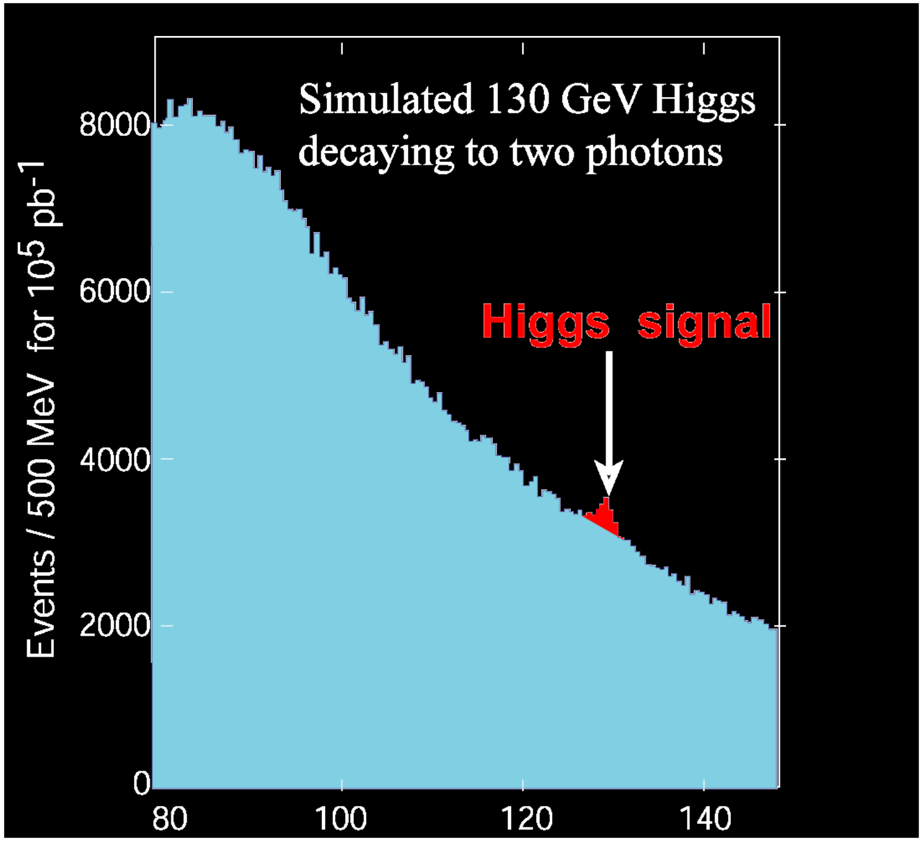
Calorimetry Lecture 3: Using Calorimeter Information



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CERN/Fermilab summer school

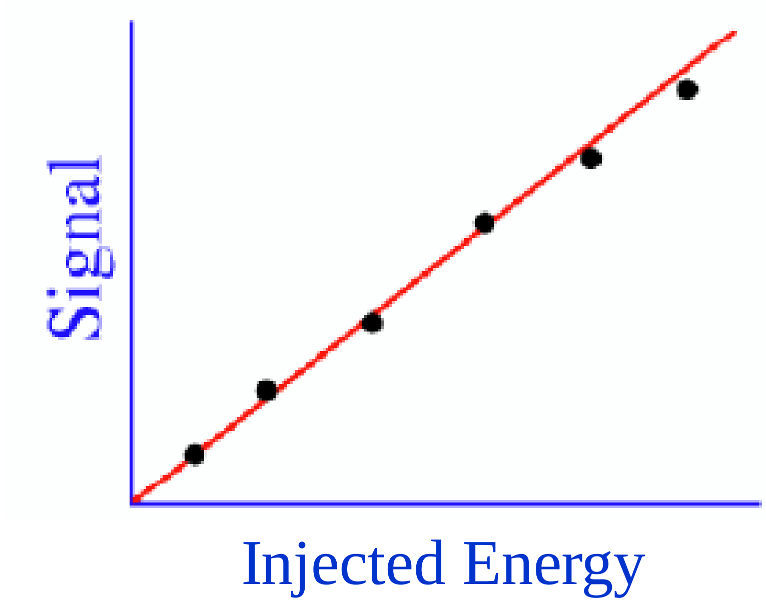
August 19, 2010

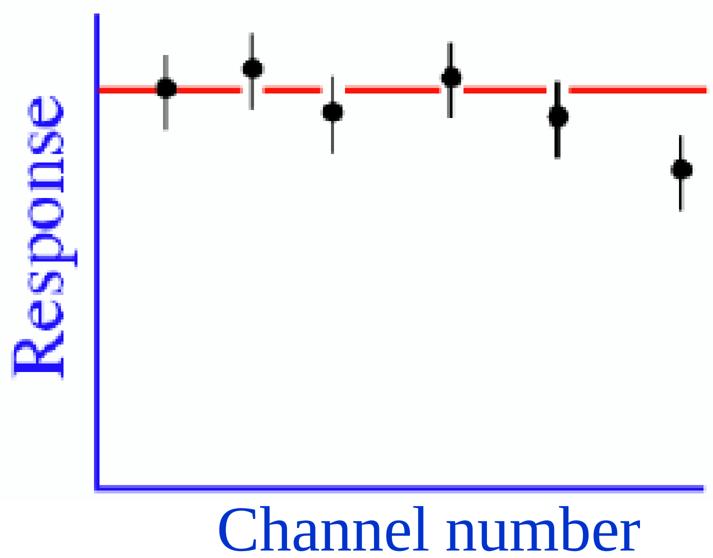
Thanks to Beate Heinemann, Chris Tully, Joanna Weng, ICHEP speakers!

Topics in Lecture 3

- Using calorimeter information
  - Calibration
  - Complementarity of tracking and calorimetry
- Reconstruction of jets
  - Algorithms
  - Jet Energy Corrections

Calibration and Linearity





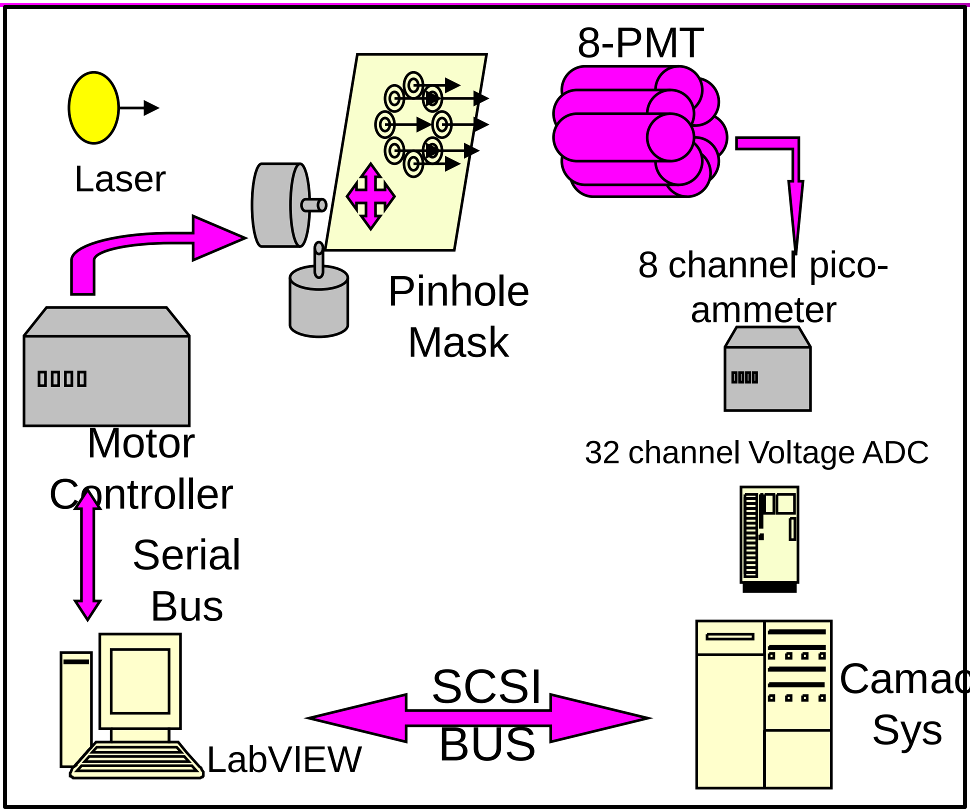
- Goal : uniform and known response to a given calorimeter signal
- For example, signal (charge) from detector is in pC, digitized to ADC counts
  - want linear response
  - channel-to-channel differences : leakage, upstream material, electronics
- Calibrations:
  - Relative calibration normalizes the response between all channels
  - Absolute calibration translates it to energy units (from ADC counts)
- How-to : testbeam, electronics calibration, in-situ, simulation

To get to physics, first must calibrate

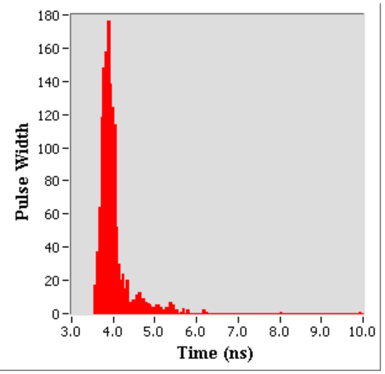
- Component calibration
  - For example, all PMT's are tested standalone
- Testbeam – operate detector (or part of) in a known-energy, known-species beam
  - In addition to R&D for new detectors, provide a testbench for the final modules of the calorimeter
- In-situ calibration
  - Pulse detector with known energy, measure response
  - Cosmic muons, single particles
- Physics object calibration
  - "tag and probe", dijet balance, photon+jet balance, W in top events

Component testing and calibration

- Example – PMT's for CMS HCAL (HF)
  - Test station – dark box, laser input
  - Individual testing, relative calibration
  - PMT's characterized, data put into database for later calibration input:
    - Double-pulse linearity,
    - Gain vs HV
    - Single photoelectron spectrum
    - X-Y scan (spatial uniformity)
    - Lifetime, pulse width, rise time
    - Transit time and spread
    - Anode dark current
    - Relative gain coupled with cathode sensitivity
    - Pulse linearity
    - Quality control decision
- All (or as many as possible) components of detector are calibrated long before they are integrated into detector

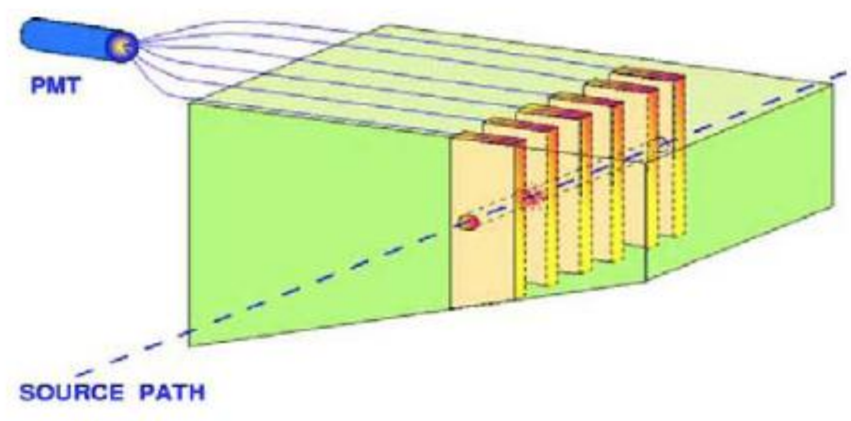


Pulse width for 1550 PMT's

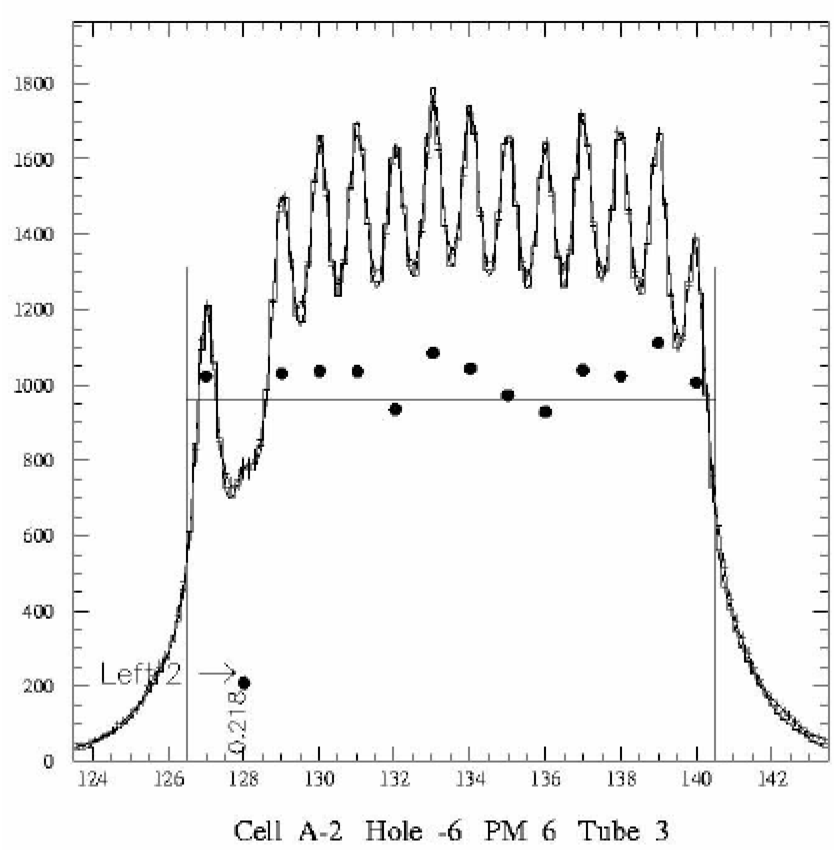


In-situ Detector/Electronics Calibration

- Example: inject known-energy pulse (eg from radioactive source or laser), then normalize readout of all channels
- Example: Atlas and CMS -- similar methods:



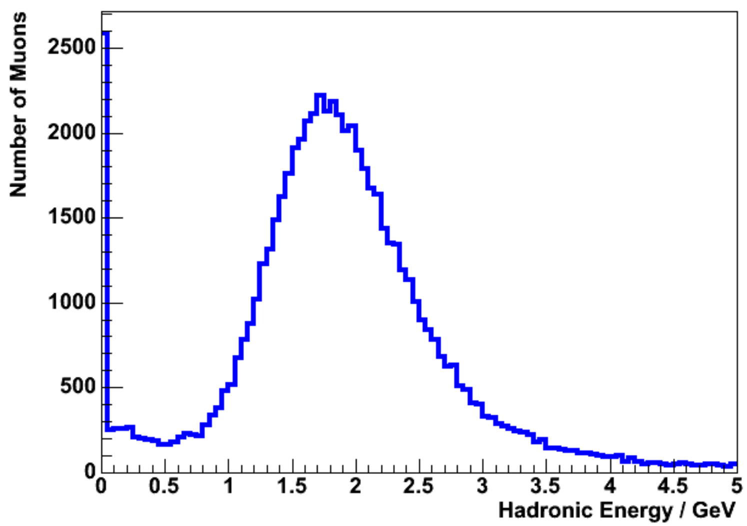
Atlas Source Path



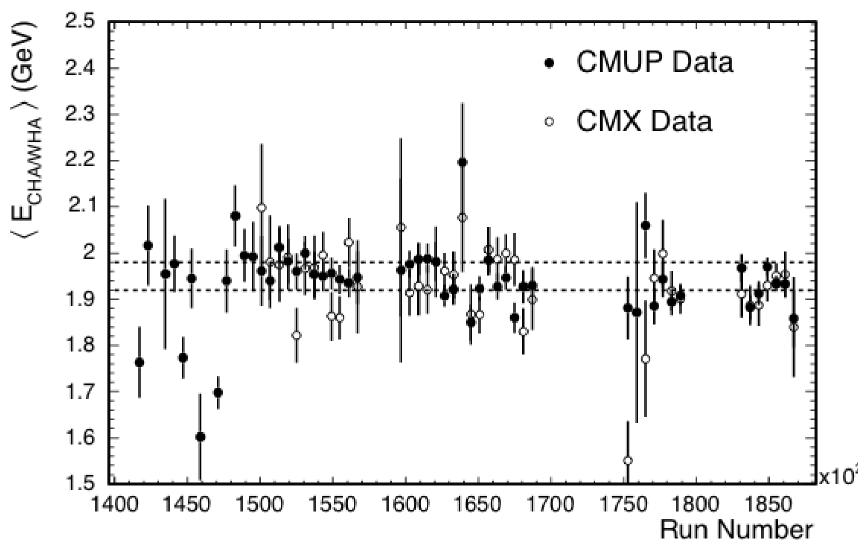
Response by location

Calibration with Muons

- Use muons from cosmic rays, testbeam, or physics events
  - ➔ Will give MIP response in calorimeter cell
  - ➔ Equalize channel-to-channel response

