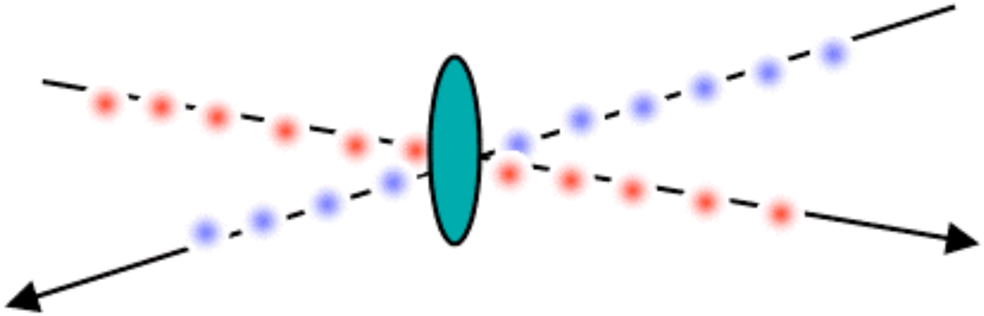
Luminosity measurement at ATLAS



Clermont-Ferrand
7/03/08
Per Grafstrom
CERN

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

Luminosity measurements-why?

- Cross sections for "Standard " processes
  - t-tbar production
  - W/Z production
  - …….

Theoretically known to better than 10% ……will improve in the future

- New physics manifesting in deviation of σ x BR relative the Standard Model predictions.
  Precision measurement becomes more important if new physics not directly seen (characteristic scale too high!)

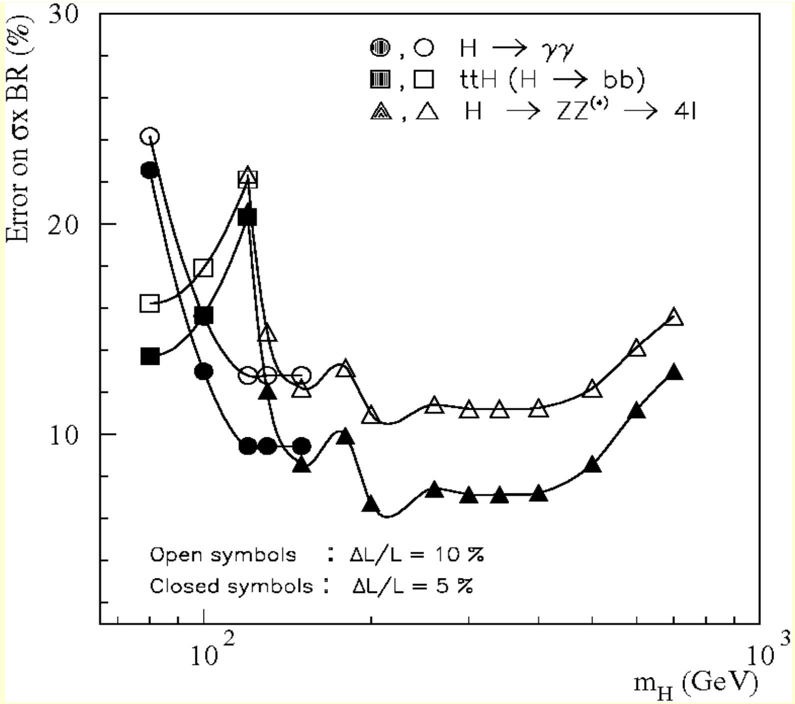
- Important precision measurements
  - Higgs production σ x BR
  - tanβ measurement for MSSM Higgs
  - …….

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

Luminosity Measurement (cont.)

Examples

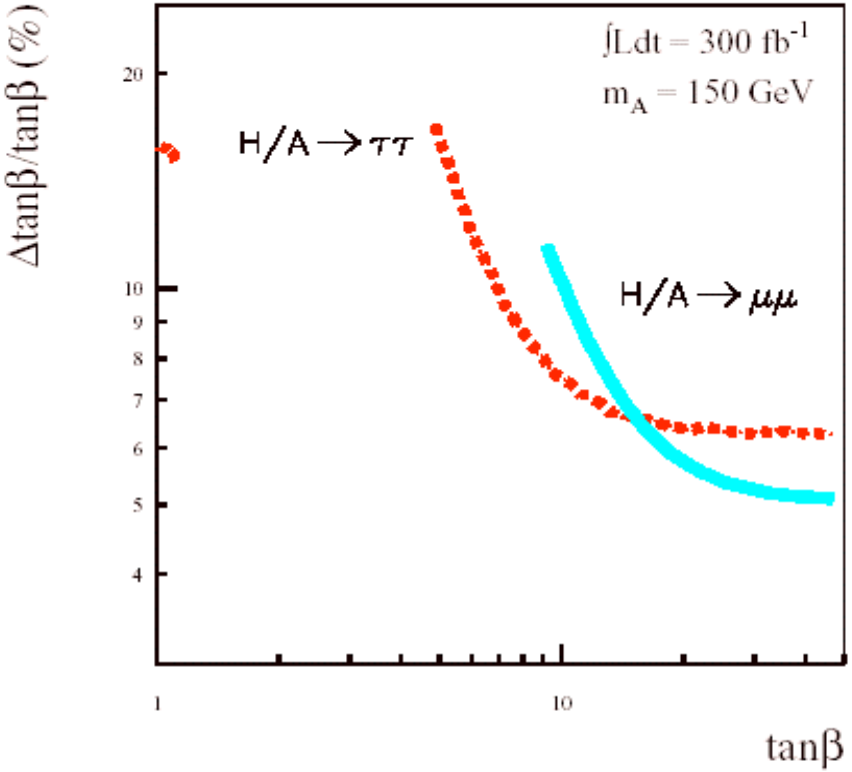
Higgs coupling



Relative precision on the measurement of σ_H×BR for various channels, as function of m_H, at $\int Ldt = 300\ \mathrm{fb}^{-1}$. The dominant uncertainty is from Luminosity: 10% (open symbols), 5% (solid symbols).

(ATLAS-TDR-15, May 1999)

tanβ measurement



Systematic error dominated by luminosity (ATLAS Physics TDR)

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

Absolute versus relative measurement

- Relative measurements or Luminosity Monitoring
  - Using suitable observables in existing detectors
    - Beam condition monitor
    - Current in Tile calorimeter PM's
    - Minimum bias scintillators

  - Using dedicated luminosity monitor
    - LUCID

- Absolute measurements
  - Several different methods-next slide

- Strategy:

1. Measure the absolute luminosity with a precise method at optimal conditions
2. Calibrate luminosity monitor with this measurement, which can then be used at different conditions

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

Absolute Luminosity Measurements

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

How? Three major approaches

- LHC Machine parameters
- Rates of well-calculable processes: e.g. QED (like LEP), EW and QCD
- Elastic scattering
  - Optical theorem: forward elastic rate + total inelastic rate:
  - Luminosity from Coulomb Scattering
  - Hybrids
    - → Use σ_{tot} measured by others
    - → Combine machine luminosity with optical theorem

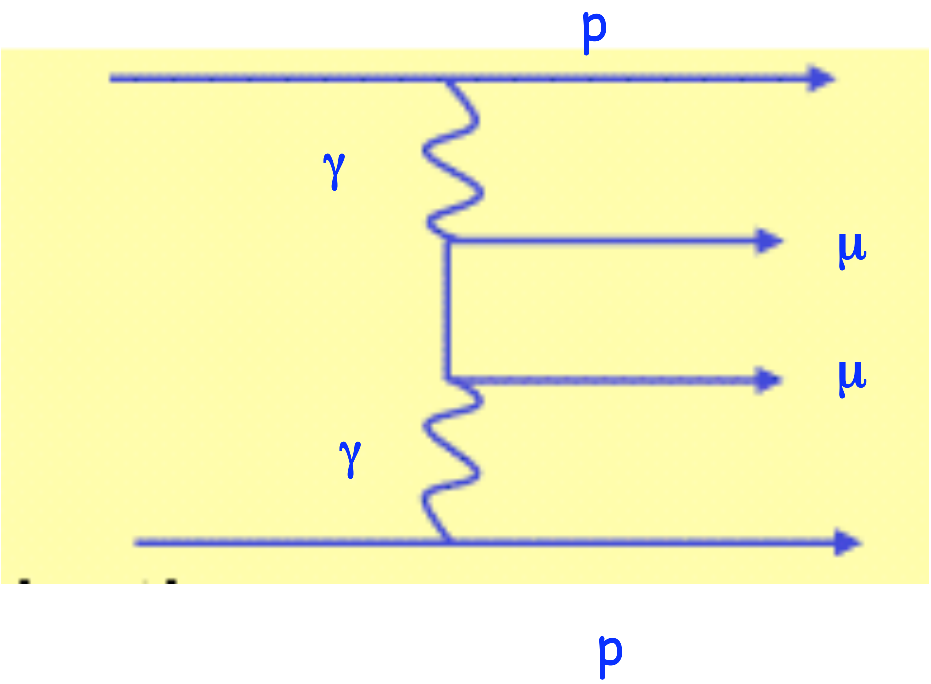
We better pursue all options

Outline

- Methods for Absolute Measurement of Luminosity
  - Use Processes with known cross sections
  - Use Machine Parameters
  - Use Elastic scattering
- Methods for Relative Measurement of Luminosity
  - LUCID
- Forward detectors - Forward physics

Muon pairs

Two photon production of muon pairs-QED



- Pure QED
- Theoretically well understood
- No strong interaction involving the muons
- Proton-proton re-scattering can be controlled
- Cross section known to better than 1 %

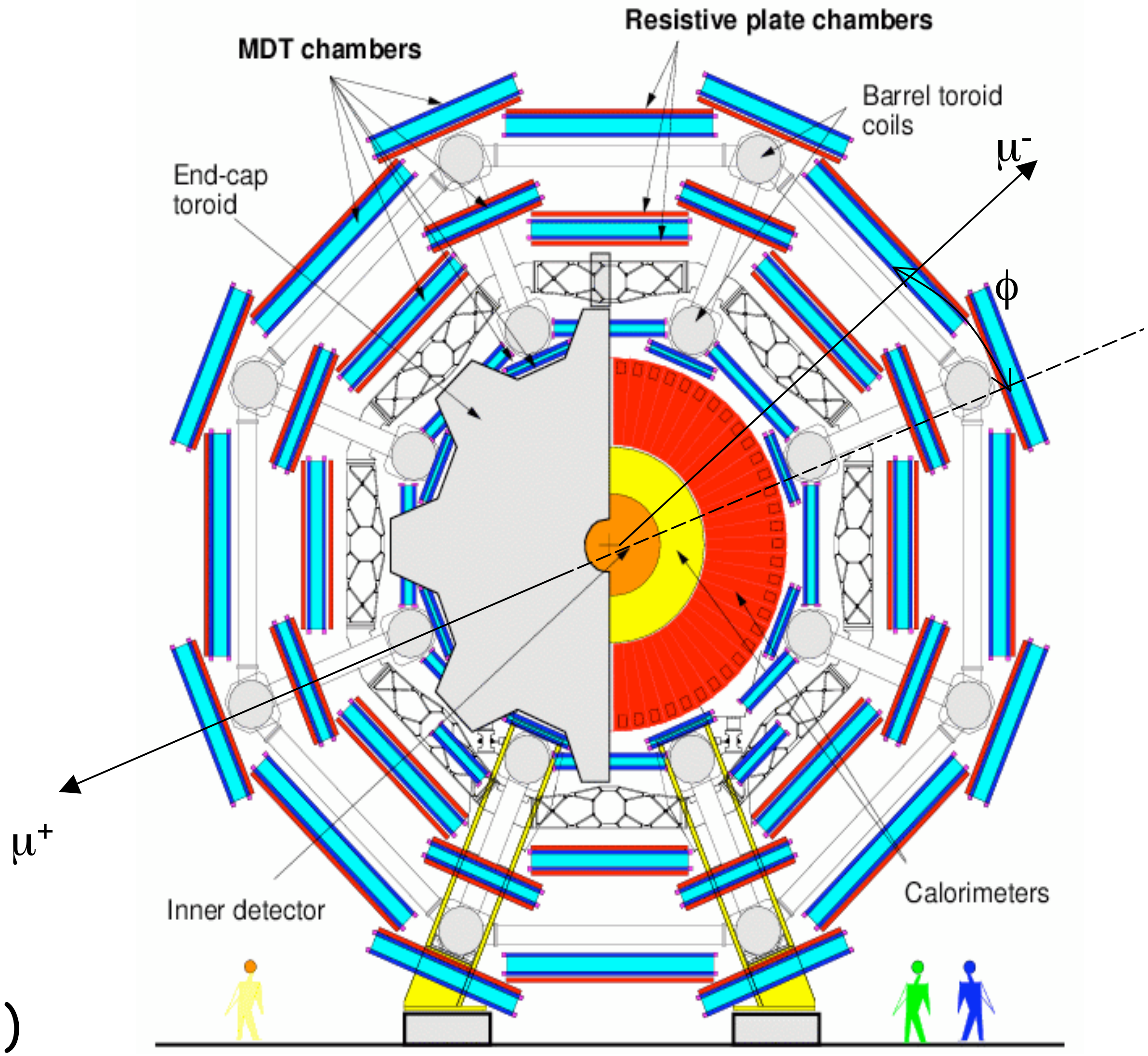
Two photon production of muon pairs

$P_t > 3$ GeV to reach the muon chambers

$P_t > 6$ GeV to maintain trigger efficiency and reasonable rates

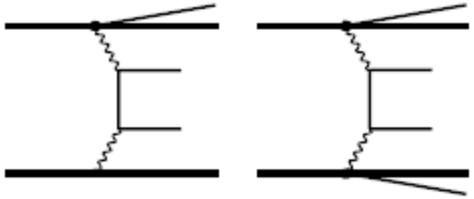
Centrally produced
$\eta < 2.5$

$P_t(\mu\mu) \sim 10\text{-}50$ MeV
Close to back to back in φ (background suppression)

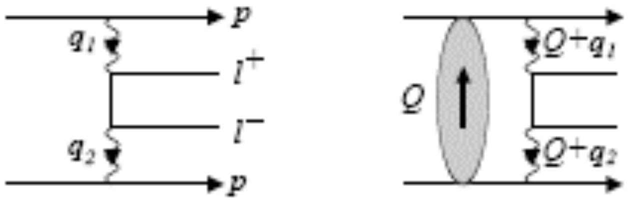


Backgrounds

- Strong interaction of a single proton



- Strong interaction between colliding proton



- Di-muons from Drell-Yan production

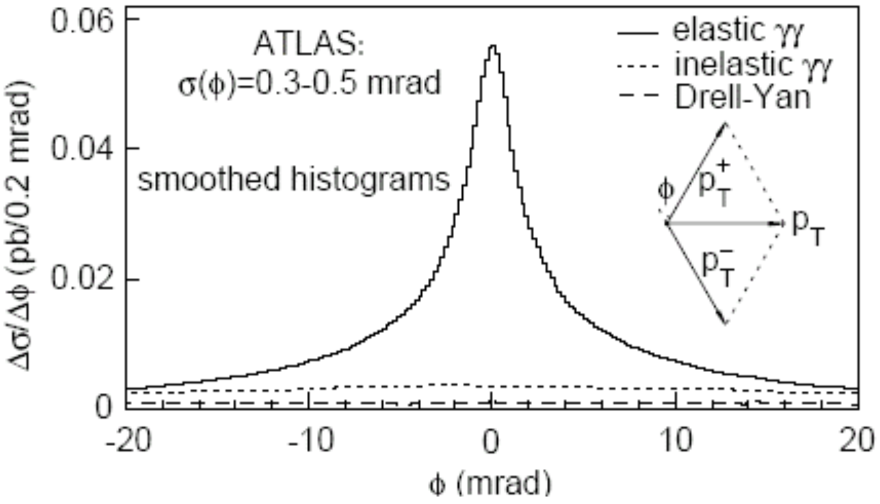
- Muons from hadron decay

Muon pairs

Event selection-two kind of cuts

- Kinematic cuts

  P_t of muons are equal within 2.5 σ of the measurement uncertainty



Suppresses efficiently proton excitations and proton-proton re-scattering

- Good Vertex fit and no other charged track

  Suppress Drell-Yan background and hadron decays

Muon pairs

What are the difficulties ?

- The rate

  The kinematical constraints ⇨ $\sigma \sim 1$ pb
  A typical $10^{33}/cm^2/sec$ year ~ 6 fb^{-1} and ~ 150 fills
  ⇨ 40 events fill ⇨ Luminosity MONITORING excluded
  What about LUMINOSITY calibration?
  1 % statistical error ⇨ more than a year of running
- Efficiencies

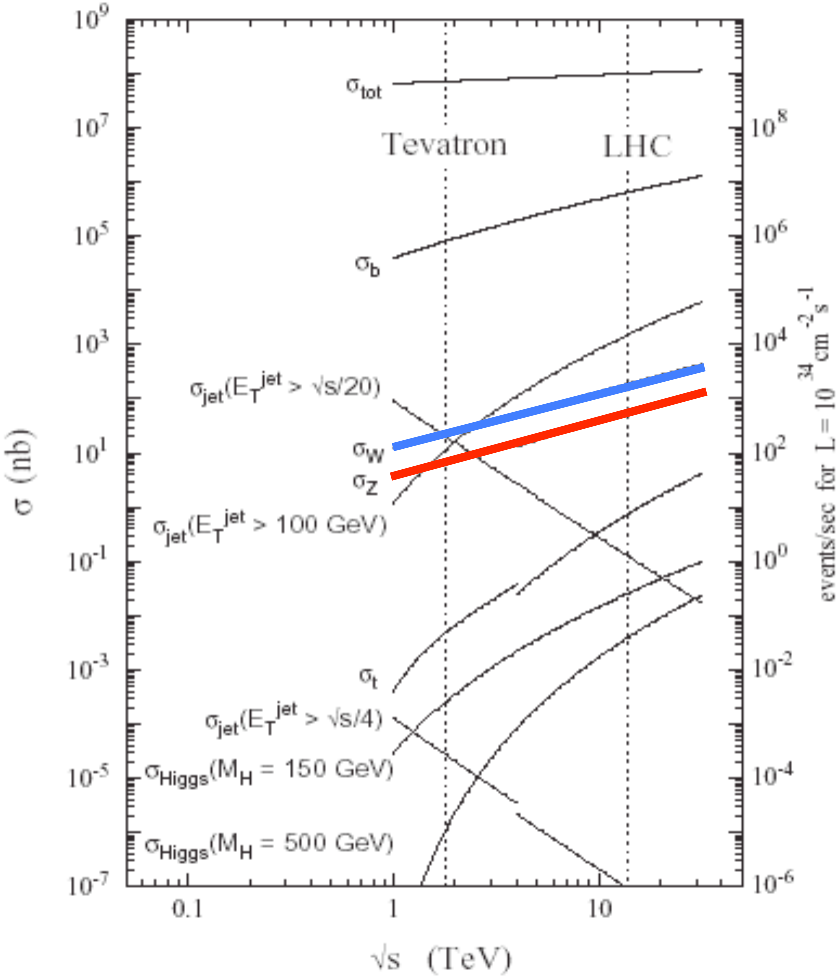
  Both trigger efficiency and detector efficiency must be known very precisely. Non trivial.
- Pile-up

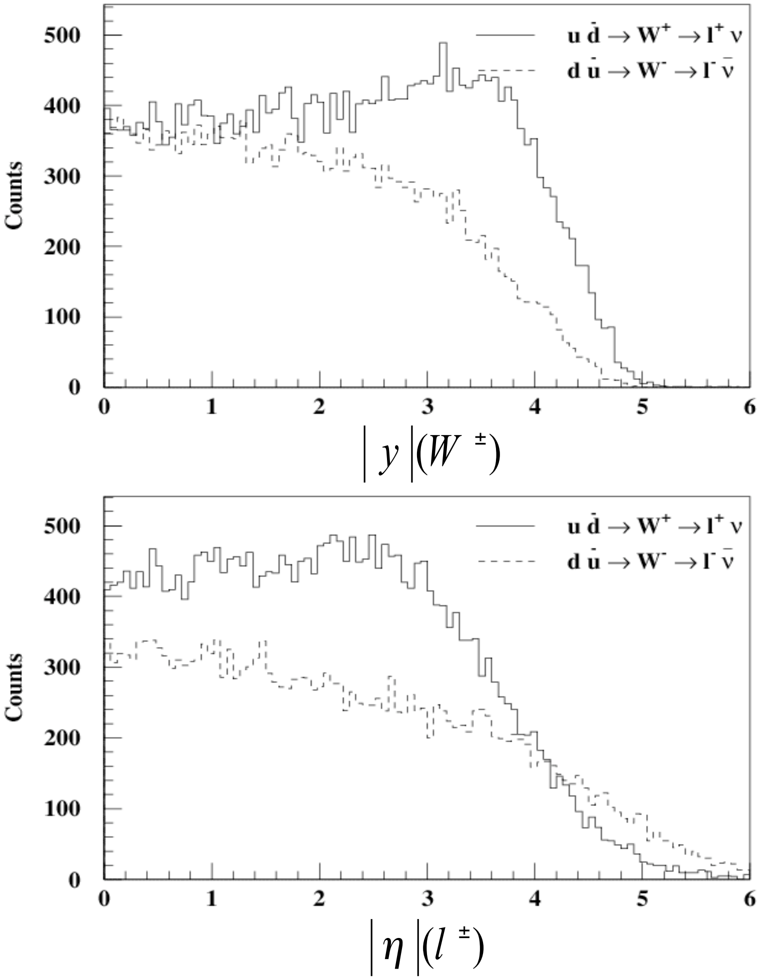
  Running at $10^{34}/cm^2/sec$ ⇨ “vertex cut” and “no other charged track cut” will eliminate many good events
- CDF result

  First exclusive two-photon observed in e^+e^-. …. but….
  16 events for 530 pb^{-1} for a σ of 1.7 pb ⇨ overall efficiency 1.6 %

Summary – Muon Pairs
Cross sections well known and thus a potentially precise method.
However it seems that statistics will always be a problem.

W and Z counting





W and Z counting

- Constantly increasing precision of QCD calculations makes counting of leptonic decays of W and Z bosons a possible way of measuring luminosity. In addition there is a very clean experimental signature through the leptonic decay channel.
- Use W in this discussion . σ (W) x BR(W → lν) has more favourable rate.

  The rate is 10 x σ (Z) x BR(Z → ll).

The Basic formula

$$L = (N - BG)/ (\varepsilon \times A_W \times \sigma_{th})$$

L is the integrated luminosity

N is the number of W candidates

BG is the number of back ground events

ε is the efficiency for detecting W decay products

A_W is the acceptance

σ_{th} is the theoretical inclusive cross section

Uncertainties on σ_{th}

- σ_{th} is the convolution of the Parton Distribution Functions (PDF) and of the partonic cross section

$$N_{pp\to W\pm} = L \ \mathrm{x}\ PDF(x_1,x_2,Q^2)\ \mathrm{x}\ \sigma_{q\bar{q}\to W^\pm}$$
$$N_{pp\to Z^0} = L \ \mathrm{x}\ PDF(x_1,x_2,Q^2)\ \mathrm{x}\ \sigma_{q\bar{q}\to Z^0}$$

- The uncertainty of the partonic cross section is available to NNLO in differential form with estimated scale uncertainty below 1 % (Anastasiou et al PRD 69, 94008.)

