The luminosity monitor of the ATLAS experiment

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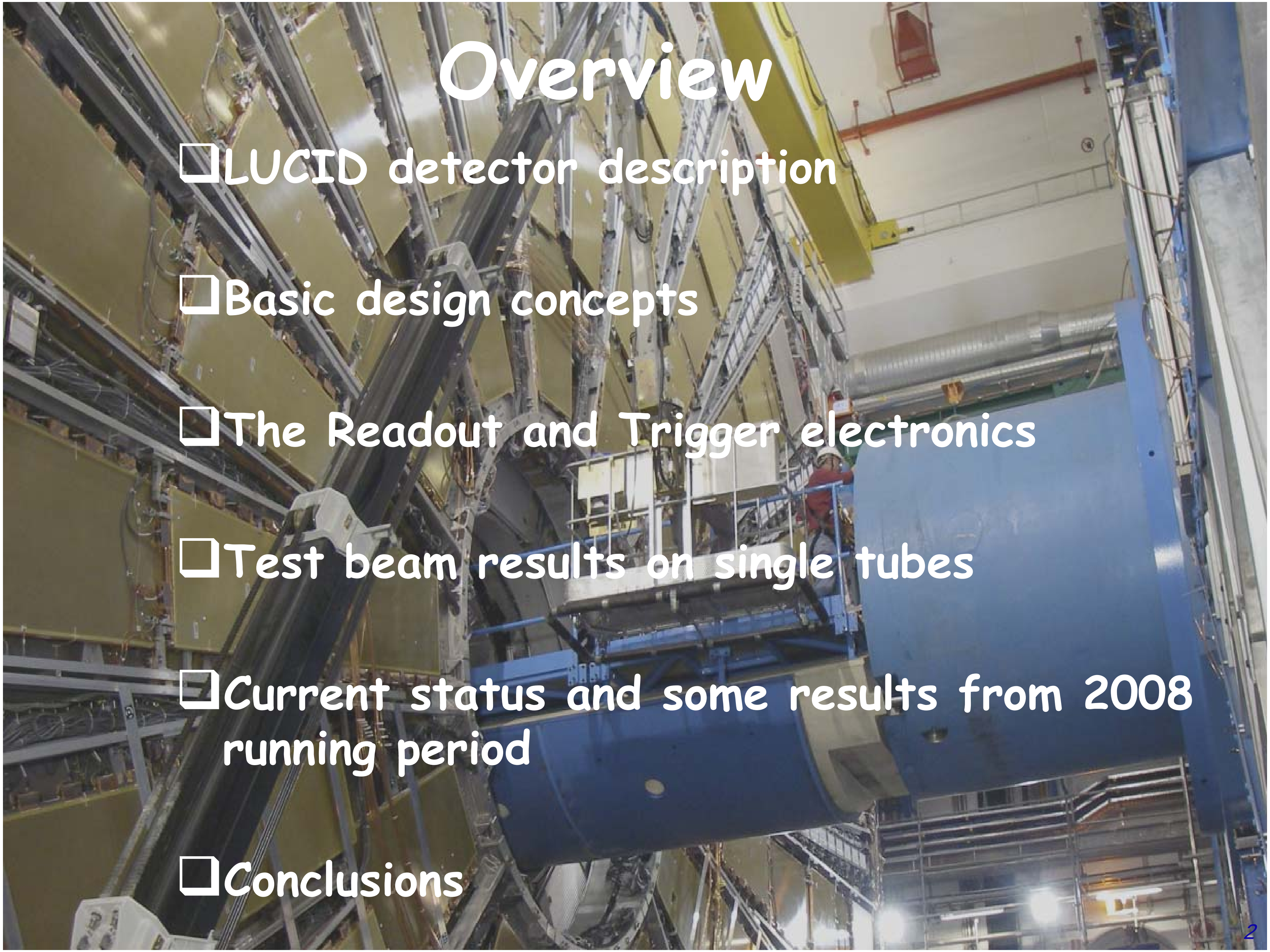
On behalf of the LUCID group in ATLAS

[Alberta (CD), CERN (CH), Lund (SW), Bologna (IT)]

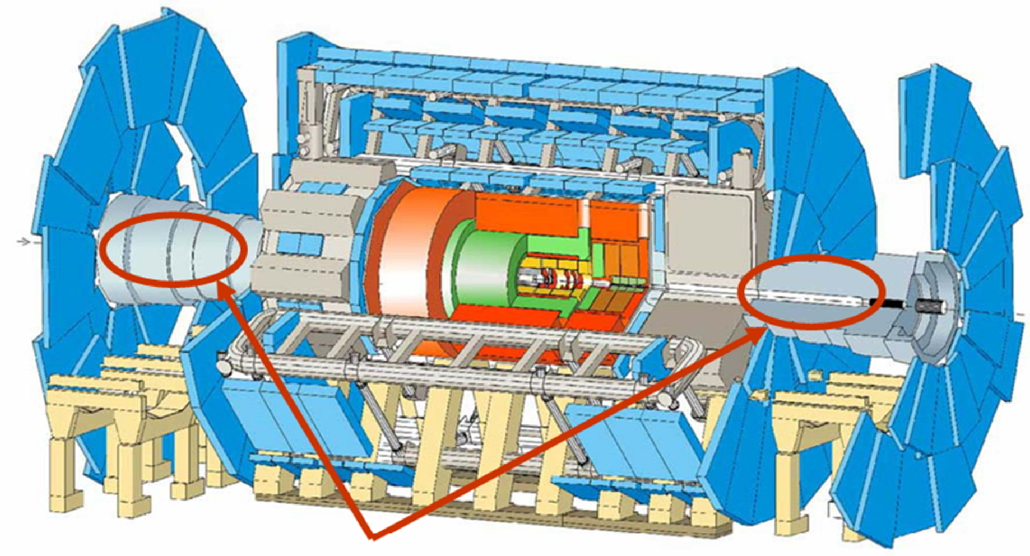


Overview

- LUCID detector description
- Basic design concepts
- The Readout and Trigger electronics
- Test beam results on single tubes
- Current status and some results from 2008 running period
- Conclusions

LUCID location and purposes

LUCID: LUminosity Cherenkov Integrating Detector

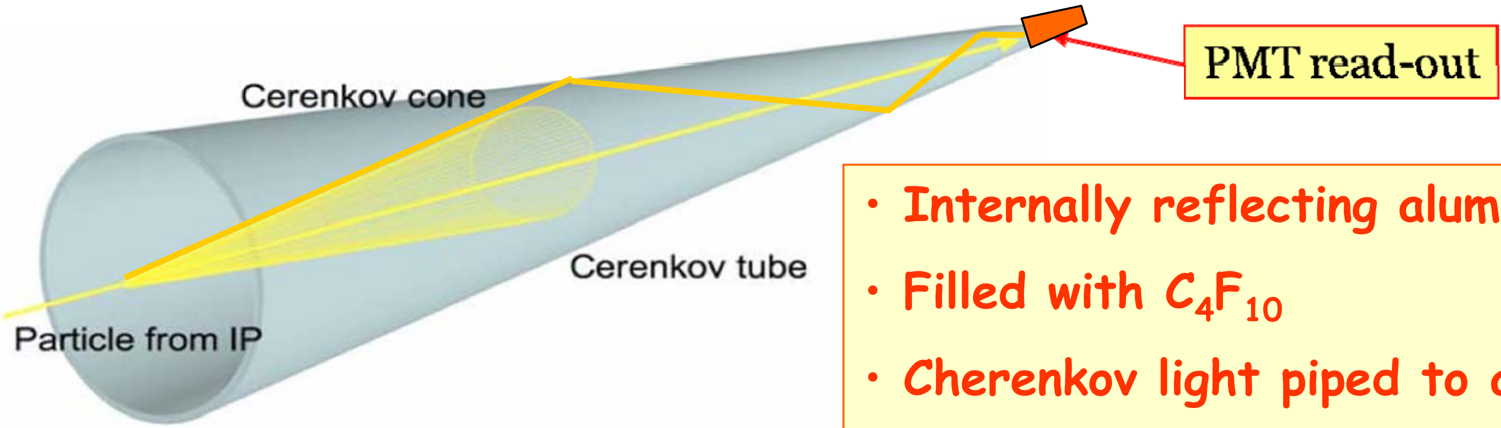


Location of LUCID modules inside ATLAS

- LUCID is made of two modules located at 17 m from the interaction point
- LUCID is designed to measure the luminosity up to $L=4x10^{33}\ cm^{-2}s^{-1}$
- Sensitive to charged particles pointing to the primary *pp* collisions

- Array of gaseous Cherenkov detectors having the following purposes:
  - Measure and monitor the ATLAS RELATIVE LUMINOSITY integrated over the time and for each Bunch Crossing
  - Provide an INTERACTION TRIGGER
- When calibrated, LUCID will provide the ATLAS ABSOLUTE LUMINOSITY measurement

LUCID detector principle



- Internally reflecting aluminum tubes
- Filled with C_4F_{10}
- Cherenkov light piped to a PMT end
- Cherenkov emission tipically at 3°

✓ Fast detector responce (few ns)

  ✓allows for single bunch crossing detection (25 ns spacing)

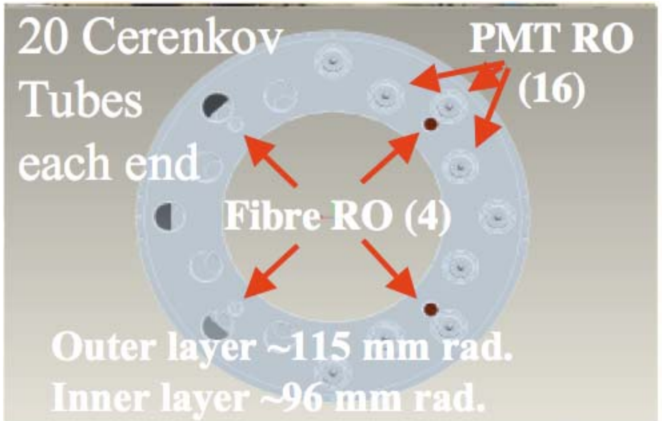
✓ Light design: intrinsically radiation tolerant

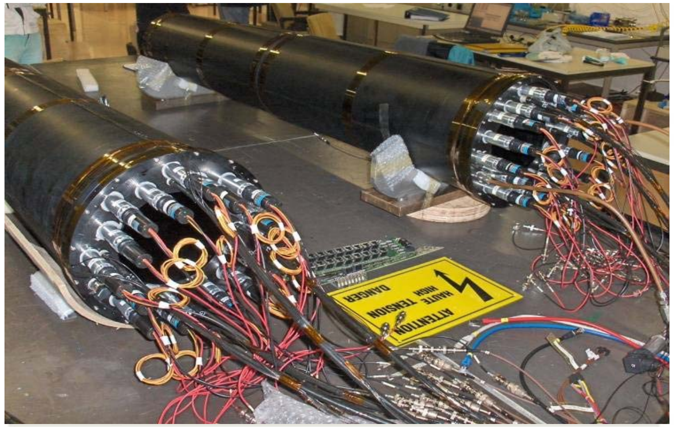
✓ Background suppression

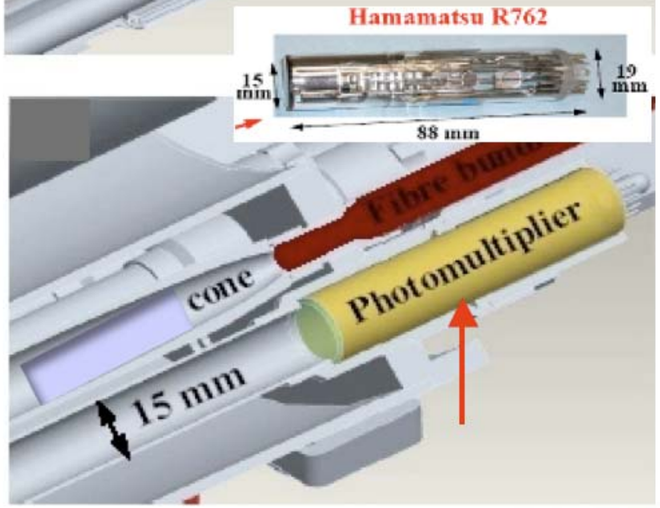
  ✓ Cherenkov threshold: 2.8 GeV/c for π in gas

  ✓ Geometry: tubes are pointing to the *pp* interaction region

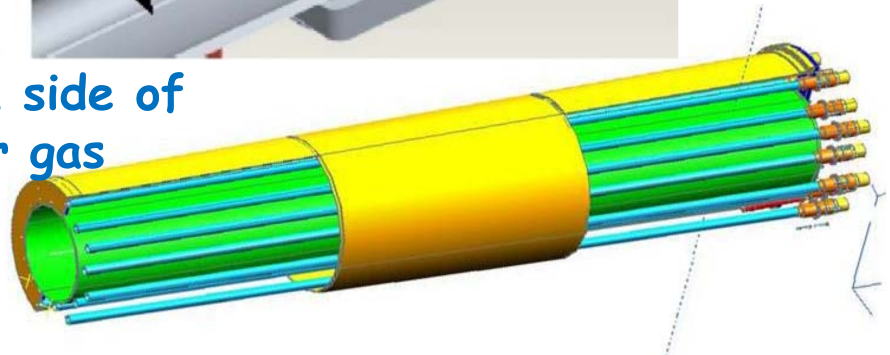
Detector Description







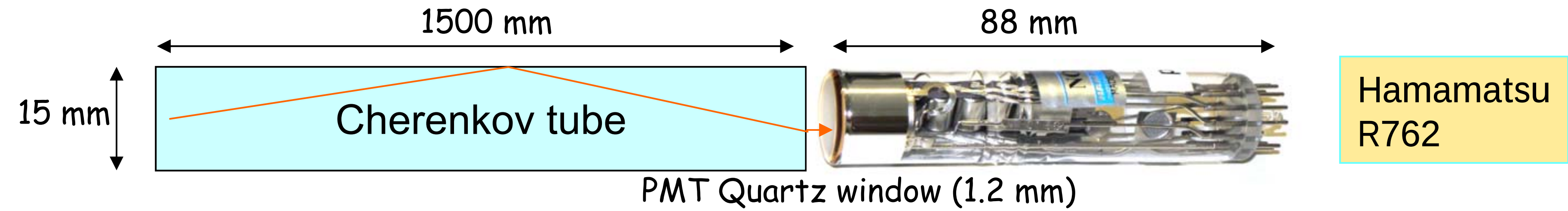
- 20 Pointing Cherenkov tubes on each side of ATLAS IP, filled with C_4F_{10} radiator gas

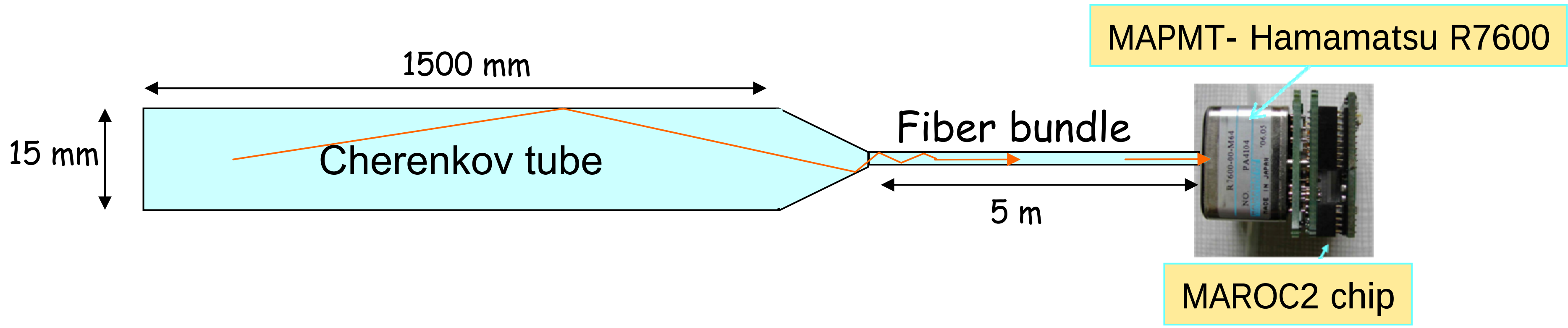


- LUCID eta coverage $5.61<\eta<5.93$

LUCID Readout Scheme

2x16 tubes are directly coupled to photomultipliers (PMT)
PMT must stand the high radiation environment (0.7 MRad/y)





2x4 tubes are coupled to a multi-anode PMT via Aluminium cones and optical fibers
Better for high luminosity runs (MAPMT not exposed to high radiation doses)

