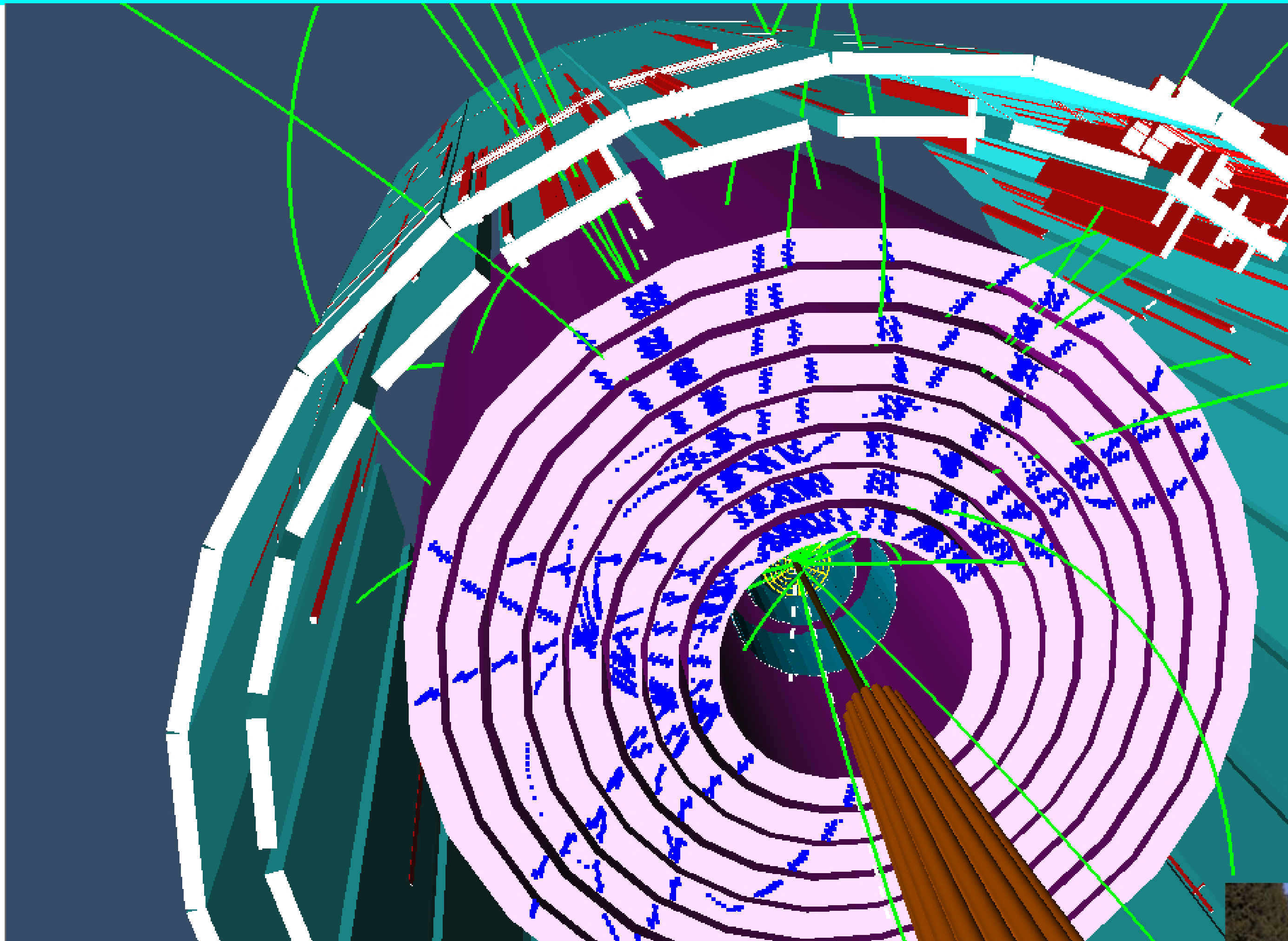
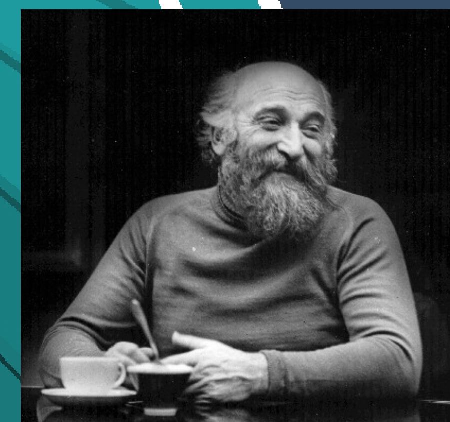
# Luminosity measurements at Hadron Colliders





**Vaia Papadimitriou, Fermilab**

*Xth Intl. Instrumentation Conference*

**Budker Institute, Novosibirsk**

**February 29, 2008**

# OUTLINE

- Motivation for Luminosity measurements

- Tevatron
  - *CDF*
  - *D0*

- HERA
  - *H1*
  - *ZEUS*

(Tevatron, HERA:)
- ✓ Technique
- ✓ Uncertainty
- ✓ Challenges
- ✓ Lessons learned

- LHC
  - *Accelerator*
  - *ATLAS*
  - *CMS*
  - *(ALICE, LHCb)*

(LHC:)
- ✓ Technique
- ✓ Expected Uncertainty
- ✓ Challenges

- Conclusion

# Motivation for Luminosity Measurements

$$L = \frac{N}{\sigma}$$

- **Cross sections for Standard Model and beyond the Standard Model processes and for New Physics.**
  - **W/Z production**
  - $t\bar{t}$ **production**
  - **Higgs production**
  - **Beauty, Charm production, …………………..**

- **Monitor the performance of the accelerator and implement adjustments as needed.**

- **Provide with the bunch by bunch luminosity measurements useful diagnostics for the accelerator as well as for the modeling of underlying event backgrounds.**

# The Tevatron

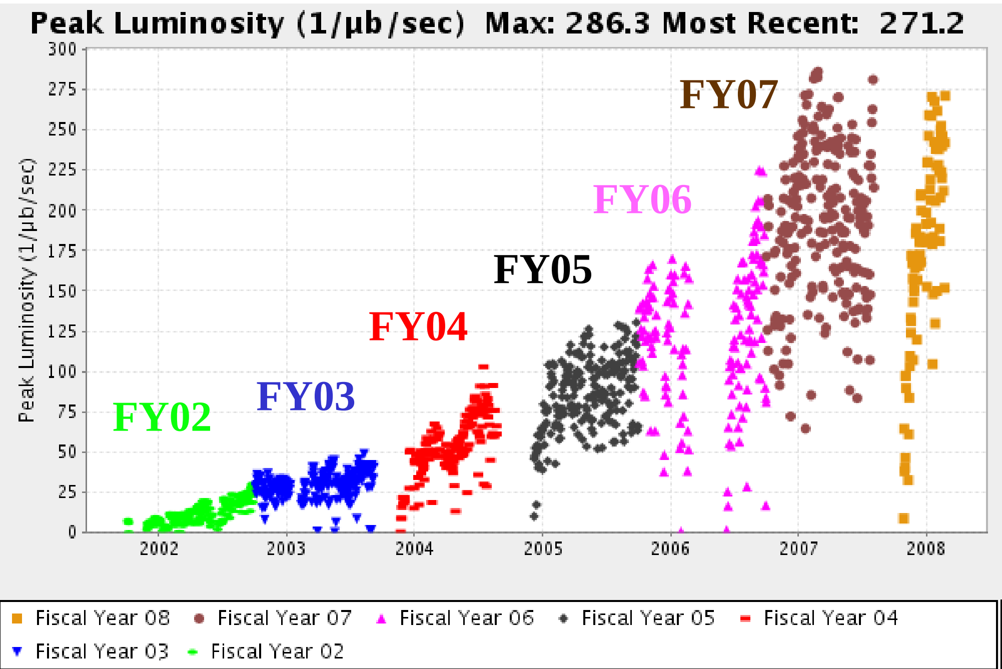
# Tevatron Performance

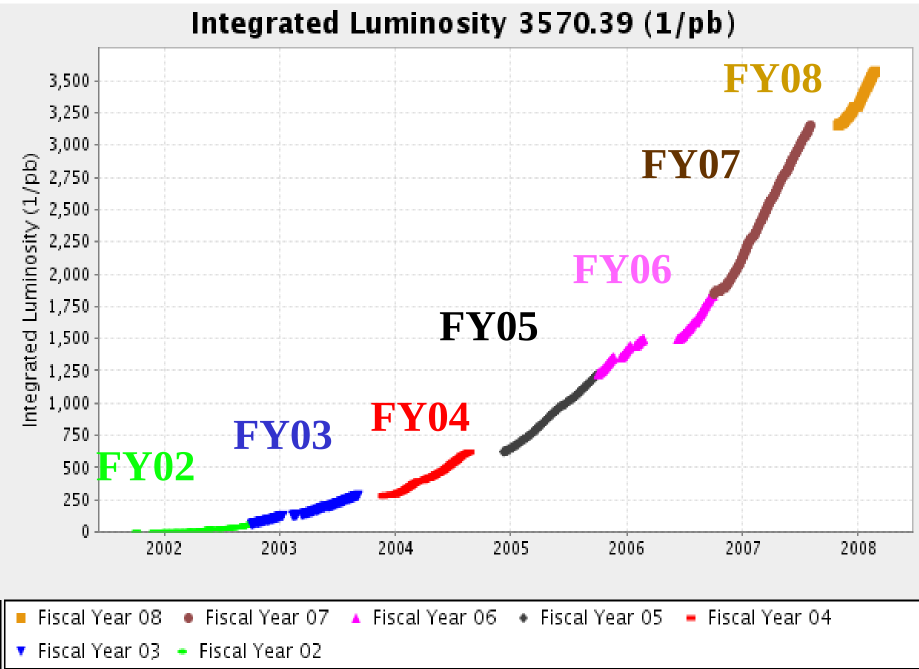
- Tevatron (Run I 1992-96, $\int \mathcal{L}\, dt$ = 110 $pb^{-1}$):
  - *p → ← pbar at* $\sqrt{s}$ *= 1.8 TeV, 3.5 μs between collisions, 6 x 6 bunches*
- Tevatron (Run II 2002-Present, $\int \mathcal{L}\, dt$ = ~3.57 $fb^{-1}$):
  - *p → ← pbar at* $\sqrt{s}$ *= 1.96 TeV, 396 ns between collisions, 36 x 36 bunches*

**( original plan for 132 ns )**

Best 2.86 x $10^{32}$ $cm^{-2}s^{-1}$

11.1 $pb^{-1}$ delivered per experiment in one store, July 31, 2007

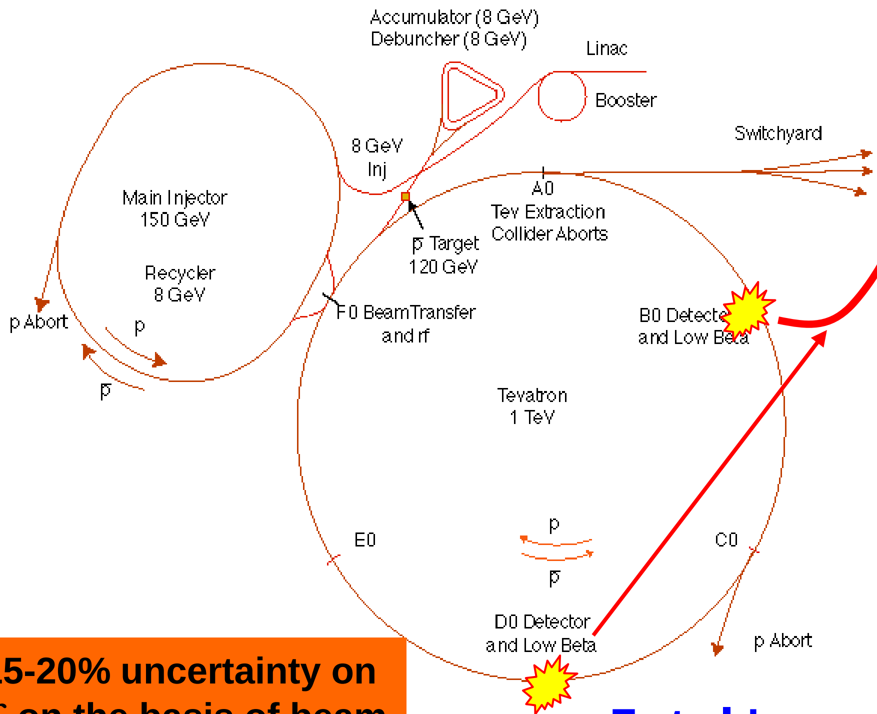


# Collider Beam Luminosity

$$n(\text{top events}) = \sigma(p\bar{p} \to t\bar{t}) \cdot L \cdot \varepsilon$$

$$\varepsilon = \text{BR} \cdot \text{Acceptance} \cdot \text{Efficiency}$$




## Instantaneous Luminosity:

$$\mathcal{L} = \frac{N_p \cdot N_{\bar{p}} \cdot B \cdot f_0}{4\pi\sigma^2} \sim (2.5)\text{x}10^{32}\ \text{cm}^{-2}\text{s}^{-1}$$

(Run II) typical

- $\mathcal{N}_p = protons/bunch\,(\sim 2.5 \cdot 10^{11})$
- $N_{\bar{p}} = anti\text{-}protons/bunch\,(\sim 7 \cdot 10^{10})$
- $B = number\ of\ bunches\ in\ ring\ (36)$
- $f_0 = 48\ kHz\ (396\ nsec\ bunch\ spacing)$
- $\sigma \sim 30 \cdot 10^{-4}\ cm$

**15-20% uncertainty on $\mathcal{L}$ on the basis of beam parameters**

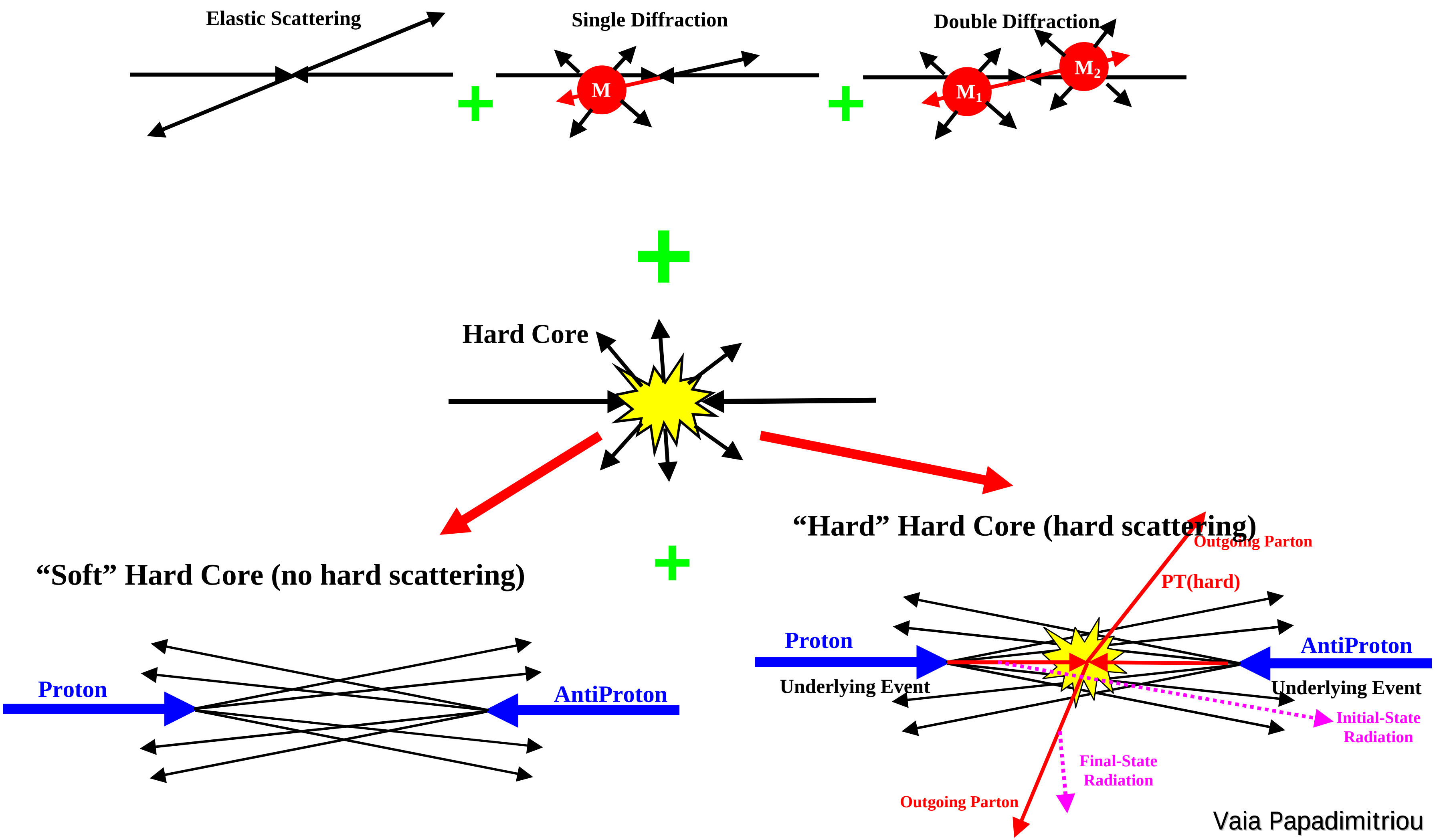
## Total Lum: $L = \int \mathcal{L} \cdot dt \sim 6 - 7\ fb^{-1}$ (Run II goal)

---

$$\mathcal{L} = \frac{N_p N_a}{4\pi\left(\varepsilon\beta^* + D^{*2}\sigma_\delta^2\right)} \cdot f \cdot H\left(\frac{\beta^*}{\sigma_z}\right) \to \mathcal{L} = N_p N_a \cdot f \cdot F\left(\varepsilon, \beta^*, D^*, D'^*, \sigma_z, \sigma_\delta, \theta\right)$$

$$F = \frac{1}{(2\pi)^{3/2}\sigma_z}\int ds \frac{1}{\sigma(s)^2}\frac{1}{\sqrt{2+\theta^2\left(\frac{\sigma(s)^2}{2\sigma_z^2}-1\right)}} \times \exp\left(-\frac{s^2\frac{2\sigma(s)^2}{\sigma_z^2}+\theta^2 s^2\left(\frac{1}{2}-\frac{\sigma(s)^2}{4\sigma_z^2}\right)}{2\sigma(s)^2+\theta^2\sigma(s)^2\left(\frac{\sigma(s)^2}{2\sigma_z^2}-1\right)}\right)$$

# The total p-pbar cross-section

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# P-pbar cross-sections

| Process (mb) | CDF meas. @ 1.8 TeV | E811 Exp. |
|---|---|---|
| $\sigma_{tot}$ | 80.03 (2.24) | 71.71 (2.02) |
| $\sigma_{el}$ | 19.70 (0.85) | 15.79 (0.87) |
| $\sigma_{in}$ | 60.33 (1.40) 2% | 55.92 (1.19) 2% |
| $\sigma_{hc}$ | [45] | |
| $\sigma_{sd}$ | 9.46 (0.44) | 8.1 (1.7) E710 |
| $\sigma_{dd}$ | 6.32 (1.70) | |

8% (difference between CDF and E811 $\sigma_{in}$)

**Average the inelastic cross sections measured by the CDF and E811 experiments and extrapolate at 1.96 TeV:**
**60.7 ± 2.4 mb**

**Fermilab-FN-0741**

# Techniques for Luminosity measurements

- **Use a relatively well known, copious, process:**
  - ***Inclusive inelastic p-pbar cross-section***
    - large acceptance at small angles

$$\mu \cdot f = \sigma_{in} \cdot \mathcal{L}$$

- μ = avg. # of interactions/b.c.
- $f$ = frequency of bunch crossings
- $\sigma_{in}$ = tot inelastic cross-section
- $\mathcal{L}$ = inst. luminosity

- **Use dedicated detector:**

$$\tilde{\mu}_{\alpha} \cdot f_{BC} = \sigma_{in} \cdot \varepsilon_{\alpha}^{\det} \cdot \mathcal{L}$$

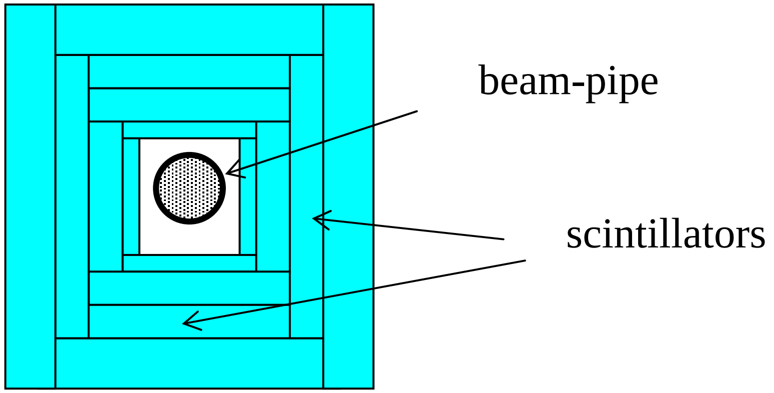
- **Use a good estimator for μ**
  - ***Measure the fraction of bunch crossings with no p-pbar interactions***
    - Use: $P_0(\mu) = e^{-\mu}$ prob. of no int.
  - ***Direct counting # of p-pbar interactions***
    - Counting particles
    - Hits
    - Counting time clusters
- **Cross-calibrate with rarer, clean, better understood processes:**

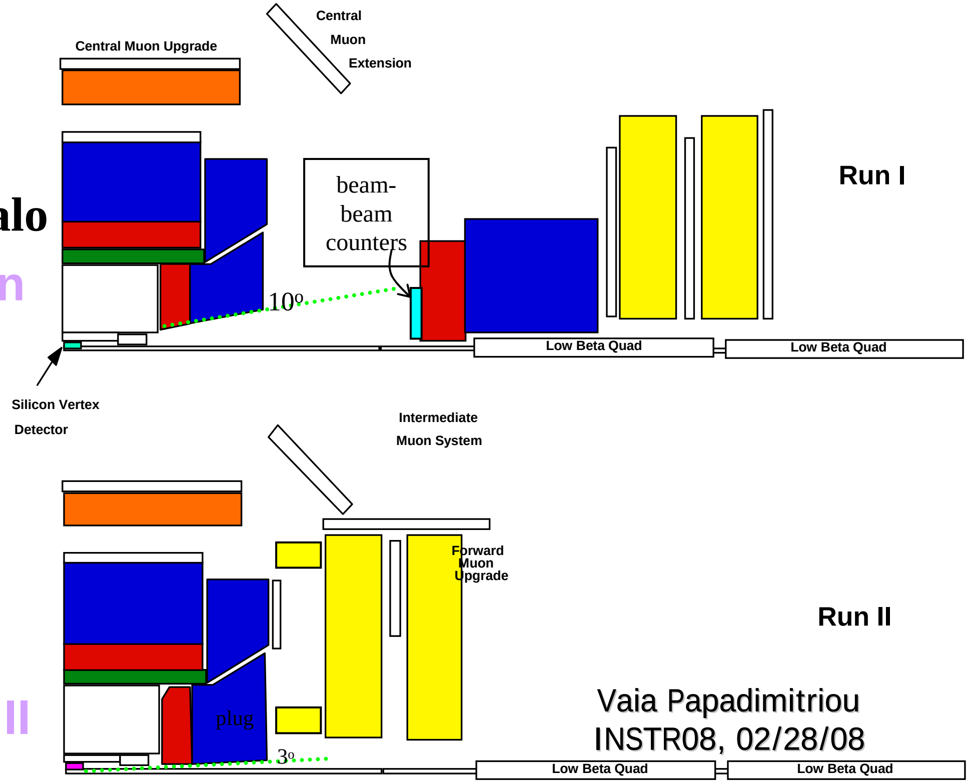
$$W \rightarrow lepton, \nu$$

- ***Need full understanding of tracking, particle-id, missing-Et, trigger, NLO, backgrounds, etc.***
- Useful for integrated lum abs. normalization

# Scintillating counters for Luminosity

- **Beam-Beam Counters – used in CDF for Run I:**
  - Segmentation too small for high lum
    - 16 counters/side/2.6 units of rapidity
  - Count "yes" or "no"
  - Counting rate saturated already @ 1.8 interactions/b.c.
  - Sensitive to all particles
  - Rate heavily dominated by secondaries
    - Calorimeter, beam-pipe, beam halo
  - CDF's 10-degree hole, 3-degrees in Run II
    - more backgrounds…
  - Performed simulations w/ more segmentation + telescopes
    - large systematics / random coincidences
  - Decided on a new device for Run II

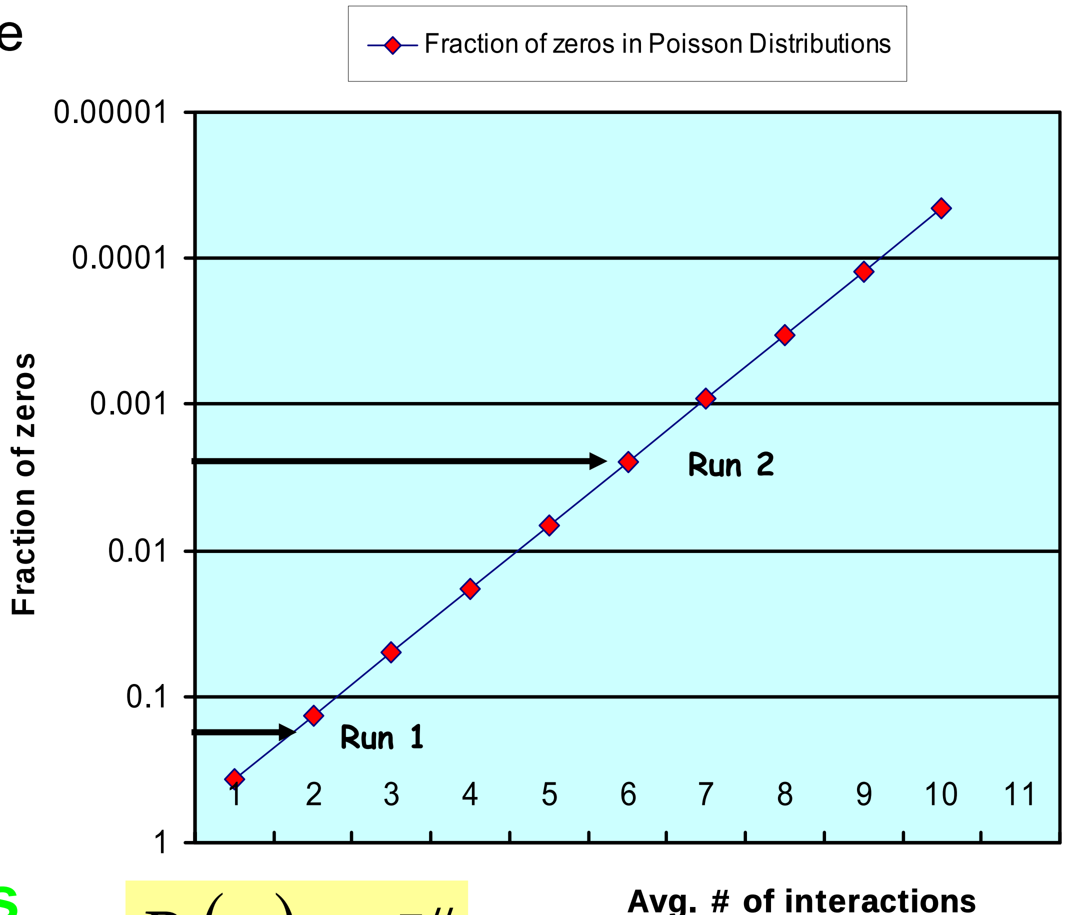


# Luminosity for Run II: try to measure μ directly

- Measuring "zeros" eliminates most of the dependence on the material model.
- At very high luminosities one may not be able to measure though rate (or "zeros") accurately enough.
- Fraction is 0.25% for 6 interactions on average.
- Systematics on acceptance only can make a precise measurement very difficult.

❖ **Try to measure the # of p-pbar interactions <u>directly</u> !**




$$P_0(\mu) = e^{-\mu}$$

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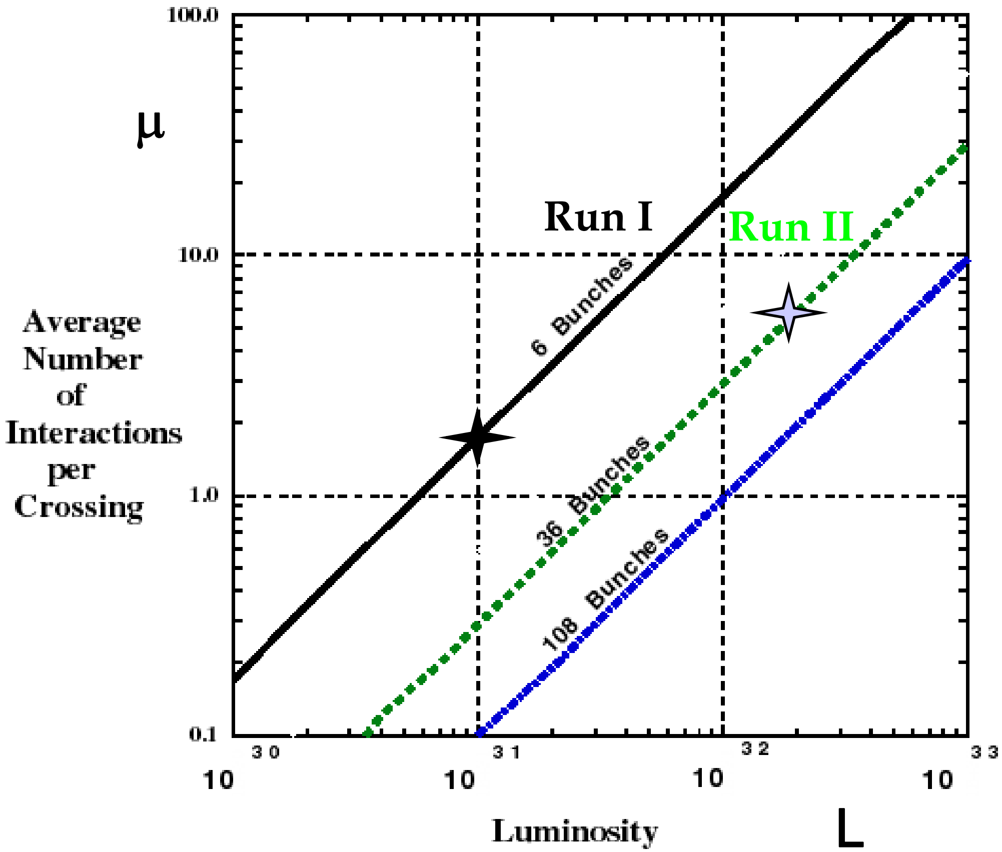
# Specifications for CDF Luminosity Detector in Run II

**Rate of $p\bar{p}$ interactions** $\dot{N}_{p\bar{p}} = \mu\, f_{BC} = \sigma_{in} L$

Operate at:

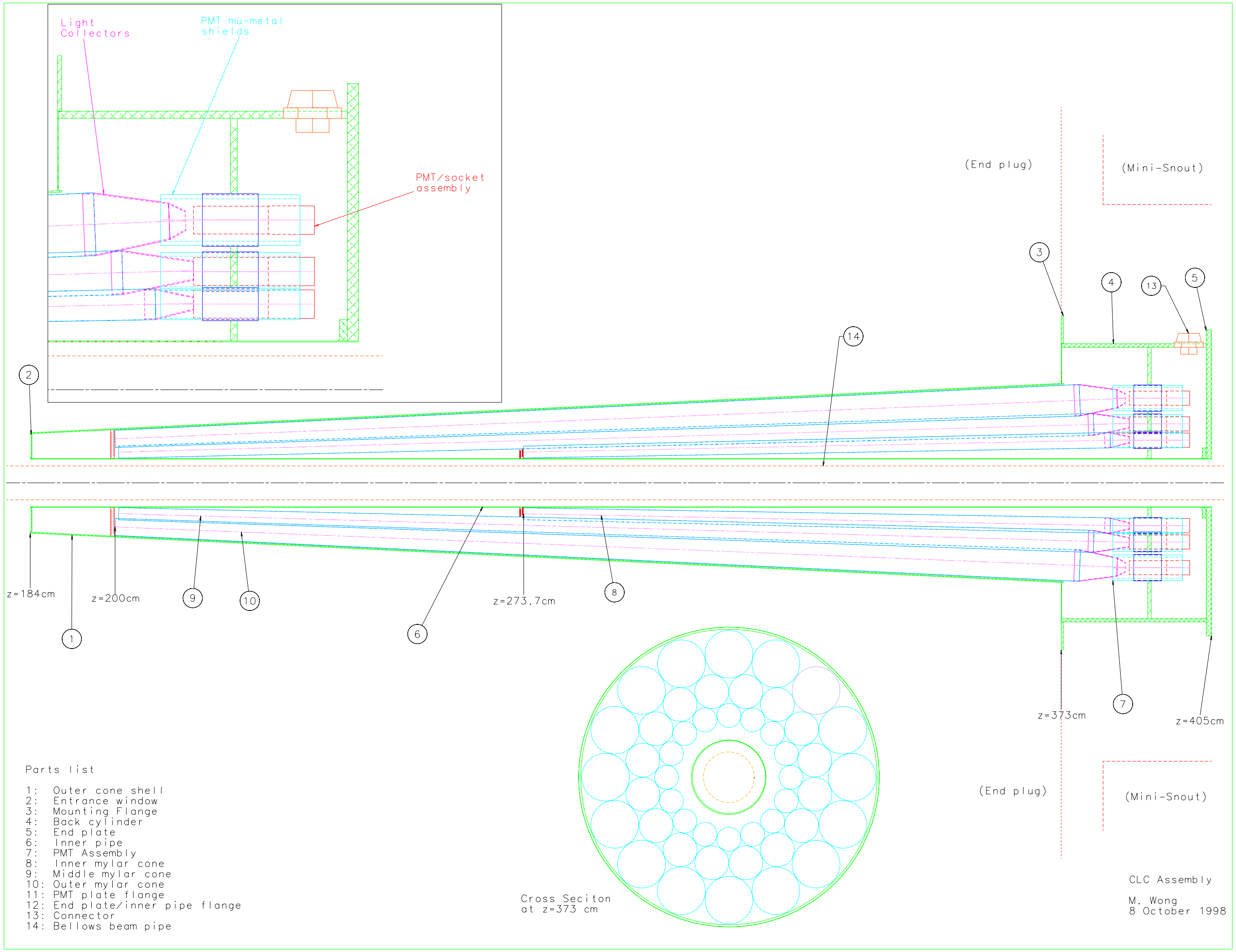
L ~2 (4) *$10^{32}$ cm$^{-2}$sec$^{-1}$ μ ~6 (10) ppbar/b.c.




