Measurement of Elastic Nuclear and Coulomb scattering, and Luminosity Determination with ATLAS

Brian Cox (for Michael Rijssenbeek)
for the
ATLAS Collaboration

Outline

- **Introduction**
  - why measure luminosity
  - different methods

- **Luminosity from Coulomb scattering**
  - the experimental technique
  - the necessary beam conditions

- **Roman Pot detector requirement and the proposed detector**

- **Luminosity performance simulation**

- **A dedicated ATLAS luminosity monitor – LUCID**

- **Conclusions**

Luminosity Measurement – WHY ?

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

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

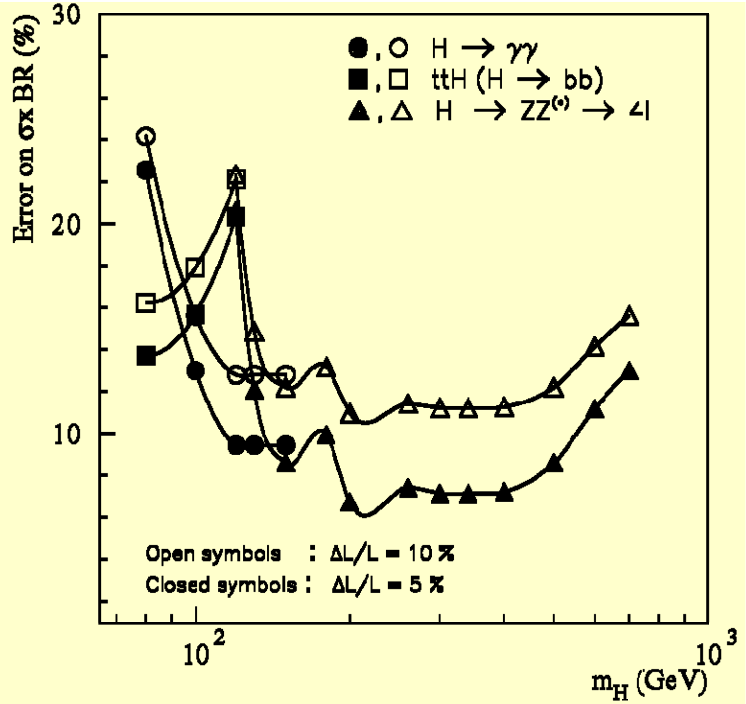
- New physics manifesting in deviation of σ x BR relative the Standard Model predictions

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

Luminosity Measurement – WHY ? (cont.)

Examples

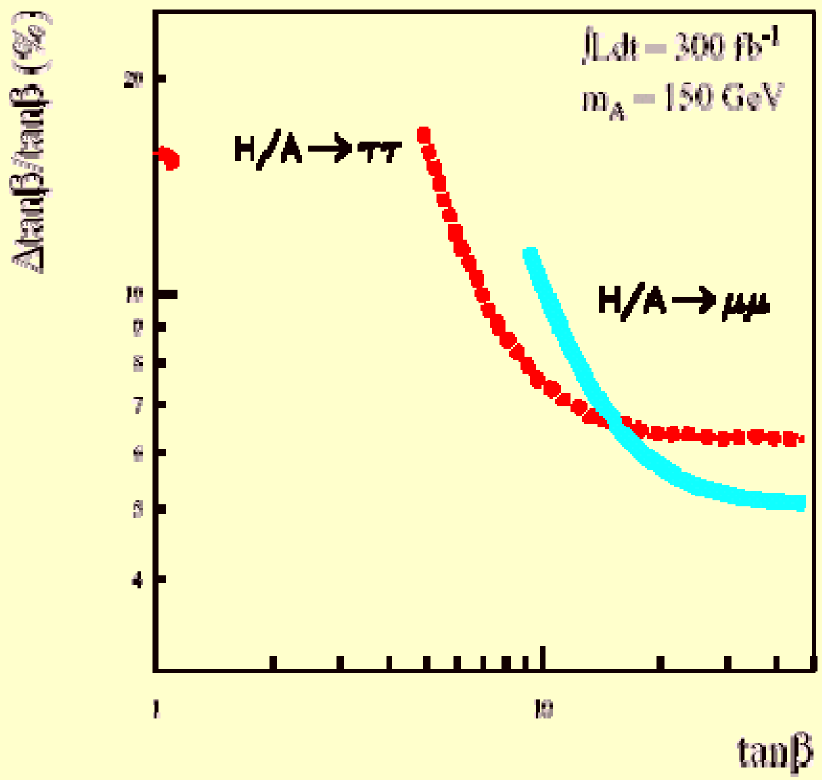
Higgs coupling



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

(ATLAS-TDR-15, May 1999)

tanβ measurement



Systematic error dominated by luminosity (ATLAS Physics TDR)

Luminosity Measurement

- Goal:
  - measure L with $\lesssim$ 2-3% accuracy

- Absolute luminosity from:
  - LHC Machine parameters (~5-10%)
  - rates of well-calculable processes:
    e.g. QED, QCD
  - optical theorem: forward elastic rate + total inelastic rate:
    - needs ~full |η| coverage-ATLAS coverage limited
  - luminosity from Coulomb Scattering

- Relative luminosity a DEDICATED luminosity monitor is needed

Luminosity from other Physics Signals

- **QED: $pp \rightarrow (p+\gamma^*)+(p+\gamma^*) \rightarrow p+(\mu^-\mu^+)+p$**
  - signal: (μμ)-pair with $|\eta(\mu)|<2.5$, $p_T(\mu) \gtrsim$ 5-6 GeV, $p_T(\mu\mu) \simeq 0$
    - small rate ~1pb (~0.01 Hz at $L=10^{34}$)
    - clean: backgrounds from DY, b, c- decays can be handled by appropriate offline cuts
    - uncertainties: μ trigger acceptance & efficiency, …
      - (A.Shamov & V.Telnov, hep-ex/0207095)
  - full simulation studies in progress (Alberta, SACLAY)

- **QCD: W/Z → leptons**
  - high rate: $W \rightarrow \ell\nu$: ~60 Hz at $L=10^{34}$ (ε = 20%)
    - current "theory" systematics: PDF and parton cross sections ≈ 4%
    - gives relevant parton luminosity directly…
    - detection systematics:
      - trigger/acceptance/identification efficiency/ backgrounds
    - detailed study for ATLAS detector needed (Alberta, SACLAY)

- Both processes will be used

Luminosity from Coulomb Scattering

- Elastic scattering at micro-radian angles:

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

  - L directly determined in a fit (along with σ_{TOT}, ρ, *and* b)

    effectively a normalization of the luminosity from the exactly calculable Coulomb amplitude

- Required reach in t :

$$t_{\min} \le -t(|f_C| = |f_N|) \approx \frac{8\pi a_{EM}}{\sigma_{TOT}} \approx 6\times 10^{-4}\ GeV^2 \rightarrow \vartheta_{\min} \le 3.5\mu rad$$

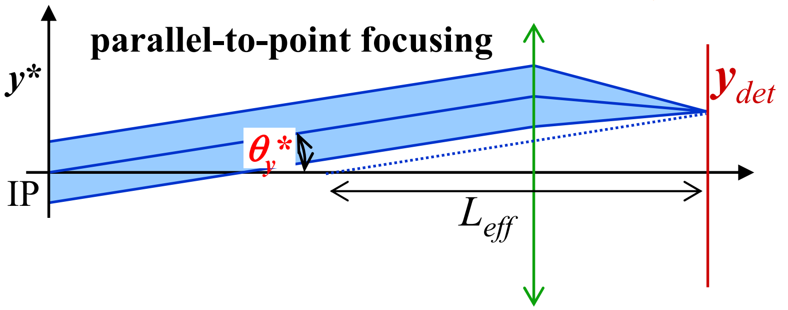
- Requires:
  - small intrinsic beam angular spread at IP
  - insensitive to transverse vertex smearing
  - large effective lever arm L_{eff}
  - detectors close to the beam, at large distance from IP

