Performance of the CDF Calorimeter Simulation in Tevatron Run II

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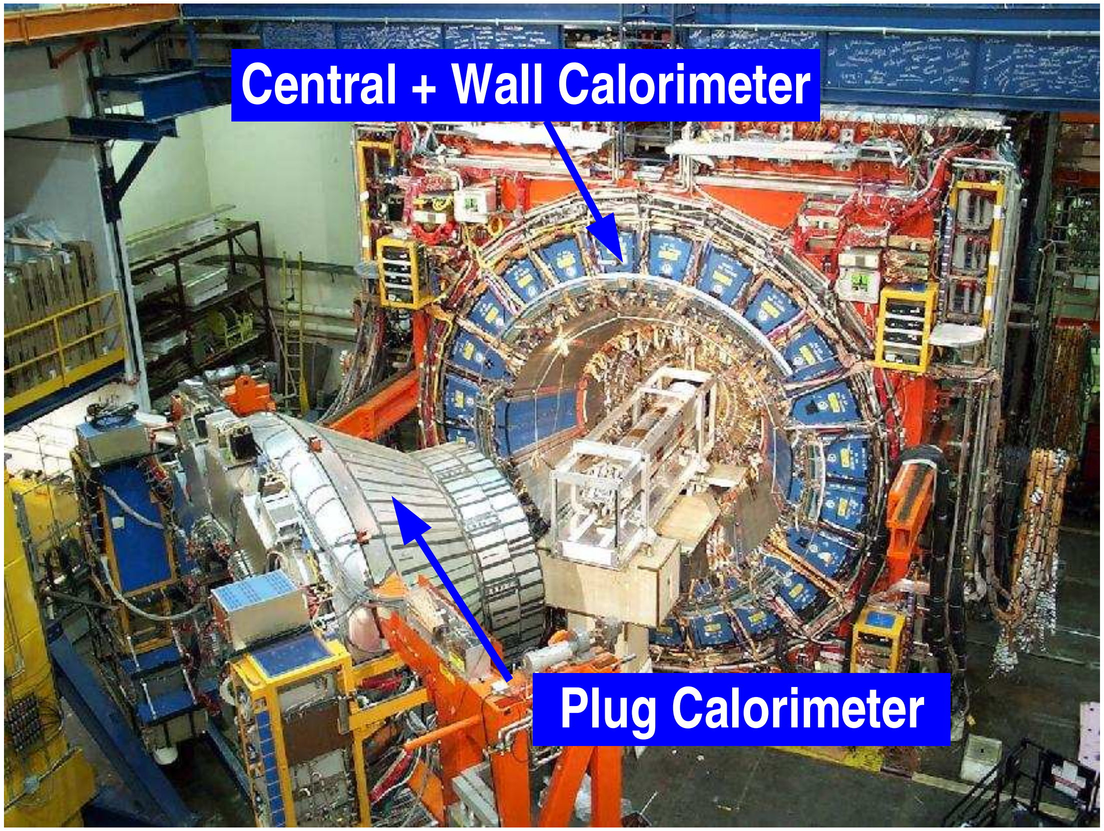
- on behalf of the CDF Collaboration -

Outline

- Introduction
  Physics Motivation
- The CDF Detector
  Calorimeter Facts
- Calorimeter Simulation
  GFLASH in a Nutshell
  Tuning Method
  Performance
- Jet Energy Scale
- Conclusions and Outlook

Collider Detector at Fermilab

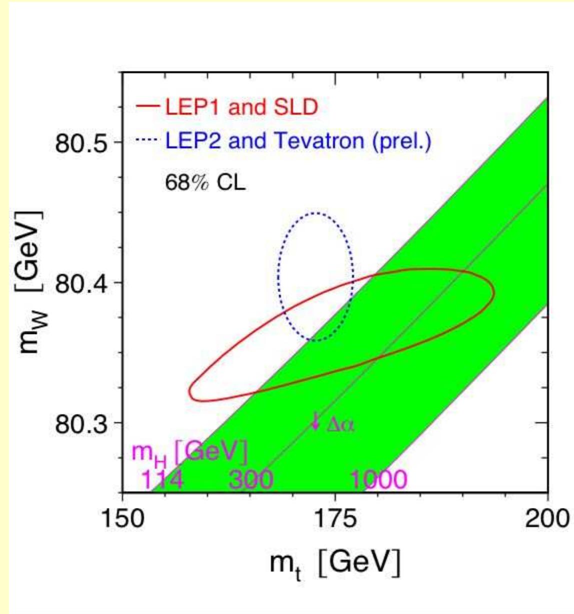


Introduction

- Many aspects of the CDF physics program crucially depend on the correct determination of the jet energy scale (JES).
- The CDF calorimeter simulation is one of the keys to control the CDF JES systematics...
  ... continuously improved during Run II.

- Impact e.g. on top quark mass:
  - important constraint for Higgs boson (together with W mass)
  - requires JES determination (top decay products)
  - JES uncertainties ~5 GeV/c^2 (early Run II) $\rightarrow$ ~2 GeV/c^2 (now)
  - total uncertainties: 2.6 GeV/c^2 (current best measurement)
  - CDF Run-II goal: < 2GeV/c^2

  ... despite improvements, JES uncertainty still dominated by data / calorimeter simulation discrepancies

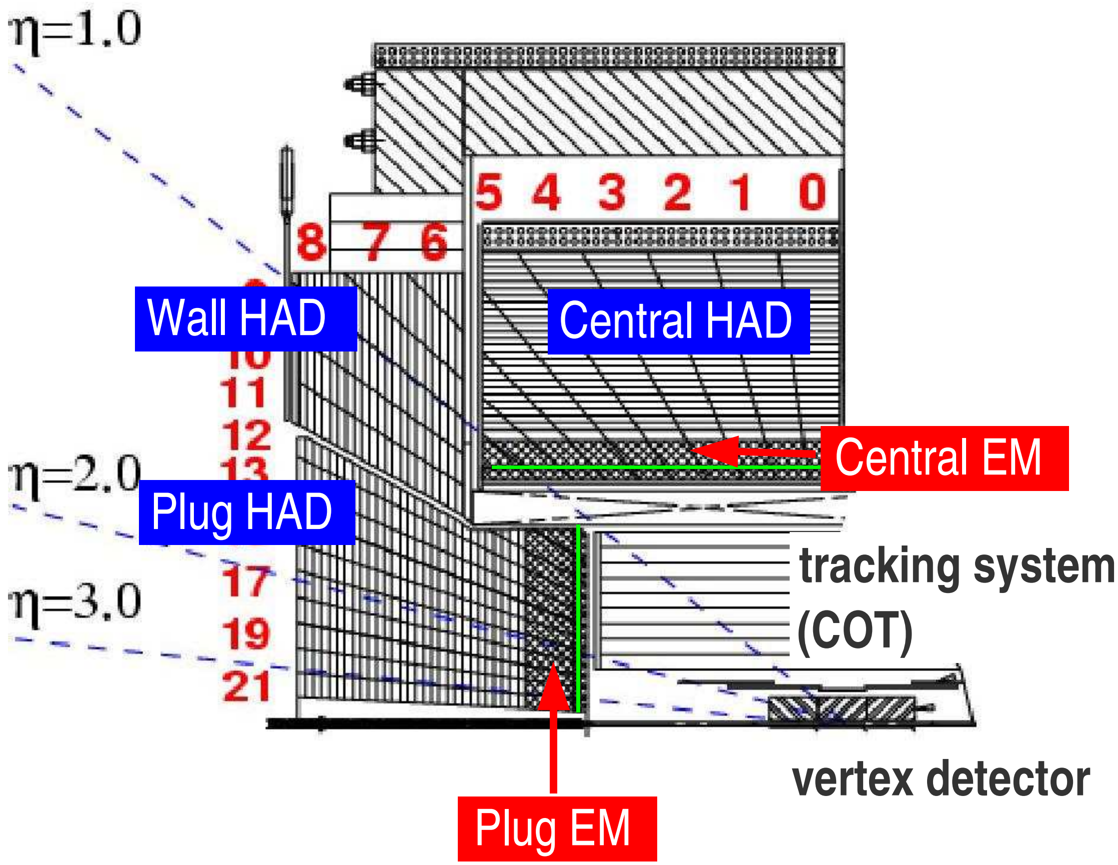


- This talk presents the *status quo* effective for current CDF publications and reports about ongoing activities to contribute to the Run-II challenge.

The CDF Calorimeter

- Sampling calorimeter:
  - scintillating tiles + WLS
  - lead/iron absorbers
  - projective tower geometry
- Divided in Central / Wall / Plug part

		Central	Plug
EM	thickness	19 X_0, 1λ	21 X_0, 1λ
	sample(Pb)	0.6 X_0	0.8 X_0
	sample(scint.)	5 mm	4.5 mm
	resolution	$\frac{13.5\%}{\sqrt{E}} \oplus 2\%$	$\frac{14.5\%}{\sqrt{E}} \oplus 1\%$
HAD	thickness	4.5 λ	7 λ
	sample(Fe)	25-50 mm	50 mm
	sample(scint.)	10 mm	6 mm
	resolution	$\frac{50\%}{\sqrt{E}} \oplus 3\%$	$\frac{70\%}{\sqrt{E}} \oplus 4\%$



- Pseudorapidity coverage: $|\eta| < 3.6$
- Granularity: 24(48) wedges per ring
- Also shower maximum / pre-shower detectors

CDF Calorimeter Simulation

CDF Run II simulation is based on **GEANT3**

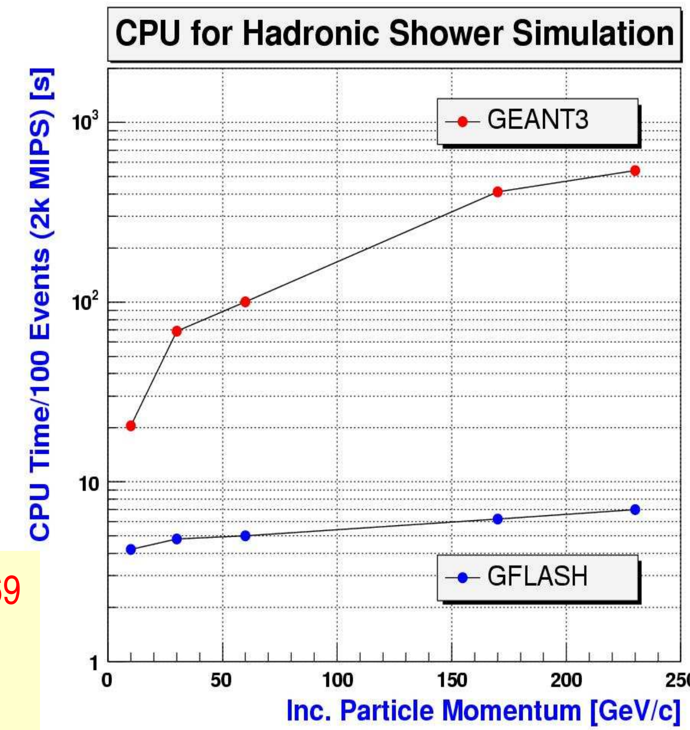
- encodes detector geometry/material composition
- propagates particle from interaction point through detector volume up to first inelastic interaction

control passed to ...

