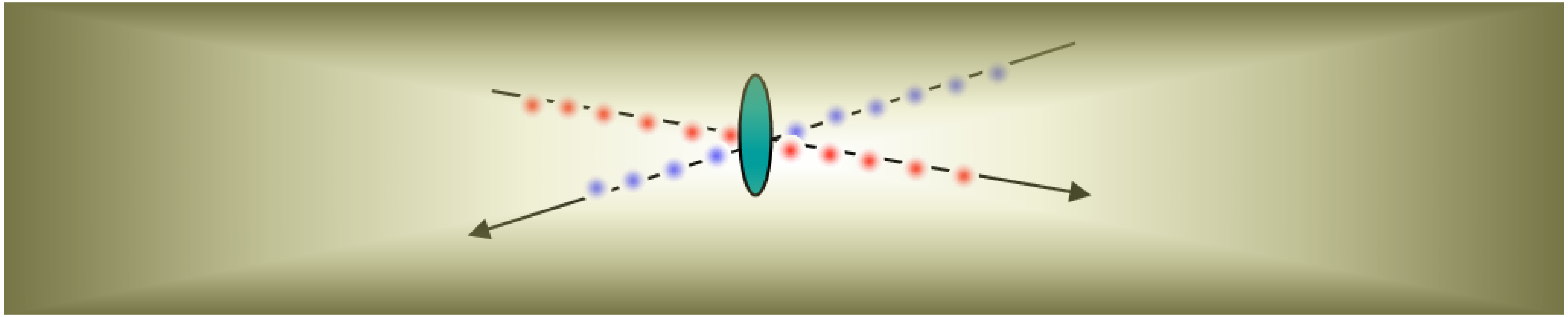
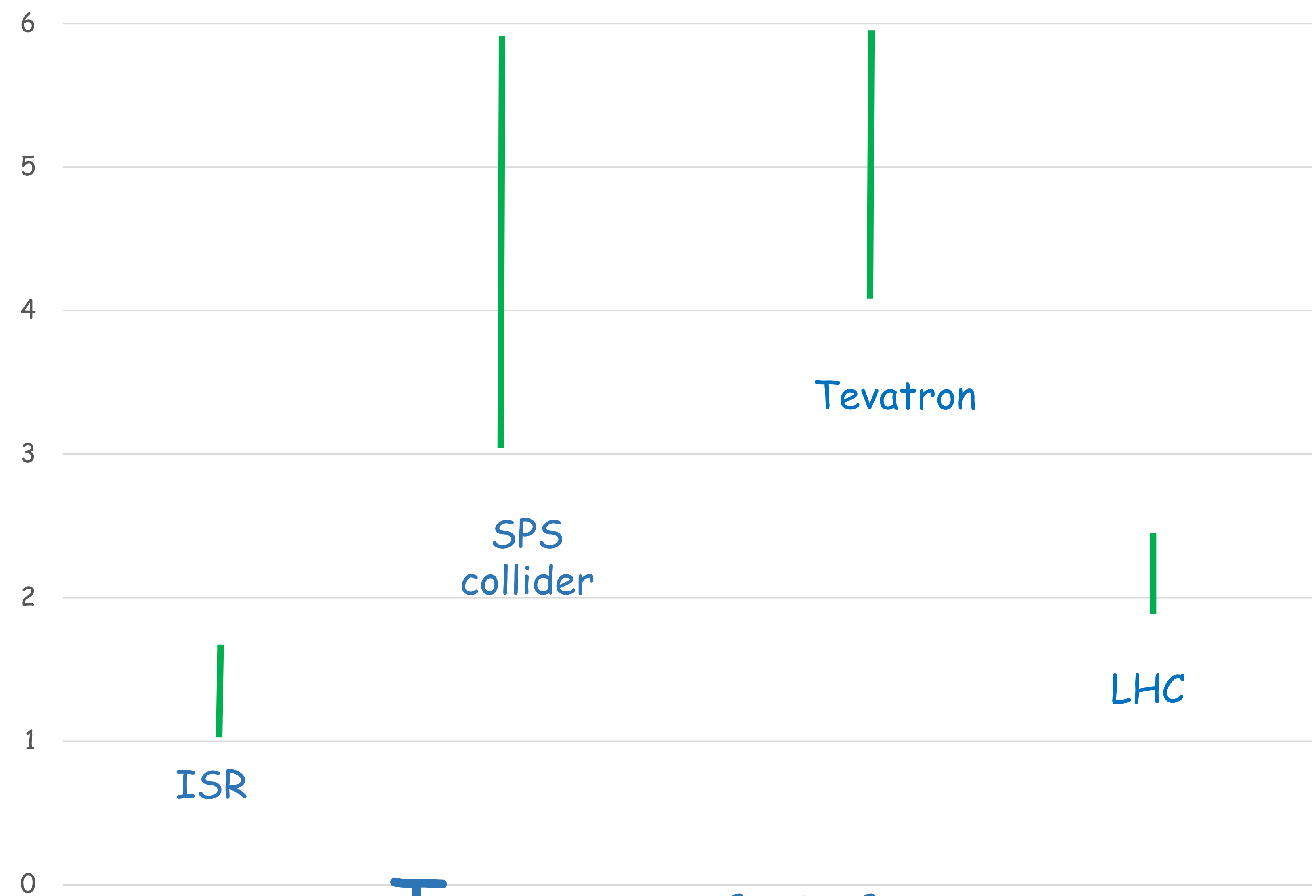
Luminosity determination at proton colliders



LABORATOIRE
DE L'ACCÉLÉRATEUR
LINÉAIRE

November 2015
Per Grafstrom
CERN and University of Bologna

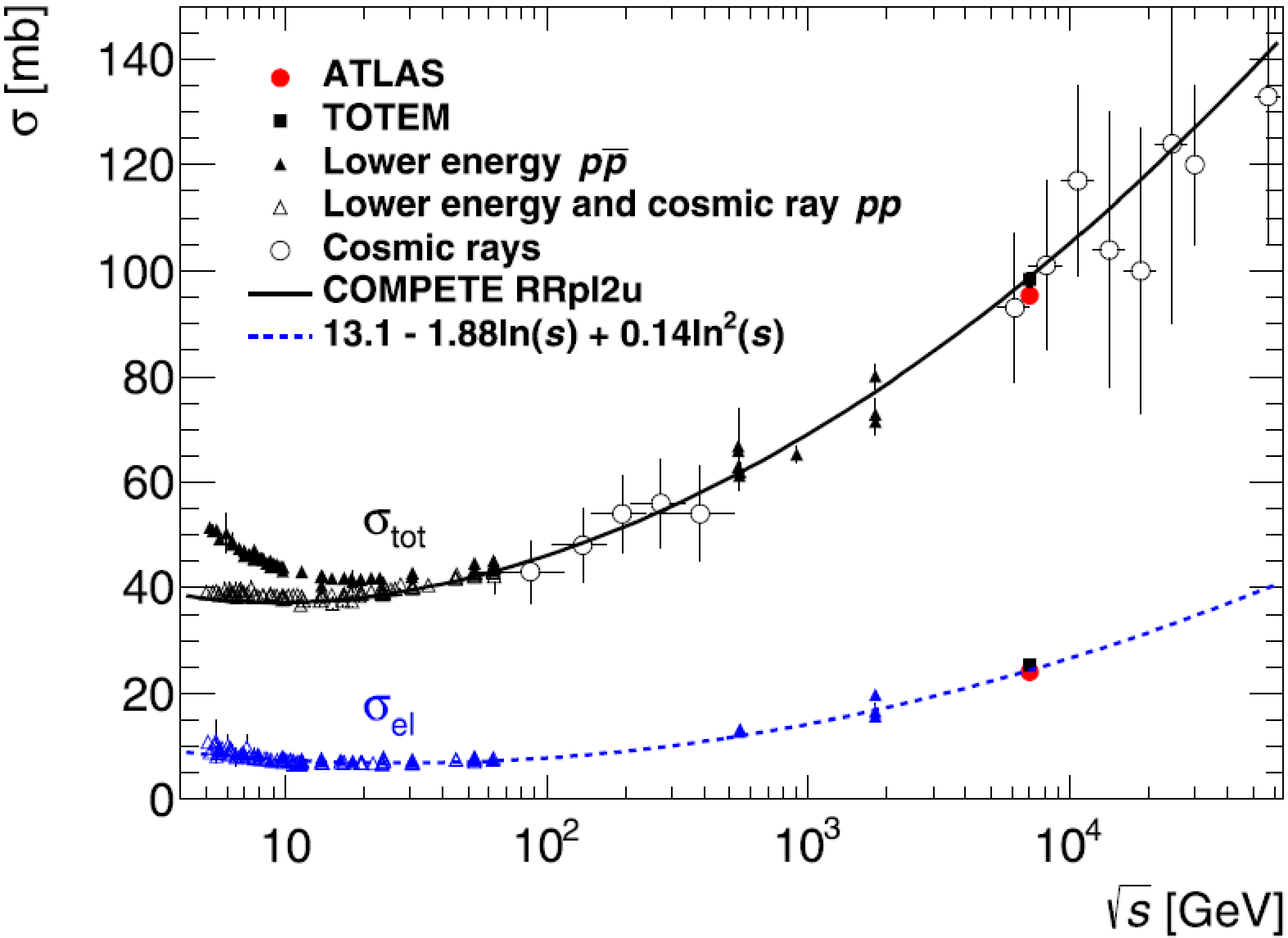
Range of precision in luminosity measurements in %



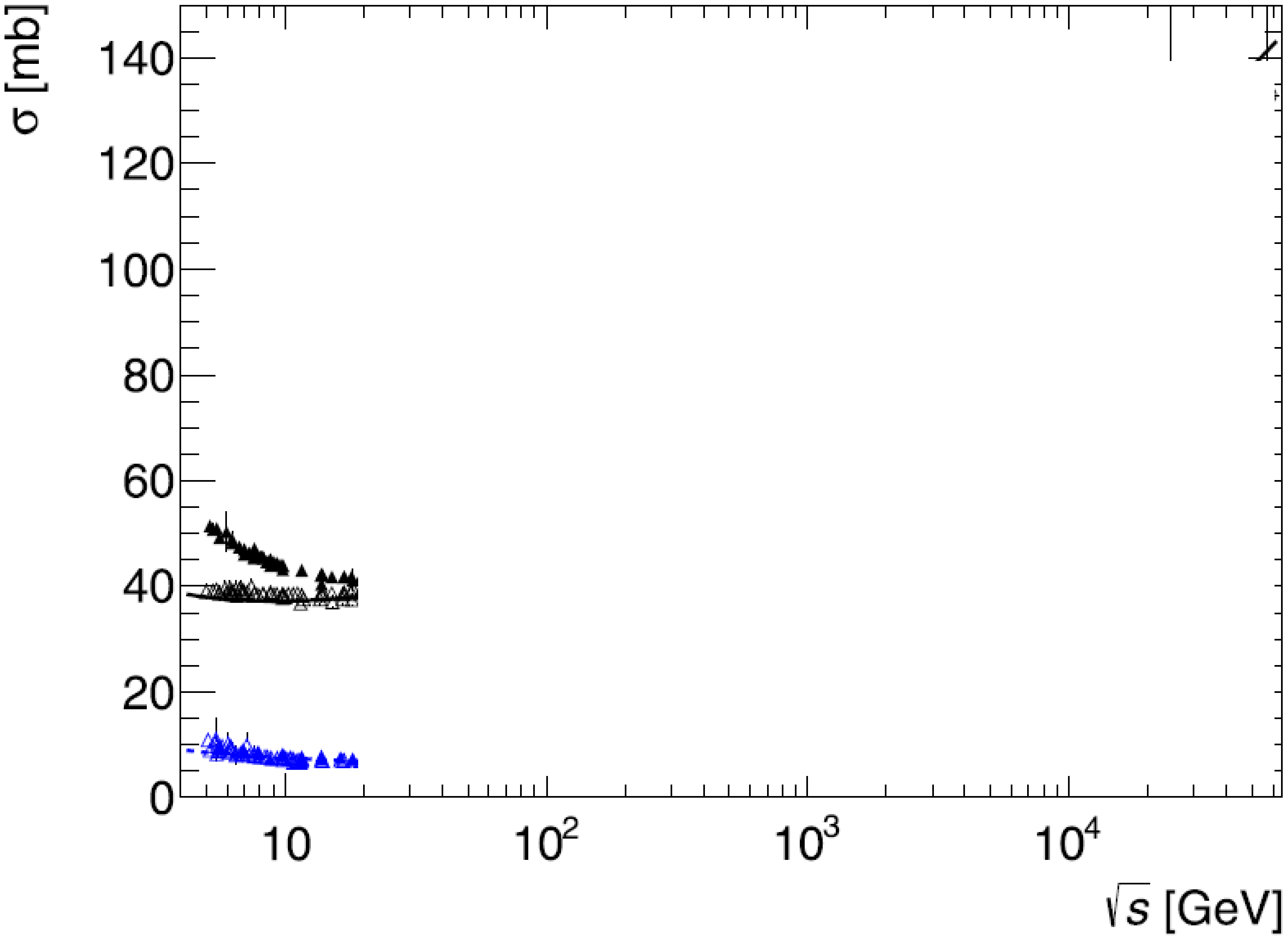
Two reasons

1. Luminosity measurements are physics driven

2. The magnetic part of the Lorenz force depends on the velocity VECTOR


σ [mb]
140
120
100
80
60
40
20
0
10
10^2
10^3
10^4
$\sqrt{s}$ [GeV]
ATLAS
TOTEM
Lower energy $p\bar{p}$
Lower energy and cosmic ray pp
Cosmic rays
COMPETE RRpl2u
13.1 - 1.88ln(s) + 0.14ln^2(s)
σ_{tot}
σ_{el}

