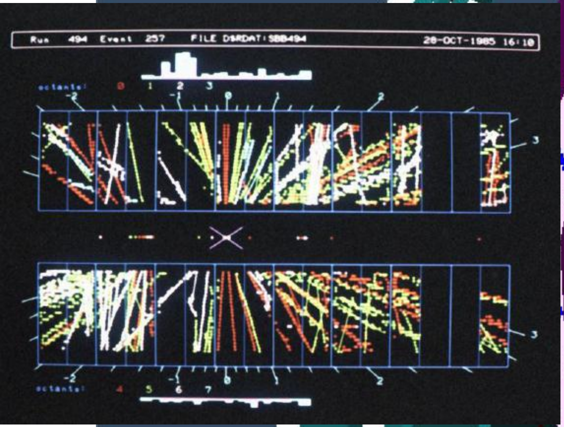
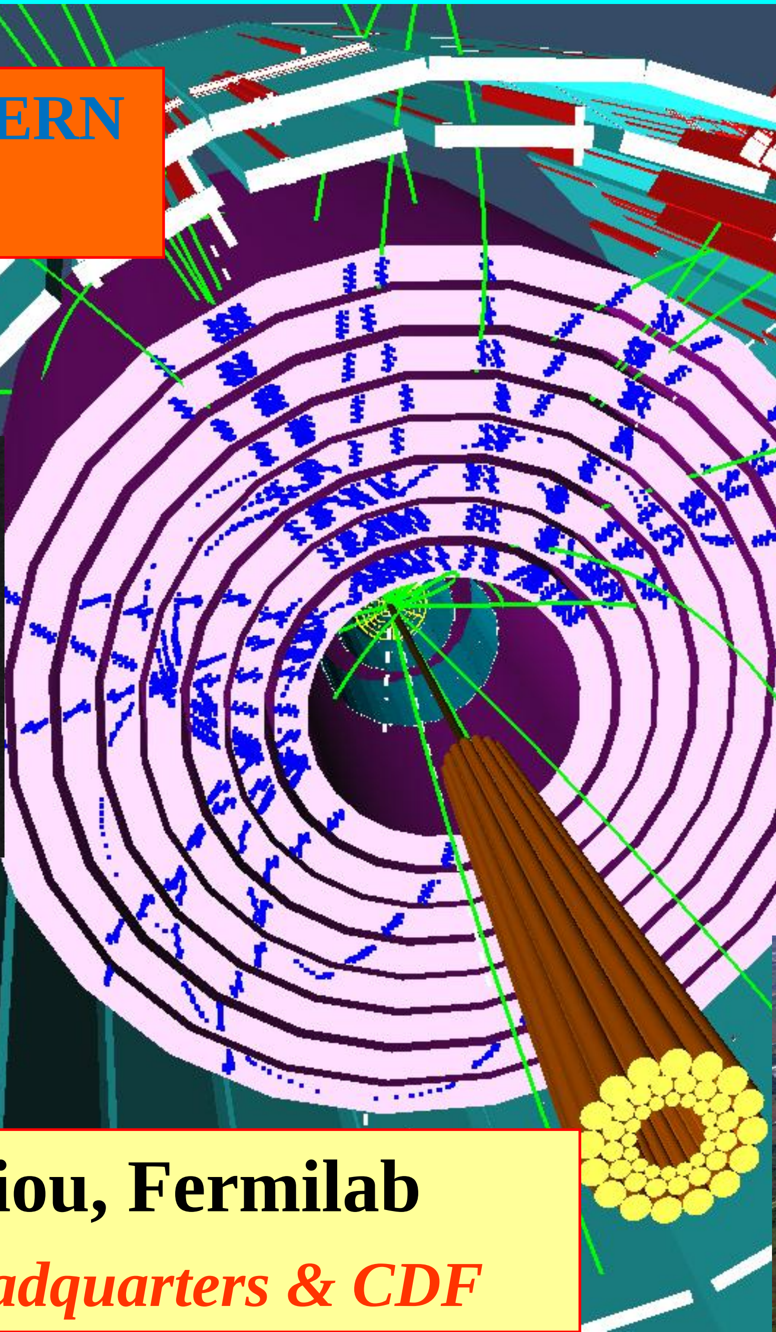
Luminosity determination at the Tevatron

LHC Lumi Days, CERN

January 14, 2011





Vaia Papadimitriou, Fermilab

Accelerator Div. Headquarters & CDF

OUTLINE

- Motivation/goals for the Luminosity measurements
- Techniques used by the Tevatron Accelerator
- Techniques used by the CDF and D0 experiments
- Uncertainties, crosschecks and calibrations
- Challenges and lessons learned
- Conclusion

Motivation for Luminosity Measurements

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

- Cross sections for Standard Model and beyond the Standard Model processes and for New Physics.

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

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

The Tevatron Accelerator Complex

- ➢ Absolute luminosity measurements by the machine based on the measurements of beam parameters (15-20% uncertainty).
- ➢ Real-time relative luminosity measurements performed by CDF and D0 which are then normalized to the inclusive, inelastic proton-antiproton cross section

(~ 6% uncertainty).

Celebrating
the 25th Anniversary of the First Tevatron Collisions

December 17, 2010

76 OCT 13 1985 Sun

3:07 DFC We DID IT!! Official first event is Run 493, event 11.

First 800 GeV Event!! $\frac{dN}{d\eta}$ is right.

Run 493 Event 11 FILE NONE 13-OCT-1985 02:32

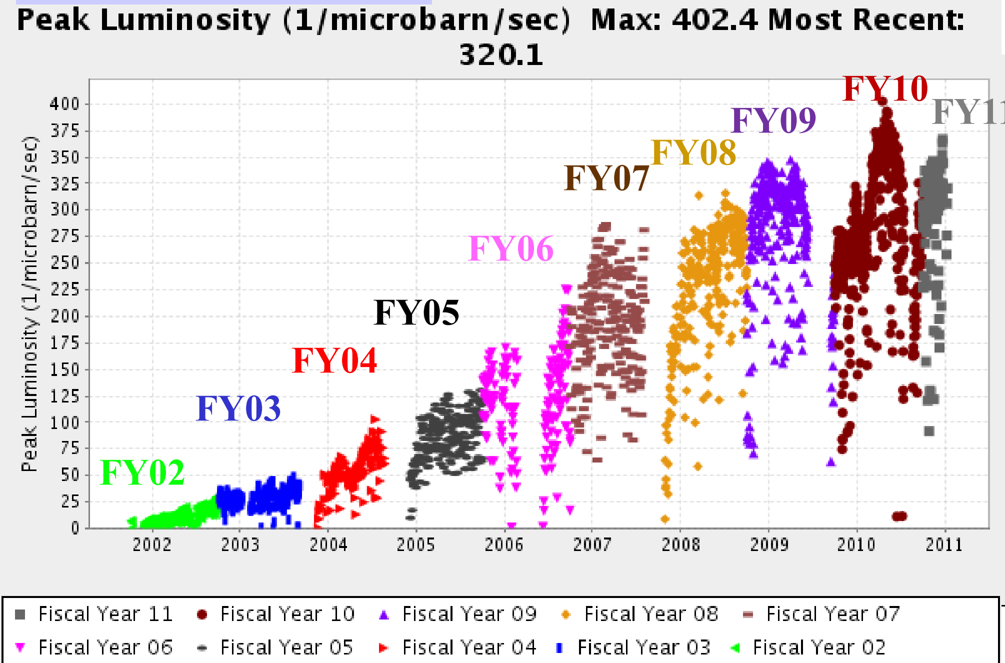
July 1979	Tevatron Ring authorized. US-Japan Accord signed. Italians & Japan join CDF.
July 1982	CDF and Pbar source authorized
July 4, 1983	First beam in Tevatron
1984	D0 Approved by DOE
Oct 17, 1985	First collisions at Fermilab
1988-1989	First real physics run for CDF
April 1992	D0 first run

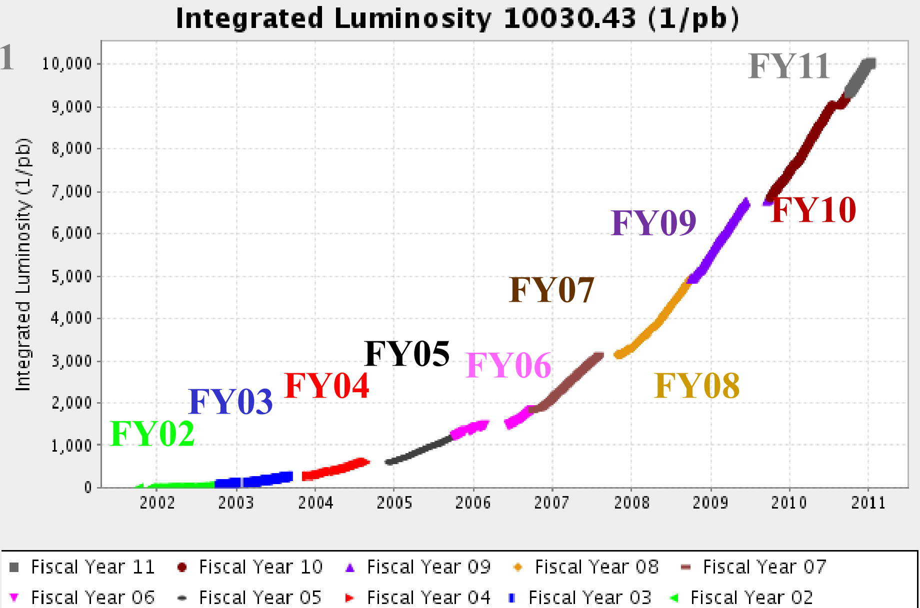
Tevatron Performance

- First Collisions in October, 1985; Run -1, 1987 ; Run 0, 1988-89
- 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, $\int \mathcal{L}\,dt = \sim 10\ fb^{-1}$):
  - *p → ← pbar at* $\sqrt{s}$ *= 1.96 TeV, 396 ns between collisions, 36 x 36 bunches*

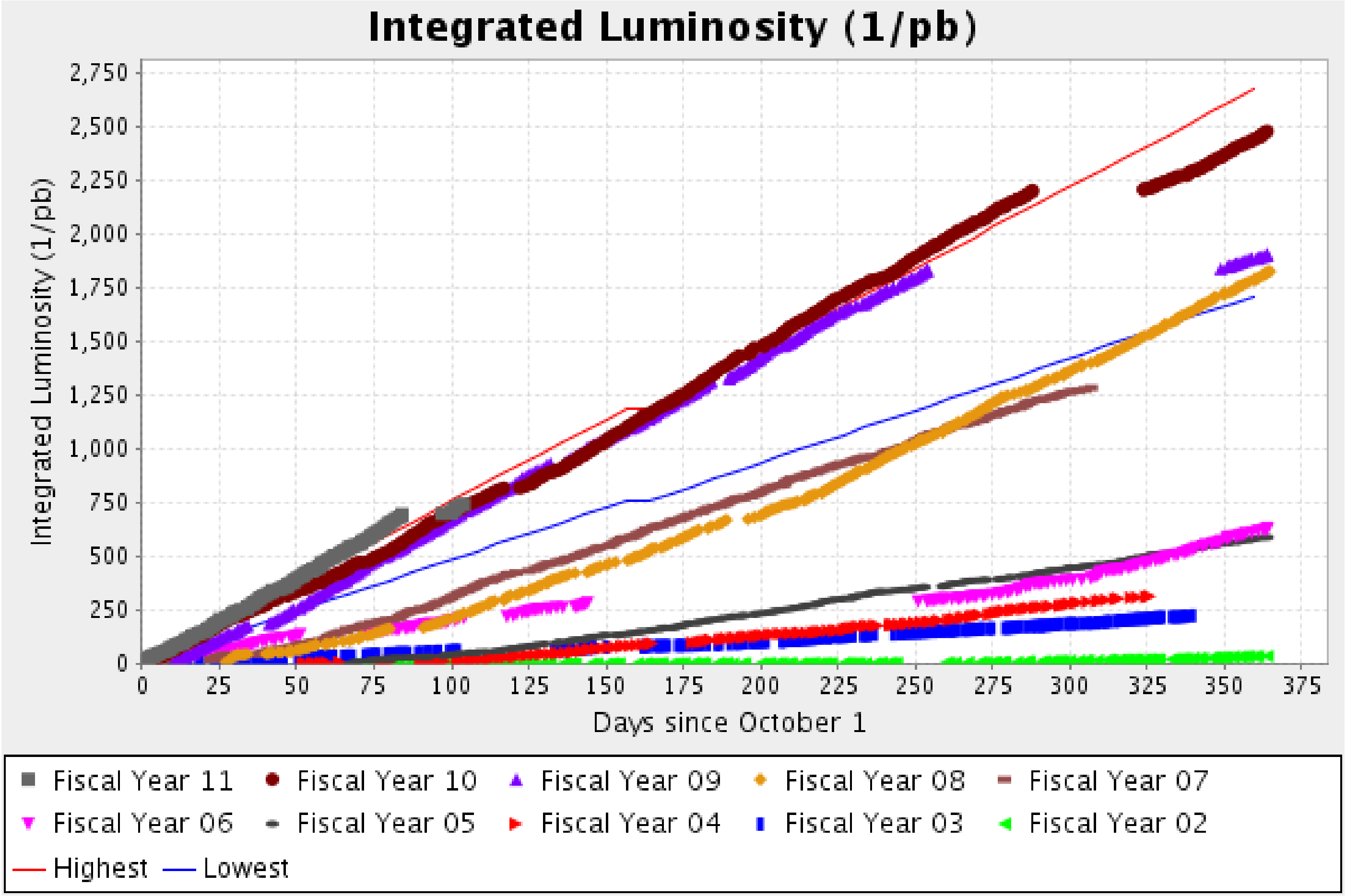
Best 4.02 x $10^{32}\ cm^{-2}s^{-1}$
April 16, 2010

12.2 pb^{-1} delivered per experiment
in one store, April 17, 2010





Yearly integrated luminosity as a function of fiscal year



Changes that improved peak/integrated luminosity

- **2005:** Completion of the Tevatron BPM electronics upgrade. Helped lattice measurements, helped identifying rolled quads, allowed in-store orbit stabilization and better store-to-store monitoring of orbits resulting in better store-to-store reproducibility and reliability.

- **September 2005:** Implementing a 28 cm β* lattice and making the electron cooling in the Recycler operational.

- **2005/2006:** Added 4 new and replaced 3 electrostatic separators. That allowed ~20% improvement in the luminosity lifetime due to improved separation especially at the first parasitic crossings around the IPs.

Changes that improved peak/integrated luminosity

- **2003-2006:** Dipole reshimming over 3 long shutdowns to address the coherent skew quadrupole component that was slowly growing. This reduced the global coupling around the machine.

- **2005-2009:** Gradual improvement of the pbar stacking rate.

- **2005:** 1.7 GHz Schottky + tune feedback. Keep p and pbar tunes in desired range. Increase luminosity lifetime.

- **2007:** 2nd order chromaticity compensation circuits allowing higher proton intensity and improved lifetime.

- **2003-2010:** Alignment in every shutdown.

- **2009-2010:** Faster shot setups (both for Accumulator to Recycler and for HEP.

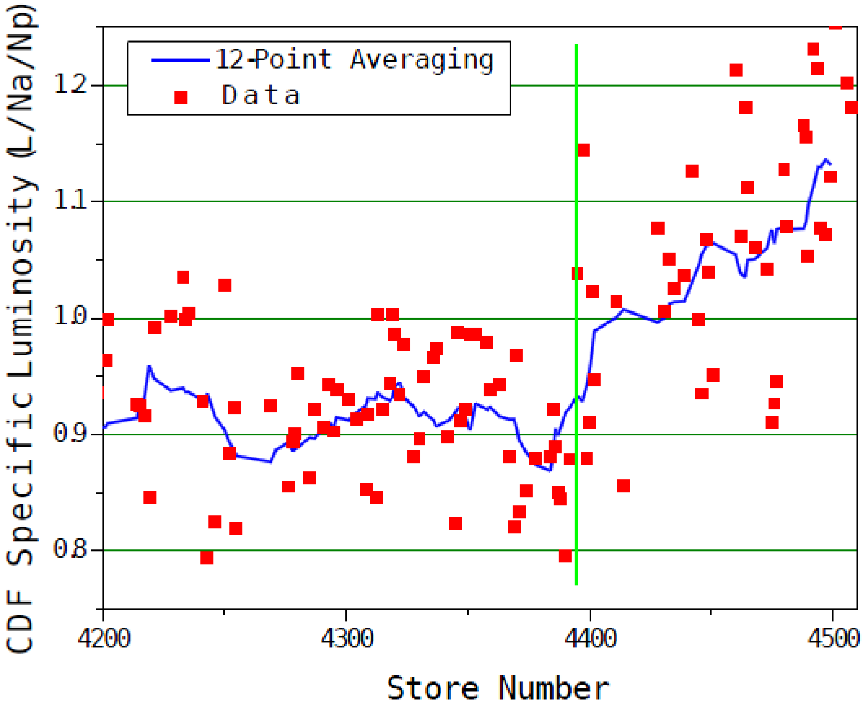


Figure 3: Specific initial luminosity ($L/N_a/N_p$) vs. store number. Green line marks the moment when the new optics was put into operation.

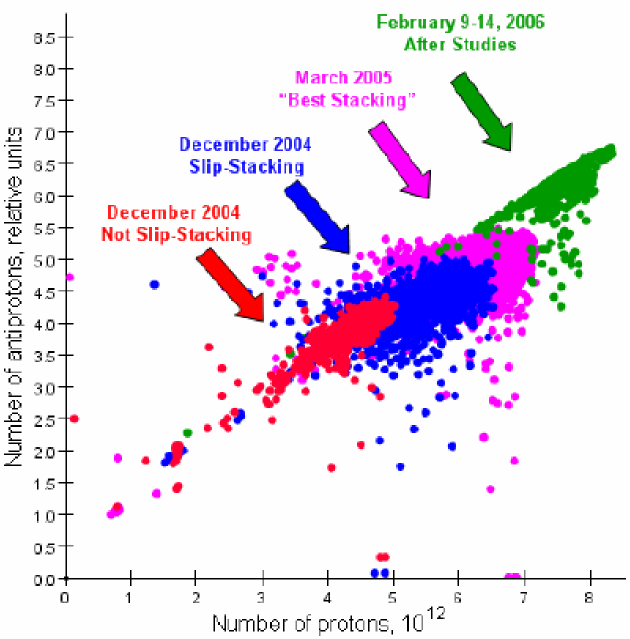
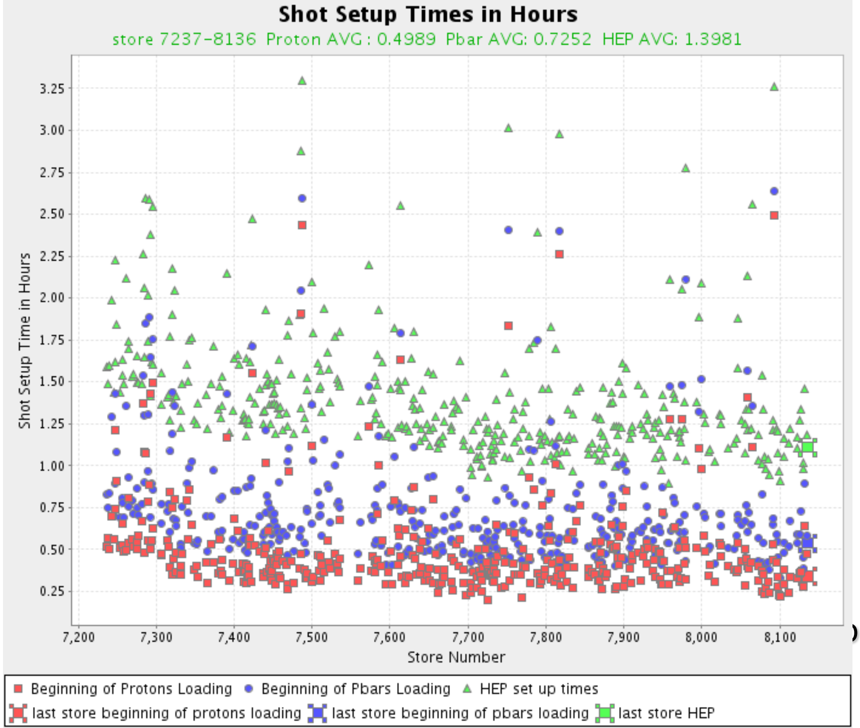


Figure 6: Historical data for the dependence of antiproton intensity on the number of protons on the target.



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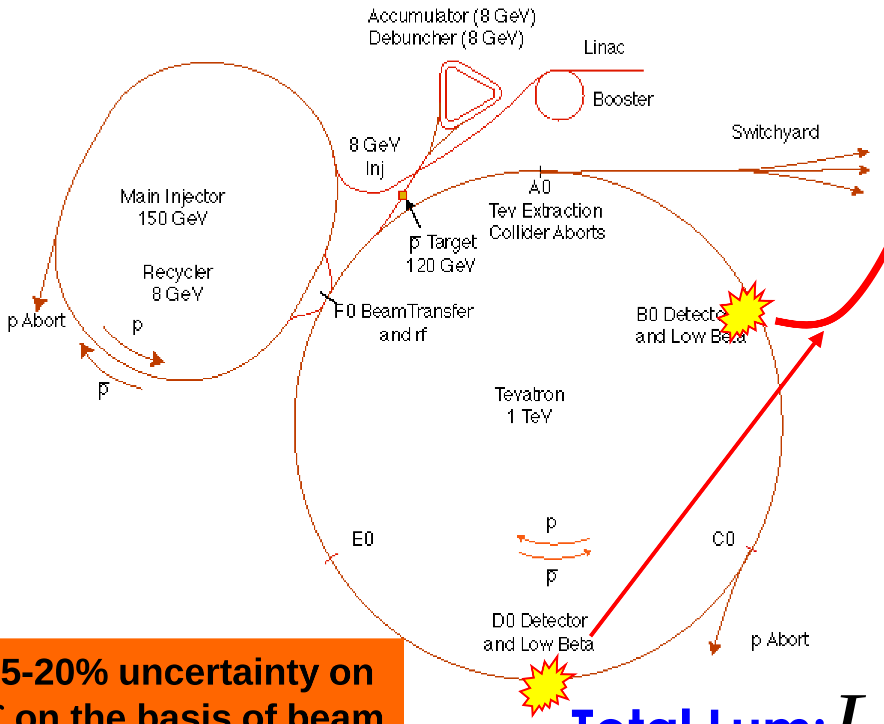
Collider Beam Luminosity Measurement

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

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



Instantaneous Luminosity:

$$\mathcal{L} = \frac{N_p \cdot N_{\bar{p}} \cdot B \cdot f_0}{4\pi\sigma^2} \sim (3.4)\text{x}10^{32}\ \text{cm}^{-2}\text{s}^{-1}$$

(Run II) typical

N_p = protons/bunch ($\sim 2.8 \cdot 10^{11}$)

$N_{\bar{p}}$ = anti-protons/bunch ($\sim 8 \cdot 10^{10}$)

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: $L = \int \mathcal{L} \cdot \text{dt} \sim$ **11.1 to 12.1 fb^{-1} through FY11**

