Workshop on Energy Calibration of the ATLAS Calorimeters, 21-24 July 02

Hadronic Energy Calibration of the H1 Experiment

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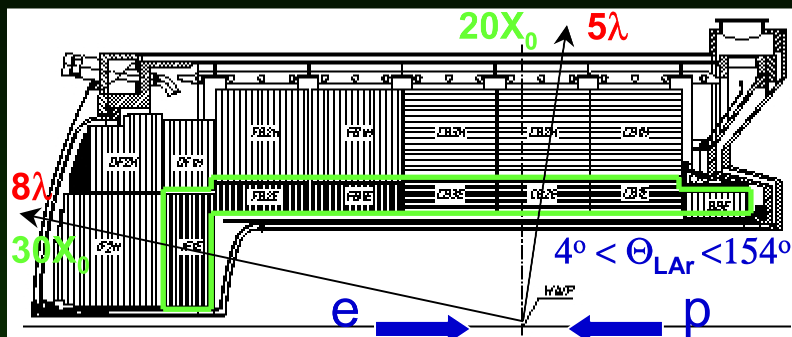
H1 Collaboration

Outline

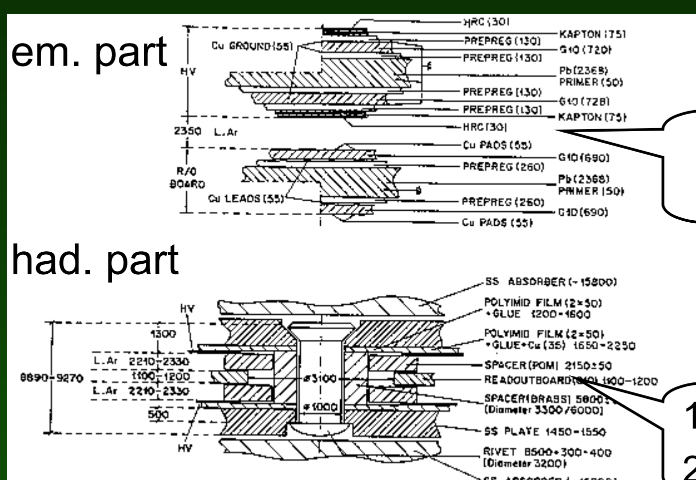
- ✓ H1 LAr calorimeter
- ✓ Hadronic energy reconstruction
- ✓ Results of CERN test beam measurements
- ✓ LAr Purity monitoring
- ✓ HV curves with μ's
- ✓ Hadron calibration in ep data
- ✓ New energy weighting method
- ✓ Summary

The H1 LAr Calorimeter

- 8 self supporting wheels



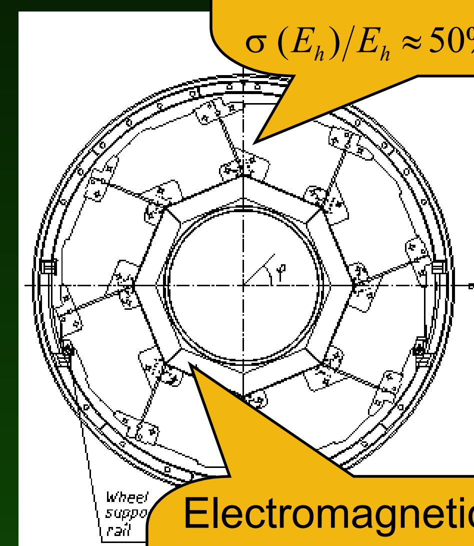
- Readout cell structure



2.40 mm Pb
2.35 mm LAr

19 mm steel
2.4 mm LAr

- 8 fold structure for each wheel



Hadronic part

Granularity: 50 - 2000 cm²
Long. Segmentation: 4-6
Number of chan. : 13568
$\sigma(E_h)/E_h \approx 50\%/\sqrt{E_h} \oplus 2\%$

Electromagnetic part

Granularity: 10 -100 cm²
Long. Segmentation: 3-4
Number of chan. : 30784
$\sigma(E_e)/E_e \approx 11\%/\sqrt{E_e} \oplus 1\%$

Electronic Calibration and Noise

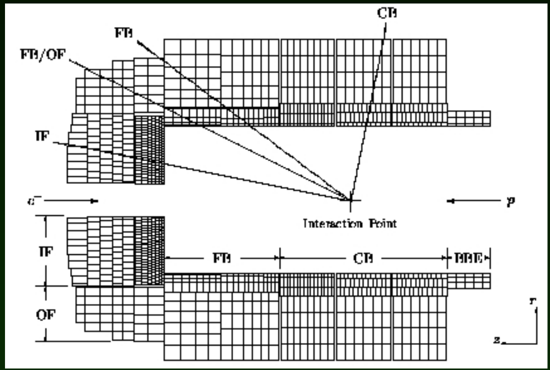
- Electronic Calibration
  - Two calibration systems: cold and warm (as backup solution)
  - Stability within 10^{-3}
  - Online charge conversion in the front end DSPs using calibration data from 3rd order polynomial fits
- Noise
  - Special noise suppression including negative noise contributions
  - 1 σ_{noise} values:

	Central Barrel	Inner Forward
Electromagnetic part	*30 MeV / 0.25 mips*	*15 MeV / 0.15 mips*
Hadronic part	*30 MeV / 0.15 mips*	*24 MeV / 0.15 mips*

  - Topological noise suppression
  - H1 MC simulations include measured noise from random triggers

CERN Test Beam Measurements

- Extensive test program at CERN SPS with e,π and μ beams
  - Measurements with calorimeter prototypes as proof of principle
  - Calibration runs with stacks of each final H1 module
  - Tests of z and ϕ crack regions



- Determine calibration constants of the electromagnetic scale

Data: $Q_i \xrightarrow{\left(c^{exp}_{EMC}, c^{exp}_{HAC}\right)_{wheel}} E^0_i$ and MC: $E_i^{vis} \xrightarrow{\left(c^{MC}_{EMC}, c^{MC}_{HAC}\right)_{wheel}} E^0_i$

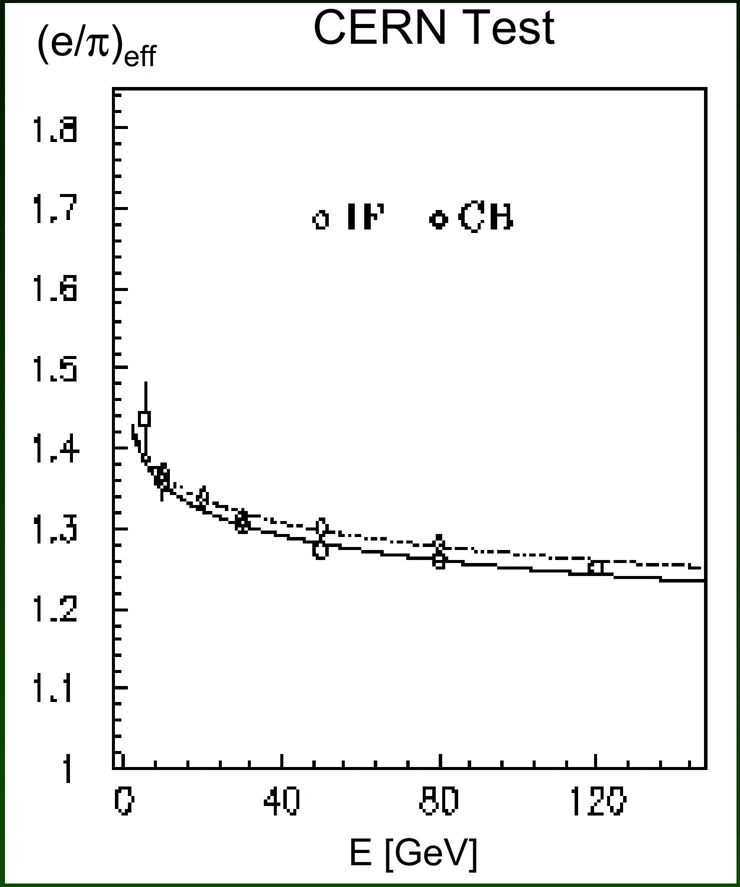
such that $E^{\exp}_{rec} = c^{\exp}_{EMC} \sum_i^{EMC} Q_i = E^{MC}_{rec} = c^{MC}_{EMC} \sum_j^{EMC} E^{vis}_j$

$$c^{exp}_{EMC} = 3.55 GeV / pC$$
$$c^{exp}_{HAC} = 7.10 GeV / pC$$

$$\Delta c^{exp}_{EMC} / c^{exp}_{EMC} = 3\%$$
$$\Delta c^{exp}_{HAC} / c^{exp}_{HAC} = 4\%$$

Energy Measurement of π's

- Measurement of the e/π ratio



- $e/\pi > 1 \Rightarrow$ non compensating Calorimeter
- $f_{em} \sim \log E_{beam} \Rightarrow$ non linear response
- π^0 fluctuations cause non gaussian contribution to the energy resolution

- Energy weighting
  $\Rightarrow$ equalize the response of the electromagnetic and hadronic component in the shower
  - software method which requires fine granularity of the calorimeter

Energy Weighting in H1 (1)

- Identify the primary electromagnetic component ($E_{cluster} > 1$ GeV)
  - Energy in the EMC
  - Fraction of energy in the first layer
  - Fraction of energy in the 4 most energetic cells

