Luminosity Measurement at Colliders

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Particle physics and the Swiss National Bank

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General

The luminosity $\mathcal{L}$ is a key quantity of each collider

For a process with a cross section σ holds:

$\dot{N}$ = σ x $\mathcal{L}$

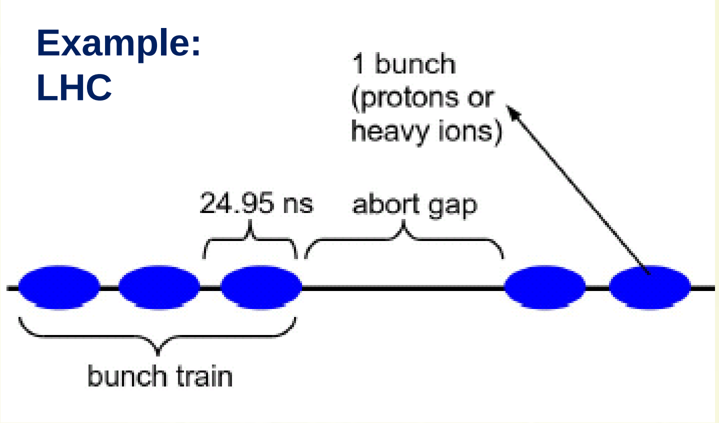
$\dot{N}$: Number of events of the process recorded per unit time

As larger the luminosity as more events of a given process you may collect in a certain time!

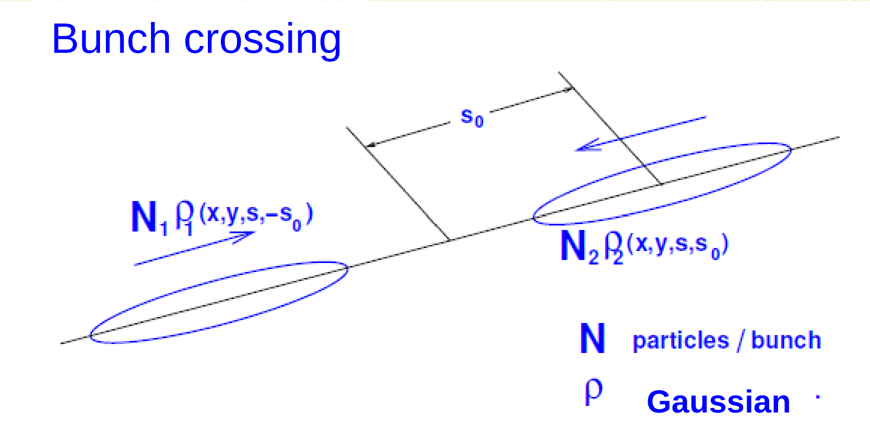
However, to measure cross sections precisely, also a precise measurement of the luminosity $\mathcal{L}$ is necessary.

General

In a Collider particles are accelerated in bunches, with N_b particles



$$\mathcal{L} = \frac{f_{rev} N_1 N_2 n_b}{4\pi\sigma_x\sigma_y} F$$

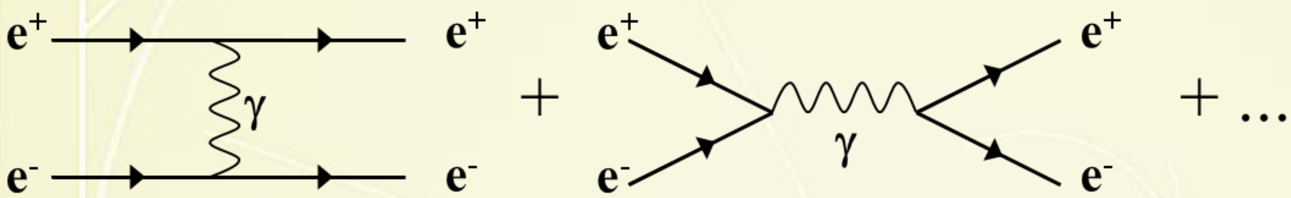


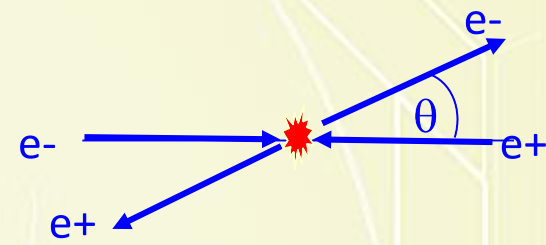
f_{rev} : revolution frequecy
n_b : number of bunches
σ_x, σ_y: Gaussian widths
F : impact of a crossing angle, at e^+e^- linear collider also a luminosity enhancement factor.

e^+e^- collider

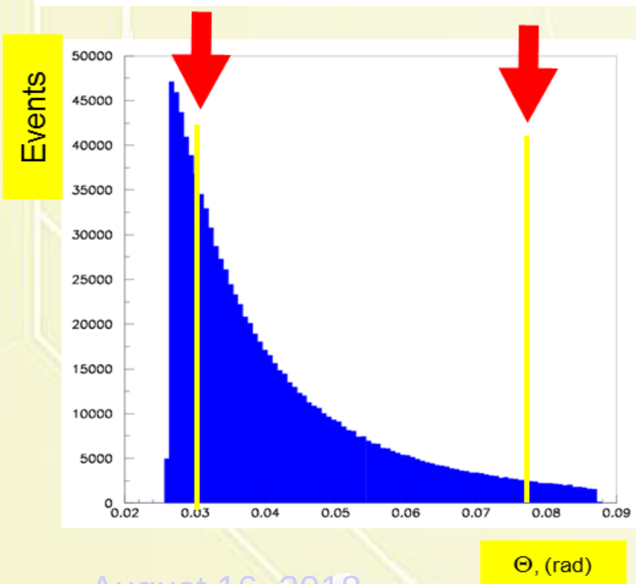
Bhabha scattering at low polar angles is used as a gauge process

$$e^+e^- \longrightarrow e^+e^- (\gamma)$$





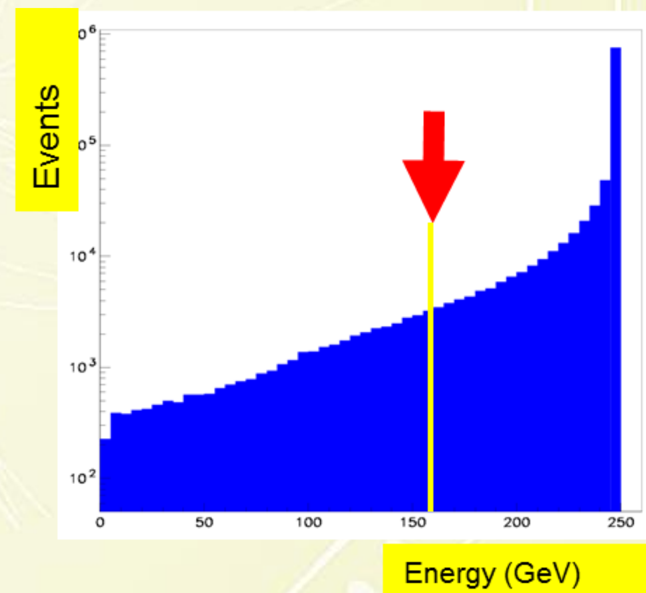
$$\frac{d\sigma_B}{d\theta} = \frac{2\pi\alpha_{em}^2}{s}\frac{\sin\theta}{\sin^4(\theta/2)} \approx \frac{32\pi\alpha_{em}^2}{s}\frac{1}{\theta^3}$$



$\mathcal{L} = N / \sigma$

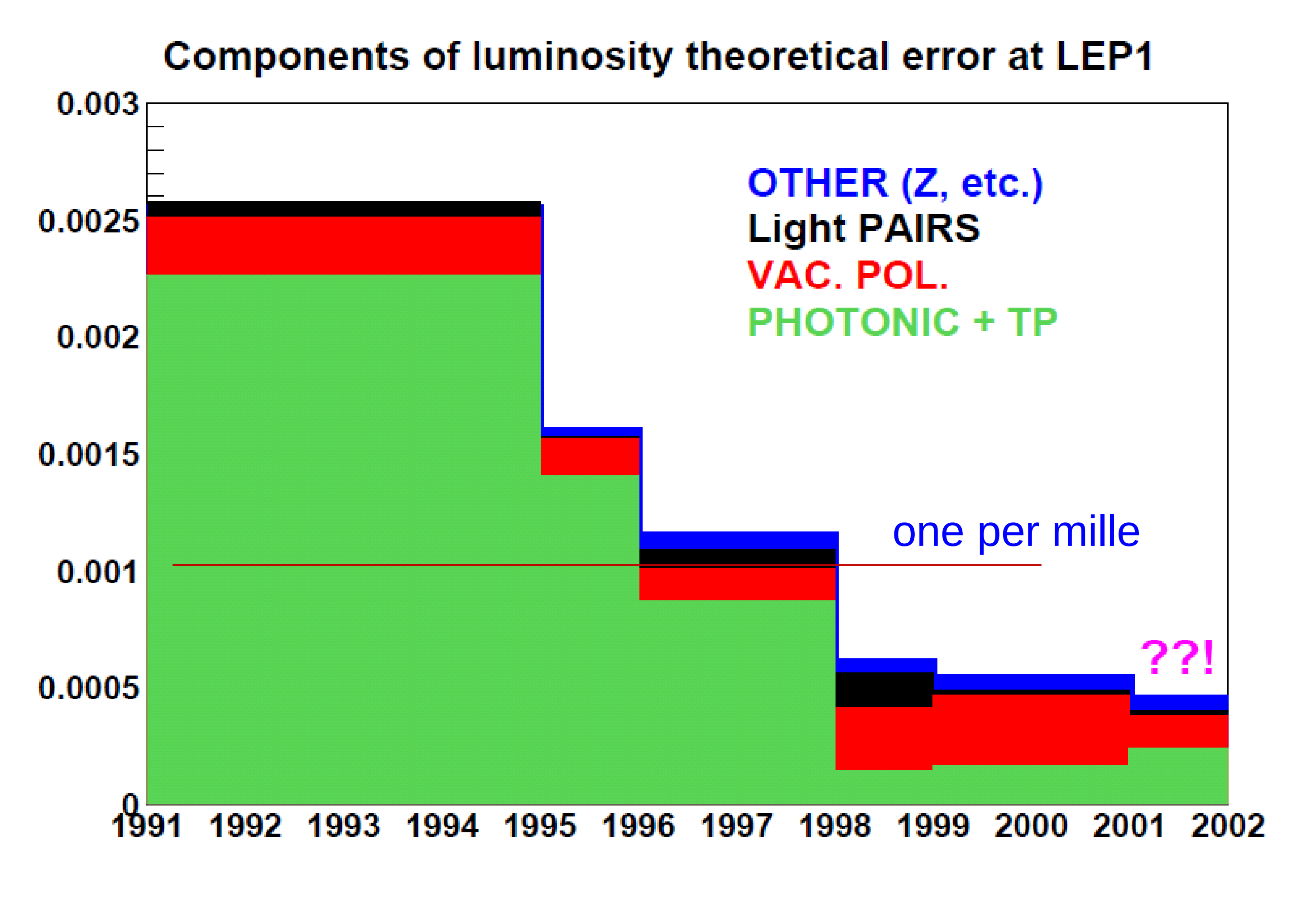
Count Bhabha events

From theory



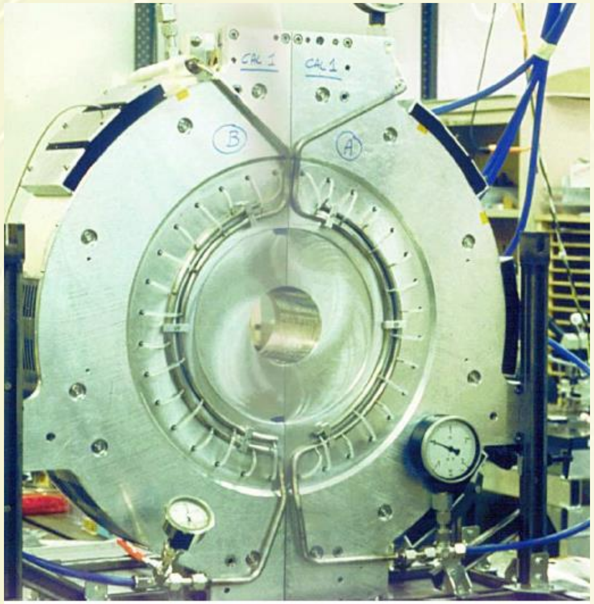
e^+e^- collider

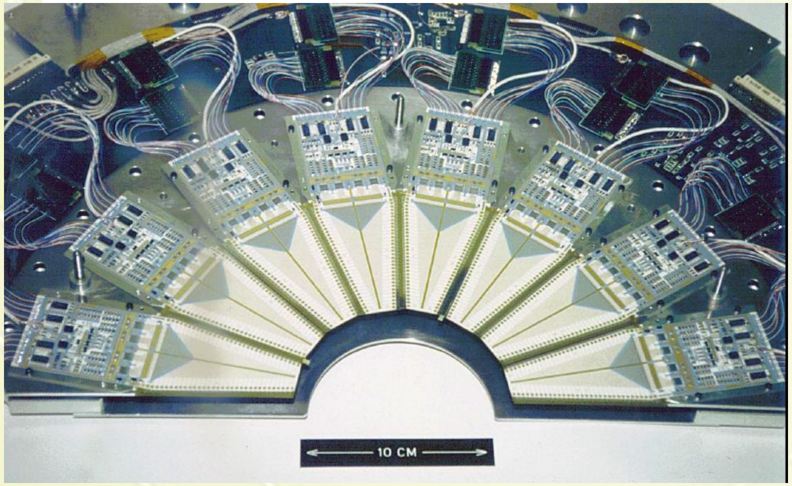
Theory uncertainties in the Bhabha cross section at LEP1 $\sqrt{s} \approx 91$ GeV (S. JADACH, FCAL workshop Cracow 2006):

