Plans for Jet Energy Correction at CMS

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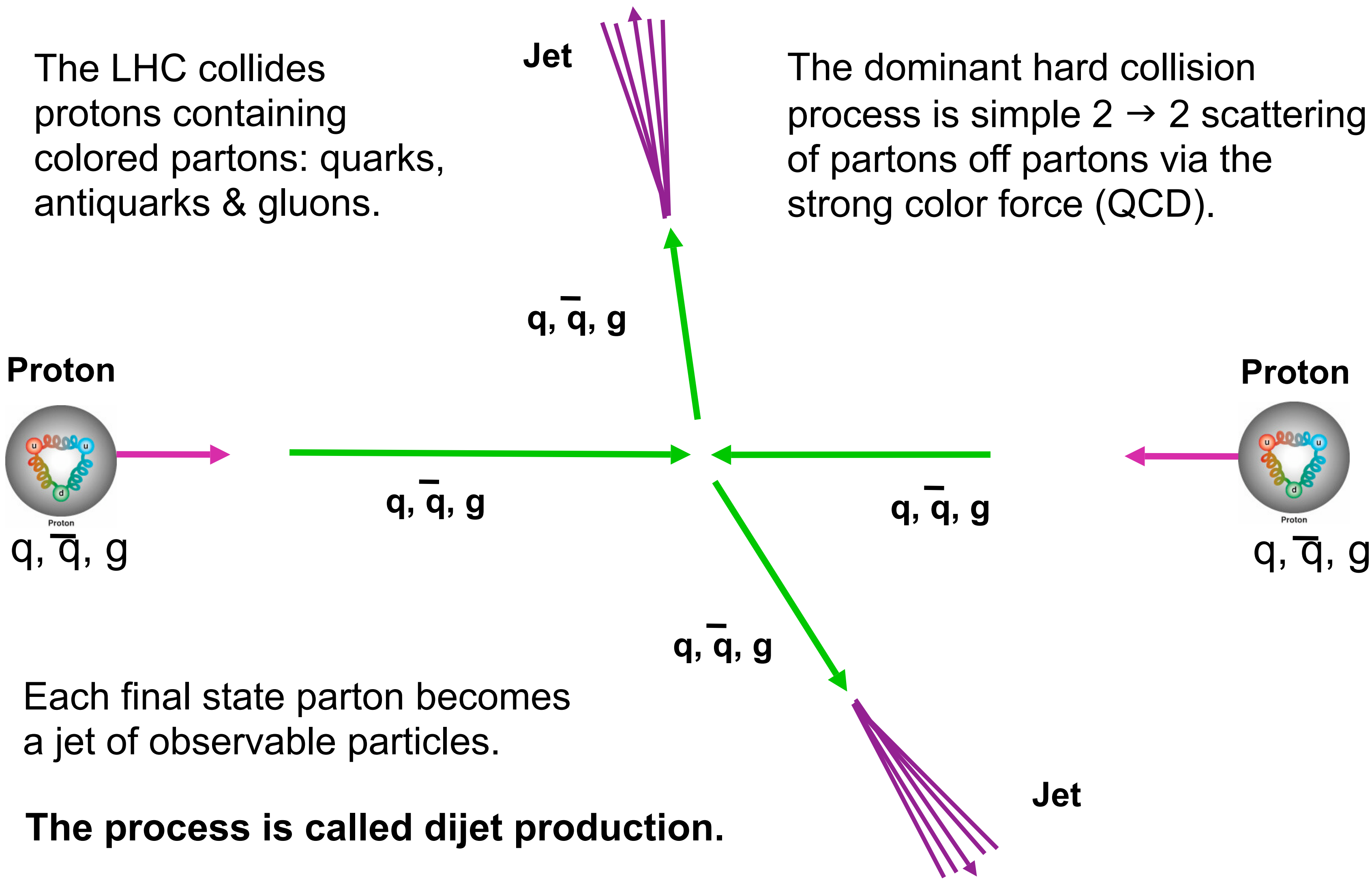
Outline of this talk

- Jets in CMS
- Introduction to jet energy correction
- CMS plans for jet energy correction
- Expected uncertainties at the startup and beyond
- Evolution of the jet corrections with data-taking
- Conclusion

Jets at LHC in Standard Model

The LHC collides protons containing colored partons: quarks, antiquarks & gluons.

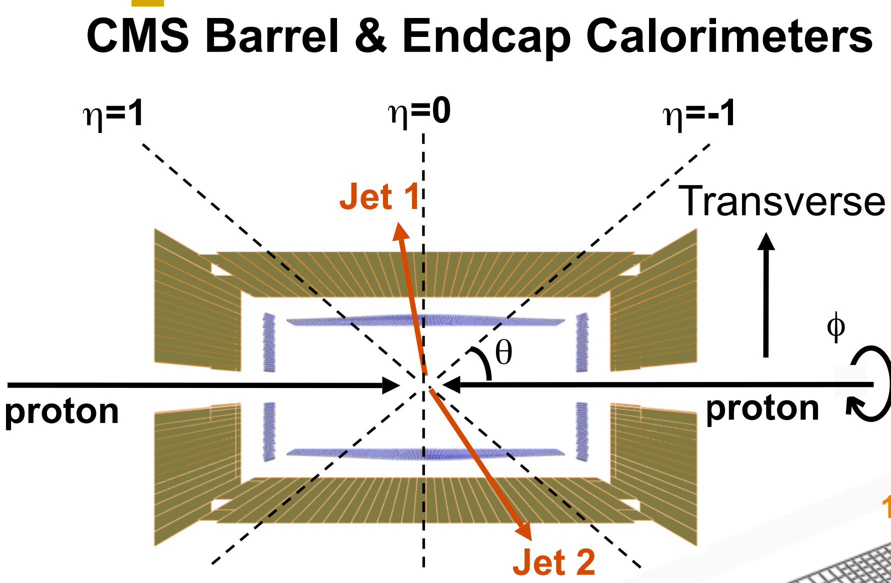
The dominant hard collision process is simple 2 → 2 scattering of partons off partons via the strong color force (QCD).

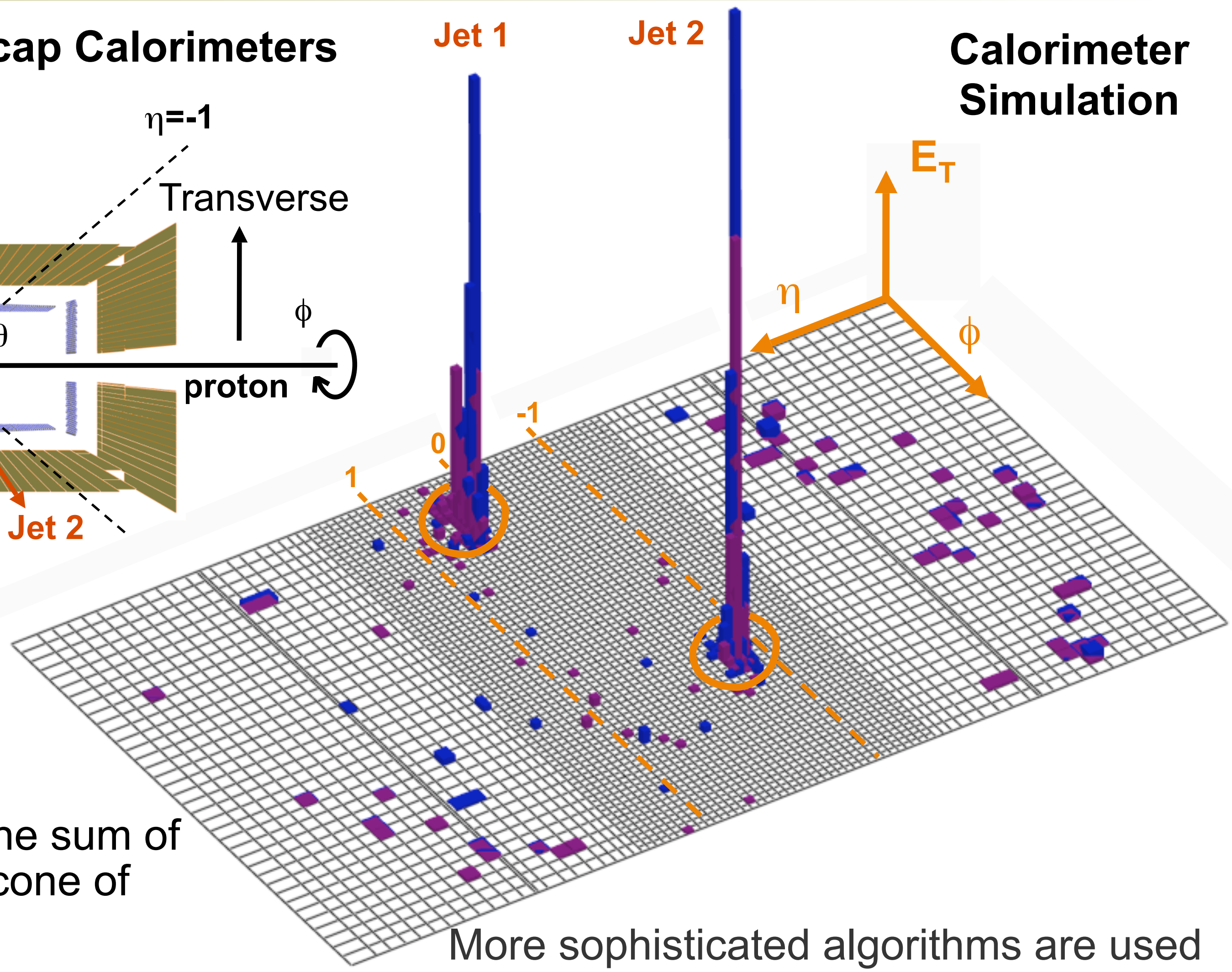


Each final state parton becomes a jet of observable particles.

