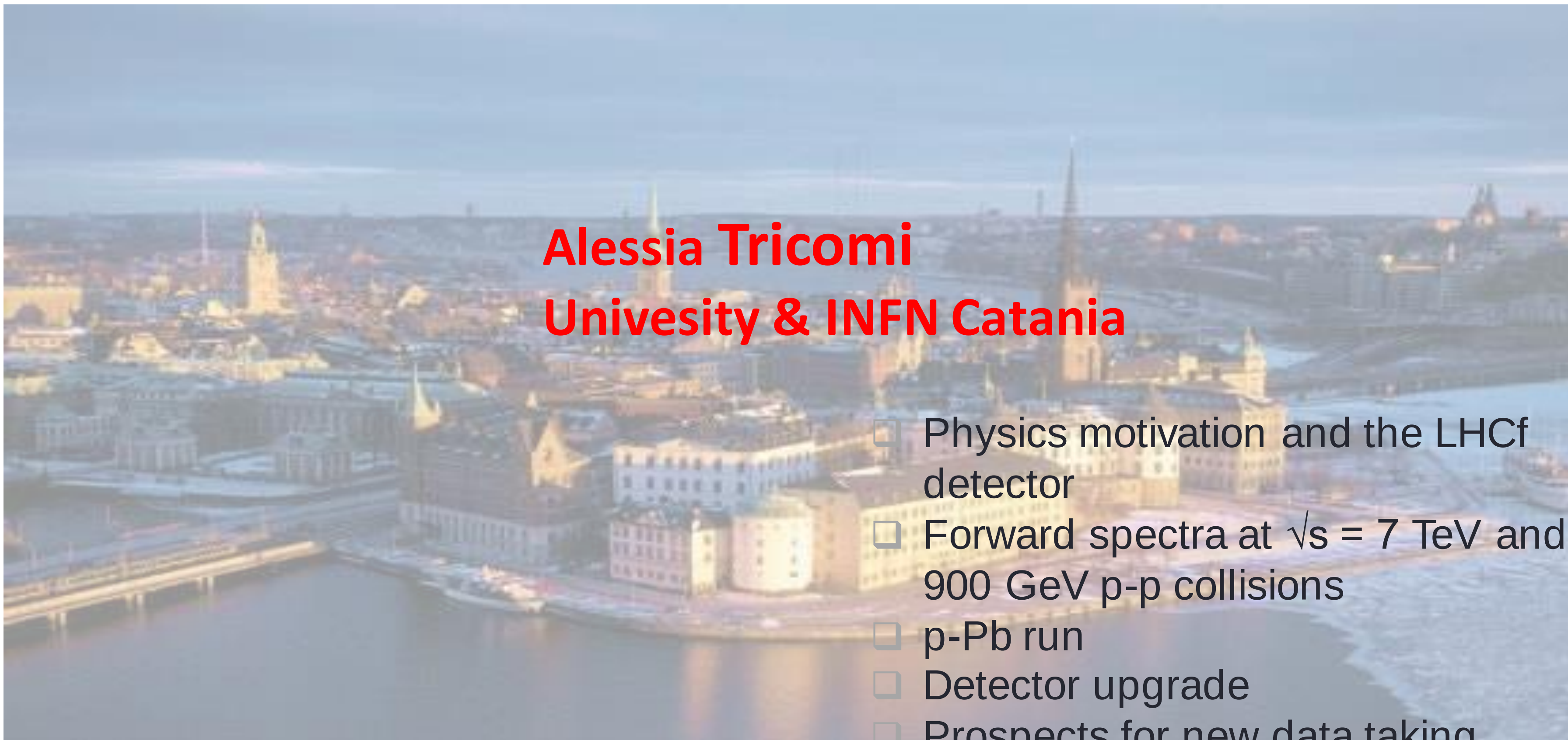
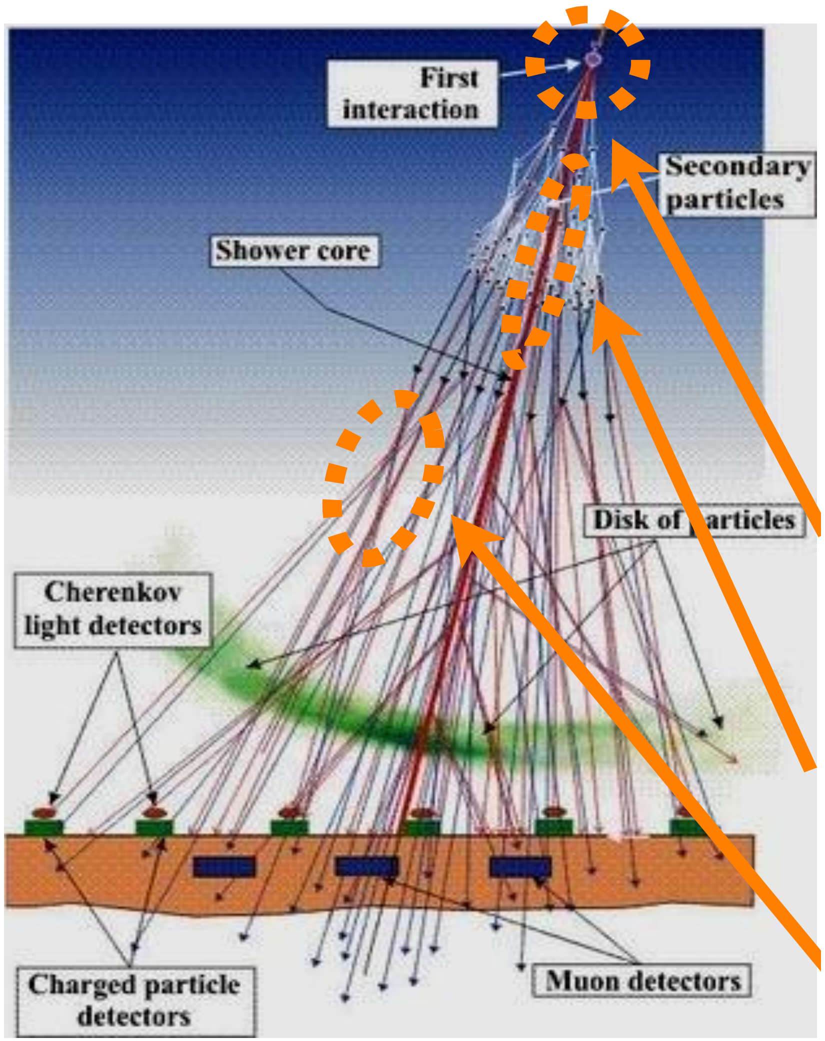
Physics results of the LHCf experiment



Alessia Tricomi
Univesity & INFN Catania

- Physics motivation and the LHCf detector
- Forward spectra at √s = 7 TeV and 900 GeV p-p collisions
- p-Pb run
- Detector upgrade
- Prospects for new data taking

p-p interactions in the very forward region



- LHC gives a unique opportunity to calibrate the hadronic intection models up to

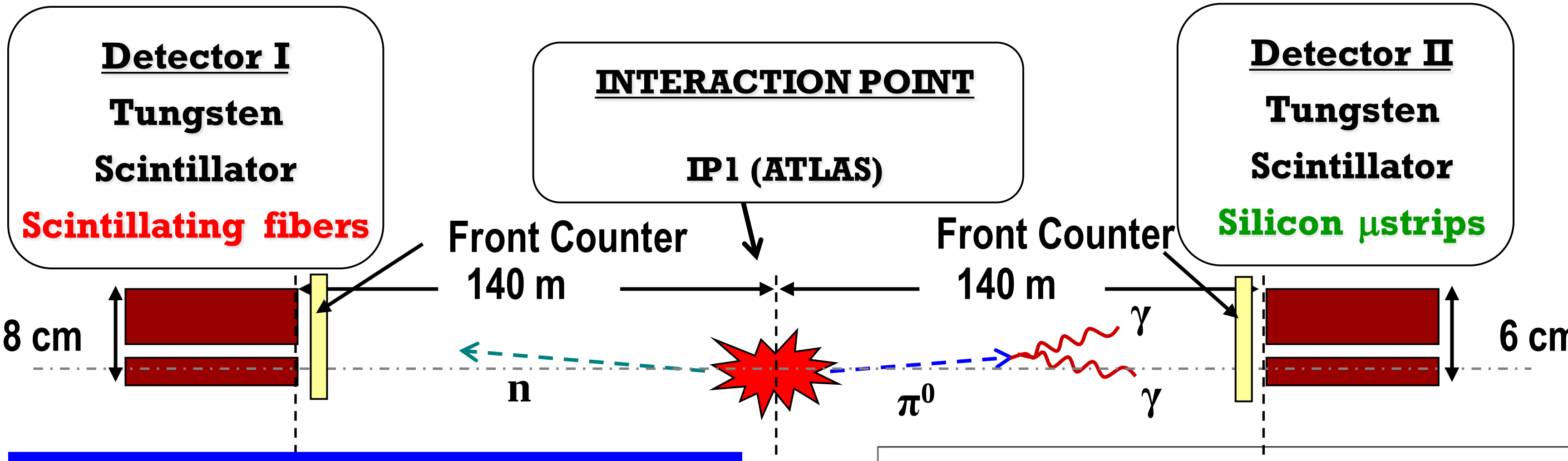
6.5TeV+6.5TeV	→ $E_{lab} = 10^{17}$eV
3.5TeV+3.5TeV	→ $E_{lab} = 2.6\times10^{16}$eV
450GeV+450GeV	→ $E_{lab} = 2\times10^{14}$eV

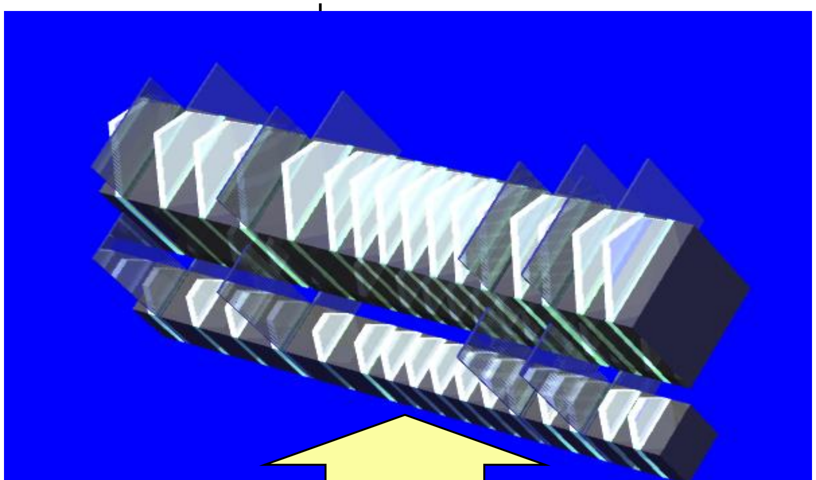
- Forward region is very effective on air shower development

Key Parameters

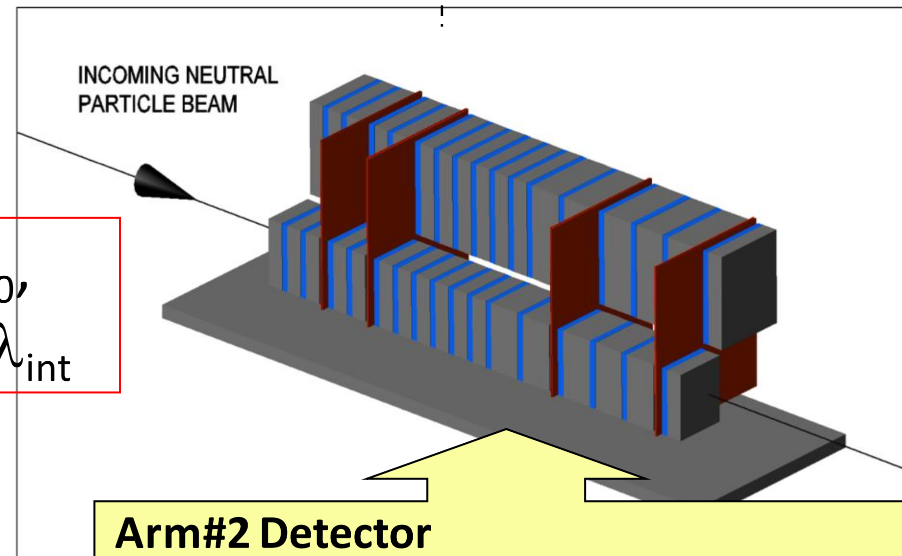
- ✓ Inelastic Cross Section
  →TOTEM, ATLAS, CMS,ALICE
- ✓ Forward Energy Spectrum
  →LHCf, ZDC and etc.
- ✓ Inelasticity k= 1-plead/pbeam
  →LHCf, ZDC and etc.
- ✓ Secondary interactions

