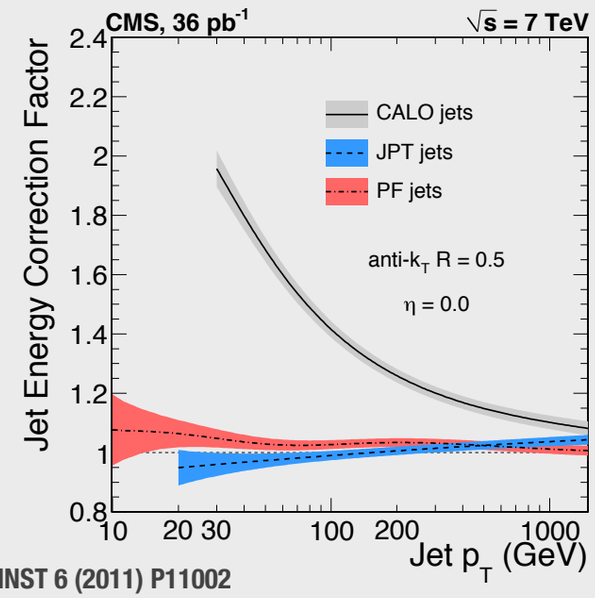


An earlier version of proposed factorization

L1 offset → L2 rel. η → L3 abs. p_T → L4 EMF → L5 flavor → L6 UE → L7 parton

CMS-PAS-JME-07-002 purely data-driven corrections were proposed before Run-I started

The total corrections for PF jets are smaller than those for Calo jets



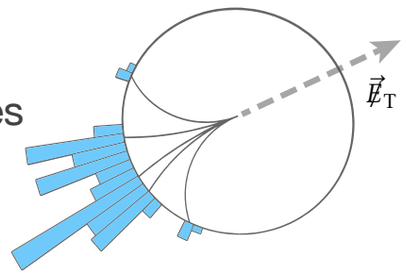
JINST 6 (2011) P11002

CMS : MET

PF MET (uncorrected)

the negative of the vector sum of p_T of all PF candidates

$$\vec{\not{E}}_{\mathrm{T}} = -\sum_{i \in \mathrm{all}} \vec{p}_{\mathrm{T}i}$$



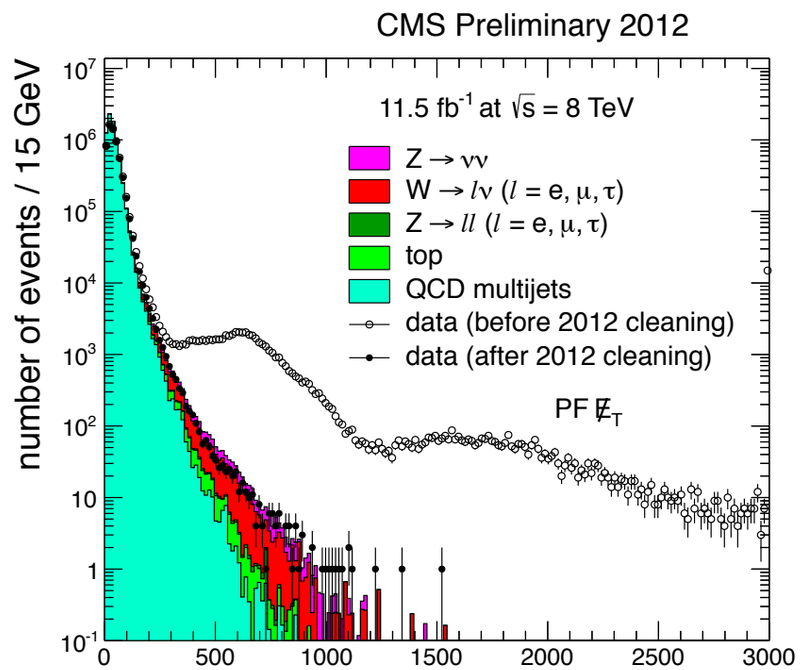
MET filters

Without a dedicated cleaning, events with large MET are predominantly triggered by false MET, caused, e.g. by detector noises, cosmic rays, beam halo

After the MET cleaning is applied, the agreement of the MET spectrum with MC, in which causes of false MET are not explicitly simulated, significantly improves

JINST 6 (2011) P09001

CMS-PAS-JME-12-002



MET corrections

Type-I: a propagation of jet energy corrections

Type-0: corrections for the calorimeter response to low energy particles produced in pile-up interactions

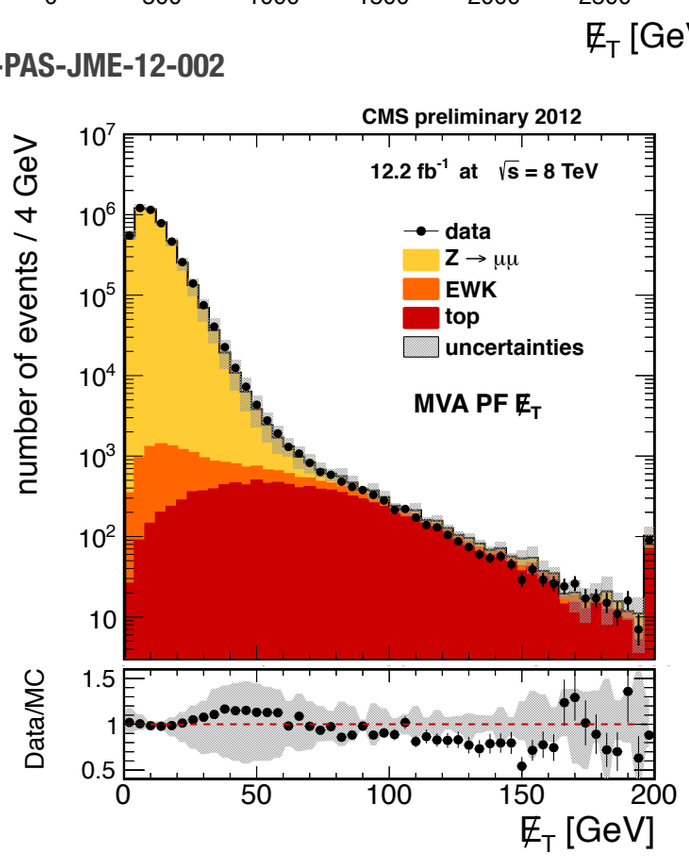
xy-Shift: corrections for the shift of the mean of MET

PF MVA MET

an advanced MET reconstruction algorithm, remarkably improves MET resolution in high pile-up events

regression, estimates MET in the primary interaction with BDT from five variations of MET, for each of which the vector sum is taken over a different set of PF candidates

CMS-PAS-JME-12-002

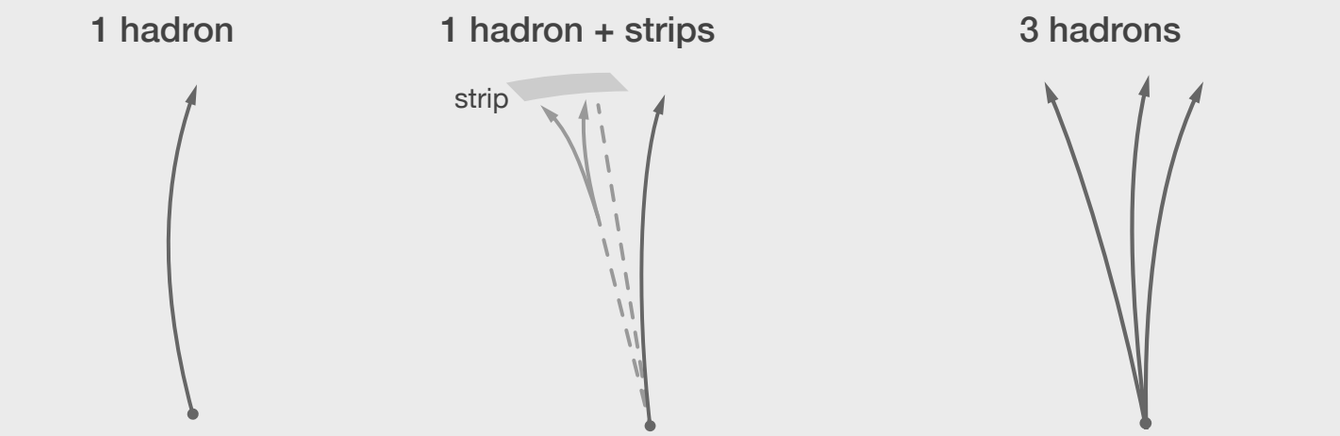


CMS : Tau

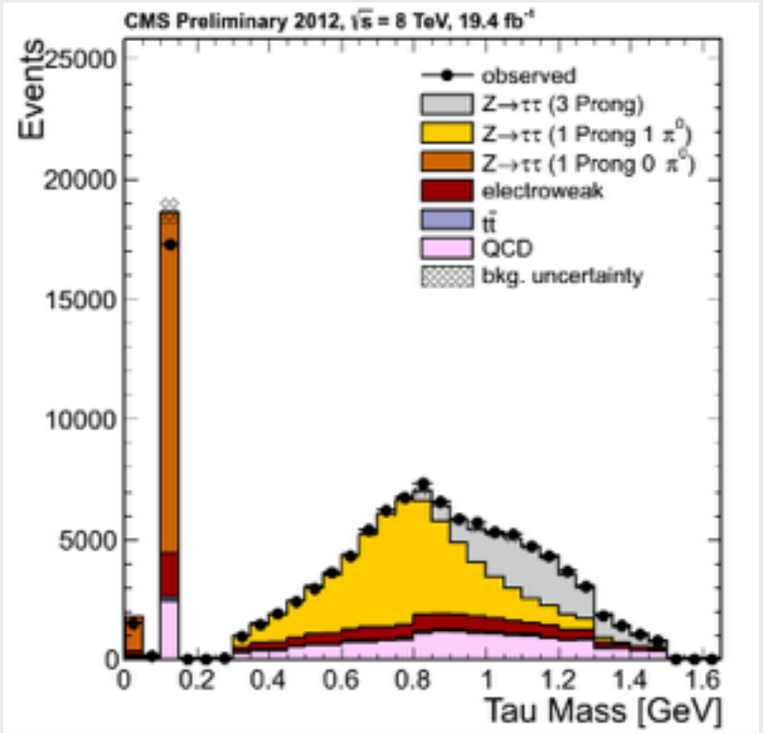
HPS (Hadron Plus Strips) JINST 7 (2012) P01001