The process is called dijet production.

Experimental observation of jets



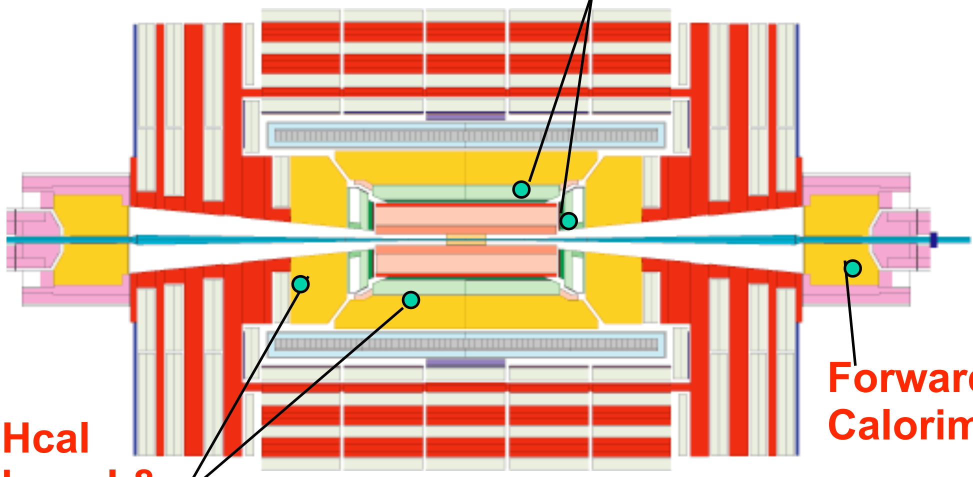


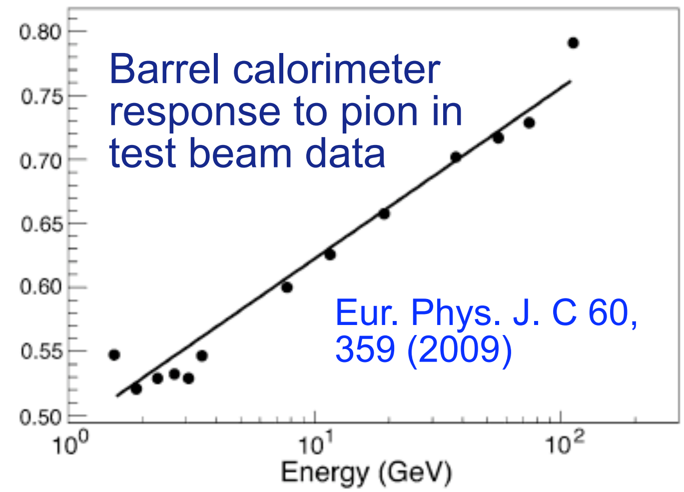
In CMS trigger, a jet is the sum of calorimeter towers in a cone of radius

$$R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.5$$

More sophisticated algorithms are used in offline analysis to reconstruct jets.

CMS calorimeter





- Organized into a barrel (HB)+tail catcher outside the solenoid (HO), endcap (HE) and forward (HF).
- Brass/Scintillator calorimeter (HB $|\eta|<1.3$) organized in wedges ($\Delta\varphi\Delta\eta$=0.087x0.087) with 17 sampling layers on a single fiber.
- Total of ~8λ at $\eta=0$.
- HE covers $1.3<|\eta|<3$ and HF $3<|\eta|<5$.
- Sampling fraction ~ 1%
- Non compensating, non-linear response to hadrons.

$$\frac{\sigma}{E} = \frac{111.5\%}{\sqrt{E}} \oplus 8.6\%$$

Why do we care about jets ?

- ✦Jets are everywhere
- ✦Their cross-section is several orders of magnitude higher than most other processes
- ✦Jets can fake isolated high p_T γ, e, μ, τ signatures

-Probability of jet faking a γ: ~ few 10^{-4}

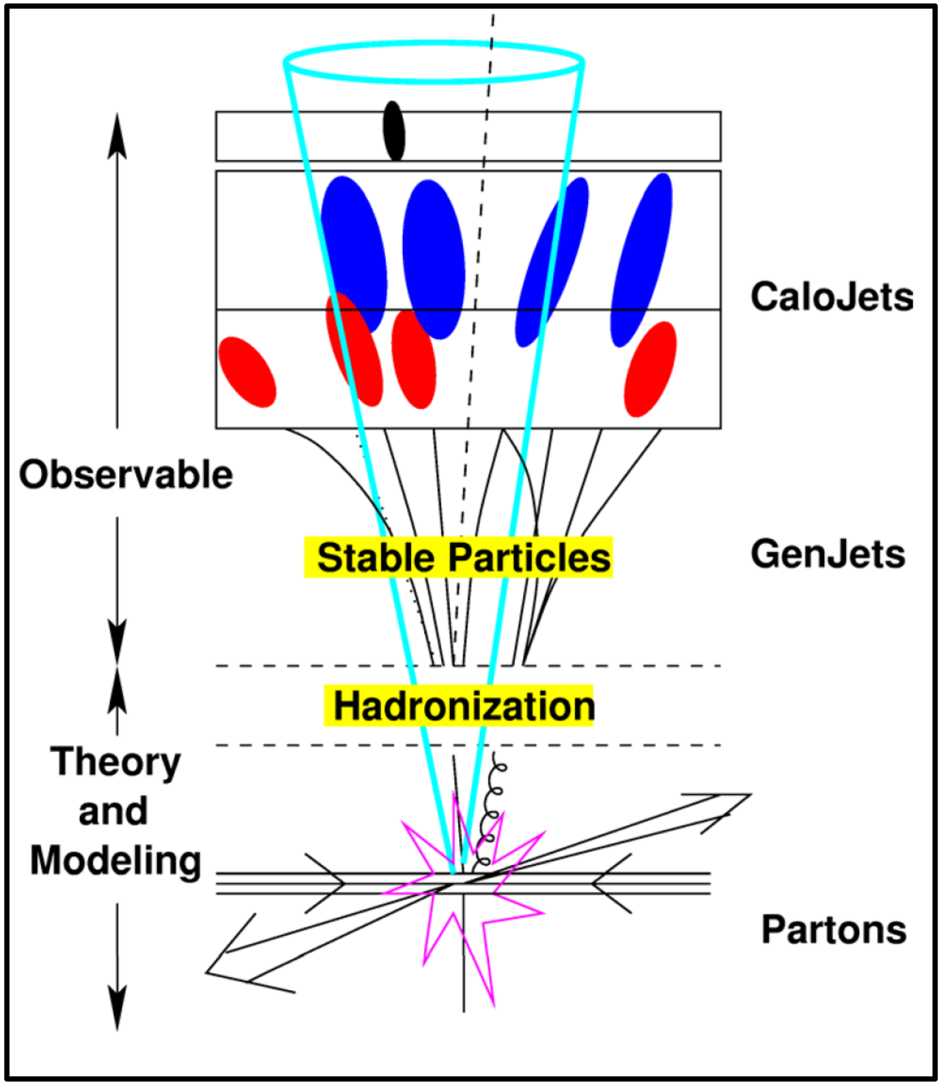
-Probability of faking e or μ ~ few 10^{-5}, but some jets have real lepton, e.g., b-jets

-Probability of faking a τ: ~ few 10^{-3}

- ✦Light quark or gluon jets can fake b-quark signature at the % level
- ✦Missing Transverse Energy (MET) must be corrected for jet energy measurements.

If jets are not your signal they are most certainly part of your background !

