IFAE 2011
Incontri di Fisica delle Alte Energie
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Primi risultati dell'esperimento LHCf per la fisica a piccolo angolo nelle interazioni protone-protone a 7 TeV

Lorenzo Bonechi (INFN – Firenze)
per la collaborazione LHCf

The LHCf international collaboration

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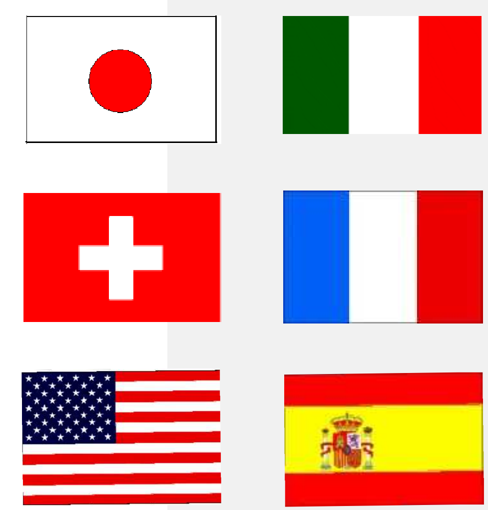


Outline

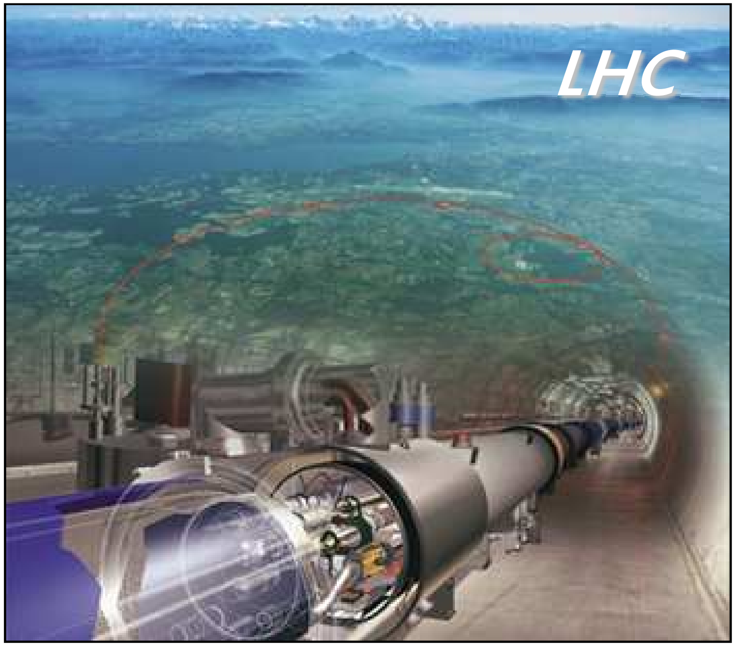
- **The Physics of LHCf**
  - Cosmic rays in the atmosphere and hadronic interaction models
  - Open issues on the HE Cosmic Ray spectrum
- **Overview of the experiment**
  - Detection of neutral particles at low angle at LHC
  - Description of detectors
- **Data analysis for 7 TeV data**
  - Relevant items
- **Results**
- **Systematic uncertainties**
- **Conclusions**

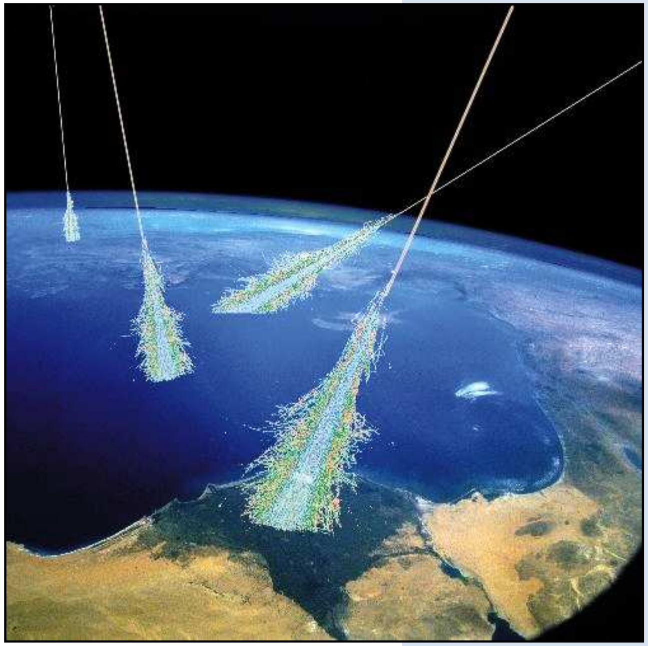
PART 1

The Physics of LHCf

Main topics

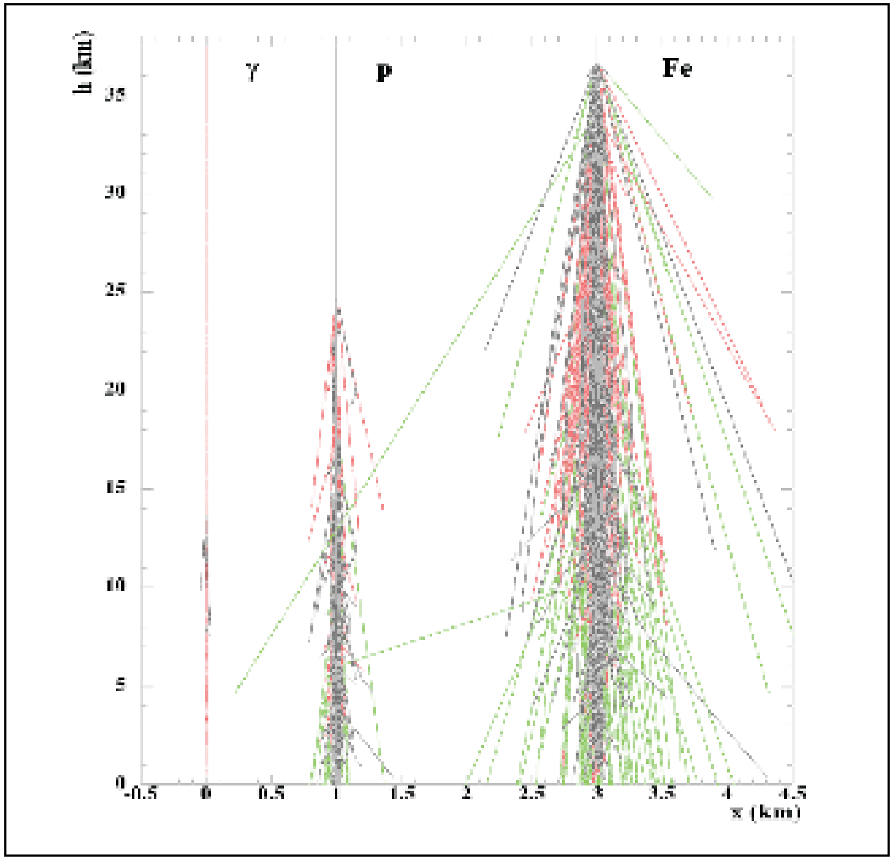
- **Experimental measurement**:
  - Precise measurement of neutral particle (γ, π^0 and n) spectra in the very forward region at LHC
- **7 TeV + 7 TeV in the c.m. frame → 10^{17} eV in the laboratory frame**:
  - We are going to simulate in the biggest's world laboratory what happens in nature when a Very High Energy Cosmic Ray interacts in the atmosphere
- **Why in the very forward region**?
  - Because the dominant contribution to the energy flux in the atmospheric shower development is carried on by the very forward produced particles





Cosmic ray showers

Air shower developments



The hadronic interaction models used in air shower simulations have a big uncertainty due to the lack of experimental data in the energy range over 10^{15}eV

Extensive air shower observation

- longitudinal distribution
- lateral distribution
- Timing

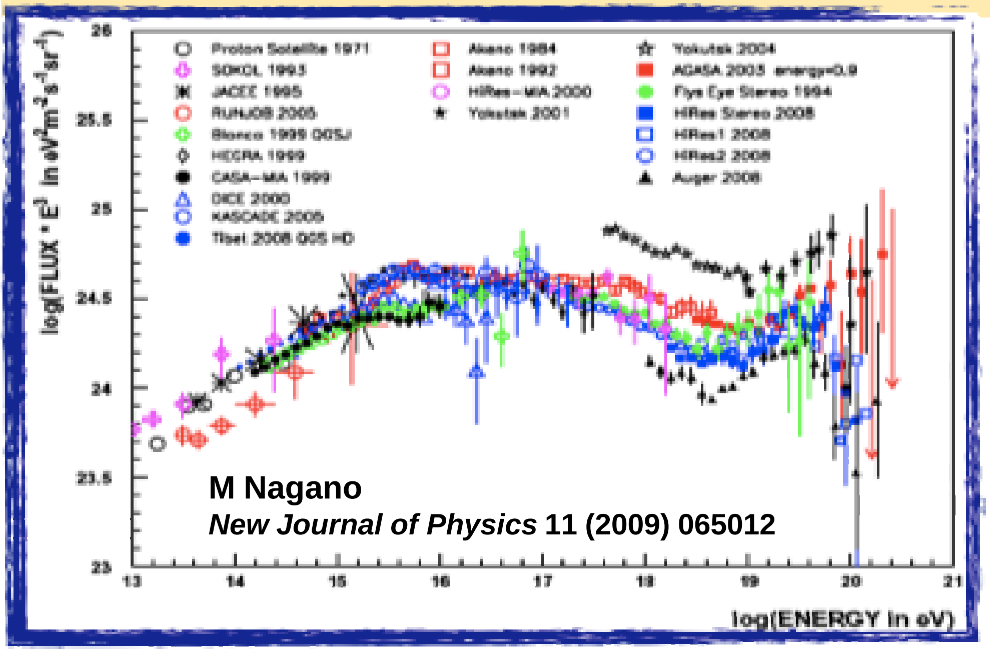
Air shower development

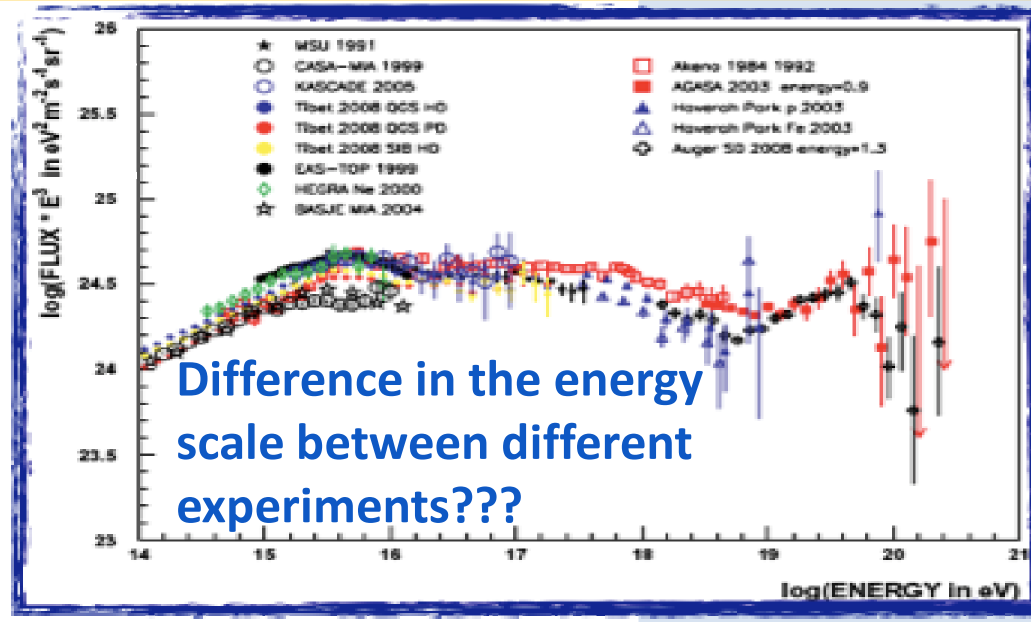
- Type of primary
- Energy
- Arrival direction

Astrophysical parameters

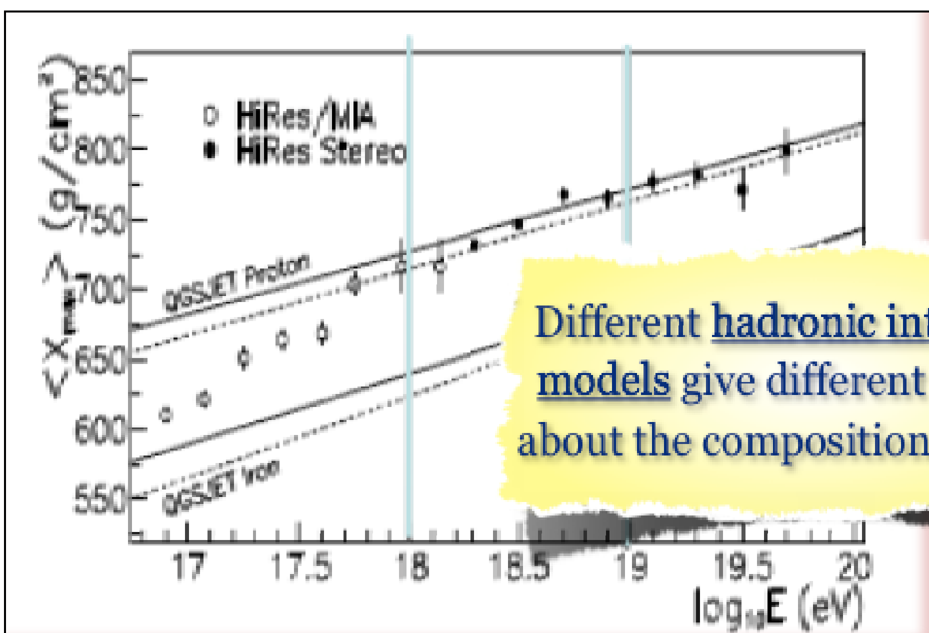
- Spectrum
- Composition
- Source distribution

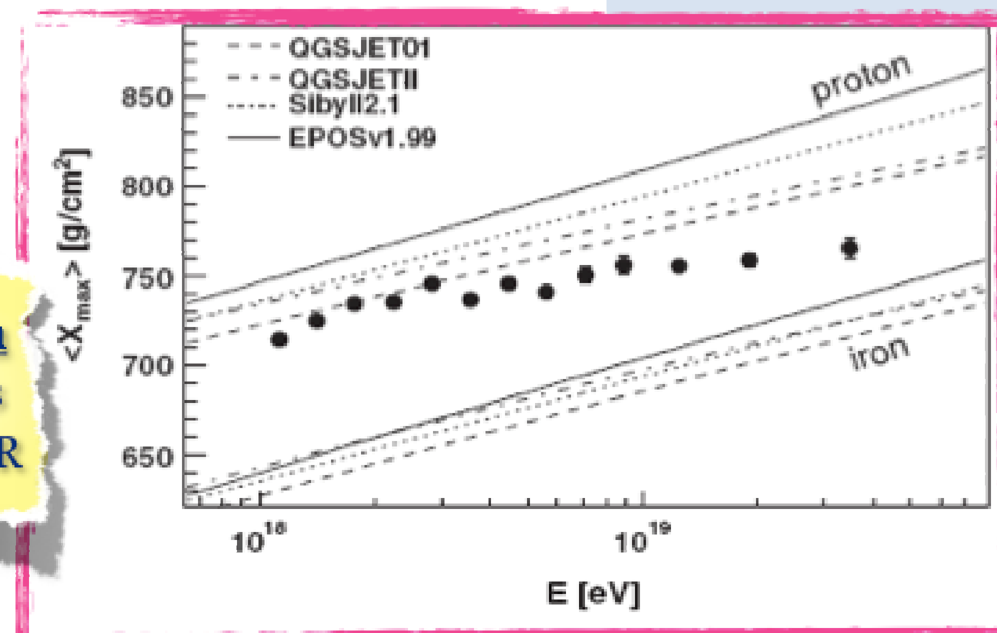
Open Issues on HECR spectrum





Difference in the energy scale between different experiments???



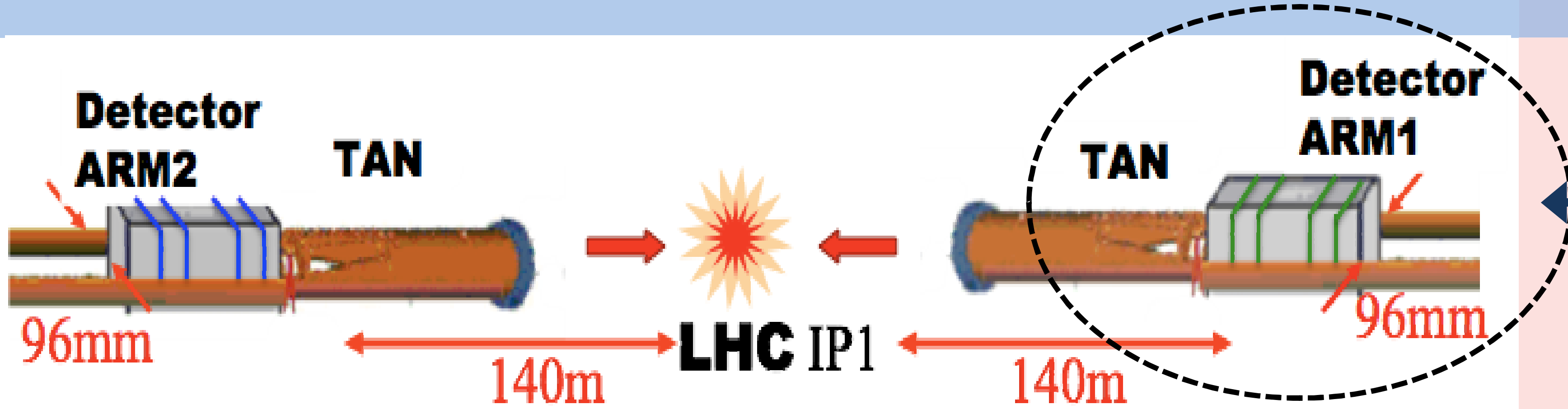


Different <u>hadronic interaction models</u> give different answers about the composition of HECR

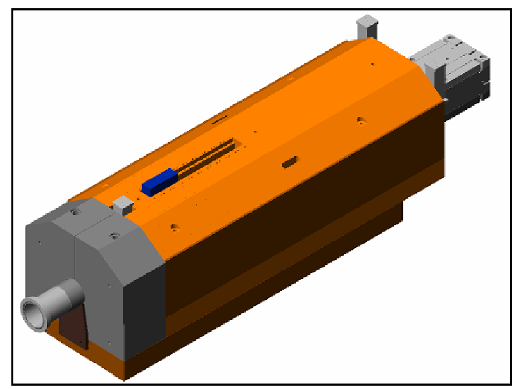
PART 2

Overview of method and detectors

Method and location



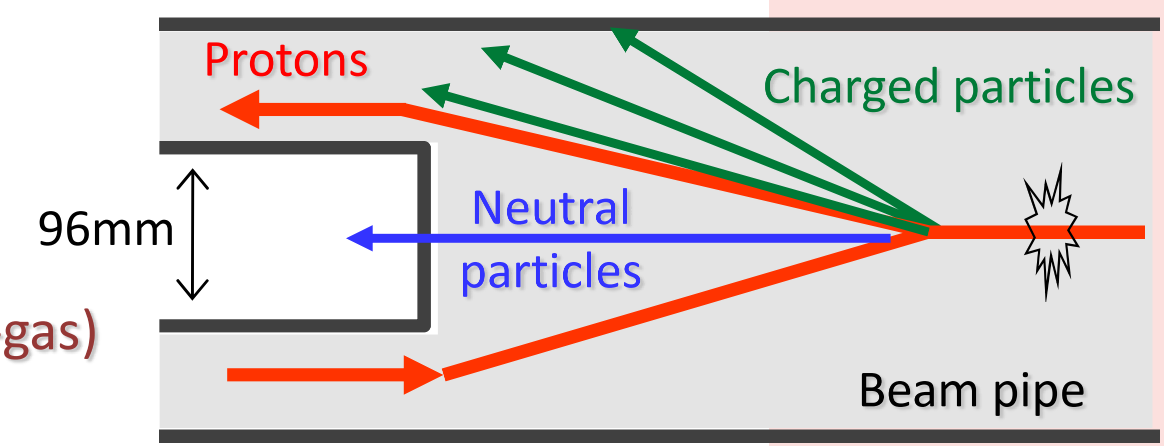
Recombination Chamber



Located Inside the TAN, absorber for neutral particles

Detectors measure energy and impact point of γ from π^0 decays

→ **e.m. calo tracking layers**



Two independent detectors on both sides of IP1

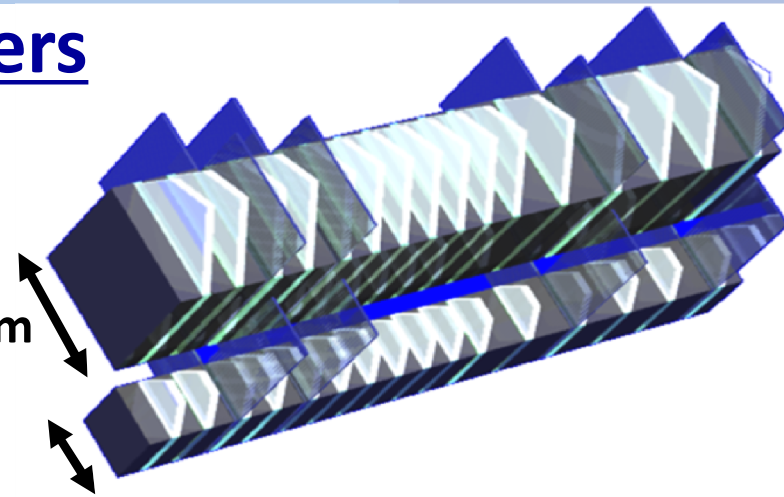
- ✓ Redundancy
- ✓ Background rejection (esp. beam-gas)

The LHCf detectors

Arm1

Sampling and imaging E.M. calorimeters

- Absorber: W (44 r.l , $1.55\lambda_I$)
- Energy measurement: plastic scintillator tiles
- 4 tracking layers for imaging:
  XY-SciFi(Arm#1) and XY-Silicon strip(Arm#2)
- **Each detector has two calorimeter towers, which allow to reconstruct π^0**



Performances

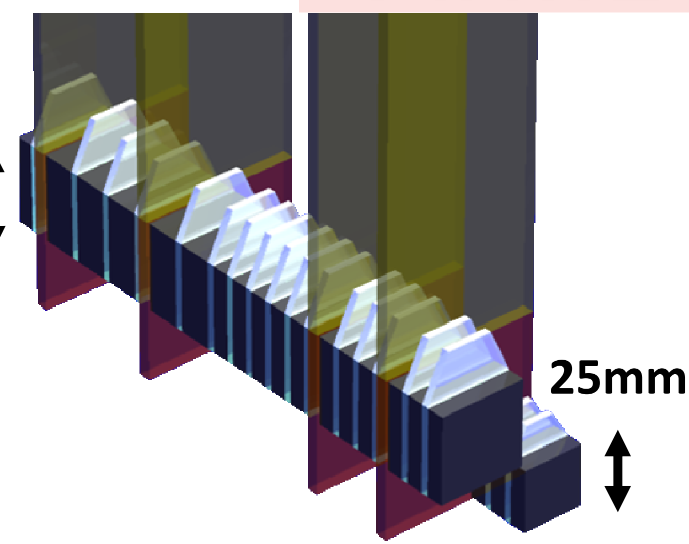
Energy resolution (> 100GeV)

< 5% for photons and ~ 30% for neutrons

Position resolution

< 200μm (Arm#1) and ~ 40μm (Arm#2)

Arm2



Front Counters

- thin scintillators 80x80 mm
- **monitoring of beam condition**
- **background rejection**
- **Van der Meer scan**


290mm
90mm
Arm#1 Detector


Arm#2 Detector

PART 3

SINGLE PHOTON SPECTRUM ANALYSIS

Paper has been submitted on **Physics Letters B** and is available on the CERN Document Service (CDS): *http://cdsweb.cern.ch/record/1344790*
It has been also submitted to **arXiv**.