- the primary tau reconstruction algorithm in CMS
- reconstructs major hadronic tau decay modes with PF candidates in PF jets
- reconstructs photons as “strips” of ΔηxΔϕ=0.05x0.2, longer in ϕ to collect photon conversions spread in ϕ in strong magnetic field
- requires the consistency with masses of intermediate resonances, ρ, a1

HPS decay modes



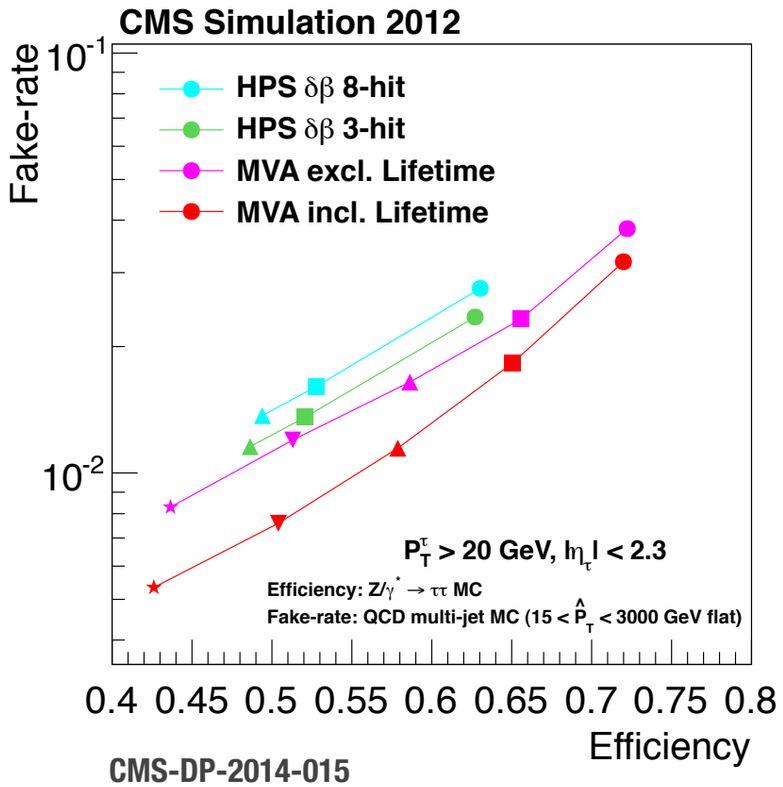
Tau invariant mass reconstruction



CMS-DP-2013-012

Tau isolation

- used to distinguish taus from quark or gluon jets
- Two approaches
  - **Cut Based Isolation:** charged particles from the hard interaction determined by the vertex and an estimate of neutral particles from the hard interaction.
  - **MVA Isolation:** variables include lifetime, impact parameters

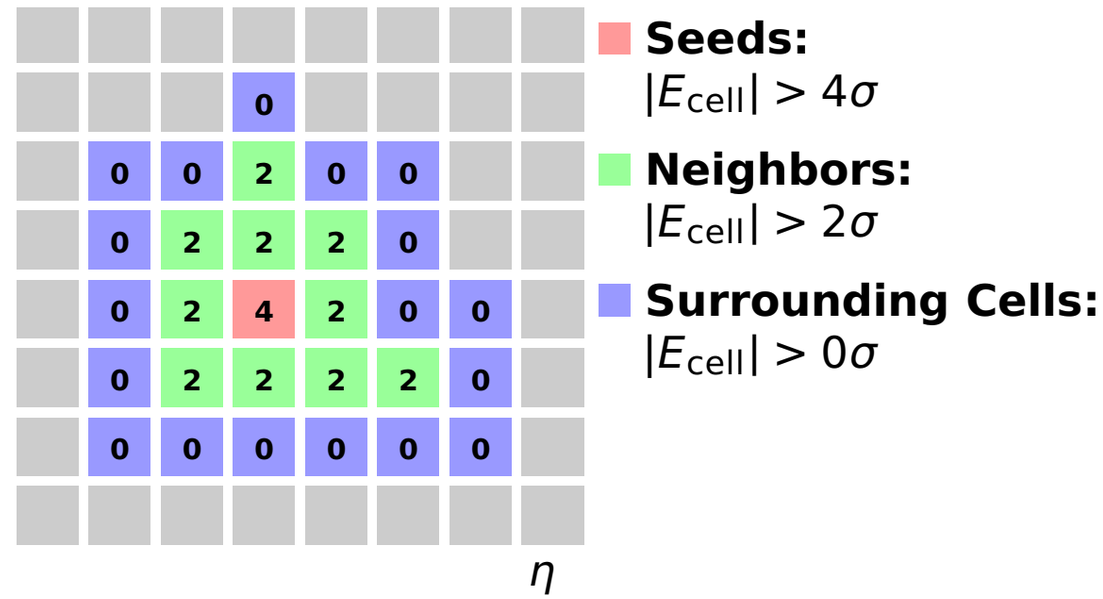


CMS-DP-2014-015

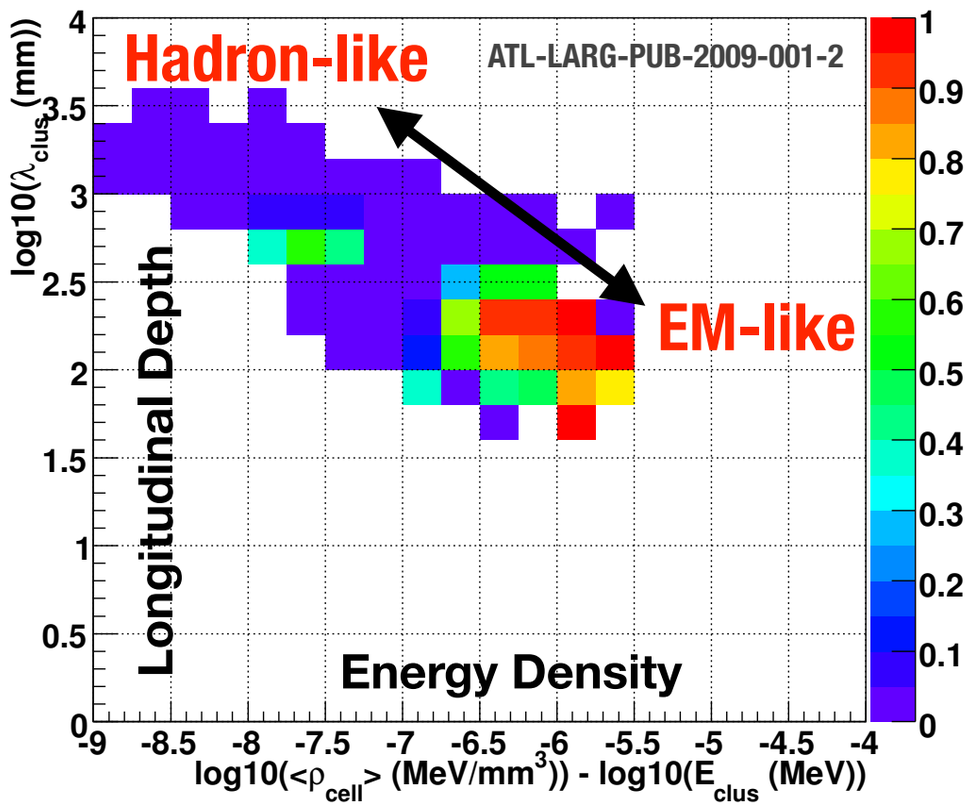
Jet/ETMiss/Tau in ATLAS

ATLAS: Topological Clusters

- **3D "Topological" clusters**
  - neighboring calorimeter cells surrounding a seed cell
    - **inputs for reconstructions of jets, ETmiss and taus**
  - clustering based on energy significance (|E| / σ) per cell
    - **σ** : sum-in-quadrature of electronic & pileup noises defined per cell
      - to suppress noise contributions
    - optimized "4-2-0" σ method



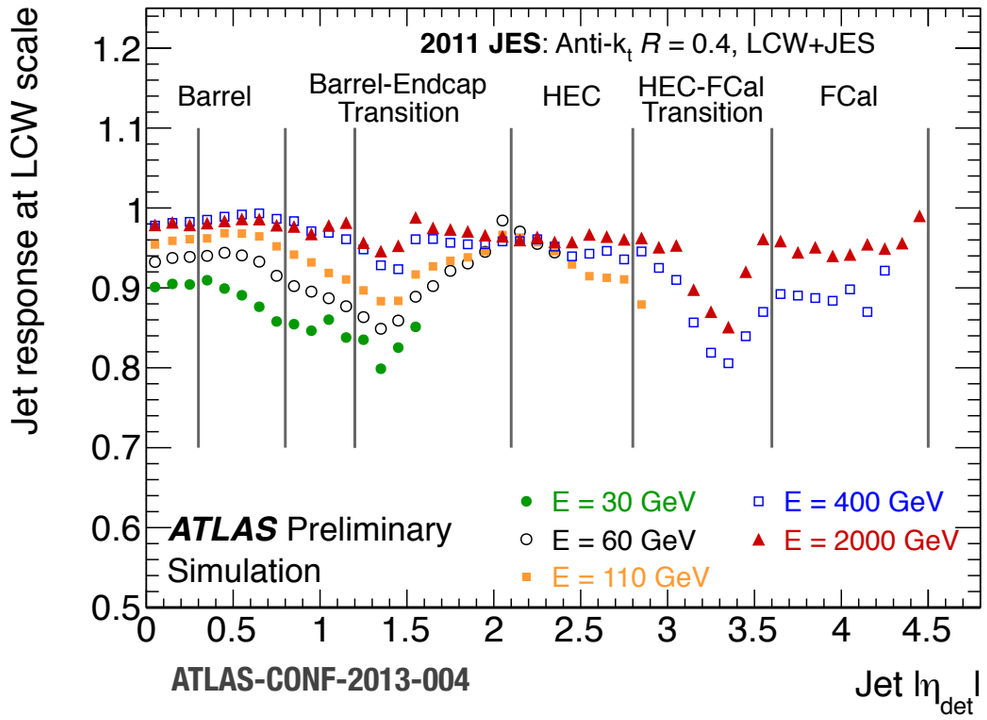
- Topo-cluster calibration
  - ElectroMagnetic scale (EM scale)
    - sum energy using baseline cell-level detector calibration (not the electron calibration)
  - **Local (hadronic) Cluster Weighting scale** (LCW scale)
    - start with topo-clusters at EM scale
    - distinguish EM (e.g., π0) from hadronic (e.g., π±) deposition via cluster moments
      - w/ energy density, longitudinal depth
    - apply weights for hadronic response, out-of-cluster energy, and dead material
      - validated by test beam, single particle E/p measurements

