ALFA

Absolute **L**uminosity measurement **F**or **A**tlas

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on behalf of the ATLAS collaboration

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United States of America
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outline

- luminosity & luminosity measurement
- ALFA
- elastic scattering
- single diffraction
- conclusion

luminosity & luminosity measurement

luminosity

luminosity (Wikipedia)

"*the number of particles per unit area per unit time times the opacity of the target, usually expressed in either the cgs units cm^{-2} s^{-1} or b^{-1} s^{-1}. The integrated luminosity is the integral of the luminosity with respect to time. The luminosity is an important value to characterize the performance of an accelerator*."

$$\frac{\mathrm{d}N}{\mathrm{d}t} = L\sigma$$

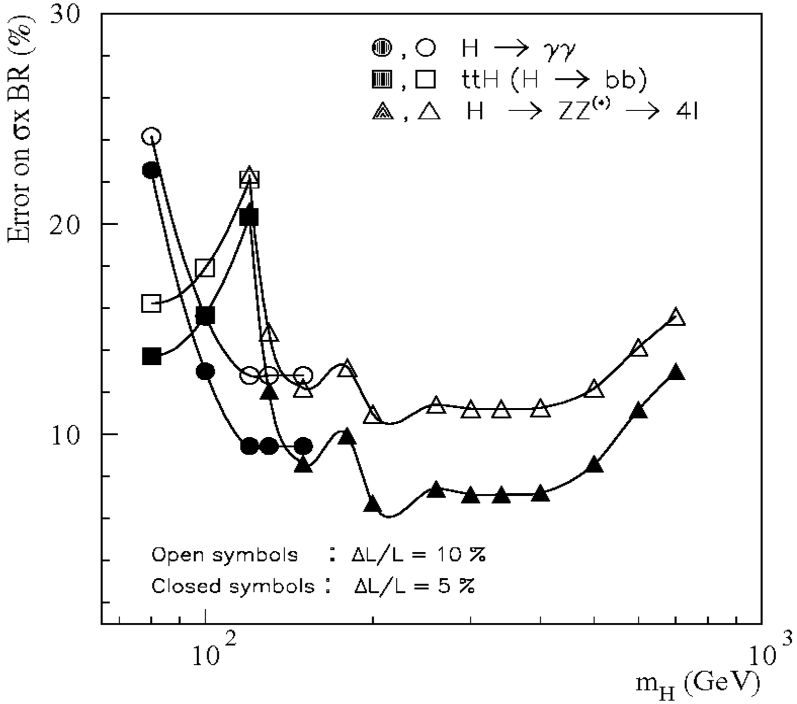
L – luminosity, N – number of interactions, σ – total cross section

need for the luminosity

integrated luminosity → cross sections ➡ precision as good as possible

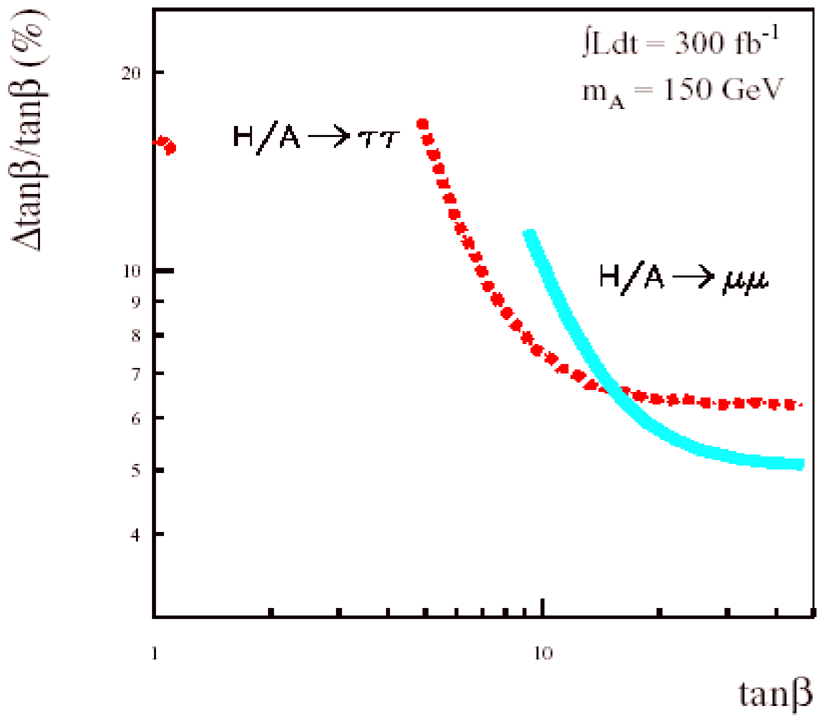
instantaneous luminosity (bunch by bunch) ➡ correcting pile-up, beam-tuning

luminosity significance – examples



Relative precision on the measurement of σ_H×BR for various channels, as function of m_H, at ∫L*dt* = 300 fb^{-1}. The dominant uncertainty comes from luminosity: 10% (open symbols), 5% (solid symbols).

[ATLAS TDR 15, p. 732]



Systematic error dominated by luminosity ~ 10%
MSSM model, tanβ=v_2/v_1, $v_{1,2}$ vacuum exp. values

[ATLAS TDR 15, p. 780]

luminosity measurement

- using any theoretically well known process (σ) with the large rate (R = dN/dt), e.g. inclusive W/Z process

$$L = \left[\frac{dN}{dt} \right] / \sigma$$

precision ~ 5-10% *, typical signal p_{Tlept} >25 GeV, $|\eta_{lept}|$< 2.5, E_{Tmiss} >25 GeV, isolated lepton

- using machine parameters

$$L = F \frac{f \sum_i N_1^i N_2^i}{(\sigma_x \sigma_y)_{ID}} = \xi F \frac{f k_b N \gamma}{r_p \beta_{ID}}$$

where f (=11kHz) is the beam-revolution frequency, F(=0.9) is non-zero crossing angle factor, $N_{1,2}^i$ is number of protons in the colliding bunches, ξ(=0.0034) is the beam-beam tune-shift parameter, k_b is the value of bunches, γ is the beam Lorentz factor, r_p is the proton classical radius

precision 10%, can be much better (ISR, intersection storage ring 1%)
Helmut Bukhardt - Absolute Luminosity from Machine Parameters, Indico 10.04.2008
H. Burkhardt and P. Grafstrom, "*Absolute luminosity from machine parameters*", LHC-Project-Report-1019 (2007).

van der Meer – transverse beam scans

large β* optics, low luminosity otherwise the measurement affected due to strong beam-beam interaction [ATLAS TDR 14, p. 438]

