CMS Luminosity Monitors and Standard Candles

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Talk Outline

- Overview on Luminosity
  - Goals
  - Design strategy
  - Method
- Other Lumi monitors at P5
- Absolute Lumi normalization.
- CMS Studies
- Conclusions

Design Goals: General Desirables

- Absolute calibration, based on a known cross section with a reliably calculated acceptance.
- Temporal stability against gain changes and other drifts: “countable objects” or self calibrating signals (e.g., MIP peak).
- Linearity over a large range of luminosities.
- Real time operation independent of full DAQ.
- Redundancy
  - There is no perfect method
  - Applies to both real time monitoring and to offline absolute normalization

Design Goals: Specific Issues

- Real time monitoring
  - Bunch by bunch
  - Update time: 1.0 s
- Offline
  - Robust logging
  - Easy access to luminosity records
- Absolute Calibration
  - Target from ~5-10%

General Strategy

- Use absolute calibration of machine luminosity or TOTEM measurement as a reference point.
- Use real time techniques (HF, Pixel Telescopes, BRAN) to extrapolate/interpolate to design luminosity
- Normalize the luminosity using processes of ~known cross section (e.g., W's and Z's)

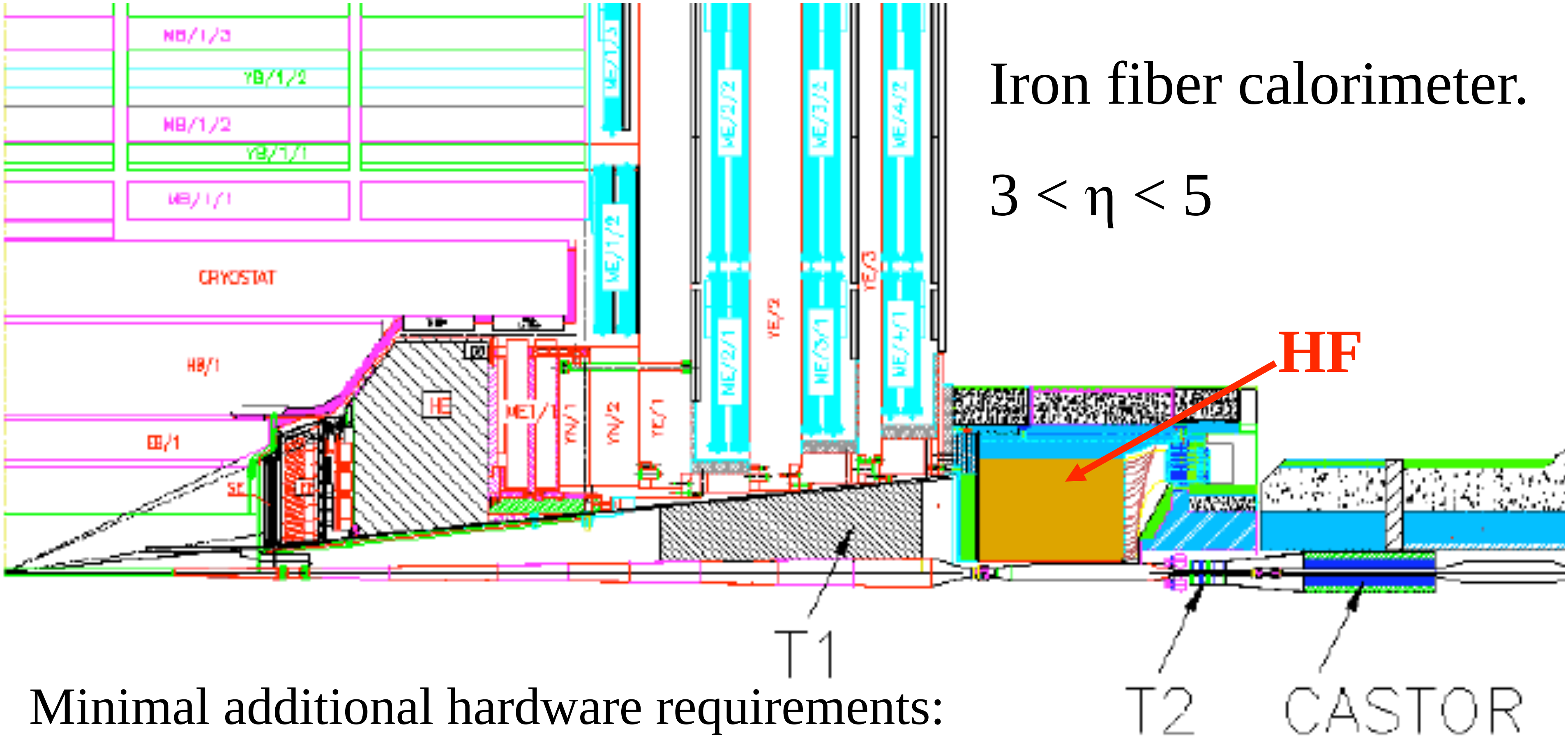
HF Based Luminosity Monitoring

The principle technique to Measure and deliver the relative online luminosity in CMS is based on the Forward Hadronic Calorimeter (HF)

Signals From HF

Iron fiber calorimeter.

$3 < \eta < 5$



Minimal additional hardware requirements:

- Mezzanine board to tap into HF data stream and forward bits to a server via Ethernet
- Autonomous DAQ system to provide "always on" operation

T1 & T2 are elements of TOTEM

HF Methods

Methods:

- Count “zeroes”
- Use also linear E_T sum, which scales directly with luminosity.

Simulations:

Full GEANT4 with realistic representation of photo statistics, electronic noise and quantization, etc. within the framework of CMSSW

Tower Occupancy Method

The average fraction *f*, of empty towers per bunch crossing is given by:

$$\langle f \rangle = e^{\mu(p-1)} \Rightarrow -\ln\langle f \rangle = (1-p)\mu$$

Where:

p = probability that a given tower is empty after ***single interaction***,

mu= mean number of interactions per bunch crossing.

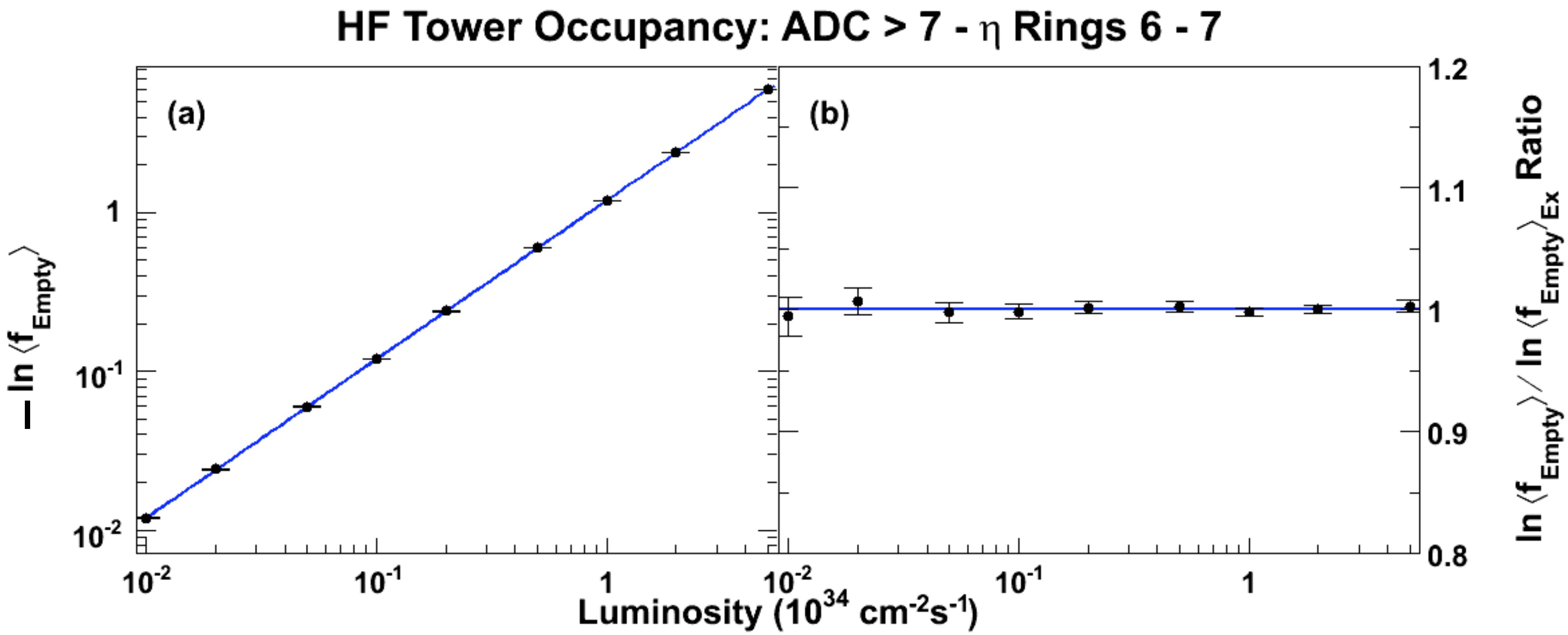
Tower Occupancy Method

In real life in order to decide whether a tower is empty we have to introduce a threshold cut which would cut somewhat into our signal and therefore introduce a correction to our previous result

$$-\ln\langle f\rangle = (1-p)(\underbrace{1-\varepsilon}) \mu + \mathrm{N}$$

This term is a measure of the overlap between the signal and noise distribution below the threshold

Tower Occupancy Status



we plan to use two sets of two rings.

E_T Sum Method

Average transverse energy per tower per BX

$$\langle E_T \rangle = \nu(1-p)\mu + \mathrm{N}$$

Where:

p = probability that a given tower is empty after ***single interaction***,

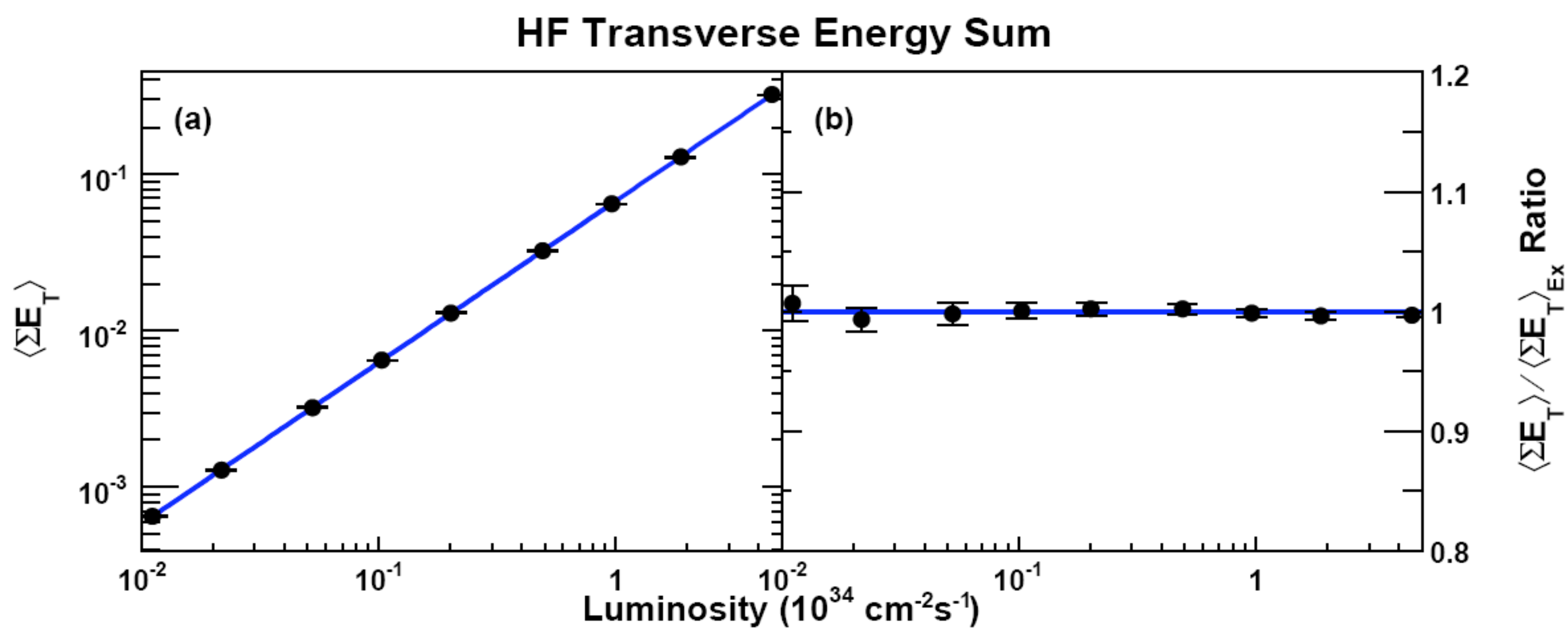
n=<ET> for a single occupied tower in a single interaction

m= mean number of interactions per bunch crossing

N= Noise contribution.

