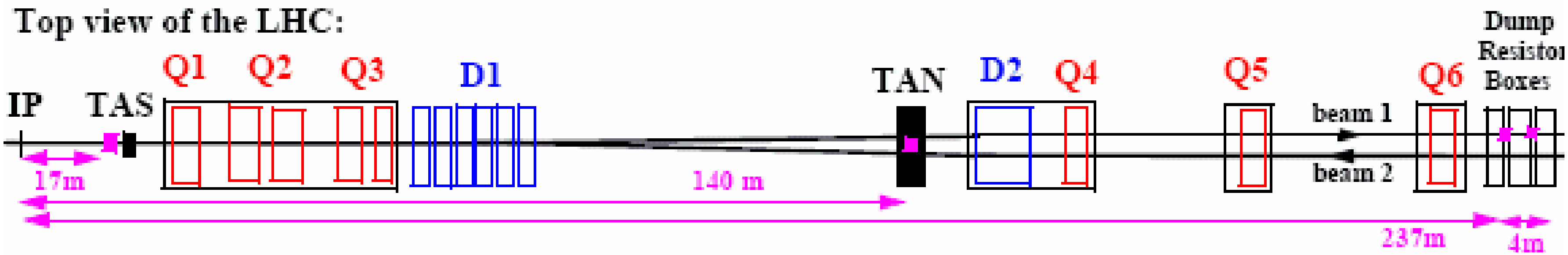
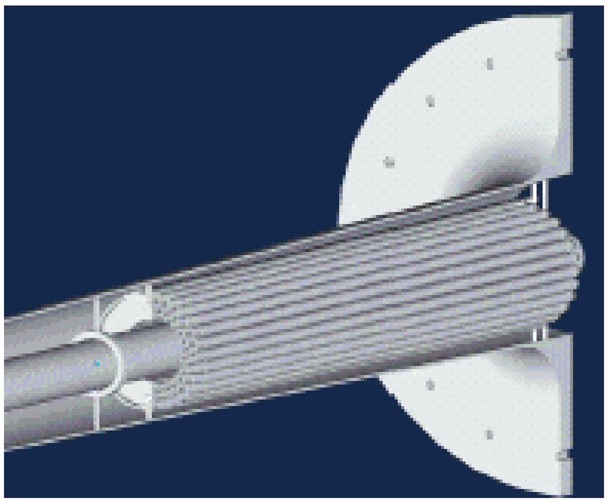
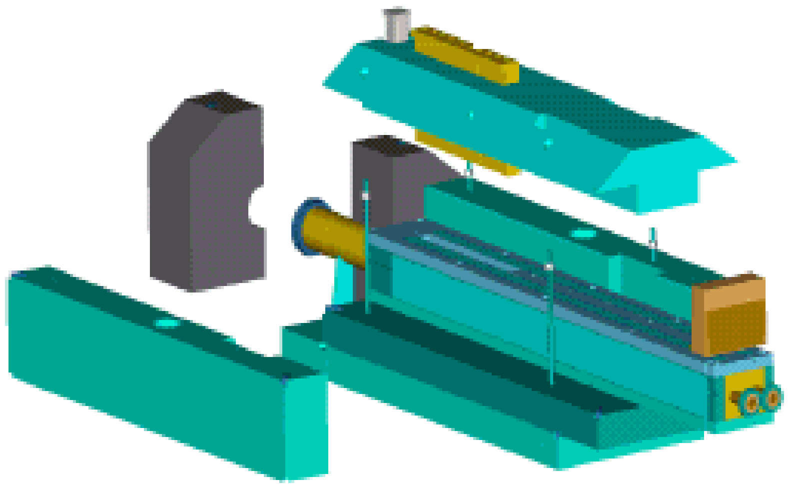
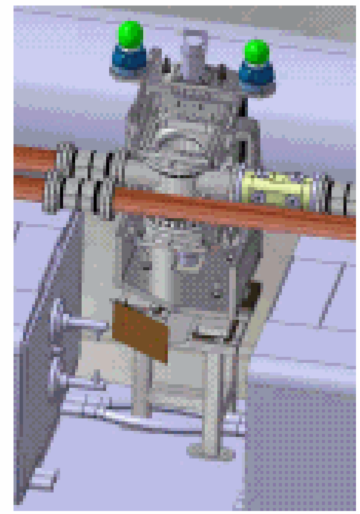
# ATLAS Forward Detectors

DESY 11/1 /2007

Per Grafstrom

# ATLAS Forward Detectors

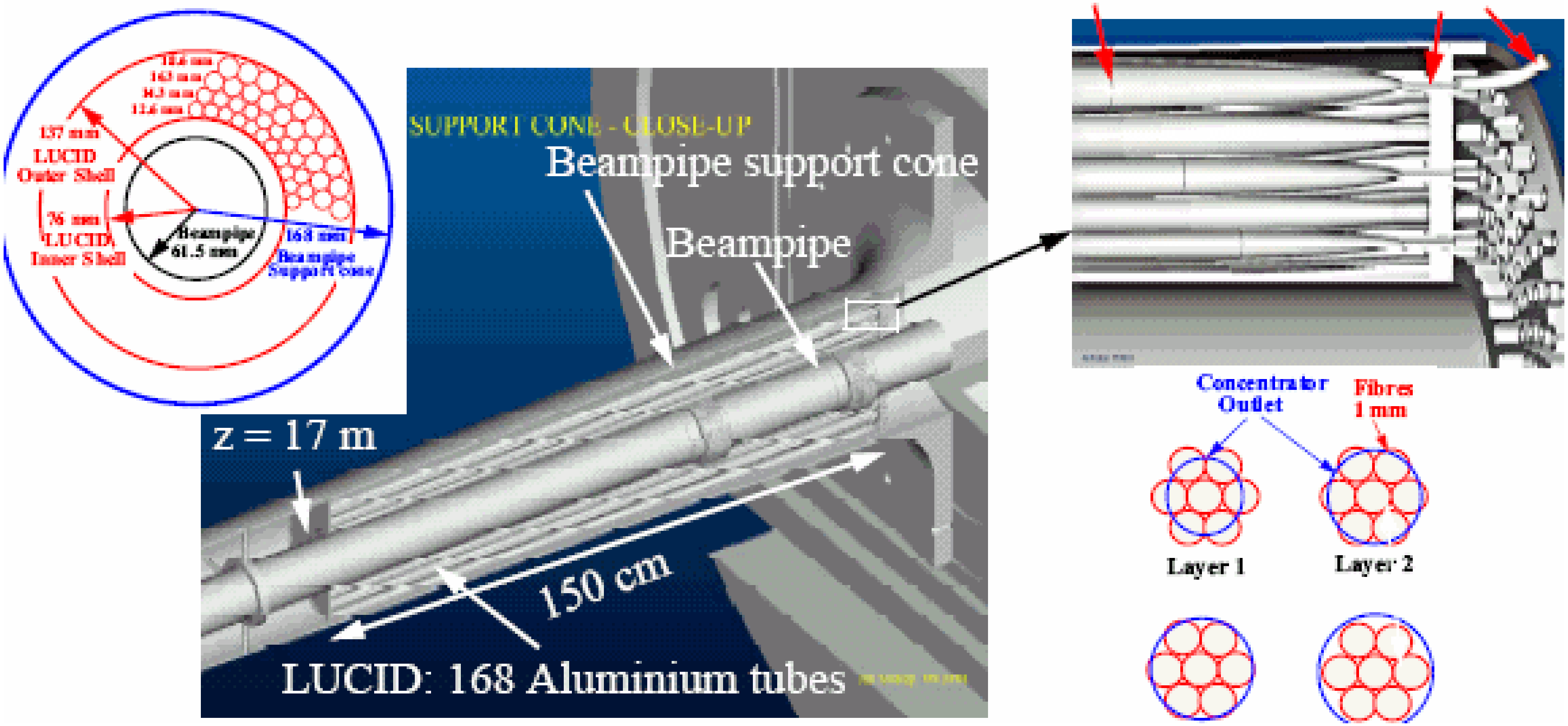



| LUCID | ZDC | ALFA |
|---|---|---|
|  |  |  |
| Cherenkov tubes | Tungsten/Quartz calorimeter | Scintillating fibres in Roman Pots |
| Relative luminosity monitoring. | Forward physics in both pp and heavy ion collisions. | Absolute luminosity in dedicated LHC runs with |

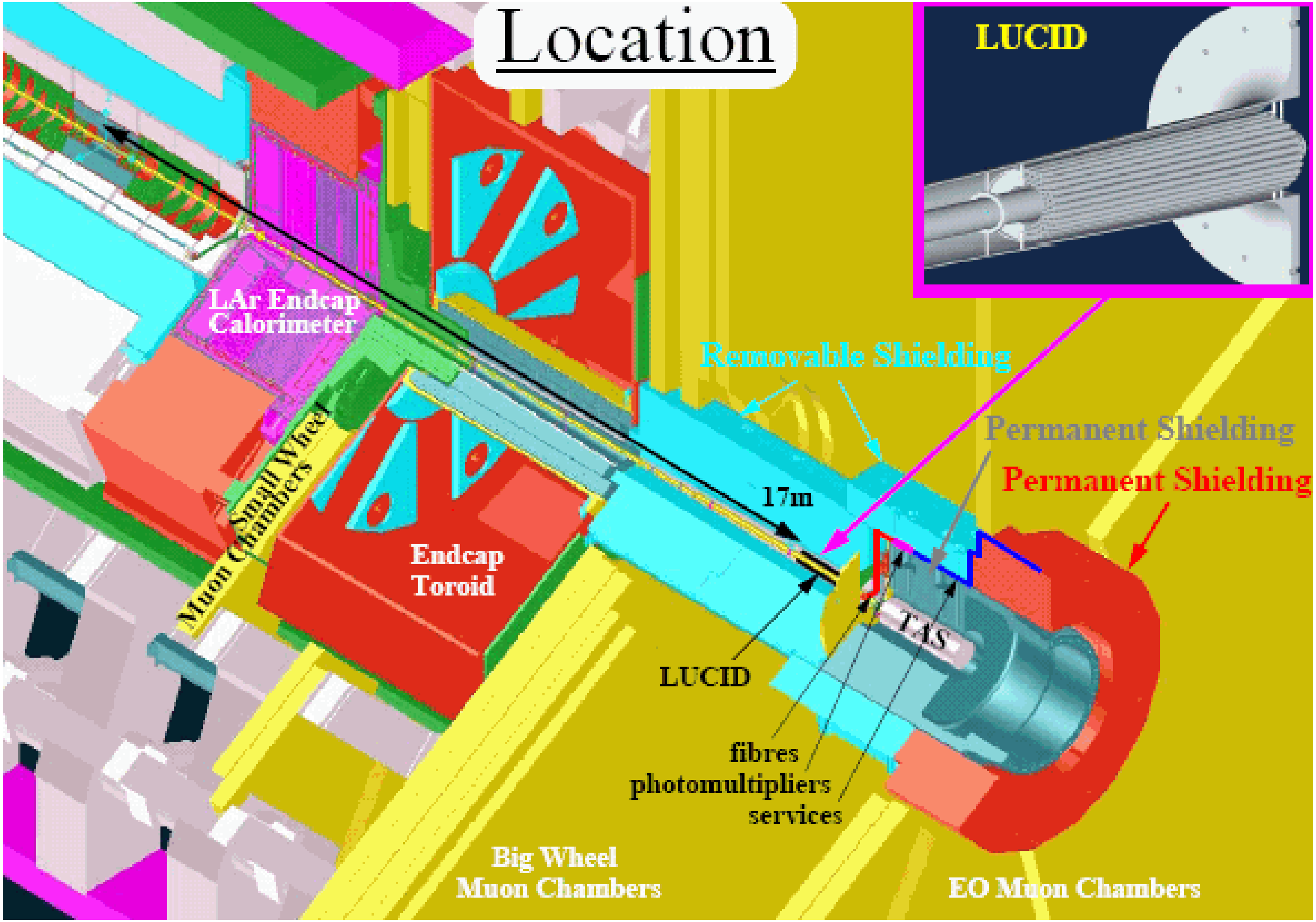
# LUCID

**LUCID: LUminosity measurement using a Cherenkov Integrating Detector**

The two LUCID detectors consist each of 168 gasfilled (isobutane) aluminium tubes. The Cherenkov light in the tubes is read out by 1176 optical fibres that are connected to multianode photomultipliers.



# Location


LUCID
LAr Endcap
Calorimeter
Removable Shielding
Permanent Shielding
Permanent Shielding
17m
Small Wheel
Muon Chambers
Endcap
Toroid
TAS
LUCID
fibres
photomultipliers
services
Big Wheel
Muon Chambers
EO Muon Chambers

# 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.

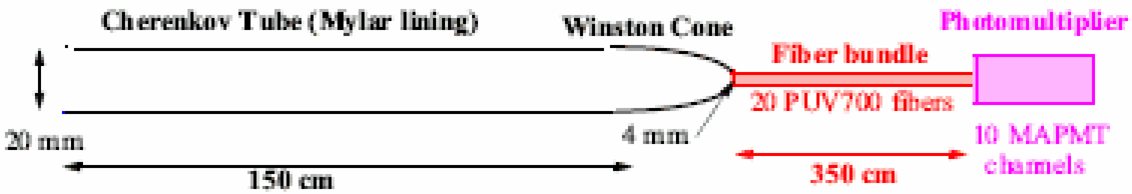
It is insensitive to soft background particles (the Cherenkov threshold is 2.7 GeV for pions and 9 MeV for electrons).

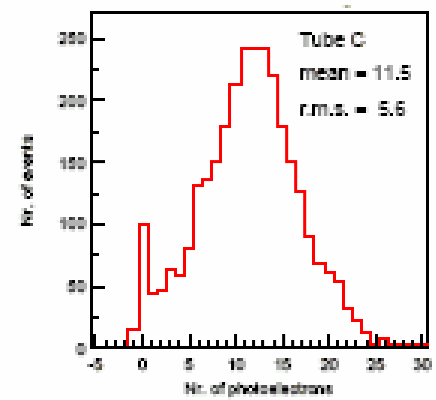
A good time resolution makes it possible to resolve individual beam crossings and to measure the luminosity of individual bunches in the LHC.

The pointing capability will help in reducing the background.

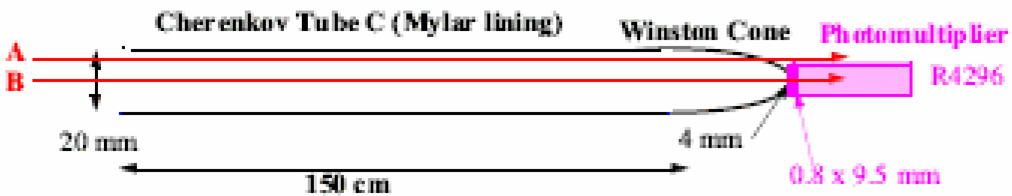
From pulseheight measurements it should be possible to measure if one or several particles have gone through a Cherenkov tube. This is important since at $10^{34}$ $cm^{-2}s^{-1}$ there will be 25 inelastic interactions per bunch crossing and the basic principle of the detector is that the number of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

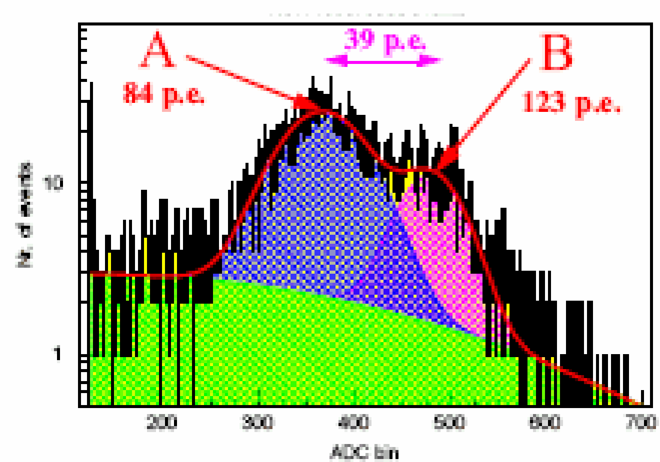
# Testbeam measurements




Testbeam studies of a prototype detector has been made twice at DESY. The number of photoelectrons in the baseline detector with fibre readout was less than expected (11 at 1.25 atm.). Another testbeam measurement with improved light collection is forseen for December.