1973



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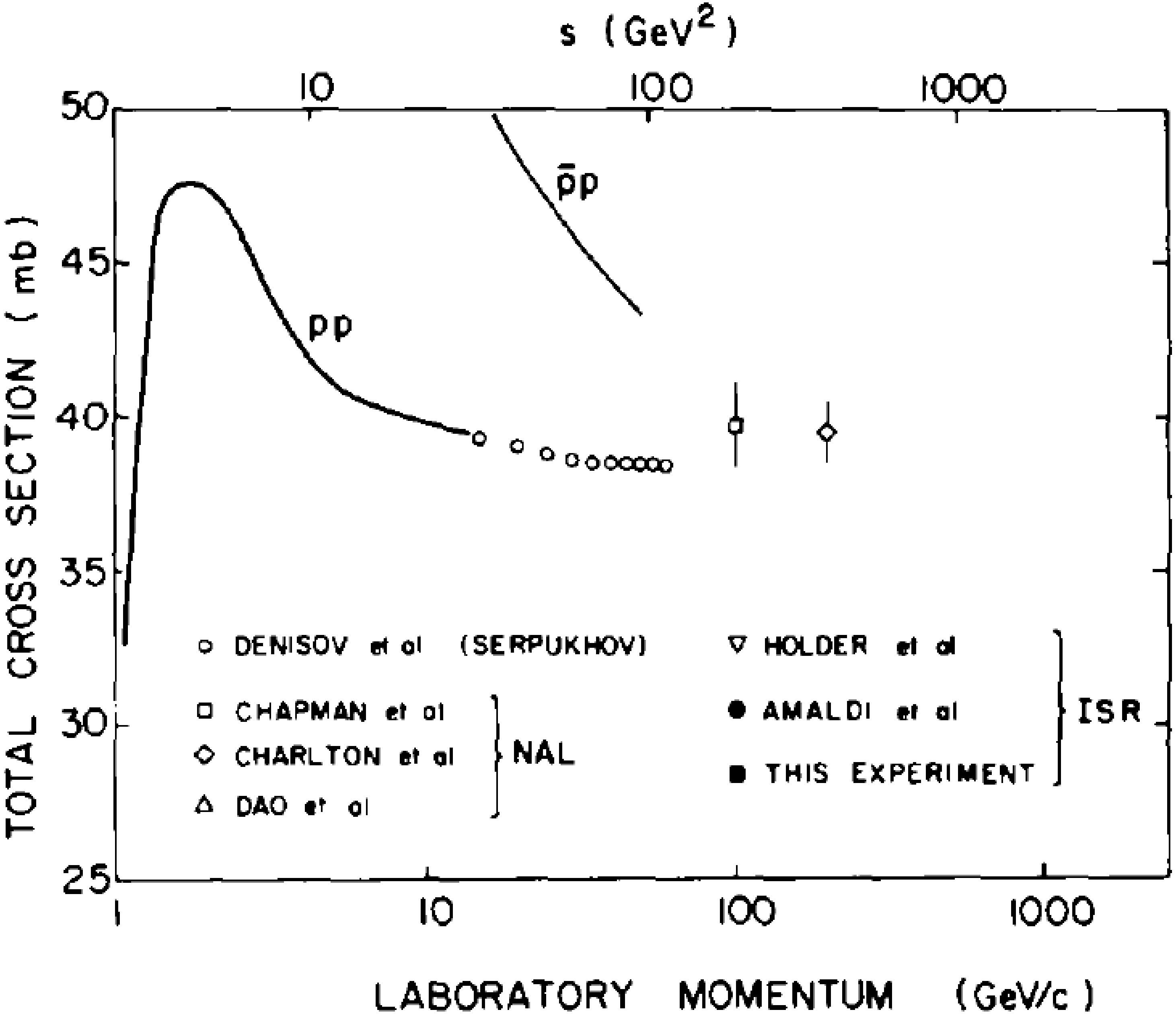
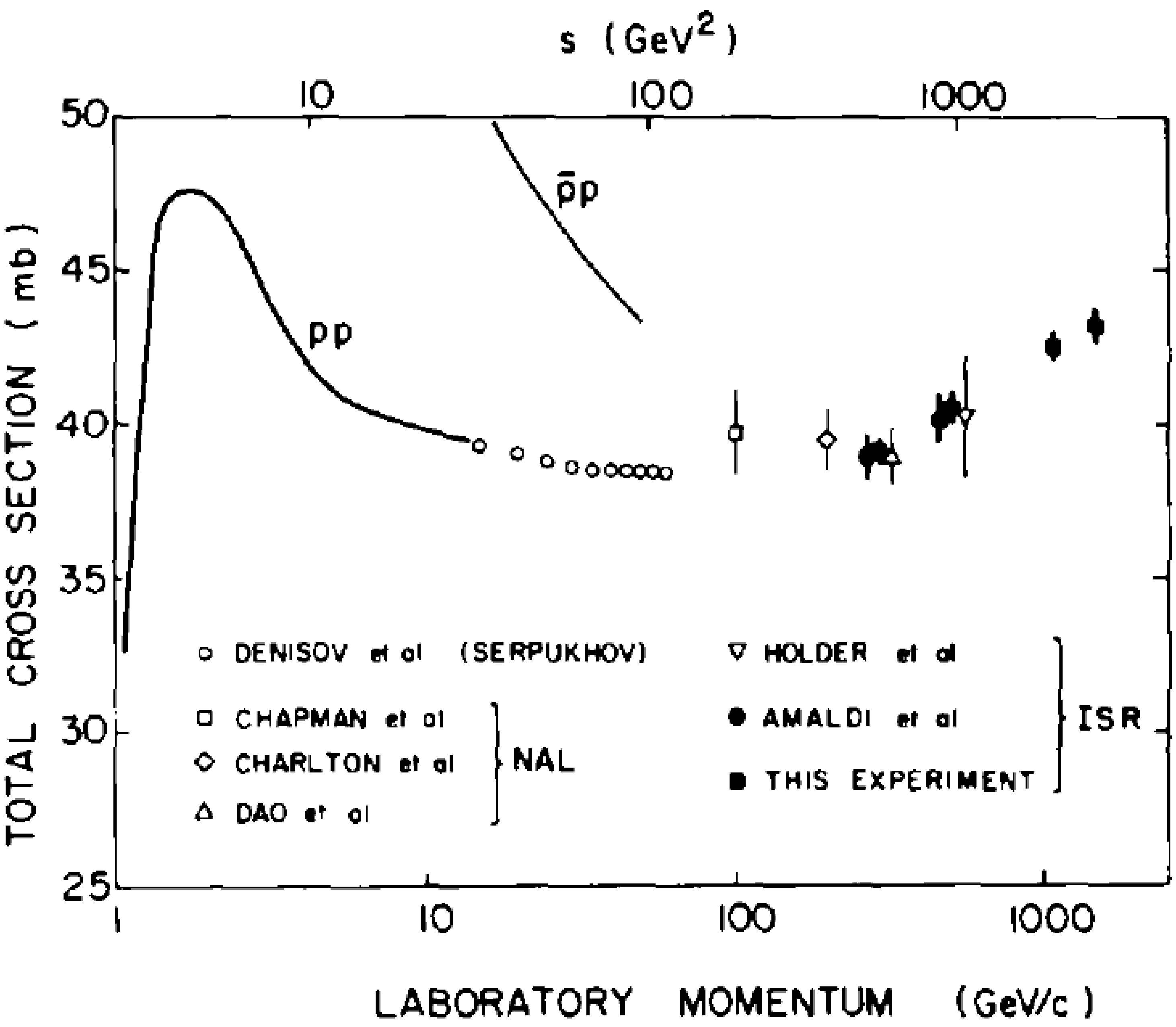

s (GeV²)
10
100
1000
50
45
40
35
30
25
TOTAL CROSS SECTION (mb)
p̄p
pp
○ DENISOV et al (SERPUKHOV)
□ CHAPMAN et al
◇ CHARLTON et al
△ DAO et al
NAL
▽ HOLDER et al
● AMALDI et al
■ THIS EXPERIMENT
ISR
1
10
100
1000
LABORATORY MOMENTUM (GeV/c)

$$L=R/\sigma$$



s (GeV^2)
10
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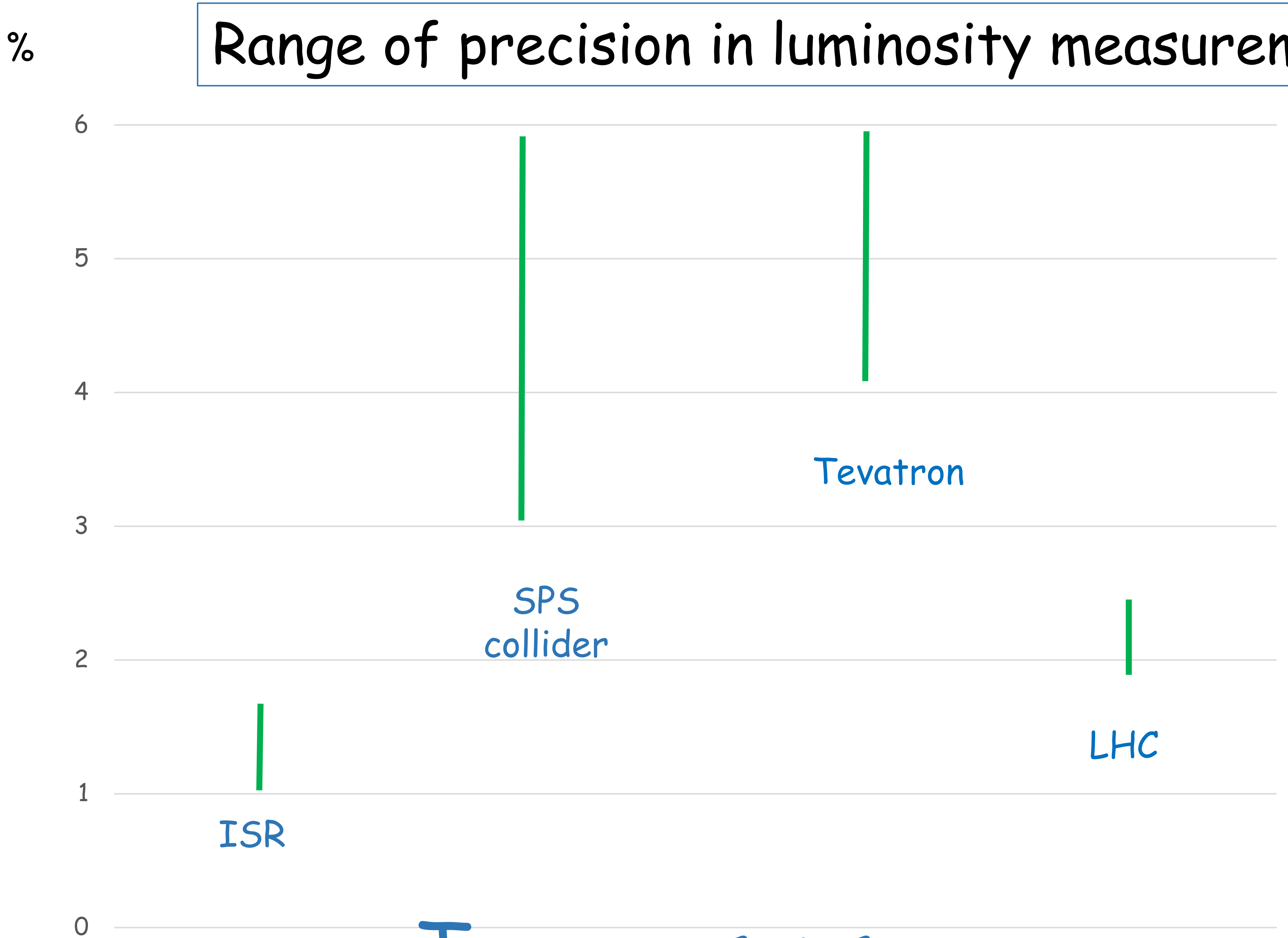
10
100
1000
LABORATORY MOMENTUM (GeV/c)