- elastic scattering at small angles ⁒

luminosity measurement

Elastic scattering at small angles

- using elastic scattering and inelastic rate

$$\frac{d\sigma_{el}}{dt} = \frac{1}{16\pi s^2}|A_{el}|^2 = \frac{1}{16\pi s^2}(|\mathrm{Re}\,A_{el}|^2 + |\mathrm{Im}\,A_{el}|^2) = \frac{1}{16\pi s^2}|\mathrm{Im}\,A_{el}|^2\left(1 + \frac{|\mathrm{Re}\,A_{el}|^2}{|\mathrm{Im}\,A_{el}|^2}\right)$$

$$\sigma_{tot} = \frac{1}{s}\mathrm{Im}\,A_{el}|_{t=0} \longrightarrow = \frac{1}{16\pi s^2}\sigma_{tot}^2 s^2\left(1 + \frac{|\mathrm{Re}\,A_{el}|^2}{|\mathrm{Im}\,A_{el}|^2}\right)$$

$$\rho = \left.\frac{\mathrm{Re}\,A_{el}}{\mathrm{Im}\,A_{el}}\right|_{t=0} \longrightarrow = \frac{\sigma_{tot}^2}{16\pi}(1 + \rho^2)$$

$$\sigma_{tot} = \frac{16\pi}{1+\rho^2}\frac{dR_{el}/dt|_{t=0}}{R_{tot}} \qquad L = \frac{1}{16\pi}\frac{R_{tot}^2}{dR_{el}/dt|_{t=0}}(1 + \rho^2)$$

$$R_x = \sigma_x L$$

high η acceptance problem, MC estimate needed, but for minimum bias events ~ 100% acceptance

$$L = (1 + \rho^2)a \Rightarrow a = \frac{L}{1 + \rho^2} \Rightarrow \frac{\Delta L}{L} = \frac{2a\rho\Delta\rho}{L} = \frac{2\rho\Delta\rho}{1 + \rho^2} \sim 2\rho\Delta\rho \qquad \rho = 0.1361 \pm 0.0015 \begin{smallmatrix} +0.0058 \\ -0.0025 \end{smallmatrix}$$

$$\frac{\Delta L}{L} \leqslant 2\rho\Delta\rho \leqslant 2 \cdot 0.15 \cdot 0.02 = 0.6\%$$

- using elastic scattering and total cross section

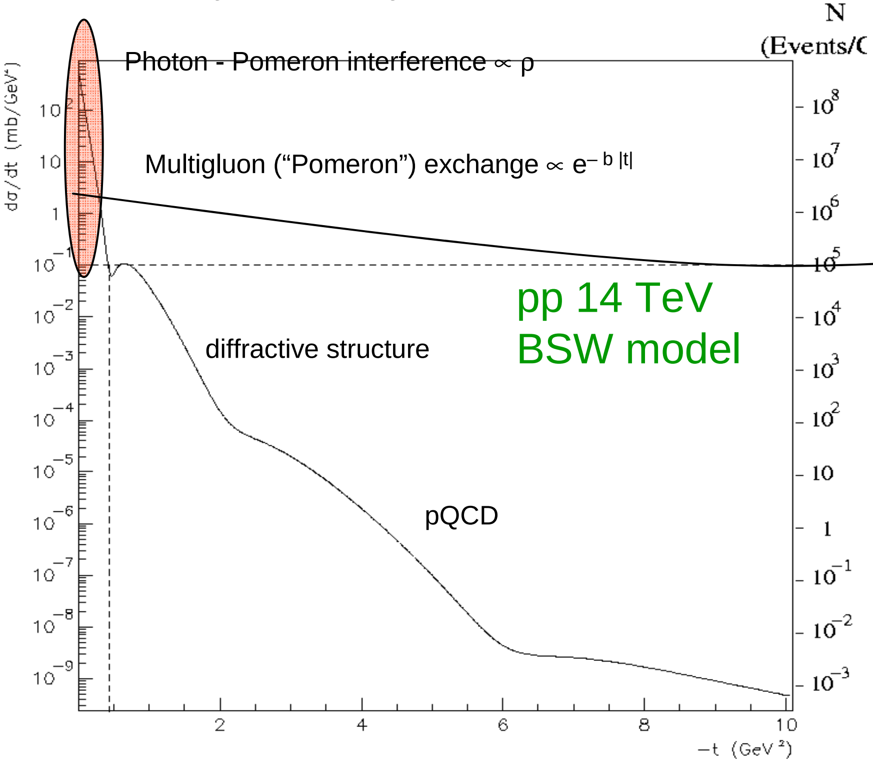
$$\frac{1}{L} = \frac{1}{16\pi}\frac{\sigma_{tot}^2}{dR_{el}/dt|_{t=0}}(1 + \rho^2)$$

independent measurement of σ_{tot} needed (e.g. by TOTEM)

luminosity measurement – Coulomb interaction region

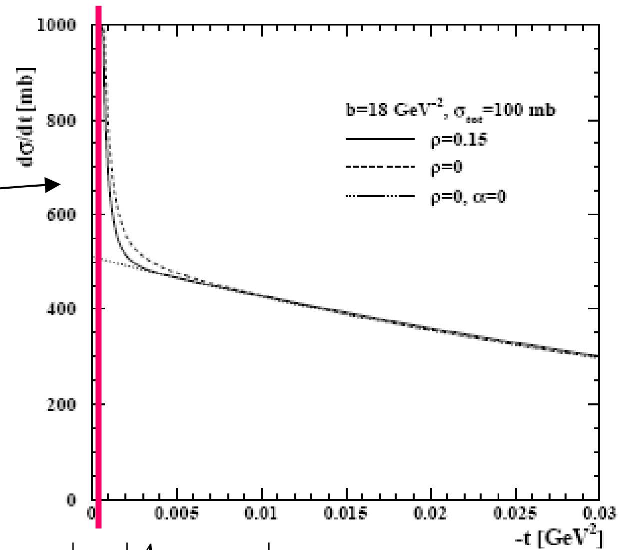
$$\frac{dN_{\text{tot}}}{dt} \sim L\,|A_{\text{coulomb}} + A_{\text{nuclear}}|^2 = L\left[\frac{4\pi\alpha^2}{t^2} - \frac{\alpha\rho\sigma_{\text{tot}}}{t}\exp\left(-\frac{B|t|}{2}\right) + \frac{\sigma_{\text{tot}}^2}{16\pi}(1+\rho^2)\exp(-B|t|)\right]$$

Photon exchange, coulomb region



BSW - M. Bauer, B. Stech and M. Wirbel, Z. Phys. C34, 103 (1987)

free parameters L, B, ρ, σ_{tot}



$$|A_{\text{coulomb}}| = |A_{\text{nuclear}}|$$

$$-t\Big|_{|A_{\text{coulomb}}|=|A_{\text{nuclear}}|} \approx \frac{8\pi\alpha}{\sigma_{\text{tot}}} \approx 6\times10^{-4}\ \text{GeV}^2$$