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

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

Collider Beam Luminosity

Instantaneous Luminosity: $\mathcal{L}$

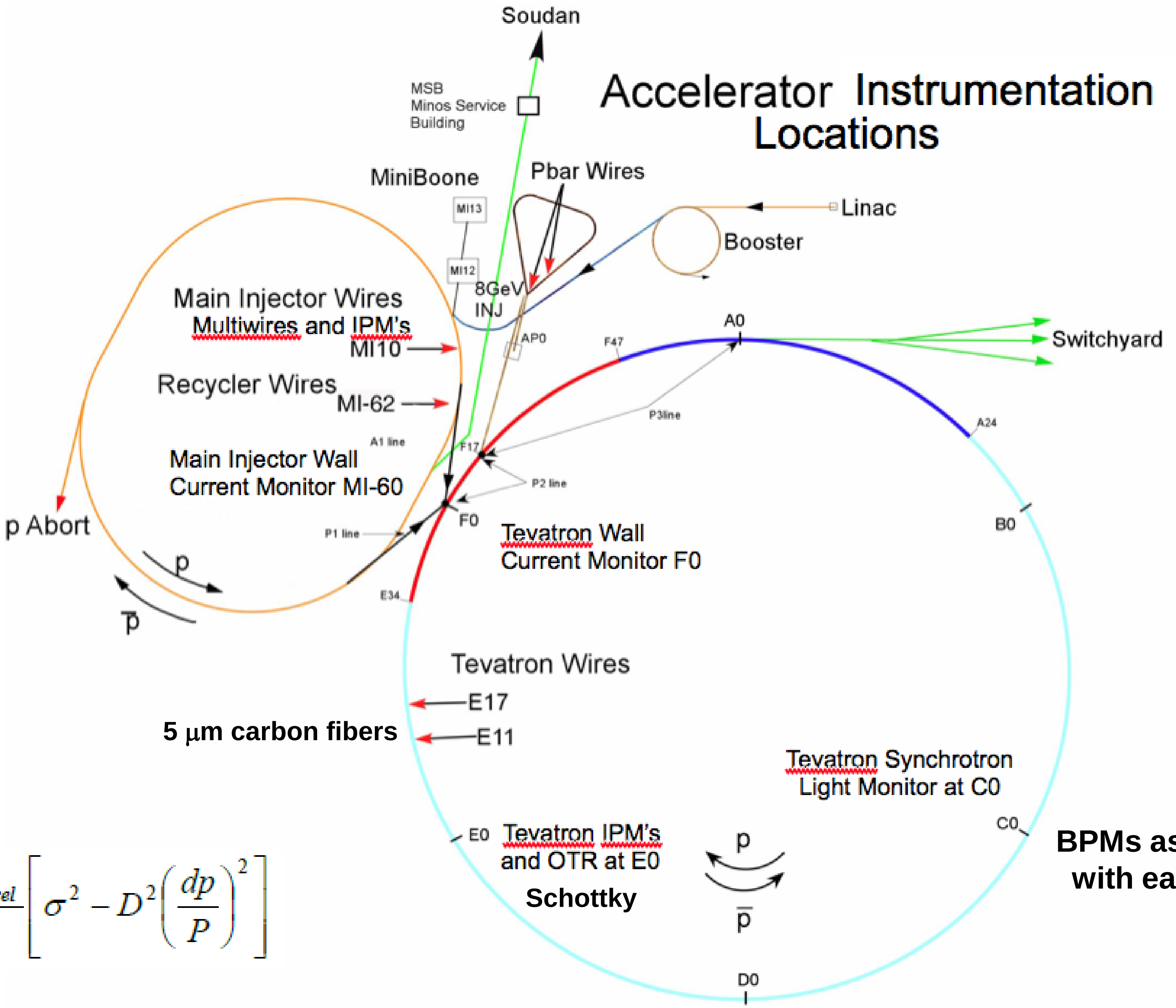
$$\mathcal{L}=\frac{N_p N_a}{4\pi\left(\varepsilon\beta^{*}+D^{*2}\sigma_{\delta}^{2}\right)}\cdot f\cdot H\left(\frac{\beta^{*}}{\sigma_z}\right)\rightarrow\ \mathcal{L}=N_p N_a\cdot f\cdot F\left(\varepsilon,\beta^{*},D^{*},D'^{*},\sigma_z,\sigma_{\delta},\theta\right)$$

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

σ_z ~ 0.5 m
β^* ~ 0.3 m

- **Intensities**
- **Emittancies**
- **Lattice**

Instrumentation used for luminosity measurements



Accelerator Instrumentation Locations

Main Injector Wires
Multiwires and IPM's
MI10

Recycler Wires
MI-62

Main Injector Wall
Current Monitor MI-60

Tevatron Wall
Current Monitor F0

Tevatron Wires
E17
E11

5 μm carbon fibers

Tevatron Synchrotron
Light Monitor at C0

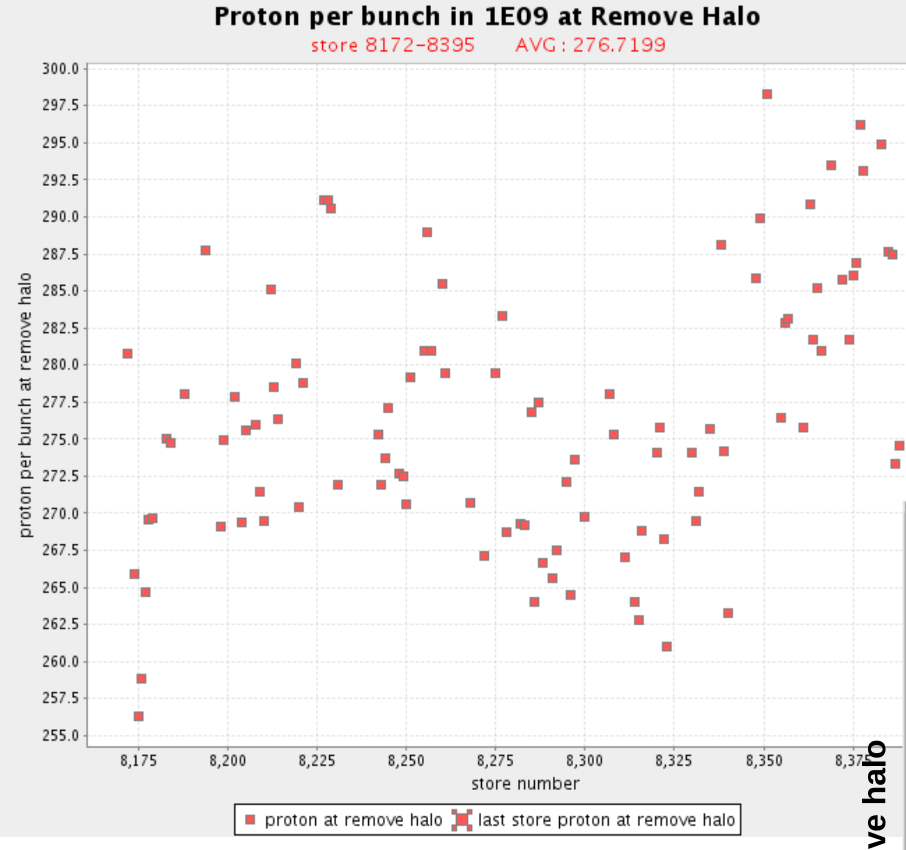
Tevatron IPM's
and OTR at E0

Schottky

BPMs associated with each quad

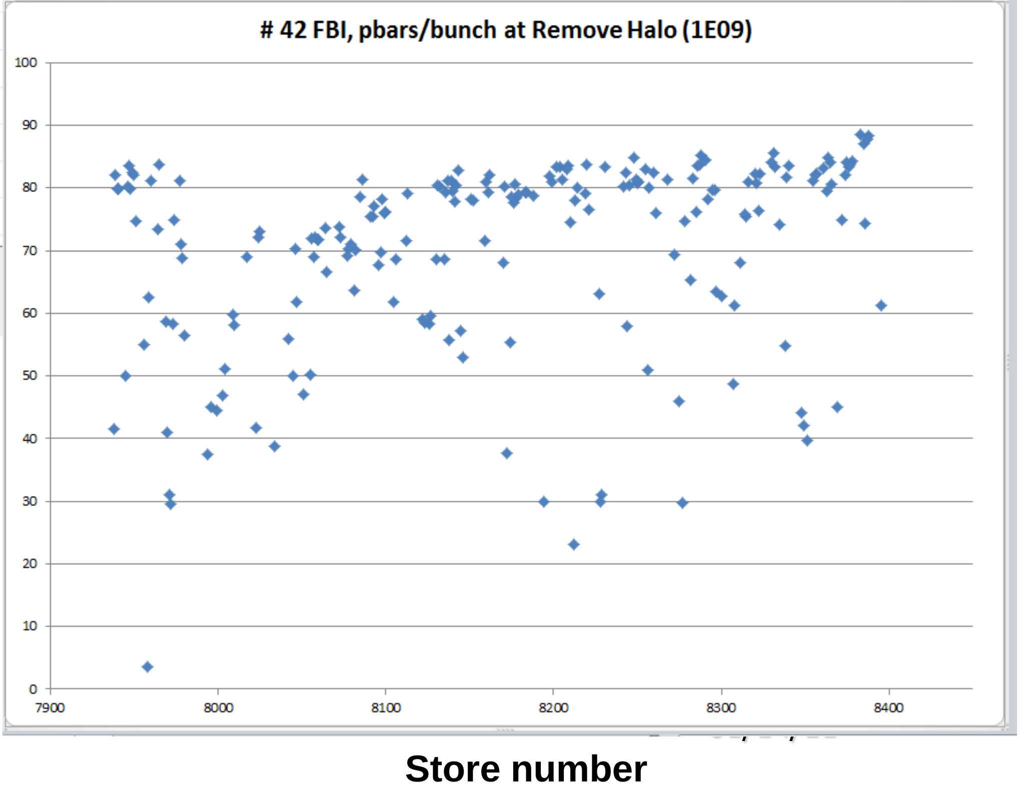
$$\varepsilon = \frac{6\pi(\beta\gamma)_{rel}}{\beta}\left[\sigma^2 - D^2\left(\frac{dp}{P}\right)^2\right]$$

Proton and Antiproton Intensities



FBI: Fast bunch integrator of a Wall Current Monitor
Syst: pedestal measurement, integration window coupled with freq. response of WCM, integrator and cable, integrator stability

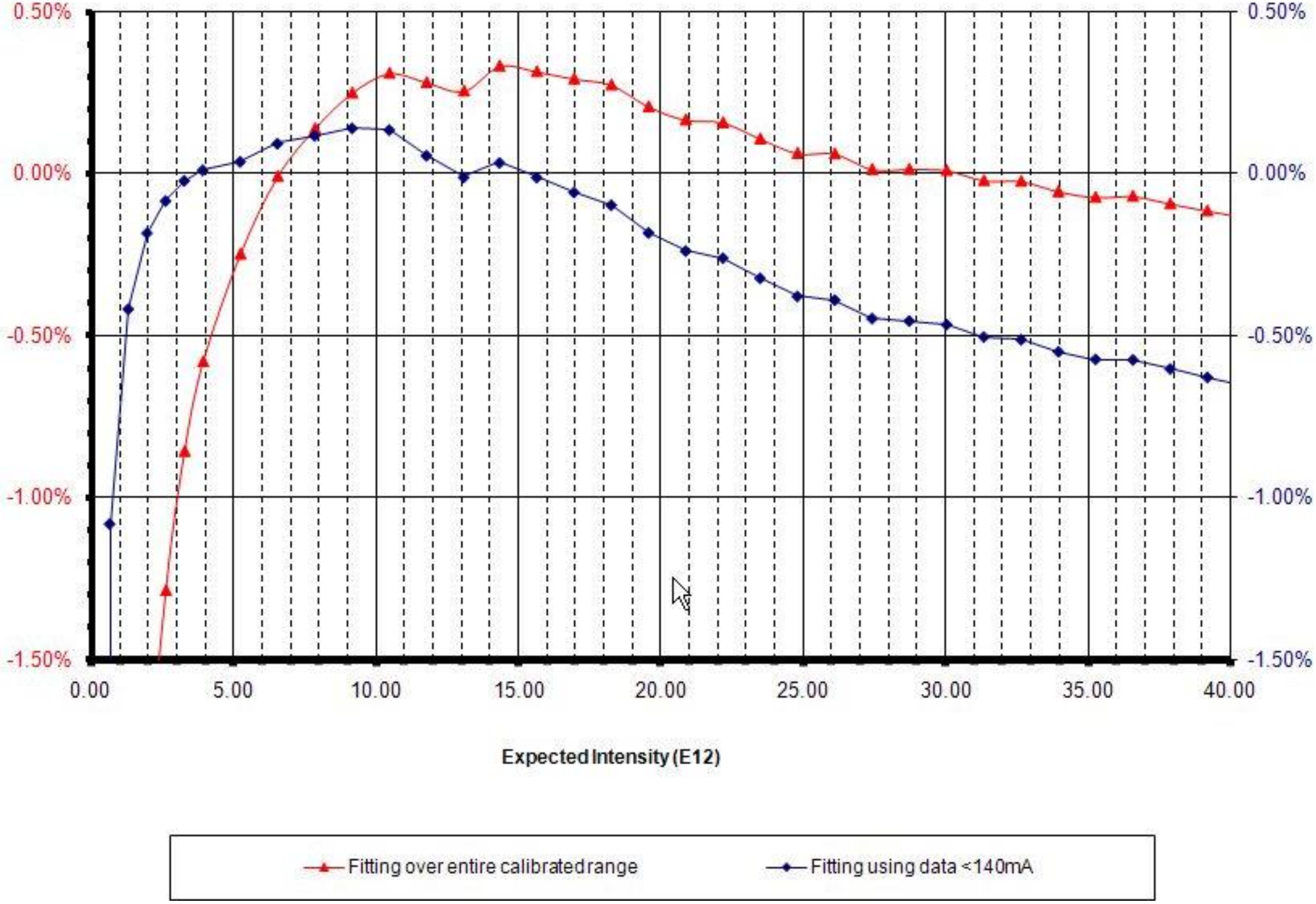
SBD: Also uses Wall Current Monitor but digitizes Signal and then sums it.
Syst:
Baseline meas. coupled with freq. response of WCM, Oscilloscope and integrator and cable, stability of oscilloscope calib.



Ultimately scaled to DC current transformer

1-2% uncertainty on beam intensity

T:BEAM : percent error at various intensities based on least square fits between expected and measured intensities for a given calibration DC current



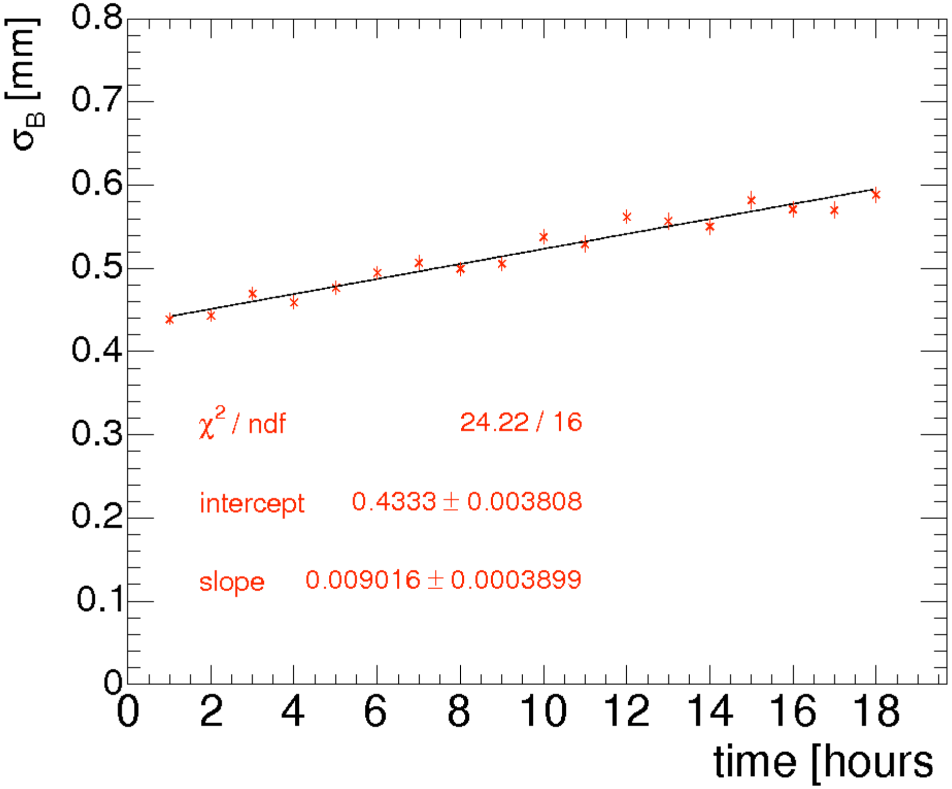
Emittances – Beam profiles

Transverse beam profiles

- **Flying wires:** systematics include wire rotation speed, scintillator acceptance vs beam position, influence from previously scattered particles, …
- **Synch. Light:** systematics include optical magnification, intensifier non-uniformity/degradation increasing with time, optical acceptance, …
- **Ionization Profile Monitors:** systematics include resolution effects, baseline subtraction, microchannel plate non-uniformities and degradation,…

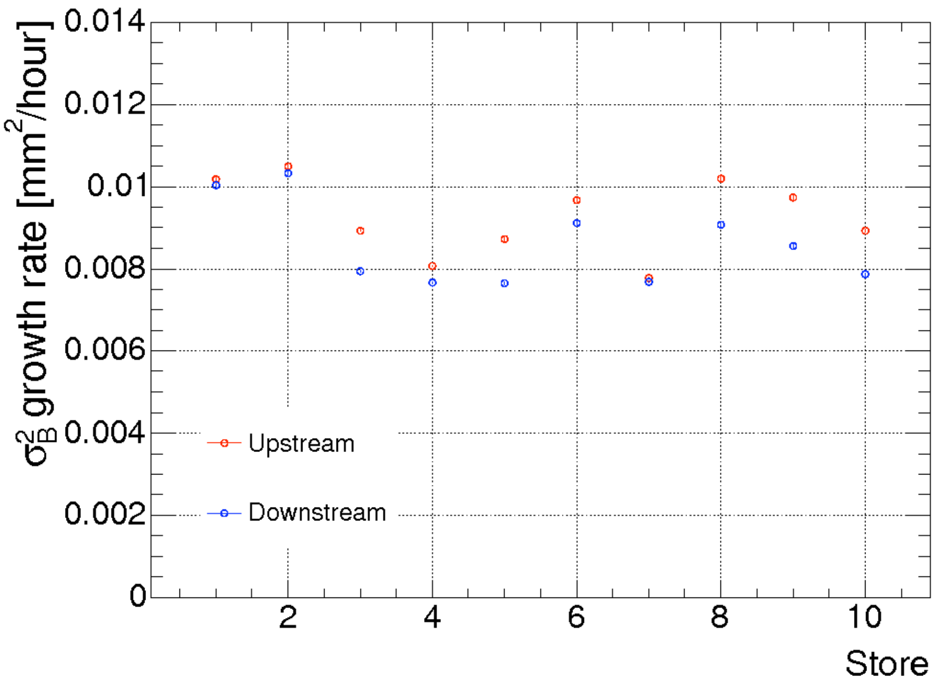
Longitudinal beam profiles measured with the SBD

Flying Wire sigmas (from beam profiles) for emittance measurements

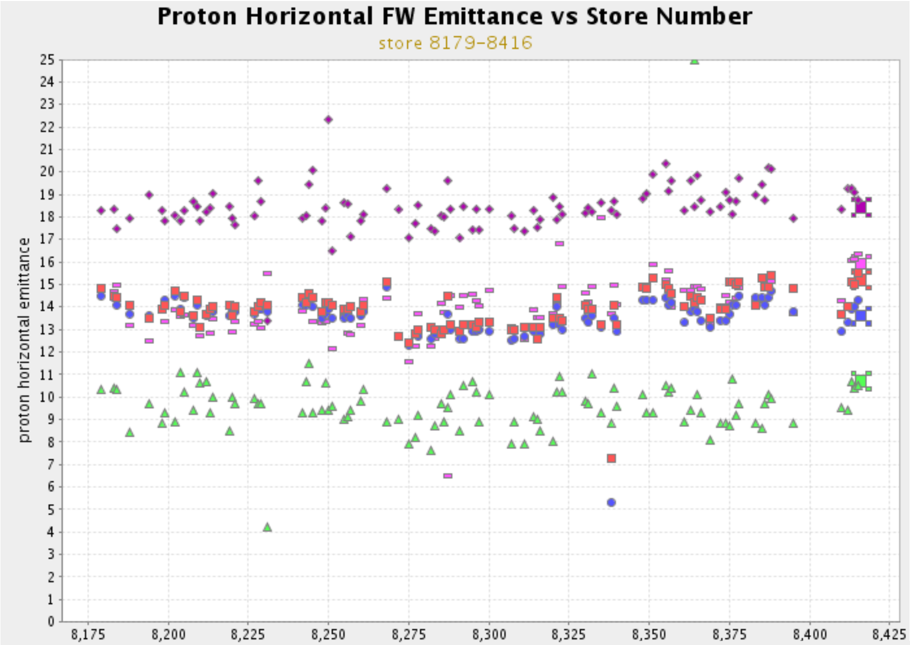


Beam width growth rate for a bunch in a store

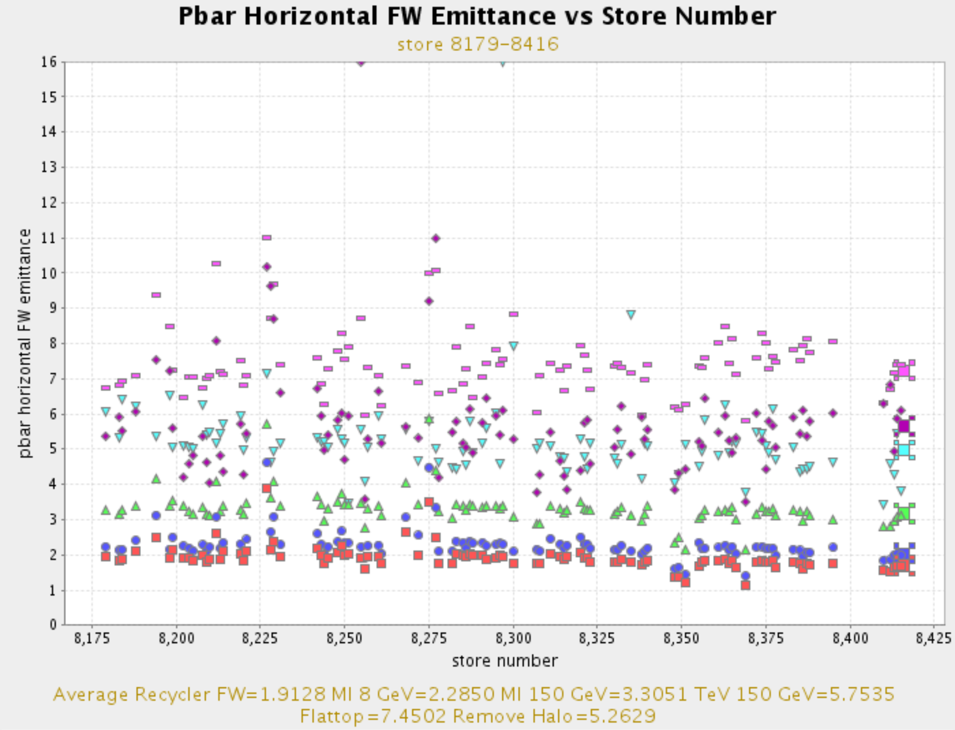
Diffusion rate for 10 stores



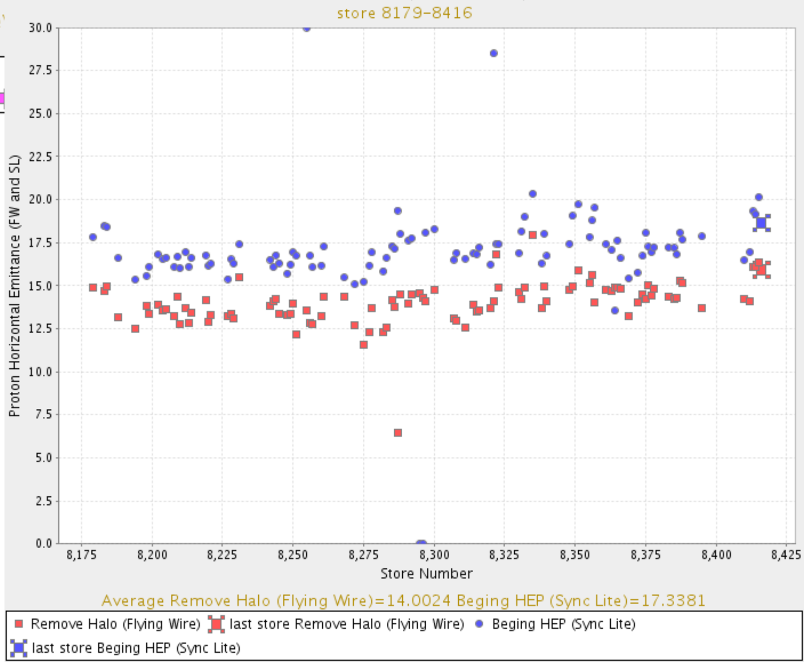
Emittances


Proton Horizontal FW Emittance vs Store Number
store 8179-8416

Average MI 8 GeV=13.9232 MI 150 GeV=13.5152 TeV 150 Ge
Remove Halo=14.0024


Pbar Horizontal FW Emittance vs Store Number
store 8179-8416

Average Recycler FW=1.9128 MI 8 GeV=2.2850 MI 150 GeV=3.3051 TeV 150 GeV=5.7535
Flattop=7.4502 Remove Halo=5.2629


