Performance and Operational Experience of the CDF Luminosity Monitor

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TIPP 2011, June 13, 2011

Outline

- Introduction and motivation
- Design of the CDF Luminosity monitor
- Performance
- Operational experience
- Summary and conclusion

Introduction and Motivation

Why Precise Luminosity Measurement Is Important In Collider Experiments?

- Measure of accelerator performance
  - Instantaneous Luminosity

$$L = N_p N_{pbar} B \times f_{BC} / 4\pi\sigma^2$$

  - Total Luminosity

$$L_{tot} = \int L \, dt$$

Typical Tevatron Performance

$N_p \sim 3\times10^{11}$ protons/bunch
$N_{pbar} \sim 6\times10^{10}$ anti-protons/bunch
$B = 36$ number of bunches in ring
$f_{BC} \sim 1.7$ MHz freq. bunch crossings
$\sigma^2 \sim 3\times10^{-4}$ cm^2 beam cross-section

$L \sim 300\times10^{30}$ cm^{-2}s^{-1}

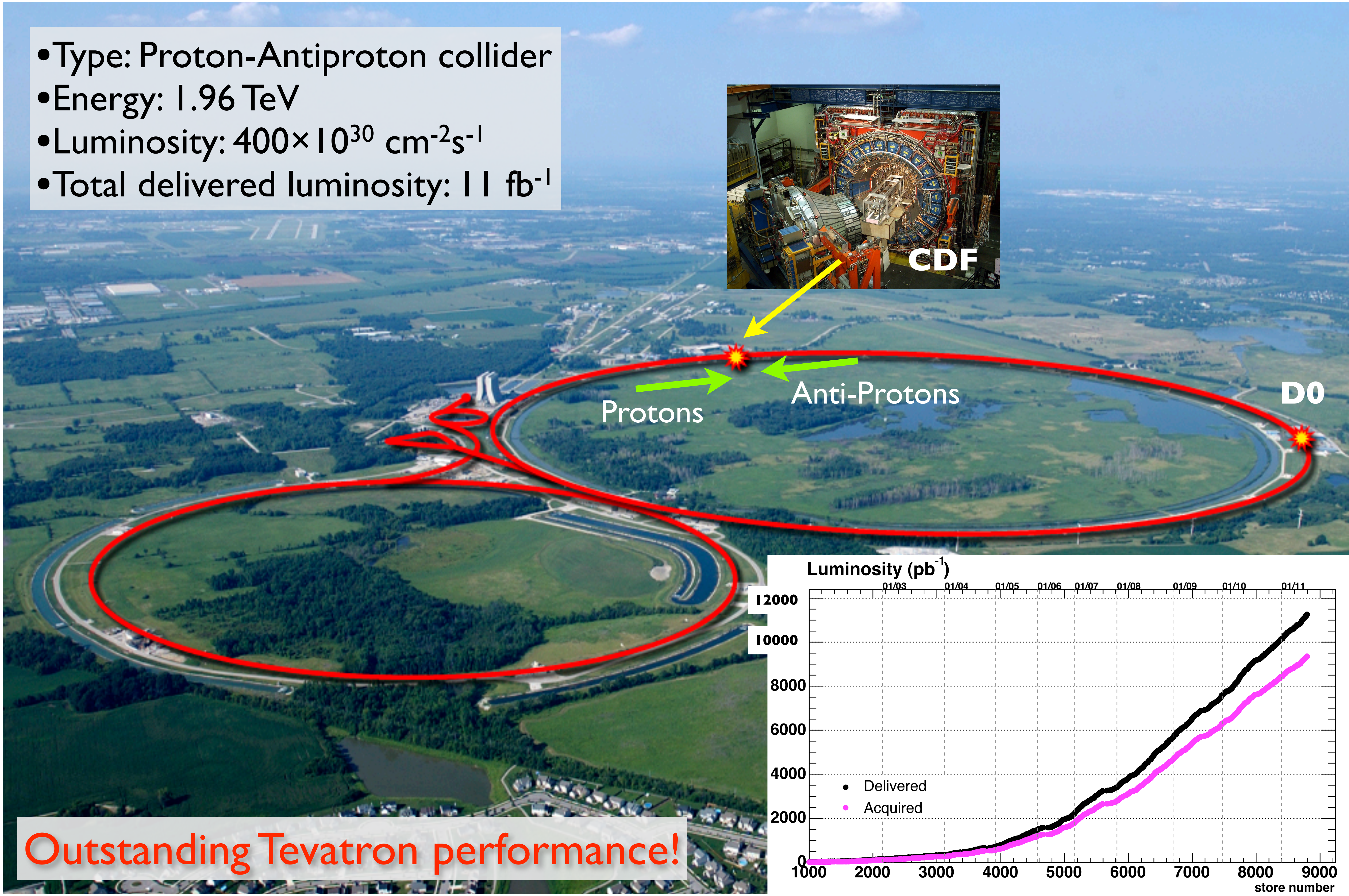
- Physics!
  - Luminosity connects experiment and theory:

$$N_{Higgs} = \varepsilon \times \sigma(ppbar \rightarrow H + X) \times L_{tot}$$

Precise absolute measurement of total luminosity is crucial for physics

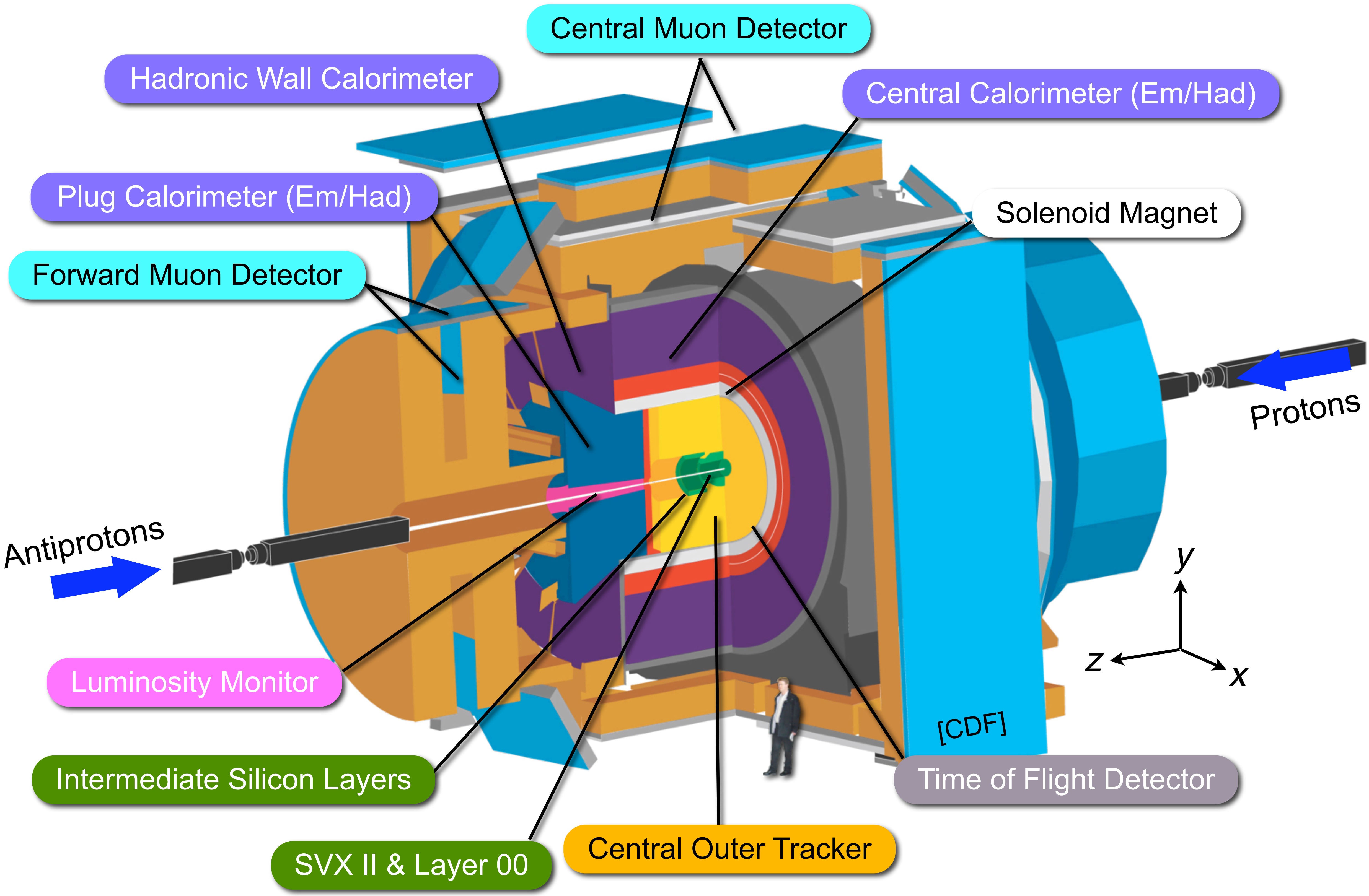
Tevatron

- Type: Proton-Antiproton collider
- Energy: 1.96 TeV
- Luminosity: 400×10^{30} cm^{-2}s^{-1}
- Total delivered luminosity: 11 fb^{-1}



Outstanding Tevatron performance!

CDF Run II Detector

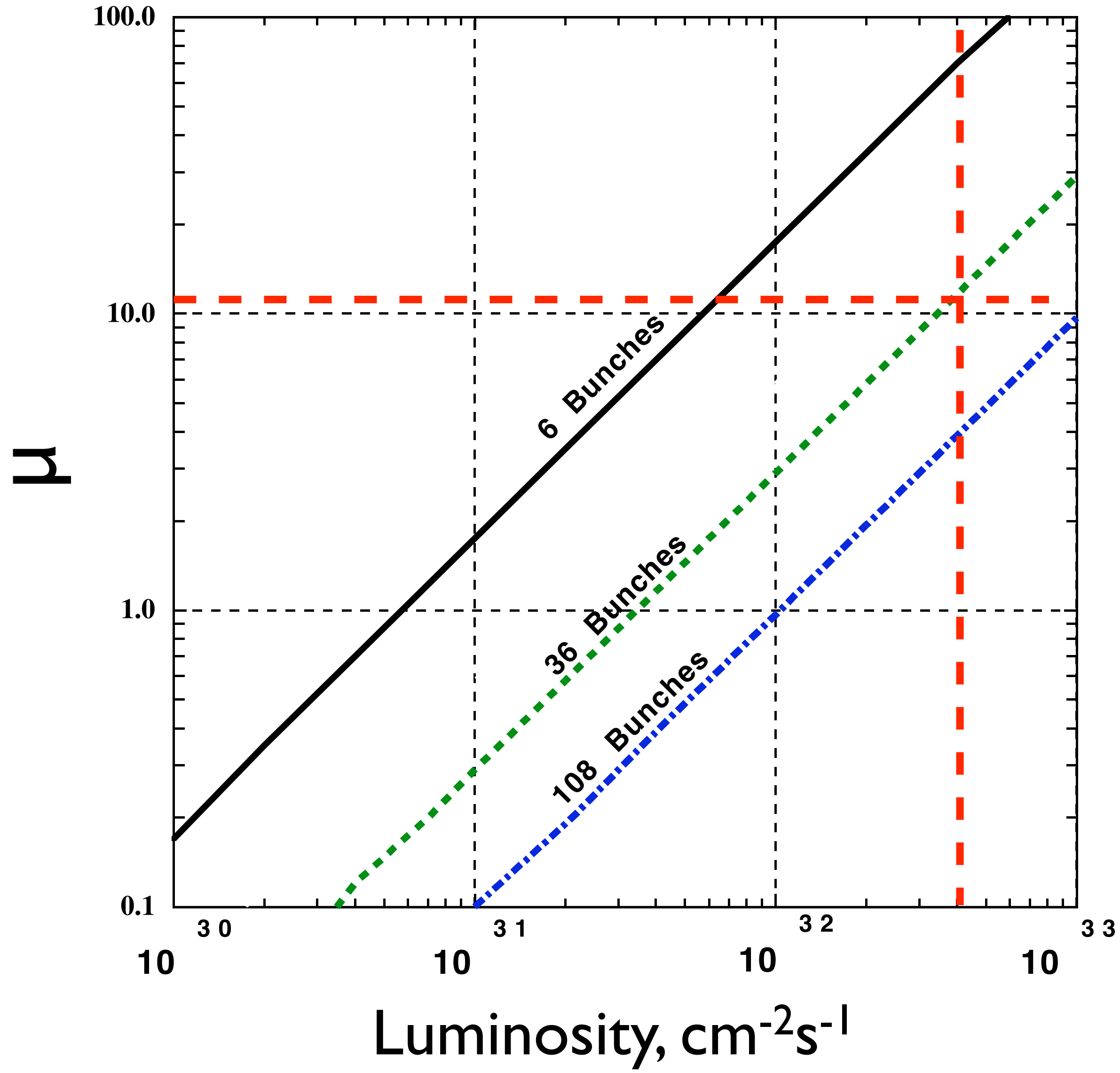


Specifications for CDF Luminosity Detector

- Rate of ppbar interactions

$$N_{pp} = \mu f_{BC} = \sigma_{in} L$$

μ - average number of ppbar interaction/BC
σ_{in} - total inelastic cross-section of ppbar interactions (61.7 mb at 1.96 TeV)

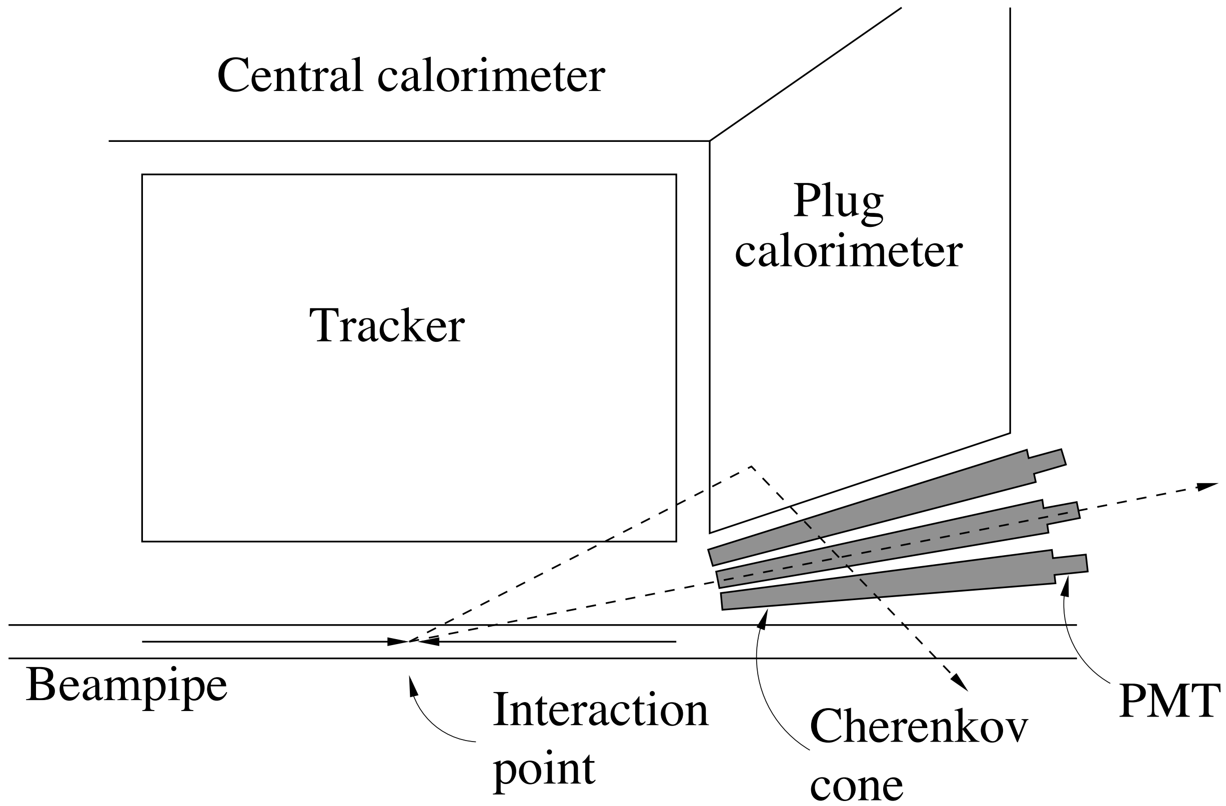


- Operate at high luminosity
  $L \sim 400\times10^{30}$ cm^{-2}s^{-1}, $\mu \sim 12$ ppbar/BC
- Measure Luminosity
  - Instantaneous and Total
  - Real-time
  - Bunch by bunch
  - Precise (few %)
- Z-profile of collisions
- Provide Minimum Bias Trigger

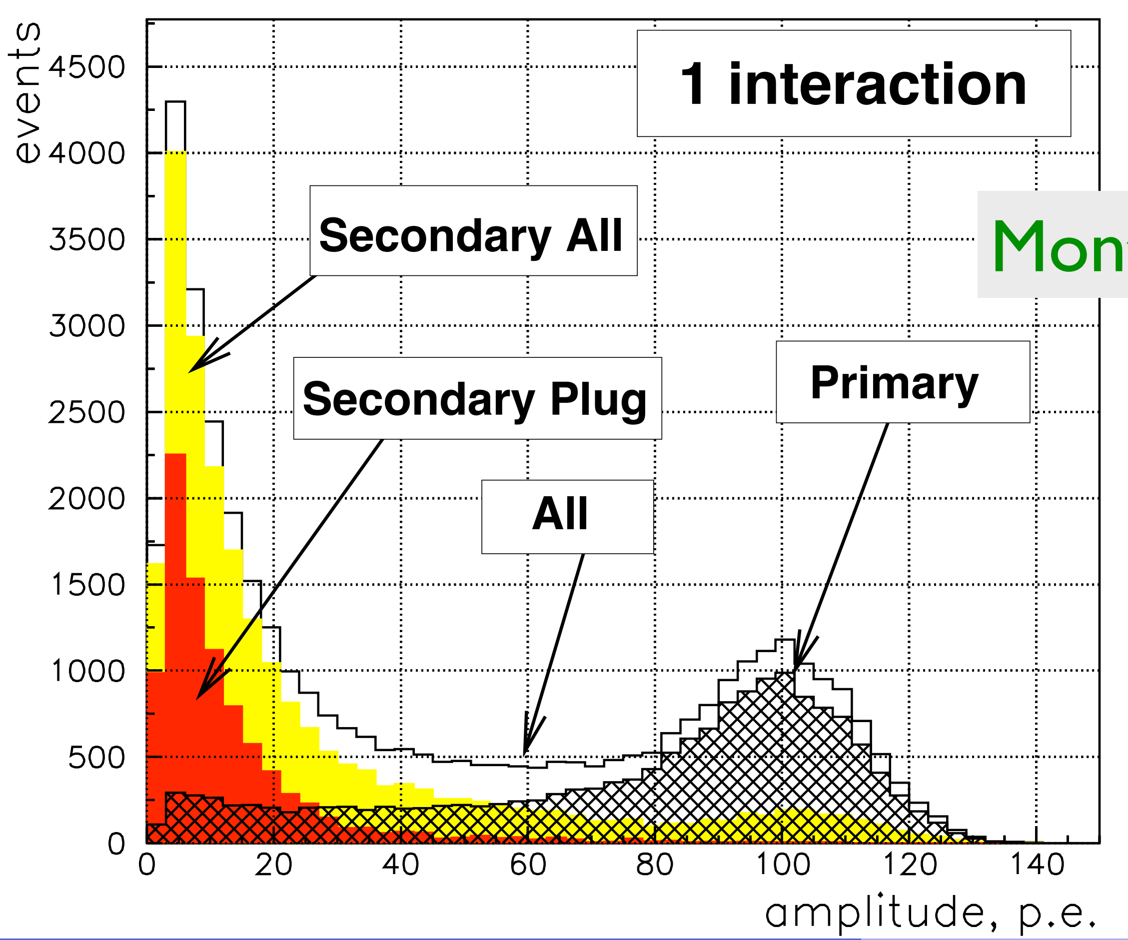
CDF: Gaseous Cherenkov Luminosity Counters

