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United Nations Educational, Scientific and Cultural Organization

IAEA
International Atomic Energy Agency

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International Workshop on QCD at Cosmic Energies III

28 May - 1 June, 2007

Lecture Notes

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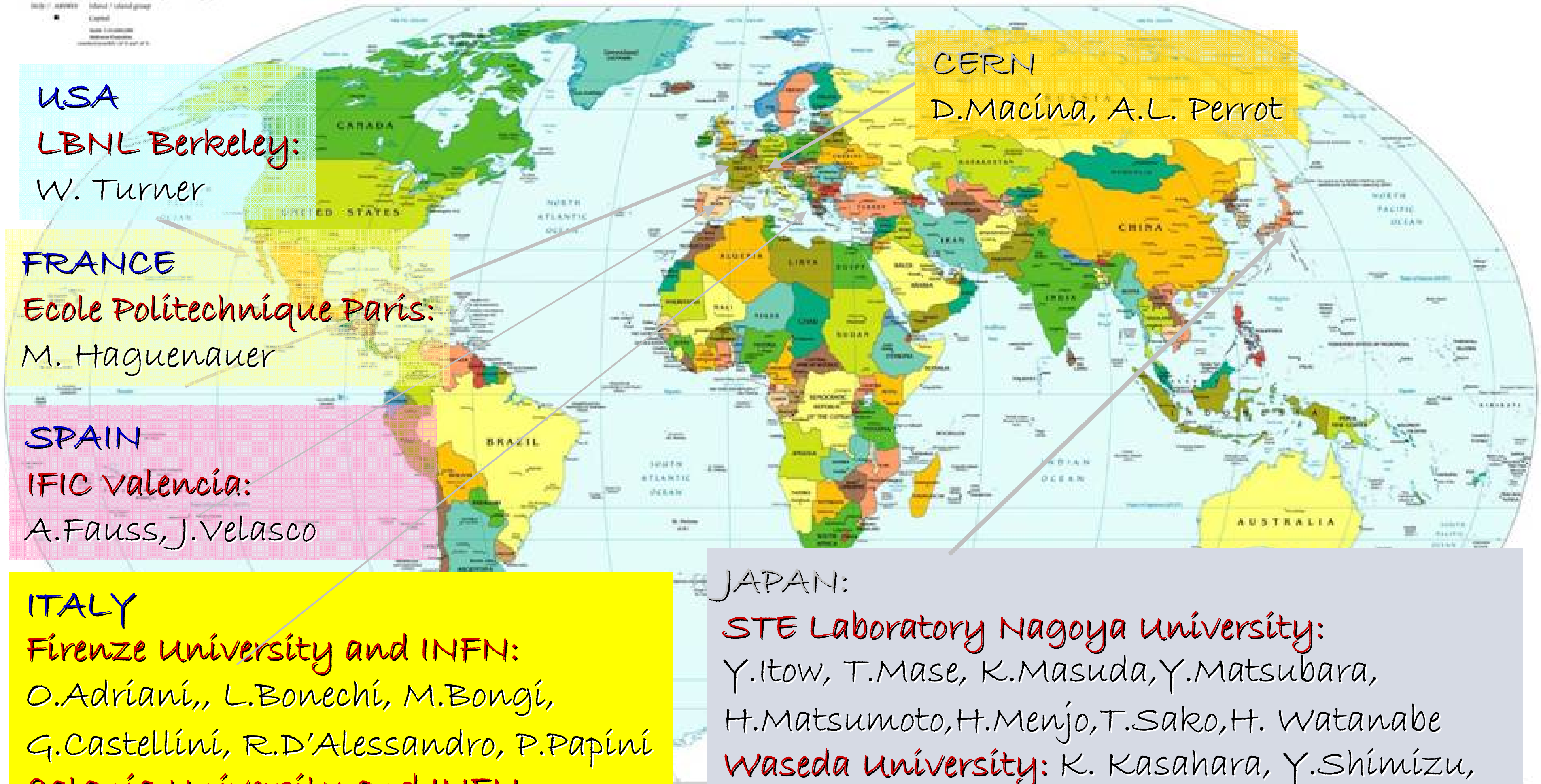
3rd International Workshop on QCD at Cosmic Energies
Trieste May 28 - June 1, 2007

LHCf: an accelerator experiment for Cosmic Ray Physics

Oscar Adriani
University and INFN Firenze
on behalf of the LHCf Collaboration

The LHCf Collaboration



USA
LBNL Berkeley:
W. Turner

CERN
D.Macina, A.L. Perrot

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A.Fauss, J.Velasco

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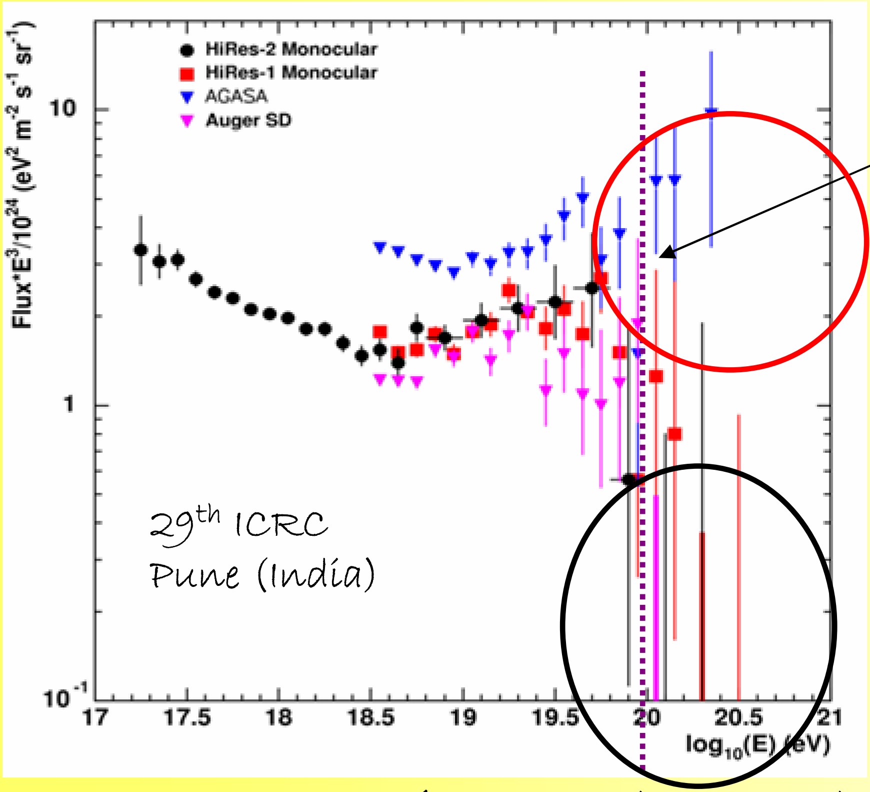
Outline

- Introduction
  - Main problems in HECR physics: GZK cut off, chemical composition
- Idea of LHCf
  - Measurement of neutral particles emitted very forward at LHC
- Simulation and test beam results
  - Performances of the detector
- Conclusions, plans and schedule
  - Toward the LHC operation

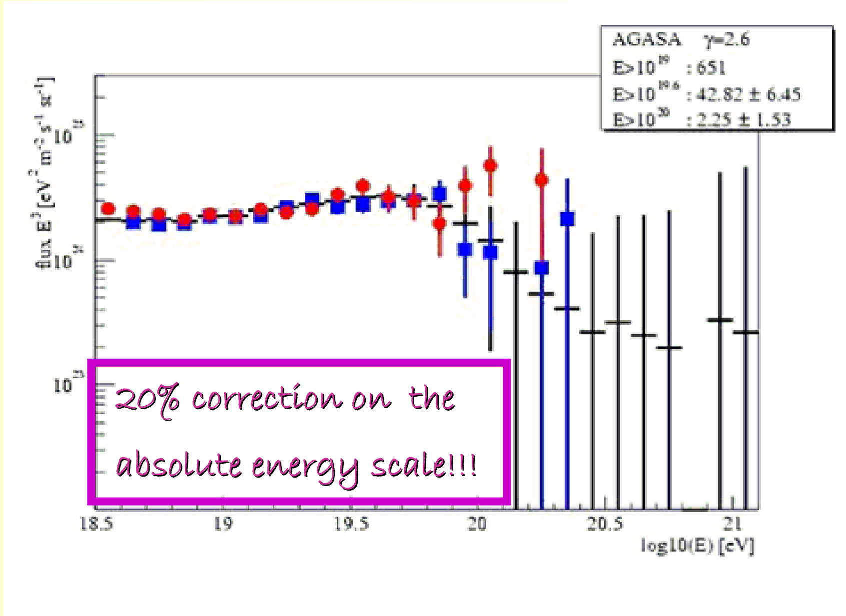
Introduction: GZK cut off



GZK cutoff: 10^{20} eV

super GZK events?!?

Huge experiment (Auger, TA) will solve the statistics



AGASA reports 18% systematic uncertainty in energy determination.

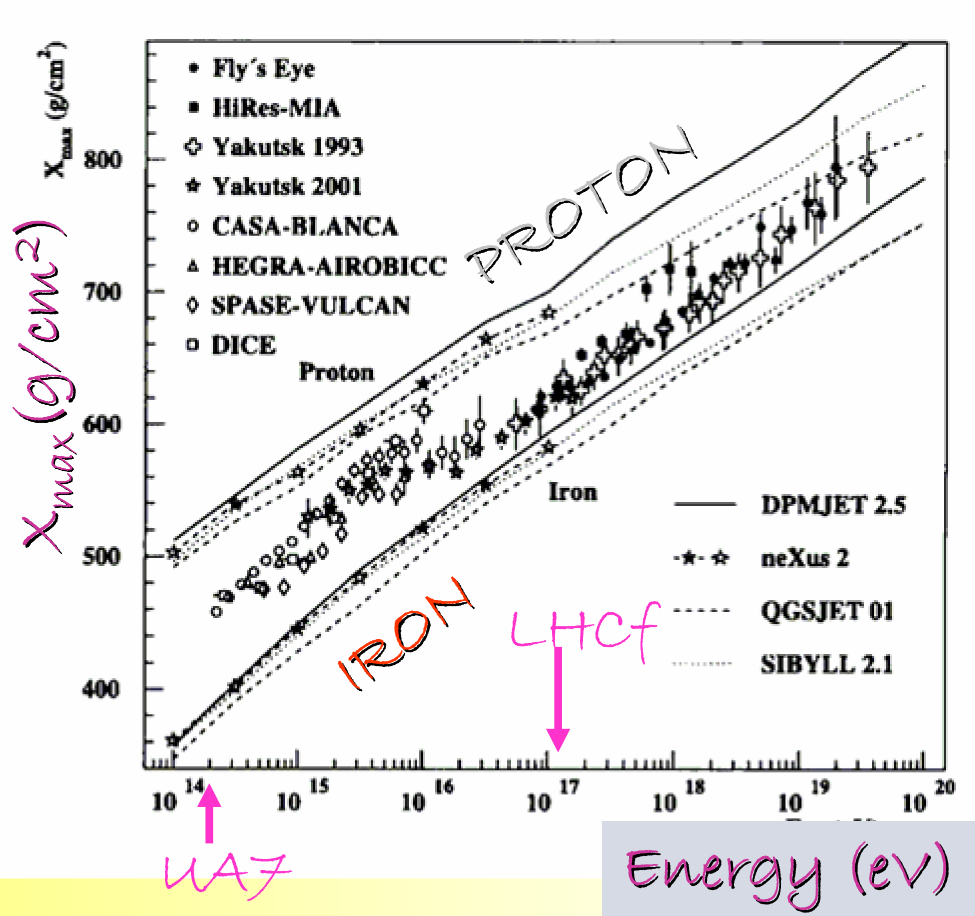
10% of systematic is due to interaction model.

Accelerator calibration is necessary.

HOWEVER

Different interaction models give different answers for the primary cosmic ray energy estimate.

Introduction: cosmic ray composition



Knapp et al., 2003

Not only GZK…

Different interaction models lead different conclusions about the composition of the primary cosmic rays.

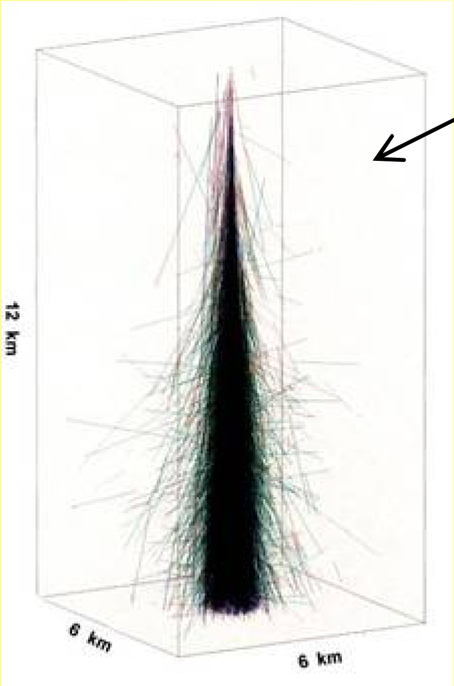
Composition: inferred from X_{max}

Spectrum: Energy is measured by counting the secondaries

Simulation plays a crucial role

LHCf is a tool to calibrate the simulation

Development of atmospheric showers

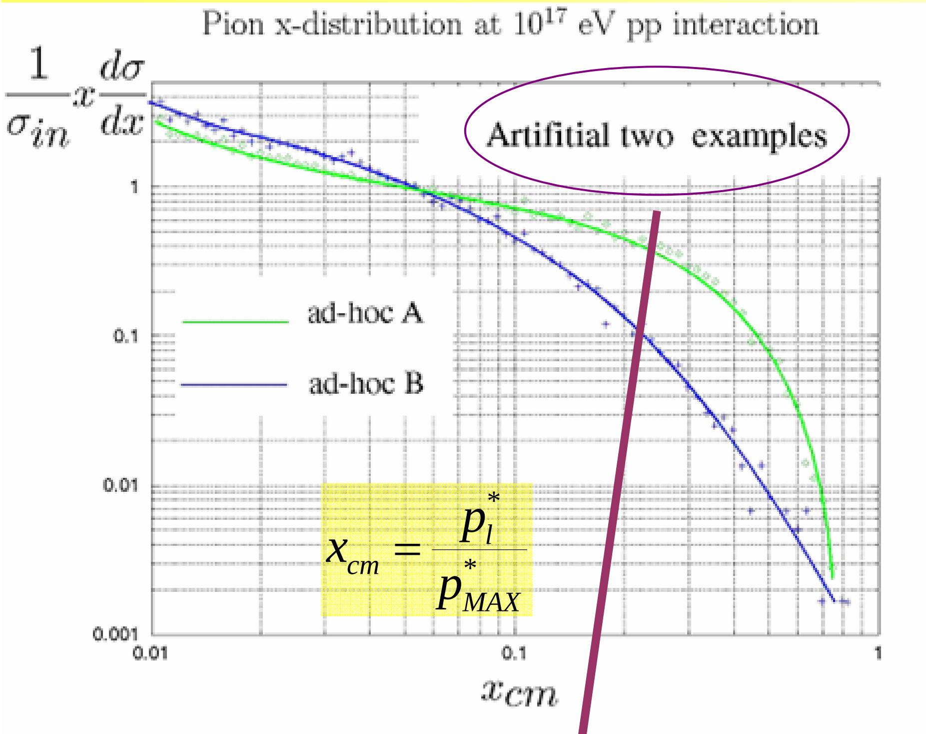


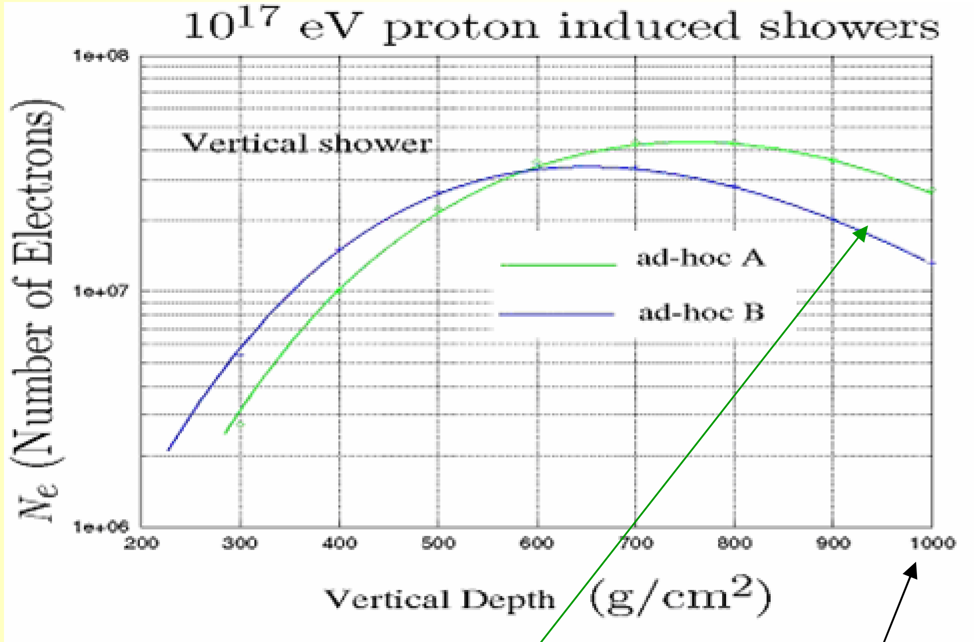
Simulation of an atmospheric shower due to a 10^{19} eV proton.

- ✓The dominant contribution to the energy flux is in the very forward region ($\theta \approx 0$)
- ✓ In this forward region the highest energy available measurements of π^0 cross section were done by UA7 ($E=10^{14}$ eV, $y= 5\div7$)

$$y = -\ln\tan\frac{\theta}{2}$$

Longitudinal development of showers





DPMJET, QGSJET, SIBYLL ...
are normally used

Factor 2 of discrepancy

Sea Level

The direct measurement of the π production cross section as function of p_T is essential to correctly estimate the energy of the primary cosmic rays

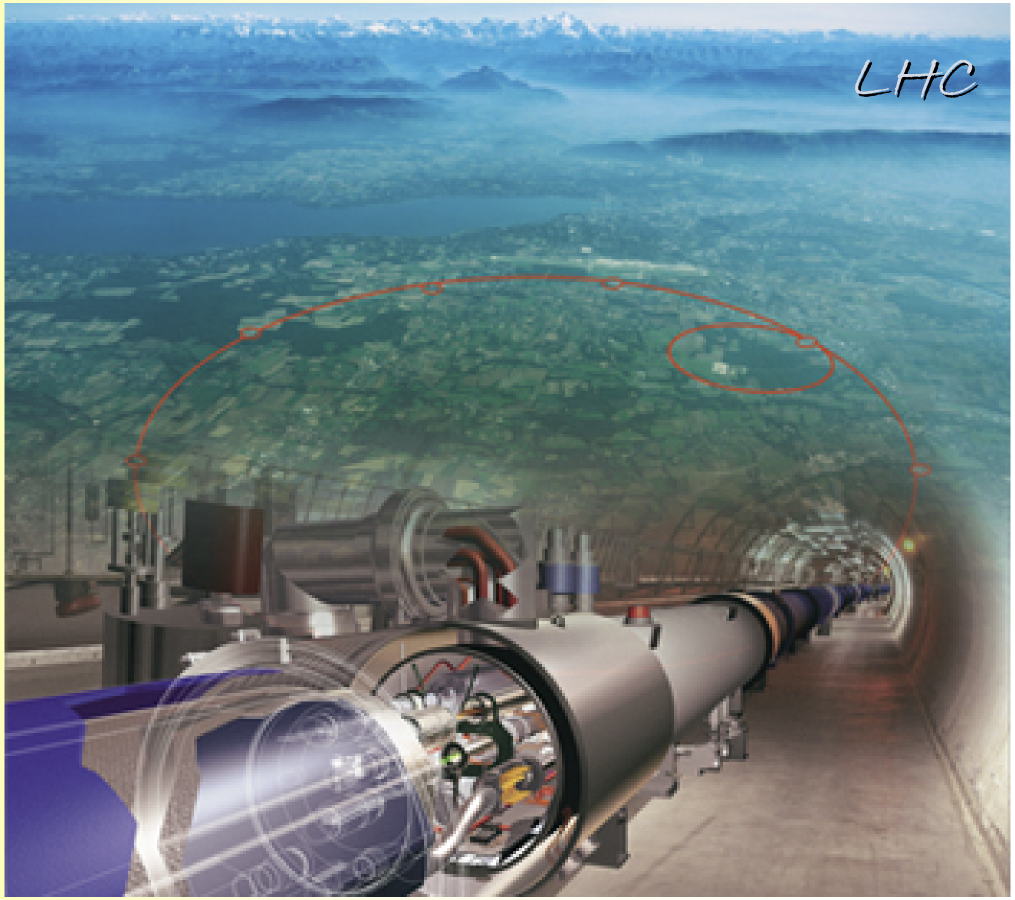
Summarizing...
LHC-HECR interplay

Calibration of the models at high energy is mandatory

We will use LHC,
the highest energy accelerator

7 TeV + 7 TeV protons
14 TeV in the center of mass

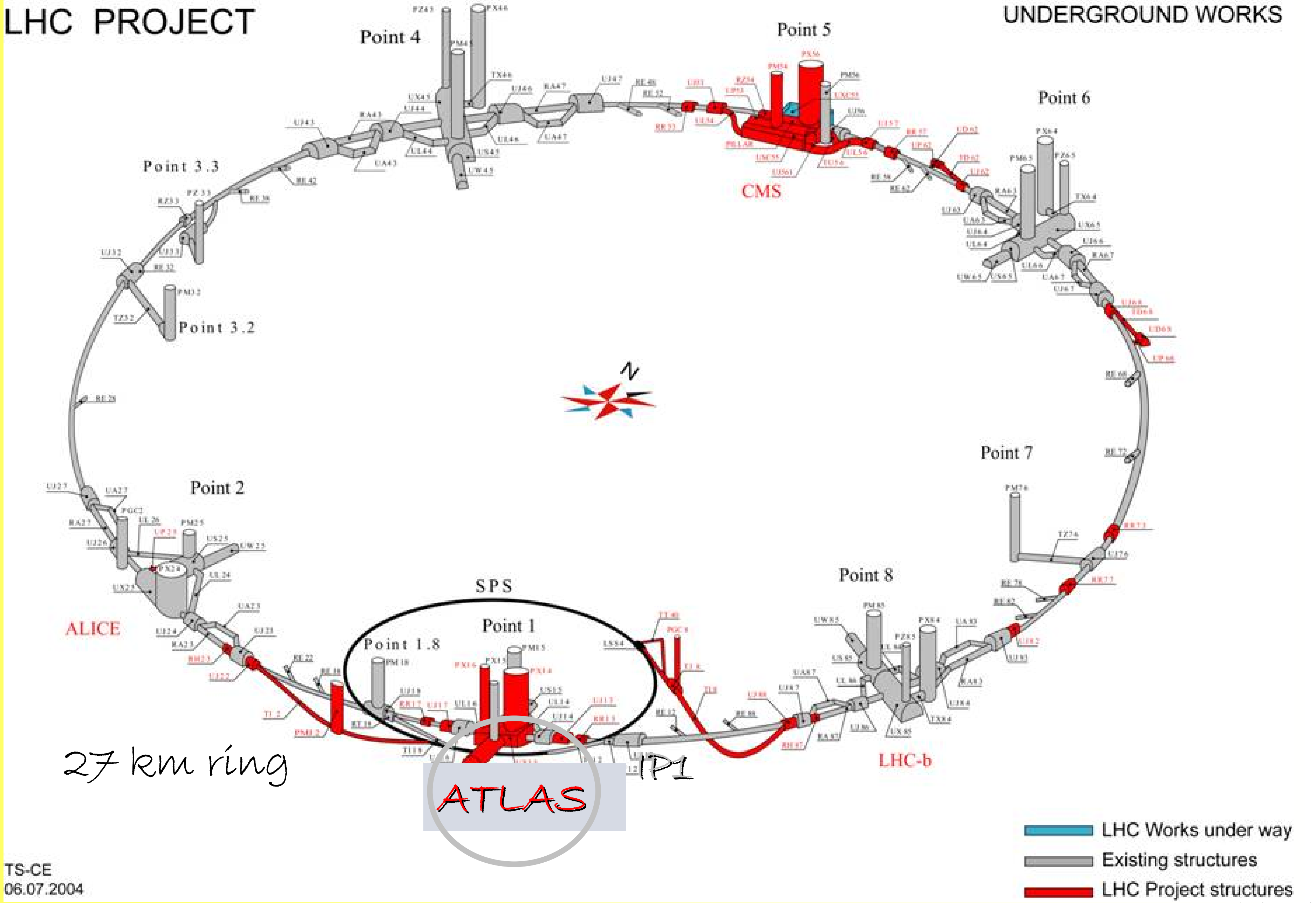
$E_{lab}=10^{17}$ eV ($E_{lab}= E^2_{cm}/2\, m_p$)



Major LHC detectors (ATLAS, CMS, LHCB) will measure the particles emitted in the central region

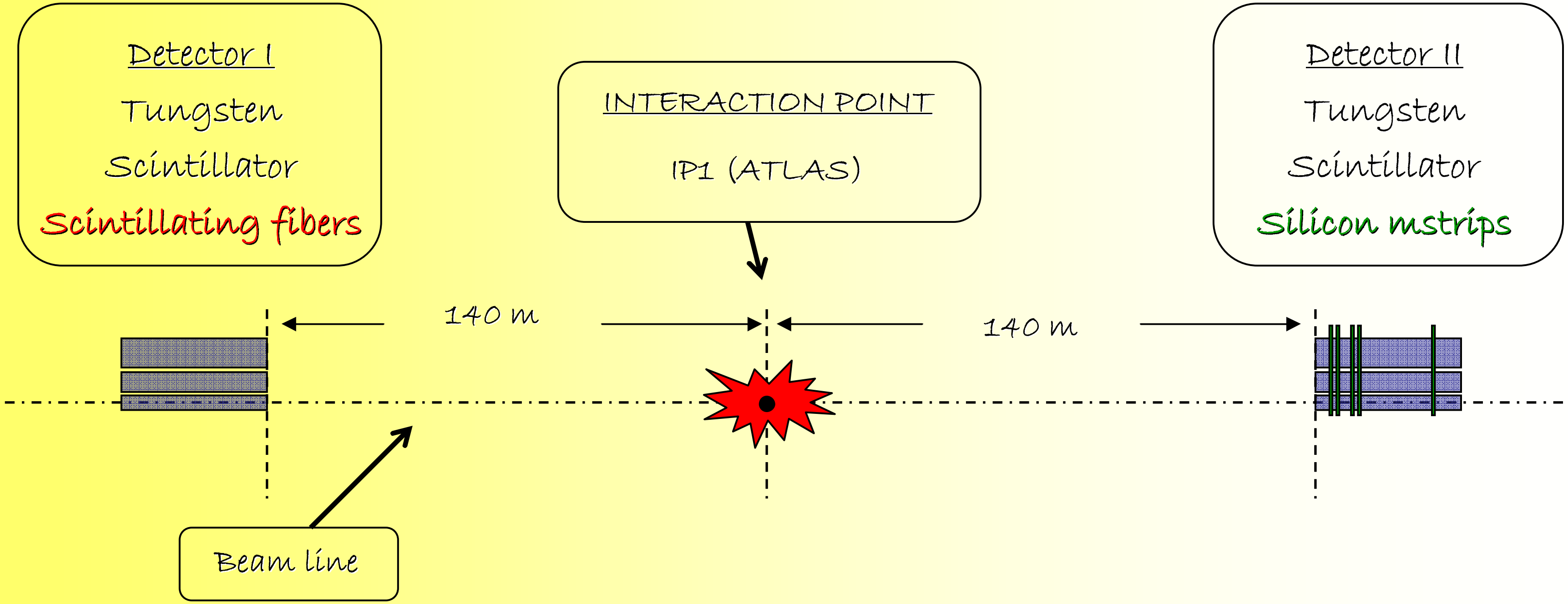
LHCf will cover the very forward part
May be also heavy ions collisions????