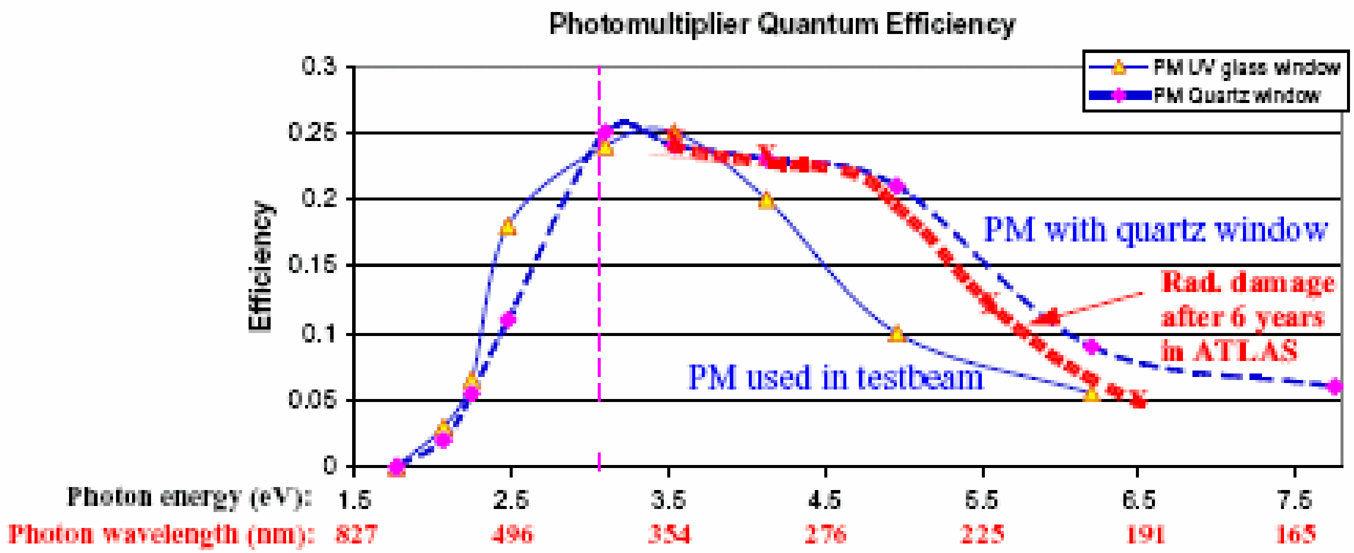




Without the fibres the number of photoelectrons is much larger but light is also produced in the photomultiplier window.

# Unresolved issues

Unresolved questions: Can we improve the light collection of the fibre readout so that we can obtain an efficient multi-particle separation ?

Can photomultipliers with quartz windows survive in our radiation environment ?




Will the detector be swamped by secondary particles (electrons) ?

Testbeam measurement, radiation hardness tests and simulations will answer these questions but the bottom line is that we are still in the R/D phase.

# Status

The proposal is now to stage the project and install a minimum detector in 2007 consisting of 8-10 tubes on each side of the interaction point and the full detector at a later stage.

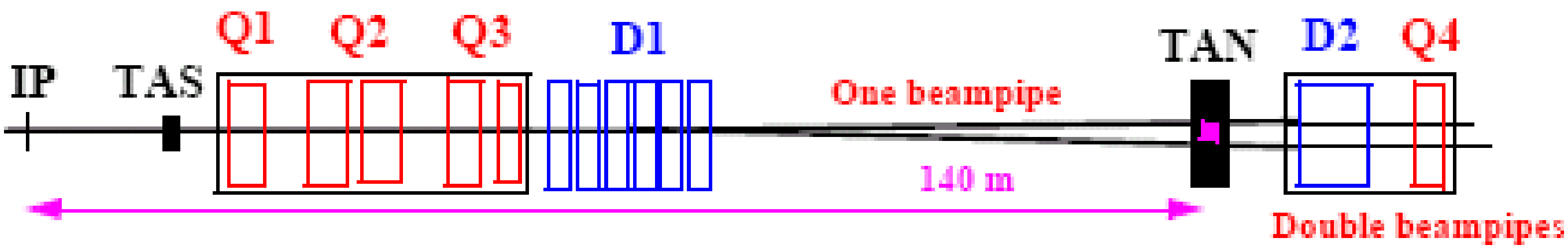
This partial deployment would still allow for a monitoring of the luminosity and would give us experience with

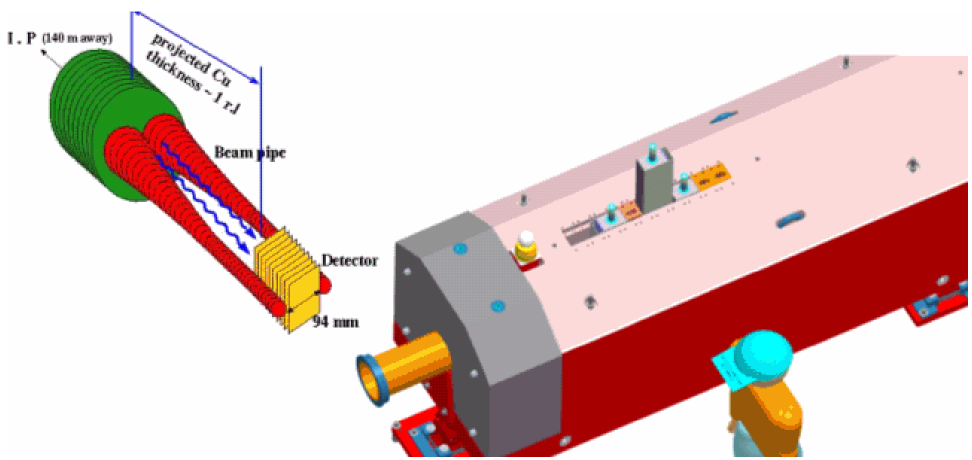
Background from secondaries and the accelerator;
Timing and the front-end and back-end readout electronics;
Installation and alignment;
Luminosity analysis and the online luminosity and background monitoring.

However, even this partial deployment of the detector in 2007 is an ambitous goal and an ATLAS review in January (after the next testbeam measurement) will conclude if this will be feasable.

# Zero Degree Calorimeter

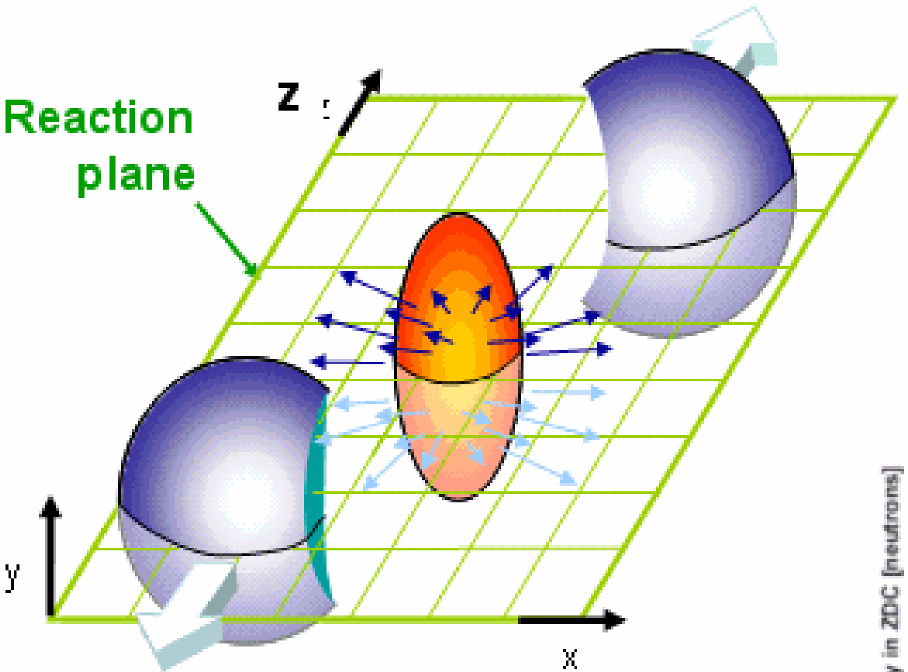
- Measures Forward neutral particles
  - Centrality measurements in heavy ion collisions
  - Beam tuning and luminosity monitoring in pp
  - Cosmic ray physics
  - pp physics measure forward neutral hadron production



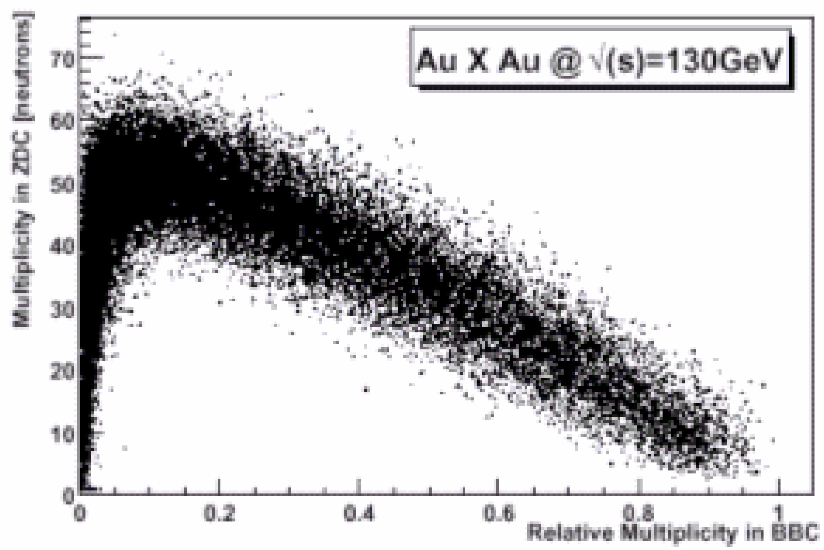
# Event characterization in Heavy Ion Running

*>>Direction and magnitude of impact parameter, b*




Magnitude from complementary parameters

$N_{participant}=2^*A-N_{spectator}$



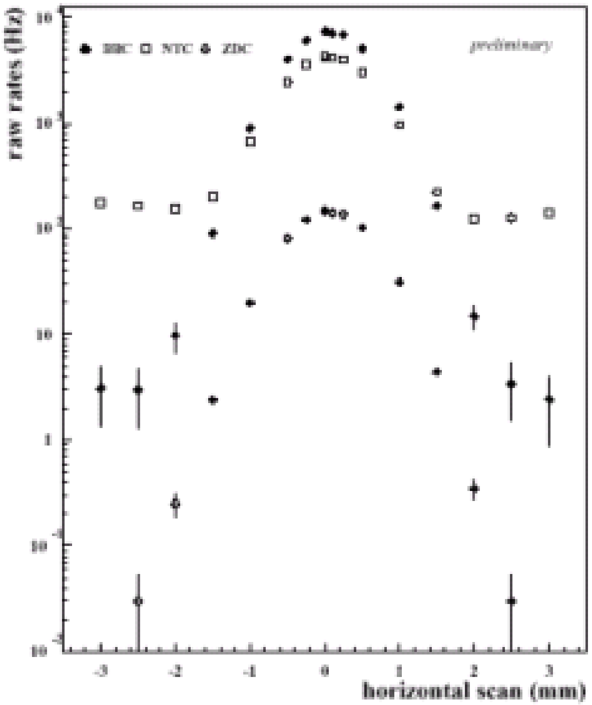

**Spectator neutrons**

•measure centrality,

•Min_min_bias trigger

(Calorimeter@θ<2mr.)

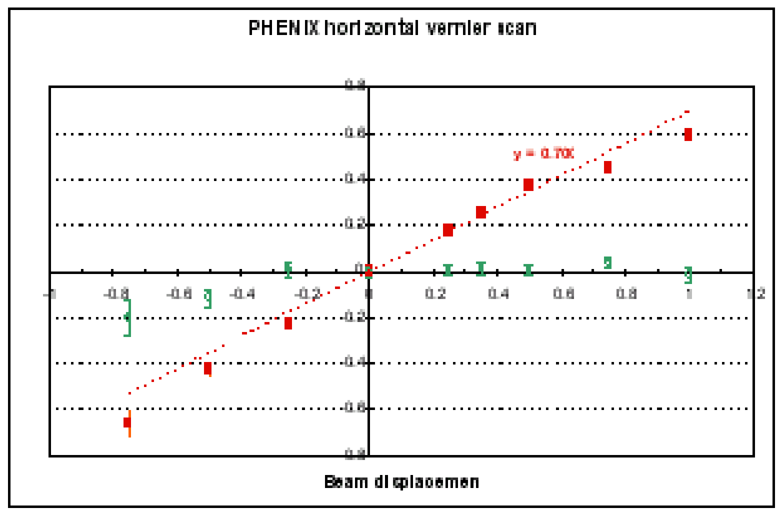
# Beam tuning



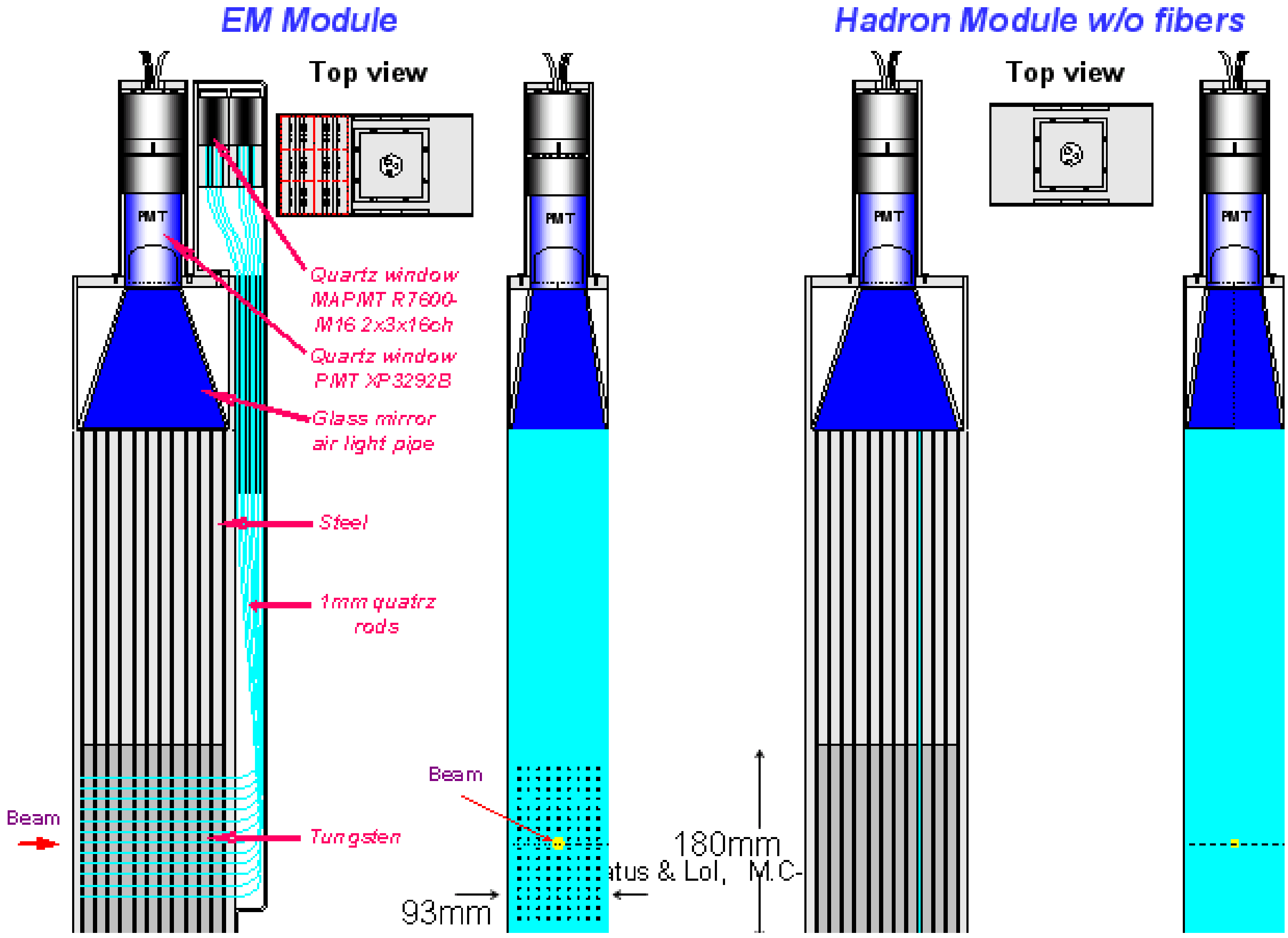

## RHIC ZDC as an accelerator tool (in pp)

- Van derMeer scan (ZDC coincidence rate vs. relative beam position)
- ZDC (lower curve) bkg free over 4 orders of magnitude

- ZDC also measures beam displacement (red points)
- Useful for crossing angle commissioning



# The ZDC Modules



# Status of the ZDC

Module construction: some quartz rods installed

- Protype constructed
- Test beam CERN Oct 2006
- LOI for LHC in pipe line
- Intend to install summer 2007 or in shutdown 2007/2008

# Absolute 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

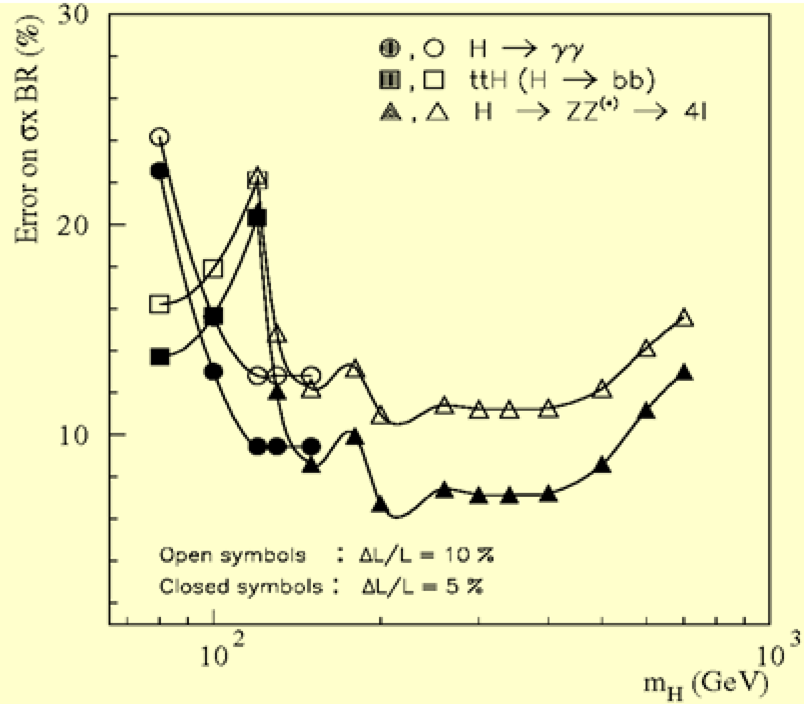
- New physics manifesting in deviation of $\sigma$ x BR relative the Standard Model predictions