Proton Horizontal Emittance (FW and SL) vs Store Number
store 8179-8416

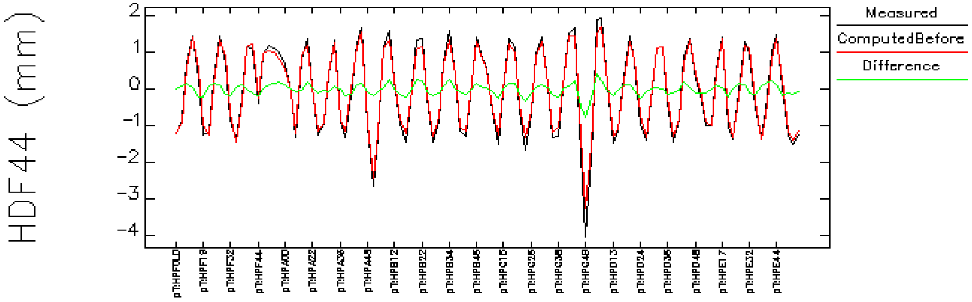
Average Remove Halo (Flying Wire)=14.0024 Beging HEP (Sync Lite)=17.3381

Linear Optics from Closed Orbit (LOCO*)

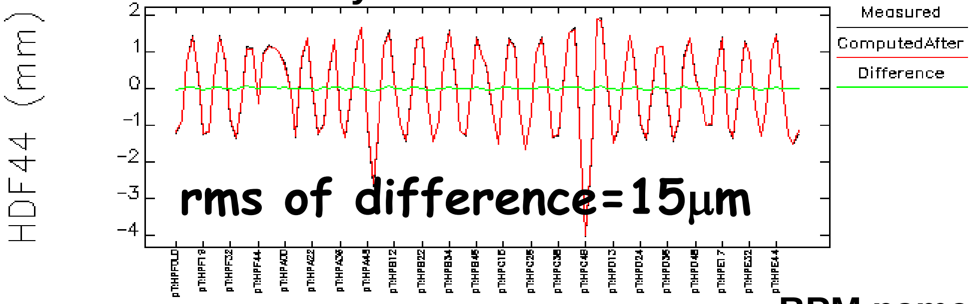
$$\begin{pmatrix}x\\ y\end{pmatrix} = M_{\substack{measured\\ model}}\begin{pmatrix}\theta_x\\ \theta_y\end{pmatrix}$$

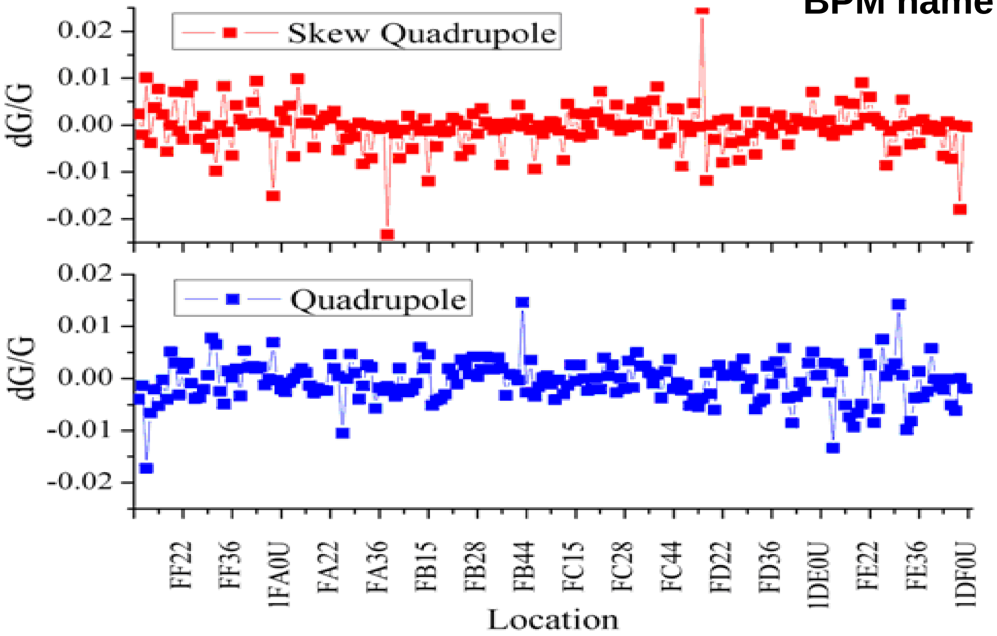
Fit Mmodel to Mmeasured

- **Model Orbit Response Matrix is a function of**
  - *Quadrupole gradient errors*
  - *Steering magnet calibrations*
  - *BPM gains*
  - *Quadrupole tilts*
  - *Steering magnet tilts*
  - *BPM tilts*
  - *Energy shift associated with steering magnet changes*

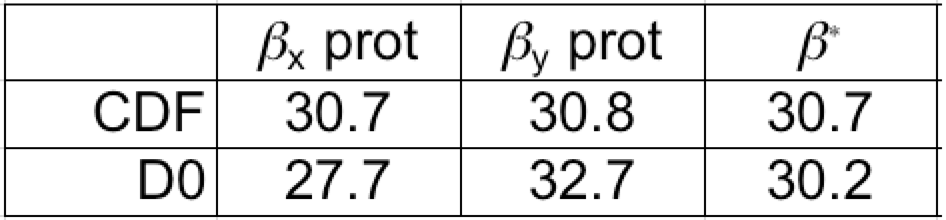


Accuracy of orbit measurement

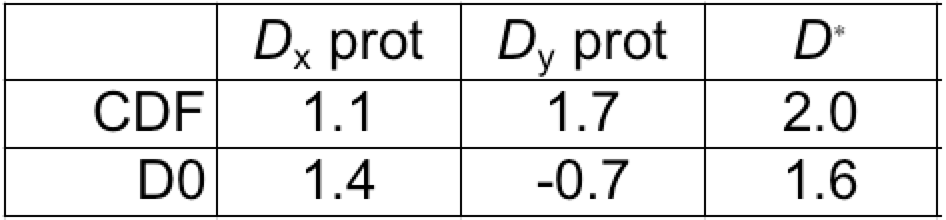




β* Summary Table
August 27, 2010



	β_x prot	β_y prot	β^*
CDF	30.7	30.8	30.7
D0	27.7	32.7	30.2

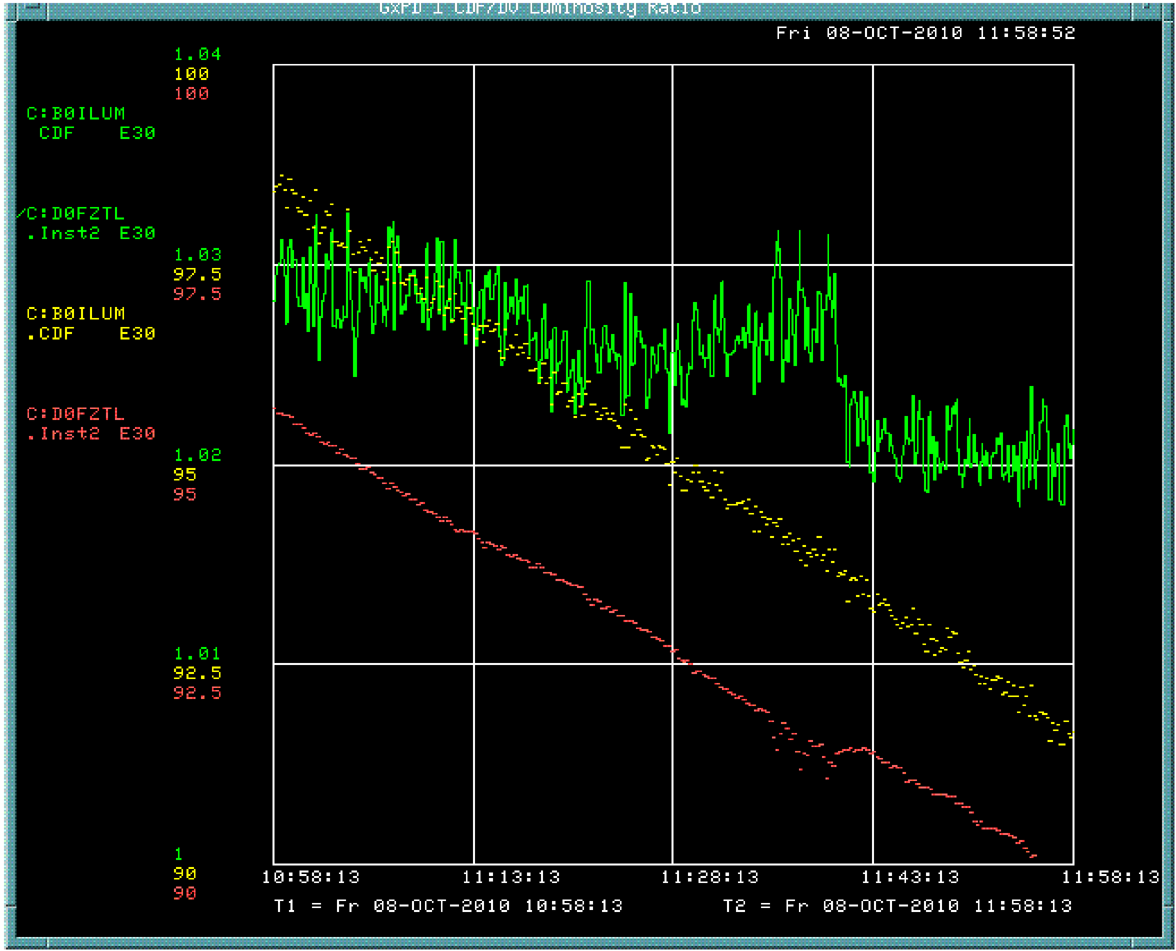


	D_x prot	D_y prot	D^*
CDF	1.1	1.7	2.0
D0	1.4	-0.7	1.6

Uncertainties vary between 5% (ideal) to 15%
Depends on the goal of the measurement and coordination with other machine studies

Lattice measurements by the machine done mainly with protons

Continue maximizing the luminosity at both IPs



Routinely perform "electrostatic separator scans" to determine if the beams are well centered.

D0 luminosity increased by 1%
After the alpha-bump and adjustment of the horizontal separation.
Change implemented in January 2011

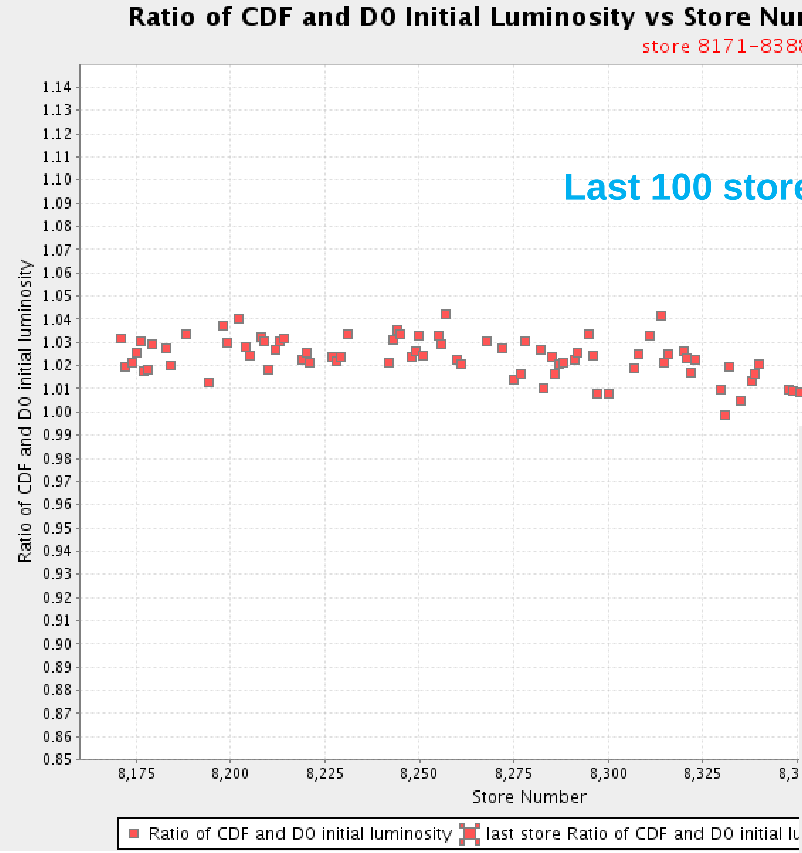
Luminosity Task Force (established in 2003)

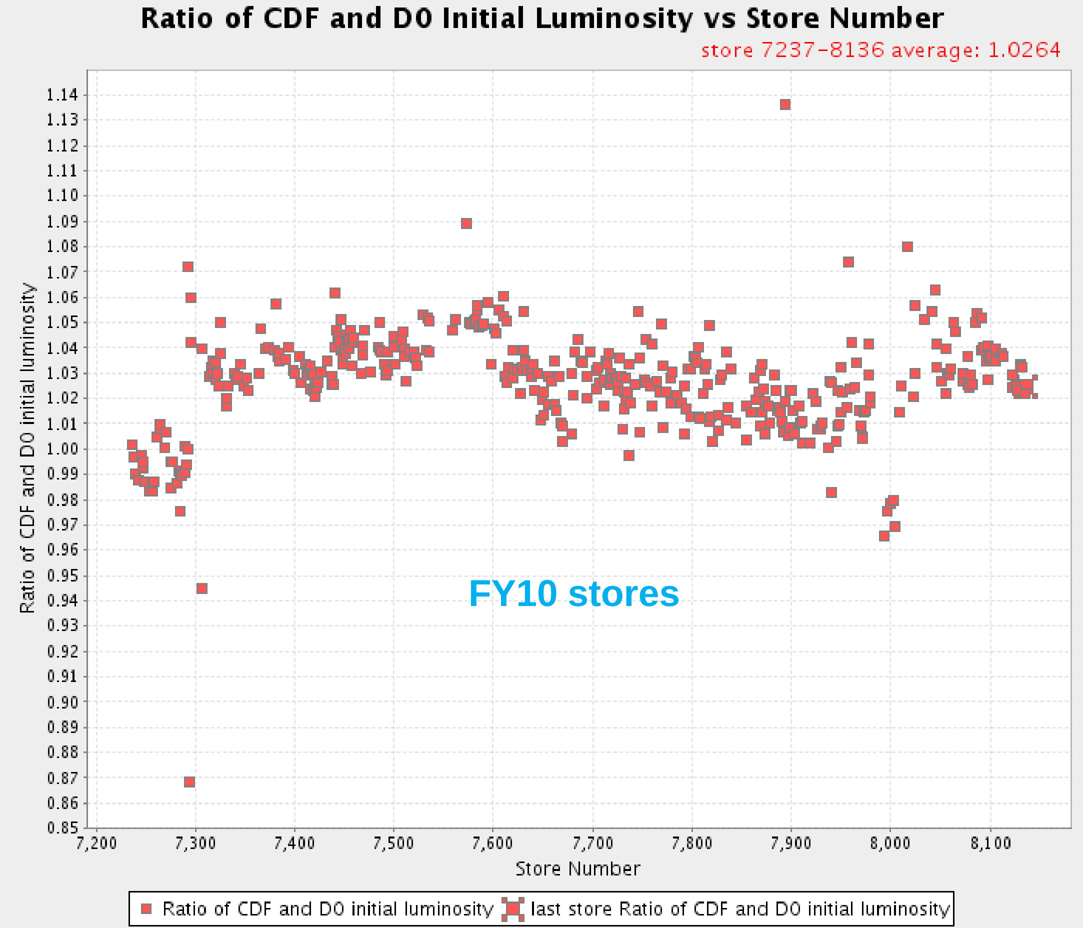
- A joint effort between Accelerator, CDF and D0 colleagues to address luminosity detector issues, beam position and beam width issues, and Tevatron issues.

- Monitor continuously (store by store basis) luminosity related quantities for CDF/D0 and their correlations with machine parameters and external factors. (eg. Luminosity ratio).

- Exchange information on a daily/weekly basis in smaller groups and meet once a month (or as needed) as a big group (~25 people).

- As a result, several machine studies have been performed and we have now a much better understanding of the Tevatron optics, crossing angles and vacuum at the IPs, emittance of the proton and pbar beams as well as of the luminosity detectors of both experiments.

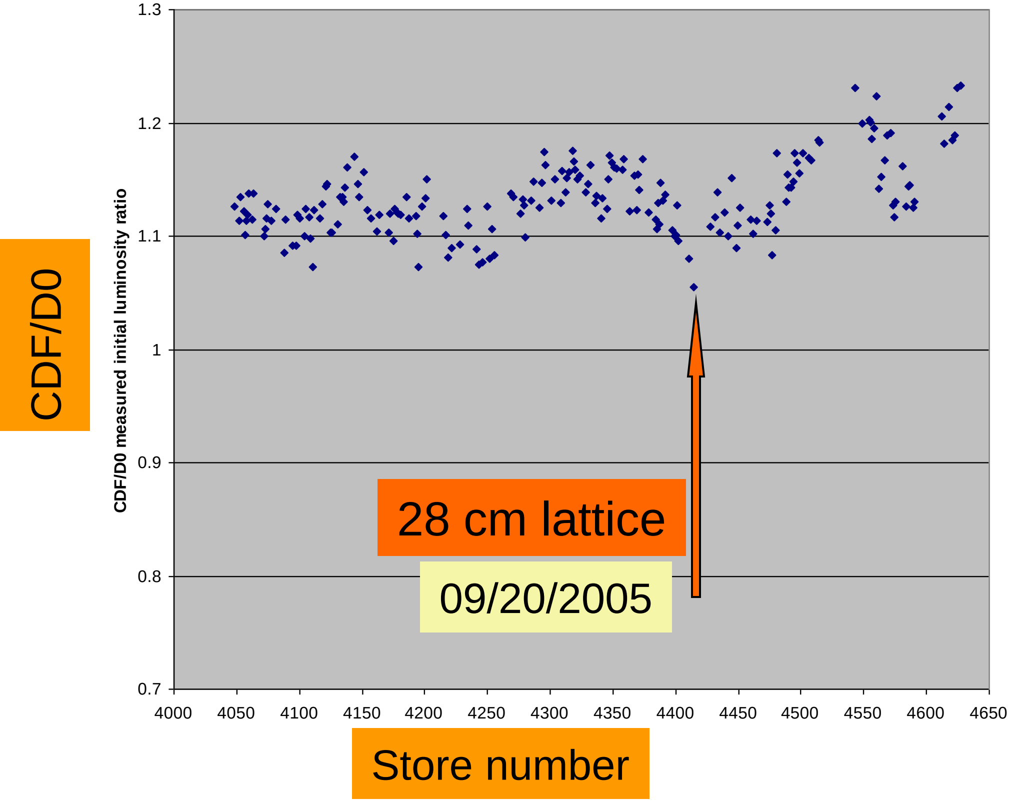


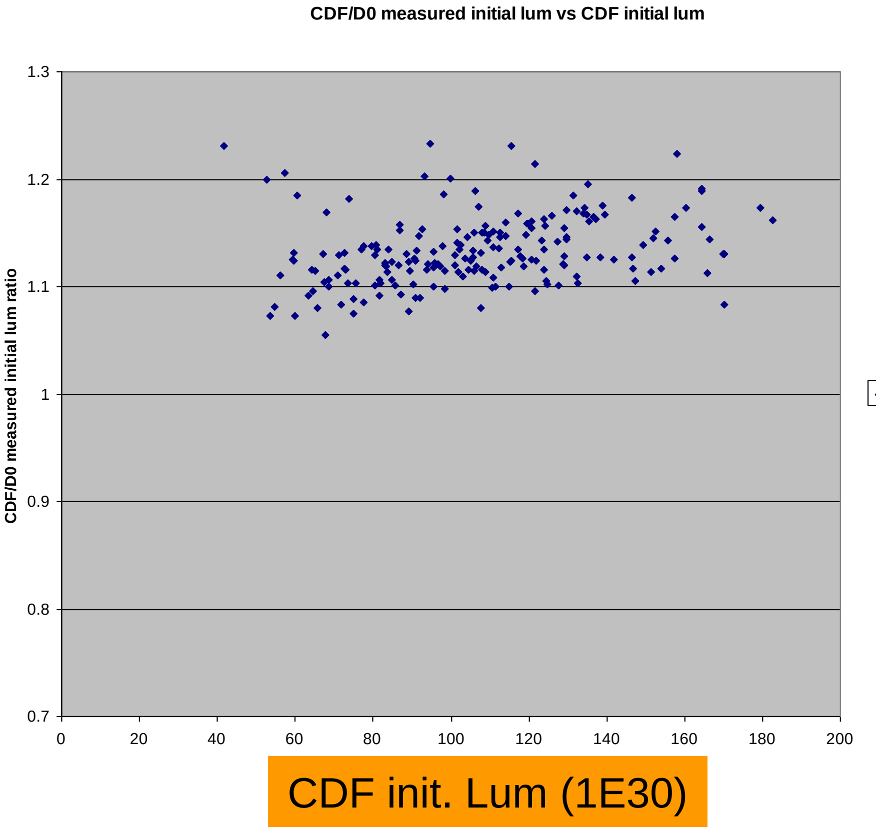


D0 electonics issues
CDF and D0 aging/radiation damage
Lattice changes
….

