The results and the future prospects from a LHC forward experiment

Hiroaki MENJO
(KMI, Nagoya University, Japan)
On behalf of the LHCf collaboration

Low-X workshop, Paphos, Cyprus, 26 June – 1 July. 2012

Contents

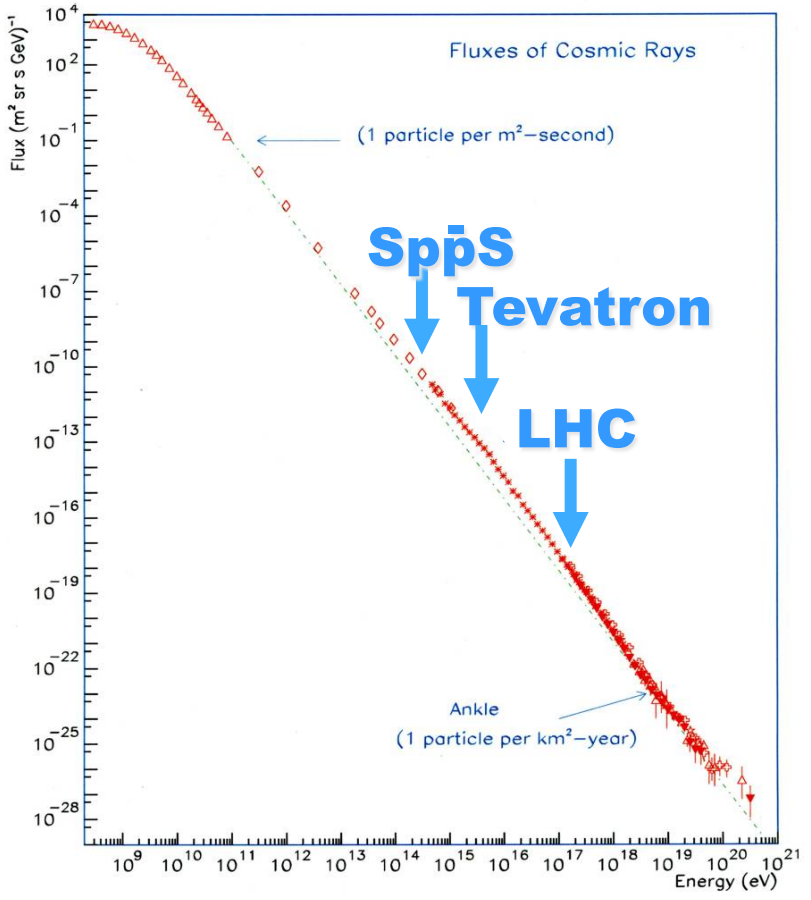
- Introduction
- The LHCf experiment
  -An LHC forward experiment-
- Recent results
  - Forward photon energy spectra at 900GeV and 7TeV p-p
  - Forward π^0 spectra
- Future plans
- Summary

Large Hadron Collider

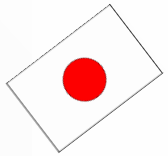
-The most powerful accelerator on the earth-

Ultra High Energy Cosmic Rays

What is the most powerful accelerator in the Universe ?



The LHCf collaboration



T.Iso, Y.Itow, K.Kawade, Y.Makino, K.Masuda, Y.Matsubara, E.Matsubayashi, G.Mitsuka, Y.Muraki, T.Sako
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*

M.Haguenauer *Ecole Polytechnique, France*

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

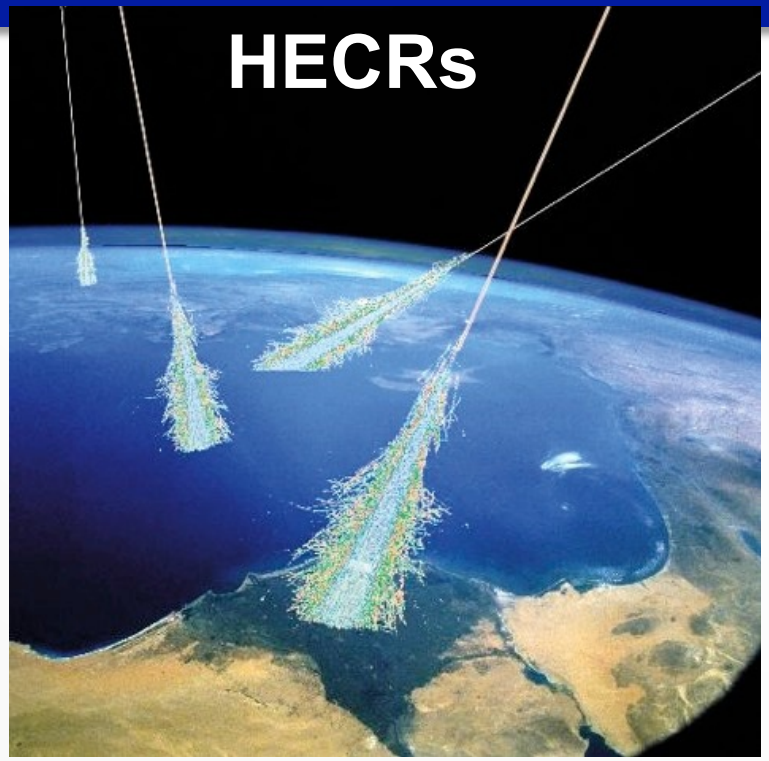
O.Adriani, L.Bonechi, M.Bongi, R.D'Alessandro, M.Grandi, P.Papini, S.Ricciarini, G.Castellini
INFN, Univ. di Firenze, Italy

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

J.Velasco, A.Faus *IFIC, Centro Mixto CSIC-UVEG, Spain*

A-L.Perrot *CERN, Switzerland*

Introduction



Extensive air shower observation

- longitudinal distribution
- lateral distribution
- Arrival direction

Air shower development

Astrophysical parameters

- Spectrum
- Composition
- Source distribution

X_{max}

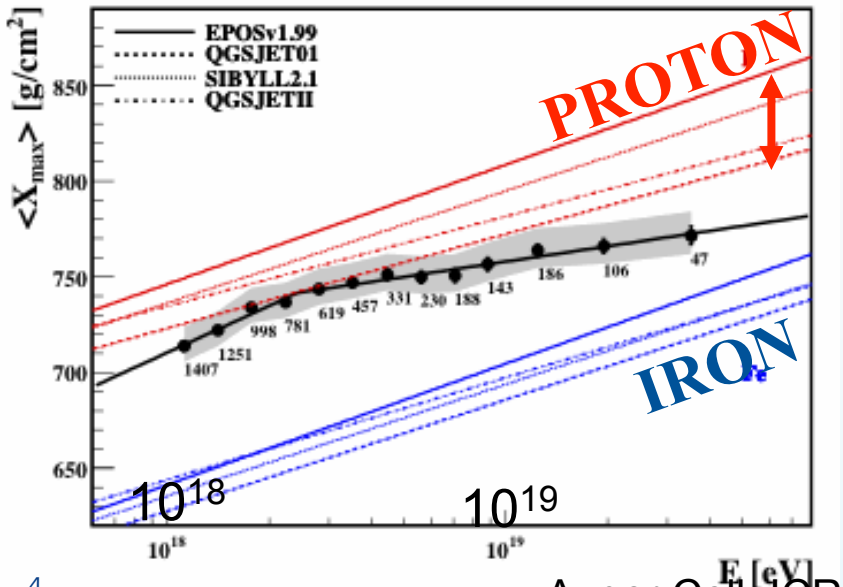
the depth of air shower maximum.
An indicator of CR composition

Uncertainty of hadron interaction models

V

Error of $<X_{max}>$ measurement

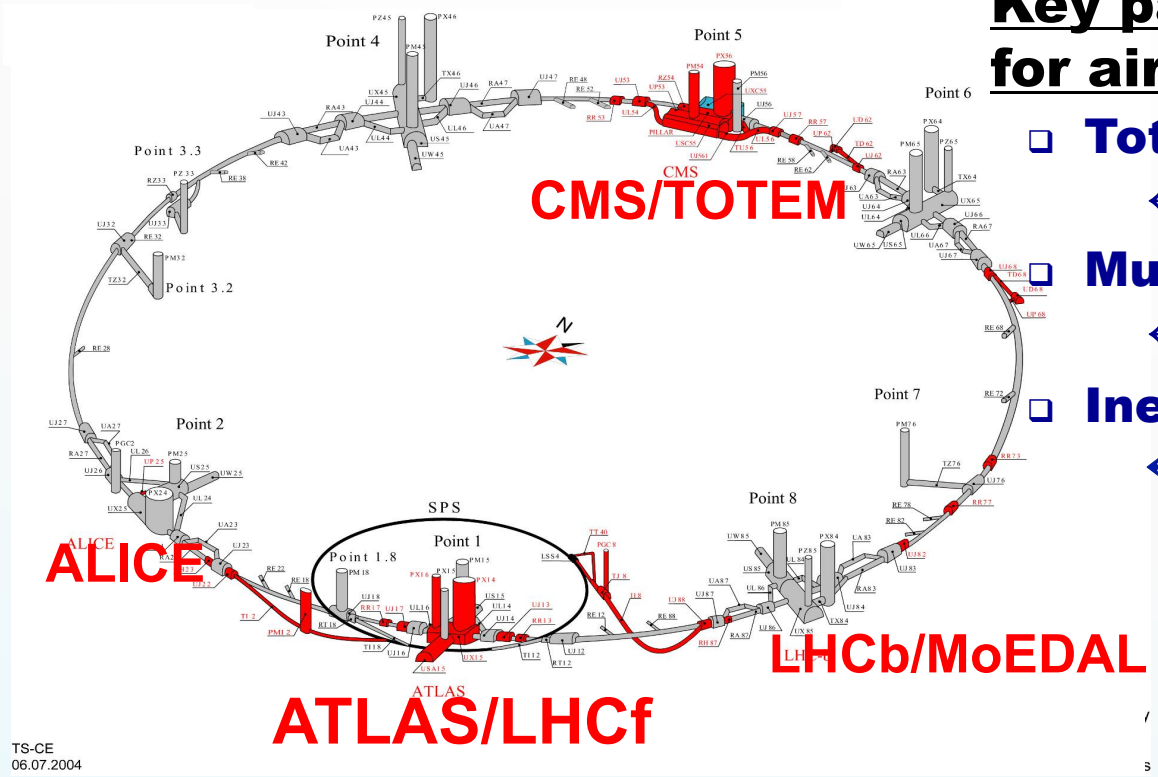
X_{max} distribution measured by AUGER



Auger Coll. ICRC2011

The Large Hadron Collider (LHC)

pp 7TeV+7TeV → $E_{lab} = 10^{17}$eV 2014-
pp 3.5TeV+3.5TeV → $E_{lab} = 2.6 \times 10^{16}$eV
pp 450GeV+450GeV → $E_{lab} = 2 \times 10^{14}$eV



