Jets and Missing Transverse Energy Reconstruction With CMS

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Outline

- A brief definition of Jets
- Jet Algorithms used in CMS
- Jet Algorithm performances; Timing, Efficiency
- Jet Energy corrections; MC based & Data-driven
- Track-based Jets
- Missing ET reconstruction & its calibrations
- Summary

what is a Jet and why interesting ?

- What are Jets:

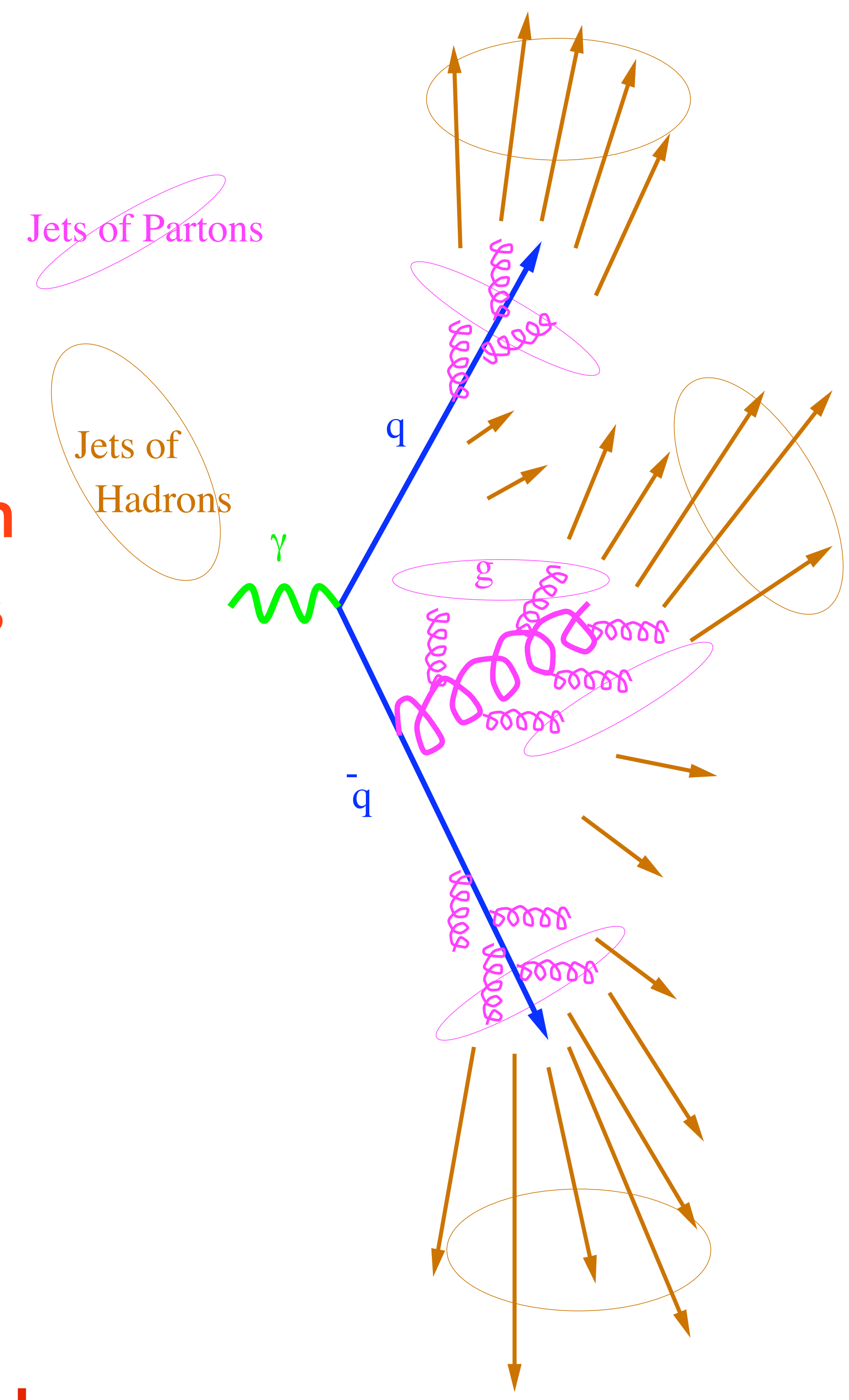
  Footprints of partons that cannot be observed directly:color confinement ➠ hadrons ➠ detector signals

- Identifying Jets(accurately) is an important issue in collider physics, many physics topologies involve jets

  - Our knowledge on QCD is based on Jet measurements: gluon was discovered in 3-jet event(PETRA), determination of α_s ...

  - Most of the searches for physics beyond the SM relies on Jet measurements:SUSY, high pT di-jets

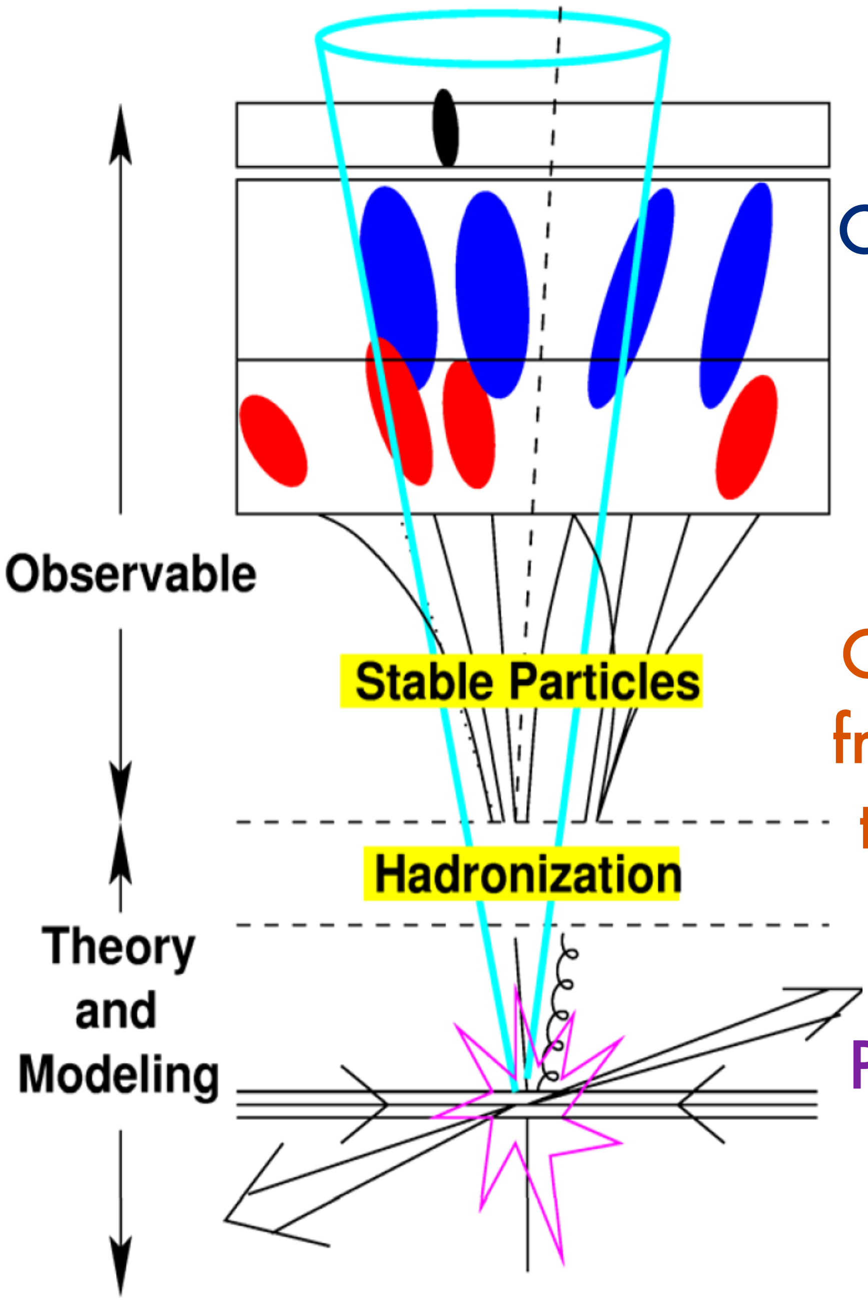
  - SM processes, top, W/Z+jets



Jet Production cross section is HUGE at the LHC !

σ(Jet pT> 100 GeV) ~10^3 nb (~1000 events/s)

Introduction



CaloJets: Clusters of Calorimeter Towers

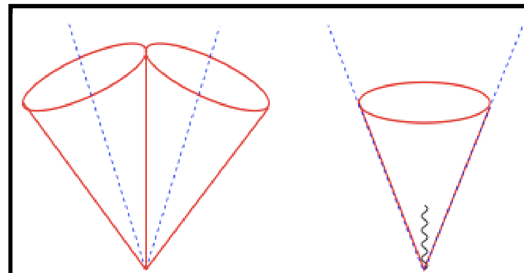
GenJets: made from stable MC truth particles

Parton Level Jets

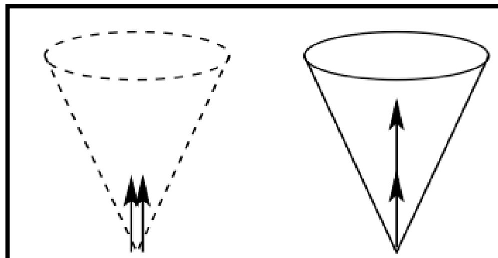
With MC simulate every step after the collision and study jets at each level

Several Jet clustering algorithms available desired properties are:

- ✦Measurable & Calculable & Accurate :
  - ✦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

* 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

Jet Algorithms in CMS

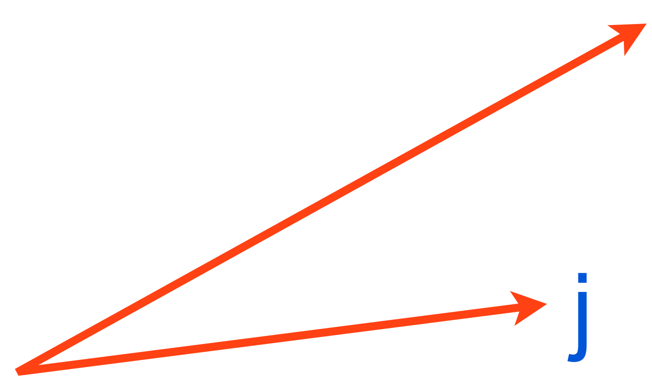
* (Fast-) k_T Algorithm

- 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

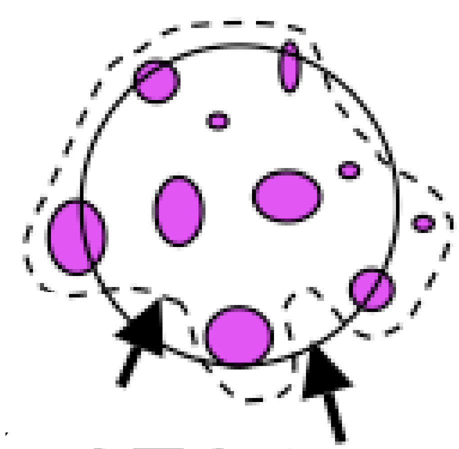


If $d_{min}=d_{ij}$ ➠ merge

if $d_{min}=d_i$ object i is excluded from the next iteration

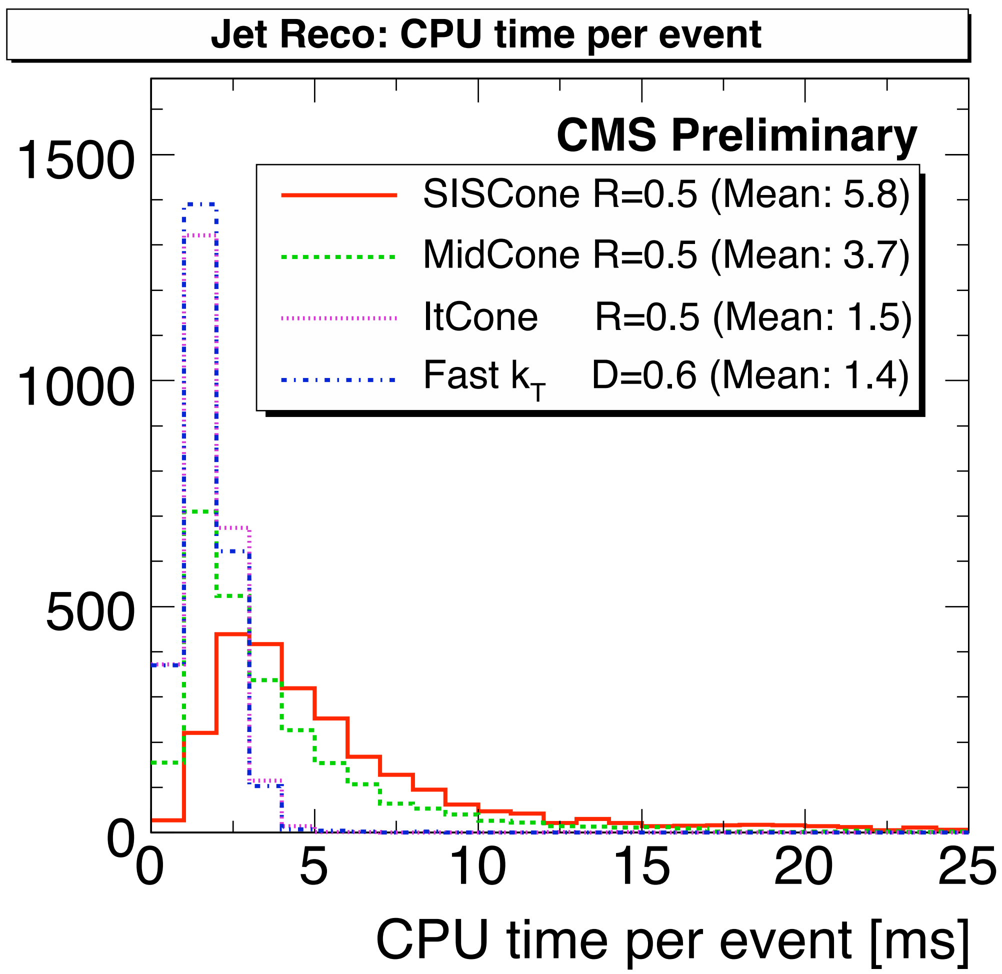
* SisCone Algorithm

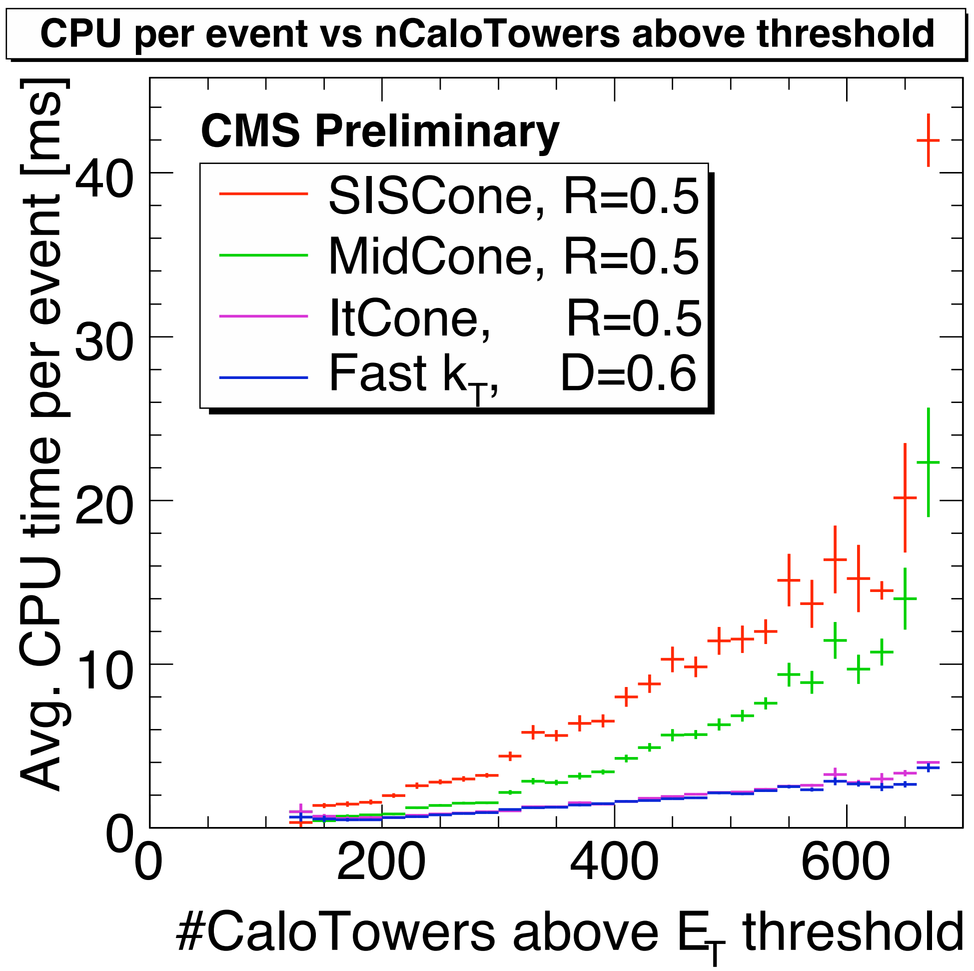
- "Seedless Infrared Safe Cone" algorithm
- searches for ALL stable cones
- applies Split&Merge procedure
- Infrared and Collinear safe
- No dark energy



