Jets at CMS

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MIT, August 1, 2008

Introduction

- I am in CMS JetMET POG since 2005
  - Since beginning of the CMSSW era
- Exclusively responsible for design and implementation of jet reconstruction chain, as well as for design and implementation of Jets Energy Corrections machinery
- Involved into and support most ongoing Jet activities
- Jet contact for the CMS RECO group

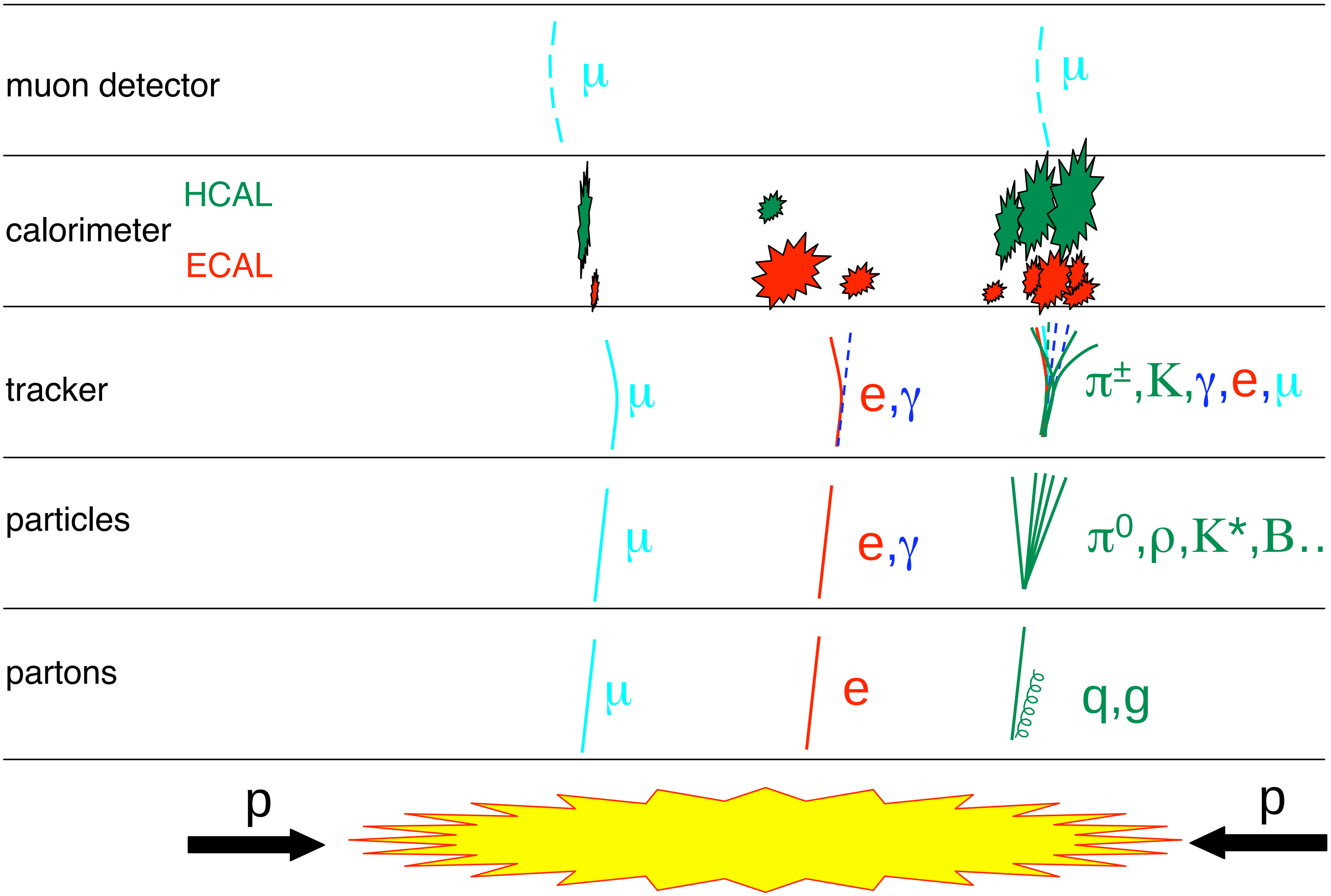
Credits

- CMS Jet/MET DPG is a big team
- This presentation includes results obtained by different people
  - A.Anastassov, A.Bhatti, V.Buege, J.Cammin, F.Chlebana, R.Harris, S.Essen, O.Kodolova, K.Kousouris, A.Nikitenko, A.Oehler, D. del Re, G.Salam, M.Zielinski

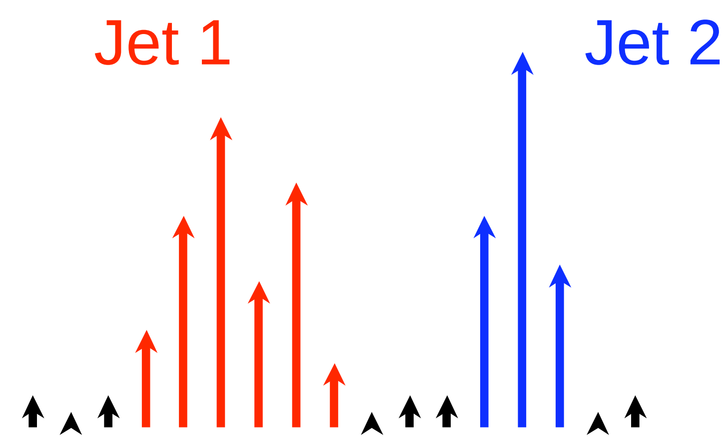
Outline

- Why jets are tricky
- Jet reconstruction algorithms
  - General requirements
  - Algorithms used at CMS
  - Performance
- Jet flavors: CaloJets GenJets, PFJets
- Jet reconstruction software design
- Resolution, efficiency
- Jet Energy Corrections
  - Generic design
  - Supported corrections
- Summary

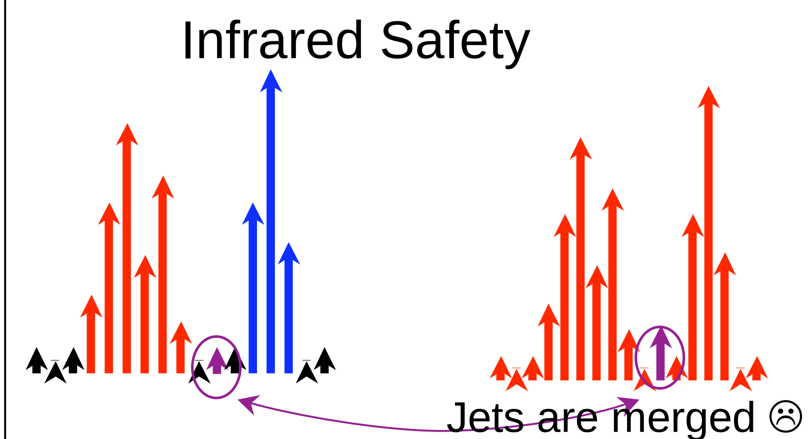
Basic Reconstructed Physics Objects

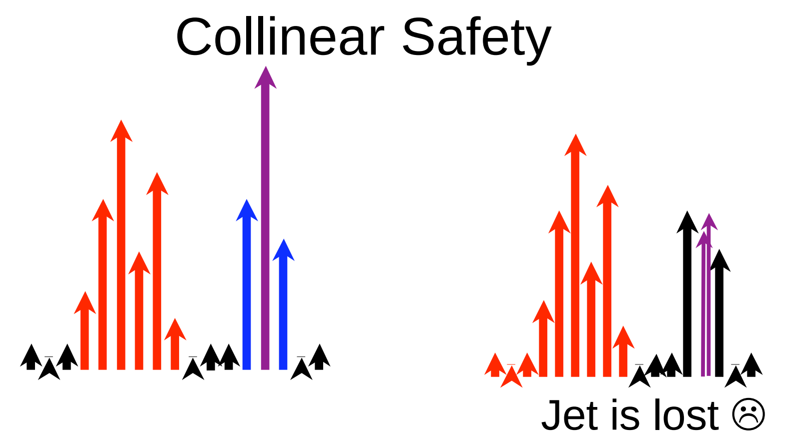


Requirements to Jet Algorithms



Procedure must be stable with respect to reasonable variations of the energy pattern





Jet Algorithms

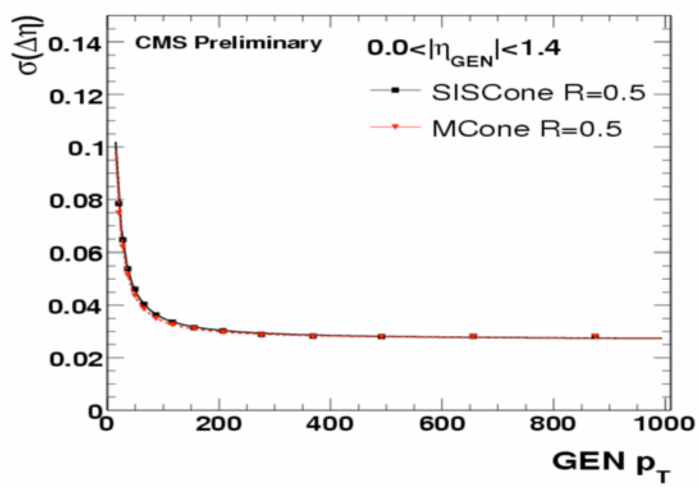
- Iterative Cone
  - Seeded
  - Single pass - fast
  - IR_2 unsafe, collinear unsafe
- CDF Midpoint Cone
  - Seeded
  - With split/merge passes
  - IR_3 unsafe, collinear unsafe