GFLASH

G.Grindhammer, M.Rudowicz and S. Peters, NIM A290 (1990) 469

- fast simulation of electromagnetic and hadronic showers (used by H1 Coll. since the early 90's, LAr Calorimeter)
  - in CDF up to 100 times faster than detailed G3 shower
  - ideal for simple geometry with repetitive sampling structure
  - very robust, sophisticated and flexible (tunable)
- generates longitudinal and lateral shower profile
- distributes energy spots according to lateral profile and sampling fluctuations
- uses GEANT material/geometry information

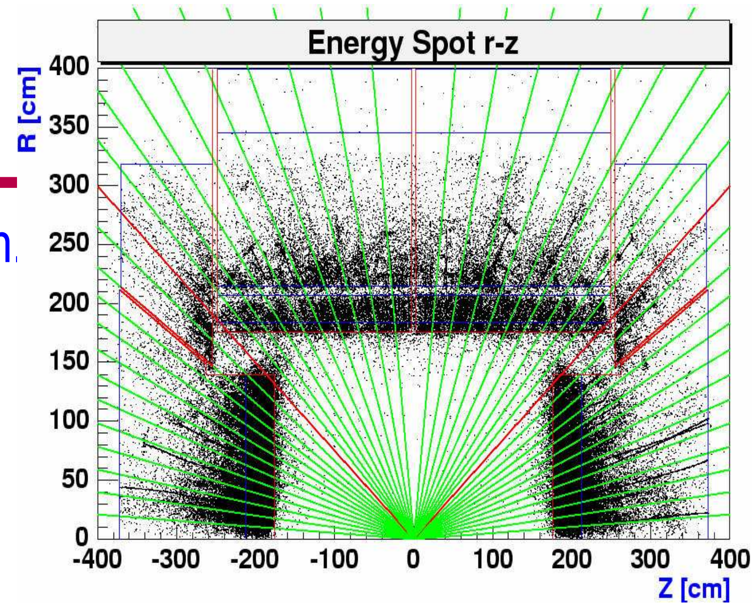


CPU time increases with E

GEANT $\propto$ E;

GFLASH $\propto$ log(E)

GFLASH in a Nutshell



- GFLASH treats calorimeter as one single effective medium.
- Parametrization for sampling structure and spatial energy distribution:

$$\hat{k} = \mathrm{EM}, \mathrm{HAD}$$

$$\mathrm{d}E_{\mathrm{vis}}(\boldsymbol{r}) = E_{\mathrm{inc}}\,\hat{m} \sum_{\hat{k}} \frac{\hat{k}}{\hat{m}}\, c_{\hat{k}}\, f_{\hat{k}}(\boldsymbol{r})\,\mathrm{d}\boldsymbol{r}$$

$\hat{m}$: MIP response

$\frac{\hat{k}}{\hat{m}}$: response relative to MIP

$c_{\hat{k}}$: relative fraction EM/HAD

$$f(\boldsymbol{r}) \propto L(z)\, T(r)$$

$L(z)$: longitudinal profile

$T(r)$: lateral profile

- EM and HAD responses are related to response of minimum ionizing particles (MIP).

longitudinal profile: interval step energy $E_{inc} \int L(z)\, dz$ → smear # of energy spots (Poisson) → **lateral profile**: distribute spots according to T(r) → integrate spots → **sampling fractions**: $\hat{m}, \frac{\hat{k}}{\hat{m}}$

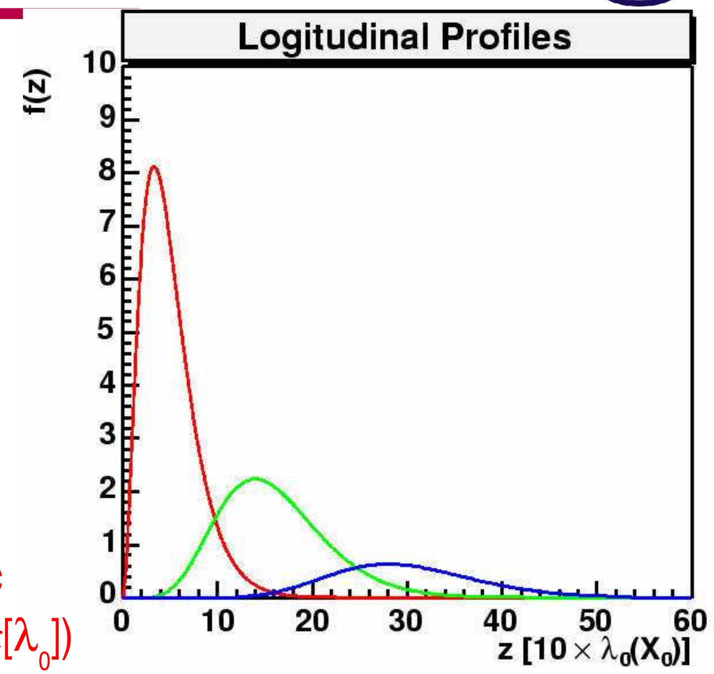
incident energy → sampling fluctuations resolution effects → deposited energy → **visible energy**

Longitudinal Shower Profile

- photons, electrons:

$$L(z)=\frac{(\beta z)^{\alpha-1}e^{-\beta z}}{\Gamma(\alpha)}$$

- Gamma functions
- z = shower depth



- hadrons: superposition of 3 shower classes:

$$L \propto f_{\mathrm{dep}}(E)\left[\boxed{c_h H_h(x)}+\boxed{c_f H_f(y)}+\boxed{c_l H_l(z)}\right]$$

$$H_h(x)=\frac{(\beta_h x)^{\alpha_h-1}e^{-\beta_h x}}{\Gamma(\alpha_h)},\quad c_h=1-f_{\pi^0}(E)$$

pure hadronic component ($x[\lambda_0]$)

$$H_f(y)=\frac{(\beta_f y)^{\alpha_f-1}e^{-\beta_f y}}{\Gamma(\alpha_f)},\quad c_f=f_{\pi^0}(E)(1-f_{\pi^0}^l(E))$$

induced by π^0's from *first* interaction ($y[X_0]$)

$$H_l(z)=\frac{(\beta_l z)^{\alpha_l-1}e^{-\beta_l z}}{\Gamma(\alpha_l)},\quad c_l=f_{\pi^0}(E)f_{\pi^0}^l(E)$$

induced by π^0 's from *later* interactions ($z[\lambda_0]$)

- incident particle energy dependence of fractions

$$f_i(E)=a+b\tanh(c\log E+d)$$

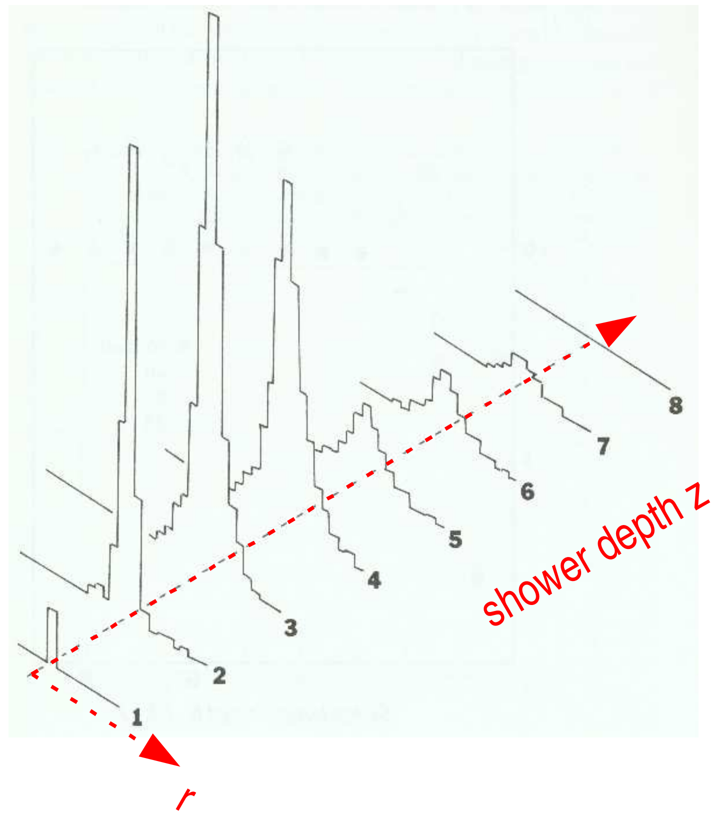
20 (correlated) parameters:
the means and widths of the class fractions f's, the α's and β's

Lateral Shower Profile

$$T(r) = \frac{2\,r\,R_0^2}{(r^2 + R_0^2)^2}$$

- r: radial distance from shower center

Integrated Lateral Profile



- R_0: log-normal distribution (in units of Moliere radius or absorptions lengths)
- parameterization for mean and width:

$$\langle R_0(E,z)\rangle = \left[R_1 + (R_2 - R_3 \log E)\, z\right]^n$$

$$\frac{\sigma_{R_0}(E,z)}{\langle R_0(E,z)\rangle} = \left[(S_1 - S_2 \log E)(S_3 + S_4 z)\right]^2$$

- photons, electrons: n=2; hadrons: n=1
- hadronic showers: linear dependence on shower depth
- logarithmic dependence on incident particle energy

7 parameters

CDF Tuning Procedure

... will mainly focus on hadronic response

1) MIP peak:
   - adjust the response of minimum ionizing particles in the EM calorimeter
   - fixed using 57 GeV/c test beam data
2) Hadronic energy scale:
   - adjust the shape of the individual responses (EM and HAD), the sum of both (TOT) and the hadronic response of particles in the HAD calorimeter appearing MIP-like in the EM (EM<670MeV)
   - fixed using 57 GeV/c test beam data
3) Energy dependence:
   - interpolate energy dependence e.g. using ⟨E/p⟩ response
   - all available test beam data plus Run-II data (added later)
4) Lateral profile:
   - adjust ⟨E/p⟩ profile in EM and HAD calorimeter
   - Run-II data only

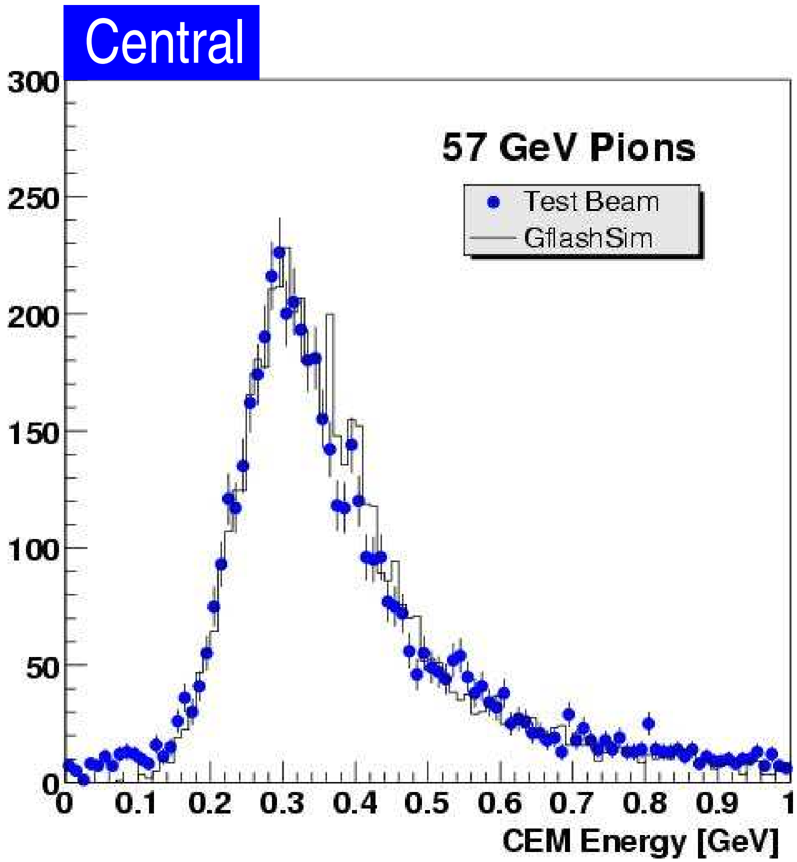
1) MIP Peak

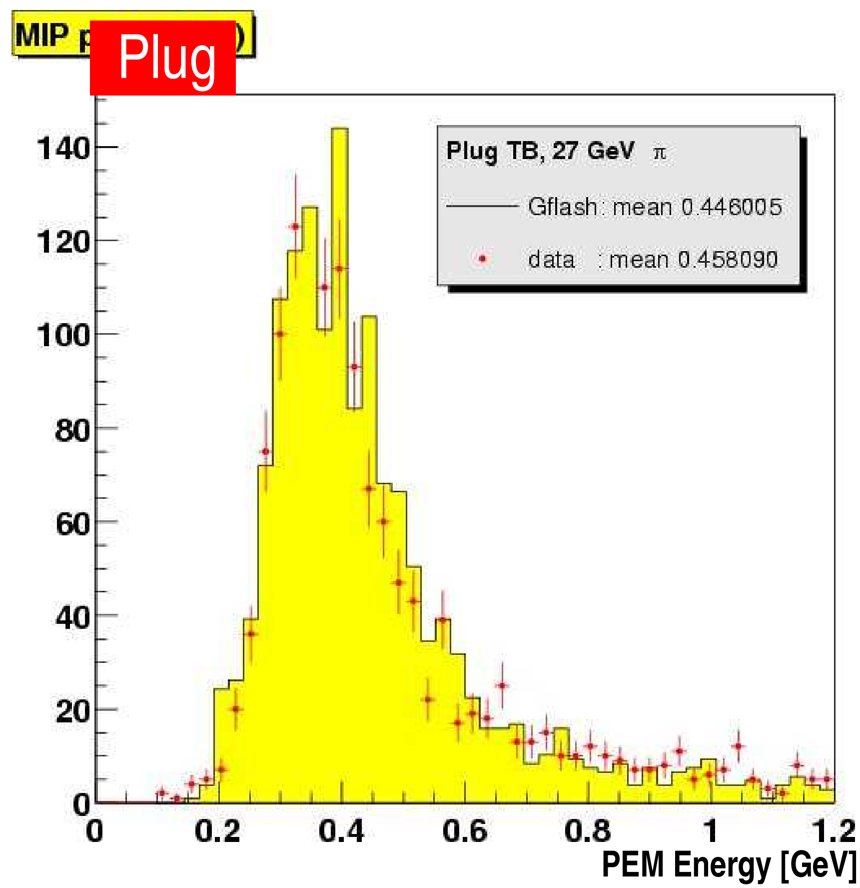
$$dE_{\mathrm{vis}}(\boldsymbol{r}) = E_{\mathrm{inc}}\,\hat{m} \sum_{\hat{k}} \frac{\hat{k}}{\hat{m}}\, c_{\hat{k}}\, f_{\hat{k}}(\boldsymbol{r})\, d\boldsymbol{r}$$