Gamma and Neutron irradiation tests

γ: ^{60}Co, E=1.22 MeV
Total dose: 20±1 MRad in 22h
30 years of LHC in phase I

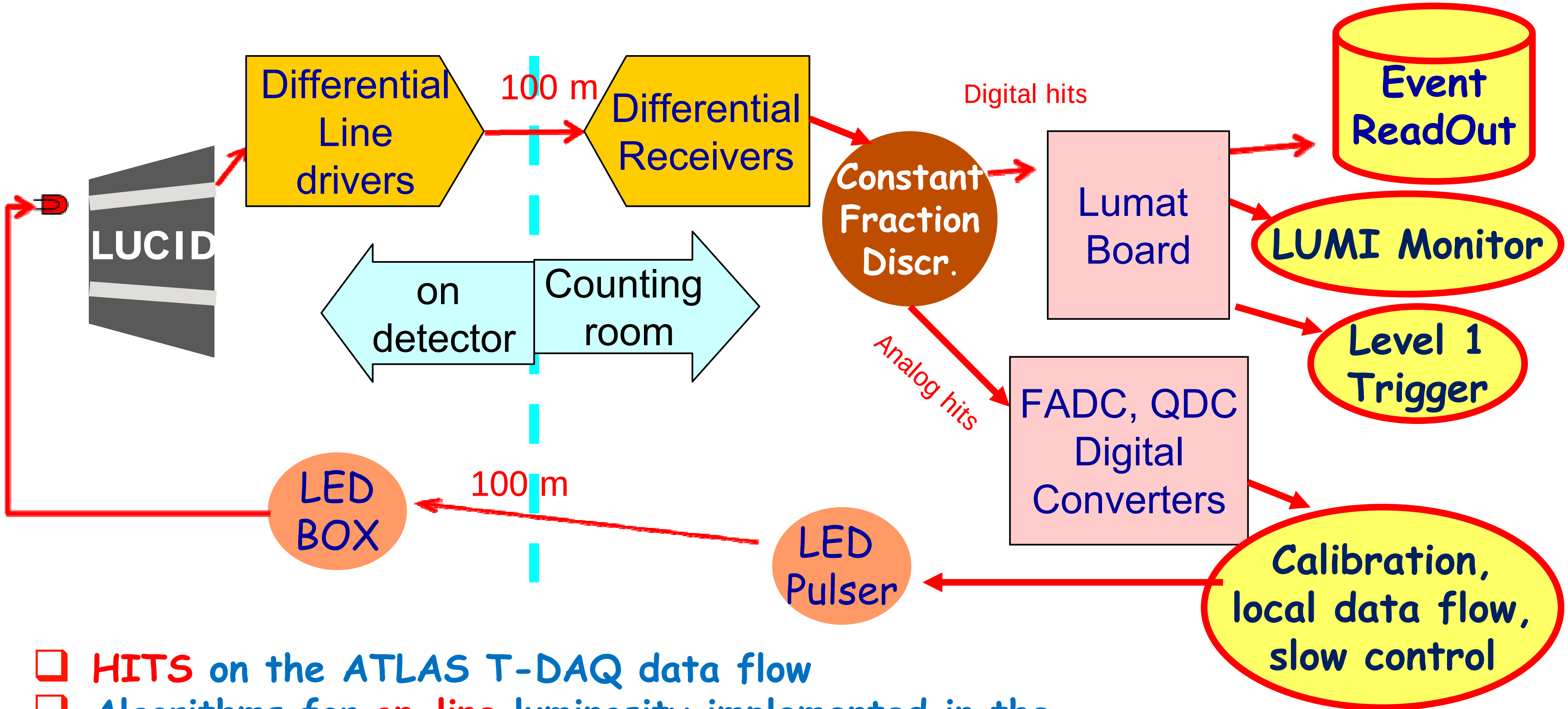
- ✓ No effects on gain and on spectral responce;
- ✓ Increase of dark current
- ✓ Darkening of the glass, no change on the quartz window

n: ENEA Casaccia Reactor
E=100 keV (average)
1.5 h at $5x10^{14}$ n/s
total dose equivalent of 20 years of LHC in phase I

- ✓ No effects on gain and on spectral responce;
- ✓ Increase of dark current
- ✓ Activation of short lived nuclei (Al, 12min)

No relevant radiation effects foreseen during the first years of LHC running (low lumi)

The LUCID readout DATA FLOW

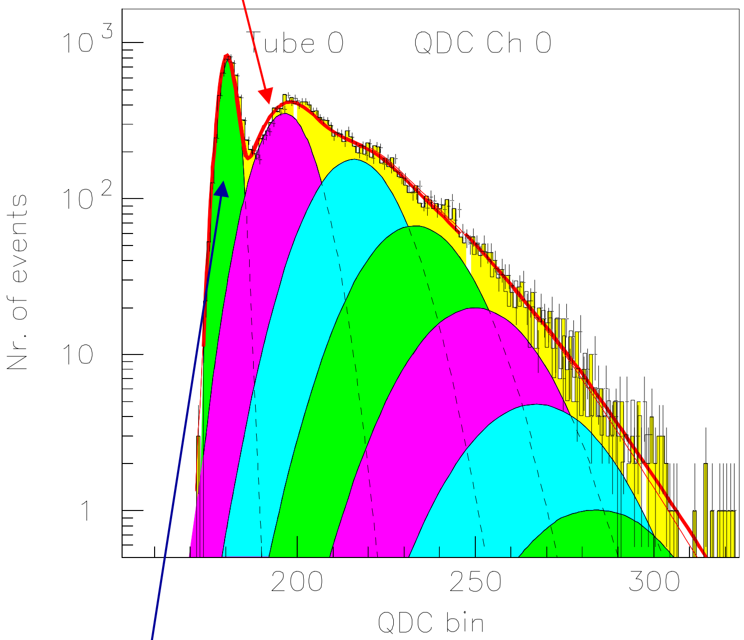


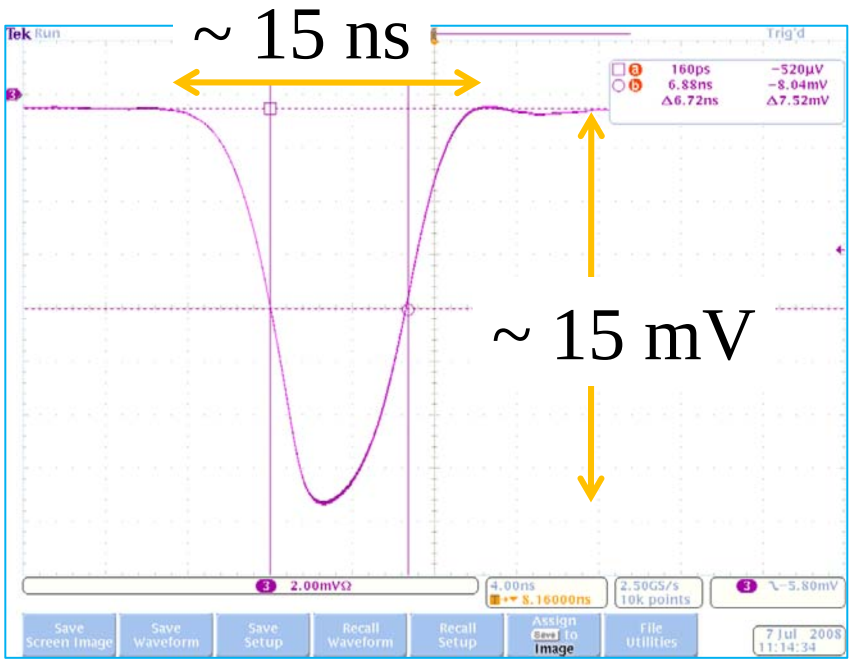
- HITS on the ATLAS T-DAQ data flow
- Algorithms for on-line luminosity implemented in the LUMinosity And Trigger monitor card
- FAST TRIGGER on HIT multiplicity
- Signal charge, shape and calibration on local VME data flow
- TIME and AMPLITUDE analysis on signals off-line

LED CALIBRATION DATA

Signal Q_1: 17-45 ch/pe
1 photo electron (pe) peak

Single photoelectron signal after ~100 m cable
LUCID READS SINGLE BUNCHES!





Noise σ_0: Pedestal width

$$\frac{S}{N} = \frac{Q_1}{\sigma_0} > 3$$

Typical 1 track signal ~ 70 pe

LUminosity Monitor And Trigger card

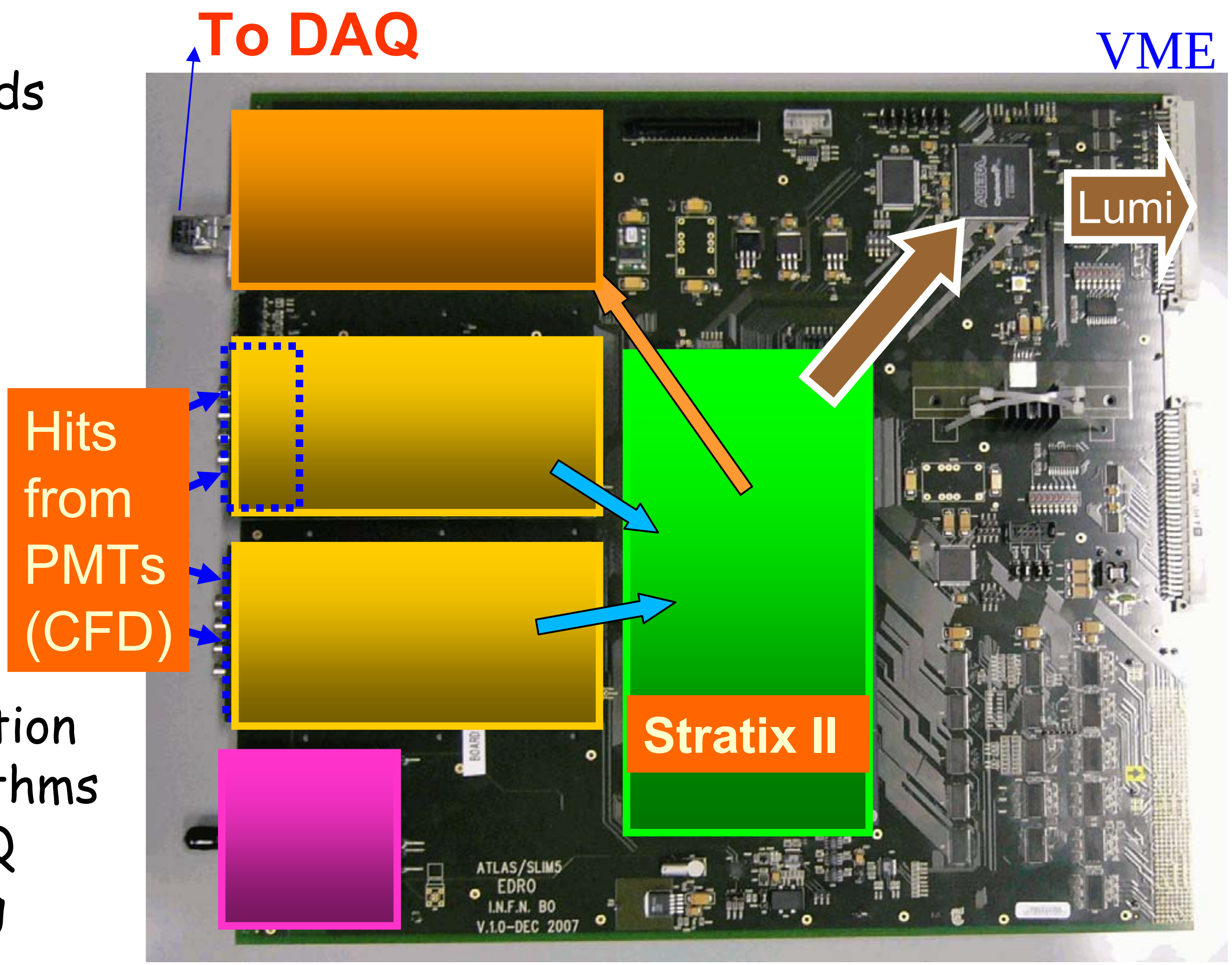
- ✓ 9U VME Board
- ✓ 5 piggy back boards
- ✓ 4 Fast FPGAs
- ✓ Programmability
- ✓ Flexibility

Performances:

40 Mhz bus clocks
8 Gbit/s input rate
1 Gbit/s output rate

Goals

- ✓ Luminosity evaluation
  - Several algorithms
- ✓ LUCID event DAQ
- ✓ LUCID Monitoring
- ✓ LUCID Triggers



Methods to measure luminosity

The rate of the pp interactions (R_{pp}) seen by LUCID is proportional to the luminosity (L):

$$R_{pp} = \mu_{LUCID} \cdot f_{BX} = \sigma_{pp} \cdot \varepsilon_{LUCID} \cdot L$$

Bunch crossing rate = $\frac{2808}{3564}$ x 40 Mhz (2808 = filled BX, 3564 = total BX)

Efficiency (and acceptance) of LUCID To detect a pp interaction

Number of pp interactions per bunch-crossing (BX) as measured by LUCID.

Zero Counting — On and Off-line

Count bunch crossings with no interactions:

$$\mu_{LUCID} = -ln\left(\frac{N_{zeroBX}}{N_{totalBX}}\right)$$

Hit Counting — On and Off-line

Count the number of tubes with a signal (hit):

$$\mu_{LUCID} = \frac{< N_{hits/BX} >}{< N_{hits/pp} >}$$

Particle Counting — Off-line

Count the number of particles in LUCID by doing several cuts on the pulseheight distributions:

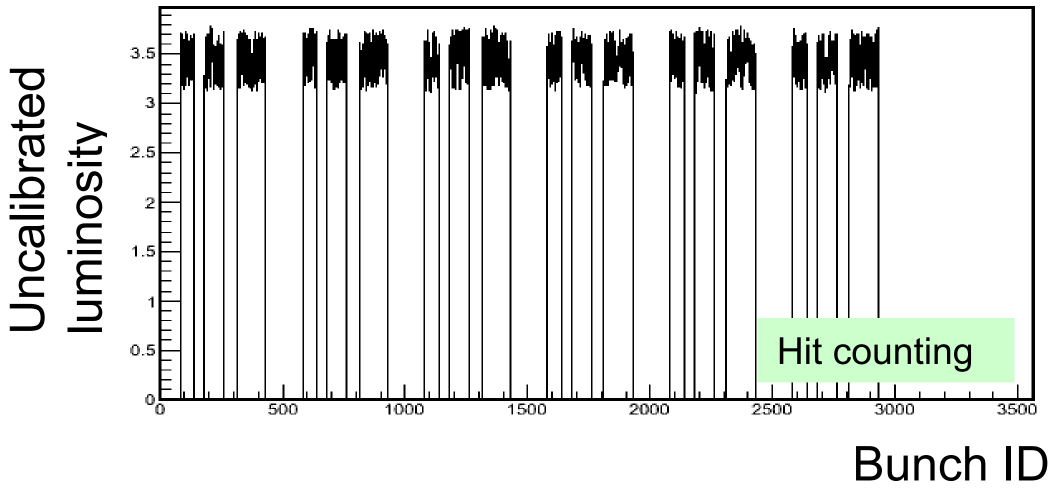
$$\mu_{LUCID} = \frac{< N_{particles/BX} >}{< N_{particles/pp} >}$$

Hardware simulation of LHC beams

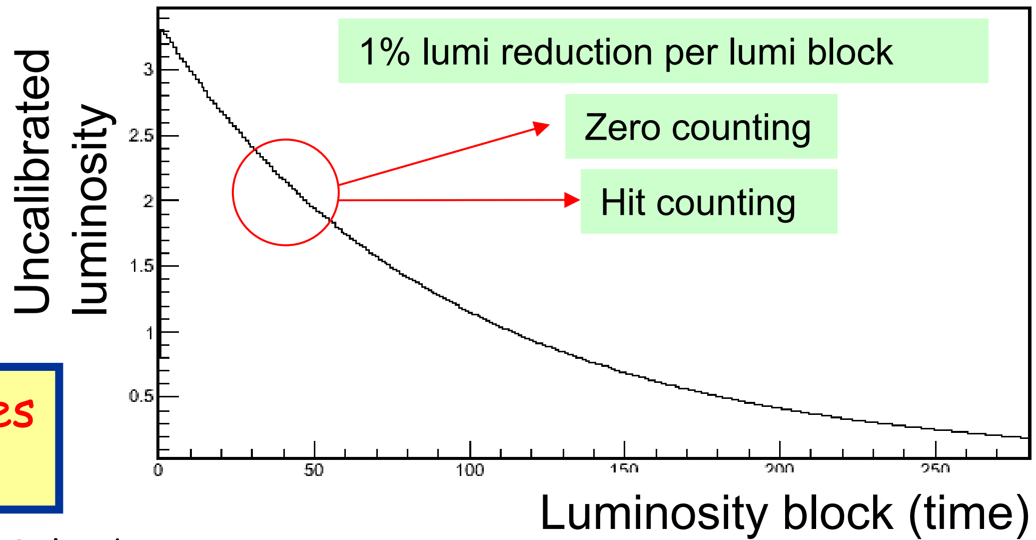
✓ Waiting for the data, we have an hardware beam simulator:

Luminosity on
A bunch-by-bunch
Basis (25 ns)

A grand total of 6 luminosity algorithms available



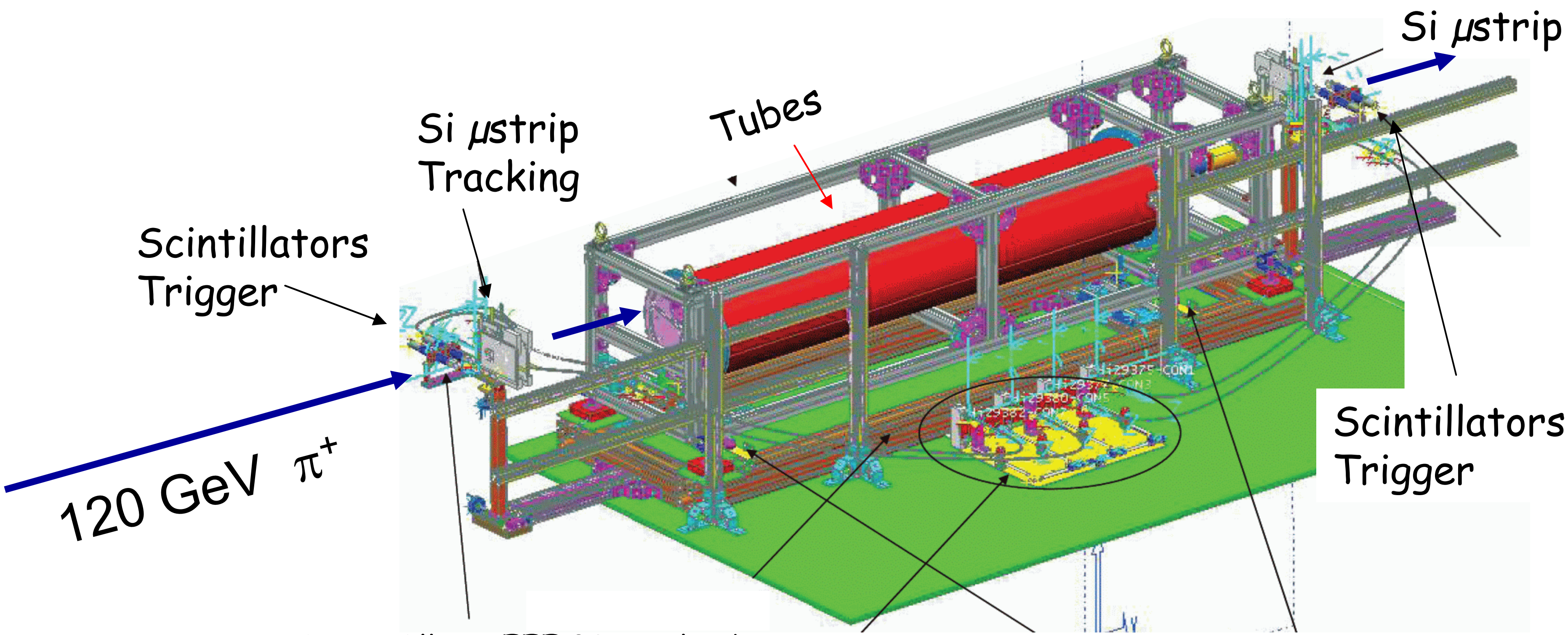
Luminosity measured every 0.1-10 minutes (lumi block) for all the time



Algorithms and infrastructures ready for real data!