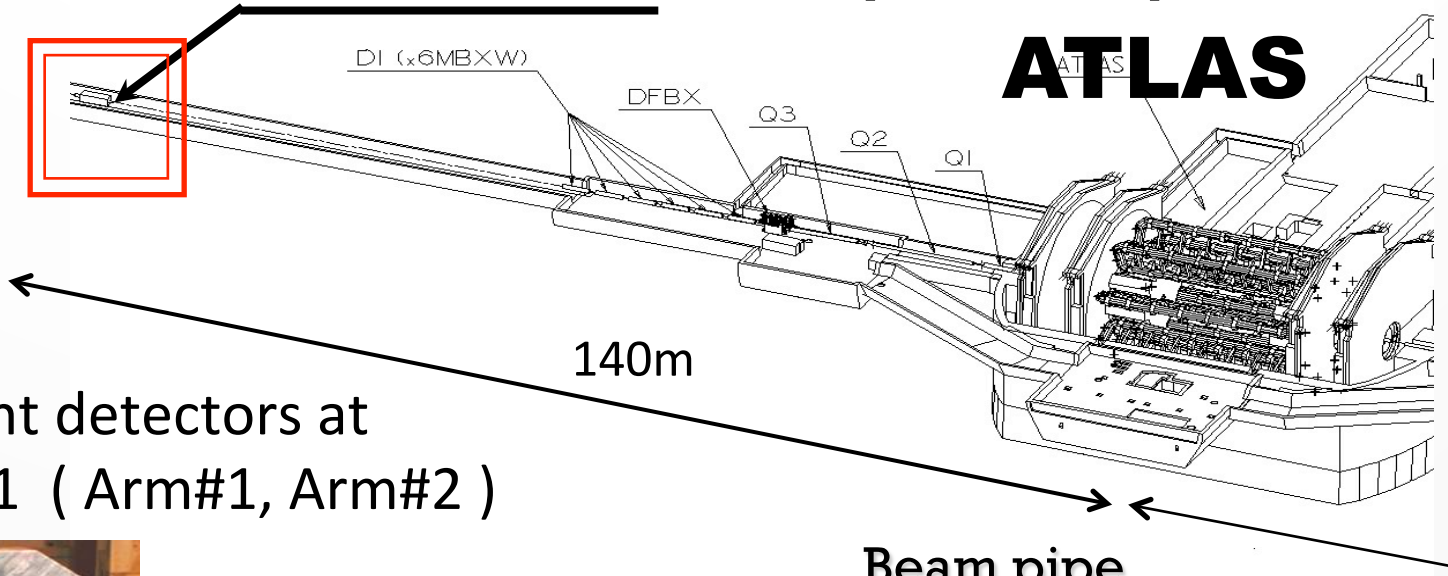
TS-CE
06.07.2004

Key parameters for air shower developments

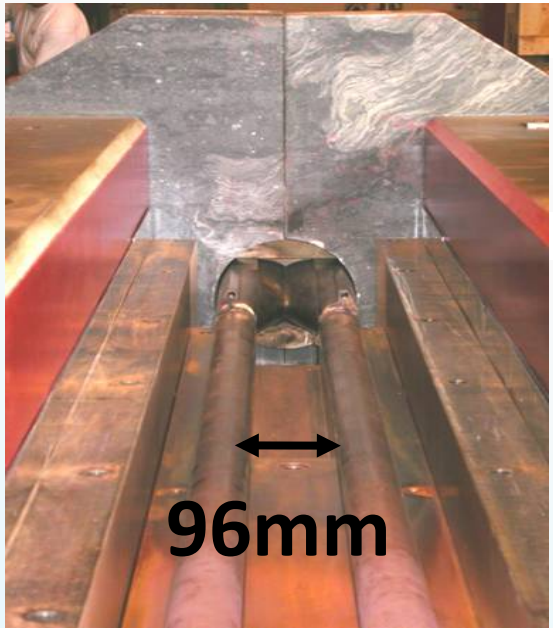
- Total cross section
  ↔ TOTEM, ATLAS, CMS
- Multiplicity
  ↔ Central detectors
- Inelasticity/Secondary spectra
  ↔ Forward calorimeters
  LHCf, ZDCs

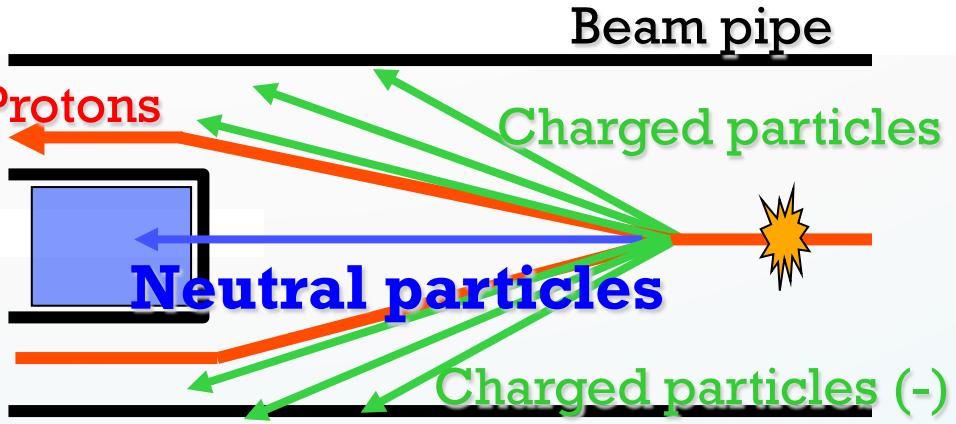
The LHCf experiment

LHCf Detector(Arm#1)



Two independent detectors at
either side of IP1 (Arm#1, Arm#2)





TAN -Neutral Particle Absorber-

transition from one common beam pipe to two pipes

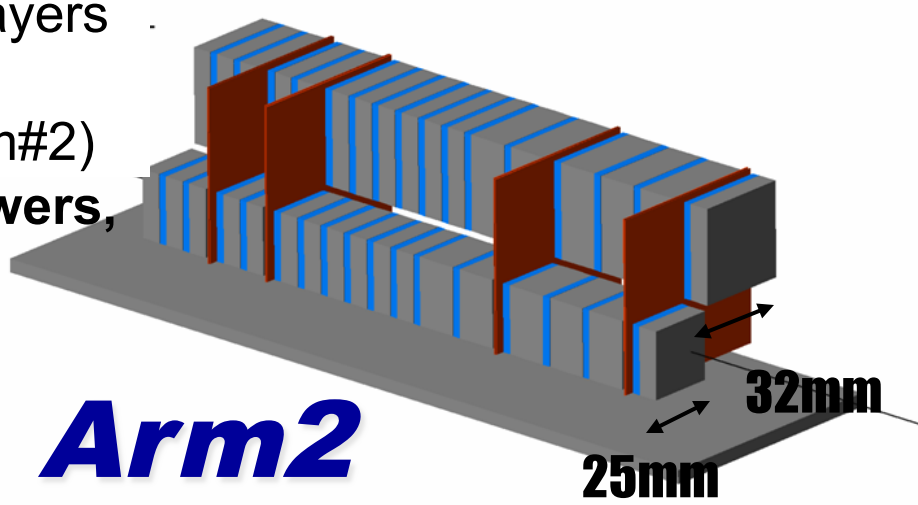
Slot : 100mm(w) x 607mm(H) x 1000mm(T)

The LHCf Detectors

Sampling and Positioning Calorimeters

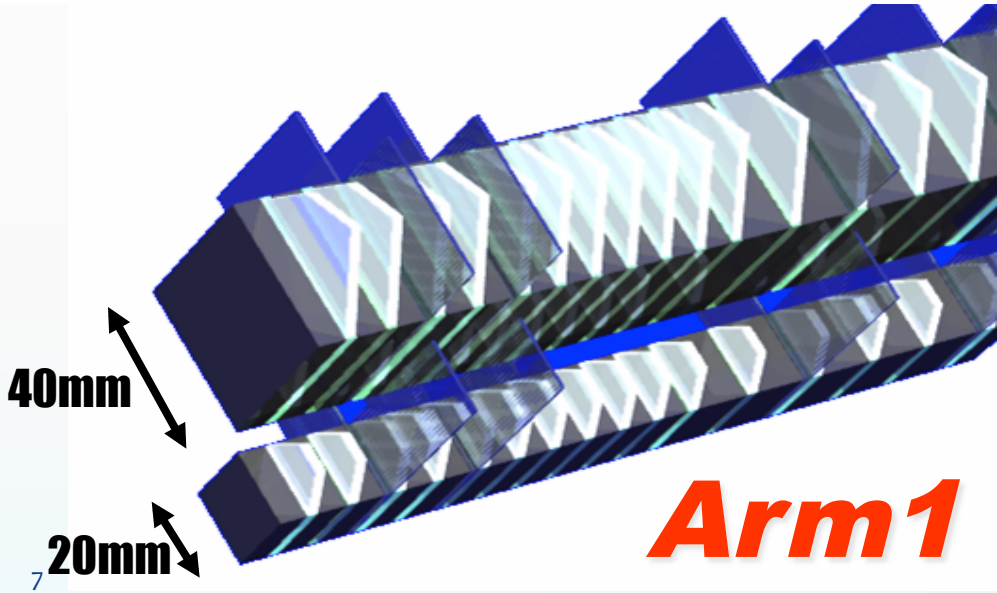
- W (44 r.l , 1.7λ_I) and Scintillator x 16 Layers
- 4 positioning layers
  XY-SciFi(Arm1) and XY-Silicon strip(Arm#2)
- **Each detector has two calorimeter towers, which allow to reconstruct π^0**

Expected Performance
Energy resolution (> 100GeV)
< 5% for photons
30% for neutrons
Position resolution
< 200μm (Arm#1)
40μm (Arm#2)



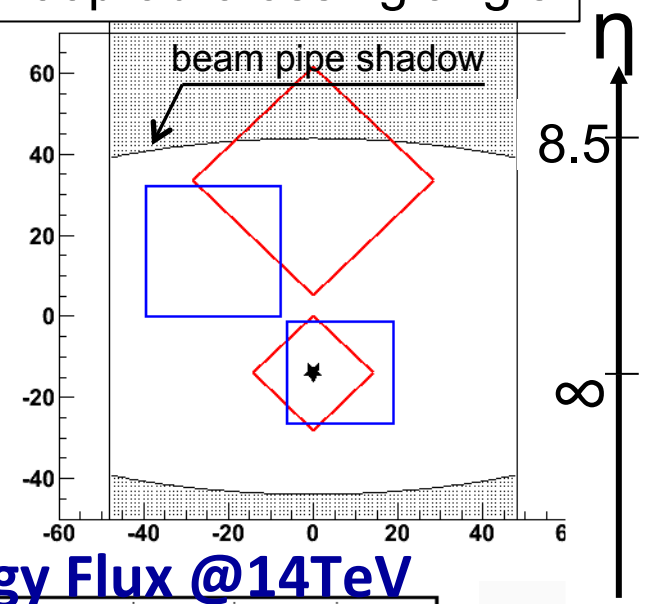
Front Counter

- thin scintillators with 80x80mm^2
- **To monitor beam condition.**
- **For background rejection of beam-residual gas collisions by coincidence analysis**



LHCf can measure

Front view of calorimeters
@ 100μrad crossing angle

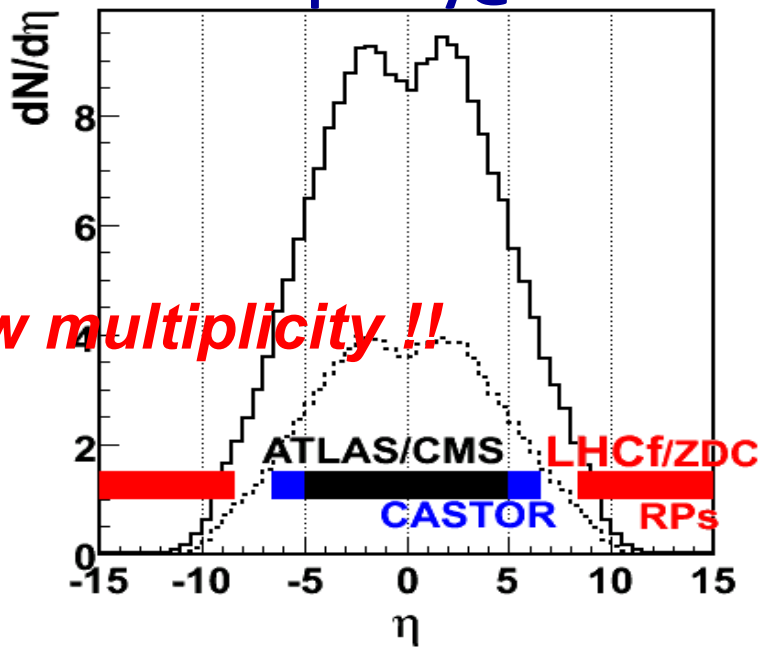


Energy spectra and
Transverse momentum distbution of

- **Gamma-rays (E>100GeV,dE/E<5%)**
- **Neutral Hadrons (E>a few 100 GeV, dE/E~30%)**
- **π^0 (E>600GeV, dE/E<3%)**

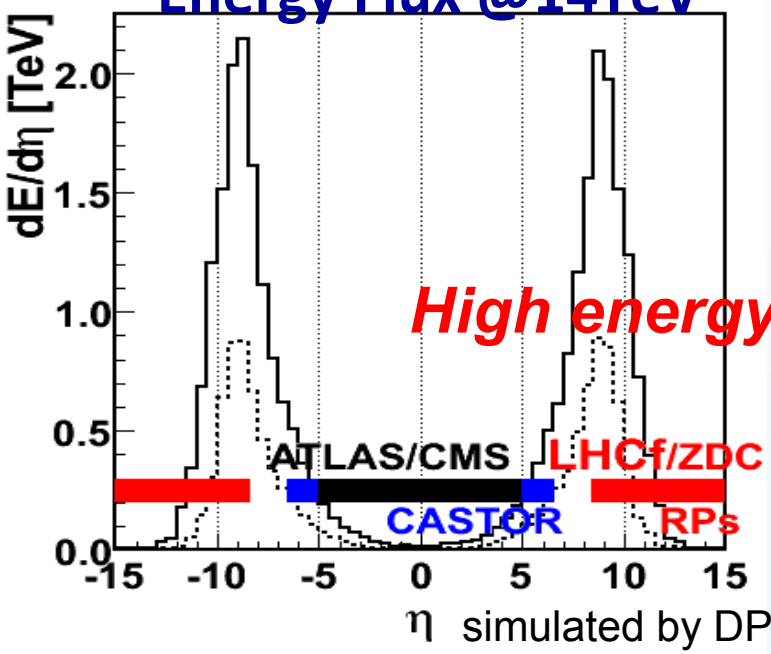
at pseudo-rapidity range >8.4

Multiplicity@14TeV



Low multiplicity !!