- MIP response theoretically well understood
- charge collection efficiencies
- serves as reference for other responses

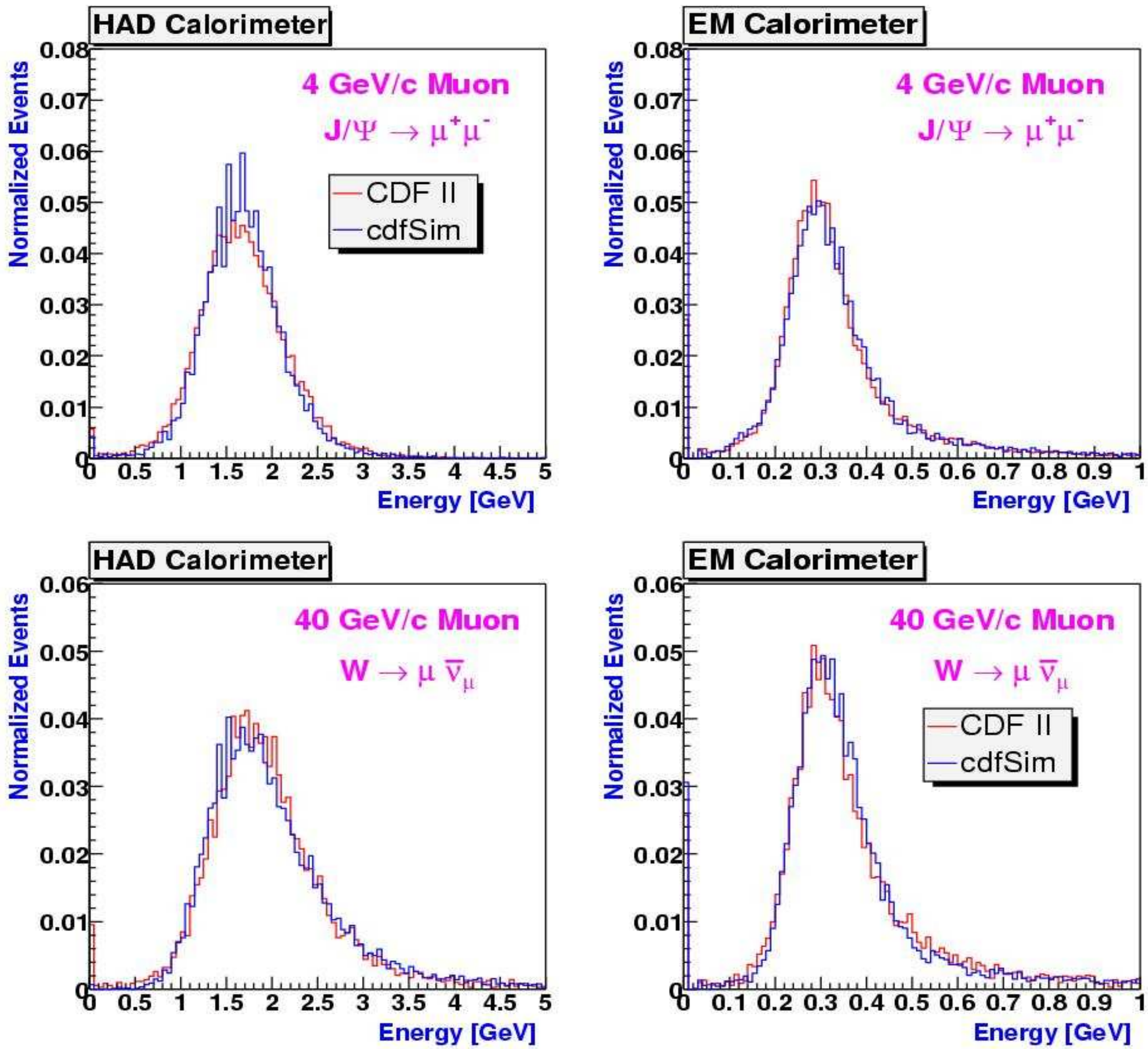
reproduce mean and width of MIP response

Test beam pions





Muon Response



... tuned later during Run II:

- Low p muons tuned using $J/\psi \rightarrow \mu^+\mu^-$
- High p muons tuned with $W \rightarrow \mu\nu$

2) Hadronic Energy Shape

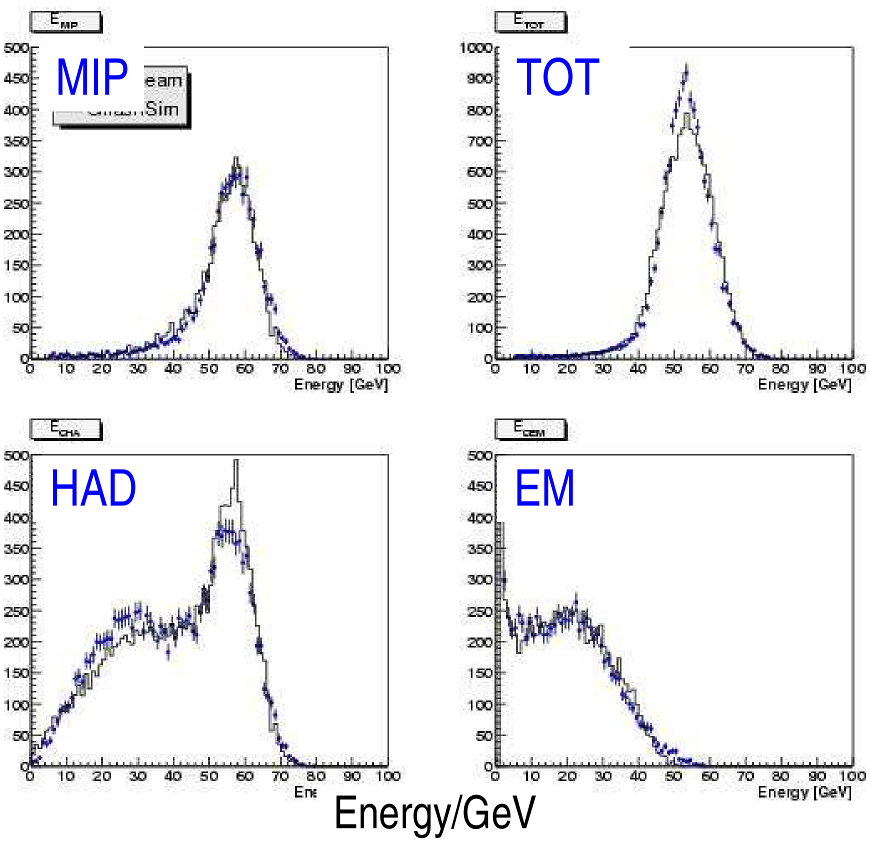
$$\mathrm{d}E_{\mathrm{vis}}(\boldsymbol{r}) = E_{\mathrm{inc}}\,\hat{m} \sum_{\hat{k}} \frac{\hat{k}}{\hat{m}}\, c_{\hat{k}}\, f_{\hat{k}}(\boldsymbol{r})\,\mathrm{d}\boldsymbol{r}$$

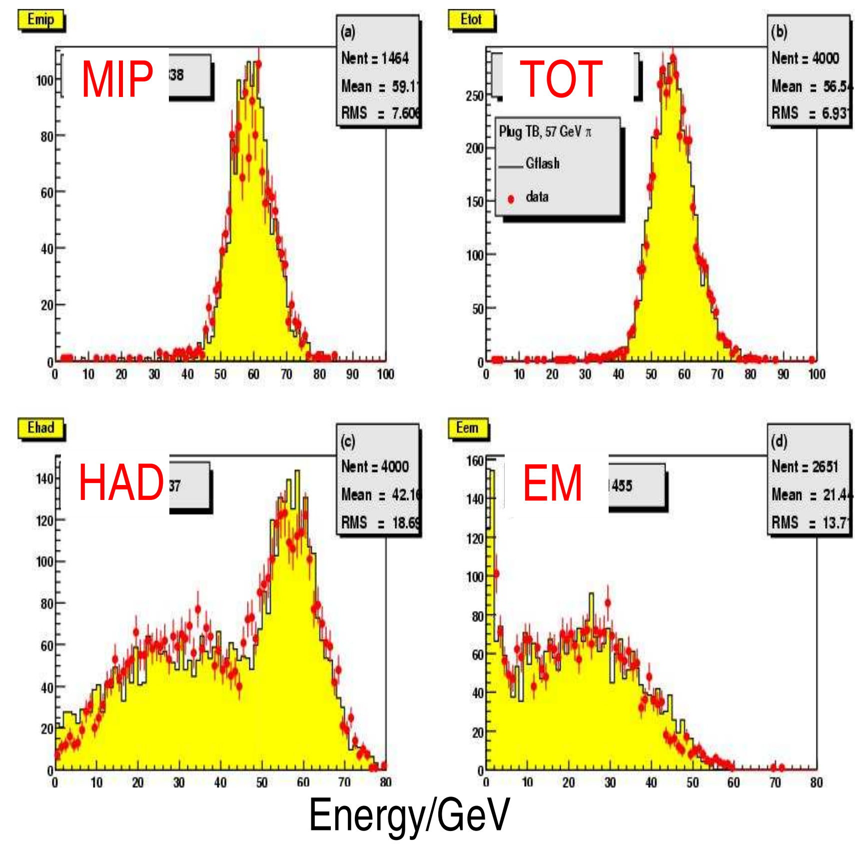
GFLASH switches:
- sampling fractions $\hat{k}/\hat{m}$
- f_{dep}, $f_{\pi 0}$, α_{l}, β_{h}, β_{l} + widths