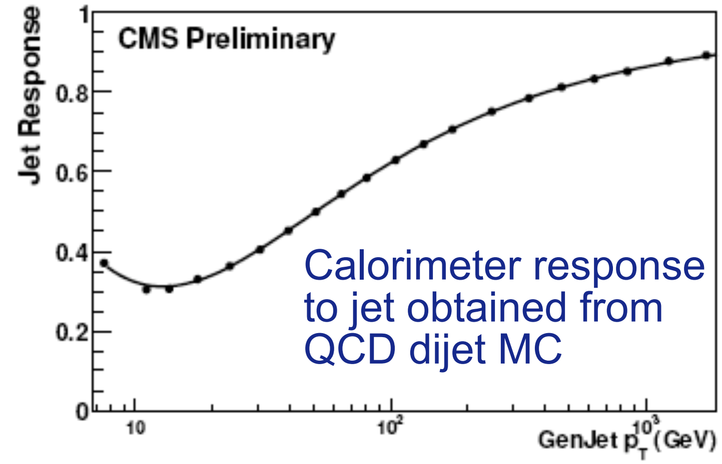
Introduction to jet energy scale



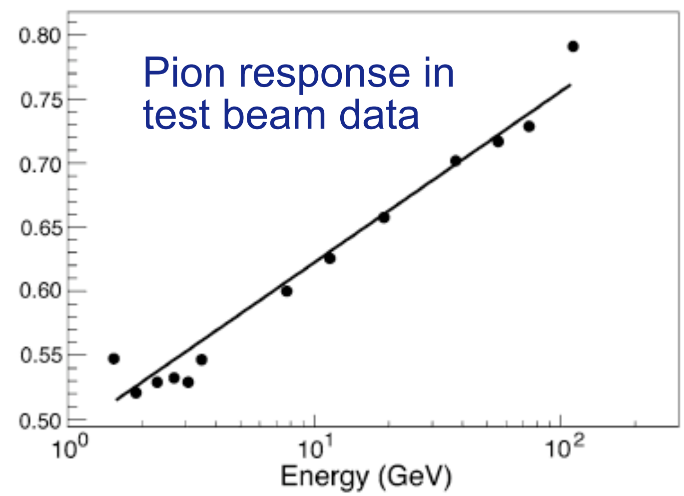
- CaloJets are what we see in the Calorimeter.
- GenJets are made from stable particles, in principle observable.
- Partons participate in hard scatter, but are not observable (colored).
- Correction goal: Correct CaloJets to have the same p_T as GenJets on average.
- In this talk the studies are for Iterative Cone R=0.5.

What is jet energy scale ?

✦We do not see quarks and gluons
- We do not see π, K, η, p, Λ, Ξ, Σ, ...
- How do we go from calorimeter ADC counts to the momentum of the outgoing partons? ⇨ Jet Energy Scale
- We know the calorimeter response to a single pion using test beam data



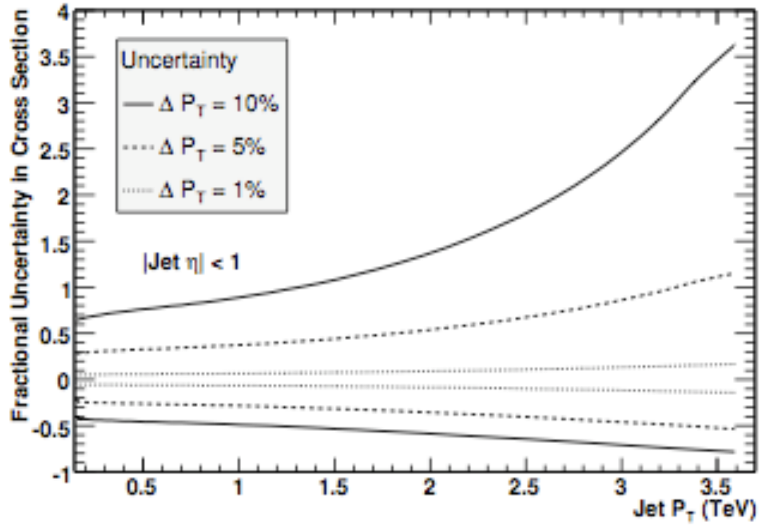
✦Factors impacting the JEC include
- Energy offset (*i.e.*, energy not from the hard scattering process)
- Material in front of the calorimeter
- Out-of-cone showering
- Resolution ⇒ unsmearing



Non-linearity of the response

✦JES uncertainties typically are the largest syst errors in jet measurements.

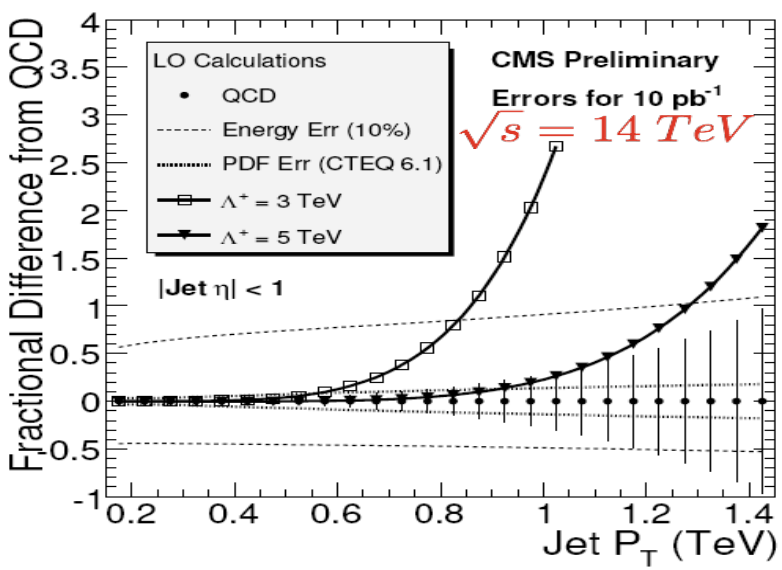
Why the jet energy scale matters ?



An example of SM measurement

Inclusive jet cross section: Typically, uncertainty in JEC translates into an order of magnitude larger uncertainty in the inclusive jet cross-section.

✦Depending on p_T, we expect 5−10% initial uncertainty in JEC.



An example of new physics search

Difference between inclusive jet cross section measurement and QCD prediction

✦Sensitive to **contact interactions**
✦The jet energy scale is the dominant experimental systematic uncertainty.

CMS jet energy calibration

✦ **Default correction to particle level** (removes the detector effects).

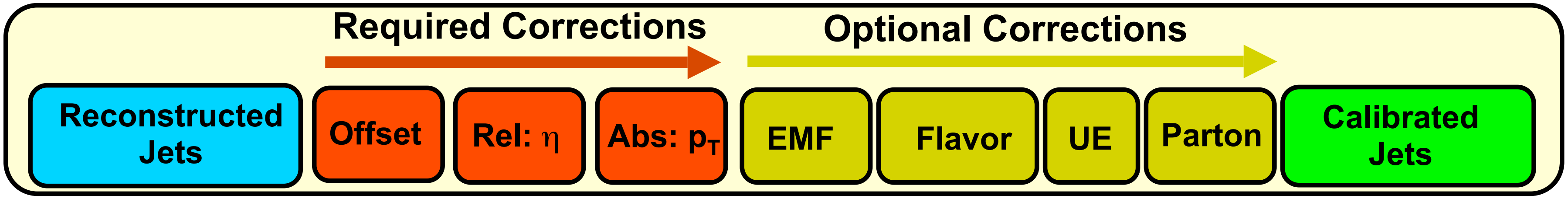
✦ **Factorized approach (like Tevatron):**
- **offset correction** (removes pile-up and noise contribution).
- **relative correction** (flattens the jet response in pseudorapidity).
- **absolute correction** (flattens the jet response in p_T).

✦ **Data driven approach: use of kinematic constraints in pp collision**
- Di-jet balancing.
- γ+jet, Z+jet balancing.

✦ **Optional corrections:**
- electromagnetic fraction dependence.
- flavor dependence.
- parton level.
- underlying event.

✦ **Systematic uncertainty ~10% at startup, improving to ~5% with first data (>100 pb^{-1}).**

Why factorize the corrections ?



- **Plan:** the jet corrections will be factorized
  - Correcting for each factor in a fixed sequence up to a level chosen by the user.
- Factorization facilitates the use of data-driven corrections
  - Breaking the correction into pieces that are naturally measured in collider data:
    - **Offset**: pile-up and noise measured in zero-bias events.
    - **Relative**: jet response vs. η relative to barrel found using dijet balance.
    - **Absolute**: jet response vs. P_T found in barrel using γ / Z + jet.
  - Allows data-driven corrections as they emerge to easily replace MC truth
- Provides a deeper understanding of jet corrections & their systematics.
  - This was the experience of the Tevatron experiments.
- Each factor is a residual correction.
  - Facilitates progress & standardization by not recreating the prior corrections.

Introduction to offset correction

"Harsh" collision environment at LHC

- **Pile-up**
  - Refers to the energy from additional proton-proton collisions, occurring close enough in time to the hard scatter to be included in the calorimeter energy within the jet
  - Statistically independent: not correlated with hard scatter
  - Increases with luminosity
  - The additional energy amounts to 2.5 GeV/10 GeV/200 GeV in a cone of radius 0.5 in the barrel for low luminosity pile-up, high luminosity pile-up and heavy ion collisions, respectively.
- **Calorimeter noise**
  - Refers to any noise above the calorimeter cell and tower thresholds for calorimeter towers included in the jet

Both pile-up and electronic noise produce an energy offset which we plan to subtract from the jet.