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

# Absolute Luminosity Measurement (cont.)

## Examples

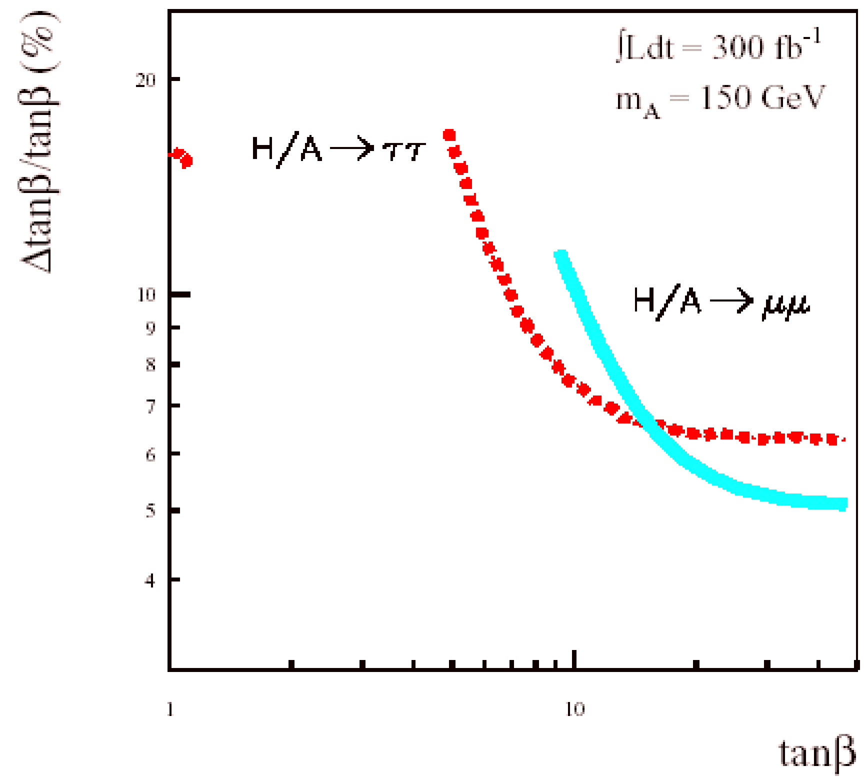
### Higgs coupling




Relative precision on the measurement of $\sigma_H \times$BR for various channels, as function of $m_H$, at $\int Ldt = 300\ \text{fb}^{-1}$. 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 )

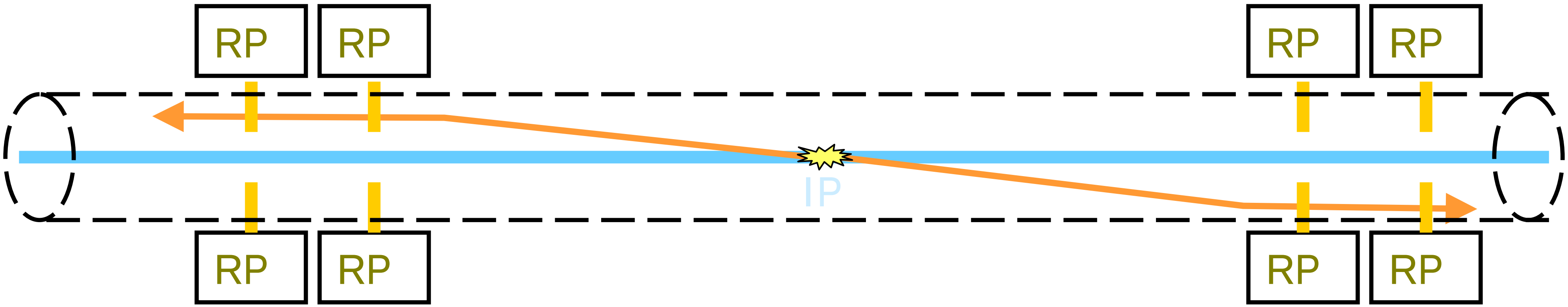
# Absolute Luminosity Measurement (cont.)

- Goal:
  - measure $L$ with $\lesssim$ 2-3% accuracy
- How:
  - LHC Machine parameters
  - Use ZDC in heavy ion runs to understand machine parameters
  - rates of well-calculable processes:
    e.g. QED, QCD
  - optical theorem: forward elastic rate + total inelastic rate: **Use Roman Pots**
    - needs ~full |η| coverage-ATLAS coverage limited
    - Use $\sigma_{tot}$ measured by others (TOTEM)
    - Combine machine luminosity with optical theorem
  - luminosity from Coulomb Scattering **Use Roman Pots**

*ATLAS pursuing all options*

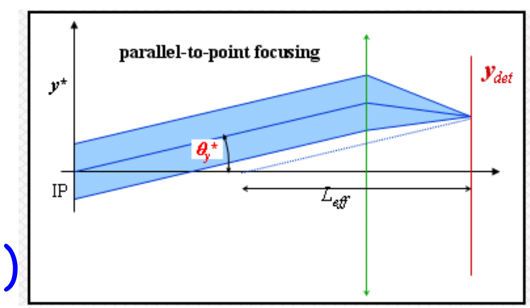
# ATLAS Roman Pots

- Goal: Determine absolute luminosity at IP1 (2-3% precision)
- Measure elastic rate dN/dt in the Coulomb interference region (à la UA4). $|t|$~0.00065 GeV$^2$ or $\Theta$ ~ 3.5 microrad.

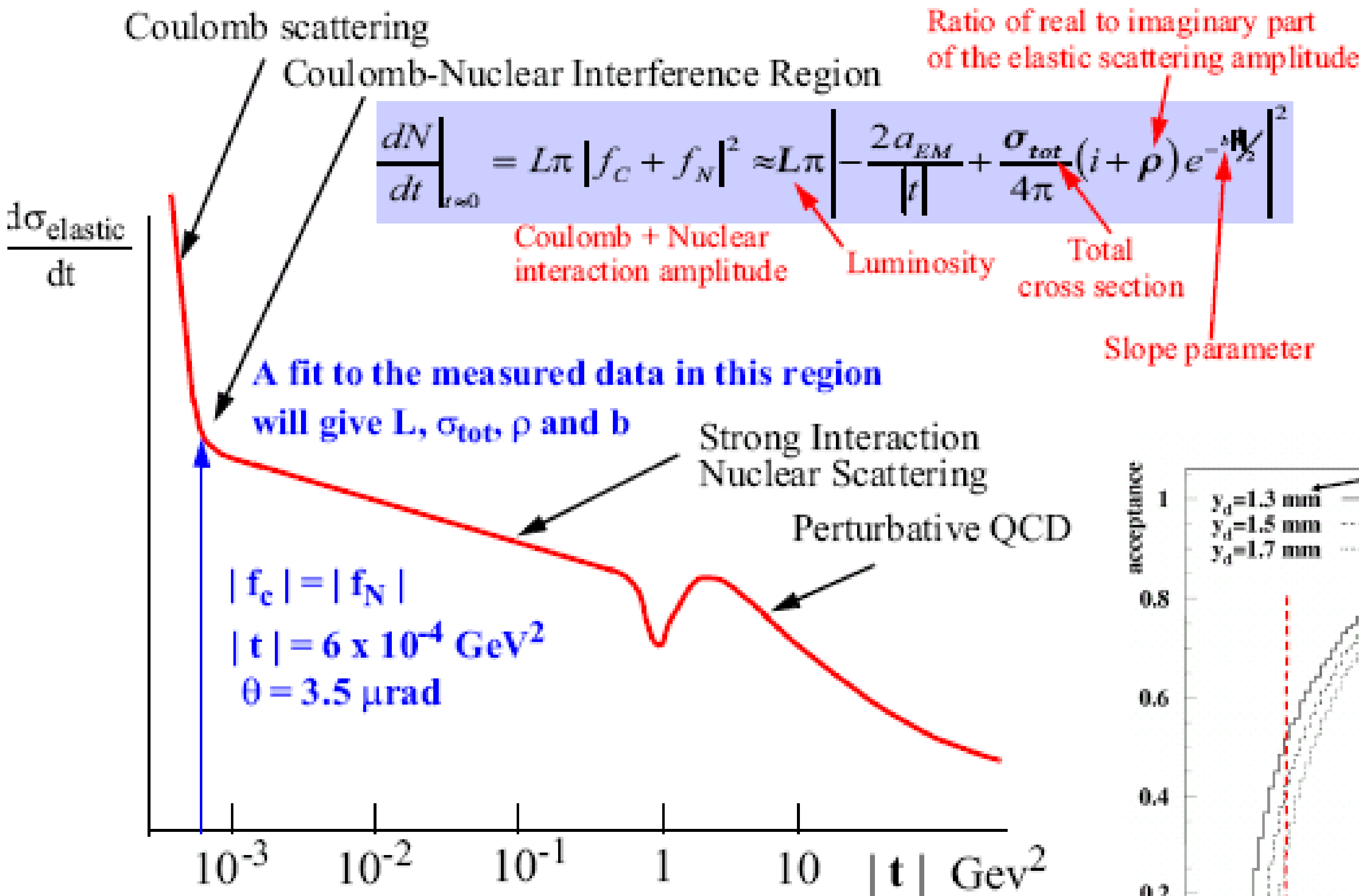


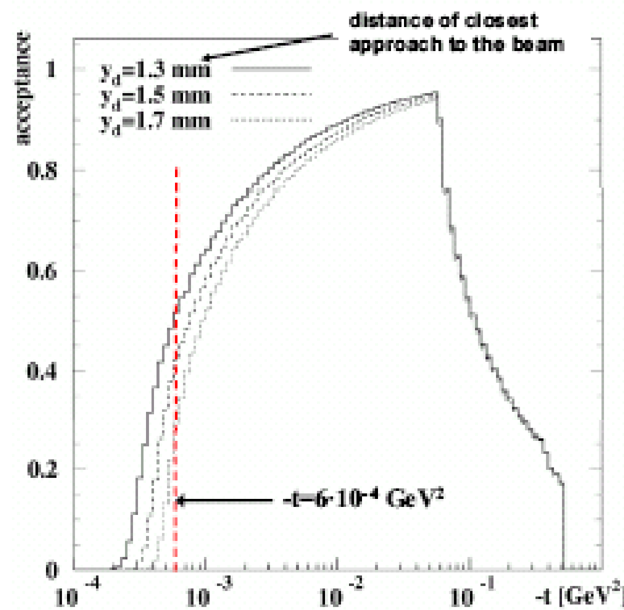

This requires (apart from special beam optics)

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

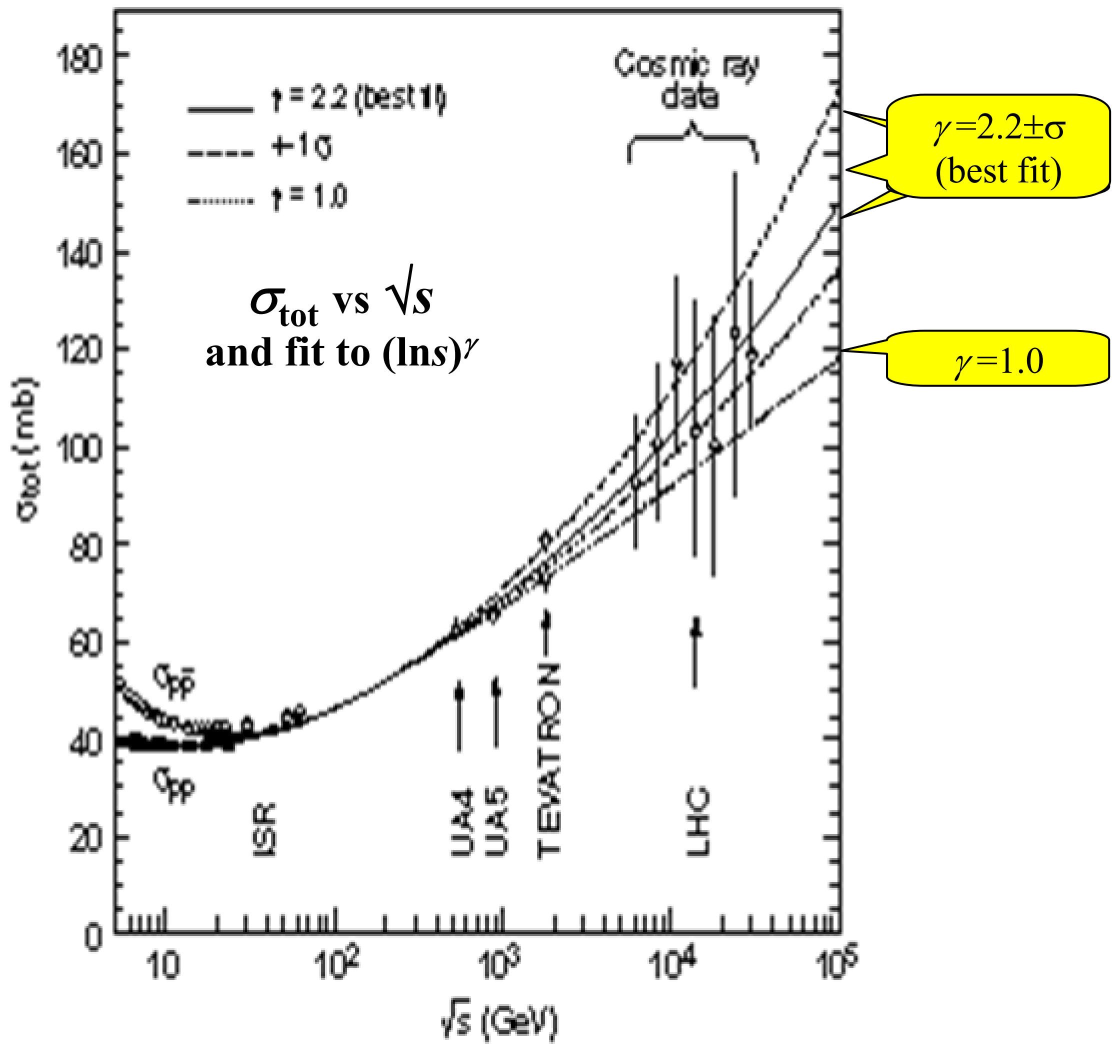


# Elastic scattering



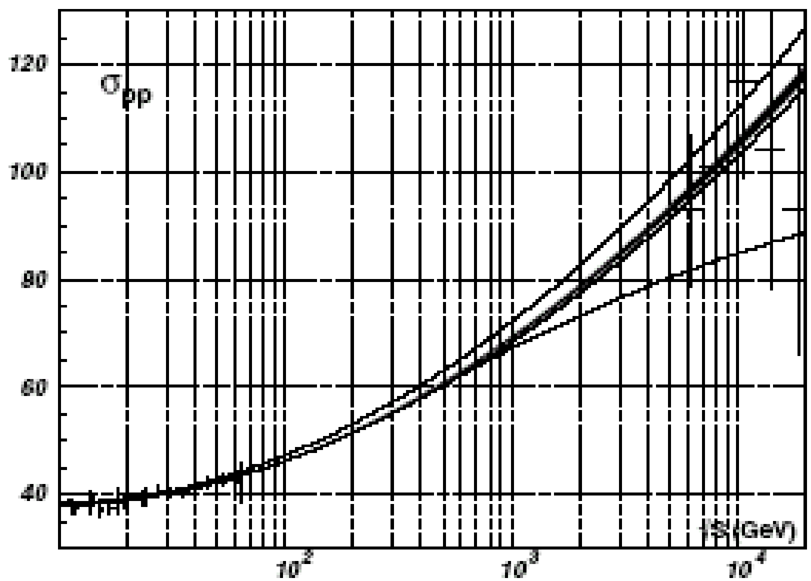



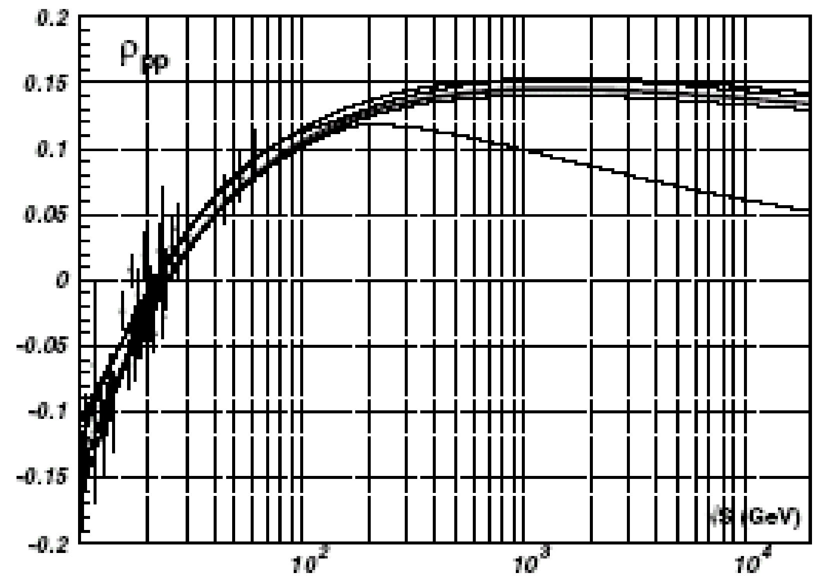
# The total cross section



# The ρ parameter

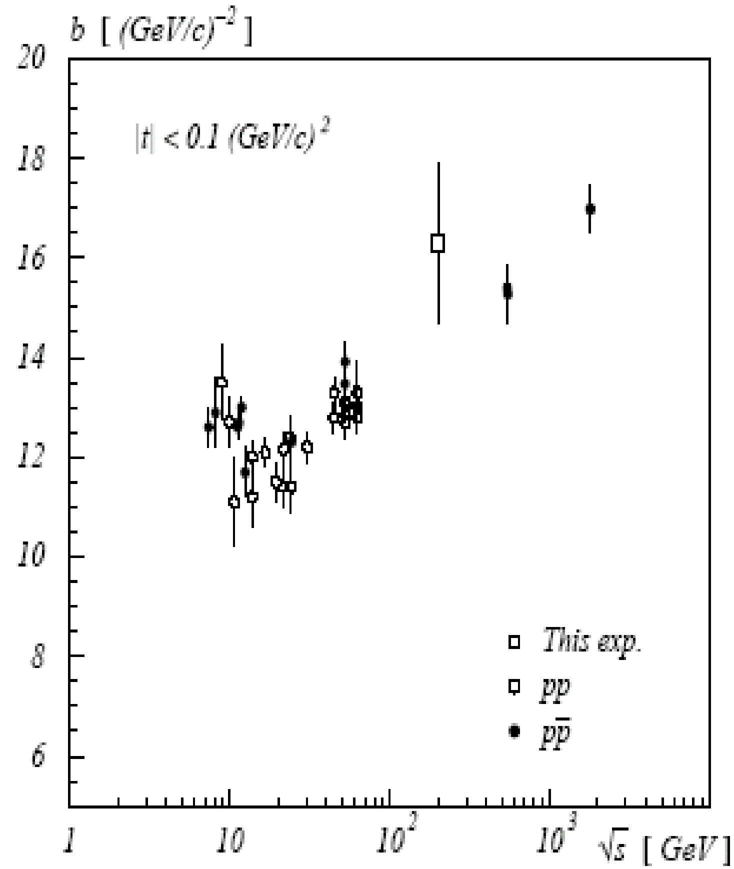
- $\rho$ = Re F(0)/Im F(0)  linked to the total cross section via dispersion relations
- $\rho$  is sensitive to the total cross section beyond the energy at which $\rho$ is measured
  $\Rightarrow$ predictions of $\sigma_{tot}$ beyond LHC energies is possible
- Inversely :Are dispersion relations still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



