physics program of ALFA

and

precision luminosity measurement in ATLAS

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behalf of the ATLAS collaboration

outline

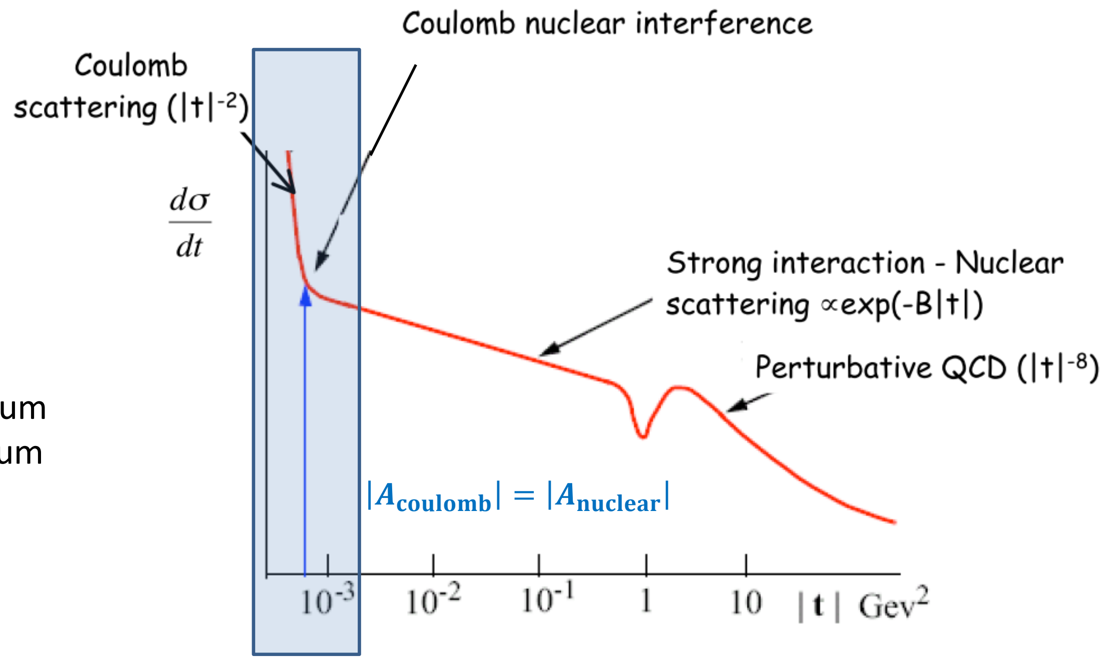
- ALFA detector and its physics program
  - absolute luminosity and total cross section measurements
  - ALFA detector system
  - program beyond luminosity measurement: single diffraction & exclusive processes
- other ATLAS luminosity precision measurements
  - counting & van der Meer scanning
  - theoretically well known processes with high rates

ALFA – mission

- ALFA – Absolute Luminosity For ATLAS – is a tracker-type detector
- primary goal is to measure absolute luminosity and to reach the level of a precision 2-3%

$t = (p-p')^2$

p – incoming proton momentum
p' – outgoing proton momentum
σ – cross section
B – nuclear slope



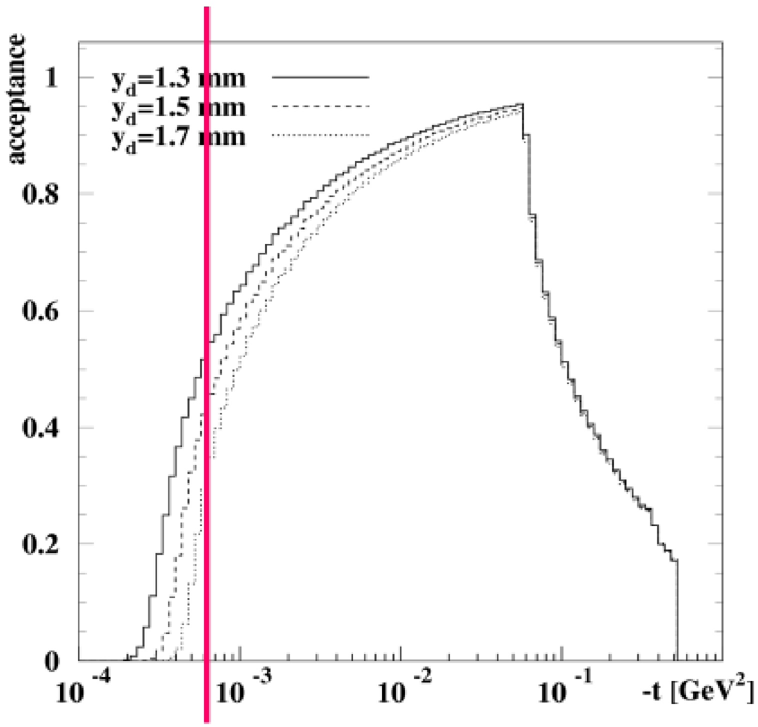
luminosity is one of the parameters of the fit, responsible for scaling of the curve

outside the Coulomb region

in case we cannot reach the Coulomb region we can write, with the help of the optical theorem

$$\sigma_{\mathrm{tot}} = \frac{16\pi}{1+\rho^2} \frac{\mathrm{d}R_{\mathrm{el}}/\mathrm{d}t|_{t=0}}{R_{\mathrm{tot}}} \qquad L = \frac{1}{16\pi} \frac{R_{\mathrm{tot}}^2}{\mathrm{d}R_{\mathrm{el}}/\mathrm{d}t|_{t=0}}(1+\rho^2) \quad \text{or} \quad \frac{1}{L} = \frac{1}{16\pi} \frac{\sigma_{\mathrm{tot}}^2}{\mathrm{d}R_{\mathrm{el}}/\mathrm{d}t|_{t=0}}(1+\rho^2)$$

ρ – ratio of real and imaginary parts of elastic scattering amplitude, $R_{\mathrm{el(tot)}}$ – elastic (total) rate



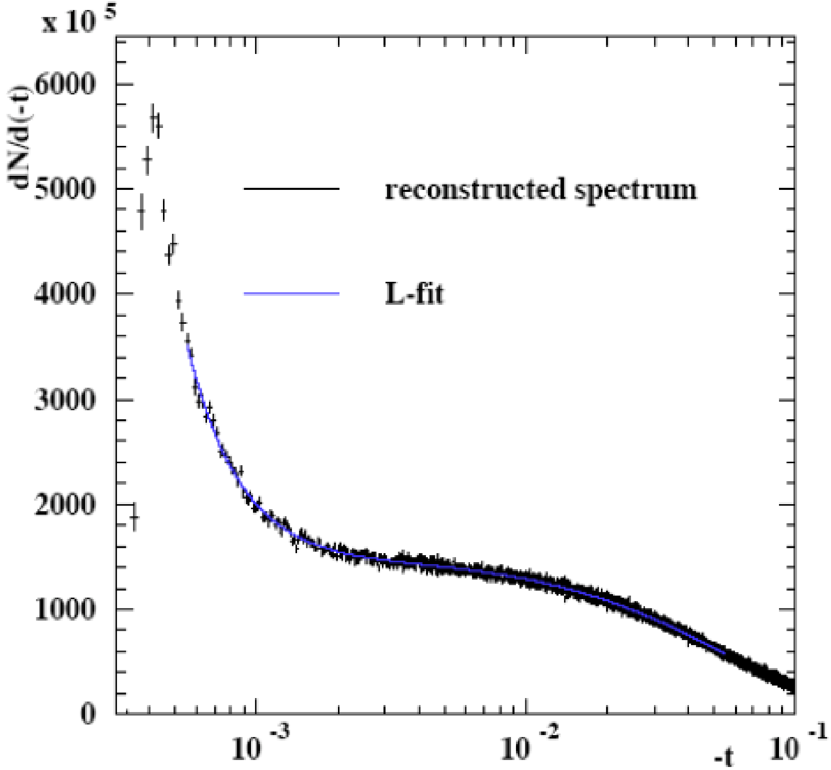
- problem with acceptance for small t – simulation needed
- knowledge of R_{tot} needed
  Minimum Bias Trigger Scintillators (MBTS) can help

$$\sigma_{\mathrm{tot}} = \sigma_{\mathrm{el}} + \sigma_{\mathrm{inel}} = \sigma_{\mathrm{el}} + \sigma_{\mathrm{ND}} + \sigma_{\mathrm{SD}} + \sigma_{\mathrm{DD}}$$

sample	MBTS/acceptance
non-diffractive	100%
double diffractive	82%
single diffractive	68%
noise	0.05%

luminosity fit

p_{beam} = 7 TeV



statistical uncertainties

	Input	Linear fit	Error [%]
L [10^{26} cm $^{-2}$ s $^{-1}$]	8.10	8.151	1.77
σ_{tot} [mb]	101.51	101.14	0.9
b [GeV^{-2}]	18	17.93	0.25
ρ	0.15	0.143	4.3
Fit range		$0.00055 < -t < 0.055$	
Fit quality [χ^2/Ndof]		2845/2723	

systematic uncertainties

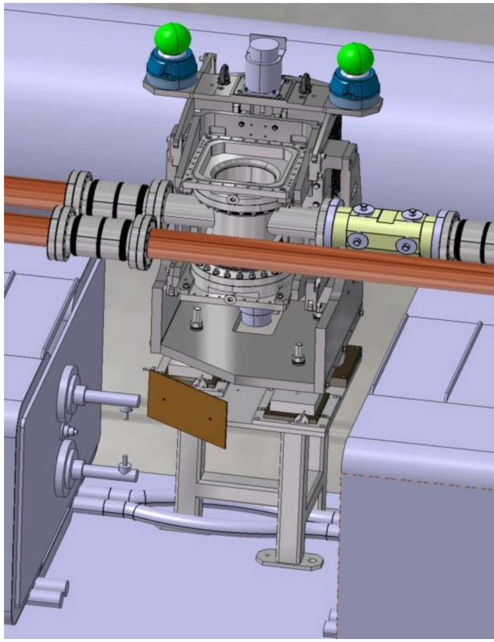
Systematic uncertainties [%]	Linear fit	
Nominal result for L	8.151	values
Statistical error	1.77	effectively
Beam divergence	0.31	correspond to
Crossing angle	0.18	(± 0.2μrad)
Optical functions	0.59	(± 1-2%)
Phase advance	1.0	(± 0.5°)
Detector alignment	1.3	
Geometrical detector acceptance	0.52	
Detector resolution	0.35	
Background subtraction	1.10	
Total experimental systematic uncertainty	2.20	
Total uncertainty	2.82	