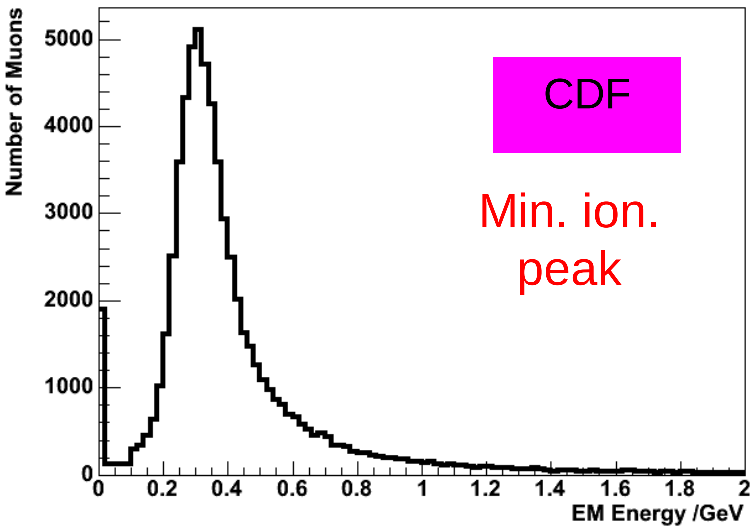


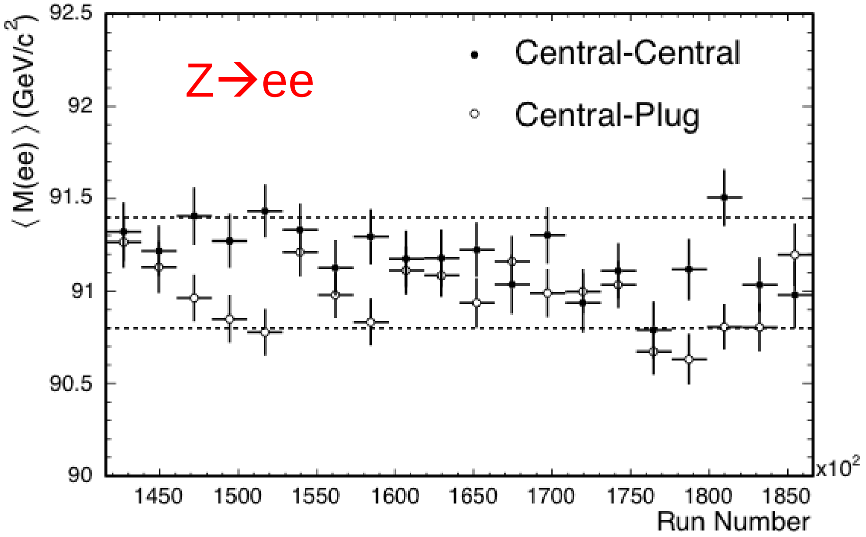
- CDF:
  - select muons from J/ψ and W
  - peak in HAD calo: ≈2 GeV (in CDF)
- Check time stability



In Situ Calorimeter Calibration: EM Energy

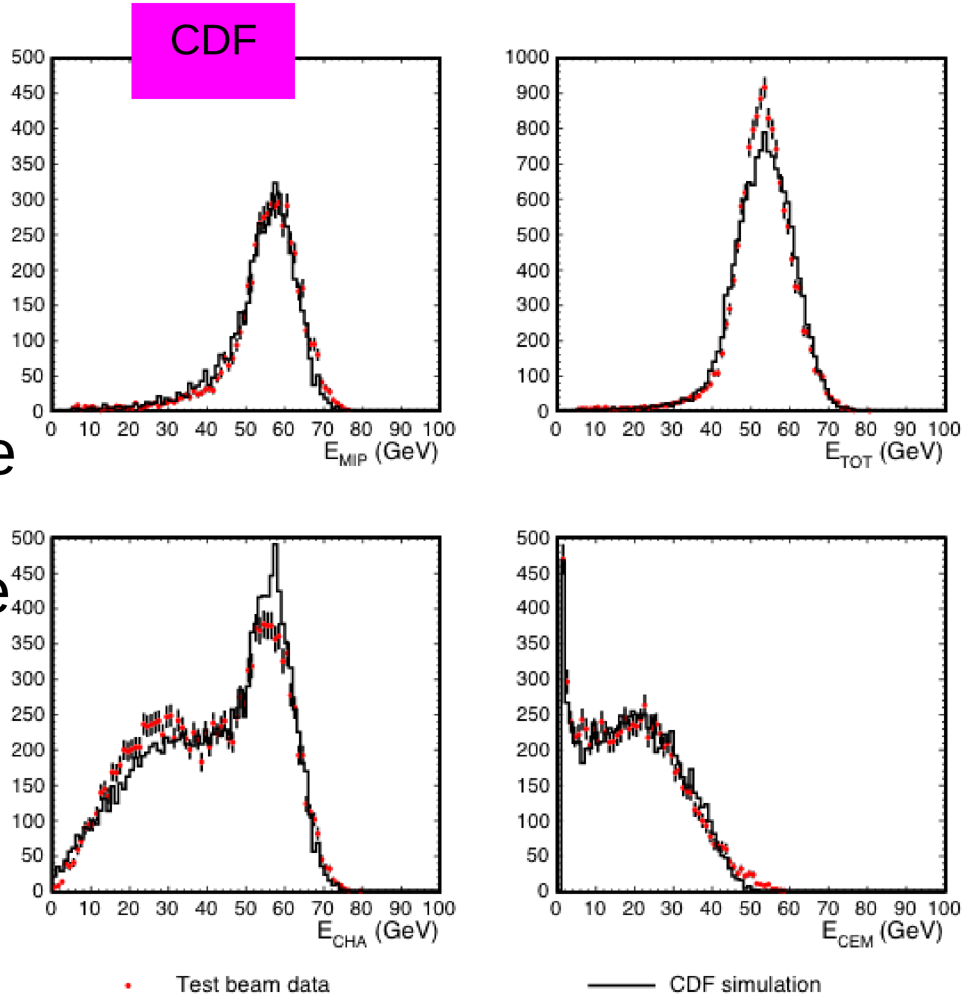
- MIP peak:
  - CDF → 300 MeV
- Z→ ee peak:
  - Set absolute EM scale in central and endcap
- E/p for electrons
  - After having calibrated p and material, see response in E



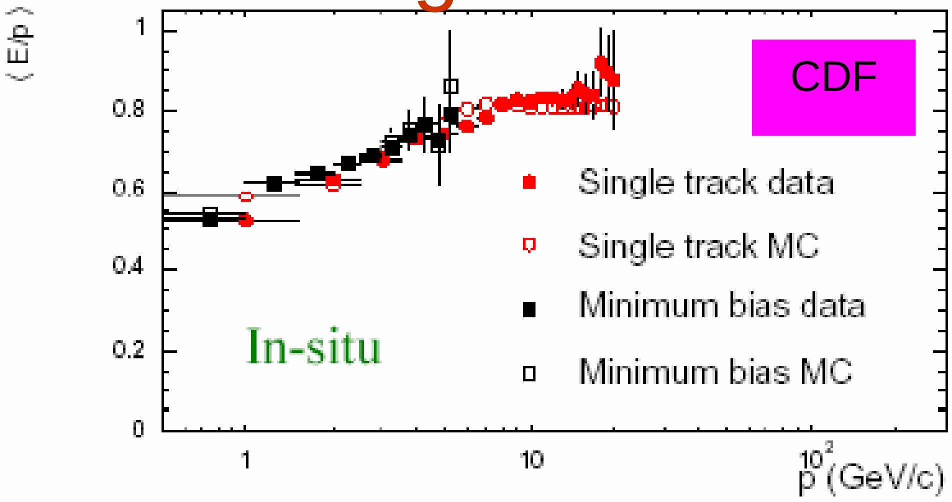


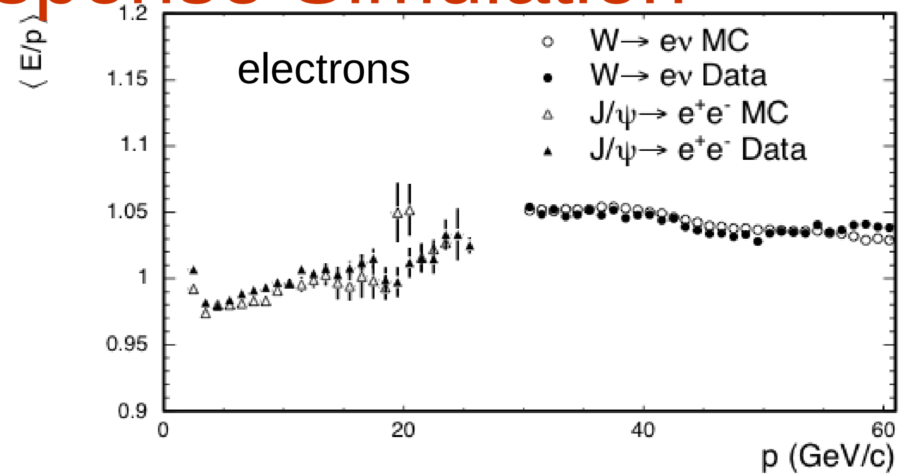
Single Particle Response Simulation

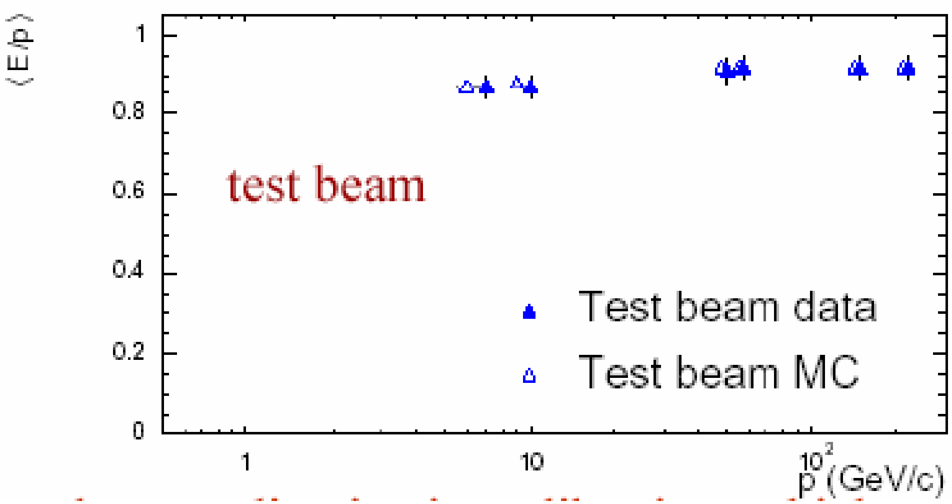
- Single particle response:
  - Measure with test beam
  - In situ:
    - Select "isolated" tracks and measure energy in tower behind them
  - Tune simulation to describe E/p distributions at each p (use π/p/K average mixture in MC)



Single Particle Response Simulation





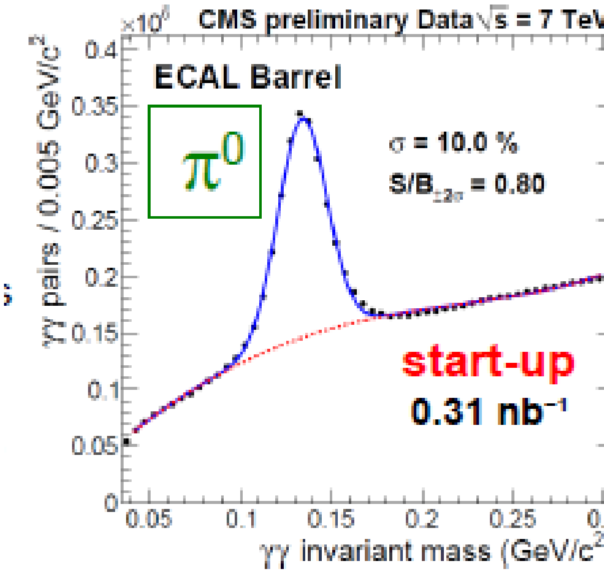


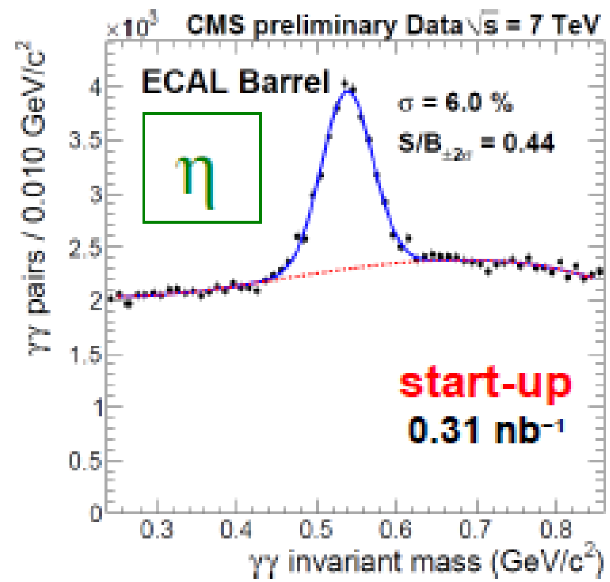
Typical jet composition:
- -60% charged particles
  - -10% protons
  - -90% pions
- -30% neutral pions (→γγ) (EM response)
- -10% other (neutrons,…)

- MC models
  - Hadron response at low p_T (in situ data) and high p_T (test beam data)
  - Electron response

CMS ECAL calibration

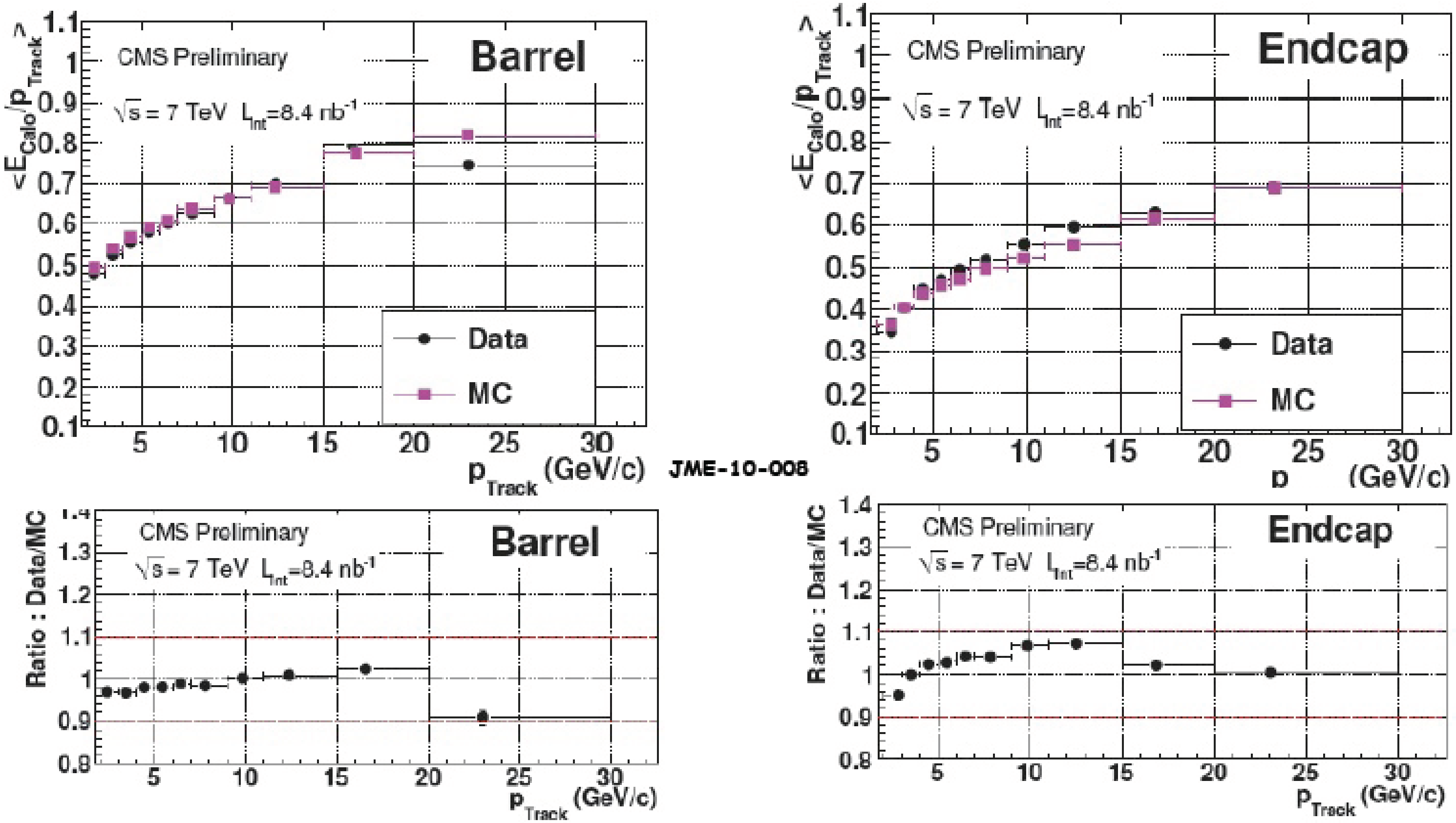
- Startup calibration based on 10 years of test beam and cosmic ray pre-calibration, π^0 calibration
- Precision of startup calibration
  - ECAL Barrel 0.5 – 2.2%
    - 1.2% in central region
  - ECAL Endcap 5%
  - Target with 10/pb: 0.5% EB, 1-2% in EE
- Calibration validated by observation of π^0 and $\eta \rightarrow \gamma\gamma$





