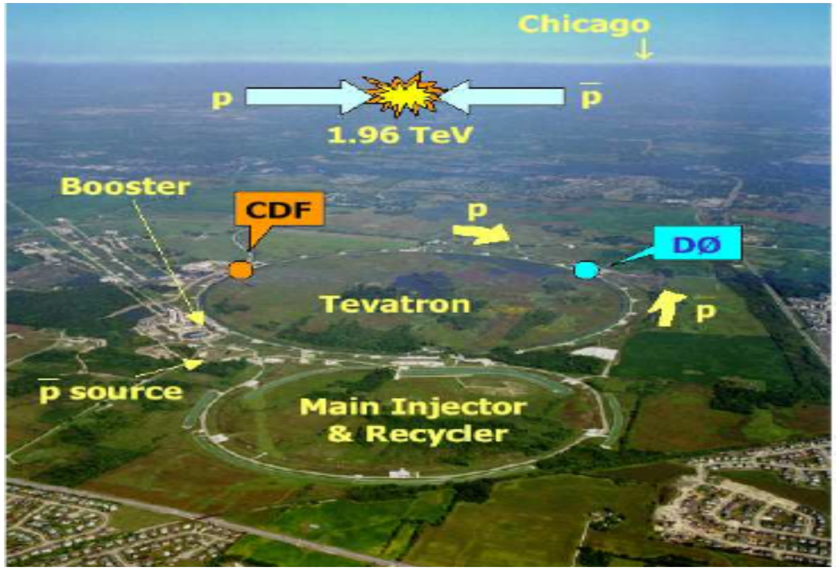
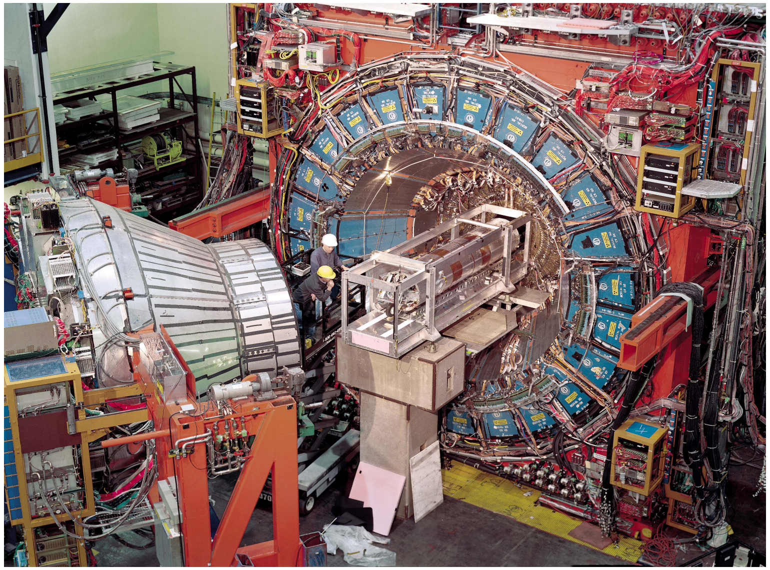
CHEF 2013

Paris April 22-25 2013





CDF Calorimetry

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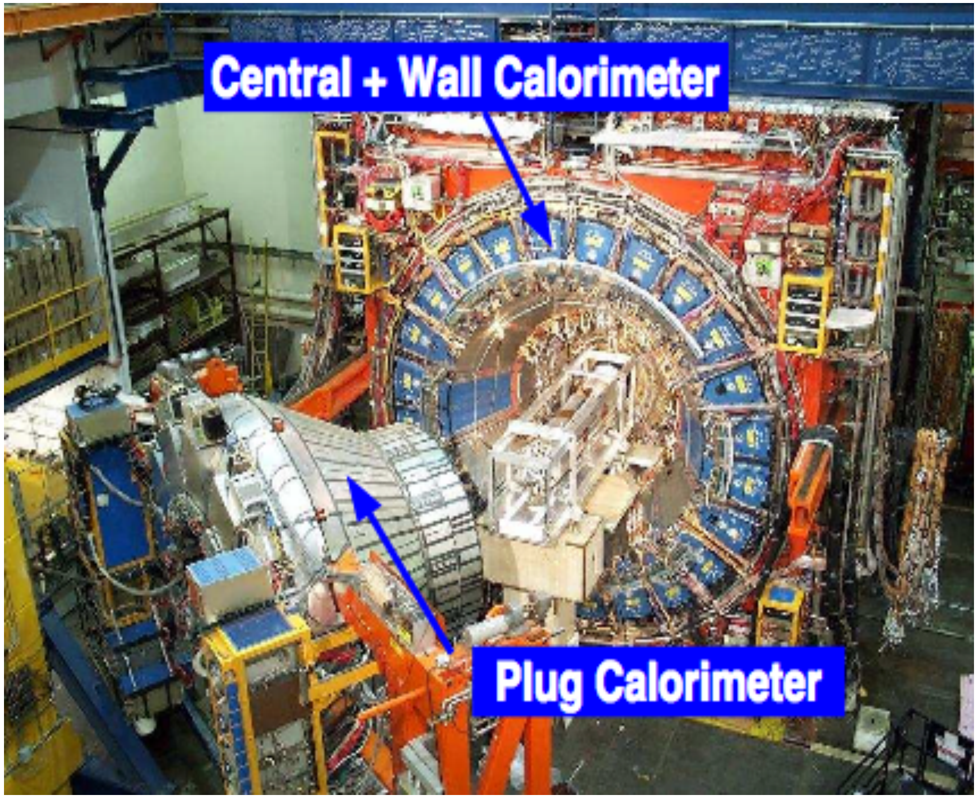
On behalf of the CDF Collaboration

Outline

- ☐ History
- ☐ The CDF detector
  Calorimeter Facts
- ☐ Operation
- ☐ Calibration/Performance
- ☐ Jet Energy scale
- ☐ Impact on physics
- ☐ Conclusion

Collider **D**etector at **F**ermilab 1985-2011



The History (1977-1981)

- Design of CDF started in the late 70's
  prior to the W/Z discovery – well before top quark ($m_t<m_W$)
- Design took into account the Tevatron parameters:
  luminosity (~10^{30}cm^{-2}s^{-1}), energy (1.8TeV), crossing time (3.5μs)
- Designed and optimized for high P_T physics:
  SM gauge bosons, top,
  explore the energy frontier region up to ~500GeV
- Low budget design, incorporating state of the art technologies available at that time

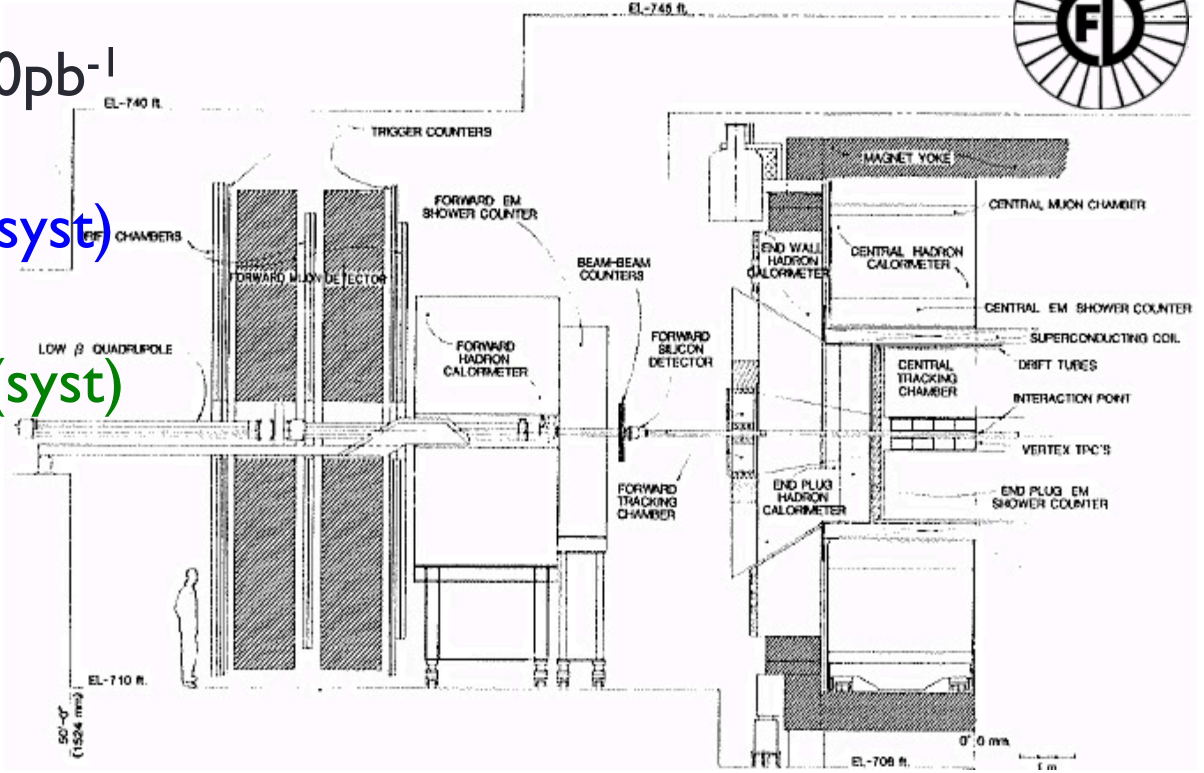
The History: August 1981 – TDR

- ☐ Concept for:
  - Almost 4π coverage ($3^\circ<\theta<177^\circ$)
  - Calorimetry in projective tower geometry
  - Two basic calorimetry sampling techniques:
    - Scintillator-BBQ wave shifter readout with pmts ($30^\circ<\theta<150^\circ$)
      Central EM/HAD and EndWall HAD calorimeters
      (better resolution, lower average particle energies/density)
    - Multiwire gas-filled chambers with cathode pad readout
      Plug and Forward EM/HAD calorimeters
      (high particle energies/density, easier mechanical design)
    - Pb and Fe absorbers for EM and HAD calorimetry
  - Tracking detector in a solenoid surrounded by the calorimeter
    separate particles, improve jet resolution, dE/dx, bkgd rejection
  - Vertex detector surrounding the IP region
  - Central Muon and Forward Toroid muon system

The History

- CDF new-born: October 1985 – CDF I
  First $p\bar{p}$ collision data at 1.6TeV – 897 triggers
- 1987 – 30nb^{-1}
- 1988-89 – Run 0: 4.7pb^{-1} W mass: 79.91±0.39GeV
- 1992-96 – Run I: ~110pb^{-1}

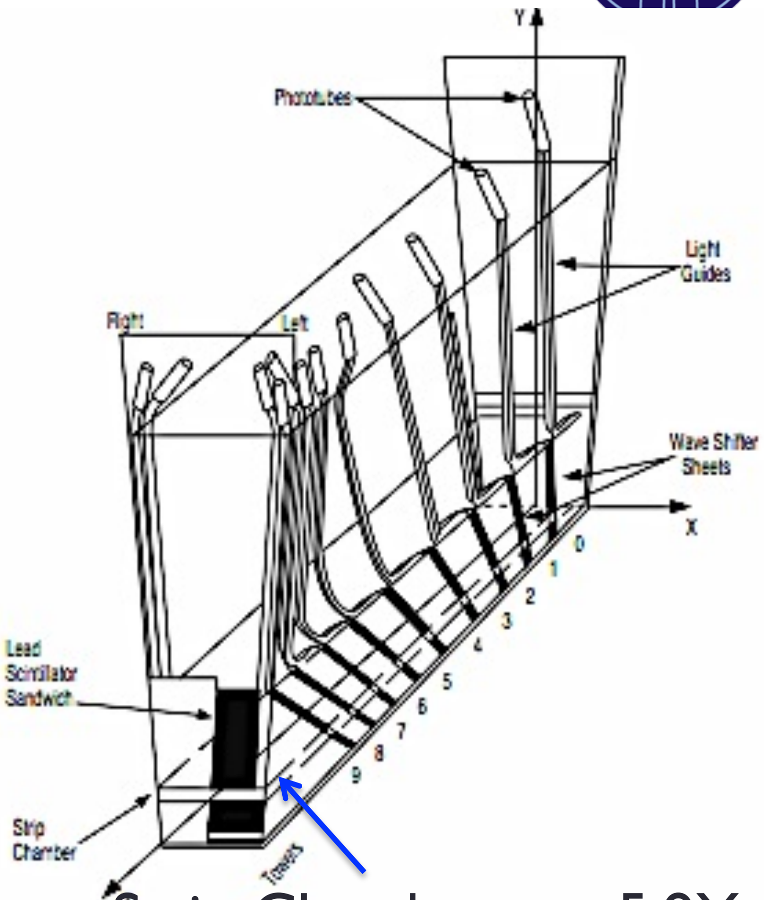
top discovery
m_t=174±10.0(stat) ±13(syst)
l+jets – run Ia
m_t=176.1±5.1(stat)±5.3(syst)
l+jets – all run I



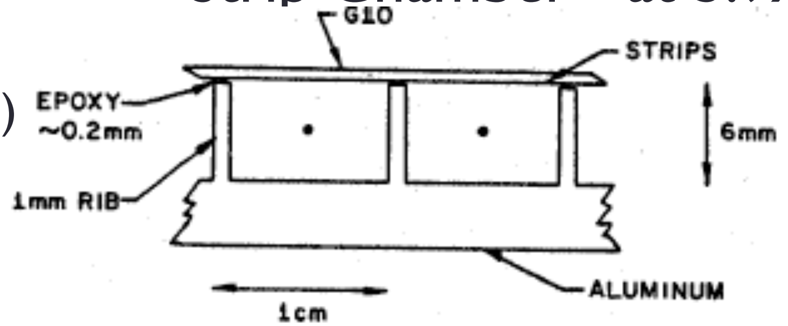
CDF calorimetry components: CEM

Parameters: $|\eta| < 1.1$

Segmentation	$\Delta\phi = 15°$, $\Delta\eta = 0.1$
Thickness	18.0 X_0, 1λ_0
Pb absorb. layer thick.	4.2mm, 0.6X_0/20-30 layer
Scint. layer thick.	5.0mm/21-31 layers
Scintillator type	polystyrene (SCSN-38)
Wave length shifter	3mm Y7 UVA acrylic
Photomultiplier (1.5”)	15-Stage Hamamatsu R580
Light yield	>100 p.e./GeV/pmt
Resolution:	$13.7\%/\sqrt{E} \oplus 2\%$
Position resolution	2mm for electrons from W



Strip Chamber - at 5.9X_0



CES wires oriented along Z,split in half, ganged in pairs for readout (except ends)