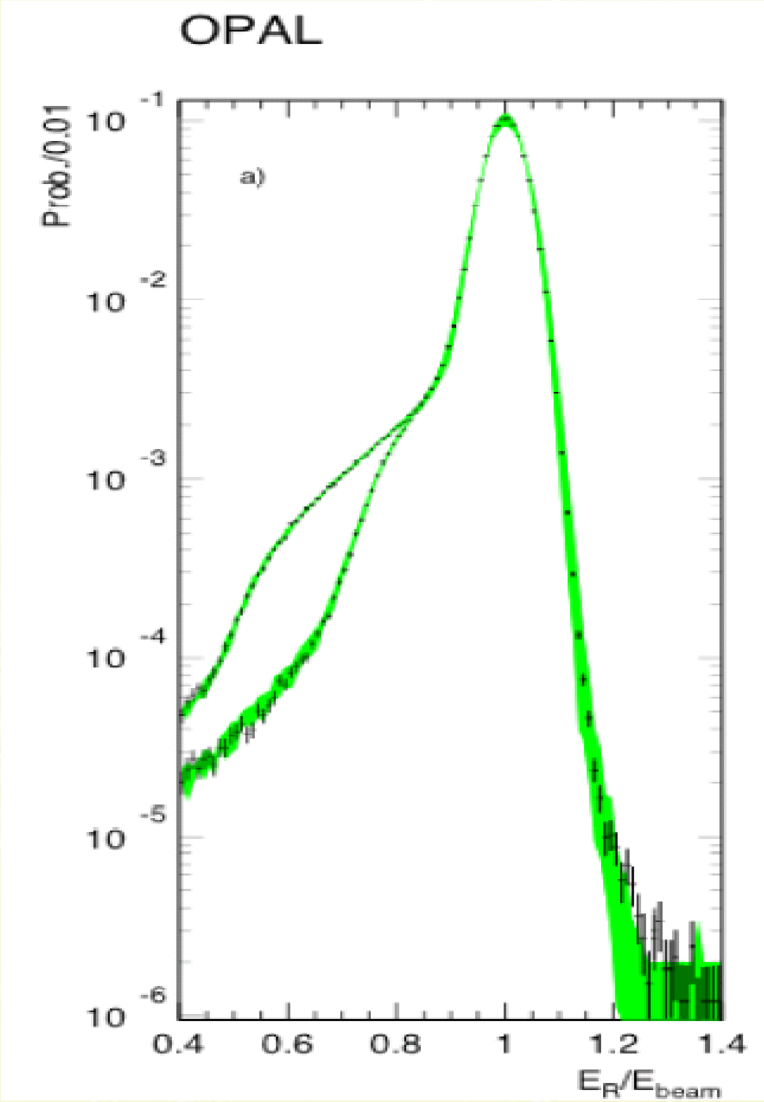


e^+e^- collider

Example of a measurement at LEP (OPAL):

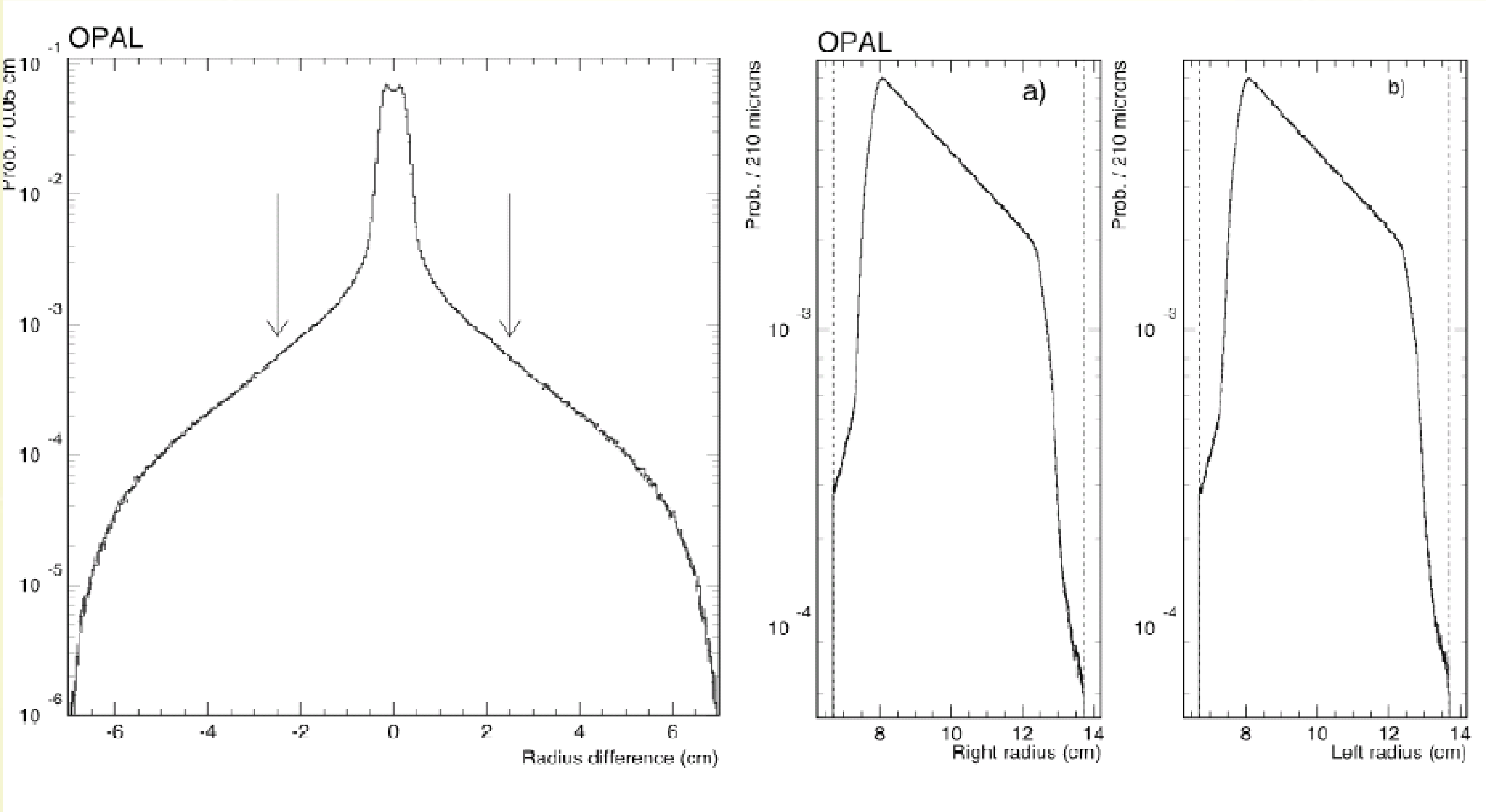






Excellent agreement between experiment and BHLUMI MC

e^+e^- collider



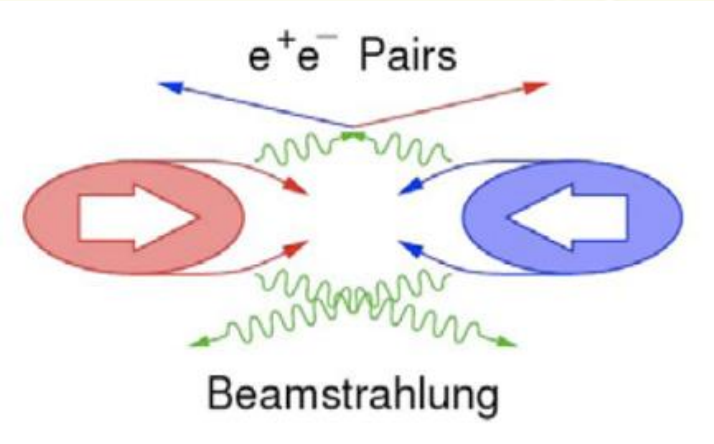
Experimental precision (OPAL): $\Delta\mathcal{L}/\mathcal{L} = 3.4 \times 10^{-4}$
Theory precision : $\Delta\mathcal{L}/\mathcal{L} = 5.4 \times 10^{-4}$

e^+e^- collider

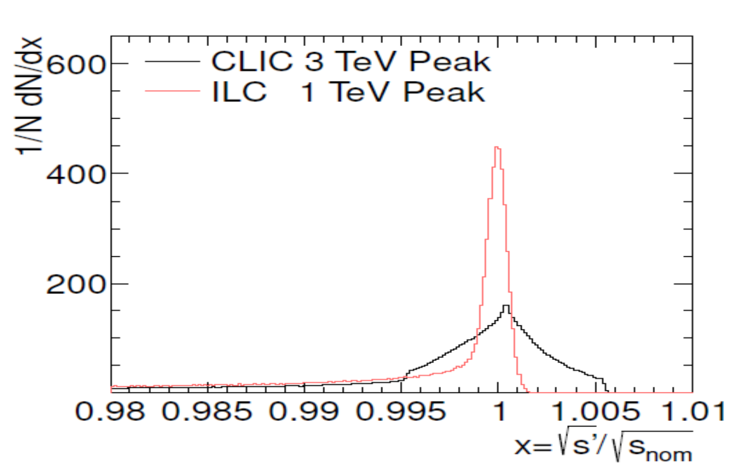
Theory uncertainties at higher energies at ILC/CLIC (S. JADACH, FCAL workshop Cracow 2006):

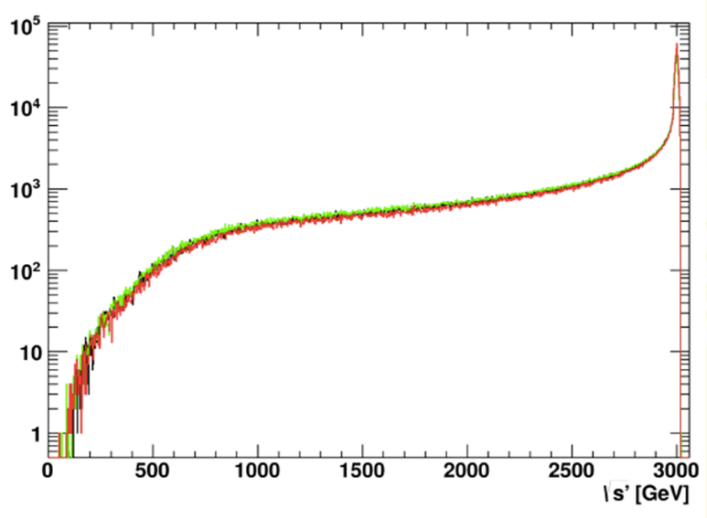
in the range of polar angles 25 – 100 mrad:

- Hadronic vacuum polarisation
- QED photonic corrections
- EW corrections to Z (t-channel)
- Light fermion pairs