Design of the CDF Luminosity Monitor

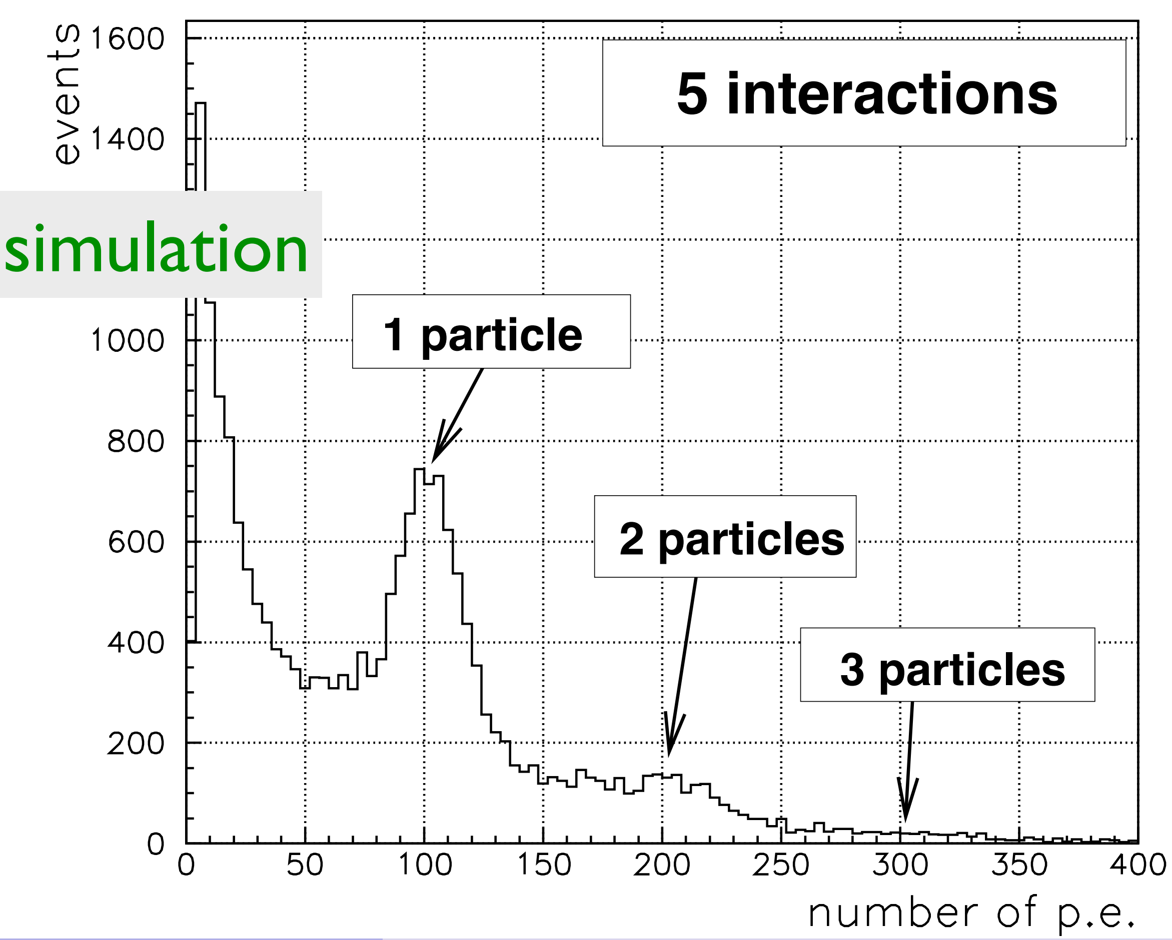
Concept of Cherenkov Luminosity Counters



- Separate particle from primary interactions and secondary particles
- Good amplitude resolution
  - about 18% (photo statistics, light collection, PMT resolution)
- Good timing resolution
  - separate collisions/losses
- Radiation hard, low mass



Monte-Carlo simulation

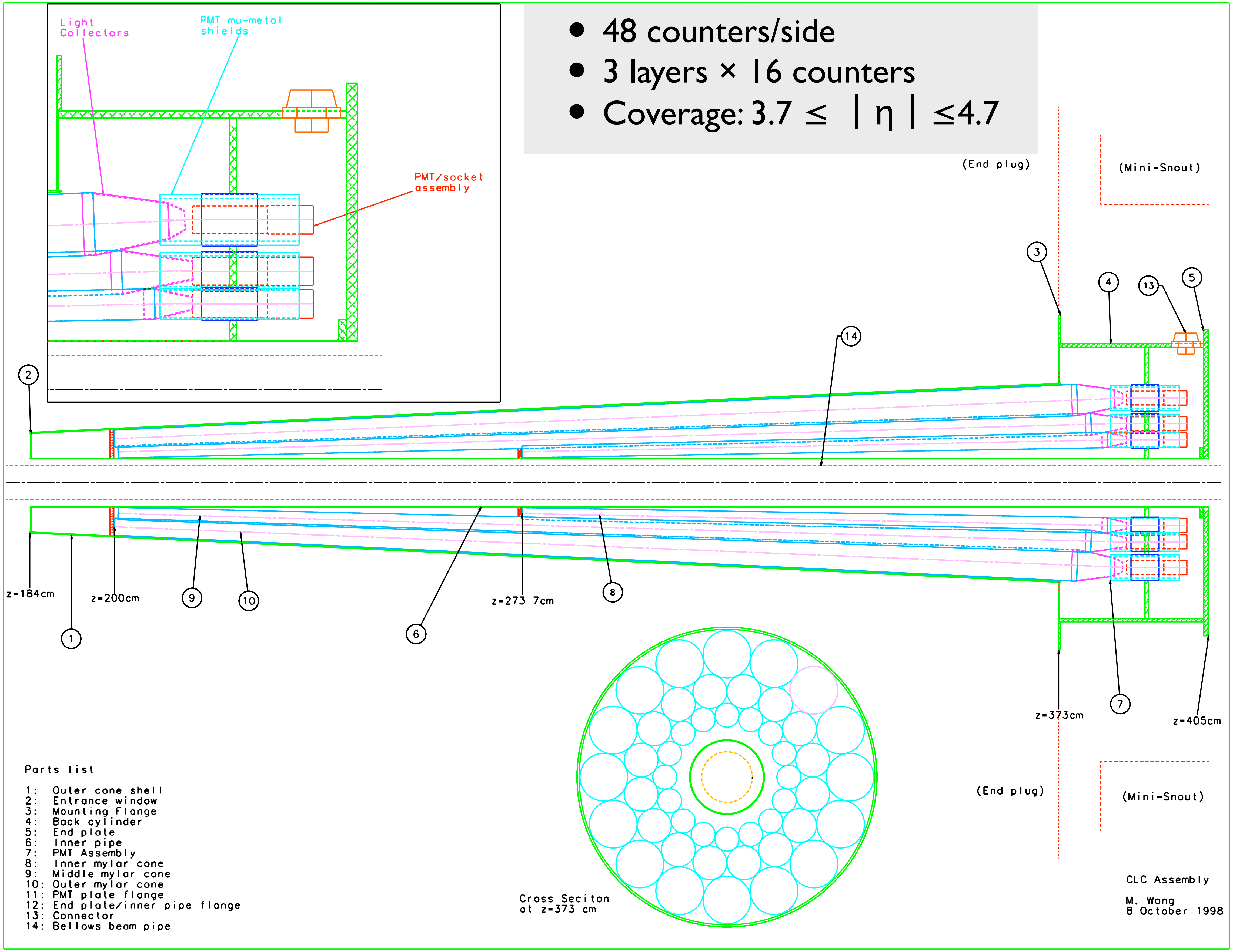


From Concept To Design

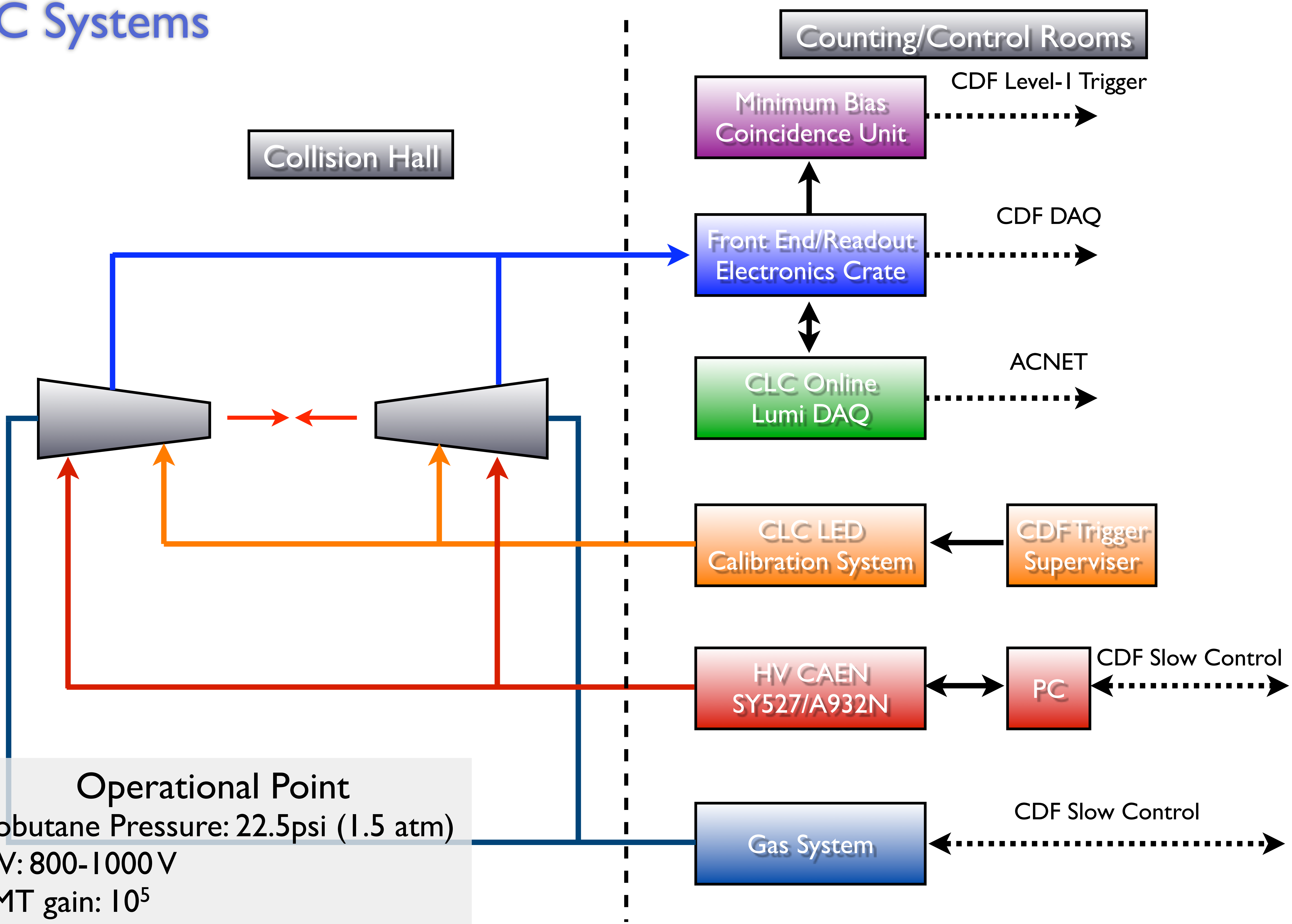
- Studies: simulation and prototype test beam
- Gas choice: Cherenkov angle ($\cos\theta_c = 1/\beta n$), light yield ($N_{p.e.} = 370 \cdot L \cdot \int \sin^2\theta_c \cdot \varepsilon \cdot dE$), ease of use, safety, cost
  - Isobutane: n=1.00143, θ_c = 3.1°, $N_{p.e.} \approx$ 100, UV transparent up to 150 nm
- Cones: reflectivity, light collection, cost
  - 2 layers of 100 µm mylar 60 nm Al coating
- Collectors: reflectivity, light collection
  - Al cones w/ 50 nm Al + 50 nm MgF_2 coating
- Choice of PMT: size, timing resolution, cost
  - Hamamatsu R5800Q w/ concave-convex quartz window, ∅25mm, gain: 2×10^6
- Mechanical design: 14 psi above atmospheric, less material
  - Thin (0.035”) Al shells with Al inner support structures, safety factor 3
- Magnetic shielding: $B_z \sim$ 100 Gauss at PMT location
  - Cylindrical “pre-shield” around PMT region ($B_z \sim$ 10-20 Gauss) + individual PMT shields

Cherenkov Luminosity Counters: Design

- 48 counters/side
- 3 layers × 16 counters
- Coverage: $3.7 \leq |\eta| \leq 4.7$



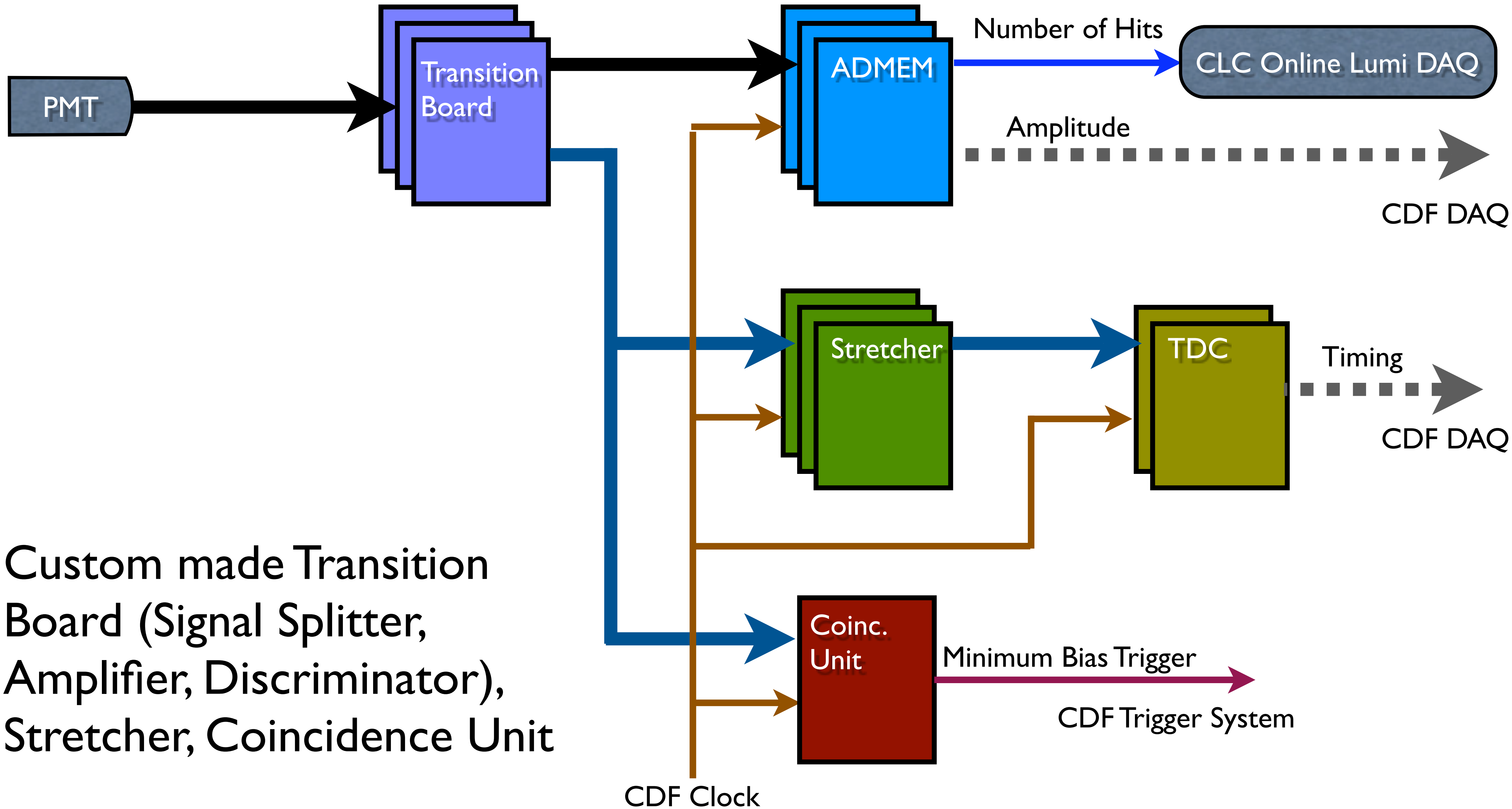
CLC Systems



Operational Point

- Isobutane Pressure: 22.5psi (1.5 atm)
- HV: 800-1000 V
- PMT gain: 10^5

CLC Readout Electronics

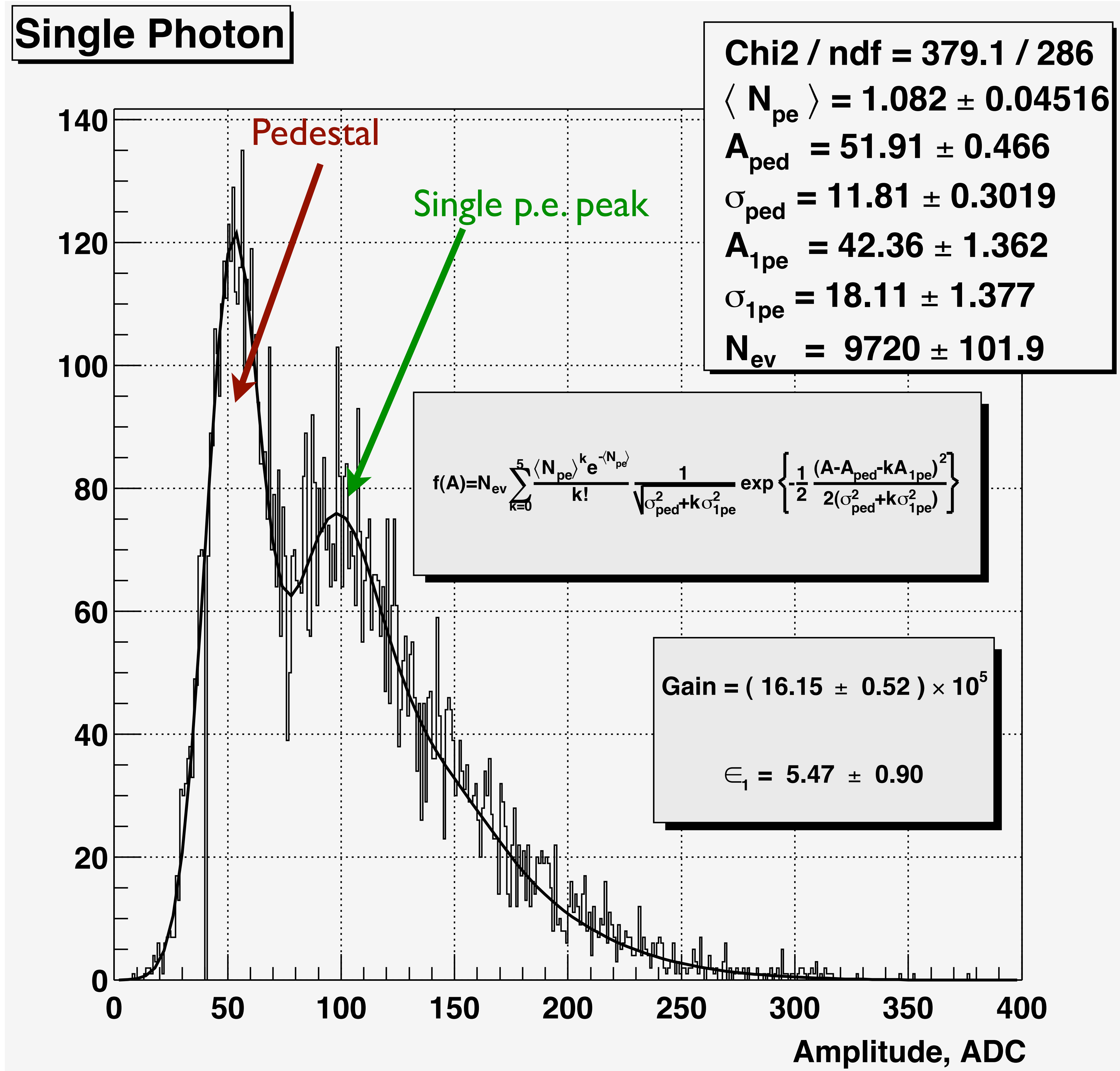


- Custom made Transition Board (Signal Splitter, Amplifier, Discriminator), Stretcher, Coincidence Unit
- Standard CDF ADMEM (w/ custom firmware for hit counting) and TDC