Range of precision in luminosity measurements in %



Two reasons

Outline

- Introduction-Basics

- Absolute versus Relative luminosity

- Precision goals (LHC as example)

- Absolute measurements
  - Known cross sections
  - Machine parameters
  - Elastic scattering

- Conclusion

Start with basics

- “luminosity “ stems from Latin “lumen”(light)…used in astronomy since long
- Picked up by particle physicist late 50th in the context of the very first collider (e^+e^- ,AdA ,Frascati) – related e^+e^- annihilation cross section to number of annihilations per unit time

$\mathcal{L} = R/\sigma$ ($cm^{-2}s^{-1}$)

Four important distinctions:

-Instantaneous luminosity- reflects the instantaneous performance of the collider

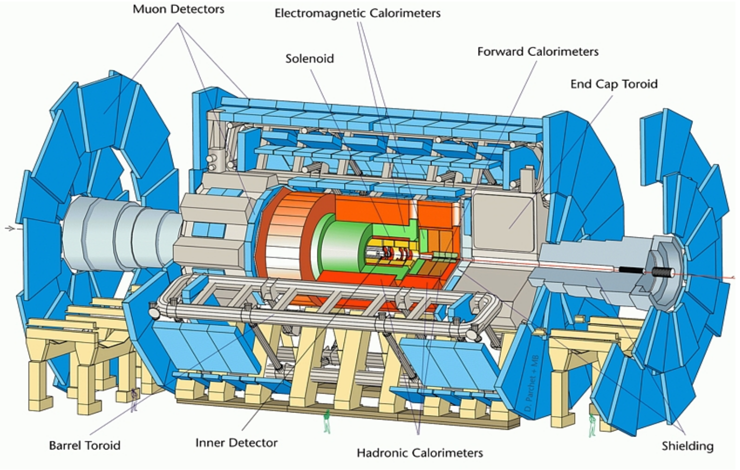
-Integrated luminosity- the integral over time- suitable units nb^{-1} , pb^{-1}, fb^{-1}….

-Absolute luminosity (absolute scale determined)

-Relative luminosity (to monitor relative variations)

Absolute versus Relative measurement

- Relative measurements or Luminosity Monitoring
  - Using suitable observables in detectors which are not primarily luminosity monitors:
    - Beam condition monitor-BCM
    - Current in Tile calorimeter PM's
    - FCAL
    - Inner detector
    - ….
  - Using a dedicated luminosity monitor
    - LUCID



- Absolute measurements
  - Several different methods

- Strategy for absolute calibration:

1. Measure the absolute luminosity with a precise method at *optimal conditions* in order to do as good calibration of the scale as possible.

2. Calibrate luminosity monitor with this precise measurement and then use the calibrated monitor at all conditions

Precision goals at the LHC

Take measurement of W and Z cross section as an example

Theoretical uncertainty dominated by uncertainty of the PDF's implying an uncertainty of the cross section of ~ 5%

We need to beat this!

Next level of uncertainty at the level of 2 %
Combination of experimental and theoretical uncertainties

- Acceptance
- Detector biases
- Reconstruction efficiencies
- Background subtraction
- Parton-parton cross section
- ……

In order to NOT be dominated by the luminosity error we should aim at a level of a couple of percent

Absolute Luminosity Measurements

Traditionally three major approaches at colliders

- (1) Rates of well-calculable processes:
  e.g. QED (like LEP), EW and QCD

- (2) Machine parameters
  - Direct measurement of beam parameters
  - Van der Meer scans
  - Beam imaging

- (3) Elastic scattering
  - Optical theorem: forward elastic rate + total inelastic rate:
  - Luminosity from Coulomb Scattering

Rates of well-calculable processes:

Use the inelastic hadronic cross section

Very first attempt in ATLAS used this method.

Uncertainty limited to a poor 20%

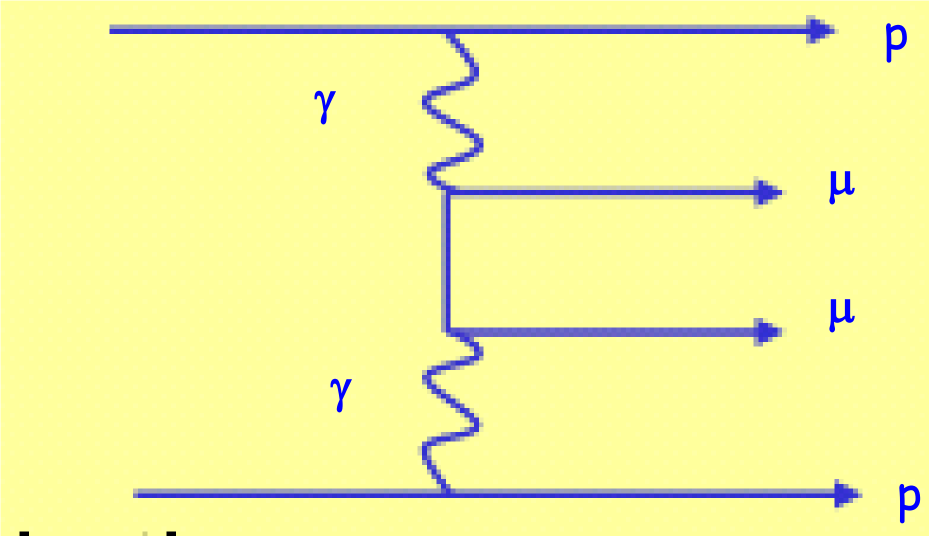
Not very surprising :

-extrapolate from lower energies
-Different generators…different results
-especially single diffractive and double diffractive cross sections are notoriously known to be unknown!

Still…. Once σ_{inel} better established at a given energy
UA2 5-6 %
CDF D0 4-6%

Rates of well-calculable processes

Use: exclusive muon production from two photons



- 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 %

Main problem…..low cross section…statistics

Rates of well-calculable process

Inclusive W and Z production

$$\int L dt = \frac{N - B}{\sigma_{th} \cdot a \cdot \varepsilon}$$

- Combination of data driven and Monte Carlo methods ⇒uncertainty in ε of 1-1.5%
- Acceptance uncertainty ~1.5-2 %
- Uncertainty in σ_{th} order of 5 % from PDF's

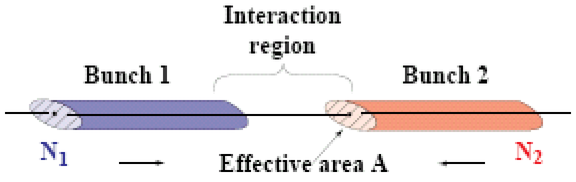
This method thus gives the absolute scale of the luminosity at the level of 5 % and is only useful if no other method can provide a better scale measurement.

If another method provides a more precise result we better go the other way around and *measure* the W,Z the cross section instead.

Luminosity from Machine parameters
(1)Direct measurement of beam parameters

- Luminosity depends exclusively on beam parameters:

Most simples case:
Bunch luminosity of two equal (N_1=N_2) and round ($\sigma_x = \sigma_y$) bunches colliding head on



$L_b = f_{rev} N^2/4\pi\sigma^2$

f_{rev} is known

N is measured with accelerator instrumentation at any point in the ring

How to measure σ at the IP?

Extrapolation of σ_x, σ_y from measurements of beam profiles elsewhere to IP; detailed knowledge of optics required $\Rightarrow$ large uncertainties

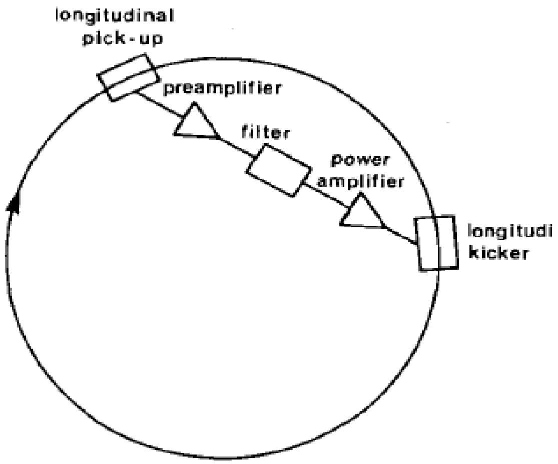
UA1 used this method:25% to start with …later down to 5-10%
Tevatron 15-20%

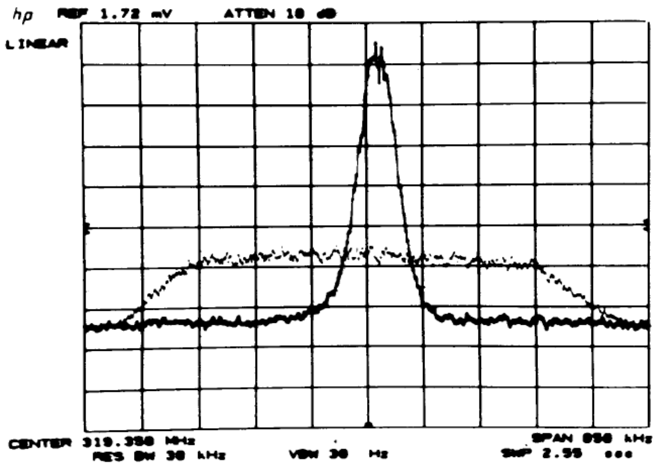
Simon van der Meer 1925 – 2011

**Nobel Prize in 1984 for the contributions
That led to the discoveries of the W and Z)**

(shared with Carlo Rubbia)

Van der Meer's crucial contribution was the stochastic cooling for accumulating enough anti-protons in conditions to be accelerated later in the SPS together with protons to provide the 630 GeV collisions needed to discover the W and Z

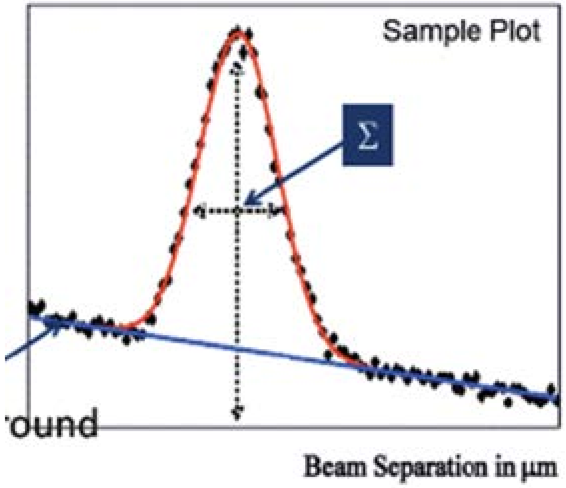


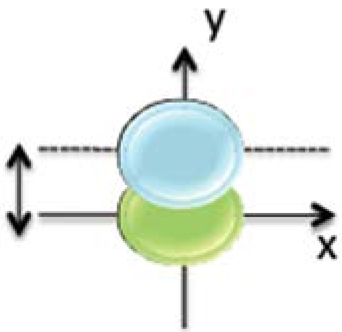


Luminosity from machine parameters

(2)Beam separation scans- van der Meer(VDM) scans

The simple idea:
Determine the convoluted beam size $\Sigma = \sqrt{\sigma_1^2 + \sigma_2^2}$ by recording the relative interaction rate as a function of beam separation





