The LHCf experiment: physics results and future perspectives

Alessia Tricomi
University of Catania & INFN Catania
On behalf of the LHCf Collaboration

- Forward photon energy spectrum at $\sqrt{s}$ = 7 TeV p-p collisions
- Prospects for new analyses
- Detector upgrade

EPS-HEP 2011 Grenoble, 21-27 July 2011

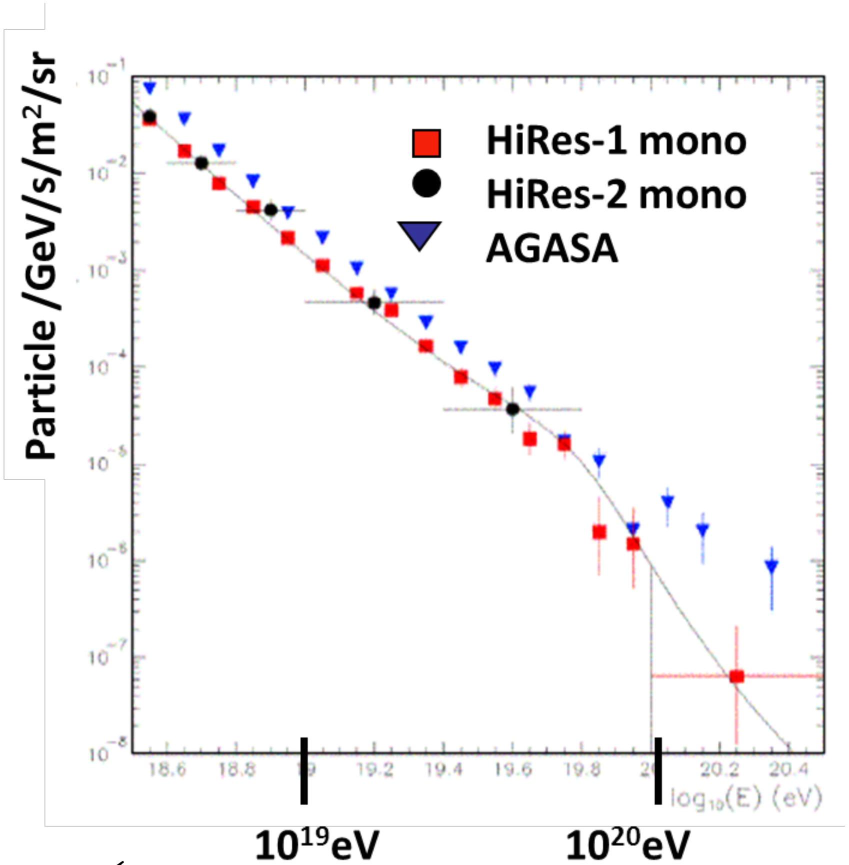
Physics motivations

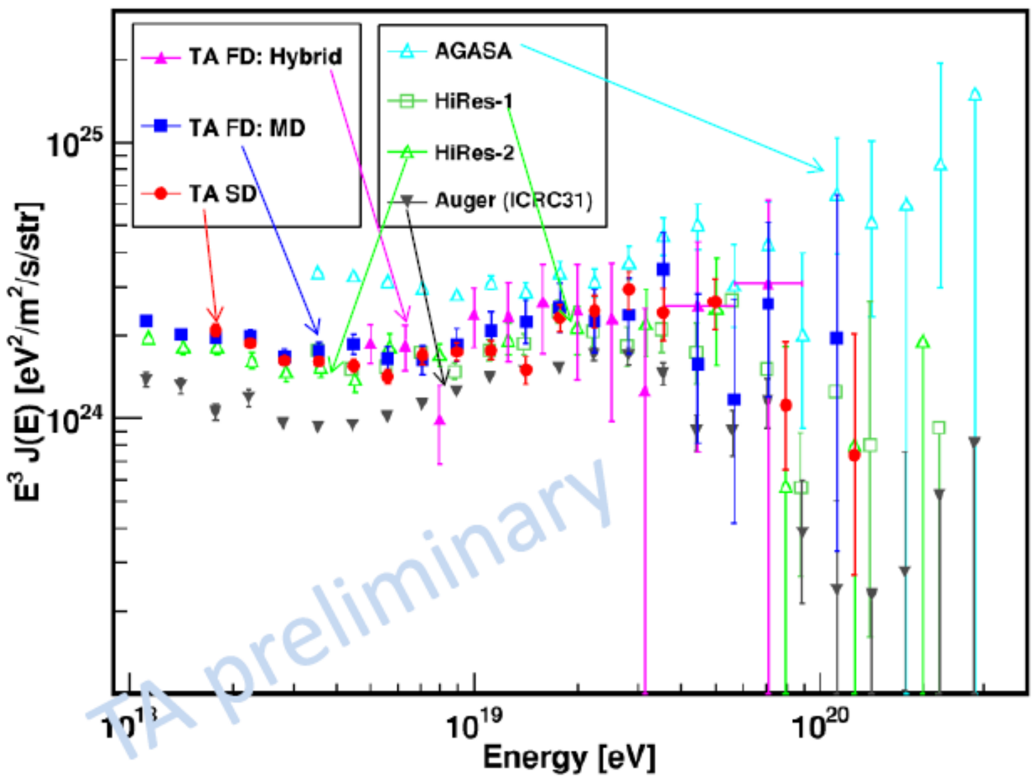
Impact on HECR physics

Alessia Tricomi

EPS-HEP 2011, Grenoble, 21-27 July 2011

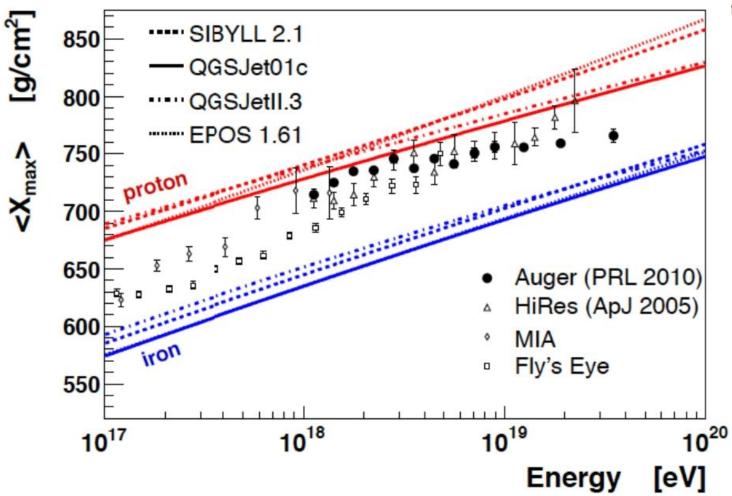
UHECR OBSERVATIONS (10 YEARS AGO AND NOW)

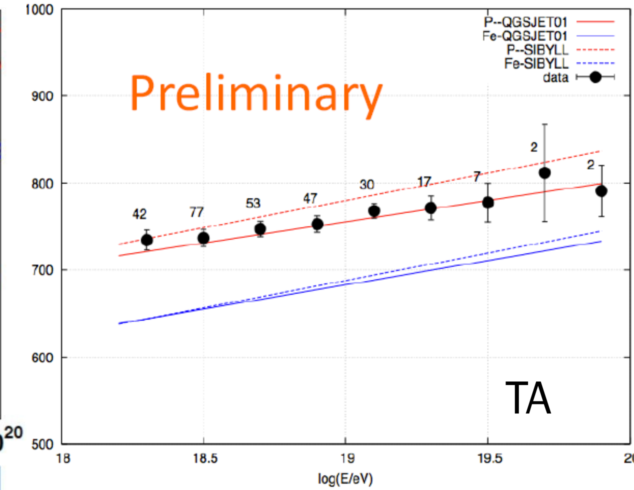


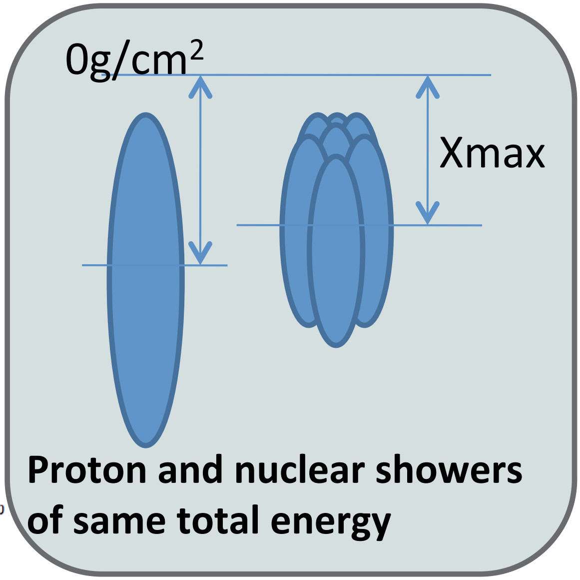


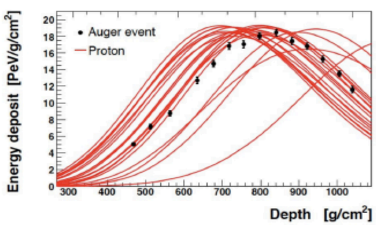
- ✓ Debate in AGASA, HiRes results in 10 years ago
- ✓ Now Auger, HiRes (final), TA indicate cutoff
- ✓ Absolute values differ between experiments and between methods

ESTIMATE OF PARTICLE TYPE (X_{MAX})



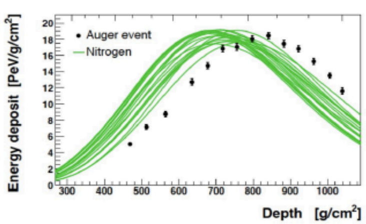


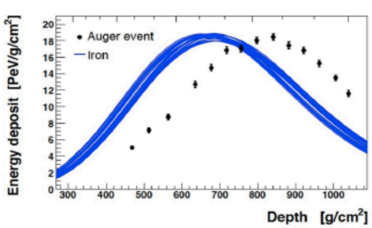




$$E \simeq 10^{20}\ \mathrm{eV}$$

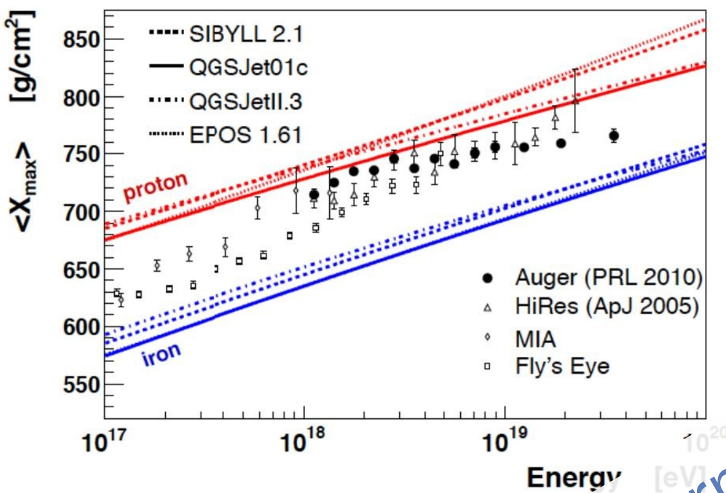
Courtesy P. LIPARI

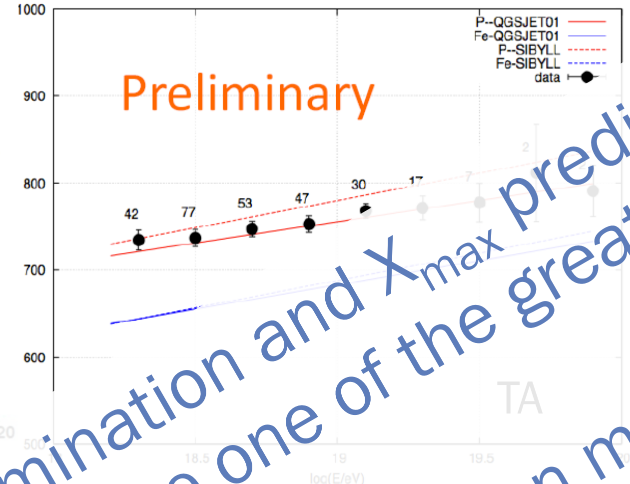


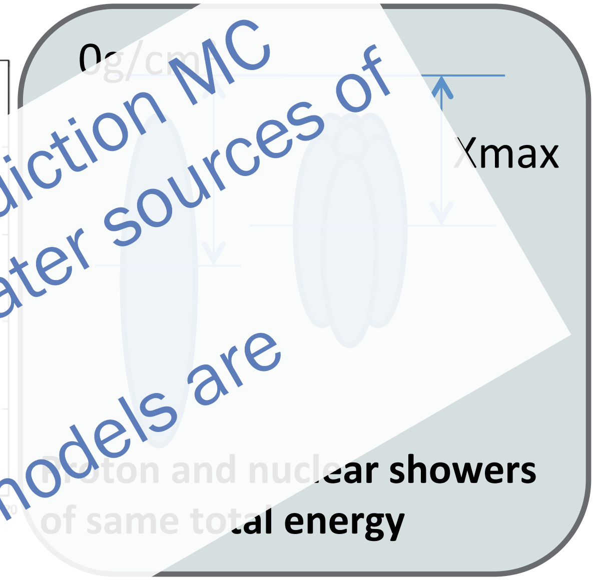


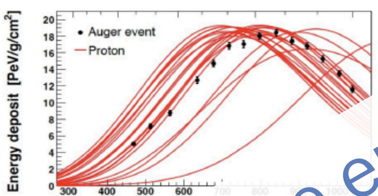
- ✓ X_{max} gives information on the primary particle
- ✓ Results are different between experiments
- ✓ Interpretation relies on the MC prediction and has quite strong model dependence

ESTIMATE OF PARTICLE TYPE (X_{MAX})









Courtesy P. LIPARI

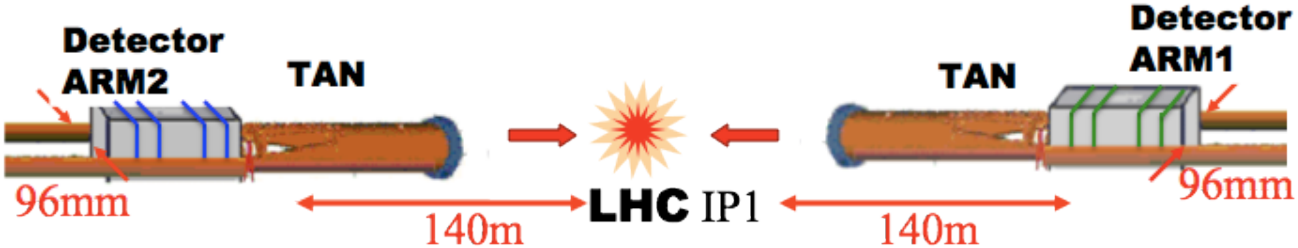
Both in the energy determination and X_{max} prediction MC simulations are used, and are one of the greater sources of uncertainty. Experimental tests of hadron interaction models are necessary! → LHCf

- X_{max} gives information on the primary particle
- Results are different between experiments
- Interpretation relies on the MC prediction and has quite strong model dependence

LHCf @ LHC

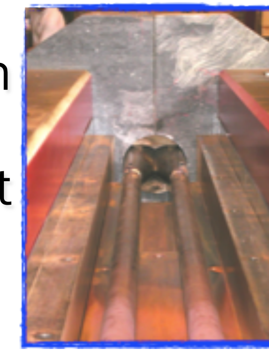
ALESSIA TRICOMI EPS-HEP 2011, GRENOBLE, 21-27 JULY 2011

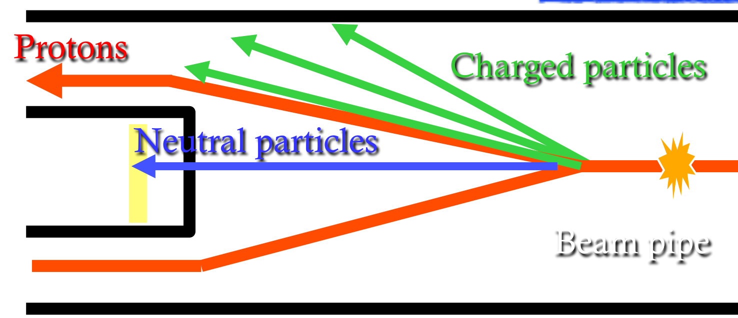
LHCf experimental set-up



Detectors installed in the TAN region, 140 m away from ATLAS Interaction Point (IP1)

- Here the beam pipe splits in 2 separate tubes.
- Charged particle are swept away by magnets
- We cover $|\eta|>8$





Front Counters: thin scintillators with $8x8cm^2$ acceptance installed in front of each main detector

ARM1 & ARM2 Detectors

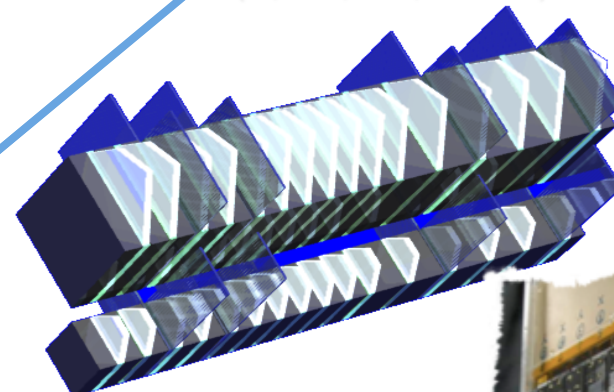
ARM1

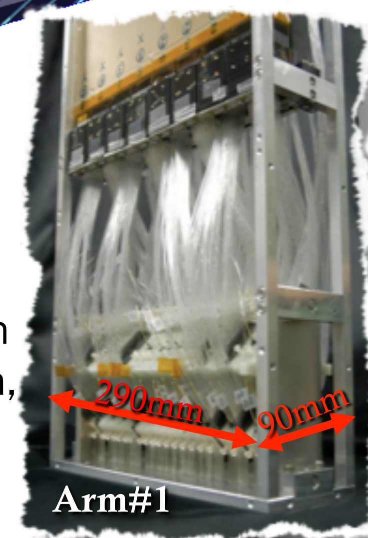
2 towers 24 cm long stacked vertically with 5 mm gap

Lower: 2 cm x 2 cm area

Upper: 4 cm x 4 cm area

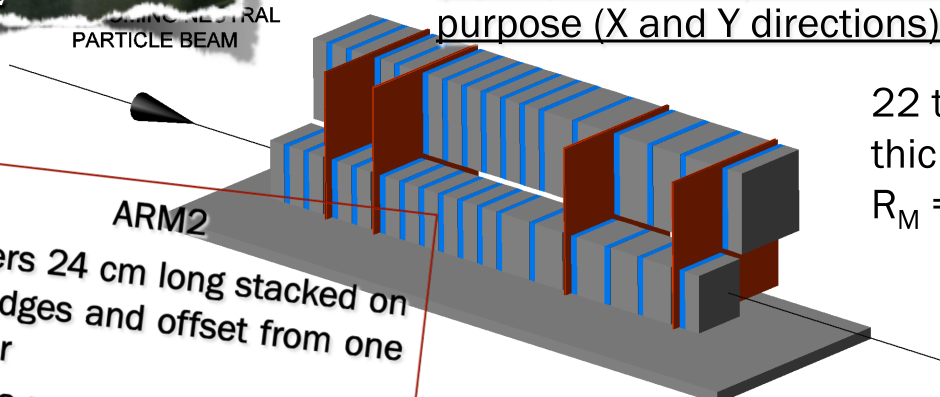
4 pairs of scintillating fiber layers for tracking purpose (6, 10, 32, 38 r.l.)