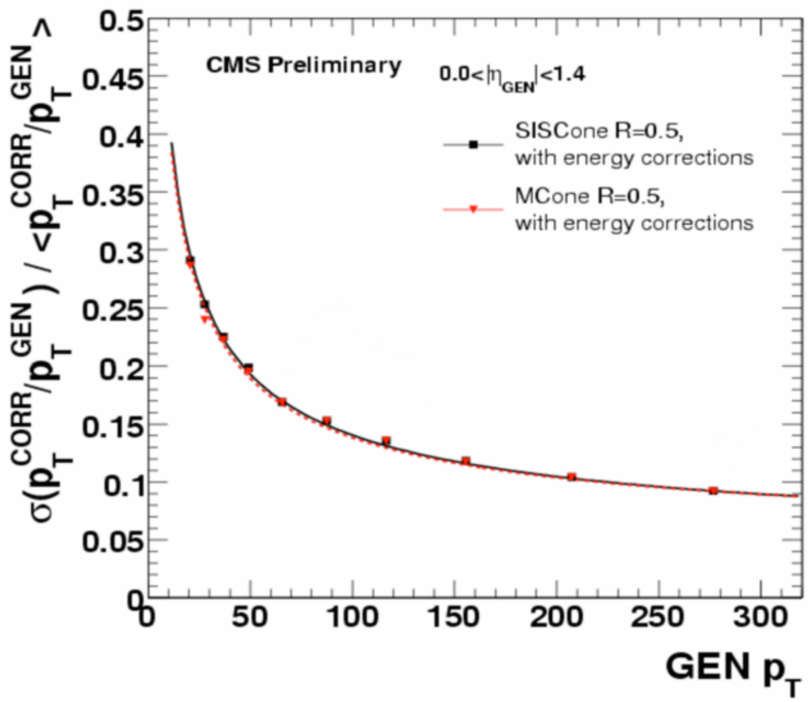
Jet Algorithms (cont)

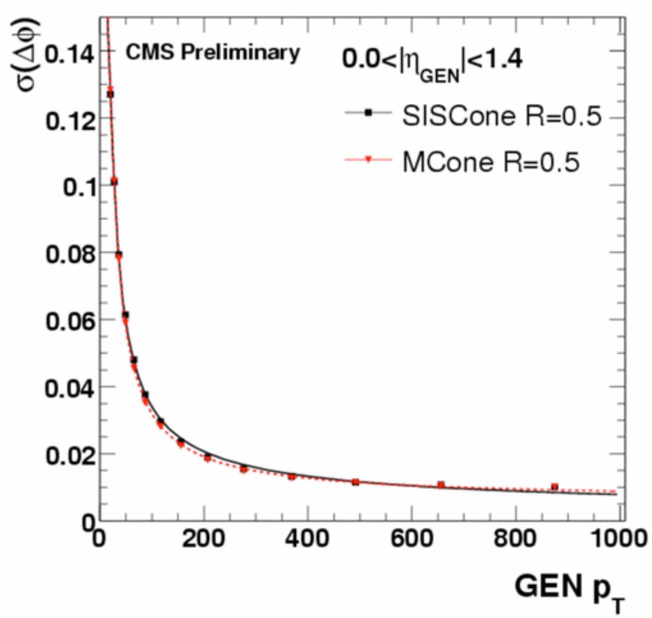
- k_T
  - Seedless
  - $N^3 \rightarrow N \cdot \ln(N)$ - fast
  - IR, collinear safe
- Seedless Infrared Safe Cone (SISCone)
  - Seedless
  - $N^4 \rightarrow N^2 \cdot \ln(N)$ - Reasonably fast
  - IR, collinear safe

- CMS routinely uses
  - IC R=0.5
  - SISC R=0.5, R=0.7
  - k_T D=0.4, D=0.6

Midpoint Cone vs SIS Cone



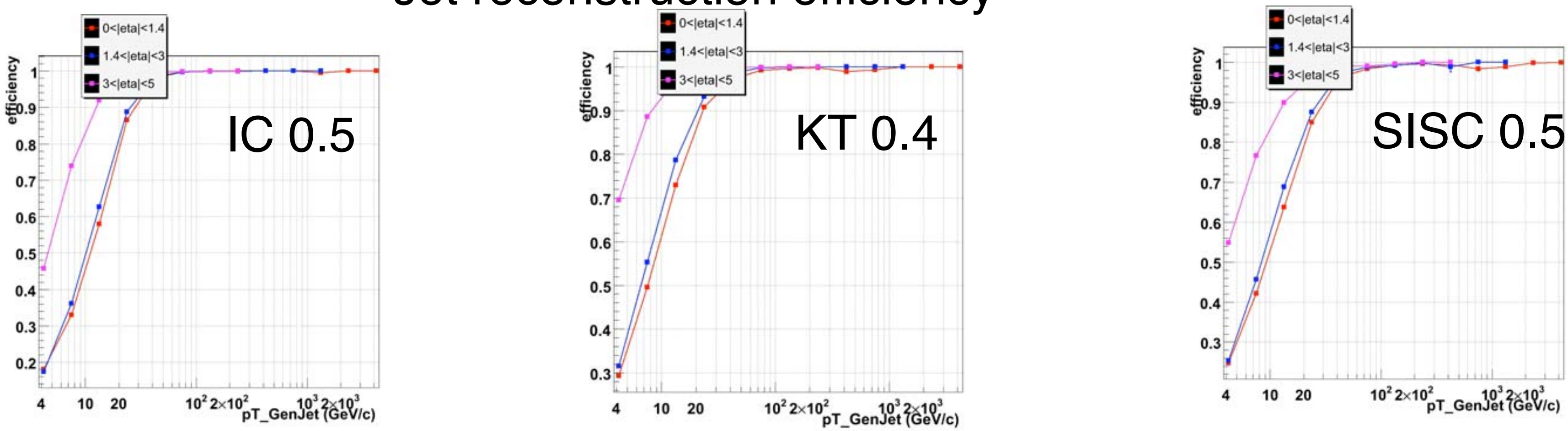




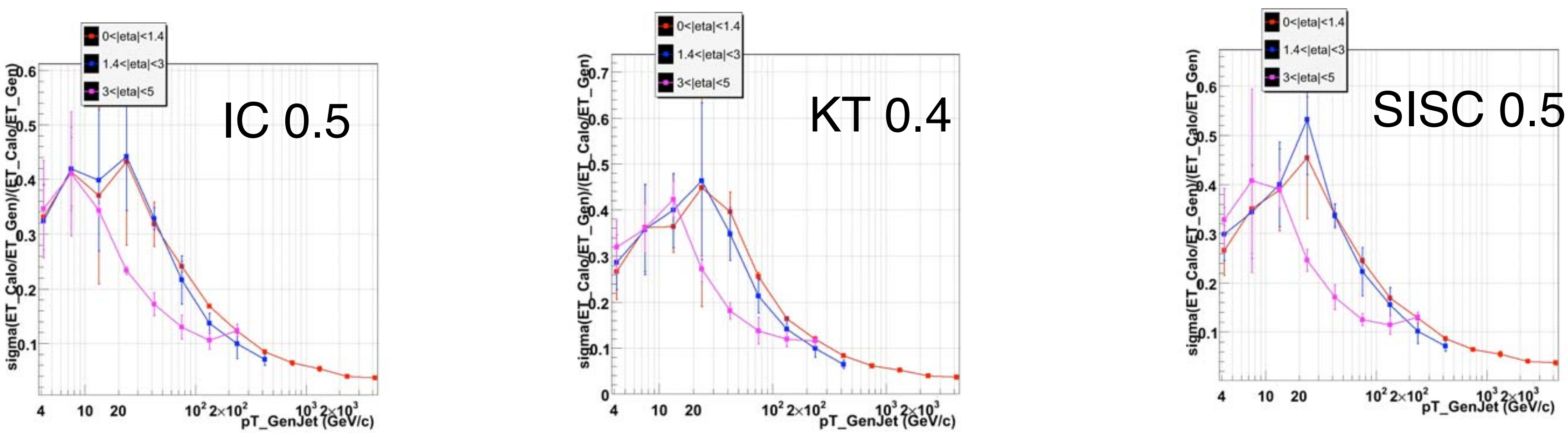
- CMS switched to using SISCone instead of Midpoint Cone recently

