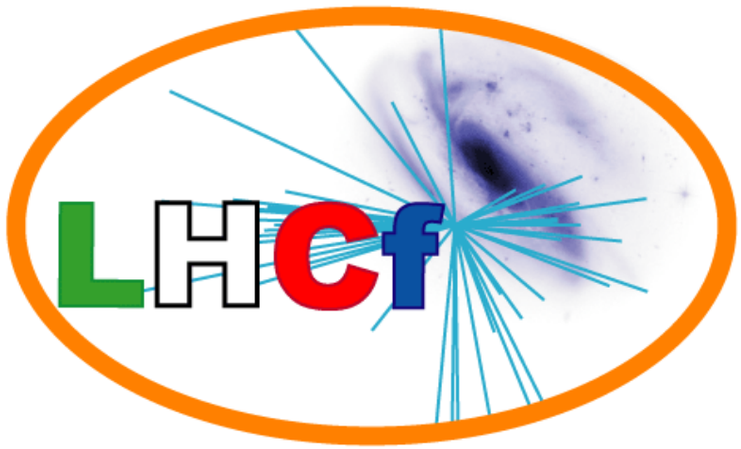
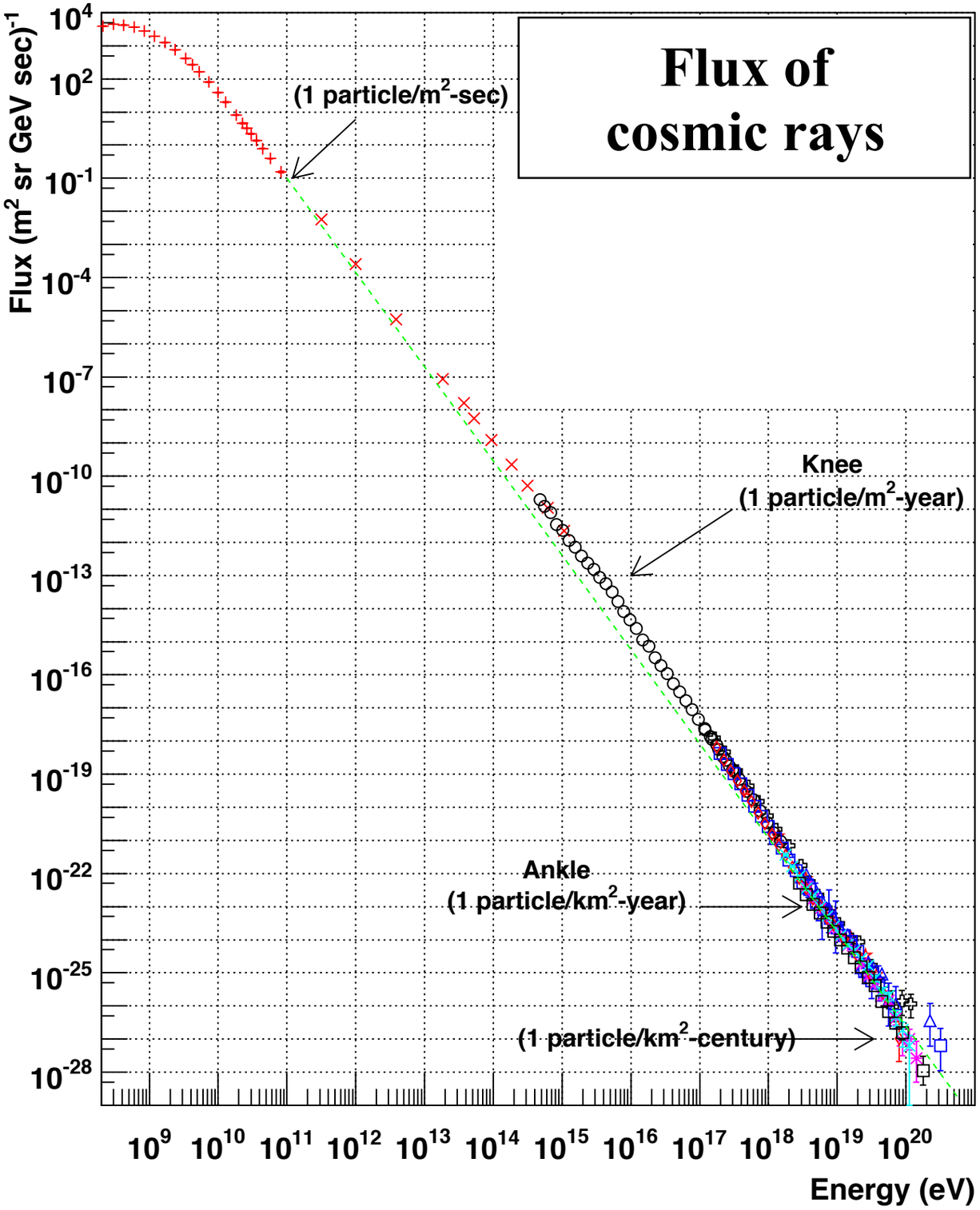


Latest results from the LHCf experiment

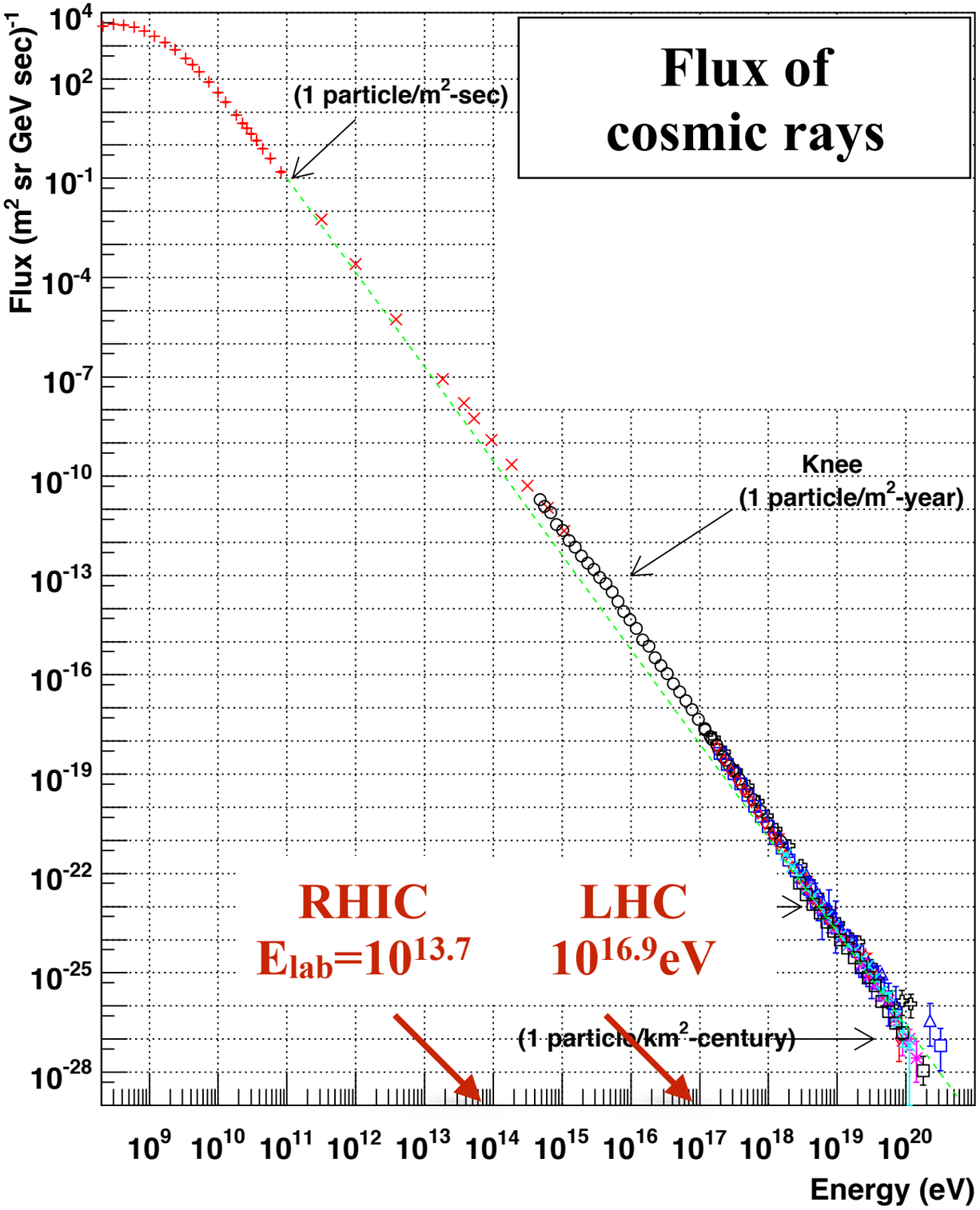
(38th International Conference on High Energy Physics, Chicago)