Single-particle response in CMS

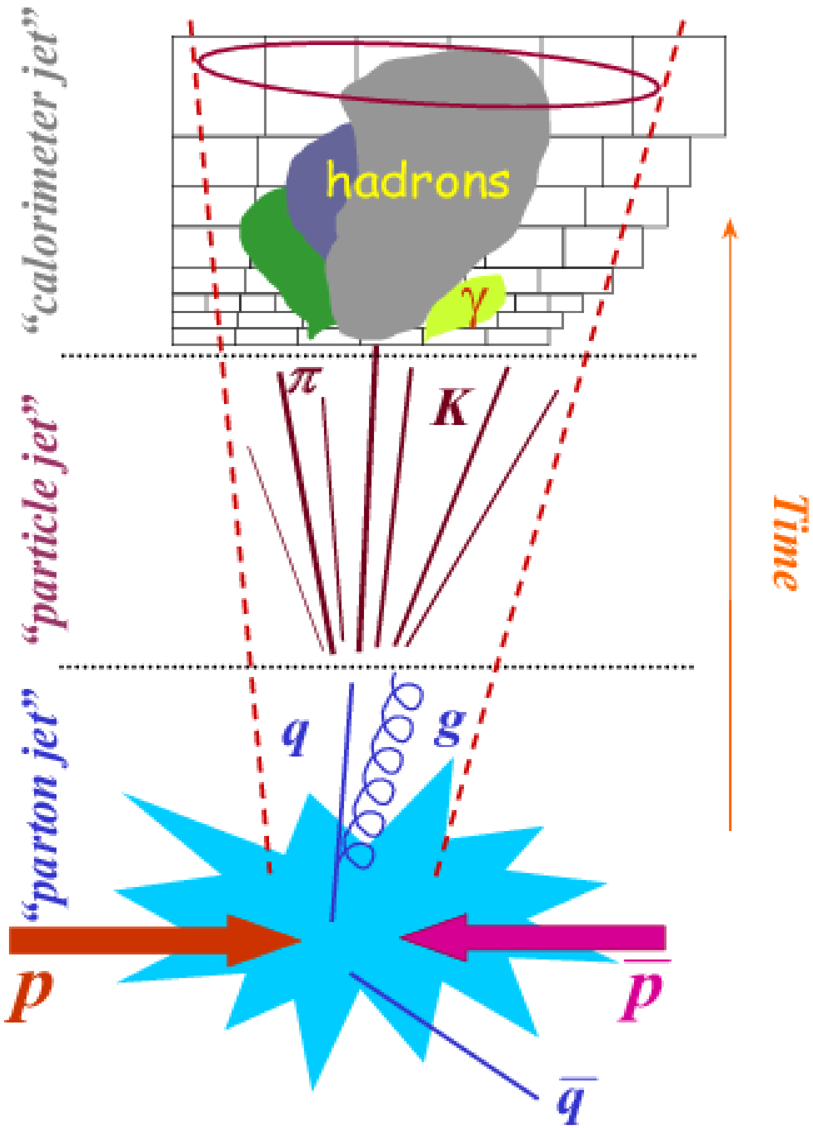
- Compare response of isolated tracks with low ECAL eneryg in MinBias events with single pions from Monte Carlo



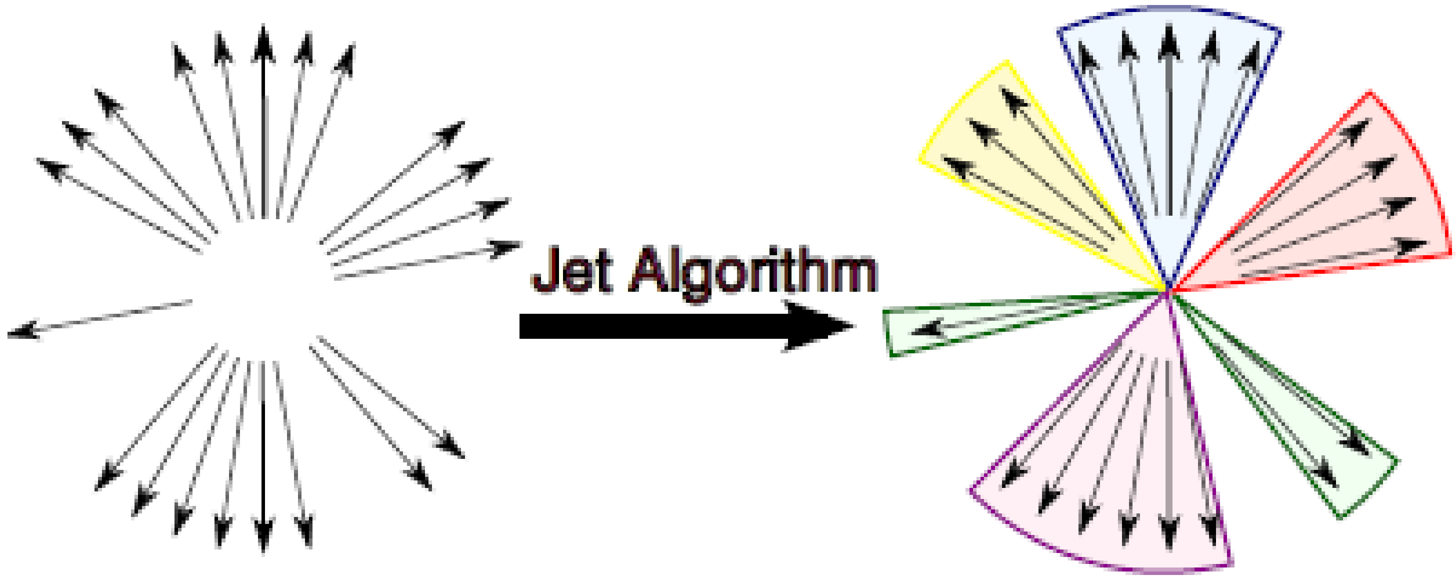
Mean response in Data and MC agree within 2-3% in barrel region
In endcap, simulation is lower than data (~4%)

Jets from Collisions

- QCD interactions → Jets
- Types of Jets
  - Parton level – quarks/gluons from initial collision
  - Hadron level – fragmentation, decay, hadronization produce particles
  - Experimental – what we see in the calorimeter, and how we interpret it
- Goal – take detector information, reconstruct parton level physics



Jet Algorithms

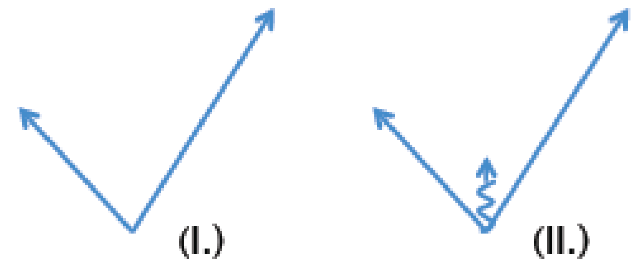


Graphics from Kerstin Perez, ISSP 2009

- Procedure to turn recorded detector info into jets
  - ➔ Or, looking at it from the other way, turn partons into jets
- Constraints:
  - ➔ Infrared and collinear safe (see next slide)
  - ➔ Invariant under boost (important for hadron colliders)
  - ➔ Independent of level (parton, hadron, calorimeter) and detector
  - ➔ Easy to implement and use (computer resources), calibrate

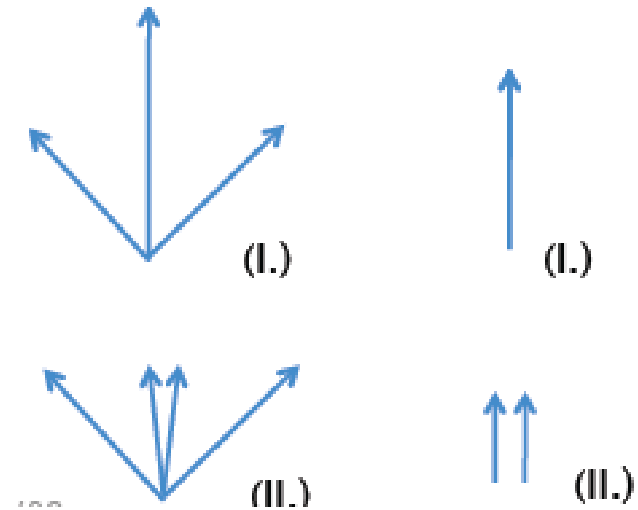
Technical terms

- Infrared safe – same jets even if one of the partons emits a soft gluon



These situations would have the same jets

- Collinear safe – same jets even if outgoing partons split



Graphics from Kerstin Perez, ISSP 2009

Jet Algorithms used at Hadron Colliders

- Choice of jet algorithms is an involved topic – theorists and experimentalists have been working together for years to find the perfect scheme
  - True to parton-level
  - True to experimental (detector) level
  - Taking into account detector effects, pileup, etc.
- There are many possible algorithms to choose from – we won't cover them all
  - Here are examples from CMS: Anti-kT, SISCone and kT jet algorithms:
    - Then, generator jets, calorimeter jets, calorimeter+track, and particle-flow jets for these jet algorithms

Cone Algorithms

- Cone (traditional)
  - clusters nearby in angular space
  - Problem : seeded – introduces bias especially with pileup
  - Problem : needs merging/overlap scheme, which every experiment implements differently
    - Difficult to compare, feedback to theorists
- If you don't seed the jets, takes N 2^N time to find jets among N particles ("unseeded")
  - unusable at hadron level (think of "simple" event with 100 particles…)
  - reduce to N^2 ln(N) time – SISCone algorithm

JADE→ Durham →kT

- kT
  - Clusters nearby in momentum space
  - Based on JADE or Durham algorithm -- exclusive iterative pairwise clustering scheme
    - JADE algorithm uses test variable yij , and a combination procedure.
    - Test if objects i and j should be combined according to whether yij < ycut.
    - Also, consider next pair to combine (smallest value of yij) .
    - Original JADE $y_{ij} = M^2_{ij}/Q^2$ where Q is the hard scale (i.e. the centre-of-mass in e+e− annihilation) and $M2_{ij} = 2E_iE_j(1 - \cos\theta_{ij})$, (invariant mass-squared)
    - Repeated until no objects can be combined further
  - Problem with JADE – not IR, collinear safe
  - Durham mod -- consists of replacing M^2_{ij} in test variable by k^2_{Tij},
    - $k^2_{Tij} = 2\min\{E_i,E_j\}^2(1 - \cos\theta_{ij})$ -- relative transverse momentum-squared of i and j.

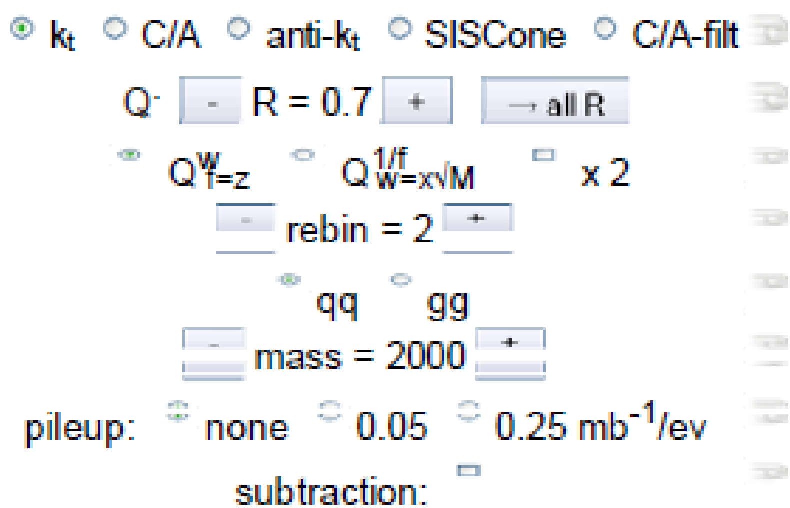
kT and anti-kT

- Advantages of kT
  - Jet identification is unique – no merge/split stage
- Disadvantage of kT
  - Resulting jets are more amorphous, energy calibration difficult (subtraction for UE?), and analysis can be very computer intensive (time grows like N^3)
- Anti-kT
  - Like kT, only uses 1/pT as the distance parameter
  - Improves performance with pileup

Testing Jet Definitions

- See this very nice webpage http://www.lpthe.jussieu.fr/~salam/jet-quality/
  - By M. Cacciari, J. Rojo, G.P. Salam, and G. Soyez arXiv:0810.1304
  - You choose two jet algorithms, set the parameters, and it compares dijet mass distributions with your conditions

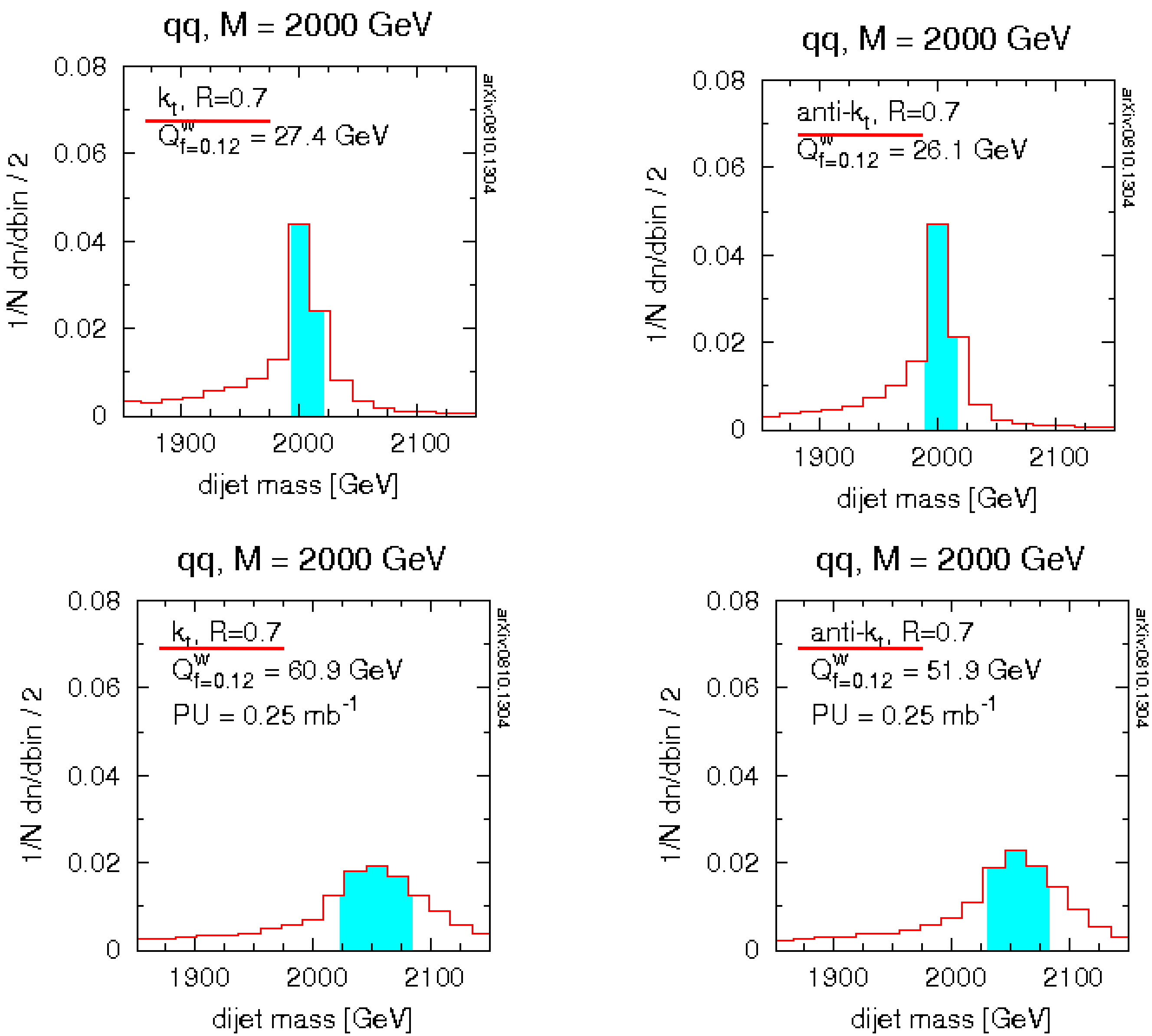
Your input – twice for comparison



Example: compare kT to anti-kT

Without Pileup

With pileup



More on jet algorithms

- Algorithms often designed from parton point of view
- From the detector point of view
  - What information goes into a jet?
    - Calorimeter, tracking
    - “Energy flow”
  - Jet corrections, systematics
  - Integration into experimental software.