E_T Sum Status

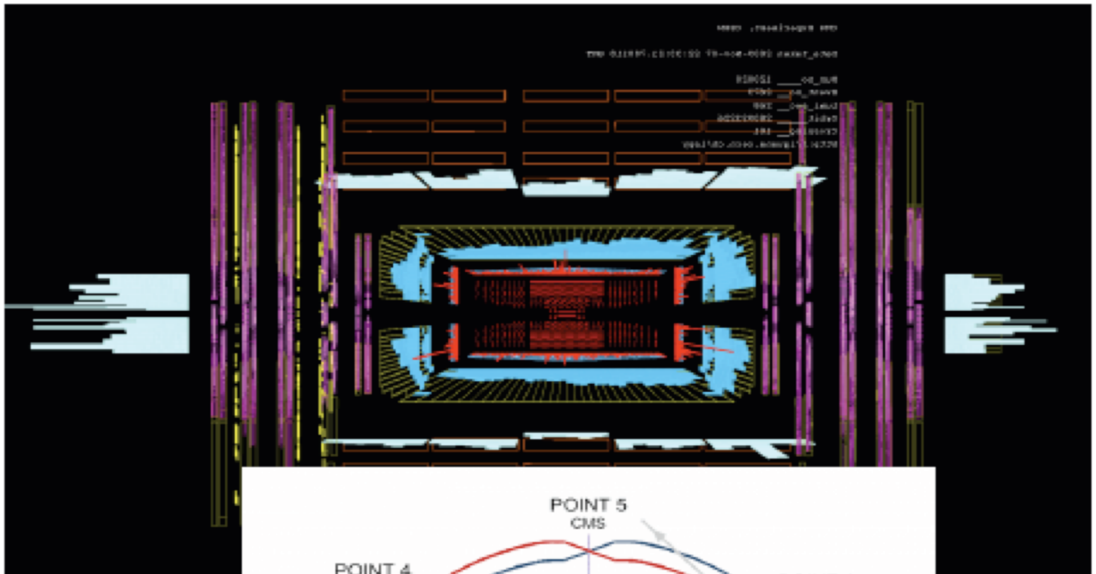
The average EtSum is linear over all the expected luminosity dynamic range



Any noise offset would be calibrated out by using the the Hlx data during the abort gap

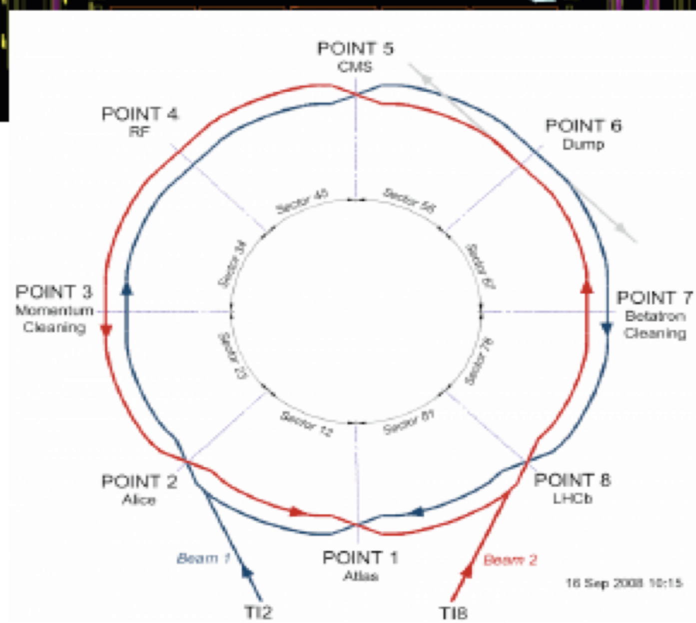
HF based Lumi Results

HF+

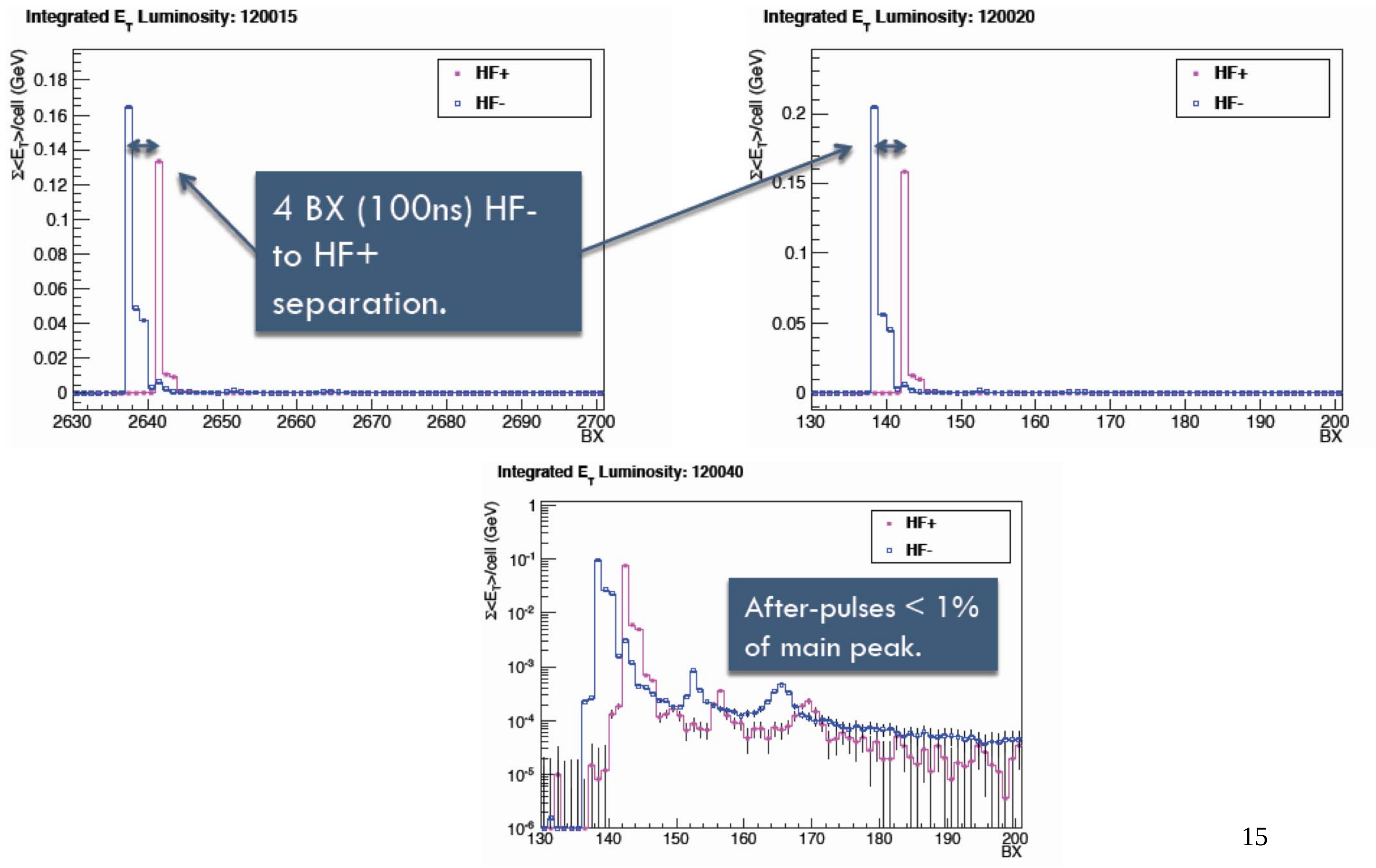


HF-

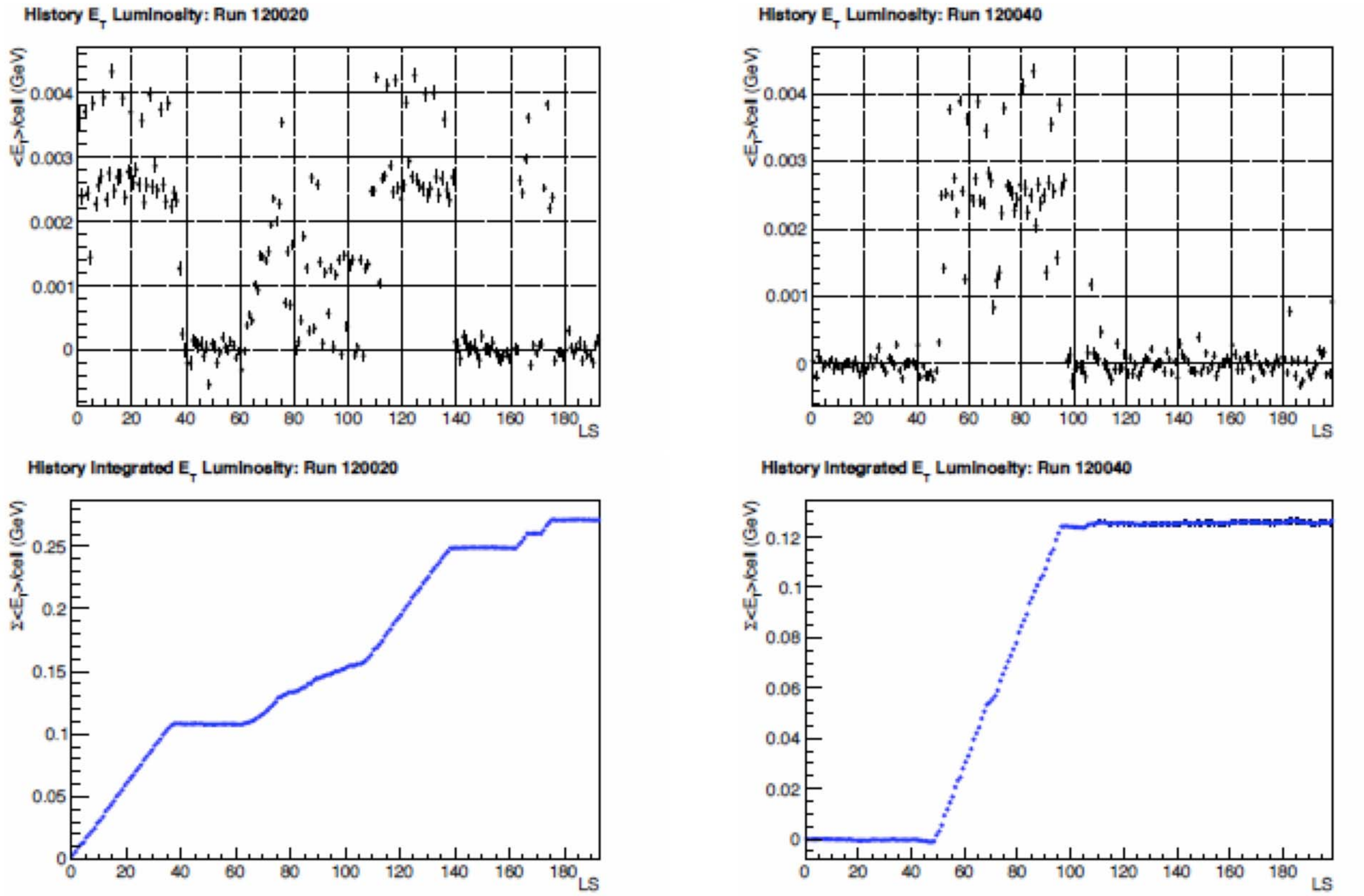
Beam 2



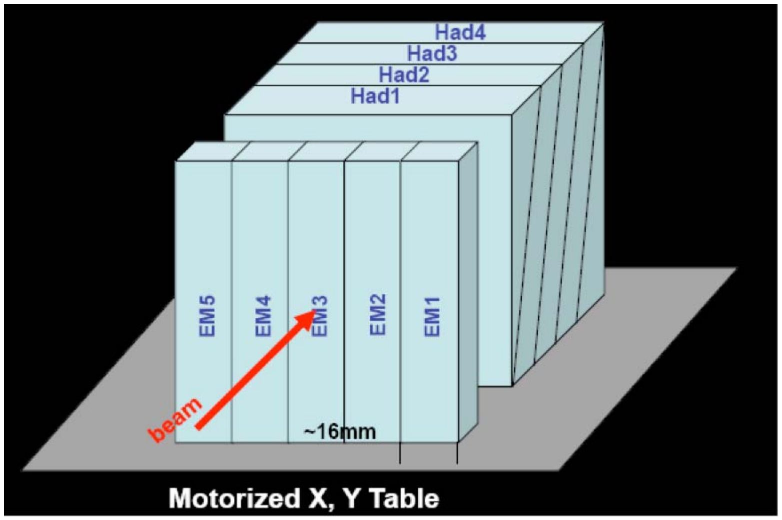
Spalsh Data 2009



Lumi History



Other Luminosity Monitor: ZDC

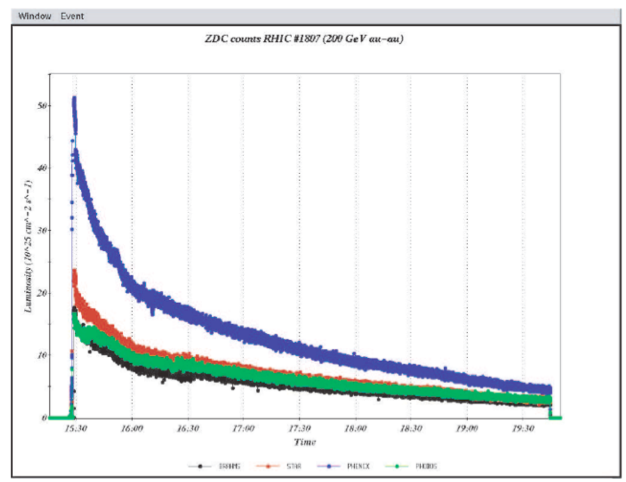


The design of each ZDC Includes (EM section) and (HAD section).

