CMS Luminosity Monitors and Standard Candles

HREA/LHC Workshop

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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

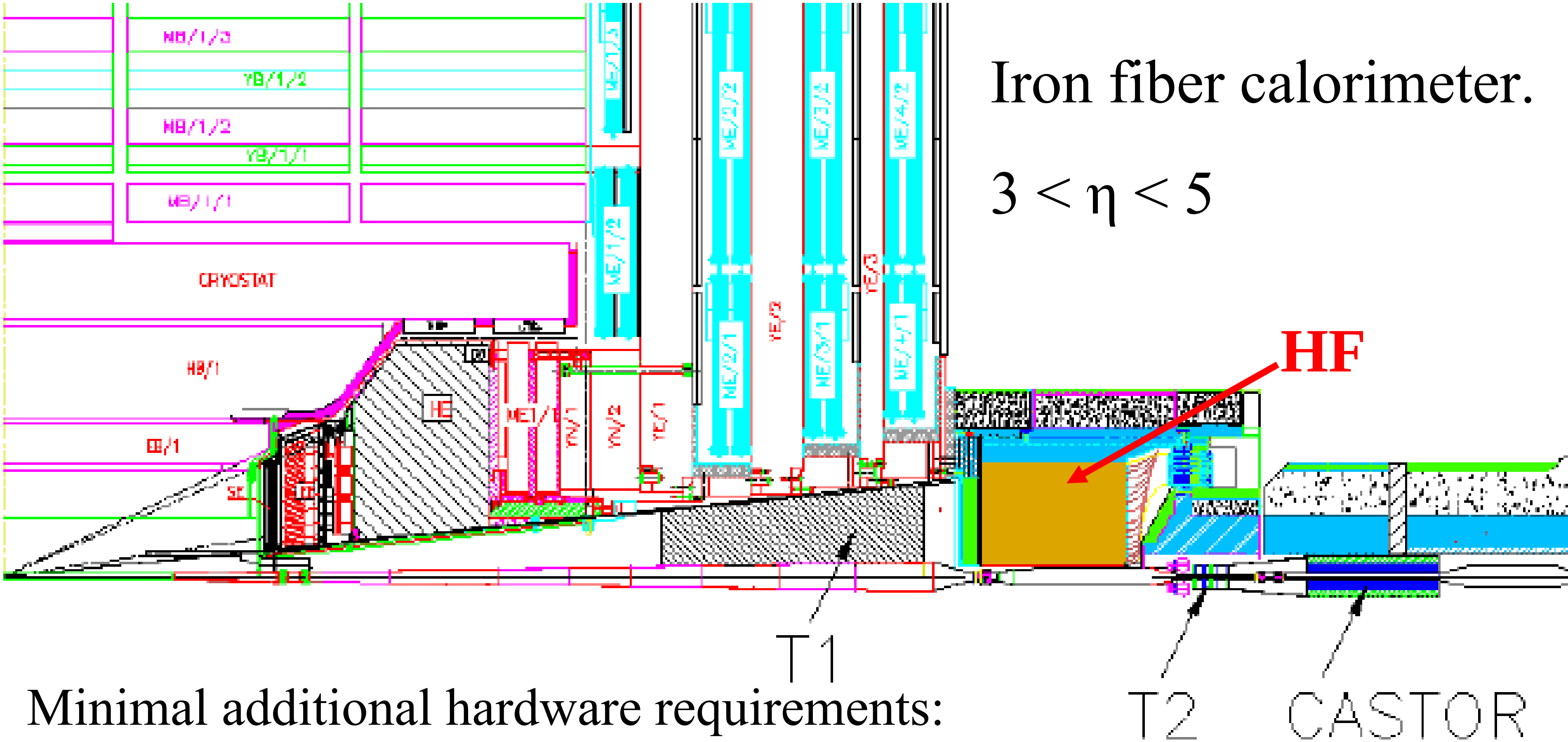
Design Goals: Specific Issues

- 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)

Signals From HF



Iron fiber calorimeter.

$3 < \eta < 5$

T1 & T2 are elements of TOTEM

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

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***,

μ= mean number of interactions per bunch crossing.