Offset correction

✦**Purpose:**

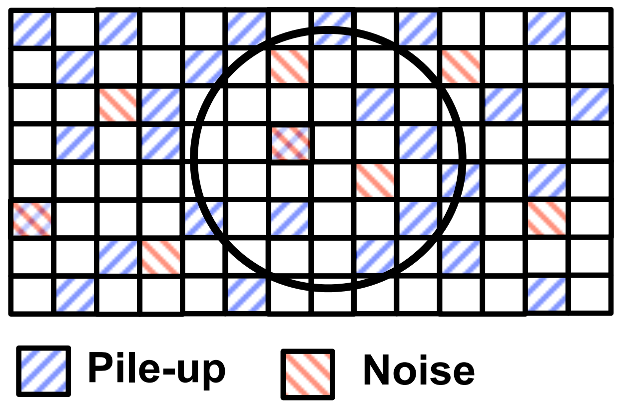
-Correct for energy from noise and pile up

✦**Plan:**

-Measure offset correction directly from early collision data

-In zero-bias collisions, which have the pile-up and noise levels appropriate to the rapidly changing accelerator and detector conditions, measure the energy in a jet area as a function of η

Offset in Jet Area In Calorimeter



The offset correction contains two sub-corrections:

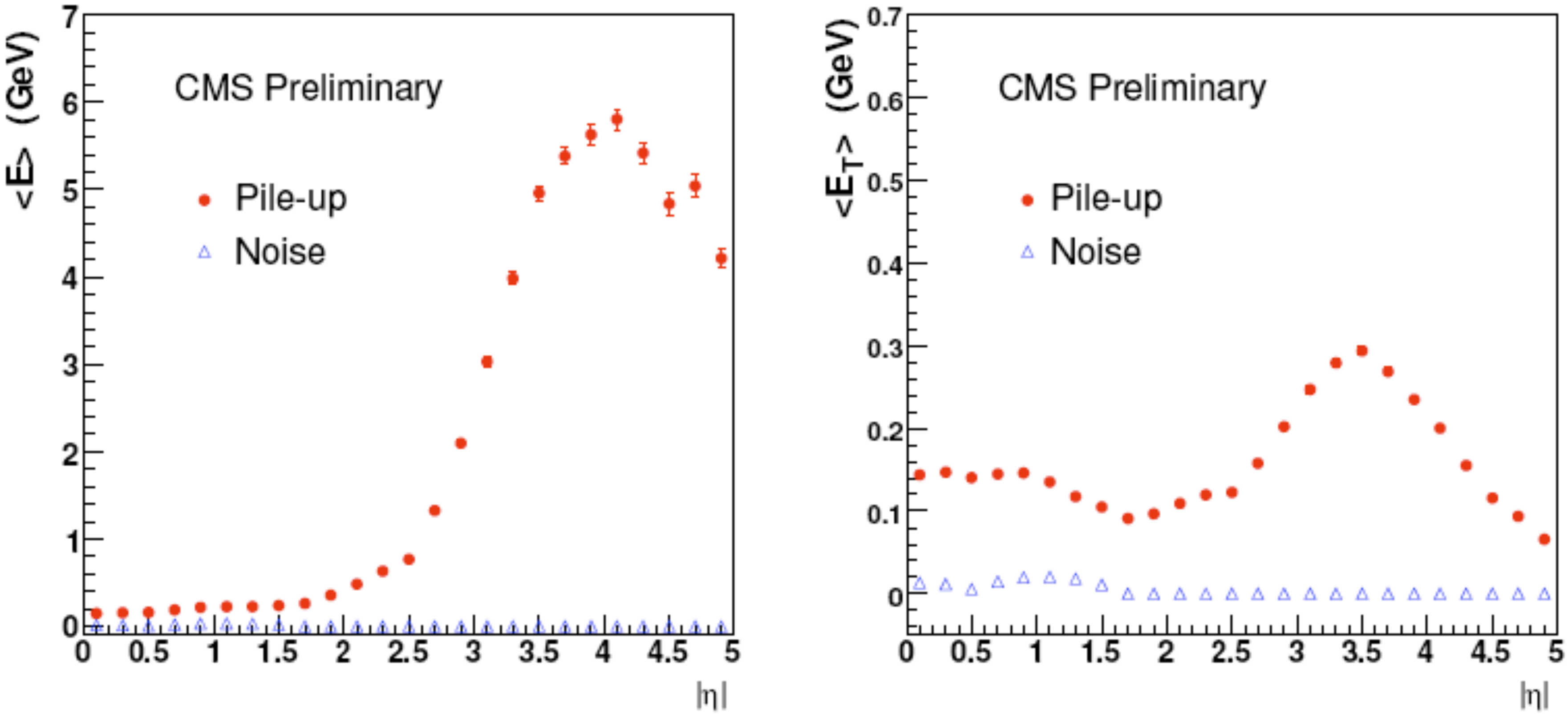
-Correction for the real jet energy lost due to cell and tower level thresholds ("zero suppression correction")

- Can estimate from Monte Carlo

-Correction for jet energy gained due to pile-up ("pile-up correction")

- Need special runs of zero-bias data

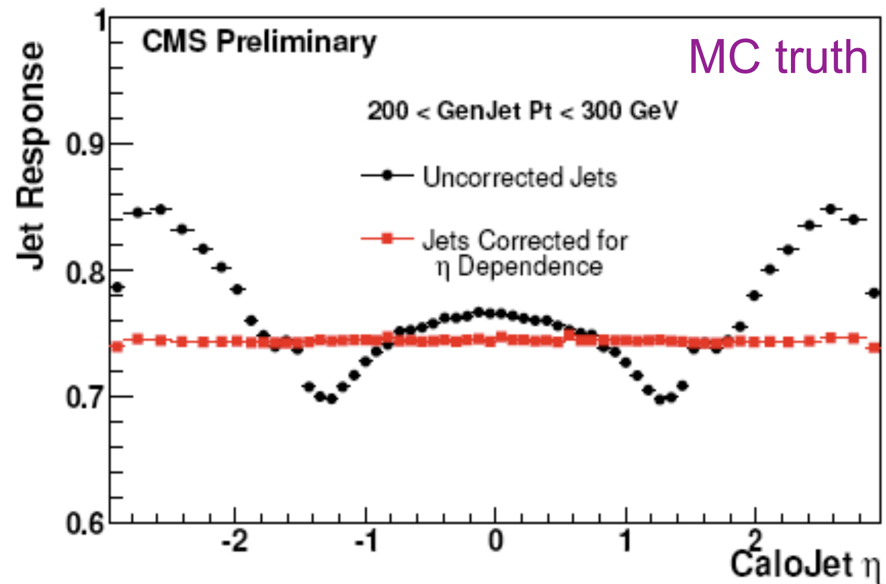
Effect of pile-up and noise



The measured jet energy and transverse momentum expected from electronic noise and pile-up of one additional "minimum bias" event.

Relative correction: η dependence

The relative correction provides answer to the question: if a particle jet with p_T^{gen} at a given η is measured in CMS with p_T^{cal}, what would be measured in the control region for the same input p_T^{gen} ?



✦**Purpose:** Correct for relative response of jets vs. η

- Make response flat vs. η
- Equal to response in |jet η|<1.3)

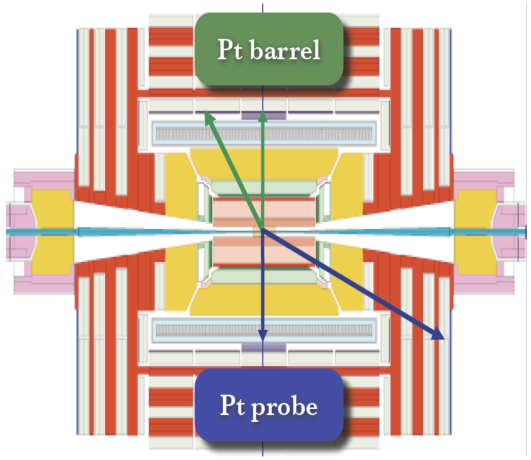
✦ **Plan:**

- Correction from MC now.
- Data-driven corrections when collision data are available.

Why choose barrel as control region ?

- is the easiest to calibrate in absolute terms
- contains the largest statistics
- provides the highest p_T reach given the |η| dependence of the inclusive jet production cross section
- the η dependence in the barrel variates little and smoothly

Relative correction from dijet balance



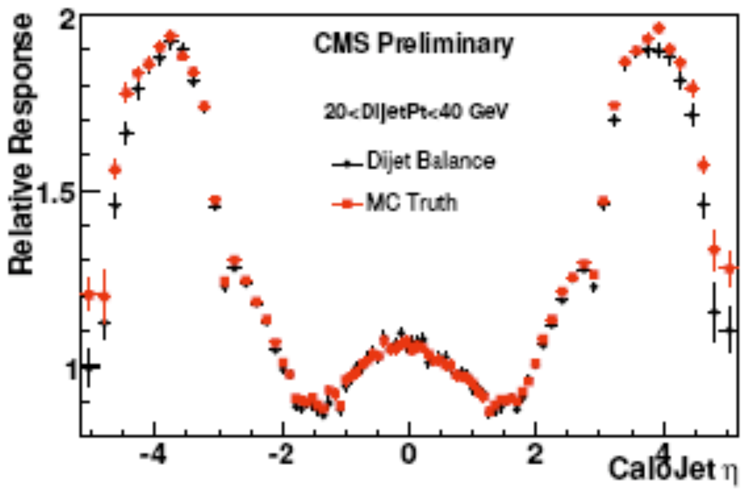
$$p_T^{dijet} = \frac{p_T^{probe} + p_T^{barrel}}{2}$$

