LHCf: a LHC experiment for astroparticle physics

- Physics motivations
- Proposed measurements
- Experimental apparatus

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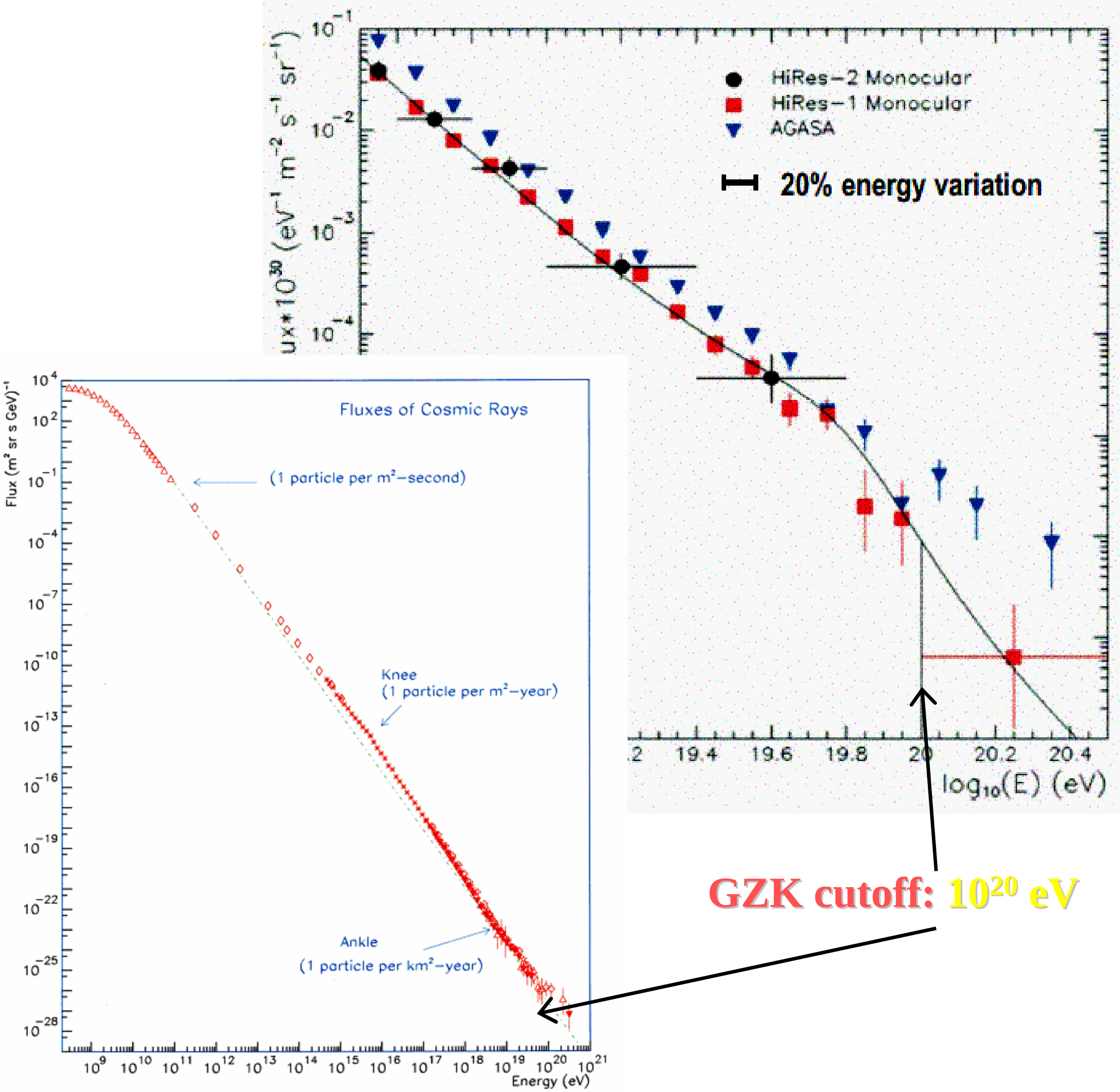
Cosmic rays

- **OMG events**
  - Cosmic ray events whose reconstructed primary energy is greater than 10^{19} eV
  - Many seen by the AGASA experiment in the region beyond 10^{20} eV.
- **GZK cutoff** (Greisen, Zatsepin, Kuzmin)
  - Interaction with 2.7K photons from the CMB.



GZK cutoff: 10^{20} eV

What are these UHECR ?

Protons:

- Interaction with 2.7K photons
- $p + \gamma \rightarrow \Delta^{+}(1232) \rightarrow \pi N$
- Threshold energy: 5.10^{19} eV
- Cutoff GZK
- Attenuation length ≅ 100 Mpc

Nuclei:

- Photo-disintegration with the 2.7K photons
- Attenuation length ≅ 10 Mpc

Neutrons:

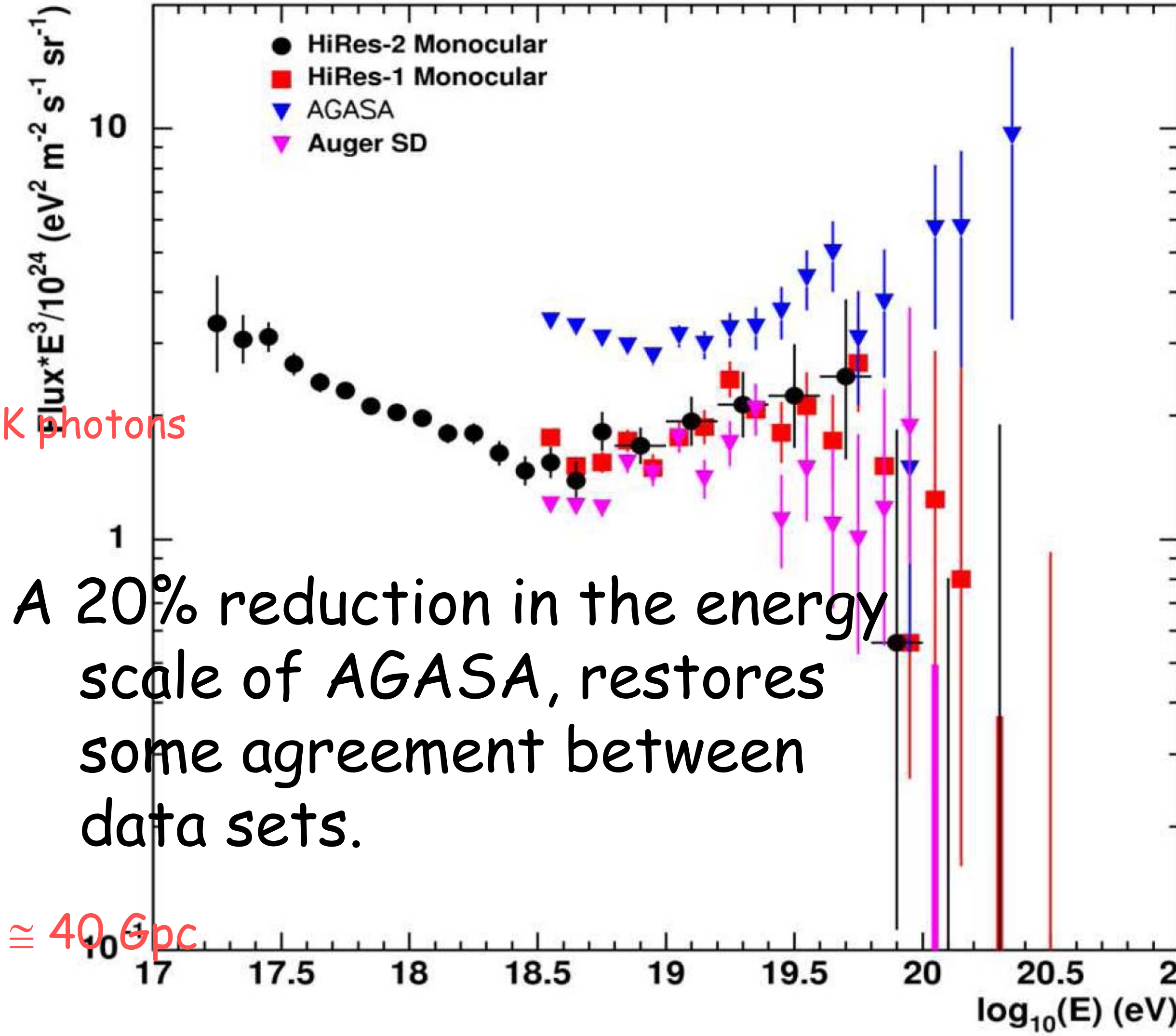
- β decay
- Range ≅ 1 Mpc ($\gamma \cong 10^{11}$)

Electrons and photons:

- Pair production with CMB
- Compton scattering
- Attenuation length ≅ 10 Mpc

Neutrinos: Attenuation length ≅ 40 Gpc

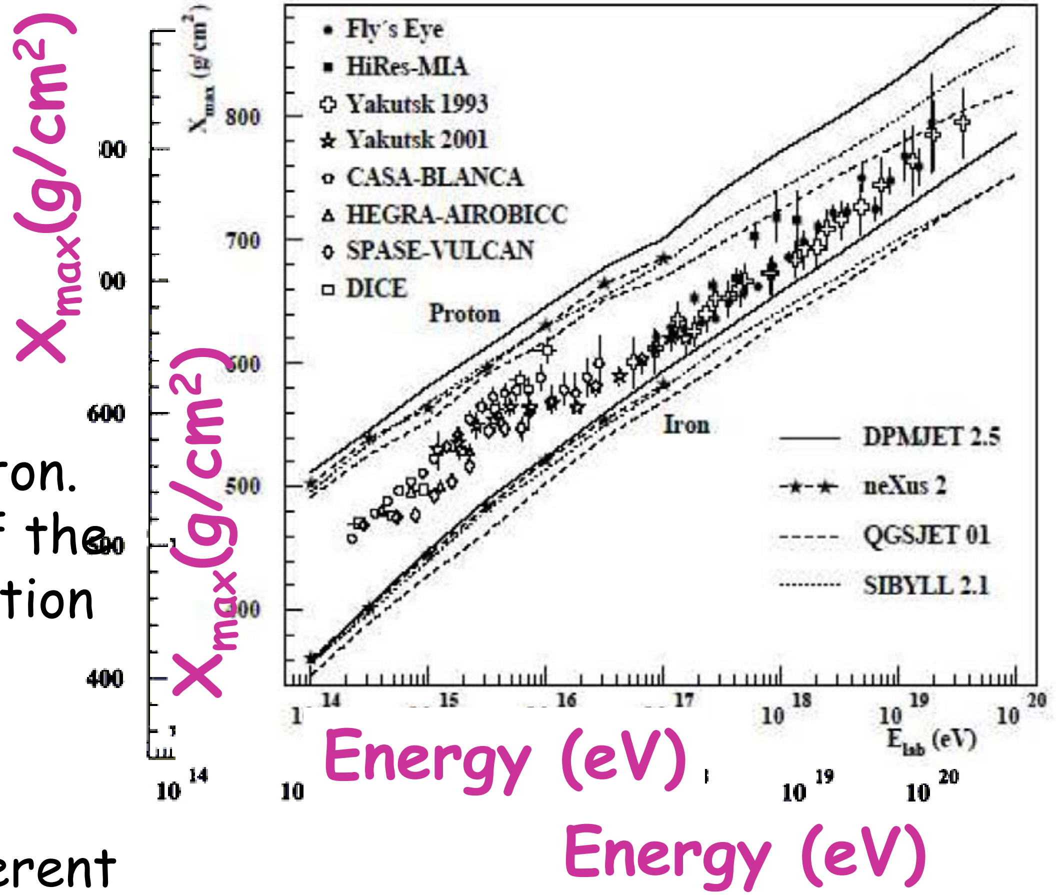
1 pc = 3.3 ly = 3.1 10^{16} m
Milky Way ~ 30 kpc



A 20% reduction in the energy scale of AGASA, restores some agreement between data sets.

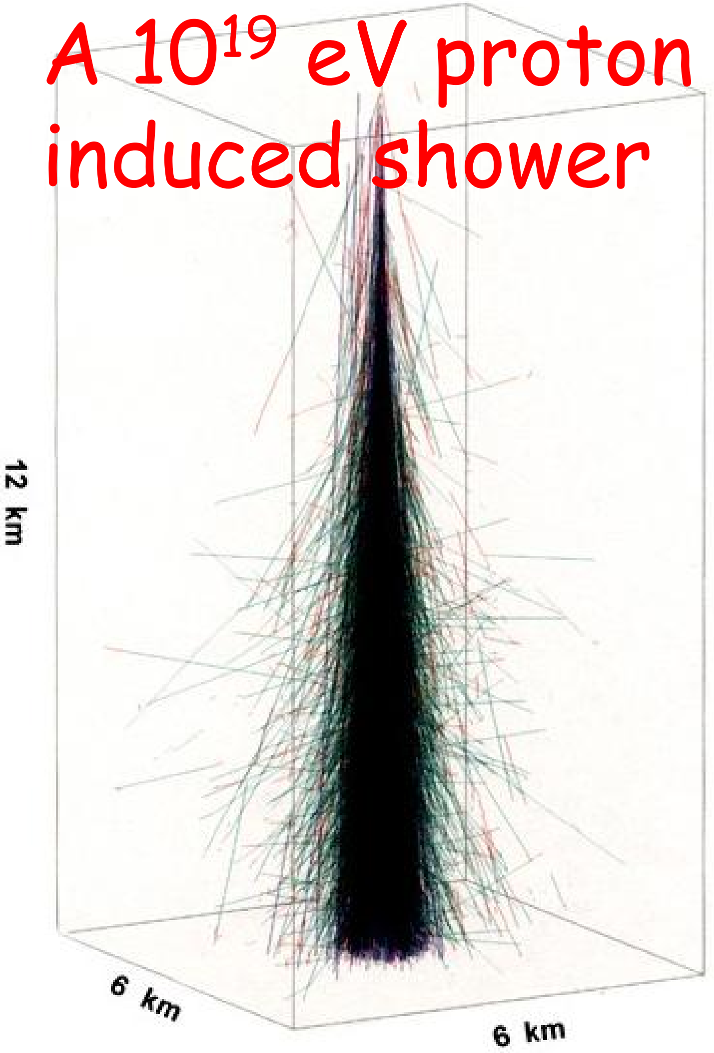
Also composition is unknown

- Knee region
- Cosmic rays not only protons also nuclei (10% Fe at high energies)
- A heavy nuclei will initiate a shower higher up in the atmosphere respect to a proton. Not knowing the behaviour of the nuclear interaction cross-section with energy gives rise to an ambiguity on the primary composition.
- Different models give a different primary composition.



Atmospheric showers

- A 10^{19} eV proton induced shower



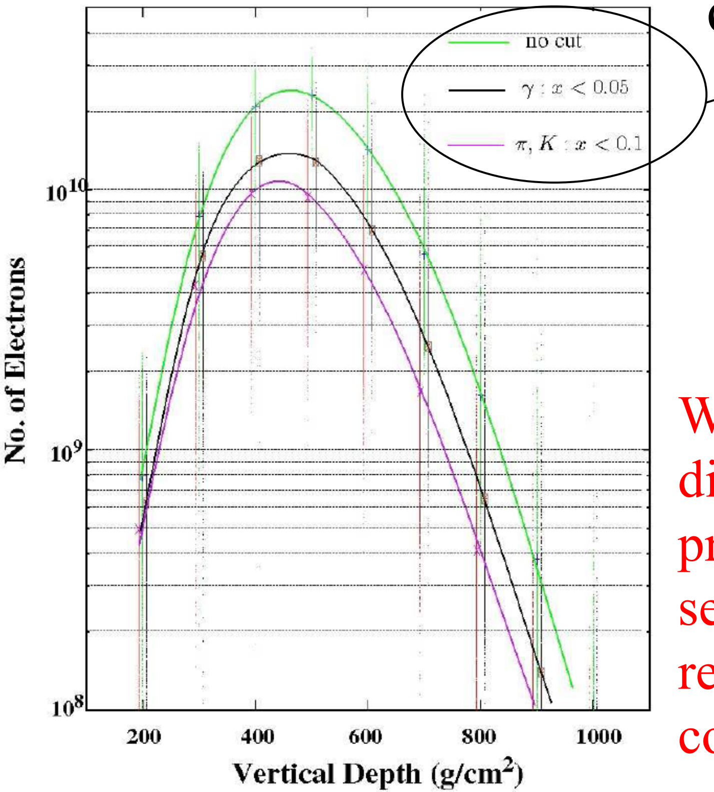
- The dominant contribution to the energy flux is in the very forward region ($\theta \approx 0$)
- In this forward region the highest energy measurements of π^0 cross section were done by UA7 **($E=10^{14}$ eV, $y = 5 \div 7$)**
- LHCf will extend these measurements to **$E_{lab}=10^{17}$ eV** ($E_{lab}= E^2_{cm}(LHC)/2\, m_P$) and $y \rightarrow \infty$.