The formalism

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

- Mean number of inelastic interactions per BX

$\varepsilon * \mu$ = Mean number of interactions per BX seen by detector

$$\mathcal{L} = \frac{\boxed{\mu}\, n_b\, f_r}{\boxed{\sigma_{inel}}} = \frac{\boxed{\mu_{vis}}\, n_b\, f_r}{\boxed{\sigma_{vis}}}$$

- Inelastic cross section (unknown)

- Cross section seen by detector

- σ_{vis} is the calibration constant which will be determined by vdM scans

Calibrating σ_{vis} in VdM scans

- The Luminosity in terms of beam densities ρ_1 and ρ_2:

$$\mathcal{L} = n_b\, f_r\, n_1 n_2 \int \rho_1(x,y)\rho_2(x,y)dxdy$$

- Only if the integral factorises into independent x & y components:

$$\mathcal{L} = \frac{n_b\, f_r\, n_1 n_2}{2\pi\, \Sigma_x \Sigma_y}$$

- This and previous slide imply

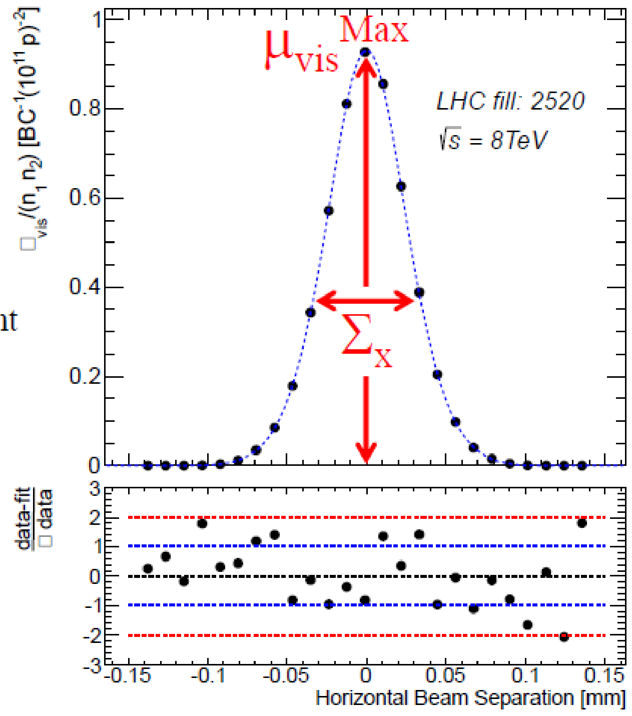
Measured in vdM scan

Detector independent

$$\sigma_{vis} = \boxed{\mu_{vis}^{Max}}\, \frac{2\pi \boxed{\Sigma_x \Sigma_y}}{\boxed{n_1 n_2}}$$

Detector dependent

Measured by beam instrumentation



Slide from Gabriel Anders

Use special runs for the VdM scans

- Calibration runs with simplified LHC conditions to increase the precision
  - 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.

What are the issues and problems….?

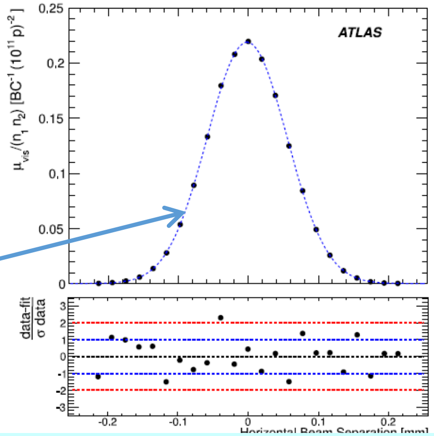
As always….
the devil is in the details…..

some examples:
Length scale calibration
Bunch population products
Bunch-by-bunch σ_{vis}
Beam-beam effects
Factorisation
Long-term drifts
μ-dependence
……..

Observe : I give estimation of these effects for 2011 data- they are public and published
2012 data is still being evaluated

Length scale calibration

How do we know that each step is 20 μm ?



The length scale is defined by LHC magnets and the LHC control system !

During a VdM scan beam1 and beam2 move in both x and y
⇒ 4 calibration constants to check

Dedicated length scale calibrations are made during which the beams are displaced in *collision* in several steps.
The movement of the luminous region is reconstructed using the primary vertex reconstructions of the inner detector.

The nominal LHC scale is checked at the level of 0.3 %

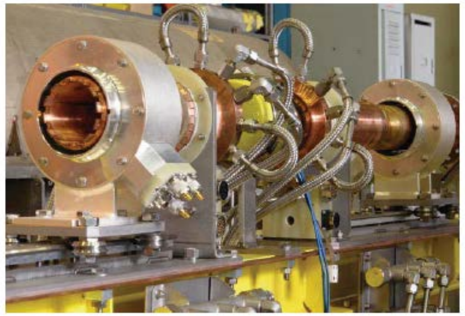
The absolute length scale of the inner detector is estimated with an uncertainty of 0.3 %

Bunch population product

Huge effort by LHC Bunch Current Normalization Working Group

Dominating systematic error 2010: 3.1 %

Reduced in 2011 to : 0.55 %



FBCT: Fast Beam Current Transformer
Measures the fraction of the current in each bunch.

DCCT: DC Current Transformer
Measures the total current

The relative measurement of the FBCT is normalized to the overall current scale from the DCCT. Corrections to be made for any out-of-time charge present in a BCID but not colliding

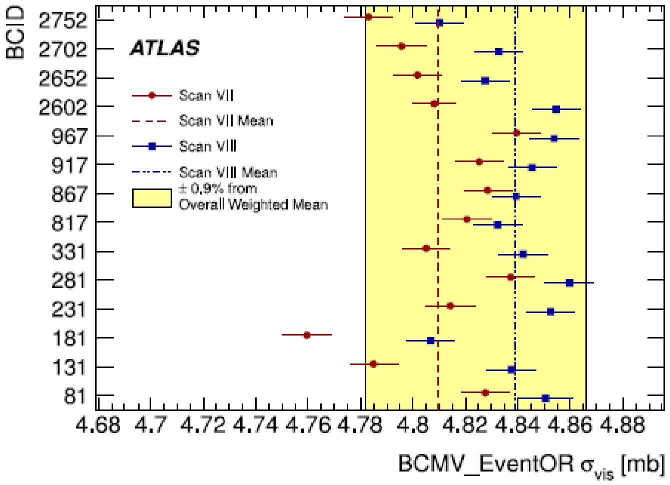
bunch-by-bunch σ_{vis}

The luminosity can be different for each colliding bunch pair!
Both the bunch population product and the beam sizes can vary
….level of variation 10-20 %….

$\Rightarrow$ We have to measure the bunch luminosity $\mathcal{L}_{BC}$

(if NOT-average procedures can give wrong results due to non-linearities
..and μ-dependent corrections can also be incorrect)

HOWEVER σ_{vis} should be the same for all BCID's !



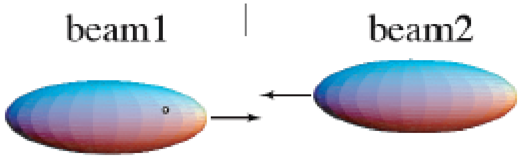
Scatter not entirely statistical!

An additional uncertainty of 0.55% has been attributed (2011) !

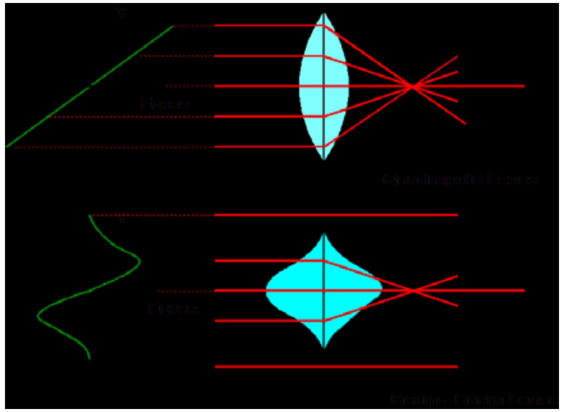
Beam-beam effects

Electromagnetic field of a bunch in beam 1 distorts corresponding bunch in beam 2

Mutual angular kick



Quadrupole effect (dynamic β)



Total correction ~ 2 % with uncertainty of 0.5 %

factorisation

The Luminosity in terms of beam densities ρ_1 and ρ_2:

$$\mathcal{L} = n_b\, f_r\, n_1 n_2 \int \rho_1(x,y)\rho_2(x,y)dxdy$$

Only if the integral factorises into independent x & y components:

$$\mathcal{L} = \frac{n_b\, f_r\, n_1 n_2}{2\pi\, \Sigma_x \Sigma_y}$$

Evidence for non factorisation can be seen in offset scans….
…and has been seen

The effect was estimated for the 2011 data:
An uncertainty of 0.5 % was assigned

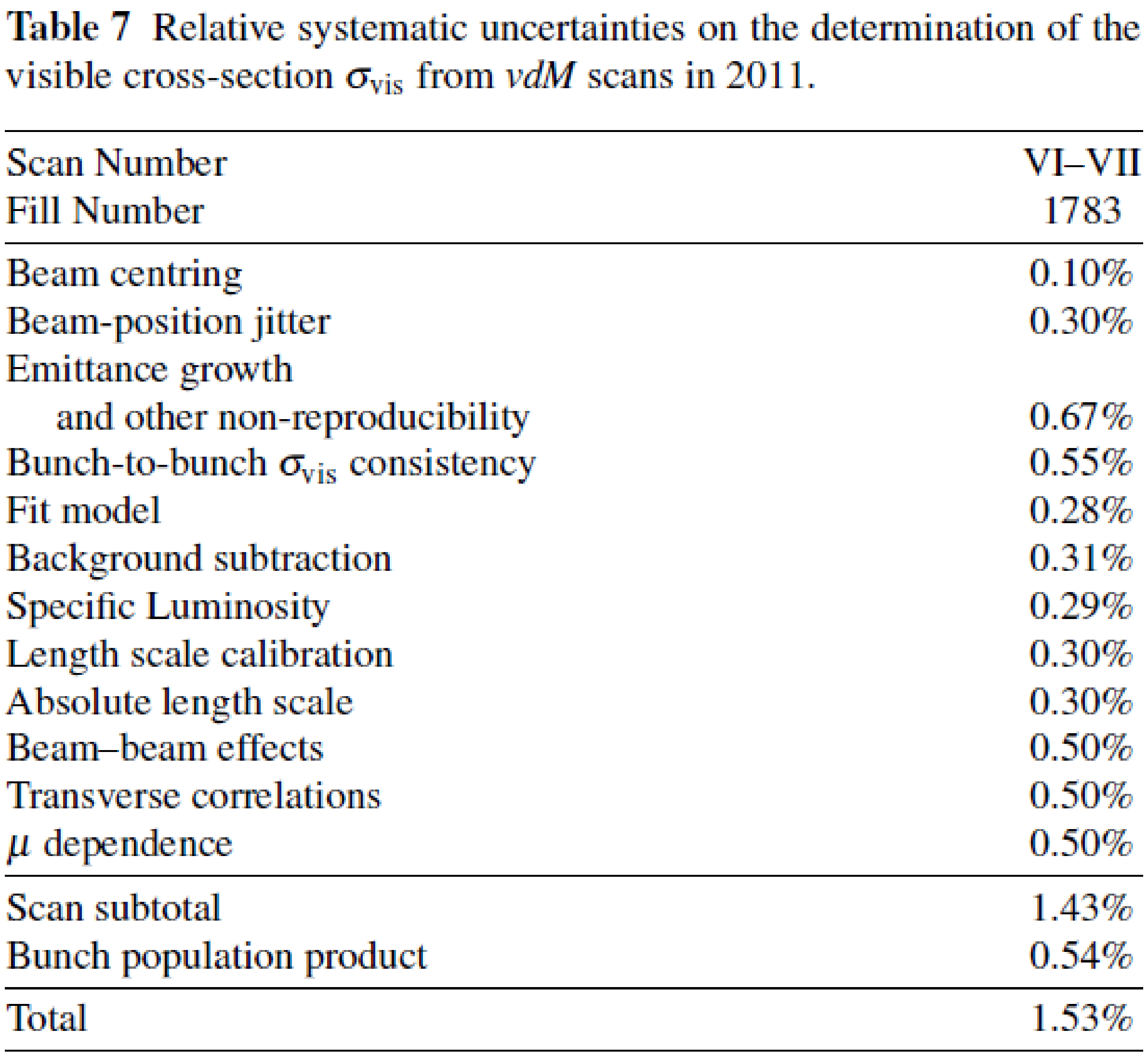


Table 7 Relative systematic uncertainties on the determination of the visible cross-section σ_{vis} from *vdM* scans in 2011.