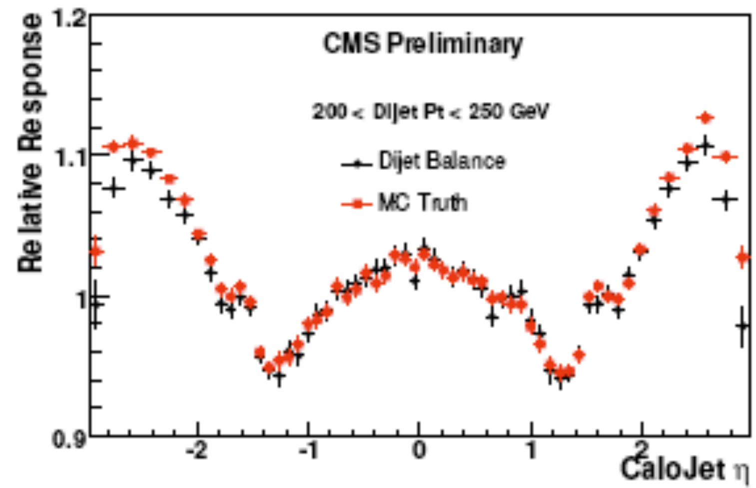
$$B = \frac{p_T^{probe} - p_T^{barrel}}{p_T^{dijet}}$$

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

- Dijet balance uses p_T conservation in data to measure relative response vs. η
  - Relative response = response as a function of η / average response in the barrel
  - Technique from SPS refined at Tevatron
- Select clean dijets for balance measurement
  - Require $\Delta\phi$ between the two jets to be close to 180^o
  - Cut hard on 3rd jet p_T
- Plan to use with first data to measure correction for η dependence.

Data-driven relative correction





✦The above figures show relative jet response determined as a function of η in two ways: from MC truth and from dijet p_T balance.

✦The response values obtained by the two methods agree to within 1% for the barrel (|η| < 1.3), 2−3% for the endcap (1.3< |η| <3), and 5−10% for the forward (3< |η| <5).

✦The agreement improves when we tighten the cut on ΔΦ and 3rd jet p_T, nevertheless, we believe this is roughly the size of the systematic uncertainty in the dijet balance technique.

Absolute correction: p_T dependence

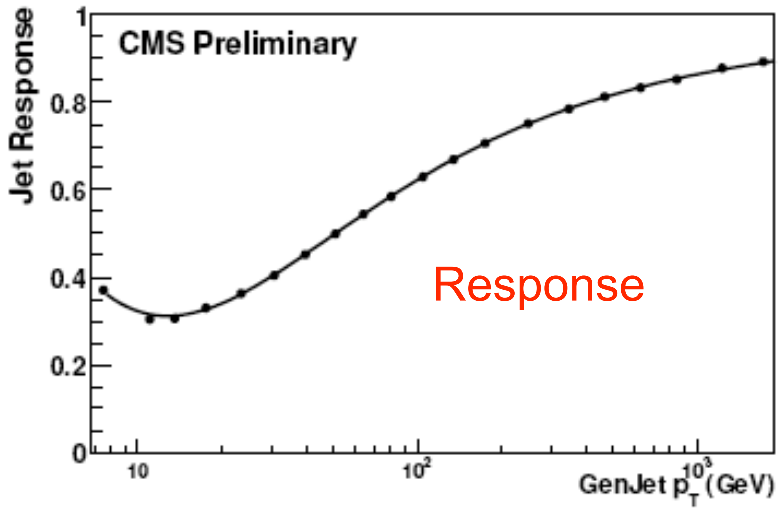
✦**Purpose:** Flatten the absolute jet response of calorimeter vs. p_T

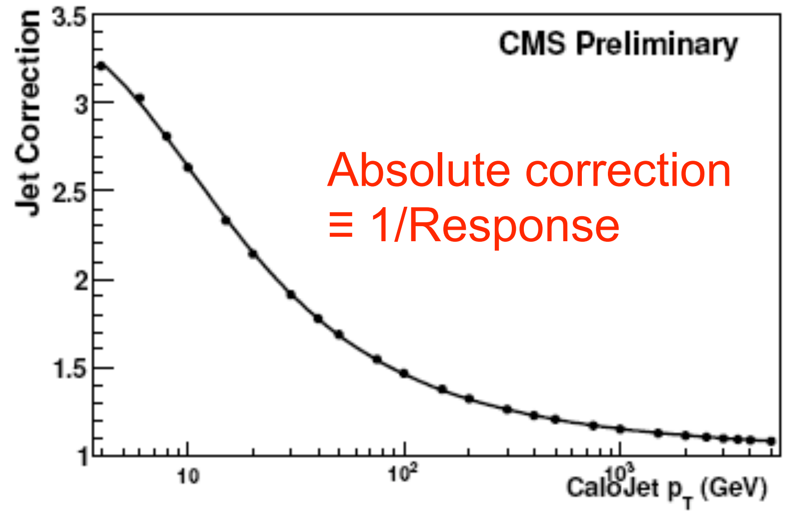
-Corrects energy of jet back to the particle level in control region ($|\eta|<1.3$)

✦**Plan:**

-Develop data driven corrections.

-Use correction from MC until data driven corrections are available from collision data.



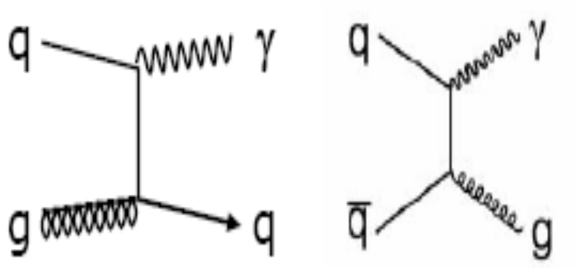


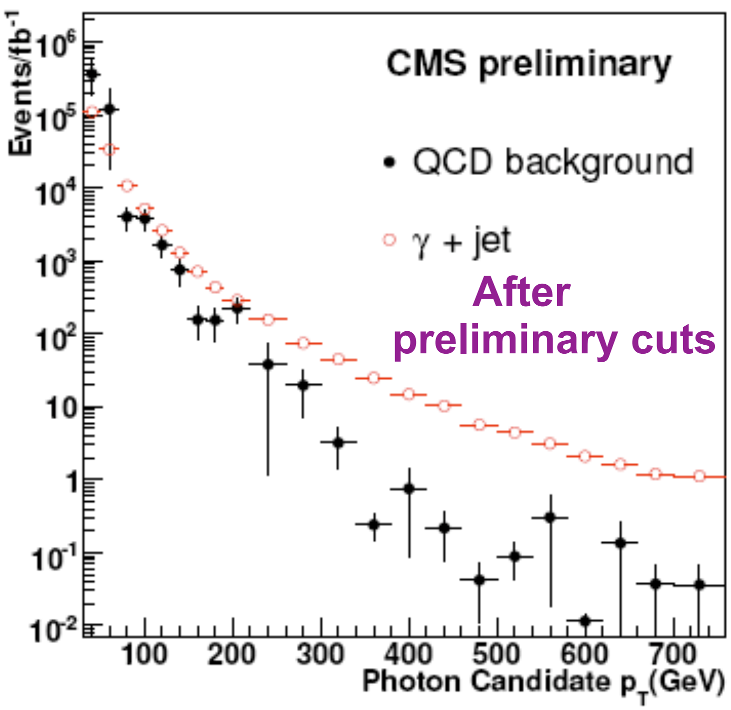
- Depends on transverse momentum: the jet response is ~ 60% for 100 GeV/c jets, ~ 80% for 1 TeV/c jets.
- Non-linear jet response in the barrel reflects non-linearity of the calorimeter response.

Absolute correction from γ/Z + jet p_T balance

- **Plan:** measure absolute jet correction from p_T conservation in γ/Z + jet process.
  - Jet in the control region: $|\eta| < 1.3$
  - Use standard γ / Z reconstruction (will get to it later)
  - Select clean events with
    - $\Delta\phi > \pi - 0.2$,
    - extra jet $p_T < 0.1\, p_T^{\gamma}$ ($0.2\, p_T^{Z}$)
- γ + jet p_T balance
  - The γ p_T is measured in ECAL, which is calibrated using test beam electrons and with *in situ* calibrations with $\pi^0 \to \gamma\gamma$, $Z \to e^+e^-$, $W \to e\nu$
  - Can measure absolute jet correction up to $p_T < 600$ GeV/c with 100 pb^{-1} integrated luminosity.
- Z + jet p_T balance
  - Z p_T is measured precisely in the ECAL (for $Z \to e^+e^-$ channel) or in the muon chamber (for $Z \to \mu^+\mu^-$ channel)
  - Can measure absolute correction up to $p_T < 300$ GeV/c with 100 pb^{-1}.

Absolute correction: γ + jet p_T balance





✦The photon+jet events are well suited for the first calibration of the absolute jet energy scale at CMS.

-will be available in large numbers at the start-up, and benefit from precise calorimetry of the ECAL.

-This channel also benefits from the accumulated jet energy calibration experience of the Tevatron experiments.