The core of each structure consists of a tungsten plate/quartz fiber ribbon stack

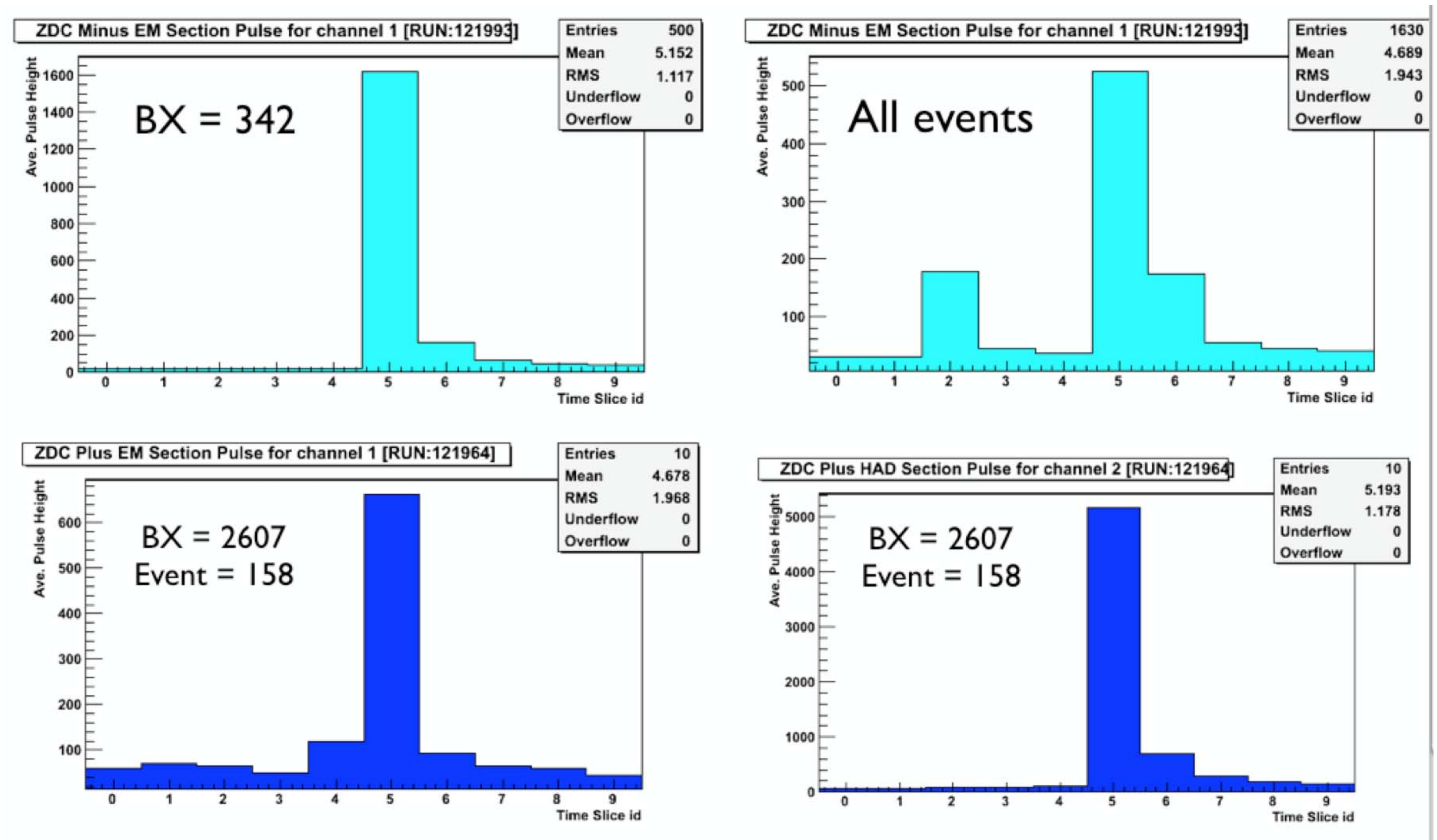
The ZDC measures the luminosity by using the coincidence rate of energy in ZDC+ and ZDC-

- The horizontal crossing angle
- A measurement of the emittance
- Average x position of the beams



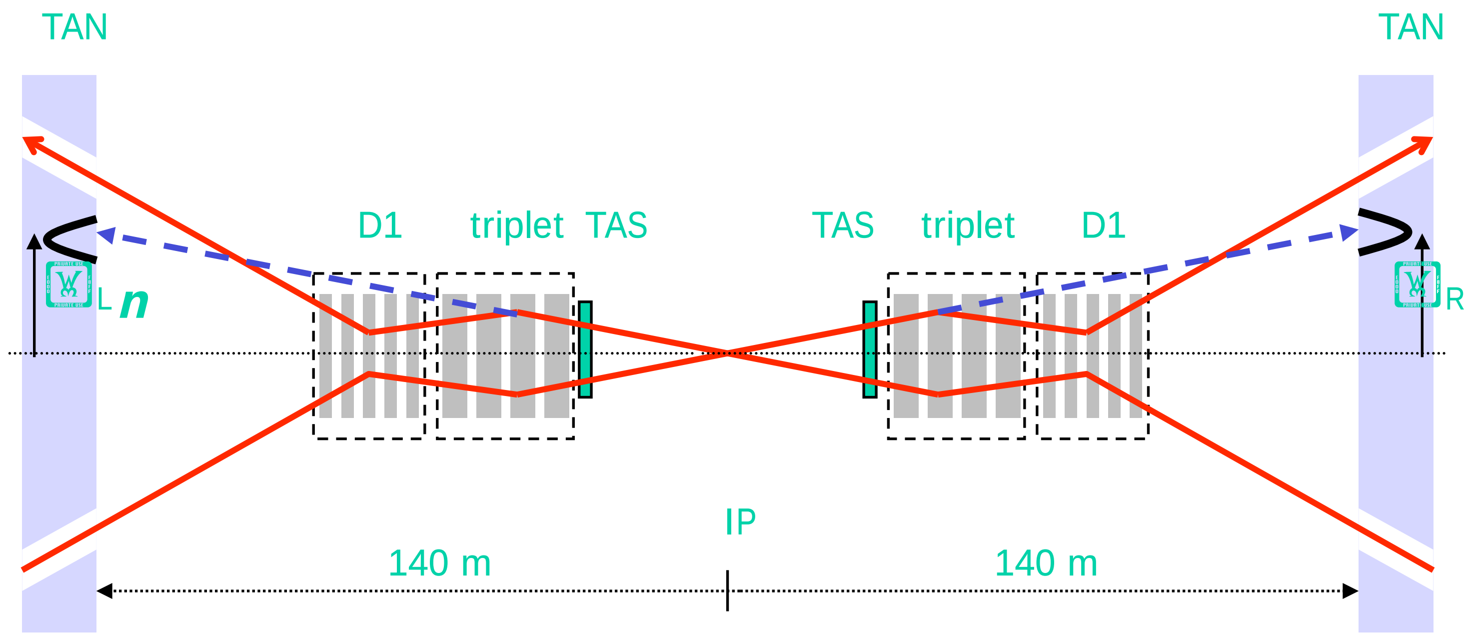
Luminosity at 4 RIHC exp

Splash Nov 2009



Other Luminosity Monitor - BRAN

The LHC accelerator project incorporated fast ionization counters, in the TAN region, which is ±140m from the IP



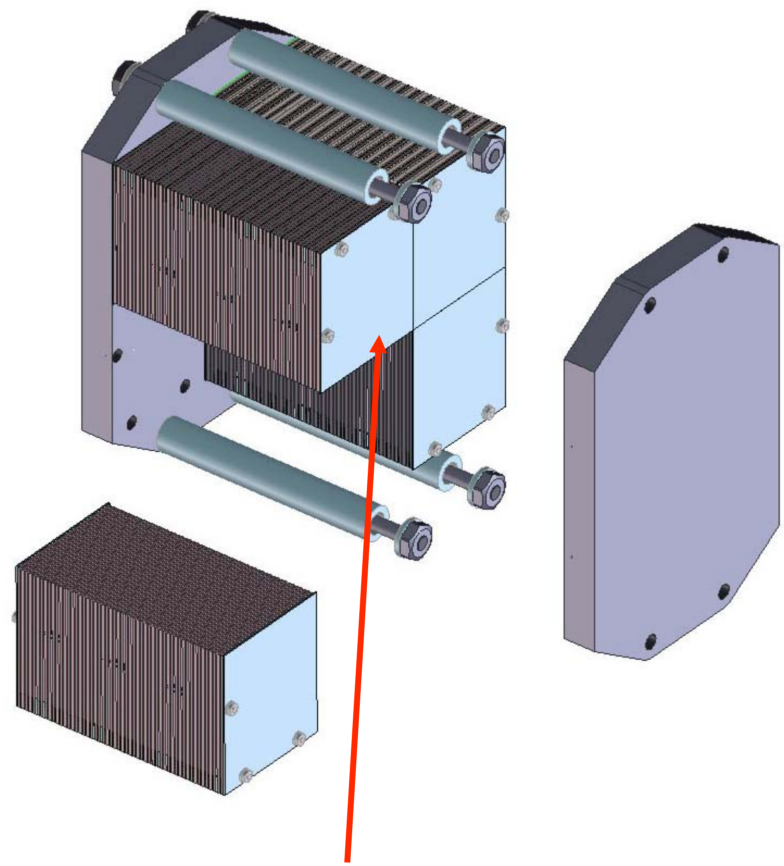
BRAN - LHC Luminosity Monitor

Target specifications:

- Dynamic range 10^{28}-10^{34} [$cm^{-2}s^{-1}$]
- Bunch-by-bunch capability
- ~1% relative precision
- High radiation environment (100 MGy/year)
- Identical installation in other IPs

Solution

- Segmented, multi-gap, pressurized $Ar+N_2$ gas ionization chamber constructed of rad-hard materials



Quadrant segmentation provides sensitivity to beam position and crossing angle at the IP

BRAN

Luminosity **[cm^{-2} s^{-1}]**	**Rate of p-p events** **[s^{-1}]**	**Int. time** **[s]** (10% error)	**Int. time** **[s]** (1% error)
1.0×10^{26}	8.0	50	5.0×10^{3}
1.0×10^{28}	800	0.5	50
1.0×10^{30}	8.0×10^{4}	5.0×10^{-3}	0.5
1.0×10^{32}	8.0×10^{6}	5.0×10^{-5}	5.0×10^{-3}
1.0×10^{34}	8.0×10^{8}	5.0×10^{-7}	5.0×10^{-5}

The expected integration times for different luminosity levels and different resolutions (1% and 10%).