Impact point (η)

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



ARM2

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

Absorber

22 tungsten layers 7– 14 mm thick (2-4 r.l.) (W: X_0 = 3.5mm, R_M = 9mm)

Energy

16 scintillator layers (3 mm thick)

Trigger and energy profile measurements

Expected Performance

Energy resolution (> 100GeV)

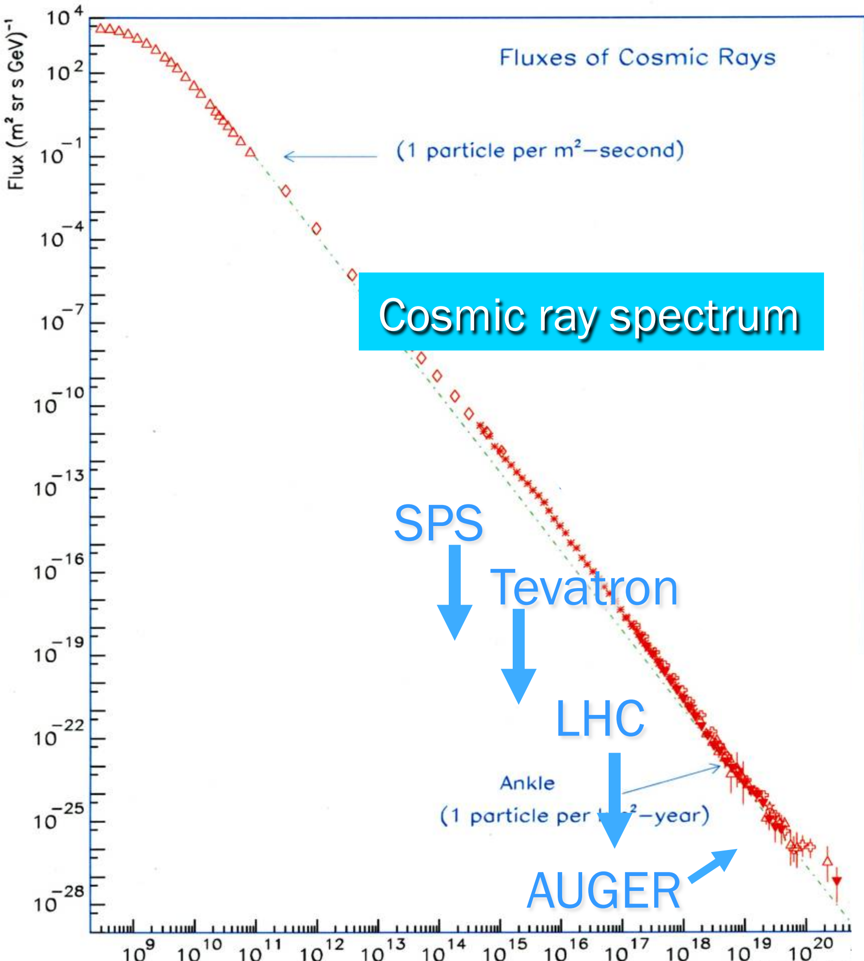
< 5% for γ & π^0, 30% for neutrons

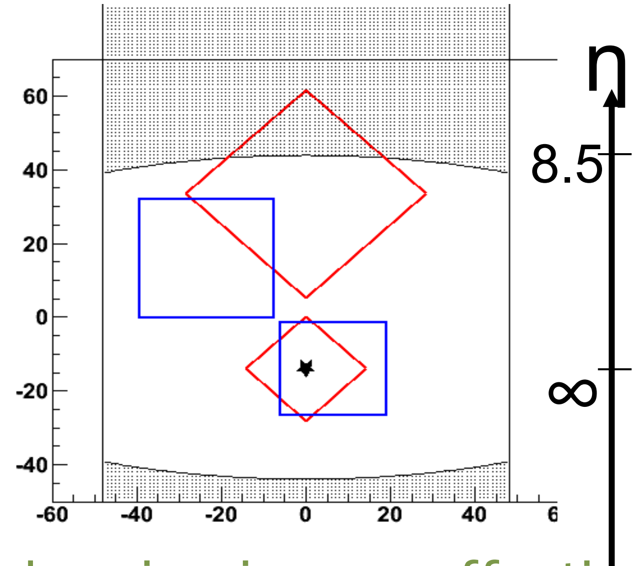
Position resolution

< 200μm (Arm#1), 40μm (Arm#2)

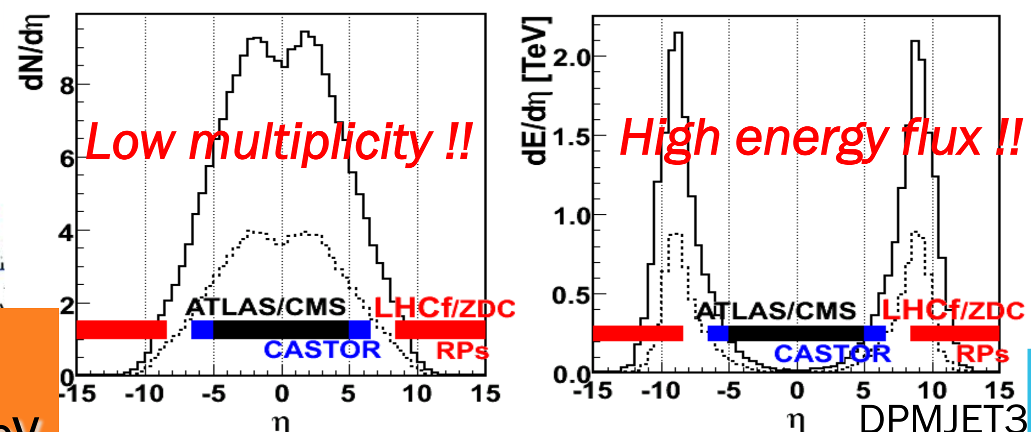
HOW LHCF CAN CONTRIBUTE?

LHC gives us the unique opportunity to measure hadronic interactions at 10^{17}eV





➔ Forward region is very effective on air shower development.



7TeV+7TeV	$\longrightarrow E_{lab} = 10^{17}$eV
3.5TeV+3.5TeV	$\longrightarrow E_{lab} = 2.6\times10^{16}$eV
450GeV+450GeV	$\longrightarrow E_{lab} = 2\times10^{14}$eV

LHCf operations @900 GeV & 7 TeV

With Stable Beam at 900 GeV Dec 6th – Dec 15th 2009

With Stable Beam at 900 GeV May 2nd – May 27th 2010

	Shower	Gamma	Hadron
Arm1	46,800	4,100	11,527
Arm2	66,700	6,158	26,094

With Stable Beam at 7 TeV March 30th - July 19th 2010

We took data with and without 100 μrad crossing angle for different vertical detector positions

	Shower	Gamma	Hadron	π^0
Arm1	172,263,255	56,846,874	111,971,115	344,526
Arm2	160,587,306	52,993,810	104,381,748	676,157

INCLUSIVE PHOTON SPECTRUM ANALYSIS

LHCF DATA TAKING

PAPER ACCEPTED FOR PUBLICATION ON PLB

"MEASUREMENT OF ZERO DEGREE SINGLE PHOTON ENERGY SPECTRA FOR $\sqrt{s}$ = 7 TEV PROTON-PROTON COLLISIONS AT LHC"

ARXIV:1104.5294

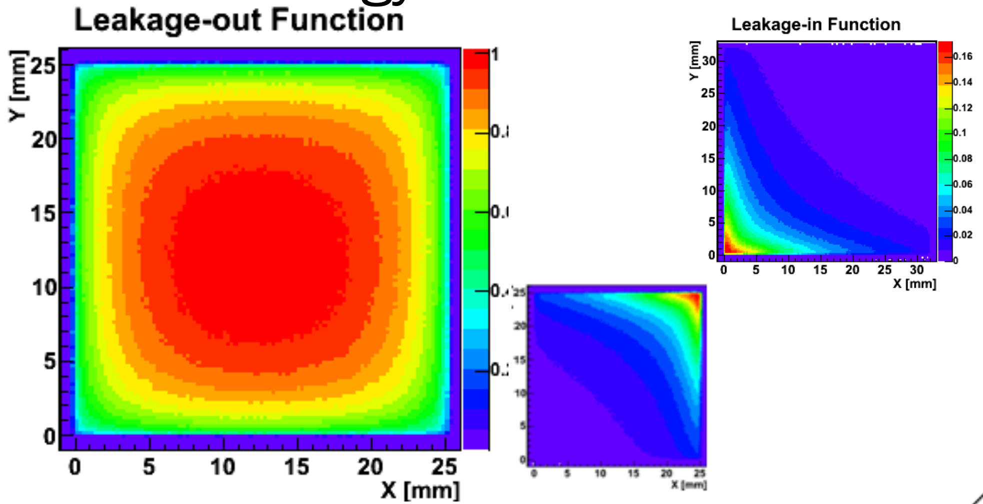
CERN-PH-EP-2011-061

Data set for inclusive photon spectrum analysis

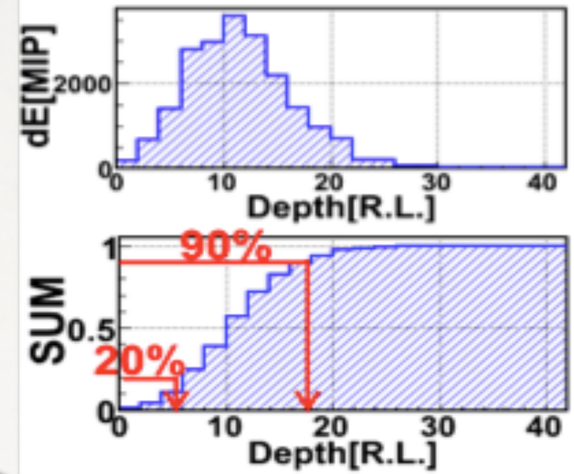
- Data
  - Date : 15 May 2010 17:45-21:23 (Fill Number : 1104) except runs during the luminosity scan.
  - Luminosity : (6.5-6.3)x$10^{28}cm^{-2}s^{-1}$,
  - DAQ Live Time : 85.7% for Arm1, 67.0% for Arm2
  - Integrated Luminosity : 0.68 nb^{-1} for Arm1, 0.53nb^{-1} for Arm2
  - Number of triggers : 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 PYTHIA8.145: about 10^7 pp inelastic collisions each

ANALYSIS WORKFLOW

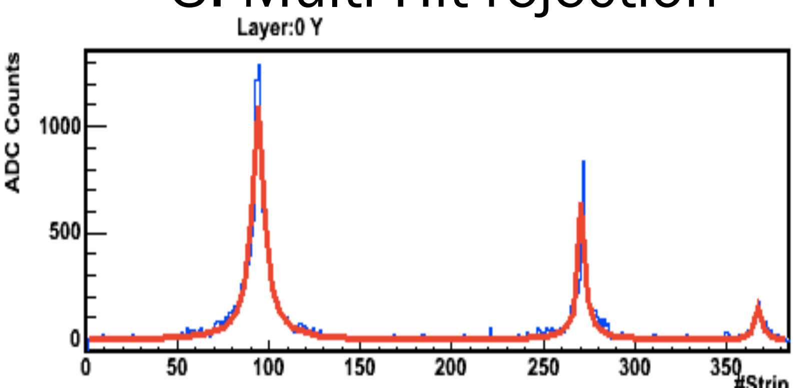
1. Energy Reconstruction

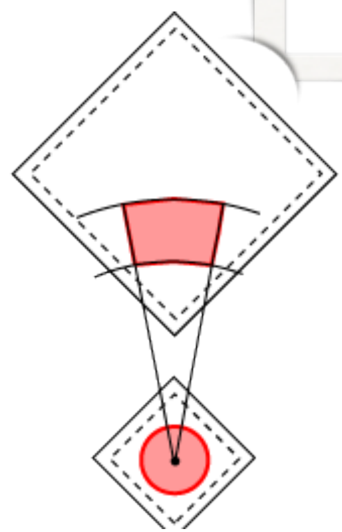


2. PID

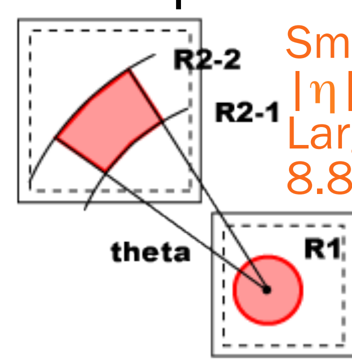


3. Multi-Hit rejection





4. Acceptance cut

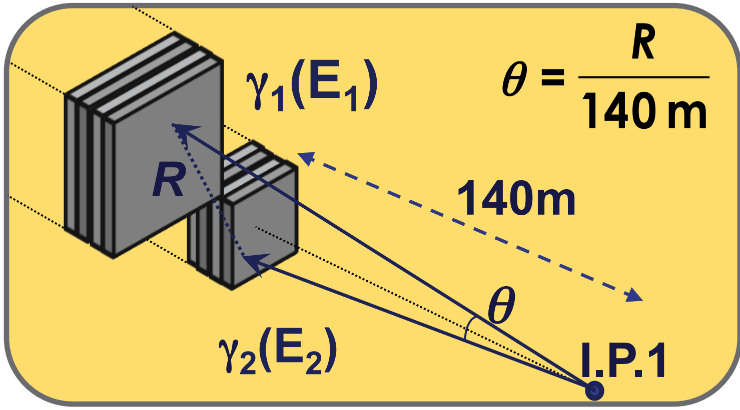


Small Tower
$|\eta| > 10.94$
Large Tower
$8.81 < |\eta| < 8.99$

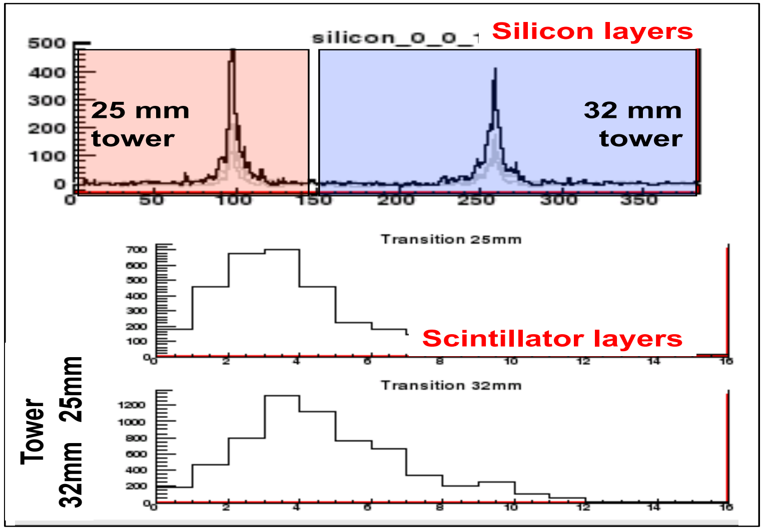
SYSTEMATIC UNCERTAINTIES

Main systematic uncertainty due to energy scale

- ✓Energy scale can be checked by π^0 identification from two tower events.
- ✓Mass shift observed both in Arm1 (+7.8%) and Arm2 (+3.7%)
- ✓**No energy scaling** applied, but shifts assigned in the systematic error in energy



$$M = \theta\sqrt{(E_1 x E_2)}$$



Uncorrelated uncertainties between ARM1 and ARM2

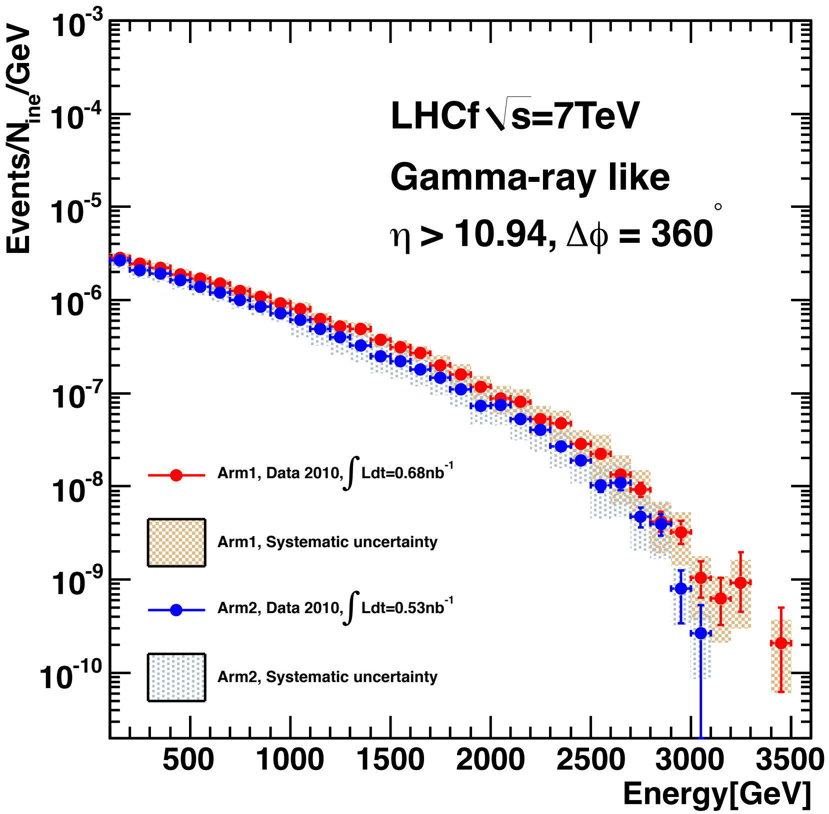
- Energy scale (except π^0 error)
- Beam center position
- PID
- Multi-hit selection

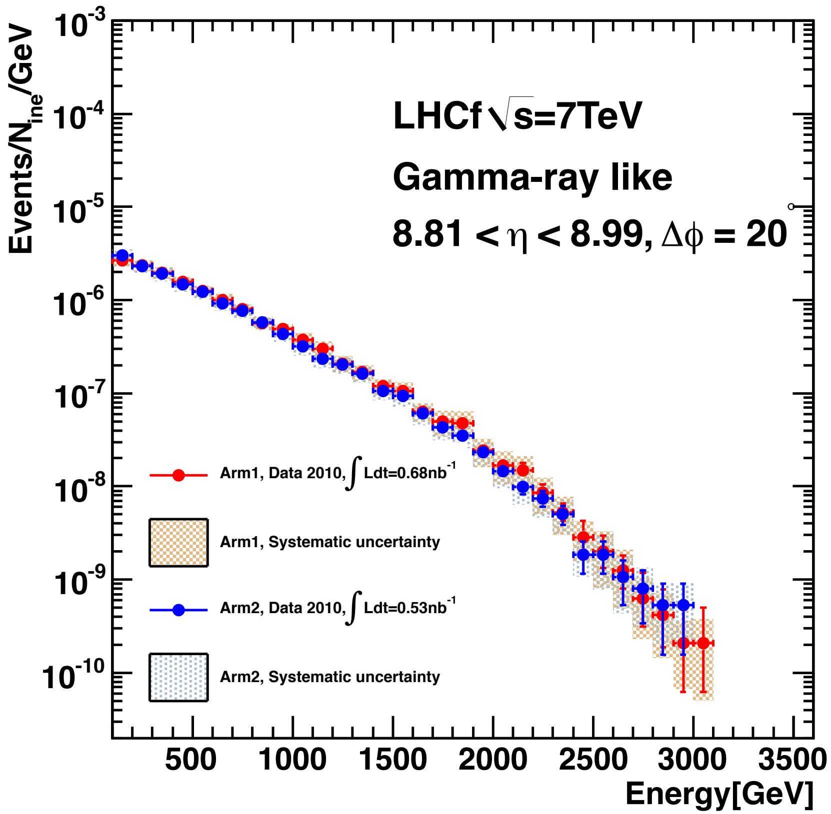
Correlated uncertainty

- Energy scale (π^0 error)
- Luminosity error

RESULTS

COMPARISON OF ARM1 AND ARM2 SPECTRA





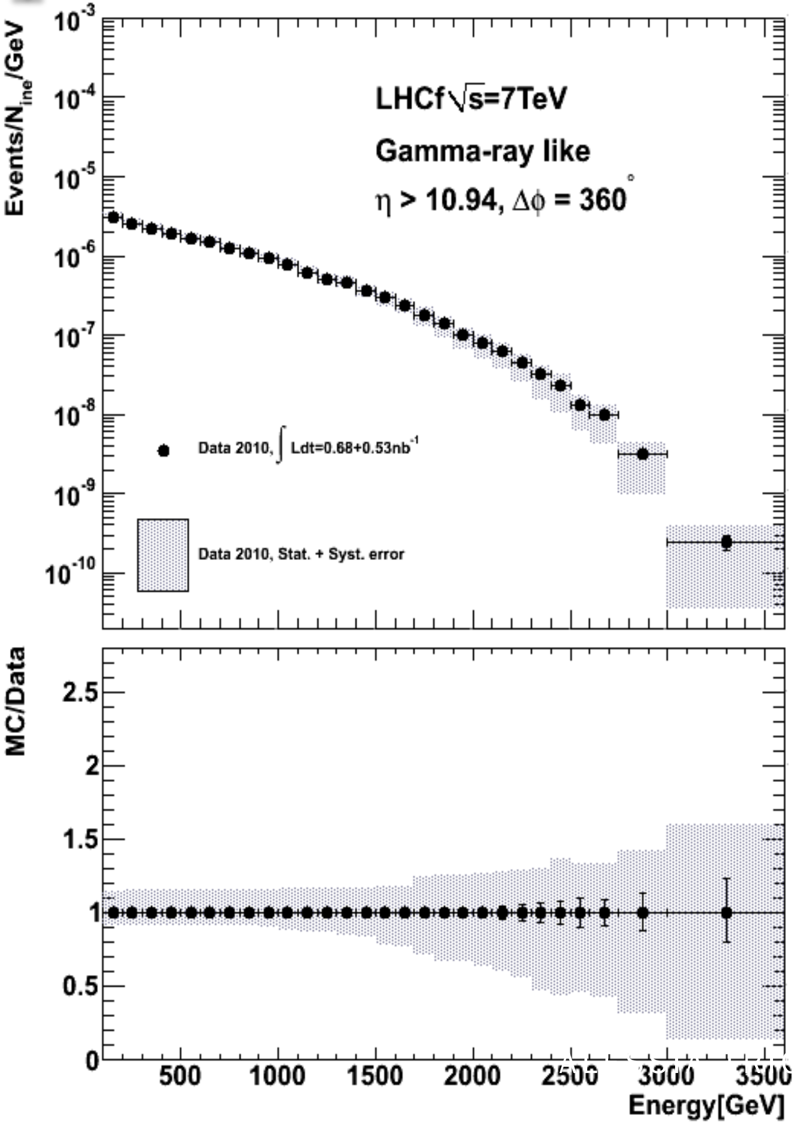
- Multi-hit rejection and PID correction applied
- Energy scale systematic not considered due to strong correlation between Arm1 and Arm2