Comparing Jet Properties

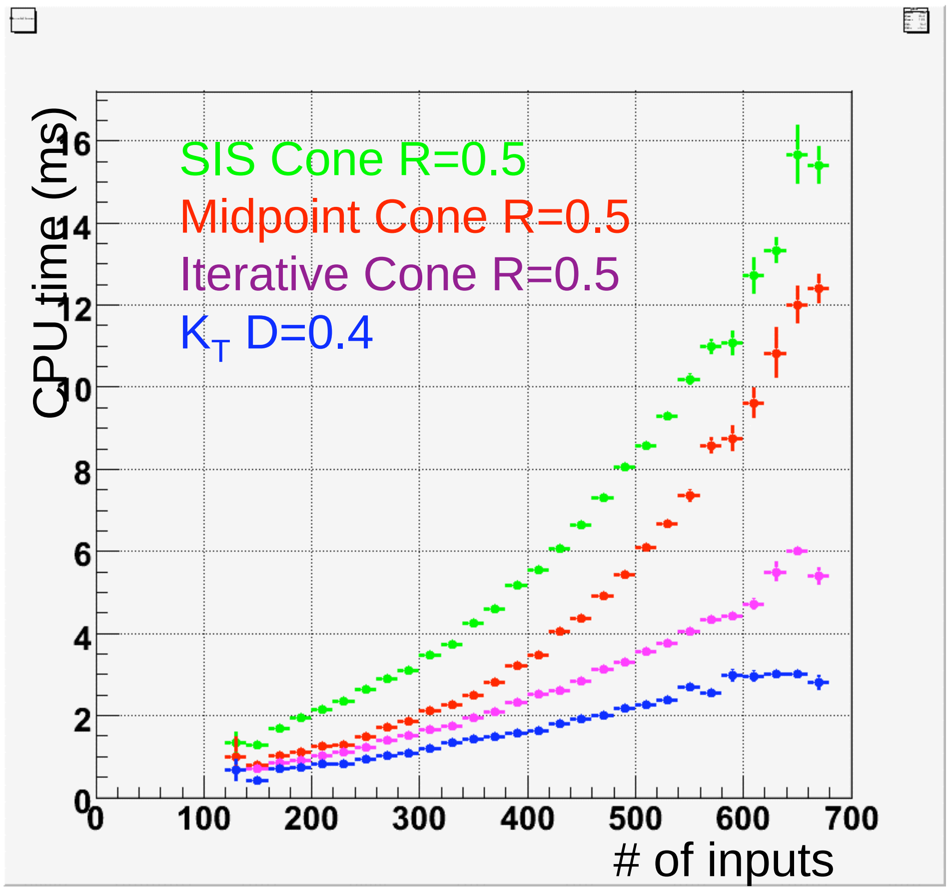
Jet reconstruction efficiency

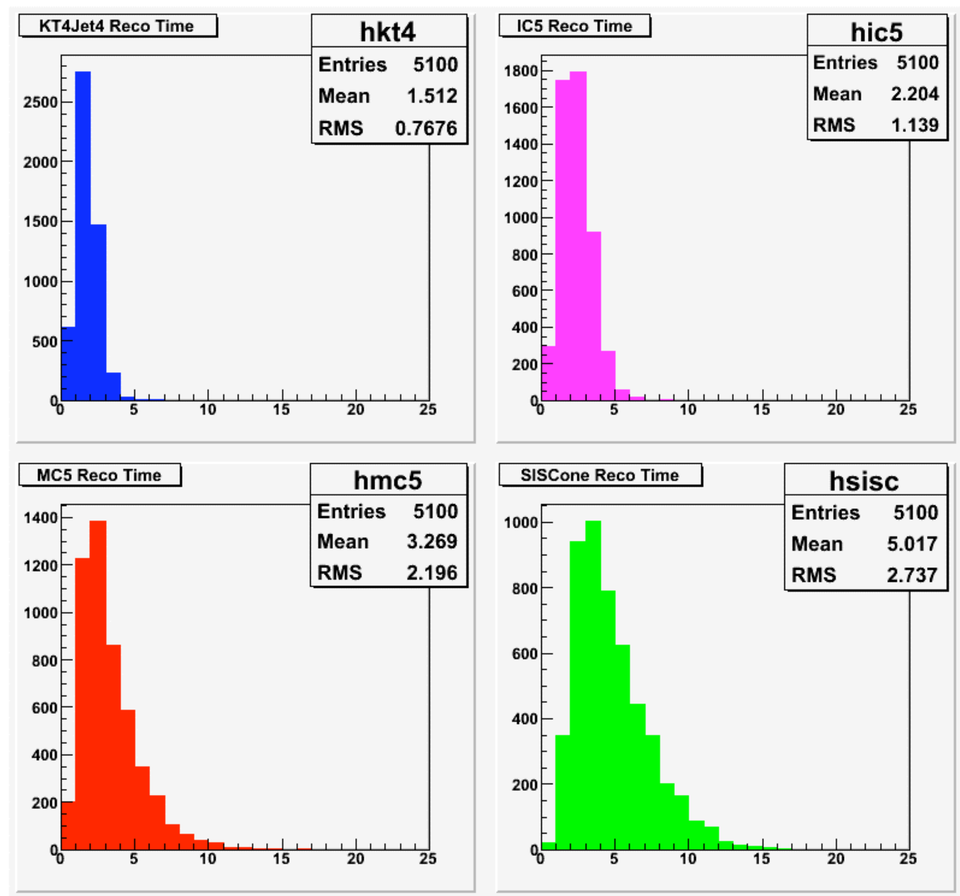


Jet energy resolution



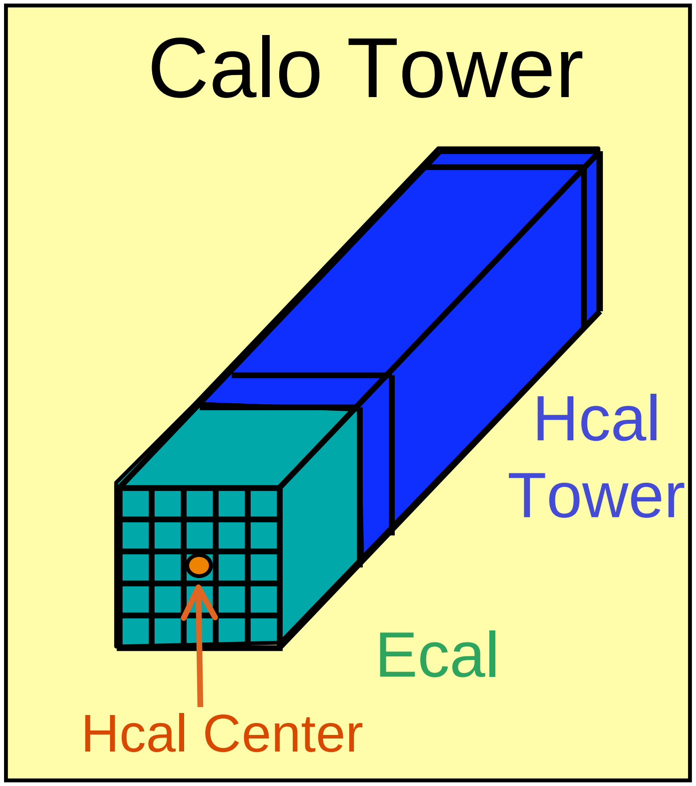
Algorithms Speed





CaloJets

- Baseline for Jet reconstruction at CMS
- Input is CaloTower
  - Mostly follow HCAL granularity
  - Contains few HCAL cells and many (25 in the barrel) ECAL cells

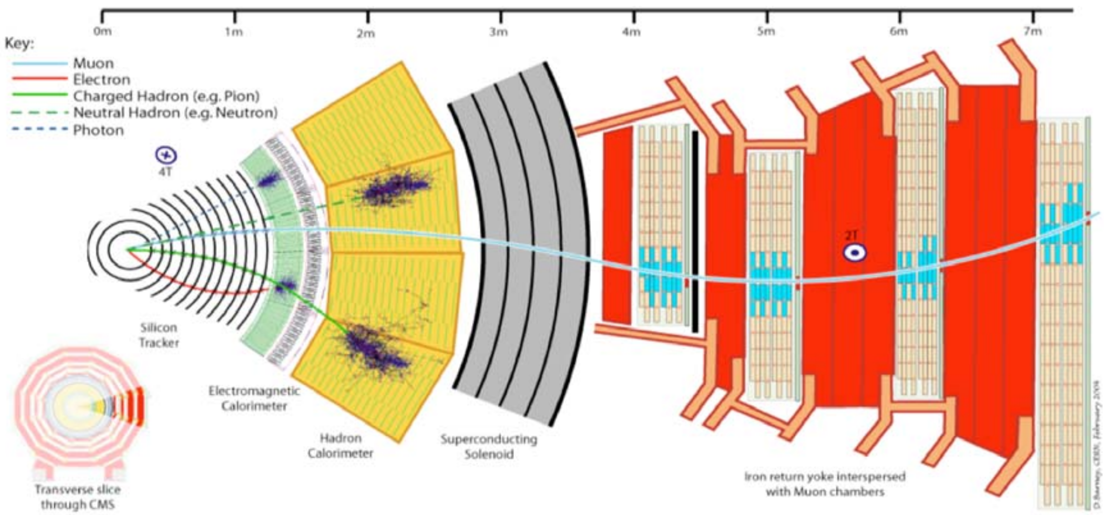


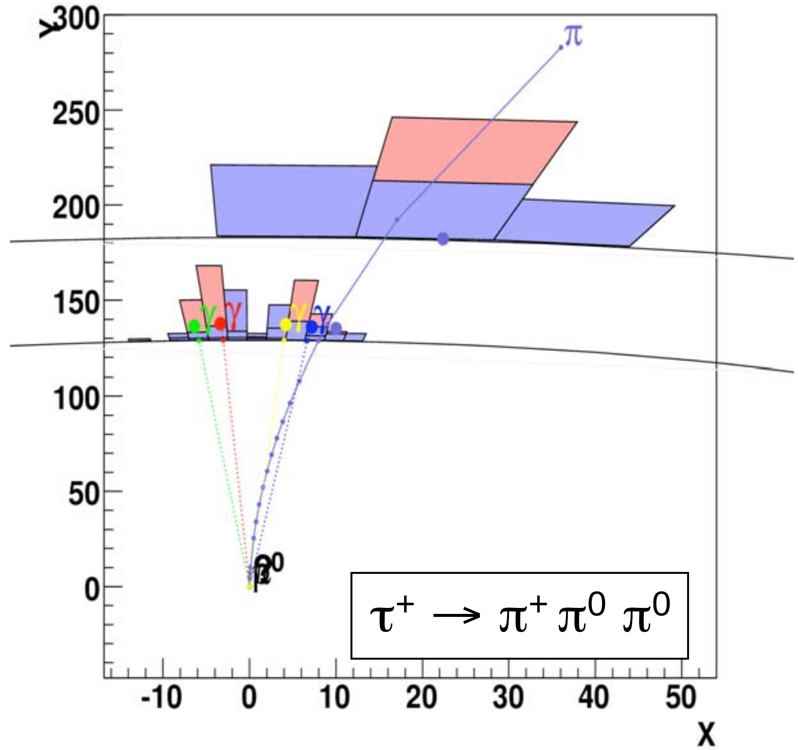
- CaloJets include information about electromagnetic fraction, energies deposited in different subdetectors etc.
- Produce CaloJets for every approved algorithm
  - Part of "RECO" sequence
- People are free to run own jet algorithm on CaloTowers
  - Necessary information is available in all standard datasets

GenJets

- Clustering energies of MC level particles
- Include “invisible” particles?
  - Muons
  - Neutrinos
  - SUSY, if any
- Current approach
  - Include all “invisible” except ones from prompt decays of gauge bosons
- Produce GenJets for every approved algorithm
  - Part of “post SIM” sequence
- People are free to make own selection of MC particles and run jet algorithm on them
  - Necessary information is available in all standard datasets