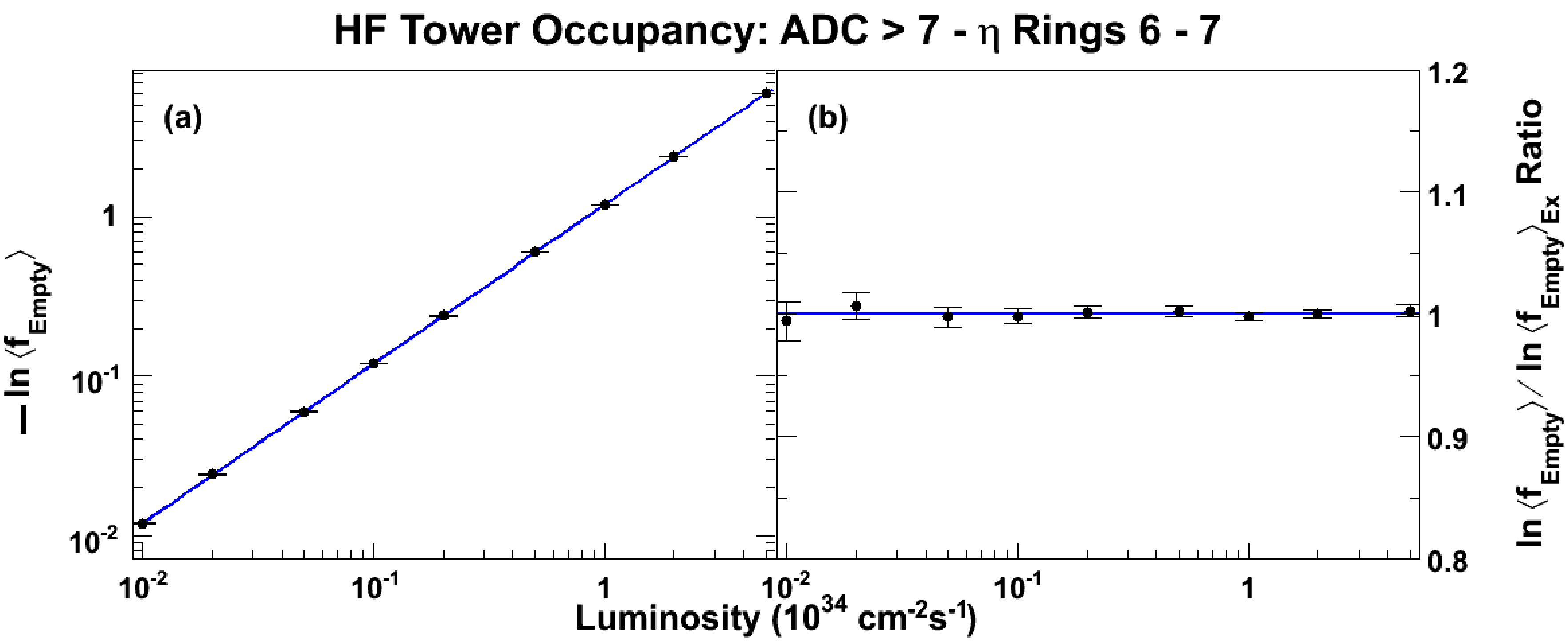
Tower Occupancy Method

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***,

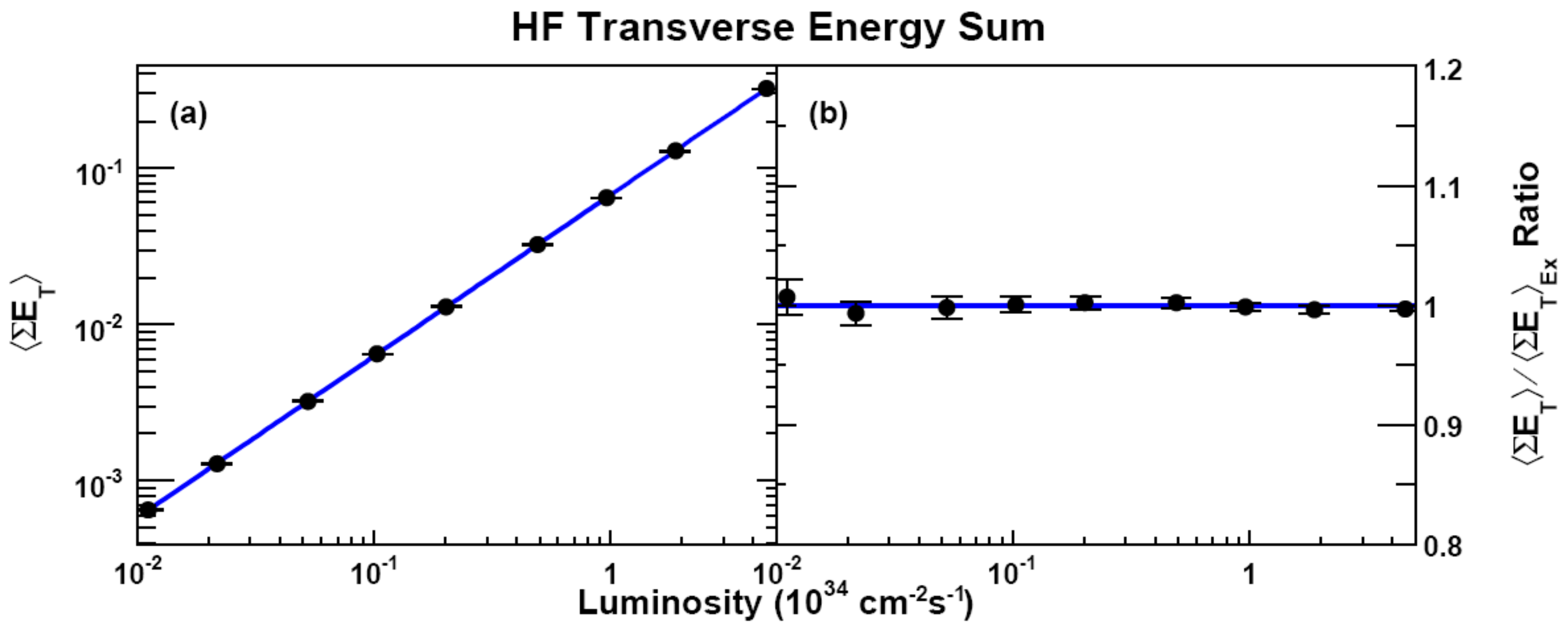
ν= <ET> for a single occupied tower in a single interaction

μ= 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

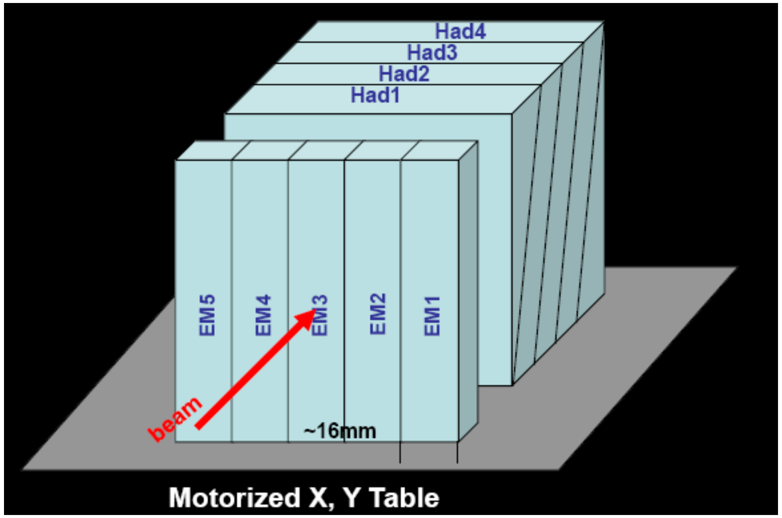


Any noise offset would be calibrated out by using the the Hlx data during the abort gap

Projected statistical Errors

Lumi Nibble (LN) = 2^{12} orbits Lumi Section (LS) = 2^{20} orbits					BX = bunch crossing N(1%) = #LN/BX for 1% error				
	$\langle E_T \rangle$				**Tower Occupancy**				
$L(cm^{-2}s^{-1})$	LN/BX	LS/BX	LN	LS	LN/BX	LS/BX	LN	LS	N(1%)
10^{29}	5900	370	110	7.0	10000	630	190	12	10^{8}
10^{30}	590	37	11	0.70	1000	63	19	1.2	10^{6}
10^{31}	59	3.7	1.1	0.070	100	6.3	1.9	0.12	10^{4}
10^{32}	6.0	0.37	0.11	0.0071	10	0.64	0.19	0.012	10^{2}
2×10^{32}	3.0	0.19	0.056	0.0035	5.1	0.32	0.096	0.0060	10
5×10^{32}	**1.3**	**0.078**	**0.024**	**0.0015**	**2.1**	**0.13**	**0.040**	**0.0025**	**1**
10^{33}	0.67	0.042	0.013	0.00079	1.1	0.070	0.021	0.0013	1
2×10^{33}	0.38	0.024	0.0072	0.00045	0.62	0.039	0.012	0.00074	10^{-1}
5×10^{33}	0.20	0.013	0.0039	0.00025	0.33	0.021	0.0063	0.00039	10^{-1}
10^{34}	0.15	0.0094	0.0028	0.00018	0.25	0.016	0.0047	0.00029	10^{-2}
2×10^{34}	0.12	0.0076	0.0023	0.00014	0.25	0.016	0.0047	0.00029	10^{-2}
5×10^{34}	0.10	0.0065	0.0019	0.00012	0.68	0.042	0.013	0.00080	10^{-2}

Other Luminosity Monitor: ZDC

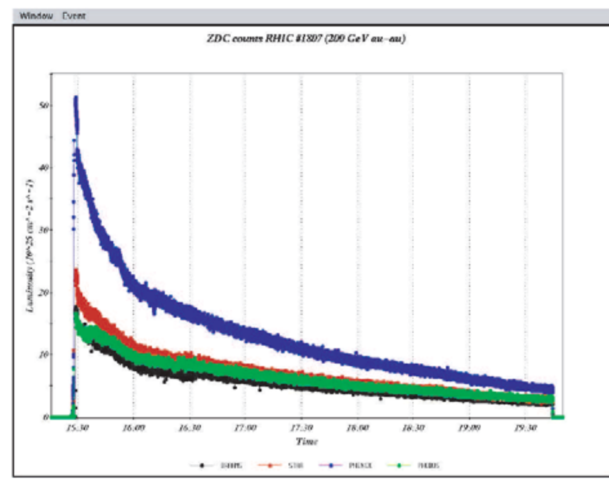


The design of each ZDC Includes (EM section) and (HAD section).