LHCf: location and detector layout





44X_0,
1.6 λ_{int}



Arm#1 Detector
20mmx20mm+40mmx40mm
4 X-Y SciFi tracking layers

Arm#2 Detector
25mmx25mm+32mmx32mm
4 X-Y Silicon strip tracking layers

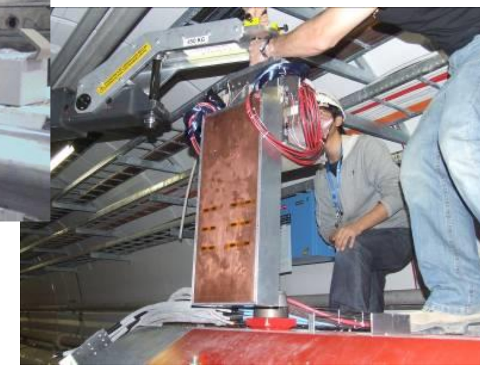
LHCf: a brief photo-history

- May 2004 LOI
- Feb 2006 TDR
- June 2006 LHCC approved

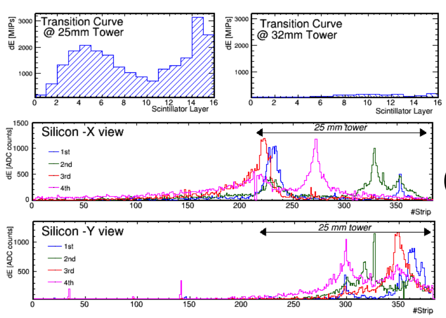
Jul 2006 construction

Aug 2007 SPS beam test

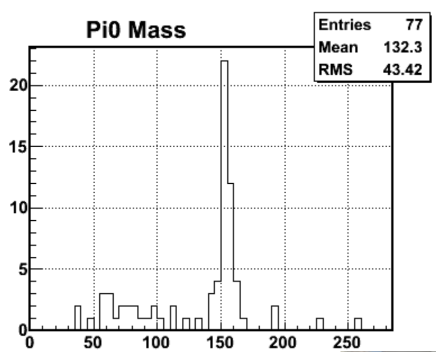
Jan 2008 Installation



Dec 2009 1st 900GeV run



Mar 2010 1st 7TeV run



Jul 2010 Detector removal

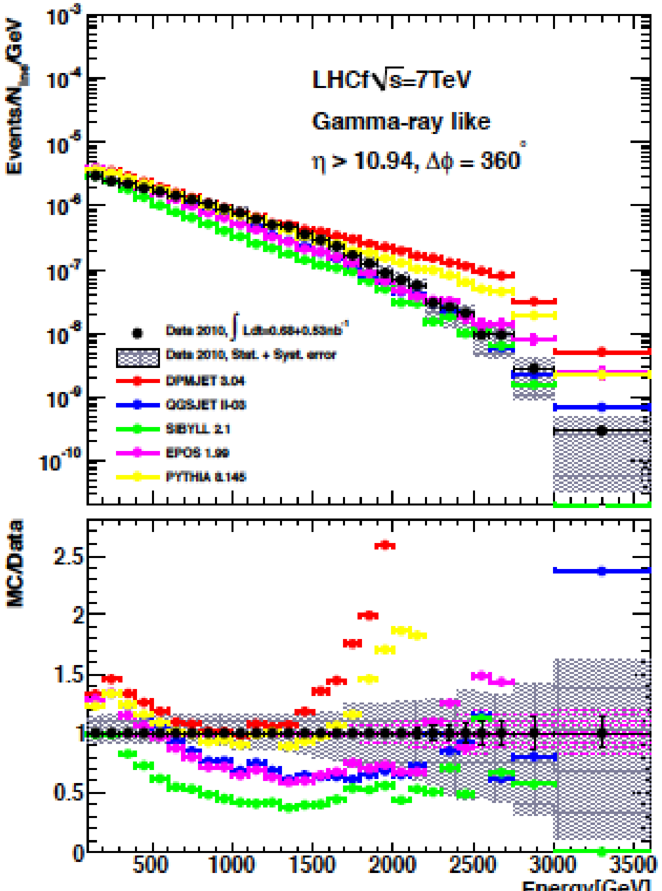
Dic 2012 ARM2 re-installation

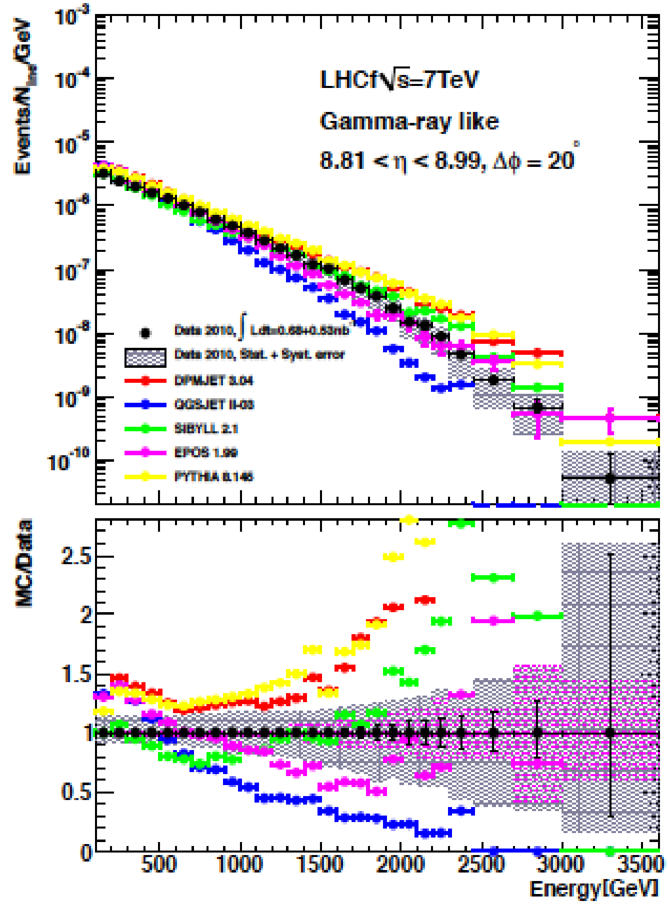
Gen-Feb 2013 p-Pb run

April 2013 → Detector removal and upgrade

Single photon spectra at 7 TeV p-p

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





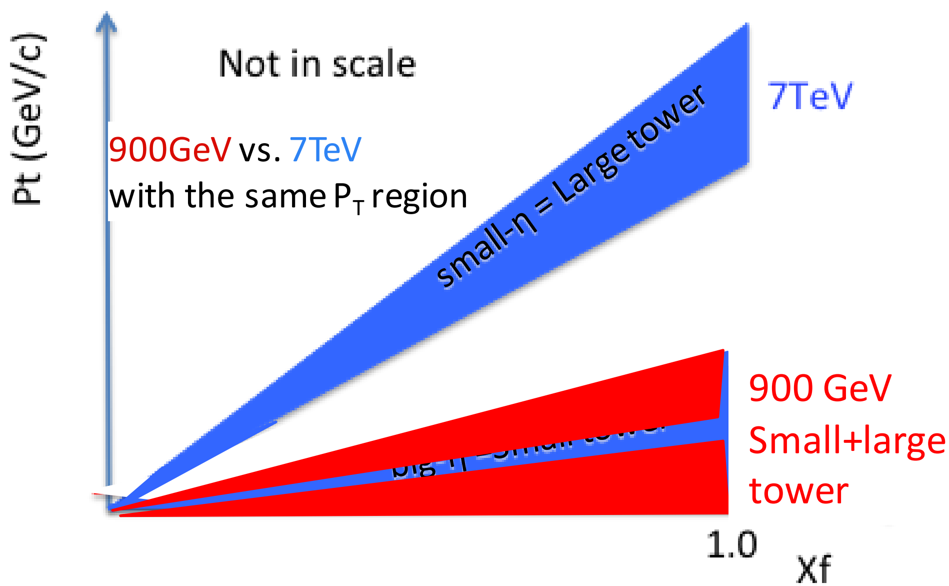
No Model able to reproduce LHCf data especially in the high-energy region

Magenta hatch: MC Statistical errors

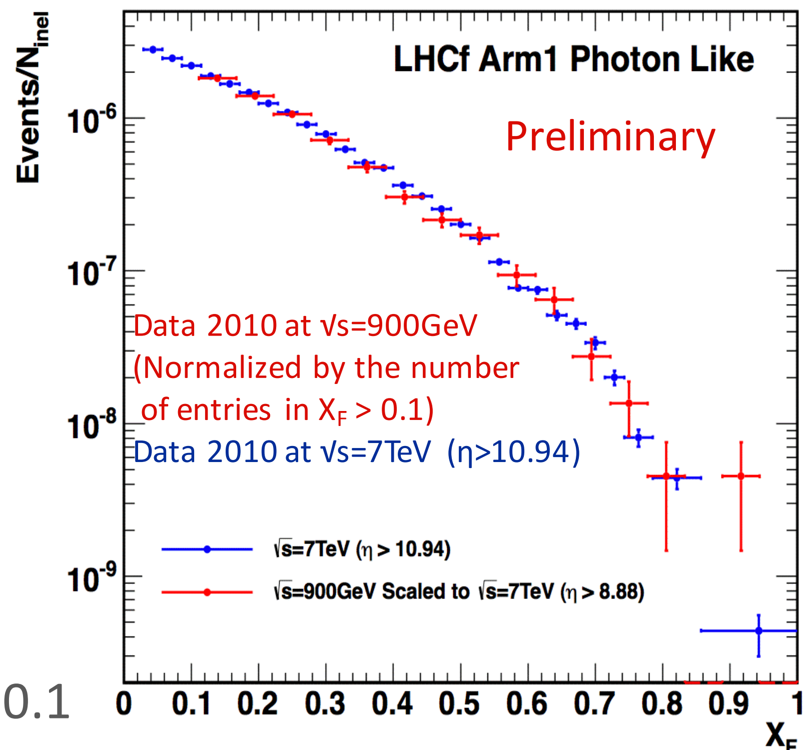
Gray hatch : Systematic Errors

Photons : 900GeV vs 7TeV spectra

Coverage of the photon spectra in the plane Feynman-X vs P_T



X_F spectra : 900GeV data vs. 7TeV data

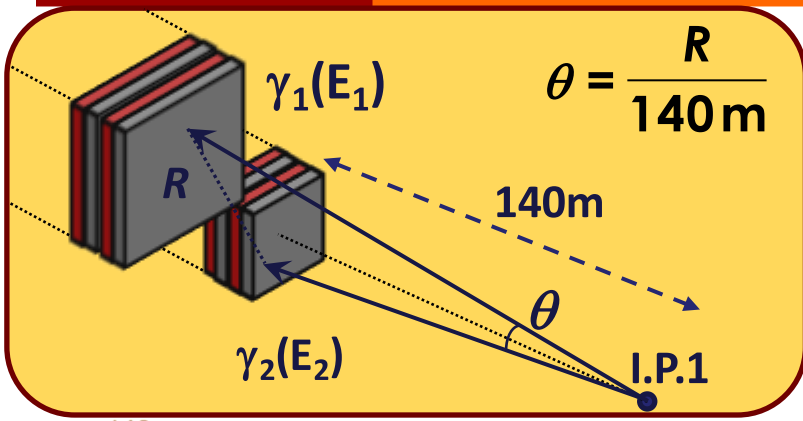


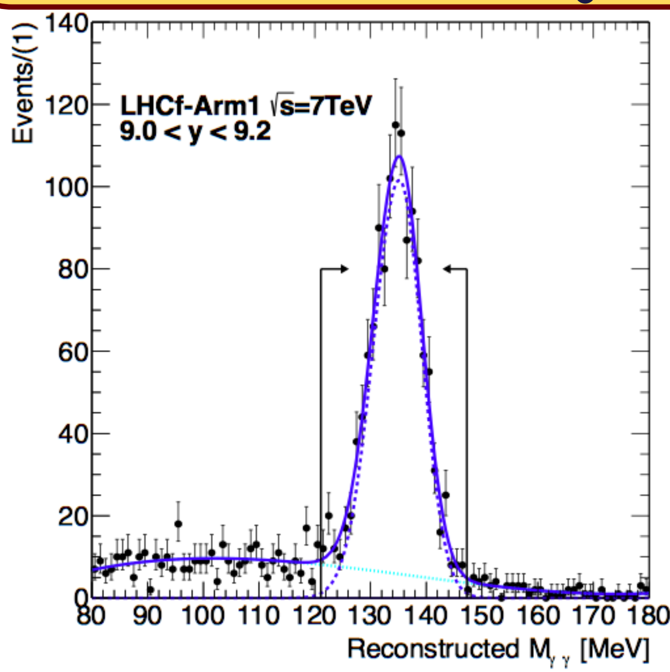
- ✓ Normalized by the number of entries in $X_F > 0.1$
- ✓ No systematic error is considered in both collision energies.

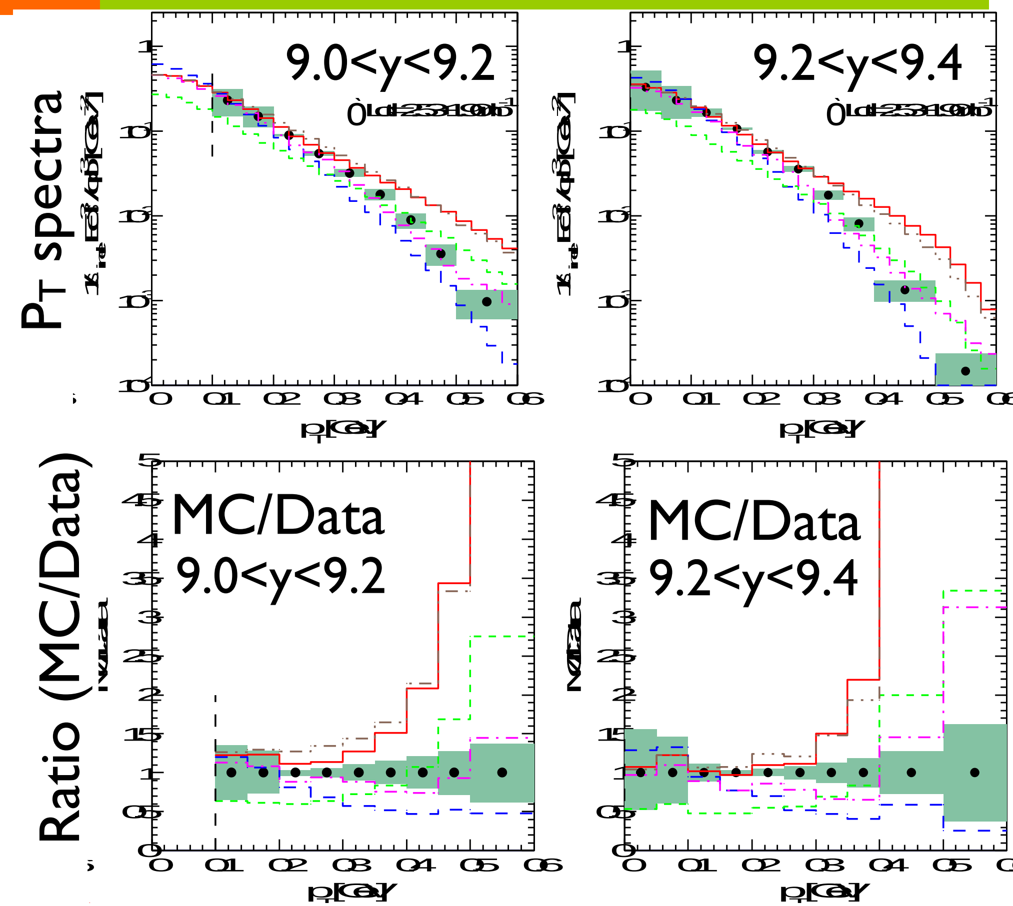
Good agreement of X_F spectrum shape between 900 GeV and 7 TeV.

➔ weak dependence of $\langle p_T \rangle$ on E_{CMS}

7 TeV π⁰ analysis







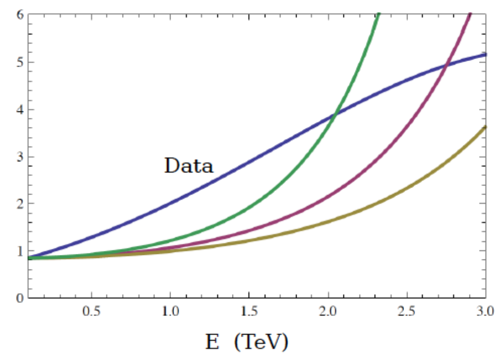
Same conclusions as for photons results

- No model able to reproduce LHCf data
- Best overall agreement with EPOS 1.99

LHCf <p_T> distribution

Courtesy P. LIPARI

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



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

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

Directly relevant for UHECR shower development

pT distribution dependence

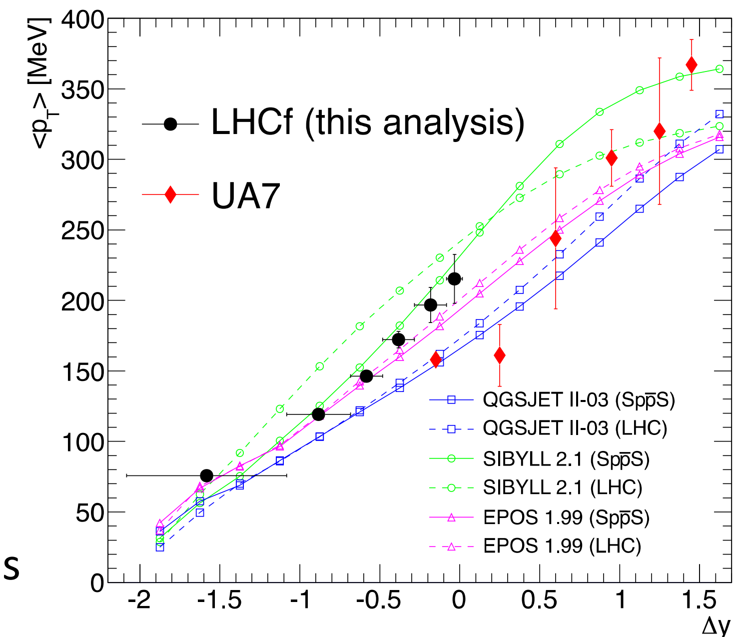
Three different approaches used to derive the average transverse momentum, ⟨p_T⟩

1. by fitting an empirical function to the p_T spectra in each rapidity range (exponential distribution based on a thermodynamical approach)

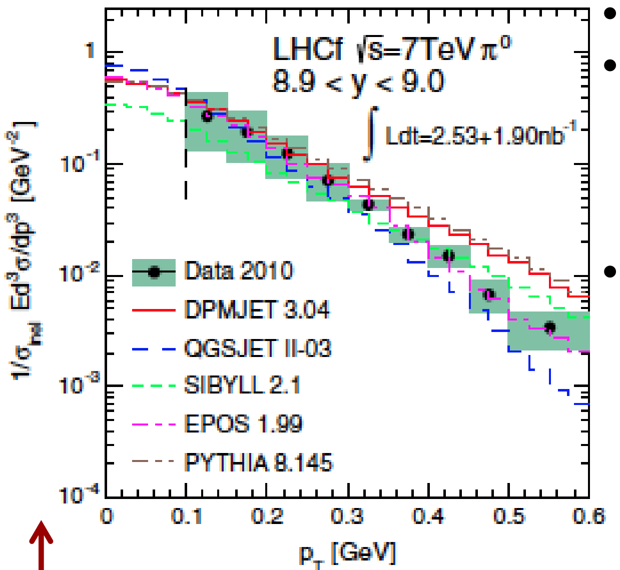
1. by fitting a gaussian distribution

2. by simply numerically integrating the p_T spectra

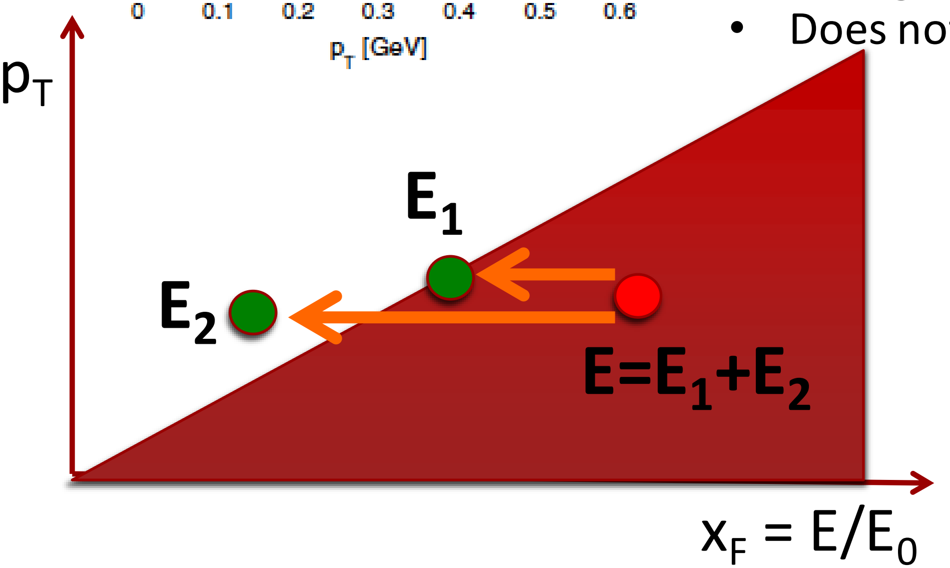
Results of the three methods are in agreement and are compared with UA7 data and hadronic model predictions

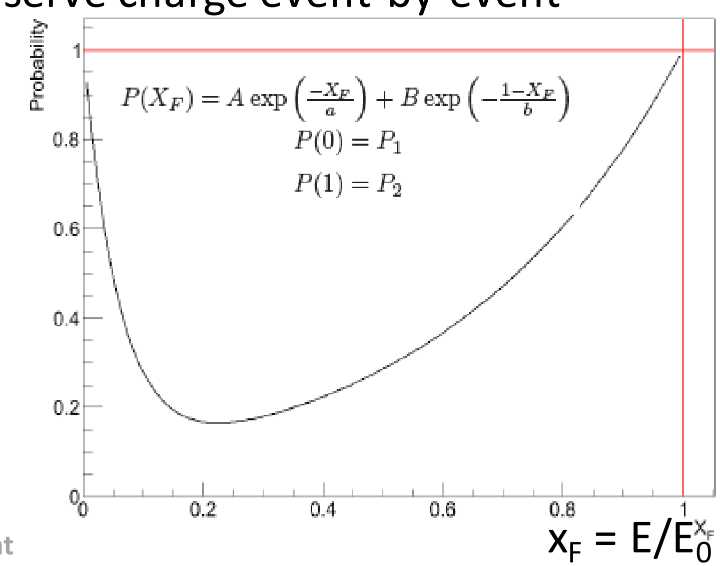


Playing a game with air shower
(effect of forward meson spectra)