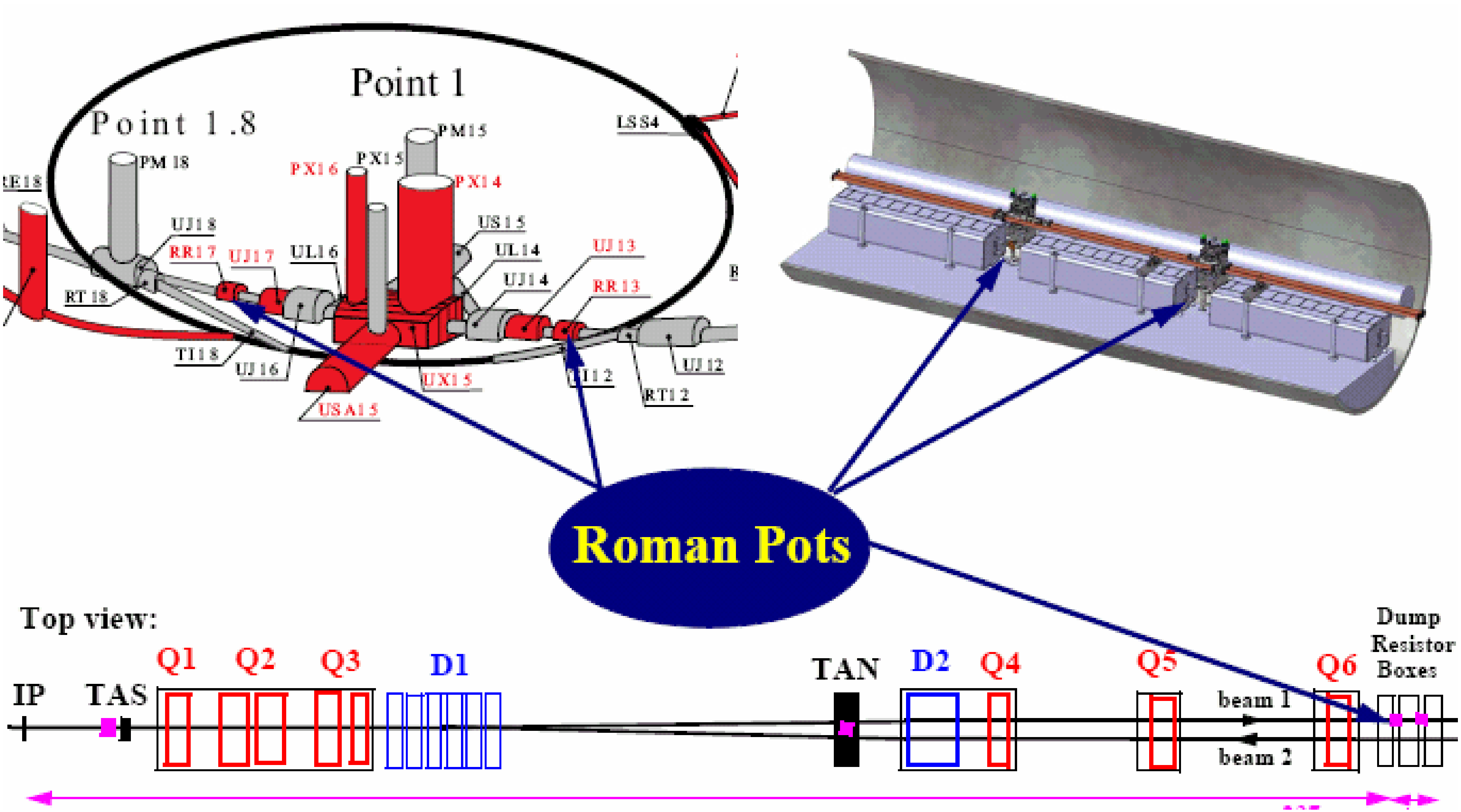



# The b-parameter or the forward peak

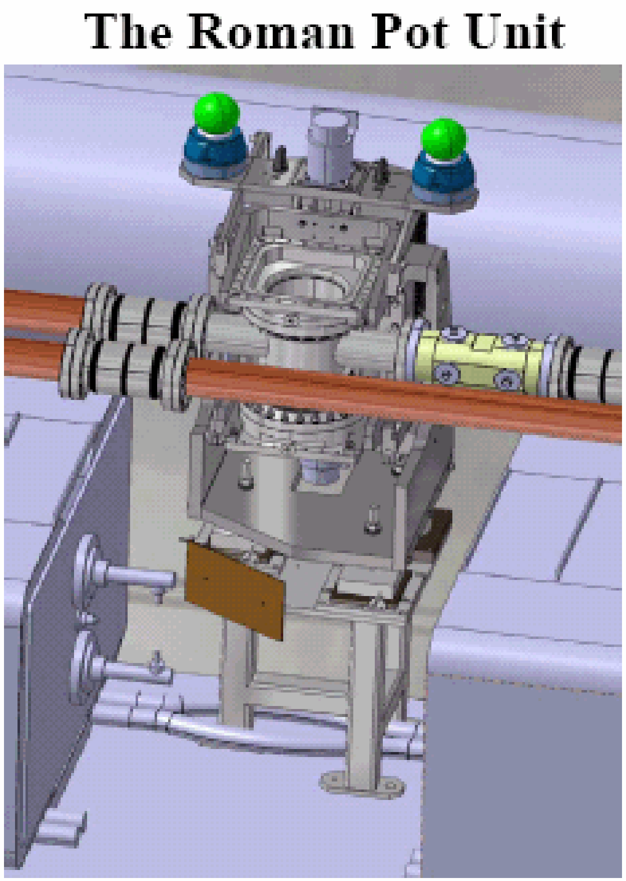
- The b-parameter for $|t| < .1\ GeV^2$
- "Old" language : shrinkage of the forward peak
  $b(s) \propto 2\ \alpha' \log s$ ; $\alpha'$ the slope of the Pomeron trajectory ; $\alpha' \approx 0.25\ GeV^2$
- Not simple exponential - t-dependence of local slope
- Structure of small oscillations?

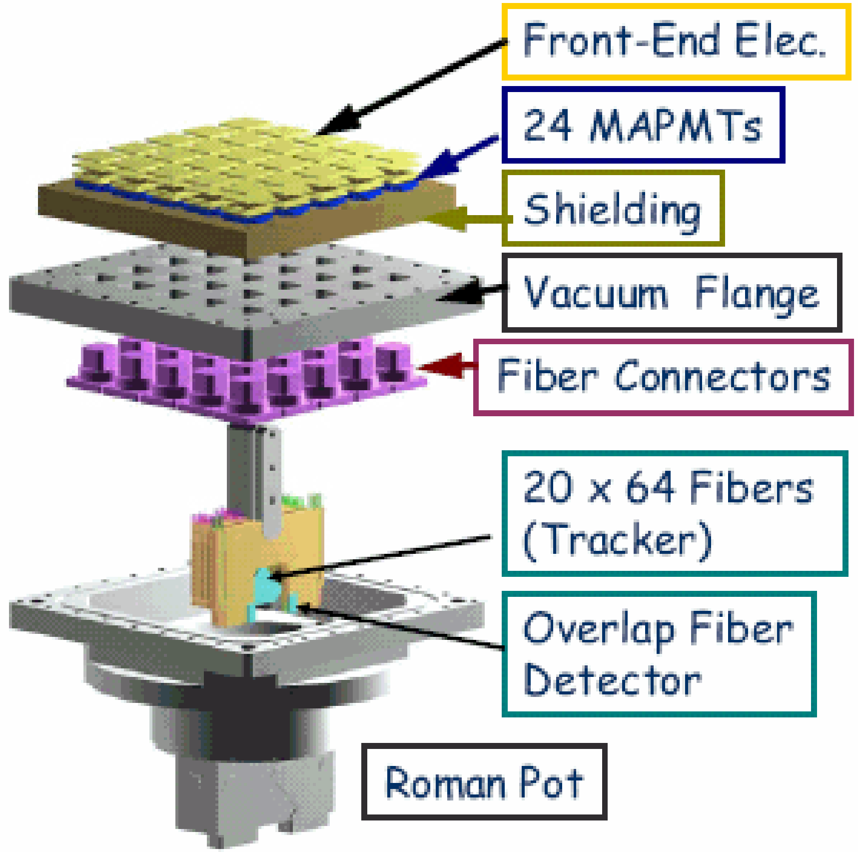


# Roman Pot locations



# The Roman Pot unit

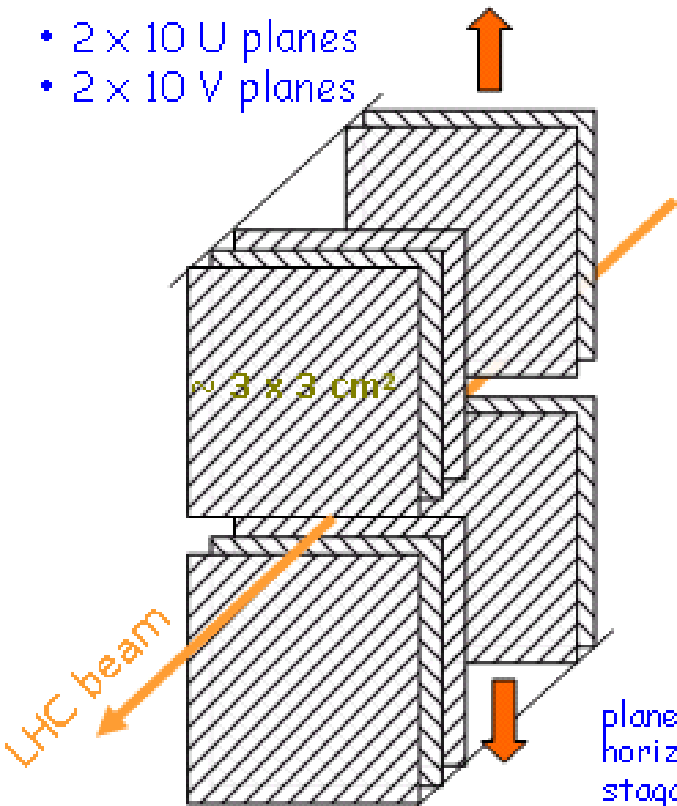


# The fiber tracker

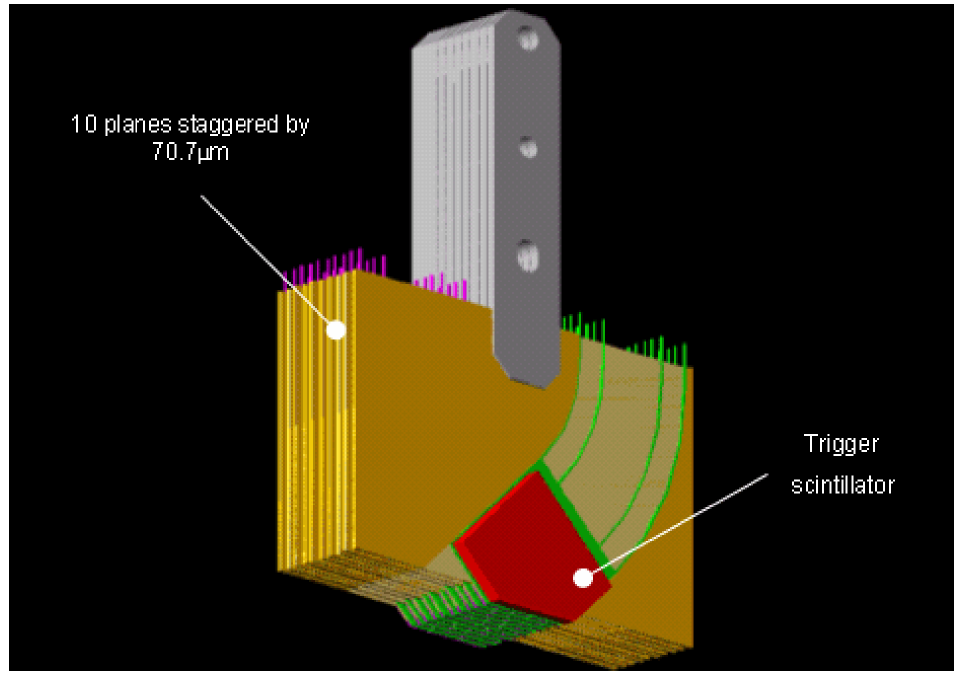
**Concept**

- 2 × 10 U planes
- 2 × 10 V planes




- scintillating fibres
- 0.5 mm² square

planes are horizontally staggered by multiples of 70.7 micrometer

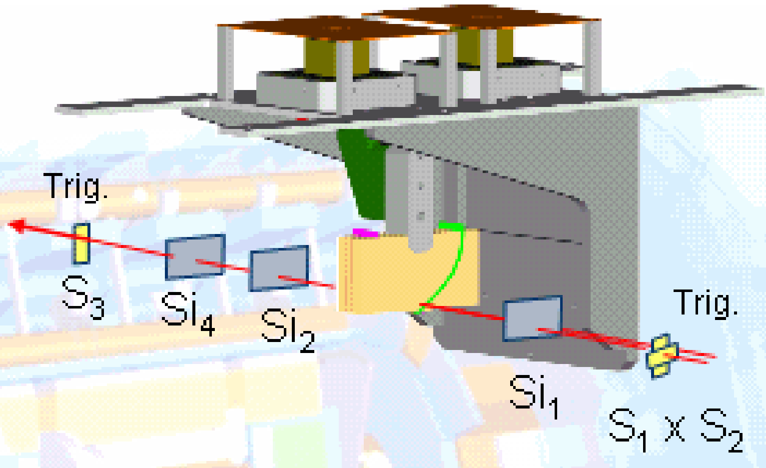


# Test Beam at Desy 2005

## Detectors

A set of different detectors was built to test: Light yield, Efficiency, Cross talk, Edge sensitivity, Resolution etc.