T. Suzuki (Waseda University)
on behalf of the LHCf Collaboration

Introduction ~ brief story about cosmic rays ~



Introduction ~ brief story about cosmic rays ~

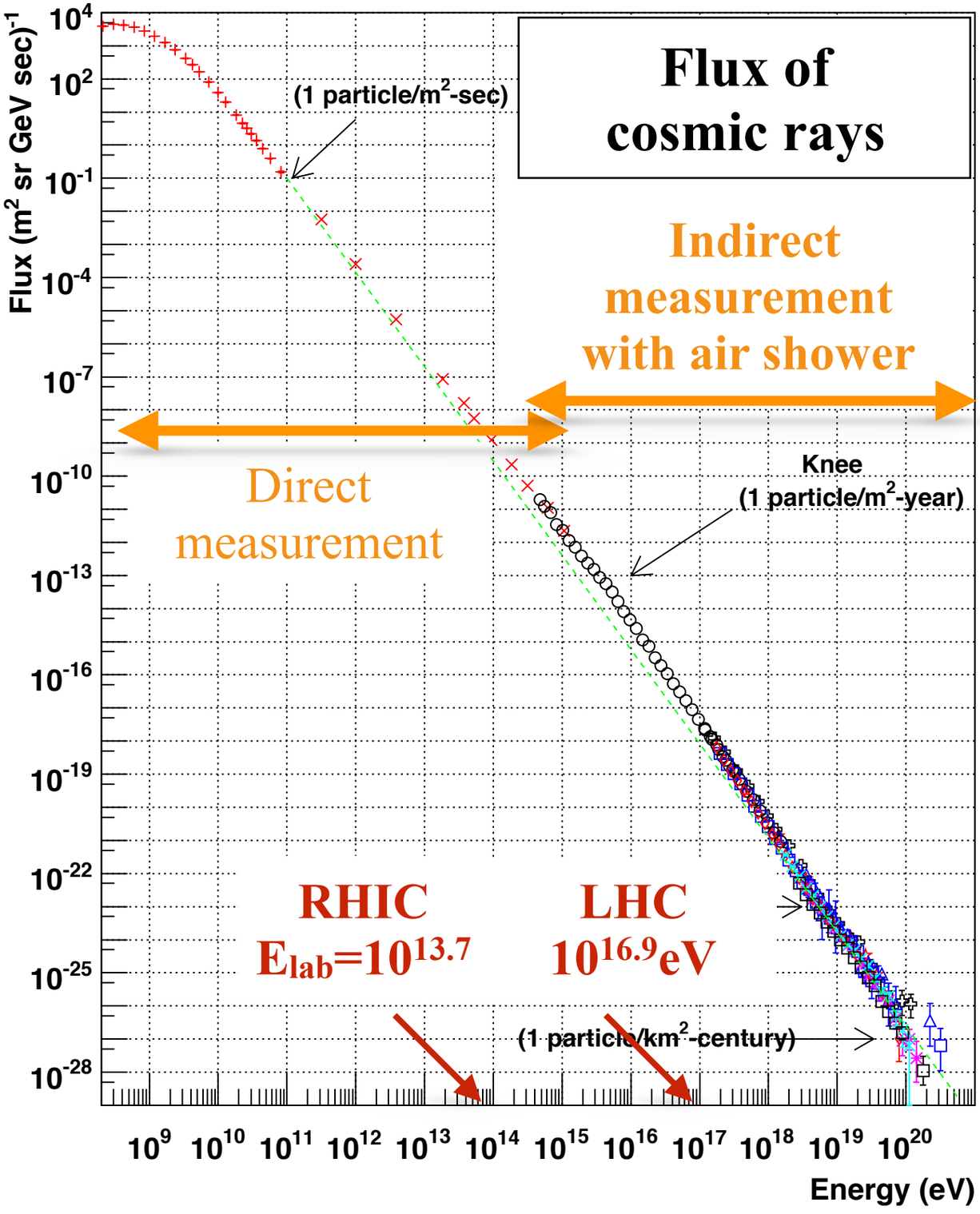


Cosmic rays at high energy

Astrophysical parameters

- Spectrum
- Mass composition (p,He,Be,…,Fe)
- Source distribution

Introduction ~ brief story about cosmic rays ~



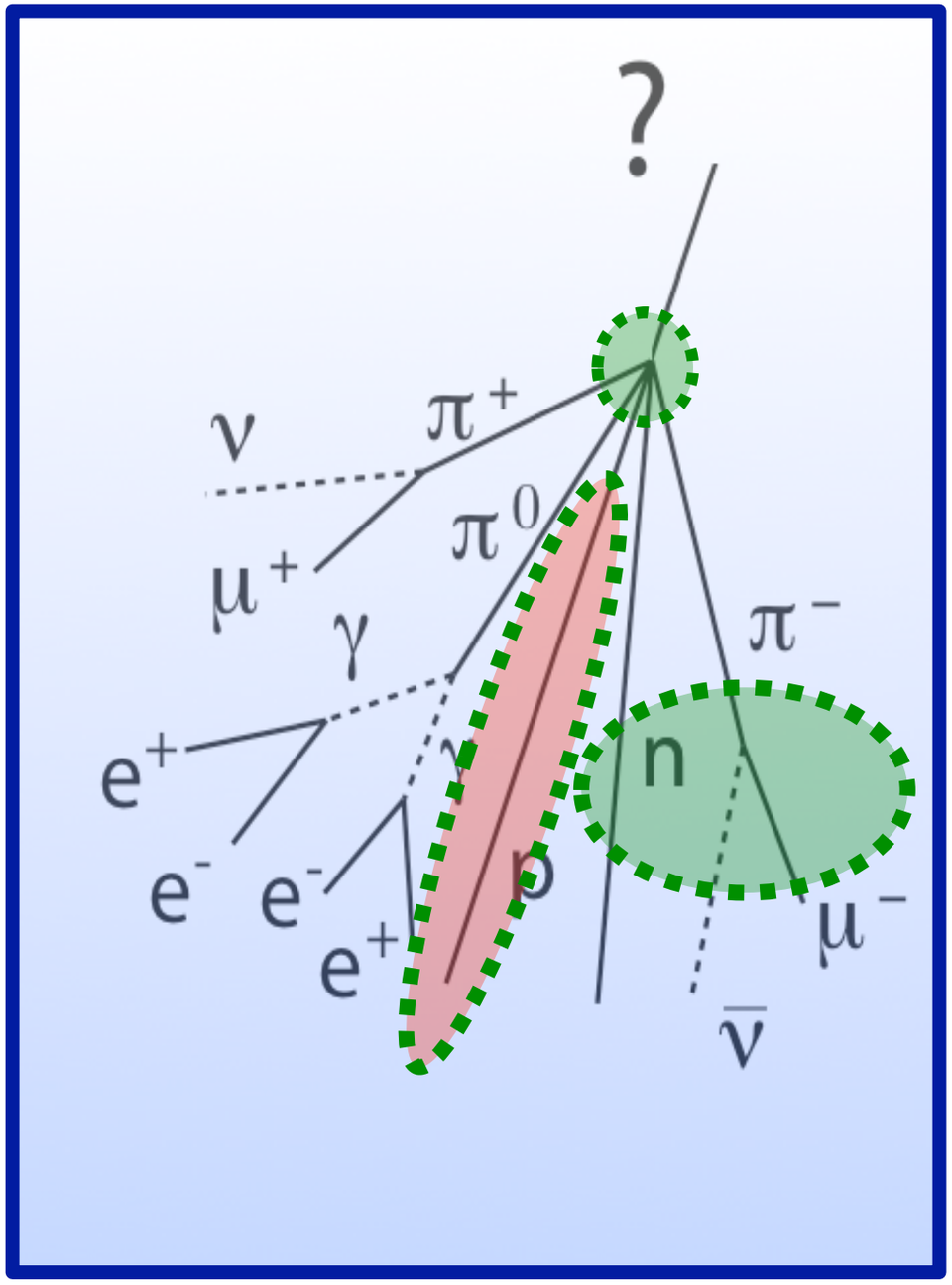
Cosmic rays at high energy

Astrophysical parameters
- Spectrum
- Mass composition (p,He,Be,…,Fe)
- Source distribution

Indirect measurements due to low flux
- Measurements are constraint to ground level with large detector arrays and telescopes
- Air showers are observed because of the atmosphere

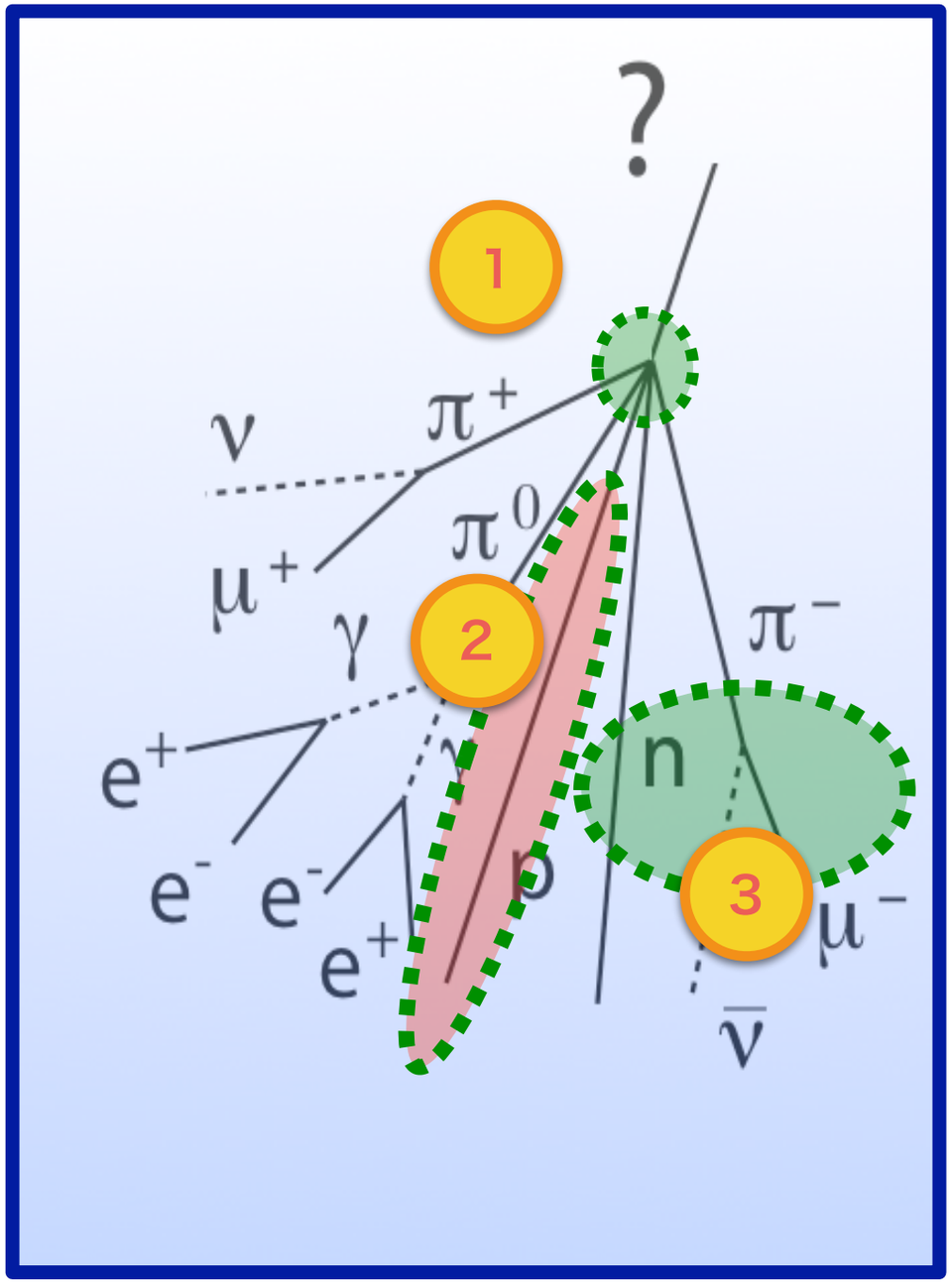
Air shower observation
- Longitudinal distribution
- Lateral distribution
- Arrival direction

Air showers to accelerators



One needs to rely on MC to reconstruct the primary cosmic ray

Air showers to accelerators

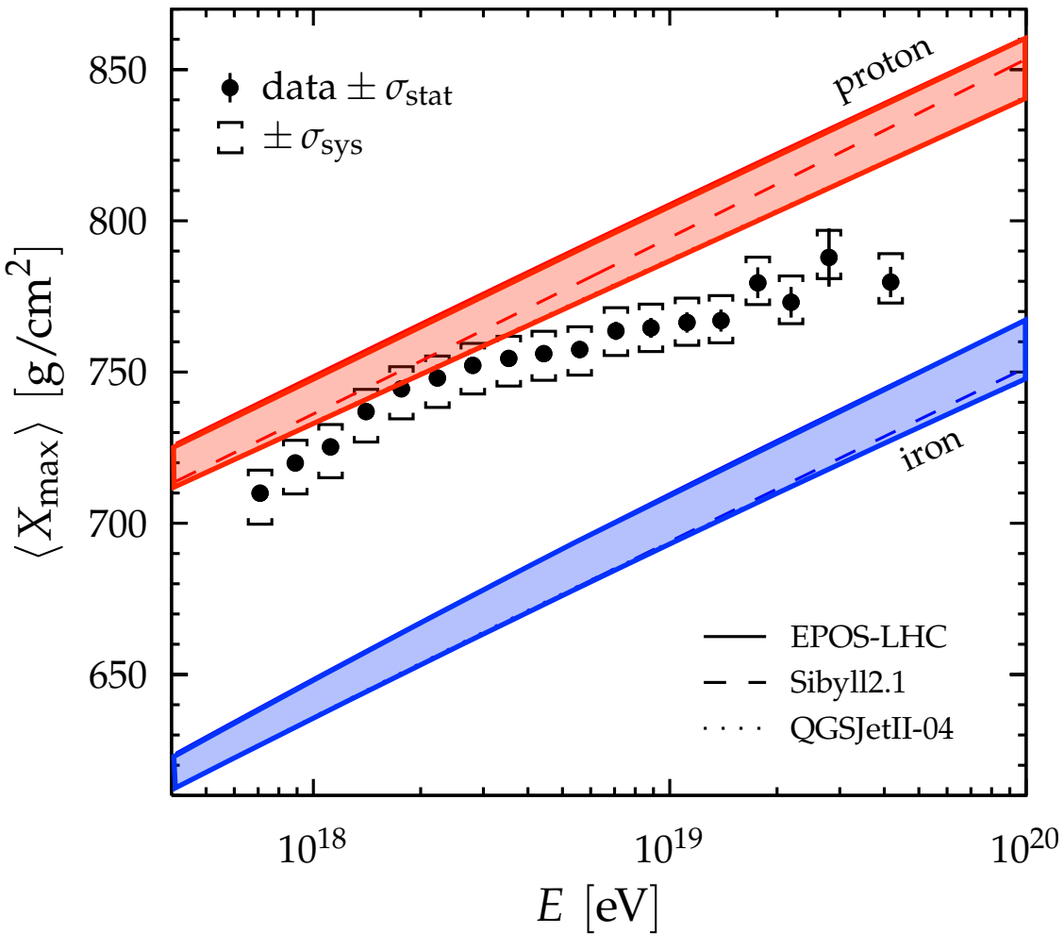


One needs to rely on MC to reconstruct the primary cosmic ray

Parameters to be tuned

1. Inelastic cross section (ex: TOTEM)
2. **Forward spectrum** (ex: **LHCf**, UA7)
3. Secondaries

Air showers to accelerators



(From Pierre Auger Observatory)

$\langle X_{max} \rangle$:Mean depth of shower maximum from the top of the atmosphere in g/cm^2