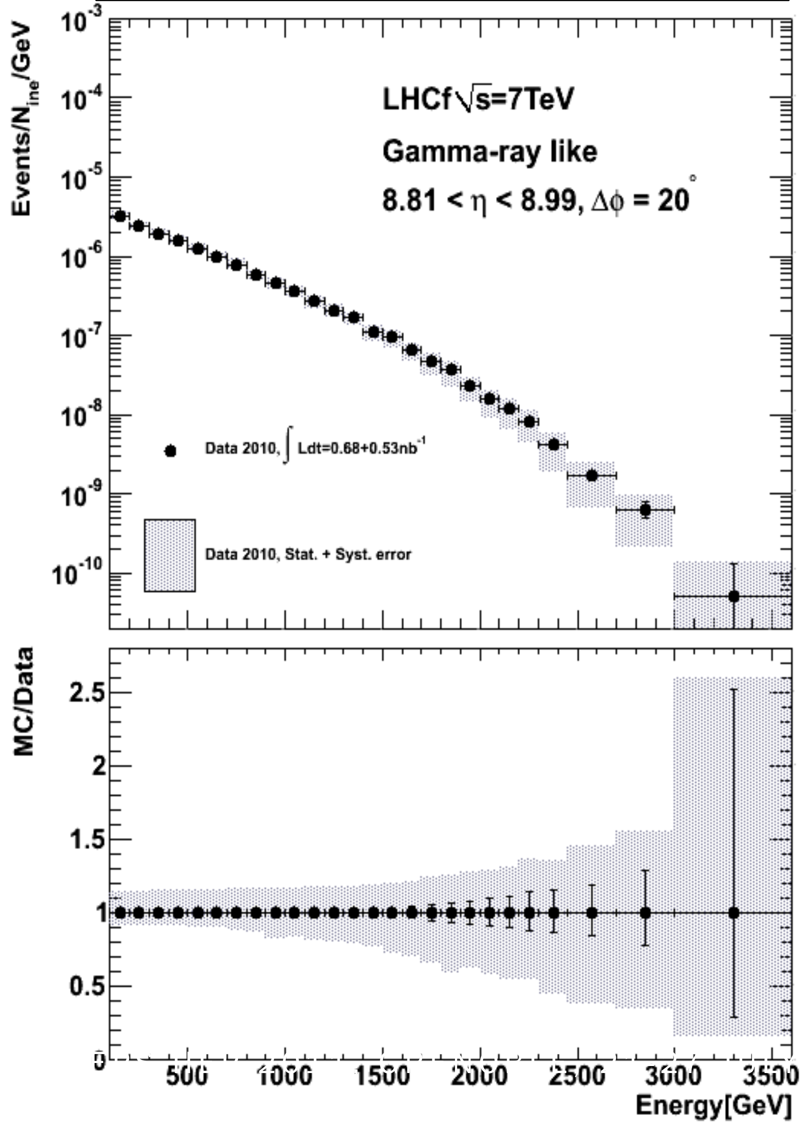
Deviation in small tower: still unclear, but within systematic errors

COMBINATION OF ARM1 AND ARM2 SPECTRA

Error bars : statistical Error

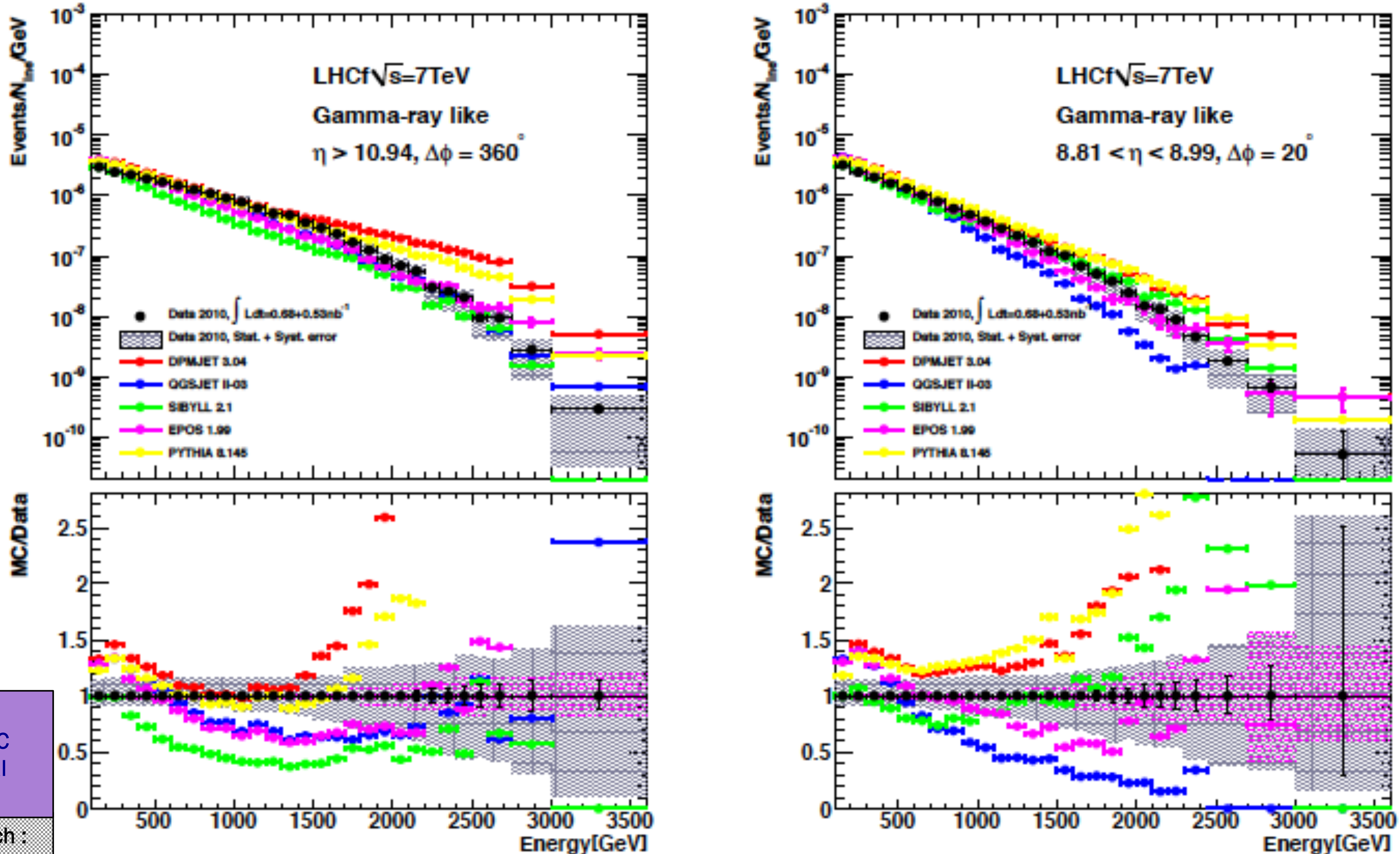
Gray hatch : Systematic Errors





Comparison between models

DPMJET 3.04 SIBYLL 2.1 EPOS 1.99 PYTHIA 8.145 QGSJET II-03



Magenta hatch: MC Statistical errors

Gray hatch : Systematic Errors

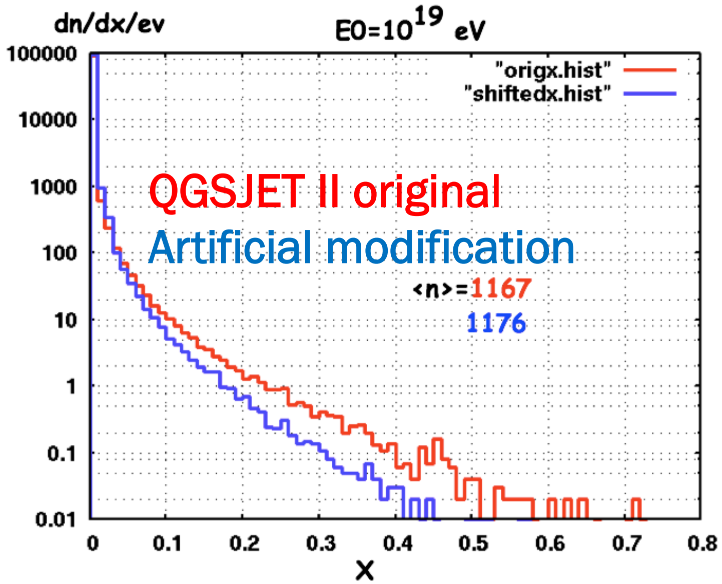
Impact on HECR physics

Understanding the impact of our measurements

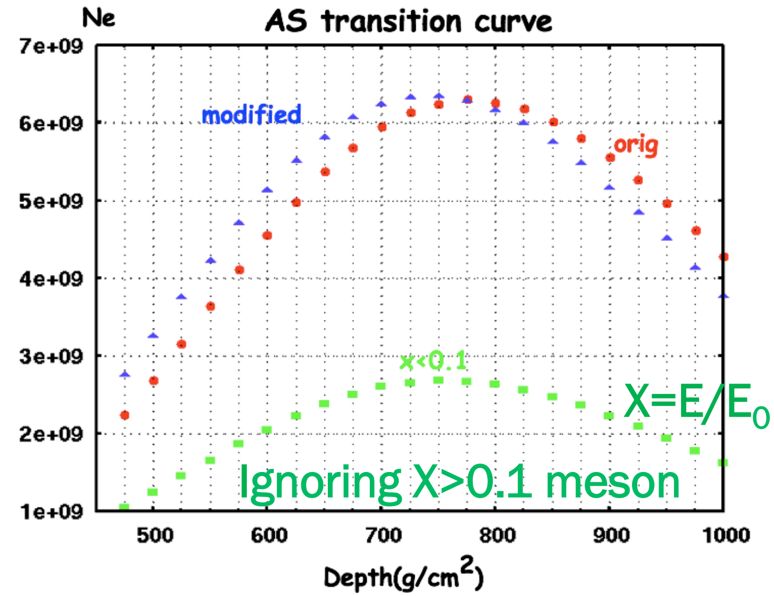
Alessia Tricomi

EPS-HEP 2011, Grenoble, 21-27 July 2011

π⁰ spectrum and air shower

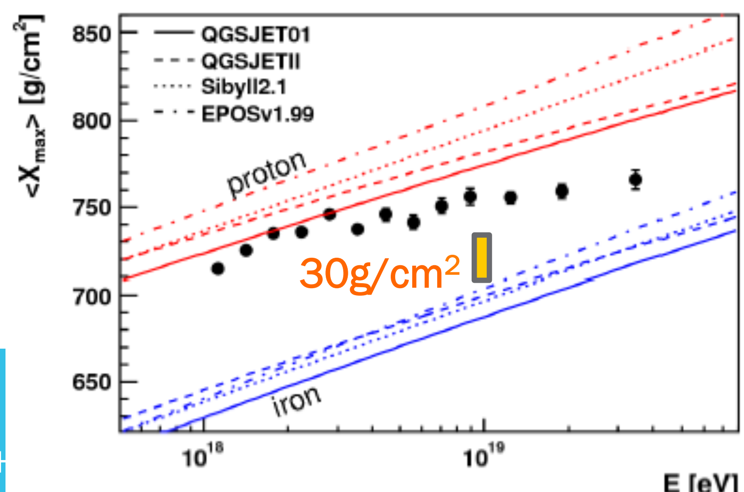


π^0 spectrum at $E_{lab} = 10^{19}$eV



Longitudinal AS development

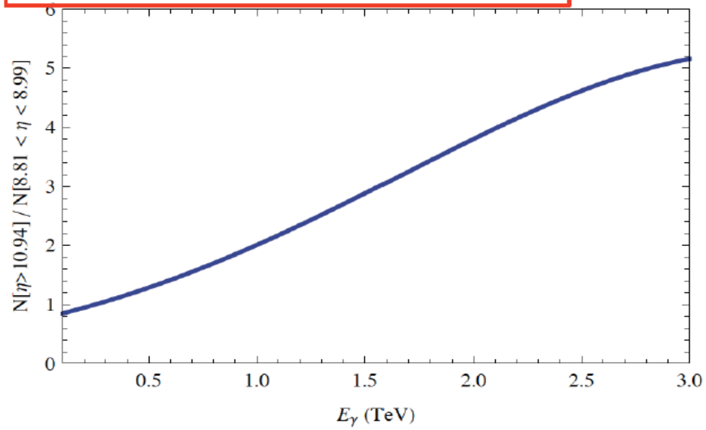
- ✓ Artificial modification of meson spectra (in agreement with differences between models) and its effect to air shower
- ✓ Importance of $E/E_0>0.1$ mesons



PT DISTRIBUTION DEPENDENCE

Ratio [High Rapidity] / [Low Rapidity]

for LHCf DATA



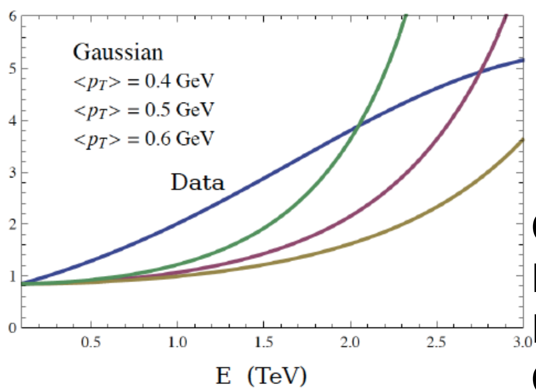
$$\left[\frac{dN_\gamma}{dE_\gamma}(E_\gamma)\right]_{8.81\le\eta\le8.99} = \frac{dN_\gamma}{dE_\gamma}(E_\gamma)\times\frac{dN_\gamma[8.81\le\eta\le8.99]}{dN_\gamma[\text{all }\eta]}$$

$$\left[\frac{dN_\gamma}{dE_\gamma}(E_\gamma)\right]_{\eta>10.94} = \frac{dN_\gamma}{dE_\gamma}(E_\gamma)\times\frac{dN_\gamma[\eta>10.94]}{dN_\gamma[\text{all }\eta]}$$

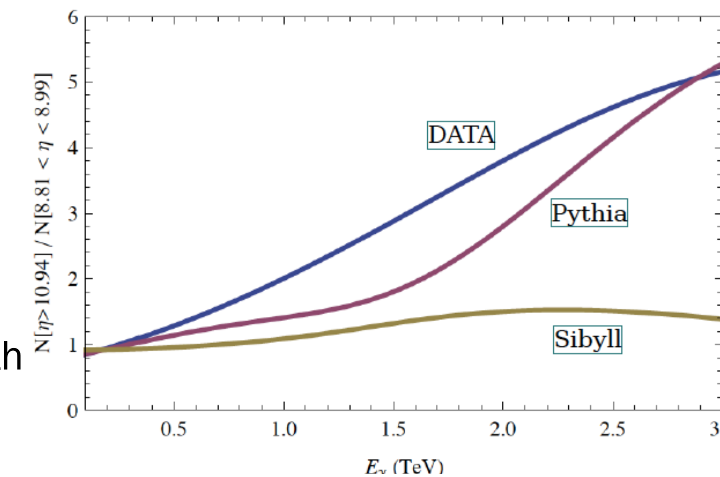
Directly relevant for UHECR shower development

pT distribution dependence

The pT distribution a sqrt[s] = 7 TeV is not a Gaussian of energy independent width.



Courtesy P. LIPARI
Interplay of LHCf data with HECR Physics Workshop, Catania, July 6 2011



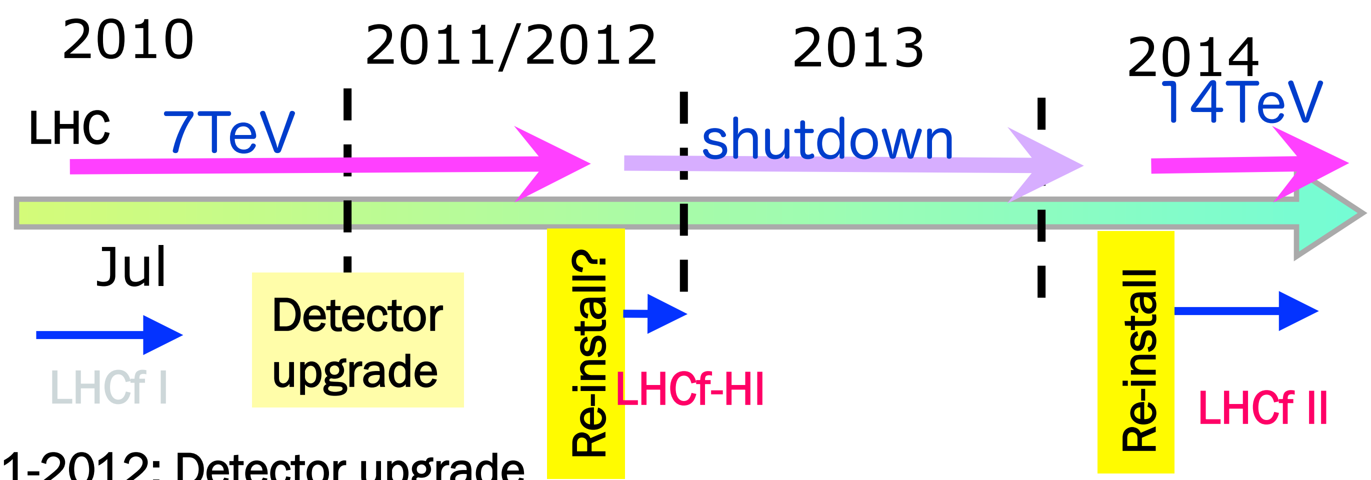
What's next

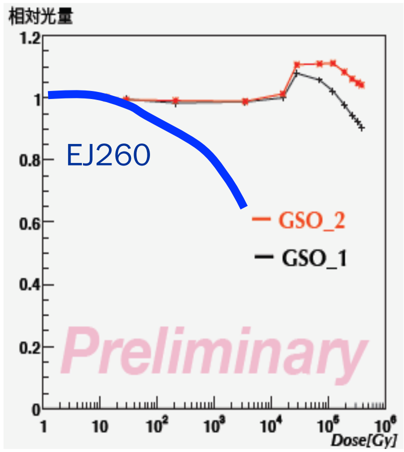
Detector upgrade, analysis, ion runs

Alessia Tricomi

EPS-HEP 2011, Grenoble, 21-27 July 2011

LHCf future plans (1)



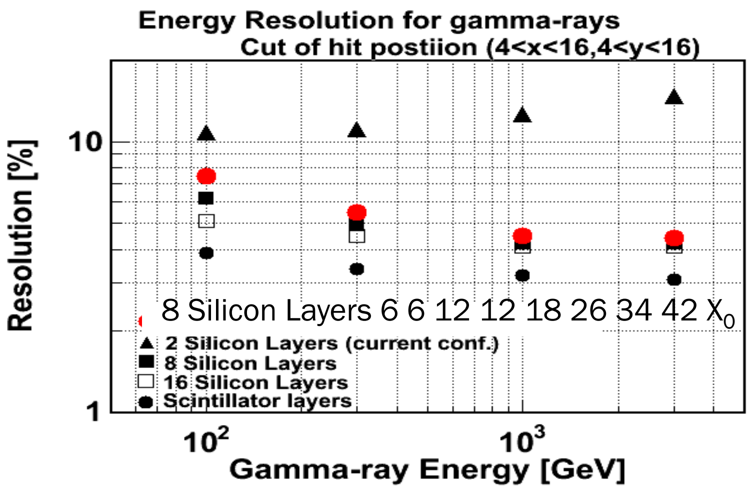


2011-2012: Detector upgrade

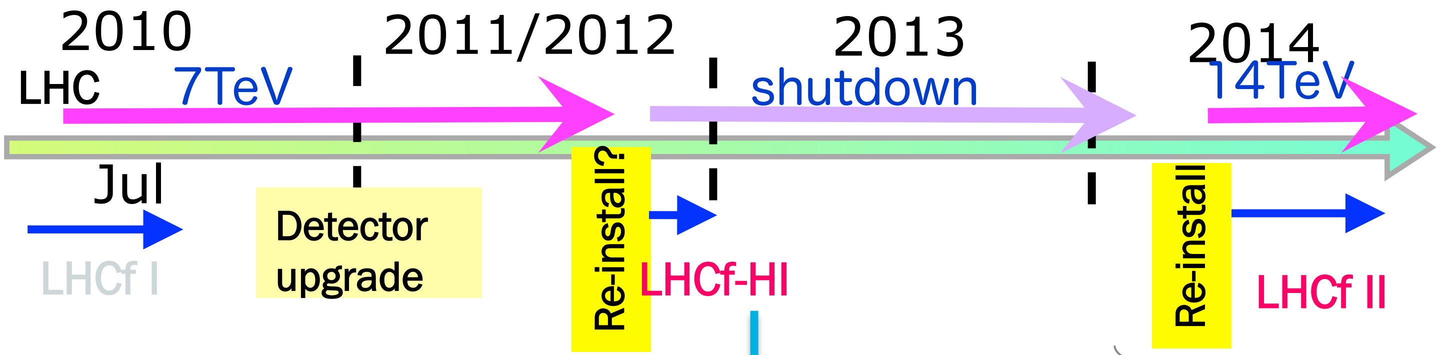
- Replace plastic scintillators with Rad Hard GSO
- Modify the silicon layers positions to improve silicon-only energy resolution
- Test beam at SPS to calibrate Arm1&Arm2
- Improve the dynamic range of silicon

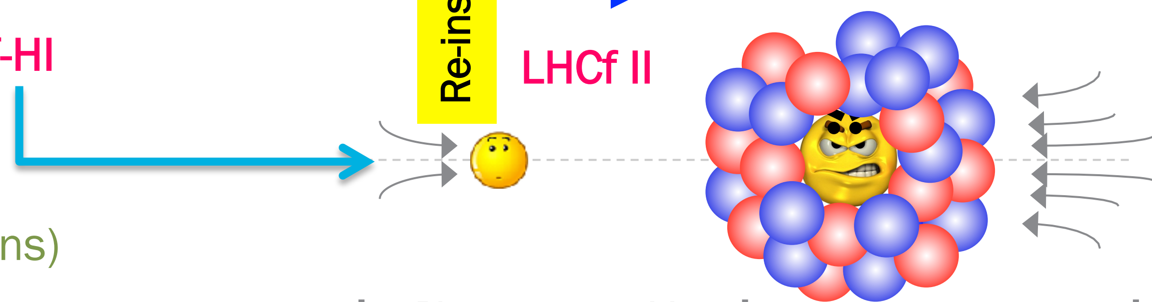
2011-2012: New analyses

- π^0 measurement
- p_T spectra
- Hadron spectra
- η, k^0, Λ ?