Central

57 GeV pion test beam

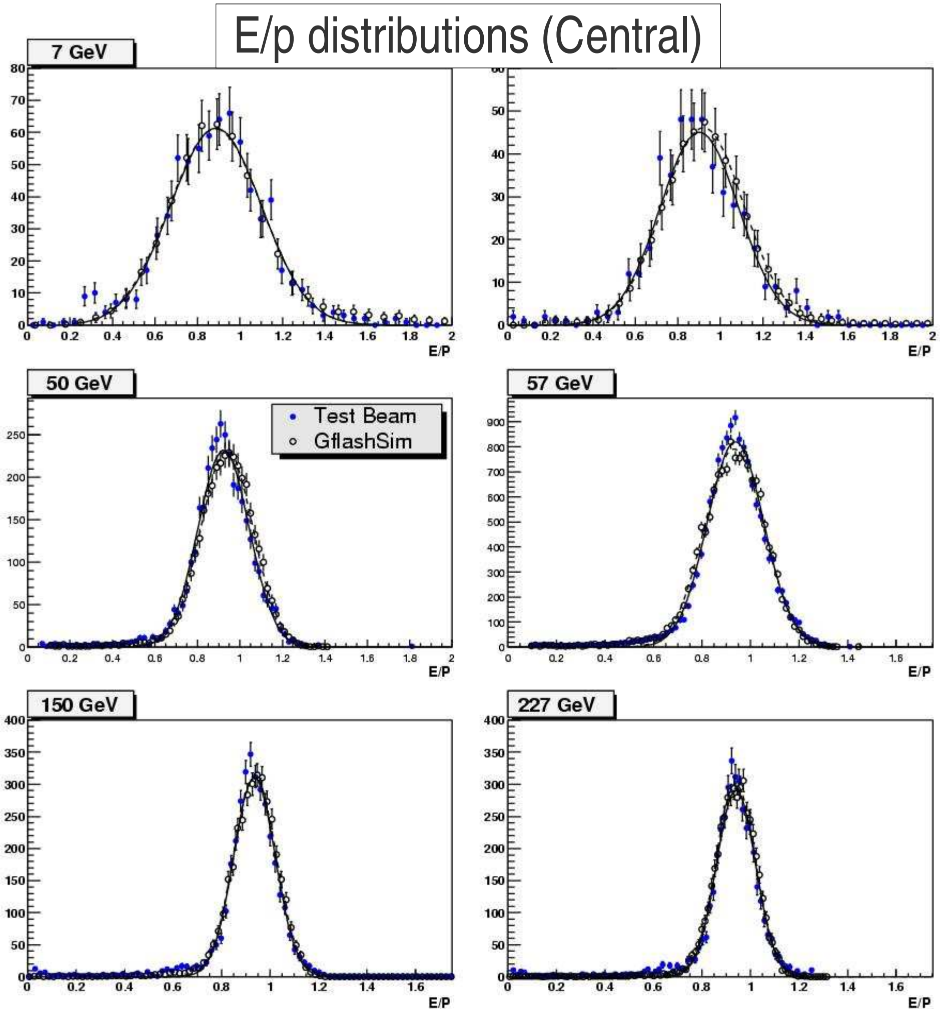
Plug

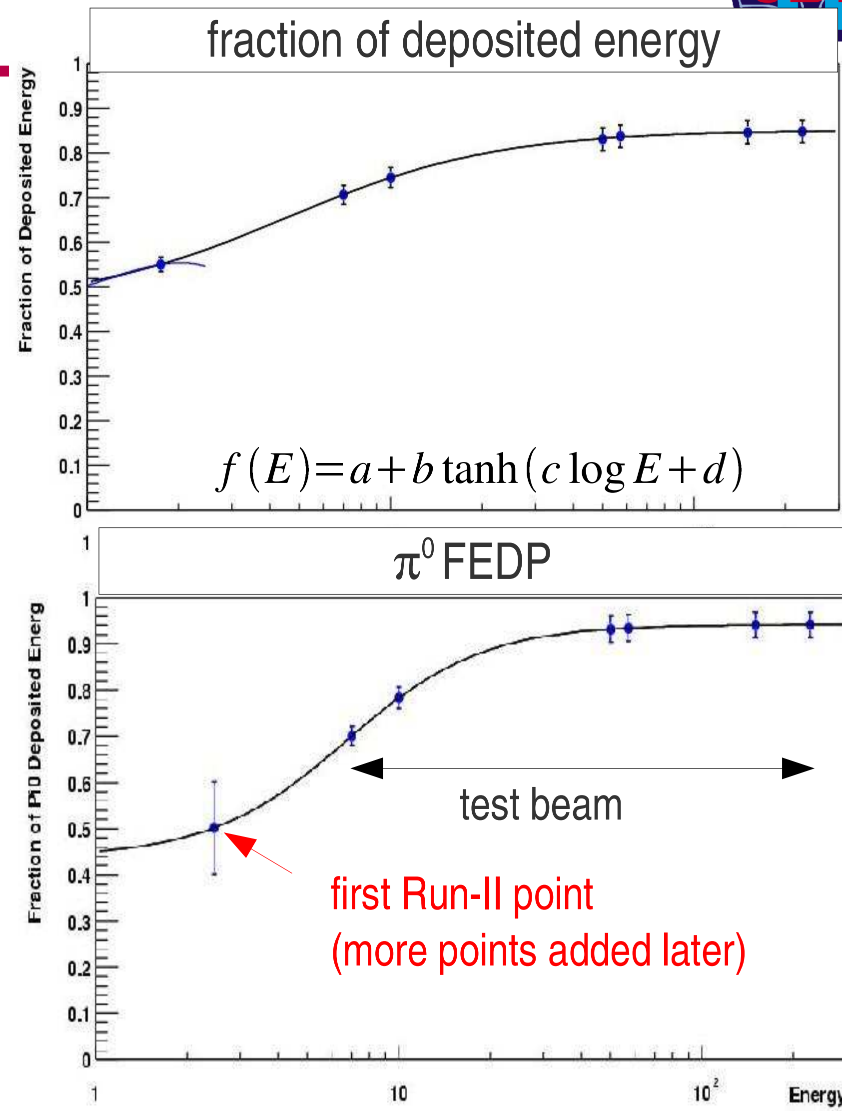




- Iterative procedure to find reasonable parameter set (underconstraint problem)

3) Energy Dependence





- Many longitudinal details are fixed using 57 GeV pion test beam data.
- Energy dependence adjusted using all available test beam data sets:
  Central: 7-227 GeV/c, Plug: 9-231 GeV/c

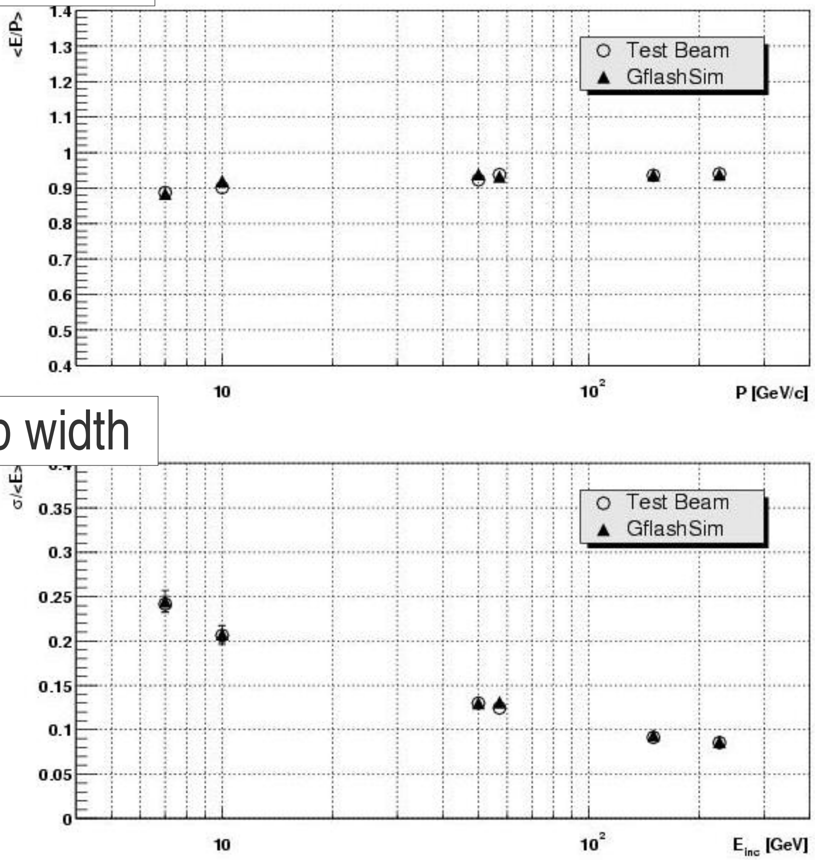
E/p Test Beam Data

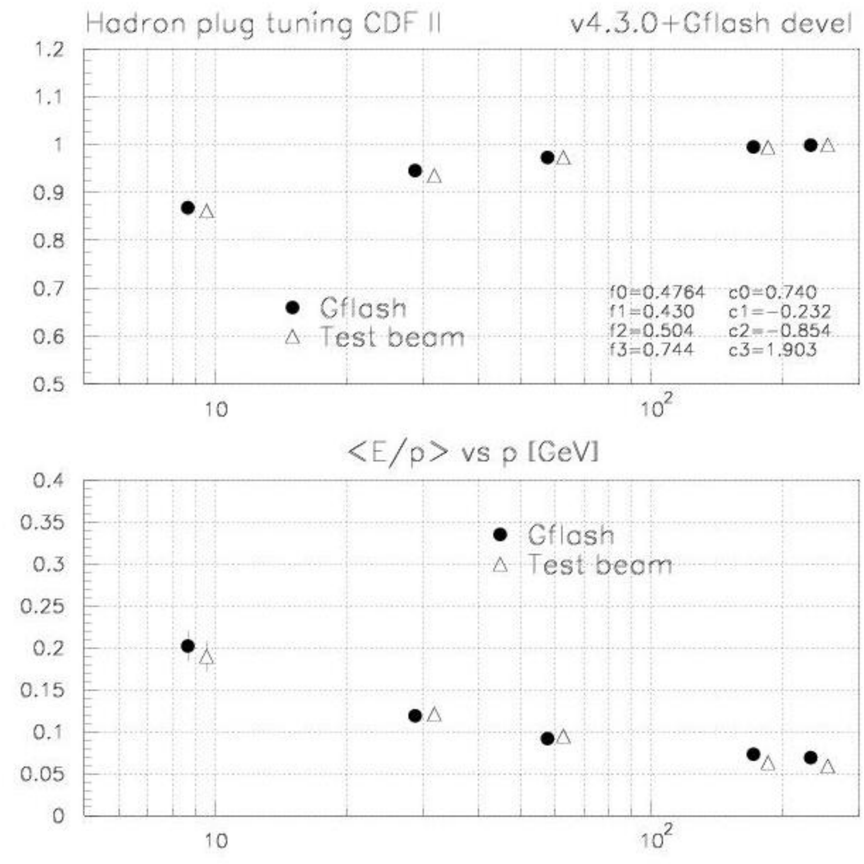
Central

Plug

E/p mean

E/p width

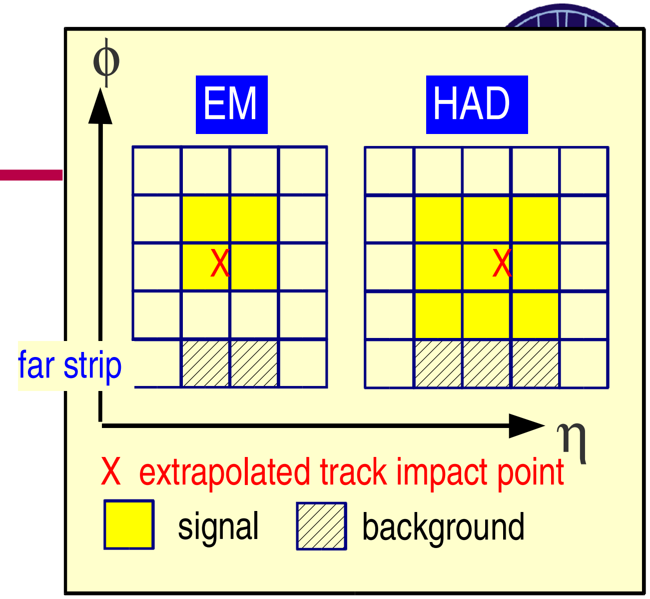




- Different parametrizations for Central/Wall/Plug
  - different sampling structures and passive material effects
- CDF has recently improved tuning using *in-situ* data (next page)
  - more direct control of parameters independent on test beam

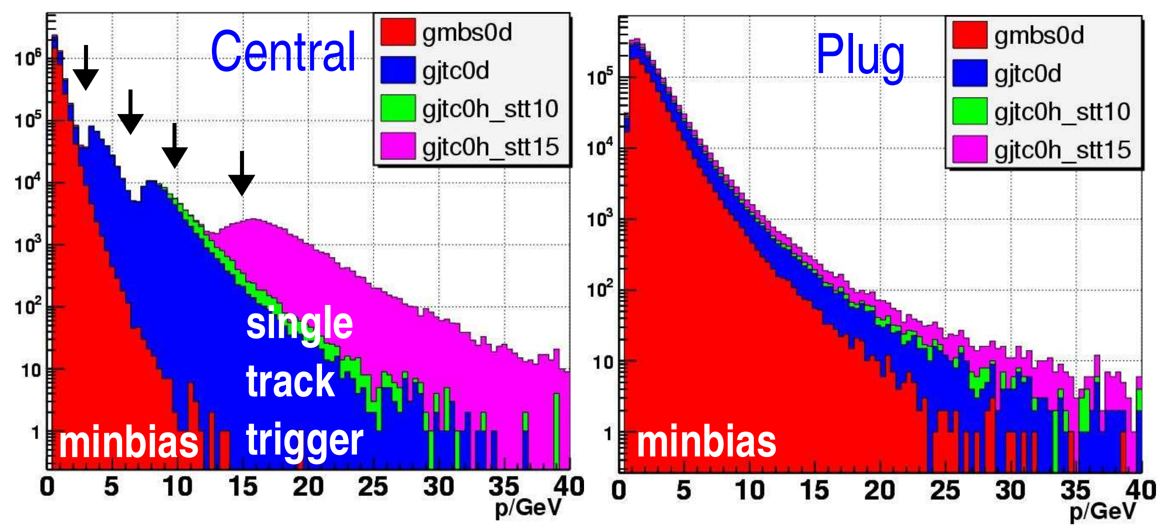
In-Situ Tuning Approach

- Run-II tuning is based on the response of <u>single charged particles</u> in EM and HAD tower blocks (plot)
- Selection of single isolated (7x7 tower blocks) high quality tracks.
- MinBias data, later also jet calibration and special single track trigger data.
- MC: usually single particle gun (flavor mixture + background modeling)