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

Jet Algorithms: Timing

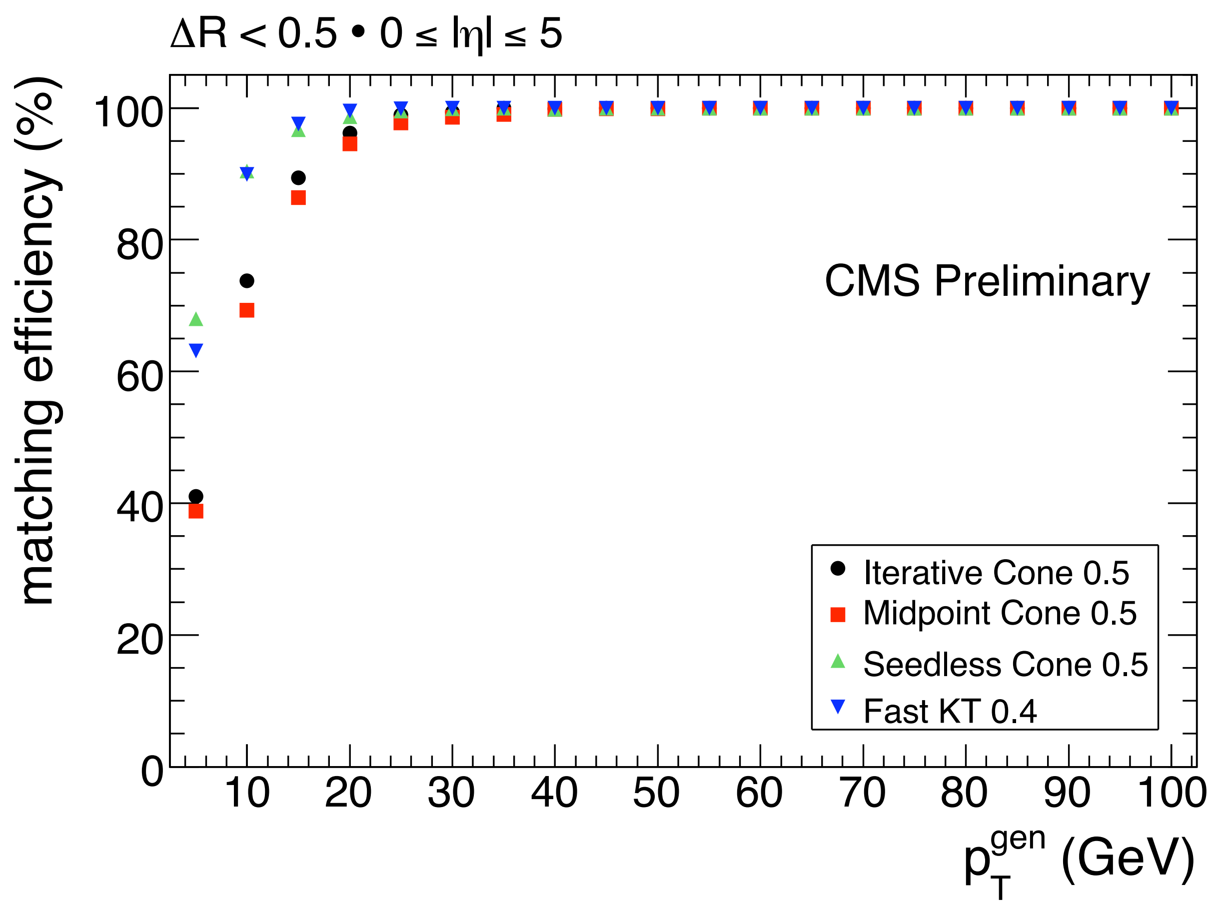


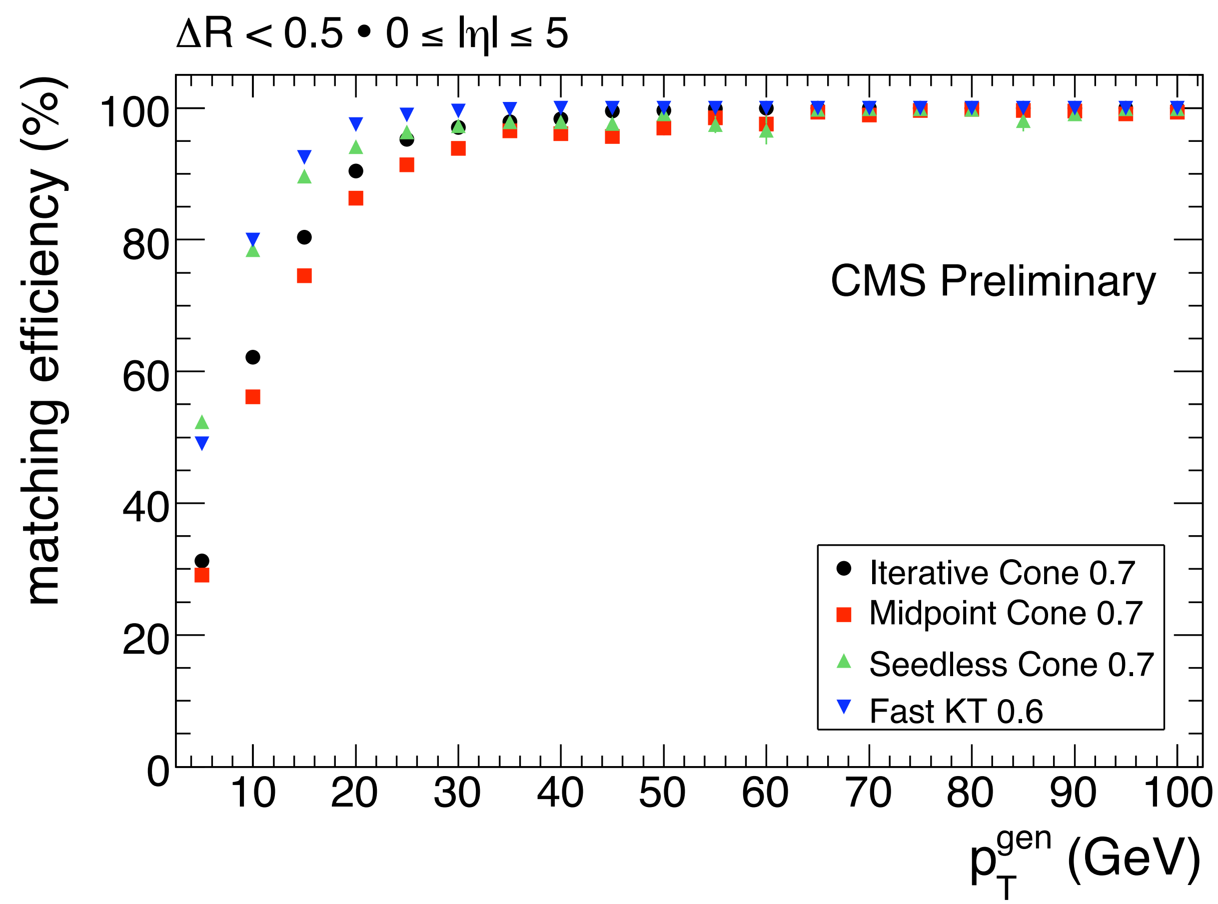


- Jet reconstruction takes ~0.5% of CPU time necessary for full event reconstruction, Jet algo choice does not have significant impact
- IterativeCone algorithm is simple and fast: will be used at HLT
- Execution time for k_T algorithm, as implemented in the FastJet package is improved dramatically w.r.t.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

Jet matching efficiency

Matching efficiency: fraction of GenJets which matches to a Calorimeter jet with a distance $\Delta R(\text{GenJet,CaloJet})<0.5$

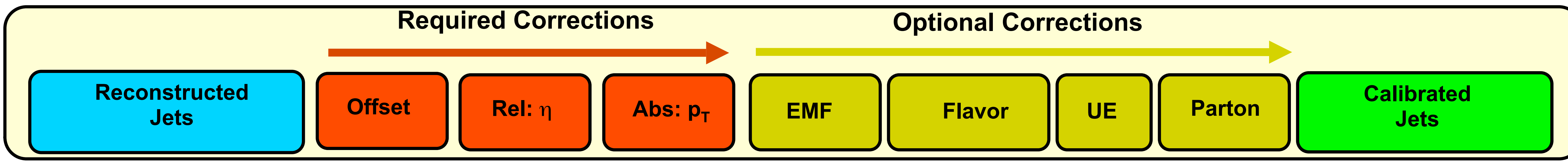




- ~100% efficiency for pT>30 GeV
- KT and SiSCone algo yields better efficiencies
- Data driven methods to measure the efficiency under development

Jet energy corrections

CMS develops a factorized multi-level jet correction



Offset: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 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 energy corrections: relative(η)

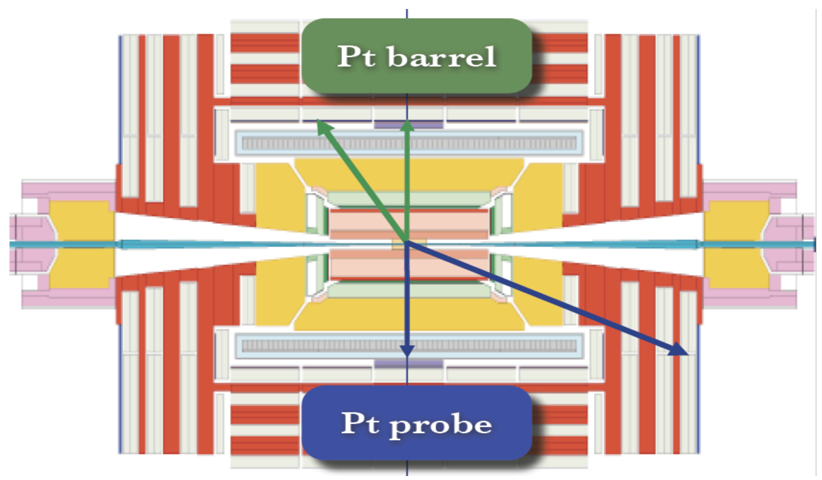
✱goal: Flatten the jet response versus η

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 $|\eta|<1.3$)

Data driven

- di-jet balance in QCD events $\Delta\Phi(jet1,jet2)>2.5$
- any 3rd jet $p_T < 0.25 p_T^{dijet}$

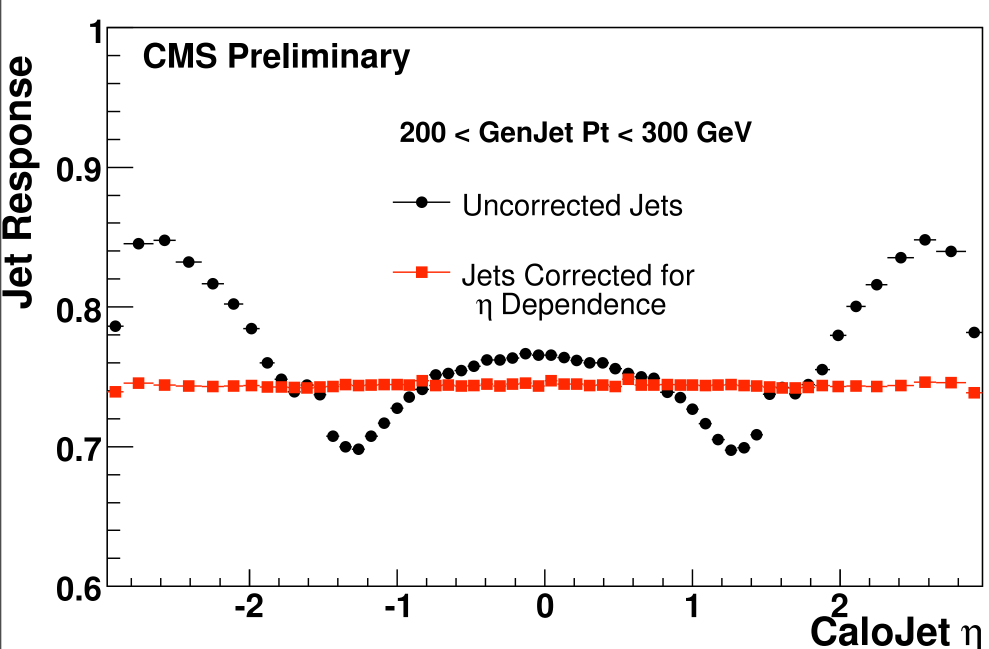


$$p_T^{dijet} = \frac{p_T^{probe} + p_T^{barrel}}{2}$$

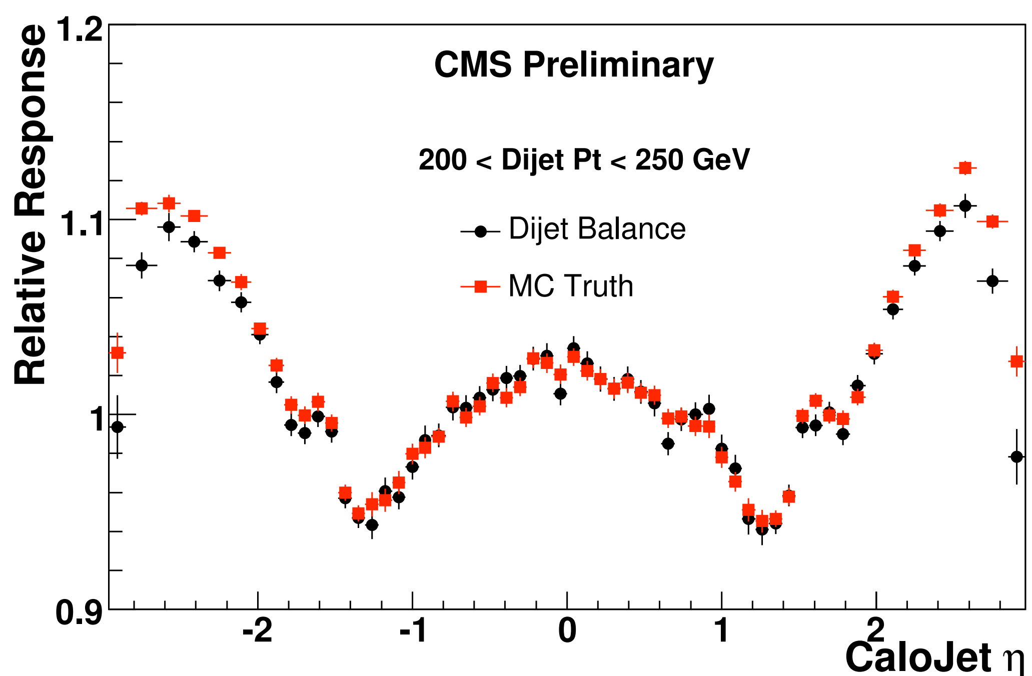
$$B = \frac{p_T^{probe} - p_T^{barrel}}{p_T^{dijet}}$$