Parallel–to–point focusing

Experimental Technique

- Independence of vertex position:

$$y_{\det} = \sqrt{\beta\beta^*}\,\vartheta_y^* = L_{eff,y}\,\vartheta_y^*$$

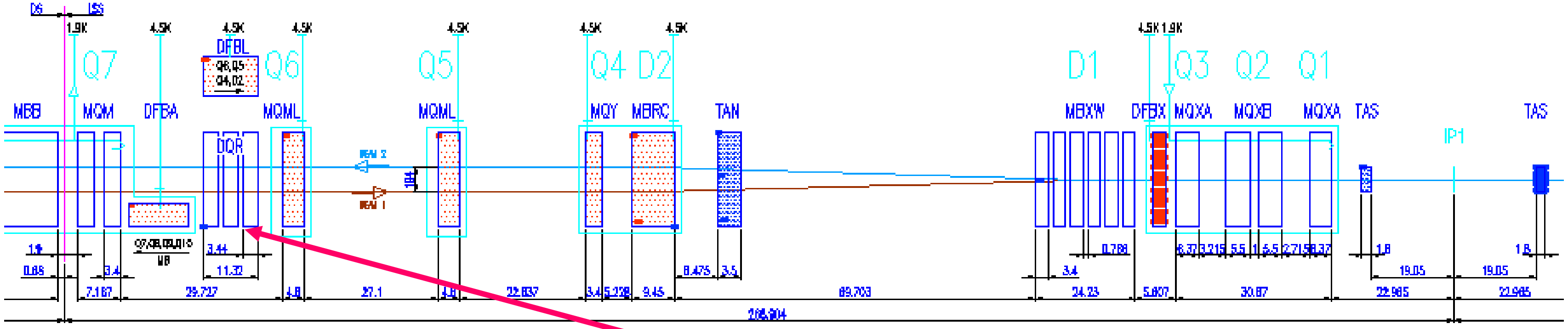


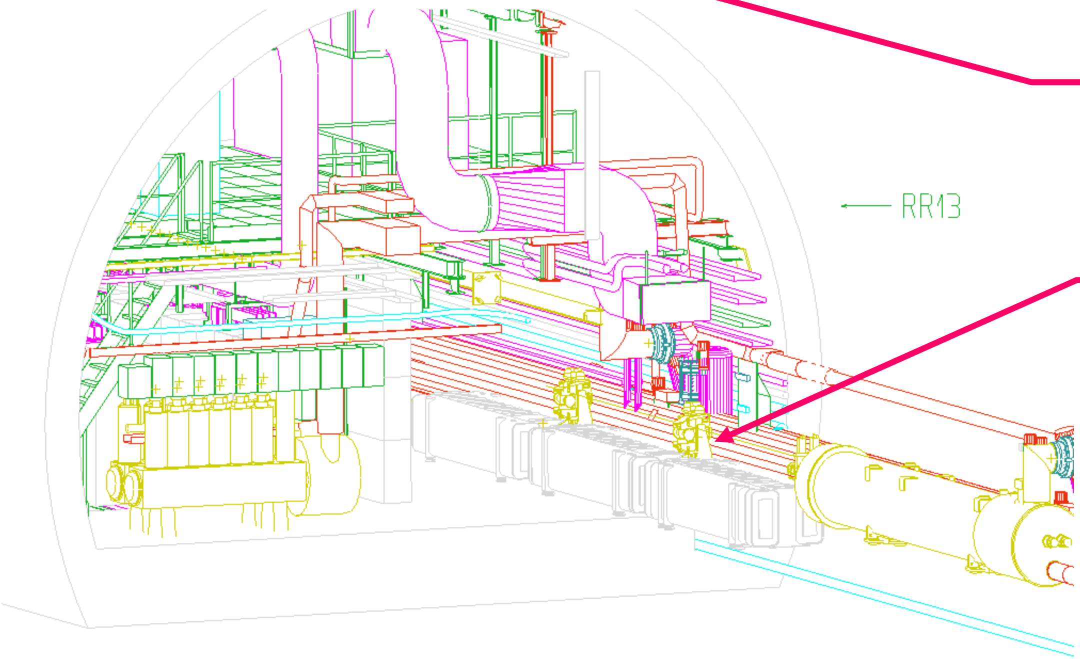
- Limit on minimum $|t|_{min}$:

$$\left.\begin{aligned}\vartheta^*_{\min} &= \frac{d_{\min}}{L_{eff,y}}\\ t_{\min} &= \left(\vartheta^*_{\min}\, p_{beam}\right)^2\end{aligned}\right\} \xrightarrow{d_{\min}=n_\sigma \sigma_y = n_\sigma \sqrt{\beta \varepsilon_N / \gamma}} t_{\min} = p_{beam}^2\, n_\sigma^2\, \frac{\left(\varepsilon_N / \gamma\right)}{\beta^*}$$

- The main potential difficulties are all derived from the above
  - **$L_{eff,y}$ large** → detectors must be far away form the IP → potential interference with machine hardware
  - **small t_{min}**⇒
    - **β* large** → special optics
    - **small emittance**
    - **small n_σ** → halo under control and the detector must be close to the beam

Roman Pot Locations





One **Roman Pot Station** per side on left and right from IP1

Each **RP station** consists of two **Roman Pot Units** separated by 3.4 m, centered at 240.0 m from IP1

TOTEM Design!

Very high β^* (2625 m) optics

- Solution with following characteristics

- **At the IP**

  $\beta^* = 2625$ m

  $\sigma^* = 610\ \mu\text{m}$, $\sigma_\theta^* = 0.23\ \mu\text{rad}$

- **At the detector**

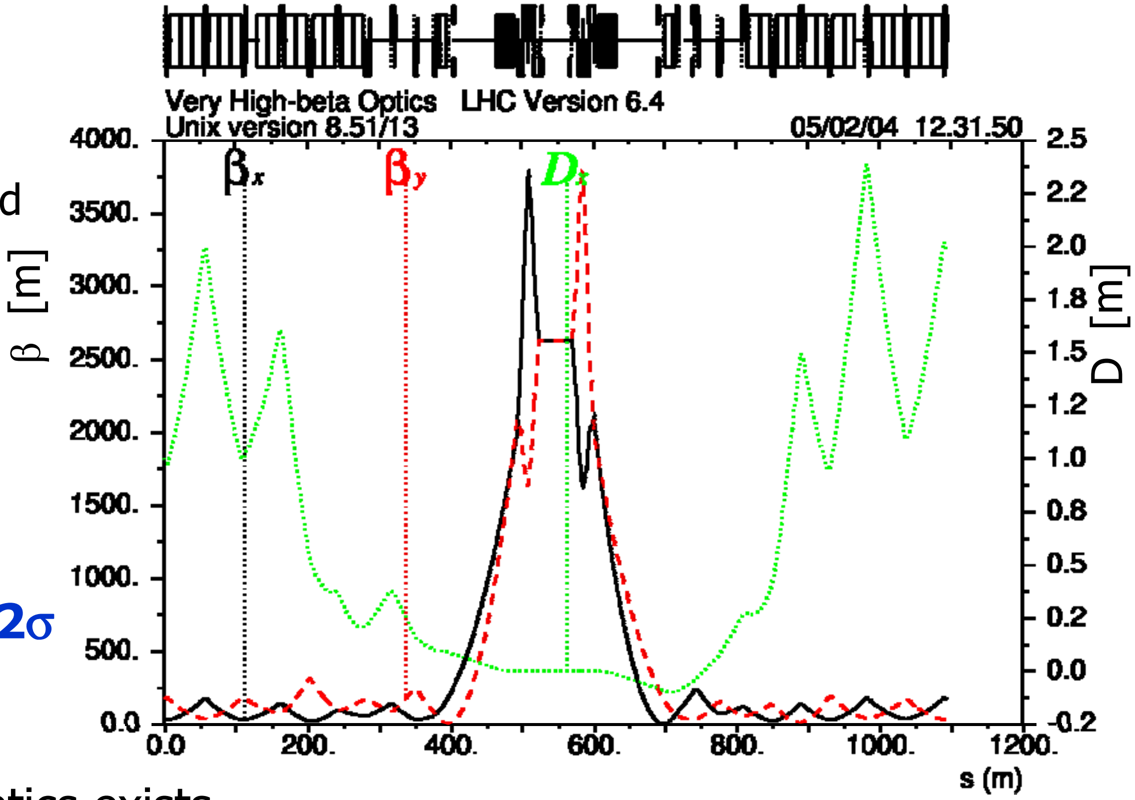
  $\beta_{y,d} = 119$ m, $\sigma_{y,d} = 126\ \mu\text{m}$

  $\beta_{x,d} = 88$ m, $\sigma_{x,d} = 109\ \mu\text{m}$

  (for $\varepsilon_N = 1\ \mu\text{m rad}$)

- **Detector at 1.5 mm or 12σ**

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



- 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

Intrinsic beam divergence < smallest scattering angle ~ $\sqrt{\varepsilon/\beta^*}$

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

$$\frac{N_p}{n^3_{\sigma,\text{coll}}\cdot\varepsilon_N^{5/2}}\leq1.6\times10^{22}$$