Pixel Luminosity Telescope (new)

- Dedicated stand-alone luminosity monitor for CMS
  - independent of CMS trigger, other detector components
- Simple device stable over lifetime of CMS
- Precision measure of relative bunch-by-bunch luminosity
  - statistical precision of 1% in real time (a few seconds)
- Self monitoring and calibrating
  - backgrounds
  - efficiency

PLT Design

Telescope Arrays

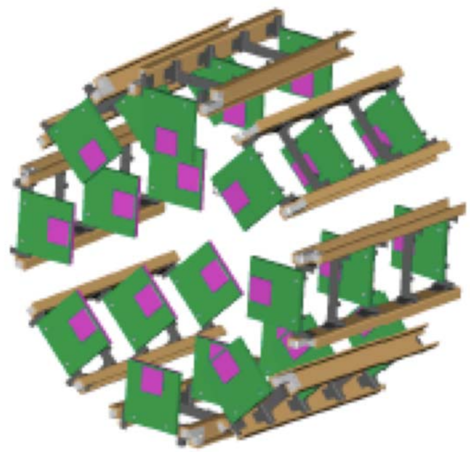
– eight telescopes per CMS end
– location: r 5 cm, z 1.75 m

Telescopes

– three planes
– total length 7.5 cm

Telescope Planes

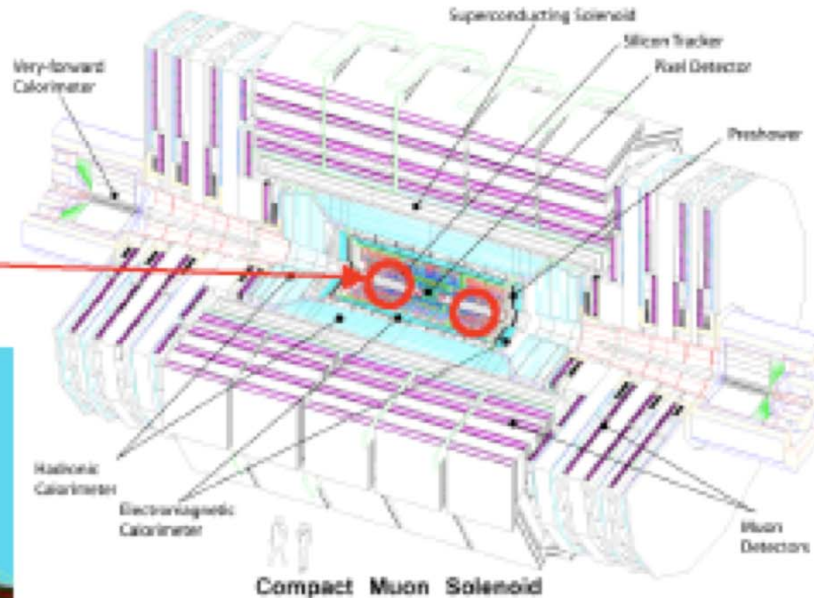
– diamond pixel sensors
– active area 4.0 mm x 4.0 mm
– bump-bonded to PSI46v2 pixel ROC

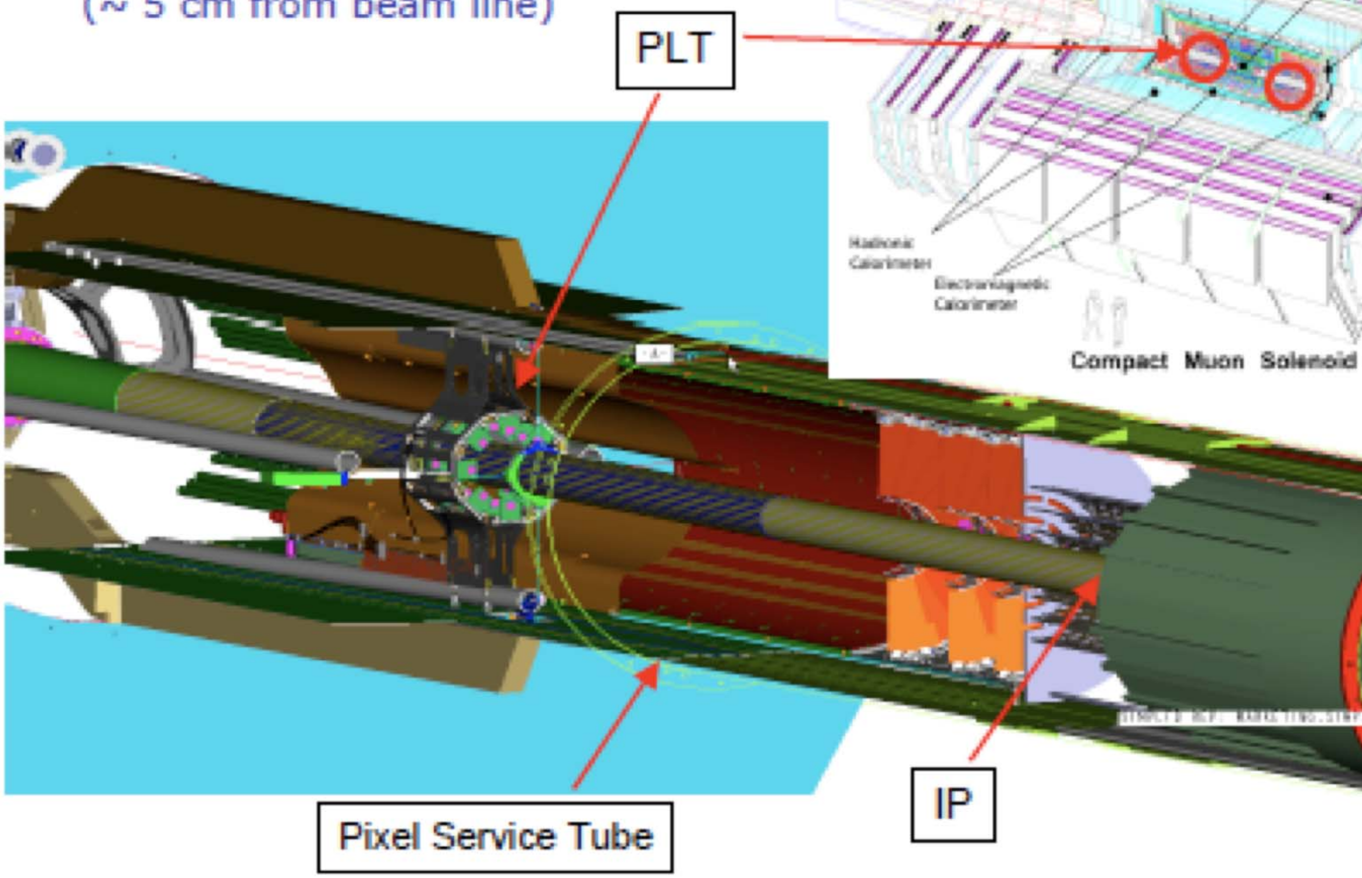


• Measure number of 3-fold coincidences in each bunch crossing (40 MHz) using fast-or outputs of the PSI46 pixel chip
• Readout full pixel hit information of each plane at 1 to 10 kHz

Location of the PLT

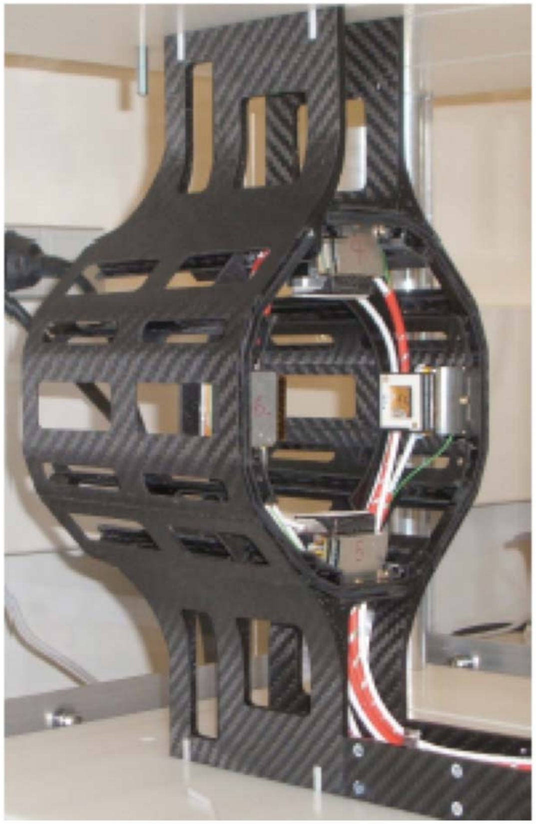
- End of Be section of beam pipe (~ 1.7 m from IP)
- Just outside of beam pipe (~ 5 cm from beam line)



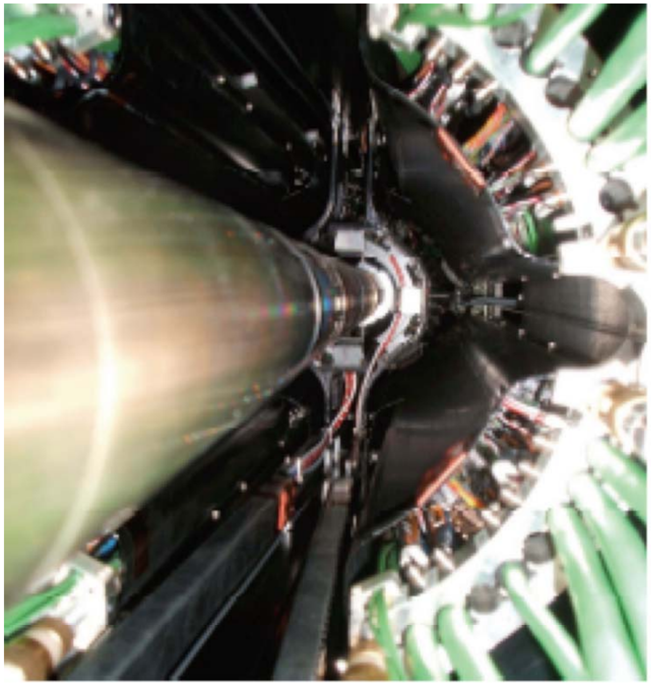


Carriage

Carriage already exists (houses BCM1)



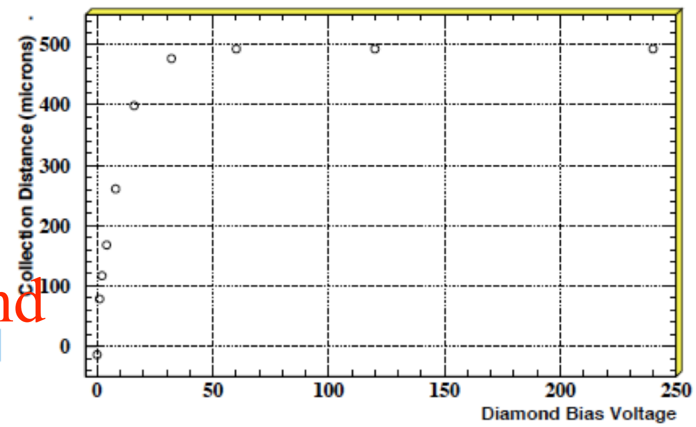
slides on rails inside of the pixel service cylinder

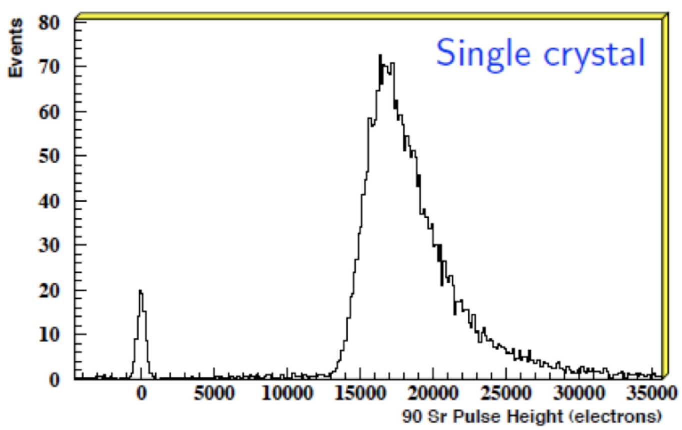


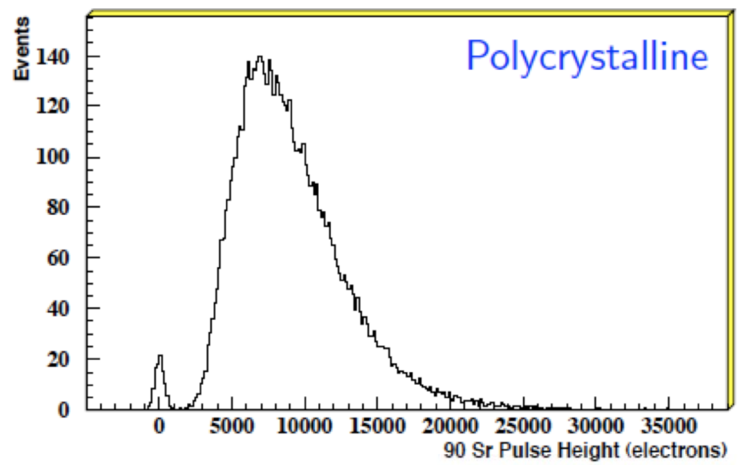
Diamond Sensors

Radiation hard (few $x10^{15}$ p/cm^2)

- No need for cooling
- Full charge collection < 0.2 V/µm
  - 18,000 e^- signal for 500 µm diamond
  - Landau 60% narrower than for Si
- Pulse height well separated from pedestal
  - compare poly crystalline diamond







Radiation Hardness

Charge particle fluence on PLT at full luminosity $3 \times 10^7/cm^2/s$ - $5\times10^7/cm^2/s$

=> $1.5 \times 10^{15}/cm^2$ to $2.5\times10^{15}/cm^2$ over lifetime of CMS

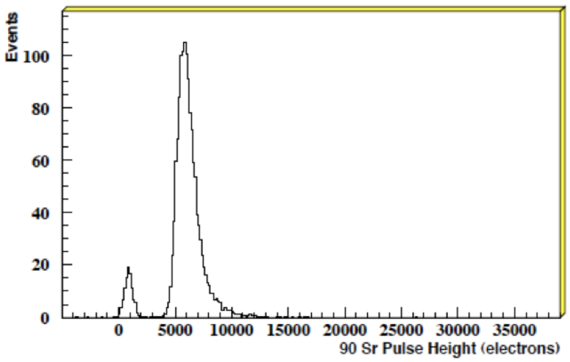
Radiation hardness of single crystal diamond to 24 Gev/c protons

24 GeV protons

Fluence (p/cm^2)	Charge Collection Efficiency
0	100%
0.5×10^{15}	62%
1.5×10^{15}	53%

Pulse height is still well separated from zero after $1.5 \times10^{15}/cm^2$.