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

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



Relative Response= $r(\eta)/r(|\eta|<1.3)$



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

Jet energy corrections:absolute p_T

MC based

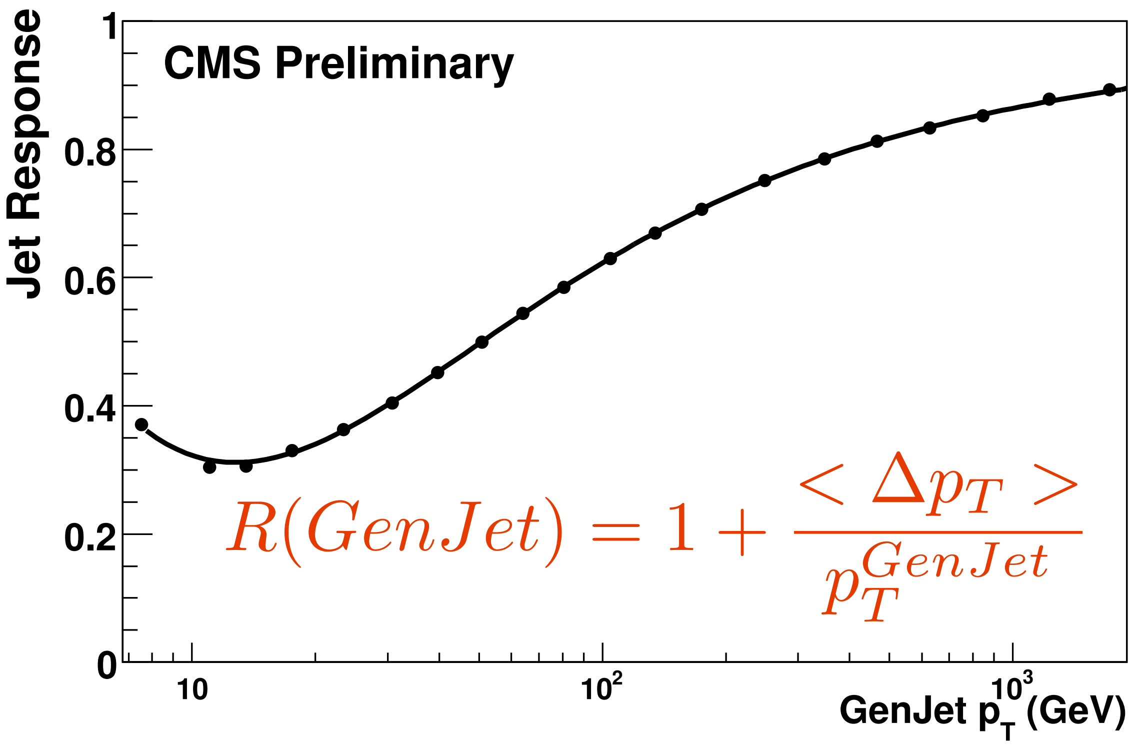
➪ Flatten the absolute jet response of calorimeter vs. p_T

Corrects energy of jet back to the particle level in control region (|η|<1.3)

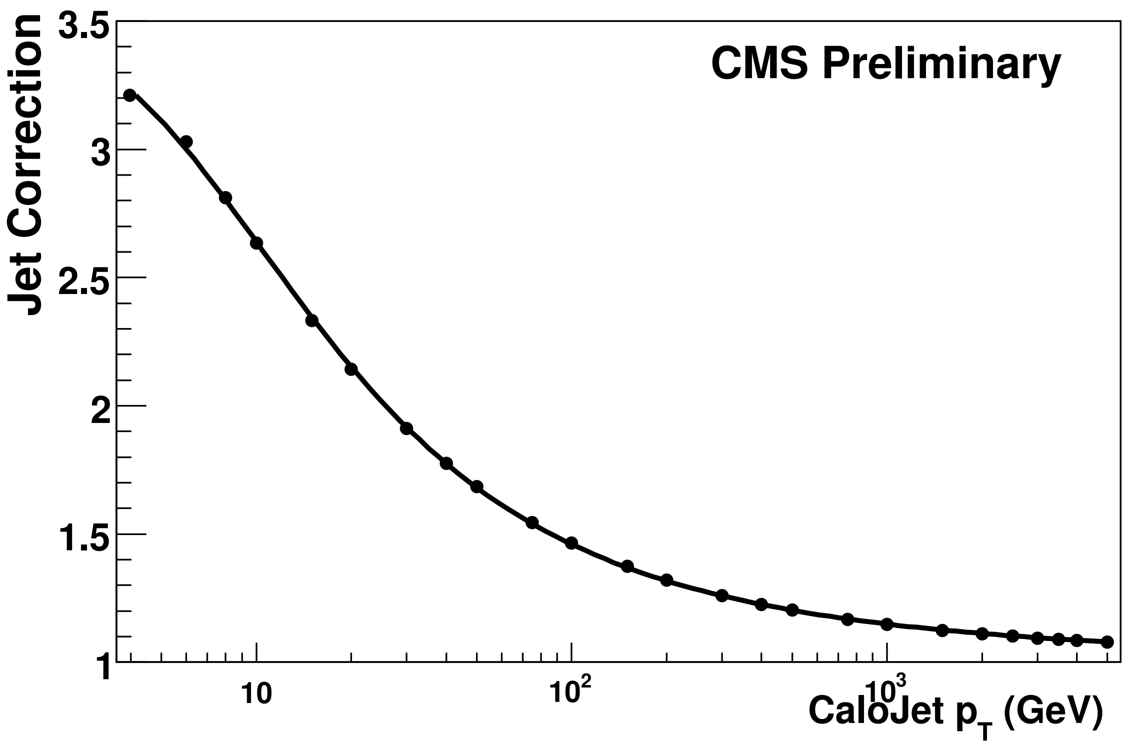
➪ Use Calorimeter jets within |η|<1.3 which are matched to GenJet ΔR<0.25

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

Absolute Jet Response vs. p_T(GenJet)



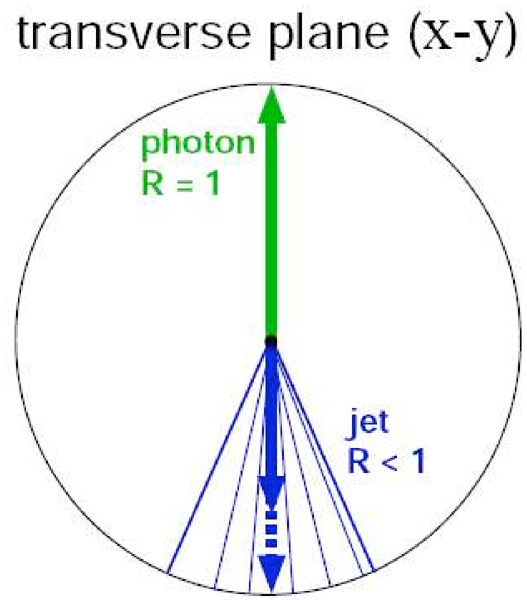
Absolute Jet Correction vs. p_T(CaloJet)

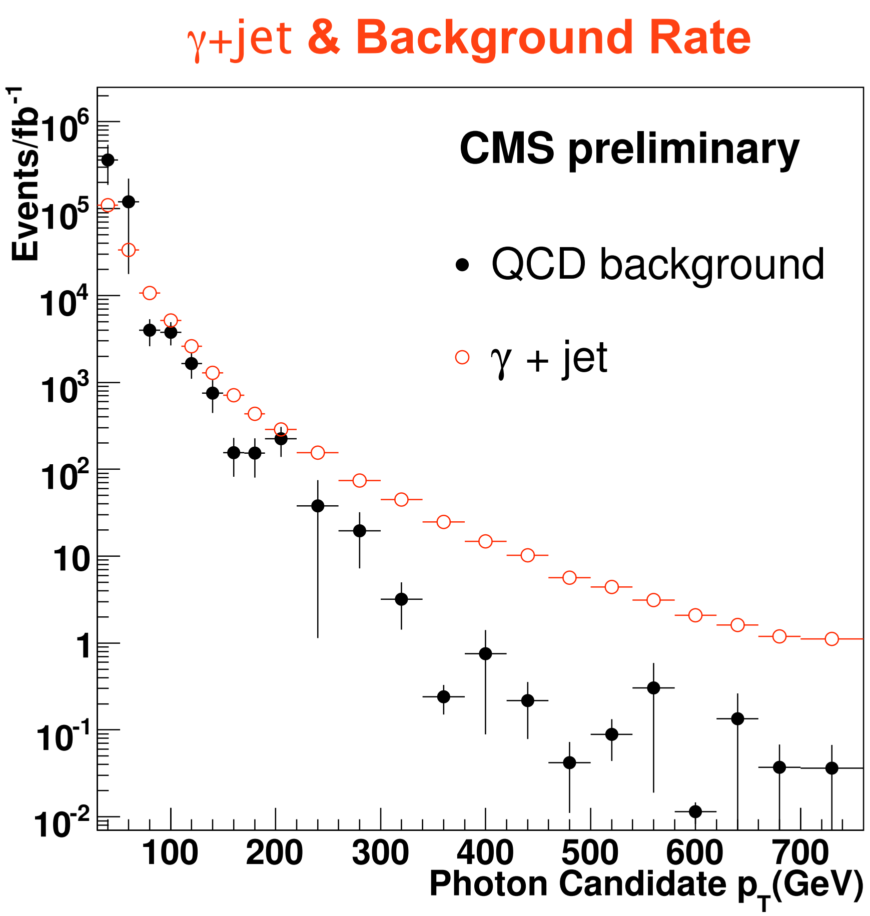


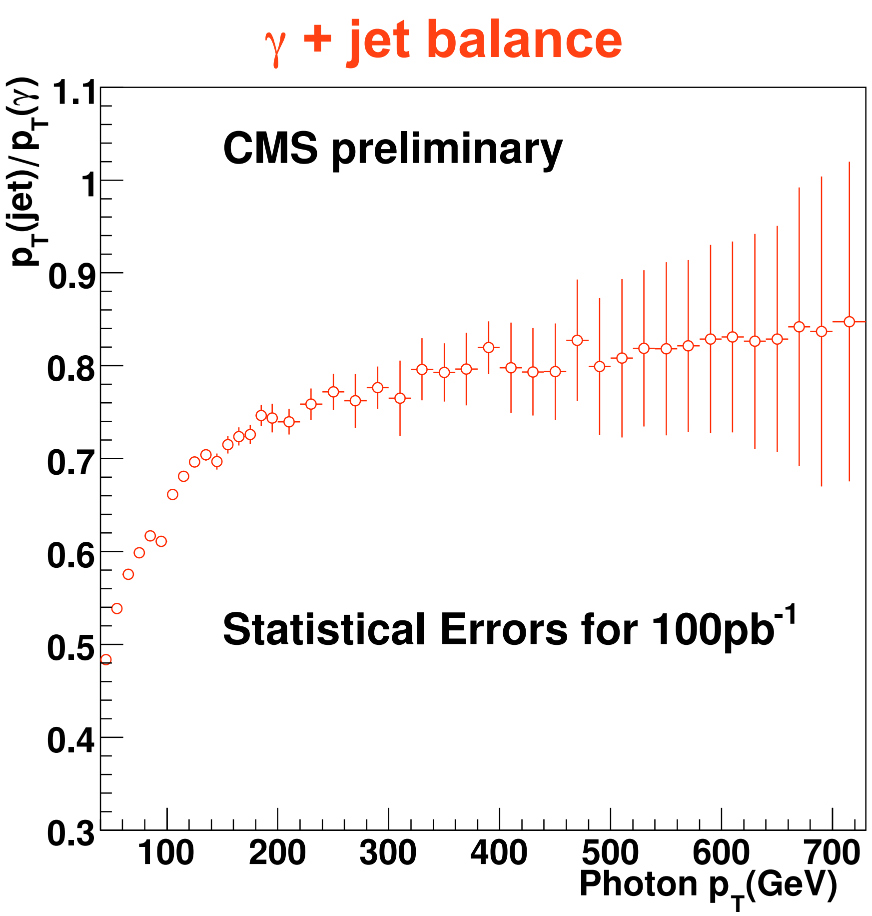
Jet energy corrections:absolute p_T

Data driven γ+jet: P_T balance in events with the jet in the control region

- consider clean events with $\Delta\Phi(\text{jets}) > \pi - 0.2$
- NO extra jet with $P_T > 0.1 P_T(\gamma)$
- isolated (ECAL,Tracker,HCAL) photons to reduce QCD bgr.



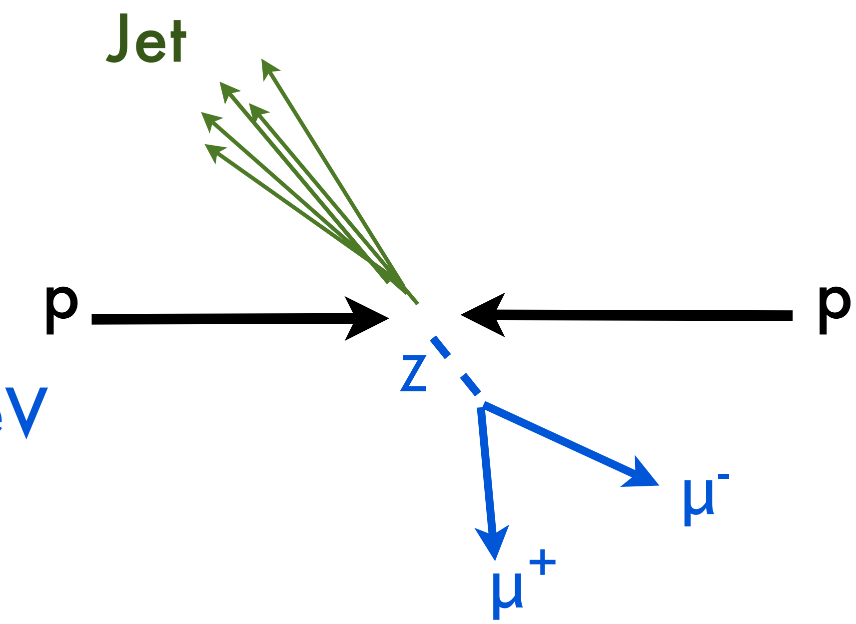




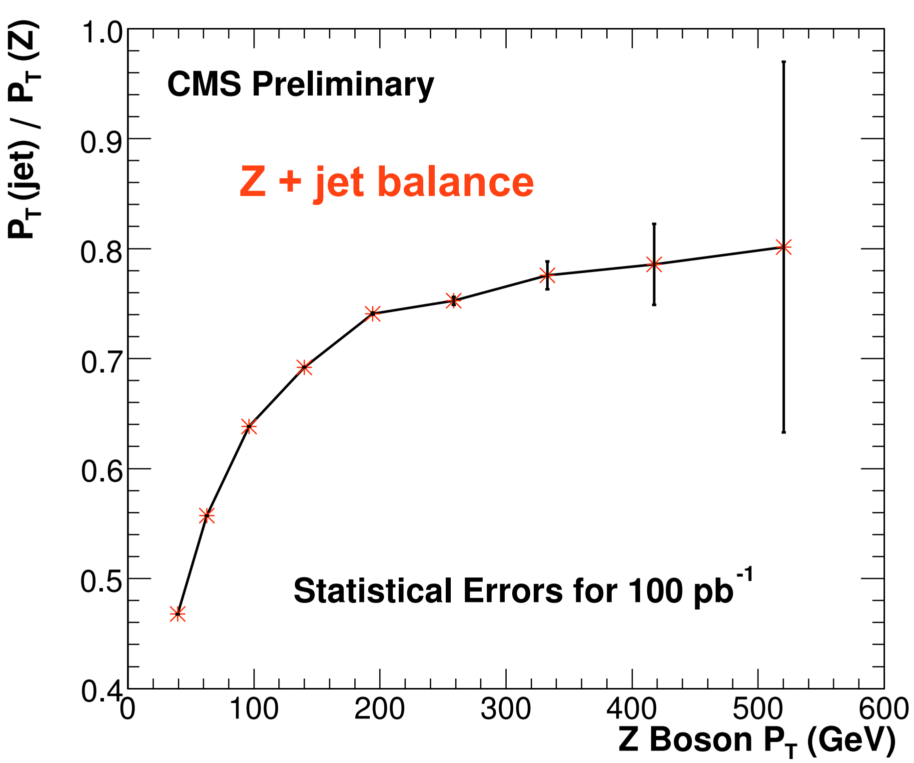
✓ calibration constants can be obtained for $P_T < 600$ GeV with a data of 100 pb^{-1}.

