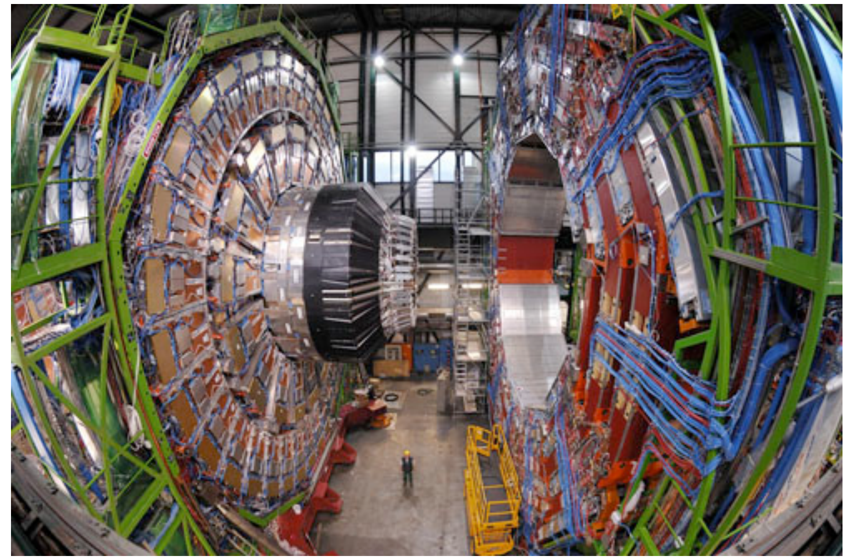

Jets and Missing Transverse Energy Reconstruction With CMS

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On be half of CMS Collaboration

4th Conference on Physics at LHC

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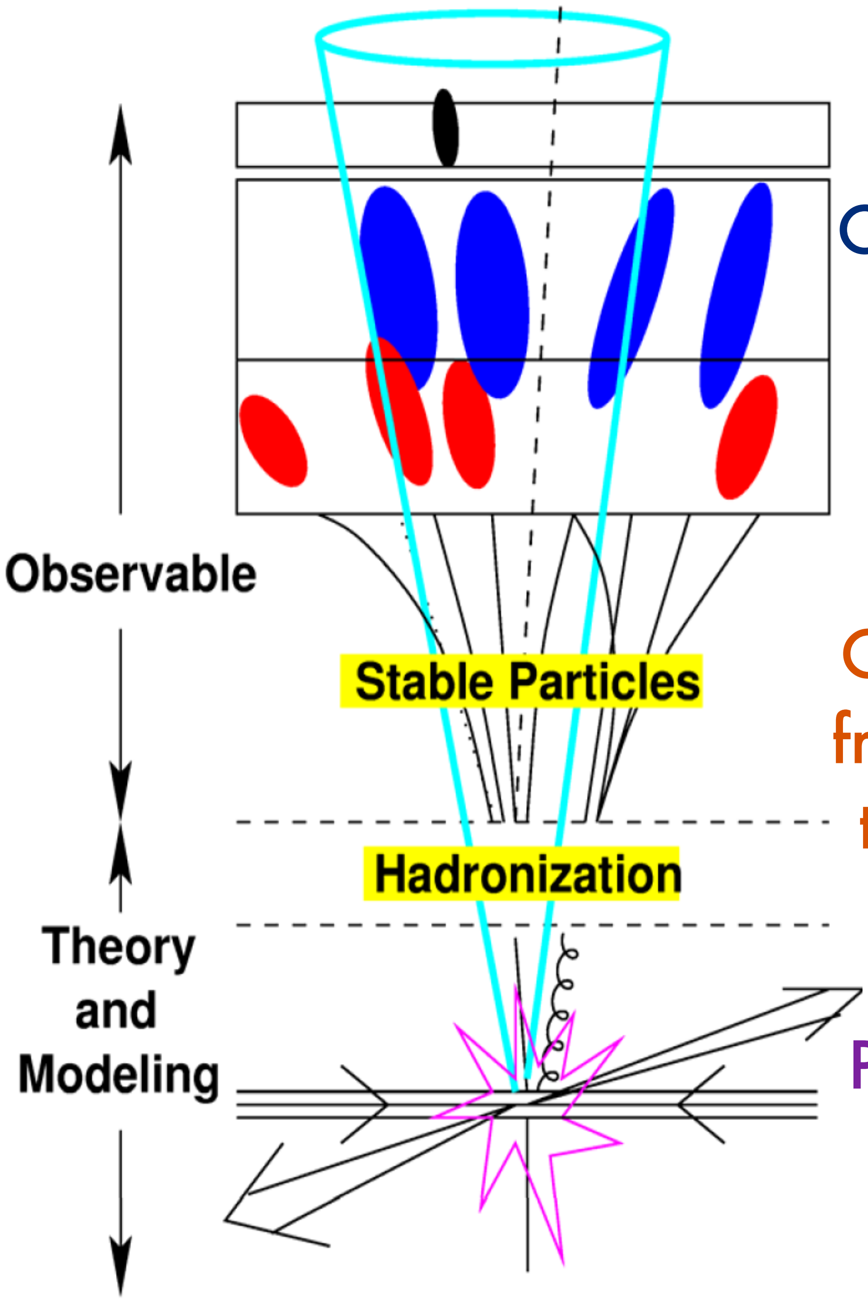
Introduction



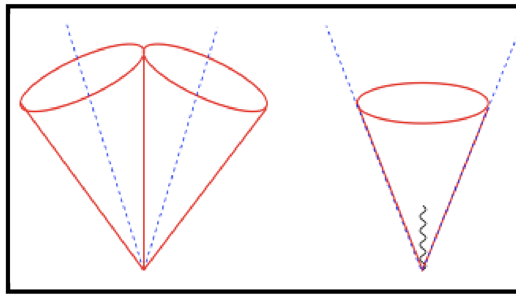
CaloJets: Clusters of Calorimeter Towers

GenJets: made from stable MC truth particles

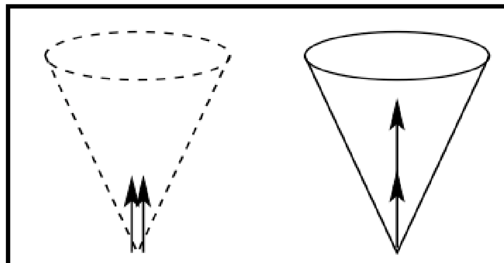
Parton Level Jets

Several Jet clustering algorithms available on the market, desired properties are:

- ✦ Good correspondence between parton-, particle-, detector-level
- ✦ Insensitivity to detector details, PileUp, underlying event
- ✦ Reliable calibration
- ✦ Fast execution
- ✦ Infrared and collinear safe



Infrared Unsafe
sensitive to the addition of soft particles



Collinear Unsafe
sensitive to splitting a 4-Vector into two smaller

Jet Algorithms in CMS

* IterativeCone Algorithm

- Input: CaloTowers/particles with E_T >1 GeV
- Iterative search for stable cones of radius R

$$R=\sqrt{\Delta\eta^2 + \Delta\phi^2}$$

- particles assigned to a stable cone are removed from the input list and iterate... No split&Merge conflict
- Not infrared & collinear safe

* (Fast-) k_T Algorithm

- Faster implementation of standard k_T
- combines 4-vectors according to their relative transverse momentum

$$d_{i,j} = min\{k_T^i, k_T^j\}\sqrt{\Delta\eta_{ij}^2 + \Delta\phi_{ij}^2}$$

$$d_i = k_T^i$$

- Infrared & Collinear Safe
- No unclustered energy

* MidPoint Cone Algorithm

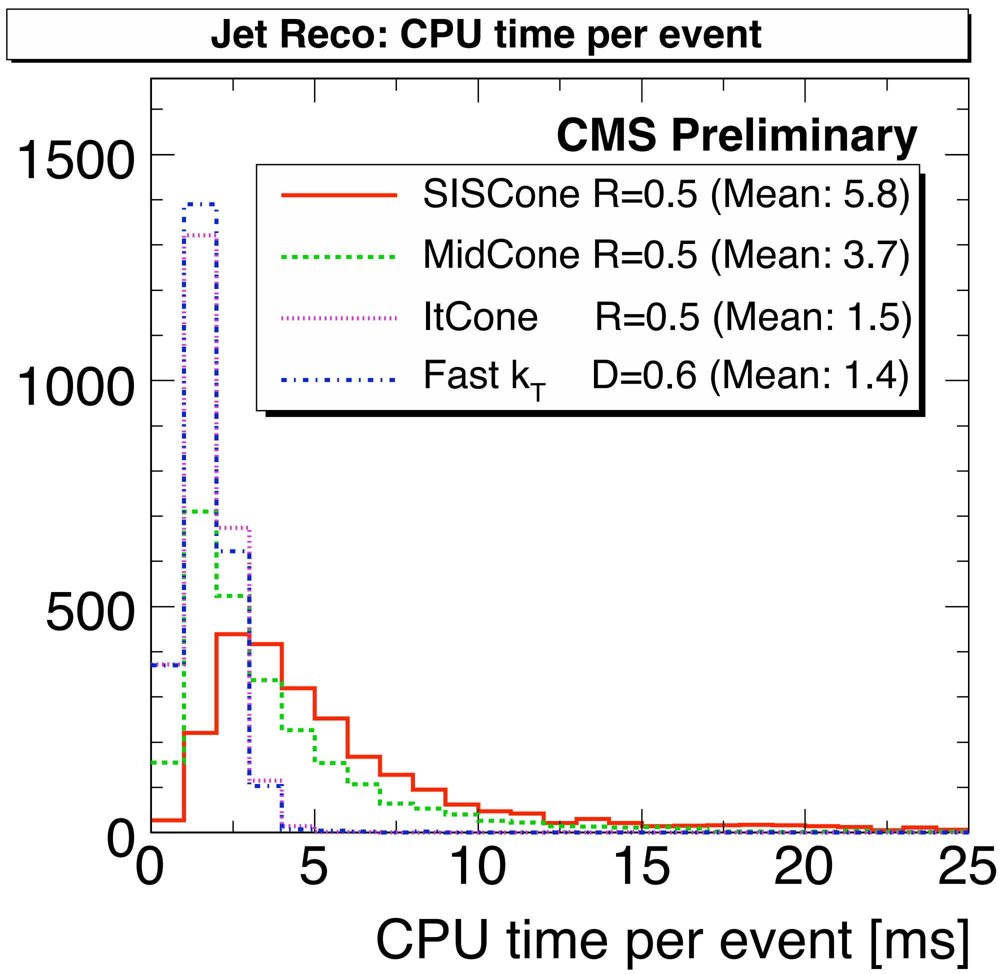
- similar to IterativeCone Algorithm
- Infrared safety introduced considering "mid-points" of proto-Jets closer than 2R. IR safe only up to NLO.
- Split&Merge necessary
- may leave unclustered energy
- Not any more part of standard reconstruction in CMS