CES strips 1.7-2cm

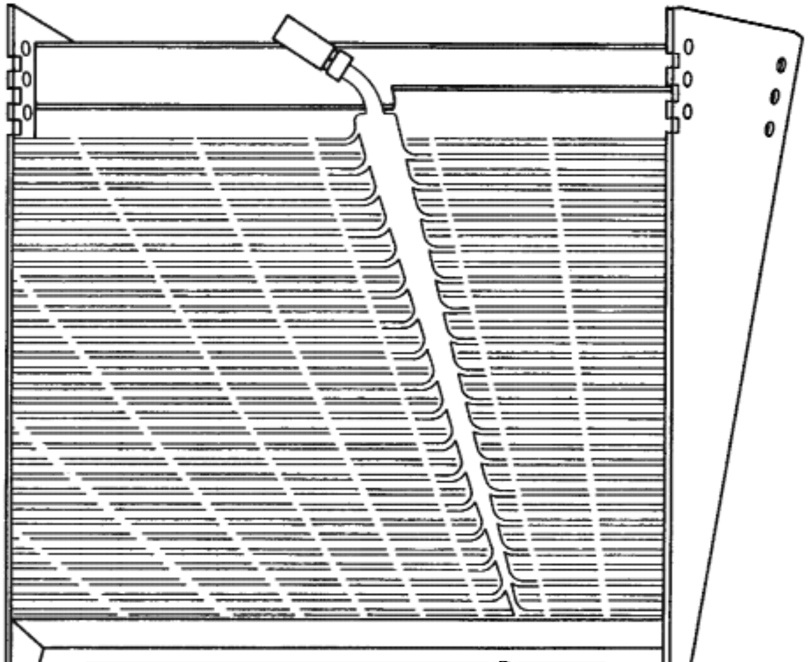
64 wires and 128 strips/module

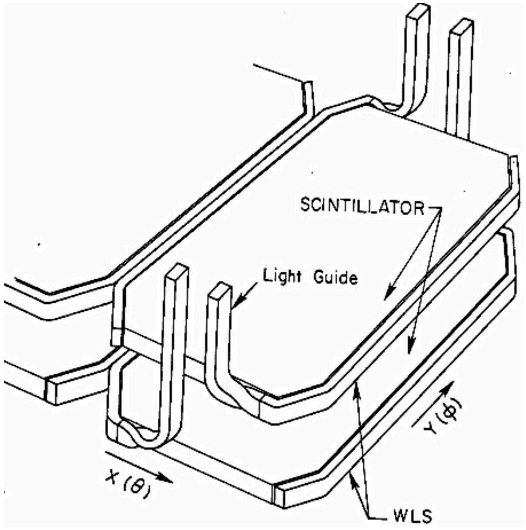
Gas 95%/5% Ar/CO_2

CDF calorimetry components: CHA

Parameters: $|\eta| < 0.9$

Segmentation	$\Delta\phi=15^{\circ}$, $\Delta\eta=0.1$
Thickness (CHA alone)	$4.7\ \lambda$
Absorb layer thickness	2.5 cm/32 layers
Scint. layer thickness	1.0 cm/32 layers
Scintillator type	PMMA doped with: 8% naphtalene 1% butyl-PBD and 0.01% POPOP
Wave length shifter	UVA PMMA doped with 30mg/l laser dye #481
Photomultiplier	12-Stage Thorn-EMI 9954 + dc LED
PMT gain stability	< 2% variation
Light yield	~20 p.e./GeV/pmt
Resolution:	$50\%/\sqrt{E} \oplus 3\%$

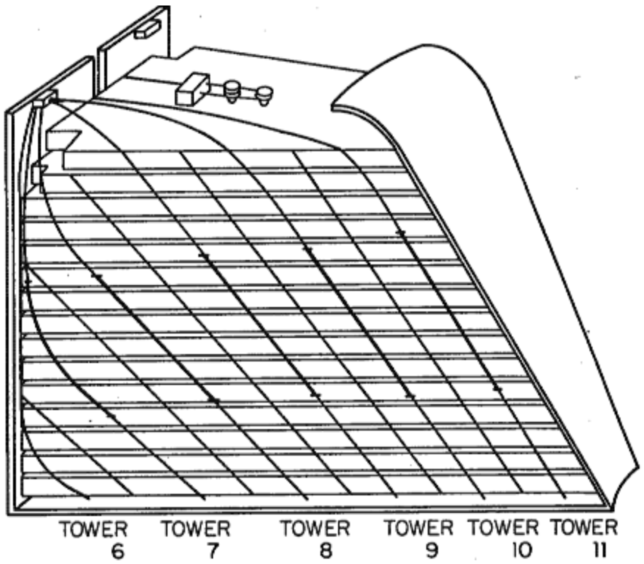




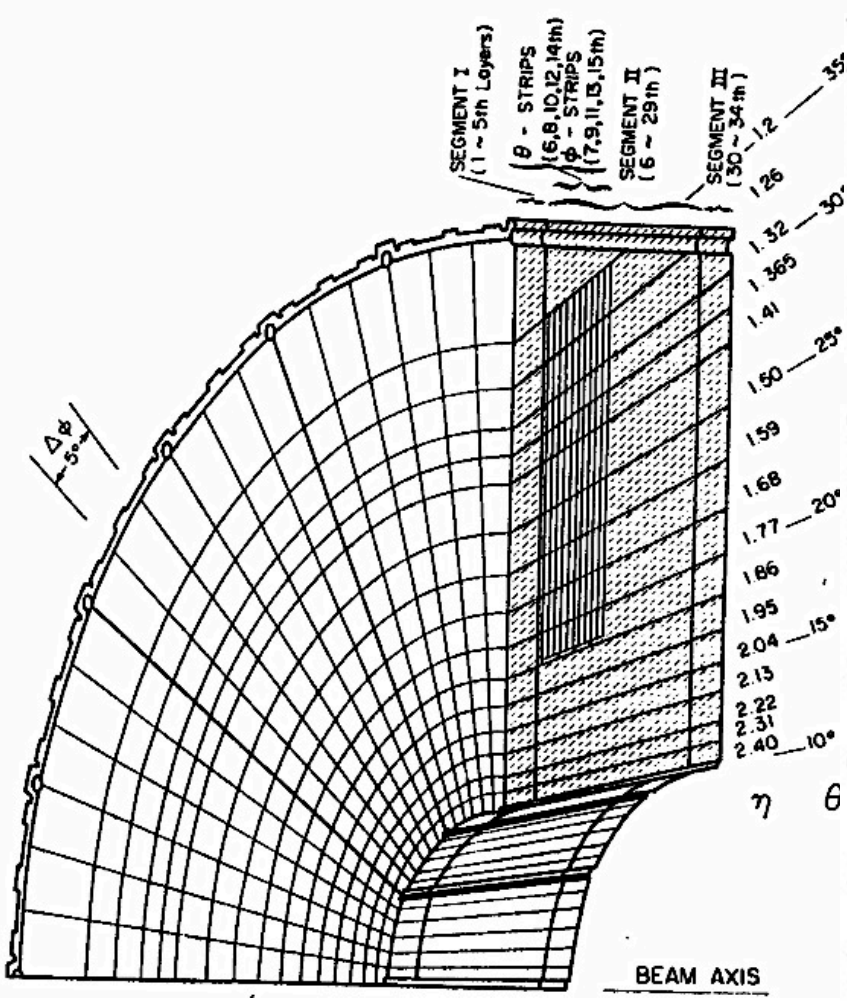
CDF calorimetry components: WHA

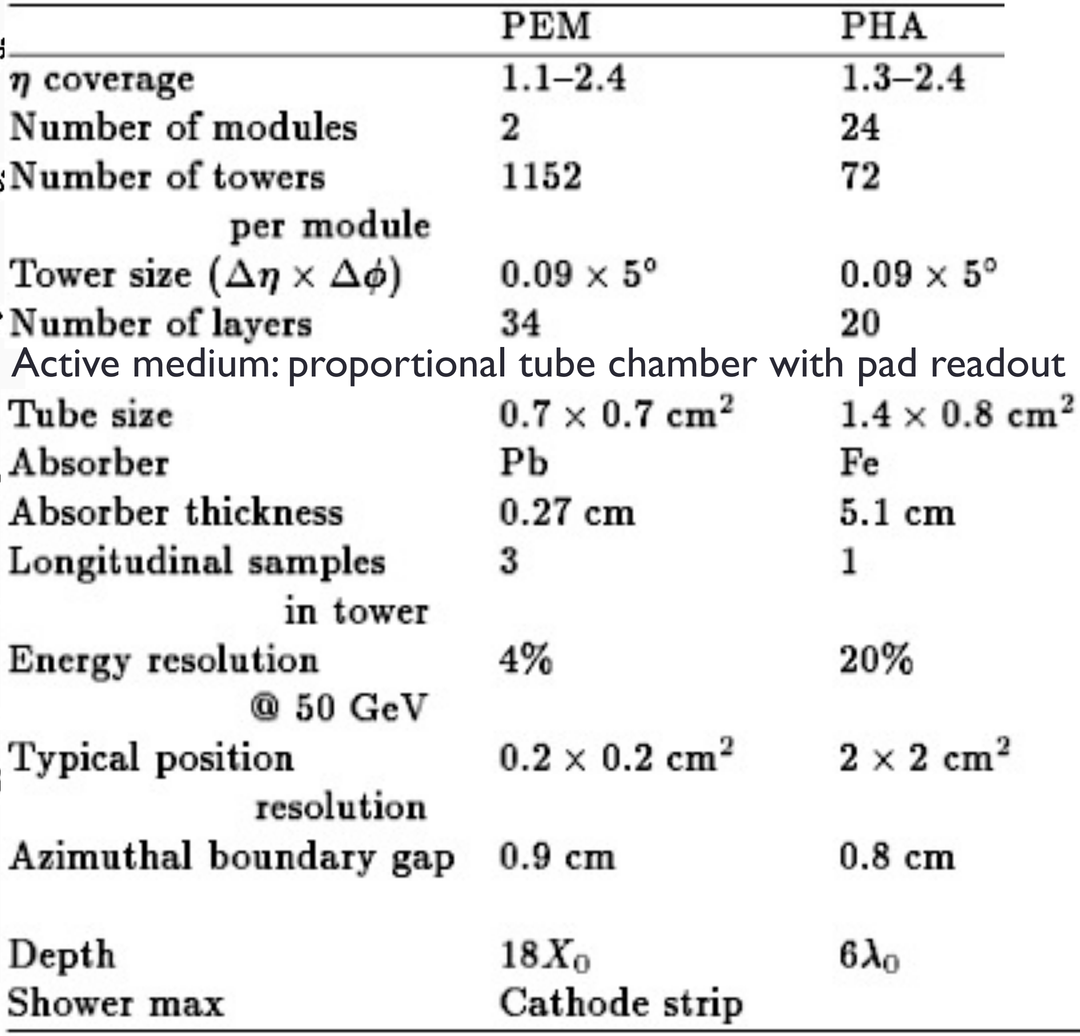
Parameters $0.7<|\eta|<1.3$

Segmentation	$\Delta\phi=15°$, $\Delta\eta=0.1$
Thickness(WHA alone)	4.5 λ
Absorb layer thickness	5.0 cm/15 layers
Scint. layer thickness	1.0 cm/15 layers
Scintillator type	PMMA doped with: 8% naphtalene 1% butyl-PBD and 0.01% POPOP
Wave length shifter	UVA PMMA doped with 30mg/l laser dye #481
PMT	10-Stage Thorn-EMI 9902
Light yield	~20 p.e./GeV/pmt
Resolution:	$75\%/\sqrt{E}\oplus 4\%$



CDF-I gas calorimetry components: PEM/PHA

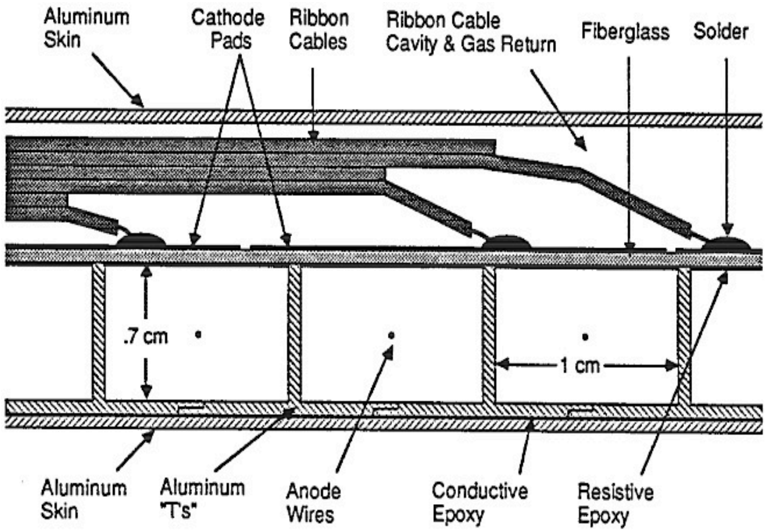


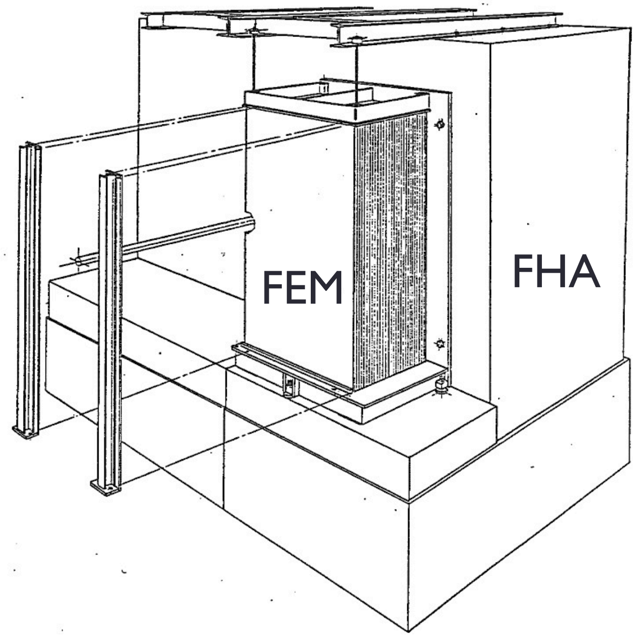


	PEM	PHA
η coverage	1.1–2.4	1.3–2.4
Number of modules	2	24
Number of towers per module	1152	72
Tower size ($\Delta\eta \times \Delta\phi$)	$0.09 \times 5°$	$0.09 \times 5°$
Number of layers	34	20
Active medium: proportional tube chamber with pad readout		
Tube size	0.7×0.7 cm^2	1.4×0.8 cm^2
Absorber	Pb	Fe
Absorber thickness	0.27 cm	5.1 cm
Longitudinal samples in tower	3	1
Energy resolution @ 50 GeV	4%	20%
Typical position resolution	0.2×0.2 cm^2	2×2 cm^2
Azimuthal boundary gap	0.9 cm	0.8 cm
Depth	$18 X_0$	$6 \lambda_0$
Shower max	Cathode strip	