LHCf future plans (II)



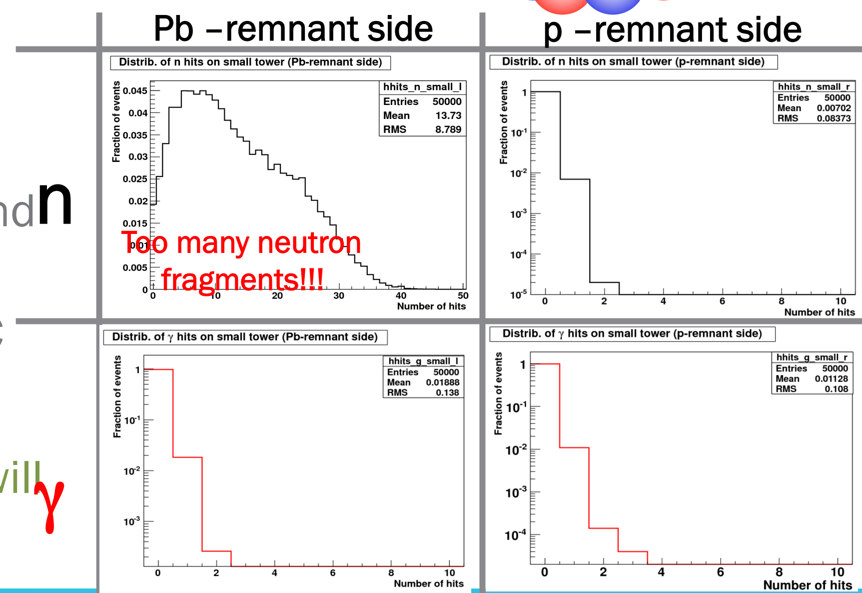


2012-2013: p-Pb runs?

- Interest in Ion runs (better if light ions)
- Physics case study is on going
- LHC Ion run and/or RHIC
  - Discussion on going with LHCC, LHC machine, ATLAS about reinstallation during p-Pb run (end of 2012?)
  - Discussion about possible data taking at RHIC

2014-2015

- Re-install Arm1&Arm2 at LHC when the energy will be raised to 13/14 TeV



Conclusions

- LHCf Inclusive photon analysis has been completed
  - Many detailed systematic checks
  - First comparison of various hadronic interaction models with experimental data in the most challenging phase space region ($8.81 < \eta < 8.99$, $\eta > 10.94$)
  - Large discrepancy especially in the high energy region with all models
  - Implications on UHECR Physics under study in strict connection with relevant theoreticians and model developers

- Other analyses are in progress (hadrons, P_T distributions, different η coverage...)
- LHCf was removed from the tunnel on July 20, 2010
- We are upgrading the detectors to improve their radiation hardness (GSO scintillators and rearrange silicon layers)
- Discussions are under way to come back in the TAN for the possible p-Pb run in 2012 (LHCC, Alice, LHC, Atlas etc.) or at RHIC for lower energy p-ions runs
- We will anyway come back in LHC for the 14 TeV run with upgraded detector!!!!

BACKUP SLIDES

THE LHCF COLLABORATION

K.Fukatsu, T.Iso, Y.Itow, K.Kawade, T.Mase, K.Masuda, Y.Matsubara, G.Mitsuka, Y.Muraki, T.Sako, K.Suzuki, K.Taki
Solar-Terrestrial Environment Laboratory, Nagoya University, Japan
H.Menjo *Kobayashi-Maskawa Institute, Nagoya University, Japan*
K.Yoshida *Shibaura Institute of Technology, Japan*
K.Kasahara, Y.Shimizu, T.Suzuki, S.Torii *Waseda University, Japan*
T.Tamura *Kanagawa University, Japan*
O.Adriani, L.Bonechi, M.Bongi, R.D'Alessandro, M.Grandi, P.Papini, S.Ricciarini, G.Castellini *INFN, Univ. di Firenze, Italy*

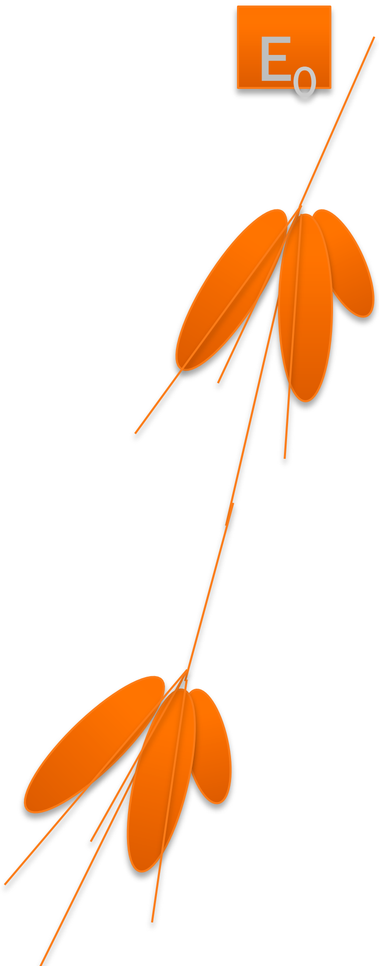
K.Noda, A.Tricomi *INFN, Univ. di Catania, Italy*

M.Haguenauer *Ecole Polytechnique, France*

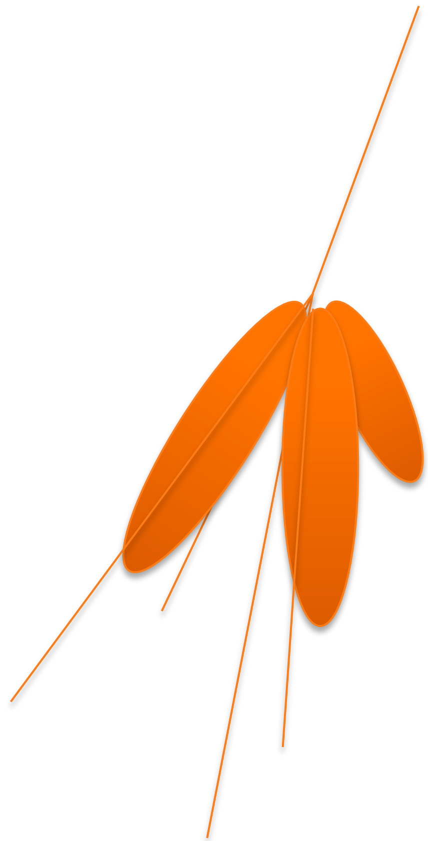
W.C.Turner *LBNL, Berkeley, USA*

A-L.Perrot *CERN, Switzerland*

KEY MEASUREMENTS

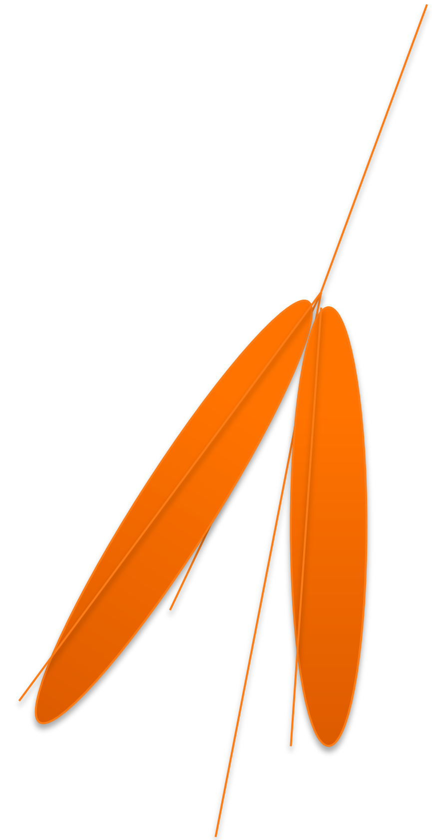


Cross section



$E_{\text{leading baryon}}$

Elasticity / inelasticity

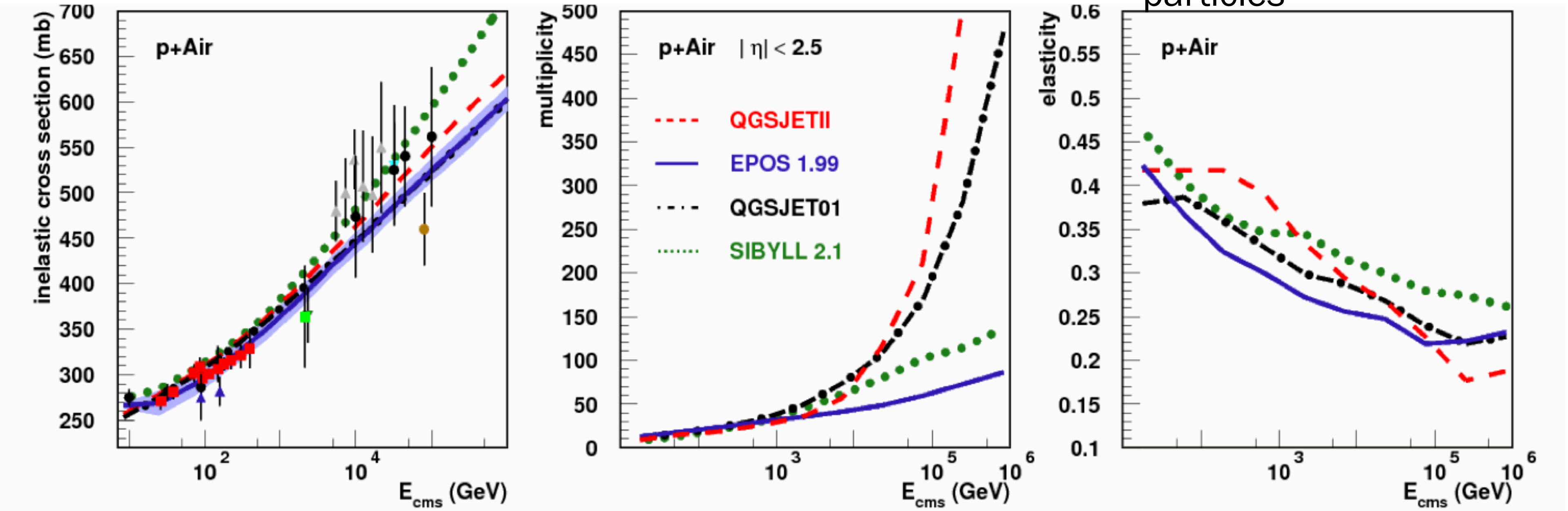


Forward spectra

(Multiplicity)

KEY PARAMETERS FOR THE DEVELOPMENT OF THE SHOWERS

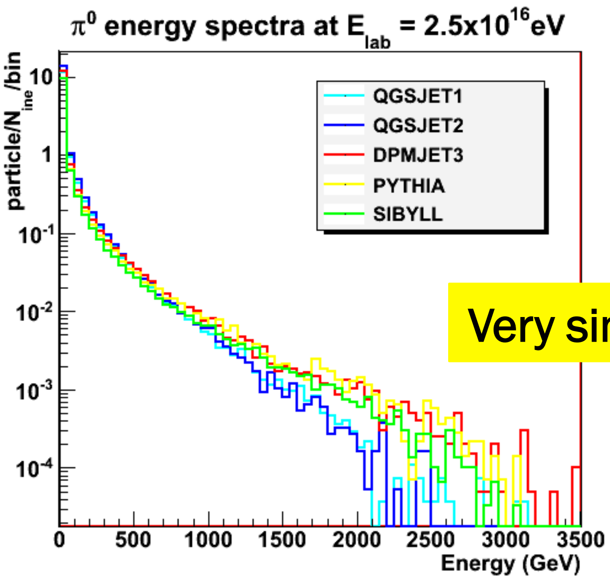
Total cross section | Multiplicity | Inelasticity/Secondary particles

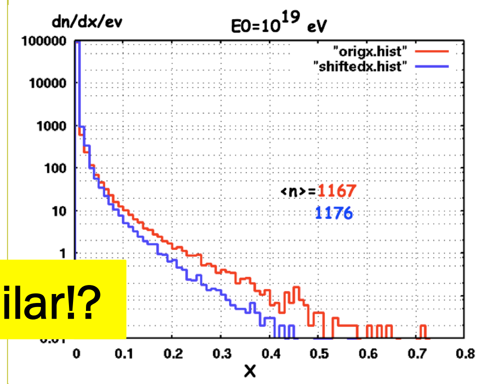


Predictions of the hadronic interaction models most commonly used in the UHECR simulation

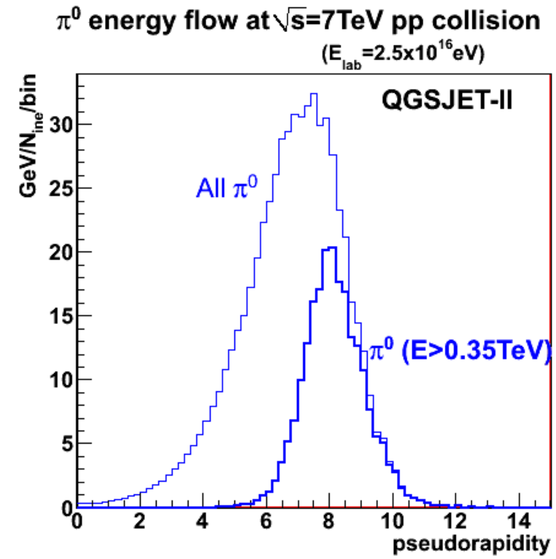
Big discrepancy in the high energy region !!!

MODEL UNCERTAINTY AT LHC ENERGY





Very similar!?

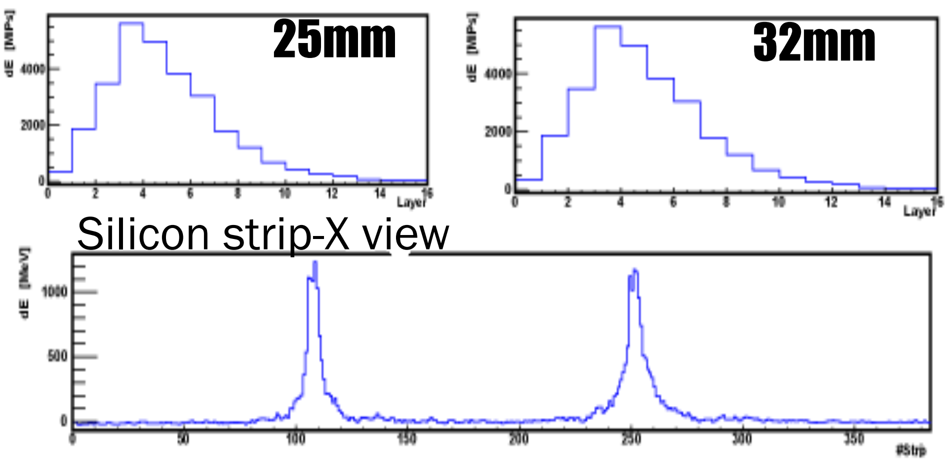


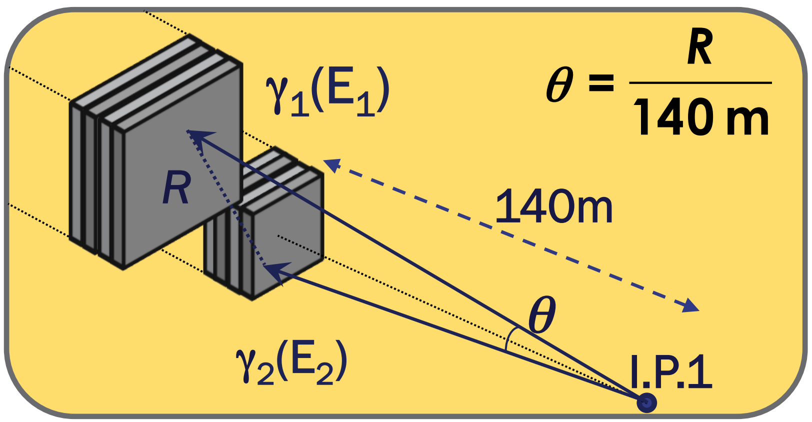
π^0 energy at $\sqrt{s}$ = 7TeV

Forward concentration of x>0.1 π^0

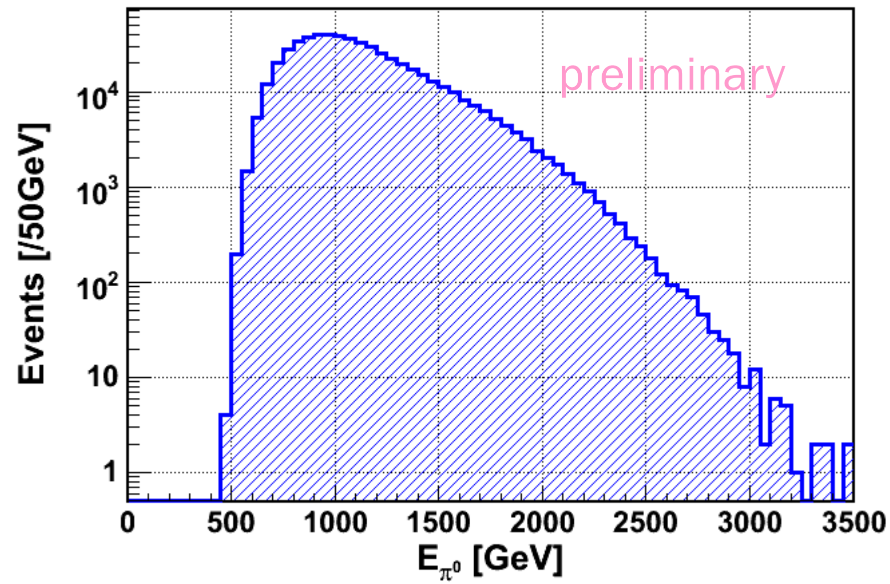
π^0 reconstruction

An example of π^0 events

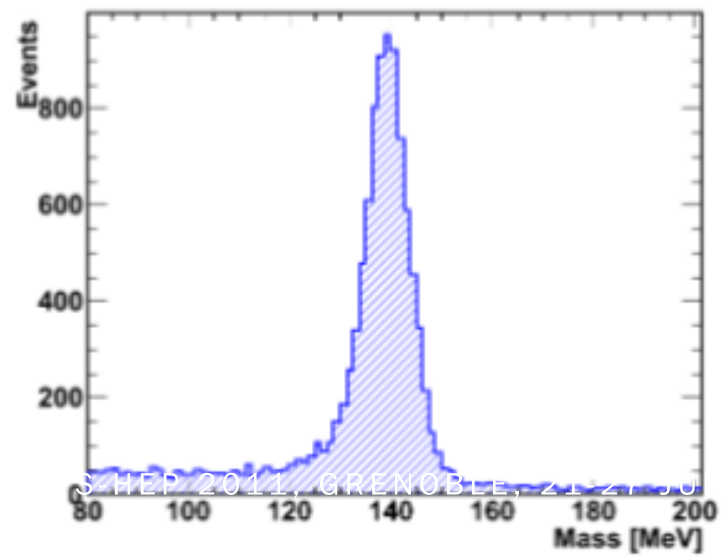




measured energy spectrum @ Arm2



Reconstructed mass @ Arm2



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

Analysis for the photon spectra

Analysis Procedure

1. Energy Reconstruction from total energy deposition in a tower (corrections for shower leakage, light yield etc.)
2. Particle Identification by analysis of the longitudinal shower development
3. Remove multi-particle events by looking at transverse energy deposit
4. Two Pseudo-rapidity regions selections, $\eta>10.94$ and $8.81<\eta<8.9$
5. Combine spectra between the two detectors
6. Compare data with the expectations from the models