Performance

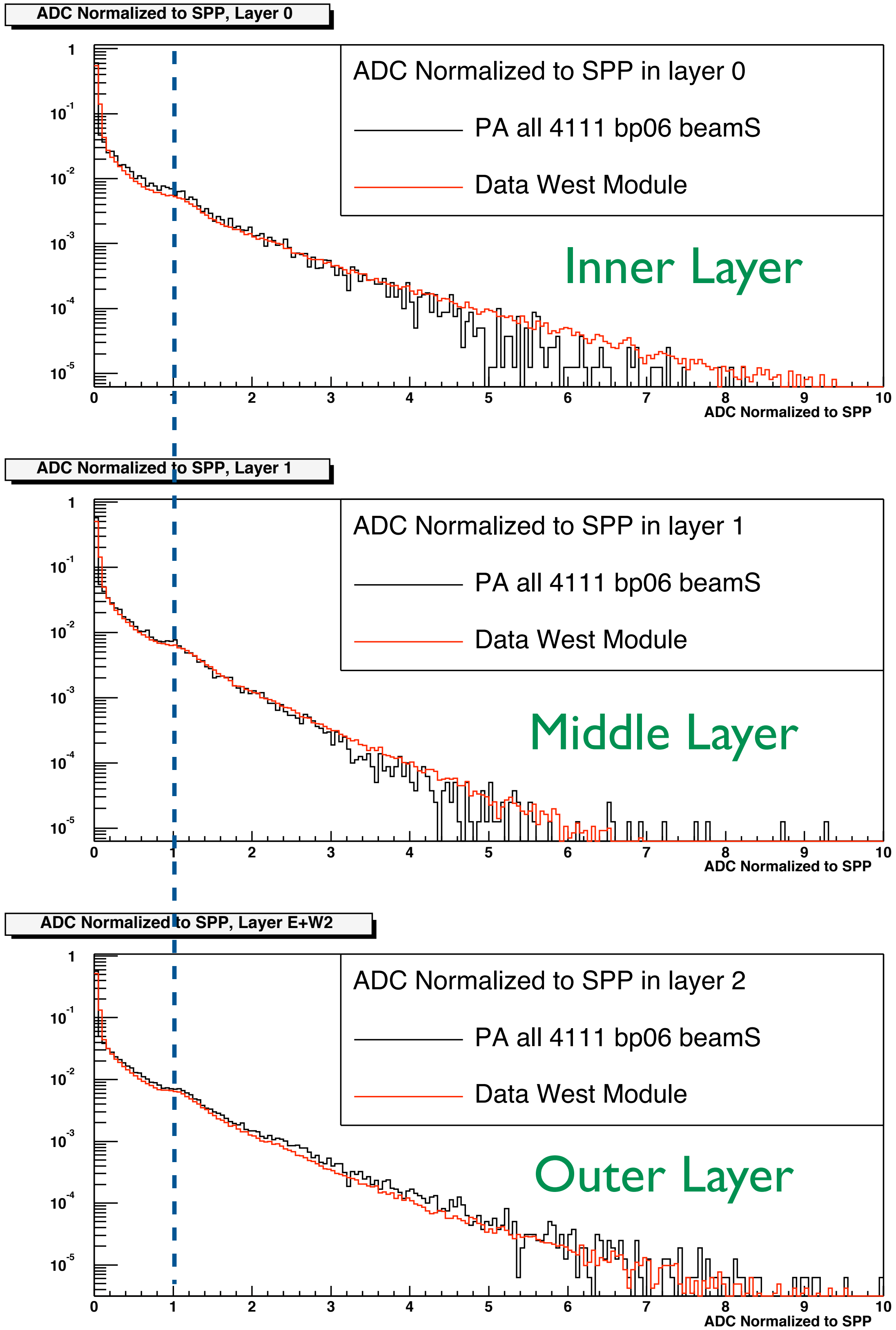
Single Photo-electron Amplitude

- PMT test stand w/ full CLC Amplitude measurement electronics
- Tested/calibrated >300 PMTs
- Clear single photo-electron peak at high gain
- CLC signal ~100 p.e. / particle

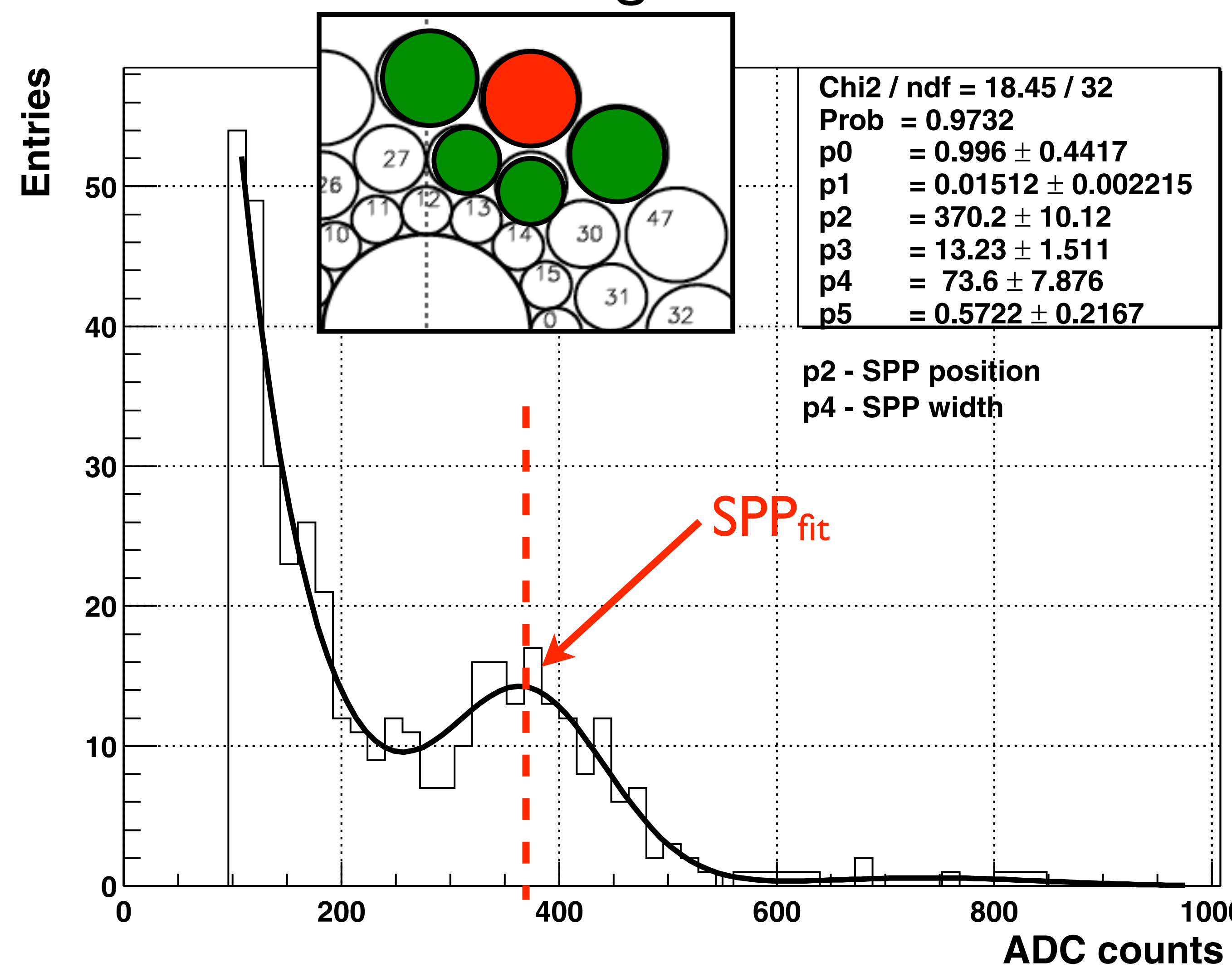


Amplitude Distributions in PPbar Collisions

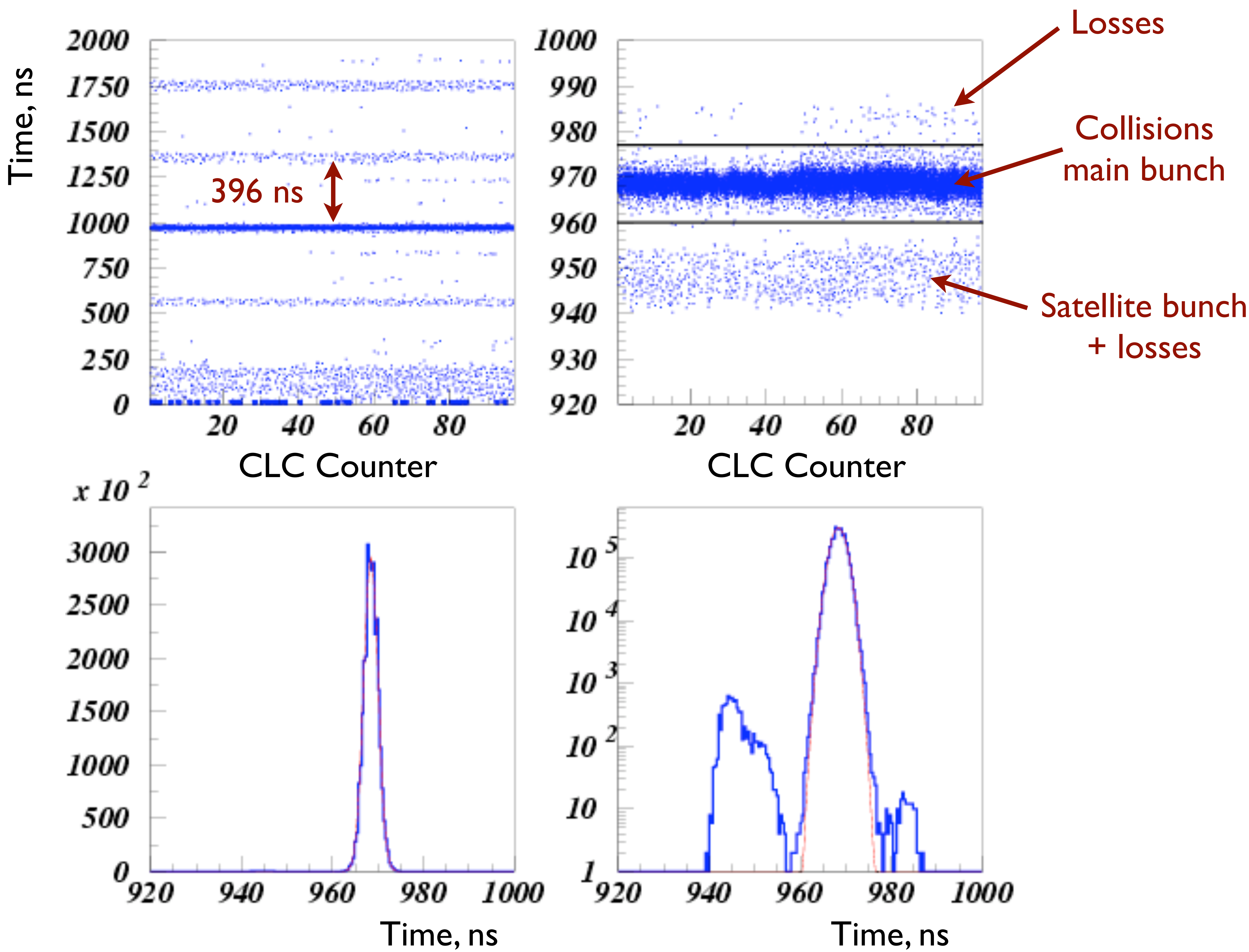
- Full detector simulation *vs* Data



- Simulation agrees well w/ data
- Single particle peak buried under secondary interactons
- Clear peak after isolation requirement:
  - Amplitude < 20 p.e. in surrounding counters