Summary of operations in 2009 and 2010

Data taking with **Stable Beam at** **(450 + 450) GeV**

- Dec 6th – Dec 15th 2009 and May 2nd – May 27th 2010
- Total of **42 hours** for physics
- About **10^5 showers** events in Arm1+Arm2

Data taking with **Stable Beam at** **(3.5 + 3.5) TeV**

- Mar 30th – Jul 19th 2010
- Total of **150 hours** for physics with different setups

  Different vertical positions to increase the accessible kinematical range

  Runs with or without **100 μrad beam crossing angle**

  ~ **$4 \cdot 10^8$ shower** events in Arm1+Arm2

  ~ **10^6 π^0** events in Arm1+Arm2

Analysis strategy

- **Selection of a clean sub-set of data** with nominal configuration of detectors, zero beam crossing angle and low luminosity
  - Measurement of luminosity by means of thin plastic scintillators in front of the detectors (**front counters**)
- **Particle identification** by using longitudinal shower development
  - Study of transition curve by means of the scintillator tiles
- **Selection of single gamma events**
  - Identification and rejection of multiple hit events by means of the tracking detectors (scintillating fibers and silicon μ-strip layers)
- **Selection of a common region** of rapidity and interval of azimuth angle for Arm1 and Arm2
  - It makes possible to compare and combine the results from the two detectors

Data set for this analysis

- **Data**
  - Date : 15 May 2010 17:45-21:23 (Fill Number : 1104) except runs during the VdM luminosity scan.
  - Luminosity : **(6.3-6.5)$\times$10^{28}cm^{-2}s^{-1}**,
  - DAQ Live Time : 85.7% for Arm1, 67.0% for Arm2
  - Integrated Luminosity : **0.68 nb^{-1}** for Arm1, **0.53nb^{-1}** for Arm2
  - Number of triggers : **2,916,496** events for Arm1
    3,072,691 events for Arm2
  - Detectors in nominal positions and normal gain
- **Monte Carlo**
  - **QGSJET II-03, DPMJET 3.04, SYBILL 2.1, EPOS 1.99 and PYTHIA 8.145**: about 10^{7} pp inelastic collisions each

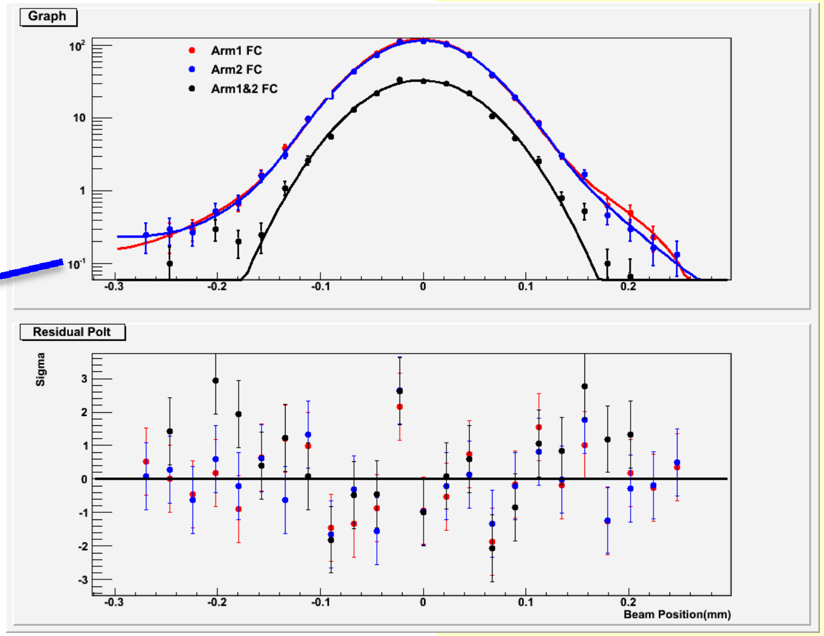
Luminosity

- Luminosity for the analysis is calculated from Front Counter rates:

$$L = CF \times R_{\mathrm{FC}}$$

- The conversion factor CF is estimated from luminosity measured during VdM scan

$$L_{\mathrm{VDM}} = n_{\mathrm{b}} f_{\mathrm{rev}} \frac{I_1 I_2}{2\pi\sigma_x\sigma_y}$$

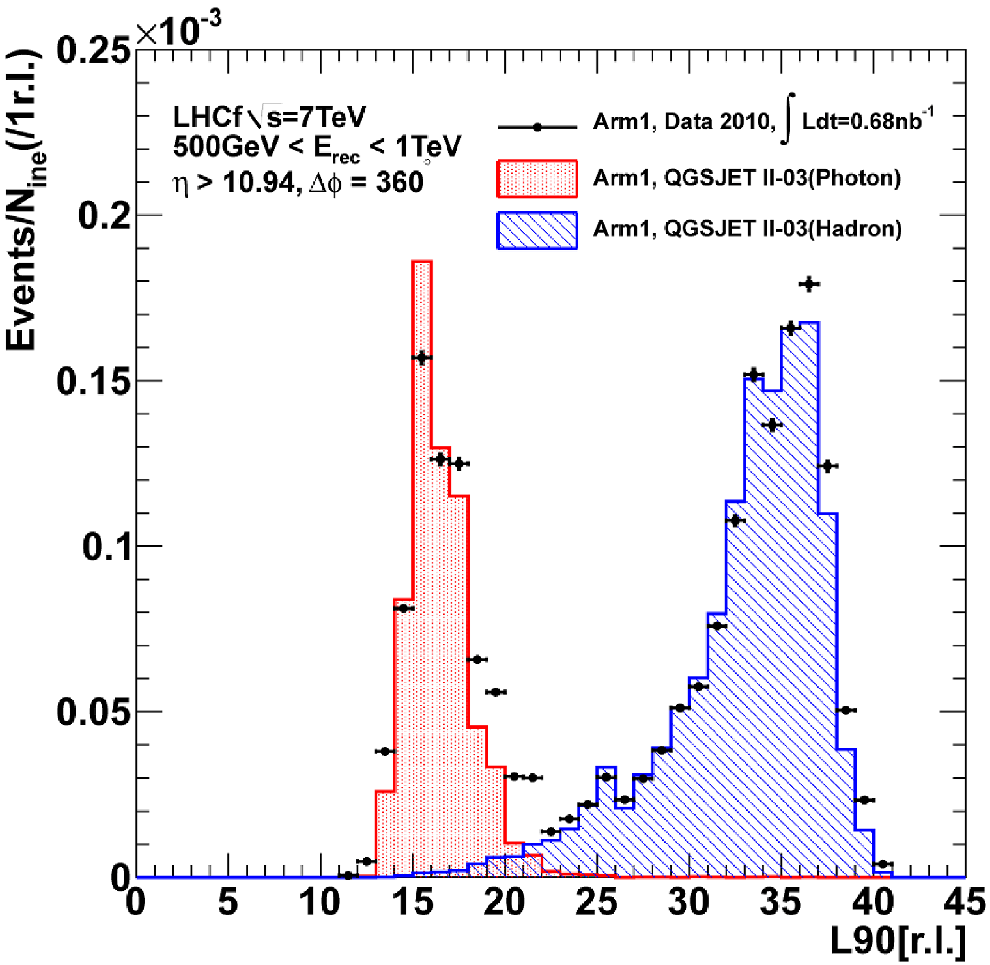


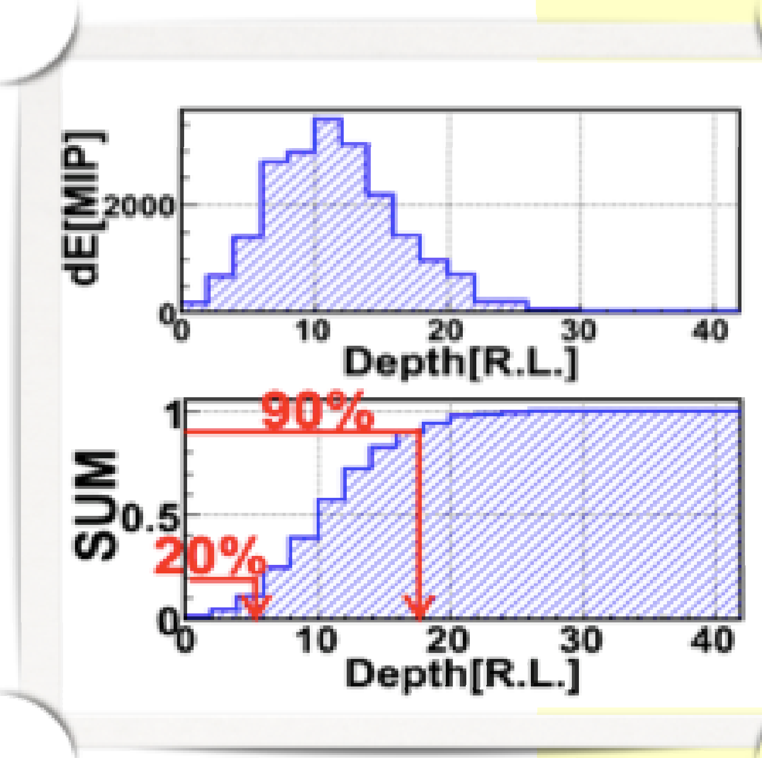
Beam sizes σ_x and σ_y measured directly by LHCf

Particle Identification (PID)

PID criteria based on transition curve

$L_{90\%}$ variable is the depth at which 90% of the signal has been released



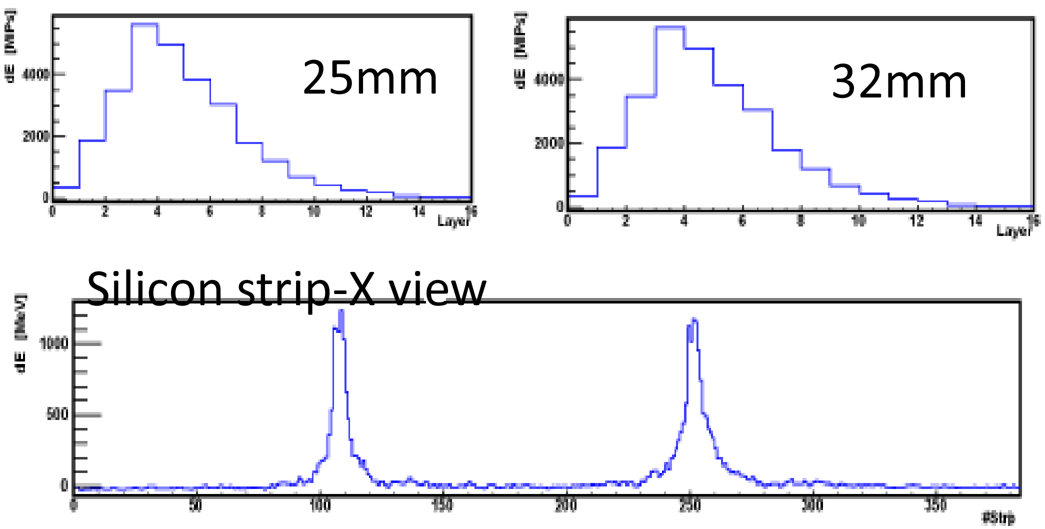


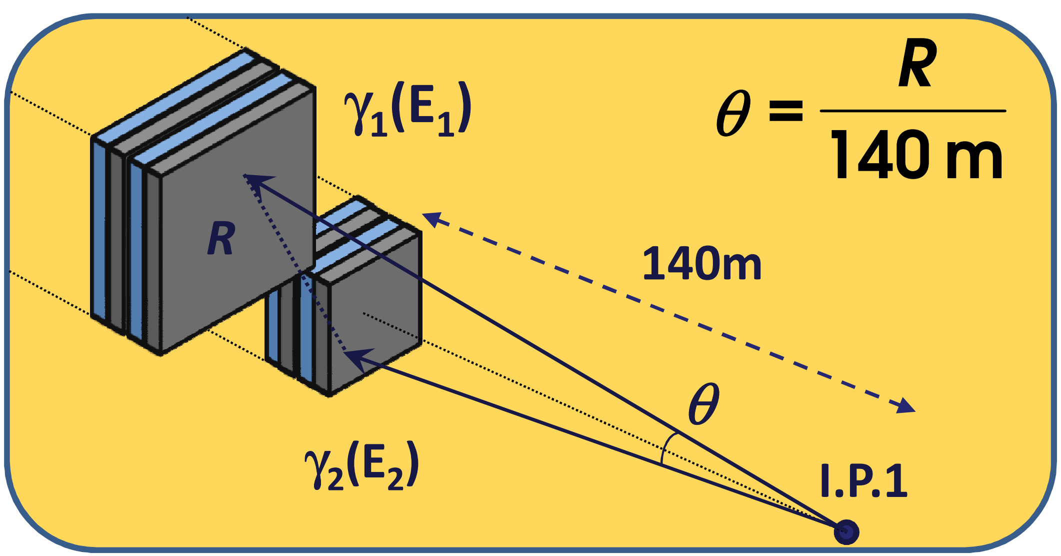
MC/Data comparison done in many energy bins

- QGSJET2-gamma and -hadron are normalized to data(/collision) independently
- LPM effects are switched on

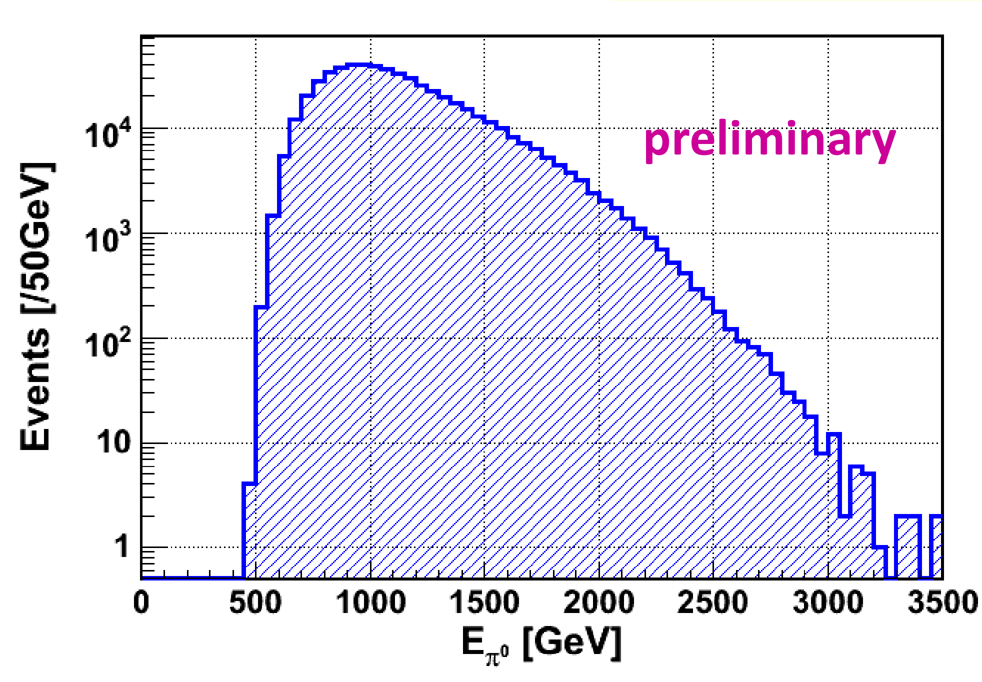
π^0 mass and energy scale issue (I)

An example of event (Arm2)



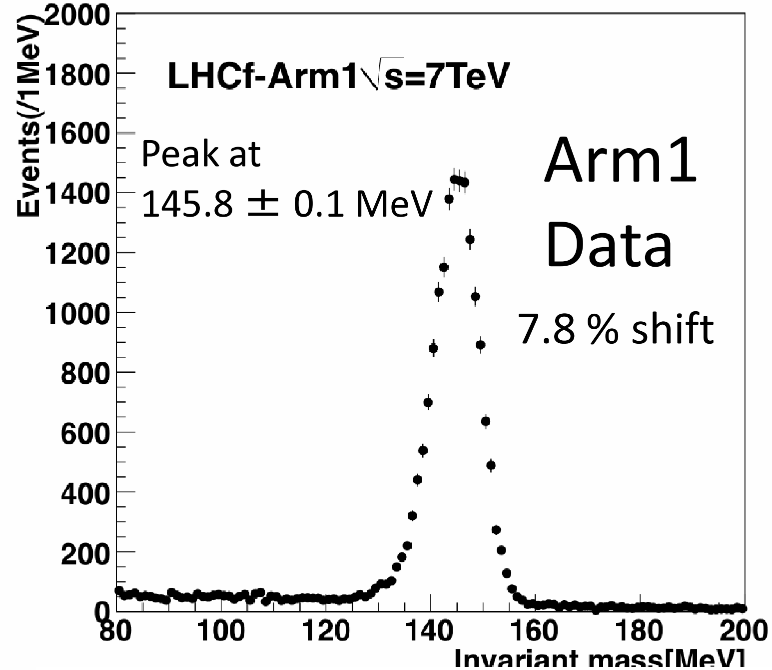


Energy spectrum (Arm2)



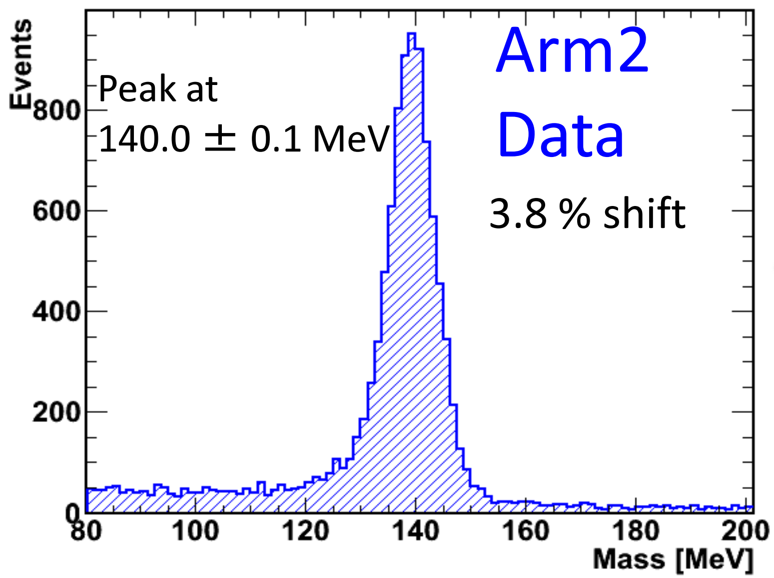
- π^0's are the main source of electromagnetic secondaries in high energy collisions
- The mass peak is very useful to check the detector performances and to estimate the systematic error on the energy scale