Gas mixture: Argon/Ethane 50%-50% with 0.9% ethyl alcohol at -3°C

CDF-I gas calorimetry components: FEM/FHA





	FEM	FHA
η coverage	2.2–4.2	2.3–4.2
Number of modules	8	8
Number of towers per module	360	360
Tower size ($\Delta\eta \times \Delta\phi$)	$0.1 \times 5^\circ$	$0.1 \times 5^\circ$
Number of layers	30	27

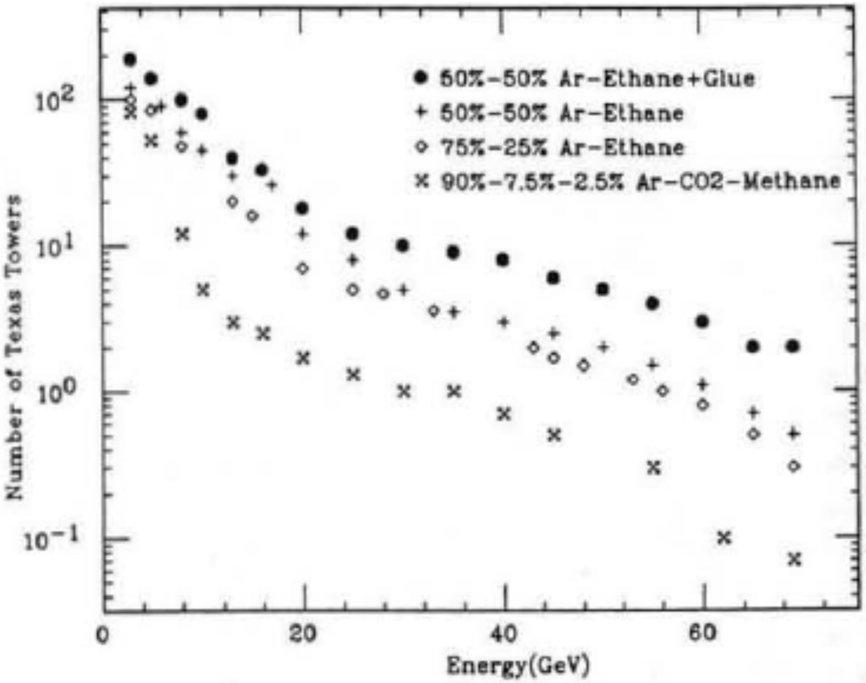
Active medium: proportional tube chamber with pad readout

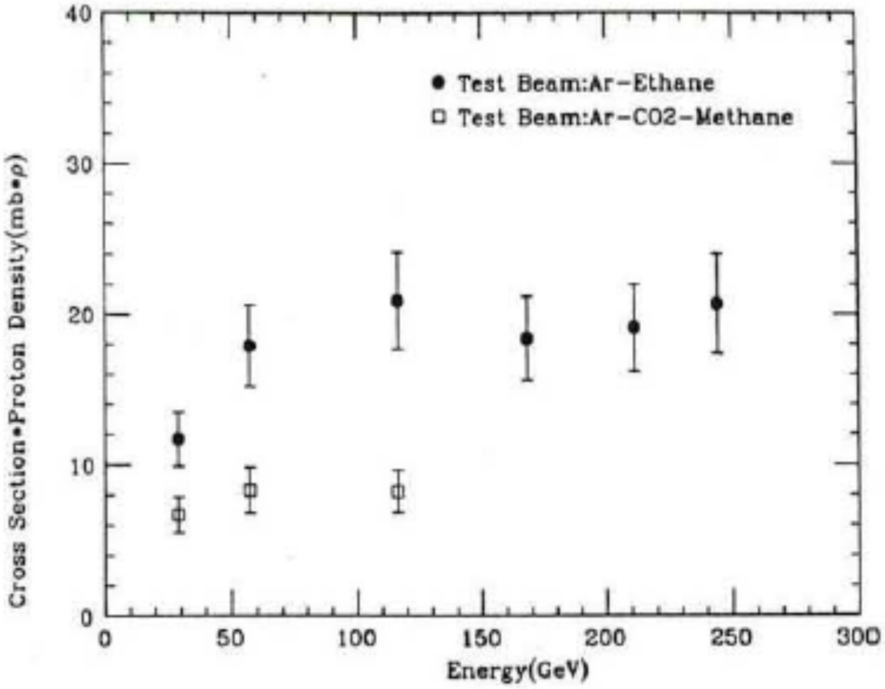
Tube size	1.0×0.7 cm^2	1.5×1.0 cm^2
Absorber	94% Pb, 6% Sb	Fe
Absorber thickness	0.48 cm	5.1 cm
Longitudinal samples in tower	2	1
Energy resolution @ 50 GeV	4%	20%
Typical position resolution	0.2×0.2 cm^2	3×3 cm^2
Azimuthal boundary gap	0.7 cm (vertical) 3.2 cm (horizontal)	1.3 cm (v) 3.2 cm (h)
Depth	$24 X_0$	$8 \lambda_0$
Shower max		

Gas: Argon/Ethane 50%-50% with 0.9% ethyl alcohol at -3°C

Gas calorimetry problems – Texas Towers

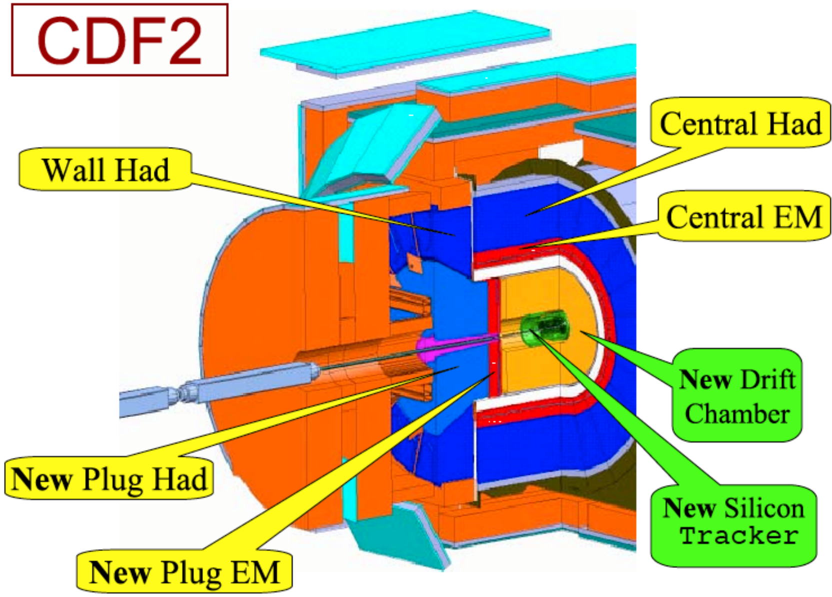
- Appearance of large energy depositions in the gas calorimeter due to small energy fluctuations in the shower in conjunction to the small sampling fraction for charged particles (~0.01%)
- Slow neutrons in the shower scatter off protons of the hydrogenous material of the calorimeter which ionize the active media creating large energy deposits aka Texas Towers





The upgraded CDF II calorimeter – 2001-2011

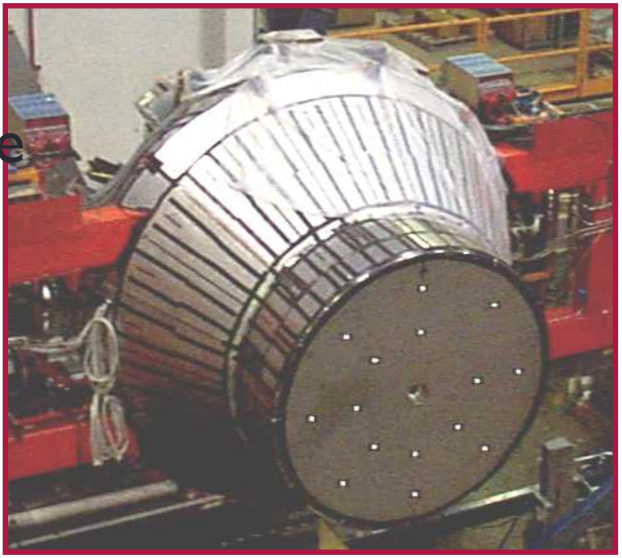
- ☐ Tevatron upgrades required changes to system, enabling integration:
  - $\sqrt{s}$: 1.8 → 1.96 TeV (PMT signals double)
  - Bunch Xing: 3.5 ms → 132 ns (new FEE/trigger)
  - Lum: 2×10^{31} $cm^{-2}s^{-1}$ ('96) → 5×10^{32} (>'04)



- ☐ Replace gas plug/forward calorimeters
  - Rate limitations at Tevatron Run 2
  - Forward noisy due to insufficient shielding, gain degradation
  - Add EM pre-shower as in central
  - Add timing measurement (existed only for central hadron)

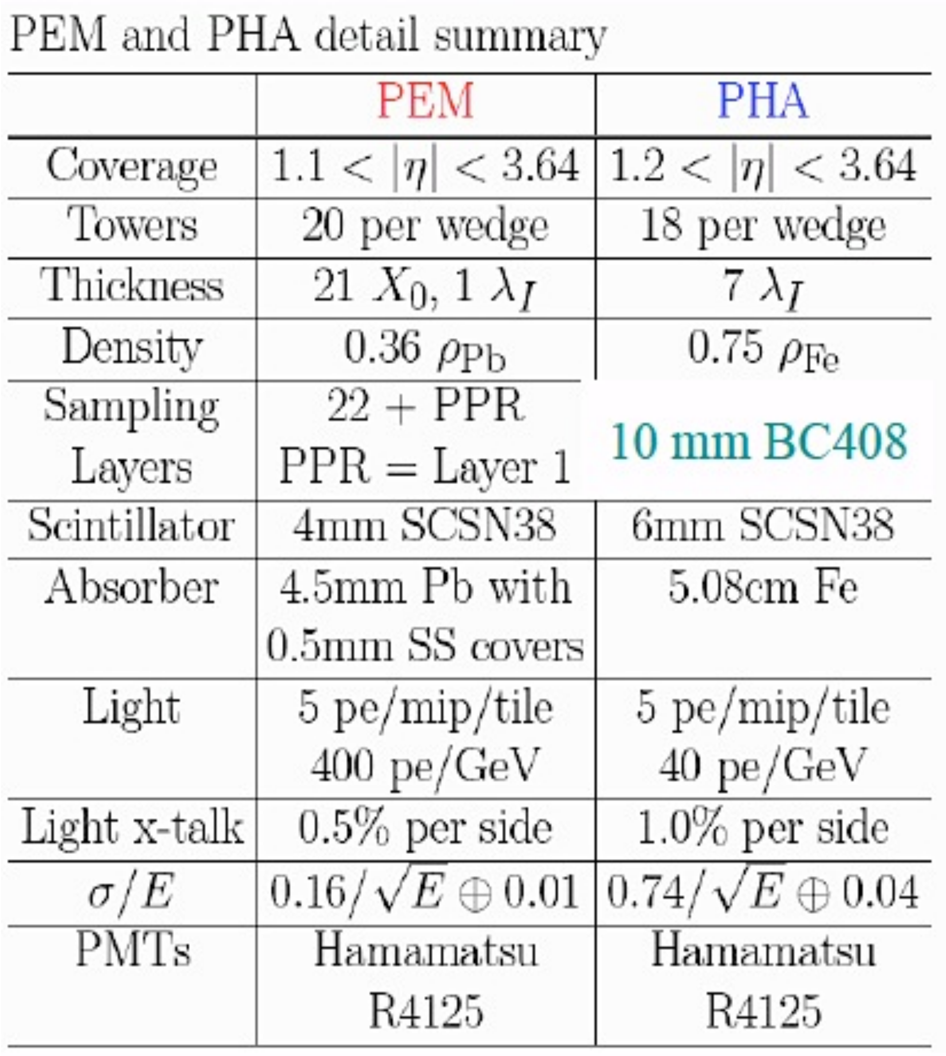
The upgraded plug (EM/HAD) calorimeter

- ❑ Scintillator – tile sampling calorimeter with w.l.s. fiber readout
  - Fast and better sampling
  - Uniform cal. technology for all $|\eta|<3.6$ range
  - More hermitic (distance from beam 9.2cm) near beam <E> ~100MeV/tower



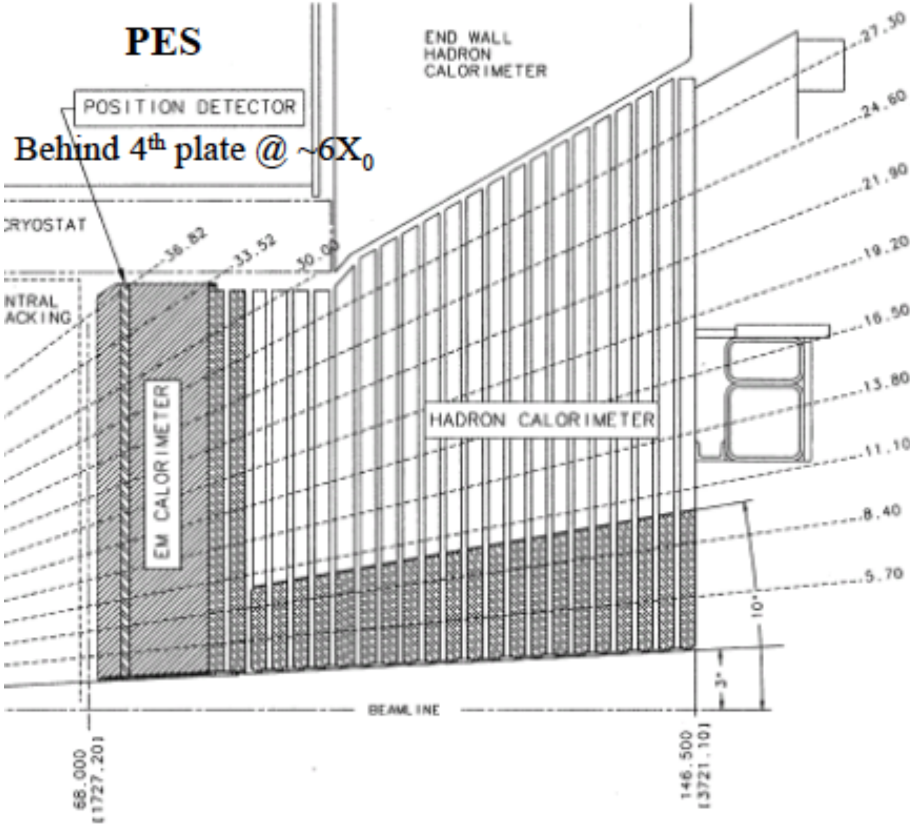
- ❑ Components:
  - ➢ Electromagnetic (EM) section
    - PEM: tile/fiber tower calorimeter
    - PPR: tile/fiber preshower detector
    - PES: strip/fiber shower-max detector
    - EMT: EM shower timing
  - ➢ Hadronic (HAD) section
    - PHA: tile/fiber tower calorimeter
    - HAT: HAD shower timing