relevance/controversy +

oversimplified, we have to include

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

theory

- acceptance

measurement

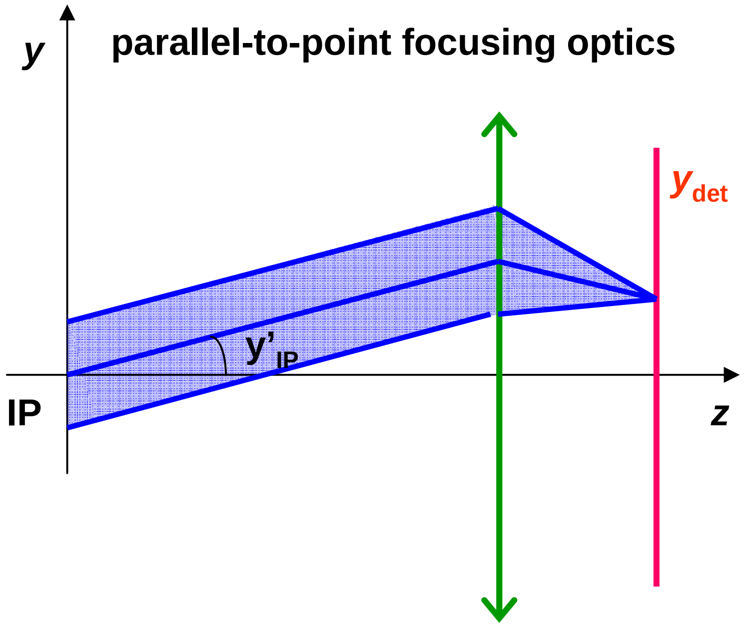
luminosity measurement – optics selection

to reach $|t| = 6\ 10^{-4}\ \mathrm{GeV}^2$ the special high β optics **paralel-to-point** was chosen
in general

$$y = \sqrt{\beta/\beta_{\mathrm{IP}}}\,(\cos\psi + \alpha^* \sin\psi)\, y_{\mathrm{IP}} + \sqrt{\beta\beta_{\mathrm{IP}}}\, \sin\psi\, y'_{\mathrm{IP}}$$

using $\psi \sim \pi/2$ and $\alpha_{\mathrm{IP}} \sim 0$ we get

$$y = \sqrt{\beta\beta_{\mathrm{IP}}}\; y'_{\mathrm{IP}}$$



$$-t = (p\vartheta)^2 \geqslant (p y'_{\mathrm{IP}})^2 = p^2 \frac{y^2}{\beta\beta_{\mathrm{IP}}} = p^2 \frac{(n\sigma)^2}{\beta\beta_{\mathrm{IP}}} = p^2 n^2 \frac{\varepsilon}{\beta_{\mathrm{IP}}} \qquad \sigma = \sqrt{\varepsilon\beta}$$

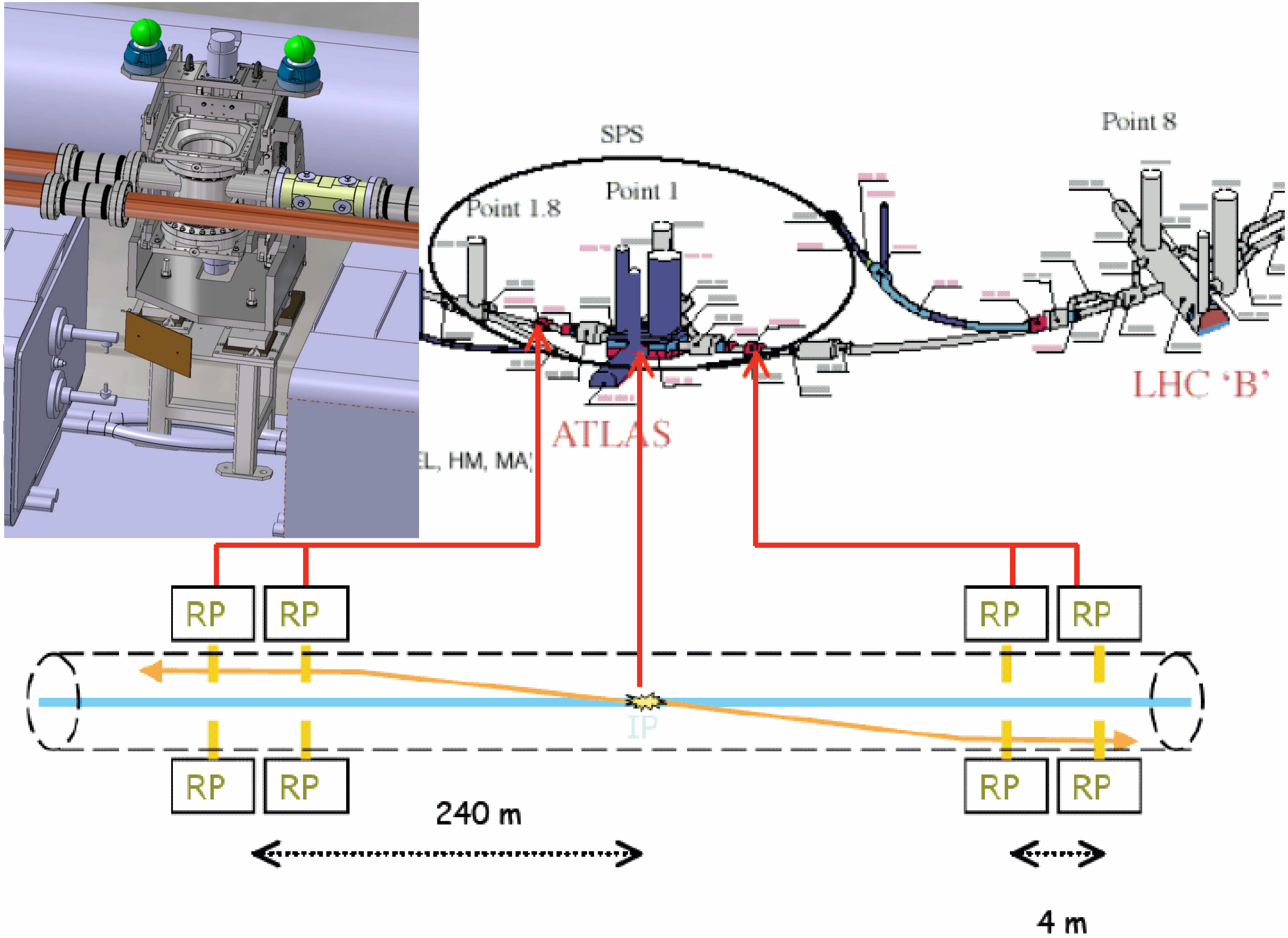
for $\varepsilon_N = \varepsilon/\gamma \sim 1\mu\mathrm{m}$ rad and keeping the safety distance of 15σ we get $\beta_{\mathrm{IP}} \sim 2600\mathrm{m}$

luminosity measurement – technical requirements

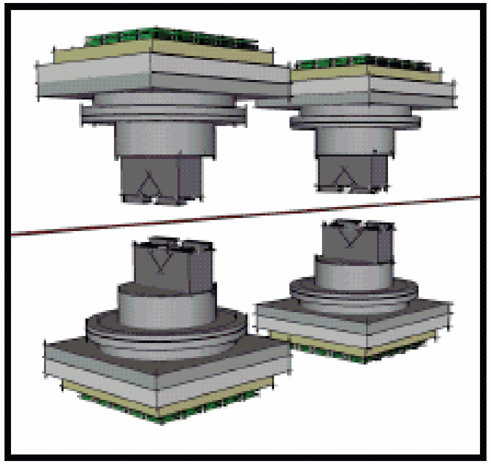
apart from a special beam optics,

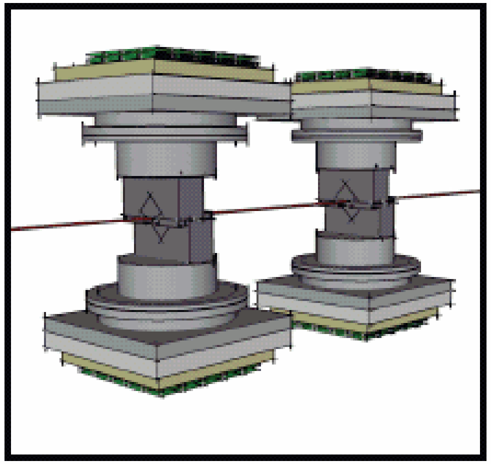
- to place detectors ~1.5 mm from LHC beam axis
- to operate detectors in the secondary vacuum of the Roman Pot
- spatial resolution $s_x = s_y$ well below 100 µm (goal 30 µm)
- no significant inactive edge (< 100 µm)