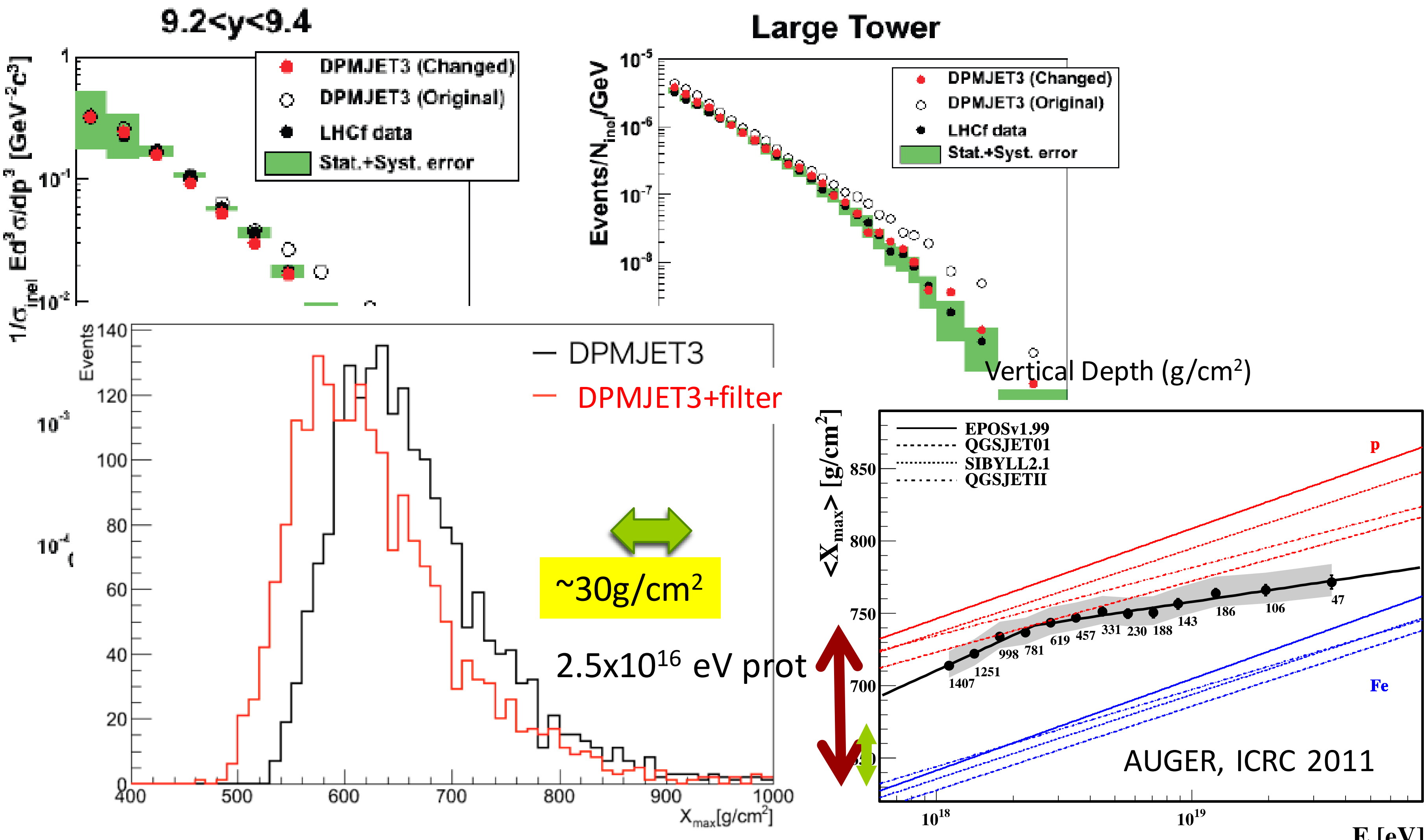


- DPMJET3 always over-predicts production
- Filtering DPMJET3 mesons
  - according to an empirical probability function, divide mesons into two with keeping p_T
  - Fraction of mesons escape out of LHCf acceptance
- This process
  - Holds cross section
  - Holds elasticity/inelasticity
  - Holds energy conservation
  - Changes multiplicity
  - Does not conserve charge event-by-event





An example of filtering

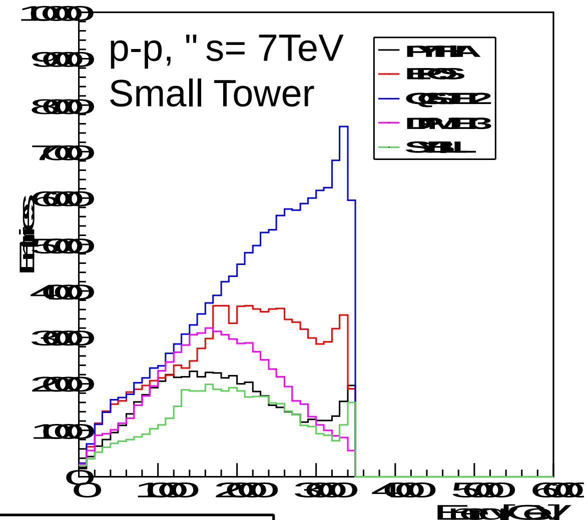


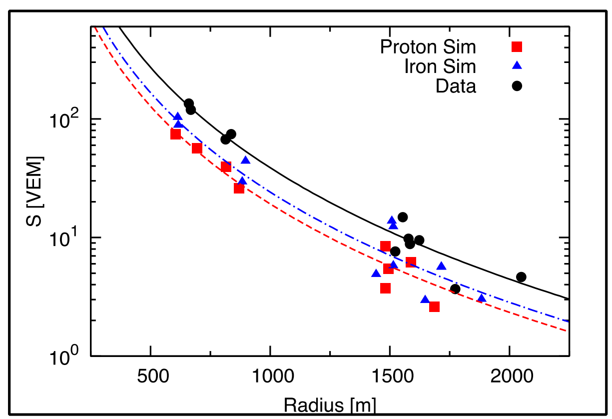
Neutron spectra

- Motivations:
  - Inelasticity measurement k=1-$p_{leading}/p_{beam}$
  - Muon excess at Pierre Auger Observatory
    - EPOS predicts more muons due to larger baryon production ((T. Pierog and K. Warner PRL 101, 171101, 2008)
    - => importance of baryon measurement
- Performance for neutrons

Efficiency	~70%
Energy Res.	35-40%
Position Res.	a few mm

Neutron spectra predicted by interaction models



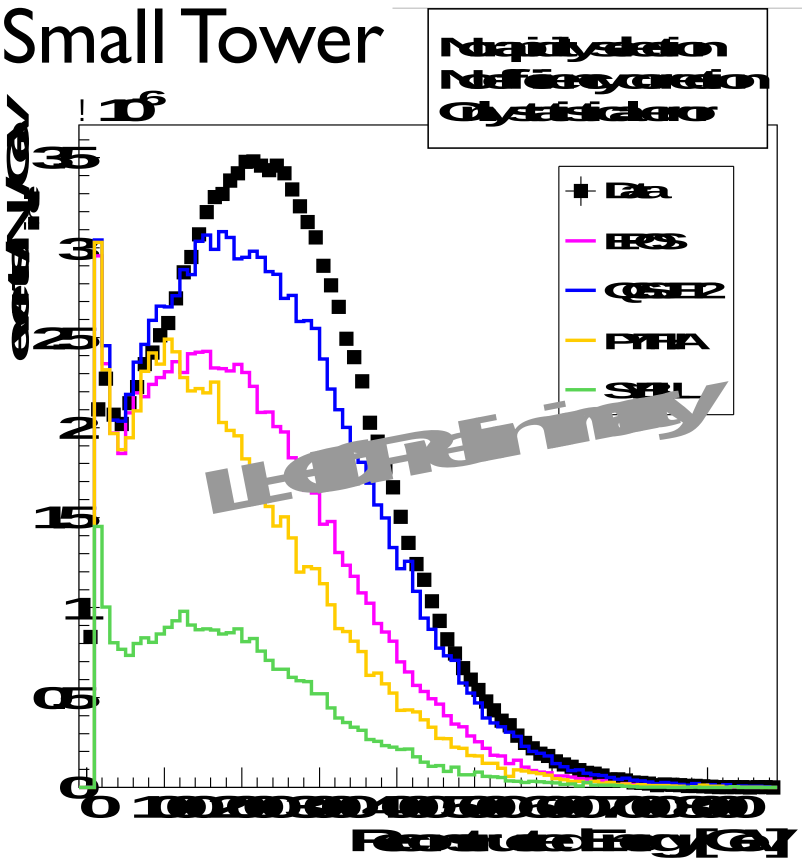


[J.Allen, et al. ICRC2011 Proceedings]

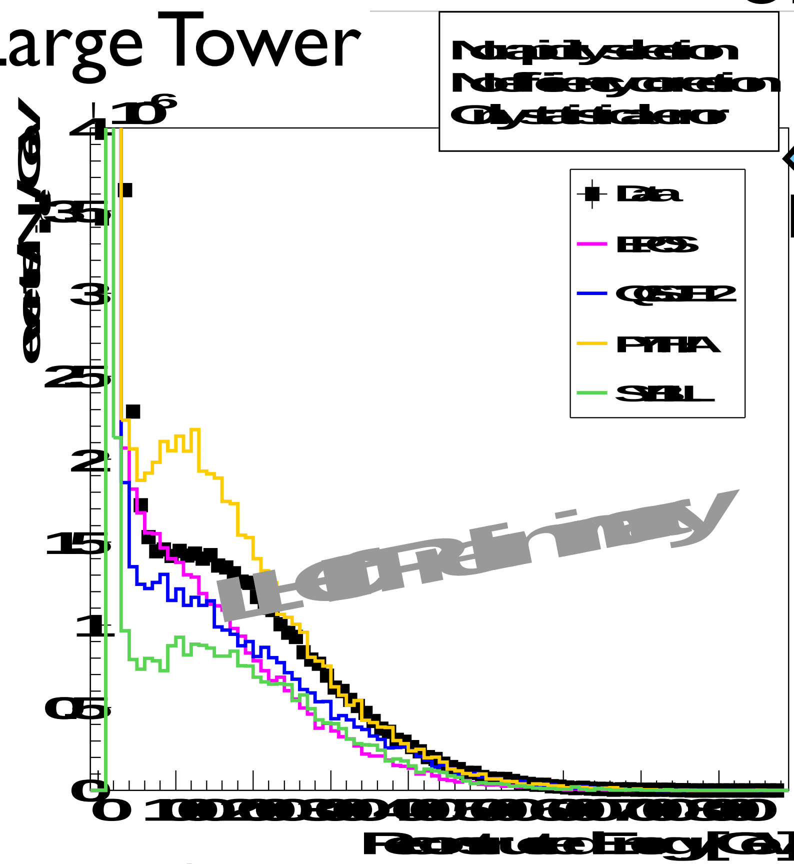
Neutron spectra

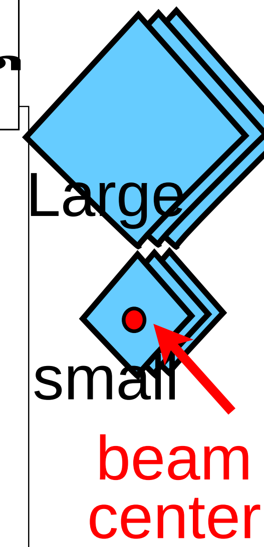
Only Arm1

Small Tower



Large Tower

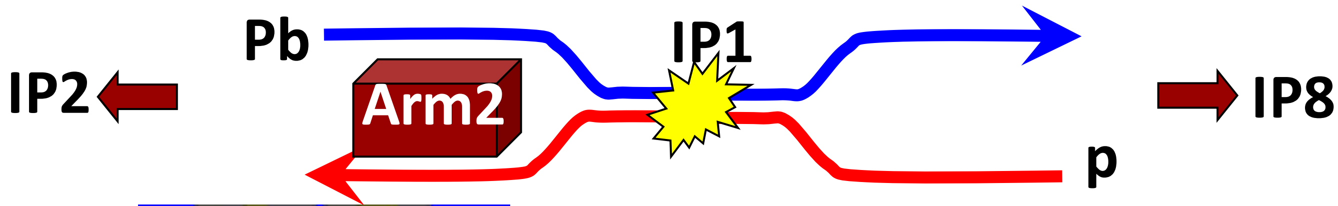


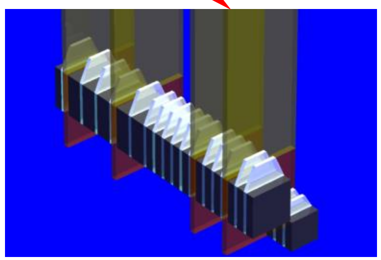


Estimations of systematic uncertainties
Study of unfolding
ARM2 analysis

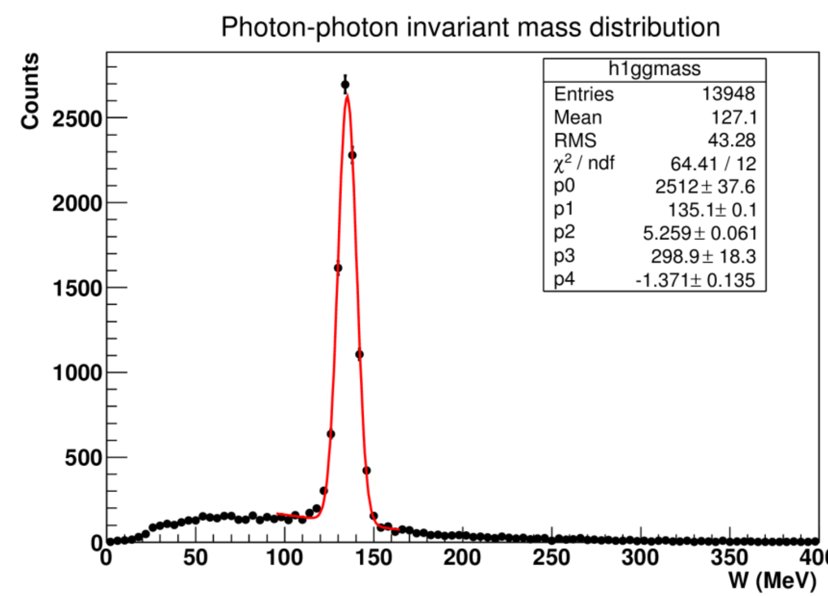
} On going

Operation in Jan-Feb 2013

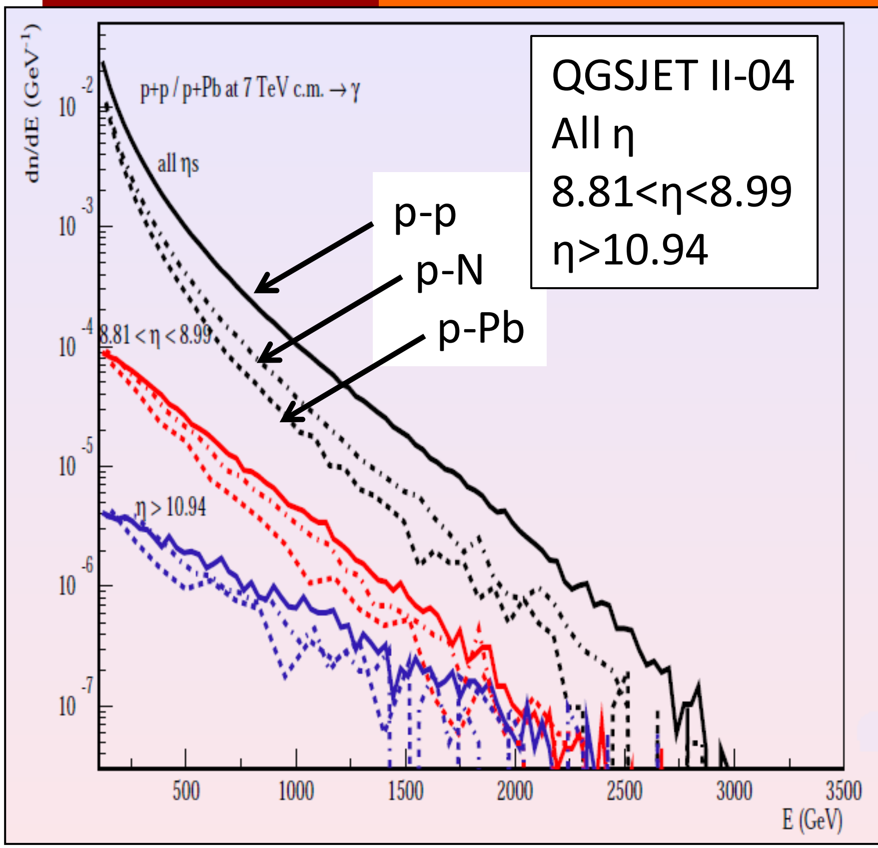


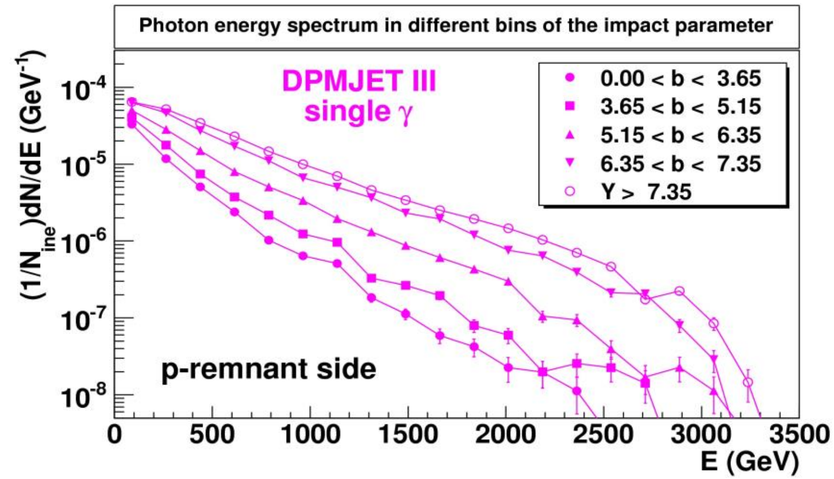


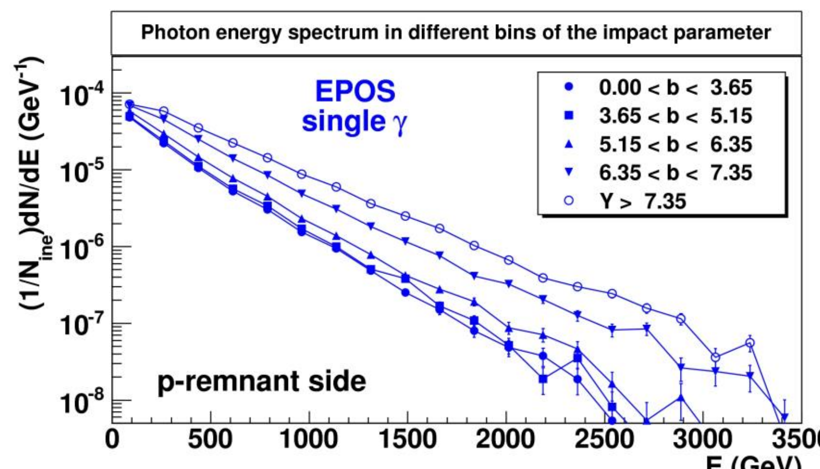
- p-Pb/Pb-p operation
  - One arm (Arm2) observation
  - p-remnant side (little Pb remnant)
  - Common trigger with ATLAS
- 2.76 TeV p-p operation