CDF/D0 initial luminosity ratio vs store number and initial luminosity

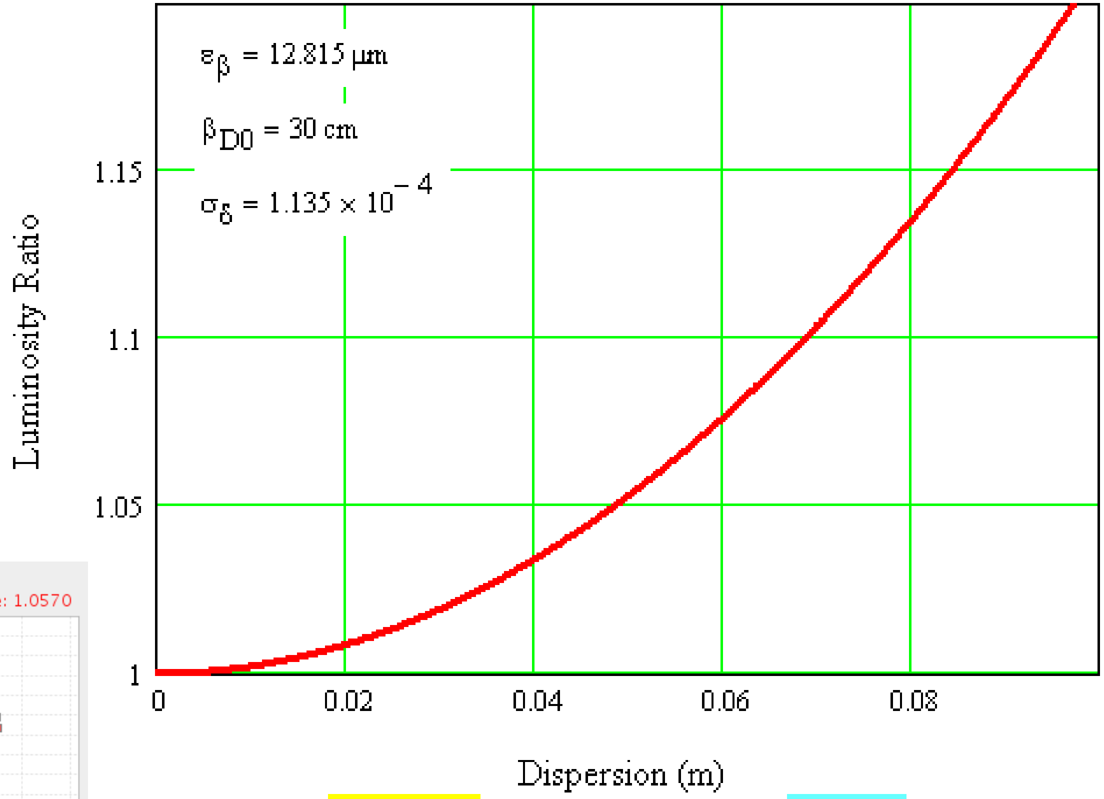
03/18/05-02/05/06

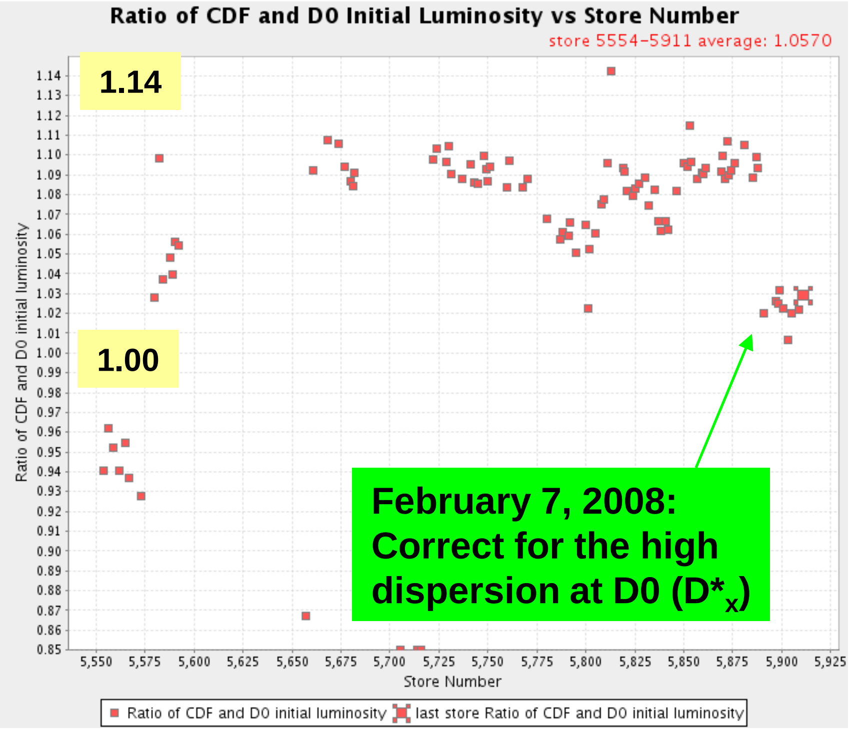




CDF/D0 Luminosity Ratio vs. *D**

$$R = 1 + \frac{D^{*2}\sigma_\delta^2}{\varepsilon\beta^*}$$





1.14

1.00

February 7, 2008: Correct for the high dispersion at D0 (D^*_x)

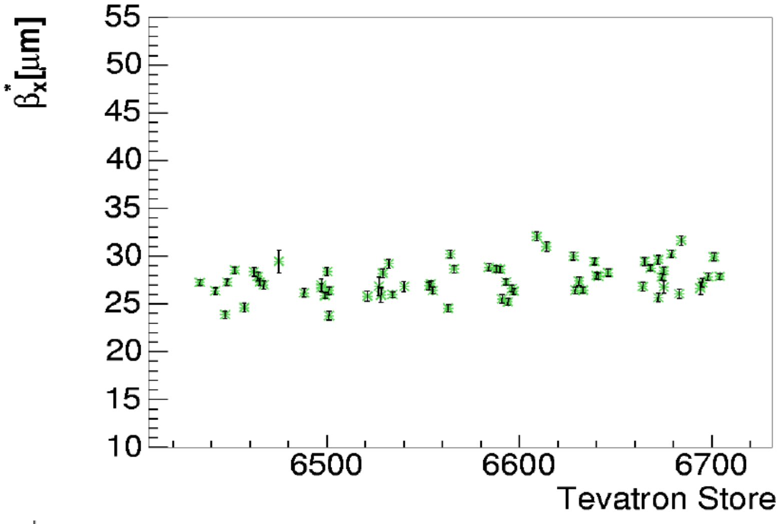
	before		after	
	β* cm	D* cm	β* cm	D* cm
CDF	33.3	1.3	29.0	1.2
D0	31.3	6.3	29.1	2.1

CDF Beam parameter measurements

- **Fit the beam width at CDF according to the following model**
  - $\sigma_{beam} = \text{sqrt}(\sigma^2_{obsv} - \kappa^2 < \sigma^2_{prim.\ vtx.} >)$
    $= \text{sqrt}(\varepsilon(\beta^* + (z - z_0)^2)/\beta^*))$

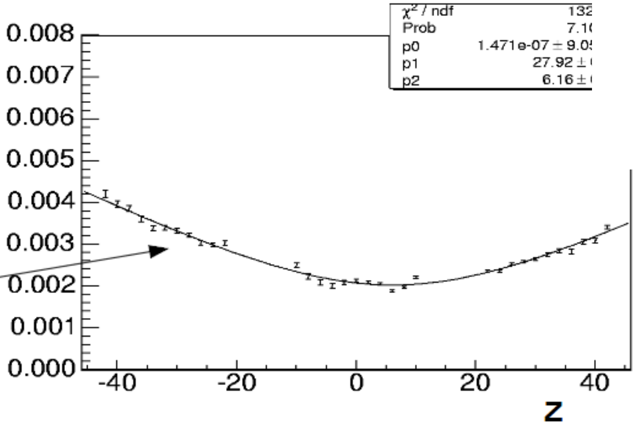
    where $\kappa = 1.5$
- **We fit σ_{beam} vs. z to extract ε, β*, and z_0**

β* in x-direction

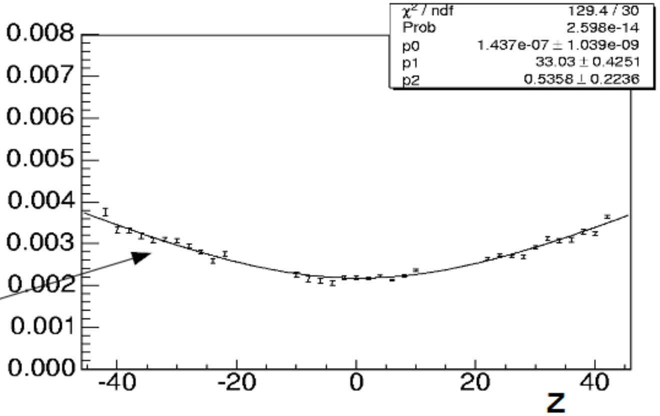


Example fit for store 6704

p0 = emittance
p1 = β*
p2 = z_0



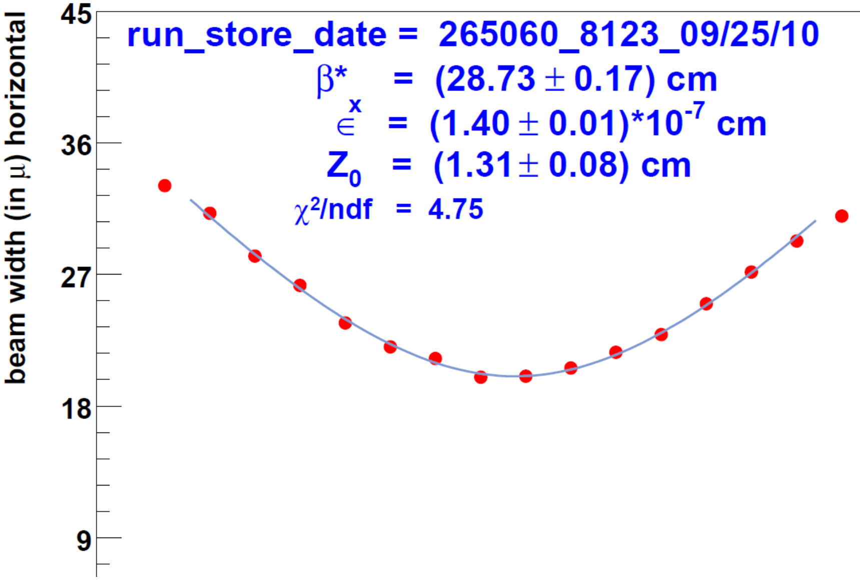
Fit in x-direction

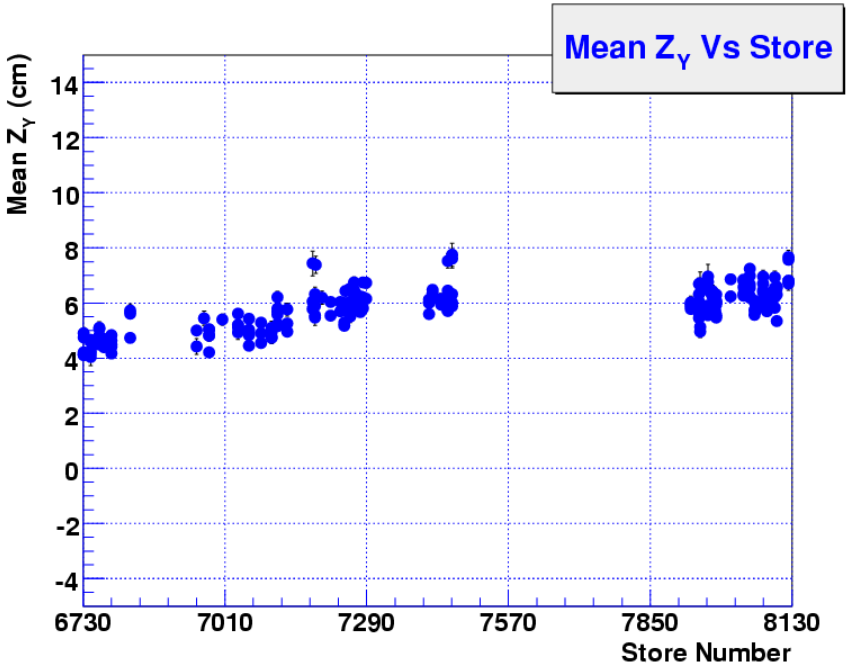


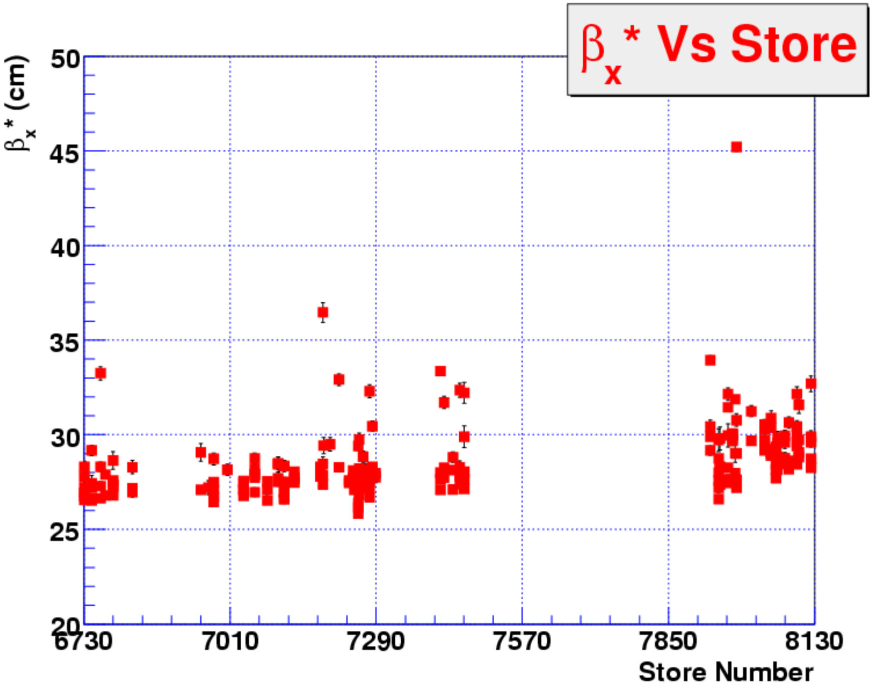
Fit in y-direction

V. Papadimitriou
01/14/11

D0 Beam parameter measurements







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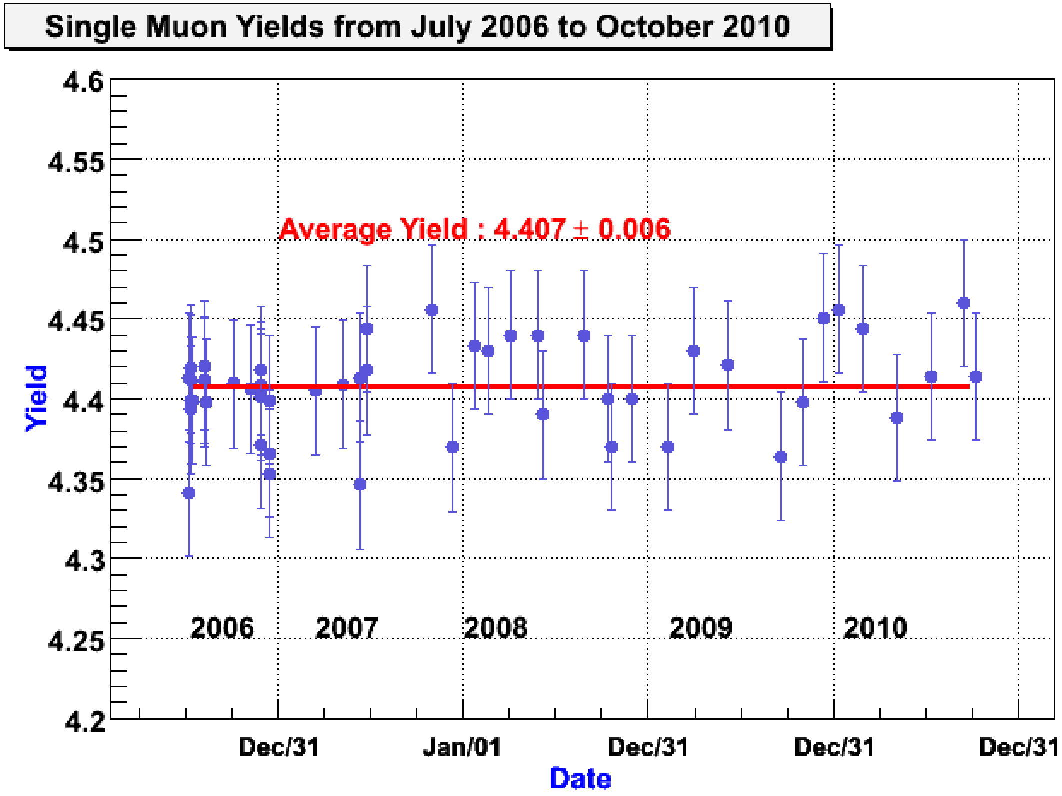
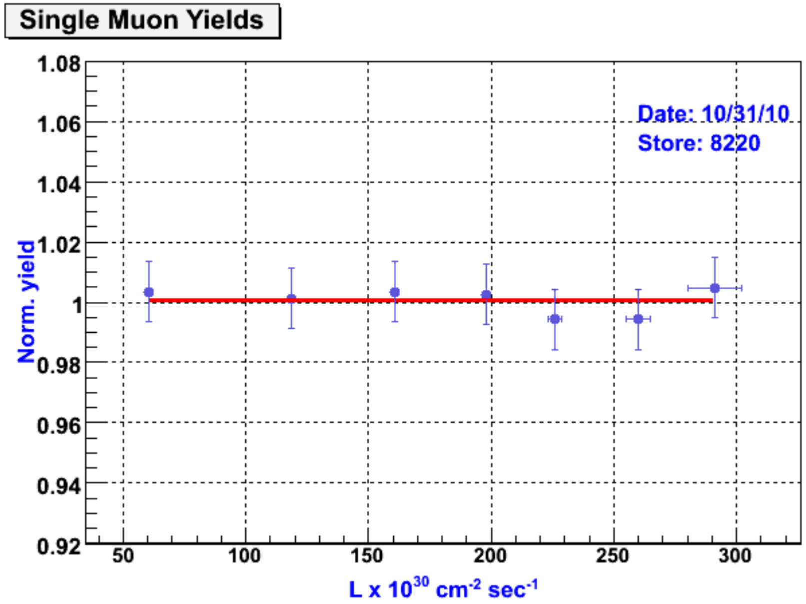
01/14/11

Checking the Luminosity with Forward Muon Yields at D0





Stability within ~1% within Run IIb

Techniques for Luminosity measurements by the experiments

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

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

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

➢ **Use dedicated detector:**

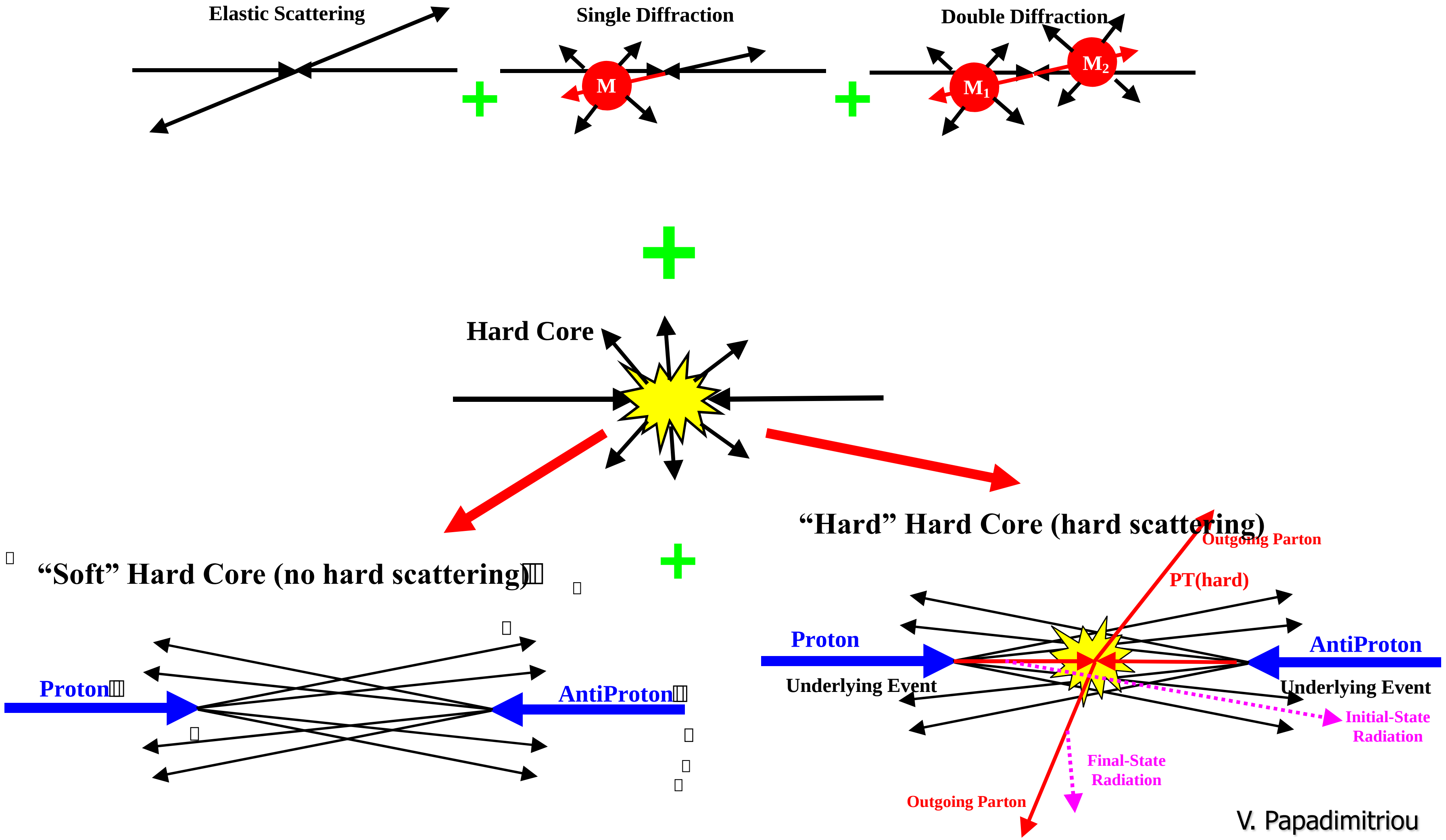
$$\boxed{\tilde{\mu}_{\alpha} \cdot f_{BC} = \sigma_{in} \cdot \varepsilon_{\alpha}^{\det} \cdot \mathcal{L}}$$

- ➢ **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:**

$$\boxed{W \to lepton, \nu}$$

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

The total p-pbar cross-section



Elastic Scattering + Single Diffraction + Double Diffraction

M

M_1 M_2

+

Hard Core

"Soft" Hard Core (no hard scattering) + "Hard" Hard Core (hard scattering)

Proton

AntiProton

Outgoing Parton

PT(hard)

Underlying Event

Initial-State Radiation

Final-State Radiation

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P-pbar cross-sections

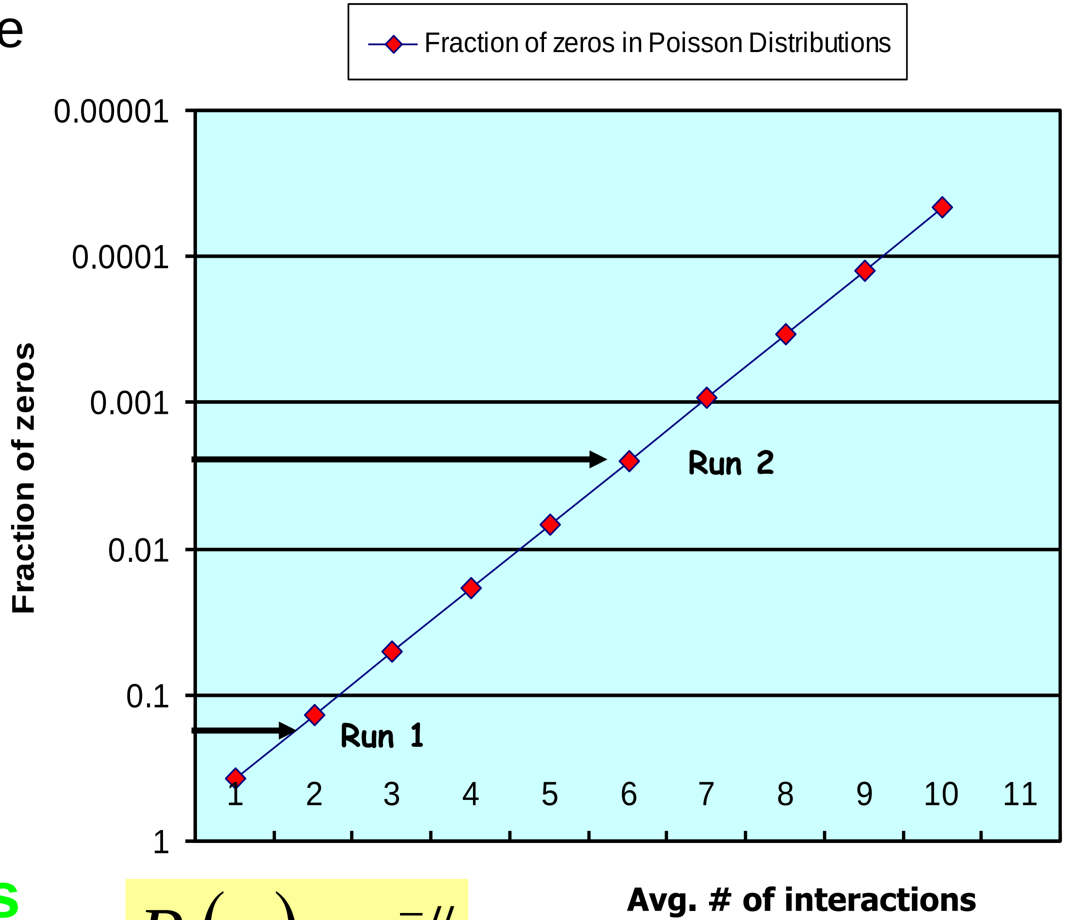
Process (mb)	CDF meas. @ 1.8 TeV	E811 Exp.
σ_{tot}	80.03 (2.24)	71.71 (2.02)
σ_{el}	19.70 (0.85)	15.79 (0.87)
σ_{in}	60.33 (1.40) 2% ← 8%	55.92 → (1.19) 2%
σ_{hc}	[45]	
σ_{sd}	9.46 (0.44)	8.1 (1.7) E710
σ_{dd}	6.32 (1.70)	

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

CDF Luminosity measurment for Run II: try to measure μ directly (Used scintillating counters in Run I)

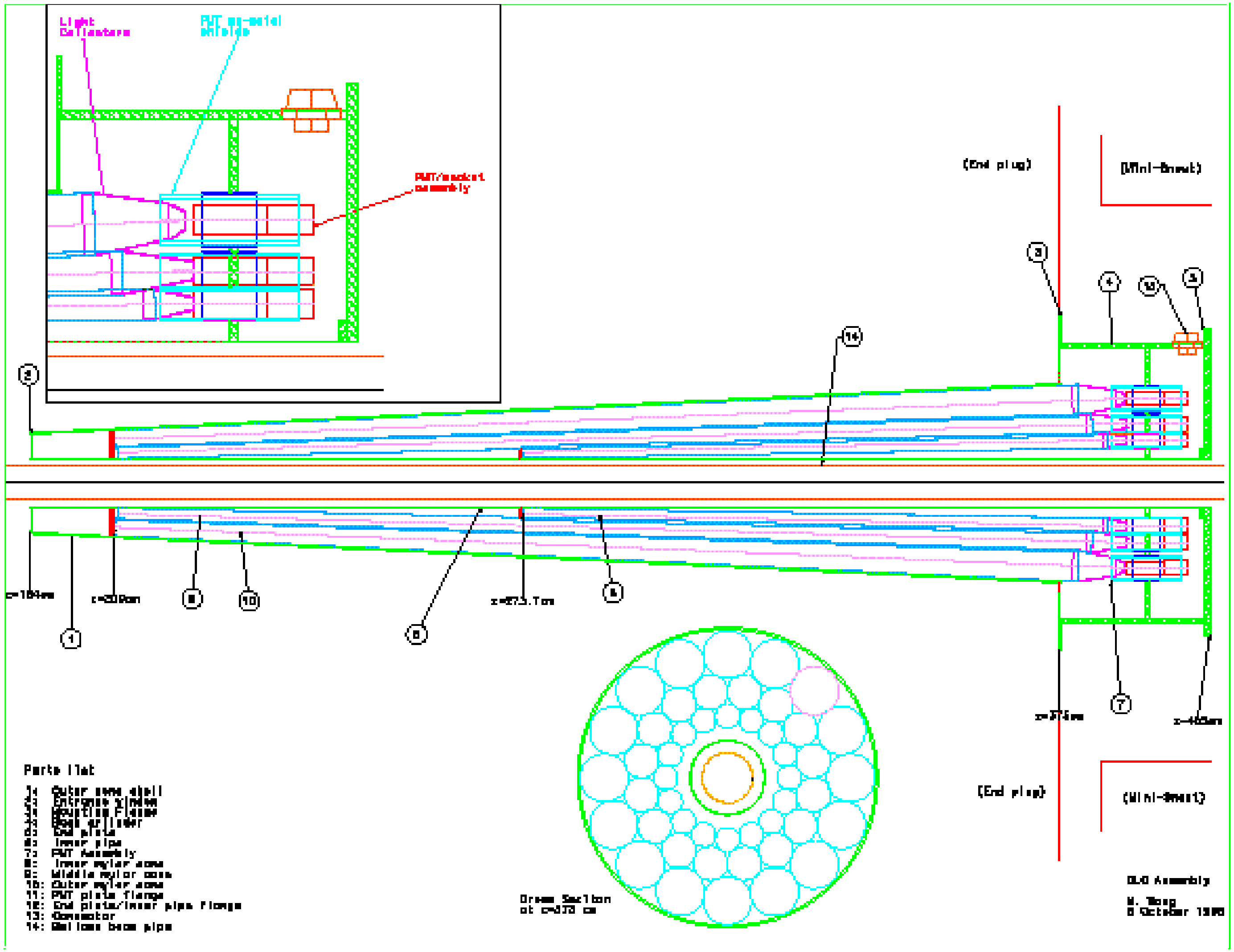
- Measuring “zeros” eliminates most of the dependence on the material model.
- At very high luminosities one may not be able to measure though rate (or “zeros”) accurately enough.
- Fraction is 0.25% for 6 interactions on average.
- Systematics on acceptance only can make a precise measurement very difficult.