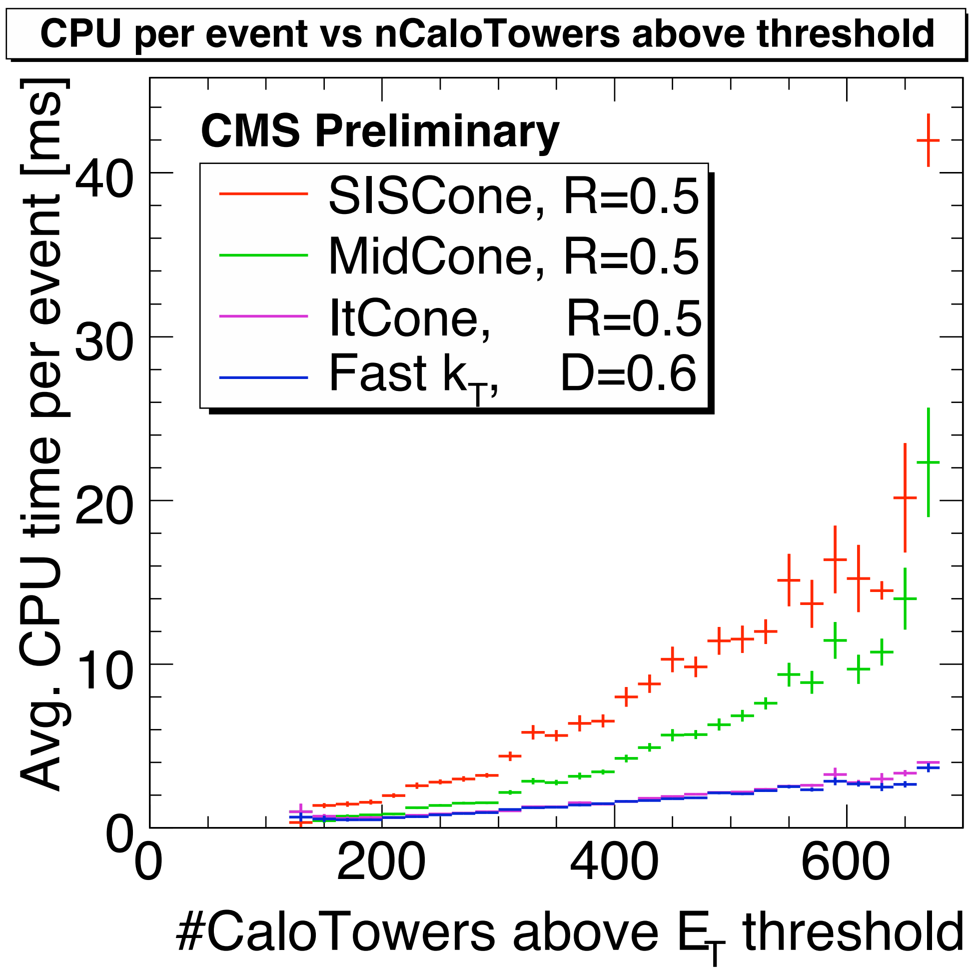
* SisCone Algorithm

- "Seedless Infrared Safe Cone" algorithm
- searches for ALL stable cones
- applies Split&Merge procedure
- Infrared and Collinear safe
- No dark energy

Recombination scheme : "E-Scheme" for all jet algorithms

Jet Algorithms: Timing

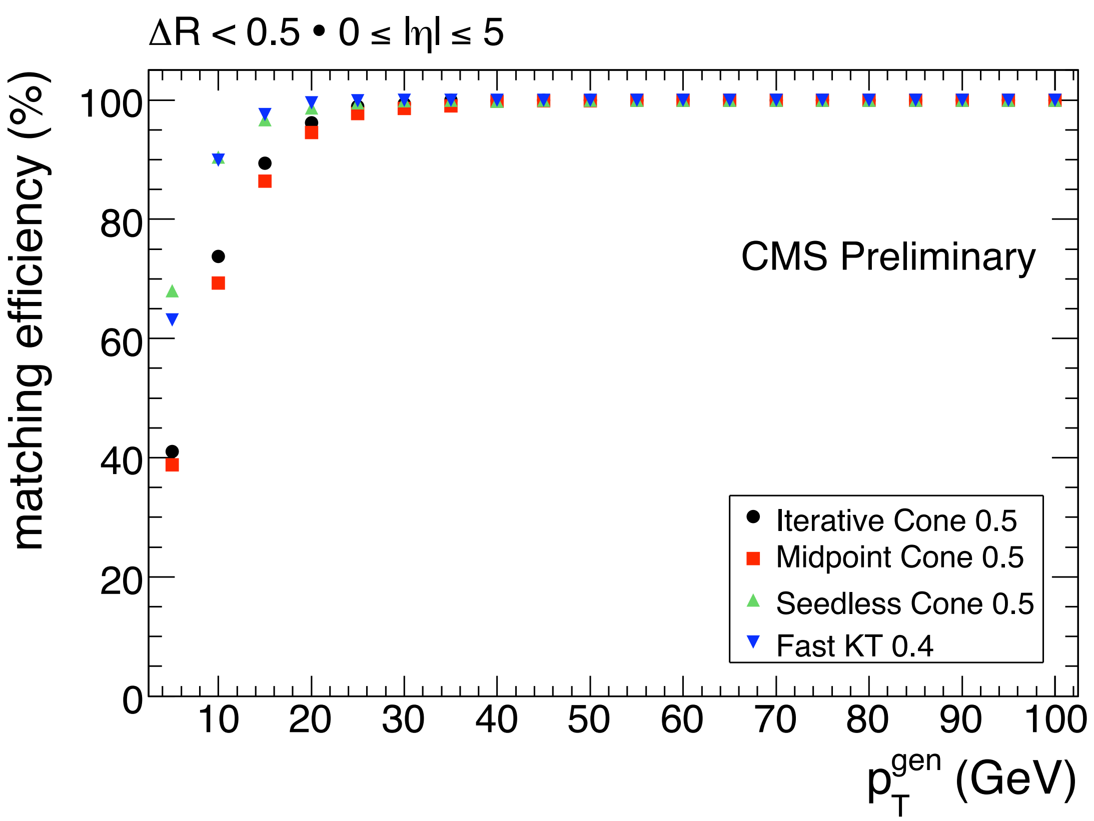


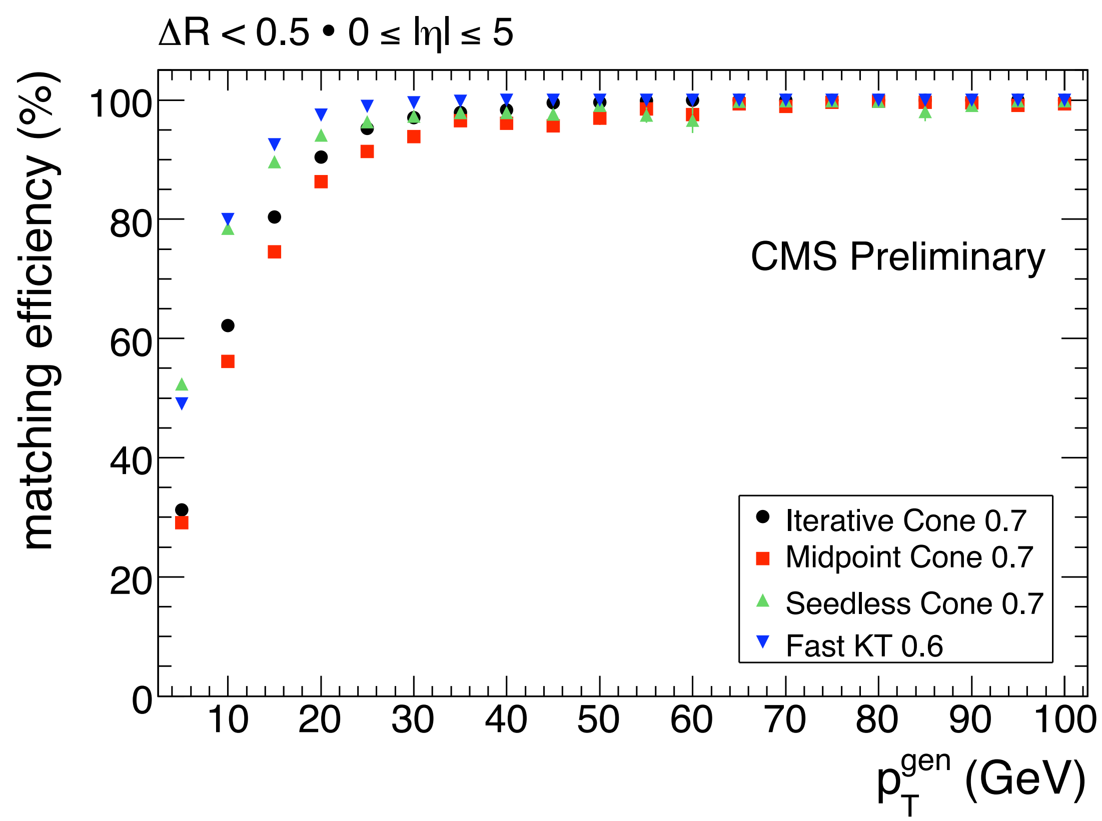


- Jet reconstruction takes ~0.5% of CPU time necessary for full event reconstruction, Jet algo choice does not have significant impact
- IterativeCone algorithm is simple and fast: will be used at HLT
- Execution time for k_T algorithm, as implemented in the FastJet package is improved dramatically w.r.t. earlier implementations

Jet matching efficiency

Matching efficiency: fraction of GenJets which matches to a Calorimeter jet with a distance ΔR(GenJet,CaloJet)<0.5

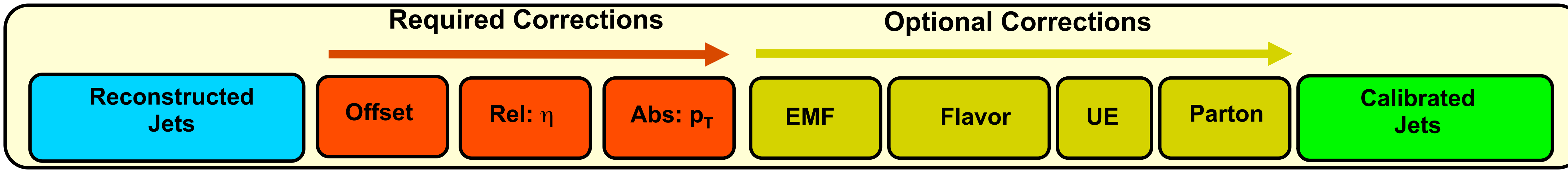




- ~100% efficiency for pT>30 GeV
- KT and SiSCone algo yields better efficiencies
- Data driven methods to measure the efficiency under development

Jet energy corrections

CMS develops a factorized multi-level jet correction



Correct CaloJets to have same pT as GenJet on average

corrections back to parton level quantities

- ✦ Offset: correct for Pile Up and electronic noise in the detector (measure in zero-bias data)
- ✦ Relative(eta): variations in jet response with eta relative to a control region
- ✦ Absolute (p_T): correcting the p_T of a measured jet to particle level jet versus jet p_T
- ✦ EMF: variations in jet response with electromagnetic energy fraction
- ✦ Flavor: variations in jet response to different jet flavor (light quark, c,b, gluon)
- ✦ Underlying Event
- ✦ Parton: correcting measured jet p_T to the parton level

➠ derive from MC simulation tuned on test-beam data at start-up, data driven when available, on the long term from simulation tuned on collision data

Jet calibrations: relative(η)

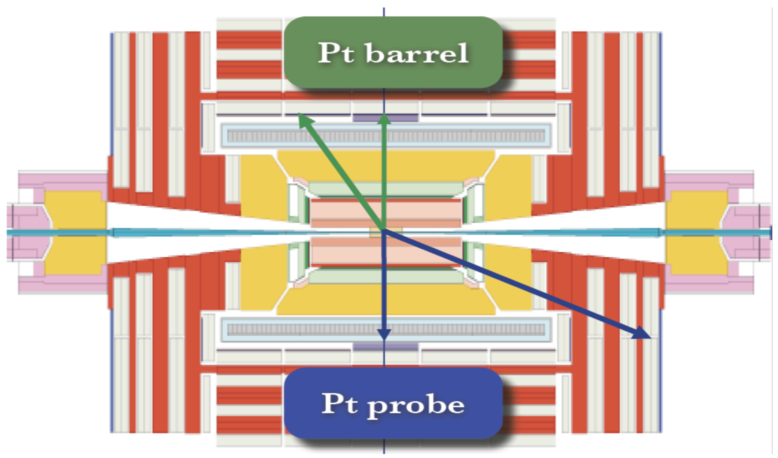
✱goal: Flatten the jet response versus η

MC based:

- QCD di-jet events
- study $\Delta p_T(\eta) = p_T^{CaloJet} - p_T^{GenJet}$
- most probable val of $\Delta p_T(\eta)$ is compared to most probable val of $\Delta p_T(\eta)|_{|\eta|<1.3}$ (reference point is the response at |η|<1.3)