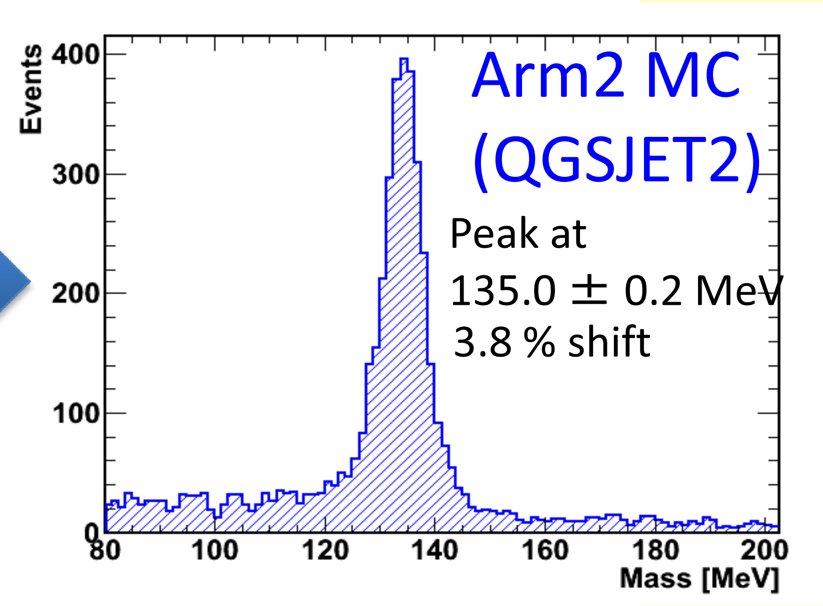
π^0 mass and energy scale issue (II)



- **Disagreement in the peak position**
  - Peak at 145.8 ± 0.1 MeV for ARM1 (7.8% shift)
  - Peak at 140.0 ± 0.1 MeV for ARM2 (3.8% shift)
- **No 'hand made correction' is applied for safety**
- **Main source of systematic error** → see later

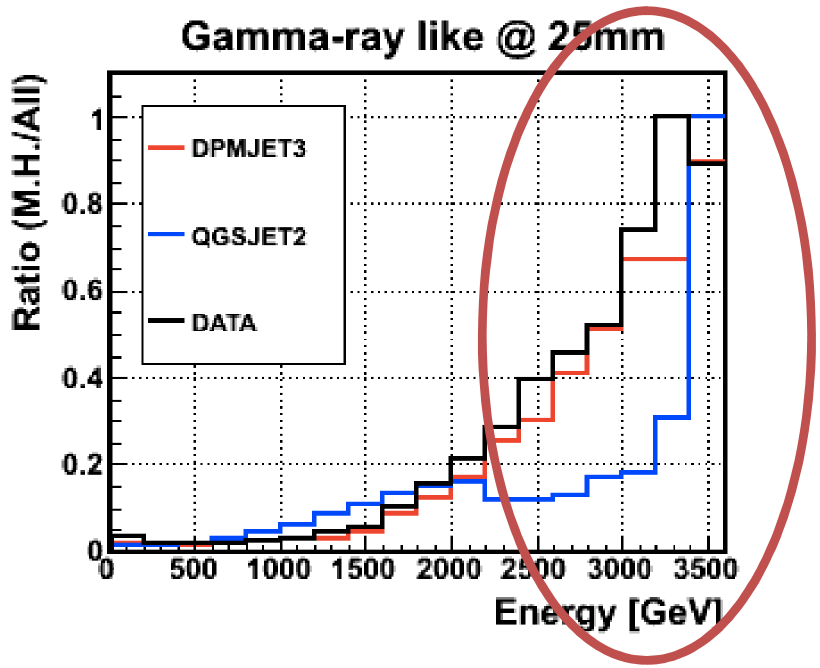
Many systematic checks have been done to understand the energy scale difference



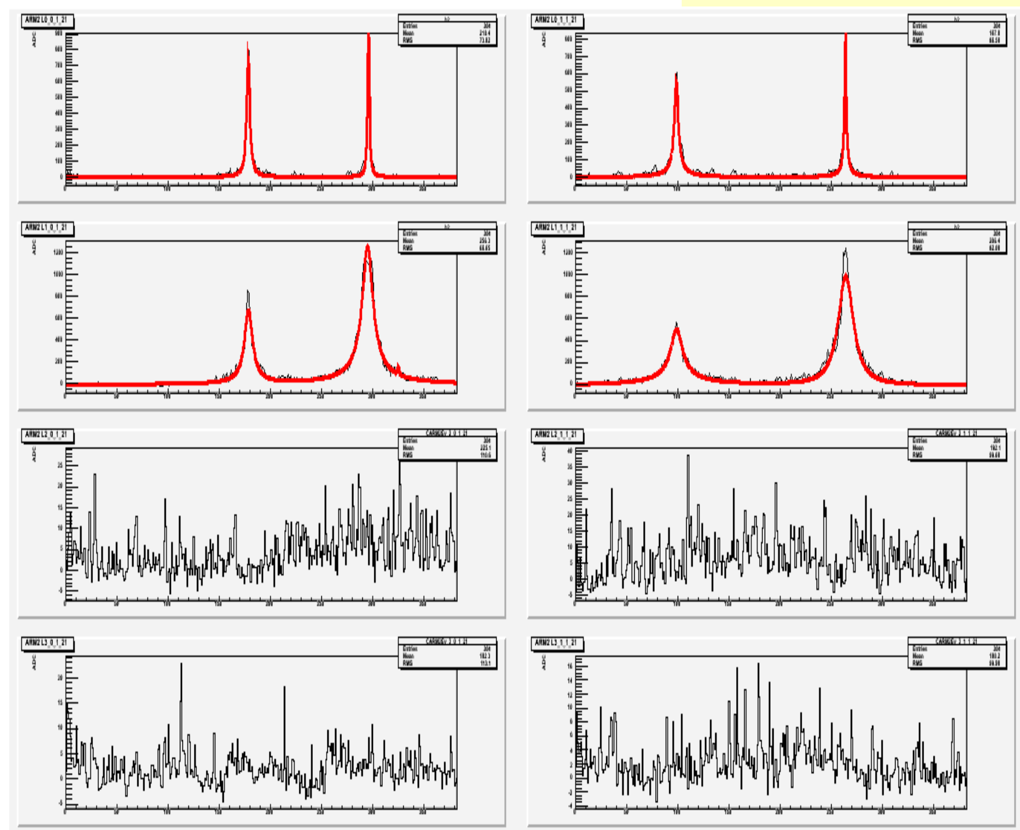


Multiple hit (MHIT) event rejection (I)

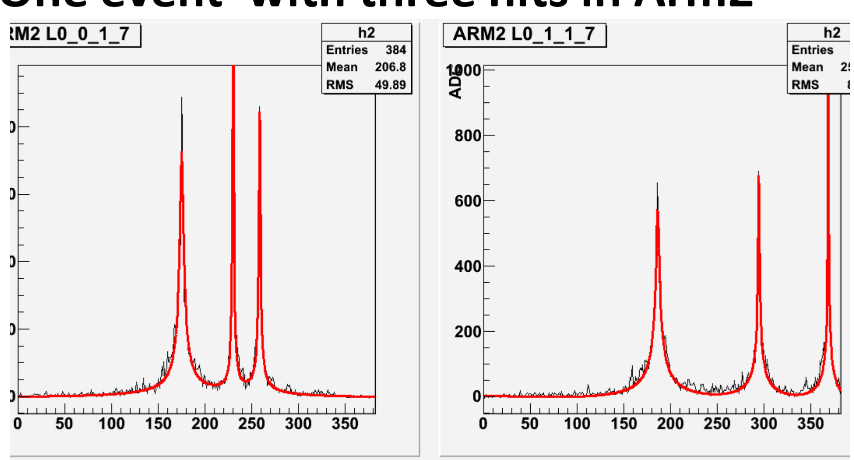
•Rejection of MHIT events is mandatory especially at high energy (> 2.5 TeV)



One event with two hits in Arm2



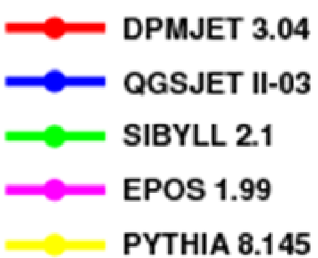
One event with three hits in Arm2



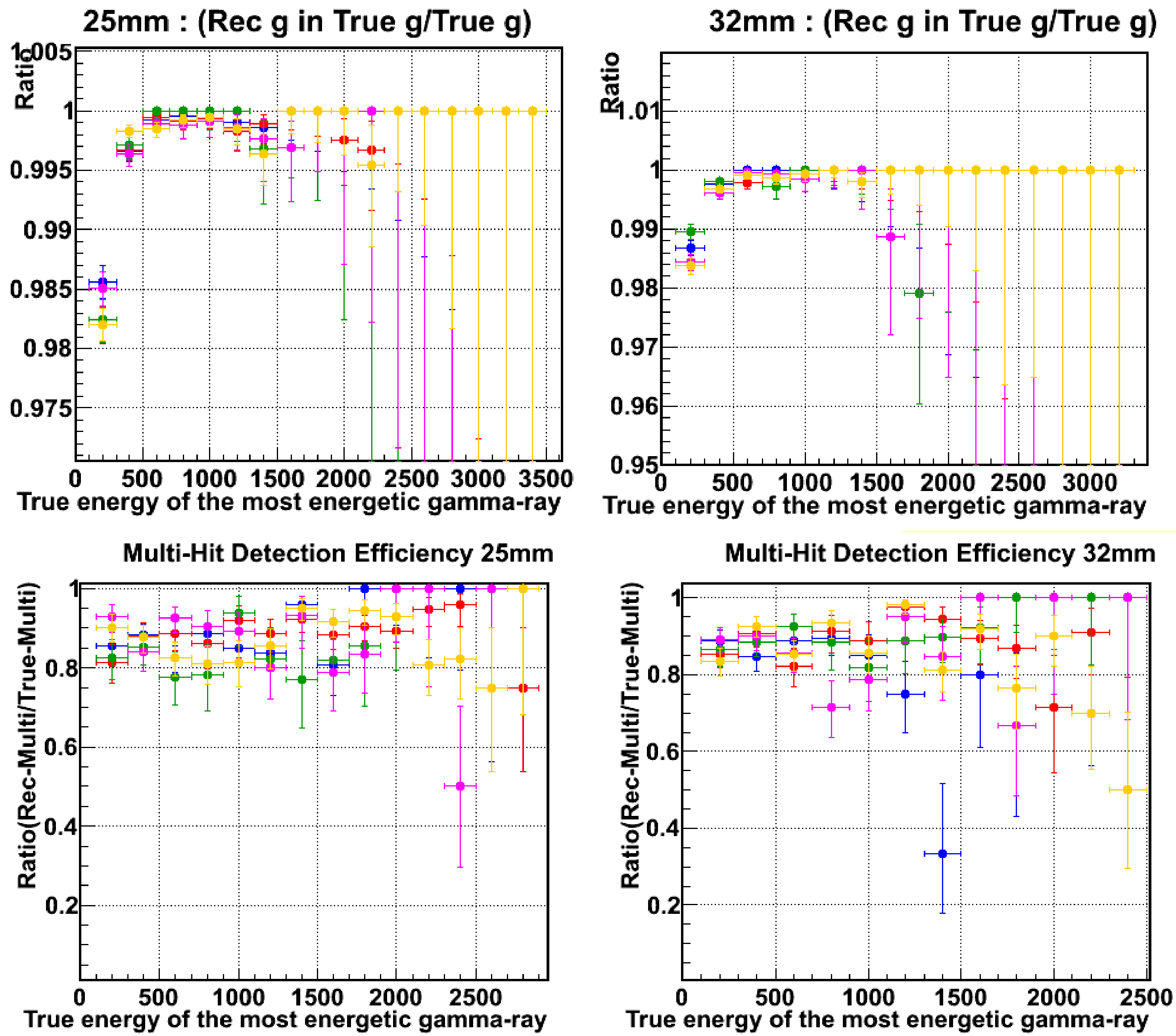
MHIT events are identified thanks to position sensitive layers in Arm1 (SciFi) and Arm2 (Si-μstrip)

Multiple hit (MHIT) event rejection (II)

Single γ detection efficiency for various MC models



Multi γ detection efficiency for various MC models



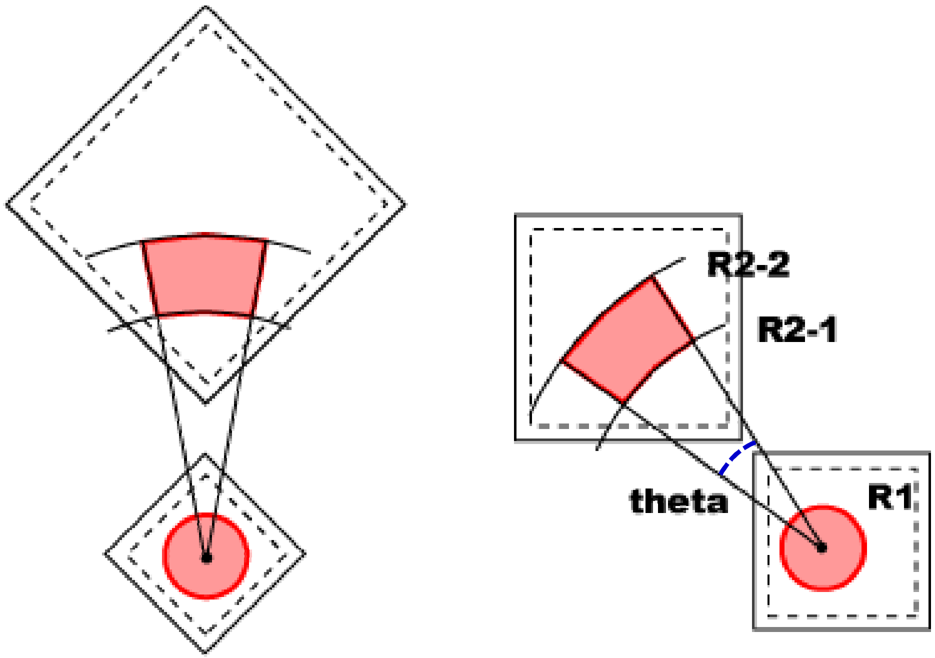
PART 4

RESULTS

Acceptance cut for combined Arm1/Arm2 analysis

For a comparison of the Arm1 and Arm2 reconstructed spectra we define in each tower a region of pseudo-rapidity and interval of azimuth angle that is common both to Arm1 and Arm2.

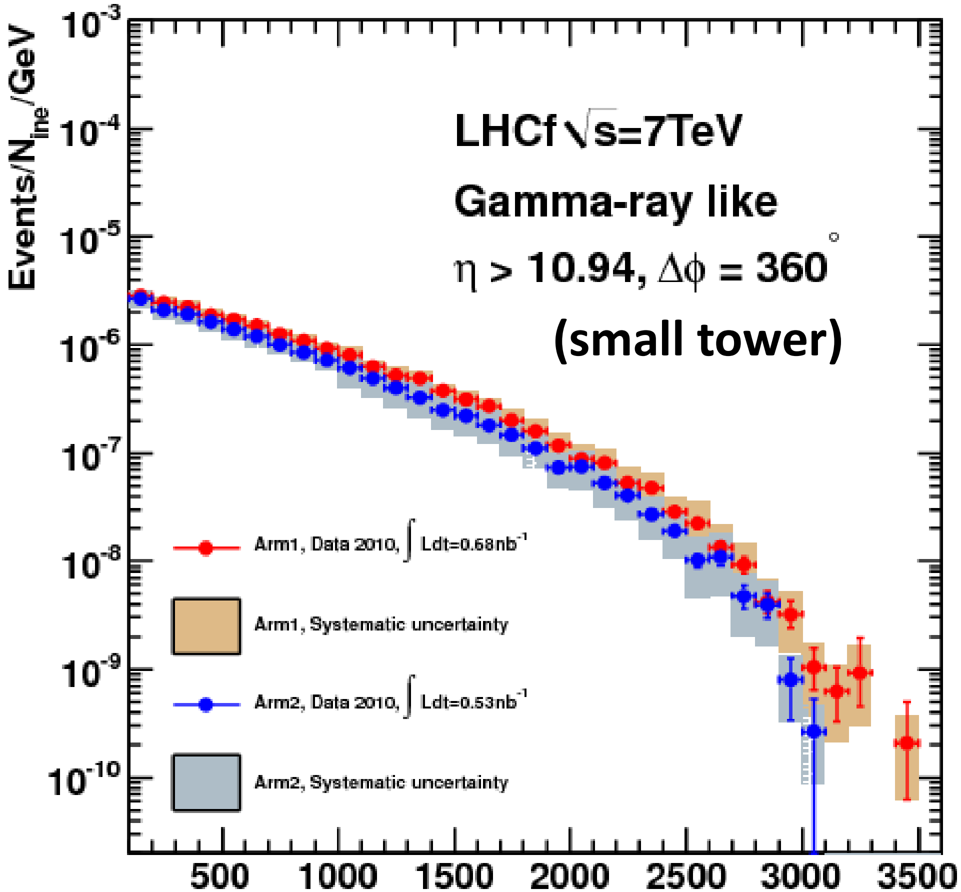
As first result we present two spectra, one for each acceptance region, obtained by properly weighting the Arm1 and Arm2 spectra