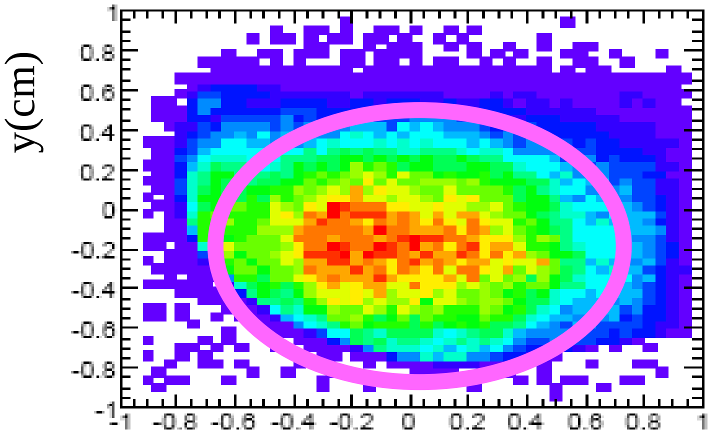
LUCID beam tests

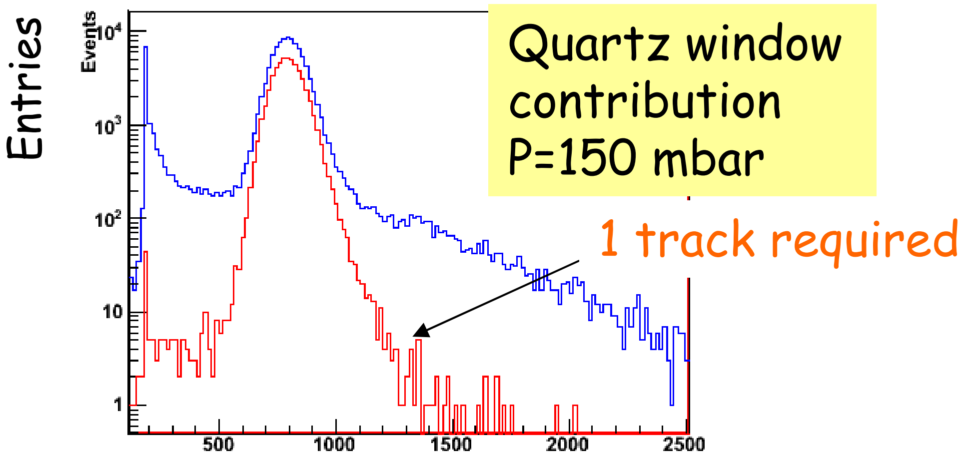
- A systematic test of tubes and gases has been performed at the H6 SPS beam line: pions, 120 GeV, 2-3x10^5 π^+/spill
- Gas studied: C_4F_{10}, Isobutane, Nitrogen. Pressure 150 to 1800 mbar
- External trigger on scintillators
- Tracks measured with a microstrip system (SLIM5 exp.)

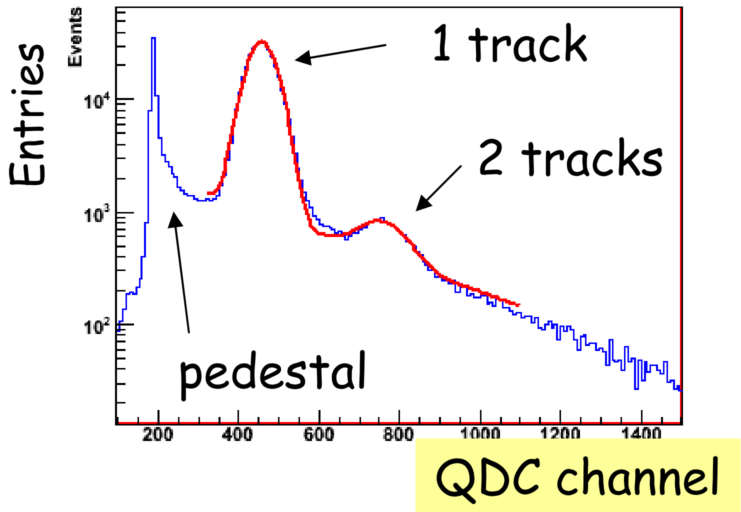


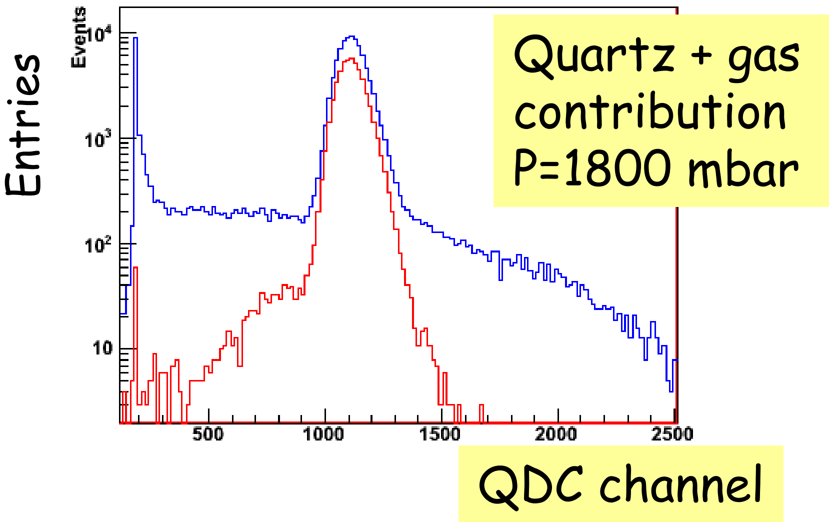
Signals types

- Two cherenkov contributions: in the PMT quartz window and in gas
- PMT contribution constant over pressure and angles (|θ|<10°)









Pressure scan

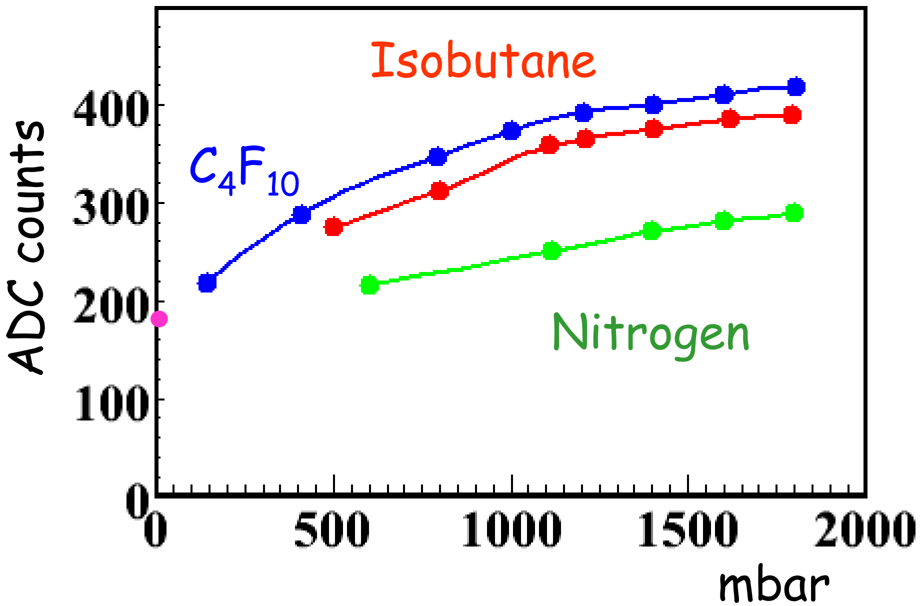
- ✓ Systematics tests on pressure and gas type

$$\frac{n(E)^2-1}{n(E)^2+2}=\frac{\alpha P/T}{\sqrt{1-(E/E_o)^2}} \qquad \theta_{ch}(E)=\frac{\sqrt{3\alpha P/T}}{\left(1-(E/E_o)^2\right)^{1/4}} \qquad N_{ch}\propto P$$

In the low n limit

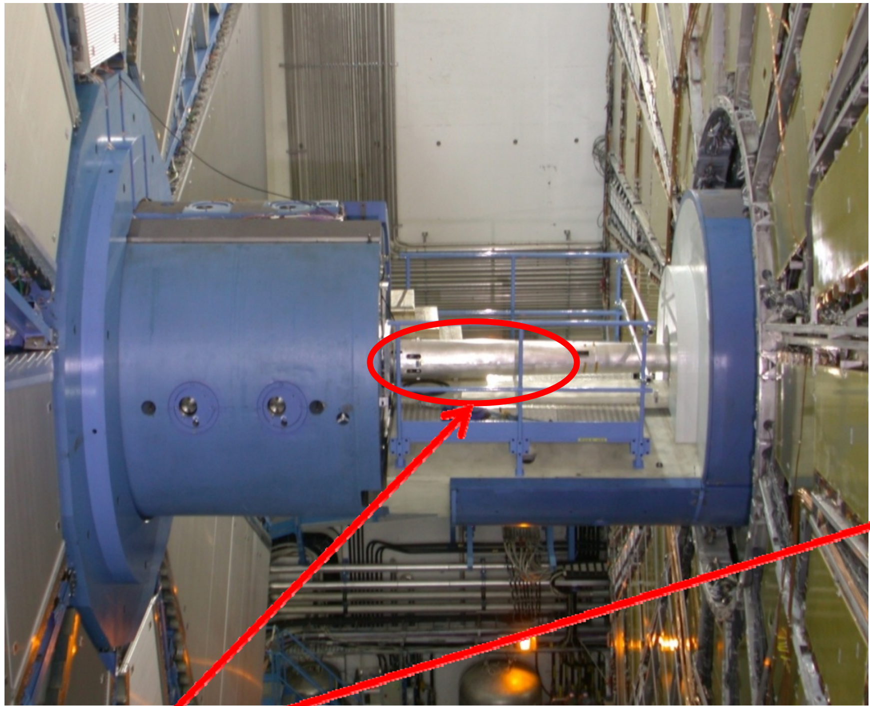
- ✓ Reflections on the Al walls: $N_R \propto \theta_{ch} \propto \sqrt{P}$ $\qquad N_{pe} \propto N_{ch} R^{N_R} \propto P R^{\beta P}$

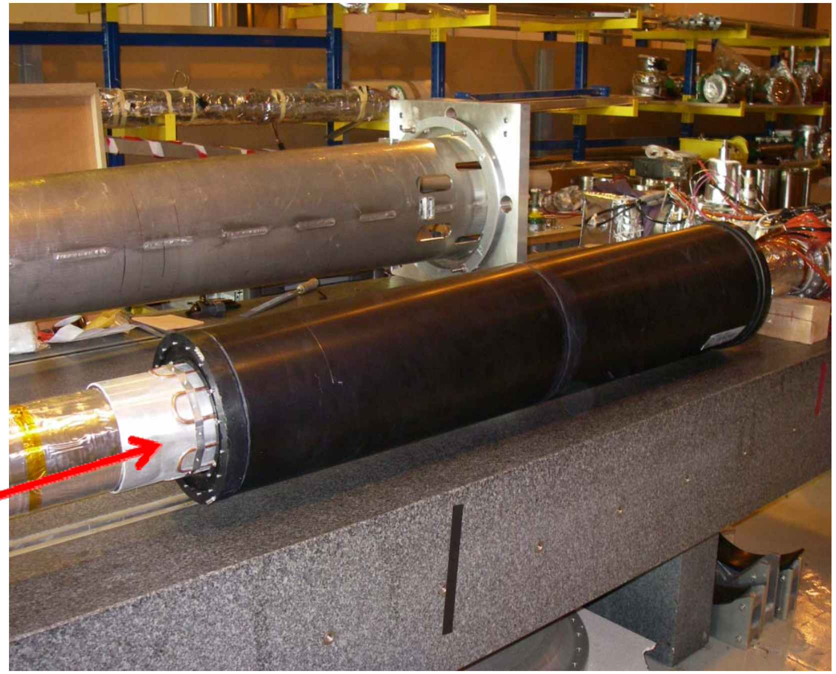
Al reflectivity



- ✓ Al reflectivity measured against angles, wavelengths and polarization
- ✓ Stringent tests for Monte Carlo (ongoing)

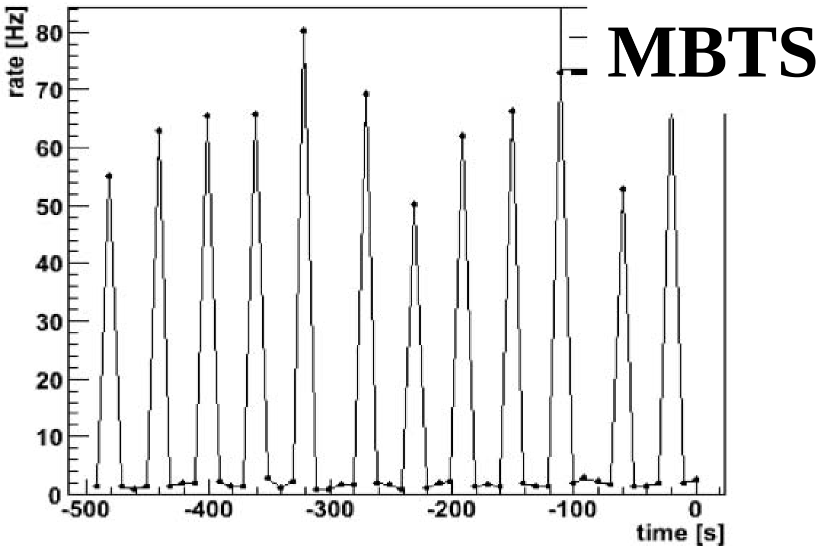
LUCID history and present status

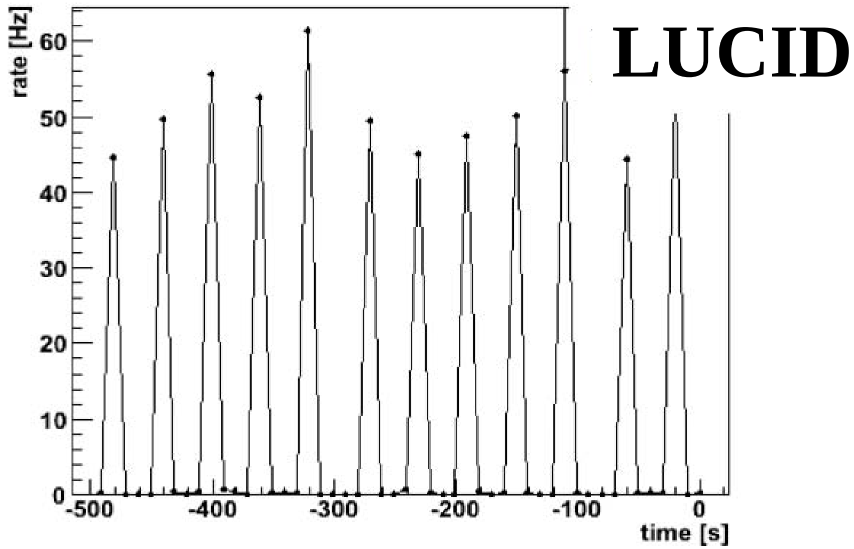




- LUCID detector construction was approved in ATLAS on February 2007
- LUCID is optimized to measure directly ATLAS luminosity during phase I of LHC (Luminosity$<4\cdot10^{33}$ cm^{-2} s^{-1})
- The detector was ready on summer 2008 to catch the first LHC beam splash events
- Although some new implementations/maintenances are still ongoing, the detector is in advanced phase of commissioning

Trigger rates during the first LHC beam





- MBTS – Minimum Bias Trigger Scintillators: Array 16+16 scintillators, placed symmetrically to the IP, covering $2.1 < \eta < 3.8$
- LUCID – At least 1 hit in one of the two arms within $5.6 < \eta < 5.9$

LUCID will provide one of the MB trigger to ATLAS

Conclusions

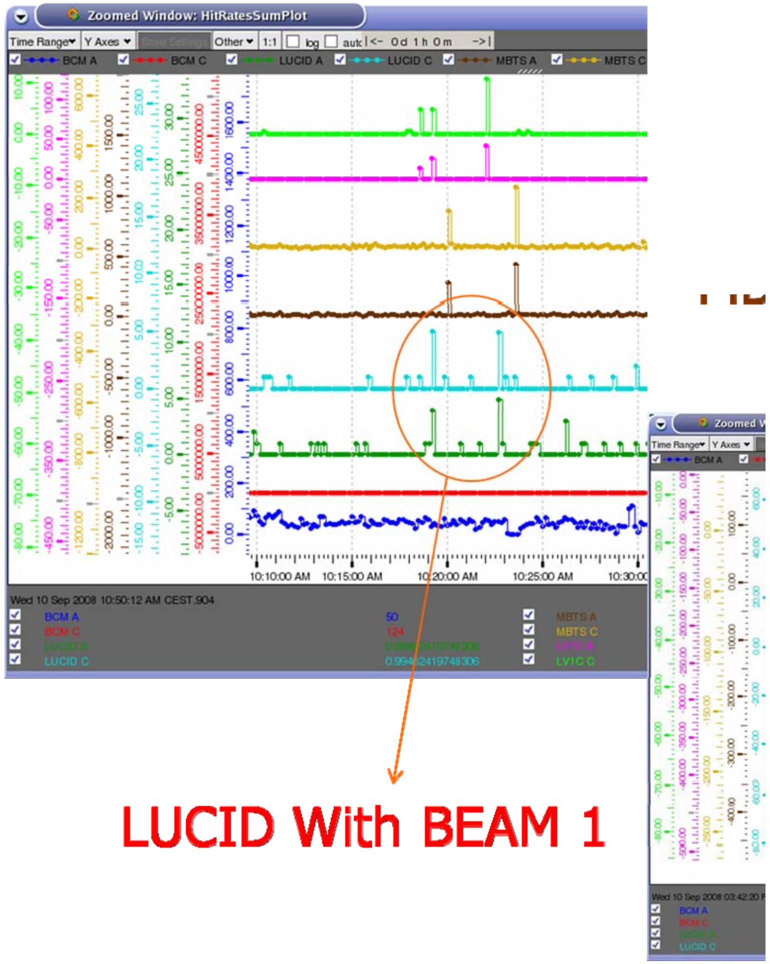
- ✓ The LUCID detector is designed to provide ATLAS with:
  - Luminosity monitor on-line/off-line
  - Luminosity for each Bunch Crossing and Integrated
  - Minimum Bias Trigger
  - Beam Control monitor
- ✓ LUCID is a running detector in advanced status of commissioning
- ✓ The luminosity will be measured using a combination of many methods
- ✓ A beam test has been performed to check tube performances in several experimental conditions → systematics used to tune the MC. Analisys ongoing.