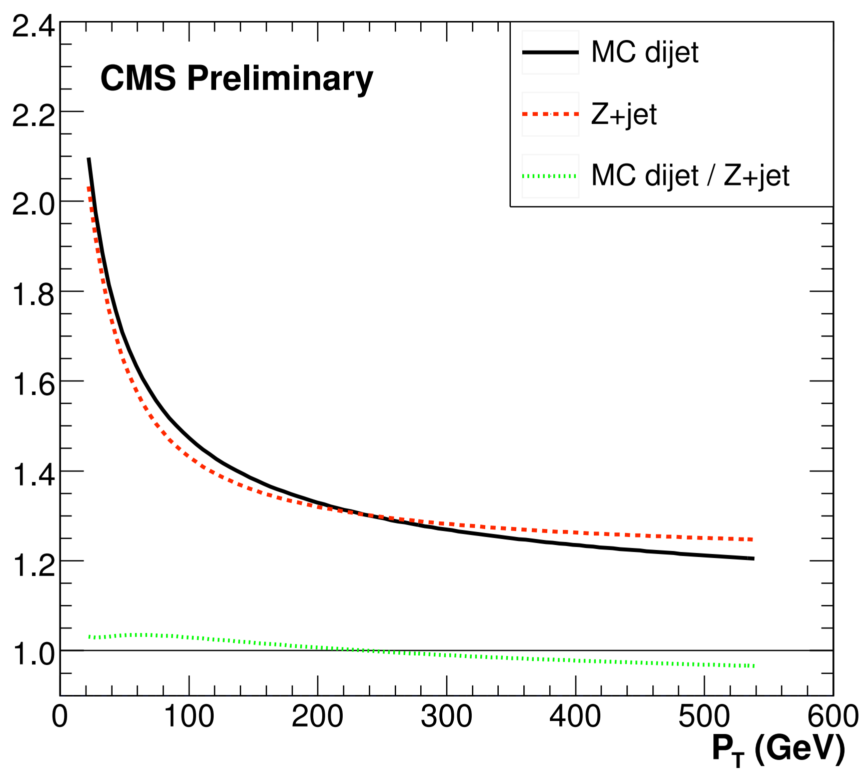
Jet energy corrections:absolute p_T

Data driven ($Z \to \mu\mu$)+jet: P_T balance in events with the jet in the control region



- muons reconstructed in the tracker (independent from calorimeter)
- clean events with well separated Jet-Z
- $p_T(\mu)$>15 GeV, opposite charge , $m_{\mu\mu}$ within m(Z)±20 GeV
- NO extra jet with P_T > $0.2P_T(Z)$.
- negligible background



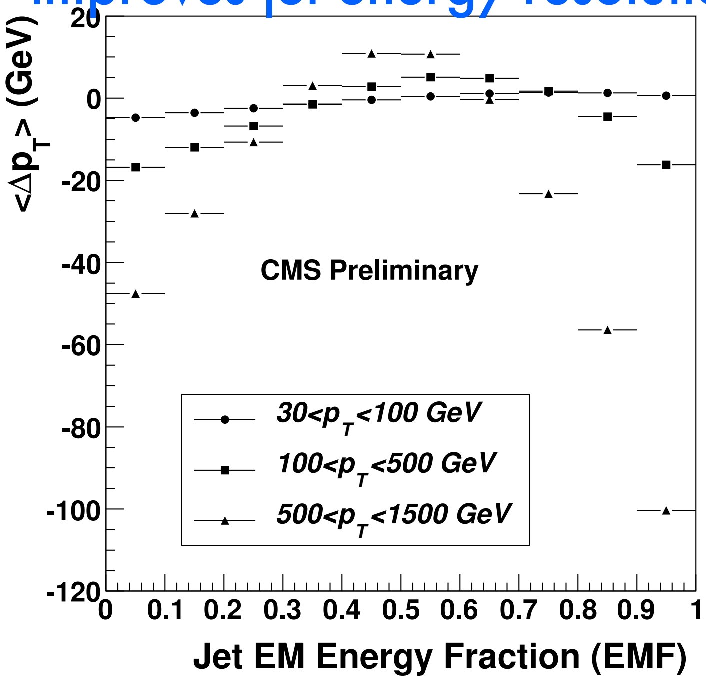


- ✓ measure jet correction up to 400 GeV with 100 pb^{-1}.
- ✓ correction factors from MC dijet & Z+jet consistent within 5%
- ✓ combine jet calibration constants from Z+jet and MC truth, extrapolate to higher p_T
- ✓ consistent results with γ+jet calibrations

Jet energy corrections: (optional)

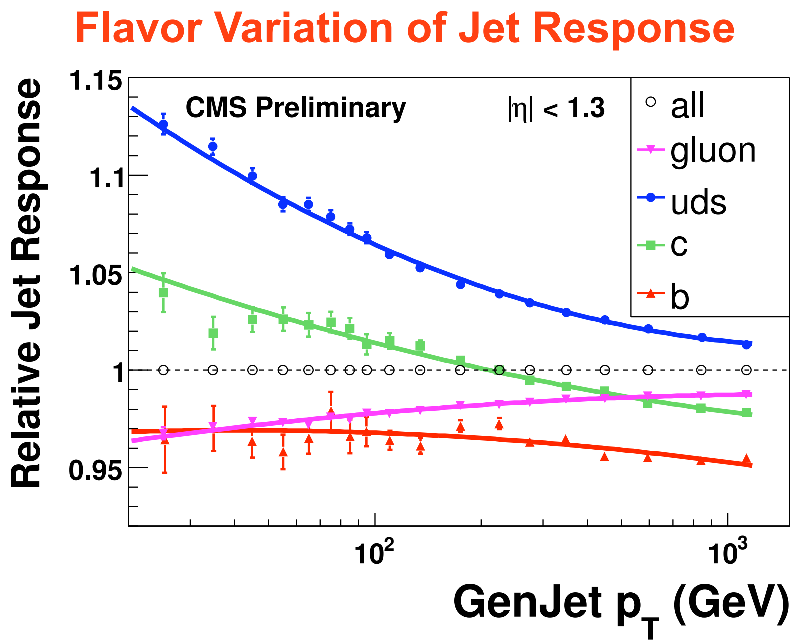
✱ EMF dependent corrections

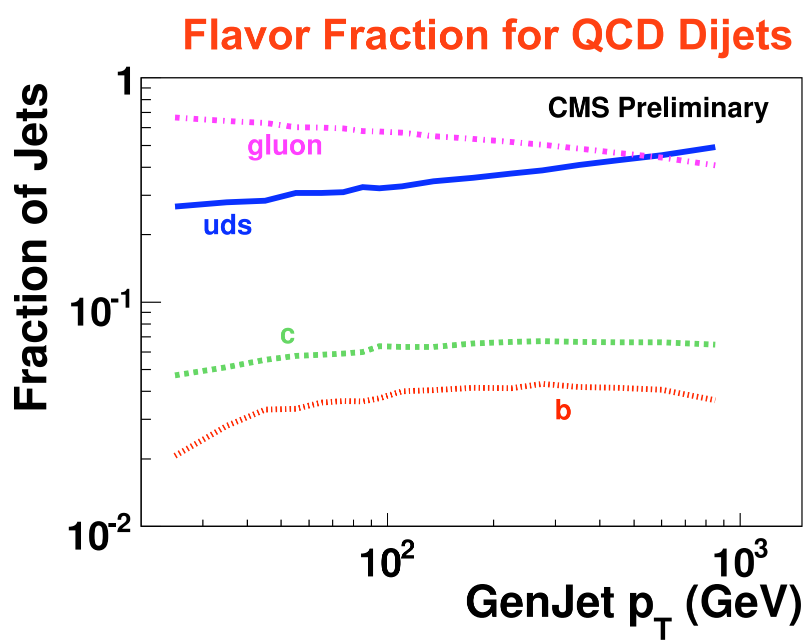
- correct for variations in jet response versus EM energy fraction of Jets
- improves jet energy resolution up to 10%



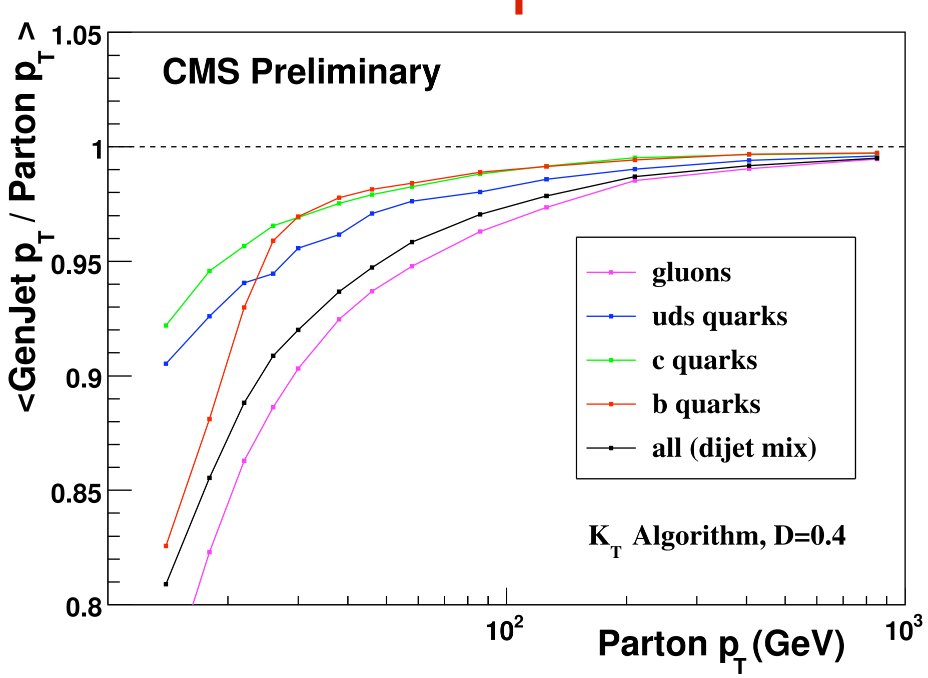
✱ Flavor dependent corrections

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





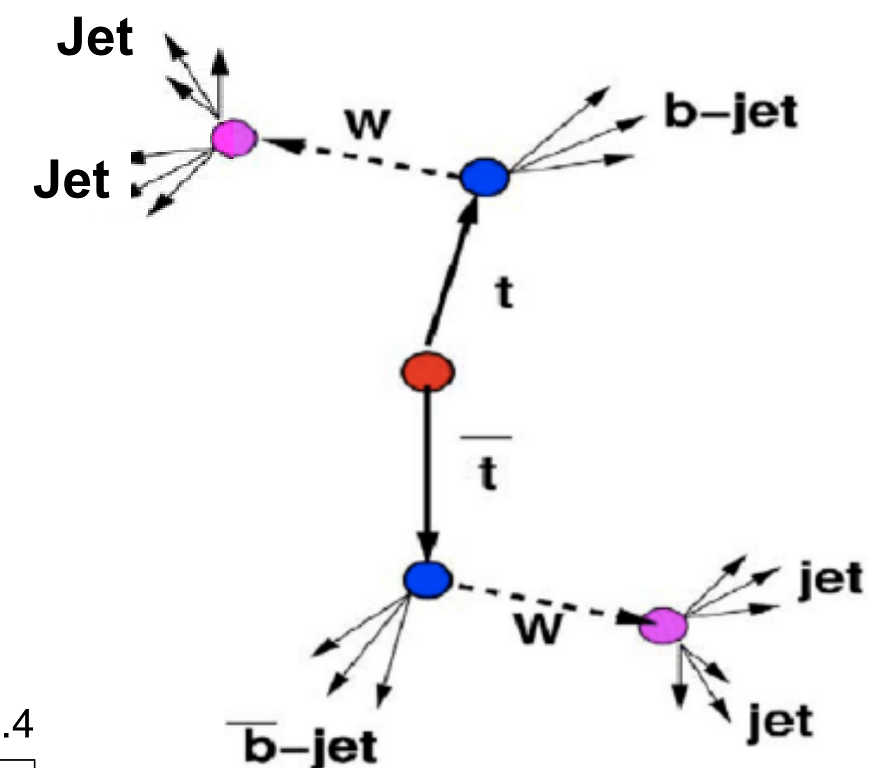
✱ Corrections to parton level

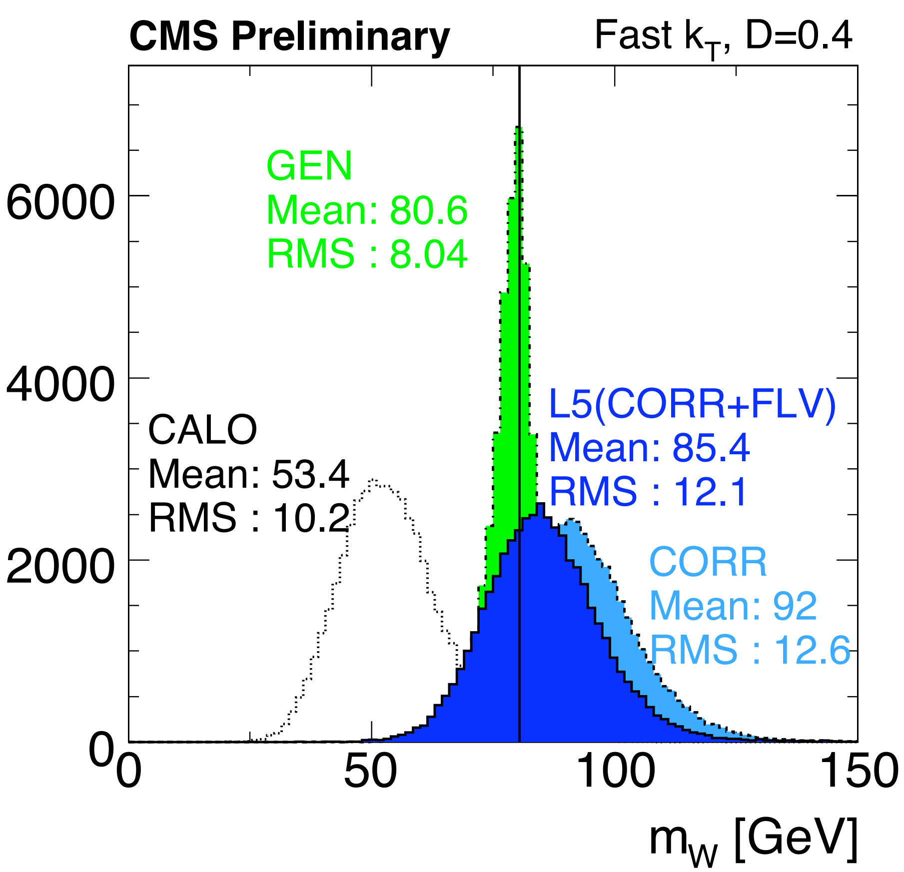


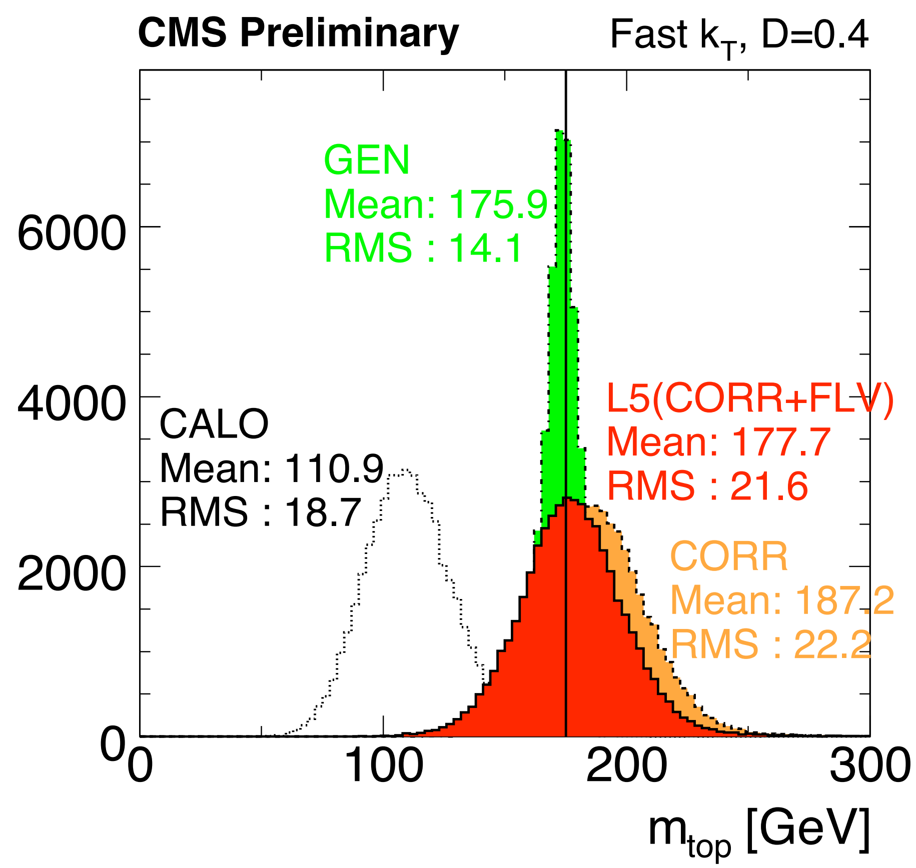
- correcting jet pT to the parton level
- gluons radiate more → lower response due to out-of-cone effect
- process dependent