Leakage current < 10 pA/cm^2 even after full irradiation.



Two Complementary Readout Modes

Fast-Or Output

- every bunch crossing (40 MHz)
- bunch-by-bunch luminosity
  - 1% statistical precision in 1 s at full luminosity
- abort gap particles

Full Pixel Readout

- 1 kHz to 10 kHz rate
- beam halo
- hit pixel addresses and pulse heights
- bunch integrated luminosity
  - 1% statistical precision in 10 s at full luminosity
- bunch-by-bunch luminosity
  - 1% statistical precision in 10 hours at full luminosity
- powerful diagnostic for fast hit output mode
- corrections for accidentals and overlaps

collision point centroid

pixel efficiencies

Rates

Pythia simulation

0.0048 tracks / pp interaction / telescope

Taking 21 interactions per bunch crossing at $L = 10^{34}\ cm^{-2} \cdot s^{-1}$

=> 1.6 tracks in PLT / bunch crossing

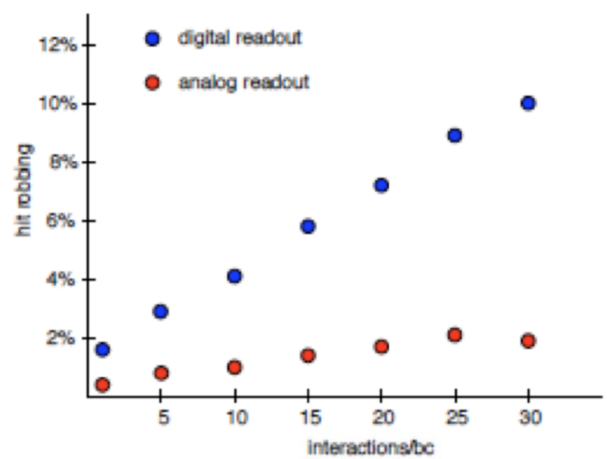
18,000 tracks per second for each of the 2835 filled orbit bunches

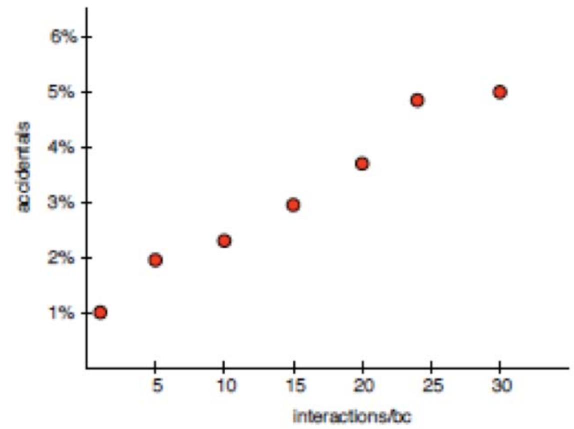
=> 0.75% precision in 1 second PLT

Systematic

Overlap fraction vs. interactions

Accidental fraction vs. interactions





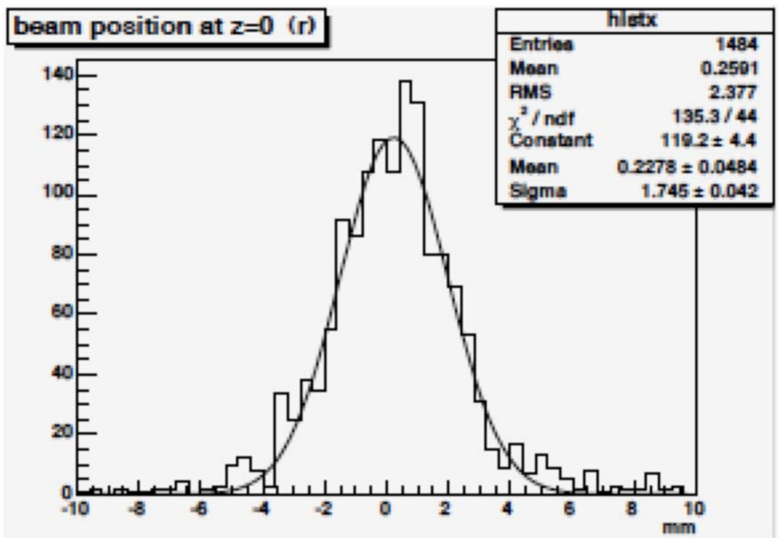
- about 8% at full luminosity (digital readout)
- about 1.5% at full luminosity (analog readout)
- correctable using full pixel data

- about 4% at full luminosity
- correctable using full pixel data
- can reduce active area if necessary
  - pixels can be dynamically masked

IP Centroid

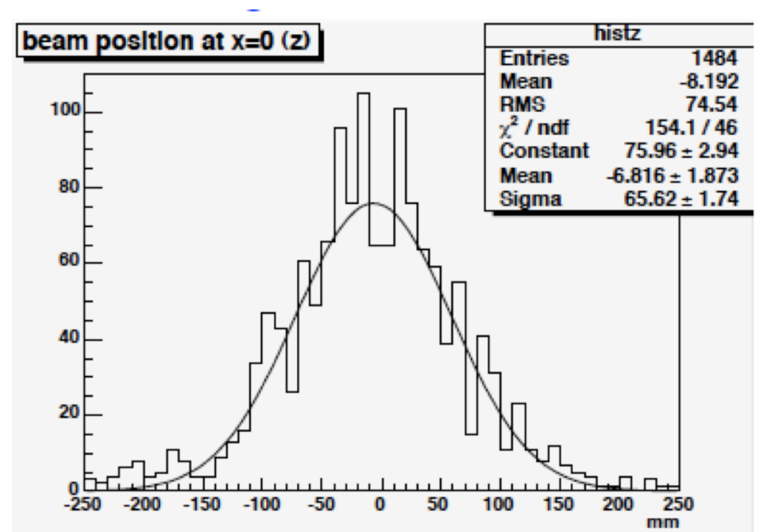
Use pixel information to linearly extrapolate tracks back to IP

Radial distribution



2.4mm

Longitudinal distribution



75mm

100 tracks / second / telescope (1 kHz pixel readout)

Precision on relative centroid position in one lumi section (93 s) at L = 10^{34} $cm^{-2}s^{-1}$

radially: 12 m longitudinally: 200 m

Summary Performance of the PLT

Bunch-by-Bunch Luminosity

- Statistical precision: 1% in 1 s at full lumnosity

Systematic Errors

- Accidentals, overlaps, effciencies

  controlled to by pixel hit information

- Acceptance at to 1%

  radially: 4 mm, longitudinally: 30 cm

- Repositioning acceptance change < 1%

IP Location

- Radial precision: 12 mm
- Longitudinal precision: 200 mm

  1 lumi section (93 s) at full luminosity

Monitoring

- Beam halo

  effective area of 1 cm^2

- Abort gap collisions

  1 count / minute /bunch for 0.1% bunch occupancy

Telescope Plane Assembly

Pixellization of sensor

– sputtered Ti/W electrodes
– pixel patterned using standard lift-off photolithography
– deposit solid electrode on back side with shadow mask

ROC bumps

– evaporated indium bumps ≈ 8 µm thick
– thick 10 µm photoresist deposited as two layers, first layer undercut
– bumps deposited on wafers

Sensor bumps

– bumps deposited on individual 5 mm × 5 mm diamonds
– challenge due to meniscus from spinning of the thick photoresist

Flip-bond sensor and ROC

– pressure bond of the tow bumps, no reflow
– bonding strength must hold 45 g

Mounting of bump-bonded detector

– ± 50 µm positioning of detector on hybrid board
– wire-bond ROC
– attach bias wire to back plane

PRISM Facility

All processing done in-house in PRISM

Princeton Institute for the Science and Technology of Materials state-of-the-art 5000sq. ft. /Class100/1000cleanroom