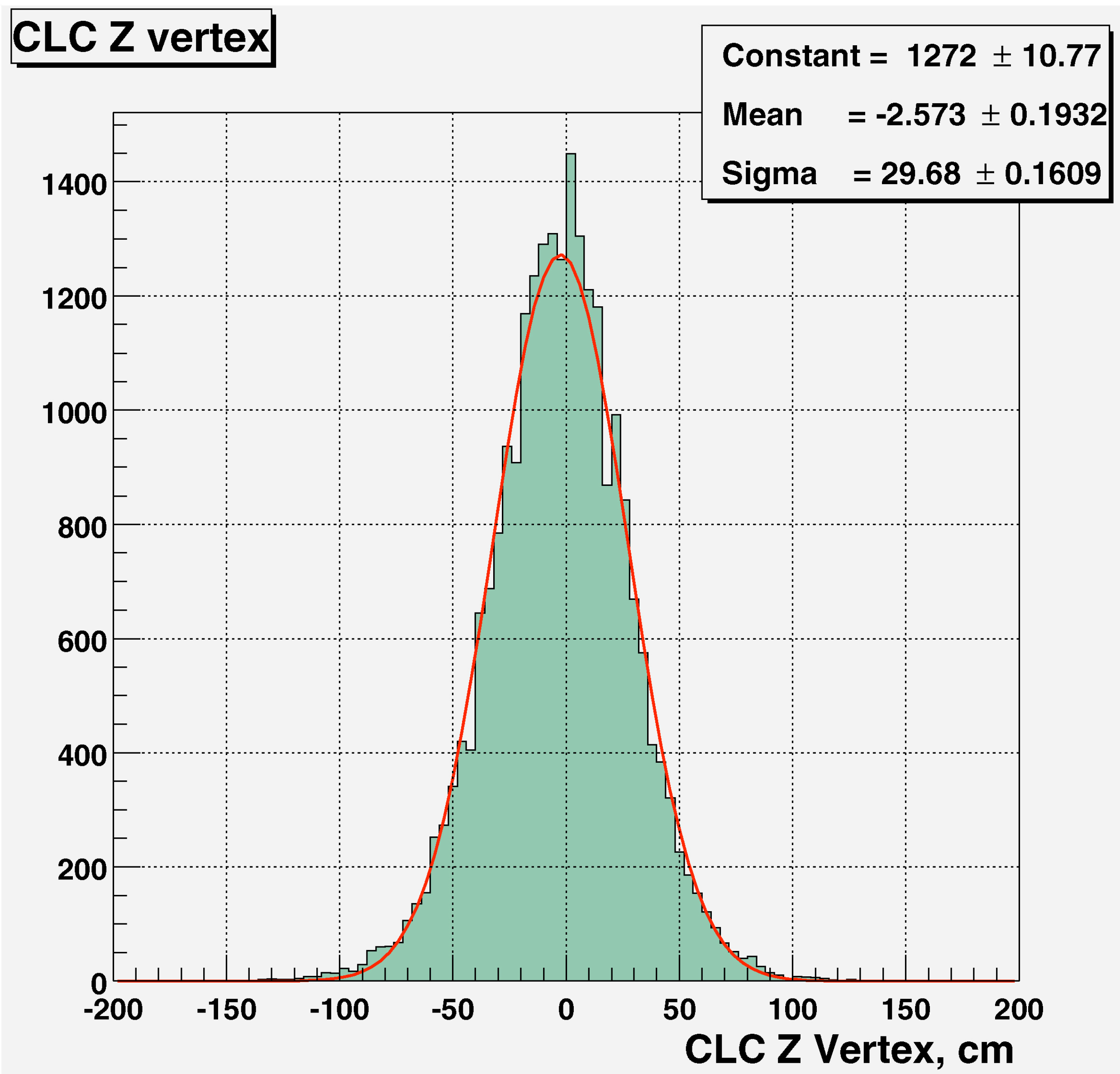


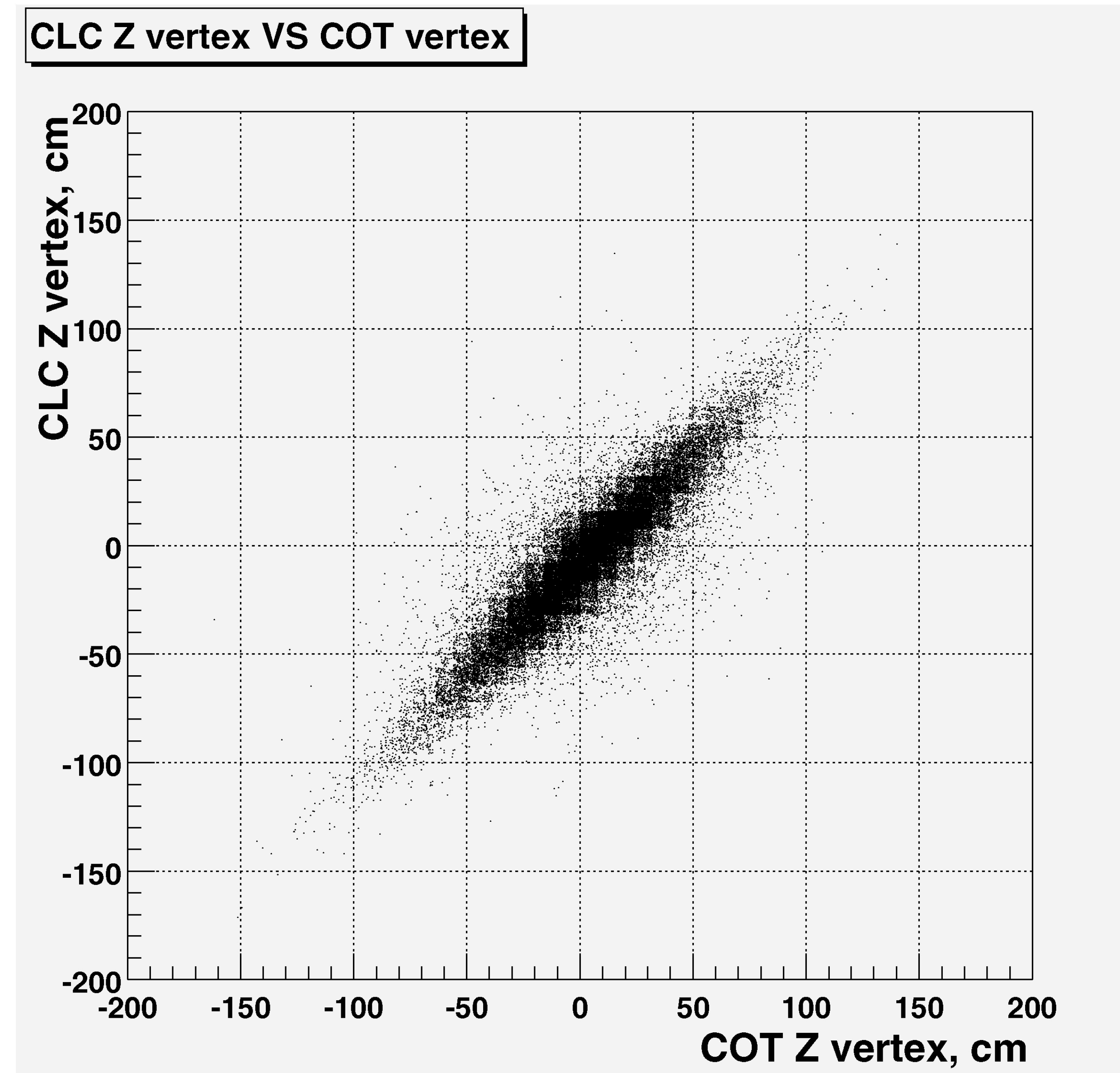
Timing: Beam Structure



Timing: Z-position of Beam

$$Z_{CLC} = (T_W - T_E) \cdot c/2$$

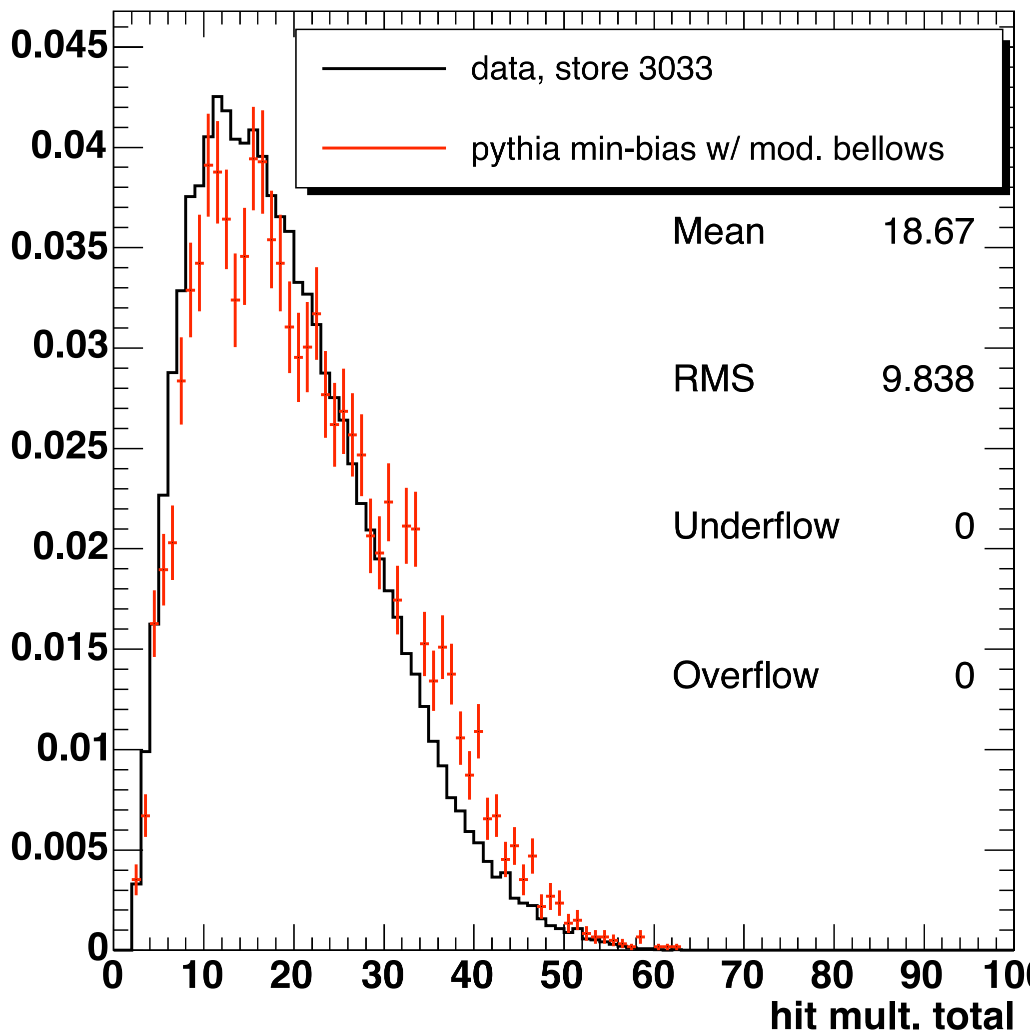


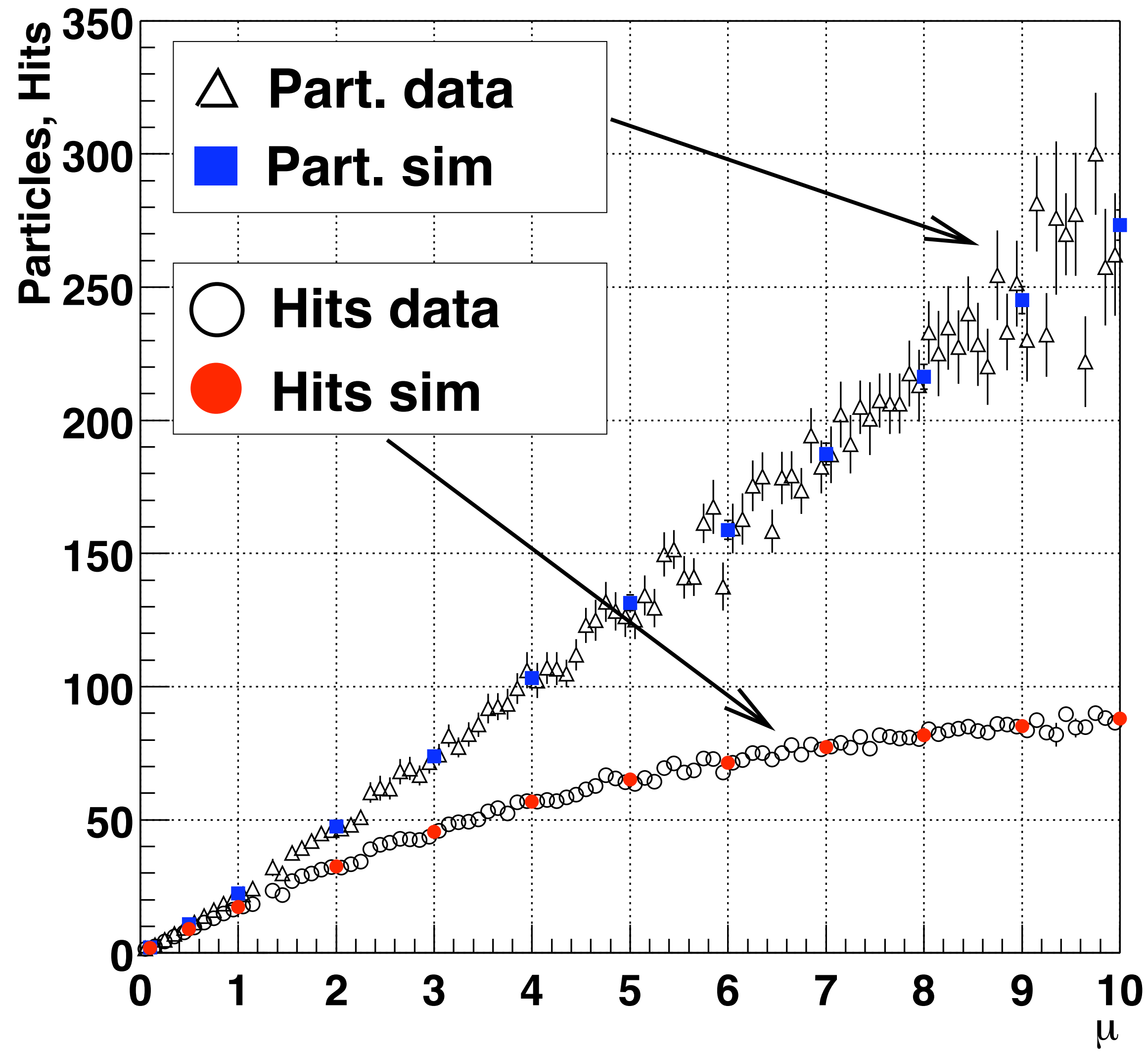


- Was very useful during Tevatron commissioning:
  - CLC was the only detector which could measure position of interaction during that time
  - Helped a lot to MCR to tune Tevatron

Multiplicity Distributions in PPbar Collisions

- Hits: counters with Amplitude > threshold (250 ADC, set in firmware)
- Particles: N_{part} = Amplitude / $Amplitude_{SPP}$





- Shape of multiplicity distributions is more sensitive to variations in PMT gain (data) and accounting for all material in front of the detector (simulation)

Good agreement between data and simulation for average multiplicities

Luminosity Measurement Basics

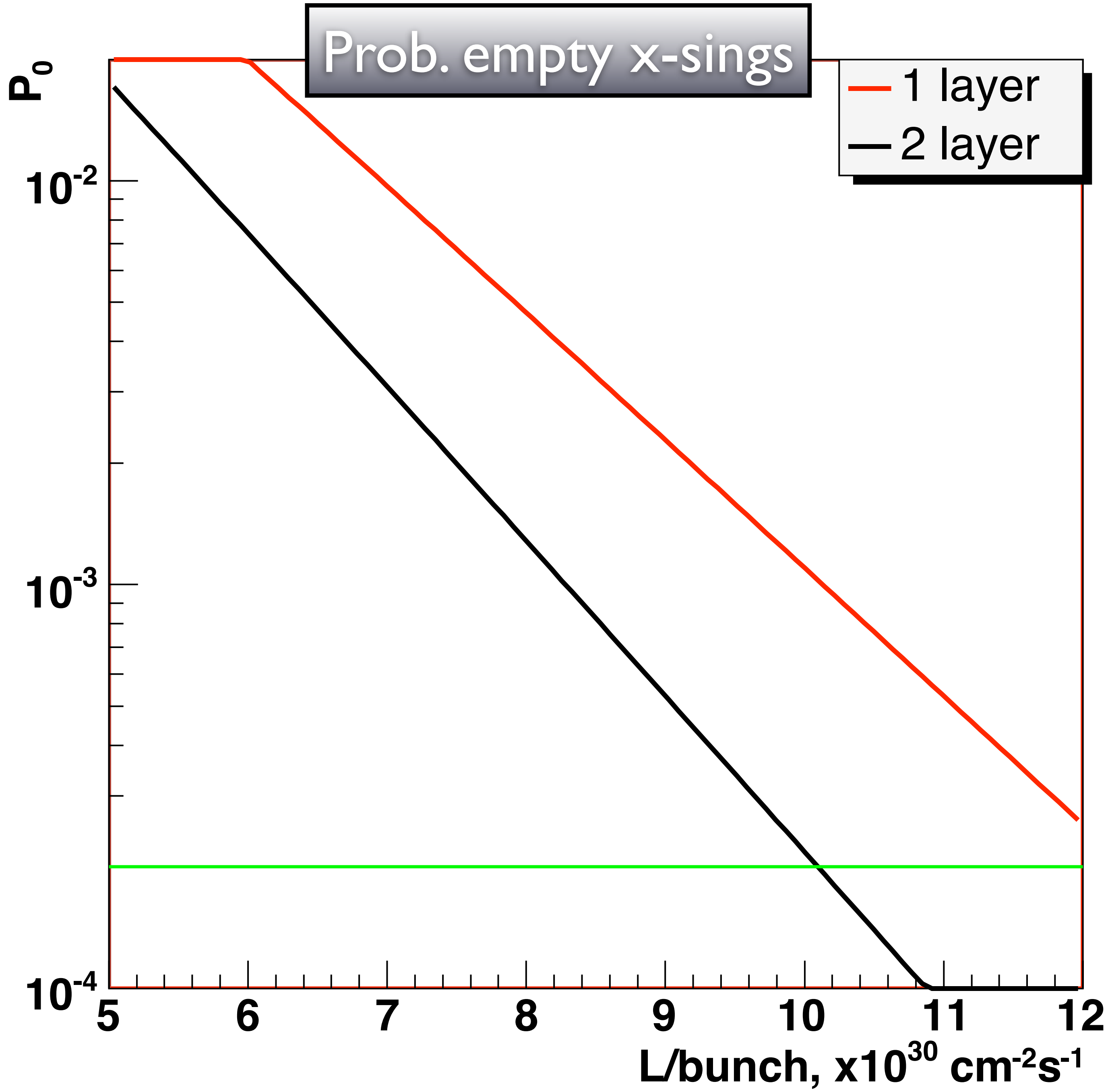
- Rate of ppbar interactions: $N_{pp} = \mu f_{BC} = \sigma_{in} L$, where
  - f_{BC} is freq. of bunch crossings
  - σ_{in}=61.7 mb is x-sec. of pp int.
  - μ is number of int./BC
- Instantaneous Luminosity

$$L = \mu f_{BC} / \sigma_{in}$$

- How to measure μ?

- Empty Crossings: BC w/o int.
  - probability: $P_0 = N_0 / N_{BC}$
  - naively: $P_0 = e^{-\mu} \Rightarrow \mu = -\log P_0$
  - need to take into account detector acceptance: $P_0=(2e^{\mu\varepsilon 1}-1) \cdot e^{-\mu(1-\varepsilon 0)}$
    - $\varepsilon 0$ is prob. of no hits in detector
    - $\varepsilon 1$ is prob. of hits only on one side
  - systematic uncertainty 4.5%
    - dominated by acceptance (4%)
- Other methods:
  - Hits: $\mu = N^{hits}{}_{BC} / N^{hits}{}_{1}$
  - Particles: $\mu \sim \sum_i A_i$

High Luminosity: Rare Empty Crossings

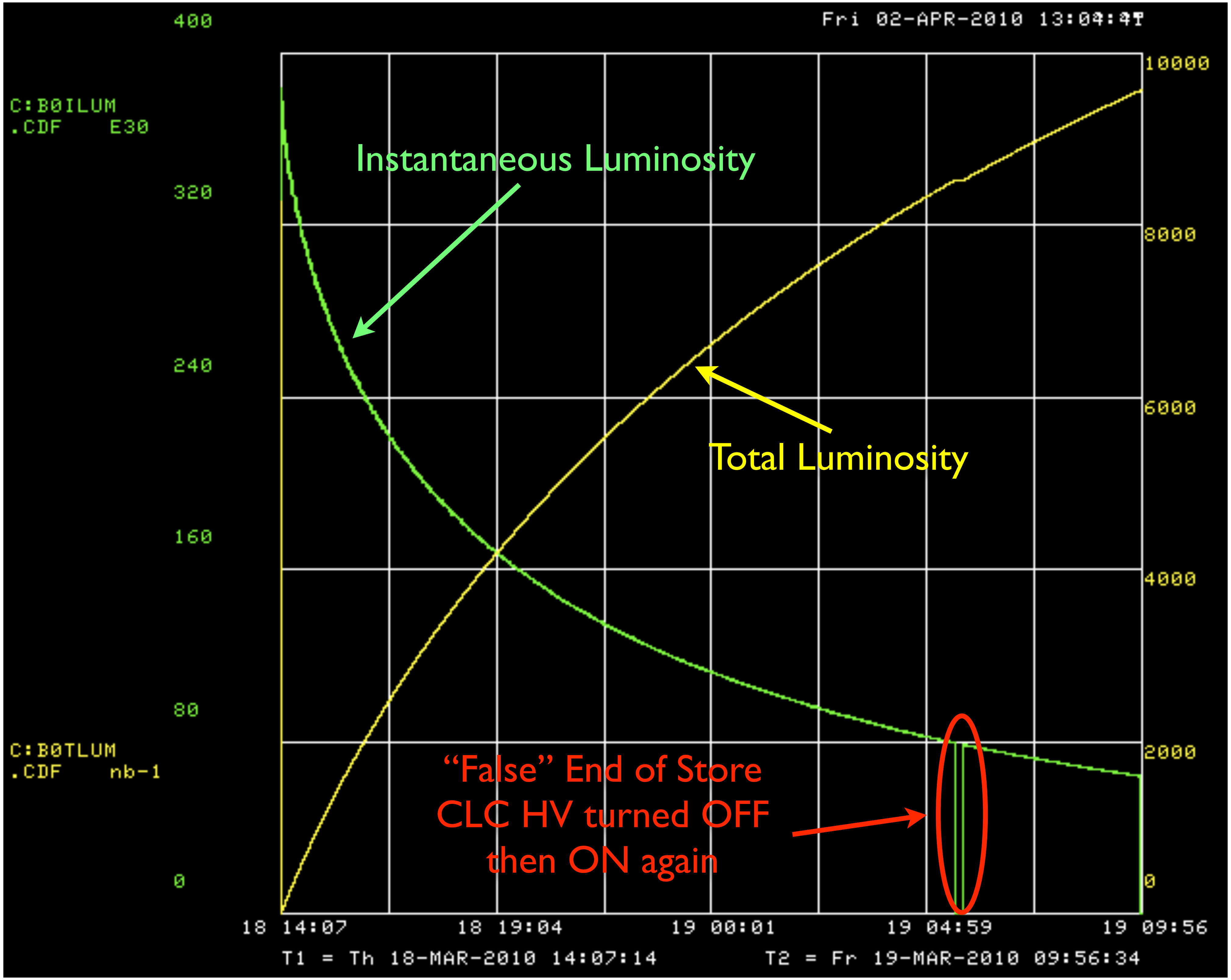


- Typical acceptances
  - 2 Layers: $\varepsilon 0 \sim \varepsilon 1 \sim 15\%$, acc ~ 55%
  - 1 Layer: $\varepsilon 0 \sim \varepsilon 1 \sim 20\%$, acc ~ 40%
- $N_{BC} \approx 20000$ per measurement
  - limited by h/w DAQ
- Cutoff (adjustable in s/w)
  - $N_0 < 4$, $P_0 < 2 \cdot 10^{-4}$
- Cutoff Luminosity (assuming equal luminosity per bunch)
  - using 2 Layers: ~ $360 \cdot 10^{30}$ cm^{-2}s^{-1}
  - using 1 Layer: ~ $400 \cdot 10^{30}$ cm^{-2}s^{-1}