PFJets

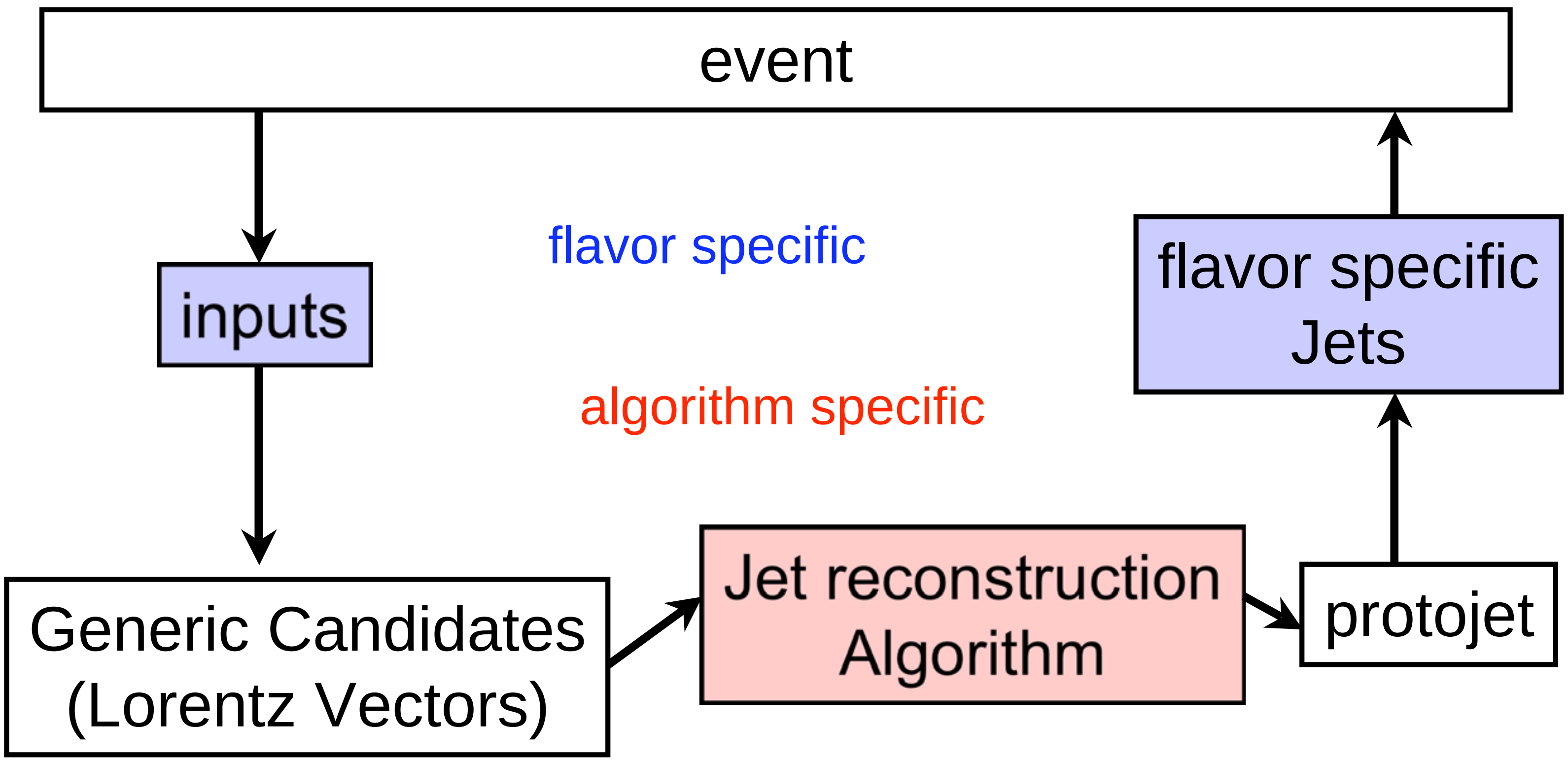




- PFCandidate combines information from various detectors to make the best combined estimation of particle properties
- PFJet is made from PFCandidates and contains information about contributions of every particle class:
  - Electromagnetic/hadronic
  - Charged/neutral

Jet Reconstruction at CMS

- Factorize algorithms and jet flavors
  - Algorithms treat inputs as set of 4-momenta
  - Flavor specific pre/postprocessing are shared by all algorithms



HI Specifics

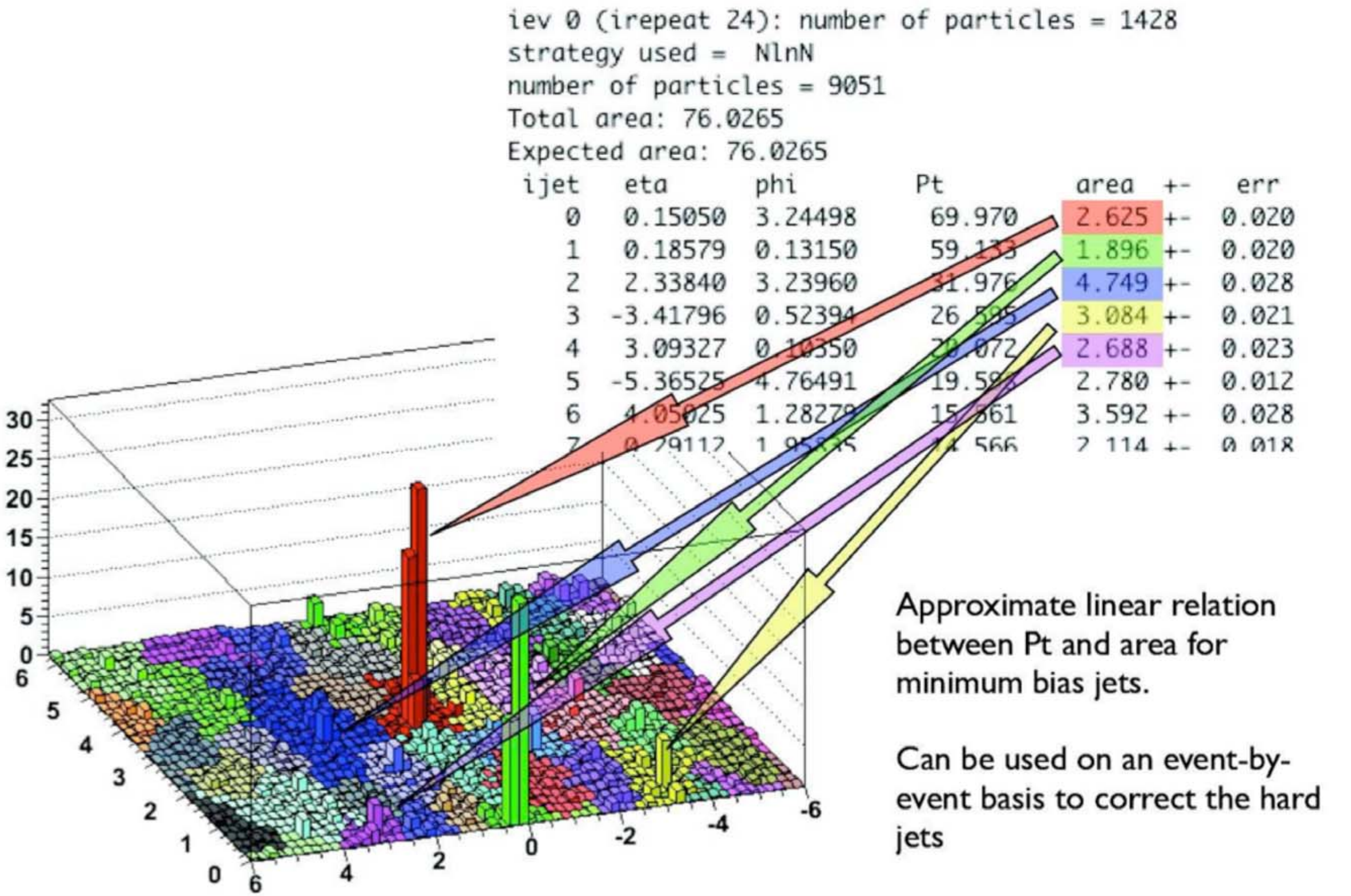
- HI events are huge on particle level
- Not a big deal for CaloJets
  - Not more than ~5K fired CaloTowers anyway
- Big deal for GenJets
  - One event - 35K particles
  - SISCone killer (remember: $N^2 LnN$ algorithm)
    - 40 min of CPU time
    - 30 Gbytes of memory
    - In most cases just crashes the reconstruction job
  - k_T survives: takes ~20 sec of CPU time

Event By Event Pileup Subtraction

- FASTJET approach
  - Applicable to IR safe algorithms only, any jet flavor
  - Calculate jet area by ghost method
    - Put extra very small ghost energies into nodes of η-φ grid
  - Assume pileup jet area proportional to p_T
  - Use low p_T jets to derive PU energy density
  - Estimate high p_T jets PU contribution using PU energy density and jet area

- CMS approach
  - Applicable to any algorithm, CaloJets only
  - Run regular jet reconstruction
  - Get average energy in CaloTowers outside reconstructed jets in every η ring
  - Subtract that energy from CaloTowers contributing to the jet
  - Re-calculate jet parameters using corrected energies of contributing towers

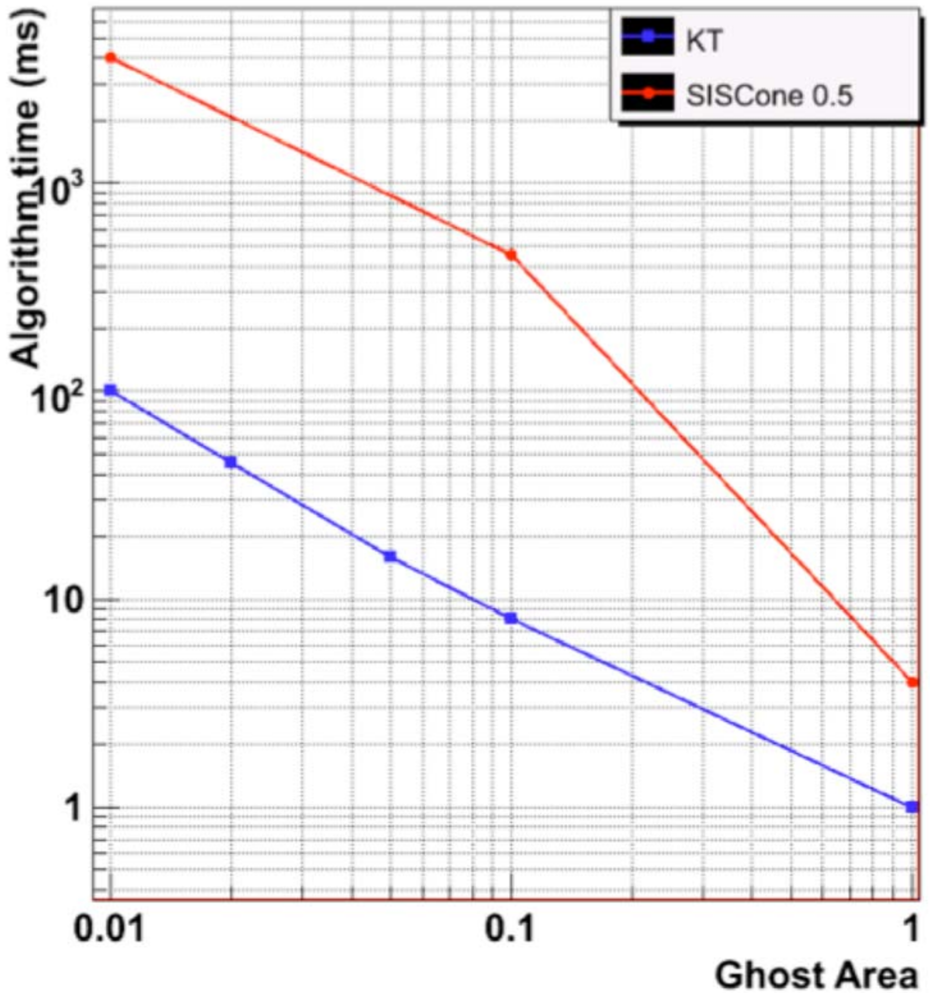
Making use of *all* jets



Approximate linear relation between Pt and area for minimum bias jets.