Details of the new calorimeter



PEM and PHA detail summary

	PEM	PHA
Coverage	$1.1 < \|\eta\| < 3.64$	$1.2 < \|\eta\| < 3.64$
Towers	20 per wedge	18 per wedge
Thickness	$21\ X_0,\ 1\ \lambda_I$	$7\ \lambda_I$
Density	$0.36\ \rho_{\mathrm{Pb}}$	$0.75\ \rho_{\mathrm{Fe}}$
Sampling Layers	22 + PPR PPR = Layer 1	10 mm BC408
Scintillator	4mm SCSN38	6mm SCSN38
Absorber	4.5mm Pb with 0.5mm SS covers	5.08cm Fe
Light	5 pe/mip/tile 400 pe/GeV	5 pe/mip/tile 40 pe/GeV
Light x-talk	0.5% per side	1.0% per side
σ/E	$0.16/\sqrt{E} \oplus 0.01$	$0.74/\sqrt{E} \oplus 0.04$
PMTs	Hamamatsu R4125	Hamamatsu R4125



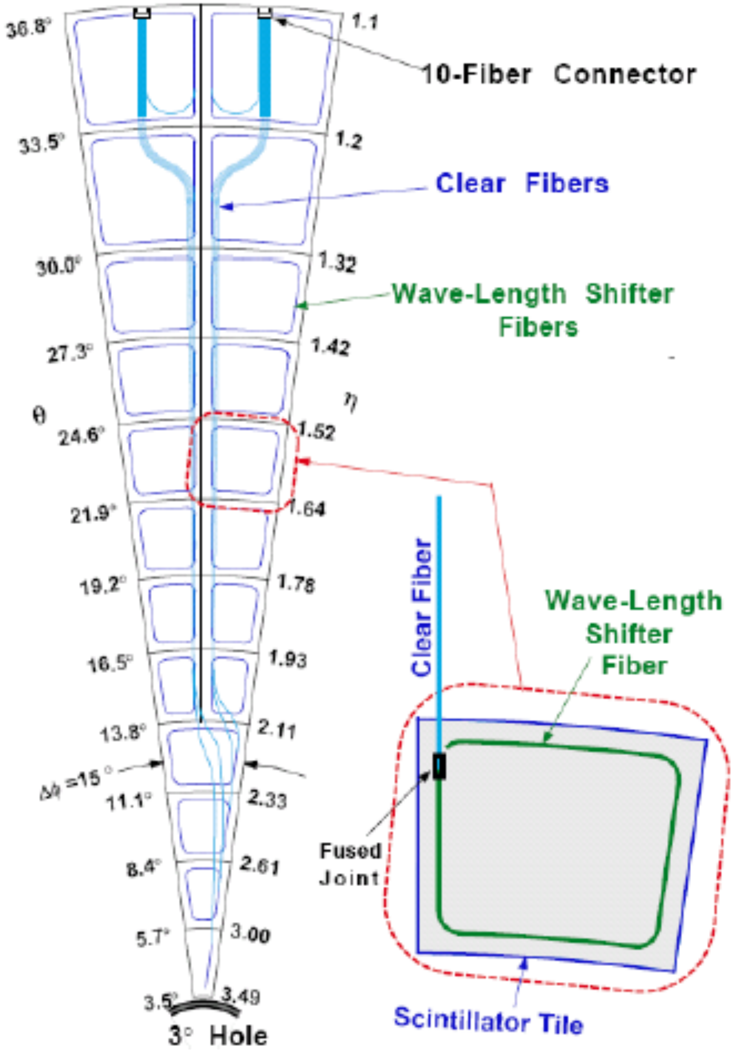
PES

Behind 4th plate @ ~$6X_0$

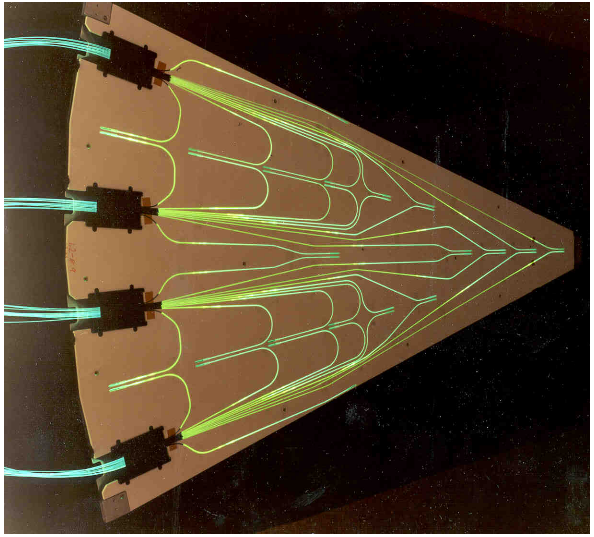
- More hermitic (distance from beam 9.2cm)

Megatile design for PEM,PHA

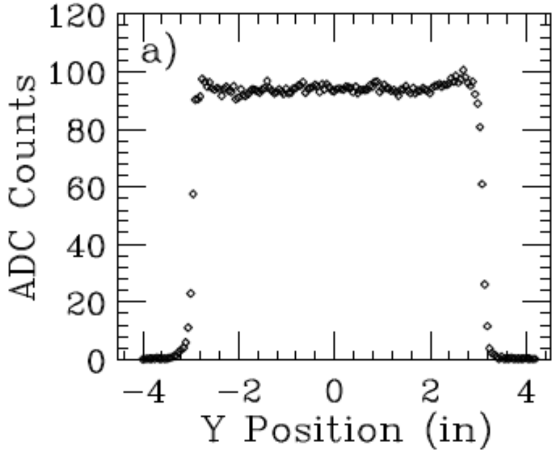
PEM / 15° megatiles



PHA 30° megatiles



Flat transverse response



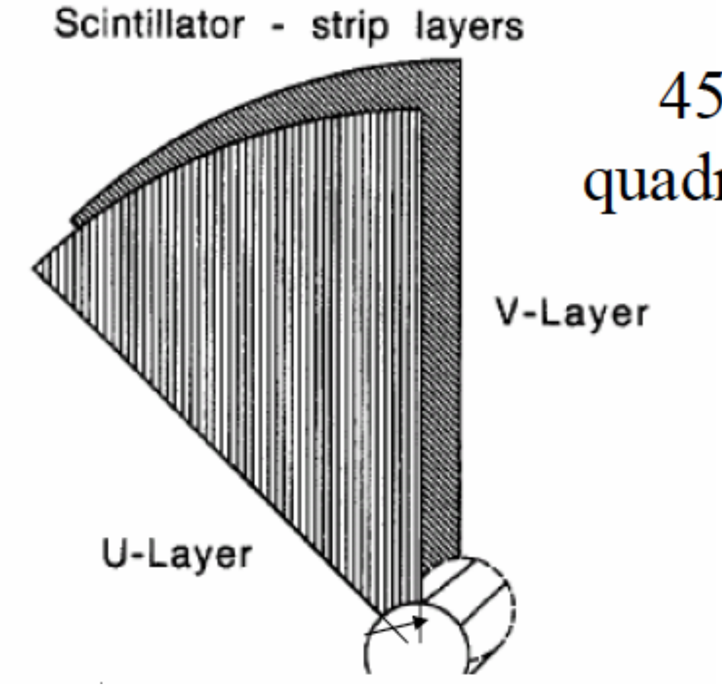
PEM uniformity ~5%

PHA uniformity ~2%

Shower-max detectors

- ☐ Central: Gas chambers w/ strips and wires
  - Important for electron, photon, pion identification
  - New FE electronics: SMQIE chip
  - <1% prob. channels, no aging
  - Upgrade CPR for Run 2b

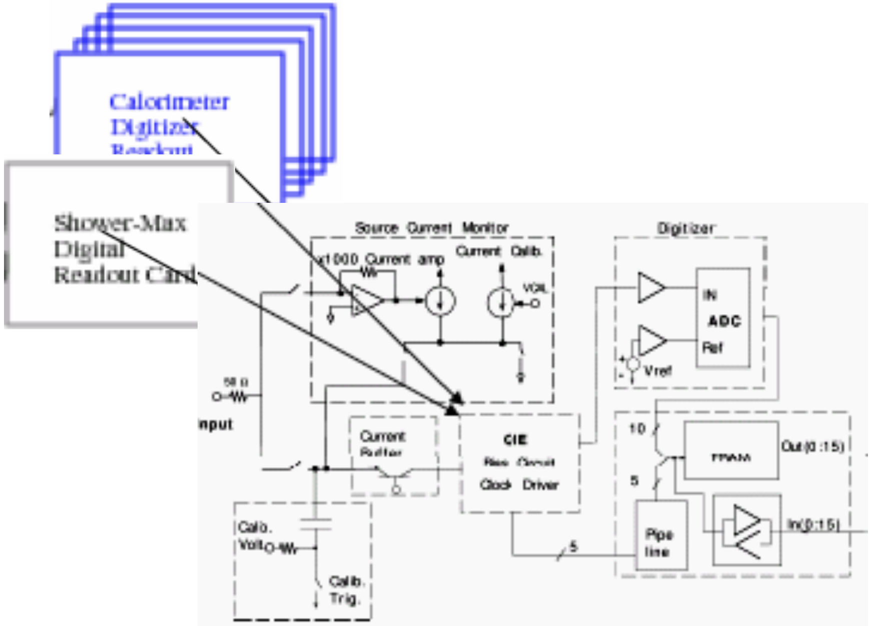
- ☐ Plug PES/PPR new in Run 2
  - Scintillating strip/WLS fiber
  - 2 layers ~6 rad lengths in
  - Energy in PES/PEM well-matched position to 1.5 cm can improve with fwd silicon



45° quadrants

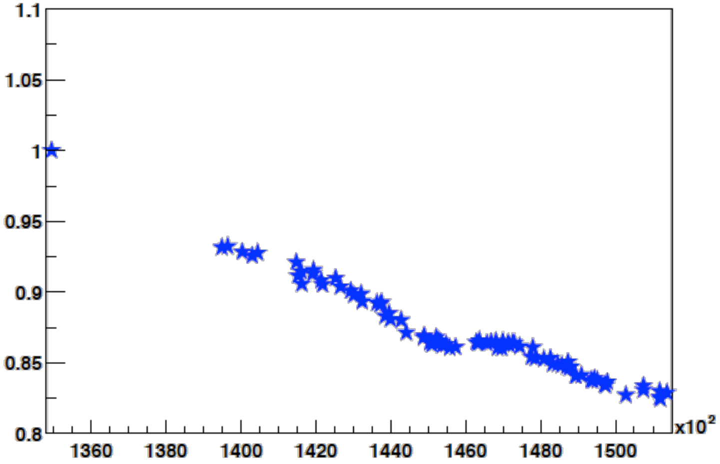
Front-end electronics – VME based

- ☐ PMT readout based on QIE6 ASIC – (no integration deadtime)
  - QIE6 uses binary weighted splitter, 8 current ranges (I/2-I/256)
  - Use of 10bit ADC gives 18bit dynamic range (1300pC or 800 GeV)
  - QIE and ADC on CAFE card along with calibration and Q-injection circuits and FADC
- ☐ ADMEM (ADC+Memory) board hold 20 CAFE cards
  - Provides Level-1 trigger with transverse energy sum using Xilinx FPGA and provides 4-buffer Level-2 storage
  - Pipelined Level-1 buffer 42 clock-cycles deep (~5.5ms) allows "deadless" readout upon L1 accept



Operational issues

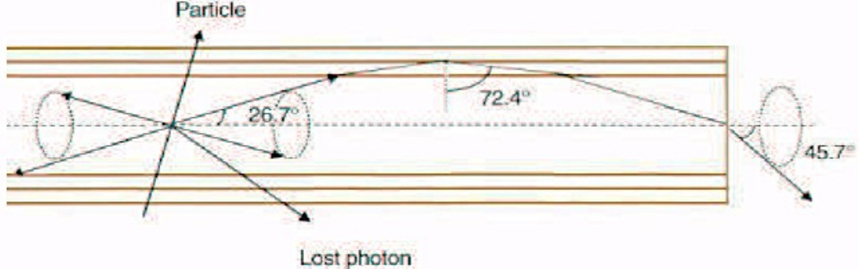
- ❑ Unexpected large PMT gain loss for PEM/PHA
  - ➢ Observed within first year of operation
  - ➢ Observed in laser runs and confirmed with source calibration
  - ➢ Sign of PMT aging – decrease in gain increasing integrating charge
  - ➢ Effect scales with PMT current



- ◆ Fix: Reduce integrated charge by reducing HV values for high η towers and compensate via correction factor
  - ➢ Fix did not solve the problem but reduced the magnitude (3% loss for low η-towers and 8% loss for high-η towers in a year)