Data driven

- di-jet balance in QCD events ΔΦ>2.5
- any 3rd jet $p_T < 0.25 p_T^{dijet}$

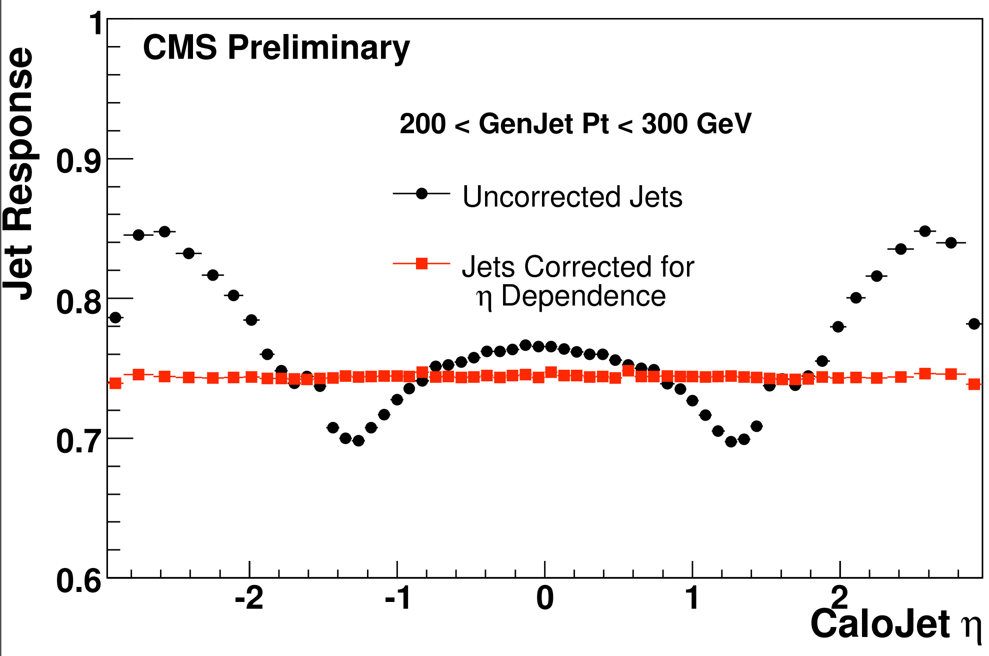


$$p_T^{dijet} = \frac{p_T^{probe} + p_T^{barrel}}{2}$$

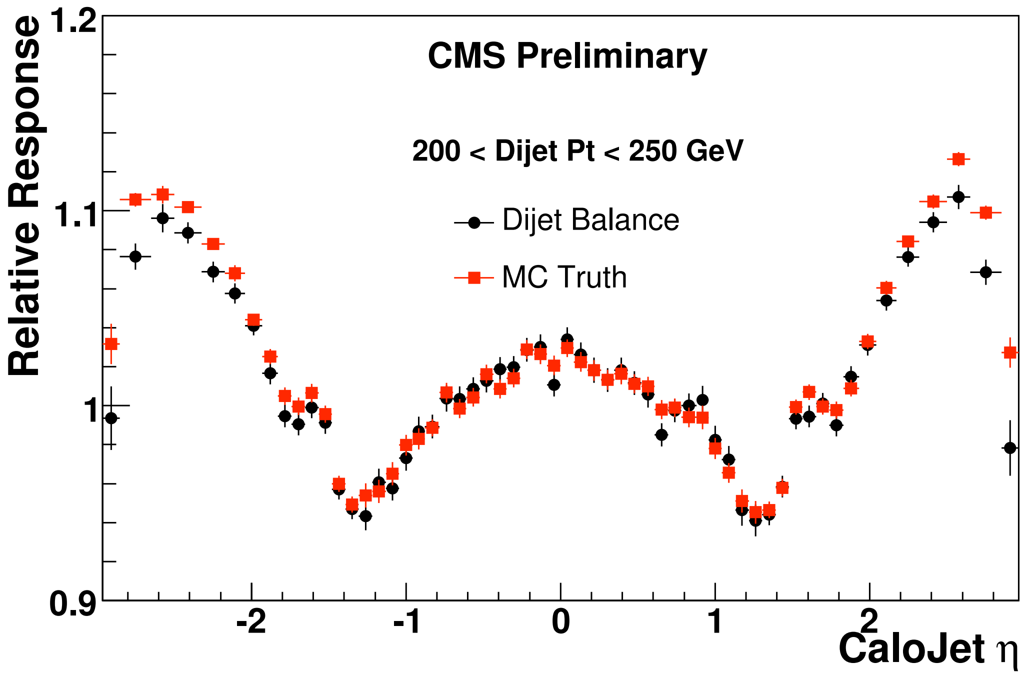
$$B = \frac{p_T^{probe} - p_T^{barrel}}{p_T^{dijet}}$$

$$r = \frac{2 + \langle B \rangle}{2 - \langle B \rangle}$$

Response= $p_T^{CaloJet}/p_T^{GenJet}$



Relative Response= r(η)/r(|η|<1.3)



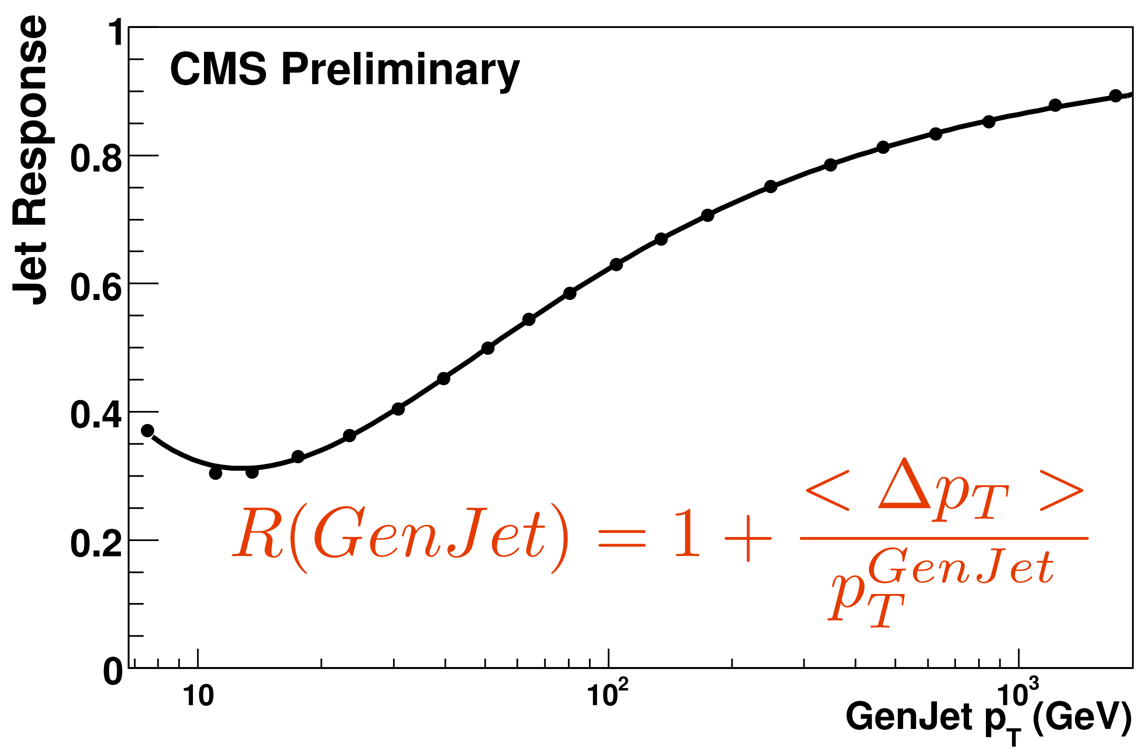
Response values from MC & dijet balance tech. are in agreement within
1% (|η|<1.3),
2-3%(1.3<|η|<3),
5-10% (3<|η|<5)

MC based

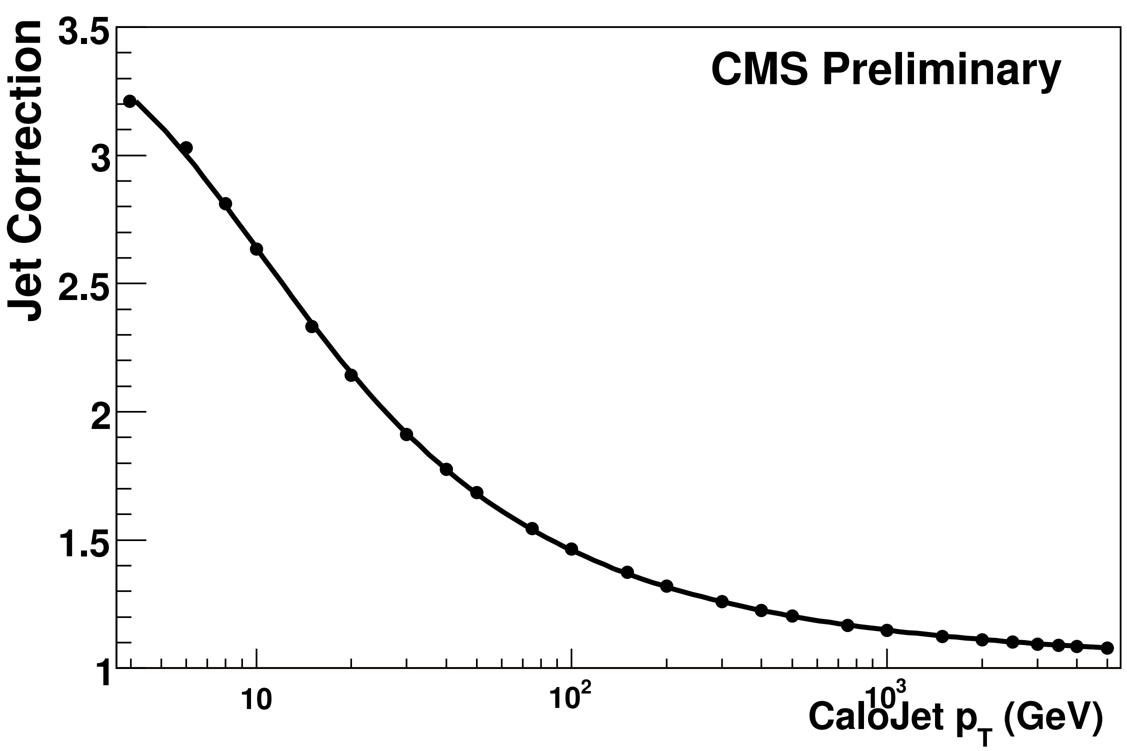
- Corrects energy of jet back to the particle level in control region (|η|<1.3)
- Use Calorimeter jets within |η|<1.3 and matched to GenJet ΔR<0.25

$$\Delta p_T = p_T^{CaloJet} - p_T^{GenJet}$$

Absolute Jet Response vs. p_T(GenJet)



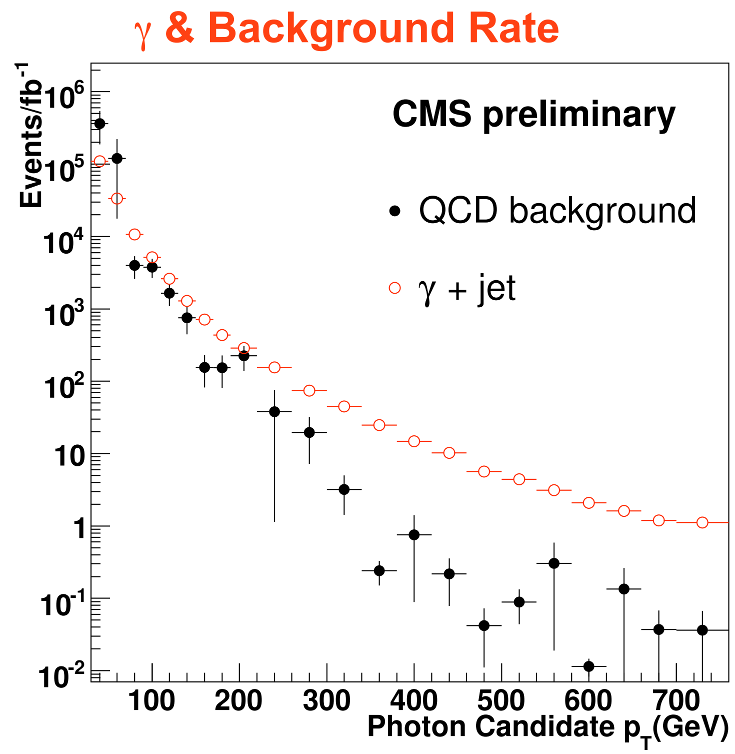
Absolute Jet Correction vs. p_T(CaloJet)