Physics in p-A







Photon spectra at different η in p-p, p-N and p-Pb collisions

Enhancement of suppression for HI

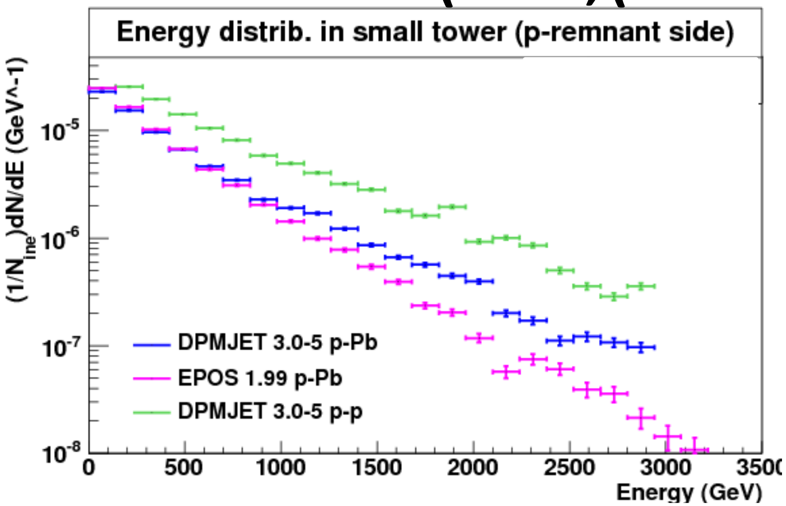
(Courtesy of S.Ostapchenko)

Nuclear effect in the forward particle production

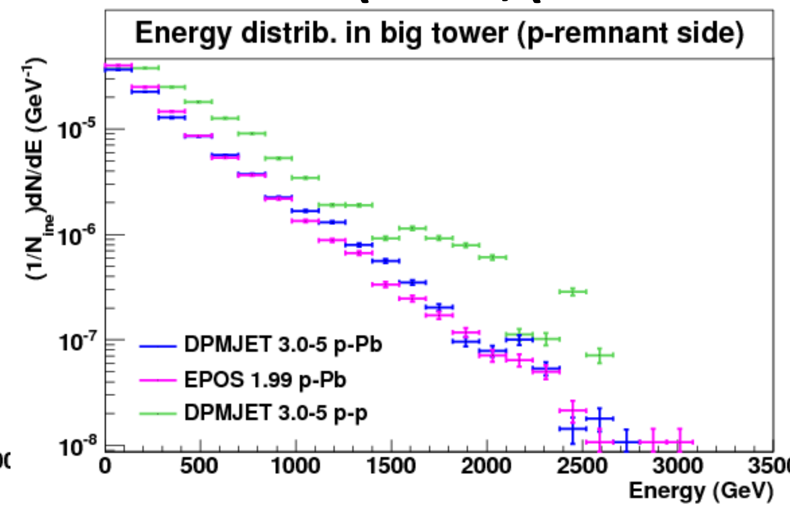
Photon spectra for different impact parameters

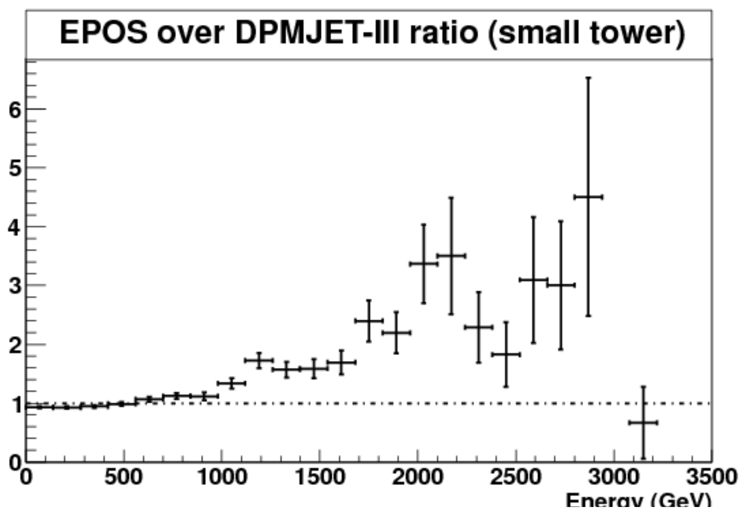
LHCf p-Pb run: Photon spectra

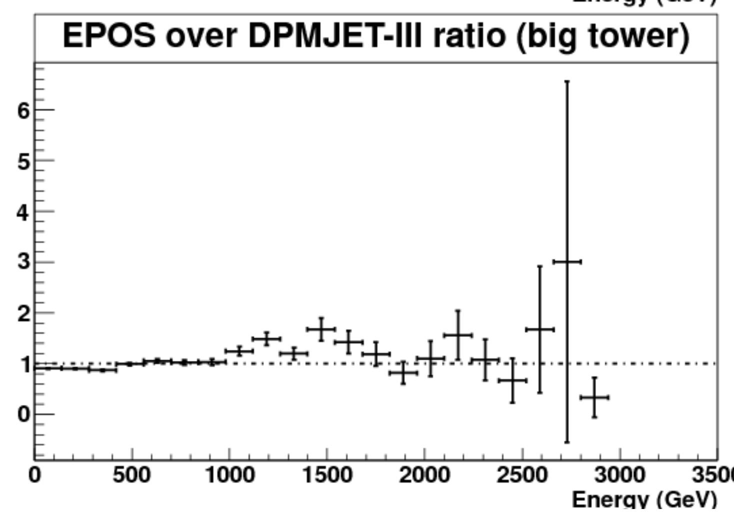
B' . C(:- L +,(



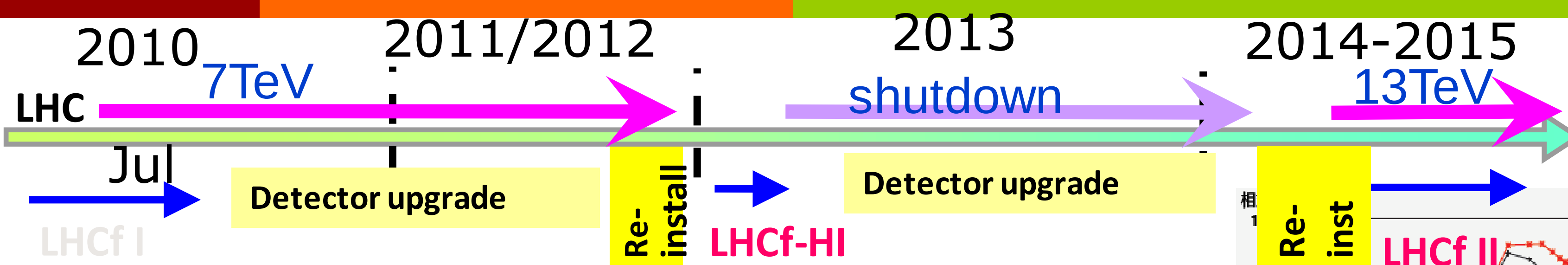
YDE(:- L +,(

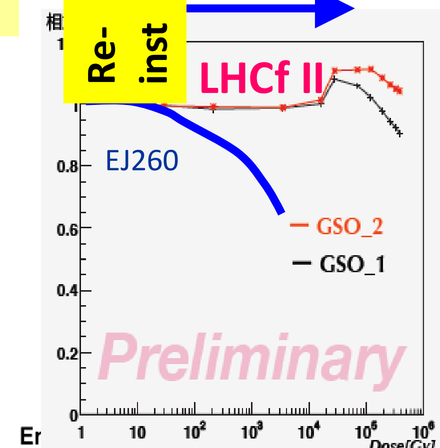






LHCf Future PLANS

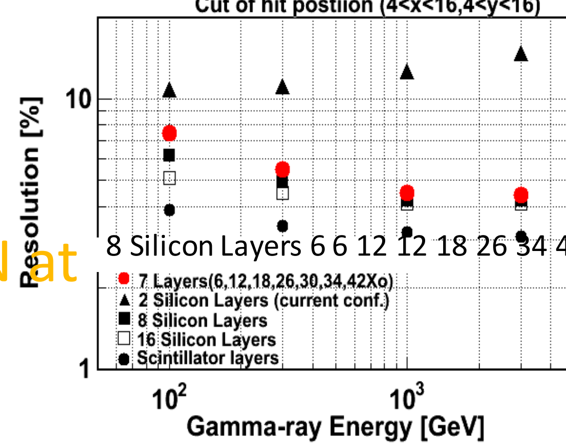




2013-2014: Detector upgrade for 13 TeV run

- Replaced plastic scintillators with Rad Hard GSO
- Modify the silicon layers positions to improve silicon-only energy resolution and improve the dynamic range of silicon
- Test beam at SPS to calibrate ARM1/2
- Re-installation of the detector

Cut of hit postion (4<x<16,4<y<16)



8 Silicon Layers 6 6 12 12 18 26 34 42 X

2015: run at 13 TeV p-p collision at LHC

2016 … Operation at RHIC, p-p at $\sqrt{s}$=500GeV, p-N at $\sqrt{s_{NN}}$=200GeV (proposal presented at BNL PAC)

2019??? Run at LHC in p-light A

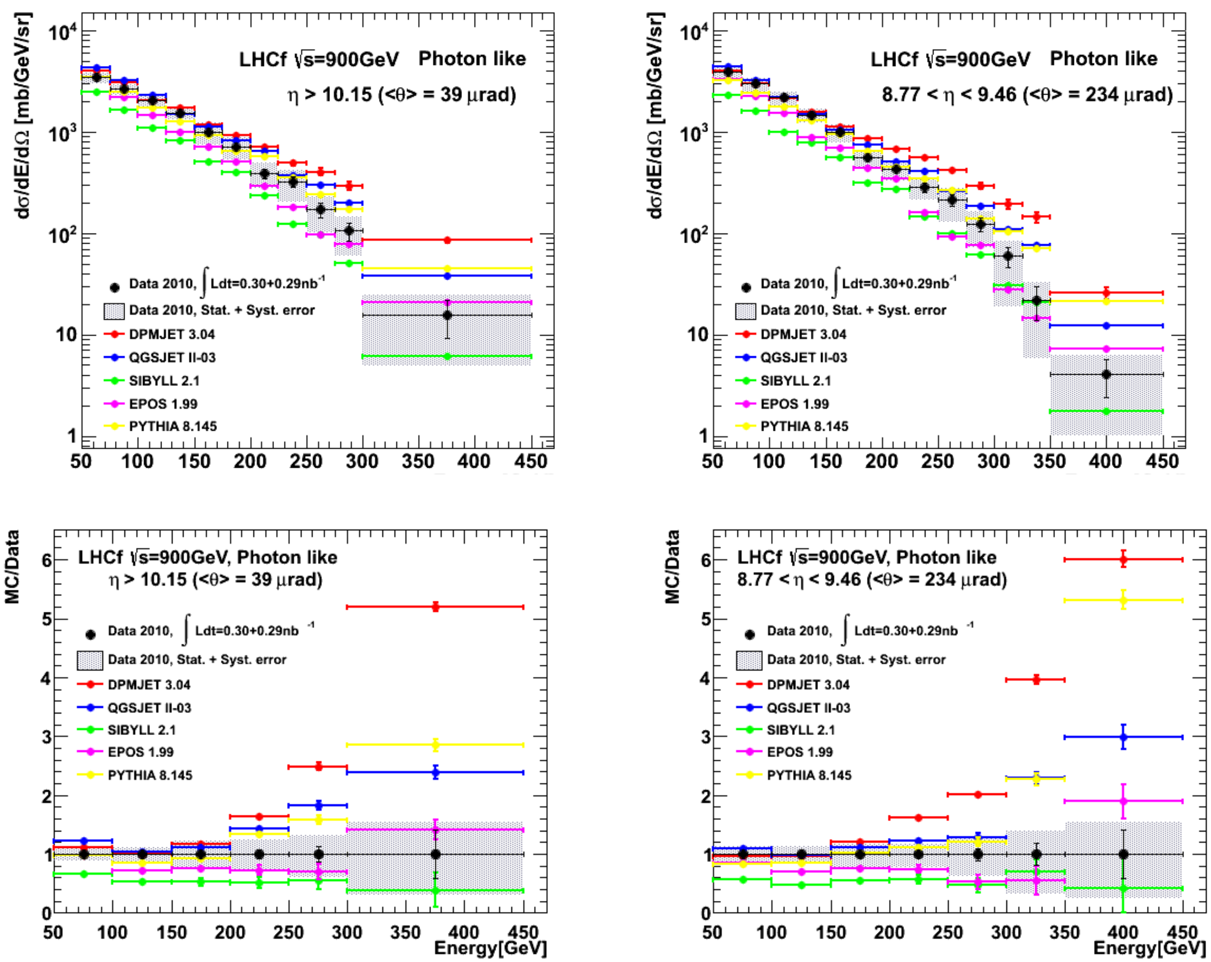
Conclusions

- The first LHCf data taking at LHC was very successful
  - 7 TeV and 900 GeV inclusive photon spectra and π^0 p_T spectra published
    - 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
    - Comparisons with models gives important hints for HECR and soft QCD Physics
  - Neutron spectra in p-p and photon spectra in p-Pb analyses are ongoing
- We have clearly demonstrated the imortance of a calibration of hadronic interaction models used in HECR Physics
  - Implications of our data in UHECR Physics under study in strict connection with relevant theoreticians and model developer
- We are upgrading the detectors to improve their radiation hardness
- We are also planning a possible run at RHIC with lighter ions (2016?) and waiting for LHC p-Light A(2019?)
- And of course...We are looking forward for the 13 TeV run with upgraded detector!!!