Operational issues

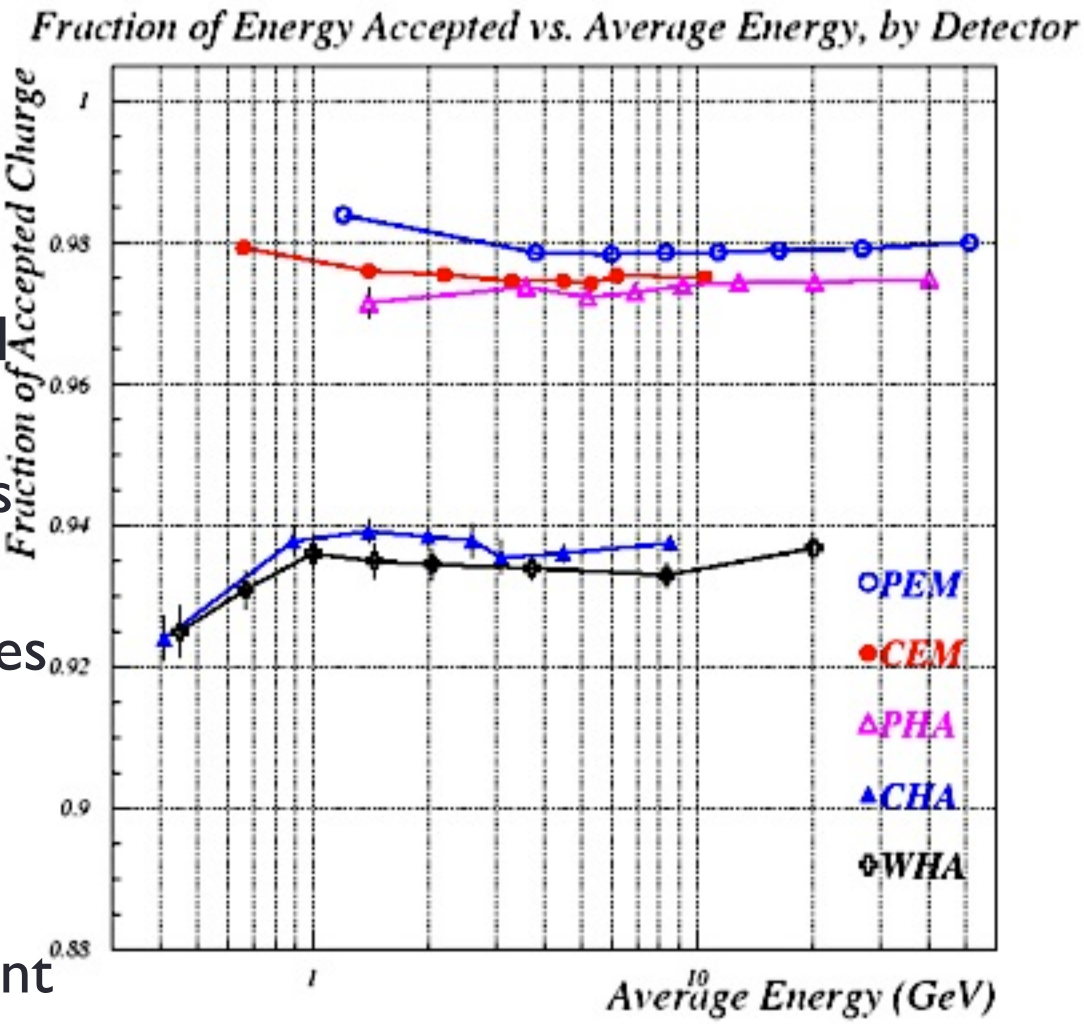
- ❑ PES and PPR unexpected large cross-talk
  - ➢ Neighboring MAPMT channel cross-talk (0.5% expected – 6% observed)
  - ➢ Effect on PES position resolution and as a result the plug electron ID (χ^2, 5/9 stip ratio)
  - ➢ Problem was identified in the larger gap between MAPMT and fiber.
  - ➢ Due to fiber dimension there is big light spread



- ➢ Fix with installation of "baffles"
  Cross-talk: ~1.4%
  Signal reduction: ~8%

Operational issues: Signal loss outside gate

- Tevatron upgrades planned for 132ns beam crossings
- ADC integration gate reduced: 1200ns to 132ns
- Event energy was measured in the gate window and next time slices using μ, jets
- CHA/WHA worst: 6.5% of energy in the next time slices
- Surprising finding – likely due to slower component of scintillation light
- Effect was taken into account in ADC to GeV scale factor

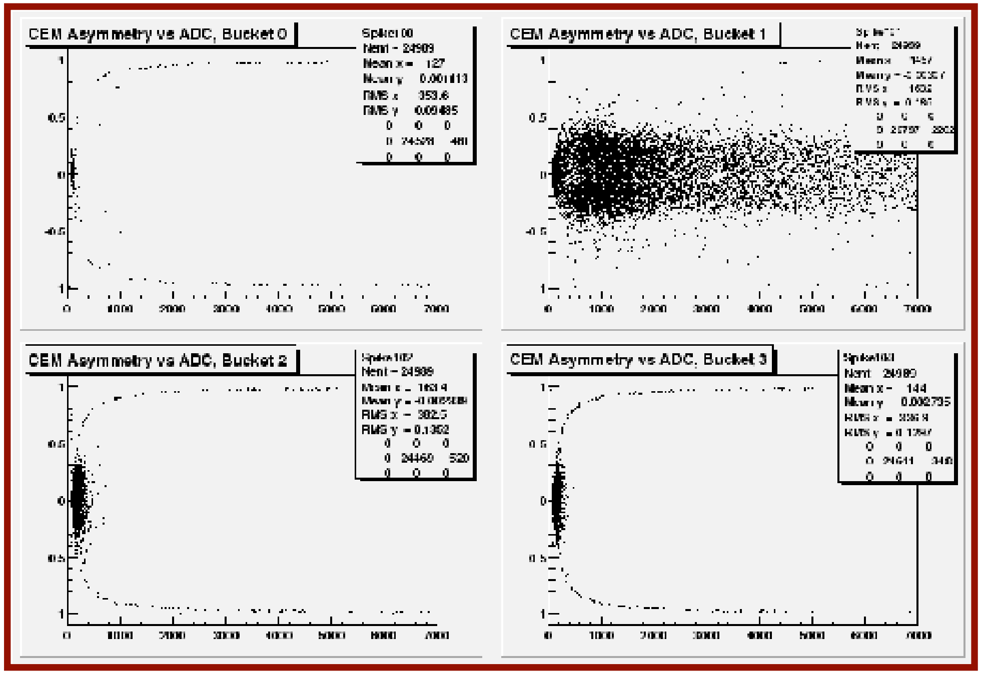


Operational issues: PMT Spike filter

- Discharging PMTs cause spike signals affecting data quality and trigger rate – problem seen more often with CEM pmt
- Implement a spike-killer algorithm both in the trigger and offline

  Asymmetric signal on the two PMTs (L-R) used to readout a Central calorimetry tower: $A = \left(ADC_L - ADC_R\right)/\left(ADC_L + ADC_R\right)$

  Look at the acquisition integration windows adjacent to the collision one



Calibration procedures

- Absolute energy scales
  - Transfer the calibrations constants established at test beam

    All HVs set to nominal gain (2pC/GeV for central)
  - Use gain check with ^{137}Cs (central) or ^{60}Co (plug)

    Use correction factors to account for differences chanel-by-channel: $Cor(t) = \frac{G_0}{G(t)}$

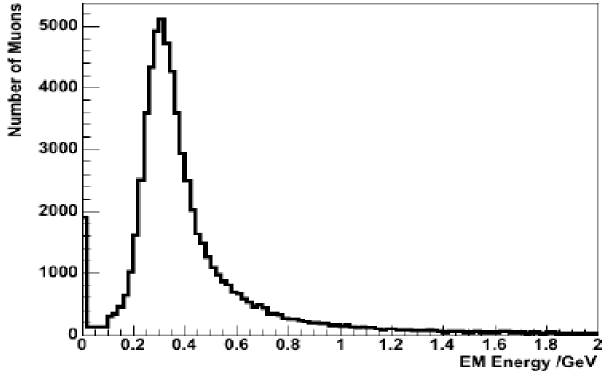
    Establish energy: $E_i(GeV) = counts_{raw} \times Cor(t) \times SCL(GeV/count)$
  - Higher level corrections: use data (e, μ, Z, tracks, jets)
- Relative energy scales
  - PMT gain variations tracked with light pulsers
  - Central/Plug use laser flasher
  - CEM use LEDs and Flasher (check also w.l.s)
- QIE electronics – charge injection
- TDC electronics – laser

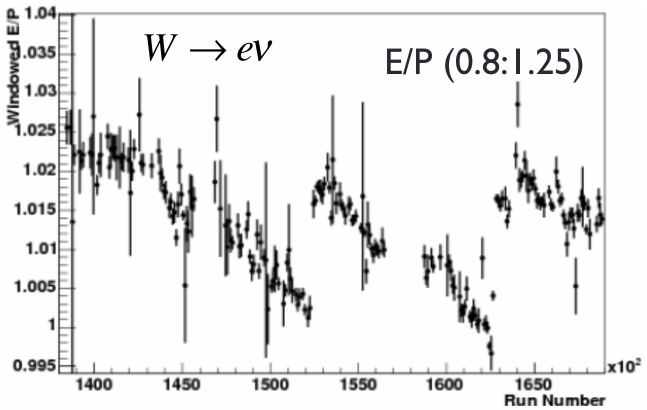
Absolute energy scale calibration: EM energy

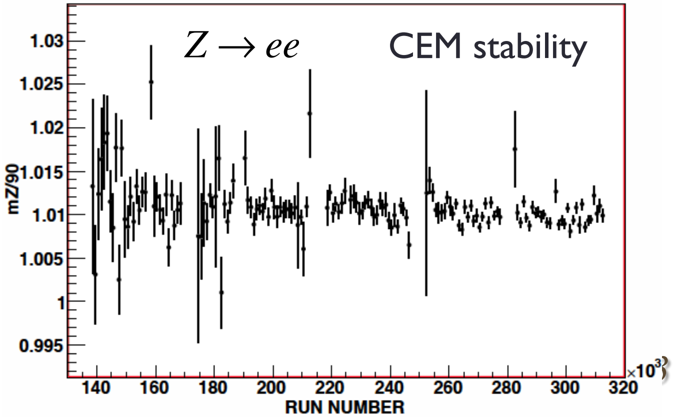
Use test beam data from early 80's and single particles "in-situ"

- Electrons from an 8GeV trigger
- E/p from W electrons
- Electrons from Z's
  check stability of Z peak and set absolute EM scale in central and plug
- "MIP" peaks when possible
- Monitor the corrections using min bias rate stability at each η-rings

CEM gain degradation is ~3%/year due to PMTs and scintillator aging



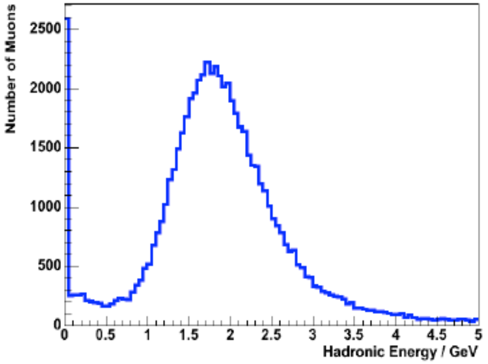




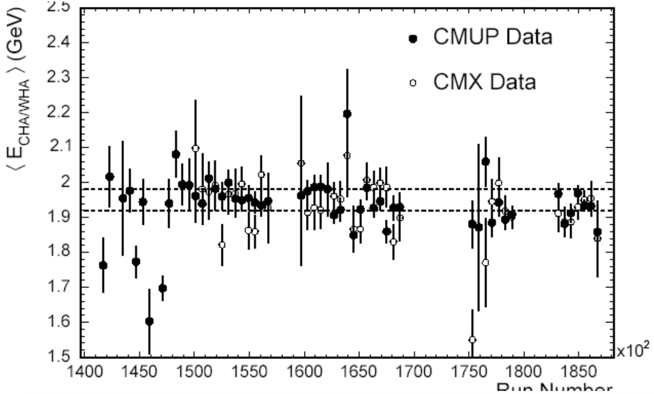
Absolute energy scale: CHA

- Energy response of the CHA is set using MIP peaks $J/\psi \to \mu\mu$

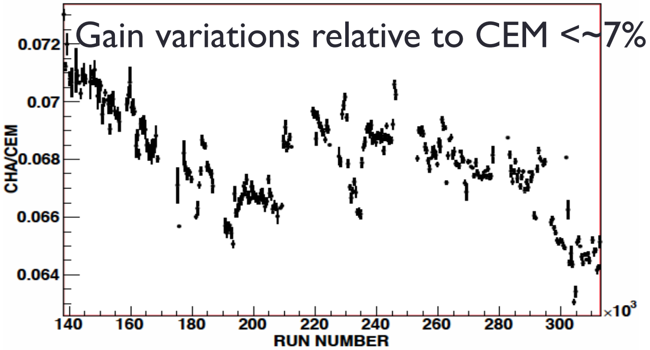
Sources are not used because of mechanical problems



- Set muon peaks to Run I values when calibration was based on source data
- Perform calibration for both PMTs on each tower
- Perform calibration every ~200pb^{-1} and scale corrections with luminosity for offline corrections in the run period
- For low statistics towers (larger eta) use minimum bias rates for that eta

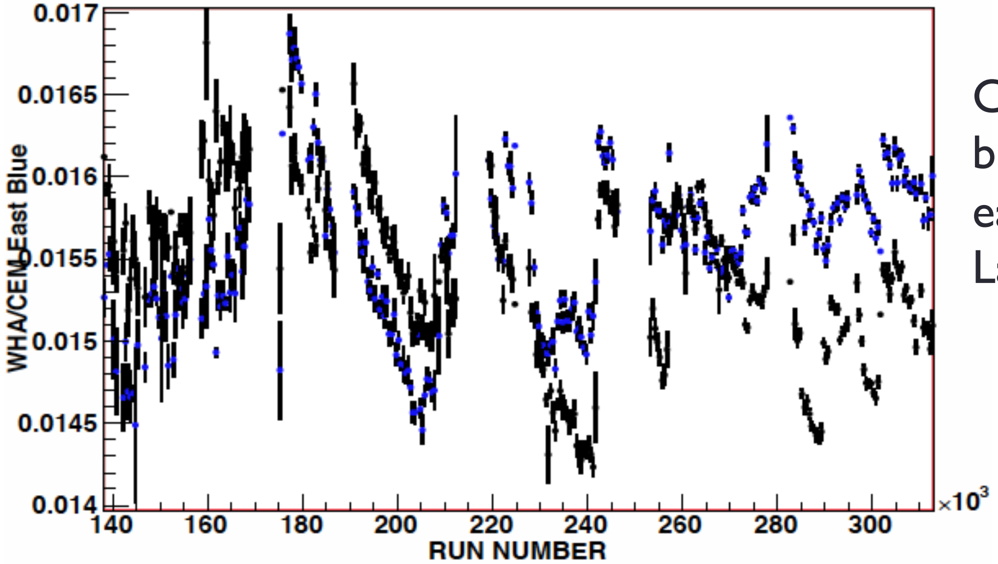


- Systematic uncertainty ~0.5%
- Gain degradation initially ~1%/y and after 2004 degradation ~2%/y and total since the initial calibrations ~30%