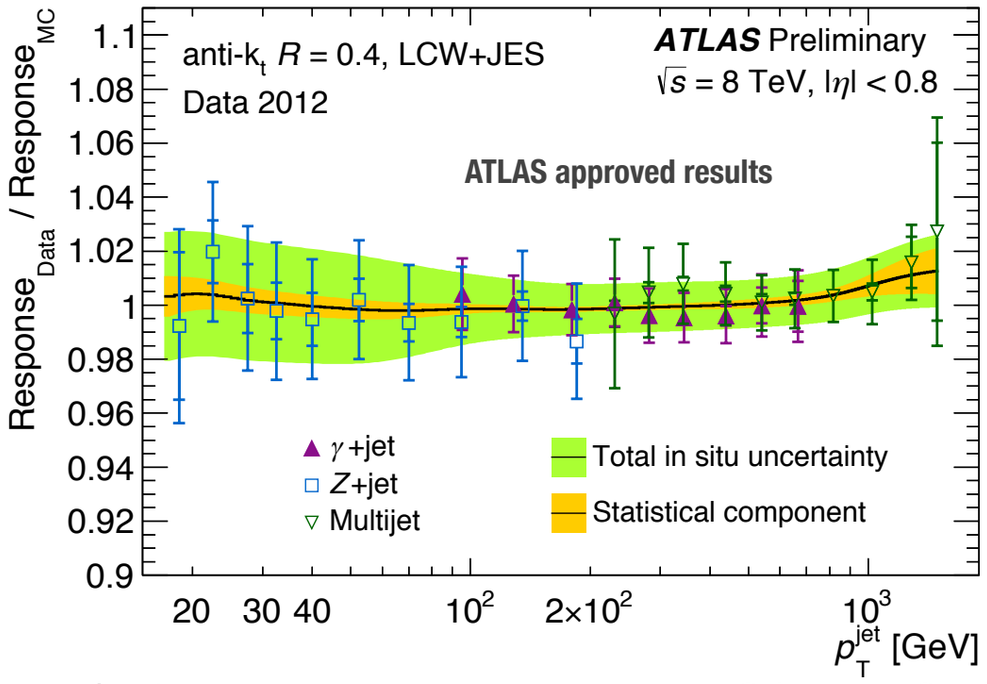


ATLAS: Jet calibration

- Calibration sequence

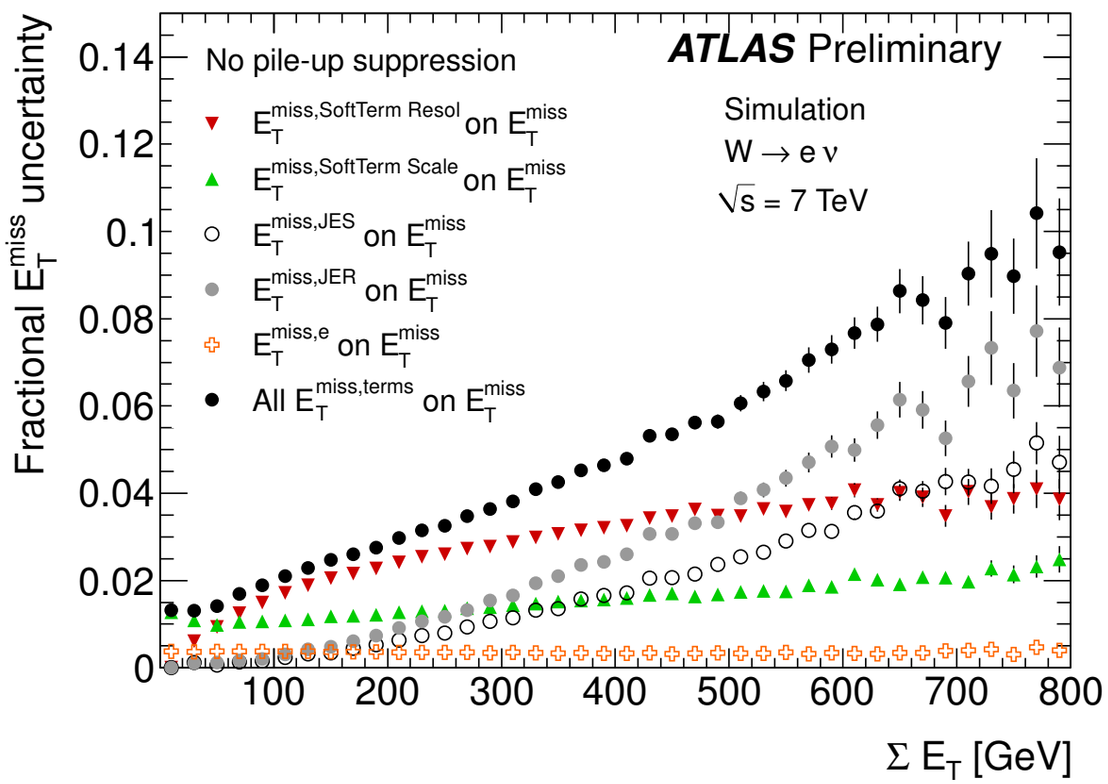
  - Anti-kt algorithm for jet reconstruction
    - with clusters in EM scale / LCW scale
  - Pile-up corrections
    - Jet area based
  - Jet Energy Scale (JES)
    - derived from MC truth information
    - (E, pT)-dependent correction factor
      - E(true)/E(calo) applied on E(calo)
  - Residual corrections in in-situ methods
    - photon + jet balance
    - Z + jet balance
    - multi-jet balance
    - di-jet balance for eta-intercalibration
  - More new techniques
    - Origin (vertex) correction
    - Global Sequencial Correction