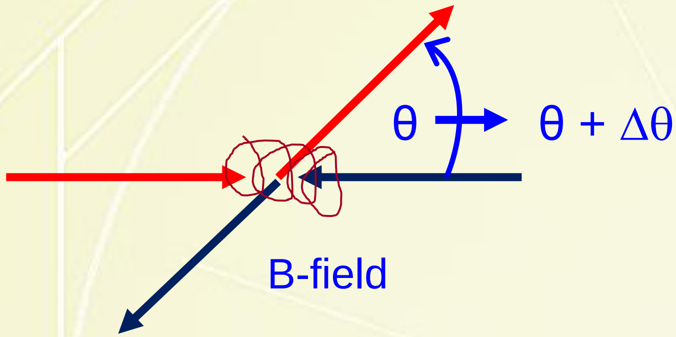
Other challenges: Beamstrahlung – luminosity spectrum

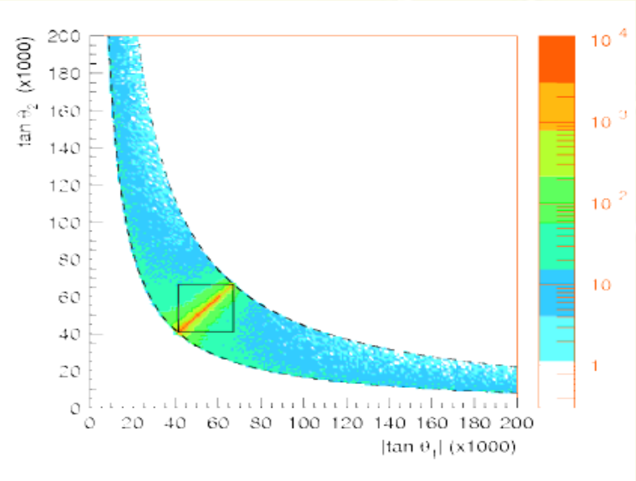




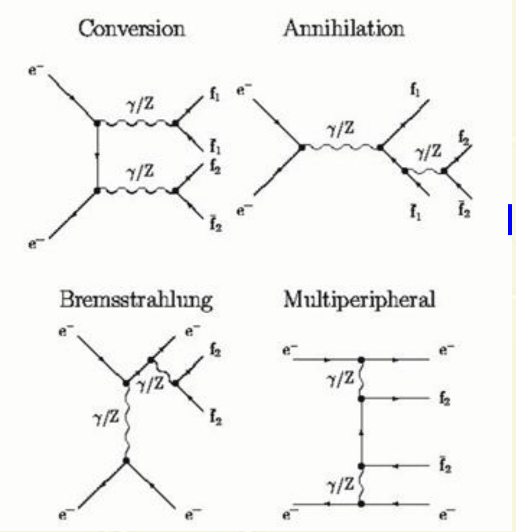
e^+e^- collider

Deflection of the scattered electron/positron in the bunch magnetic field

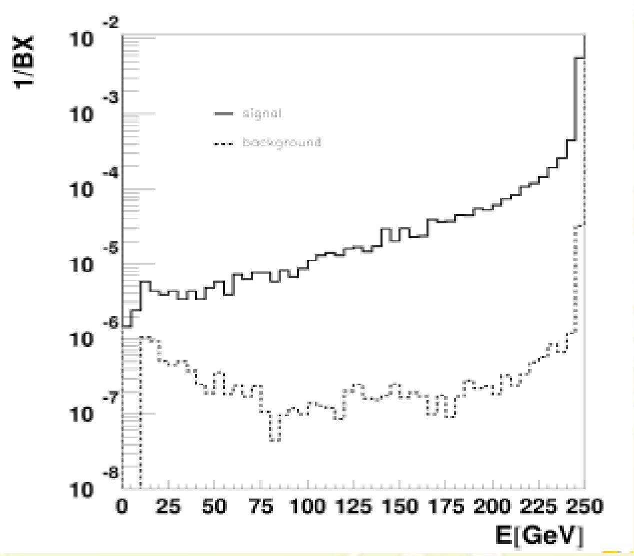




Physics background: four-fermion processes



not easy to calculate-
likely need to be measured



e^+e^- collider

Precision needed at ILC ($\sqrt{s}$ = 500 GeV) $\Delta\mathcal{L}/\mathcal{L} = 10^{-3}$

No problem with statistical precision
Systematics:

Table 2: Systematic uncertainties in the ILC luminosity measurement.

Source of uncertainty	$\Delta L/L$ (10^{-3}) 500 GeV	1 TeV
Bhabha cross section [63]	0.54	0.54
Polar-angle resolution [5]	0.16	0.16
Polar-angle bias [5]	0.16	0.16
Energy resolution [5]	0.1	0.1
Energy scale [5]	1	1
Beam polarization [5]	0.19	0.19
Physics background [62]	2.2	0.8
Beam-beam effects [59]	0.9	1.5
Total	2.6	2.1

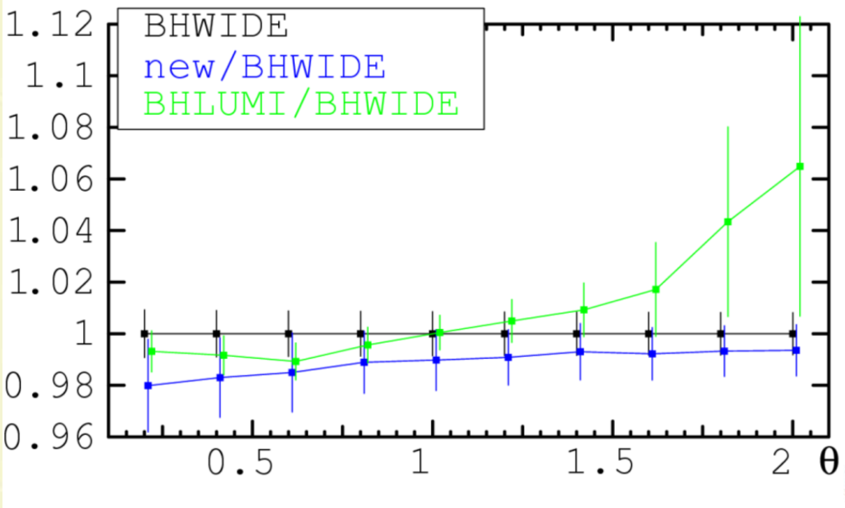
Likely underestimated

Precision needed at CLIC ($\sqrt{s}$ = 3 TeV) $\Delta\mathcal{L}/\mathcal{L} = 10^{-2}$

More detailed studies needed

e^+e^- collider

V. Makarenko made comparison of different codes (JINR 2016):



- BHWIDE for wide angle scattering
  S. Jadach, W. Placzek, Z. Was et al., *Comp.Phys.Comm. 102 (1997) 229-251*
  Precision: 0.1 – 0.5% (depending on c.m.s. energy);
- BHLUMI for forward region (~ 20*mrad*)
  S. Jadach, W. Placzek et al., *Phys.Lett. B390 (1997) 298-308*
  Precision: up to 0.06% (at LEP1 energy).

- The NLO generator allows to achieve only about 1% precision.
  - The error imposed by using of BHWIDE is of the same size.

Summary given by A. Arbusov (FCAL workshop JINR 2016)

SECOND ORDER CORRECTIONS

The complete $\mathcal{O}(\alpha^2 L)$ analytic result was first received in A.A., V. Fadin, E. Kuraev, L. Lipatov, N. Merenkov, L. Trentadue [Nucl.Phys.B '1997]

Two-loop virtual pure QED RC were computed by A. Penin [PRL'2005, NPB'2006]

Emission of one or two real photons was also added, see e.g. C. Carloni Calame, H. Czyz, J. Gluza, M. Gunia, G. Montagna, O. Nicrosini, F. Piccinini, T. Riemann, M. Worek *NNLO leptonic and hadronic corrections to Bhabha scattering and luminosity monitoring at meson factories* JHEP 1107 (2011) 126

A. A. Penin and G. Ryan, *Two-loop electroweak corrections to high energy large-angle Bhabha scattering*, JHEP'2011

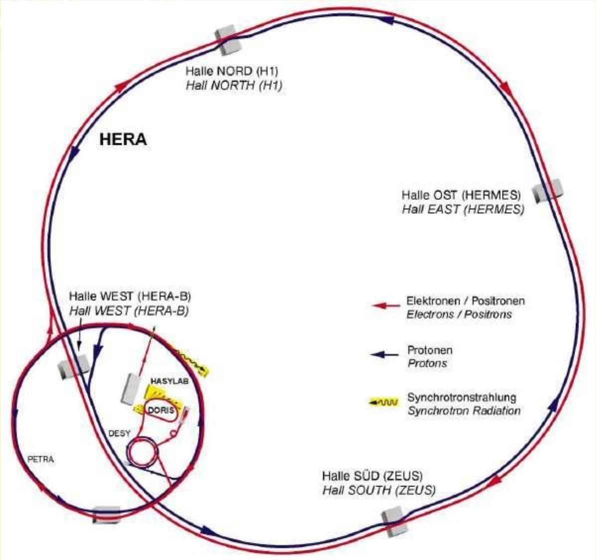
e^+e^- collider

further statements by A. Arbusov

- Precision theoretical description of small-angle Bhabha scattering is of ultimate importance for e^+e^- colliders
- Several effects of different nature should be taken into account
- Matching of those effects should be organized
- Common efforts of different group can give us reliable theoretical predictions
- Tuned comparisons should be performed
- Features of theoretical codes should meet experimental requirements
- The SANC team plans to contribute . . .

$e^{\pm}$ p collider

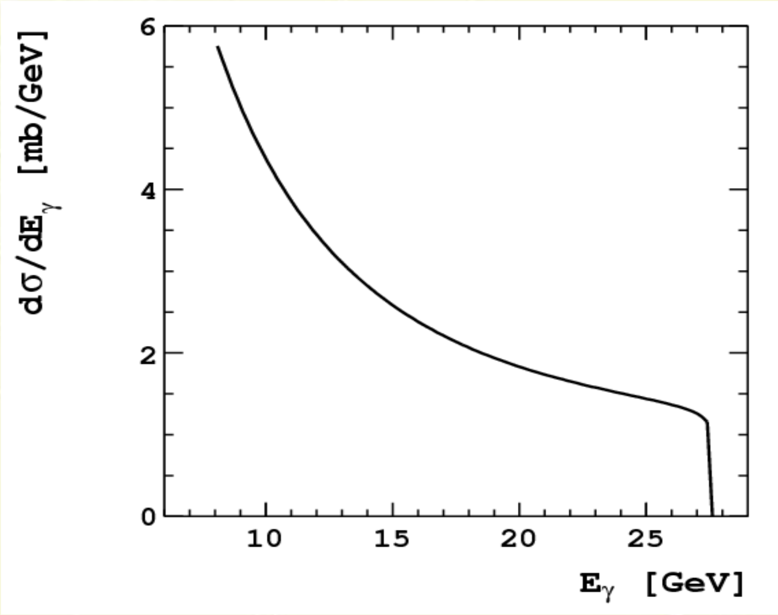
Unique example: HERA



Gauge process: electron Bremsstrahlung

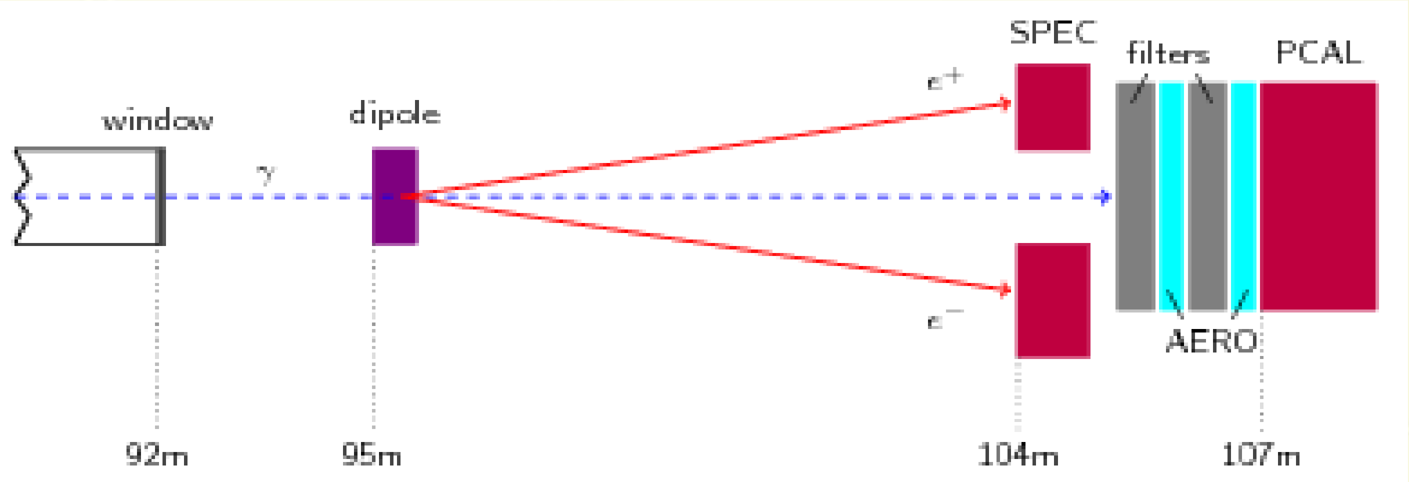
$e^{\pm}$ p ⟶ $e^{\pm}$ p γ

$$\frac{d\sigma}{dE_\gamma} = 4\alpha r_e^2 \frac{E'_e}{E_\gamma E_e}\left(\frac{E_e}{E'_e}+\frac{E'_e}{E_e}-\frac{2}{3}\right)\left(\ln\frac{4E_pE_eE'_e}{m_pm_eE_\gamma}-\frac{1}{2}\right)$$