- Energy weighting of hadronic objects
  - Hadronic cluster are prominent cluster ($\Sigma (E_i/\sigma_{noise})^2)^{1/2} > 8$) penetrating deeply into the calorimeter
  - Hadronic objects are formed by hadronic cluster together with cells in a cylinder of $r_{EMC} < 25$ cm and $r_{HAC} < 50$ cm in the direction of the I.P.
  - Apply the weighting function to the cells of the hadronic objects

$\boxed{E_F = \omega \cdot E_1^i}$ with $\boxed{\omega = C_1 \cdot e^{-C_2 \cdot \frac{E_i^{em}}{Vol_i}} + C_3}$ for $E_{group} > 10$ GeV

Energy Weighting in H1 (2)

- Weighting parameters

$$\boxed{\begin{aligned} C_{1/2} &= C_{1/2}(E_{group}) \\ C_3 &= C_3(E_{group}, \theta) \end{aligned}}$$

- generated using jet data of detailed MC simulations
- different for EMC and HAC
- parametrization of the jet energy E_{group} (determined in 10° cones) and of θ

- Hadronic energy reconstruction at low energies

  - Linear correction for $E_{group} < 7$ GeV using the measured e/π ratio:

$$\boxed{E_F = \omega \cdot E_1^i}$$

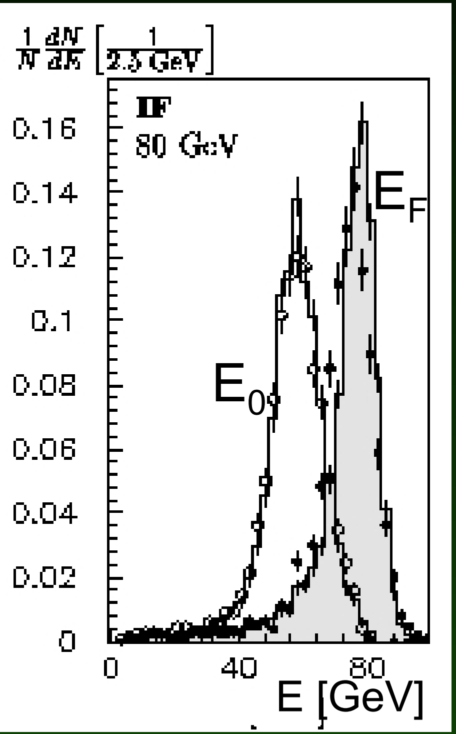
$$\boxed{\omega^{HAC} = 1.608}$$

$$\boxed{\omega^{EMC} = 1.353}$$

  - Smooth transition between both methods for 7 GeV $< E_{group} <$ 10 GeV

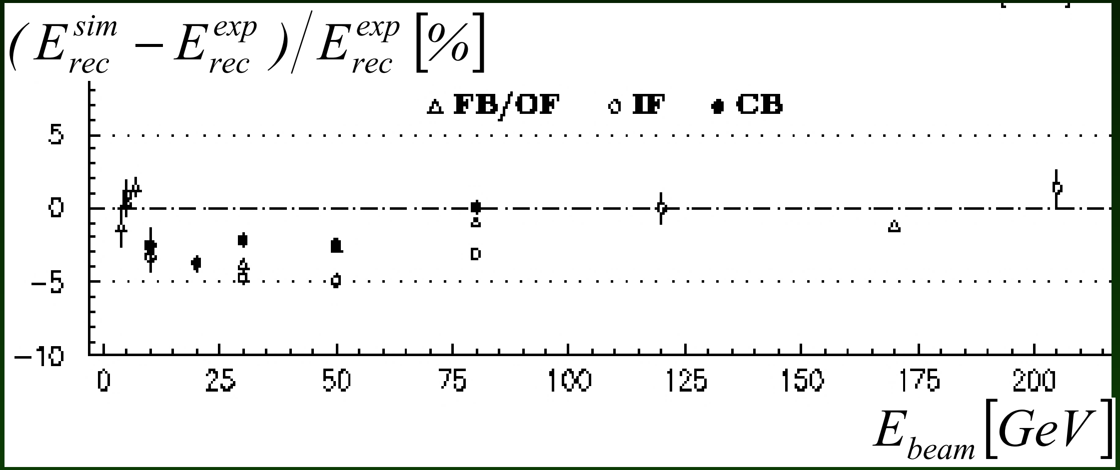
CERN Test Beam - π Results

- Energy measurement of π's



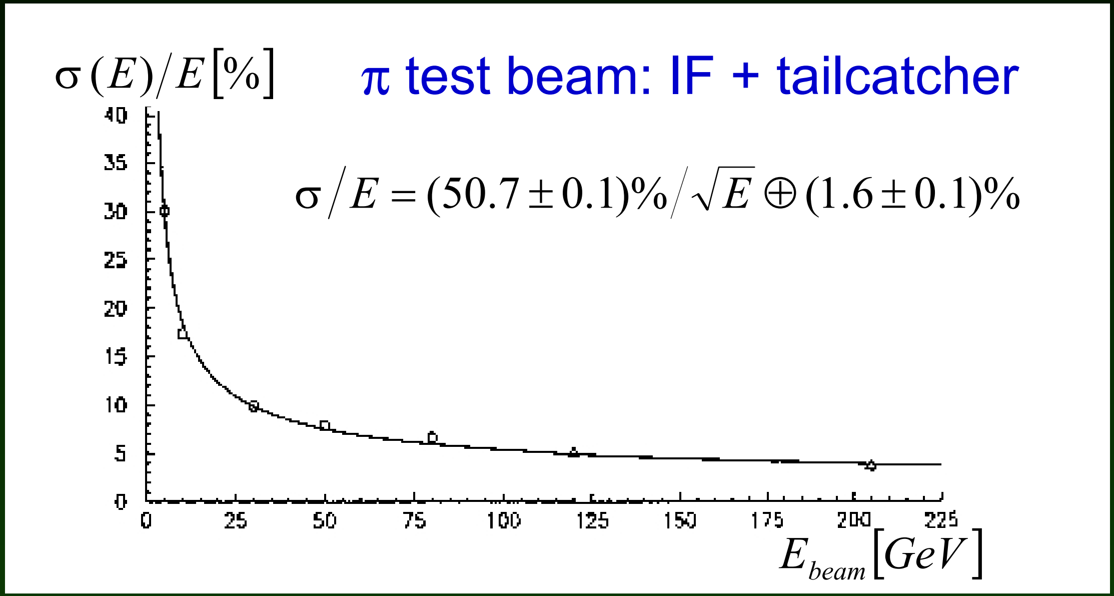
Reconstructed energy on the E_0 and E_F scale

Deviation of the MC simulation from data (final energy scale)



CERN Test Beam - π Results

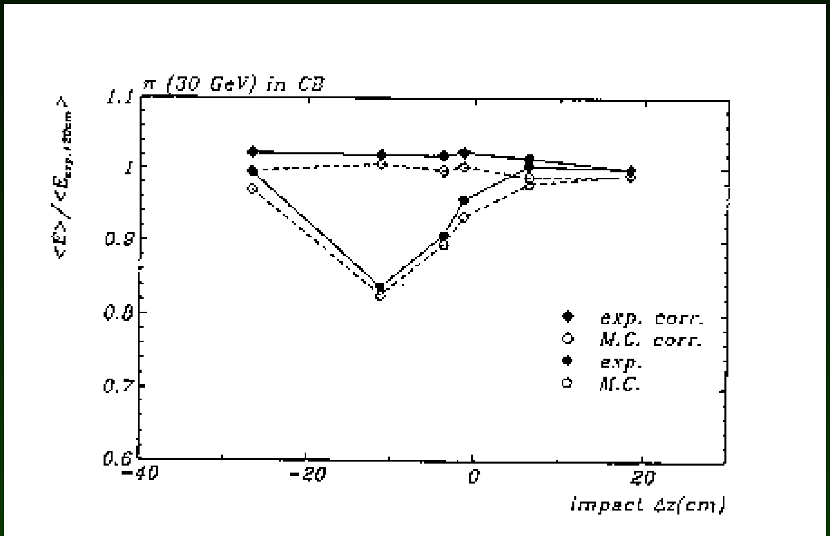
- Energy resolution after energy weighting, Inner Forward calorimeter



- Energy weighting compared to a linear calibration (jets, detailed MC)
  - Constant term is reduced by factor 2
  - Sampling term improves by ~30 %

CERN Test Beam – z,ϕ Cracks

- CB2/CB3 z crack in a 30 GeV π beam



- z crack is almost pointing to the interaction vertex
- Crack correction

$$\boxed{E_{loss}^{j} = \beta \cdot f_{loss}^{j} \cdot \frac{E_r^j \cdot E_l^j}{E_r^j + E_l^j}} \qquad \boxed{\beta_{em} \neq \beta_{had}}$$

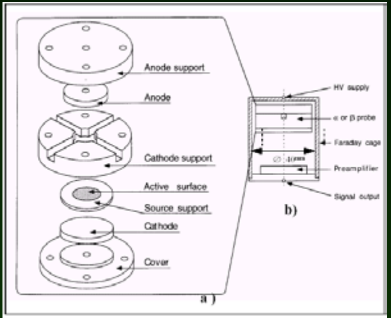
- Position independent response after the crack correction
- Response is well described by the simulation

- Crack correction parameters determined for hadrons are used for both shower components