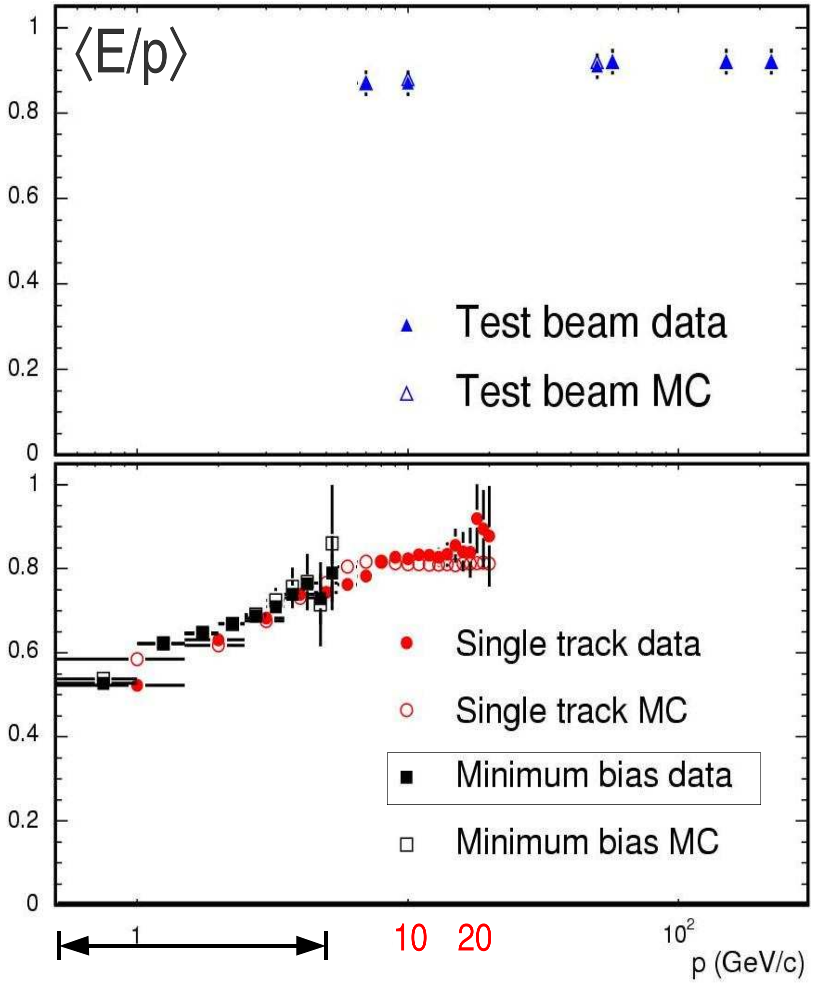
Signal:	2x2 (EM)	3x3 (HAD)
Backg:	2∗far strip	3∗far strip

- Single track triggers developed with thresholds up to 15 GeV/c.
- Extension of single track analysis from 5GeV/c (early Run-II) up to 40 GeV/c (now)



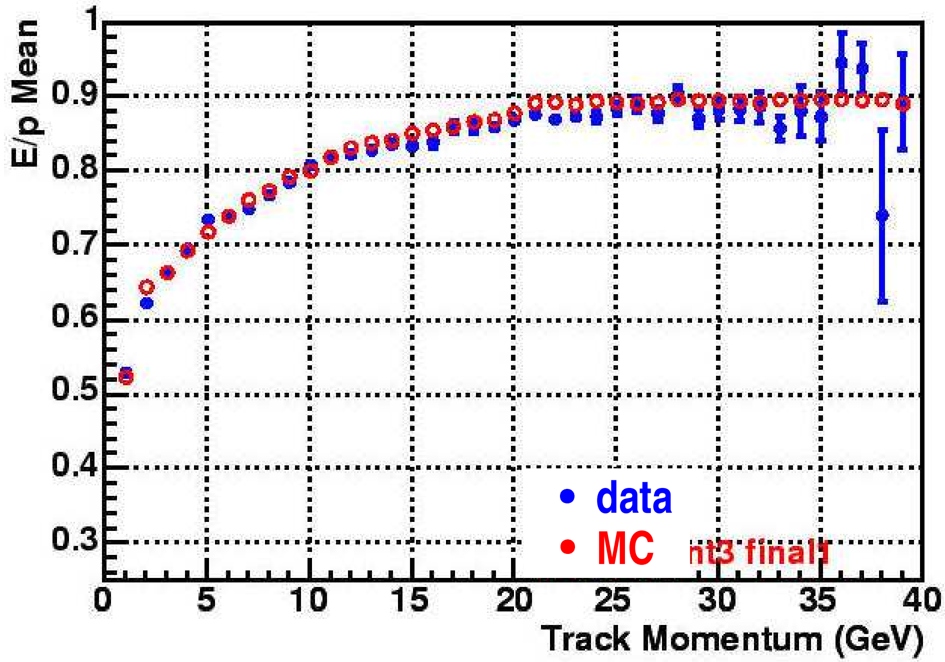
High P Response (Central)

early Run-II



initial Run-II tuning

now



- Significant gain of control *in situ* up to 40GeV/c (in Plug up to ~20GeV/c).
- Single track analysis continuously improved during Run-II.
- Verification/replacement of test beam data.

4) Lateral Profile

- Measure ⟨E/p⟩ in 5 towers adjacent in η.

  ...signal = target tower strip + 2 adjacent towers strips in φ.

- Define relative η coordinates normalized to tower bounderies

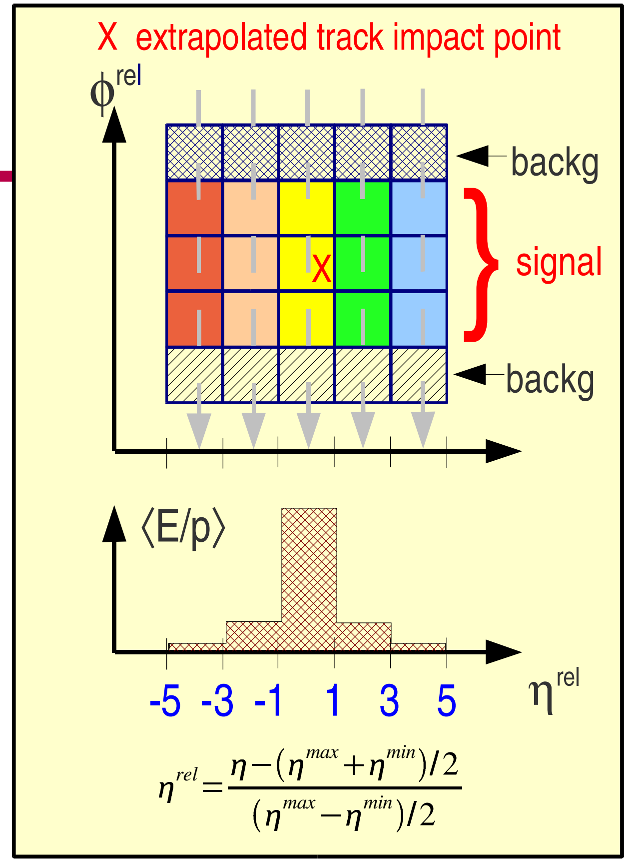
  → experimental profile ⟨E/p⟩ (η^{rel}) (plot)

  ...useful observable sensitive to lateral profile parameter R_0:

$$\langle R_0(E_{\mathrm{inc}}, z)\rangle = \left[R_1 + \left(R_2 - R_3 \ln E_{\mathrm{inc}}\right) z \right]^n$$

core term R_1 **spread term Q**

- shower depth
- incident particle energy



Signal: 1x3 strips (ηxφ)

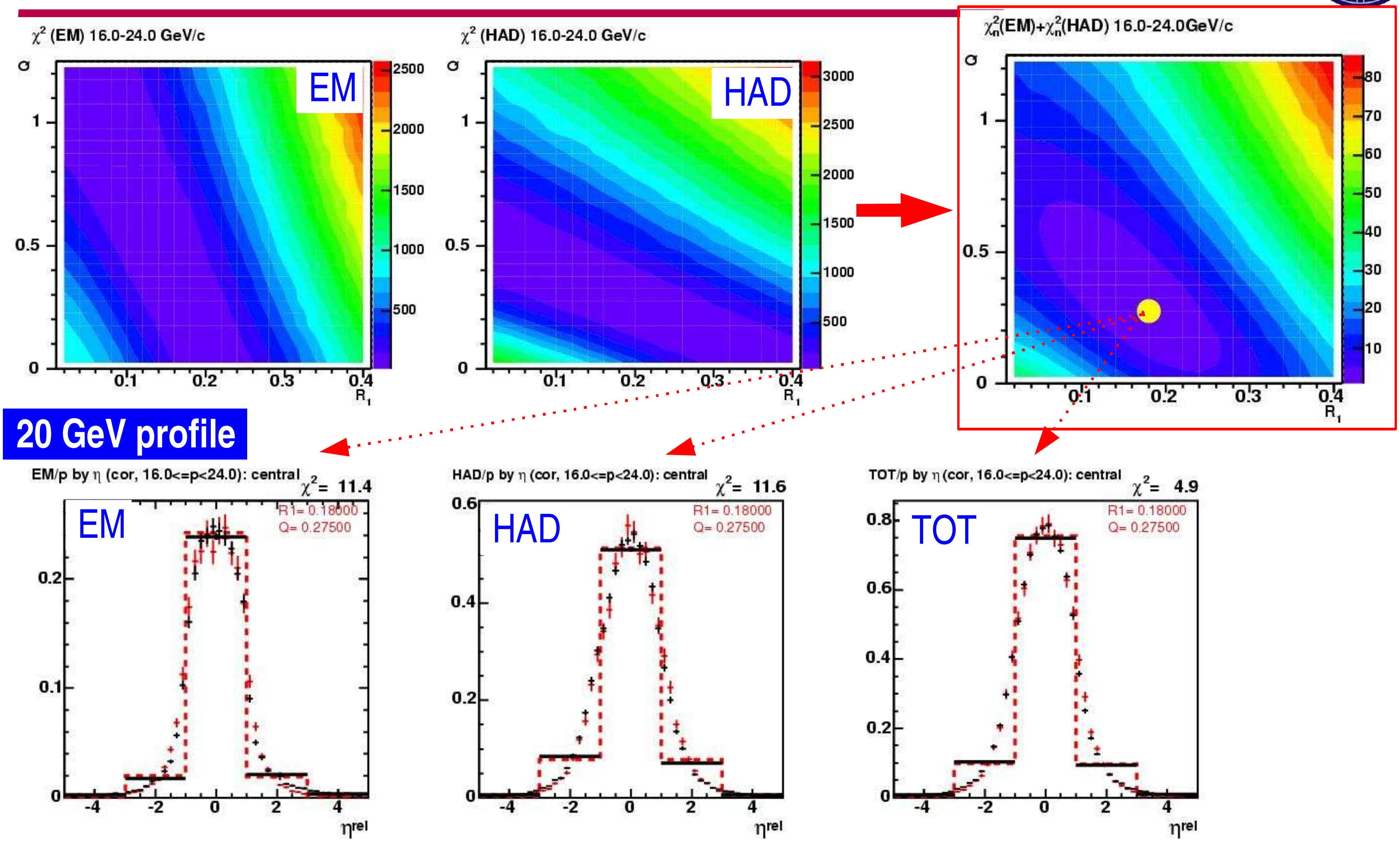
Backg: 3/2∗(both side φ towers)

Systematic tuning approach:

- Scan (R_1,Q) space for different momentum bins and compare with data (χ^2).
- HAD and EM calorimeter probe different parts of the hadronic shower development

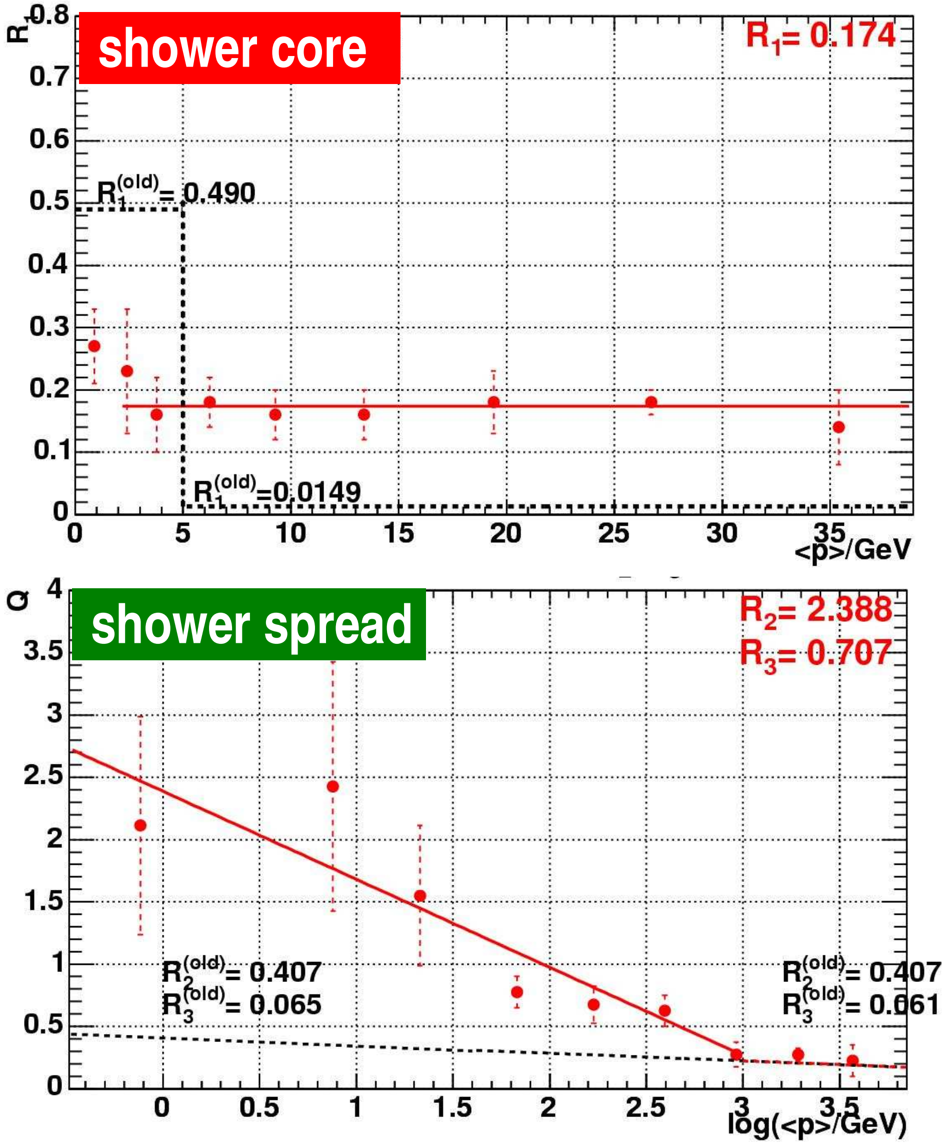
  → helps to constrain R_1 and Q at each momentum bin.
- R_2 and R_3 derived from Q dependence on p using R_1 constraint.