Reliable Luminosity measurements up to L ~ $400 \cdot 10^{30}$cm^{-2}s^{-1}

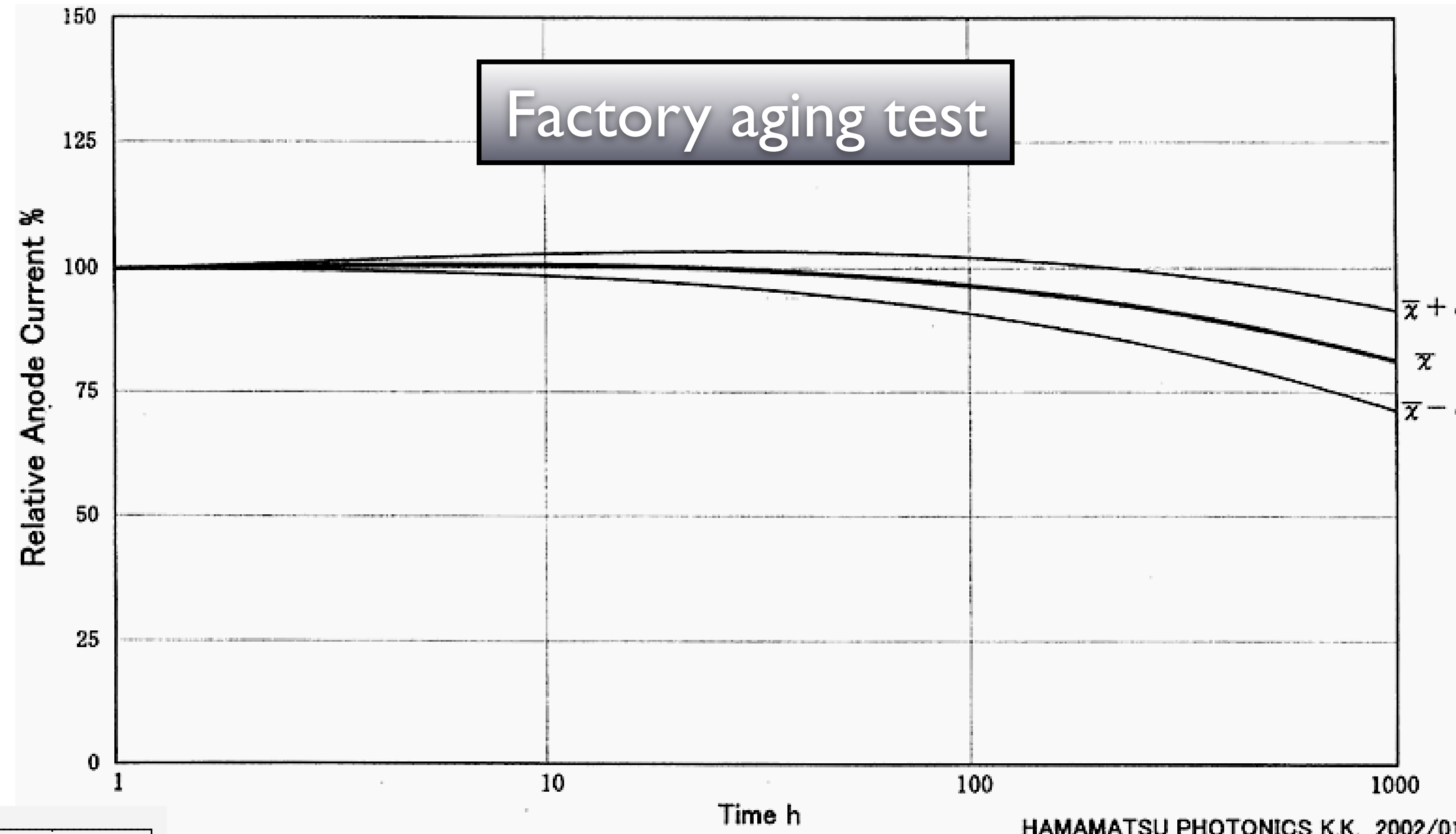
Recent Record Luminosity Tevatron Store

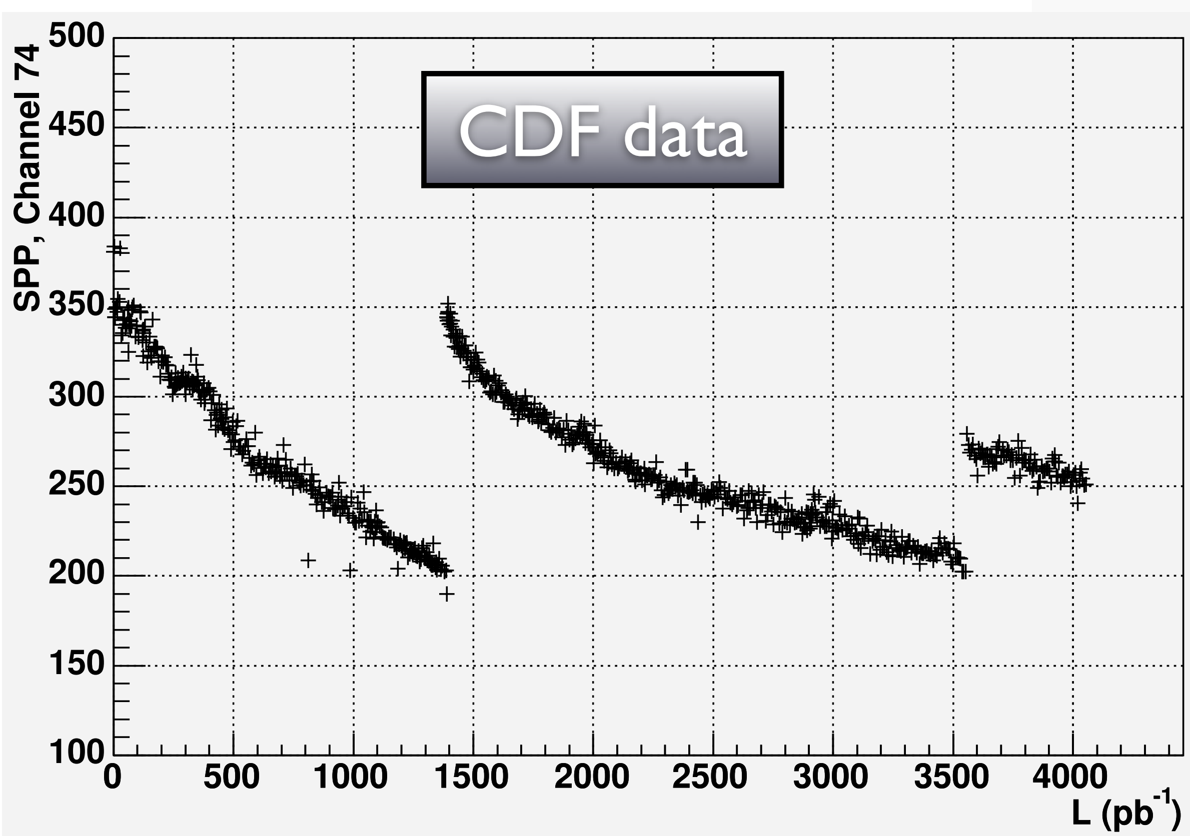
- Store 7685
- Initial Inst. Luminosity: $381 \cdot 10^{30}$ cm^{-2}s^{-1}
- Total Luminosity: 9.6 pb^{-1}



Large Total Luminosity: Aging

- Factory aging test
  - 1000 h at 10 μA
  - ΔI / I = 10 - 35%
- Corresponds to 30 - 80 % per fb^{-1}



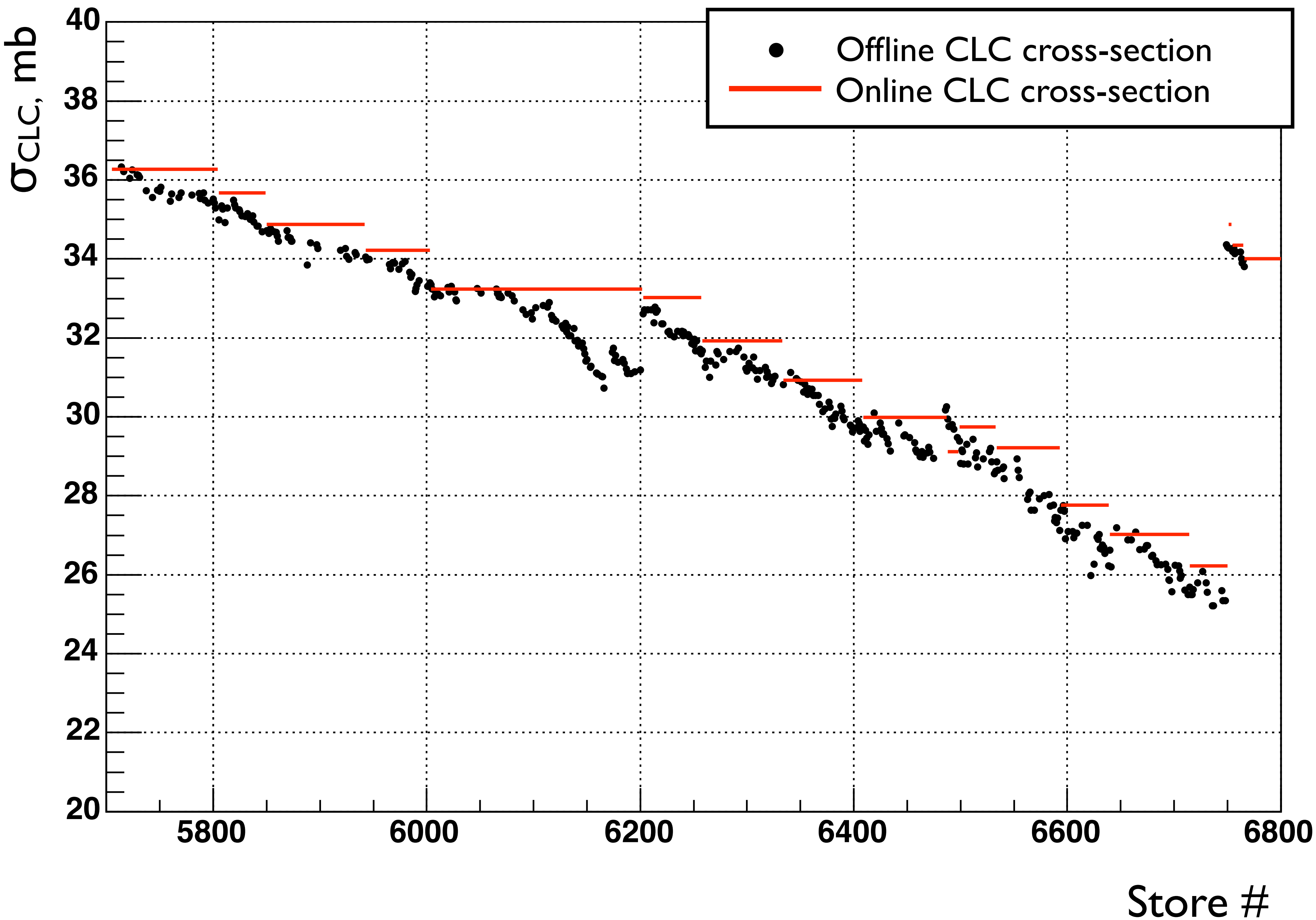


- PMT aging in detector
  - hard to calibrate Ampl. < 200
  - aging rate aprox. 30% per fb^{-1}
  - agrees well w/ Hamamatsy spec.
- HV/gain adjustments:
  - same aging rate

Survive few fb^{-1}

CLC Effective Cross-section

- CLC cross-section *vs* store #



In situ calibrations

- Use real data
- Fit SPP
- Feed SPP values to Monte-Carlo simulation
- Get new effective CLC cross-section
- Adjust online
- Apply offline corrections

Offline corrections applied for every store: Physics is not affected

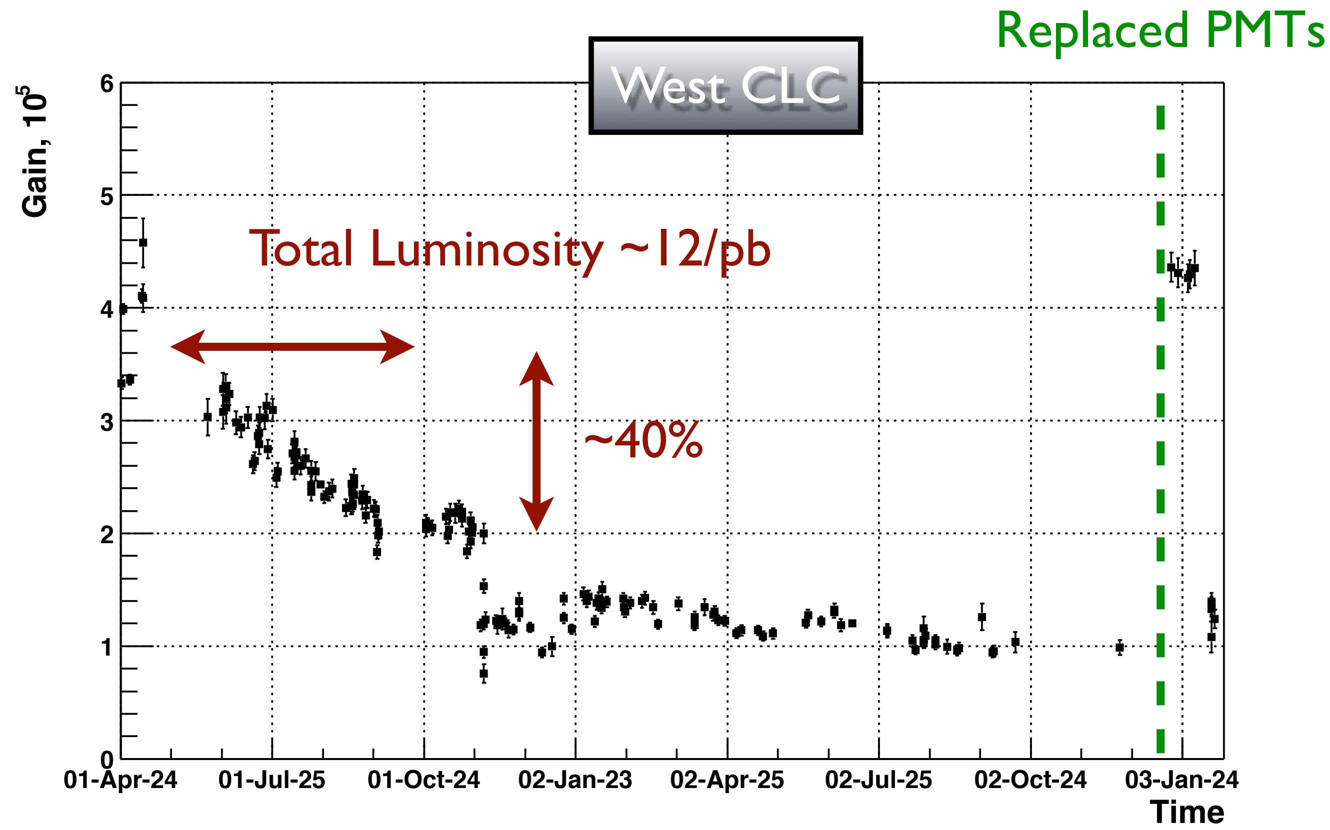
Operational Experience

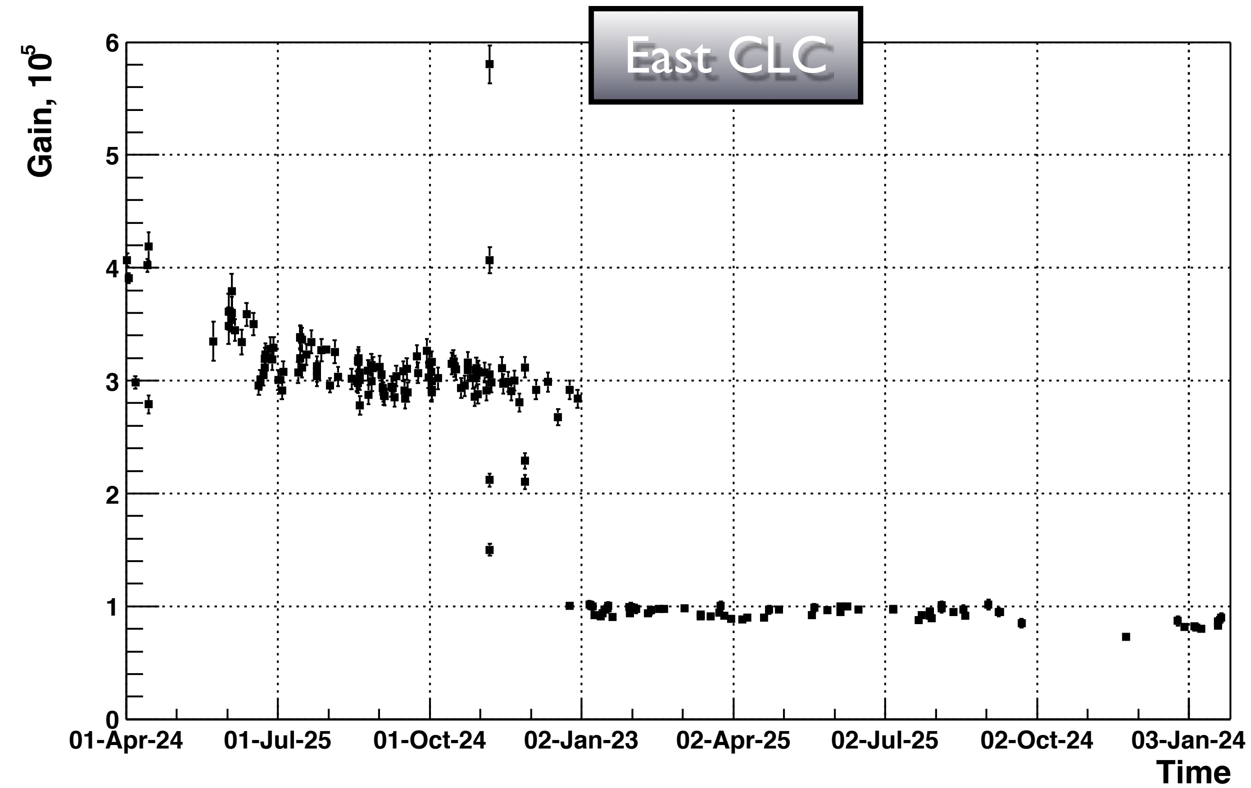
Overview of Operational Issues

- Keep CLC operational and on day-by-day basis provide precise luminosity measurements for physics and accelerator adjustments until the end of Tevatorn Run II (September 2011)
- Electronics failures
  - Transition Boards: 1/4 year (after modification adding protection to input amplifier)
  - ADMEMs: 1/2 year (FPGA code corruption, re-programmed on spot)
  - Coincidence Unit: 1/2 year (FPGA code corruption, re-programmed on spot)
  - Stretches: 1 failure
  - CAEN HV power supplies: 1 year (various problems)
- Gas leaks
  - West CLC module leaks Isobutane 0.1 psi/day. Does not leak when filled with Nitrogen.
- Helium contamination of PMTs
- PMT HV bases failures

Helium Contamination of PMTs

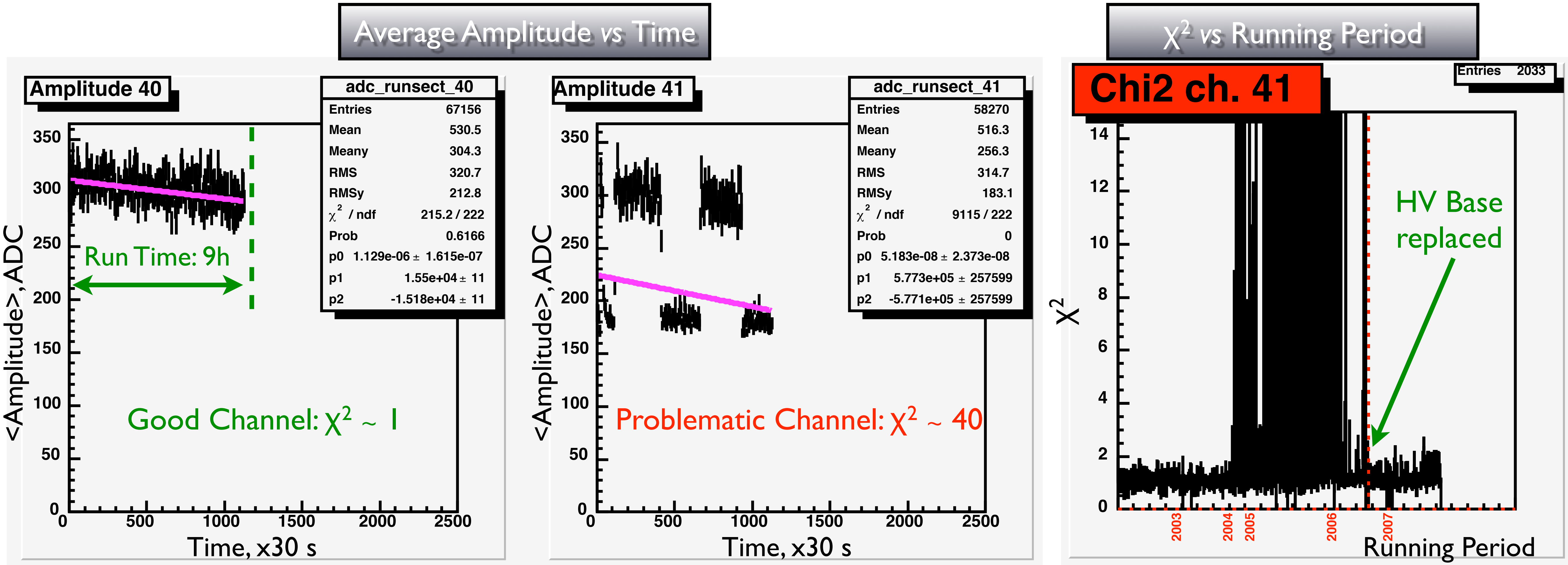
- Very quick gain deterioration of PMTs in the West CLC (x200 faster than expected)
- Checked and excluded various possible effects: HV power supplies/electronics/ magnetic field/environment *etc*
- Large after-pulses in PMT signal (>20%, ~350 ns after main signal) - indication of excessive number of ions inside PMT
- Destructive test of PMTs at Hamamatsu found Helium inside PMTs
- Test of Isobutane samples: found large amount of Helium. Isobutane was the source of contamination
- Switched Isobutane supplier, tested samples of every new bottle, implemented new very strict procedure of refilling CLC
- Replaced PMT in the detector, keep spare in a "vacuum" storage