LAr Purity Monitoring System

Aim: control longterm stability of the LAr signal

- Purity measurements by 10 LAr ionization chambers (^{207}Bi and ^{241}Am sources) inside the cryostat



ε

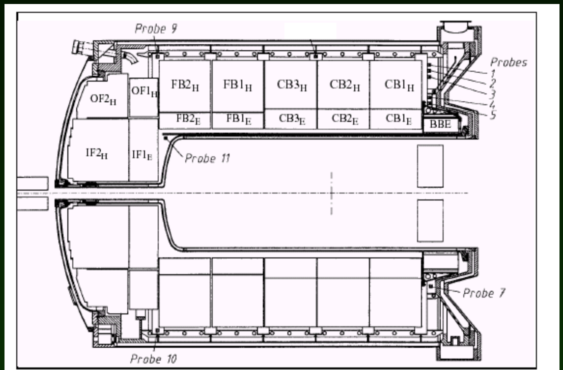


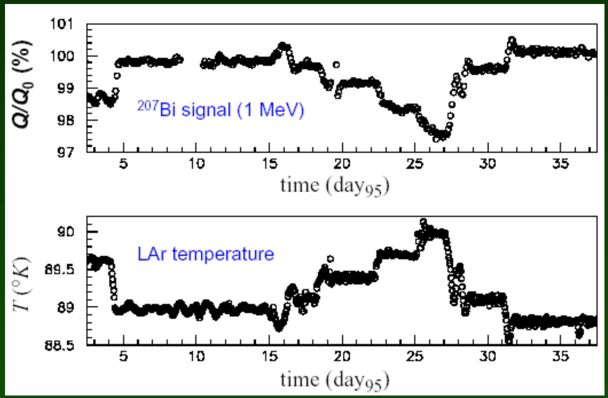
Figure 2: Location of purity probes inside the H1 LAr cryostat.

Determine the ionization charge Q and relate the mean free path λ_e

- LAr temperature effect for ^{207}Bi

$\Delta Q/Q = -\kappa \ \Delta T$, $\kappa \cong 1.5$ % / K^0

LAr temperature oszillation
in 24 h operation: $^{+0.1}_{-0.2} K^o$

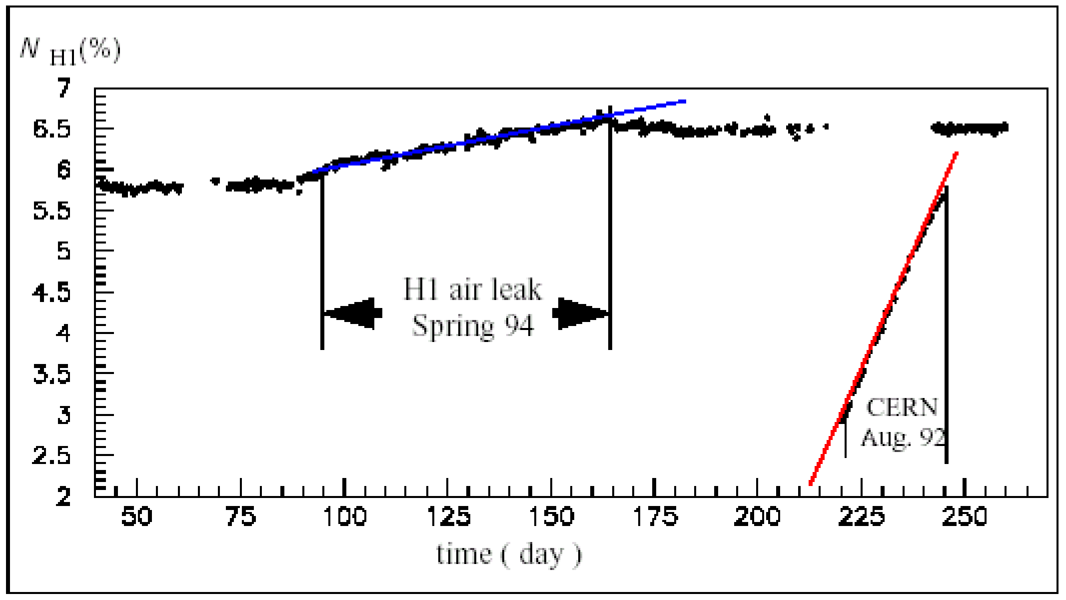


LAr Impurity Measurement (1)

- Impurity N_{H1} of a ^{207}Bi probe converted from the measured charge

  During the CERN tests there was a continuous release of impurities into the LAr at the % level / month (no oxygen pollution)

  This was a factor 100 larger than the observed measurements in H1

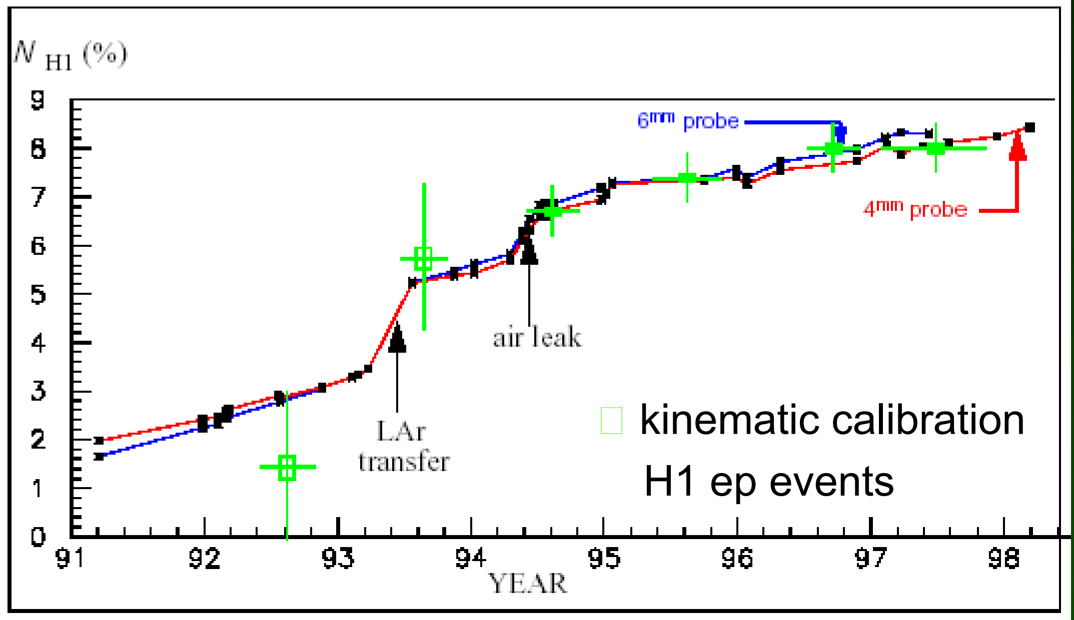


LAr Impurity Measurement (2)

- Average impurities N_{H1} in H1 from 91 to 98 using HV curves

Convert HV curves into impurity curves using a relation between the mean free path and the electrical field determined from the data

Obtain the average impurity for fields 0.35 cm/kV < E^{-1} < 0.9 cm/kV

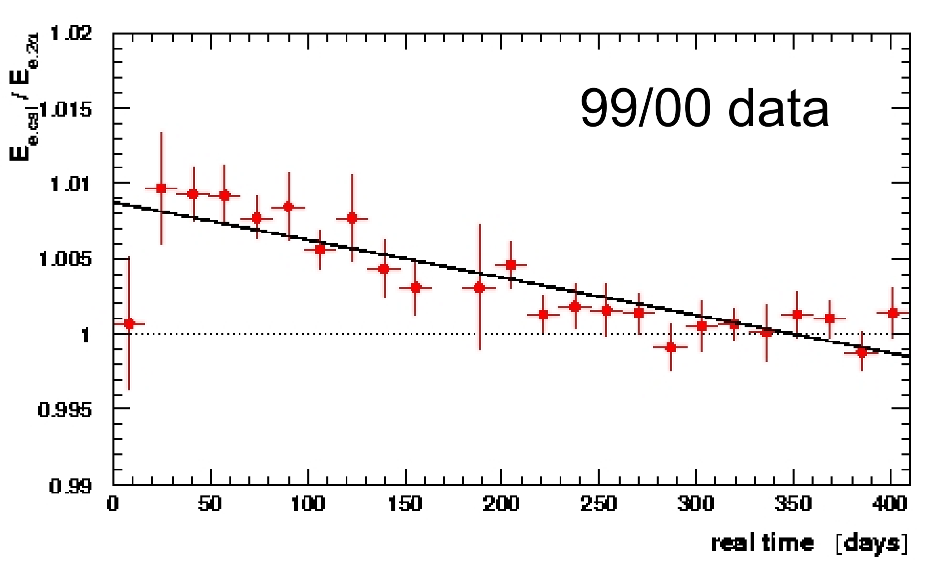


Over 6 years of operation the cumulative effect of the LAr pollution on the energy measurement is ~ 2.5%

Details:
see hep-ex 0111066

LAr Purity Monitoring in ep Data

➢ Signal degradation directly observed in NC DIS high Q^2 data



Measure $E_{2\alpha}/E_e$ vs time

The sensitivity is clearly on the ‰ level

Use data for the correction

For physics analysis corrections are needed when combining data from different running periods

Still unknown is the sensitivity of the data to temperature gradients

T gradients are stable $\Rightarrow$ covered within the octant wise offline calibration

Charge Collection Efficiency

- Measurement of high voltage curves with cosmic and beam halo μ‘s
  - Determine the charge collection efficiency by a fit to