The LHC ring



LHC PROJECT
UNDERGROUND WORKS
Point 4
Point 5
Point 6
Point 3.3
Point 3.2
CMS
Point 7
Point 2
Point 8
SPS
Point 1
Point 1.8
ALICE
LHC-b
27 km ring
IP1
ATLAS
LHC Works under way
Existing structures
LHC Project structures
TS-CE
06.07.2004

LHCf: location and experimental layout

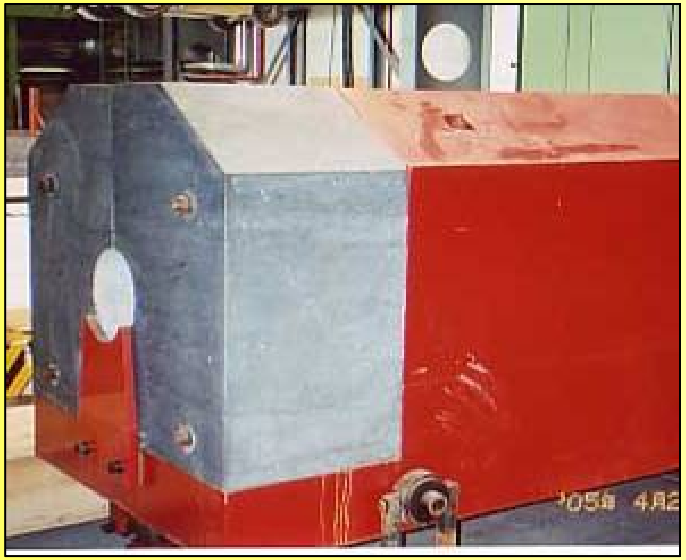


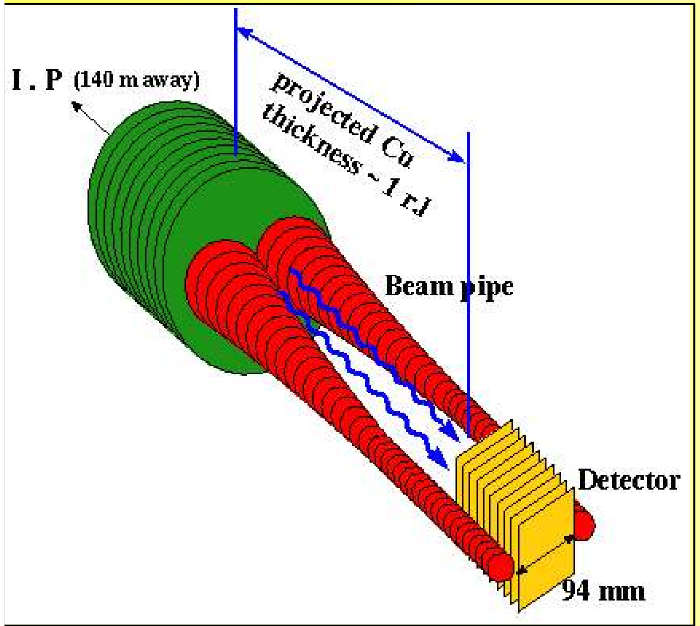
Detectors should measure energy and position of γ from π^0 decays → e.m. calorimeters with position sensitive layers

Two independent detectors on both side of IP1

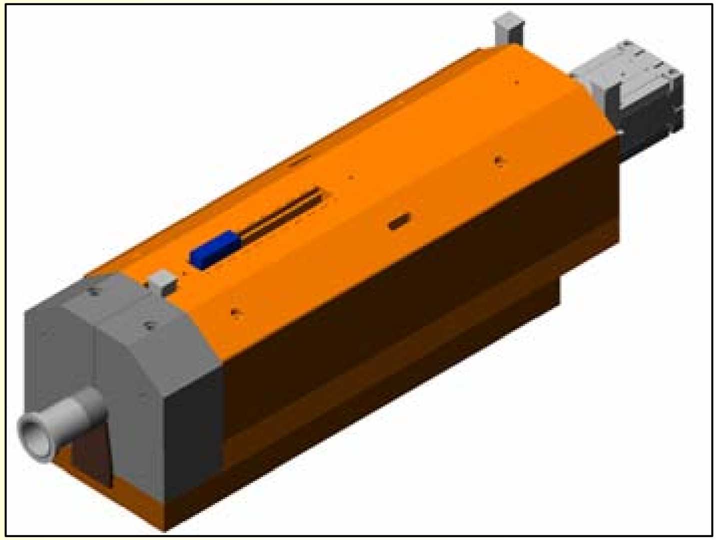
- ✓ Redundancy
- ✓ Background rejection (especially beam-gas)

LHCf location





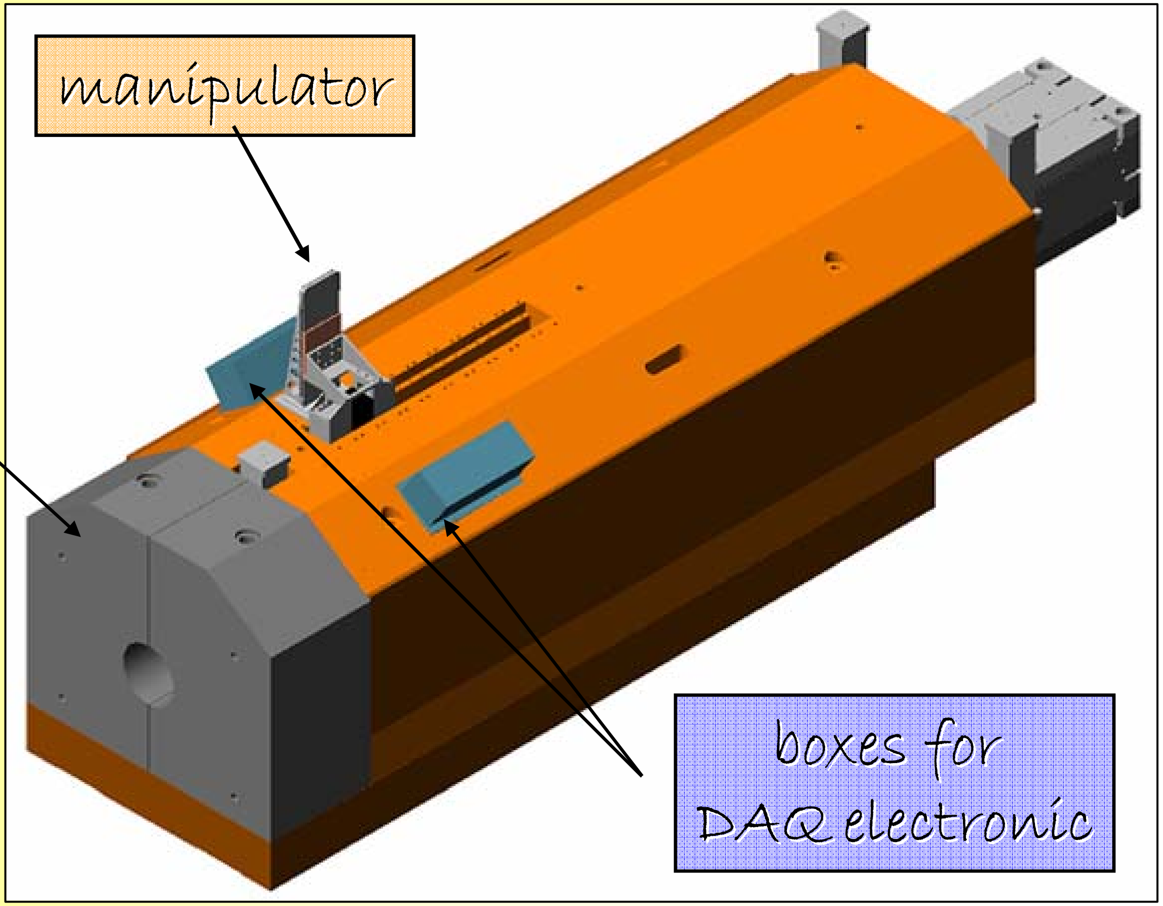
Detectors will be installed in the TAN region, 140 m away from the Interaction Point, in front of luminosity monitors

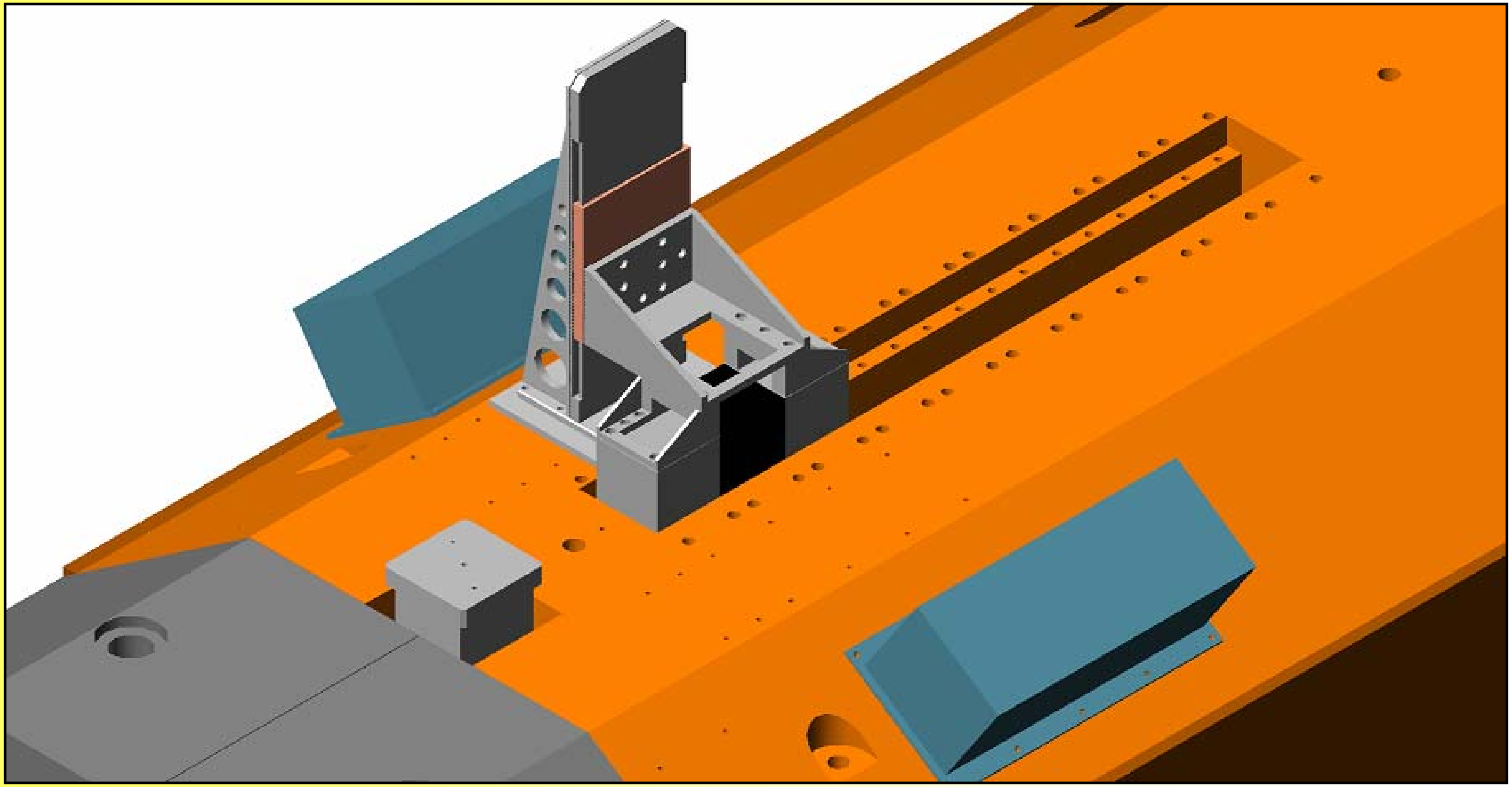


- Here the beam pipe splits in 2 separate tubes.
- Charged particle are swept away by magnets!!!
- We will cover up to $y \rightarrow \infty$

The TAN and LHCf

marble shielding





Detector #1

2 towers ~24 cm long stacked vertically with 5 mm gap

Lower: 2 cm x 2 cm area

Upper: 4 cm x 4 cm area

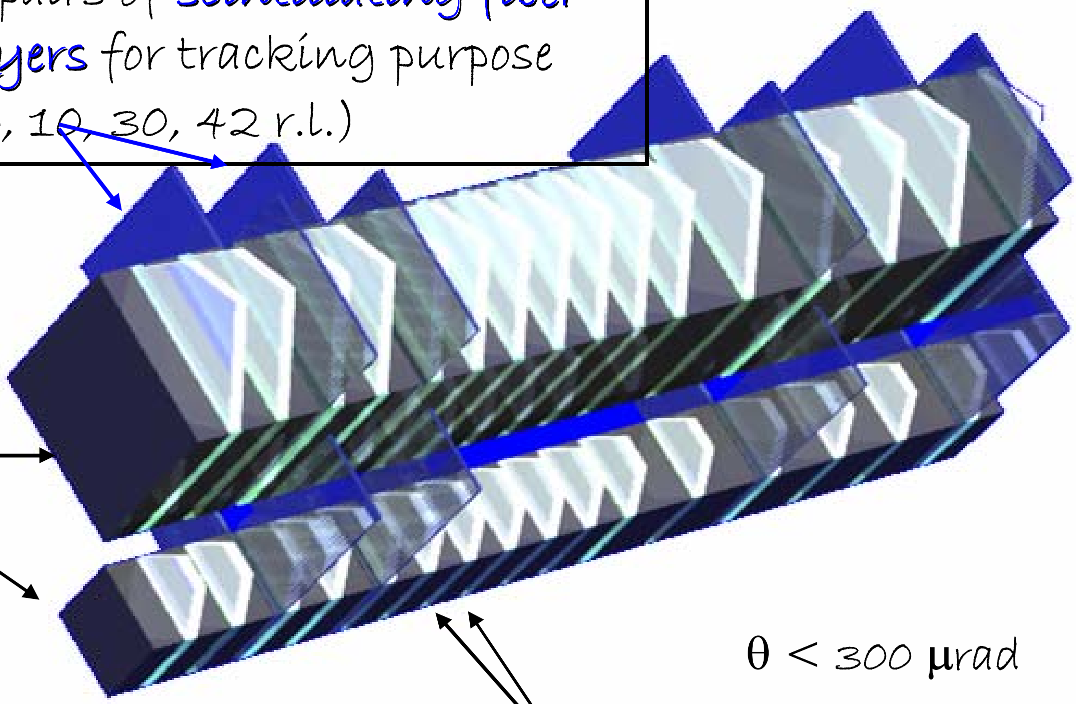
Absorber

22 tungsten layers 7mm thick →
44 X_0 (1.6 λ_I) in total

(W: X_0 = 3.5mm, R_M = 9mm)

Impact point (η)

4 pairs of **scintillating fiber layers** for tracking purpose (6, 10, 30, 42 r.l.)



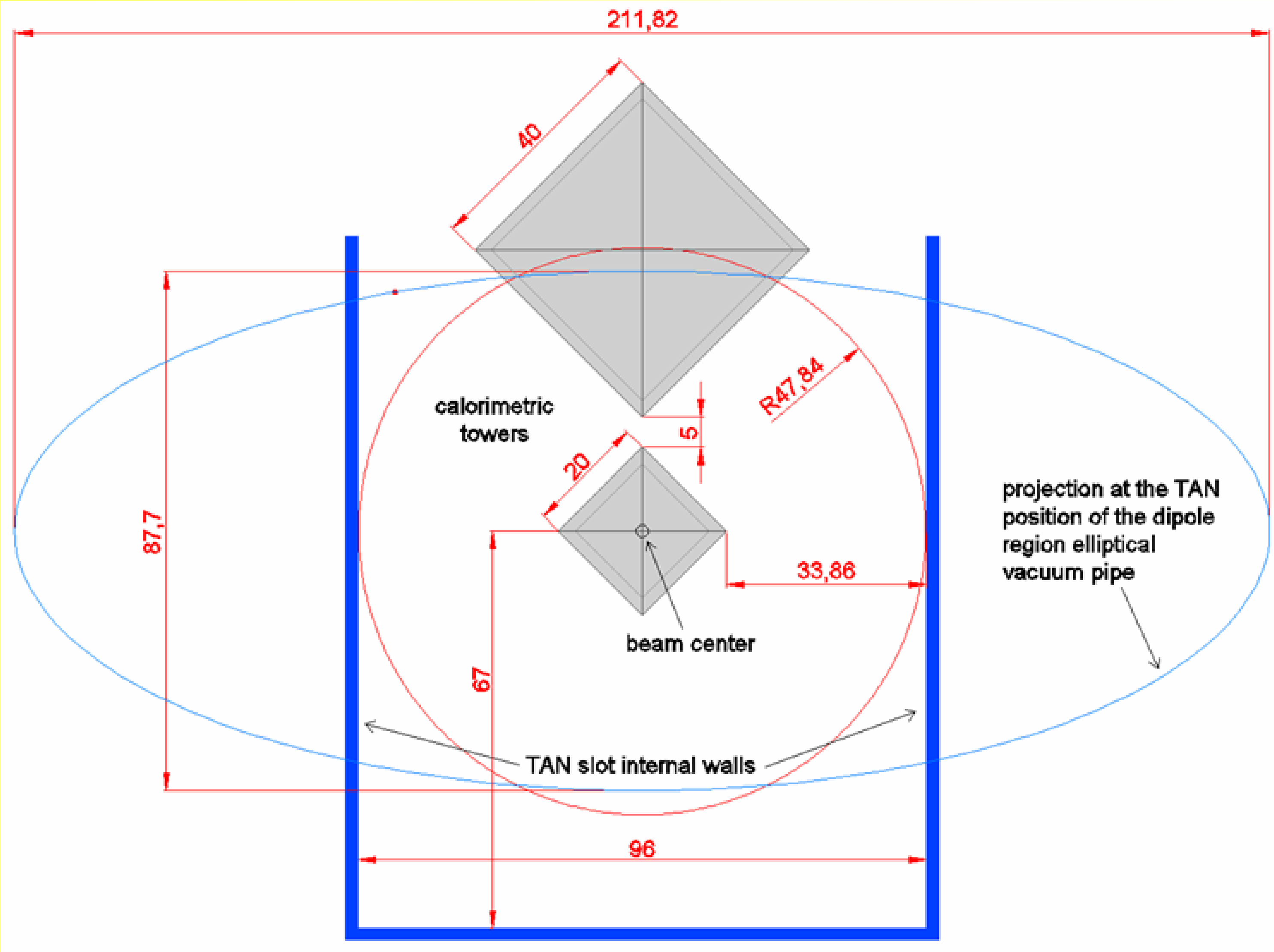
θ < 300 μrad

16 scintillator layers (3 mm thick)

Trigger and energy profile measurements

Energy

Transverse projection of detector #1 in the TAN slot



Detector # 2

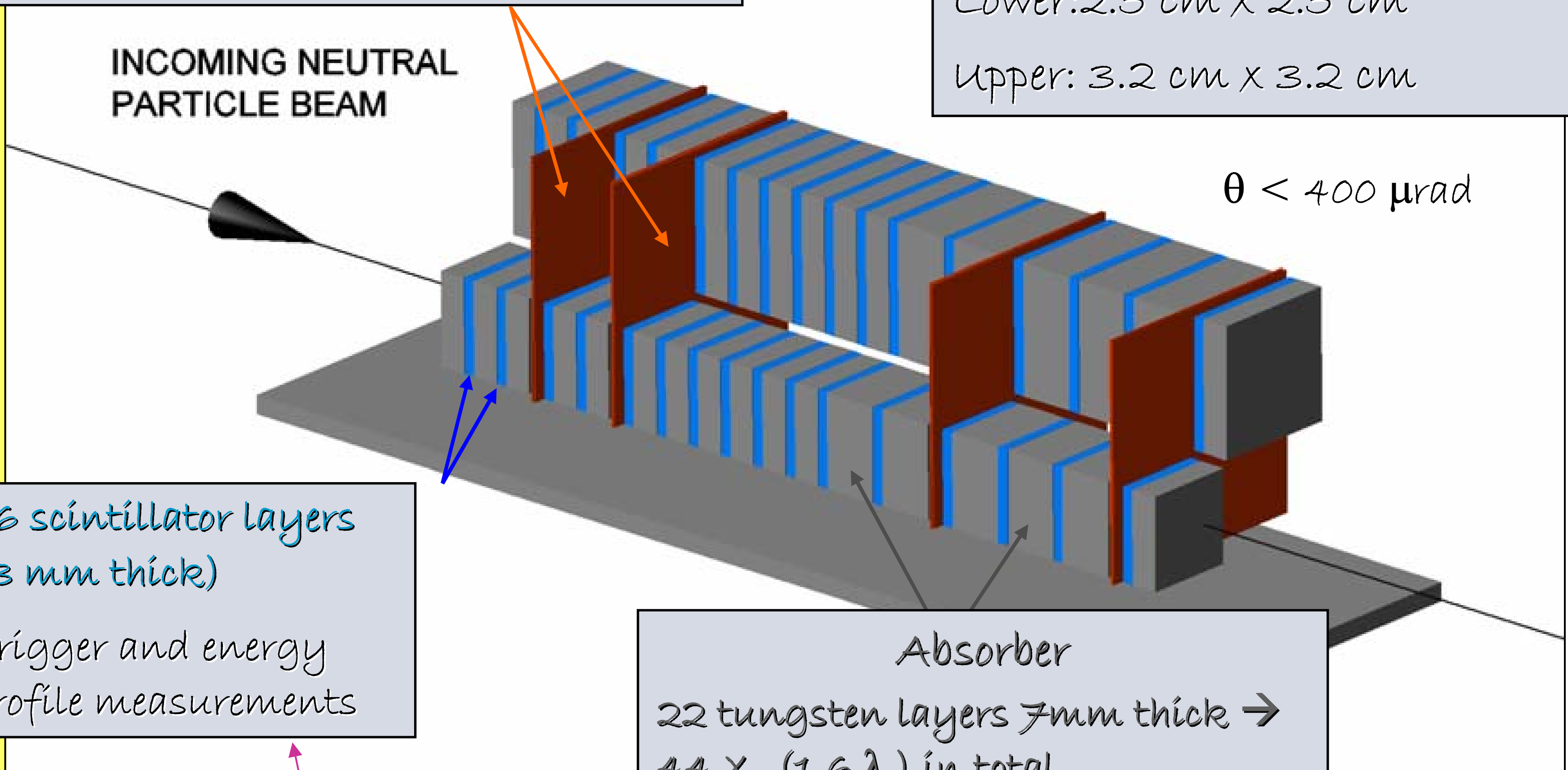
We use LHC style electronics and readout