Gain variations relative to CEM <~7%

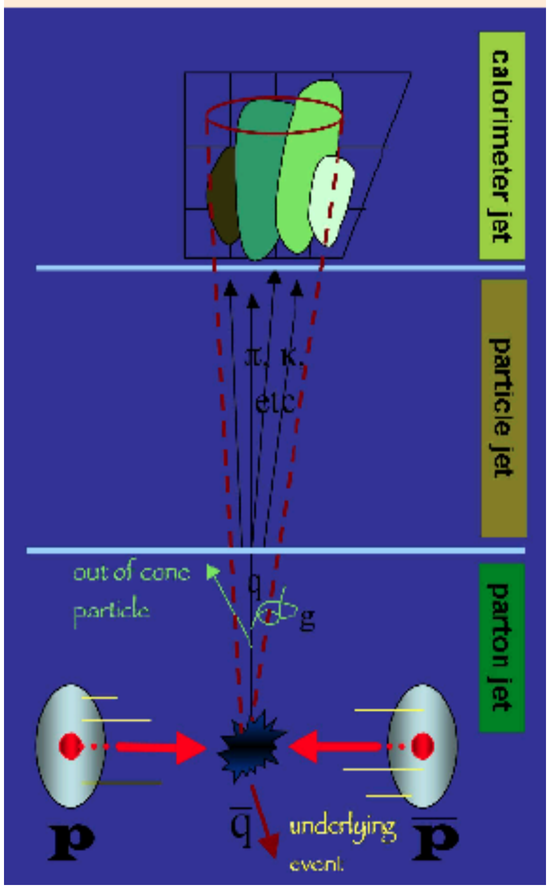
Absolute energy scale: WHA

- Energy response of the WHA is set using ^{137}Cs source data run every ~0.5y
- PMT Gain variations were monitored with Laser and min bias rates relative to CEM
- ~3.5%/y gain degradation was seen in the beginning of run-II (2001-2003) and it was reduced to 2.3%/y for the rest of the running period
- Overall gain drop for WHA since initial calibrations ~50%



Count variation from min bias data relative to CEM for east(blue) and west WHA
Larger variation ±8%

Calorimetry in physics analyses



- Jet energy scale corrections (JES)
  - ❑ Instrumental effects:
    - response to hadrons
    - poorly instrumented regions
    - multiple interactions
  - ❑ Physics related effects:
    - Hadronization
    - Underlying event
  - ❑ Dependence on jet definition:
    - Cone algorithm (JETCLU, Midpoint)
    - K_T algorithm
  - ❑ Need reliable MC tuned to appropriate data:
    - GFLASH for fast EM and HAD shower simulation, using parameterizations of longitudinal and lateral shower profiles

JES determination method

- Relative corrections(f_{rel}) - response uniform in η relative to central
- Multiple Interactions(MPI) – energy from different interactions
- Absolute Corrections(f_{abs}) – non-linearity and non-compensation

$$P_{Tjet}^{particle}(R)=\left[P_{Tjet}^{raw}(R)\times f_{rel}(R)-MPI(R)\right]\times f_{abs}(R)$$

- Going to parton energy additional corrections apply:
  - Hadron to parton correction(OOC) – particles going out of jet definition space
  - Underlying event (UE) – energy associated with spectators

$$P_{T}^{parton}(R)=P_{Tjet}^{particle}(R)-UE(R)+OOC$$

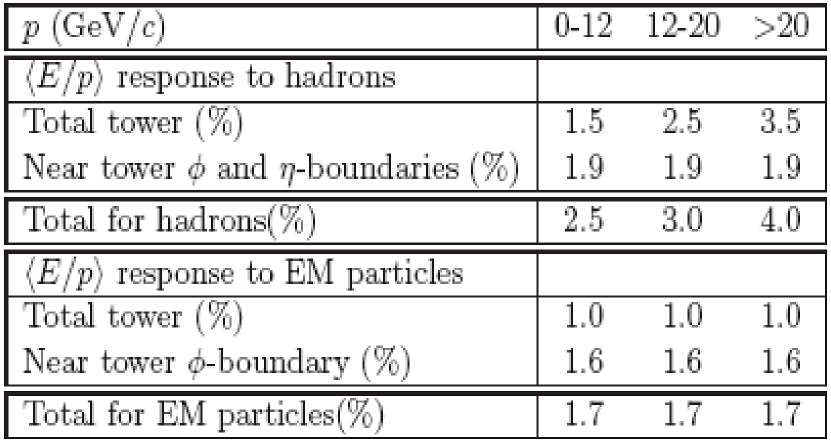
Each step comes with its own systematic uncertainty

Single particle response simulation

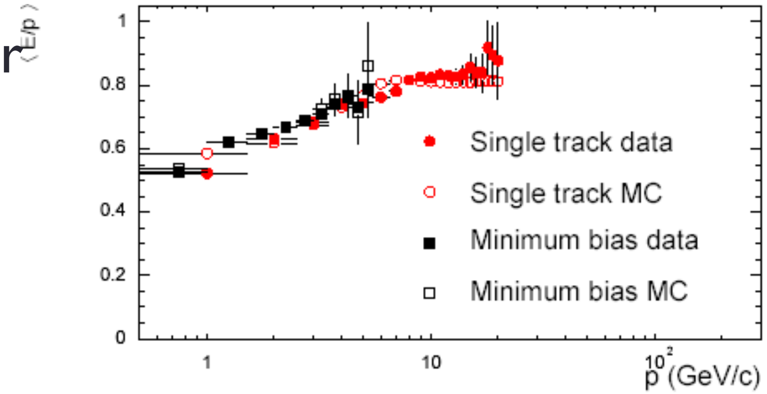
MC needs to reproduce accurately detector response to single particle

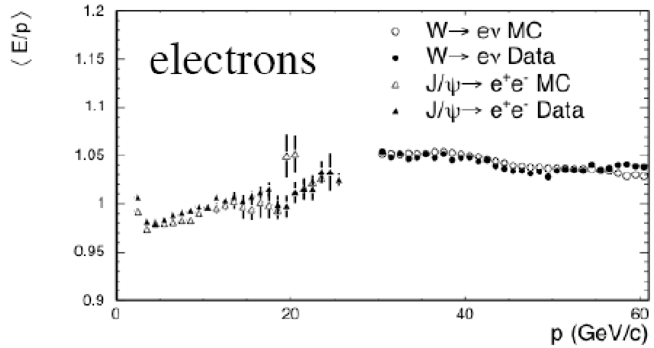
Tune GFLASH based on in-situ CDF data

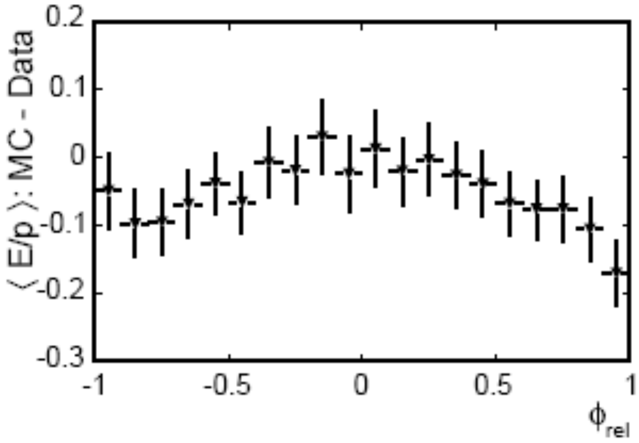
- E/p response as a function of particle momentum p
  - Test beam
  - In situ using isolated tracks and measuring the energy behind them
  - Tune simulation to describe E/p distr. at each p



p (GeV/c)	0-12	12-20	>20
$\langle E/p\rangle$ response to hadrons			
Total tower (%)	1.5	2.5	3.5
Near tower ϕ and η-boundaries (%)	1.9	1.9	1.9
Total for hadrons(%)	2.5	3.0	4.0
$\langle E/p\rangle$ response to EM particles			
Total tower (%)	1.0	1.0	1.0
Near tower ϕ-boundary (%)	1.6	1.6	1.6
Total for EM particles(%)	1.7	1.7	1.7

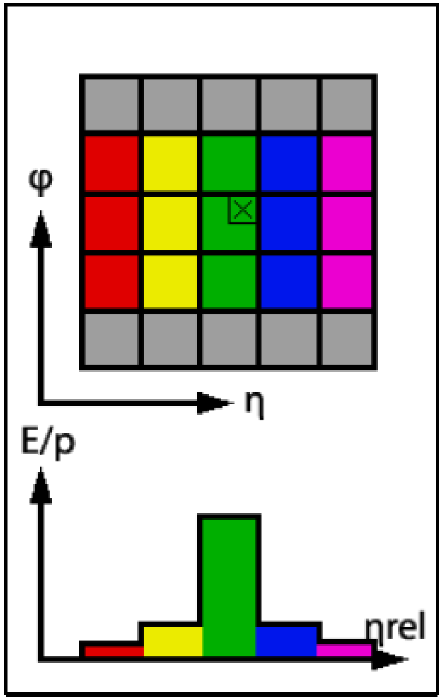


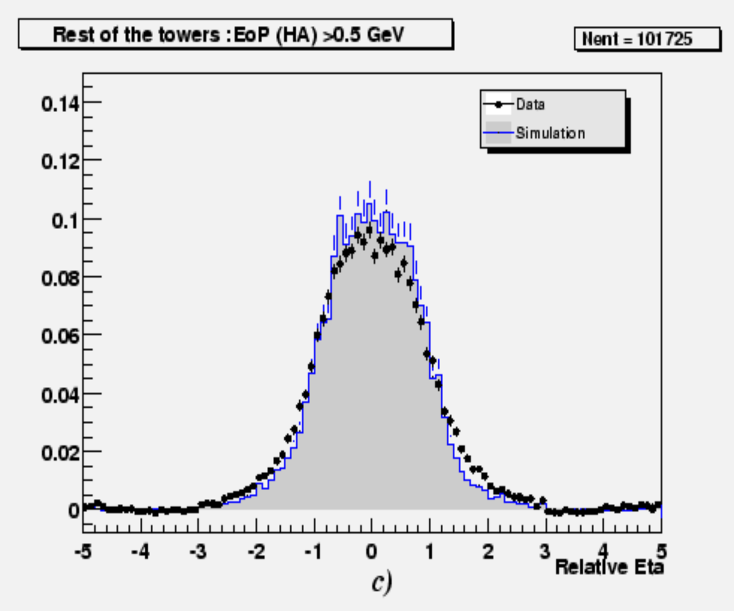




Single particle response simulation

- Lateral shower profile
  - ☐ Measure E/p signal in 5 towers adjacent in η
  - ☐ Plot E/p vs relative position of the towers
  - ☐ In Gflash use formula for lateral profile
  - ☐ Use EM and HAD to probe different parts of the hadronic shower



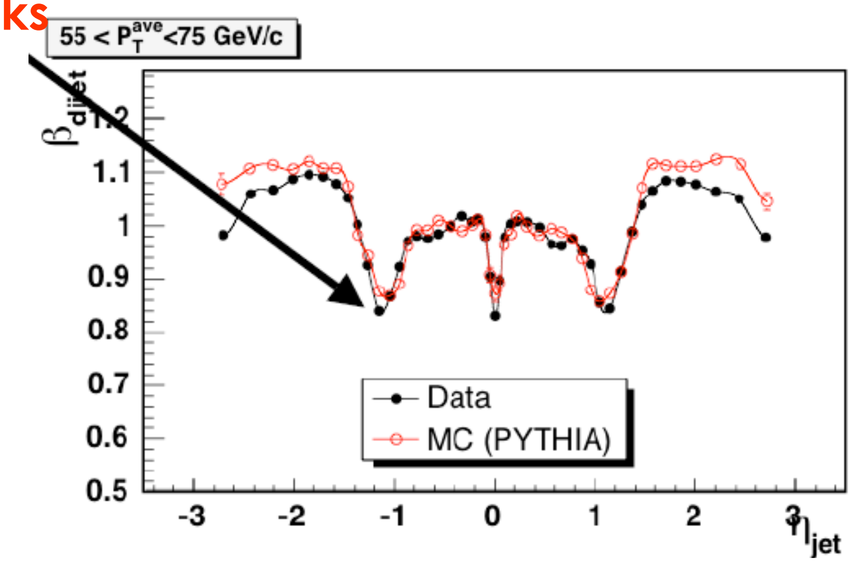


$$\eta_{rel} = \frac{\eta(\text{center of tower}) - \eta(\text{track})}{\eta(\text{width of tower})/2}$$

Detector effect corrections

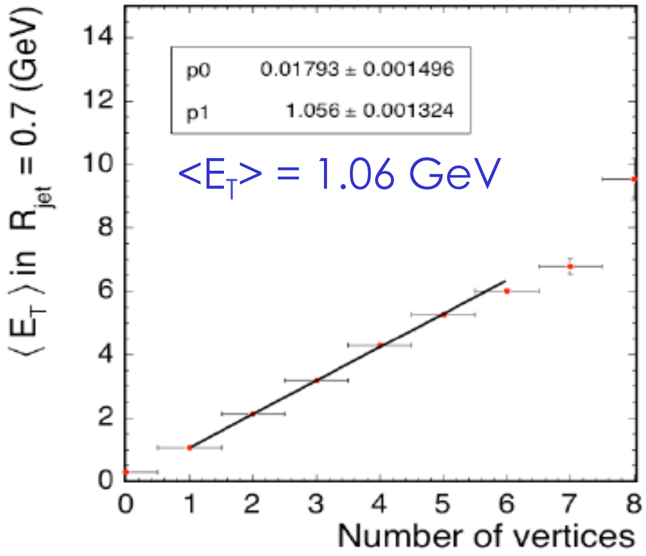
- **Relative Jet corrections**
  correct detector response
  to the central calorimeter

$$\beta = p_T^{probe} / p_T^{trigger}$$



cracks

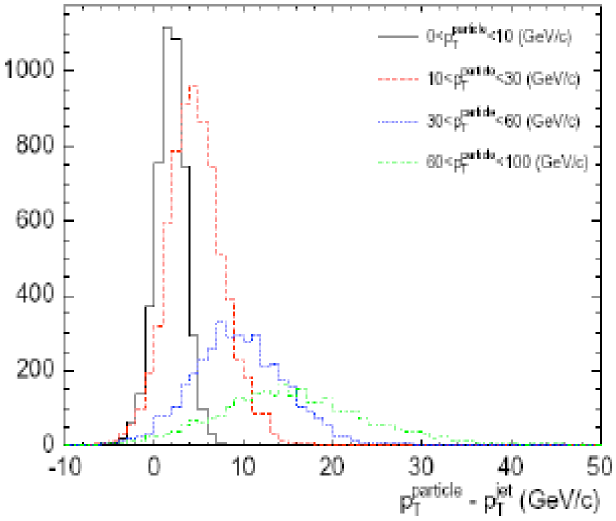
- **Multiple interactions**
  Number depends on luminosity
  For Tevatron L=2x10^{32}cm^{-2}s^{-1}: <N>=6
- ☐ Linear correlation between number of multiple interactions and number of vertices
- ☐ Determine average E_T associated with random cones (R=0.7) in 0<η<0.6