One needs to rely on MC to reconstruct the primary cosmic ray

Parameters to be tuned

1. Inelastic cross section (ex: TOTEM)
2. **Forward spectrum** (ex: **LHCf**, UA7)
3. Secondaries

Uncertainty of hadron interaction

▼

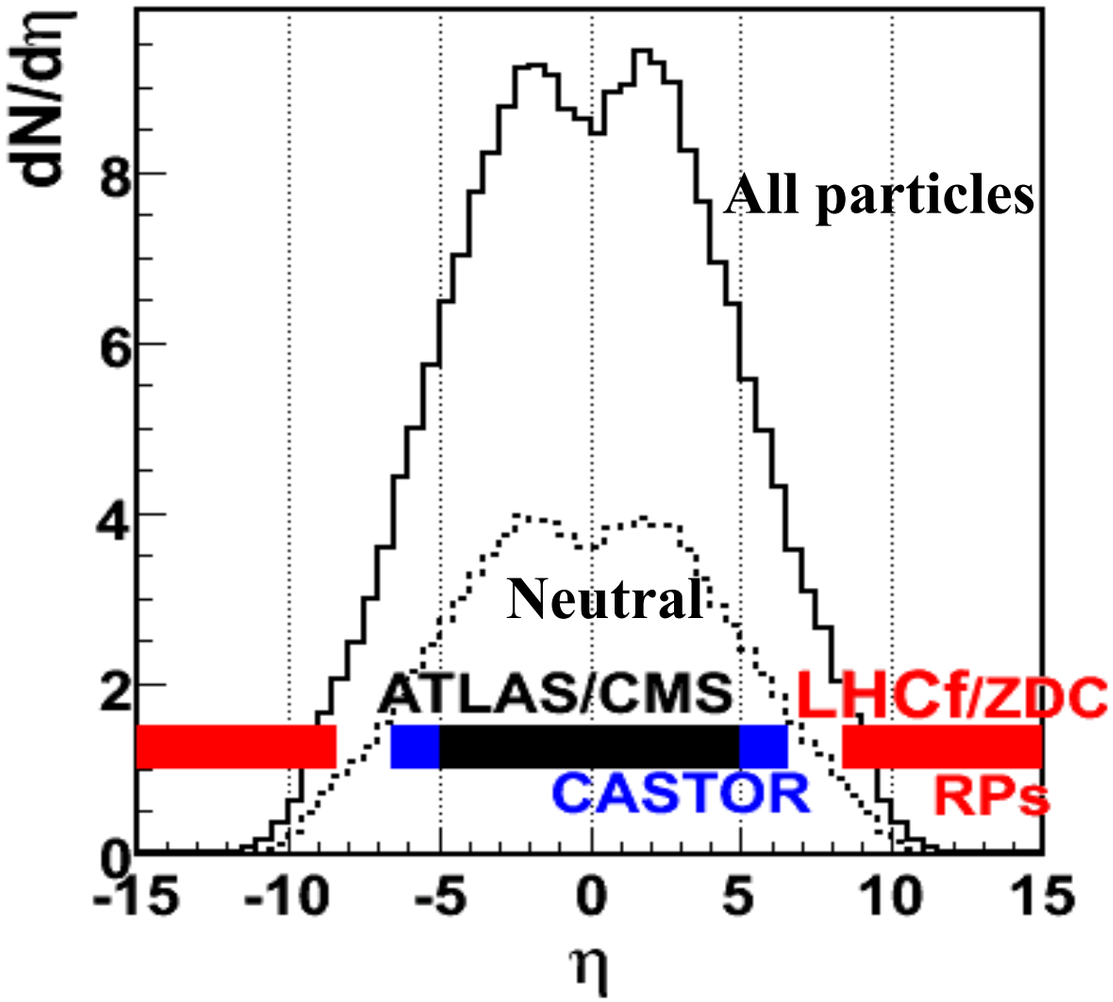
Uncertainty of interpretation of $\langle X_{max} \rangle$

MC simulations of air showers with accurate hadronic interaction models are needed

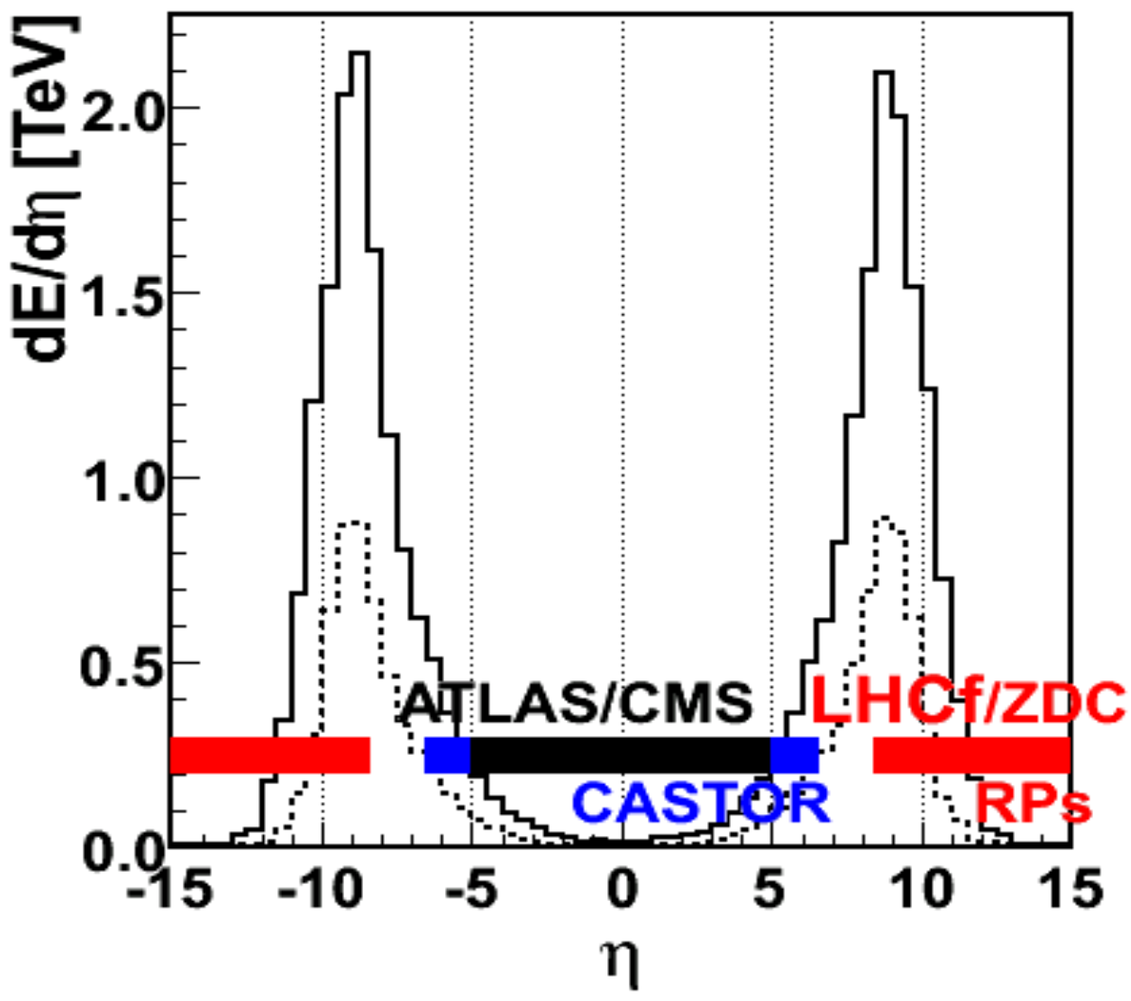
Calibration with accelerators are needed

Forward measurement

Multiplicity@√s=14TeV

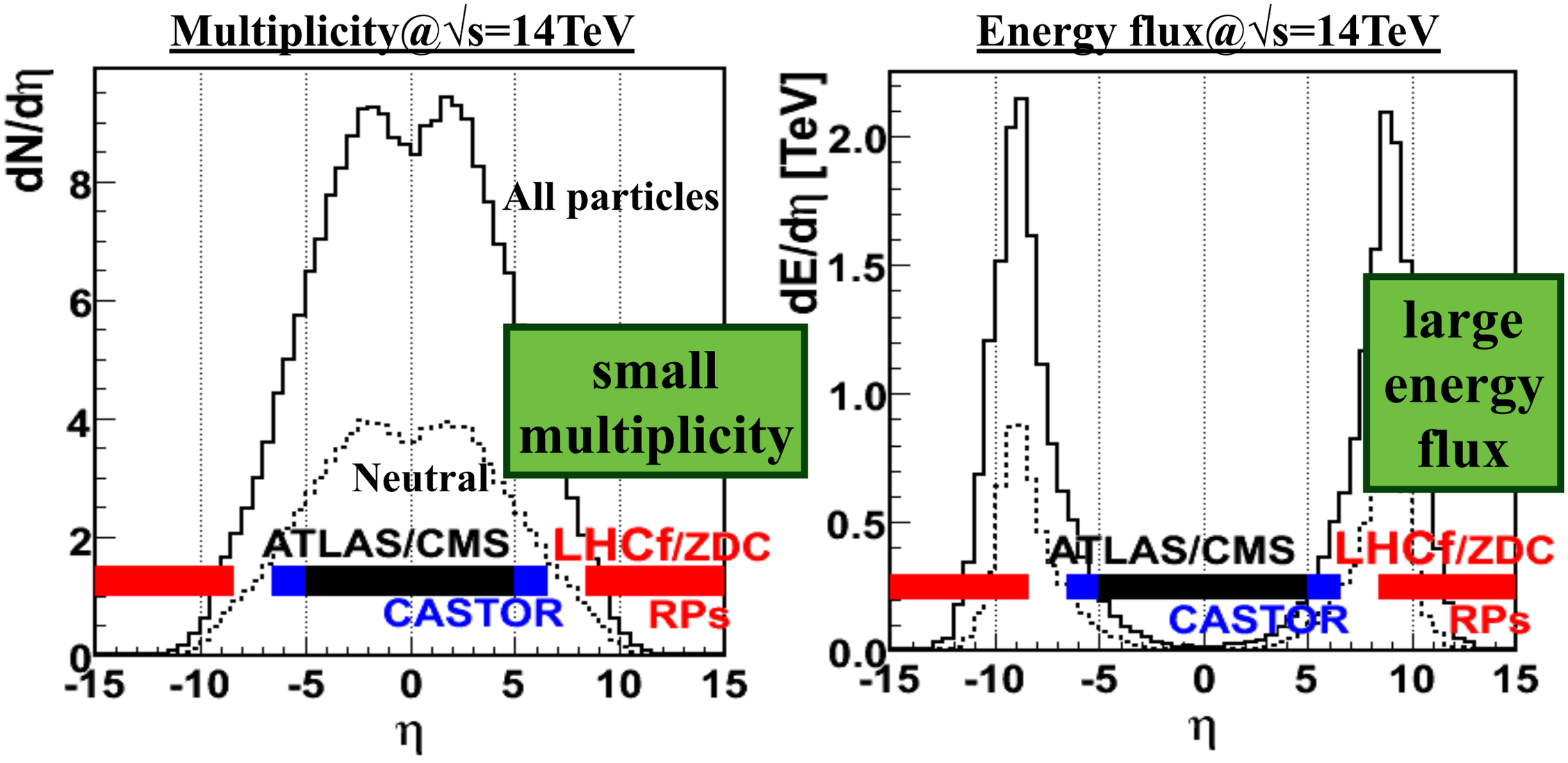


Energy flux@√s=14TeV



Most of the particles produced into central region,
Most of the energy is concentrated in the forward region

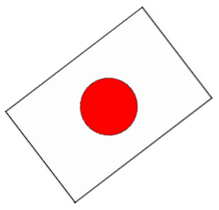
Forward measurement



Most of the particles produced into central region,
Most of the energy is concentrated in the forward region

Small but thick calorimeter are needed

The LHCf Collaboration



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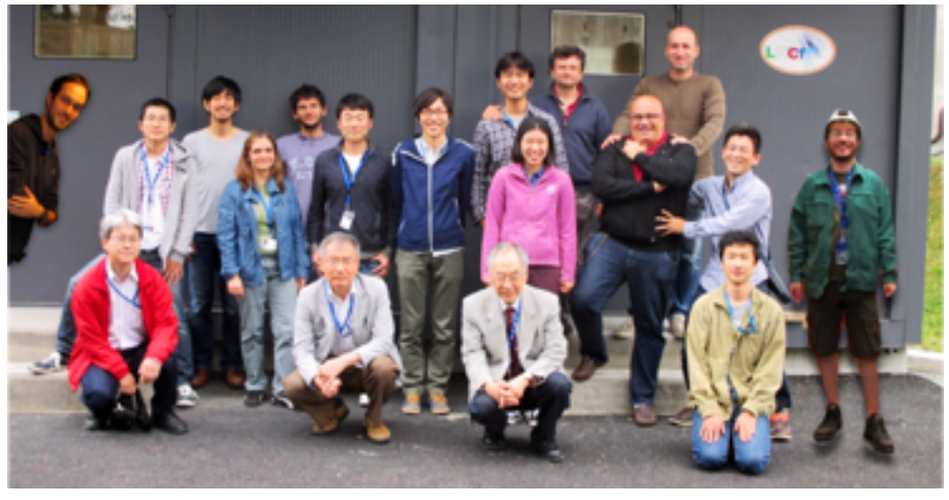
N.Sakurai *Tokushima University, Japan*

M.Haguenauer *Ecole Polytechnique, France*

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

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

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



History of LHCf

Jun 2006 approved by LHCC

Jul 2006 Detector construction

Aug 2007 Beam test at SPS

Jan 2008 1st installation at LHC

Dec 2009-Jul 2010 p-p@0.9&7TeV

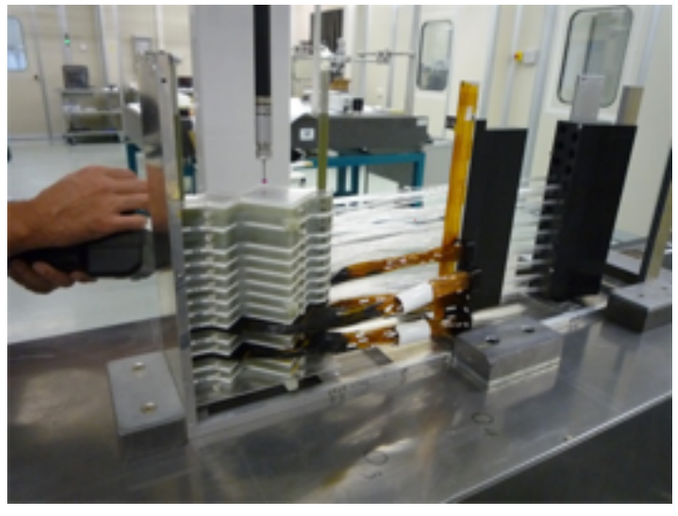
Dec 2012-Feb 2013 p-Pb@5TeV/n & p-p@2.76TeV