$e^{\pm}$ p collider

ZEUS luminometers

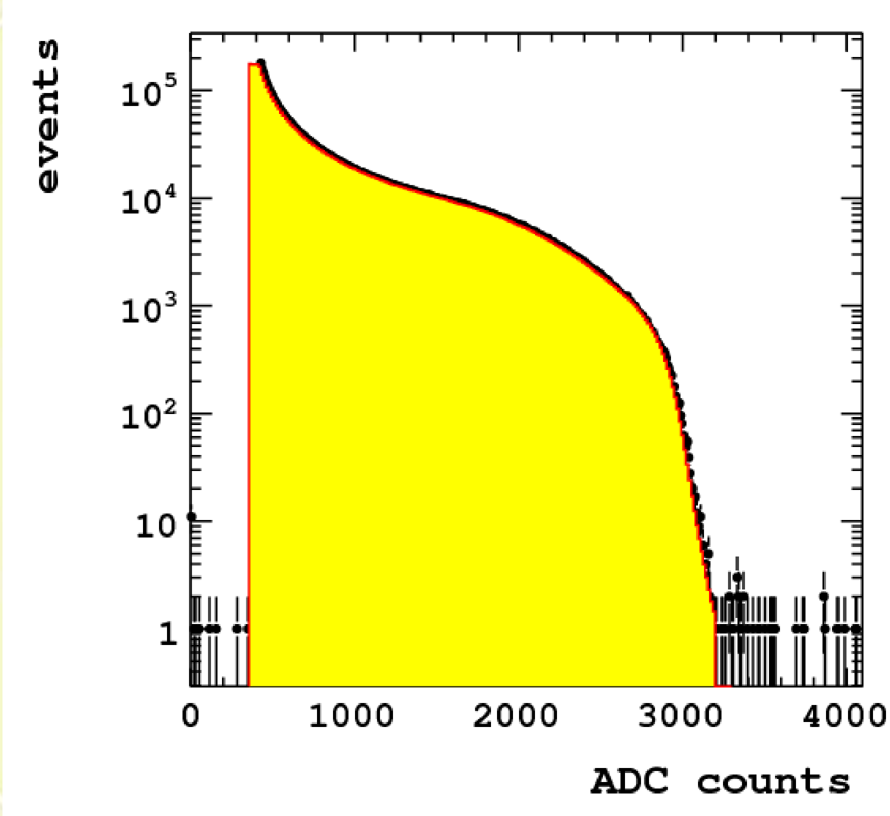


- PCAL is an electromagnetic sampling calorimeter – photon energy
- SPEC measures $e^{\pm}$ from conversions in the window of the vacuum chamber using two sampling calorimeters

$e^{\pm}$ p collider

PCAL

Photon spectrum of $e^{\pm}$ Bremsstrahlung on residual gas atoms



Used for calibration

Problem: high photon rate - pile-up

n_γ – number of photons per BX

$$n_\gamma = \frac{R_\gamma \cdot \sigma_b}{\sigma(E_\gamma > E_{thr}) \cdot f_r \cdot N_{cb}},$$

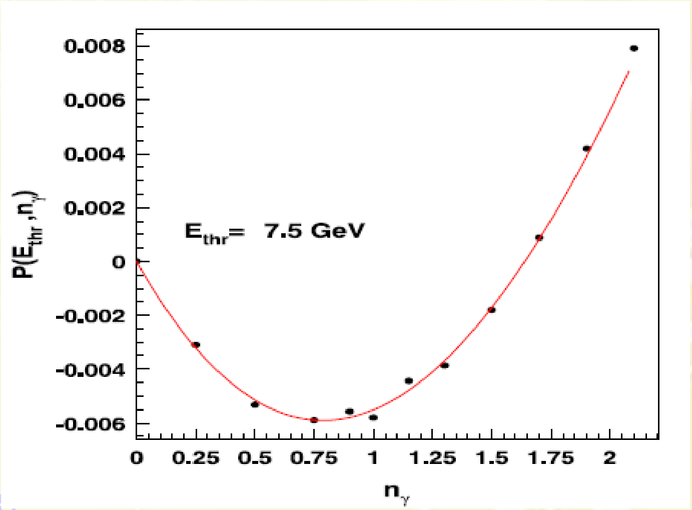
R_γ – total photon rate

f_r – beam revolution frequency

N_{cb} – number of bunches

$$R'_\gamma = R_\gamma \cdot (1 + P(E_{thr}, n_\gamma))$$

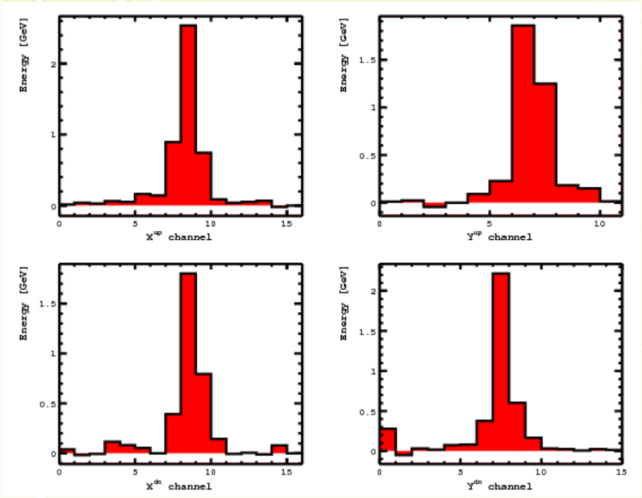
Used for luminosity calculation



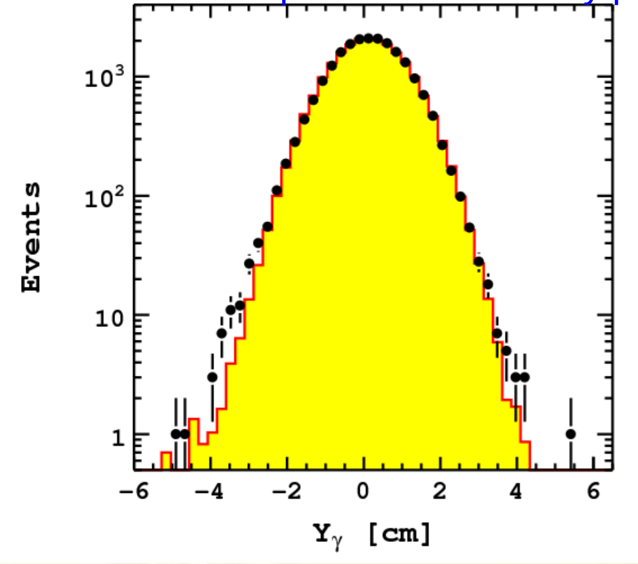
$e^{\pm}$ p collider

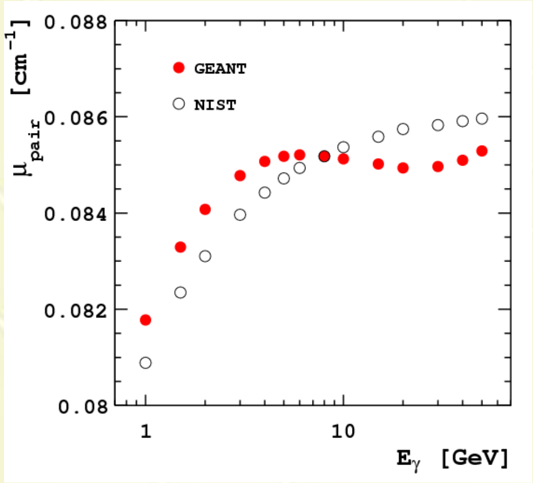
SPEC

Showers from the $e^+ e^-$ in the sampling calorimeter



Data/MC comparison of shower y position



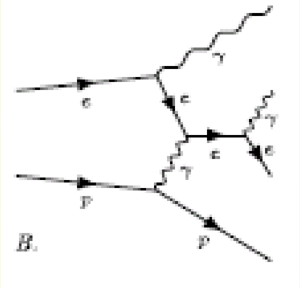


Critical issue: photon conversion probability in the exit window

Done by Vladimir Drugakov, published in NIM

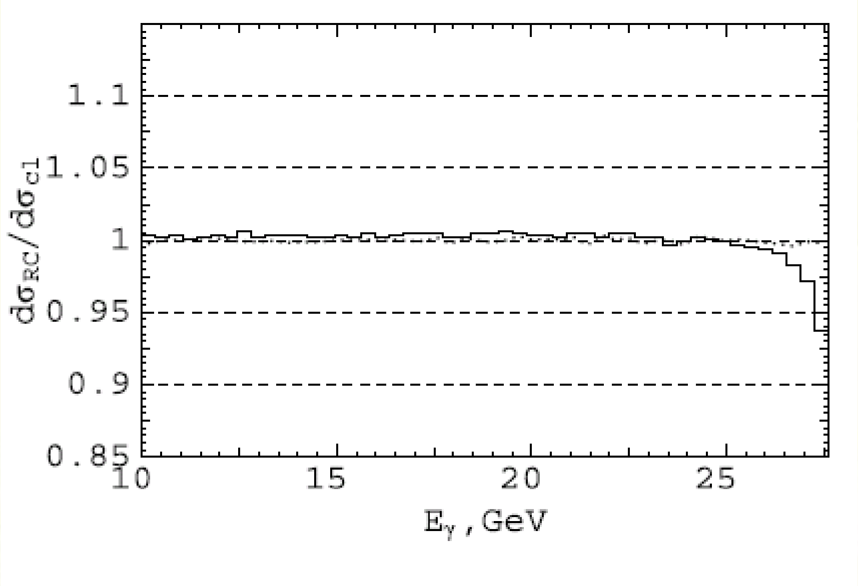
$e^{\pm}$ p collider

Impact of radiative corrections (α^4):



+ more α^4 and loop diagrams

(Makarenko&Marfin)



Uncertainty due to radiative corrections

Impact of the proton form factor: negligible

Precision reached again limited by the systematics

Source of systematics	2005/2006 e^-p	2006/2007 e^+p
Aperture and detector alignment	1.0	1.0
x-position of the photon beam	1.2	1.1
Sum	1.6	1.5