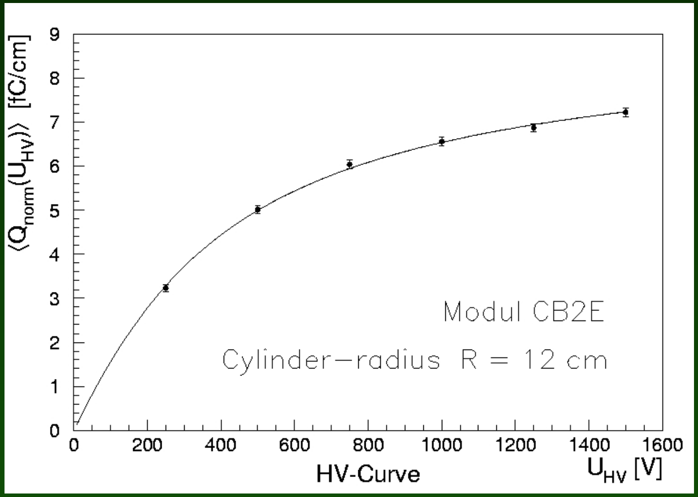
$$\varepsilon(U_{HV}) = \frac{Q(U_{HV})}{Q_0} = 2\frac{\alpha U_{HV}}{pd^2_{gap}}\left[1 - \frac{\alpha U_{HV}}{pd^2_{gap}}\left(1 - e^{-\frac{pd^2_{gap}}{\alpha U_{HV}}}\right)\right]$$

Before the beam operation of H1 in 91/92:
(at E = 1500 kV)

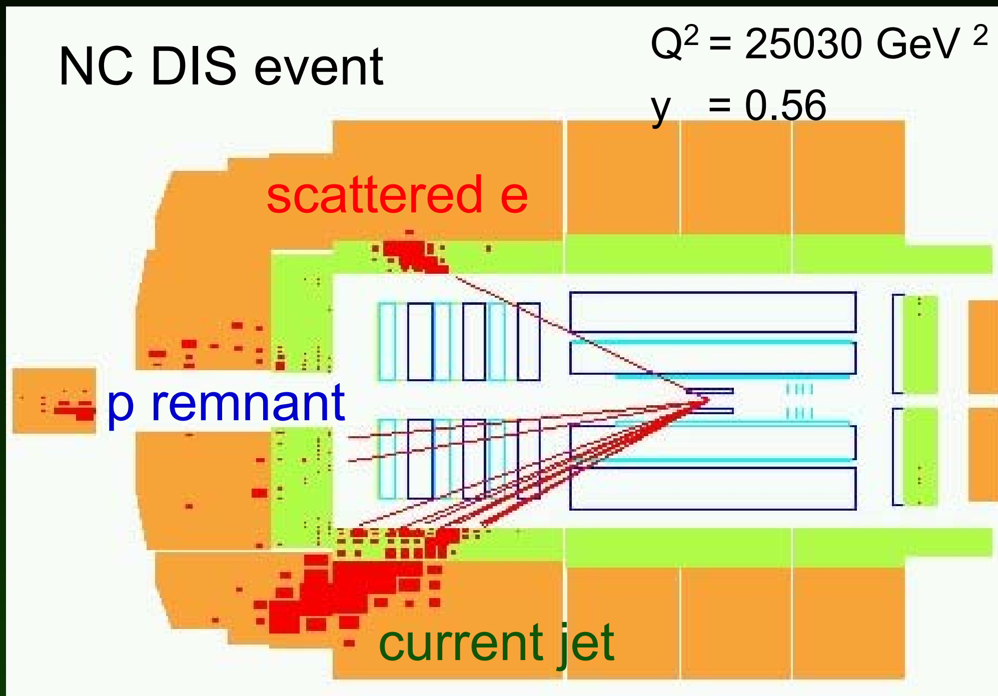
$$\varepsilon = 0.944 \pm 0.014$$
$$p = 0.55 \pm 0.14\, ppm$$

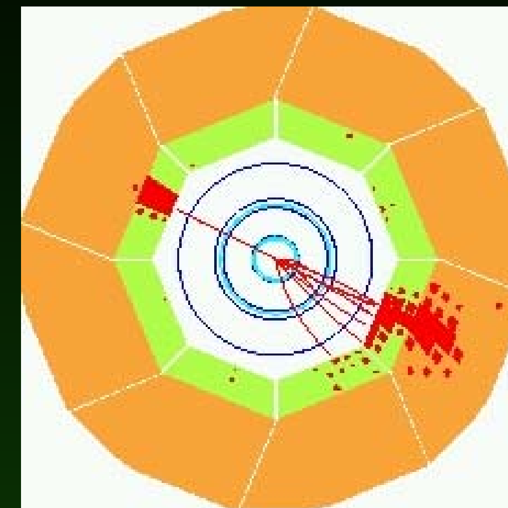
  - Derive wheel wise calibration coefficients in EMC and HAC using cosmic and beam halo μ‘s

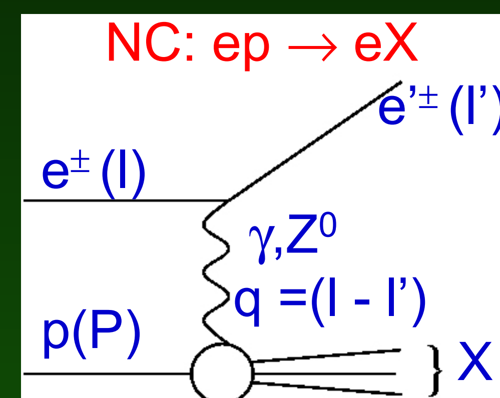
    Difficult: low signal/noise
  - Long term stability checks inside modules



Calibration with NC DIS Data







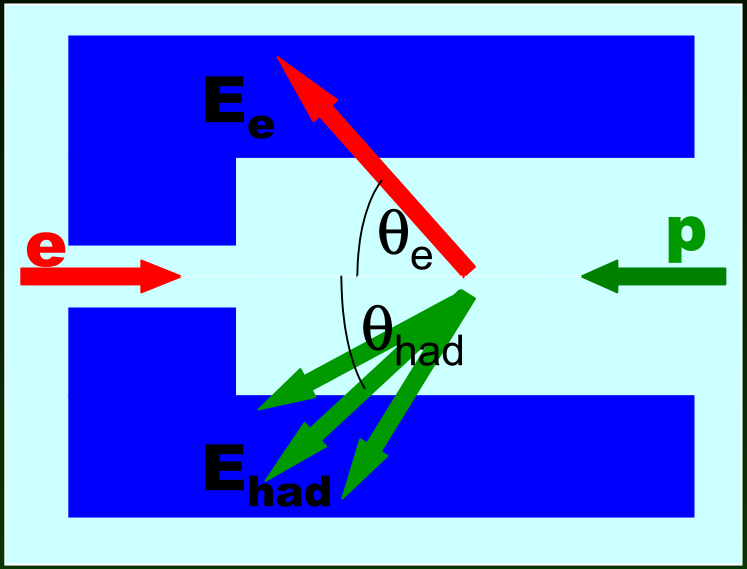
$Q^2 = -q^2$ resolving power of the probe

$y = (P\bullet q) / (P\bullet l')$ inelasticity parameter

$x = -q^2 / 2(P\bullet q)$ fraction of p momentum

Measurements and Constraints

- Four measurements:



- ❖ Energy and angle of the scattered lepton and the hadronic final state
- ❖ Inclusive hadronic angle

$$\tan\frac{\theta_{had}}{2} = \frac{(E-p_z)^{had}}{p_t^{had}}$$

- ❖ 2 variables describe kinematics

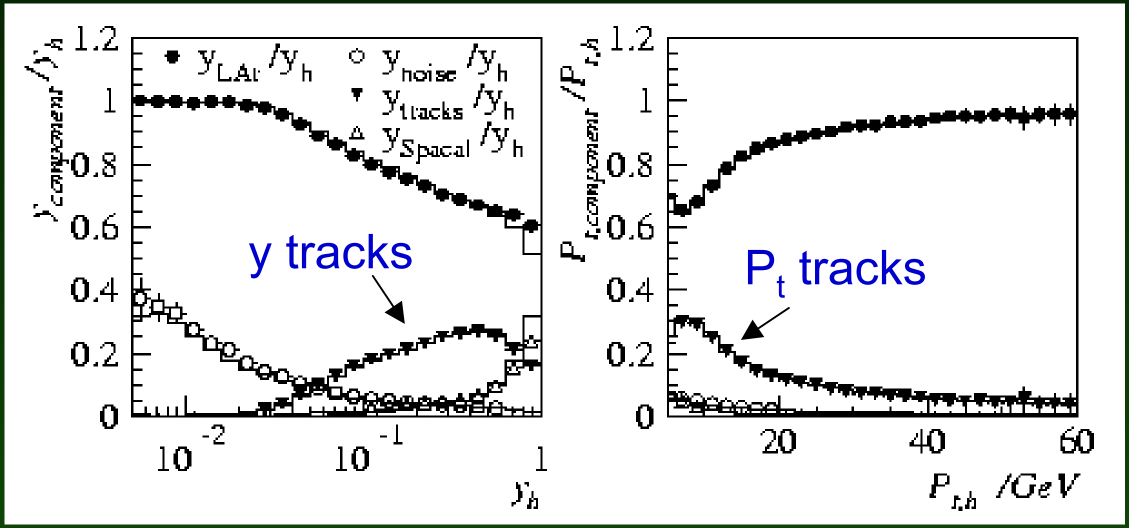
- Over constraint system offers calibration and checking possibilities
  - ❖ Transverse momentum (P_t) balance: $P_t^e = P_t^{had}$
  - ❖ Longitudinal momentum (E-p_z) balance: $(E-p_z)^e + (E-p_z)^{had} = 2E^e_{beam}$
  - ❖ Double angle method: predict E^e, E^{had} from measured (θ_e, θ_{had})

Cluster Track Combination

The hadronic final state is measured using calorimeter energy depositions and low momentum tracks to improve the response.