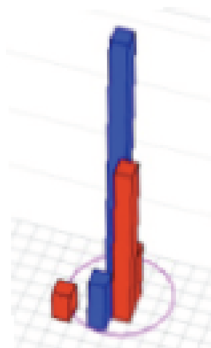
For Example, CMS Jets

- CMS has chosen the anti-kT algorithm, with R=0.5, as the default. Then, 4 types of jets reconstructed:

Calorimeter Jets

Jets clustered from ECAL and HCAL deposits (Calo Towers)
Accordingly:

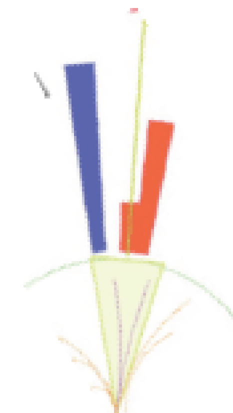
Calo MET



Jet-Plus-Track Jets (JPT)

Subtract average calorimeter response from CaloJet and replace it with the track measurement
Accordingly:

Tc MET



Particle Flow Jets (PF)

Cluster Particle Flow objects: Unique list of calibrated particles "a la Generator Level"
Accordingly:

PF MET

F. Beaudette
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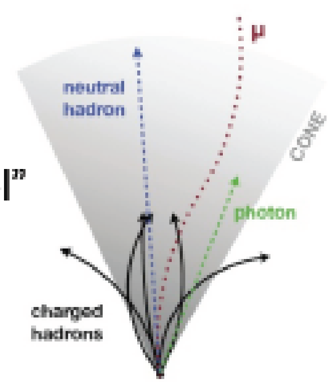


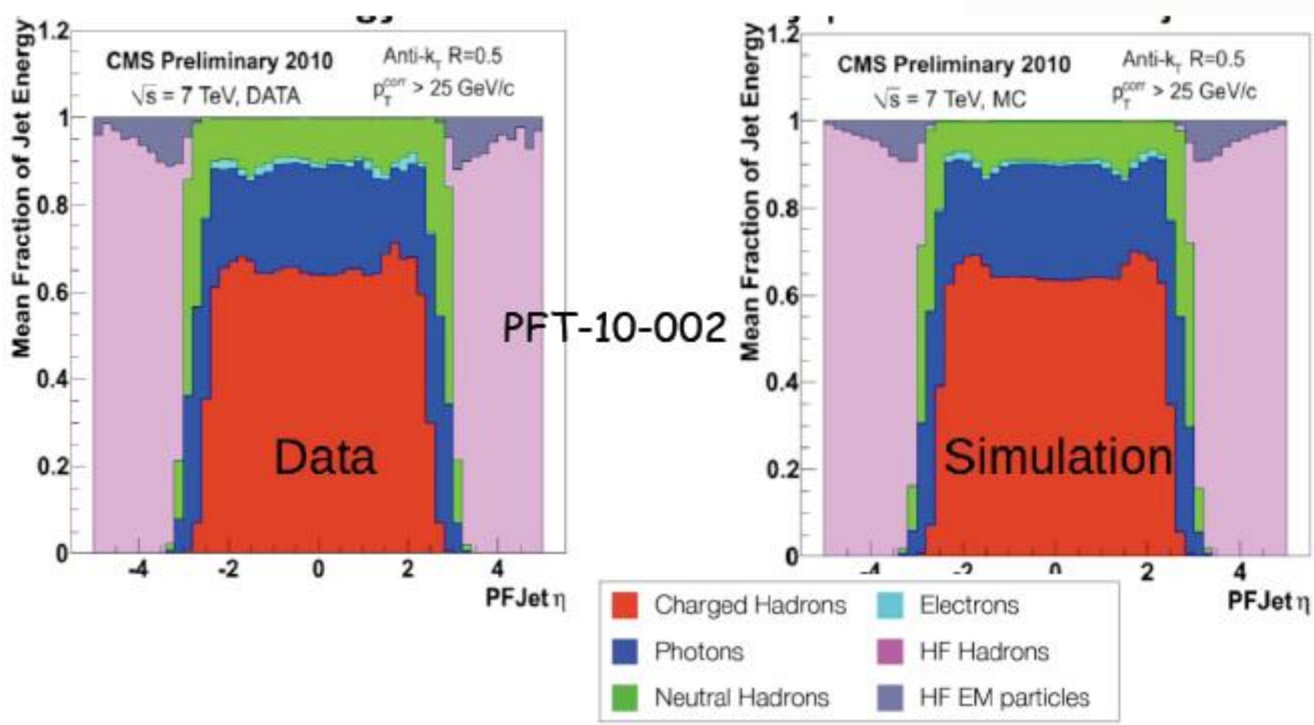
Track Jets

Reconstructed from tracks of charged particles, independent from calorimetric jet measurements

From Joanna Weng

Particle Flow Jets

- Combines info from all subdetectors to produce particles
  - Charged hadrons – from tracks
  - Photons, neutral hadrons from ECAL, HCAL energy
    - Clusters with no tracks
  - Neutral particle overlapping with charged particles – subtract charged pt from cluster, remaining is neutral particle
- jets from resulting particles – charged hadrons and γ are 90% of jet energy

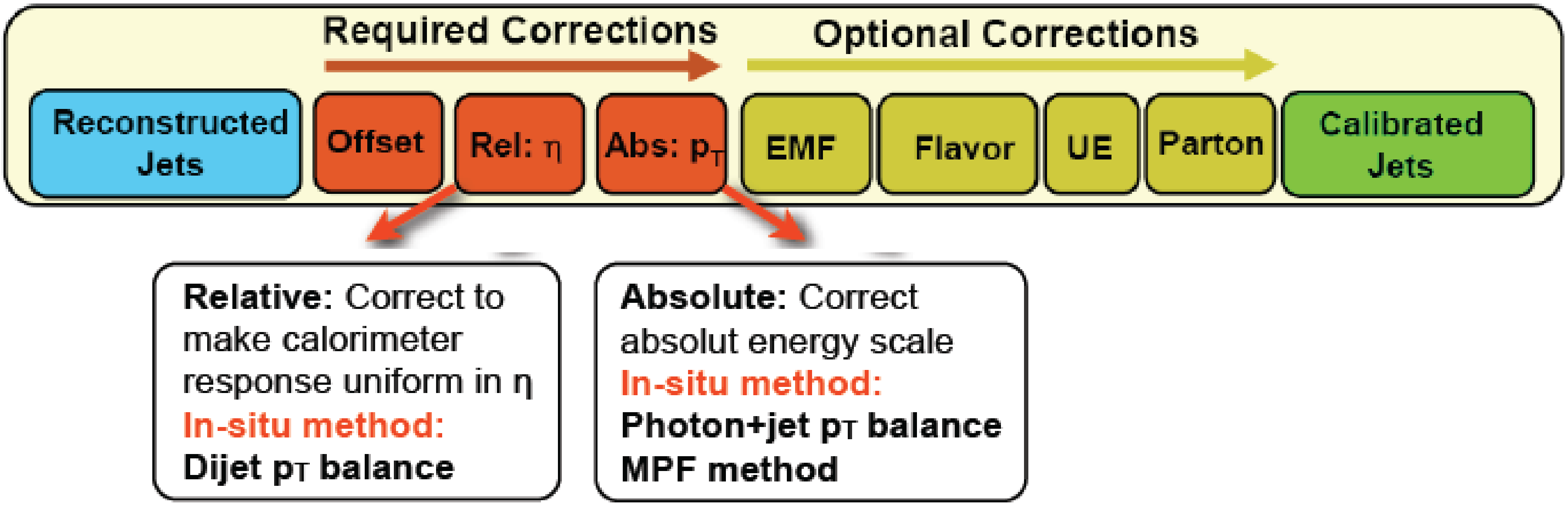


Jet Energy Scale

- Determine the energy of the partons produced in the hard scattering process
- Corrections needed for:
  - Detector effects:
    - Non-linearity of calorimeter
    - Response to hadrons
    - Poorly-instrumented or non-functional regions
  - Physics effects:
    - Initial and final state radiation
    - Hadronization
    - Underlying event
    - Parton flavor
- Need corrections for data and MC, validate in both

Jet Corrections

- Use CMS as an example, also show others
  - ➔ CMS uses factorized approach

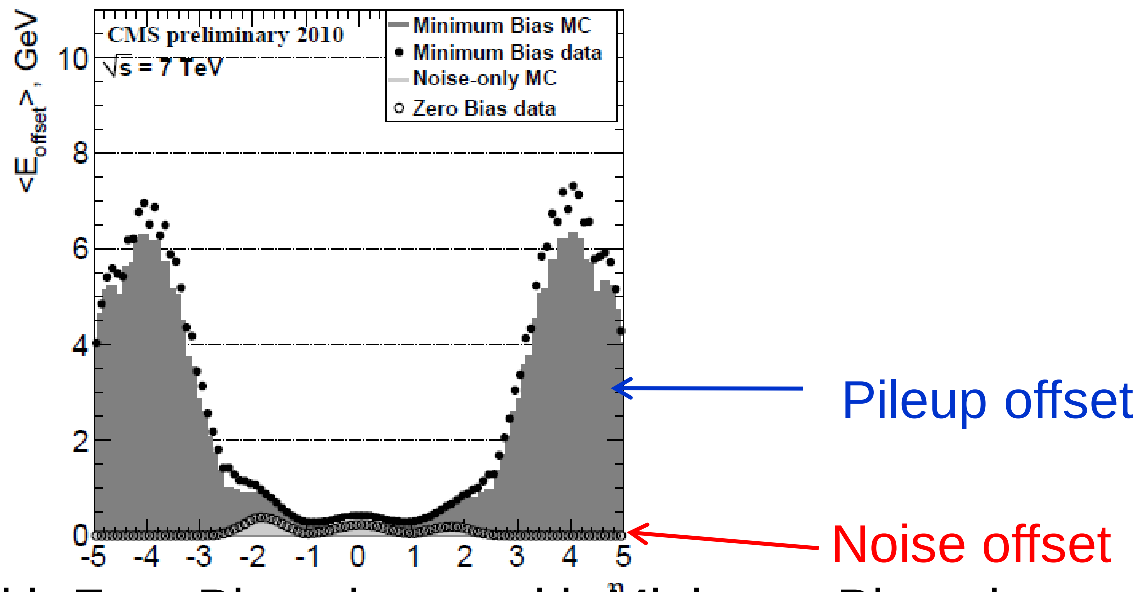


- apply Jet Corrections as :

$$E_{corrected} = (E_{uncorrected} - E_{offset}) \times C_{rel}(\eta, p''_T) \times C_{abs}(p'_T)$$

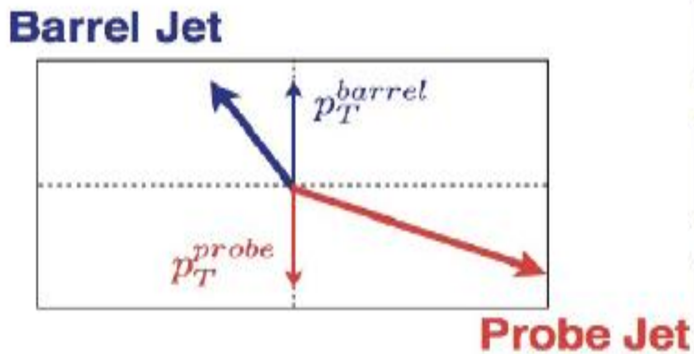
Where p''_T is the jet pT corrected for offset, and p'_T is corrected for offset and η dependence (Relative corr).

Offset correction



- Measure noise with Zero Bias trigger, with Minimum Bias trigger vetoed (MinBias requires coincidence in Beam Scintillating counters, indicating pp interaction)
- Measure pileup – select MinBias events in early data (most events 0,1 int.)
- E_{offset} -- average calorimeter energy summed in a cone of radius R=0.5 at a given η -- Offset from noise is below 400 MeV in energy
- Offset from one pile-up event: Up to 7 GeV in energy
- Probability of pile-up in 2010 data typically ~50%
- correction is small -- not yet being applied on CMS jets

Relative Correction from Dijet pT balance



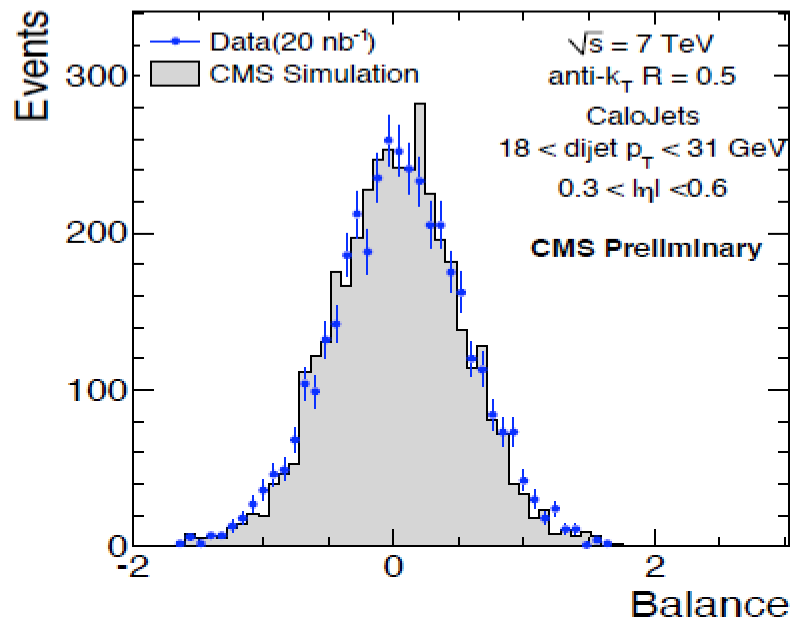
$$p_T^{dijet} = \frac{p_T^{probe} + p_T^{barrel}}{2}$$

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

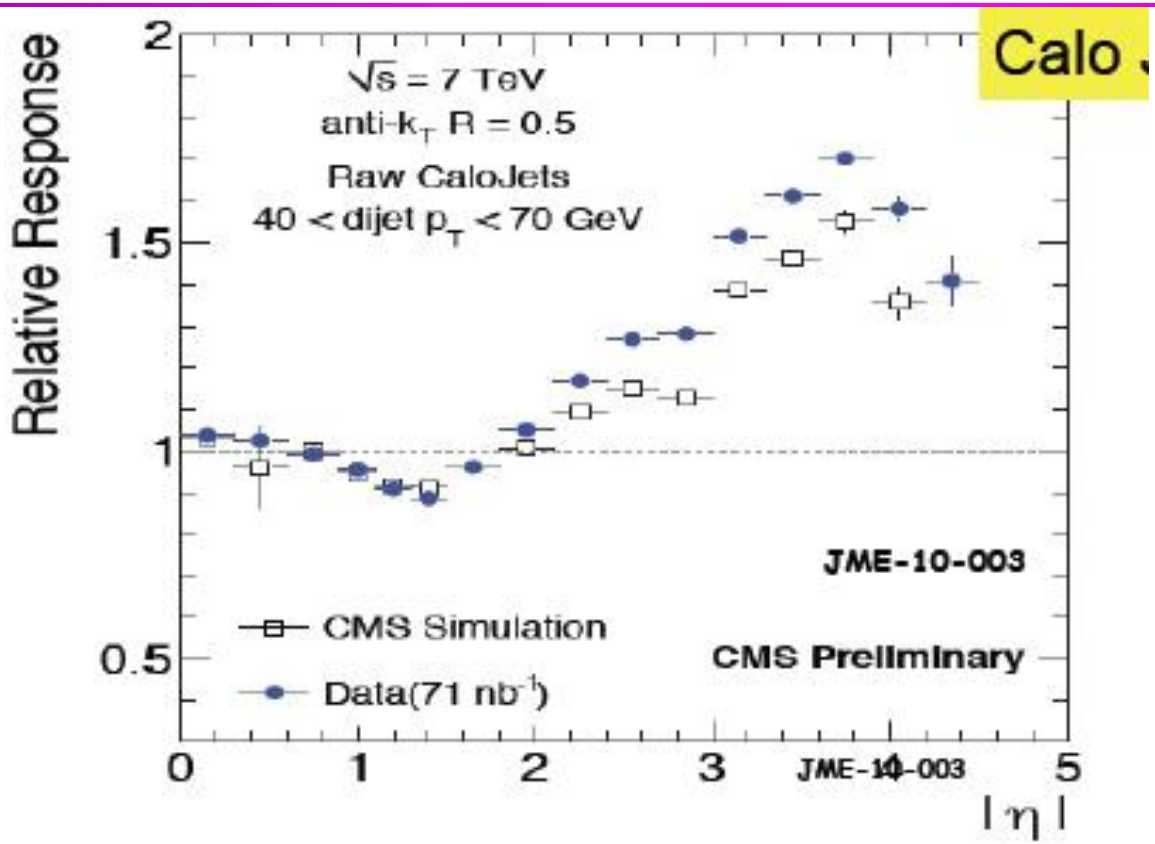
$$r = \frac{2 + \langle B \rangle}{2 - \langle B \rangle}$$