Lateral Profile Scans



- Profiles are normalized to absolute data response
  → lateral tune in first order decoupled from longitudinal profile details.

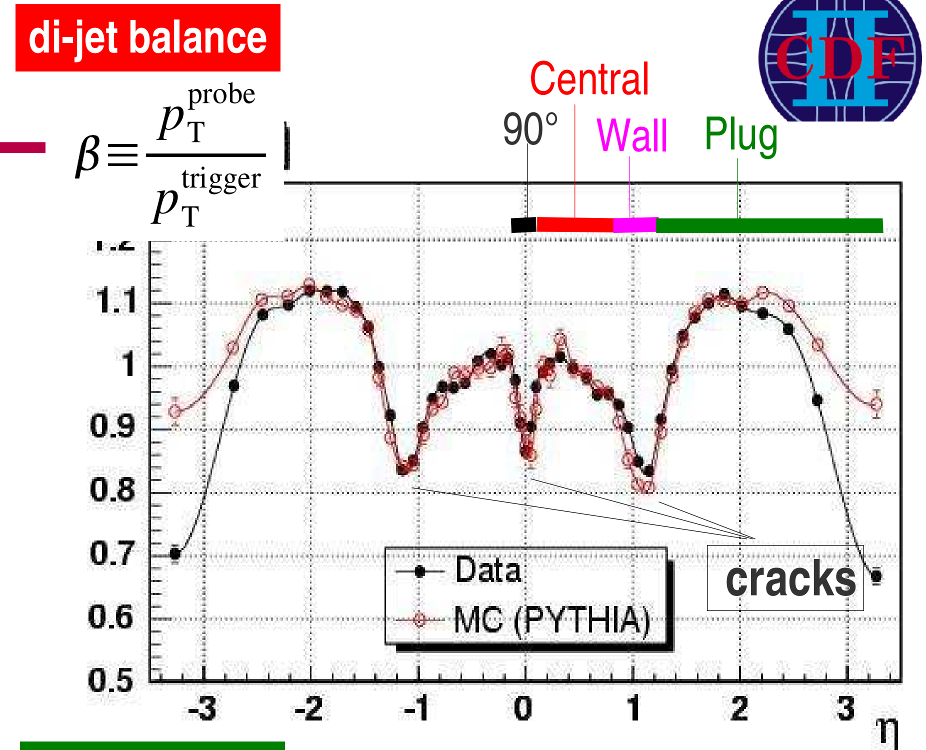
Lateral Profile Tune (Central)

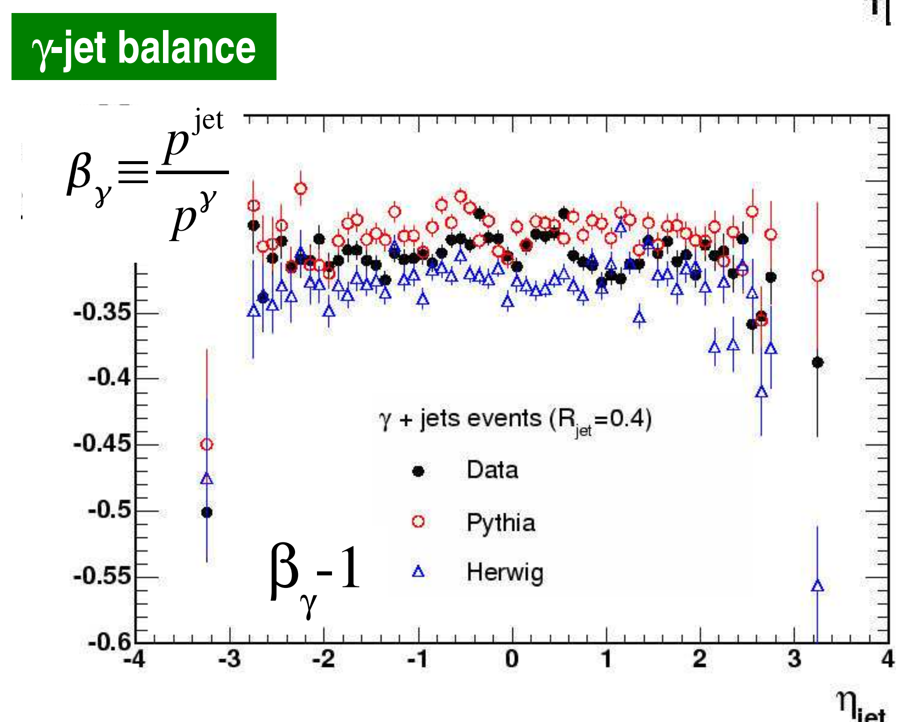


- Consistent global tuning of lateral profile in Central up to 40 GeV/c and in Plug up to 20 GeV/c.
- Replaces H1 default parametrization.
- Further work in progress to impose tighter constraint at low momenta...

Plug/Wall Response

- Inhomogeneous calorimeter response:
  - cracks (passive material) between Wall and Plug and the two halves of Central
  - different sampling structure in Plug
- Di-jet balancing technique corrects for imperfections in data and simulation (β)
  - response in Central is better understood
  - energy of non-central jet ("probe") is recalibrated using central jet ("trigger", $0.2<|\eta|<0.6$)
- Photon-jet balancing: monitors corrected jet energies using photon energies as reference (β_γ)
- Tuning is reproducing detector particularities along η.
- Work in progress to further improve picture (Plug, high jet p_T)...

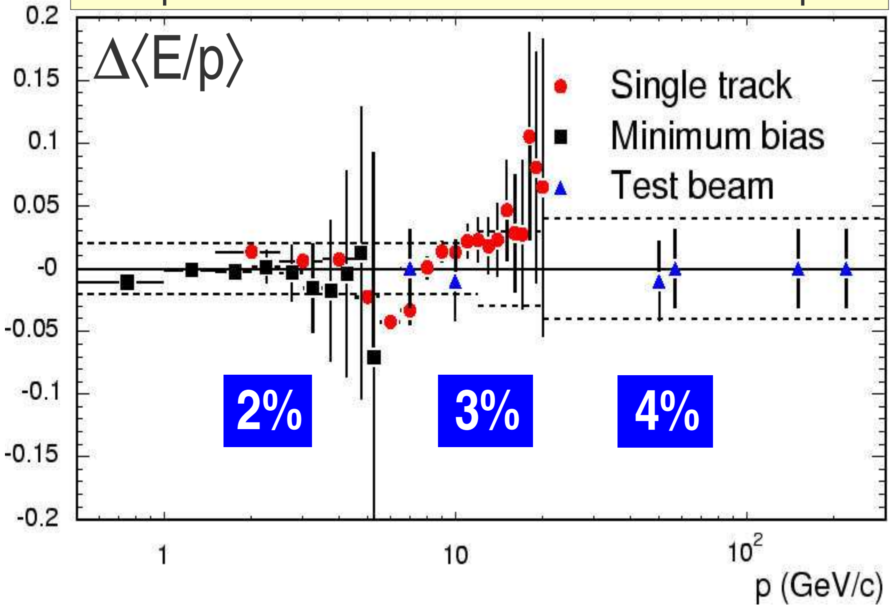




Simulation Performance

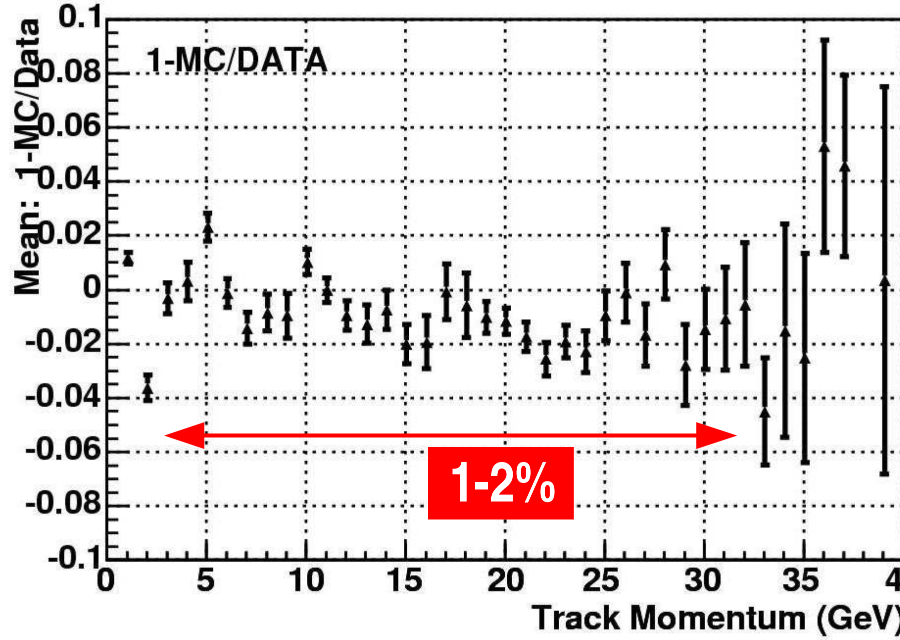
early Run-II

MC performance effective for current CDF publ.



- Early Run-II picture (above) currently imprinted into ongoing CDF publications.
  - *in-situ* tuning up to 5 GeV/c
  - reasonable performance, but *in-situ* validation at higher p (red points) limited by statistics
- Percentages directly translate into JES uncertainties (next page).

now

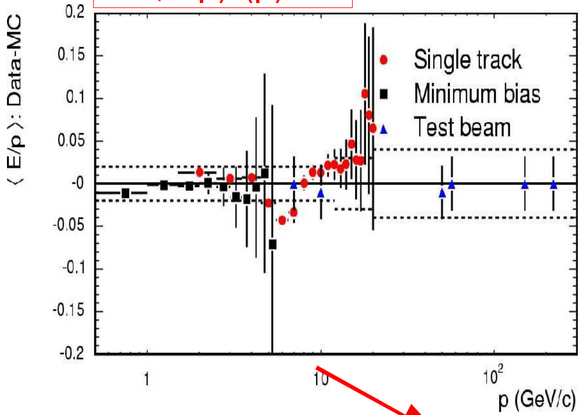


- Steadily increased *in-situ* single track data statistics.
- Better and more consistent tuning.

Jet Energy Scale Uncertainties

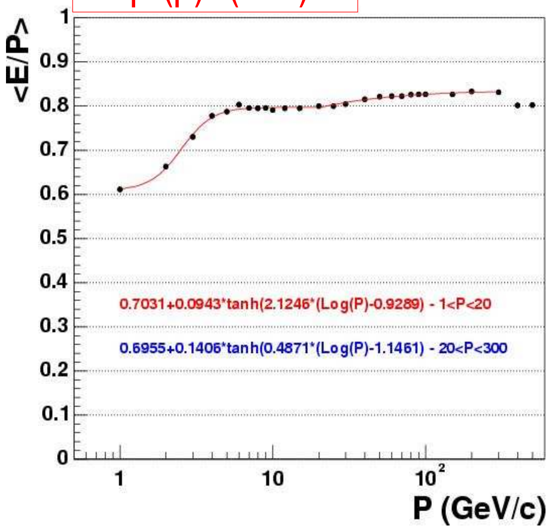
- Major part of MC/data difference enter JES uncertainties through “absolute jet energy corrections”:
  ...relates bunch of calorimeter towers within a cone (“jets”) to the “true” momenta of the underlying particles.
- Crucial for almost all physics analyses in CDF...