Study of air-shower development

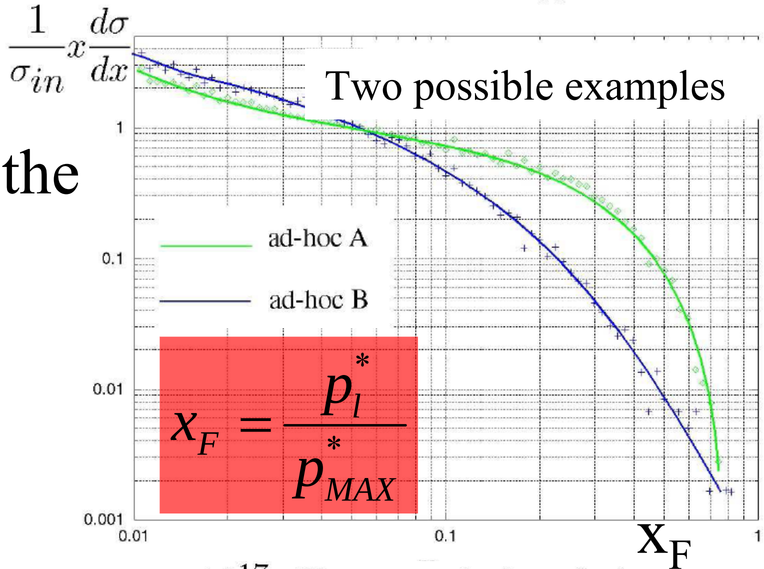
Importance of the neutral foward component !

5x10^{19} eV proton initiated showers

Zenith angle 60 deg.



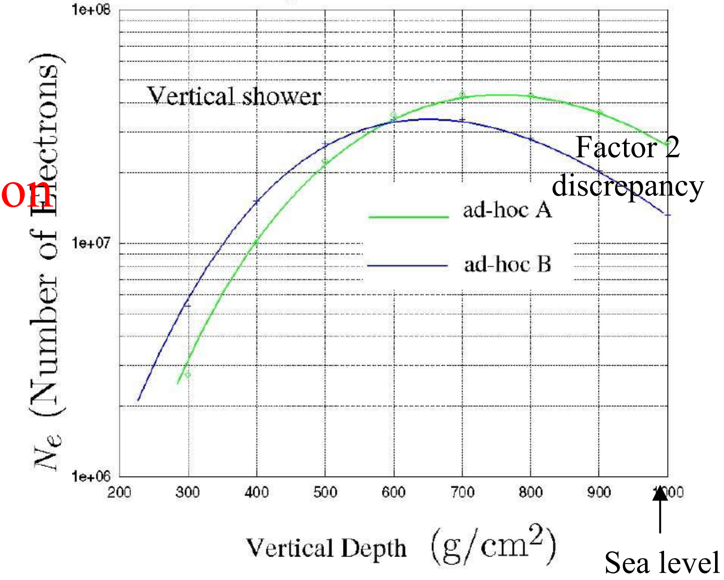
Pion x-distribution at 10^{17} eV pp interaction



Two possible examples

$$x_F = \frac{p_l^*}{p_{MAX}^*}$$

10^{17} eV proton induced showers



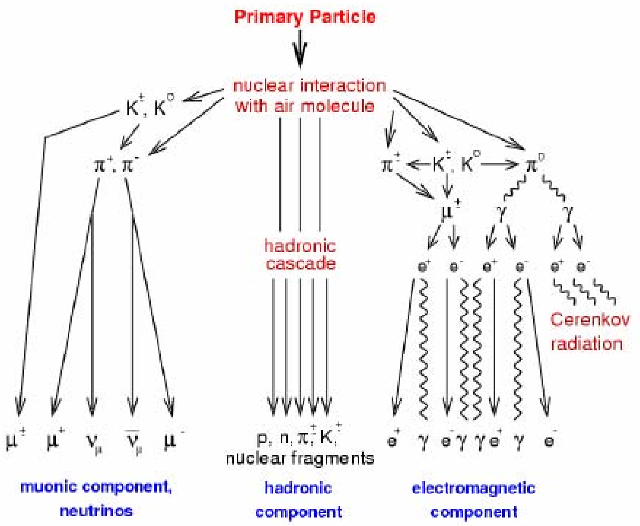
Factor 2 discrepancy

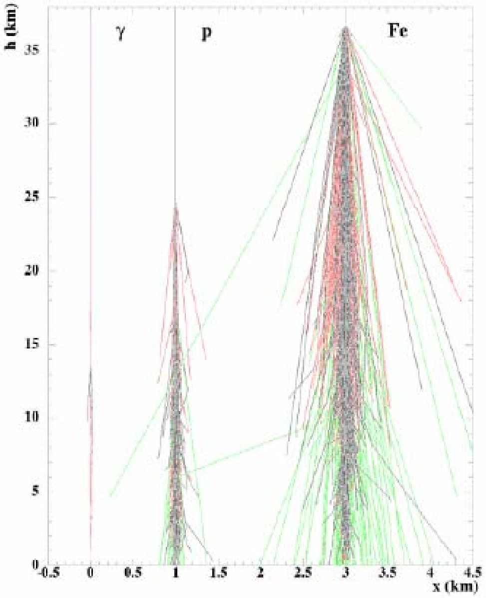
Sea level

We need to measure directly the neutral pion production cross-section in the foward region, in order to correctly estimate the primary cosmic ray energy.

No High Energy Data available!

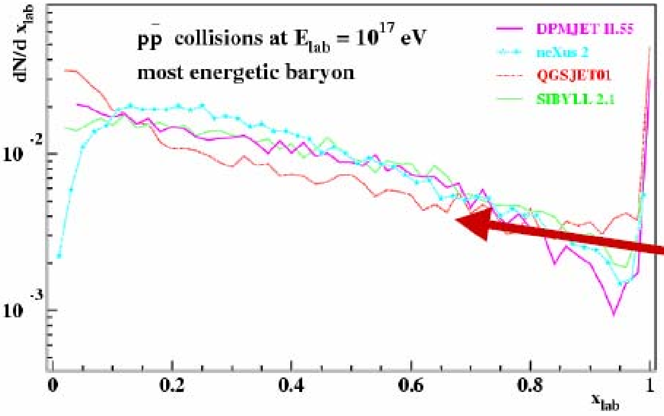
High Energy Cosmic Rays





Cosmic ray showers: Dynamics of the high energy particle spectrum is crucial

Karlsruhe,
La Plata

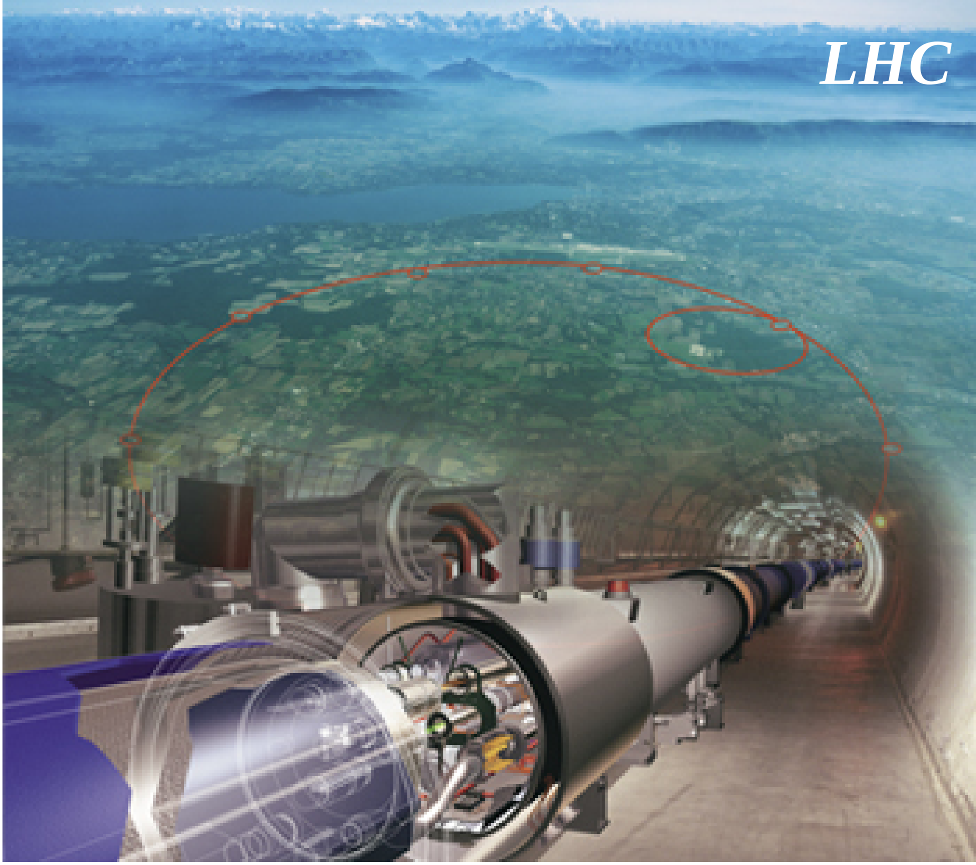


Interpreting cosmic ray data depends on hadronic simulation programs
Forward region poorly know/constrained
Models differ by factor 2 or more
Need forward particle/energy measurements
e.g. dE/dη…

e

The experiment

- Calibration of the models at high energy is mandatory
- We propose to use LHC,the highest energy accelerator
- 7 TeV + 7 TeV protons 14 TeV in the centre of mass $\rightarrow$**$E_{lab}=10^{17}$ eV**

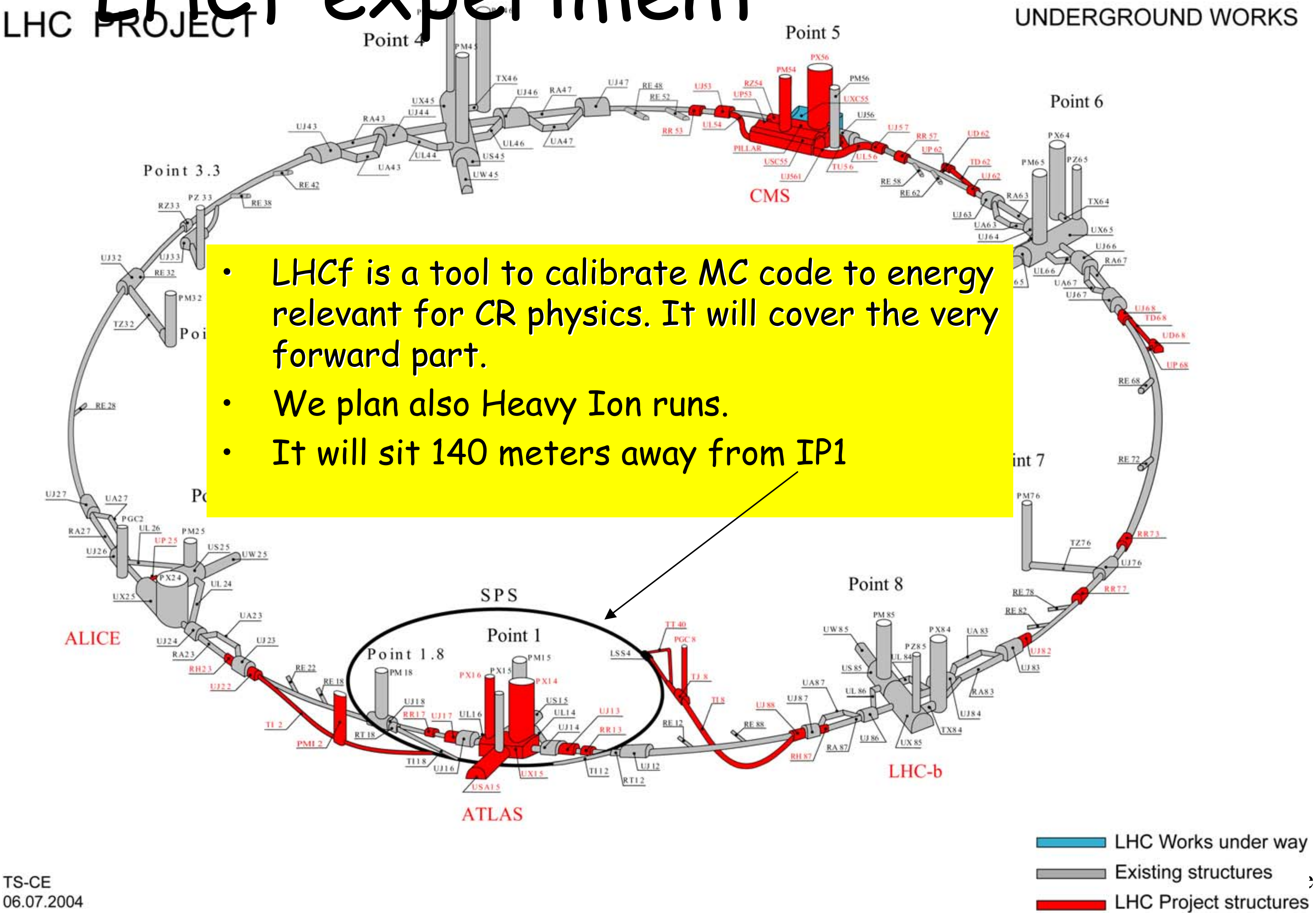


ISSUES:

- The forward production spectra of photons and π^0 .
- The leading particle spectra.
- The total inelastic cross-section.

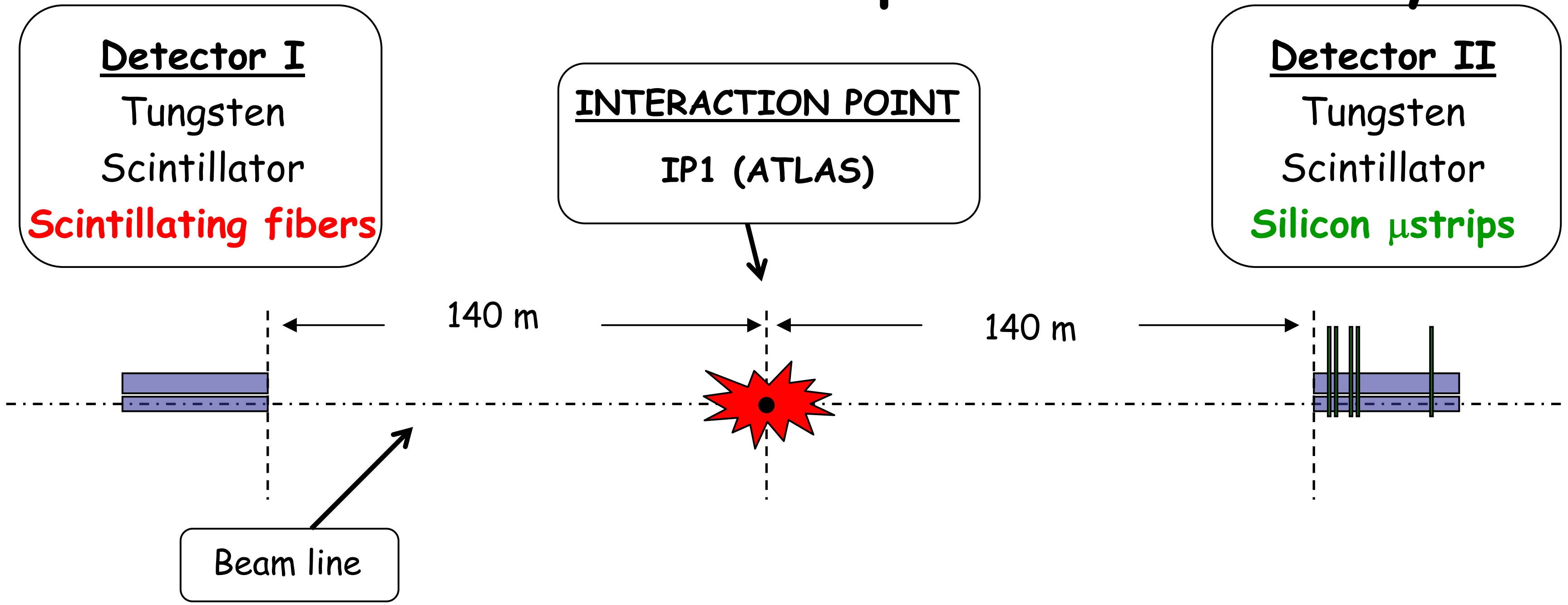
LHCf can provide information on the first two points.
The TOTEM experiment will provide an accurate measurement of the third.