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-

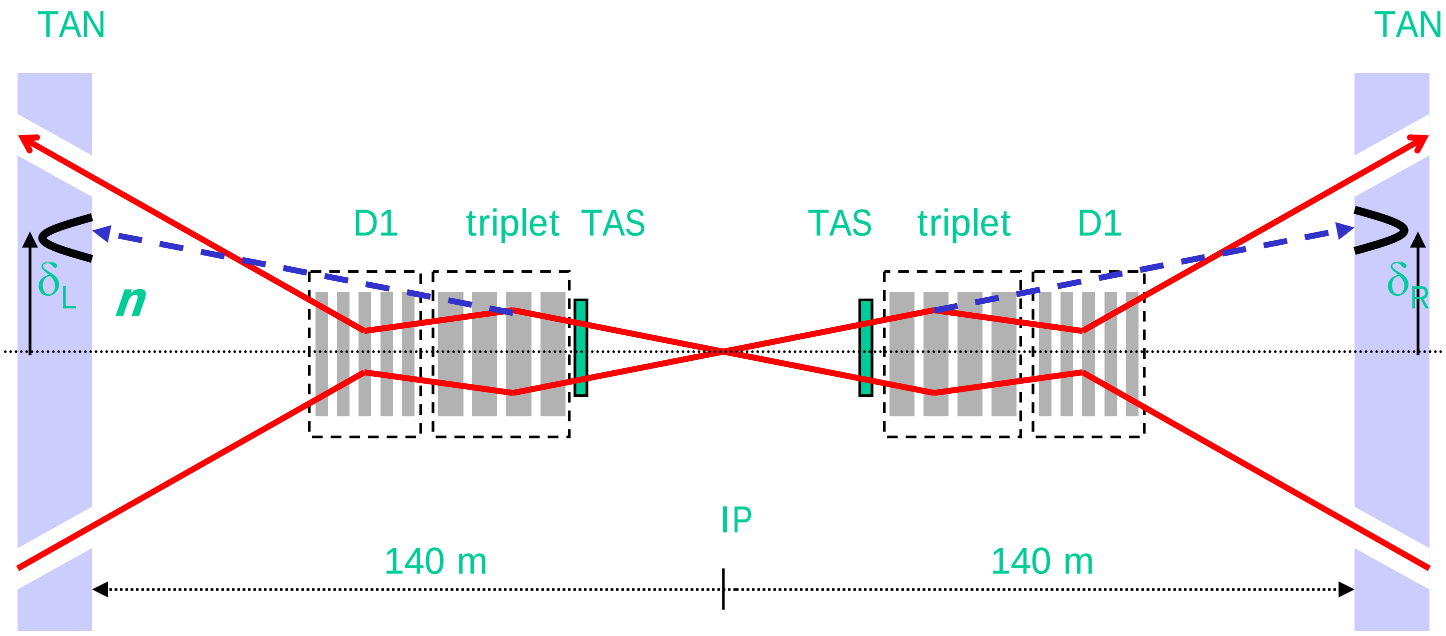
- The horizontal crossing angle
- A measurement of the emittance
- Average x position of the beams



Luminosity at 4 RIHC exp

Other Luminosity Monitor - BRAN

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



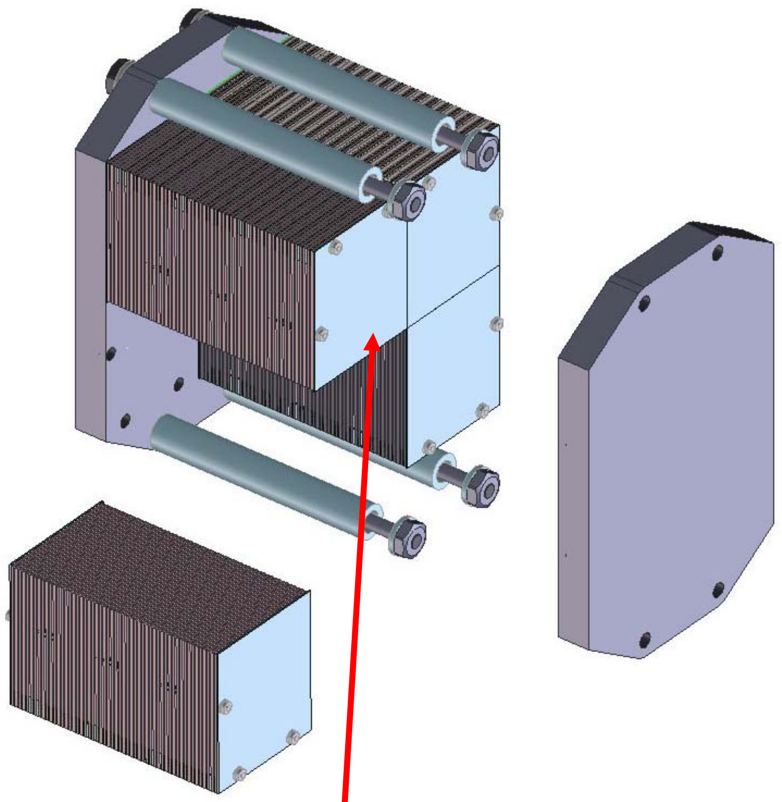
BRAN - LHC Luminosity Monitor

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%).

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)

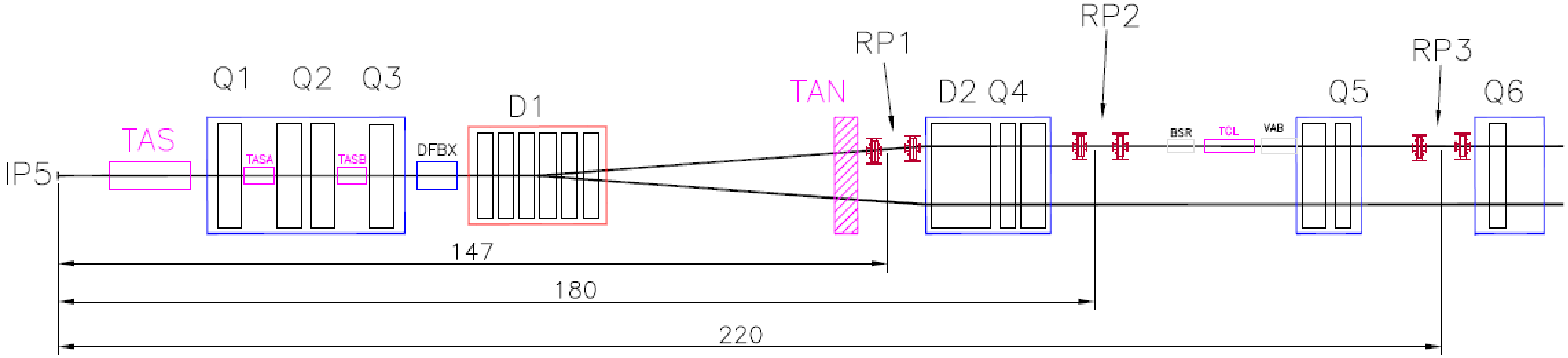
Part of the systematic results from:

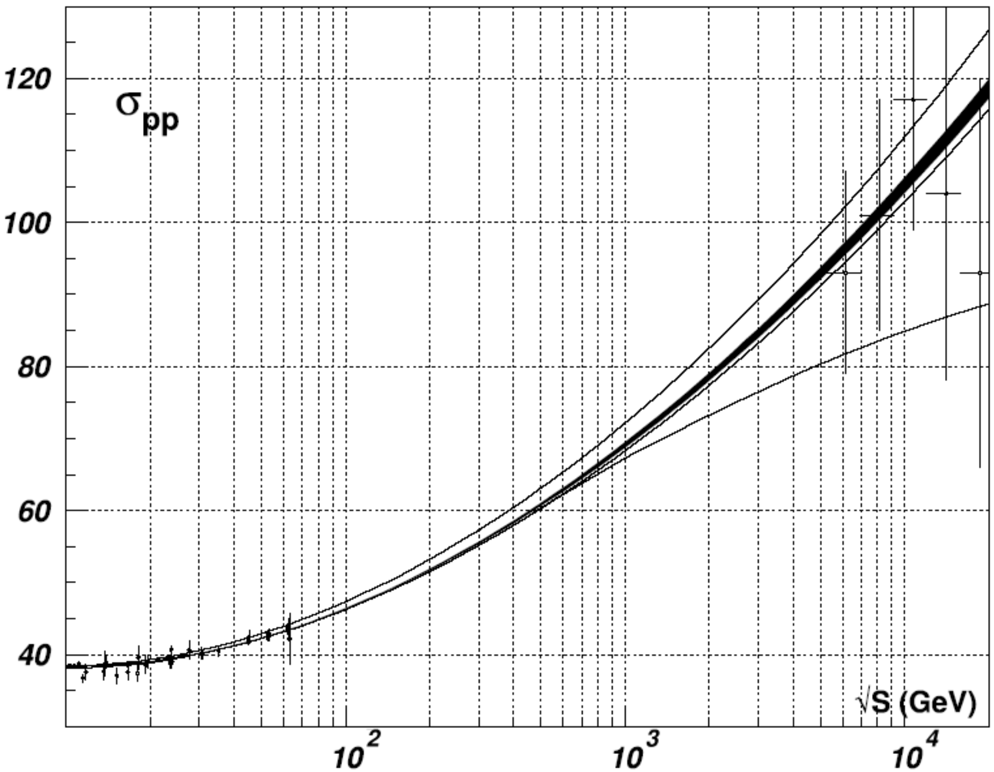
- The precision of the Beam Position Monitors (BPM)
- The uncertainty in the beam intensities as measured with beam current transformers

- 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 β^*=90m during 7 TeV beam commissioning is being negotiated

- At an early stage with β^*= 90m and $2x10^{28}\ cm^{-2}s^{-1} < L < 3x10^{30}\ cm^{-2}s^{-1}$ TOTEM will measure the total cross-section and the luminosity with a precision of about 5% and 7% respectively.

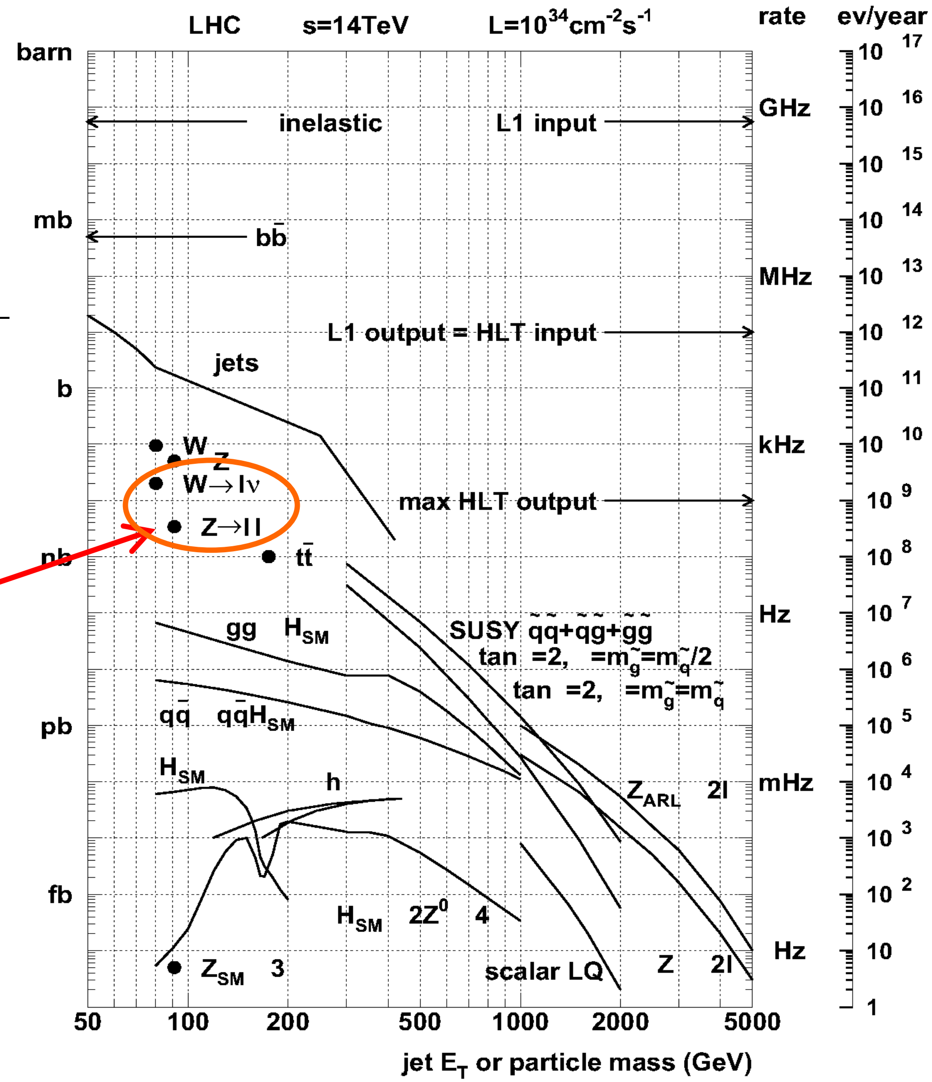
Normalization Using W's and Z's

Basic idea is to use

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

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/ATLAS note XX , Frixione,Mangano (hep-ph/0405130,

JHEP 0405 (2004) 056) ,Adam,Halyo,Yost (arXiv:0802.3251, JHEP05(2008)062)

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

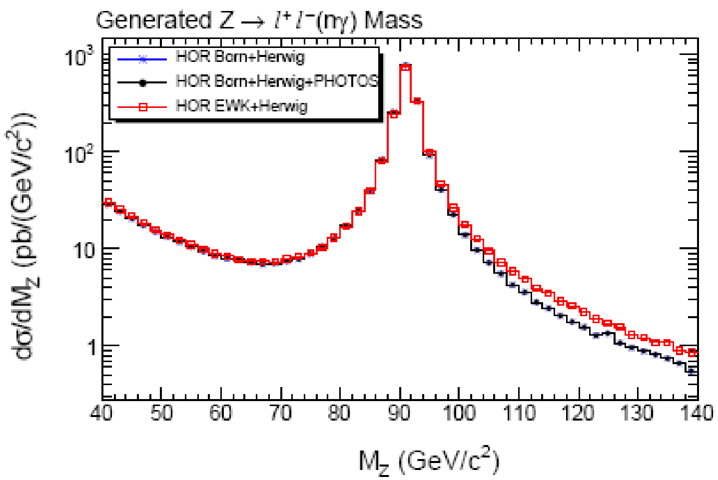
Corrected Yield within the fiducial region