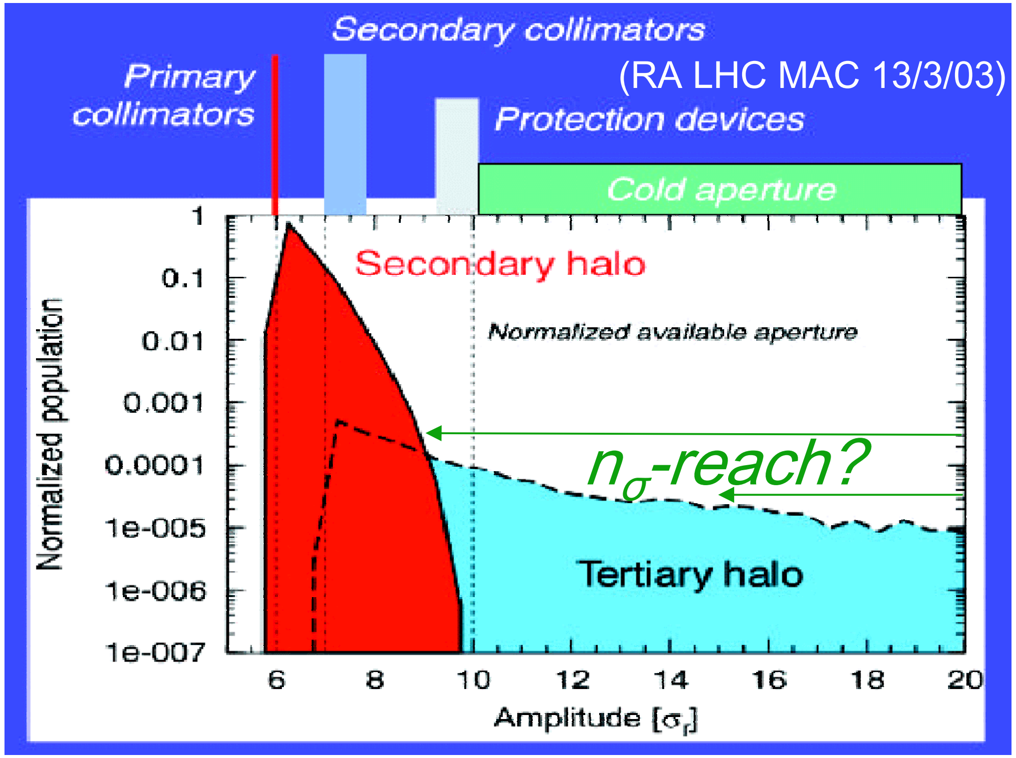
thus: $\varepsilon_N\geq1.5\times10^{-6}$ m for $N_p=10^{10}$, $n_{\sigma,\text{coll}}=6$

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

Beam Halo: limit on n_σ

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

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



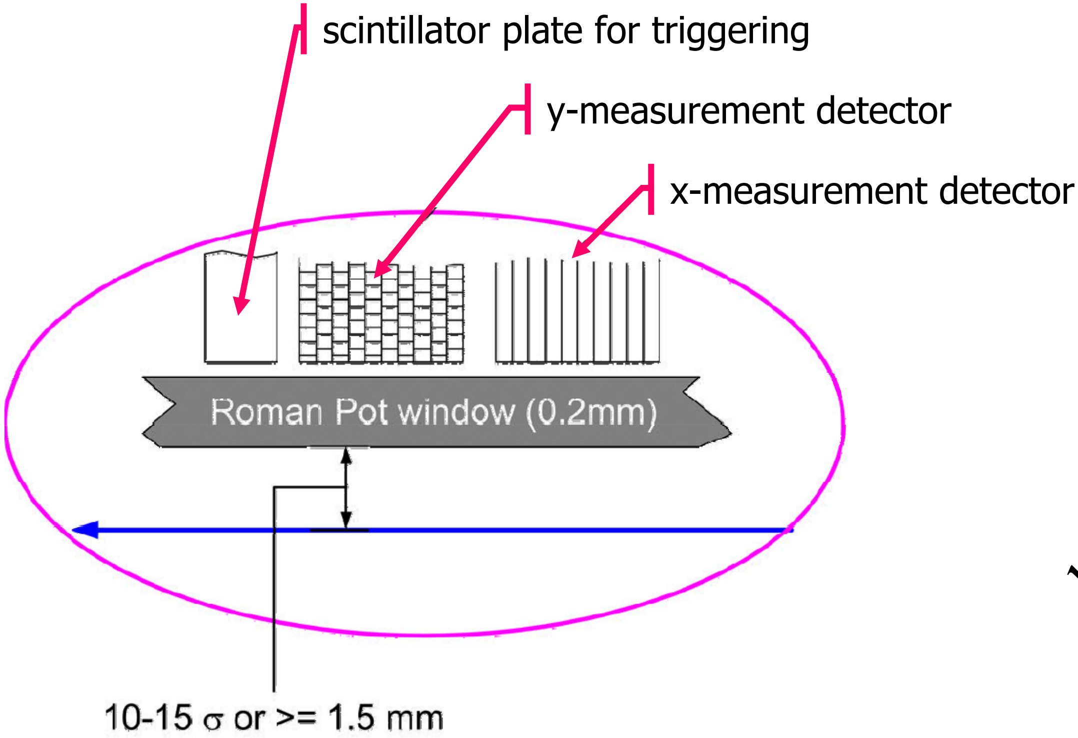
- Expected **halo rate** (43 bunches, $N_p=10^{10}$, $\varepsilon_N = 1.0$ μm rad, $n_\sigma=10$): **6 kHz**

Requirements for Roman Pot Detectors

- “Dead space” d_0 at detector’s edge near the beam :
  $\underline{d_0 \lesssim 100}$ (full/flat efficiency away from edge)
- Detector resolution: $\underline{\sigma_d = 30\ \mu\text{m}}$
- Same $\underline{\sigma_d = 10\ \mu\text{m}}$ relative position accuracy between opposite detectors (e.g. partially overlapping detectors, …)
- Radiation hardness: $\underline{100\ \text{Gy/yr}}$
- Operate with the induced **EM pulse** from circulating bunches (shielding, …)
- Rate capability: **O**(MHz) (40 MHz); time resolution σ_t = **O**(1 ns)
- Readout and trigger compatible with the experiment DAQ
- Other:
  - simplicity, cost
  - extent of R&D needed, time scale, manpower, …
  - issues of LHC safety and controls

Roman Pot Detectors

- Square scintillating fibres
    - Kuraray 0.5 mm × 0.5 mm fibers
    - 10 layers per coordinate
    - 50 μm offset between layers