LHCf experiment



- LHCf is a tool to calibrate MC code to energy relevant for CR physics. It will cover the very forward part.
- We plan also Heavy Ion runs.
- It will sit 140 meters away from IP1

LHCf: location and experimental layout



Detector I
Tungsten
Scintillator
Scintillating fibers

INTERACTION POINT
IP1 (ATLAS)

Detector II
Tungsten
Scintillator
Silicon μstrips

140 m

140 m

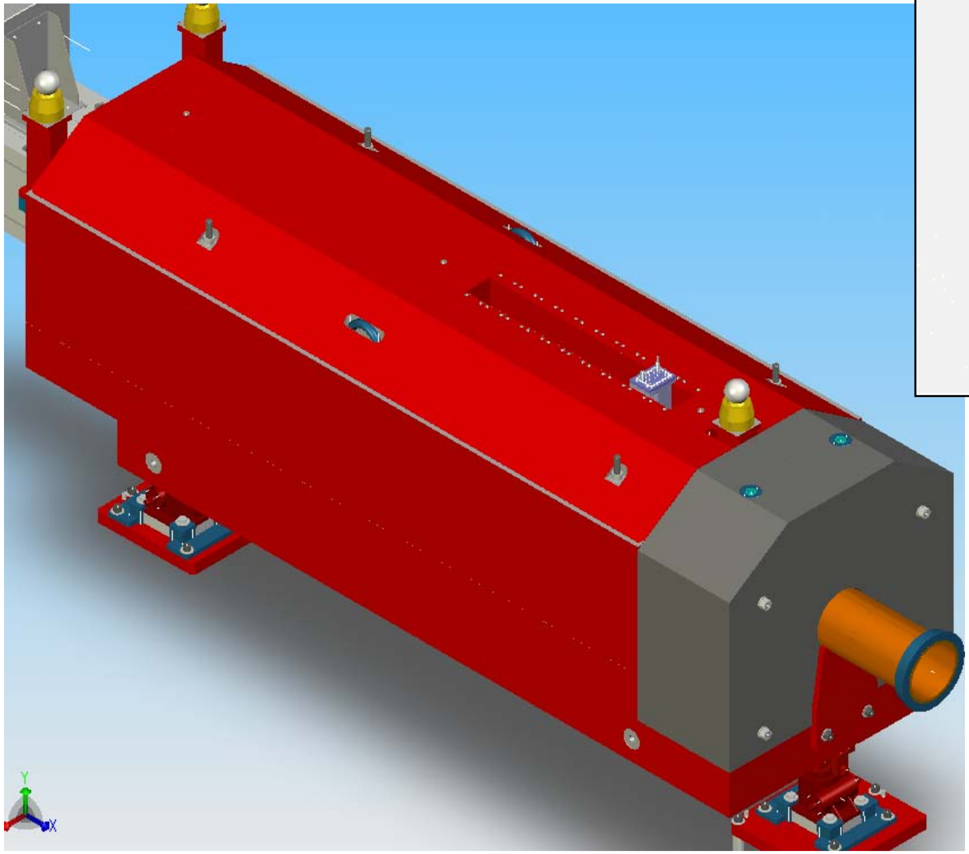
Beam line

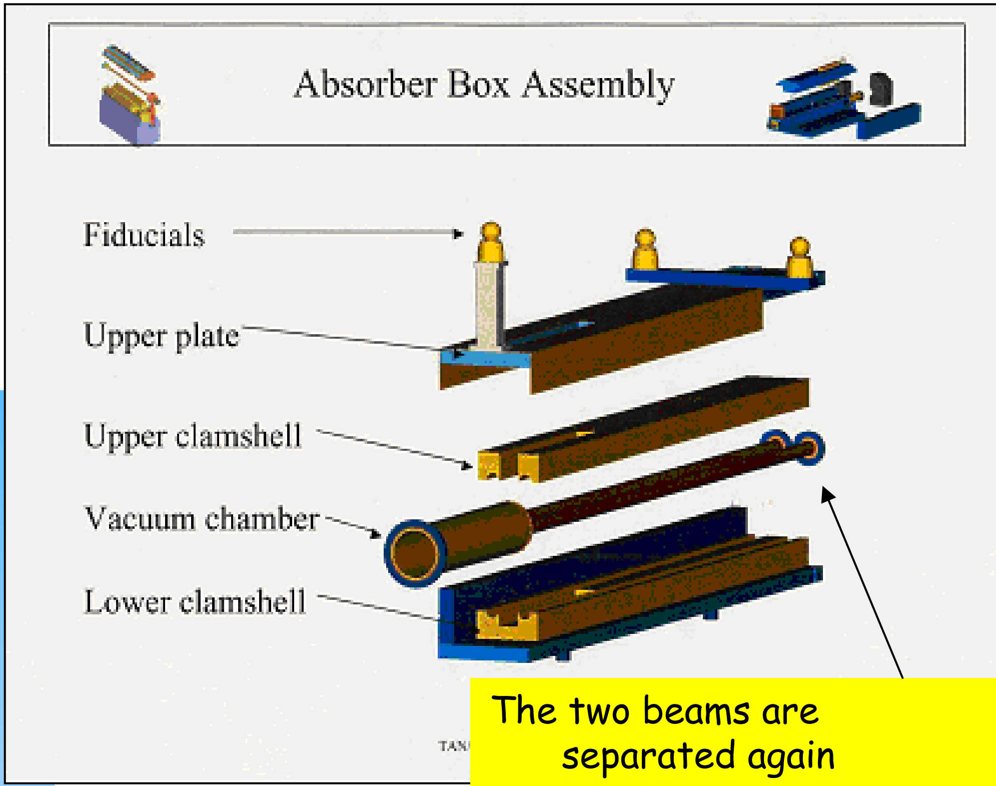
Detectors should measure energy and position of γ from π^0 decays ➡ e.m. calorimeters with position sensitive layers

Two independent detectors on both side of IP1

- ✓ Redundancy
- ✓ Eventually background measurement and/or rejection (especially beam-gas)

Neutral Beam Absorber (TAN)





The two beams are separated again

Charged particles are swept away by magnets!!!

The calorimeters will be installed in the TAN, 140m away from the Interaction Point, in front of the luminosity monitors.

Detector #1

2 towers 24 cm long stacked vertically with 5 mm gap

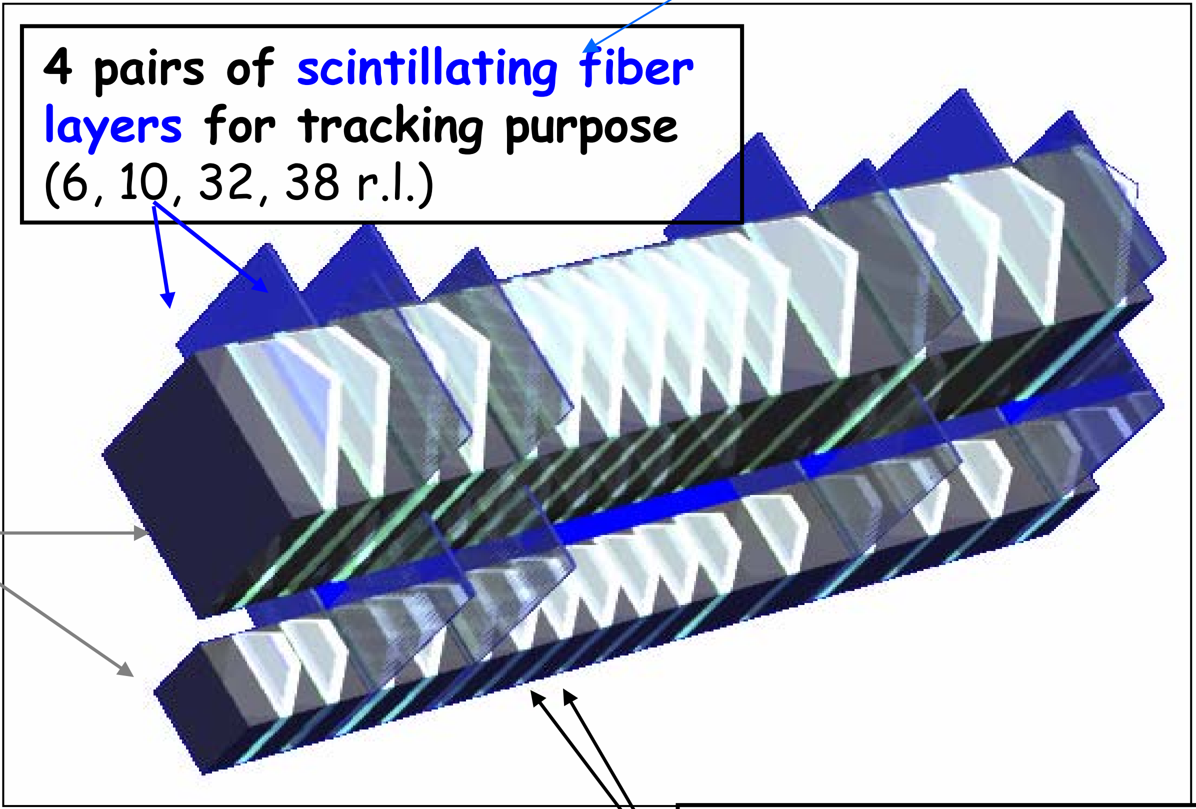
Lower:2 cm x 2 cm area

Upper: 4 cm x 4 cm area

Absorber

22 tungsten layers 7mm – 14 mm thick

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



Impact point (η)

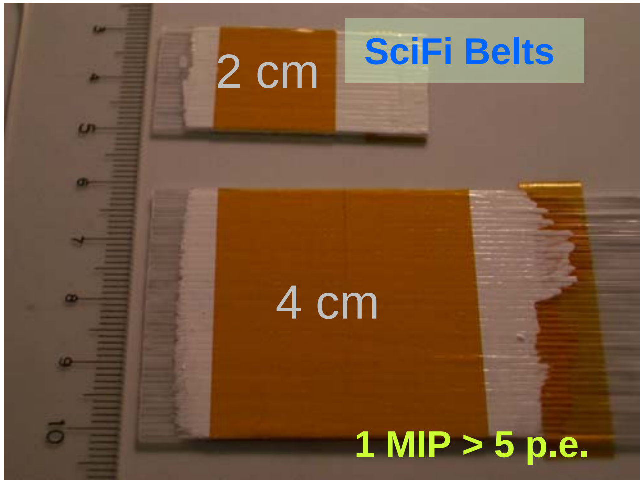
4 pairs of scintillating fiber layers for tracking purpose (6, 10, 32, 38 r.l.)

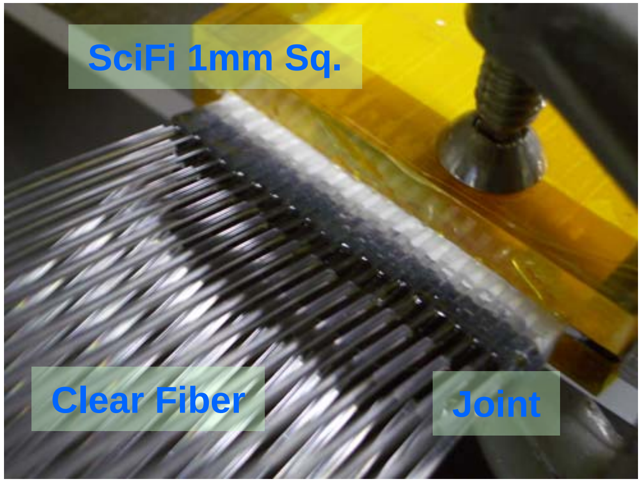
16 scintillator layers (3 mm thick)

Trigger and energy profile measurements

Energy

Scintillating fibers readout

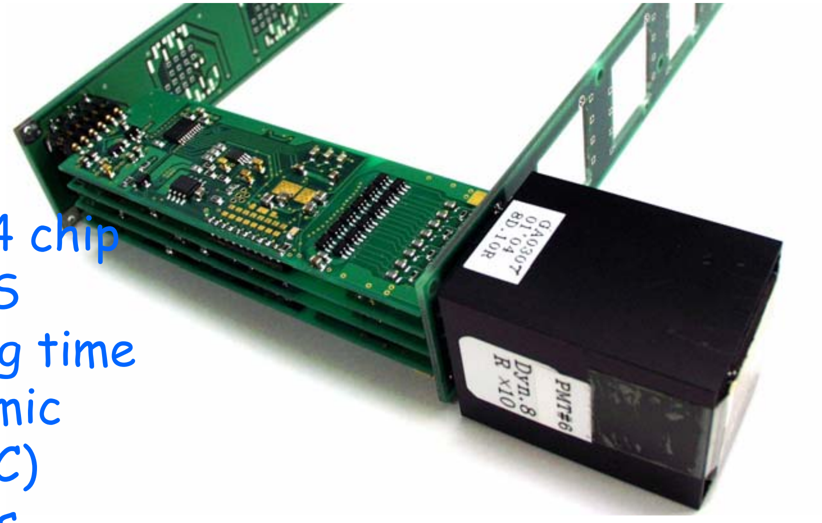




Hamamatsu
64 ch (8x8)
8 dynode

MAPMT

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



MAPMT+FEC

Detector # 2

We used LHC style electronics and readout

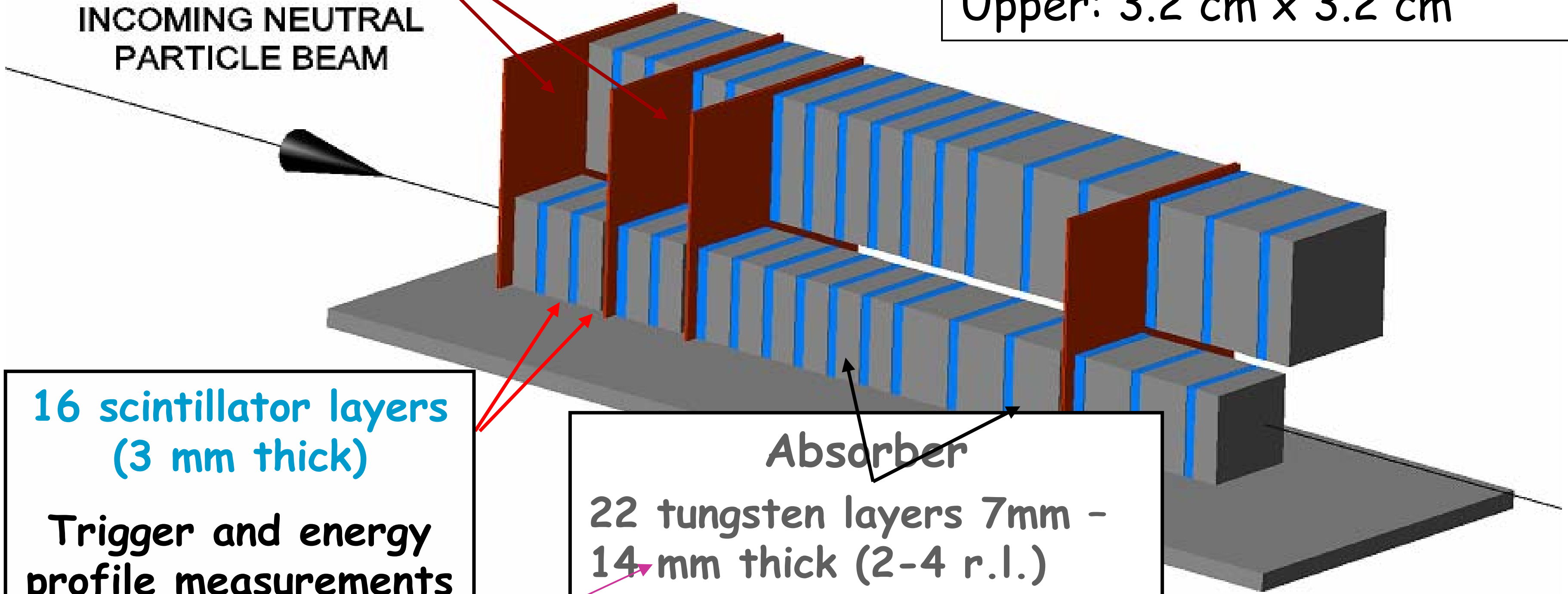
Impact point (η)

4 pairs of silicon microstrip layers (0, 6, 8, 34 r.l.) for tracking purpose (X and Y directions)

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

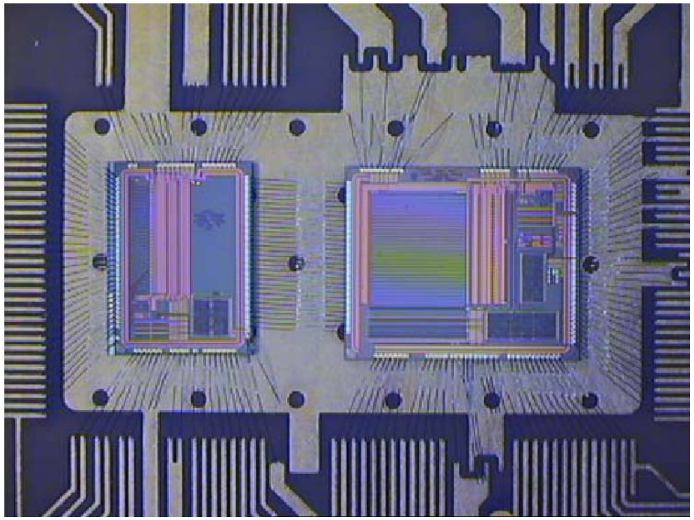
Absorber

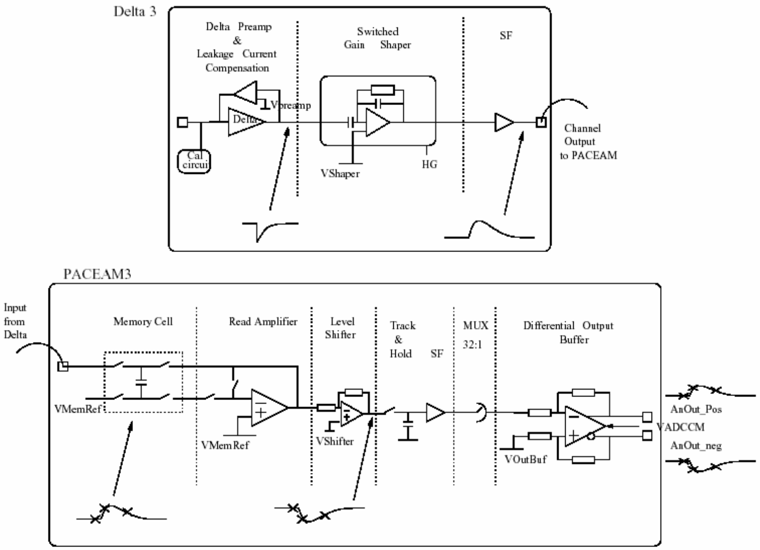
22 tungsten layers 7mm – 14 mm thick (2-4 r.l.)