- **Try to measure the # of p-pbar interactions directly !**

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

Cherenkov Luminosity Counters (CLC): Design

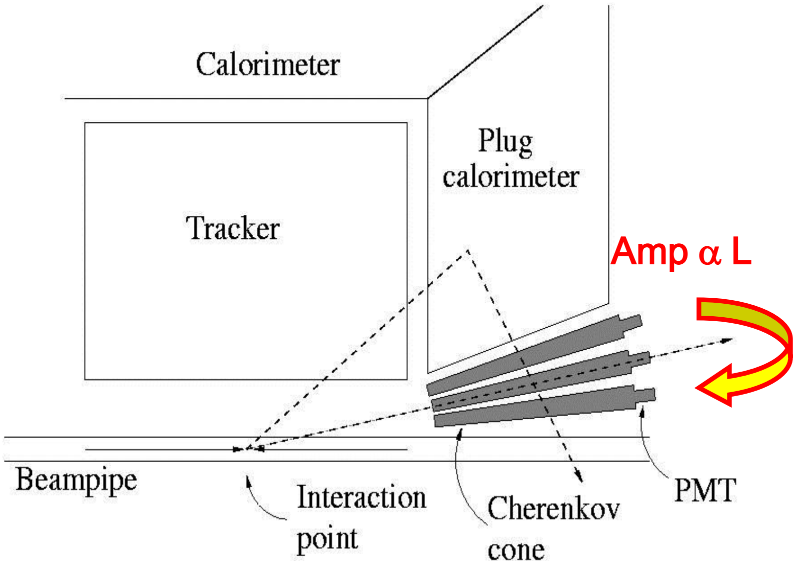


- **48 counters/side**
- **3 layers with 16 counters each**
- **coverage: 3.7≤ |η| ≤4.7**
- **Isobutane pressure: up to 2atm**

  η = 1.000143

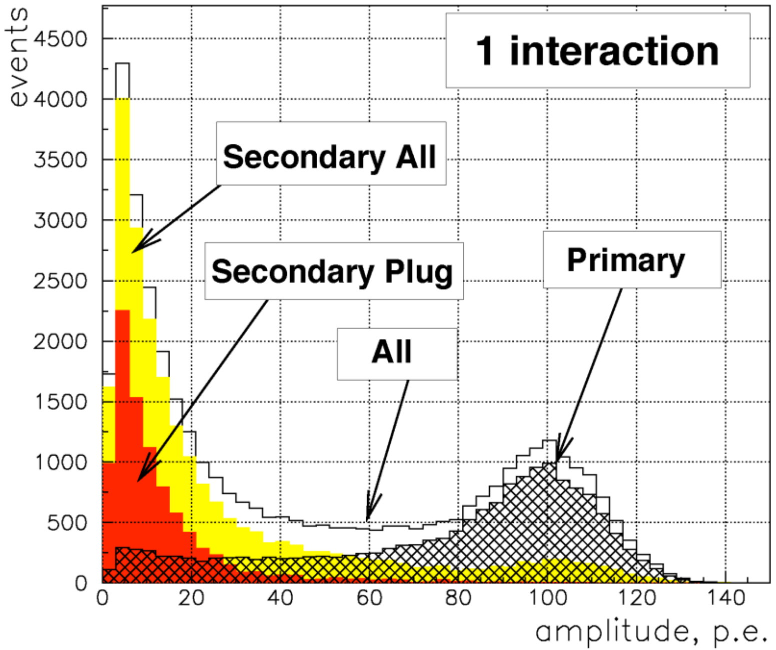
  θ_C = 3.1°
- **PMT: Hamamatsu R5800Q CC with quartz window, gain 10^5**

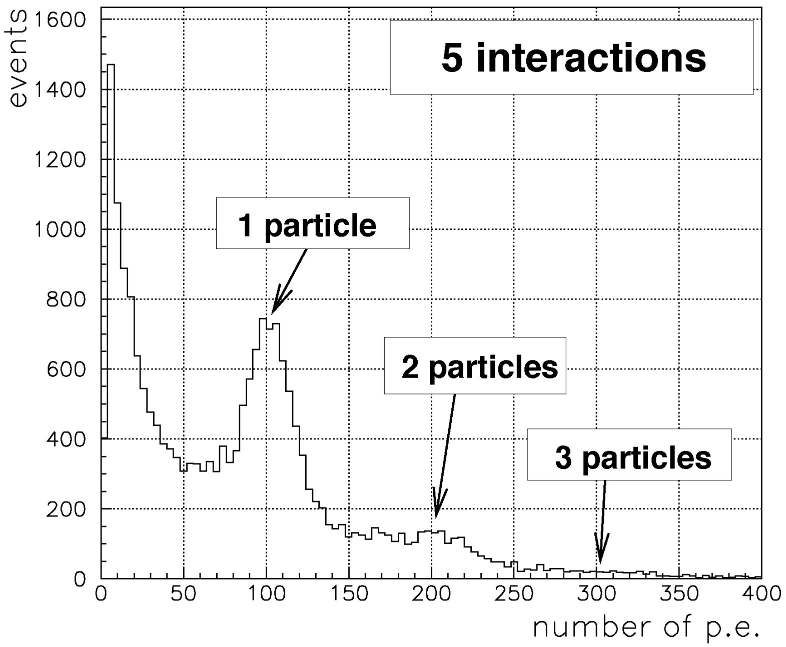
Gas Cherenkov Counters – basic ideas



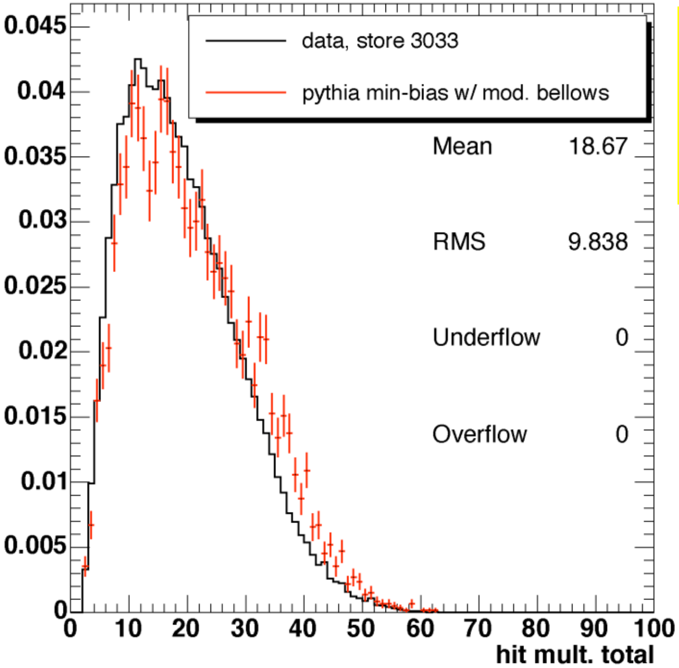
- o Measure the number of p-pbar interactions directly by counting <number> of primary particles
- o Separate primaries from secondaries
- o Good amplitude resolution (~18% from photo stat, light collection, PMT collection)
- o Good timing resolution (separate collisions from losses)
- o Radiation hard,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

➢Expected signal (simulation)



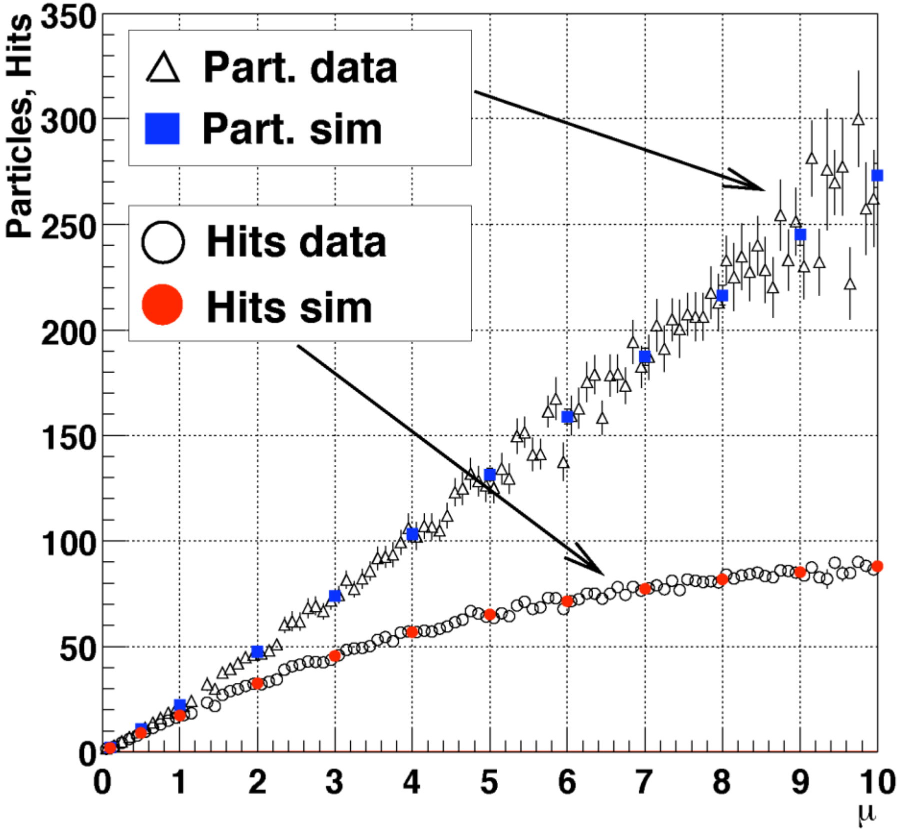


Measuring Luminosity at High Inst. Luminosity Multiplicity Distributions in $p\bar{p}$ Collisions



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

Working on improvement of the simulation



Hits:

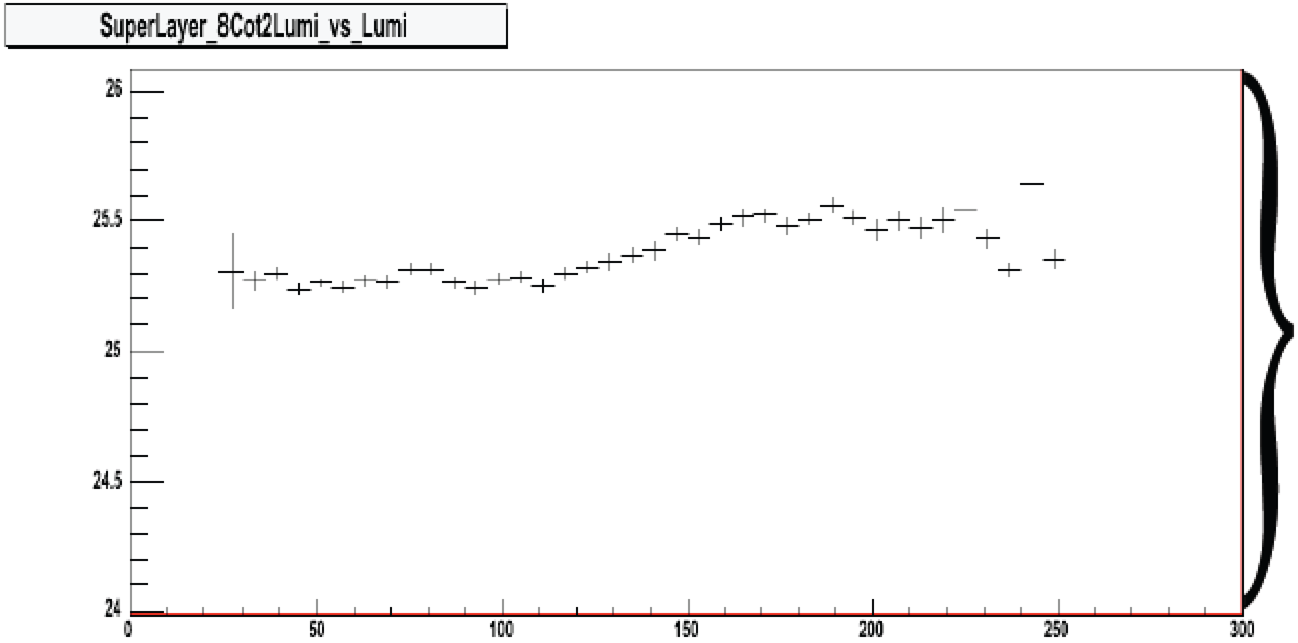
Counters with amplitude above a threshold. (threshold is ~ 0.7 A_0)

“Particles”:

Total amplitude / Ao

Ao = amplitude of single particle peak

Precise high luminosity measurements are feasible !!!



4.2%-CLC uncertainty

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

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 $p\overline{p}$	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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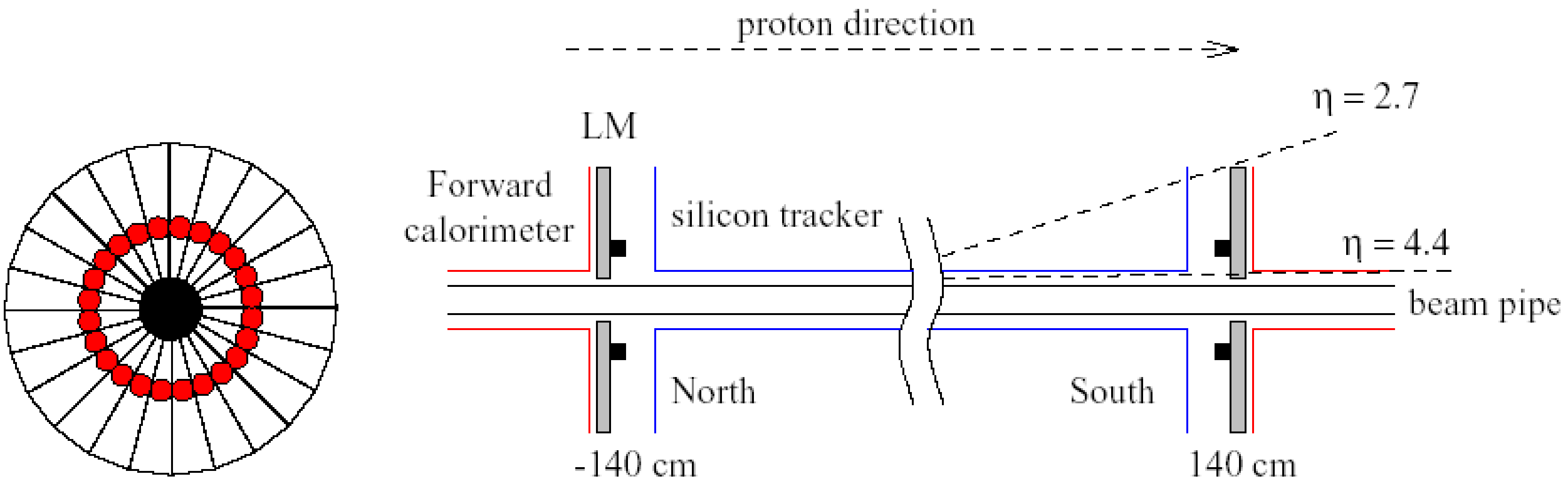
DØ Luminosity measurement in Run II



- **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.**

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 challenges
    - Deadtime potential
    - 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.

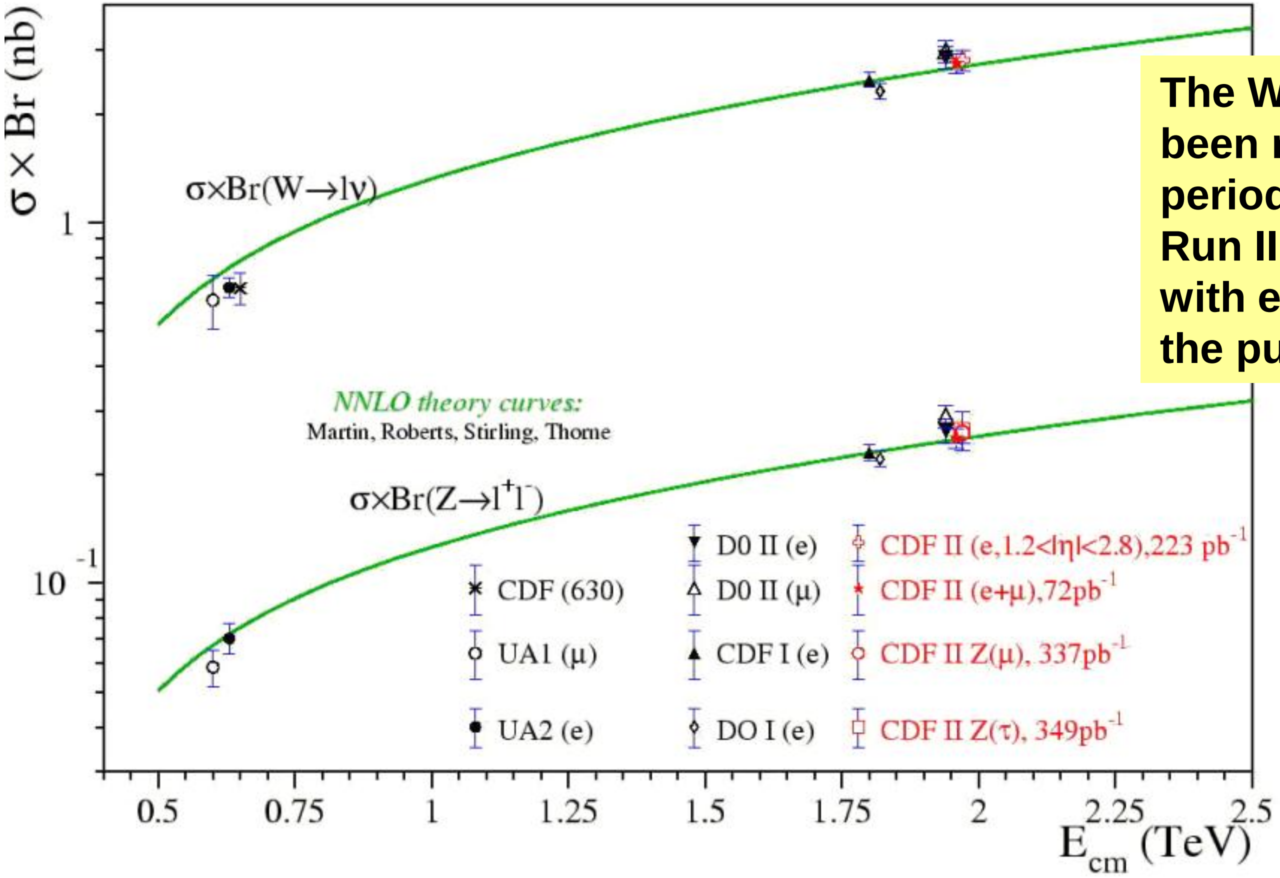
Uncertainty in the D0 Luminosity Measurement

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

Run II A

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%

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**

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

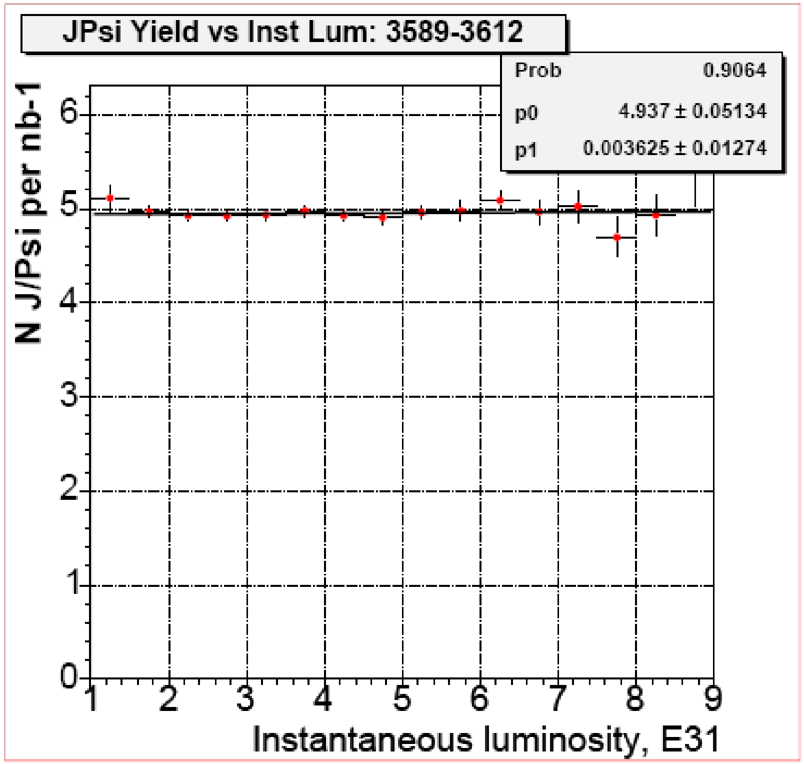
$$\sigma_W \,.\, Br(W \rightarrow e\,\nu) = 2.796 \pm 0.013\,(stat)^{+0.095}_{-0.090}\,(syst) \pm 0.162\,(lum)\,nb$$