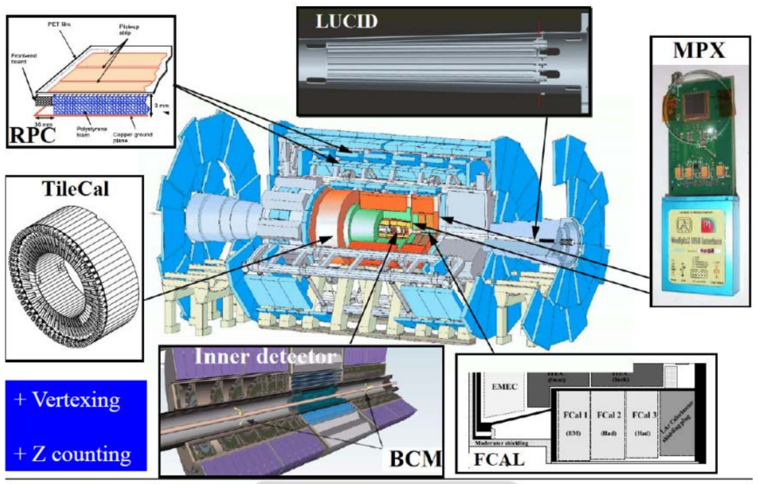
Scan Number	VI–VII
Fill Number	1783
Beam centring	0.10%
Beam-position jitter	0.30%
Emittance growth and other non-reproducibility	0.67%
Bunch-to-bunch σ_{vis} consistency	0.55%
Fit model	0.28%
Background subtraction	0.31%
Specific Luminosity	0.29%
Length scale calibration	0.30%
Absolute length scale	0.30%
Beam–beam effects	0.50%
Transverse correlations	0.50%
μ dependence	0.50%
Scan subtotal	1.43%
Bunch population product	0.54%
Total	1.53%

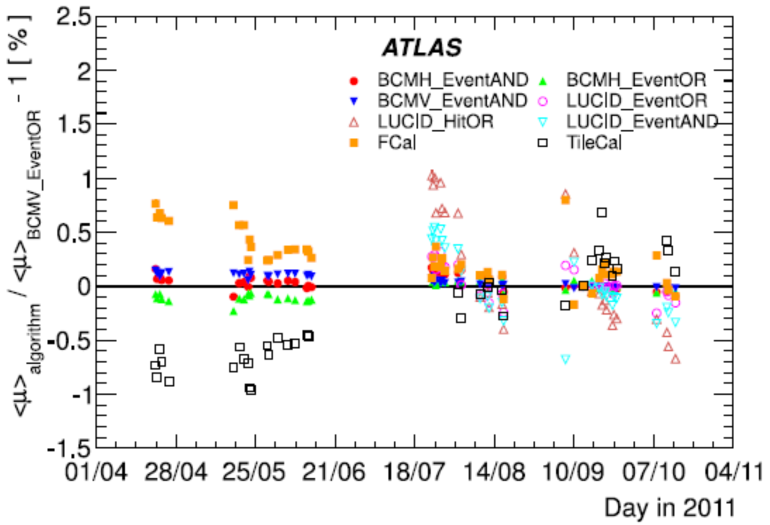
Non VdM issues –Long term stability

Fundamental ingredient in the ATLAS strategy is to compare measurements of many different luminosity detectors

Different acceptance
Different background
Different response to pile-up
.....

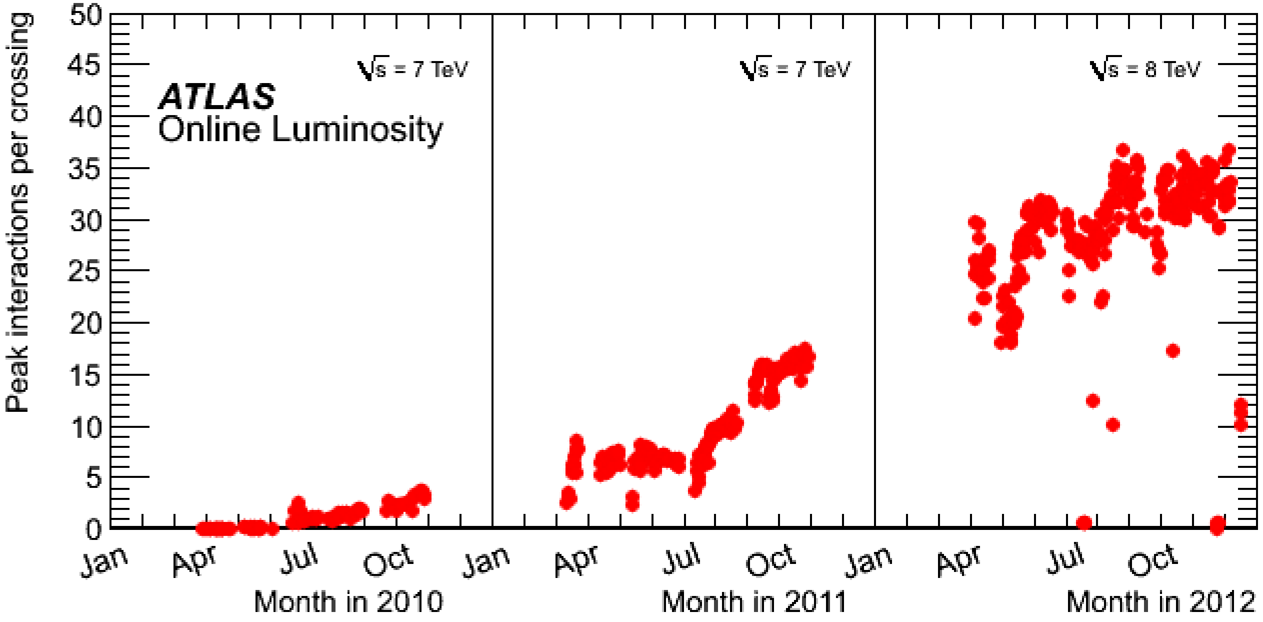
Luminosity Detectors 2012





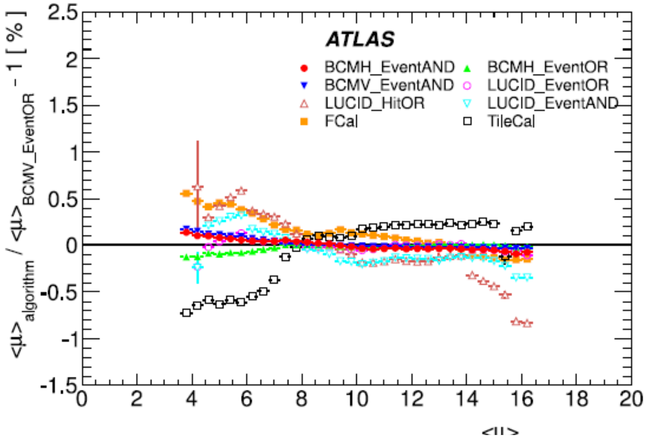
Long-term stability (2011)
0.7 %

μ-dependence



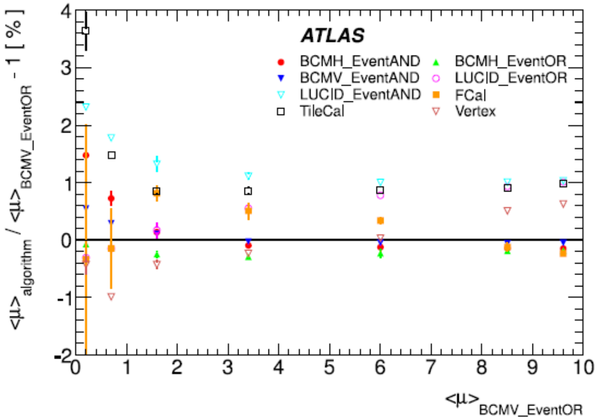
Linearity in response with μ….this is a challenge…..

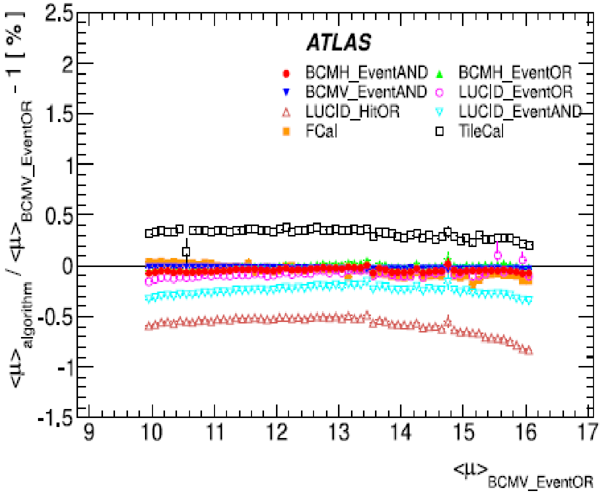
μ-dependence(cont.)



However ramp up of μ with time

⇒ time stability or μ-dependence ?





μ-scans…..successively separate the beams during one hour

Only one fill…ratio of algorithms

0.5 % has been assigned to the uncertainty of the μ extrapolation

Summary of 2011 uncertainties

Uncertainty source	uncertainty in %
Bunch population product	0.5
Other vdM related	1.4
Afterglow correction	0.2
BCM stability	0.2
Long term stability	0.7
Mu dependence	0.5
Total	1.8

A Historical Parenthesis

This method was used at the ISR and at the LHC
BUT not at the SPS collider and at the Tevatron

proton-antiproton more difficult

A proton going in one direction and an anti-proton in the other
can not be magnetically separated……
the magnetic part of the Lorenz force depends on the velocity VECTOR
the electric part of the Lorenz force independent of the velocity vector
⇒ Electrostatic separators needed for VdM scans..not strong enough…