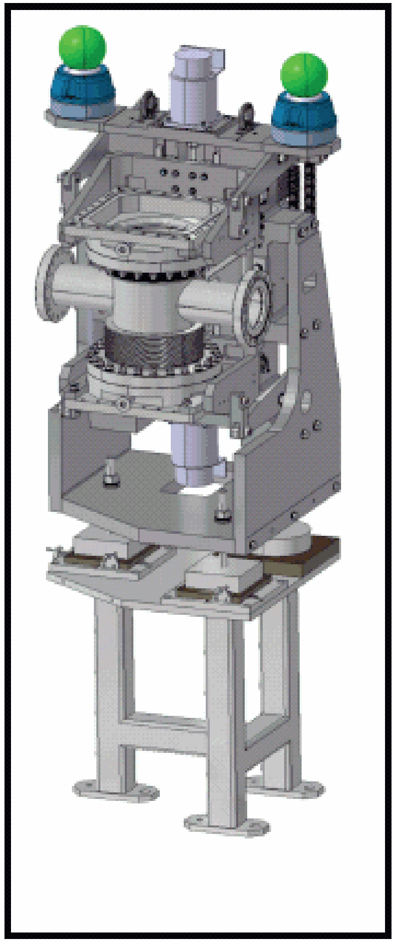
ALFA

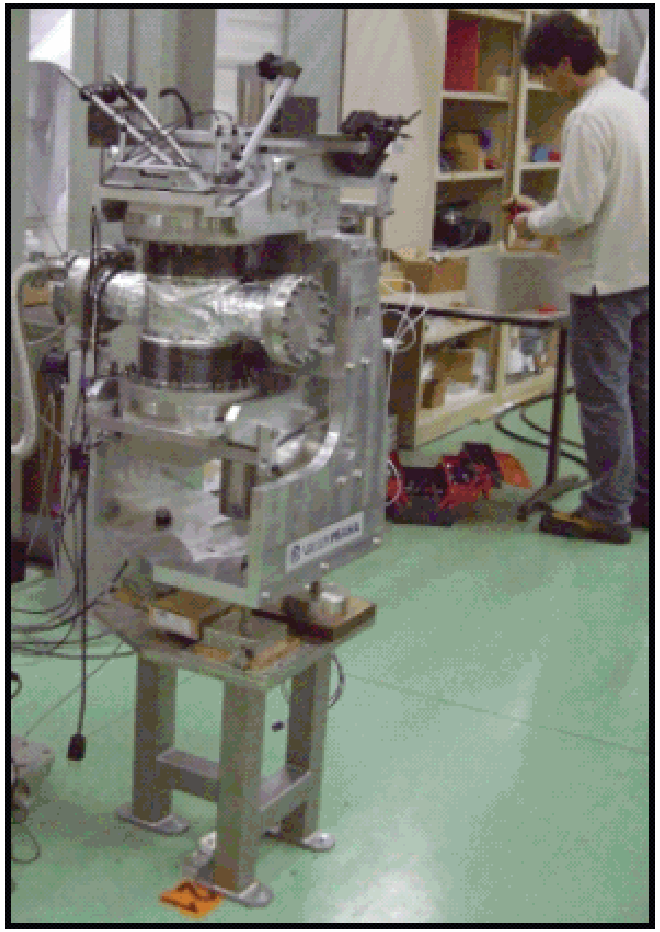

SPS
Point 1.8
Point 1
Point 8
ATLAS
LHC 'B'
RP
RP
RP
RP
IP
RP
RP
RP
RP
240 m
4 m

Extracted position



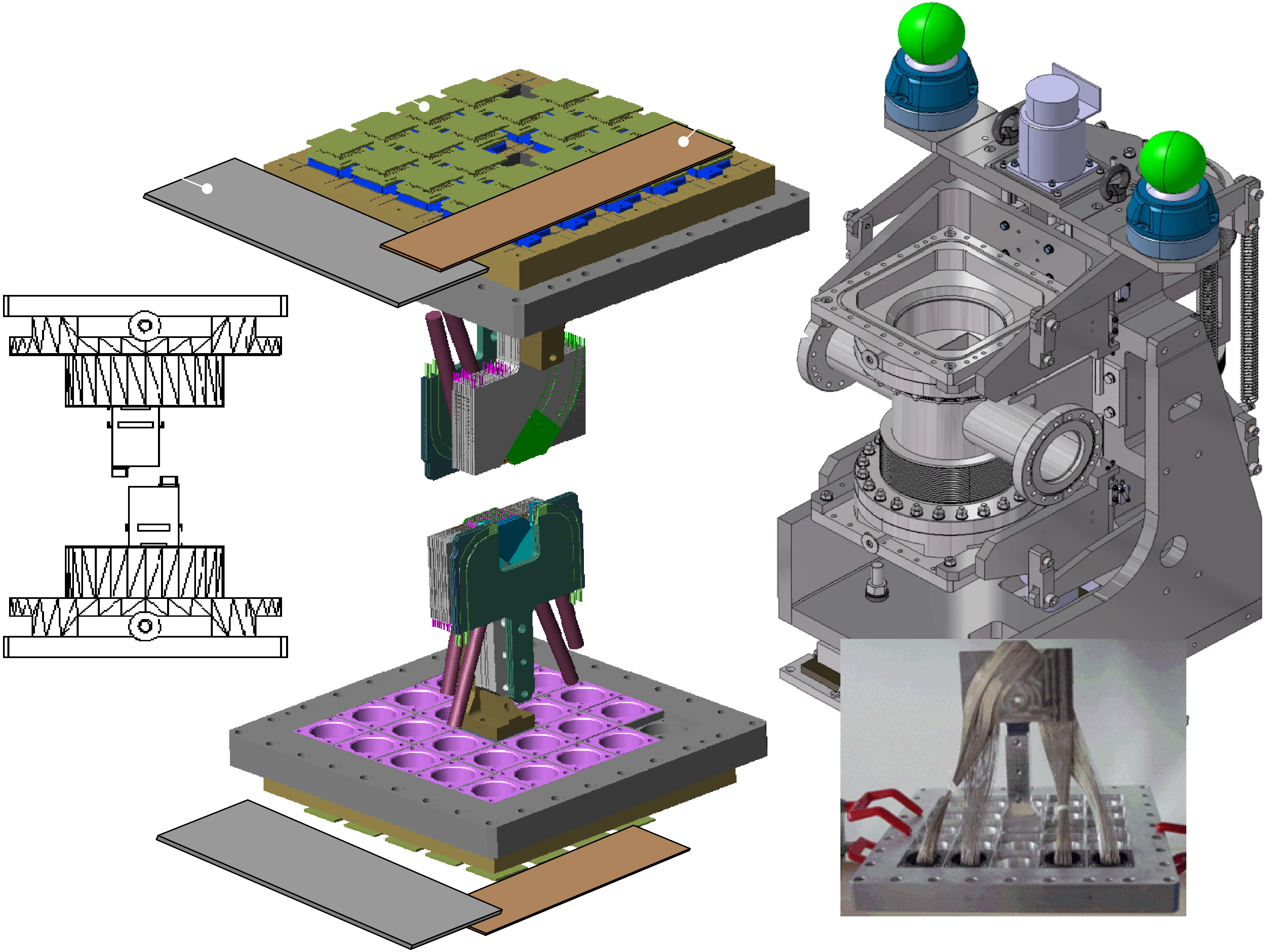






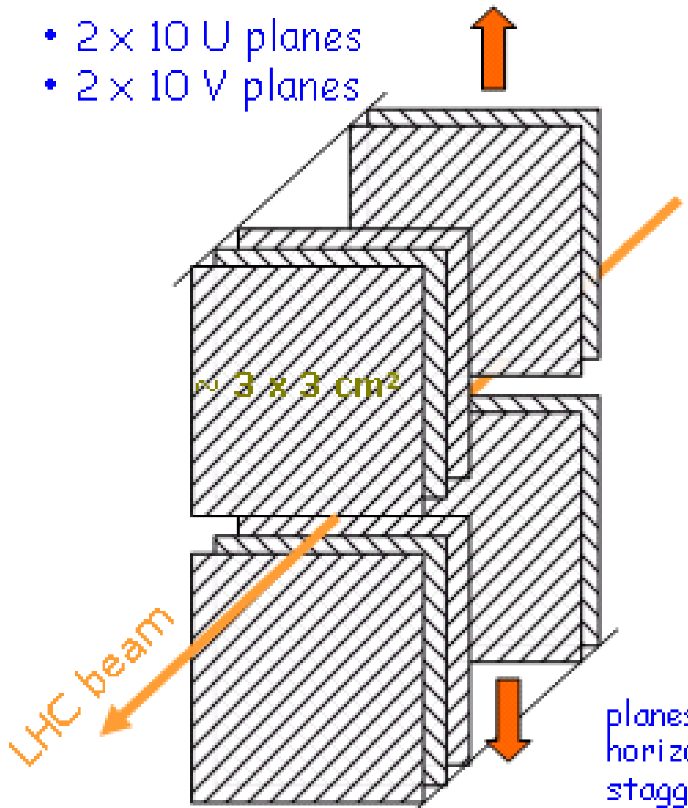
Working position

Roman Pot unit



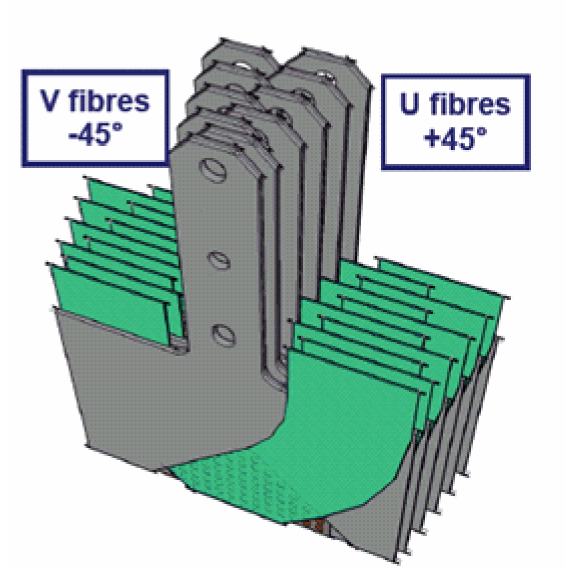
Concept

- 2 × 10 U planes
- 2 × 10 V planes



- scintillating fibres
- 0.5 mm² square