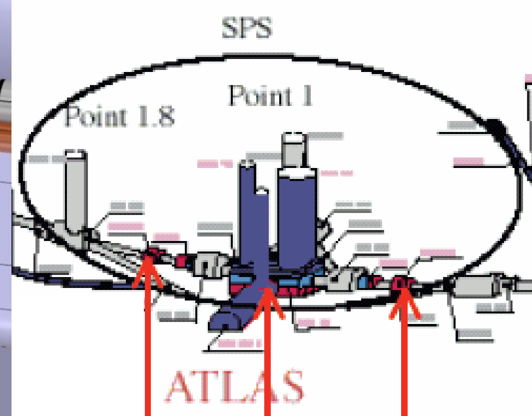
- expected absolute luminosity measurement precision 2-3%
- total cross section measurement precision 1-1.5%
- nuclear slope *B* and *ρ* precision 4-5%
- result nontrivially depends on energy: some contributions are getting bigger, some smaller → would be good to make a measurement for each energy

- final uncertainty will be higher as the need of an extrapolation to high luminosity

ALFA – Roman Pot stations

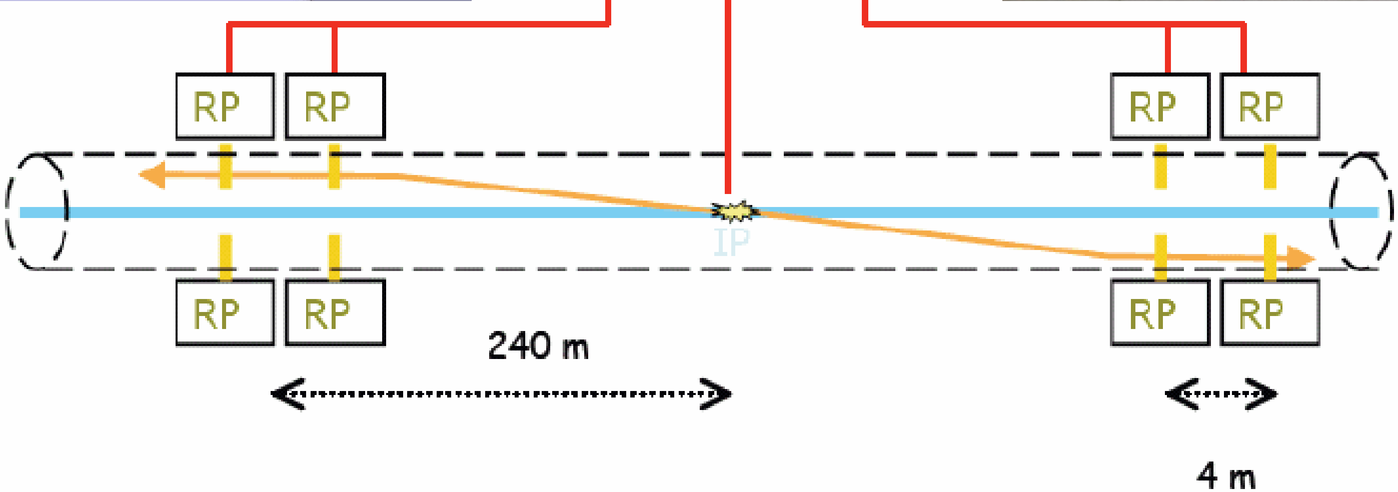
design…



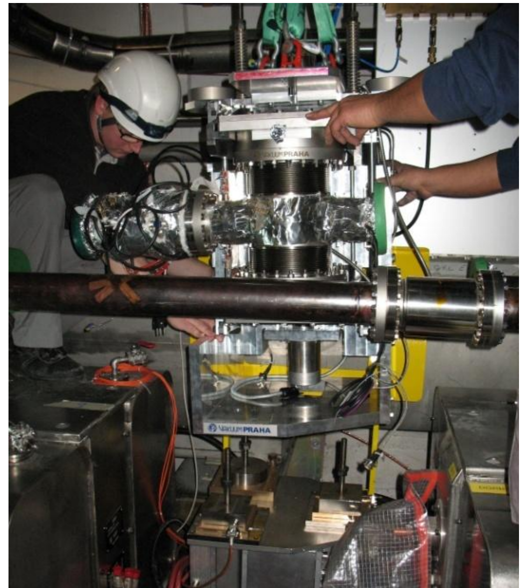


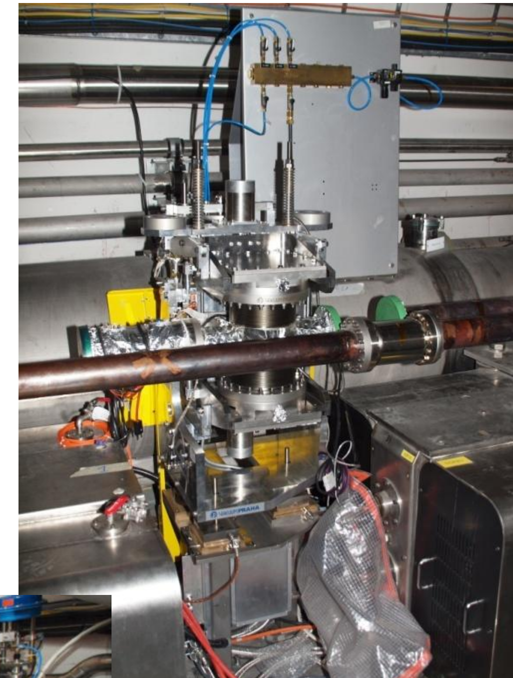
and reality

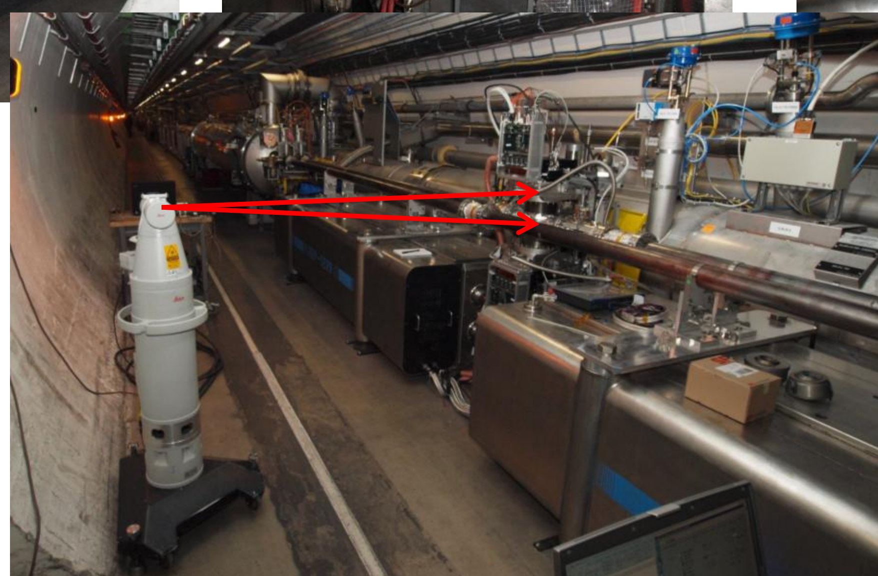
locations:



installation…

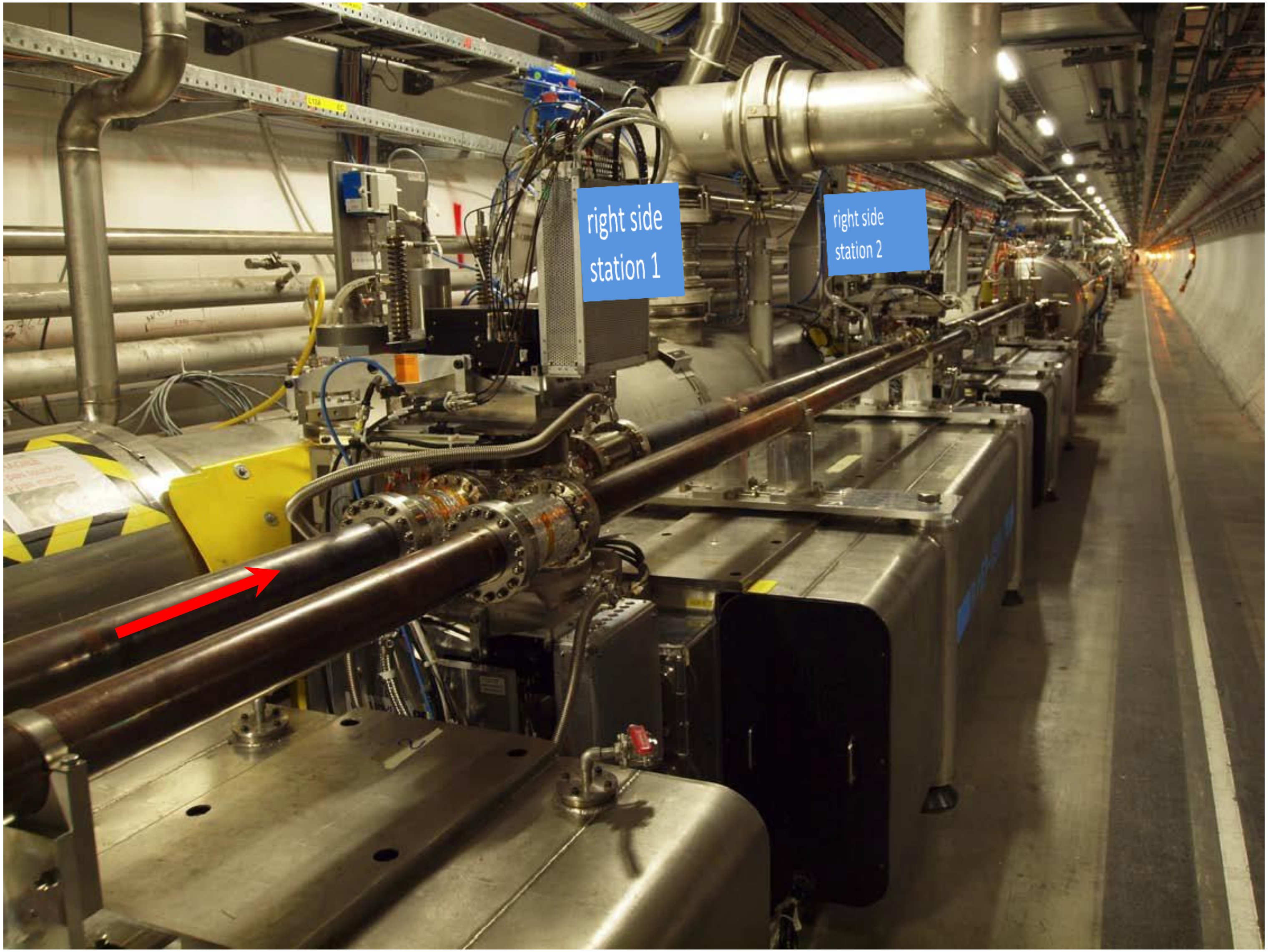




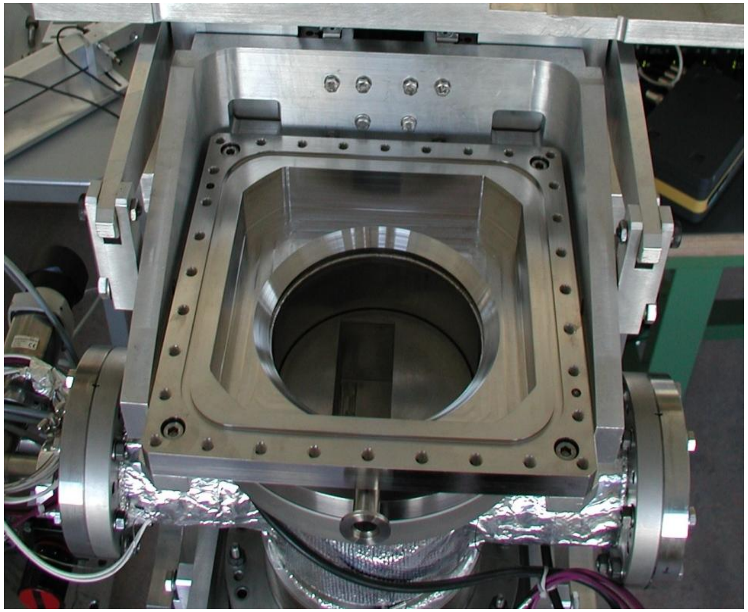


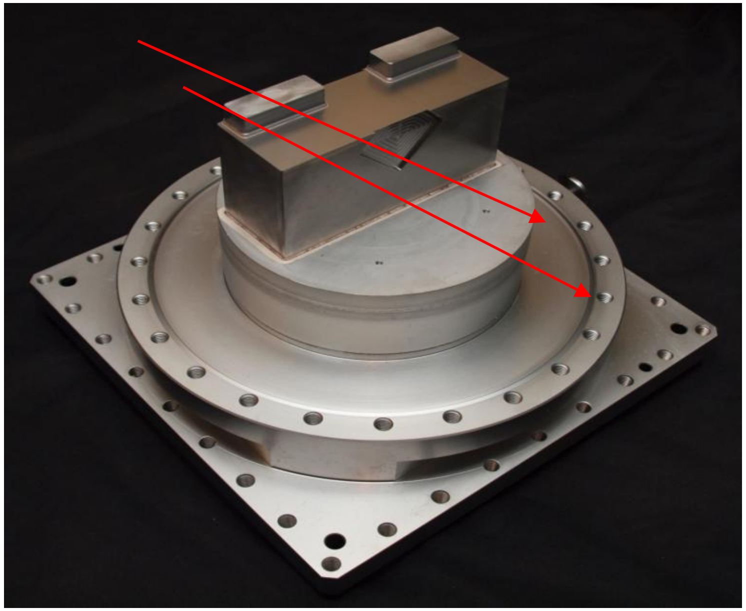
metrology

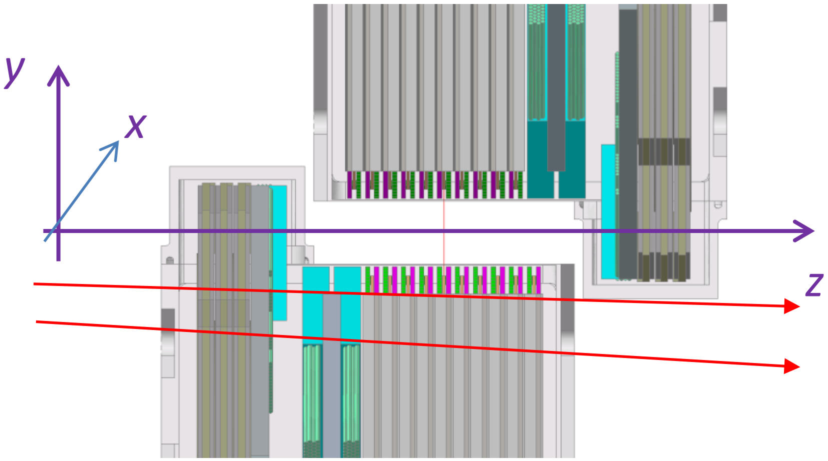
… and ready for action!