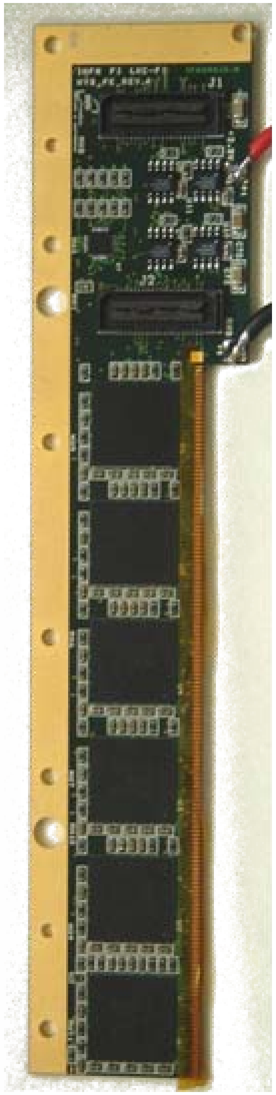
(W: X_0 = 3.5mm, R_M = 9mm)

Energy

Silicon μstrips readout



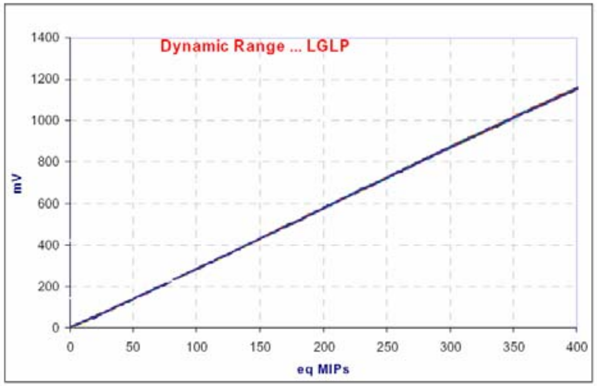




Pace3 chips

(Courtesy of CMS preshower)

- 32 channels
- 25 ns peaking time
- High dynamic range (> 400 MIP)
- 192x32 analog pipeline
- Hybrid contains 12 packaged chips!



Geometry explained ....

1. Different towers dimension (small one close to the beam, big one far away from the beam): minimization of multi hit events
2. Minimize the energy leakage from one tower to the adjacent one
3. Separation of the showers given by the 2 γ from π^0 decay: excellent tool to calibrate the absolute energy scale (invariant mass constraint).
4. Less bending of fibers (limited transverse space) Detector #1.
5. For Detector #2 we chose to rotate a little the towers in order to simplify tracking detector requirements and maximize acceptance

Two detectors because ...

Advantages of Silicon μstrips (80 μm pitch):

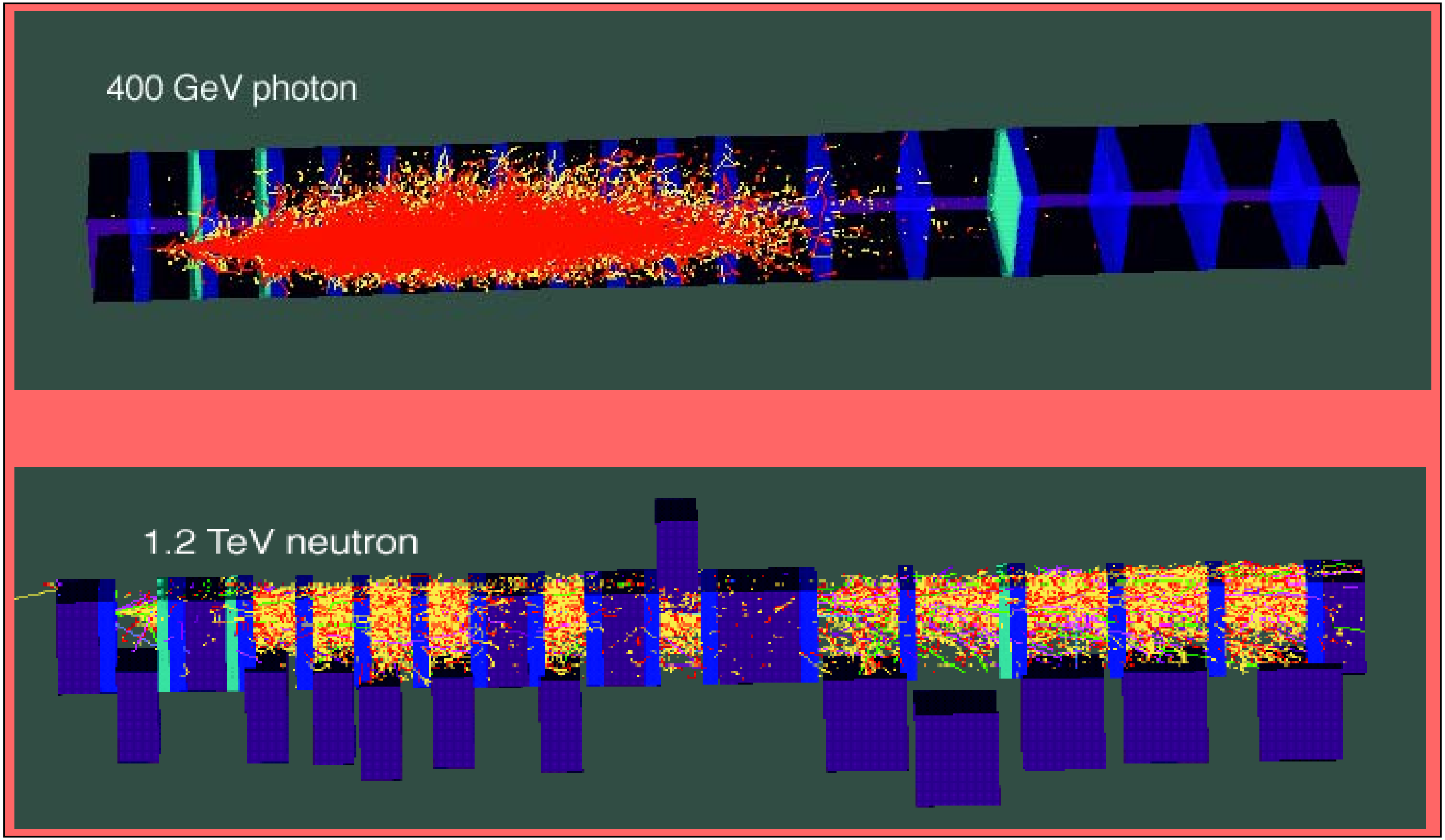
- impact point measurement
- selection of clean events (1 γ)
- π^0 mass reconstruction (energy calibration)

Different geometry:

- different systematics
- different acceptance
- important for 'unknown' environment (LHC background ????)

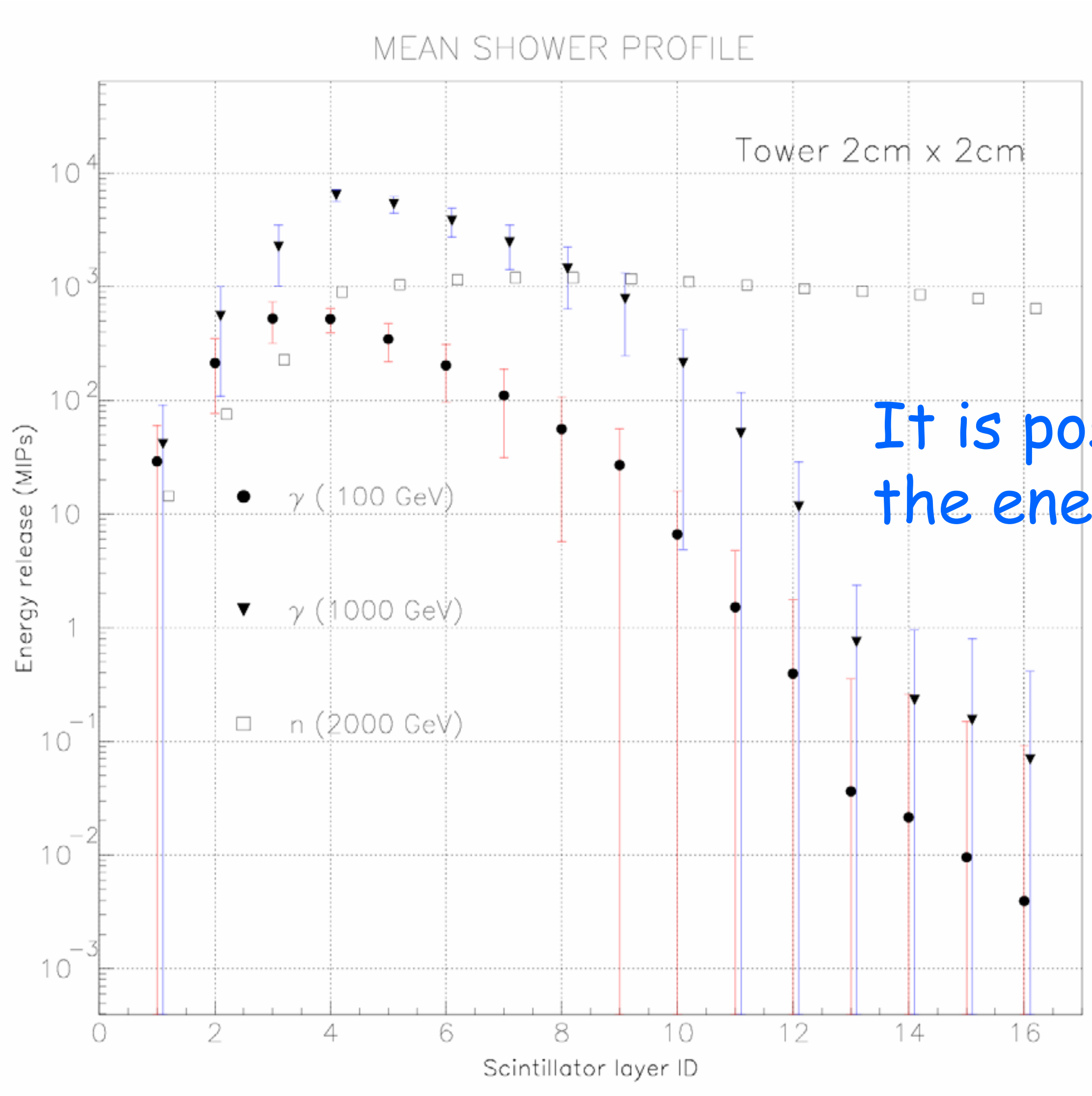
Common data taking/trigger (diffractive physics ??)

Particle response



Longitudinal shower profile (γ/n)

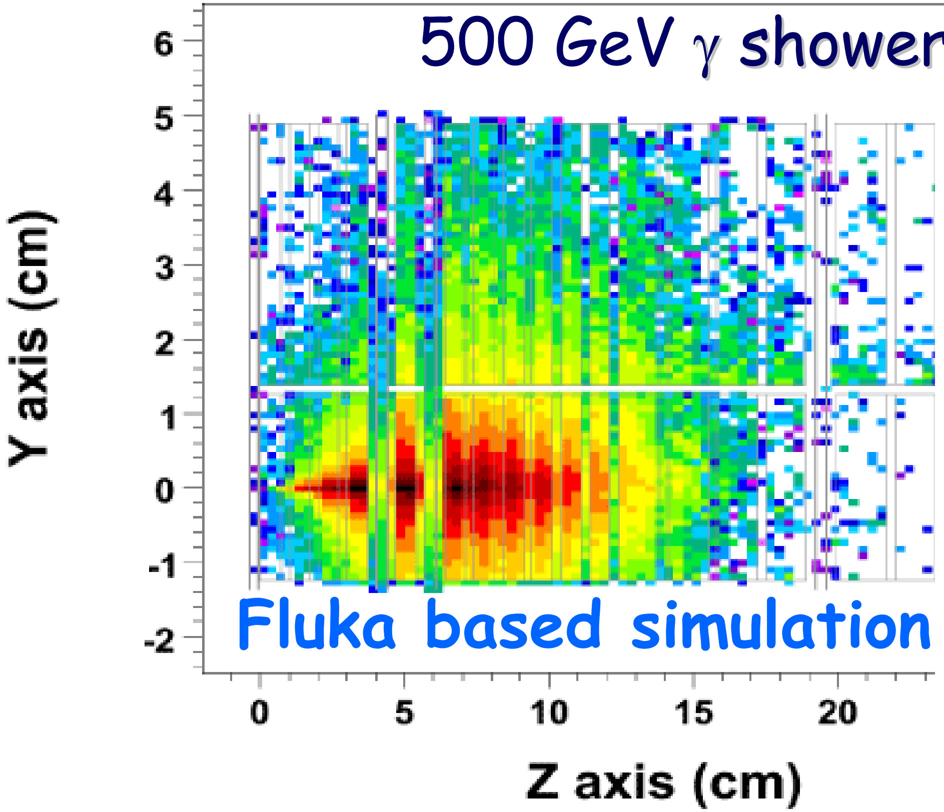
Fluka



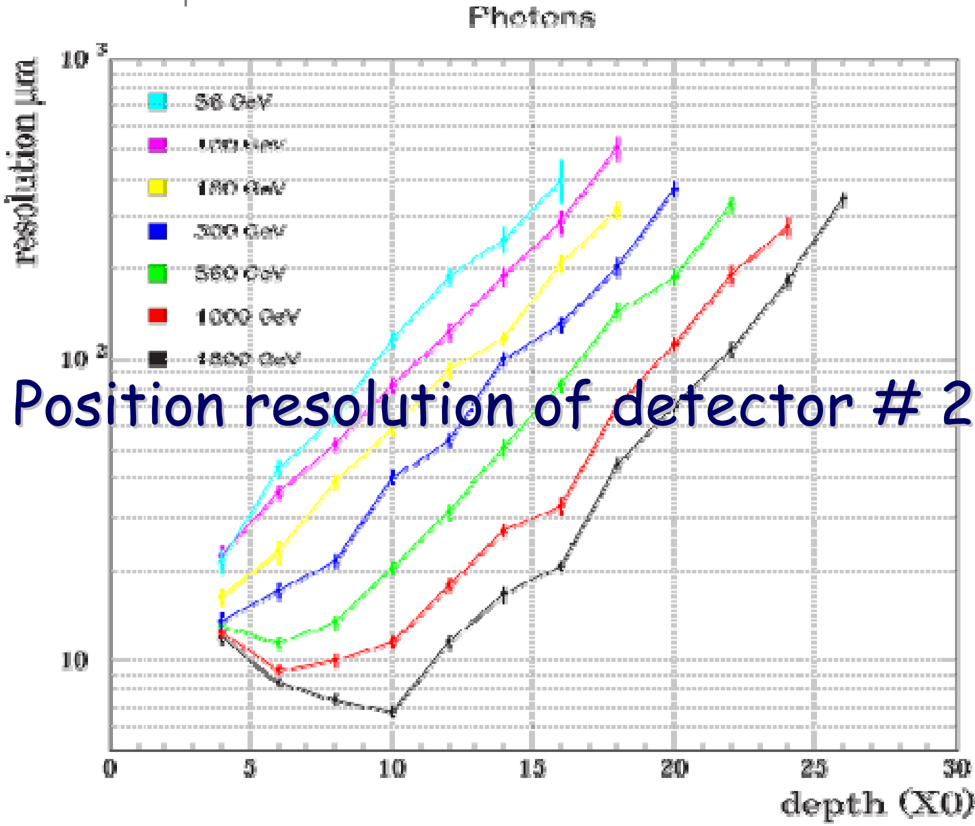
It is possible to measure the energy of neutrons ?