Forward electrons

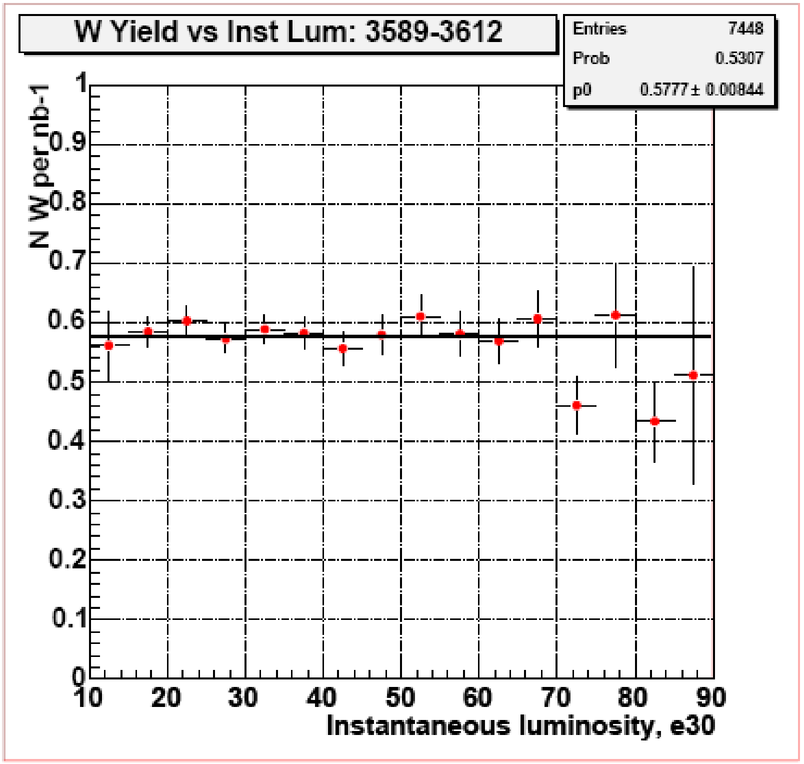
$$\sigma_{\gamma^*/Z} \,.\, Br(\gamma^*/Z \rightarrow ll) = 254.9 \pm 3.3\,(stat) \pm 4.6\,(syst) \pm 15.2\,(lum)\,pb$$

Checking physics objects yields as a function of instantaneous luminosity

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



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



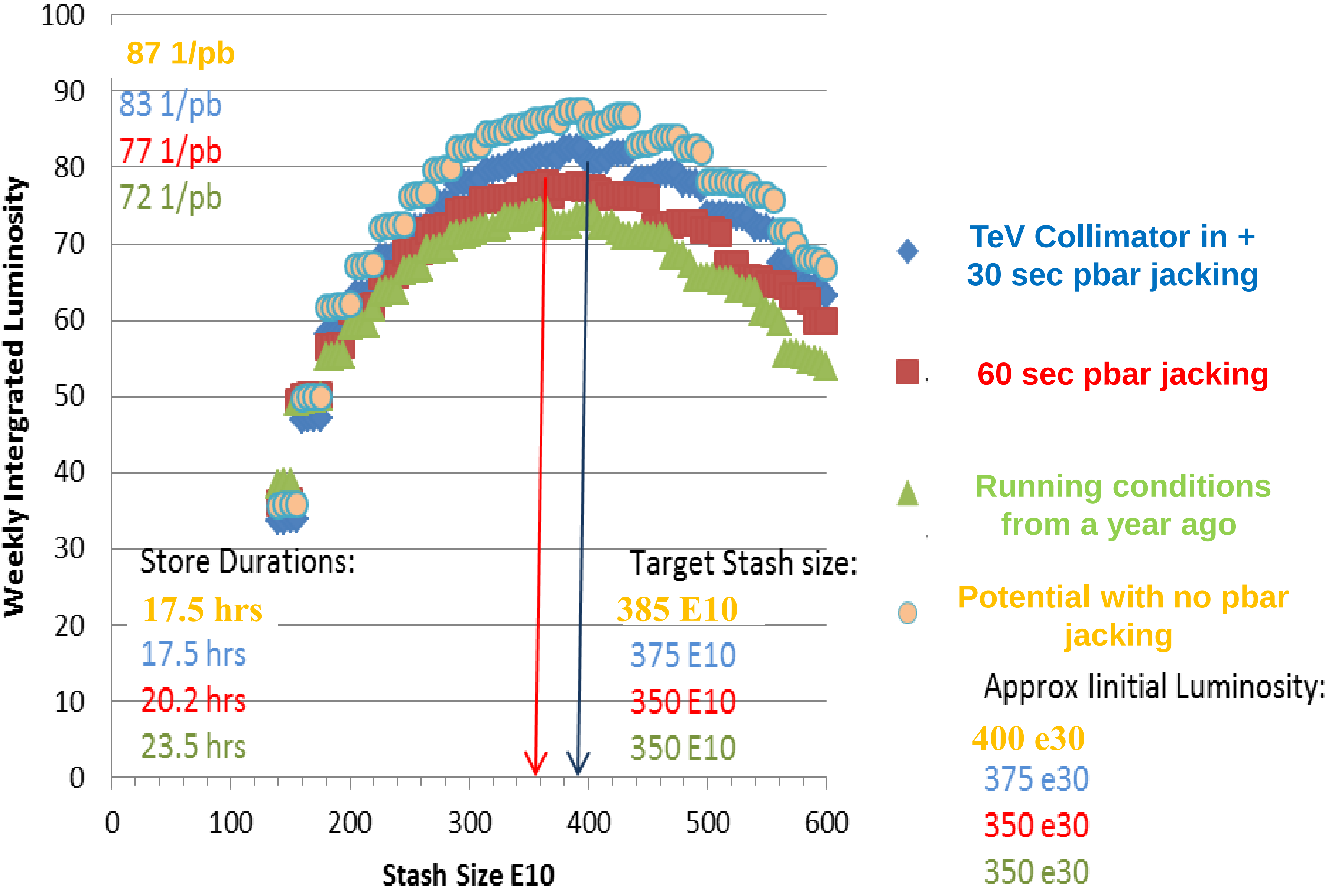
Lessons learned - Tevatron

- 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).

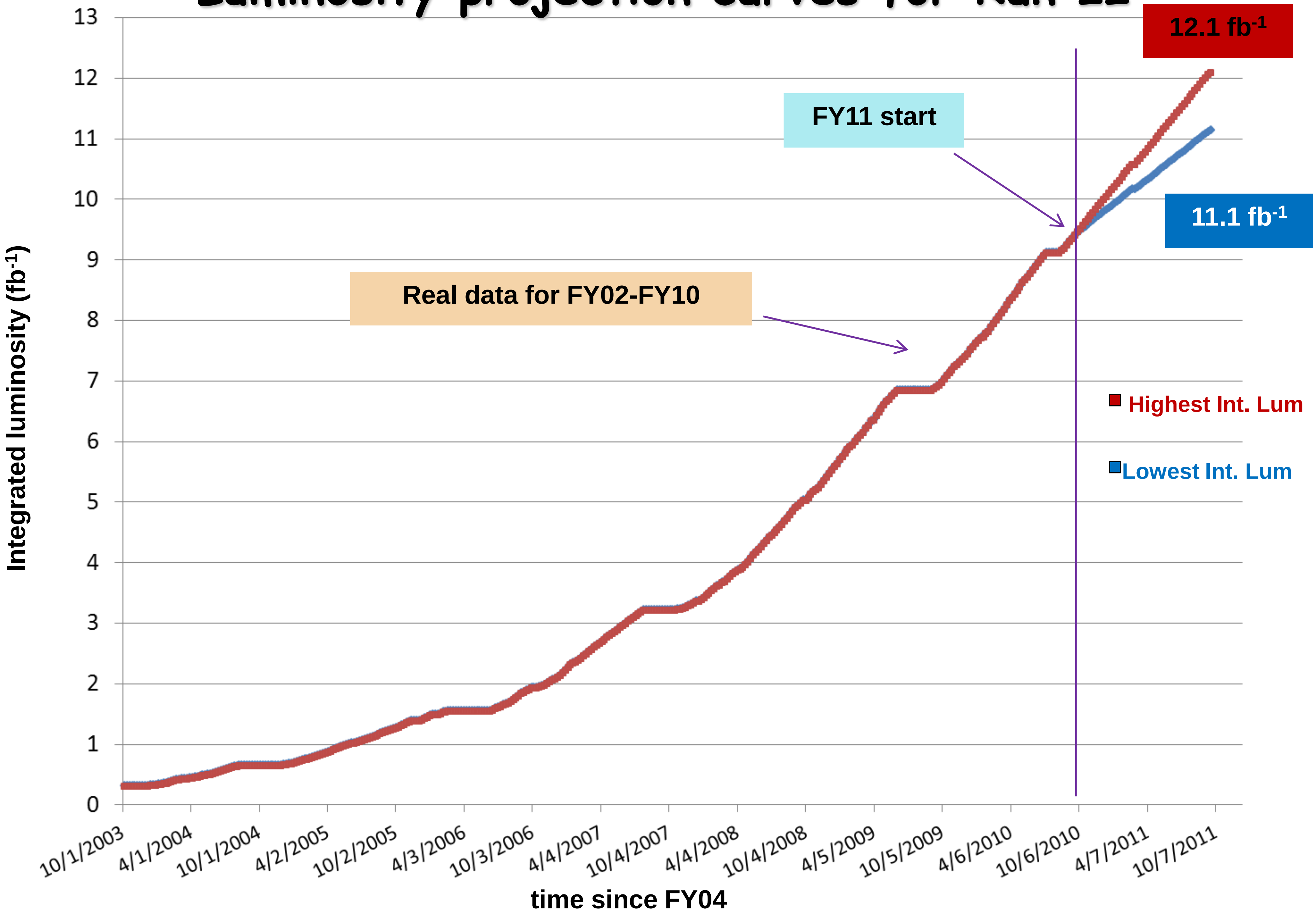
Lessons learned - Tevatron

- 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.

Weekly integrated luminosity potential vs Recycler stash size



Luminosity projection curves for Run II



12.1 fb^{-1}

FY11 start

11.1 fb^{-1}

Real data for FY02-FY10

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 the Tevatron will be very useful for LHC which is already producing impressive physics results.

Backup Plots:

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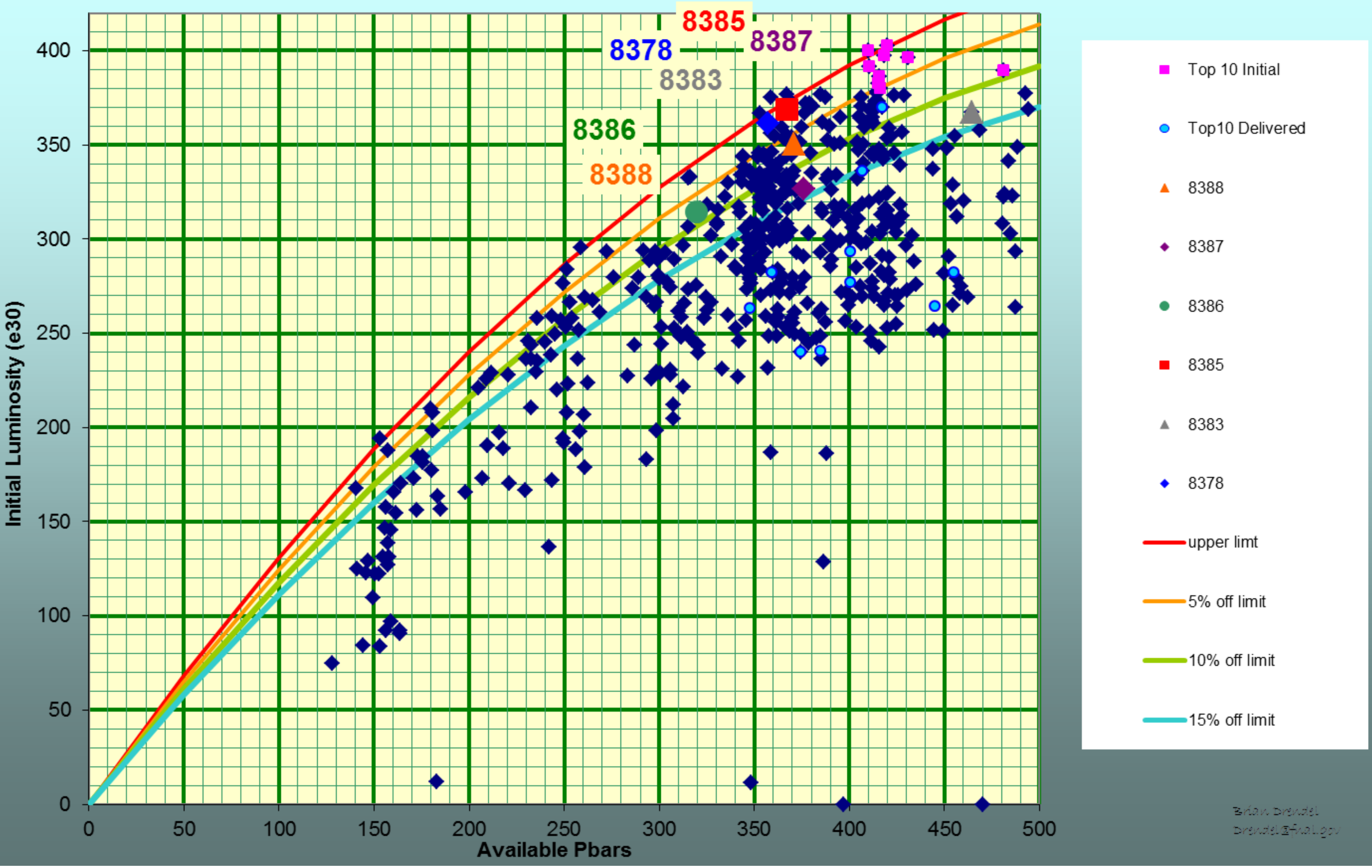
Initial Luminosity vs Available Pbars



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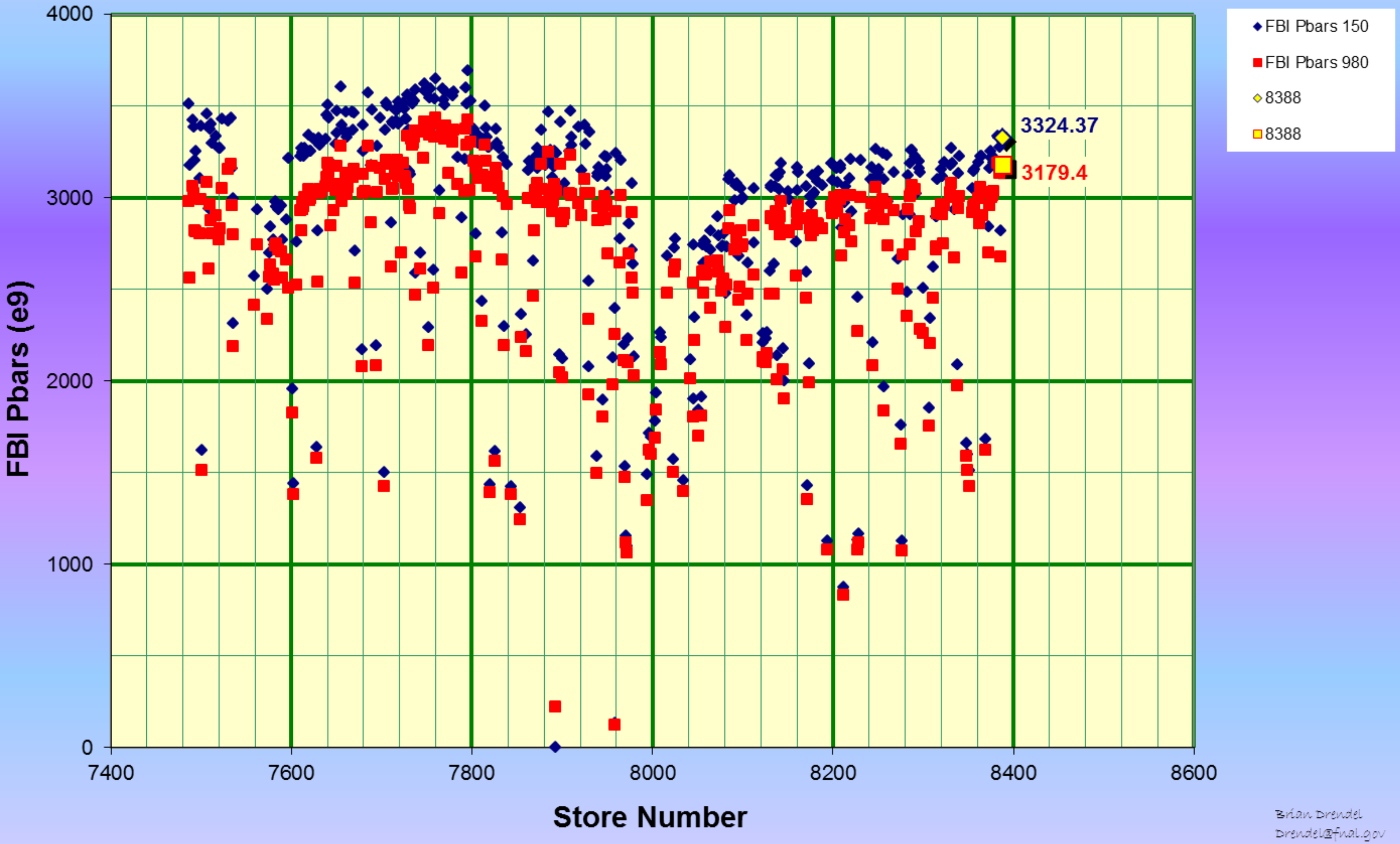
FBI Pbars in the Tevatron



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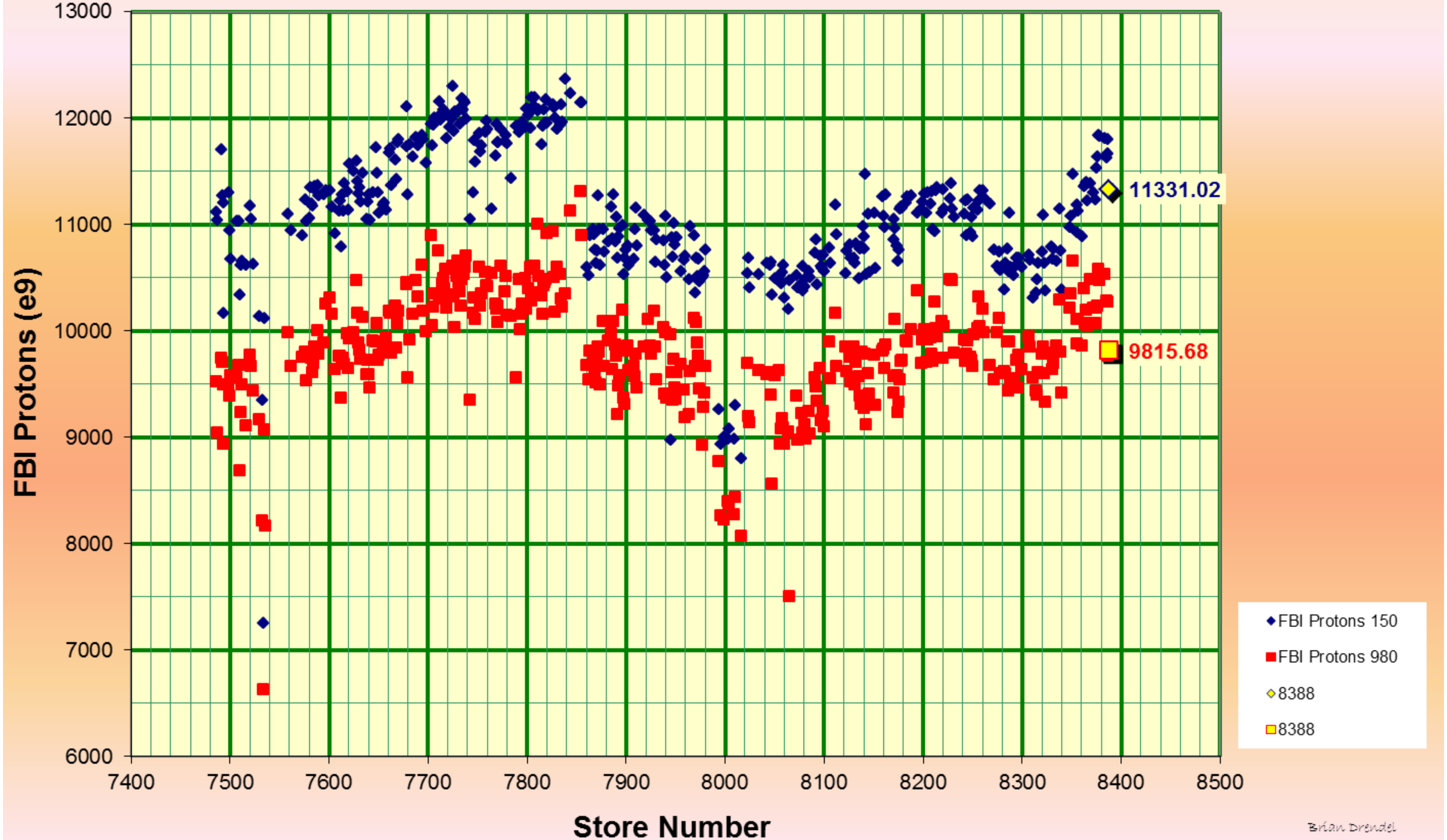
FBI Protons in the Tevatron



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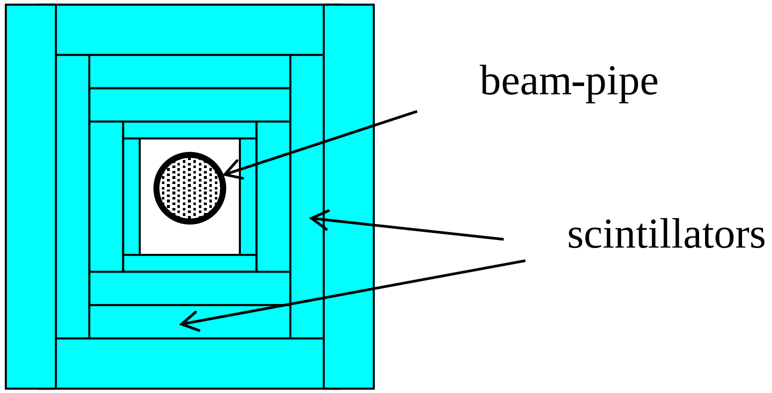
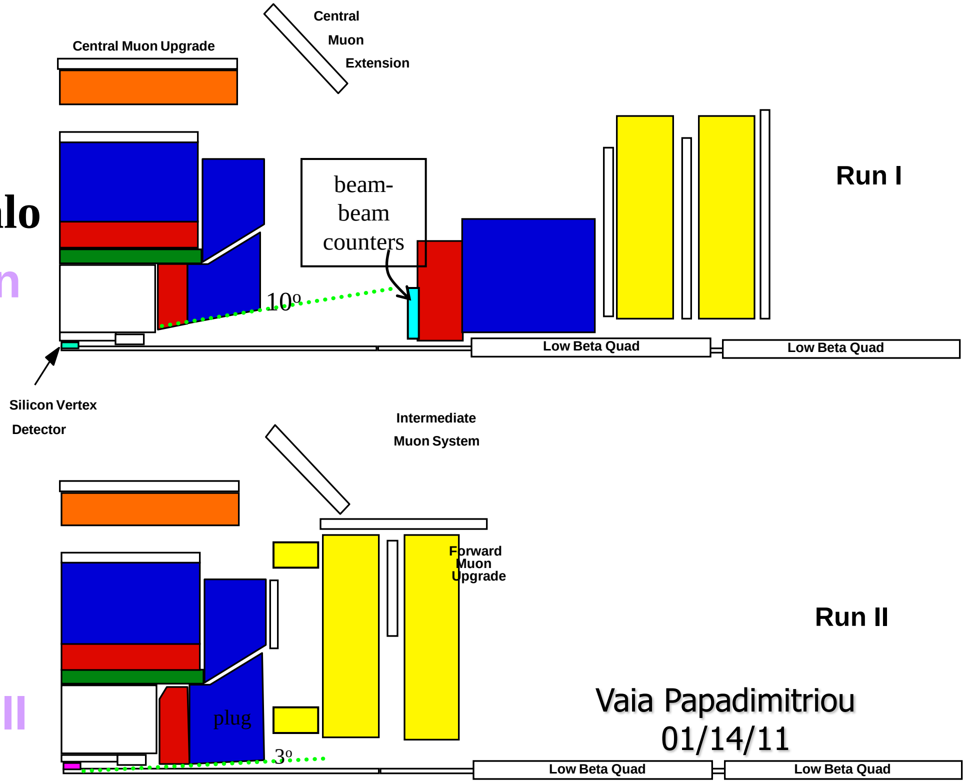
Scintillating counters for Luminosity