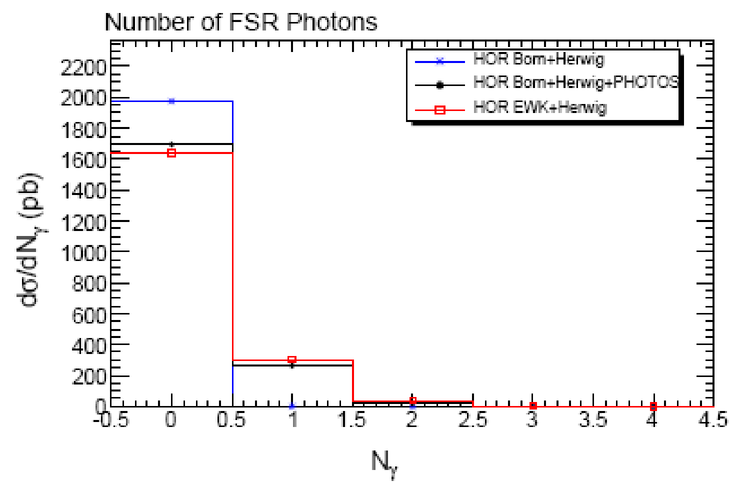
$$A_{Z/\gamma^*}(p_{\rm T}^{min}, \eta_{max}) = \frac{1}{\sigma^{\rm tot}\,{\rm BR}(Z/\gamma^* \to \ell^+\ell^-)} \int_{p_{\rm T}^{min}}^{\sqrt{s}/2} \int_{-\eta_{max}}^{\eta_{max}} dp_{\rm T}{}^{\ell^+}\, dp_{\rm T}{}^{\ell^-}\, d\eta_{\ell^+}\, d\eta_{\ell^-} \times \frac{d^4\sigma(pp \to Z/\gamma^*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

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:



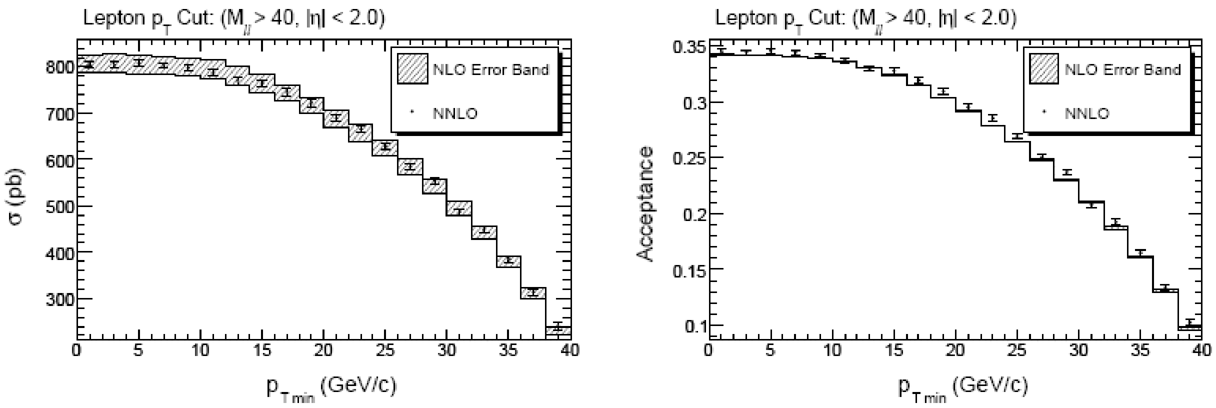


We compared the Born + PS + PHOTOS to HORACE and

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

	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:

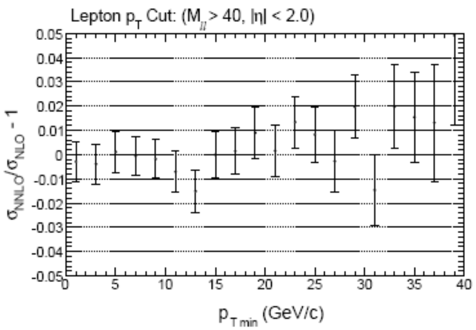


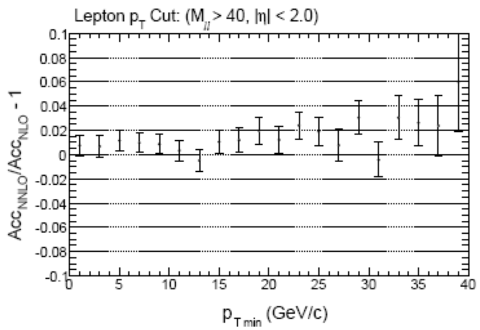
(a) (b)

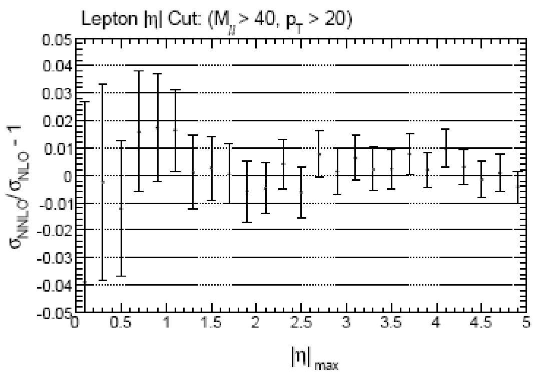
- Reduction in the scale variation hence confidence in the NNLO result
- Acceptance plot shows usually preference for larger acceptance

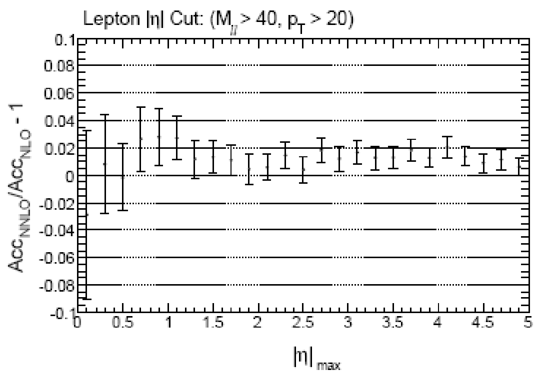
Cross-sections

Acceptances



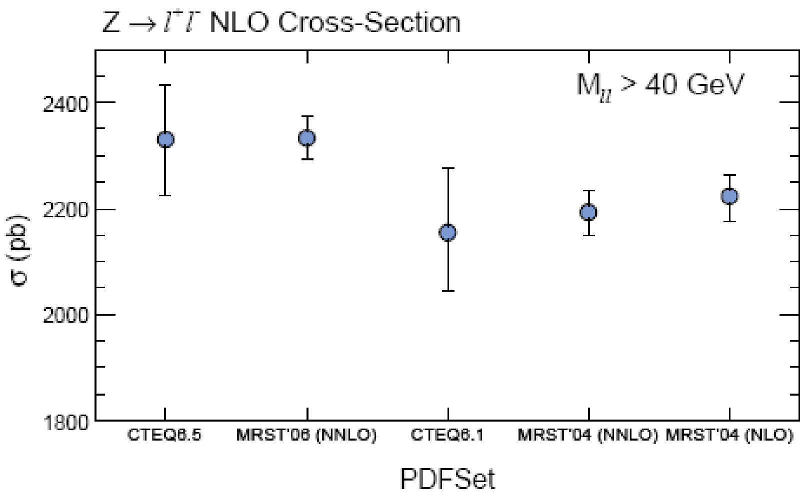


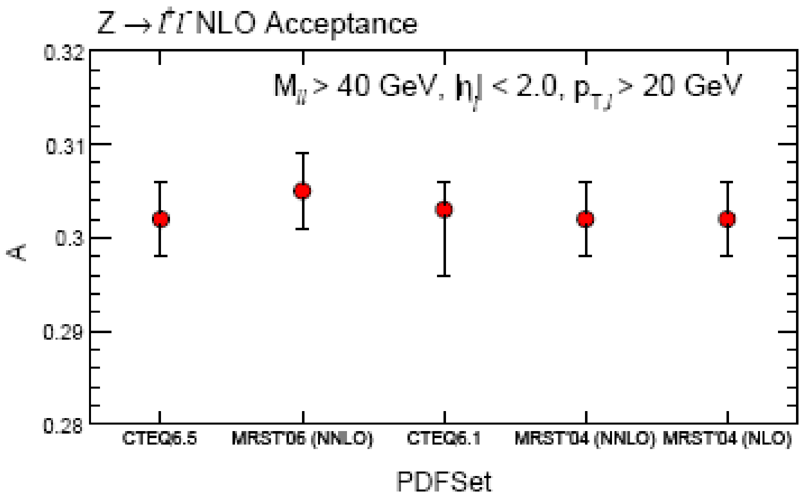




The Fractional difference in the NNLO and NLO cross-sections (left-hand side) and acceptances (right-hand side) as a function of the lepton (a) pT,and eta