Energy Flux @14TeV



High energy flux !!

η simulated by DPMJET3

Status of the LHCf experiment

2008

- First data taking

2009

- First full data taking with $\sqrt{s}$ = 900 GeV p-p collisions.

2010

- Physics programs with $\sqrt{s}$ = 900 GeV and 7 TeV p-p collisions has been completed.

2012

- Calibration of detectors with beams at SPS (Aug.)
- Operation with p-Pb collisions (Nov.)

2014

- Operation with $\sqrt{s}$ = 14 TeV p-p collisions

Published results :

Forward photon spectra at $\sqrt{s}$ = 900 GeV and 7 TeV

Forward π^0 spectra at $\sqrt{s}$ =7 TeV

On going analysis :

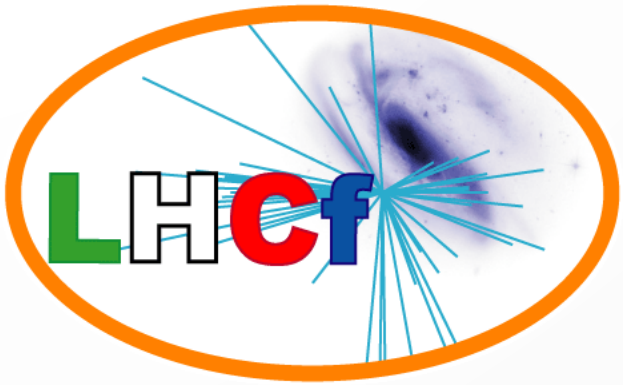
Forward neutron spectra (Next talk)

Mesons (η, K^0, Λ)

Future operations

- *Nuclear effect*
- *Energy dependency*

Results from $\sqrt{s}$ = 900 GeV and 7 TeV p-p data



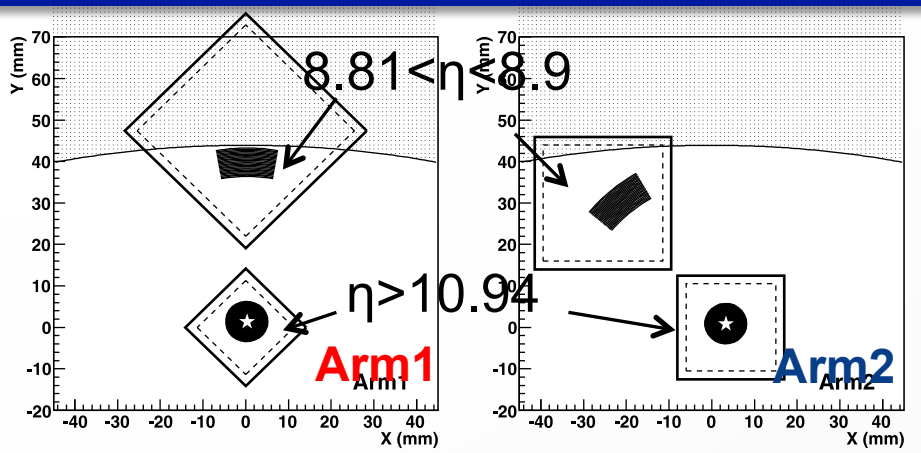
- " Measurement of zero degree single photon energy spectra for $\sqrt{s}$ = 7 TeV proton-proton collisions at LHC "
  O. Adriani, et al., PLB, Vol.703-2, p.128-134 (09/2011)

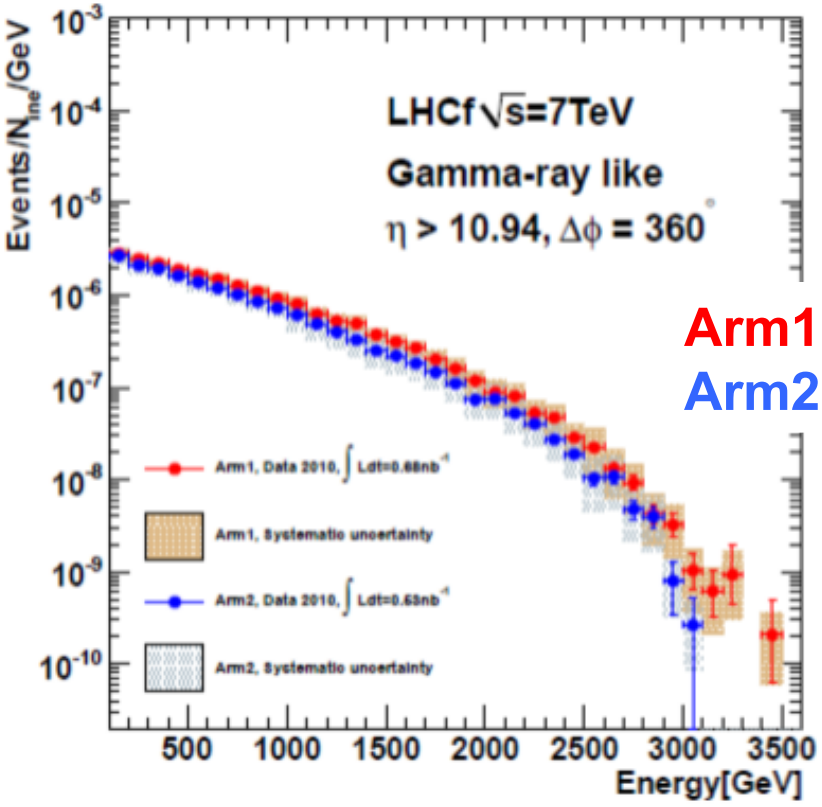
- "Measurement of zero degree inclusive photon energy spectra for $\sqrt{s}$ = 900 GeV proton-proton collisions at LHC"
  O. Adriani, et al., Submitted to PLB.,CERN-PH-EP-2012-048

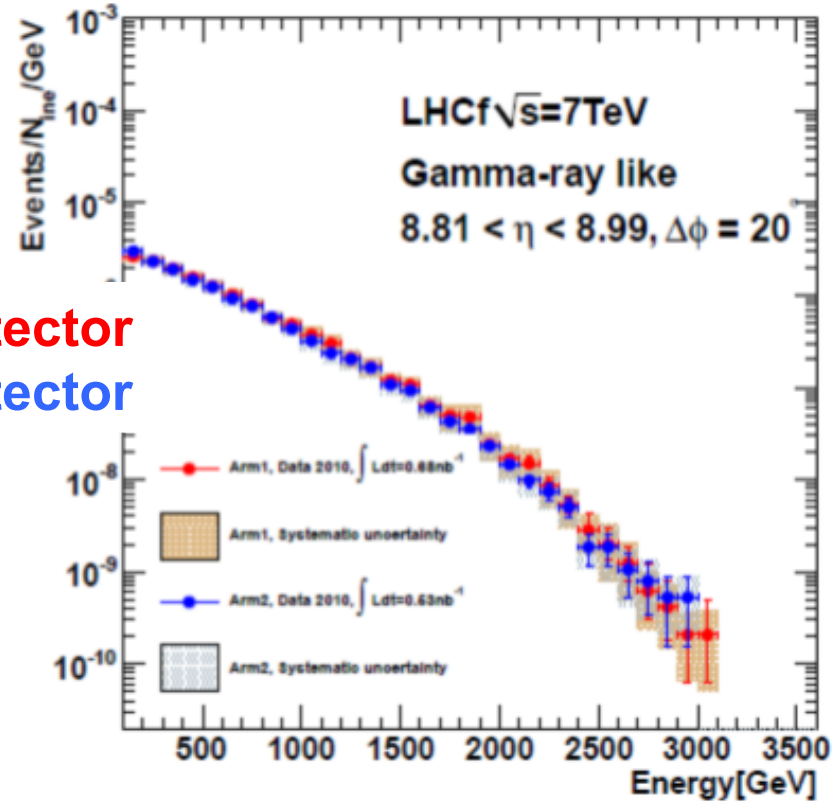
- "Measurement of forward neutral pion transverse momentum spectra for $\sqrt{s}$ = 7TeV proton-proton collisions at LHC"
  O. Adriani, et al., Submitted to PRD, arXiv:1205.4578

Photon spectra at √s = 7 TeV *p-p*

- Pseudo-rapidity,
  η>10.94 and 8.81<η<8.9
- The spectra of two detectors are consistent within the errors.