- Require at least 2 jets, one in central region (Tag)
- $\Delta\phi > 2.7$
- Veto 3rd jet ($pT^{3rd}/pT^{dijet} < 0.2$)

- Measure Balance variable B in bins of pT(dijet) and η
- <B> in each bin is used to construct r
  - ➔ Measure of relative response

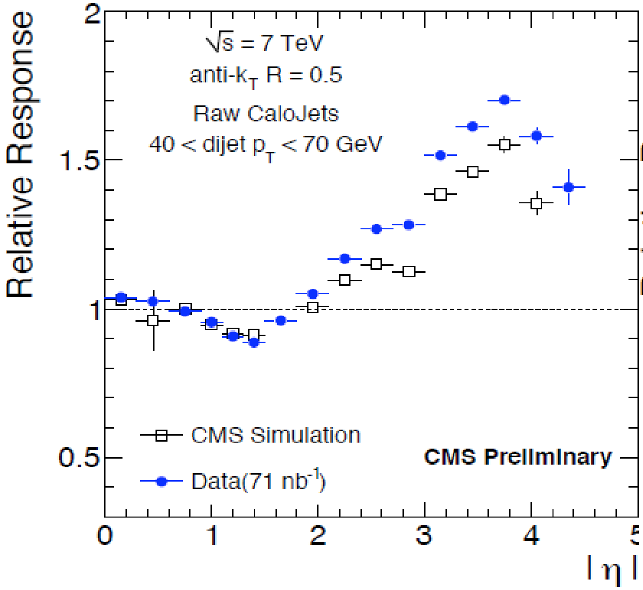


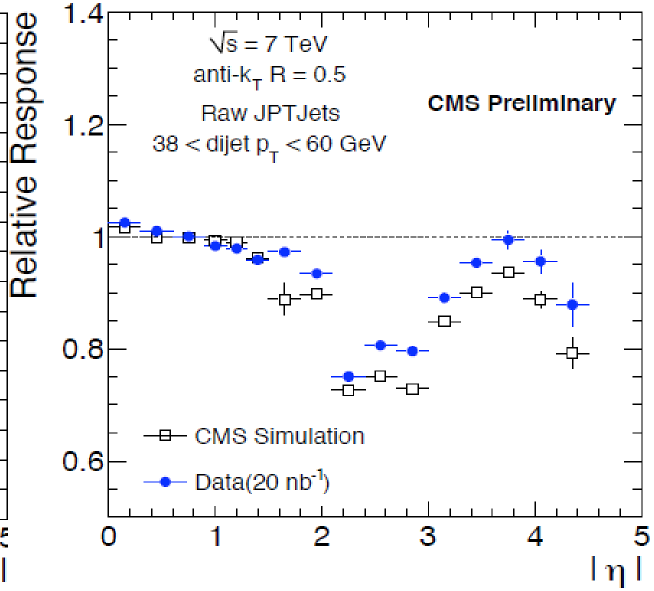
Relative response in η

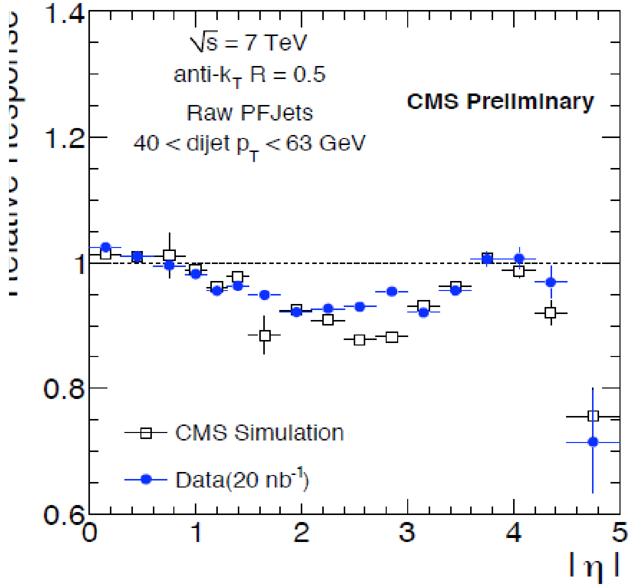


- Same dijet balance is applied to simulation
- Good agreement Data/MC for $|\eta|<2$
- Calorimeter transition
  - Barrel to endcap at $|\eta|=1.3$
  - Endcap to forward at $|\eta|=3$

Compare different CMS jets

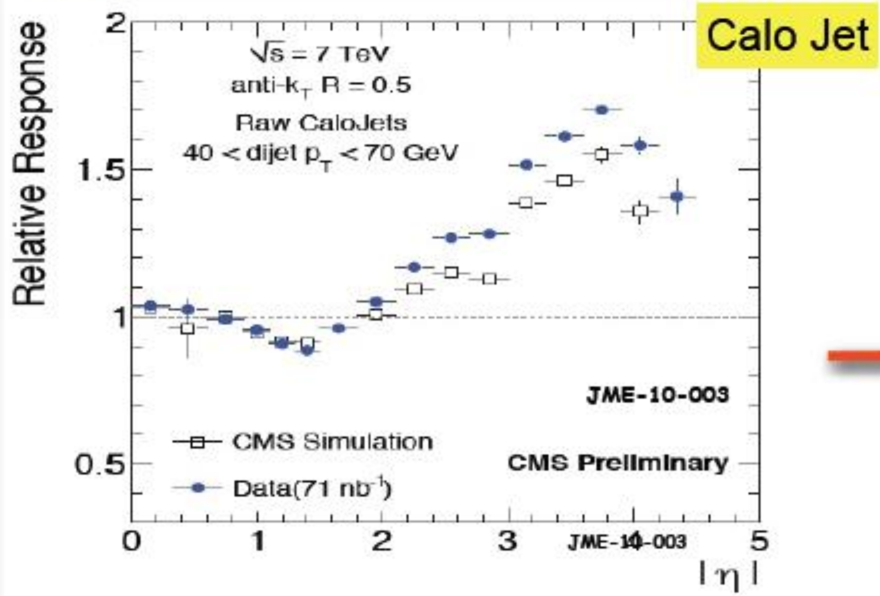




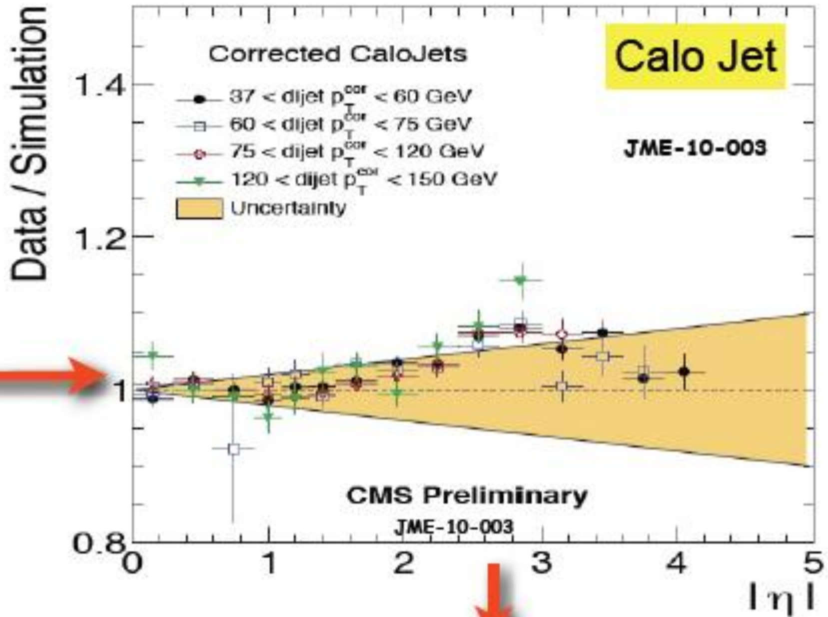


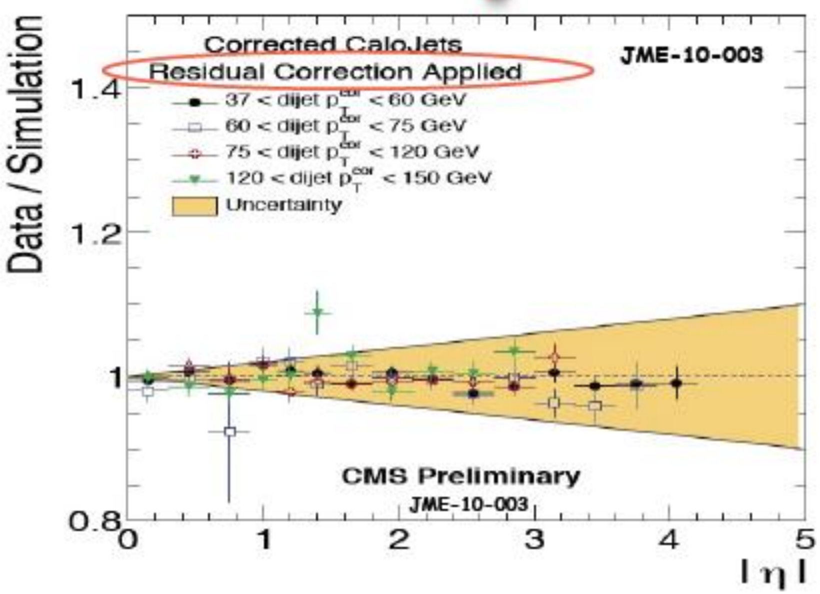
- JPT and PF jets – rely on tracking with calorimetry – response reflects tracking detector coverage as well as calorimeter
  - ➔ Steep falloff in track efficiency and resolution for $|\eta|>2$, none for $|\eta|>2.5$

Relative JEC : Data/MC



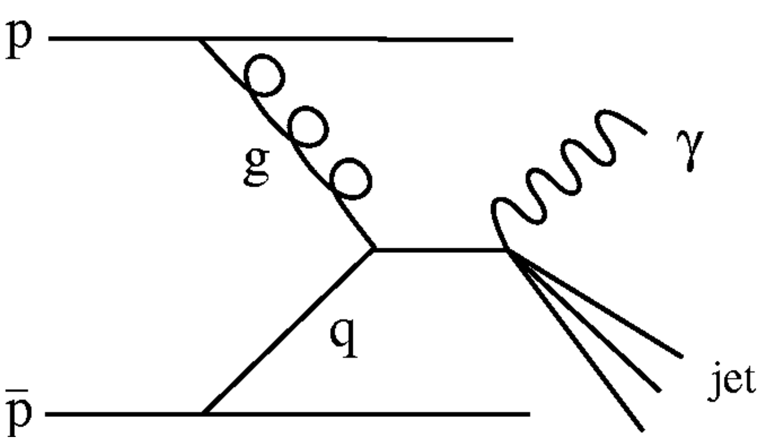
- Good agreement up to |η| =2
- Relative response in data ~10% higher compared to simulation for |η| > 2





=> Data/MC close to unity after the residual correction
=> Data/MC deviations are covered by conservative η-dependent systematic uncertainty of **±2% x |η|**

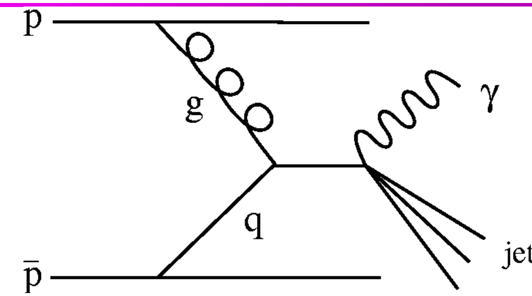
Absolute Jet Energy Correction at CMS

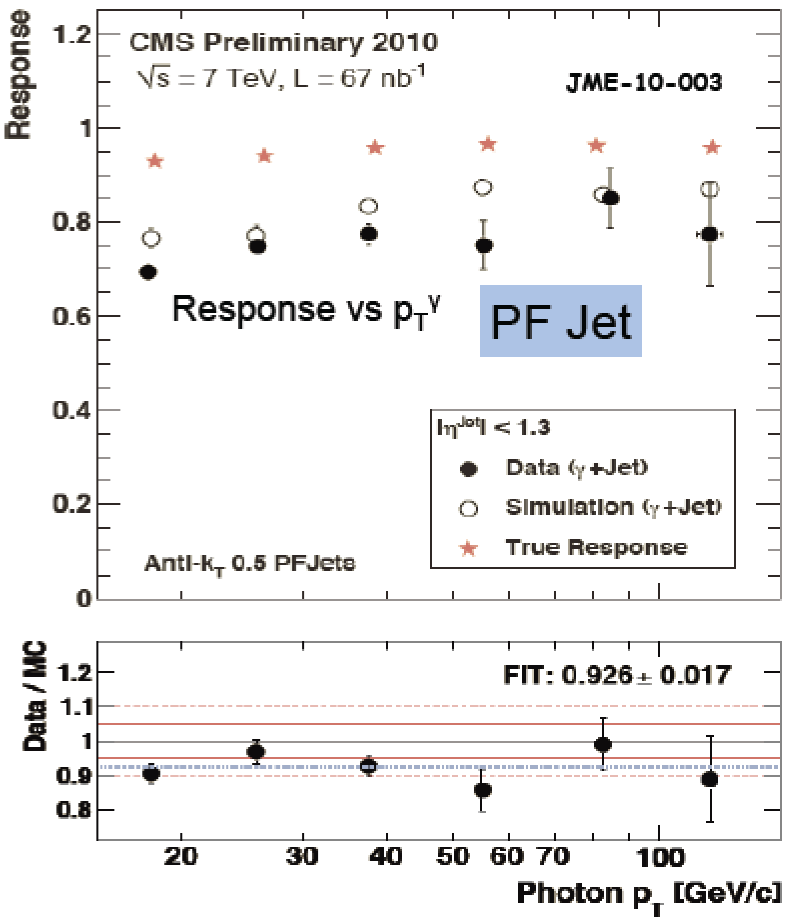


- Goal – want calorimeter energy response to a particle jet to be 1 and independent of pT
  - ➔ Absolute Jet Energy Correction
- When combined with offset and relative corrections, this is all that is needed for most analyses
- Use photon+jet events
  - ➔ γ+jet balance
  - ➔ MPF
- Start with isolated photon, pt>15 GeV, in barrel region (|η|<1.3), + 1 barrel jet

Absolute Correction from Photon + jet

- pT balance in back-to-back γ+jet events
  - ➔ γ is the reference, test response p_T/p_T^{γ}