Oct 2014 Beam test at SPS

May-Jun 2015 p-p@13TeV

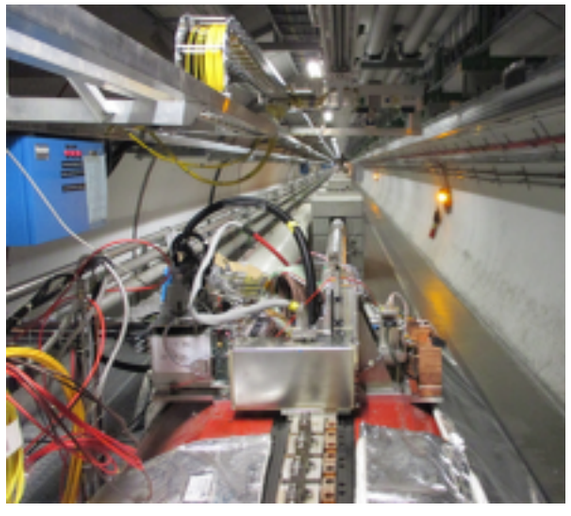
Run1 | **Run2**

(LHC long shutdown) Improve radiation hardness of LHCf

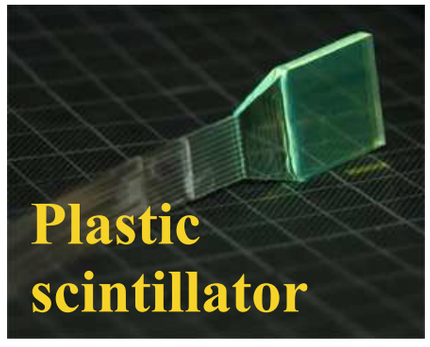


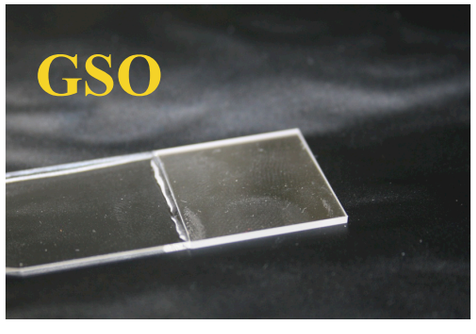
Construction

Beam test



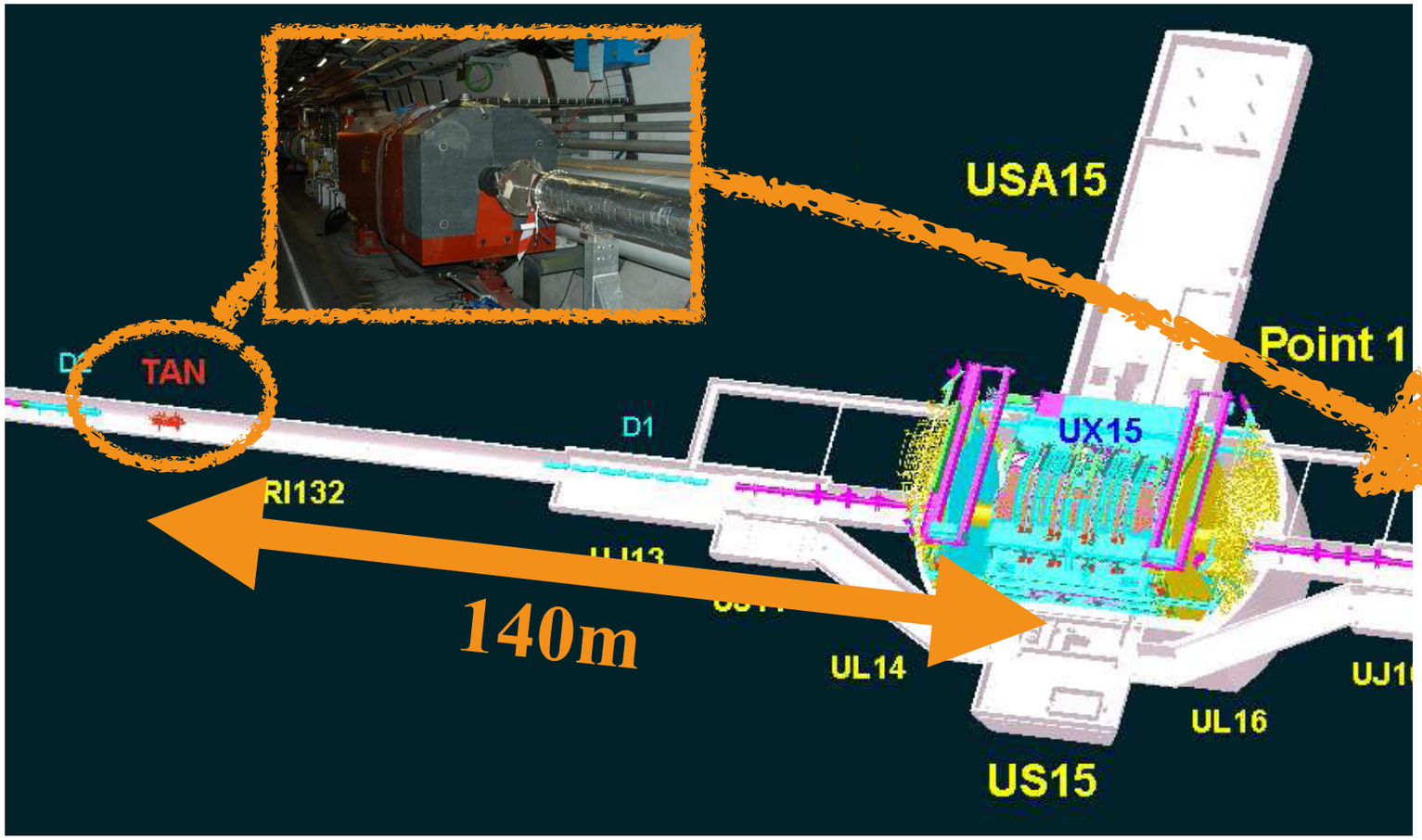
Installation

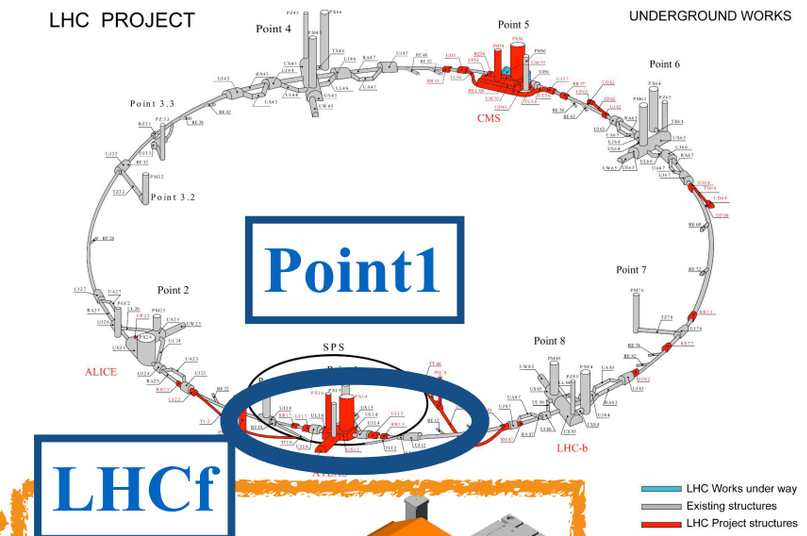




Upgrade

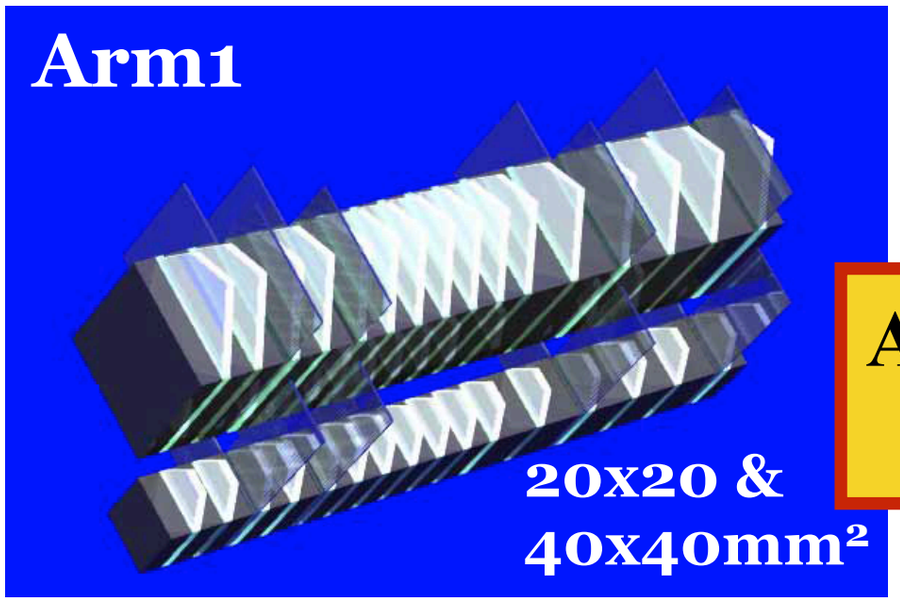
LHCf experiment



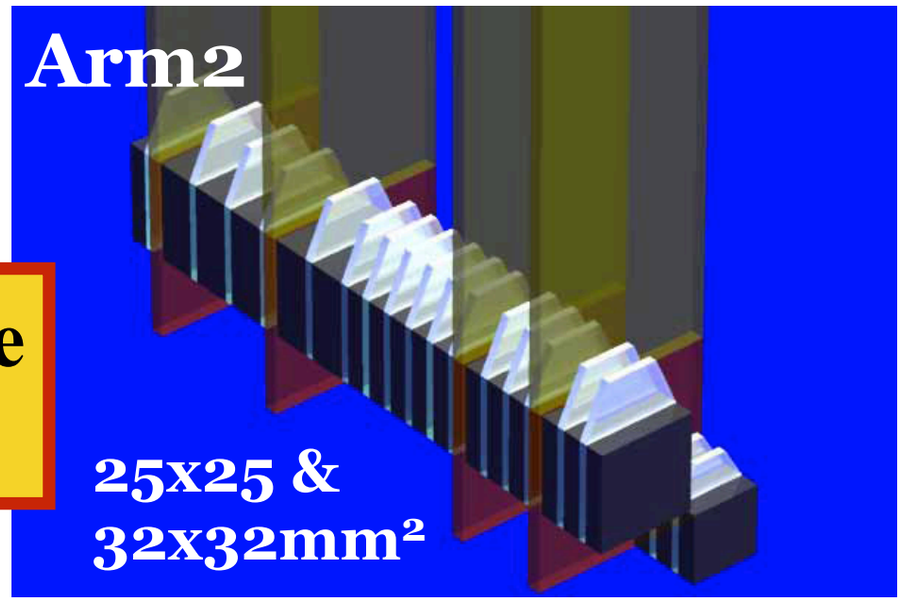


- Located at 140m from ATLAS interaction point
- Charged particles are swept aside by D1 magnetic field
  - ✤ Targets are photon and neutron
- Detectors are set on each side
- The space allowed is about 9x30cm

The detectors

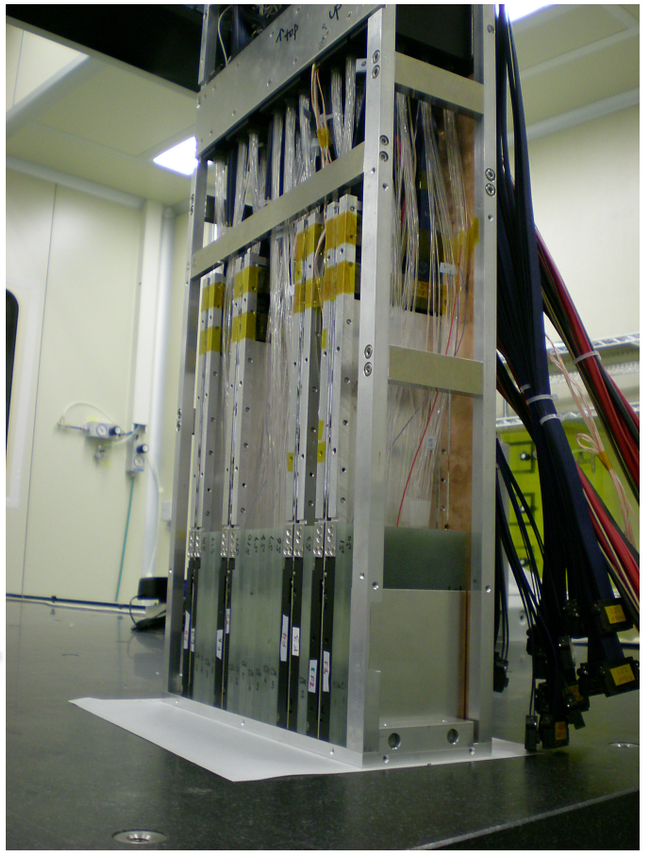


Acceptance
η>8.4



- 2 sampling calorimeters
  - 16 GSO scintillators interleaved with tungsten plates (44 X_0 or 1.6λ)
  - Energy resolution σ_E<5% for photons (~40% for neutrons)
- Different position sensitive layers
  - Arm1: Thin GSO scintillator (σ_p<200μm)
  - Arm2: Silicon strip (σ_p~40μm)

Small but Effective!