- PDF’s more controversial and complex

W and Z

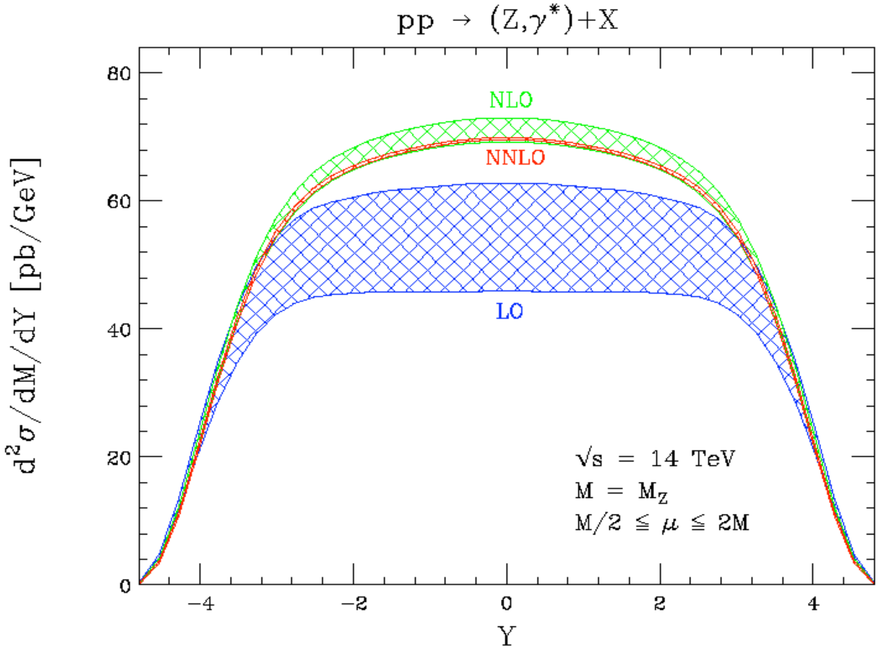
NNLO Calculations

Bands indicate the uncertainty from varying the renormalization (μ_R) and factorization (μ_F) scales in the range:

$M_Z/2 < (\mu_R = \mu_F) < 2M_Z$

- At LO: ~ 25 - 30 % x-s error
- At NLO: ~ 6 % x-s error
- At NNLO: < 1 % x-s error

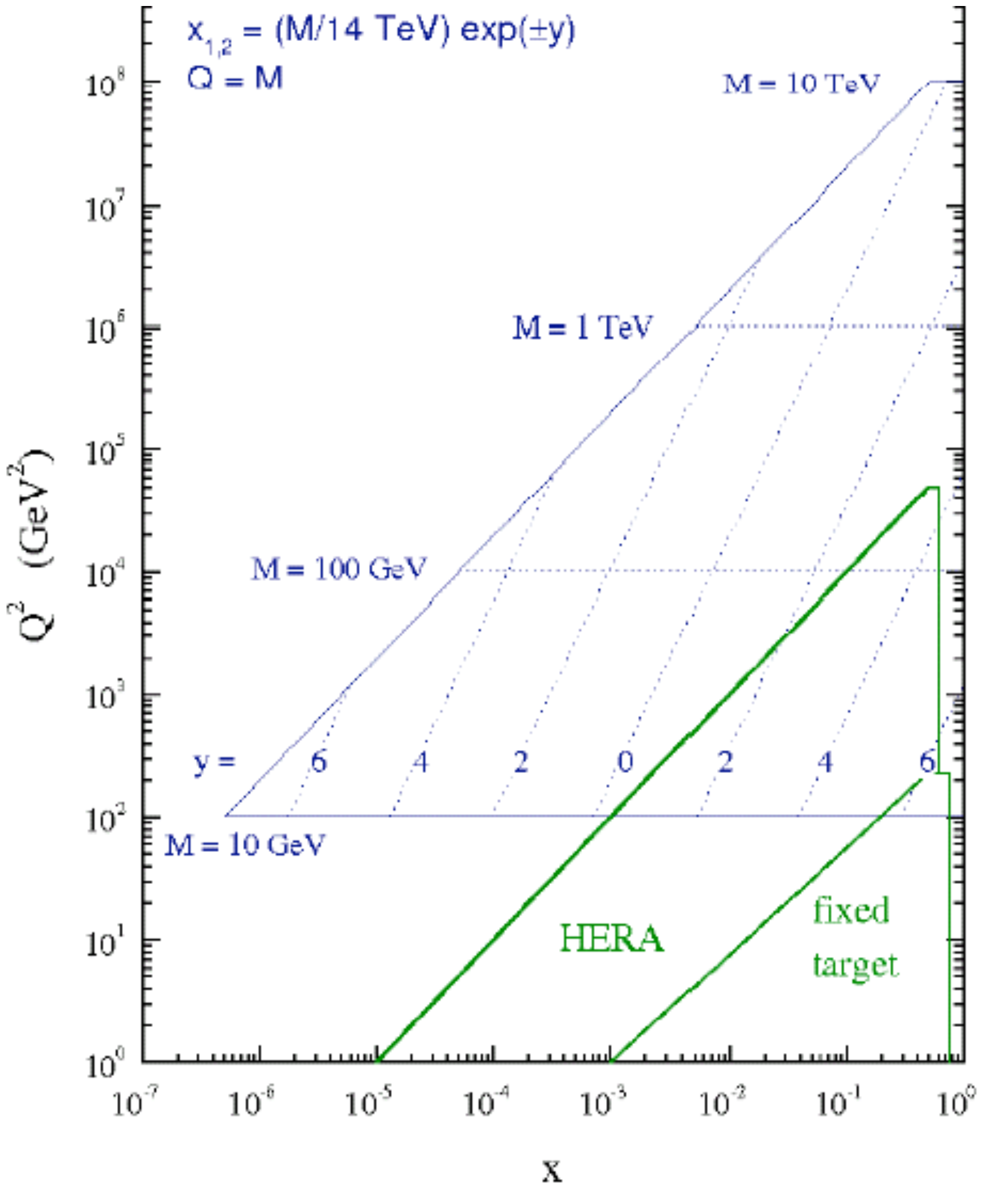
Anastasiou et al., Phys.Rev. D69:094008, 2004



Perturbative expansion is stabilizing and renormalization and factorization scales reduces to level of 1 %

W and Z

x and Q^2 range of PDF's at LHC



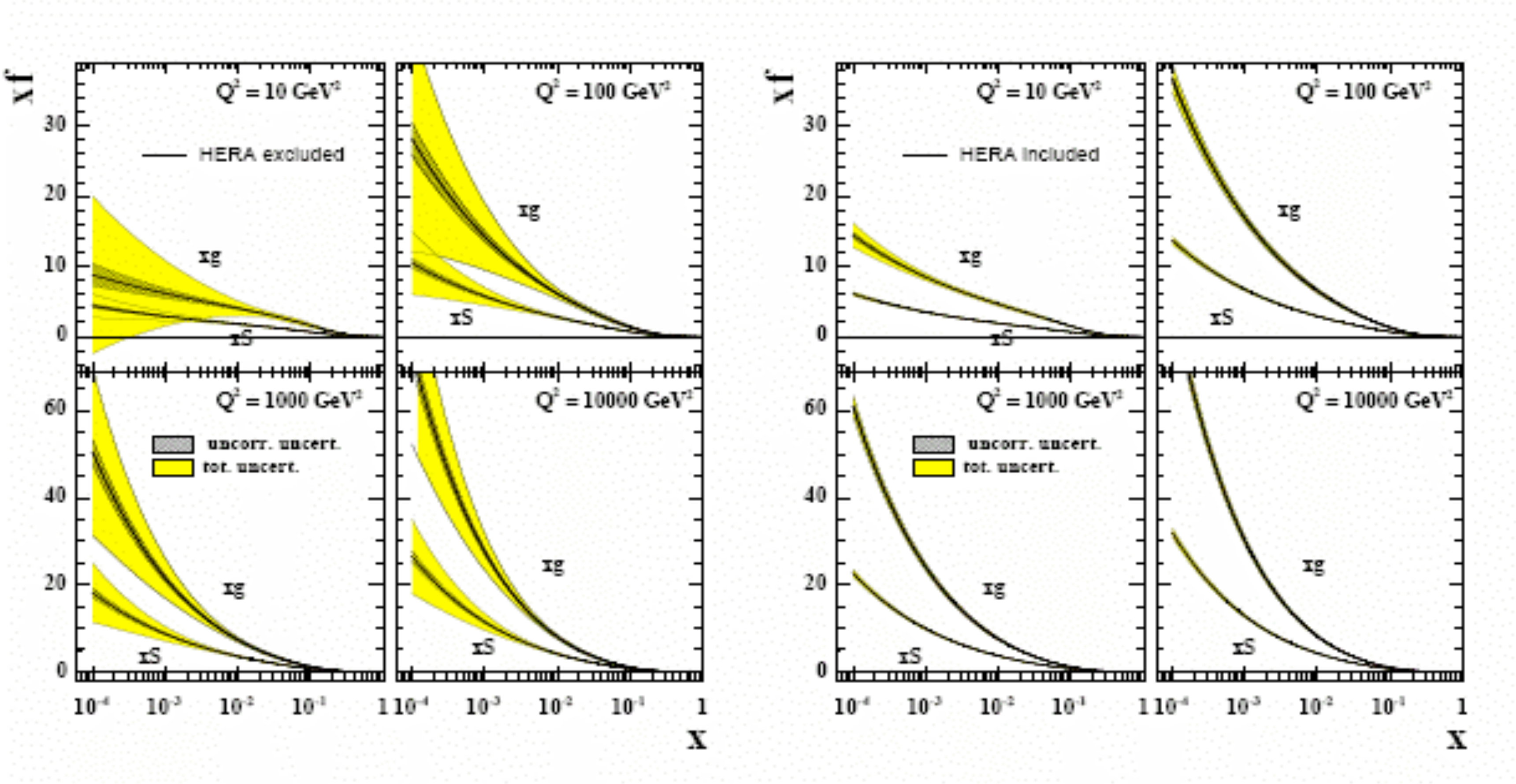
Sensitive to x values
$10^{-1} > x > x10^{-4}$

Sea quarks and antiquark dominates
g→qqbar

Gluon distribution at low x

HERA result important

Sea(xS) and gluon (xg) PDF’s



PDF uncertainties reduced enormously with HERA.

Most PDF sets quote uncertainties implying error in the W/Z cross section < 5 %

However central values for different sets differs sometimes more !

Uncertainties in the acceptance A_W

The acceptance uncertainty depends on QCD theoretical error.
Generator needed to study the acceptance

The acceptance uncertainty depends on polarization of W and on PDF's

Uncertainty estimated to about 2 %

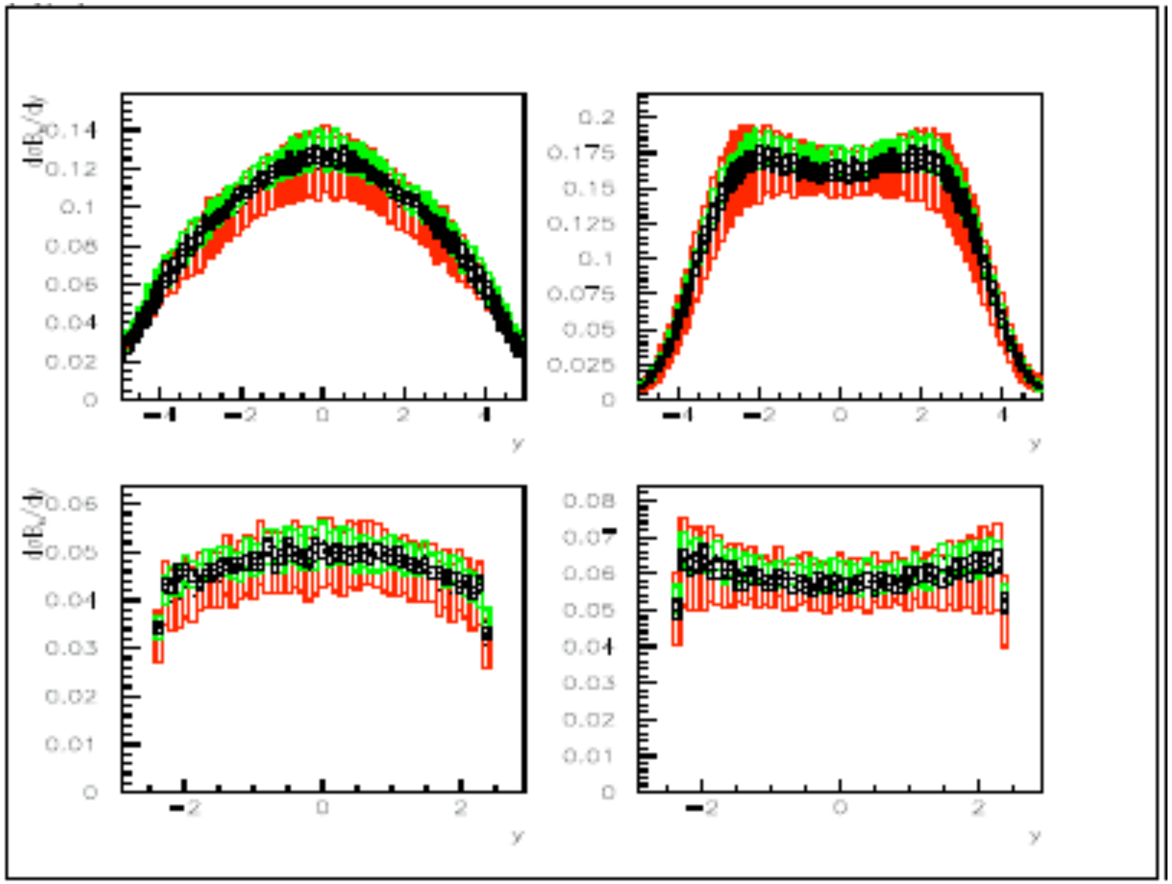
Uncertainties on ε

Uncertainty on trigger efficiency for isolated leptons

Uncertainty on lepton identification cuts

CTEQ6.1 red
ZEUS-S green
MRST2001 black

e^- and e^+ rapidity spectra



← Generated

← After detector simulation and cuts

PDF uncertainties only slightly degraded after detector simulation and selection cuts

Summary – W and Z

W and Z production has a high cross section and clean experimental signature making it a good candidate for luminosity measurements.

The biggest uncertainties in the W/Z cross section comes from the PDF's. This contribution is sometimes quoted as big as 8 % taking into account different PDF's sets .
Adding the experimental uncertainties we end up in the 10 % range.

The precision might improve considerable if the LHC data themselves can help the understanding of the differences between different parameterizations ….. (A_W might be powerful in this context!)

The PDF's will hopefully get more constrained from early LHC data .

Aiming at 3-5 % error in the error on the Luminosity from W/Z cross section after some time after the LHC start up

Luminosity from Machine parameters

- Luminosity depends exclusively on beam parameters:

$$\mathcal{L} = \frac{N^2 f_{\mathrm{rev}}\, n_b}{4\pi\sigma^{*2}}$$

Depends on f_{rev} revolution frequency
n_b number of bunches
N number of particles/bunch
σ^* beam size or rather overlap integral at IP

$$\sqrt{1+\left(\frac{\theta_c\sigma_z}{2\sigma^*}\right)^2}$$

The luminosity is reduced if there is a crossing angle (300 μrad)
1 % for β^* = 11 m and 20% for β^* = 0.5 m

- Luminosity accuracy limited by
  - extrapolation of σ_x, σ_y (or ε, β_x^*, β_y^*) from measurements of beam profiles elsewhere to IP; knowledge of optics, …
  - Precision in the measurement of the the bunch current
  - beam-beam effects at IP, effect of crossing angle at IP, …

> " We expect to be able to predict absolute luminosities for head-on collisions based on beam intensities and dimensions, to maybe 20-30 % and potentially much better if a special effort is made. "
>
> **(Helmut Burkhardt)**

Machine parameters

What means special effort?

Calibration runs

i.e calibrate the relative beam monitors of the experiments during dedicated calibration runs.

- Calibration runs with simplified LHC conditions
  - Reduced intensity
  - Fewer bunches
  - No crossing angle
  - Larger beam size
  - ….

- Simplified conditions that will optimize the condition for an accurate determination of both the beam sizes (overlap integral) and the bunch current.

Machine parameters

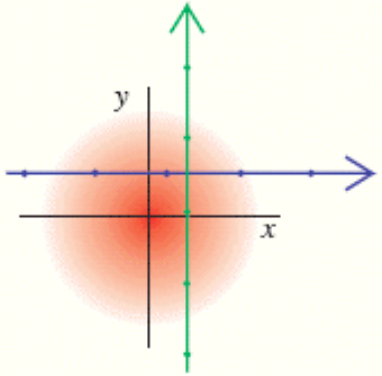
Determination of the overlap integral (pioneered by Van der Meer @ISR)

Luminosity with separation

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

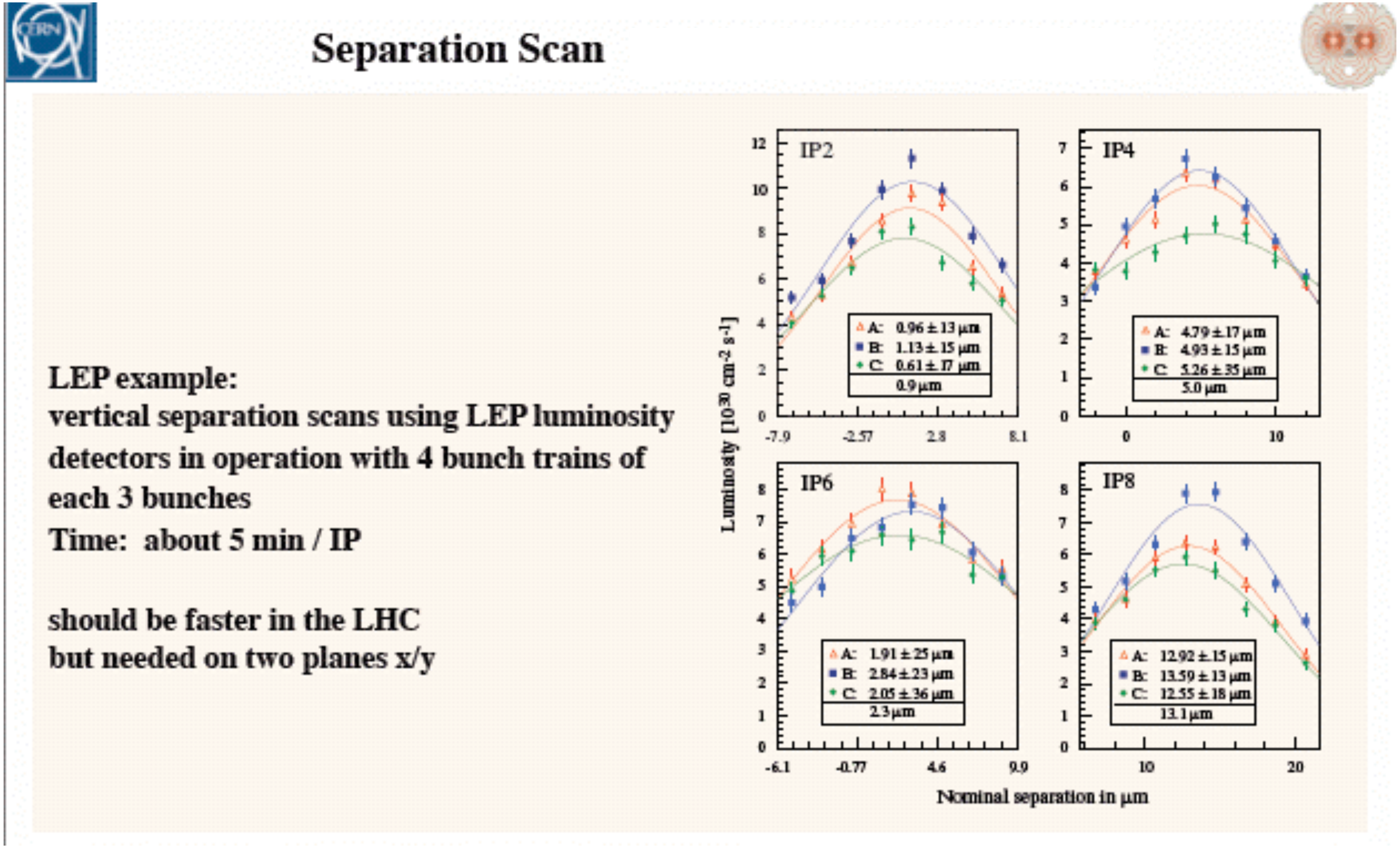
$\frac{\delta x}{\sigma_x}$	$\frac{\delta y}{\sigma_y}$	$\frac{\mathcal{L}}{\mathcal{L}_0}$
0	0	1
1/2	0	0.9394
1/2	1/2	0.8825
1	0	0.7788
1	1	0.6065
2	0	0.3679
2	2	0.1353

Commissioning : simple, orthogonal x / y scan



Machine parameters

Example LEP



Separation Scan

LEP example:
vertical separation scans using LEP luminosity detectors in operation with 4 bunch trains of each 3 bunches
Time: about 5 min / IP

should be faster in the LHC
but needed on two planes x/y

Summary – Machine parameters

- The special calibration run will improve the precision in the determination of the overlap integral . In addition it is also possible to improve on the measurement of N (number of particles per bunch). Parasitic particles in between bunches complicate accurate measurements. Calibration runs with large gaps will allow to kick out parasitic particles.

- Calibration run with special care and controlled condition has a good potential for accurate luminosity determination. About 1 % was achieved at the ISR.

- Less than ~5 % might be in reach at the LHC (will take som time !)