3. PDF Uncertainties:





Summary:

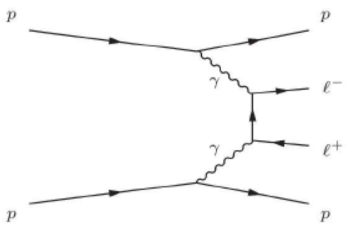
	Invariant Mass (GeV/c^2)	Pseudorapidity	Transverse Momentum (GeV/c)
Cut 1	$M_{\ell\ell} > 40$	$\lvert\eta_\ell\rvert < 2.0$	$p_T^\ell > 20$

Total Theoretical Uncertainty (%)

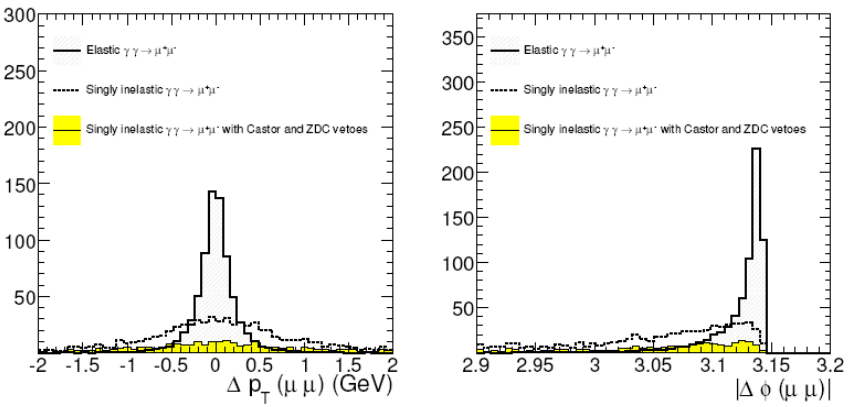
Uncertainty	Cross-section $\Delta\sigma$	Acceptance ΔA
Missing O(α) EWK	0.38 ± 0.26	0.96 ± 0.21
Total QCD Uncertainty	1.51 ± 0.75	2.55 ± 0.79
PDF Uncertainty	3.79	1.32
Total Uncertainty	4.1 ± 0.3	3.0 ± 0.7

Total theoretical uncertainty on the Z production cross-section σ, and acceptances A.

pp → ppμμ



PAS DIF-07-001



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

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

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

Background level without CASTOR/ZDC

pp → ppμμ

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

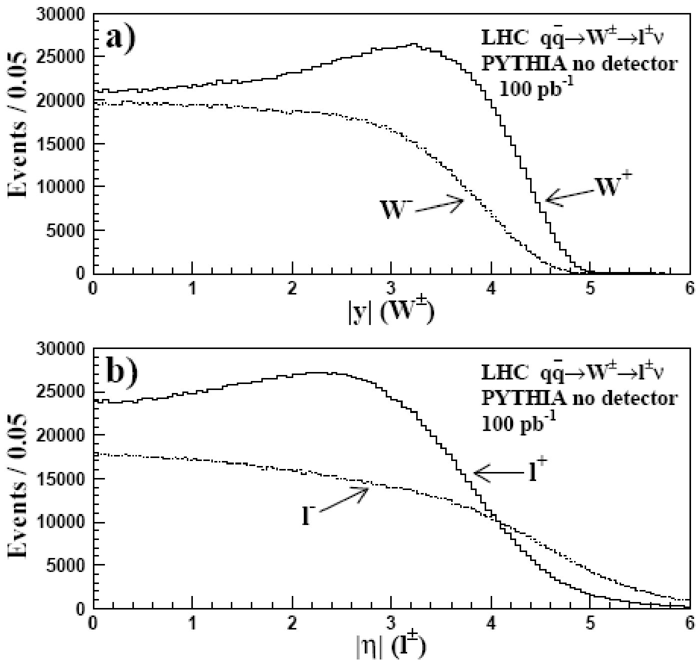
- However phase two of data taking looks promising!
- 200pb-1 yield <3% statistical uncertainty
- Forward detectors will help suppress the background
- Comparable or better the Z measurement

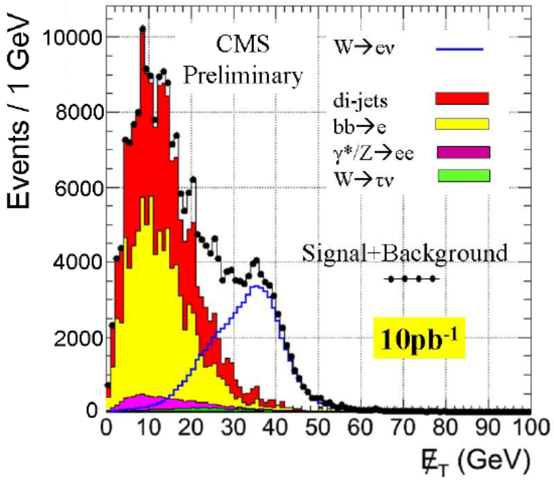
CMS Studies

Use early data to constraint the PDF making robust measurements

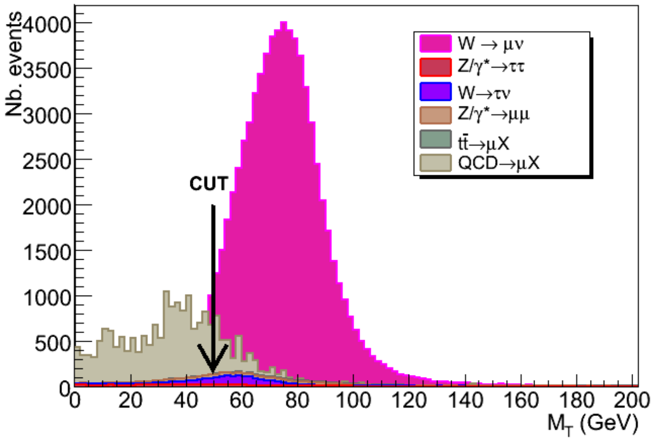
For many observables statistics is not an issue however systematic must be controlled