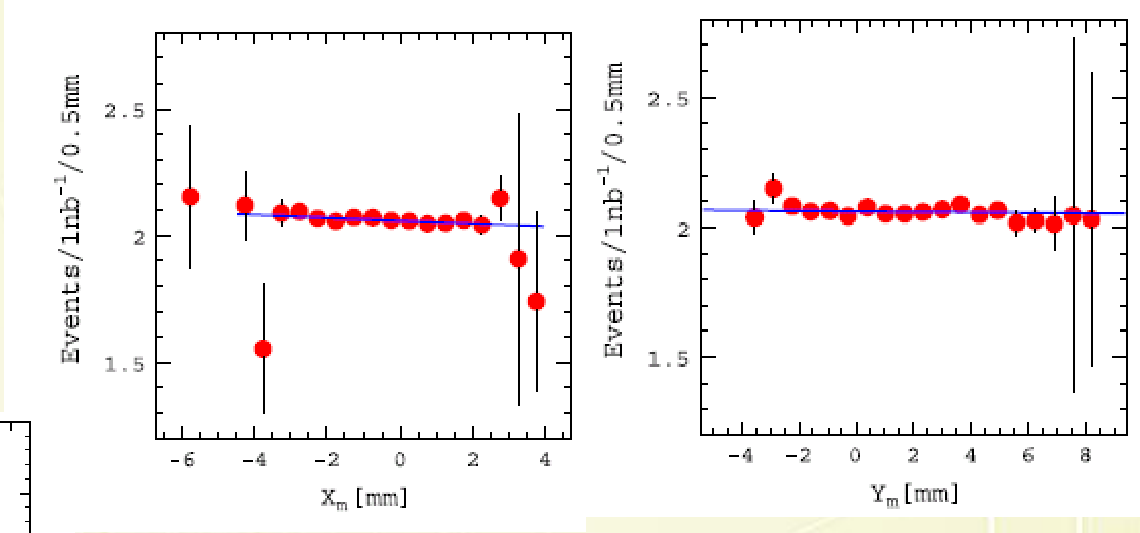
Source of systematics	Photon calorimeter	Spectrometer	
		2005/2006 e^-p	2006/2007 e^+p
Common systematics	1.6	1.6	1.5
Photon conversion In the beam exit window		0.7	0.7
Rms-cut correction		0.5	
Pedestal shifts	1.5		
Photon rate			0.6
Pile-up	0.5		
Sum	2.2	1.8	1.8

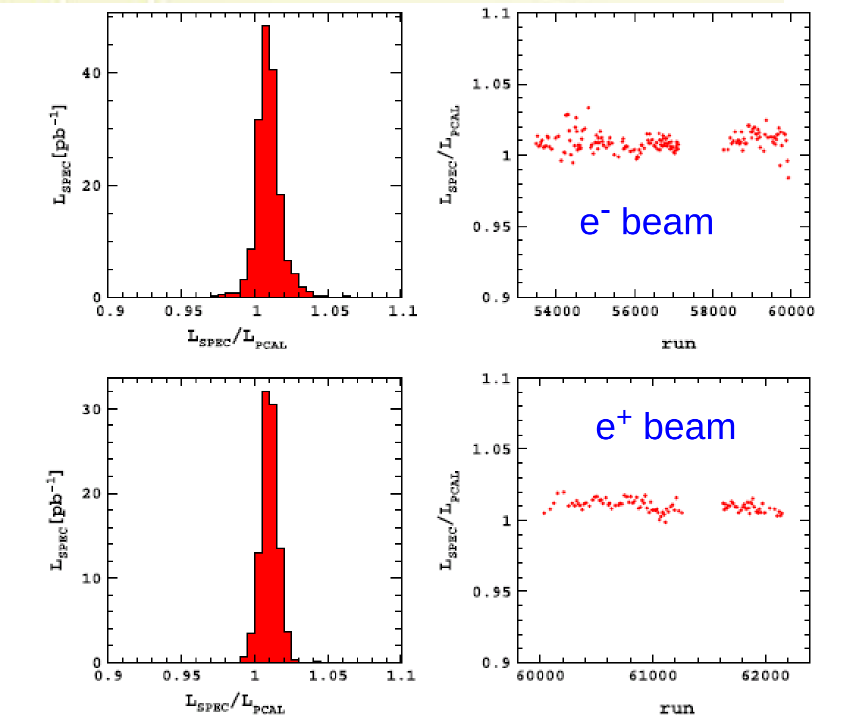
Final uncertainty $\Delta\mathcal{L}/\mathcal{L}$ = 1.7 %
Valid for all structure function measurements at HERA !

e± p collider

Control data and comparison PCAL - SPEC

Ratio between NC event rate and luminosity as function of the x- and y- position of the photon beam





Ratio of the luminosities measured with PCAL and SPEC

(Done by Vladimir Drugakov, published in NIM)

It was a good idea to have two luminometers at ZEUS !

pp collider

Van der Meer scan

Coming back to the original definition:

$$\mathcal{L} = \frac{f_{rev} N_1 N_2 n_b}{4\pi\sigma_x\sigma_y} F,$$

f_{rev} : revolution frequency
n_b : number of bunches
σ_x, σ_y: Gaussian widths
F : impact of a crossing angle

f_{rev} and n_b are known numbers

σ_x, σ_y: Gaussian widths to be determined using van der Meer scans moving beam with respect to each other in *x* and *y*

N_1, N_2: to be obtained from other (machine) mesurements

F : applied as a correction

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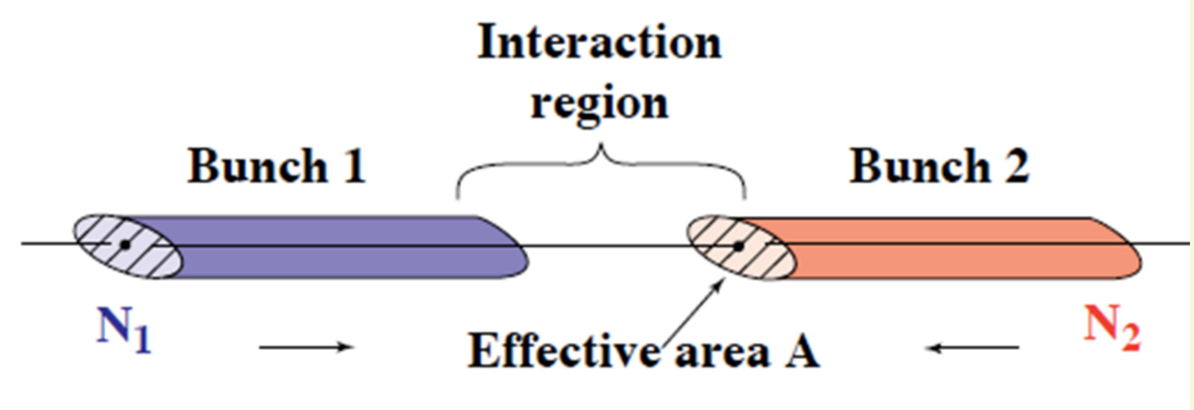

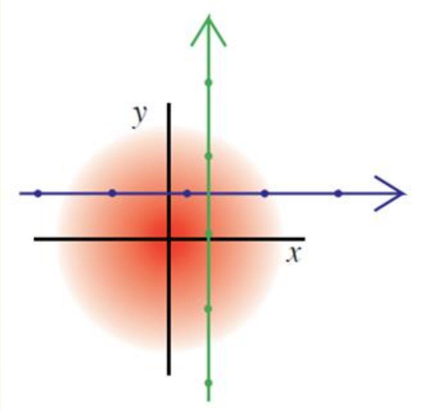

Assuming Gaussian particle densities in the bunches:

$$\rho_{iz}(z) = \frac{1}{\sigma_z\sqrt{2\pi}} \exp\left(-\frac{z^2}{2\sigma_z^2}\right) \text{ where } i = 1,2, \quad z = x, y \; ,$$
$$\rho_s(s \pm s_0) = \frac{1}{\sigma_s\sqrt{2\pi}} \exp\left(-\frac{(s \pm s_0)^2}{2\sigma_s^2}\right) \; .$$

And introducing a displacement *d* in *x* between the two beams we obtain:

$$\mathcal{L} = \frac{N_1 N_2 f N_b}{4\pi\sigma_x\sigma_y} \cdot W$$

with $W = e^{-t}$, and $t = d^2/4\sigma_x^2$

From a measurement of $\mathcal{L}(d)/\mathcal{L}(0)$ W, and finally σ_x , is obtained.

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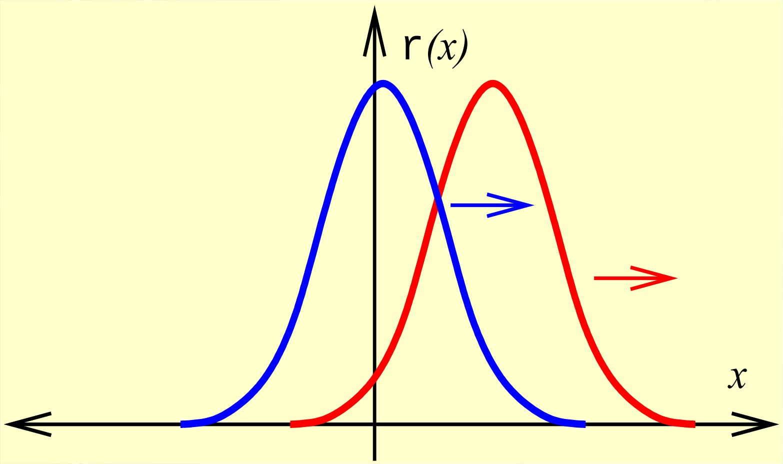
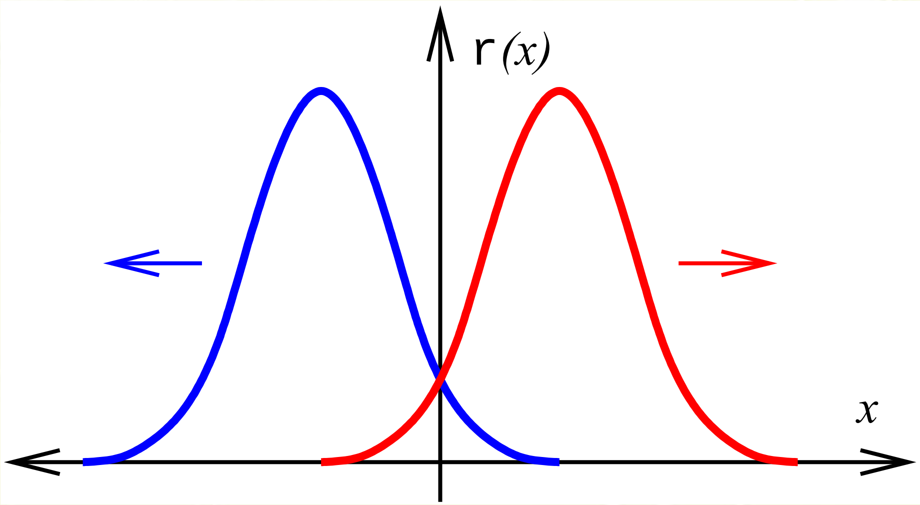
Example CMS

Determination of the lengths scale:



Both beams, separated by about 1 σ, are moved simulataneously in units of sigma The absolute length scale is determined by reconstructing the position of the luminous region using the distribution of the vertices measured by the pixel tracker.