Performance in ttbar events

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







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

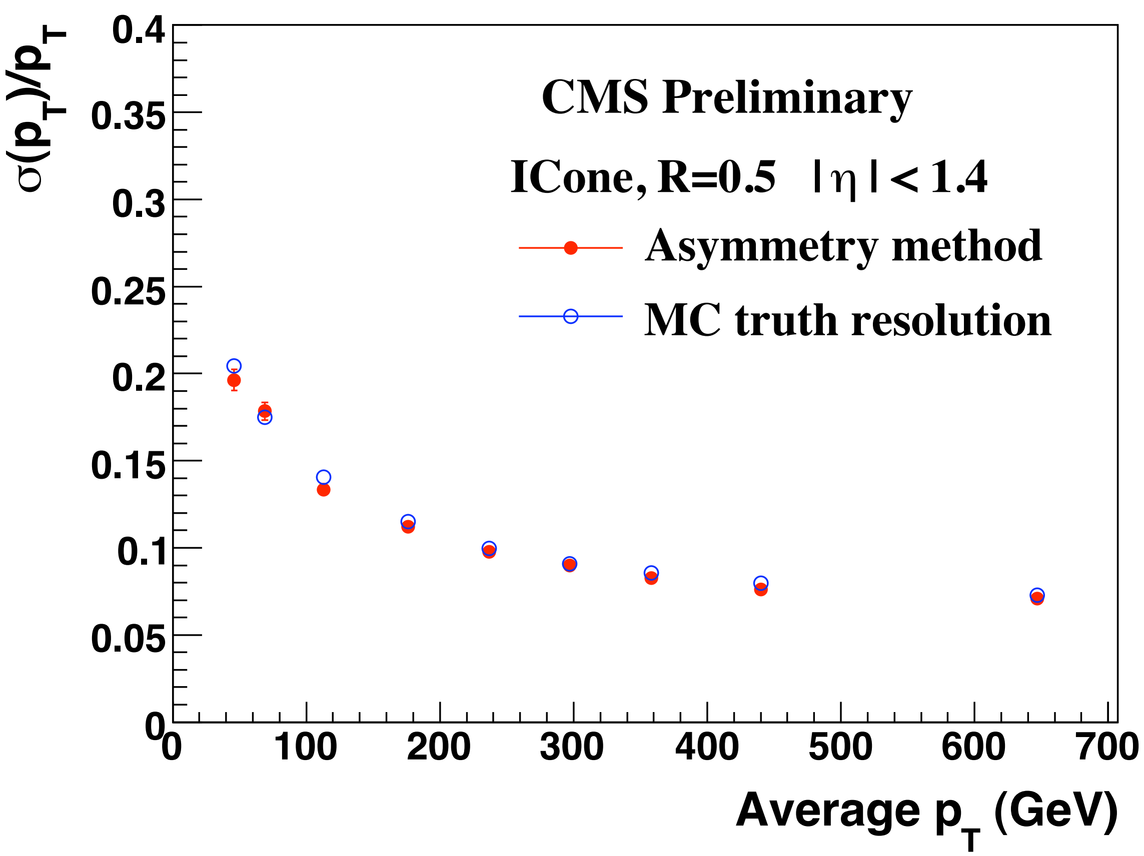
Jet energy resolution : Data-Driven

Asymmetry method

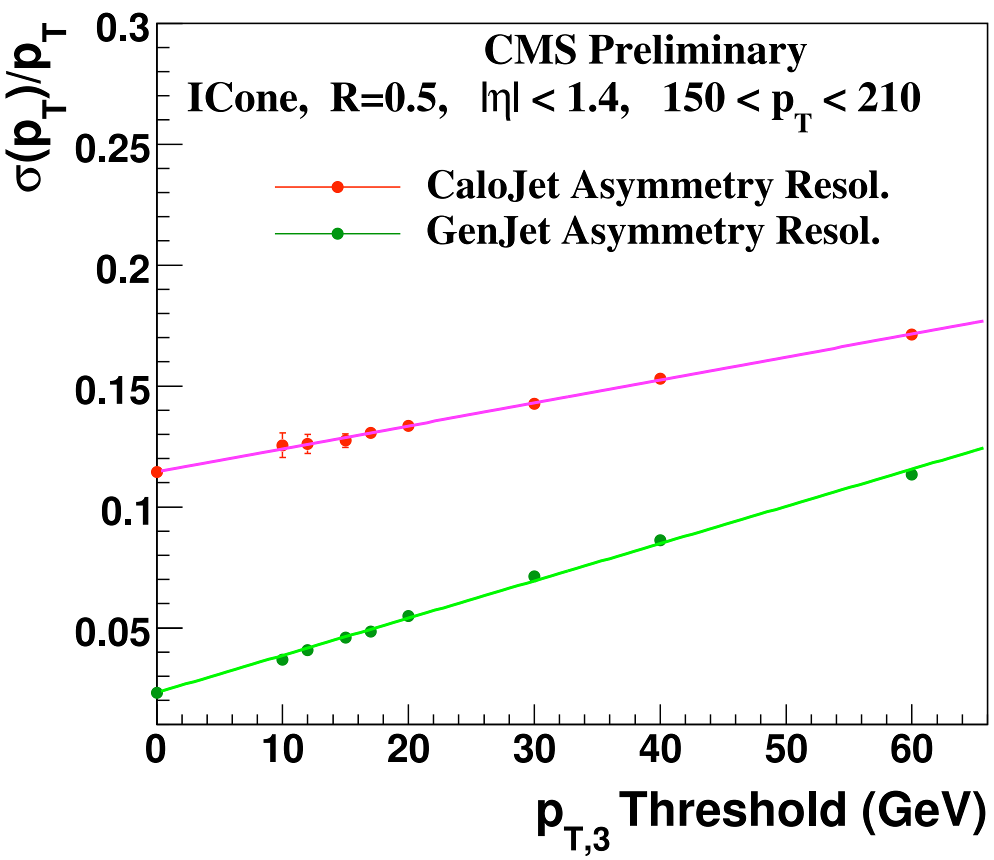
- select the back-to-back ($\Delta\Phi>2.7$) jets in the barrel region
- relate resolution to Asymmetry variable A

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

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



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



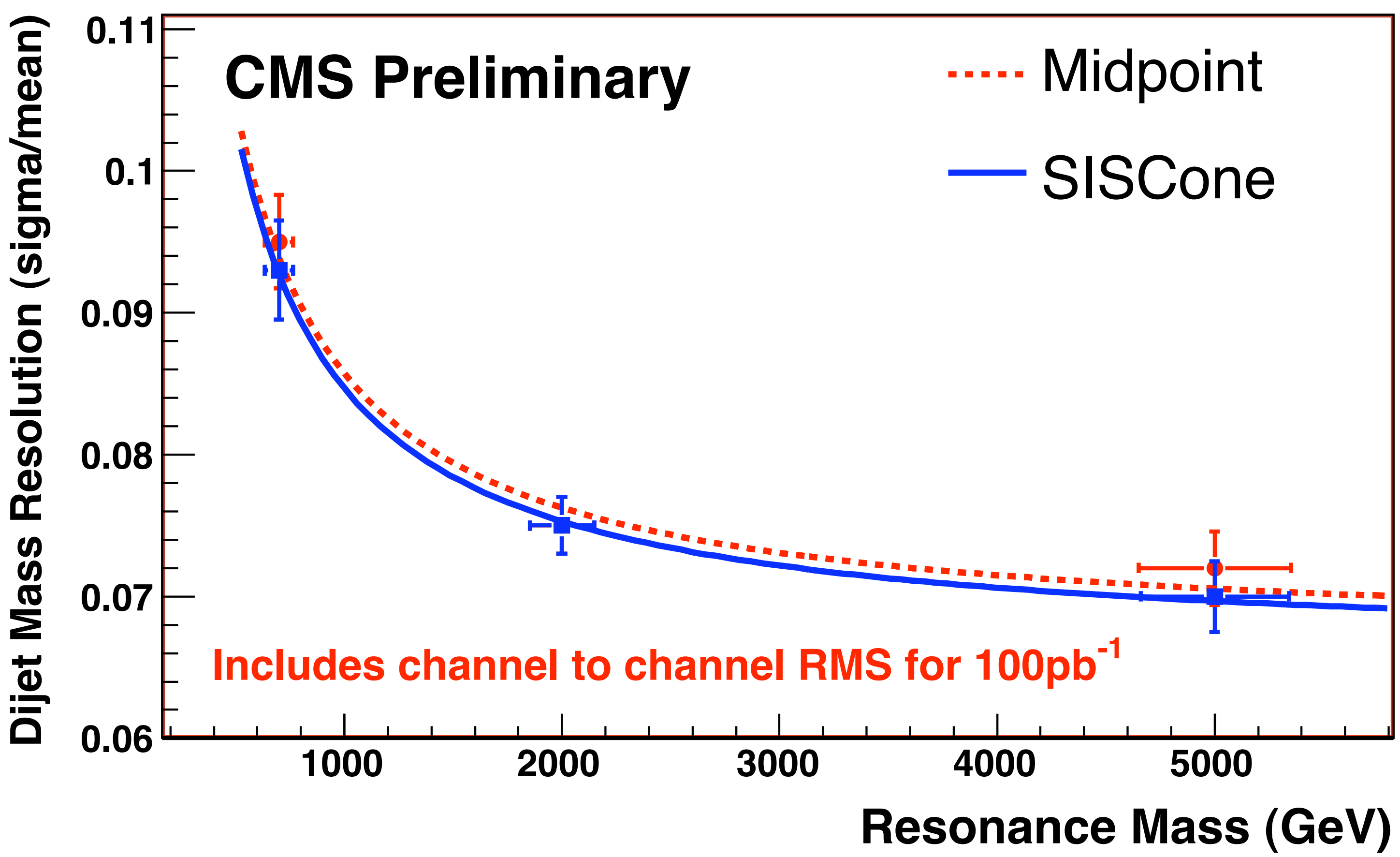
di-jet Mass resolution

- Study Mass resolution in $Z' \rightarrow q\bar{q}$ → both position&energy resolution participates

- MC Samples miss-calibrated according to expectations of 100/pb data, m(Z')= 700, 2000, 5000 GeV
- two leading jets in the barrel region of HCAL η<1.3

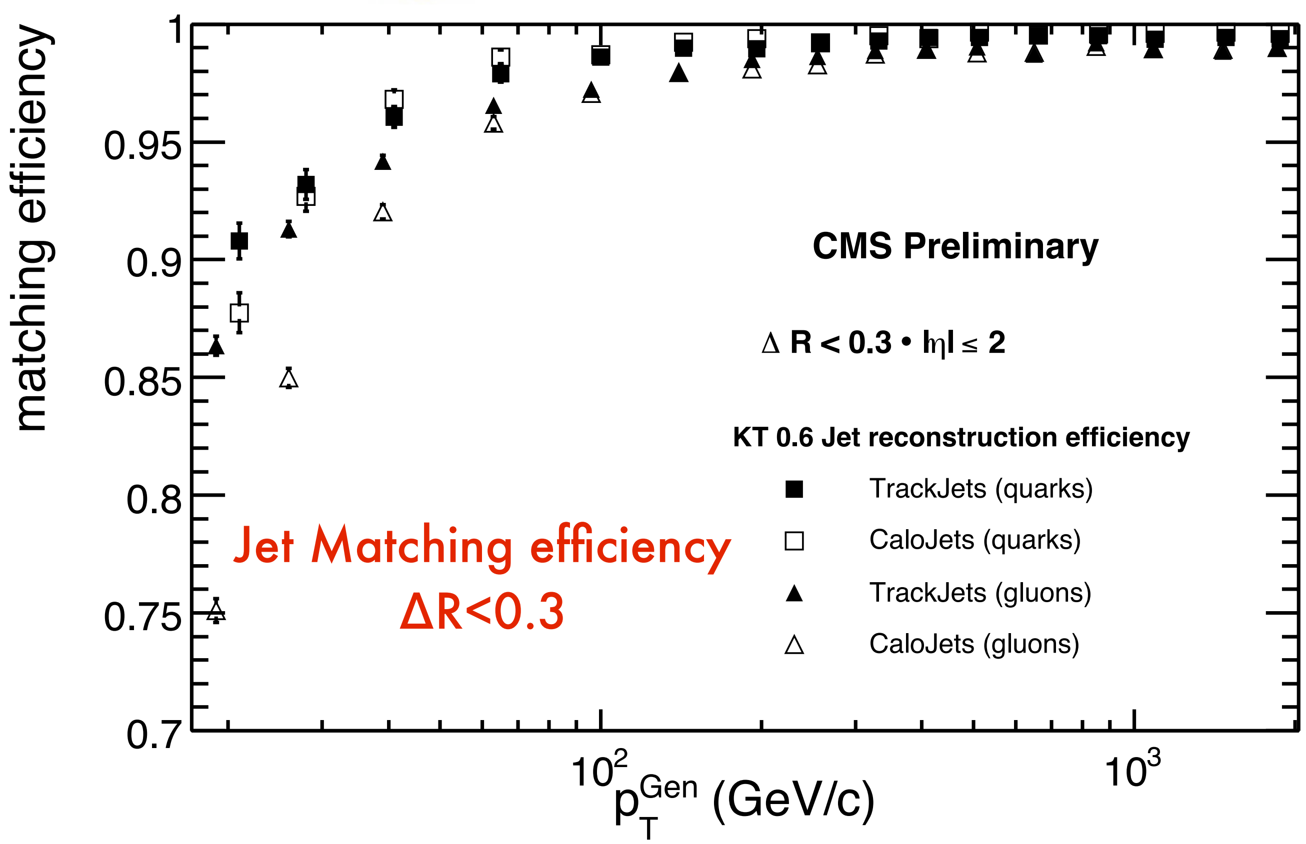
- m(Z')=m(jet1,jet2)

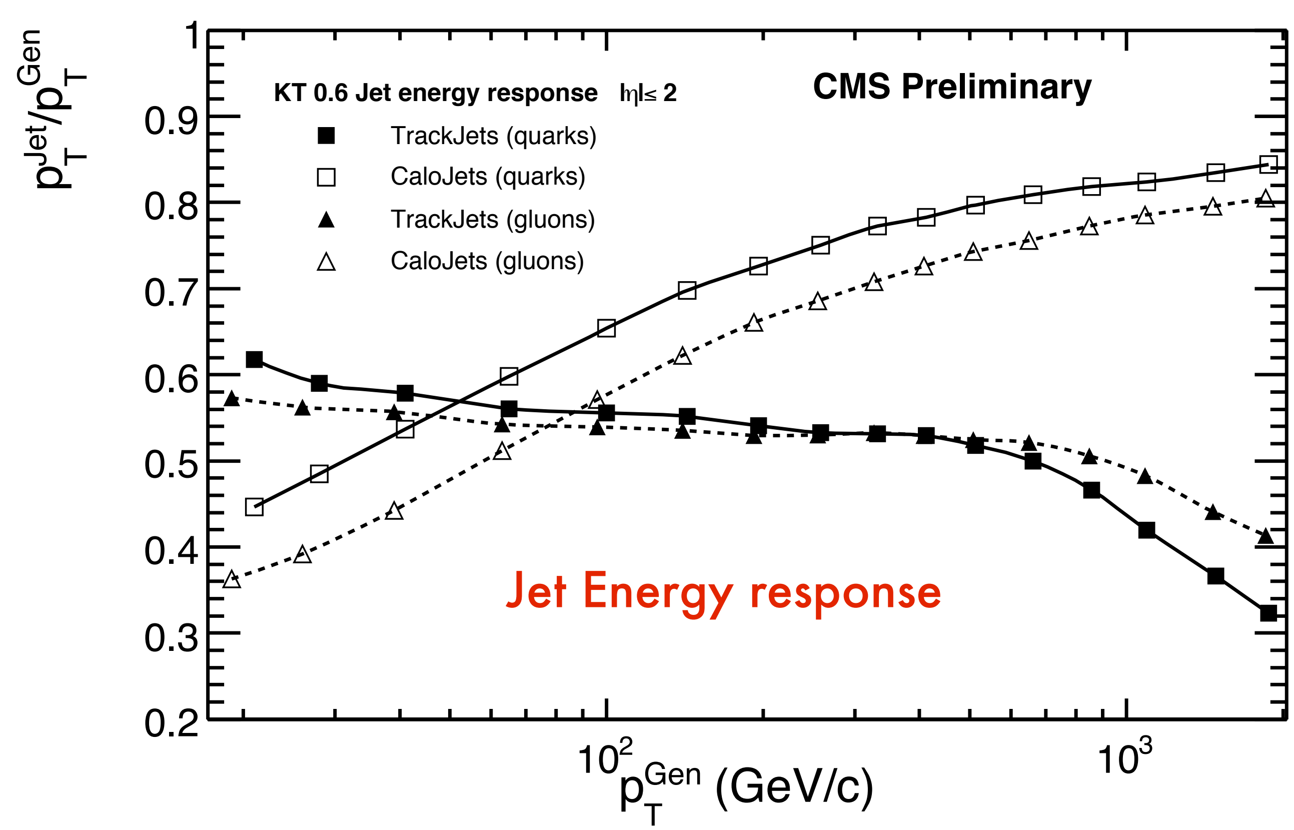
☑Similar resolutions from SiSCone & MidPoint



Jet Reconstruction with Tracks (1)

- CMS can profit from excellent tracker measurements also for measuring Jets
- Reconstruct jets using charged tracks only, independent from calorimeter
  - independent systematics
  - can be used to cross check Calorimeter Jets
  - data driven efficiencies, tag&prob
- charged fraction of hadronic jets is about 60% (large fluctuations:bad Jet energy resolution)