Can be used on an event-by-event basis to correct the hard jets

JetArea/PU Subtraction Costs



d - ghosts grid step
R - jet radius

$$\Delta S \approx \sqrt{\frac{2\pi R}{d}}$$

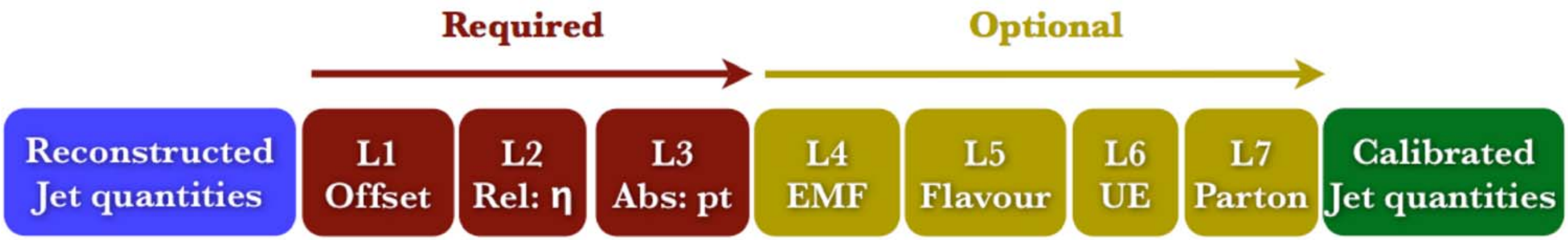
$$S \approx \frac{\pi R^2}{d^2}$$

$$\frac{\Delta S}{S} \approx \left(\frac{d}{R}\right)^{3/2}$$

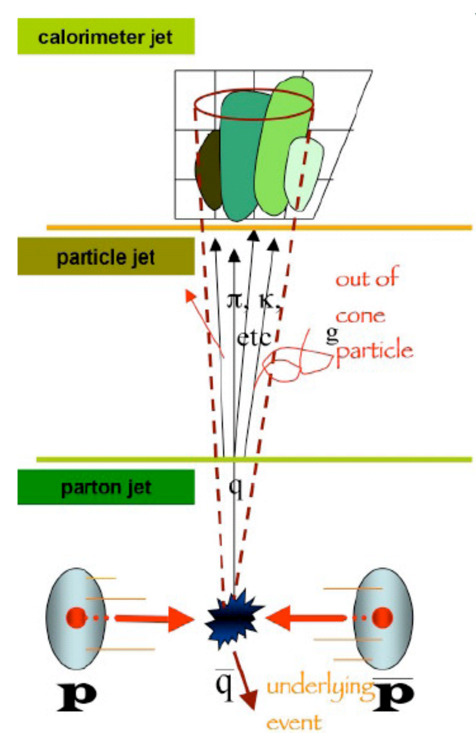
$$\left.\begin{aligned} R &\approx 0.5 \\ \frac{\Delta S}{S} &\approx 10\% \end{aligned}\right\} \Rightarrow d \approx 0.1$$

$$\Rightarrow GhostArea \approx 0.01$$

Jet Energy Scale

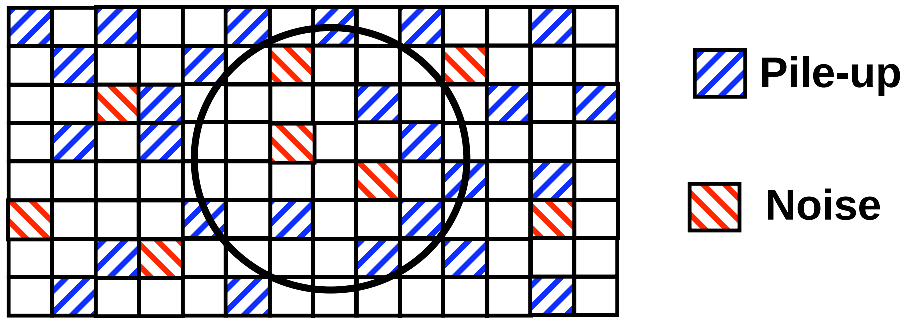


- Jet corrections
  - Generic: applied to all jets
  - Optional: fine tuning for specific jet types/hypothesis
- Factorized (chained) corrections approach
- Different jet correctors are services in CMSSW
  - Chained corrector is a service on top of individual correctors
- Use cases:
  - Producers to apply corrections to all jets, produce new jet correction
  - Use correction services directly from analysis modules
  - Use simple corrections (not including extra event information) from FWLite/ROOT scripts



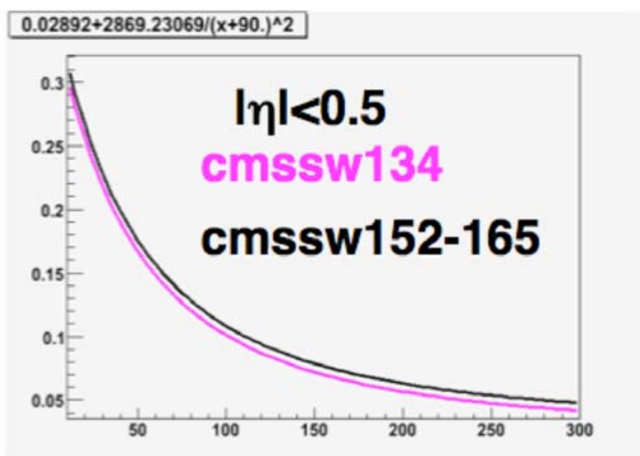
L1: Offset/Zero Suppression

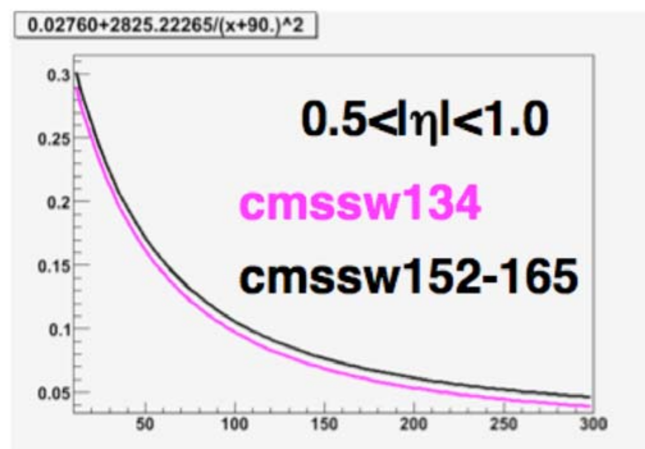
Offset in Jet Area In Calorimeter



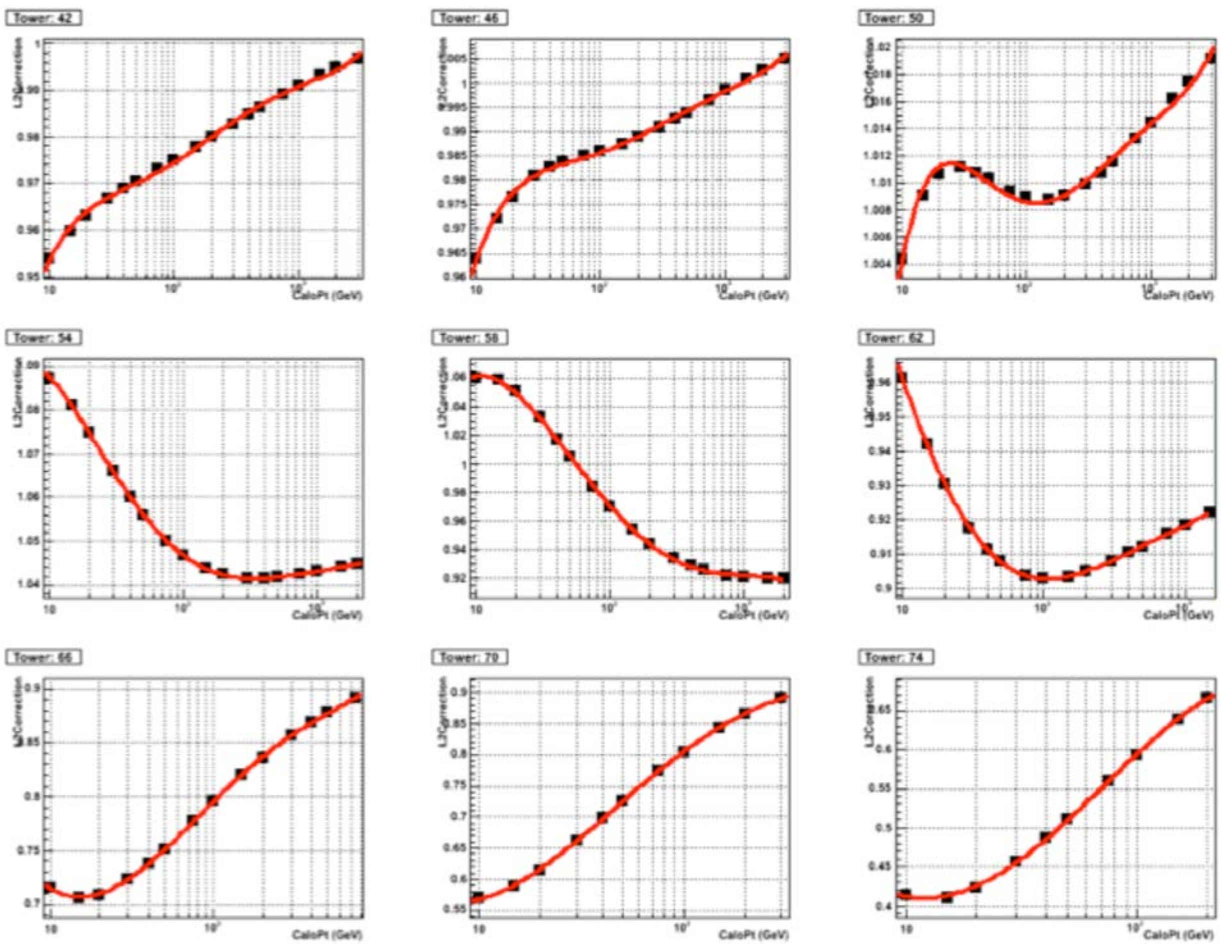
Parametrization:

$$(E_{Trec}^{NoCut} - E_{Trec}^{SchemaB})/E_{Trec}^{SchemaB} = A0 + A1/(E_{Trec}^{SchemaB} + A2)^2$$





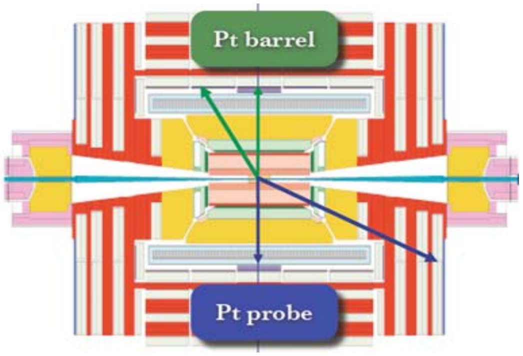
L2: Relative to Barrel (η, p_T)



The fitting function is flexible enough to be used in all η bins although the Barrel scale is considerably smaller than the Endcap and Forward *(backup III)*.