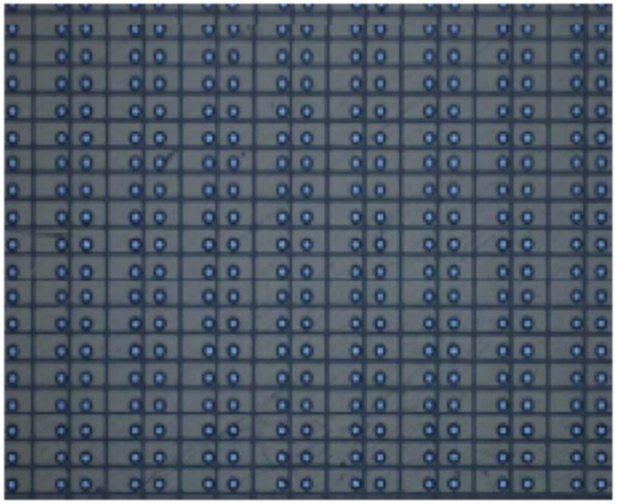
Karl Suss's MA-6

Edwards/E306A
Indium Evaporator Coating System

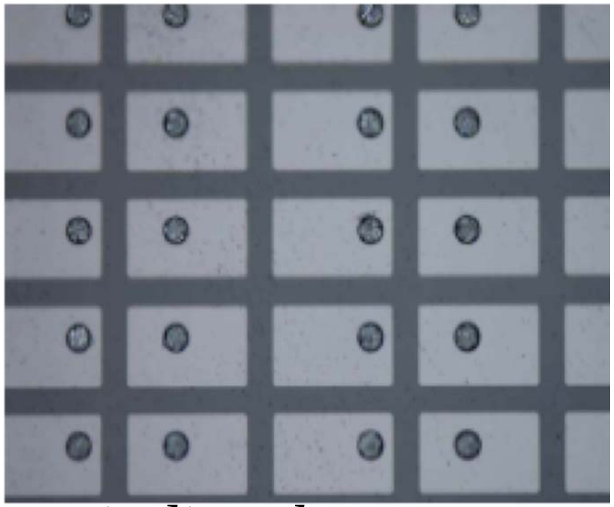
Angstrom Engineering's Metal Sputterer

Research Devices M8A
Flip Chip Bonder

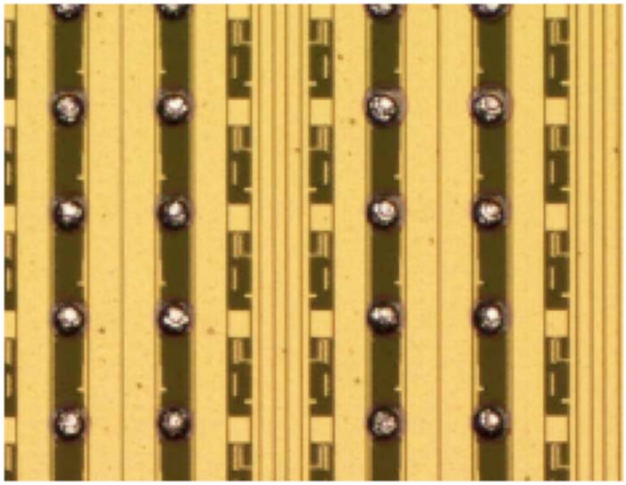
Detector Fabrication



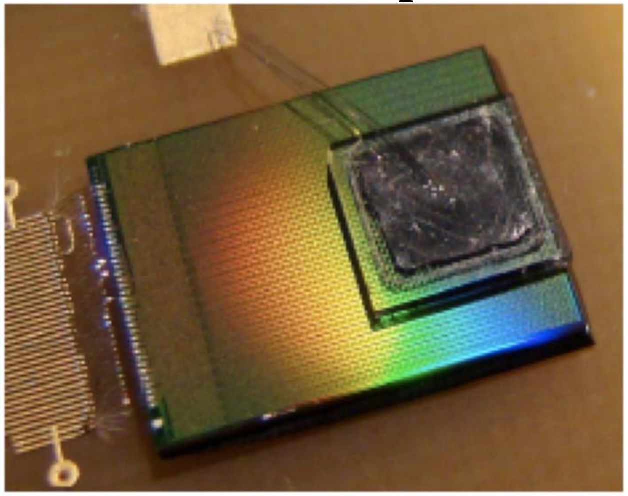
patterned diamond



indium bumps



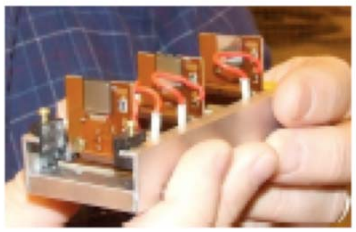
bumped ROC

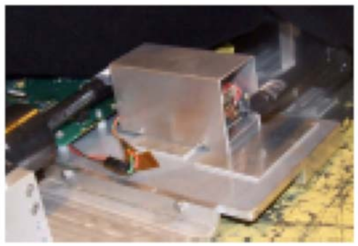


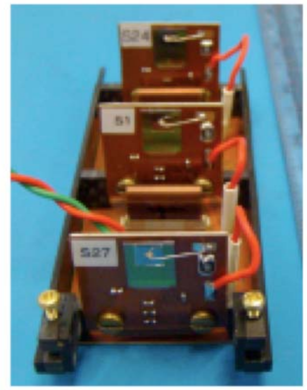
bumped detector

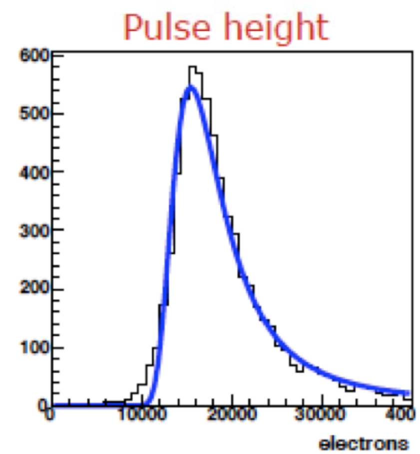
May 09 Test Beam

150 GeV/c π+ beam at H4 line of SPS;

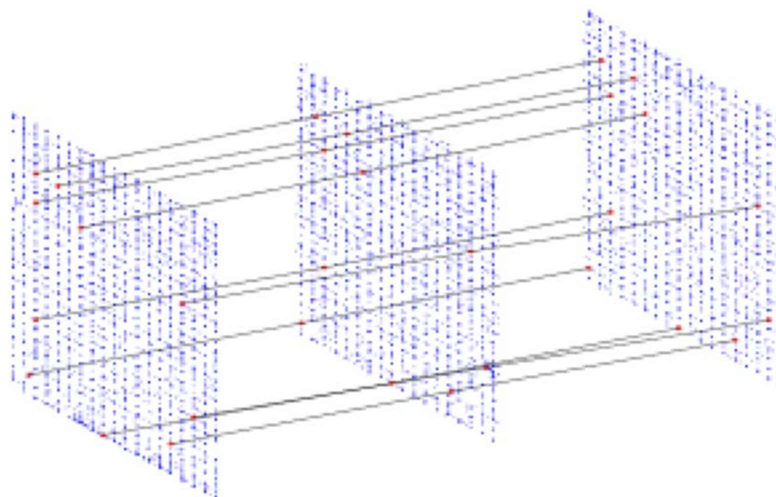








- Good bumps: > 98%
- Pulse height: 18,000 e- (mp)
- Pulse heights well above thresholds
- Tracks readily reconstructed
- Rapid offline alignment
- Fast-or efficiency: > 99% in all planes



First tracks in diamond pixel telescope

The Luminosity Calibration

- None of the methods discussed provides an absolute calibration for the luminosity
- Initially determine a luminosity calibration using the luminosity measurement from the LHC's measurement of beam parameters.
- Stick with that normalization until we have had a chance to study
    - CMS measurement of $\sigma_{W/Z.}$
    - Total cross section from TOTEM

Machine : Van Der Meer Scan

- Vernier Scans yield transverse beam sizes as well as maximum luminosity
- Two beams with Gaussian distribution in both, horizontal and vertical directions, the luminosity is given by

$$\mathcal{L} = \frac{k_b f_{rev} N_1 N_2}{2\pi\sqrt{(\sigma_{x1}^2 + \sigma_{x2}^2)(\sigma_{y1}^2 + \sigma_{y2}^2)}}.$$

- Sweeping one beam though the other yield the effective beam area and the max collision rate from the detector (ZDC/HF)

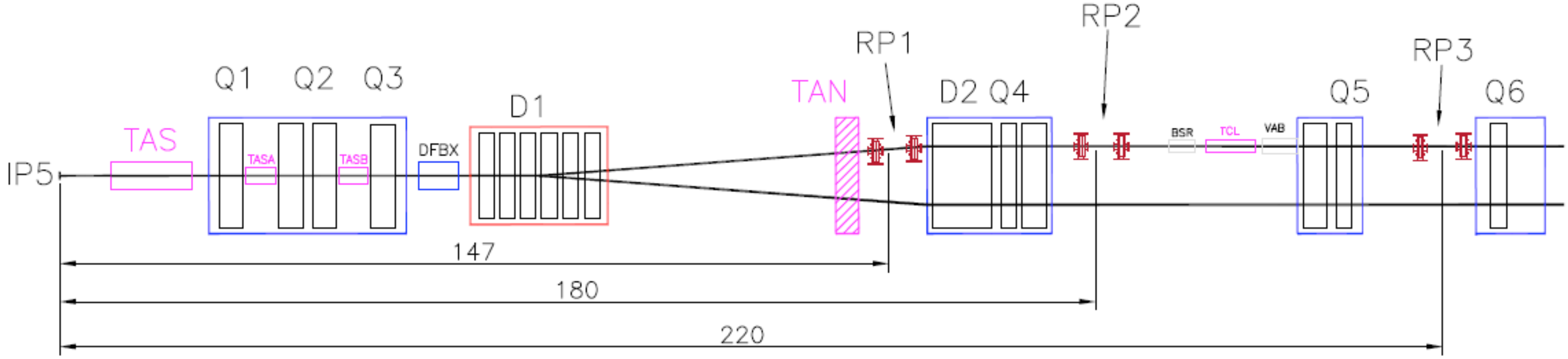
Part of the systematic results from:

- The precision of the Beam Position Monitors (BPM)
- The uncertainty in the beam intensities as measured with beam current transformers

- Multiple calibration would be necessary to optimize the running conditions for the needs of the absolute machine luminosity

- The total systematic error in the absolute machine luminosity calibration is expected be of the order of 10%.

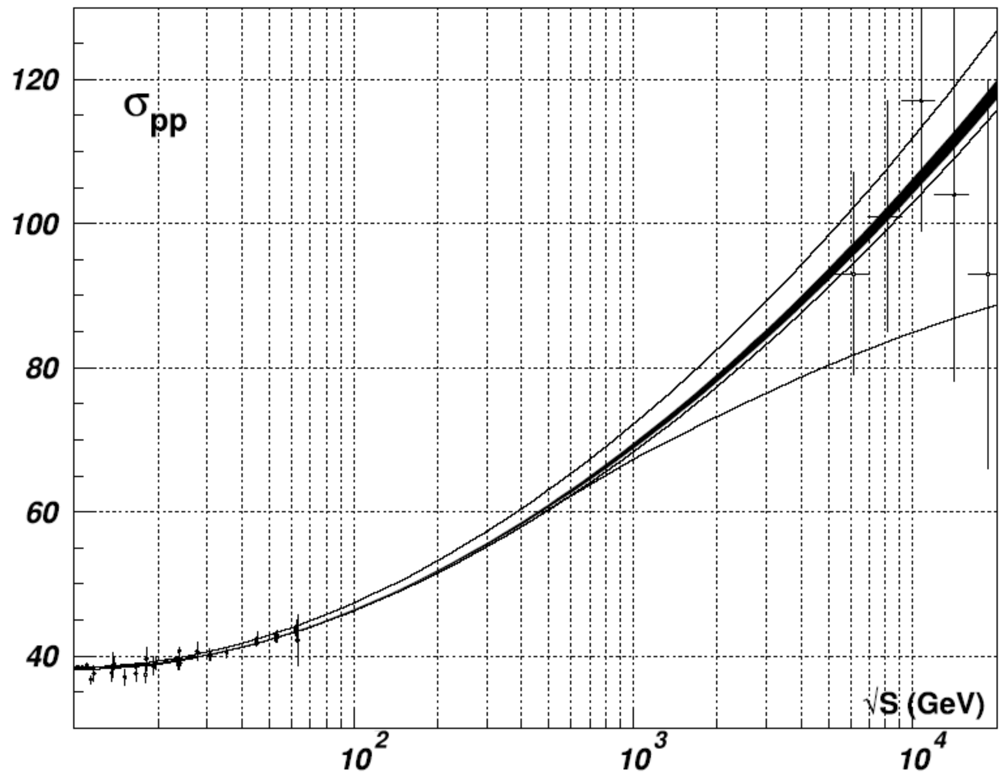
TOTEM



Measure independently

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

$$\mathcal{L} = \frac{1+\rho^2}{16\pi} \cdot \frac{(N_{el}+N_{inel})^2}{dN_{el}/dt|_{t=0}}.$$



Measure elastic scattering in Roman Pots and inelastic in T1 and T2 (see next slide). Should give result good to ~1%.

TOTEM Status

- The Luminosity and total pp cross-section measurement require special beam optics
- T1, and RP will be available at startup
- The schedule for the b*=90m during 7 TeV beam commissioning is being negotiated
- At an early stage with b*= 90m and $2\text{x}10^{28}$ $\text{cm}^{-2}\text{s}^{-1} < L < 3\text{x}10^{30}$ $\text{cm}^{-2}\text{s}^{-1}$ TOTEM will measure the total cross-section and the luminosity with a precision of about 5% and 7% respectively.

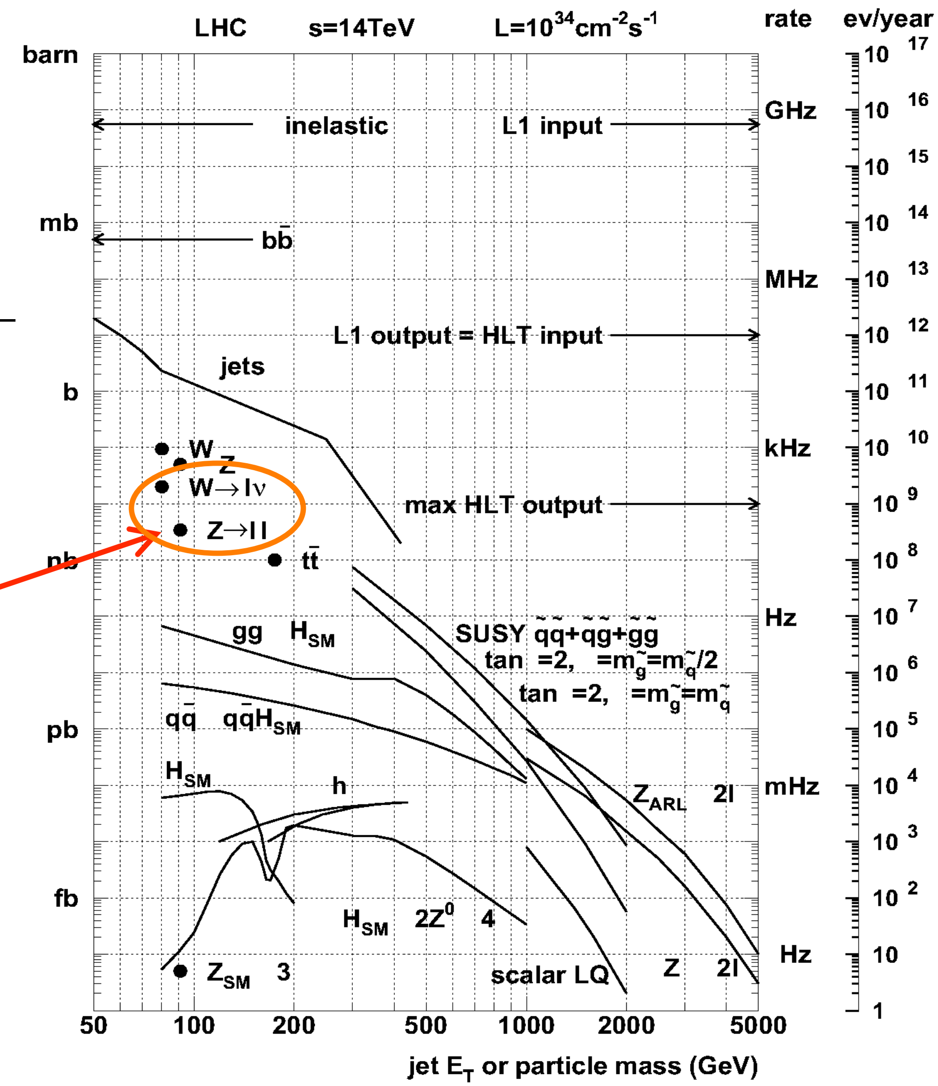
Normalization Using W's and Z's

Basic idea is to use

$$pp \rightarrow W \rightarrow \ell\nu \;\; \& \;\; pp \rightarrow Z \rightarrow \ell^+\ell^-$$

The ideal process needs to be:

- Large Xsec
- Clean signature
- Xsec and acceptance that can be reliably calculated



LHC event rates at 'nominal luminosity' CMS Trigger TDR

Theoretical Aspects of the W/Z production

Multiple factors contribute to the W/Z cross-section at the percent level :