- Cluster track combination

  Extrapolate tracks (p < 2 GeV) in the central area to the calorimeter and replace $E_{cluster}$ within a radius (r_{em}= 25cm, r_{had} =50cm) by p_{track}

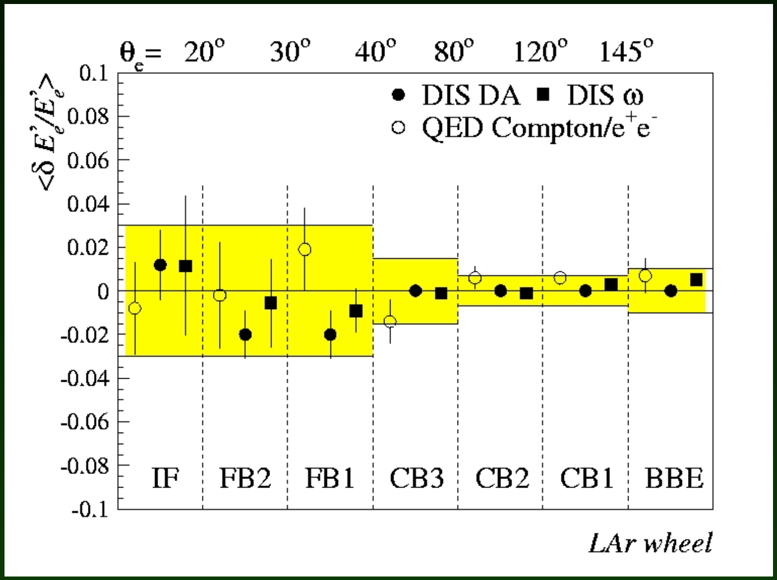


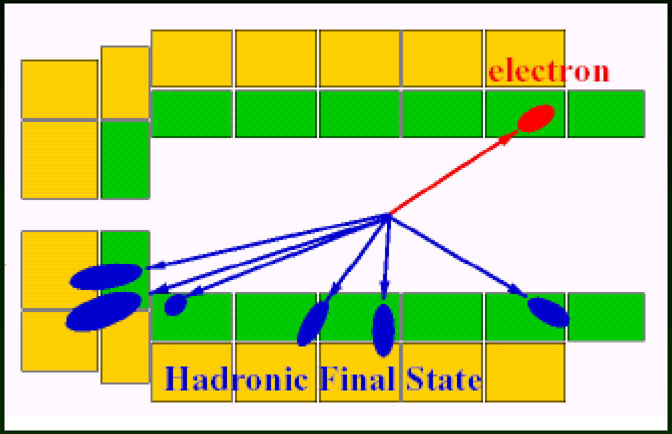
$$y_{had} = \frac{\sum_i (E^i - p_z^i)}{2E_{beam}}$$

Isolated low energy calorimetric deposits are classified as noise

Calibration Fundamentals

- Calibrate the electron using the NC double angle e energy prediction





transverse + longitudinal momentum balance

Statistical techniques on large samples to establish energy and position dependent hadron calibration

Hadronic Energy Calibration (1)

- Calorimeter calibration approach

  Determine calibration coefficients for different hardware regions of the LAr calorimeter in order to describe data / MC of various observables (p_t, $E-p_z$, y, Q^2 ,..) in different kinematic regimes

  - Lagrange Method

$$L = \sum_{i=1}^{events} \frac{1}{\sigma_i^2} \left(p_t^e - p_t^{track} - \sum_{j=1}^{M} p_{t\,i}^{\,j} \cdot \alpha_j \right)^2 \rightarrow min$$

120 coefficients (wheel, octant)

  - Iterative Method

$$\Delta_j = 1 - \sum_{i=1}^{events} \delta^i W_j^i$$

$p_\perp^{LAr}$ =: p_t projected onto the electron direction

$p_\perp^{LAr} = \Sigma_i \; p_t^i \bullet \cos(\phi^i - \phi^{el})$

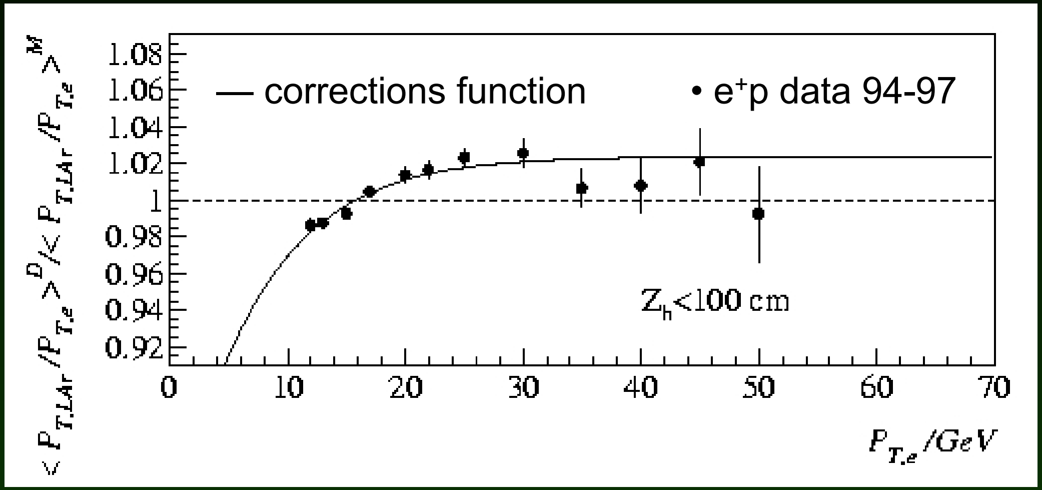
$w^j_{ev} = p_t^j / p_t$ fractional p_t in wheel j

$\delta^{ev} = p_\perp^{LAr} / p_t$ event pull

$<\Delta_j^{data}> / < \Delta_j^{MC}> \rightarrow$ 15 coefficients (wheel wise)

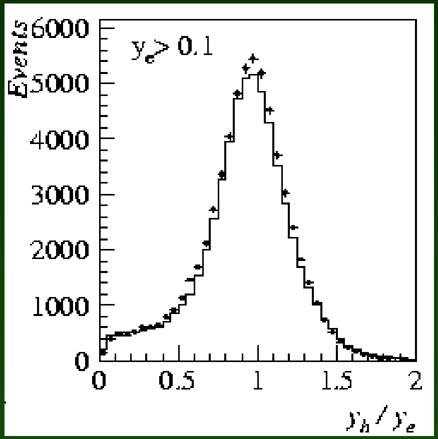
Hadronic Energy Calibration (2)

- p_t dependence of the description of the data by the MC



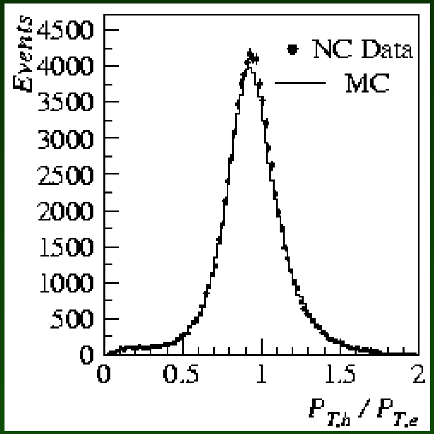
After the correction of the p_t dependence the hadronic energy measurement for data and MC agrees within 2 %

Final Calibration



E-p_z measurement

p_t measurement

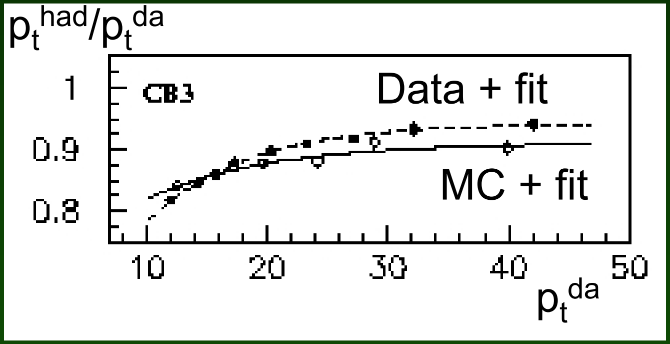


Hadronic Energy Calibration (3)

- Alternative approach

  (p_t, θ) dependent calibration using the jets of the hadronic final state

  - Select NC DIS high Q^2 (1+1) jet events
  - Adjust $< p_t^{had} / p_t^{da} >^{data}$ and $< p_t^{had} / p_t^{da} >^{MC}$ in θ_{jet} ranges
  - Fit $p_t^{balance} = F\,(\theta_{jet}, p_t^{da})$ for data and MC
  - Correct the quantities of each jet iterating with $F\,(\theta_{jet}, p_t^{da})$
  - The method provides an absolute hadronic scale