M. Dittmar et al. – 1997





The Missing ET from electrons

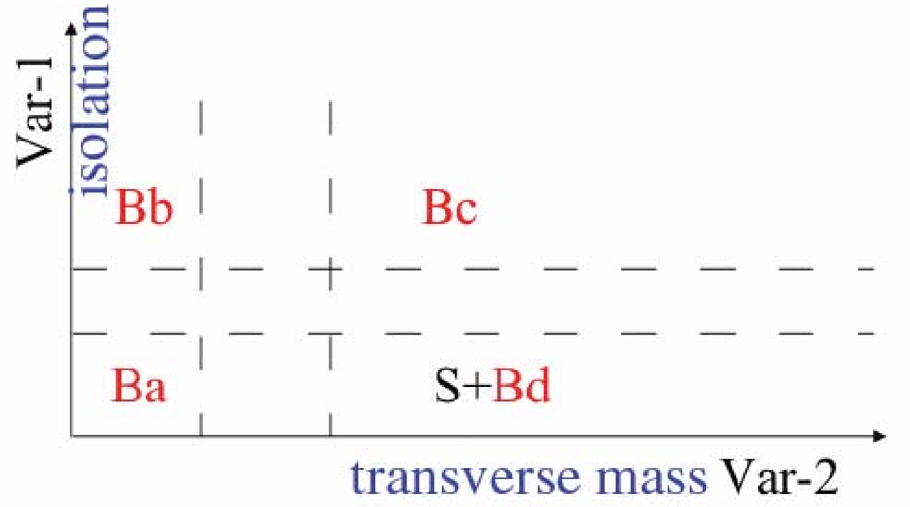


The W transverse mass from muons

Data-driven background studies

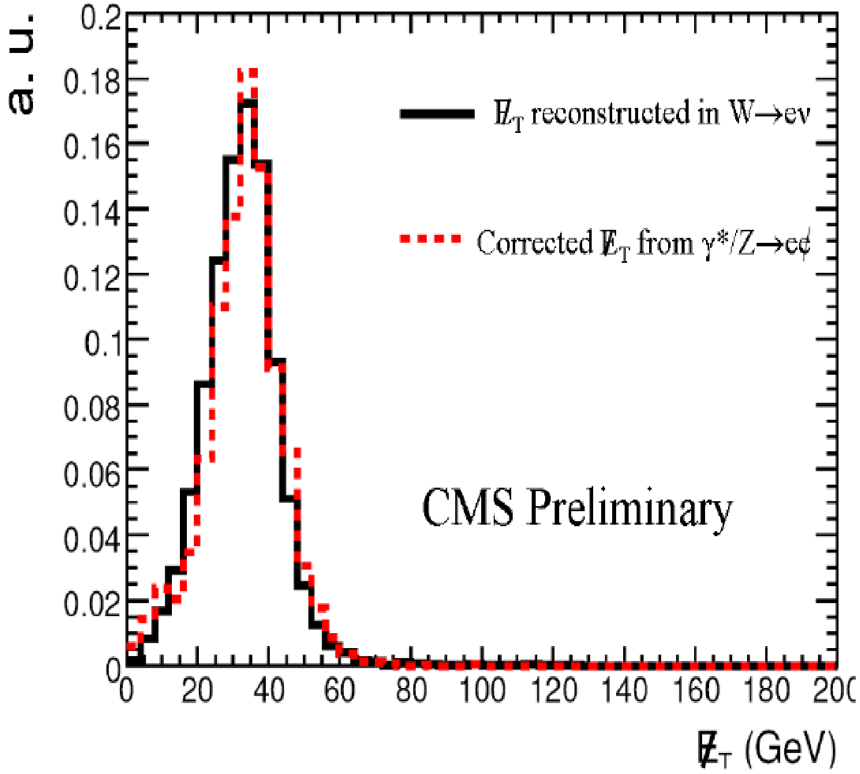
Take two uncorrelated variables with
 discriminating power
(e.g. isolation and MT)