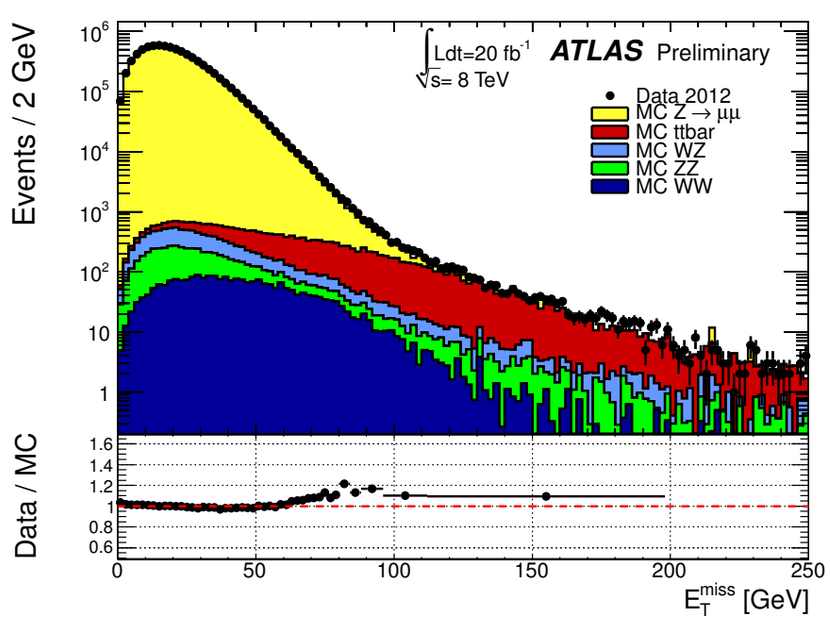


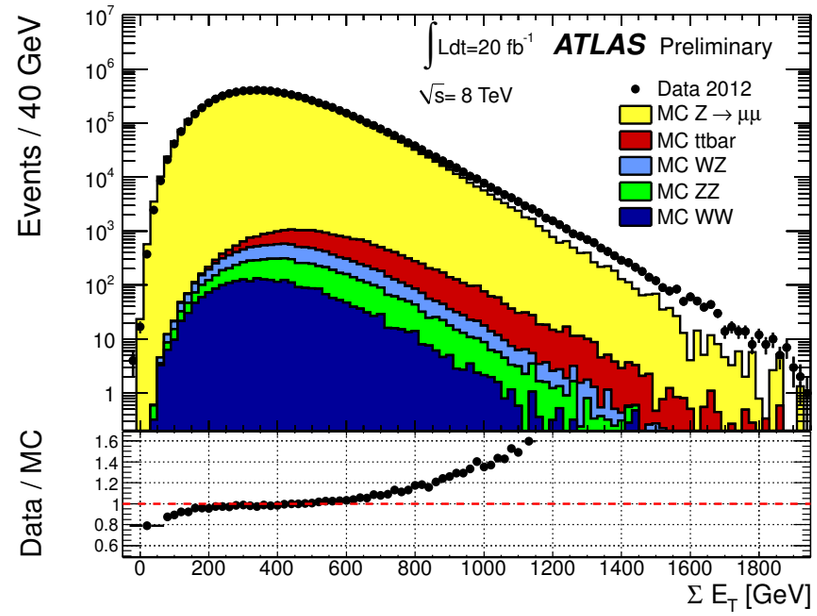


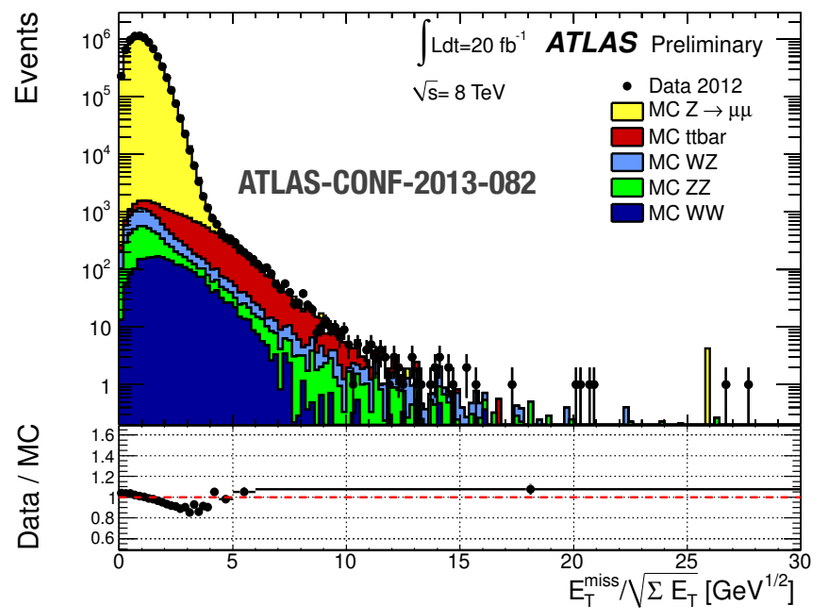
ATLAS: MET configurations

- MET reconstruction
  - add up all the **calibrated physics objects,** then see what's missing:
    - $E_{x(y)}^{\text{miss}} = E_{x(y)}^{\text{miss},e} + E_{x(y)}^{\text{miss},\gamma} + E_{x(y)}^{\text{miss},\tau} + E_{x(y)}^{\text{miss,jets}} + E_{x(y)}^{\text{miss,SoftTerm}} + E_{x(y)}^{\text{miss},\mu}$
- Soft Term
  - tracks that match topo-clusters unassociated to reconstructed physics objects
    - tracks have better momentum resolution at low pT
  - dominates systematic uncertainty in low pT region



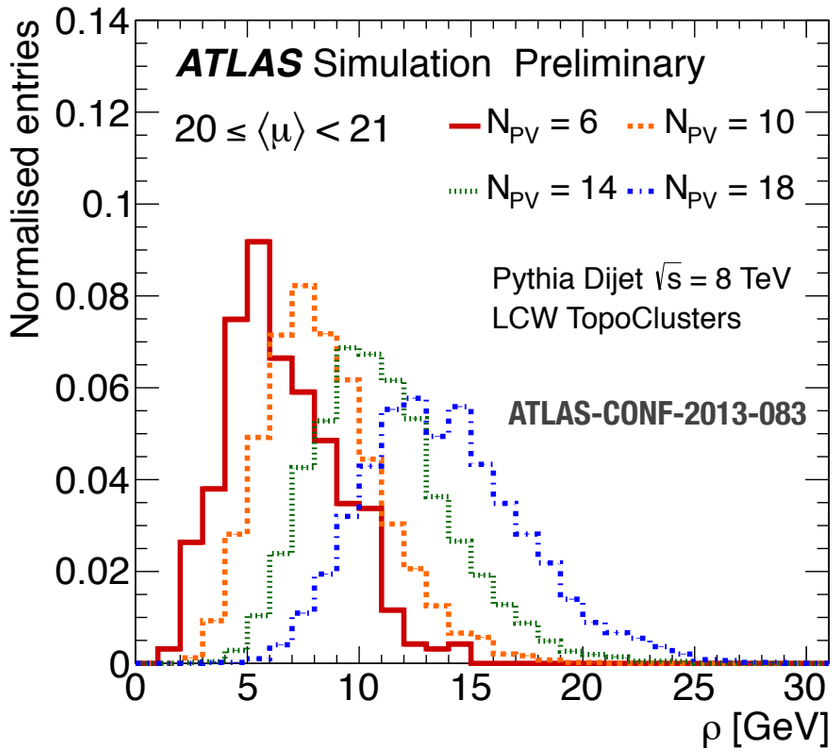




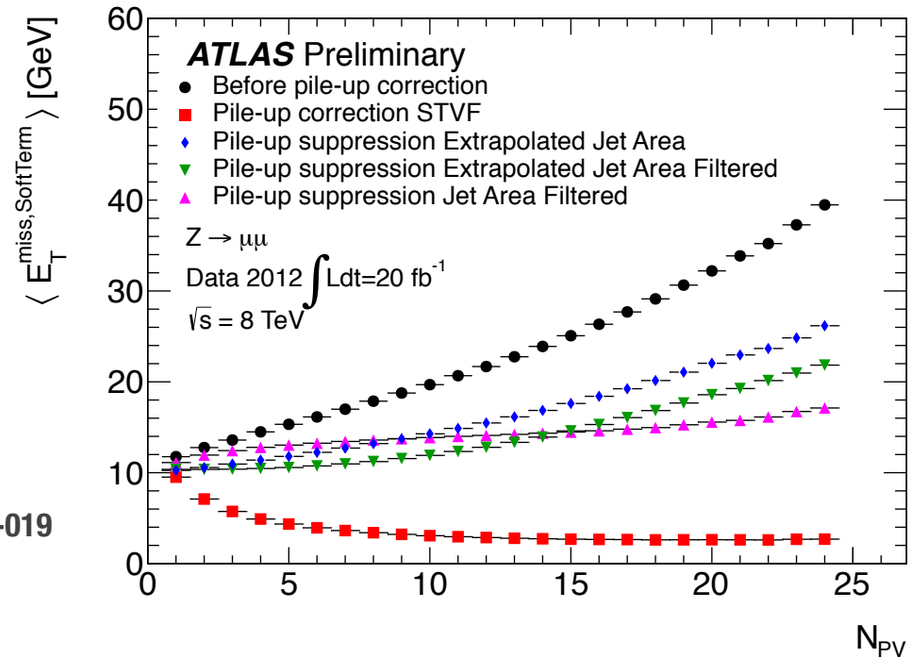


ATLAS: Pileup corrections

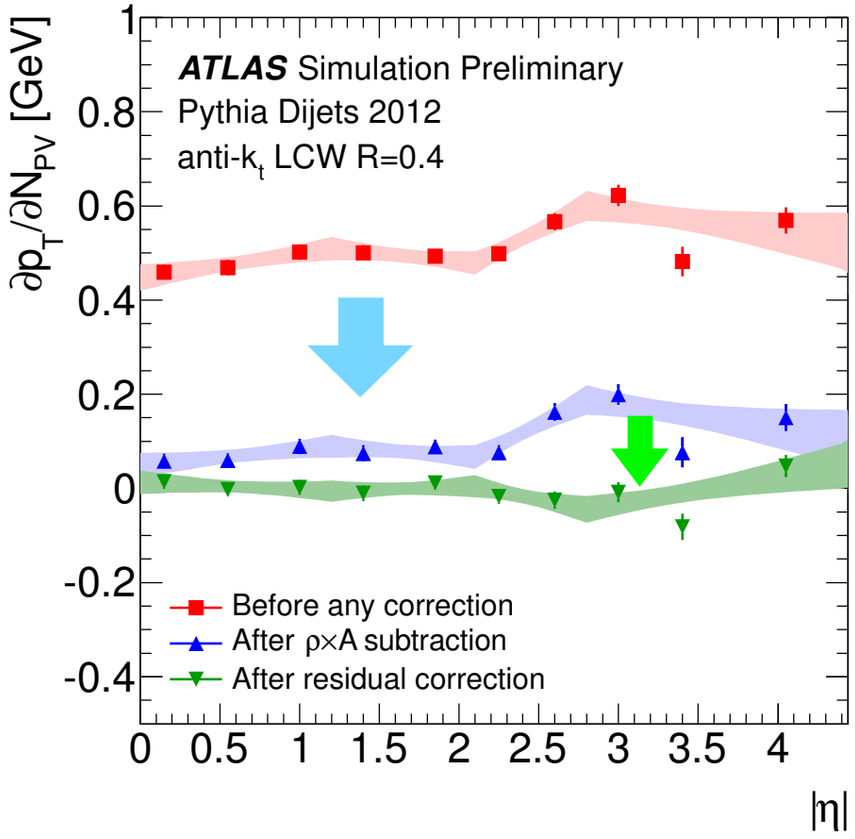
- Subtract pileup contributions
  - based on median event density and jet area
    - $p_T^{\mathrm{corr}} = p_T - \rho \cdot A - \alpha(N_{\mathrm{PV}} - 1) - \beta(\mu)$
      - mean and width of ρ increases with μ
      - similar JES residuals independent of jet size
- Jet Area based pileup subtraction
  - improves energy response of the calorimeter,
  - jet energy resolution, and
  - substructure performance at high μ
  - also used for pileup correction in MET



- Soft Term Vertex Fraction (STVF) for MET
  - the fraction of momenta of tracks matched to the MET Soft Term which are associated with the hard scattering vertex