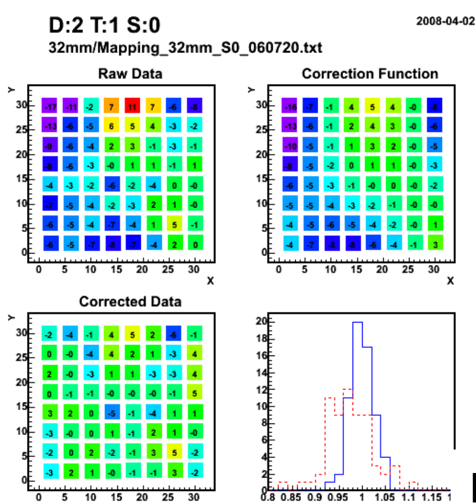
ANALYSIS 1. - ENERGY RECONSTRUCTION

- ✓ Energy reconstruction : $E_{photon} = f(\Sigma(dE_i))$ (i=2,3,…,13)

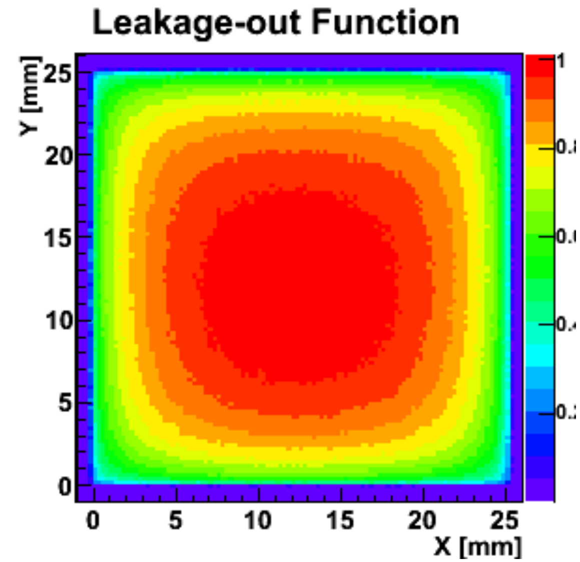
  ($dE_i = AQ_i$ determined at SPS. f() determined by MC.
  E : EM equivalent energy)

- ✓ Impact position from lateral distribution

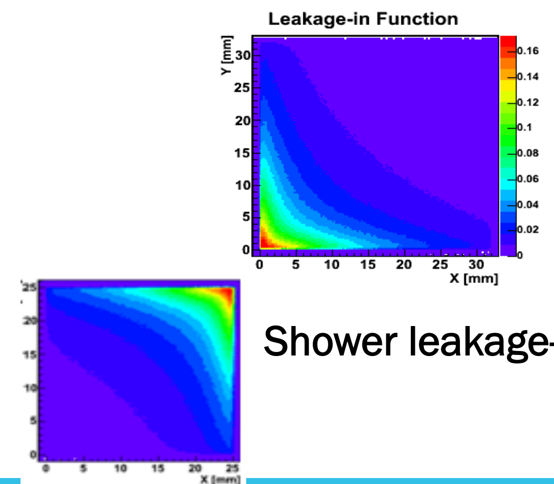
- ✓ Position dependent corrections
  - Light collection non-uniformity
  - Shower leakage-out
  - Shower leakage-in (in case of two towers event)



Light collection nonuniformity



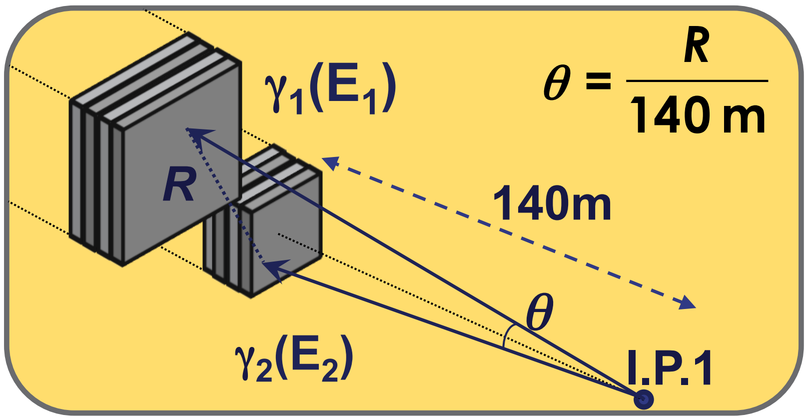
Shower leakage-out

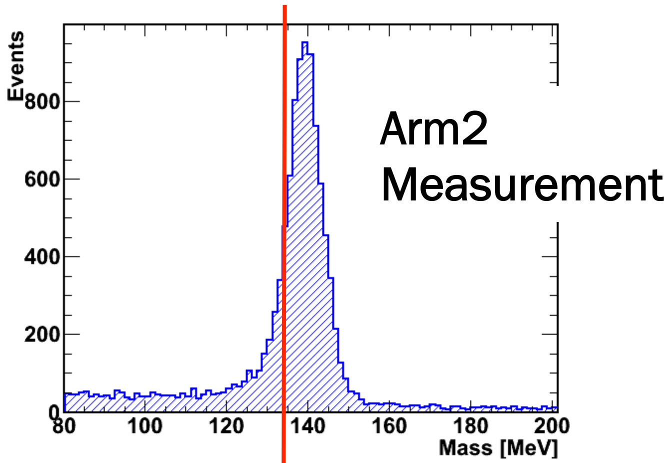


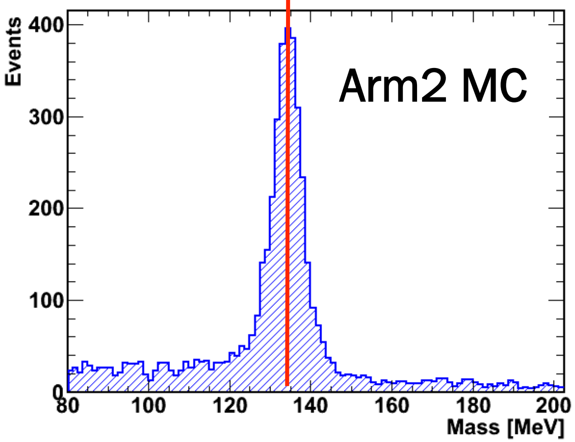
Shower leakage-in

ANALYSIS 1. - ENERGY RECONSTRUCTION

- ✓ Energy scale can be checked by π^0 identification from two tower events.
- ✓ Mass shift observed both in Arm1 (+7.8%) and Arm2 (+3.7%)
- ✓ No energy scaling applied, but shifts assigned in the systematic error in energy



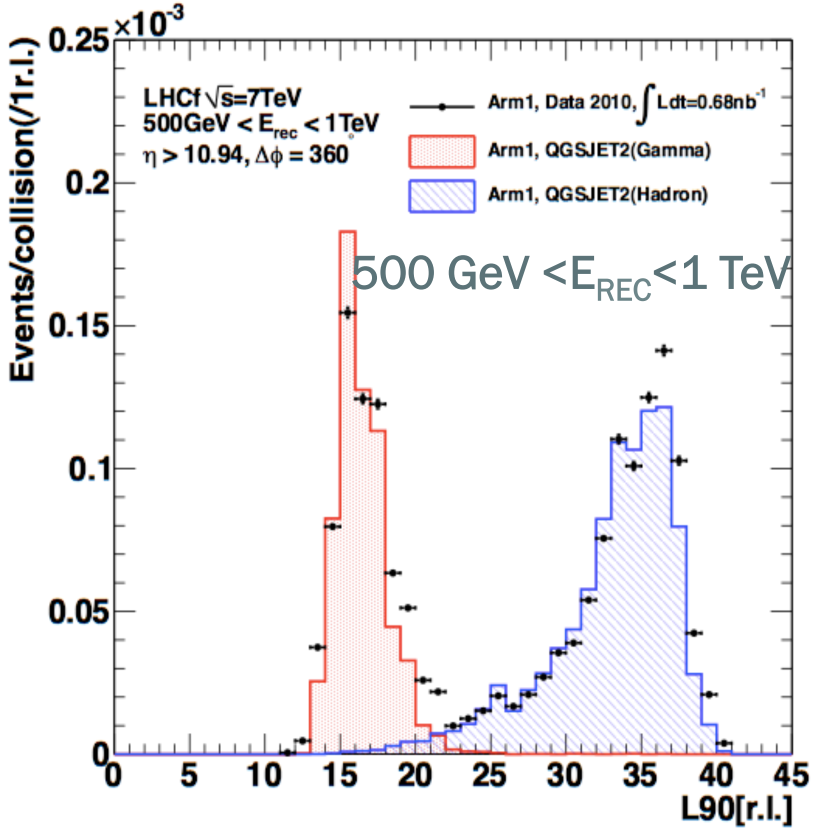


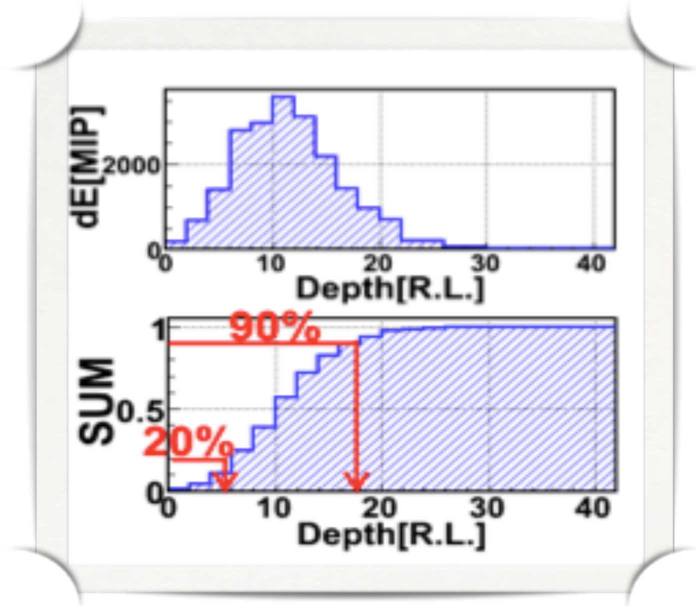


$$M = \theta\sqrt{(E_1 x E_2)}$$

Analysis 2. - Particle Identification

PID criteria based on transition curve





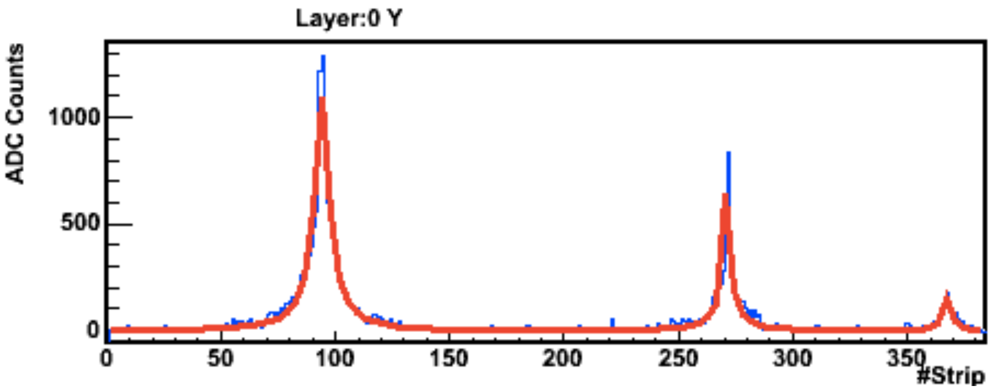
MC/Data comparison done in many energy bins

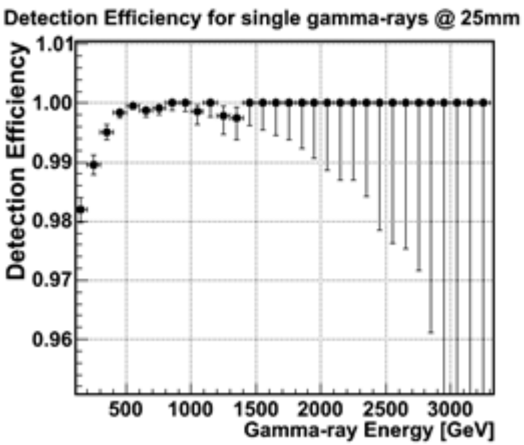
- QGSJET2-gamma and -hadron are normalized to data(/collision) independently
- LPM effects are switched on

ANALYSIS 3. -MULTI-HIT IDENTIFICATION

Reject events with multi-peaks

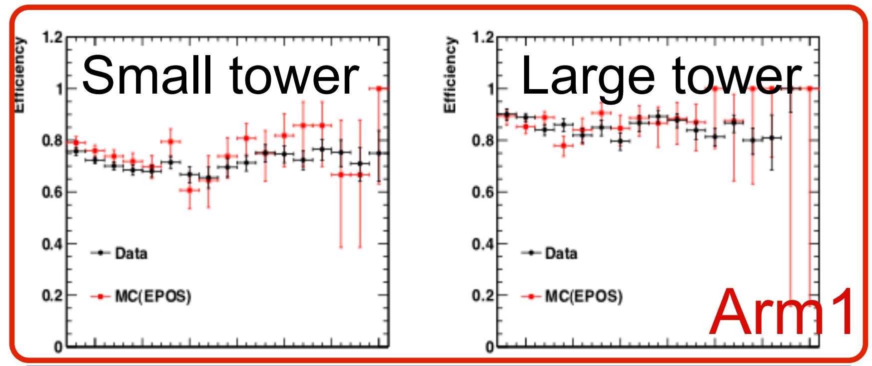
- Identify multi-peaks in one tower by position sensitive layers.
- Select only the single peak events for spectra.

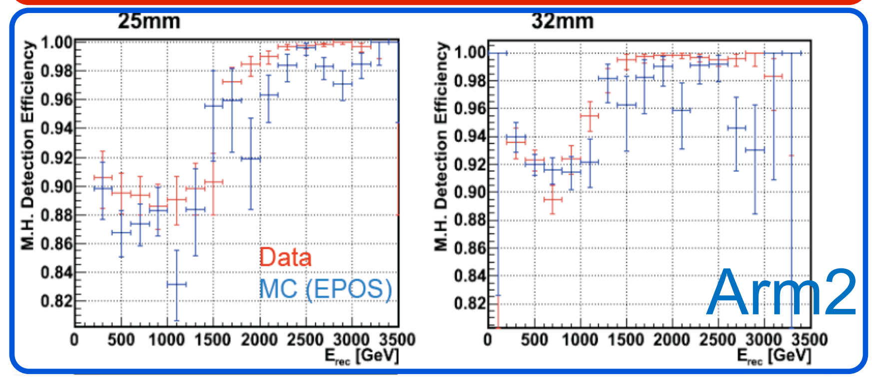




Single hit detection efficiency

Double hit detection efficiency

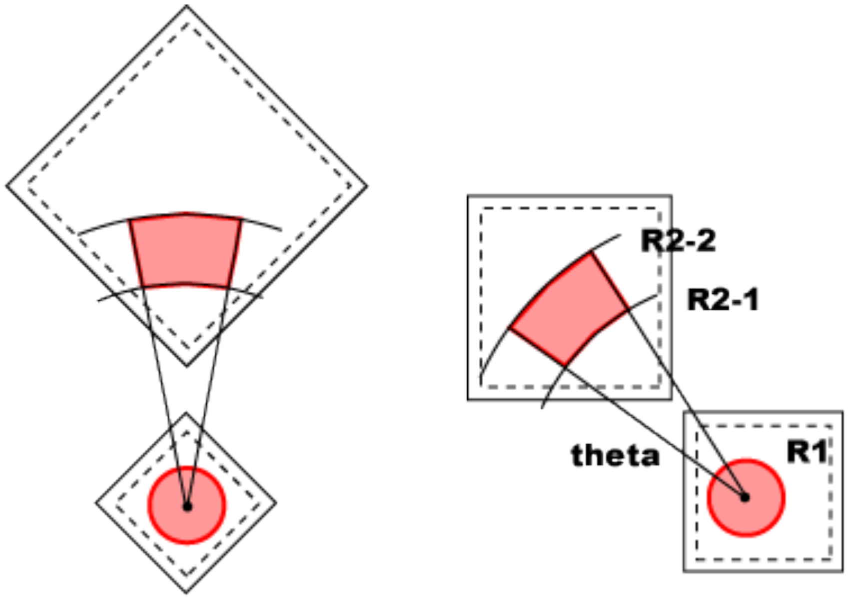




Analysis 4. - Acceptance cut

We define in each tower a region common both to Arm1 and Arm2, to compare the Arm1 and Arm2 reconstructed spectra.

Our final results will be two spectra, one for each acceptance region, obtained by properly weighting the Arm1 and Arm2 spectra



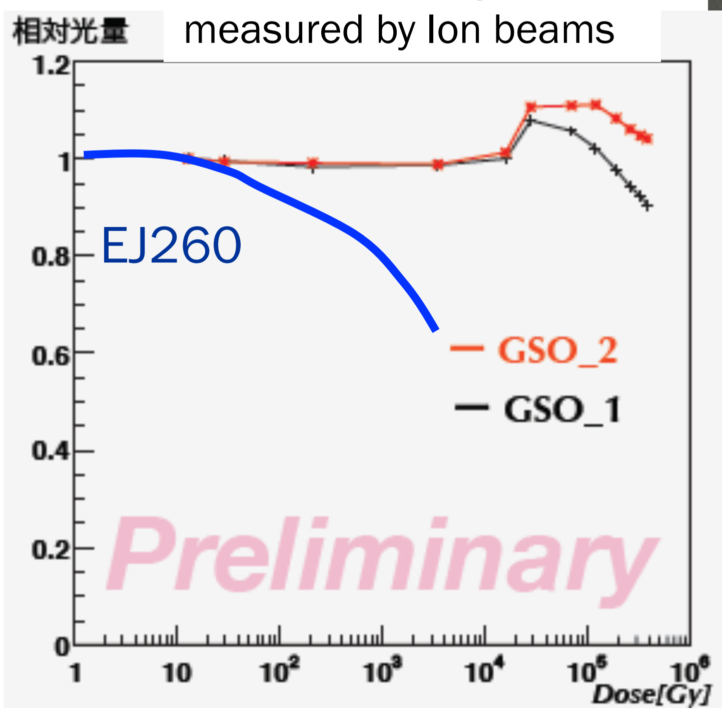
R1 = 5mm
R2-1 = 35mm
R2-2 = 42mm
$\theta = 20^o$

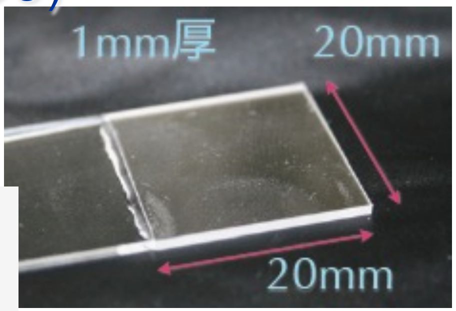
For Small Tower
$\eta > 10.94$
For Large Tower
$8.81 < \eta < 8.99$

R&D FOR THE DETECTOR UPGRADE

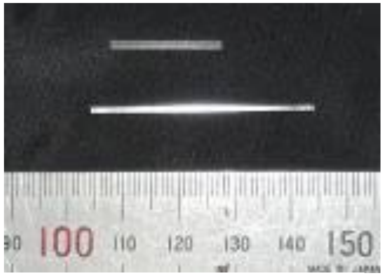
Plastic scintillators (EJ260)
⇒ GSO scintillators