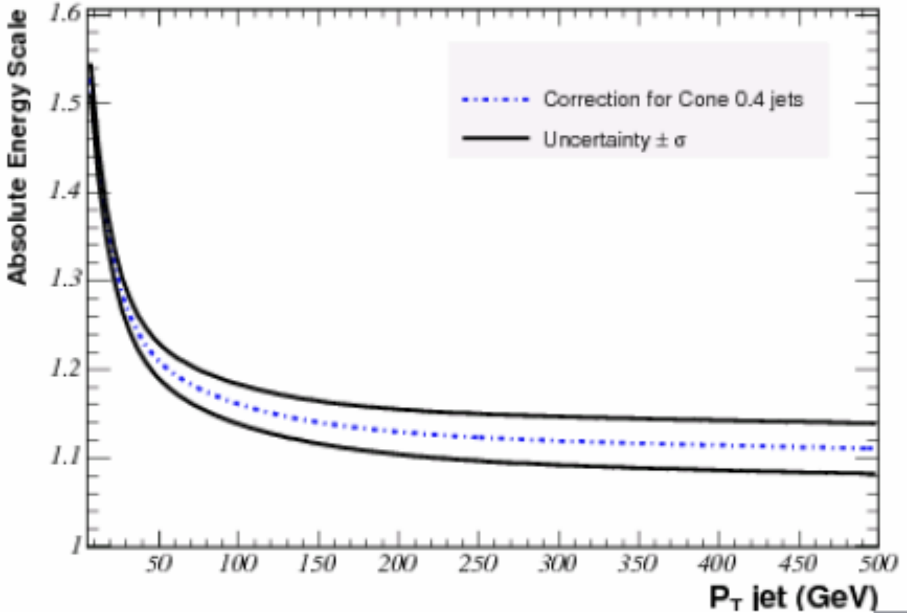


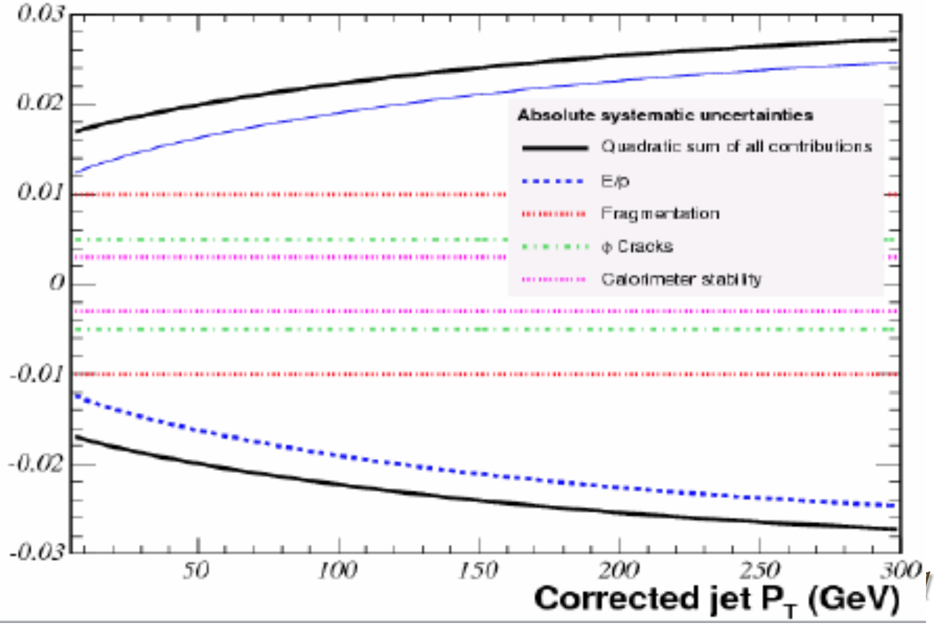
$<E_T>$ = 1.06 GeV

Detector effect corrections

- **Absolute Jet corrections**
  Comparison of MC jets (particles) to calorimeter jets
- Depends on how well MC simulation models the data and on fragmentation
- Uncertainties mainly due calorimeter simulation



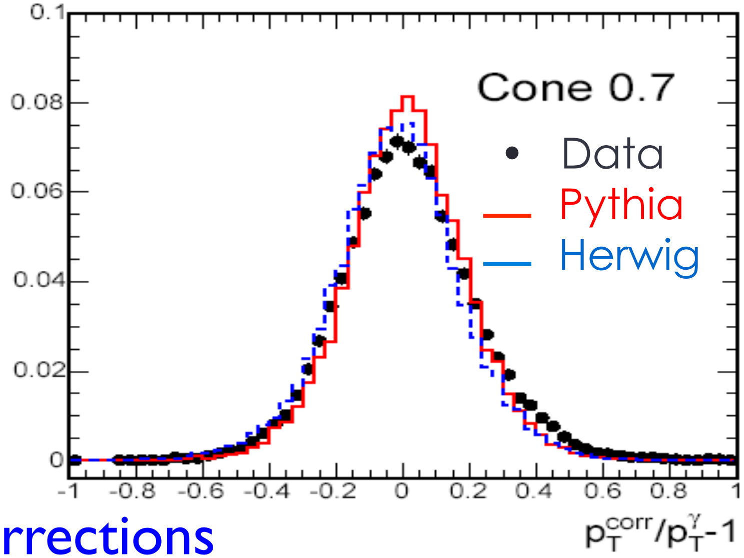




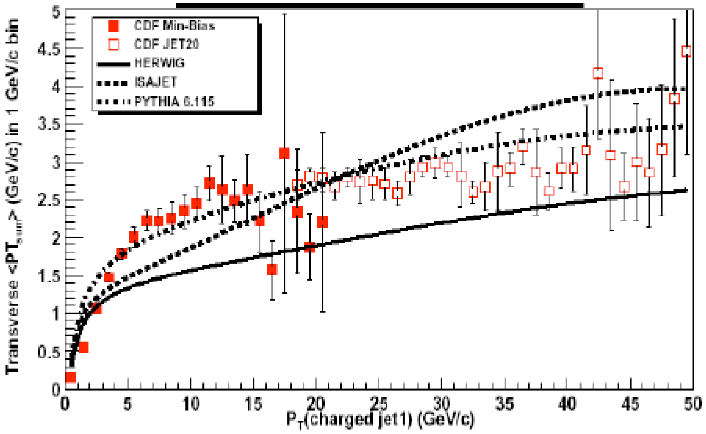
Validate the corrections

Use photon+jets and Z+jets balancing to validate corrections and also estimate OOC and JES systematic uncertainties due to Data/MC differences

Agreement Data/MC within 3%

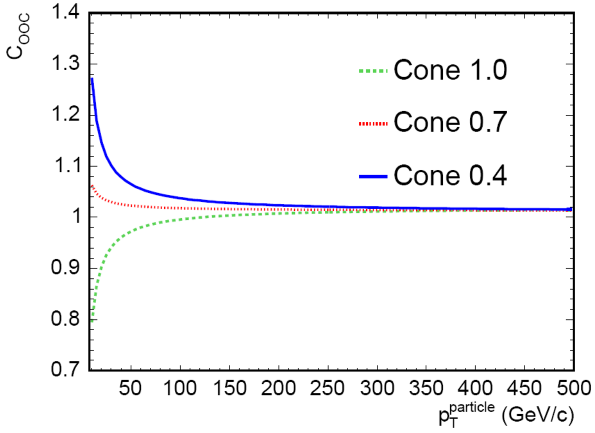


- **Underlying event corrections**
  - Use min bias and dijet to tune MC on data



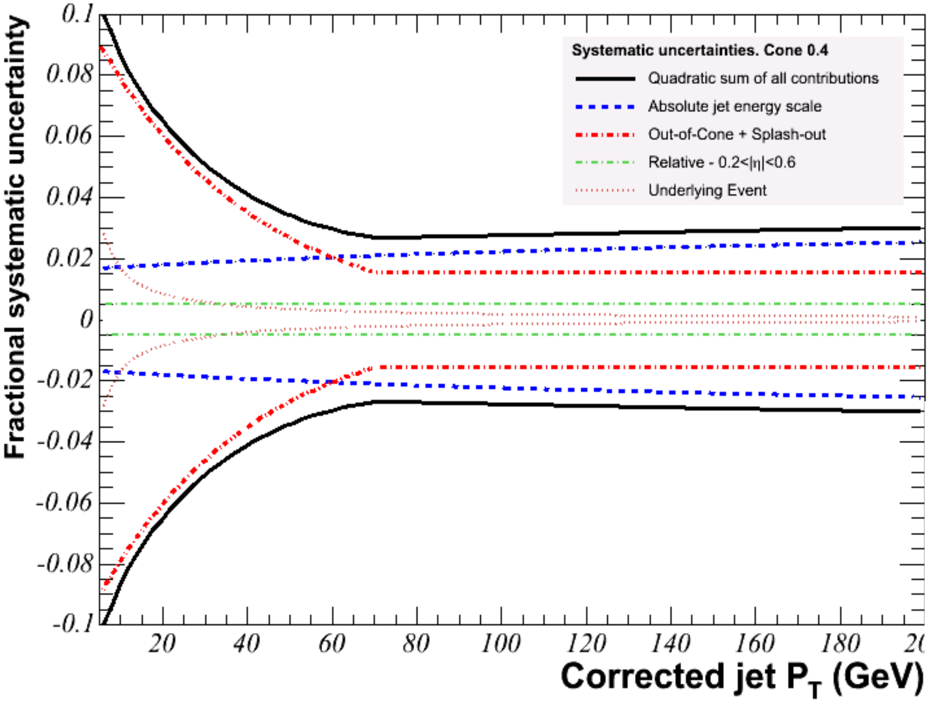
- **OOC corrections**

  Use PYTHIA dijet samples to measure the ratio: $P_T^{parton} / P_T^{particle}$



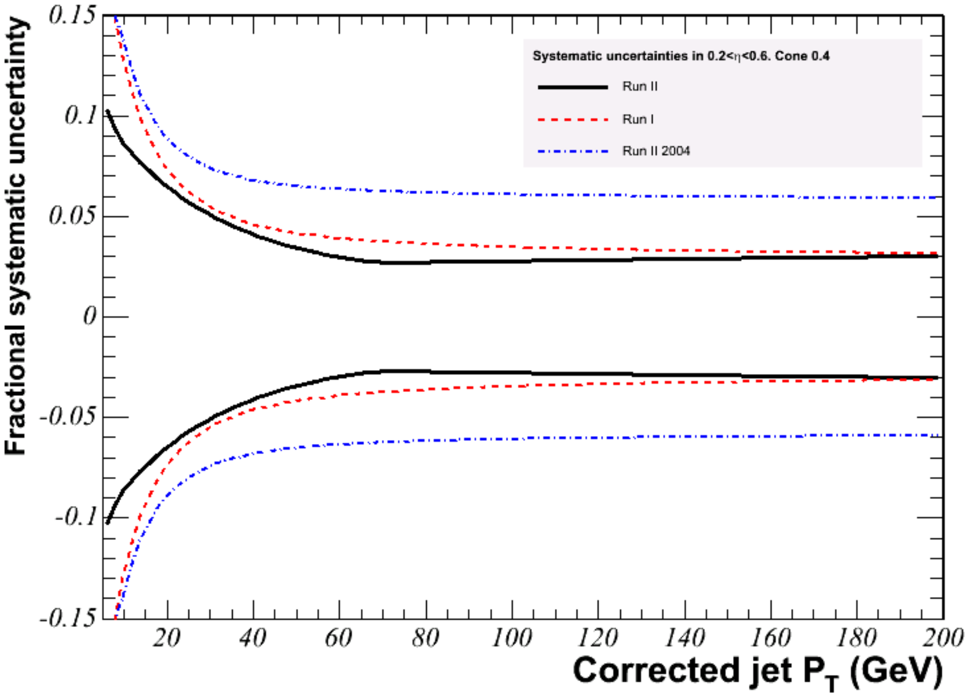
Total JES systematic uncertainty

Total uncertainty varies between 2-3% depending on Jet P_T



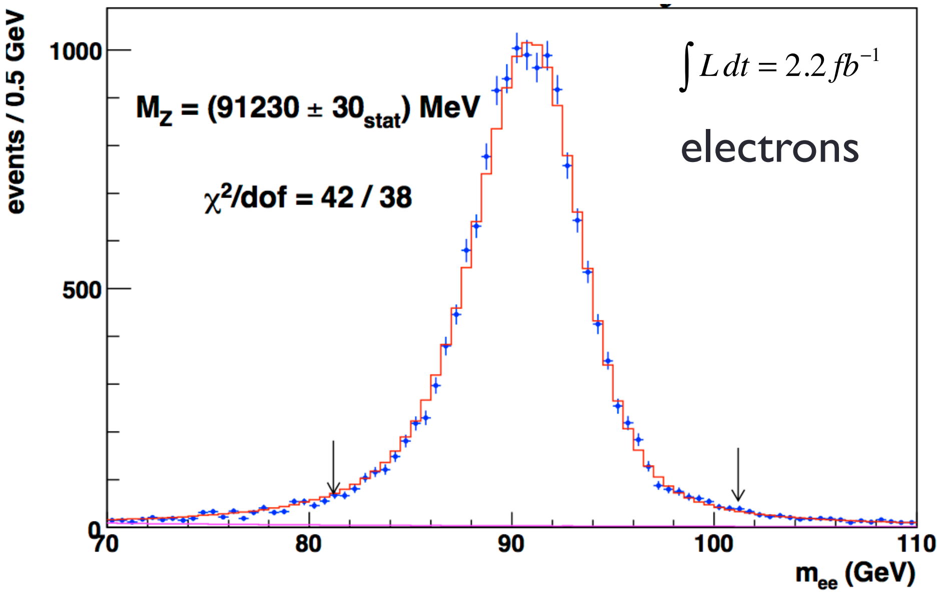
- Low P_T region is dominated by MC/Data uncertainties (OOC)
- High P_T region is dominated by calorimeter simulation uncertainties (absolute JES scale)