- Ph.D student in the machine department will start to work on this (supervisor Helmut Burkhardt)

Elastic scattering and the Optical theorem

The optical theorem relates the total cross section to the forward elastic rate

$\sigma_{tot} = 4\pi \,\mathrm{Im}\; f_{el}(0)$ →

$$L = \frac{1+\rho^2}{16\pi}\,\frac{N_{tot}^{\;2}}{\left.\frac{dN_{el}}{dt}\right|_{t=0}}$$

Thus we need

- Extrapolate the elastic cross section to t=o
- Measure the total rate
- Use best estimate of ρ (ρ ~ 0.13 +- 0.02 ⇨ 0.5 % in ΔL/L)

Optical theorem

What is required

- $dN_{el}/dt|_{t=0}$ requires small $-t \sim 0.01$ GeV^2
  ⇨ $\theta \sim 15$ μrad (nominal divergence is 32 μrad)
  ⇨ beam with smaller divergence
  ⇨ large β* ~ 1000 m (divergence $\propto 1/\sqrt{\beta^*}$)

- Zero crossing angle ⇨ fewer bunches

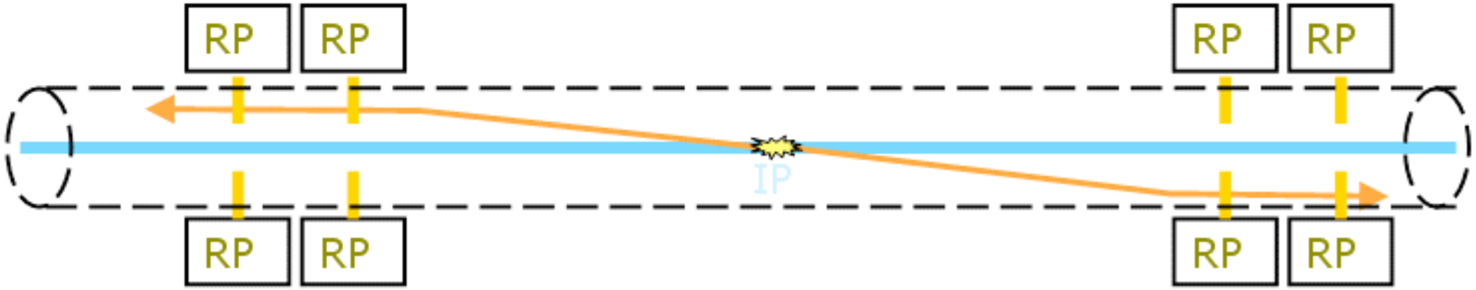
  ⇨ Special run at low luminosity

- N_{tot}: need large coverage detectors to make accurate extrapolation over the full phase space (98% coverage requires |η| up 7-8)
- ATLAS cover |η| up 5
  ⇨ We get model dependent estimation of the full rate

Coulomb

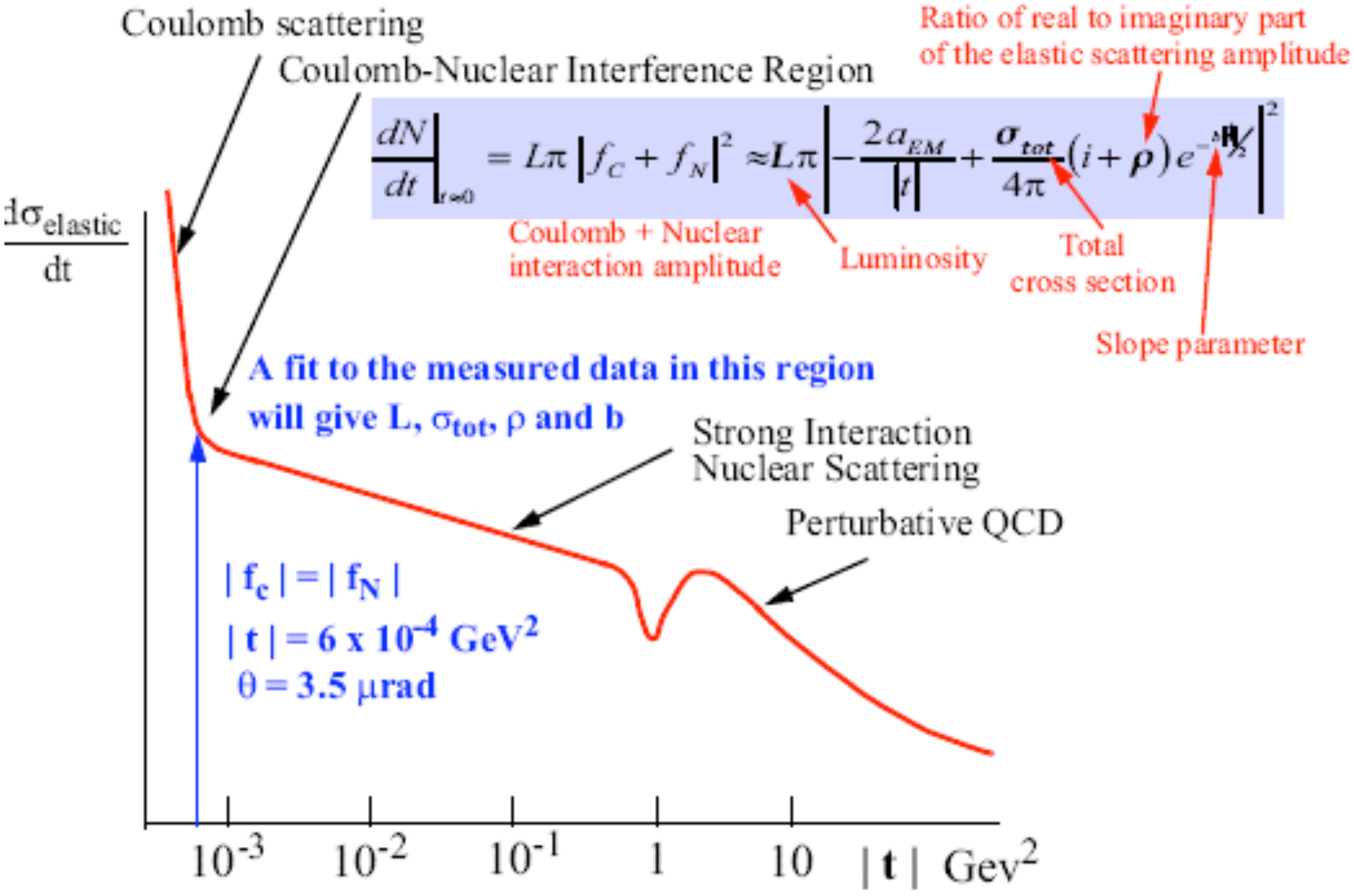
Elastic scattering at very small angles

- Measure elastic scattering at such small t-values that the cross section becomes sensitive to the Coulomb amplitude
- Effectively a normalization of the luminosity to the exactly calculable Coulomb amplitude
- No total rate measurement and thus no additional detectors near IP necessary
- UA4 used this method to determine the luminosity to 2-3 %



Coulomb

Elastic scattering at very small angles



$$\left.\frac{dN}{dt}\right|_{t\approx 0} = L\pi\left|f_C + f_N\right|^2 \approx L\pi\left|-\frac{2a_{EM}}{|t|} + \frac{\sigma_{tot}}{4\pi}(i+\rho)e^{-b|t|/2}\right|^2$$

Ratio of real to imaginary part of the elastic scattering amplitude

Coulomb + Nuclear interaction amplitude

Luminosity

Total cross section

Slope parameter

A fit to the measured data in this region will give L, σ_{tot}, ρ and b

$|f_c| = |f_N|$

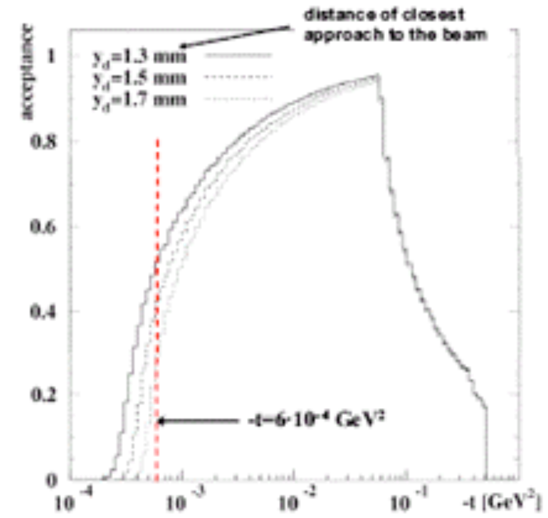
$|t| = 6 \times 10^{-4}$ GeV^2

$\theta = 3.5\ \mu$rad

Coulomb

What is required

- Need closest possible approach to the beam



- Need to measure extremely small angles using detectors in "Roman pots" far away from the IP

Coulomb amplitude ≈ Strong amplitude for $-t=0.00065$Gev^2

This corresponds to 3.5 μrad -The Coulomb region at the collider at 120 μrad

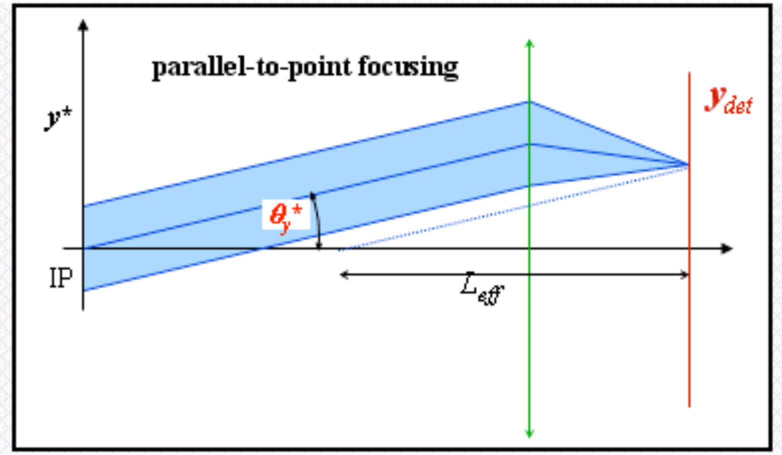
Two factors make it harder at the LHC

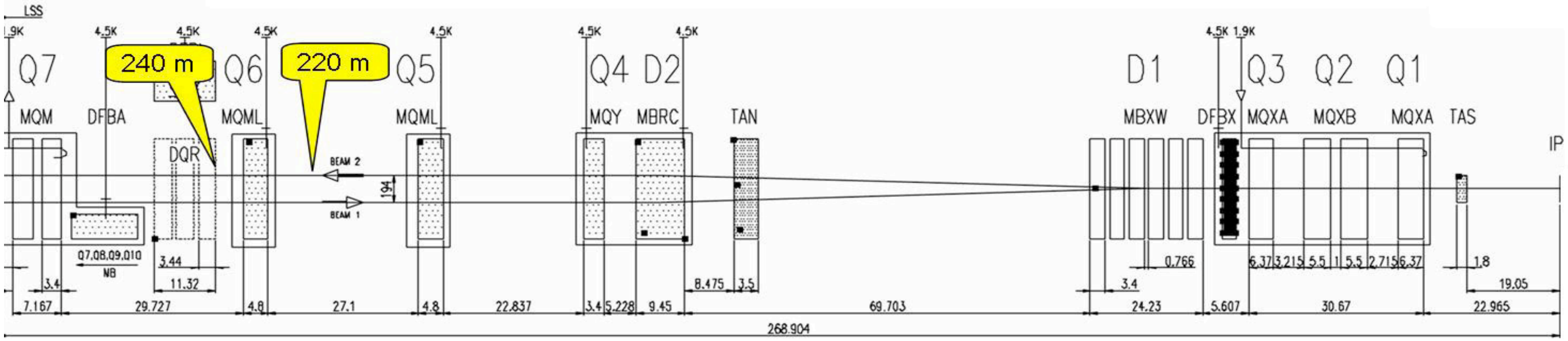
- Momentum larger ; $t = (p\ \theta)^2 \Rightarrow$ factor 25
- Cross section larger ⇒ factor 1.3

Coulomb

How to measure such small angles?

- Use optics with parallell to point from IP to detector and then measure the distance of the scattered particles from the beam axis and use "Roman Pots" far away from the IP to come as close as possible to the beam

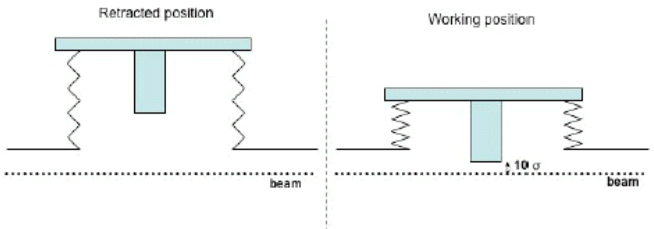


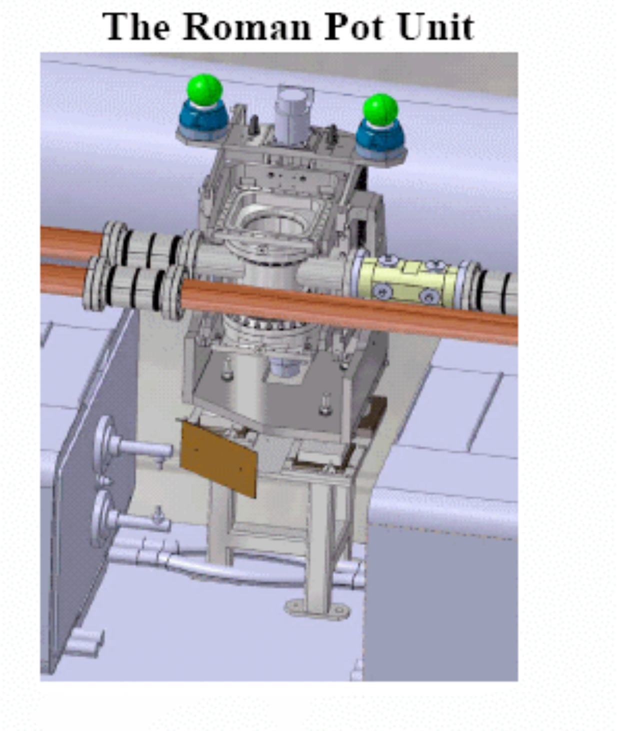


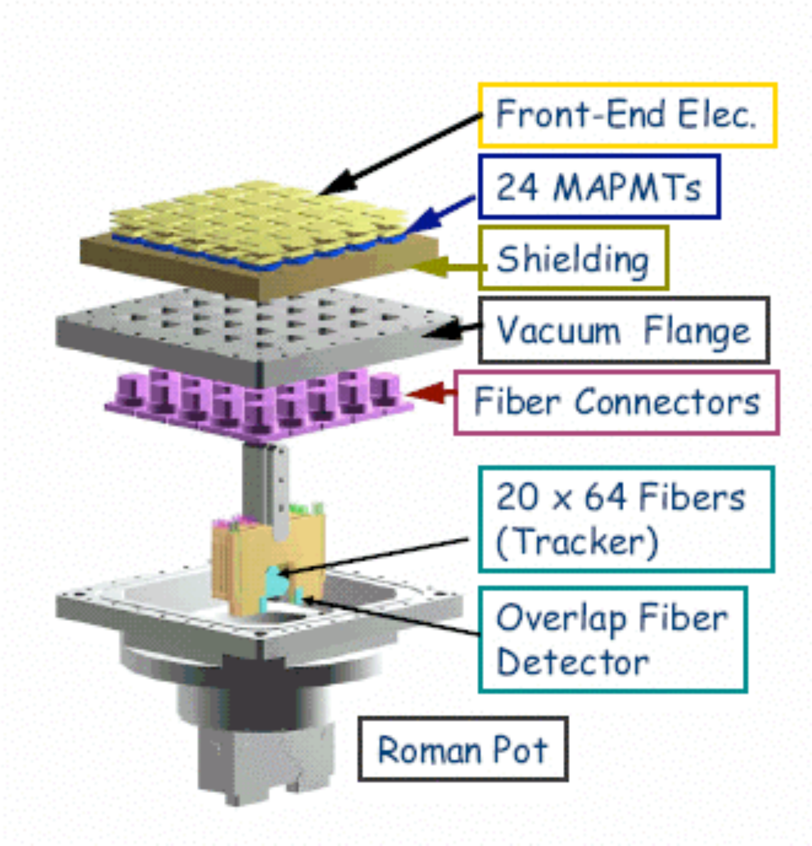
The Roman Pots

ALFA = Absolute Luminosity For ATLAS

Roman Pot Concept






Front-End Elec.
24 MAPMTs
Shielding
Vacuum Flange
Fiber Connectors
20 x 64 Fibers (Tracker)
Overlap Fiber Detector
Roman Pot

Coulomb

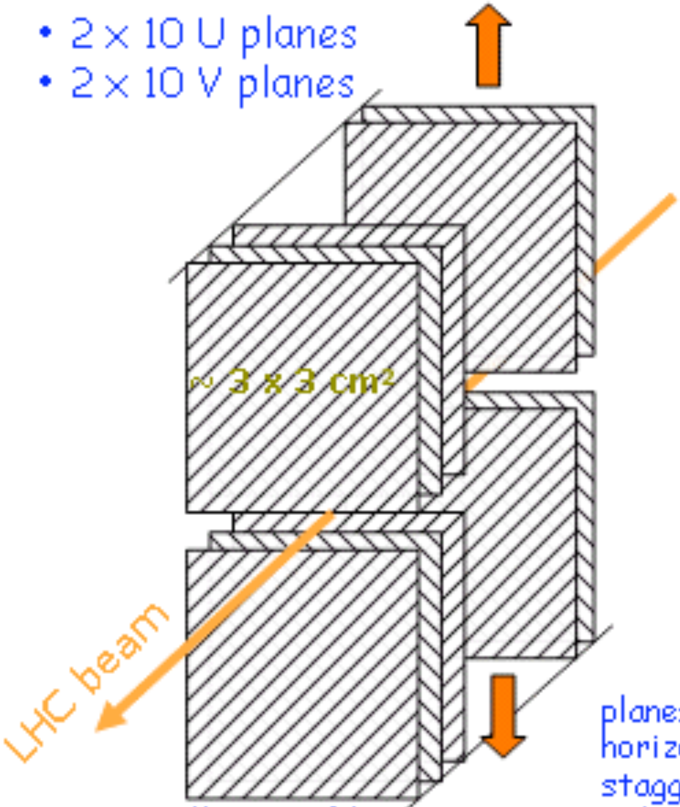
Requirements of Roman Pot Detectors

- "Dead space" d_0 at detector's edge near the beam :
  $d_0 \lesssim 100\ \mu m$ (full/flat efficiency away from edge)
- Operate with the induced EM pulse from circulating bunches (shielding, …)
- Detector resolution: $\sigma_d = 30\ \mu m$
- Some 10 μm relative position accuracy between opposite detectors (e.g. partially overlapping detectors, …)
- Radiation hardness: 100 Gy/yr (10^{5-6} Gy/yr at full L)
- Rate capability: O(Mhz) (40 MHz); time resolution σ_t = O(ns)
- Readout and trigger compatible with ATLAS TDAQ
- Other:
  - Simplicity, Cost
  - extent of R&D needed, time scale, manpower, …
  - issues of LHC safety and controls

The fiber tracker

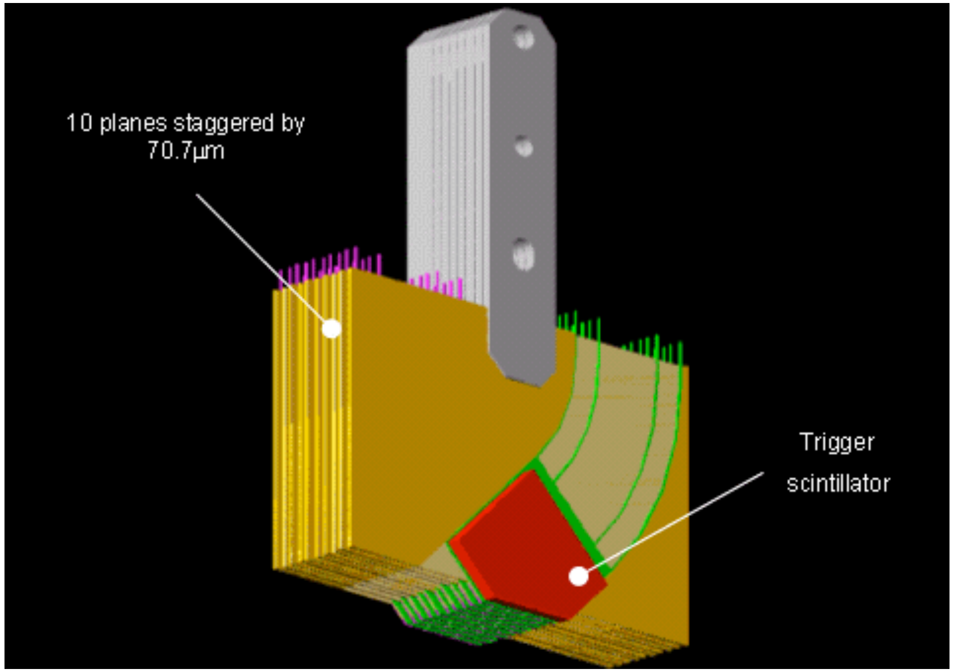
Concept

- 2 × 10 U planes
- 2 × 10 V planes



- scintillating fibres
- 0.5 mm² square

planes are horizontally staggered by multiples of 70.7 micrometer



Summary - Coulomb

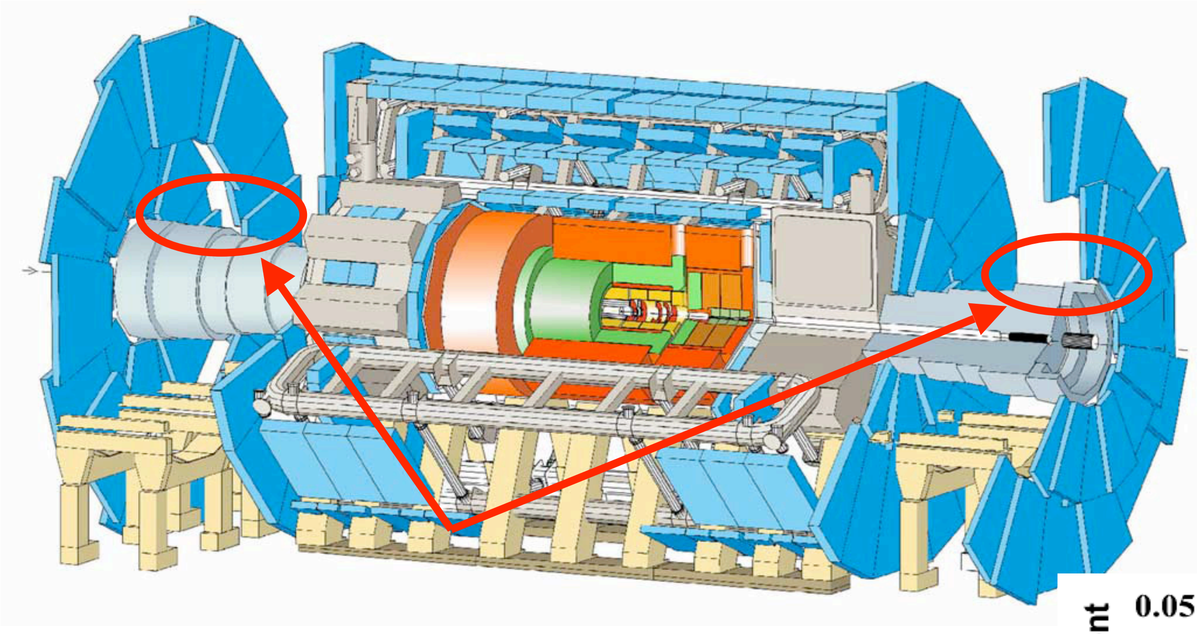
- Getting the Luminosity through Coulomb normalization will be extremely challenging due to the small angles and the required closeness to the beam.
- Main challenge is not in the detectors but rather in the required beam properties
- Will the optics properties of the beam be known to the required precision?
- Will it be possible to decrease the emittance as much as we need?
- Will the beam halo allow approaches in the mm range?

No definite answers before LHC start up

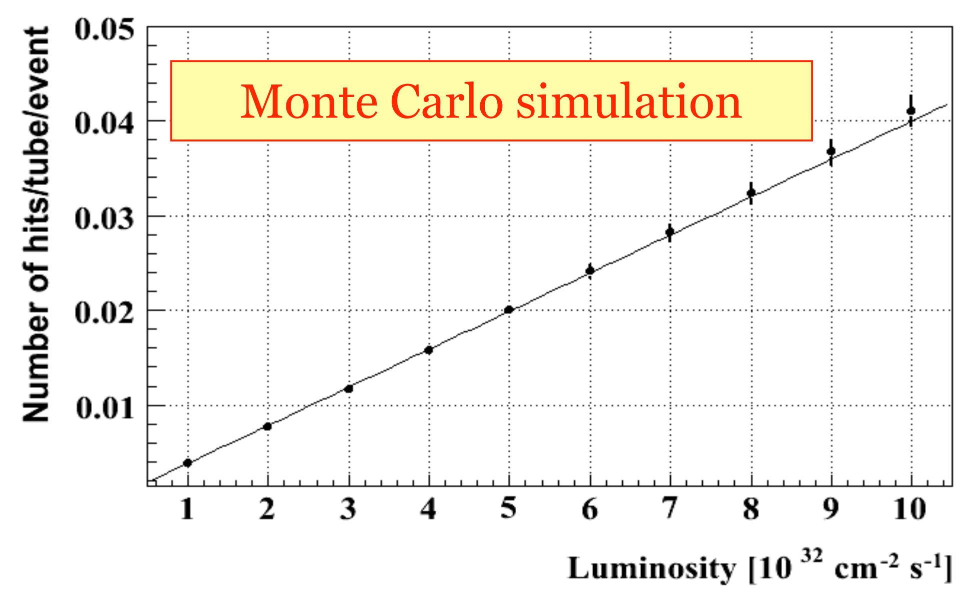
- UA4 achieved a precision using this method at the level of 2-3 % but at the LHC it will be harder .....