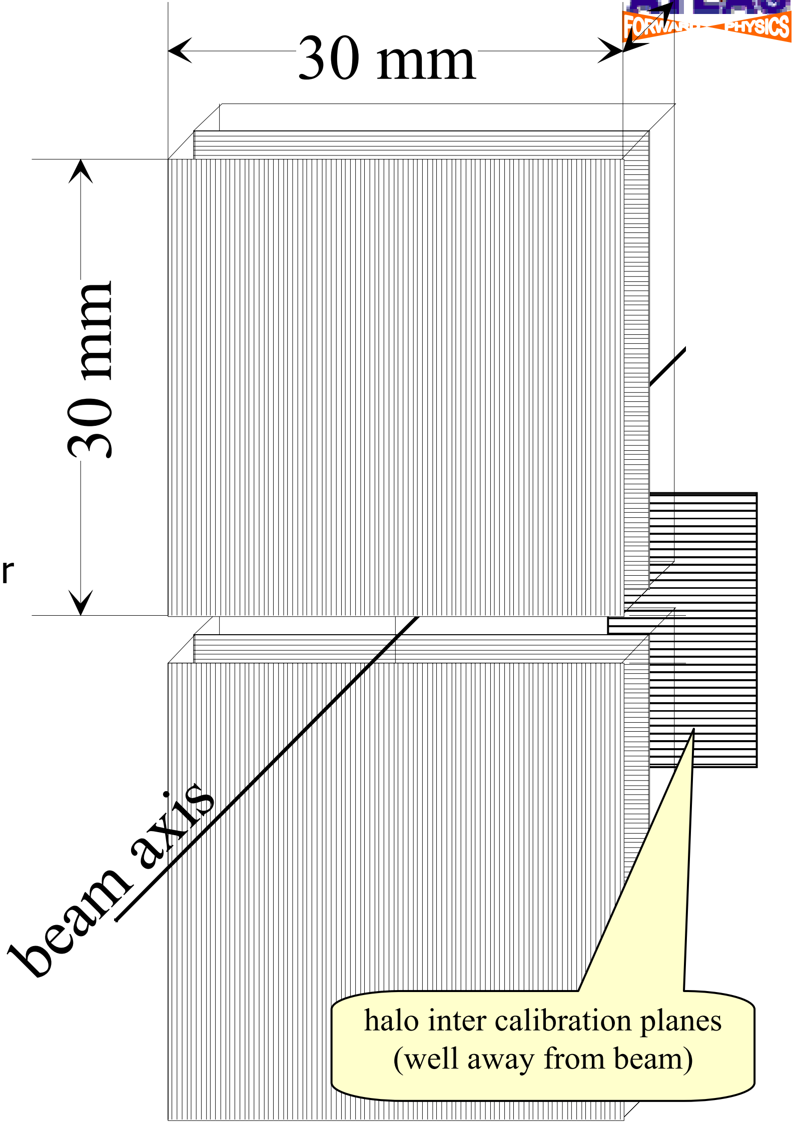
scintillator plate for triggering

y-measurement detector

x-measurement detector

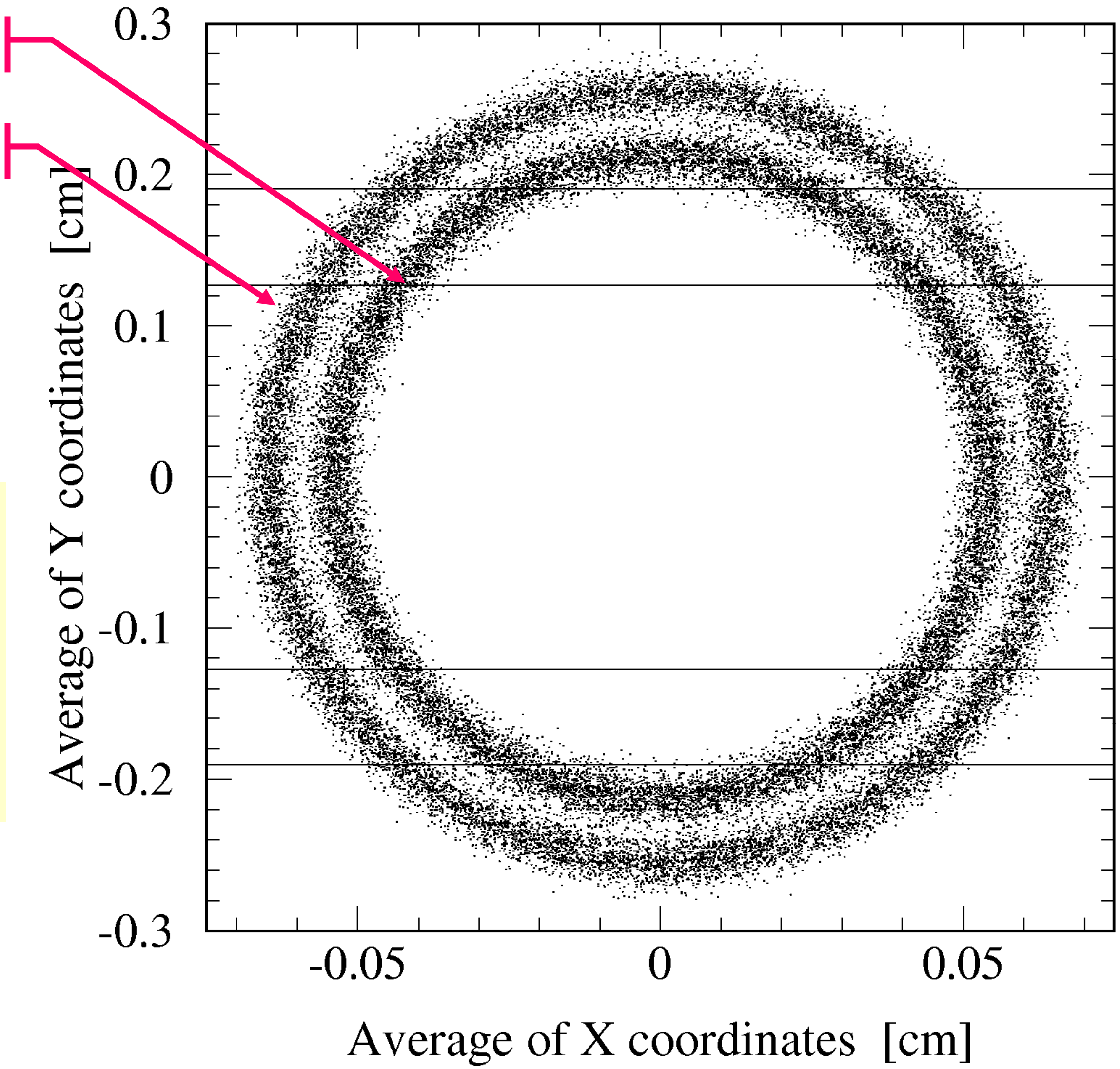
Roman Pot window (0.2mm)

10-15 σ or >= 1.5 mm



halo inter calibration planes
(well away from beam)

Simulated Elastic Scattering



Inner ring: $t = -0.0007\ \mathrm{GeV}^2$

Outer ring: $t = -0.0010\ \mathrm{GeV}^2$

- Reconstruct θ^*:

$$\theta^* = \sqrt{\overline{\theta_x}^2 + \overline{\theta_y}^2} = \sqrt{\left(\frac{\bar{x}}{L_{eff,x}}\right)^2 + \left(\frac{\bar{y}}{L_{eff,y}}\right)^2}$$

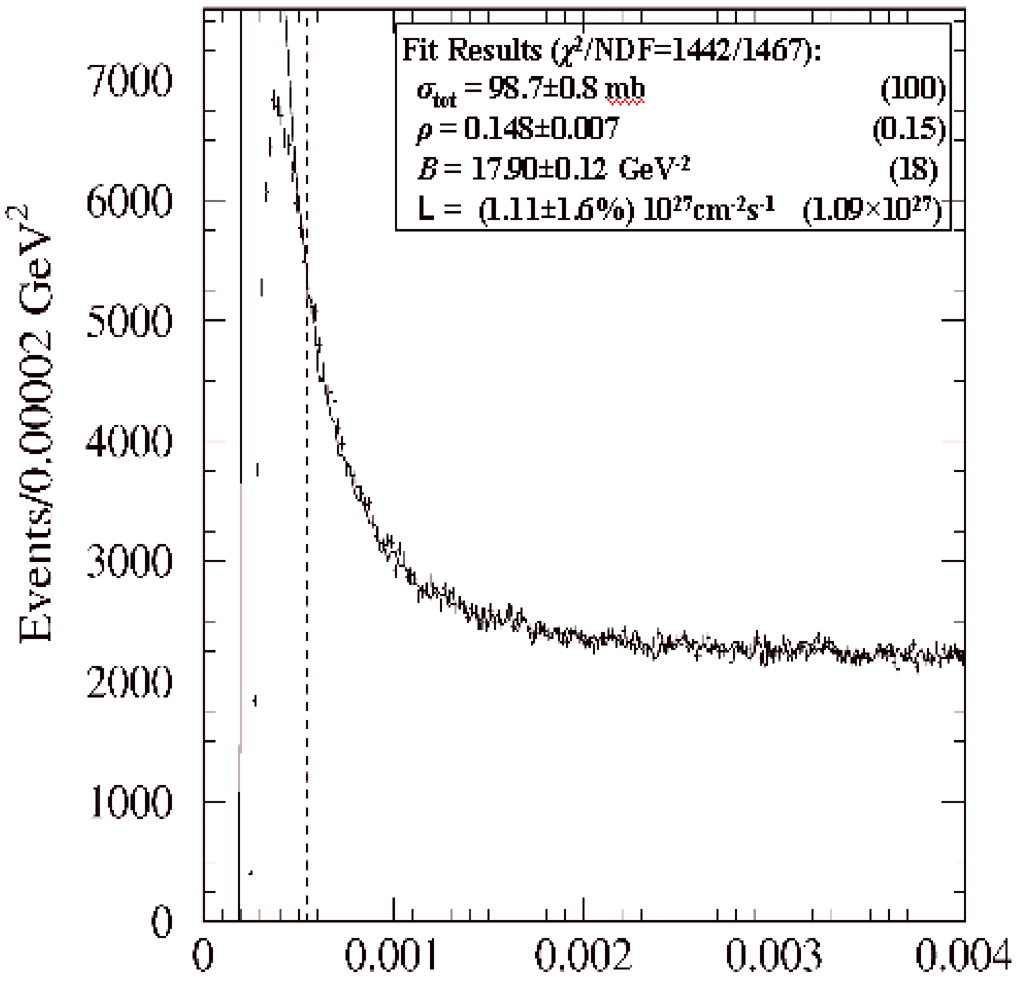
Simulated dN_{el}/dt and simple fit

Event generation:

- 5 M events generated corresponding to ~90 hr at L≈ 10^{27} cm^{-2} s^{-1}
- NO systematics on beam optics!
- Only 1 Roman Pot unit/arm

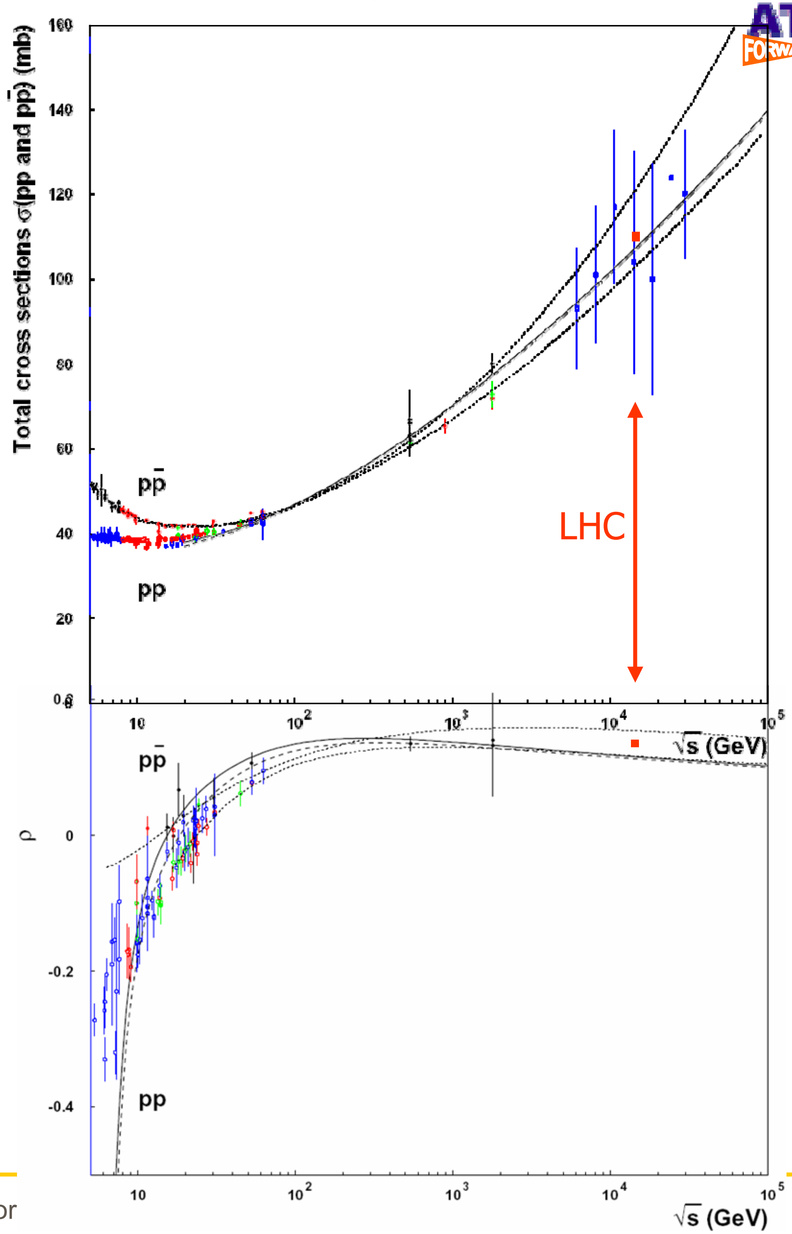
Simple fit to *unsmeared* theory

- range for fitting:
  - $0.00056 < |t| < 0.030$ GeV^2
- ~4 M events "measured" for *dN*/*dt*



Total Cross Section and Rho Parameter

- ATLAS views the L measurement as the primary goal…
  However, the measurement of the nuclear slope $B(t)$, σ_{tot} and the ratio ρ of real to imaginary parts of the scattering amplitude at small t are important physics “by-products”!
- For 5 M (generated) events, these parameters are “recovered” with good accuracy; for $t_{\text{min}} = 6\times10^{-4}$ GeV^2:
  - $\delta\sigma_{\text{tot}}/\sigma_{\text{tot}} \leq 1\%$,
  - $\delta\rho/\rho \approx 5\%$,
  - $\delta B/B \leq 0.5\%$



Towards Large-*t* and the Perturbative Regime

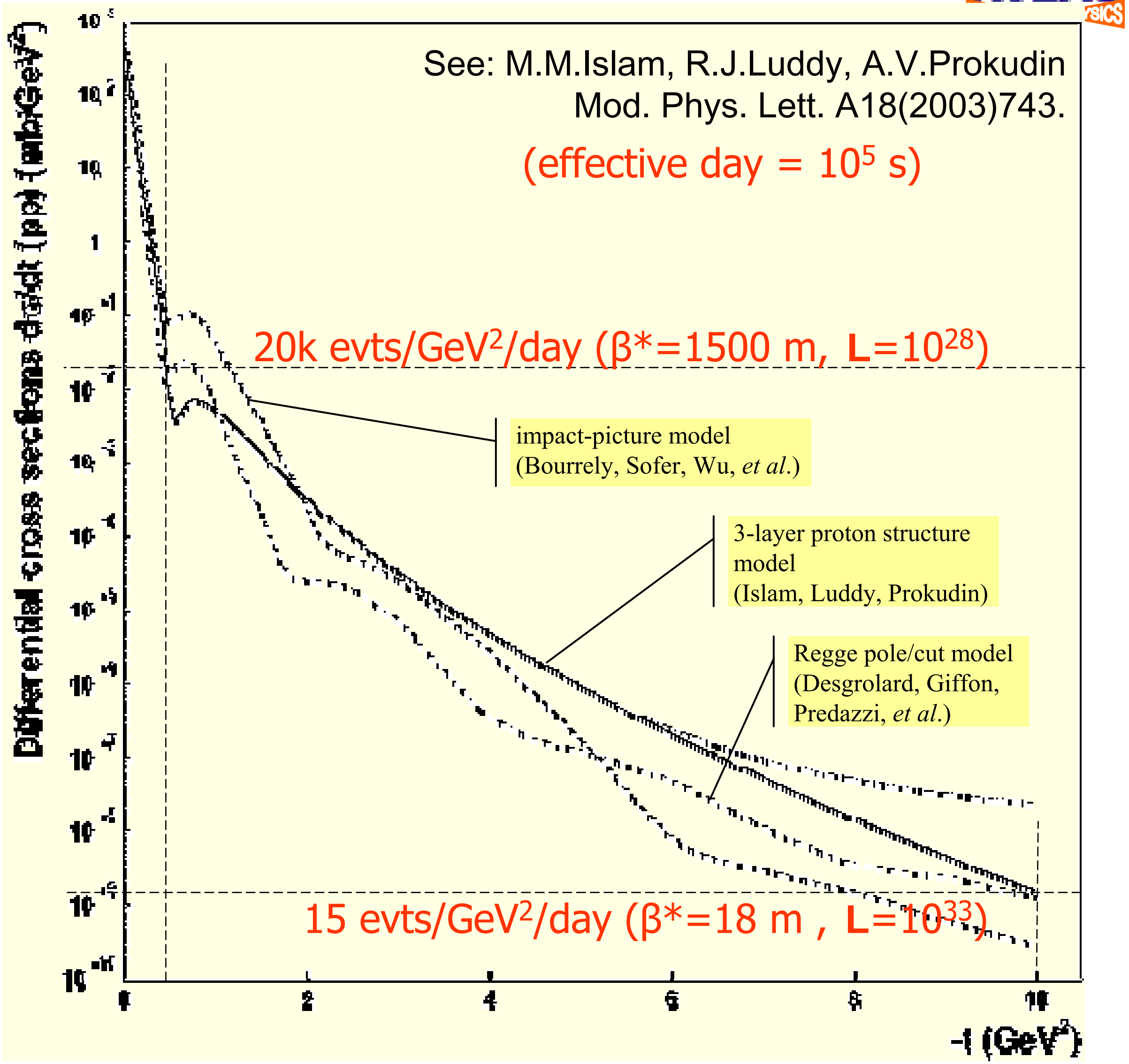
- The small angle measurement will allow us to gain experience in the measurement close to the beam and may lead to future expansions of the ATLAS physics program in the forward regions.