JES uncertainty comparison Run I- Run II

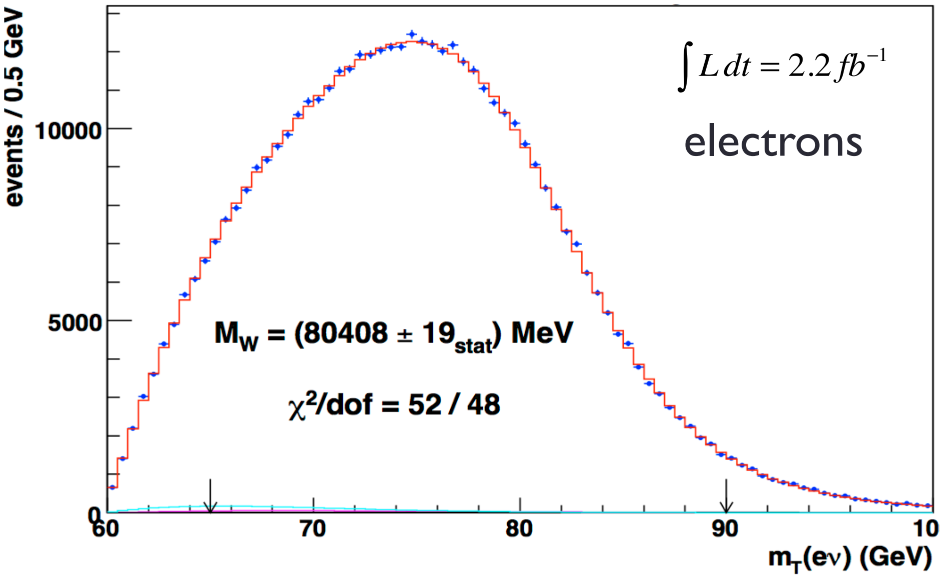


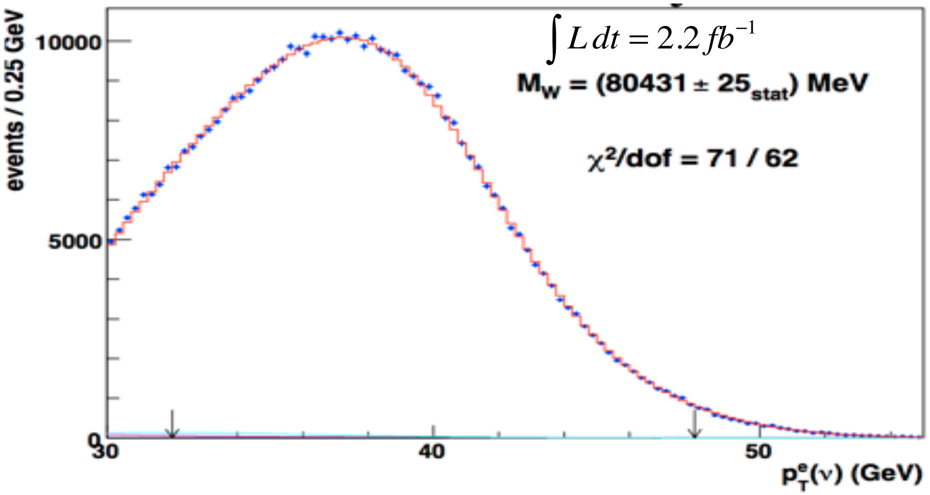
W/Z mass

$M_Z=91230 \pm 30_{stat} \pm 10_{cal} \pm 8_{mom} \pm 5_{QED} \pm 2_{align}$ MeV



$M_{W(e)}$ = 80408 ± 19_{stat} ± 18_{sys} MeV





W transverse mass fit uncertainties

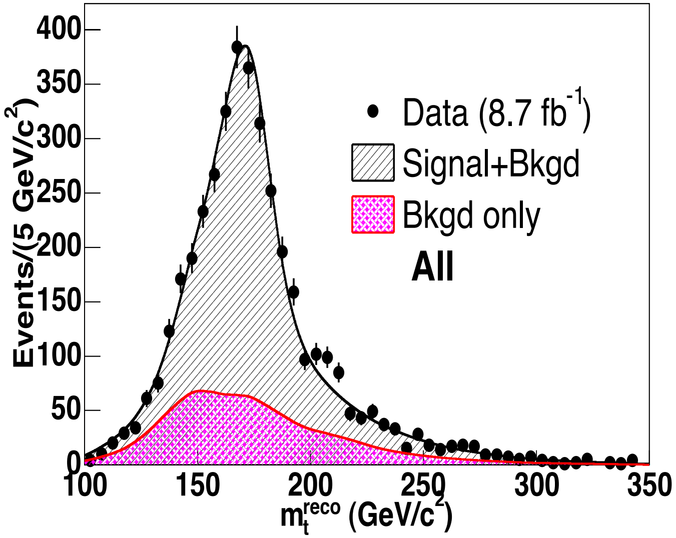
Systematic (MeV)	Electrons	Muons	Common
Lepton Energy Scale	10	7	5
Lepton Energy Resolution	4	1	0
Recoil Energy Scale	5	5	5
Recoil Energy Resolution	7	7	7
$u_{\|\|}$ Efficiency	0	0	0
Lepton Removal	3	2	2
Backgrounds	4	3	0
$p_T(W)$ Model (g_2, g_3, α_s)	3	3	3
Parton Distributions	10	10	10
QED Radiation	4	4	4
Total	18	16	15

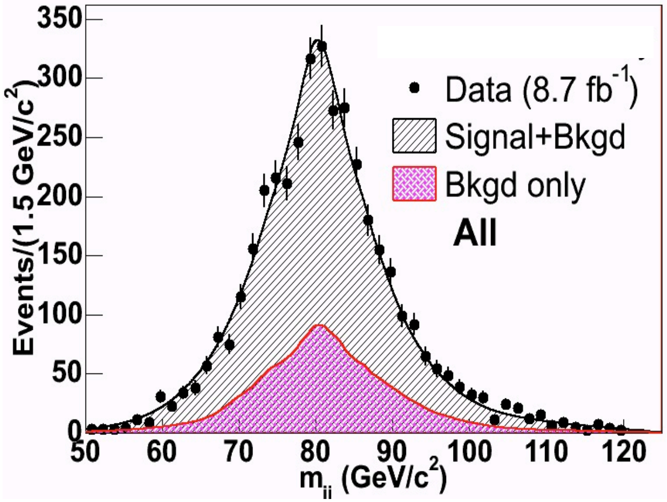
Top mass – l+jets

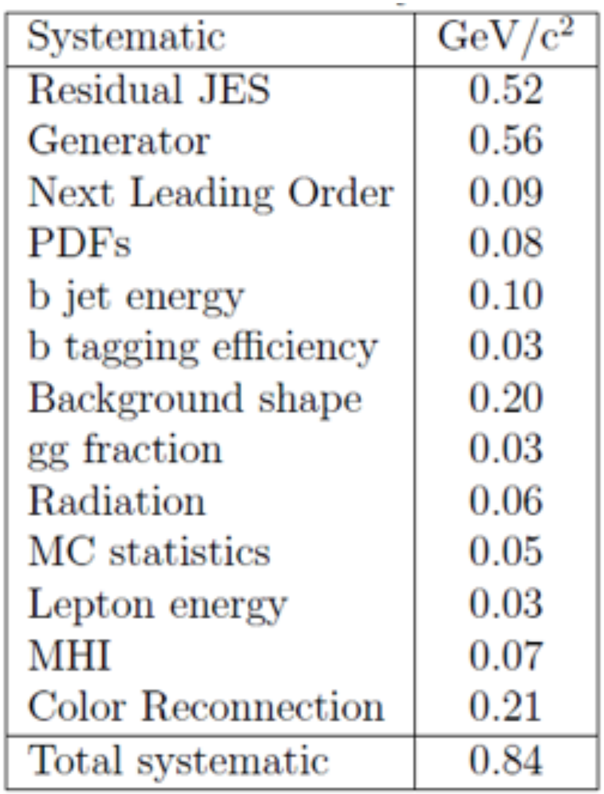
$$M_{top} = 172.85 \pm 0.71(\text{stat.+JES}) \pm 0.84(\text{syst.})\ \text{GeV}/c^2$$

0.52(stat.)

0.49(JES)

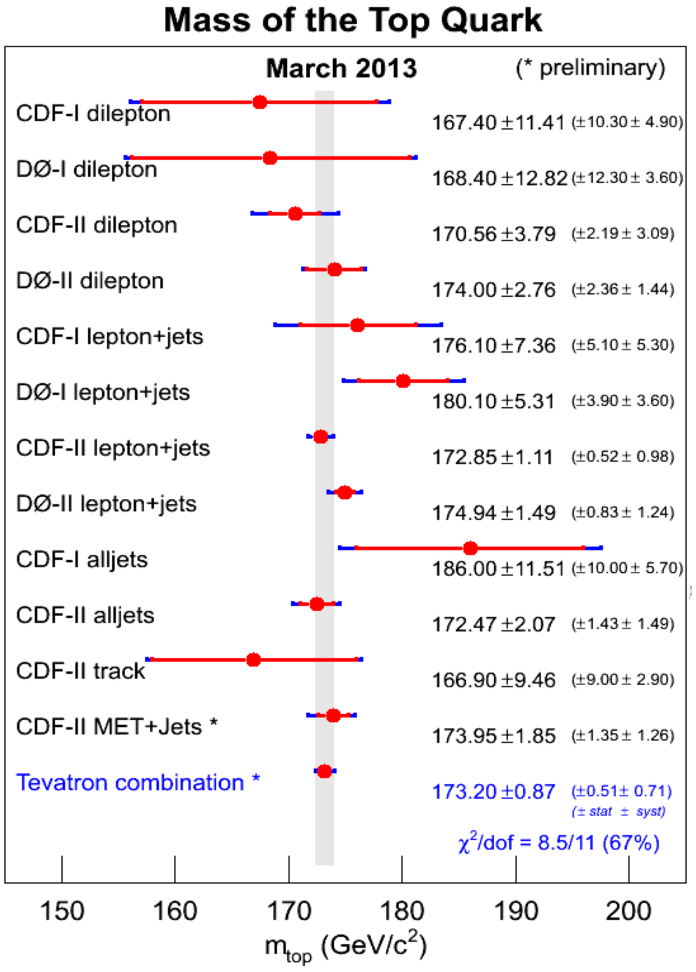


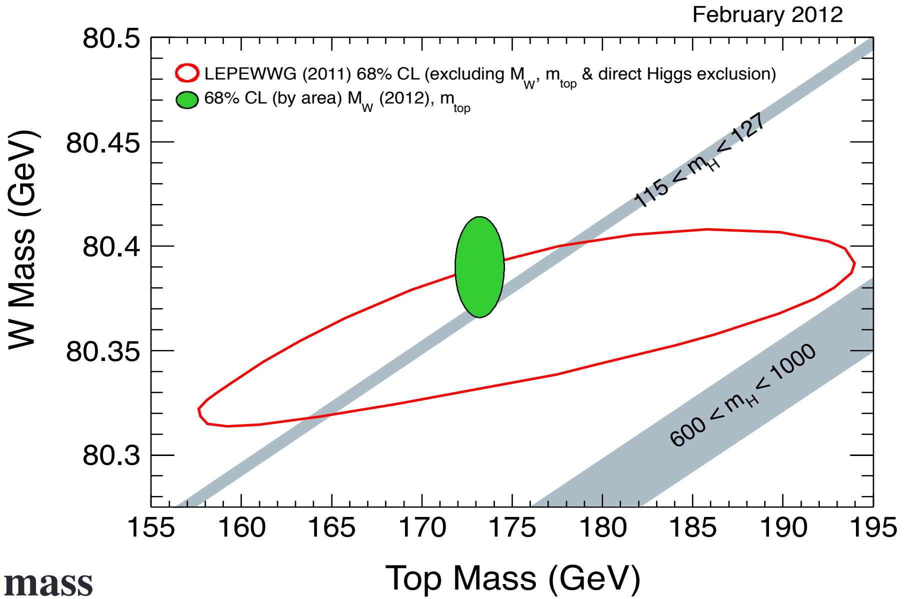




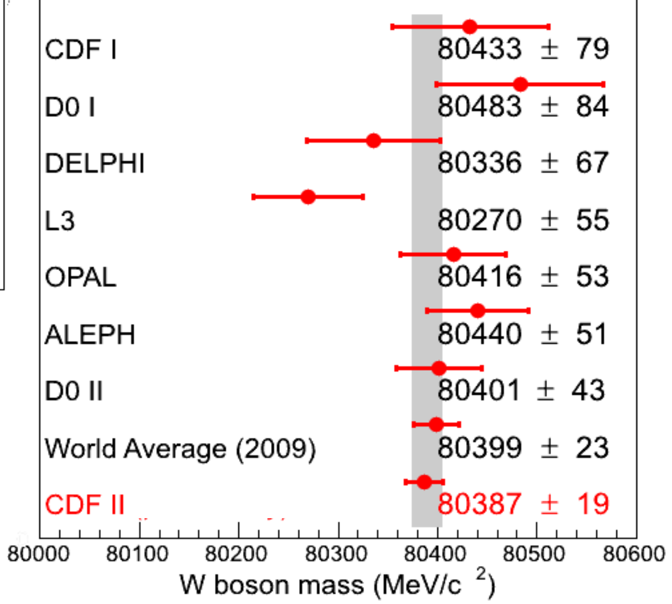
Systematic	GeV/c^2
Residual JES	0.52
Generator	0.56
Next Leading Order	0.09
PDFs	0.08
b jet energy	0.10
b tagging efficiency	0.03
Background shape	0.20
gg fraction	0.03
Radiation	0.06
MC statistics	0.05
Lepton energy	0.03
MHI	0.07
Color Reconnection	0.21
Total systematic	0.84

Updated M_H from M_W vs M_{top}





W mass



Conclusions

- CDF calorimetry was conceived some 30 years ago and after 25 years of operation its performance and longevity surpassed initial expectations
- Hard and ingenious work of many people corrected detector deficiencies and minimized the impact on physics
- CDF has gone far beyond any expectation in making precise measurements and providing important EWK constraints
- The top quark, central to the Tevatron program, reached an unthinkable level of precision $\Delta m_t < 1.0$ GeV/c^2
- Performance of the calorimeters assisted many analyses on searches for physics BSM and improve our understanding of PQCD
- Two years after CDF ceased operations, there are still ongoing analyses exploiting the full 10fb^{-1} of data collected
  - But the baton has passed to the far superior LHC detectors