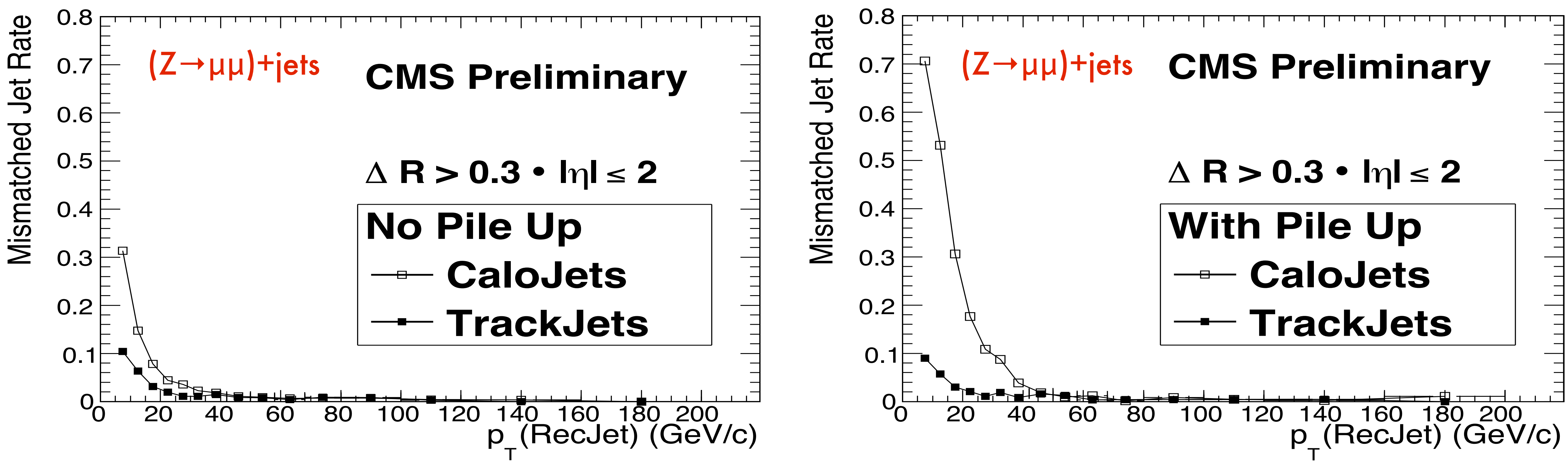


- good jet matching efficiencies: better angular resolution (Φ)
- stable jet energy response up to ~1 TeV

Jet Reconstruction with Tracks (2)

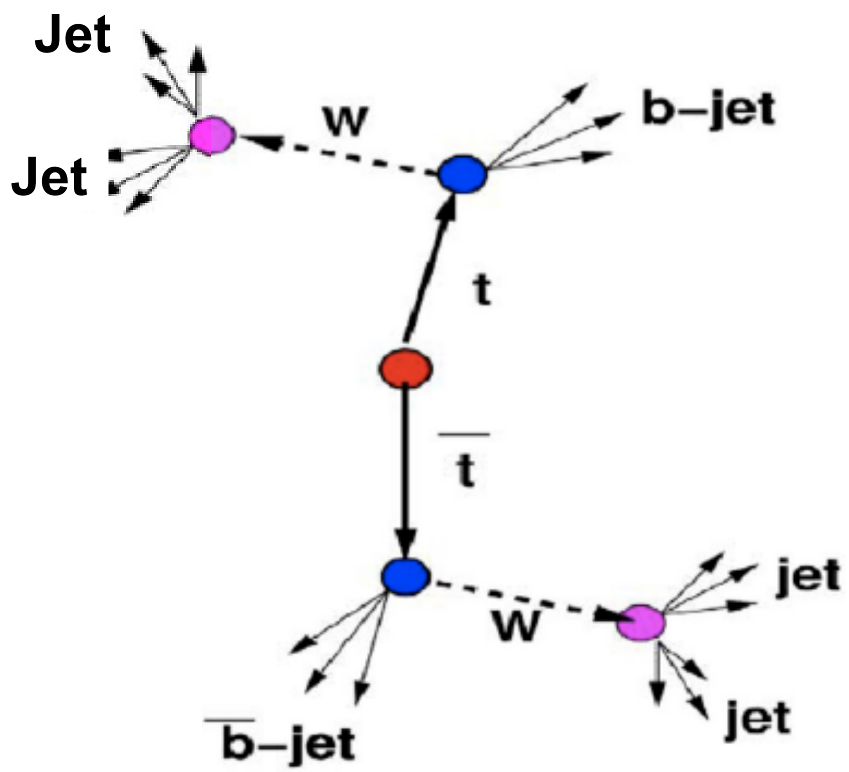
- Performance in Z+jets + PlieUP(average 5 interaction per bunch crossing)
    - Tracks are measured at the IP origin : tracks coming from other vertices can be rejected a prior to jet clustering
    - Tracks compatible with muon vertex are selected

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



TrackJets are transparent to PU effects

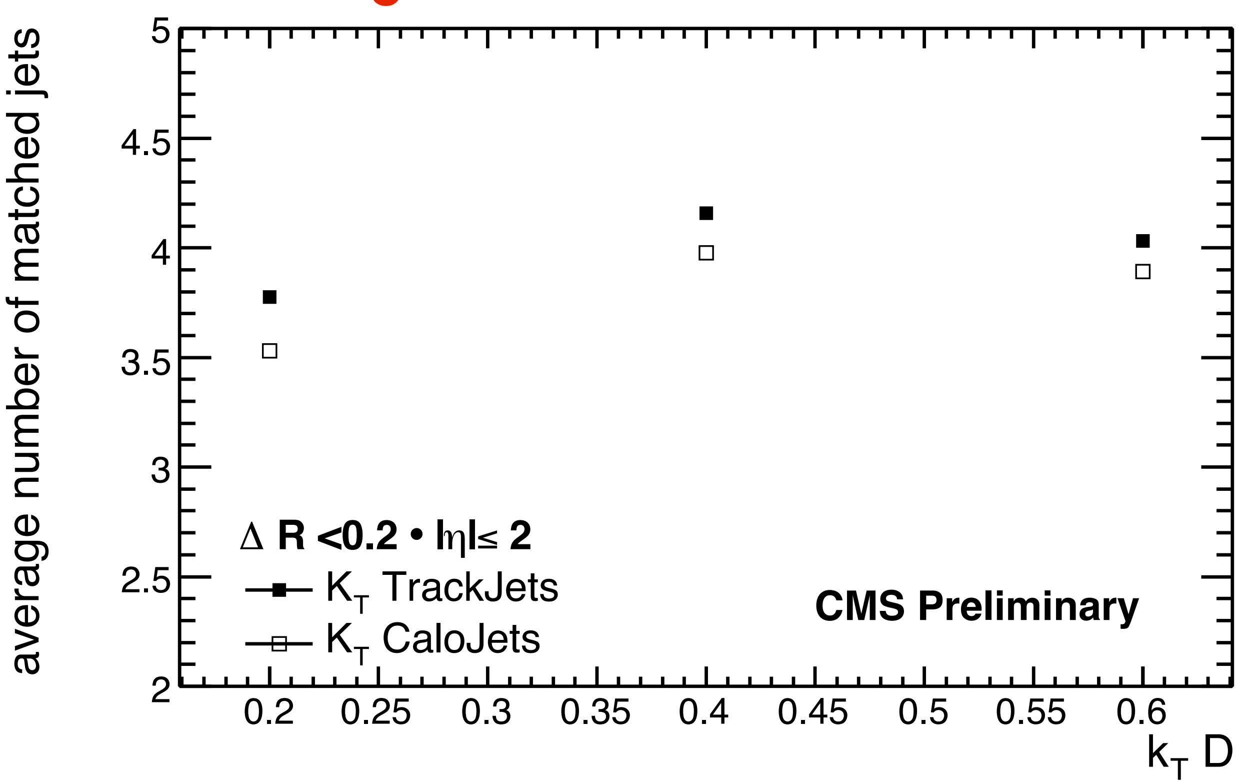
Jet Reconstruction with Tracks (3)



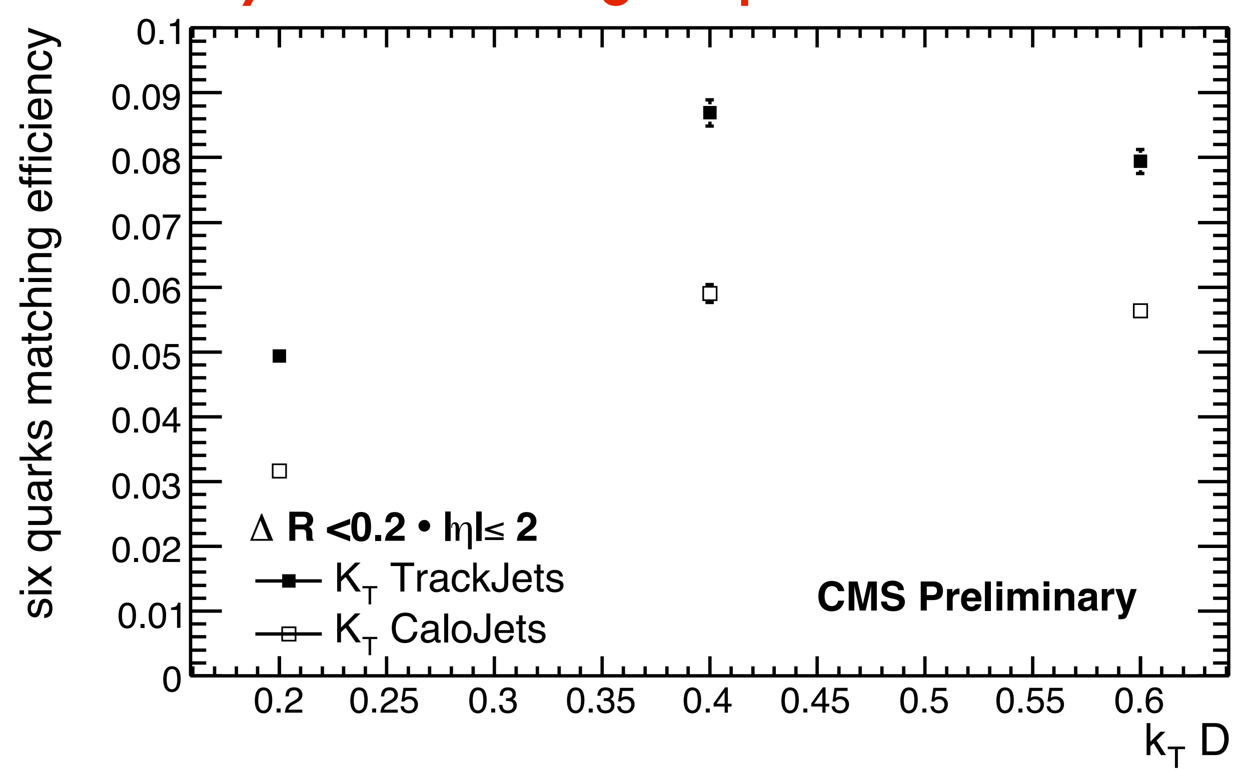
- Performance in "crowded" events: fully hadronic decays of ttbar

Select hadronic decays $t\bar{t} \rightarrow b\bar{b}q\bar{q}q\bar{q}$ (45% of total) with all six quarks within |η|<2. (15% of total)

Averaged number of Matched Jets

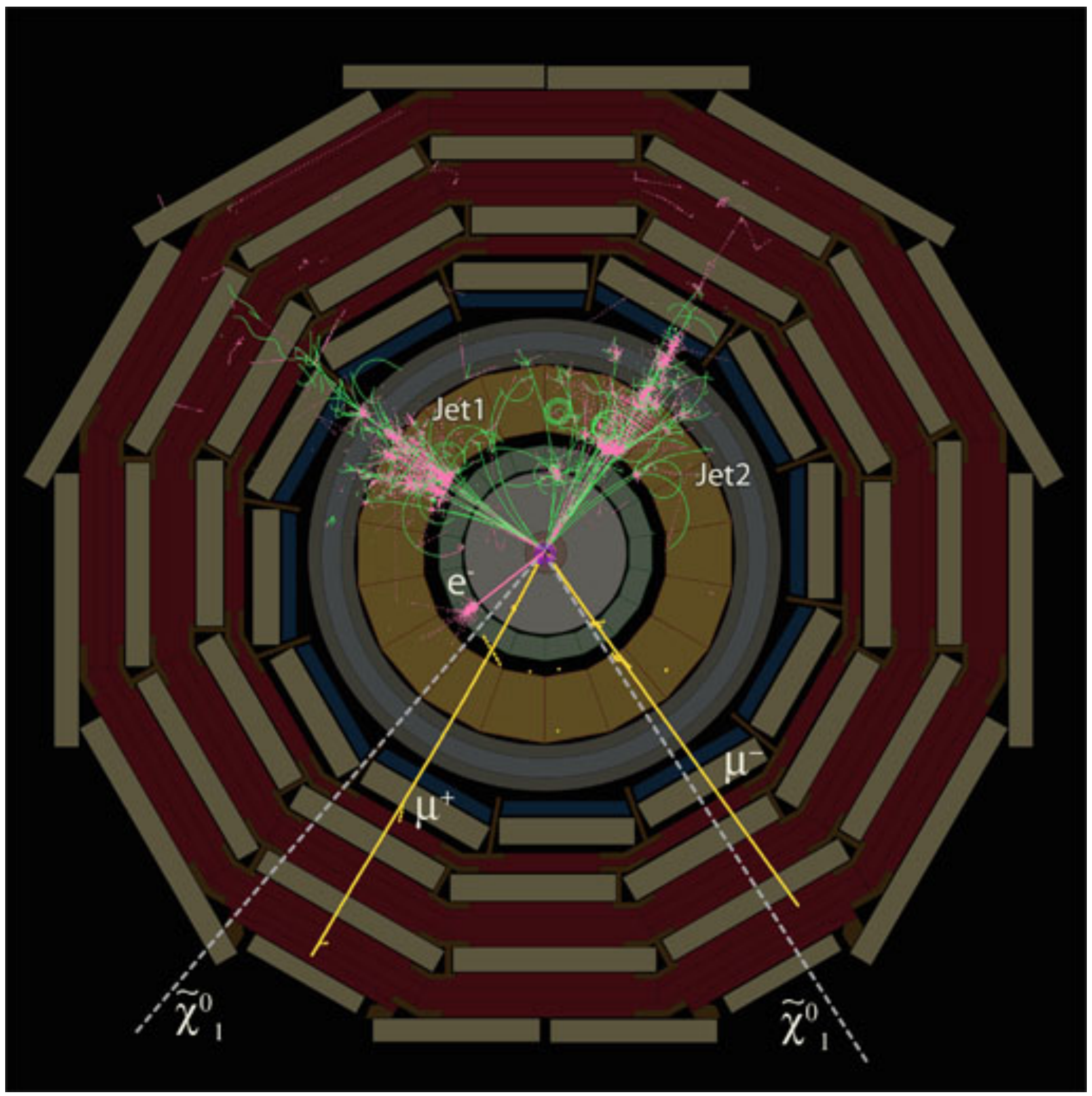


efficiency of matching 6 quarks to a reco Jet



Missing Transverse Energy

* Imbalanced transverse energy in the event
* signature of only weakly or non-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)

<u>Challenges</u>:

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

Missing E_T performance

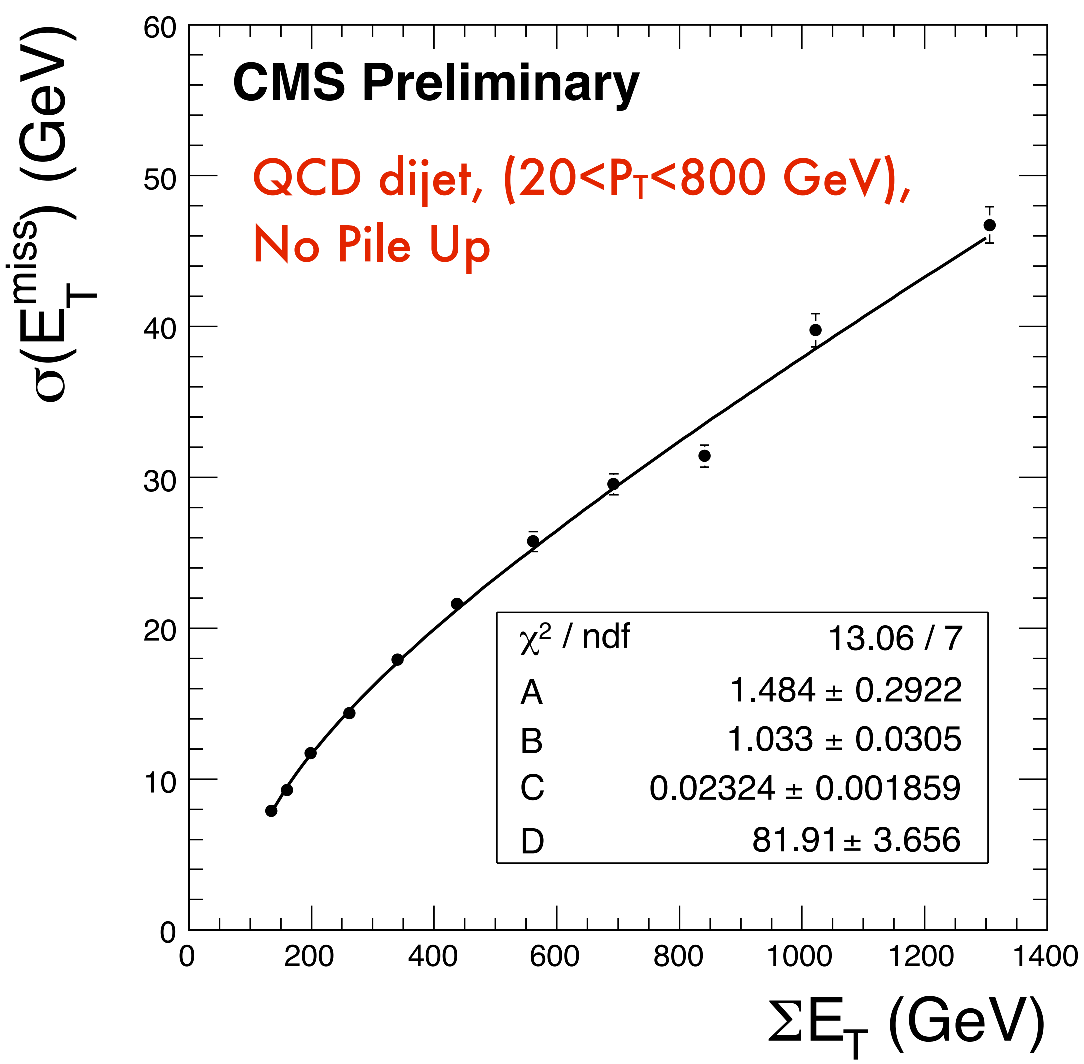
MET is calculated from uncorrected energy deposits in projective Calorimeter Towers