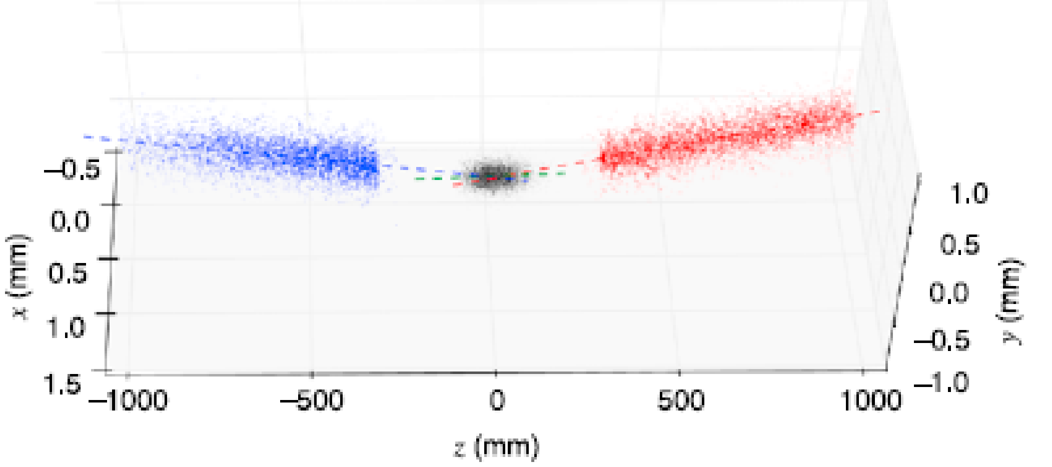
LHCb

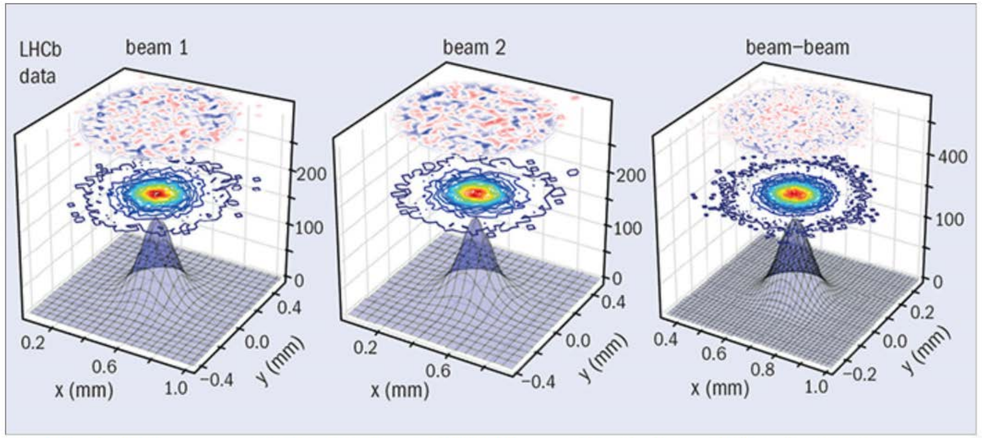
Luminosity from Machine parameters

(3)Beam Gas Imaging

Method:
Inject residual gas in the beam pipe (i.e. neon)
Measure vertices using high resolution micro vertex detectors
Determine three dimensional distributions for

Beam1, Luminous region, Beam2





Results of a global pluridimensional shape fit of the individual LHC beams (left and centre) and of the luminous region (right), based on the distributions of beam–gas and beam–beam interaction vertices. The results are shown here for a selected colliding bunch pair and a central slice on the longitudinal axis.

Complementary method to determine the beam overlap
Advantage: do not need to move the beams

σ_{vis} uncertainty
1.43%

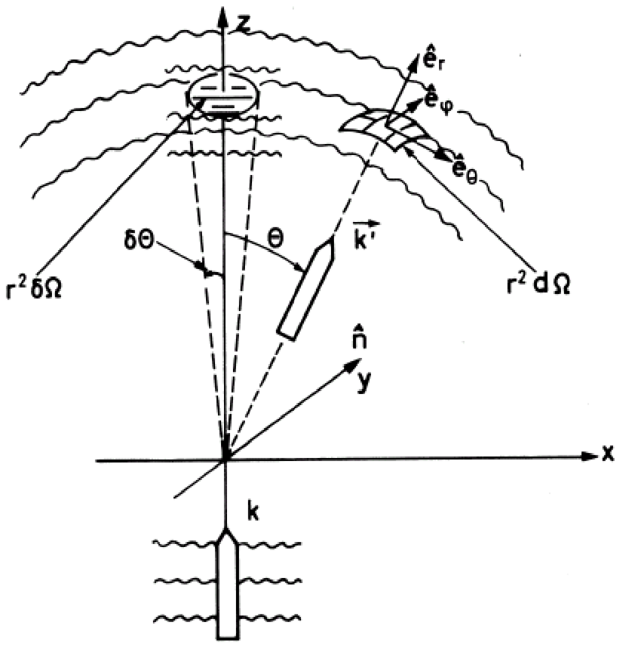
Elastic scattering and luminosity

Elastic scattering has traditionally provided a handle on luminosity at colliders.

(Totally different approach relative machine parameters-complementary)

The basis for this is the Optical Theorem which relates the total cross-section to the forward elastic scattering amplitude

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



The optical theorem is a general law of wave scattering theory derived from conservation of probability using quantum mechanics

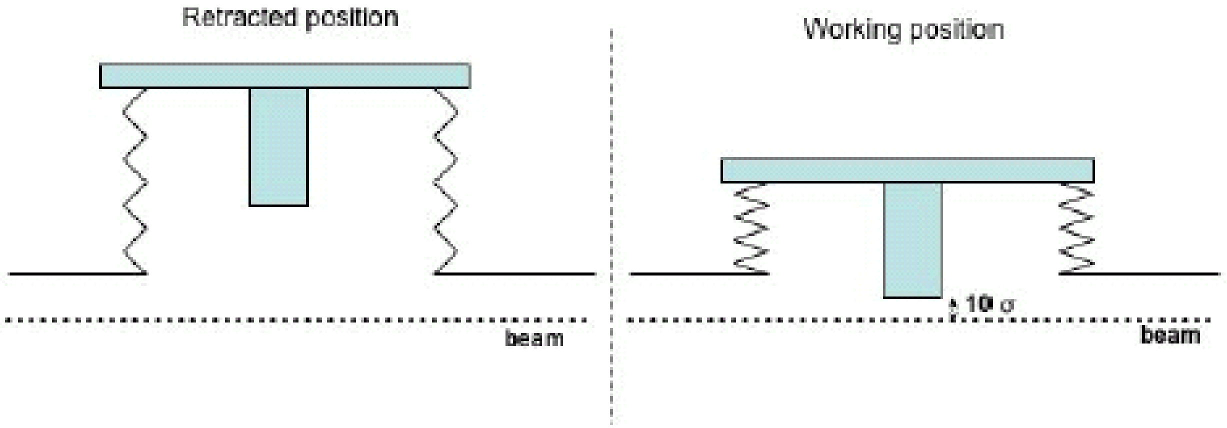
- Scattering situation: incoming plane wave and outgoing spherical wave .
- The bigger total cross section is, the more has to be taken away from the incoming wave.
- This is done by destructive interference with the incoming wave. The incoming wave is at θ=0 and thus the outgoing destructive interference must also be at θ=0…….this means that the bigger the total cross section is the bigger the amplitude will be in the forward direction.

What is needed for the small angle elastic scattering measurements?

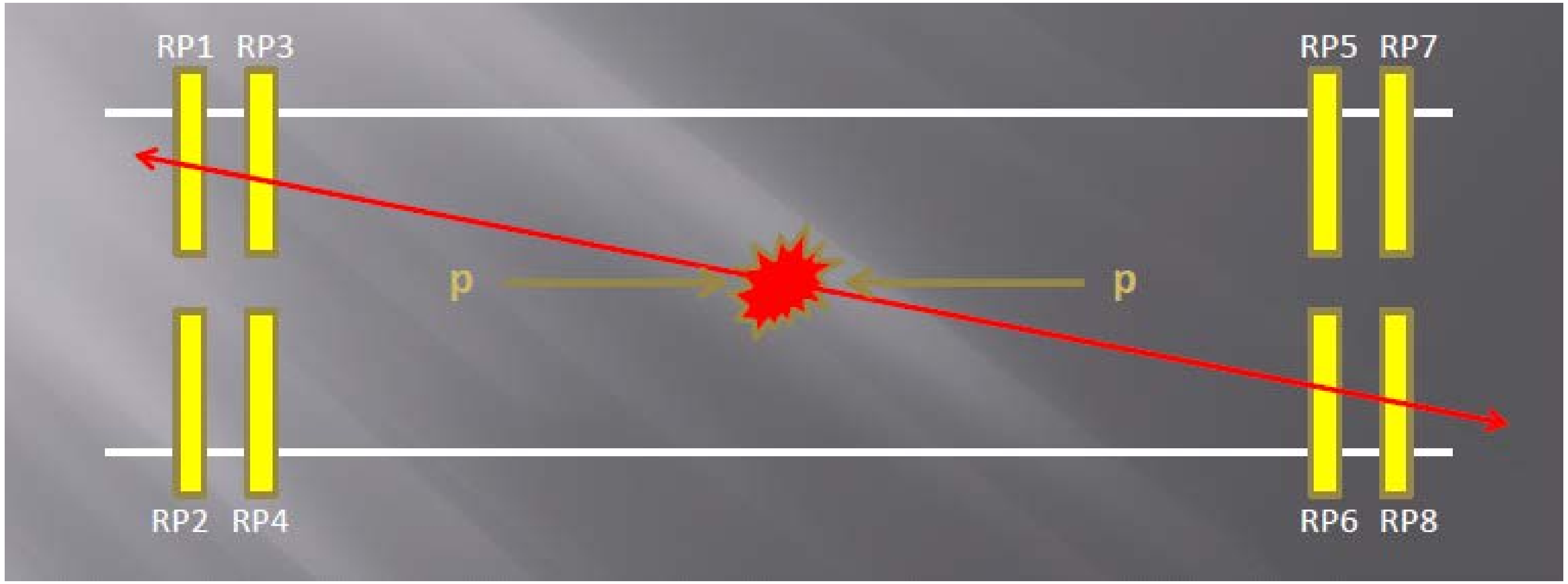
- Special beam conditions
- “Edgeless” Detector
- Compact electronics
- Precision Mechanics in the form of Roman Pots to approach the beam

The Roman Pot concept

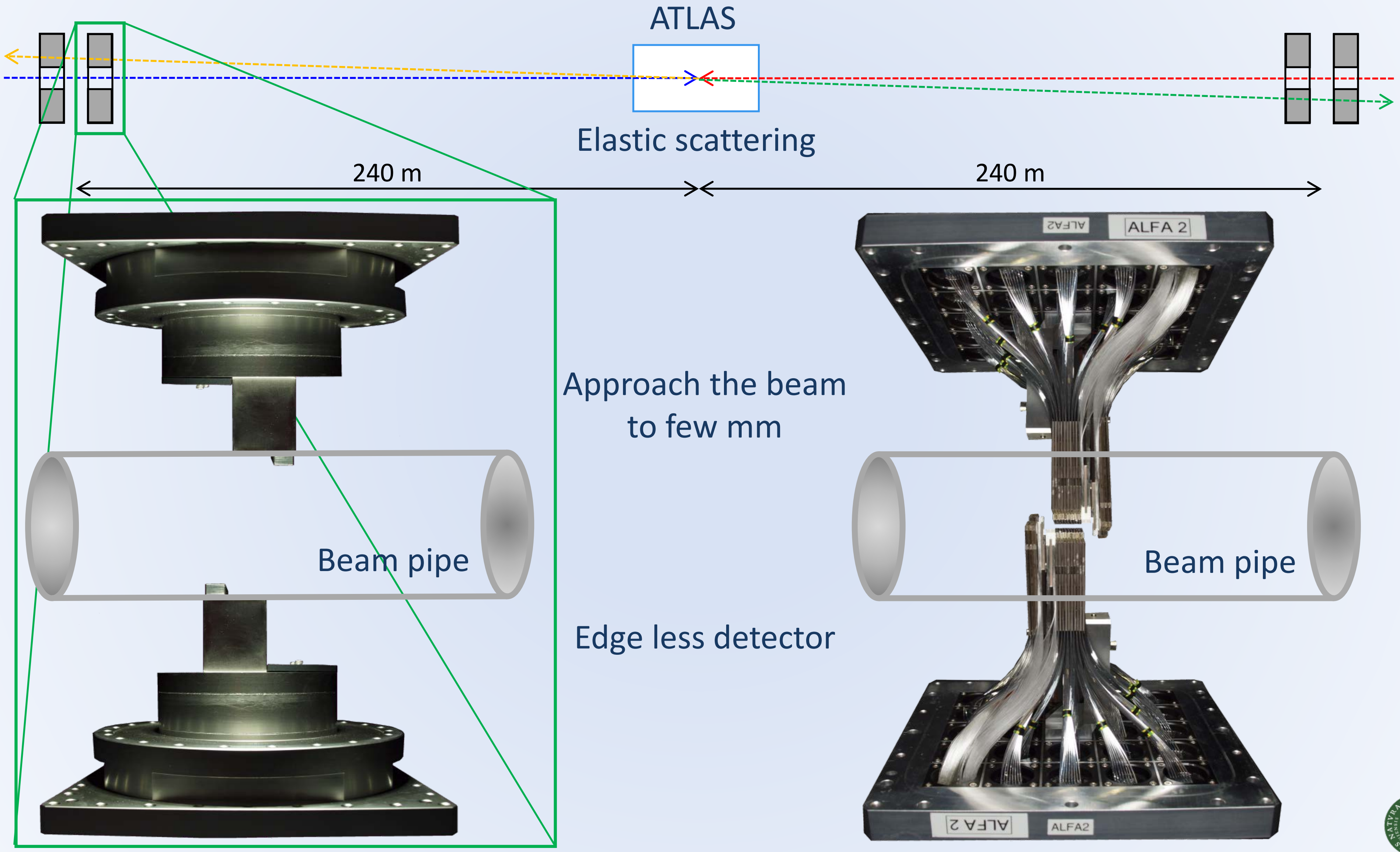
Roman Pot Concept



Basic principle



The ALFA detector system



Approach the beam to few mm

Edge less detector

The Optical theorem can be used in several ways for luminosity determination.