4 pairs of silicon microstrip layers (6, 12, 30, 42 r.l.) for tracking purpose (X and Y) → impact point

2 towers 24 cm long stacked on their edges and offset from one another

Lower:2.5 cm x 2.5 cm

Upper: 3.2 cm x 3.2 cm



16 scintillator layers (3 mm thick)

Trigger and energy profile measurements

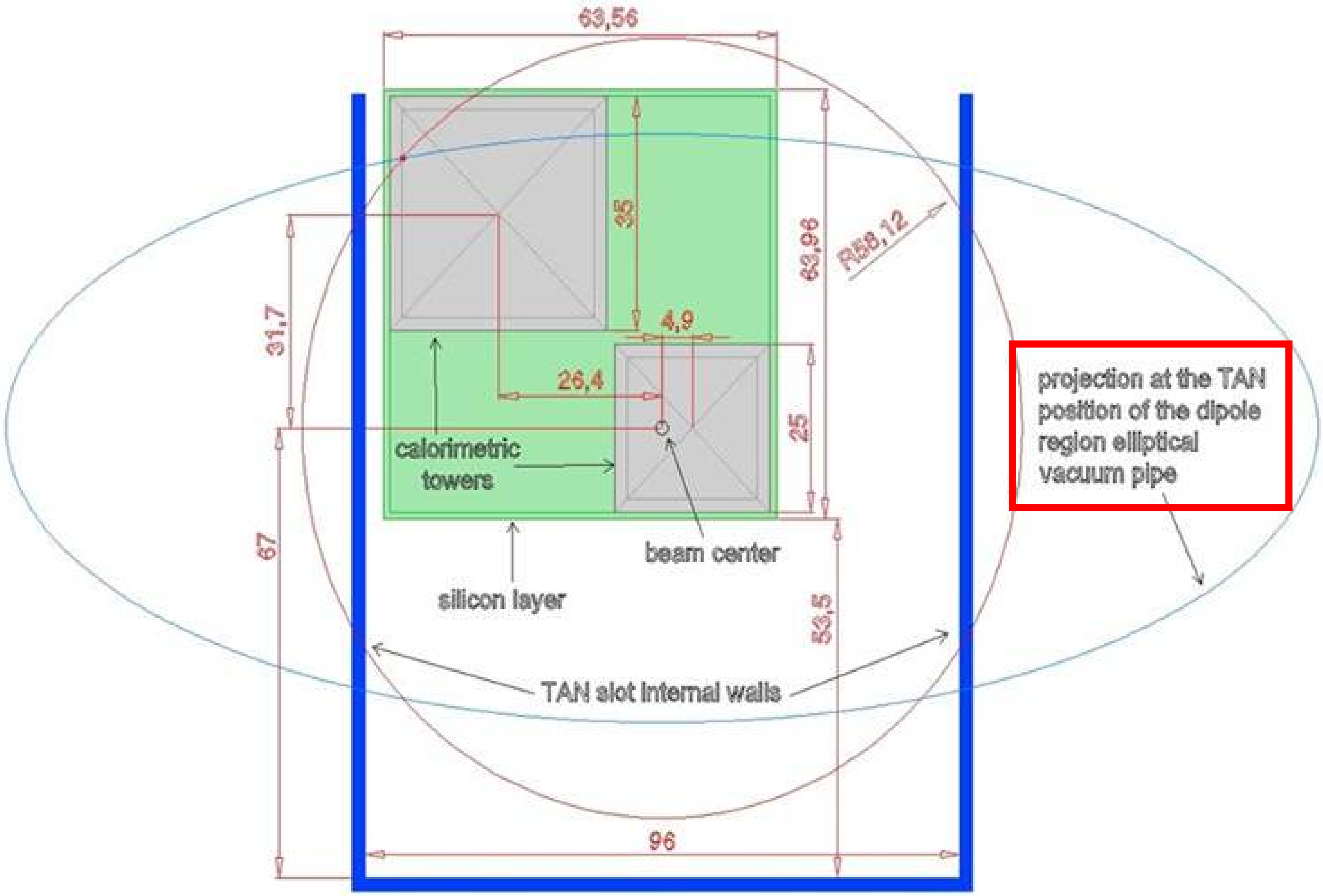
Absorber

22 tungsten layers 7mm thick → $44\ X_0$ ($1.6\ \lambda_I$) in total

(W: X_0 = 3.5mm, R_M = 9mm)

Energy

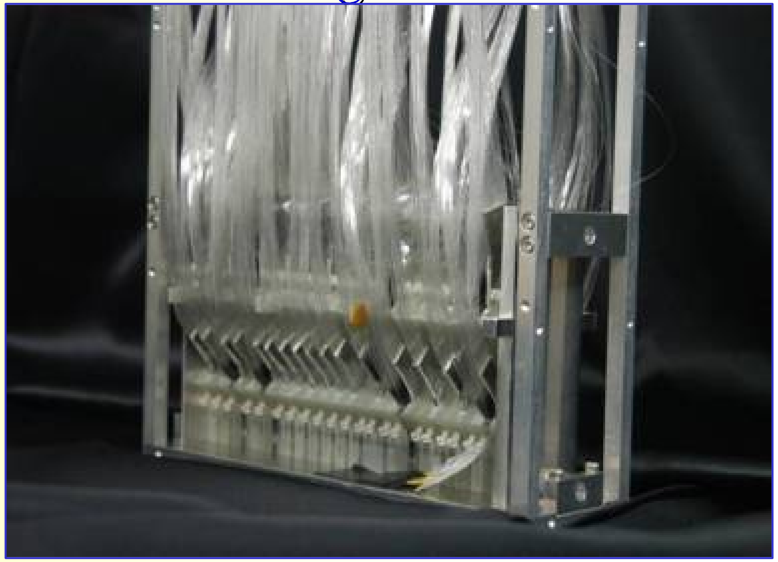
Transverse projection of detector #2 in the TAN slot

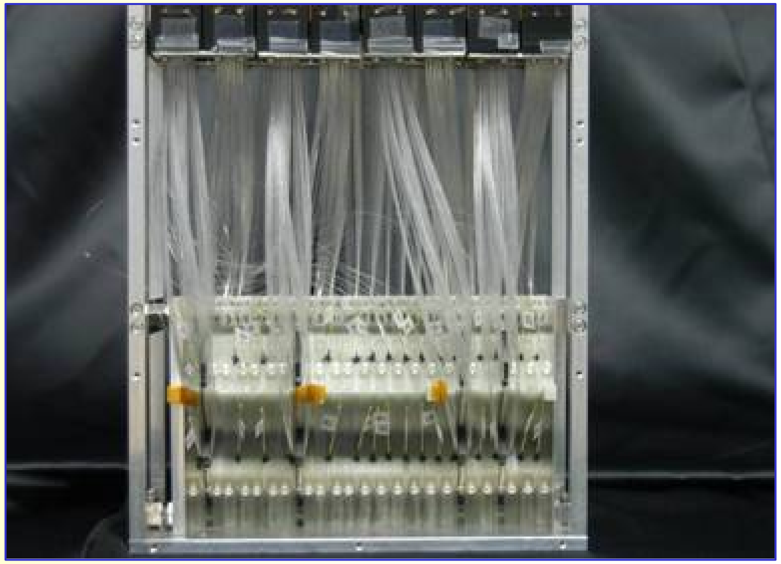


Maximization of the acceptance in R (distance from beam center)

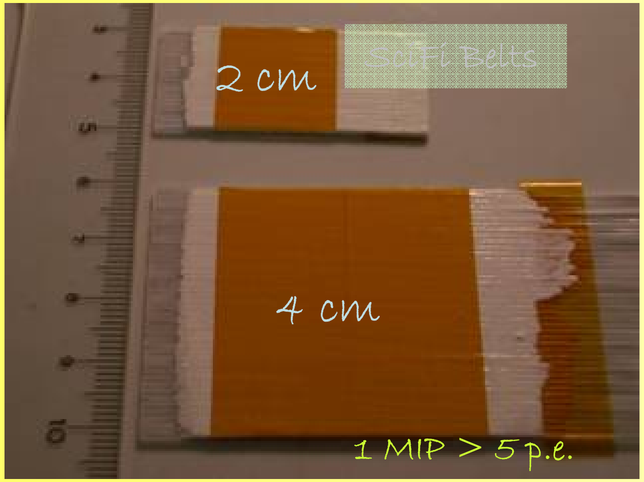
Arm 1

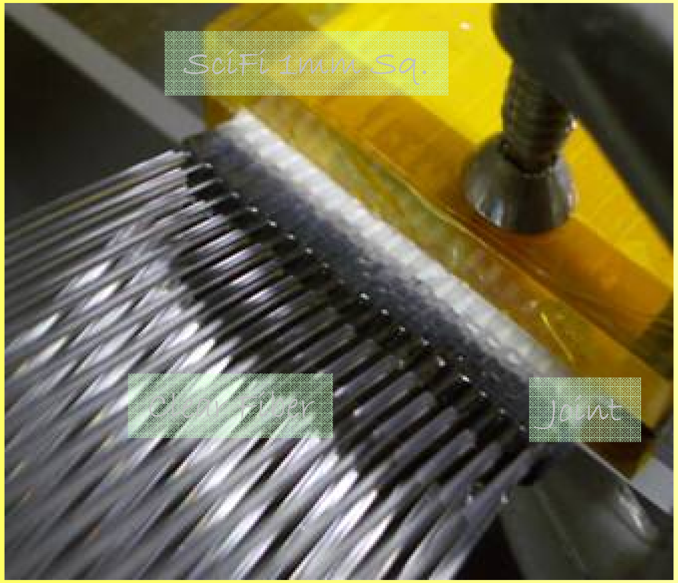
Arm1 was fully assembled in Japan in July 2006 (scintillators + fibers + Tungsten) and fully tested at CERN in August 2006 beam test





Scintillating fibers readout (Arm1)





Hamamatsu
64 ch (8x8)
8 dynode

MAPMT

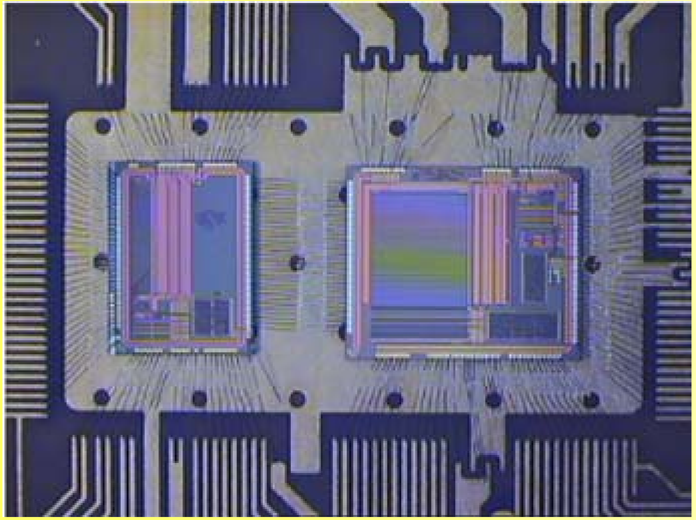
VA32HDR14 chip
from IDEAS
- 1 μs shaping time
- Huge dynamic range (30 pC)
- 32 channels

MAPMT+FEC

Arm 2

- Arm2 was partially assembled in Florence in July 2006 and brought to CERN for the Beam Test of August 2006
- Arm2 was fully assembled in Florence in April 2007

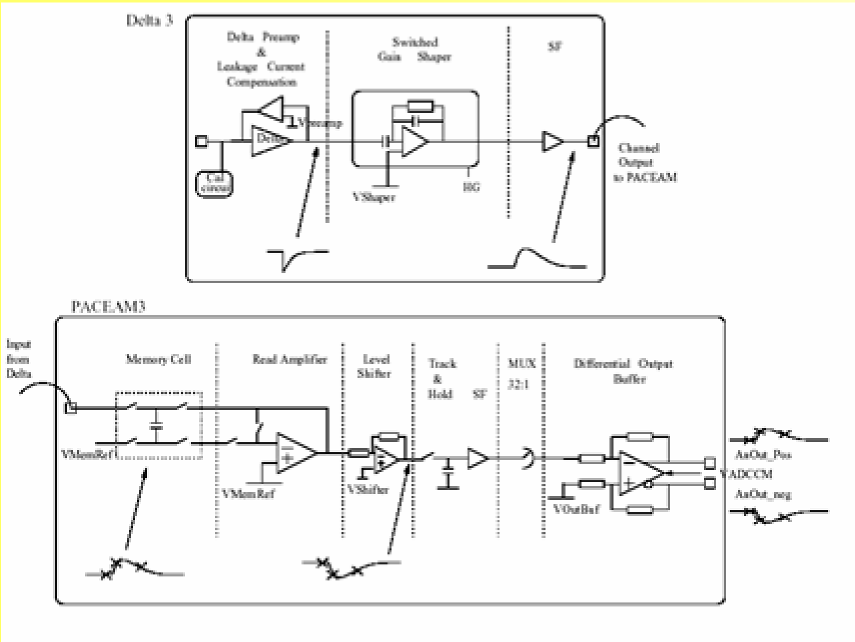
Silicon μstrips readout

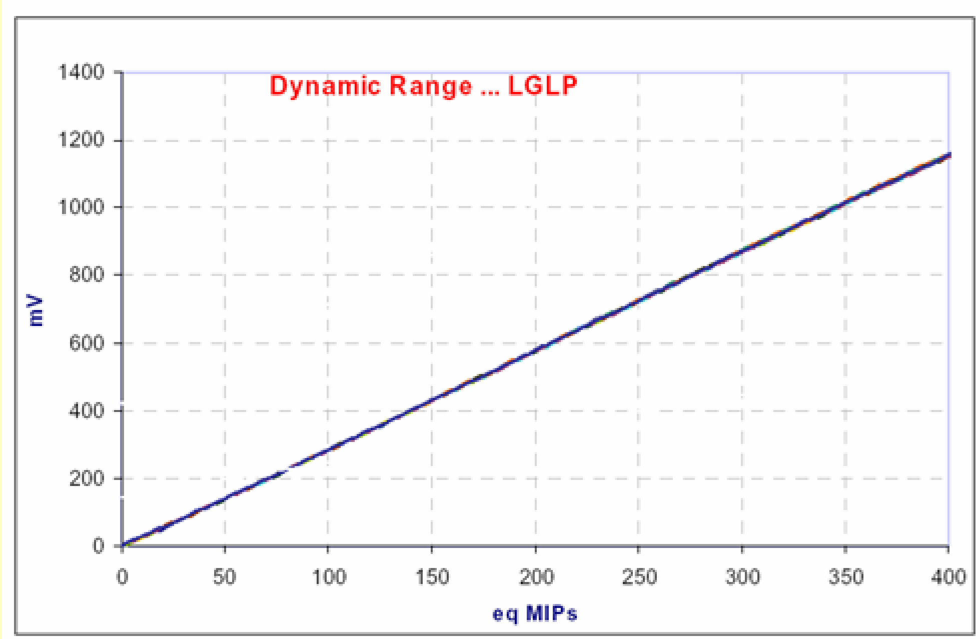


Pace3 chips

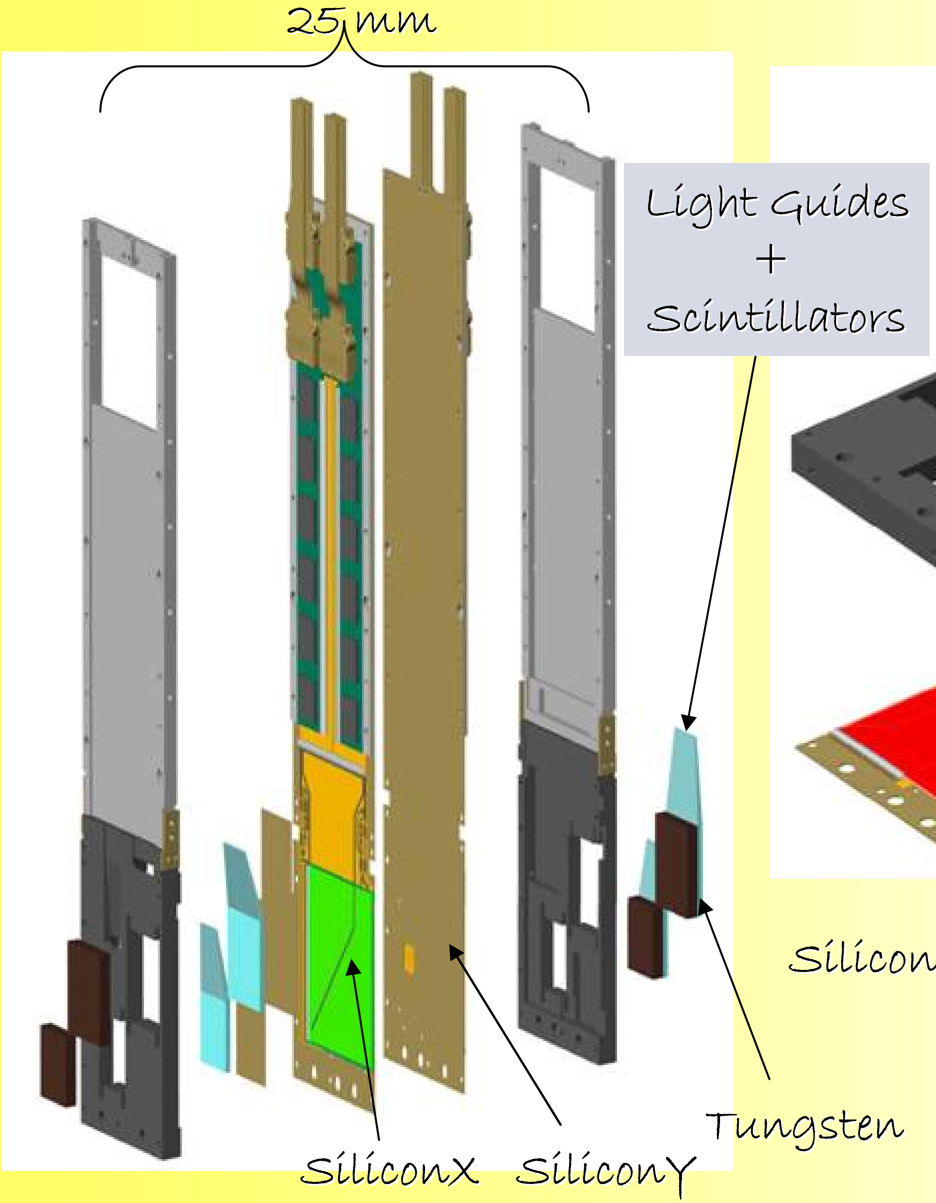
(many thanks to CMS preshower!!!!)

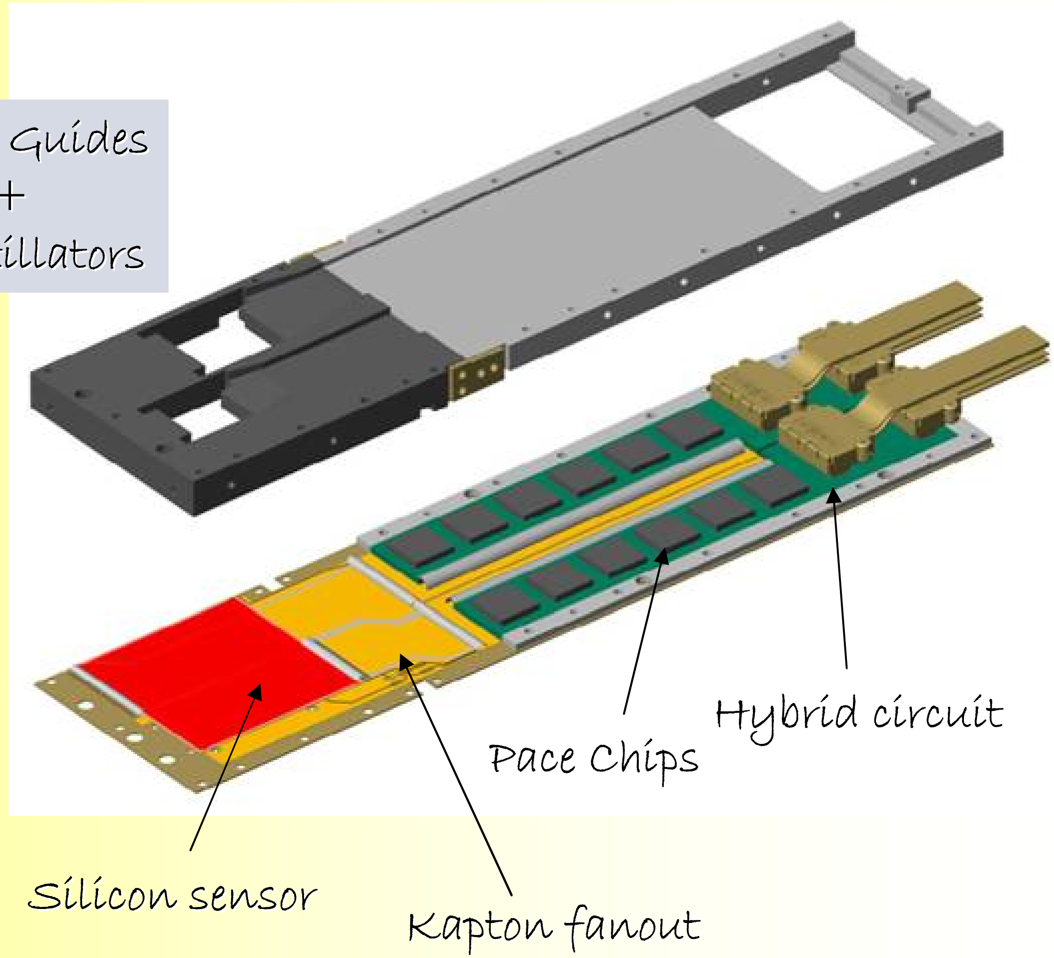
- 32 channels
- 25 ns peaking time
- High dynamic range (> 400 MIP)
- 192x32 analog pipeline