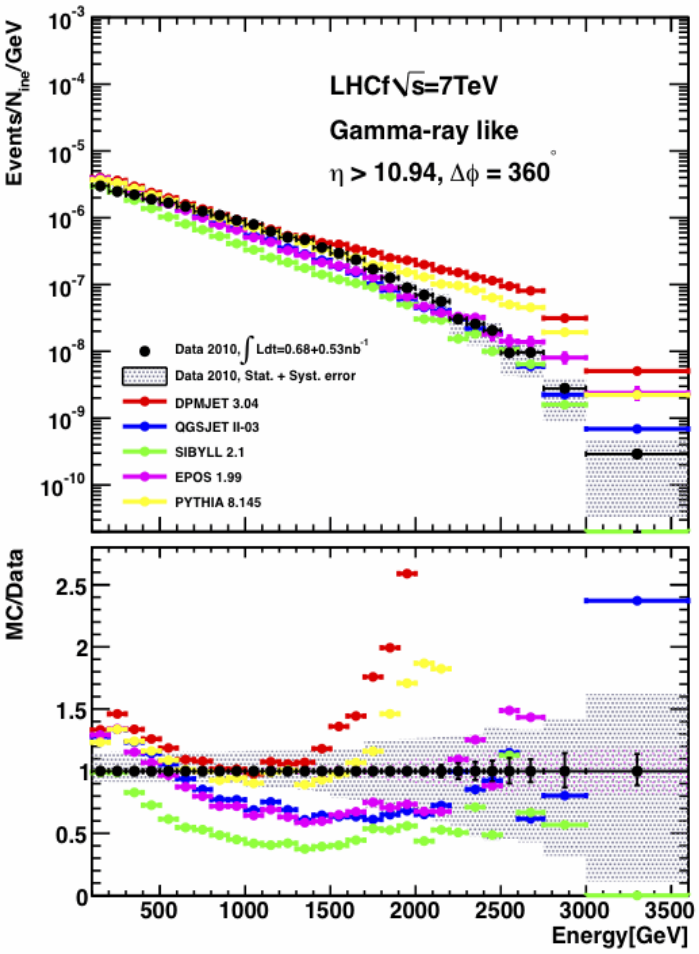


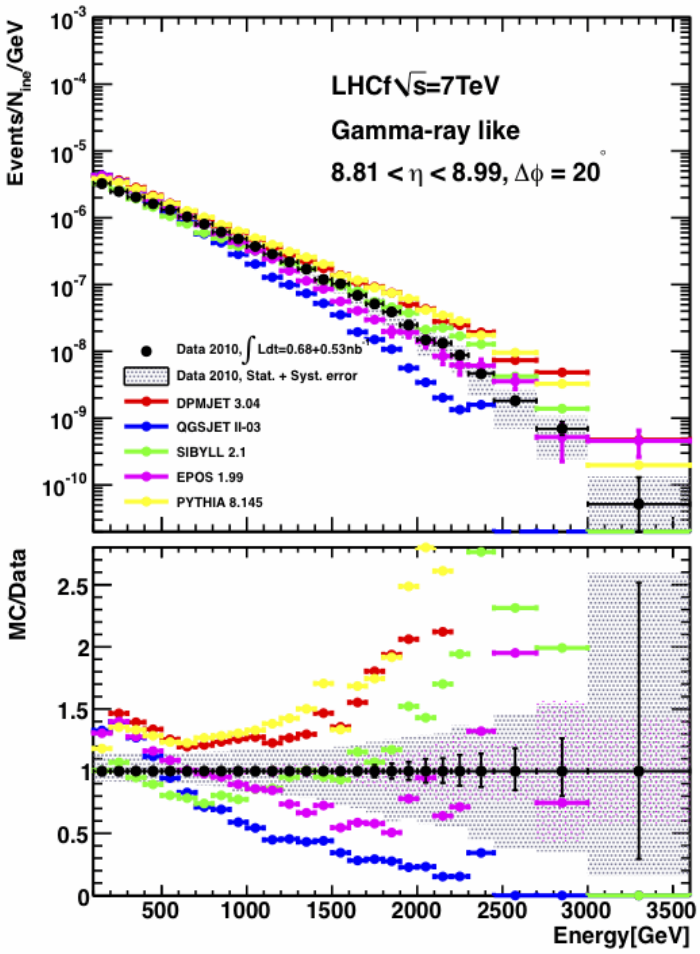




Arm1 detector
Arm2 detector

Photon spectra at √s = 7 TeV *p-p*





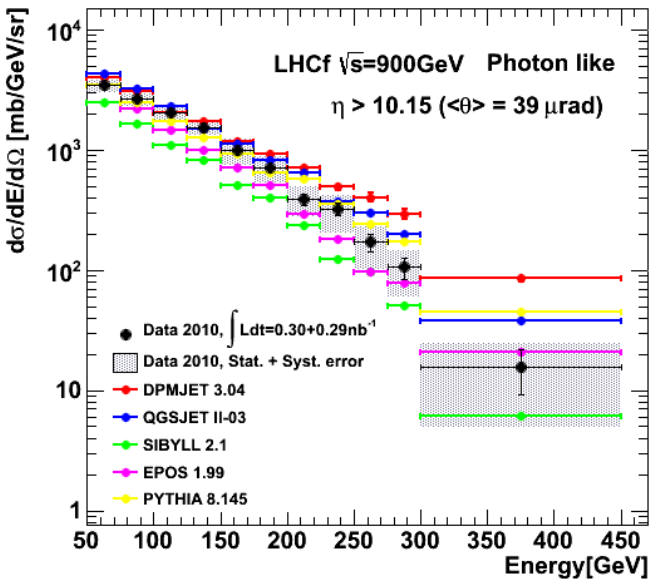
Data

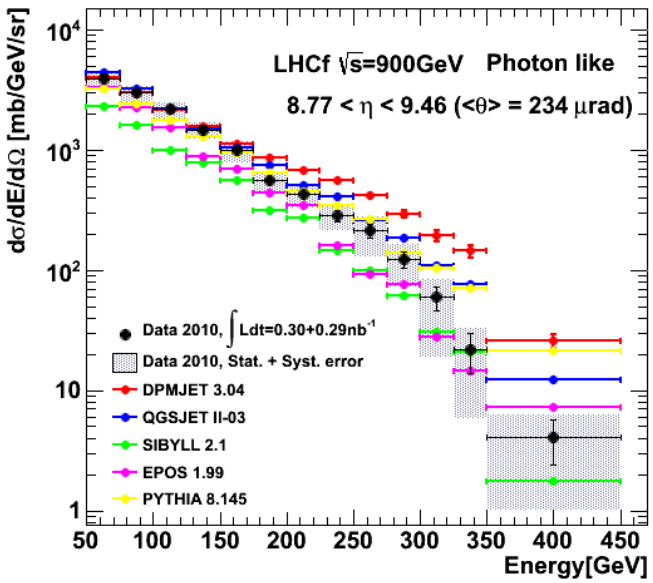
Sys.+Stat.

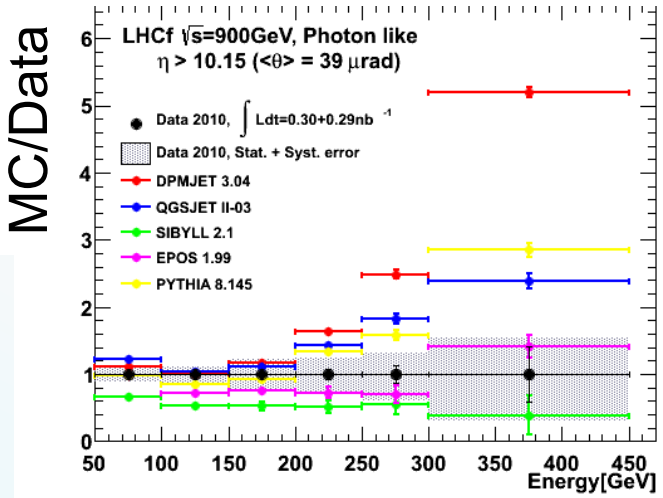
DPMJET 3.04
QGSJETII-03
SIBYLL 2.1
EPOS 1.99
PYTHIA 8.145

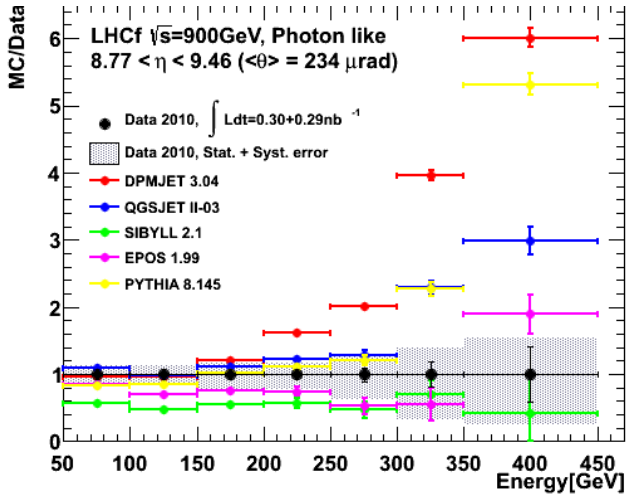
- No model can reproduce the LHCf data perfectly.
- DPMJET and PYTHIA are in good agreement E_γ<1.5TeV, but harder in E>1.5TeV.
- QGSJET and SIBYLL shows reasonable agreement of shapes in high-η but not in low-η
- EPOS has less η dependency against the LHCf data.

Photon spectra at √s = 900 GeV *p-p*









Data

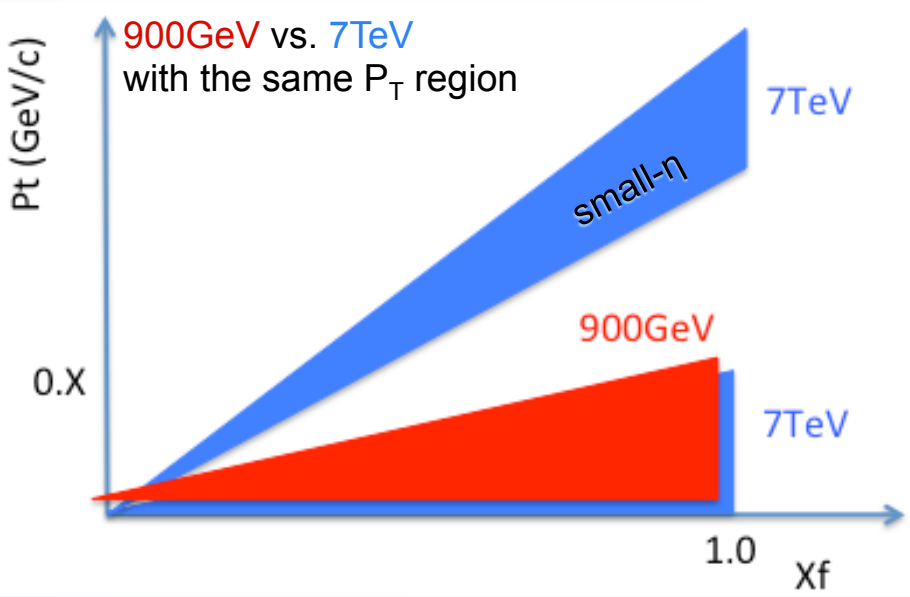
Sys.+Stat.

DPMJET 3.04
QGSJETII-03
SIBYLL 2.1
EPOS 1.99
PYTHIA 8.145

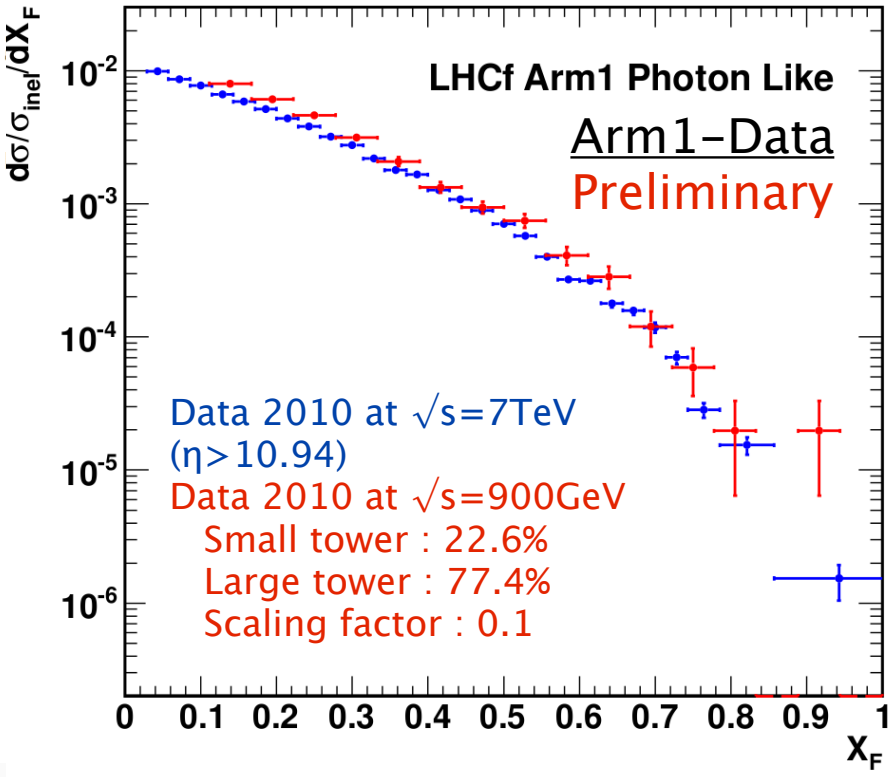
- Both of Data and MC show little η dependency.
- The tendencies of MC against Data are very similar to one of 7 TeV in η > 10.94.