PMT HV Base Failures

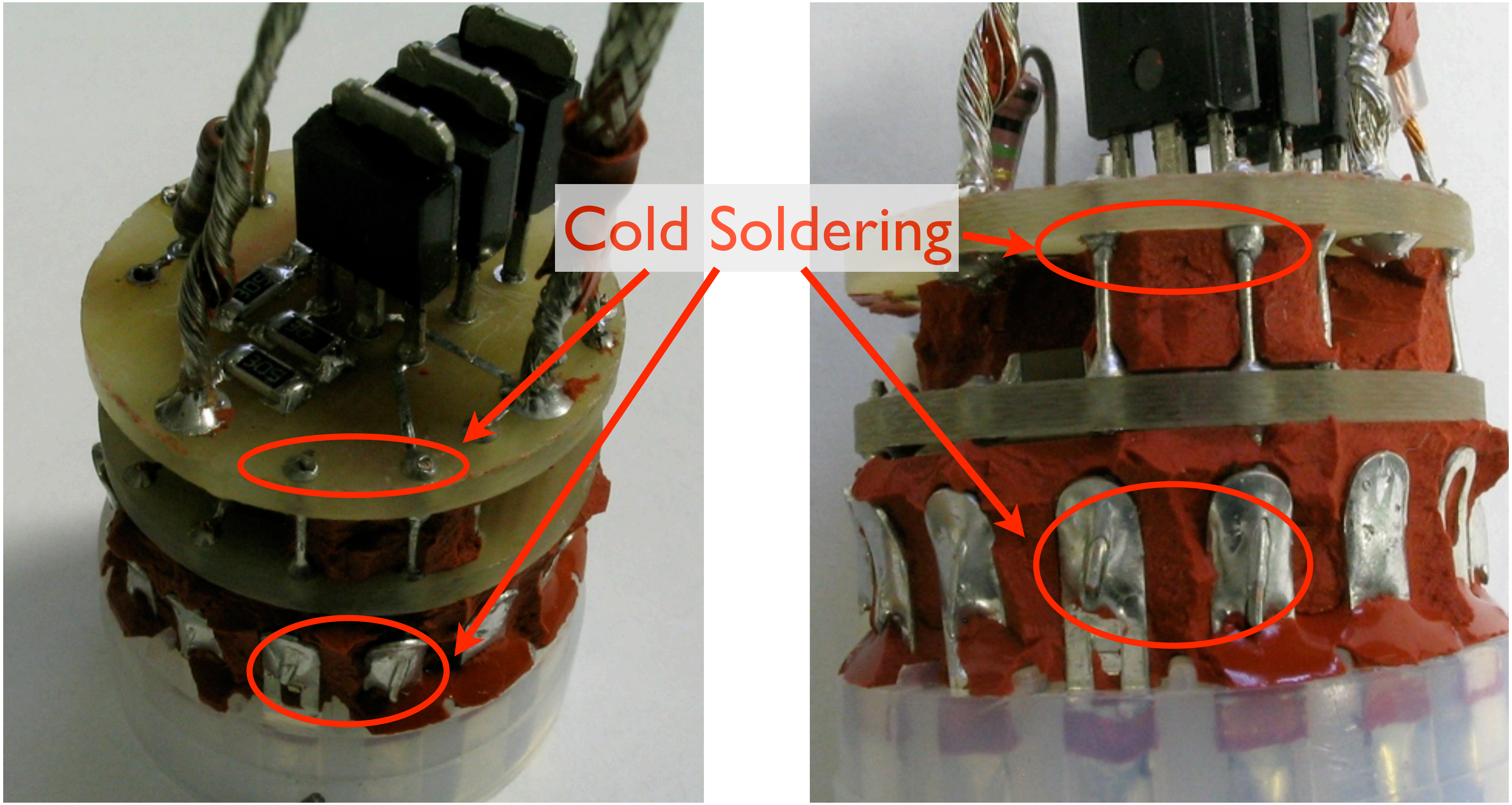
- Small (~1%) but unexpected instability in instantaneous luminosity measurements
- Traced down to amplitude instability in some channels



- Checked and excluded effects from readout electronics, HV power supplies, HV distribution board on the detector (patch panel)
- Were not able to reproduce problem in test stand
- Suspected PMT HV bases

PMT HV Base Failures

- Found cold soldering in HV bases in problematic channels



- Replaced problematic bases

Summary

- CDF Cherenkov Luminosity Counters is robust, capable instrument for precise luminosity measurements at Tevatron
  - *in situ* calibration from data allows to correct for various instability effects on store by store basis
- CLC performance is great at luminosities up to 400 $\cdot 10^{30}$ cm^{-2}s^{-1} with uncertainty of 4.5% [$\oplus$ 4% from σ_{in} uncertainty, 6% total uncertainty]
- Longevity is not an issue: with PMT replacement / gain adjustment it will stay in operation until end of Run II
- Excellent contribution to Physics results from CDF!

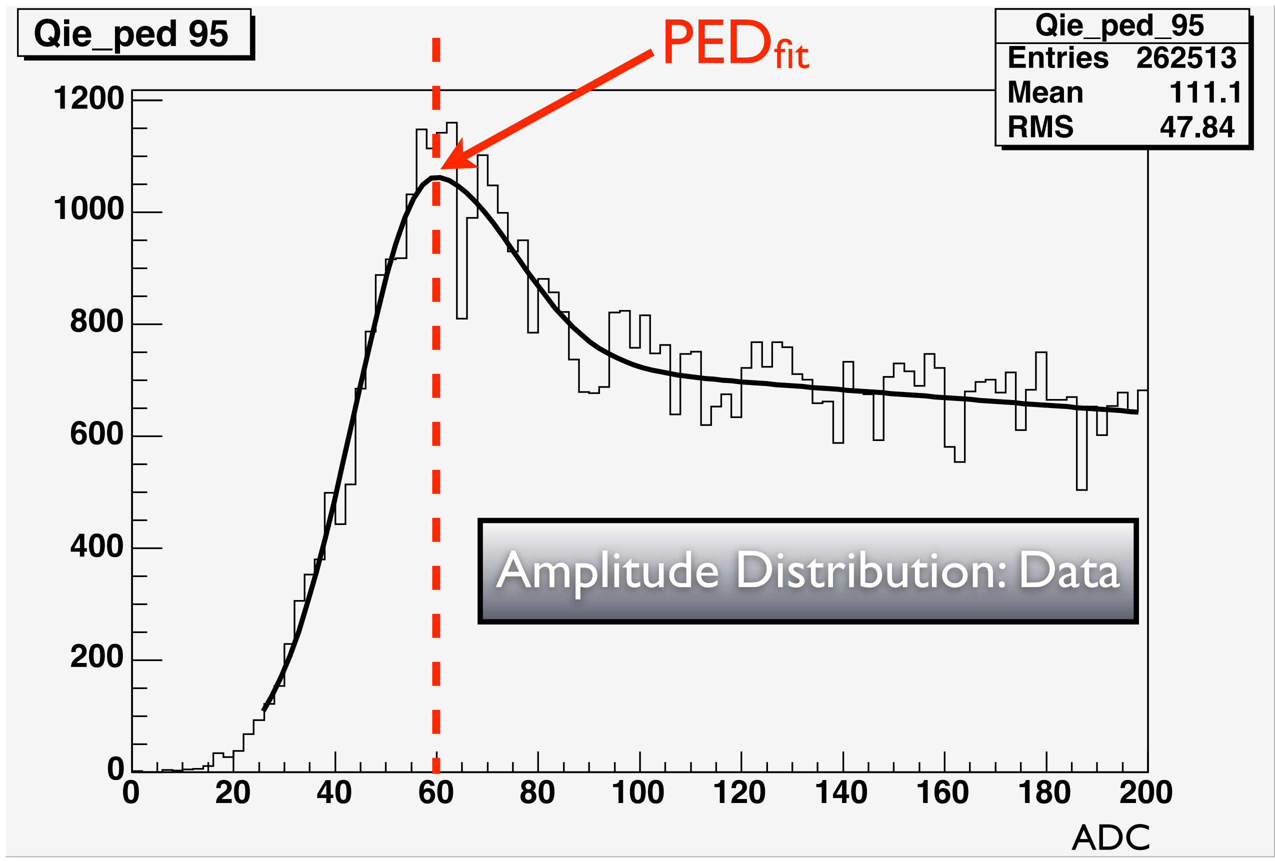
Backup Slides

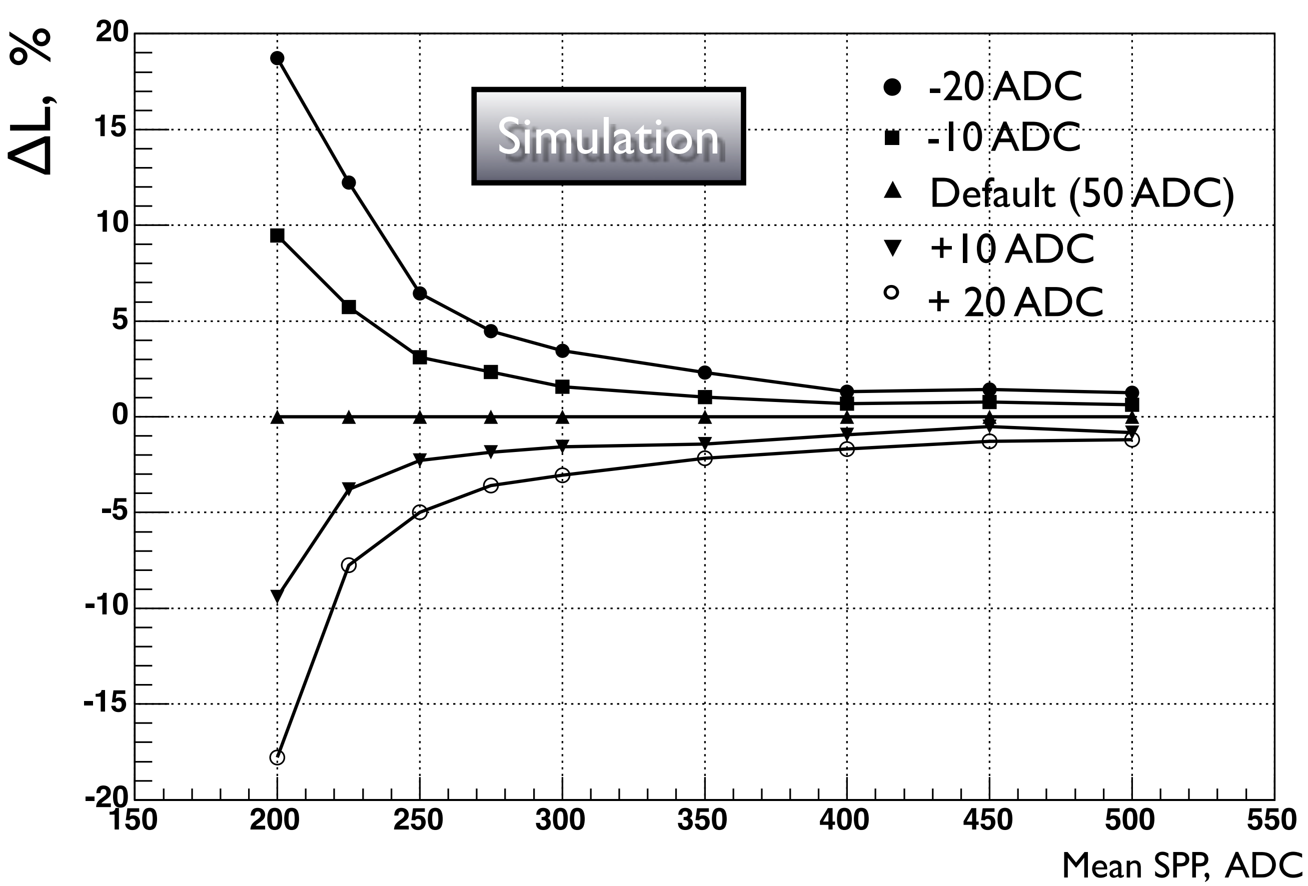
Pedestal Effect on Luminosity Measurement

- SPP_{fit} and PED_{fit} are obtained from data
- Acceptances are calculated using Monte-Carlo simulation
- SPP are corrected for pedestal and then we add default constant term of 50 ADC:

$$SPP_{acc} = SPP_{fit} - PED_{fit} + 50$$

- Method is fine for PMTs working at high gain. As PMTs age and gain drops, effect of deviation of pedestals from default value become more evident