Run1 (2009-2013)

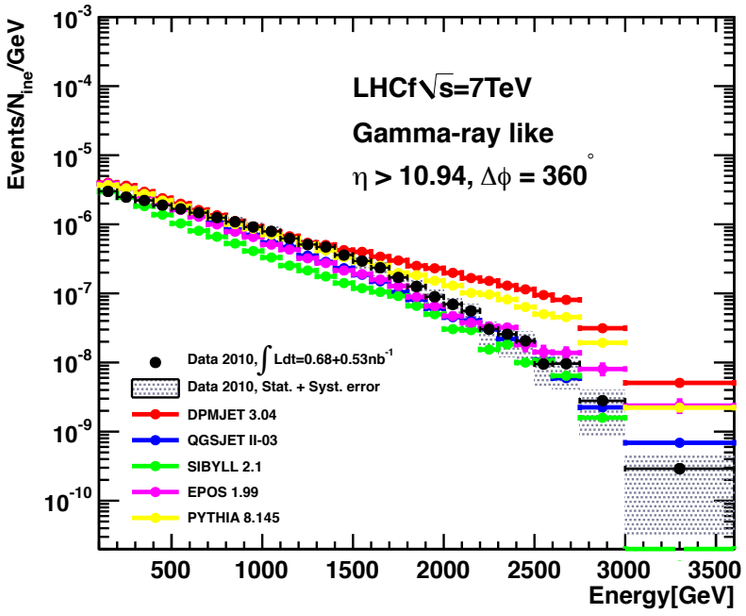
p-p@$\sqrt{s}$=0.9, 2.76 &7TeV

p-Pb@$\sqrt{s}$=5.02TeV

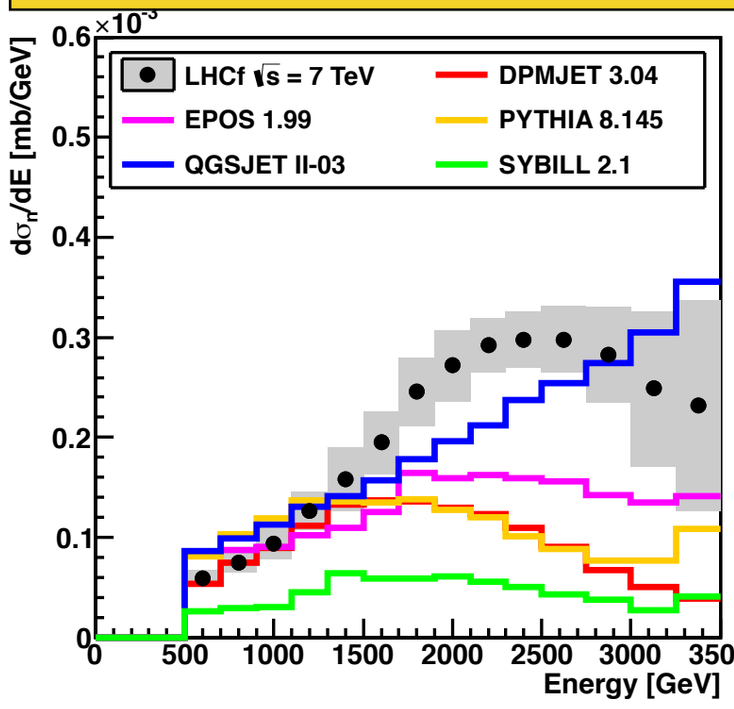
Results of p-p at √s=7TeV

We compare the data with expectations from different models.

Photon inclusive energy spectrum



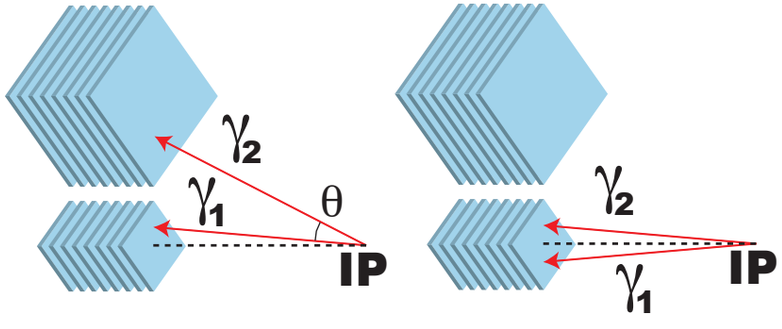
Neutron inclusive energy spectrum

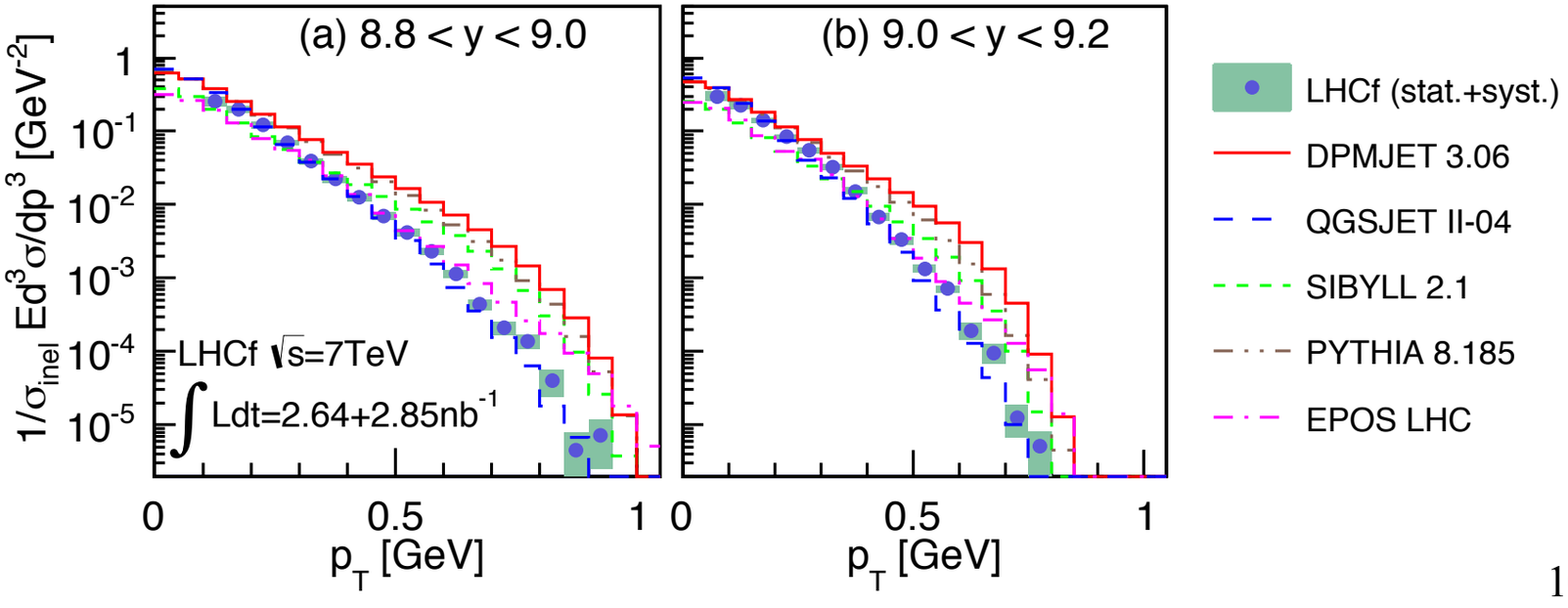


References

1. Phys. Lett. B 703, 128 (2011)
2. Phys. Lett. B 715, 298 (2012)
3. Phys. Rev. D 86, 092001 (2012)
4. Phys. Lett. B 750 360 (2015)

π^0 P_T spectrum





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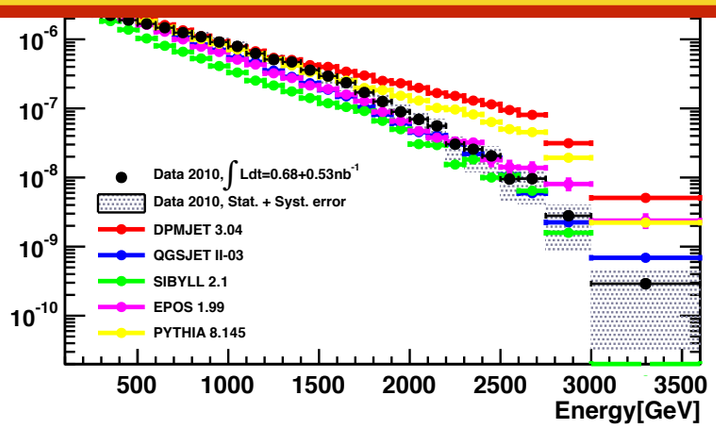
Photon inclusive energy spectrum

No model explains the data, but bracket them



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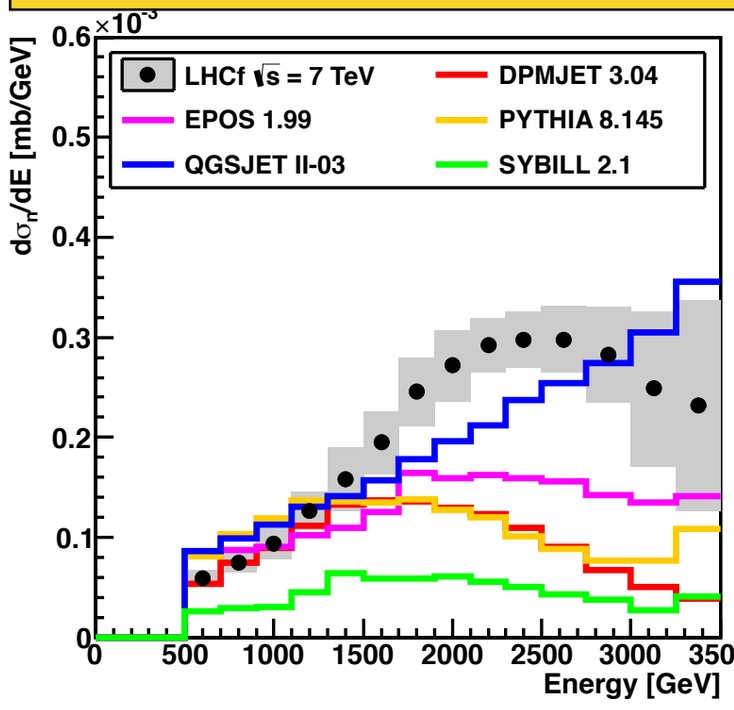

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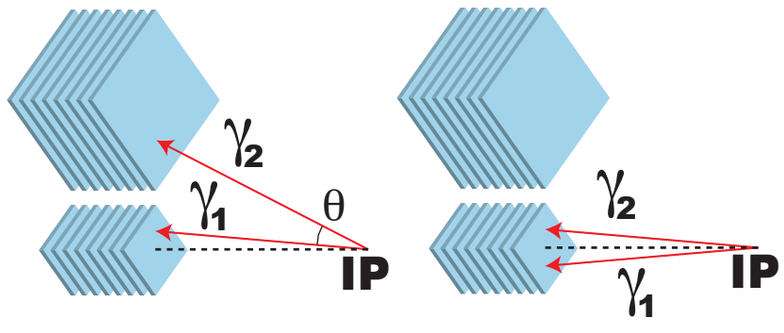