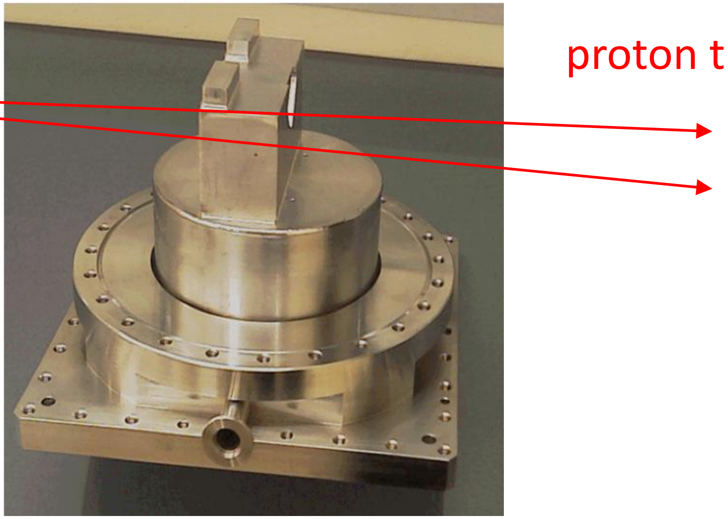


Roman Pot



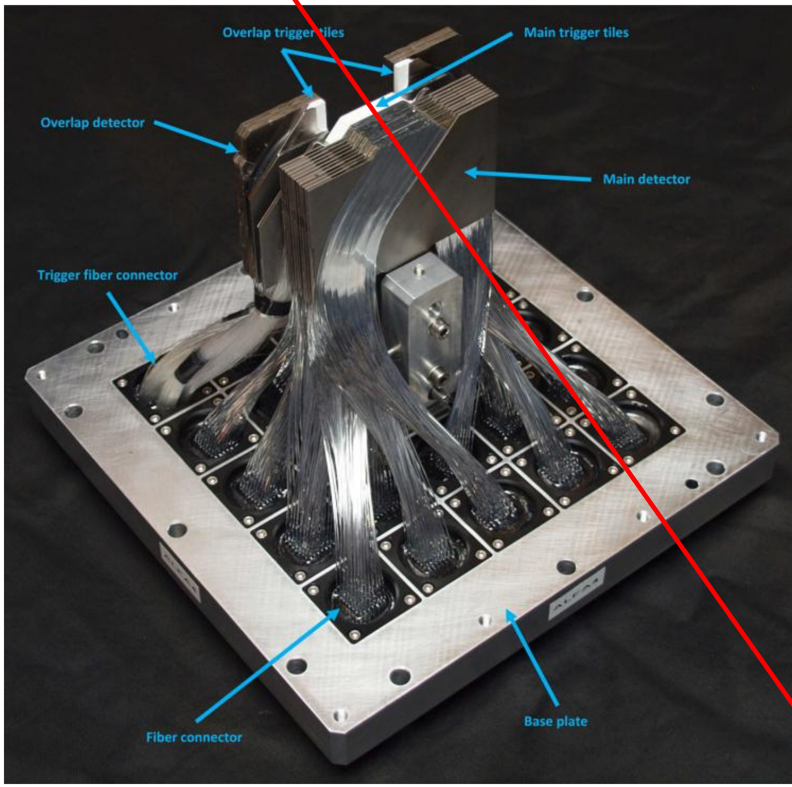




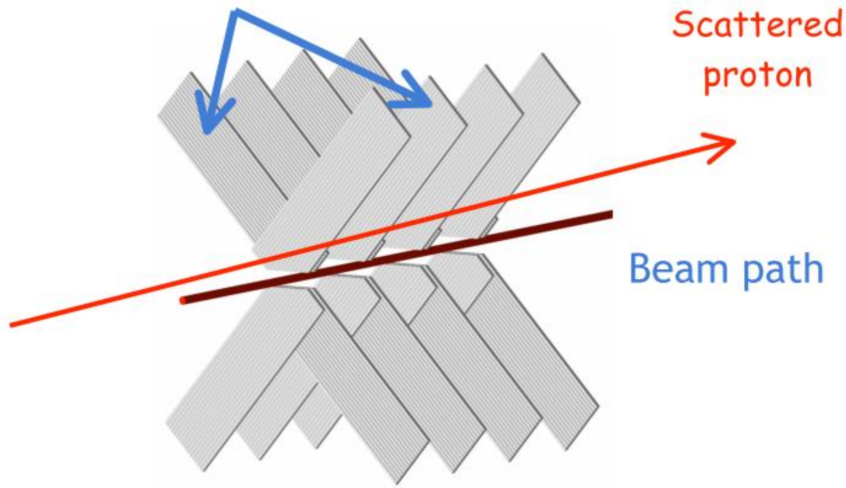


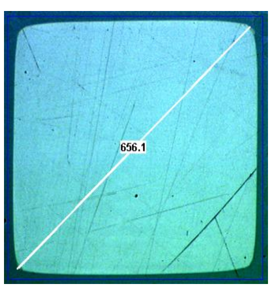
proton tracks

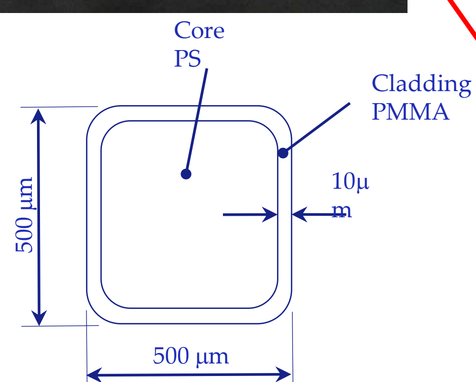
detector

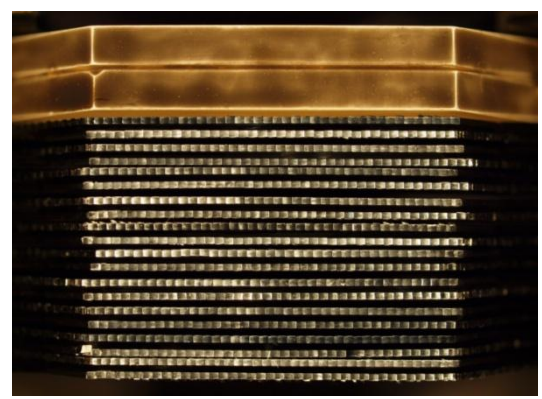


Scintillating fibers in UV geometry



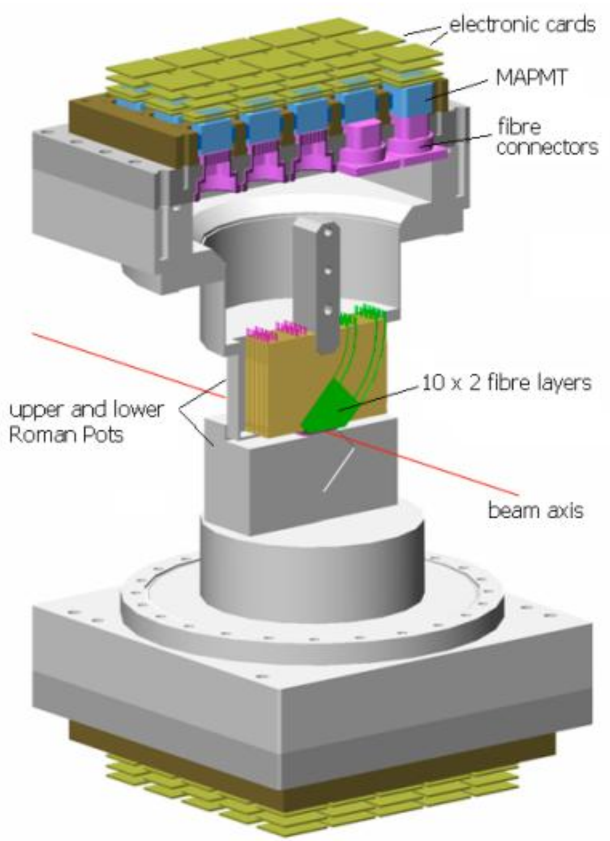




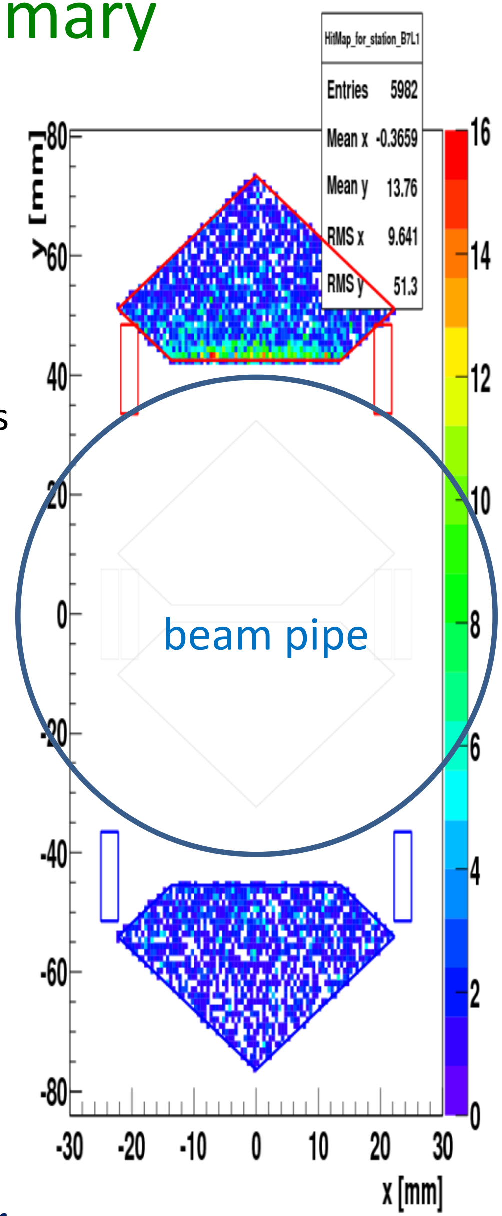


staggering

detector properties – summary

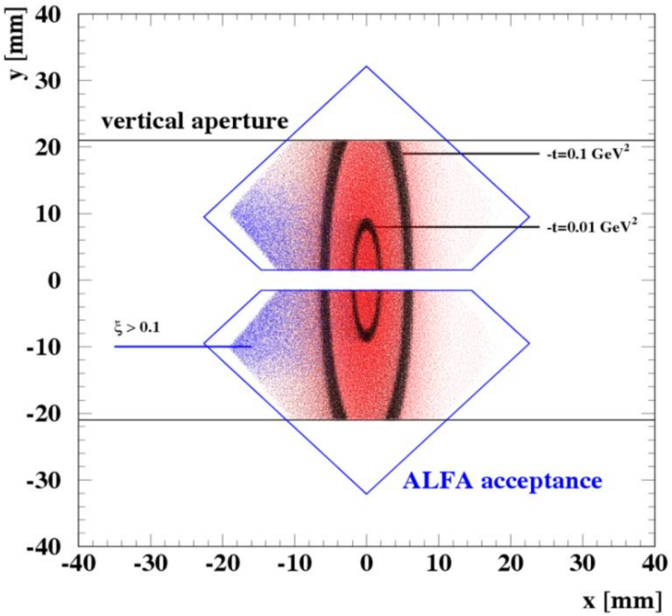


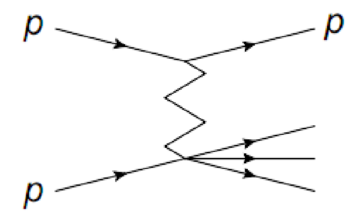
first tunnel output
detectors in parking positions