DATA : Comp. 900GeV/7TeV

Coverage of 900GeV and 7TeV results in Feynman-X and P_T



X_F spectra : 900 GeV data vs. 7 TeV data

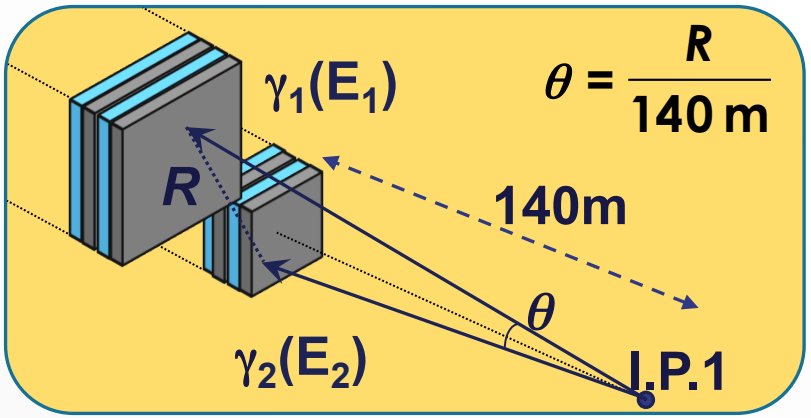


Good agreement of X_F spectrum shape between 900 GeV and 7TeV.
➔weak dependence of <p_T> on E_{CMS}

Note : No systematic error is considered in both collision energies. 21% of the luminosity determination error allows vertical shift.

$$\frac{1}{\sigma_{\text{inel}}}\frac{d\sigma_\gamma}{dX_F}\Big|_{\eta<\text{limited}} \propto \frac{1}{\sigma_{\text{inel}}}\frac{d\sigma_\gamma}{p_T dp_T dX_F}\langle p_T\rangle dp_T$$

π^0 analysis



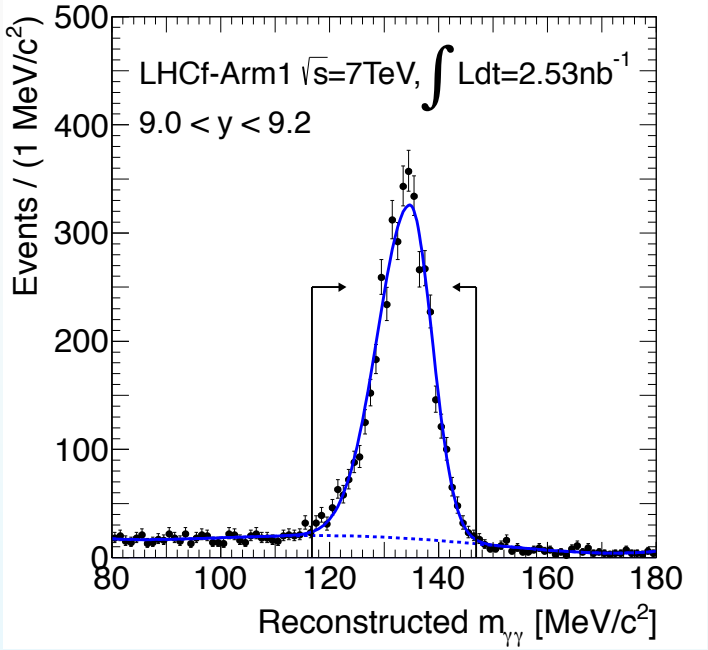
Mass, energy and transverse momentum are reconstructed from the energies and impact positions of photon pairs measured by each calorimeter

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

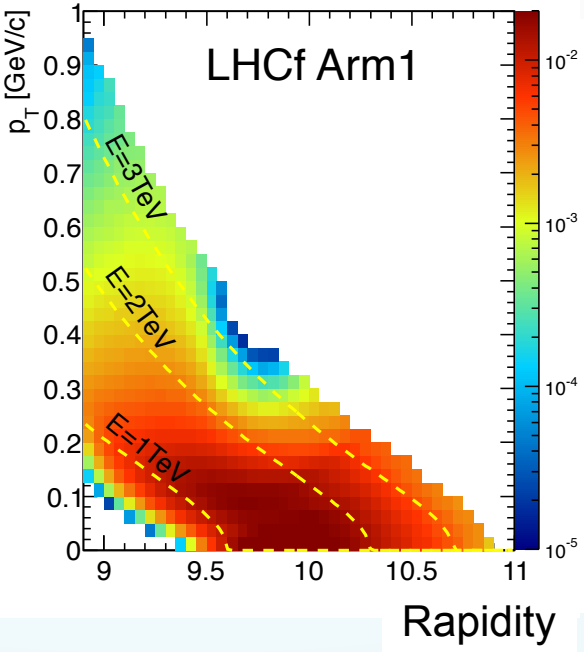
$$E_{\pi^0} = E_{\gamma 1} + E_{\gamma 2},$$

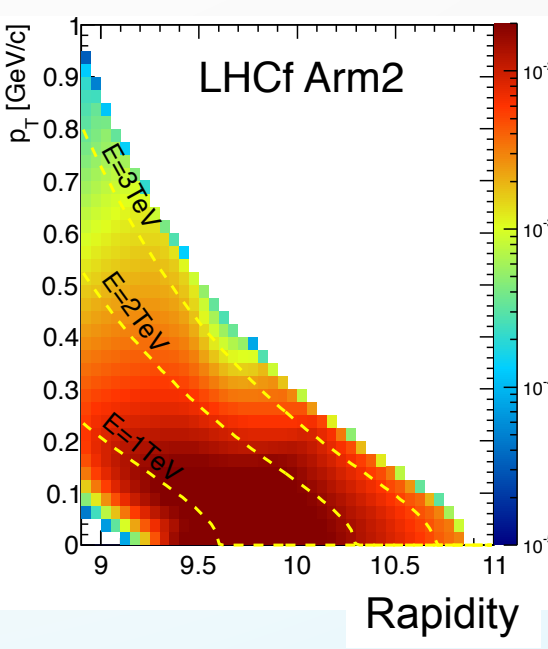
$$P_{T\pi^0} = P_{T\gamma 1} + P_{T\gamma 2}$$

Mass reconstructed from photon pairs

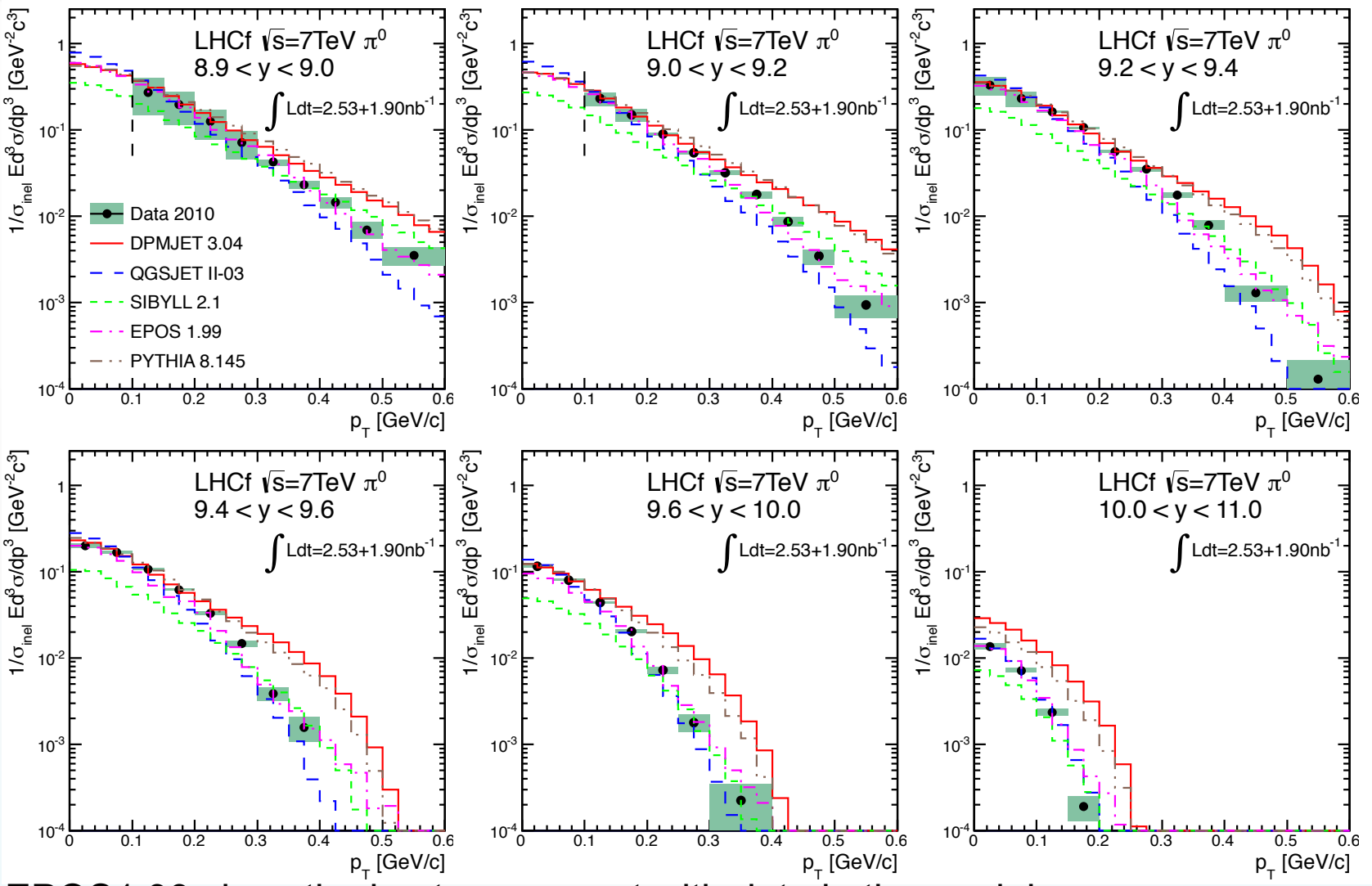


Acceptance Rapidity - P_T





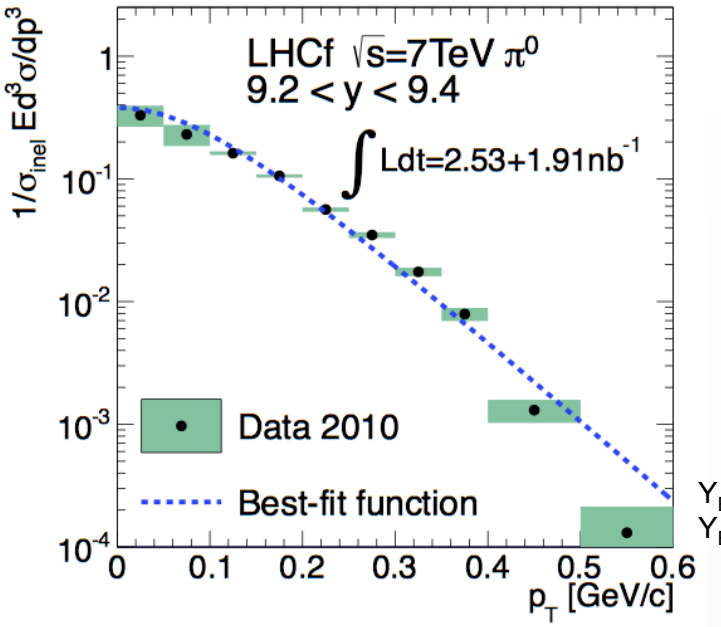
π^0 spectra at $\sqrt{s}$ = 7 TeV *p-p*



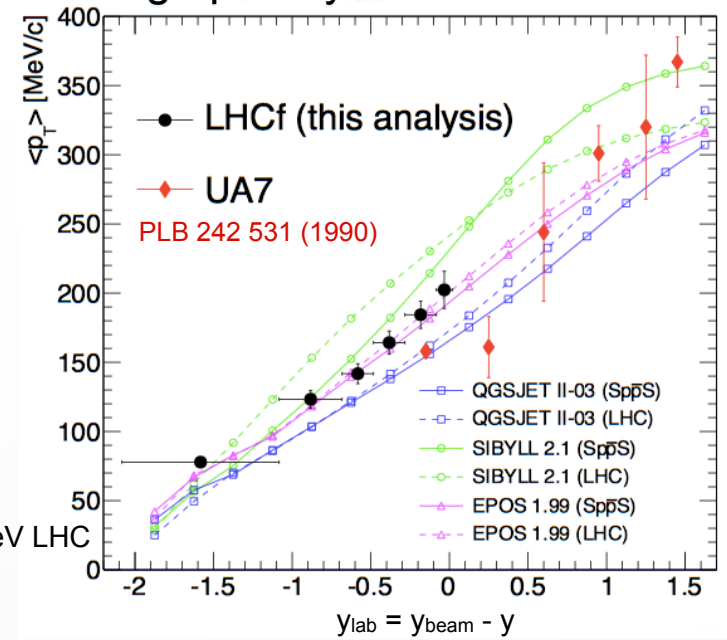
- EPOS1.99 show the best agreement with data in the models.
- DPMJET and PYTHIA have harder spectra than data (“popcorn model”)
- QGSJET has softer spectrum than data. (only one quark exchange is allowed)