- Thus, it may become possible to investigate large-*t* elastic scattering and test various semi-phenomenological models and even approach the perturbative regime where nuclear elastic scattering becomes accessible to QCD calculations…

Example $d\sigma_{elastic}/dt$ Predictions:

- Example of phenomenological model calculations for $d\sigma_{el}/dt$ at 14 TeV:

- VERY steep fall off in rate:
  - at high $|t|$:
    - needs Hi-**L**
    - serious background problem…



See: M.M.Islam, R.J.Luddy, A.V.Prokudin
Mod. Phys. Lett. A18(2003)743.

(effective day = 10^5 s)

20k evts/GeV^2/day (β^*=1500 m, **L**=10^{28})

impact-picture model
(Bourrely, Sofer, Wu, *et al.*)

3-layer proton structure model
(Islam, Luddy, Prokudin)

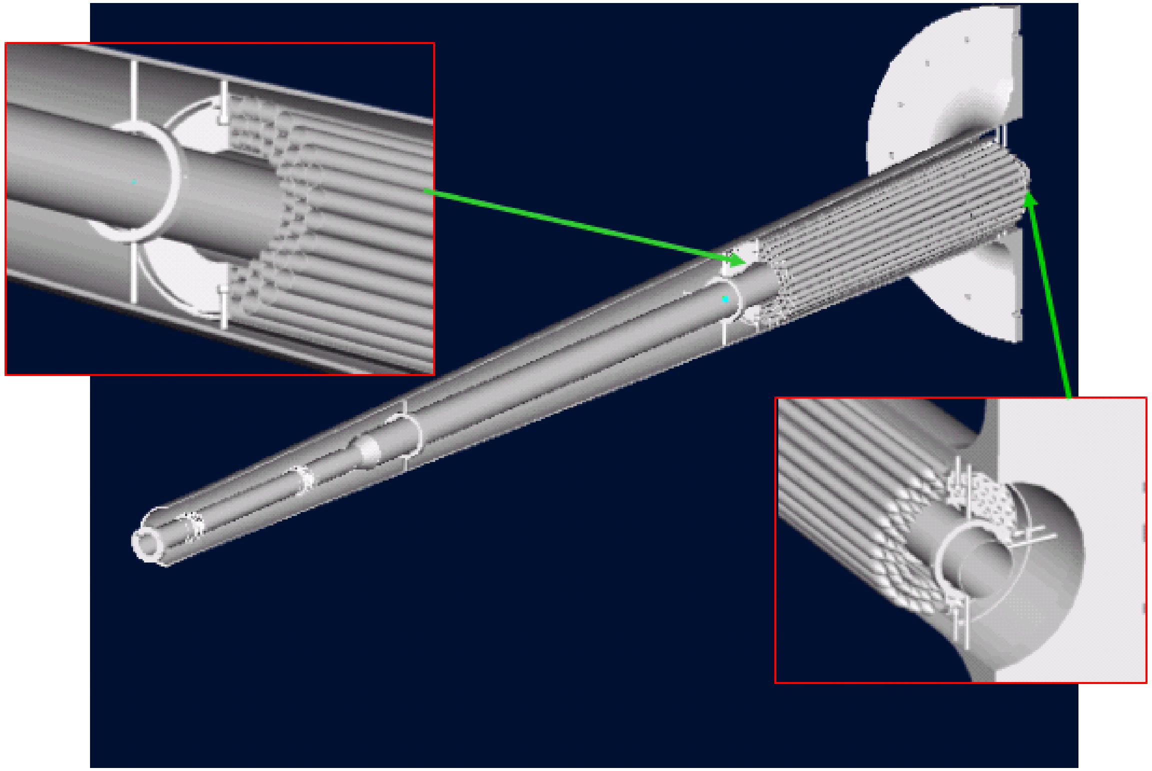
Regge pole/cut model
(Desgrolard, Giffon, Predazzi, *et al.*)

15 evts/GeV^2/day (β^*=18 m , **L**=10^{33})

Luminosity Monitoring

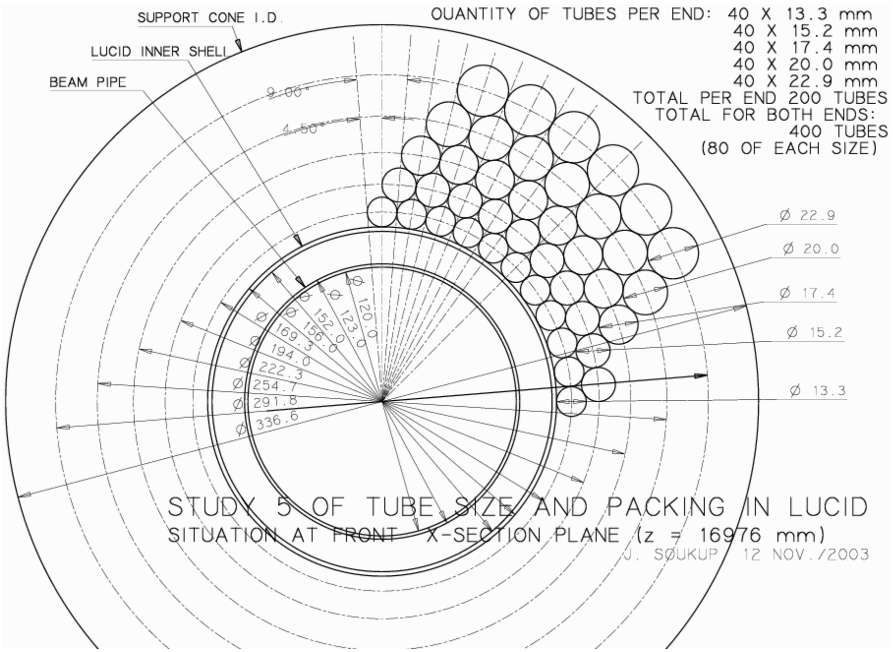
- **We propose a dedicated detector- LUCID**
  “LUminosity measurement using Cerenkov Integrating Detector”

- **Bundle of projective Cerenkov tubes around the beam pipe**

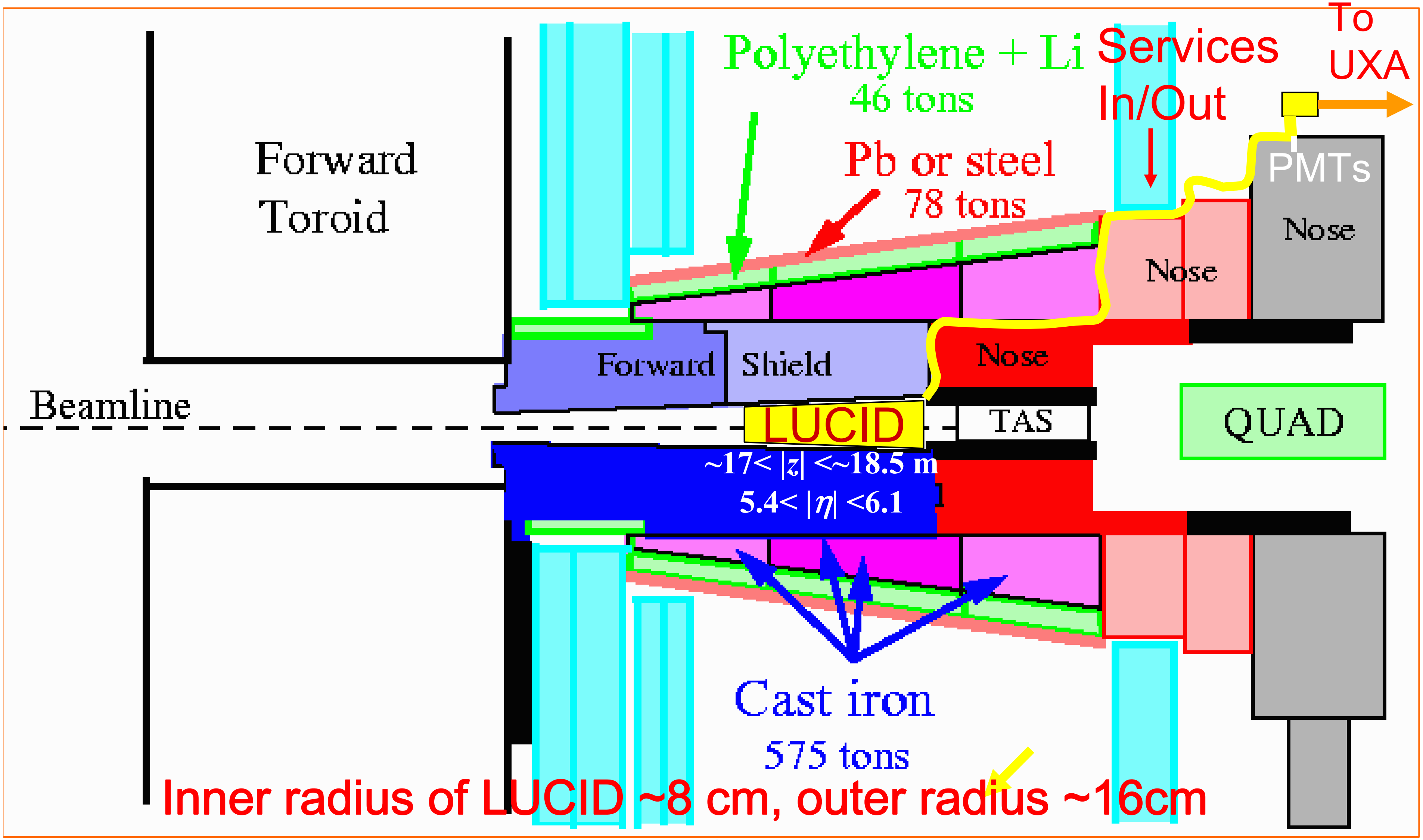


Luminosity monitoring LUCID

- 200 gas filled (C_4F_{10}) Cerenkov tubes per end.
- Al lined Carbon fibre Cerenkov tubes for heat resistance.
- The tubes are deployed in 5 layers of increasing diameter
  - each row has 40 tubes.
- Tube orientation allows some directional sensitivity