$$N_{QCD} = N_d = N_a \times \frac{N_c}{N_b}$$

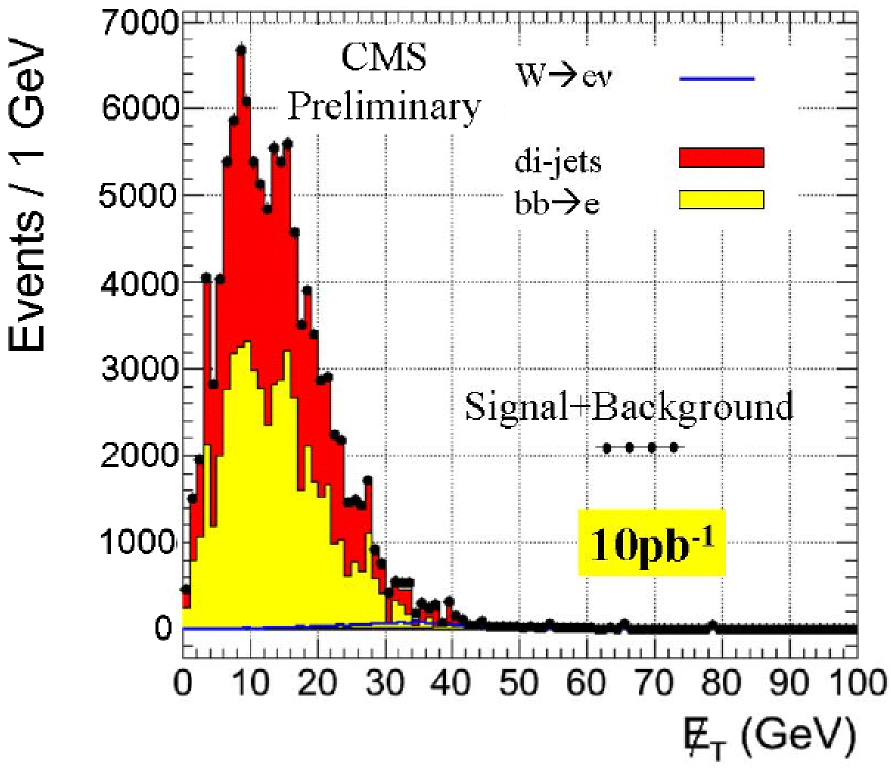


Data-driven background studies - template method (electrons) -

Shape of signal from Z → ee

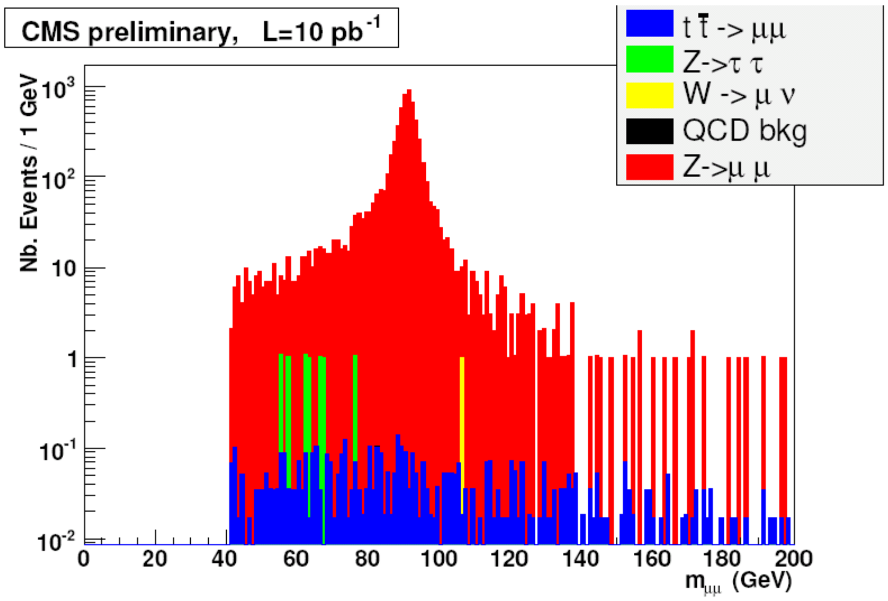


Single electrons with inverted isolation

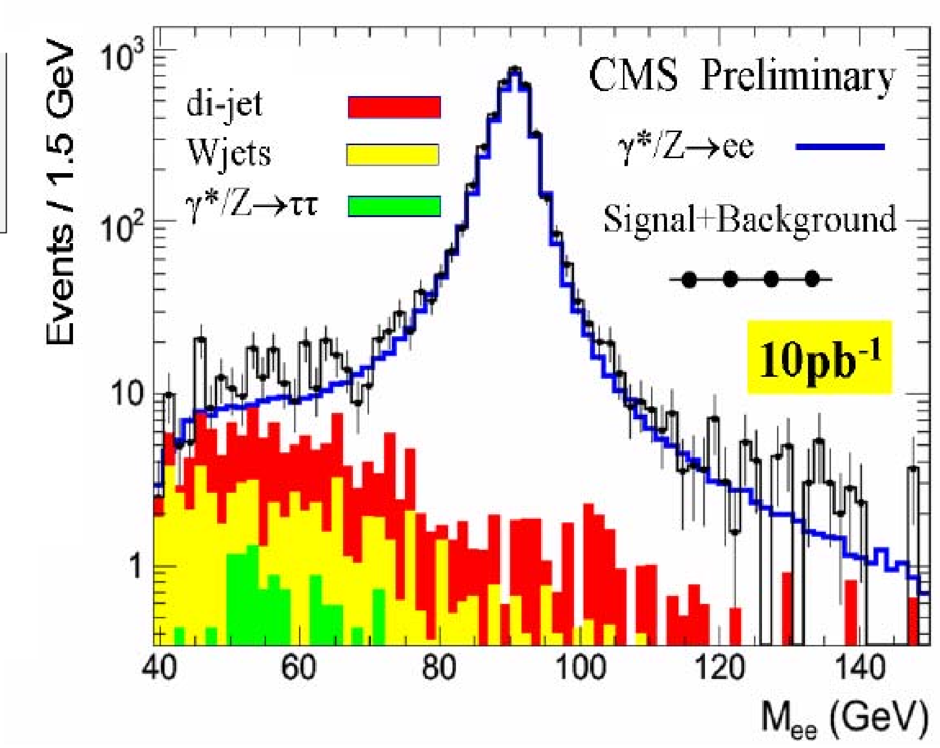


Efficiencies from the Z: T&P

muons



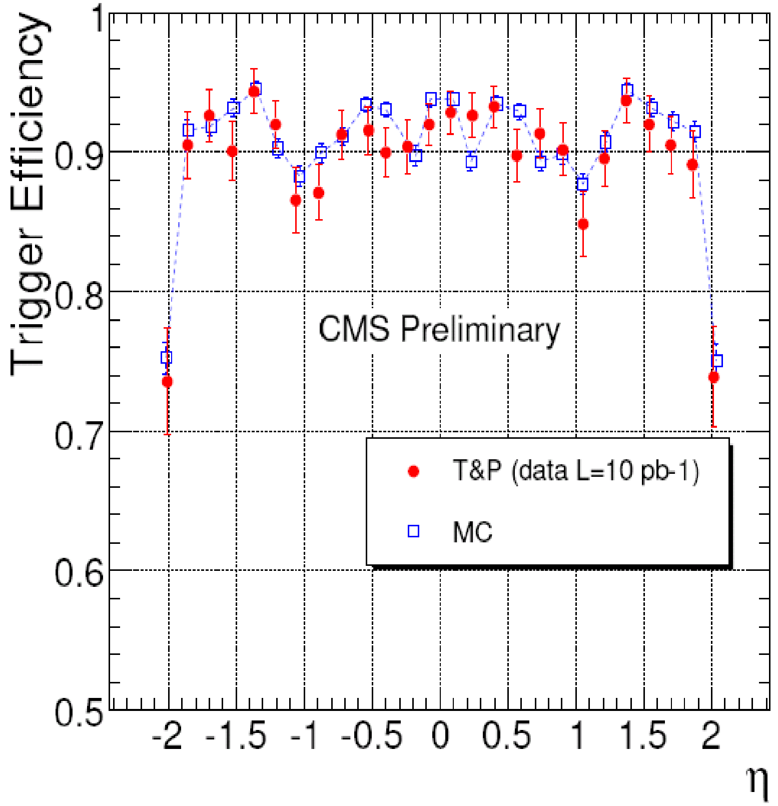
electrons



Can get easily pure samples at the Z

Efficiencies from tag&probe at the Z peak

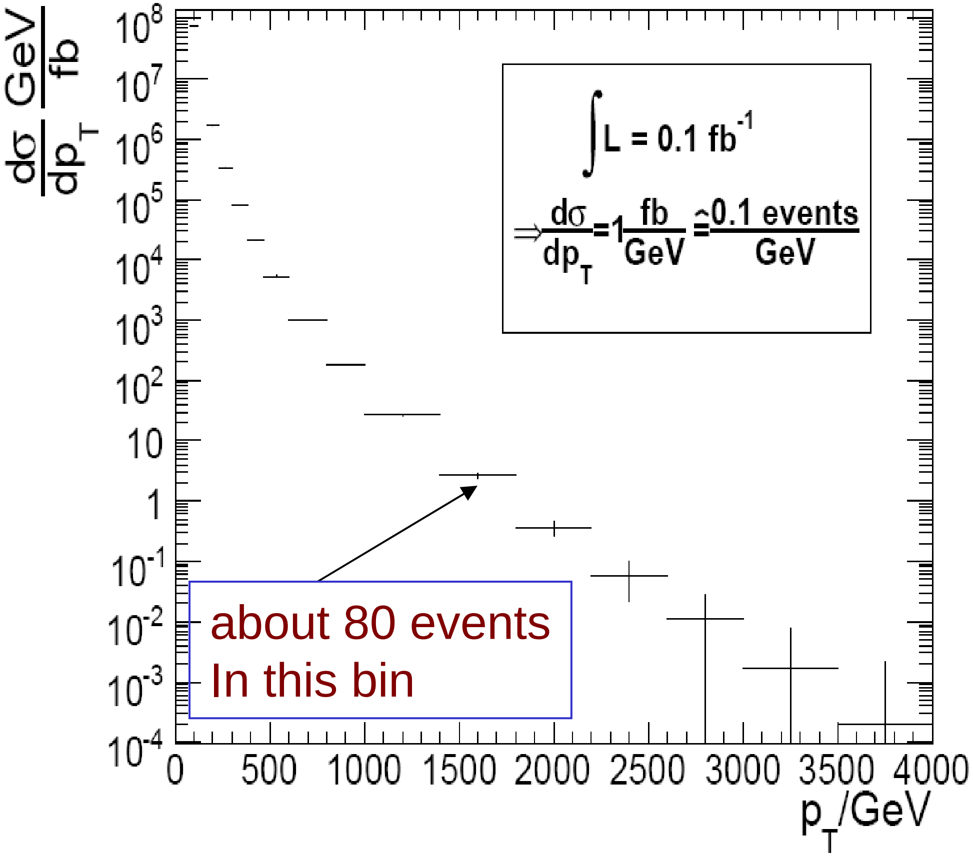
- One object, the tag, has strict criteria imposed on it to identify it.
- The probe is another object with looser criteria to meet.
- The Z resonance links tag-and-probe, ensuring a pure sample.



Inclusive Jet cross-section (CMS)

•We will have quickly a measurement of the Jet cross section with good statistical precision…

•… however, we expect 10% error on the Jet Energy Scale instead of ~3%



Other channels

- Started work on Z+jet, potentially very clean channel for gluon PDFs
- Preliminary work on strange-quark PDF done for the LHC workshop of 2000
- (s g $\rightarrow$ W c channel; charm tagging from semileptonic decay to muon) plan to restart it

Conclusions

- CMS will use mutiple relative luminosity monitors
- The Calibration procedure is well planed
- Several studies on data driven methods to make robust assessment of W,Z observables.
- Studies on specific W,Z observables (W charge asym, Z rapidity) recently started.
- Studies on other channels (using jets, gammas, etc.) ongoing
- CMS very interested in devising a common LHC strategy to constraint the PDFs from observables measured at 14 TeV

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