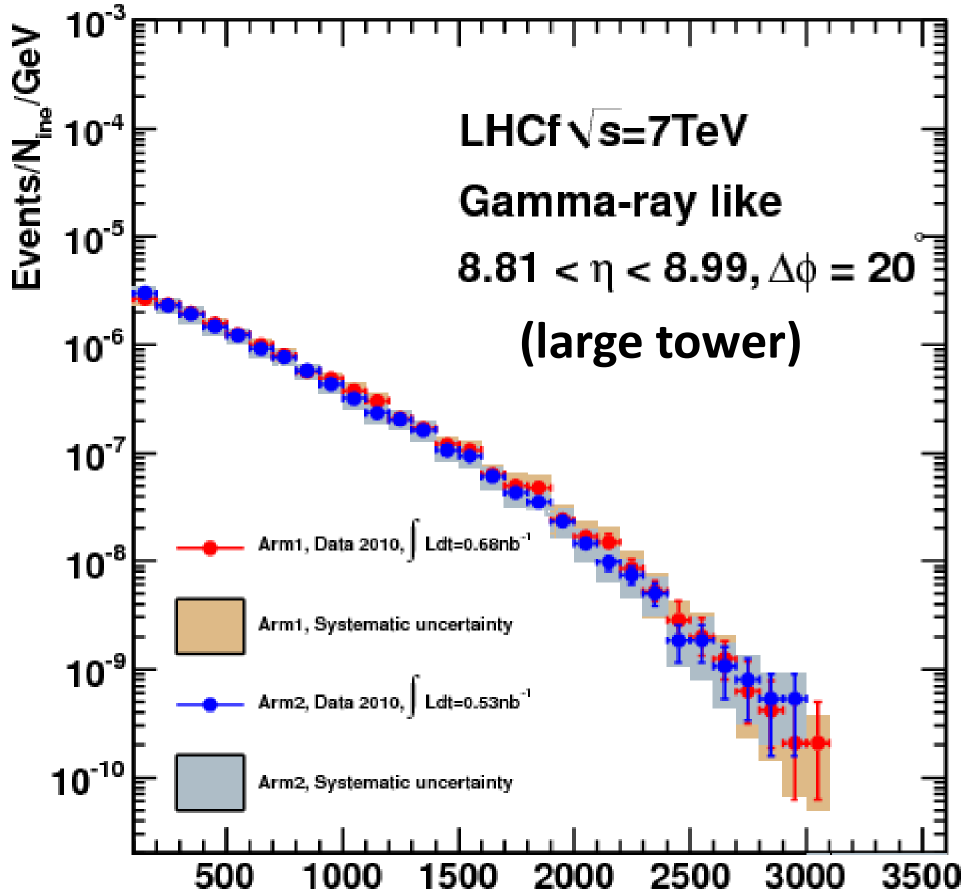


R1 = 5mm
R2-1 = 35mm
R2-2 = 42mm
$\theta = 20^o$

For <u>Small Tower</u>
η > 10.94
For <u>Large Tower</u>
8.81 < η < 8.99

Comparison Arm1/Arm2

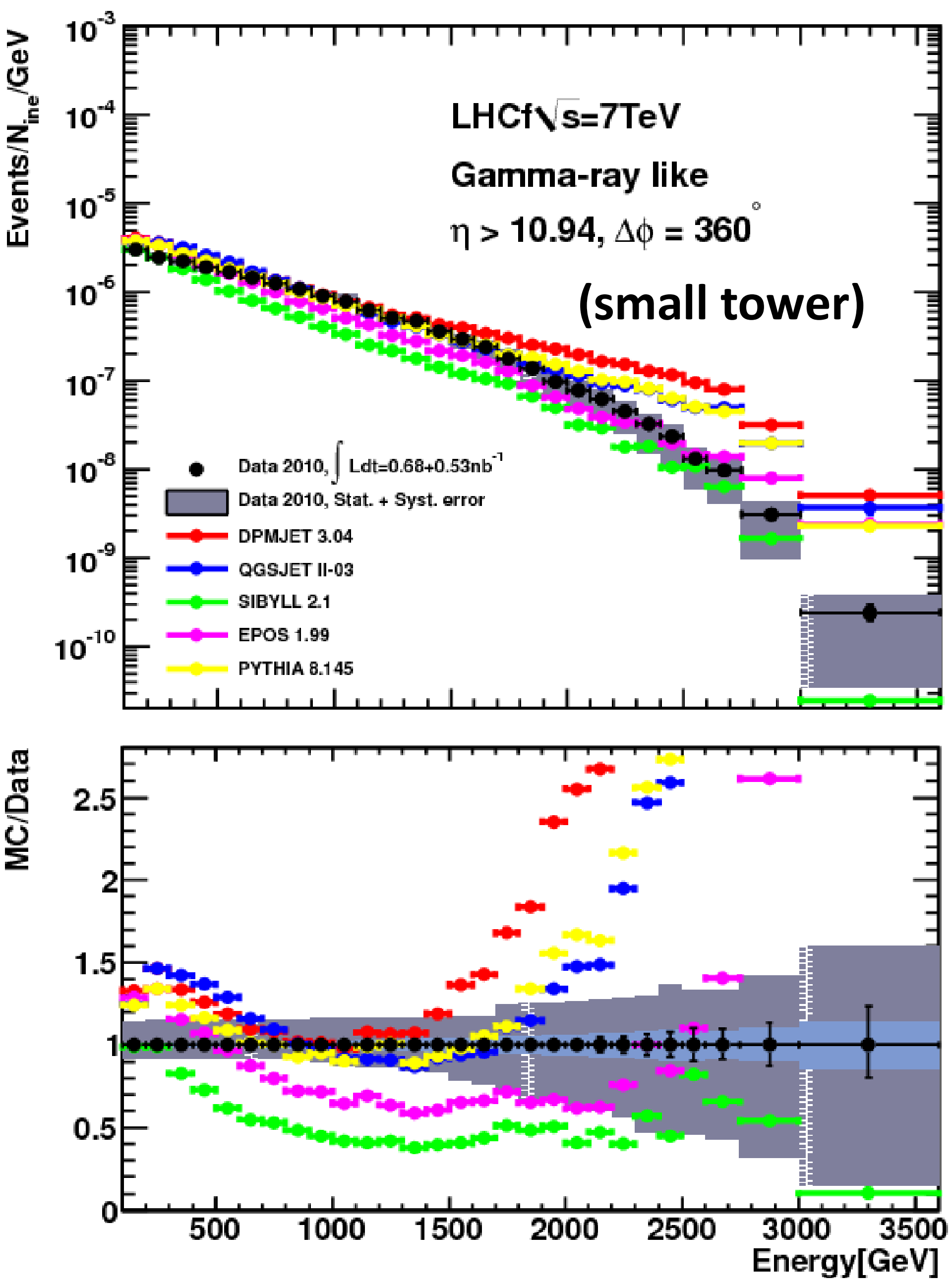


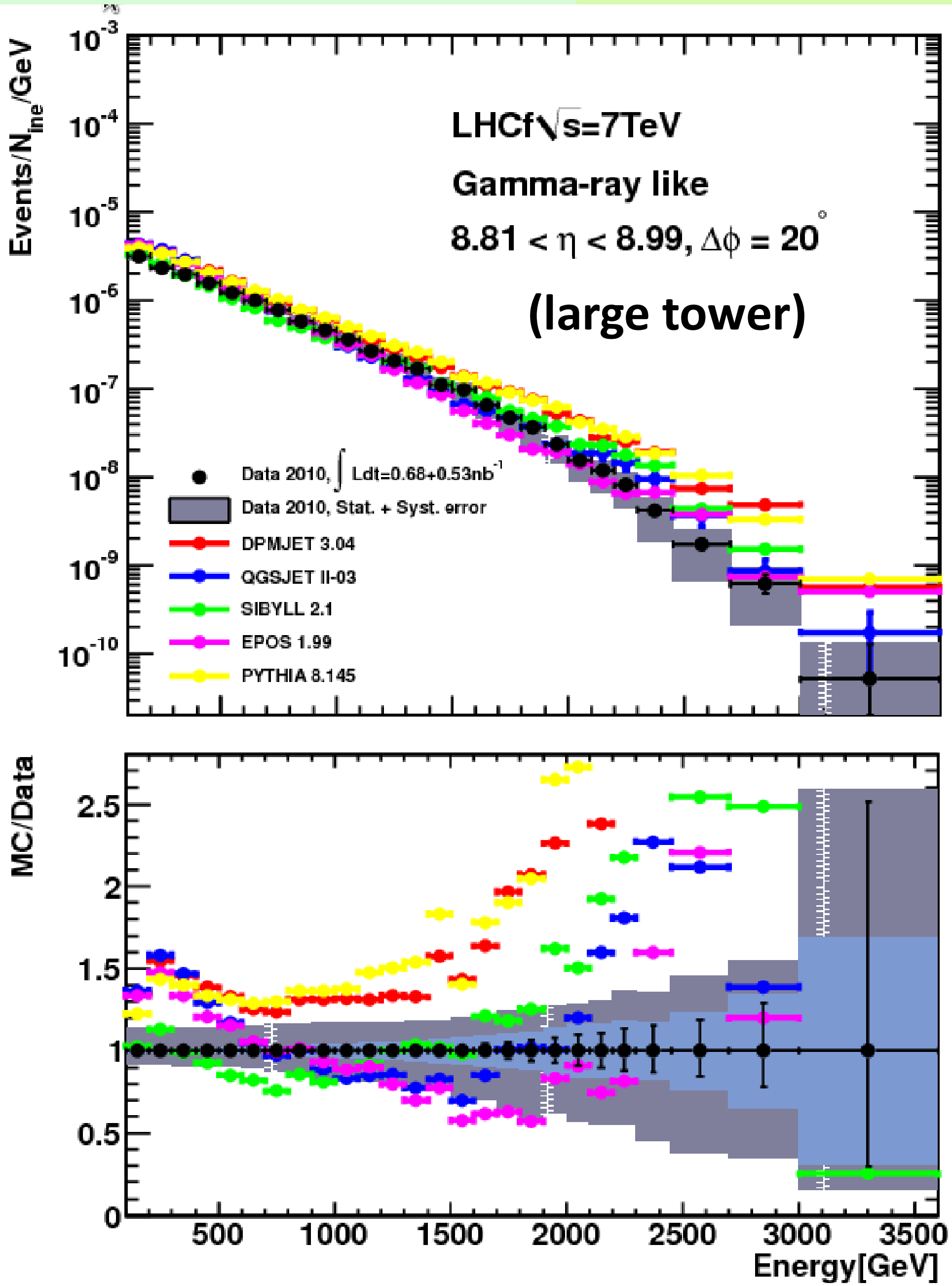


Multi-hit rejection and PID correction applied. Energy scale systematic (correlated between Arm1 and Arm2) has not been plotted to verify the agreement between the two detectors within the non correlated uncertainties.

Deviation in small tower is still not clear. Anyway it is within systematic errors.

Comparison of combined spectra with models





PART 5

SYSTEMATIC UNCERTAINTIES

Summary of systematics (I)

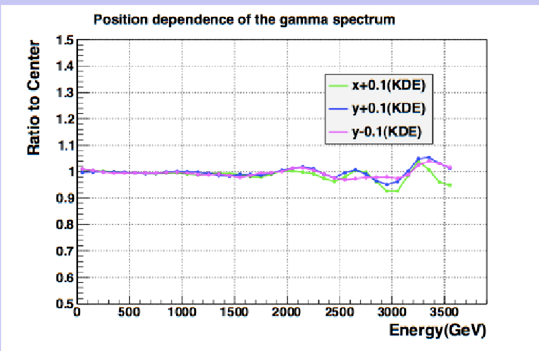
- Uncorrelated uncertainties between ARM1 and ARM2
  - Energy scale (except π^0 shift) : 3.5%
  - Beam center position : 1 mm
  - PID : 5% for E<1.7TeV, 20% for E>1.7TeV
  - Multi-hit selection :
    - Arm1 small tower: 1% for E<1TeV, 1%→20% for E>1TeV
    - Arm1 large tower: 1% for E<2TeV, 1%→30% for E>2TeV
    - Arm2 small tower: 0.2% for E<1.2TeV, 0.2%→2.5% for E>1.2TeV
    - Arm2 large tower: 0.2% for E<1.2TeV, 0.2%→4.8% for E>1.2TeV

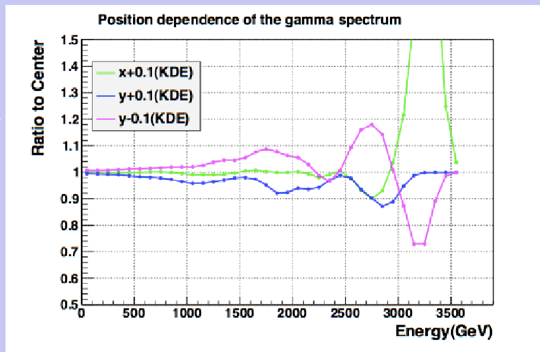
Estimated for Arm1 and Arm2 by same methods but independently

- Correlated uncertainties
  - Energy scale (π^0 shift): 7.8% for Arm1 and 3.8% for Arm2 (asymmetric)
  - Luminosity : 6.1%

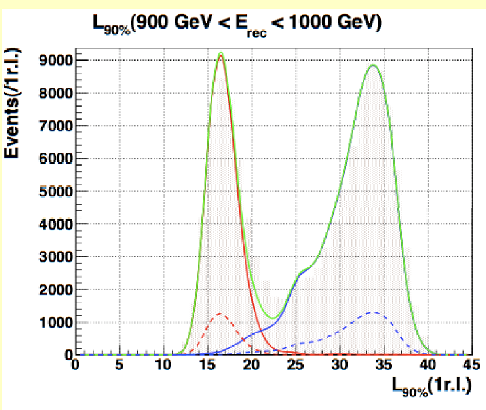
Summary of systematics (II)

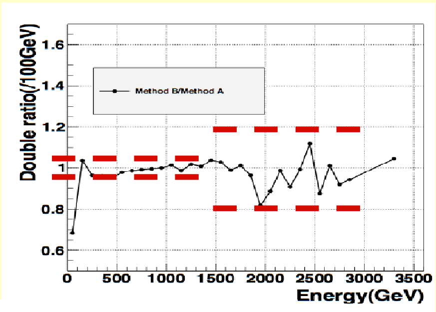
Beam center position

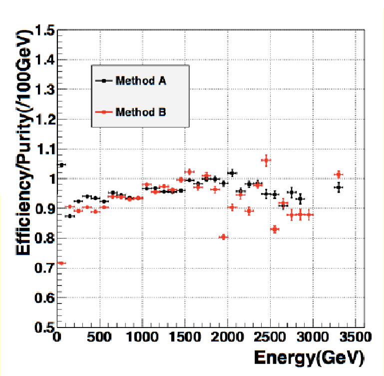




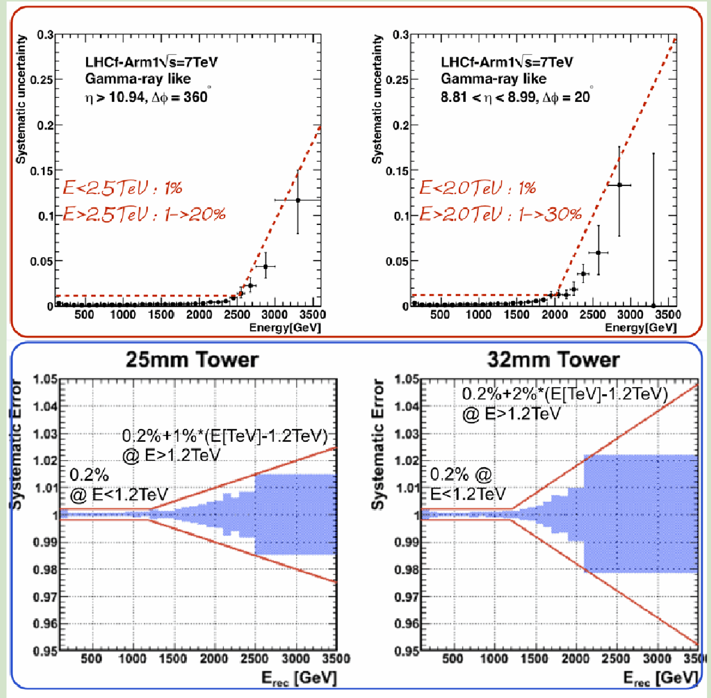
Particle ID







Multiple hit cut



More details in paper

Measurement of zero degree single photon energy spectra for √S=7TeV proton-proton collisions at LHC

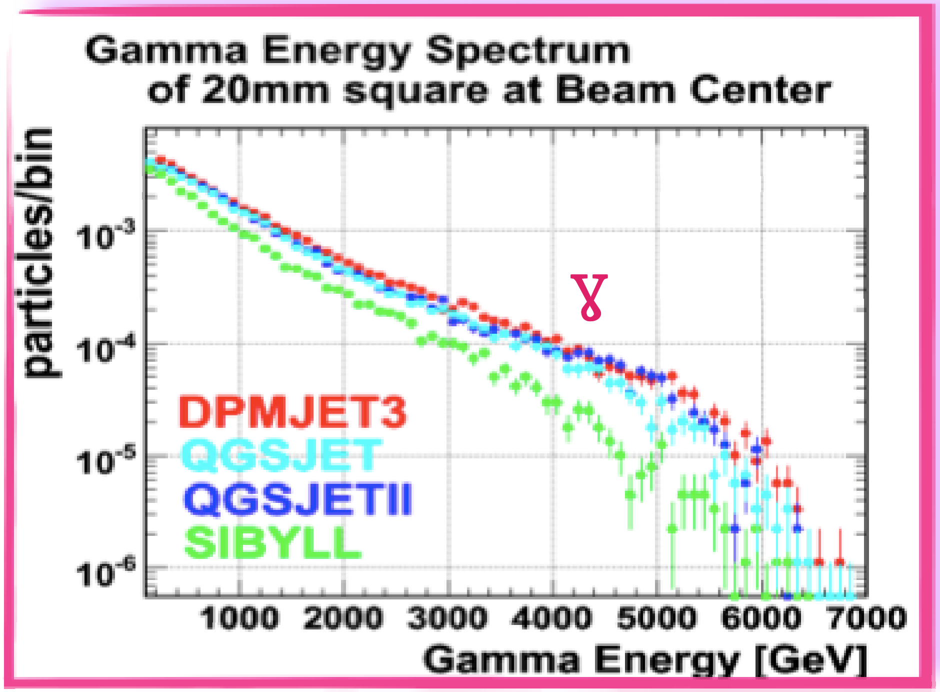
Submitted to Physics Letters B

Conclusions

- Analysis of **LHCf single photon spectra** has been completed
  - Many detailed systematic checks were necessary!
  - First comparison of various hadronic interaction models with experimental data in the phase space region $8.81 < \eta < 8.99$ and $\eta > 10.94$
  - Important contribution to the study of atmospheric showers
- **Other analysis** are in progress (hadrons, P_T distributions, different η coverage, interactions at 900 GeV etc.)
- We are **upgrading the detectors** to improve their radiation hardness (GSO scintillators) and to correct some minor problem
- Discussion are under way to come back in the TAN for the possible **p-Pb run in 2013** (LHCC, Alice, LHC, Atlas etc.)
- LHCf detectors will be re-installed again for the **14 TeV run**, to complete its physics program with upgraded detectors

Backup slides

What do we expect from LHCf?

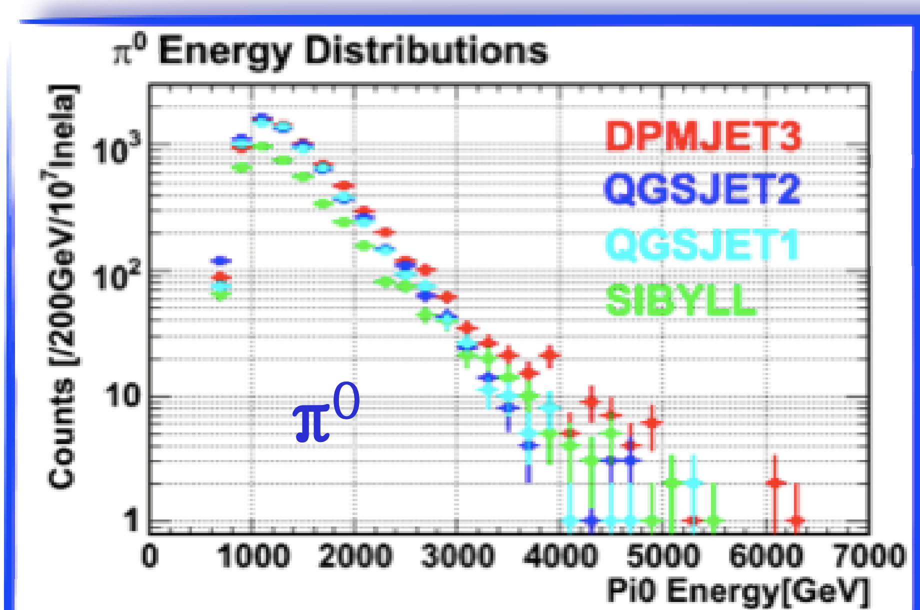


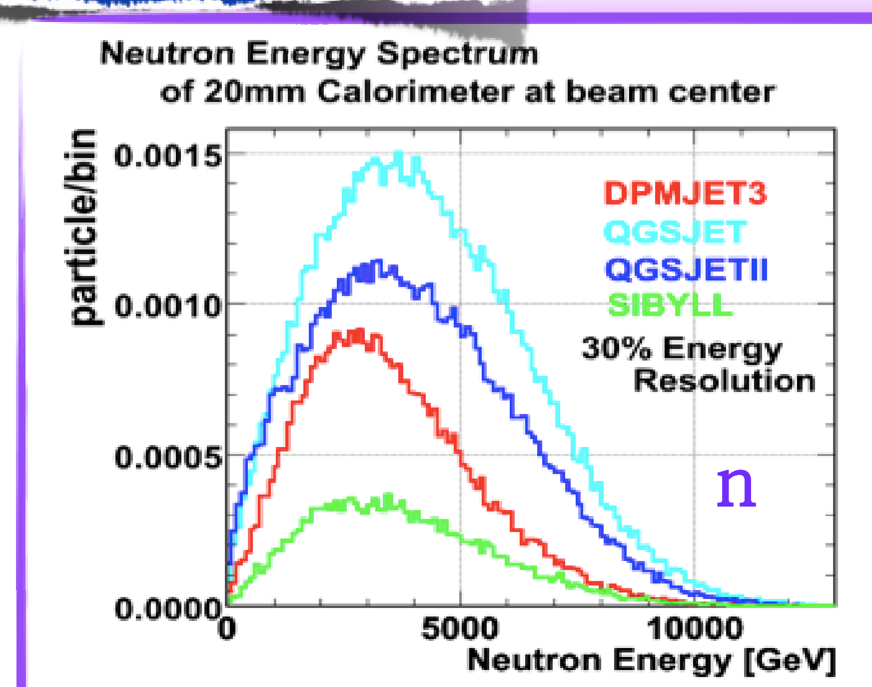
Energy spectra and transverse momentum distribution of