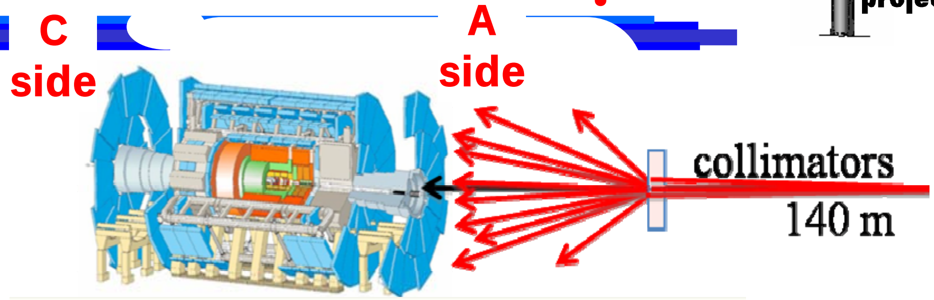
Back up slides

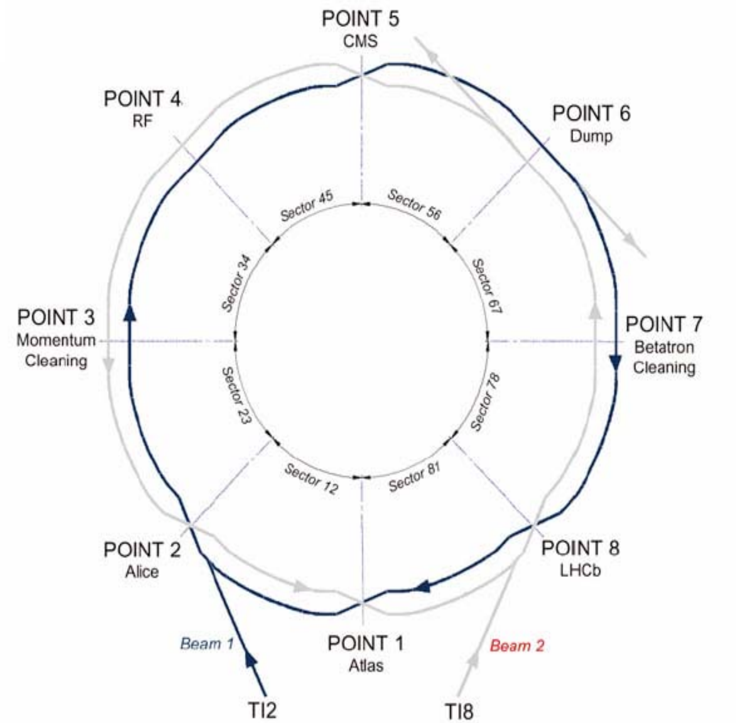
Back up slides

Splash events

First HITS seen at LHC startup





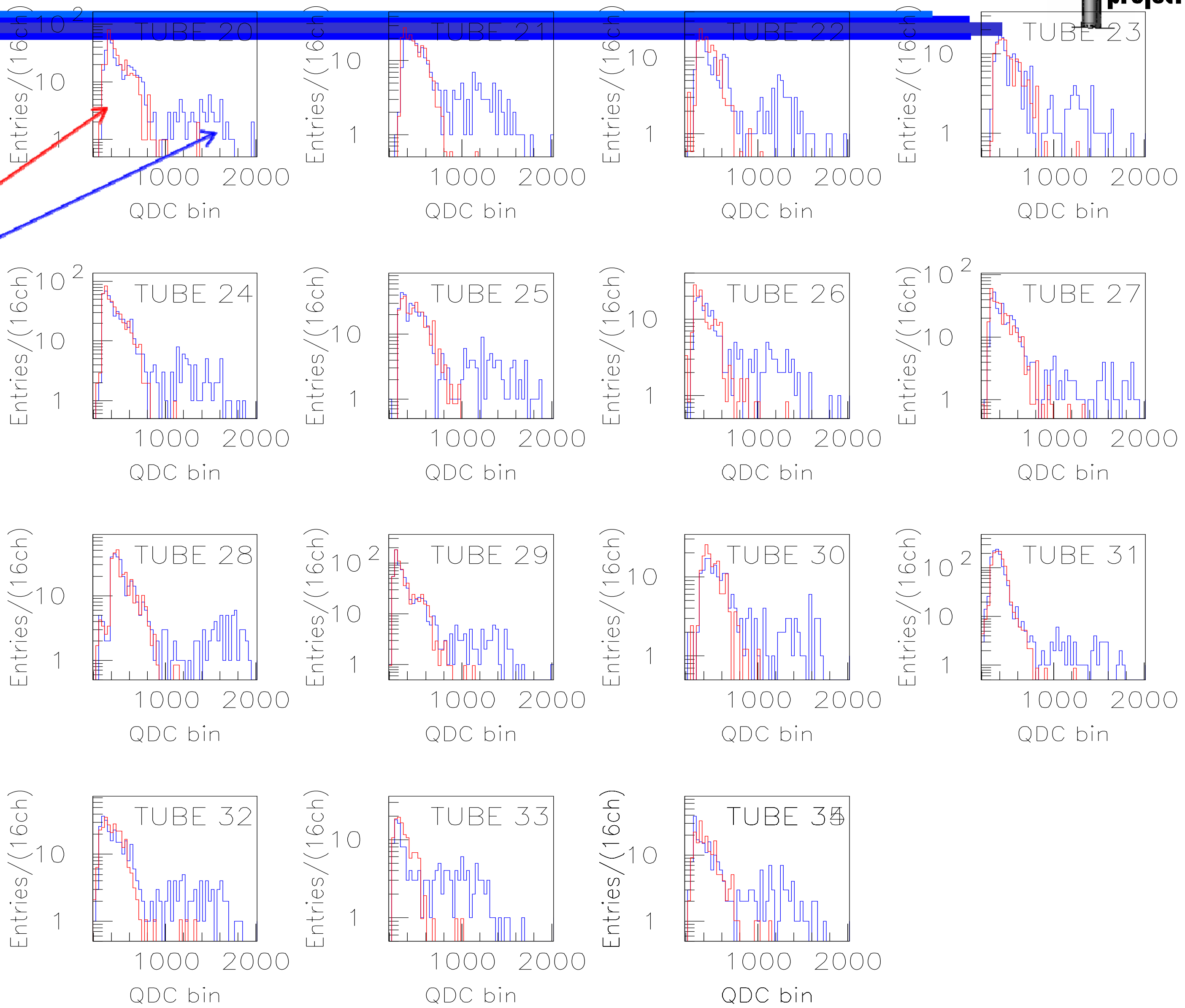


- **LUCID recorded the very first LHC "splash" events from the two beams**

September 10th events with Beam 2

- Charge distributions on LUCID SIDE C

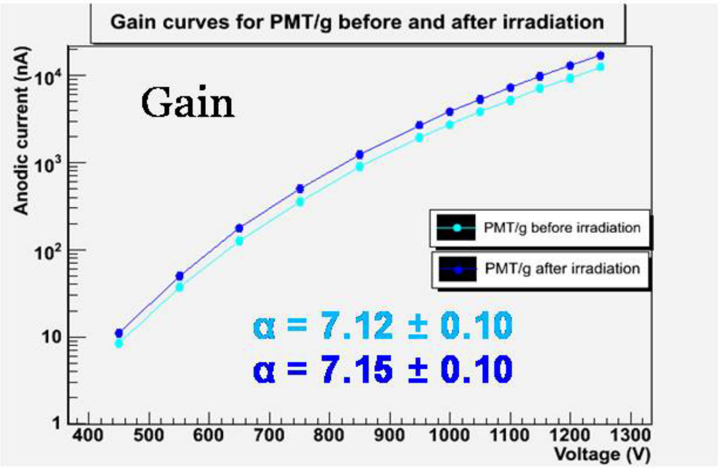
- Dark current
- Beam 2

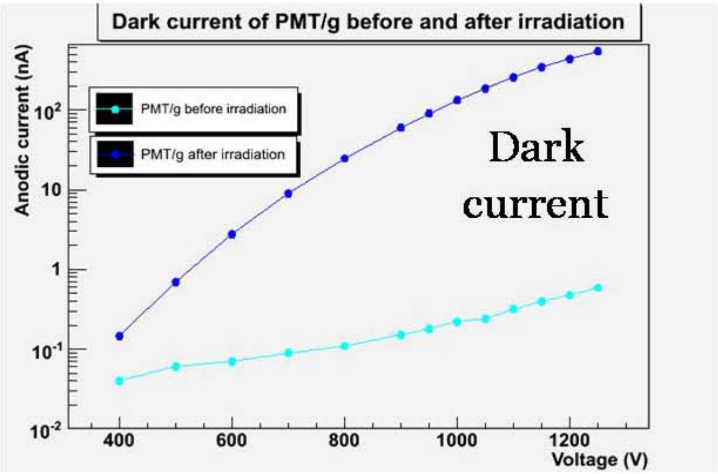


Evidence of signals from tracks crossing the detector

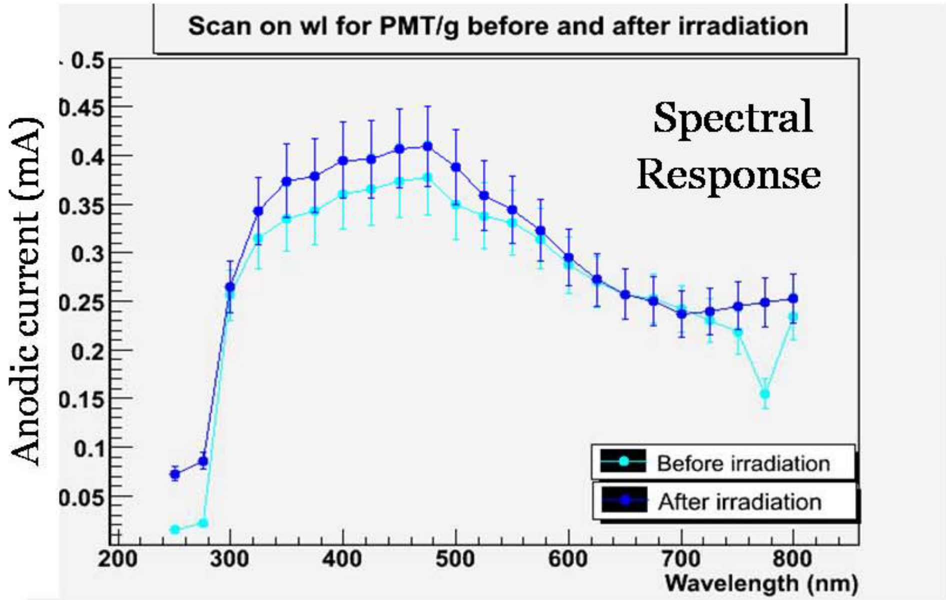
Irradiation tests

Gamma irradiation tests



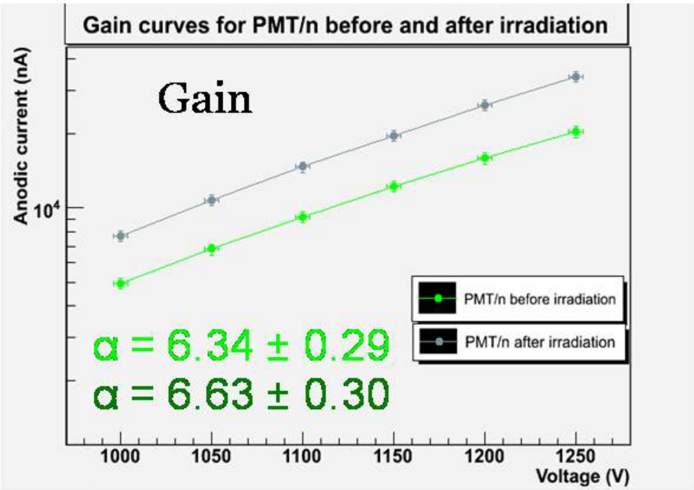


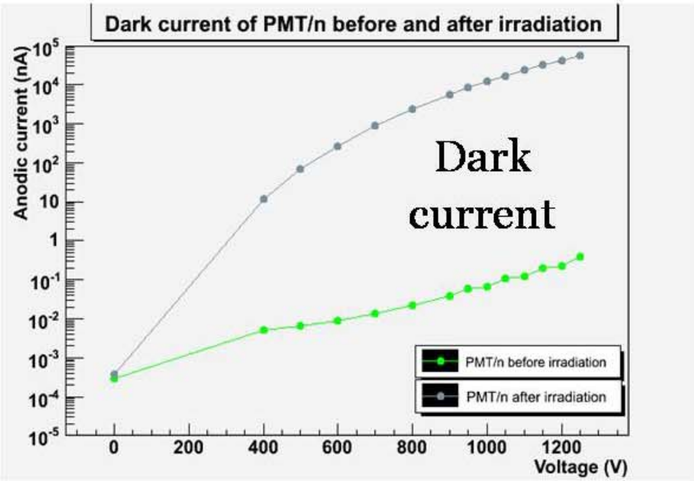
γ: ^{60}Co, E = 1.22 MeV
Dose = 20±1 Mrad
30 years of LHC in phase I



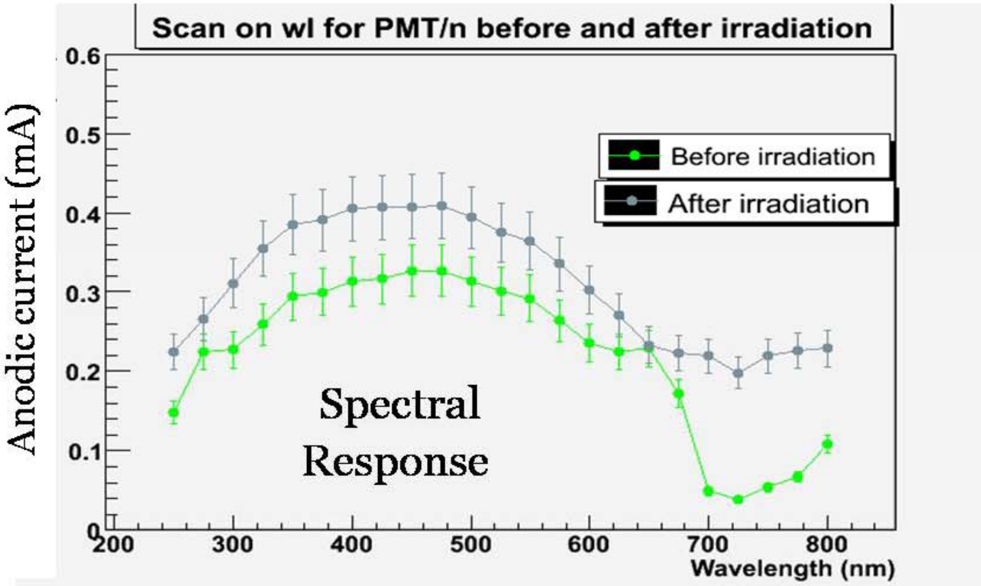
No relevant effects for phase I

Neutron irradiation test





n: ENEA-Casaccia reactor
E = 100 KeV
Dose = 10 years of LHC in phase I



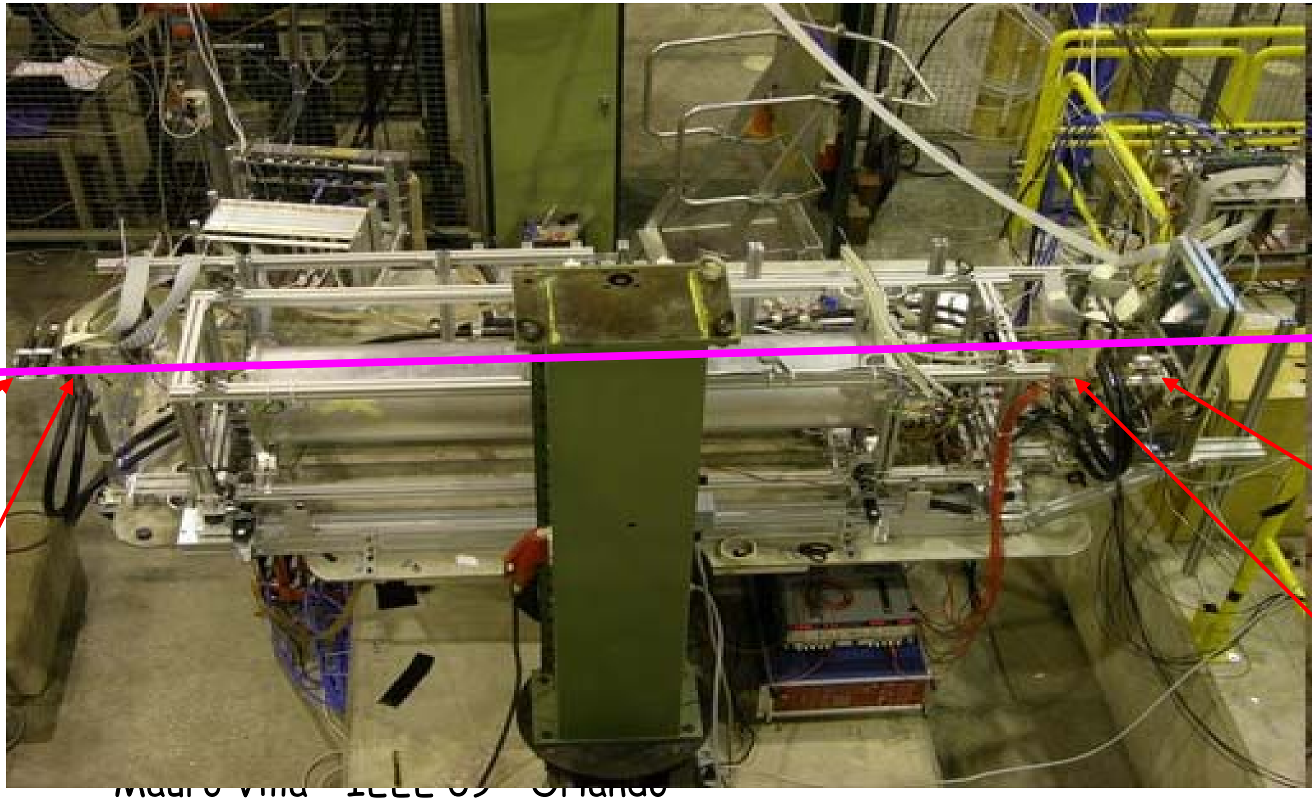
No relevant effects for phase I

Beam test

Set up del Detector

LUCID con 6 tubi

- 3 come quelli installati in Atlas CERI
- 1 non lucidato internamente CERN RAV
- 1 rivestito internamente di mylar DESY M
- 1 mecchanically polished DESY M