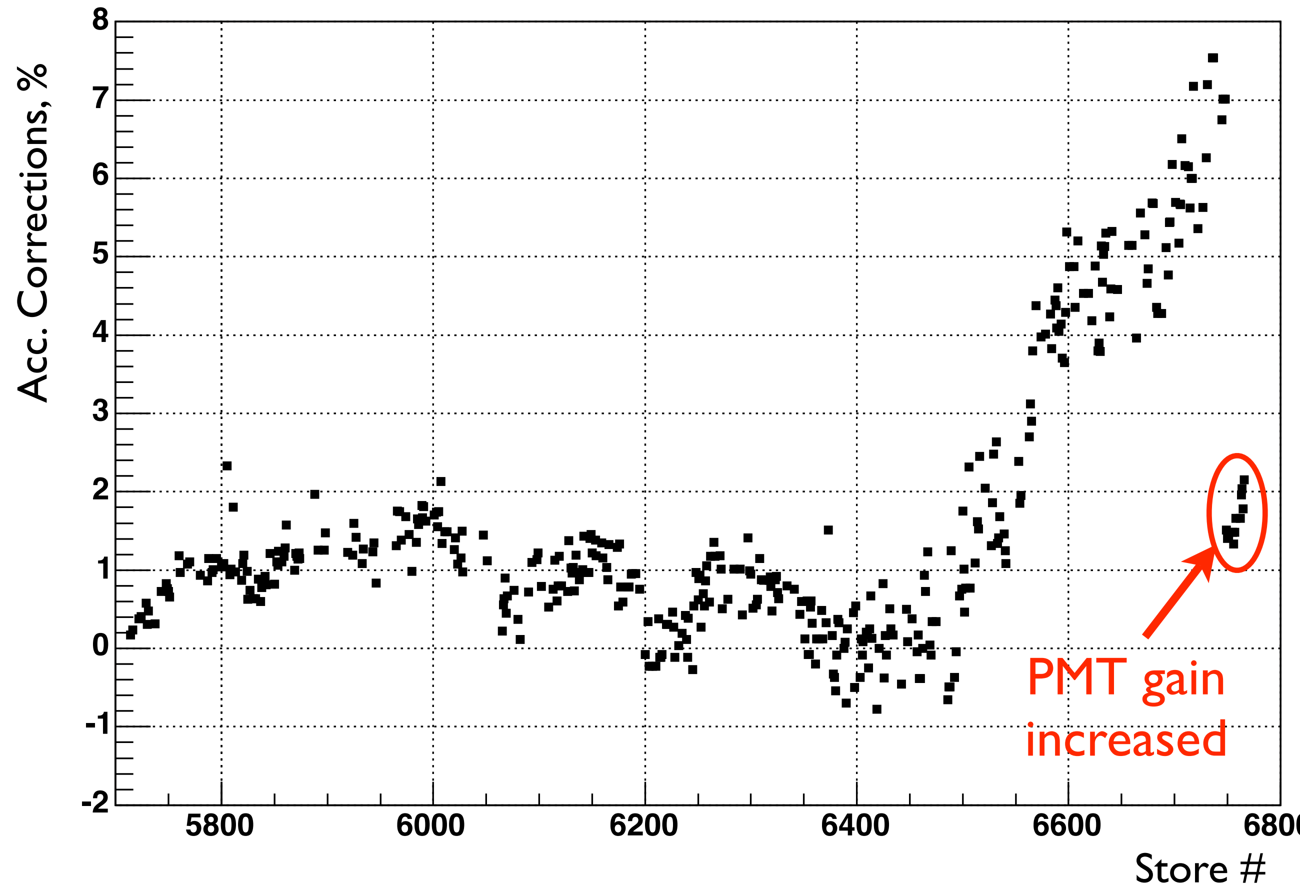


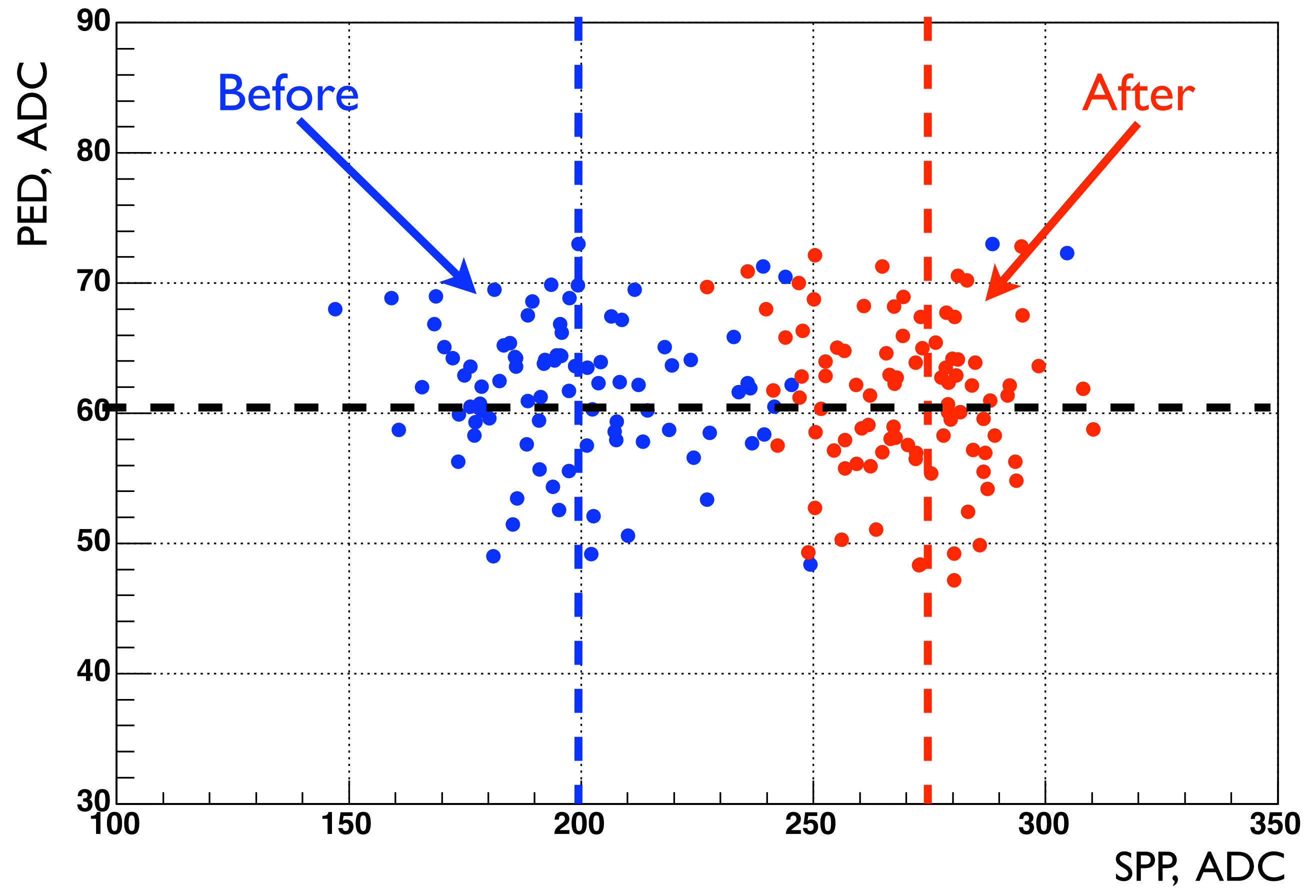


Easily fixed by offline corrections

Recent Pedestal Effect on Luminosity Measurement

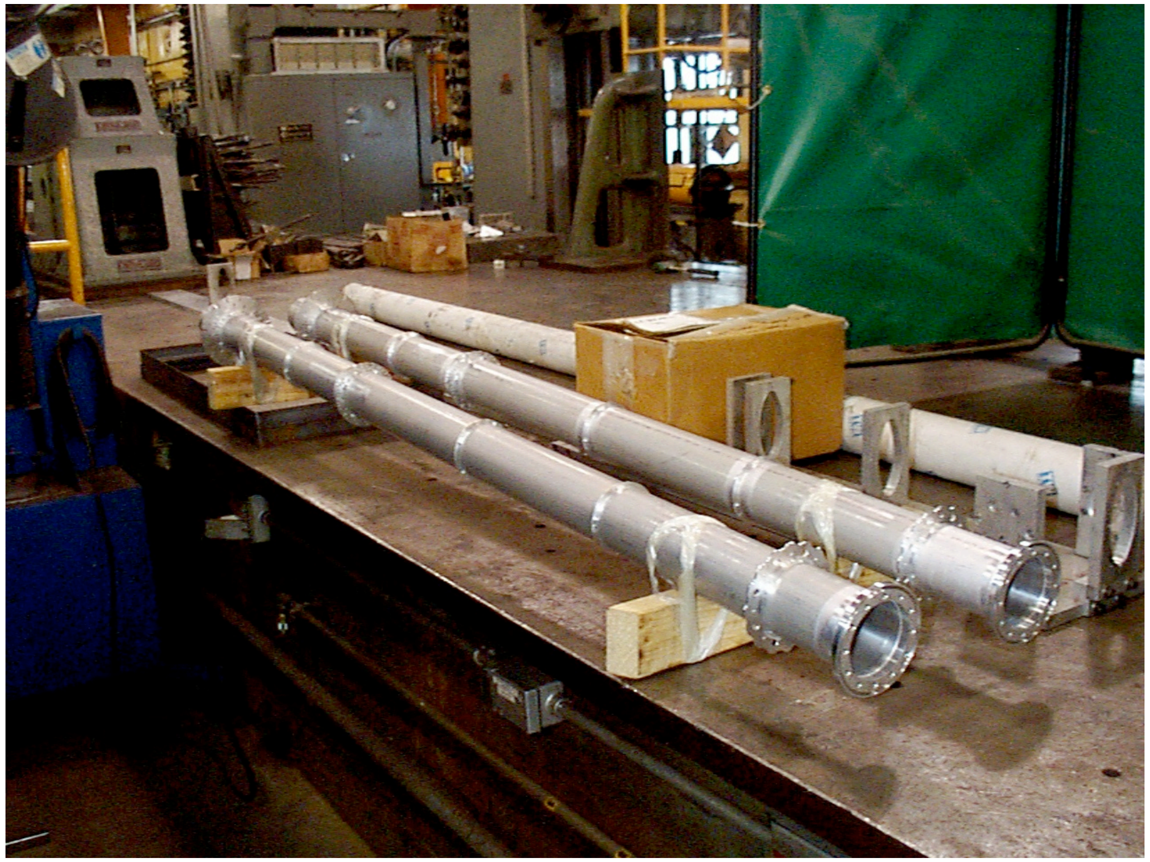
- After October 2008 shutdown gain of our PMTs reached critical region and we begun gradually underestimate acceptance due to pedestal shift effect
- It is directly translated into Luminosity overestimation
- Increased PMT gain beginning Store 6749: reduced pedestal effect to 1.5-2%
    - We will use real pedestal values for *online* acceptances calculation: further eliminates these 1.5-2%

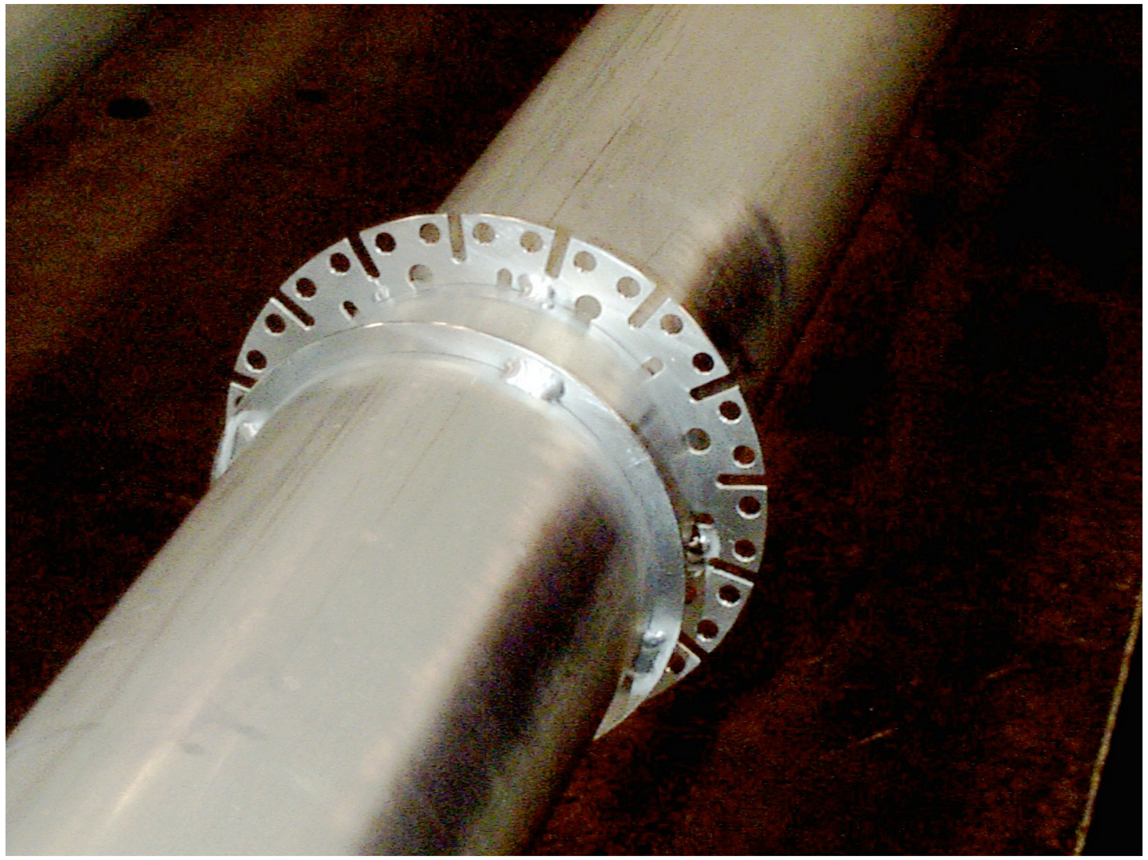


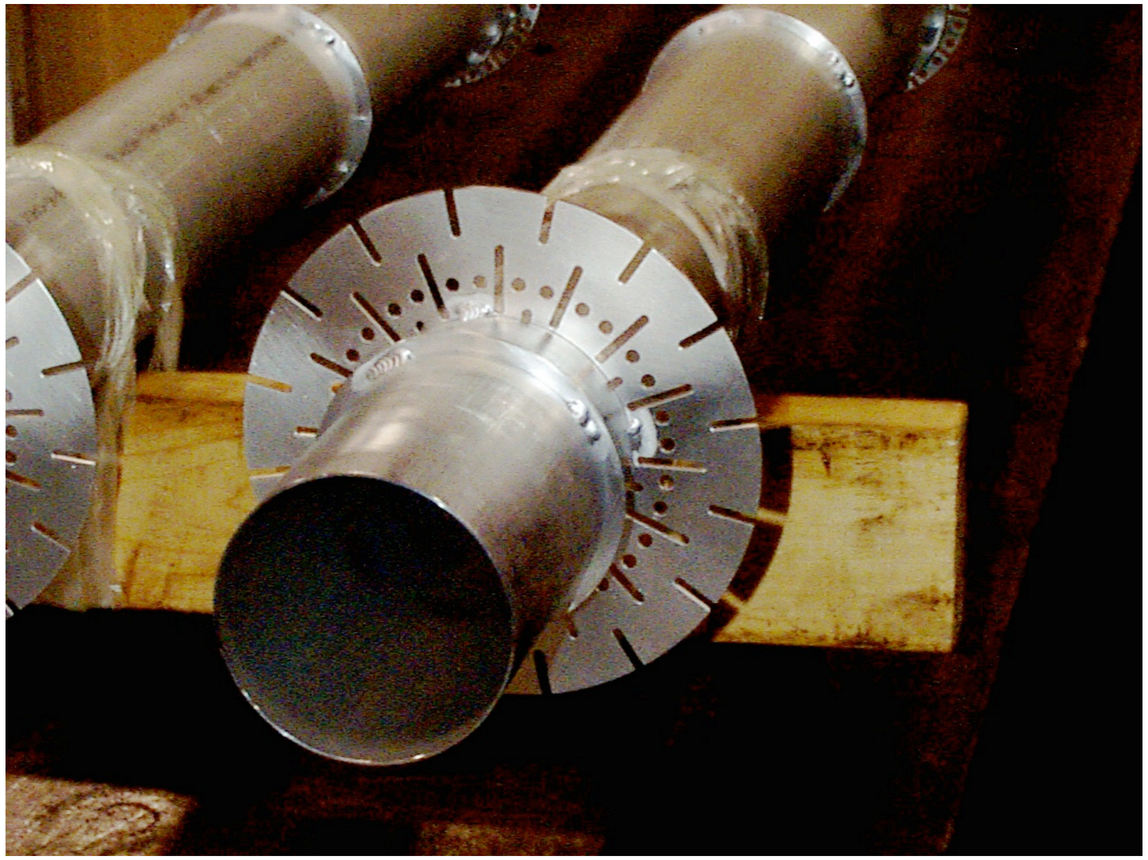


Pedestal effect is easily taken into account by offline corrections: Physics will not be affected

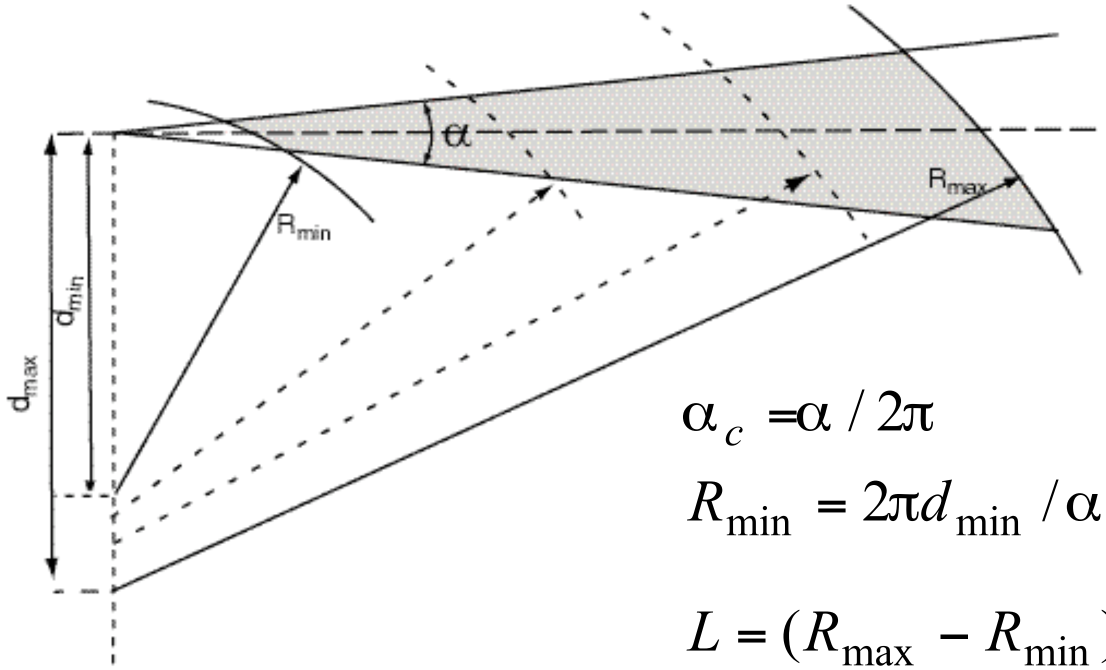
CLC Support Cylinder







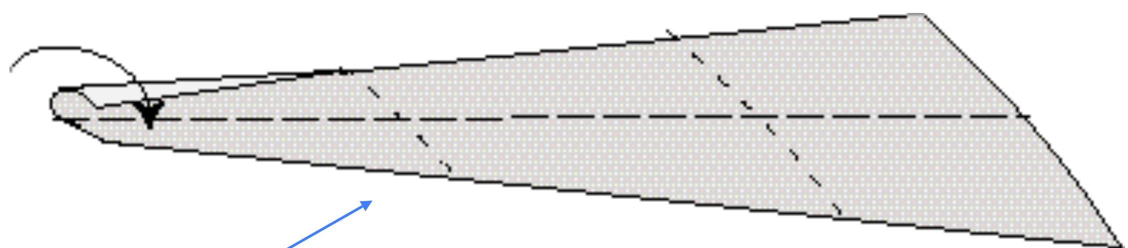
Aluminized Mylar Cones



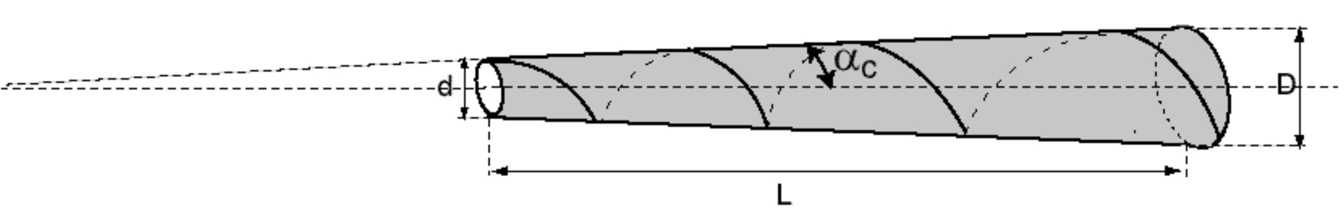
$$\alpha_c = \alpha / 2\pi$$

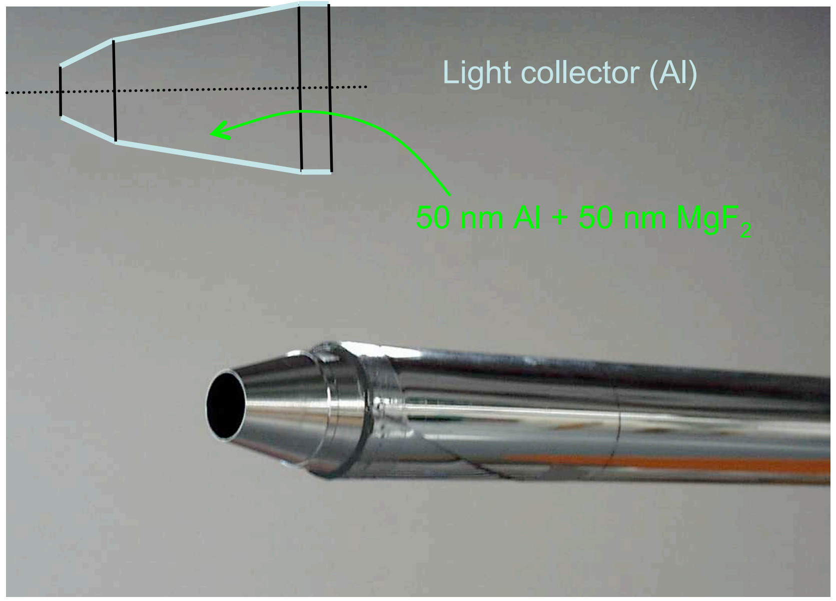
$$R_{min} = 2\pi d_{min} / \alpha$$

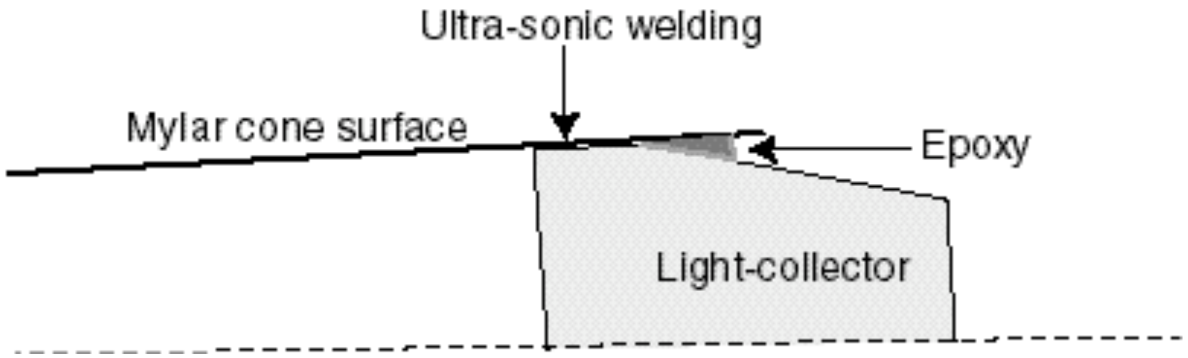
$$L = (R_{max} - R_{min}) \cos \frac{\alpha_c}{2}$$