Δ(E/p) (p)

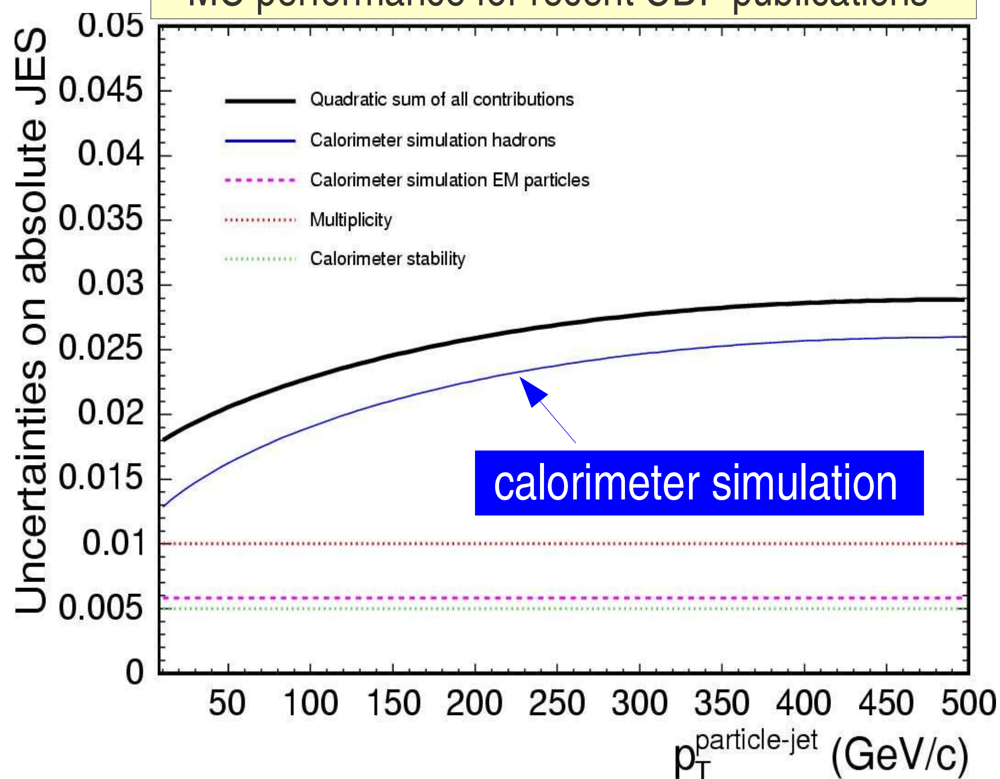


convolution with particle spectrum

E/p (p) (MC)

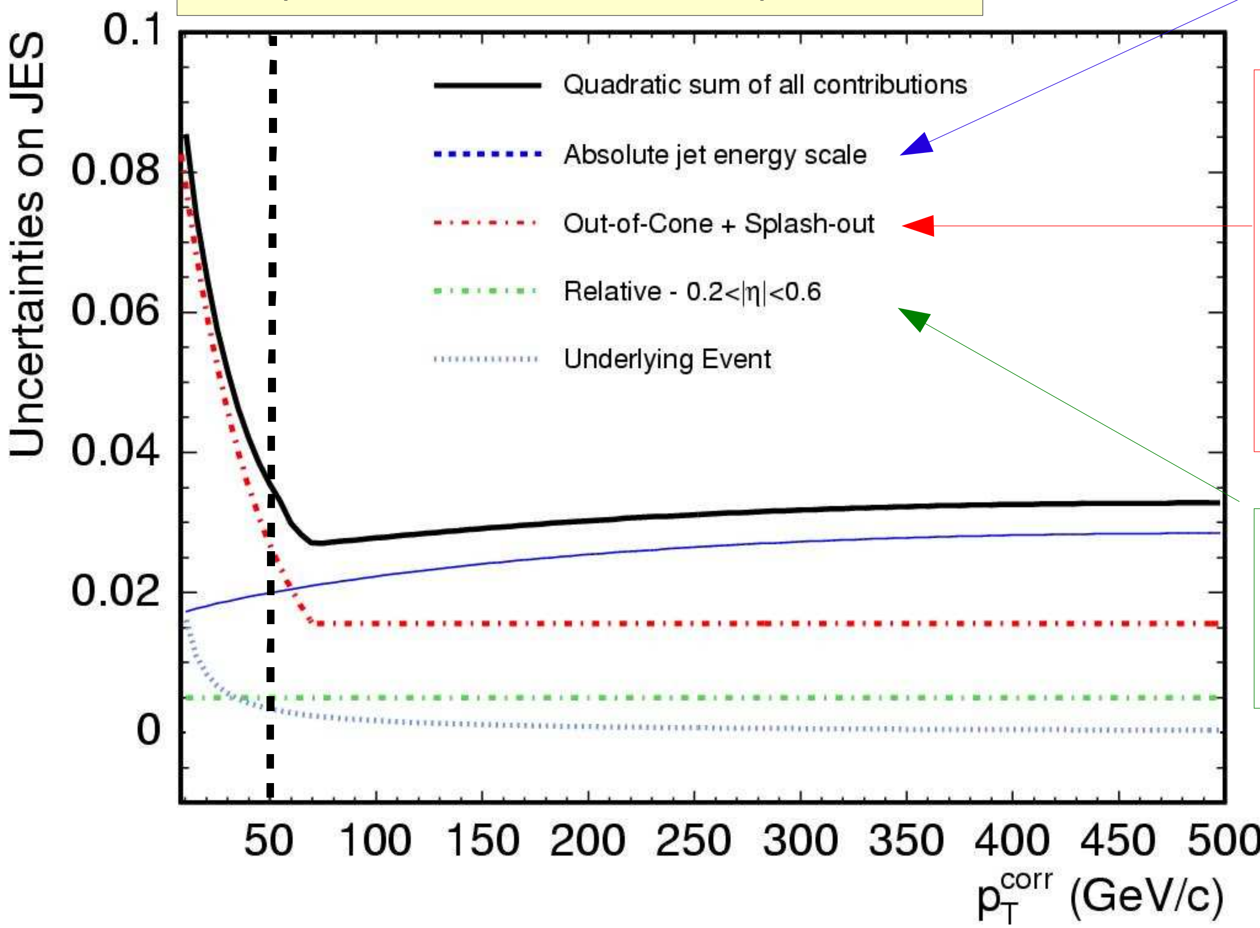


MC performance for recent CDF publications



CDF Total JES Uncertainty

MC performance for recent CDF publications



"Absolute jet energy scale":
- simulated E/p response

"Out-of-Cone":
- MC/data energy flow mismatch outside the jet cone
- direct contribution from lateral profile (leakage effects at cone boundaries)

"Relative":
- contribution from imperfection of Plug/Wall simulation

- Calorimeter simulation uncertainties still dominant.

Conclusions

- GFLASH has proved to be a **fast**, **flexible** and **improvable** tool to simulate electromagnetic and hadronic showers in the CDF calorimeter
- Central calorimeter data/MC discrepancy effective for ongoing CDF publications:

  hadronic charged particle response: 2-4%

  electron response: 1-2% (not covered by this talk)
- MC improvements successfully contributed to CDF physics program through reduction of JES systematics.

For more details, see accepted NIM paper: **"Determination of the Jet Energy Scale at CDF"**, **hep-ex/0510047** (see also Mark Mattson's CDF talk of June 5th for further selected physics results).

	$M_{top} \pm$ stat. $\pm$ JES $\pm$ other	Method
Run I 109/pb	$176.1 \pm 5.1 \pm 4.4 \pm 2.9$	Template
Run II 162/pb	$177.8 \pm 4.5/5.0 \pm 5.3 \pm 3.2$	Dyn. Likelihood
Run II 680/pb	$173.4 \pm 1.7 \pm 2.2 \pm 1.3$	Template + in situ W→jj calibration

excerpt of CDF "best" individual top mass measurements (lepton+jets channel)

- ***We are good but need to get better ...***

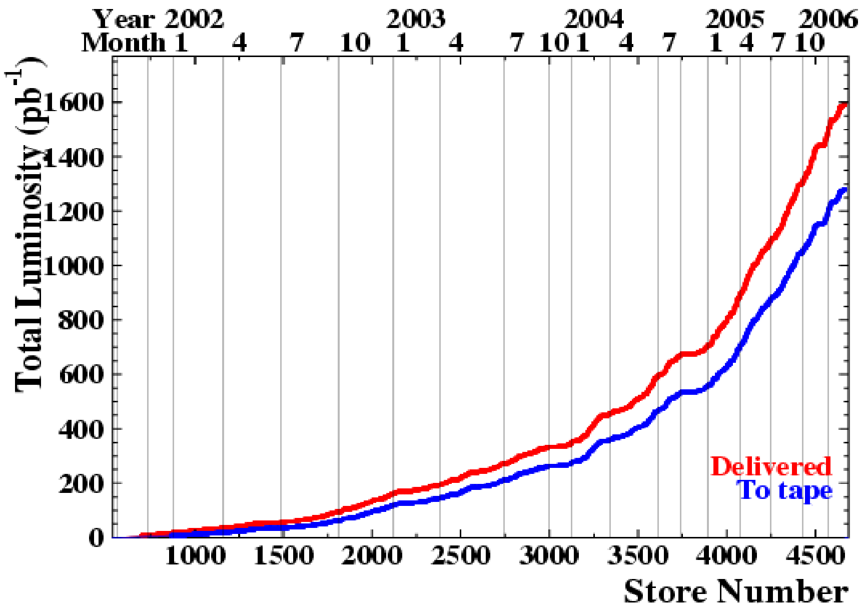
Outlook

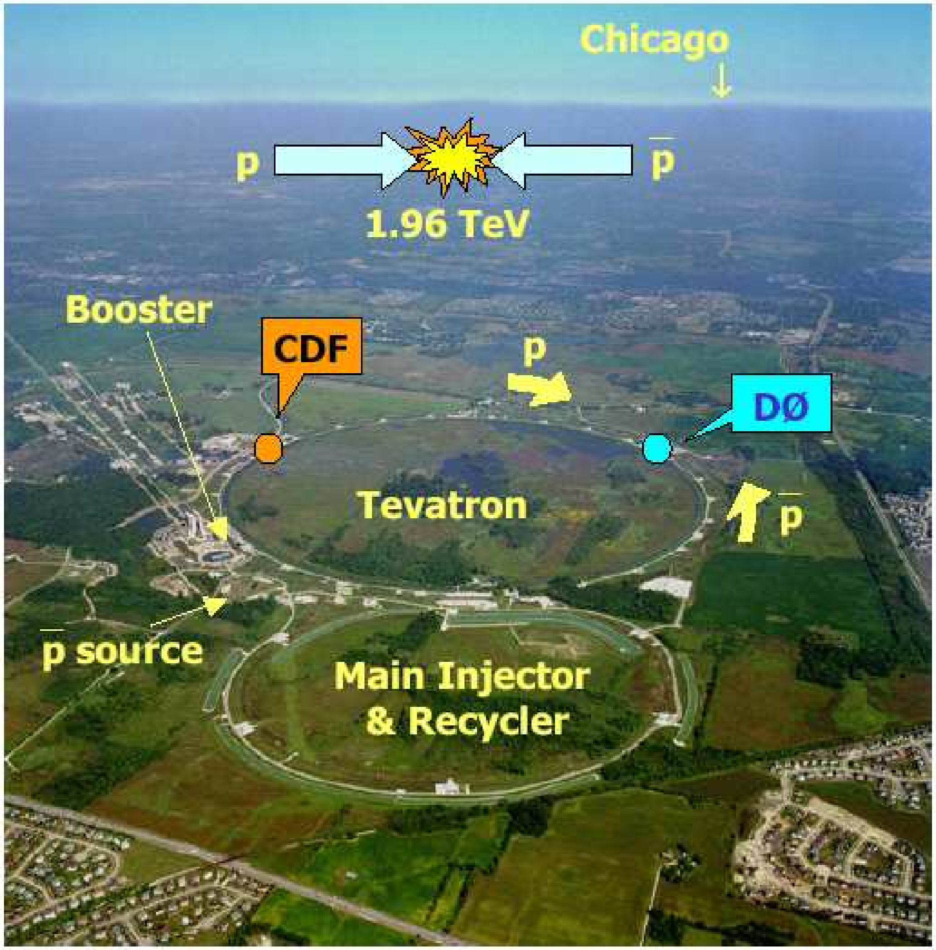
- CDF is aiming at <2% in hadronic and <1% in electron response uncertainty (essential for physics program).
- Ongoing efforts to further improve Plug tuning (background effects, track quality) and simulated e.m. responses in cracks between tower wedges.
- *In-situ* tuning based on newly available single isolated track samples (replacing test beam) crucial to overcome all current performance limits.
  - ➔ consider single track trigger runs (high thresholds) in early LHC run periods
- GFLASH might be a promising simulation tool for LHC experiments (ongoing feasibility studies at ATLAS/CMS)
  - ➔ more flexibility than GEANT
  - ➔ tunable
  - ➔ excellent CPU performance