- Tracce ricostruite e fittate nei 4 strati di silicio

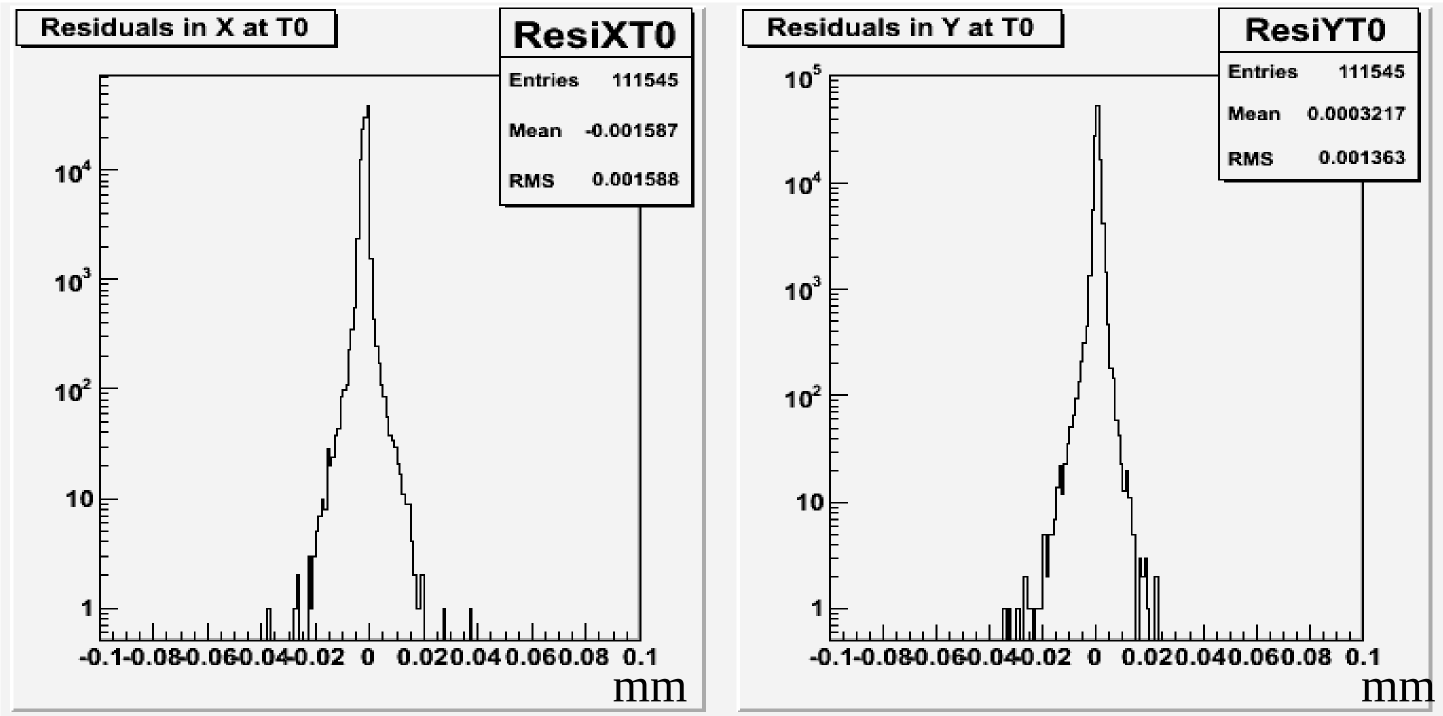
Metodo dei residui:

coordinata fittata nel primo strato di silicio – coordinata ricostruita

informazioni su allineamento e risoluzione (ok per scopi LUCID)

Tracce ricostruite se è trovato almeno un hit in ogni strato di silicio entro 0.5 mm della regione aspettata

Precisione dell'estrapolazione delle tracce nel LUCID ~20 μm



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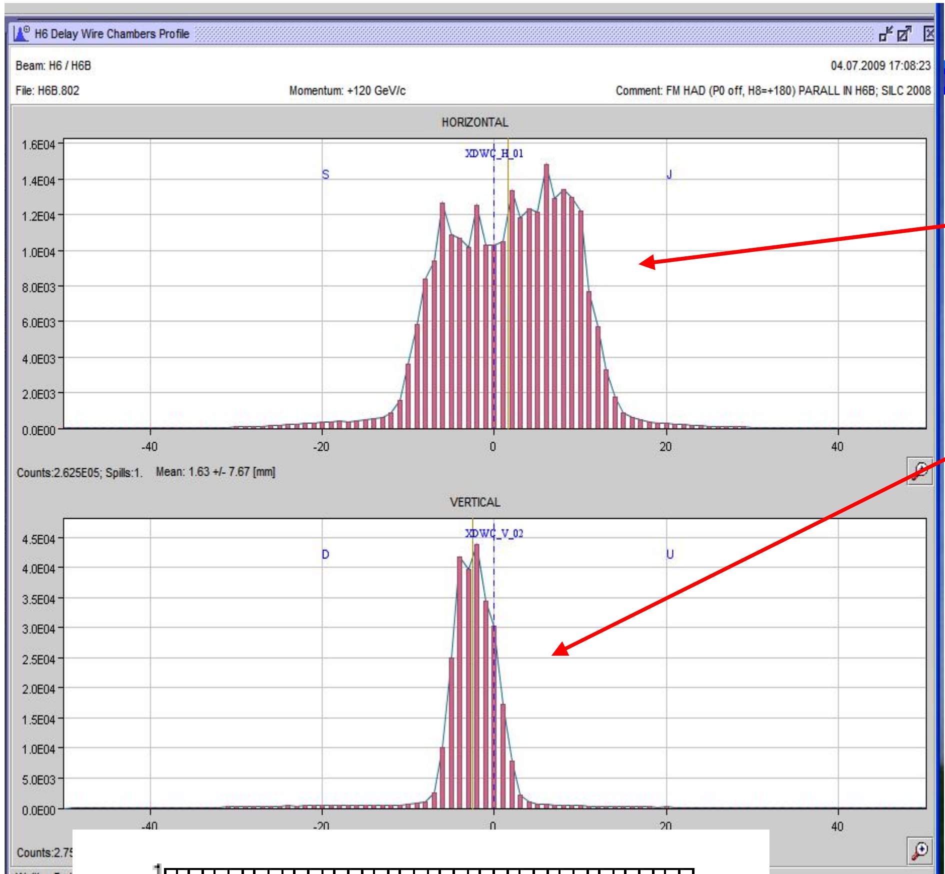
CONDIZIONI DEL FASCIO