Luminosity monitoring LUCID



Inner radius of LUCID ~8 cm, outer radius ~16cm

Luminosity monitoring LUCID

- Sensitive to right particles -- Much more light from primary particles than secondaries & soft particles:
  - shorter paths (secondaries moving across detector)
  - Cerenkov thresholds

- No Landau fluctuations for Cerenkov Light emission: expect a narrow single particle peak (SPP)
  - Excellent amplitude resolution
  - one can count particles (even in the same tube)
  - no saturation

- Excellent time resolution (~140ps measured at CDF)
  - distinguish number of interactions by time (follow bunches).

- Radiation hard, low mass

- The LUCID approach has been tested at CDF
- Linear relationship between luminosity and tracks

Conclusion

ATLAS Baseline

- Absolute Luminosity measurement using Coulomb Normalization
  - the CN normalization is **very challenging but seems attainable**
    - critically dependent on control of the beam and backgrounds
  - Roman Pot detectors: no show stoppers

- Luminosity monitoring using LUCID
  - LUCID prototyping is well underway

- Cross checks with:
  - W/Z rates
  - double photon exchange production of muon pairs
  - elastic slope of $dN/dt|_{t=0}$ plus machine L
  - machine parameters alone
  - others…

- Experience with this may prepare us for expanding towards a Forward Physics program with ATLAS as a possible future upgrade

Back up slides

- additionally remove slides 13, 15, 16, 26 if time is less than 30’

Scheduling

- ATLAS considers the dedicated runs for the luminosity measurement as a second priority, likely just following the initial years of running, when the LHC operation is well understood

- Nevertheless, if early luminosity runs will be scheduled, ATLAS will put its best effort to participate and have the luminosity detectors and all the installation completed

- Independently of the year of data-taking, we would like to factor out the installation of the Roman Pot Units with the detectors, and resolve all the interface issues with the LHC machine as soon as possible in order to follow the LHC machine installation in the tunnel and minimize any potential impact

- ATLAS is prepared to submit an ECR with all the installation details already in May 2004 should this Letter of Intent be encouraged to proceed

ECR - Interface issues with LHC machine

- ATLAS plans to use the same RP unit design as TOTEM therefore for the major part of the interface issues the same solutions will be adopted

- The ECR will be focused on the issues concerning the RP installation at IP1, namely:
    - Layout modification for the DQR location to accommodate the two RP units
        - displace DQR-2 by 100mm and DQR-3 by 200mm towards Q6
    - Installation of a polarity switch for the Q4 quadrupole
    - Modification in the vacuum tube for the one beam to allow openings for the RPs
        - special vacuum pieces and flanges to connect to the RPs
        - until the RP units are actually installed, the space will be filled with vacuum pipes
    - Cable routing and space in the trays between the RP location and the USA15

The above has been discussed with the relevant experts and represents minor modifications

Fit of Luminosity Parameter

- Fit results (5 M events):
  - calculate n_σ as: $$n_\sigma \equiv \left. \frac{L_{eff,y}\sqrt{t_{\min}}}{p_{\text{beam}}} \cos 45° \right|_{\varphi\text{-acceptance}} \Big/ \sigma_{d,y}$$
  - note: acceptance is somewhat arbitrary: proper fit will NOT use $\Delta\varphi$ cut!

$t_{\min}$ (GeV^2) ($t_{\max}$=0.05)	n_σ	**δL/ L** (full simulation + $\Delta\varphi$ cut)	**δL/ L** (generated t + $\Delta\varphi$ cut)	**δL/ L** (generated t)
5.00E-04	10.0	1.6%	1.8%	1.1%
5.60E-04	10.6	1.8%	1.8%	1.3%
6.00E-04	11.0	2.0%	2.0%	1.4%
8.00E-04	12.7	2.9%	3.0%	2.2%
10.00E-04	14.2	4.1%	4.3%	3.2%
12.00E-04	15.5	5.8%	5.8%	4.4%

Detector Performance Simulations

First simulation results

- strip positioning $\sigma_{\mathrm{fiber}} \approx 20\ \mu\mathrm{m}$
- light and photo-electron yield:

$$N_{pe} = \langle dE/dx \rangle\, d_{\mathrm{fiber}}\, (dn_\gamma/dE)\, \varepsilon_A\, \varepsilon_T\, \varepsilon_C\, g_R\, \varepsilon_Q\, \varepsilon_d$$

		Baseline detector SCSF-38 (λ=428 nm) 0.5 mm square **MAPMT**	**Alternative configuration** SCSF-3HF (λ=530 nm) 0.5 mm square **GM-APD**
<dE/dx>	specific energy loss of a MIP in scintillator	200 keV/mm	200 keV/mm
d_{fiber}	active thickness of fiber	0.48 mm	0.48 mm
dn_γ/dE	scintillation light yield	8.3 / keV	8.3 / keV
ε_A	geometrical acceptance	0.042	0.042
ε_T	attenuation in fiber	0.85	0.85
ε_C	coupling efficiency fiber/photodetector	0.80	0.80
g_R	Gain due to reflection from rear end	1.4	1.4
$\boldsymbol{\varepsilon_Q}$	**quantum efficiency photodetector**	**0.18**	**0.15 (0.3 in future ?)**
ε_d	detection efficiency (electronics/DAQ)	0.85	0.85
$\mathbf{N_{pe}}$	**Photoelectron yield**	**4.9**	**4 (8 in future ?)**

Cost Estimates & Participants

	Item	Cost (KCHF)
LUCID	Cerenkov tubes	68.0
	Quartz fibers	62.0
	Readout	62.0
	Infrastructure	125.0
	R&D	62.0
	Total	***379.0***
Roman Pot system	RP units	220.0
	Q4 polarity inverters	60.0
	Scintillating fiber detectors	175.0
	Readout	650.0
	Integration	75.0
	R&D	100.0
	Total	***1280.0***

Participating institutes:

(as a subsystem, fully part of the ATLAS collaboration)

University of Alberta
CERN
Ecole Polytechnique
Institute of Physics Academy of Science, Czech Republic
University of Manchester
University of Montreal
University of Texas
University of Valencia
SUNY at Stony Brook

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 σ_{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 σ_{tot} and all other cross sections relative to σ_{tot} with a factor 2 better precision than from the machine parameters