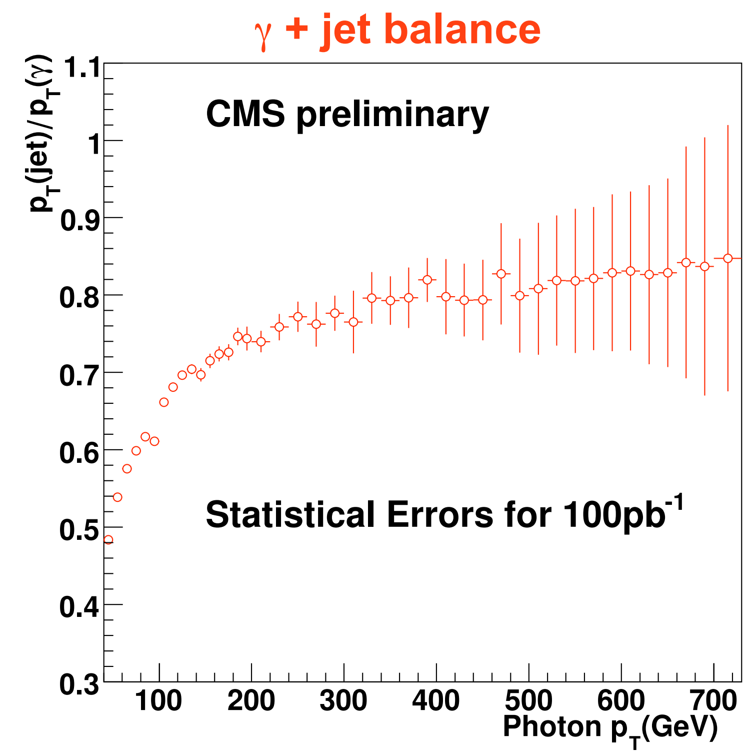


Jet energy correction:absolute p_T

Data driven: key point is pT balance, in Z/γ+jet events with the jet in the control region

- ➠ consider clean events with well separated Jet-Z(γ)
- ➠ NO extra jet with $P_T > 0.1 P_T(\gamma)$ $(0.2 P_T(Z))$.





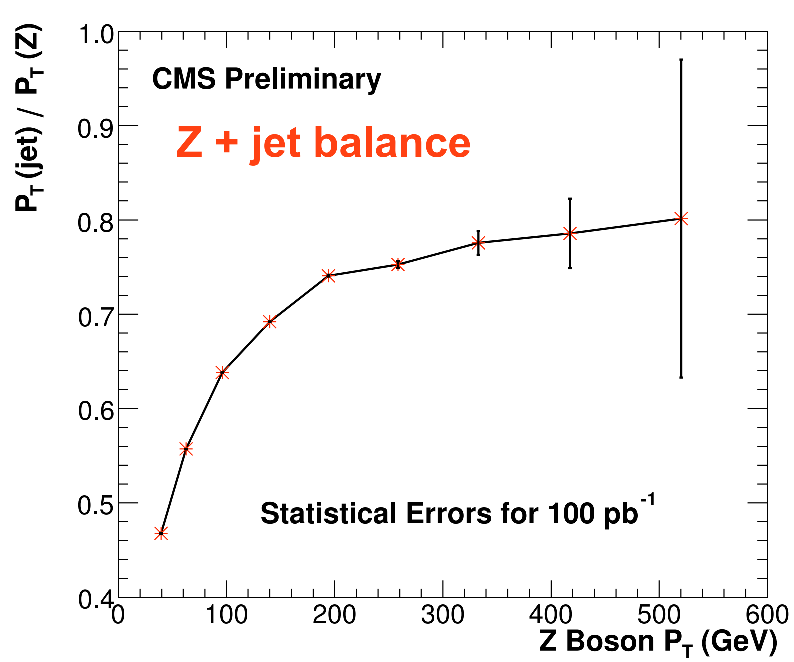
γ + jet:

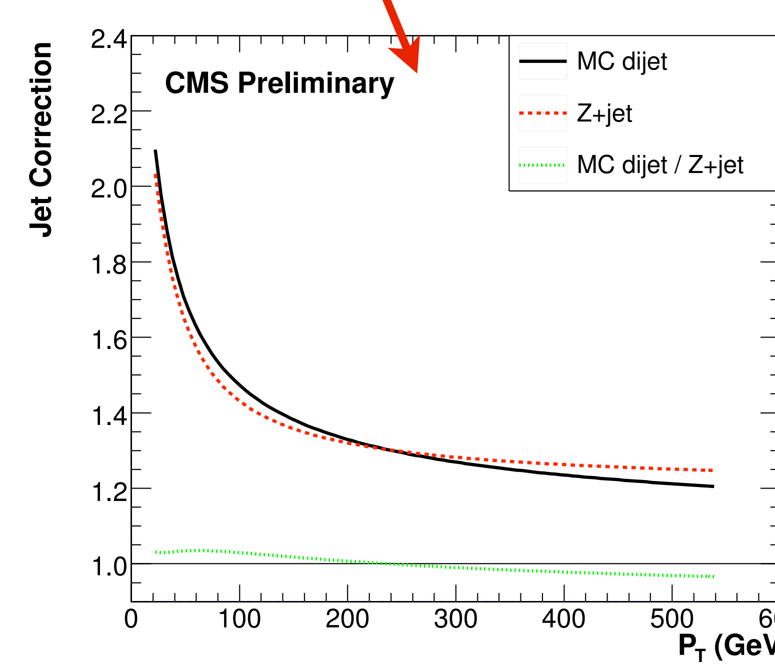
- isolated photons to reduce QCD bgr.
- Measure calibration for $p_T < 600$ GeV for 100 pb-1.

correction factors from MC dijet & Z+jet consistent within 5%

(Z→μμ) + jet:

- muons reconstructed in the tracker (independent from calorimeter), $m_{\mu\mu}$ within m(Z)±20 GeV
- negligible bkg
- measure absolute jet correction with $p_T < 400$ GeV for 100 pb^{-1}.

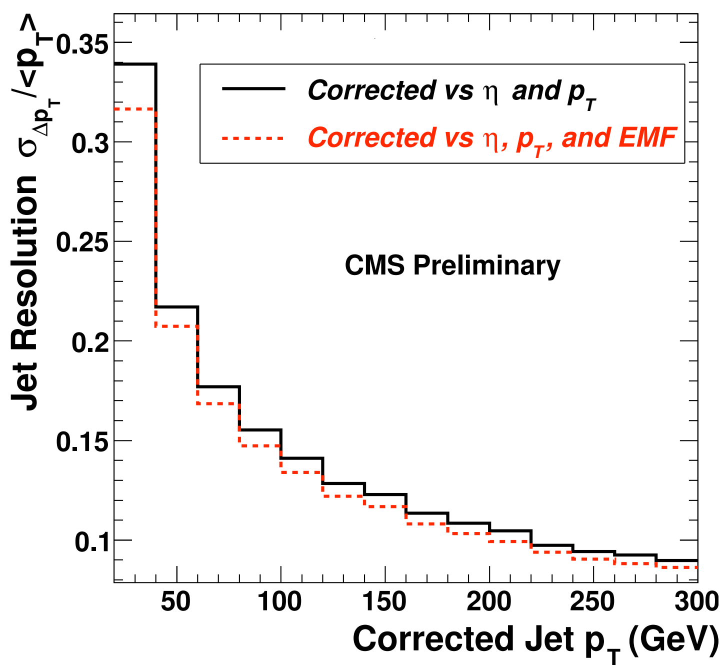




Jet energy correction(optional)

* EMF dependent corrections

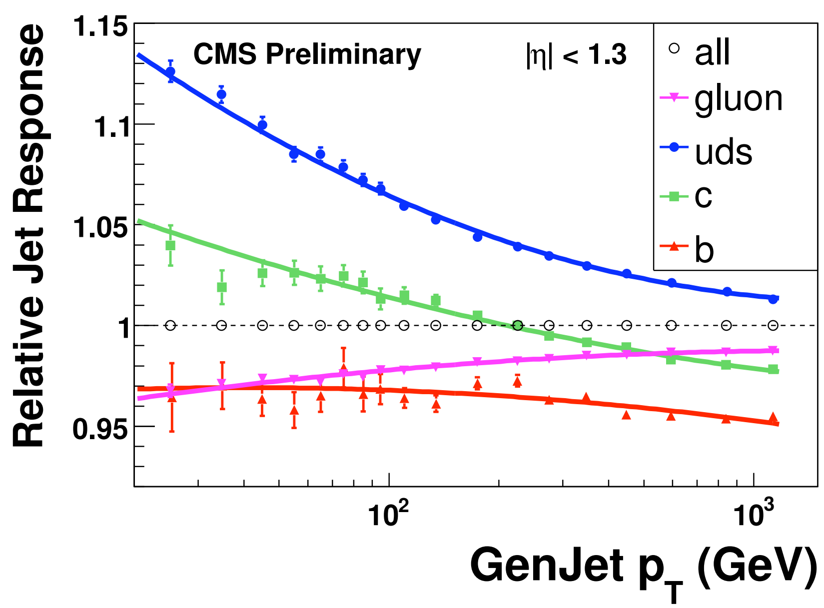
- correct for variations in jet response versus EMF of Jets
- improves jet energy resolution up to 10%



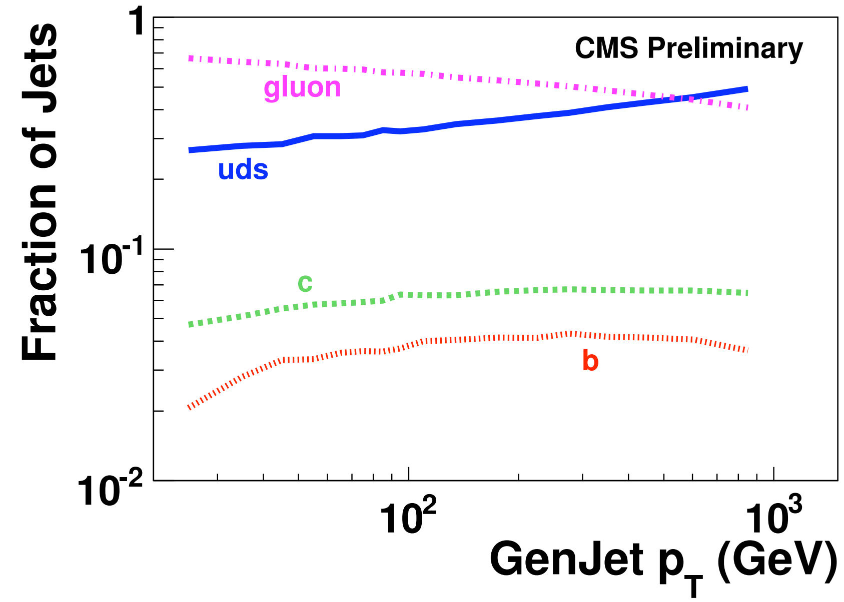
* Flavor dependent corrections

- Gluon, c quark, and b quark jets all have lower response than light quark jets

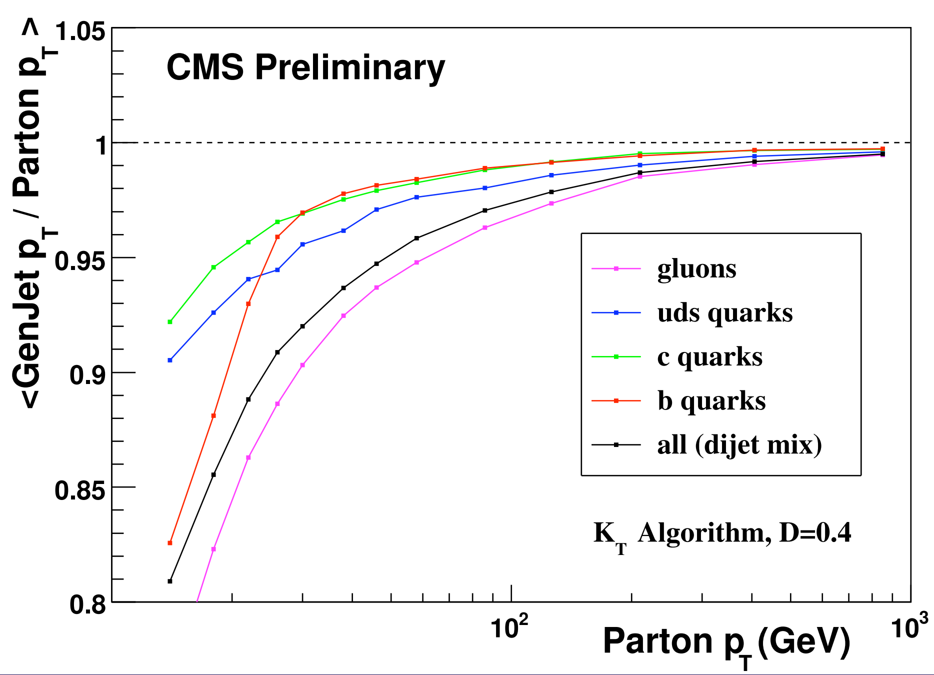
Flavor Variation of Jet Response



Flavor Fraction for QCD Dijets



* Corrections to parton level



- correcting jet pT to the parton level
- gluons radiate more → lower response due to out-of-cone effect
- process dependent