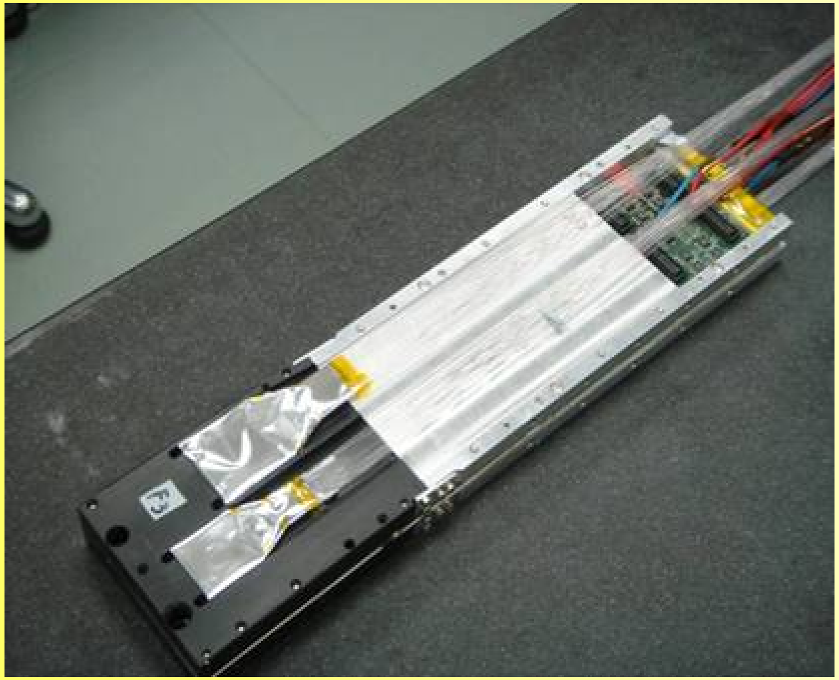




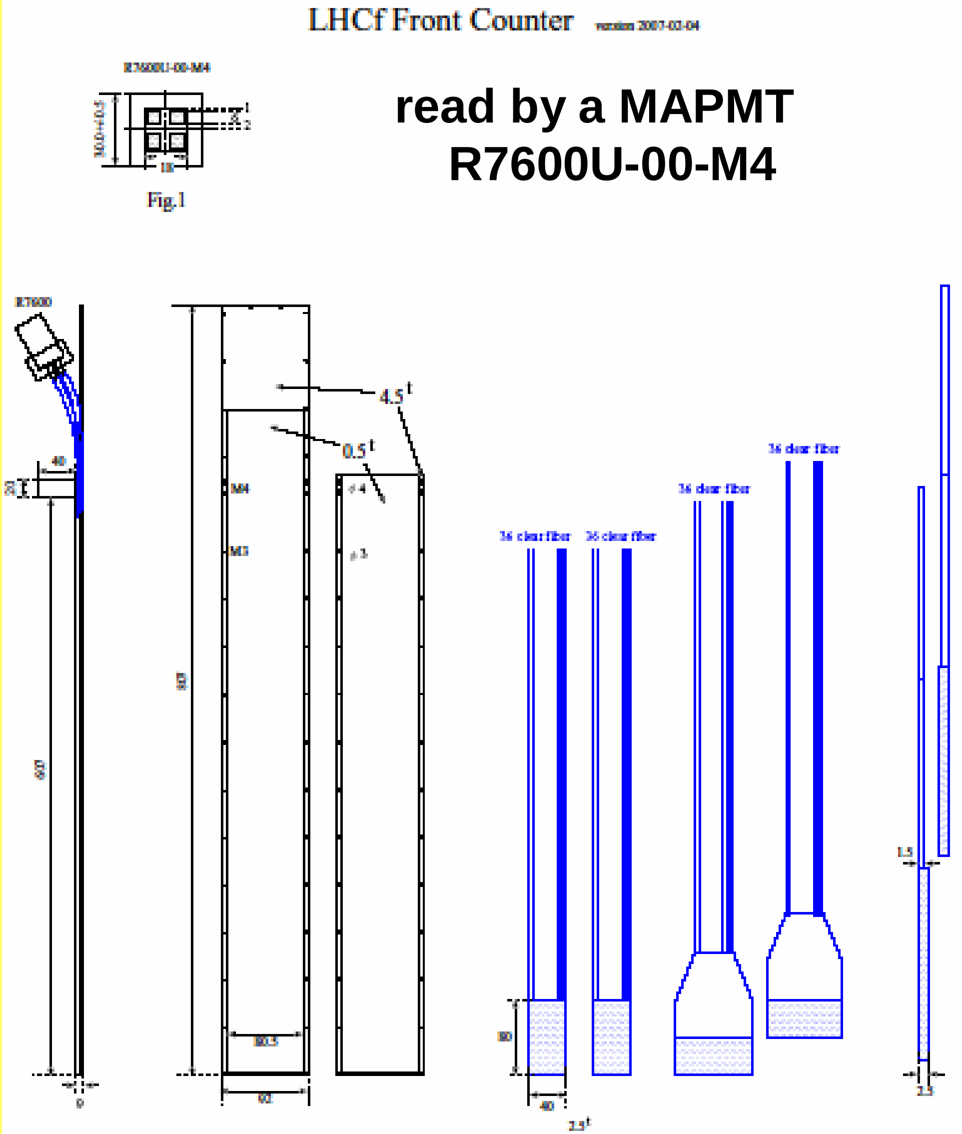
The mechanics of the module



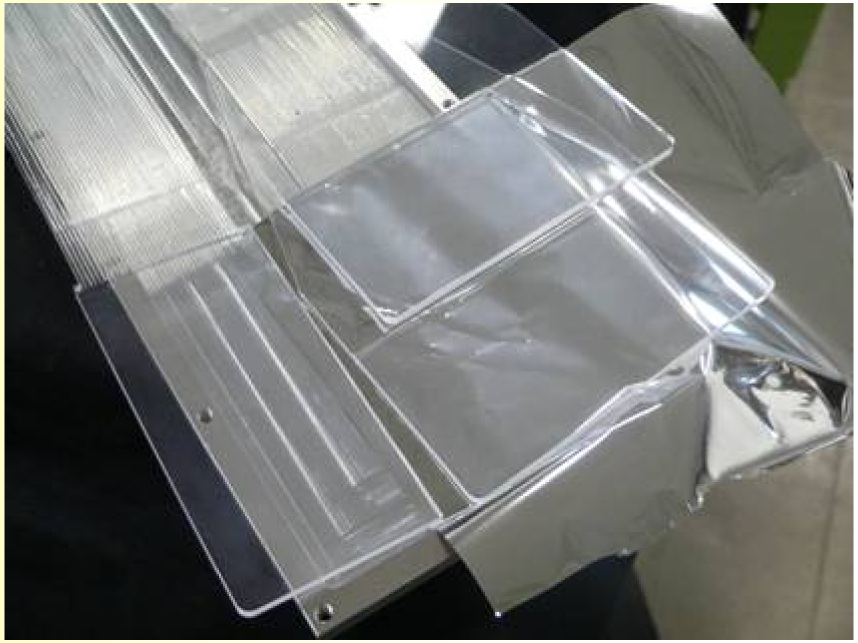


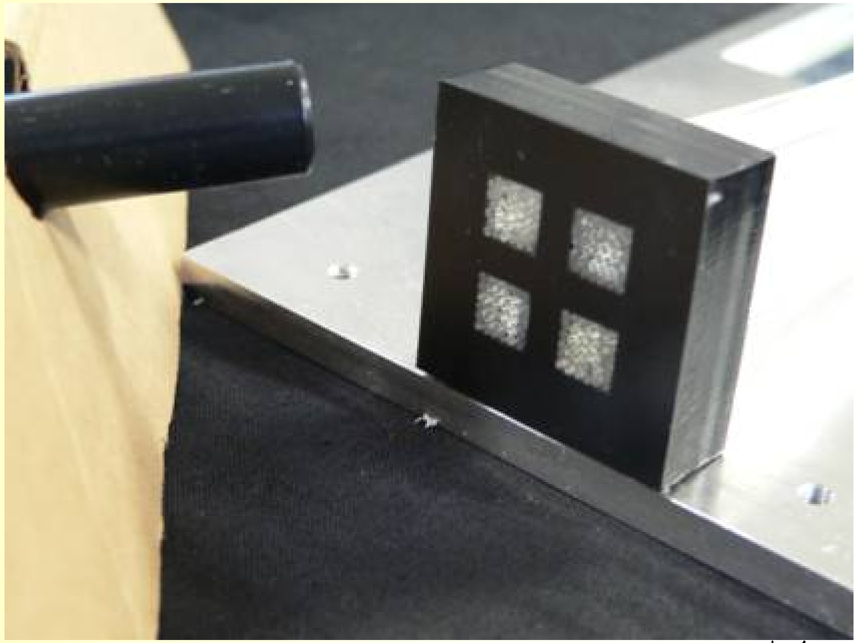




Front Counter (Both for Arm1&2)



read by a MAPMT R7600U-00-M4





Now the real installation in LHC…

The idea is that installation takes place in 2 steps:

- **Pre-installation**
- **Final installation**

In between the 2 installation the baking out of the beam pipe will be done (200 °C), so the detectors should be removed

Pre-Installation dates have been fixed in Fall 2006

- LSS1L (Arm1)
  - 8/01/2007 to 26/01/2007 → FINISHED!
- LSS1R (Arm2)
  - 23/04/2007 to 11/05/2007 → FINISHED

The dates for the final installation are still under discussion

Arm1 pre-installation

From 8/01/2007 to 26/01/2007

No major problems came out

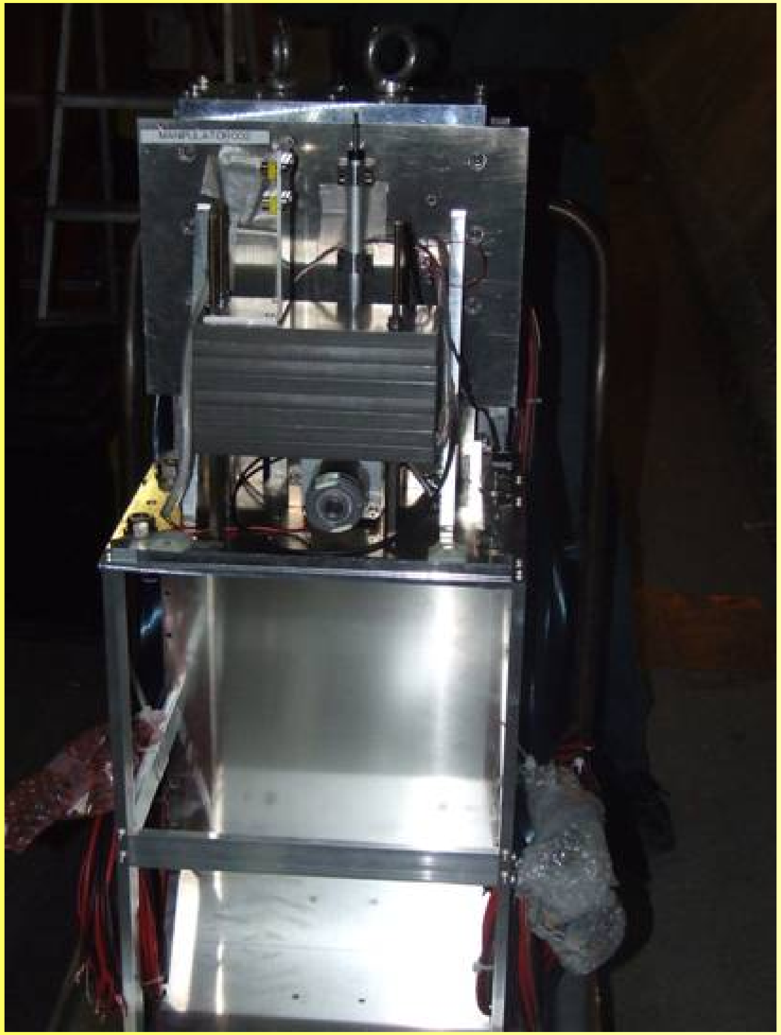
Cables → OK
Transport and installation → OK
Laser calibration → OK
Power supply from USA15 → OK
Manipulator and movements → OK

Arm1 was dismounted at the end

Transport and insertion in the TAN

LHCf Arm 1 – Installation completed within 15 minutes!

Arm2 pre-installation



From 23/04/2007 to 11/05/2007

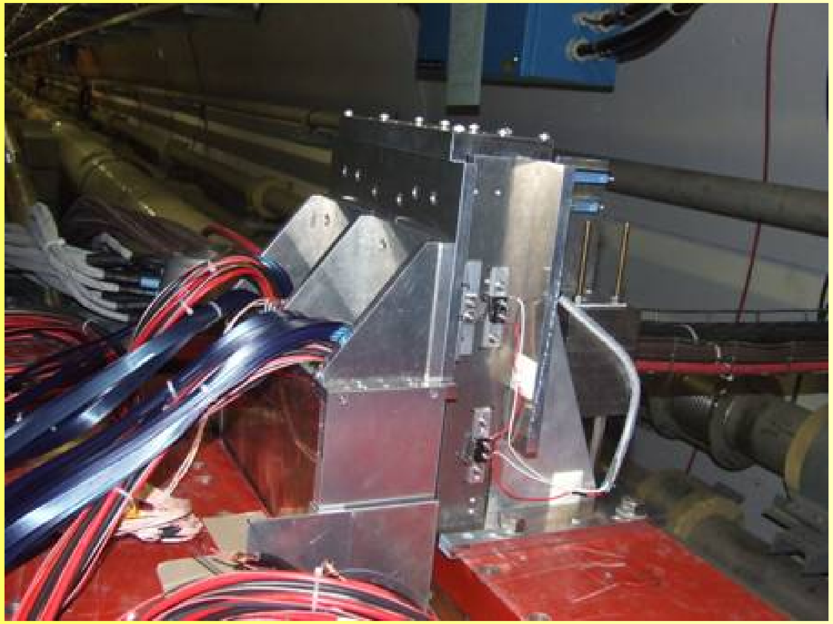
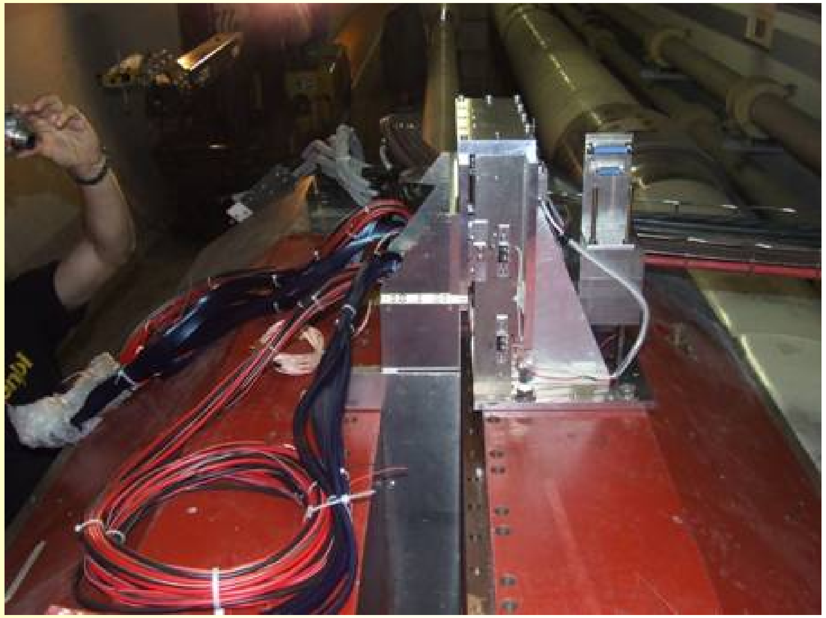
No major problems came out

Cables → OK
Transport and installation → OK
Laser calibration → OK locally
→ TBD from remote
Power supply from USA15 → OK
Manipulator and movements → OK

No interference with BRAN

Arm2 was dismounted on May 9



450 KG



LHCf Physics performance

1. Single photon spectrum
2. π^0 fully reconstructed (1 γ in each tower)

π^0 reconstruction is an important tool for energy calibration (π^0 mass constraint)

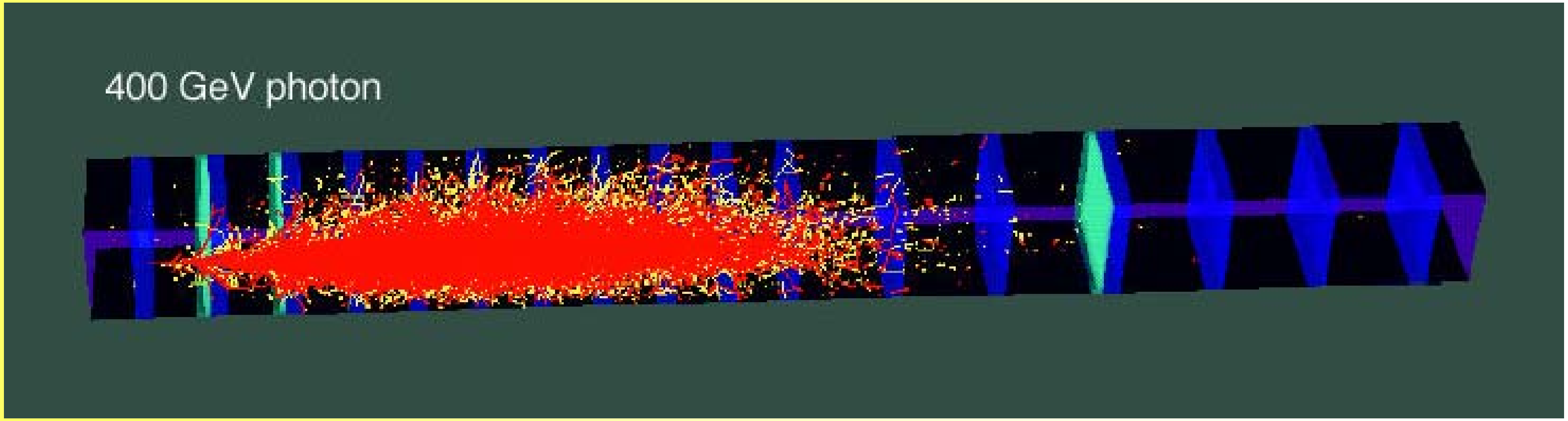
Basic detector requirements:

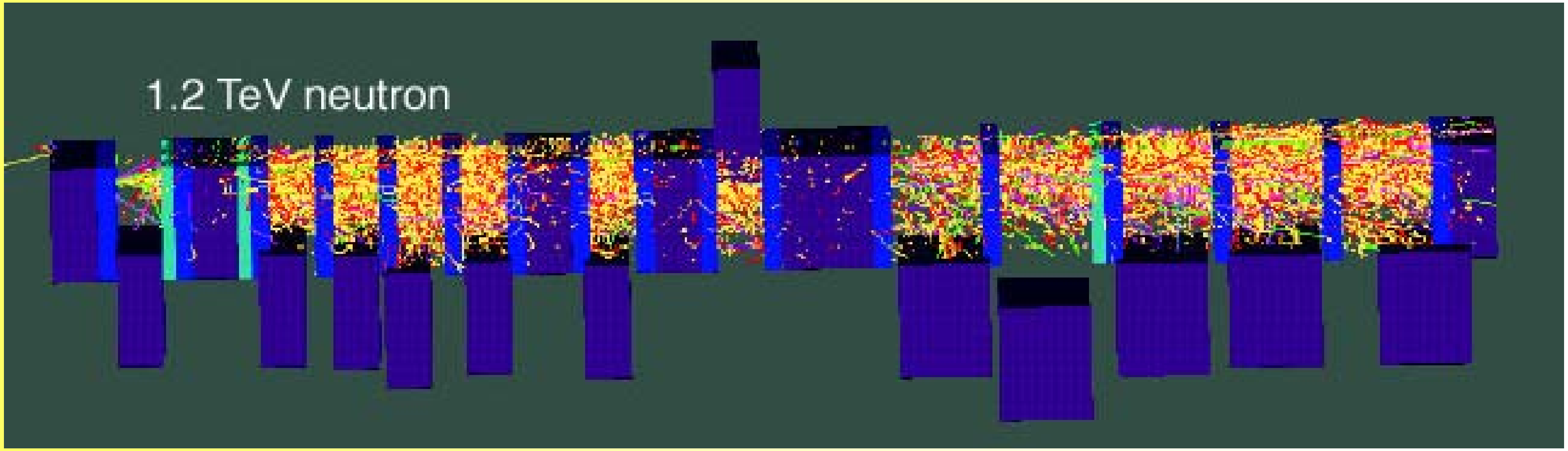
- minimum 2 towers (π^0 reconstruction)
- Smallest tower on the beam (multiple hits)
- Dimension of the tower → Moliere radius
- Maximum acceptance (given the LHC constraints)