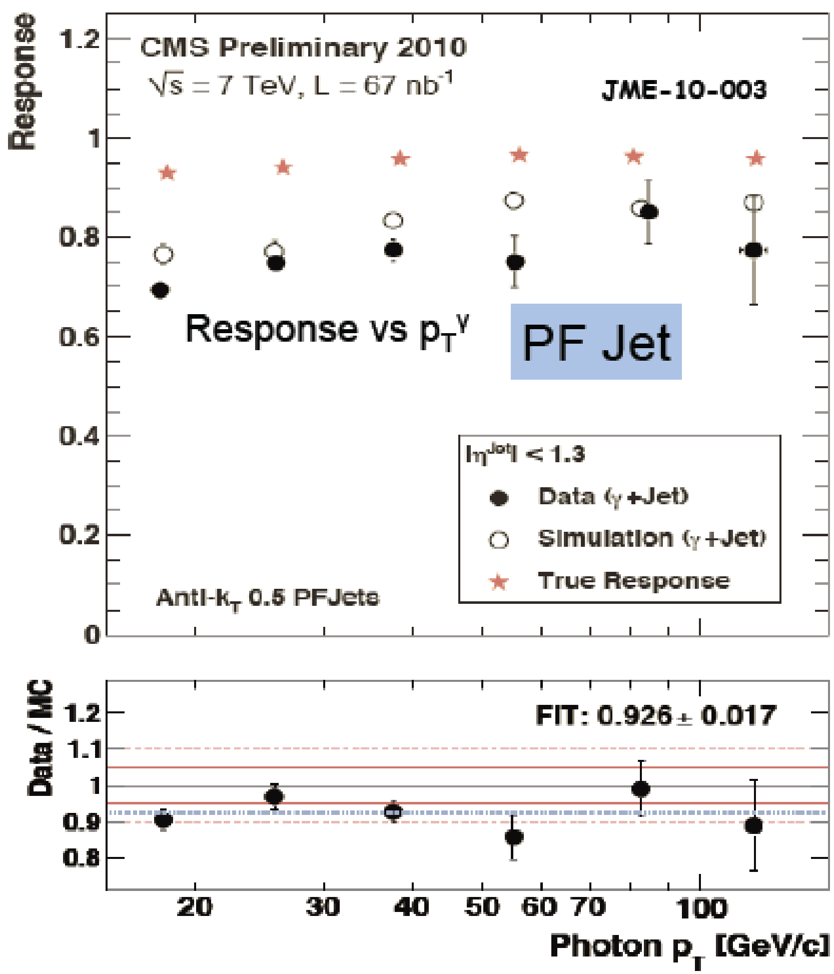
- Compare data, simulation to true from MC
- Bias due to soft veto on 2nd jet
- D0 – developed MPF method
- Missing ET Projection Fraction – uses MET to measure the balance, less sensitive to QCD radiation

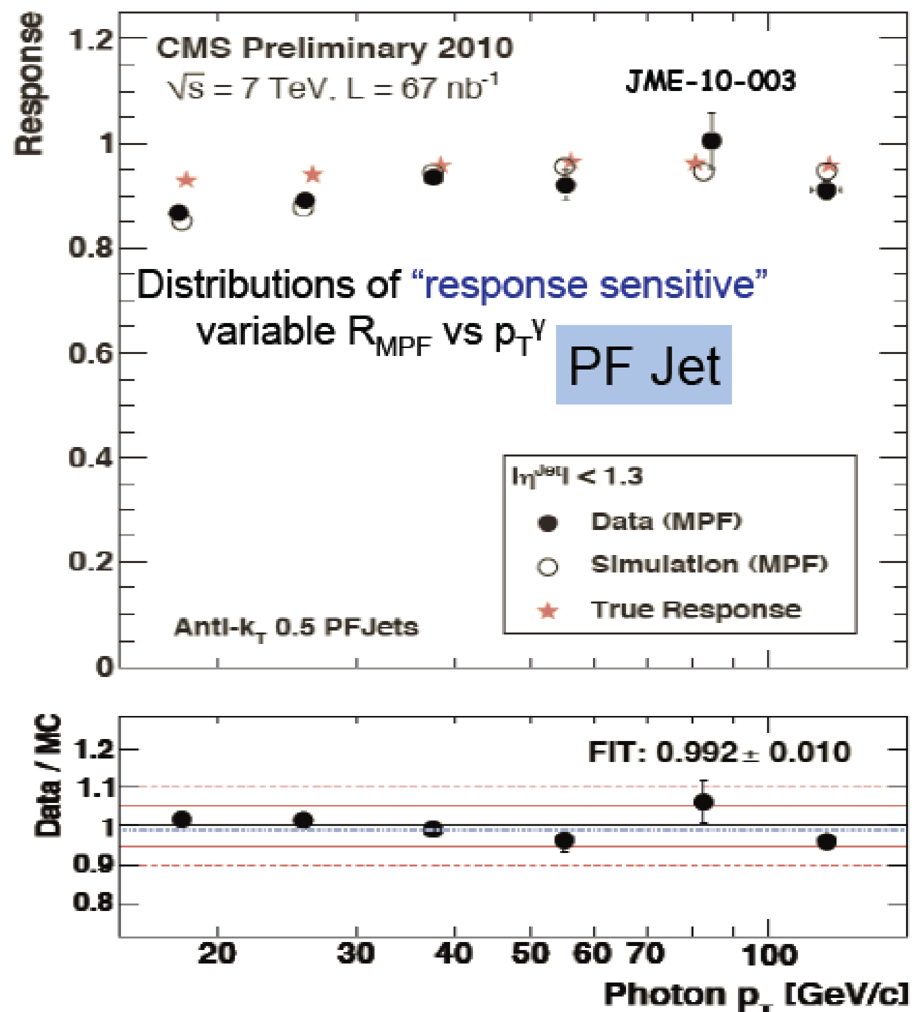
Jet Response from MPF in γ+jet

- Basics of MPF (Missing Momentum Fraction; developed at D0)
  - Ideally: $$\vec{p}_{\rm T}^{\,\gamma} + \vec{p}_{\rm T}^{\,\rm recoil} = \vec{0}$$
  - Add in the detector: $$R_\gamma \vec{p}_{\rm T}^{\,\gamma} + R_{\rm recoil} \vec{p}_{\rm T}^{\,\rm recoil} = -\vec{E}_{\rm T}^{\rm miss}$$
  - Solving: $$R_{\rm recoil}/R_\gamma = 1 + \frac{\vec{E}_{\rm T}^{\rm miss} \cdot \vec{p}_{\rm T}^{\,\gamma}}{|\vec{p}_{\rm T}^{\,\gamma}|^2} \equiv R_{\rm MPF}$$
    - → R_{MPF} is assigned as the response of the recoil jet
- Advantage of MPF: Low sensitivity to extra radiation
  - → Smaller error bars: Widths of distributions are narrower → fewer fluctuations from the impact of extra radiation
  - → Smaller bias wrt MC-truth than p_T^{jet}/p_T^{γ} for current very loose cuts on extra radiation
  - → Helps to fully exploit the accuracy of PF method
- MPF method demonstrates the accuracy of JES for different types of jets more clearly than γ-jet balancing method does

MPF at CMS

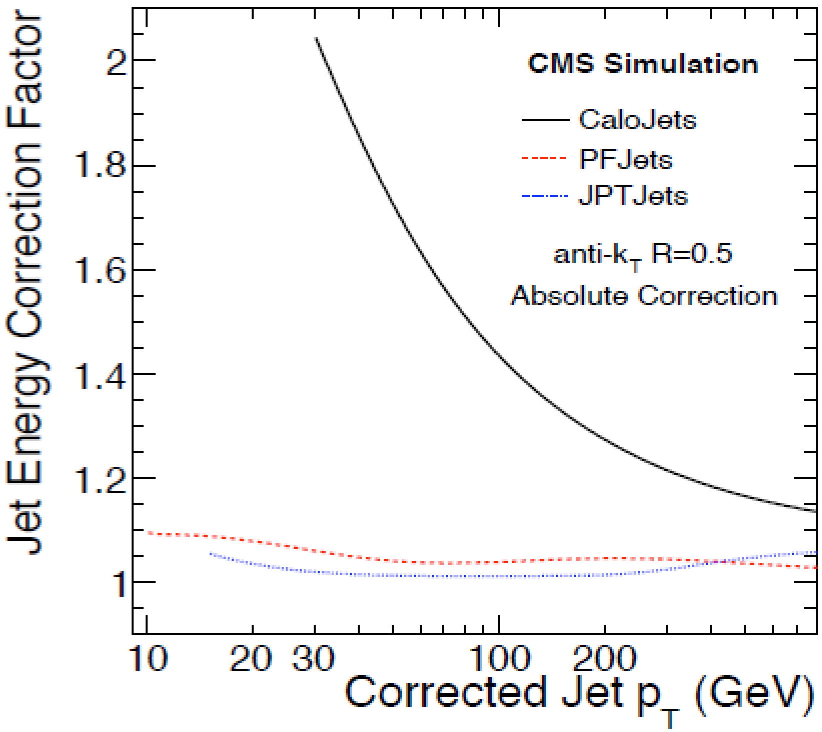
γ+jet → MPF





Absolute Correction Factors

- Absolute jet energy correction factors C_{abs} derived from simulation for CaloJets, PF Jets, JPT jets, at 7 TeV, as a function of corrected jet pT

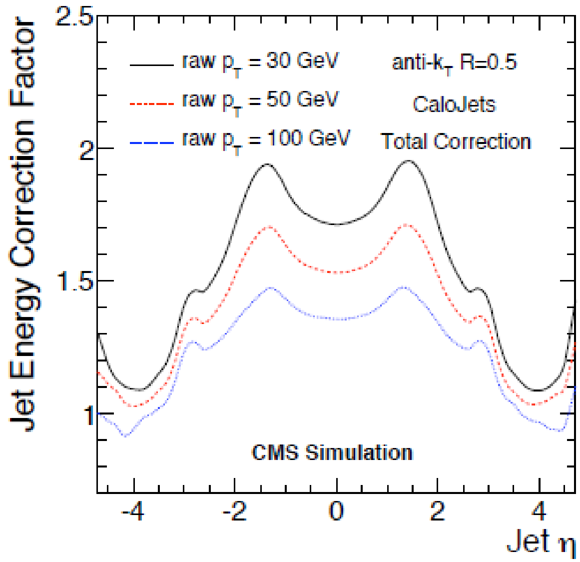


Note large correction factors at low pT for CaloJets – due to non-compensation of CMS calorimeters

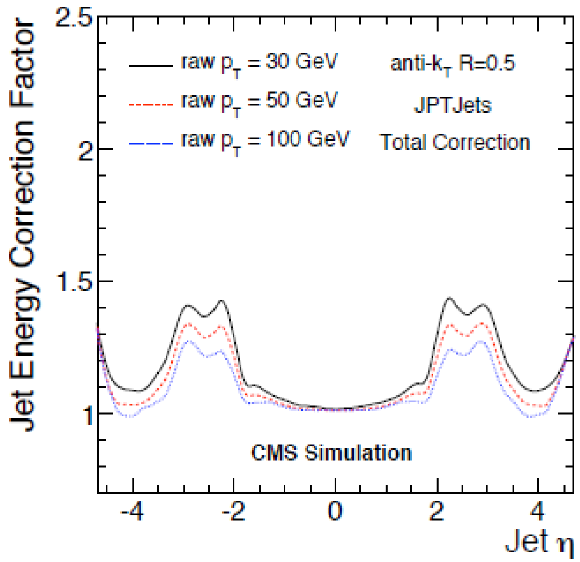
Correcting Simulated Jets

- Derive corrections for Monte Carlo jets – match reconstructed jets to MC-generator level jets
- In CMS, first three levels are put together in one correction (offset, relative, absolute)

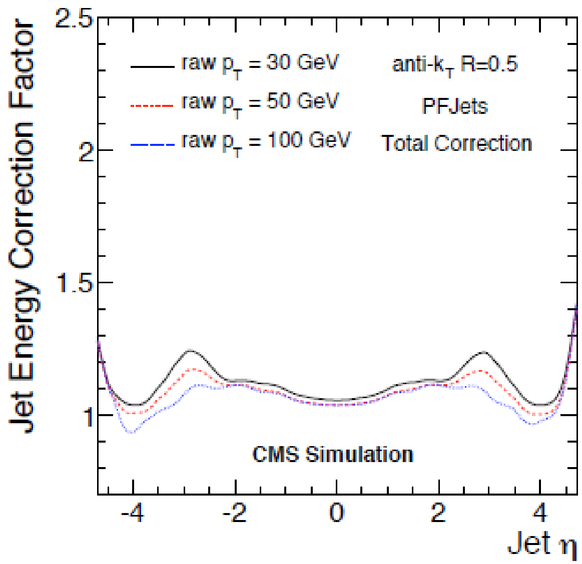
Calojets



JPT Jets



PF Jets

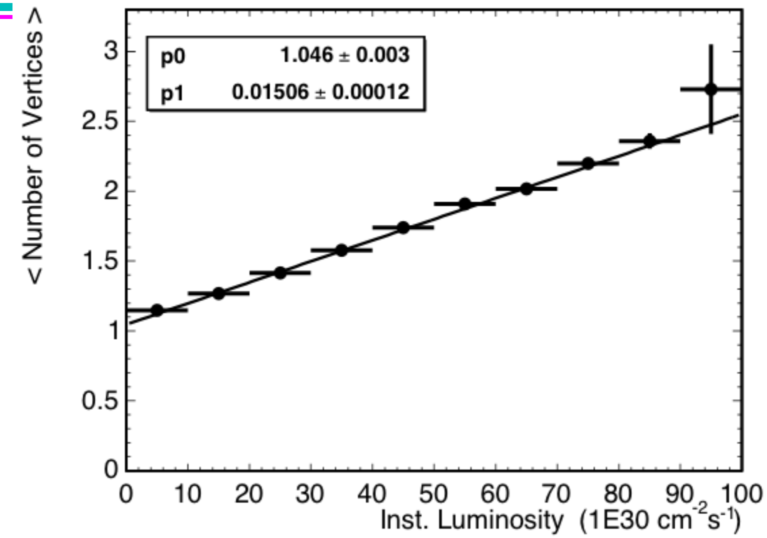


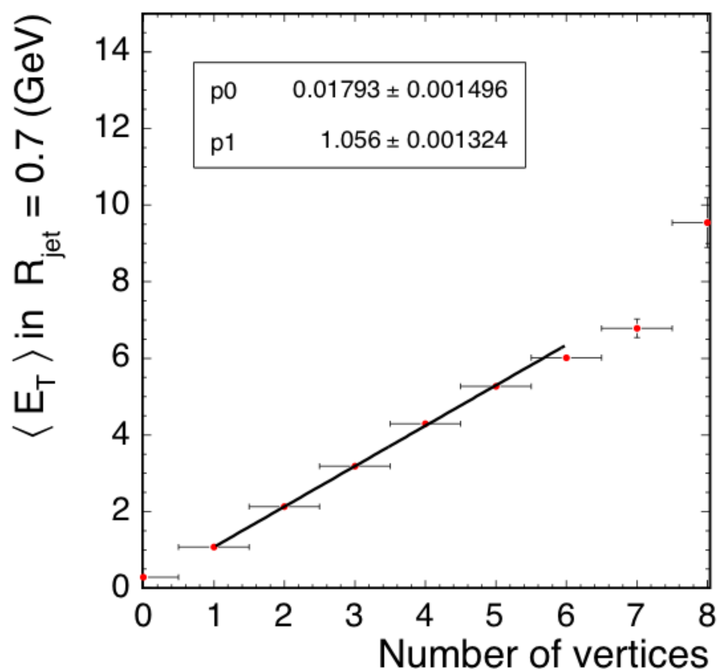
Jet Corrections/Calibrations from Tevatron

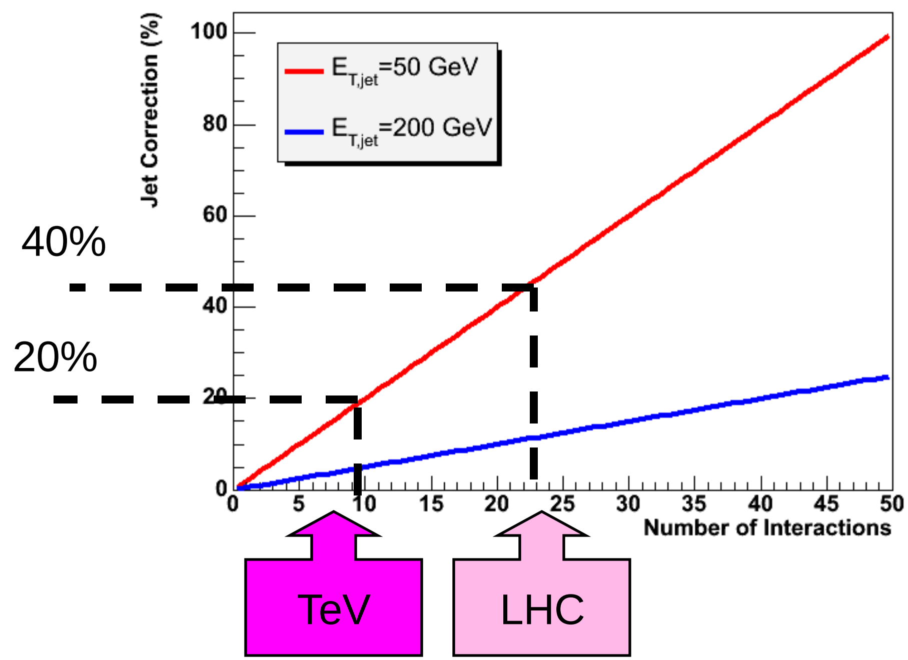
- Mature Tevatron experiments have sophisticated jet correction algorithms
  - Use some of the same that I showed for CMS
- I will show some examples