- NNLO QCD corrections
- Scale dependence
- NLO EWK corrections
- PDF uncertainties
- QCD and EW showering
- Experimental acceptance

CMS-AN 2006-82 , Frixione,Mangano (hep-ph/0405130, JHEP 0405 (2004) 056) + *JHEP* **09** 2008 133 [N. Adam V. Halyo, S. Yost]

JHEP **05** (2008) 062 [N. Adam V. Halyo, S. Yost]

$$N^{\mathrm{obs}}_{Z/\gamma^*} = \sigma^{\mathrm{tot}}\,\mathrm{BR}(Z/\gamma^* \to \ell^+\ell^-) A_{Z/\gamma^*} \int \mathcal{L} dt.$$

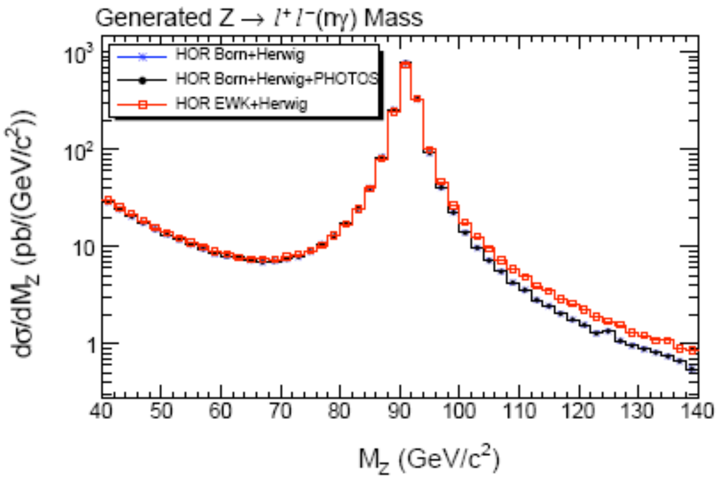
Corrected Yield within the fiducial region

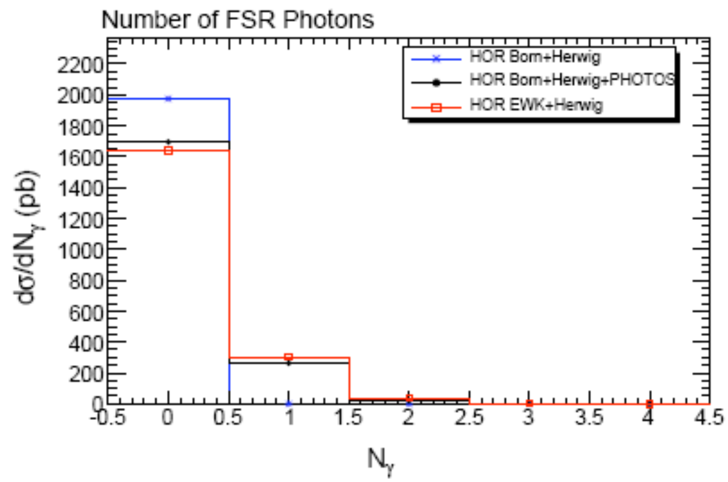
$$A_{Z/\gamma^*}(p_{\mathrm{T}}^{min}, \eta_{max}) = \frac{1}{\sigma^{\mathrm{tot}}\,\mathrm{BR}(Z/\gamma^* \to \ell^+\ell^-)} \int_{p_{\mathrm{T}}^{min}}^{\sqrt{s}/2} \int_{-\eta_{max}}^{\eta_{max}} dp_{\mathrm{T}}{}^{\ell+}\, dp_{\mathrm{T}}{}^{\ell-}\, d\eta_{\ell+} d\eta_{\ell-} \times \frac{d^4\sigma(pp \to Z/\gamma^* \to \ell^+\ell^-)}{dp_{\mathrm{T}}{}^{\ell+}\, dp_{\mathrm{T}}{}^{\ell-}\, d\eta_{\ell+} d\eta_{\ell-}}. \quad ($$

Acceptance obtained after applying the selection criteria demonstrate the impact of physics effects on the acceptances depending on the selection criteria

Alternatively the Z^c yield can be used as a luminosity monitor !

1. Electroweak Corrections:



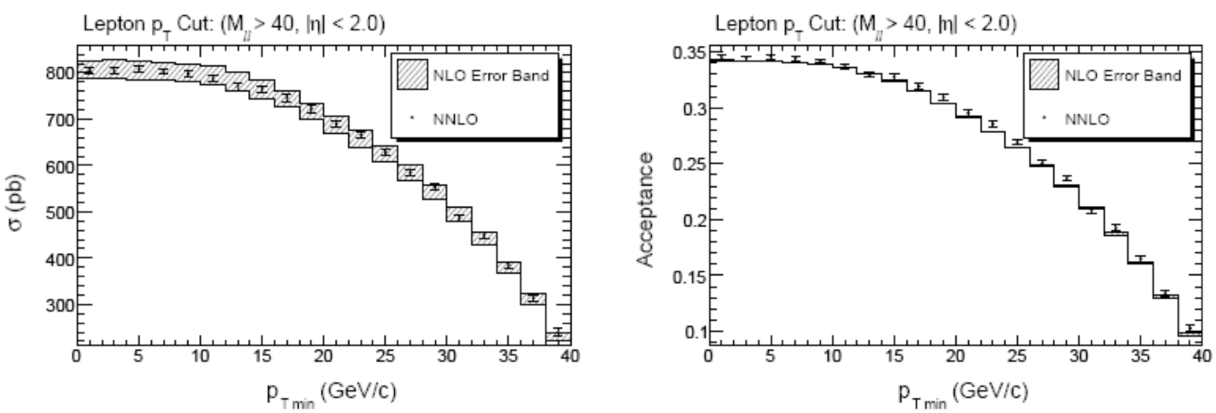


We compared the Born + PS + PHOTOS to HORACE and

Tight Cut : $40 < M_{\ell\ell} < 140\,GeV/c^2,\quad p_T^{\ell} > 20\,GeV/c,\quad |\eta_\ell| < 2.0.$

	Born	Born+FSR	ElectroWeak	Difference
σ(Tight Cut)	612.5 ± 1.1	597.6 ± 1.1	595.3 ± 1.1	$0.38 \pm 0.26\%$
A (Tight Cut)	0.3087 ± 0.0005	0.3012 ± 0.0005	0.2983 ± 0.0005	$0.96 \pm 0.21\%$

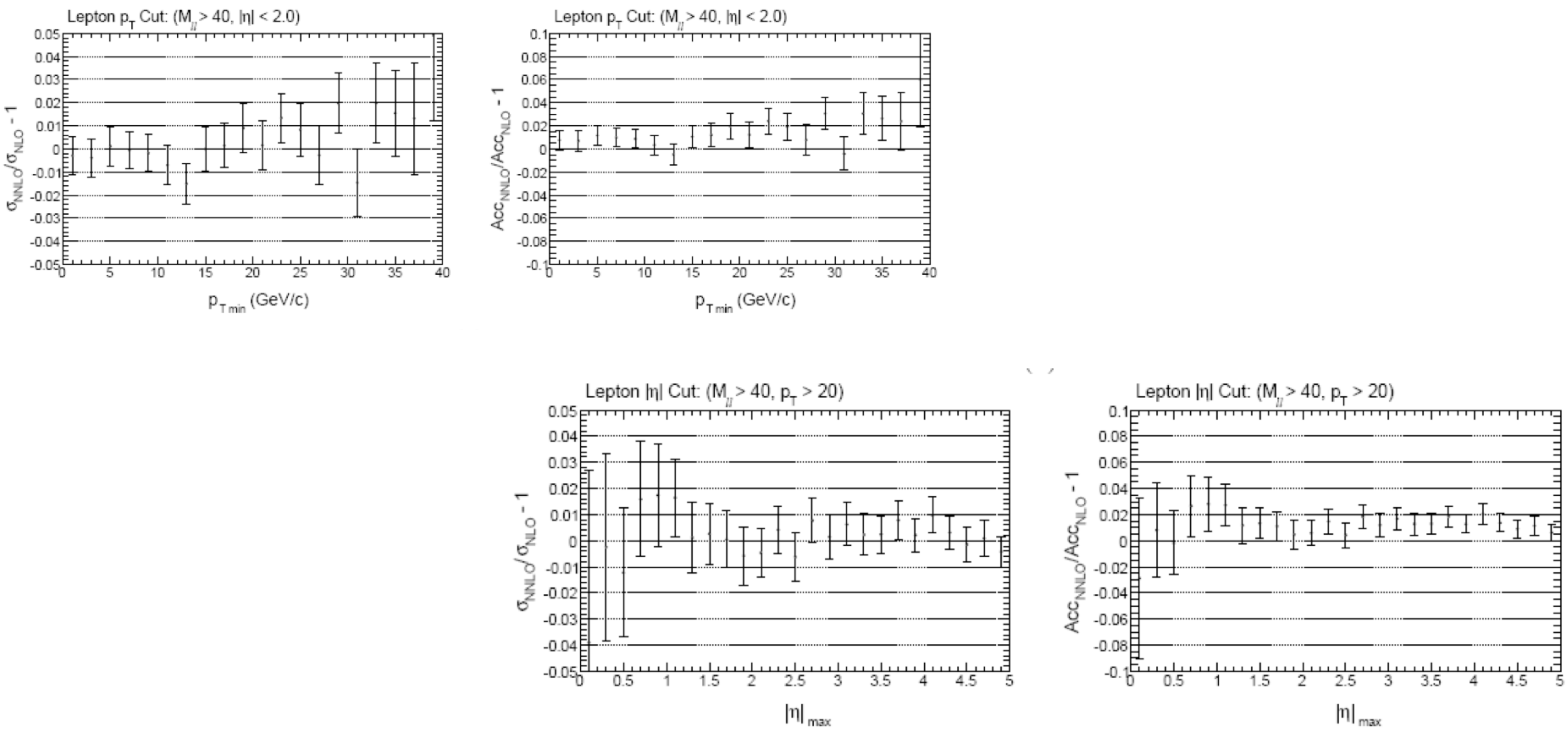
2. NNLO QCD Uncertainties:



(a) (b)

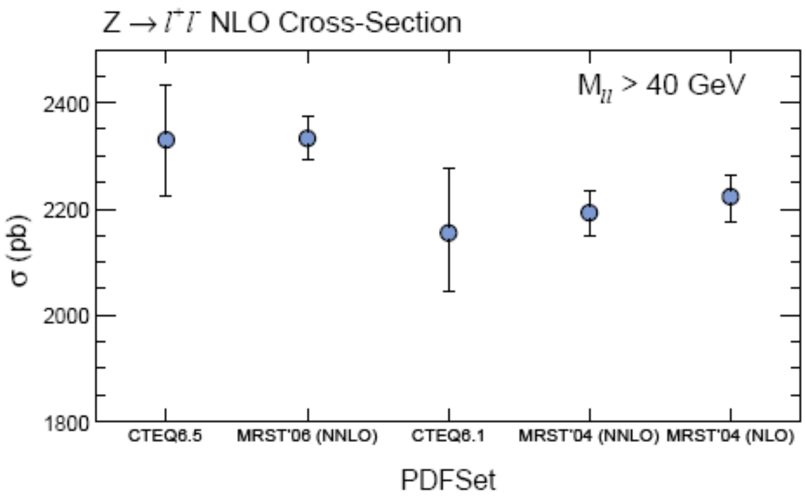
• Reduction in the scale variation hence confidence in the NNLO result

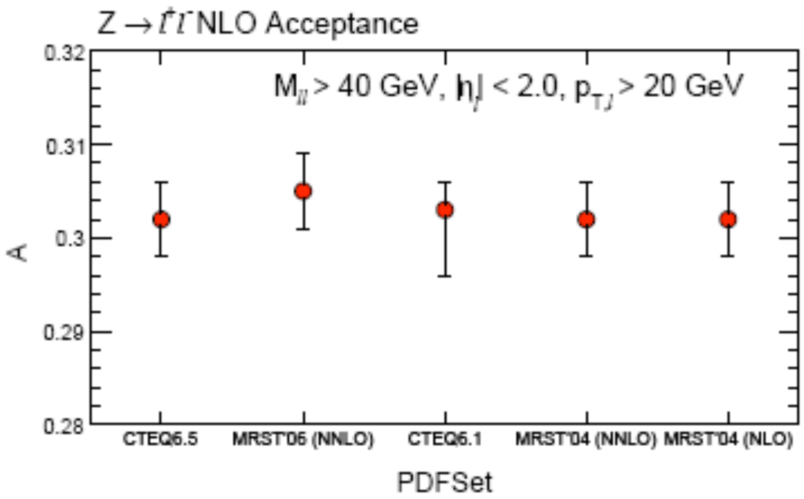
Cross-sections Acceptances



The Fractional difference in the NNLO and NLO cross-sections (left-hand side) and acceptances (right-hand side) as a function of the lepton (a) pT,and eta

3. PDF Uncertainties:





Missing in this slide !
PDF errors (MSTW2008):
Asymmetric Hessian method

Update on Lumi from Z cross section

Our recent study shows the systematic error on the Z cross section to be the following

	Z	
Error	$\Delta\sigma$ (%)	ΔA (%)
Higher Order	0.23 ± 1.25	-1.97 ± 1.51
QCD Scale	0.92 ± 0.61	1.58 ± 1.35
PDF	2.75 ± 0.00	1.03 ± 0.00
Total	2.91 ± 0.22	2.73 ± 1.35

Hence the absolute luminosity will be measured to less <5% systematic error.