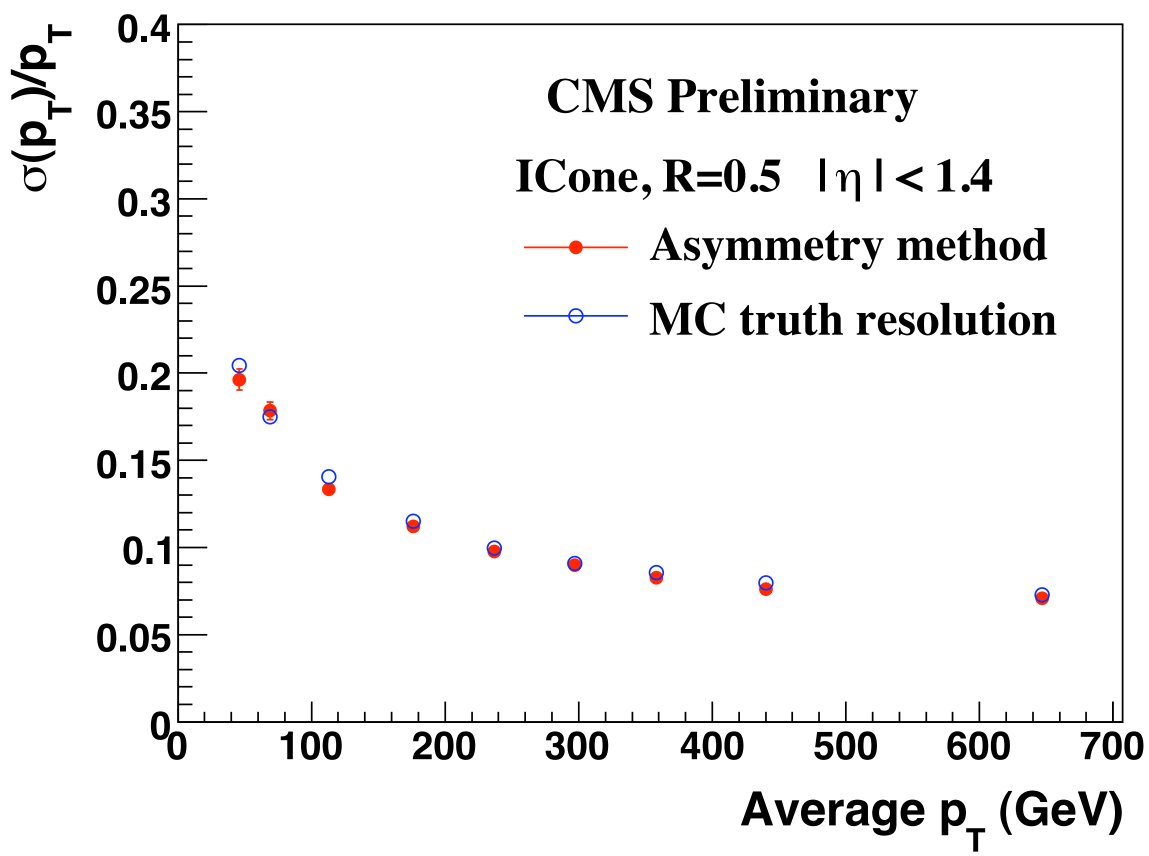
Jet energy resolution : Data-Driven

Asymmetry method

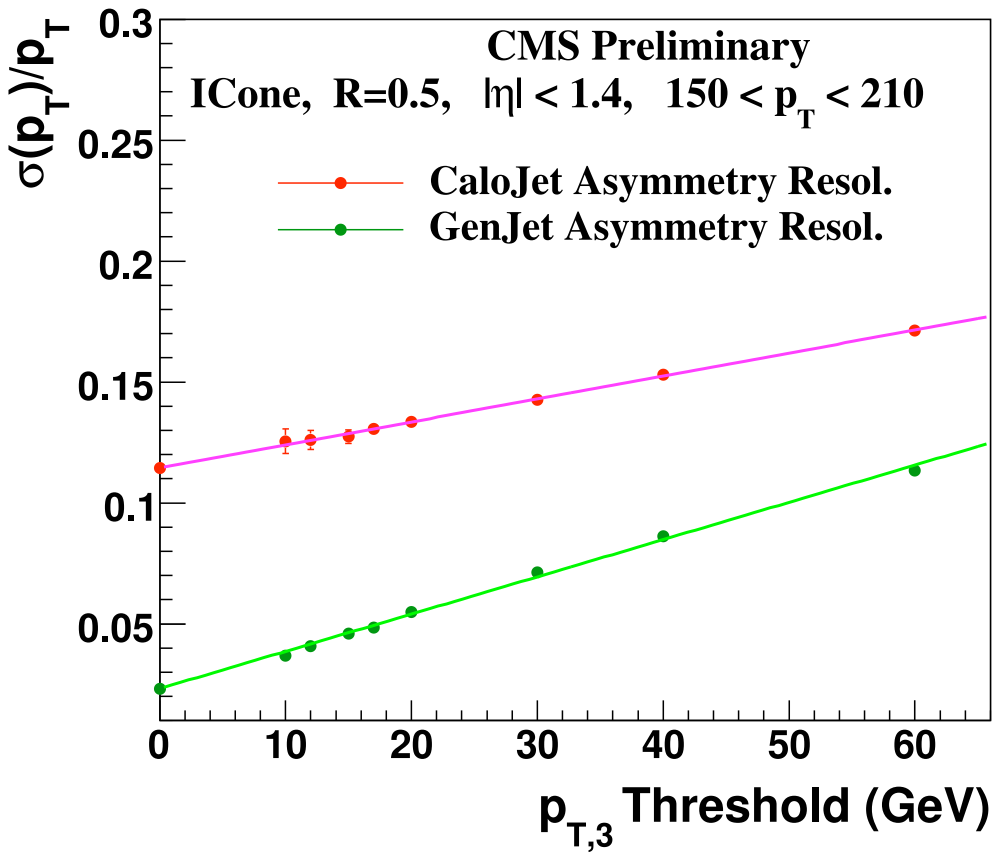
- select the back-to-back ($\Delta\Phi > 2.7$) jets in the barrel region
- relate resolution to Asymmetry variable A

$$A = \frac{p_T^{Jet1} - p_T^{Jet2}}{p_T^{Jet1} + p_T^{Jet2}} \qquad \frac{\sigma(p_T)}{p_T} = \sqrt{2}\sigma_A$$

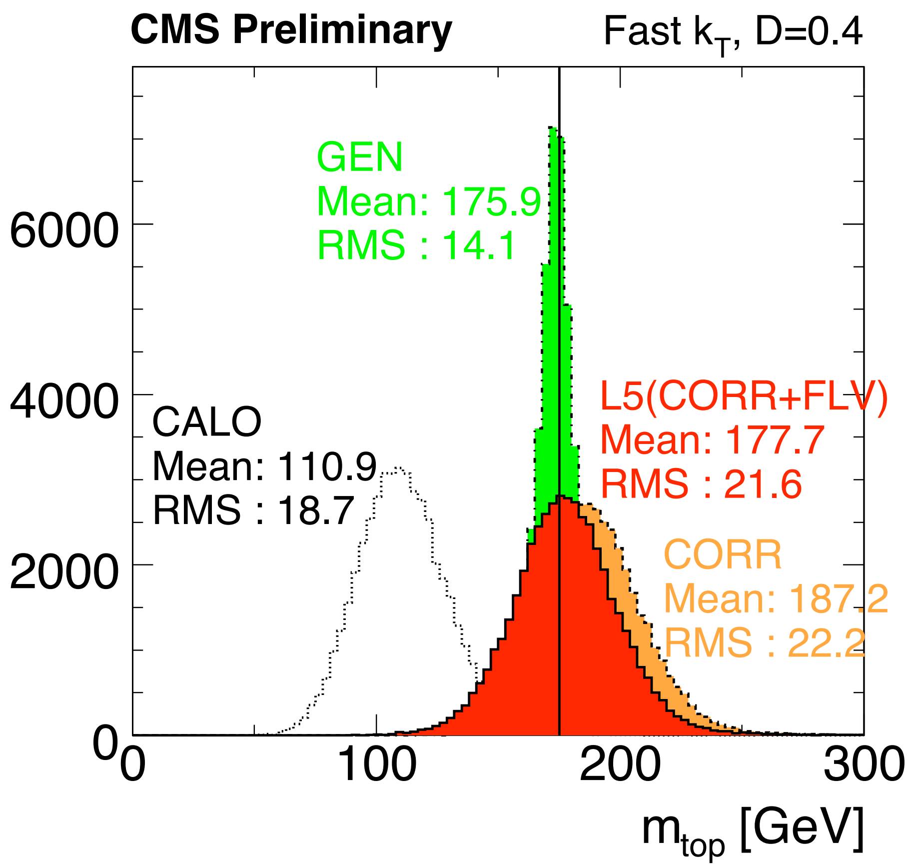
- Good agreement between data-driven and MC-driven resolutions



- Resolution as a function of the p_T threshold on the third jet



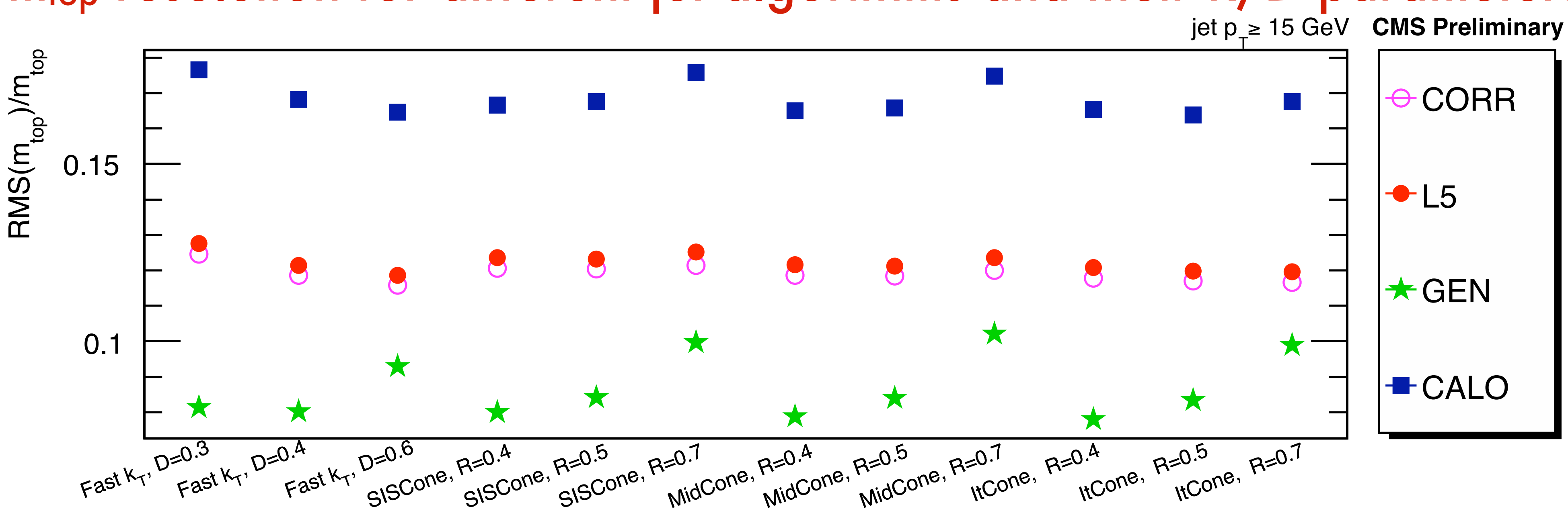
Performance in ttbar events



- hadronic decays in ttbar ALPGEN sample
- select uniquely matched jets to top(W) decay products
- Apply MC based jet calib & flavor dependent corrections
- $m_{top}=m_{trhee\text{-}Jet}$