Simulation

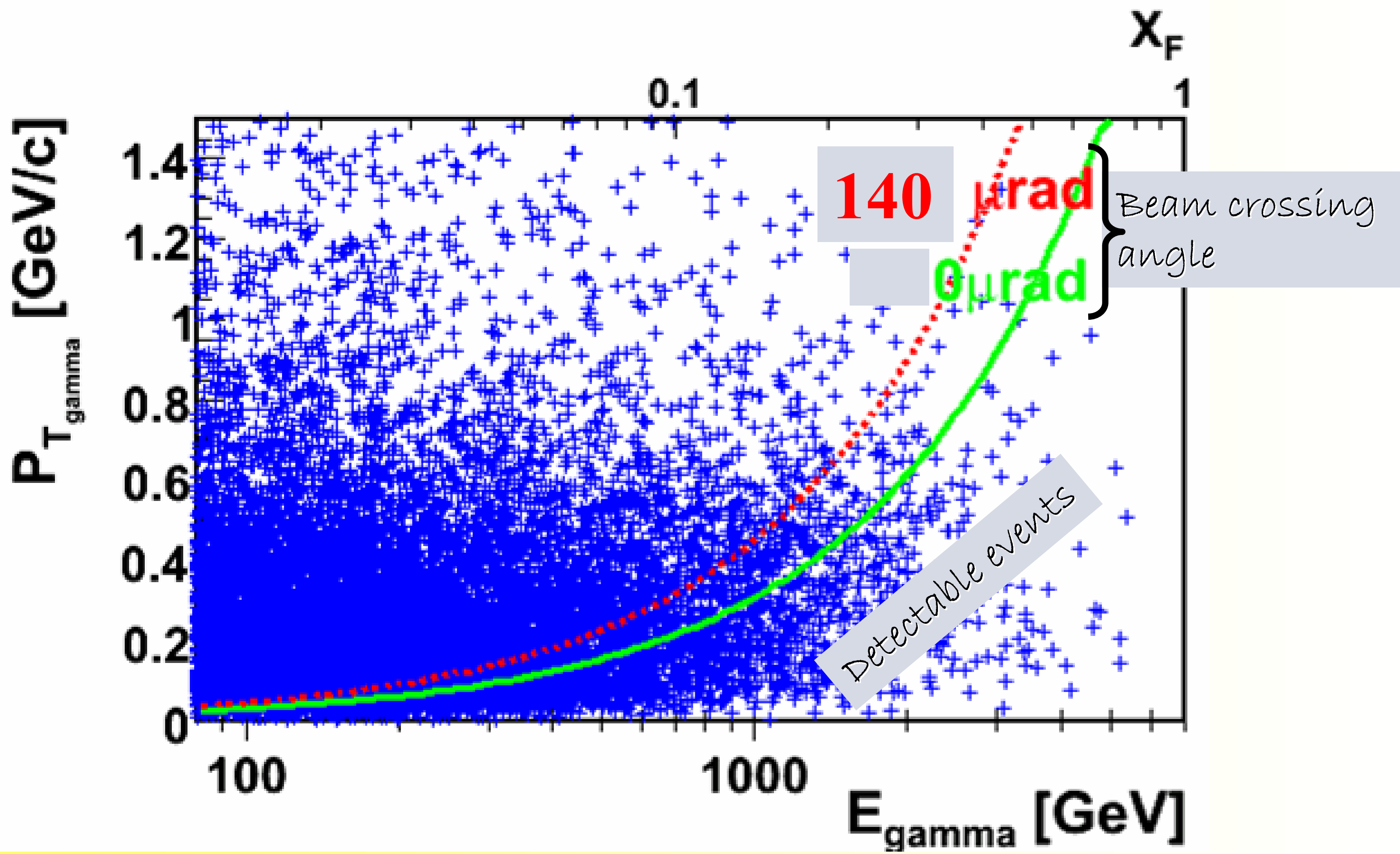
Beam Test

Examples of simulated events for γ and n



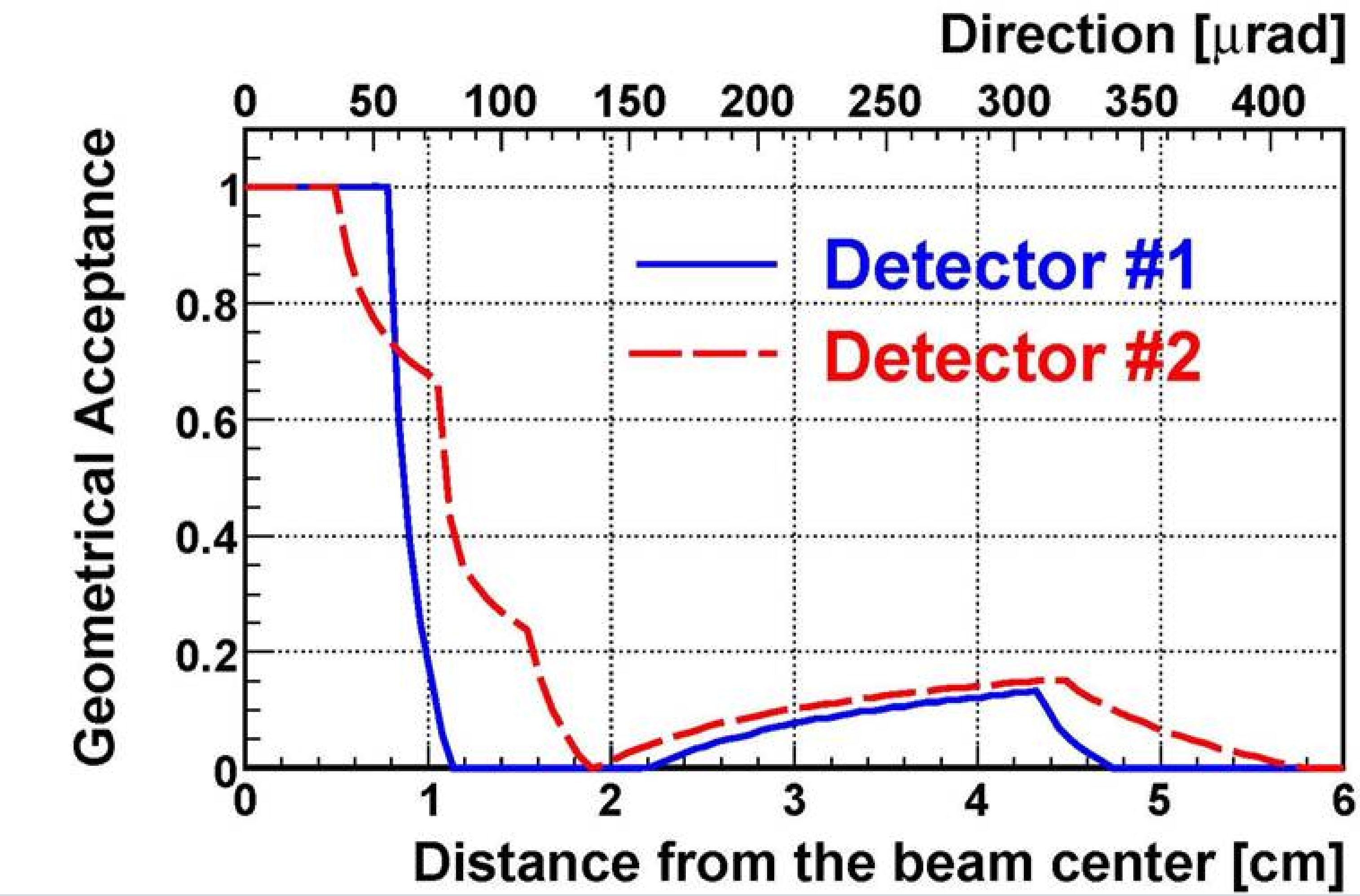


LHCf performances: acceptance on $P_{T\gamma}$-E_γ plane



A vertical beam crossing angle > 0 will increase the acceptance of LHCf

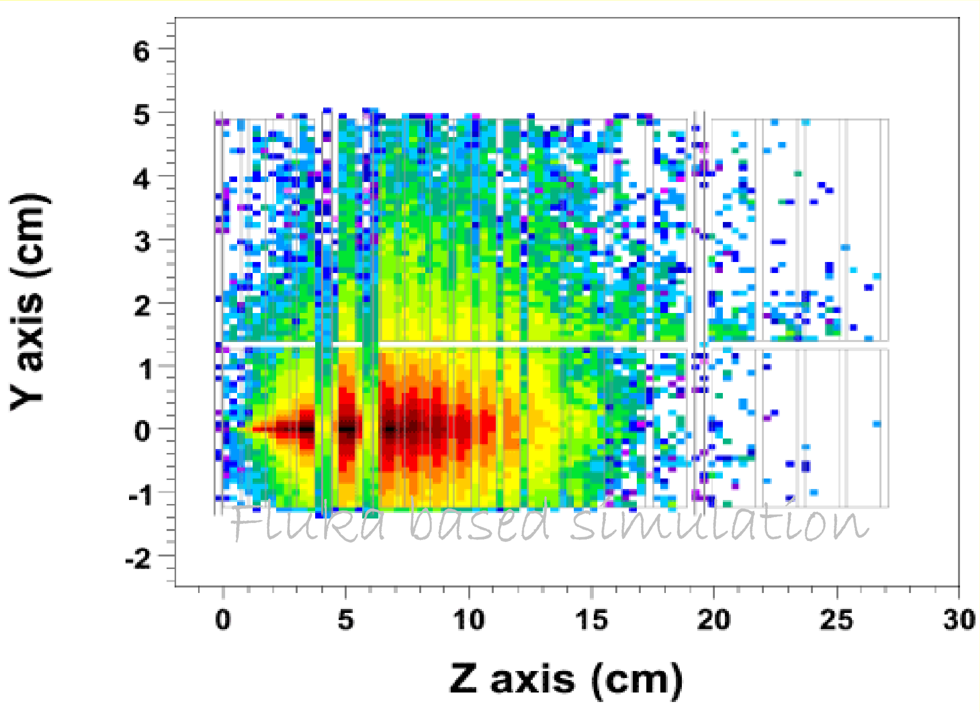
LHCf performances: single γ geometrical acceptance



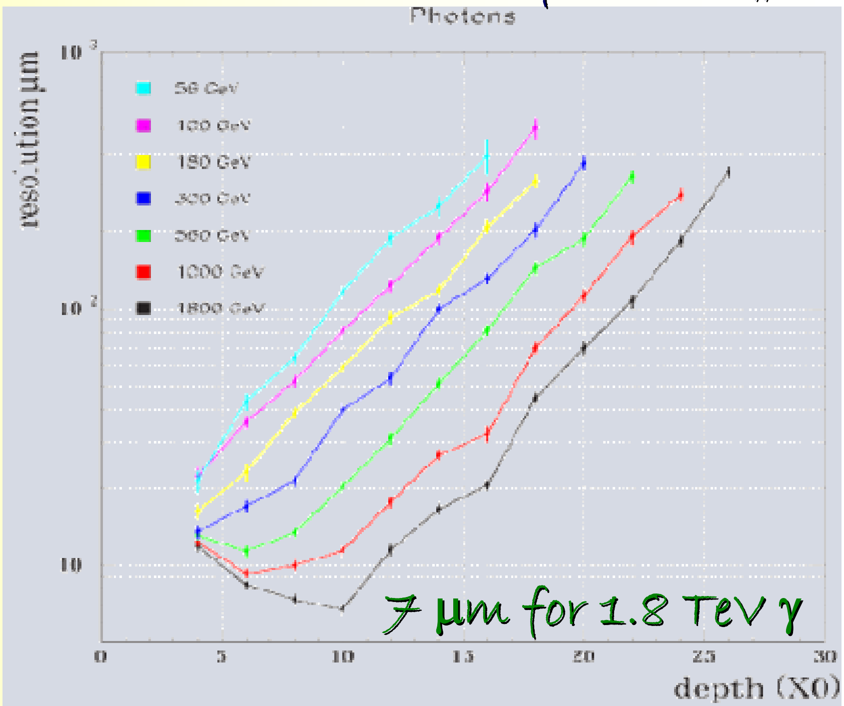
Some runs with LHCf vertically shifted few cm will allow to cover the whole kinematical range

LHCf performances: γ shower in Arm #2

500 GeV γ shower



Position resolution of detector # 2

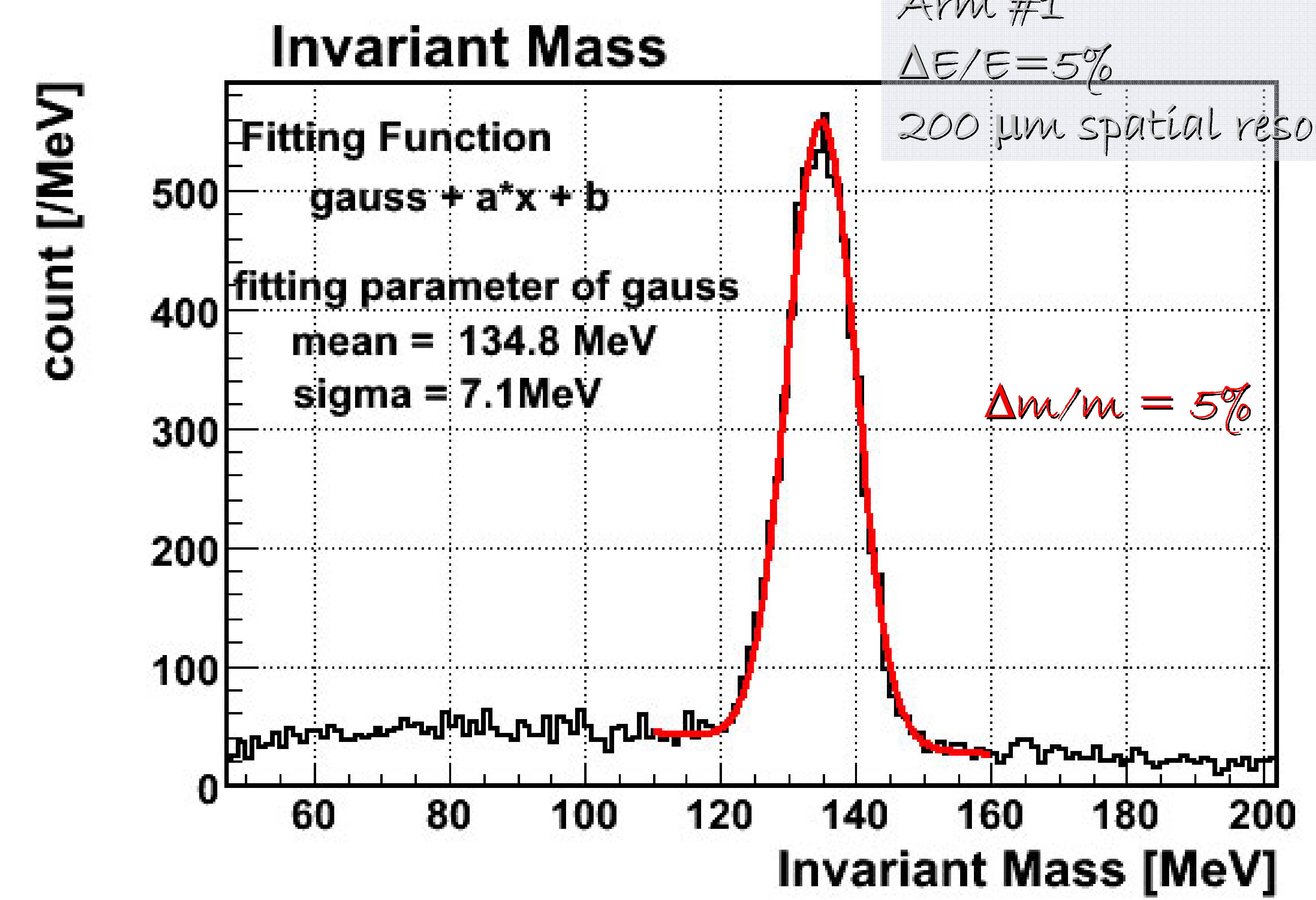


LHCf performances: π^0 mass resolution

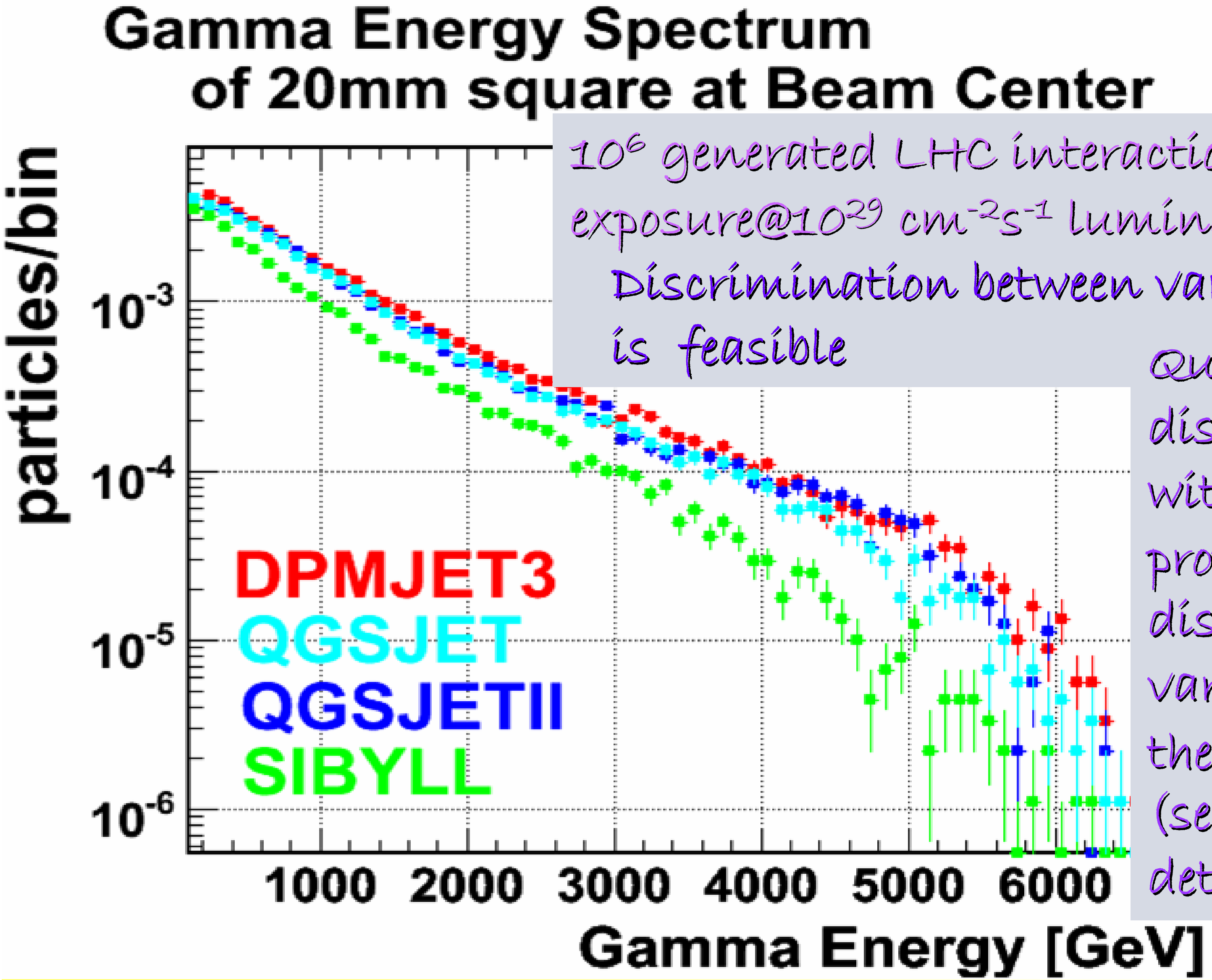
Arm #1

$\Delta E/E = 5\%$

200 μm spatial resolution



LHCf performances: Monte Carlo γ-ray energy spectrum (5% Energy resolution is taken into account)

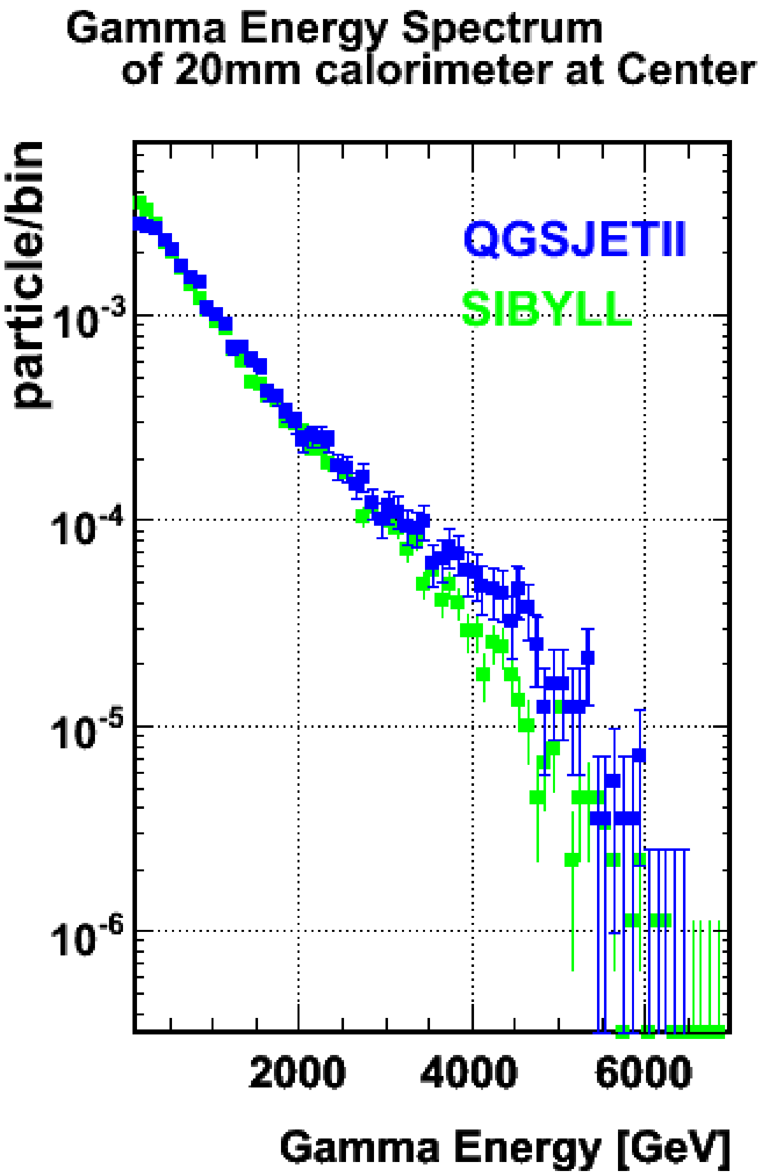


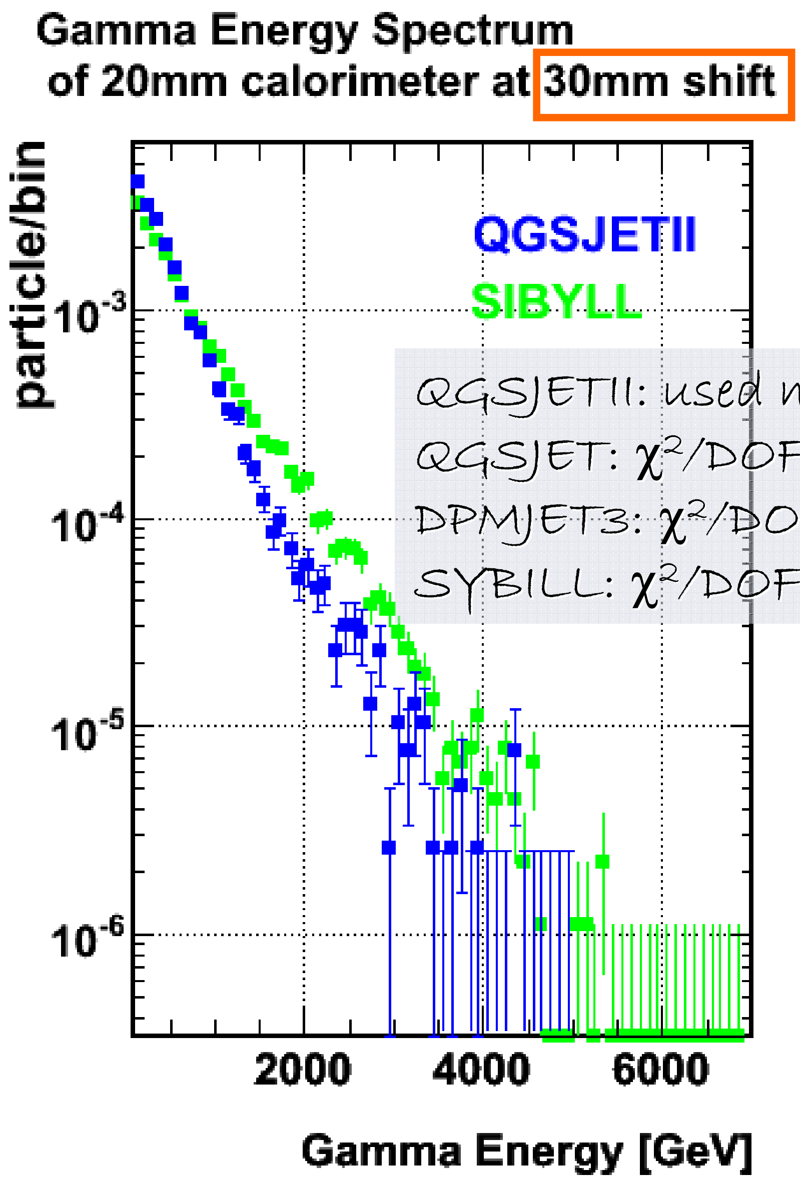
10^6 generated LHC interactions → 1 Minute exposure@10^{29} $cm^{-2}s^{-1}$ luminosity

Discrimination between various models is feasible

Quantitative discrimination with the help of a properly defined χ^2 discriminating variable based on the spectrum shape (see TDR for details)

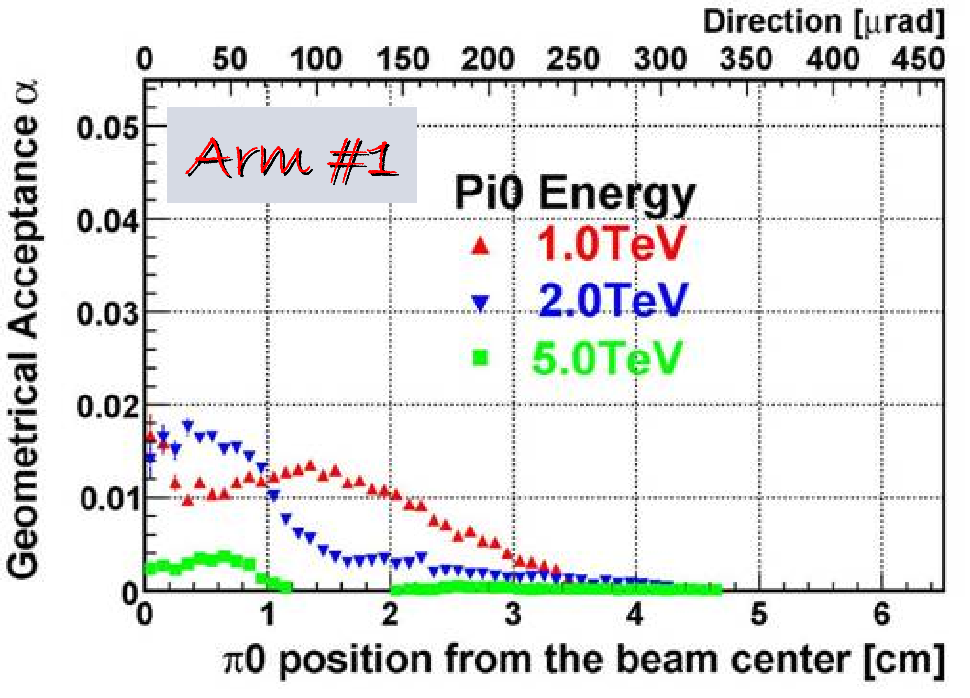
γ ray energy spectrum for different positions