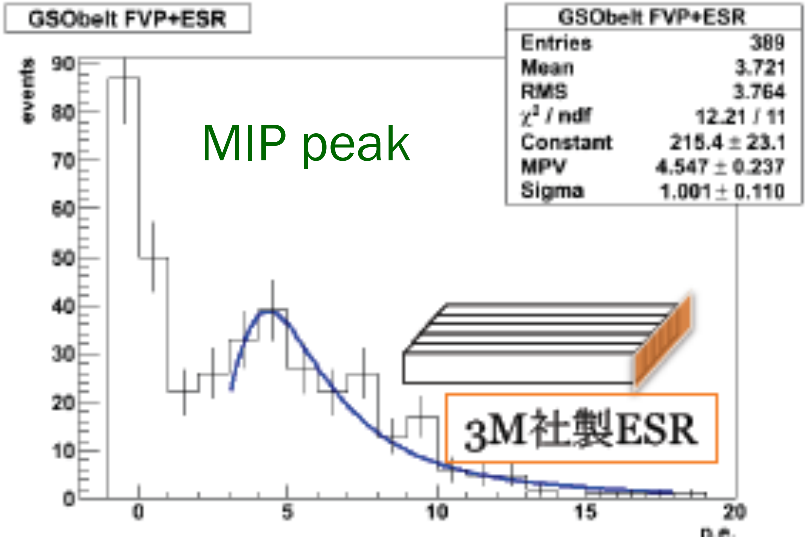
Radiation damage measured by Ion beams



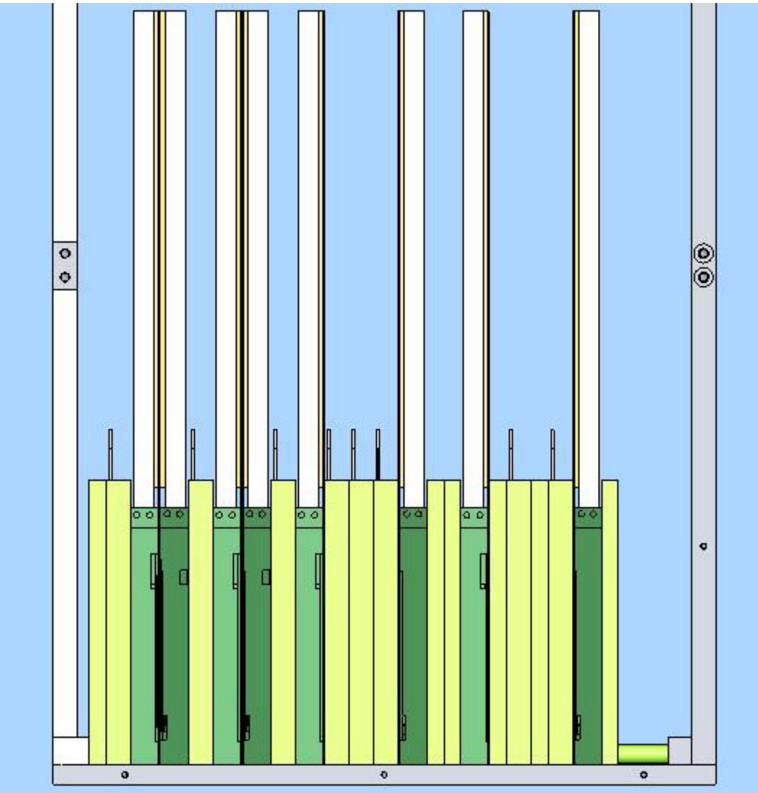


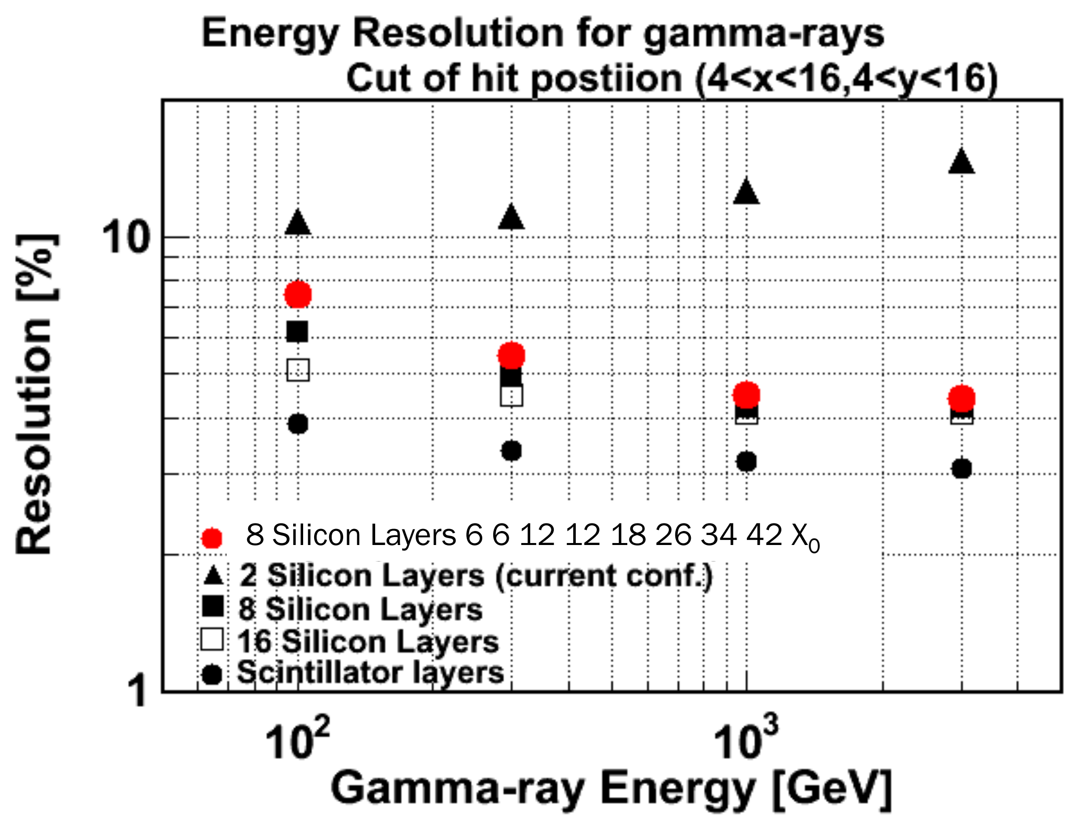
Scintillating Fibers
⇒ GSO bars





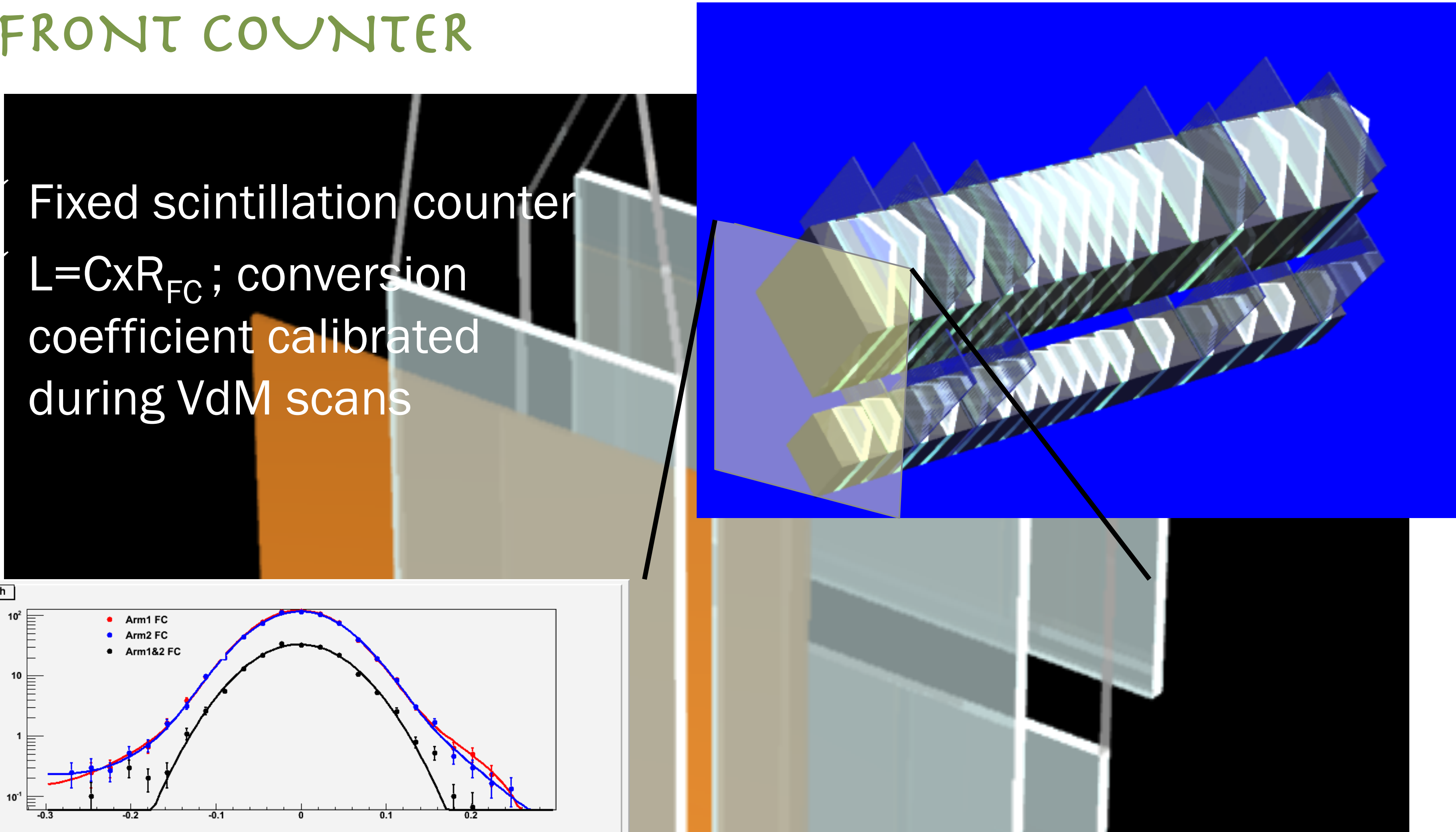
New Silicon Layers Arrangement

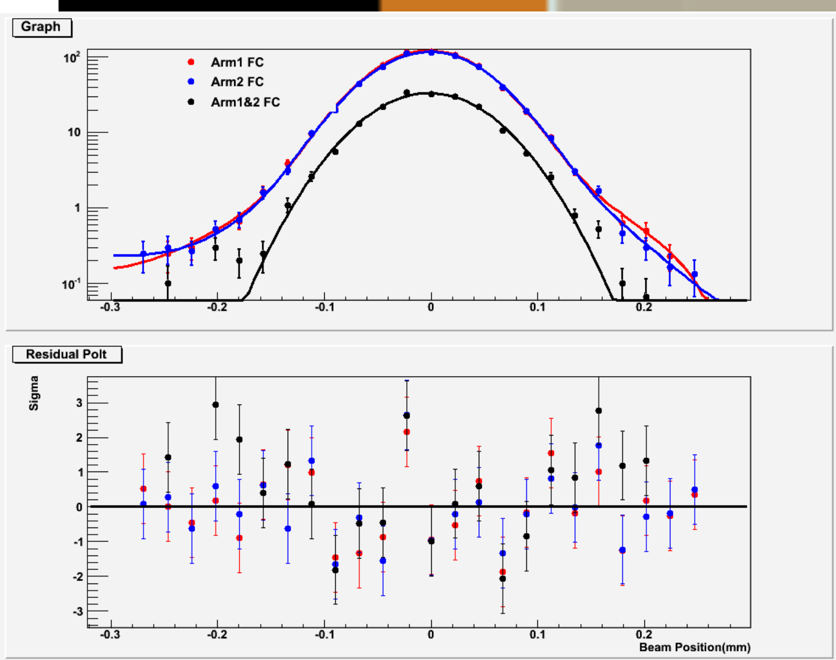




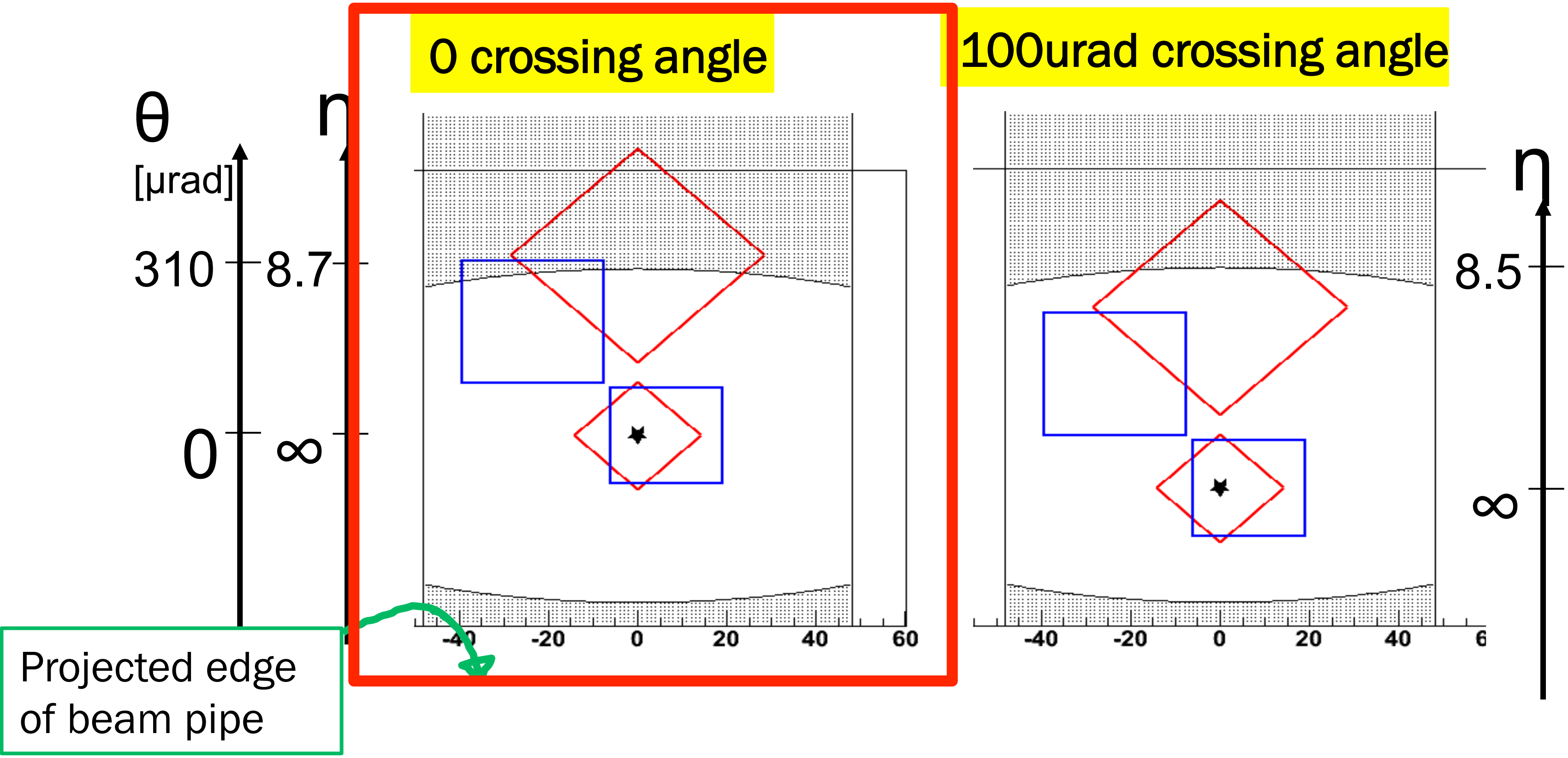
FRONT COUNTER

- Fixed scintillation counter
- $L = C \times R_{FC}$; conversion coefficient calibrated during VdM scans





CALORIMETERS VIEWED FROM IP



Geometrical acceptance of Arm1 and Arm2

Crossing angle operation enhances the acceptance

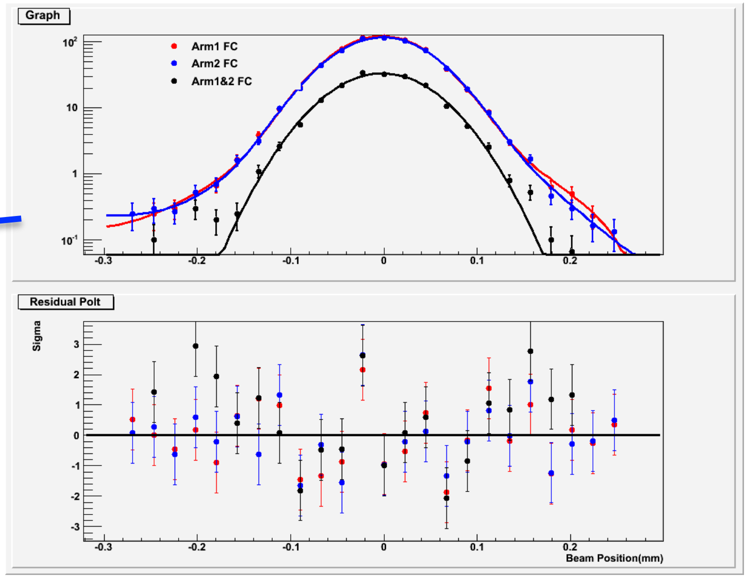
LUMINOSITY ESTIMATION

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 Van der Meer 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

BCNWG paper

https://lpc-afs.web.cern.ch/lpc-afs/tmp/note1_v4_lines.pdf

Estimation of pile up

When the circulated bunch is 1x1, the probability of N collisions per Xing 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

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

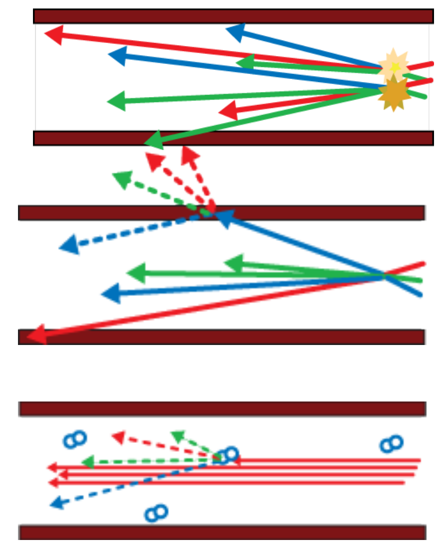
The maximum luminosity per bunch during runs used for the analysis is $2.3 \times 10^{28} \mathrm{cm}^{-2}\mathrm{s}^{-1}$

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

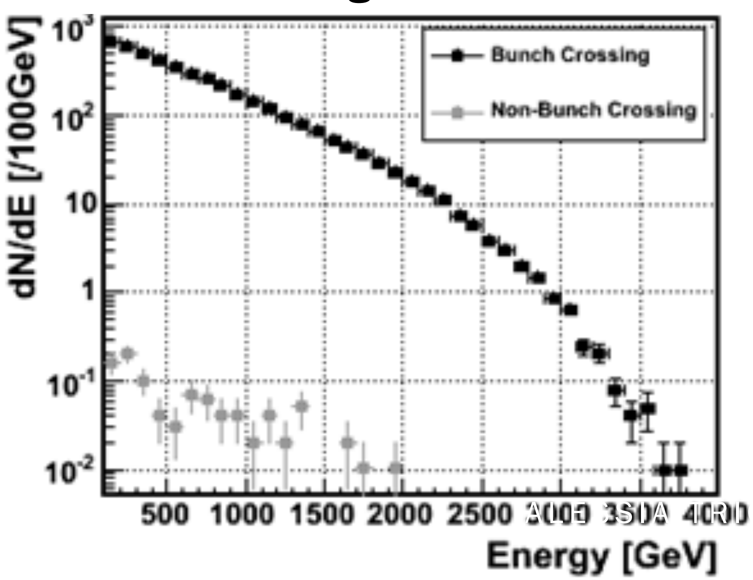
Taking into account the calorimeter acceptance (~0.03) only 0.2% of events have multi-hit due to pile-up. It does not affect our results

BACKGROUNDS

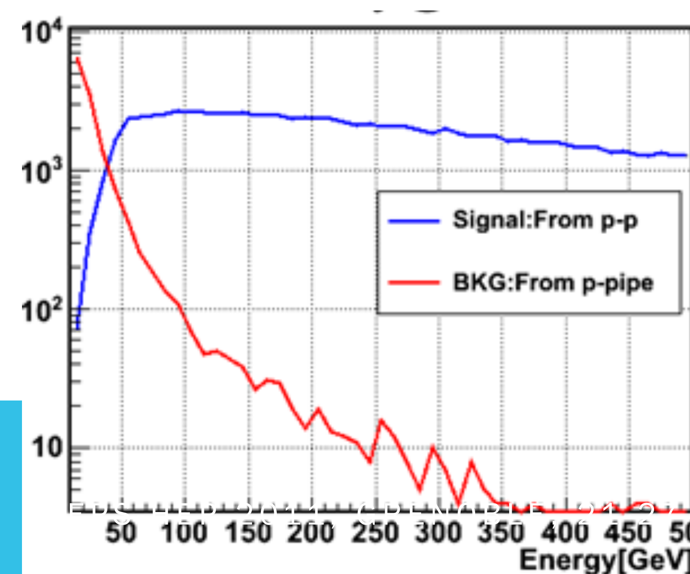
1. **Pileup of collisions in one beam crossing**
   - Low Luminosity fill, $L=6\times10^{28}cm^{-2}s^{-1}$
     ➔ 7% pileup at collisions, 0.2% at the detectors.
2. **Collisions between secondary's and beam pipes**
   - Very low energy particles reach the detector (few % at 100GeV)
3. **Collisions between beams and residual gas**
   - Estimated from data with non-crossing bunches.
     ➔ <0.1%