- γ (E>100GeV, $\Delta E/E$<5%)
- Neutrons (E> few 100 GeV, $\Delta E/E$~30%)
- π^0 (E>500GeV, $\Delta E/E$<3%)

in the pseudo-rapidity range η>8.4

10^6 collisions
↔ 2min. exposure @ $10^{29}cm^{-2}s^{-1}$

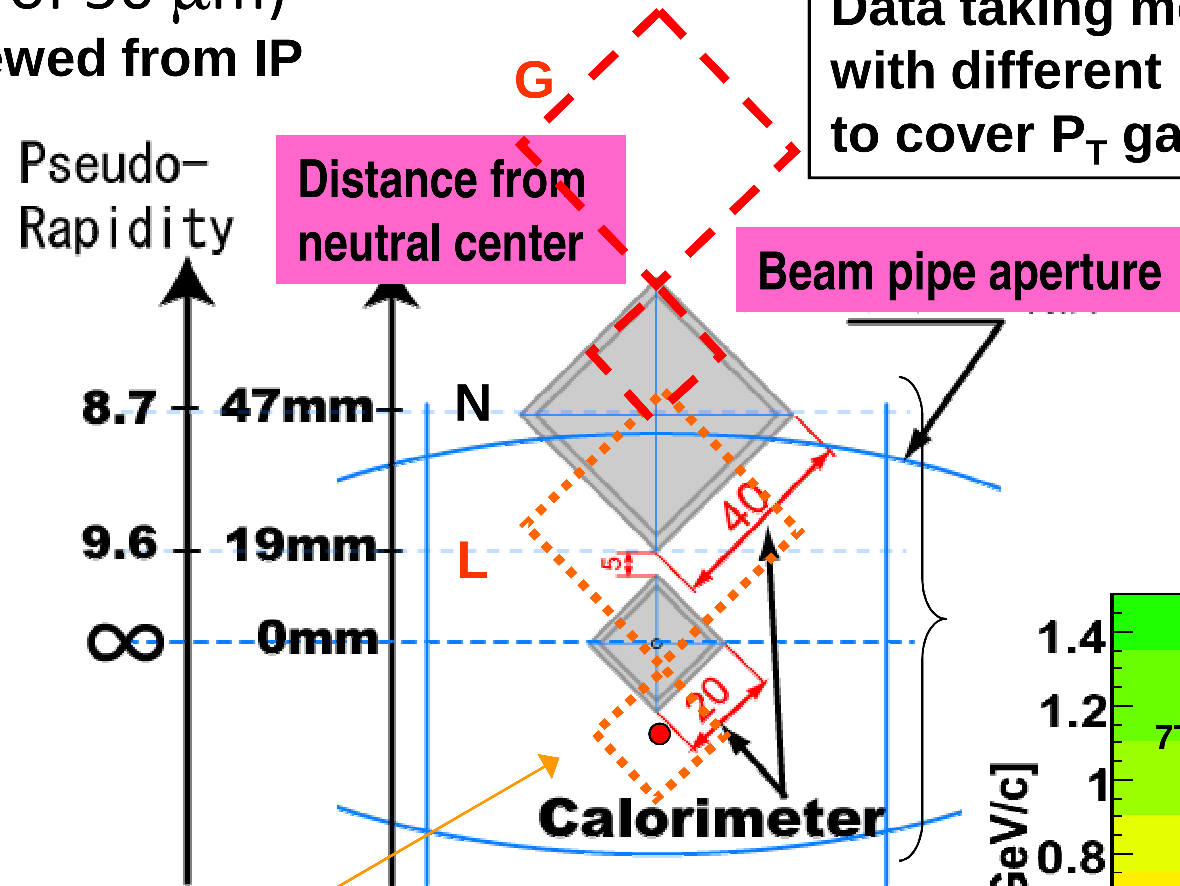




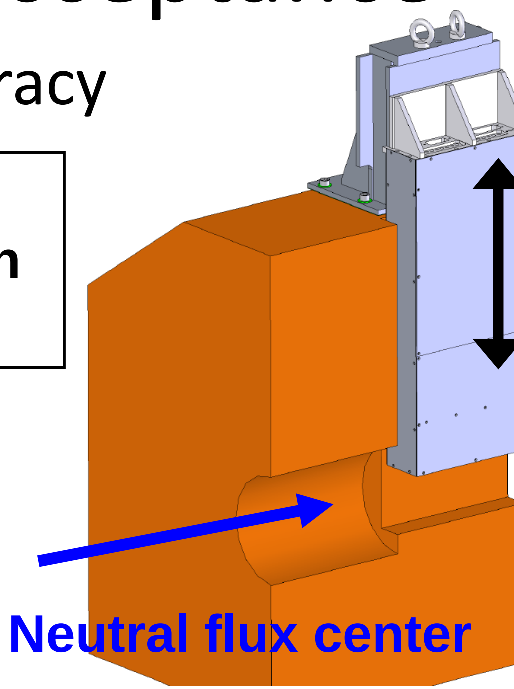
Detector vertical position and acceptance

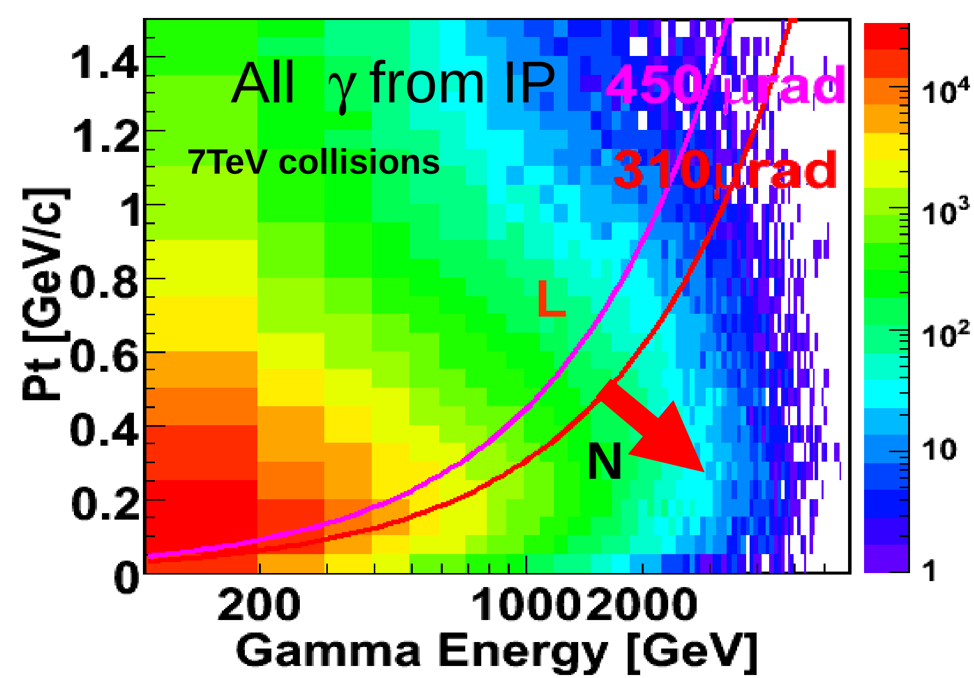
- Remotely changed by a manipulator(with accuracy of 50 μm)

Viewed from IP



Data taking mode with different position to cover P_T gap



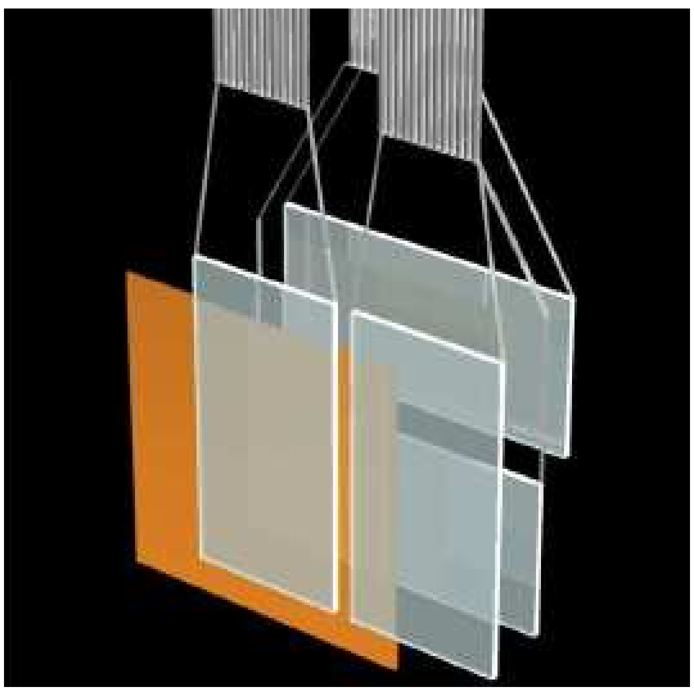


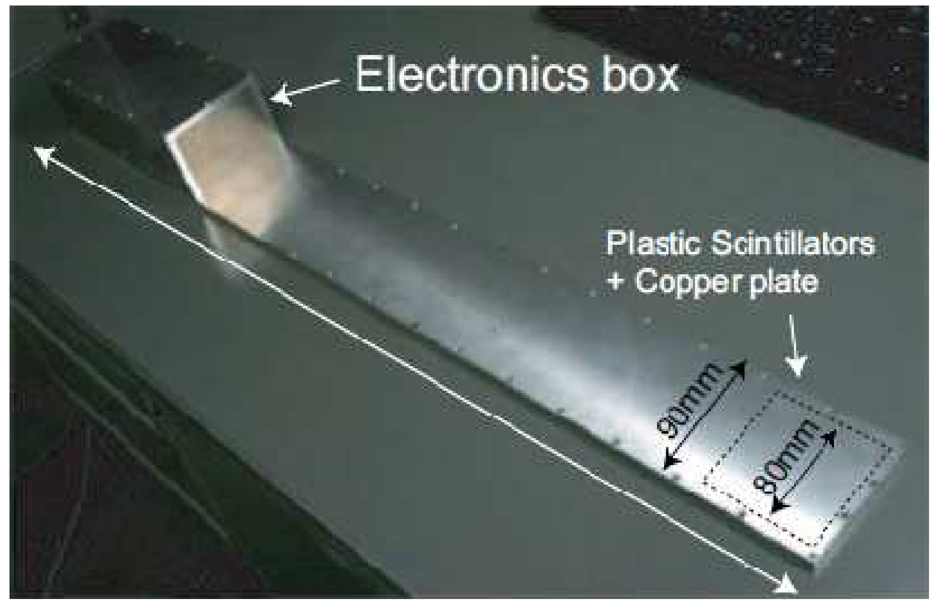
Collisions with a crossing angle lower the neutral flux center thus enlarging P_T acceptance

Front counters

- Thin scintillators with 8x8cm^2 acceptance, which have been installed in front of each main detector.

Schematic view of Front counter

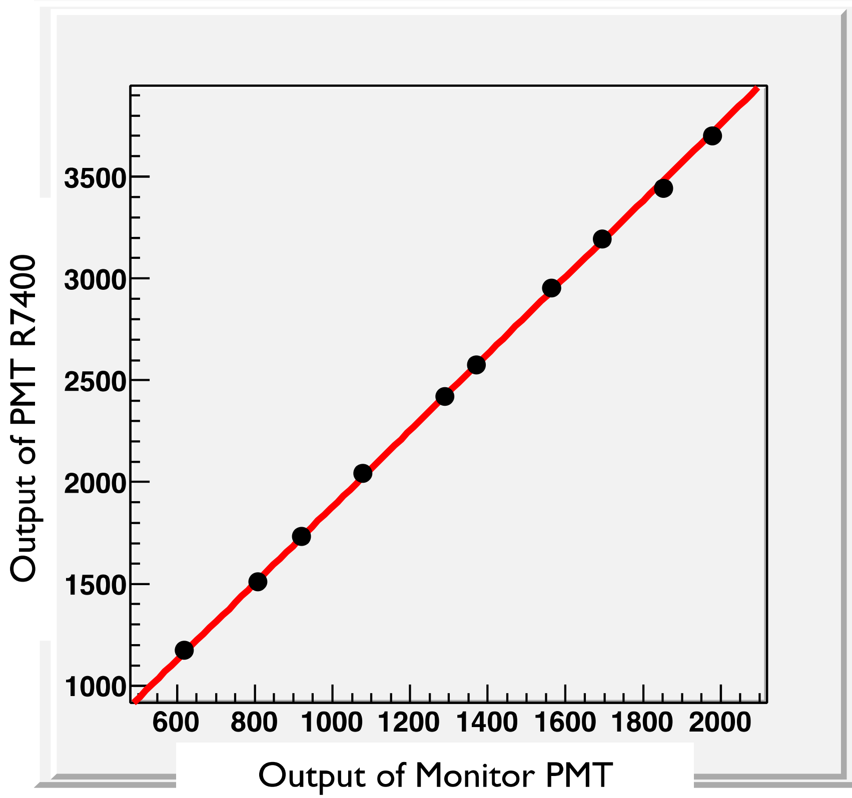


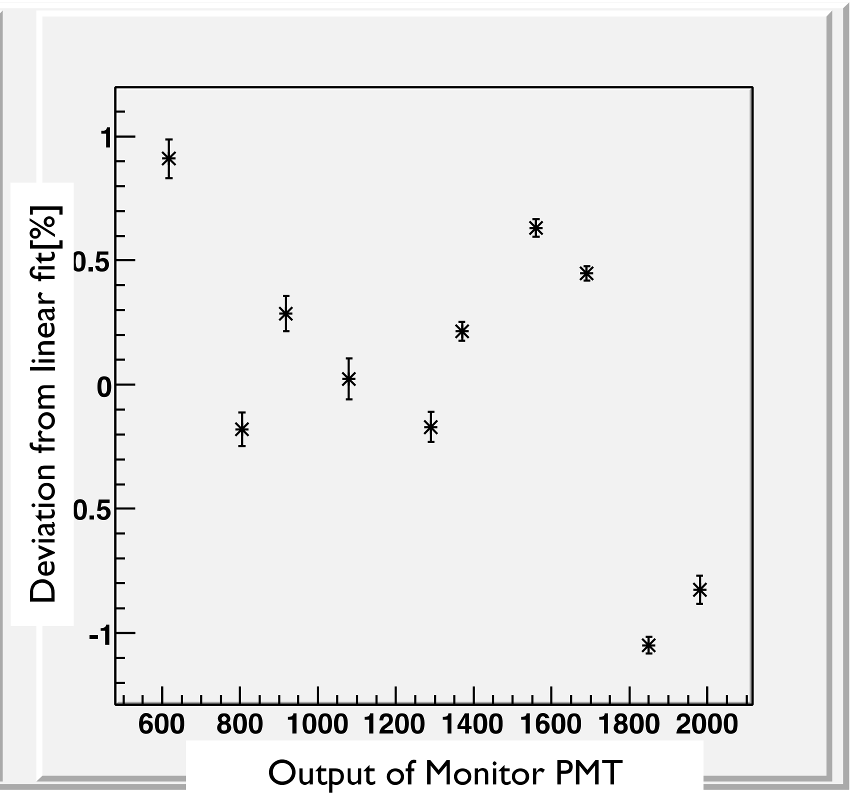


- **To monitor beam condition.**
- **For background rejection of beam-residual gas collisions by coincidence analysis**
- **To study the luminosity by VdM scan**

Linearity of PMTs (Hamamatsu R7400)

- PMTs R7400 are used in current LHCf system coupled to the scintillator tiles
- Test of linarity was held at HIMAC using Xe beam
- PMT R7400 showed good linearity within 1% up to signal level corresponding to 6TeV showerMAX in LHCf.

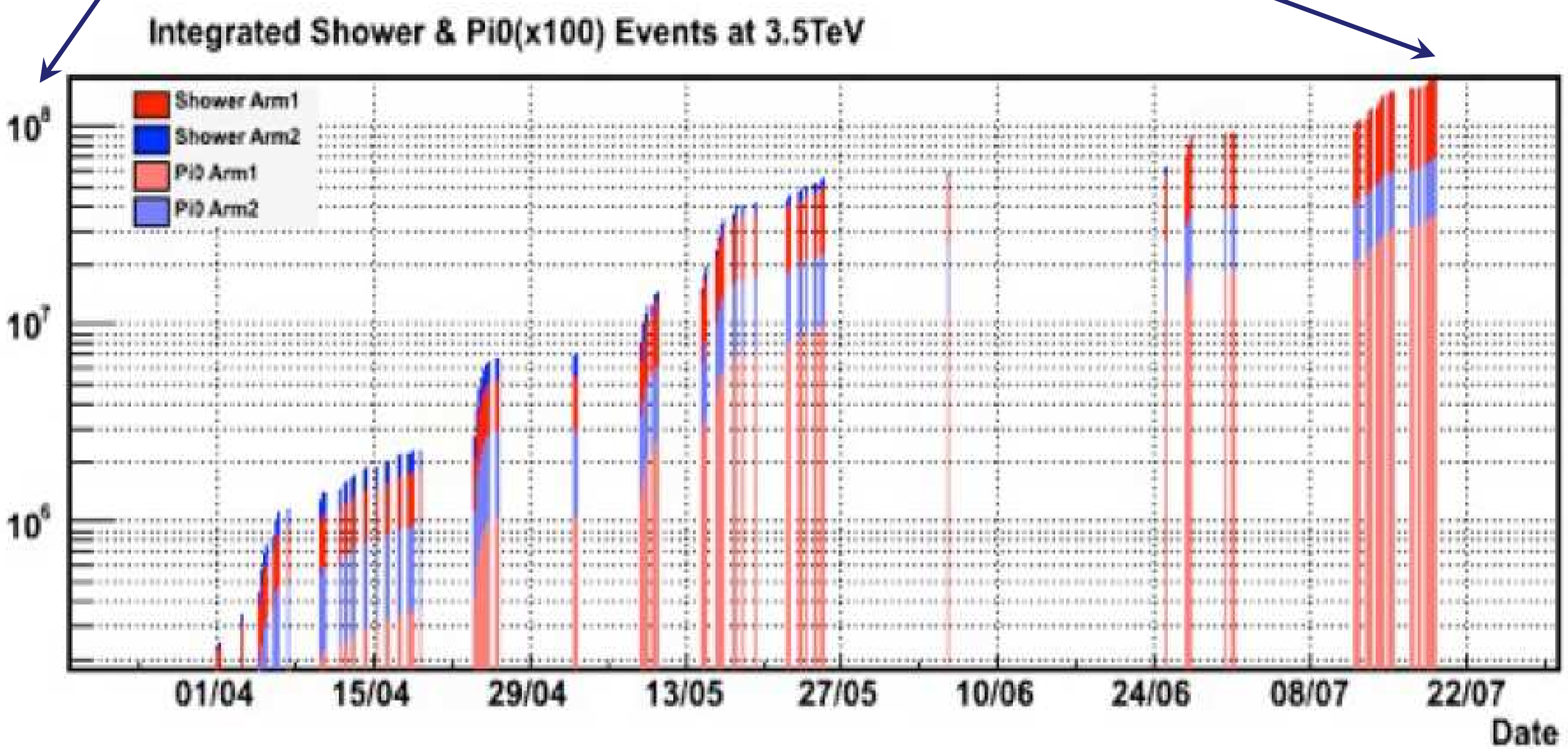




Accumulated events in 2010

10^8 events!

LHCf removal



Pile-up events

When the configuration of beams is 1x1 interacting bunches, the probability of N collisions per crossing is

$$P(N) = \frac{\lambda^N \exp[-\lambda]}{N!}$$

$$\lambda = \frac{L \cdot \sigma}{f_{\mathrm{rev}}}$$

The ratio of the pile up event is

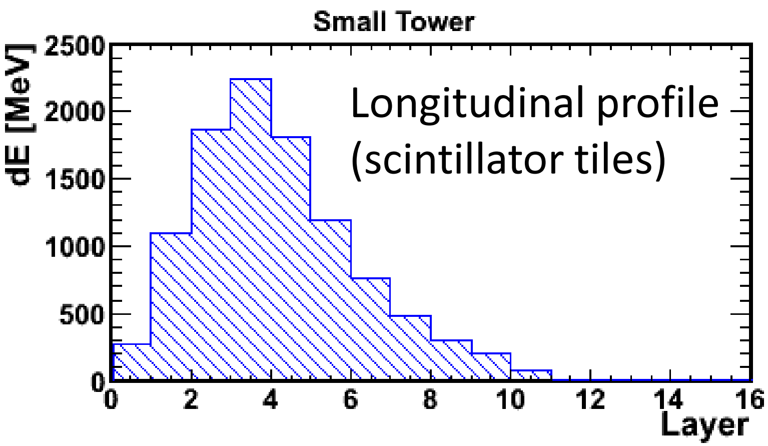
$$R_{\mathrm{pileup}} = \frac{P(N \geq 2)}{P(N \geq 1)} = \frac{1-(1+\lambda)e^{-\lambda}}{1-e^{-\lambda}}$$

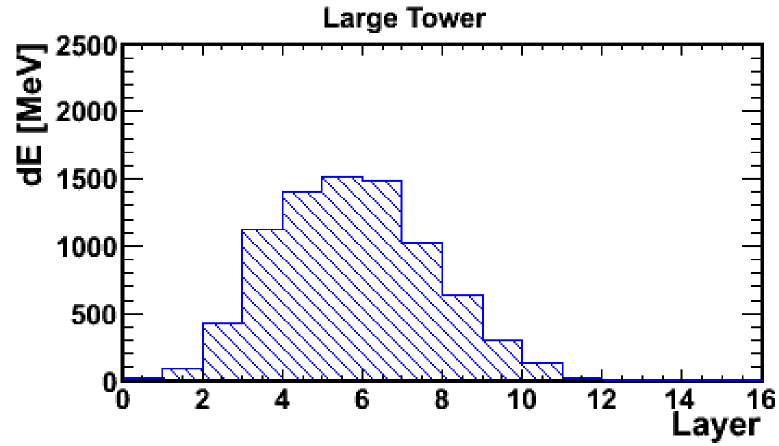
The maximum luminosity per bunch during runs used for the analysis is $2.3 \times 10^{28} cm^{-2}s^{-1}$

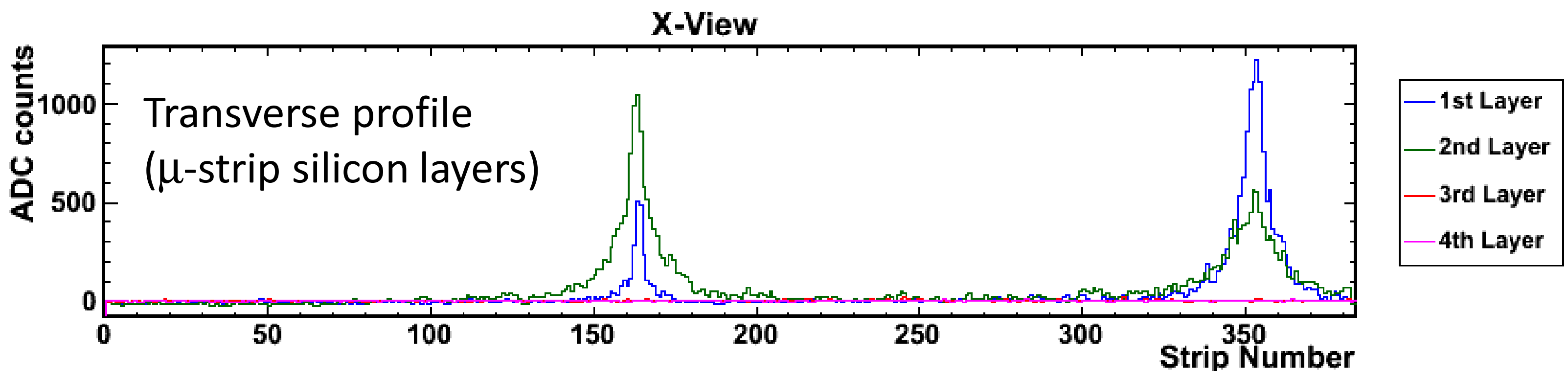
So the probability of pile up is estimated to be 7.2% with σ of 71.5mb