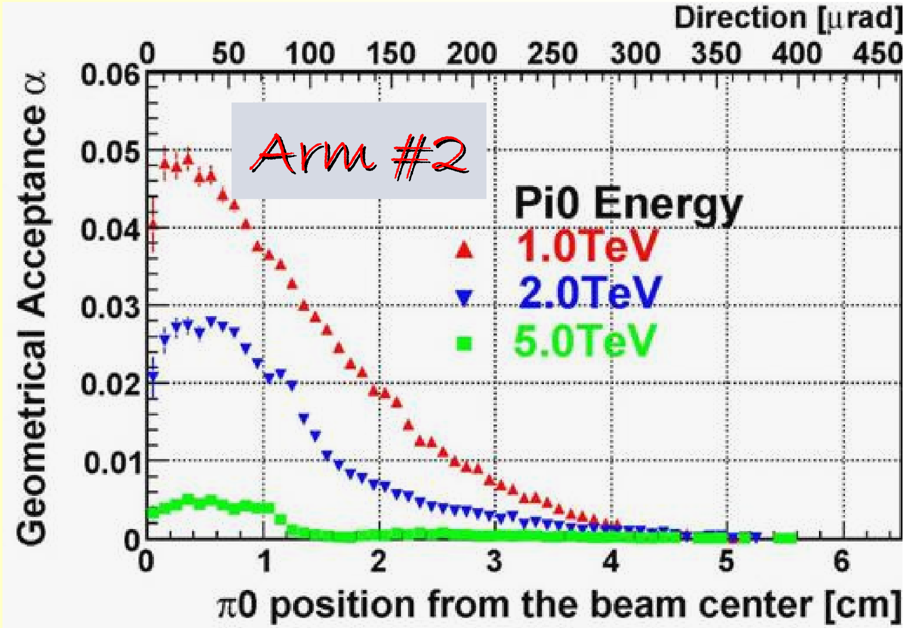




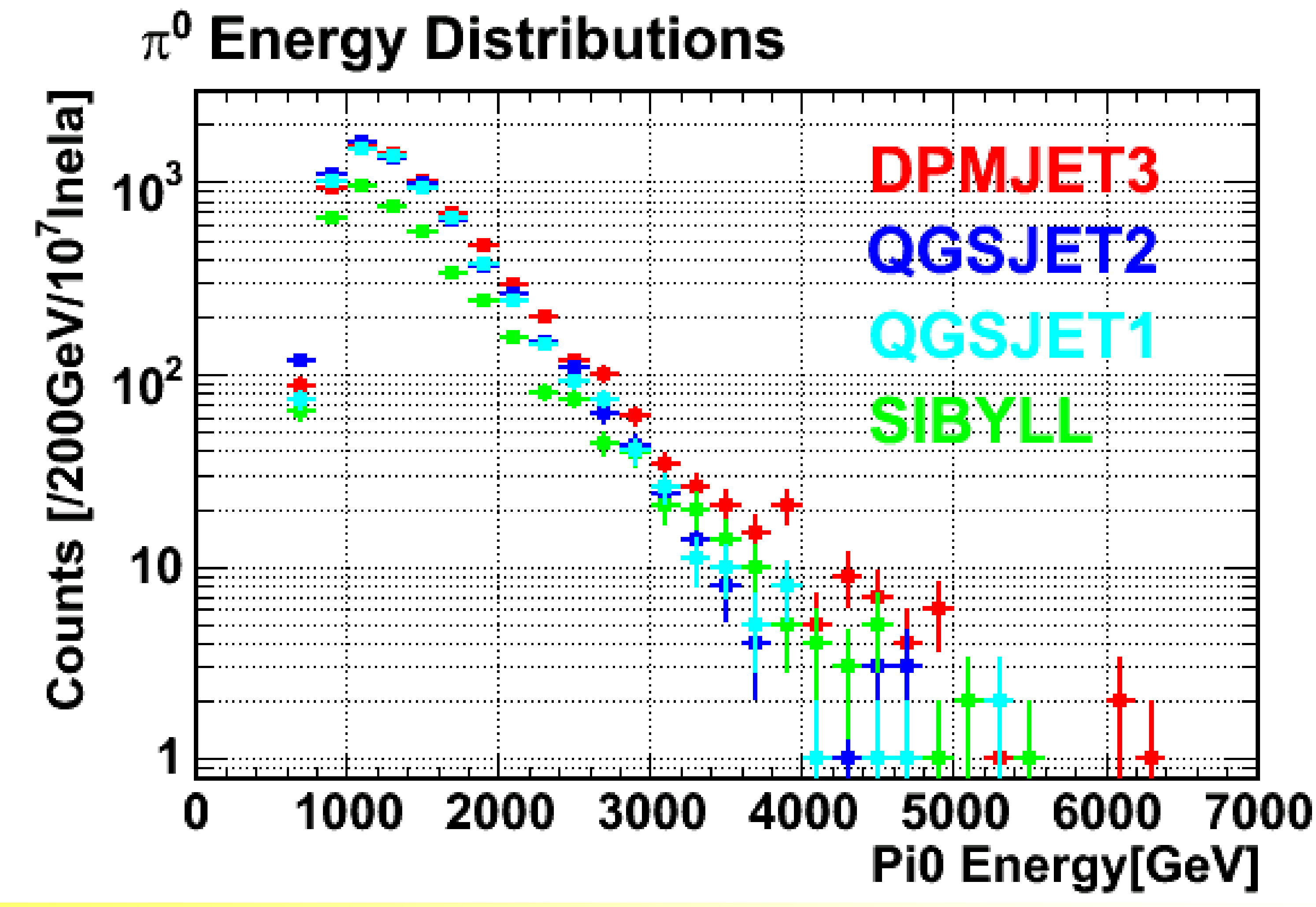
QGSJETII: used model
QGSJET: χ^2/DOF=107/125
DPMJET3: χ^2/DOF=224/125
SYBILL: χ^2/DOF=816/125

LHCf performances: π^0 geometrical acceptance





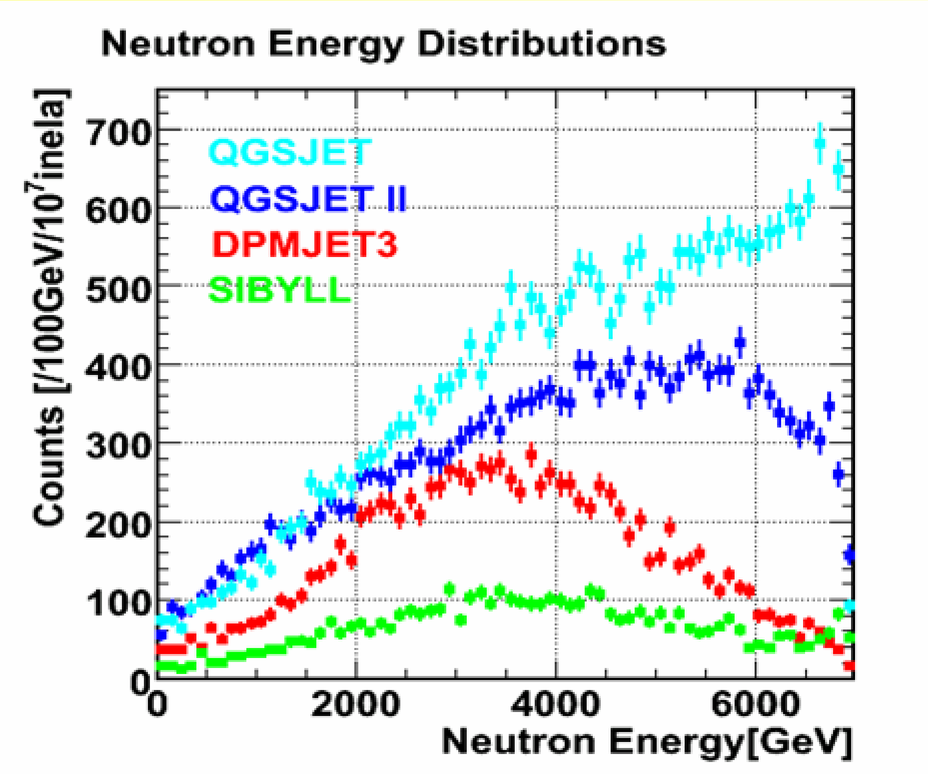
LHCf performances: energy spectrum of π^0



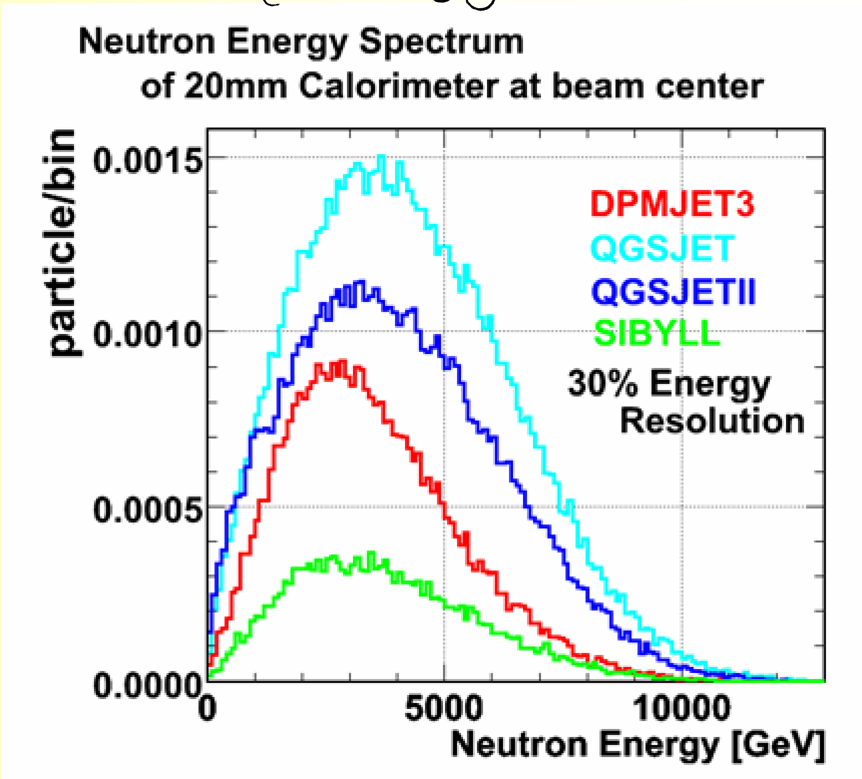
Typical energy resolution of γ is 3 % at 1TeV

LHCf performances:
model dependence of neutron energy distribution

Original n energy

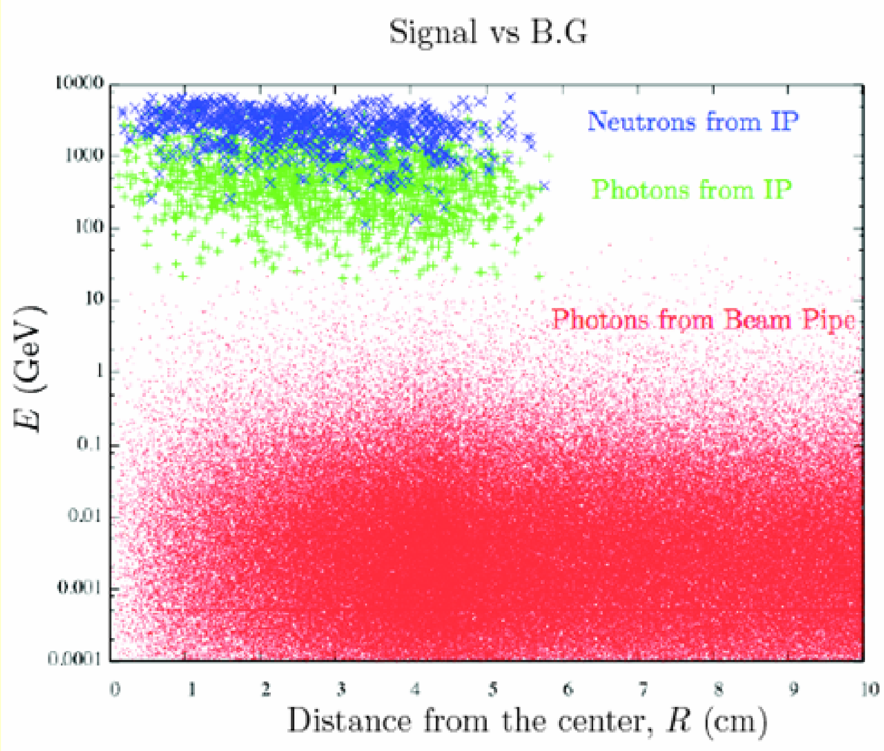


30% energy resolution



Estimate of the background

- beam-beam pipe
  - → E_γ(signal) > 100 GeV, OK
    background < 1%



- beam-gas
  - → It depends on the beam condition
    background < 1% (under 10^{-10} Torr)

- beam halo-beam pipe
  - → It has been newly estimated from the beam loss rate

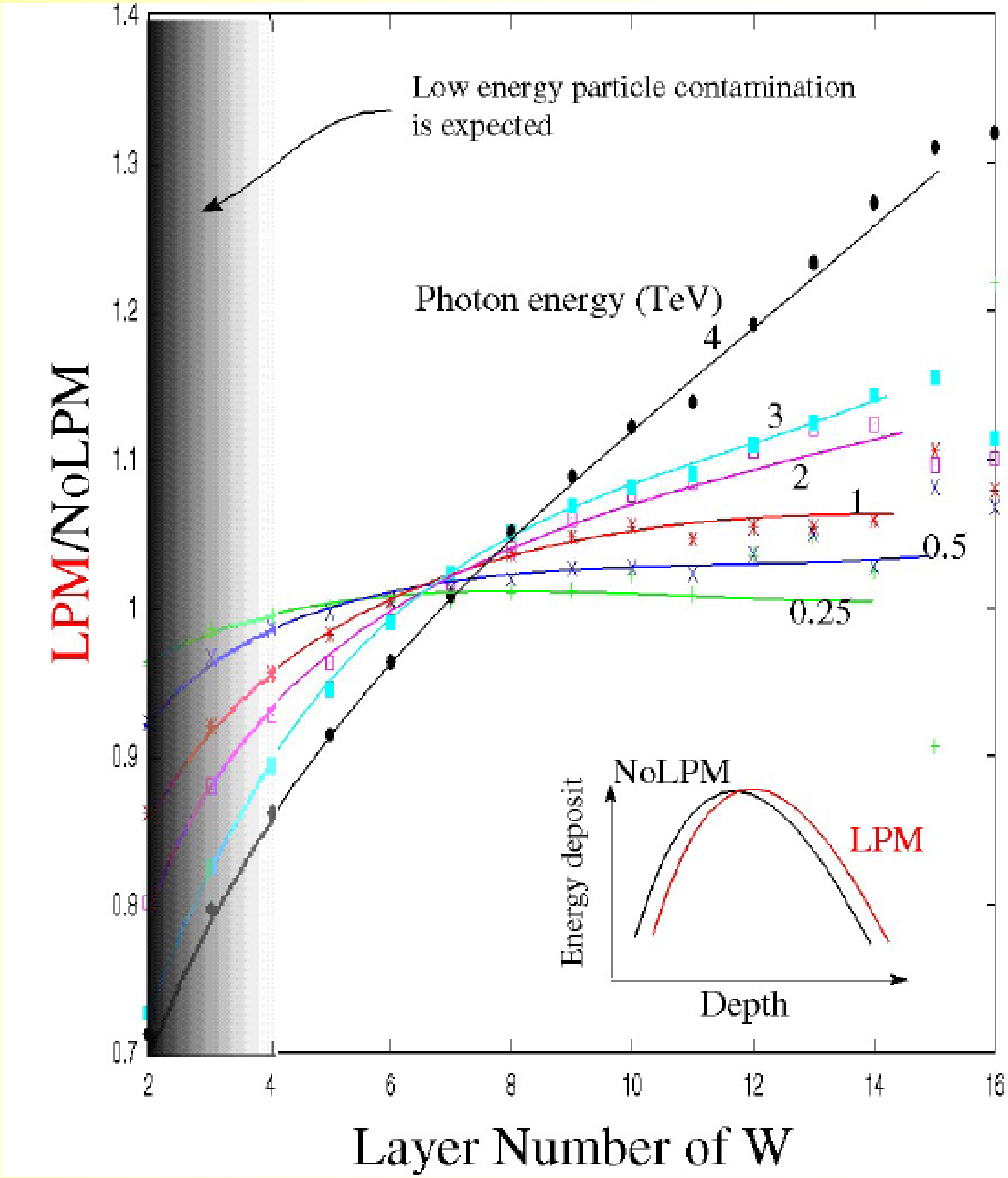
    Background < 10% (conservative value)

The LPM effect

Landau – Pomeranchuk - Migdal

Increase of X0 with increasing γ energy

LHCf is able to directly measure the LPM effect!



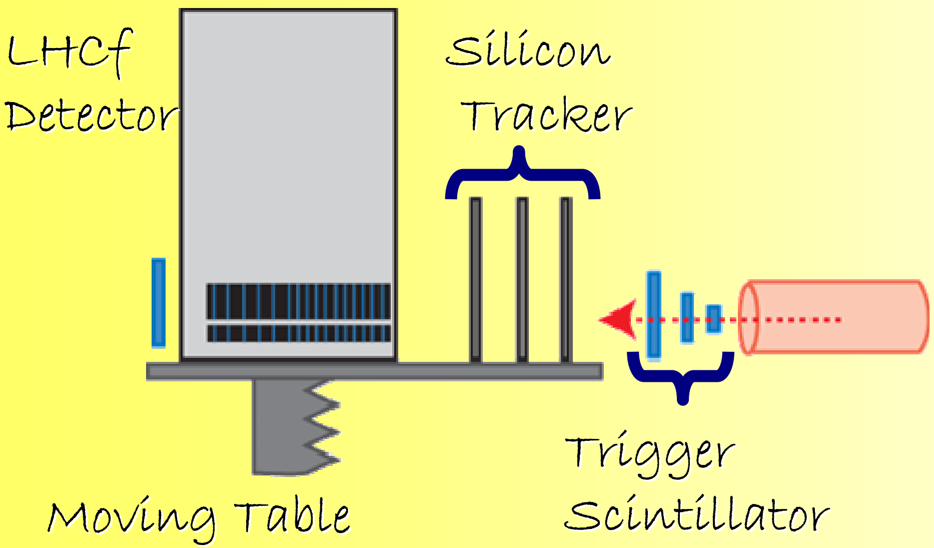
SPS Beam Tests: 2004 & 2006

- ✓ CERN : SPS T2 H4
- ✓ Incident Particles
  - Proton 150,350GeV/c
  - Electron 100,200GeV/c
  - Muon 150GeV/c

Tests were successful

✓Energy resolution
✓Energy calibration
✓Spatial resolution of the tracking systems

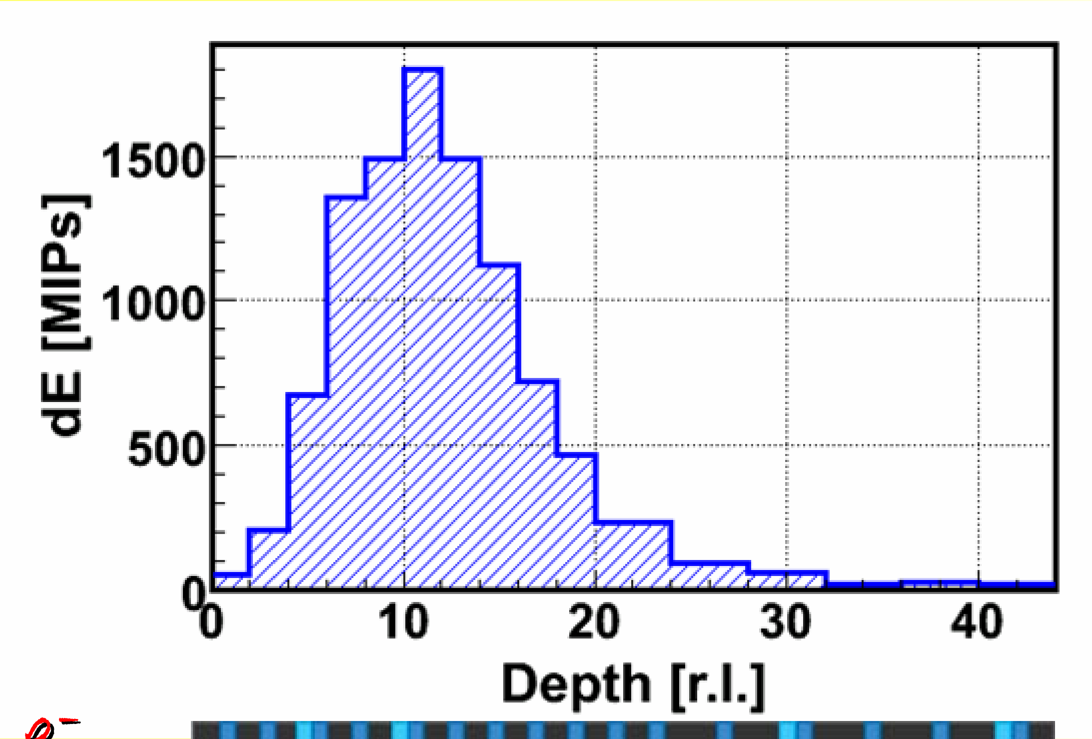
Setup



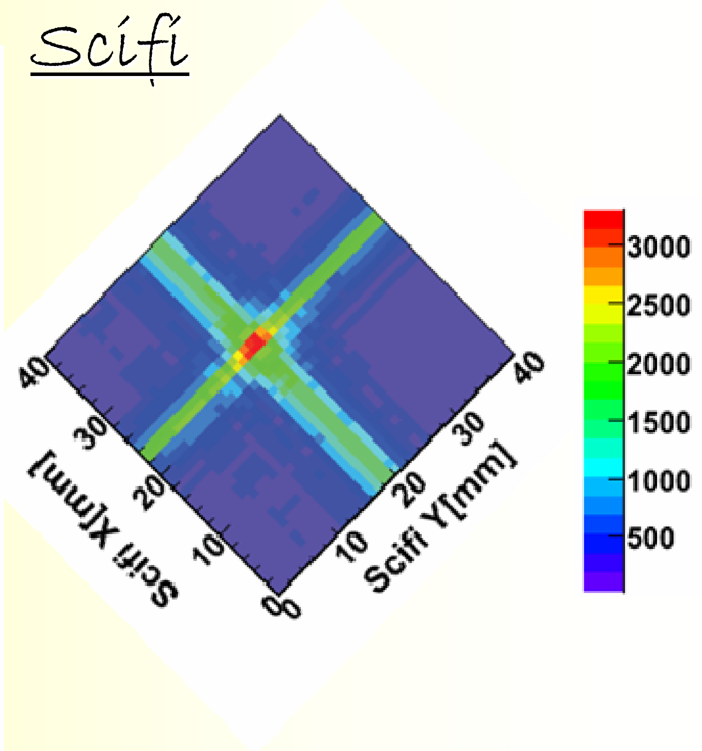
An electron event as seen by Arm1

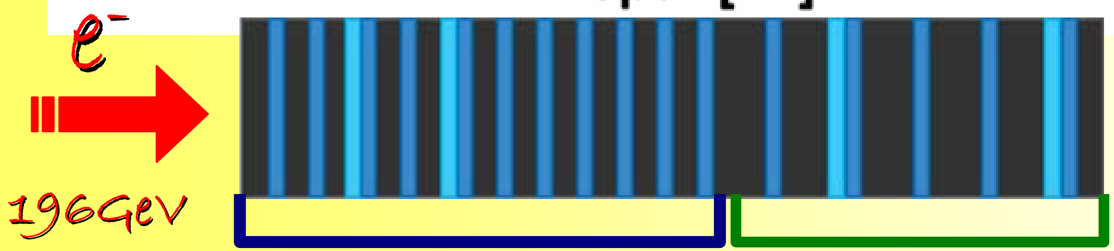
40mm Calorimeter : 196 GeV electron

Transition Curve



Scifi

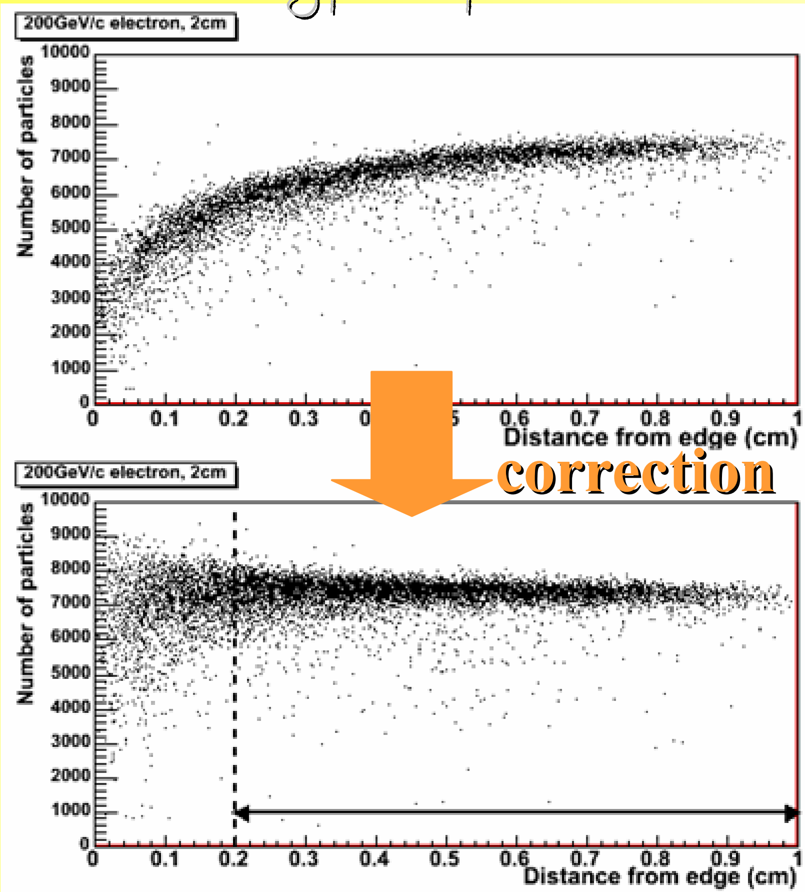




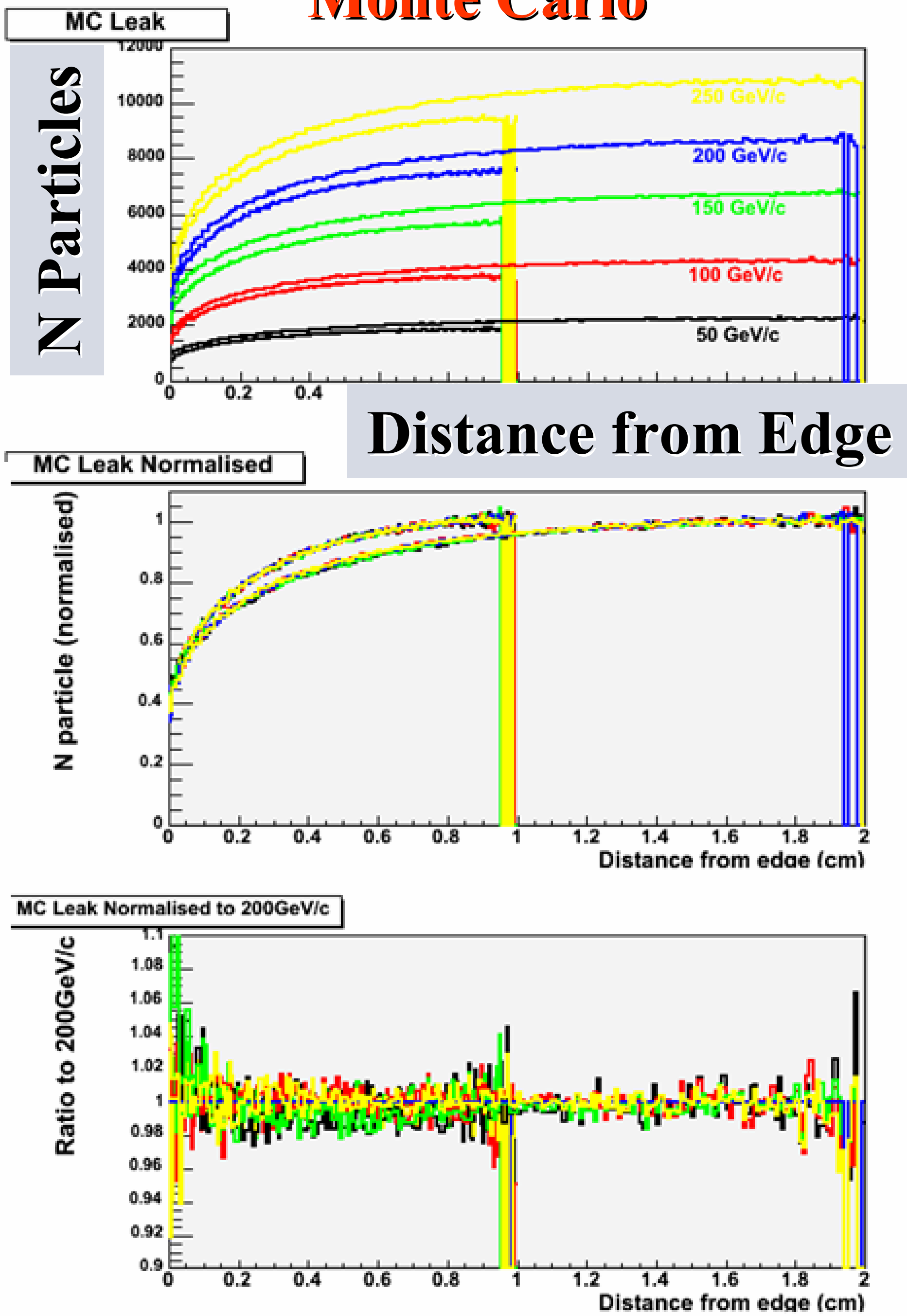
Leakage Correction

MC predicts that the leakage is energy independent!