Backup slides

Some additional material

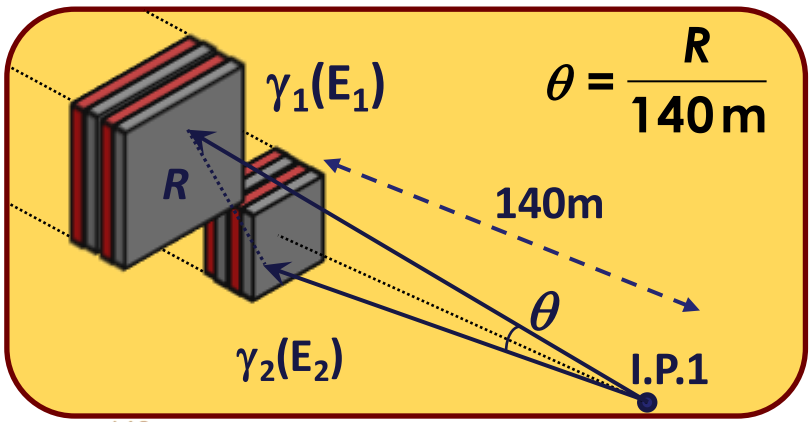
Single photon spectra at 900 GeV p-p



Results in agrrement with 7 TeV spectra

No Model able to reproduce LHCf data especially in the high-energy region

7 TeV π⁰ analysis

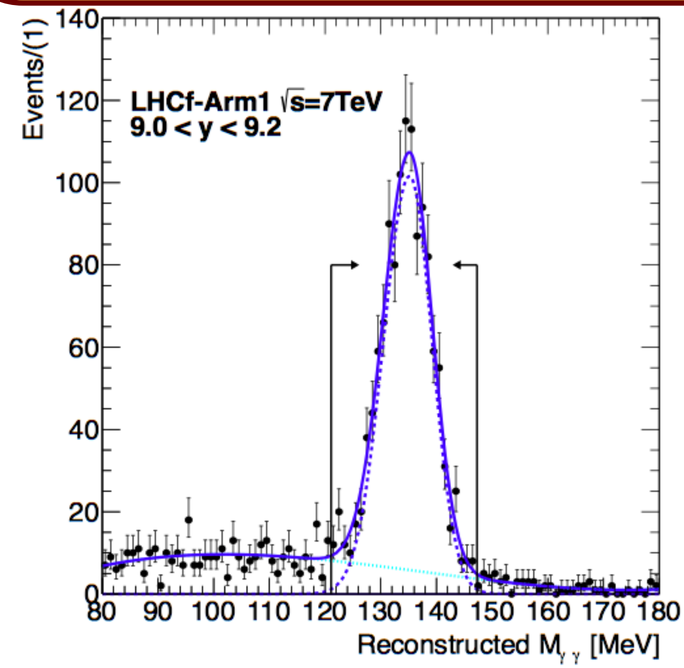


Mass, energy and transverse momentum are reconstructed from the energies and impact positions of photon pairs measured by each calorimeter

$$M_{\pi^0} = \sqrt{E_{\gamma 1} E_{\gamma 2} \theta^2},$$

$$E_{\pi^0} = E_{\gamma 1} + E_{\gamma 2},$$

$$P_{T\,\pi^0} = P_{T\,\gamma 1} + P_{T\,\gamma 2}$$



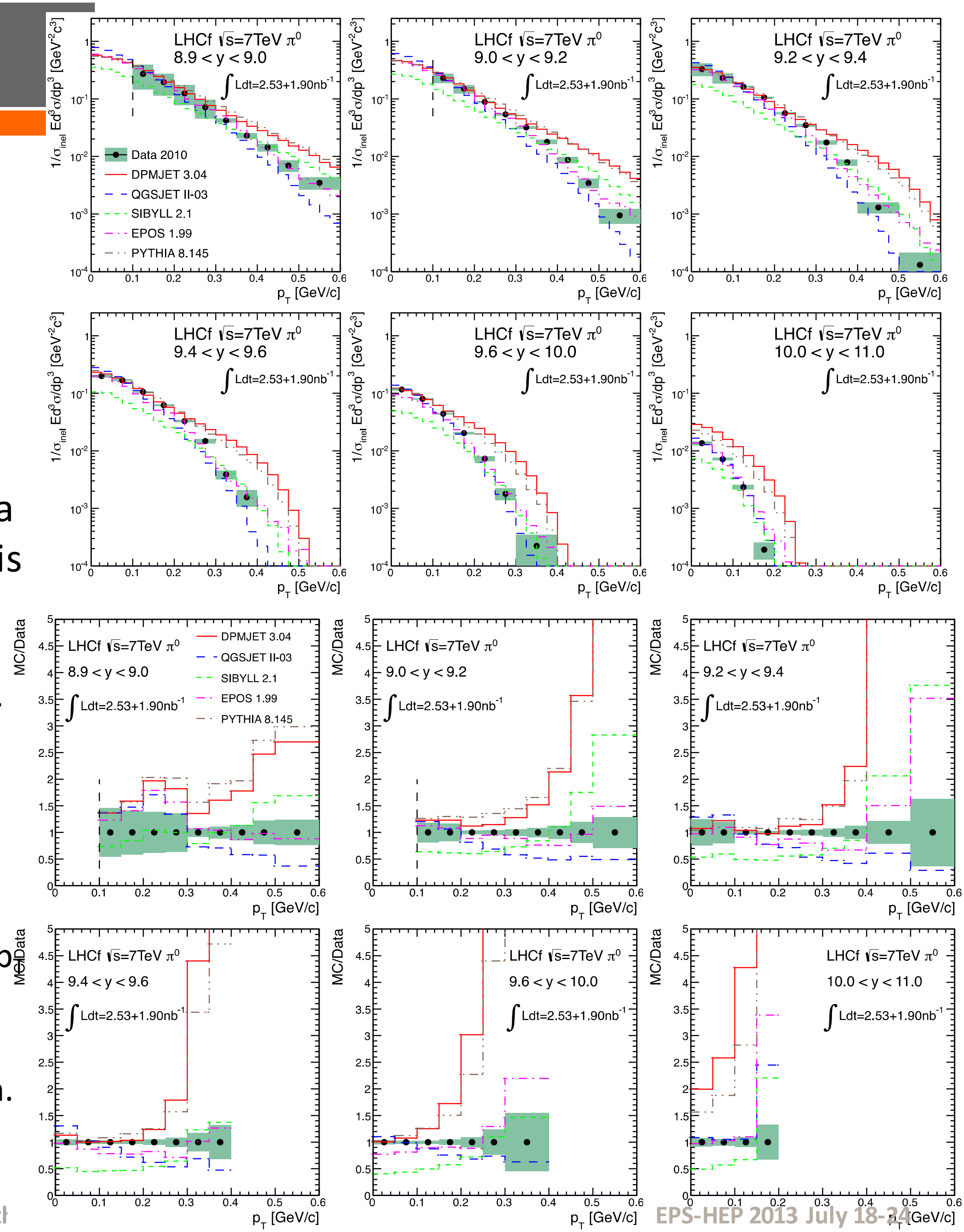
Analysis Procedure

- Standard photon reconstruction
- Event selection
  - one photon in each calorimeter
  - reconstructed invariant mass
- Background subtraction by using outer region of mass peak
- Unfolding for detector response.
- Acceptance correction.

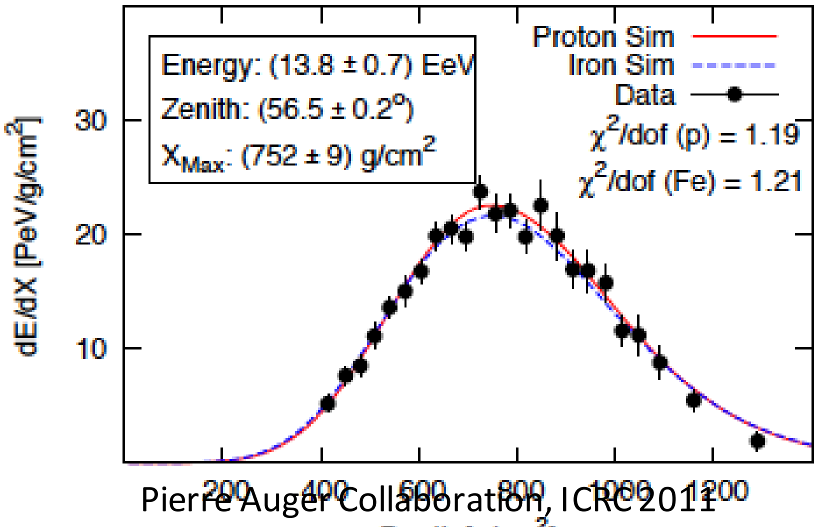
Dedicated part for π^0 analysis

7 TeV π^0 spectra

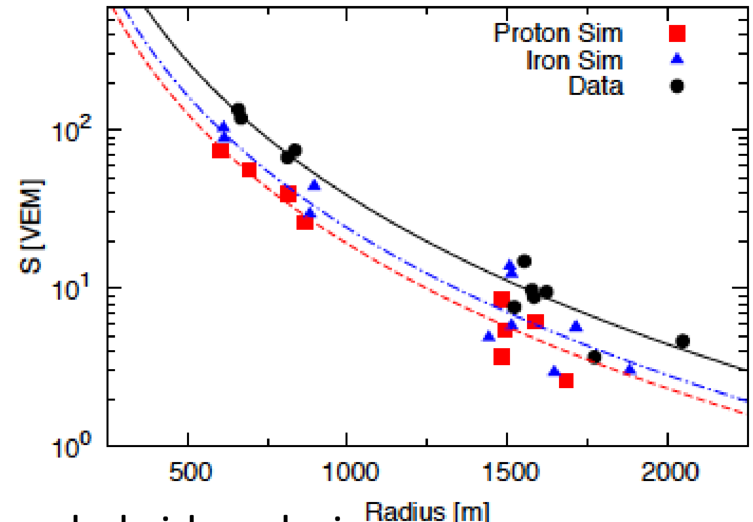
- dpmjet 3.04 & pythia 8.145 show overall agreement with LHCf data for 9.2<y<9.6 and p_T <0.25 GeV/c, while the expected π^0 production rates by both models exceed the LHCf data as p_T becomes large
- sibyll 2.1 predicts harder pion spectra than data, but the expected π^0 yield is generally small
- qgsjet II-03 predicts π^0 spectra softer than LHCf data
- epos 1.99 shows the best overall agreement with the LHCf data.
  - behaves softer in the low p_T region, p_T < 0.4GeV/c in 9.0<y<9.4 and p_T <0.3GeV/c in 9.4<y<9.6
  - behaves harder in the large p_T region.

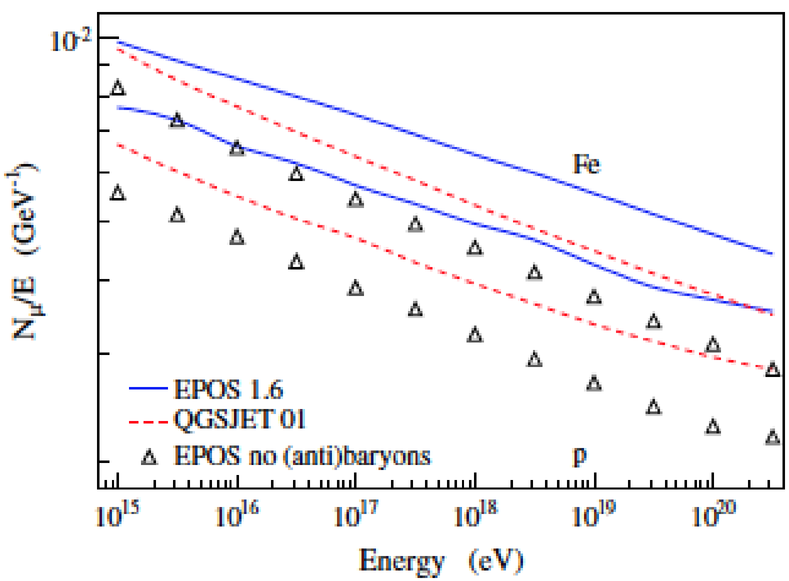


Muon excess at Pierre Auger Obs.



Pierre Auger Collaboration, ICRC 2011





Auger hybrid analysis

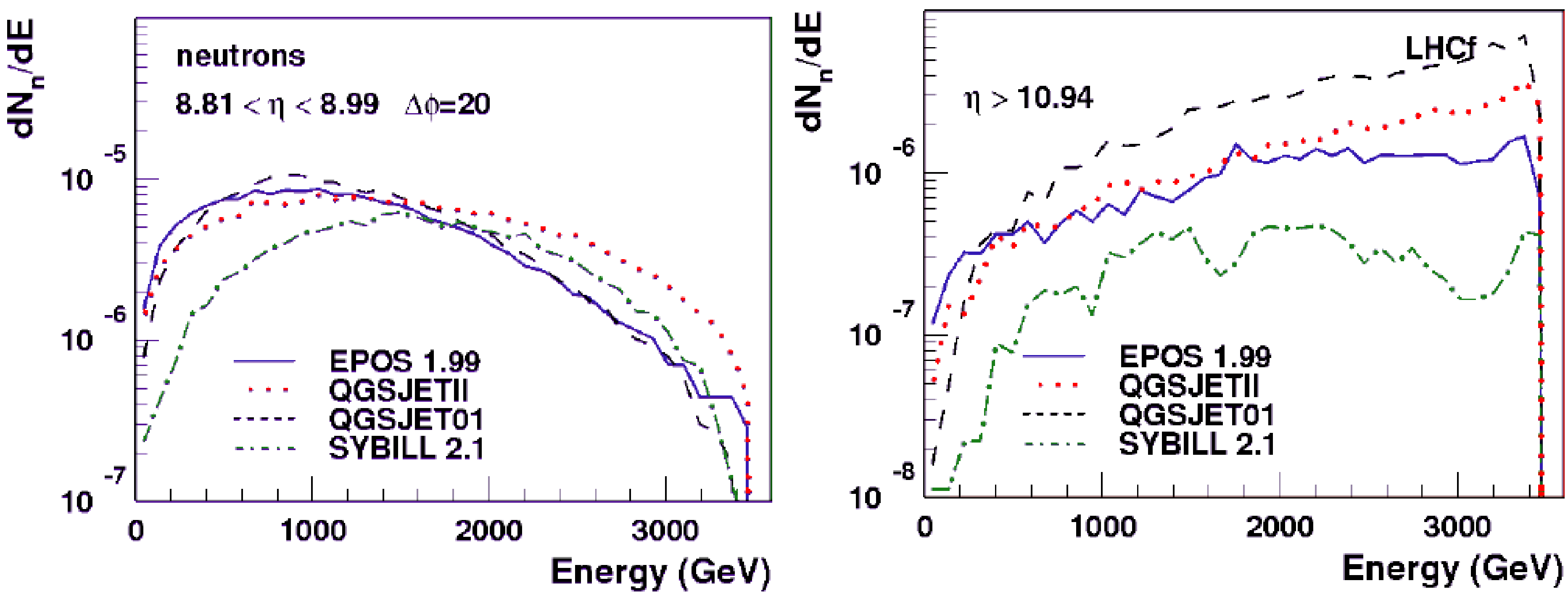
- event-by-event MC selection to fit FD data (top-left)
- comparison with SD data vs MC (top-right)
- muon excess in data even for Fe primary MC

EPOS predicts more muon due to larger baryon production

=> importance of baryon measurement

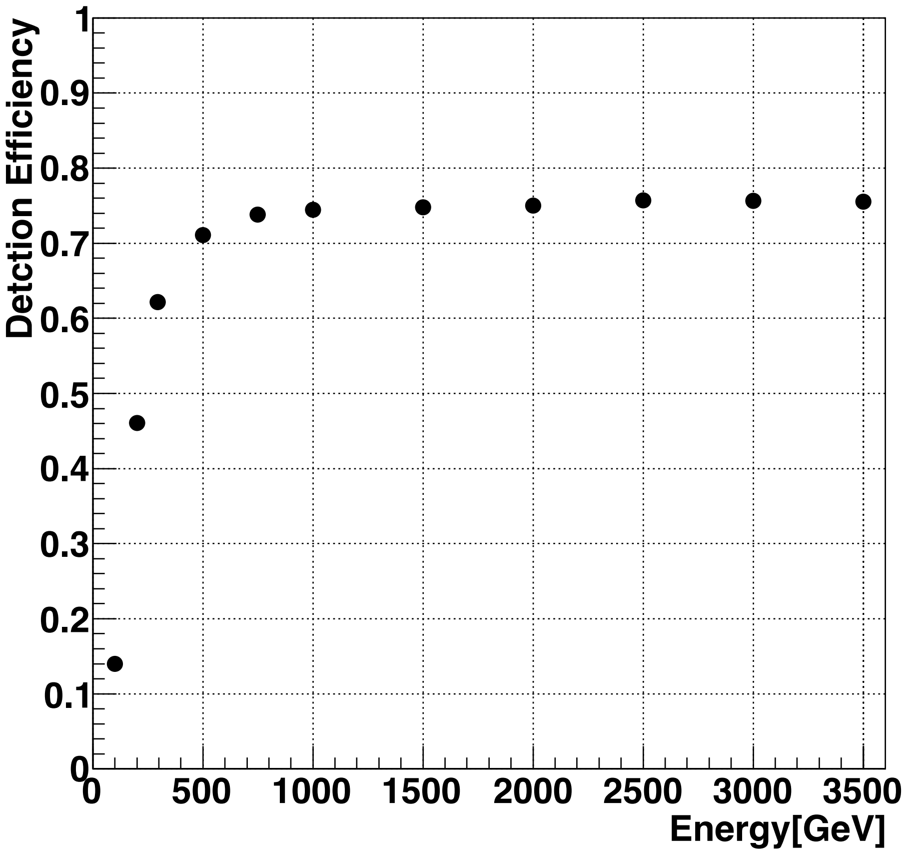
Pierog and Werner, PRL 101 (2008) 171101

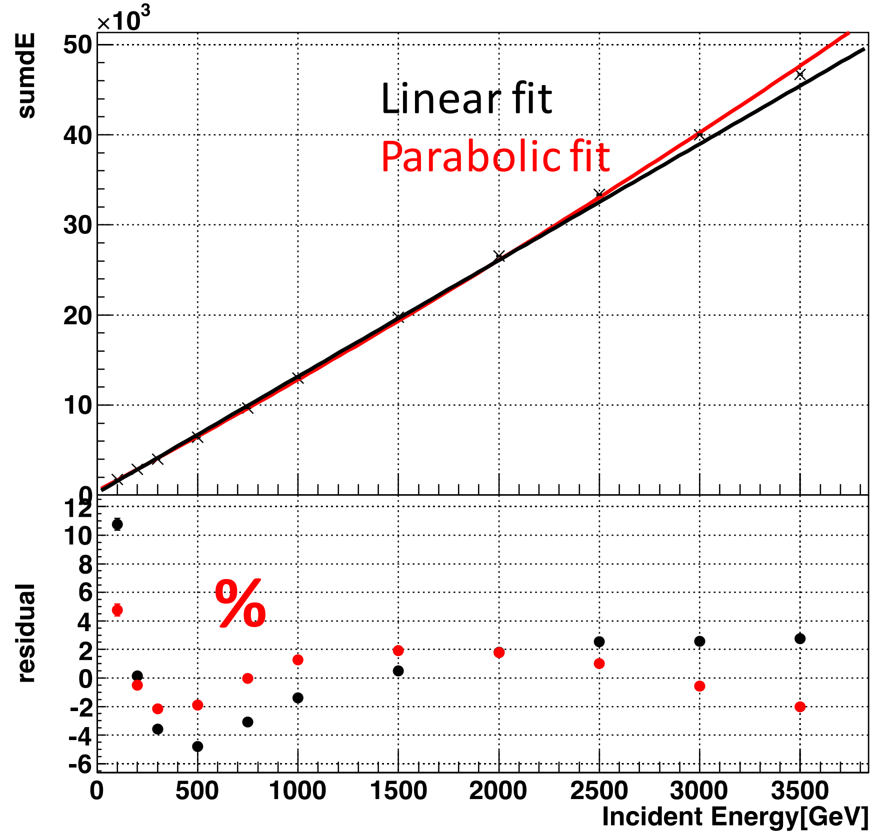
Neutron at LHCf phase-space



By Tanguy Pierog,
Modelists waiting for LHCf!!