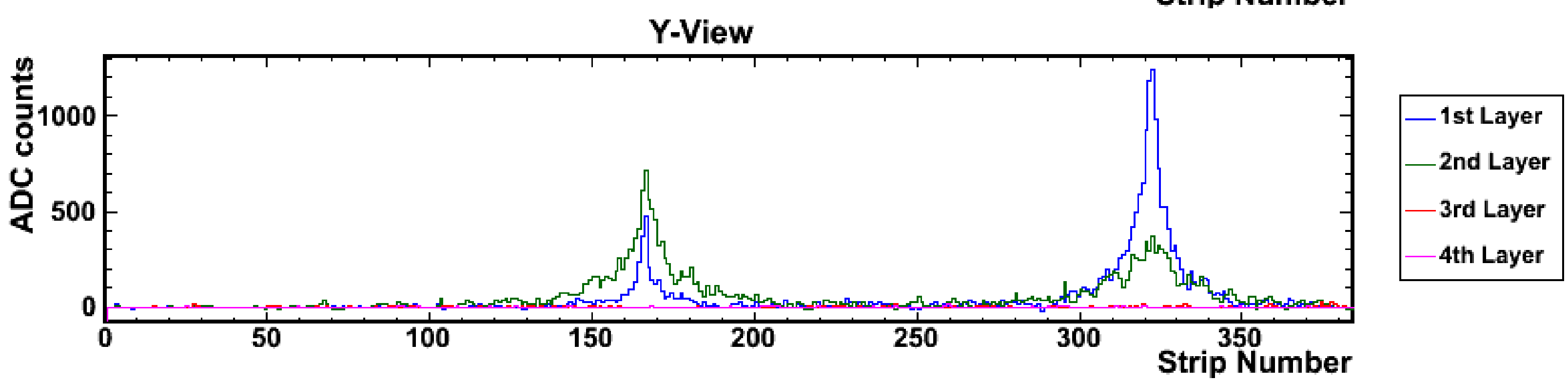
Taking into account the calorimeter acceptance (~0.03) only 0.2% of events have multi-hit due to pile-up. It does not affect our results

π^0 candidate event @ 1 TeV







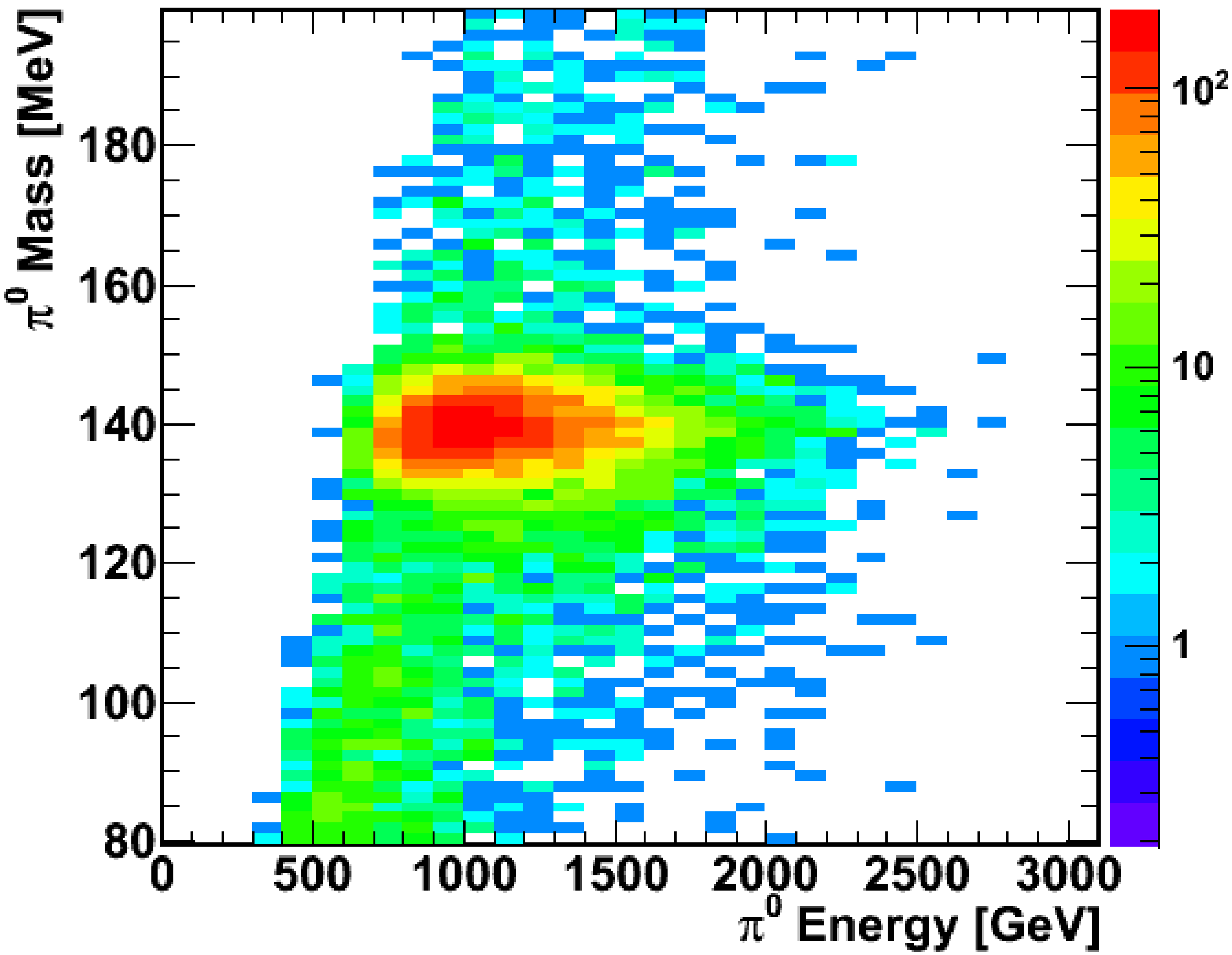


π^0 event:

599 GeV γ-ray in 25mm tower

419 GeV γ-ray in 32mm tower

π^0 mass versus π^0 energy



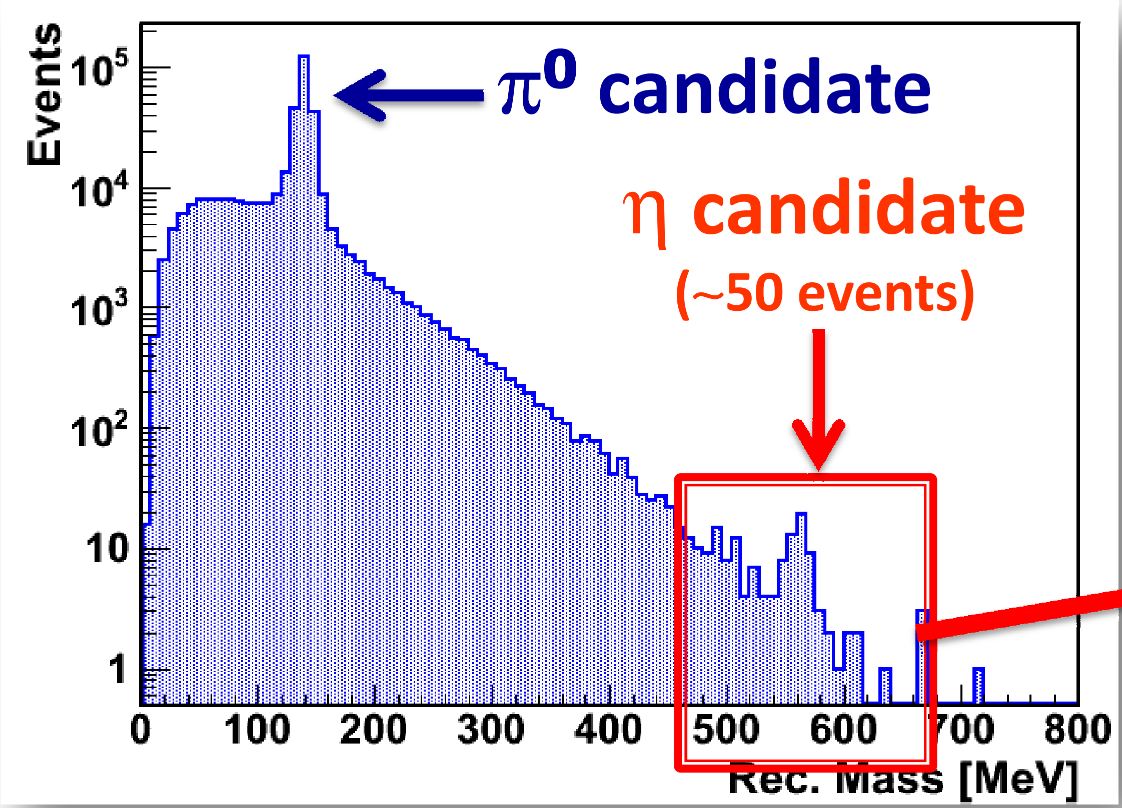
Arm2 Data

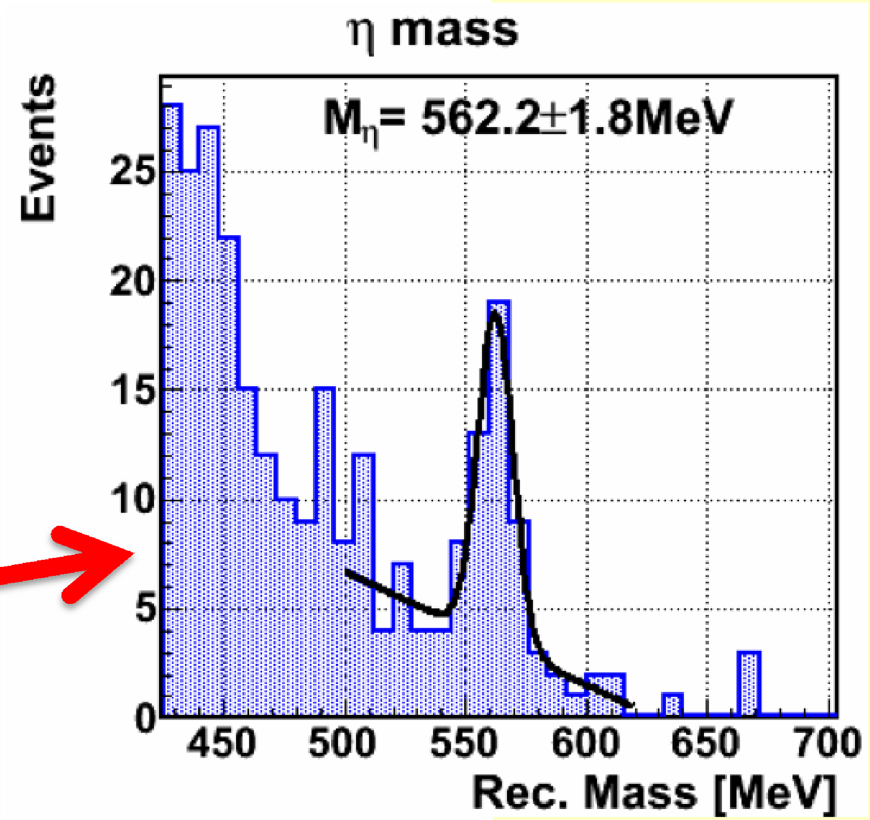
No strong energy dependence of reconstructed mass

2γ invariant mass and η mass

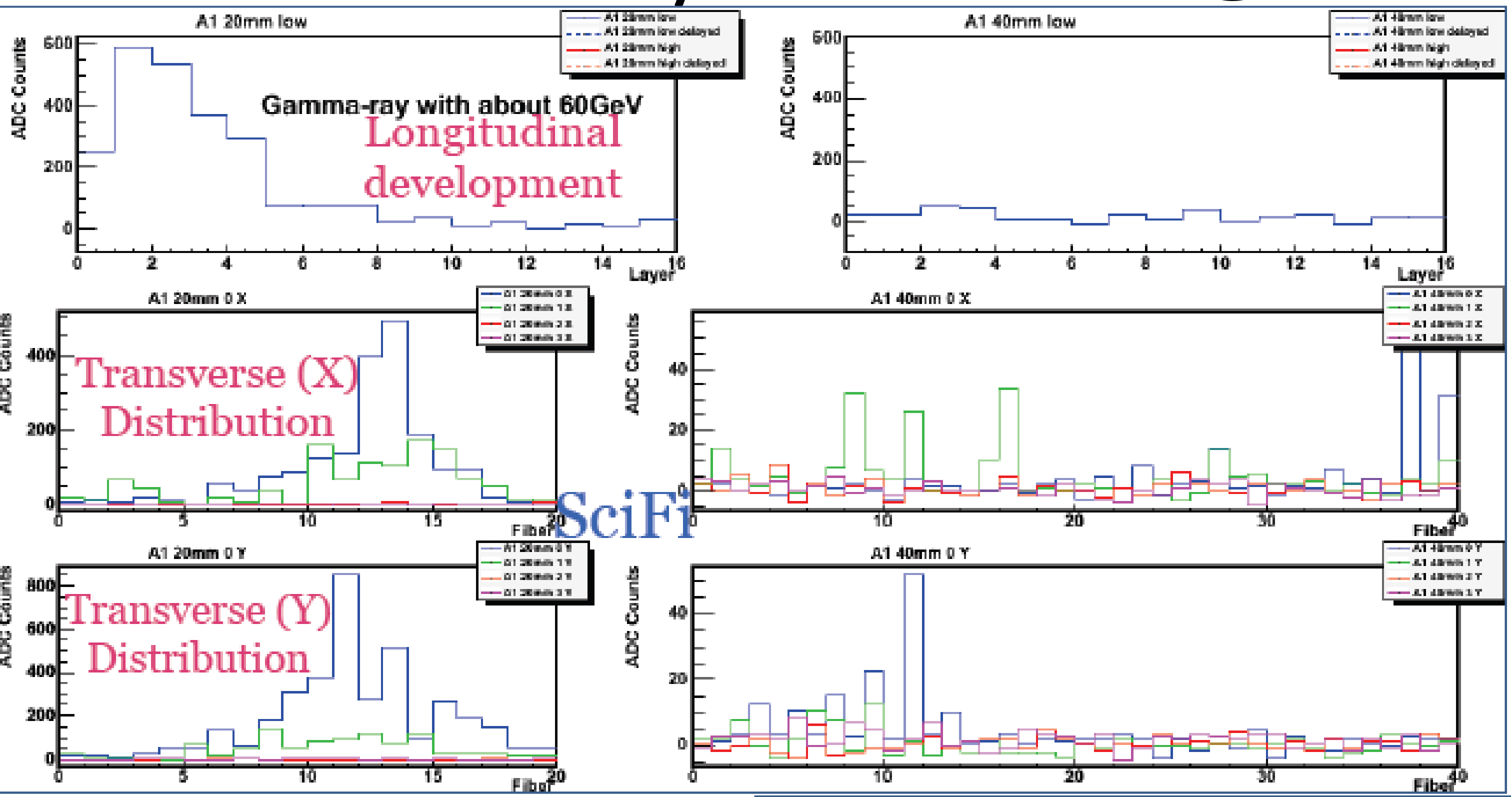
Arm2 detector: all runs with zero crossing angle

True η Mass:	547.9 MeV	
MC Reconstructed η Mass peak:	548.5 ± 1.0 MeV	
Data Reconstructed η Mass peak:	**562.2 ± 1.8 MeV**	**(2.6% shift)**