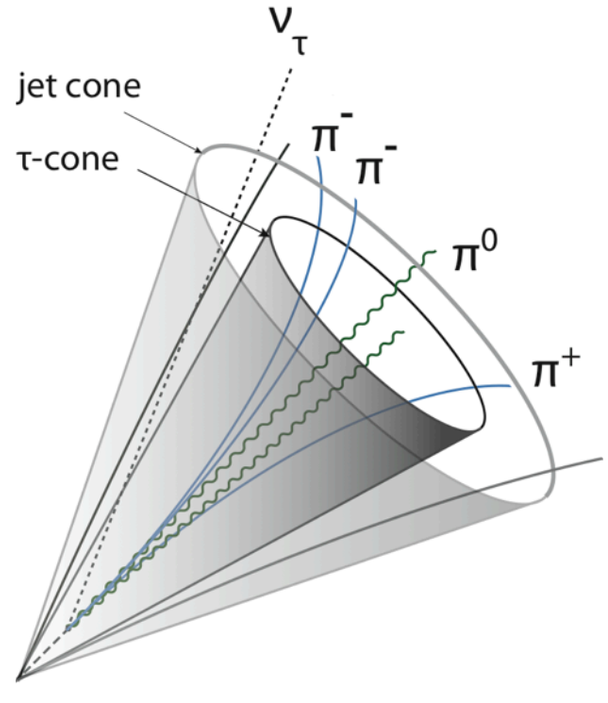


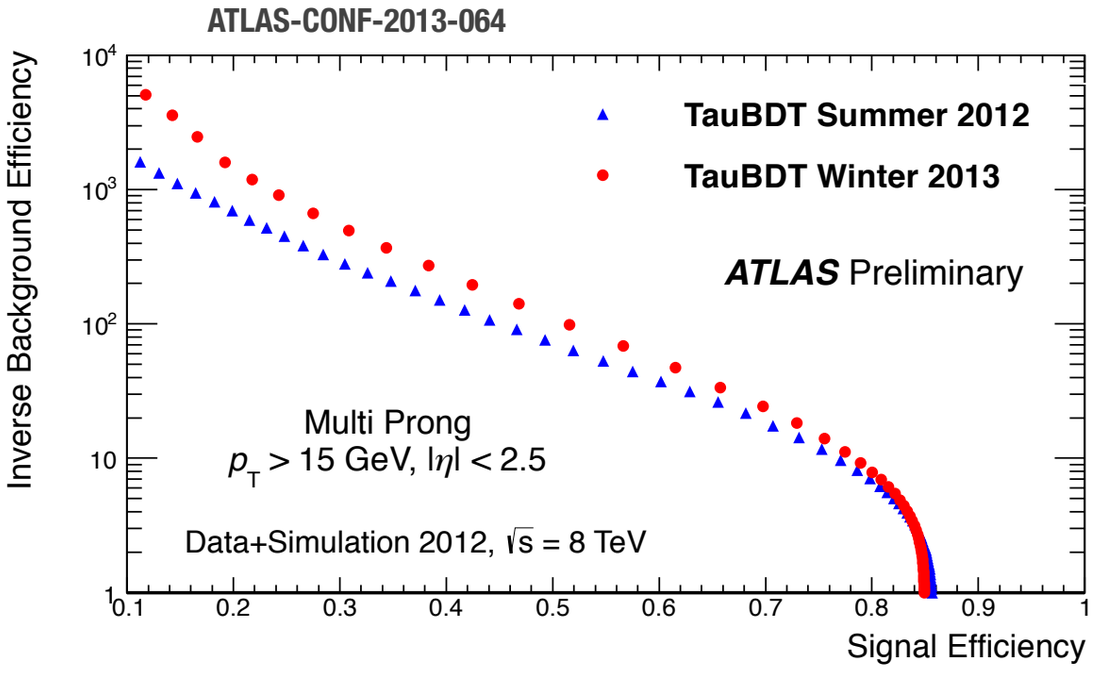
ATLAS-CONF-2014-019

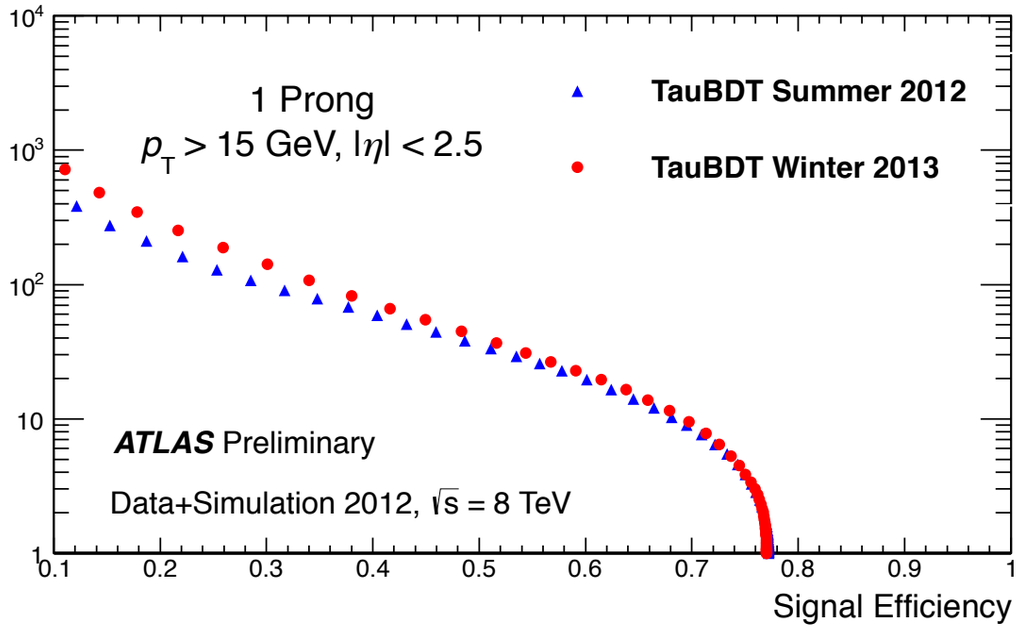


ATLAS: Tau

- BDT to discriminate
  - τ vs. jets
  - τ vs. electrons
  - in addition cut-based μ-veto
- In winter 2013
  - added pi0 reconstruction within tau candidates
  - significant improvement in jet rejection in tau ID