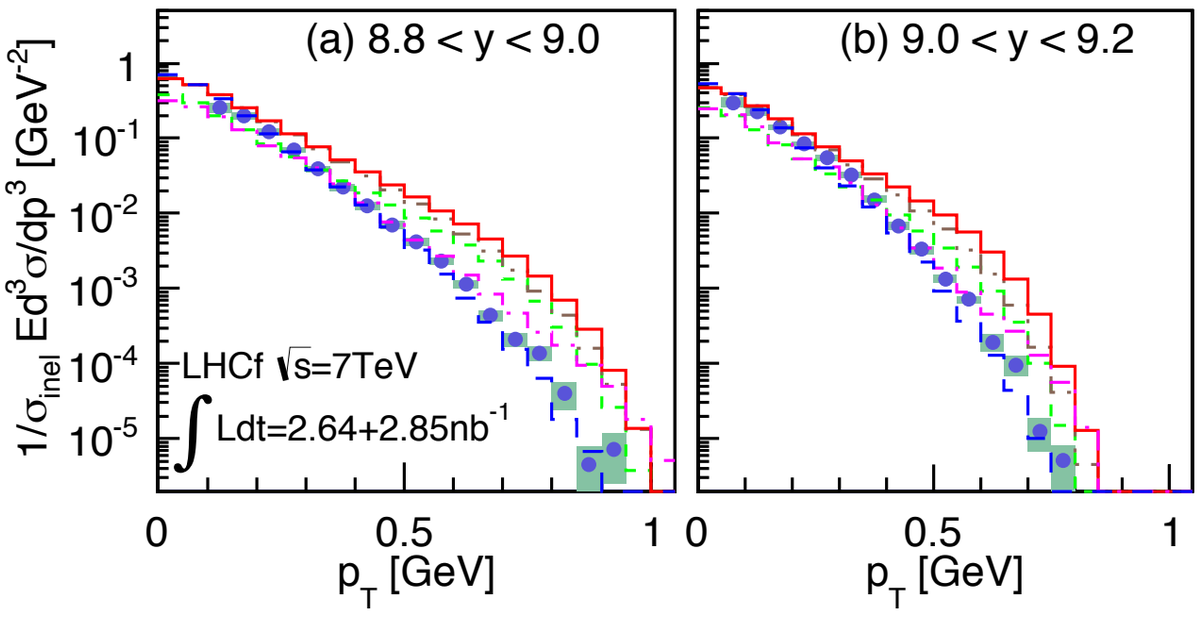

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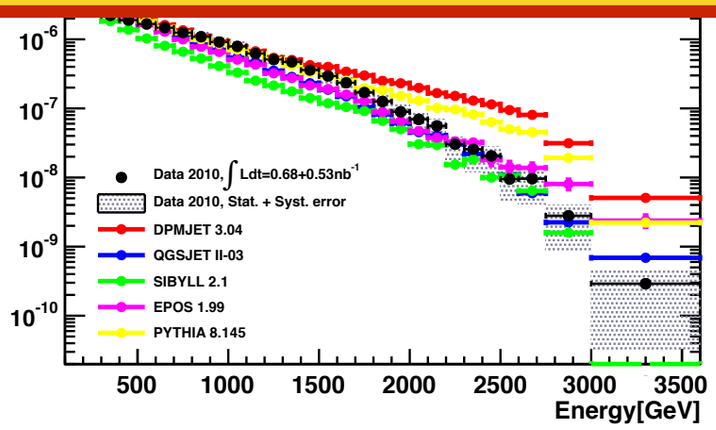
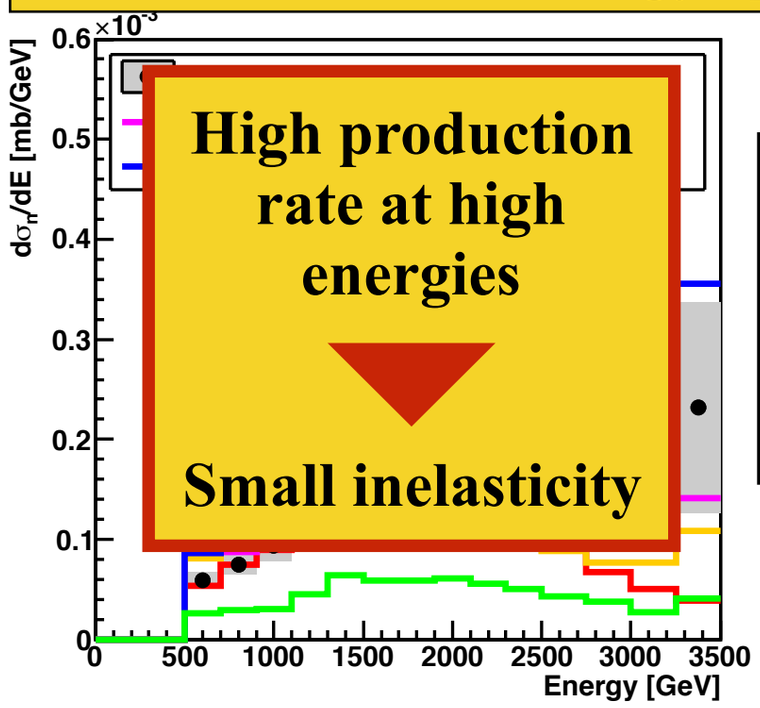


Neutron inclusive energy spectrum



High production rate at high energies

Small inelasticity

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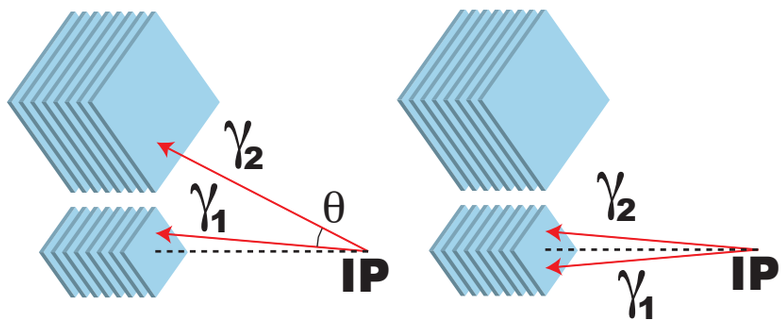

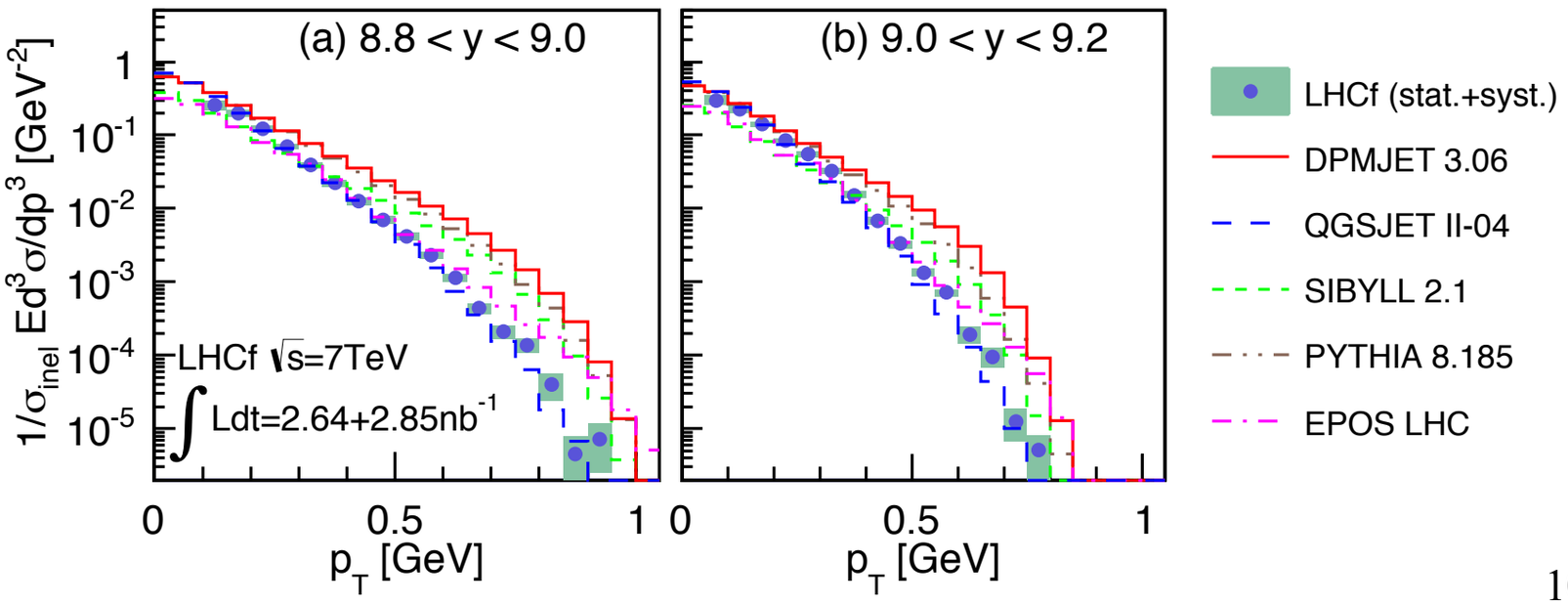

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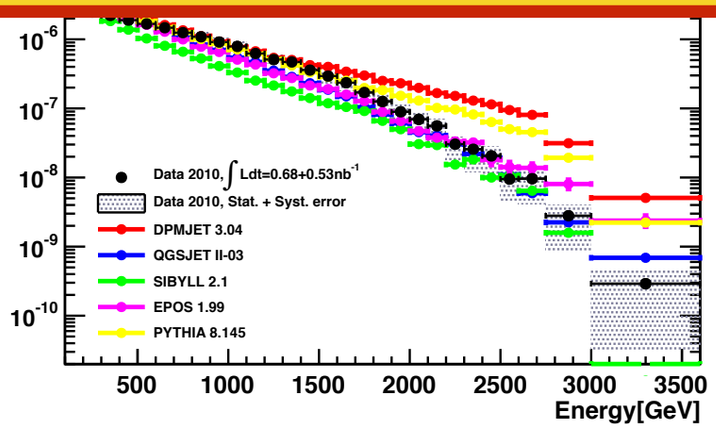
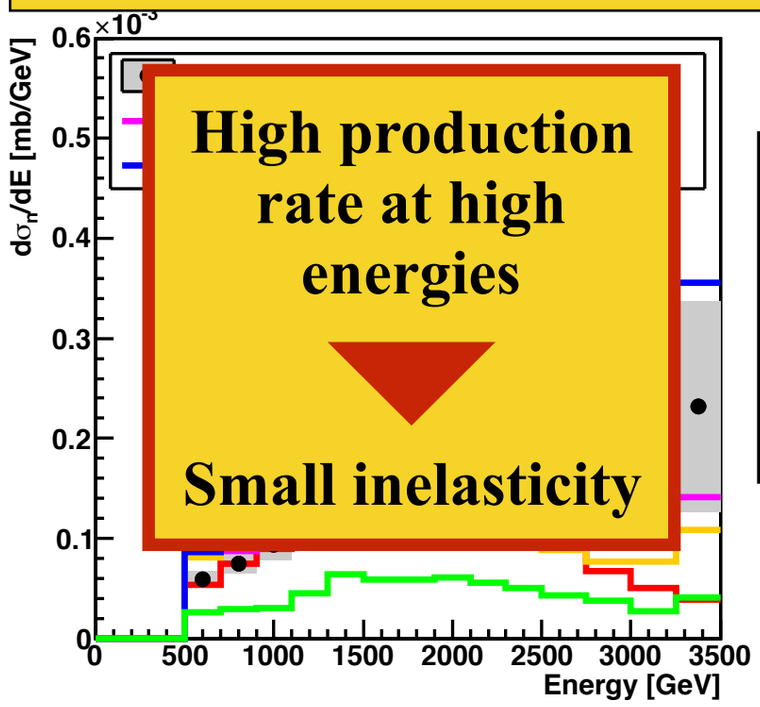


Neutron inclusive energy spectrum



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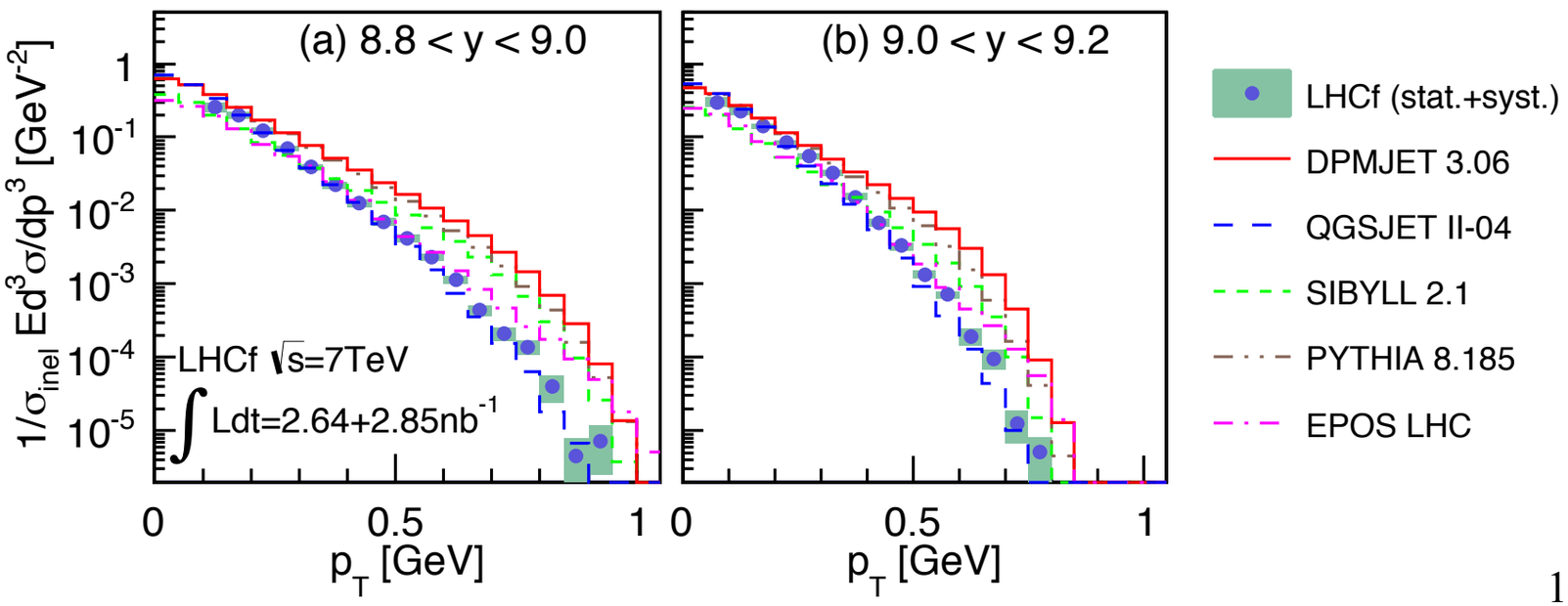
3. Phys. Rev. D 86, 092001 (2012)
4. Phys. Lett. B 750 360 (2015)