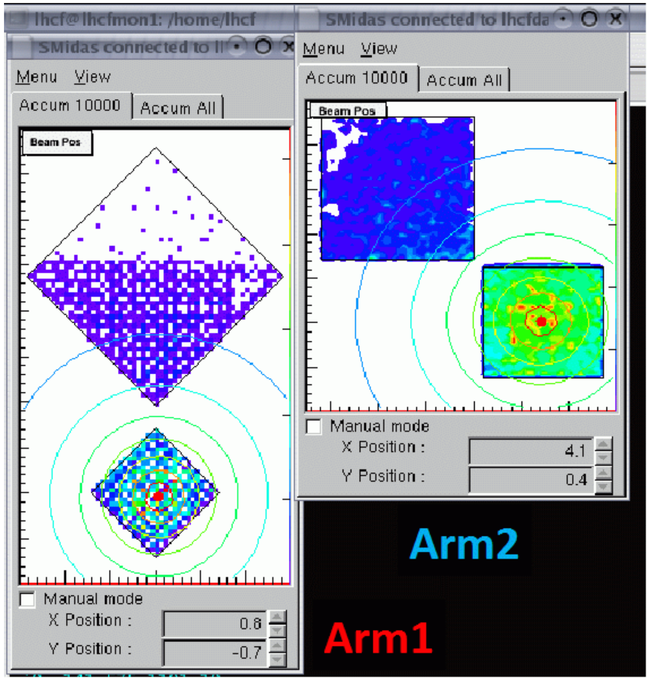
Beam-Gas backgrounds



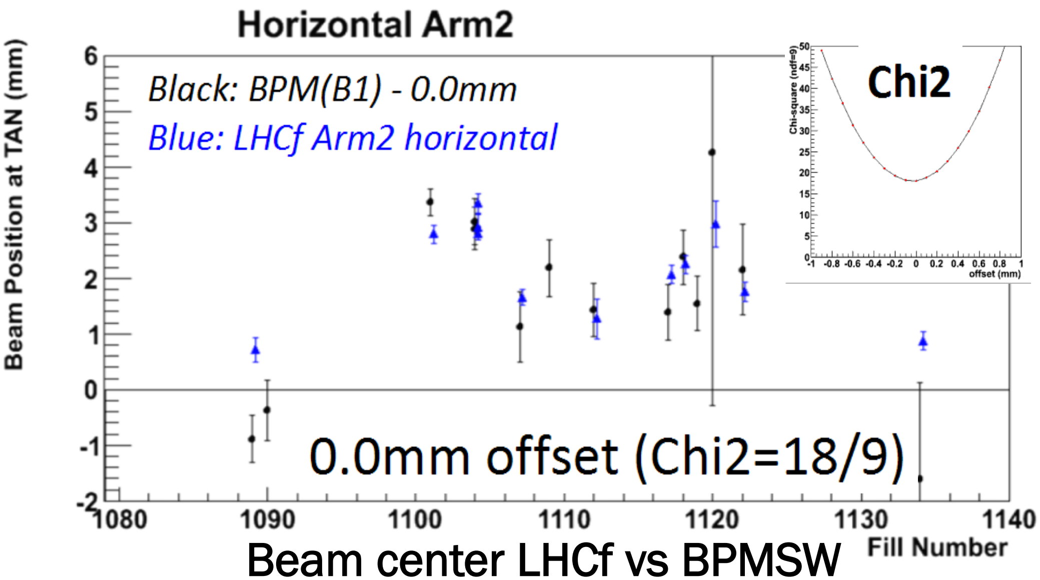
Secondary-beam pipe backgrounds



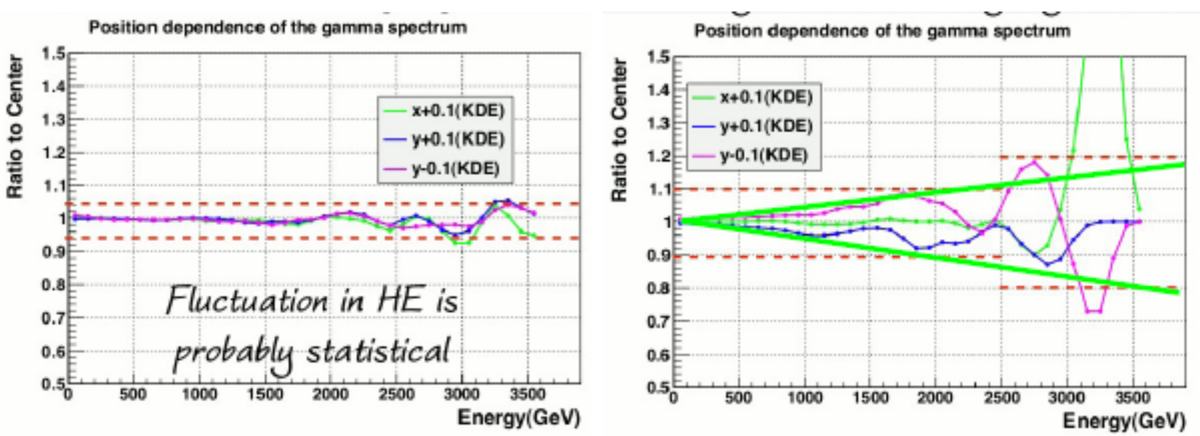
BEAM CENTER MEASUREMENT



LHCf online hit-map monitor



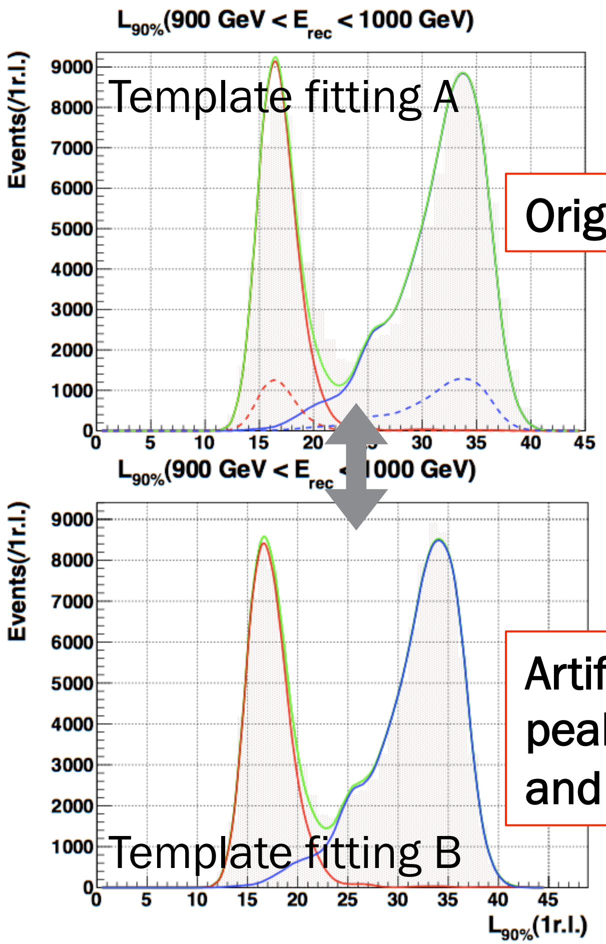
Beam center LHCf vs BPMSW



Effect of 1mm shift in the final spectrum

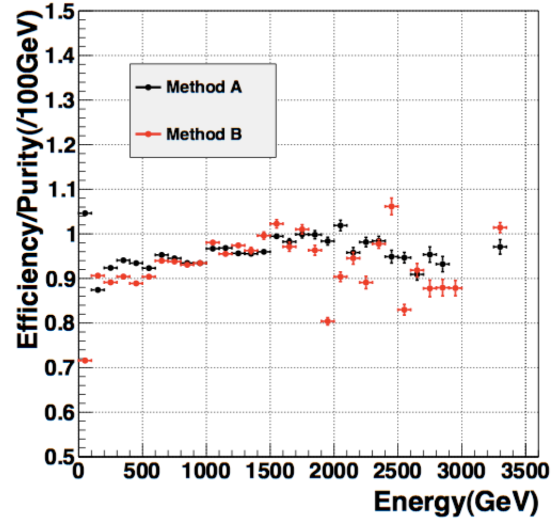
Uncertainty in step.2

✓ Imperfection in $L_{90\%}$ distribution

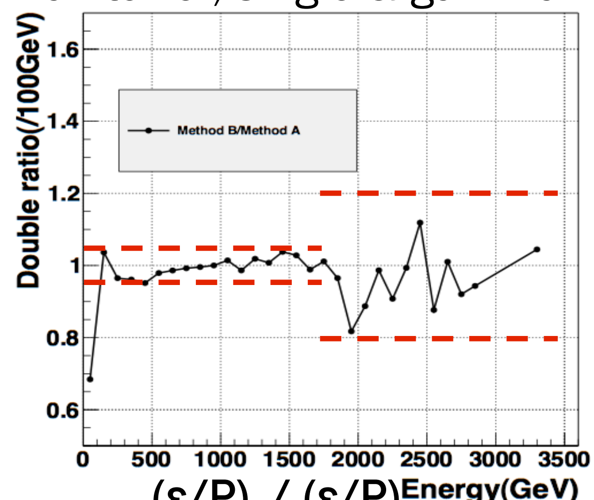


Original method

Artificial modification in peak position (<0.7 r.l.) and width (<20%)



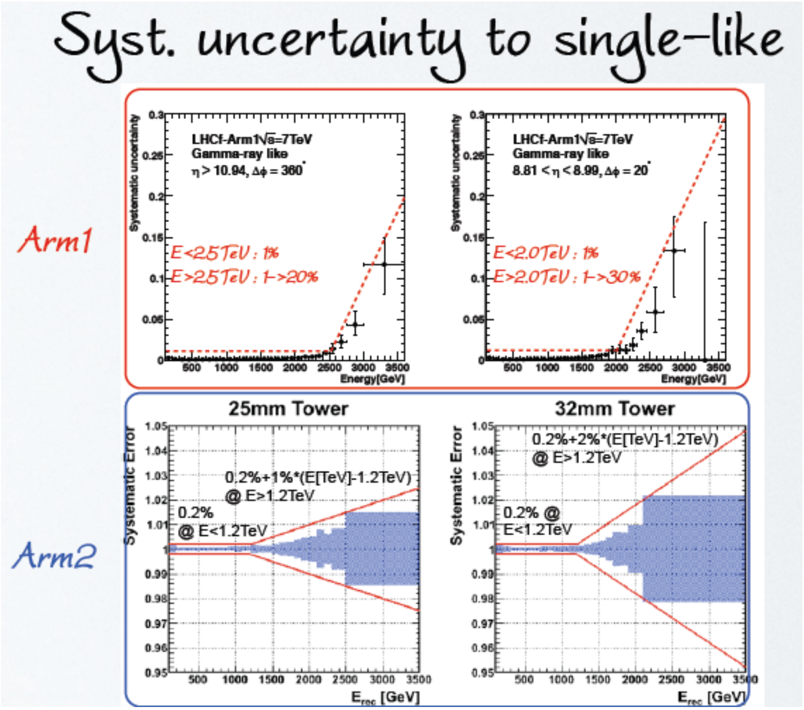
ε/P from two methods
(Small tower, single & gamma-like)



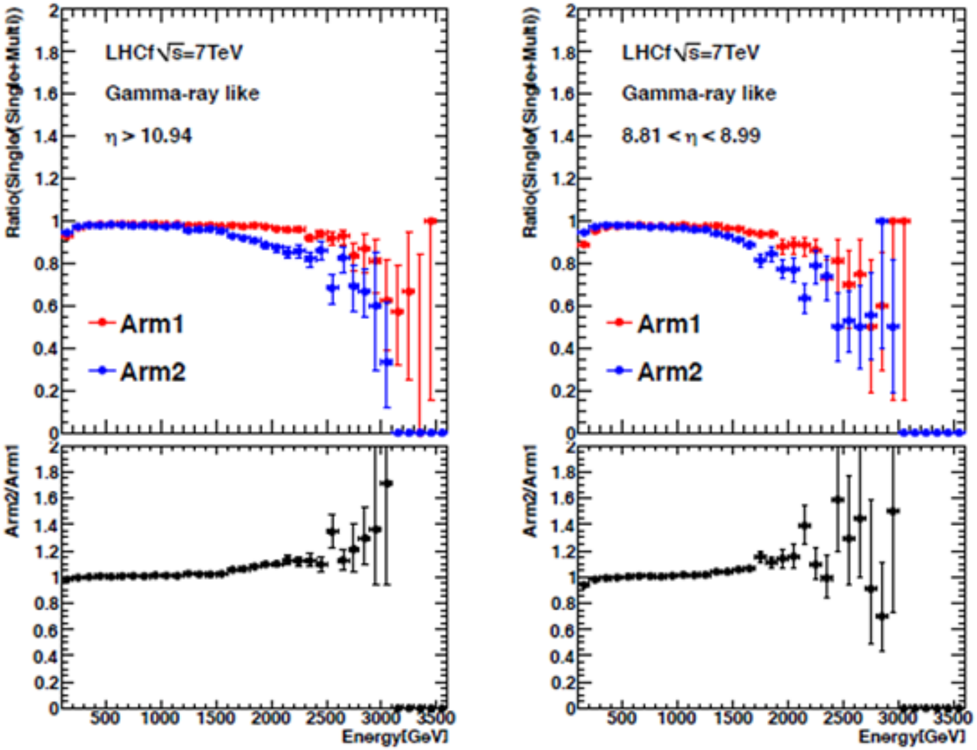
$(\varepsilon/P)_B / (\varepsilon/P)_A$

UNCERTAINTY IN STEP.3

- ✓ Fraction of multi-hit and $\Delta\varepsilon_{\text{multi, data-MC}}$
- ✓ Effect of multi-hit 'cut' : difference between Arm1 and Arm2



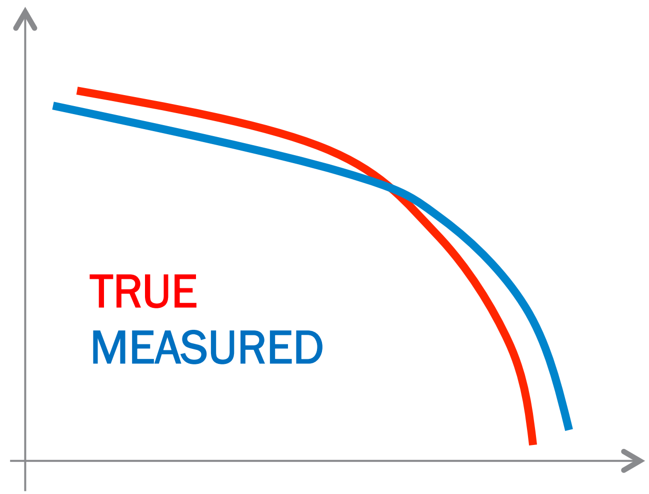
Effect of $\Delta\varepsilon_{\text{multi}}$ to single photon spectra



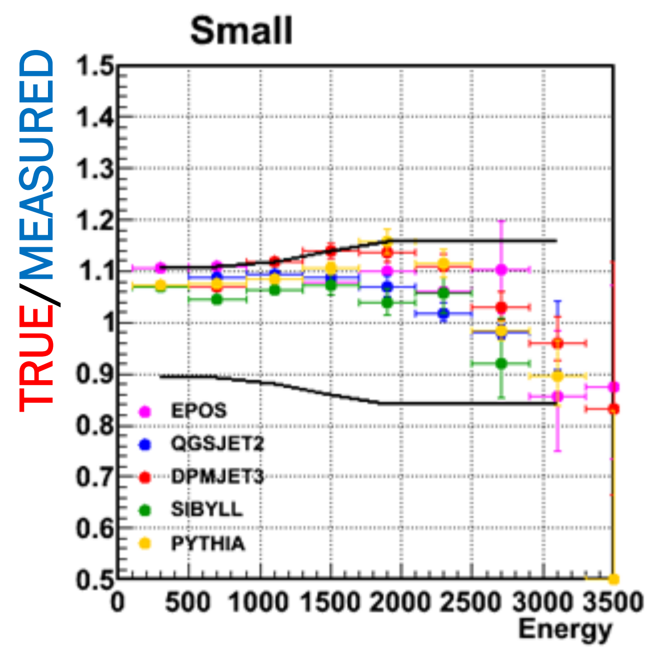
Single / (single+multi), Arm1 vs Arm2

SPECTRAL DEFORMATION

- ✓ Suppression due to multi-hit cut at medium energy
- ✓ Overestimate due to multi-hit detection inefficiency at high energy (mis-identify multi photons as single)
- ✓ No correction applied, but same bias included in MC to be compared



True: photon energy spectrum at the entrance of calorimeter



Systematic error from 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

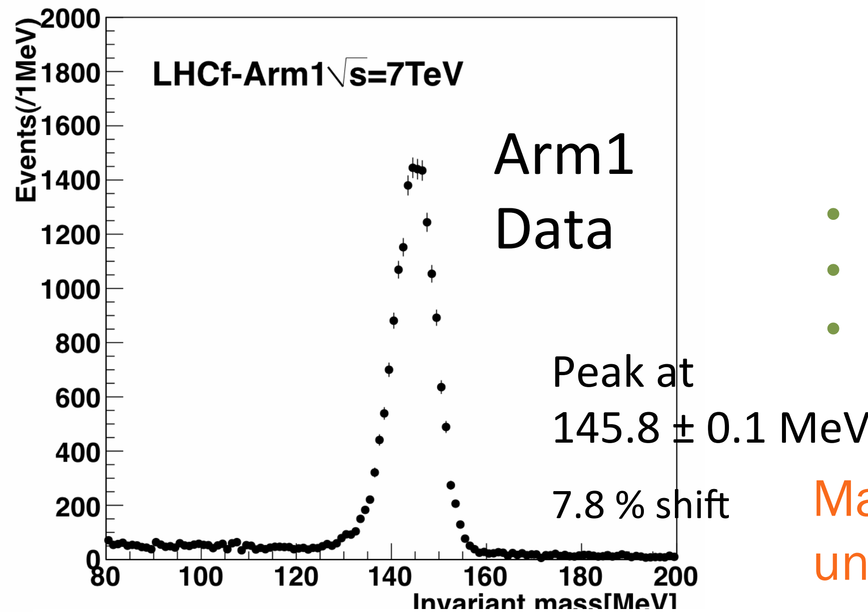
Total uncertainty is

-9.8% / +1.8% for Arm1

-6.6% / +2.2% for Arm2

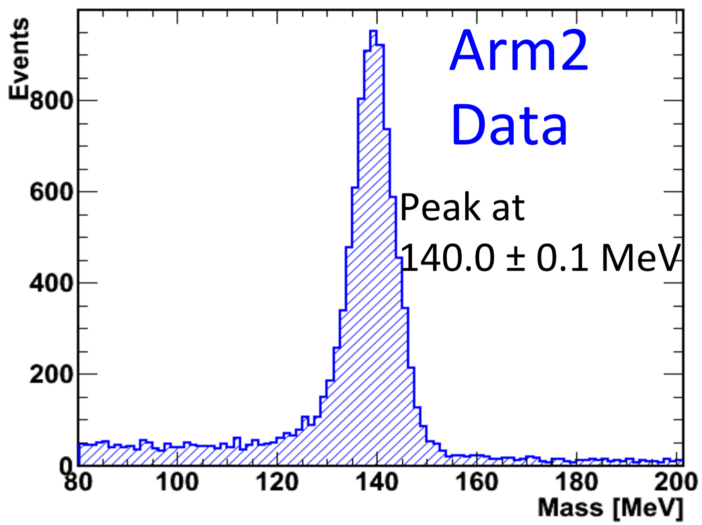
Systematic Uncertainty on Spectra is estimated from difference between normal spectra and energy shifted spectra.

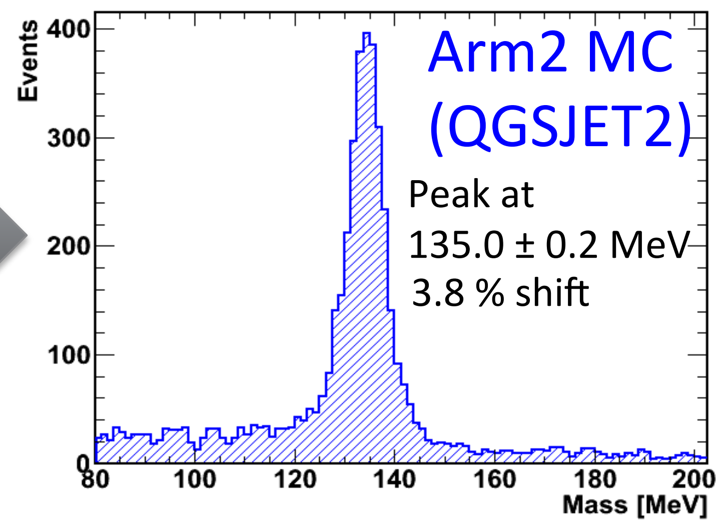
π^0 MASS



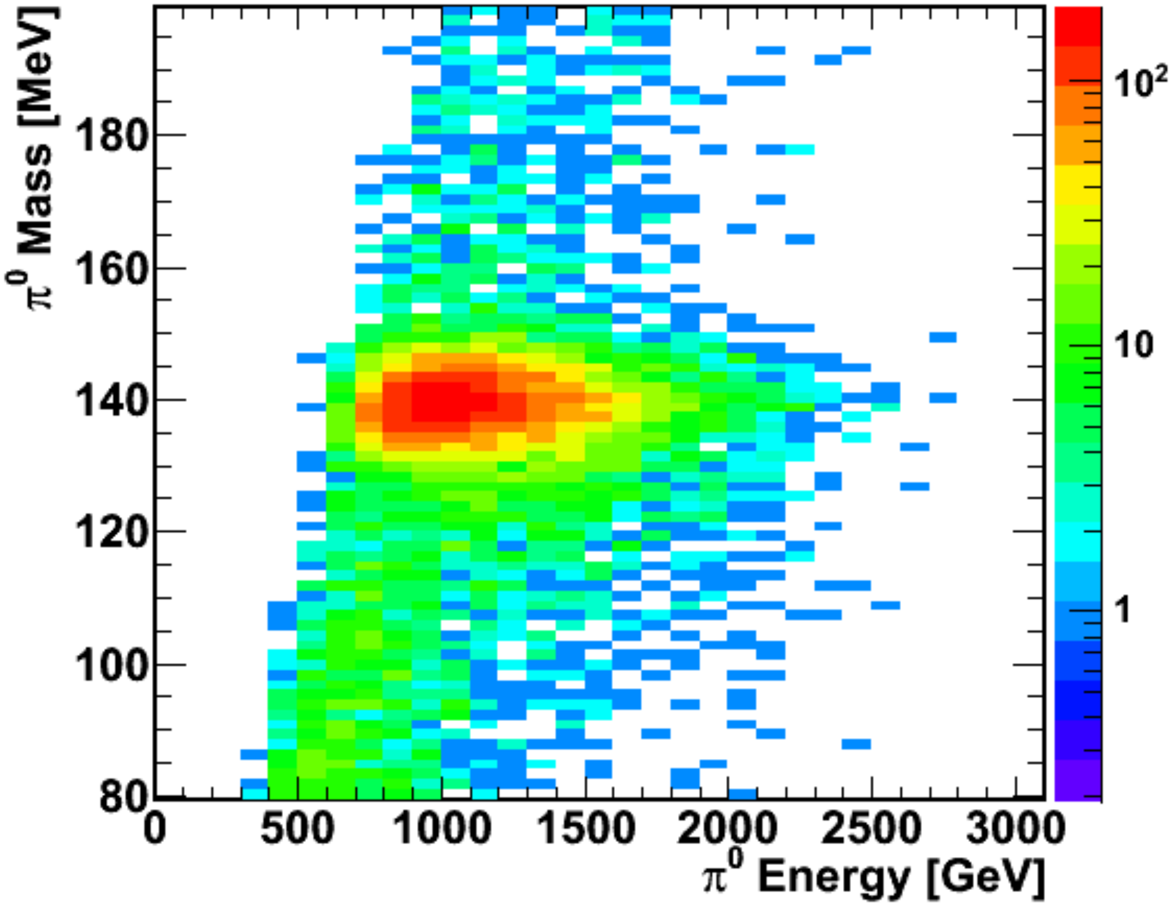
- Disagreement in the peak position
- No ‘hand made correction’ is applied for safety
- Main source of systematic error → see later