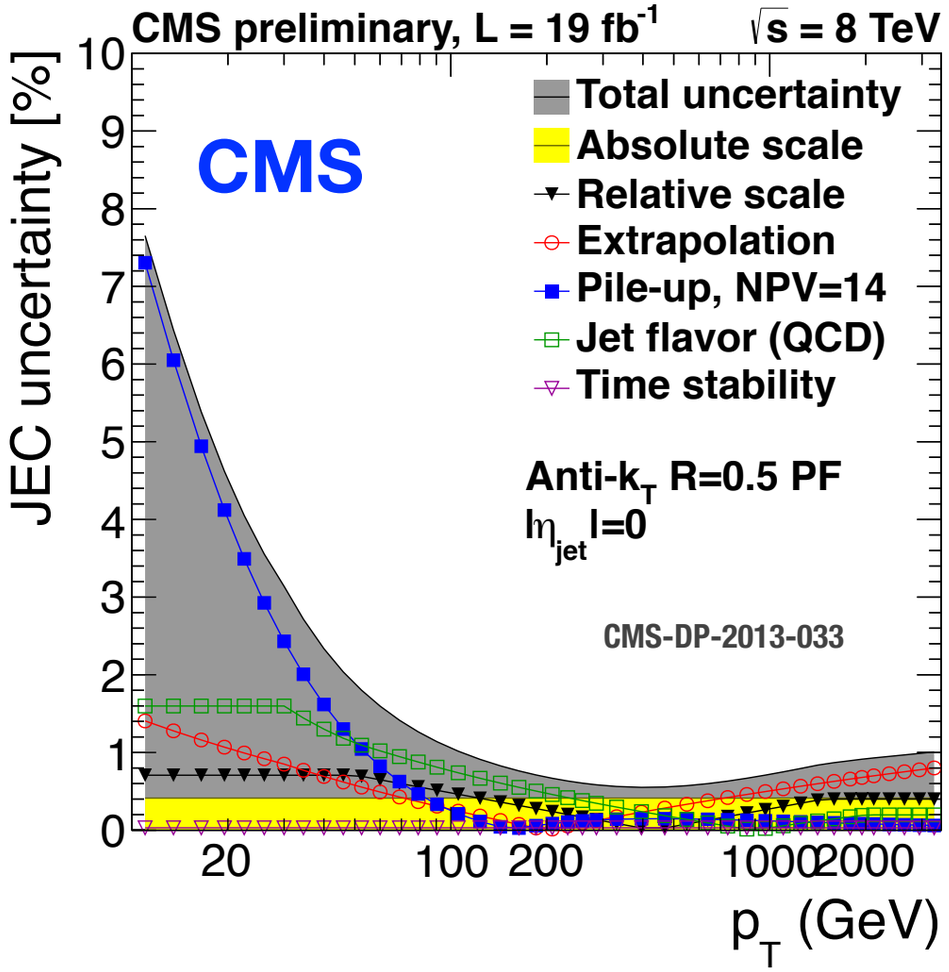


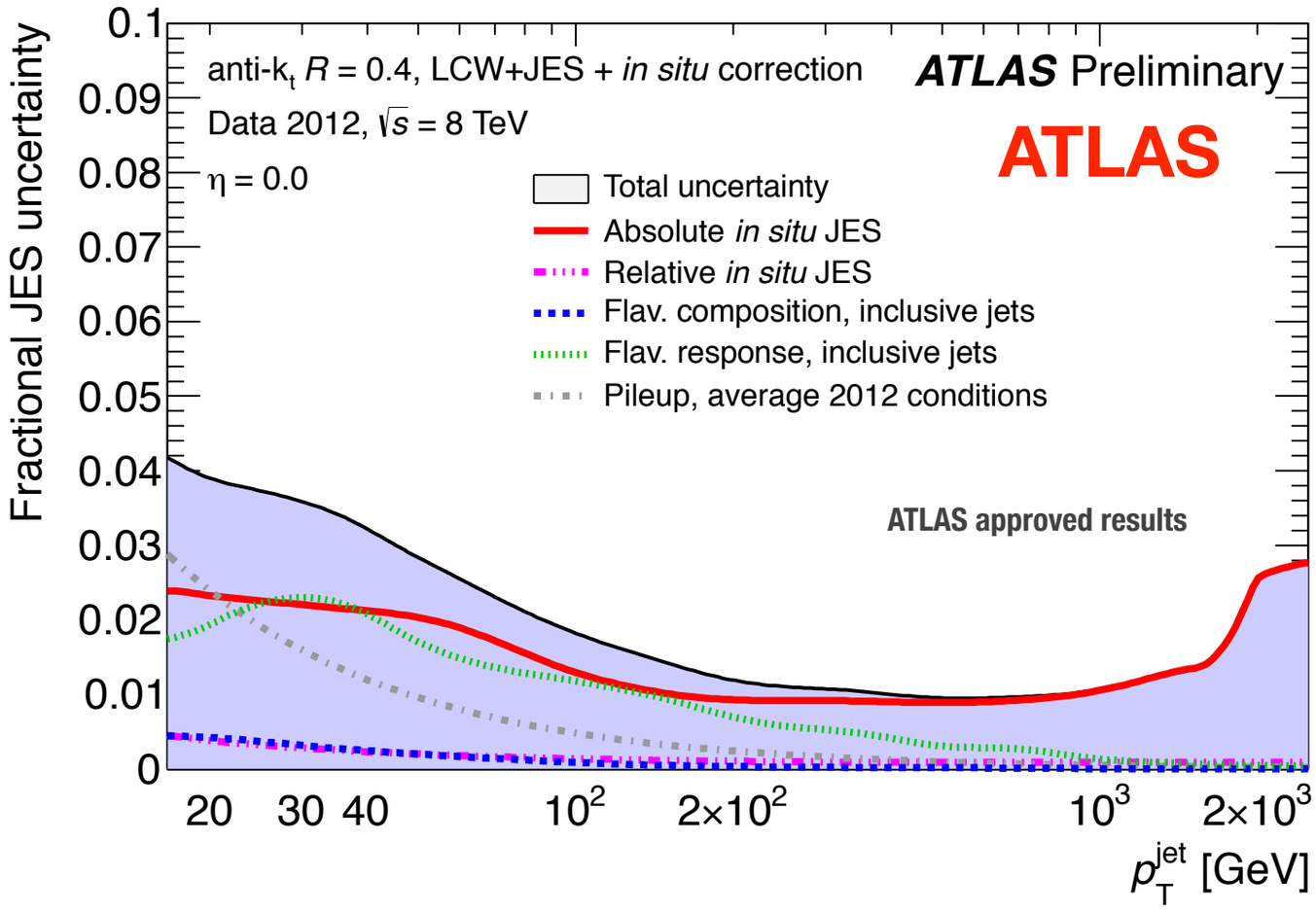


Comparison of two experiments

Comparison: Jets

- JES systematic uncertainties
  - **CMS : PF jet**
    - pT-independent absolute scale
    - Larger pileup uncertainty in low pT region
    - MC JES uncertainty @ 100 GeV extrapolated to high pT region
  - **ATLAS : Calo jet**
    - Uncertainty in the in-situ measurements directly propagated
      - purely data-based, larger uncertainty in high pT ~ 2 TeV due to limit of the multi-jet method

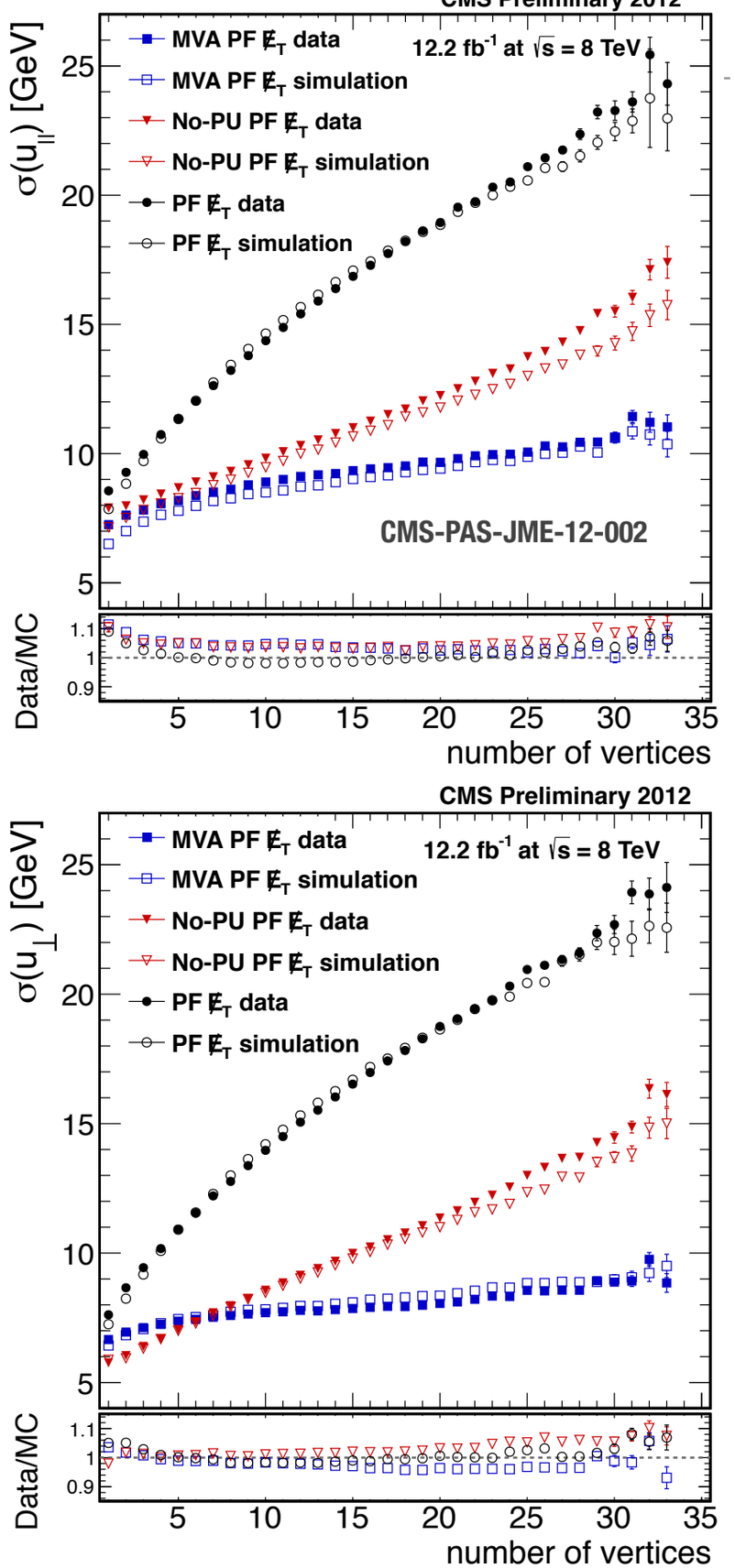




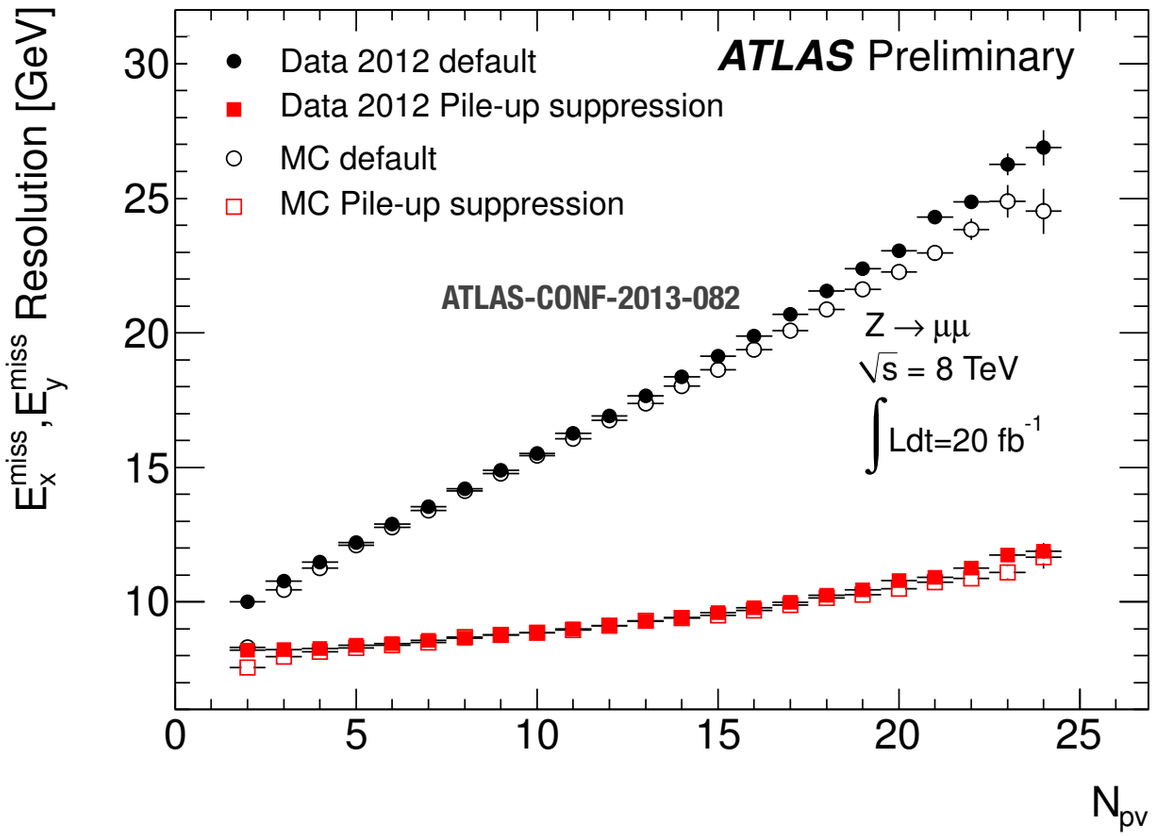
Comparison: MET

- MET resolution in Z→μμ events
  - **CMS : MVA PF MET**
    - longitudinal / perpendicular component to Z momentum direction
    - improved from PF MET
  - **ATLAS : physics object based MET**
    - in x/y-axis
    - resolution improved in the STVF pileup correction

CMS



ATLAS



Summary

- Performances and comparisons between ATLAS and CMS in the LHC-Run 1 on measurements of “hadronic” physics objects
  - **Jet** energy calibration and its uncertainties
  - **ETMiss** reconstruction methods and pileup corrections
  - **Tau** identification methods

    - ✓ Both experiments have been exploiting the detector performances, even in different concepts, to the full !

- Toward Run 2
  - Pile-up corrections essential in Jet/ETMiss/Tau analyses
    - Big challenge in the higher luminosity
  - Many changes, new techniques expected
    - CMS moving to Anti-kt R=0.4 for jet reconstruction
      - More direct comparison will be possible
    - ATLAS using tracks more for pile-up corrections / suppressions
      - Particle Flow, vertex tagging for jets, track-based MET, etc.