π^0 P_T spectrum

Best agreement:
- **QGSJetII-04**
- **EPOS-LHC**

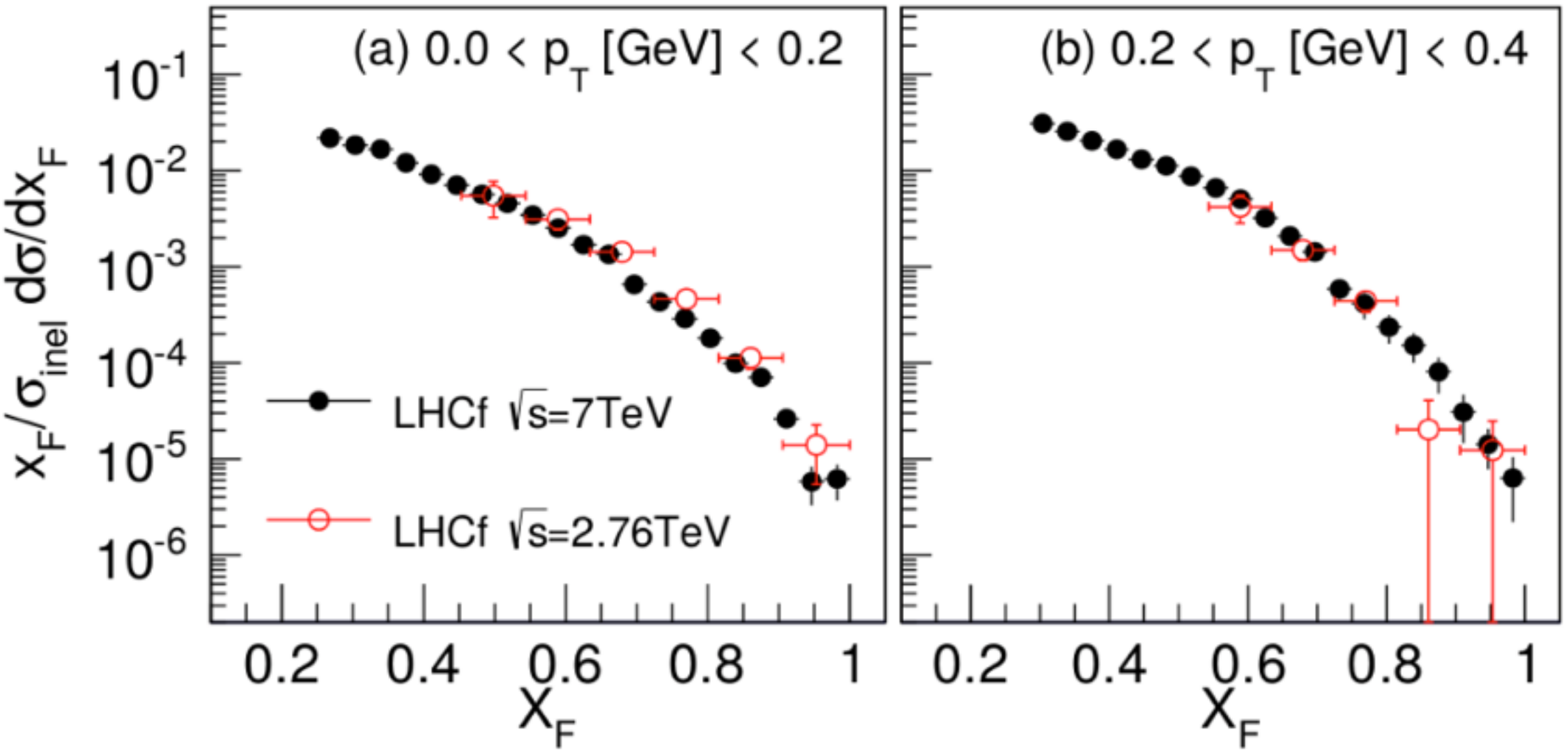
(pT<0.5GeV)

IP



Feynman scaling

Cross sections of secondary particles as a function of x_F are independent from the incident energy in the forward region (x_F >0.2)

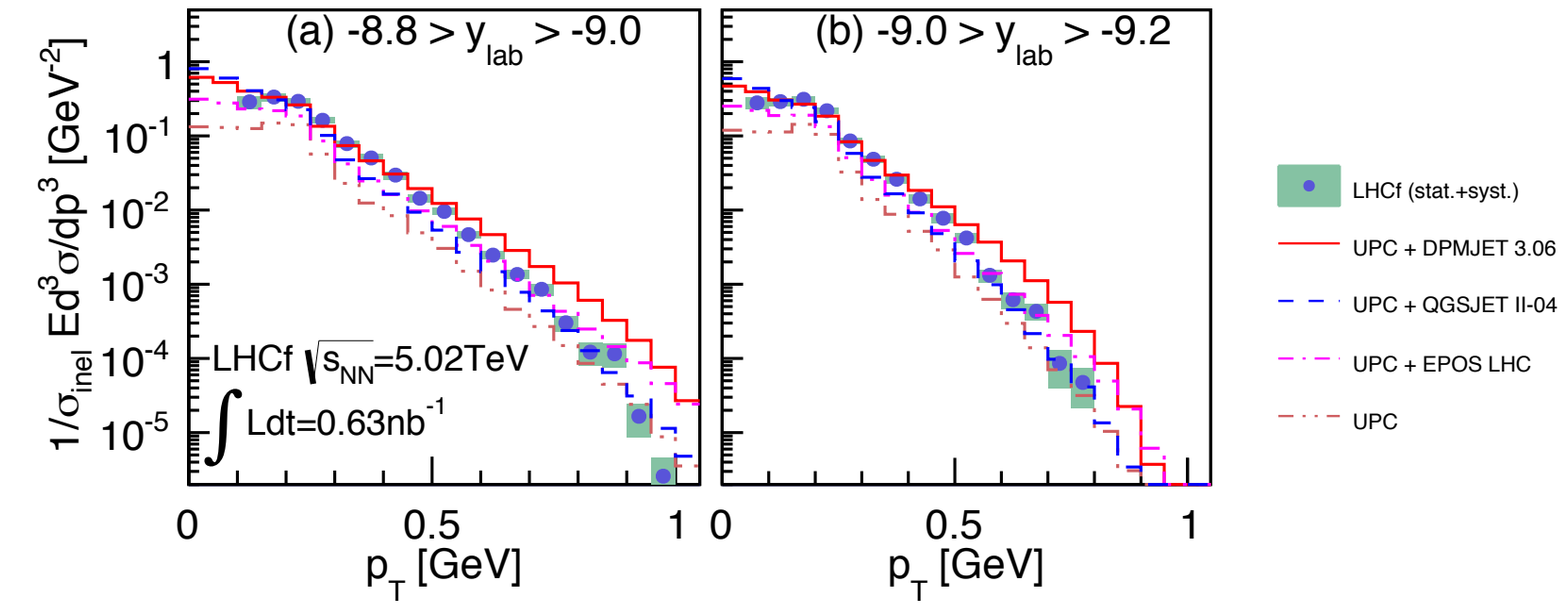


$x_F \equiv 2p_z/\sqrt{s}$

This hypothesis for π^0 is true at the level of ±20%

Results of p-Pb@$\sqrt{s_{NN}}$=5.02TeV

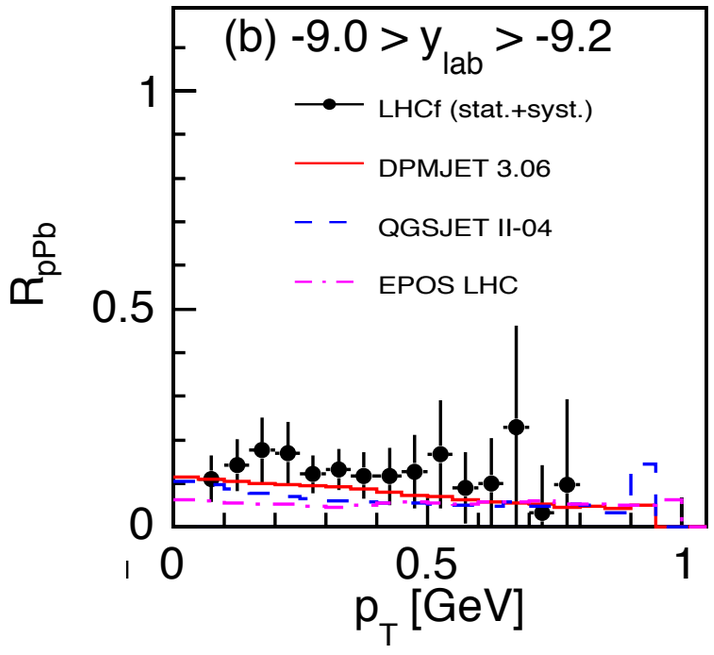
P_T spectrum of π^0



References

1. Phys. Rev. C 89, 065209 (2014)
2. "Measurements of longitudinal and transverse momentum distributions for neutral pions in the forward-rapidity region with the LHCf detector", Accepted in PRD (2016)

Nuclear modification factor of π^0



High suppression of production rate for p-Pb respect to p-p collisions

$$R_{\mathrm{pPb}}(p_{\mathrm{T}}) \equiv \frac{\sigma_{\mathrm{inel}}^{\mathrm{pp}}}{\langle N_{\mathrm{coll}} \rangle \sigma_{\mathrm{inel}}^{\mathrm{pPb}}} \frac{Ed^3\sigma^{\mathrm{pPb}}/dp^3}{Ed^3\sigma^{\mathrm{pp}}/dp^3}$$

$$\langle N_{\mathrm{coll}} \rangle = 6.9$$

Good agreement for all models

Run2 (2015)

p-p@√s=13TeV
What next?