Neutron Detection Efficiency and energy linearity

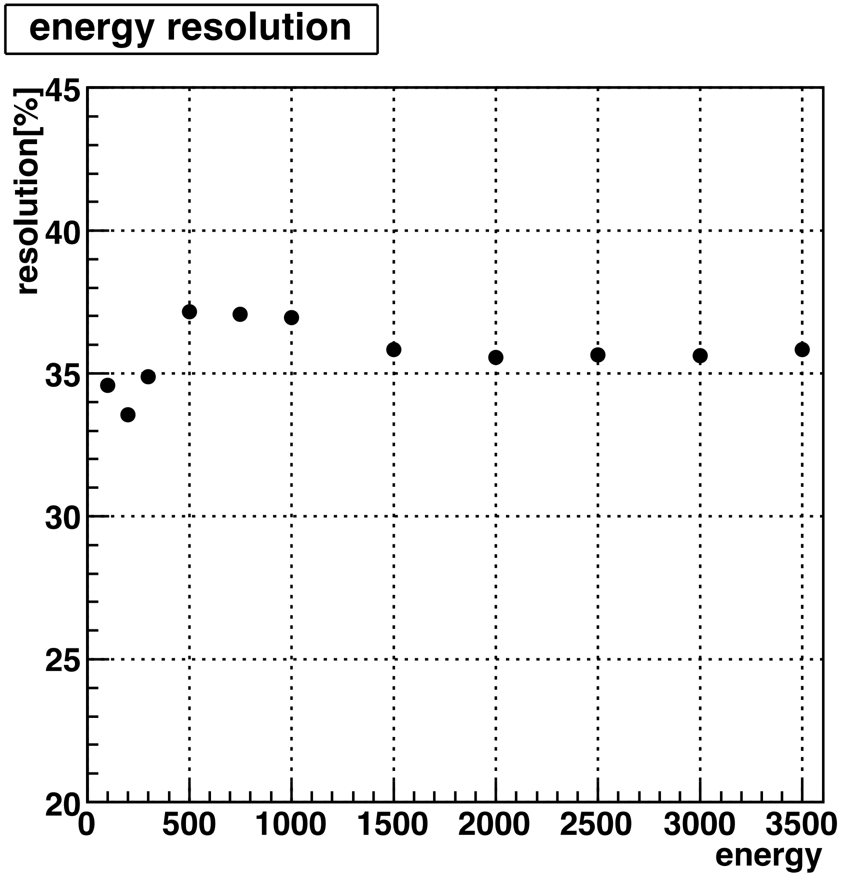




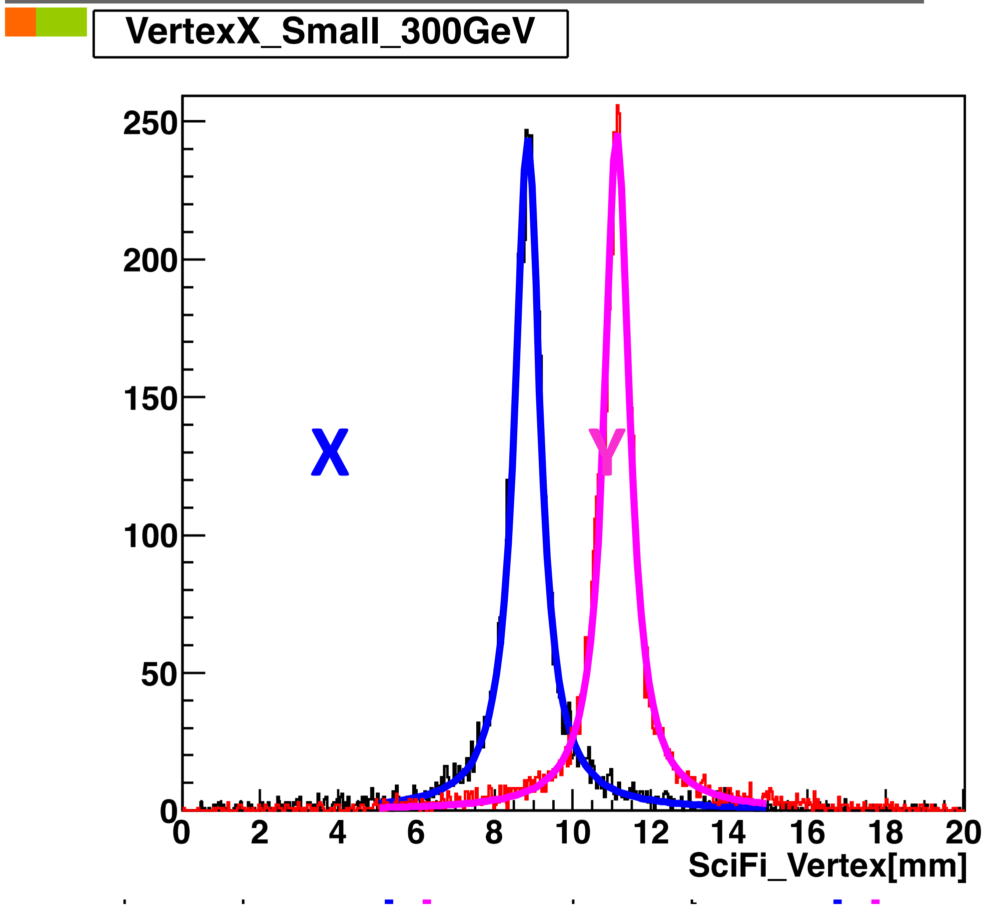
Efficiency at the offline shower trigger

Flat efficiency >500GeV

Energy and Position Resolution



We are trying to improve the energy resolution by looking at the 'electromageticity' of the event



Neutron incident at (X,Y) = (8.5mm, 11.5mm)
~1mm position resolution
Weak dependence on incident energy

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

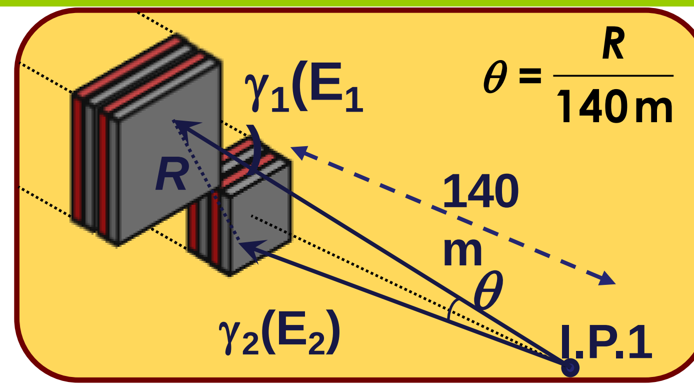
	Shower	Gamma	Hadron	π^0
Arm1	172,263,255	56,846,874	111,971,115	344,526
Arm2	160,587,306	52,993,810	104,381,748	676,157

Data Set for inclusive photon spectrum analysis at 7 TeV

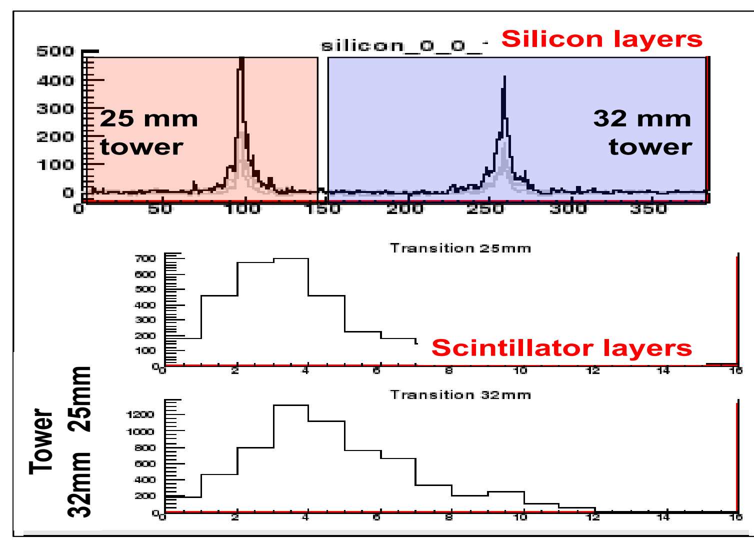
- Data
  - Date : 15 May 2010 17:45-21:23 (Fill Number : 1104) except runs during the luminosity scan.
  - Luminosity : (6.5-6.3)x10^{28}cm^{-2}s^{-1},
  - DAQ Live Time : 85.7% for Arm1, 67.0% for Arm2
  - Integrated Luminosity : 0.68 nb^{-1} for Arm1, 0.53nb^{-1} for Arm2
  - Number of triggers : 2,916,496 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

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



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

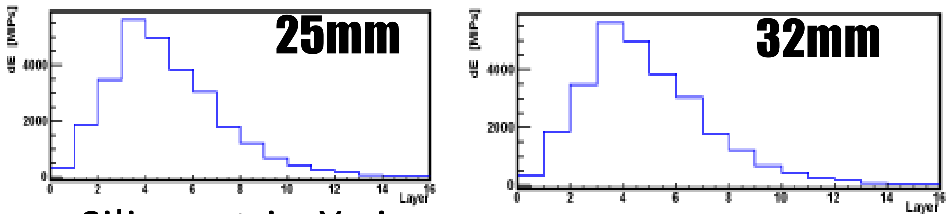


- Uncorrelated uncertainties between ARM1 and ARM2
  - Energy scale (except π^0 error)
  - Beam center position
  - PID
  - Multi-hit selection

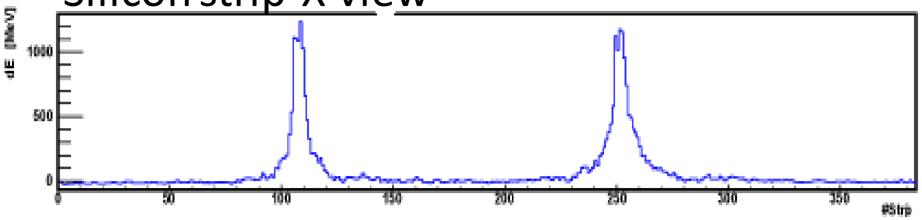
- Correlated uncertainty
  - Energy scale (π^0 error)
  - Luminosity error

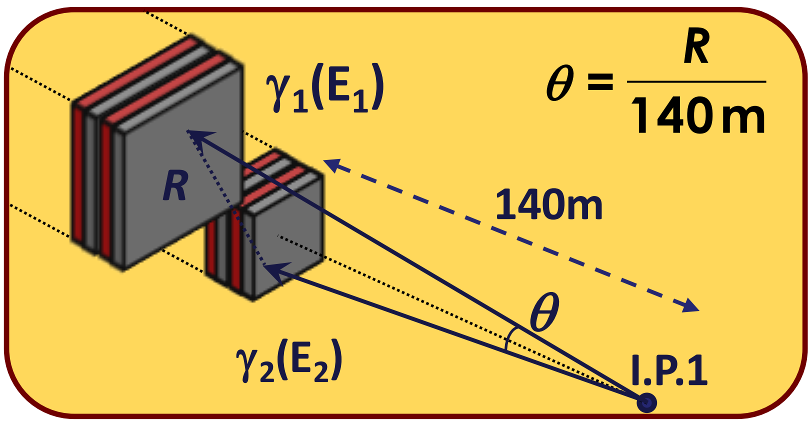
π^0 reconstruction

An example of π^0 events

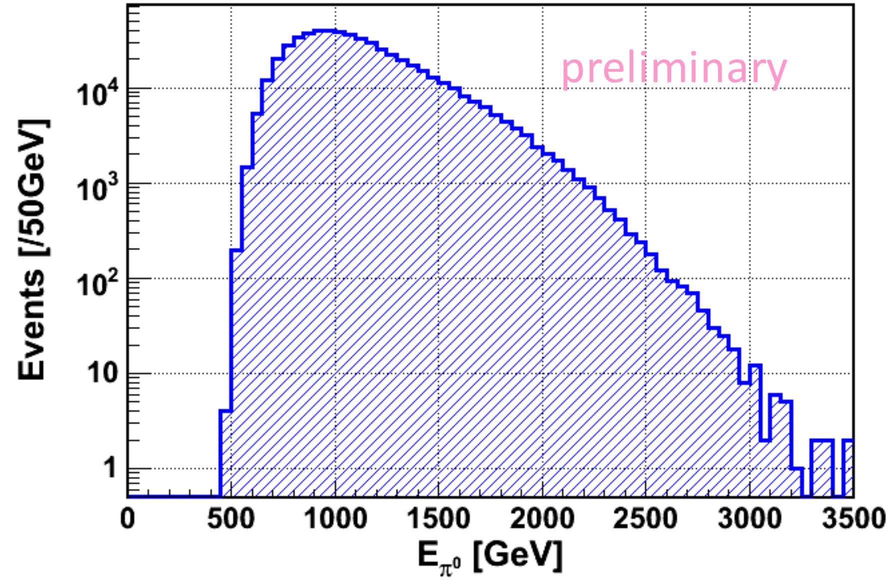


Silicon strip-X view

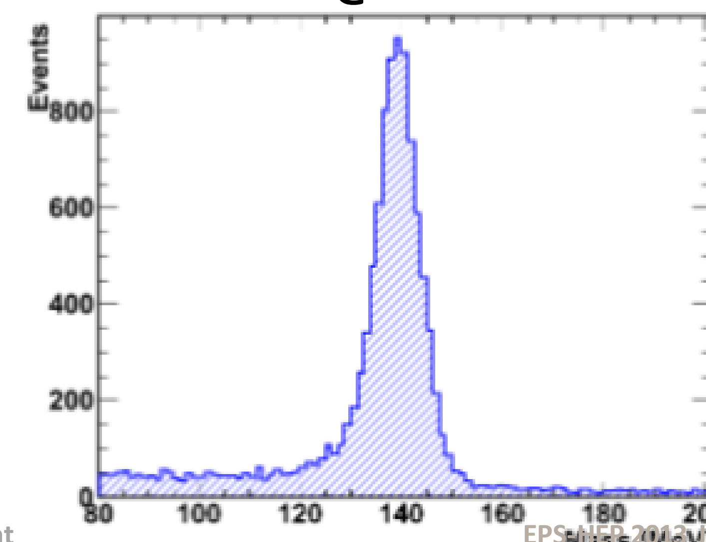




measured energy spectrum @ Arm2

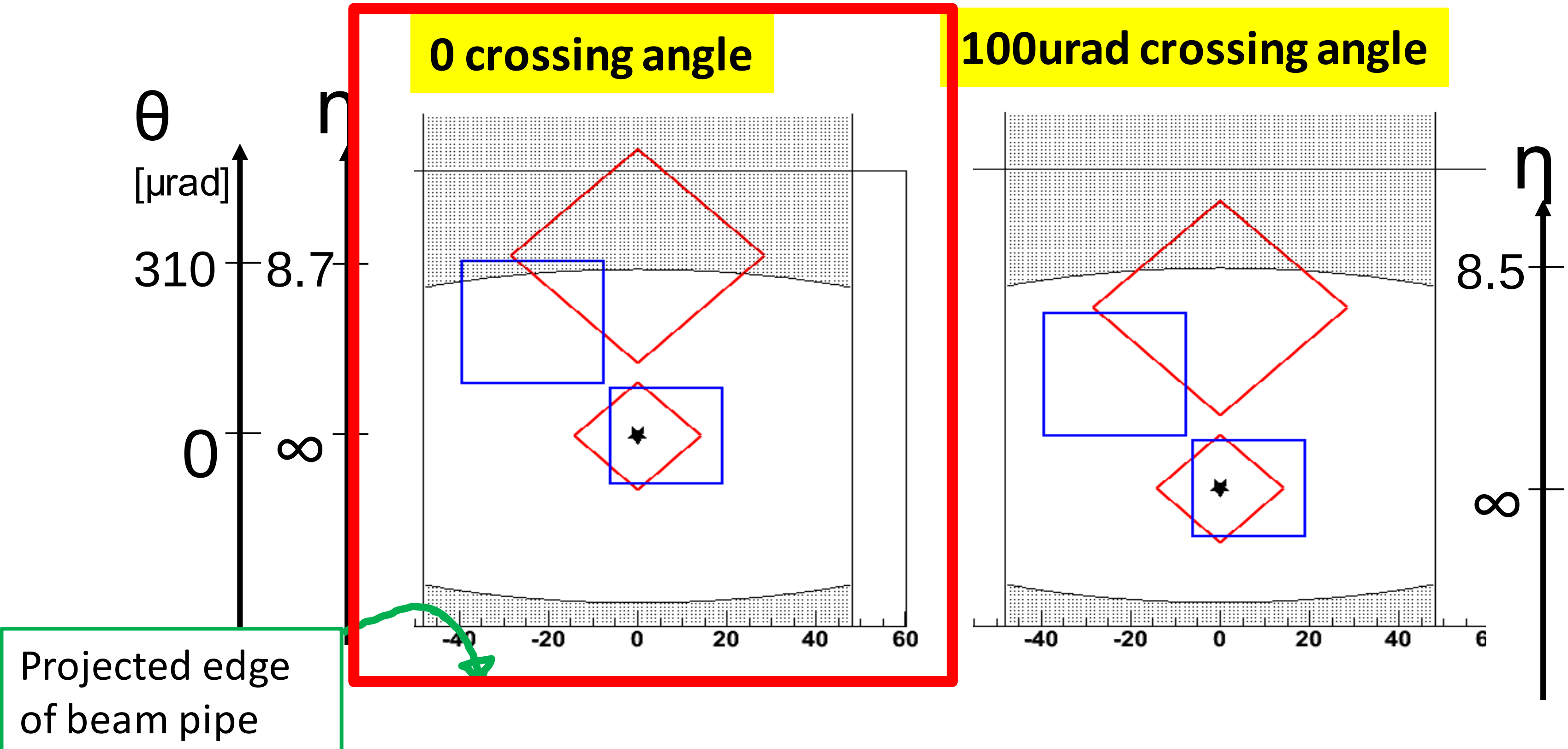


Reconstructed mass @ Arm2



- 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.