Backup

References: ATLAS

- CONF NOTES
  - https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/
- Jet
  - Jet Pull
    - http://cds.cern.ch/record/1741708
  - Tagging and suppression of pileup jets with the ATLAS detector
    - http://cds.cern.ch/record/1700870
  - Jet Shape
    - http://cds.cern.ch/record/1572979
  - JES systematics
    - http://cds.cern.ch/record/1509552
    - http://arxiv.org/abs/arXiv:1406.0076
  - Pileup suppression for jets
    - https://cds.cern.ch/record/1570994
  - Jet energy resolution
    - https://cds.cern.ch/record/1281311
  - b-jet, track jet
    - http://cds.cern.ch/record/1504739
  - Underlying Event
    - http://cds.cern.ch/record/1497185
- MET
  - MET systematics
    - http://cds.cern.ch/record/1570993
  - pileup in MET
    - http://cds.cern.ch/record/1702055
- Tau
  - Tau ID hadronic
    - https://cds.cern.ch/record/1562839
  - TES
    - https://cds.cern.ch/record/1544036

References: CMS

- Jets
  - "8 TeV Jet Energy Corrections and Uncertainties based on 19.8 fb-1 of data in CMS", CMS-DP-2013-033, CDS:1627305
  - "Determination of Jet Energy Calibration and Transverse Momentum Resolution in CMS", 2011 *JINST* **6** P11002, DOI:10.1088/1748-0221/6/11/P11002
  - "Boosted Top Jet Tagging at CMS", CMS-PAS-JME-13-007, CDS:1647419
  - "Performance of quark/gluon discrimination using pp collision data at 8 TeV", CMS-PAS-JME-13-002, CDS:1599732
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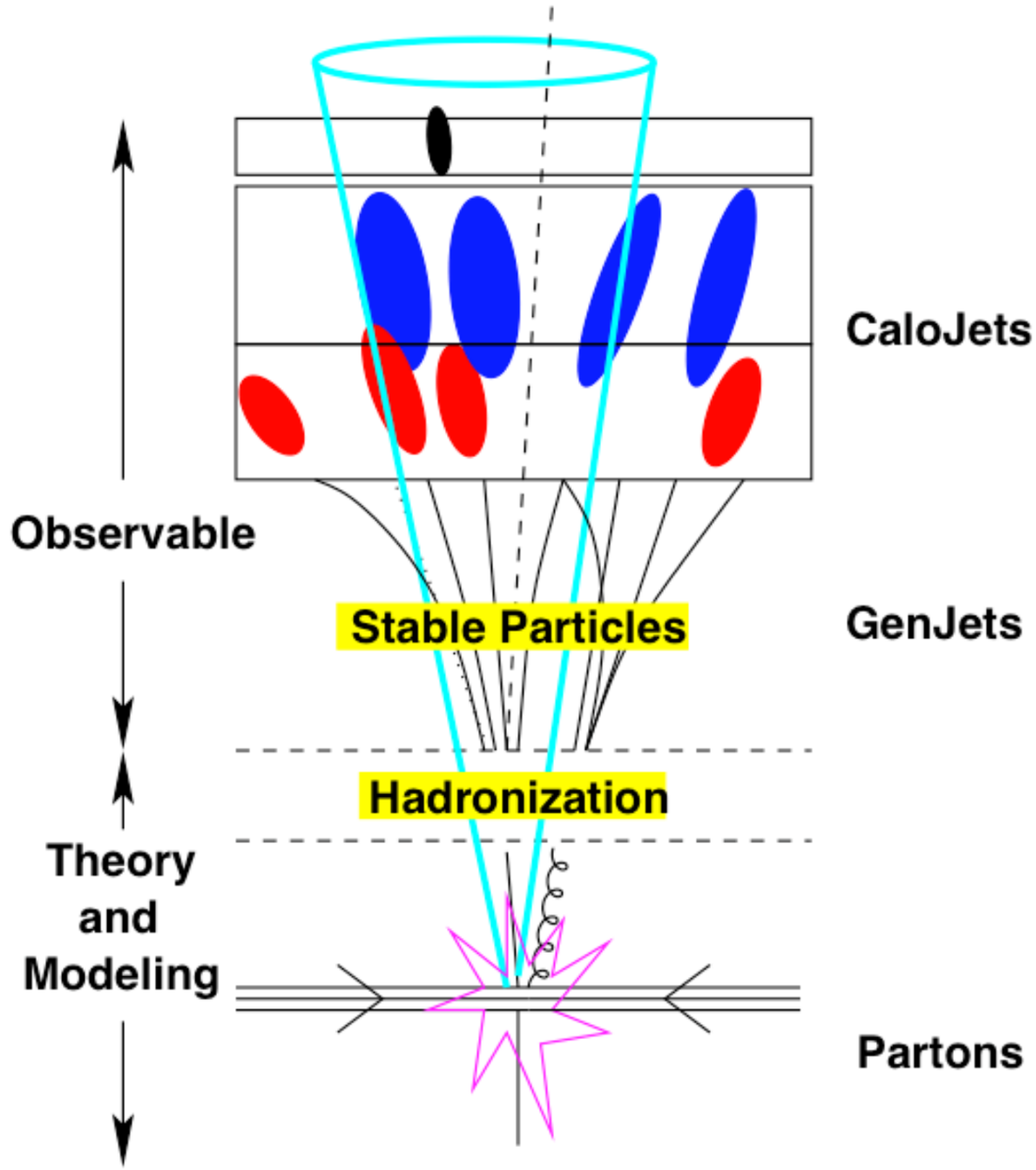
  - "Pileup Jet Identification", CMS-PAS-JME-13-005, CDS:1581583
- MET
  - "Performance of Missing Transverse Momentum Reconstruction Algorithms in Proton-Proton Collisions at 8 TeV with the CMS Detector", CMS-PAS-JME-12-002, CDS:1543527
  - "Missing transverse energy performance of the CMS detector", 2011 *JINST* **6** P09001, doi:10.1088/1748-0221/6/09/P09001
- Taus
  - "Tau ID Performance Plots", CMS-DP-2014-015, CDS:1704439
  - "Performance of tau-lepton reconstruction and identification in CMS", 2012 *JINST* **7** P01001, DOI:10.1088/1748-0221/7/01/P01001

What are jets ?

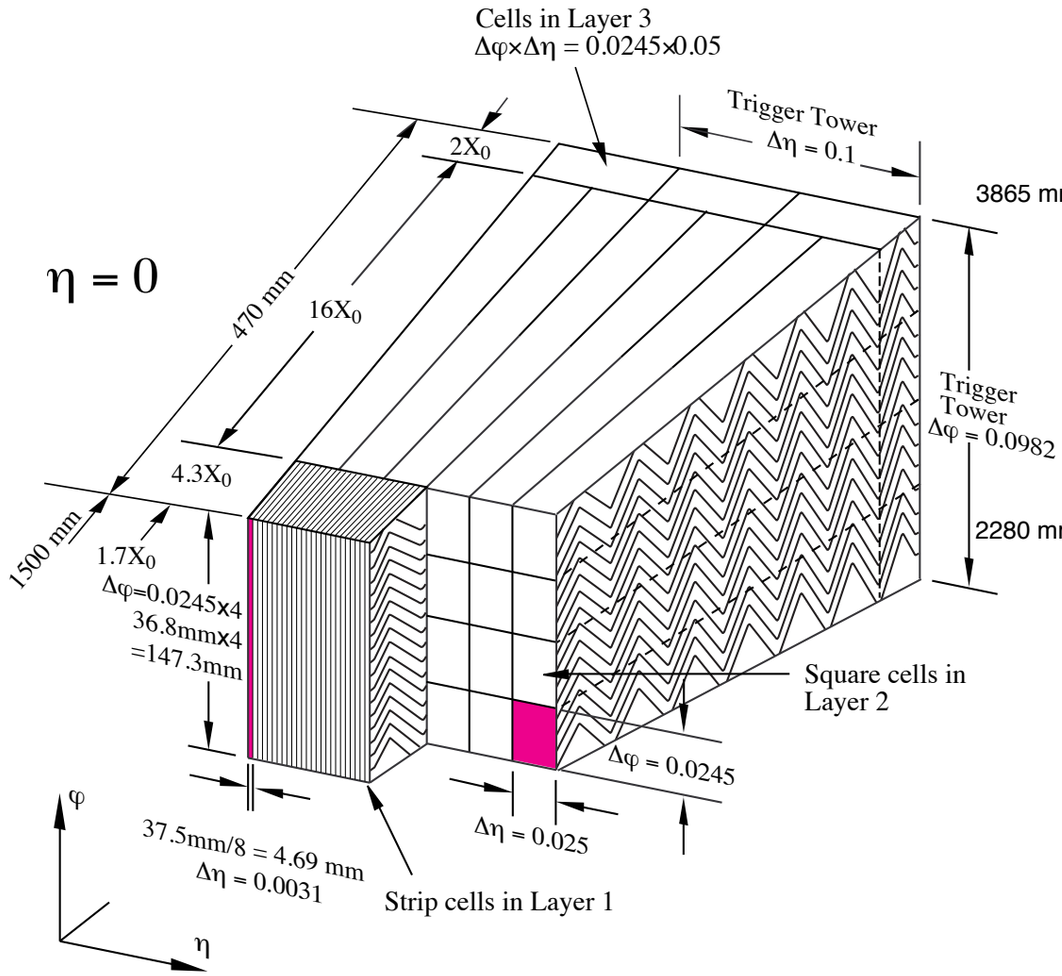
- Collimated bunches of stable hadrons
  - originating from partons (quarks & gluons) after fragmentation/hadronization