Prototype Experiment



Monte Carlo

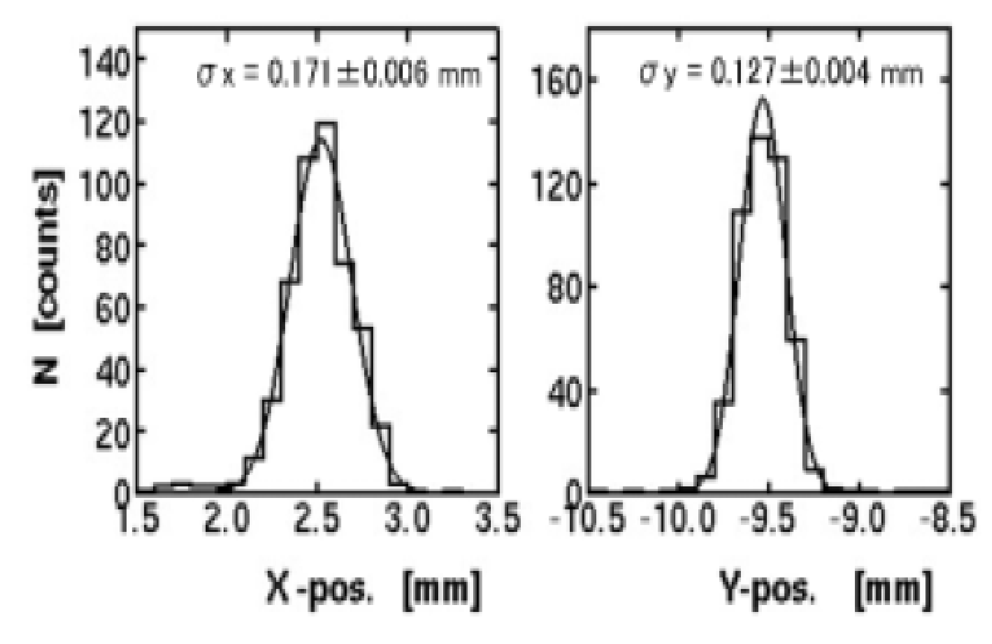


Performances of the LHCf Detector

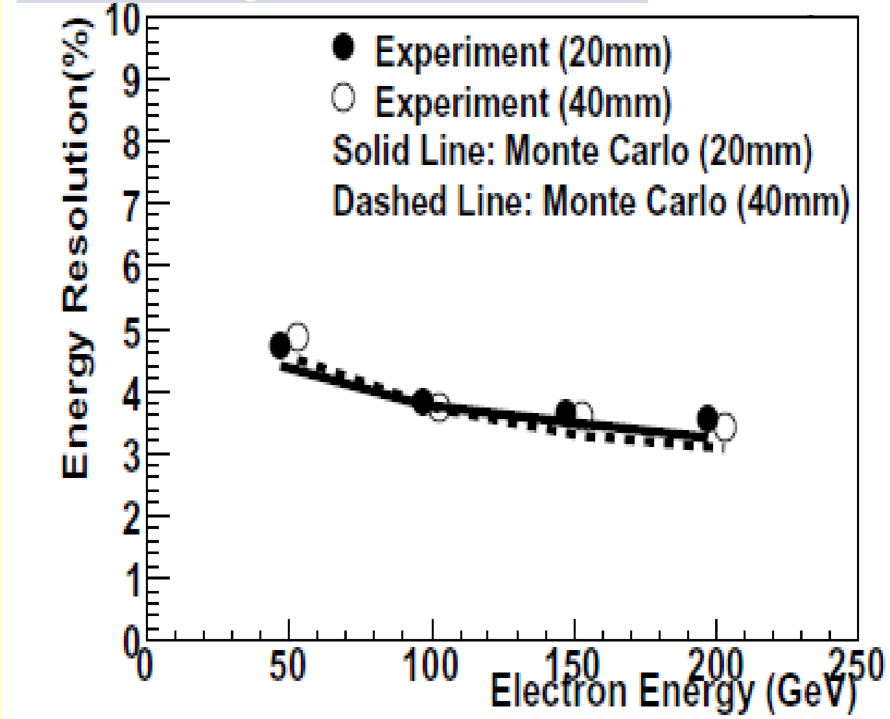
Measured at the SPS

Beam Test in 2004

SciFi Position Resolution



Energy Resolution



LHCf can measure (and provide to LHC) the center of neutral flux from the collisions

If the center of the neutral flux hits LHCf → << 1 mm resolution

Energy Calibration

Problem: Determination of the conversion factor from ADC to Energy in each calorimeter layer

⇒ A_i [ADC counts/MeV] (i: Layer)

How to do?

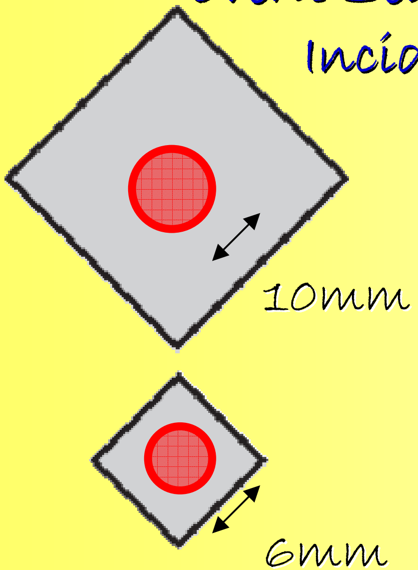
Compare data with simulation (EPICS), tuning with beam test data

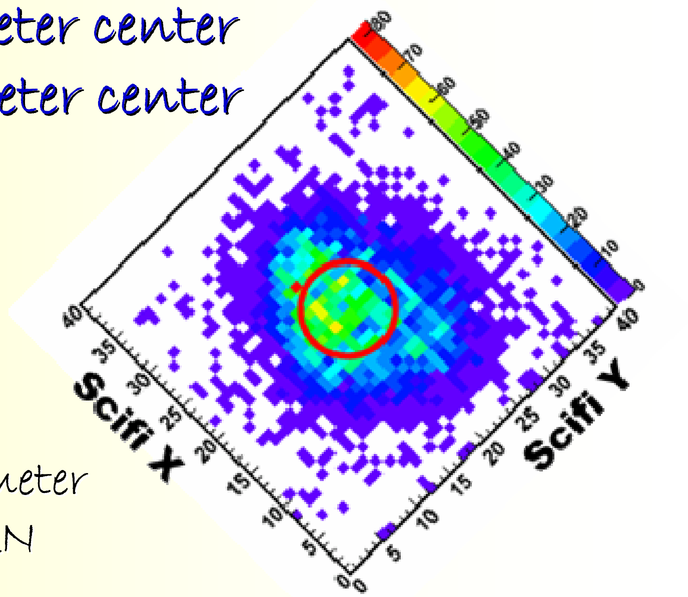
Event Selection (Centered events)

Incident point

20mm →3mm from calorimeter center

40mm →5mm from calorimeter center





Beam Profile

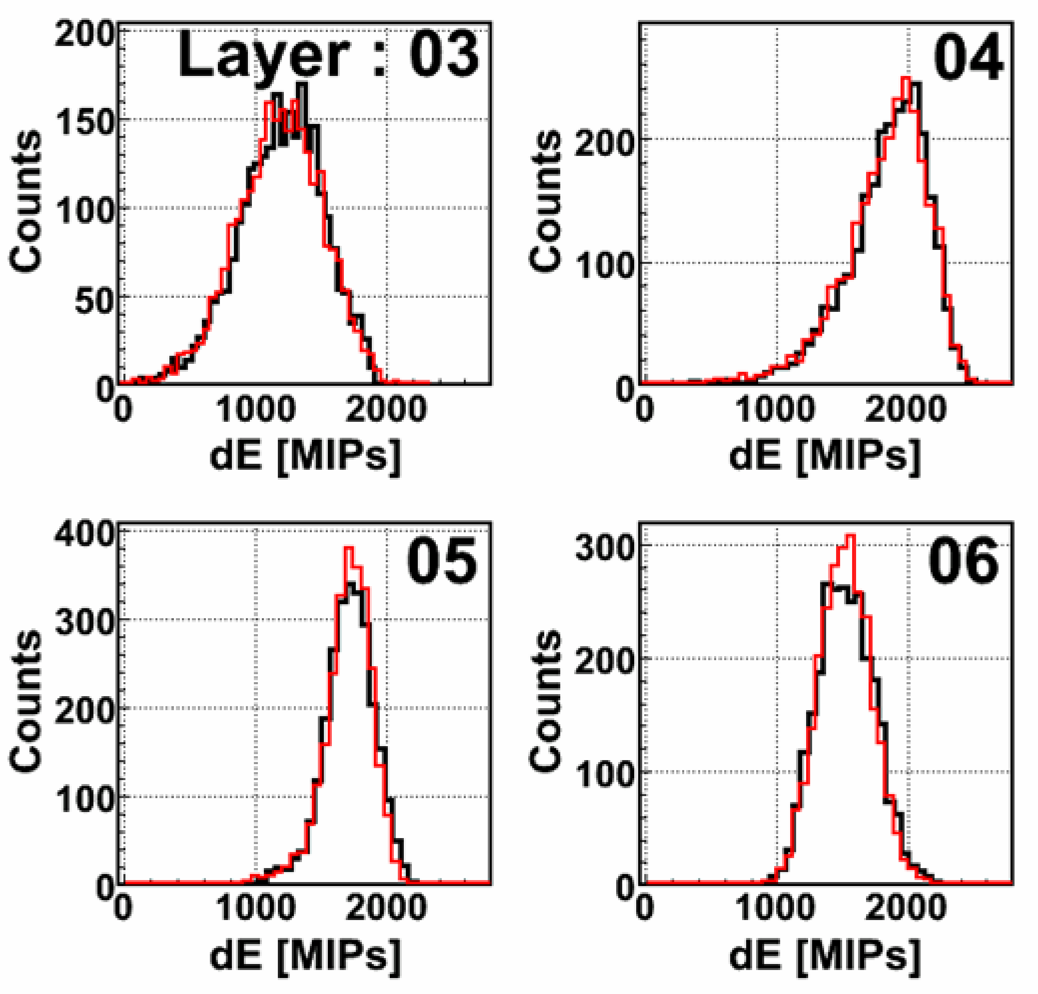
40mm Calorimeter

196 GeV e^- RUN

Data vs. Simulation

40mm Calorimeter : 196 GeV

Red : Simulation   Black : Experiment



Ai = Mean(data) / Mean(simulation)

Layer	χ^2	D.O.F.
3	42.6 /	60
4	23.8 /	48
5	50.0 /	36
6	64.5 /	38

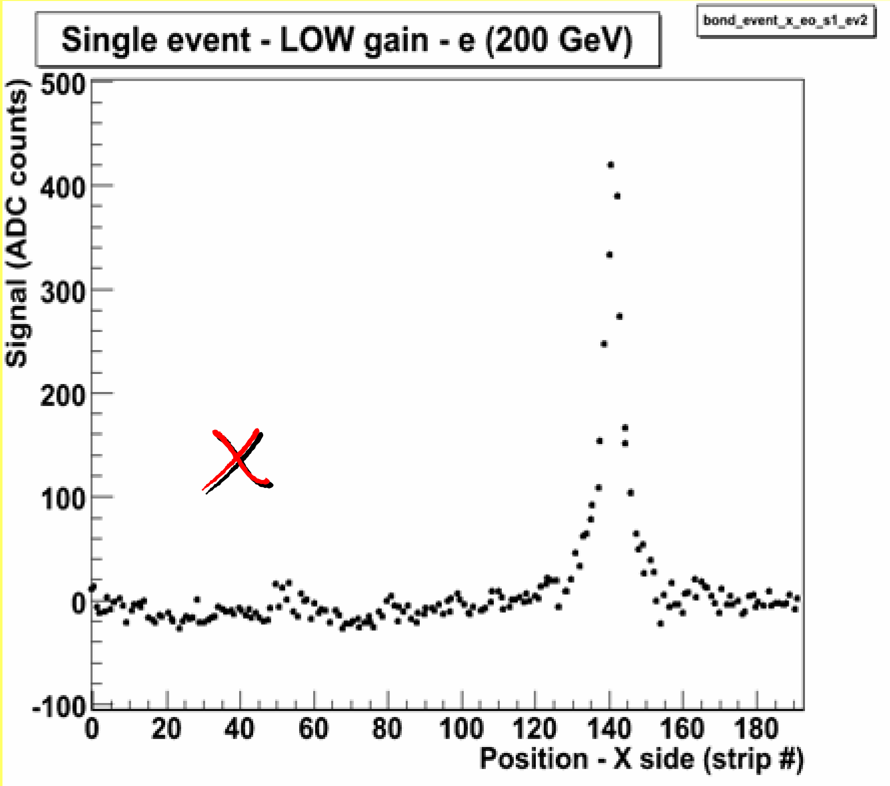
Simulations and data agrees well!!!

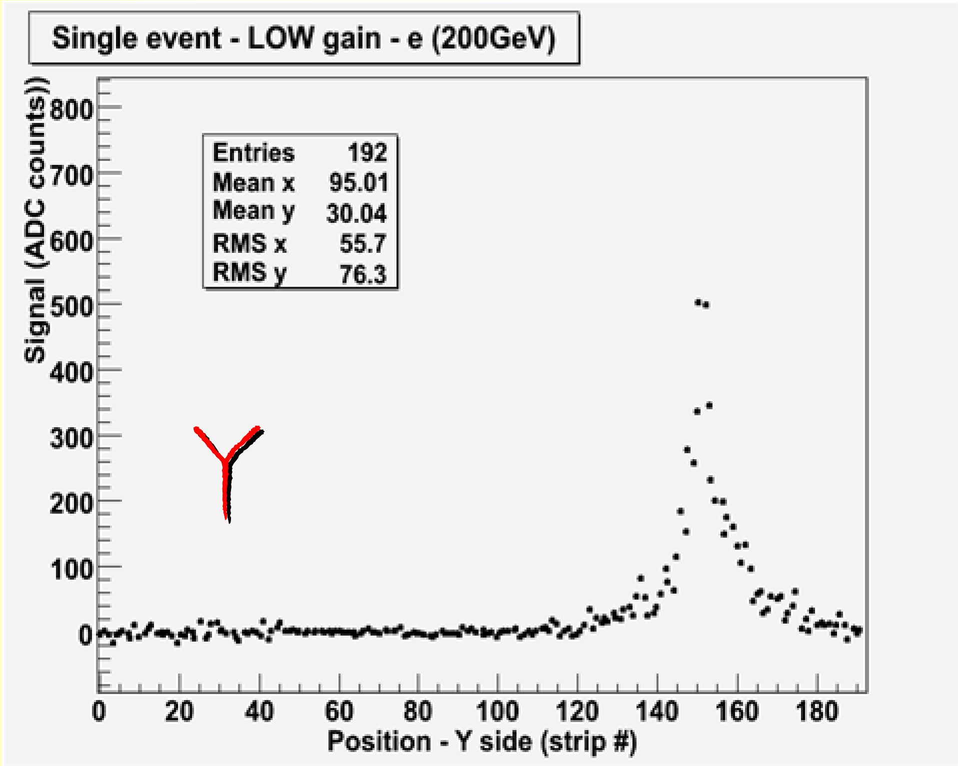
Energy scale can be well inferred

Work in progress to check the energy scale for different energies

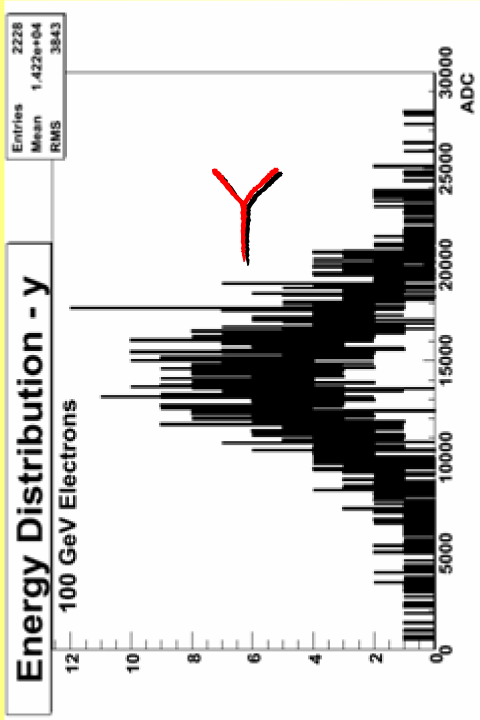
Few plots of the beam test results for silicon

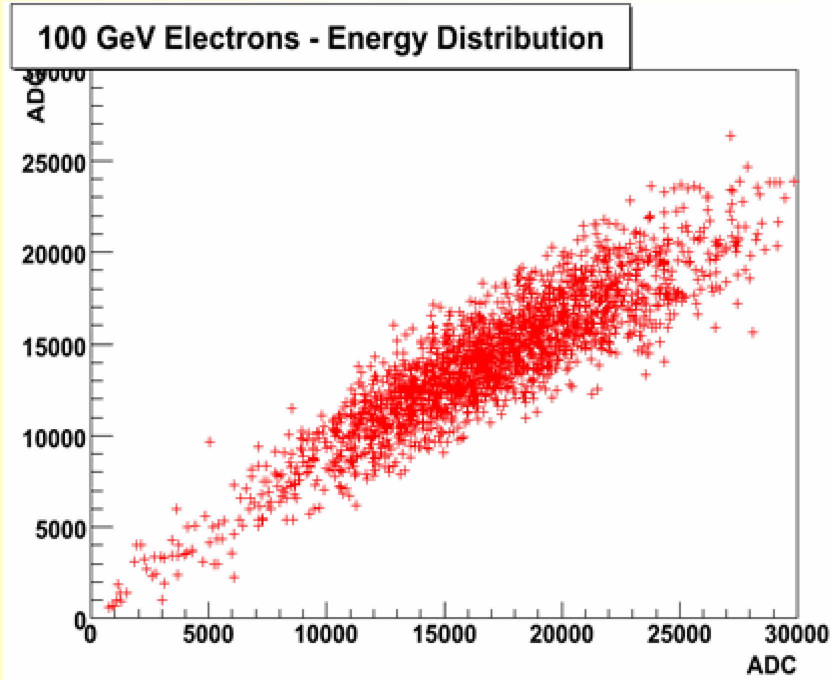
A high energy electron shower seen on x and y silicon

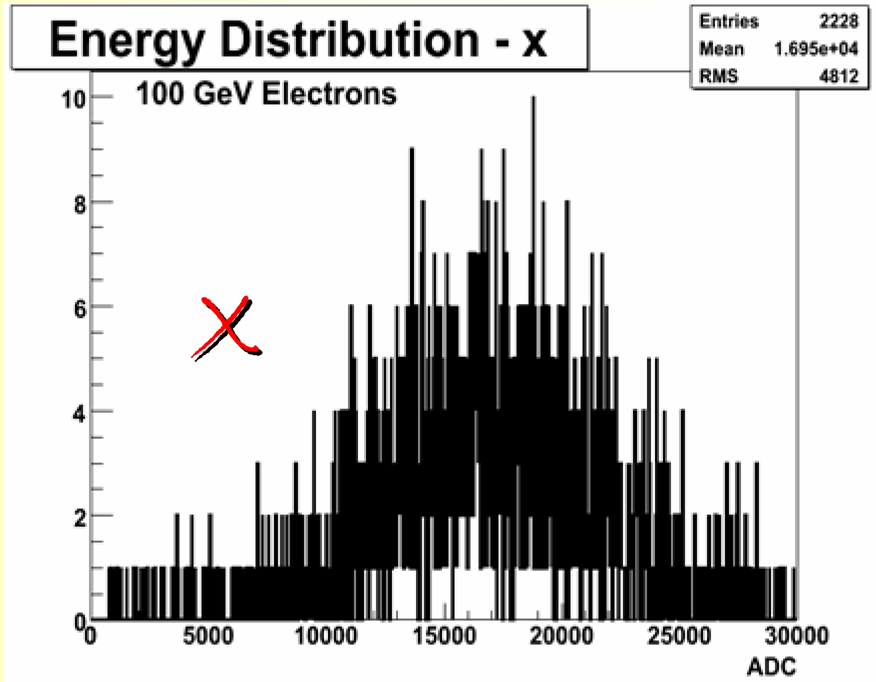




<Noise> ~ 5 ADC counts







Energy measured
100 GeV electrons
High Gain

The LHCf operation in LHC

Optimal LHCf run conditions

Beam parameter	Value
# of bunches	$\leq$ 43
Bunch separation	> 2 μsec
Crossing angle	0 rad 140 μrad downward
Luminosity per bunch	$< 2 \times 10^{28}$ cm^{-2}s^{-1}
Luminosity	$\leq \sim 10^{30}$ cm^{-2}s^{-1}
Bunch intensity	4×10^{10} ppb ($\beta^* = 18$ m) 1×10^{10} ppb ($\beta^* = 1$ m)

Beam parameters used for commissioning are good for LHCf!!!

No radiation problem for 10kGy by a "year" operation with this luminosity

From R. Bailey presentation at January 2007 TAN workshop

Parameter evolution and rates

$$L = \frac{N^2 k_b f \gamma}{4\pi \varepsilon_n \beta^*} F \qquad Eventrate / Cross = \frac{L \sigma_{TOT}}{k_b f}$$

Optimal conditions for LHCf running!