- Method 1

  Extrapolate elastic scattering to t=0 (the optical point) and in addition measure the total rate.

- Method 2

  Measure elastic scattering as such small angles that the cross section is also sensitive to the Coulomb part of the differential cross section.

Method 1: Extrapolate elastic scattering to t=0 (the optical point) and in addition measure the total rate.

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

$$\boxed{N_{tot} = \sigma_{tot} \cdot L}$$

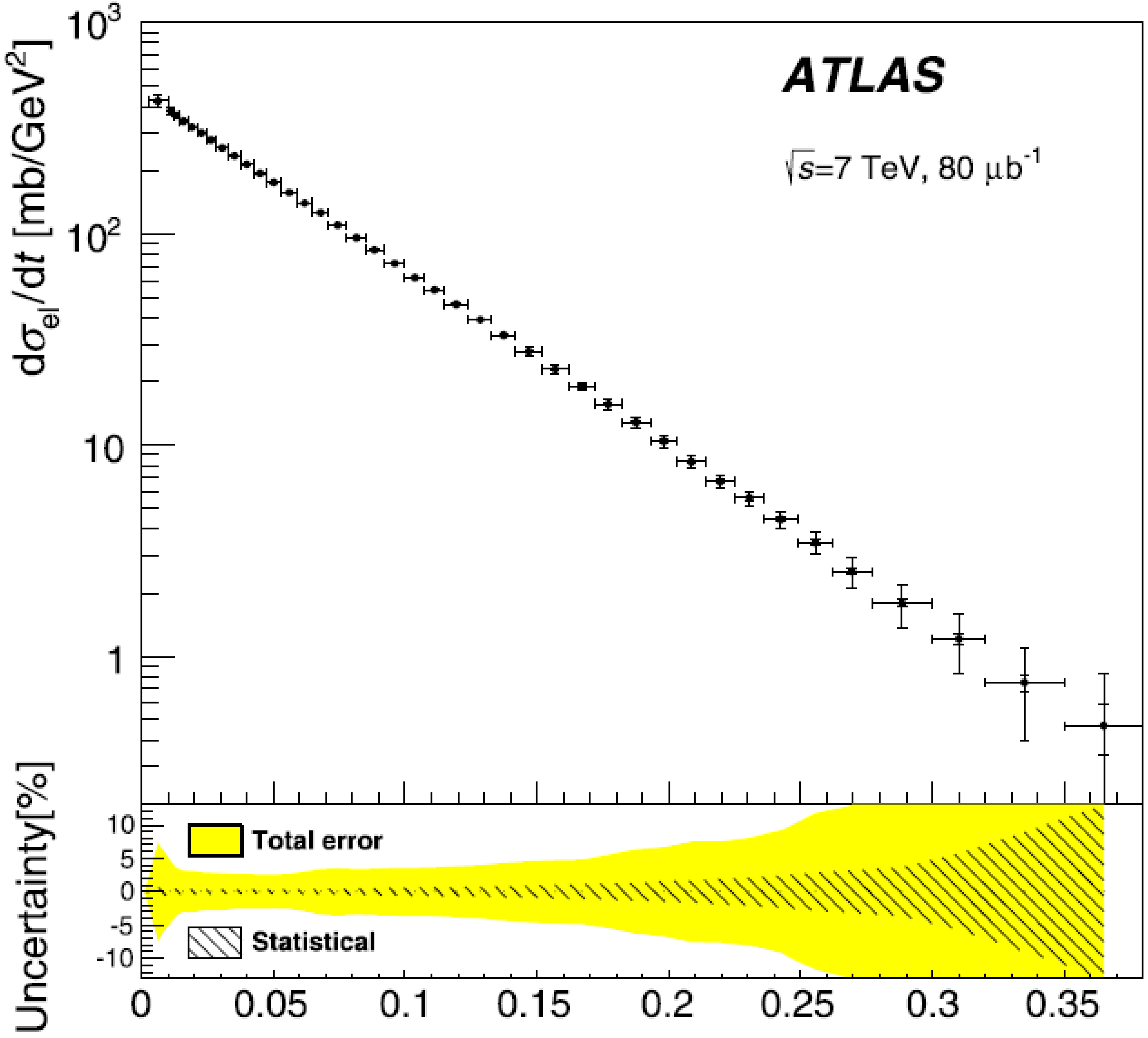
$$\Rightarrow \quad \boxed{L = \frac{1+\rho^2}{16\pi} \frac{N_{tot}^{\;2}}{\left.\frac{dN_{el}}{dt}\right|_{t=0}}}$$

where $\rho = \mathrm{Re}\, f_{el}(t=0)/\mathrm{Im}\, f_{el}(t=0)$

Thus we need to

- (1) Extrapolate the elastic cross section to t=o
- (2) Measure the total rate
- and in addition use best estimate of ρ ($\rho \sim 0.13$ +- 0.02 ⇨ 0.5 % in $\Delta L/L$)

(1) Extrapolate to t=0

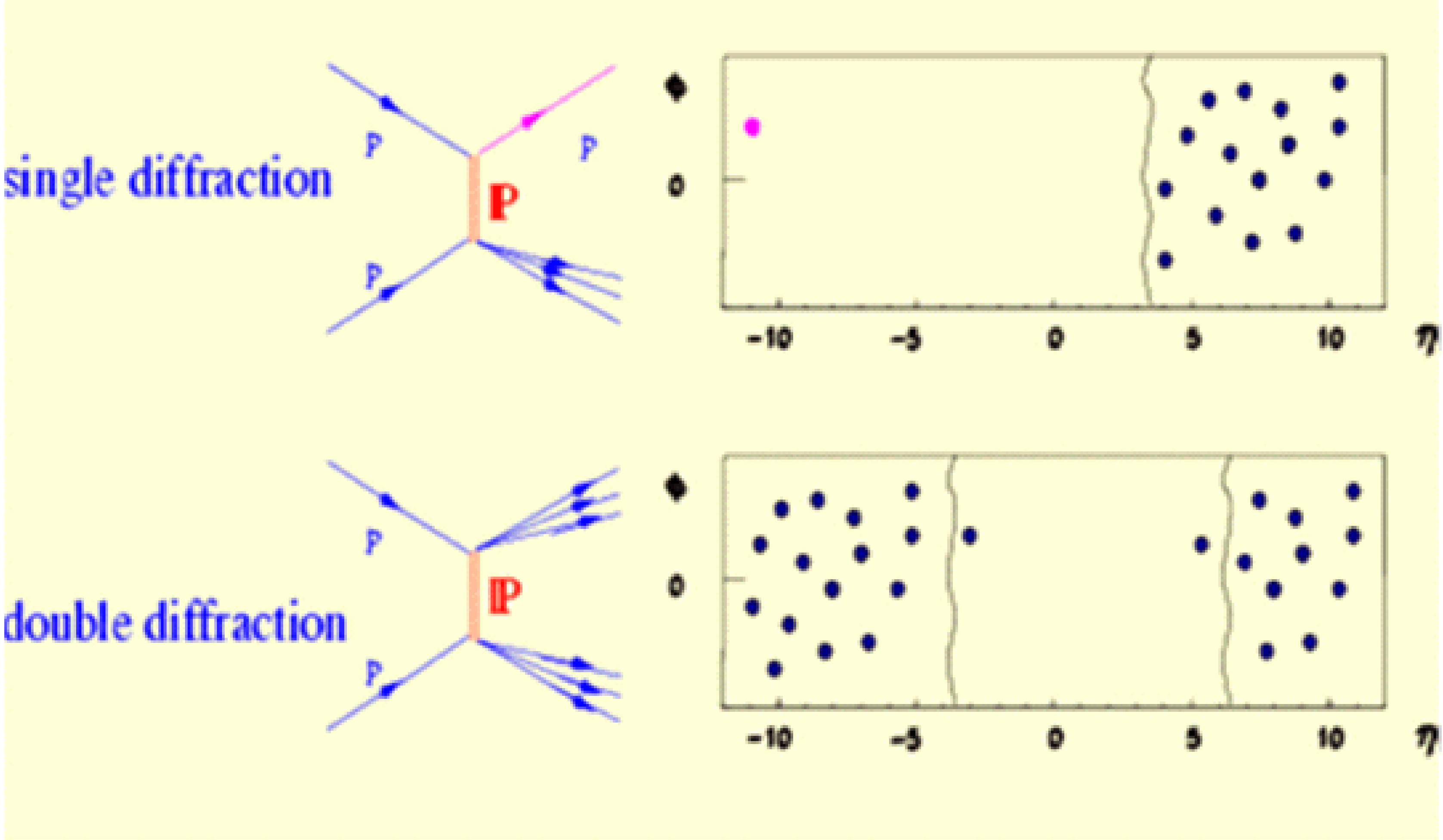


$t=-(p\theta)^2$

(2) Measure the total rate

$N_{total}=N_{el}+N_{inel}$

$N_{inel}=N_{nd}+N_{sd}+N_{dd}$



ISR : good η-coverage in the forward direction → Luminosity precision 1-2 %

SPS collider: intermediate η-coverage → Luminosity precision 3-4 %

What to expect at LHC ?

ATLAS do not cover the η range above 5
May be 10-15 % of cross section not measured
Estimate at 20% level (example)
2-3 % Uncertainty in the total rate

→ Luminosity precision 4-6 %

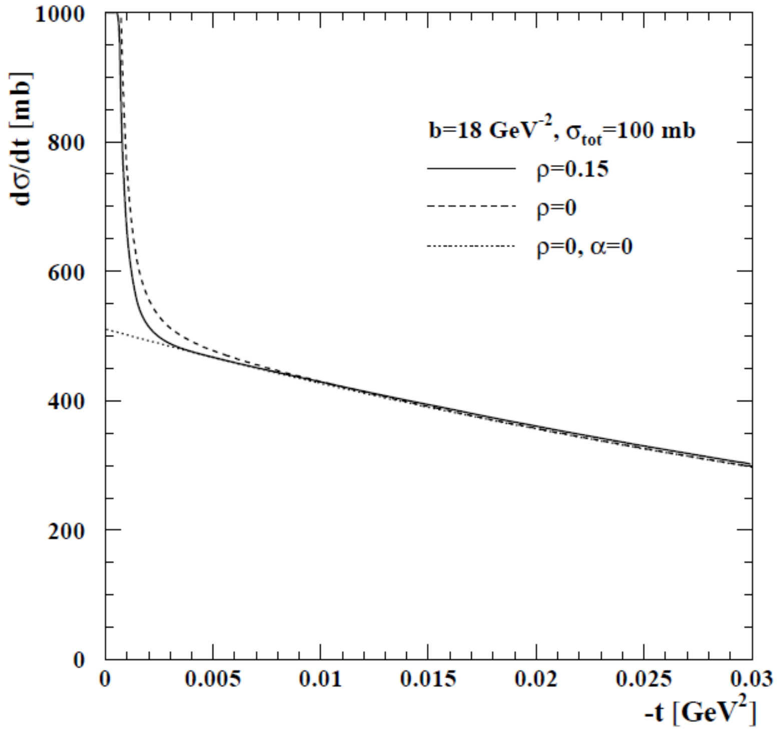
(TOTEM with better coverage
in the forward direction
obtained 3.8 %)

Method 2: Optical theorem and measuring of 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 needed



Precision at the ISR : ~4 %

Precision at the SPS collider: 2-3 %

Conclusion

- An overview of methods to measure the luminosity at hadron colliders has been given