Relative measurement

LUCID in ATLAS



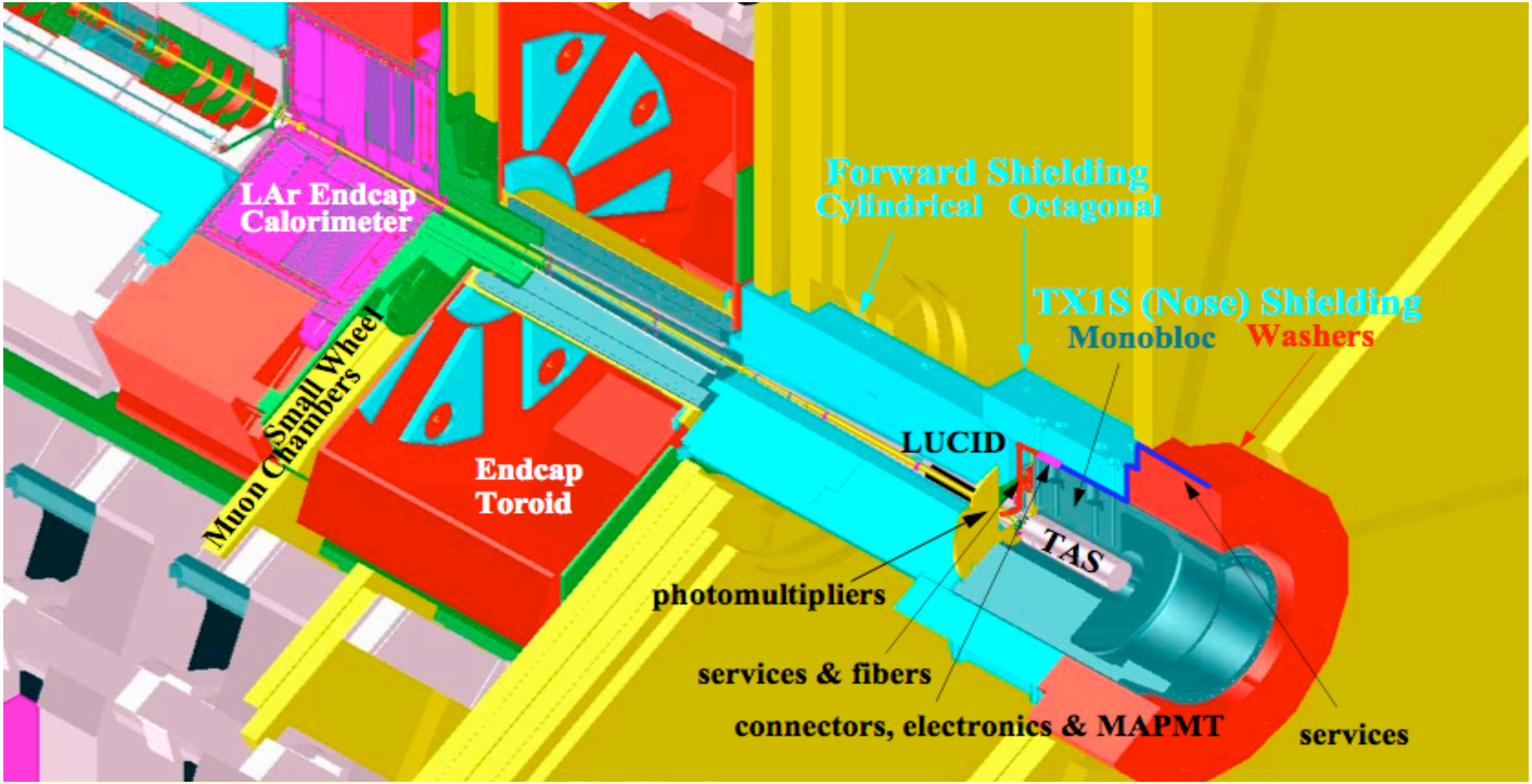
Two symmetrical arms at
17 m from the *pp* interaction region.



- Measure the LHC luminosity.
- Count the number of charged particles per BX, pointing to the primary *pp* interactions.

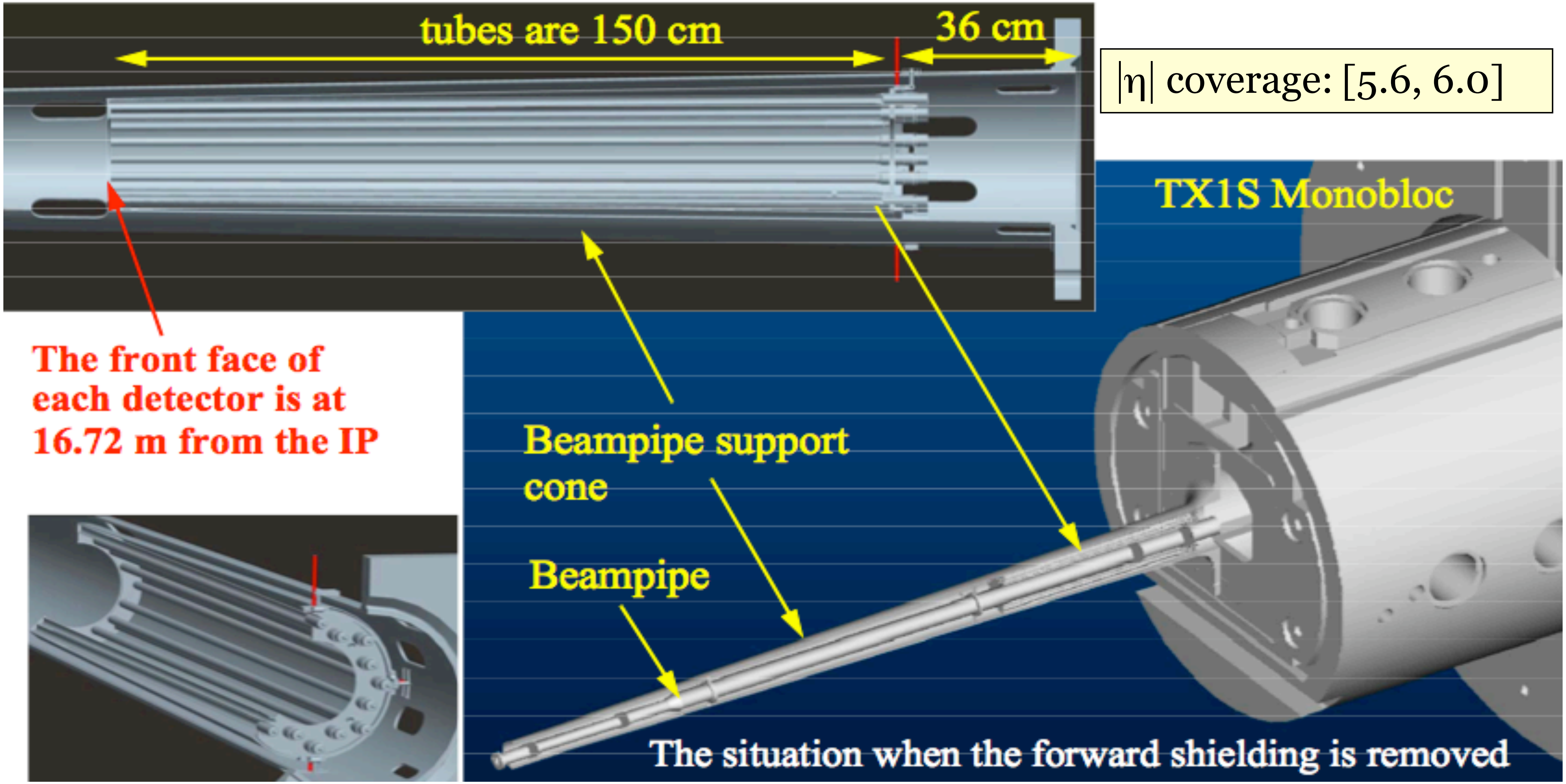
Relative measurement

LUCID location



Expected dose: 7 Mrad/year @ higest luminosity (10^{34} cm^{-2}s^{-1})

LUCID detector



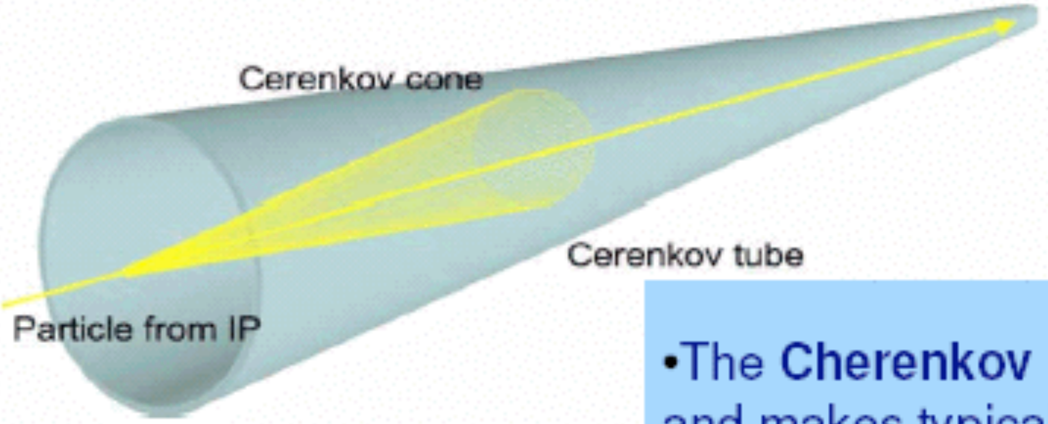
The front face of each detector is at 16.72 m from the IP

The situation when the forward shielding is removed

|η| coverage: [5.6, 6.0]

Array of mechanically polished Aluminum tubes in a Cherenkov gas (C_4F_{10}).
C_4F_{10} pressure mantained at 1.25/1.5 bar (Leak <10 mbar/day).

The basic detector concept



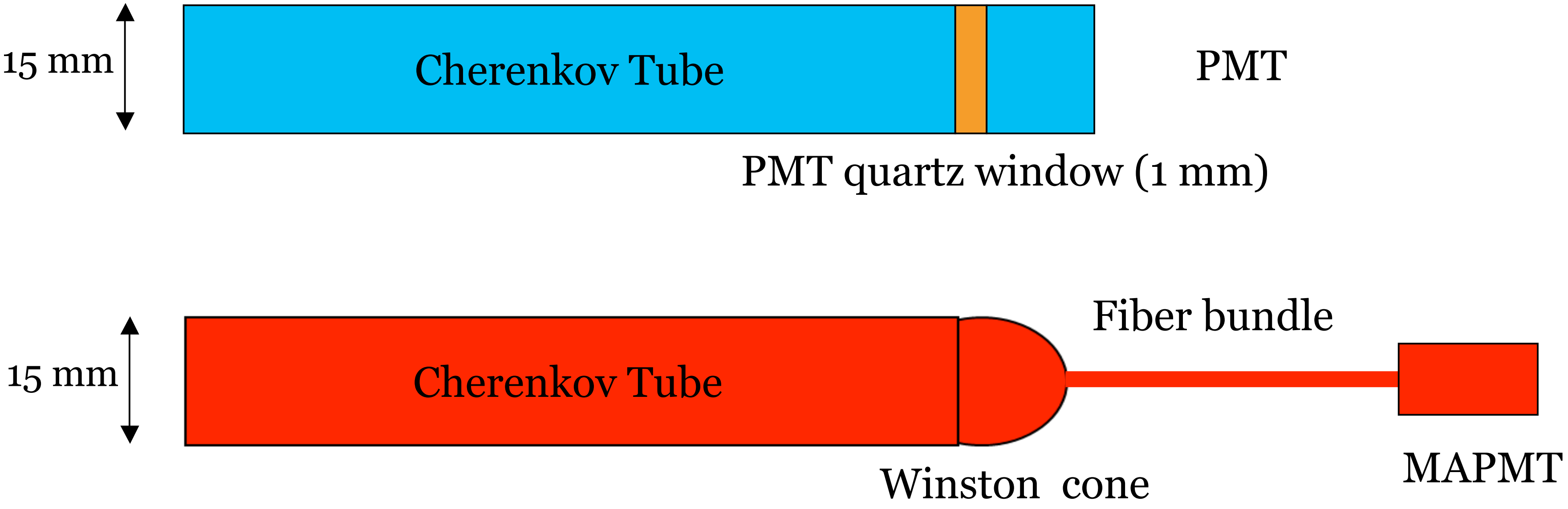
LUminosity measurement with a Cherenkov Integrating Detector

- The **Cherenkov light** is produced at a 3° angle and makes typically 3 reflections while passing down the tube.
- The **Cherenkov light** is read out by Photo Multipliers (PMT) at the end of the tubes

- The Cherenkov threshold (10 MeV for elec. and 2.8 GeV for pions) and the pointing of the tubes suppresses background
- The lack of Landau fluctuations makes it easier to count several particles going through the same tube.
- A good time resolution makes it possible to study individual beam crossings.

Read-Out scheme

Direct coupling to Photo-Multiplier Tubes (PMT, Hamamatsu R762).
PMT must be radiation hard.



15 mm

Cherenkov Tube

PMT

PMT quartz window (1 mm)

15 mm

Cherenkov Tube

Fiber bundle

Winston cone

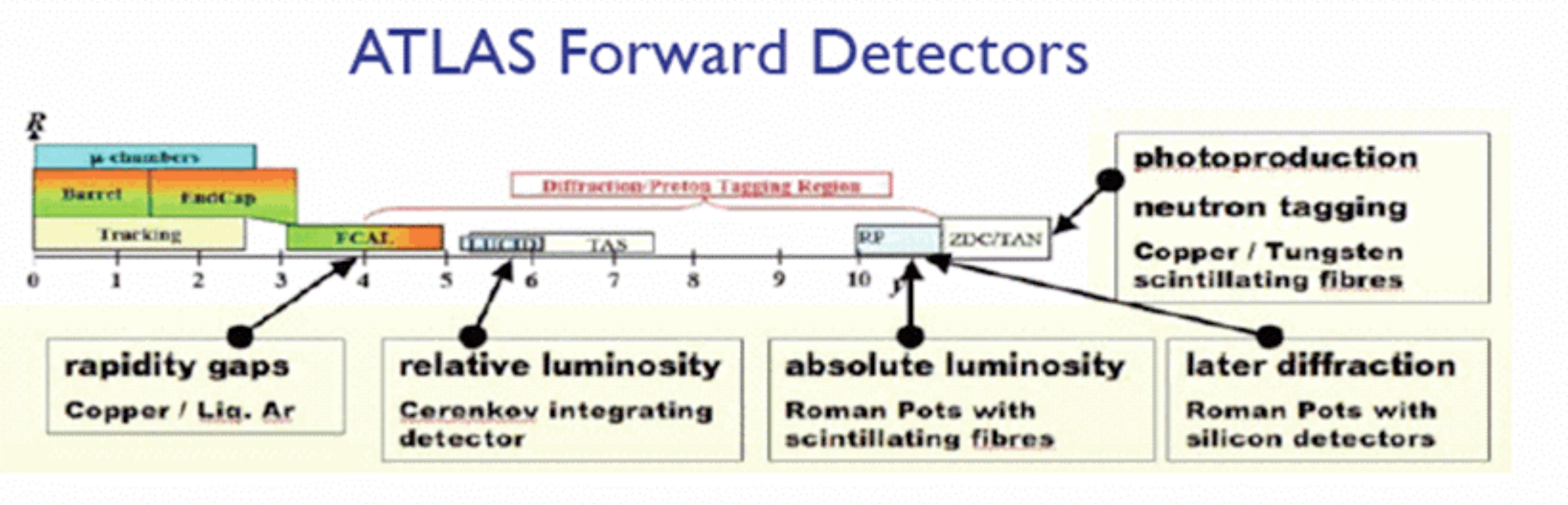
MAPMT

Optical fibers (PUV700) via Winston Cone to multi-anode PMT (Hamamatsu H7546B).
Better for high luminosity runs (MAPMT not exposed to high radiation doses).

Forward detectors – Forward Physics

Forward Physics Topics

- Total cross section
- Soft diffraction
- Hard Diffraction
- Small x physics – saturation
- Cosmic ray Monte Carlos
- Central exclusive Higgs production


ATLAS Forward Detectors

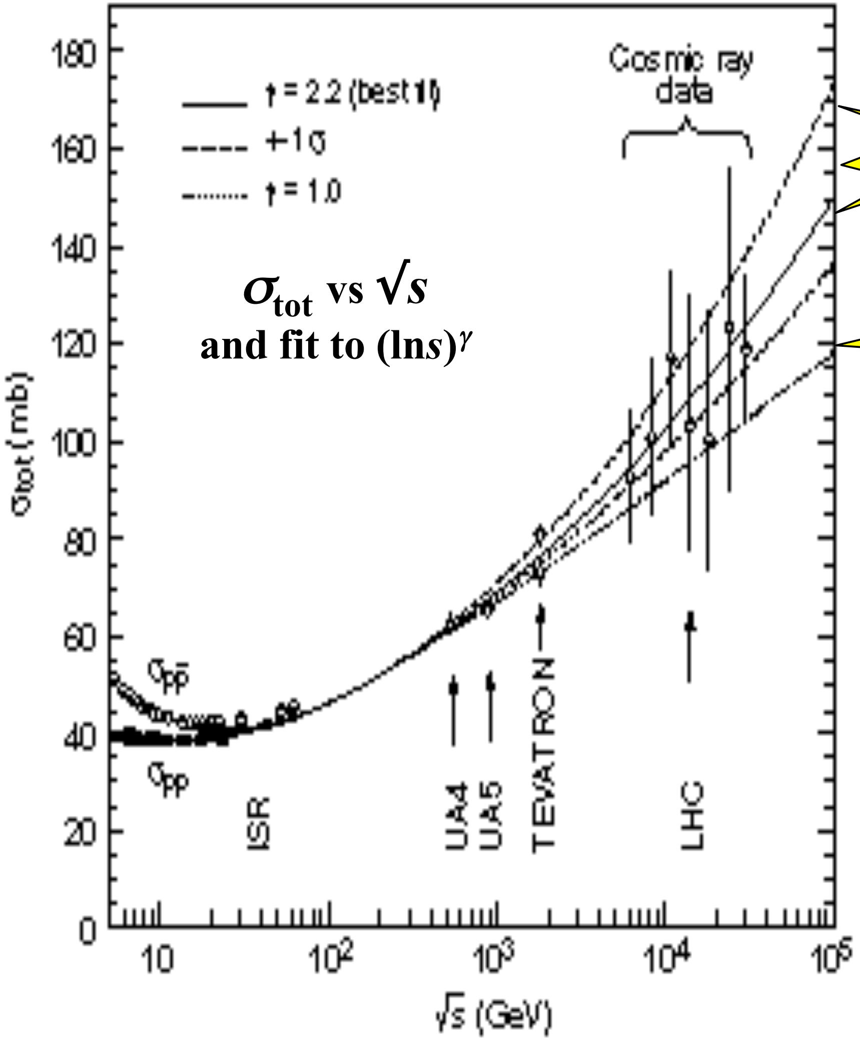
The total cross section

σ_{tot} is a fundamental parameter to be measured at any new energy regime.

σ_{tot} can be measured by measuring elastic scattering in the forward direct

Froissart-Andre bound

$\sigma_{tot} < \text{Const} \ln^2 s$



σ_{tot} vs $\sqrt{s}$
and fit to $(\ln s)^{\gamma}$

$\gamma = 2.2 \pm \sigma$ (best fit)

$\gamma = 1.0$

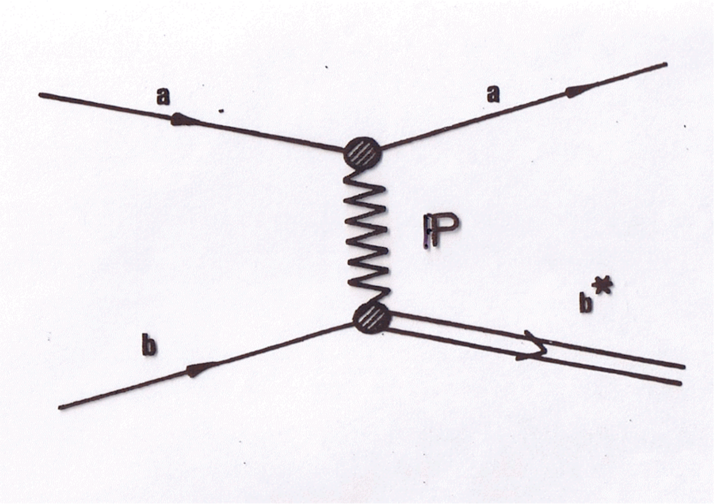
Diffraction

- Simplest diffractive process is elastic scattering
- However more general: diffraction occurs when there is no exchange of quantum number:

$$a + b \rightarrow a^* + b^*$$

where a^* and b^* have the same quantum numbers as a and b

POMERON



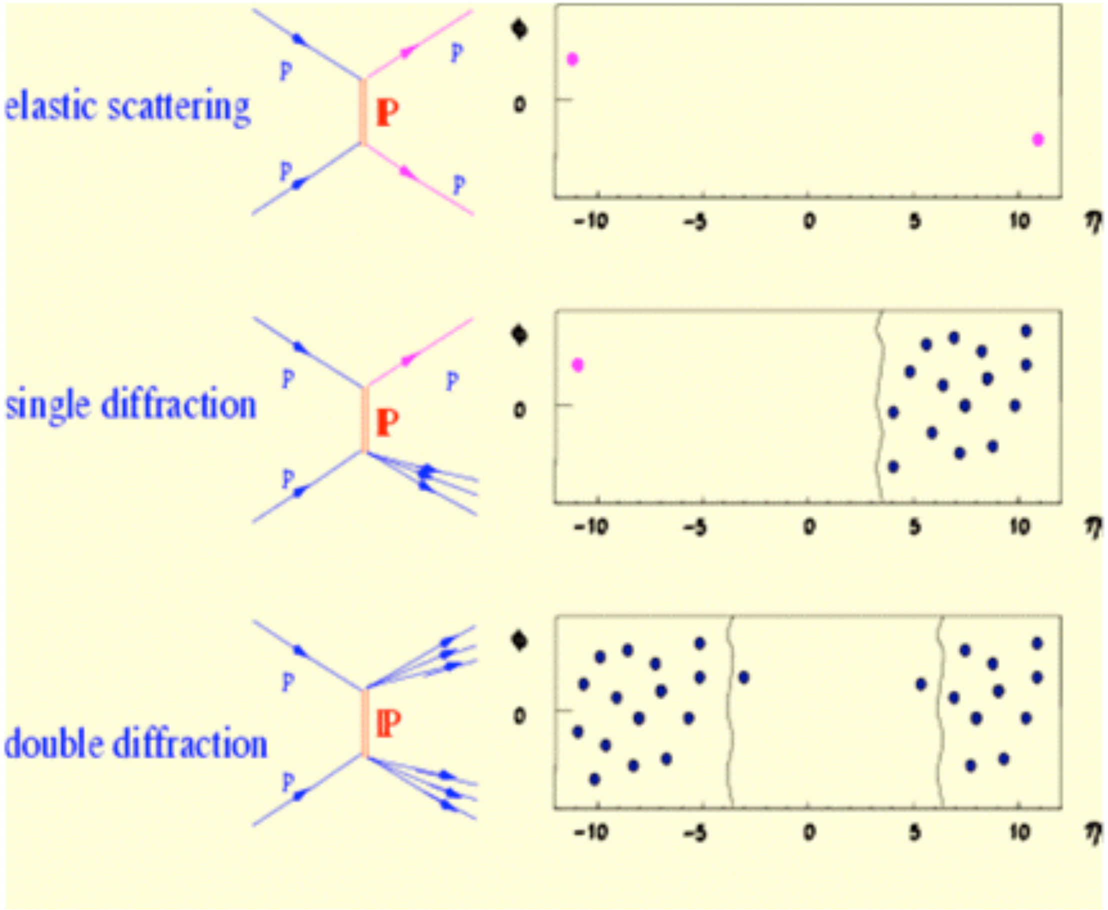
No colour flow

(the Pomeron is a colour singlet)