Base line fiber: (SCSF-78, S-type) Kuraray 0.5mm² single cladded

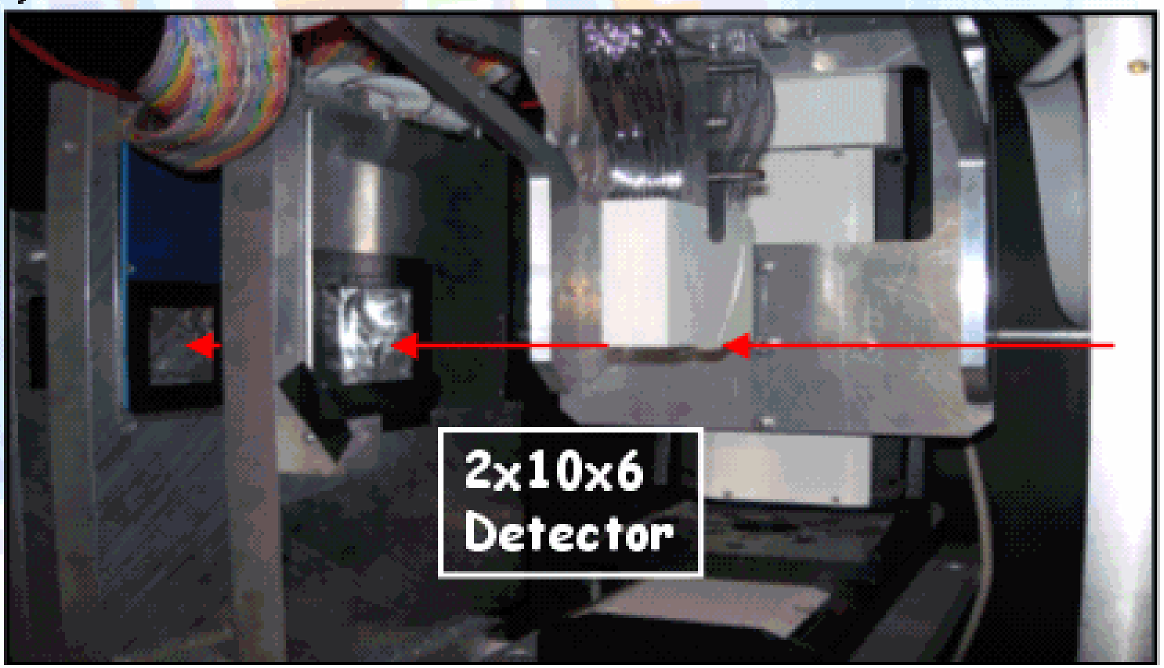



## Beam

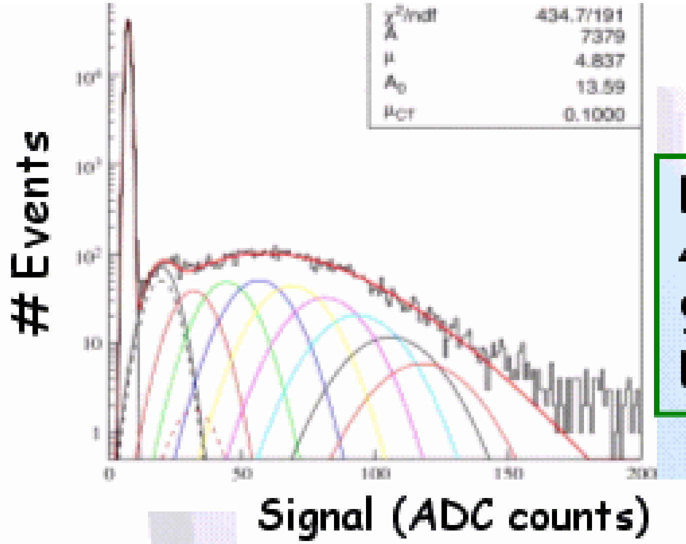
- 6 GeV electrons
- Beam spot ~ 1 cm²

## Setup

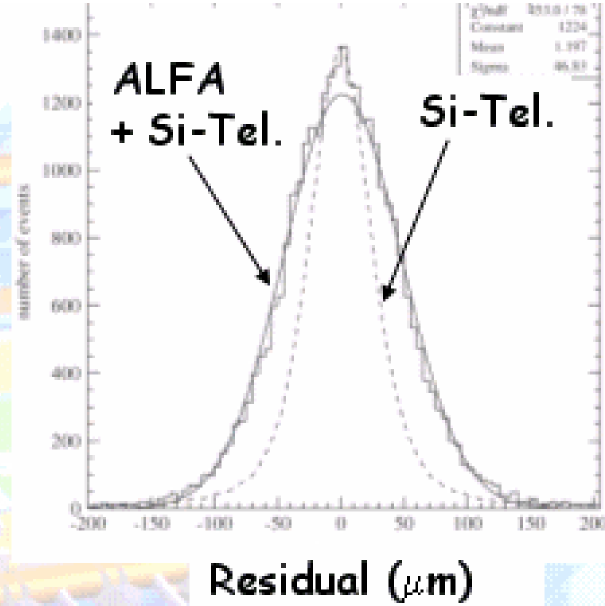
- Si telescope (~30 μm resolution)
- MAPMT – CAEN QDCs – PC

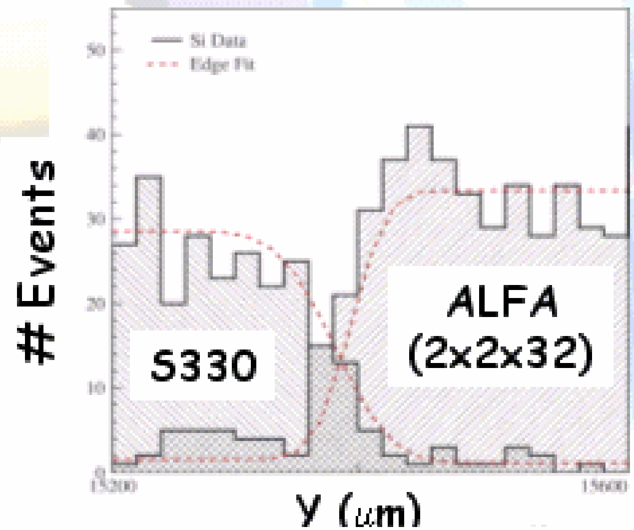


# DESY test beam results




Light yield:
45° cut → 3.9 p.e.
90° cut → 4.5 p.e.
Efficiency ~ 95%




Non-Active Edge
Region << 100μm

ALFA Resolution:
$\sigma_{x,y}$ ~ 36 μm

Potentially increased by multiple scattering of the relatively low energy electrons

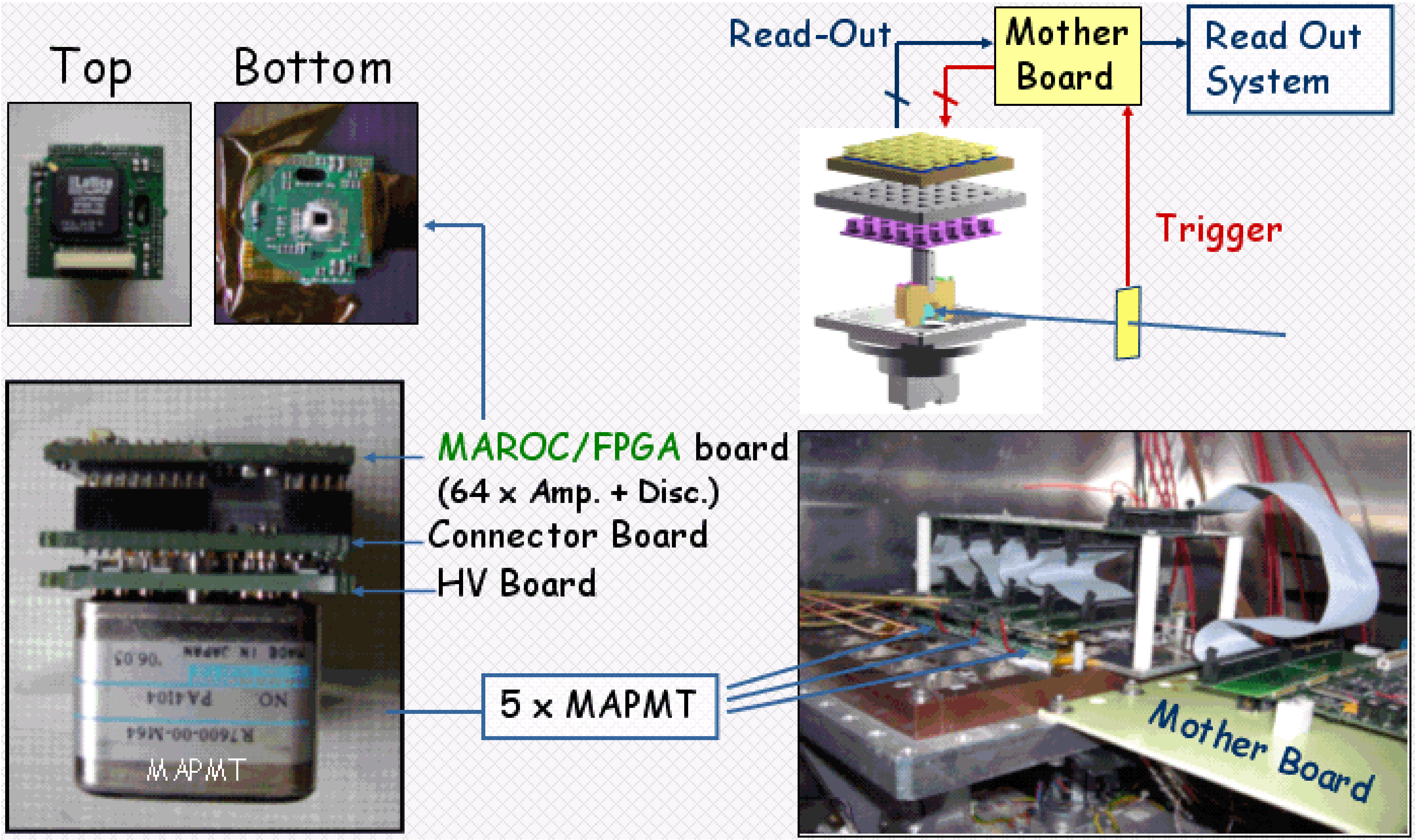
# The test beam at DESY November 2005

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

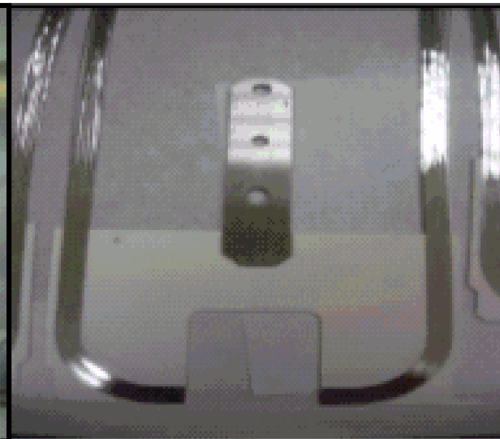
- Technology appears fully appropriate for the
  proposed Luminosity measurement.

# FE electronics -Test beam CERN (Oct 2006)

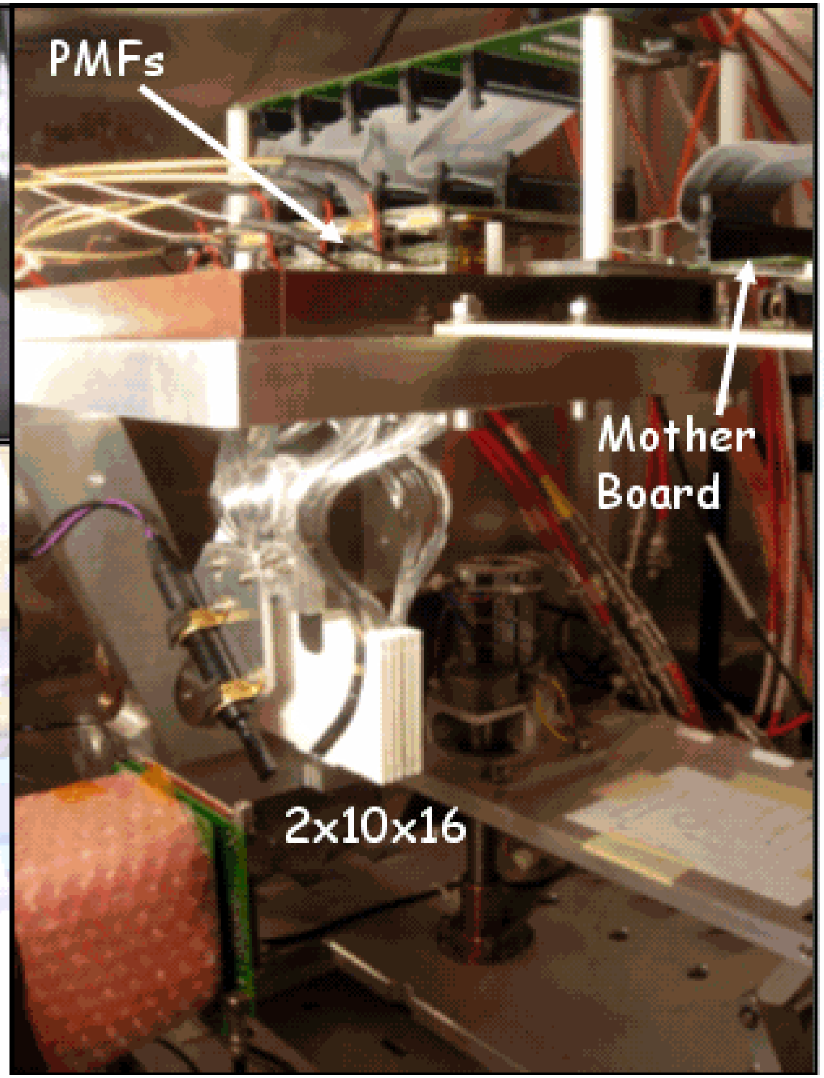


# Test beam CERN October 2006

2x2x64 + Final Trig.



Overlap Detectors




**Detectors**

- Two ALFA trackers (larger wrt DESY TB)
- Overlap Detectors

**Beam**

- 230 GeV protons ($\pi^{+/-}$)

**Setup**

- 5 x MAPMT - 5 x PMF - Motherboard - PC

# Test Beam CERN October 2006

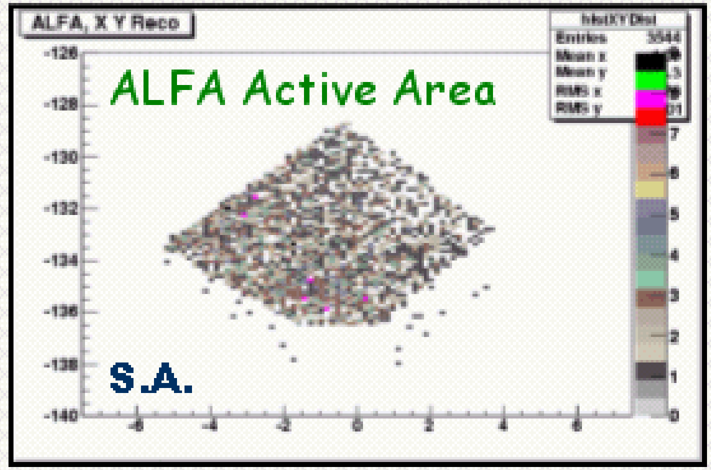
Analysis Ongoing !

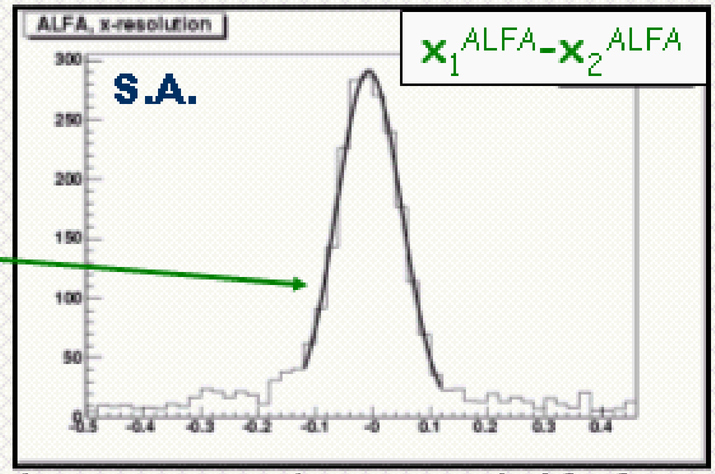
Preliminary Conclusions:

- Possible to operate ALFA using the first version of the FE-electronics !
- Using standard ATLAS infrastructure, such as the TTC system and ATLAS DAQ
- Data quality results indicates good tracking results, e.g. "2xHalf ALFA resolution"

  $\sigma$ ~ 56um (simple online algo.)

  vs $\sigma$ ~ 48um (Ideal "geometrical" MC)
  (48um MC → 25um full ALFA resolution)




(Reconstructed using 2 x half of ALFA)