Gen:at GenJet Level
CALO: uncalibrated CaloJets
CORR: MC based jet calibrations applied
L5:calibrations+flavor dependent corrections

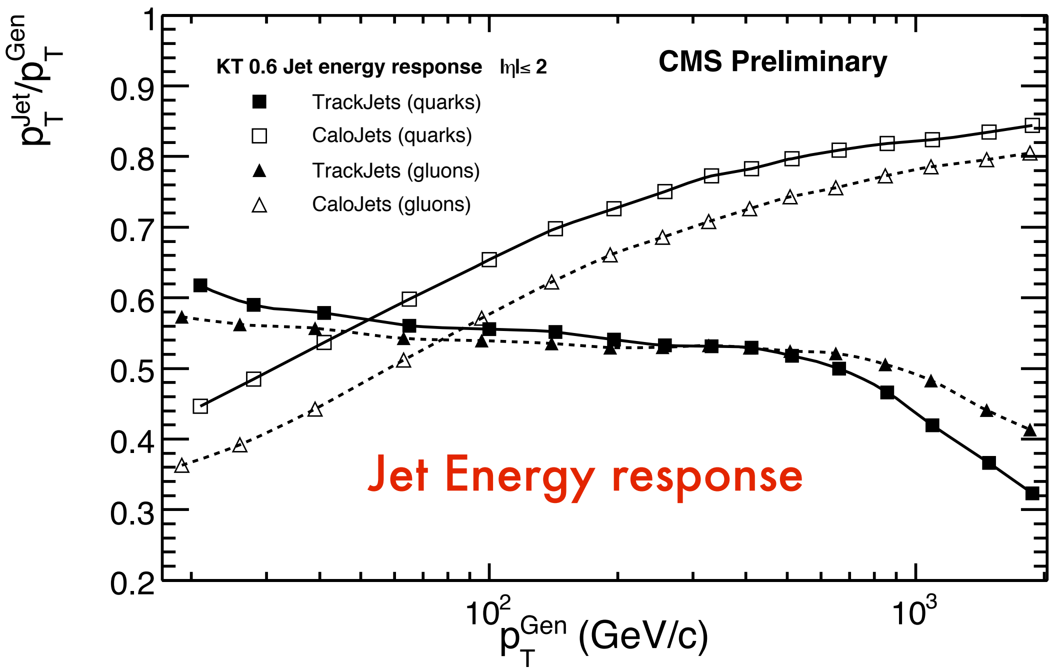
m_{top} resolution for different jet algorithms and their R/D parameters

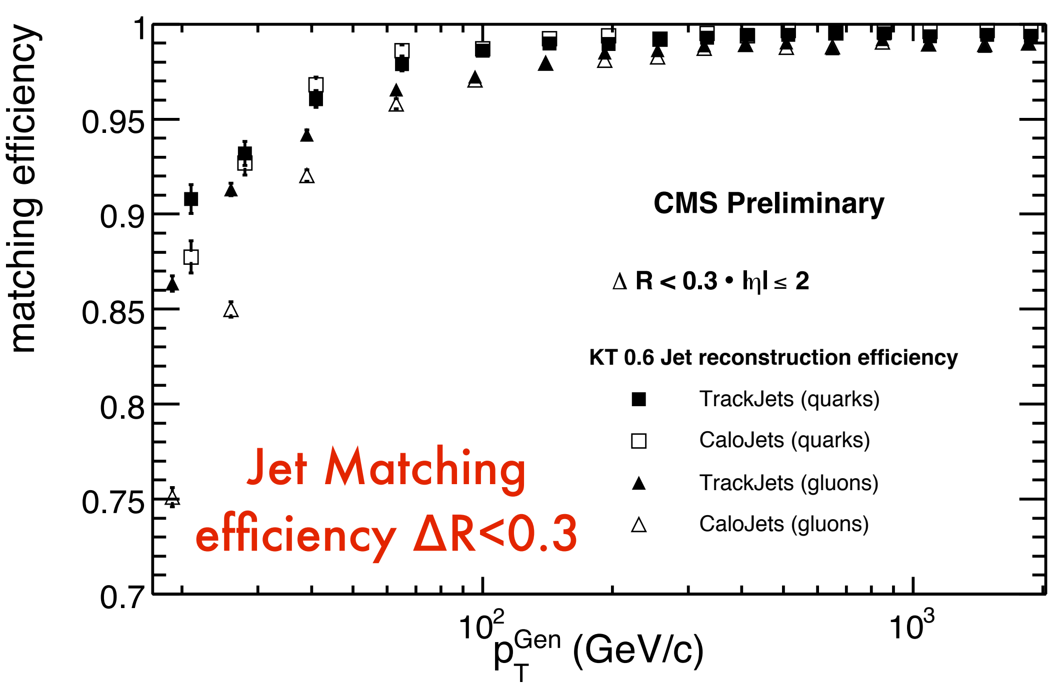


- ☑ Gen Level:smaller R/D parameter is favored
- ☑ kT algorithm performs better with D=0.6 at RecoLevel

Jet Reconstruction with Tracks

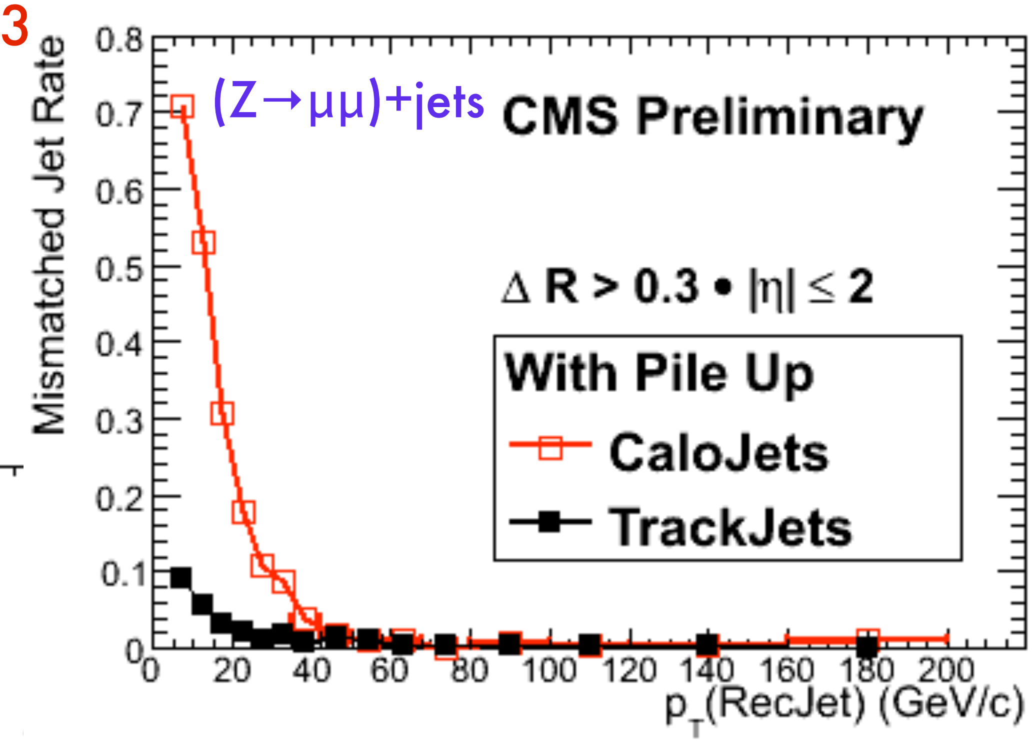
- Reconstruct jets using charged tracks, independent from calorimeter
- charged fraction of hadronic jets is about 60% (large fluctuations!)
- Provides good jet efficiencies, better angular resolution (Φ)

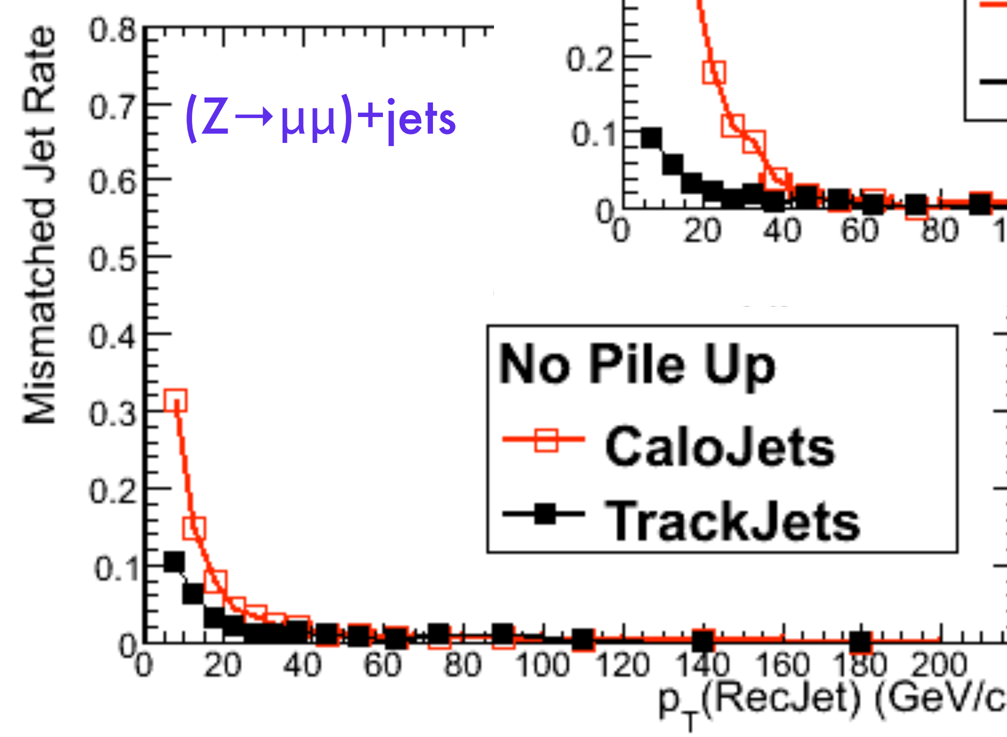




- Tracks compatible with muon vertex are selected

Fraction of RecoJets which are not matched to a GenJet ΔR<0.3

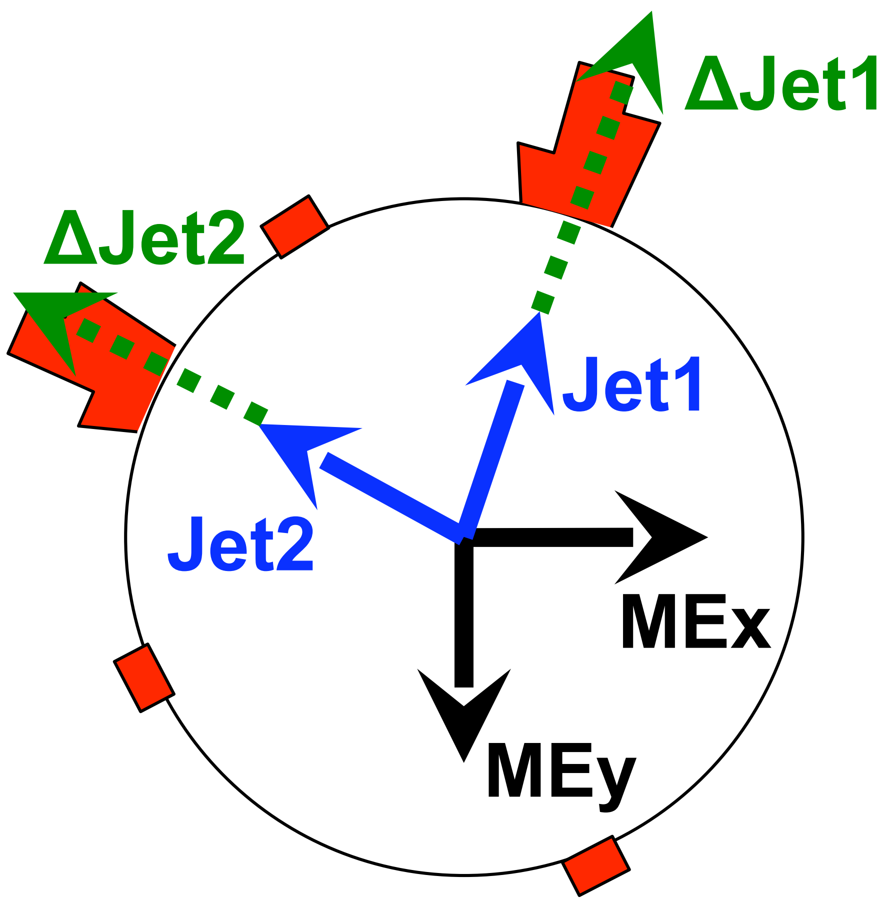




TrackJets are transparent to PU effects

Missing Transverse Energy

- Imbalanced transverse energy in the event
- signature of only weakly interacting particles
- Crucial object for many measurements



- Medium/low MET (~20-100 GeV)
  - SM measurements (top, W, Higgs, τ, ...)
- Large MET (>200 GeV)
  - SUSY(gluino searches: jets+MET, ...)
  - Extra Dimension searches(monojets)

Challenges:

- MET triggering
- Corrections on MET:
  - jet energy corrections
  - μ/e/τ corrections
  - vertex corrections
  - hot/dead channels
- ...