planes are horizontally staggered by multiples of 70.7 micrometer



elastic scattering

luminosity measurement – MC realization

elastic generator
PYTHIA 6.4
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

↓

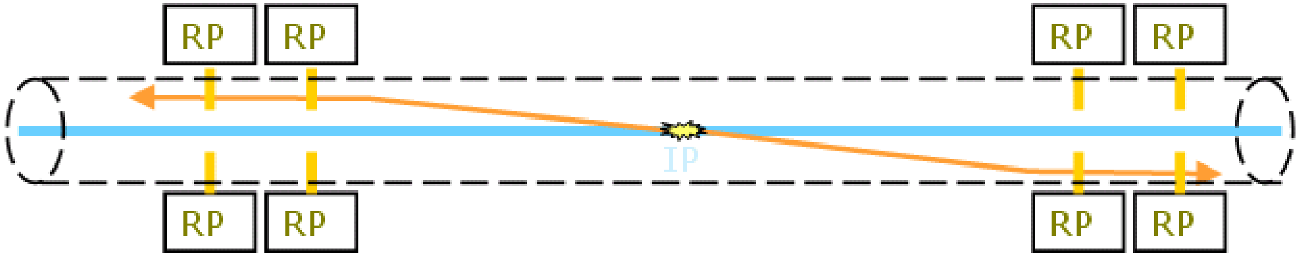
beam transport
MadX
tracking IP1→RP
high β^* optics V6.5
including apertures

↓

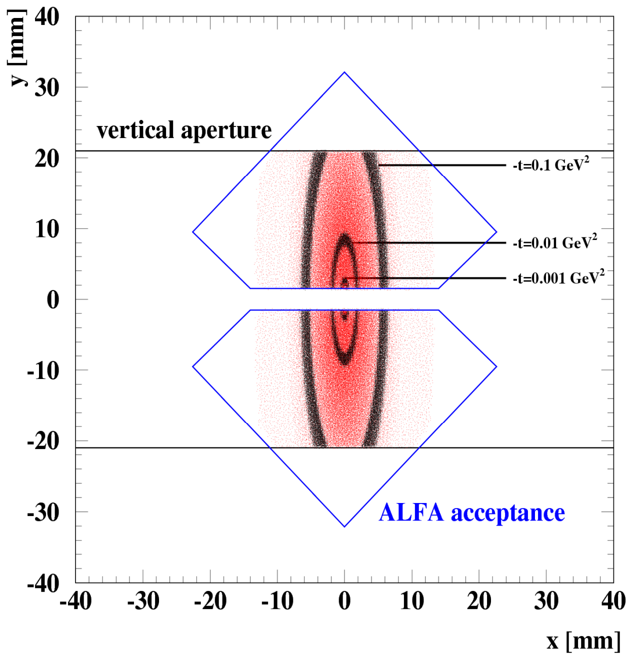
ALFA simulation
track reconstruction
t-spectrum
luminosity determination
(later: GEANT4 simulation)