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

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

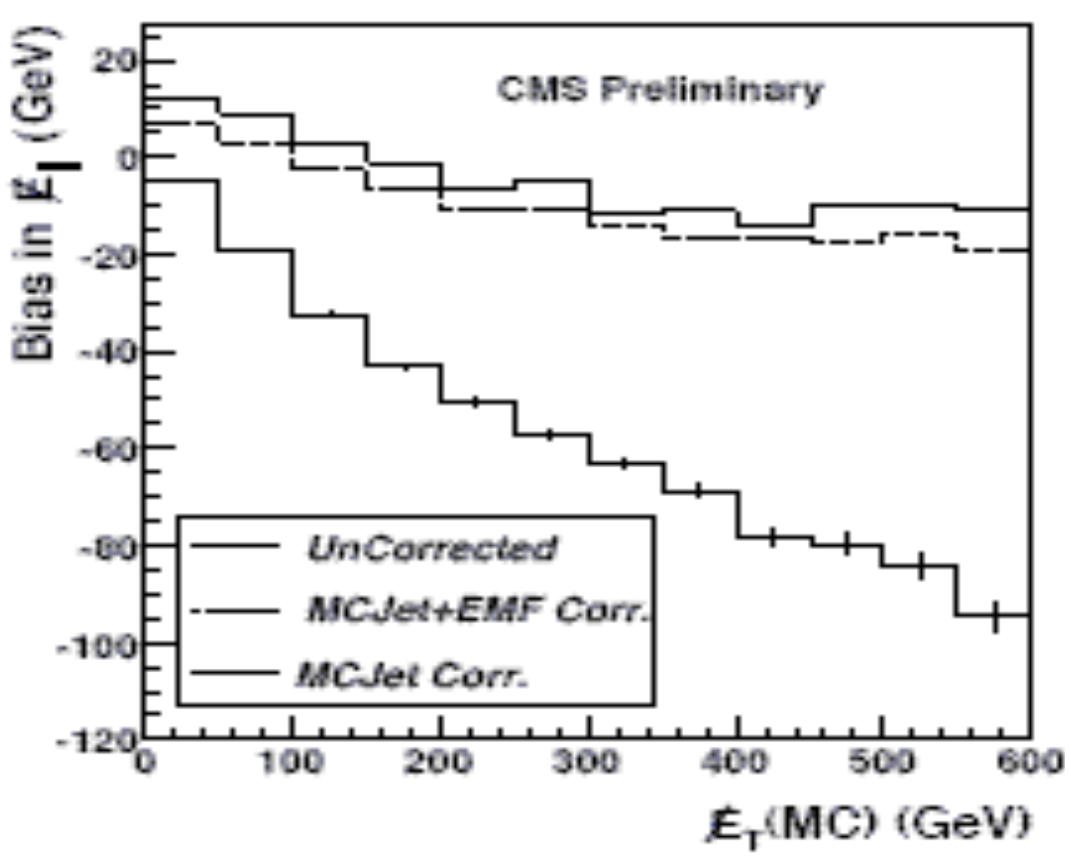


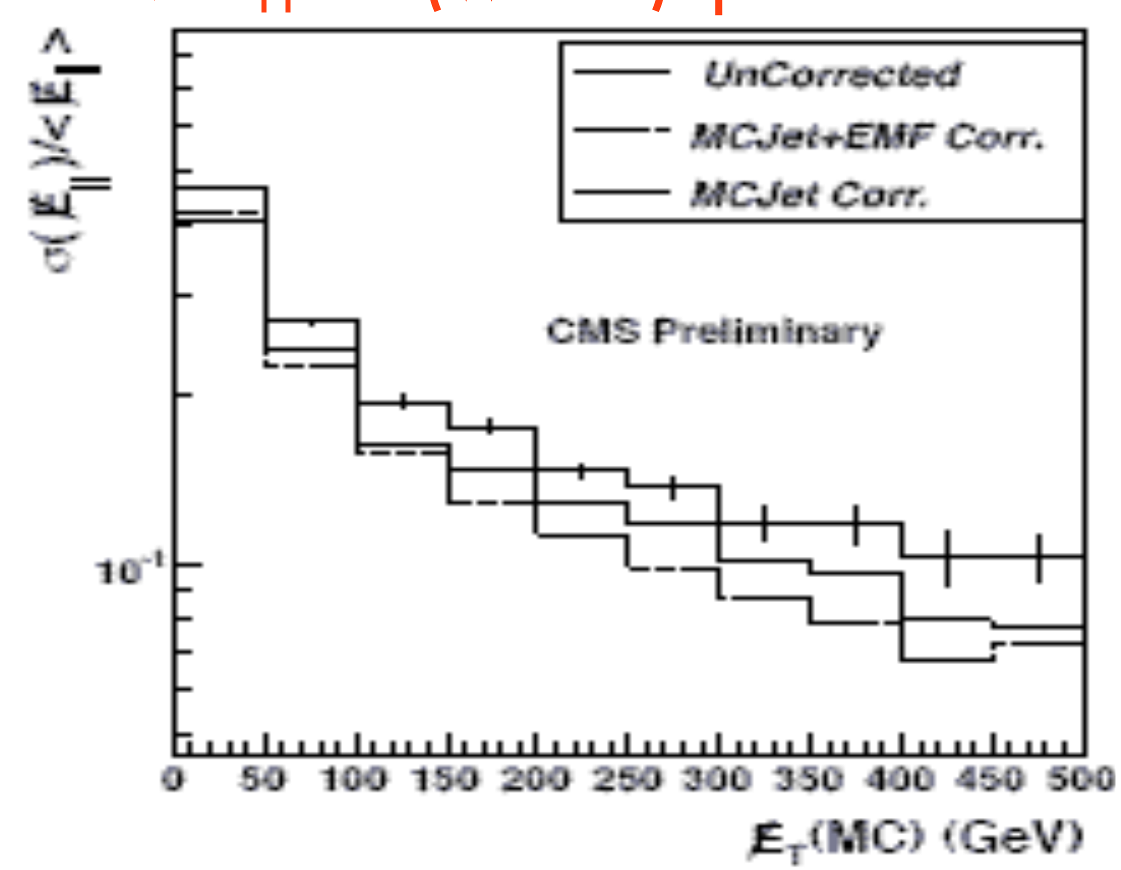
Missing E_T Calibrations

- MET is calculated from un-calibrated CaloTowers, needs to be corrected for non-linearities in response versus P_T and η
- standard jet calibrations for jets can be used to correct MET
- CMS has a non-compensating calorimeter system, e/h≠1
- 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 and relative resolution on $MET_{||}$ for (W→eν)+jets





Muon corrections on missing E_T

➠ Muon leaves a small fraction of its energy in calorimeter

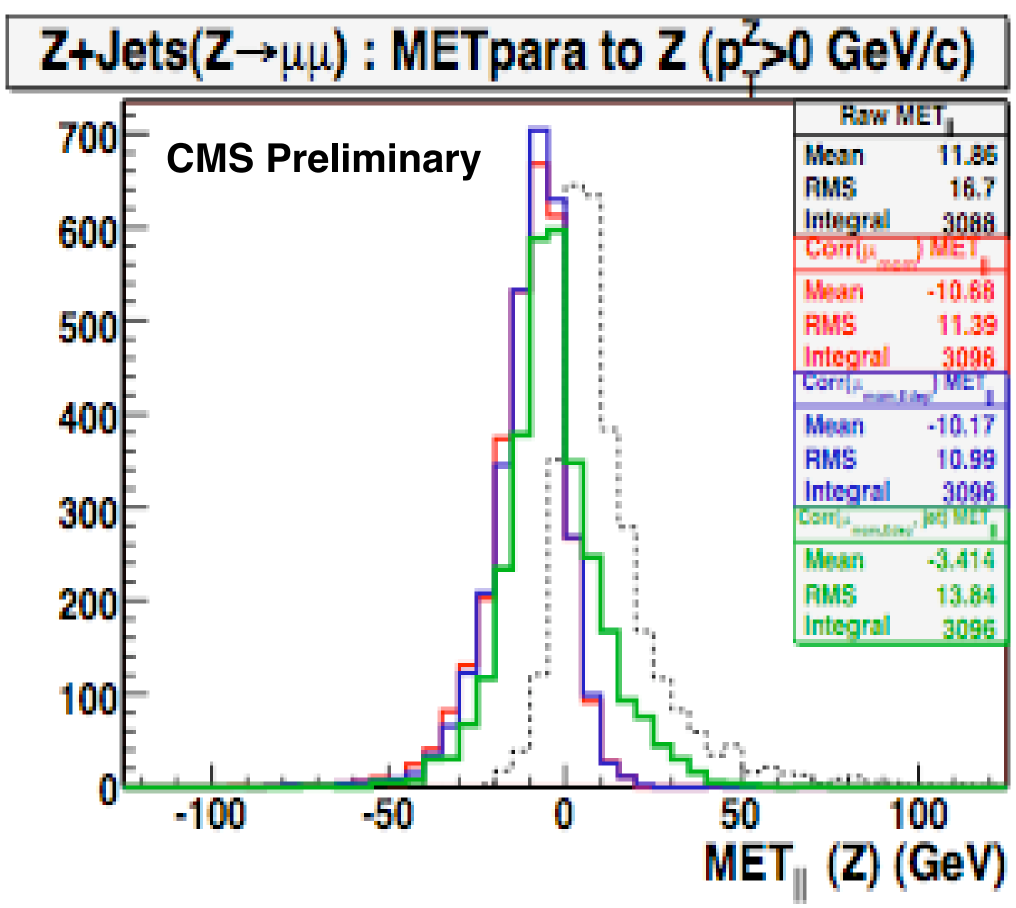
$$\vec{\not{E}}_T = -\sum_{i=1}^{\text{towers}} \vec{E}_T^{\,i} - \sum^{\text{muons}} \vec{p}_T^{\,\mu} + \sum_{i=1}^{\text{deposit towers}} \vec{E}_T^{\,i}.$$

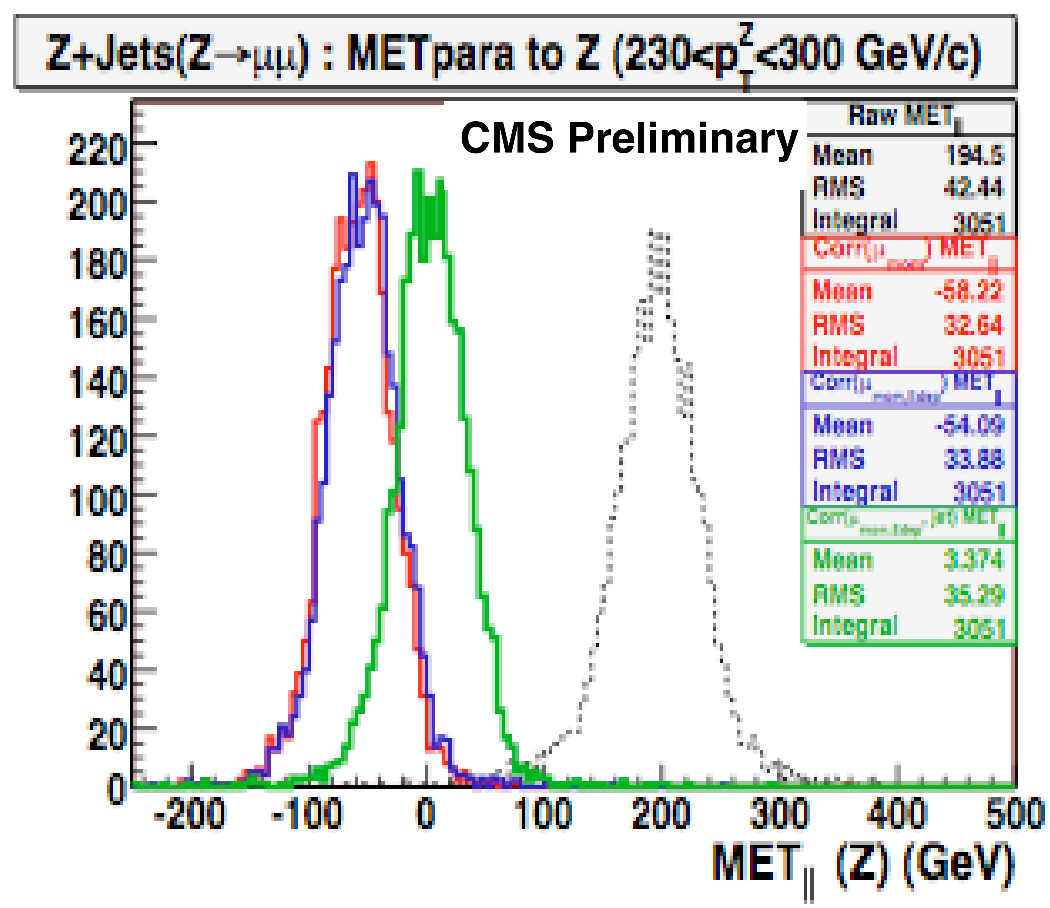
energy deposited in calorimeter by muon

➠ Muons are identified in the Tracker and muon system, well separated in η-ϕ with jets & $P_T^{\mu}>10$ 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