- **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



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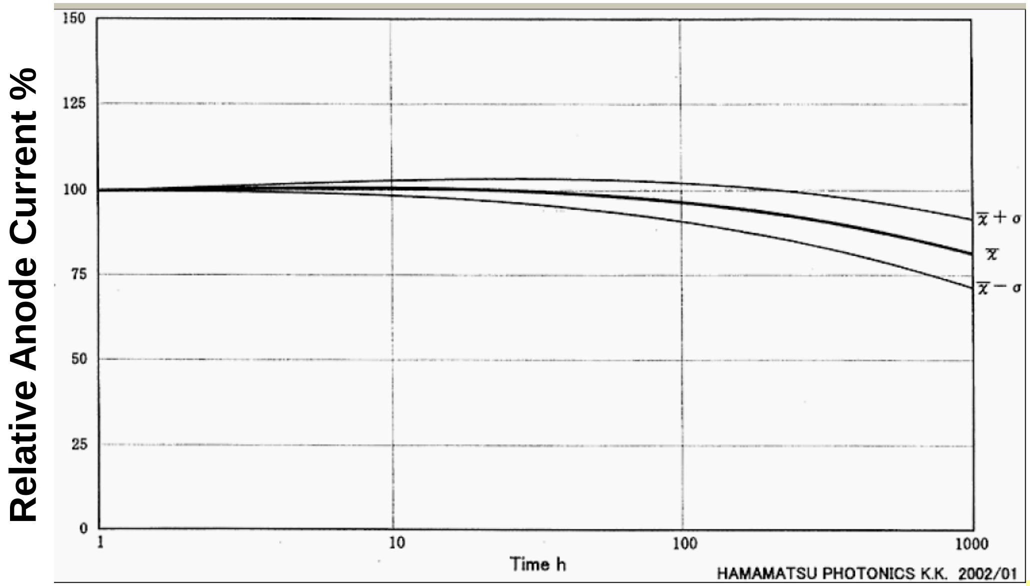
Luminosity by counting empty crossings

"empty" = bunch crossings with no PPbar interactions

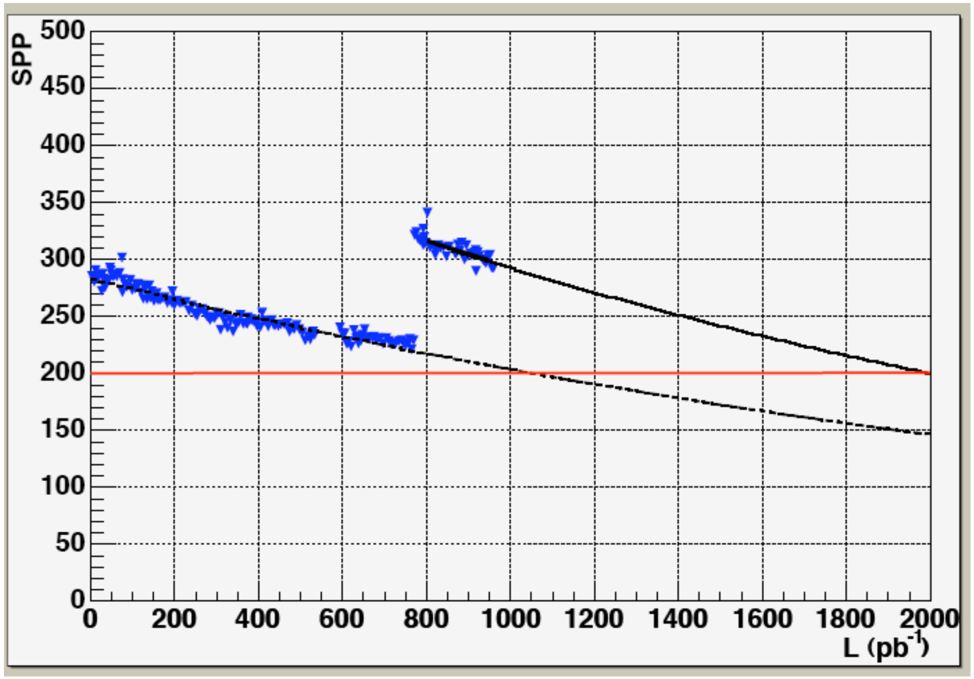
- probability of empty crossings:
  - *full acceptance detector:* $P_0(\mu) = e^{-\mu}$
  - *"real" detector:* $\widetilde{P}_0(\mu, \varepsilon_0, \varepsilon_W, \varepsilon_E) = e^{-\mu(1-\varepsilon_0)}(e^{\mu.\varepsilon_W} + e^{\mu.\varepsilon_E} - 1)$
    - ε_0 - probability to have no hits in 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"

Large Total Luminosity: Aging



- Factory aging test:
  - ❑ 1000 h at 10 μA
  - ❑ $\Delta I/I$ = 10-35%
- Corresponds to 30-80% fb^{-1}

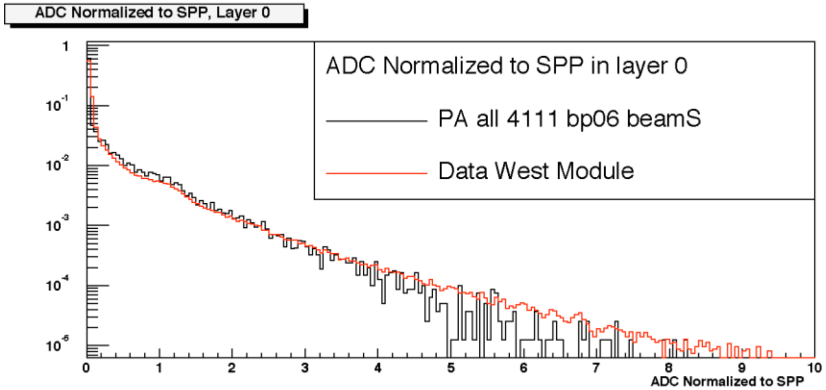


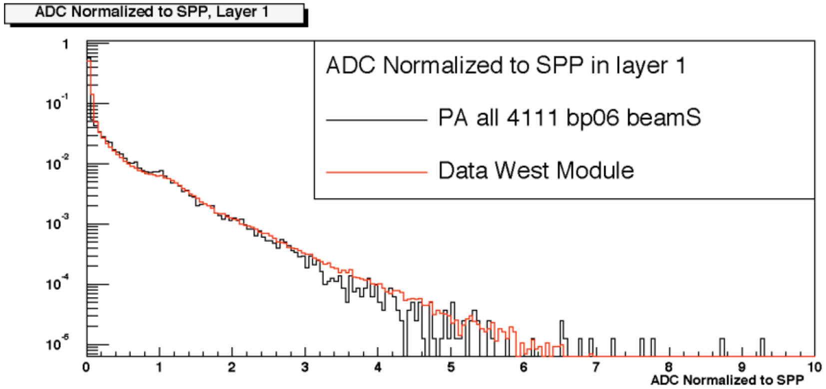
- PMT aging in detector:
  - ❑ hard to calibrate

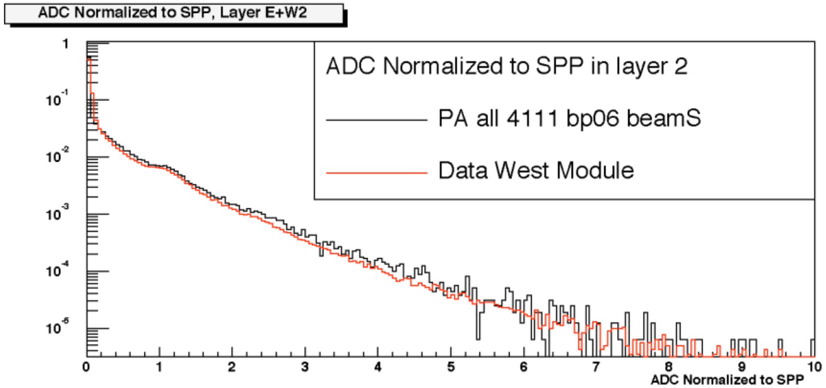
    Ampl < 200
  - ❑ aging rate ~ 35%/fb^{-1}
- Agrees well with Hamamatsu spec
- HV/gain adjustment:
  - ❑ same aging rate
- Survive a few fb^{-1}

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

o Full simulation vs data



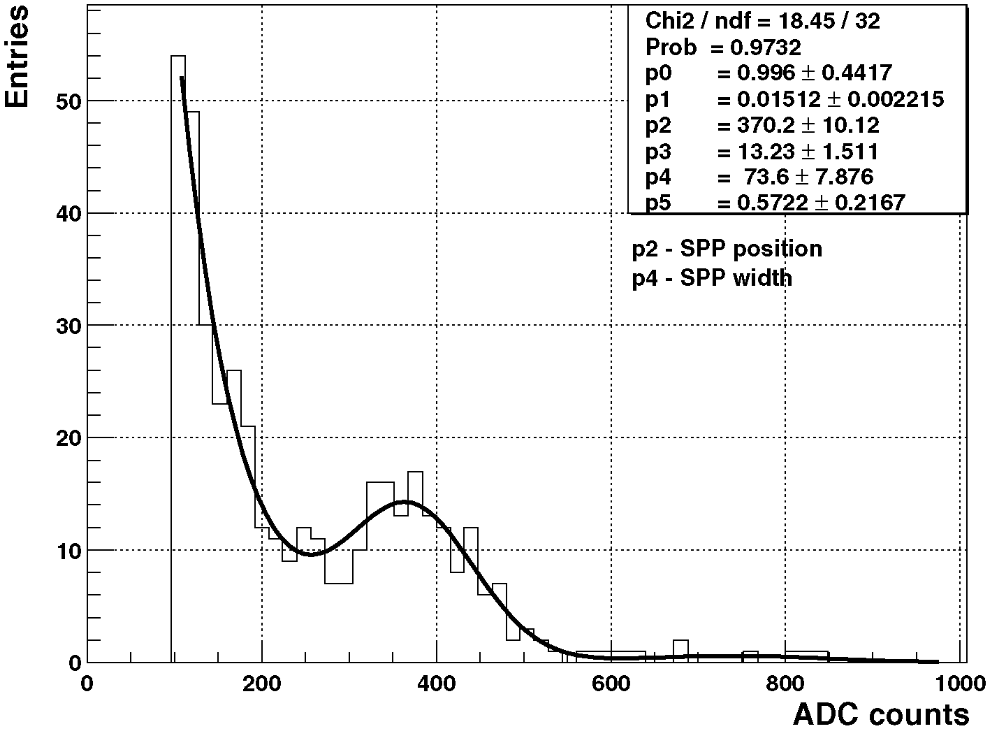




- ➢ **Simulation agrees well with data**
- ➢ **Single particle peak buried under secondary interactions**

➢ **Clear peak after the isolation requirement:**

- ❖ **Amplitude < 20 p.e. in surrounding counters**



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Hit Counting Method

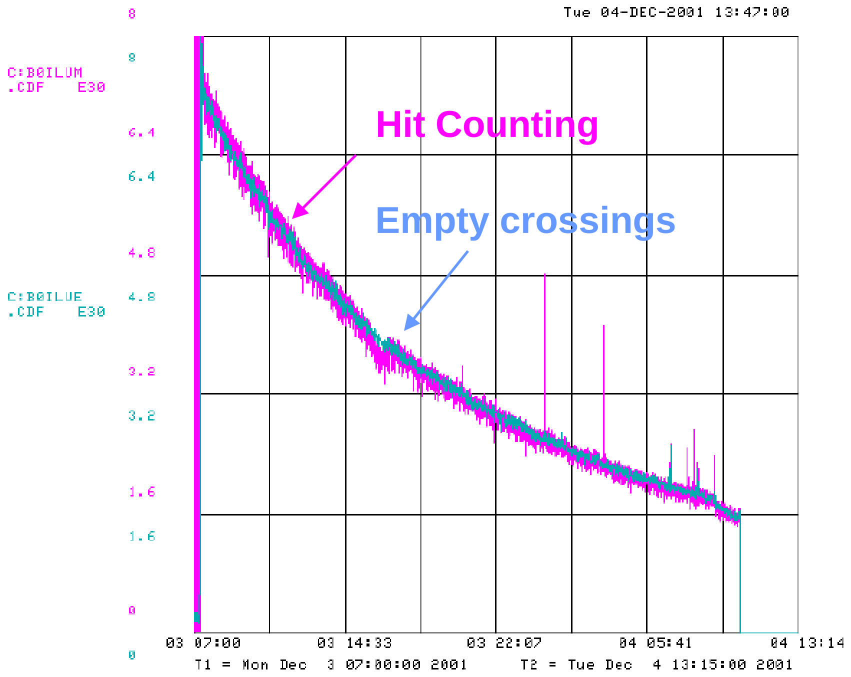
$$\boxed{\mathcal{L} = \frac{f_{BC}}{\sigma_{in} \cdot \varepsilon_{\alpha}} \cdot \frac{< N_H >_{\alpha}}{< N_H^1 >_{\alpha}}}$$

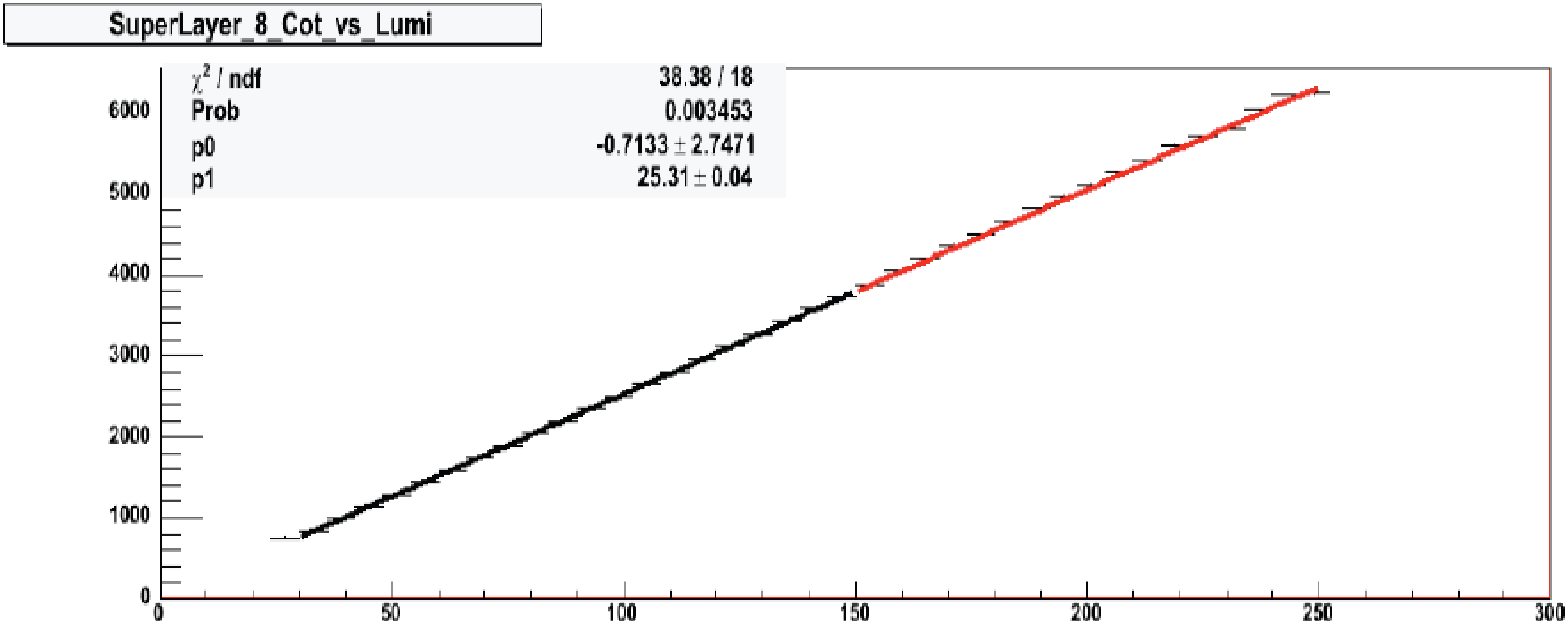
$< N_H^1 >_{\alpha}$ = avg. # hits for a single p-pbar interaction.

Measured at low luminosity from 0-bias data

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

- **We estimate ε_{α}:**
- **From simulations**
  - *Need all relevant material in CDF*
  - *Need "correct" generator…*
- **From real data**
  - *CLC vs. calorimeters / trackers*
  - *W's*





Here we plot:

SL8 VS B0lum

X axes -> Lum[E30cm-2s-1]

Y axes -> SL8 current

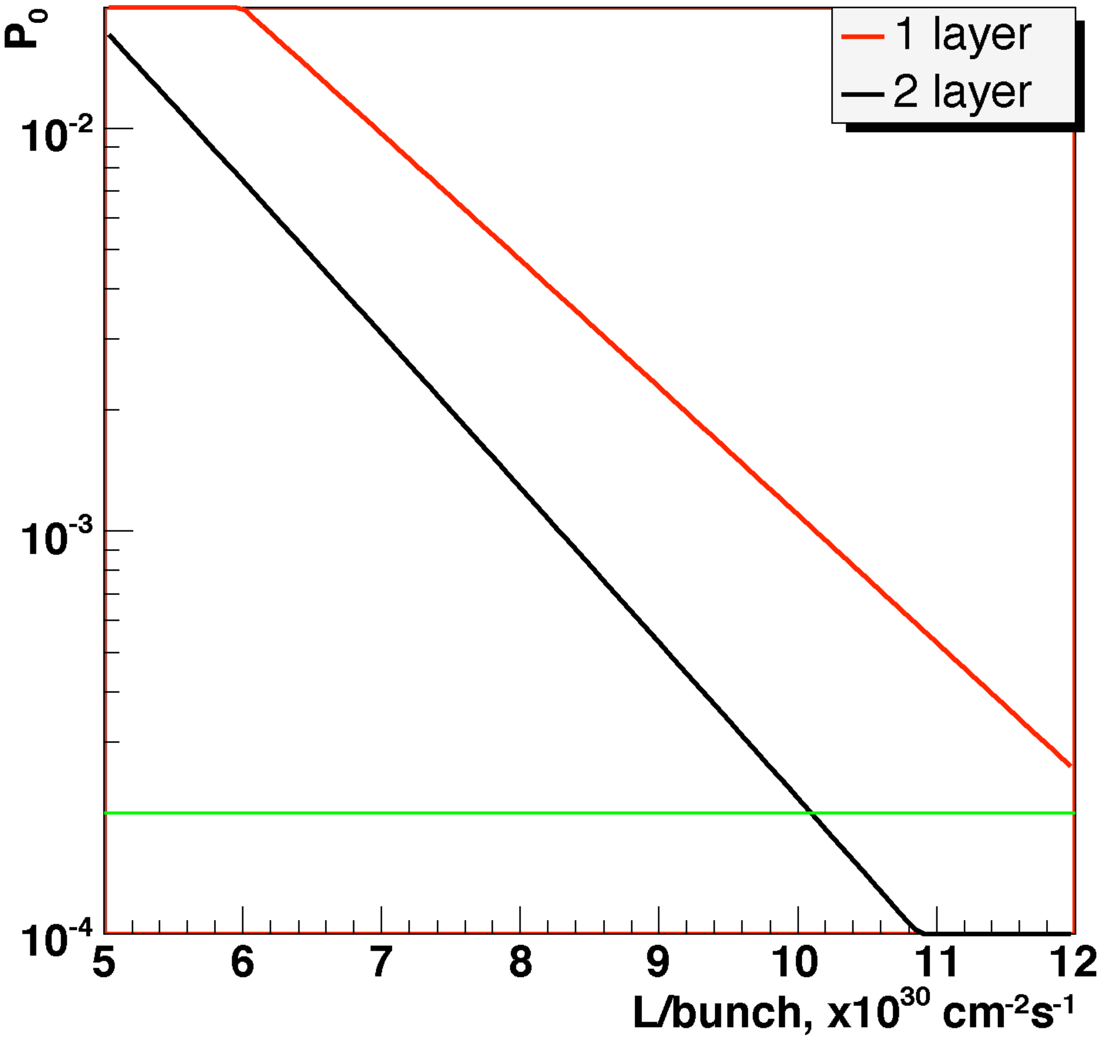
Fit(black) up to 150E30.

Extrapolated(red) to guide the eye.

Data collected in February 2007

Period contains the record store 5245 and few other stores with Lumi>280E30

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}

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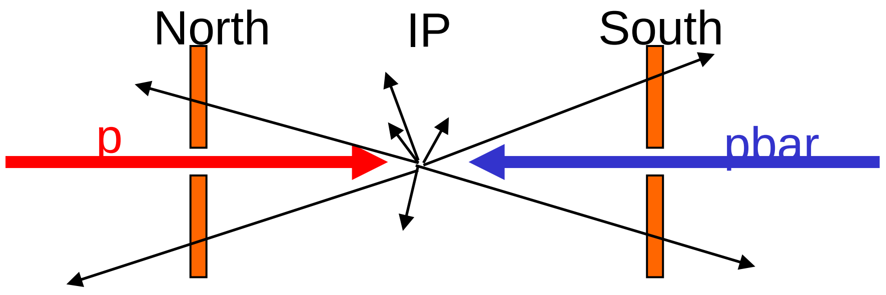
How to identify the process?

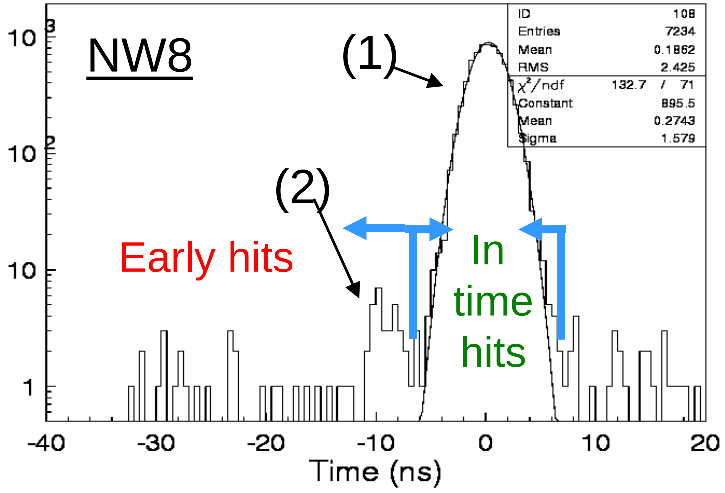
(1) Double or single side p-pbar interaction.



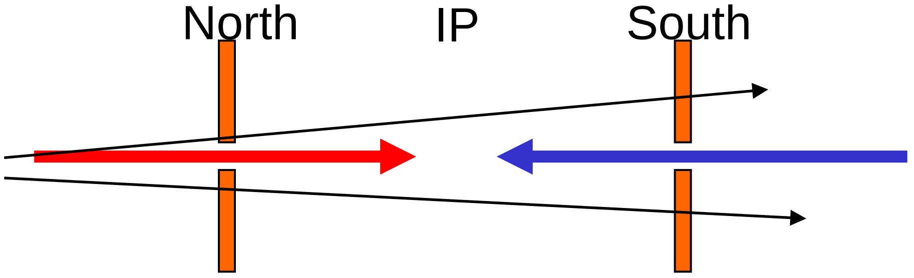
Scattering particle come from IP.

Timing : ~ 0 ns

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



(2) p-Halo or ap-Halo



Halo comes from upstream

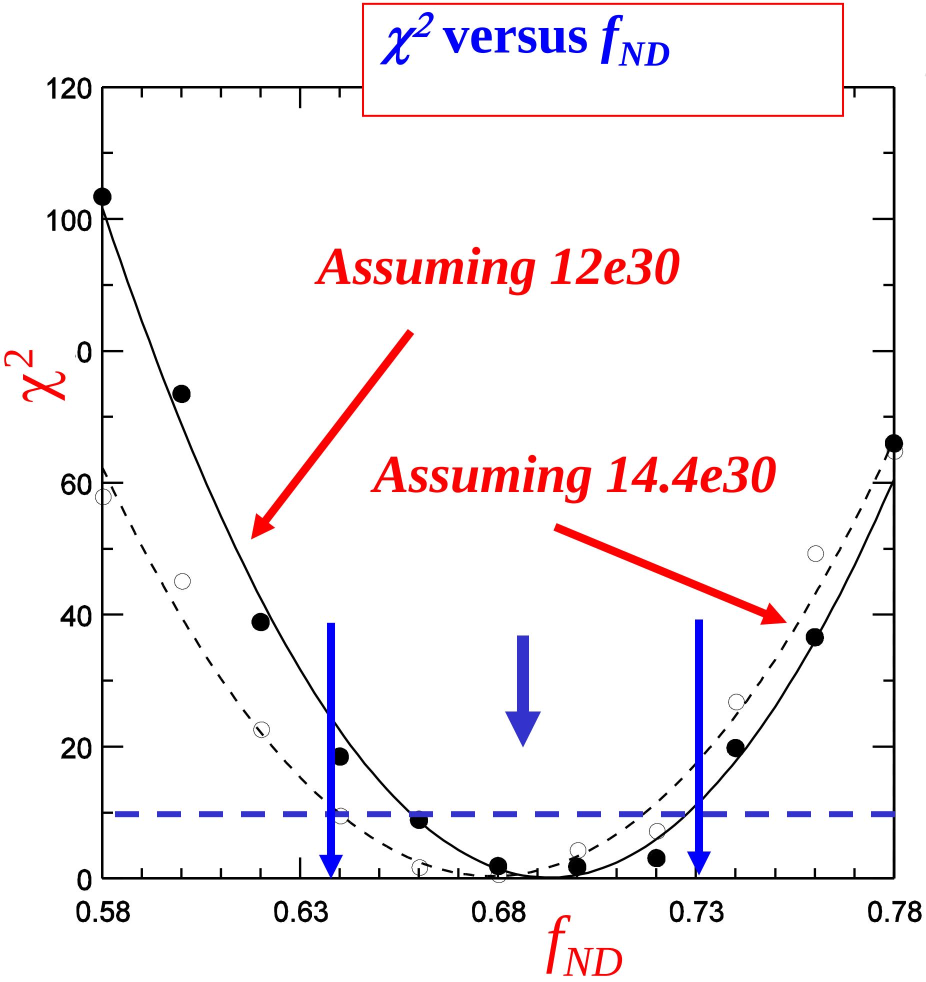
Timing : ~ - 9.5 ns.