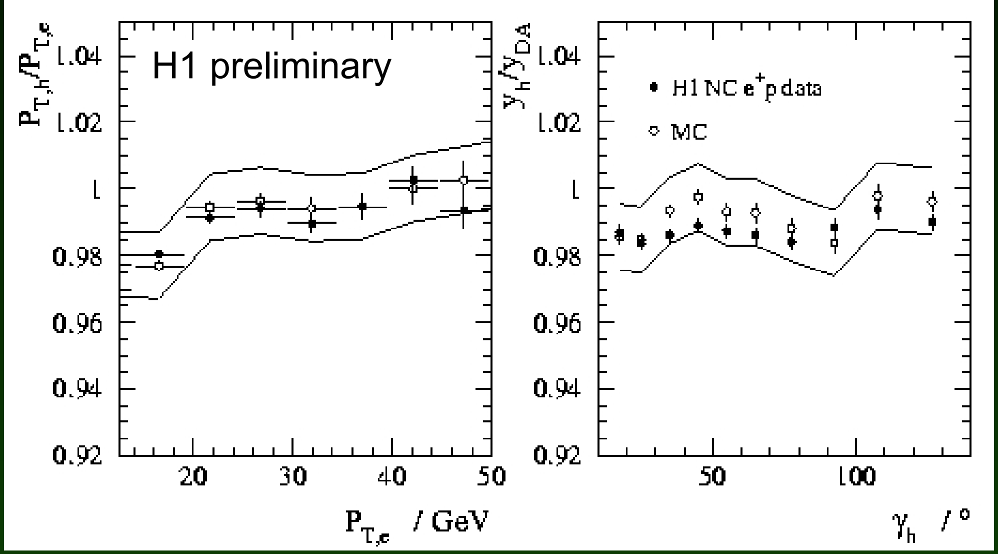


The procedure yields equivalent precision

Hadronic Energy Calibration (4)

➢ Improved precision of the hadronic scale including all e^+p NC DIS data

12 GeV < p_t^{had} < 50 GeV and $\gamma_{had} > 15^o$



❖ Correct the p_t dependence for data and MC in bins of γ_{had}

❖ $E-p_z$ and p_t measurement well described within ±1%

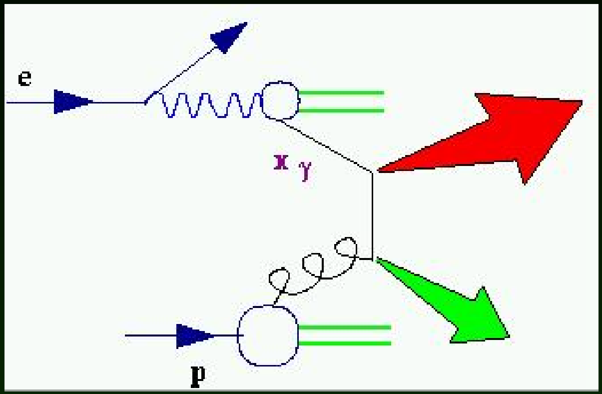
❖ 1% correlated error from electron measurement

❖ Wheel dependent calibration from y balance

Adjust y^{had} / y^e for data and MC in different areas of the LAr calorimeter

→ equivalent results

Dijets in Photoproduction



- Dijet cross section measurement

  Hadronic energy calibration is an important aspect
- Large transverse energy selection

  E_t (1. Jet) > 25GeV

  E_t (2. Jet) > 15GeV
- Jet definition

  Inclusive $k_\perp$ algorithm using energy deposits in the calorimeters and low momentum tracks
- Application of the NC DIS high Q^2 calibration

  As a cross check: select a NC DIS sample with $E_t^e > 15$ GeV and show that p_t^{had} / p_t^e of the data is described within ± 2% by MC
- Energy scale error in the dijet data

  Deviations for subselections and various dependencies < 2 %

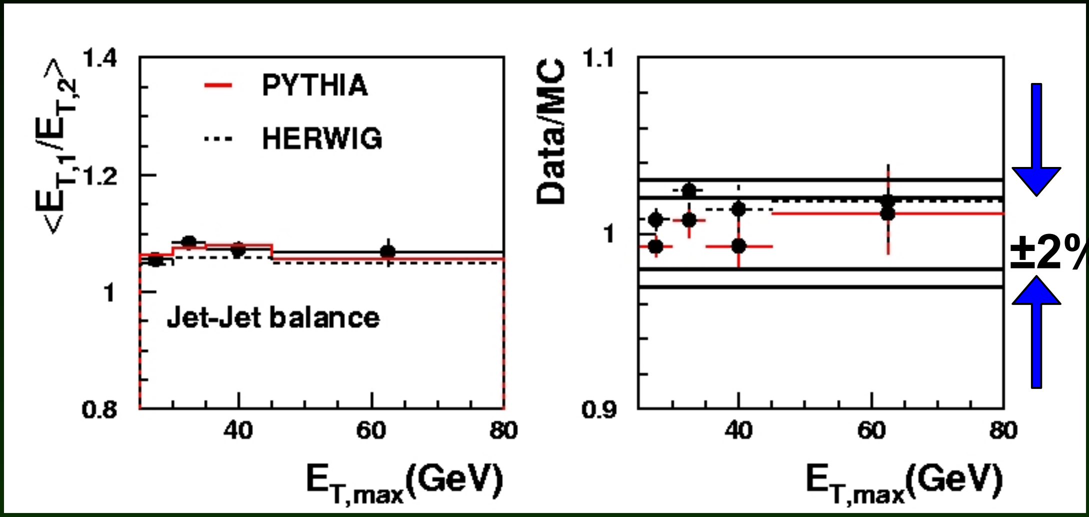
Dijet Data – Energy Calibration (1)

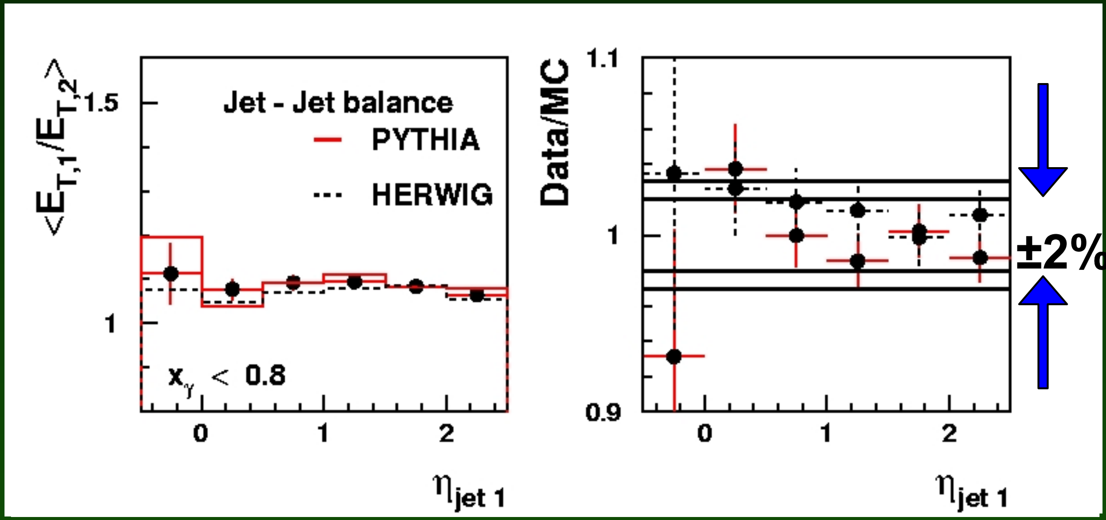
- Jet Jet balance
  $E_{t,Jet1}$ / $E_{t,Jet2}$

  - $E_{t,Max}$ dependence
  - η_{Jet1} dependence

  - x_γ > 0.8 (direct processes)