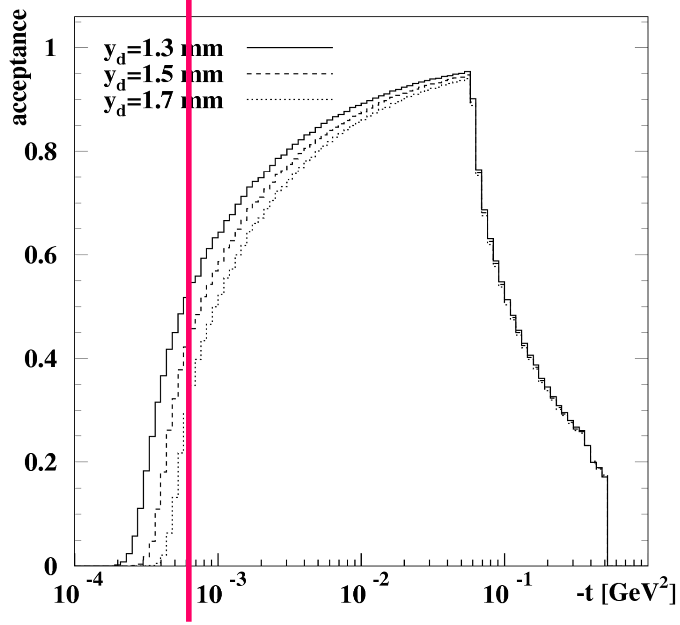
now PYTHIA 8.1
with
Electromagnetic form factor
&
the Coulomb phase implemented

luminosity measurement – optics



- 10 M events corresponding to 100 hours at L = 10^{27} cm^{-2} s^{-1}
- the detector edge 1.5 mm from the beam





$$-t\big|_{|A_{\mathrm{Coulomb}}|=|A_{\mathrm{nuclear}}|} \approx \frac{8\pi\alpha}{\sigma_{\mathrm{tot}}} \approx 6\times10^{-4}\,\mathrm{GeV}^2$$

luminosity measurement – fit

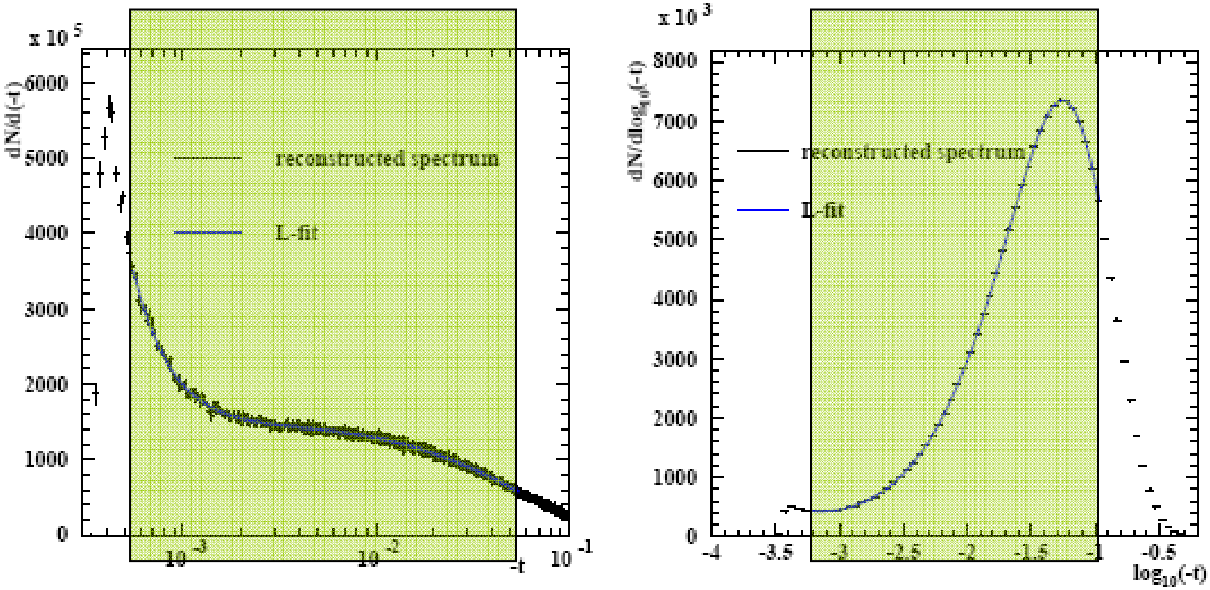


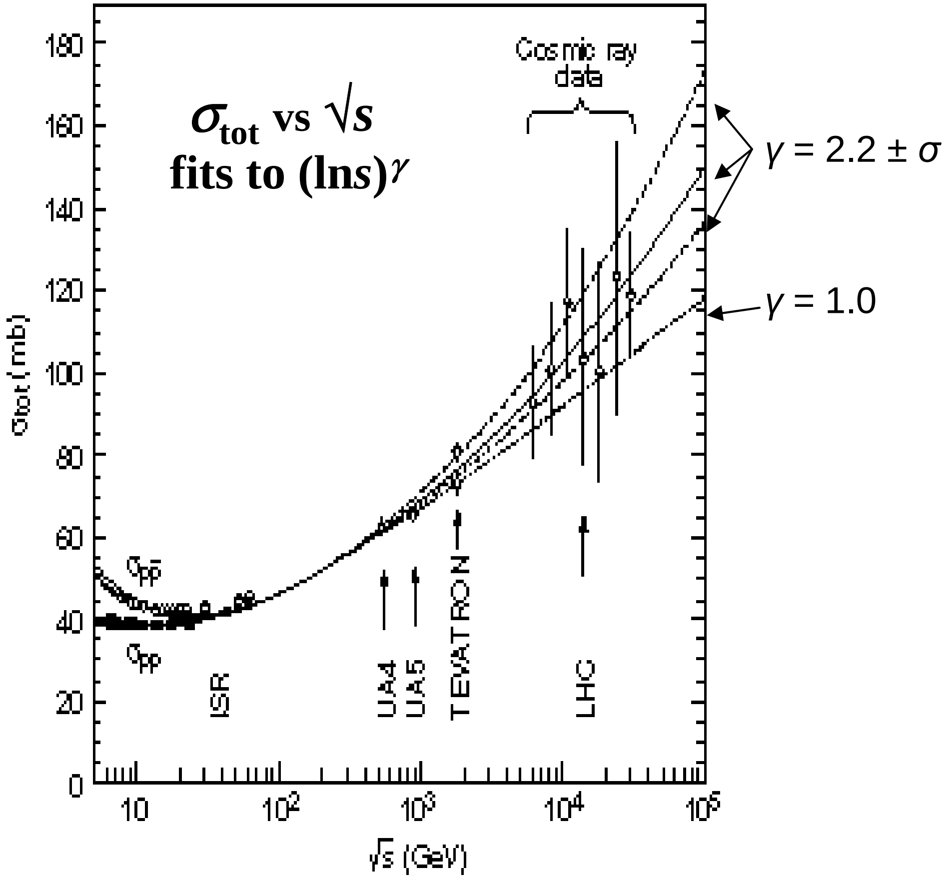
Figure 9-10 The reconstructed and corrected t-spectrum in two representations, linear(left) and logarithmic (right), together with the resulting luminosity fit.