Calorimeters viewed from IP



- Geometrical acceptance of Arm1 and Arm2
- Crossing angle operation enhances the acceptance

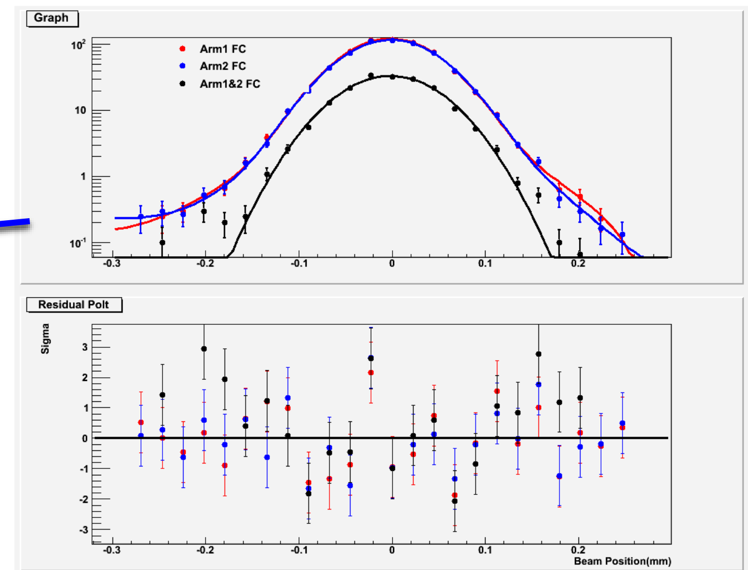
Luminosity measurement

- 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

Pile-up estimation

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

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

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

The ratio of the pile up event is

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

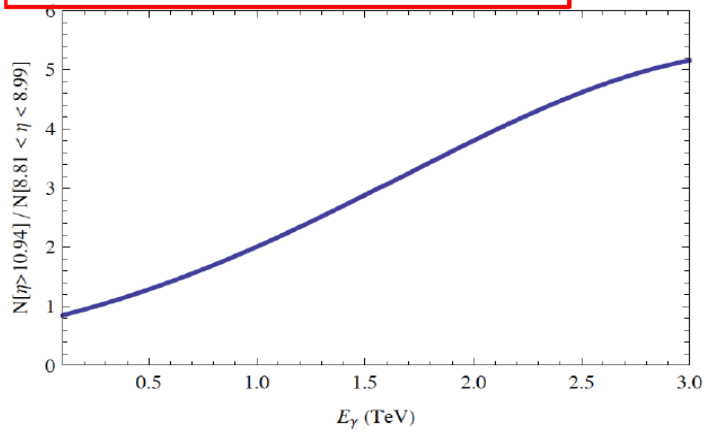
The maximum luminosity per bunch during runs used for the analysis is $2.3 \times 10^{28} \mathrm{cm}^{-2} \mathrm{s}^{-1}$

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

p_T distribution dependence

Ratio [High Rapidity] / [Low Rapidity]
for LHCf DATA



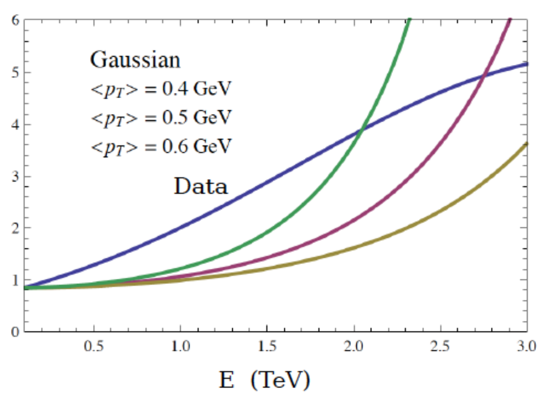
$$\left[\frac{dN_\gamma}{dE_\gamma}(E_\gamma)\right]_{8.81\le\eta\le 8.99} = \frac{dN_\gamma}{dE_\gamma}(E_\gamma) \times \frac{dN_\gamma[8.81 \le \eta \le 8.99]}{dN_\gamma[\text{all } \eta]}$$

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

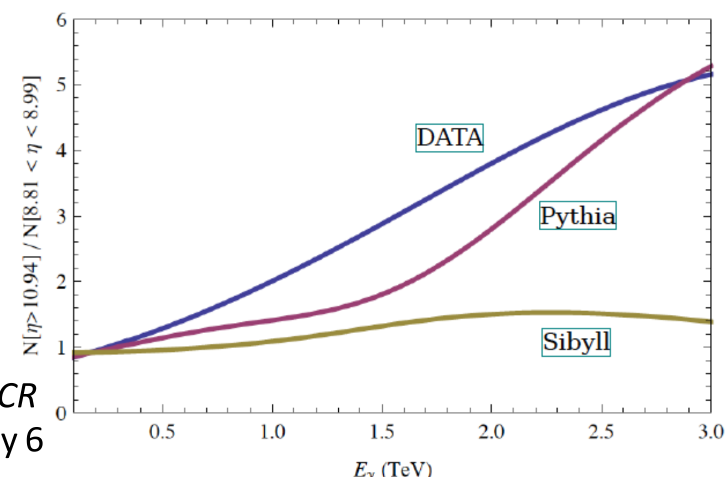
Directly relevant for UHECR shower development

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

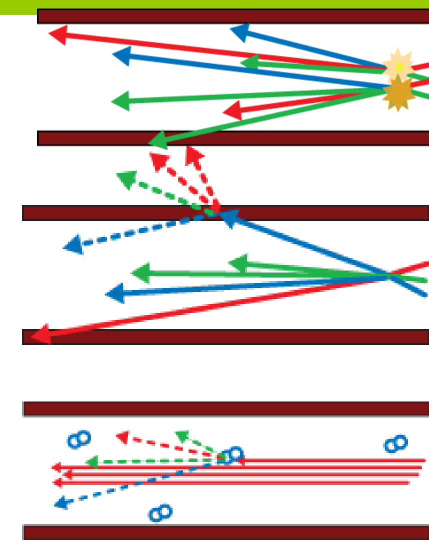


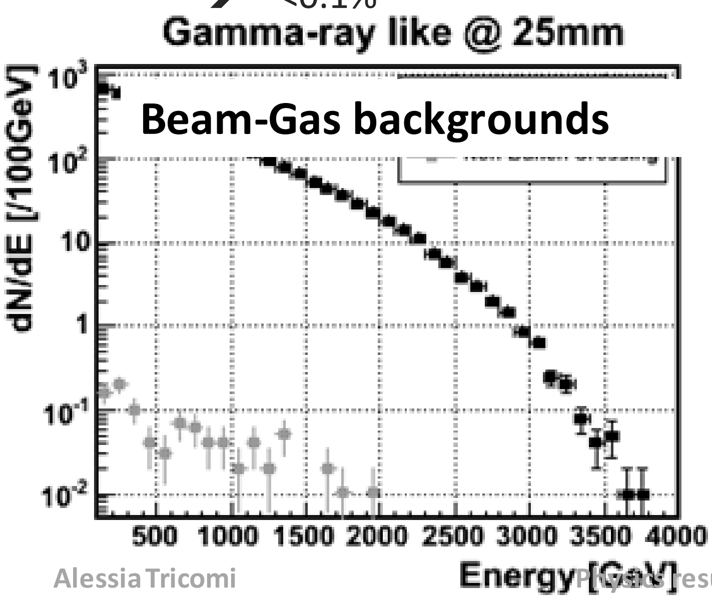
Backgrounds

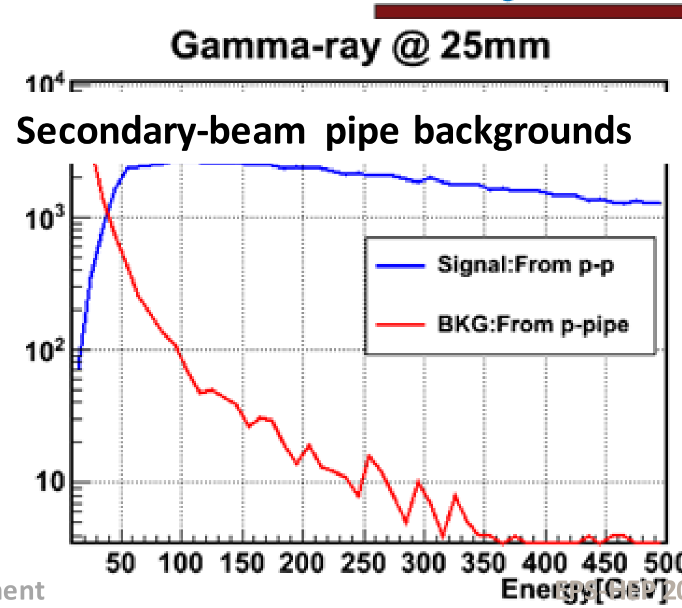
1. Pileup of collisions in one beam crossing
   - Low Luminosity fill, L=6x10^{28}cm^{-2}s^{-1}
     ➔ 7% pileup at collisions, 0.2% at the detectors.

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%





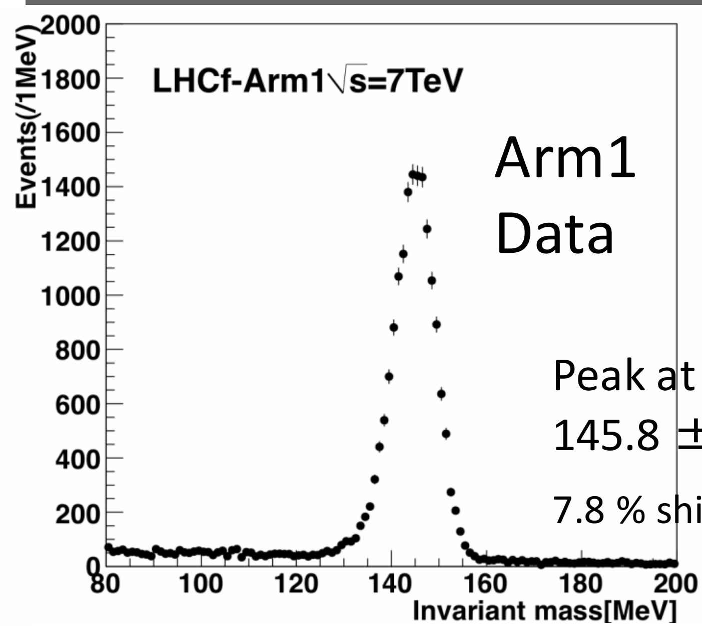


Systematic error from Energy scale

- 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

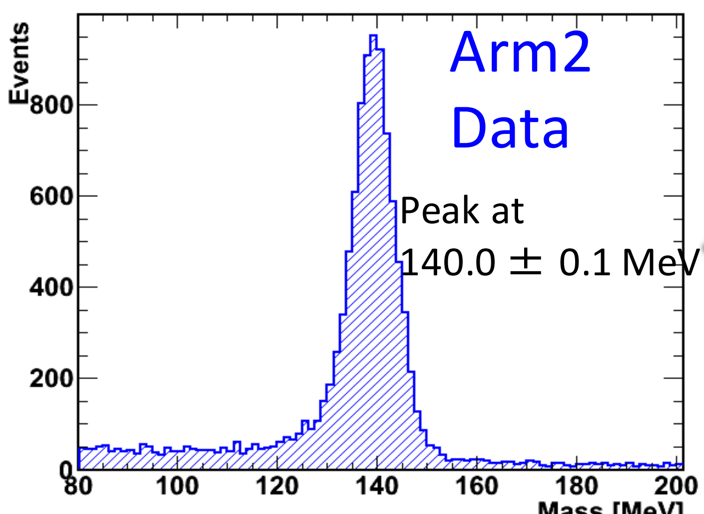
Systematic Uncertainty on Spectra is estimated from difference between normal spectra and energy shifted spectra.

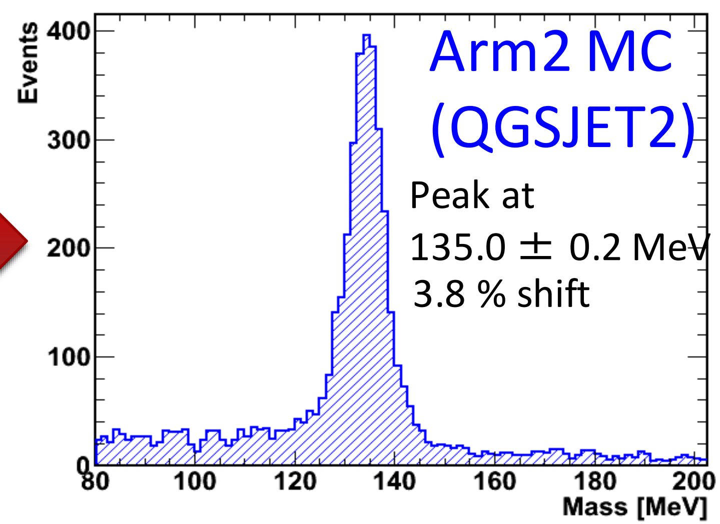
π^0 Mass



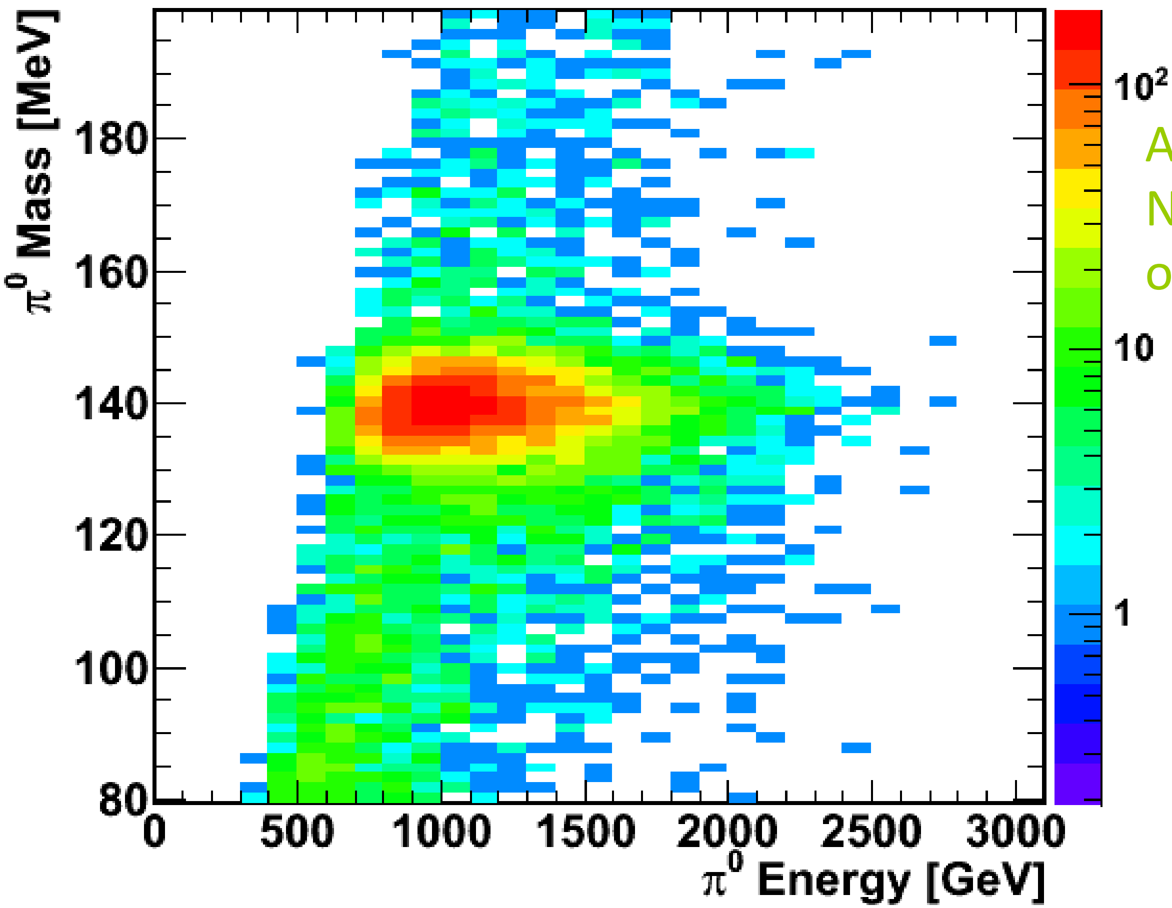
- Disagreement in the peak position
- No 'hand made correction' is applied for safety
- Main source of systematic error → see later