- *Measure instantaneous and integrated luminosity for CDF and Tevatron*
  - in real-time (~ 1 Hz)
  - delivered and live luminosity
  - bunch by bunch luminosity
  - keep good precision at high luminosity: ( few %)
- *Measure z profile of collisions*
- *Provide a minimum bias trigger for CDF.*

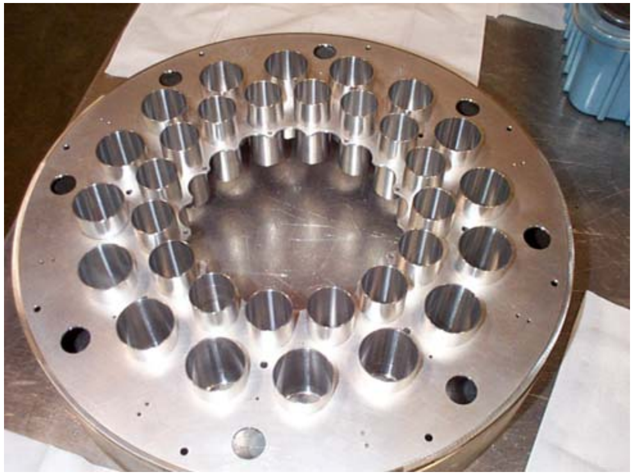
*Choice: Gas Cherenkov Counters*

# Cherenkov Luminosity Counters (CLC): Design

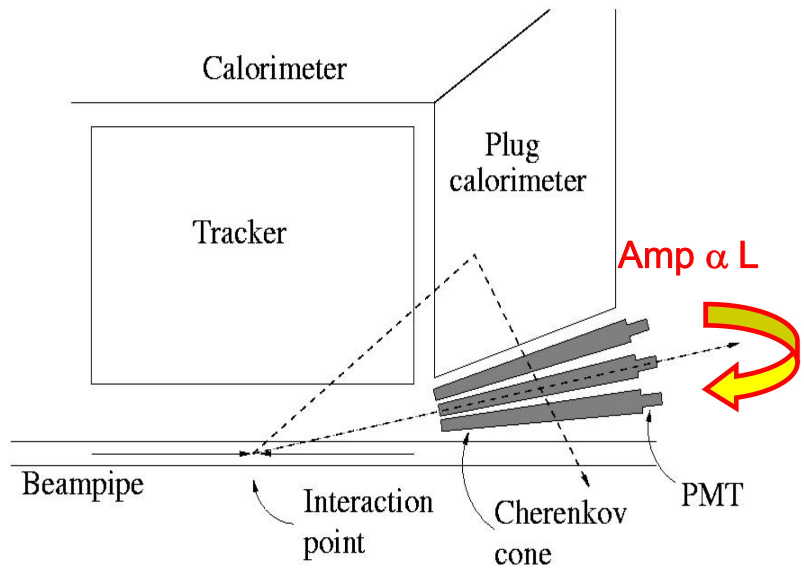



- **48 counters/side**
- **3 layers with 16 counters each**
- coverage: $3.7 \leq |\eta| \leq 4.7$
- **Isobutane pressure: up to 2atm**
  **$\eta = 1.000143$**
  **$\theta_C = 3.1^o$**
- **PMT: Hamamatsu R5800Q CC with quartz window, gain $10^5$**

# The CLC modules

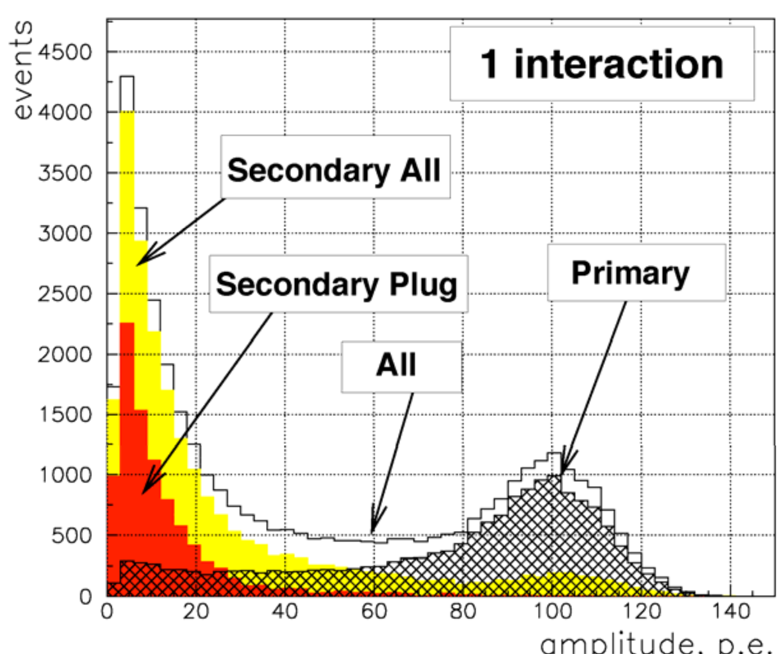


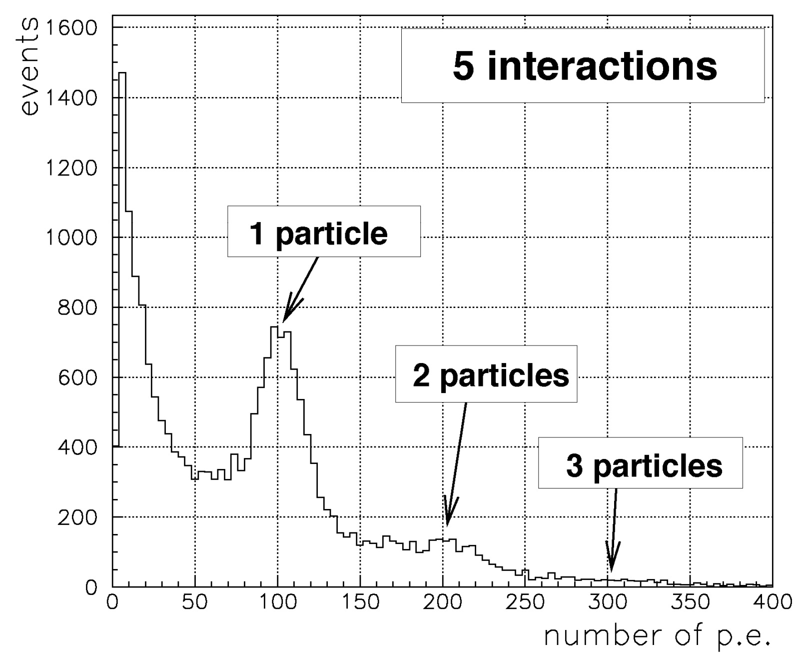
# Gas Cherenkov Counters – basic ideas




- o Measure the number of p-pbar interactions directly by counting <number> of primary particles
- o Separate primaries from secondaries
- o Good amplitude resolution (~18% from photo stat, light collection, PMT collection)
- o Good timing resolution (separate collisions from losses)
- o Radiation hard, low mass

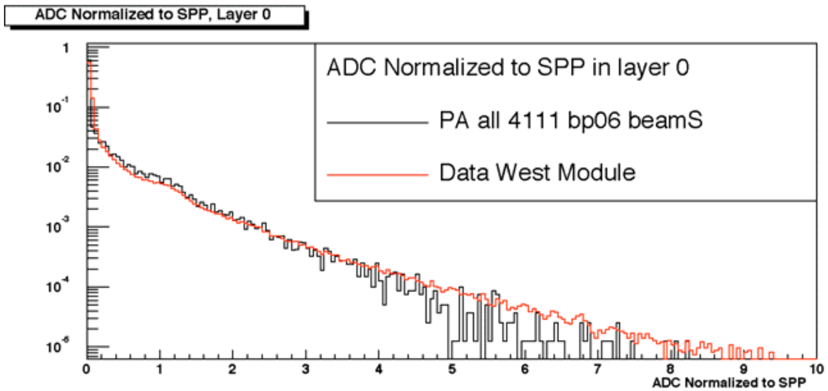
➢ Expected signal (simulation)

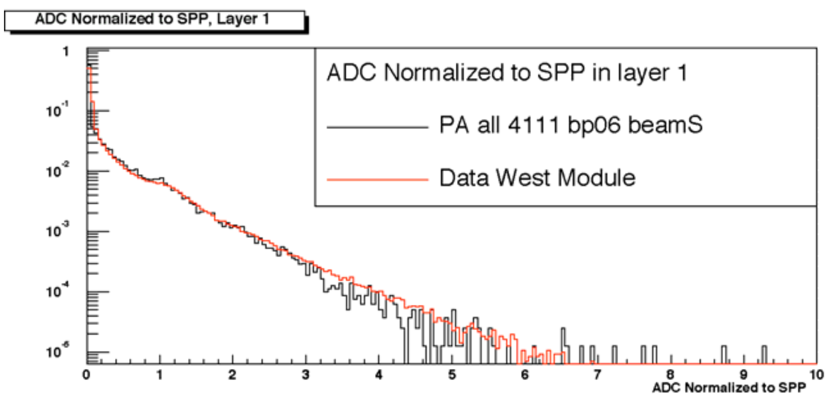


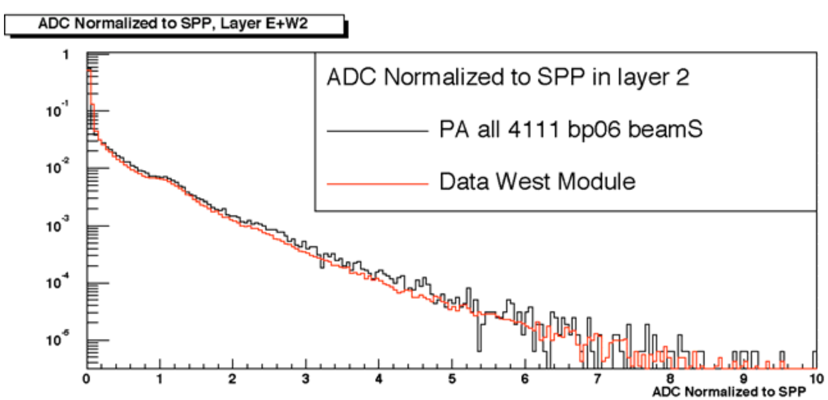



# Amplitude Distributions in $p\bar{p}$ Collisions

o **Full simulation vs data**

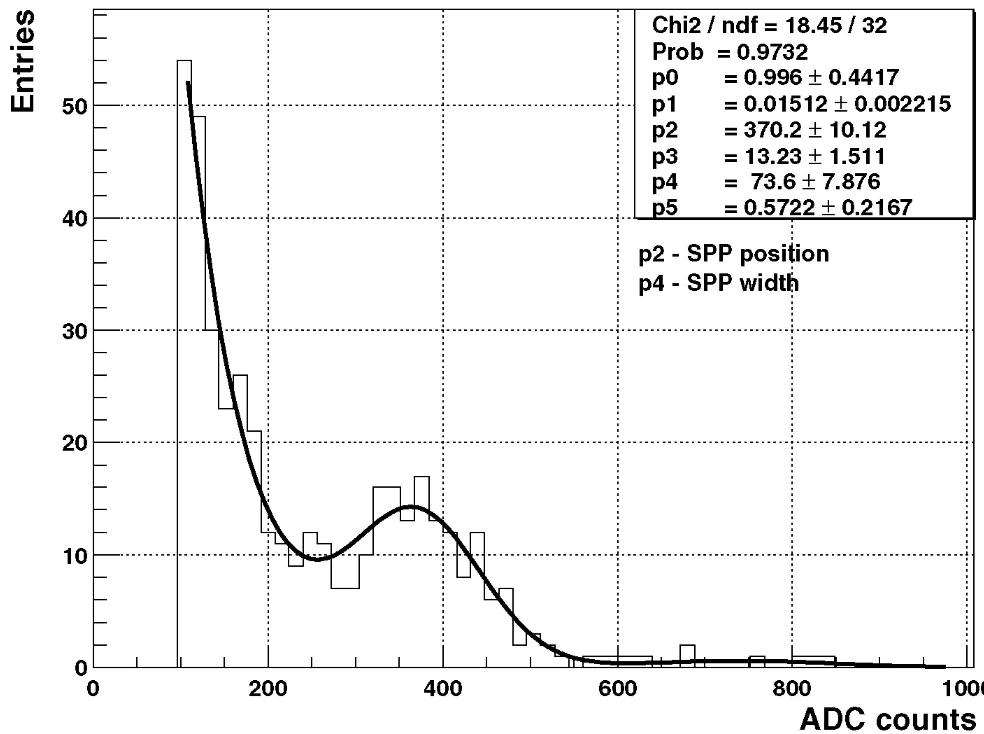



- **Simulation agrees well with data**
- **Single particle peak buried under secondary interactions**

- **Clear peak after the isolation requirement:**
  - **Amplitude < 20 p.e. in surrounding counters**

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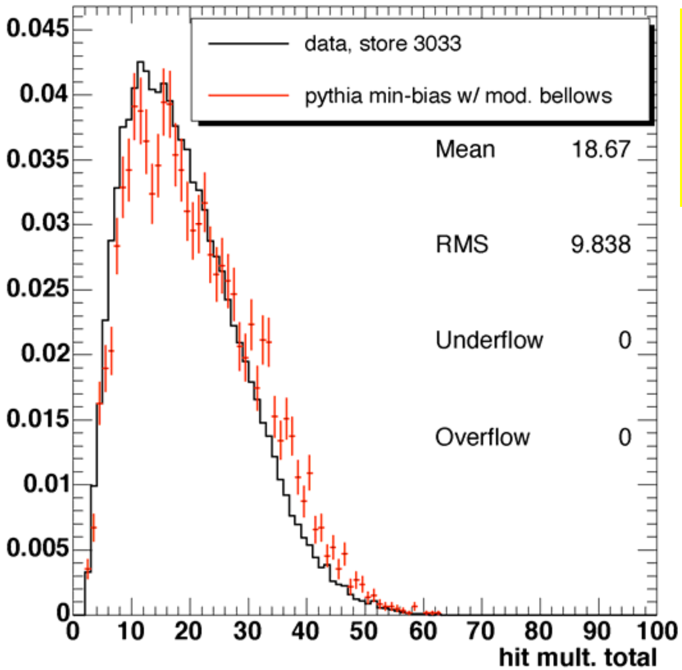
# Luminosity by counting empty crossings

"empty" = bunch crossings with no PPbar interactions

- probability of empty crossings:
  - *full acceptance detector:* $P_0(\mu) = e^{-\mu}$
  - *"real" detector:* $\tilde{P}_0(\mu, \varepsilon_0, \varepsilon_W, \varepsilon_E) = e^{-\mu(1-\varepsilon_0)}(e^{\mu.\varepsilon_W} + e^{\mu.\varepsilon_E} - 1)$
    - **$\varepsilon_0$** - probability to have no hits in CLC (~7%) (~15% when requiring two layers only and ~ 20% when requiring one layer)
    - **$\varepsilon_{W/E}$** - probability to have hits exclusively in one CLC module (~12%) (~15% when requiring two layers only and ~ 20% when requiring one layer)
  - *More sensitive to beam losses*
  - *Sensitive to pileup at high lum*

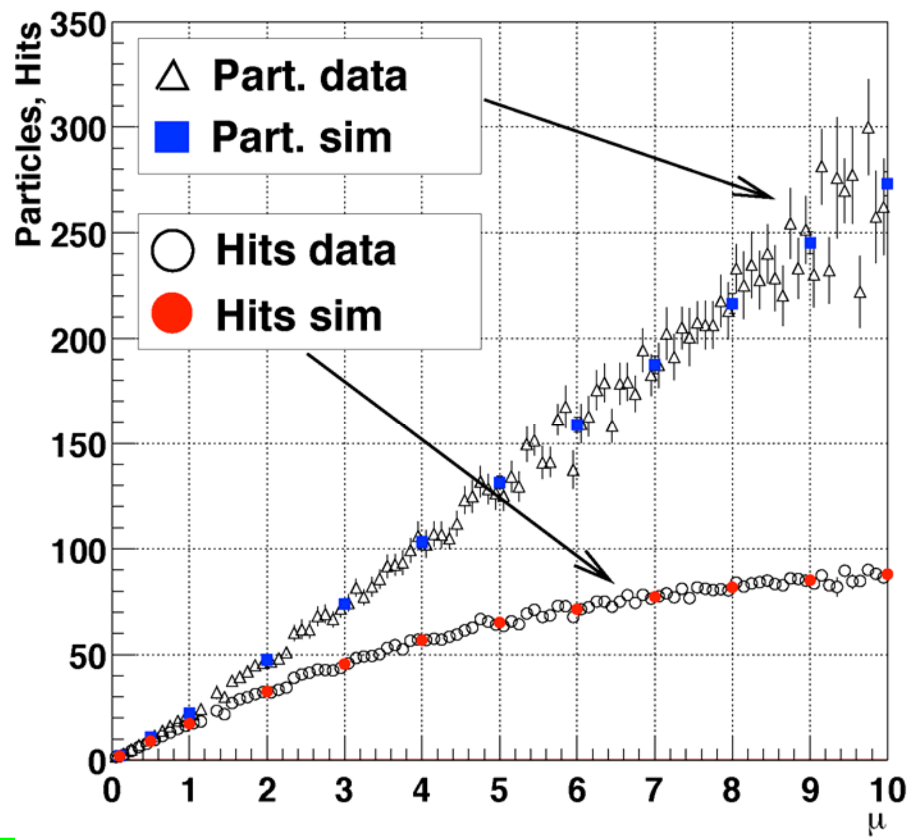
**Less dependent on the "material model"**

# Measuring Luminosity at High Inst. Luminosity
# Multiplicity Distributions in $p\bar{p}$ Collisions




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

**Working on improvement of the simulation**




Hits:
Counters with amplitude above a threshold. (threshold is ~ 0.7 $A_0$ )

"Particles":
Total amplitude / Ao
Ao = amplitude of single particle peak

**Precise high luminosity measurements are feasible !!!**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# Uncertainty in the CDF Luminosity Measurement

| Systematic Effect | Uncertainty |
|---|---|
| Geometry | 3% |
| Generator | 2% |
| Beam Position | <1% |
| CLC simulation | 1% |
| SPP calibration | <1% |
| Acceptance stability | 1% |
| Backgrounds | <1% |
| Online to Offline transfer | negligible |
| Luminosity method $p\bar{p}$ | negligible |
| Statistical uncertainty | negligible |
| Total from lum. Det/meth. | <4.2% |
| Inelastic cross section | 4% |
| Total lum uncertainty | 5.8% |

$$\varepsilon^{clc} = \frac{\varepsilon^{h} \cdot \sigma_{h} + \varepsilon^{d} \cdot \sigma_{d} + \varepsilon^{dd} \cdot \sigma_{dd}}{\sigma_{inel}}$$

$$\varepsilon^{h} = 88.6\,(0.5)\,\%$$

$$\varepsilon^{d} = 9.1\,(0.4)\,\%$$

$$\varepsilon^{dd} = 31.8\,(0.7)\,\%$$

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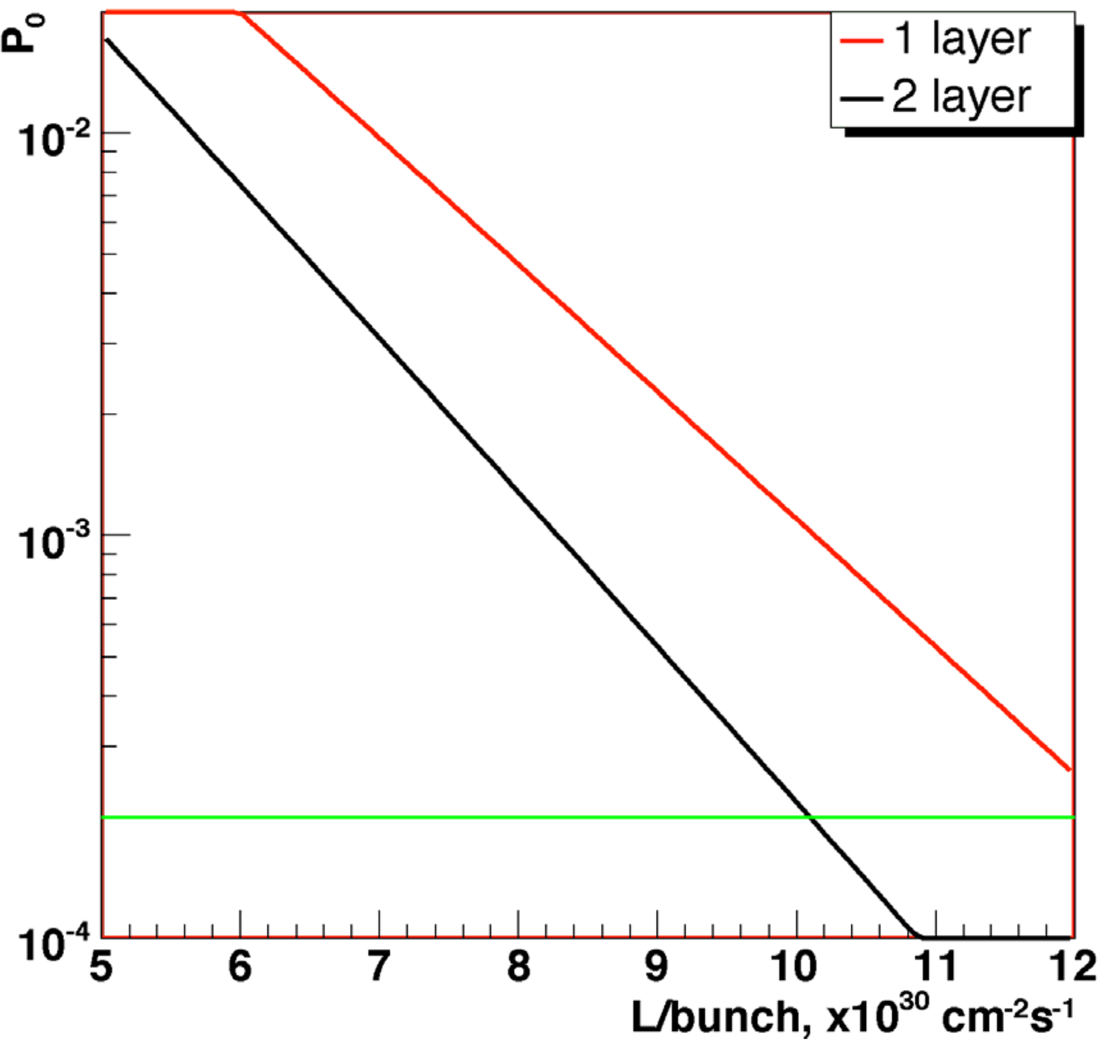
# High Luminosity: Rarer empty crossings



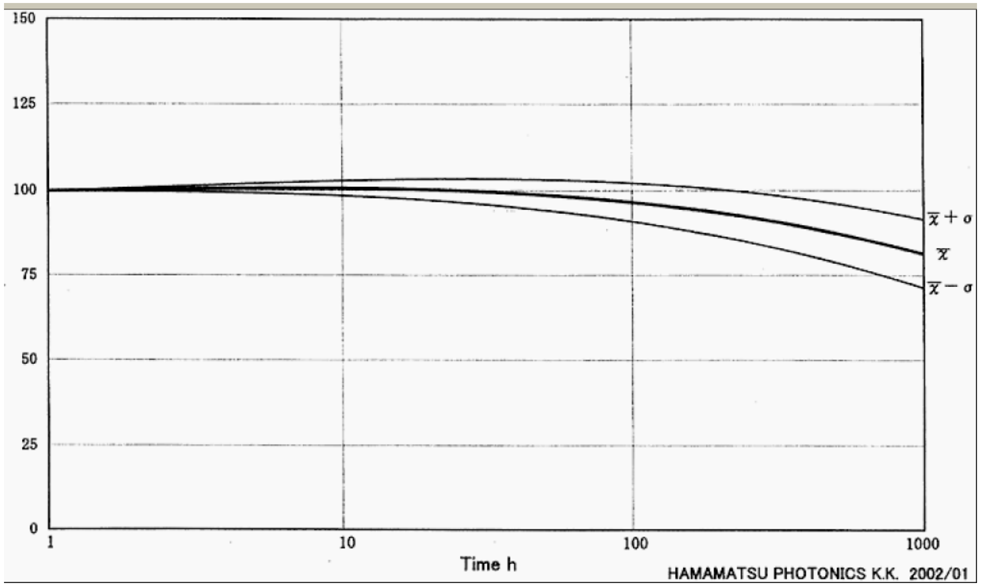

**Probability: $P_0 = N_0/N_{BC}$**

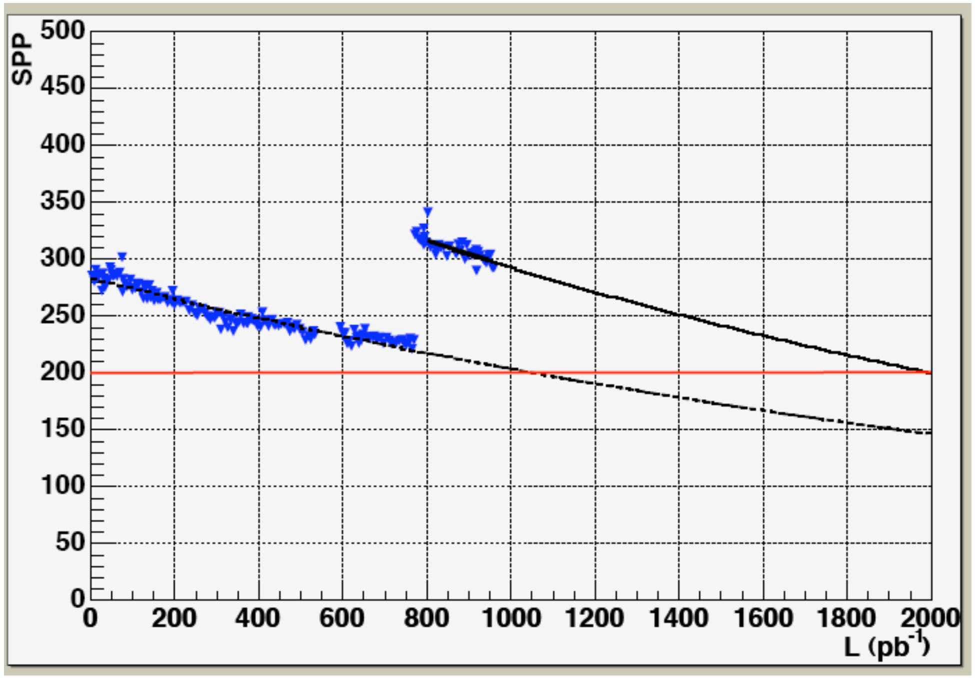
- **$N_{BC} \cong$ 20000 per measurement limited by h/w DAQ**
- **Cutoff (adjustable in s/w): $N_0 < 4$, $P_0 < 2x10^{-4}$**
- **Highest luminosity bunch: 15-20% higher than average**
- **Cutoff luminosity:**
  - **$L_{2L}$ ~ 300 x $10^{30}$ $cm^{-2}s^{-1}$**
  - **$L_{1L}$ ~ 360 x $10^{30}$ $cm^{-2}s^{-1}$**

➢ **CDF: Reliable luminosity measurements up to $\mathcal{L}$ ~ 360 x $10^{30}$ $cm^{-2}$ $s^{-1}$**

# Large Total Luminosity: Aging

Relative Anode Current %




- Factory aging test:
  - 1000 h at 10 μA
  - ΔI/I = 10-35%

- Corresponds to 30-80% $fb^{-1}$

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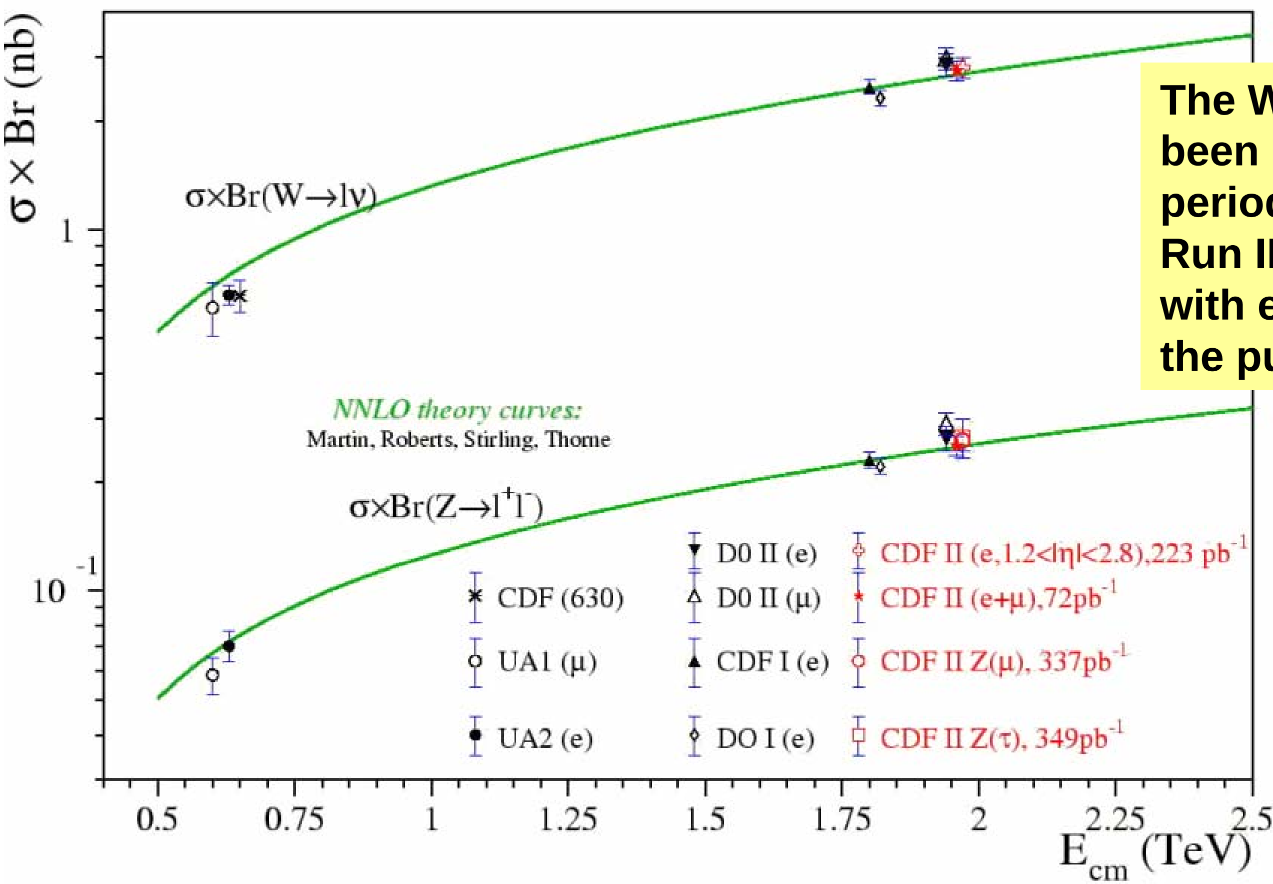
# Inclusive W and Z cross sections




**The W → eν cross section has been measured in 3 different time periods with the first fb$^{-1}$ of data in Run II. The results agree within 1% with each other and very well with the published value.**

- **CDF: J. Phys. G: Nucl. Part. Phys. 34 (2007) and PRL 98, 251801**

$$\sigma_W \,.\, Br(W \rightarrow l\nu) = 2.749 \pm 0.010\,(stat) \pm 0.053\,(syst) \pm 0.165\,(lum)\,nb$$

$$\sigma_W \,.\, Br(W \rightarrow e\nu) = 2.796 \pm 0.013\,(stat)^{+0.095}_{-0.090}\,(syst) \pm 0.162\,(lum)\,nb$$

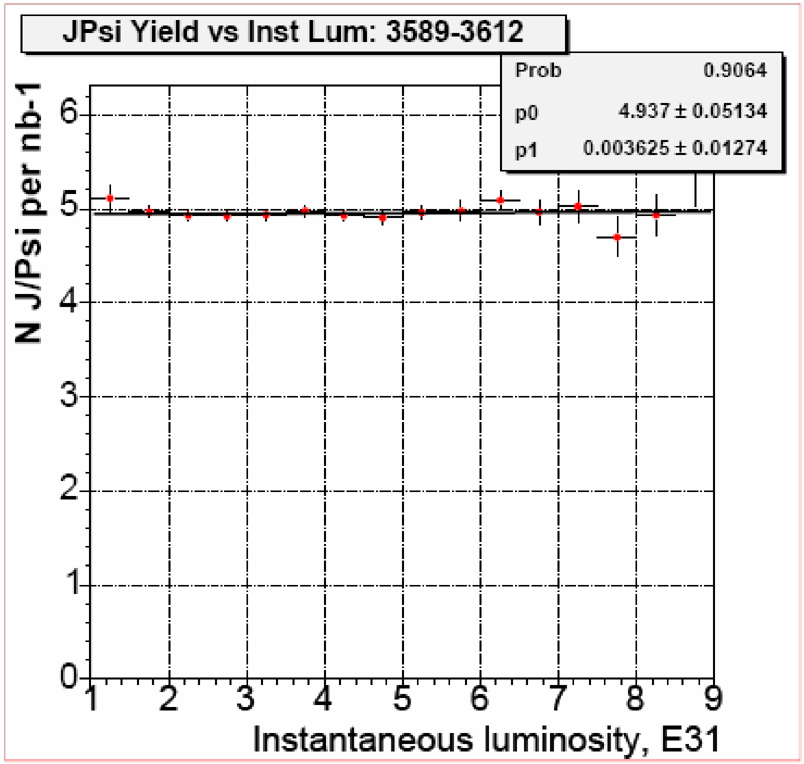
**Forward electrons**

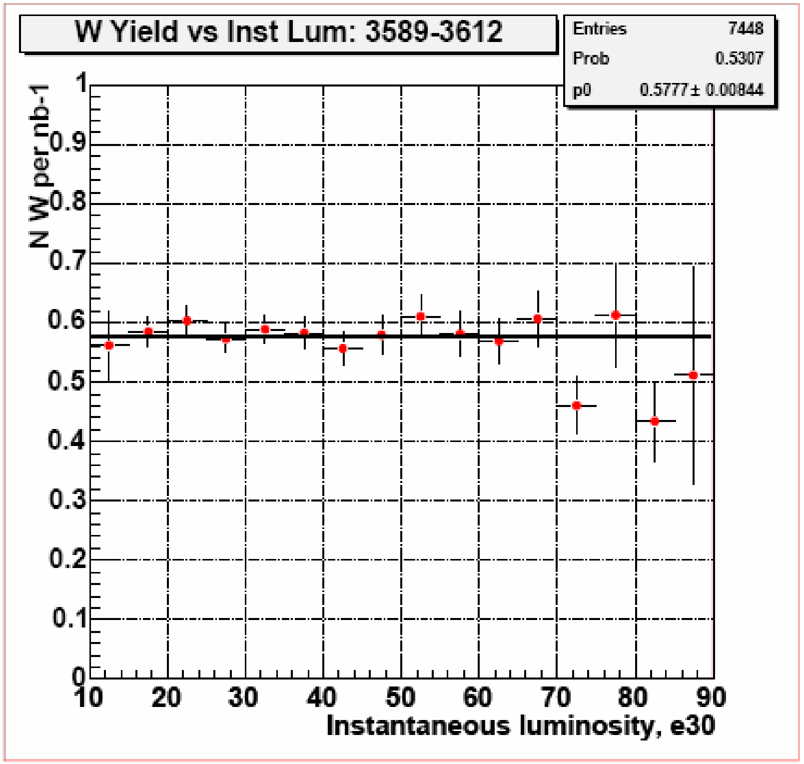
$$\sigma_{\gamma^*/Z} \,.\, Br(\gamma^*/Z \rightarrow ll) = 254.9 \pm 3.3\,(stat) \pm 4.6\,(syst) \pm 15.2\,(lum)\,pb$$

# Checking physics objects yields as a function of instantaneous luminosity

$J/\psi \to \mu$ **yield**

$W \to e\nu$ **yield**



# D0 Luminosity counters (Run I)

- Hodoscopes of scintillation counters used by D0 in Run I:
  - Two planes rotated by 90º were mounted on each end-cap calorimeter, 140 cm from the center of the detector.
  - Each hodoscope had 20 short (7x7 $cm^2$ squares) scintillation elements with single PMT readout and 8 long (7x65 $cm^2$ rectangles) elements with PMT readout on each end.
  - Partial coverage for the $1.9 < \eta < 4.3$ range and nearly full coverage for the $2.3 < \eta < 3.9$ range.
  - Decided on better granularity for Run II.