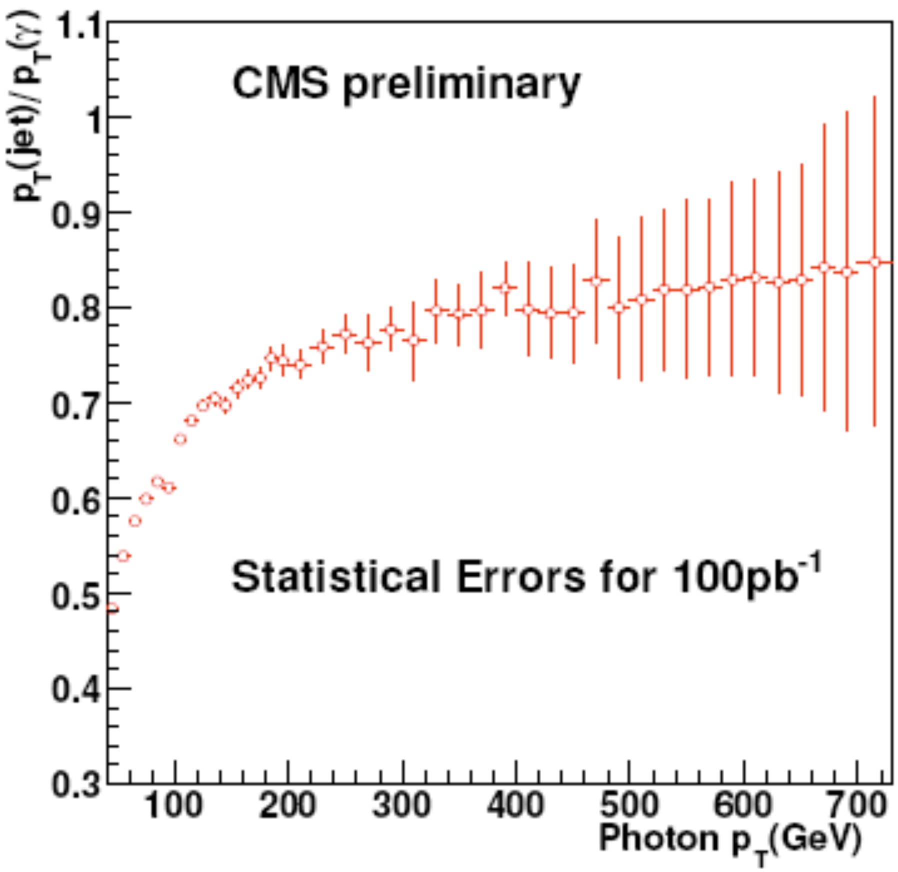
✦The main background is the QCD dijet events where one jet is misidentified as a photon.

-To reduce this background, we consider only isolated photons

-The photon isolation requires minimal activity in the tracker, ECAL, and HCAL in a cone around the photon candidate

Absolute correction: γ + jet p_T balance

Jet response in γ+jet events



- The jet response in γ+jet events is ~ 60% for 100 GeV/c jets and ~78% for 500 GeV/c jets.
- Since in the region $p_T^\gamma < 100$ GeV/c, the signal to background ratio is less than 1, the systematic error is expected to be large. In this region, Z+jet p_T balance will provide important contribution to the determination of absolute correction.
- Above $p_T^\gamma > 200$ GeV/c, the QCD background is small and therefore the systematic error should be under control (a few percent).

Absolute correction: Z+jet p_T balance

✦These events allow us to reach lower P_T range (10-300 GeV/c with 100 pb^{-1}) than photon+jet and also cross check photon+jets results.

✦Use both $Z \to \mu^+\mu^-$ + jet and $Z \to e^+e^-$ + jet samples.

✦Plan to combine corrections derived from γ+jet, $Z \to \mu^+\mu^-$ + jet, and $Z \to e^+e^-$ + jet samples into a single absolute correction.

✦Event selection:

-Consider only isolated electron/muon candidates, requiring minimal activity in the tracker, ECAL, and HCAL in a cone around the candidate

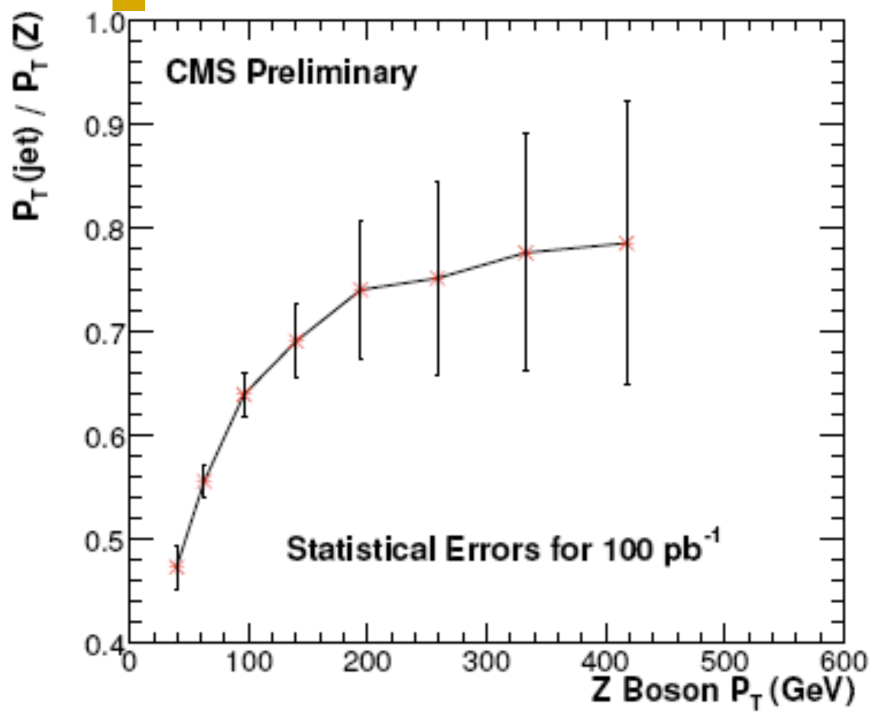
-Require muons reconstructed in the muon chambers to be matched to a track

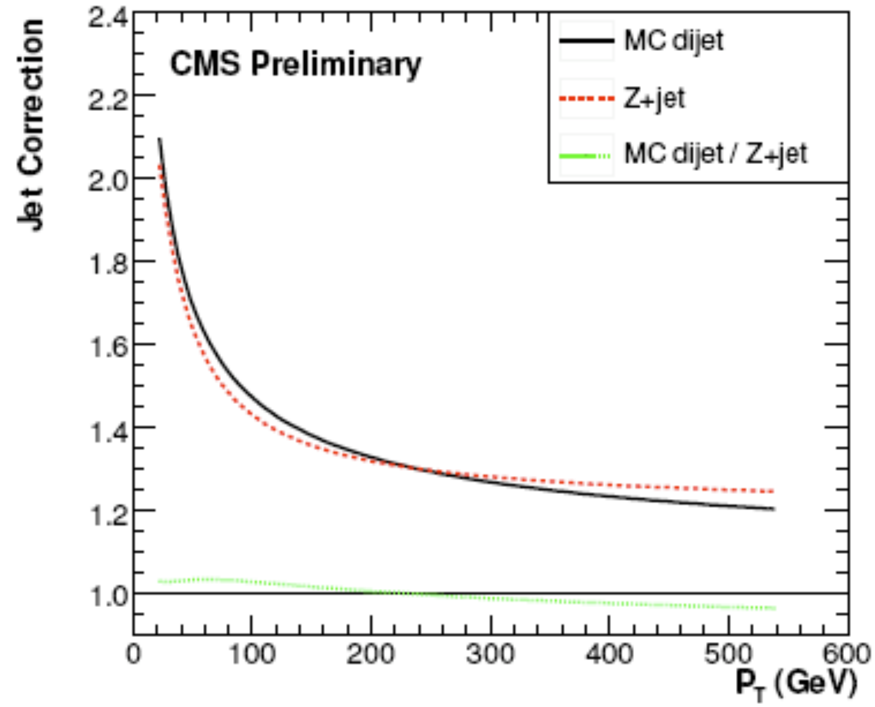
-For electrons, require a super cluster in the ECAL to be matched to a track.

-Require the dilepton invariant mass to be close to the nominal Z mass

✦Negligible background (about ~ 2−3 %) after all selection cuts. Mostly from QCD dijet events.

Correction from Z+jet p_T balance





Corrections derived from Z+jet p_T balance and from QCD dijet MC truth are the same to within 5% for p_T>100 GeV/c. The small difference is expected due to two effects:

- In the p_T balance measurement the conservation of momentum holds at the parton level, whereas in MC truth measurement at the particle level.
- The mix of quarks and gluons are different in the two samples.

Steps to measure absolute correction

- γ / Z + jet p_T balance
  - Measures jet corrections to the parton level for special mix of quarks/ gluons.
  - Doesn't measure jet corrections over the complete p_T range needed.
- Need to transform corrections to particle jet level for a "generic" jet
- Need to extrapolate to higher jet p_T we need for QCD jet analysis.