- No assumptions about $\pm\eta$ symmetry

Measuring Relative Scale: Dijet Balance

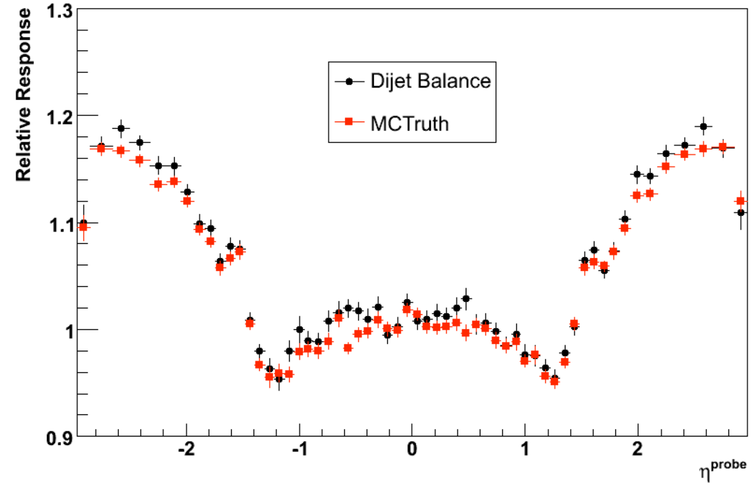


$$p_T^{dijet} = \frac{p_T^{probe} + p_T^{barrel}}{2}$$

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

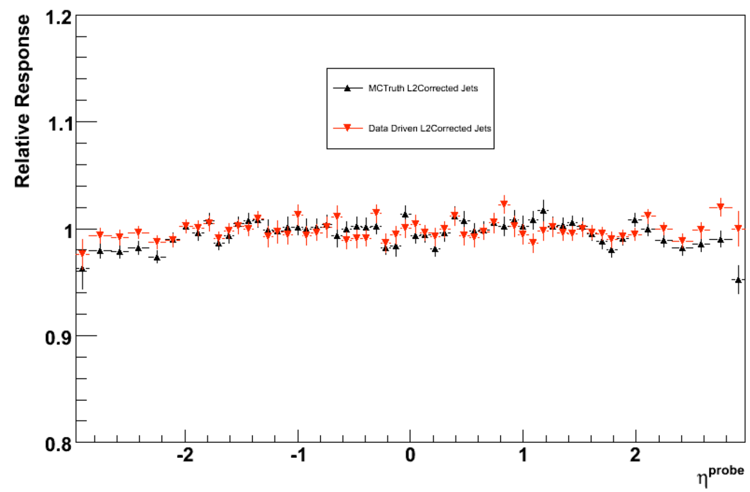
$$r = \frac{2 + \langle B \rangle}{2 - \langle B \rangle} \qquad r_{th} = \langle \frac{p_T^{probe}}{p_T^{barrel}} \rangle$$

Before Corrections

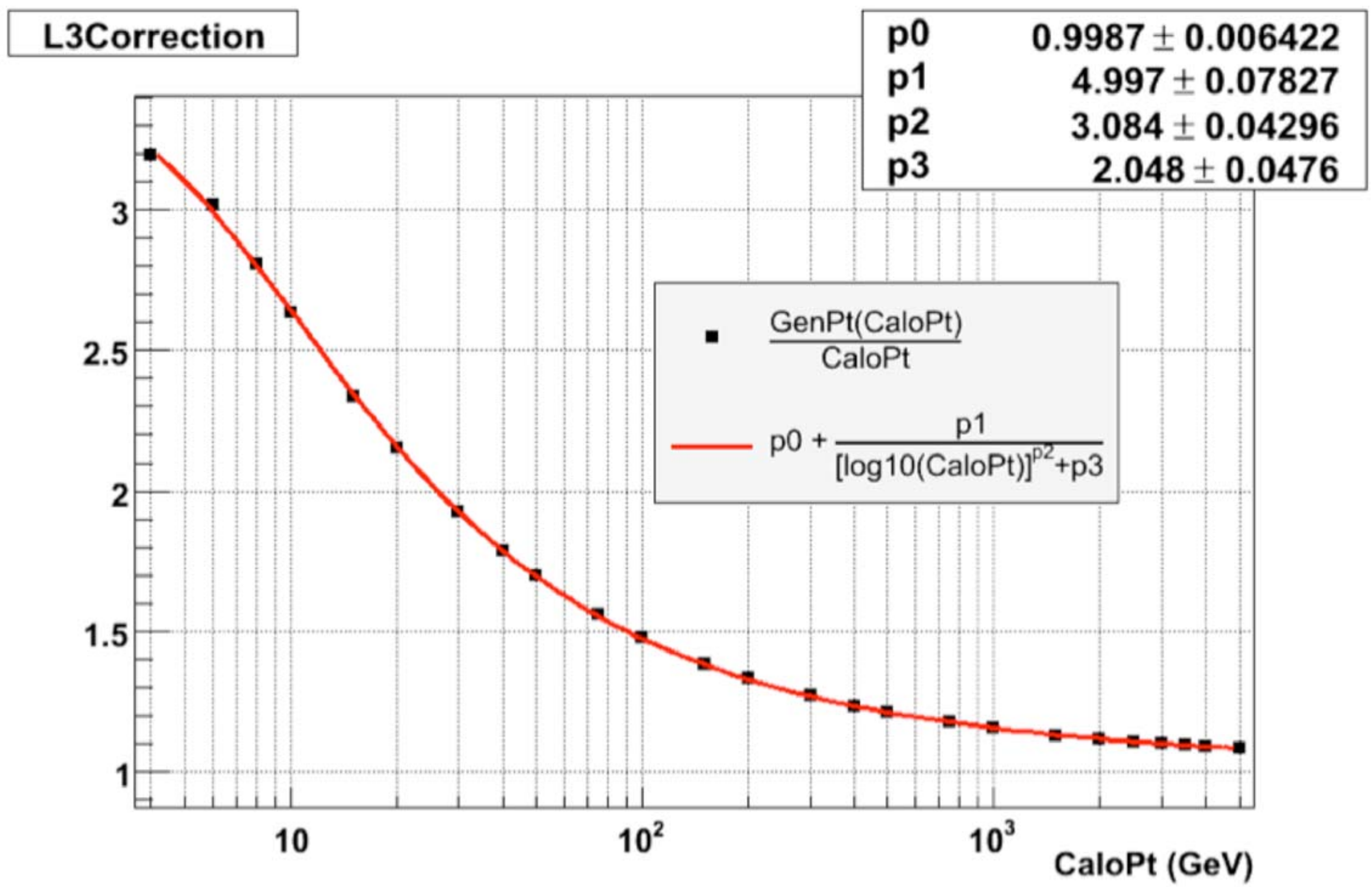


- Utilize p_T conservation for dijet events
- Use dedicated calibration triggers to collect dijet events

After Corrections



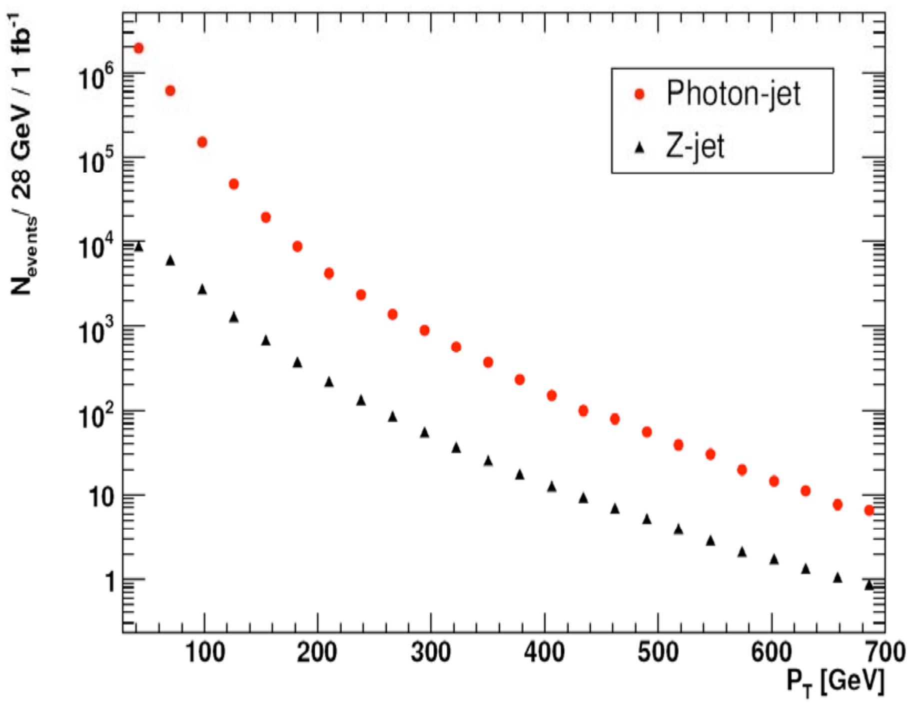
L3: Absolute Scale (p_T)