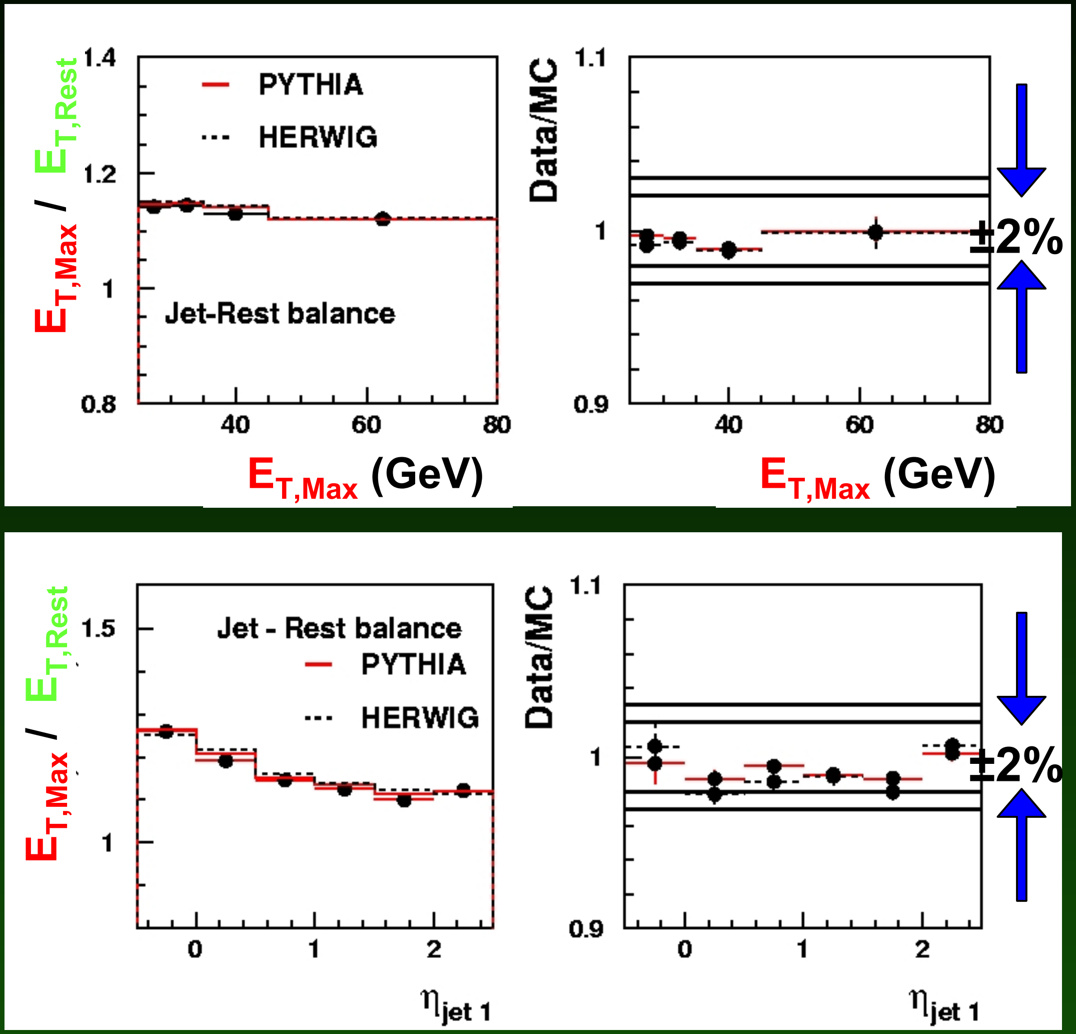
  - x_γ < 0.8 (resolved processes)





Dijet Data – Energy Calibration (2)

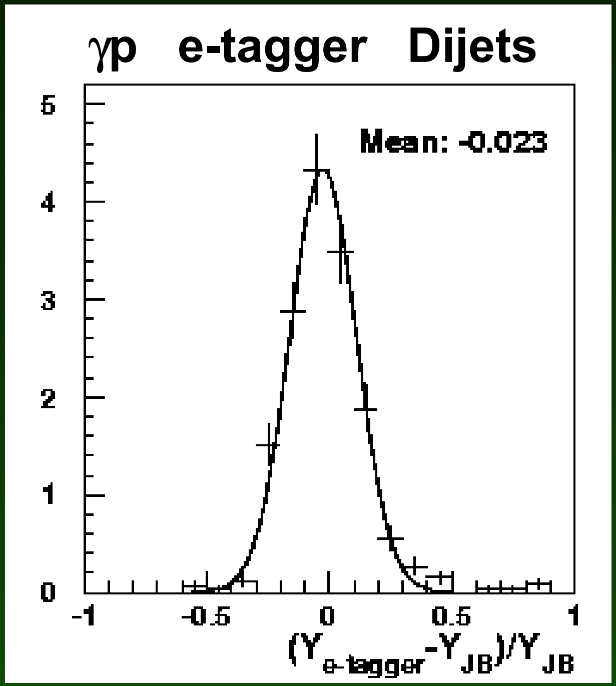
- Jet-Rest balance
  $E_{t,Max} / E_{t,Rest}$
  - $E_{t,Max}$ dependence
  - $\eta_{Jet\ 1}$ dependence

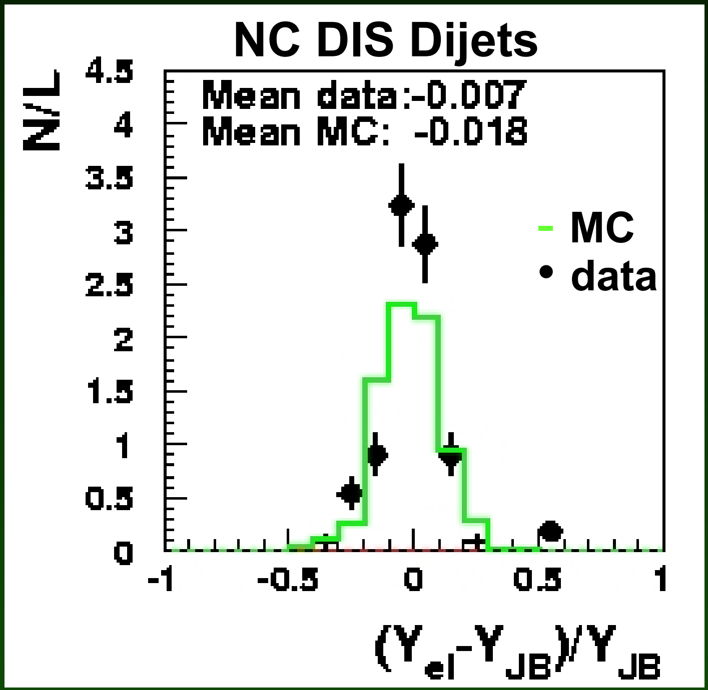


Dijet Data – Energy Calibration (3)

- y balance

  Compare y_{el} measured with the electron and y_{JB} reconstructed from the hadronic final state



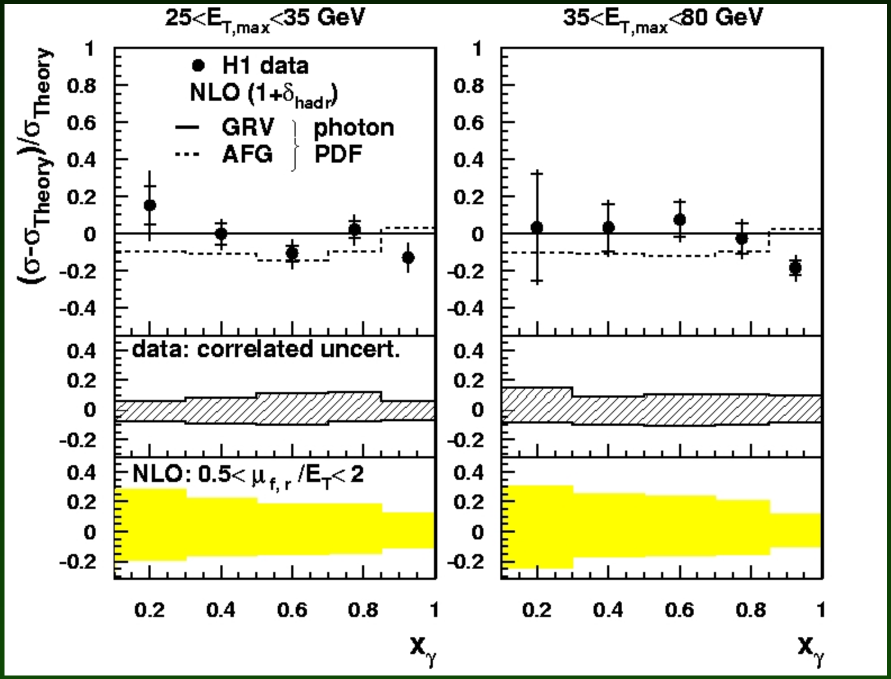


Dijet Data – Calibration Results

➢ Relative difference between measured and theoretical cross sections

Compare different error contributions to the cross section measurement

Hadronic energy scale: the MC's describe the data within ± 2 %.



energy scale uncertainties

renormalization and factorization scale uncertainties NLO calc.

New Energy Weighting Scheme (1)

- Weighting procedure

Non iterative procedure using tabulated correction factors ω on the cell level:

$$E_w = \omega(E_i^0 / Vol_i , E_{group}) \cdot E_i^0$$

- Evaluate for each cell the energy density (E^i_0 / Vol_i)
- Determine the energy scale E_{group} for the weighting procedure by searching for groups of neighbour clusters within an η,ϕ – grid
- Apply the correction factor to each cell of the group E_{group} depending on the energy density

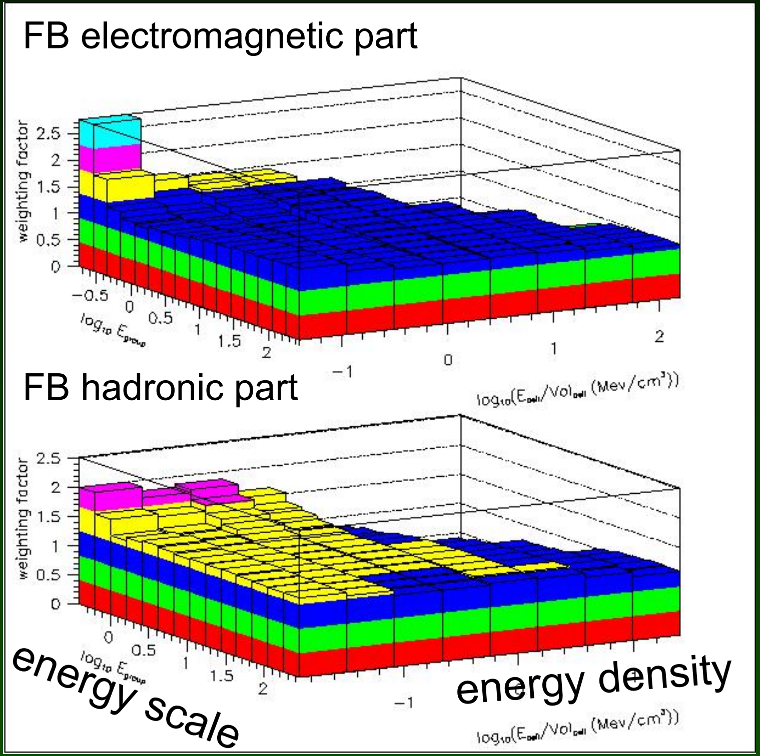
- Determination of the weighting factor tables