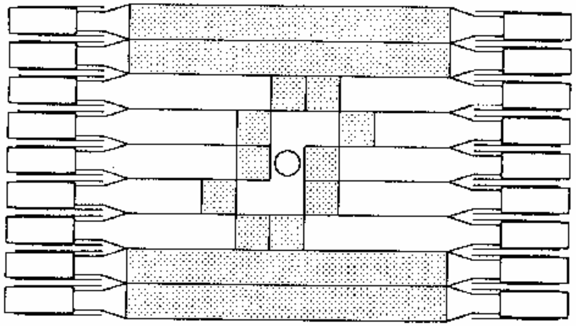


Figure 68 (a)

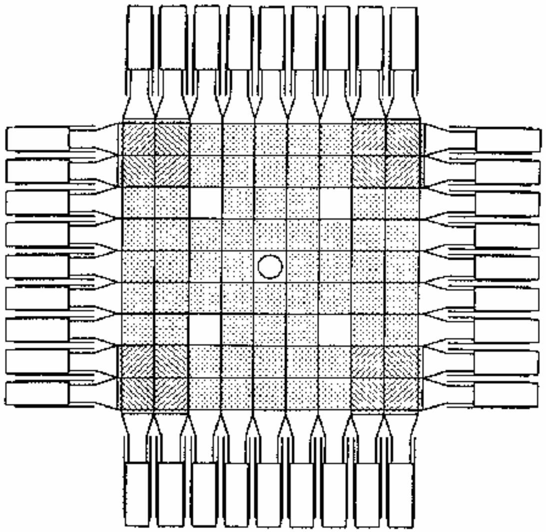


Figure 68 (b)

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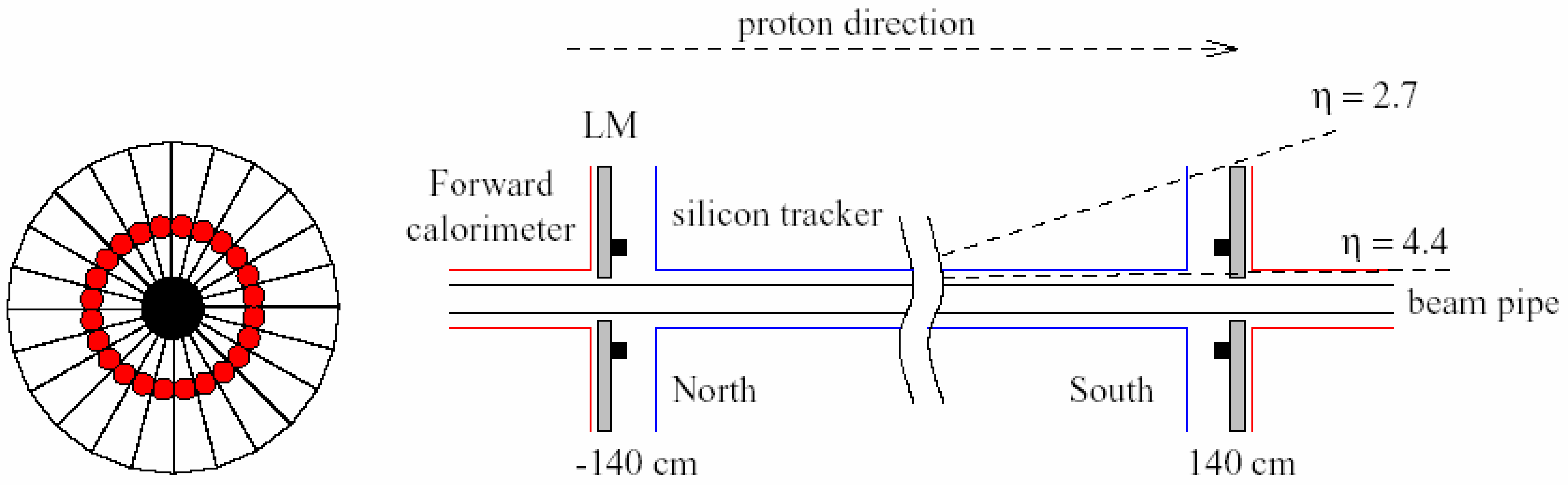
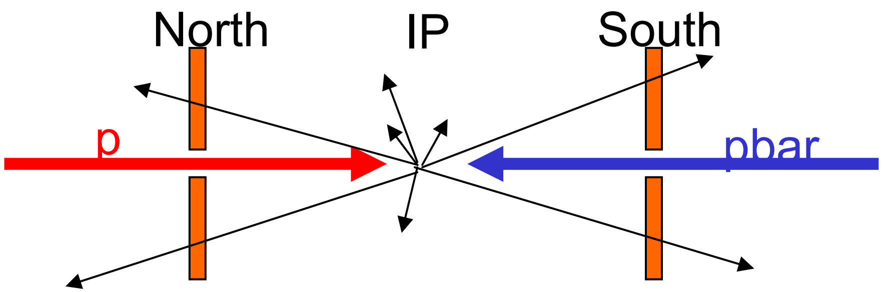
# DØ Luminosity measurement in Run II

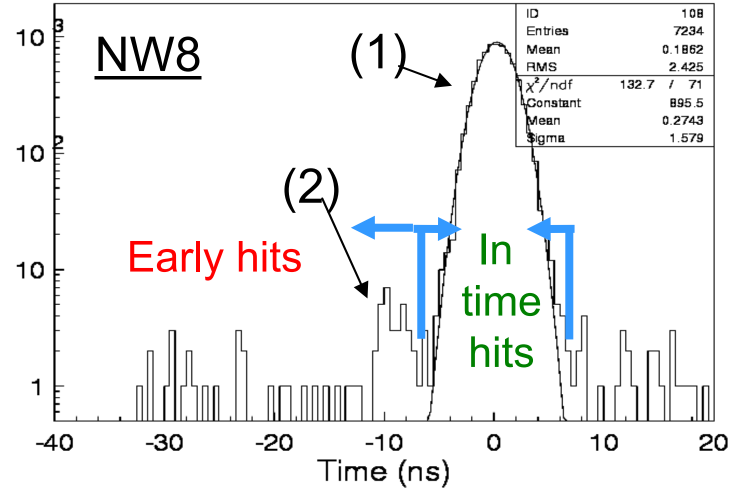



- Measured by determining the average number of inelastic collisions per unit time and normalizing to the measured inelastic cross section
- Detector: Two forward scintillator arrays. 24 wedges per array, each read out with a Fine Mesh PMT.
- Inelastic collision identified using the coincidence of in-time hits in the two arrays.

# How to identify the process?

(1) Double or single side p-pbar interaction.



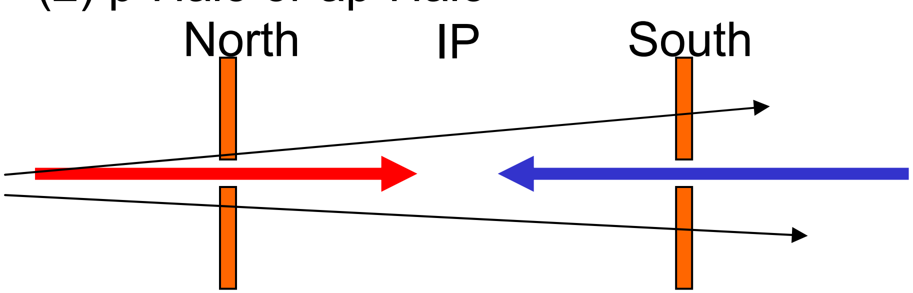




**Scattering particle come from IP.**

**Timing : ~ 0 ns**

**In time hit: - 6.4 < t < 6.4 (ns)**

(2) p-Halo or ap-Halo




**Halo comes from upstream**

**Timing : ~ - 9.5 ns.**

**Early hit: t < - 6.4 (ns)**

| | North | South |
|---|---|---|
| p-pbar | In-time | In-time |
| p-Halo | Early hit | In-time |
| ap-Halo | In-time | Early hit |

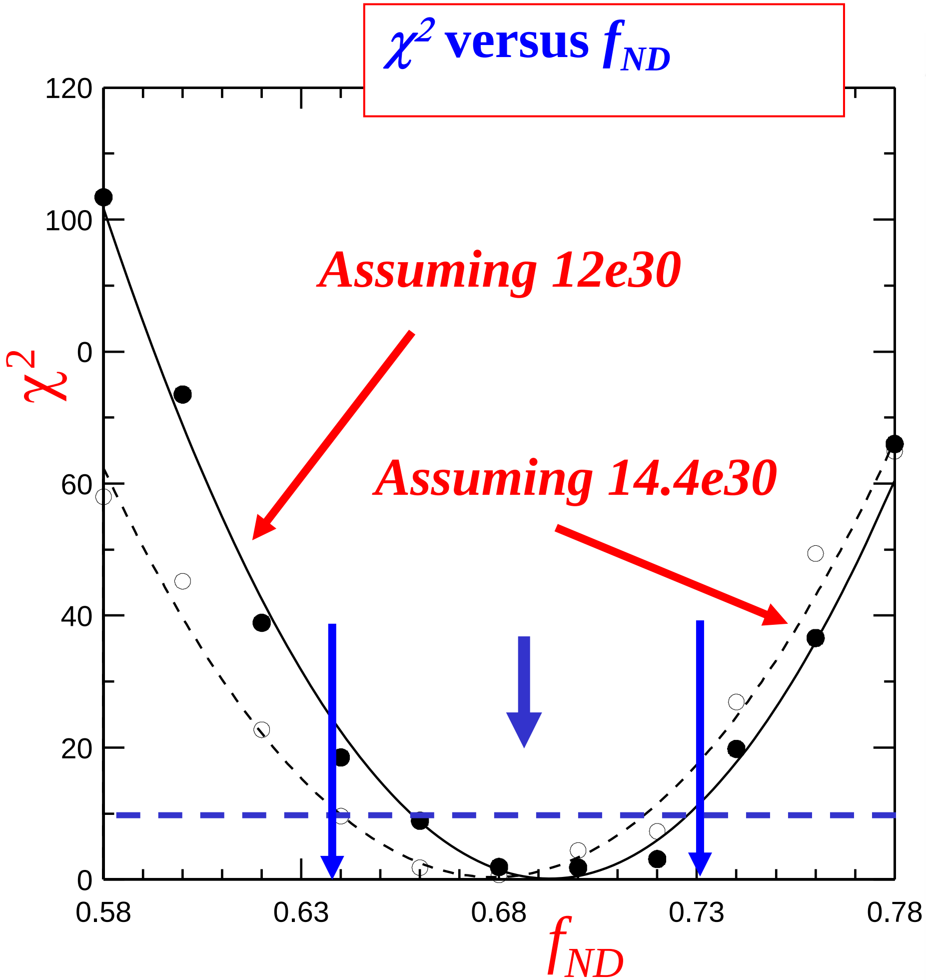
**Each process can be identified by taking "AND" for hit in each timing region.**

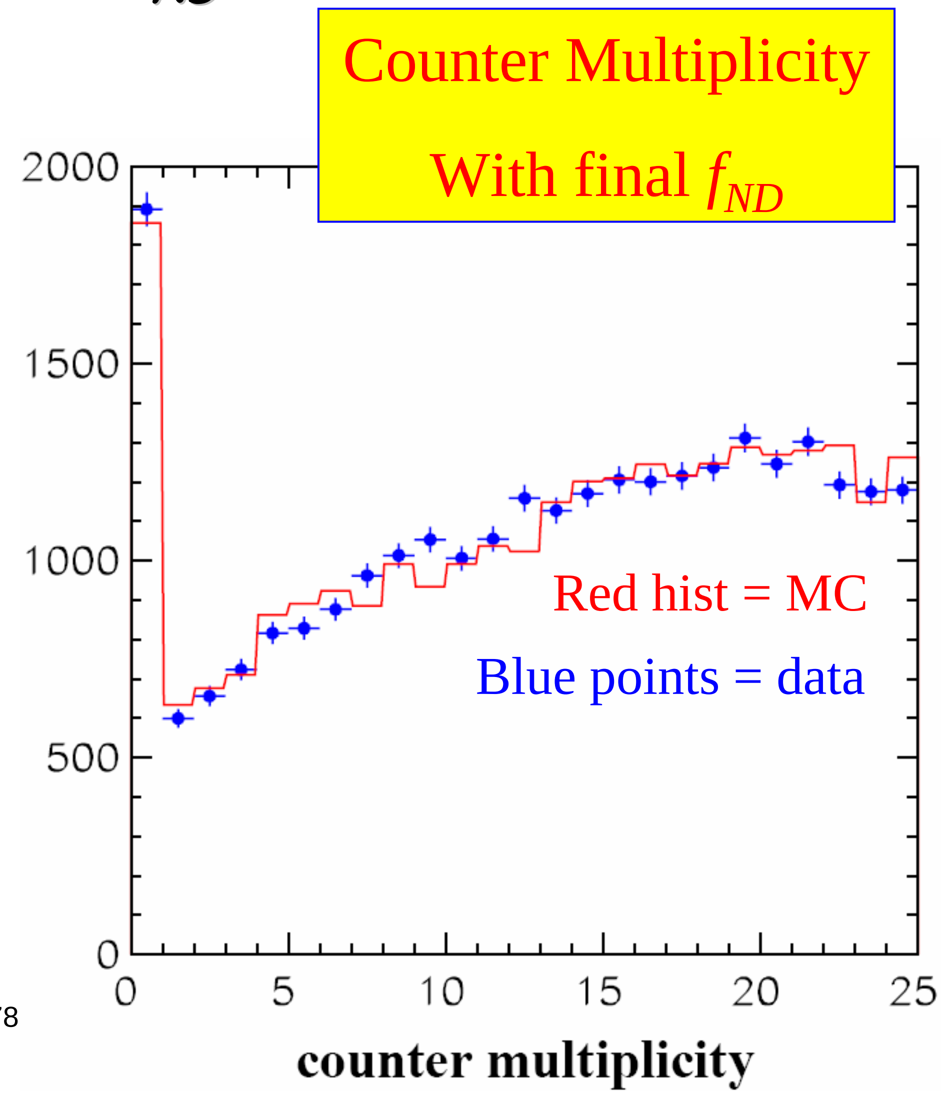
# Luminosity Readout Electronics

- **Original system based on Run I NIM electronics**
  - ***Analog sum of all PMT signals in each array***
  - ***Single discriminator for each array***
    - Dynamic range problems
    - Deadtime problems
    - No information on charge or time offline

- **New custom VME electronics (after October 20, 2005)**
  - ***Each channel discriminated separately***
  - ***Digitized and calibrated in real time on board***
  - ***All information sent to DAQ for triggered events***
    - Possible to optimize the single channel performance and make a calibrated Monte Carlo detector simulation.

# Determination of the non-diffractive fraction - $f_{ND}$



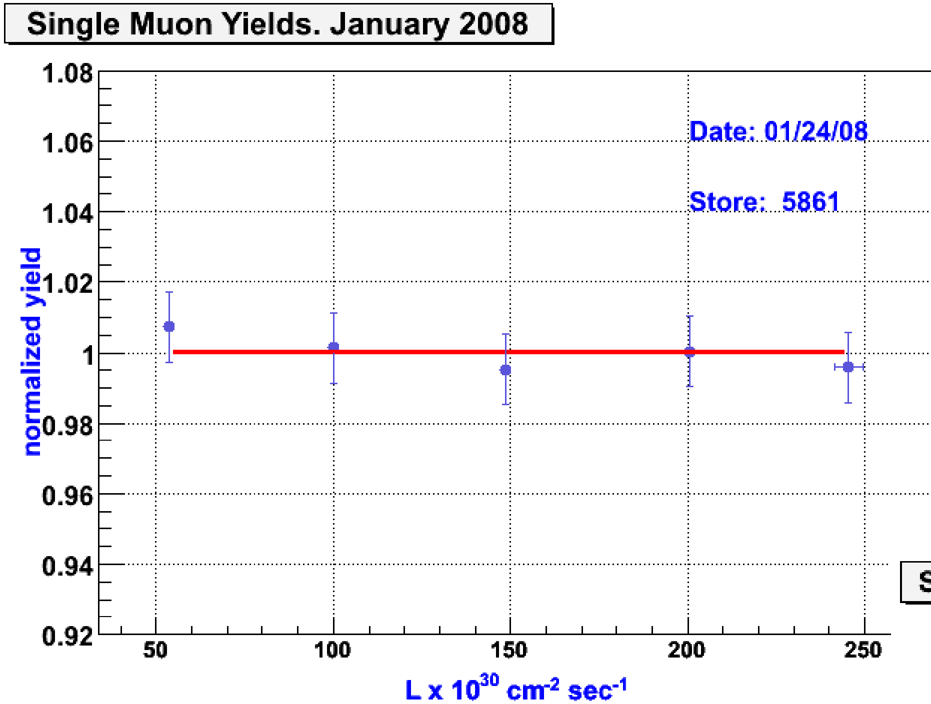

Generate template MC multiplicities for each $f_{ND}$ and fit the data.
Change assumptions, regenerate, refit

# Uncertainty in the D0 Luminosity Measurement

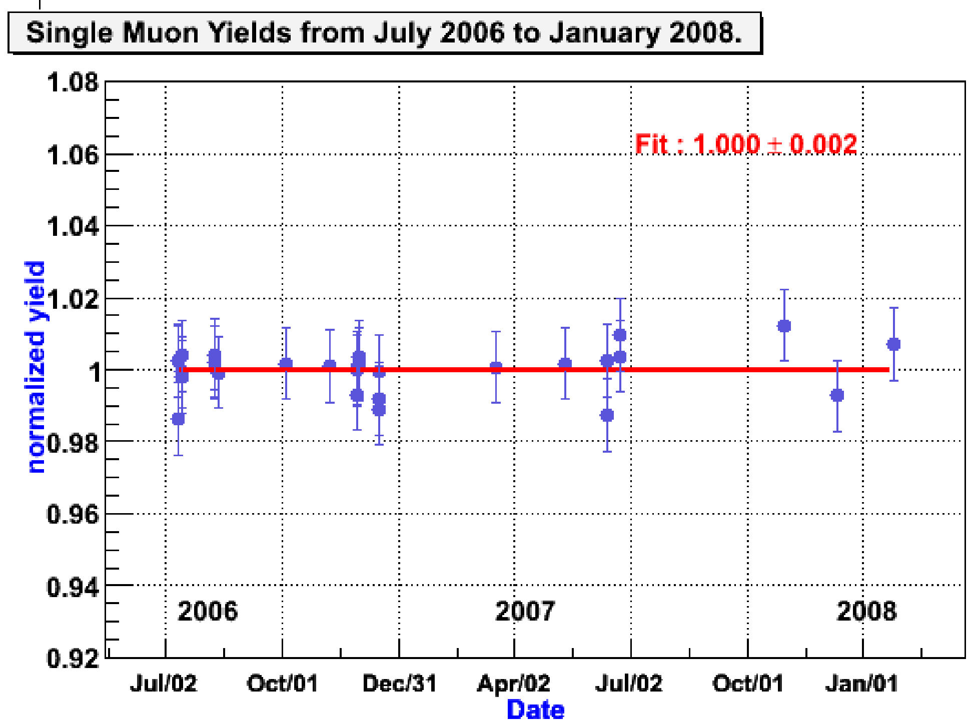
| | |
|---|---|
| non-diffractive efficiency | $0.981 \pm 0.009$ |
| single diffractive efficiency | $0.330 \pm 0.024$ |
| double diffractive efficiency | $0.436 \pm 0.026$ |
| $f_{ND}$ | $0.687 \pm 0.044$ |
| $f_{SD}/(f_{SD} + f_{DD})$ | $0.57 \pm 0.21$ |
| inelastic efficiency | $0.792 \pm 0.029$ |
| inelastic cross-section | $60.7 \pm 2.4$ mb |
| effective cross-section | $48.0 \pm 2.6$ mb |

| Systematic Effect | Uncertainty |
|---|---|
| Non-Diffractive fraction | ~4% |
| Acceptance | ~1% |
| Diffraction modeling | ~1% |
| Inelastic $p\bar{p}$ cross section | 4% |
| Total uncert. in inst. lum. | ~5.4% |
| Long term stability | ~2.8% |
| Total lum. uncertainty | 6.1% |

# Checking the Luminosity with Forward Muon Yeilds at D0

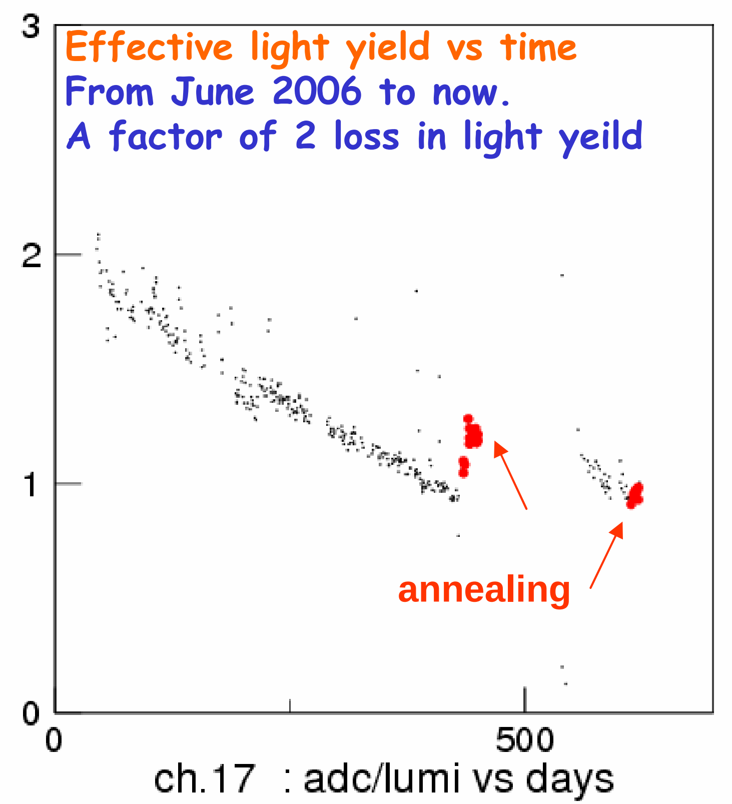



Stability within ~1% within Run IIb

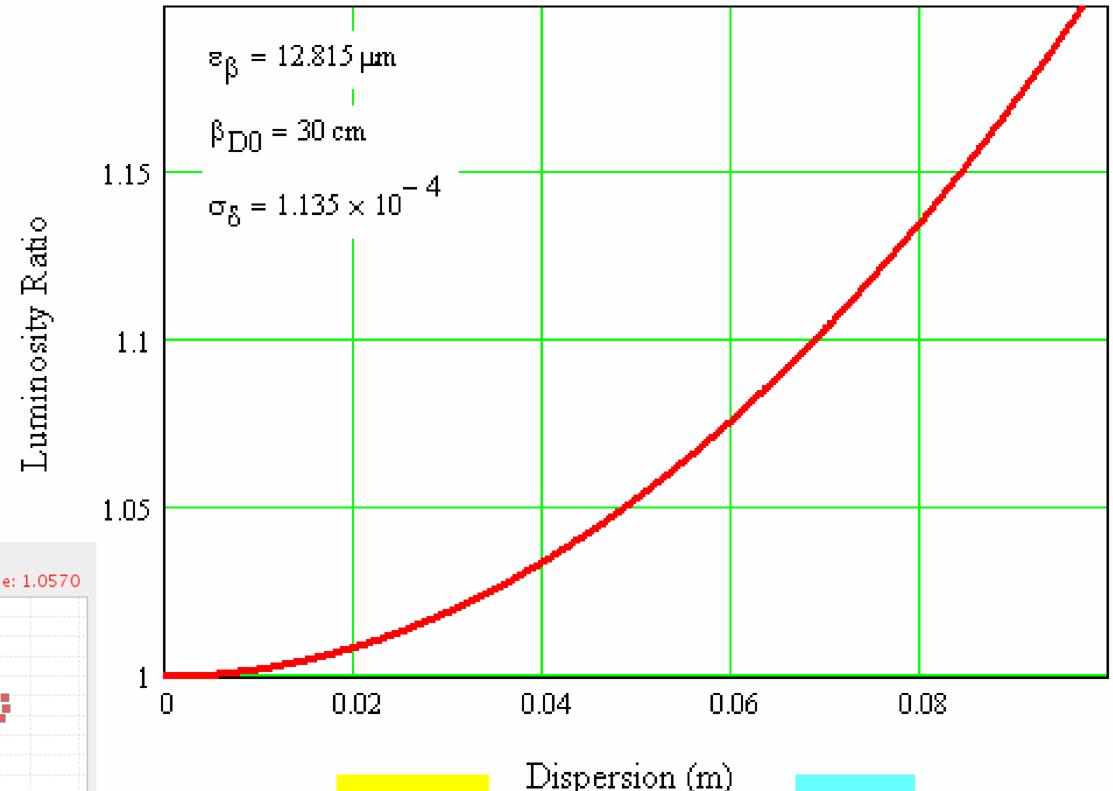


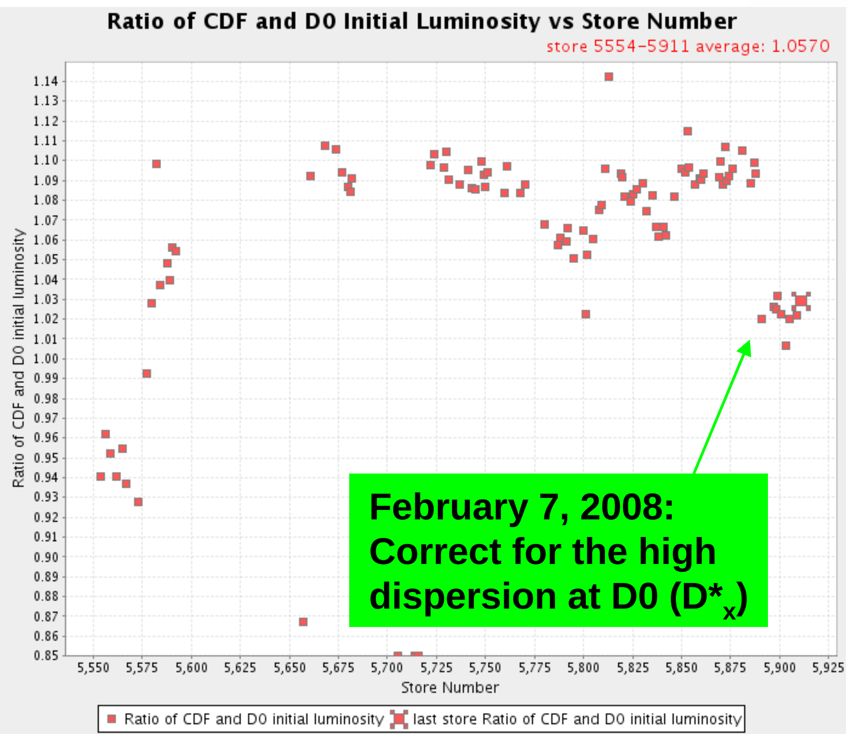
# Scintillator radiation damage at D0

Scintillator becomes yellow due to radiation damage.
Integrated radiation dose is ~ 0.5 Mrad every 1.0-1.5 $fb^{-1}$.
Scintillator was replaced in March 2006 and August 2007. (The same PMT is being used).



# CDF/D0 Luminosity Ratio vs. *D**




before

after

| | β* cm | D* cm | β* cm | D* cm |
|---|---|---|---|---|
| CDF | 33.3 | 1.3 | 29.0 | 1.2 |
| D0 | 31.3 | 6.3 | 29.1 | 2.1 |

# Lessons learned - Tevatron

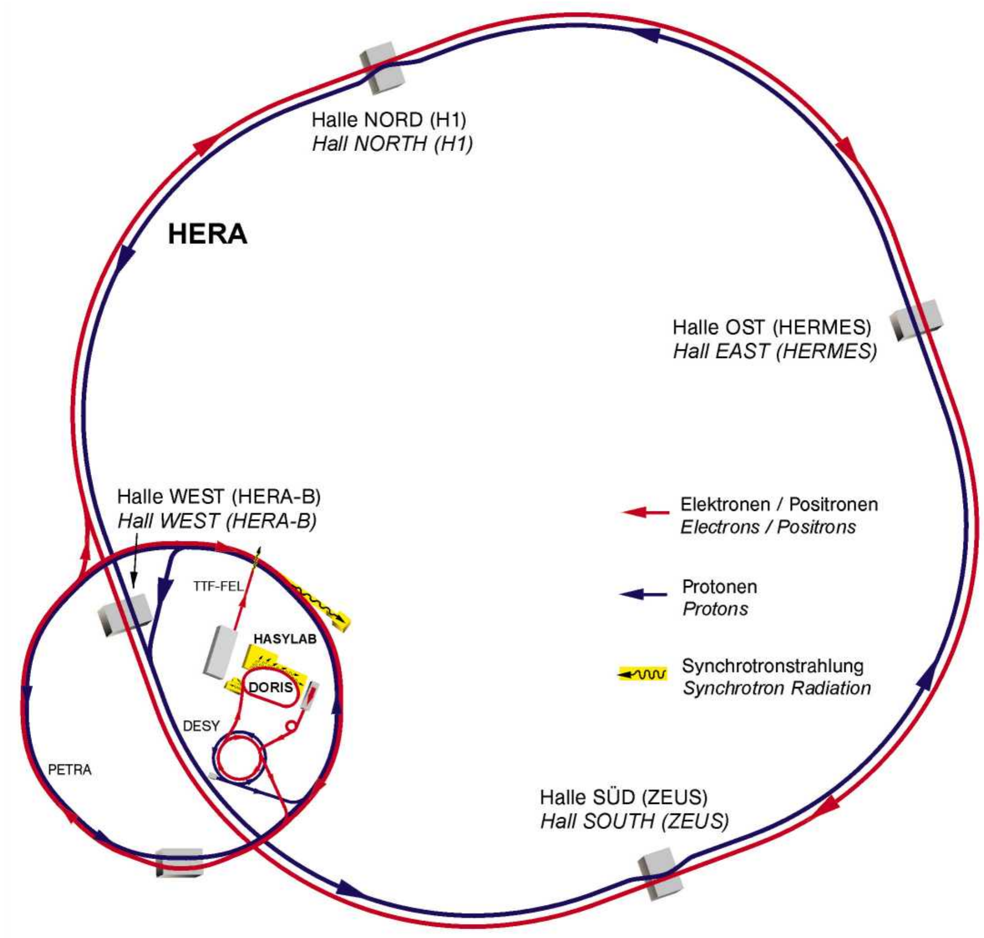
- A fine granularity detector is needed for high instantaneous luminosities (Tevatron Run I vs Run II).
- In situ calibration of the detector, using the same data, is very important.
- Detector stability is crucial since the luminosity measurement method relies on this (e.g. PMT gain stability).
- A good simulation of the processes involved and the luminosity detector is needed as early as possible.
- A good knowledge of the physics cross section the measurement relies upon is necessary.
- Careful monitoring of gas purity when you have a gas detector is a must (e.g. unexpected He contamination).

# Lessons learned - Tevatron

- Minimizing (eliminating) the dead time of the system is critical.
- Watchfullness is needed for aging due to large total luminosity and readiness to replace consumables.
- The "counting zero's" method works well for the current Tevatron luminosities.
- Continuous cross checking between the machine expectations and the measured luminosities by the experiments as well as between the experiments themselves is very valuable.