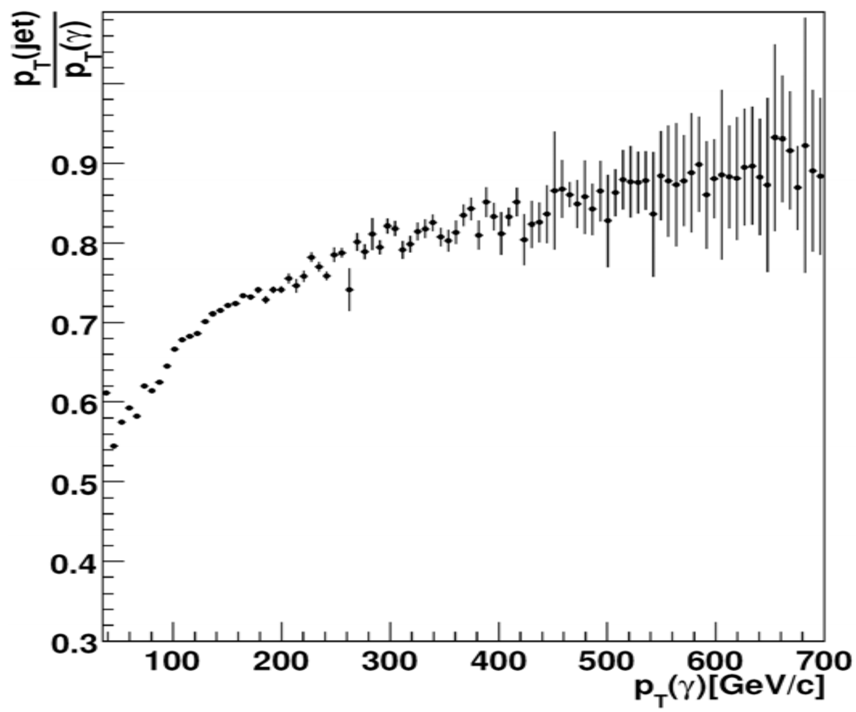
Measuring Absolute Scale: γ/Z Balance

- Utilize p_T conservation for γ-jet and Z(μμ)-jet events
- Rescale back from parton level to particle level using MC