Monitor di fascio

Direzione X:
“scatola” di ~2 cm di larghezza

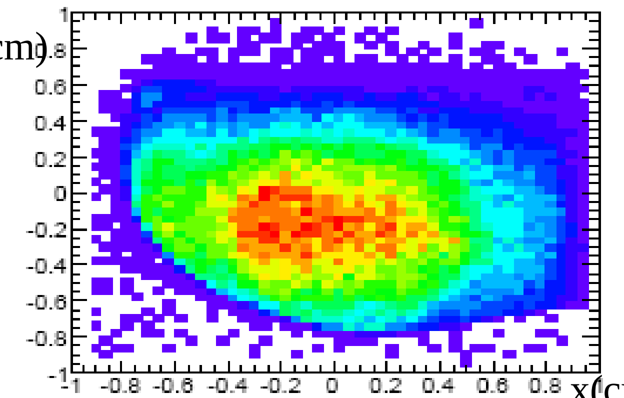
Direzione Y:
“gaussiana” di σ = 5.7 mm

~35x10^{11} protoni per bunch dal SPS

~2.2x10^{5} pioni positivi da 120 GeV sulla linea H6B

Bunch di 9s ogni 30s

Run 5212

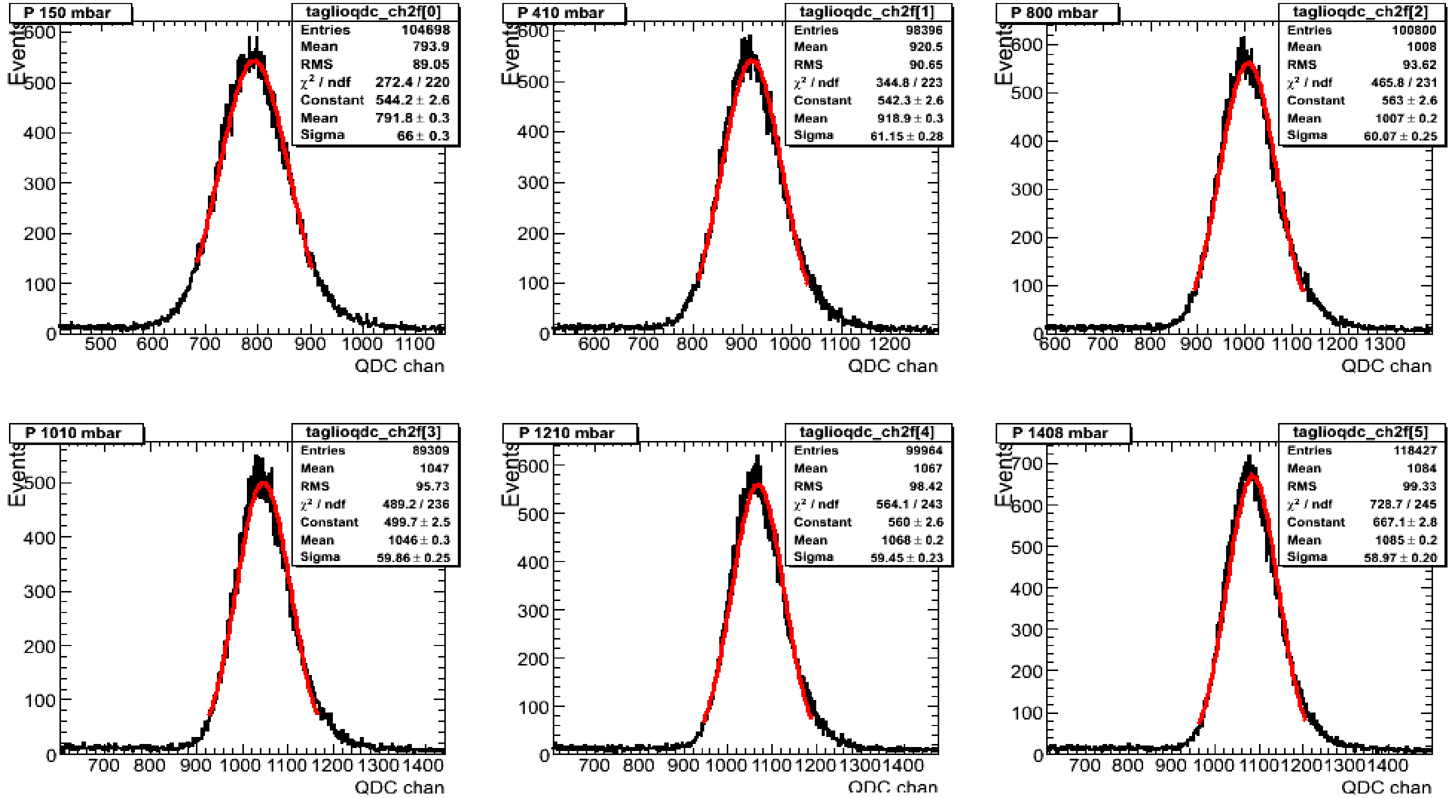


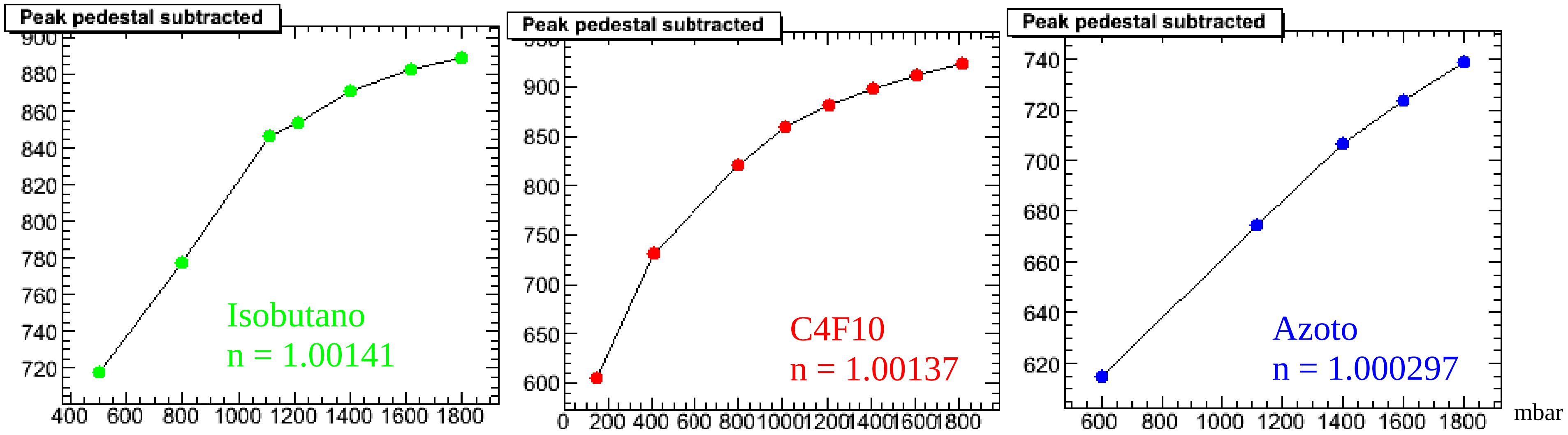
Fascio visto dai layer di silicio

- Orlando

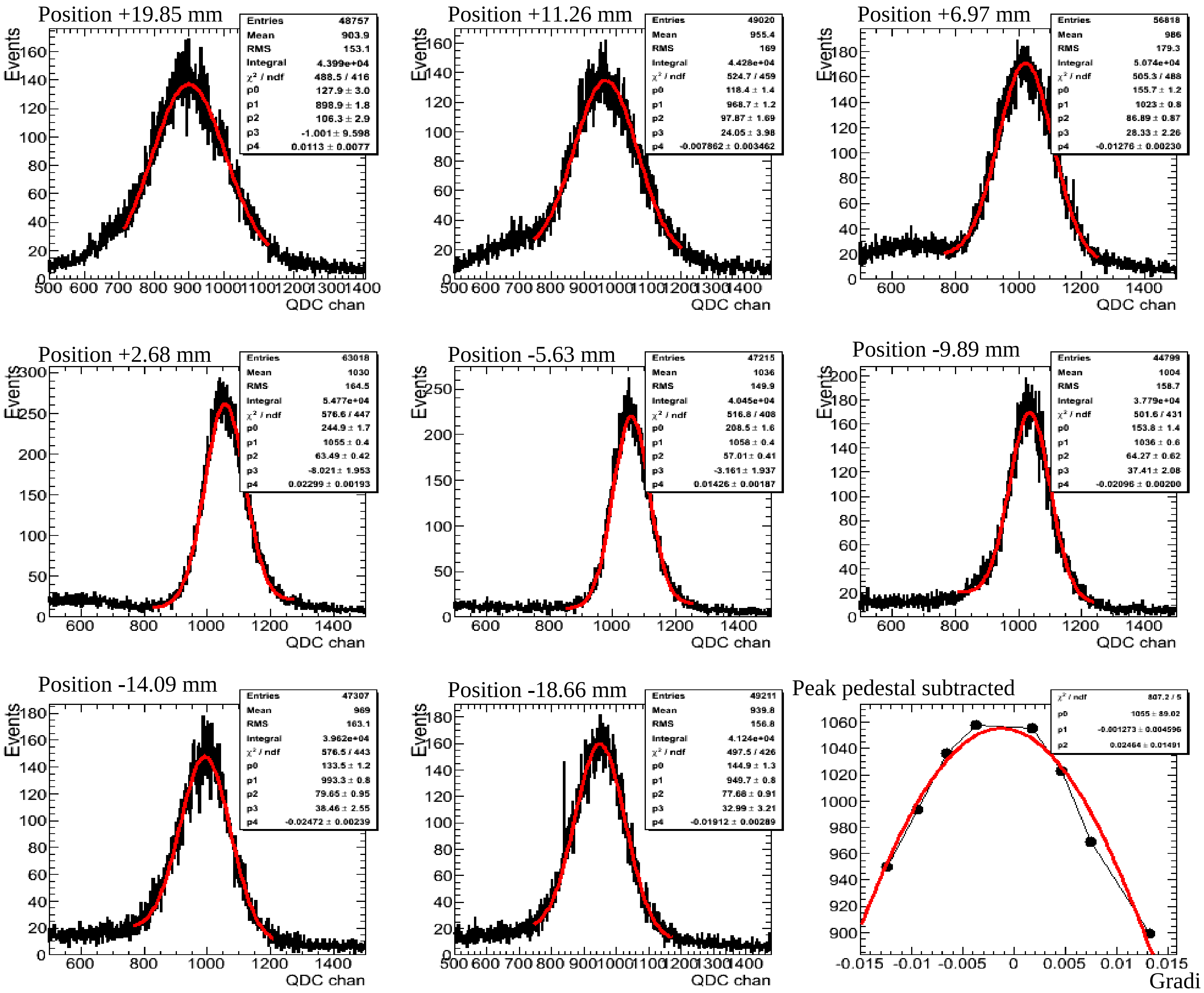
SCAN IN PRESSIONE

Cern 3
C4F10





SCAN ANGOLARE



Cern 3

C4F10
P = 1 bar

Luminosity

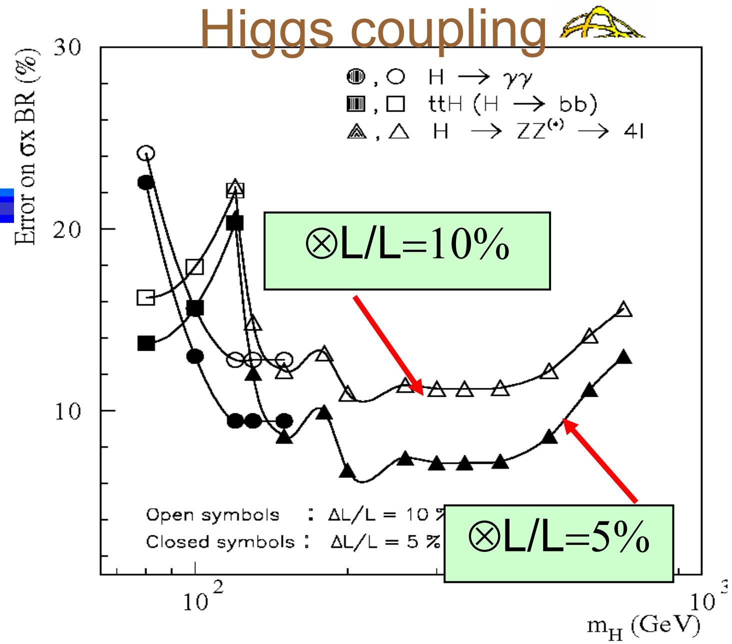
Physics Interest in L

- Absolute Luminosity:
  - measure cross sections for standard physics
  - measure Higgs production cross section
  - observe deviations from SM and New Physics
- Requirements:
  - ultimate precision at the 2-3% level
    - different methods needed for cross check
    - minimize systematics

COMBINED EFFORT FROM DIFFERENT DETECTORS

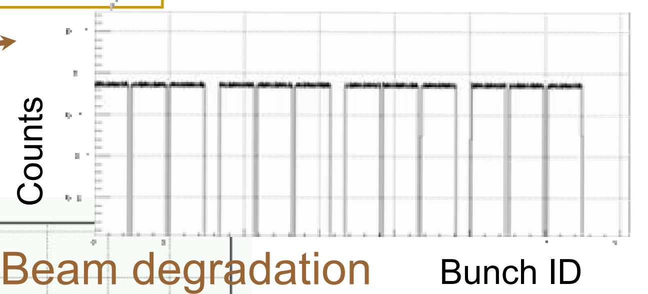
- Relative luminosity:
  - beam stability
  - beam degradation (efficient use of trigger)
  - evaluate trigger & DAQ dead-times
  - determine beam background
  - Luminosity Block spread

Higgs coupling

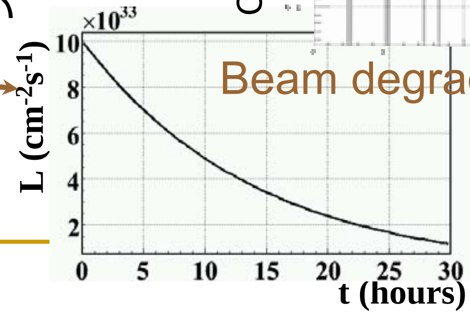


Systematic error due to luminosity (ATLAS TDR)

Beam structure



Beam degradation



Luminosity from LHC parameters

$$L = \frac{f\sum_{i=1}^{k_b} N_{1i}N_{2i}}{\text{Impact surface}} = \frac{f\sum_{i=1}^{k_b} N_{1i}N_{2i}}{4\pi\sigma_x^*\sigma_y^*} = \frac{f k_b N^2}{4\pi\varepsilon_N \frac{\beta^*}{\gamma}}$$

N_{xi} = number of protons in bunch i of beam x; f=revolution frequency; σ_x,σ_y=transverse beam dimensions at the IP; k_b = number of bunches; $\beta^*=\beta$ function at IP; $\varepsilon_N=\sigma^*_x\sigma^*_y\gamma/\beta^*$ normalized emittance; $\gamma=E/m_p$ (~7460)

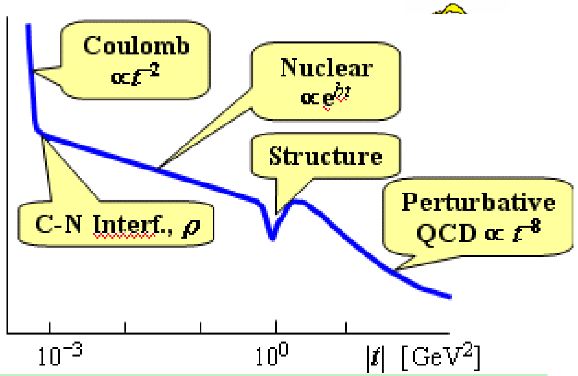
Accuracy limited by

- Extrapolation of $\sigma_x\sigma_y$ from measurement point to IP
- Precision in measurement of bunch currents
- Beam-beam effects at IP, beam crossing angle, ...

Maximum precision obtainable from machine 5-10%

ATLAS Strategy

Goal precision on L ~ 2-3%



- Elastic scattering in Coulomb-Nuclear Interference region to get L and σ_{tot} at L ~ 10^{27} $cm^{-2}s^{-1}$
- optical theorem as a back-up solution

ALFA detector in Roman Pots

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

$$\sigma_{tot} = \frac{16\pi}{1+\rho^2}\times\frac{\left.(dN/dt)\right|_{t=0}}{N_{el}+N_{inel}}$$

- Luminosity monitor calibrated at low lumi but working up to L ~ $10^{34}cm^{-2}s^{-1}$

LUCID

$$\mu_{LUCID} = \frac{\sigma_{pp}\cdot\varepsilon_{LUCID}\cdot L}{f_{BX}}$$

- Absolute L from QED (pp →ppμμ) and QCD (W→lν, Z→ll) processes (need to control PDF)

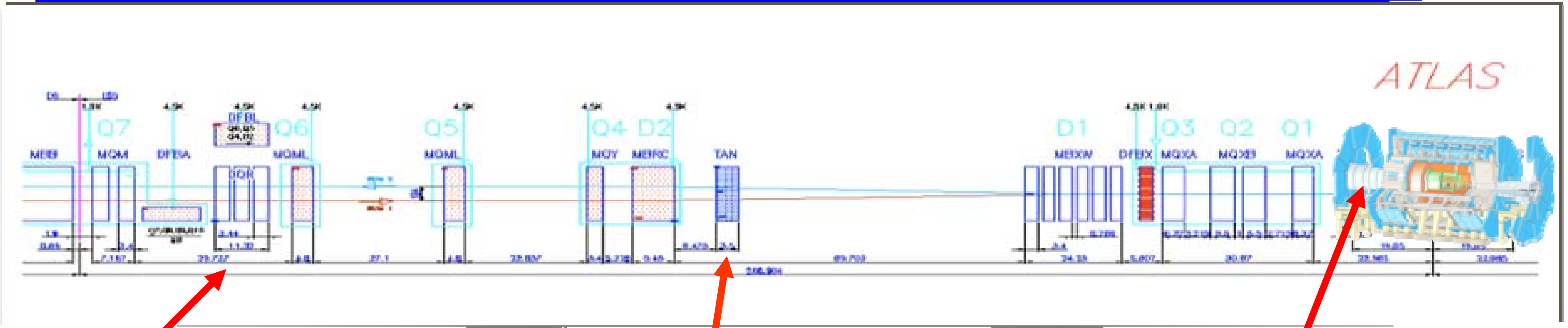
$$R_X = \sigma_X \cdot L$$

- Improve Luminosity from machine with ZDC

$\sigma_x\,\sigma_y$ from Van der Meer Scan

- Further luminosity/beam monitoring with BCM, MBTS...

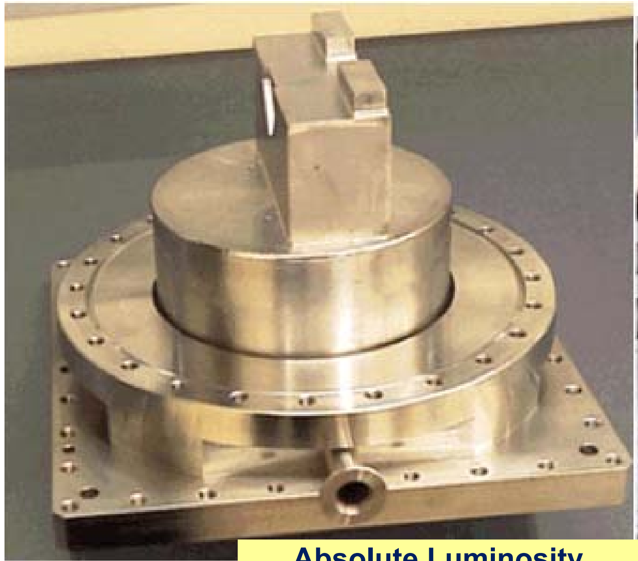
ATLAS Forward Detectors



ALFA at 240 m

ZDC at 140 m

LUCID at 17 m



Absolute Luminosity for ATLAS

2010

Zero Degree Calorimeter

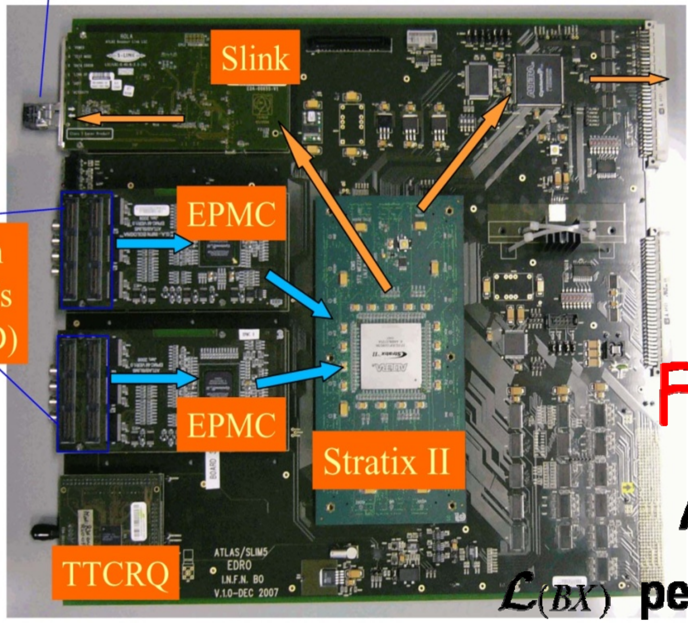
2009

Luminosity Čerenkov Integrating Detector

2008

LUminosity Monitor And Trigger card

- ✓ 9U Board
- ✓ VME A32, D32
- ✓ 5 board piggy back:
  - ✓ Main FPGA
    - ✓ (Stratix II)
  - ✓ 2 EPMC
    - ✓ (cyclone II)
  - ✓ S-link
  - ✓ TTCrq



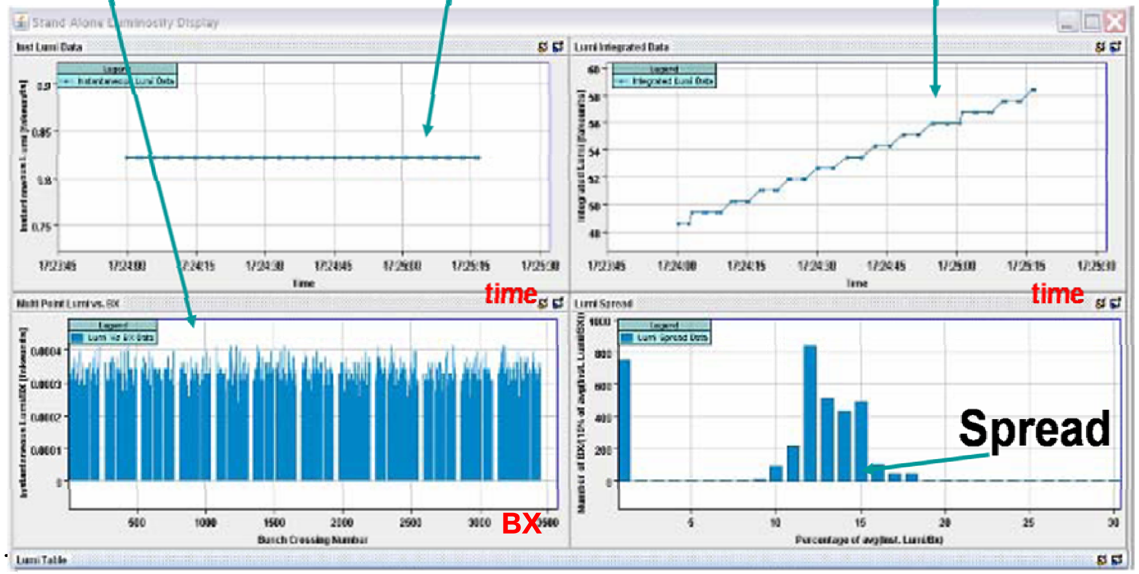
Performance:
40 Mhz bus clocks
8 Gbit input rate
1 Gbit output rate

Final goal: online monitor

Average $\mathcal{L}(t)$: beam stability

$$L(T) = \int_0^T \mathcal{L}(t)dt$$

$\mathcal{L}(BX)$ per-bunch



- ✓ Luminosity by BC
- ✓ Flexibility on luminosity and trigger algorithms
- ✓ Lucid hits in the ATLAS data stream

Luminosity

$$L_{BX} = \frac{\mu_{BX}}{\sigma_{pp}^{inel}} = \frac{L}{f_{BX}}$$

$$f_{BX} = \frac{n_{BX}}{3564} \times 40MHz$$

L_{BX}[cm^{-2}]	Average bunch luminosity
μ_{BX}	Mean number of inelastic proton-proton interactions per bunch crossing
σ_{pp}^{inel} [cm^2]	Inelastic proton-proton cross section (MB + SD + DD)
L [cm^{-2}, s^{-1}]	Instantaneous luminosity
f_{BX} [s^{-1}]	Bunch crossing frequency

- σ_{pp}^{inel} = 79.2 mb (PYTHIA6.2)
- σ_{pp}^{inel} = 84.5 mb (PHOJET1.12)
- Luminosity ranges from 10^{27} (calibration) to 10^{34} (LHC design)
- At design luminosity, n_{BX} = 2808 → μ_{BX} ~ 25

LUCID calibration

Measured by the calibration method.

$$L = \frac{f_{BX}}{\sigma_{pp} \cdot \varepsilon_{LUCID}} \frac{\langle N_{\text{hits/BX}} \rangle}{\langle N_{\text{hits/pp}} \rangle}$$

Calibration constant

Measured at low luminosity
~ 0.29 according to Monte Carlo

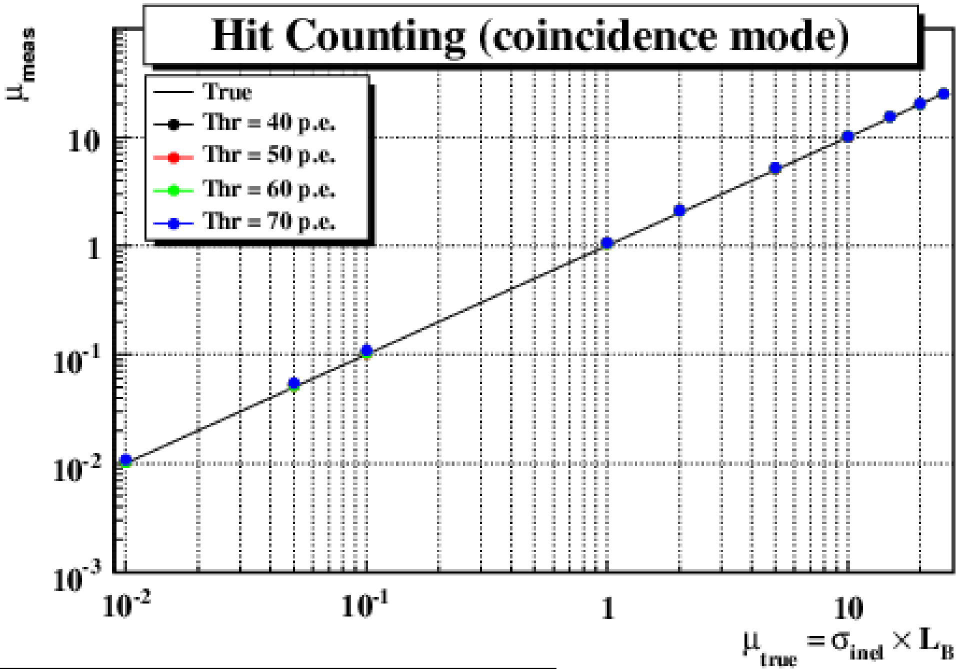
Initially. LHC Machine Parameters (Precision: ~ 10%)

Medium term. Physics processes, W/Z & μμ/ee (Precision: ~ 5-10%)

Final (>2010) Roman Pot (ALFA) measurement (Precision: ~ 2-3%)

Luminosity monitoring

- Average number of tracks per tube per event proportional to luminosity.
- Monitor bunch by bunch stability. Measure relative luminosity
- Calibration needed:
  - LHC machine parameters
  - Know reactions e.g. Z,W
  - ALFA calibration in special runs



$$\mu_{MEAS} = \frac{\langle M \rangle}{\langle N \rangle \cdot \varepsilon} = L \cdot \sigma_{inel} \Longrightarrow L = \frac{\langle M \rangle}{\langle N \rangle \cdot \varepsilon \cdot \sigma_{inel}}$$

μ = average number of interactions per bunch crossing

ε = interaction efficiency

<M> = average number of charged particles per bunch crossing

σ_{inel} = inelastic cross sec.