- single cladded 0.5 mm x 0.5 mm (square) fibers
- 10 layers in U, 10 in V; staggering
- ~ 30 µm position resolution
- efficiency ~ 90% per plane → ~ 100% efficiency of the detector

single diffraction





hit pattern for 10 M single diffraction events simulated with PYTHIA (6.4, modified) & MADX

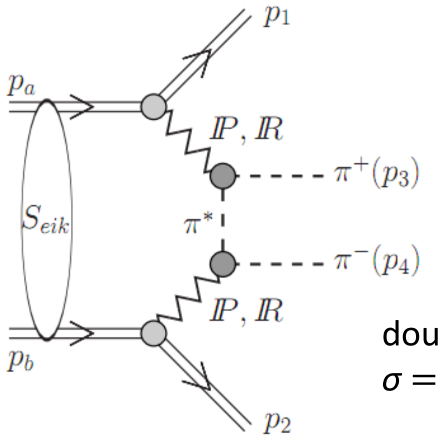
$10.6 < |\eta| < 13.5$

cross section [mb]	Pythia	Phojet
Elastic scattering	34.2 (modified) 22.2 (default)	34.5
Single diffraction	14.3	11.0
Double diffraction	10.2	4.1
Minimum bias non-diffractive	54.7	67.9
Total cross section	101	119

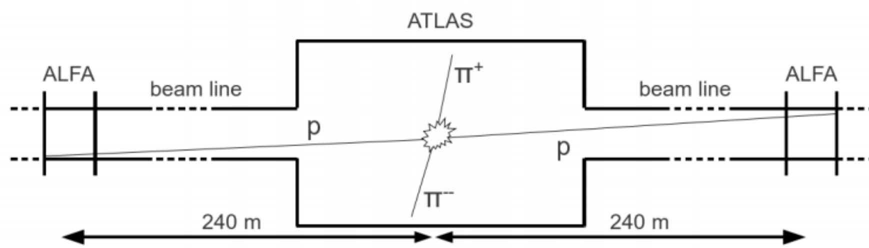
Efficiency [%]	Pythia	Phojet
Pre-selection		
ξ<0.2	97.1	94.8
ZDC [E>1 TeV]	53.9	38.7
LUCID [1 track]	45.2	57.3
Total pre-selection	75	74
RP selection relative to pre-selection		
ALFA	60.1	54.2
Total acceptance	45.0	40.1

p_{beam} = 7 TeV, results based on Geant 4 (generator level), should be re-done in the full ATLAS framework

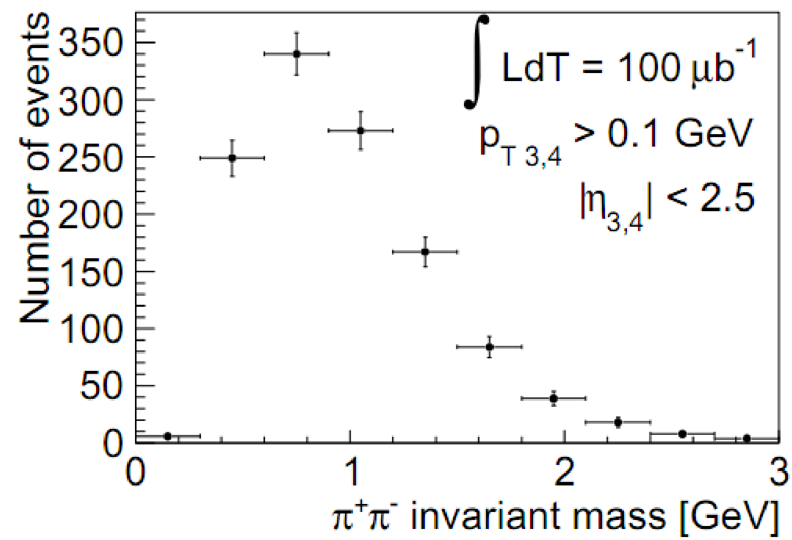
exclusive processes



double diffraction
$\sigma = 200\ \mu$b for $\sqrt{s}$ = 7 TeV



3 (4) $\leftrightarrow$ $\pi^{+(-)}$



- measurement of $pp \to pp\ \pi^+\pi^-$ possible, expect ~ 2000 events for L = 10^{27} cm^{-2}s^{-1}, 30 hours
- it requires ALFA elastic AND trigger + low-p_T tracking
- so far only measurements were performed at $\sqrt{s}$ = 62 & 63 GeV by ABCDHW Collaboration, ISR
- observed asymmetry in $\pi^+\pi^-$ may be a signal of odderon interaction

- other processes such as K^+K^- or p^+p^- can be studied
- with enough statistics, other exclusive processes involving $f_2(1270)$, glueballs, charmonia

Exclusive $pp \to pp\ \pi^+\pi^-$ reaction: from the treshold to LHC
P. Lebiedowicz, A. Szczurek, Phys. Rev. **D81** (2010) 0360

R. Staszewski, P. Lebiedowicz, M. Trzebinski, J. Chwastowski and A. Szczurek, archiv:1104.3568

ATLAS luminosity measurements in the pre-ALFA era

based on

- observed event rates (event counting) and van der Meer scan

  detectors: LUCID – LUminosity Using Cerenkov Integrating Detector (LUCID)

  MBTS – Minimum Bias Trigger Scintillators (MBTS)

  BCM – Beam Condition Monitor (BCM)

- using any theoretically well known process with large rates (R = dN/dt) like W/Z production

detector event rates and van der Meer scan

- for the luminosity we can write:

$$L = \frac{\mu n_b f_r}{\sigma_{\text{inel}}} = \frac{\varepsilon \mu n_b f_r}{\varepsilon \sigma_{\text{inel}}} = \frac{\mu_{\text{vis}} n_b f_r}{\sigma_{\text{vis}}} \qquad (+)$$

ε – efficiency, μ – number of inelastic events per bunch crossing,
n_b – number of bunches, f_r – accelerator frequency

from here we can determine

$$\sigma_{\text{vis}} = \frac{\mu_{\text{vis}} n_b f_r}{L}$$

as a calibration constant, knowing luminosity

- luminosity can be determined via

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

n_1, n_2 – numbers of particles in bunches

beam characterizing widths Σ_i are measured in van der Meer scans

- relation between μ_{vis} and the number of measured events The probability P to observe at least 1 event is

$$\mathrm{P}_{\text{Event\_OR}}(\mu_{\text{vis}}) = \frac{N_{\text{OR}}}{N_{\text{BC}}} = 1 - \mathrm{P}_0(\mu_{\text{vis}}) = 1 - e^{-\mu_{\text{vis}}} \sim \mu_{\text{vis}}$$

assumptions:
- Poisson distribution
- efficiency (pile up)

verified up to $\mu = 12$

having σ_{vis} and μ_{vis} we can determine luminosity using (+)

Uncertainty Source	$\delta\mathcal{L}/\mathcal{L}$
Statistical	< 0.1%
Bunch charge product	3.1%
Beam centering	0.1%
Emittance growth and other non-reproducibility	0.4%
Beam position jitter	0.2%
Length scale calibration	0.3%
Absolute ID length scale	0.3%
Fit model	0.2%
Transverse correlations	0.9%
μ dependence	0.6%
Long-term consistency	0.5%
Total	3.4%

Relative uncertainty on the luminosity calibration using **LUCID**_EventOR algorithm, 2010 running

ATLAS-CONF-2011-011, Eur.Phys.J.C71:1630,2011

integrated luminosity via *W* and *Z* boson production

- by rearranging the equation

$$\sigma_{W/Z} \times BR_{W/Z \to l\nu/ll} = \frac{N_S - N_B}{A_{W/Z} \cdot C_{W/Z} \cdot \int \mathcal{L}dt}$$

and knowing integrated luminosity can be obtained

$\sigma_{W/Z}$ – cross section

$BR_{W/Z \to l\nu/ll}$ – branching ratio

$A_{W/Z}$ – detector acceptance

$C_{W/Z}$ – detector correction factor

N_S – number of selected events

N_B – number of background events

- the measurement of the statistical component is not critical with ~ 300k *Z* bosons ($\leftrightarrow \int Ldt \sim 1$ fb^{-1})
- detector performance studies can reduce relative uncertainty below 1% on $C_{W/Z}$
- lower bound on theoretical uncertainty $\sigma_{W/Z}$ 0.6-0.8 %,
  currently ~ 3% due to PDF uncertainties

- main contribution comes from the theoretical uncertainty on $A_{W/Z}$ which currently is 3-4% but can be reduced by measurement of the cross section in detector acceptance region

expect a final precision between 1-3%

ATL-PHYS-PROC-2011-026

conclusion

- the detector system ALFA is installed and functioning

plan:

- 2011: *t*-spectrum and total cross section measurements

  σ_{tot} measurement precision < 5% (conservative estimate)

- 2012: continue of luminosity and total cross section measurements at 3.5 TeV

- 2014: luminosity and total cross section measurements at 7 TeV

- ALFA program offers both an independent ATLAS luminosity measurement to check previous algorithms and allows us to study elastic *p*-*p* scattering