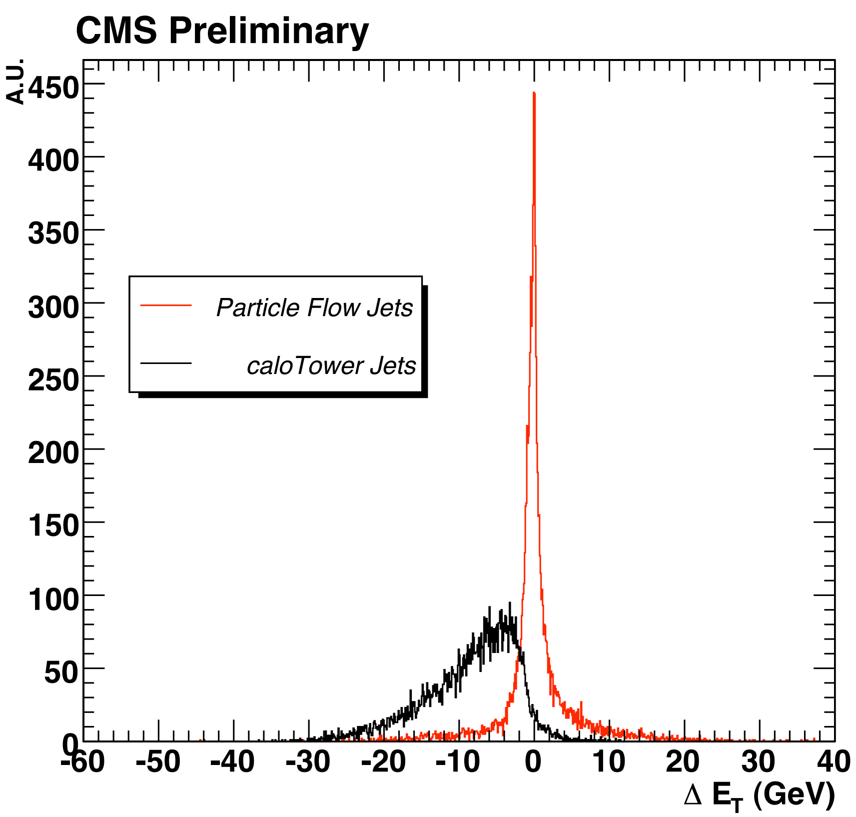
Tau corrections on missing E_T

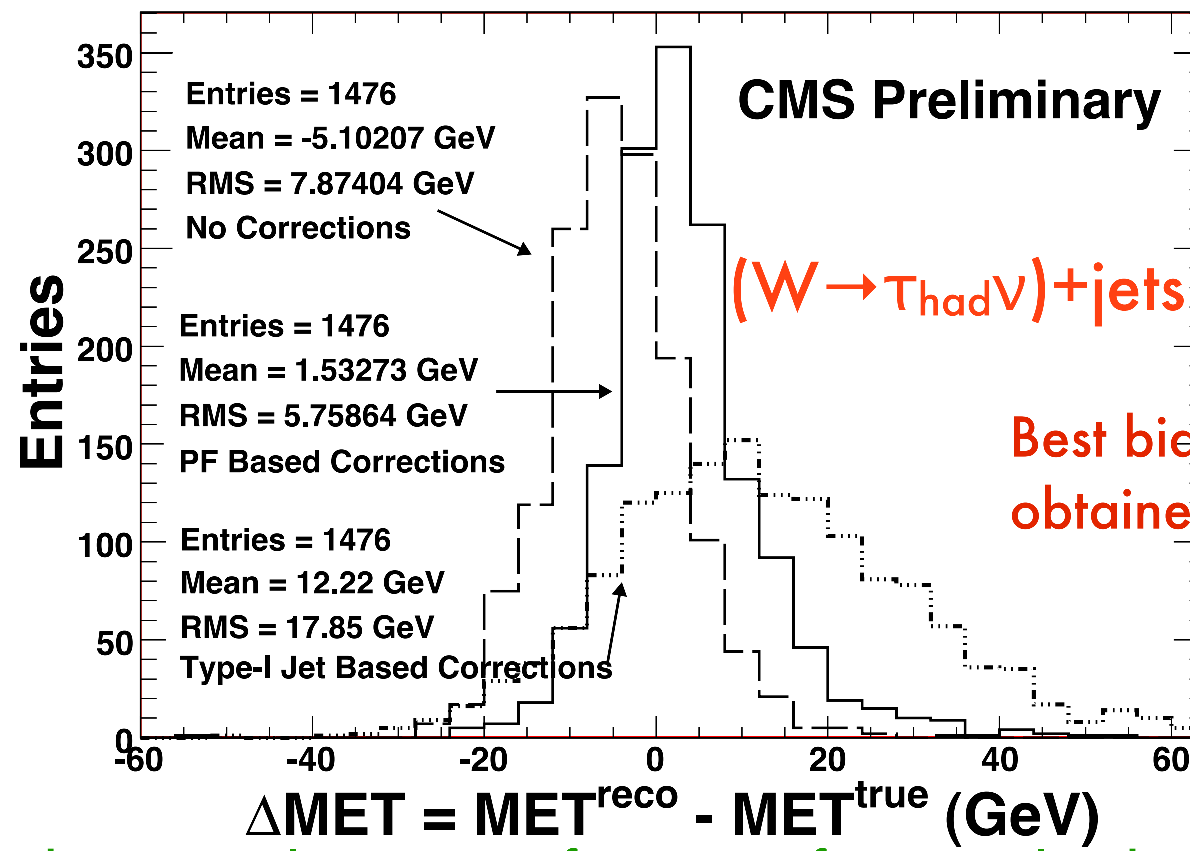
- Tau jets are different from ordinary QCD jets, typically less constituents with fairly high energy ➟ applying standard jet corrections to hadronic tau jets will result in significant overcorrection on ME_T
- Tau-specific corrections have been derived using Particle-flow algorithm and propagated into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





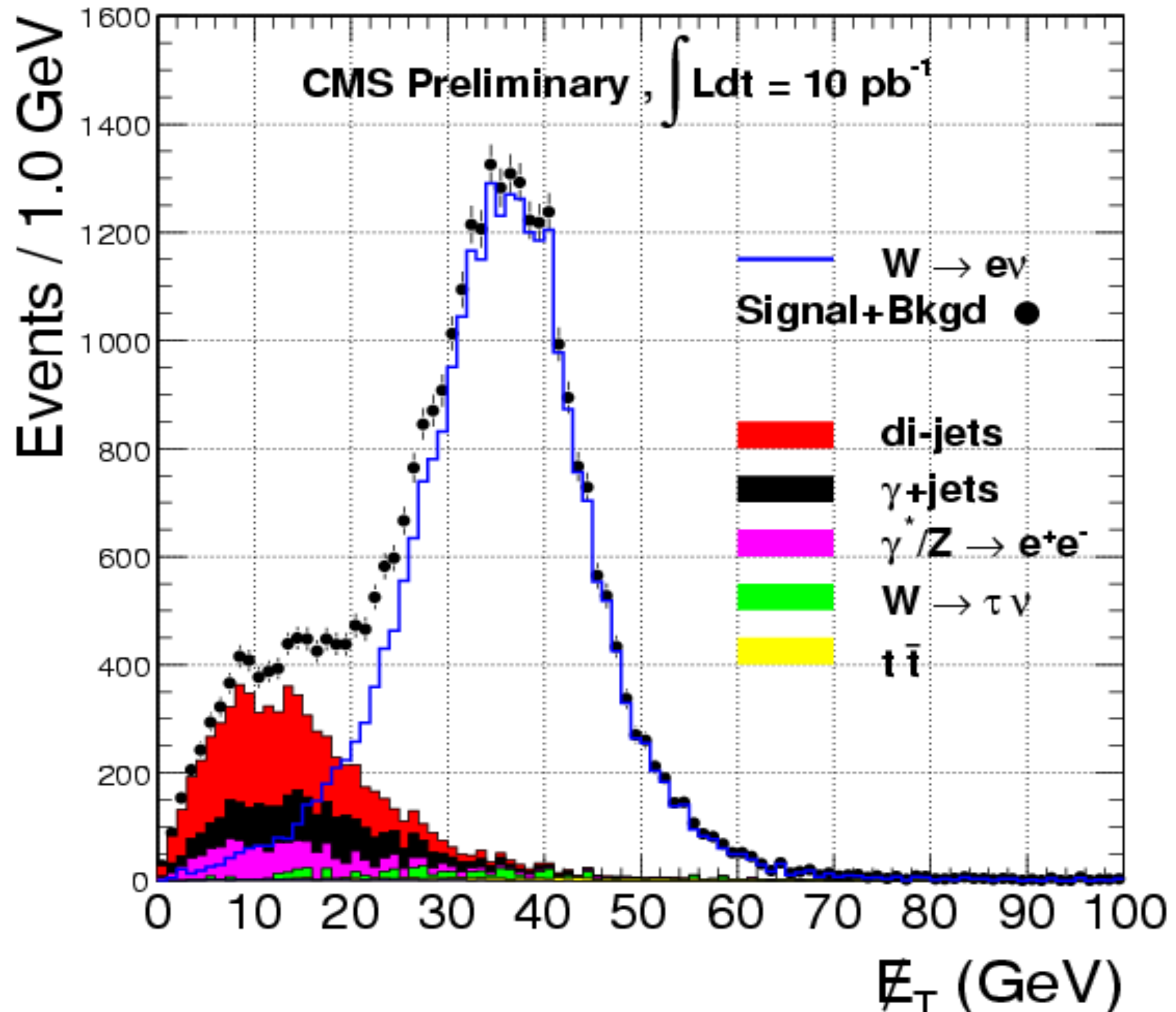
Best bias & resolution obtained after correction

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

MET in W→eν events

$W \rightarrow e^{\pm}\nu$

- Single Isolated electron HLT
- A high E_T electron (E_T>30 GeV) within |η|<2.5
- Isolated: no tracks with P_T>1.5 GeV in a cone of ΔR<0.6 around the electron.
- Electron Id: H/E, Δη, Δφ, $\sigma_{\eta\eta}$
- Reject events with a 2nd electron having E_T>20 GeV.

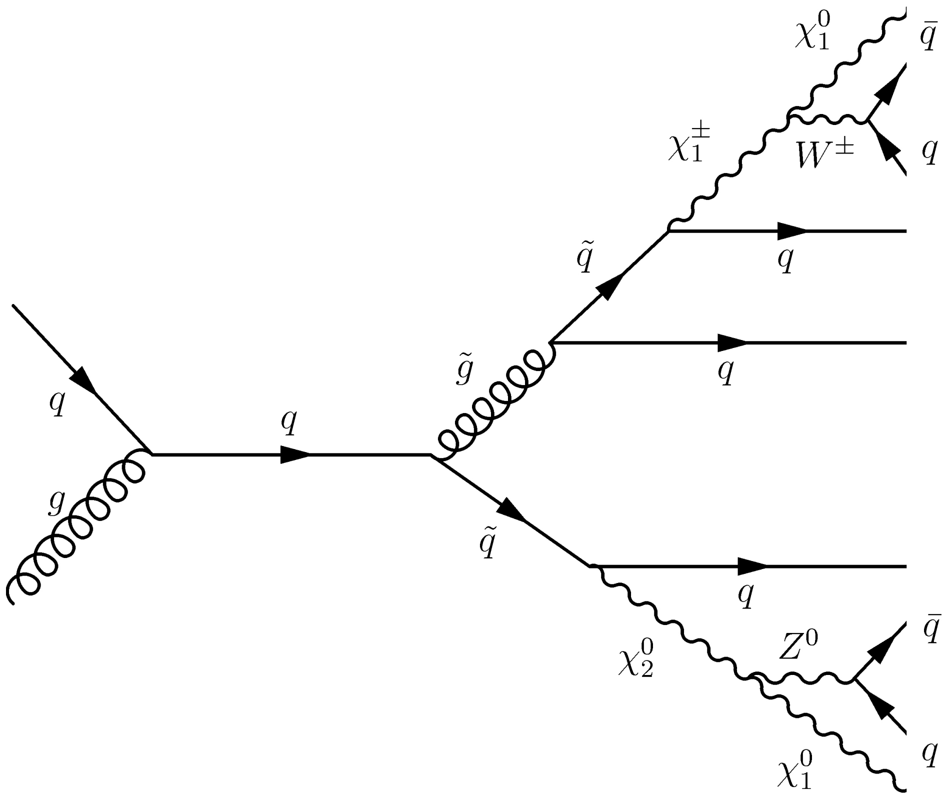


✓ MET shows clear separation of signal from Background

✓ QCD is the major background and methods to estimate it from data are developed, while EWK background estimation is based on MC

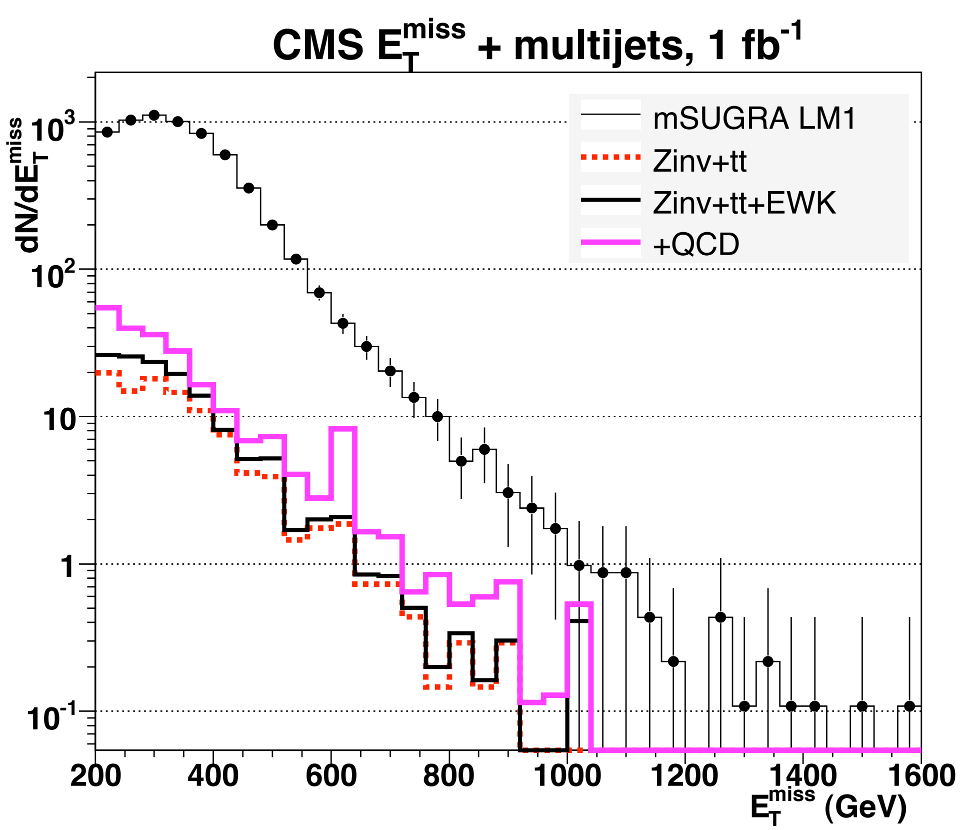
✓Assuming cross sections at 14 TeV and 10pb^{-1} of ∫Ldt we expect: ~28K W→eν events and ~ 6K QCD events

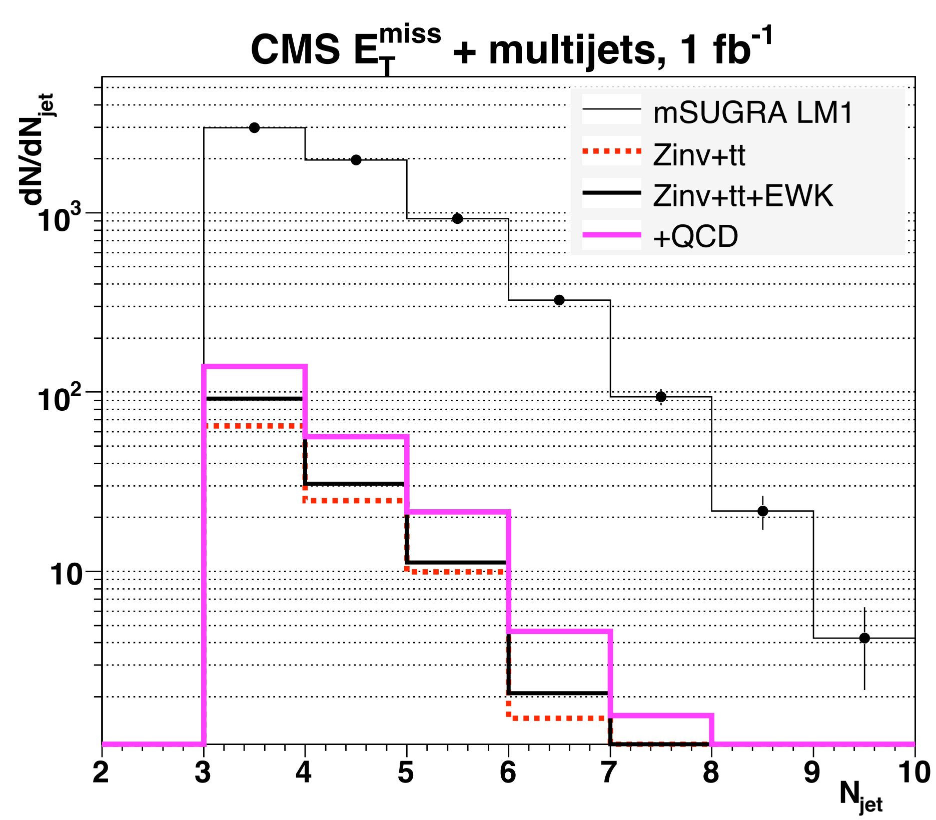
Jets & MET in SUSY events



Signature:

- Cascade decay of primarily produced SUSY particles
- R-Parity conserving models --->> LSP ---> MET
- Many jets, jet-pair mass comparable with W or Z





- lepton veto
- MET > 200 GeV
- P_T of 1_{st} jet > 180 GeV
- 2_{nd} jet > 110 GeV
- 3_{rd} jet > 30 GeV
- HT > 500 GeV
- Further MET clean-up and QCD rejection cuts are applied

Jets/MET from other objects

- Most of the results that I presented are being updated
- CMS explores excellent tracker measurement also for jets and MET
  - Only Calorimeter/Track-only based Jets/MET is presented
  - Many new results with a lot of improvement in resolutions coming soon
  - Jets and MET using ParticleFlow objects
  - Corrections on Jets (JetPlusTrack) and MET (tcMET) using tracks

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 using different/combined detectors are well under study: Tracks-only; Particle-Flow Objects; Jets corrected precisely measured tracks

- 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 collision data will be crucial to understand both objects and their calibrations