Multiple Interactions (MI) at the Tevatron

- Need to know how many interactions there were:
  - ➔ # of z-vertices ~ # of interactions
- Throw random cones in Minimum Bias events
  - ➔ Determine average E_T per cone, e.g. CDF: 1 GeV for R=0.7

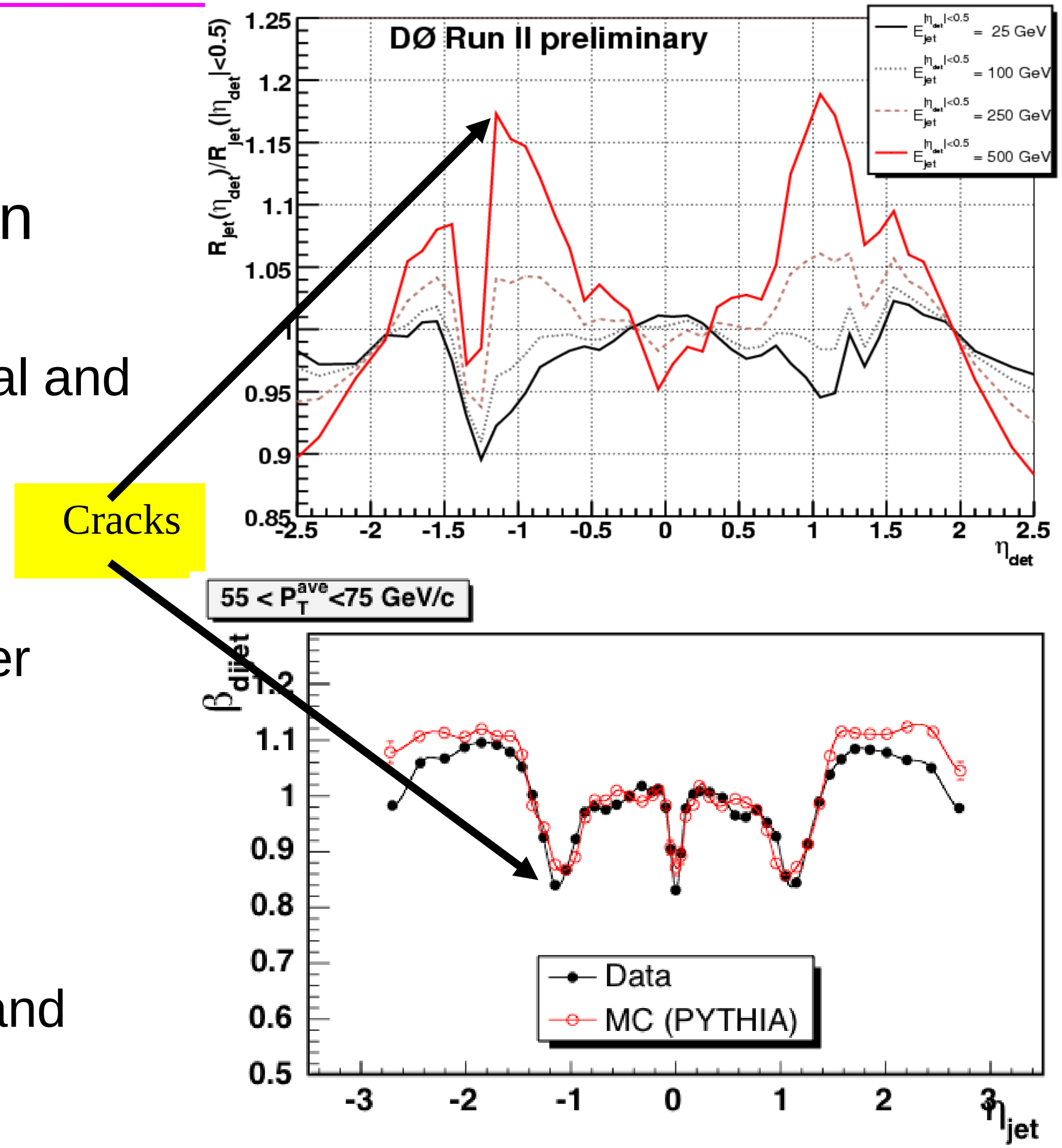






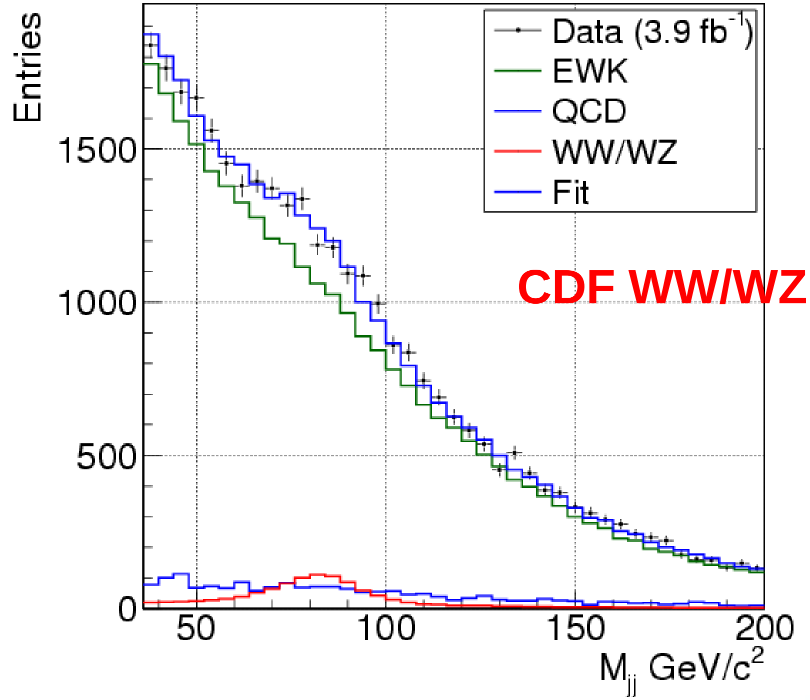
Relative Corrections

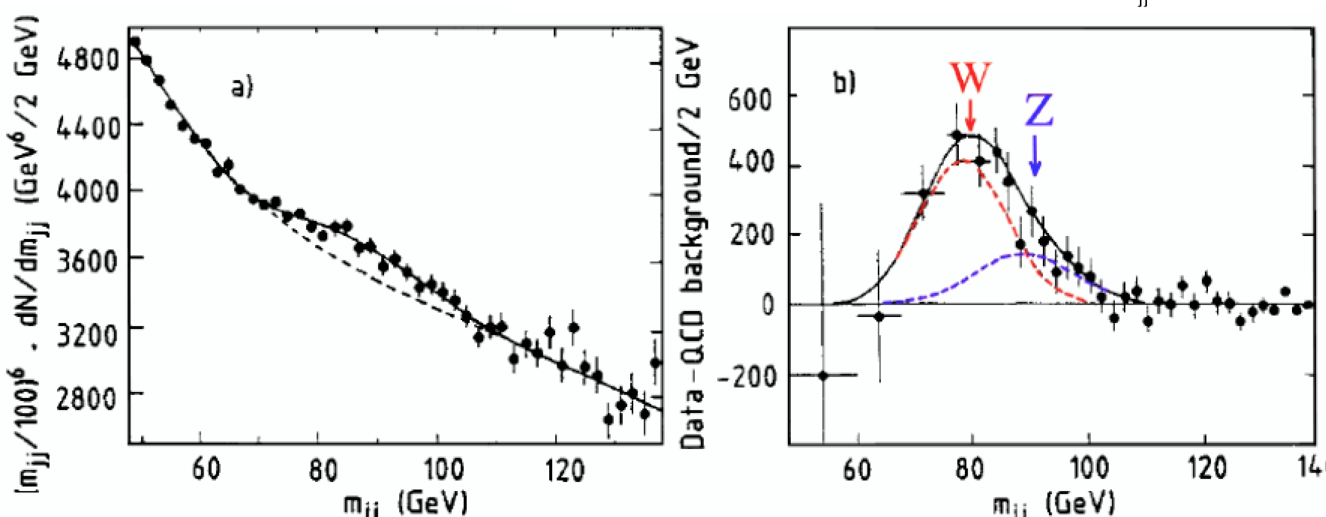
- Mapping out cracks and response of calorimeter
- Central at ~1 by definition
- D0:
  - Response similar in central and forward
  - Two rather large cracks
- CDF:
  - Response of forward better than of central
  - Three smaller cracks
- Difficulties:
  - depends on E_T
  - Can be different for data and MC



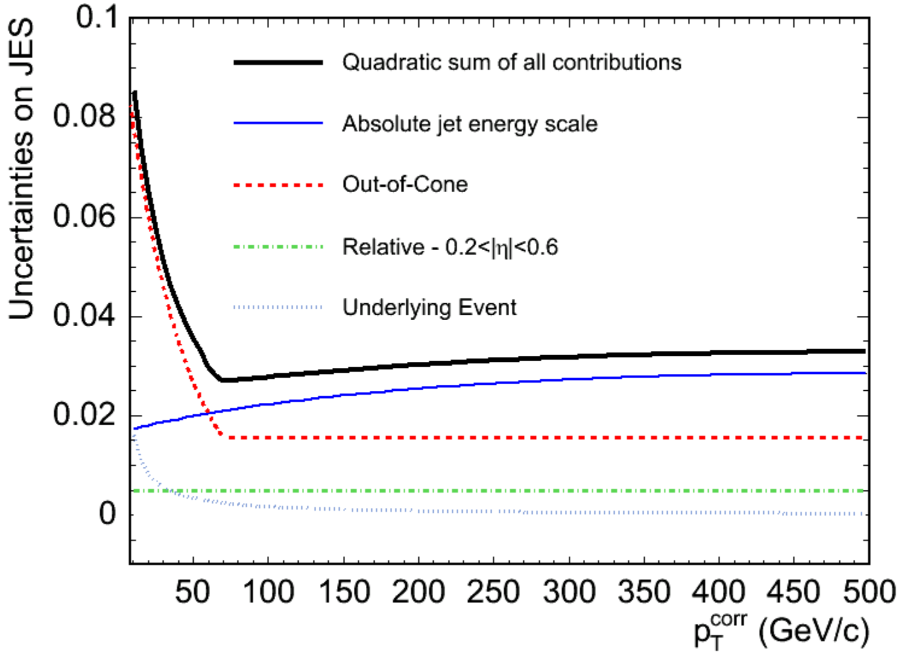
Calibration Peaks from W's and Z's

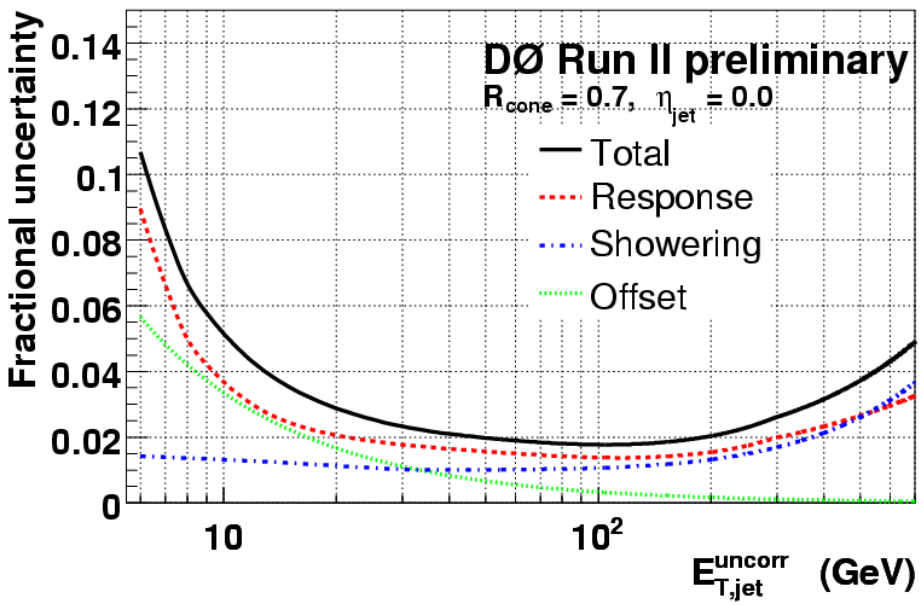
- Would like to use W,Z for calibration – same mass scale as Higgs
- Difficult to see inclusive decays of W's and Z's to jets
  - Small signal on huge background
- Two best opportunities:
  - W in top quark decays
  - Z in bb decay mode





Jet Energy Scale Uncertainties





- Uncertainty on Jet Energy Scale determines how well you can measure mass (of W, H, new resonance, etc) – extremely important to reduce, and understand
- CDF and DØ achieve similar uncertainties
- CMS – 10% based on Monte Carlo studies – initial data validates that this is conservative →Will improve with more data

Summary

- I've tried to show aspects of calibration of calorimeters at many levels
  - detector components
    - Testbeam, in-situ
  - Single-particle
  - Physics objects
- Using calorimeter information
  - Jet construction algorithms
- Corrections at the physics level
  - It comes back to how the detector was designed and built
  - Important to physics results!

Thanks for your attention and participation!!

Enjoy the rest of the summer school!!

Extra slides

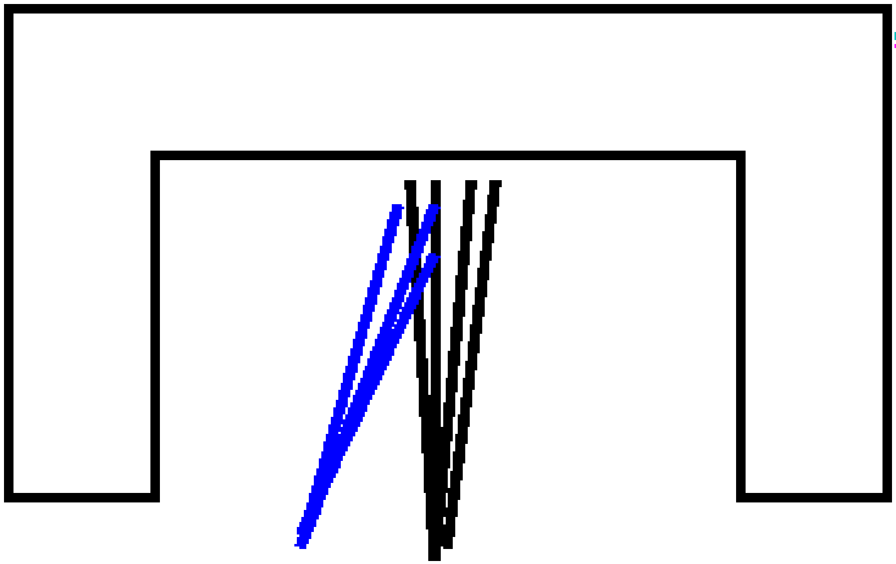
Backup : Anti K_T

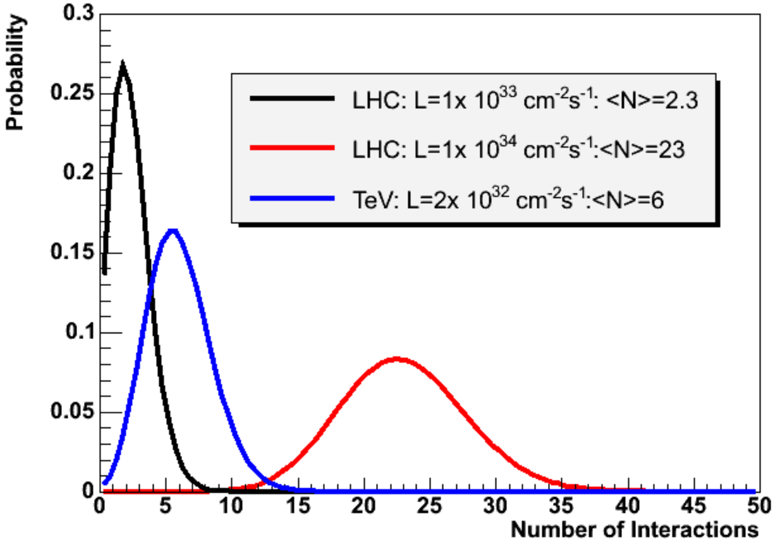
$$d_{ij} = min\left(k_{T,i}^{-2}, k_{T,j}^{-2}\right)\frac{\Delta R_{ij}^2}{R^2}$$

$$\Delta R_{i,j}^2 = (y_y - y_j)^2 + (\phi_i - \phi_j)^2$$

- New development in the jet clustering theory.
- Tends to cluster the energy around the hardest particles.
  - essentially behaves like a cone algorithm giving perfectly round jet areas
- Belongs to the "k_T" family.
  - merging of 4-vector pairs based on transverse momentum weighted distance in y-φ plane.
  - the clustering terminates when the weighted distance between particles is greater than a specific value **R** (resolution parameter).
  - the quantity **R** is of the order of unity.
- infrared and collinear safe (suitable for theory calculations).