Gluon radiation suppressed

⇒ Rapidity gaps

Diffraction



Impossible to go beyond phenomenology to describe soft diffraction

Diffraction (soft) is outside realm of perturbative QCD

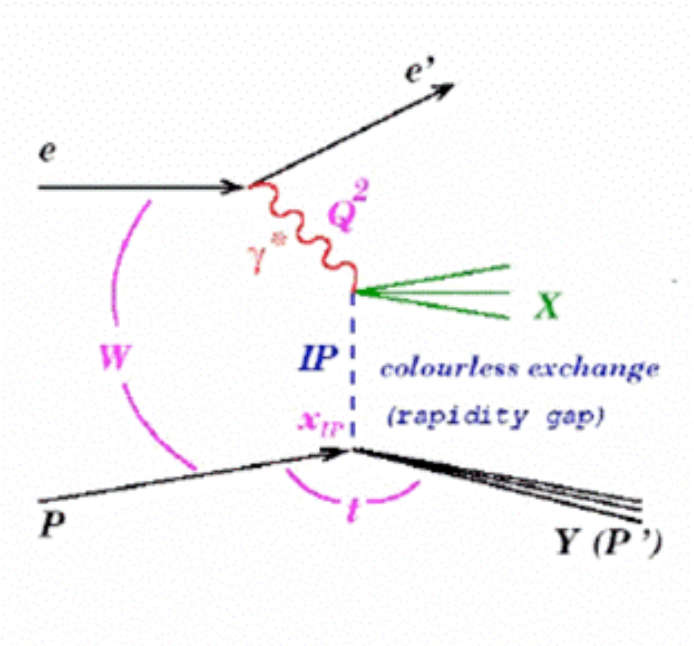
Constitutes 20 % of total inelastic cross section

Important for understanding of pile-up and underlying event

Hard diffraction

Striking discovery at HERA

~ 10 % of event in DIS has a leading proton and a large rapidity gap between proton remnant and other hadrons



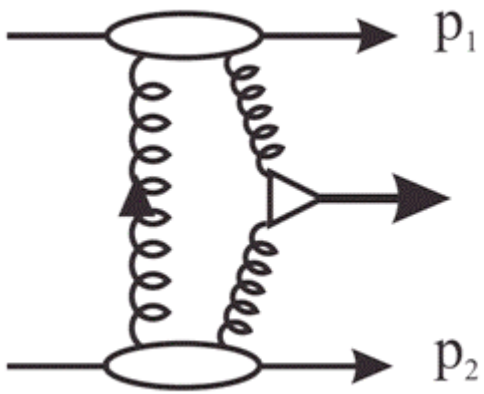
Combines features of hard and soft scattering

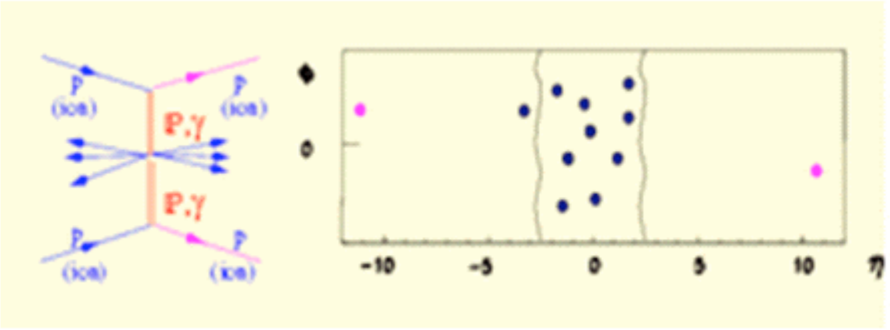
- The electron receives large momentum transfer-High photon virtuality
- The proton hardly change momentum

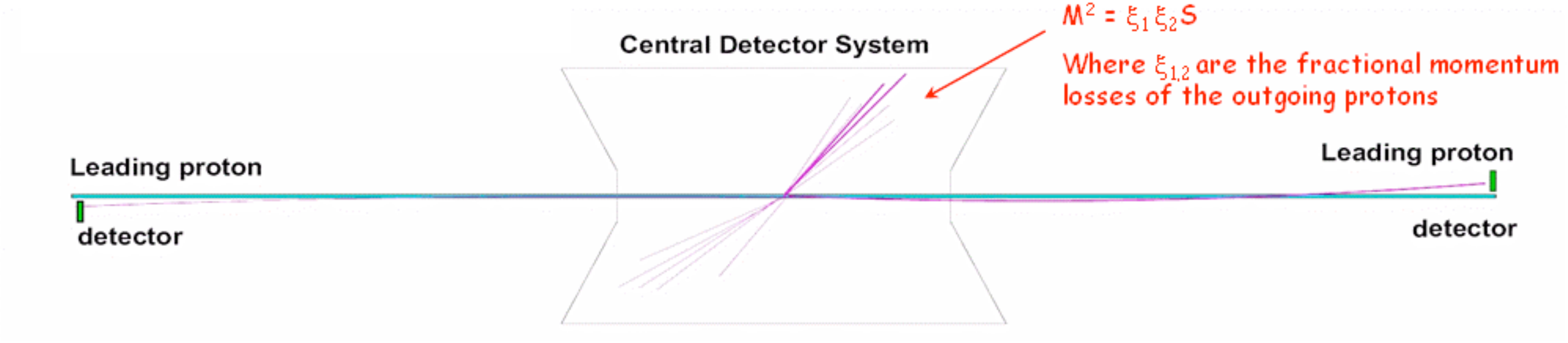
Hard diffraction at LHC

Example: Central Exclusive Production of heavy particles

The full diffractive energy is used to create a hard system in the central rapidity region and no remnants of the diffractive interactions.





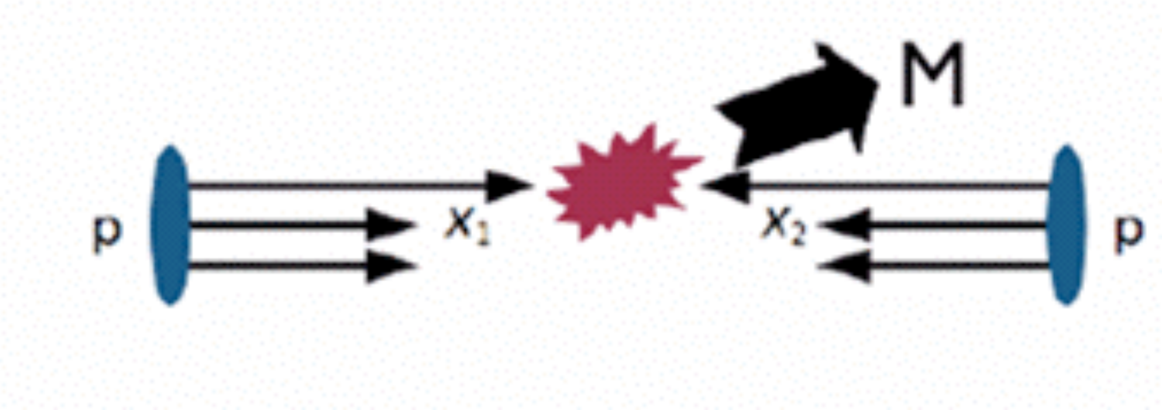


$M^2 = \xi_1 \xi_2 s$

Where $\xi_{1,2}$ are the fractional momentum losses of the outgoing protons

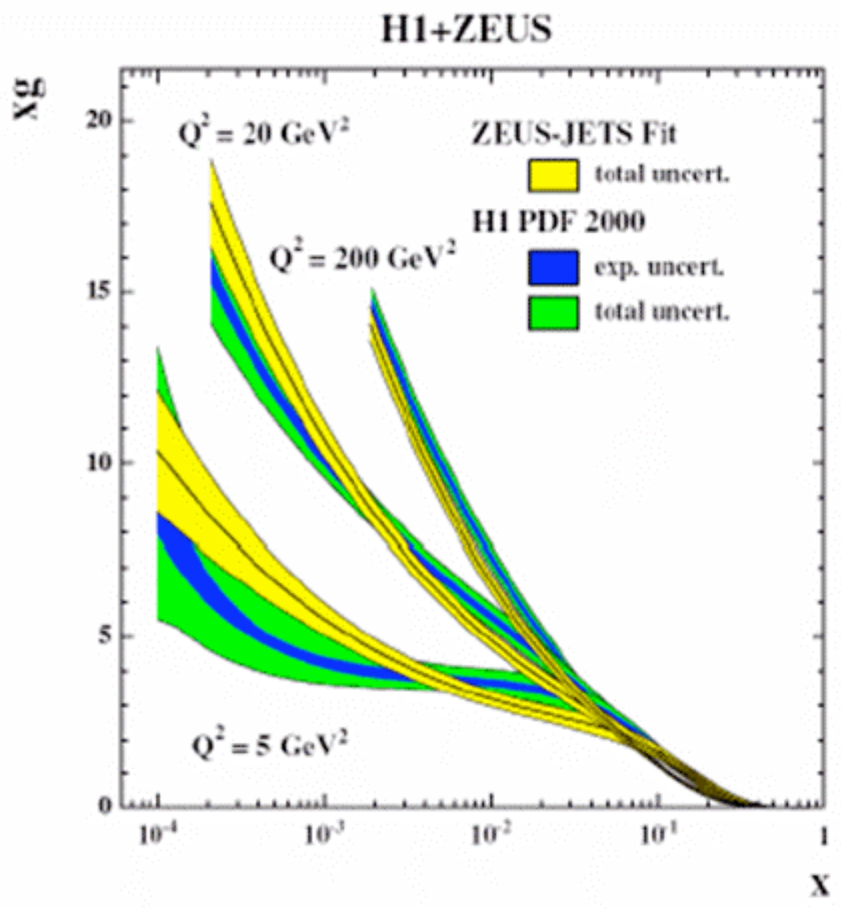
Low x physics

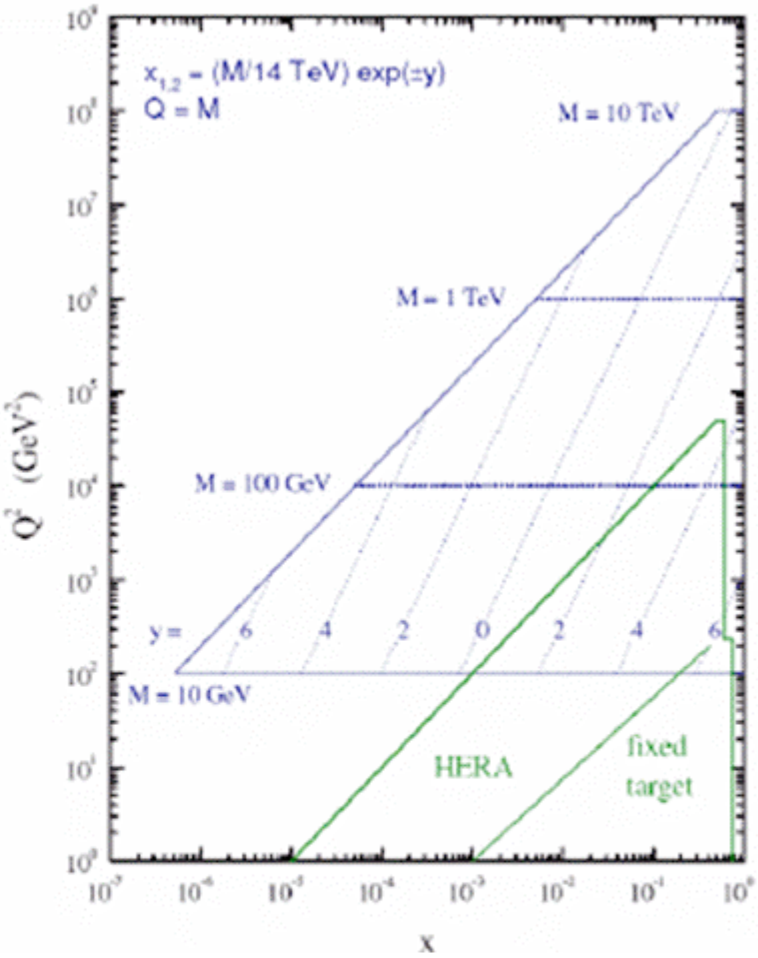
Forward energy flow related to low-x physics



M goes forward if x2 << x1
i.e one parton must have low-x

Low x physics





Strong rise at low-x observed at HERA

What happens at the LHC?

Can saturation be seen??

Overall conclusions

- We have looked at the principle methods for luminosity determination at the LHC

- Each method has its weakness and its strength

- Accurate luminosity determination is difficult and will take time (cf Tevatron). First values will be in the 20 % range.

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

- We better exploit different options in parallell

- In addition: Forward Detectors give access to a rich forward physics program

Back up

How to select events and eliminate background(N-BG)

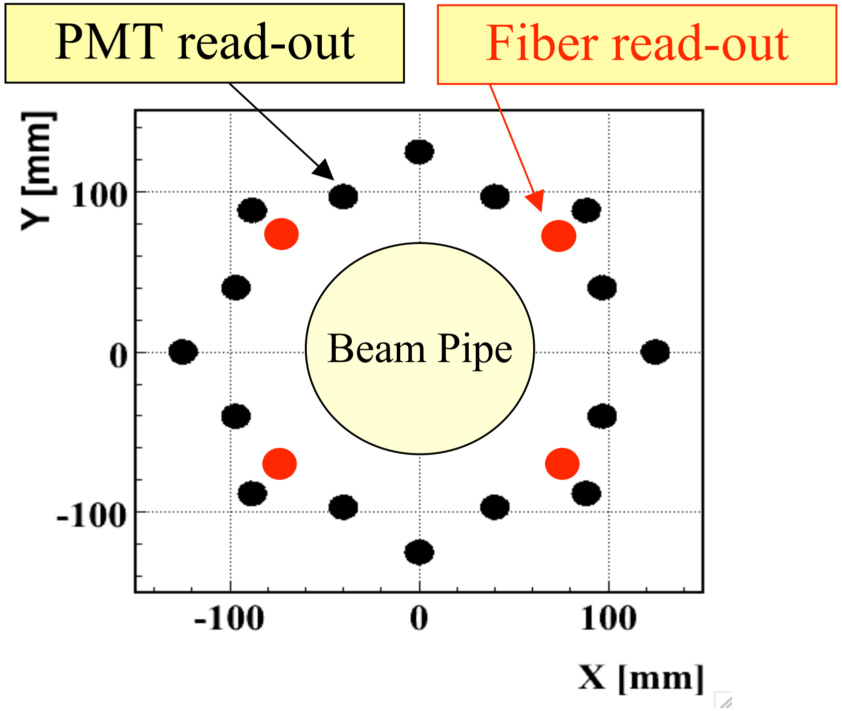
- QCD background and heavy quarks
- $Z \rightarrow e^+e^-$ where the second lepton is not identified

  $Z \rightarrow \tau^+\tau^-$ where one τ decay in the electron channel
- ttbar background
- $W \rightarrow \tau \rightarrow l$; τ decaying in the electron channel

- Pseudorapidity $\eta < 2.4$ (no bias at edge)
- $P_t > 25$ GeV (efficient electron ident)
- Missing $E_t > 25$ GeV
- No jets with $P_t > 30$ GeV (QCD background)

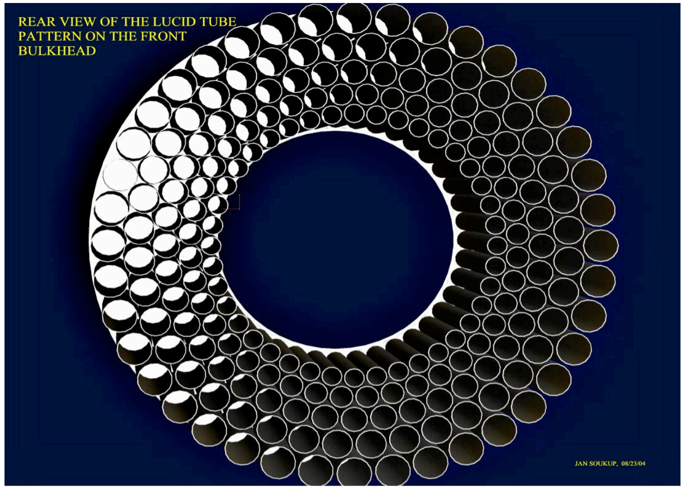
Phase I and II detectors

PHASE 1 - Low luminosity	PHASE 2 - High luminosity
L < 10^{33} cm^{-2} s^{-1} [end 2009] Goal: σ_{sys}~4-5% + σ_{pp} [CDF:~4%]	L = 10^{34} cm^{-2} s^{-1} [after 2009] Goal: σ_{sys}~2-3% + σ_{pp}



PMT read-out

Fiber read-out

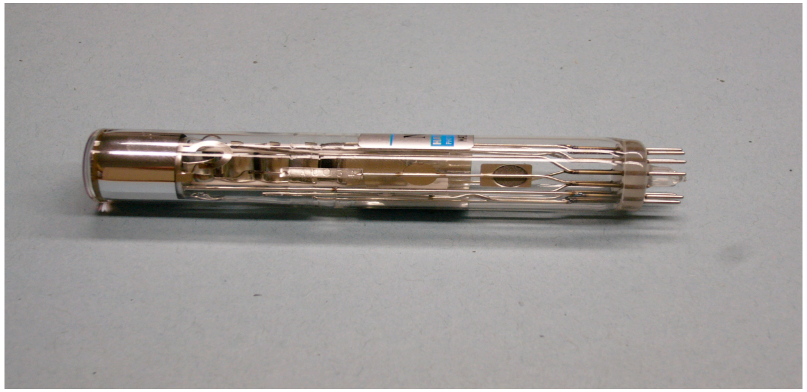


LUCID under construction

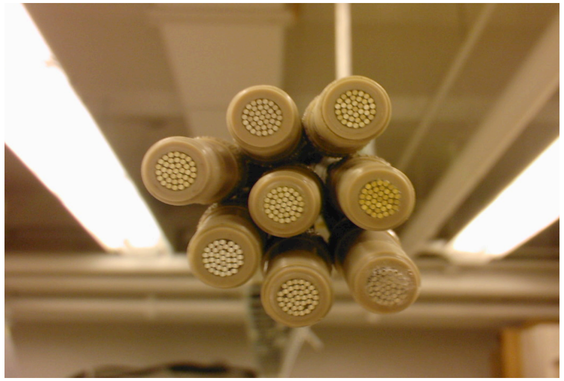
LUCID vessel

Cherenkov tubes

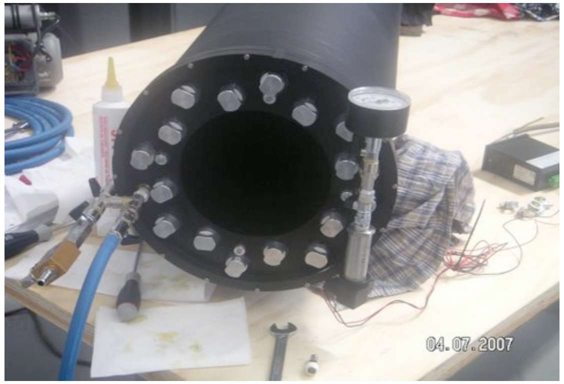
PMT (Hamamatsu R762)



PMT holders

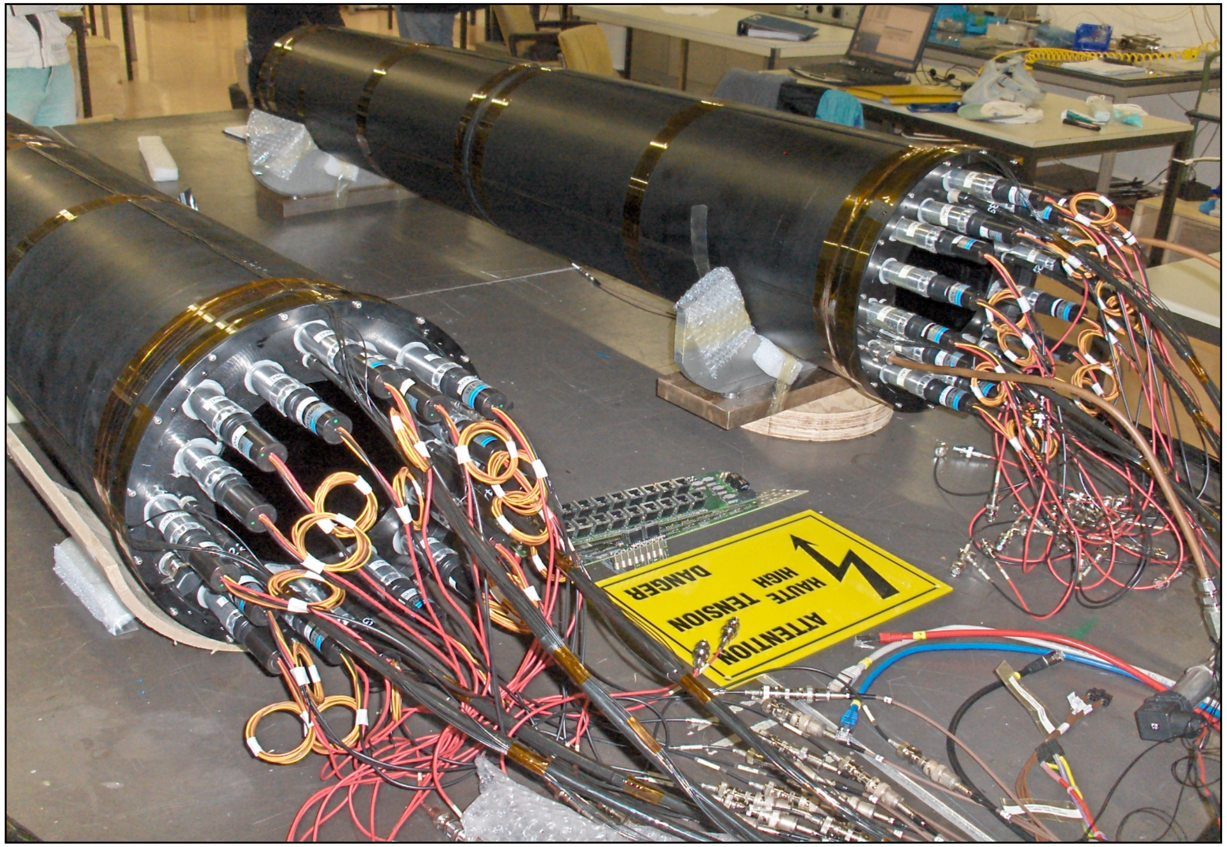


Fiber bundles



Gas pressure test

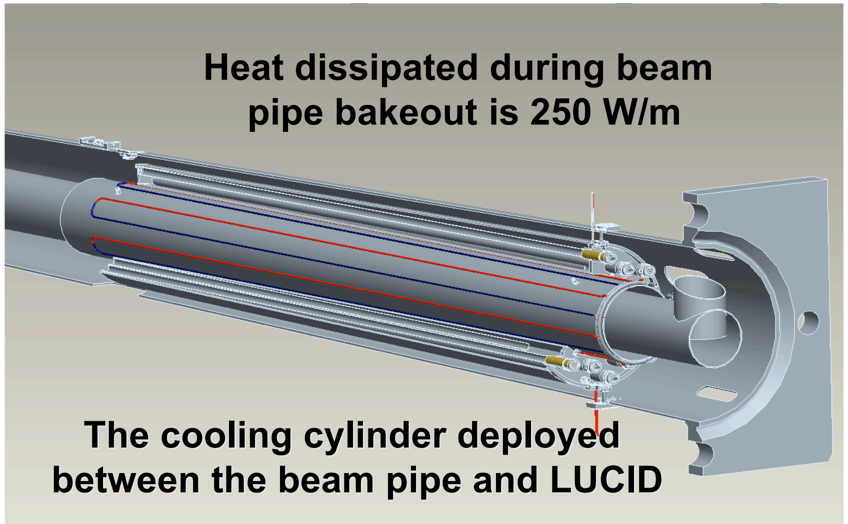
LUCID assembly



LUCID assembled at CERN by the Alberta, Bologna, LUND, CERN team.