# 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 $\beta^*$ optics V6.5
including apertures

←

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

# Simulation of elastic scattering

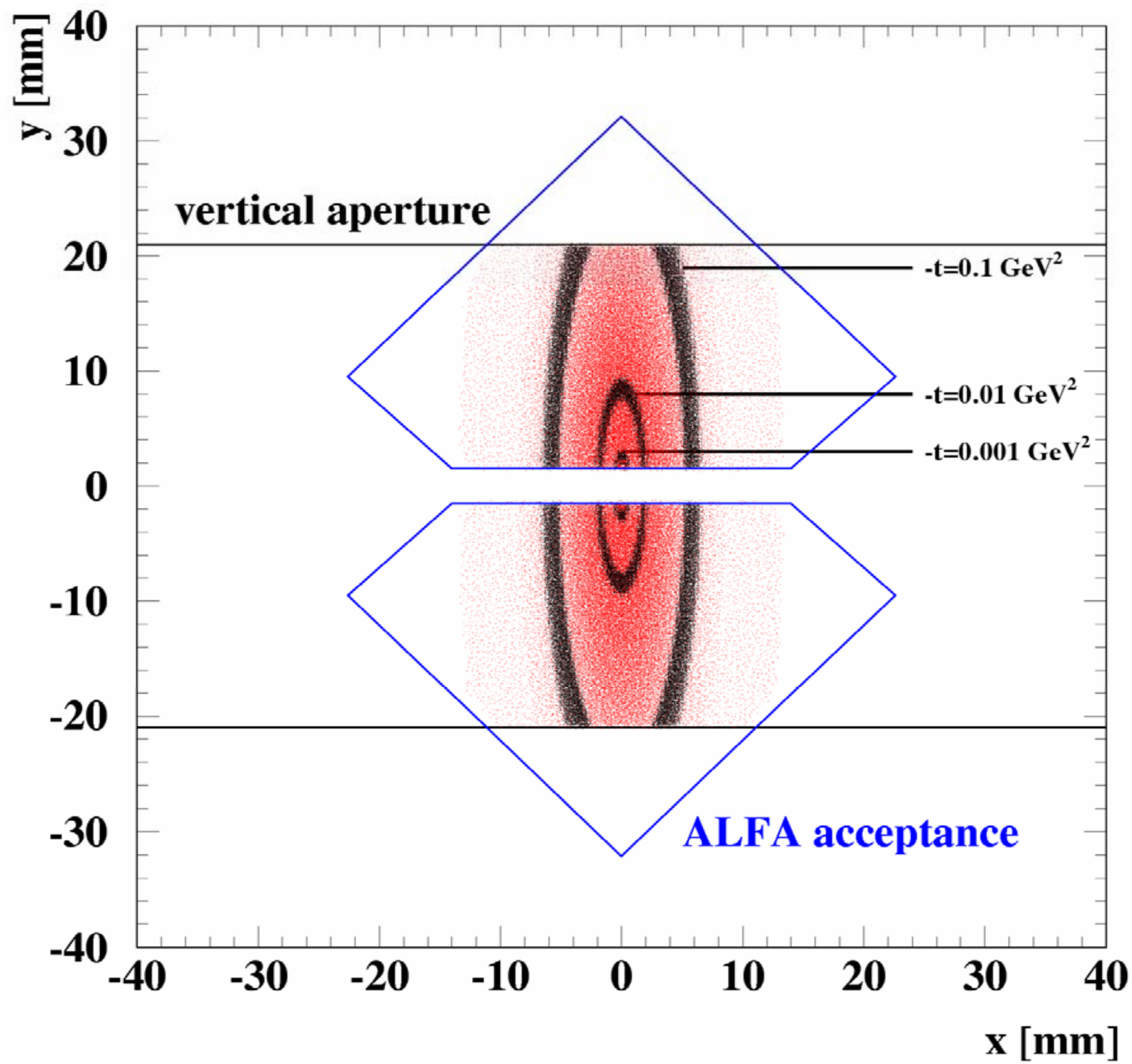
*hit pattern for 10 M elastic events simulated with PYTHIA + MADX for the beam transport*

## *t* reconstruction:

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

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

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



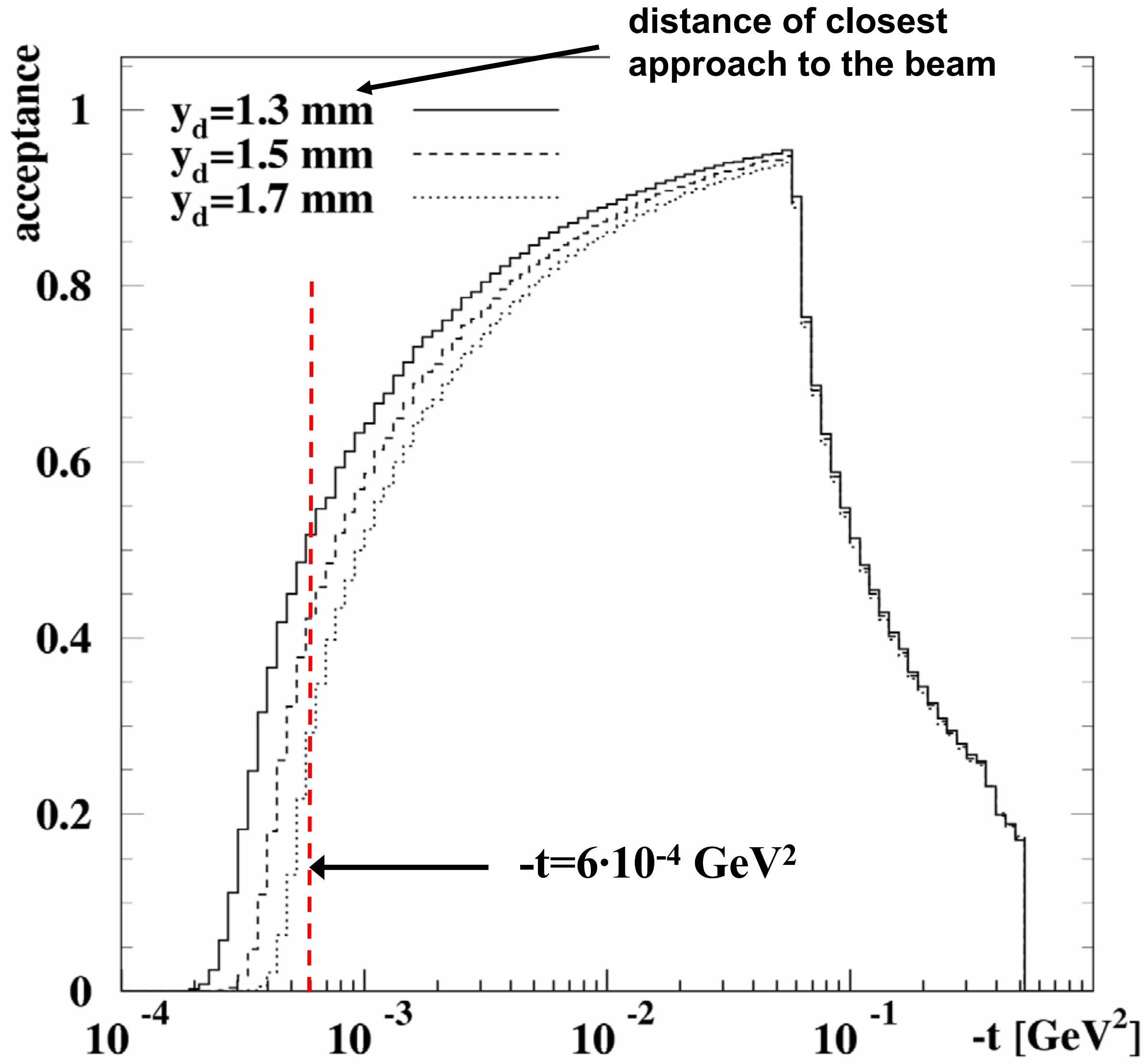
# Acceptance

**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 : $|f_C| = |f_N|$

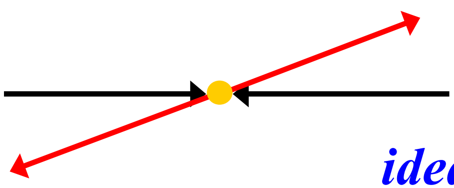
$$t \approx \frac{8\pi a_{EM}}{\sigma_{TOT}} \approx 6\times10^{-4}\ GeV^2 \rightarrow \theta \approx 3.5\,\mu rad$$



# t-resolution

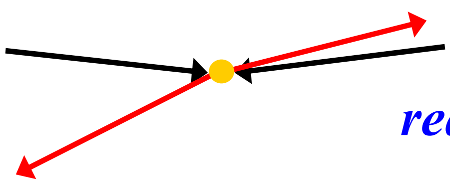
**The *t*-resolution is dominated by the divergence of the incoming beams.**

**σ'=0.23 μrad**

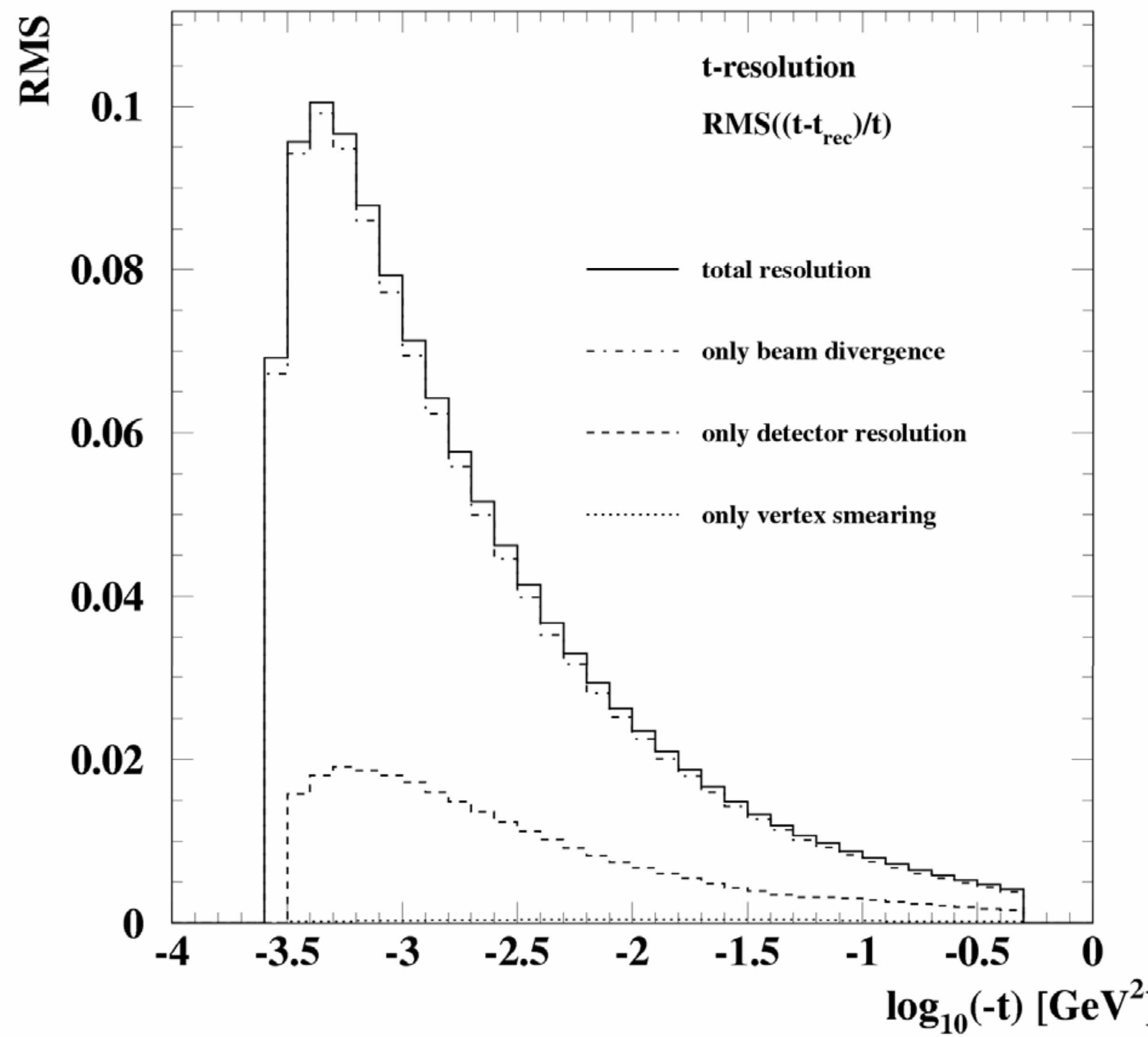


*ideal case*

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



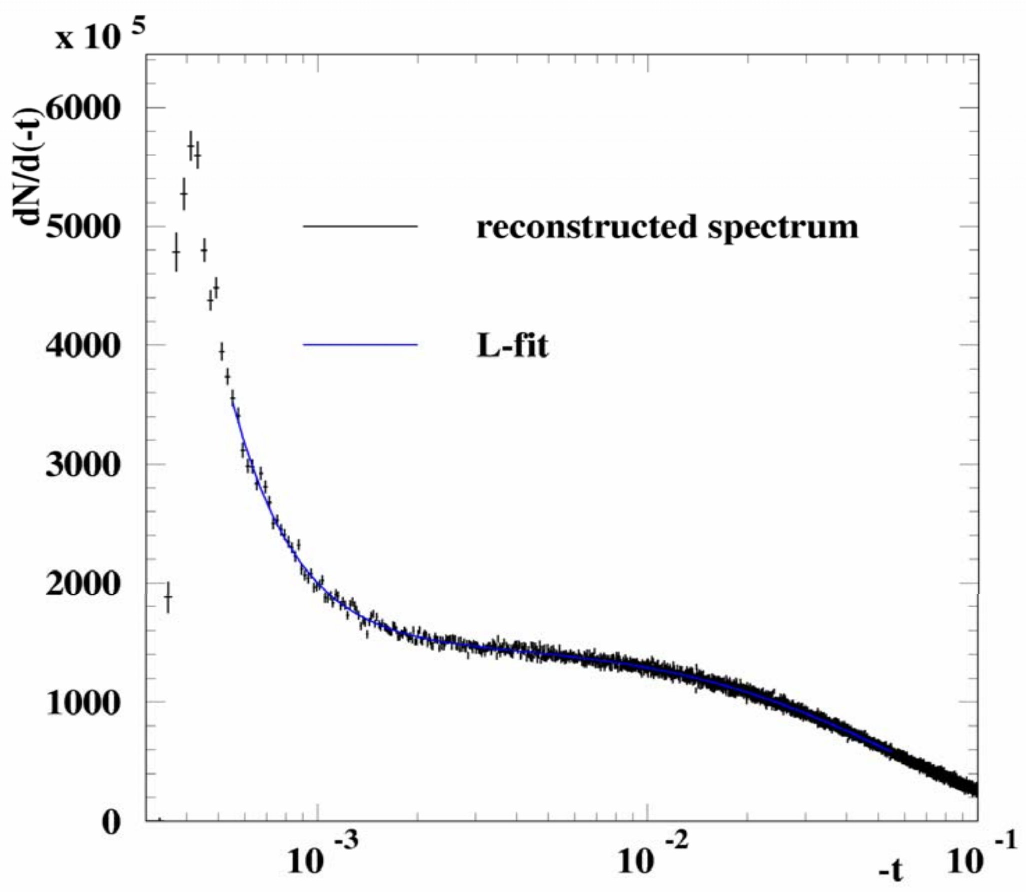
*real world*



# L from a fit to the t-spectrum

$$\frac{dN}{dt} = L\pi \left| F_C + F_N \right|^2$$

$$= L \left( \frac{4\pi\alpha^2 (\hbar c)^2}{|t|^2} - \frac{\alpha\rho\sigma_{tot} e^{-B|t|/2}}{|t|} + \frac{\sigma_{tot}^2 (1+\rho^2) e^{-B|t|}}{16\pi (\hbar c)^2} \right)$$




**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 % | |
| $\sigma_{tot}$ | 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**

# Experimental systematic uncertainties

**Currently being evaluated**

- **beam divergence**
- **detector resolution**
- **acceptance**
- **alignment**
- **beam optics**

**$\Delta L/L \approx$ 1.9-2.1 %**

**missing: background studies**
**(are under way)**

**total error ≈ 2.6-2.8 %**

# Status and Plans

Testbeam studies at DESY in 2005 have verified the basic detector concept (efficiency and light yield of Kuraray SCSF-78 fibres, 4 photoelectrons, low optical cross talk, 36μm spatial resolution, sufficient edge sensitivity, 99% track reconstruction efficiency etc.).

A prototype of the read-out electronics was evaluated in a testbeam at CERN in October 2006. The basic design was shown to work but problems with cross talk and connectivity are still under study.

The design of the mechanics of the ATLAS Roman Pot unit is ready. A pre-production unit made by Vakuum Praha is at CERN for evaluation. The pot itself will be designed and manufactured by CERN.

The cabling of the detector in the LHC tunnel is finished.

Next step is to write a Technical Design Report.

Schedule: Possible installation windows for the RP units are May 2007 or the 2007-2008 shutdown. Installation of the detectors at the earliest in the 2008-2009 shutdown.
The funding of the detector construction has still to be resolved.