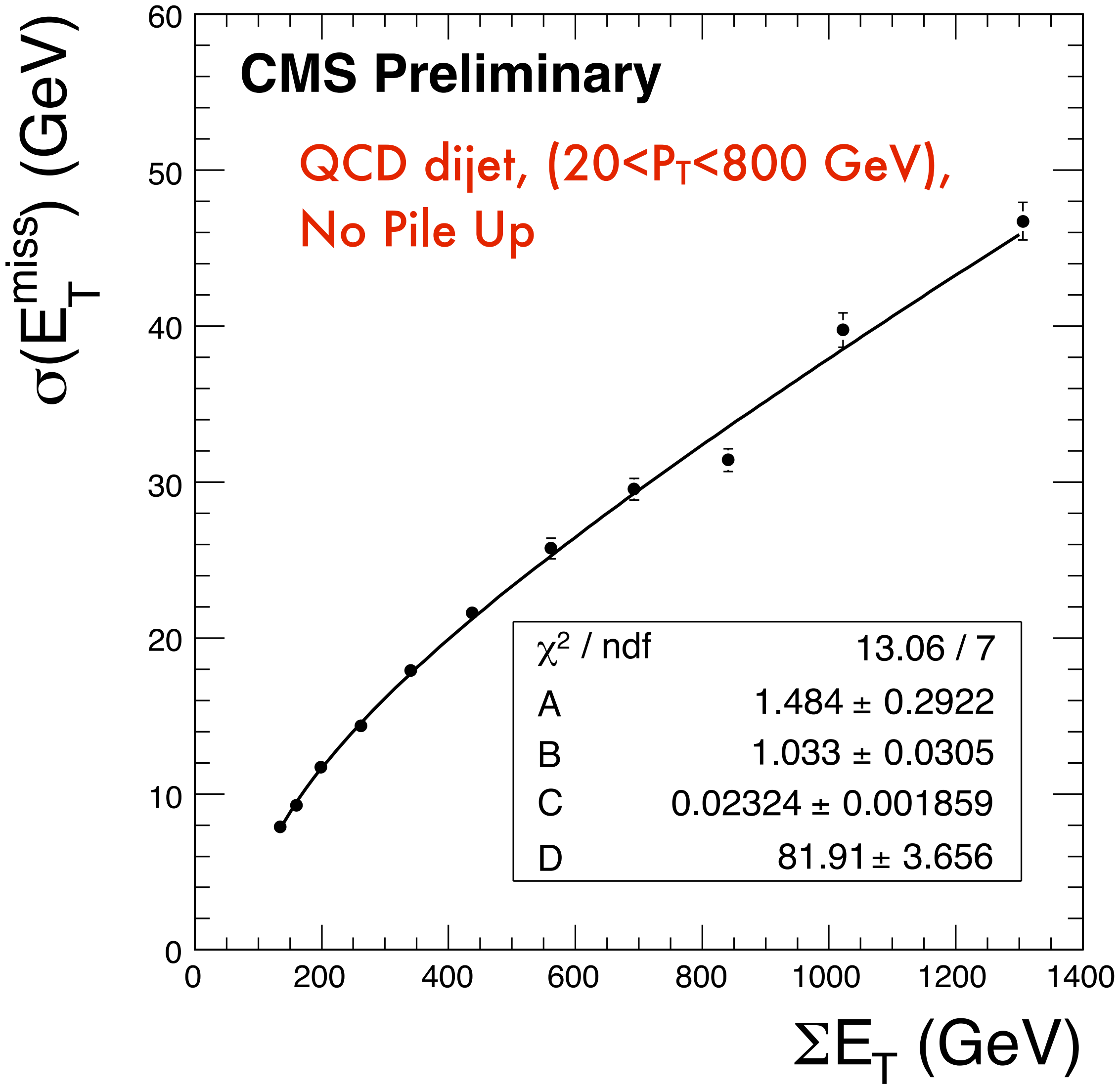
MET is calculated from uncorrected energy deposits in projective Calorimeter Towers

$$\vec{\not{E}}_T = -\sum_n (E_n \sin\theta_n \cos\phi_n \hat{\mathbf{i}} + E_n \sin\theta_n \sin\phi_n \hat{\mathbf{j}}) = \not{E}_x \hat{\mathbf{i}} + \not{E}_y \hat{\mathbf{j}}$$

Resolution

$\sigma(E_T) = A \oplus B\sqrt{(\sum E_T - D)} \oplus C(\sum E_T - D)$

- Noise(A): electronic, underlying event, Pile Up
- Stochastic(B): sampling effects, e/π
- Constant(C): non-linearities, cracks,hot/dead channels
- offset(D): effects of Pile Up, underlying event on $\sum E_T$, anti-correlated with noise term

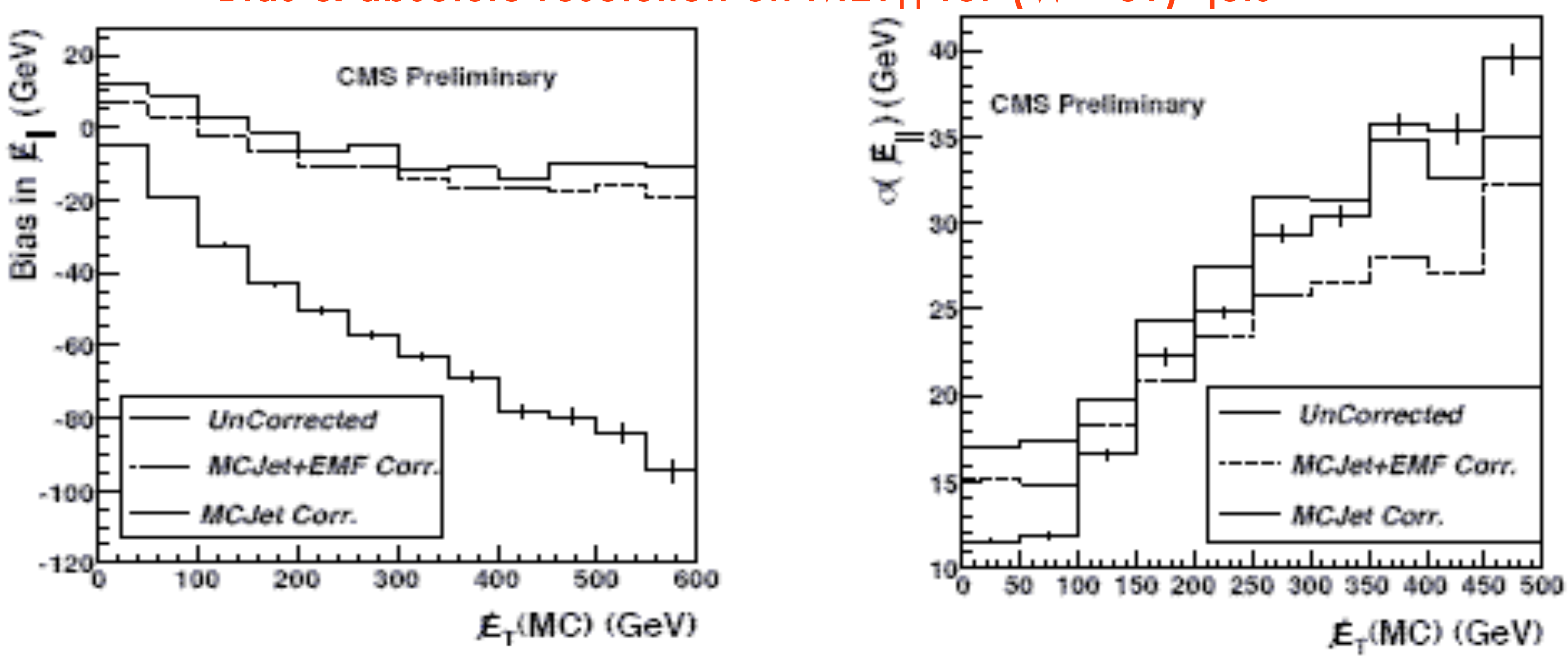


Missing E_T Calibrations

- MET is calculated from un-calibrated CaloTowers, needs to be corrected for non-linearities in response versus P_T and η
- standard jet calibrations used to correct MET
- CMS has a non-compensating calorimeter system, add third variable EMF
- Use calibrated jets with EMF < threshold, i.e 90%, & P_T^{jet}(Uncor) > 10 GeV

$$\vec{\not{E}}_T^{\,\mathrm{corr}} = \vec{\not{E}}_T - \sum_{i=1}^{\mathrm{N_{jets}}} \left[\vec{p}_{T_i}^{\,\mathrm{corr}} - \vec{p}_{T_i}^{\,\mathrm{raw}}\right]$$

Bias & absolute resolution on $MET_{||}$ for (W→eν)+jets



Muon corrections on missing E_T

➠Muon leaves small fraction of its energy in calorimeter for which MET needs to be corrected

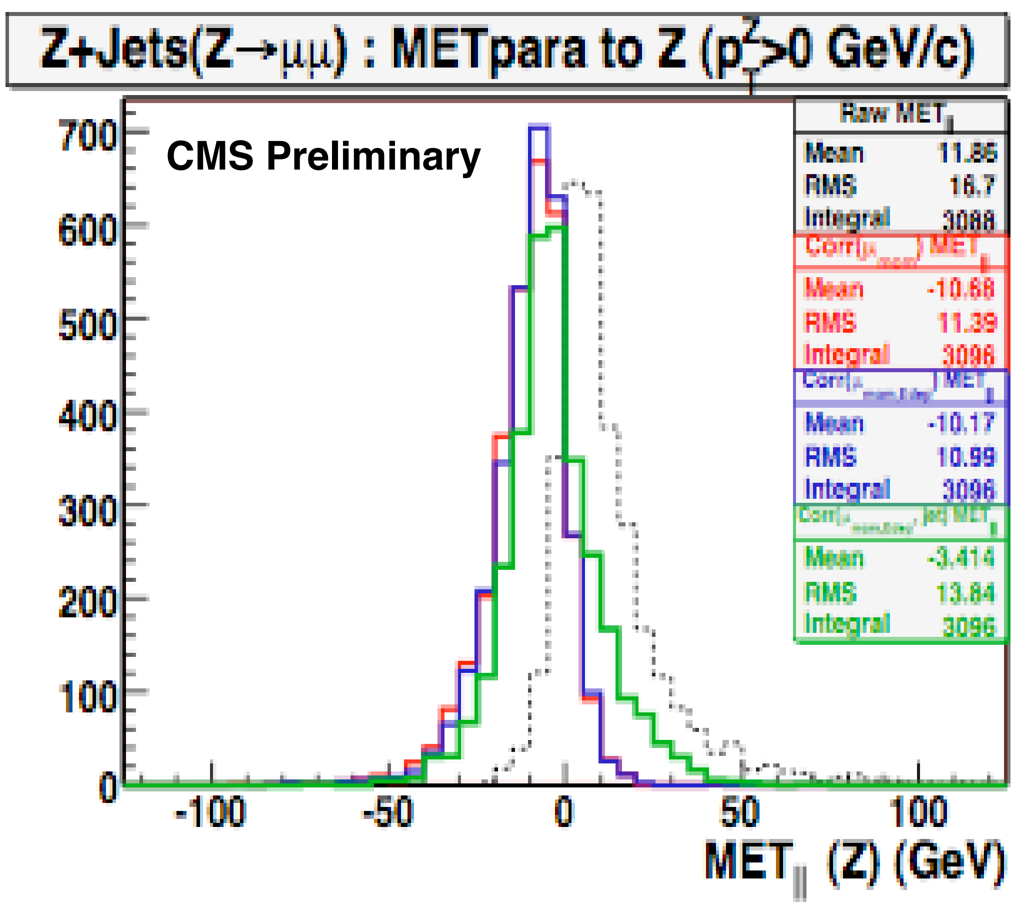
$$\vec{\not{E}}_T = -\sum_{i=1}^{\text{towers}} \vec{E}_T^{\,i} - \sum^{\text{muons}} \vec{p}_T^{\,\mu} + \sum_{i=1}^{\substack{\text{deposit}\\ \text{towers}}} \vec{E}_T^{\,i}.$$