- Use single π events simulated in H1 with detailed simulation
  (low cuts, energy range [50MeV,300GeV], angular range of the LAr calorimeter)
- The scale of the weighting is determined by the leading energy group E_{group}
- The true energy E^i_{True} and the measured energy E^i_0 enter 2 D histogramms in the energy density ($\log_{10}(E^i_0 / Vol_i)$) and the group energy ($\log_{10}(E_{group})$)

New Energy Weighting Scheme (2)

- Weighting factors

  Wheel wise weighting factor tables for the electromagnetic and hadronic part of the LAr calorimeter



- Noise correction

  Noise cuts on read out level → missing reconstructed energy
  (few % level at high energies and up 20% at low energies)

- Dead material correction

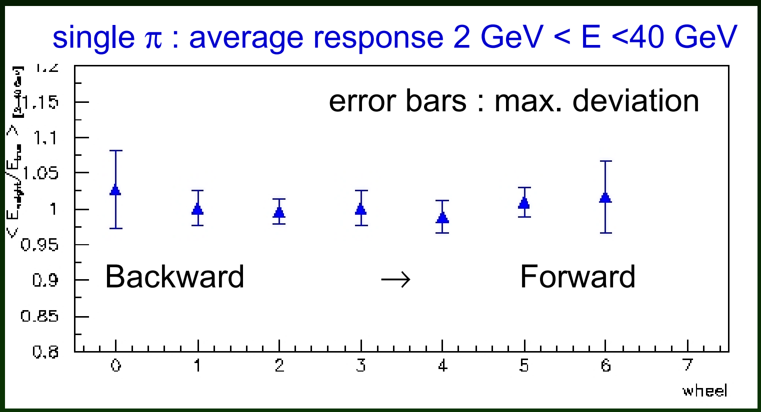
  As already discussed

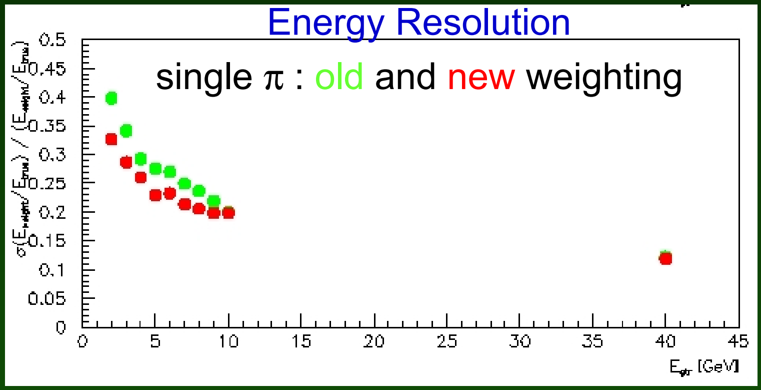
- Final calibration using NC DIS data

  Determine wheel wise factors by adjusting the average $<p^t_{had} / p^t_e>$ for both data and MC to 1

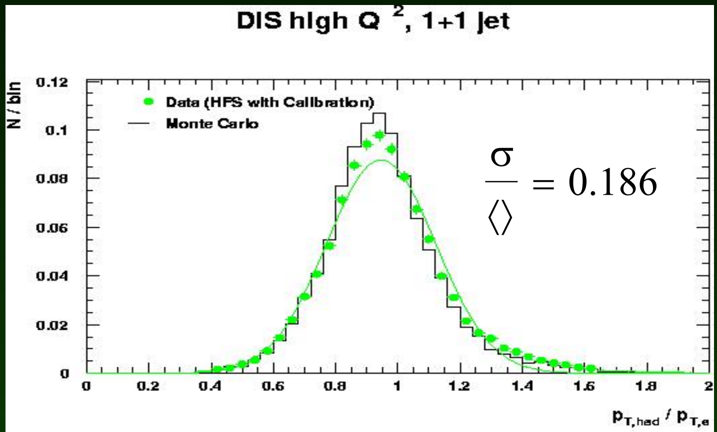
New Energy Weighting Results (1)

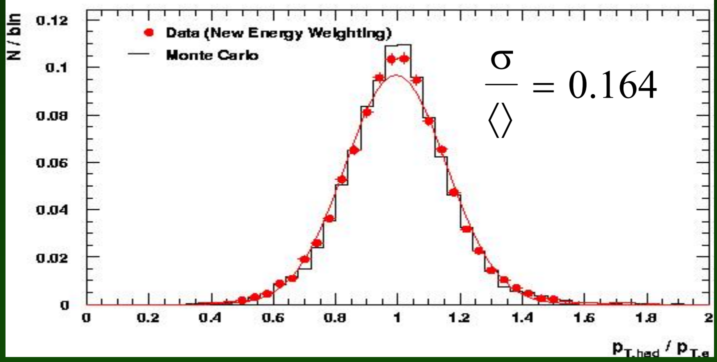
- Single π simulation
  - Improved linearity at low E
  - Improved resolution





- NC DIS high Q^2 data
  - Improved resolution and gaussian shape in p_t balance

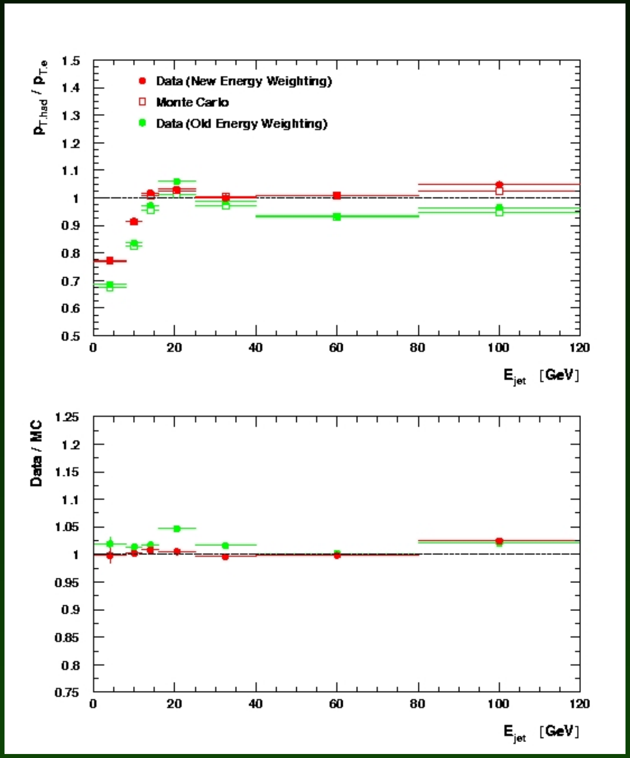




New Energy Weighting Results (2)

- ❖ **Jet energy dependence of p^t_{had} / p^t_e**

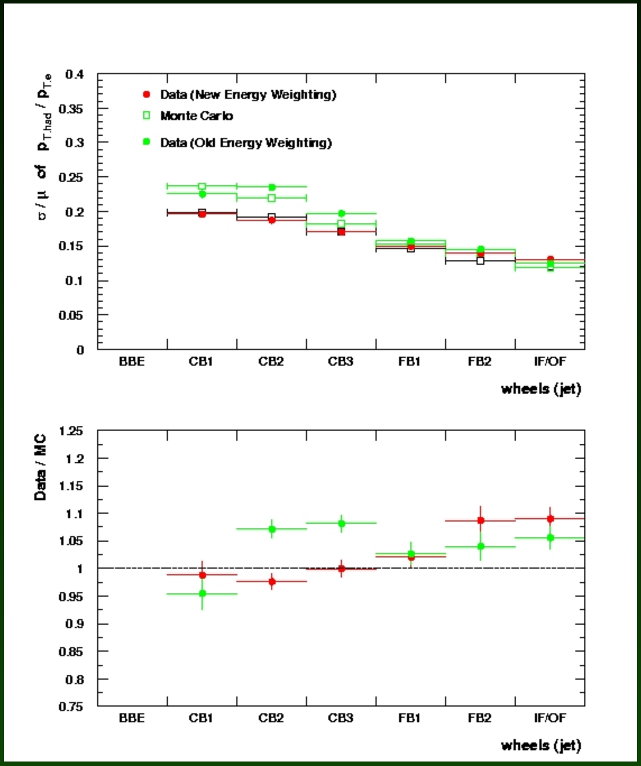
  Response improved at low energies



Cluster track combination needed

- ❖ **Wheelwise resolution in p^t_{had} / p^t_e**

  Improved resolution at low E



- ❖ **No p^t dependence $(p^t_{had}/p^t_e)_{MC/data}$**

Summary

It was a long way to go for H1 from the first beam test setup in 1986 to the 1.4 % data / MC description of the hadronic final state in Neutral Current DIS in 2002.

Good Luck to the ATLAS calorimeter group