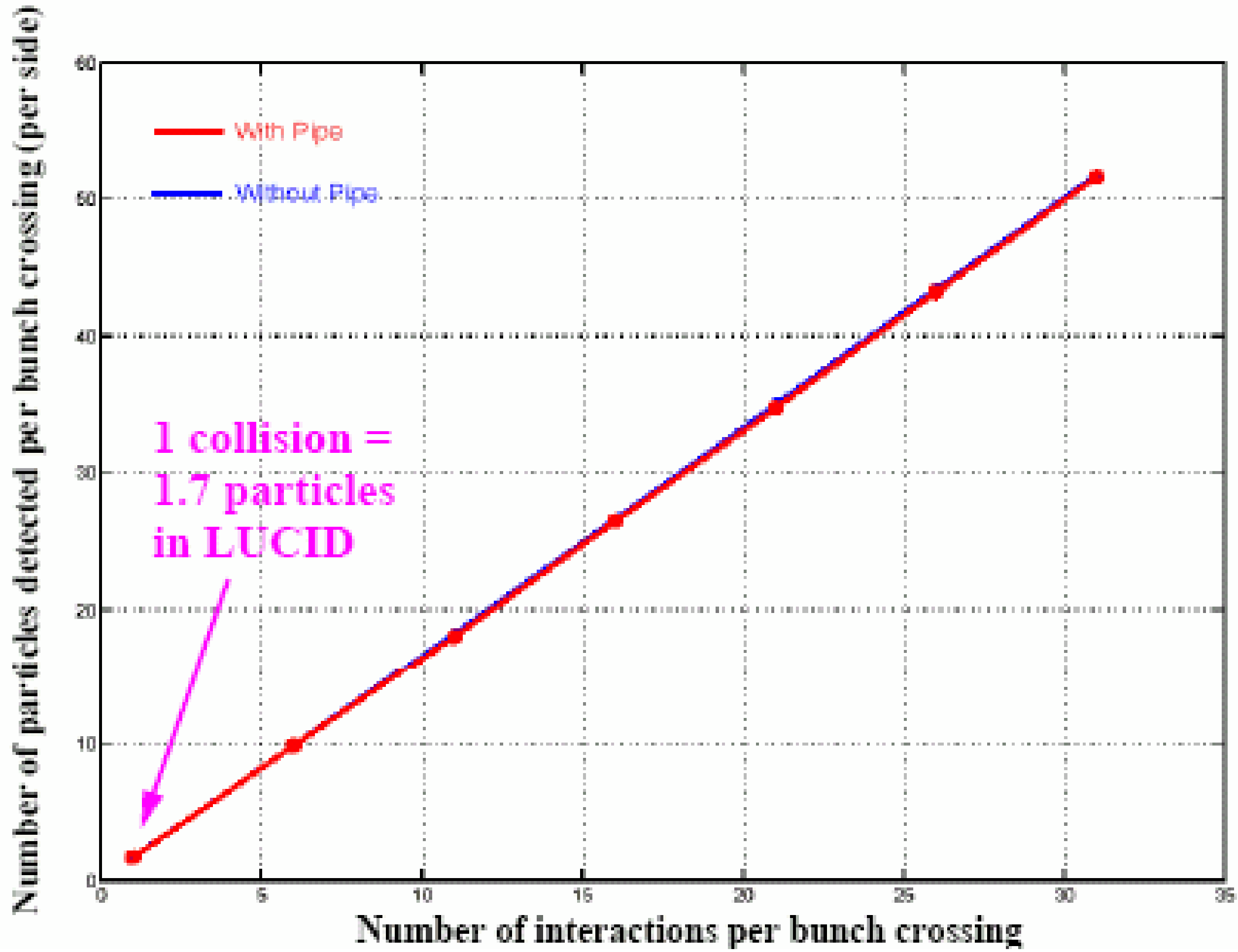
# Funding situation today

| updated 4/10/06 | Estimated cost | Already paid/funded | Possible further funds |
|---|---|---|---|
| | | | |
| Infrastructure (cables ,rp pedestal ,polarity inverter) | 210 | 80 ATLAS TC/ISRAEL | ATLAS TC |
| RP mechanics (pot proper, rp-unit,instrumentation) | 200 | 50 CERN /ATLAS TC | 30 Prague |
| Electronics, PS, readout | 415 | 20 Lund<br>55 Orsay<br>10 CERN | 80 HV PS Dresden<br>Lund<br>CERN |
| Detector including prototype and tests | 290 | 10 Prague<br>70 CERN | 40 Lisbon<br>20 Humboldt<br>10 Prague<br>?? Giessen |
| PM's | 300 | | ALL??? |
| | | | |
| TOTAL | 1415 | 300 | 180 |

# Back up

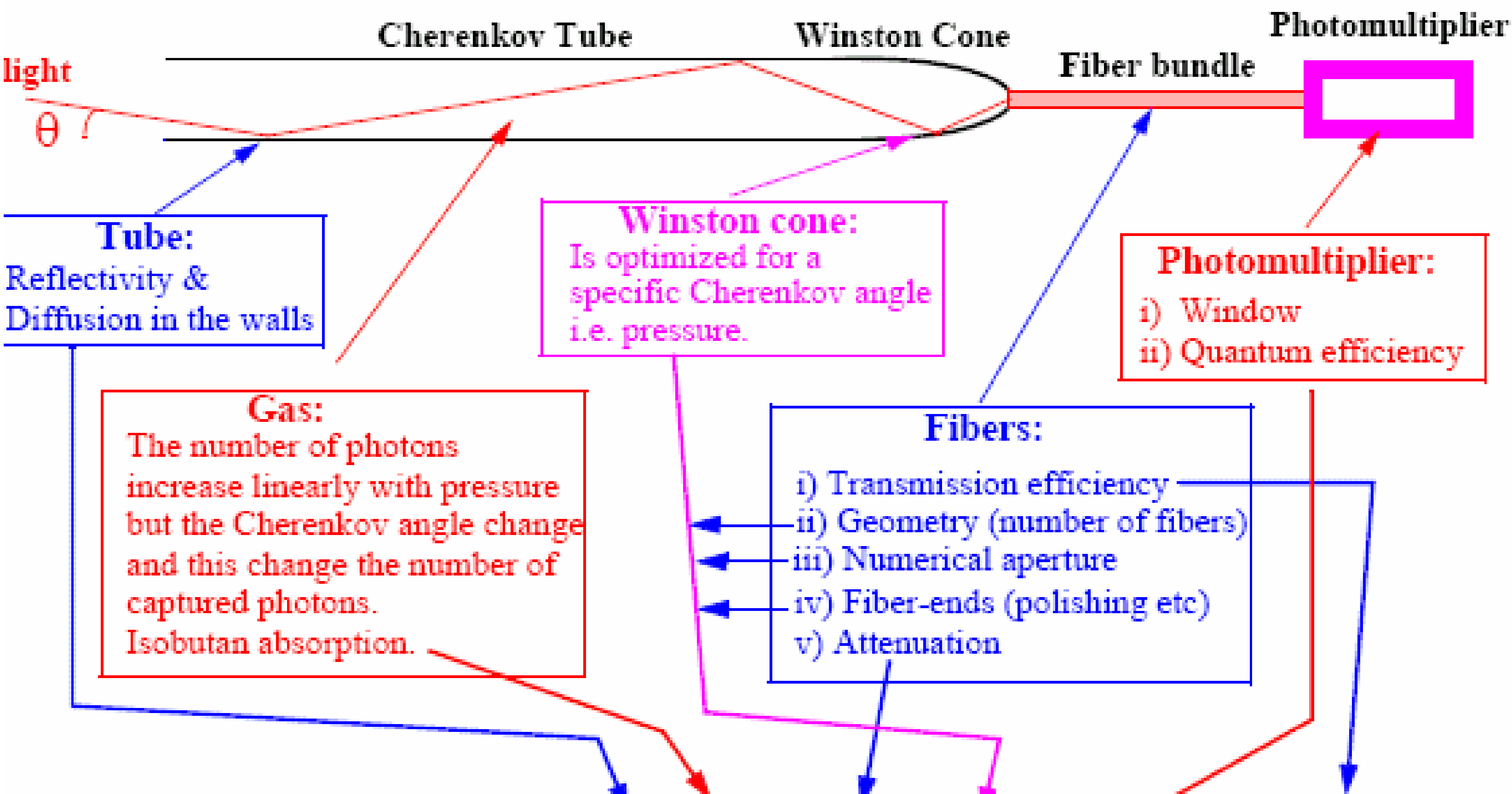
# LUCID: Principle

Simulations shows a perfectly linear relationship between the number of particles measured in LUCID and the luminosity.




V. Hedberg

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

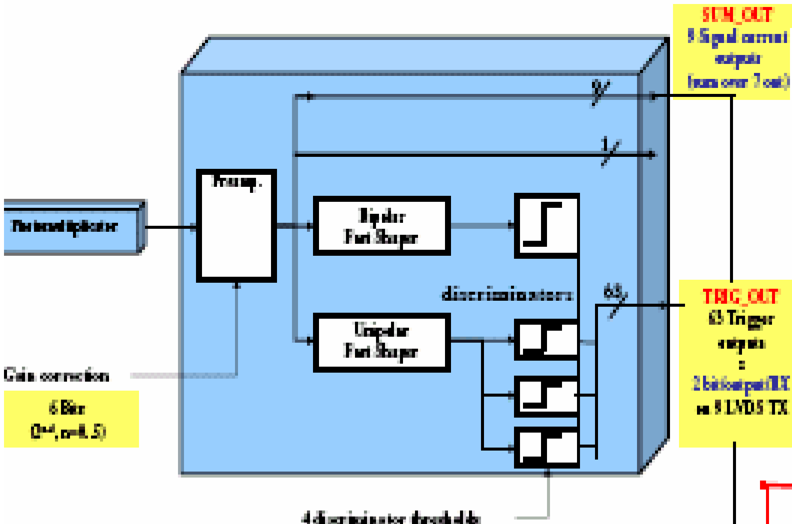


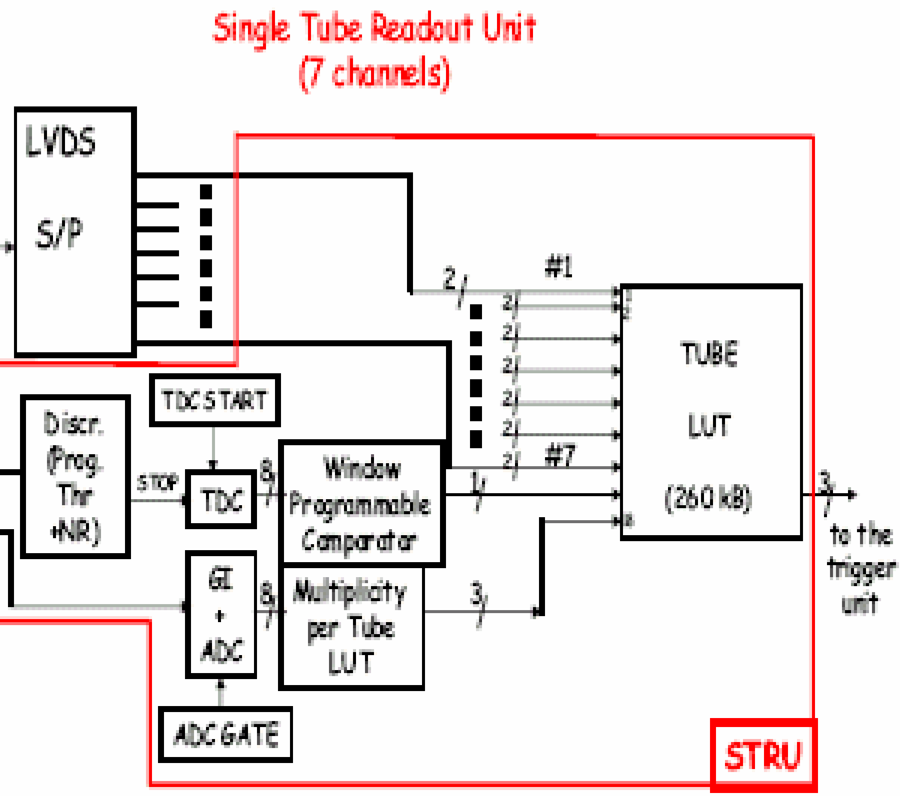

$$N_{pe} = 370 \cdot L \cdot \langle \sin^2 \theta_c \rangle \cdot \varepsilon_T \cdot \varepsilon_I^{abs} \cdot \varepsilon_F^{att} \cdot \varepsilon_{C+F} \int \varepsilon_{PMT}(E) \cdot \varepsilon_F(E) dE$$

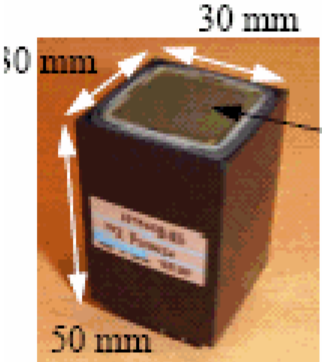
# Electronics

The front-end will use the MAROC chip that has been developed by Orsay for the Roman Pots.

The Bologna group is developing the back-end electronics which includes both TDC and ADC measurements on the summed signals from one tube as well as hitpatterns from individual fibers




**MAPMT**

64 channels in a 8 x 8 matrix

**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 x$10^{-4}$ interactions per bunch to 20 interactions/bunch

  ⇓

- Required dynamic range of the detector ~ 20

- Required background < ‹ 2 x$10^{-4}$ 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

# Very high $\beta^*$ (2625 m) optics

- Solution with following characteristics

- **At the IP**

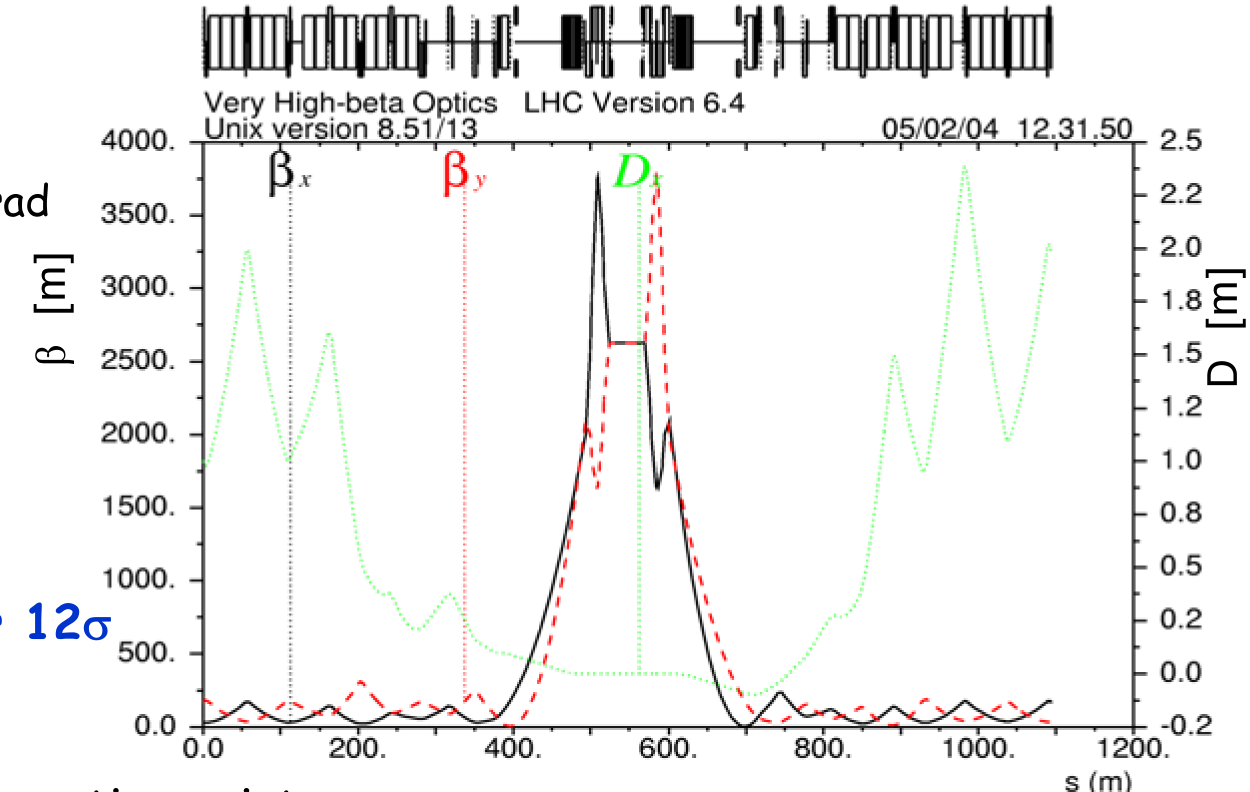
  $\beta^* = 2625$ m
  $\sigma^* = 610\ \mu m$ , $\sigma_\theta^* = 0.23\ \mu rad$

- **At the detector**

  $\beta_{y,d} = 119$ m, $\sigma_{y,d} = 126\ \mu m$
  $\beta_{x,d} = 88$ m, $\sigma_{x,d} = 109\ \mu m$
  (for $\varepsilon_N = 1\ \mu m$ rad)

- **Detector at 1.5 mm or 12$\sigma$**

  $t_{min} = 0.0004\ GeV^2$




- Smooth path to injection optics exists
- All Quads are within limits
- **Q4 is inverted w.r.t. standard optics!**

Endorsed by LTC
Compatible with TOTEM optics
see LEMIC minutes 9/12/2003

# Emittance

- Emittance of ~$1\times10^{-6}$ m·rad needed to reach Coulomb region
- Nominal LHC emittance: $3.75\times10^{-6}$ m·rad
- Emittances achieved during MD's in SPS:
  - Vertical plane $1.1\times10^{-6}$ m·rad and Horizontal plane $0.9\times10^{-6}$ m·rad for $7\text{x}10^{10}$ protons per bunch
  - 0.6-$0.7\times10^{-6}$ m·rad obtained for bunch intensities of $0.5\times10^{10}$ protons per bunch

- **However**
  - Preserve emittance into LHC means that injection errors must be controlled (synchrotron radiation damping might help us at LHC energy)
  - emittance $\varepsilon_N$, number of protons/bunch $N_p$ , and collimator opening $n_{\sigma,\text{coll}}$ (in units of σ) are related via a resistive (collimator) wall instability limit criterion:

$$\frac{N_p}{n_{\sigma,\text{coll}}^3 \cdot \varepsilon_N^{5/2}} \leq 1.6\times10^{22}$$