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.

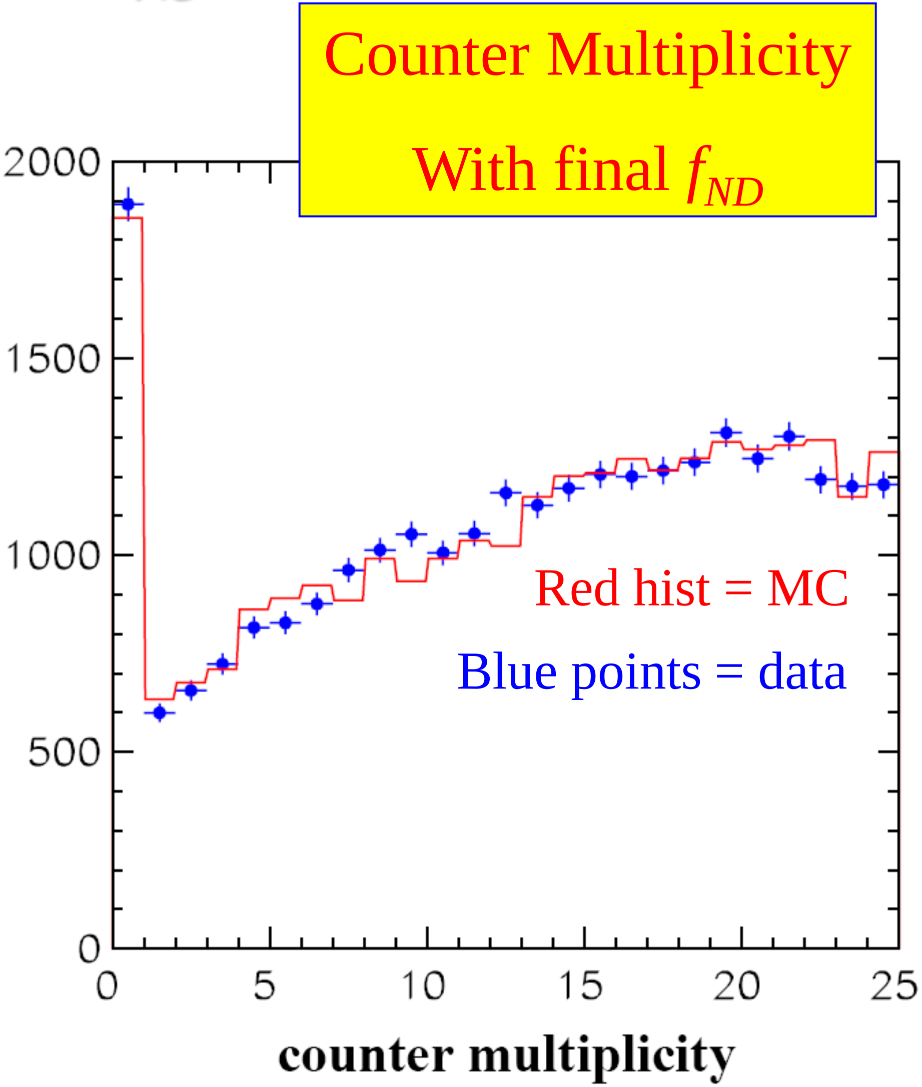
Determination of the non-diffractive fraction - f_{ND}



χ^2 versus f_{ND}

Assuming 12e30

Assuming 14.4e30



Counter Multiplicity

With final f_{ND}

Red hist = MC

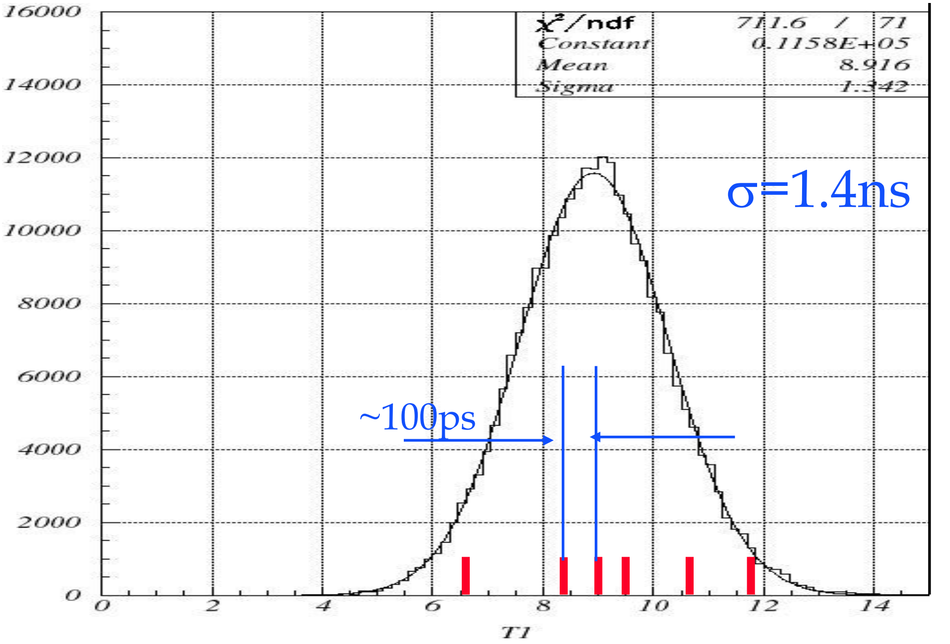
Blue points = data

Generate template MC multiplicities for each f_{ND} and fit the data.

Change assumptions, regenerate, refit

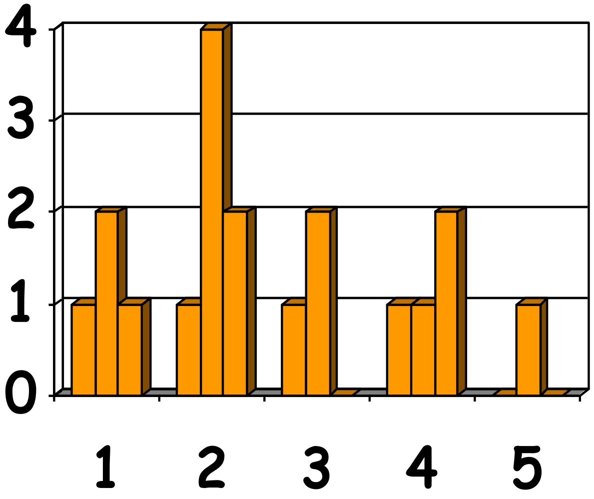
Luminosity counting time clusters

Measure the number of p-pbar interactions using precise timing



interaction time

Time clusters



counter arrival times

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CLC Absolute normalization

$$\begin{tikzcd}[column sep=small]
 & & \sigma_h \sim 44.5 \pm 1.3\,\text{mb} & \text{hard core} & \\
 & \sigma_{inel} \sim 61.9 \pm 1.4\,\text{mb} \arrow[ur] \arrow[r] \arrow[dr] & \sigma_d \sim 10.3 \pm 0.5\,\text{mb} & \text{diffractive} & \text{MBR} \\
\sigma_{tot} \sim 81.9 \pm 2.3\,\text{mb} \arrow[ur] \arrow[dr] & & \sigma_{dd} \sim 7.0 \pm 0.5\,\text{mb} & \text{double diffractive} & \\
 & \sigma_{el} \quad \text{(0 acceptance)} & & &
\end{tikzcd}$$

- Acceptance: $\varepsilon^{clc} = \dfrac{\varepsilon^{h} \cdot \sigma_h + \varepsilon^{d} \cdot \sigma_d + \varepsilon^{dd} \cdot \sigma_{dd}}{\sigma_{inel}}$

- From CLC MC simulation alone:

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

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

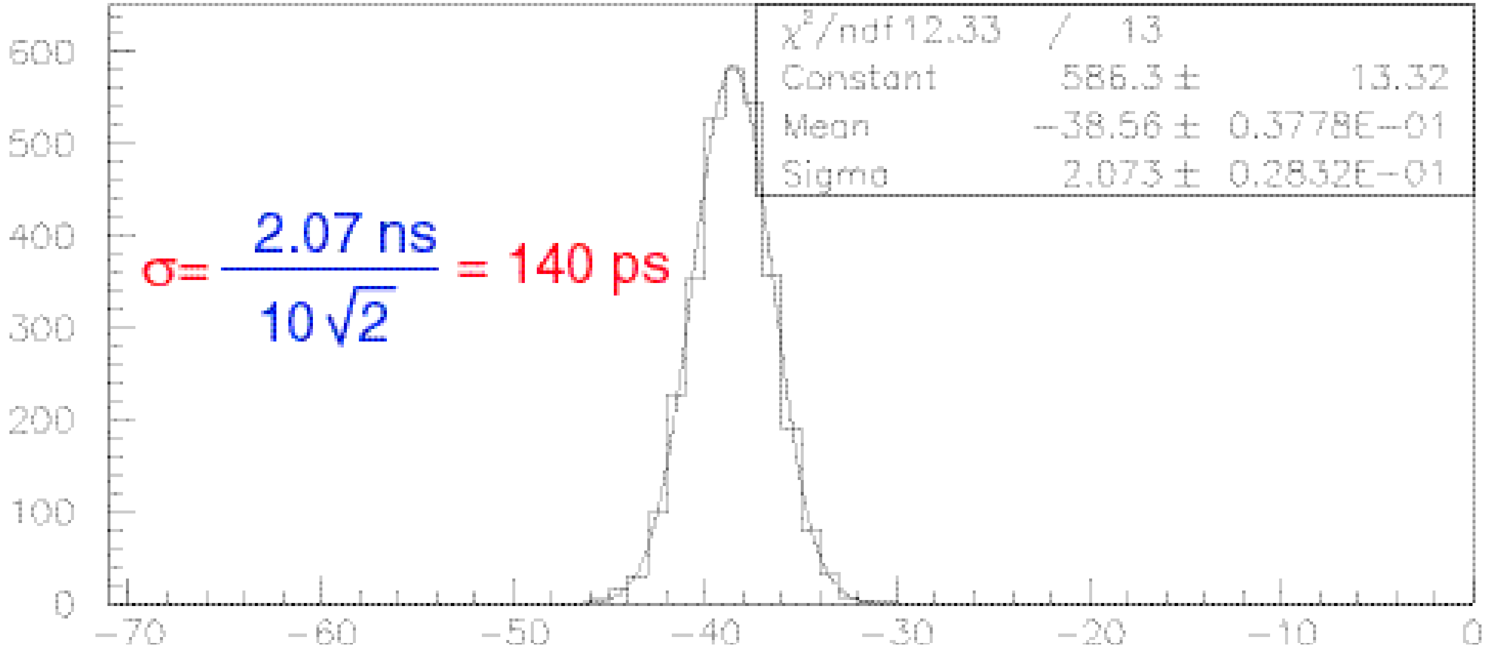
$$\varepsilon^{dd} = 31.8\,(0.7)\,\%$$

$$\varepsilon_{\alpha}^{clc} \sim 68\,\%$$

$$\boxed{\sigma_{\alpha}^{clc} = \sigma_{in} \cdot \varepsilon_{\alpha}^{clc} \sim 42\,\text{mb}}$$

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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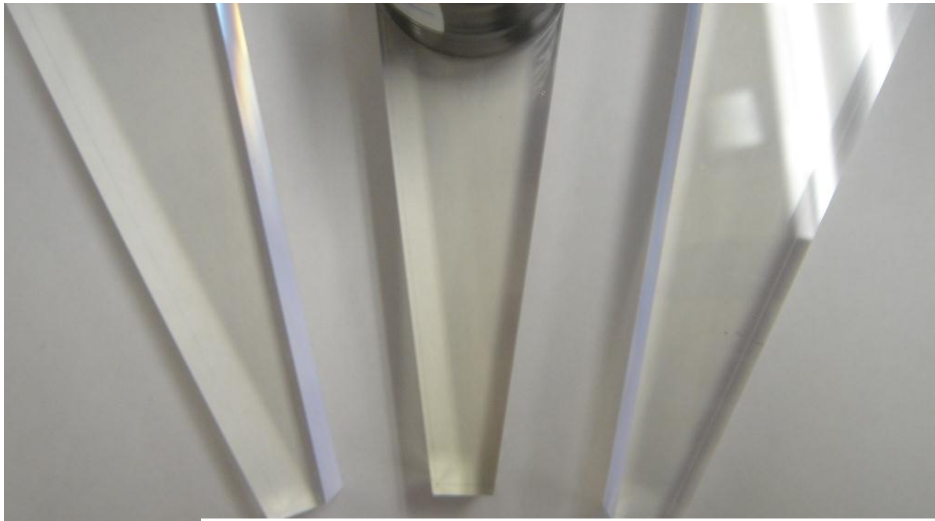
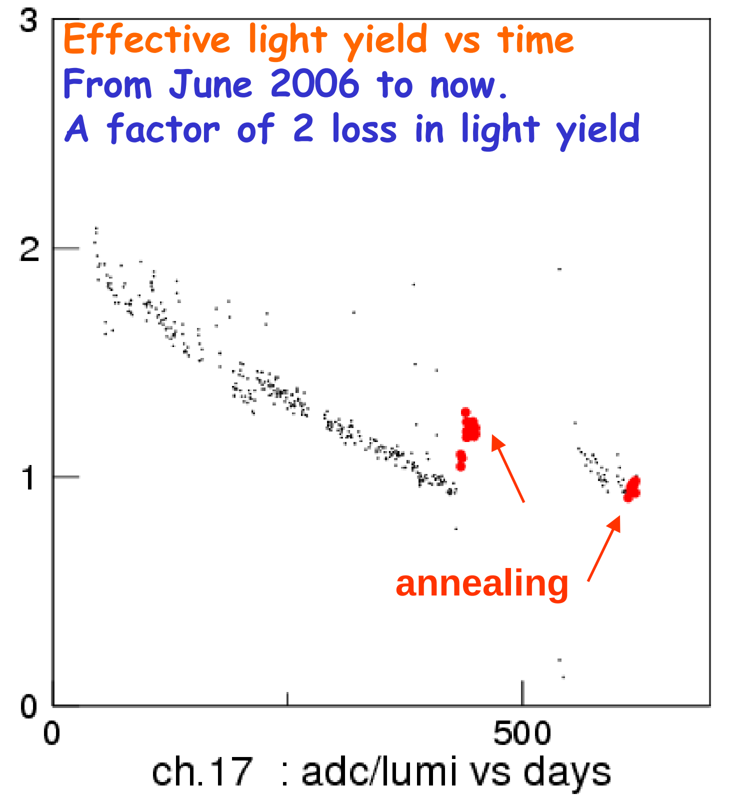
01/14/11

Scintillator radiation damage at D0

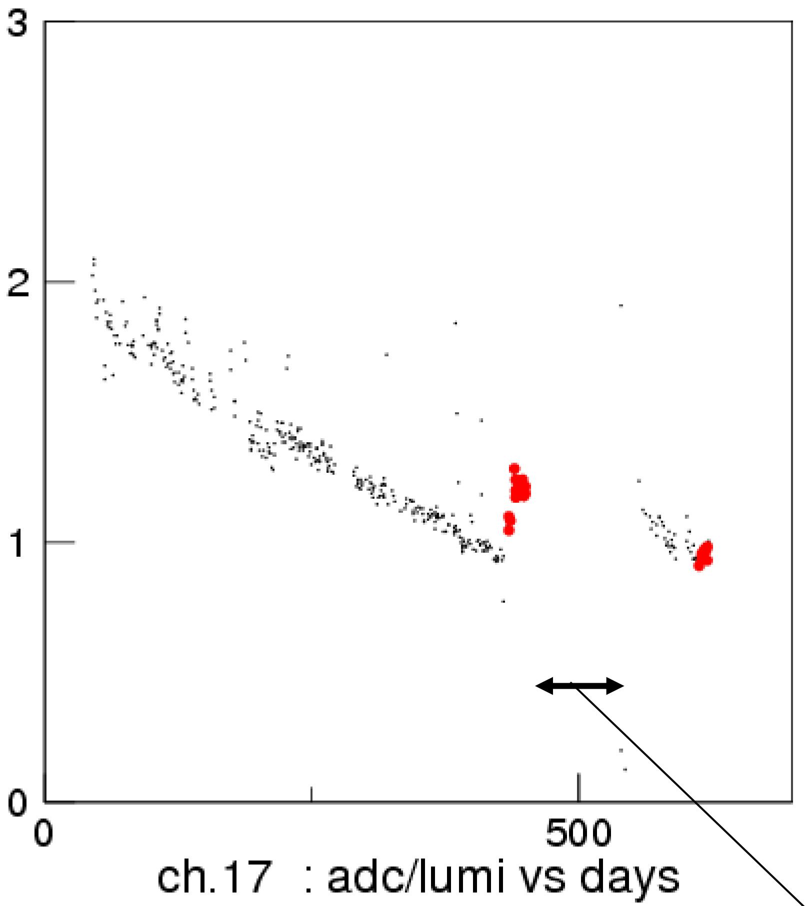




Scintillator becomes yellow due to radiation damage.

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).



- **Effective light yield vs time at D0**
  - *From 2006 Jun to now.*
  - *We observed 40~50 % degradation with radiation dose of ~ 0.5 Mrad.*
- **During normal operation (black points), Scintillator is in nitrogen purge.**
- **We see annealing effect. Red points are data with dry air.**
  - *2007.7.11- 2007.8.3*
  - *2008.1.11 - 2008.1.20.*

Shutdown, we replaced scintillator.
Same PMT is used before and after shutdown.

Luminosity Formula

$$L = \frac{3\gamma f_0}{\beta^*}\left(BN_{\bar{p}}\right)\left(\frac{N_p}{\varepsilon_p}\right)\frac{F\left(\beta^*,\theta_{x,y},\varepsilon_{p,\bar{p}},\sigma^L_{p,\bar{p}}\right)}{\left(1+\varepsilon_{\bar{p}}/\varepsilon_p\right)}$$

The major luminosity limitations are

- The number of antiprotons ($BN_{\bar{p}}$)
- The proton beam brightness (N_p/ε_p)
- $F<1$

Reference Processes

Process of inelastic PPbar scattering

- ***Large x-section:*** $\sigma_{inel} = 60.4 \pm 1.4 mb$ **(CDF)**
  - *Total x-section is measured also by E710 and E811 (2.8σ discrepancy with CDF)*

$$R_{pp} = \mu \cdot f_{BC} = \sigma_{inel} \cdot \varepsilon_{clc} \cdot L$$

L – luminosity
μ– # of interactions / BC
σ_{inel} – inelastic x-section
ε_{clc} – CLC acceptance
f_{bc} – Bunch Crossing rate

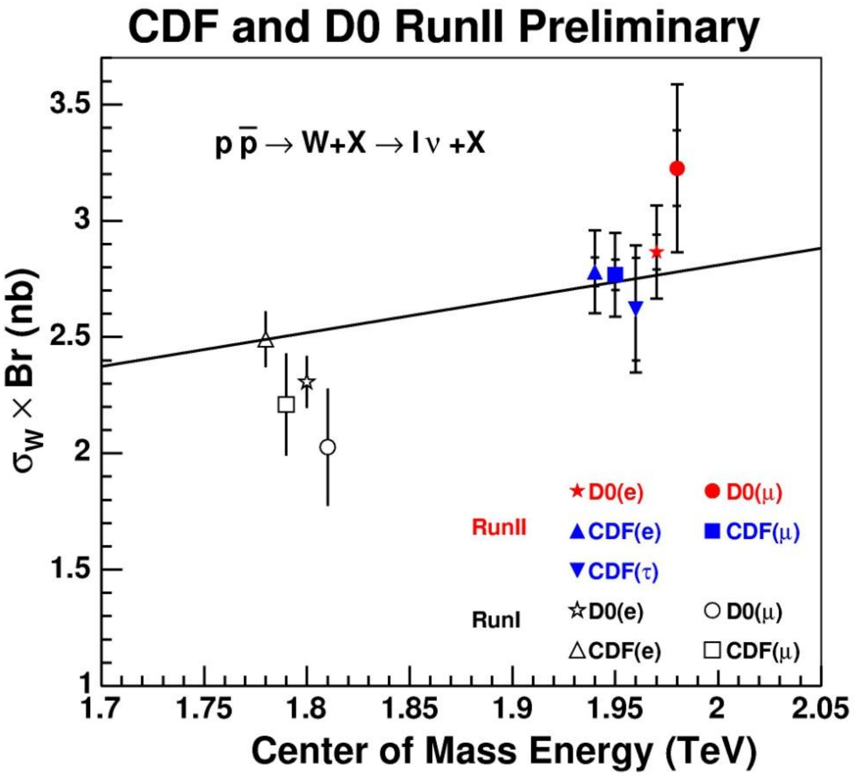
Process: *W → lν*

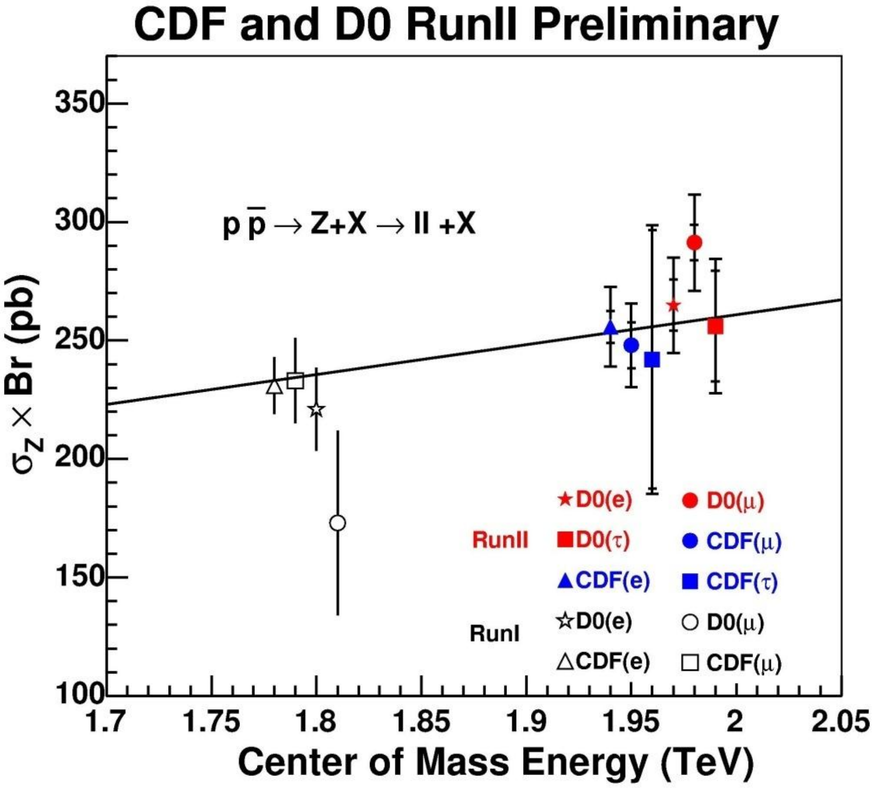
- *Complementary L measurement with different systematic error*
- *Cross-section ~2.5nb (well known theoretically:20%NLO,3%NNLO)*
- *Expected rate (@L=2 10^{32}) 0.5Hz (good for integrated L)*
- ***Trigger&selection efficiency ~25% (rate of ~0.1Hz after cuts)***

$$R_{W\to l\nu} = \sigma_{W\to l\nu} \cdot \varepsilon_{W\to l\nu} \cdot L$$

$\boxed{R = rate}$

Luminosity checks with W's and Z's





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