# HERA II Overview

Electron (positron) - Proton Collider




Beam energies
- protons 920 GeV
- electrons 27.5 GeV

Beam currents
- protons 100 mA
- positrons 50 mA

180 bunches, 96 ns spacing

Instantaneous Luminosity

$4.6 \times 10^{31}$ cm$^{-2}$ s$^{-1}$

($1.8 \times 10^{31}$ cm$^{-2}$ s$^{-1}$ in HERA I)

# HERA Luminosity History

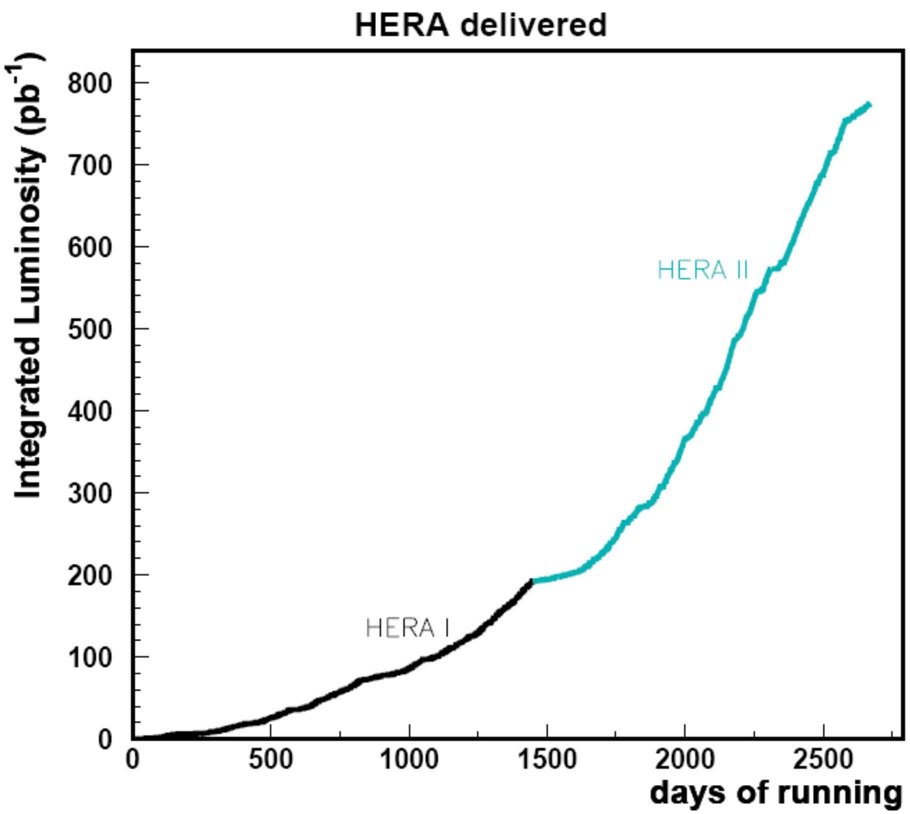
**Total HERA delivered (24 May 1993 – 30 June , 2007): 779.9 $pb^{-1}$**

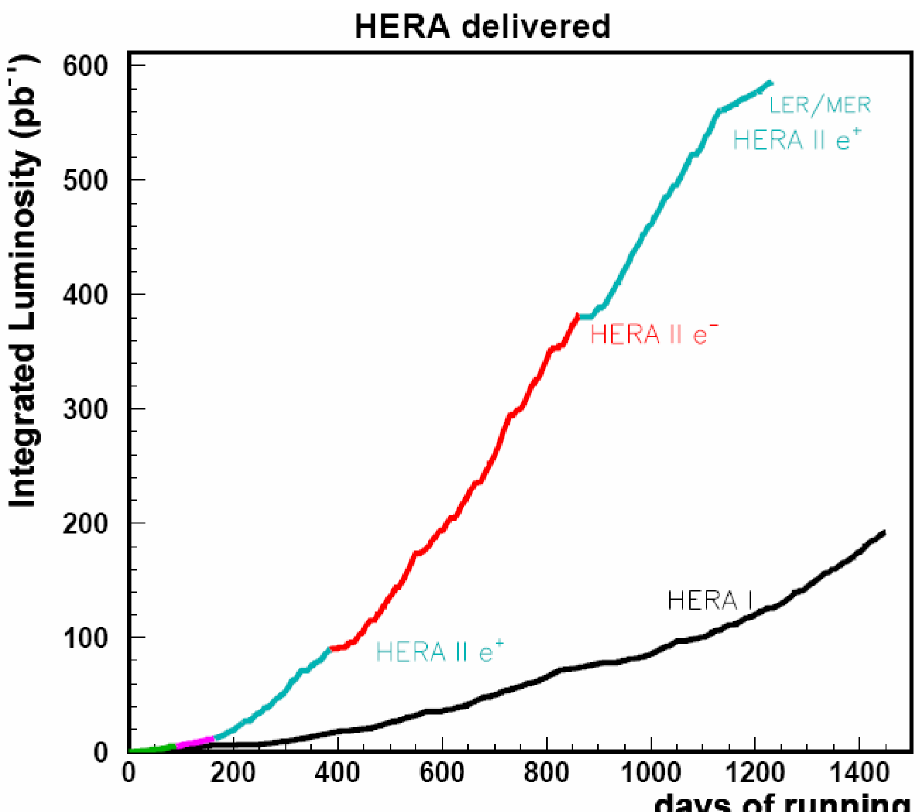
**HERA I delivered (24 May 1993 – 23 August, 2000): 193.2 $pb^{-1}$**

**HERA II delivered (01 November 2002 – 21 March, 2007): 561.6 $pb^{-1}$**

**HERA II LER delivered (24 March 2007 – 31 May, 2007): 15.7 $pb^{-1}$**

**HERA II MER delivered (1 June 2007 – 30 June, 2007): 9.4 $pb^{-1}$**



# Luminosity measurements at HERA

- Two very different beams/storage rings and in practice the optics not fully ideal and symmetric between the H1 and ZEUS IPs. Therefore one cannot rely upon/expect that the luminosity is equal across the ring.
- Conflicting demands to machine operation which make "perfect luminosity" conditions difficult.
  - *Compromise between best luminosity and best background conditions (mostly decided in favour of acceptable backgrounds due to safety and efficiency considerations).*
  - *Compromise between good luminosity and high polarization, etc.*

# Luminosity measurements at HERA

- Two methods used to measure luminosity:
  - *H1 and ZEUS used their own luminosity systems counting the rate of Bethe-Heitler events ( 2-5) % uncertainty online and*

*(1-3) % offline.*

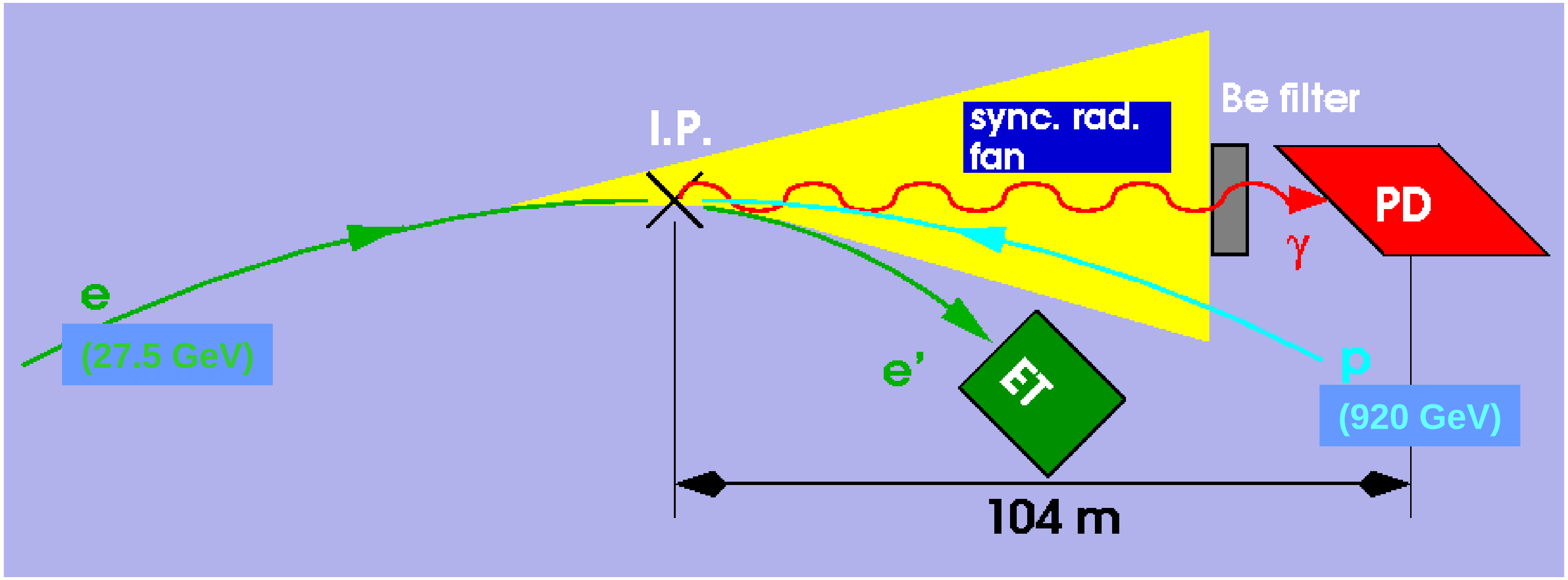
  - *Measure transverse beam profiles, calculate from them emittances and estimate the expected luminosity folding in beta functions and assuming perfect beam spot overlaps at the IPs ( ~ 10 % uncertainty, mainly from the beta function at the IP).*

*(5-10) % difference at the two IPs.*

- The main two challenges of HERA II were:
  - *increased synchrotron radiation level (higher total power and harder spectrum).*
  - *increased B-H event rate due to the higher luminosity and hence pile-up.*

*These required fast and radiation hard detectors and electronics*

# Luminosity measurements at HERA




Method: measure rate of bremsstrahlung process $ep \rightarrow e' p\gamma$

$$E_e = E_{e'} + E_\gamma$$

$$\mathcal{L} = 1/\sigma_{BH}^{obs}\left[R_{tot} - (I_{tot}/I_0)R_0\right]$$

**Bethe-Heitler cross section** $\sigma_{BH}^{obs} = A_\gamma \sigma_{BH}^{corr}$

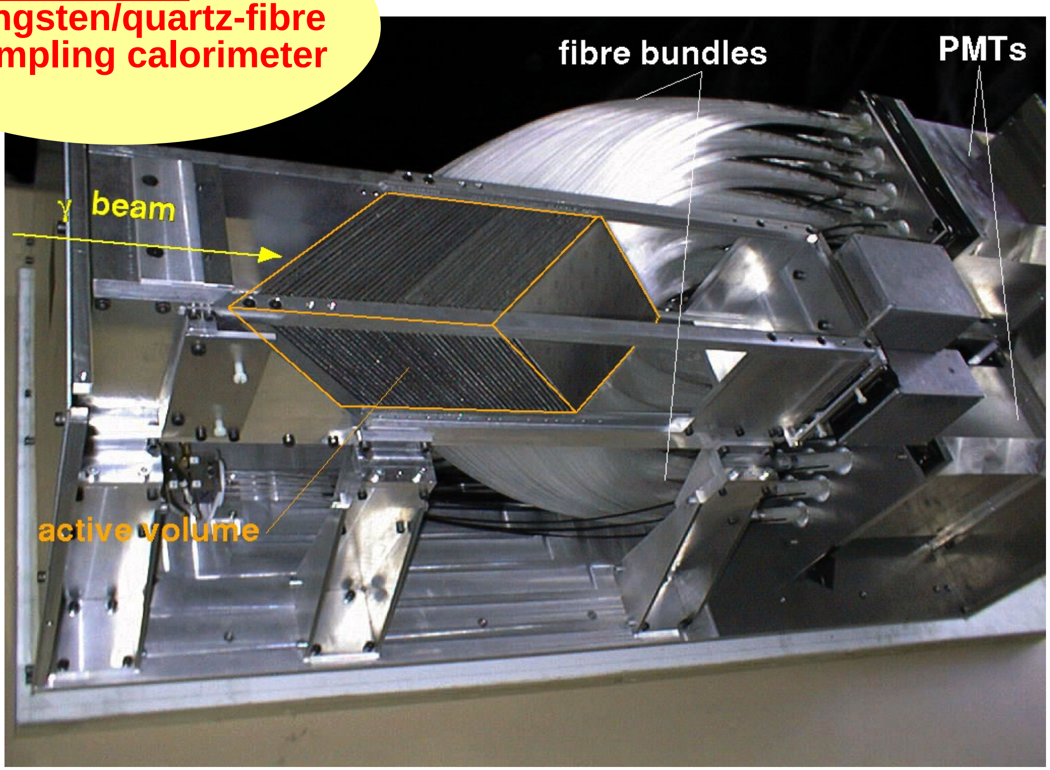
**Accurately calculable cross section with sufficient rate for real time monitoring**

Main background comes from beam gas scattering: Subtracted using electron pilot bunches (rate $R_0$, electron current $I_0$)

o bunch structure: p 180, e 294, colliding 174

# Overview of the H1 Luminosity System

**Photon Detector at 104m: tungsten/quartz-fibre sampling calorimeter**




**Key Parameters**
- 15422 quartz fibres
- (total length ~11km)
- **W/fibre V ratio: 1.68**
- total depth: 25 $X_0$
- **sampling freq.: 0.36**
- average $X_0$: 7.8mm
- Moliere radius: 17mm

**Geometry**
- **12(x)+12(y) 1cm strips**
- **alternating layers**
  **⇒ indep. sampling**

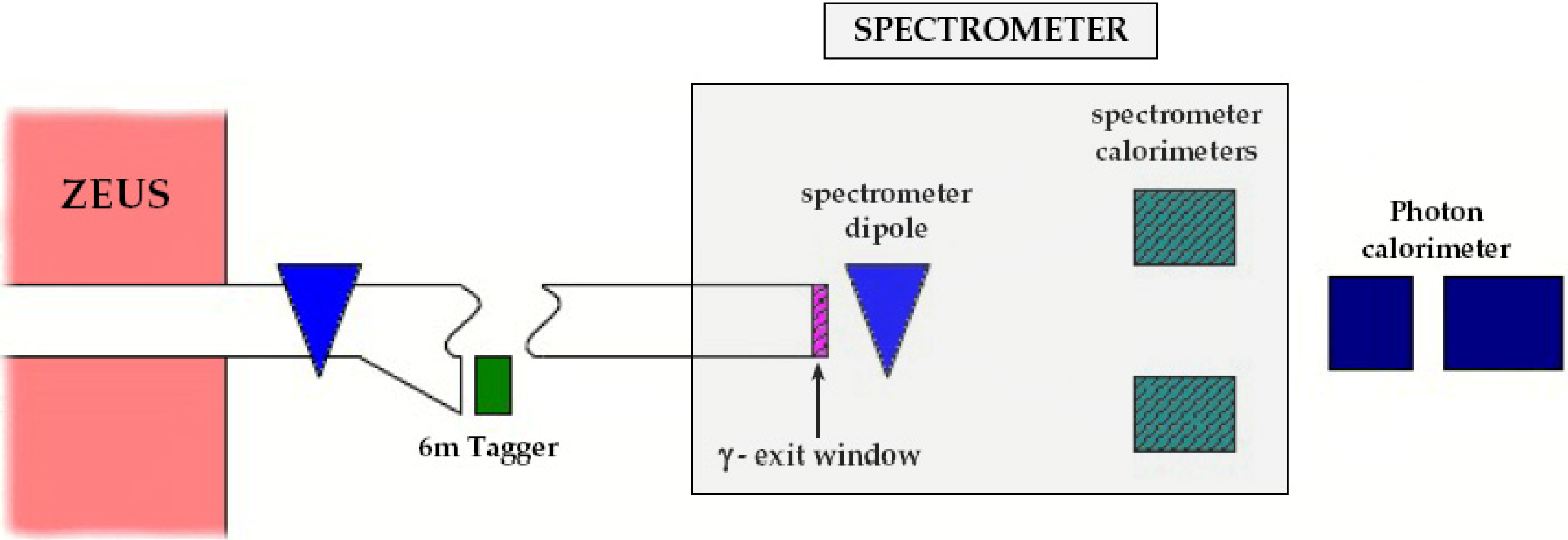
**Design Performance**

| | |
|---|---|
| **stoch. term:** | **19.8%/ $\sqrt{E}$** |
| sampling: | 16.4%/ $\sqrt{E}$ |
| photostat.: | 11.1%/ $\sqrt{E}$ |

**Synchrotron radiation filter: 2 $X_0$ Beryllium**

**Electron tagger at 6m: compact lead/scintilling fibre SpaCal**

# HERA - ZEUS




**Technique**

process: $ep \rightarrow e'p\gamma$

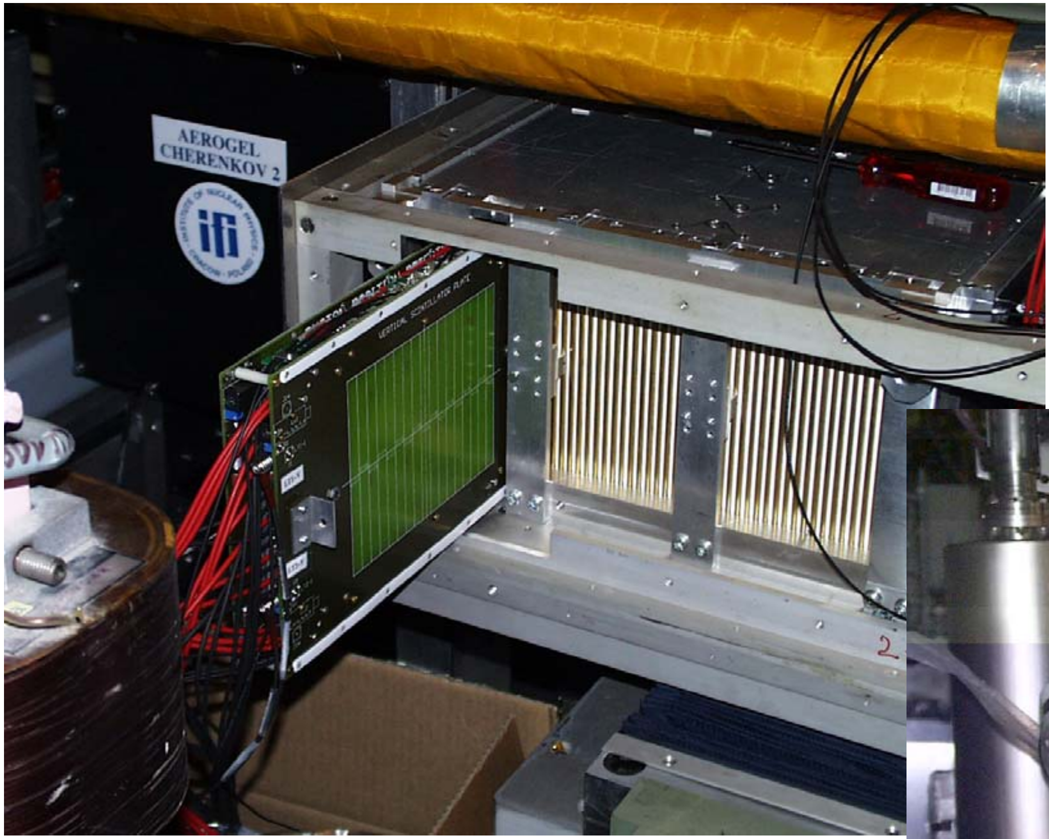
method: γ-measurement downstream

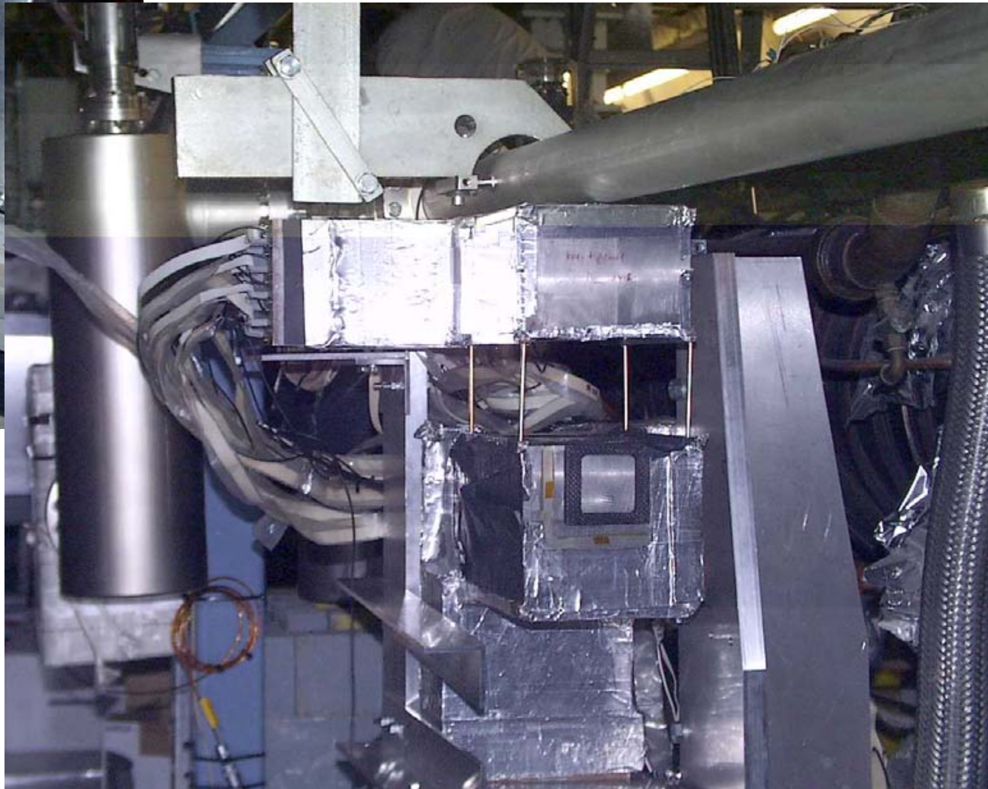
- photons follow electron beam
- ep are magnetically separated

**Experimental Setup**

- detects $e^+e^-$ pairs from bremstrahulng photons converted in the exit window (~9%)
- away from synchrotron radiation plane
- away from bremstrahlung photon beam

# ZEUS Photon Calorimeter and Spectrometer Calorimeters



# Luminosity uncertainty at ZEUS

Typical systematic errors

| | |
|---|---|
| Acceptance error | 0.8% |
| Cross section calculation | 0.5% |
| e gas background substr. | 0.1% |
| Multiple event correction | 0.03% |
| Energy scale error | 0.5% |
| Total error | 1.05% |

**HERA I**

theory
- 0.5%
- working with theorists on update

aperture and detector alignment
- 1%
- to be improved with ongoing acceptance study

window conversion
- 2%
- to be improved with ongoing acceptance study

correction
- 0.5%

X-position
- 1.2%
- to be improved with ongoing acceptance study

all other systematics checked
- negligible

**HERA II so far**

2.6 %

**2 % expected eventually**

# Luminosity uncertainty at H1

HERA II so far

| | Uncertainty |
|---|---|
| Theory (BH cross section) | 0.5 % |
| Geom. Acceptance (compromise between lum. Acceptance & good background) | 1-2 % |
| Satellite bunch Corrections | 0.3-0.7 % |
| Calibration, pileup, trigger, e-gas background | 0.1-0.3 % |
| Total | 2.5-3.0 %<br>2% expected |

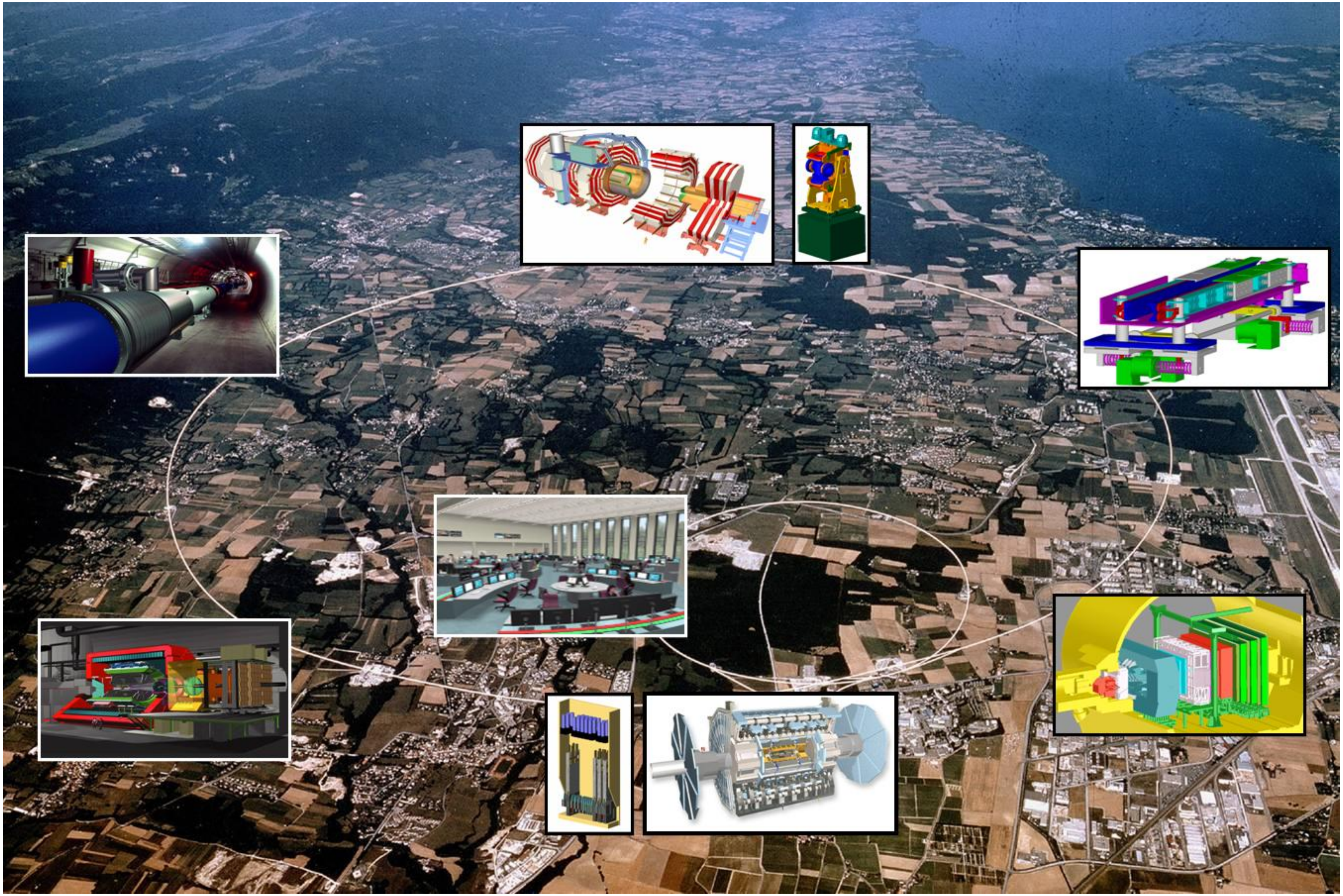
0.8% in HERA I

1.5% in HERA I

# Lessons learned - HERA

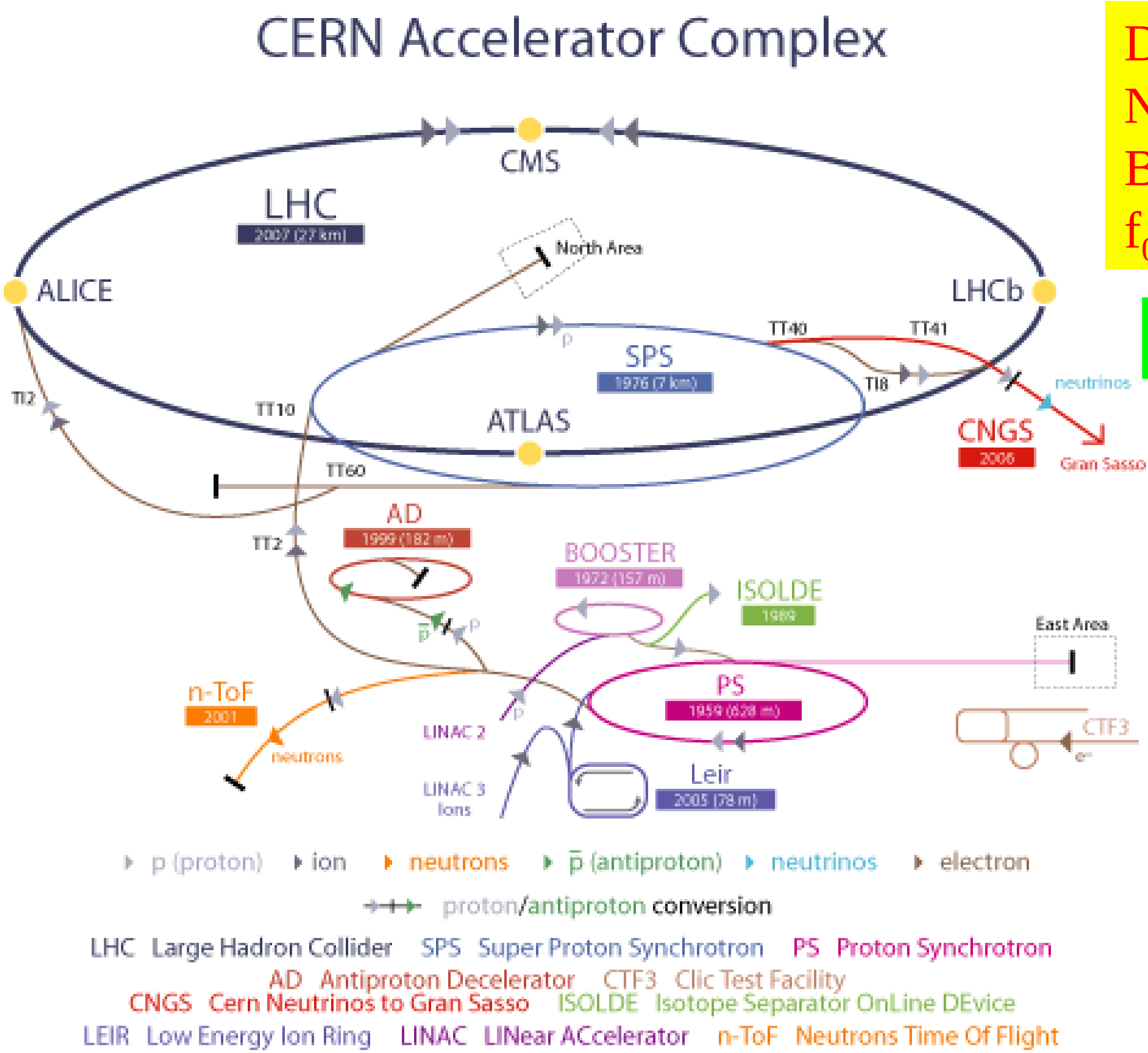
- For detectors close to beams and/or exposed to harsh conditions estimate radiation levels thoroughly. (One may see less up-time than originally planned but much harsher conditions than anticipated as well).
- Do not count on calculated optics, perfect alignment, ideal running conditions. The real machine is difficult. (In the end radiation resistance was achieved using efficient shielding etc. and it was "just sufficient").
- Be ready for surprises. (E.g. there were unexpected proton satellites. Also running at compromised geometrical acceptance (85% in 2005-2007 as compared to 97% in case of ideal optics) turned out to be a major limiting factor in achieving high precision. Background underestimation was remedied by additional sheilding and dynamic pedestal subtraction.)
- Use more than one method for luminosity determination. This will help in reducing the systematics. (E.g. using wide angle Compton events measured with a different detector component and having different systematics).
- You never have too many slow control and cross calibration systems, especially in harsh environmnets that you cannot reproduce but with real beam.
- The pile-up was expected and well handled.

# The Large Hadron Collider - CERN



# The Large Hadron Collider - CERN

- p → ← p at √s = 14 TeV, 25 ns between collisions




Design lum: $10^{34}$ cm$^{-2}$s$^{-1}$

$N_p$ = protons/bunch ($10^{11}$)

B = number of bunches (2808)

$f_0$ = 11 kHz

Low lum phase: $10^{32}$ cm$^{-2}$s$^{-1}$

# Absolute and relative luminosity measurements

- **Strategy:**
  - Measure the absolute luminosity with a precise method at optimal conditions (experiments, machine).
  - Provide relative (real time) luminosity measurements using dedicated luminosity monitors provided either by the experiments or by the machine.
  - Calibrate the luminosity monitors with the absolute luminosity measurement.

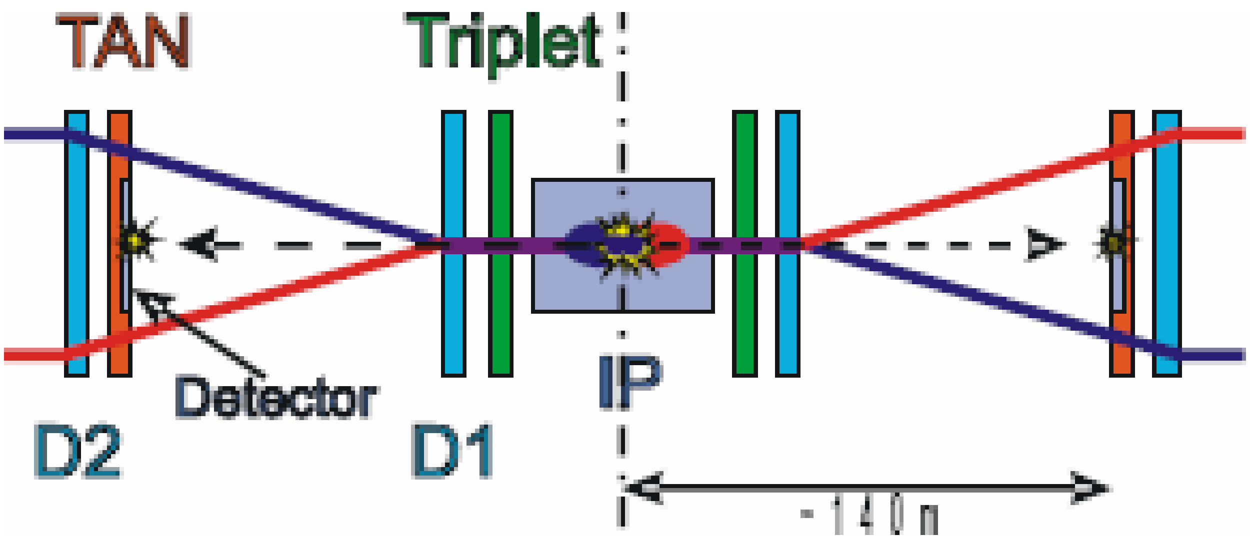
- **Expected Uncertainty:**

First values expected to be in the 20 % range.

Aiming to a precision well below 5 % after some years.

# Collision Rate Monitors at LHC
# Real time measurement - machine

- Devices that measure the rate of a particular group of events at LHC.
- E.g. intercept neutrals at a location where the two proton beams are sufficiently deviated by the bending magnets D1 and D2.
- Absorbers made of copper several meters long, the TANs, are installed just in front of the D2 magnets.




- Fast Ionization Chambers (FIC) to be installed inside the TANS for IP1 and IP5.
- Solid state (CdTe) detectors at IP2 and IP8.

Need to withstand high radiation loss and resolve p-p events bunch by bunch.

# Absolute luminosity measurement – machine parameters

## Determination of the overlap integral (pioneered by Van der Meer @ISR)

**Absolute luminosities for head-on collisions based on beam intensities and dimensions can be estimated to within 20-30% and potentially much better with special effort.**

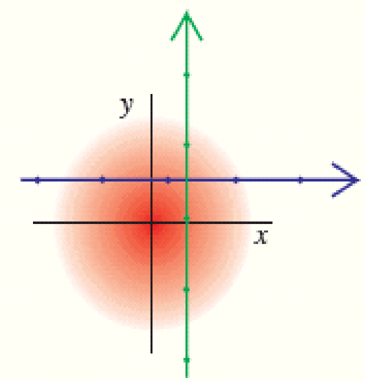
**Luminosity with separation**

$$\frac{\mathcal{L}}{\mathcal{L}_0} = \exp\left[-\left(\frac{\delta x}{2\sigma_x}\right)^2 - \left(\frac{\delta y}{2\sigma_y}\right)^2\right]$$

| $\frac{\delta x}{\sigma_x}$ | $\frac{\delta y}{\sigma_y}$ | $\frac{\mathcal{L}}{\mathcal{L}_0}$ |
|---|---|---|
| 0 | 0 | 1 |
| 1/2 | 0 | 0.9394 |
| 1/2 | 1/2 | 0.8825 |
| 1 | 0 | 0.7788 |
| 1 | 1 | 0.6065 |
| 2 | 0 | 0.3679 |
| 2 | 2 | 0.1353 |

**Special calibration runs will improve the precision of the determination of the overlap integral. About 1% was achieved at ISR. Less than 5% accuracy might be possible at LHC but it will take some time.**

**Commissioning : simple, orthogonal x / y scan**

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# Absolute Luminosity Measurements -Experiments

**Goal: Measure $L$ with $\lesssim$ 3% accuracy (long term goal)**

**Two major approaches:**

- Use rates of well-calculable processes (EW, QED, QCD). Theory cross sections: W/Z (5-10 %) – high rate , $\mu\mu$ production via two $\gamma$ exchange (~1%) – low rate & difficult efficiency.