- ALFA also has the potential to study soft diffraction & exclusive processes backup

ALFA - institutes

Contributing institutes to the ALFA part of ATLAS

- CERN European Laboratory for Particle Physics (CERN)

Czech Republic
- Institute of Particle & Nuclear Physics, Faculty of Mathematics and Physics, Charles University, Prague
- Institute of Physics, Academy of Science of the Czech Republic, Prague
- Palacky University, Olomouc

France
- Laboratoire de l'Accélérateur Linéaire, Univ. Paris-Sud, CNRS/IN2P3, Orsay, France

Germany
- Justus-Liebig University Giessen, Giessen
- DESY, Hamburg und Zeuthen
- Institute fur Physics, Humboldt Universität Berlin, Berlin

Great Britain
- Department of Physics and Astronomy, University of Mancherster, Manchester

Poland
- University of Cracow

Portugal
- Laboratorio de Fisica Experimental e Instrumentacao em, Particulas, Lisbon, Portugal

Spain
- Instituto de Fisica Corpuscular IFIC, Univ. de Valencia

Sweden
- Department of Experimental High Energy Physics, University of Lund, Lund

United States of America
- Department of Physics and Astronomy, Stony Brook University, Stony Brook

some optics equations

$$u^* = \frac{u_1 - \sqrt{\beta_1\beta^*} sin(\Delta\mu_1) u'^*}{\sqrt{\beta_1/\beta^*} cos(\Delta\mu_1)}$$

$$u^* = \frac{u_8 - \sqrt{\beta_8\beta^*} sin(\Delta\mu_1)(-u'^*)}{\sqrt{\beta_8/\beta^*} cos(\Delta\mu_8)}$$

$\Rightarrow$

$$\frac{u_1 - \sqrt{\beta_1\beta^*} sin(\Delta\mu_1) u'^*}{\sqrt{\beta_1/\beta^*} cos(\Delta\mu_1)} = \frac{u_8 - \sqrt{\beta_8\beta^*} sin(\Delta\mu_8)(-u'^*)}{\sqrt{\beta_8/\beta^*} cos(\Delta\mu_8)}$$

Same β* $\Rightarrow$

$$u'^* = \frac{1}{\sqrt{\beta^*}\,(tan(\Delta\mu_1) + tan(\Delta\mu_8))} \left(\frac{u_1}{\sqrt{\beta_1} cos(\Delta\mu_1)} - \frac{u_8}{\sqrt{\beta_8} cos(\Delta\mu_8)} \right)$$

Different β* $\Rightarrow$

$$u'^* = \frac{1}{\beta_1^* tan(\Delta\mu_1) + \beta_8^* tan(\Delta\mu_8)} \left(\frac{u_1}{\sqrt{\beta_1/\beta_1^*} cos(\Delta\mu_1)} - \frac{u_8}{\sqrt{\beta_8/\beta_8^*} cos(\Delta\mu_8)} \right)$$

Transfer matrix between s_0 and s

$$M(s_0 \to s) = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix}$$

$$M_{11} = \sqrt{\frac{\beta(s)}{\beta(s_0)}} (\cos\Delta\mu + \alpha(s_0)\sin\Delta\mu)$$

$$M_{12} = \sqrt{\beta(s)\beta(s_0)} \sin\Delta\mu$$

$$M_{21} = \frac{((\alpha(s) - \alpha(s_0))\cos\Delta\mu - (1 + \alpha(s)\alpha(s_0))\sin\Delta\mu)}{\sqrt{\beta(s)\beta(s_0)}}$$

$$M_{22} = \sqrt{\frac{\beta(s)}{\beta(s_0)}} (\cos\Delta\mu - \alpha(s)\sin\Delta\mu)$$

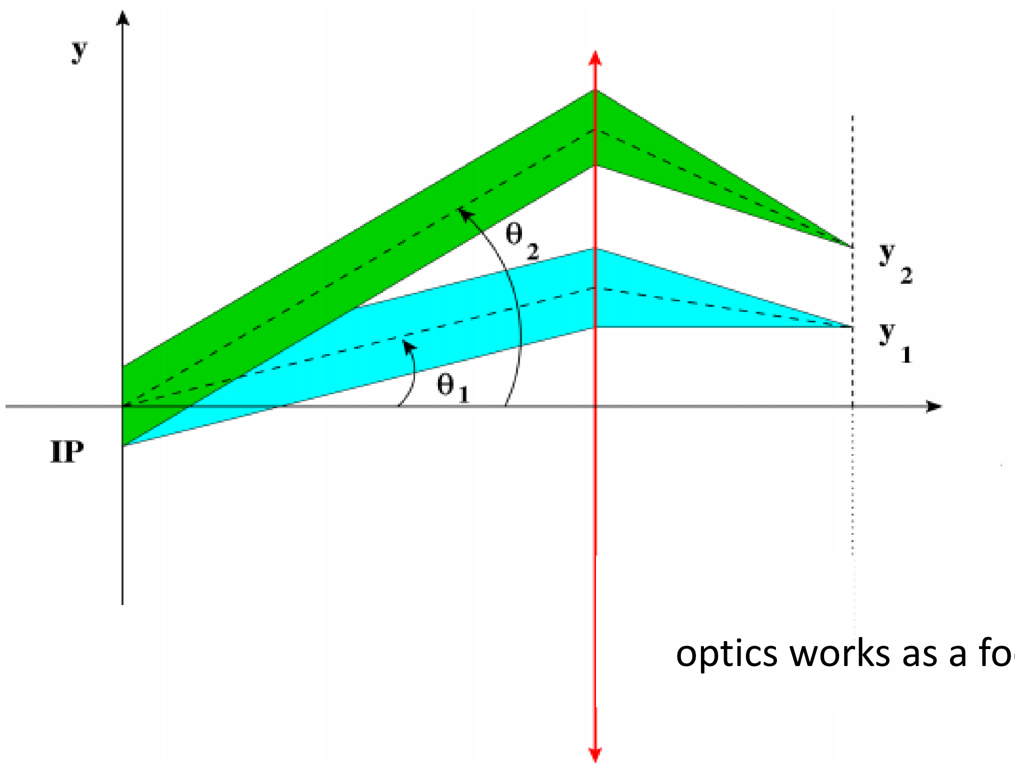
Position and slope at a given s in the accelerator

$$u(s) = \sqrt{\frac{\beta(s)}{\beta(s_0)}} (\cos(\Delta\mu) + \alpha(s_0)\sin(\Delta\mu))\, u(s_0) + \sqrt{\beta(s)\,\beta(s_0)} \sin(\Delta\mu)\, u'(s_0)$$

$$u'(s) = \frac{((\alpha(s) - \alpha(s_0))\cos(\Delta\mu) - (1 + \alpha(s)\,\alpha(s_0))\sin(\Delta\mu))}{\sqrt{\beta(s)\,\beta(s_0)}} u(s_0) + \sqrt{\frac{\beta(s)}{\beta(s_0)}} [\cos(\Delta\mu) - \alpha(s)\ \sin(\Delta\mu)]\ u'(s_0)$$

Coulomb region – optics

to reach $|t| \sim 10^{-4}$ GeV^2 the special – parallel-to-point – optics was chosen



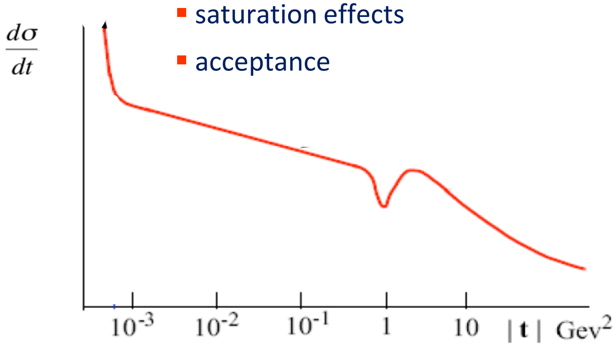
optics works as a focusing lens

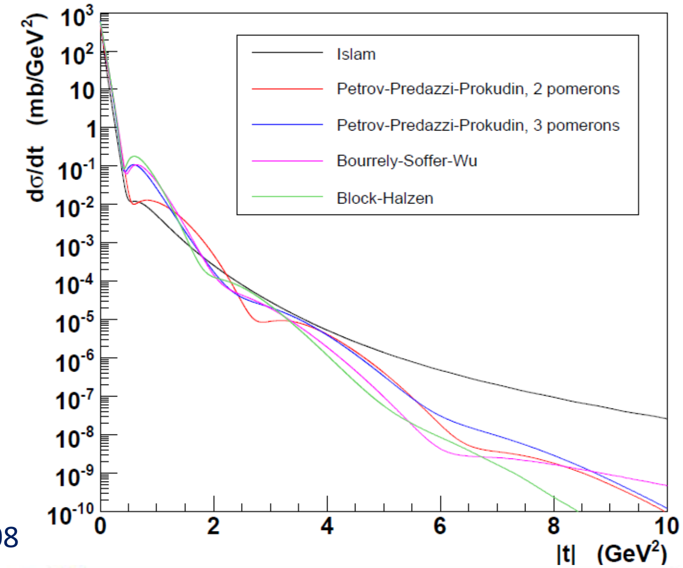
not standard (nominal) ATLAS optics → special (dedicated) runs simultaneously with TOTEM