Measurement of $\mathcal{L}(d)/\ \mathcal{L}(0)$ by moving the beams step-by-step in opposite directions to measure σ_x and σ_y



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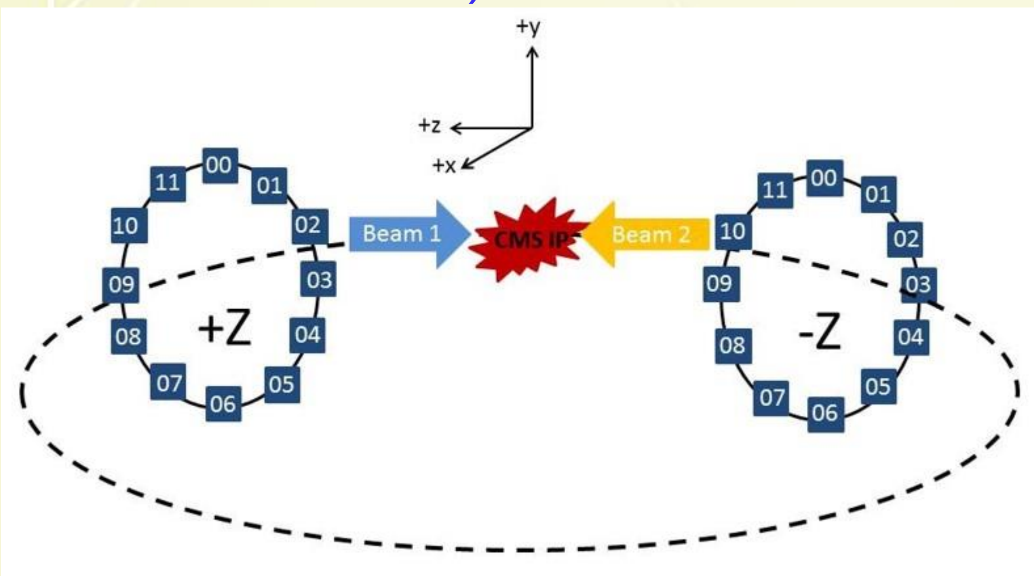
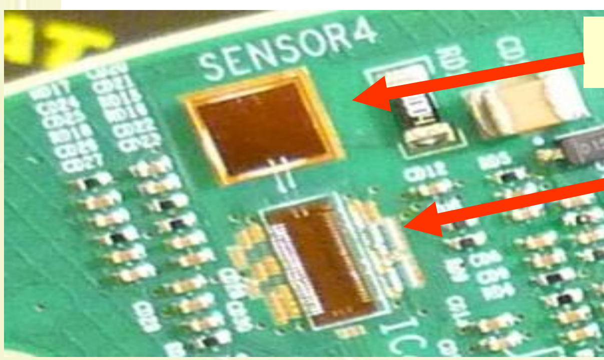
BCM1F

Provides bunch-by-bunch measurement of beam background flux and collision products

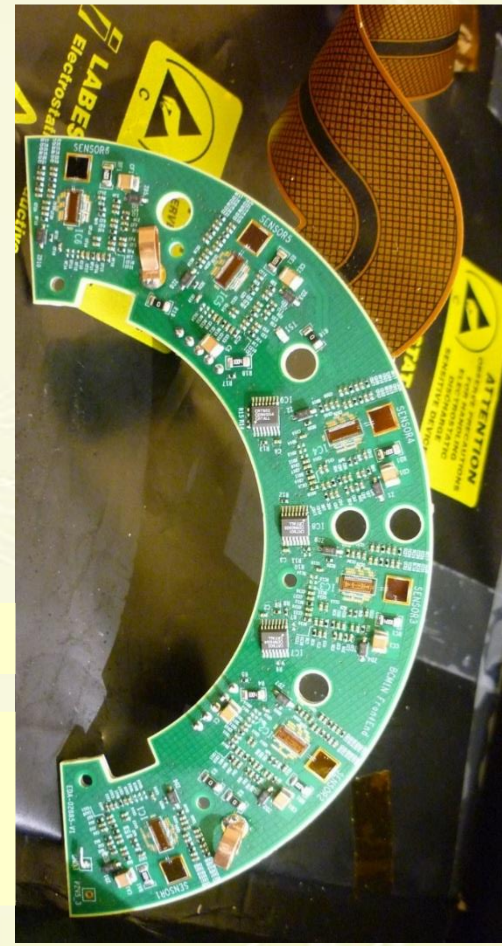
24 5x5mm^2 single-crystal CVD diamond sensors (Run I: 8 sensors)





5x5 mm^2 Diamant-sensor, 2 pads

Front-end ASIC, (sub-nanosecond time resolution, UST Crocow)



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BCM1F assembly and installation

Assembly workshop DESY
autumn 2014

Test and complition at
CERN (December 2014)

Installation inside CMS
Januar 2015

Successful function test
(Februar 2015)

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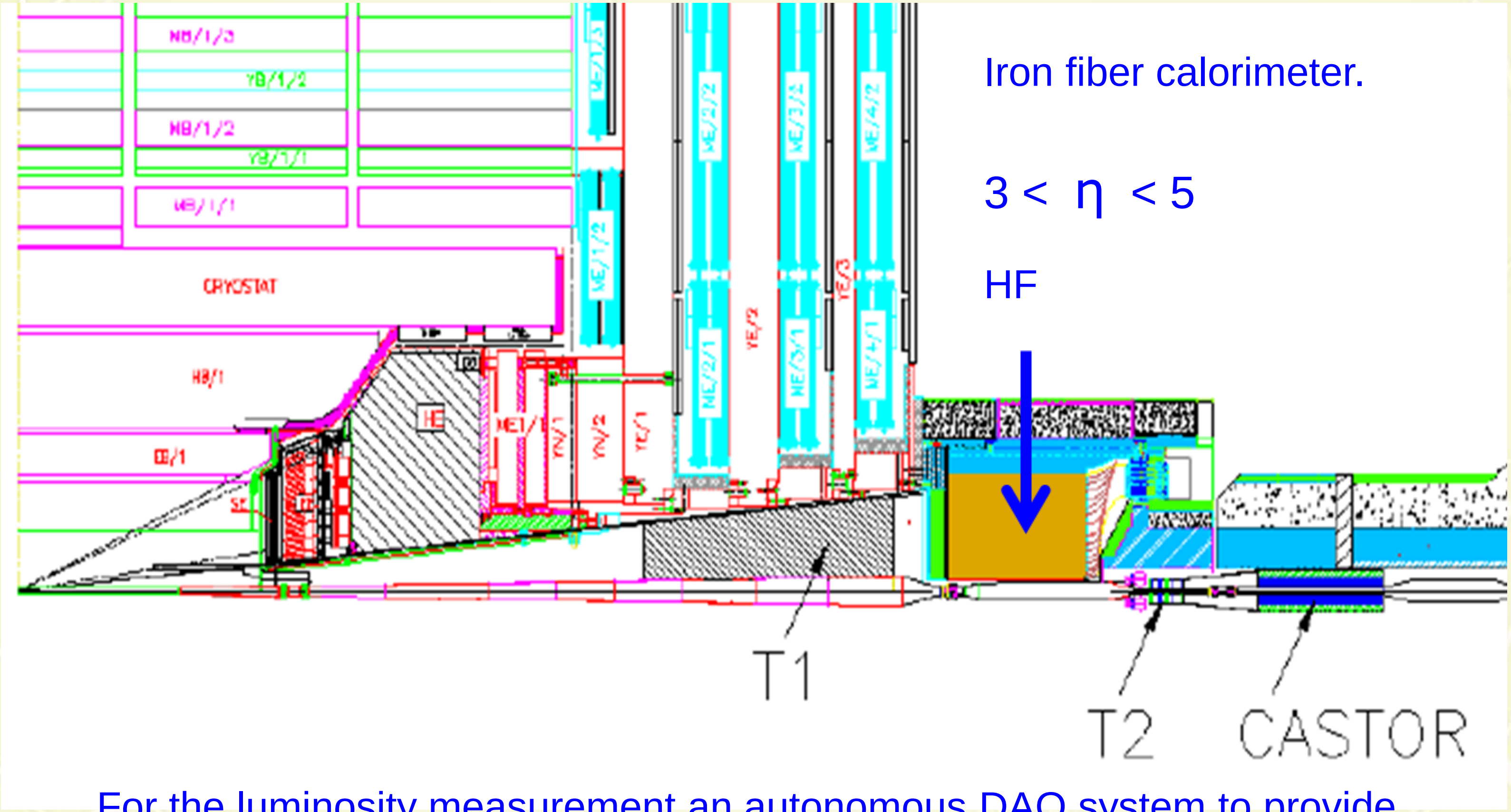
Devices used for the luminosity measurement (CMS)

Hadron Forward calorimeter HF



For the luminosity measurement an autonomous DAQ system to provide "always on" operation was supplemented to the HF readout

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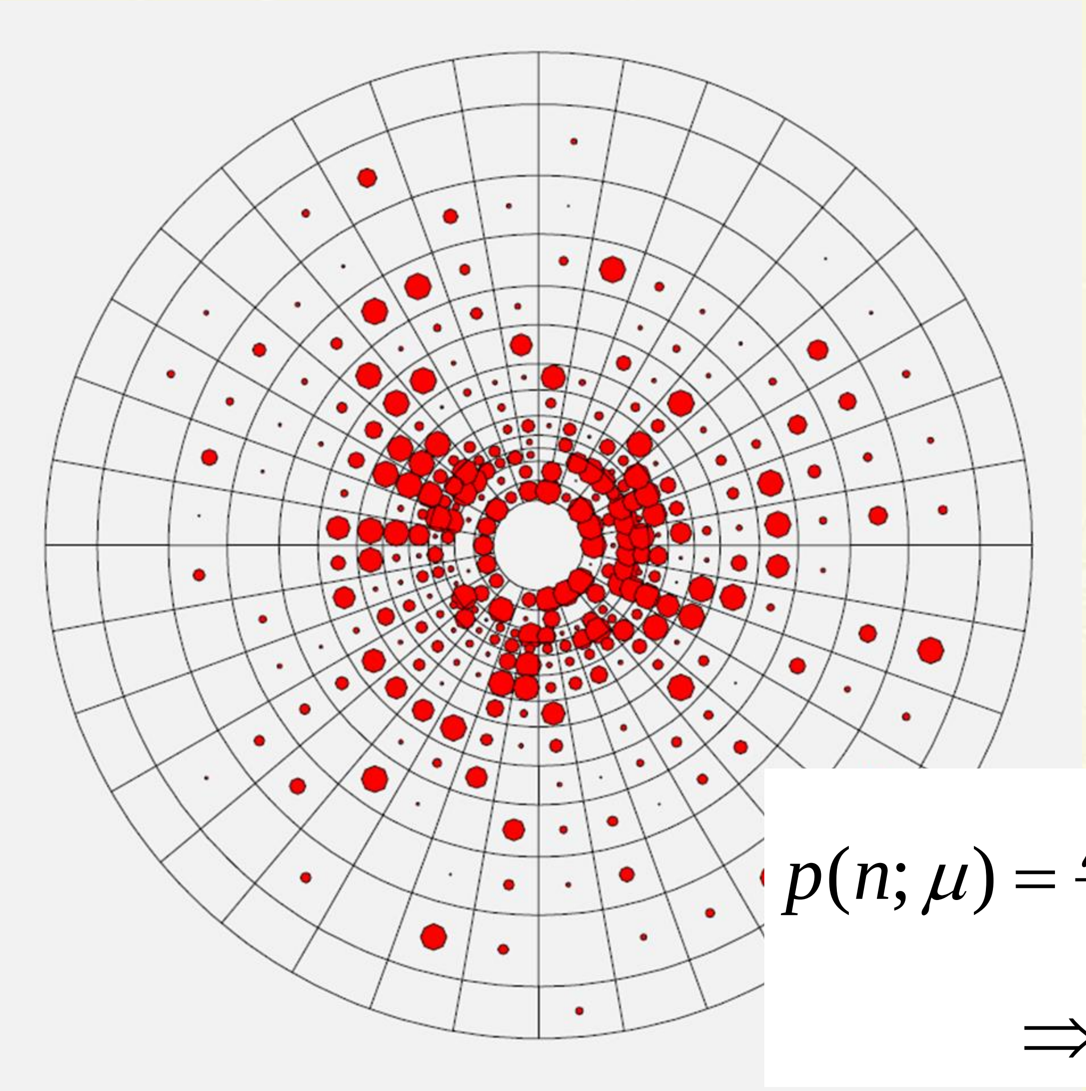
Hadron Forward calorimeter HF