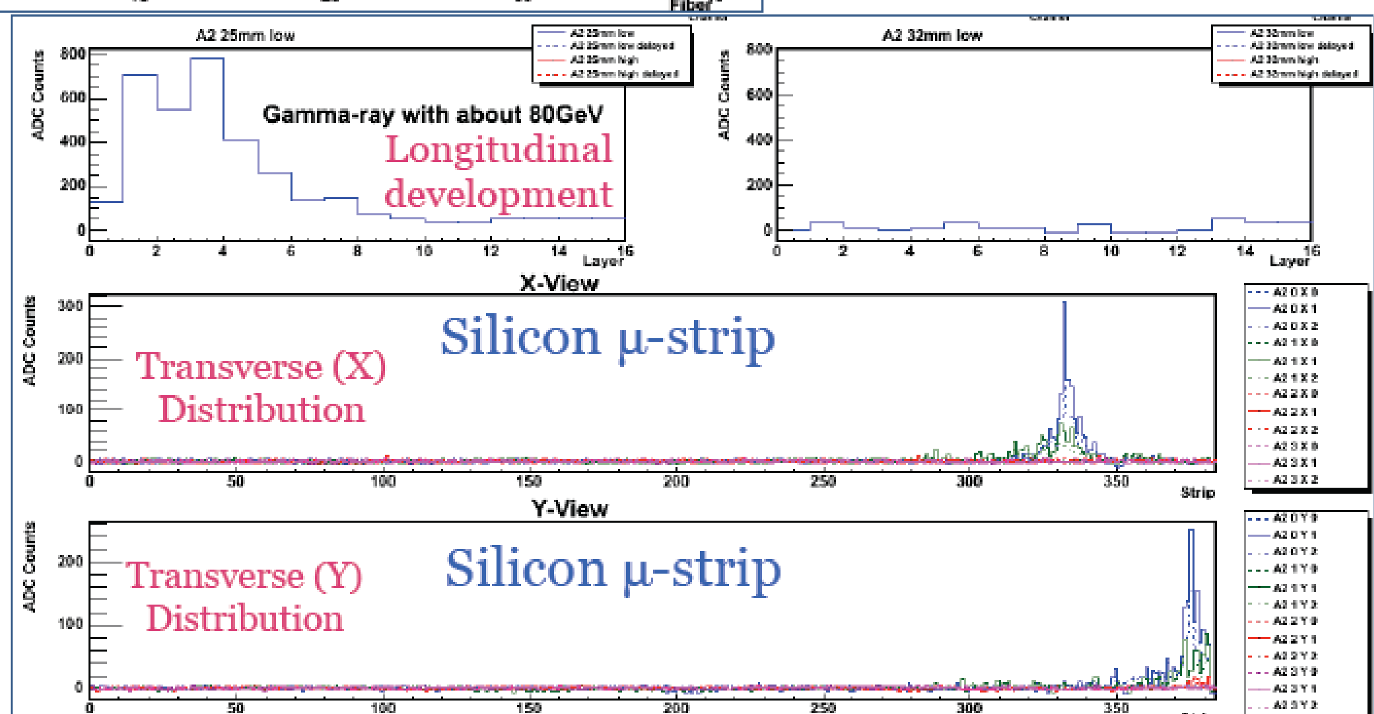




Analysis of events @ 900 GeV

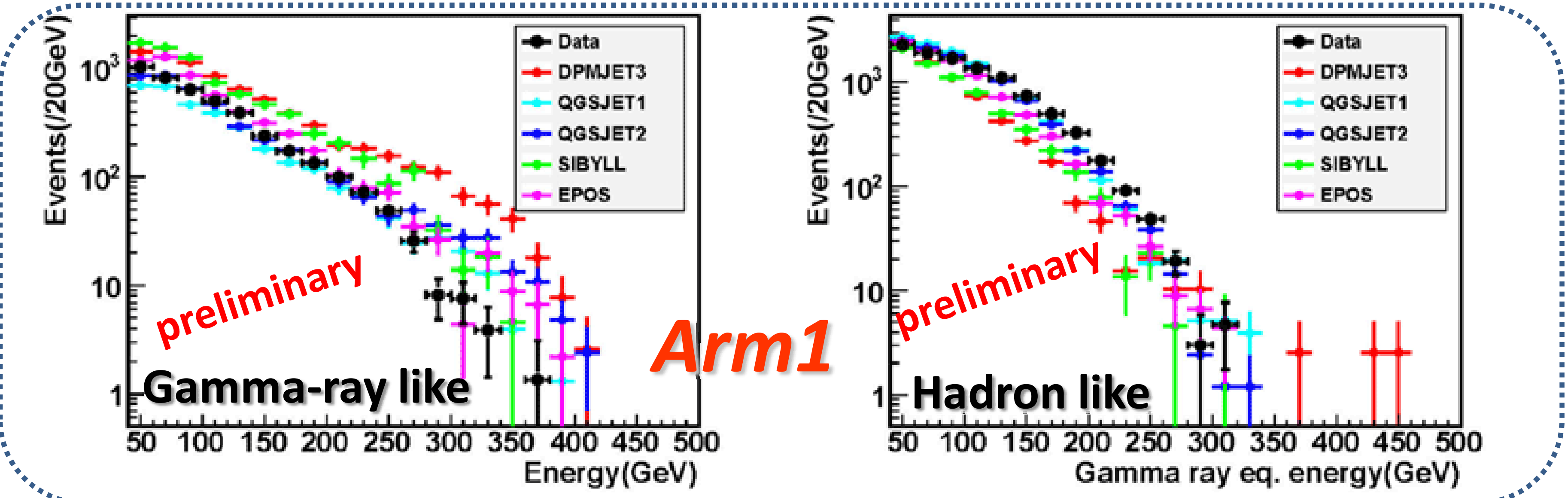


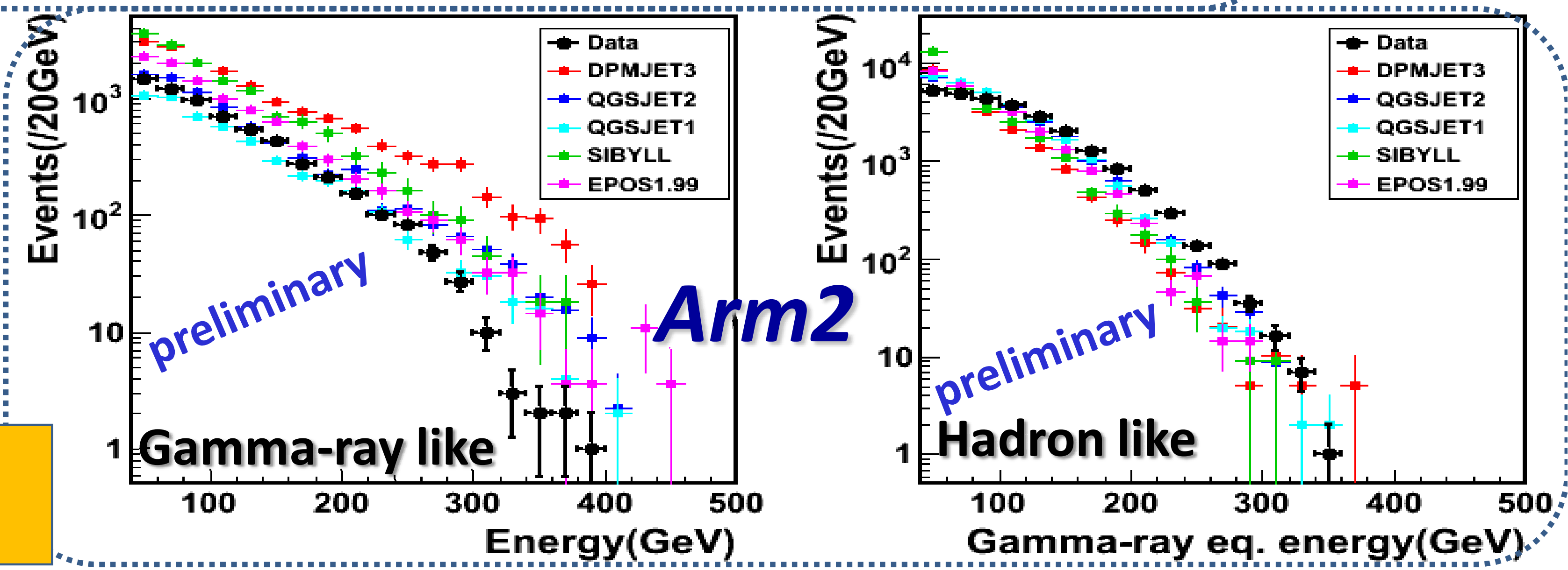
Event sample @ Arm1



Event sample @ Arm2

Spectra @ 900GeV



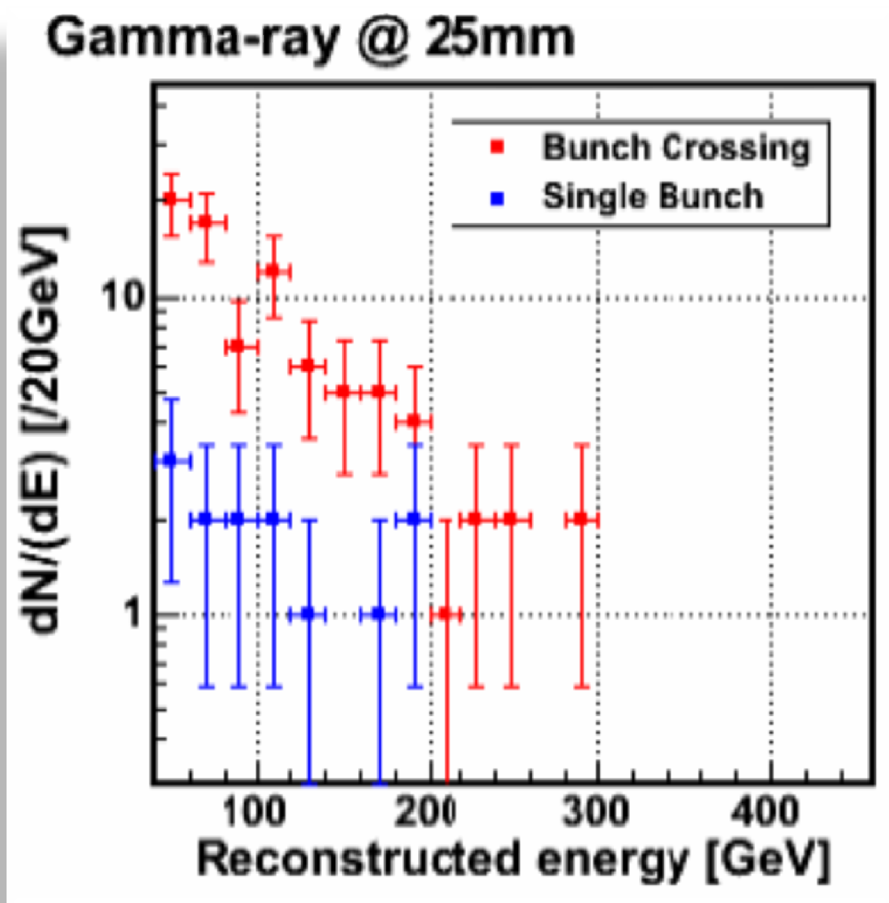


Only statistical errors are shown

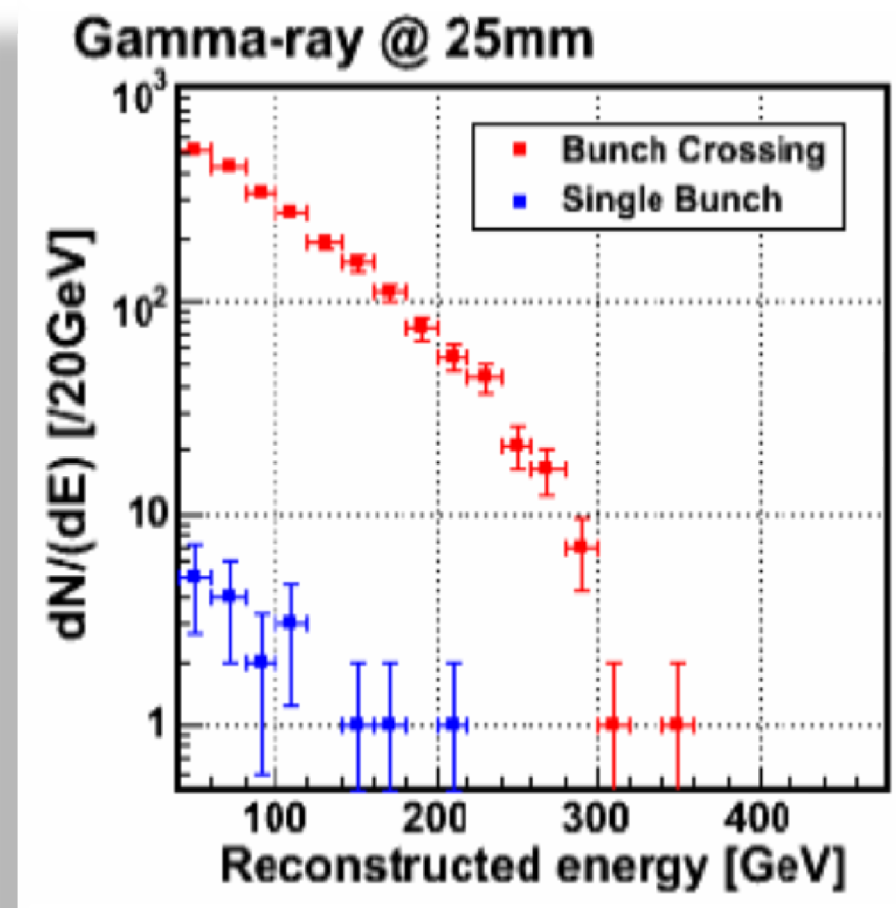
Spectra are normalized by # of gamma-ray and hadron like events. Response for hadrons and systematic errors (mainly absolute energy scale) are under study.

Beam-gas backgroud @ 900 GeV

2009



2010

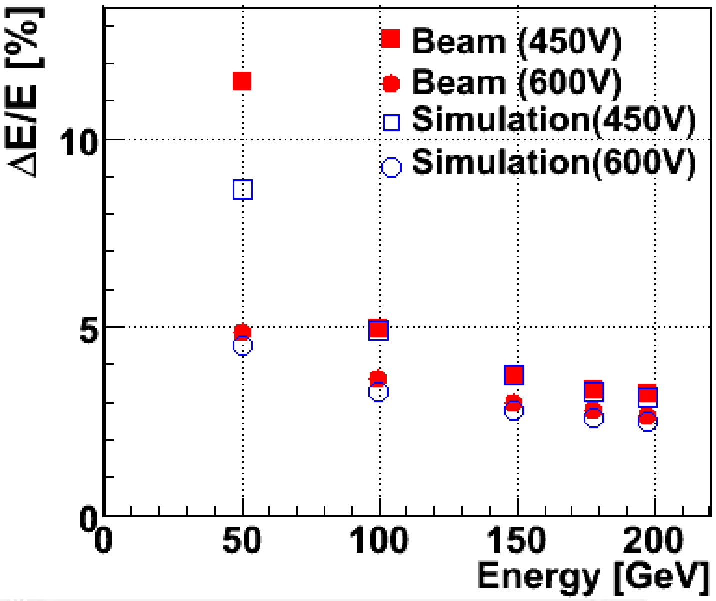


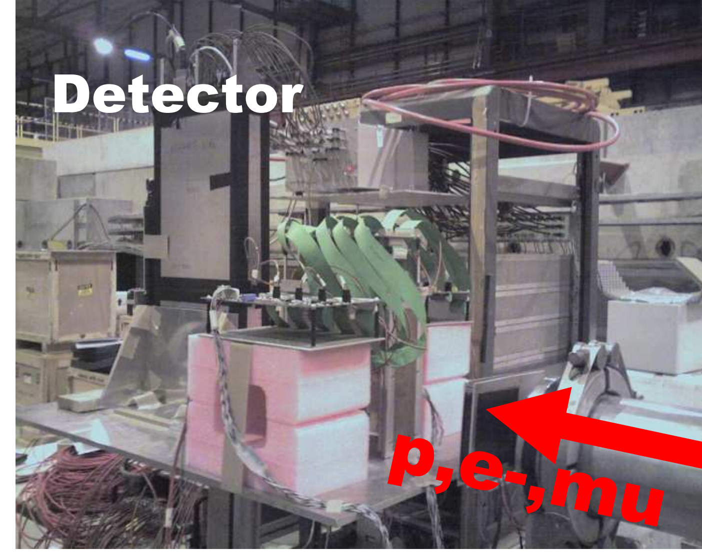
Very big reduction in the Beam Gas contribution!!!!

Beam gas ~ I, while interactions ~ I^2

Beam test @ SPS

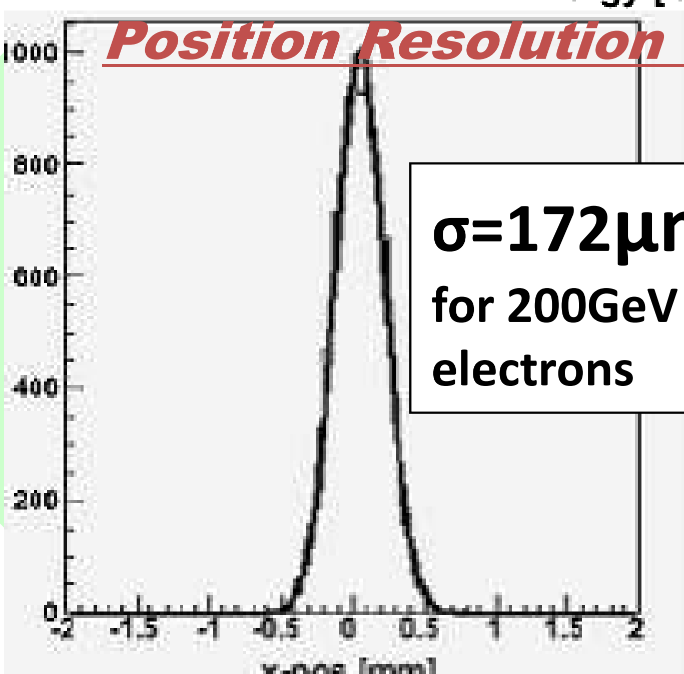
Energy Resolution for electrons with 20mm cal.



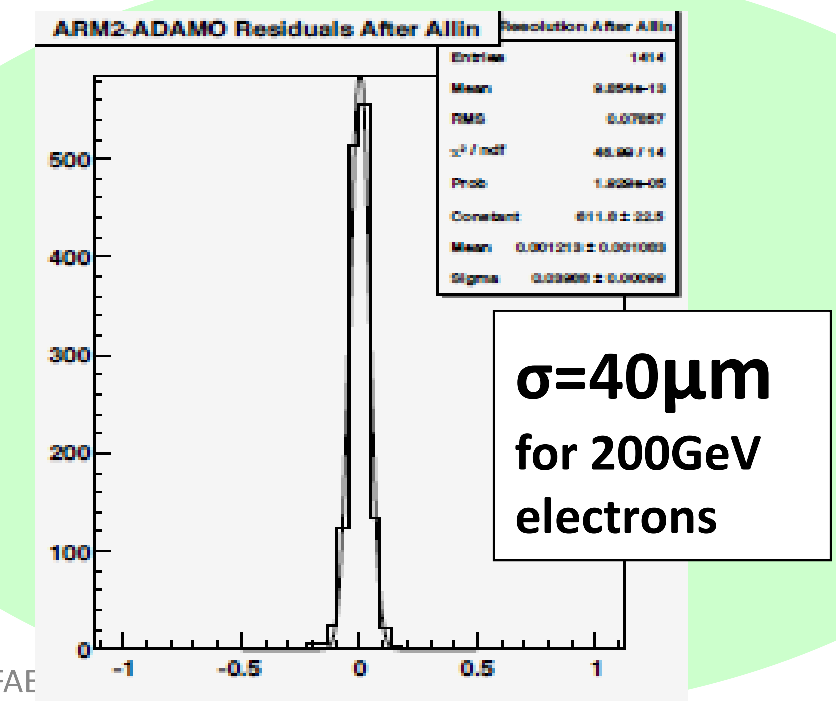


- Electrons 50GeV/c – 200GeV/c
- Muons 150GeV/c
- Protons 150GeV/c, 350GeV/c

Position Resolution (Scifi)

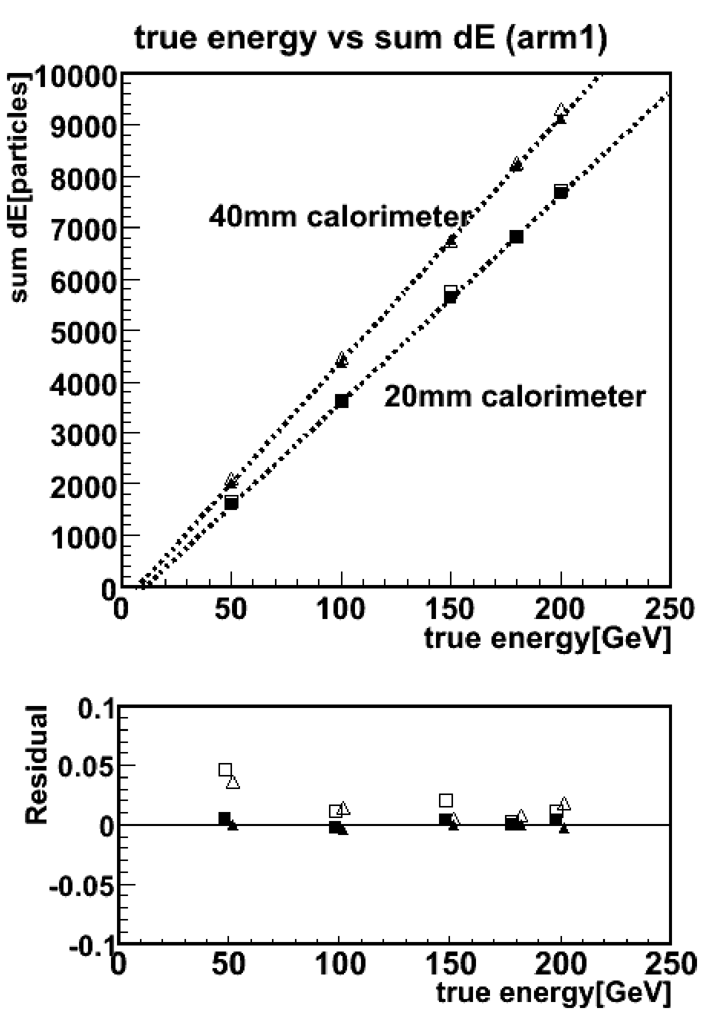


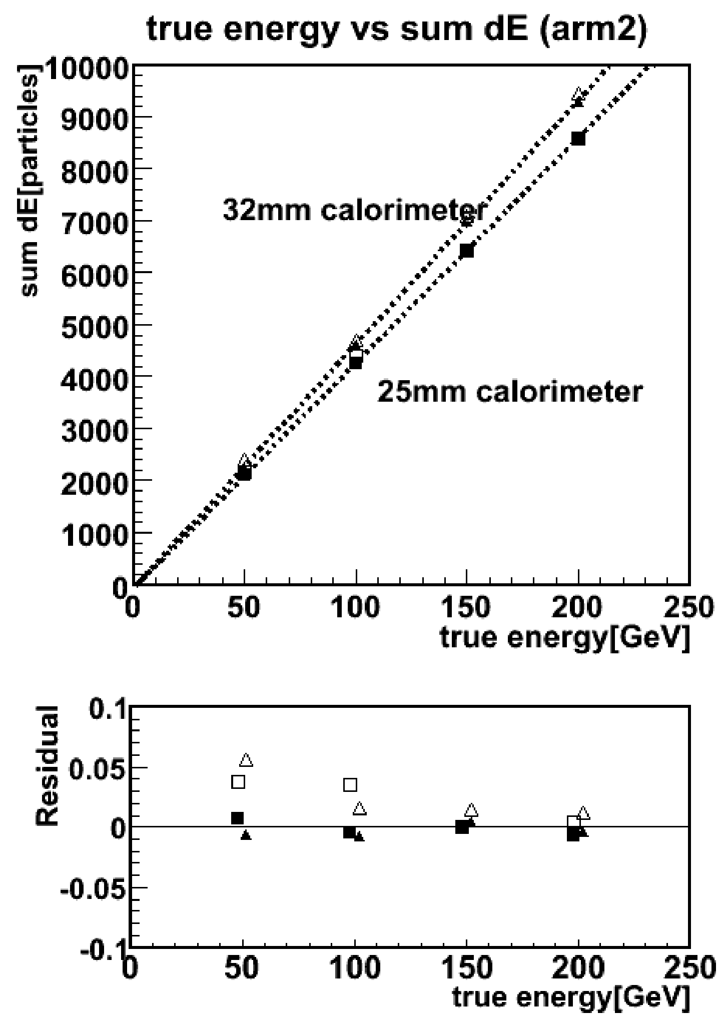
Position Resolution (Silicon)



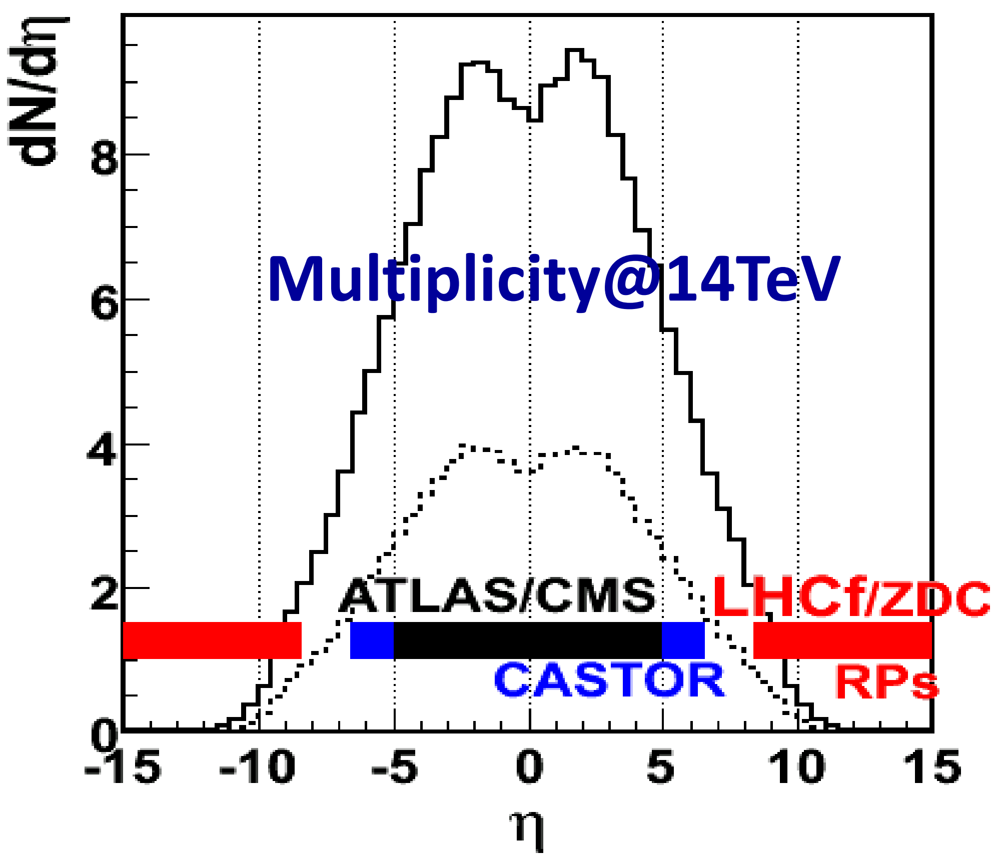
Energy reconstruction @ SPS

Difference of energy reconstruction at SPS between data and MC is < 1%.
Systematic error for gain calibration factor layer by layer is 2%