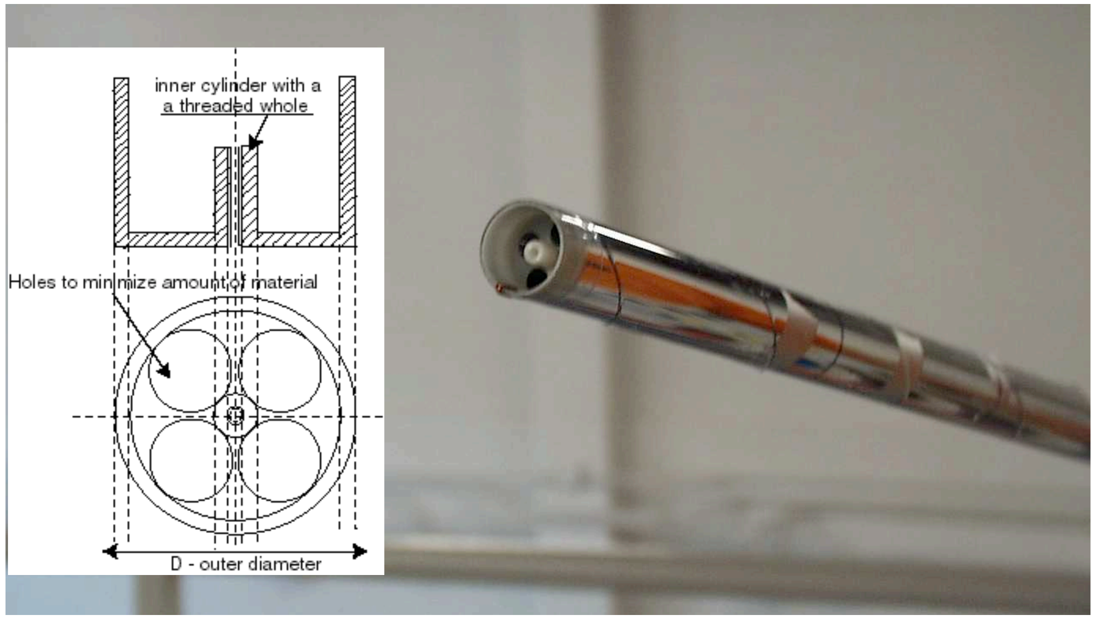


2 layers; 0.1 mm each; 60 nm Al coating



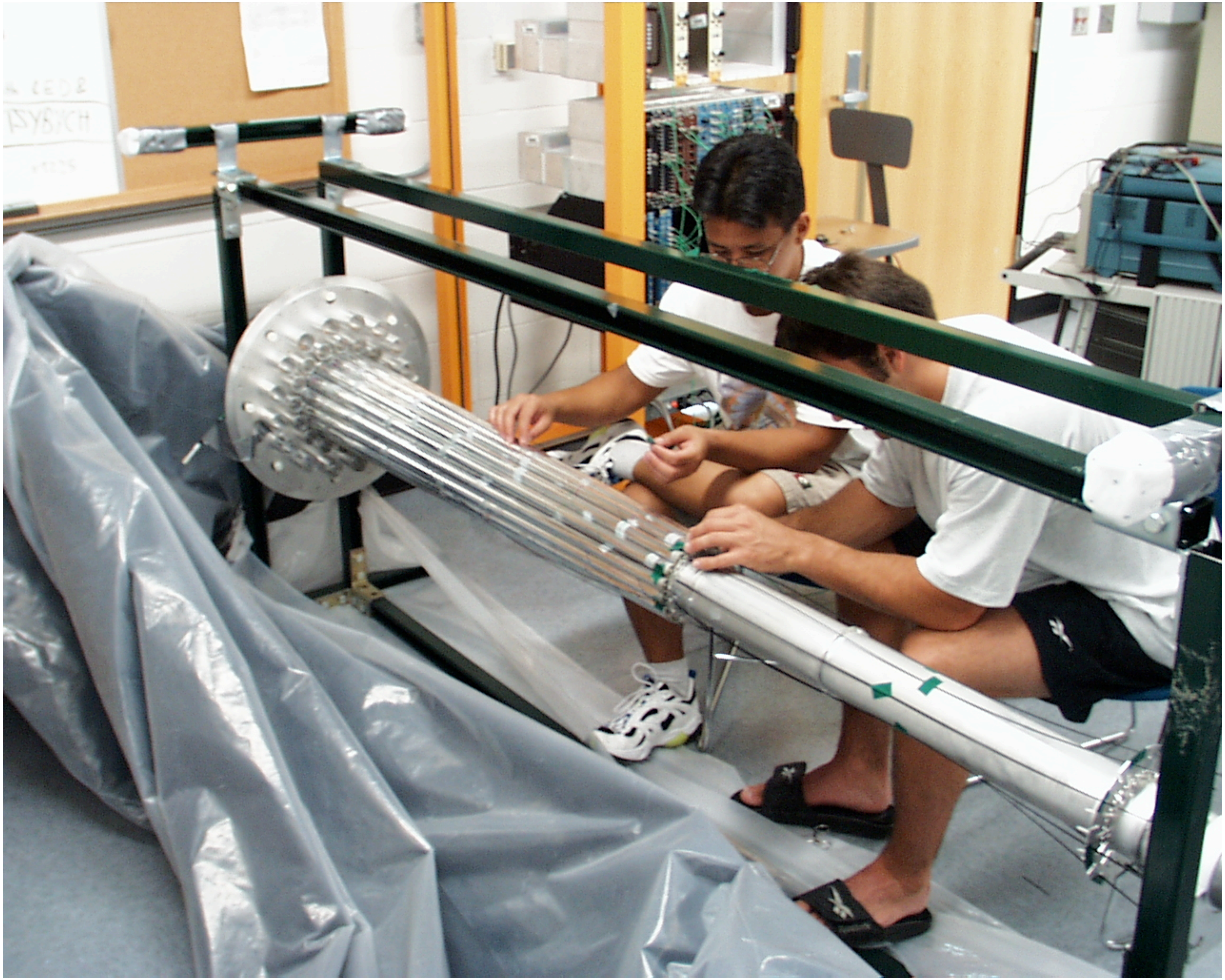




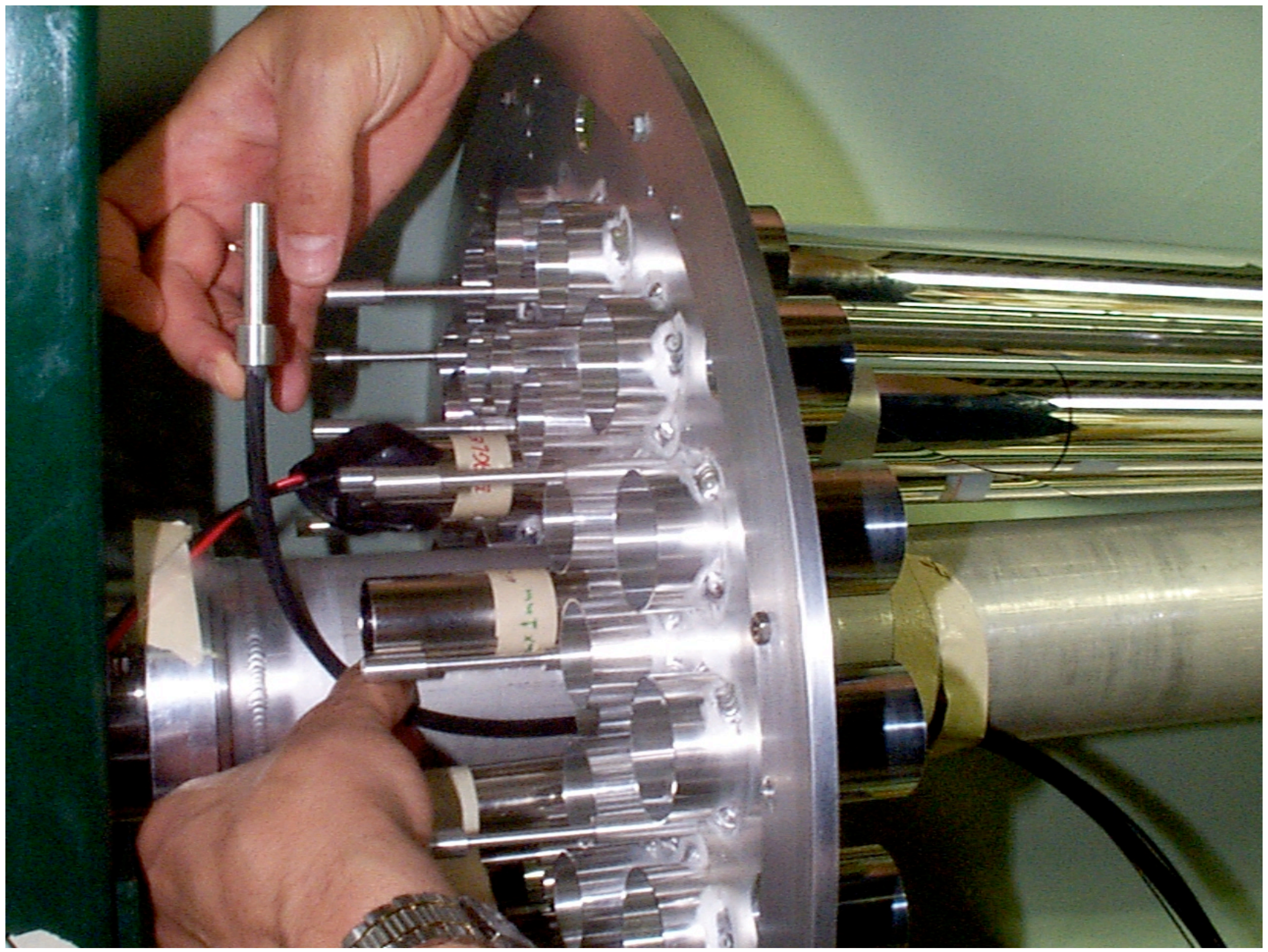


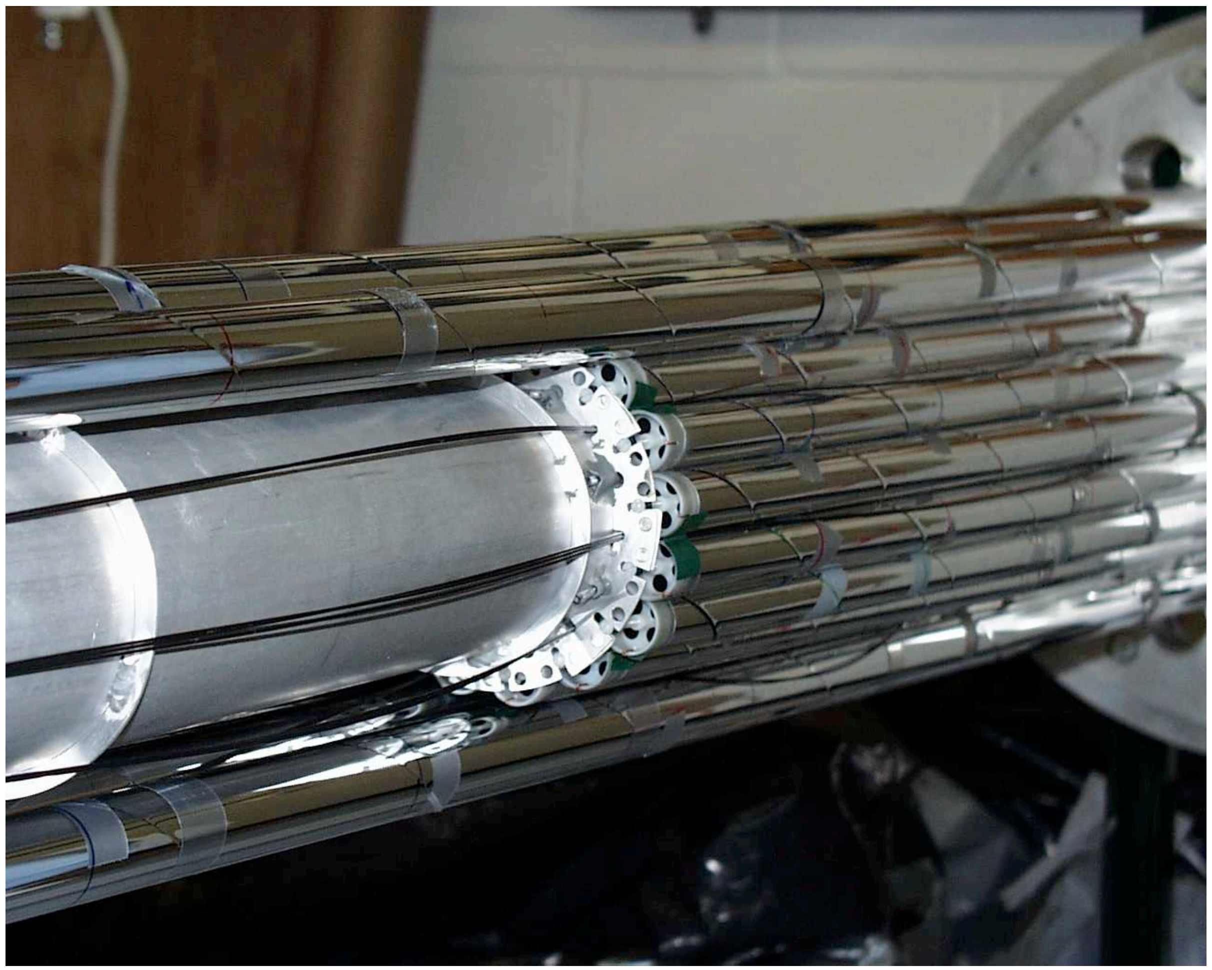
Outer Layer Cone and Light Collector

Inner Structure Assembly (at UF)

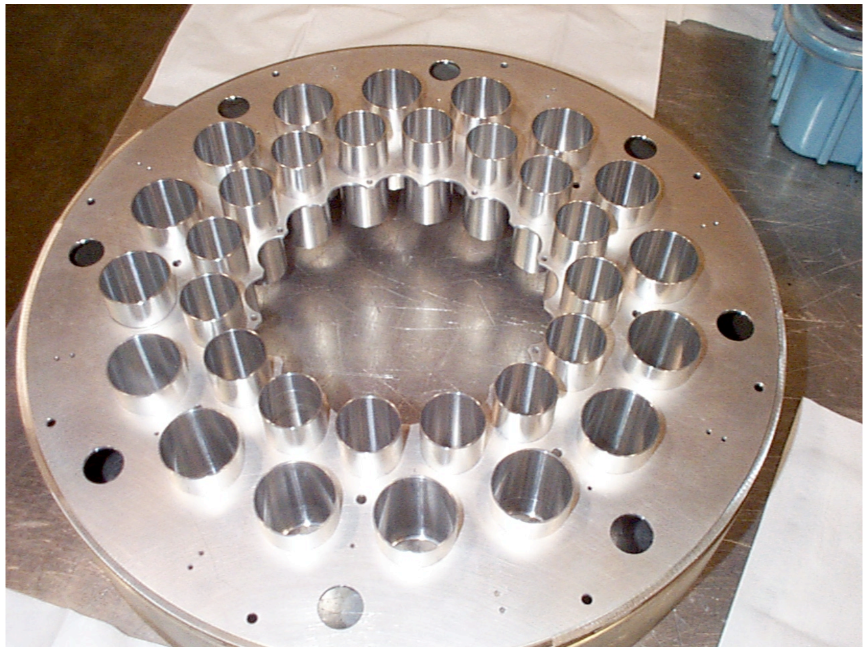


Quartz Fiber Bundles: LED Calibration System





CLC Modules



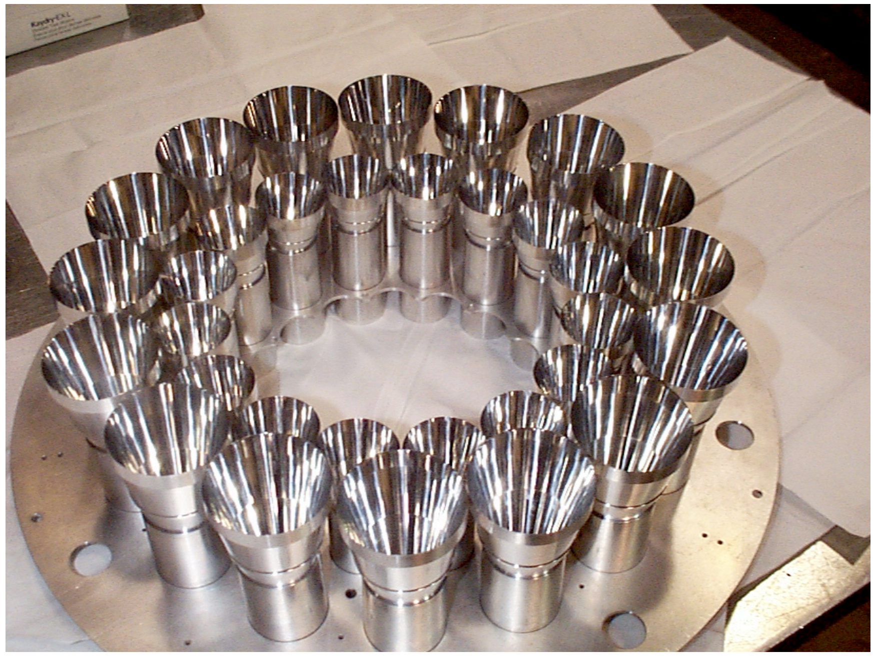
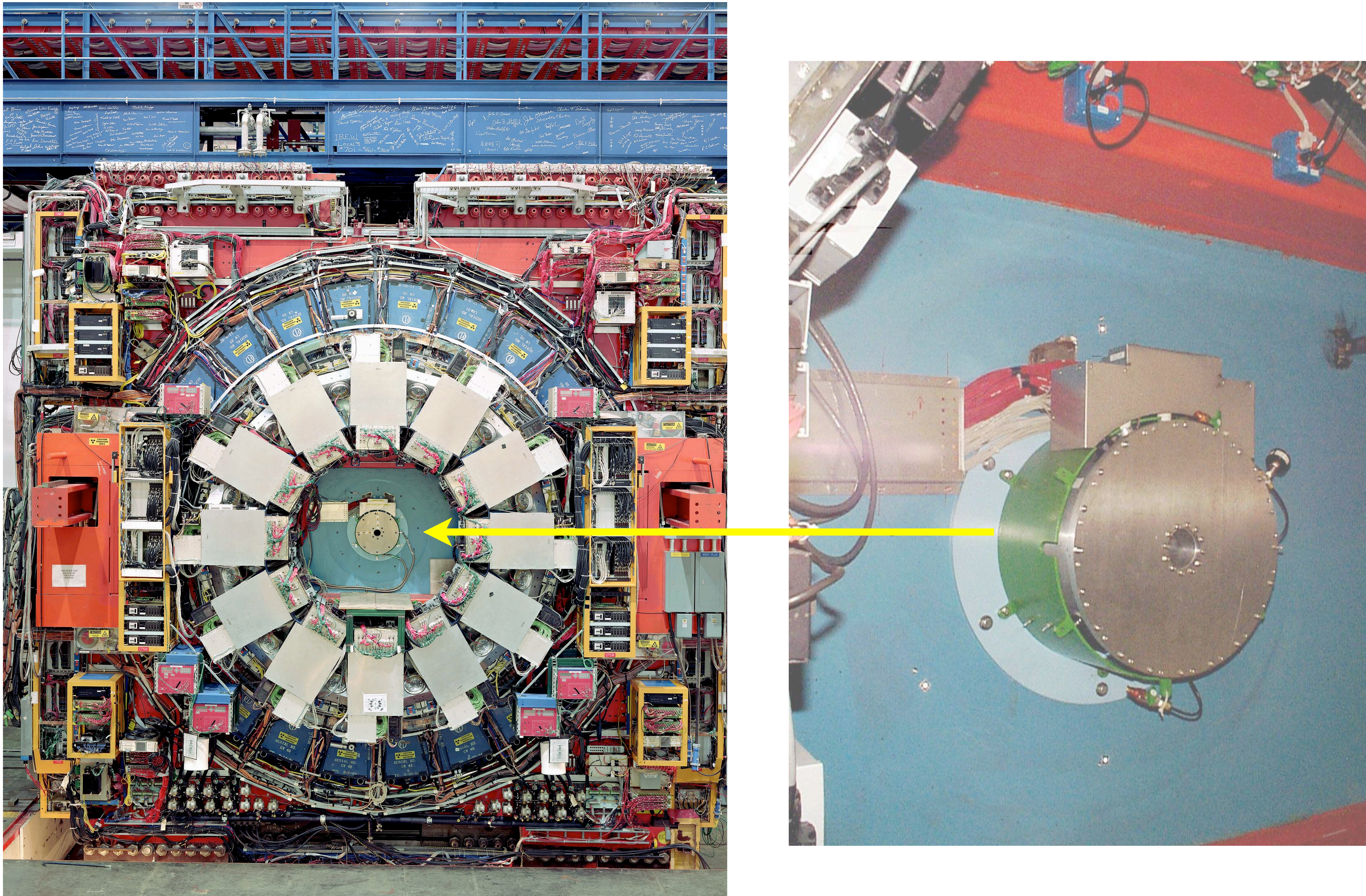


Photo-multiplier Tubes Assembly

Installed in CDF



Complete Modules