LUCID cooling system

During beam pipe bake-out LUCID could reach ~250 °C.
The temperature must be well below 50°C (PMT specs.).

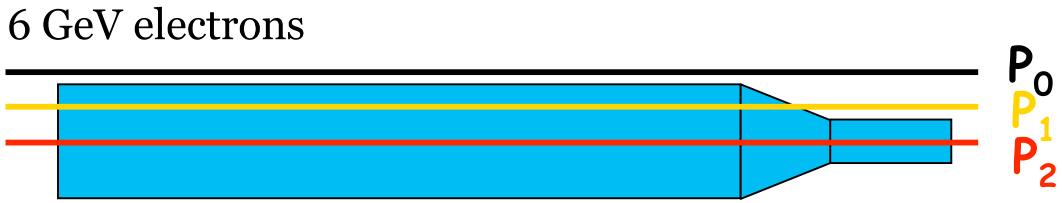


Heat dissipated during beam pipe bakeout is 250 W/m

The cooling cylinder deployed between the beam pipe and LUCID

Aluminum cylinder with 6 copper cooling loops (20 litres/hr each).
Assuming perfect connection between cooling pipes and Aluminum: T ~20°C.

Test Beam results: PMT read-out

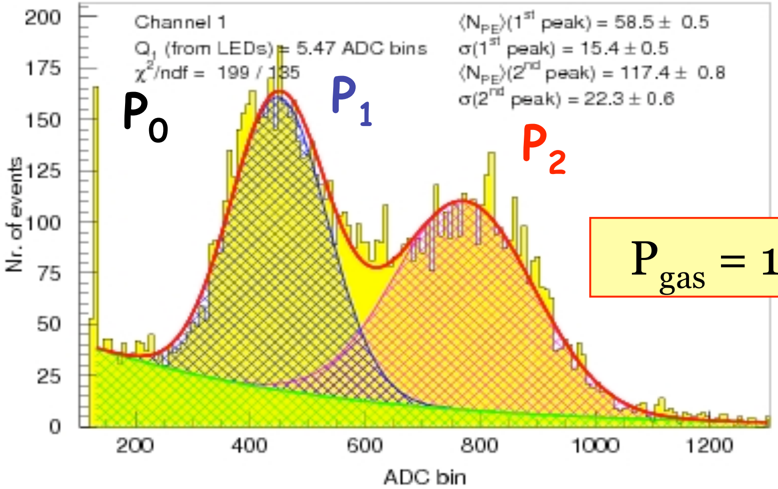


P_0 Particles not crossing the tube

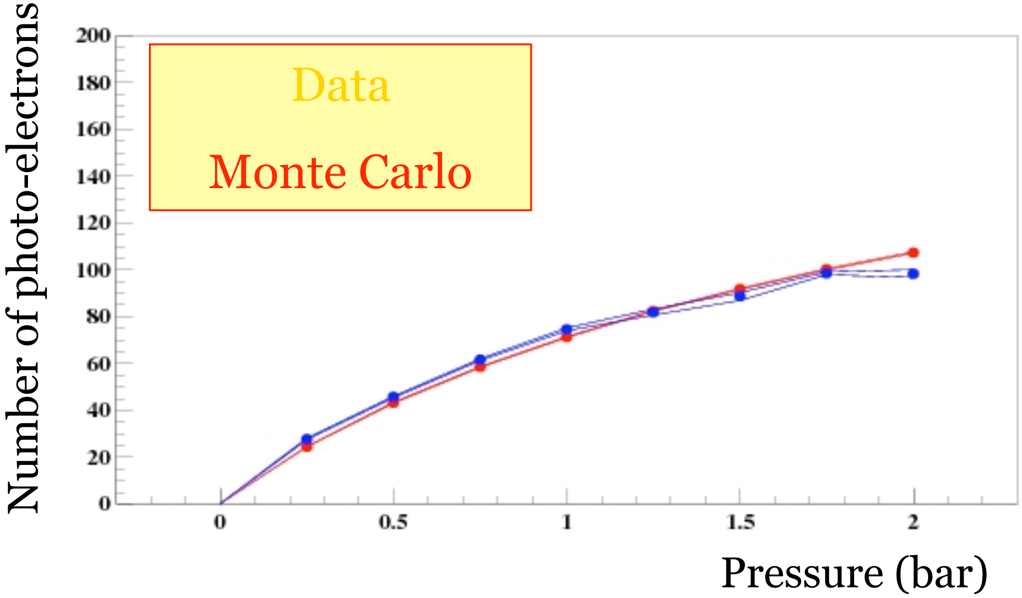
P_1 Photo-electrons in gas (70)

P_2 Photo-electrons in gas and PMT (120)

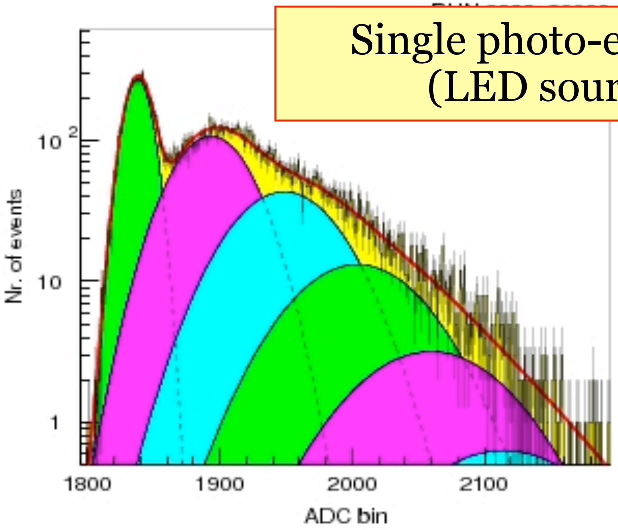
The signal from the PMT quartz window is at lower level.



P_{gas} = 1 bar

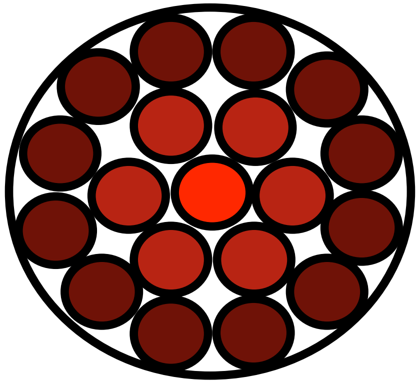


Single photo-electron (LED source)

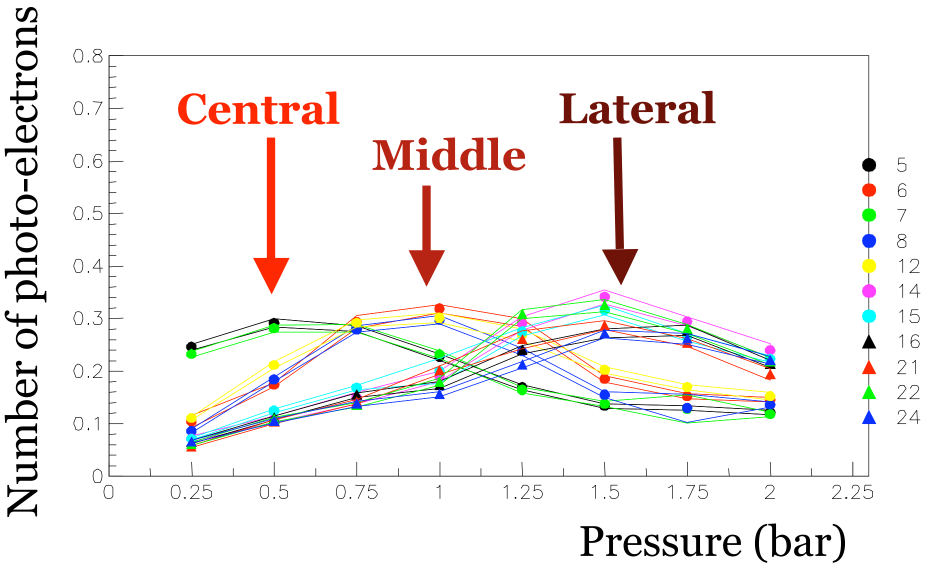


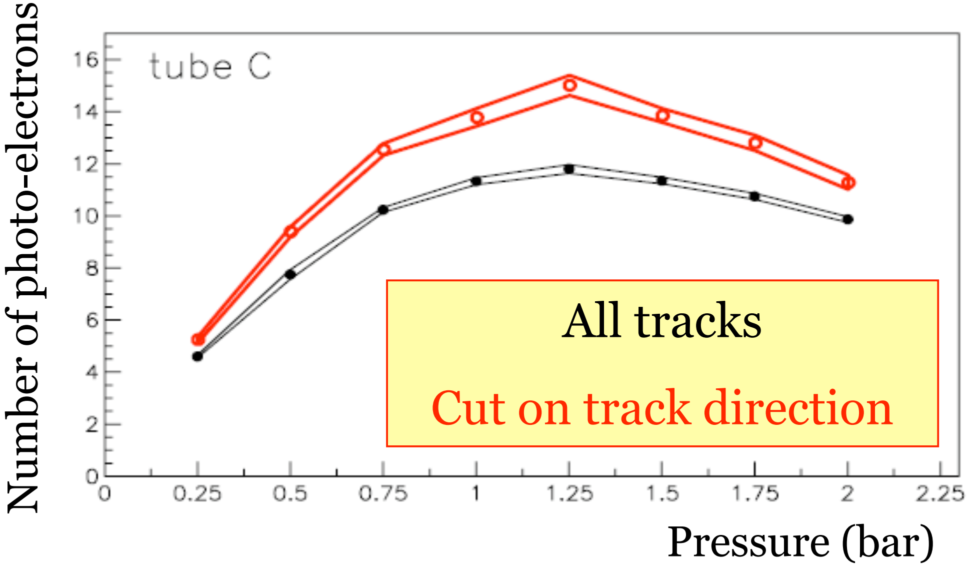
Test Beam results: Fiber read-out

Fiber Bundle



Maximum N_{pe} per tube = 12-15



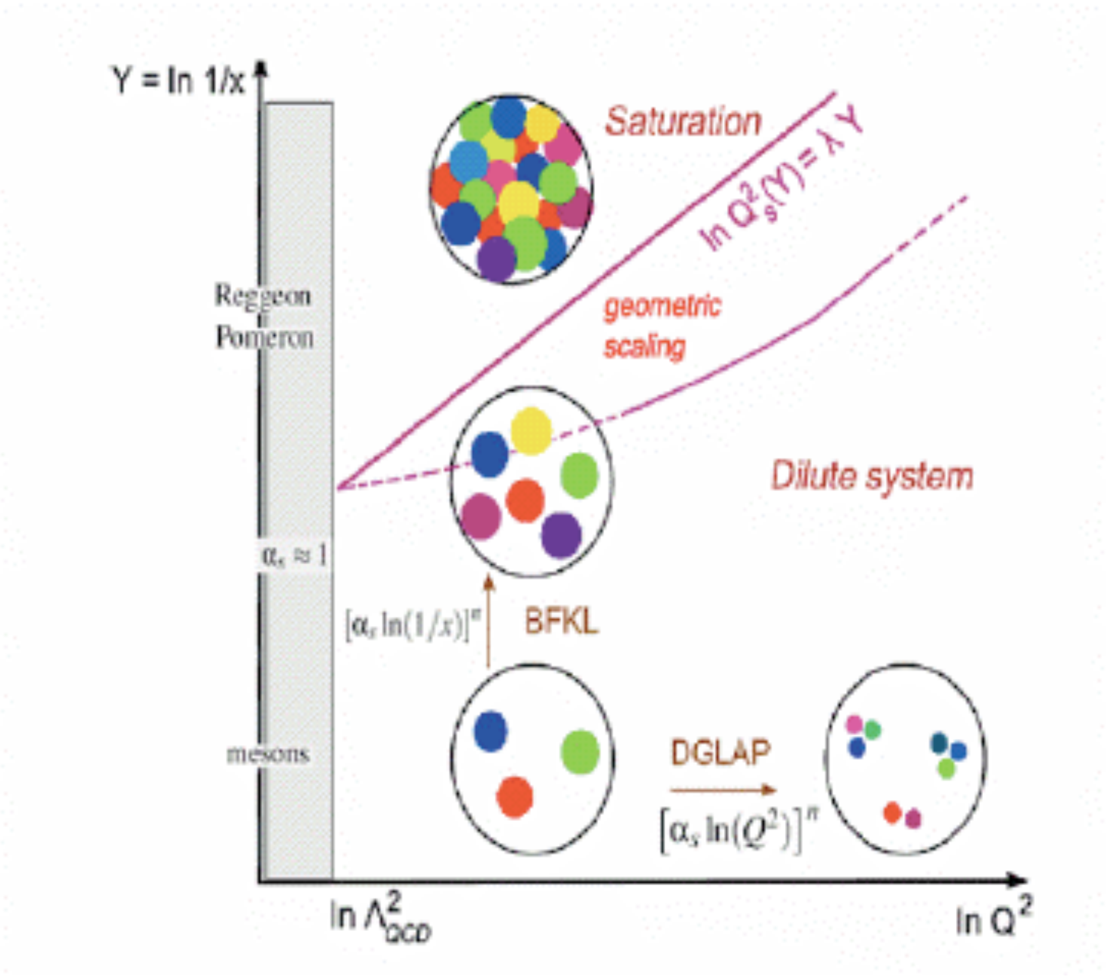


All tracks

Cut on track direction

Fiber read-out less efficient than PMT.

Low x physics



May be Gellis

$\rho \sim xG(x,Q^2)/\pi R^2$

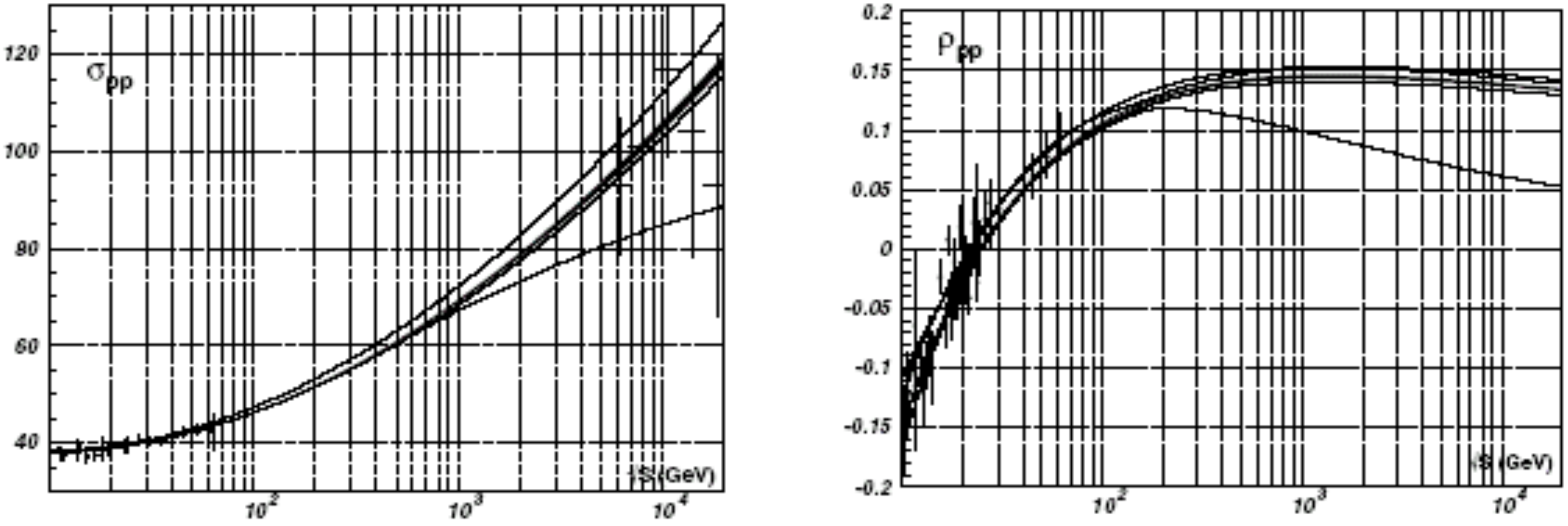
$\sigma \sim \alpha_s/Q^2$

$\rho\sigma > 1$

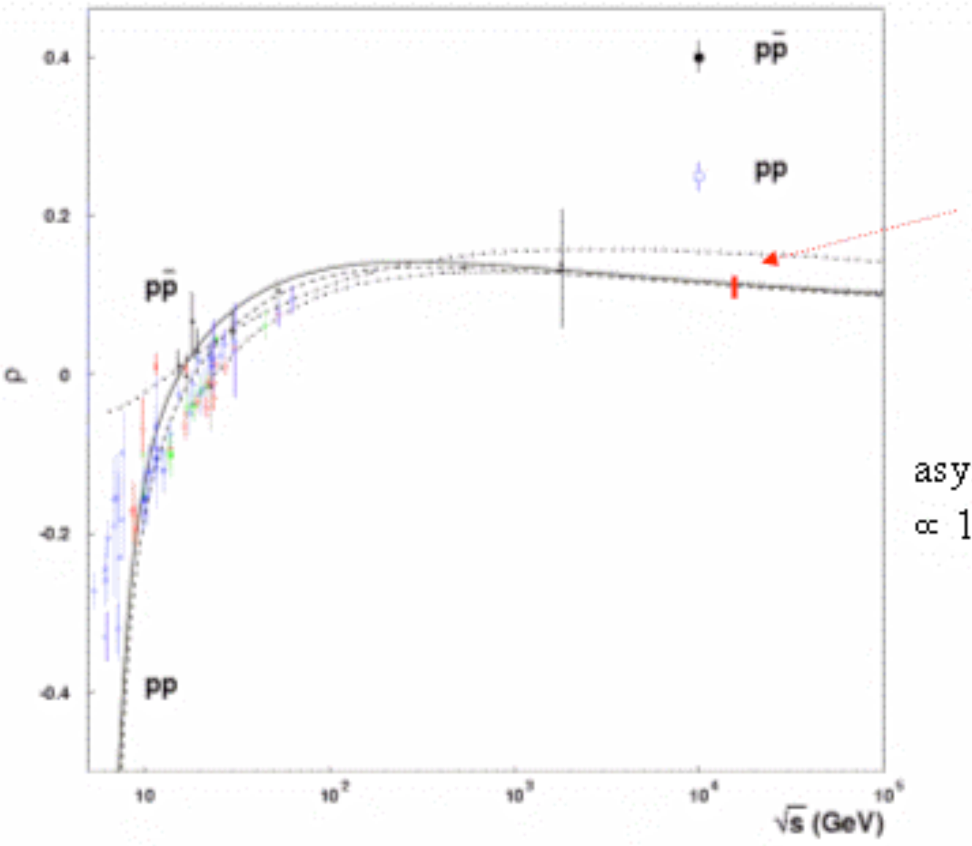
$Q^2_s = \alpha_s x\, G(x,Q^2s)/\pi\, R^2$

The ρ parameter

- ρ = Re F(0)/Im F(0) linked to the total cross section via dispersion relations
- ρ is sensitive to the total cross section beyond the energy at which ρ is measured
  $\Rightarrow$ predictions of σ_{tot} beyond LHC energies is possible
- Inversely :Are dispersion relations still valid at LHC energies?



Optical theorem



Prediction for LHC:

$$\rho = 0.1361 \pm 0.0015 \begin{array}{l} +0.0058 \\ -0.0025 \end{array}$$

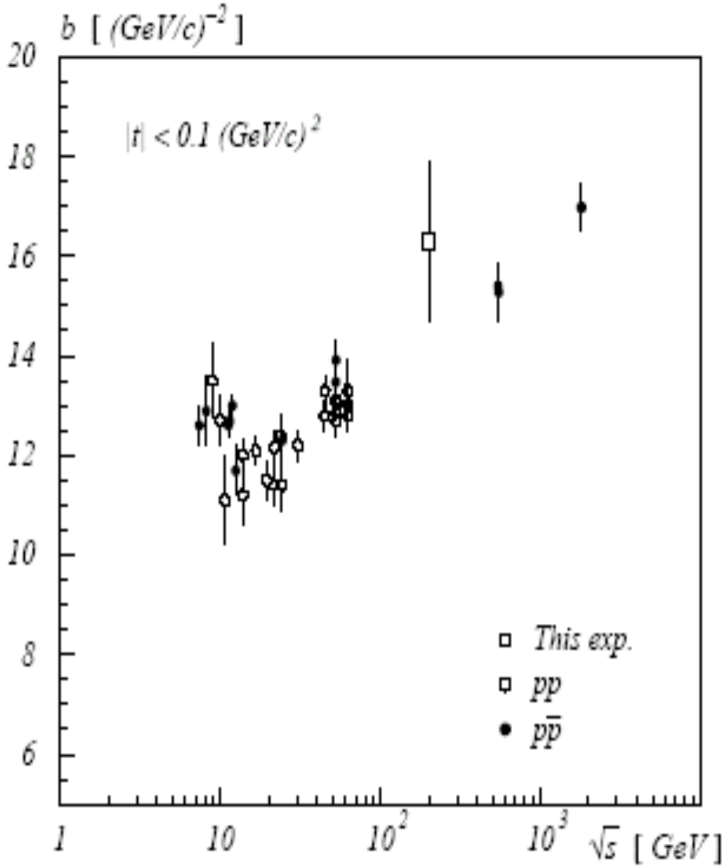
asymptotic behaviour:

$\propto 1/\ln s$ for $s \to \infty$

The b-parameter or the forward peak

- The b-parameter for $|t| < .1$ GeV^2
- "Old" language : shrinkage of the forward peak

  $b(s) \propto 2\,\alpha' \log s$; α' the slope of the Pomeron trajectory ; $\alpha' \approx 0.25$ GeV^2
- Not simple exponential - t-dependence of local slope
- Structure of small oscillations?