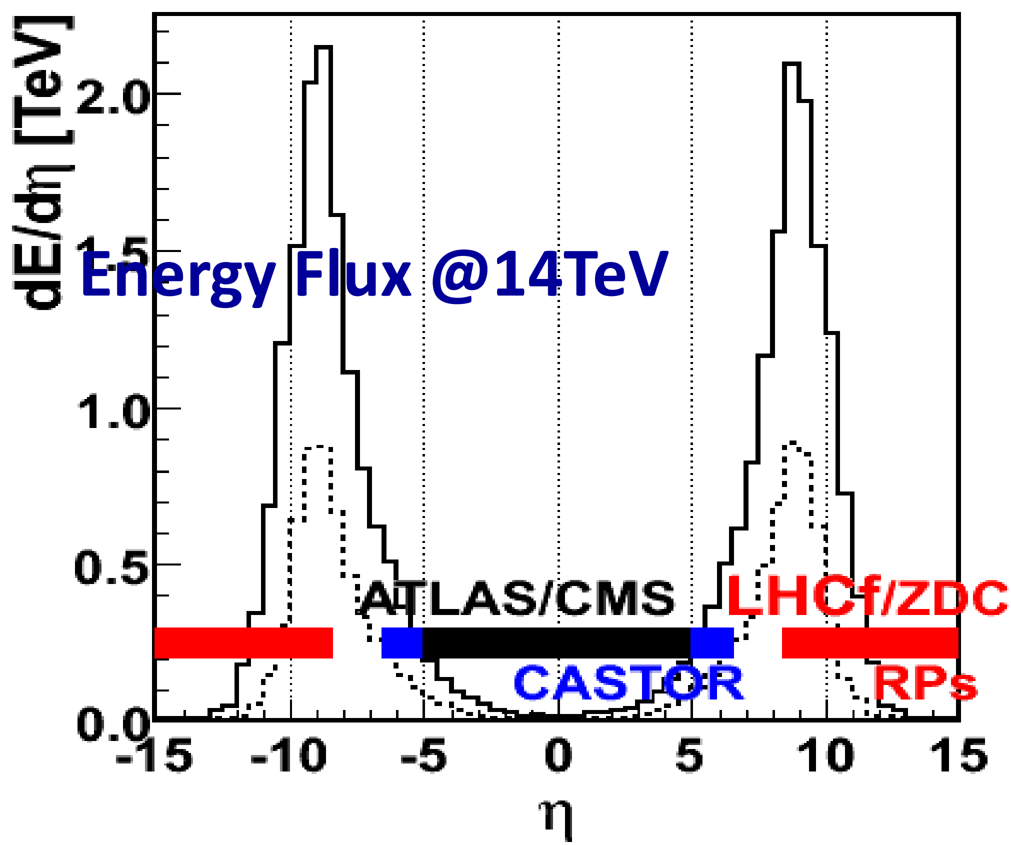




Particle and energy flow vs rapidity



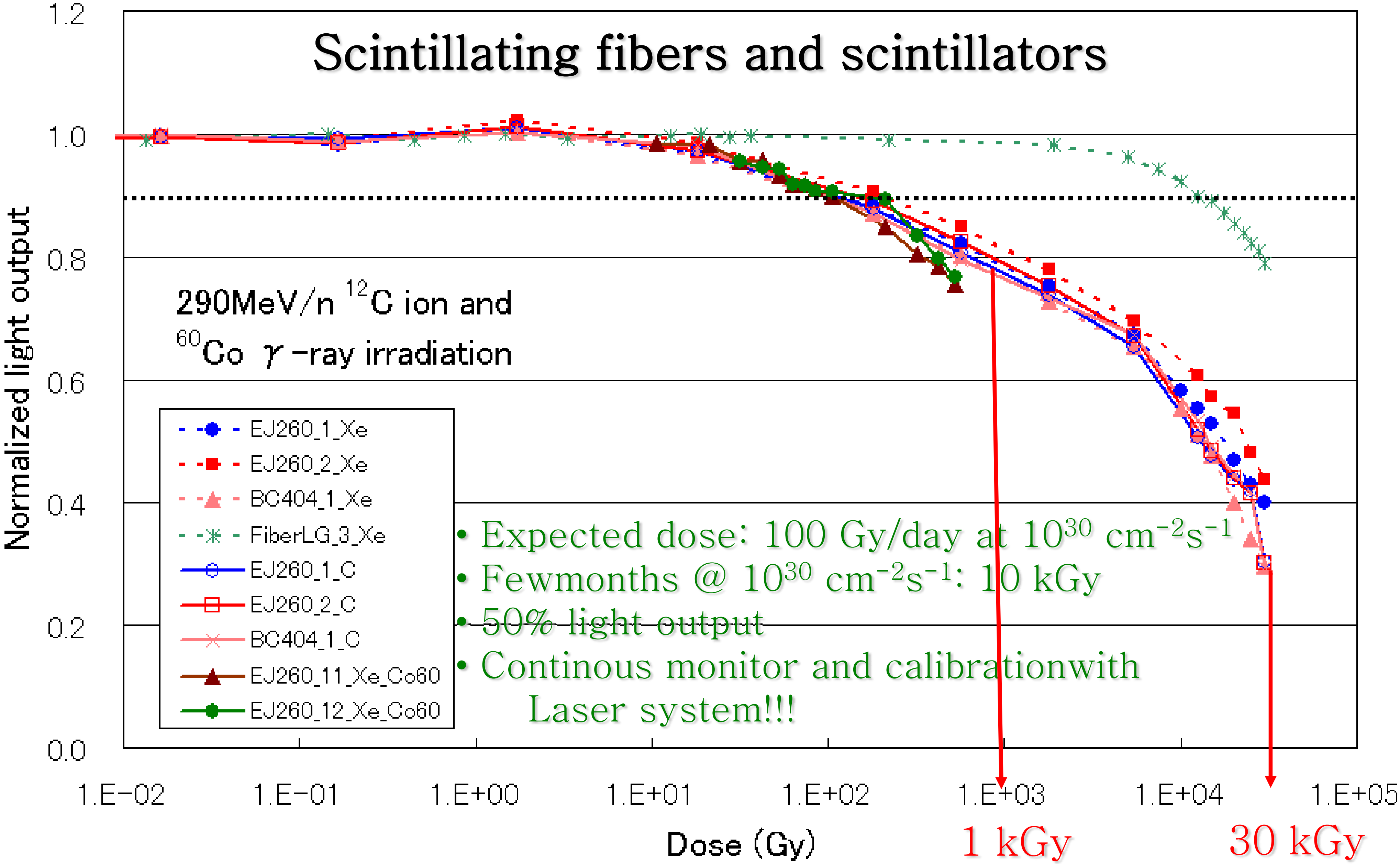
Low multiplicity !!



High energy flux !!

simulated by DPMJET3

Radiation damage



- Expected dose: 100 Gy/day at 10^{30} cm^{-2}s^{-1}
- Fewmonths @ 10^{30} cm^{-2}s^{-1}: 10 kGy
- ~~50% light output~~
- Continous monitor and calibrationwith Laser system!!!

Uncertainty on the energy scale

- Two components:
  - Relatively well known: Detector response, SPS => 3.5%
  - Unknown: π^0 mass => 7.8%, 3.8% for Arm1 and Arm2.
- Please note:
- - 3.5% is symmetric around measured energy
- - 7.8% (3.8%) are asymmetric, because of the π^0 mass shift
- - No 'hand made' correction is applied up to now for safety
- Total uncertainty is

  -9.8% / +1.8% for Arm1

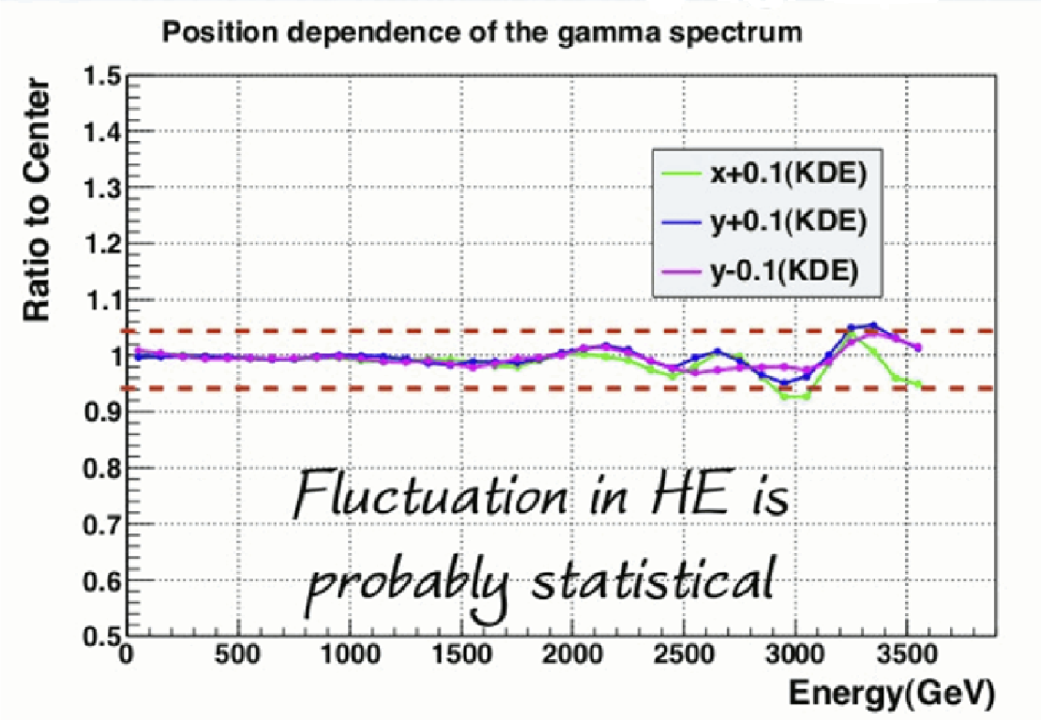
  -6.6% / +2.2% for Arm2

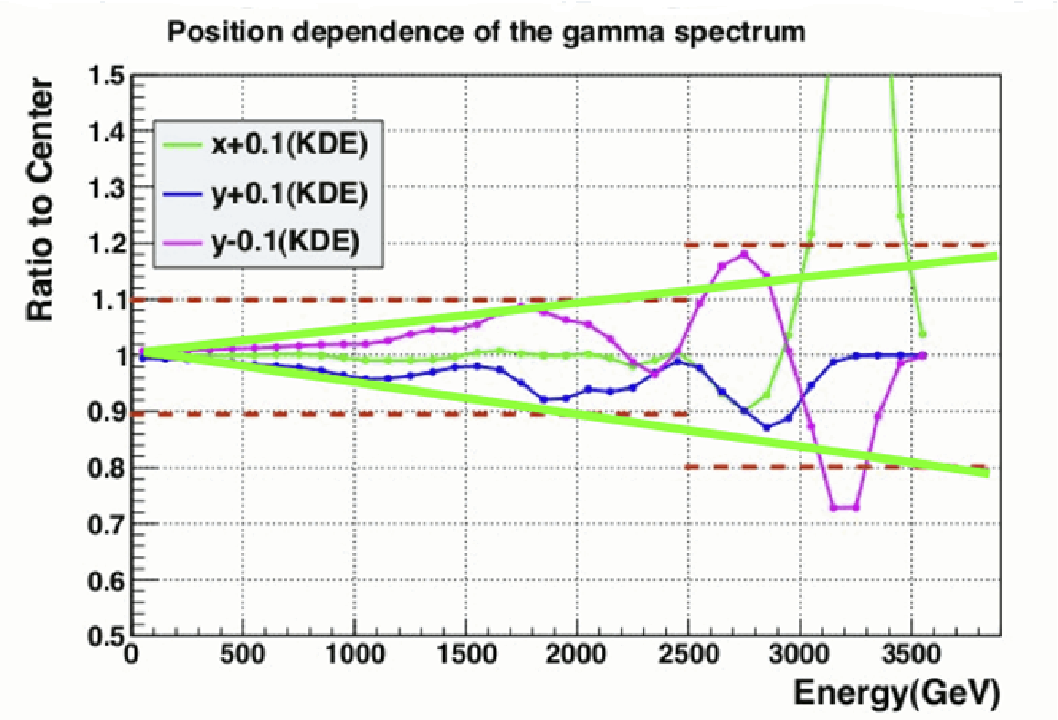
Systematic Uncertainty on Spectra is estimated from difference between normal spectra and energy shifted spectra.

Uncertainty on the beam center

- Error of beam center position is estimated to be 1 mm from comparison between our results and the BPM results
- The systematic errors on spectra were estimated from the difference between spectra with 1 mm shift of acceptance cut area.

Arm1 Results - true single gamma events



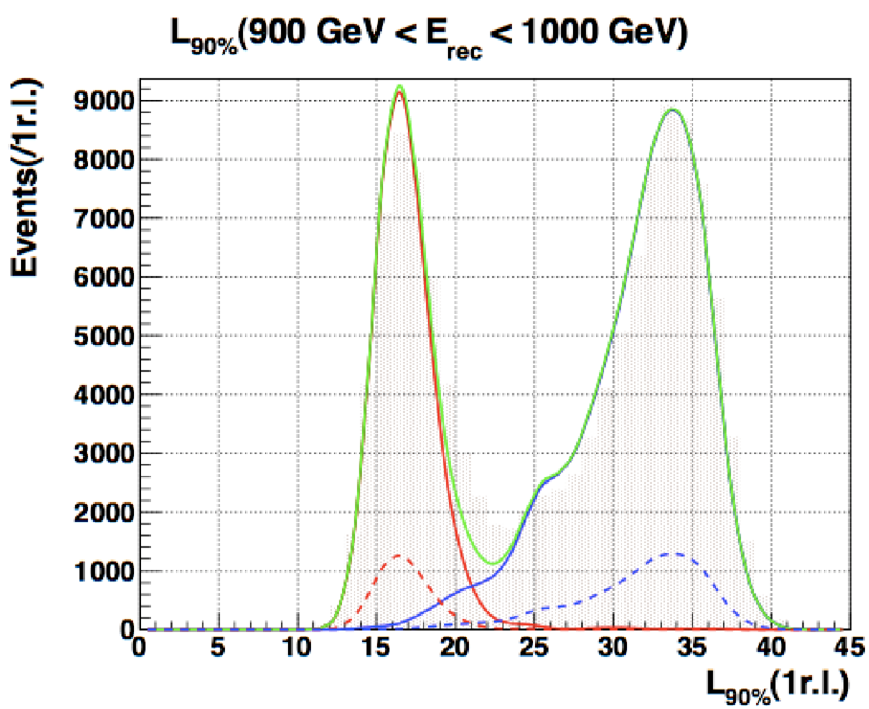


100 GeV<E<3.5 TeV : 5%

5% to 20% linear rise from 100 GeV to 3.6 TeV

Uncertainty from PID

Efficiency and purity are estimated with two different approaches



Template fitting A:
1 degree of freedom:
- Absolute normalization

Template fitting B:
3 degrees of freedom:
- Absolute normalization
- Shift of L90% distribution
- Width of L90% distribution

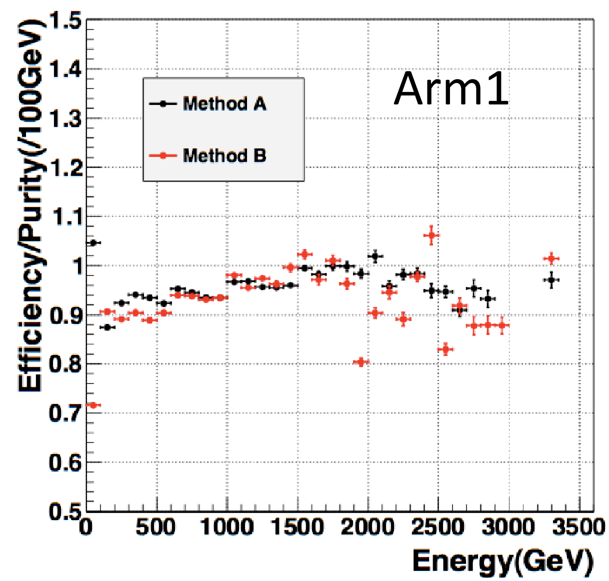
Hatched : data
Red : true-gamma
Blue : true-hadron
Green : Red+Blue

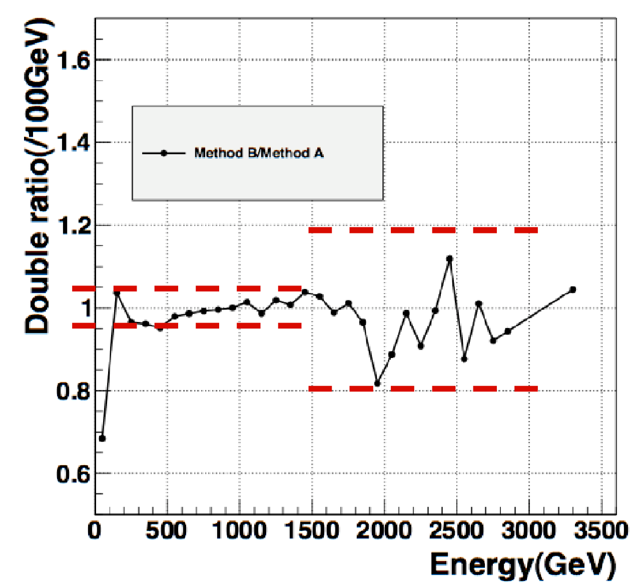
Systematic error from PID are assumed:

5% for 100GeV < E < 1.7TeV

20% for E > 1.7TeV

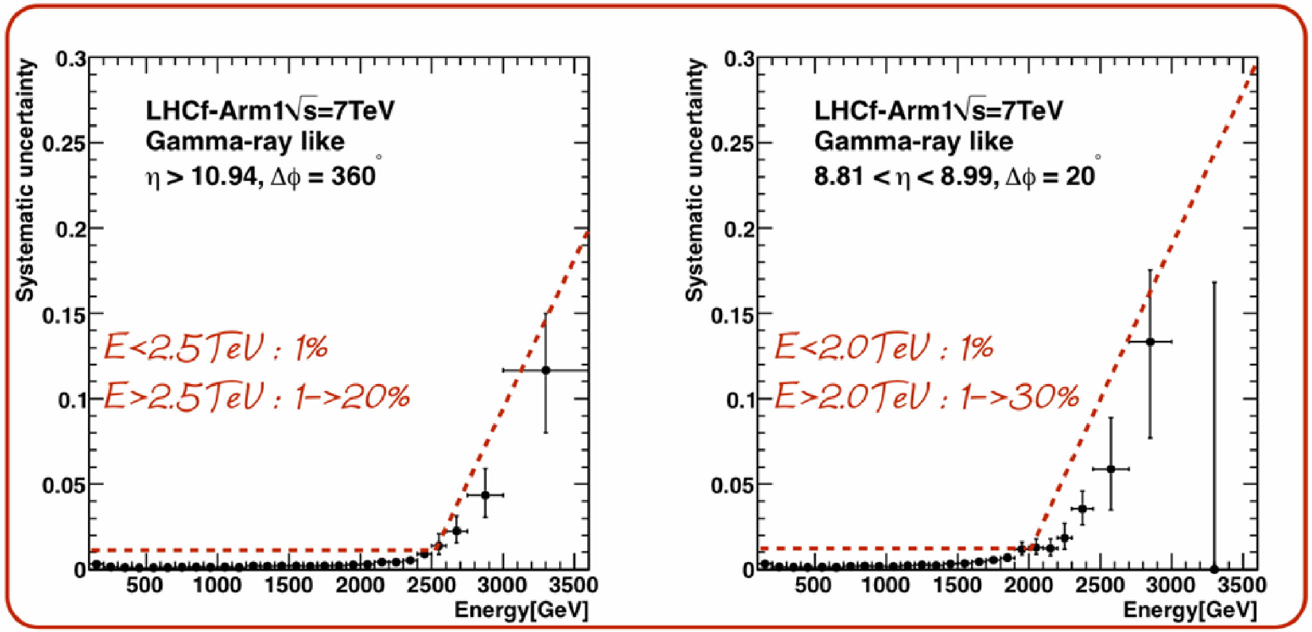
Both on small and large tower





Uncertainty from Multiple Hit corrections

ARM1



ARM2