<P_T> of π^0 at $\sqrt{s}$ = 7 TeV *p-p*

p_T spectra vs best-fit function



Average p_T vs y_{lab}



Y_{Beam}=6.5 for SPS
Y_{Beam}=8.92 for7 TeV LHC

1. Thermodynamics
(Hagedron, Riv. Nuovo Cim. 6:10, 1 (1983))

$$\frac{1}{\sigma_{\rm inel}} E\frac{d^3\sigma}{dp^3} = A\cdot\exp(-\sqrt{{p_{\rm T}}^2c^2+m_{\pi^0}^2c^4}/T)$$

$$\langle p_{\rm T}\rangle = \sqrt{\frac{\pi m_{\pi^0}c^2T}{2}}\frac{K_2(m_{\pi^0}c^2/T)}{K_{3/2}(m_{\pi^0}c^2/T)}$$

2. Numerical integration

$$\langle p_{\rm T}\rangle = \frac{\int_0^\infty 2\pi p_{\rm T}^2 f(p_{\rm T})dp_{\rm T}}{\int_0^\infty 2\pi p_{\rm T} f(p_{\rm T})dp_{\rm T}}$$

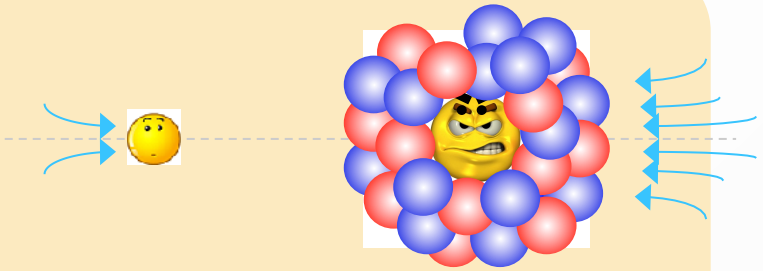
actually up to the upper bound of histogram

- Systematic uncertainty of LHCf data is 5%.
- Compared with the UA7 data (√s=630GeV) and MC simulations (QGSJET, SIBYLL, EPOS).
- Two experimental data mostly appear to lie along a common curve
  → no evident dependence of <p_T> on E_{CMS}.
- Smallest dependence on E_{CMS} is found in EPOS and it is consistent with LHCf and UA7.
- Large E_{CMS} dependence is found in SIBYLL

Future operations

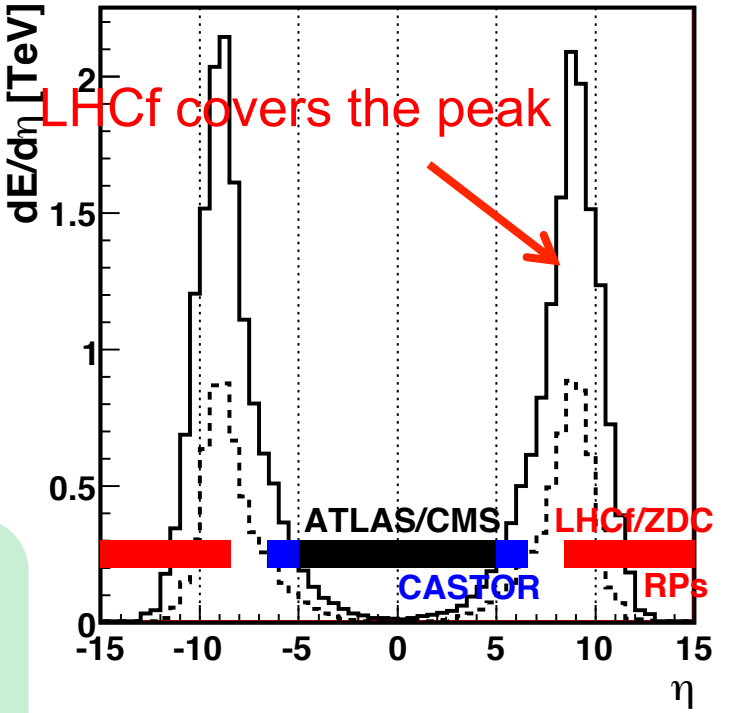
p-Pb operation (Nov. 2012)

Install the one of the LHCf detector.
Nuclear effect at the proton remnant side.
LOI, O.Adriani, et al.CERN-LHCC-2011-2015



p-p at 14TeV (2014)

Measurement at the LHC design energy.
Energy scaling by comparison with
$\sqrt{s}$ = 900 GeV and 7 TeV data
TDR, O.Adriani, et al. CERN-LHCC-2006-004



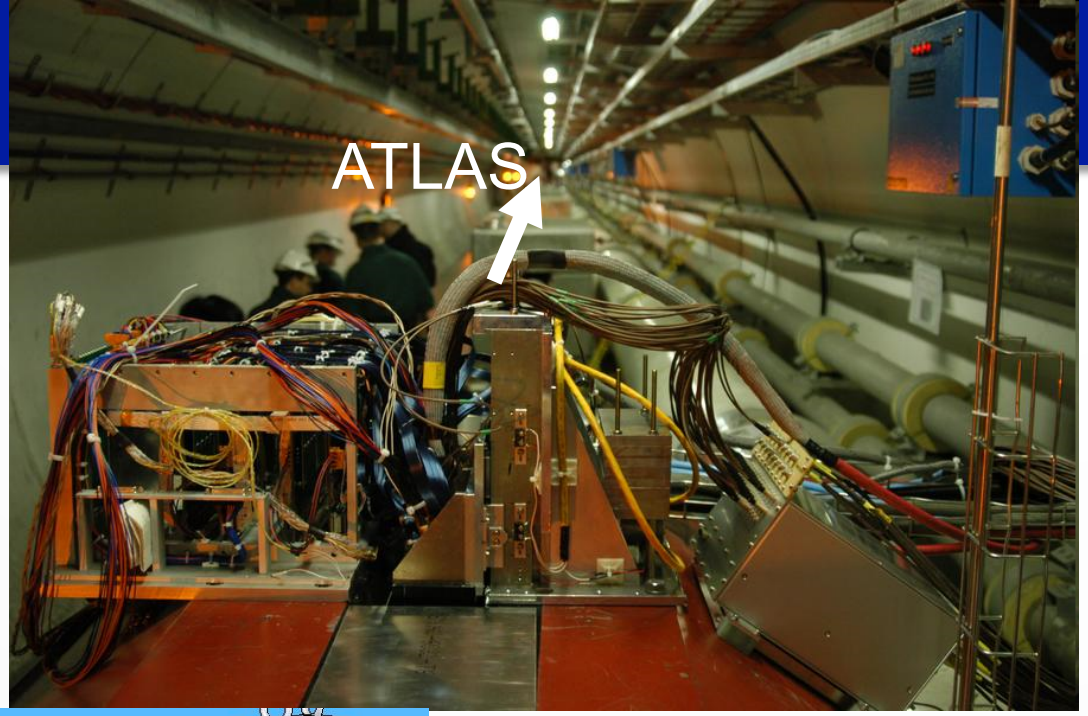
Operations at RHIC (after 2015 ?)

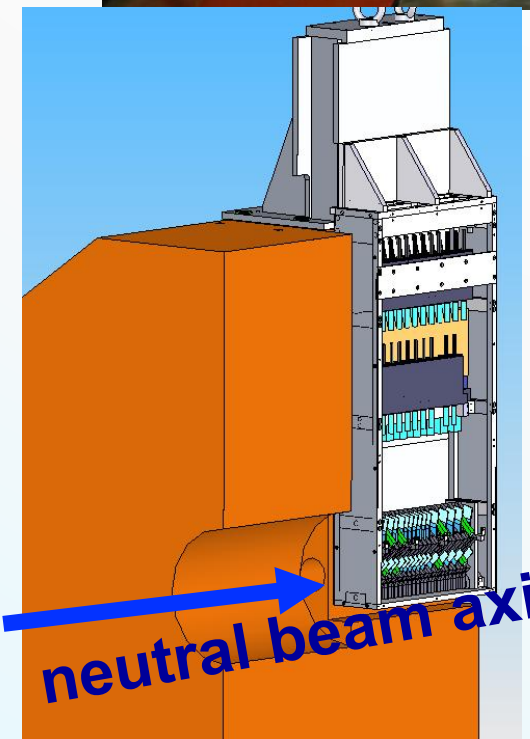
Lower collision energy, ion collisions.
Starting discussion with RHIC people.

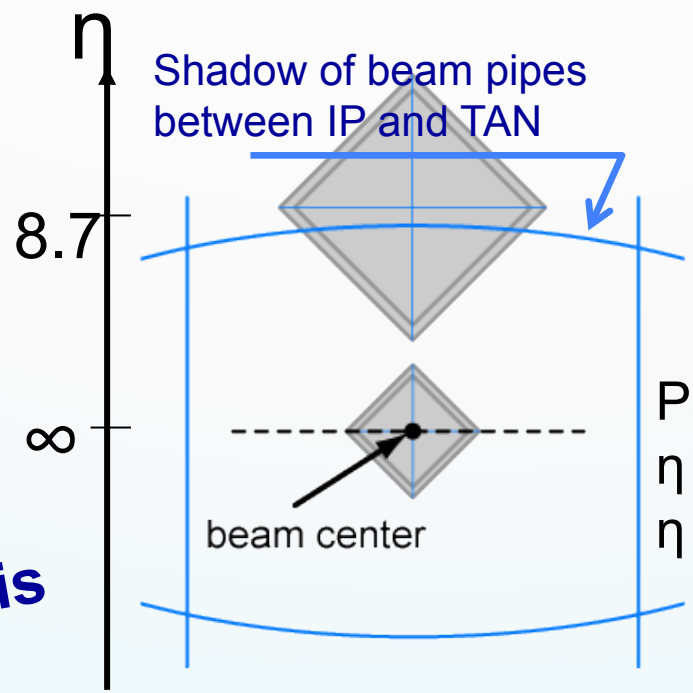
Summary

- LHCf has measured the energy and transverse momentum spectra at the very forward region of $\sqrt{s}$ = 900GeV and $\sqrt{s}$ =7TeV *p-p* collisions in 2010.
- We showed the spectra of very forward photons at $\sqrt{s}$ = 900 GeV and 7 TeV p-p collisions and π^0s at $\sqrt{s}$ = 7 TeV p-p collisions. No model can produce data perfectly but the data are located in the middle of the model predictions.
- Many analyses are ongoing,
  - Hadron analysis
  - P_T spectrum of photons
- Future operations will provide many data at the forward region.
  - p-Pb collisions (the end of this year.)
  - p-p collisions at $\sqrt{s}$ = 7TeV (2014 or 2015)
  - operations at RHIC
- Analysis with the central data (ATLAS)
  - LHCf recorded the ATLAS event ID in our events.
  - Looking for possibility of trigger exchange between LHCf and ATLAS