Coulomb

How to measure such small angles

One can easily show that for a parallell to point optics t_{min} is given by

$$t_{min} \propto n_d^2 \, \varepsilon_N / \beta^*$$

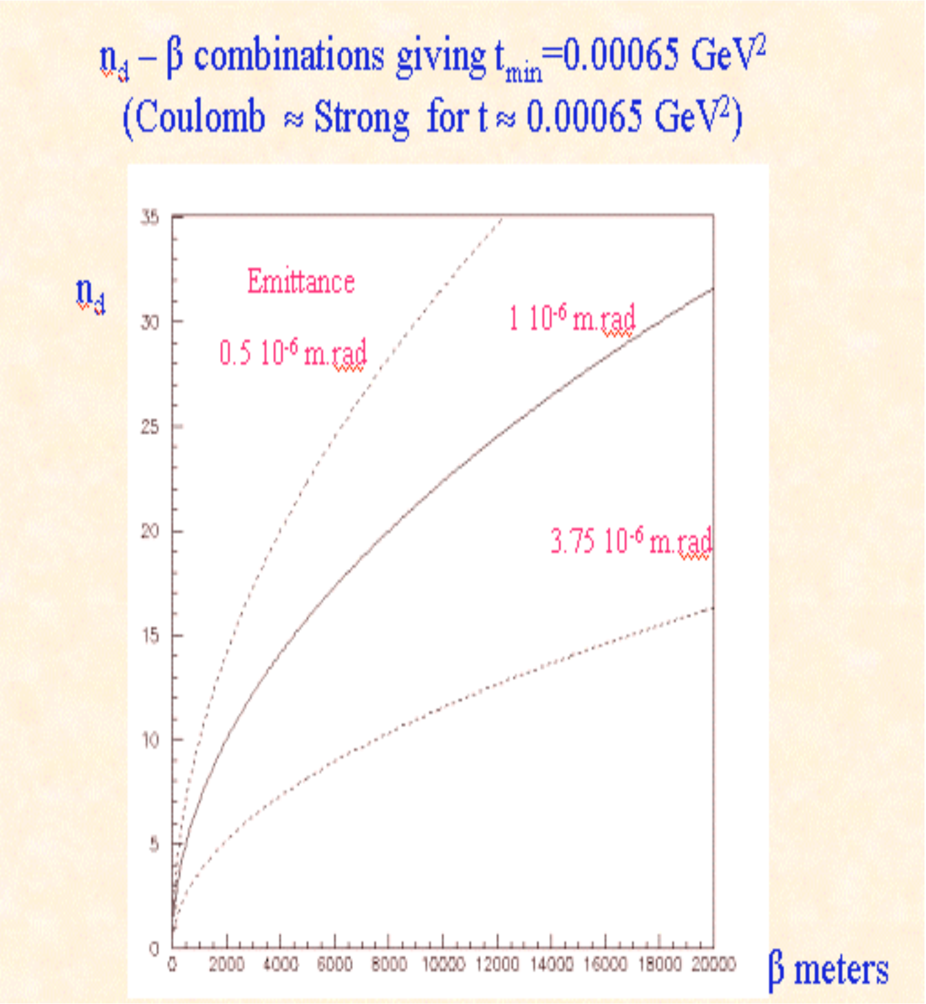
where

n_d = closes possible approach to the beam in units of the beam size at the detector

ε_N = Normalized emmitance of the beam

β^* = beta at the IP

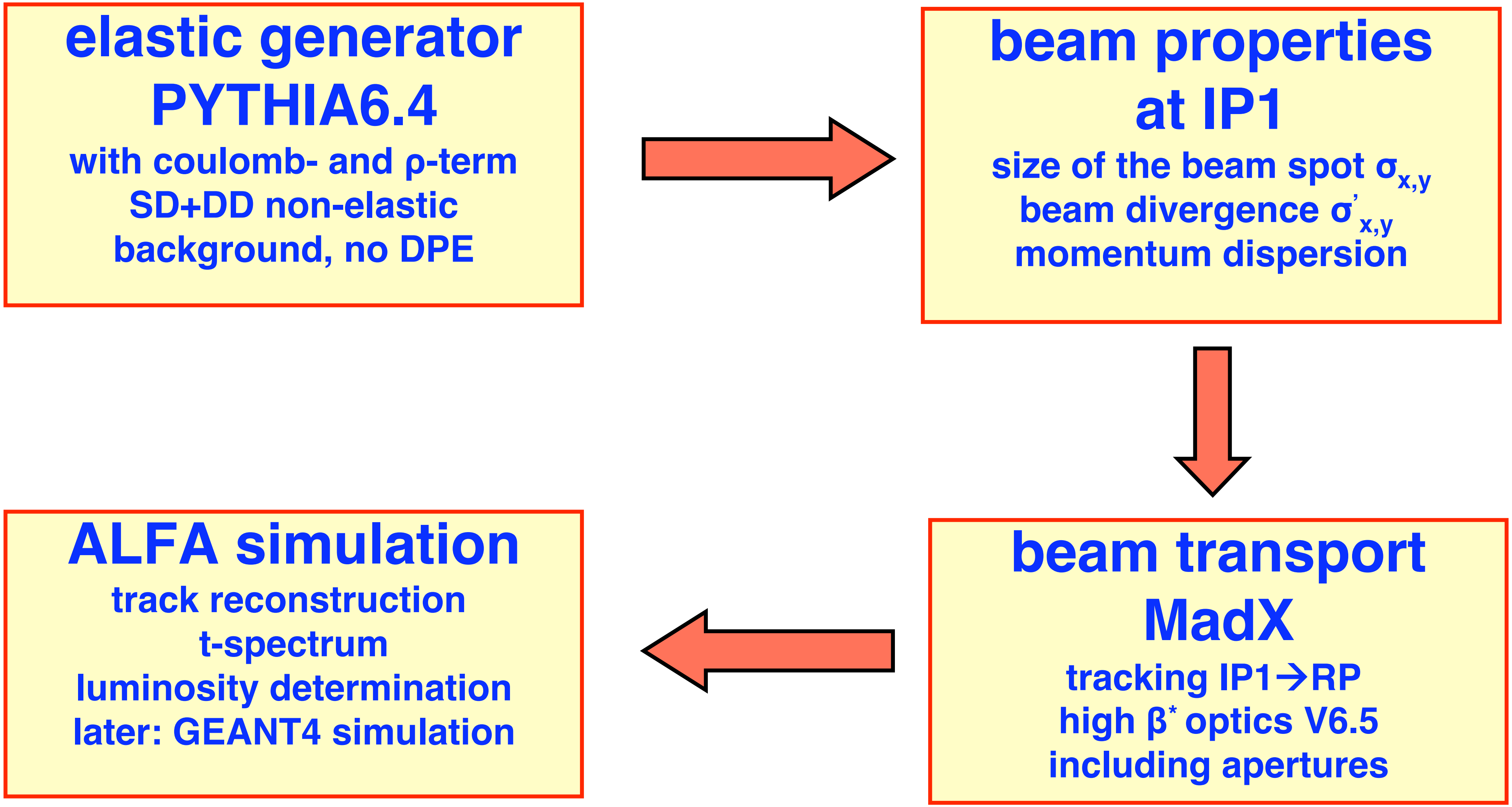
⇒ Hard work on all three parameters



n_d – β combinations giving t_{min}=0.00065 GeV^2

(Coulomb ≈ Strong for t ≈ 0.00065 GeV^2)

Simulation of the LHC set-up



elastic generator PYTHIA6.4

with coulomb- and ρ-term
SD+DD non-elastic
background, no DPE

beam properties at IP1

size of the beam spot $\sigma_{x,y}$
beam divergence $\sigma'_{x,y}$
momentum dispersion

beam transport MadX

tracking IP1→RP
high β^* optics V6.5
including apertures

ALFA simulation

track reconstruction
t-spectrum
luminosity determination
later: GEANT4 simulation

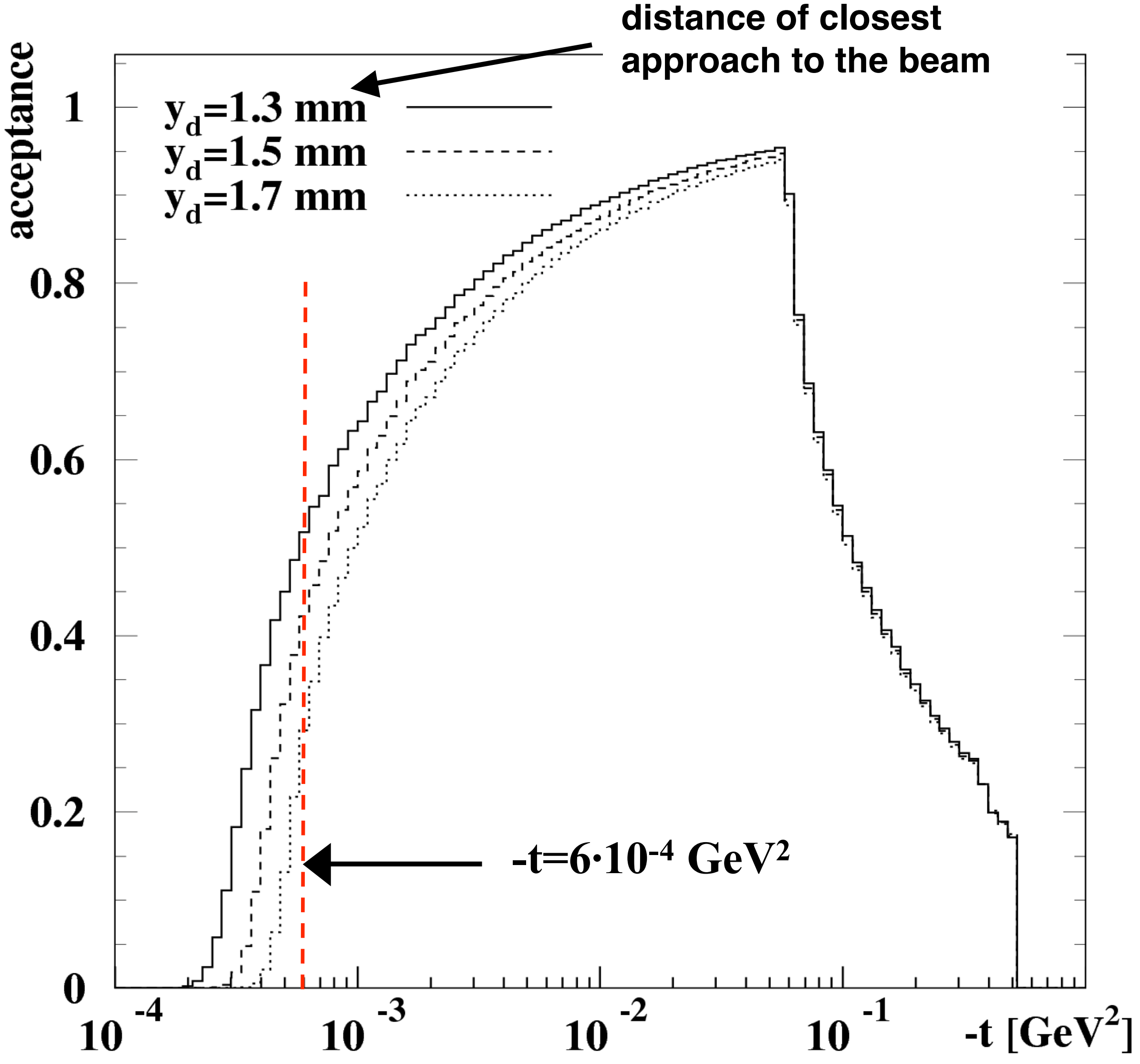
Acceptance

Global acceptance = 67% at yd=1.5 mm, including losses in the LHC aperture. Require tracks 2(R)+2(L) RP's.

Detectors have to be operated as close as possible to the beam in order to reach the coulomb region!

Coulomb Region : $|f_C| = |f_N|$

$$t \approx \frac{8\pi a_{EM}}{\sigma_{TOT}} \approx 6\times10^{-4}\ GeV^2 \rightarrow \theta \approx 3.5\mu rad$$

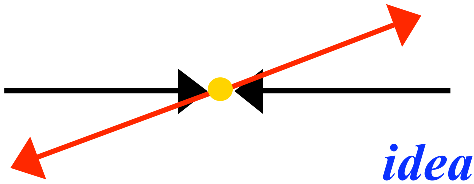

distance of closest approach to the beam

$-t = 6\cdot10^{-4}$ GeV²

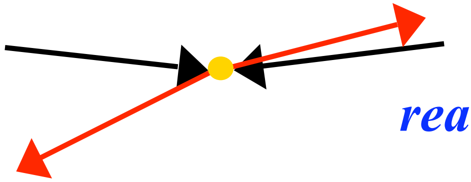
t-resolution

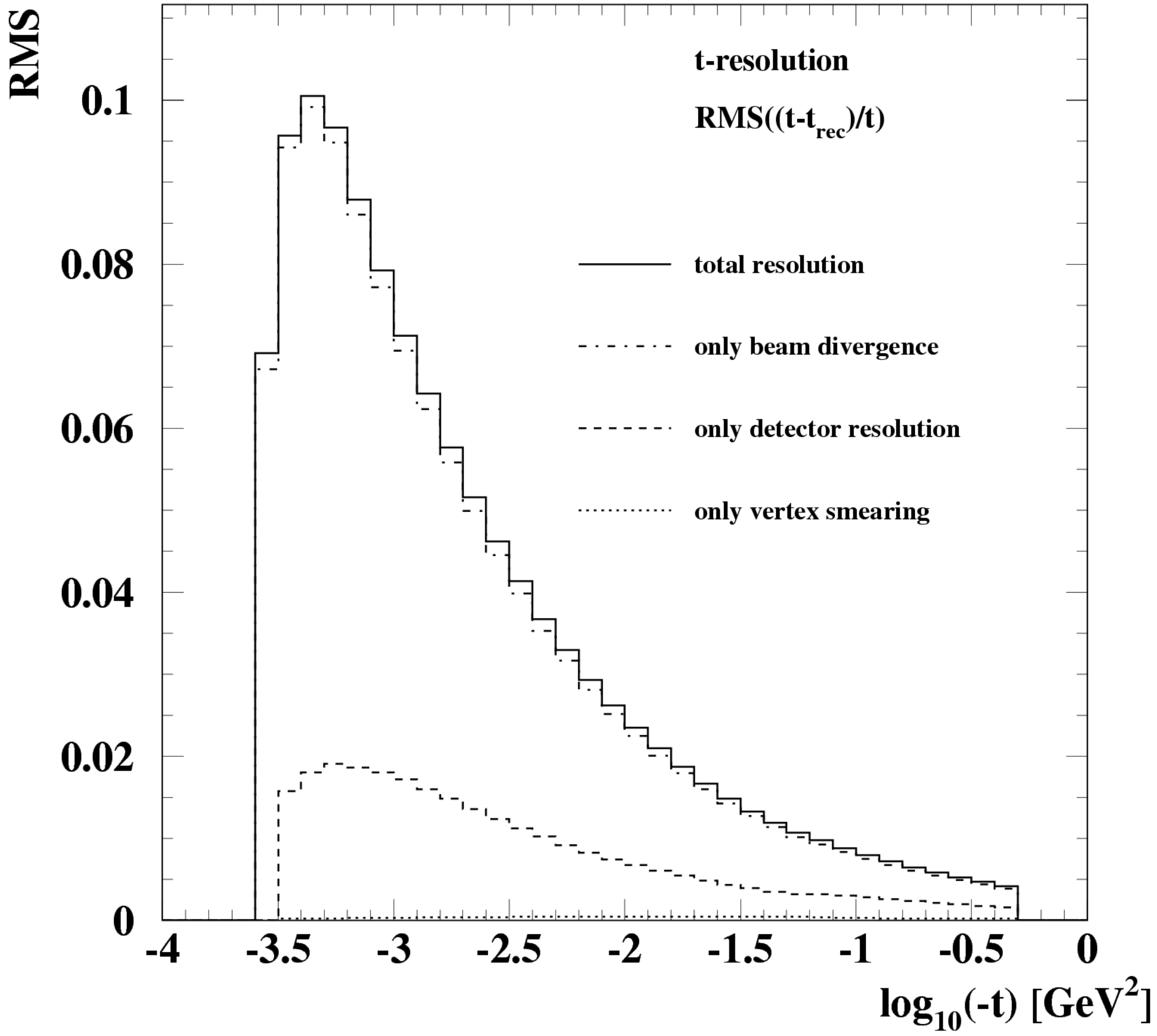
The *t*-resolution is dominated by the divergence of the incoming beams.

σ’=0.23 *μ*rad



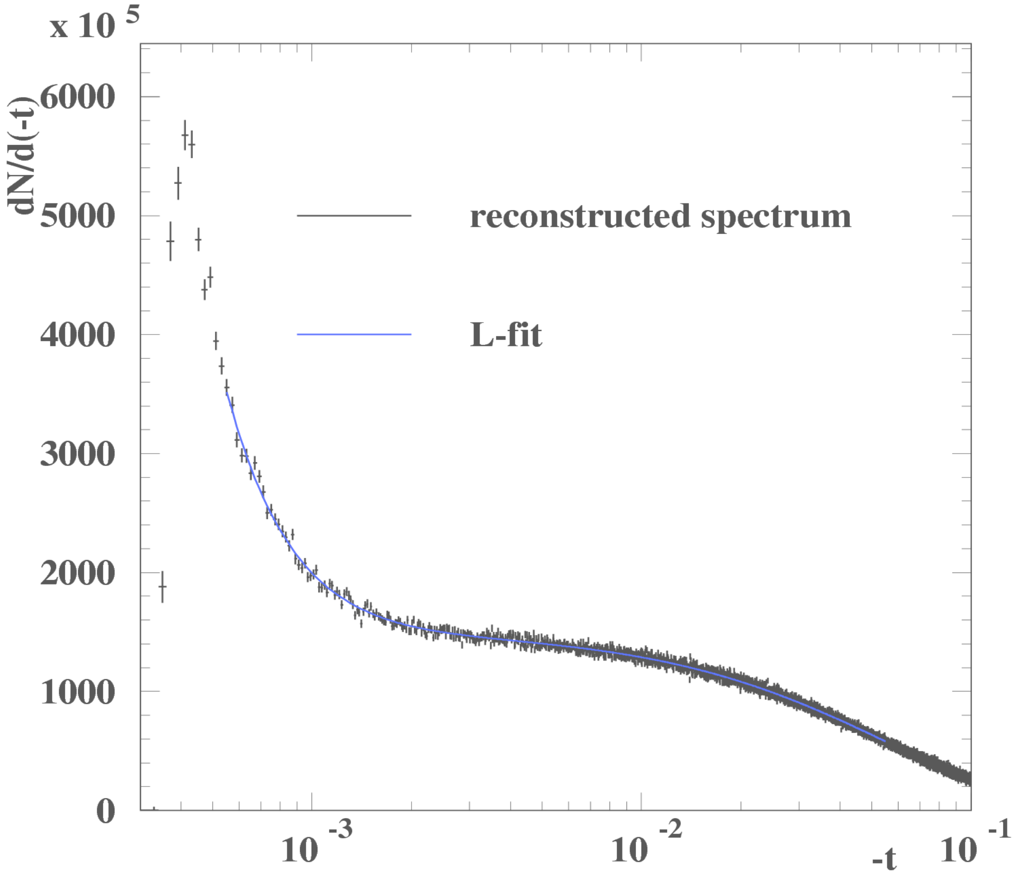
$$-\hat{t} = (p_1 - p_3)^2 \approx (p\theta^*)^2$$





L from a fit to the t-spectrum

$$\begin{aligned}\frac{dN}{dt} &= L\pi\left|F_C + F_N\right|^2 \\ &= L\left(\frac{4\pi\alpha^2(\hbar c)^2}{|t|^2} - \frac{\alpha\rho\sigma_{tot}e^{-B|t|/2}}{|t|} + \frac{\sigma_{tot}^2\left(1+\rho^2\right)e^{-B|t|}}{16\pi(\hbar c)^2}\right)\end{aligned}$$



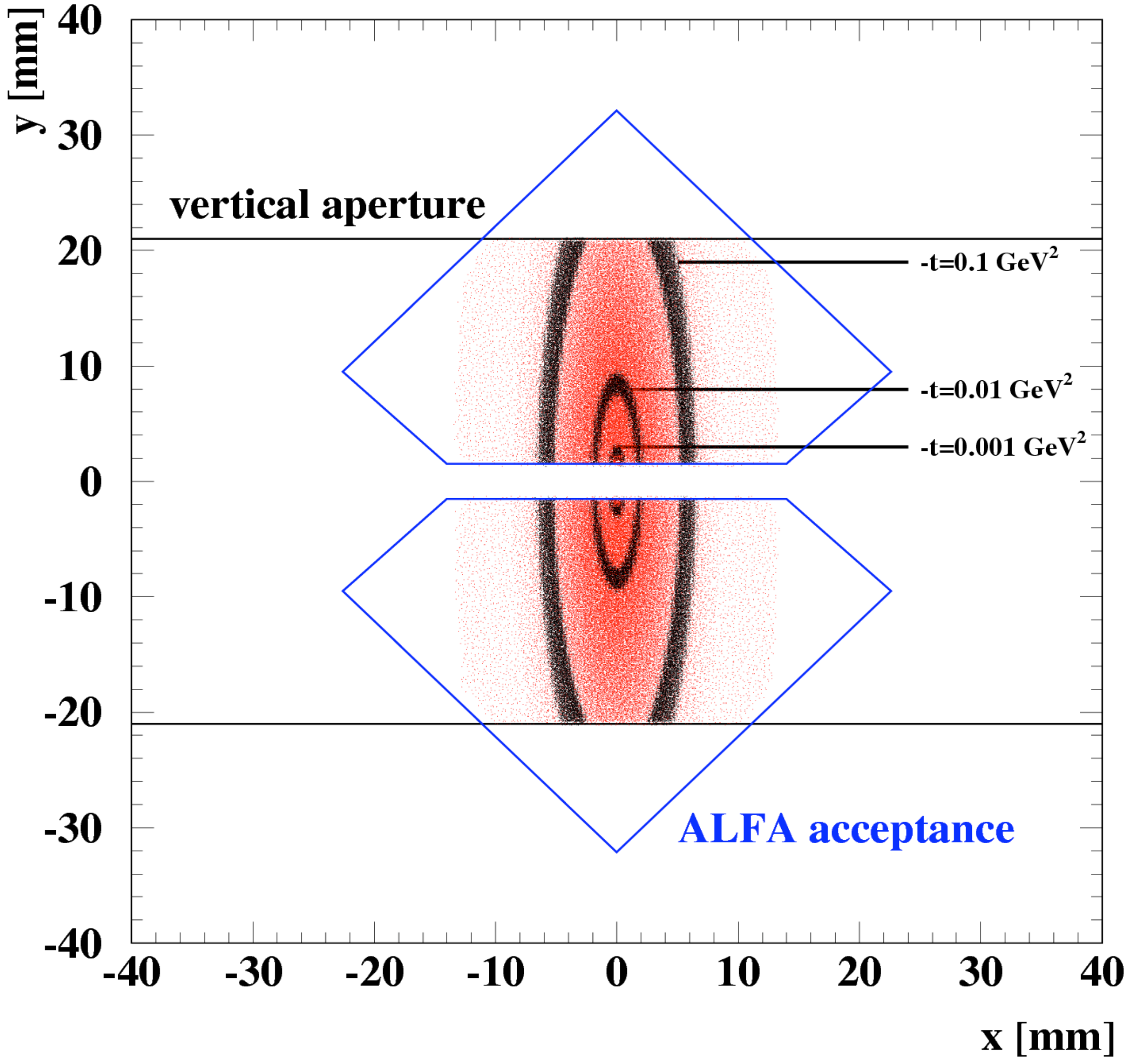
Simulating 10 M events,
running 100 hrs
fit range 0.00055-0.055

	input	fit	error	correlation
L	$8.10\ 10^{26}$	$8.151\ 10^{26}$	1.77 %	
σ_{tot}	101.5 mb	101.14 mb	0.9%	-99%
B	18 Gev^{-2}	17.93 Gev^{-2}	0.3%	57%
ρ	0.15	0.143	4.3%	89%

large stat.correlation between
L and other parameters

Simulation of elastic scattering

hit pattern for 10 M elastic events simulated with PYTHIA + MADX for the beam transport