- Elastic(inelastic) scattering (measure at lower inst. luminosities)
  - *Optical theorem: forward elastic rate + total inelastic rate:*
  - *Luminosity from Coulomb Scattering*
  - *Hybrids*
    - Use $\sigma_{tot}$ measured by others
    - Combine machine luminosity with optical theorem

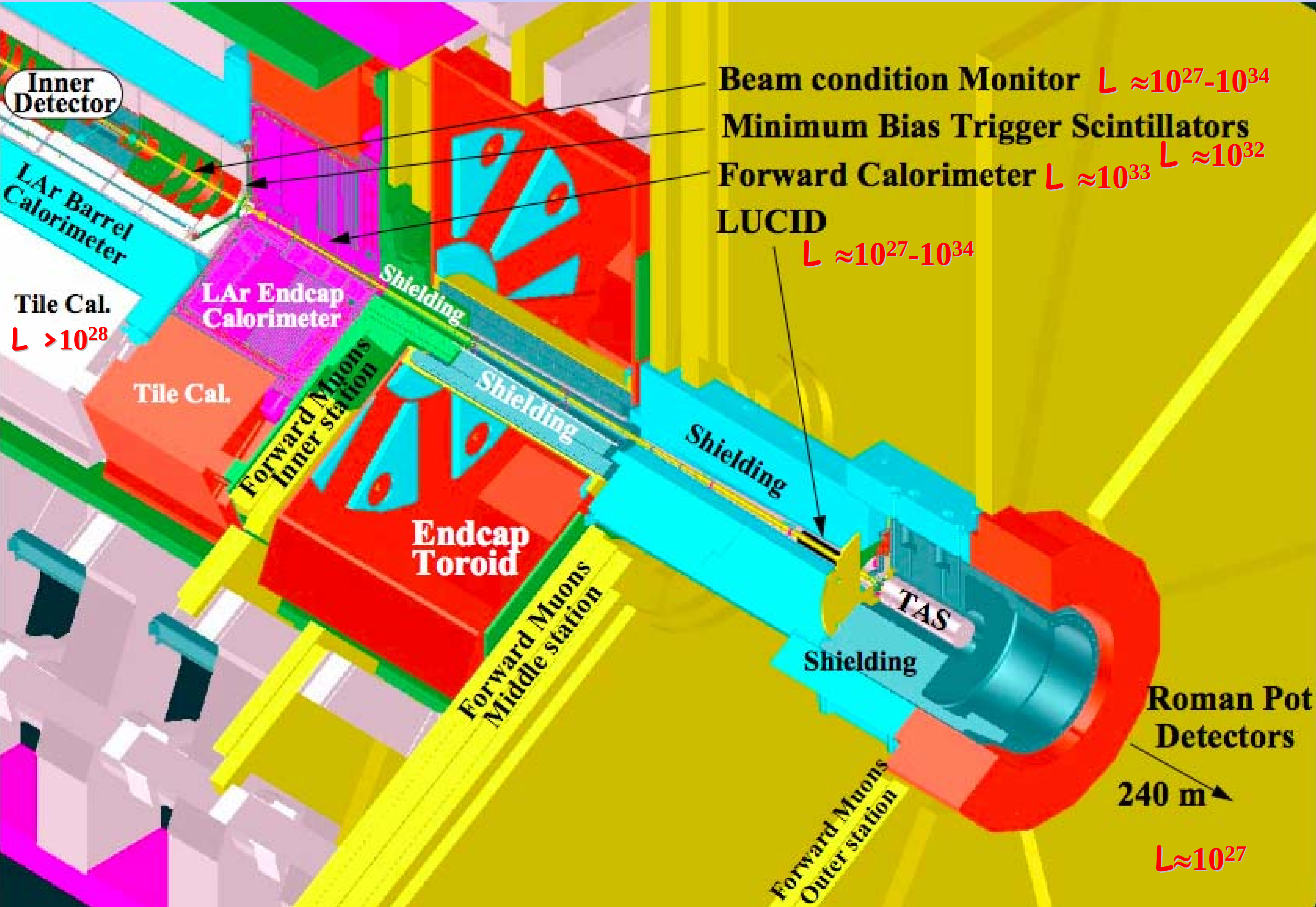
**Roman Pots, TOTEM**
**~ few % but demanding beam conditions, special runs**

# Luminosity Measurements -Experiments

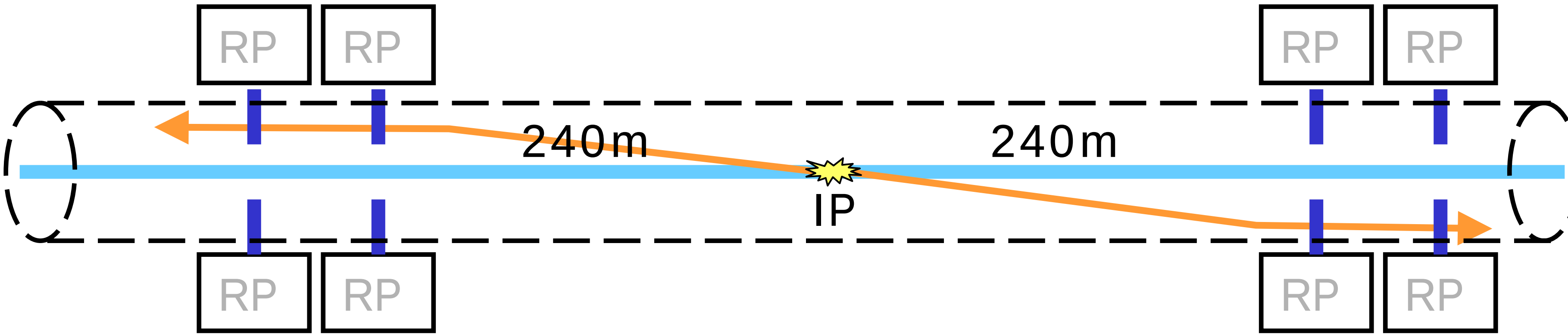
- **ATLAS**
- **Real Time**
  - *LUCID (Cherenkov counter)*
- **Absolute**
  - *Roman Pots (at lower luminosity) - extrapolate*
  - *Rates of physics processes (at all luminosities)*

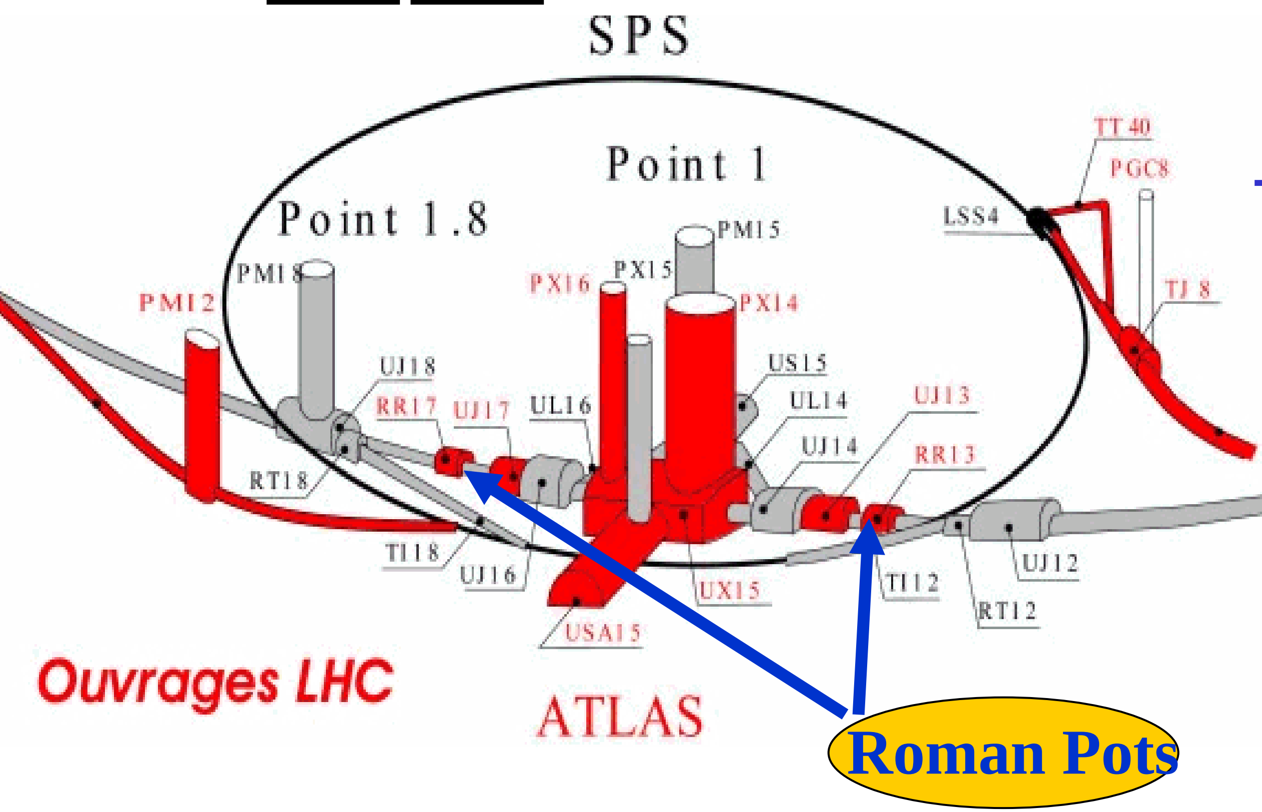
- **CMS**
- **Real Time**
  - *Hadronic Forward Calorimeter (HF)*
  - *Pixel Telescope ( to be approved )*
- **Absolute**
  - *TOTEM (at lower luminosity) - extrapolate*
  - *Rates of physics processes (at all luminosities)*

# Forward Detectors @ ATLAS



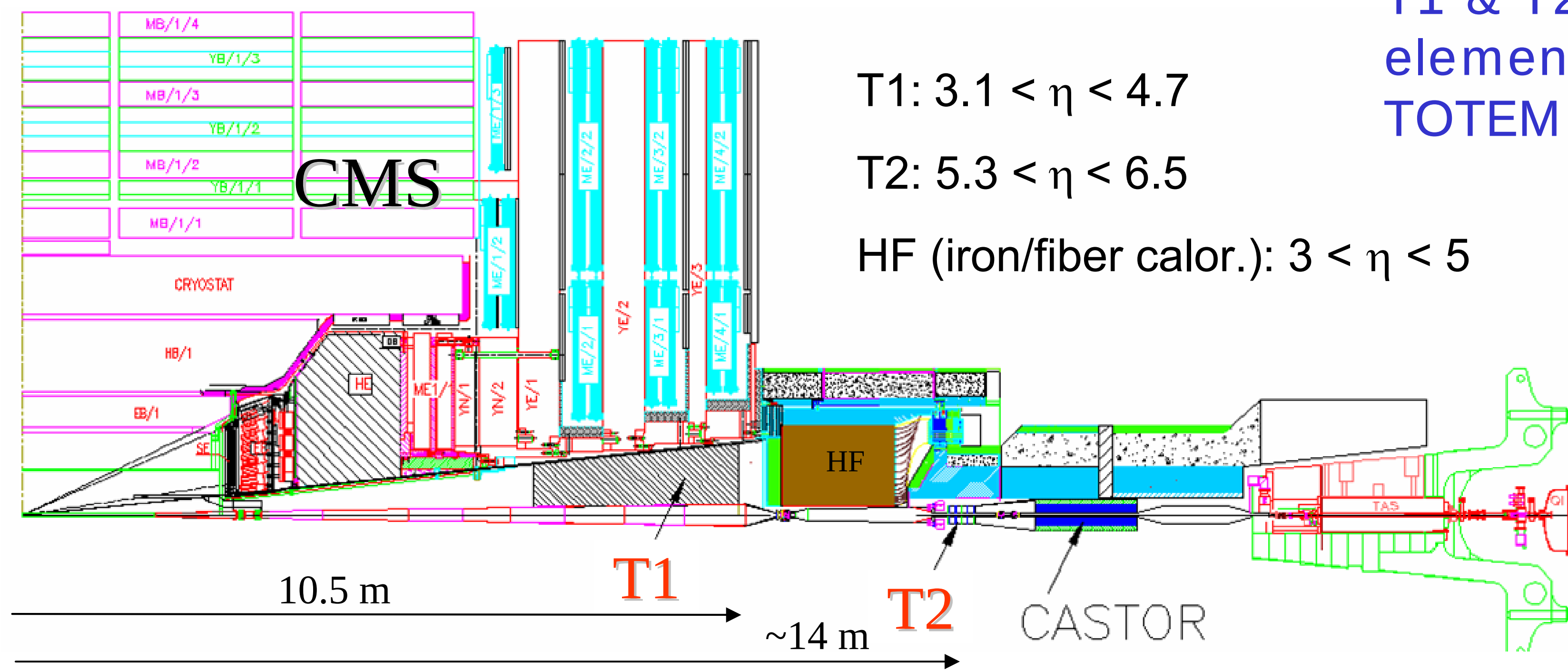
# Roman Pots for ATLAS




**Two Roman Pot stations with top and bottom vertical pots, separated by 4 m, at each side 240 m from IP1**

# TOTEM Detector Configuration

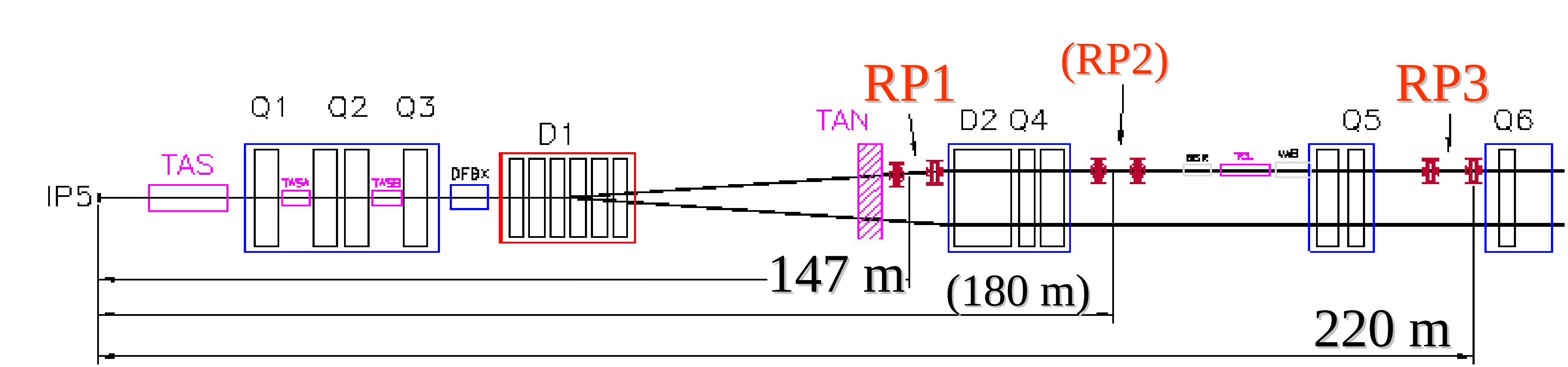



T1: $3.1 < \eta < 4.7$

T2: $5.3 < \eta < 6.5$

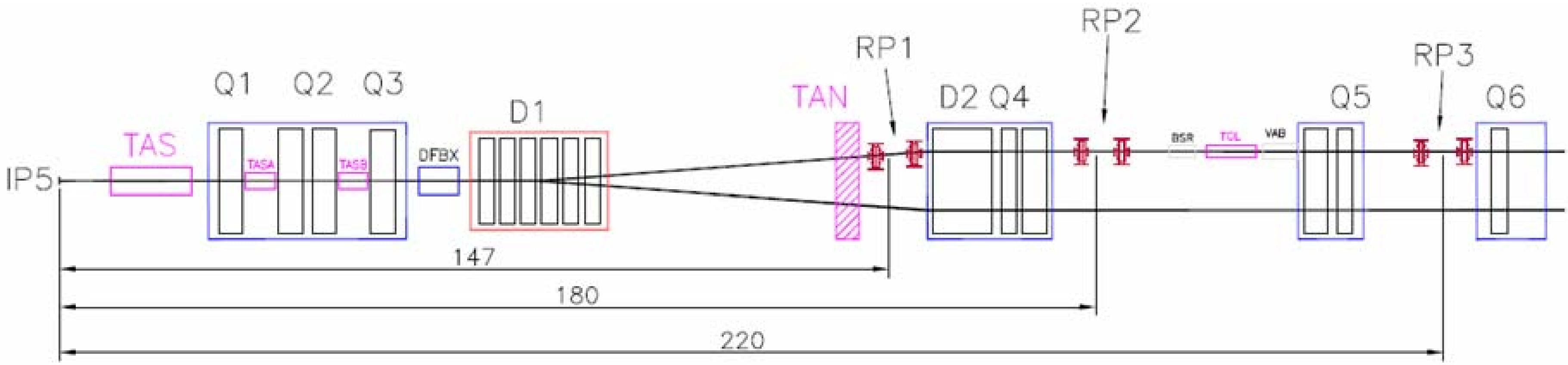
HF (iron/fiber calor.): $3 < \eta < 5$

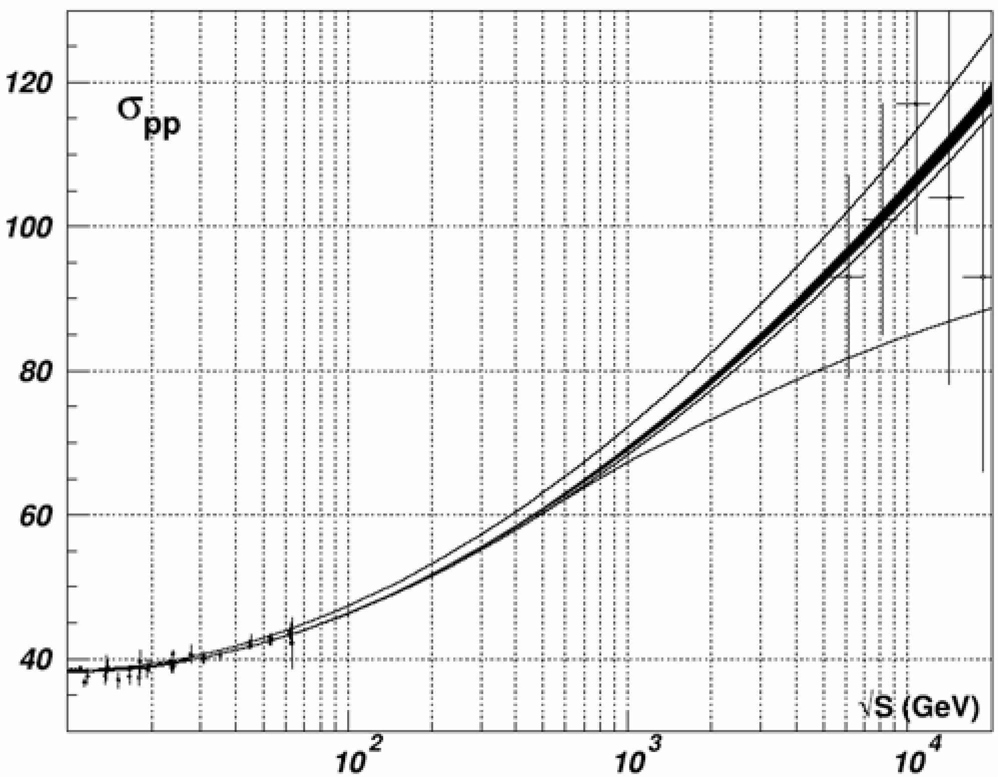
T1 & T2 are elements of TOTEM




**Symmetric experiment: all detectors on both sides!**

# TOTEM




## Luminosity Independent Method

$$\sigma_{tot} = \frac{16\pi}{(1+\rho^2)} \frac{(dN_{el}/dt)_{t=0}}{N_{el}+N_{inel}}$$

Measure elastic scattering in Roman Pots and inelastic in T1 and T2. Should give result good to a ~few %.

# Conclusions

- Luminosity measurements at hadron colliders are very challenging.
- 1-3 % uncertainty at HERA, ~6% uncertainty at the Tevatron (there is room for improvements).
- We are enjoying and utilizing every single collision and look forward to many-many more!!
- We expect that the lessons learned from HERA and the Tevatron will be very useful for LHC which is to start very soon. The expected luminosity uncertainty at the LHC is of the order of 20% in the beginning and well below 5% after some years.

# Thank you!

- To the organizers for a very informative and stimulating Conference.
- Several Colleagues from the Tevatron, HERA and LHC for discussions on the information presented here. In particular:
  - *B. Casey, M. Corcoran, Y. Enari, J. Konigsberg, G. Snow, A. Sukhanov, A. Valishev*

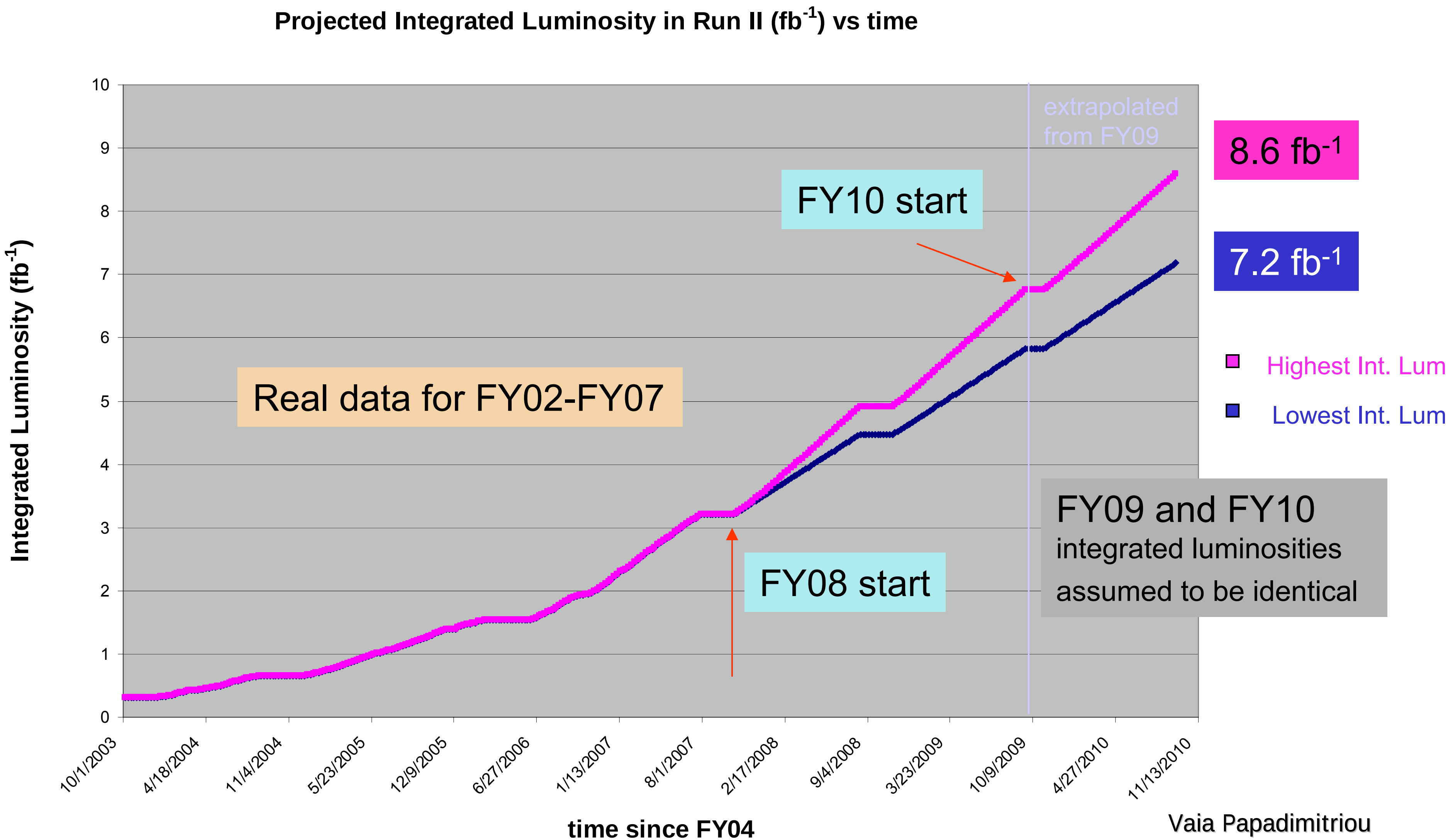
    *(from the Tevatron)*
  - *V. Boudry, S. Levonian, U. Schneekloth, A. Specka*

    *(from HERA)*
  - *H. Burkhardt, P. Grafstrom, V. Halyo, D. Marlow*

    (from LHC)

# Backup Plots:

# Luminosity projection curves for Run II

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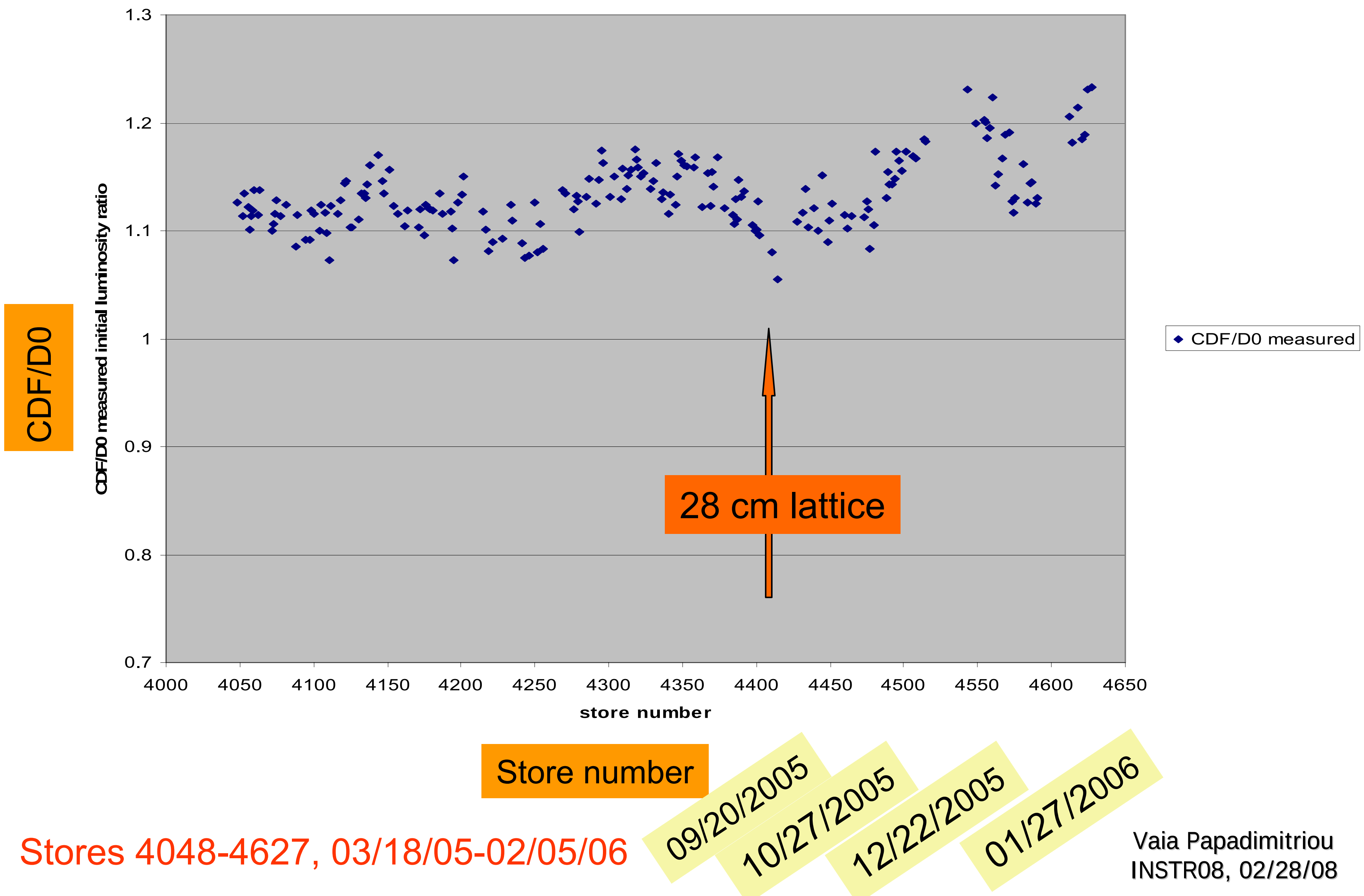
# CDF/D0 init. lum vs store number




Stores 4048-4627, 03/18/05-02/05/06

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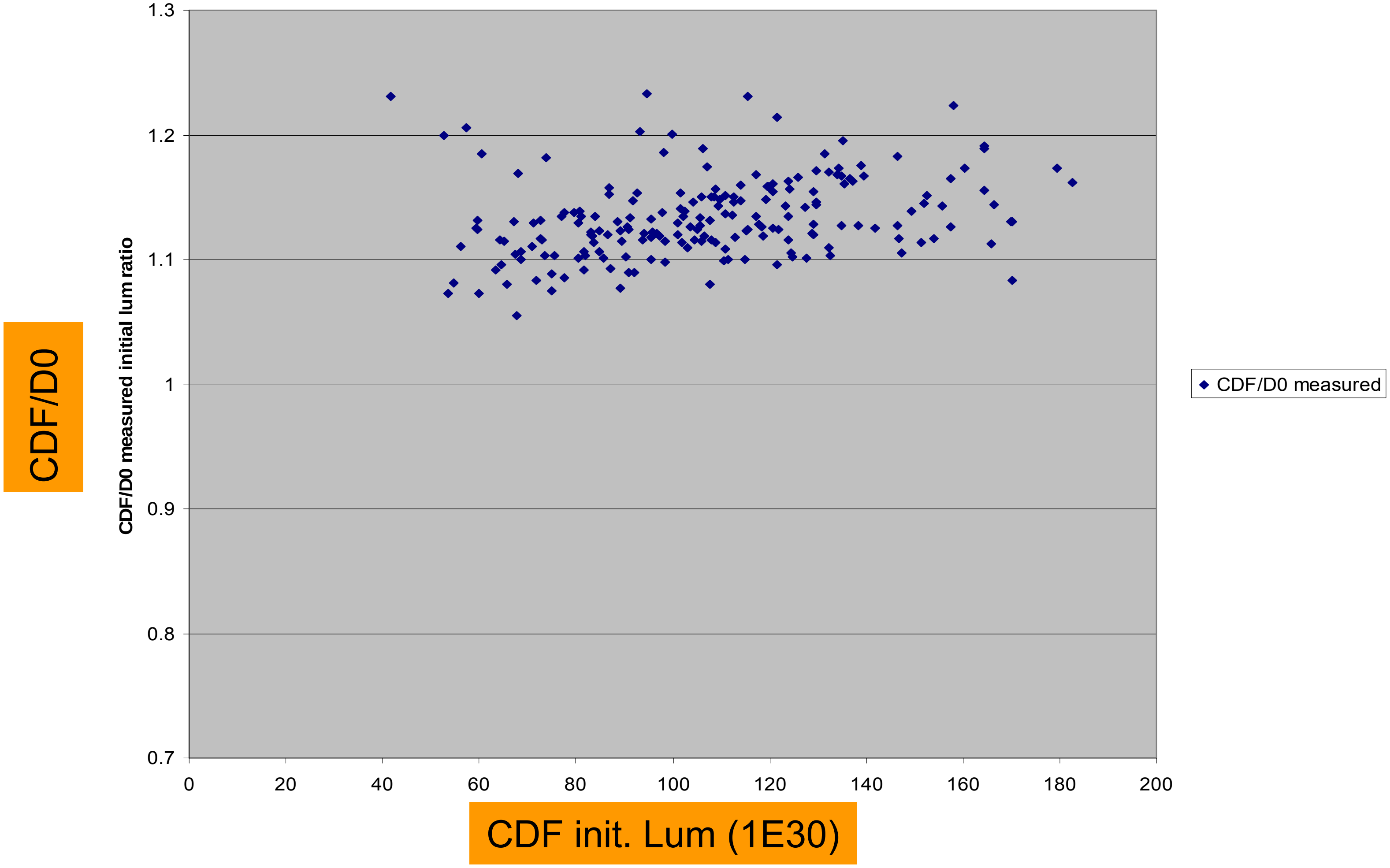
# CDF/D0 init. lum vs CDF init. lum




Stores 4048-4627, 03/18/05-02/05/06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# Hit Counting Method

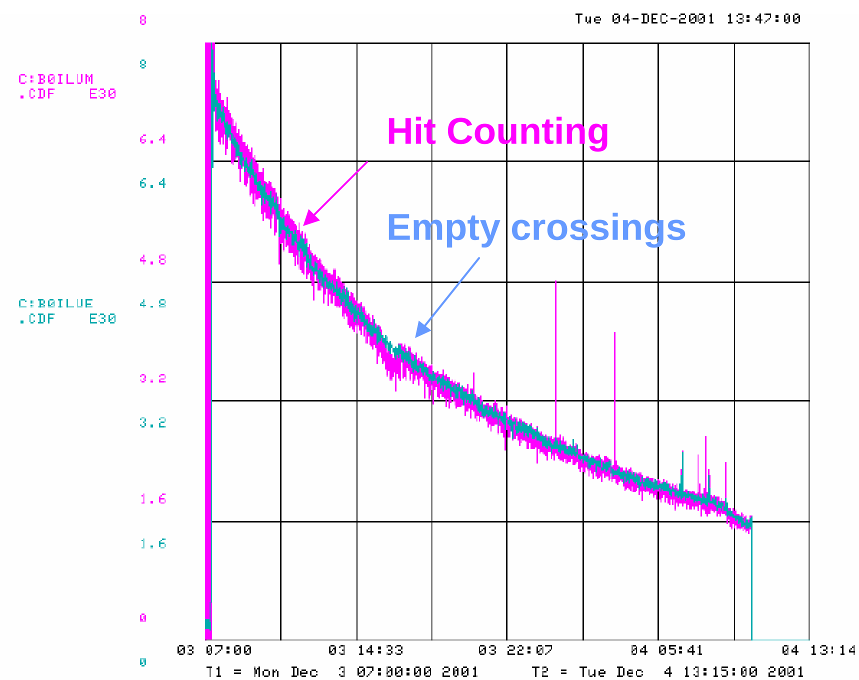
$$\mathcal{L} = \frac{f_{BC}}{\sigma_{in} \cdot \varepsilon_\alpha} \cdot \frac{< N_H >_\alpha}{< N_H^1 >_\alpha}$$

$< N_H^1 >_\alpha$ = avg. # hits for a single p-pbar interaction.