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





π^o mass vs π^o energy

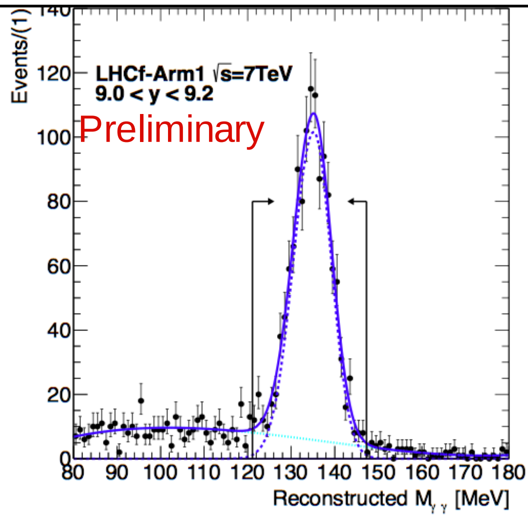


Arm2 Data

No strong energy dependence of reconstructed mass

7 TeV π^0 analysis

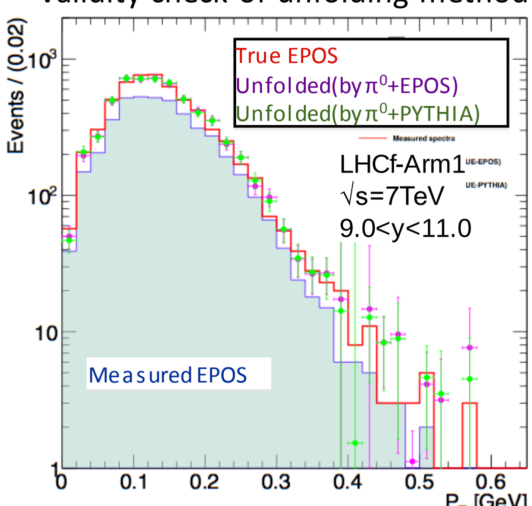
Signal window : [-3σ, +3σ]
Sideband : [-6σ, -3σ] and [+3σ, +6σ]

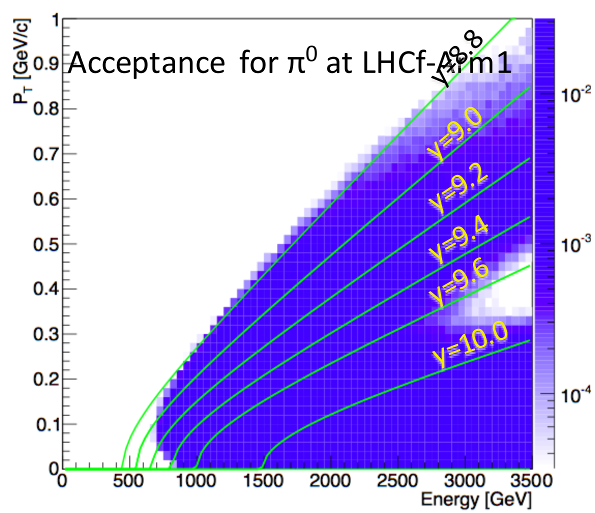


Remaining background spectrum is estimated using the sideband information, then the BG spectrum is subtracted from the spectrum made in the signal window.

$$Signal = f(E, P_T)^{signal} - f(E, P_T)^{BG} \frac{\int_{\hat{M}-3\sigma_l}^{\hat{M}+3\sigma_u} \mathcal{L}_{BG} dM}{\int_{\hat{M}-6\sigma_l}^{\hat{M}-3\sigma_l} \mathcal{L}_{BG} dM + \int_{\hat{M}+3\sigma_u}^{\hat{M}+6\sigma_u} \mathcal{L}_{BG} dM}$$

Validity check of unfolding method



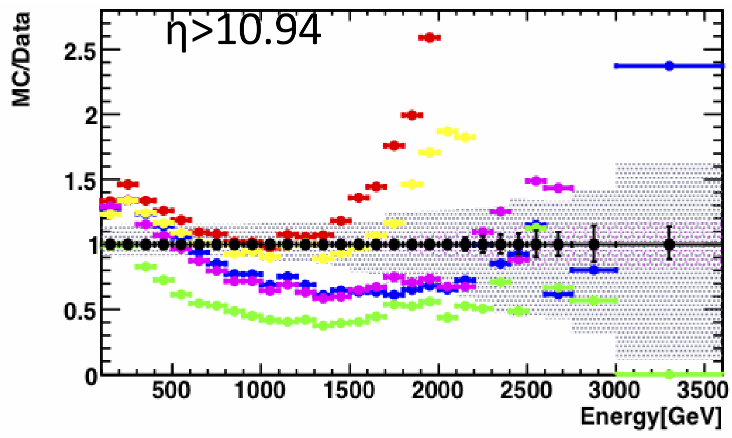


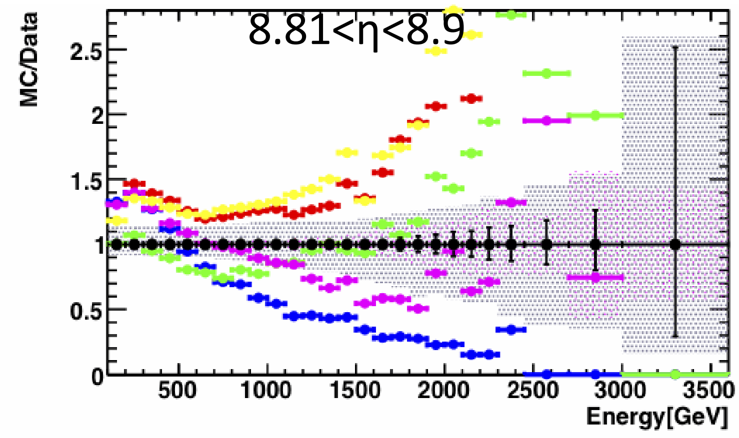
Detector responses are corrected by an unfolding process that is based on the iterative Bayesian method.
(G. D' Agostini NIM A 362 (1995) 487)

Detector response corrected spectrum is proceeded to the acceptance correction.

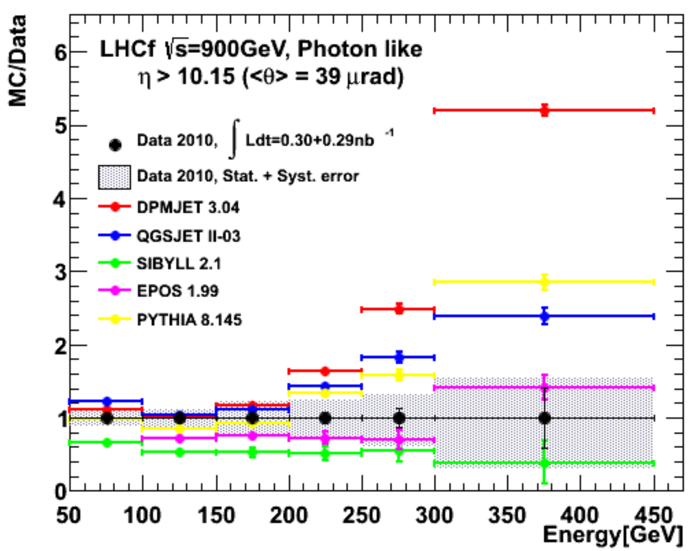
DATA-MC : comp. 900GeV/7TeV

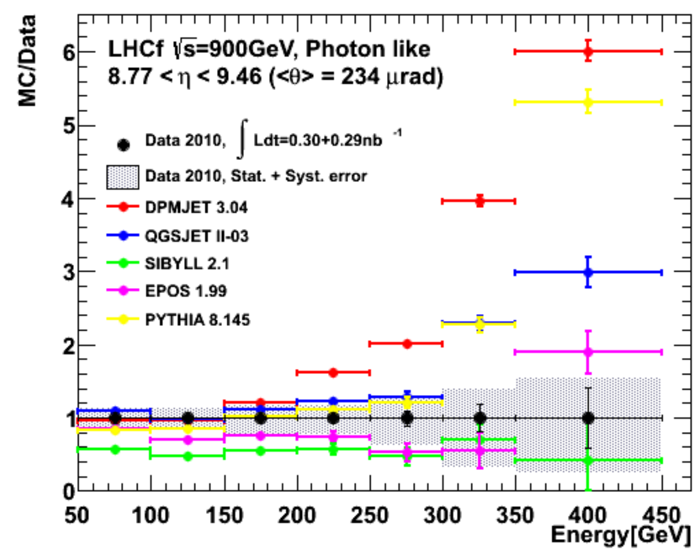
7TeV





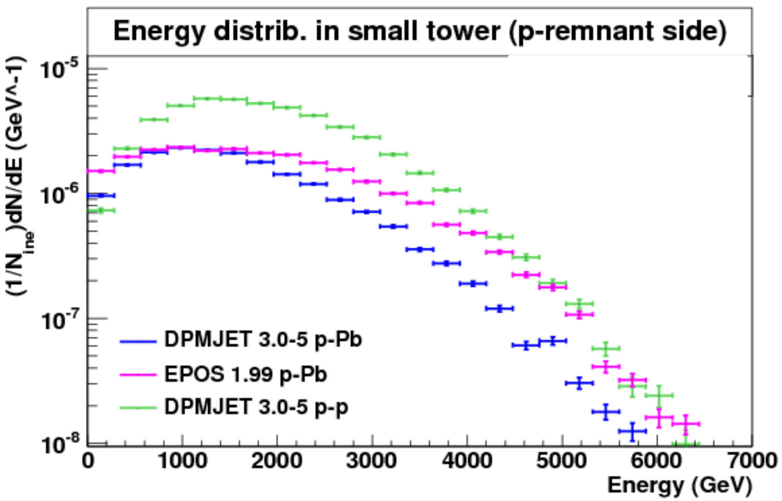
900GeV

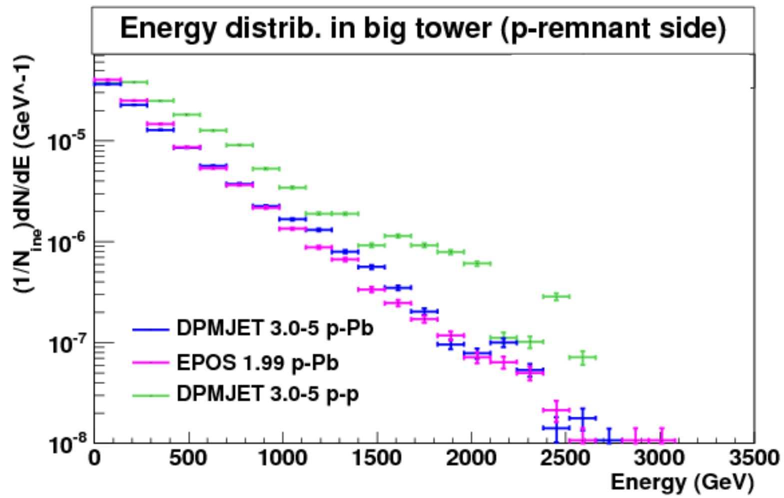


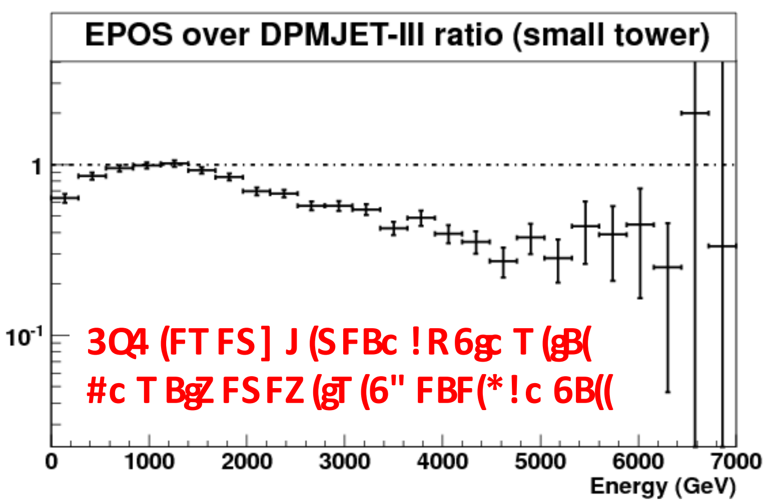


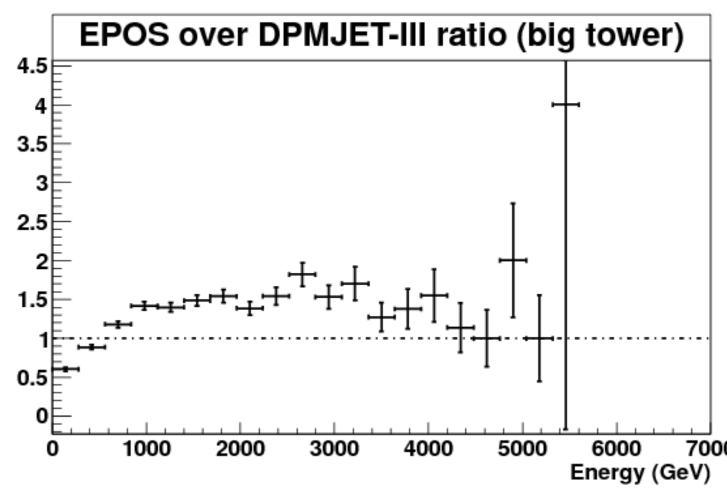
LHCf p-Pb run: Neutron spectra

B' . C(:- L +,(YDE(:- L +,(









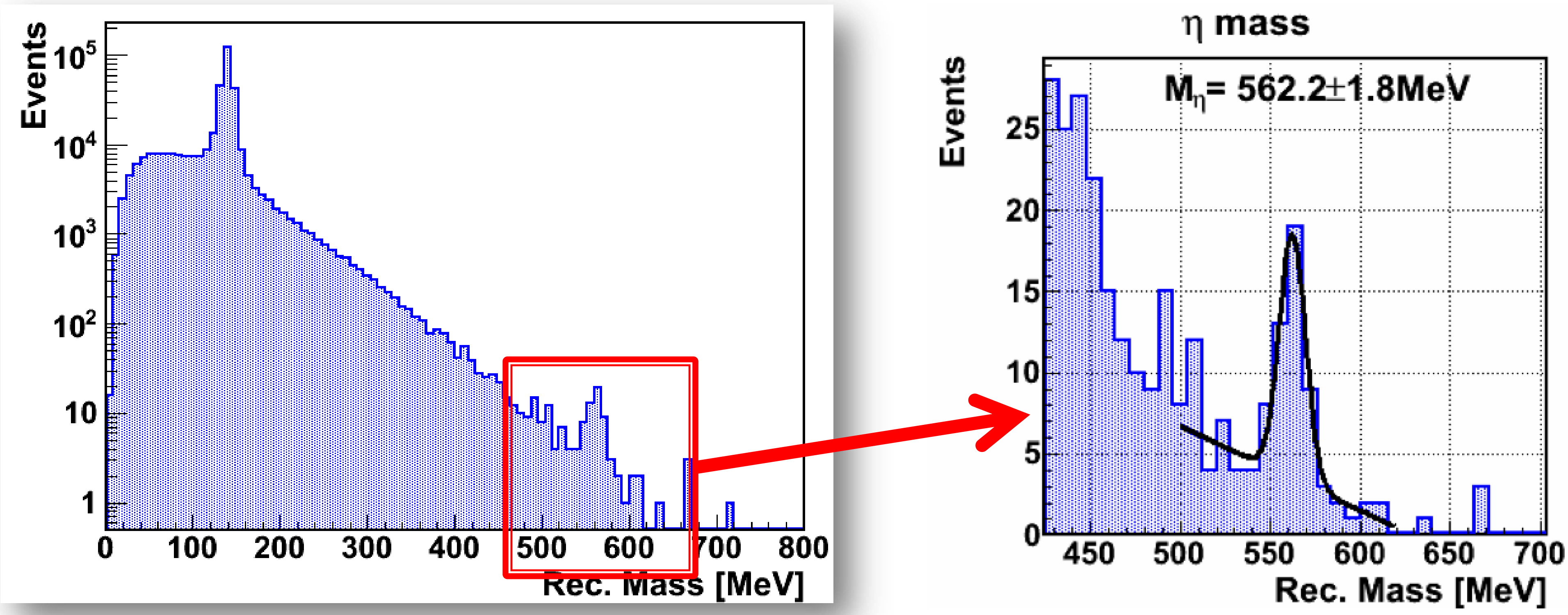
η Mass

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)

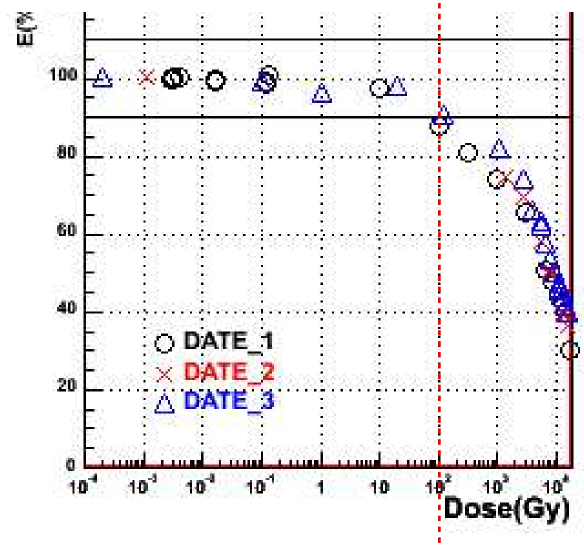


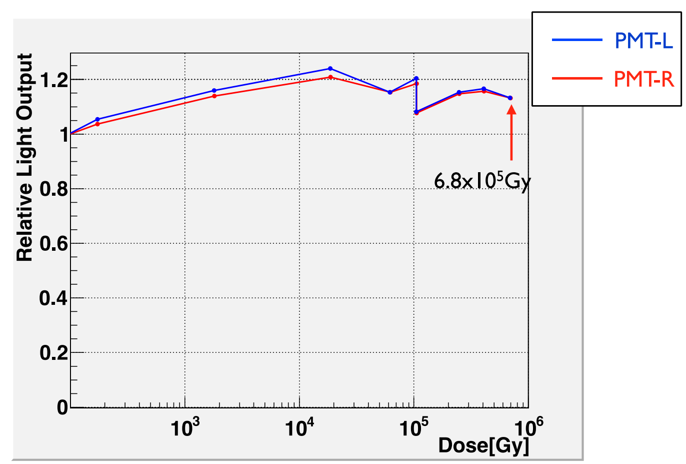
Comparison of EJ260 and GSO -Radiation Hardness-

- 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