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





π^0 mass vs π^0 energy



Arm2 Data
No strong energy dependence of reconstructed mass

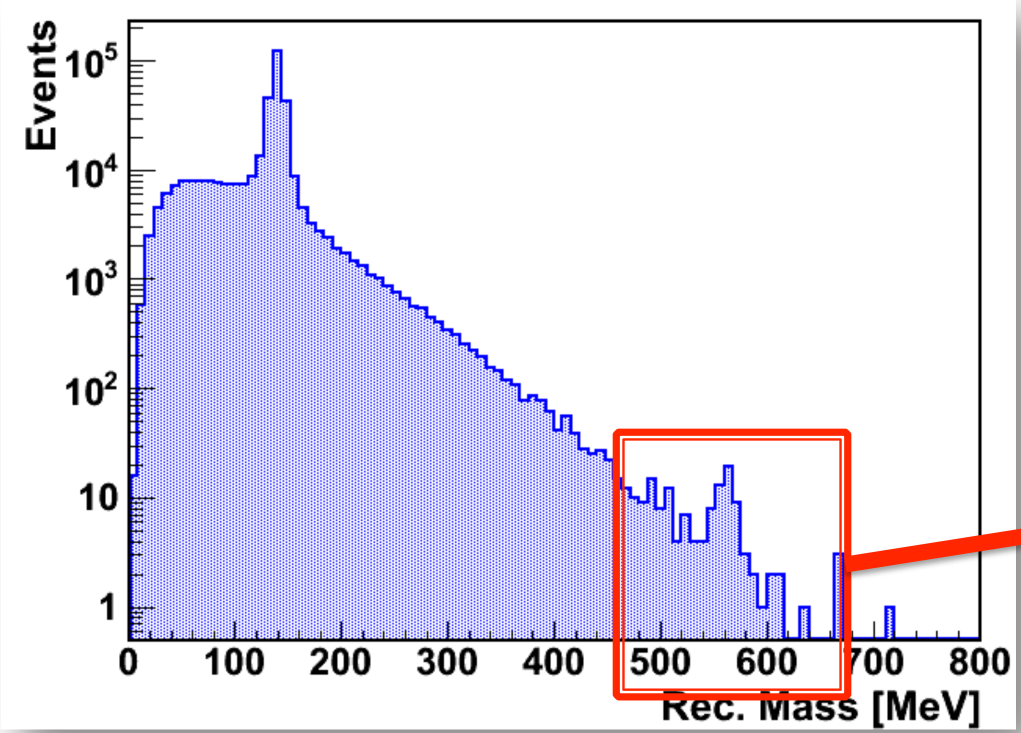
η MASS

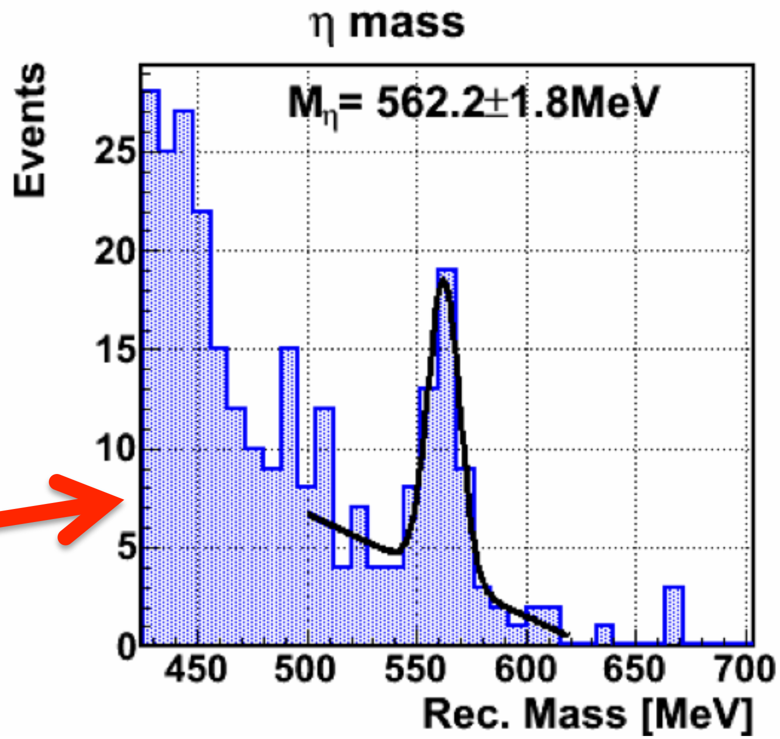
Arm2 detector, all runs with zero crossing angle

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)

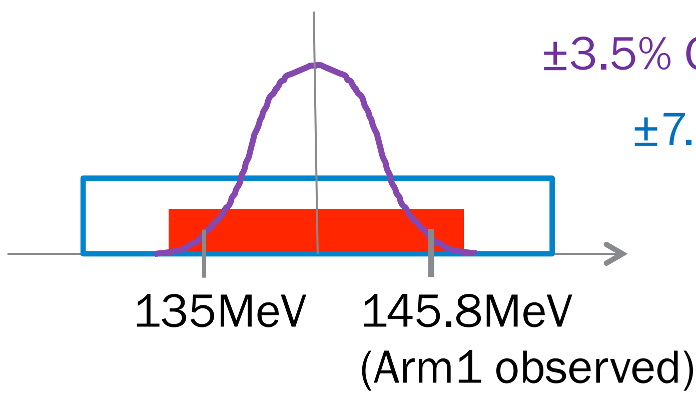




EFFECT OF MASS SHIFT

- ✓ Energy rescaling **NOT** applied but included in energy error
- ✓ $M_{inv} = \theta \sqrt{(E_1 \times E_2)}$
  - $(\Delta E/E)_{calib} = 3.5\%$
  - $\Delta\theta/\theta = 1\%$
  - $(\Delta E/E)_{leak\text{-}in} = 2\%$

  => $\Delta M/M = 4.2\%$; not sufficient for Arm1 (+7.8%)



Quadratic sum of two errors is given as energy error (to allow both 135MeV and observed mass peak)

π^0 mass shift in study

Reanalysis of SPS calibration data in 2007 and 2010 (post LHC) <200GeV

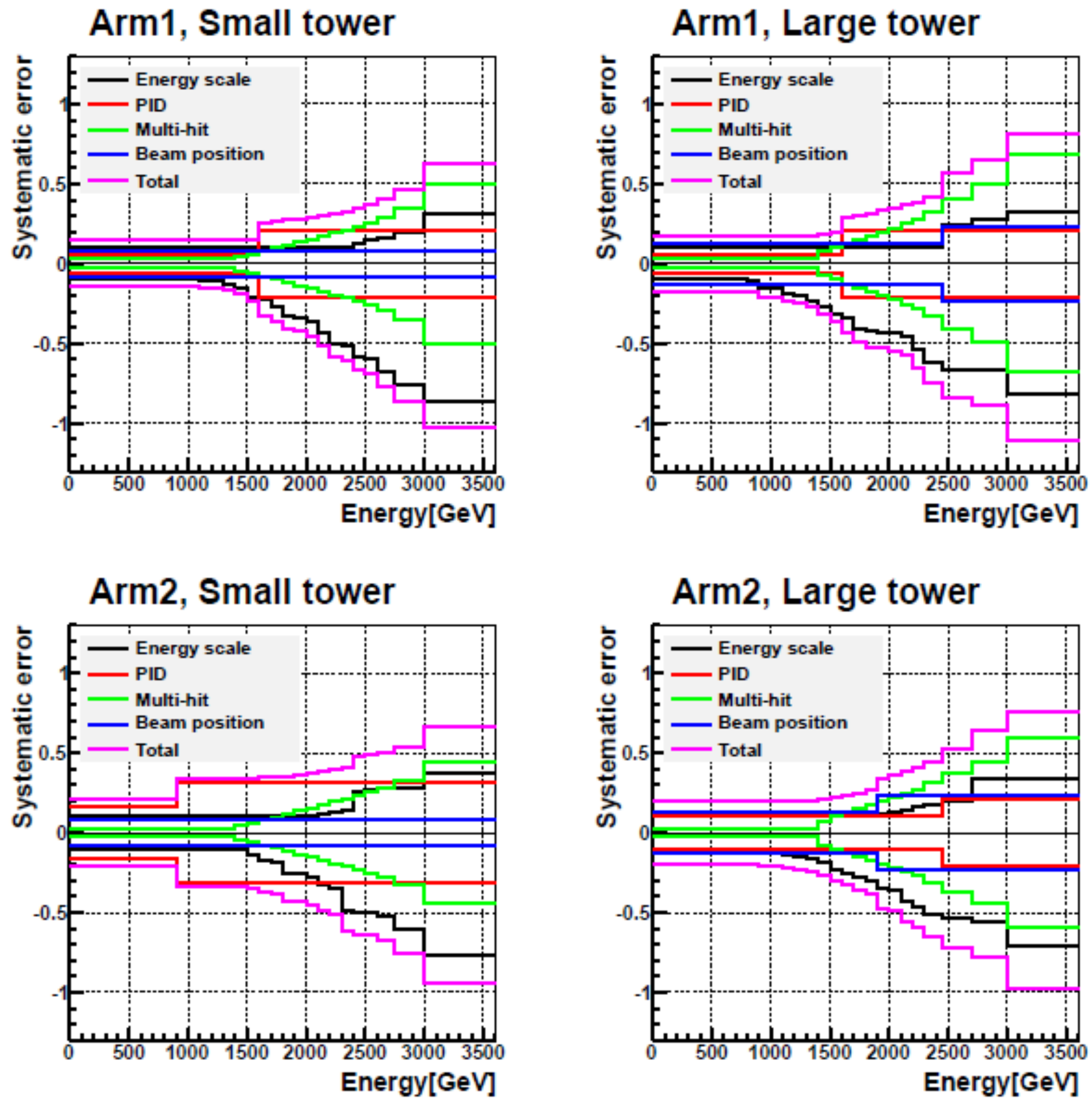
Reevaluation of systematic errors

Reevaluation of EM shower using different MC codes (EPICS, FLUKA, GEANT4)

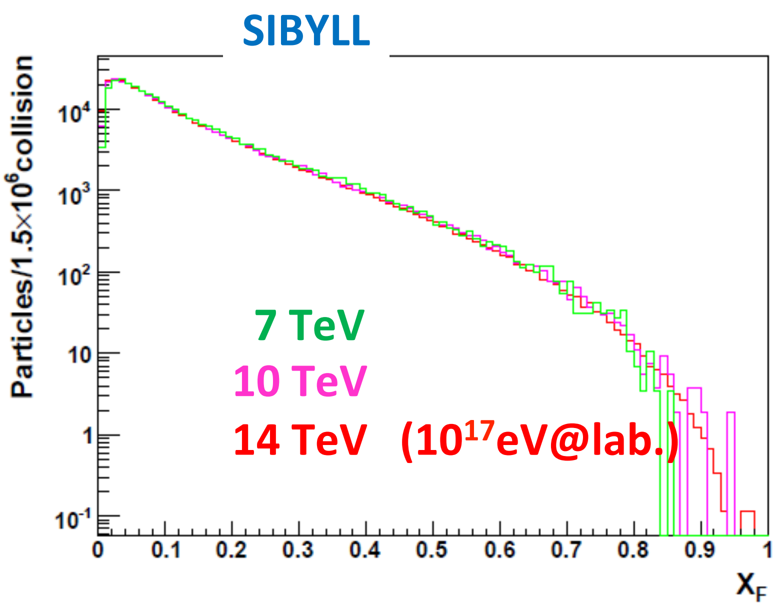
Cable attenuation recalibration(1-2% improve expected)

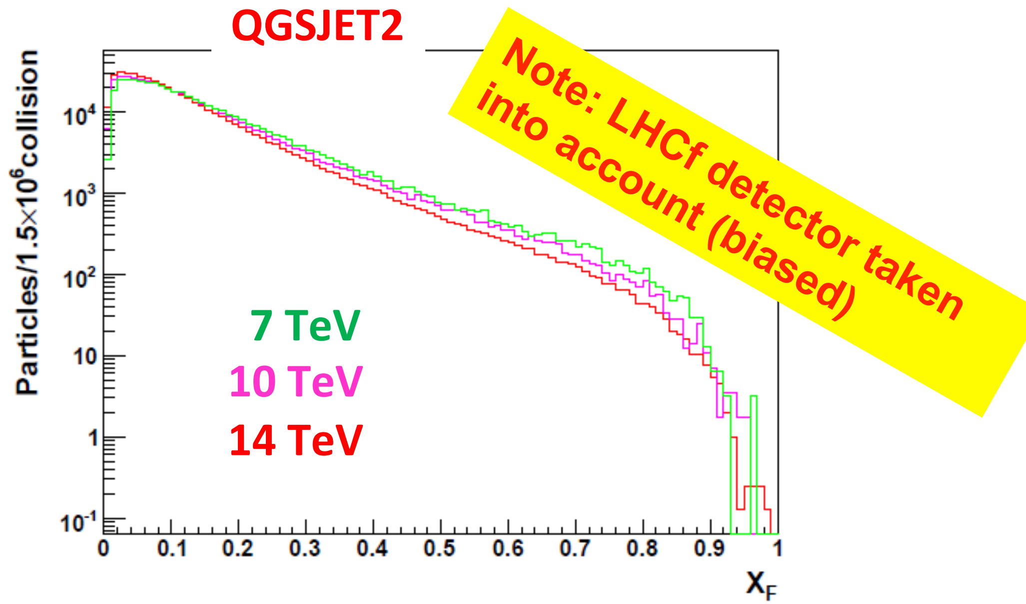
Re-check all 1-2% effects…

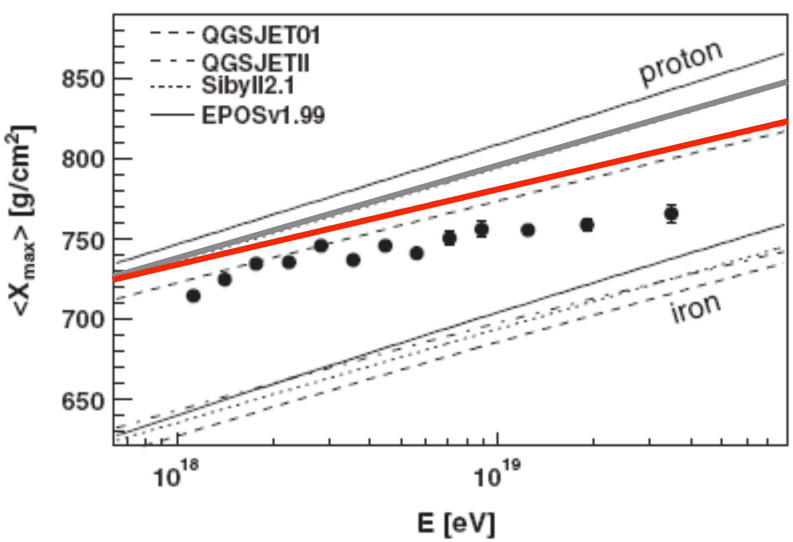
SUMMARY OF SYSTEMATIC ERRORS



14TEV: NOT ONLY HIGHEST ENERGY, BUT ENERGY DEPENDENCE…







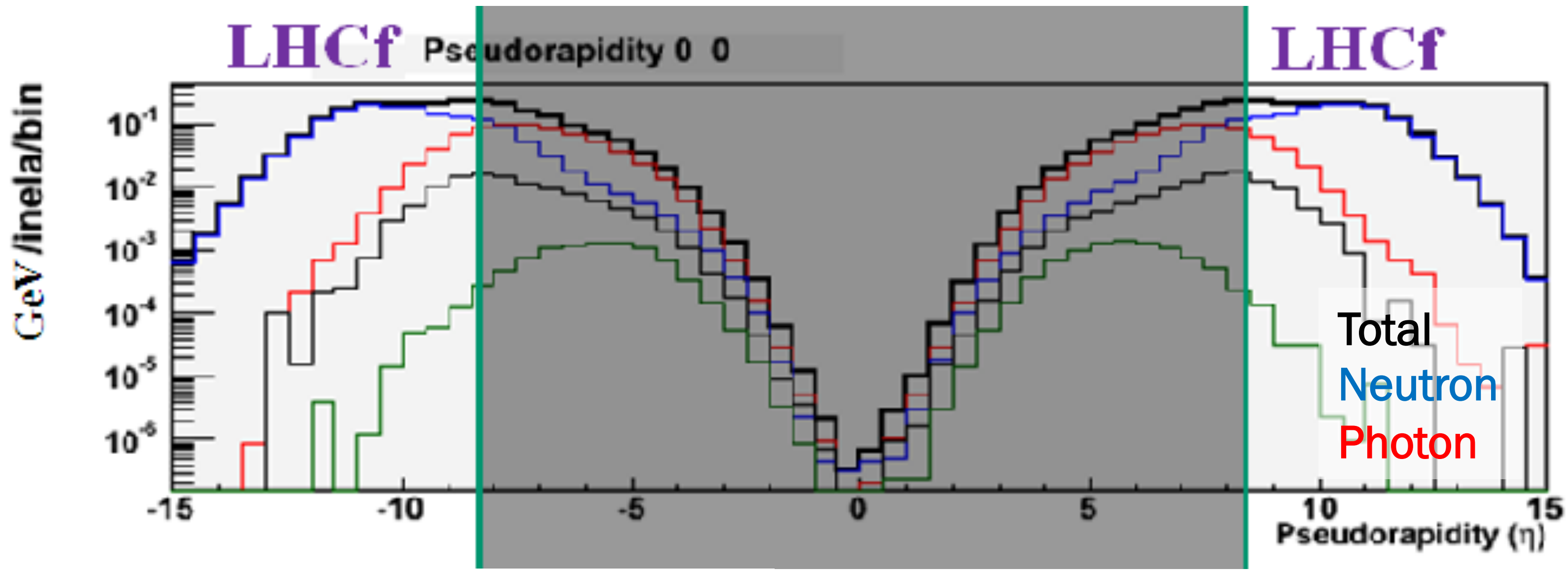
Secondary gamma-ray spectra in p-p collisions at different collision energies (normalized to the maximum energy)

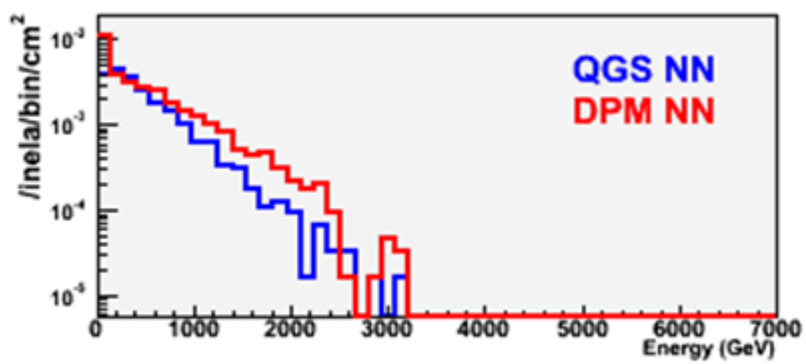
SIBYLL predicts perfect scaling while QGSJET2 predicts softening at higher energy

Qualitatively consistent with Xmax prediction

LHC-COSMIC ?

- ✓ p-Pb relevant to CR physics?
- ✓ CR-Air interaction is not p-p, but A_1-A_2 (A1:p, He,…,Fe, A2:N,O)





LHC Nitrogen-Nitrogen collisions

Top: energy flow at 140m from IP

Left : photon energy spectra at 0 degree

COMPARISON OF EJ260 AND GSO -RADIATION HARDNESS-

- EJ260 (HIMAC* Carbon beam)
  10% decrease of light yield after exposure of 100Gy
- GSO (HIMAC Carbon beam)
  No decrease of light yield even after 7*10^5Gy exposure,
  BUT increase of light yield is confirmed
- The increase depend on irradiation rate (~2.5%/[100Gy/hour])

*HIMAC : Heavy Ion Medical Accelerator in Chiba