Backup slides

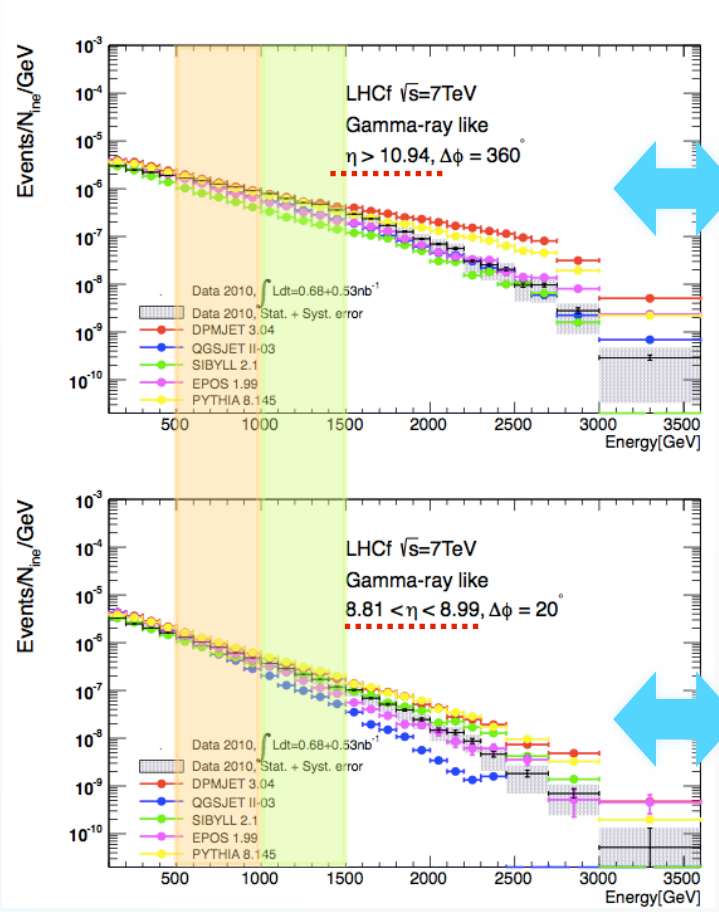


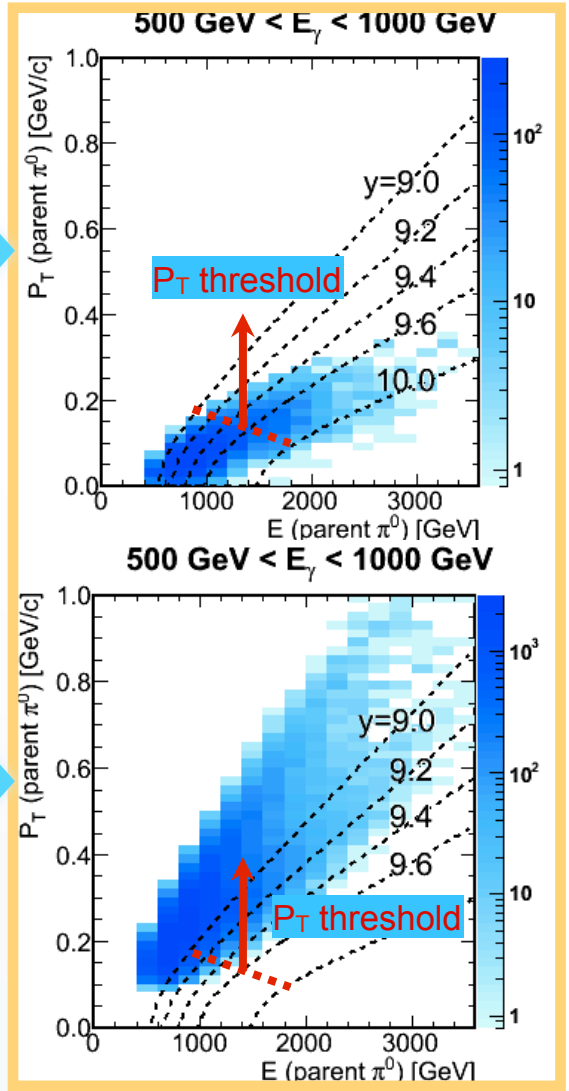


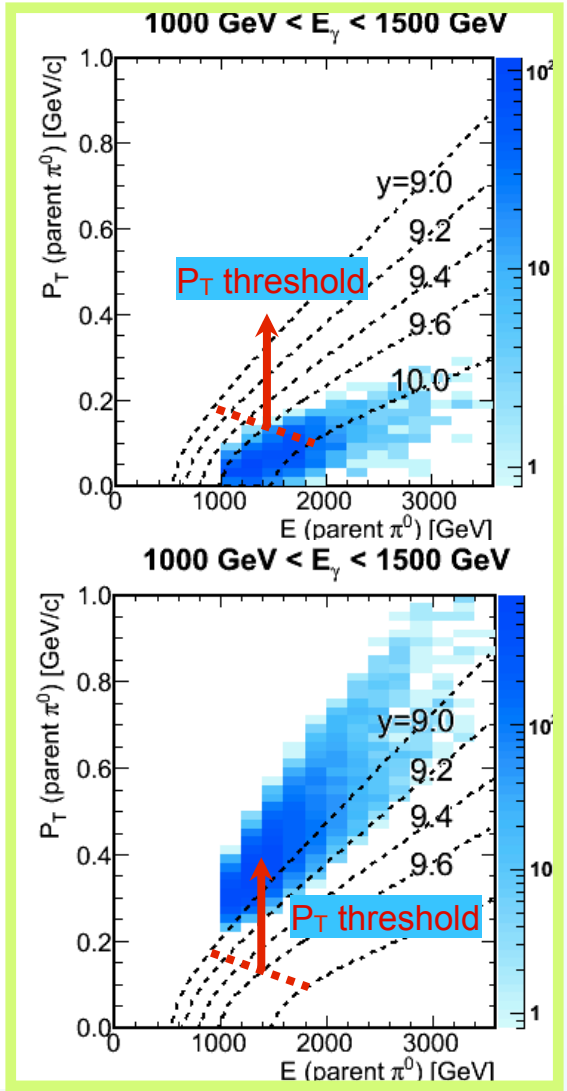


Pseudo-rapidity range.
η > 8.7 @ zero crossing angle
η > 8.4 @ 140urad

7TeV π^0 analysis





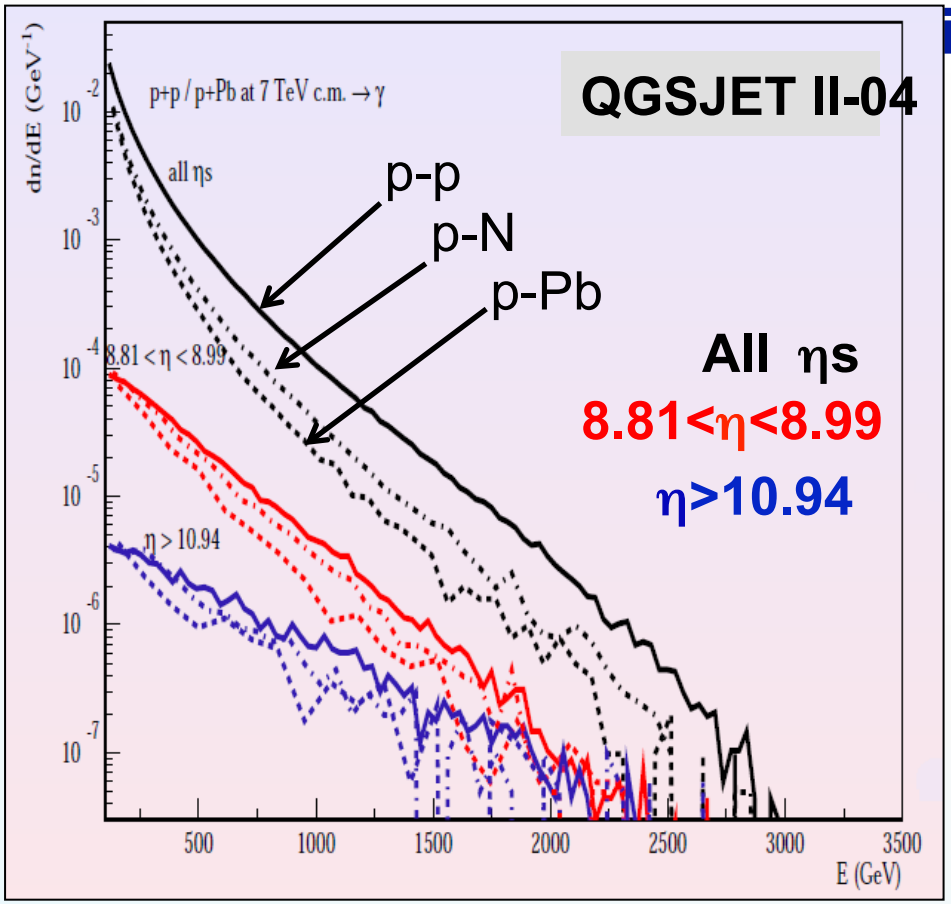


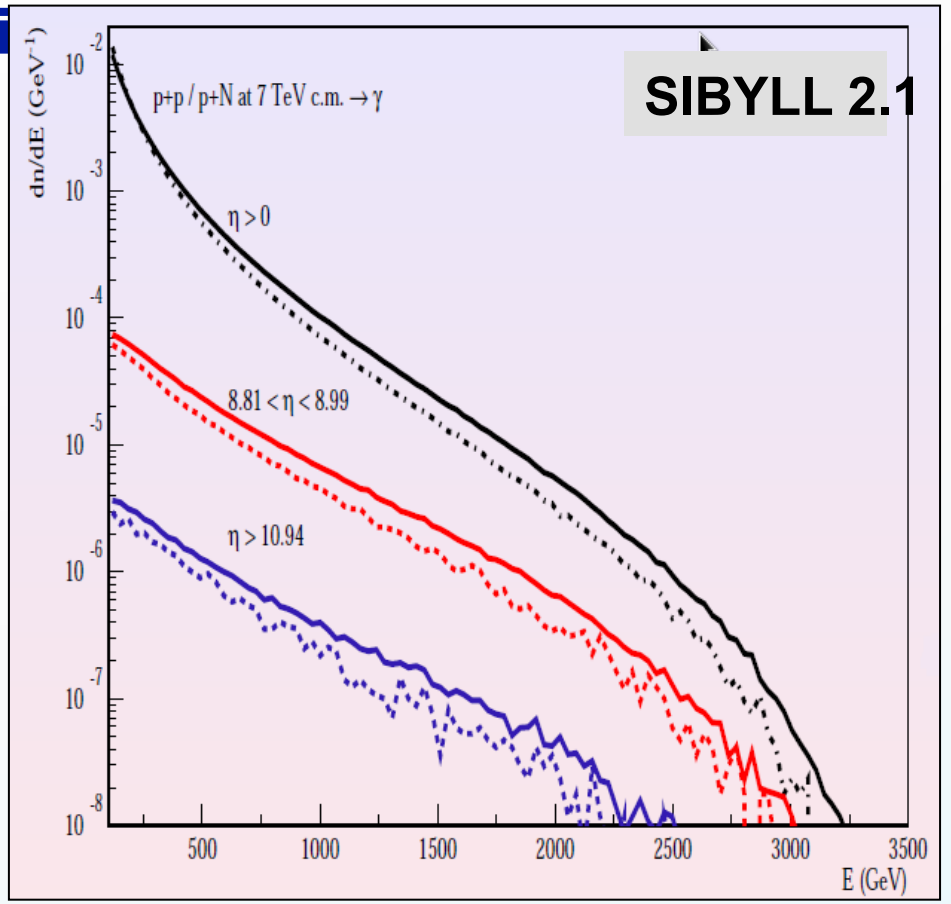
- Photon analysis and π^0 analysis compensate each missing information.
  - High energy photon originates from large P_T π^0 events.
  - Photon spectrum includes a contribution from other hadrons/baryons.