1 TeV γ fully contained

LHCf : γ shower in Detector #2


500 GeV γ shower

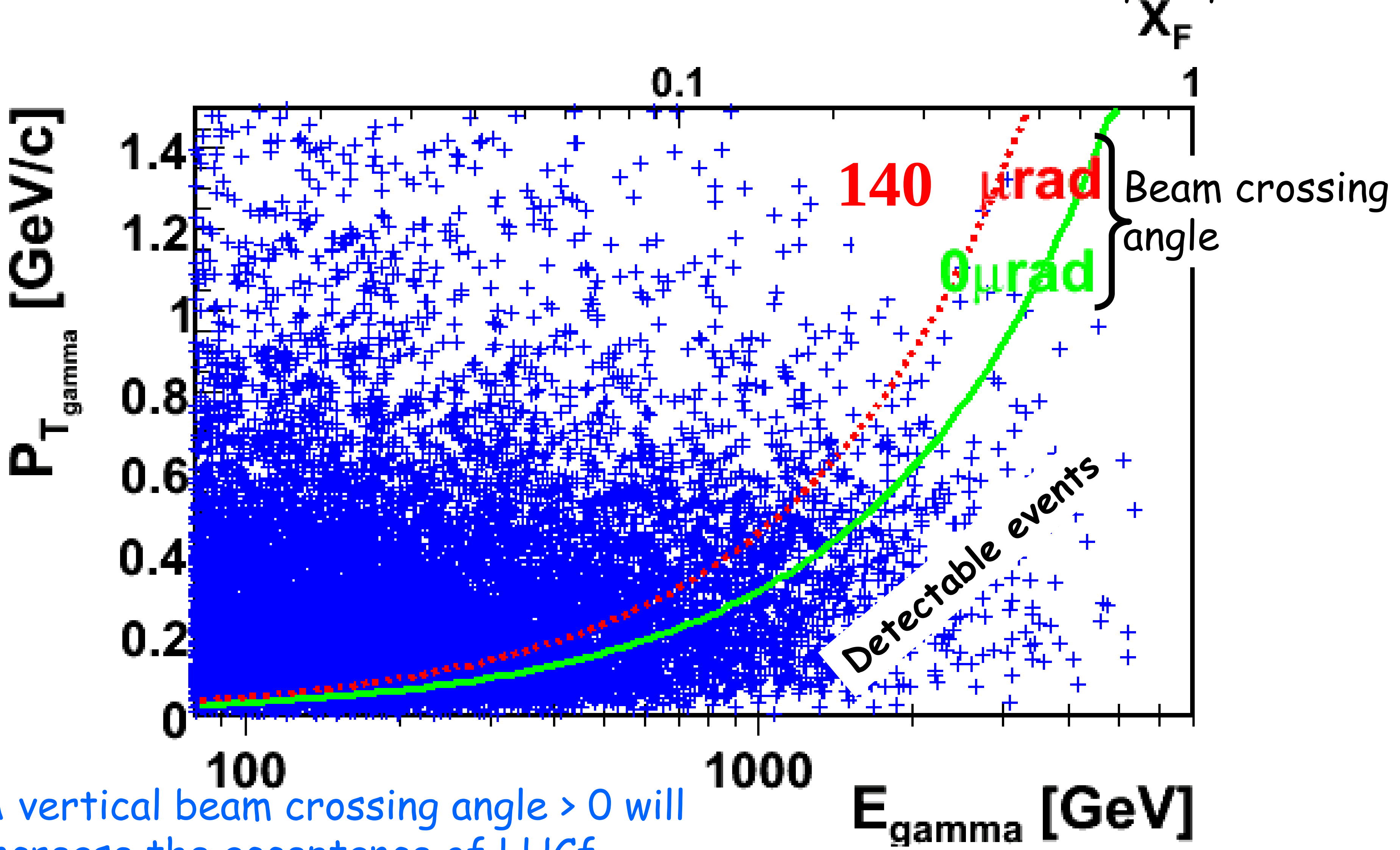
Fluka based simulation


Position resolution of detector # 2

More important still, double shower separation obtainable with a μstrip detector

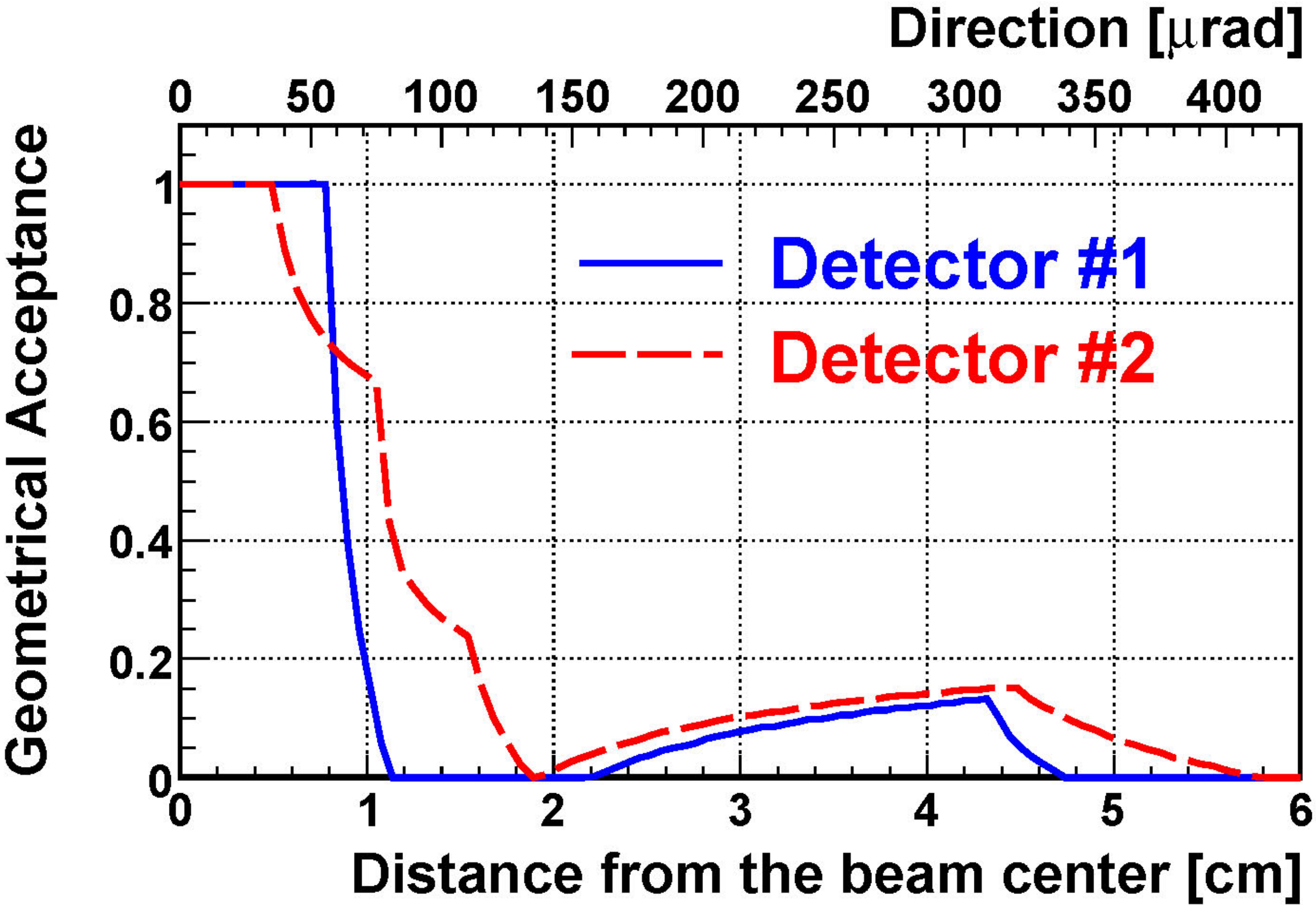
7 μm for 1.8 TeV γ

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



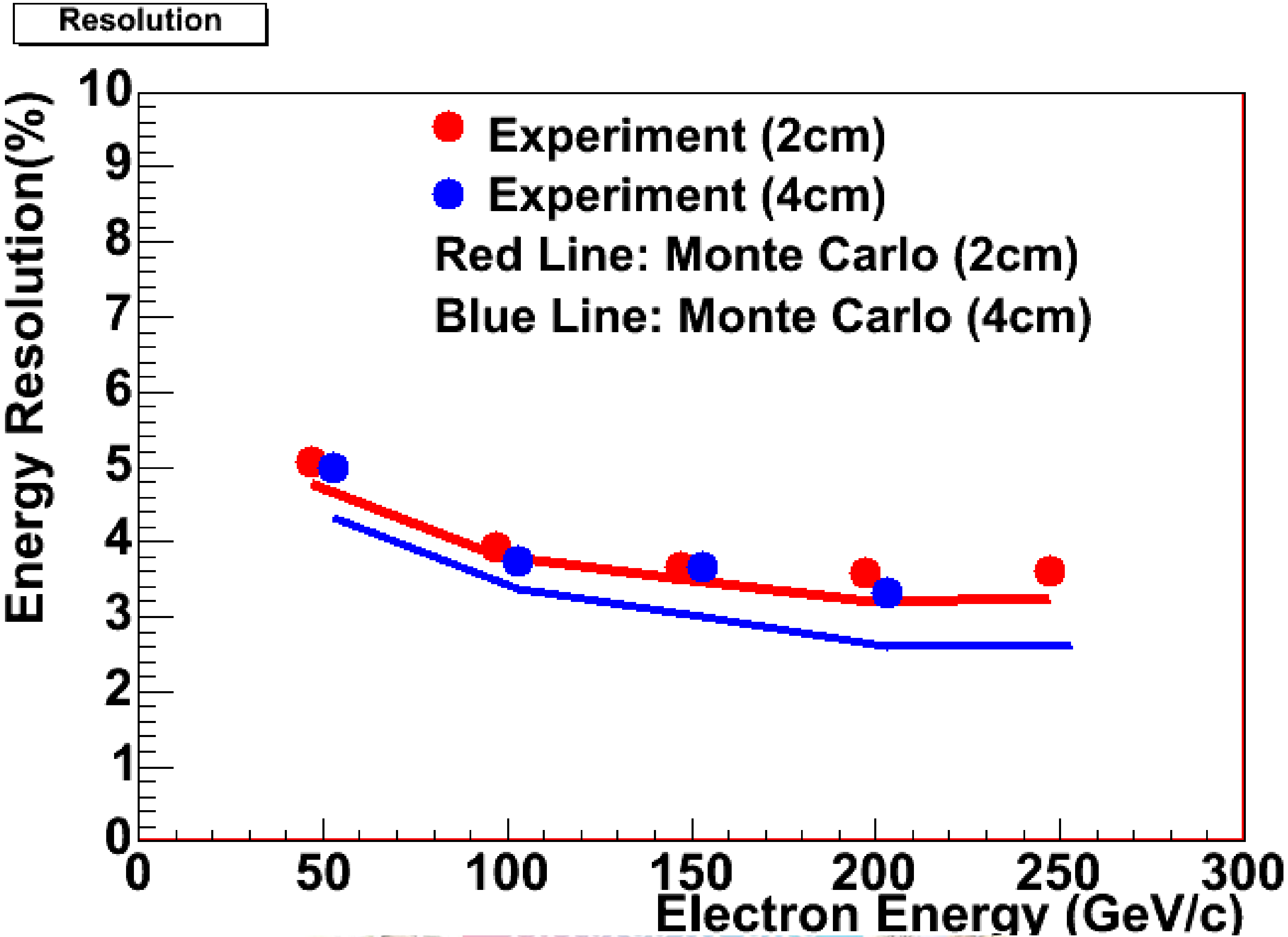
A vertical beam crossing angle > 0 will increase the acceptance of LHCf

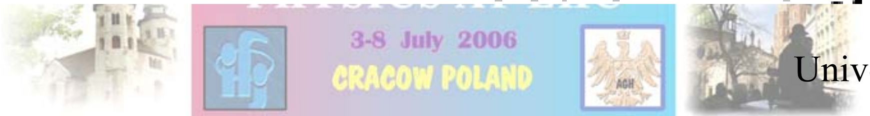
LHCf performances: single γ geometrical acceptance



Some runs with LHCf vertically shifted few cm will allow to cover the whole kinematical range (not essential for the experiment goals)

Energy Resolution (2004 test beam)





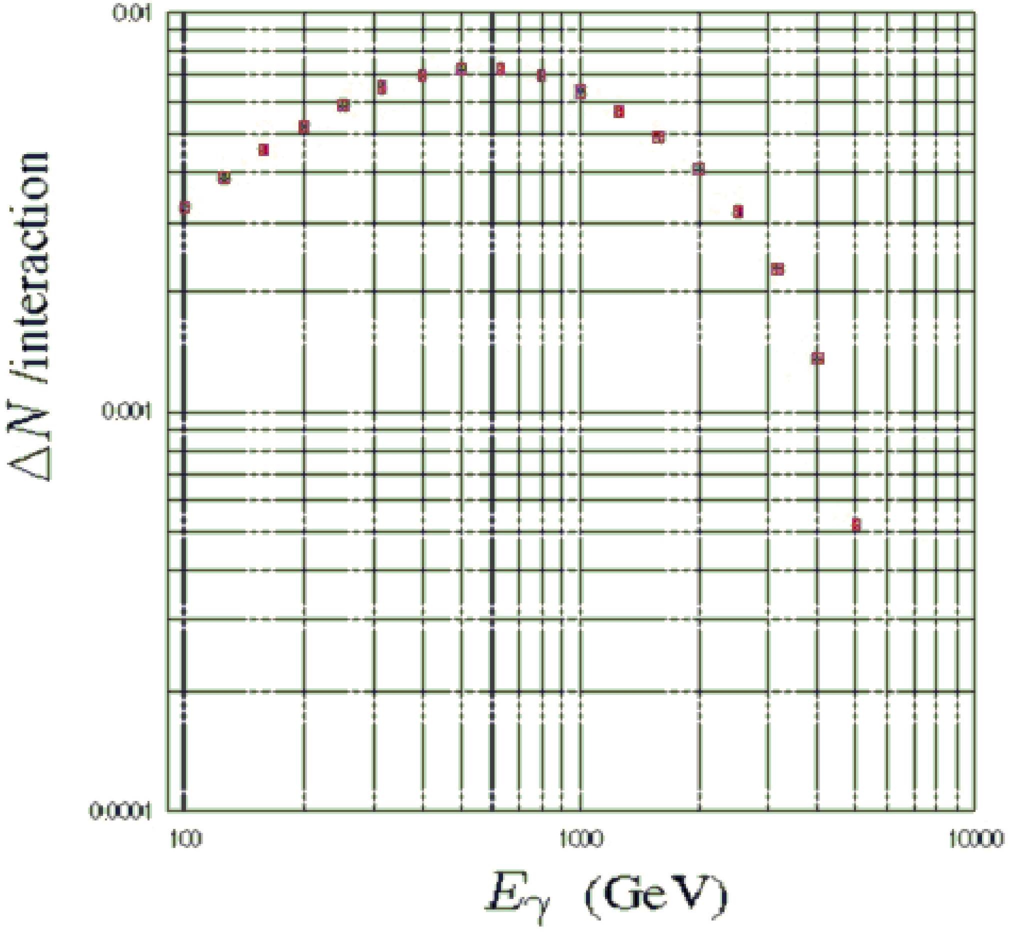
Single γ detection

1 γ with 100 GeV<E<1 TeV every 15 LHC interactions (<100 μsec)