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

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

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

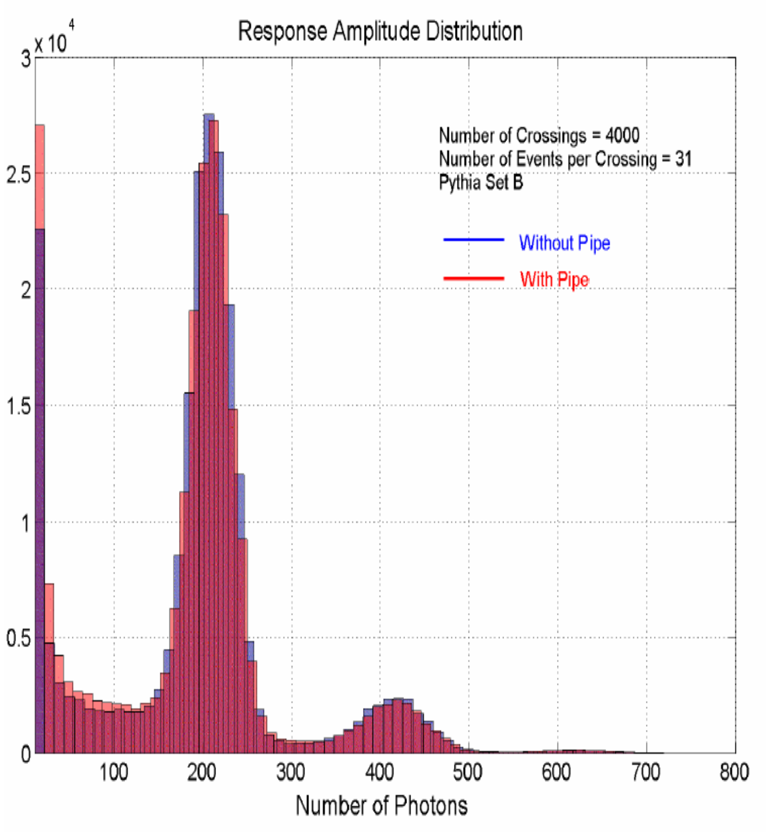
  ⇓

- Required dynamic range of the detector ~ 20

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

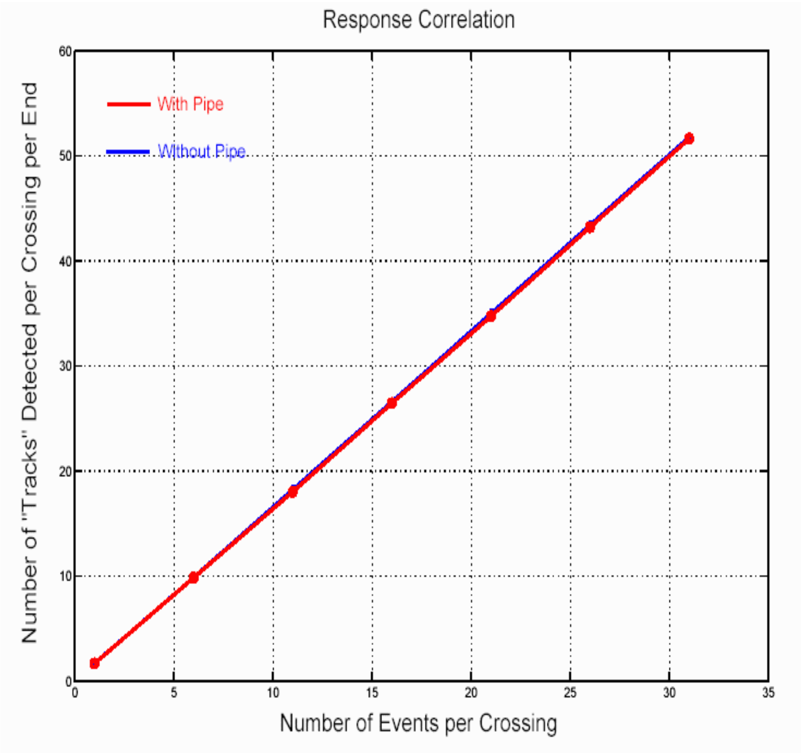
LUCID Performance Simulations

- Simulation of a 20 GeV muon incident along the axis of a LUCID Cerenkov tube gives ~320 photons and ~230 photons are collected at the Winston cone exit.

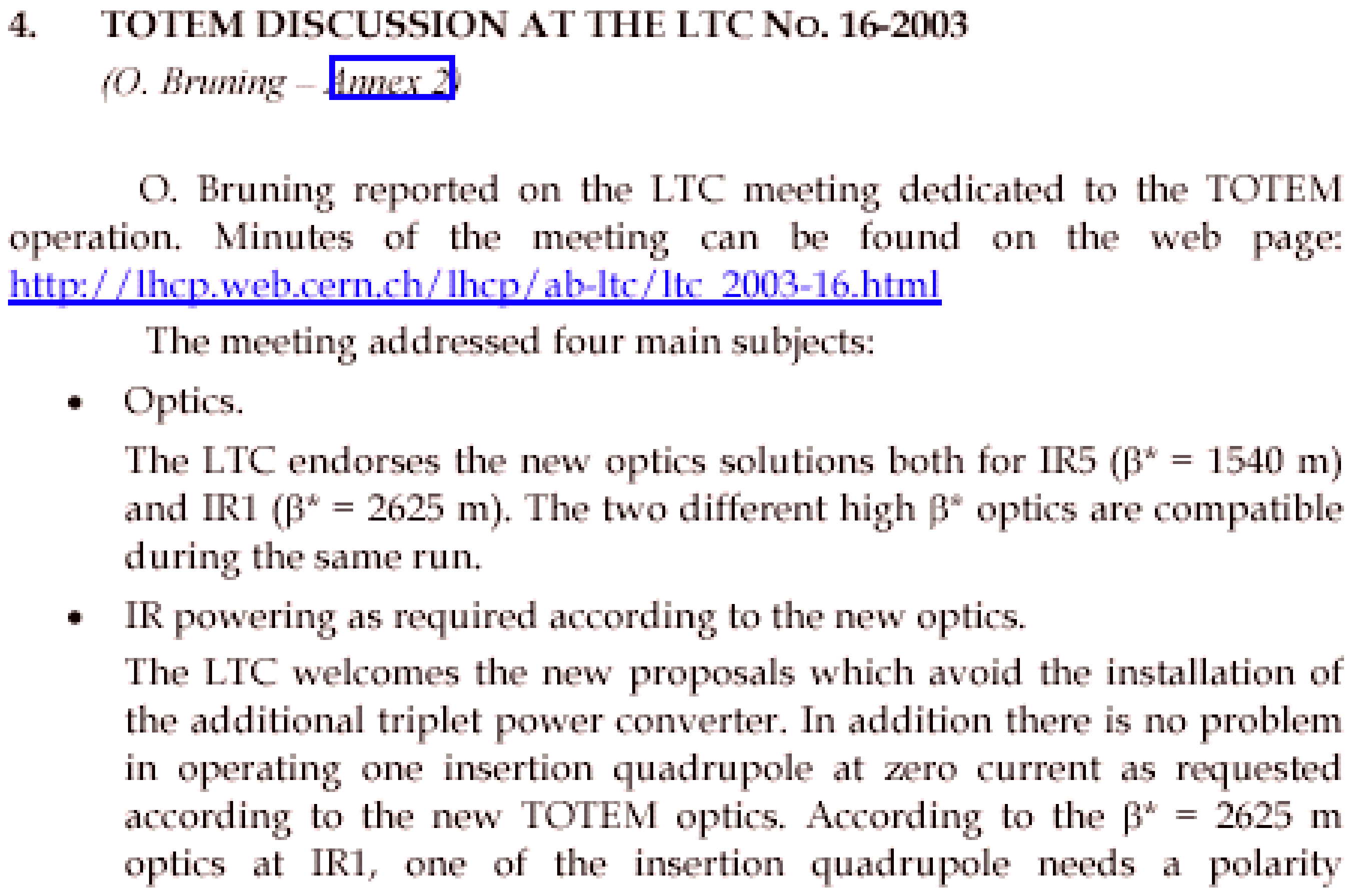


- PYTHIA-6 events generated with increasing numbers of pileup

- Perfect linearity, with little sensitivity for secondaries



Statement of the machine group on the feasibility/possible problems about chosen beam optics ?



4. TOTEM DISCUSSION AT THE LTC No. 16-2003

(O. Bruning – Annex 2)

O. Bruning reported on the LTC meeting dedicated to the TOTEM operation. Minutes of the meeting can be found on the web page: http://lhcp.web.cern.ch/lhcp/ab-ltc/ltc_2003-16.html

The meeting addressed four main subjects:

- Optics.

  The LTC endorses the new optics solutions both for IR5 (β^* = 1540 m) and IR1 (β^* = 2625 m). The two different high β^* optics are compatible during the same run.

- IR powering as required according to the new optics.

  The LTC welcomes the new proposals which avoid the installation of the additional triplet power converter. In addition there is no problem in operating one insertion quadrupole at zero current as requested according to the new TOTEM optics. According to the β^* = 2625 m optics at IR1, one of the insertion quadrupole needs a polarity

BPM nearby the RPs

For protection and optimization it might be good to install beam position monitors in the near of the RP station. Has this been considered ?

- Certainly a good possibility we should study in detail
- The BPM's can help in a first setting up of the beam
  - note that there are BPMs (cold) next to each quadrupole at ~10m distance from the RPs
- However for the final alignment with high precision we must rely upon data from our own detectors in the RP (overlap detectors)
- Given our space constraints we have to carefully evaluate the additional complexity that will be introduced, including cost

Roman Pot Locations