**Measured at low luminosity from 0-bias data**

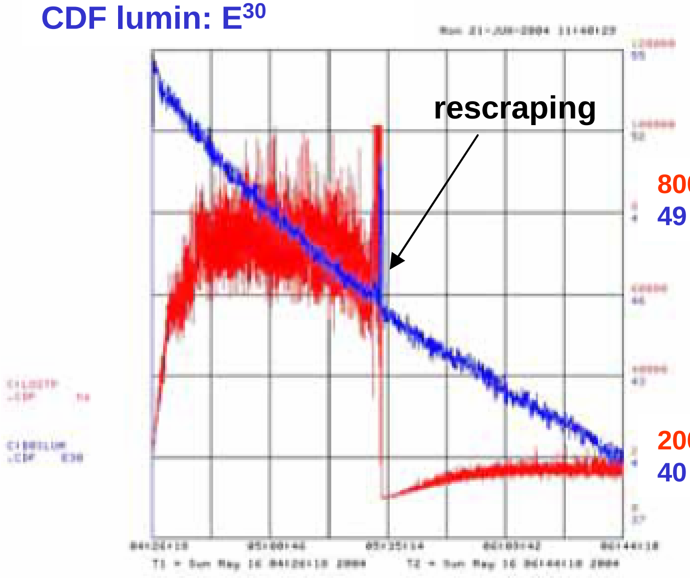
$< N_H >_\alpha$ = measured avg. # hits/bunch crossing

- **We estimate $\varepsilon_\alpha$:**
- **From simulations**
  - *Need all relevant material in CDF*
  - *Need "correct" generator…*
- **From real data**
  - *CLC vs. calorimeters / trackers*
  - *W's*

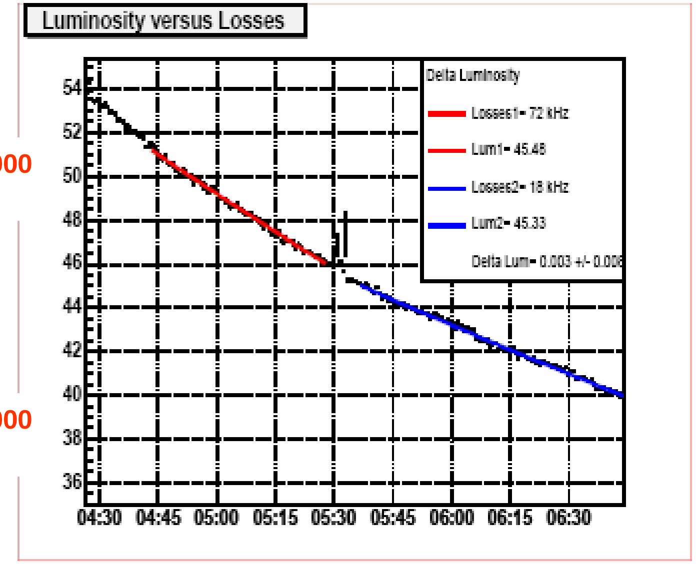


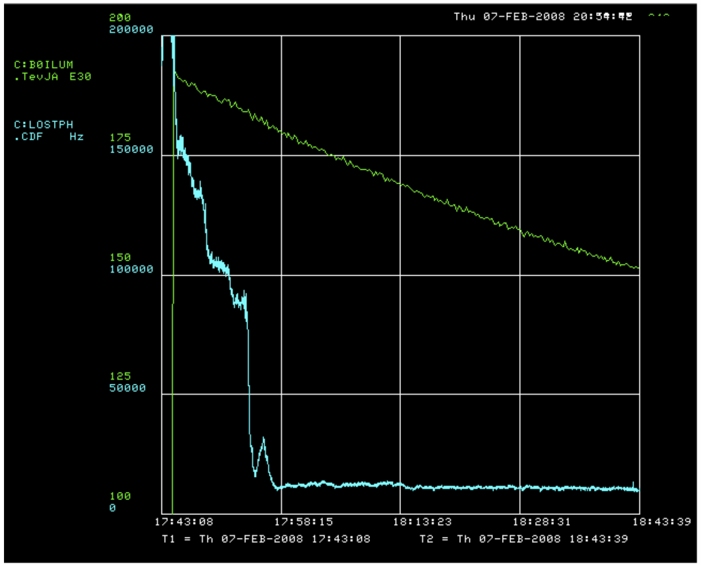
# Beam losses and the CLC

Beam losses at CDF:hz
CDF lumin: $E^{30}$




Time into the store



# Cerenkov light

- Light emitted if $\beta > 1/n$ $\quad$ $\cos\theta = 1/n\beta$
- At $\beta \sim 1$ n needs to be small for small angle emission
- The number of photons emitted per unith path lenght is:

$$\frac{dN}{dx} = 2\pi\alpha \int_{\beta n > 1} \left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right) \frac{d\lambda}{\lambda^2}$$

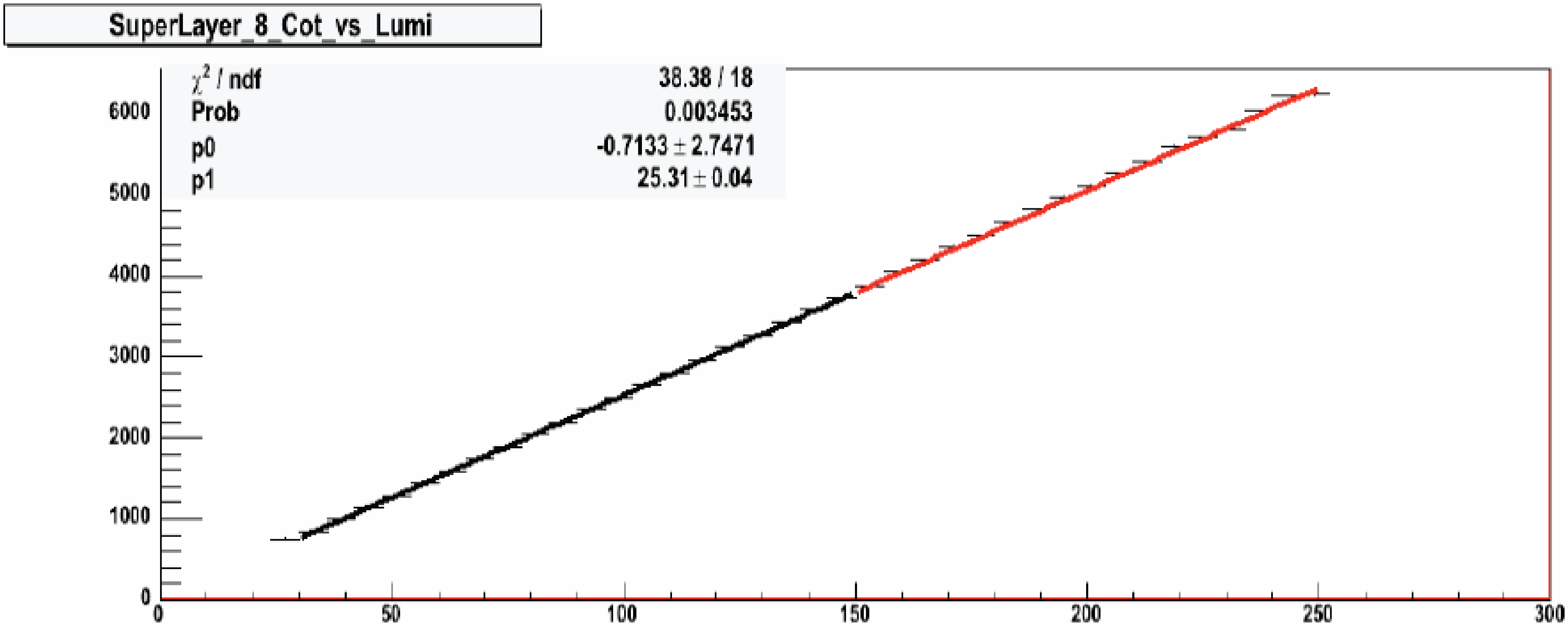
- For $n(\lambda)$ const. over a relevant wavelength interval:

$$\frac{dN}{dx} = 2\pi\alpha \cdot \sin^2\theta \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)$$

- For smaller angles, smaller yields (UV dominated)
- For wavelenghts between 350 to 500 nm:

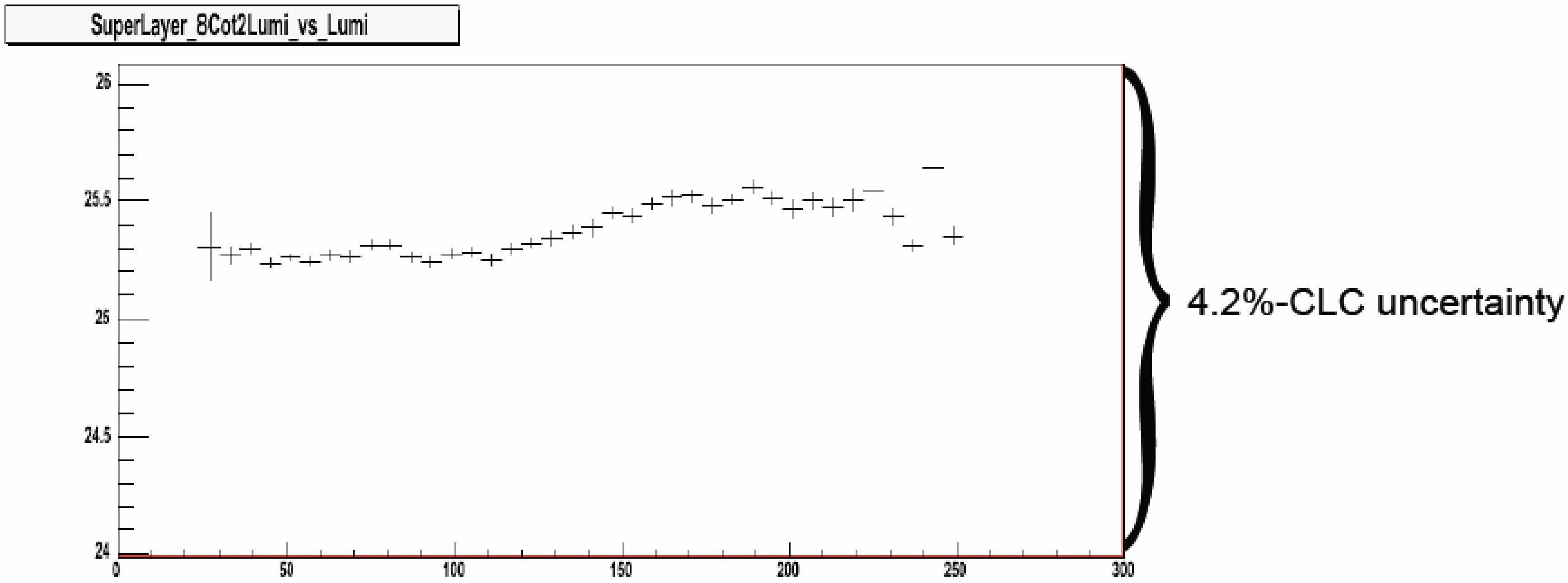
$$\frac{dN}{dx} = 390 \ \sin^2\theta \quad \text{photons / cm}$$

- For scintillators ~ $170$ photons / cm




Here we plot:
SL8 VS B0lum
X axes -> Lum[E30cm-2s-1]
Y axes -> SL8 current
Fit(black) up to 150E30.
Extrapolated(red) to guide the eye.

Data collected in February 2007
Period contains the record store 5245
and few other stores with Lumi>280E30




Here we plot:
SL8/B0lum VS B0lum
X axes -> Lum[E30cm-2s-1]
Y axes -> SL8/Lum.
Full range is 4.2%. CLC uncertainty

Data collected in February 2007

# CLC Absolute normalization

- Reference detector ($\varepsilon_R \rightarrow 100\%$)    CLC+PLUG: $\varepsilon_R \sim 94\%$

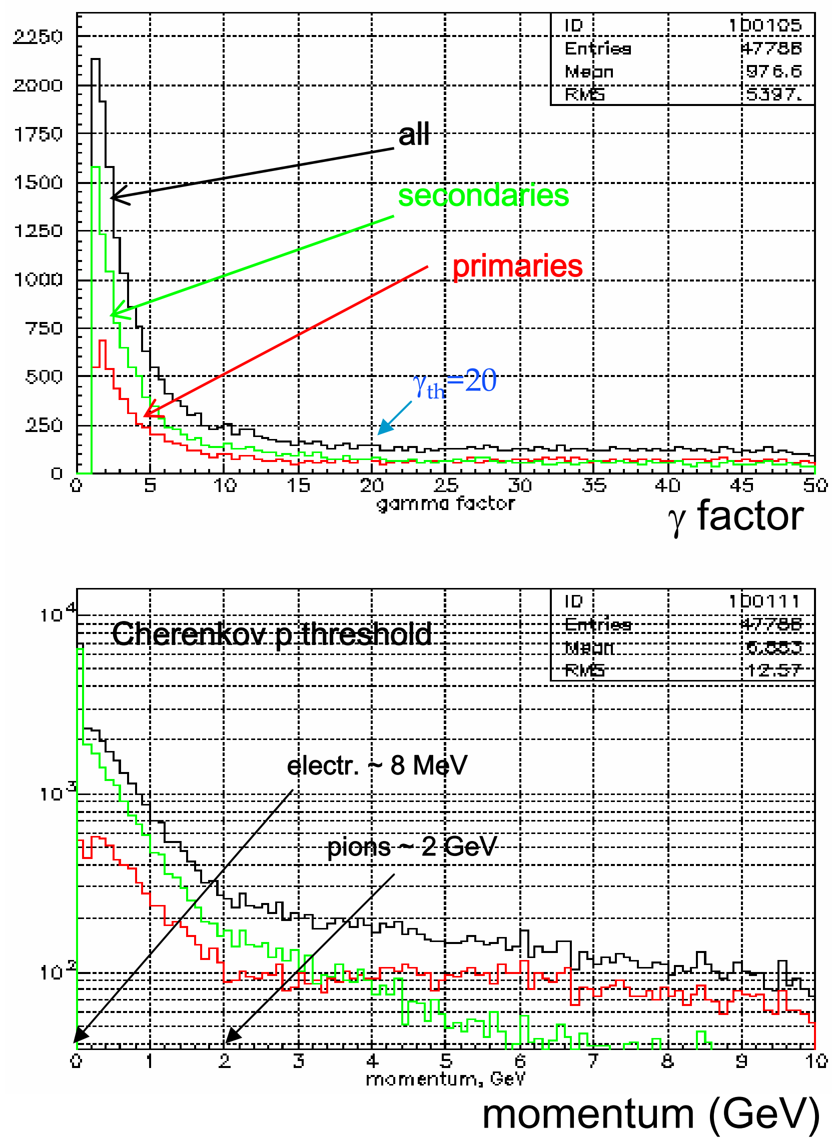
- CLC acceptance :  $$\varepsilon_{clc} = \left( \frac{\varepsilon_{clc}}{\varepsilon_R} \right) \cdot \varepsilon_R \sim 67\% * 94\% = 63\ \%$$

Measure experimentally    Find from simulation

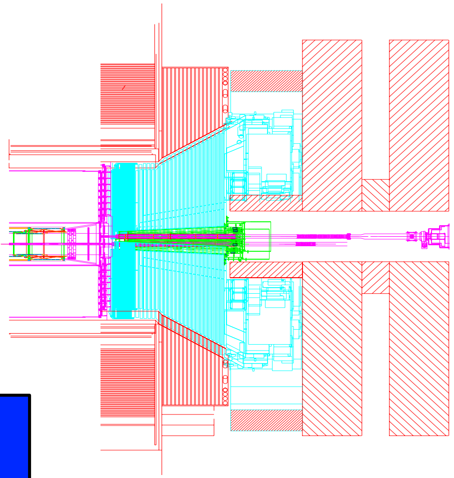
$$\sigma_{\alpha}^{clc} = \sigma_{in} \cdot \varepsilon_{\alpha}^{clc} \sim 39 \text{ mb}$$

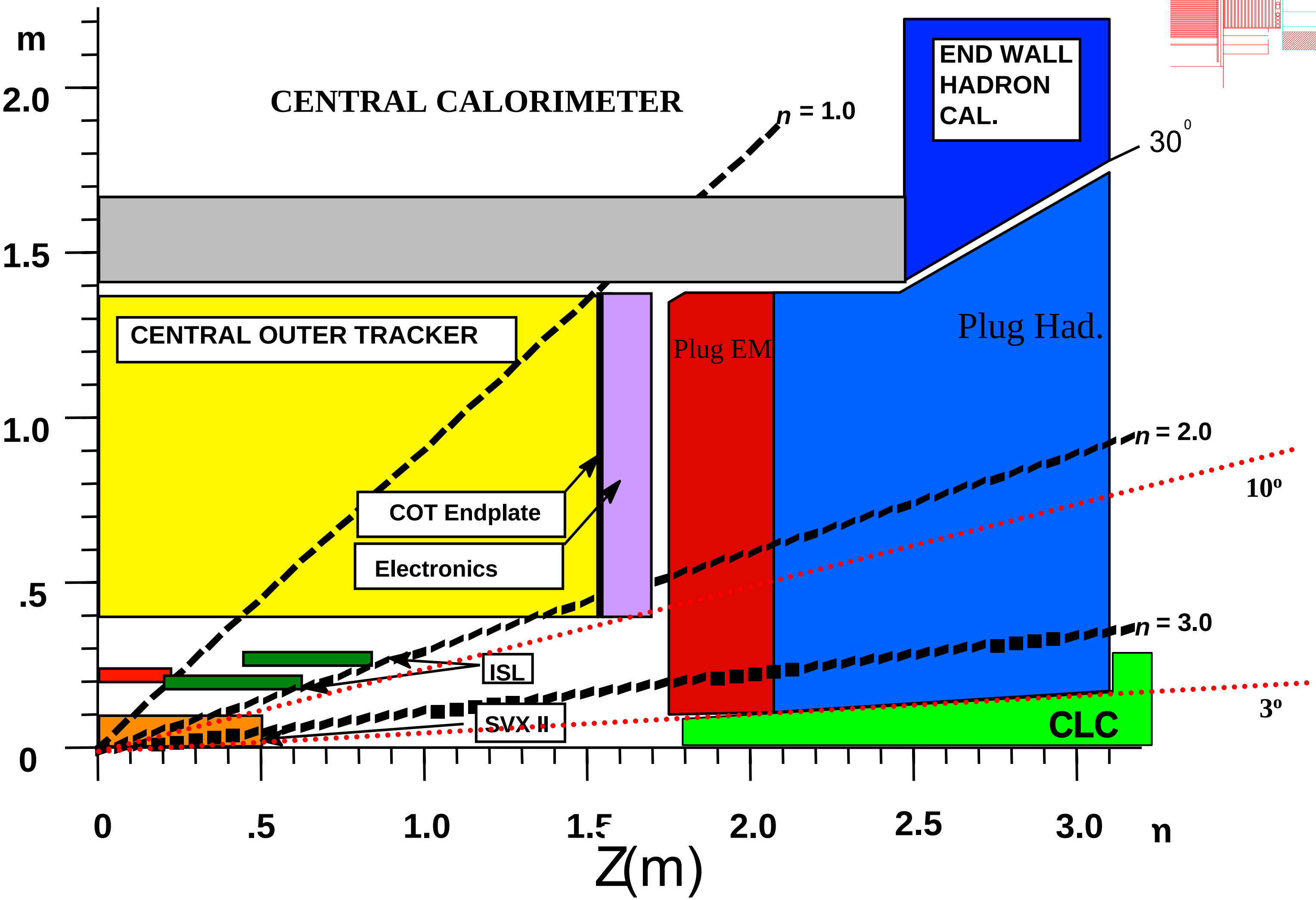
- ~7 % difference with pure CLC simulation. But possibly more accurate…

# Cherenkov Momentum Threshold



# CDF II cross-section

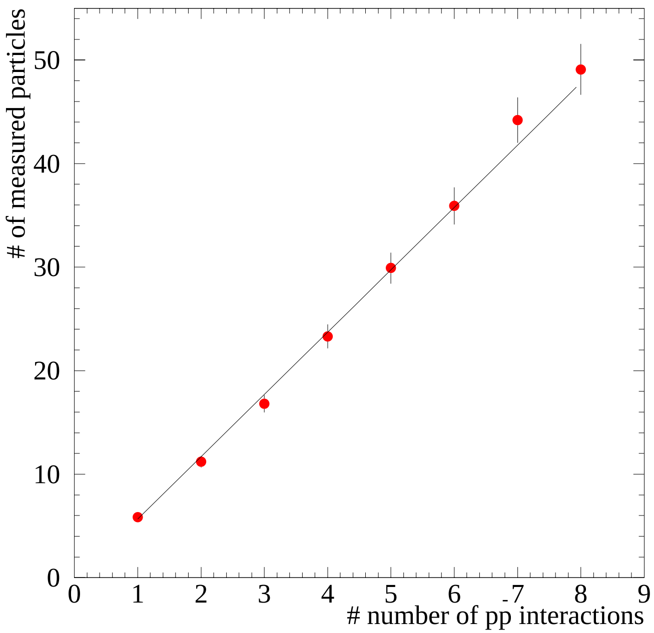




# Pointing Gas Cherenkov Counters

- *Sensitive to the right particles!*
  - → **Much light for particles from interactions**
  - → **Little light from secondaries and soft particles**
    - ***Cherenkov thresholds***
    - ***Shorter paths***
  - → **Not too sensitive to particles from back (halo)**
- *Excellent amplitude resolution*
  - → **Count # hits and # particles**
  - → **No saturation → nice linearity**
- *Excellent time resolution*
  - → **Distinguish # of interactions by time**
- *Robustness*
  - → **Radiation hard / low mass**
- *Disadvantages:*
  - → **Needs gas system (small volume)**
- *New idea, more interesting....*

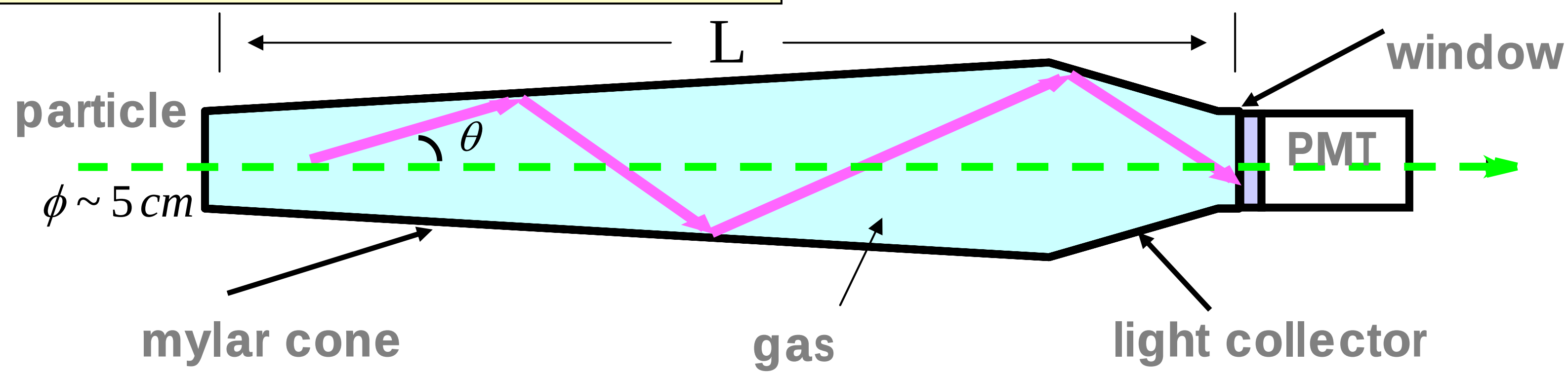
Operate @ L=2*10**32 @ ~6 interactions/beam crossing




From CDF II GEANT simulations w/ real geometry and Cherenkov light tracing

# Cherenkov Counters - prototype

**Light emitted if** $\beta > 1/n$ **UV dominated**




## Cherenkov radiation

- $\cos\theta = 1/(n\beta)$
- $N_{pe} = N_o\, L\, \langle \sin^2\theta \rangle$
- $N_o = 370\ cm^{-1}\, eV^{-1} \int \varepsilon_{col}(E)\,\varepsilon_{det}(E)\, dE$

$\varepsilon_{col}$ - *light collection efficiency*

$\varepsilon_{det}$ - *PMT quantum efficiency*

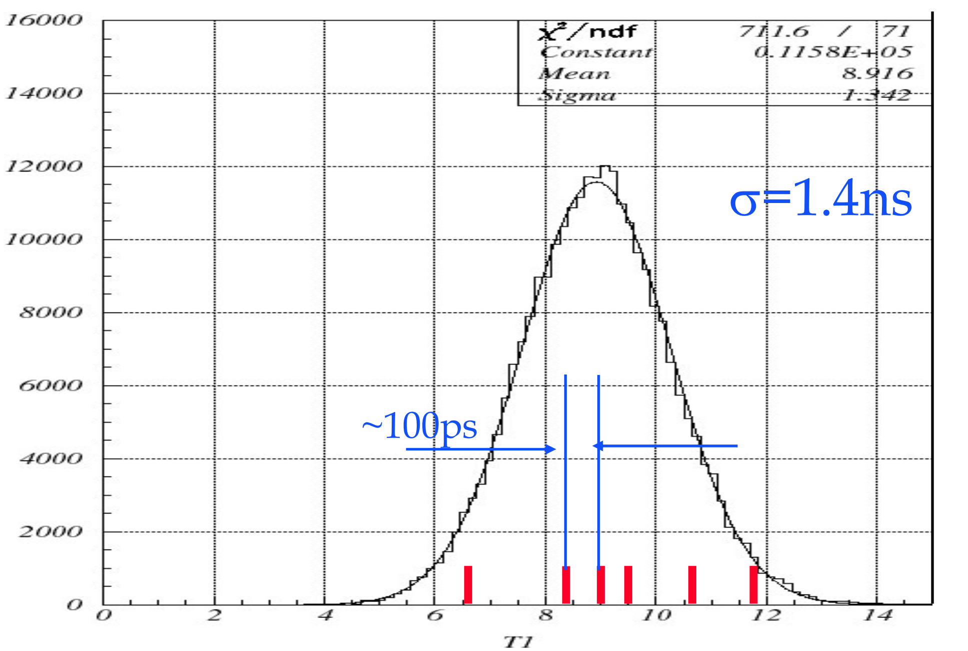
## Isobutane @ 1atm

- $n=1.00143$
- $\theta=3.1^o$
- $\sin^2\theta \sim 0.0027$
- $\langle\varepsilon_{col}\rangle \sim 0.80 \times 0.80 = 0.64$
- $\int \varepsilon_{det}(E)\, dE \sim 0.84$ *(quartz window)*
- $No \sim 200$

*Pions > 2 GeV & Electrons > ~9 MeV* ⇒ ***Np.e.~110*** *(L=200cm)*

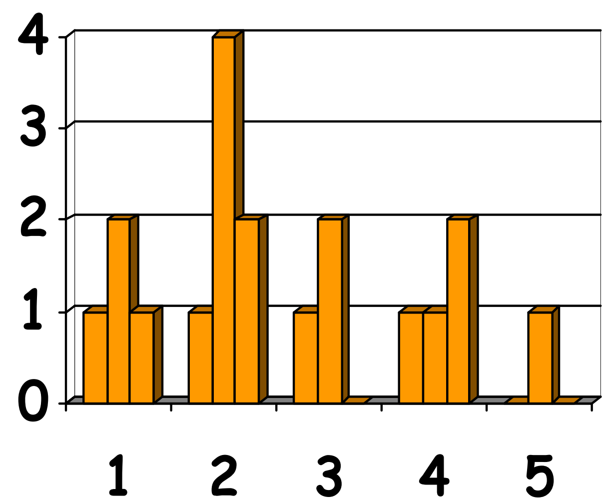
# Luminosity counting time clusters

Measure the number of p-pbar interactions using precise timing




interaction time

Time clusters

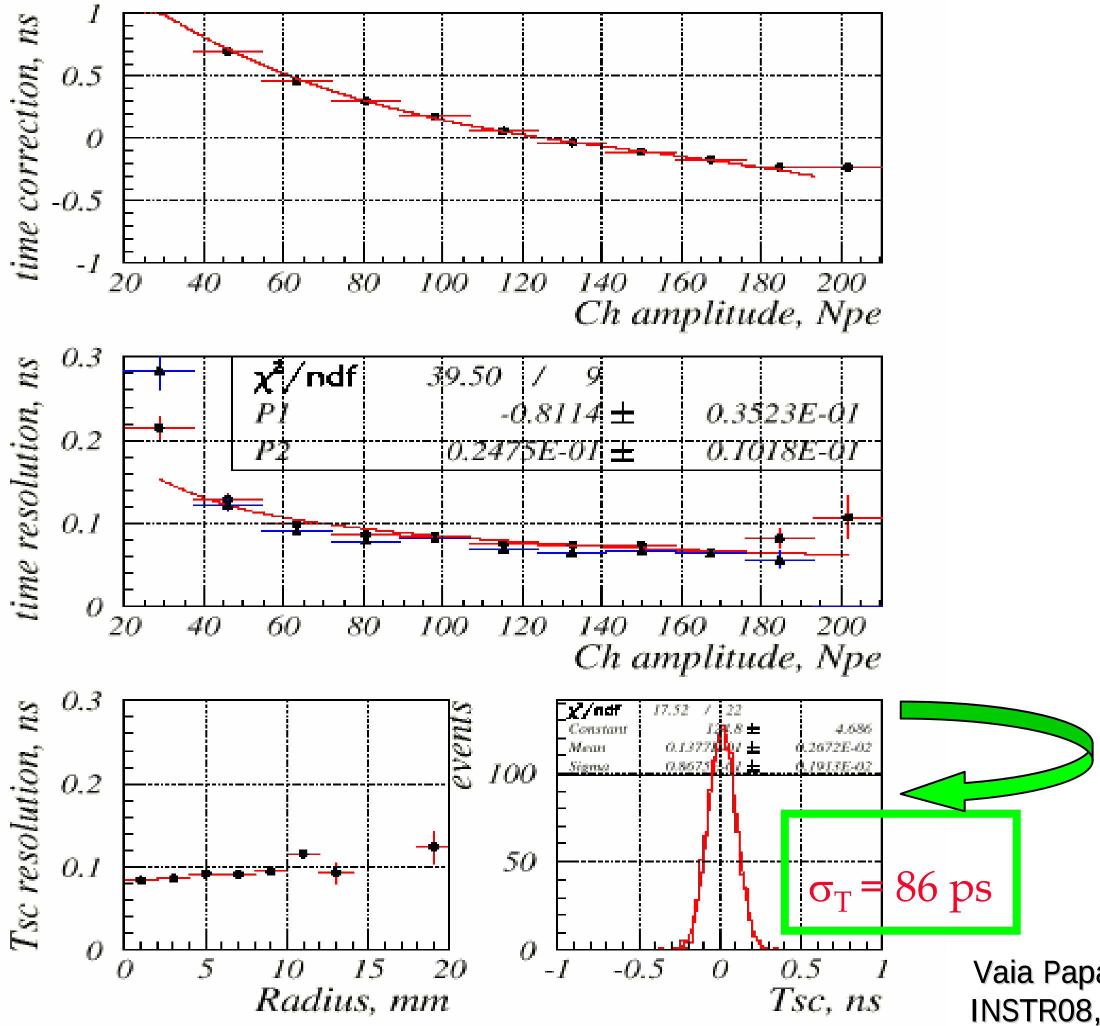



counter arrival times

# Time Resolution - Testbeam

## For the R5800Q PMT

**(75<Amp<125p.e.)**

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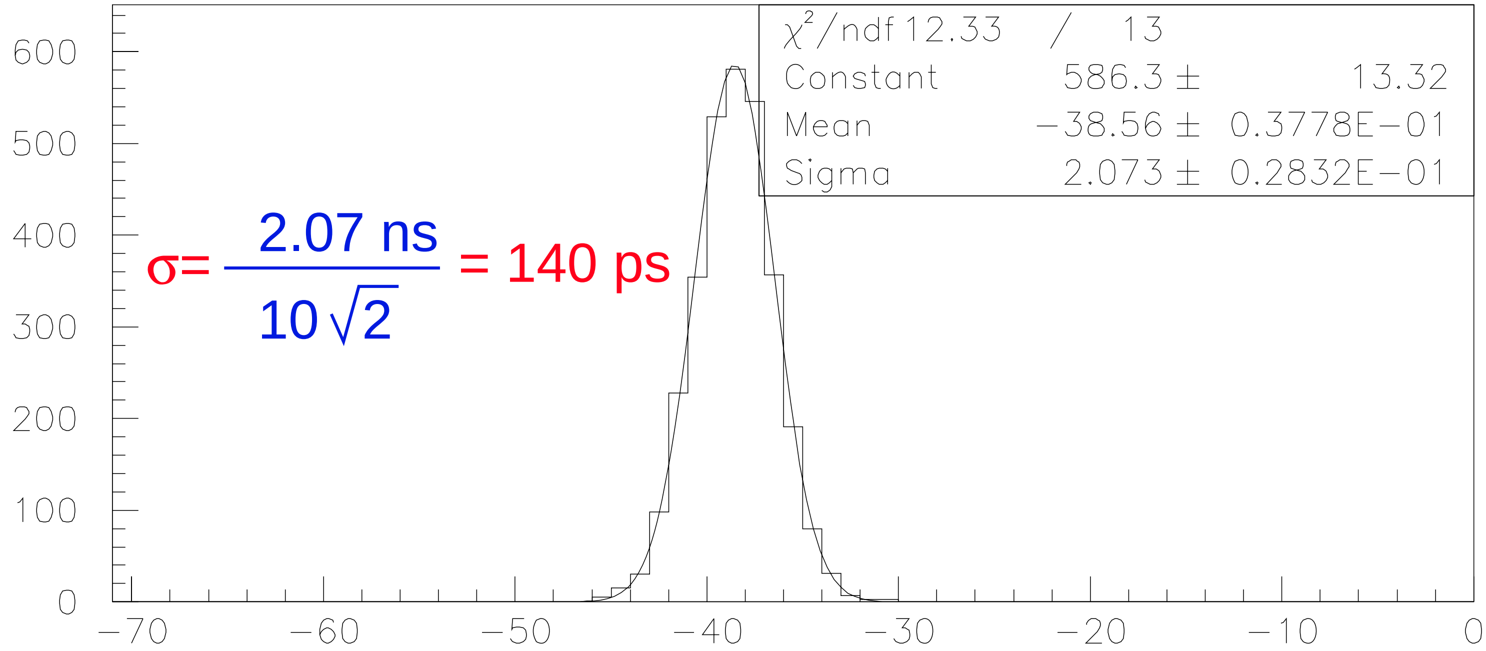
# Quick look at precise timing (higher gain)

## Timing resolution (using stretchers)




$$\sigma = \frac{2.07\ \text{ns}}{10\sqrt{2}} = 140\ \text{ps}$$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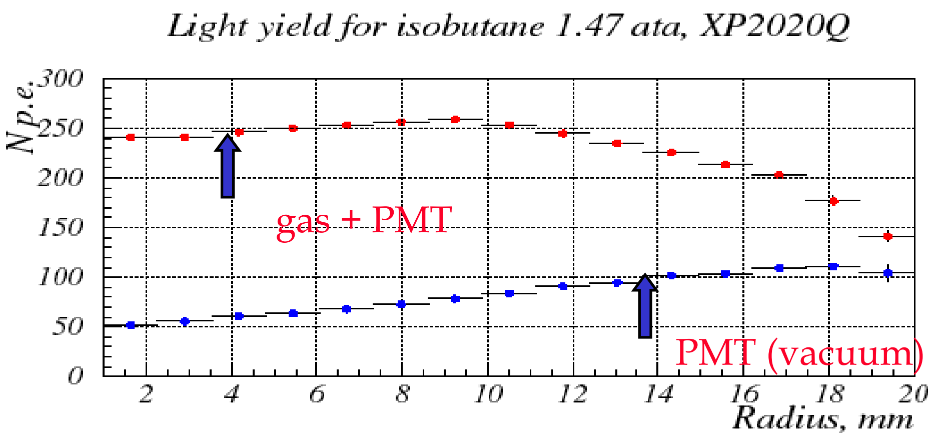
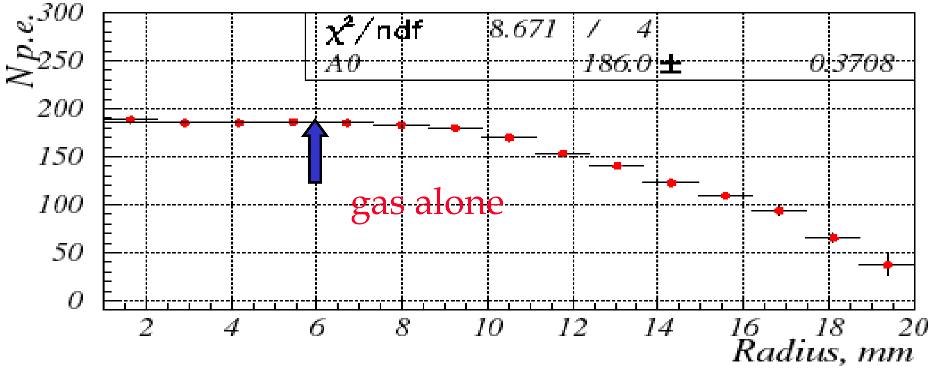
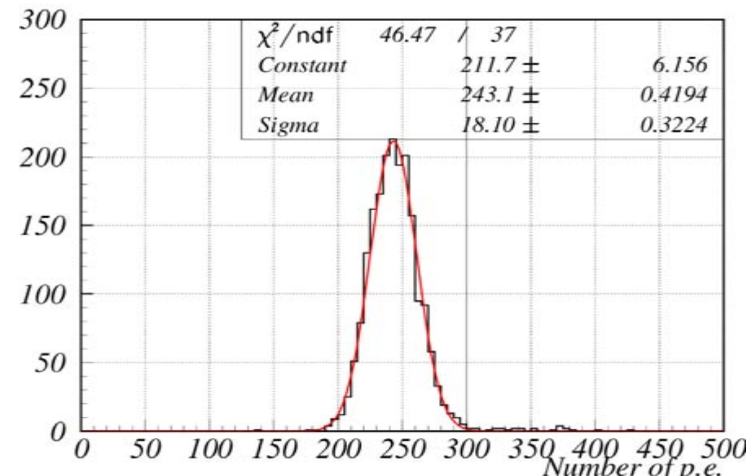
# Isobutane Light Yield - Testbeam

**In isobutane, $C_4H_{10}$,** **(as a function of radius relative to the cone & PMT axis)**




126 photoelectrons @ 1atm.




~ 7% resolution for r<6mm

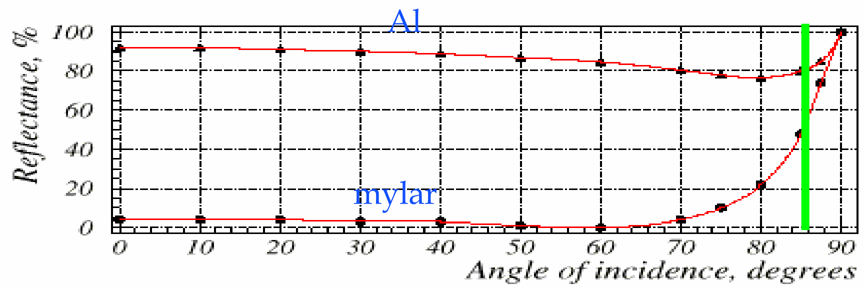
Isobutane

- *Good UV transparency*
- *Largest refractive index at normal P for common gases*
- *Tested other gases:*

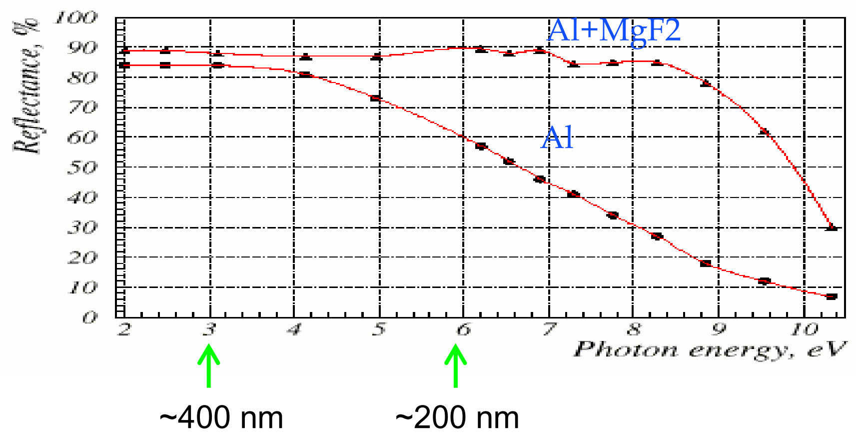
$C_2F_6$ , $C_3F_8$ , $C_4F_8$, $SF_6$, $N_2$ etc.