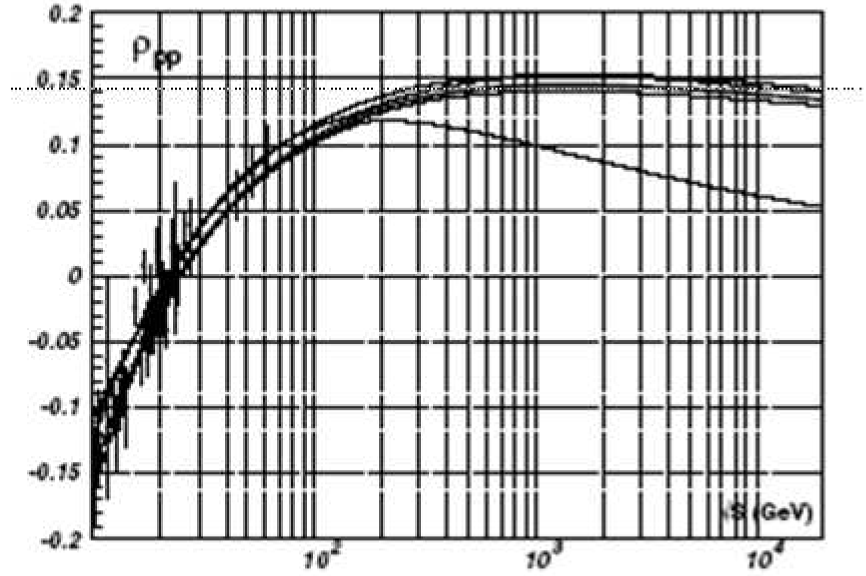
Table 9-2 Fit results for the luminosity and forward physics parameters.

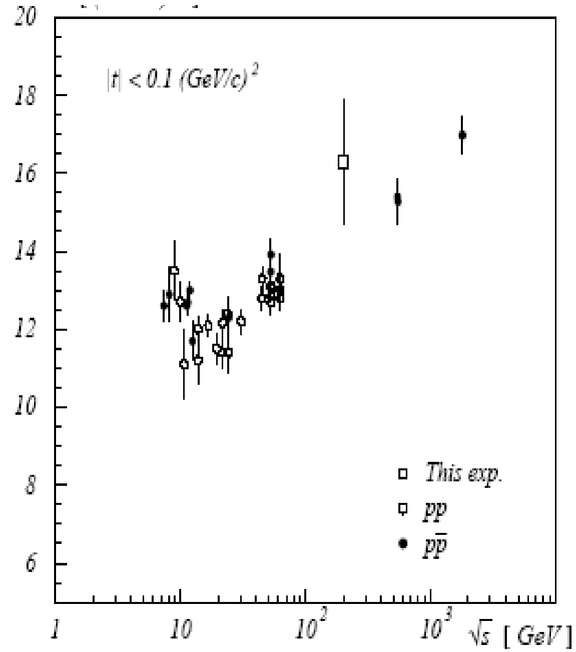
	Input	Linear fit	Error [%]	Log. fit	Error[%]	**Correlation with L** [%]
L [10^{26} cm $^{-2}$ s^{-1}]	8.10	8.151	1.77	8.057	1.89	
σ_{tot} [mb]	101.511	101.14	0.9	101.77	1.0	-99
b [GeV^{-2}]	18	17.93	0.25	17.97	0.12	57
ρ	0.15	0.143	4.3	0.146	3.8	89
Fit range		$0.00055 < -t < 0.055$		$-3.2 < \tau < -1.0$		
Fit quality [χ^2/Ndof]		2845/2723		33.2/44		

Ndof = number of degrees of freedom

elastic collisions – physics







total cross section

rho

b

models

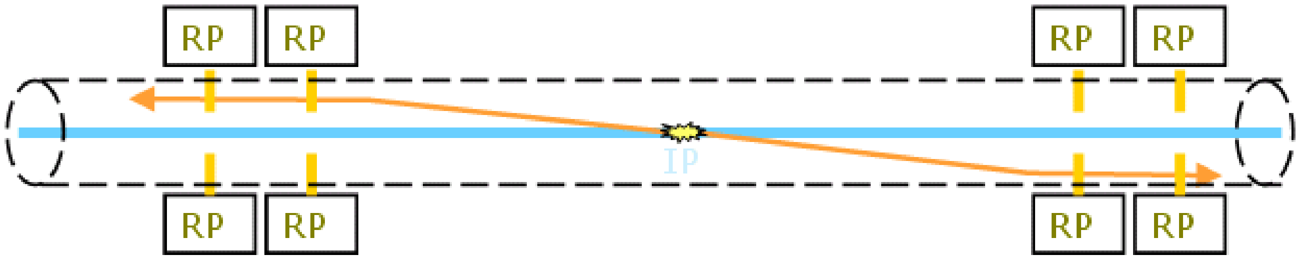
luminosity – uncertainties

Systematic uncertainties	Linear fit	Logarithmic fit
Statistical error [%]	1.77	1.89
Beam divergence [%]	0.31	0.30
Crossing angle [%]	0.18	0.15
Optical functions [%]	0.59	0.76
Phase advance [%]	1.0	1.4
Detector alignment [%]	1.3	0.9
Geometrical detector acceptance [%]	0.52	0.43
Detector resolution [%]	0.35	0.19
Background subtraction [%]	1.10	1.51
Total experimental systematic uncertainty [%]	2.20	2.57
Total uncertainty [%]	2.82	3.19

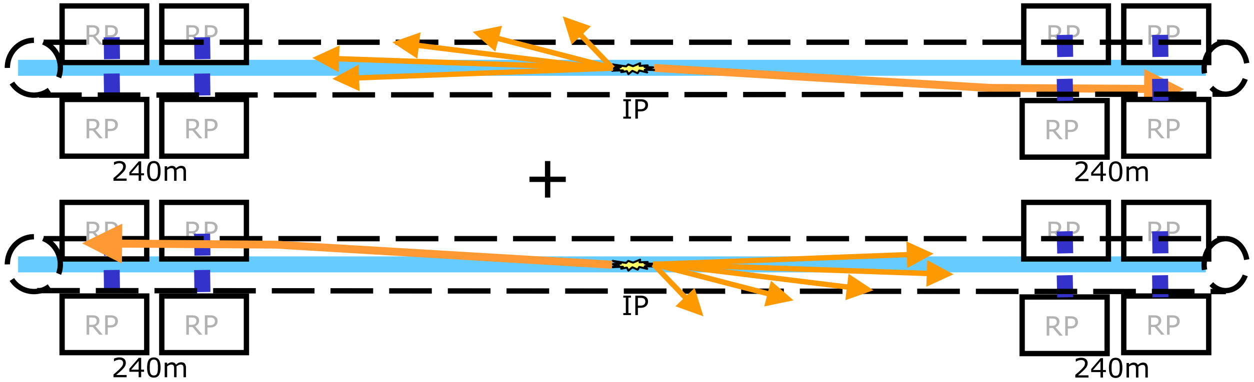
single diffraction

diffraction

elastic process



single diffraction - background for the elastic processes



SD as the background can be rejected by means of vertex and acollinearity cuts and can be reduced to a negligible level BUT in the same time SD represents the interesting subject and can be studied independently on the luminosity measurement

diffraction – motivation

- measurement – cross section, t & x_{IP}-distributions, …
- parameters finding – existence of large model uncertainties
- luminosity calibration – if the Coulomb region for elastic scattering unreachable

$$\sigma_{tot} = \frac{1}{s} \operatorname{Im} A_{el}\Big|_{t=0} \qquad L = \frac{R_{tot}}{\sigma_{tot}}$$

$$\sigma_{tot} = \frac{16\pi}{1+\rho^2} \frac{\left. dR_{el}/dt \right|_{t\to 0}}{R_{tot}} \qquad L = \frac{1+\rho^2}{16\pi} \frac{R_{tot}^2}{\left. dR_{el}/dt \right|_{t\to 0}}$$

requires measurements of the *total* rate & extrapolation of the elastic rate to $t = 0$

for the total rate the MBTS can be used

$$\sigma_{tot} = \sigma_{el} + \sigma_{inel} = \sigma_{el} + \sigma_{ND} + \underbrace{\sigma_{SD} + \sigma_{DD}}_{\text{minimum bias events}}$$