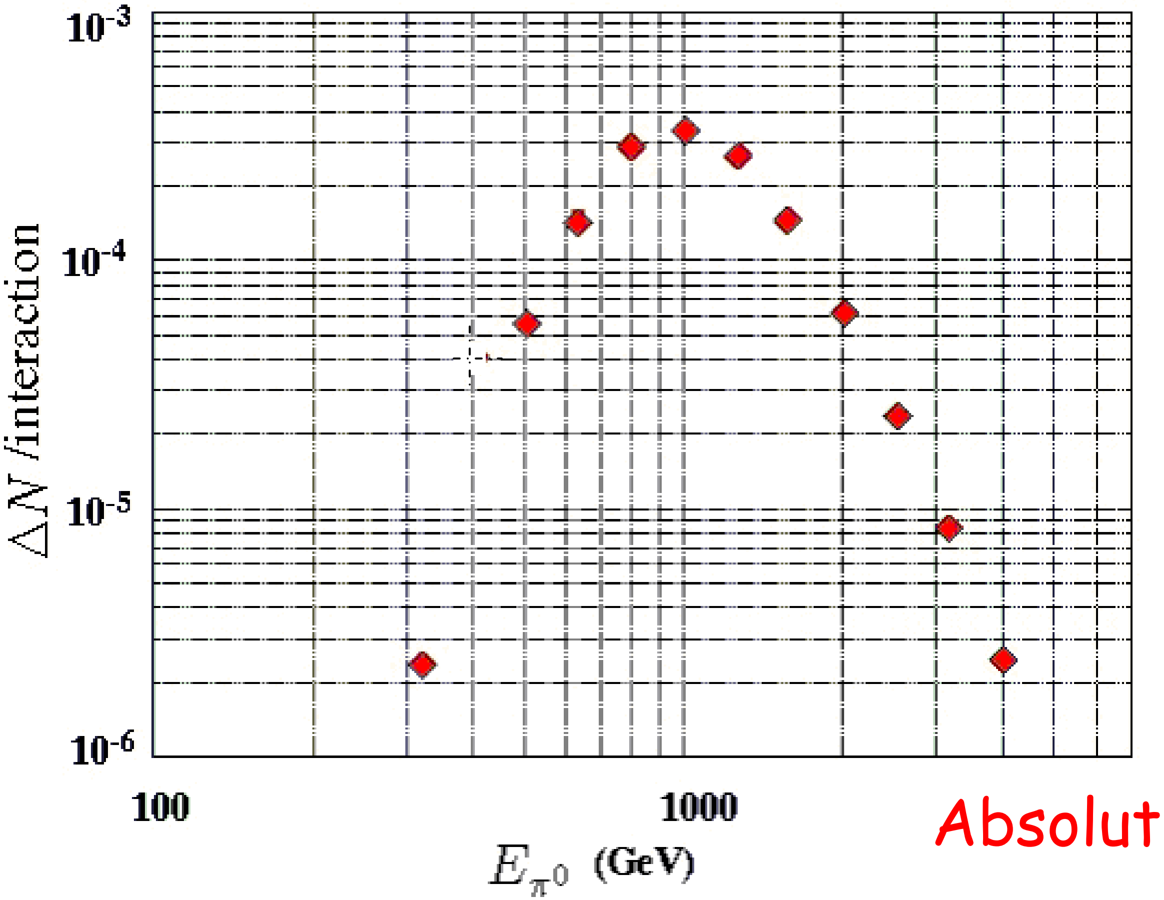
1 γ with E > 1 TeV every 50 LHC interactions

Few hours of data taking at L=10^{29} cm^{-2}s^{-1} should be enough

The number of observable photons per interaction in each energy bin with the standard detector configuraion



2 photons from π^0decay



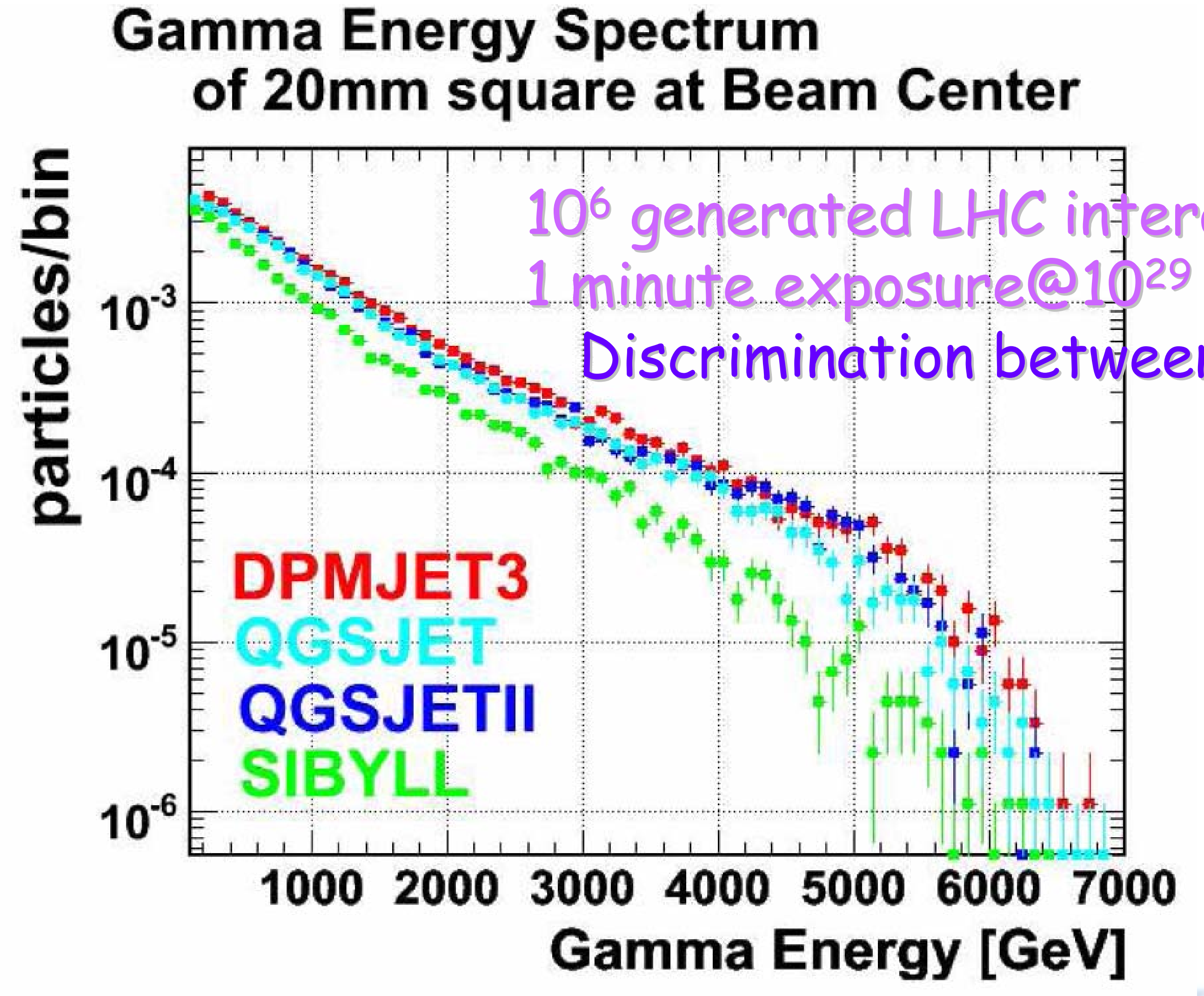
The number of observable pi zeros per interaction in each energy bin with the standard detector configuraion

We require
2 γ in 2 different towers

1 π^o with E>1 TeV every 1000 LHC interactions (<10 ms)

Absolute Energy Calibration!!!!

LHCf expected performance

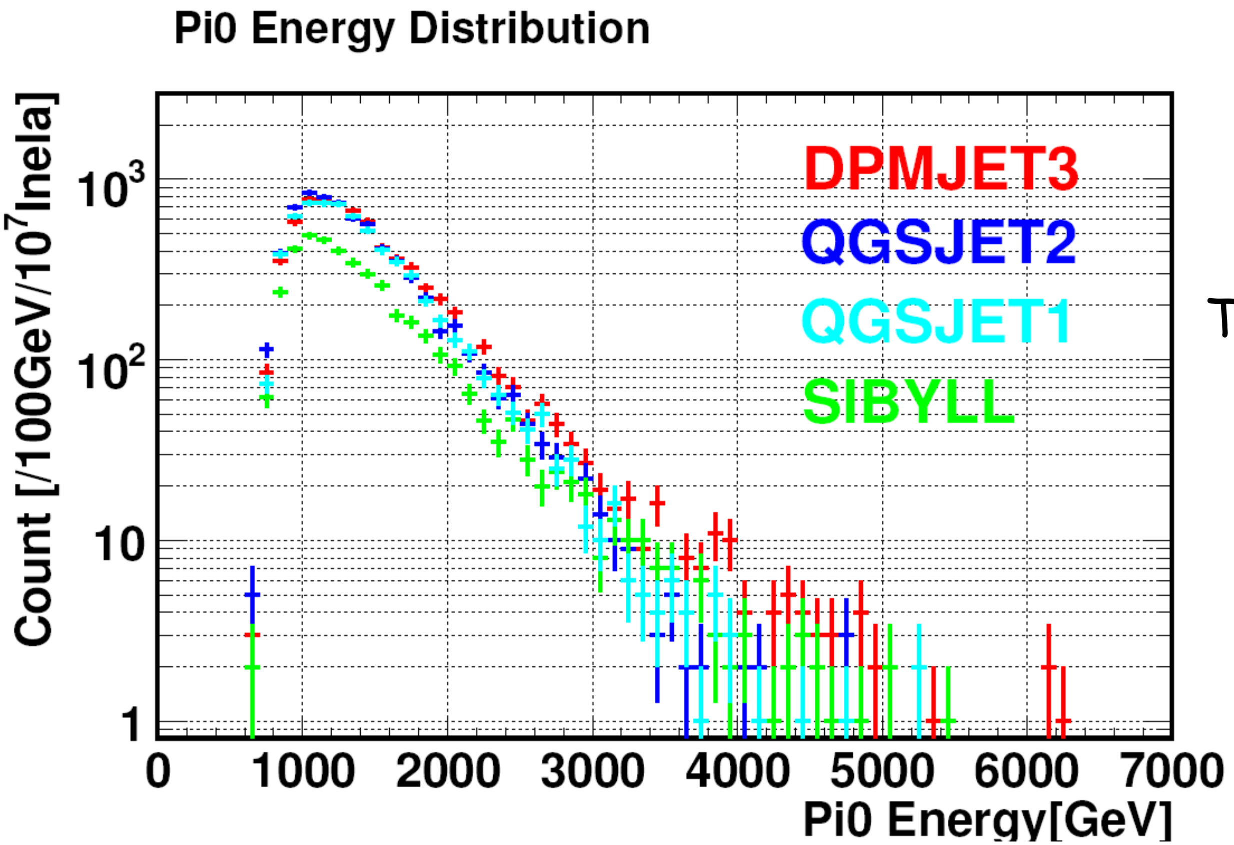


10^6 generated LHC interactions →
1 minute exposure@10^{29} $cm^{-2}s^{-1}$ luminosity

Discrimination between some models

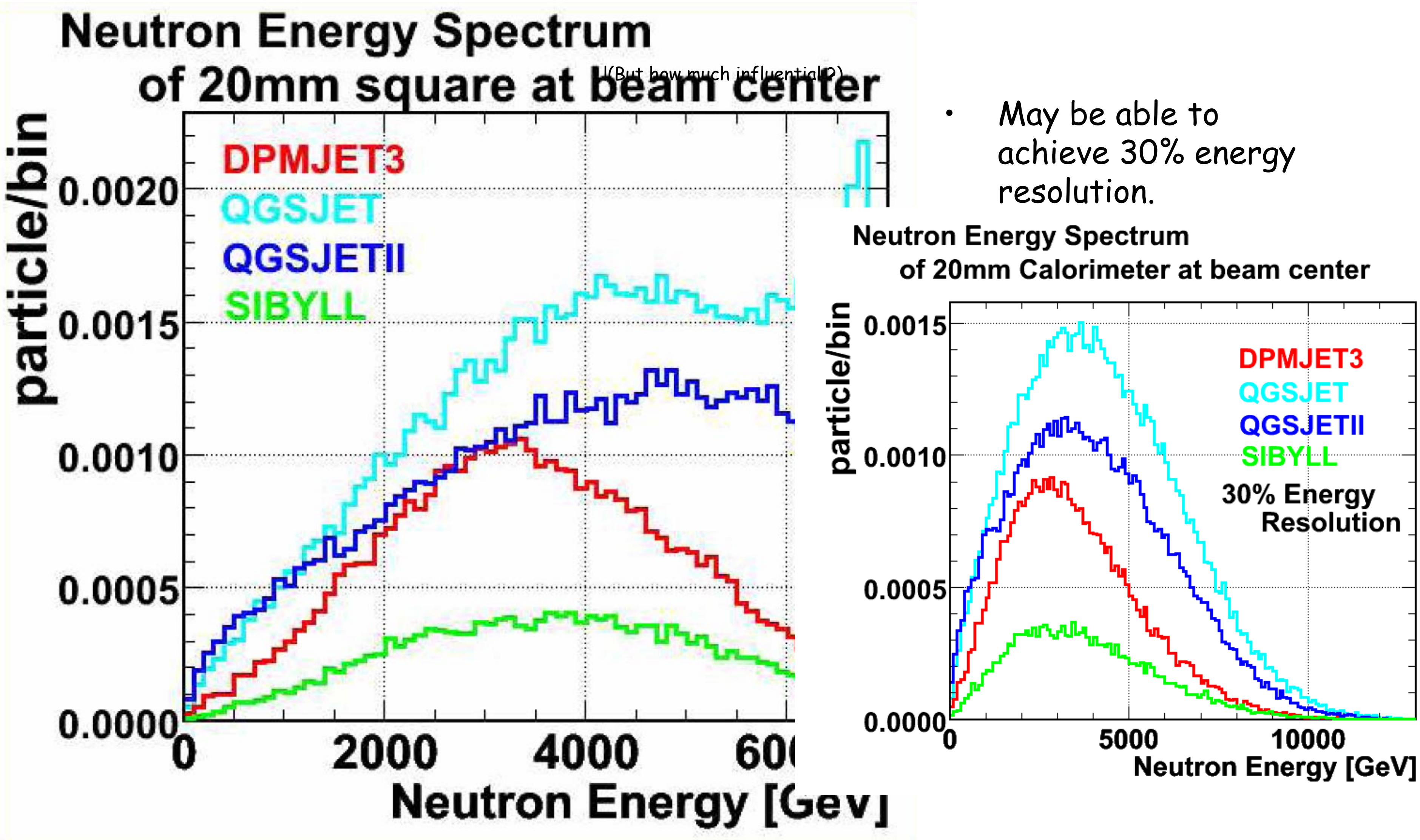
- 5% energy resolution inside

π^0 expected energy distributions (inside two tower acceptance)



Typical energy resolution for a 1 TeV γ is 3 %.

Neutron possible discrimination



!(But how much influential?)

- May be able to achieve 30% energy resolution.

Running scenario .....

- 2004 Test Beam has already provided many answers on the detector expected performance
- Now at the end of August another test beam will validate final detector design
- Installation beginning at the end of this year (yes 2006)!