# Collection Efficiency

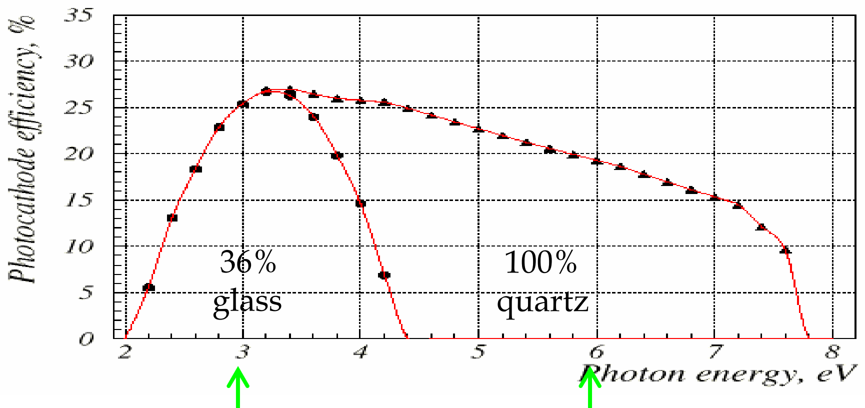
- Cone reflectivity ~80%
  - grazing angles < 4deg.
  - 2 reflections in average




- Collector reflectivity ~80%
  - large angles
  - one reflection




- Quartz window
  - x2-3 UV light collection (cutoff @ ~ 160 nm)
  - rad hard
  - ~ 25 p.e./mm (make thin)

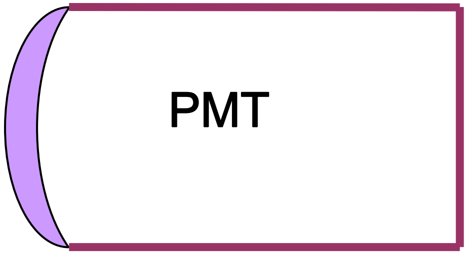


# PMT choice

- **Geometrical constraints**
  - ***~ 25 mm diameter (all layers…)***
    - Larger doesn't fit
    - Smaller requires large angle collector (losses)
- **Performance**
  - ***Quartz window***
    - UV transparent
    - Rad hard
    - Thin
      - *Less light*
      - *Better timing resolution*
  - ***Timing resolution***
    - Sub 100 ps resolution
- **Cost**

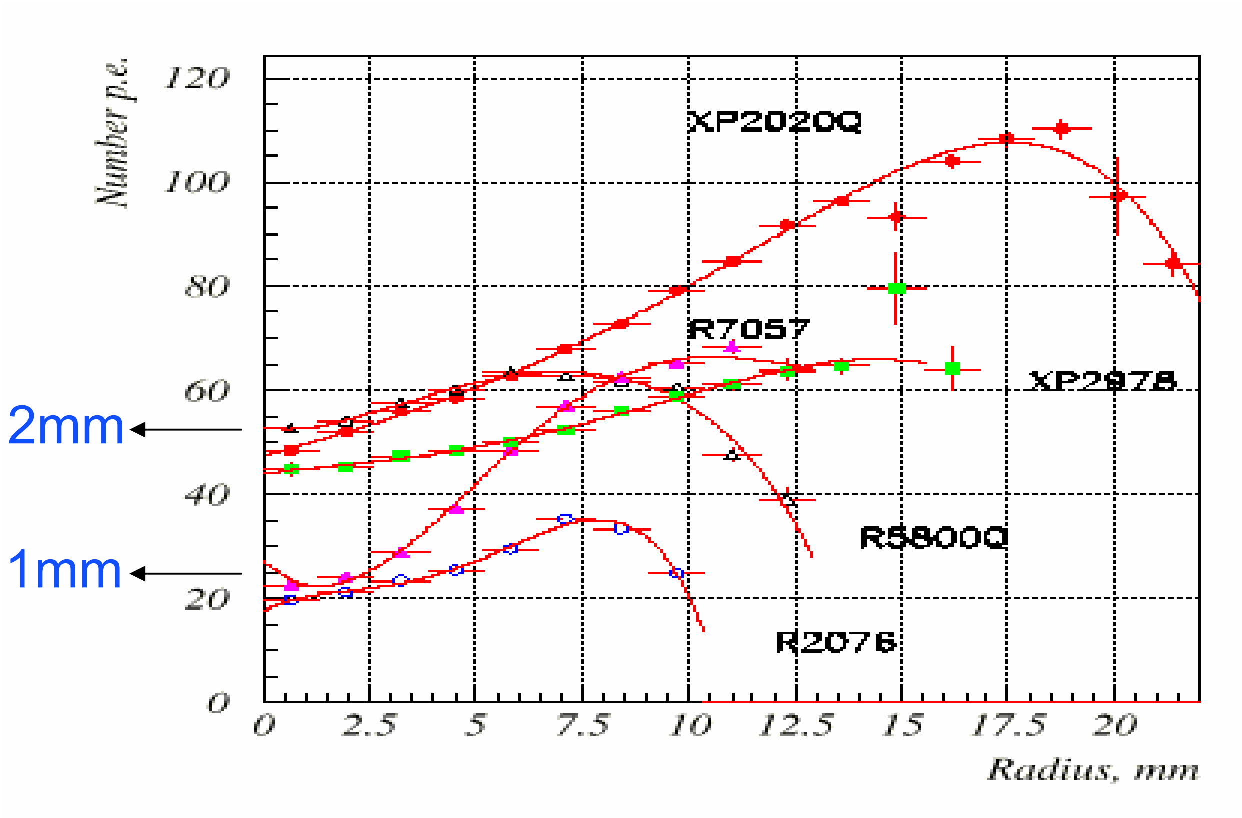
…

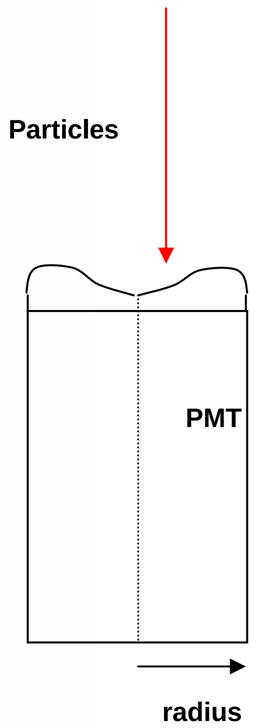
R5800Q Hamamatsu
10-stage / $10^6$ gain
0.8 mm concave-convex quartz window
25 mm x 60 mm
1.5 ns rise-time
~12 ns pulse width



# PMT Window Light Yield - Testbeam

quartz → 25 p.e./mm





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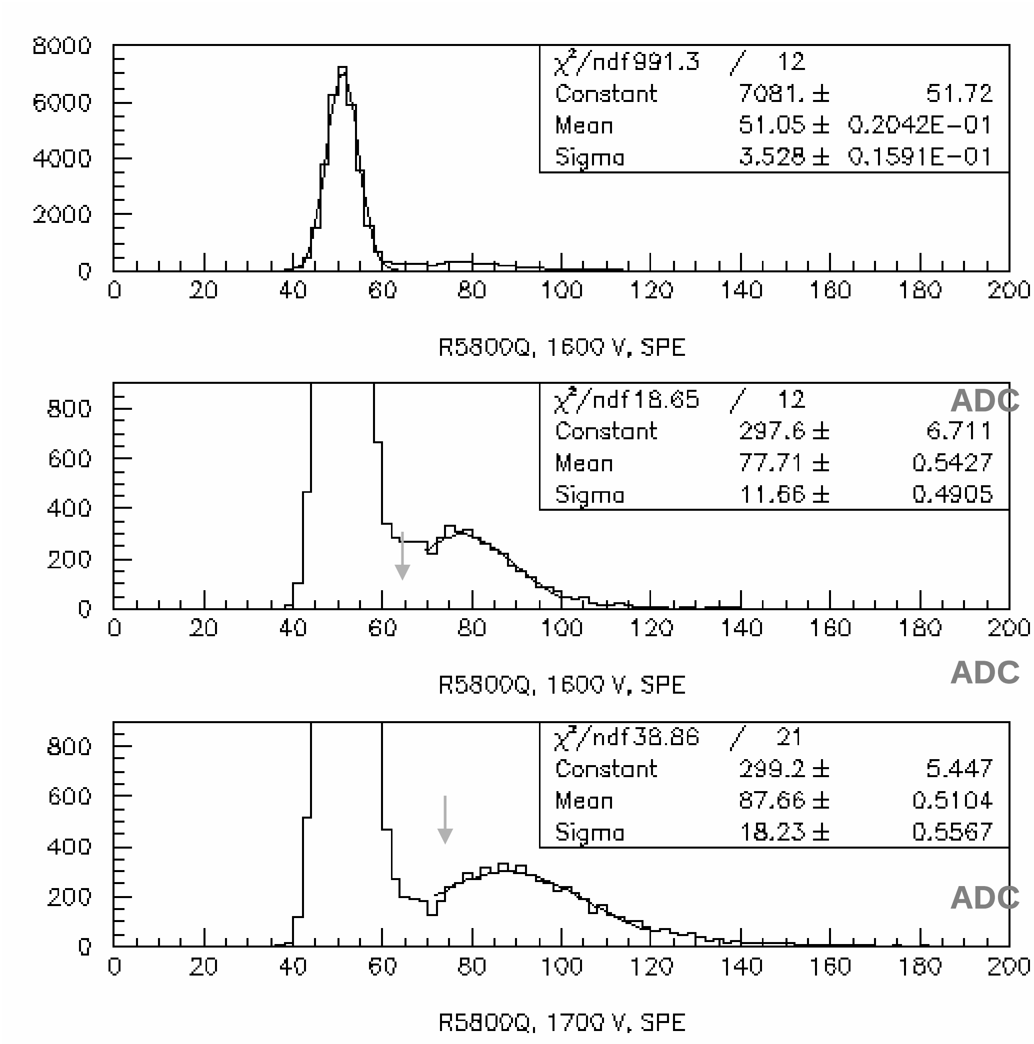
# Single p.e. peak




gain ~ 2.10*6

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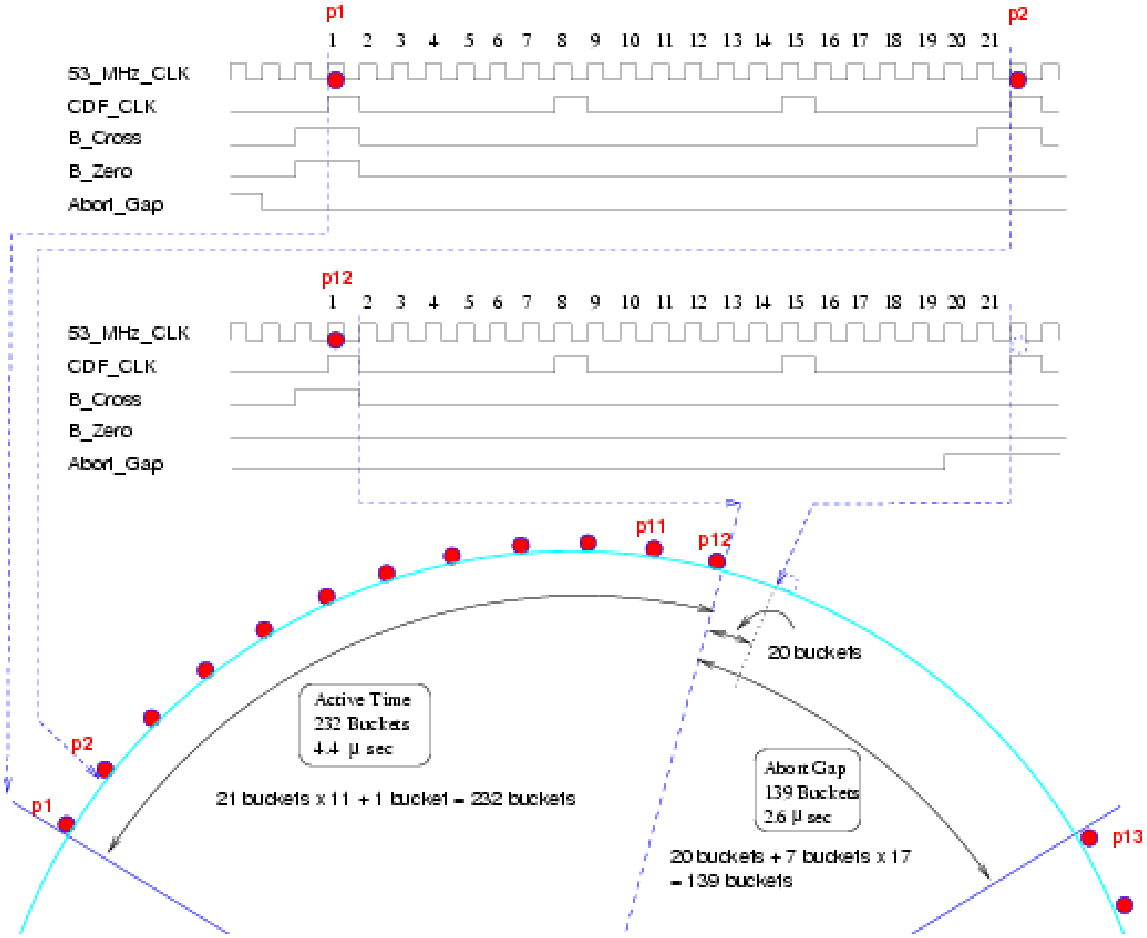
# 36x36 Bunch Structure





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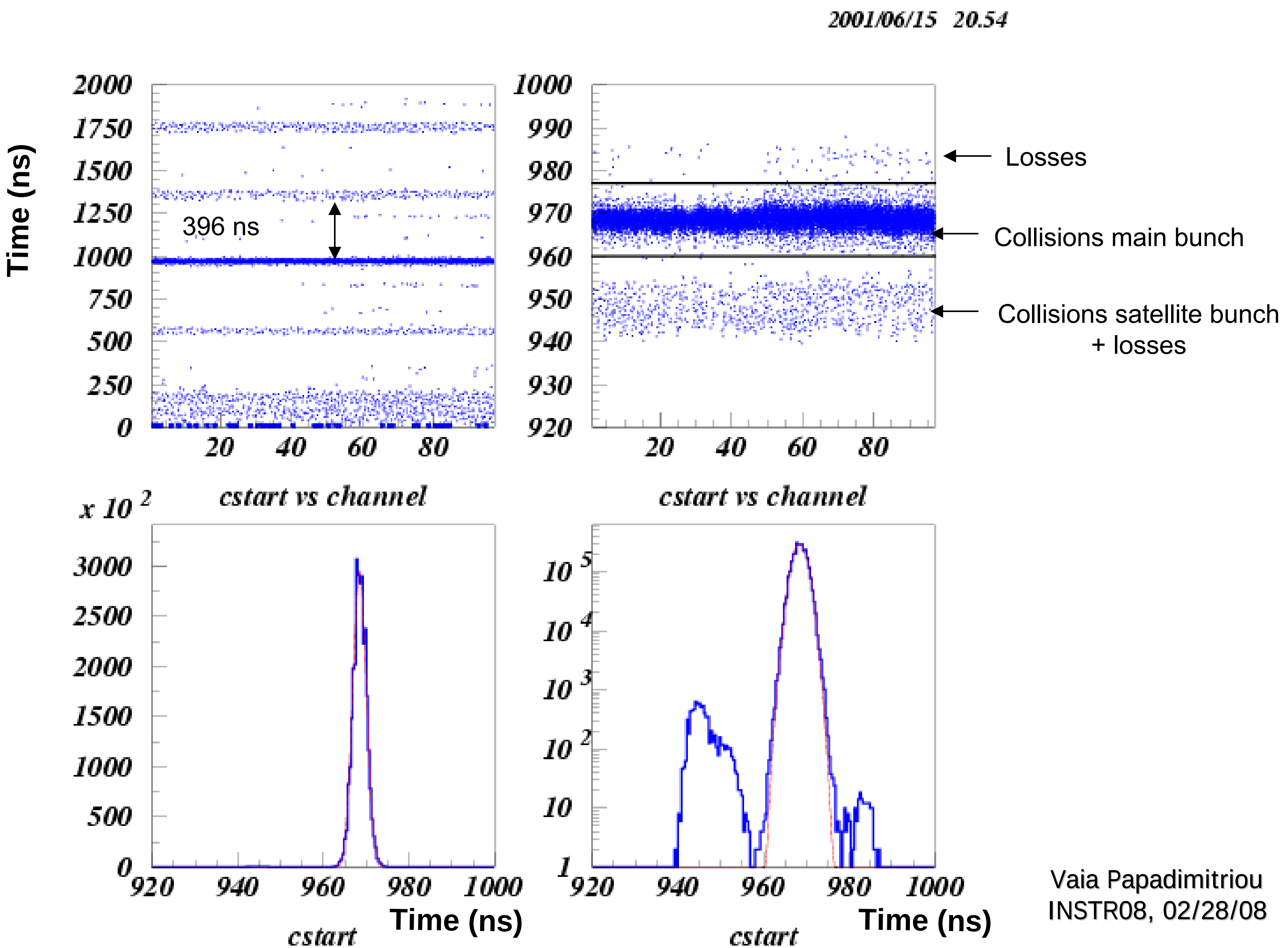
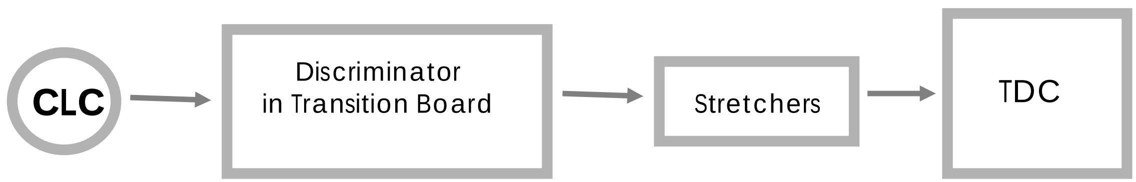
# Beam structure: timing

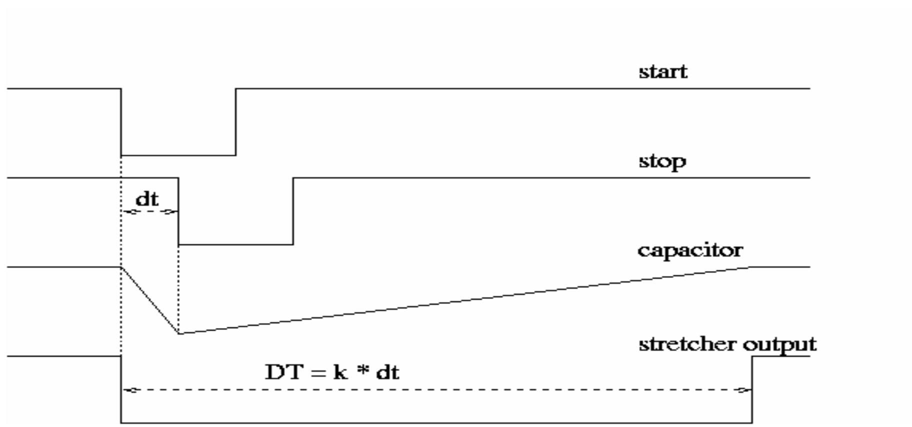


# CLC timing

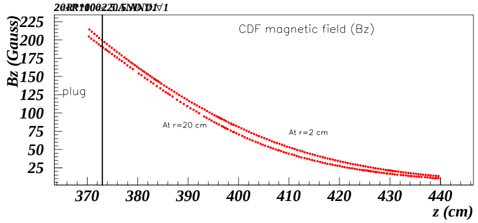
- **Precise Timing measurements:**
  - ***Use 1ns TDC (standard CDF)***
  - ***Use time stretcher circuitry***
    - ~ x 10 stretching factor

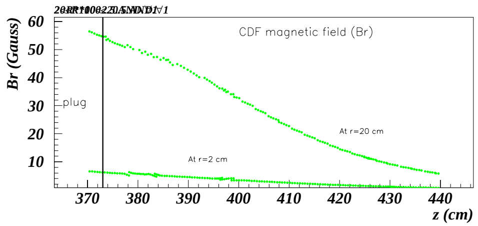
sub 100 ps resolution

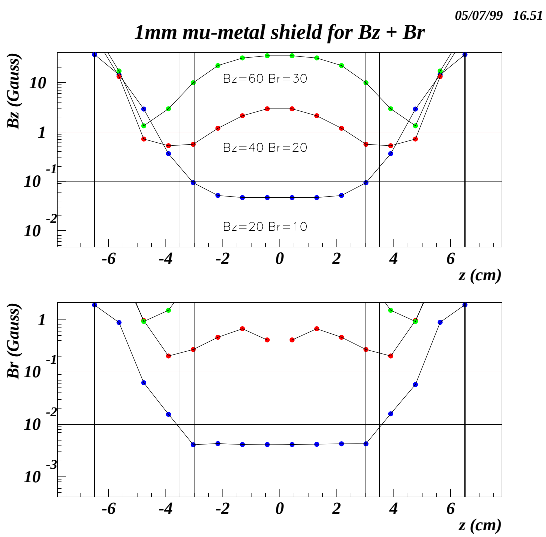


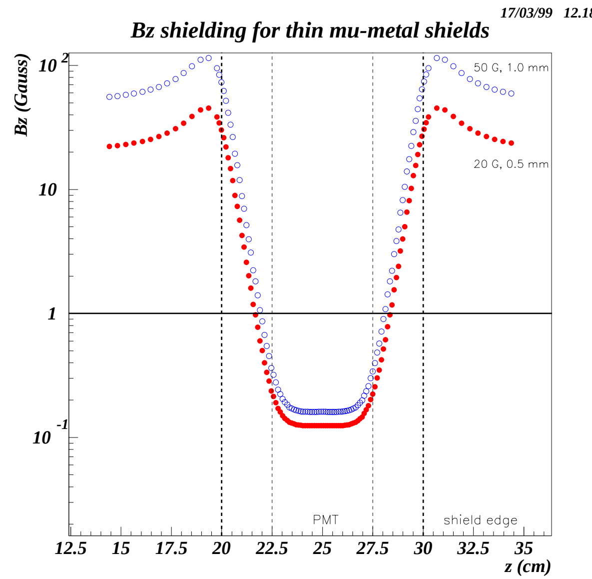



# Magnetic Shielding





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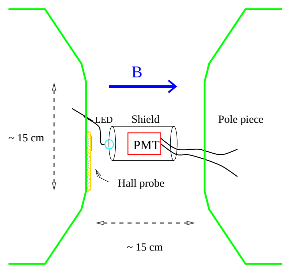
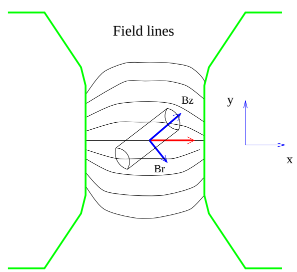
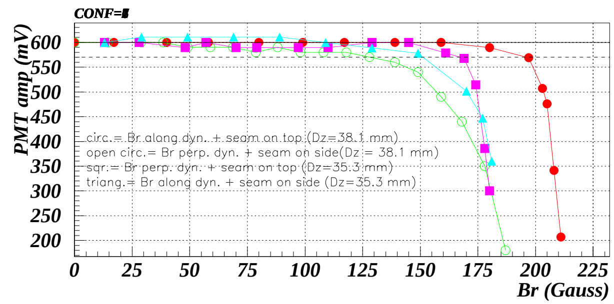
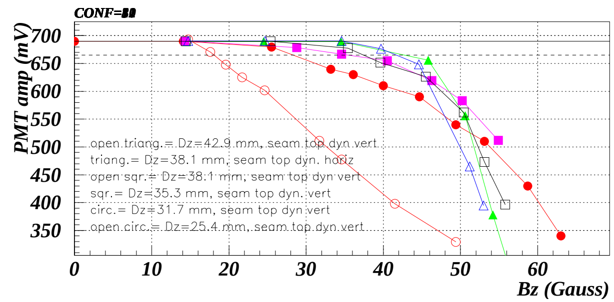
# Magnetic Shielding

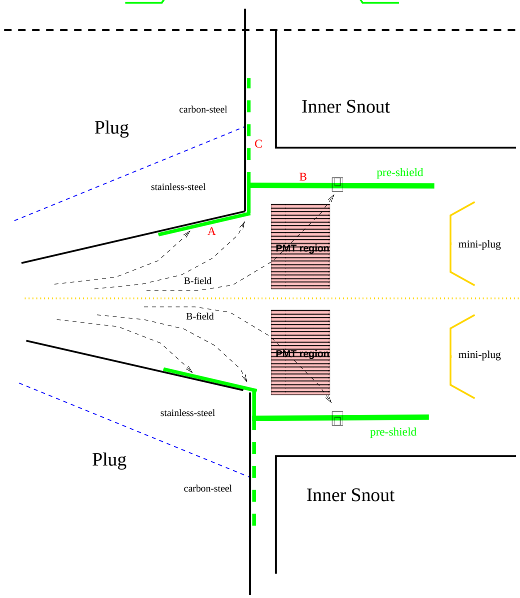


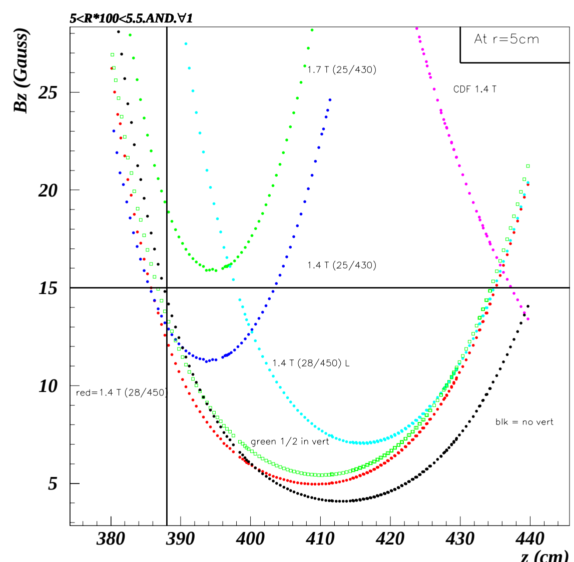




Individual Mu-metal shields



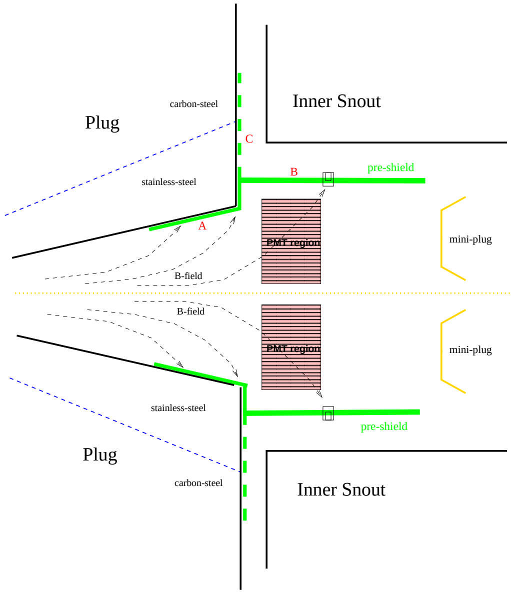

Bz (G)

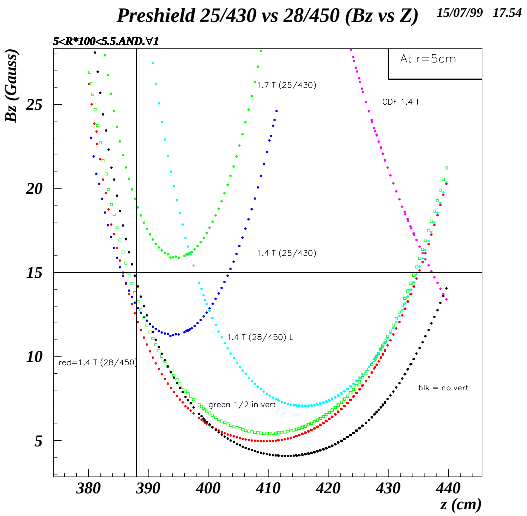



"pre-shield" optimization

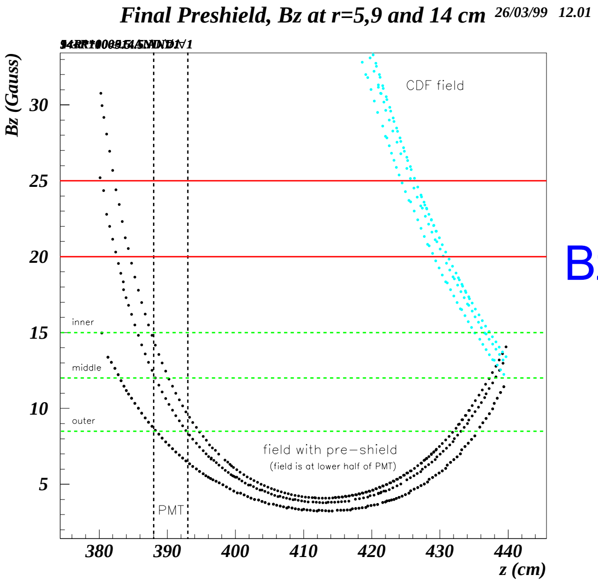
Z (cm)

# Magnetic Shielding – "pre-shield" simulation

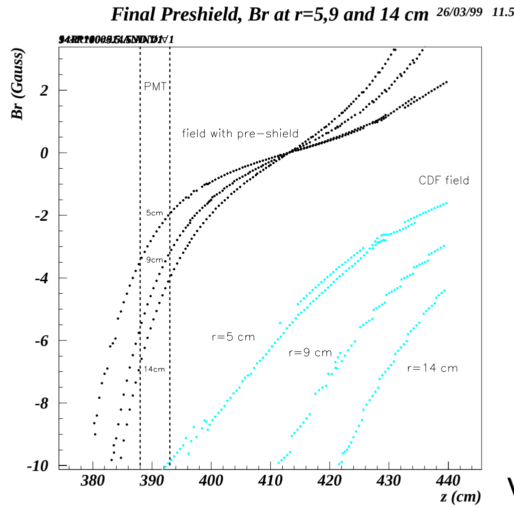



"pre-shield" optimization"




Bz




Br

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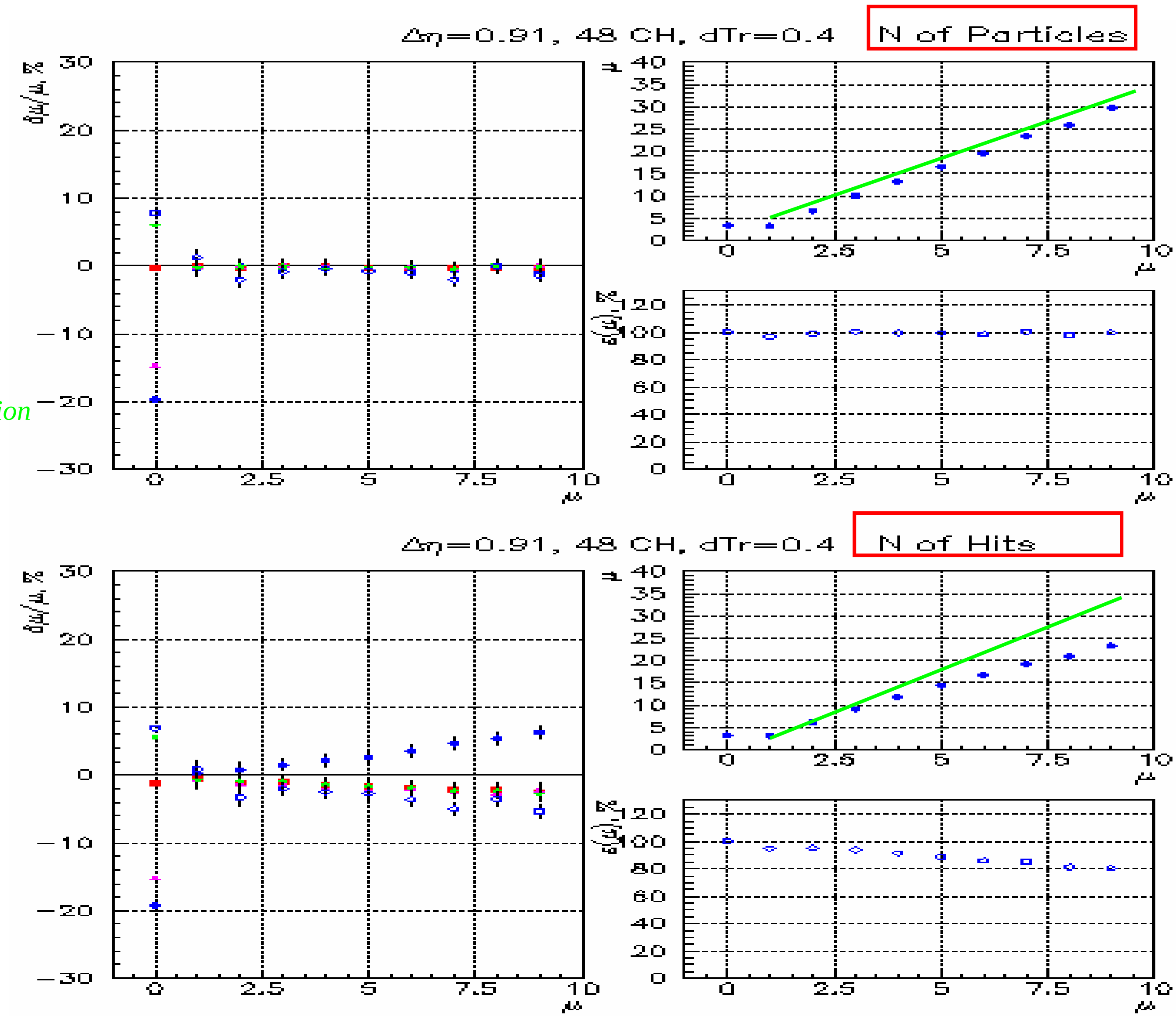
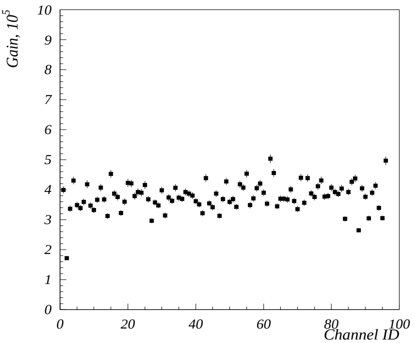
# Cerenkov - 48 chann.