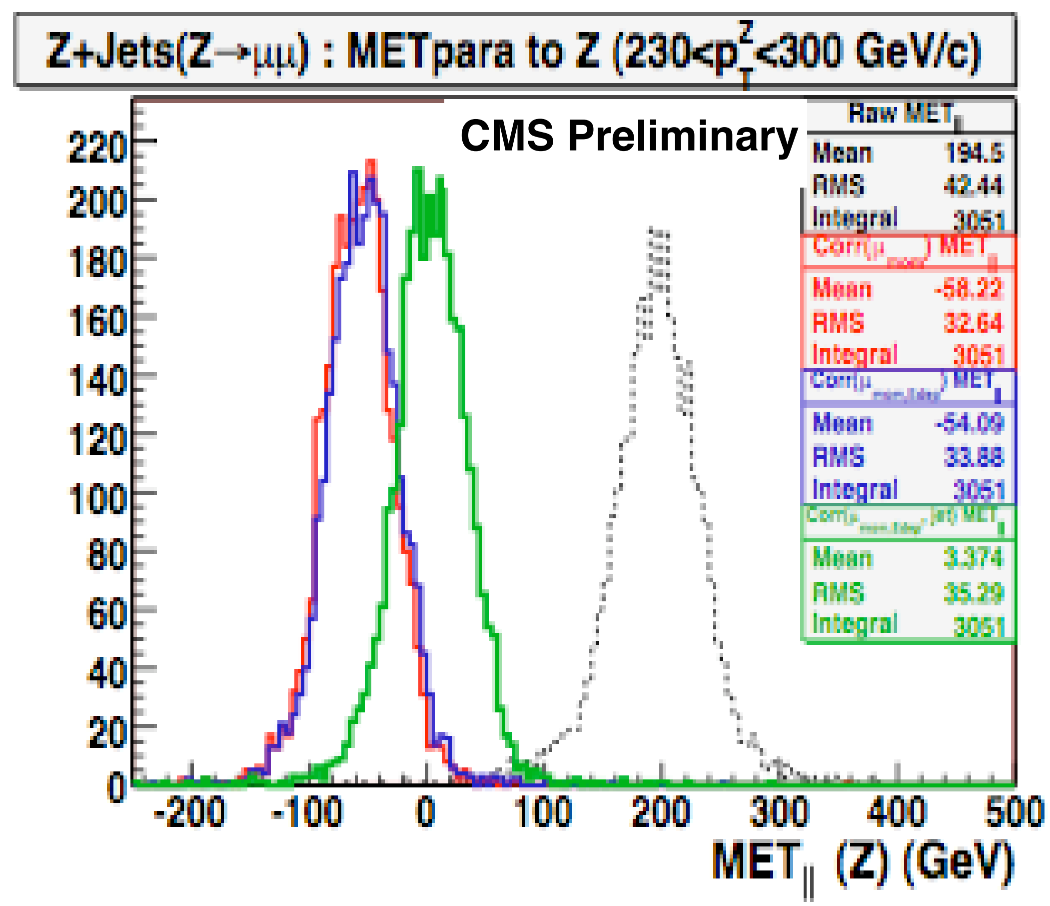
energy deposited in calorimeter by muon

➠Muons are identified in the Tracker and muon system, well separated in η-ϕ with jets & P_T^μ>10 GeV are used

➠ further study for selection criteria for high pT muons underway

MET component parallel to Z for different correction levels





Raw MET||
+Muon Corr
+Corr for muon Energy dep. in CAL
+Jet calibtarions

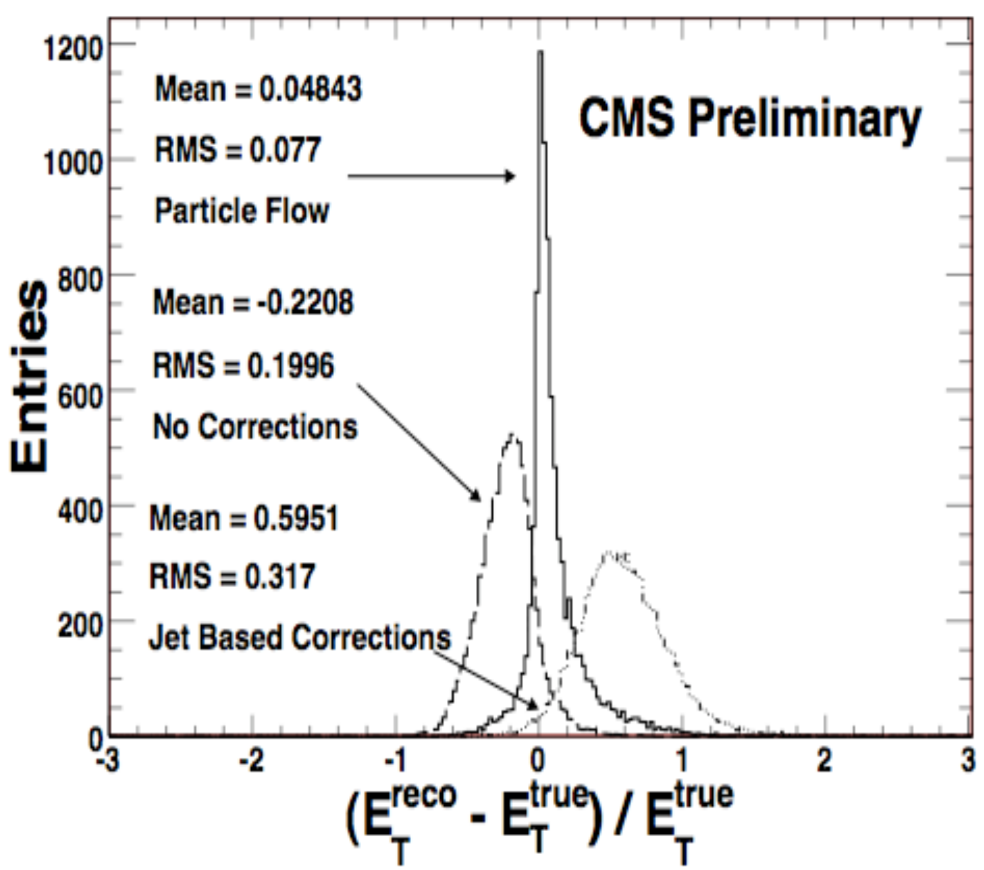
Tau corrections on missing E_T

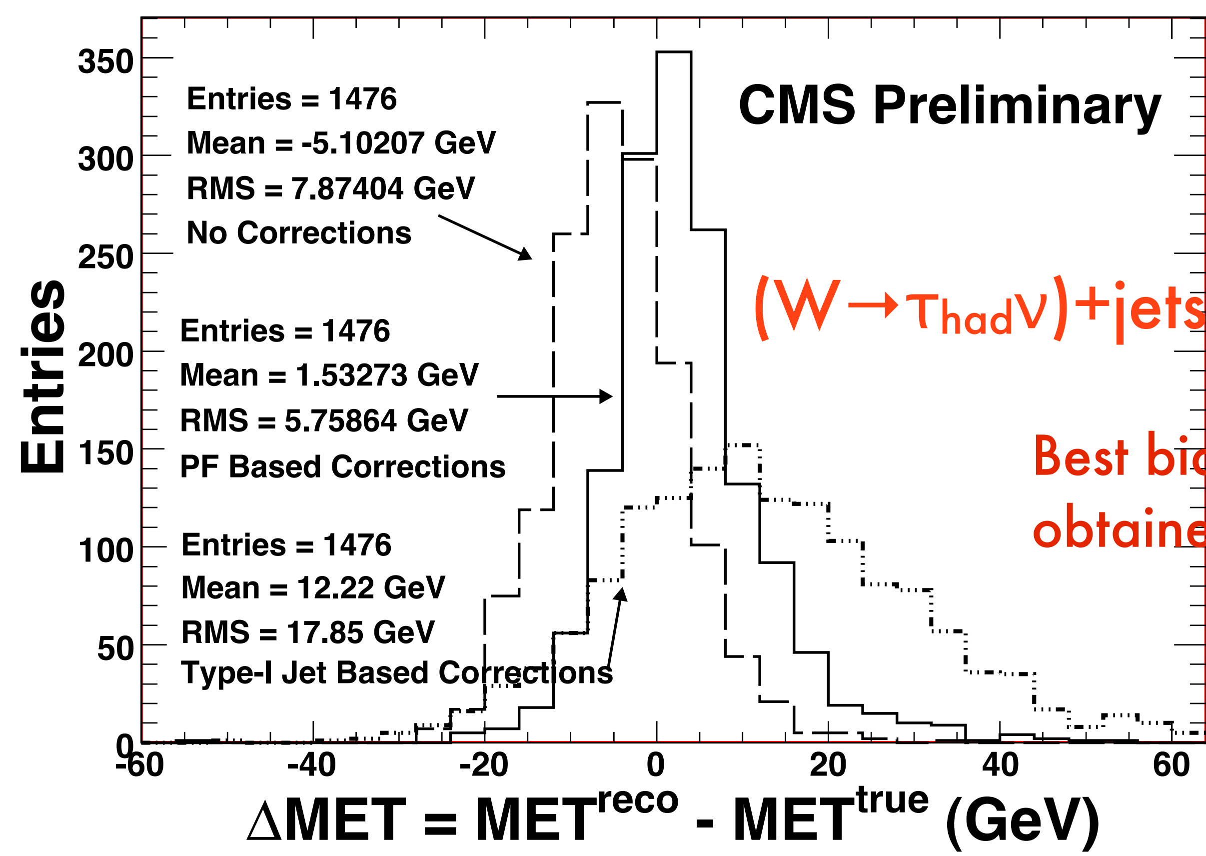
- Tau jets are different than ordinary QCD jets, typically less constituents with fairly high energy ➠ applying standard jet corrections to hadronic tau jets will result in significant overcorrection on ME_T
- Tau-specific corrections have been derived using Particle-flow algorithm and propagated into ME_T corrections

Correction on MET

$$\Delta \vec{\not\!E}_T = \sum \vec{E}_T^{\text{cal jet } 0.5} - \vec{E}_T^{\text{PF } \tau}$$

very accurate τ energy with Particle-Flow*





$(W \rightarrow \tau_{had}\nu)$+jets

Best bias & resolution obtained after correction

* Particle Flow is an algorithm that uses Tracking & Calorimeter information for particle id and energy measurement, not covered here

Summary

- CMS exercises several jet algorithms and their parameters, recent developments on algorithmic side, timing, IRC safety...
- A lot of effort on Jet calibrations,
  - A multi-level factorized correction
  - MC based as well as data driven techniques
- Jets reconstructed using charged Tracks only & Jets+Tracks & Particle-Flow objects are under development and promising

- Missing E_T is a complicated object but it is important
- Calibrations to improve resolutions are promising
- biggest problems with MET will be known when beams collide (beam effects, dead/hot channels are important)

First data will be crucial to understand both objects and their calibrations