Plan

- Measure nominal correction ($p_T^{\gamma,Z}$ / p_T^{JET}) for γ and Z.
- Transform to jet correction at the particle jet level for QCD dijet mix of quarks and gluons using the MC
- Combine converted corrections together based on errors
- Extrapolate to higher jet pt with the QCD MC correction curve

Applying corrections to physics analysis

- In physics analysis one is interested in the final correction as a function of the corrected p_T after applying all the required corrections

$$p_T^{cor} = Abs(p_T \cdot Rel(\eta, p_T)) \times Rel(\eta, p_T) \times p_T$$

Absolute correction is applied to the jets which have already been corrected for η dependence

Relative correction is applied to the jets which have already been "offset" corrected

Offset correction is applied to the uncorrected jets

- The combined correction brings back the jet to the particle level.
- Since the absolute correction is a monotonically decreasing function of p_T, the induced error by the relative correction on the fully corrected jet is always smaller than the error of the relative correction itself (anti-correlation): if a jet is overcorrected by the relative correction it will be corrected less by the absolute correction and vise versa.
- The largest uncertainty comes from the absolute correction.

Flavor correction

✦ The optional flavor correction is intended to correct a jet to the particle level assuming the jet originated from a specific parton flavor

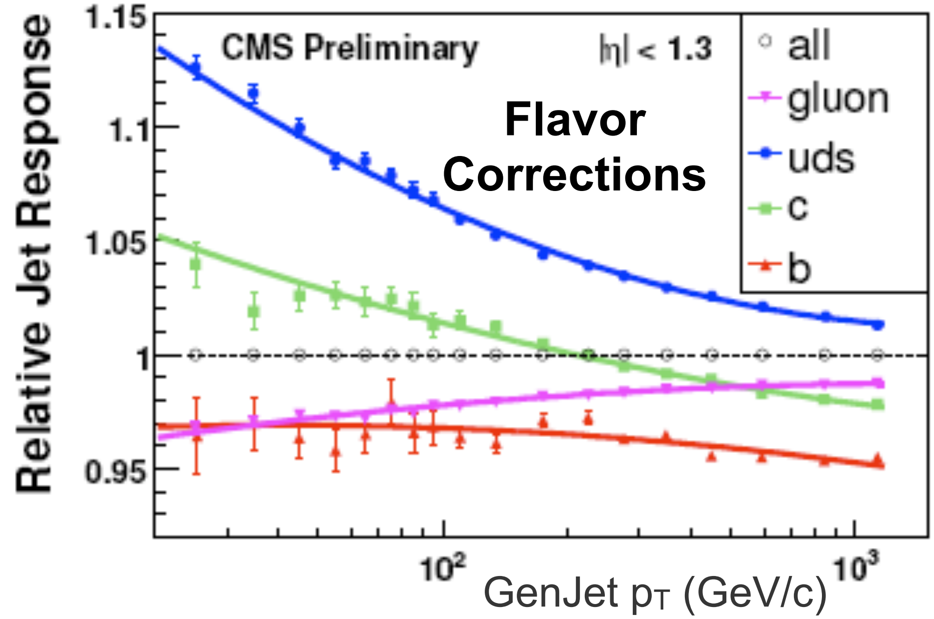
–Light quarks have higher response than gluons because they fragment into higher momentum particles

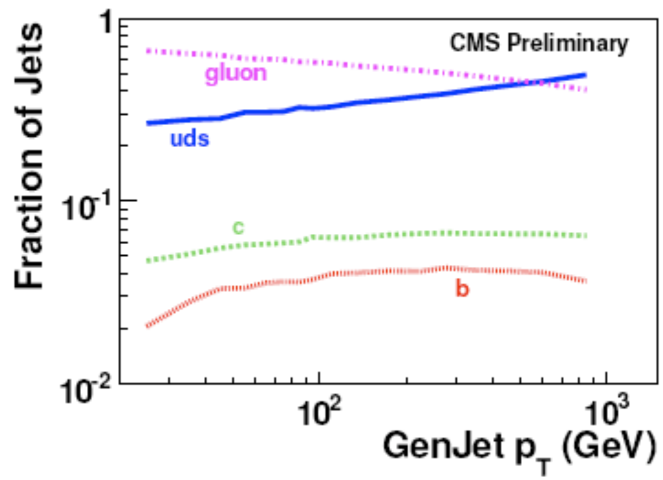
–QCD dijet events have mostly gluons

– γ /Z + jet events are rich in quarks, have higher jet response

✦ Presently flavor correction developed from MC truth

✦In real data, can be done in situ from samples like ttbar.





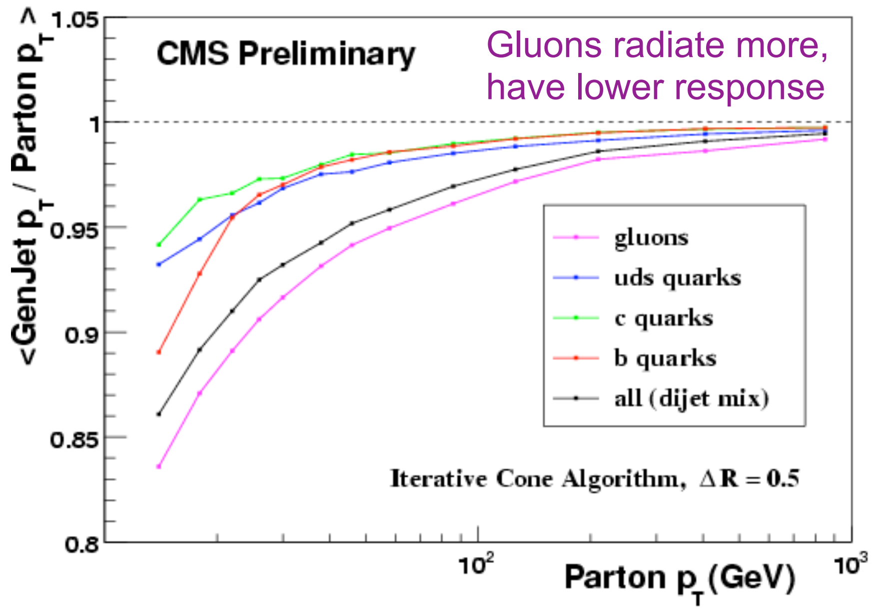
The fraction of jets from each flavor in the QCD dijet sample

Parton corrections

- The parton correction attempts to correct the jet back to its originating parton after the previous corrections.
- Conceptually intended to provide correction between the GenJet and parton level jet for any parton shower and hadronization effects, but excluding the underlying event and flavor effects.
- Remember γ/Z+jet p_T balance corrects back to the parton level.

-The absolute correction is defined to the particle jet level, therefore, the need for parton correction.

-Purely MC based.



Ambiguities

- The correspondence between a jet and a parton is not always well defined.
- Jets are massive and partons are massless, so a simple scaling of the Lorentz vector is not strictly correct.
- Amount of final and initial state radiation in a GenJet depends on the process, parton flavor, and the jet size.

Evolution of corrections and syst. uncertainty

- ✦Jet corrections at CMS are currently derived from simulation using data-driven techniques.
- ✦Systematic uncertainty and bias in the techniques are being studied, but will likely be dominated by effects in real collider data we cannot anticipate in advance.
- ✦We expect from prior HEP experience that a systematic uncertainty of ~10% on JEC is achievable initially using simulation tuned on particle beam data.
- ✦Once collision data is available we plan to derive corrections from data, and simultaneously constrain the uncertainty in MC. We expect that this process will allow to reduce the systematic uncertainty to ~5%.
- ✦The long term JEC with a target uncertainty of ~1% will probably take significant time and effort to achieve, and will be based on both well understood samples of collider data and a highly tuned data-driven simulation.
- ✦The strategy and plan will evolve over time.

Jet correction & trigger

✦CMS does not plan to include JEC into jet triggers at the startup.

✦Observed large jet response variation in η has important implications for triggering on jets

-The same threshold applied to the uncorrected jet p_T in trigger corresponds to different corrected values in different sub-detector regions.

-When triggered on uncorrected jet p_T, vastly different jet trigger rates are expected in, e.g., the forward region (HF) than in the barrel (HB).

-It is desirable to take out η non-uniformity at the triggering stage

-BUT do not want to introduce large biases in the distributions of jets, which may prove to be difficult to correct later at the analysis stage

✦Therefore, we plan to apply a simple factor of 0.7, as determined from MC, to HF towers at the triggering stage.

✦Will also take a few fills of data without any correction factors applied to the calorimeter towers to have a control sample of raw data with which we can study for any possible biases.