Easy to distinguish between no event or one or more events, but impossible to count the number of events per bunch crossing;
Use ‘zero counting’ method, e.g. in a given ring, inverting the Poisson distribution:

$$p(n;\mu) = \frac{\mu^n e^{-\mu}}{n!} \Rightarrow p(0;\mu) = e^{-\mu}$$

$$\Rightarrow \mu = -\log[p(0)]$$

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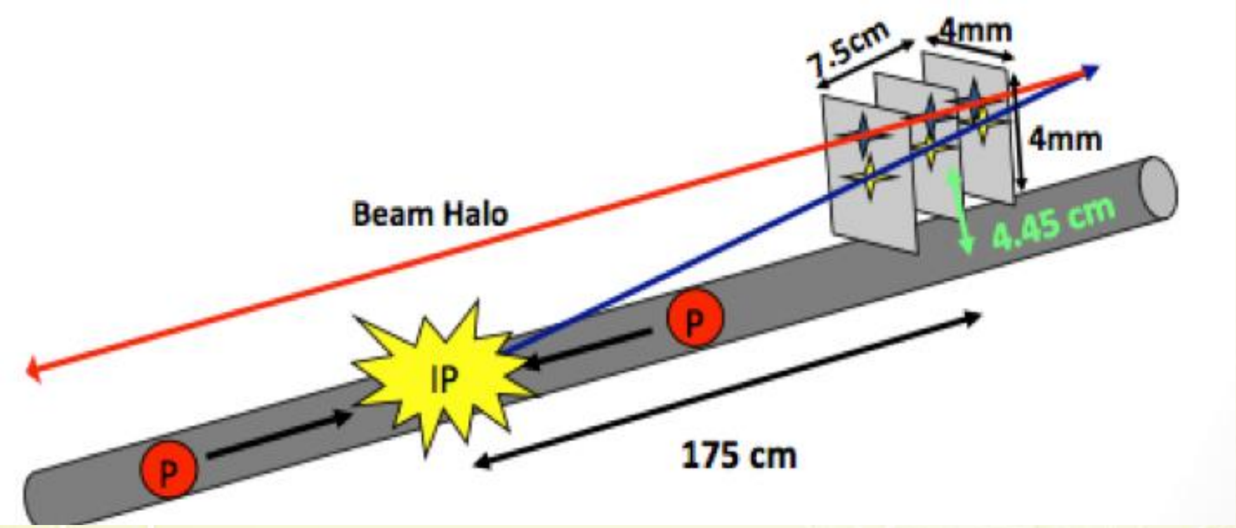
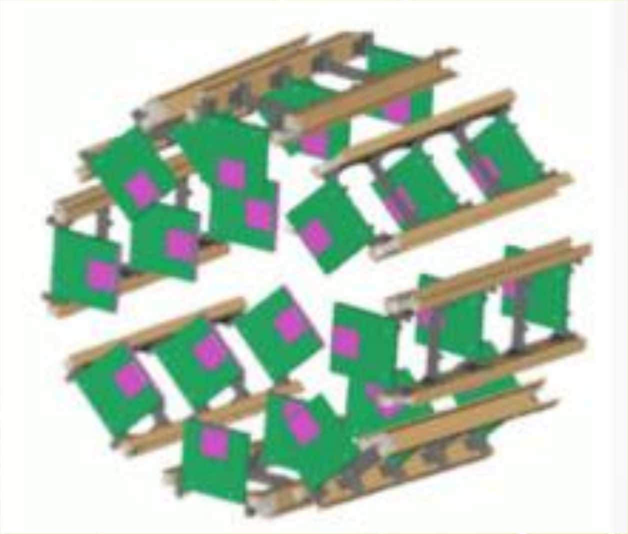
CMS pixel luminosity telescope PLT





- 16 telescopes (8 on either side of CMS), each containing 3 pixel sensors
- Mounted outside of pixel endcap (|η|~ 4.2)
- Uses same sensors and readout chips (PSI46v2) as in CMS pixel detector
- Total area of 8mm x 8mm
  - 80 rows of pitch 100 μm
  - 52 columns of pitch 150 μm

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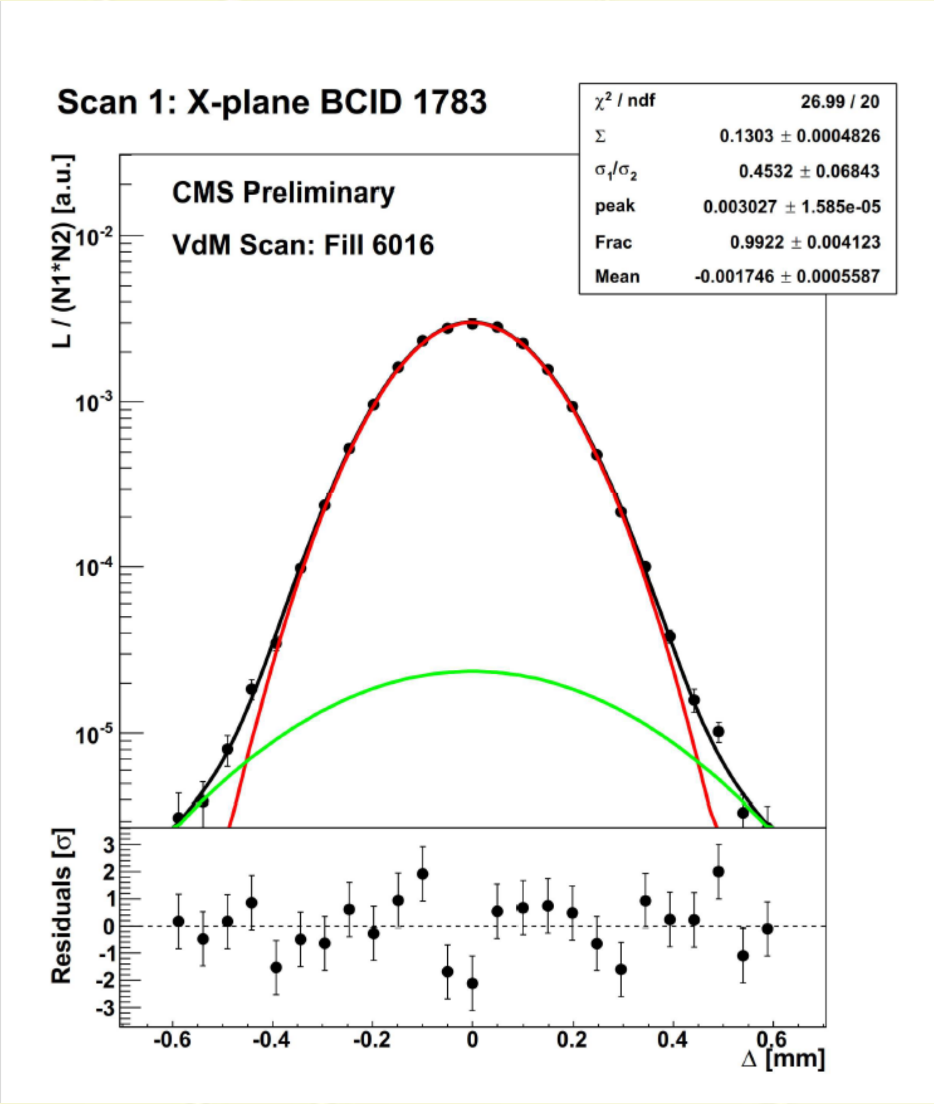
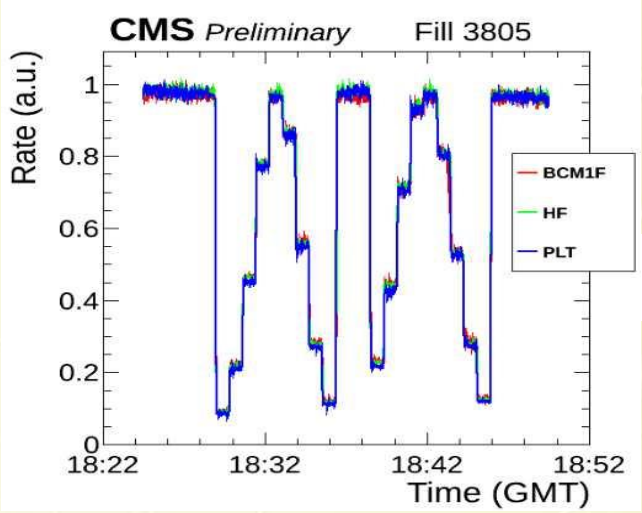
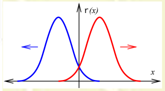
First fit with two Gaussians (2018)

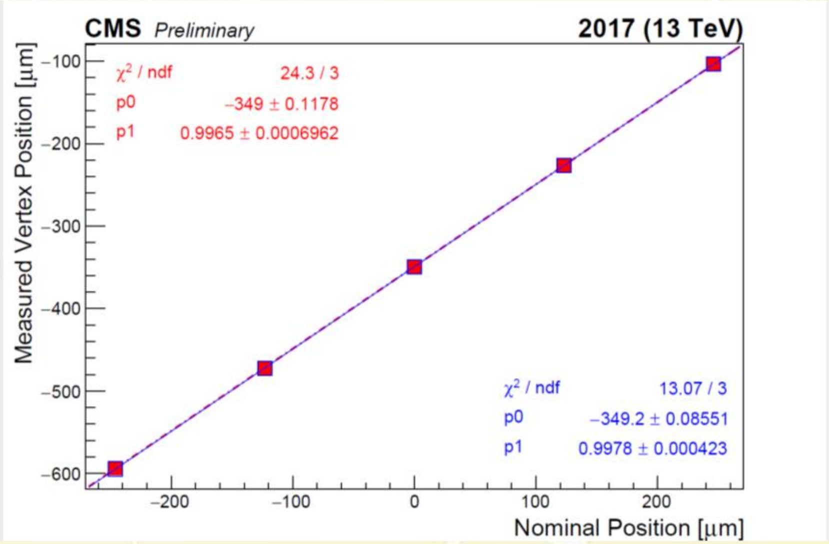
$\mathcal{L}(d)/\mathcal{L}(0)$



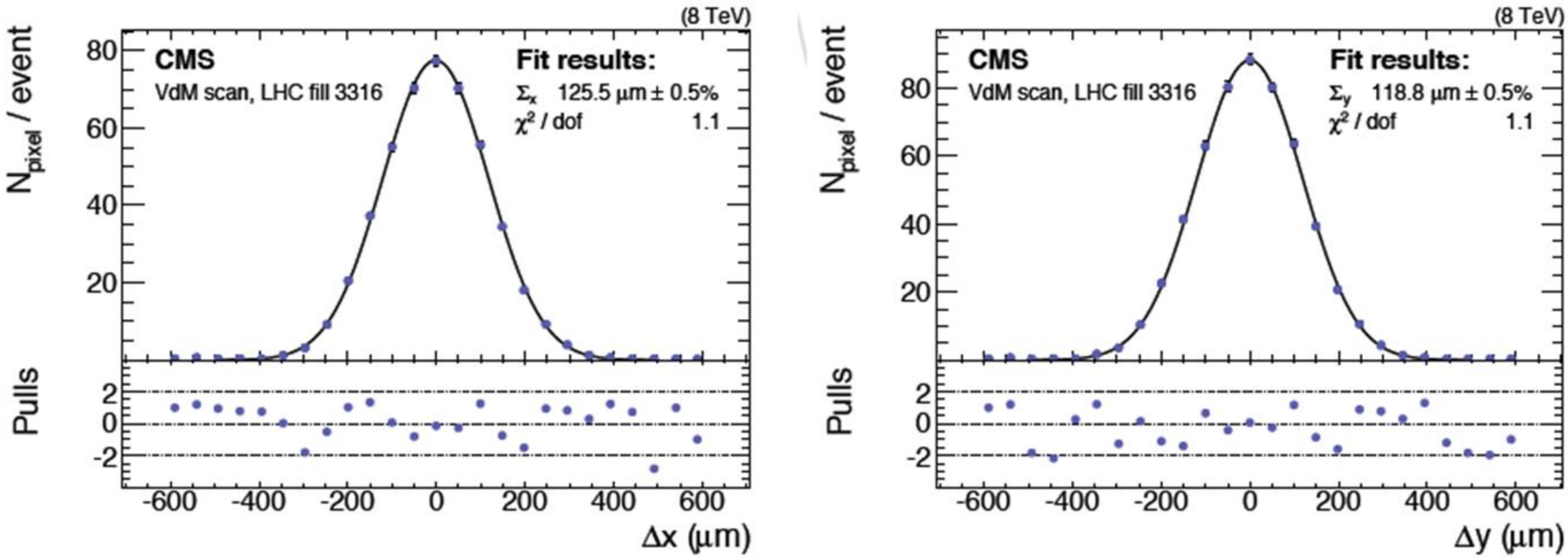




CMS 2017 data
Length scale calibration



pp collider



LHC made effort to deliver Gaussian beams, with no or small correlations in x and y;
As a result excellent fits with one Gaussian are obtained.

After having determined σ_x and σ_y, and getting N_1 and N_2 from bunch charge/beam current measurements, the measured rate of the device is used to determine its "visible cross section".