Some sources of systematics:

- *Particle multiplicity/interaction*
- *Fraction of secondaries*
- *Source of secondaries*
- *PMT window thickness*
- *Gas index of refraction*

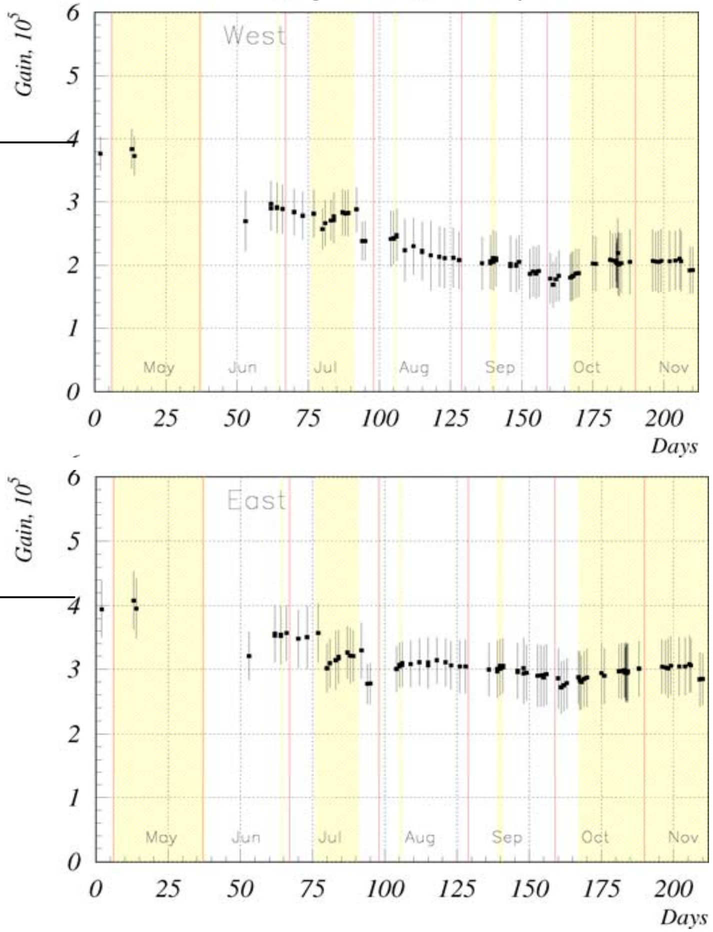



# Gain Stability

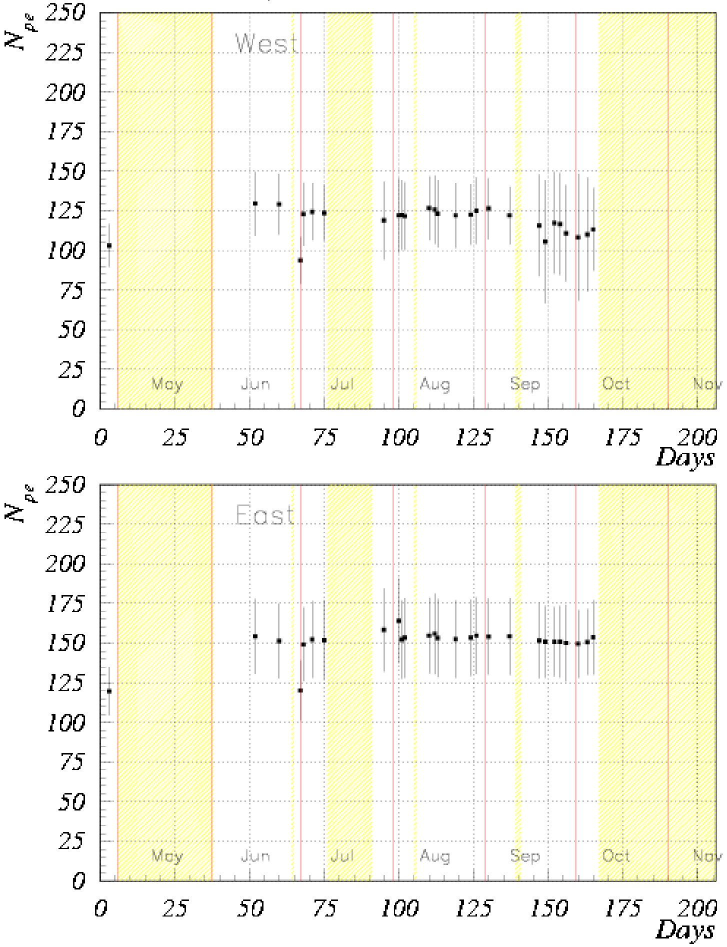
*PMT gain stability*

stable

stable



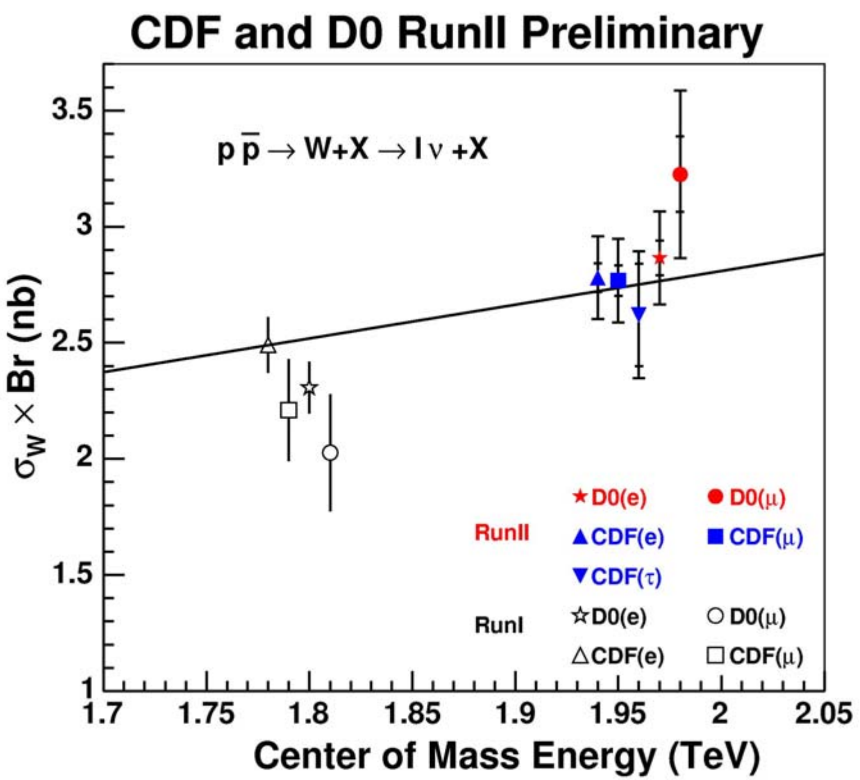

*Average $N_{pe}$ in single particle peak*

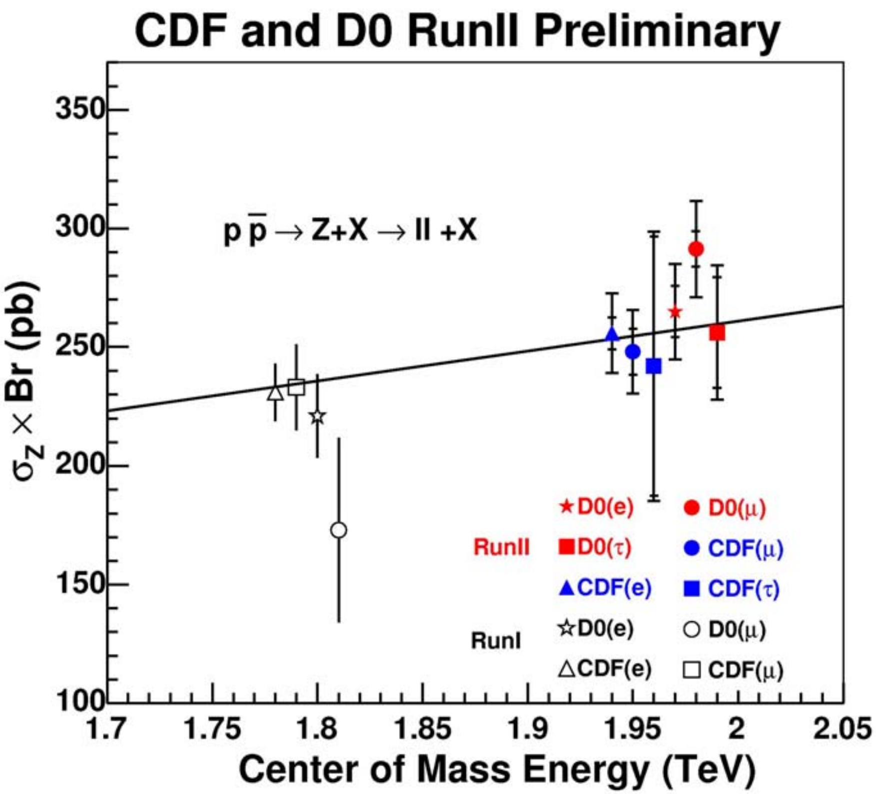



**After much investigation→ Helium contamination… → reduced gain / new afterpulse-free PMT / lifetime tests**

**Lum measurements ok, just more work…**

# Luminosity checks with W's and Z's



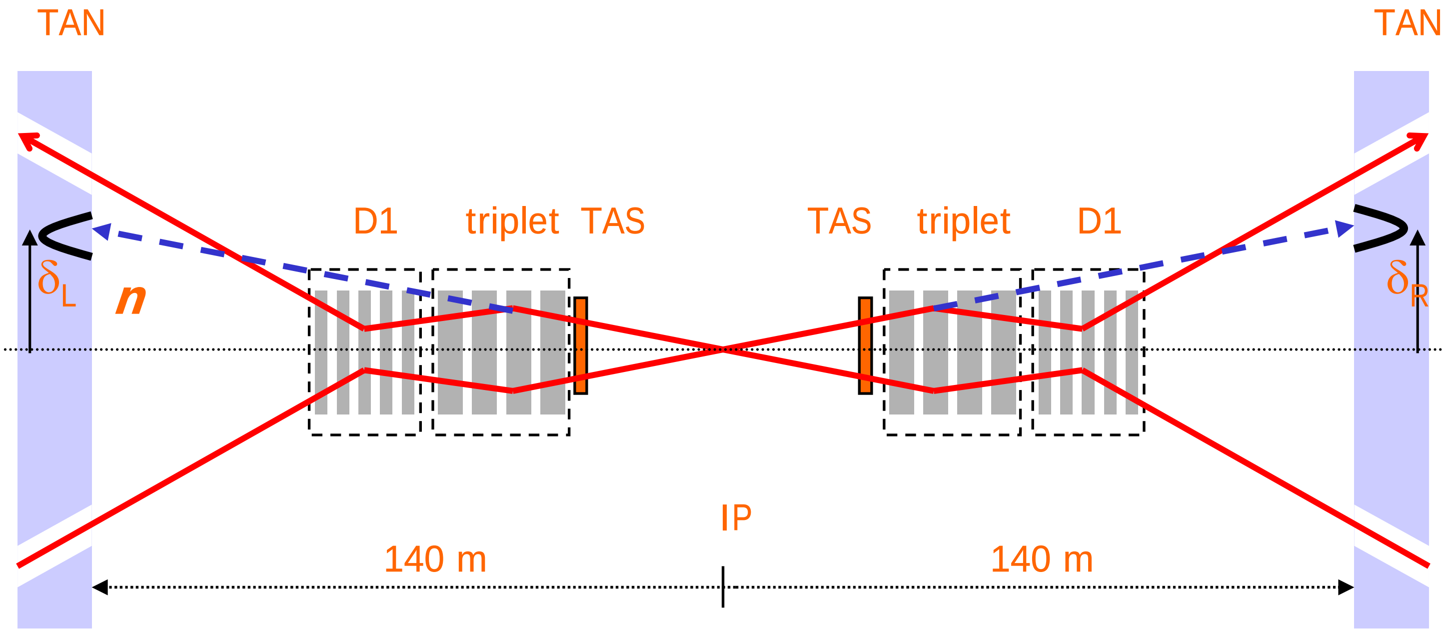



# Summary – Machine parameters

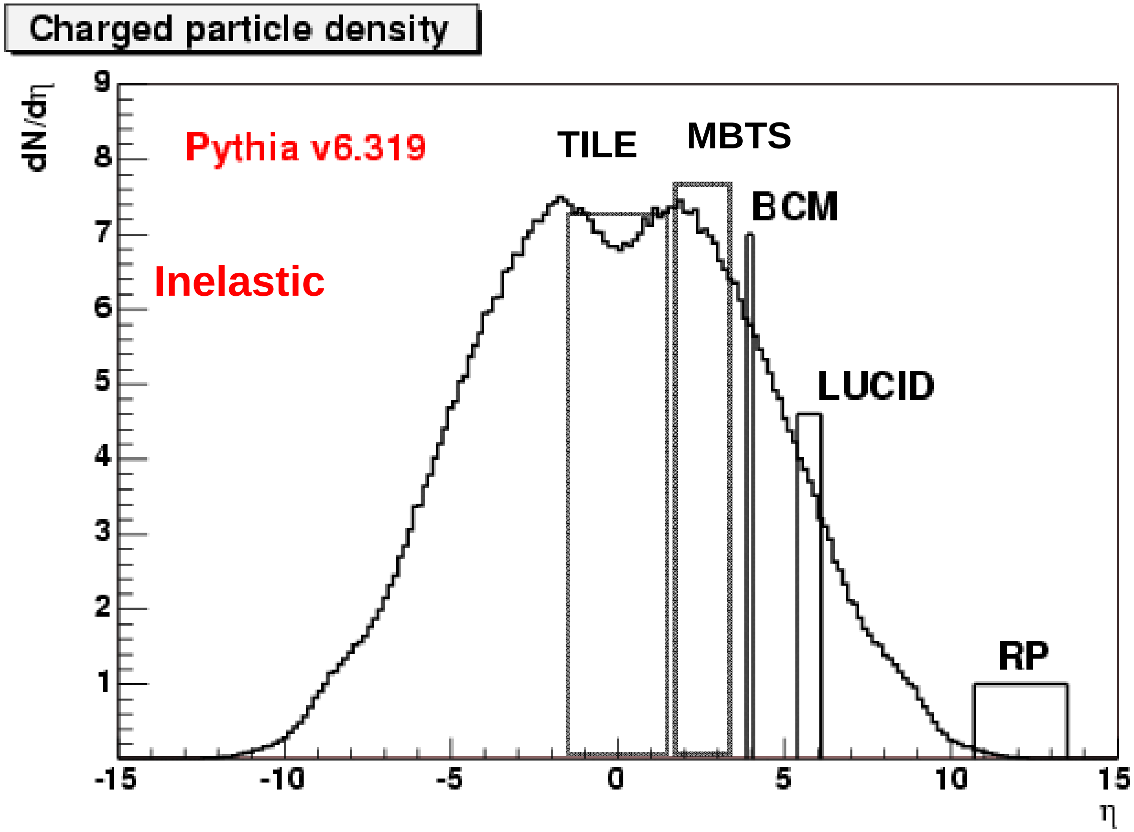
- The special  calibration run will improve the precision in the determination of the overlap integral . In addition it is  also possible to improve on the measurement of N (number of particles per bunch). Parasitic particles in between bunches complicate accurate measurements. Calibration runs with large gaps will allow  to kick out parasitic particles.
- Calibration run with special care and controlled condition has a good potential for accurate luminosity determination.  About 1 % was achieved  at the ISR.
- Less than ~5 % might  be in reach at the LHC but it will take some time.

# LHC Luminosity Monitor

- We also hope to use the TAN-region (z= ±140m) luminometers being developed by the LHC.

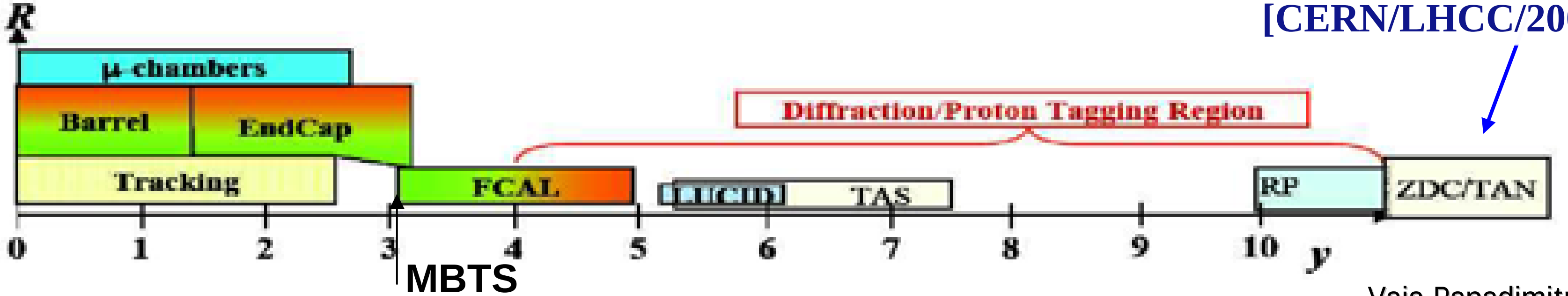


# η coverage




LoI

[CERN/LHCC/2007-001]

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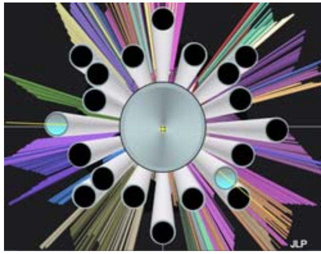
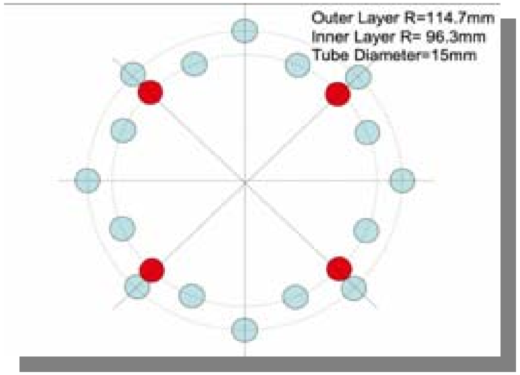
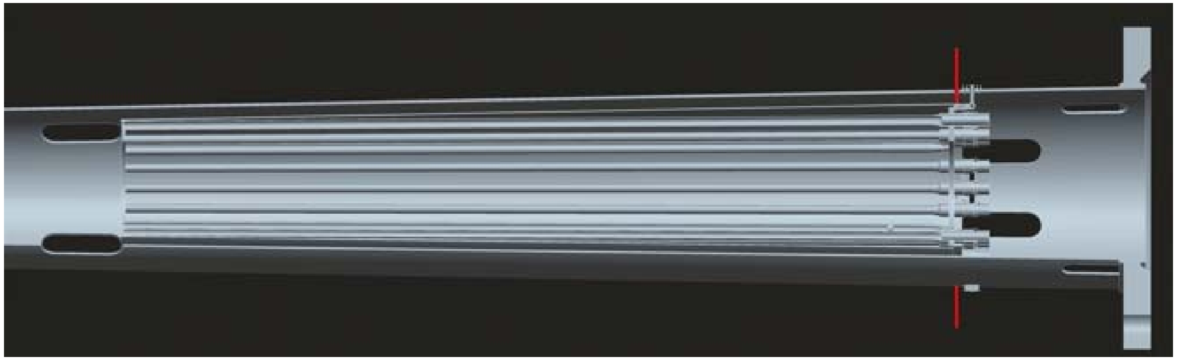
# LUCID: luminosity monitor



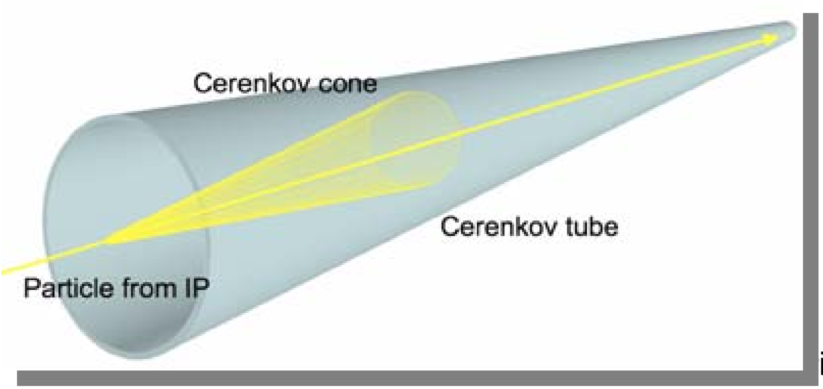
LUCID : “LUminosity measurement using Cerenkov Integrating Detector



- 2 symmetric arrays of 20 x 1.5 m polished Aluminum tubes (Ø=1.5cm), filled with $C_4F_{10}$, surrounding the beam pipe and pointing at the IP (Z~17 m )
- It fit in available space & has low mass (< 25 kg/end)

- **Charged particles emit Cherenkov light at ~3 degrees**
- **Photons propagate along the tube with multiple reflections (~2.6) and are read out by a PMT (Radiation hard)**



## Pixel Luminosity Telescope (PLT)

- The HF method is based on an existing detector, and thus has the advantage of being inexpensive and relatively easy to implement.
- It does not, however, really fit the bill when it comes to providing a luminosity measurement based on "countable objects."
- Motivated by the CDF approach of counting MIPs using Cherenkov telescopes, we have proposed a charged-particle telescope system based on single-crystal diamond detectors readout by the CMS pixel chip.
- This system is not yet approved or funded.

# Pixel Luminosity Telescope (PLT)

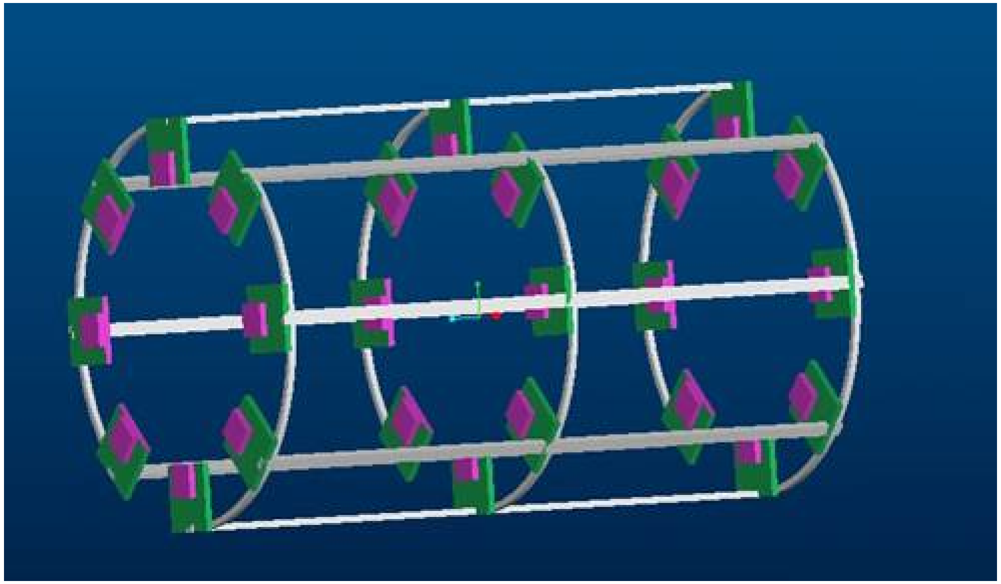
Measure luminosity bunch-by-bunch

- Small angle (~1$^{o}$) pointing telescopes
- Three planes of diamond sensors (8 mm x 8 mm)
- Diamond pixels bump bonded to CMS pixel ROC
- Form 3-fold coincidence from ROC fast out signal
- Located at r = 4.9 cm, z = 175 cm
- Total length 10 cm
- Eight telescopes per side

Rutgers/Princeton/UC Davis

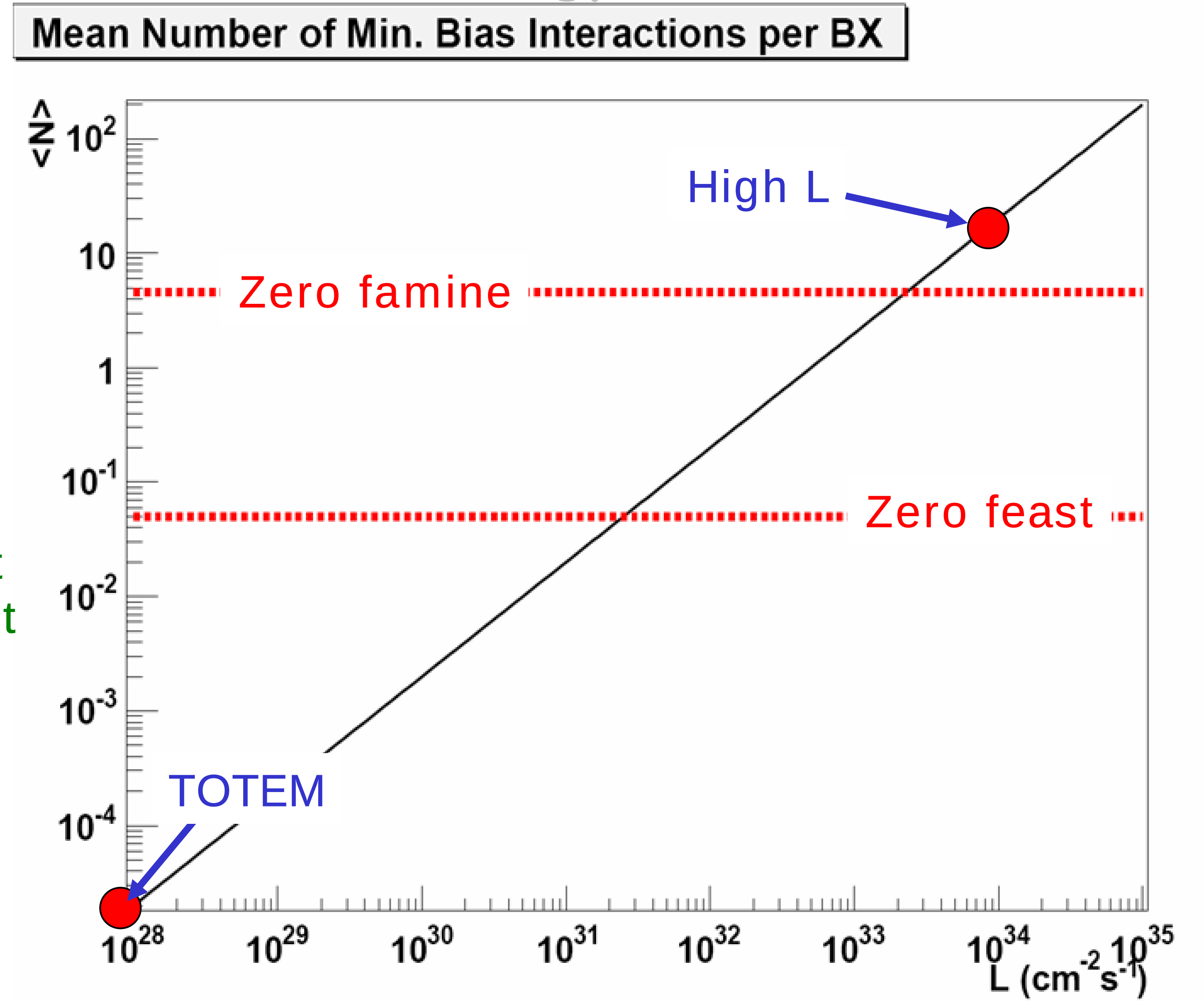
Count 3-fold coincidences on bunch-by-bunch basis.

PLT systematics are complementary to those of the HF

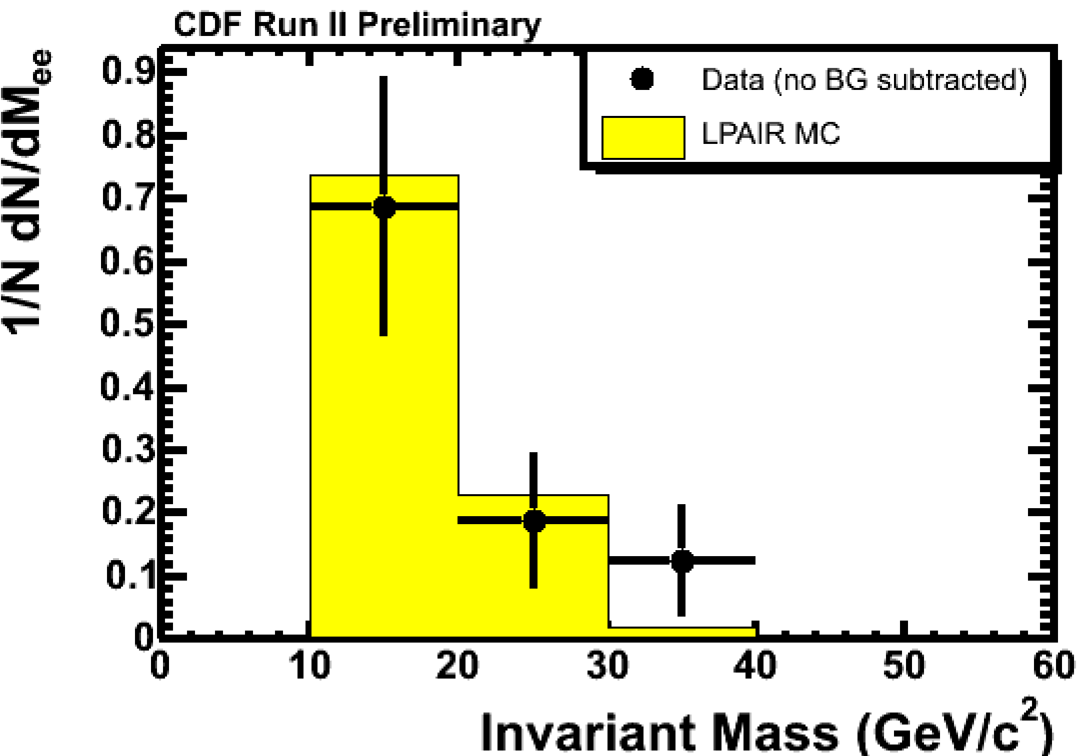


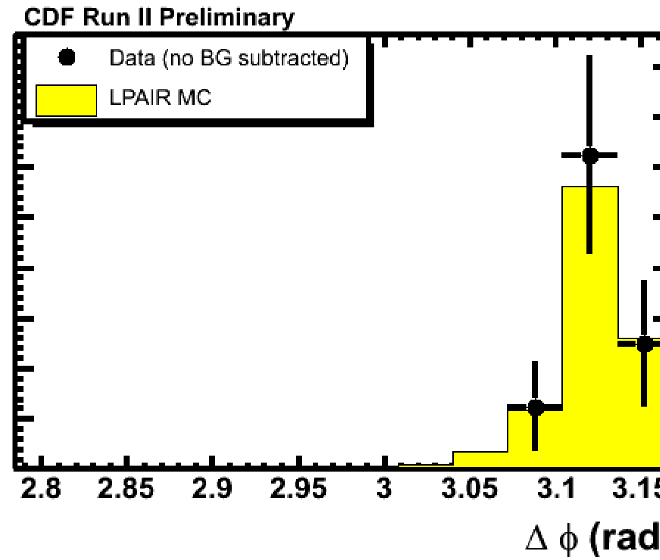
# General Strategy

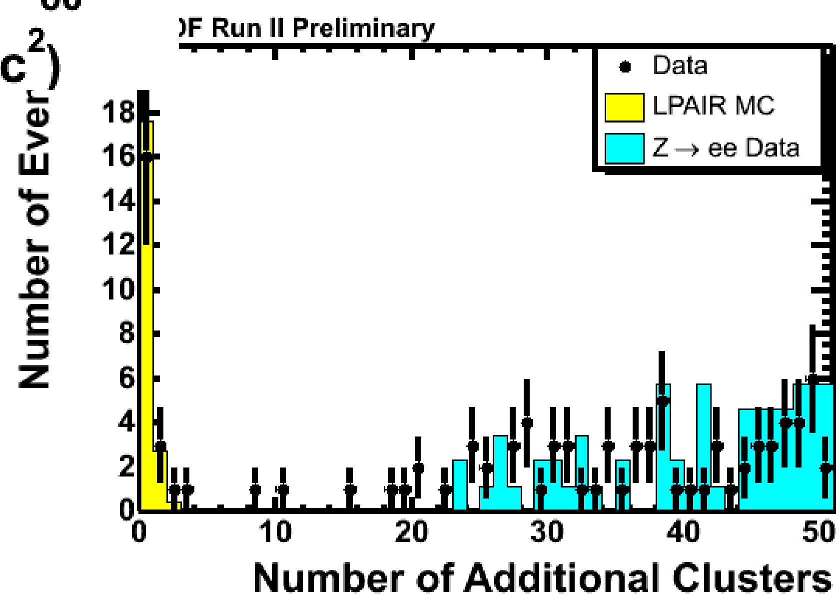
Although there is a very large spread in luminosity from commissioning conditions (and also TOTEM running), the extrapolation isn't quite as large as it first seems, since the low-lumi running will be done with fewer filled bunches.



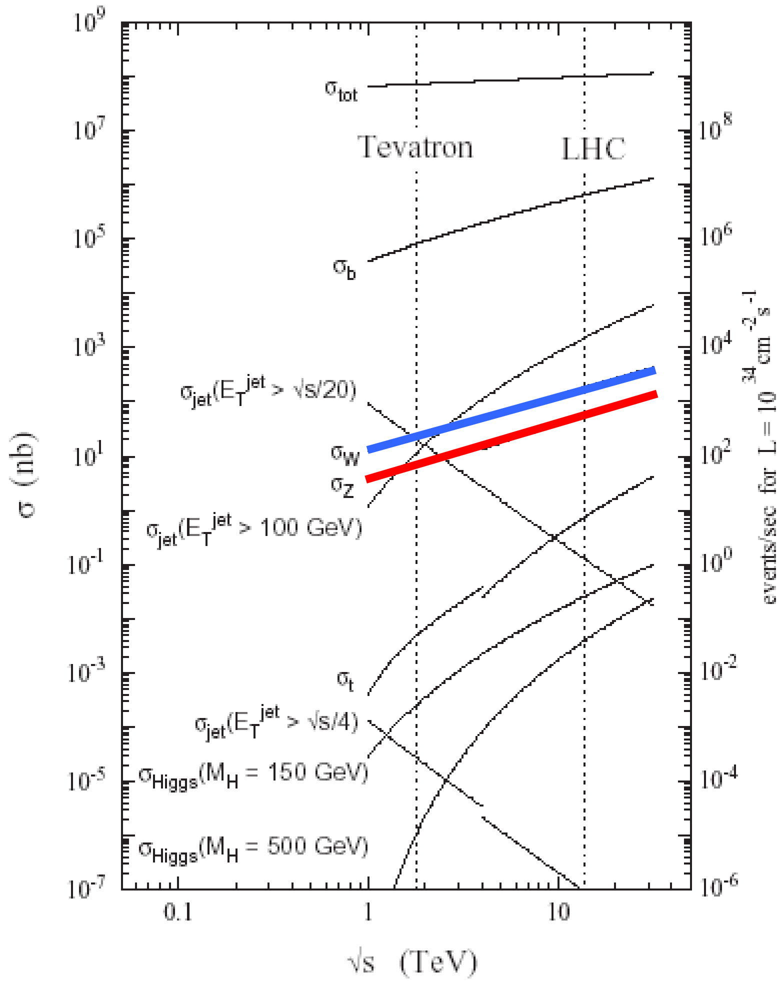
# Two photon production of electron pairs - CDF

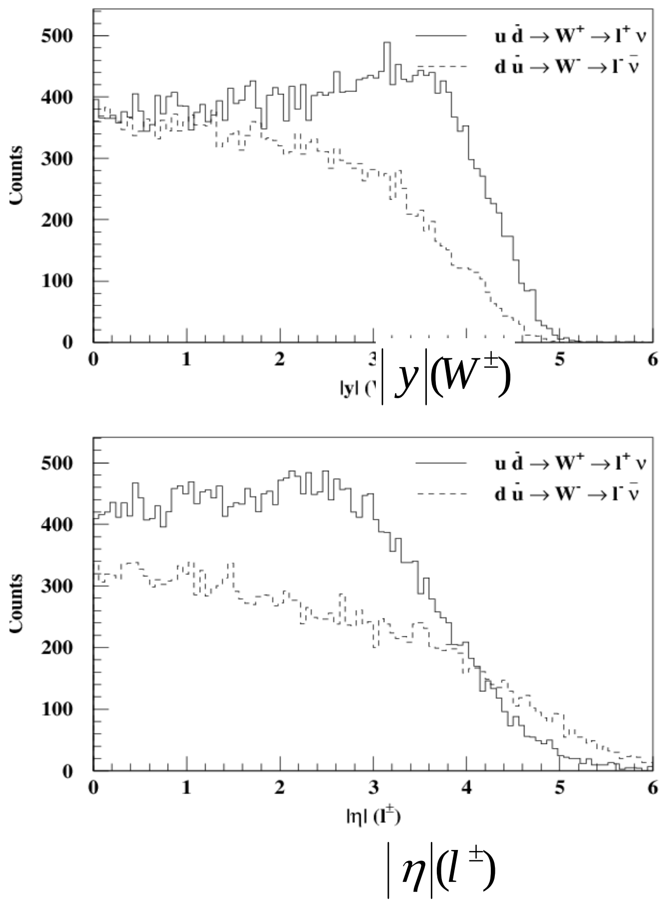


# W and Z counting

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