Conclusions

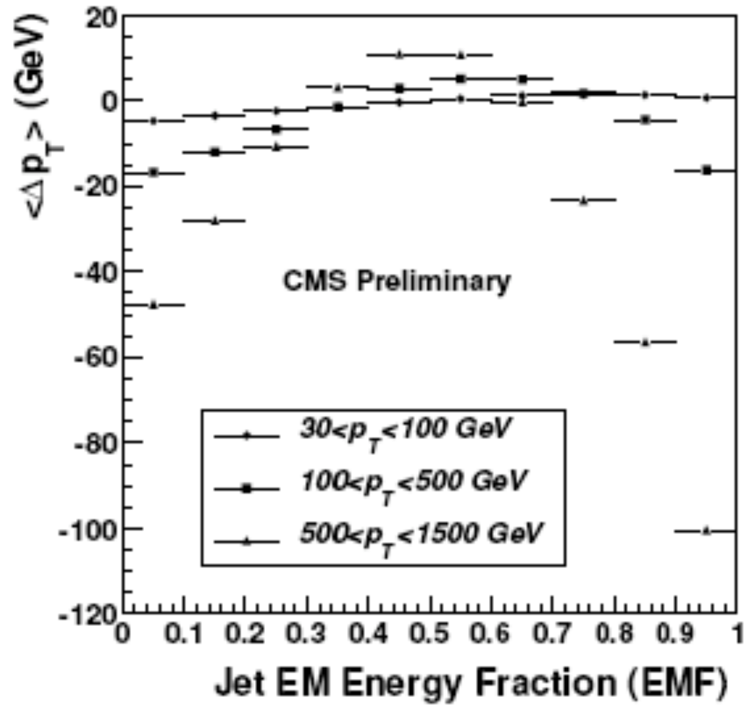
- There is a plan in place for jet energy corrections at CMS
  - -With plots to describe the correction techniques
- The experience of prior experiments, especially the Tevatron, has been applied to the CMS environment in developing this plan.
- The most important feature of the plan is the factorization of the jet energy correction into a fixed sequence of sub-corrections
  - -Required corrections: offset, relative (η), absolute (p_T)
- Jet corrections at CMS will be mostly data-driven
  - -Will measure many of the sub-corrections directly from collision data
  - -Data-driven techniques agree with MC truth and await real data
- The correction techniques and plan will evolve over time.

Backup

EMF correction

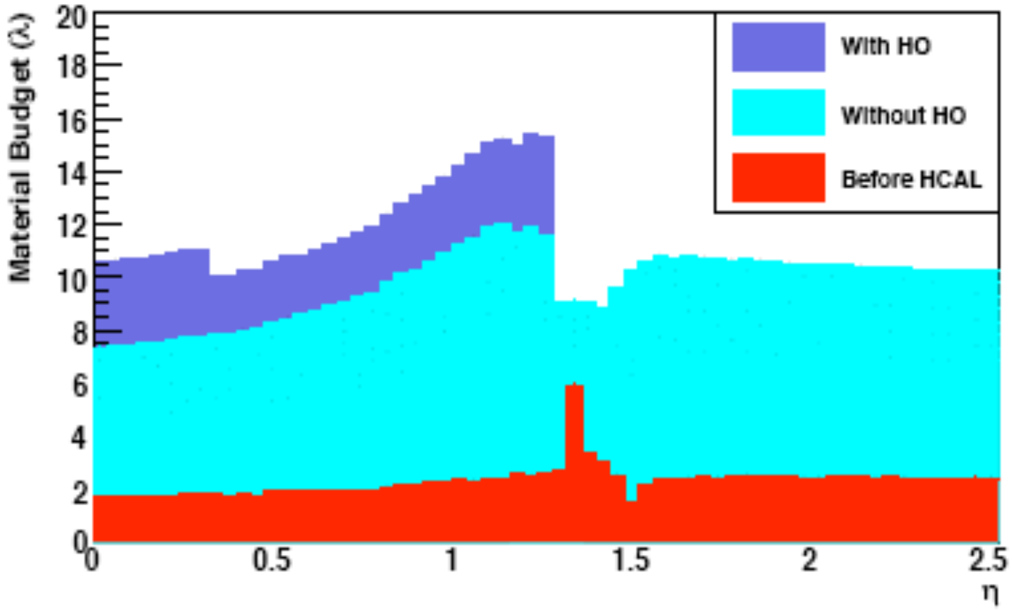
✦EMF represents the fraction of energy deposited by a hadron in the ECAL.
✦In addition to energy, EMF depends on details of the detector elements and incident angles of particles, since these can modify the sampling of showers in the calorimeter.
✦The definition of the EMF dependent correction is the difference between GenJet p_T and corrected CaloJet p_T as a function of the EMF.
✦Plan to apply an EMF-dependent correction after offset, relative, and absolute corrections.
✦An optional correction, developed from MC truth, for CMS physics analysis requiring optimal jet resolution.

Difference between GenJet p_T and corrected CaloJet p_T as a function of the EMF for three different p_T regions.



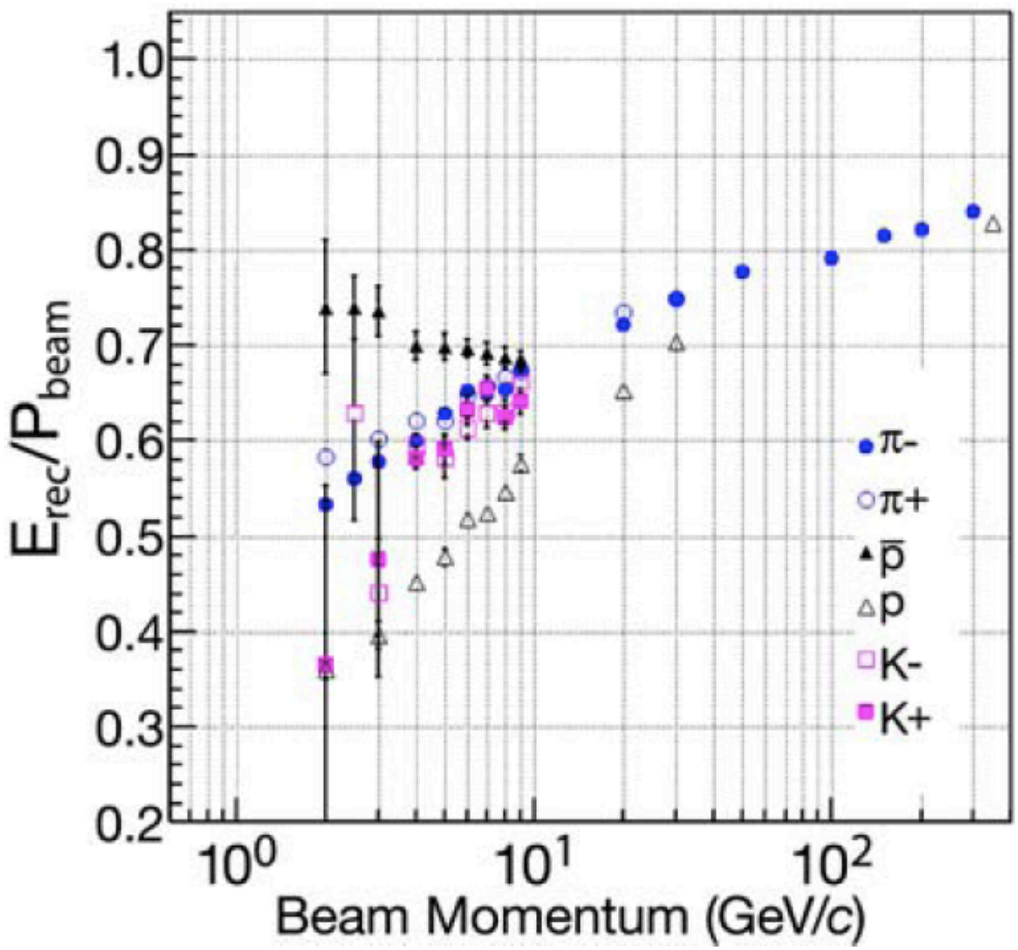
Material budget of the calorimeter

Thickness of HCAL in terms of interaction lengths



7-8 Interaction Lengths at η=0 with HCAL alone and is insufficient to fully contain the shower generated by pions above 100 GeV

Calorimeter response in test beam data



- The figure shows the combined response of EB+HB calorimeter to different particles as a function of beam momentum.
- The response is normalized to 1 for electron.
- At 100 GeV/c, the pion response is 80 % of the electron response.
- The proton response is always lower than the pion response.
- In collision data the response is expected to be lower than in test beam because of additional material in front of the calorimeter.
- The calorimeter response is clearly non-linear.

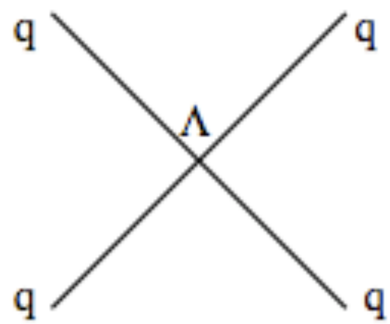
Physical meaning of "response"

The ratio of conversion efficiencies of the electromagnetic and hadronic energy depositions to electrical signals is called the intrinsic e/h ratio. The ratio of responses to incident pions to incident electrons at a given energy is related to e/h as "π/e" $= [1+(e/h-1)f_0]/(e/h)$ where f_0 is the electromagnetic fraction, $f_0 = 0.1 \log P_b$, and P_b is the beam momentum.

$$R = a_0 - \frac{a_1}{[\log(p_T)]^{a_2}}$$

a_0 should be close to 1 and a_1, $a_2 > 0$

Contact interaction



Contact interaction Lagrangian:

$$L_{qq} = \frac{Ag^2}{2\Lambda^2}(\bar{q}_L \gamma^\mu q_L)(\bar{q}_L \gamma_\mu q_L)$$

where A = ±1 determines the sign of the interference with QCD, Λ is the contact interaction scale, and $\Lambda^\pm$ denotes Λ with the choice A = ±1.