<N> = average number of particles per interaction

Calibration

$$L_{BX} = \frac{\mu_{BX}}{\sigma_{pp}^{inel}} = \frac{\langle M \rangle}{\sigma_{pp}^{inel} \times \varepsilon_{pp} \times \langle C \rangle} = k_{LUCID} \times \langle M \rangle$$

k_{LUCID} is the LUCID calibration constant

Calibration with Monte Carlo

$$k_{LUCID} = \frac{1}{\sigma_{pp}^{inel} \times \varepsilon_{pp} \times \langle C \rangle}$$

ε_{pp} and $<C>$ are extracted from single *pp* interaction events

Calibration with Data at low luminosity ($\mu_{BX} << 1$)

$$k_{LUCID} = \frac{L_{BX}^{ALFA,LHC}}{\langle M \rangle}$$

$<M>$ is measured by LUCID

L_{BX} is measured by LHC or ALFA

$<C>$ can also be measured by LUCID at low luminosity and cross-checked with MC

Summary of sys uncertainties

	Mode	Calibration	Range	Systematics
Zero counting	Single side	Monte Carlo	$\mu < 2$	1 %
Zero counting	Coincidence	Monte Carlo	$\mu < 2$	2 %
Hit counting	Single side	Monte Carlo	$\mu < 2$	2.6 %
Hit counting	Coincidence	Monte Carlo	$\mu < 2$	6 %
Hit counting	Single side	Data	any μ	3 %
Hit counting	Coincidence	Data	any μ	4 %

Thr = 50 *p.e.*

Monte Carlo

The number of reflections in the Cherenkov tube

$$\cos\theta_c = \frac{1}{\beta n(E)}$$

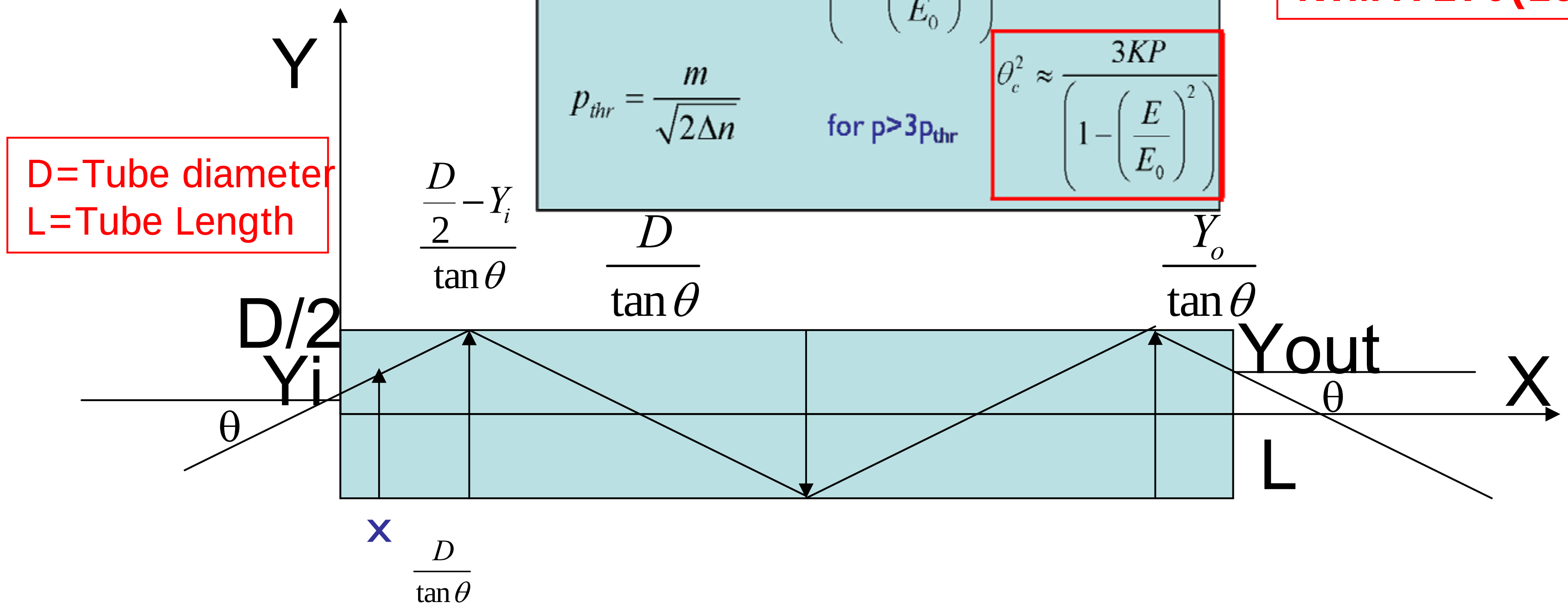
$$\theta_c^2 \approx 2(\Delta n - \Delta\beta) = \frac{3KP}{\left(1-\left(\frac{E}{E_0}\right)^2\right)} - \left(\frac{m}{p}\right)^2$$

(DELPHI Cherenkov Detector coll.) NIM A 270(1988)289

$$p_{thr} = \frac{m}{\sqrt{2\Delta n}}$$

for $p>3p_{thr}$

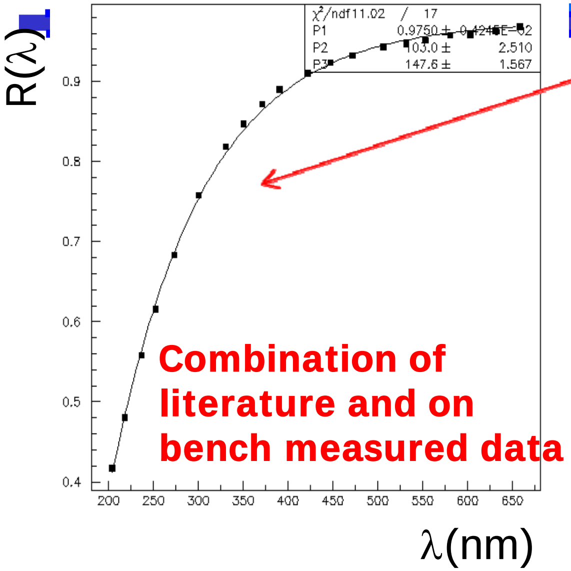
$$\theta_c^2 \approx \frac{3KP}{\left(1-\left(\frac{E}{E_0}\right)^2\right)}$$



$$N_r(E,x) \approx \frac{(L-x)}{D}\sqrt{\frac{3KP}{1-\left(\frac{E}{E_0}\right)^2}} + \frac{Y_i}{D}$$

In the following we will develop all calculation for Yi=0.

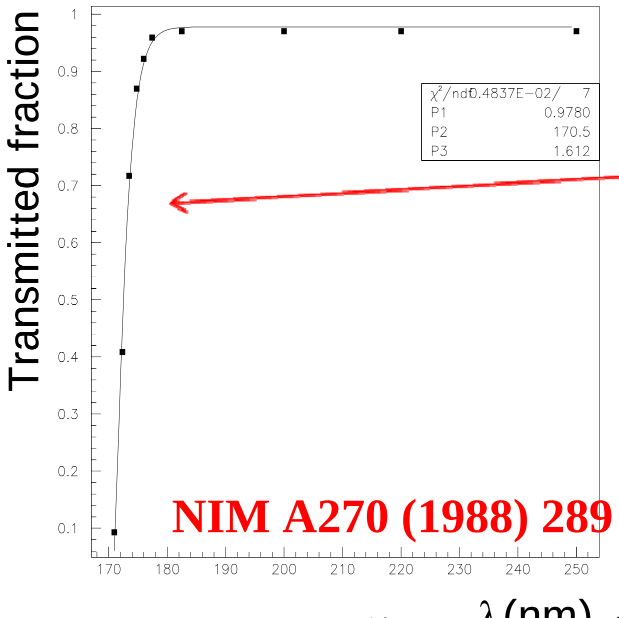
Aluminum reflectivity and Isobutane Transmittivity



$$R(\lambda)=R_0\left(1-e^{-\frac{(\lambda-\lambda_{R0})}{\lambda_R}}\right)$$

$$\begin{cases}\rho(\lambda,x)=R(\lambda)^{N_r(\lambda,x)}=R(\lambda)^{\frac{(L-x)}{D}\sqrt{\frac{3KP}{1-\left(\frac{C_{\lambda E}}{E_0\lambda}\right)^2}}}=e^{\frac{(L-x)}{D}F_R(\lambda,P)}\\ F_R(\lambda,P)=\sqrt{\frac{3KP}{1-\left(\frac{C_{\lambda E}}{E_0\lambda}\right)^2}}\ln(R(\lambda))\end{cases}$$

Functions used to fit the data



$$\left.\frac{I}{I_0}\right|_{\xi=75cm,P=1bar}=T_0\left(1-e^{-\frac{\lambda-\lambda_{T0}}{\lambda_T}}\right)^2$$

$$\begin{cases}T(\lambda,x)=\frac{I}{I_0}(\lambda,x)=e^{\frac{(L-x)P}{\xi P_0}\ln\left(T_0\left(1-e^{-\frac{\lambda-\lambda_{T0}}{\lambda_T}}\right)^2\right)}=e^{-\frac{(L-x)}{\xi}F_T(\lambda,P)}\\ F_T(\lambda,P)=-\frac{P}{P_0}\ln\left(T_0\left(1-e^{-\frac{\lambda-\lambda_{T0}}{\lambda_T}}\right)^2\right)\end{cases}$$

distribution
at the tube exit

ATLAS project

$$N_{ph} = -370\times C_{\lambda E}\iint \sin^2\theta_c \times \frac{d\lambda}{\lambda^2}dx = -370\times C_{\lambda E}\iint \frac{3KP}{1-\left(\frac{C_{\lambda E}}{E_0\lambda}\right)^2}\times\rho(\lambda,x)\times T(\lambda,x)\frac{d\lambda}{\lambda^2}dx =$$

$$= 370\times C_{\lambda E}\times 3KP\int_{\lambda_{MAX}}^{\lambda_{MIN}}\frac{1}{1-\left(\frac{C_{\lambda E}}{E_0\lambda}\right)^2}\frac{d\lambda}{\lambda^2}\int_0^L \rho(\lambda,x)\times T(\lambda,x)\,dx$$

$$K \equiv K(293.16\,^0K)$$

$$K(T) = \frac{0.257}{T}\frac{^0K}{bar}$$

$\lambda_{MIN} = 170nm$

Photocathode sensitivity range

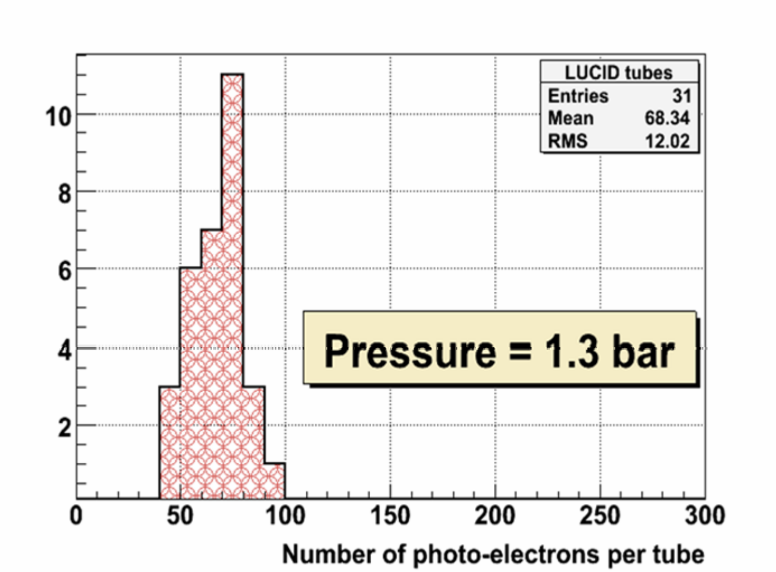
$$\frac{dN_{ph}}{d\lambda} = \frac{370\times C_{\lambda E}\times 3KP}{1-\left(\frac{C_{\lambda E}}{E_0\lambda}\right)^2}\times\frac{D\xi e^{-\frac{L}{\xi}F_T}\left(e^{\frac{L}{D}F_R}-e^{\frac{L}{\xi}F_T}\right)}{DF_T-\xi F_R}\times\frac{1}{\lambda^2}$$

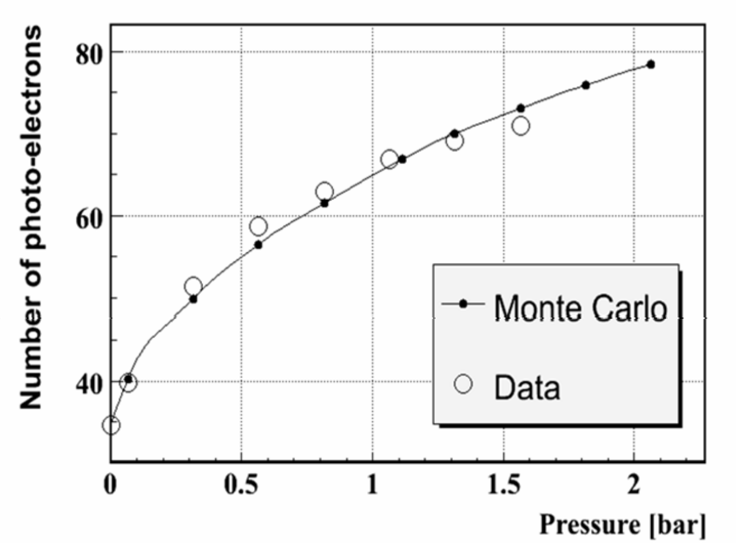
Table of Constants			
	Symbol	Value	Units
	$C_{\lambda E}$	1240	nm·eV
Isobutane Rindex	E_0	13.5	eV
	K	$8.767\cdot 10^{-4}$	^{0}K/bar
Aluminum reflectivity	R_0	0.975	
	λ_{R0}	147.6	nm
	λ_R	103.0	nm
Isobutane transmittivity	ξ	75.0	cm
	T_0	0.978	
	λ_{T0}	170.5	nm
	λ_T	1.612	nm

- The photomultiplier window Quantum Efficiency can not be easily included in the model and a numerical computation is necessary

prediction and the Monte Carlo simulation

LUCID has been tested and calibrated with a beam of 180 GeV pions (SPS H8)





	P(bar)	0.1	0.3	0.6	0.8	1.1	1.3	1.6	1.8	2.1
# of p.e.	MC	40	50	57	62	67	70	73	76	79
	Model	33	45	53	57	63	67	71	74	78
	Δ(%)	11	11	6	6	5	5	3	3	1

A very good agreement is found between the photoelectron yields of this model and the LUCID MC simulation

The gas Refractive Index

NIM A270 (1988) 289 (DELPHI Cherenkov Detector coll.)

$$\frac{n^2-1}{n^2+2} = \frac{0.257}{1-\left(\frac{E(eV)}{13.5}\right)^2} \times \frac{P(bar)}{T} = (at\ T = 20^0K) = \frac{8.767 \cdot 10^{-4} P(bar)}{1-\left(\frac{E(eV)}{13.5}\right)^2} = \frac{KP(bar)}{1-\left(\frac{E(eV)}{E_0}\right)^2}$$

n=1+Δn , β=1−Δβ

$$\Delta n = \frac{\frac{3}{2}KP(bar)}{1-\left(\frac{E(eV)}{E_0}\right)^2}, \quad \Delta\beta = \frac{1}{2}\left(\frac{m}{p}\right)^2$$

$$\cos\theta_c = \frac{1}{\beta n(E)}$$

$$\theta_c^2 \approx 2(\Delta n - \Delta\beta) = \frac{3KP}{\left(1-\left(\frac{E}{E_0}\right)^2\right)} - \left(\frac{m}{p}\right)^2$$

$$p_{thr} = \frac{m}{\sqrt{2\Delta n}}$$

for $p>3p_{thr}$

$$\theta_c^2 \approx \frac{3KP}{\left(1-\left(\frac{E}{E_0}\right)^2\right)}$$

At the production threshold the angle θ_c is about 0

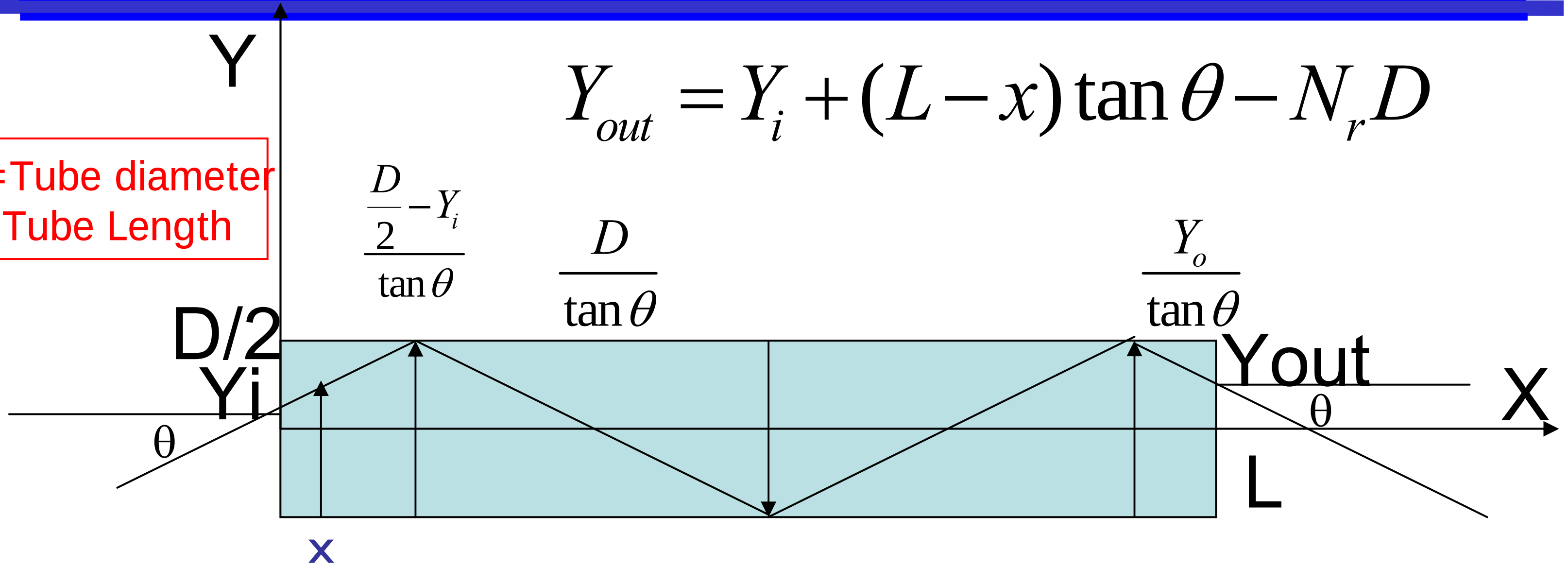
$$C_{\lambda E} = \lambda(nm)E(eV) = 1240\ nm \cdot eV$$