All values for nominal emittance, 7TeV and 10m β* in points 2 and 8

Stage 1

Parameters			Beam levels		Rates in 1 and 5		Rates in 2 (and 8)	
k_b	N	β* 1,5 (m)	I_{beam} proton	E_{beam} (MJ)	Luminosity ($cm^{-2}s^{-1}$)	Events/ crossing	Luminosity ($cm^{-2}s^{-1}$)	Events/ crossing
43	$4\ 10^{10}$	11	$1.7\ 10^{12}$	2	$1.1\ 10^{30}$	<< 1	$1.2\ 10^{30}$	0.15
43	$4\ 10^{10}$	2	$1.7\ 10^{12}$	2	$6.1\ 10^{30}$	0.76	$1.2\ 10^{30}$	0.15
156	$4\ 10^{10}$	2	$6.2\ 10^{12}$	7	$2.2\ 10^{31}$	0.76	$4.4\ 10^{30}$	0.15
156	$9\ 10^{10}$	2	$1.4\ 10^{13}$	16	$1.1\ 10^{32}$	3.9	$2.2\ 10^{31}$	0.77
936	$4\ 10^{10}$	11	$3.7\ 10^{13}$	42	$2.4\ 10^{31}$	<< 1	$2.6\ 10^{31}$	0.15
936	$4\ 10^{10}$	2	$3.7\ 10^{13}$	42	$1.3\ 10^{32}$	0.73	$2.6\ 10^{31}$	0.15
936	$6\ 10^{10}$	2	$5.6\ 10^{13}$	63	$2.9\ 10^{32}$	1.6	$6.0\ 10^{31}$	0.34
936	$9\ 10^{10}$	1	$8.4\ 10^{13}$	94	$1.2\ 10^{33}$	7	$1.3\ 10^{32}$	0.76
2808	$4\ 10^{10}$	11	$1.1\ 10^{14}$	126	$7.2\ 10^{31}$	<< 1	$7.9\ 10^{31}$	0.15
2808	$4\ 10^{10}$	2	$1.1\ 10^{14}$	126	$3.8\ 10^{32}$	0.72	$7.9\ 10^{31}$	0.15
2808	$5\ 10^{10}$	1	$1.4\ 10^{14}$	157	$1.1\ 10^{33}$	2.1	$1.2\ 10^{32}$	0.24
2808	$5\ 10^{10}$	0.55	$1.4\ 10^{14}$	157	$1.9\ 10^{33}$	3.6	$1.2\ 10^{32}$	0.24

R.Bailey, January 2007

LHCf proposed running scenario

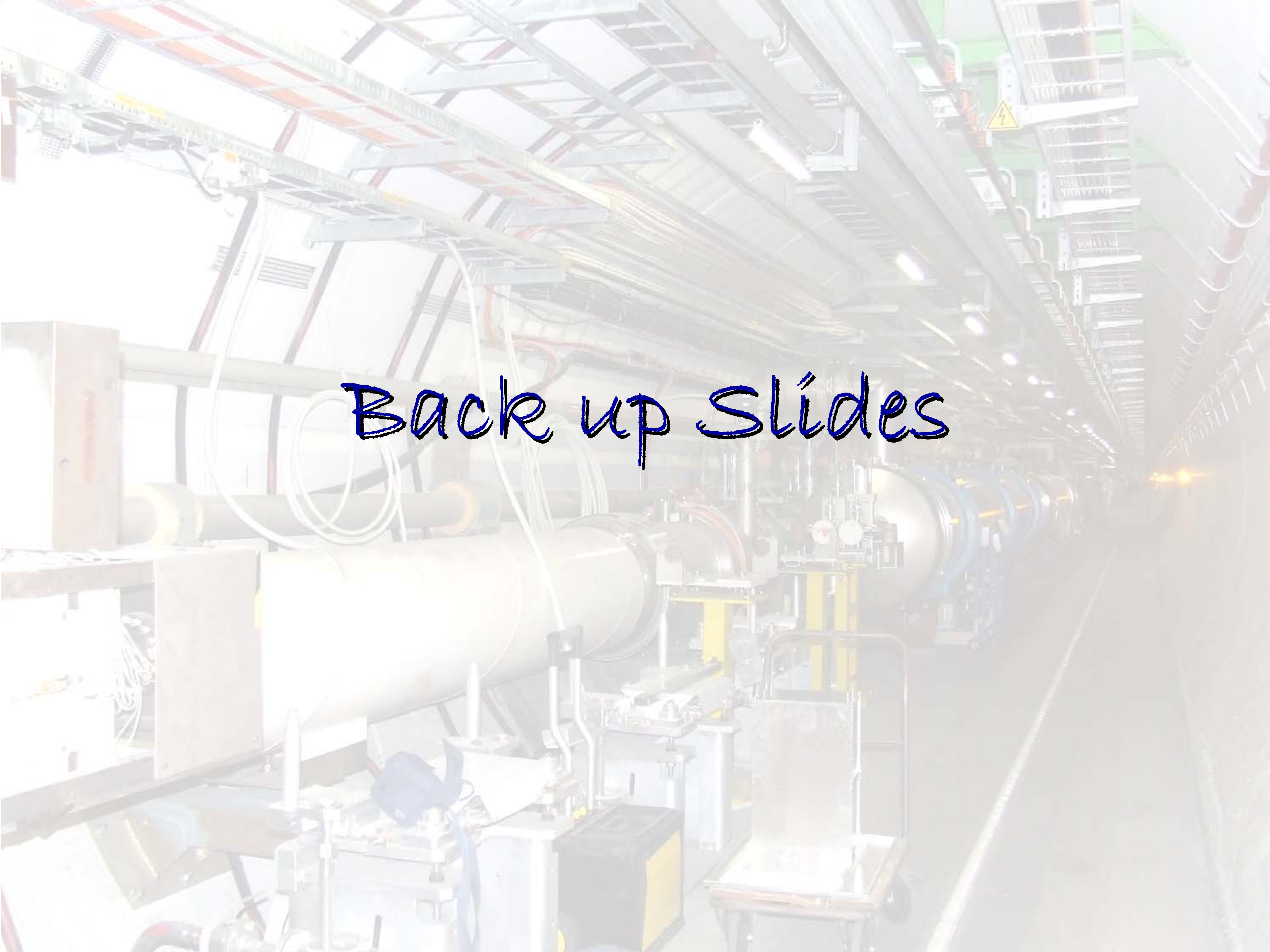
- Phase-I
  - Run since the very beginning of LHC operations (Stage 1, 43 bunches)
  - Remove the detector for radiation issues when the machine goes to the Stage II (luminosity reaches $10^{31}cm^{-2}s^{-1}$) and reinstall the 3 Cu bars
- Phase-II
  - Re-install the detector at the next opportunity of low luminosity run after removal of Cu bars (Totem dedicated runs? Possible LHCf dedicated runs?)
- Phase-III
  - Future extension for p-A, A-A run with upgraded detectors?

LHCf: conclusions and plans

- LHCf approved in June 2006 by the LHCC
- **Physics performances:**
  - able to measure π^0 mass with 5% resolution.
  - able to distinguish the models by measurements of π^0 and γ
  - able to distinguish the models by measurements of n
- **Detectors:**
  - Arm1 & Arm2 are fully ready
  - Test beams were done in 2004 & 200[...] [...]e performances
- **Installation phase well adv[...]**
  - ARM1 already succe[...] [...]stalled in January 07,
  - ARM2 already [...] pre-installed in April-May 07
  - Final installati[...] [...]s under discussion
- **Running conditions:**
  - Three foreseen phases
    - Phase I: Run at the beginning of LHC operations (43 bunches)
    - Phase II: operation during low luminosity TOTEM runs or dedicated runs
    - Phase III: Heavy Ion runs ?

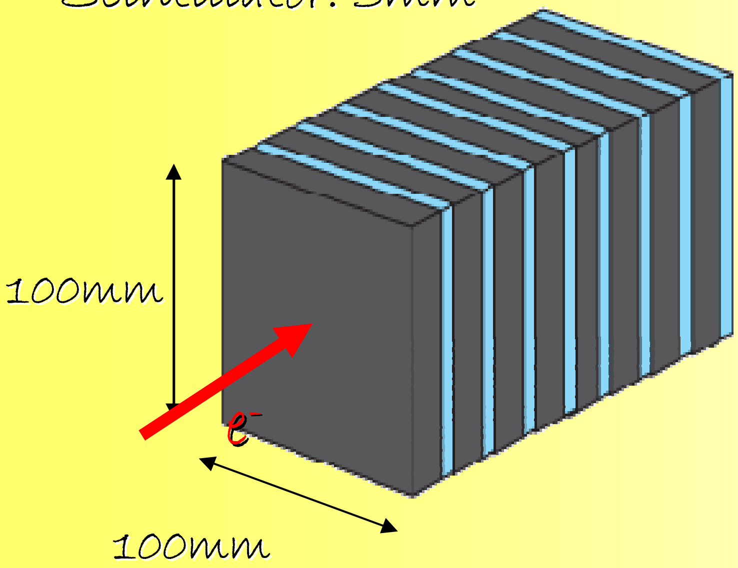
Waiting for LHC beams!!!

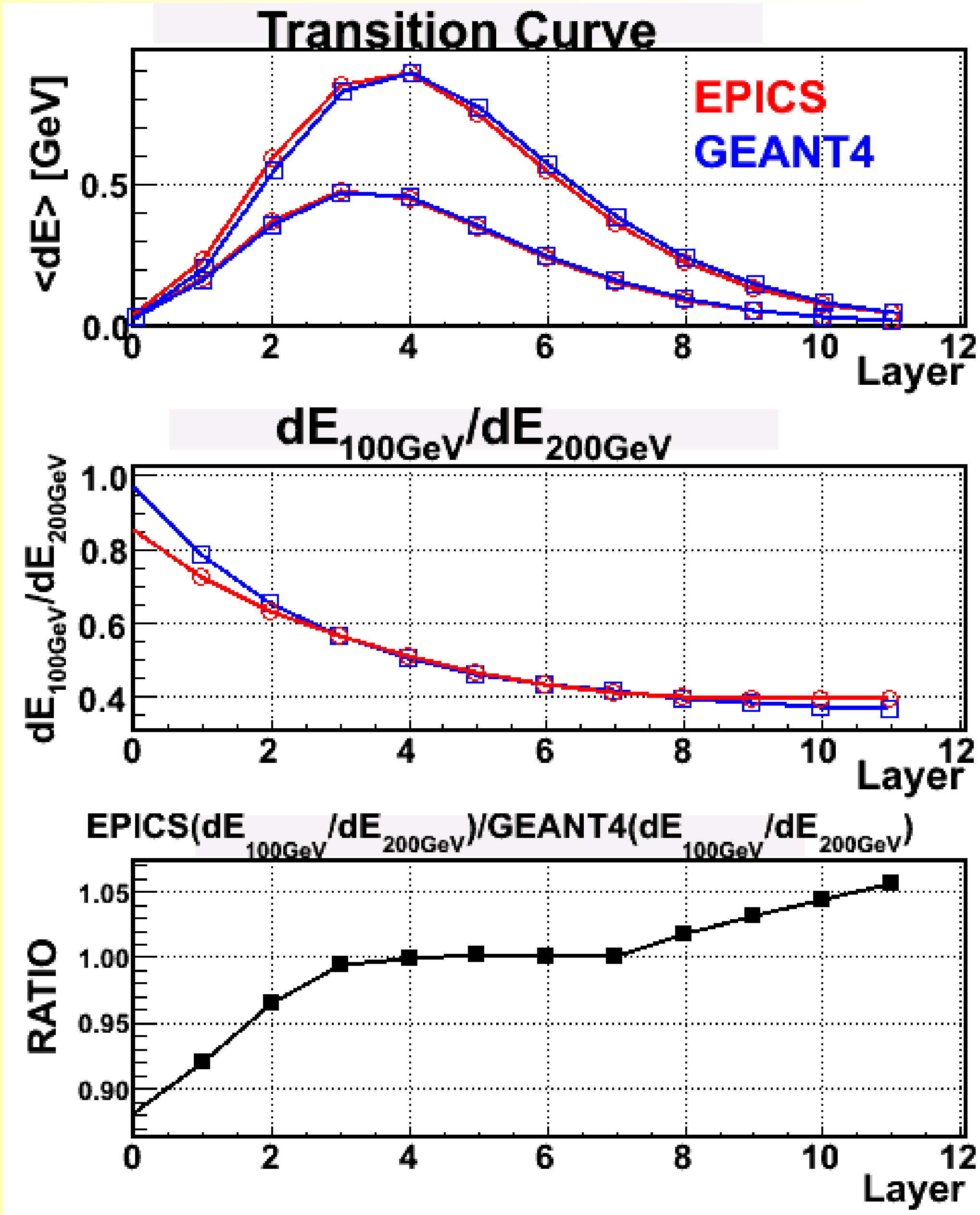
Back up Slides

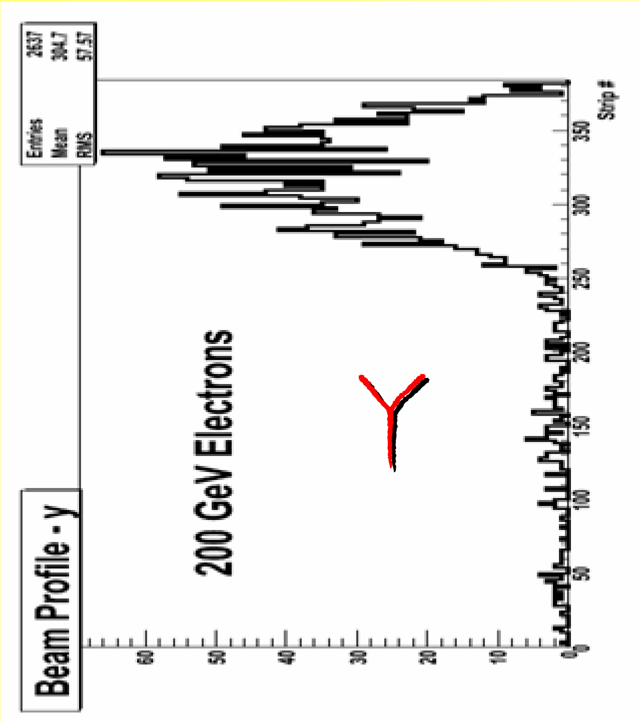


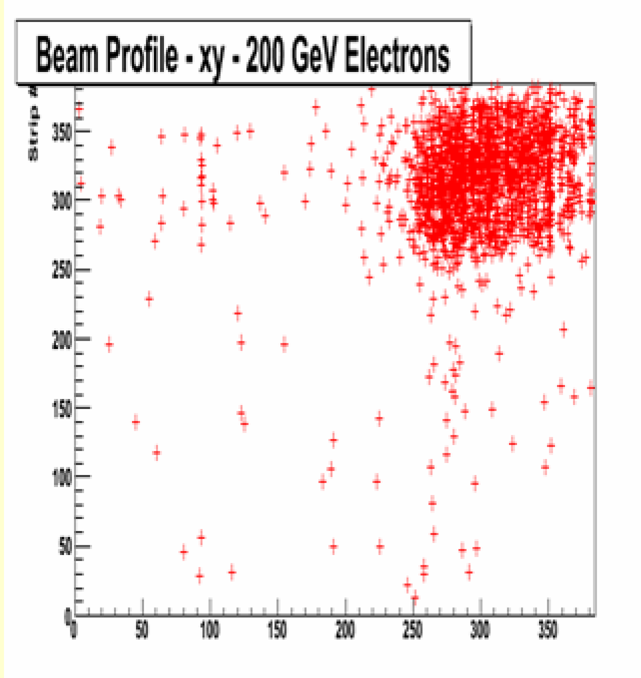
Epics v.s. Geant4

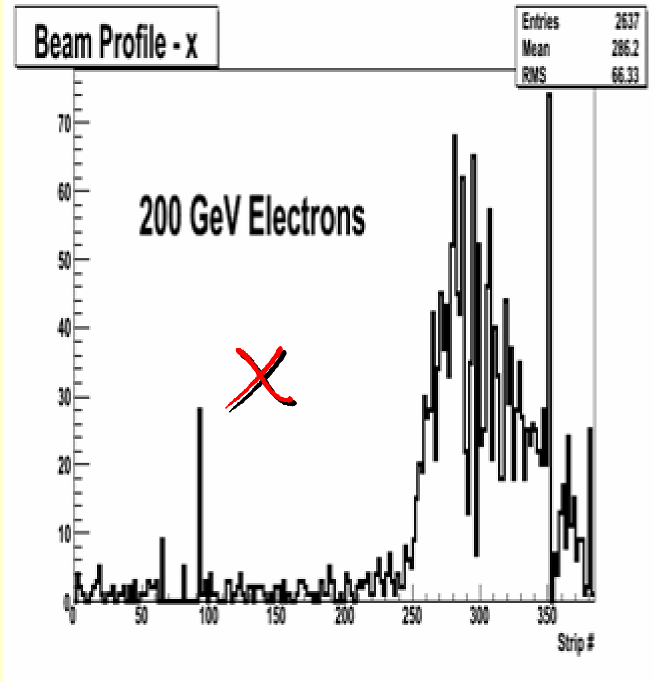
W: 7mm
Scintillator: 3mm x 16











Beam profile
200 GeV electrons

γ rate

	20mm x 20mm	40mm x 40mm
1. Sum E > 100GeV	0.0674	0.0465
2. One Gamma Incident	0.0478	0.0353
3. One Hadron Incident	0.0146	0.0052
4. One Gamma in fiducial	0.0297	0.0272
5. One Neutron in fiducial	0.0006	0.0001

Table 3: Event rate of single γ's and hadrons per inelastic collision for the Detector #1. Here the 2cm×2cm tower is at the center of beam-pipe and without beam crossing angle..

	20mm × 20mm	40mm × 40mm
1. Sum E > 100GeV	0.0674	0.0869
2. One Gamma Incident	0.0478	0.0623
3. One Hadron Incident	0.0145	0.0081
4. One Gamma in fiducial	0.0297	0.0511
5. One Neutron in fiducial	0.0006	0.0002

Table 4: Event rate of single γ's and hadrons per inelastic collision for the Detector #1. Here the 2cm×2cm tower is at the center of the neutral particle flux and with beam crossing angle of 140μrad.

	20mm × 20mm	40mm × 40mm
1. Sum E > 100GeV	0.0949	0.0721
2. One Gamma Incident	0.0654	0.0528
3. One Hadron Incident	0.0198	0.0078
4. One Gamma in fiducial	0.0445	0.0427
5. One Neutron in fiducial	0.0009	0.0002

Table 5: Event rate of single γ's and hadrons per inelastic collision for the Detector #2. Here the detector is at default position and without beam crossing angle.

π^0 rate

1. One Particle Incident on each Calorimeter	0.0040
2. Gamma Incident on each Calorimeter	0.0032
3. Invariant mass cut (125 MeV $< M_{\gamma\gamma} <$ 145MeV)	0.0007

Table 6: Event rate of π^0 production per inelastic collision for Detector #1. Here the 2cm×2cm calorimeter is at the center of beam-pipe and the beam crossing angle is zero.

1. One Particle Incident on each Calorimeter	0.0066
2. Gamma Incident on each Calorimeter	0.0052
3. Invariant mass cut (125 MeV $< M_{\gamma\gamma} <$ 145MeV)	0.0011

Table 7: Event rate of π^0 production per inelastic collision for Detector #1. Here the 2cm×2cm tower is at the center of the neutral particle flux and te beam crossing angle is 140μrad.

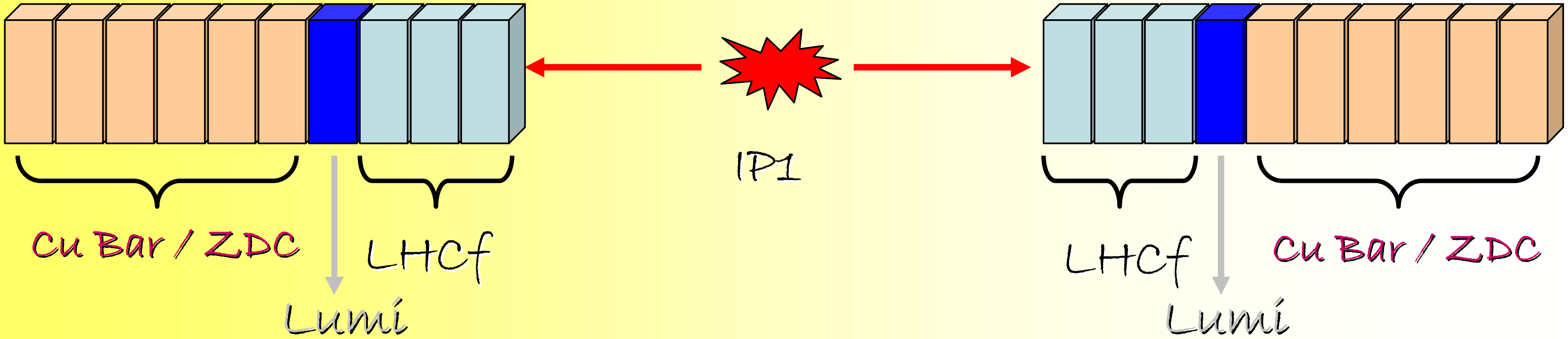
1. One Particle Incident on each Calorimeter	0.0080
2. Gamma Incident on each Calorimeter	0.0063
3. Invariant mass cut (125 MeV $< M_{\gamma\gamma} <$ 145MeV)	0.0015

Table 8: Event rate of π^0 production per inelastic collision for Detector #2. Here the 2.5cm×2.5cm calorimeter is at the center of neutral particle flux and the beam crossing angle is 0μrad.

74

Effect of LHCf on BRAN measurement

LUMI monitor (BRAN) inside TAN is beyond LHCf (replacing 4th copper bar)



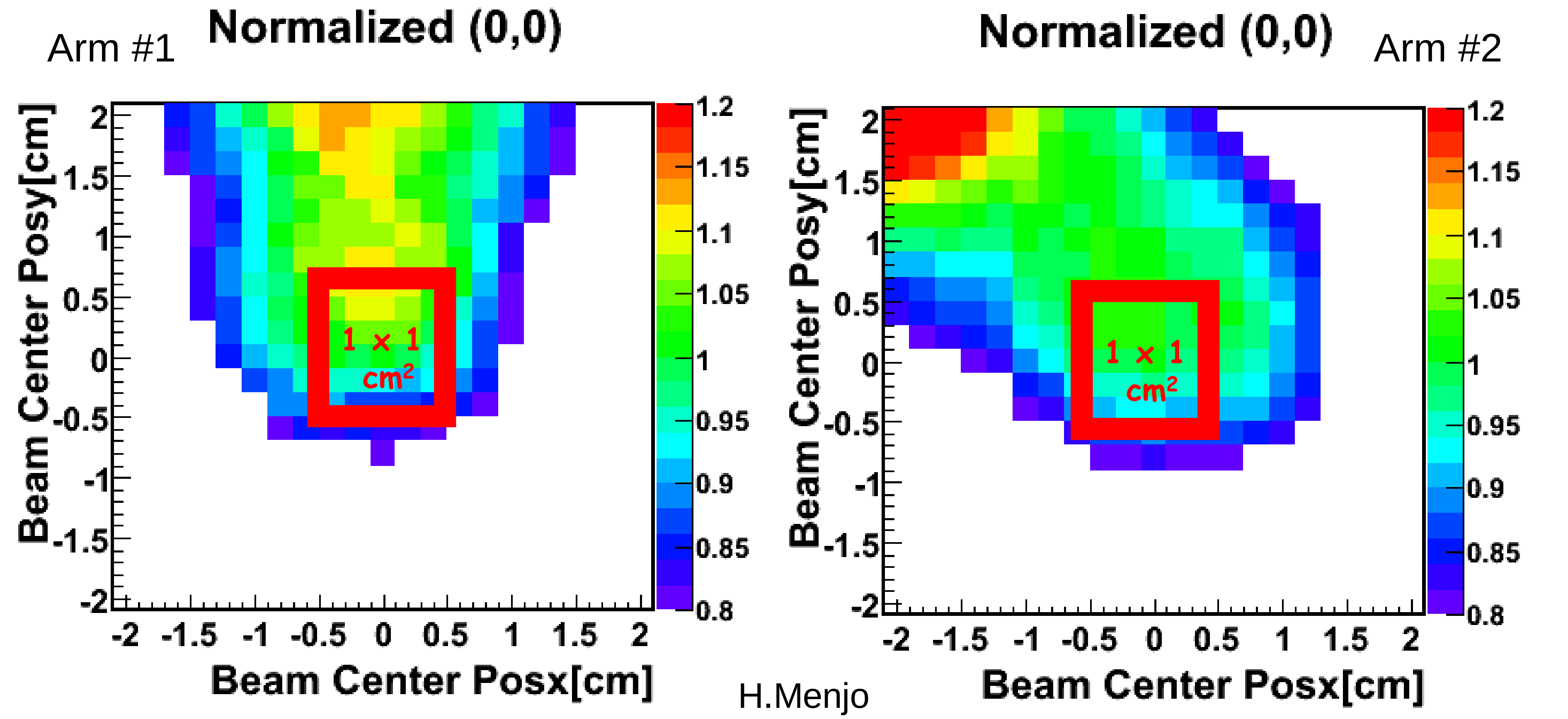
The effect of LHCf on BRAN measurements has been studied in the last months by simulation

- Reduction of shower particles at BRAN
- Position dependence on beam displacement (question from machine peoples: if we shift by 1 mm the real beam, does the center of the measured neutral energy shifts by 1 mm?)

BRAN response vs beam position

Relative change of the reduction factors for BRAN with respect to the nominal value (center of the beam: nominal one)

If the position of beam center stays within a few mm from the beam-pipe center, the reduction factors do not change more than 10%



H.Menjo