Multiple pp Interactions



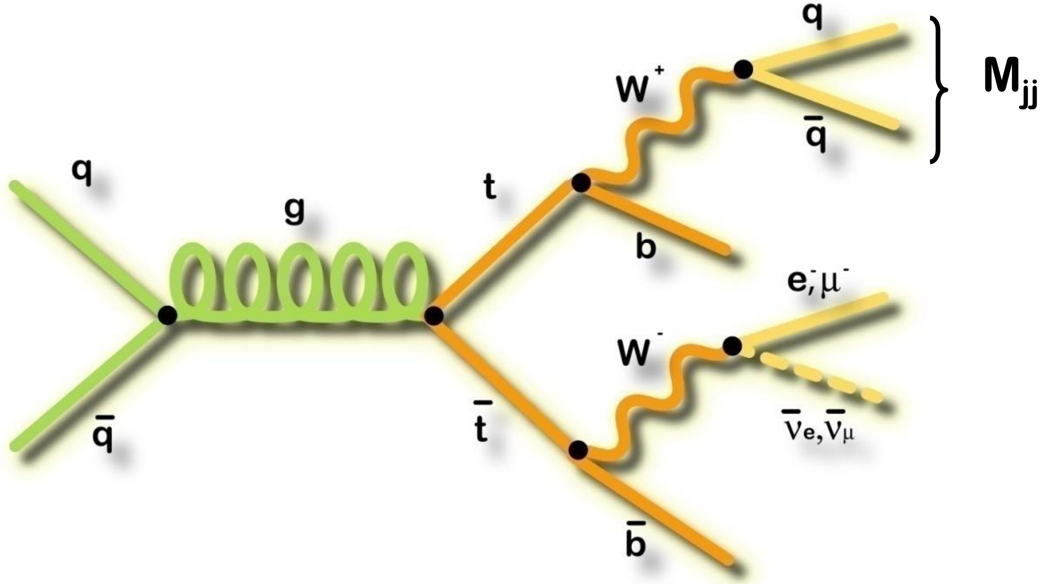


- Overlapping interactions can overlap the jet
- Number of extra interactions depends on luminosity
  - LHC:
    - Low lumi ($L=1x10^{33}$ $cm^{-2}s^{-1}$): <N>=2.3
    - High lumi ($L= 1x10^{34}$ $cm^{-2}s^{-1}$): <N>=23
  - Tevatron:
    - $L= 2x10^{32}$ $cm^{-2}s^{-1}$: <N>=6

Offset depending on number of interactions

In-situ Measurement of JES

- Additionally, use $W \rightarrow jj$ mass resonance (M_{jj}) to measure the jet energy scale (JES) uncertainty



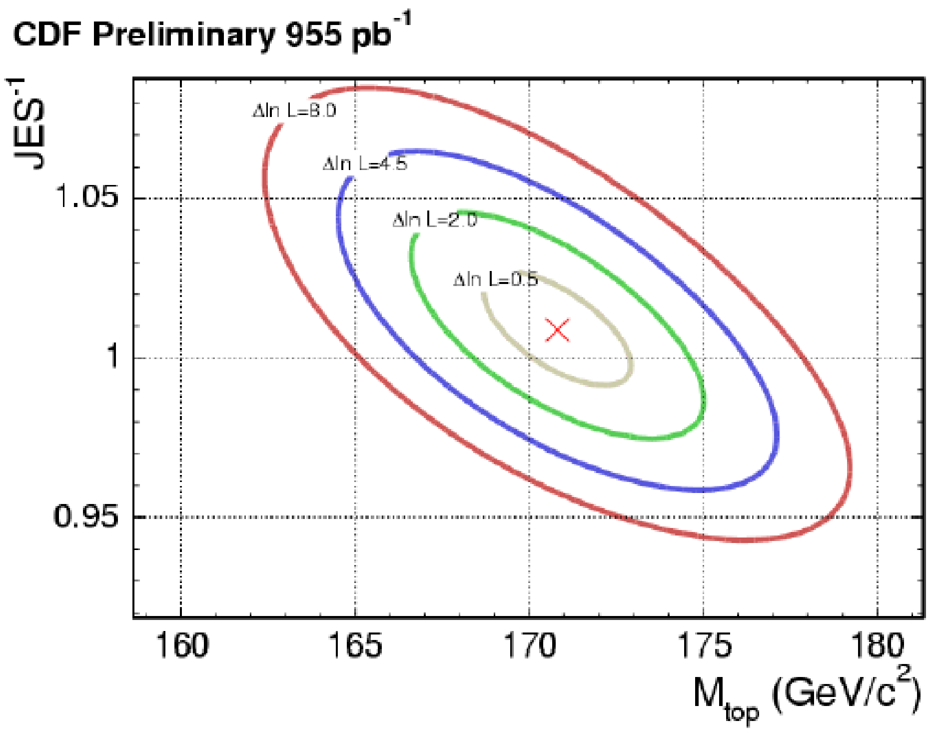
2D fit of the invariant mass of the non-b-jets and the top mass:

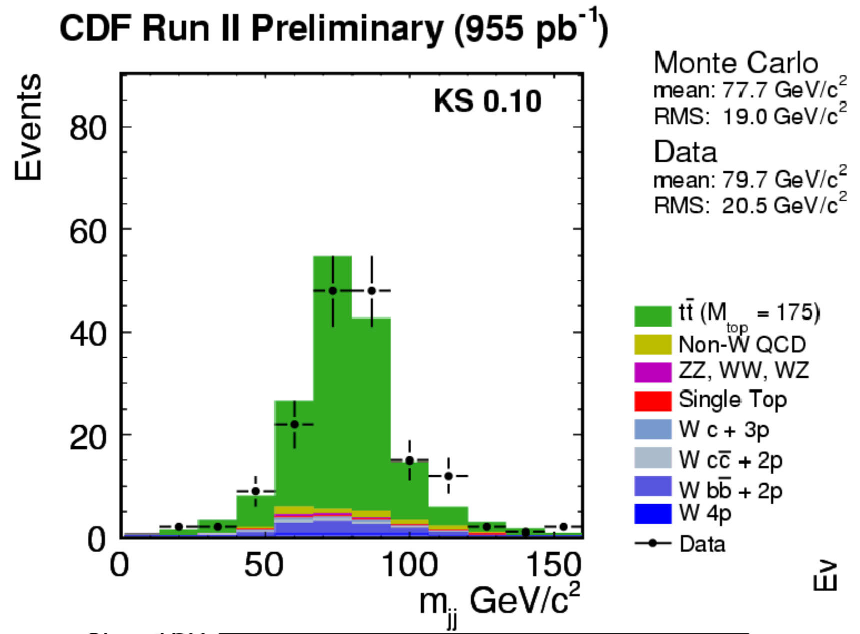
$JES \propto M(jj) - 80.4\ GeV/c^2$

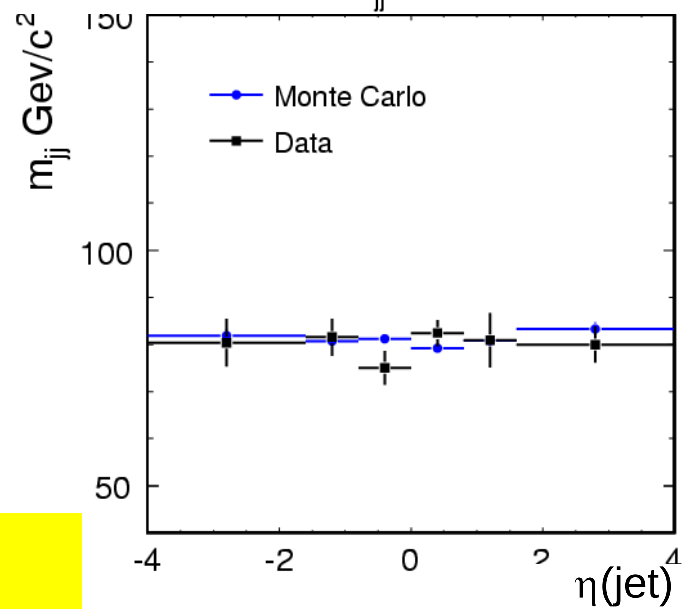
Measurement of JES scales directly with data statistics

W→jj Calibration in Top Events

- Fit for ratio of JES in data to JES in MC
  CDF (1 fb^{-1}): δ_{JES} = 0.99 ± 0.02
  DØ (0.3 fb^{-1}): δ_{JES} = 0.99 ± 0.03
- Constrain JES to 2% using 166 events







At LHC will have 45,000 top events/month!

Streamlined Seedless Algorithm

- Data in form of 4 vectors in (η,φ)
- Lay down grid of cells (~ calorimeter cells) and put trial cone at center of each cell
- Calculate the centroid of each trial cone
- If centroid is outside cell, remove that trial cone from analysis, otherwise iterate as before
- Approximates looking everywhere; converges rapidly
- Split/Merge as before

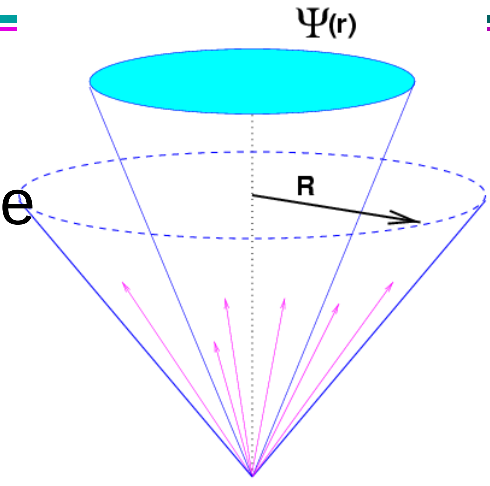
Corrections from Particle Jet to Parton

- Underlying event (UE) and Out-of-cone (OOC) energy
  - Only used if parton energy is wanted
  - Requires MC modeling of UE and OOC
    - Differences are taken as systematic uncertainty

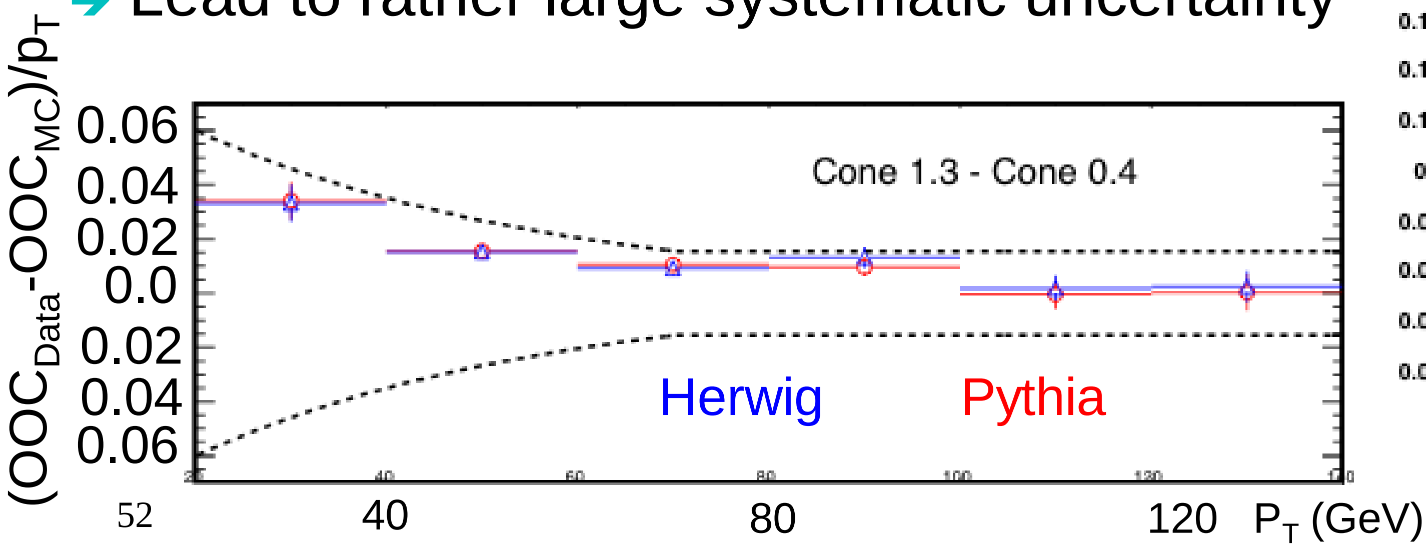
$$P_{T,parton} = P_{T,particle} - UE + OOC$$

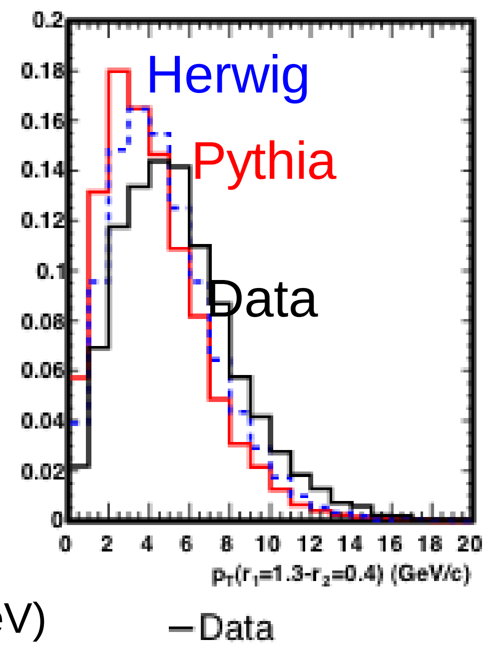
Out of Cone Energy (OOC)

- Out-of-Cone Energy:
  - ➔ Original parton energy that escapes the cone
    - → E.g. due to gluon radiation
  - ➔ Jet shape in MC must describe data:
    - → measure energy flow in annuli around jet

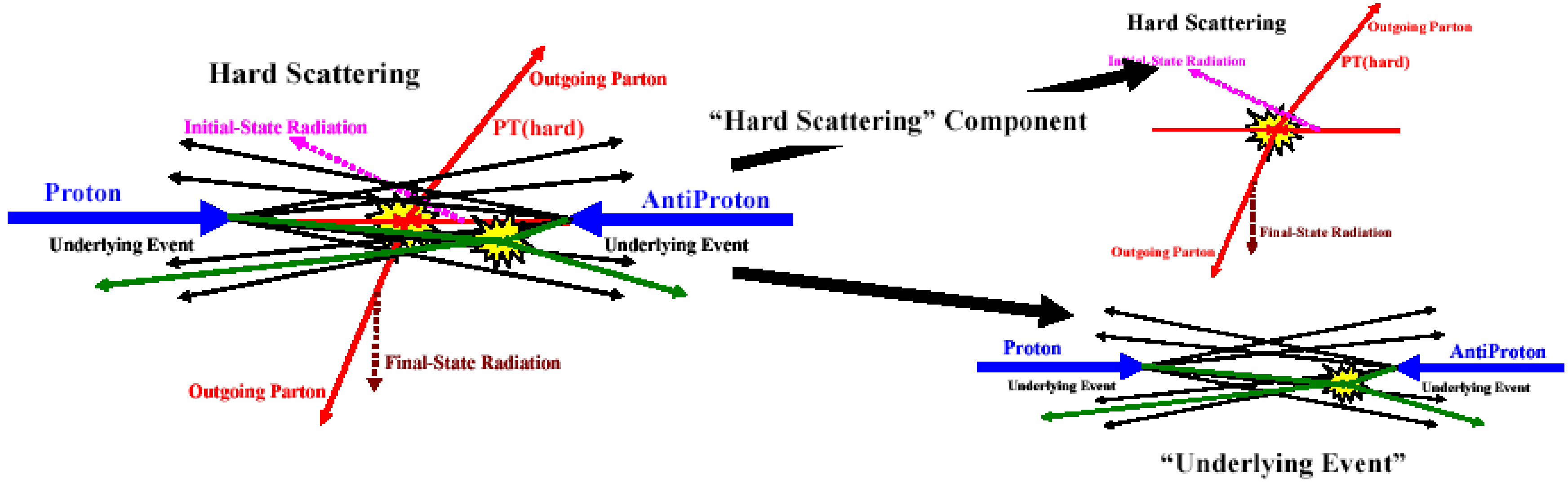


- Differences between data and MC
  - ➔ Lead to rather large systematic uncertainty





Underlying Event



- Consists of:
  - "beam-beam remnants": energy from interaction of spectator partons
  - "Initial state radiation": energy radiated off hard process before main interaction

Measuring the Underlying Event

Leading Jet Direction