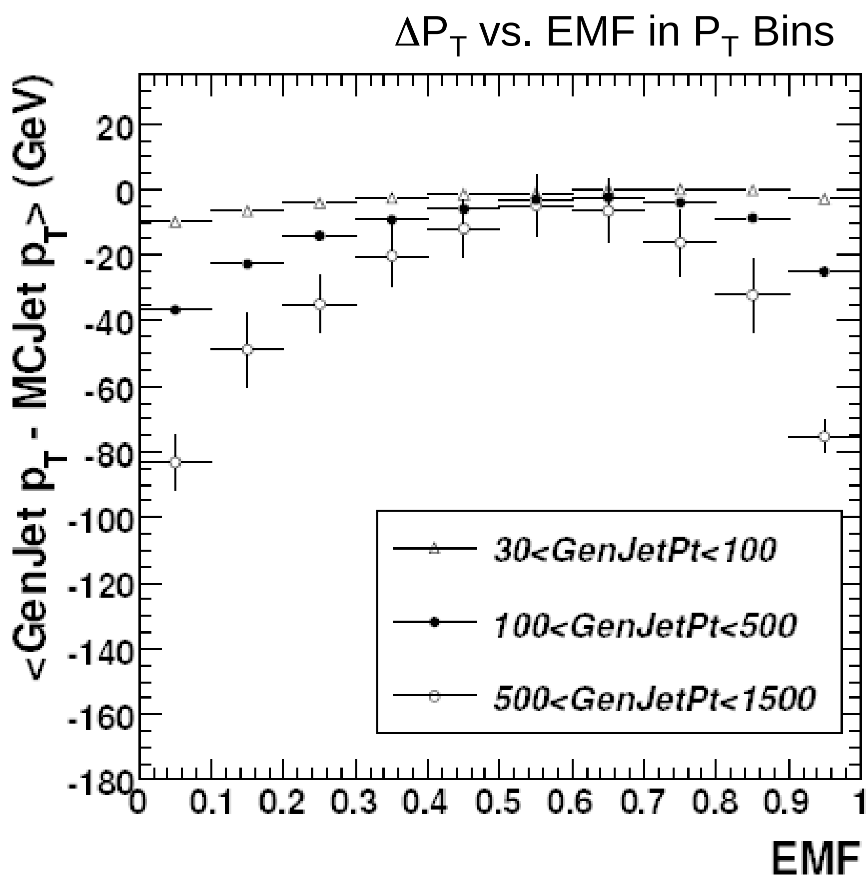
Statistics for 1 fb^{-1}

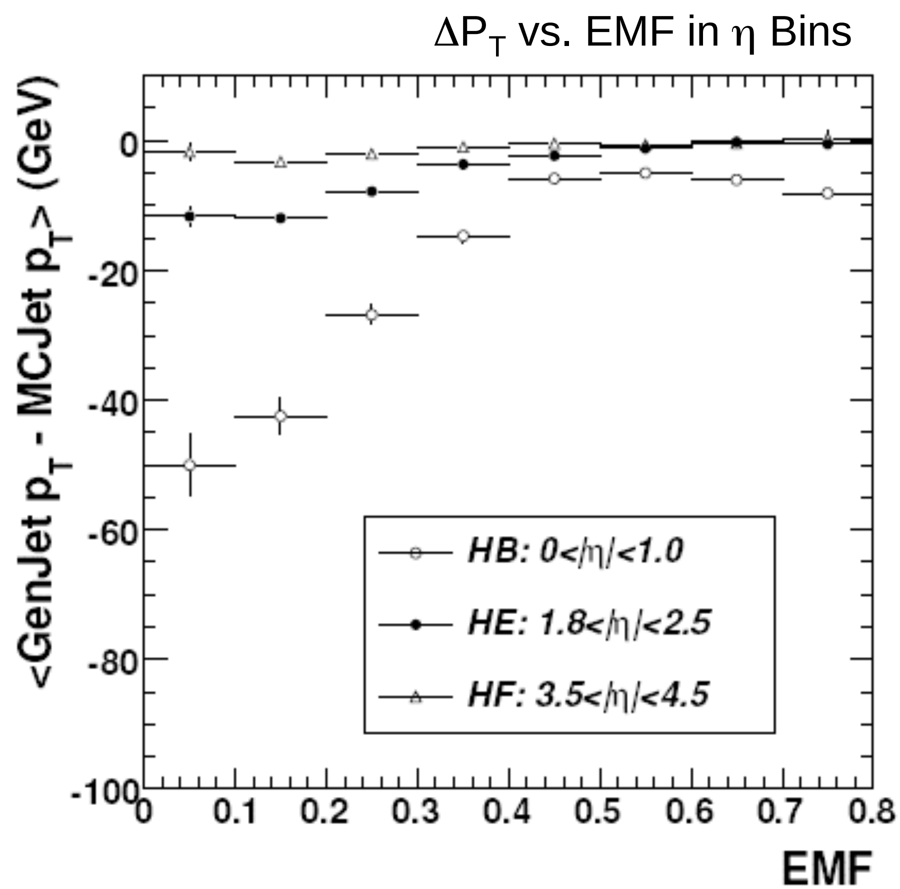


Precision
γ-jet balance for 1 fb^{-1}



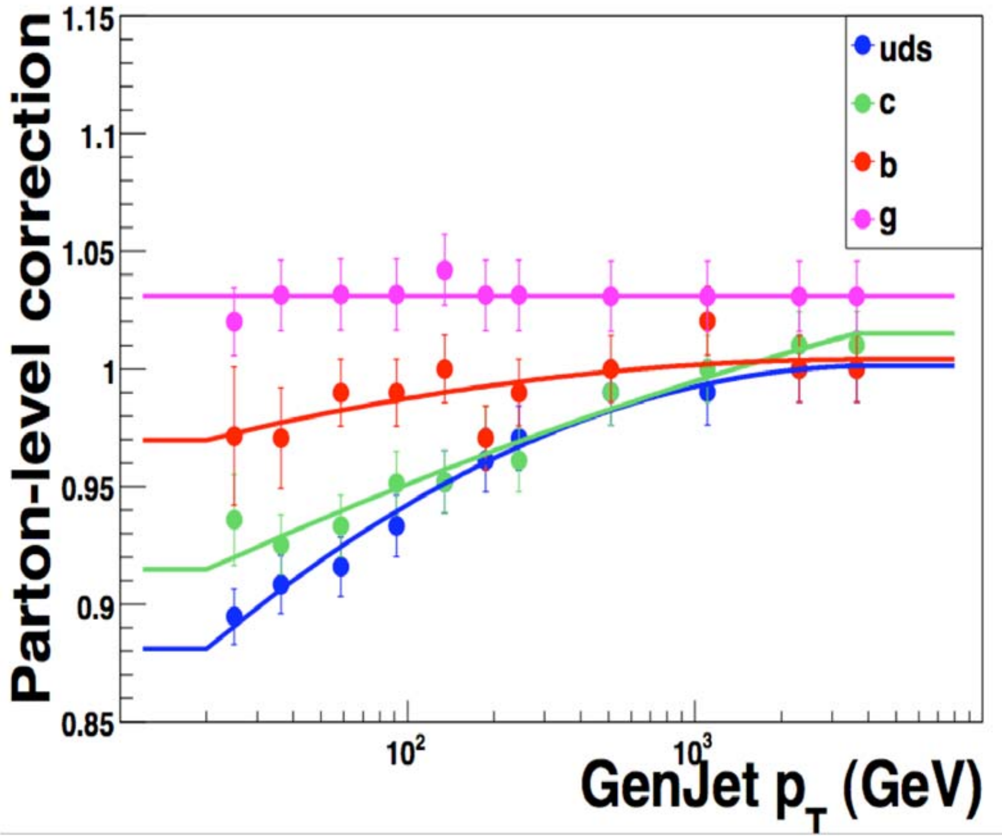
L4: Electromagnetic Fraction

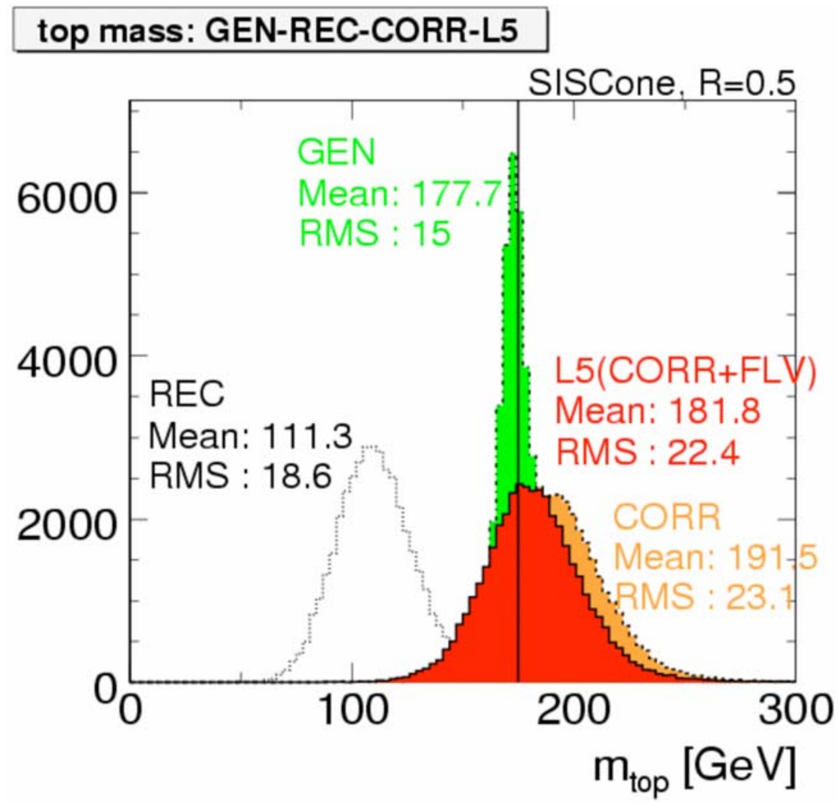




- Corrects uncompensated Calorimeter response

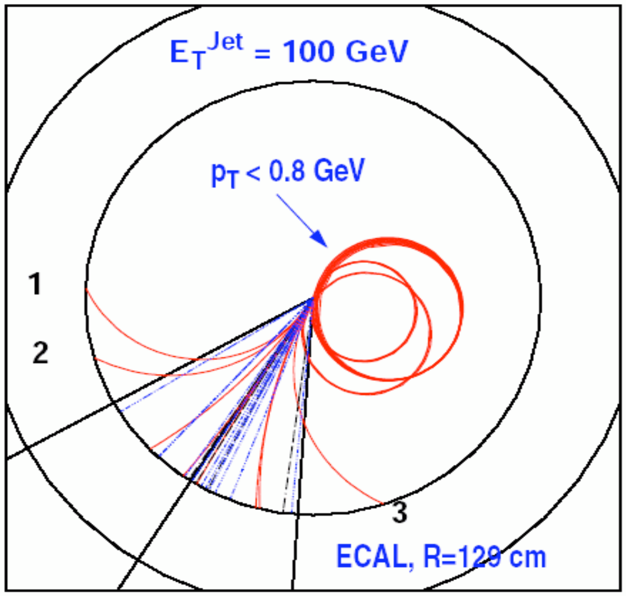
L5: Flavor Corrections



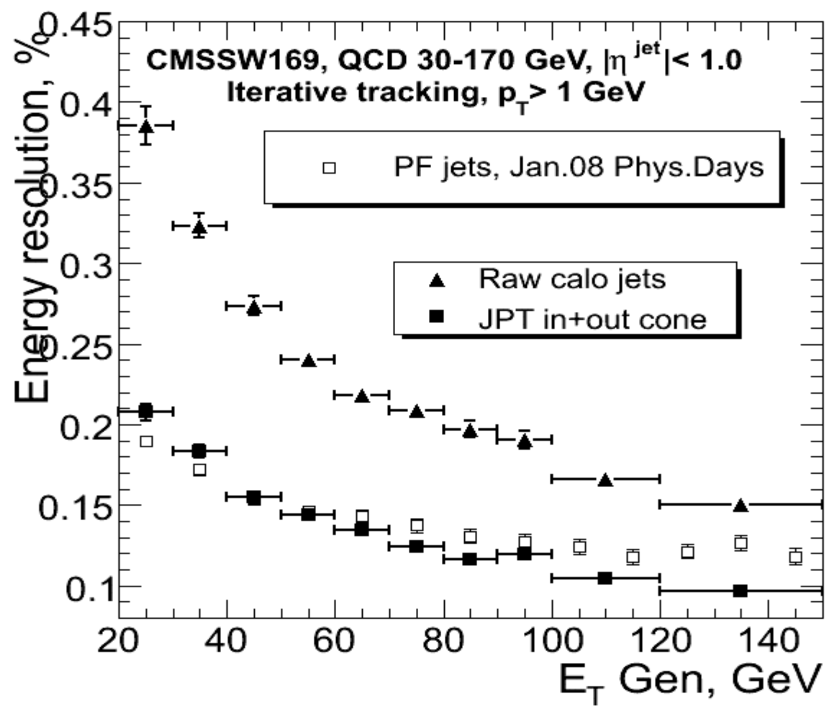


- Scales jet energy to particle level
  - Needs jet flavor hypothesis *a priori*

Track Corrections



1. Reconstruct calorimeter jet
2. Subtract expected response of "in-calo-cone" tracks from calo jet E_T and add track momentum
3. Add momentum of "out-calo-cone" tracks

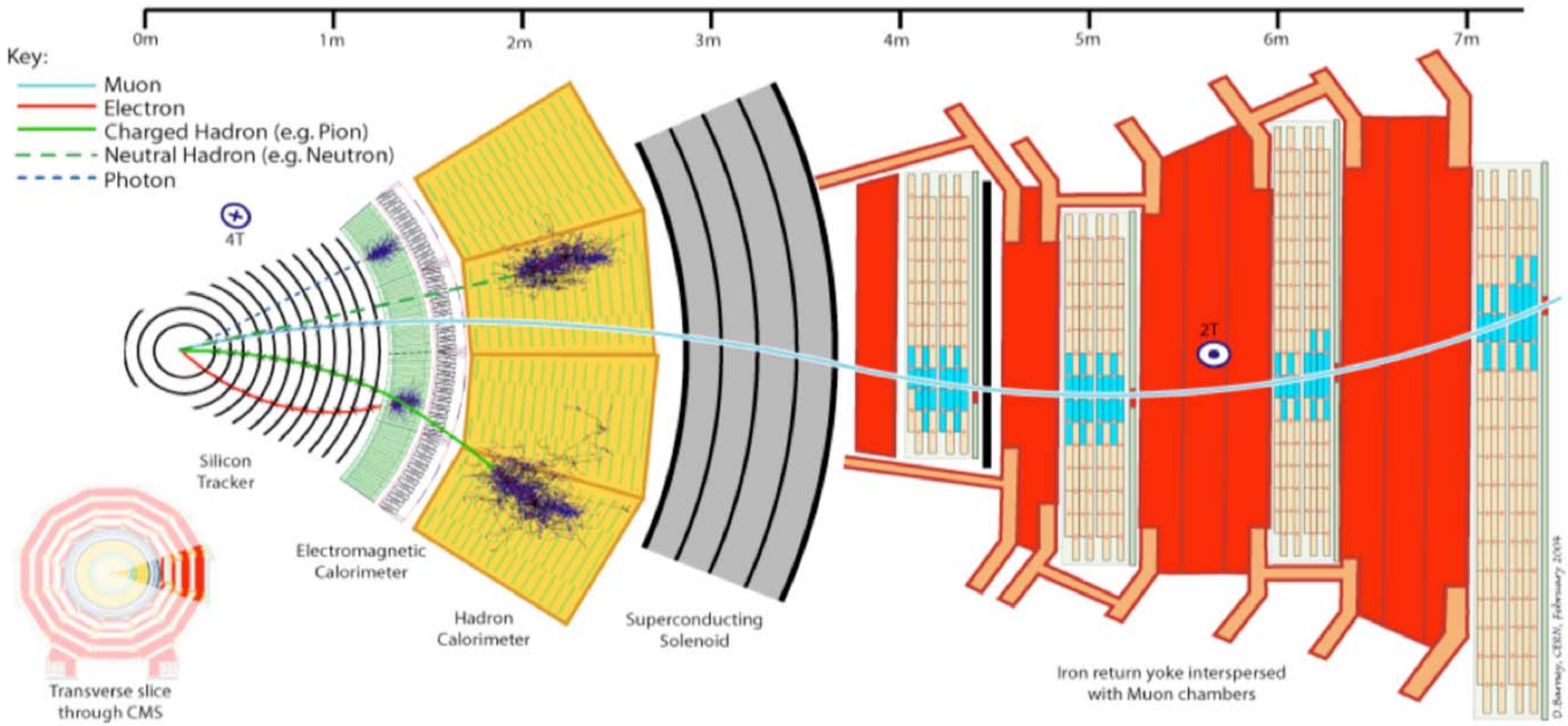


Conclusions

- Jet reconstruction in CMS is mature
  - Infrastructure is stable for years
  - Bells and twisters still being added, further polishing
    - Infinite process anyway
  - Algorithms to be used in CMS analysis are established
    - At least for the beginning of data taking
  - Still flexible enough to accommodate special desires for special analysis
- Jet calibrations are ready for data taking
  - MC based corrections for the very beginning of data taking
  - Calibration data samples and procedures to extract corrections from data ($10pb^{-1}$, $100pb^{-1}$ scenarios)

BACK UP SLIDES

CMS Detector



Jet Energy Clusterization

- We are mostly interested to reconstruct parton level objects parameters basing on visible measurables
  - Direct measurements for muons
  - Corrections for bremsstrahlung / conversion for electrons and photons
  - Multiple steps conversions for quarks/gluons:

original partons

↳hadronization into long living particles

↳showering in EM and HAD calorimeters

↳measured energies

  - Original parton is seen as energy cluster in the calorimeter (and tracker), a.k.a. Jet
  - Algorithms for energy clusters search
    - a.k.a. Jet Reconstruction

FastJet Package

- Stand alone C++ package supported by G.Salam&Co
- Contains
  - Fast implementation of k_T algorithms family
  - SISCone
  - Ancient: MidPoint, JetClu, etc.
  - Newer: anti-kt
- Provide bridges
  - Between different experiments
  - Between experiments and theory
- CMS uses FastJet for k_T, SISCone

Jet Area

- May be well defined for IR safe algorithms only