Backup Slides

The Tevatron at Fermilab

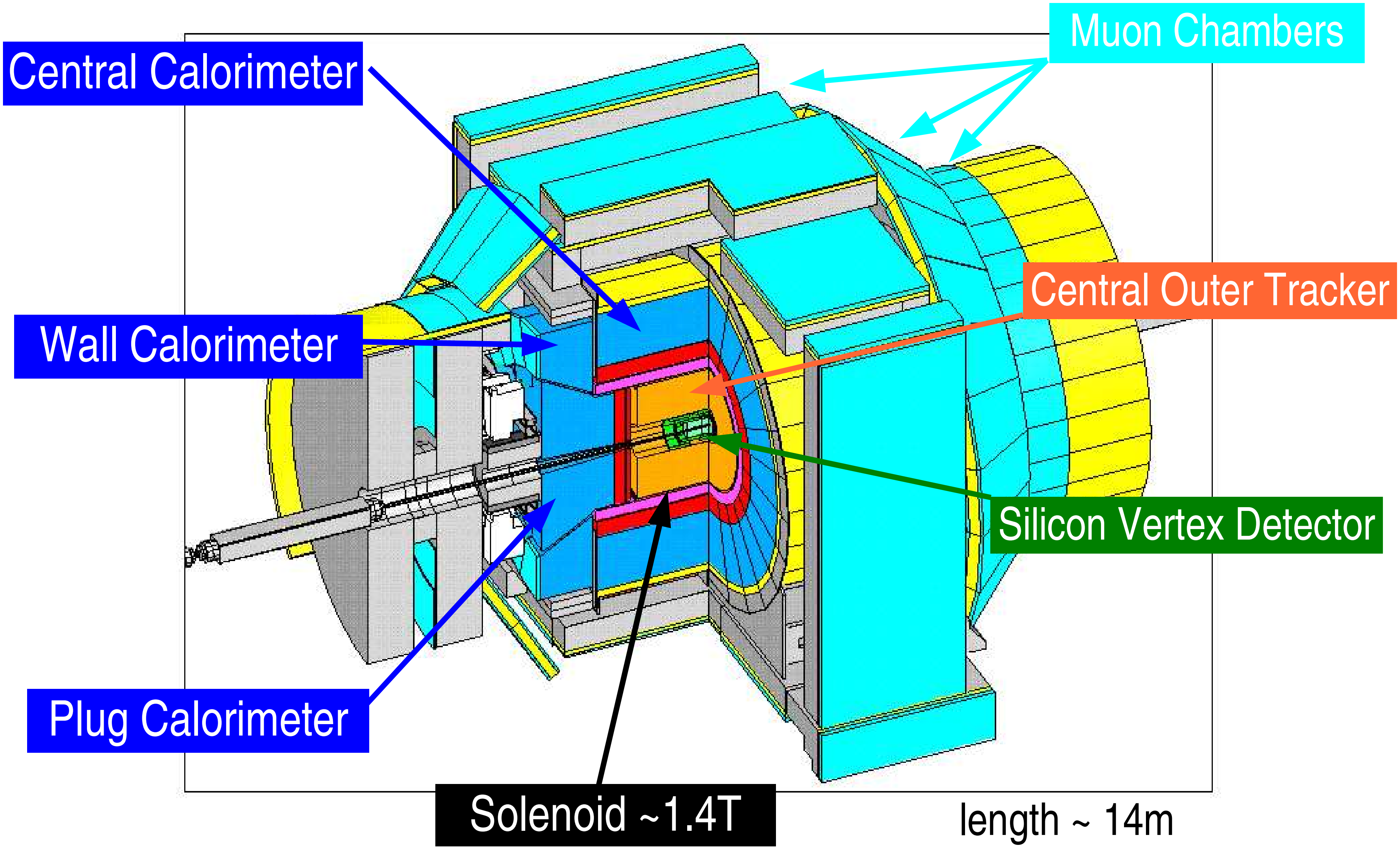
- Run-I (1992-1996):
  $\sqrt{s}$=1.8TeV, inst. L. = $10^{31}cm^{-2}s^{-1}$, $\int L$ ~109/pb (CDF)
- Run-II (since 2001):
  - $\sqrt{s}$=1.96TeV
  - 36 x 36 bunches at 396 ns spacing
  - Main Injector & Recycler
  - New anti-proton target





- Substantially improved and steadily increasing luminosity:
  - inst. L. ~ $14 \times 10^{34}cm^{-2}s^{-1}$
  - $\int L$ ~ 1.3/fb (CDF March 2006)

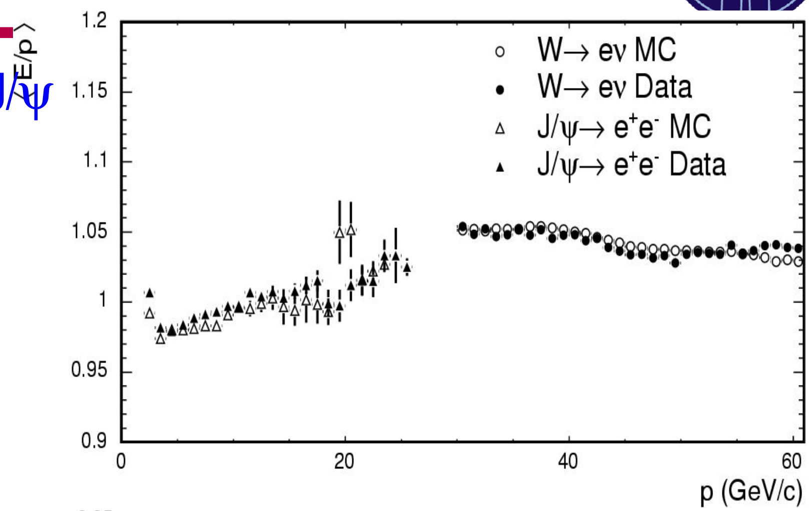
The CDF Detector

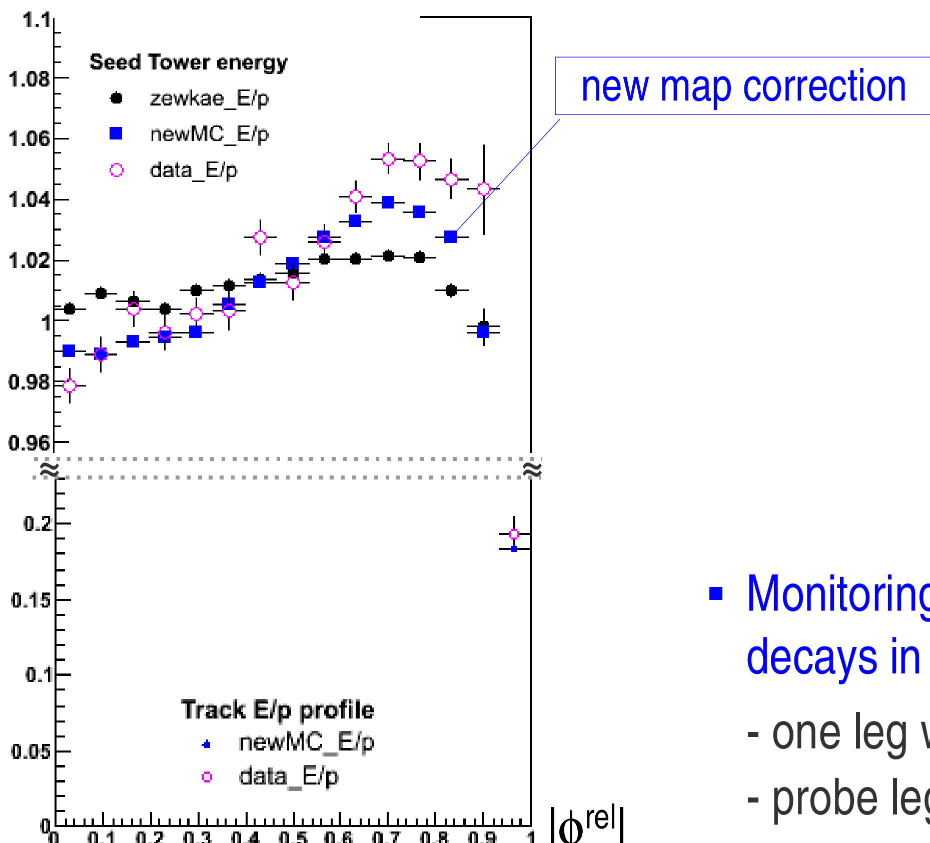


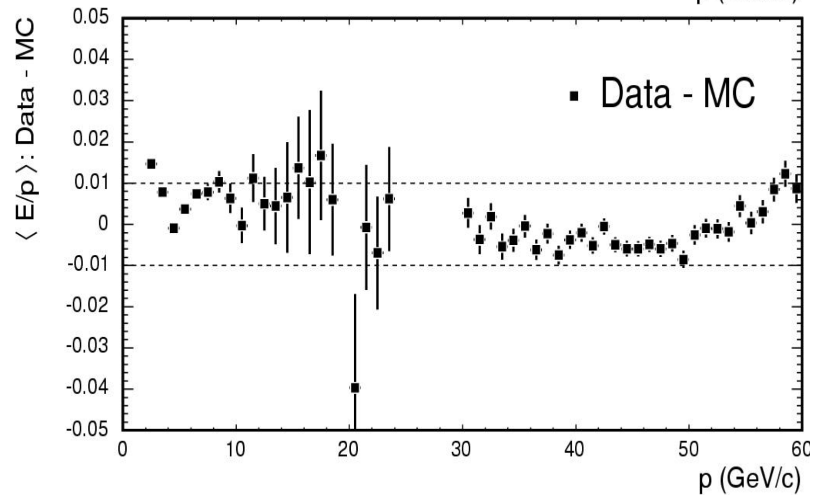
length ~ 14m
height ~ 11m

Absolute Electron Response

- Electromagnetic scale is tuned in-situ using electrons from J/ψ (low p)or W (high p) decay
- MC – data discrepancy ...
  - electrons pointing to inner 0.9x0.9 of target tower: 0.5%
  - electrons pointing to φ cracks (WLS, steel bar): 1.6%
- Ongoing efforts to reduce crack mismatch



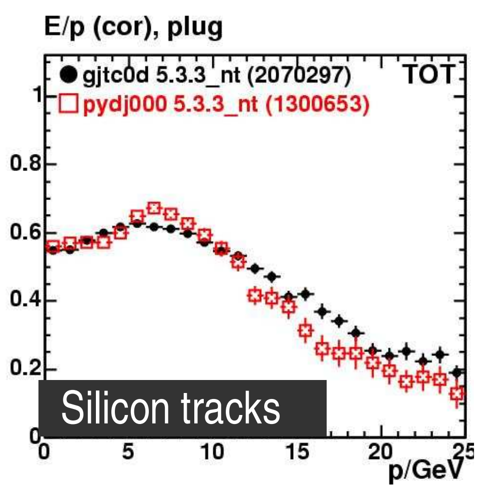


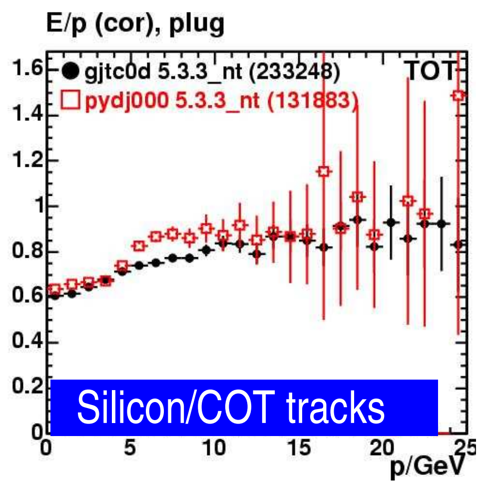


- Monitoring of cracks using electron pairs from Z^0 decays in mass window around m_{Z0}:
  - one leg well contained in a central target tower
  - probe leg scans φ up to crack

Plug/Wall Particularities

- Different sampling structures Plug vs. Central, Wall crack at |η|~1.1
  → requires region dependent parametrization of f_{dep}
- Low track reconstruction efficiency, worse track quality
  → Plug tuning using tower groups for which COT tracks are available (towers 12-15).





...effect of resolution folded with minbias spectrum

- Larger interdependence between lateral and longitudinal shower profile due to finer segmentation
  → requires best possible tuning of lateral profile prior to tuning absolute response