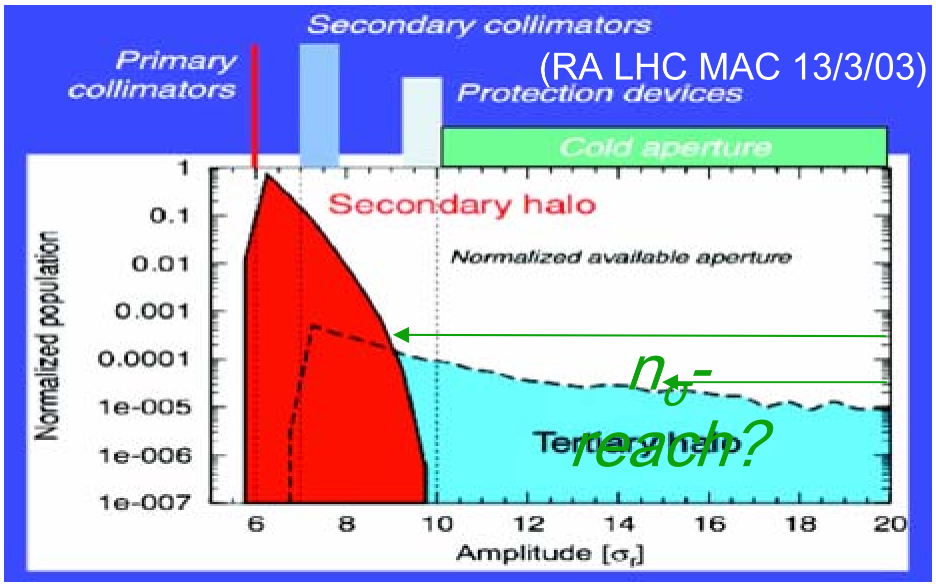
thus: $\varepsilon_N \geq 1.5\times10^{-6}$ m for $N_p = 10^{10}$, $n_{\sigma,\text{coll}} = 6$

**⇒ Best parameter space from beam tuning sessions**

# Beam Halo: limit on $n_\sigma$

- Beam halo is a serious concern for Roman Pot operation
- it determines the distance of closest approach $d_{min}$ of (sensitive part of) detector:

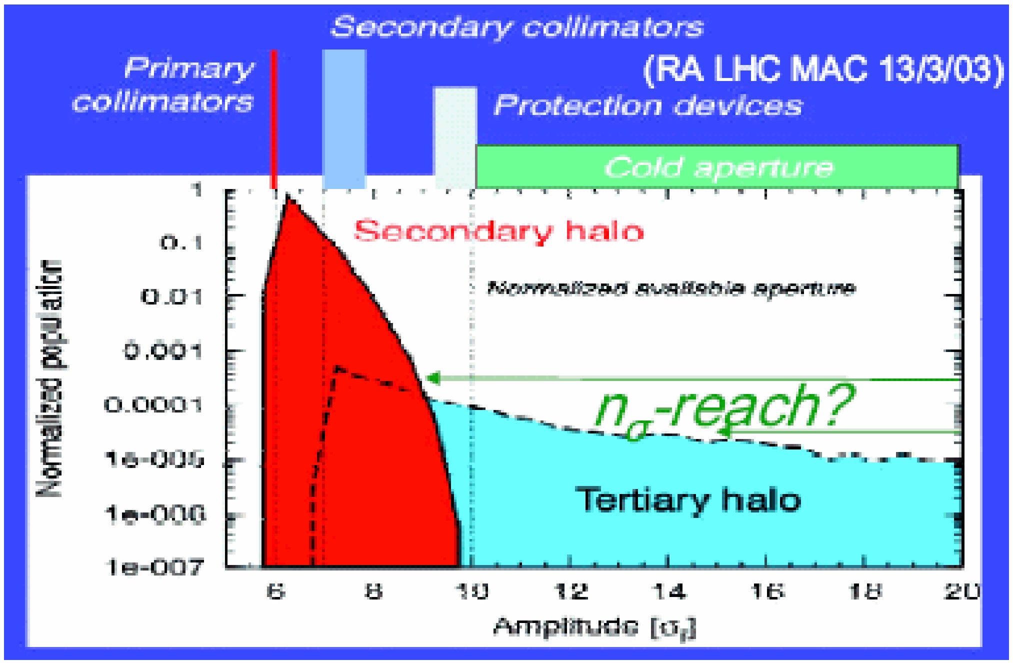
  $n_\sigma = d_{min}/\sigma_{beam}$: $\mathbf{9 \leq n_\sigma \leq 15}$




- Expected **halo rate** (43 bunches, $N_p=10^{10}$, $\varepsilon_N = 1.0$ μm rad, $n_\sigma=10$): **6 kHz**

Halo:

- Beam halo is a serious concern for Roman Pot operation
  - Determines the distance of closest approach $d_{min}$ of (sensitive part of)
  - Detector: $n\sigma = d_{min}/\sigma_{beam}$: **9 ≤ $n\sigma$ ≤ 15**
  - Expected **halo rate** (43 bunches, $N_p$=1010, $\varepsilon_N$ = 1.0 μm, $n\sigma$=10): **6 kHz**




Signal rate = 30Hz

Background should be under control when using Coincidence (UA4 experience)

# Summary on emittance and beam halo issues

"Looks feasible but no guarantees can be given"

**However**, if we don't reach the Coulomb region the effort is not in vain

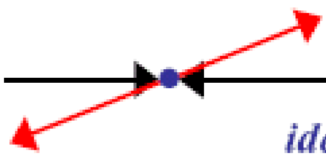
we can still:

- Use $\sigma_{tot}$ as measured by TOTEM/CMS and get the luminosity by measuring elastic scattering in a moderate t-range( $-t=0.01$ GeV$^2$ ) and use the Optical theorem for the rest

- Use the luminosity measured by machine parameters and again via the Optical theorem get $\sigma_{tot}$ and all other cross sections relative to $\sigma_{tot}$ with a factor 2 better precision than from the machine parameters

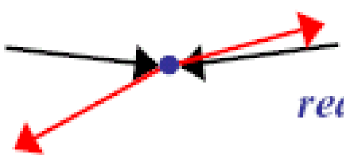
The $t$-resolution is dominated by the divergence of the incoming beams.

σ'=0.23 μrad

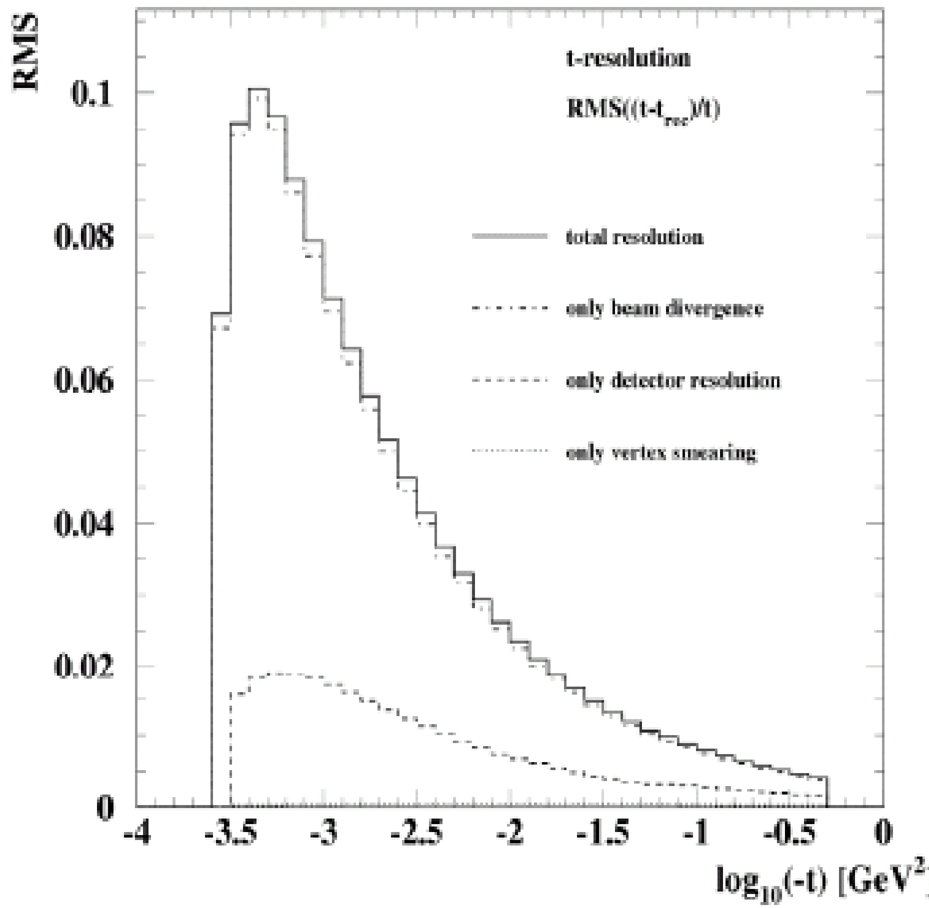


*ideal case*

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



*real world*



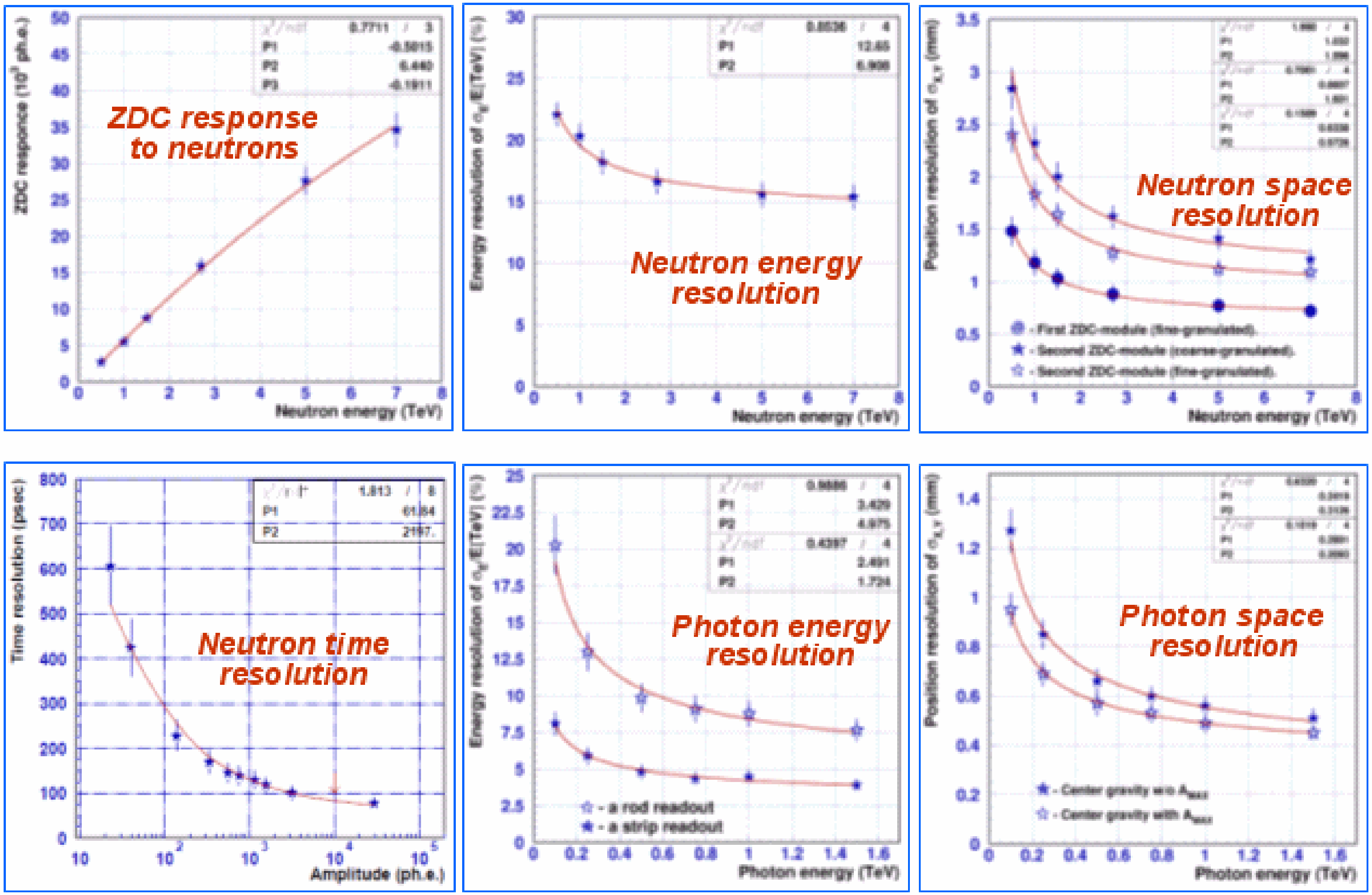
| | |
|---|---|
| Divergence + 10% | ± 0.31% |
| Alignemnt ±10μm | ± 1.3% |
| Acceptance ±10μm (edge) | ± 0.52% |
| β ± 2 % | ± 0.69% |
| Ψ ± 0.2 % | ± 1.0% |
| Detector resolution | ± 0.29% |
| Total exp.syst. error | ± 1.9% |

- Background subtraction ~ 1%

# Conclusion

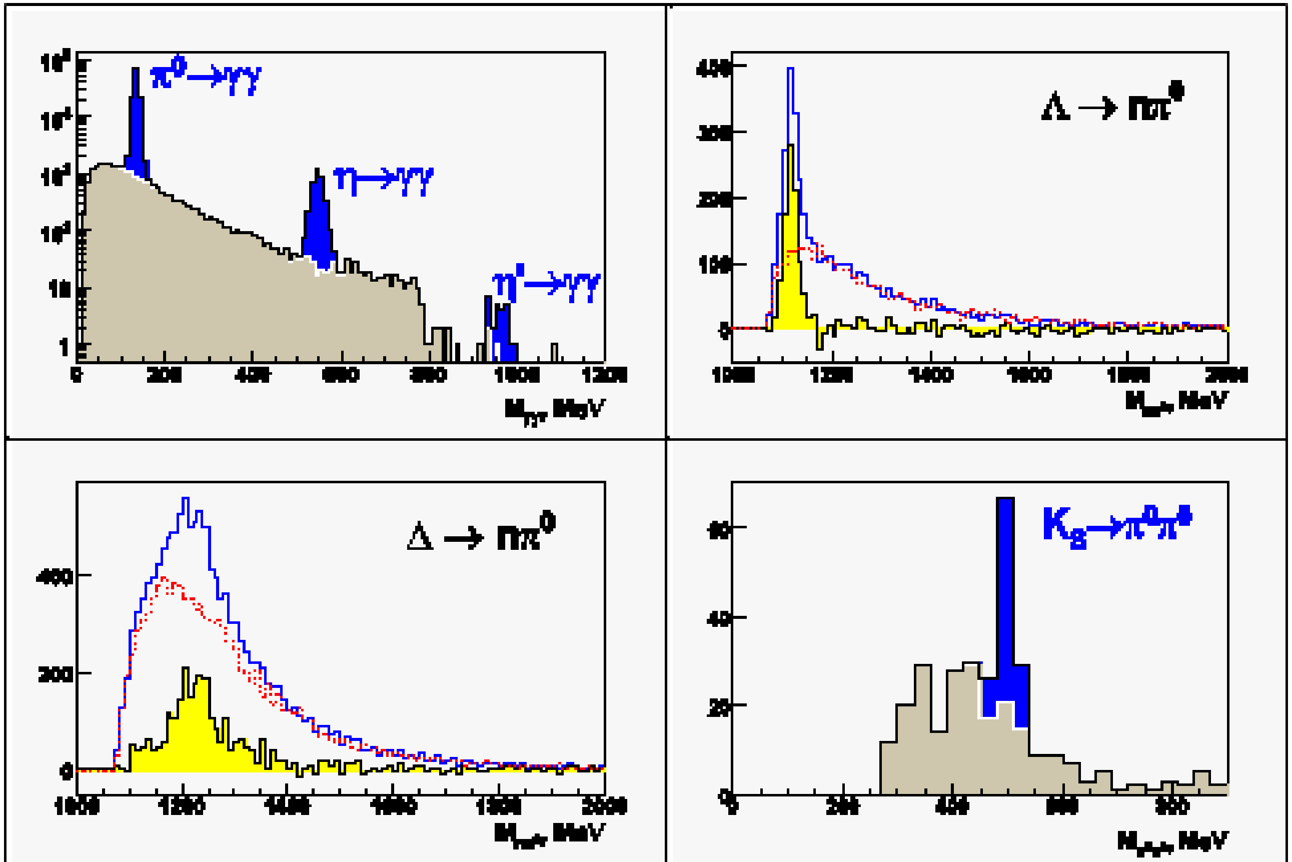
- **ATLAS pursues a number of options for Absolute Luminosity Measurement**
  - Coulomb normalization
  - W/Z rates
  - production of muon pairs via double photon exchange
  - elastic slope extrapolated to $dN/dt|_{t=0}$ plus machine $L$
  - elastic slope extrapolated to $dN/dt|_{t=0}$ plus $\sigma_{tot}$ from TOTEM
  - machine parameters alone
  - Cross calibration from ZDC in Ion runs
  - others…
- **The Coulomb Interference measurement is very challenging but seems within reach.**
- **Small angle elastic scattering will address "old fashion" physics in terms of $\sigma_{tot}$ , $\rho$ and b**
- **This experience of working close to the beam will prepare us for a Forward Physics Program with ATLAS in a possible future upgrade**

# ZDC time, space and energy resolution (Average over active area)



# ZDC in pp( Phase II configuration)

*In pp, the ZDC can measure forward production cross sections for several types of particles at very high energies. This will be useful for adjusting parameters for simulations and models, and for cosmic ray physics where the energy in one proton's rest frame is $10^{17}$ eV – a very interesting energy for extended air showers.*




*What happens when a high energy proton hits the upper atmosphere?*

*The ZDC can find a pi0 in the midst of several neutrons.*

*(1M Pythia events analyzed by a ZDC)*