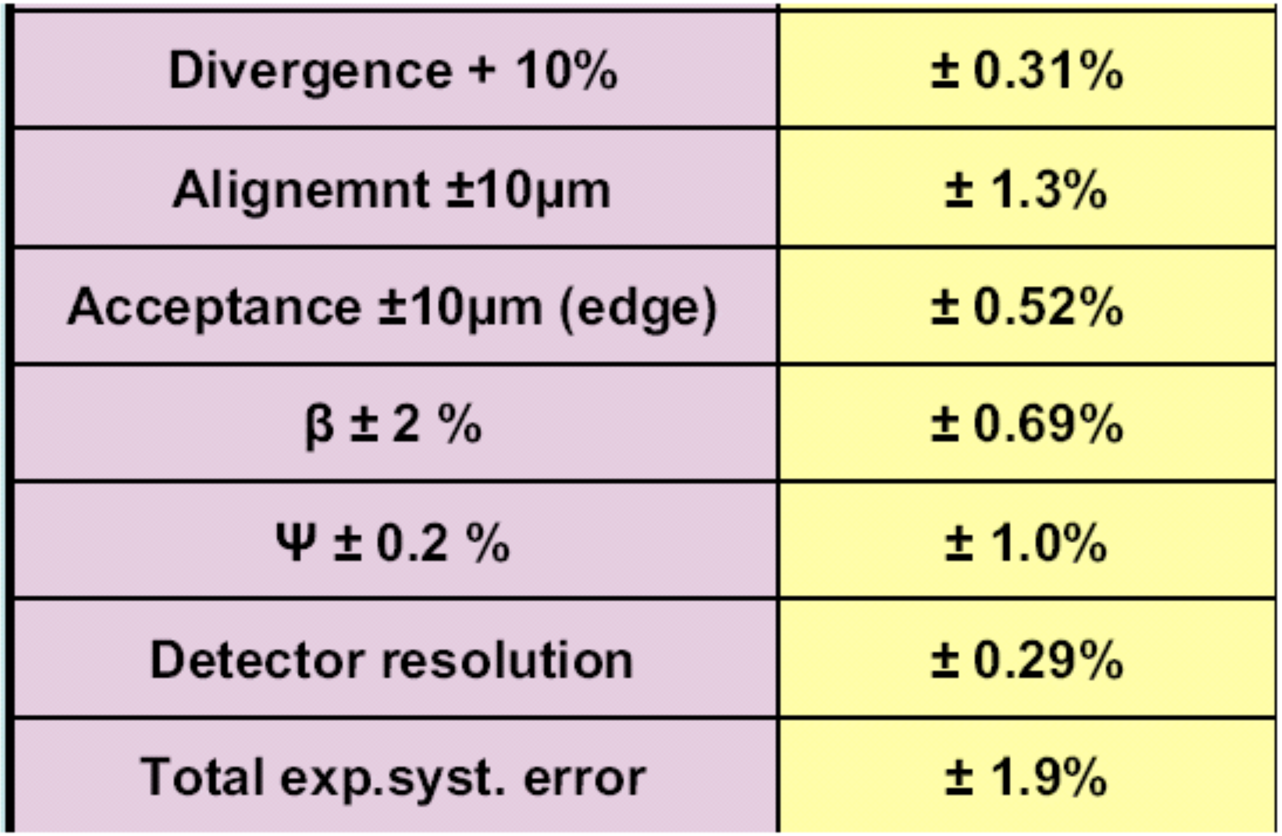
t reconstruction:

$$-t = (p\theta^*)^2 = p^2\left(\bar{\theta}_x^2 + \bar{\theta}_y^2\right)$$
$$= p^2\left(\left(\frac{\bar{x}}{L_{eff,x}}\right)^2 + \left(\frac{\bar{y}}{L_{eff,y}}\right)^2\right)$$

- special optics
- parallel-to-point focusing
- high β*

$$L_{eff} = \sqrt{\beta\beta^*}\cdot\sin\Psi$$
$$\Psi \approx \tfrac{\pi}{2}$$

Systematic errors



Divergence + 10%	± 0.31%
Alignemnt ±10μm	± 1.3%
Acceptance ±10μm (edge)	± 0.52%
β ± 2 %	± 0.69%
Ψ ± 0.2 %	± 1.0%
Detector resolution	± 0.29%
Total exp.syst. error	± 1.9%

Background subtraction ~ 1%

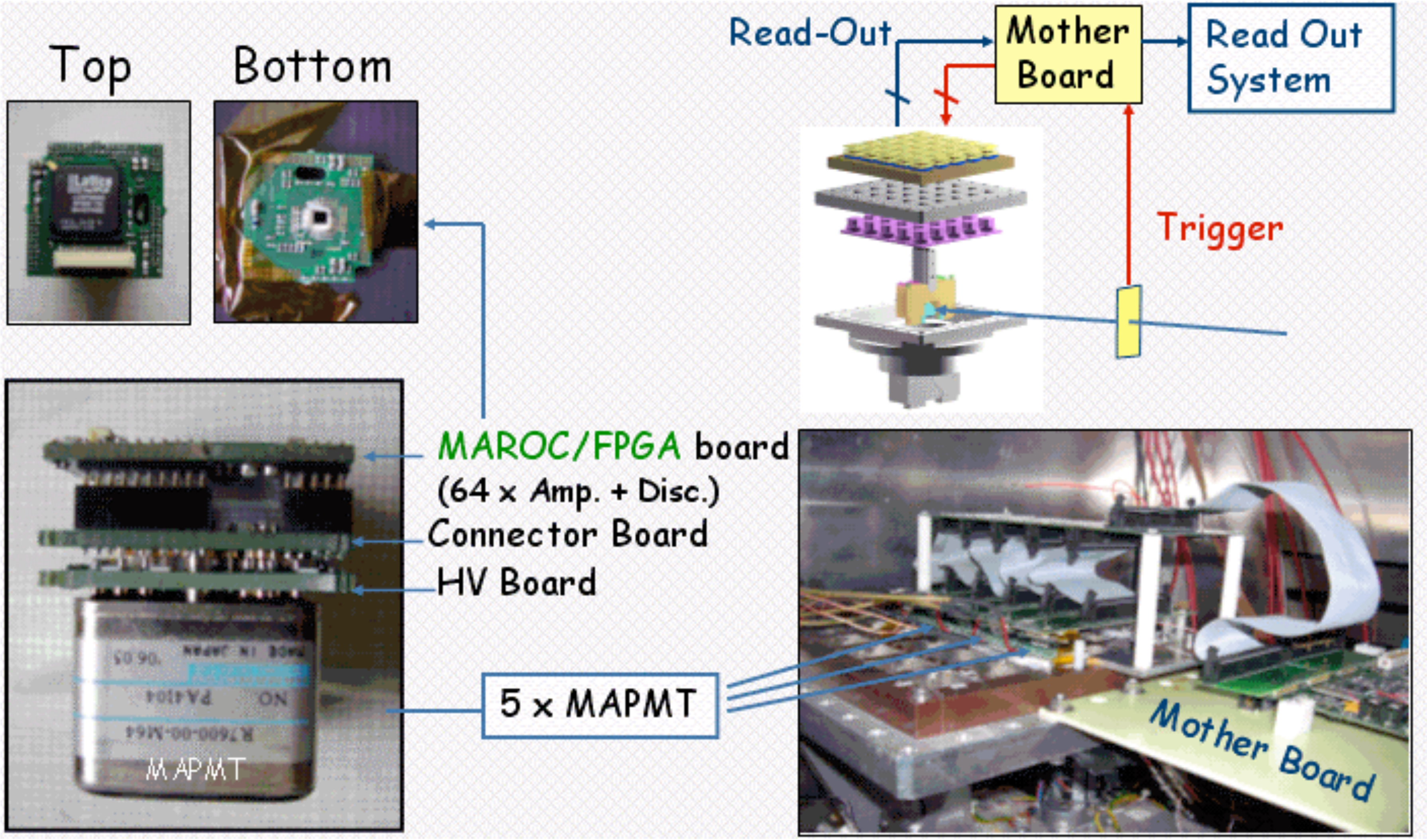
The test beam at DESY November 2005

Conclusions from DESY test beam

- the validity of the chosen detector concept with MAPMT readout
- the baseline fibre Kuraray SCSF-78 0.5 mm2 square
- expected photoelectric yield ~4
- low optical cross-talk
- good spatial resolution
- high track reconstruction efficiency
- No or small inactive edge

- Technology appears fully appropriate for the proposed Luminosity measurement.

FE electronics –Test beam CERN (Oct 2006)



Top

Bottom

Read-Out

Mother Board

Read Out System

Trigger

MAROC/FPGA board

(64 x Amp. + Disc.)

Connector Board

HV Board

5 x MAPMT

Detector characteristic

The detector design is simple, robust and relatively cheap and it is based on an existing luminosity monitor at CDF.

The detector iself is very radiation hard which is important since it will see 60-70 kGray per year. The radiation hardness of the fibres needs, however, to be tested.

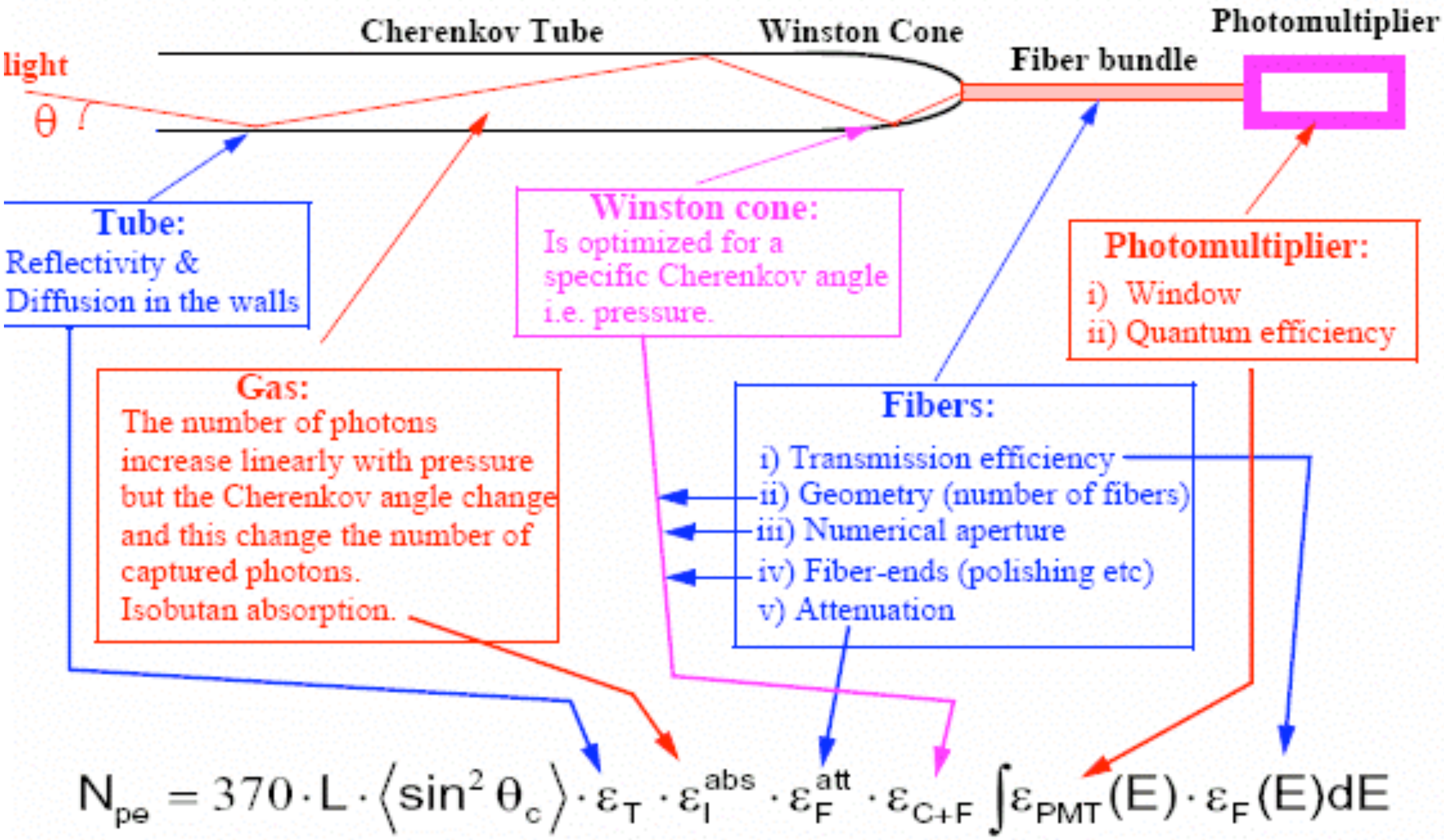
It is insensitive to soft background particles (the Cherenkov threshold is 2.7 GeV for pions and 9 MeV for electrons).

A good time resolution makes it possible to resolve individual beam crossings and to measure the luminosity of individual bunches in the LHC.

The pointing capability will help in reducing the background.

From pulseheight measurements it should be possible to measure if one or several particles have gone through a Cherenkov tube. This is important since at 10^{34} cm^{-2}s^{-1} there will be 25 inelastic interactions per bunch crossing and the basic principle of the detector is that the number of charged particles in the detector is proportional to the number of inelastic interactions.

LUCID: Factors that influence the number of p.e.



Tube:
Reflectivity &
Diffusion in the walls

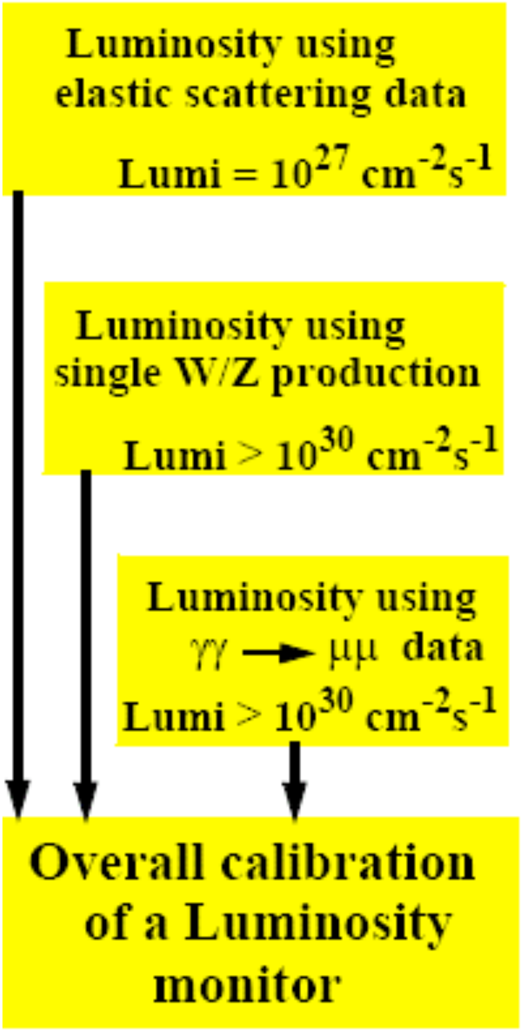
Gas:
The number of photons increase linearly with pressure but the Cherenkov angle change and this change the number of captured photons.
Isobutan absorption.

Winston cone:
Is optimized for a specific Cherenkov angle i.e. pressure.

Fibers:
i) Transmission efficiency
ii) Geometry (number of fibers)
iii) Numerical aperture
iv) Fiber-ends (polishing etc)
v) Attenuation

Photomultiplier:
i) Window
ii) Quantum efficiency

$$N_{pe} = 370 \cdot L \cdot \left\langle \sin^2 \theta_c \right\rangle \cdot \varepsilon_T \cdot \varepsilon_l^{abs} \cdot \varepsilon_F^{att} \cdot \varepsilon_{C+F} \int \varepsilon_{PMT}(E) \cdot \varepsilon_F(E) dE$$



Luminosity using elastic scattering data

Lumi = 10^{27} cm^{-2}s^{-1}

Roman Pots equipped with scintillating fibre detectors will be used to measure the protons in elastic scattering events.

Luminosity using single W/Z production

Lumi > 10^{30} cm^{-2}s^{-1}

The rate of $W \rightarrow l\nu$ is expected to be 60 Hz at high luminosity

The uncertainty in the rate of W/Z events is currently about 4%

Luminosity using $\gamma\gamma \rightarrow \mu\mu$ data

Lumi > 10^{30} cm^{-2}s^{-1}

QED process

About 10k events/day at high lumi if P_T>3 GeV (1.5k if P_T>6 GeV)

Overall calibration of a Luminosity monitor

LUCID: A detector consisting of Cherenkov tubes that surrounds the beampipe. No absolute luminosity measurement !

Luminosity transfer 10^{27}-10^{34} cm^{-2} sec^{-1}

- Bunch to bunch resolution ⇒ we can consider luminosity / bunch

  ⇒ ~ 2 x10^{-4} interactions per bunch to 20 interactions/bunch

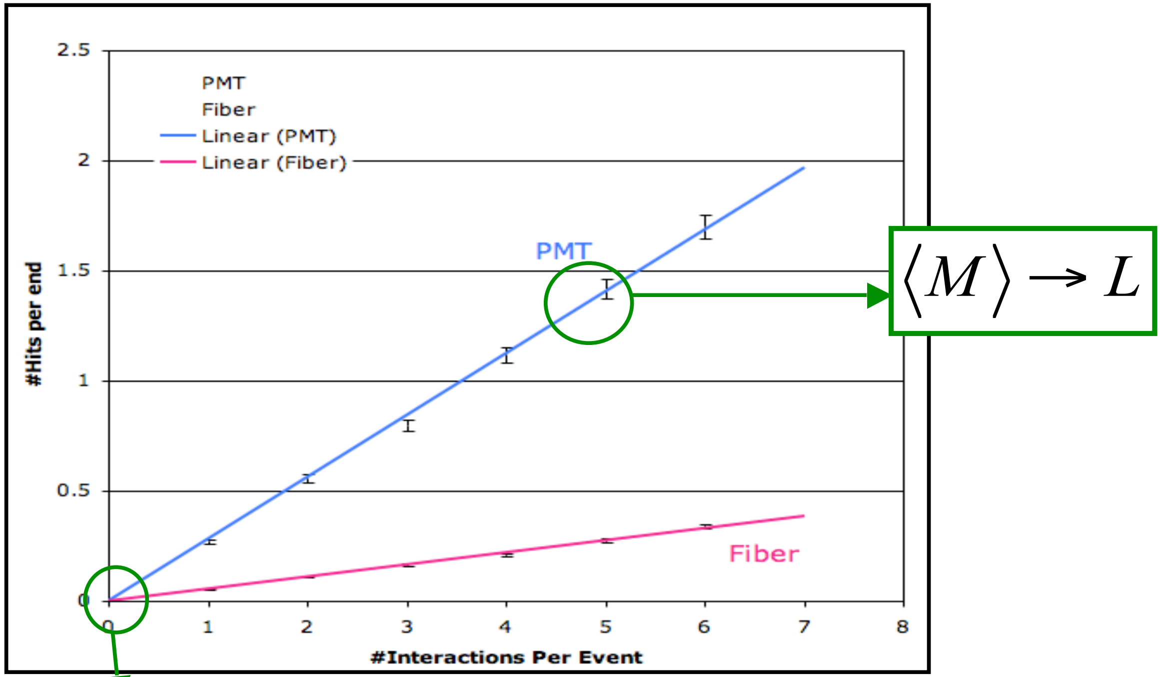
  ⇓

- Required dynamic range of the detector ~ 20
- Required background < < 2 x10^{-4} interactions per bunch
  - main background from beam-gas interactions
  - Dynamic vacuum difficult to estimate but at low luminosity we will be close to the static vacuum.
  - Assume static vacuum ⇒ beam gas ~ 10^{-7} interactions /bunch/m
  - We are in the process to perform MC calculation to see how much of this will affect LUCID

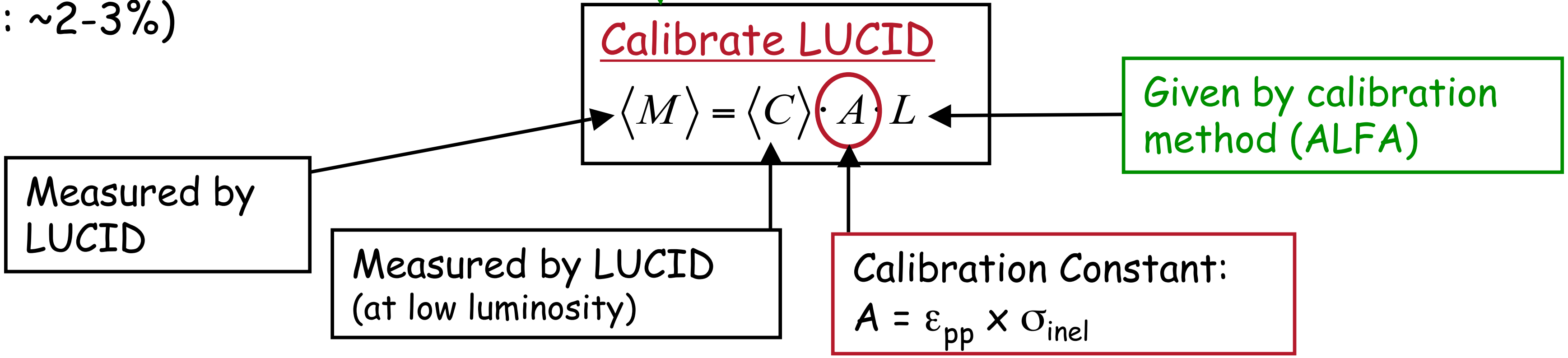
LUCID Calibration Strategy

Run LUCID in parallel with absolute measurement

- Initially,
  LHC Machine Parameters
  (Precision: ~10%)
- Medium term
  Physics processes, W/Z & $\mu\mu$/ee
  (Precision: ~5-10%)
- During 2009
  Roman Pot (ALFA) measurement
  (Precision: ~2-3%)



$\langle M \rangle \rightarrow L$



Calibrate LUCID

$\langle M \rangle = \langle C \rangle \cdot A \cdot L$

Measured by LUCID

Measured by LUCID
(at low luminosity)

Calibration Constant:
$A = \varepsilon_{pp} \times \sigma_{inel}$

Given by calibration method (ALFA)