From the CSC note on minimum bias:

[Moraes Arthur, Minimum Bias CSC Note Results]

Sample	MBTS_1_1	MBTS_2
Non-diffractive	99%	100%
Double diffractive	54%	82%
Single diffractive	45%	68%
Noise	0.05%	0.05%

diffraction – MC realization

now PYTHIA 8.1

elastic

elastic generator
PYTHIA 6.4
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
x_{IP} - spectrum
luminosity determination

diffraction

PYTHIA6.4
modified elastic with coulomb- and ρ-term
single diffraction

PHOJET1.1
elastic & single diffraction

beam properties at IP1
size of the beam spot $\sigma_{x,y}$
beam divergence $\sigma'_{x,y}$
momentum dispersion

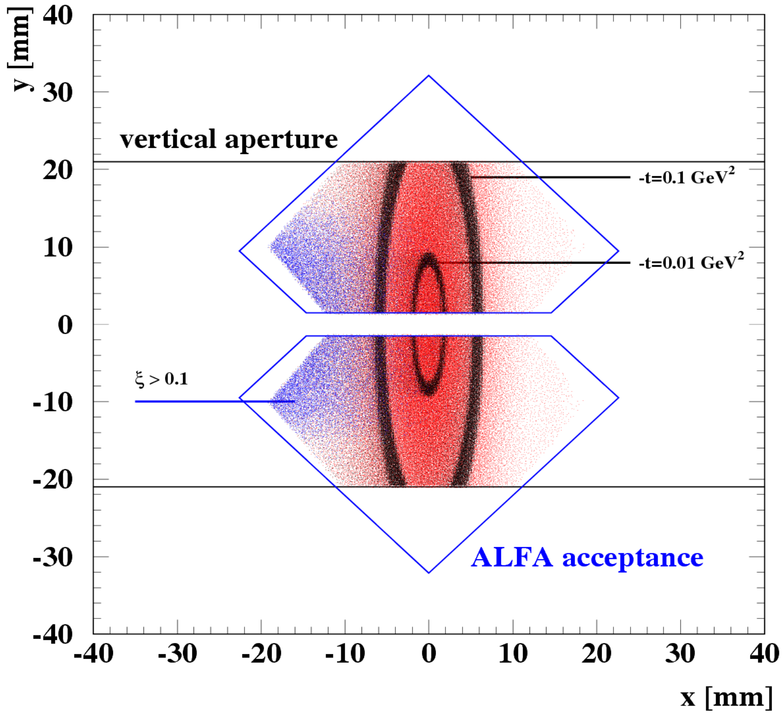
single diffraction L1 filter

single diffraction trigger
ALFA.AND.(LUCID.OR.ZDC)
central detector not considered yet
using the MBTS would be an asset

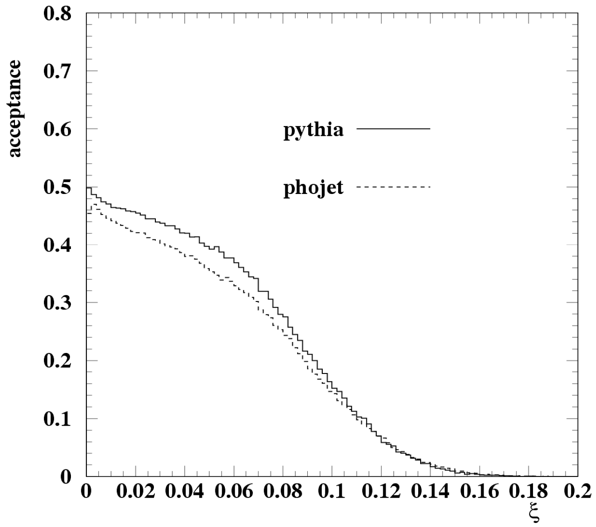
beam transport MadX
tracking IP1→RP
high β^* optics V6.5
including apertures

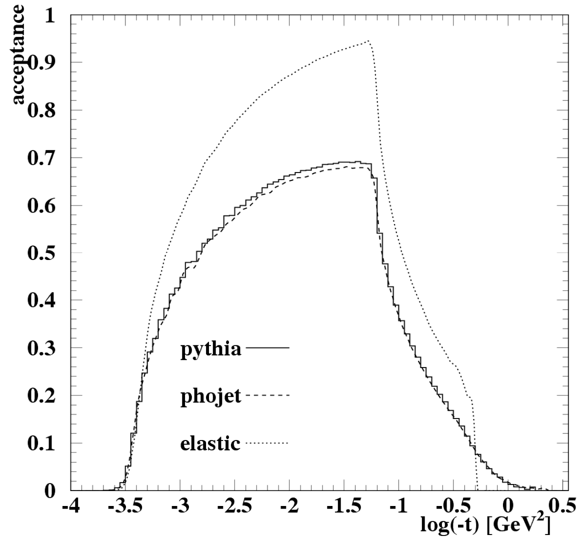
ALFA simulation
track reconstruction
t-spectrum
x_{IP} - spectrum
luminosity determination

single diffraction – in plots



hit pattern for 10 M single diffraction events
simulated with PYTHIA & MADX





global acceptance:

PYTHIA 45.0 %
PHOJET 40.1 %

single diffraction – in numbers

[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 preselection	75	74
RP selection relative to pre-selection		
ALFA	60.1	54.2
Total acceptance	45.0	40.1

status & conclusion

- the institutions from CERN, Czech Republic, France, Germany, Great Britain, Poland, Portugal, Spain, Sweden and United States participate on the ATLAS ALFA project

- the series of the test beam measurements 2005, 2006, 2007 indicated that the resolution < 30µm can be reached

- two prototypes were constructed yet:
  - prototype_1 – used for assembling tests
  - prototype_2 – the full pot with all final components presently in assembling at CERN

- 4 weeks of test beam measurements -- July & August 2008

- mass production of 8 pot units plus 2 spares till the end of 2008

- the installation of 8 Roman pots - shut down 2008/2009

- the insert of sensitive detector components - earliest spring 2009 or shut down 2009/10

- the primary goal of the ALFA is the absolute luminosity measurement and the calibration of LUCID

- the ALFA stations are an important test ground for the upgrade projects RP220 & FP420

- a later upgrade of ALFA for a higher luminosity diffraction measurement can be considered