Photon P_T analysis can connect each measuremen

Photons on the p-remnant sid

- Photon energy distrib. in different η intervals at $\sqrt{s_{NN}}$ = 7 TeV
- Comparison of p-p / p-N / p-Pb

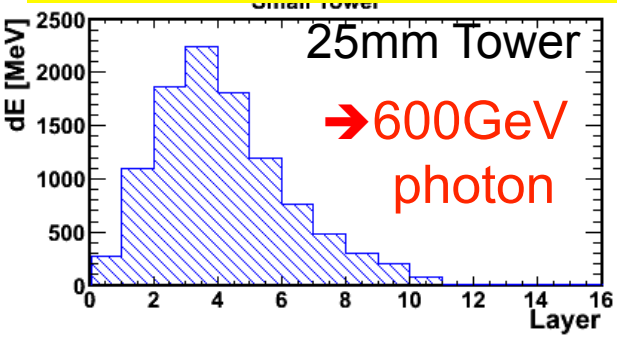


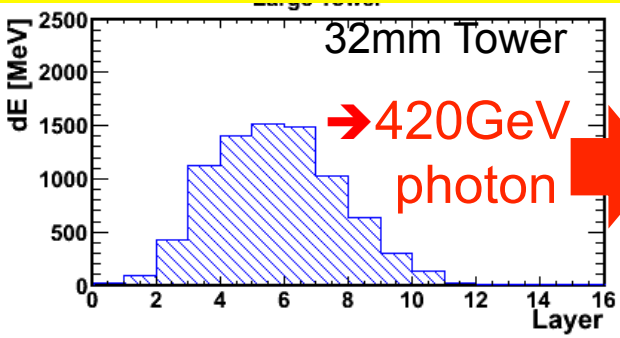


Courtesy of S. Ostapchenk

Event sample

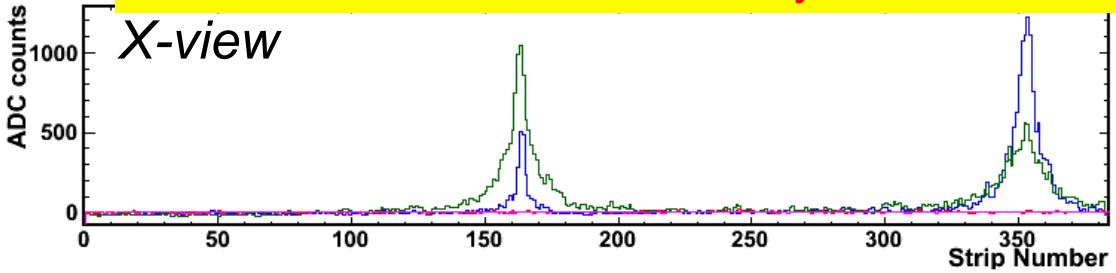
Longitudinal development measured by scintillator layers

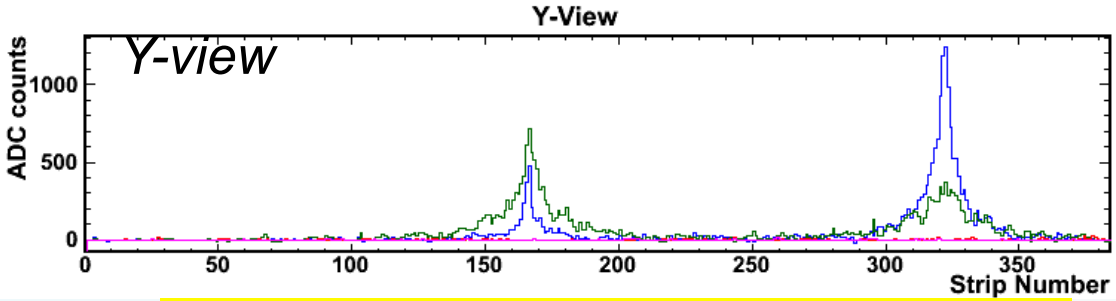




Total Energy deposit
➔Energy
Shape
➔PID

Lateral distribution measured by silicon detectors





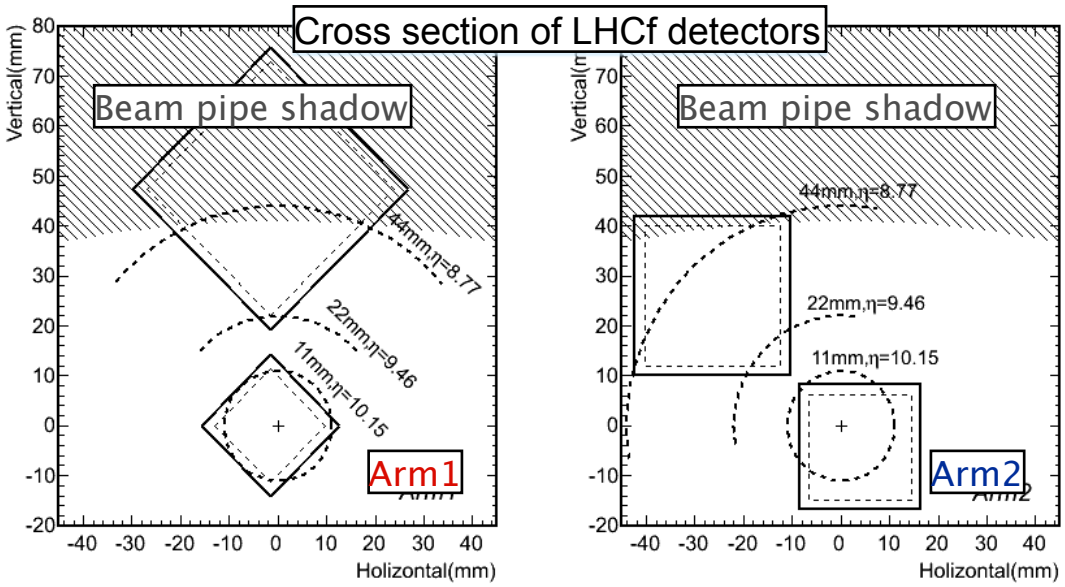
Hit position,
Multi-hit search.

π^0 mass reconstruction from two photon.

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

Systematic studies

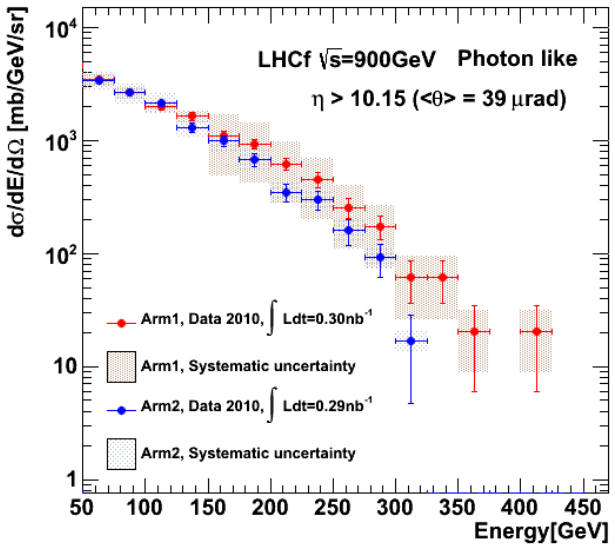
900GeV photon analysis

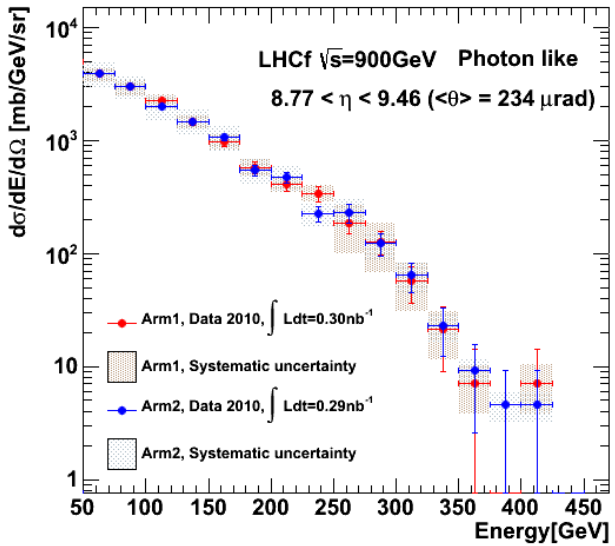


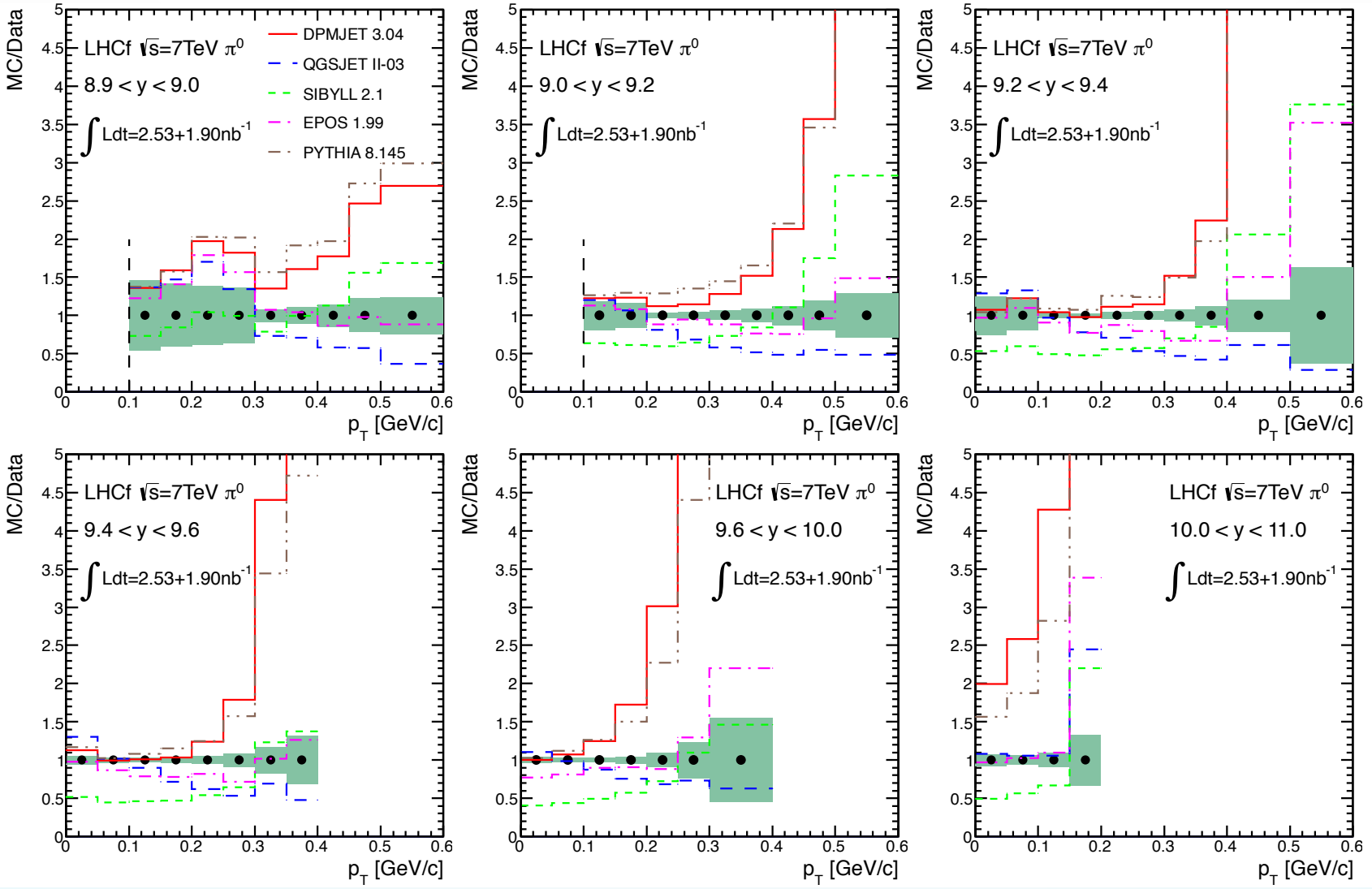
Two pseudo-rapidity ranges
- η>10.15
- 8.77<η<9.46

Arm1 and Arm2 data show an overall good agreement within their systematic uncertainties.

Arm1 data vs Arm2 data






LHCf √s=7TeV π0
8.9 < y < 9.0
∫ Ldt=2.53+1.90nb-1
DPMJET 3.04
QGSJET II-03
SIBYLL 2.1
EPOS 1.99
PYTHIA 8.145
9.0 < y < 9.2
9.2 < y < 9.4
9.4 < y < 9.6
9.6 < y < 10.0
10.0 < y < 11.0
MC/Data
pT [GeV/c]