- the VDM method was invented at the ISR and achieved a precision in the best case around 1 %

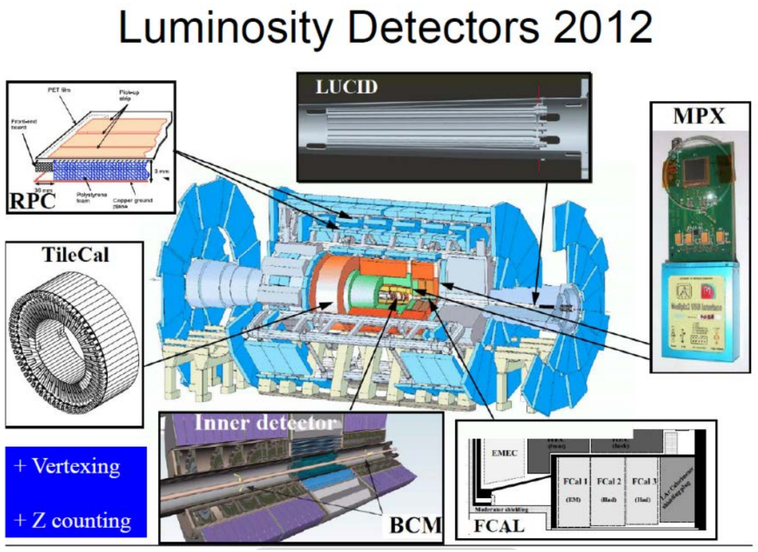
- Luminosity measurements at the one ring proton-antiproton colliders SppS and Tevatron were less accurate with precision around 3-6 %

- With the LHC we are back to higher precision using VDM scans and Beam Imaging methods giving 1.5-2 %

Recommended reading: Luminosity determination at proton colliders
P.Grafstrom and W.Kozanecki
Progress in Particle and Nuclear Physics , Volume 81, March 2015, pages 97-148.

Back up

Calibrate each detector and each algorithm with the VdM scans



LUCID(Cerenkov) and BCM(diamond) are capable of measuring the luminosity bunch-by-bunch

EVENT counting:
Determine fraction of bunch crossings during which a detector register an "event" satisfying a given criteria.

Examples of algorithms:
LUCID_EventOR
LUCID_EventAND
BCMH(V)_EventOR
BCMH(V)_EventAND
LUCID_HitOR

HIT counting:
Determine number of "hits" per bunch crossing in a given detector

Motivation-why we need to measure the luminosity

- Measure the cross sections for "Standard " processes
  - Top pair production
  - Jet production
  - ……

Theoretically known to ~5-8%

- New physics manifesting in deviation of $\sigma \times BR$

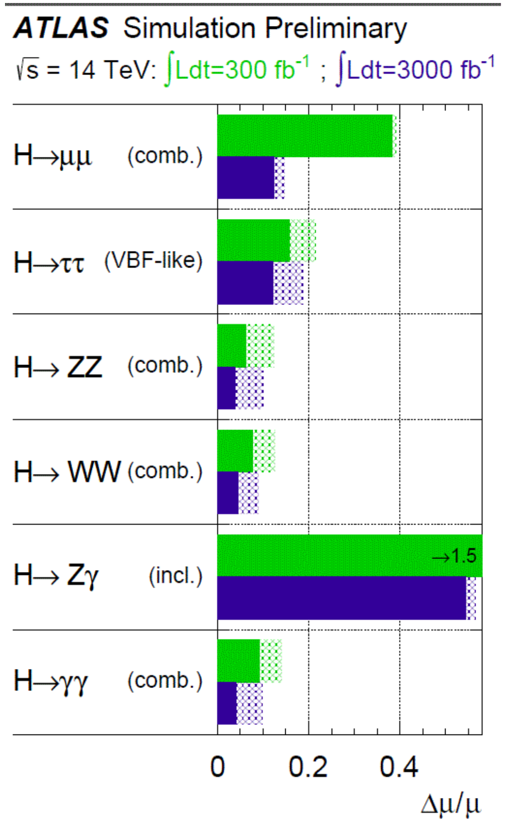
  relative to the Standard Model predictions.

  Precision measurement becomes more important if new physics not directly seen.

  (characteristic scale too high!)

- Important precision measurements
  - Higgs production $\sigma \times BR$
  - $\tan\beta$ measurement for MSSM Higgs
  - …….

Higgs coupling



What are the difficulties ?

- The resolution

  The p_t resolution has to be very good in order to use the $P_t(\mu\mu) \sim$ 10-50 MeV cut.

- 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 ABSOLUTE 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

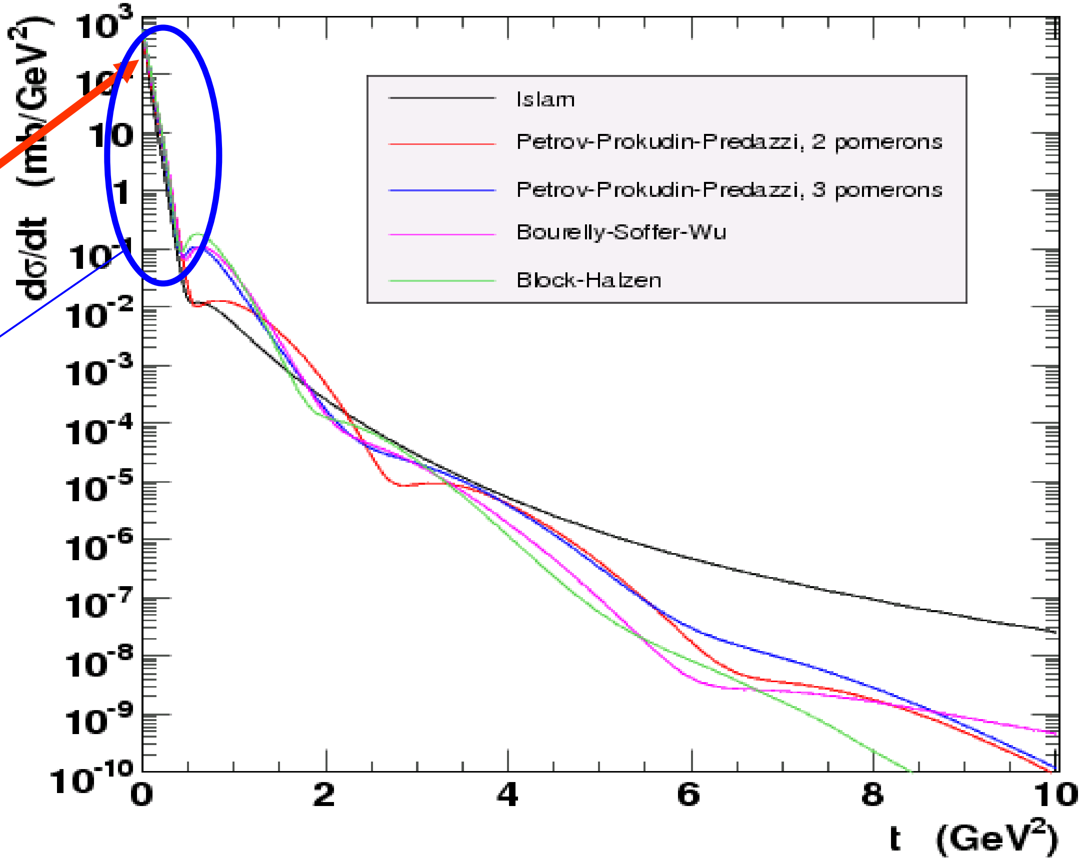
  First exclusive two-photon observed in e^+e^-. …. but….
  16 events for 530 pb^{-1} for a σ of 1.7 pb ⇨ overall efficiency 1.6 %

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

Different approach: Consider parton-parton luminosity

(suggested by M.Dittmar,F.Pauss,D.Zurcher)

Measure simultaneously the event rate of production of W and Z and the pseudorapidity distributions of W and Z leptonic decays. In this way the x distribution of quarks and antiquarks would be constrained and allow percent-level prediction of other quark-antiquark related scattering processes without knowing the proton-proton luminosity.



Extrapolate to t=0

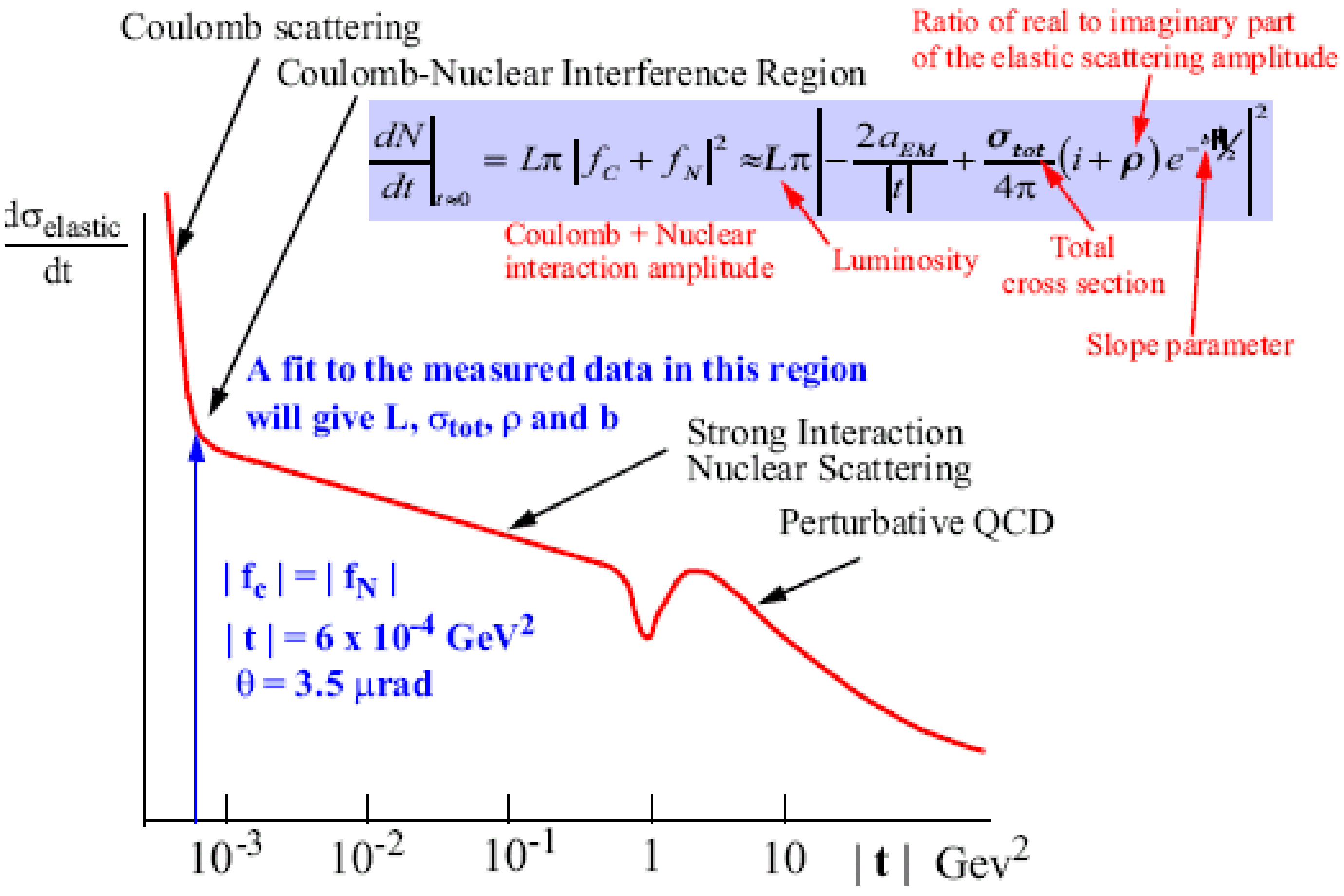
Exponential region

- t range 0.1 - 0.005 GeV^2

Statistical error for 10^7 events :	0.1 %
Experimental effects (beam divergence, beam energy, crossing angle, effective length)	0.5 %
Theoretical error due to non-exponential behavior	0.25 %

Be very conservative ⇒ 1 % error in extrapolation

Elastic scattering at very small angles



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

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

$\theta = 3.5$ µrad