CMS AN-2009/088

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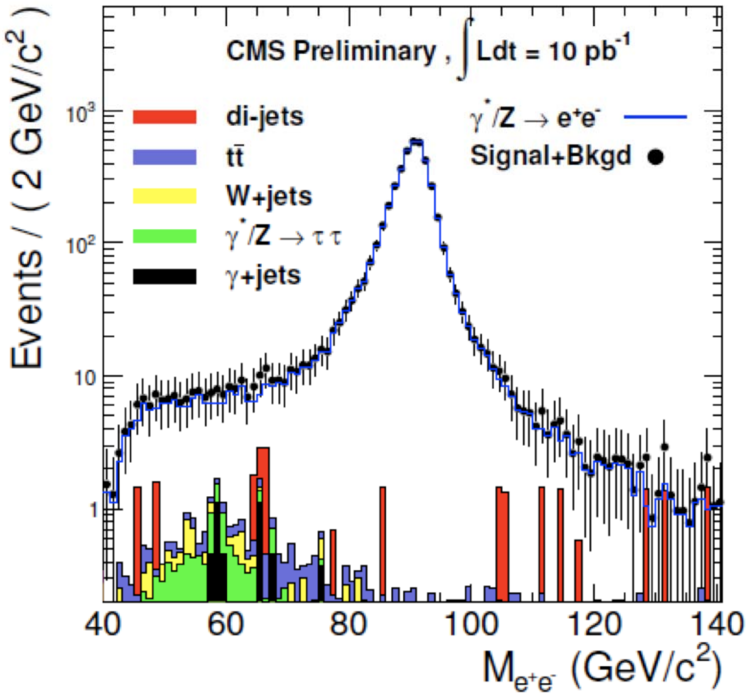
Z->ll

$$\sigma_{Z/\gamma^*} \times BR(Z/\gamma^* \to e^+e^-) = \frac{N^{pass}_{Z/\gamma^*} - N^{bkgd}_{Z/\gamma^*}}{A_{Z/\gamma^*} \times \epsilon_{Z/\gamma^*} \times \int Ldt}$$



$$\varepsilon_{total} = \varepsilon^2_{offline} \times \varepsilon_{trigger}$$

$$\varepsilon_{trigger} = 1 - (1 - \varepsilon_{online})^2$$

$N_{selected}$	4273 ± 65
N_{bkgd}	assumed 0.0
Tag&Probe $\varepsilon_{offline}$	90.37 ± 0.32 %
Tag&Probe $\varepsilon_{trigger}$	99.88 ± 0.016 %
Tag&Probe ε_{total}	81.57 ± 0.58 %
Acceptance Int. Luminosity	40.42 ± 0.18 % $10\ pb^{-1}$
$\sigma_{Z/\gamma^*} \times BR(Z/\gamma^* \to e^+e^-)$	1296 ± 23 pb
cross section used	1296 pb

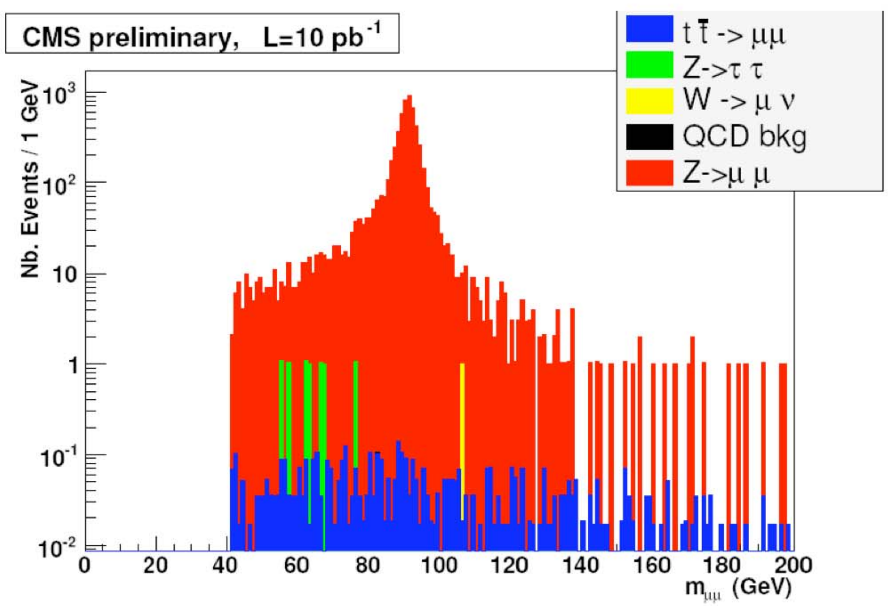
Systematic uncertainties:

Acceptance: 2.37% ⊕ Bkgd: 0.35% ⊕ Eff. from T&P: 0.35% = 2.42%

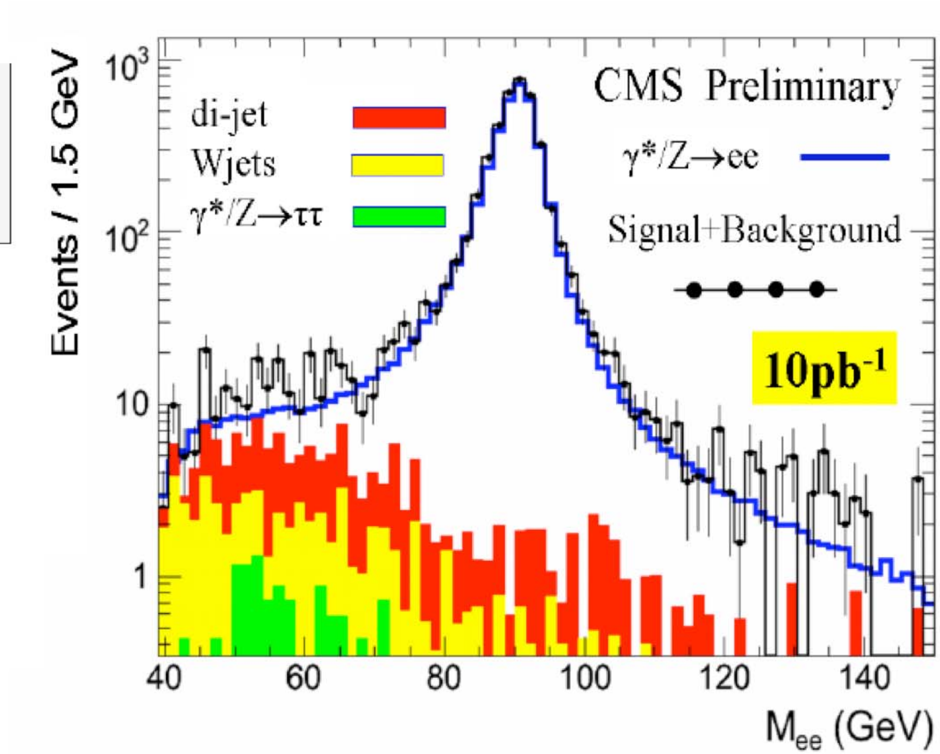
10% for Lumi;

Efficiencies from the Z: T&P

muons



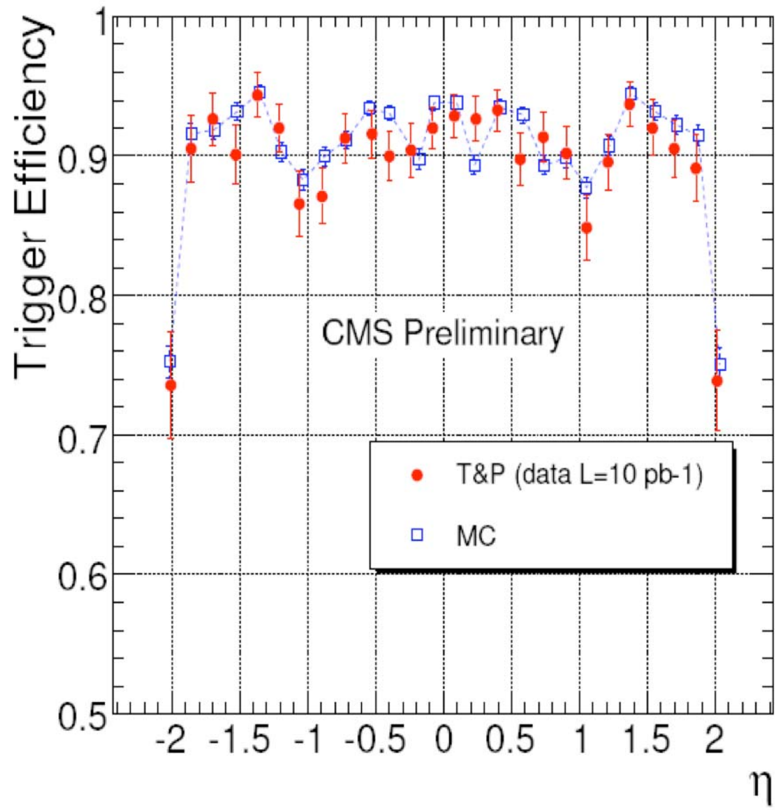
electrons



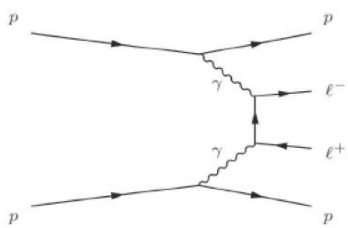
Can get easily pure samples at the Z

Efficiencies from tag&probe at the Z peak

- One object, the tag, has strict criteria imposed on it to identify it.
- The probe is another object with looser criteria to meet.
- The Z resonance links tag-and-probe, ensuring a pure sample.



pp → ppmm



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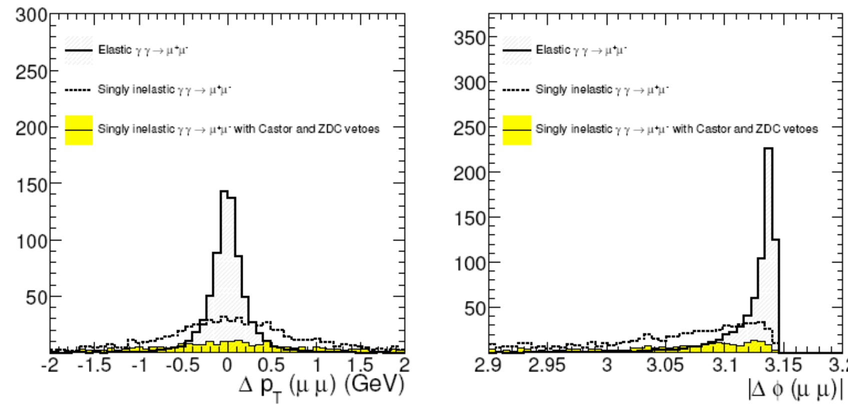

$$N_{elastic}(\gamma\gamma \to e^+e^-) = 67 \pm 8,$$
$$N_{inelastic}(\gamma\gamma \to e^+e^-) = 31 \pm 6 \pm 6(model)$$

$$N_{elastic}(\gamma\gamma \to \mu^+\mu^-) = 709 \pm 27,$$
$$N_{inelastic}(\gamma\gamma \to \mu^+\mu^-) = 223 \pm 15 \pm 42(model)$$

$$N_{inelastic}(\gamma\gamma \to \mu^+\mu^-) = 636 \pm 25 \pm 121(model),$$
$$N_{inelastic}(\gamma\gamma \to e^+e^-) = 82 \pm 9 \pm 15(model)$$

Background level without CASTOR/ZDC

pp → ppmm

- The systematic uncertainties on the process are ~1%
- Hard to achieve enough statistic at phase one to improve upon the VdM measurement

- However phase two of data taking looks promising!
- 200pb-1 yield <3% statistical uncertainty
- Forward detectors will help suppress the background
- Comparable or better the Z measurement

Conclusions

- CMS will use multiple relative luminosity monitors
- Diamond detector is will be installed by next year
- The Calibration procedure is well planed
- Several studies on data driven methods to make robust assessment of W,Z observables and to measure the W/Z cross section
- Both the Z and QED process will be used to measure the absolute luminosity

Z rate for different run condition

#BX	Lumi	Z Rate Hz	Rate/day
43	3.8 10^{29}	0.001	90
156	5.6 10^{31}	0.16	14K
936	5 10^{32}	1.4	121K
2808	2.8 10^{33}	8	600K
2808	10^{34}	28	2.4M