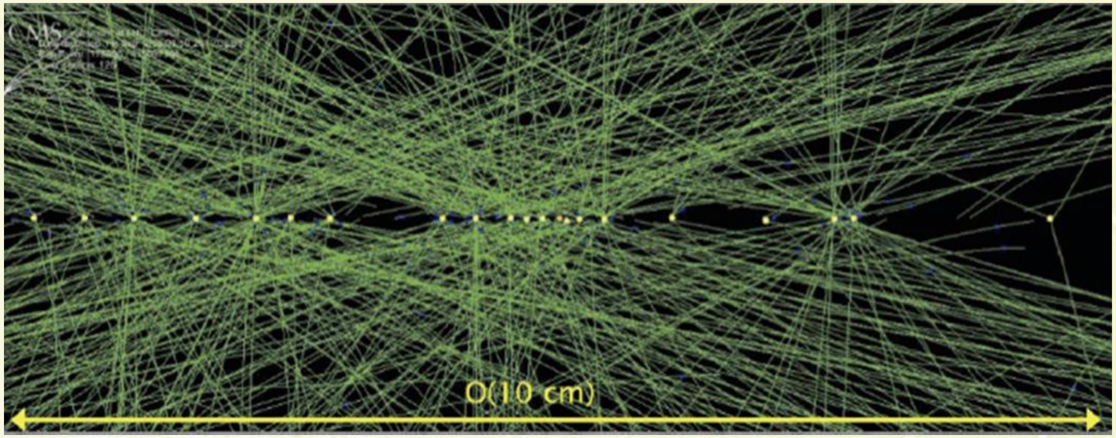
$$\sigma_{vis} = \dot{N} / \mathcal{L}$$

σ_{vis} is then used to measure the luminosity during the whole data taking period by measuring $\dot{N}$.

pp collider

Other methods:

- Vertex counting
- Pixel cluster counting
- Track counting
- SM processes



Vertex counting and track counting are used as control data for

- Short term failures in the luminosity system (data validation)
- Long term drifts and other effects (here also SM processes like W and Z - production are used)

pp collider

Current state of the art (CMS):

Category	Source	Correction	Error (%)
Normalization	Fit Model	—	$2 \sim 4$
	Beam Current	—	0.3
	Ghosts and Satellites	−0.4	0.2
	Length Scale	−0.9	0.5
	Emittance Growth	−0.1	0.2
	Orbit Drift	0.2	0.2
	Beam-beam	1.5	0.5
	Dynamic β	—	0.5
Integration	Stability and Linearity	—	1
	Dynamic Inefficiency	—	0.5
	Afterglow	~ 2	0.5
	Total	—	$2.5 \sim 4.4$

The fit-model uncertainty really refers to the beam-correlations effect (two Gaussians), which we believe is now understood. Once we gain confidence, we will assume the lower value.

pp collider

Optical theorem

$\sigma_{tot} = \sigma_{el} + \sigma_{inel}$ ⟶ $\sigma_{tot} \ x \ \mathcal{L} = N_{inel} + N_{el}$

Using $$\sigma_{tot} = \frac{4\pi}{k} \operatorname{Im} f(0),$$ $f(\theta)$ elastic scattering amplitude

We obtain $$\lim_{t\to 0} \frac{d\sigma_{el}}{dt} = (1+\rho^2)\frac{\sigma_{tot}^2}{16\pi} = \frac{1}{\mathcal{L}}\frac{dN_{el}}{dt}|_{t=0}$$

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

Counting $N_{inel} + N_{el}$

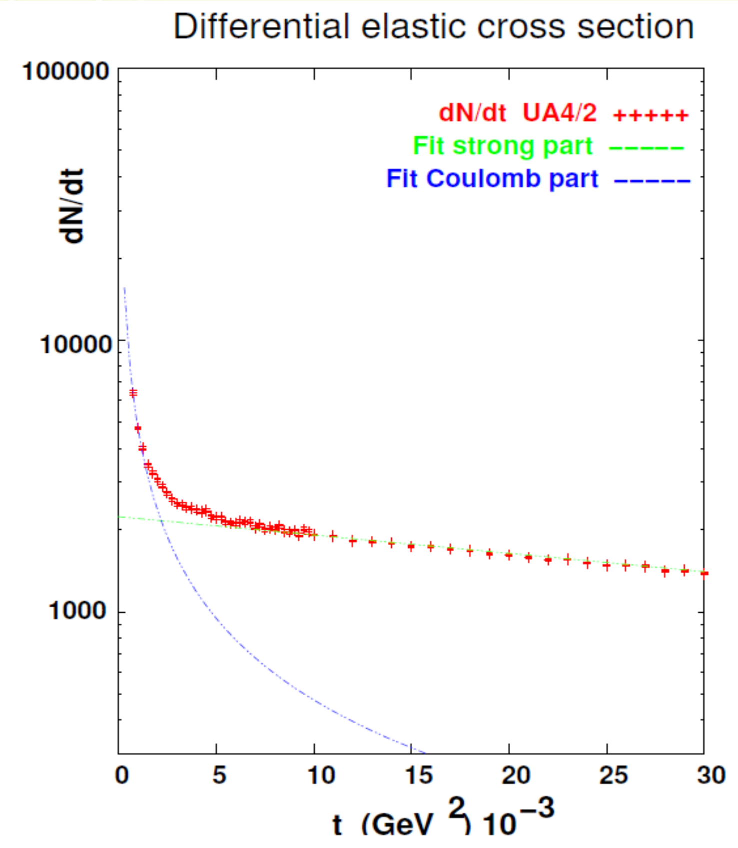
needs an hermetic detector,

dN_{el}/dt measurements at very small polar angle

pp collider

Optical theorem and interference with the Coulomb amplitude

$$\lim_{t\to 0}\frac{d\sigma_{\rm el}}{dt}=\frac{1}{\mathcal{L}}\frac{dN_{\rm el}}{dt}|_{t=0}=\pi\mid f_c+f_s\mid^2\simeq\pi\mid\frac{2\alpha_{\rm em}}{-t}+\frac{\sigma_{\rm tot}}{4\pi}(\rho+i)e^{B\frac{t}{2}}\mid^2\simeq\frac{4\pi\alpha_{\rm em}^2}{t^2}\mid_{|t|\to 0}$$



Example: SPS

Needs zero crossing angle

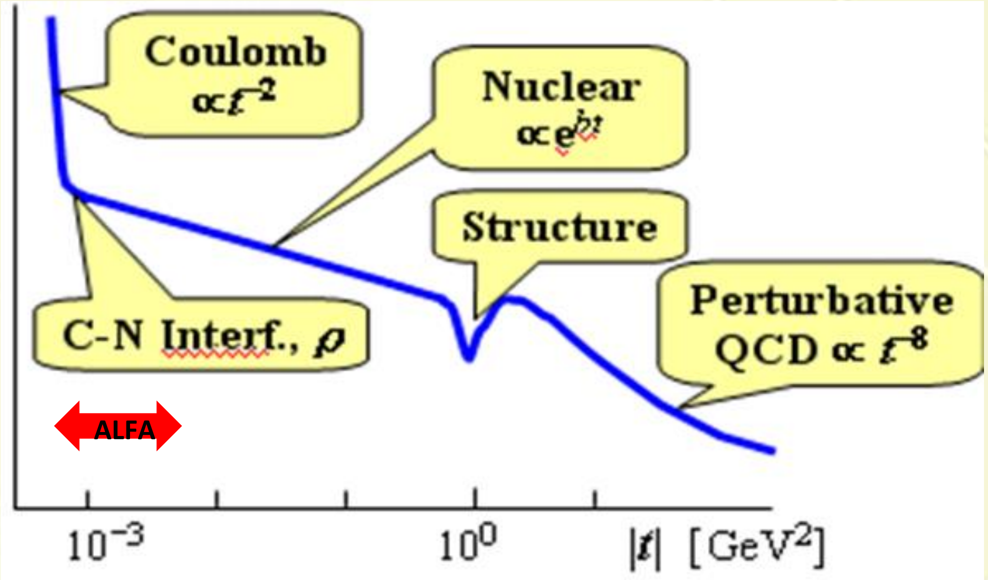
Very low angular spread (large β*)

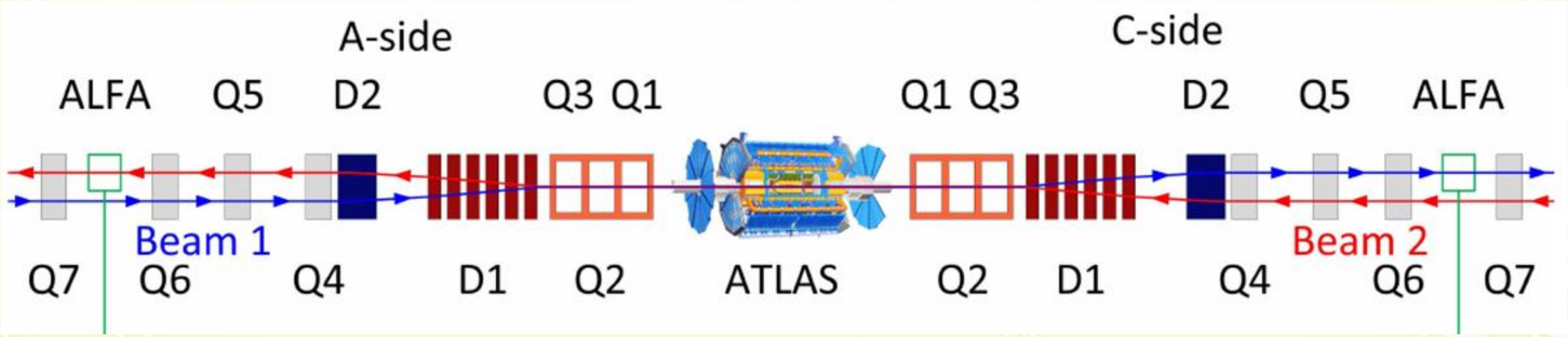
Detectors near the beam

Technology: Roman pots

pp collider

Ongoing projects: ALFA at ATLAS





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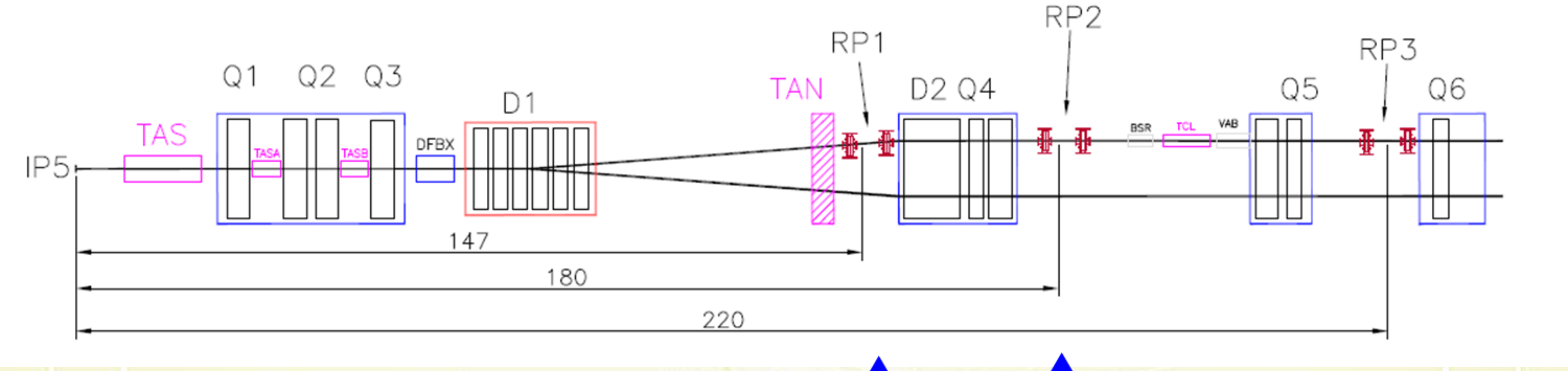
Ongoing projects: TOTEM at CMS



Interaction point CMS detector

Roman pot detectors

Summary

The luminosity $\mathcal{L}$ is a key quantity of each collider

- In e^+e^- collider at 90 GeV cms energy an accuracy $\Delta\mathcal{L}/\mathcal{L} = 3.4 \times 10^{-4}$ was reached at LEP (experimental) and $\Delta\mathcal{L}/\mathcal{L} = 5.4 \times 10^{-4}$ (theory)

- At future e^+e^- linear collider 10^{-3} and 10^{-2} is sufficient, however due to new phenomena at higher energy effort is needed, both from theory and R&D

- At the $e^\pm p$ collider HERA an accuracy $\Delta\mathcal{L}/\mathcal{L} = 1.7$ % was reached Experimentally there is room for improvement. Ongoing projects like LHeC must do effort to understand the issue

- At LHC currently an accuracy of $\Delta\mathcal{L}/\mathcal{L} = 2.3$ % is reached. Effort and ideas are needed to bring this number down, since it approaches the dominant error on cross section measurements