elastic scattering – models I

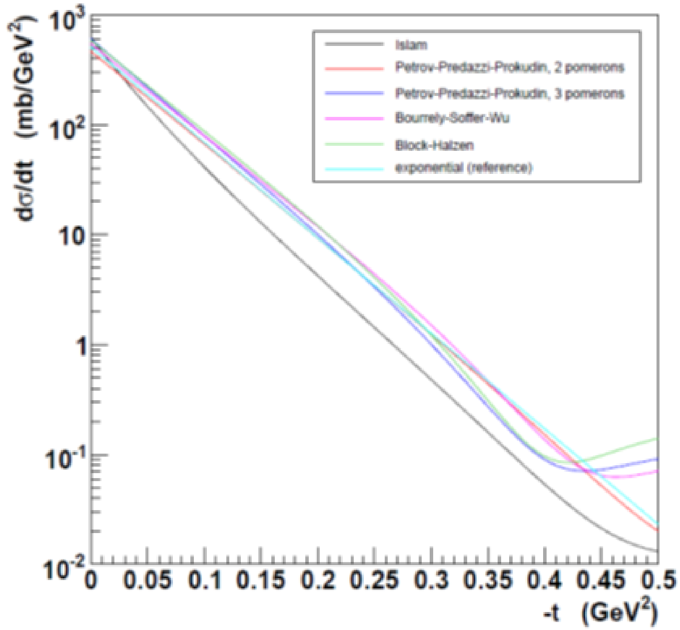
oversimplified, we have to include

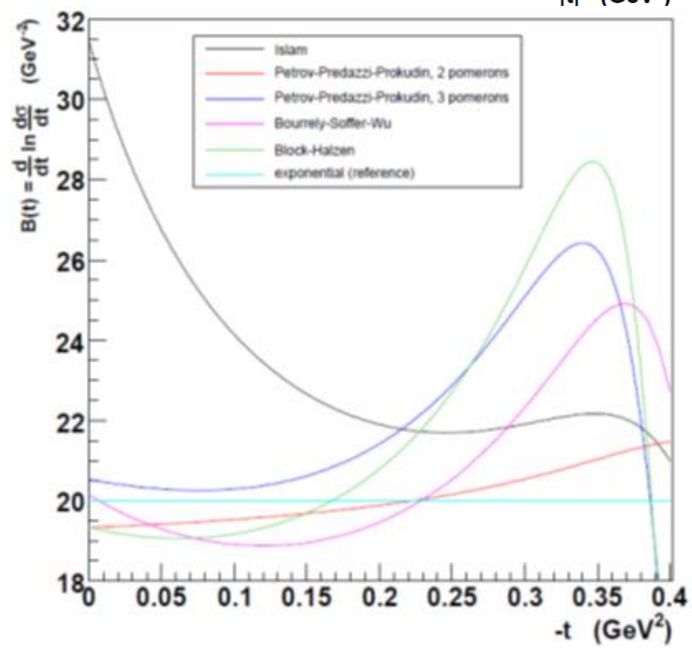
- electromagnetic form factor
- t-dependence of ρ and B
- saturation effects
- acceptance





HUBERT NIEWIADOMSKI – doctoral thesis, TOTEM, 2008





elastic scattering – models II

• $|t| < 6.5 \times 10^{-4}$ GeV^2 (at $\sqrt{s}$=14TeV): The Coulomb region where elastic scattering is dominated by photon exchange: $d\sigma/dt \approx 1/t^2$.

• 10^{-3} GeV^2 < $|t|$ < 0.5 GeV^2 : The nuclear region described in a simplified way by "single-Pomeron exchange"* with an approximately exponential cross section $d\sigma/dt \approx e^{-B|t|}$ (Figure 3.7, left). This quasi-exponential domain is important for the extrapolation of the nuclear part dN_{el}/dt of the differential counting-rate to t = 0, needed for the measurement of σ_{tot}. The t-dependence of the exponential slope $B(t) = d/dt \ln d\sigma/dt$ reveals slight model dependent deviations from the exponential shape (right figure). This theoretical uncertainty contributes to the systematic error of the total cross section measurement.

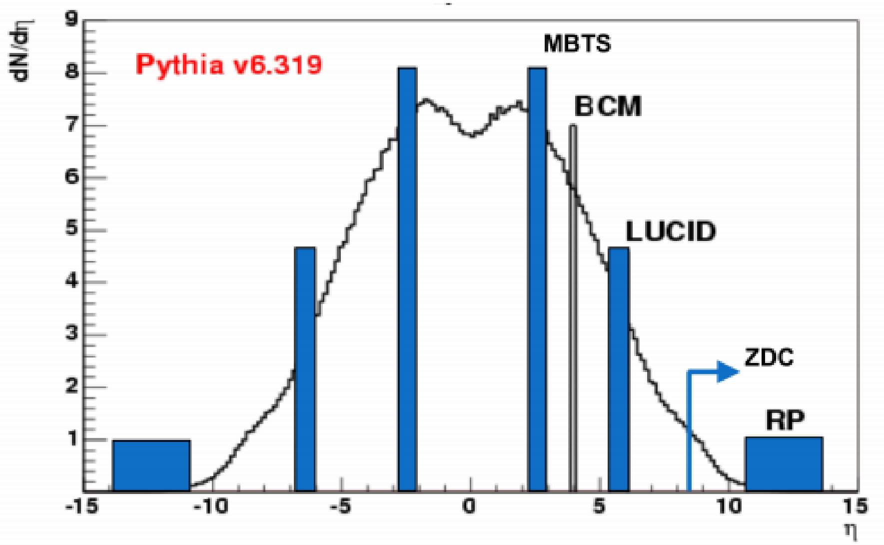
• Between the above two regions, the nuclear and Coulomb scattering interfere, complicating the extrapolation of the nuclear cross-section to t = 0.

• 0.5 GeV^2 < $|t|$ < 1 GeV^2: A region exhibiting the diffractive structure of the proton (diffractive peak).

• $|t|$ > 1 GeV^2: The domain of central elastic collisions at high $|t|$, described by perturbative QCD, e.g. in terms of triple-gluon exchange with a predicted cross-section proportional to $|t|^{-8}$. The model dependence of the predictions being very pronounced in this region, measurements will be able to test the validity of the different models.

HUBERT NIEWIADOMSKI – doctoral thesis, TOTEM, 2008

ATLAS η coverage



Detector	Pseudorapidity Coverage	# Readout Channels
Pixel	$\|\eta\| < 2.5$	8×10^7
SCT	$\|\eta\| < 2.5$	6.3×10^6
TRT	$\|\eta\| < 2.0$	3×10^5
MBTS	$2.09 < \|\eta\| < 3.84$	32
LAr: EMEC	$2.5 < \|\eta\| < 3.2$	3×10^4
LAr: FCal	$3.1 < \|\eta\| < 4.9$	5632
BCM	$\|\eta\| = 4.2$	8
LUCID	$5.6 < \|\eta\| < 6.0$	32
ZDC	$\|\eta\| > 8.3$	16

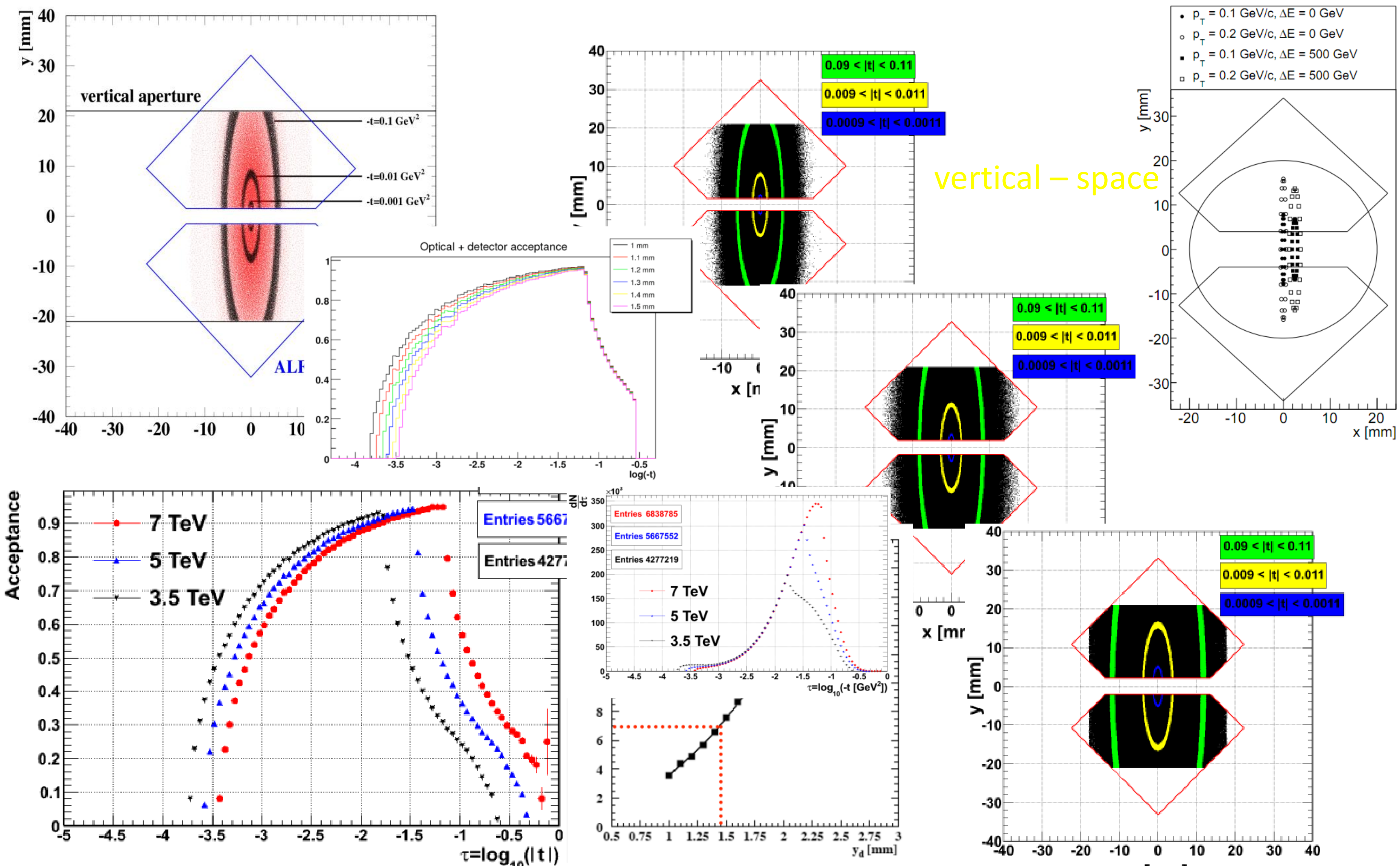
Table 1. Summary of relevant characteristics of the detectors used for luminosity measurements. For the ZDC, the number of readout channels only includes those used by the luminosity algorithms.