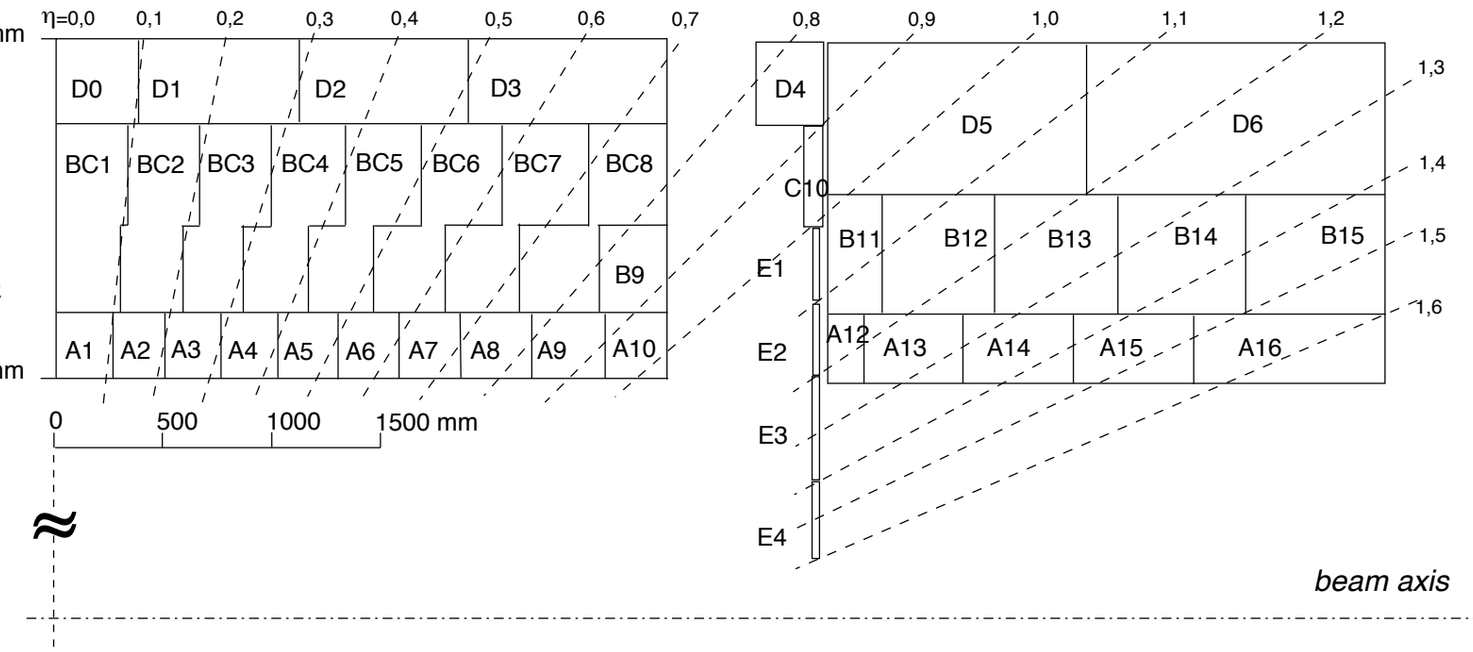
- Difficulties in the jet measurement
  - Prediction by theory
    - parton distribution
      - quark/gluon
    - hadronization
  - Jet Finding
    - approximate attempts to reverse-engineer the quantum mechanical processes of hadronization
  - Calorimeter response
    - in the EM scale
    - to hadrons



ATLAS calorimeter

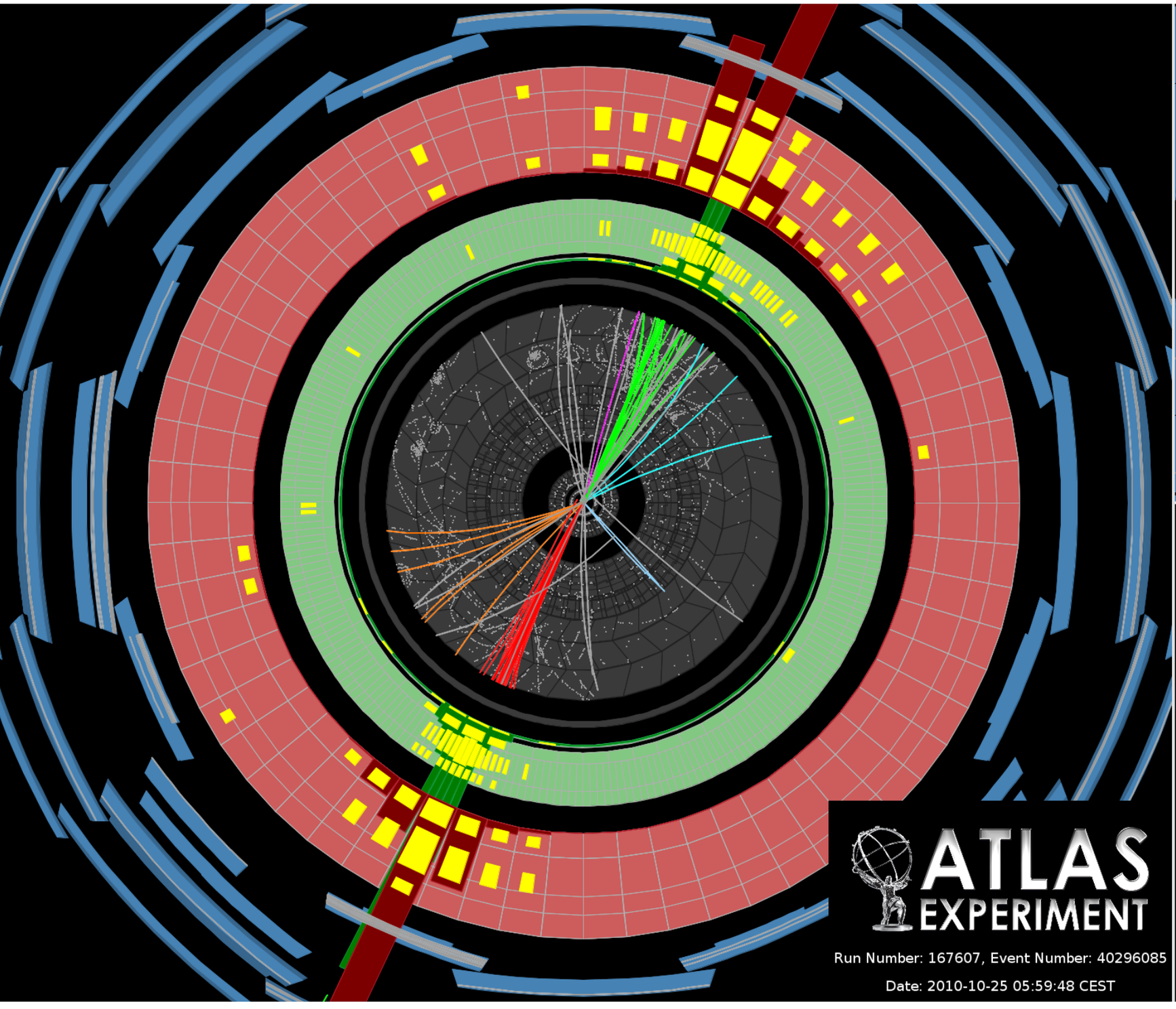
- LAr, TileCal

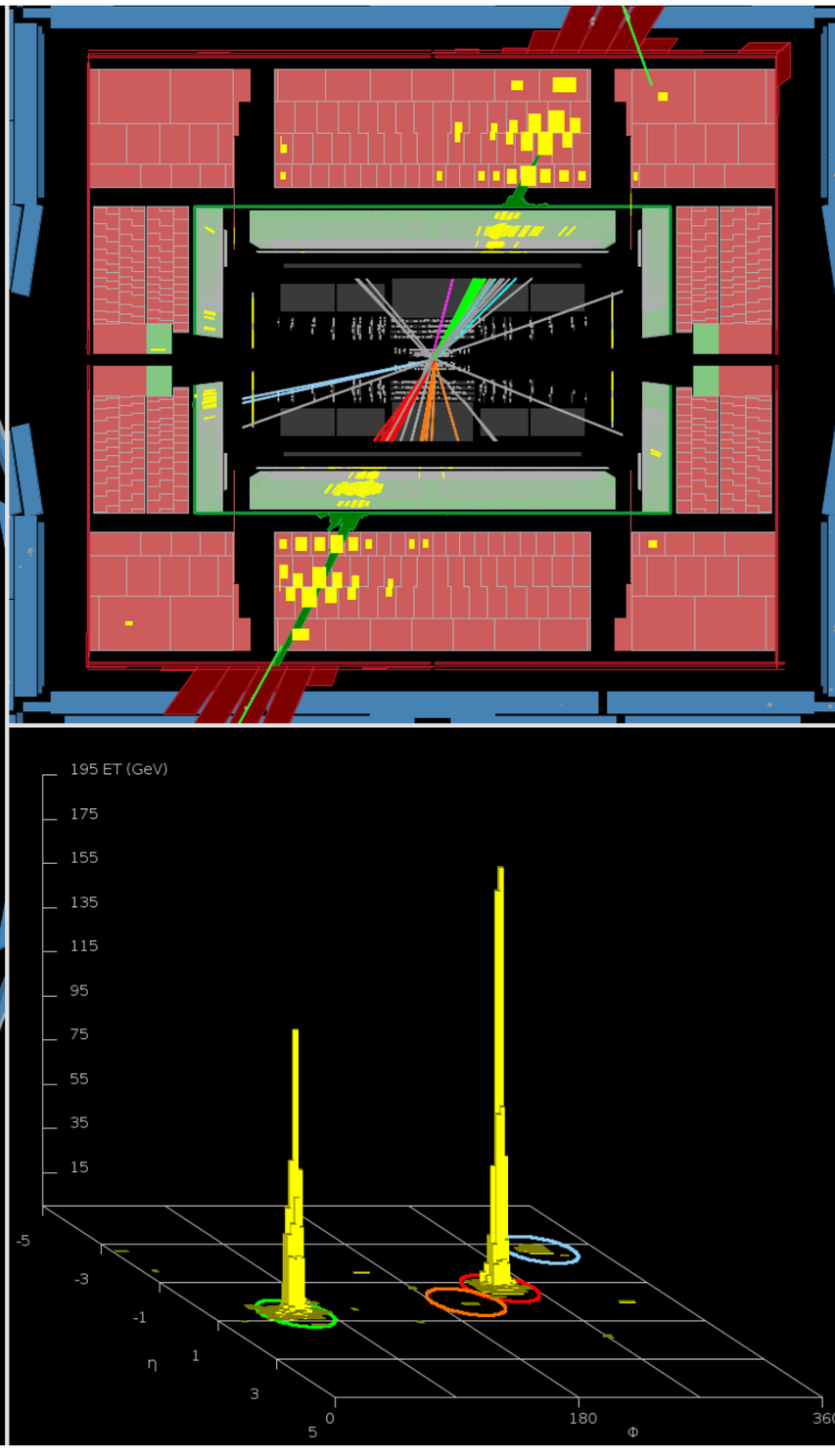




ATLAS: Event Display

- Di-jet event in 2010 with the highest invariant mass





ATLAS: Further pile-up mitigation

- Can exploit tracking/vtx information in order to reject pileup
- Jet vertex fraction (JVF) broadly used in Run1, but can lead to hard-scatter jet efficiency loss increasing with pileup
- Jet vertex tagger (JVT) developed in order to have a flat efficiency vs NPV
- Much more discussed at pileup mitigation workshop (May 16-18)
  - https://indico.cern.ch/event/306155/