Constant used in the following to transforn photons energy in wavelength

The number of reflections inside a tube

$$Y_{out} = Y_i + (L - x)\tan\theta - N_r D$$

D=Tube diameter
L=Tube Length

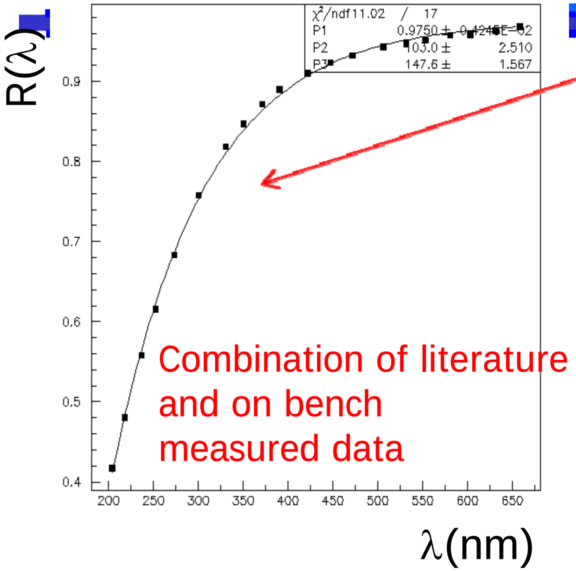


$$N_r(\theta, x) = INT\left(\frac{(L-x)\tan\theta}{D} + \frac{Y_i}{D} + \frac{1}{2}\right) \approx \frac{(L-x)\tan\theta}{D} + \frac{Y_i}{D}$$

$$N_r(E, x) \approx \frac{(L-x)}{D}\sqrt{\frac{3KP}{1-\left(\frac{E}{E_0}\right)^2}} + \frac{Y_i}{D}$$

In the following we will develop all calculation for Yi=0.

Aluminum reflectivity and Isobutane Transmittivity

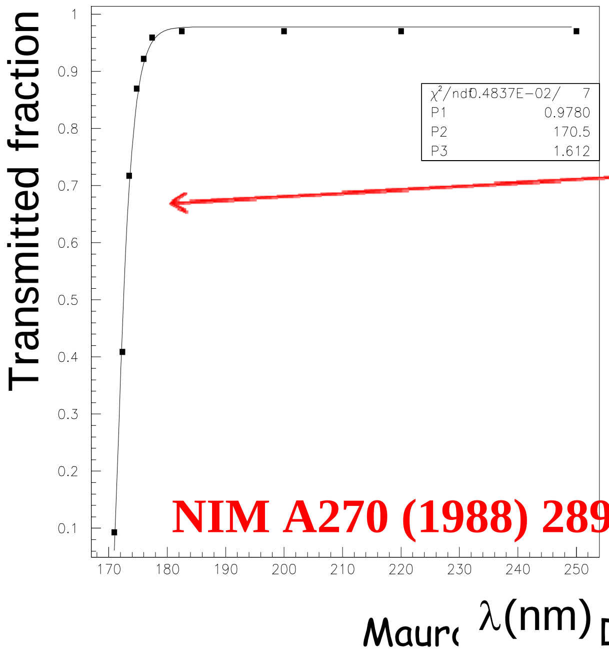


Combination of literature and on bench measured data

$$R(\lambda)=R_0\left(1-e^{\frac{(\lambda-\lambda_{R0})}{\lambda_R}}\right)$$

$$\begin{cases}\rho(\lambda,x)=R(\lambda)^{N_r(\lambda,x)}=R(\lambda)^{\frac{(L-x)}{D}\sqrt{\frac{3KP}{1-\left(\frac{C_{\lambda E}}{E_0\lambda}\right)^2}}}=e^{\frac{(L-x)}{D}F_R(\lambda,P)}\\ F_R(\lambda,P)=\sqrt{\frac{3KP}{1-\left(\frac{C_{\lambda E}}{E_0\lambda}\right)^2}}\ln(R(\lambda))\end{cases}$$

Functions used to fit the data



NIM A270 (1988) 289

$$\left.\frac{I}{I_0}\right|_{\xi=75cm,P=1bar}=T_0\left(1-e^{-\frac{\lambda-\lambda_{T0}}{\lambda_T}}\right)^2$$

$$\begin{cases}T(\lambda,x)=\frac{I}{I_0}(\lambda,x)=e^{\frac{(L-x)P}{\xi P_0}\ln\left[T_0\left(1-e^{-\frac{\lambda-\lambda_{T0}}{\lambda_T}}\right)^2\right]}=e^{-\frac{(L-x)}{\xi}F_T(\lambda,P)}\\ F_T(\lambda,P)=-\frac{P}{P_0}\ln\left(T_0\left(1-e^{-\frac{\lambda-\lambda_{T0}}{\lambda_T}}\right)^2\right)\end{cases}$$

distribution at the tube exit

$$N_{ph} = -370 \times C_{\lambda E} \iint \sin^2 \theta_c \times \frac{d\lambda}{\lambda^2} dx = -370 \times C_{\lambda E} \iint \frac{3KP}{1-\left(\frac{C_{\lambda E}}{E_0 \lambda}\right)^2} \times \rho(\lambda, x) \times T(\lambda, x) \frac{d\lambda}{\lambda^2} dx =$$

$$= 370 \times C_{\lambda E} \times 3KP \int_{\lambda_{MAX}}^{\lambda_{MIN}} \frac{1}{1-\left(\frac{C_{\lambda E}}{E_0 \lambda}\right)^2} \frac{d\lambda}{\lambda^2} \int_0^L \rho(\lambda, x) \times T(\lambda, x) dx$$

$$= 370 \times C_{\lambda E} \times 3KP \int_{\lambda_{MAX}}^{\lambda_{MIN}} \frac{1}{1-\left(\frac{C_{\lambda E}}{E_0 \lambda}\right)^2} \frac{d\lambda}{\lambda^2} \int_0^L e^{\frac{L-x}{D} F_R(\lambda, P)} \times e^{-\frac{L-x}{\xi} F_T(\lambda, P)} dx$$

$$= 370 \times C_{\lambda E} \times 3KP \int_{\lambda_{MAX}}^{\lambda_{MIN}} \frac{1}{1-\left(\frac{C_{\lambda E}}{E_0 \lambda}\right)^2} \frac{D\xi e^{-\frac{L}{\xi} F_T(\lambda, P)} \left(e^{\frac{L}{D} F_R(\lambda, P)} - e^{\frac{L}{\xi} F_T(\lambda, P)} \right)}{D F_T(\lambda, P) - \xi F_R(\lambda, P)} \frac{d\lambda}{\lambda^2}$$

$\lambda_{MIN} = 170 nm$

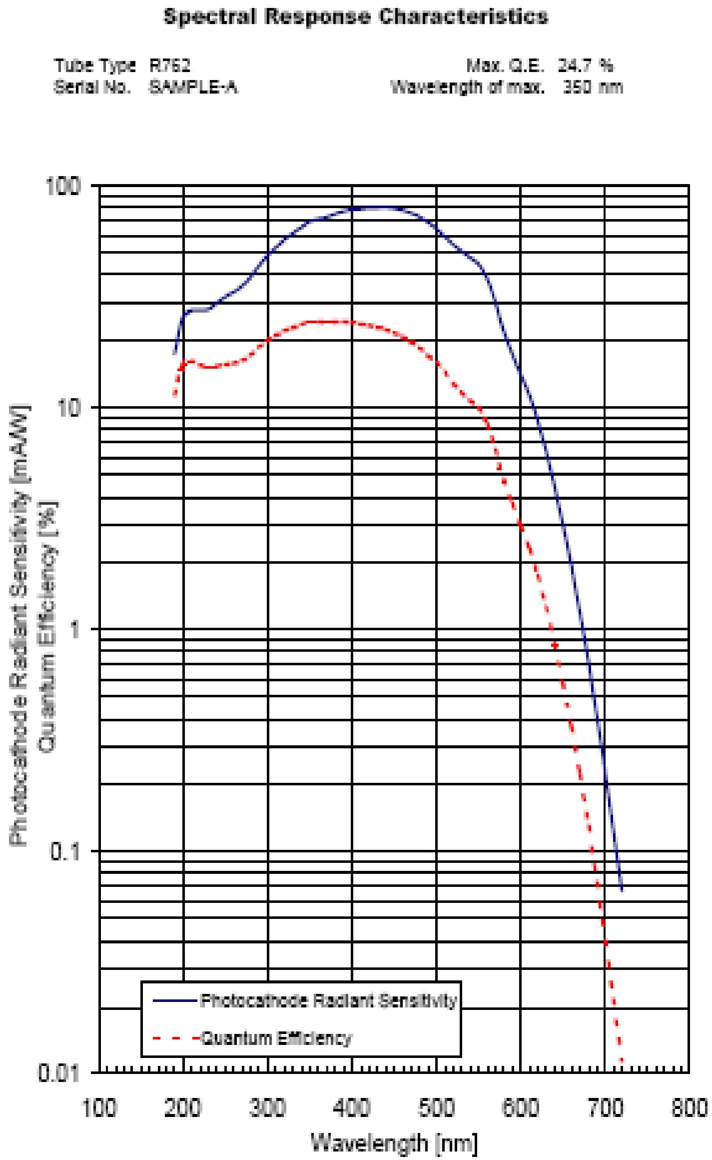
$\lambda_{MAX} = 700 nm$

Photocathode sensitivity range

$$\frac{dN_{ph}}{d\lambda} = \frac{370 \times C_{\lambda E} \times 3KP}{1-\left(\frac{C_{\lambda E}}{E_0 \lambda}\right)^2} \times \frac{D\xi e^{-\frac{L}{\xi} F_T} \left(e^{\frac{L}{D} F_R} - e^{\frac{L}{\xi} F_T} \right)}{D F_T - \xi F_R} \times \frac{1}{\lambda^2}$$

- The photomultiplier window Quantum Efficiency can not be easily included in the model and a numerical computation is necessary

Table of constants and Quantum Efficiency typical plots



Spectral Response Characteristics

Tube Type R762
Serial No. SAMPLE-A

Table of Constants			
	Symbol	Value	Units
	$C_{\lambda E}$	1240	nm·eV
Isobutane Rindex	E_0	13.5	eV
	K	$8.767 \cdot 10^{-4}$	^{0}K/bar
Aluminum reflectivity	R_0	0.975	
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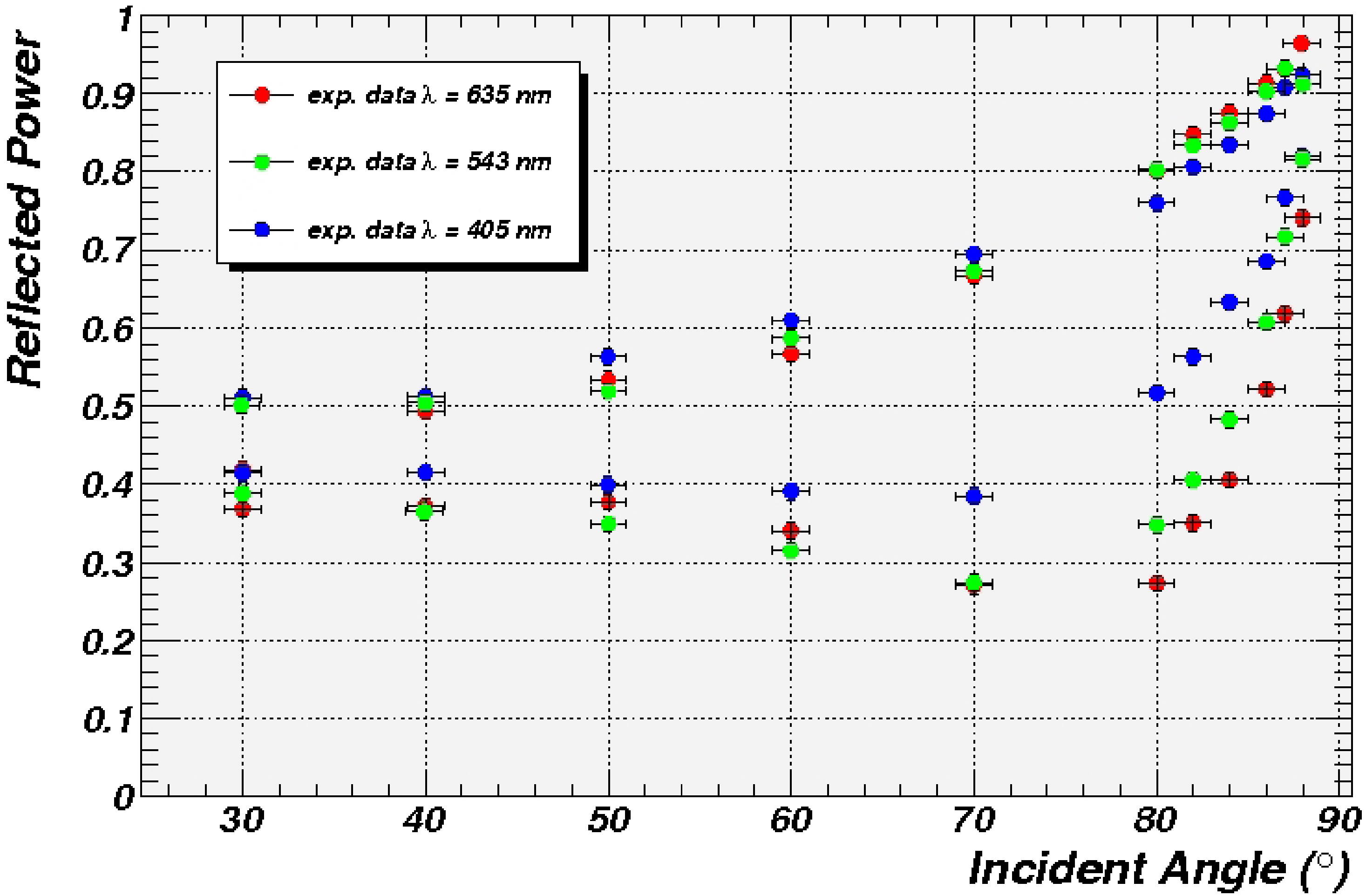
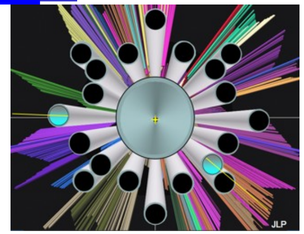
Isobutane transmittivity	ξ	75.0	cm
	T_0	0.978	
	λ_{T0}	170.5	nm
	λ_T	1.612	nm

$$K \equiv K(293.16^0 K)$$

$$K(T) = \frac{0.257}{T} \frac{^0K}{bar}$$

Aluminium reflectivity measurements





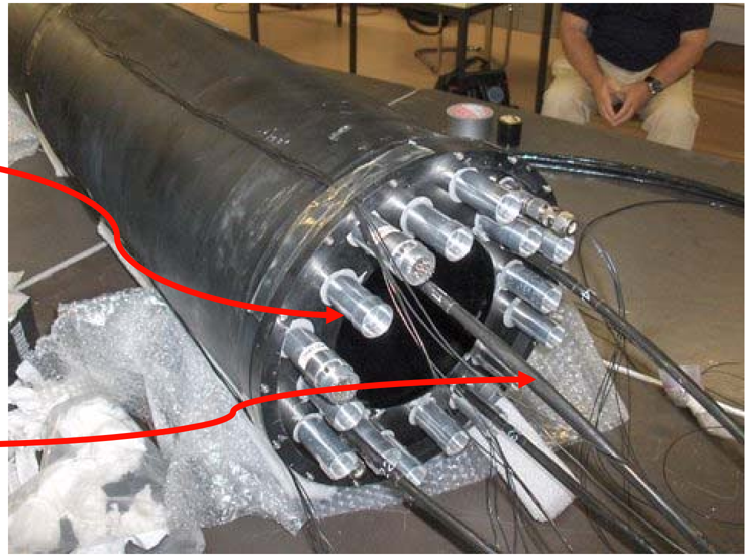
project approved in February 2007

construction and assembly by Bologna + Alberta groups

for installation in ATLAS

’s

ers



completed tests:

final test beam next week

- vessel sealing, LED’s read out, calibration