Forward detectors

- MBTS $2.1 < |\eta| < 3.8$
- LUCID $5.6 < |\eta| < 5.9$
- ZDC $|\eta| > 8.3$
- ALFA $10.6 < |\eta| < 13.5$

elastic scattering – simulation

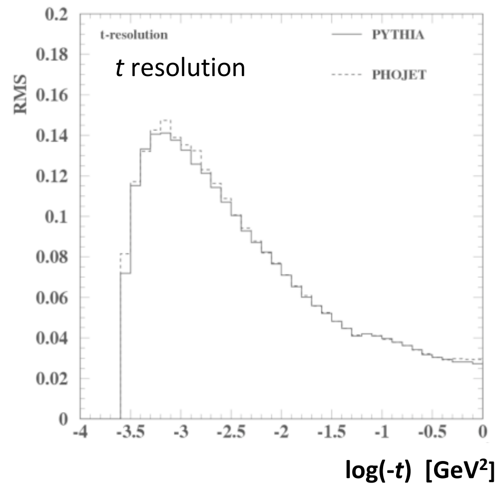
β*=90m

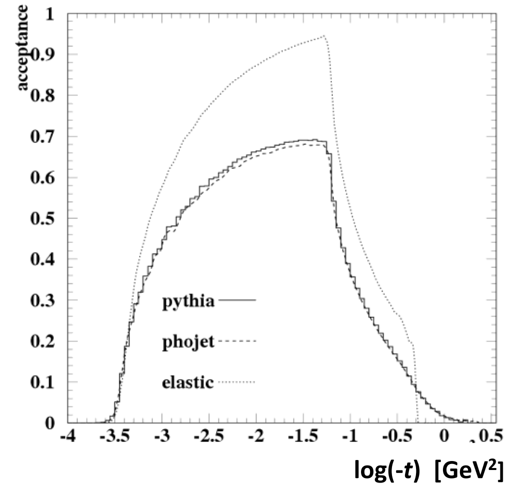


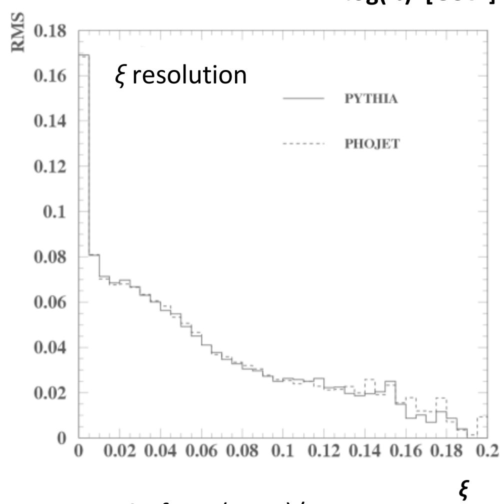
fitted parameters and uncertainties

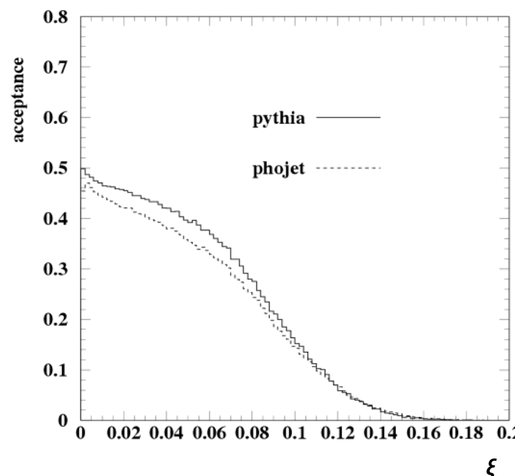
Paramètres	Énergie	Type de Fit	Valeur	erreur absolue	erreur relative
$\mathcal{L}$ $[10^{25}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}]$	7 TeV	log	66.97	2.28	3.4
		lin	70.00	3.46	4.9
	5 TeV	log	74.07	1.72	2.3
		lin	73.33	1.82	2.5
	3.5 TeV	log	79.32	1.04	1.3
		lin	79.85	1.12	1.4
σ_{tot} [mb]	7 TeV	log	111.30	1.92	1.73
		lin	108.83	2.73	2.50
	5 TeV	log	105.06	1.23	1.17
		lin	105.56	1.32	1.25
	3.5 TeV	log	100.71	0.65	0.64
		lin	100.37	0.69	0.69
b $[\mathrm{GeV}^{-2}]$	7 TeV	log	17.95	0.02	0.10
		lin	18.02	0.02	0.12
	5 TeV	log	17.99	0.042	0.23
		lin	18.02	0.045	0.25
	3.5 TeV	log	18.08	0.11	0.61
		lin	18.19	0.12	0.65
ρ	7 TeV	log	0.110	0.007	6.24
		lin	0.122	0.009	7.32
	5 TeV	log	0.124	0.007	5.34
		lin	0.125	0.007	5.52
	3.5 TeV	log	0.135	0.006	4.65
		lin	0.139	0.006	4.70
$\chi^2/ndof$	7 TeV	log	1.01744		
		lin	0.99452		
	5 TeV	log	0.90496		
		lin	1.04061		
	3.5 TeV	log	0.97198		
		lin	0.98628		

single diffraction









RMS of $x \equiv (x-x_{rec})/x$

$\xi \equiv 1-E/E_0$

global acceptance:

PYTHIA 45.0 %
PHOJET 40.1 %

luminosity – ATLAS counting algorithms

- LUCID_EventAND – reports the number of events with at least one hit on each LUCID detector side,
- LUCID_EventOR – reports the number of events for which the sum of hits on both detector sides is at least one,
- BCM_EventOR – reports the number of events for which the sum of hits on both BCM detector sides is at least one,
- MBTS_Timing – reports the number of events with at least one hit on each MBTS detector side plus a requirement that the timing of these hits occur within 10 ns,
- PrimVtx – reports the number of events with a primary vertex containing at least 4 tracks with $p_T > 150$ MeV.

integrated luminosity via *W* and *Z* boson production

- $W \to e\nu$: $E_T^e > 20$ GeV, $|\eta| < 2.47$, excluding $1.37 < \eta < 1.52$, $E_T^\nu > 25$ GeV, $m_T > 40$ GeV
- $W \to \mu\nu$: $p_T^\mu > 20$ GeV, $|\eta| < 2.4$, $E_T^\nu > 25$ GeV, $m_T > 40$ GeV
- $Z \to e^+e^-$: $E_T^e > 20$ GeV, $|\eta| < 2.47$, excluding $1.37 < \eta < 1.52$, 66 GeV $< m_{ee} <$ 106 GeV
- $Z \to \mu^+\mu^-$: $p_T^\mu > 20$ GeV, $|\eta| < 2.4$, 66 GeV $< m_{\mu\mu} <$ 106 GeV

The lower bound on the theoretical uncertainty on the W and Z boson production cross-section predictions is given by renormalisation and factorisation scale uncertainties (0.6%-0.8%) which cannot be lowered without significant improvements on the higher order QCD calculations. The current theoretical uncertainties for cross-section predictions in the fiducial region of the detector are estimated at the $\approx 3\%$ level, dominated by PDF uncertainties [9]. Those are expected to be significantly lowered in the coming years by future precision measurements at the LHC while a quantitative statement on the expected uncertainty reduction cannot be made. The expected experimental uncertainties are expected to be significantly below 1%. The expected precision on the integrated luminosity determination via W and Z boson production at the ATLAS detector is therefore expected to be $1 - 3\%$.

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optics parameters for different runnings

	β* = 2650 14 TeV	β* = 90m, intermediate optics 7 TeV	collision optics, β* = 1.5 m 7 TeV
divergence [µrad]	0.226	3.3	21
emittance [µradm]	1	3.75	2.5
crossing angle [µrad]	0	0	240