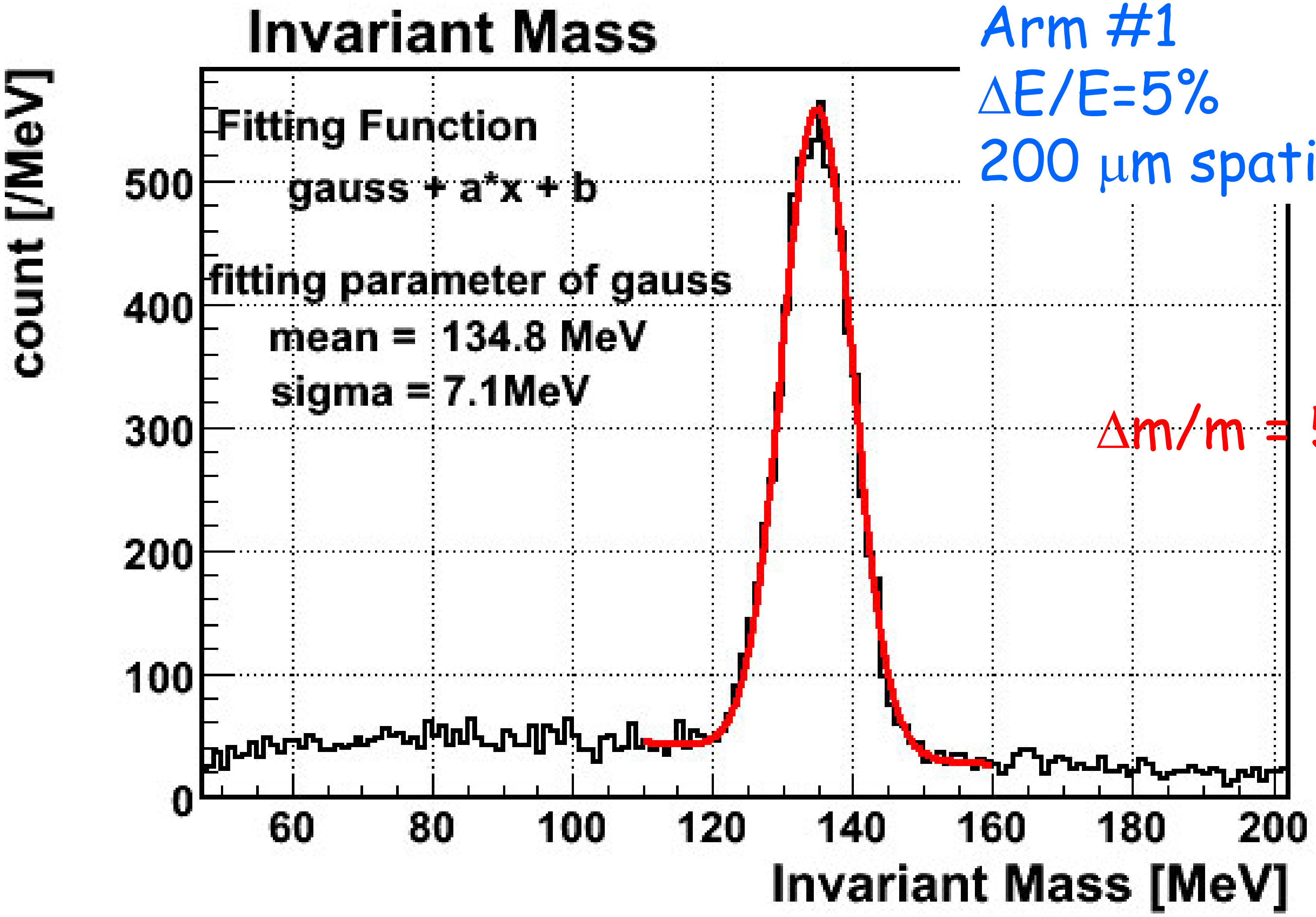
- Phase-I
  - Parasite running during the early stage of LHC commissioning (end of 2007 – beginning of 2008)
  - Remove the detector when luminosity reaches $10^{30}cm^{-2}s^{-1}$ for radiation reason
- Phase-II
  - Re-install the detector at the next opportunity of low luminosity run
- Phase-III
  - Future extension for p-A, A-A run.

Conclusions

- LHCf just approved: LHCC 16 May
- Physics performances:
  - able to measure π^0 mass with $\pm$5% resolution.
  - able to distinguish the models by measurements of π^0 and γ
  - able to distinguish the models by measurements of *n*
  - Beam crossing angle $\neq$0 and/or vertical shifts of LHCf by few cm will allow more complete physics measurements
- Running conditions:
  - Three foreseen phases
    - Phase I: parasitic mode during LHC commisioning
    - Phase II: parasitic mode during TOTEM run
    - Phase III: Heavy Ion runs ?
- Beam Test in August 2006:
  - Full detector #1 will be tested
  - Part of detector #2 will be tested

Backup

LHCf performances: π^0 mass resolution



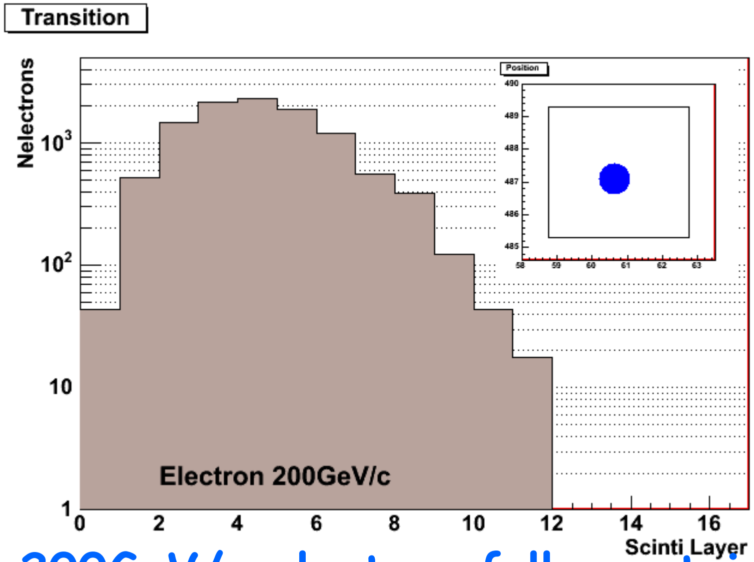
Arm #1

$\Delta E/E=5\%$

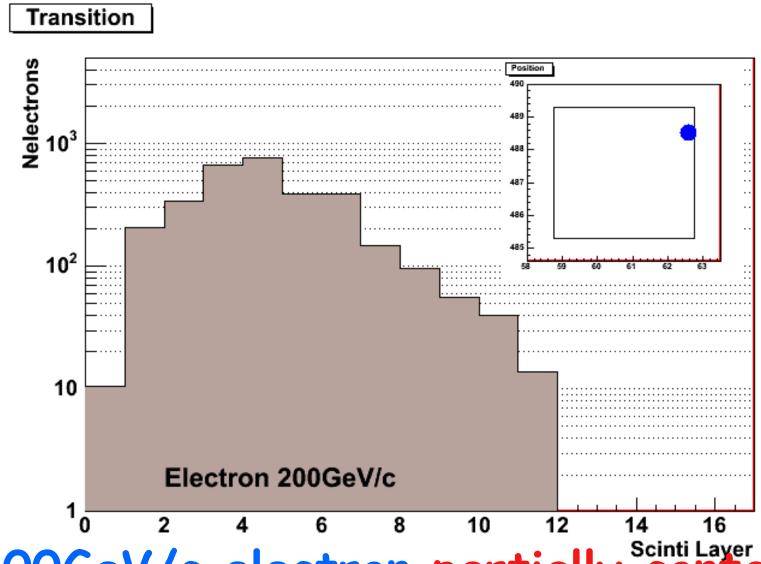
200 μm spatial resolution

$\Delta m/m = 5\%$

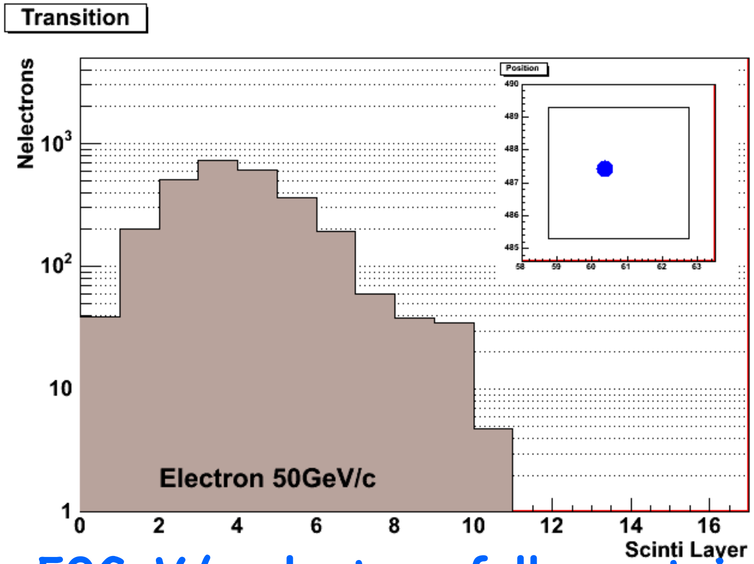
Some results: longitudinal profile of the showers



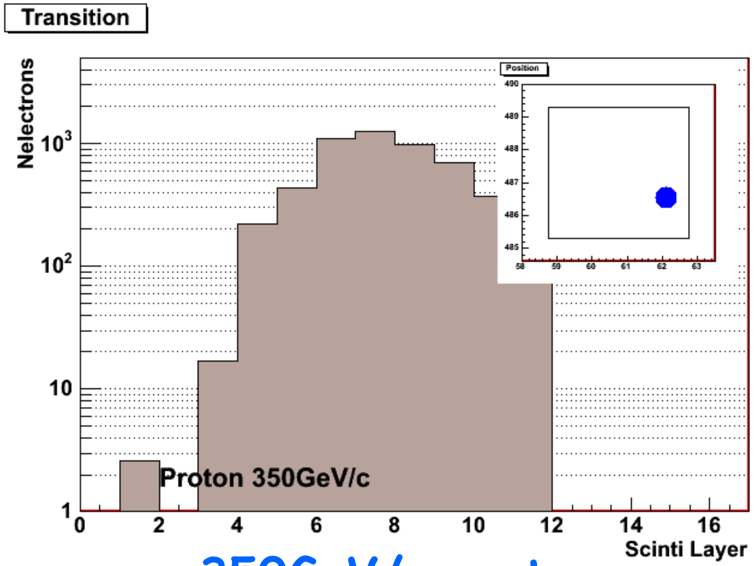
200GeV/c electron fully contained



200GeV/c electron partially contained



50GeV/c electron fully contained

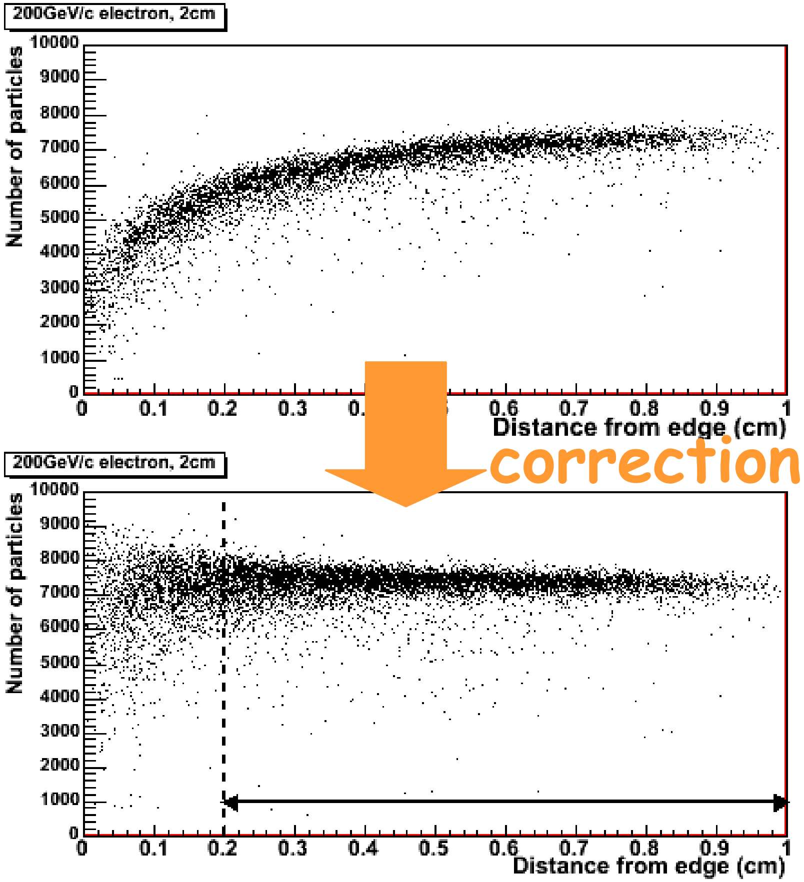


350GeV/c proton

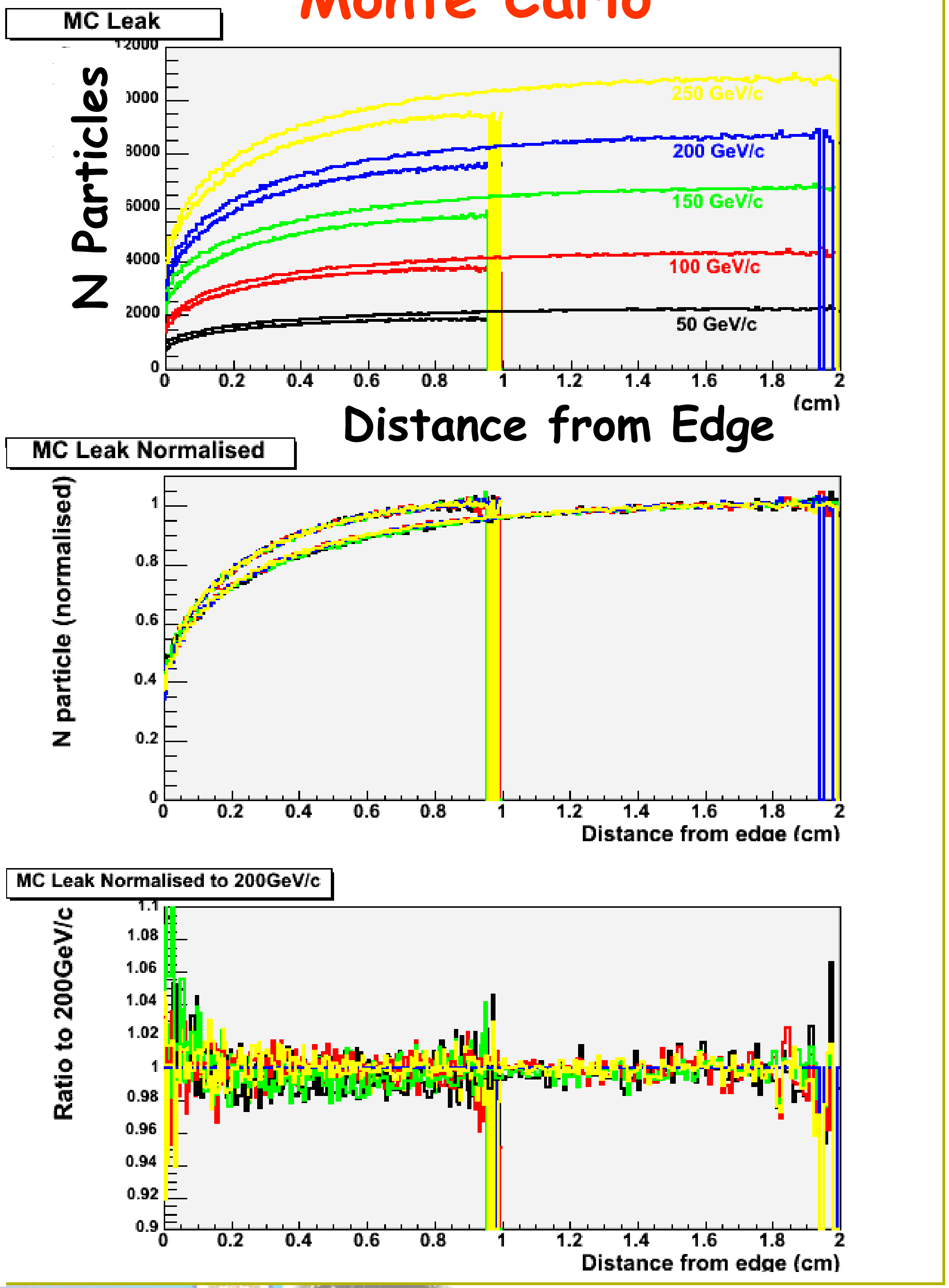
Leakage Correction

MC predicts that the leakage is energy independent!

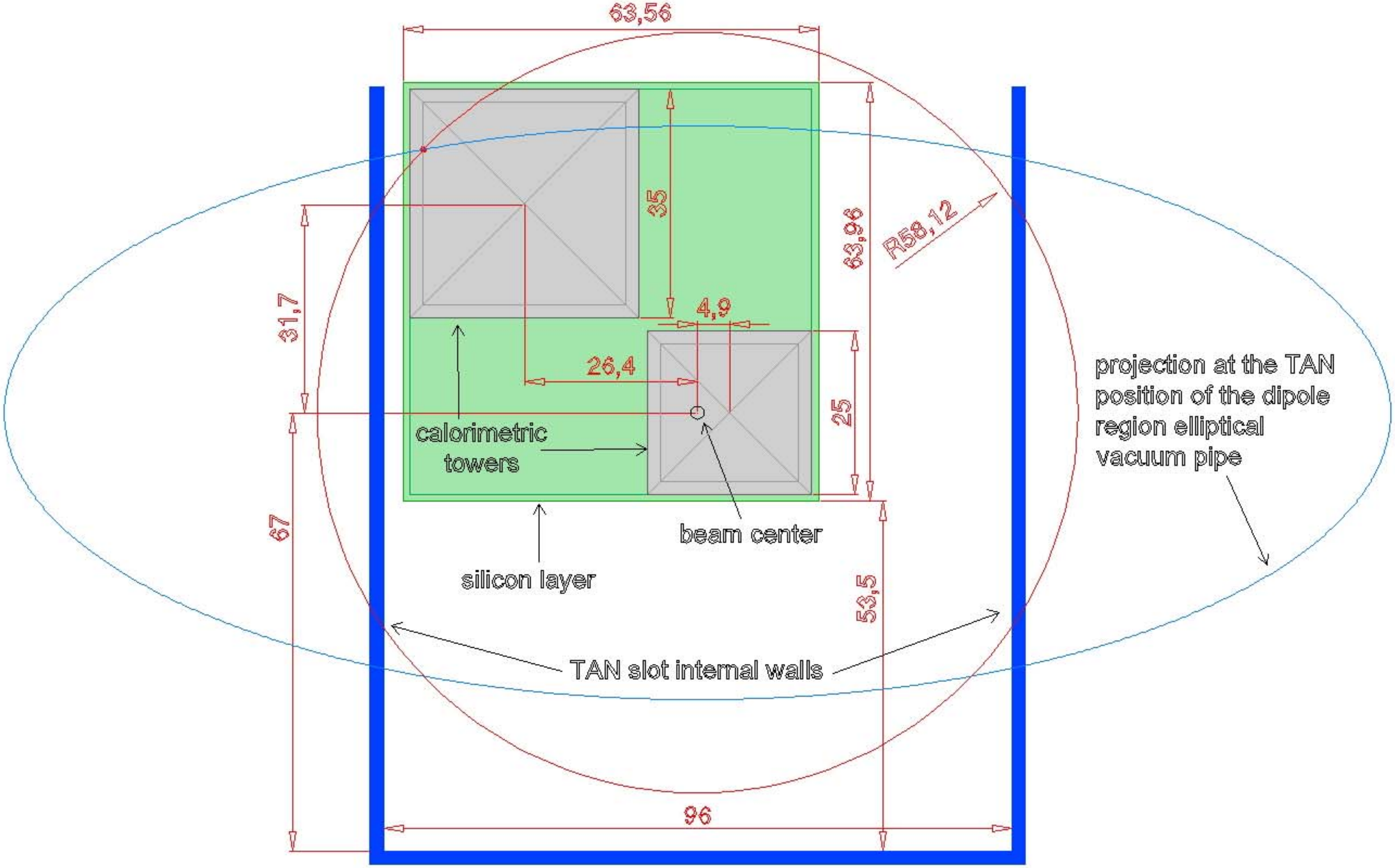
Prototype Experiment



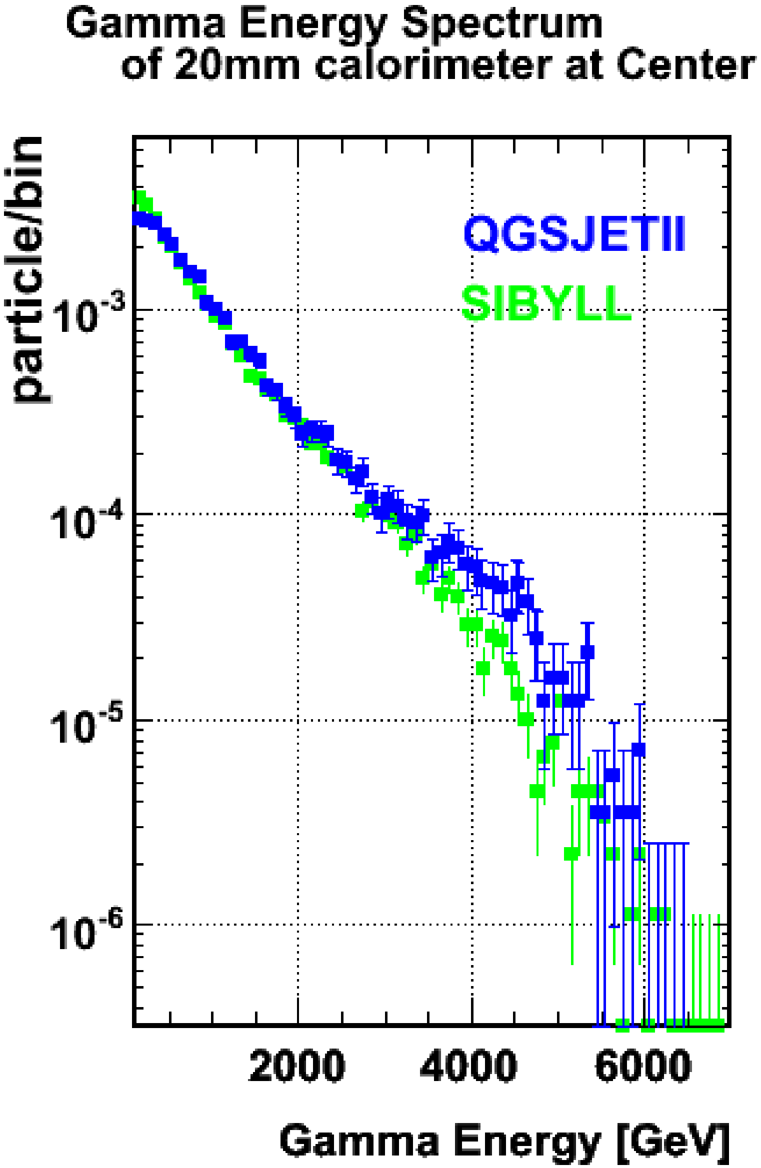
Monte Carlo

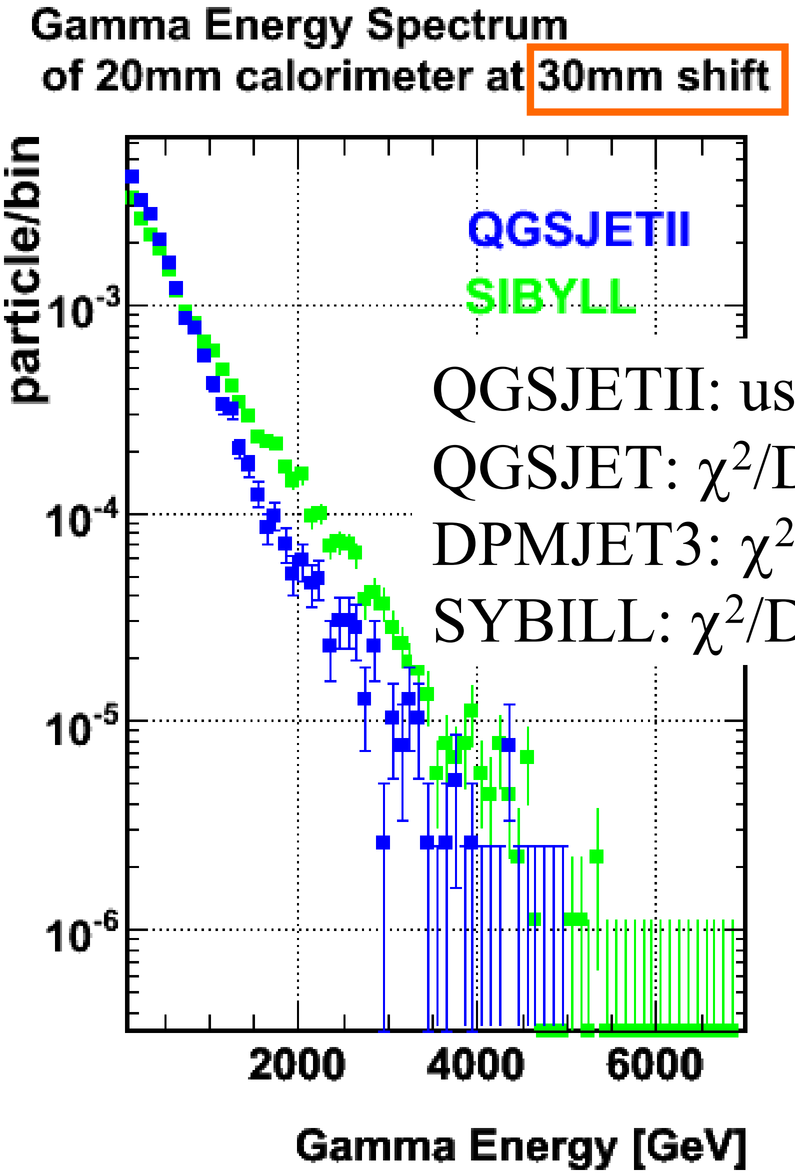


Transverse projection of detector #2 in the TAN slot

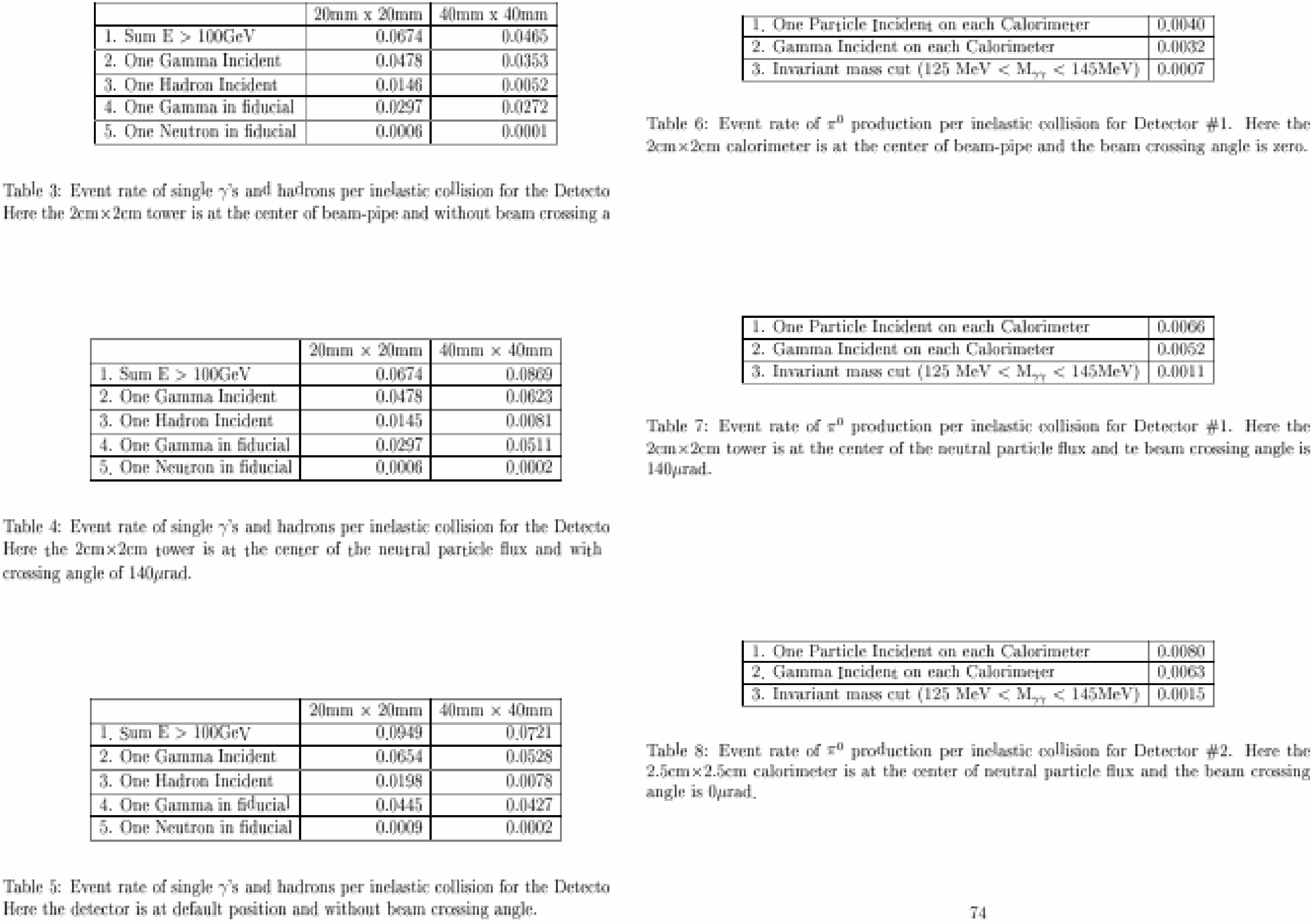


γ ray energy spectrum for different positions





QGSJETII: used model
QGSJET: χ^2/DOF=107/12
DPMJET3: χ^2/DOF=224/1
SYBILL: χ^2/DOF=816/12



	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 Detecto Here the 2cm×2cm tower is at the center of beam-pipe and without beam crossing a

	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 Detecto Here the 2cm×2cm tower is at the center of the neutral particle flux and with 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 Detecto Here the detector is at default position and without beam crossing angle.

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.

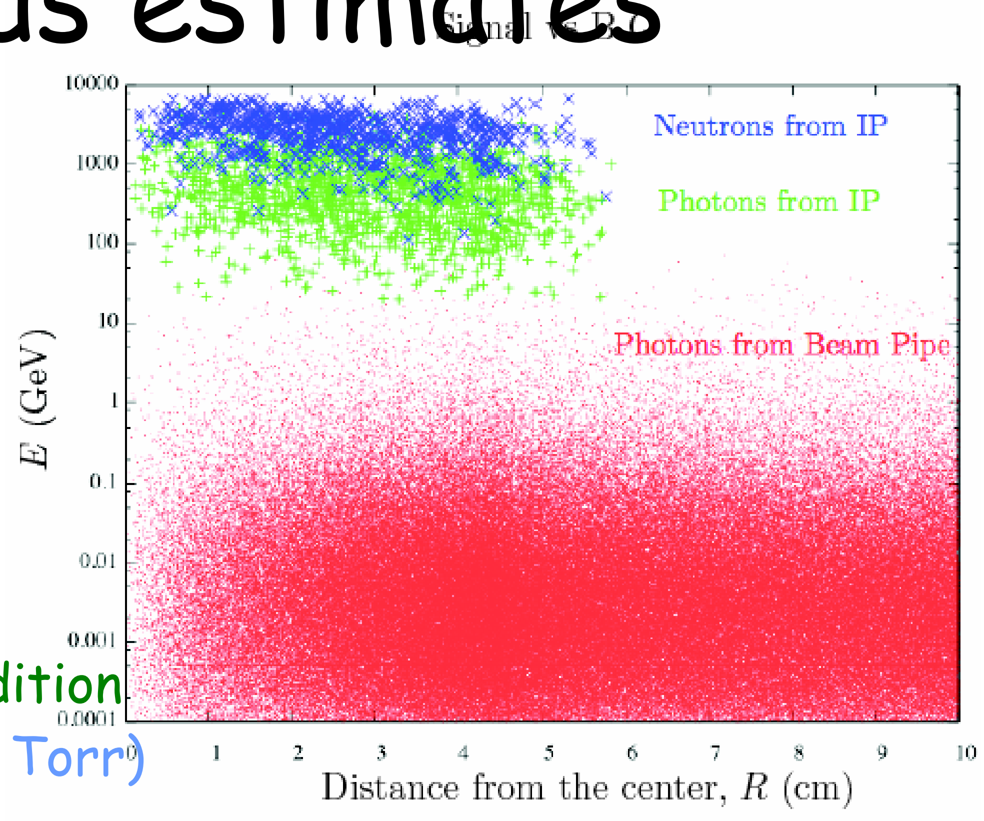
1. One Particle Incident on each Calorimeter	0.0066
2. Gamma Incident on each Calorimeter	0.0052
3. Invariant mass cut (125 MeV < $M_{\gamma\gamma}$ < 145MeV)	0.0011

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.

Backgrounds estimates



- beam-beam pipe

→ E_γ(signal) > 200 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)

Optimal LHCf run conditions

Beam parameter	Value
# of bunches	≤ 43
Bunch separation	$> 2\ \mu\text{sec}$
Crossing angle	0 rad 140 μrad downward
Luminosity per bunch	$< 2 \times 10^{28}\ \text{cm}^{-2}\text{s}^{-1}$
Luminosity	$< 0.8 \times 10^{30}\ \text{cm}^{-2}\text{s}^{-1}$
Bunch intensity	4×10^{10} ppb (β^*=18m) 1×10^{10} ppb (β^*= 1m)

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

(No radiation problem for 10kGy by a “year” operation with this luminosity)

Energy reconstruction and resolution

1. Linearity up to > TeV
2. ΔE/E ~ 2%
3. 15% energy loss @ 2 mm from the edge (small tower)