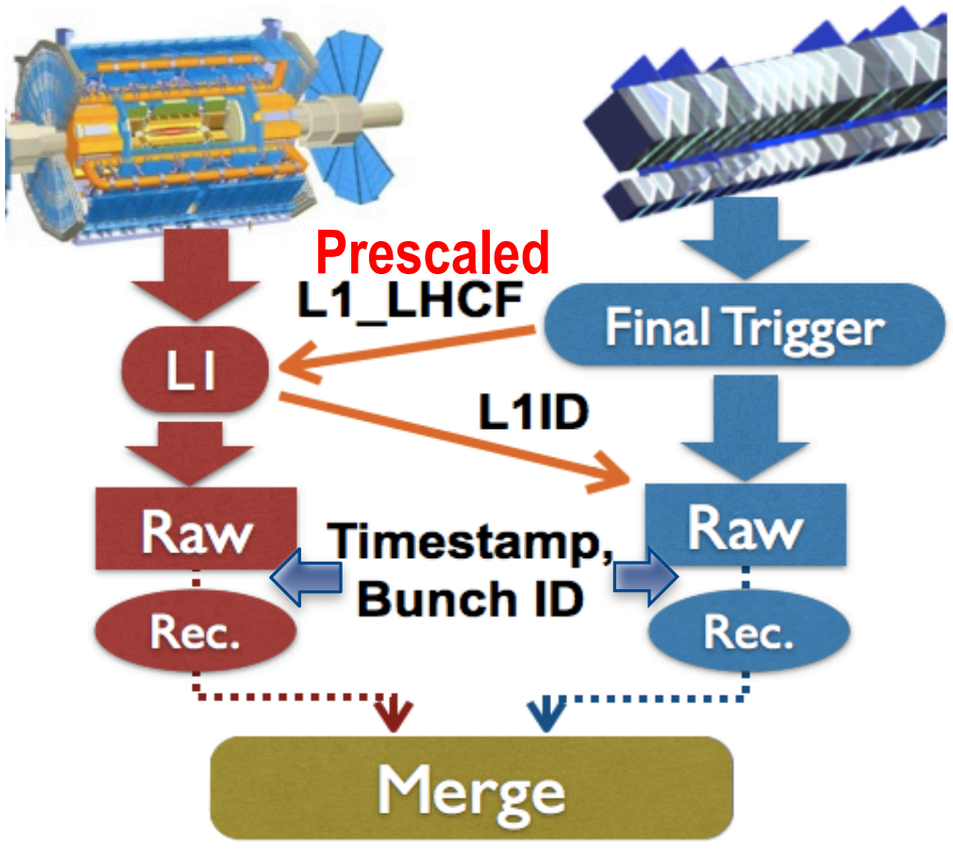
Operation at √s=13TeV

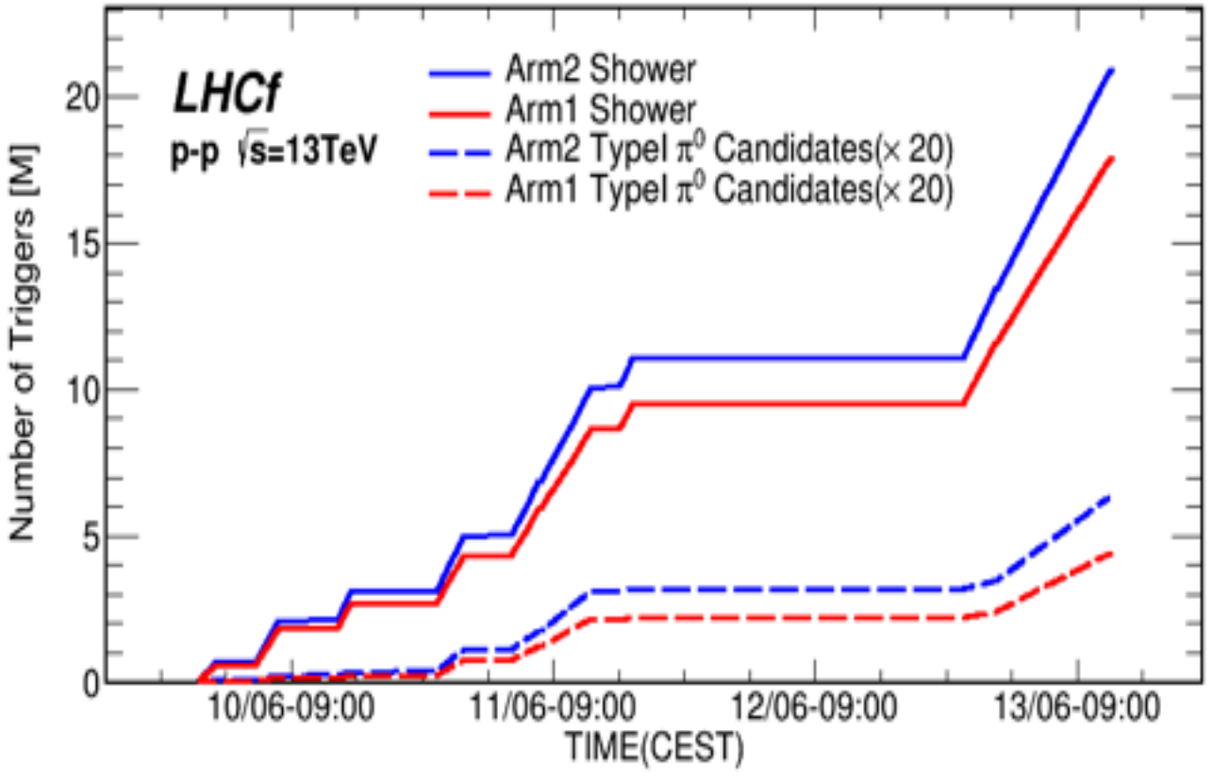
Motivation

- Evaluate hadronic interaction models at $E_{lab}=10^{16.9}$eV
- Check scaling law at higher energy
- Enlarge p_T coverage
- Trigger exchange with ATLAS (Event matching is successfully achieved)

Summary of Run2
(Dedicated run for LHCf)

Period	Jun9-13 2015
Luminosity	$0.5\sim1.6\times10^{29}$cm^{-2}s^{-1}
	16nb^{-1}
Shower events	39M events
π^0 candidates	0.5M events





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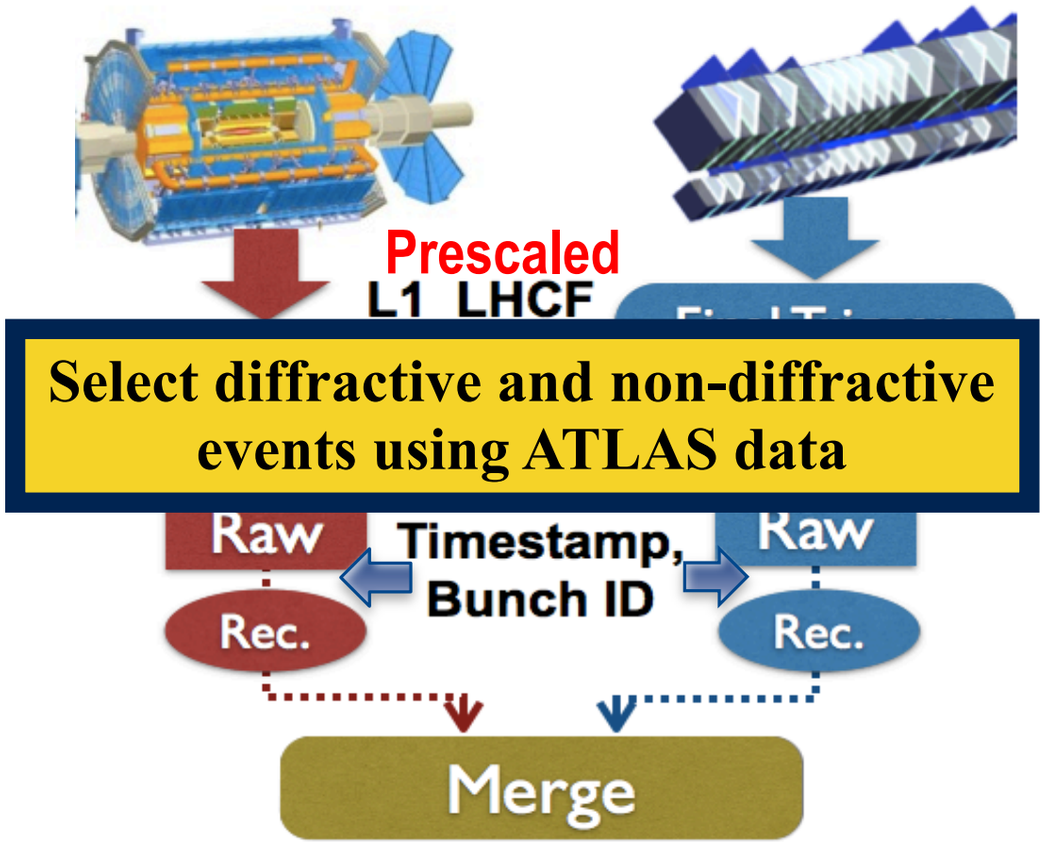
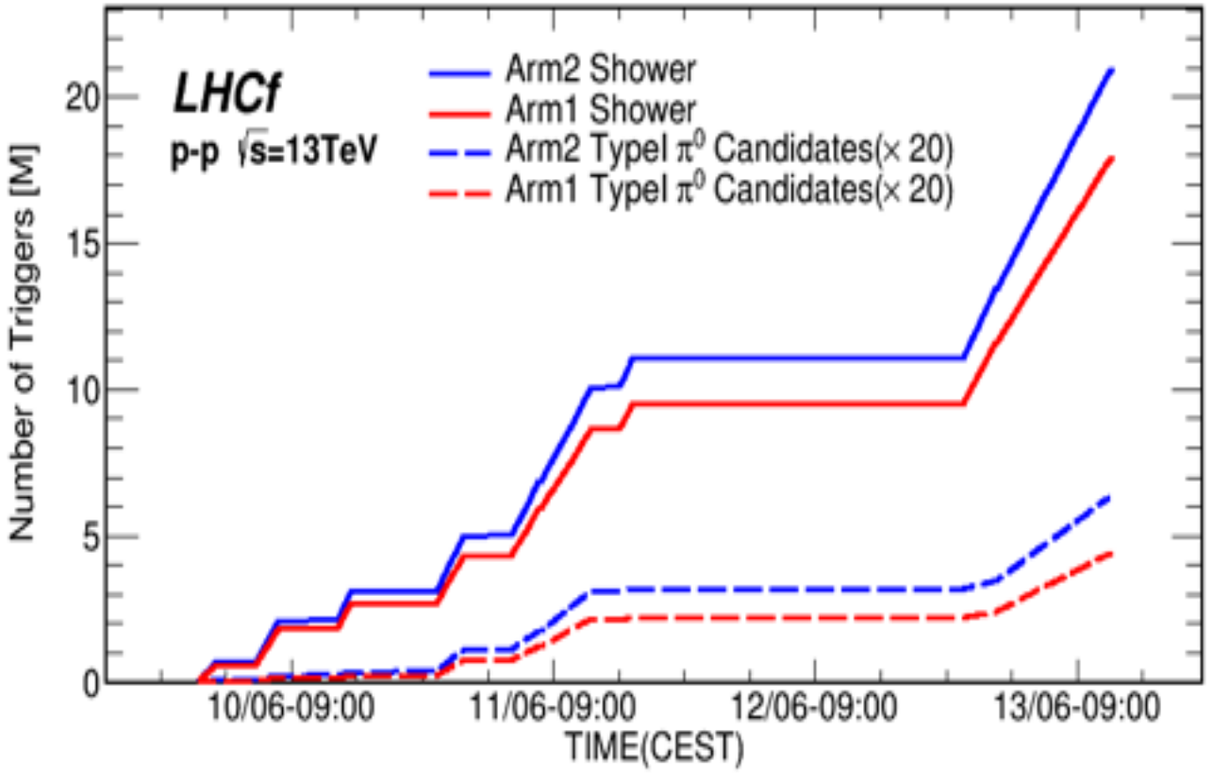
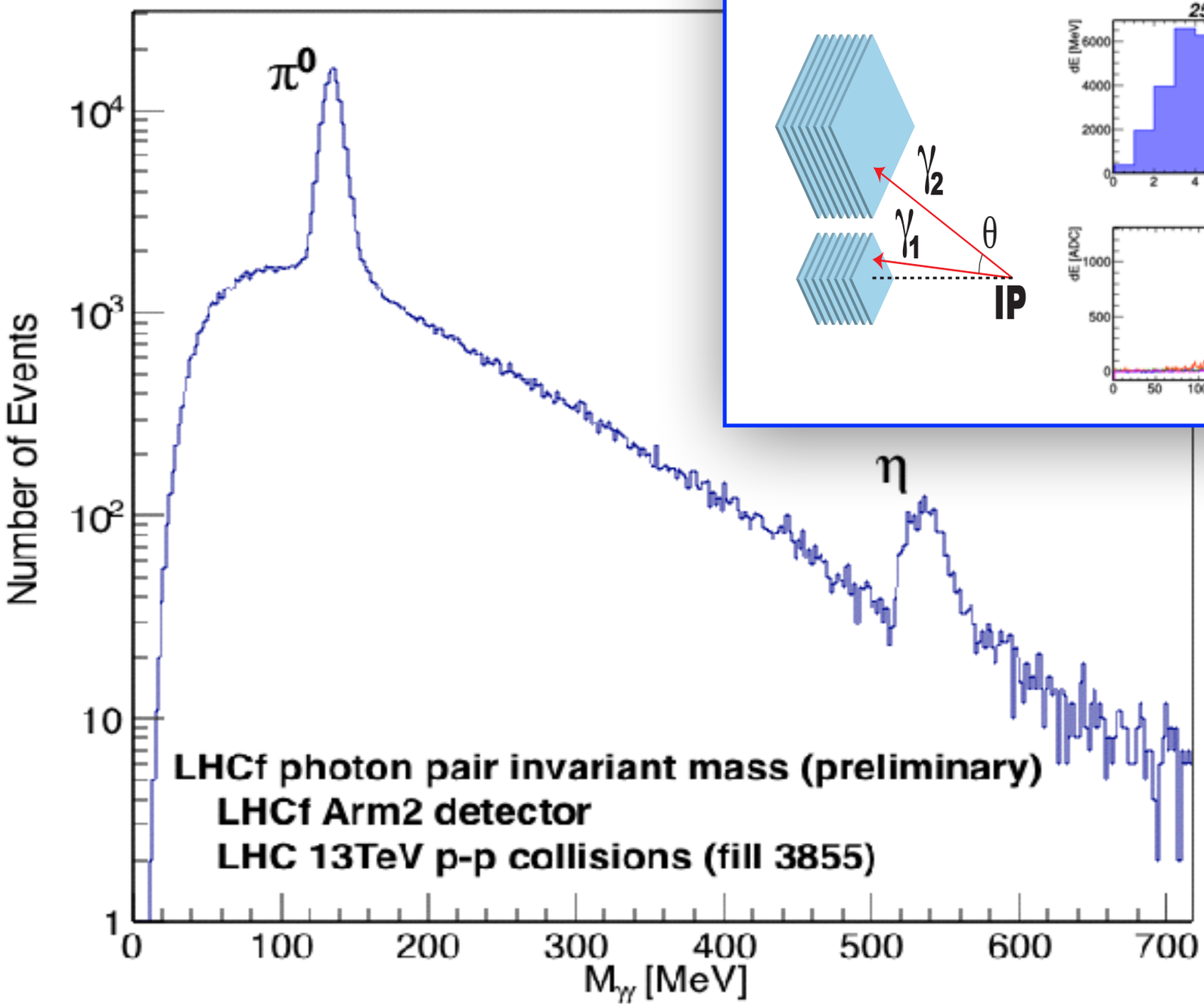
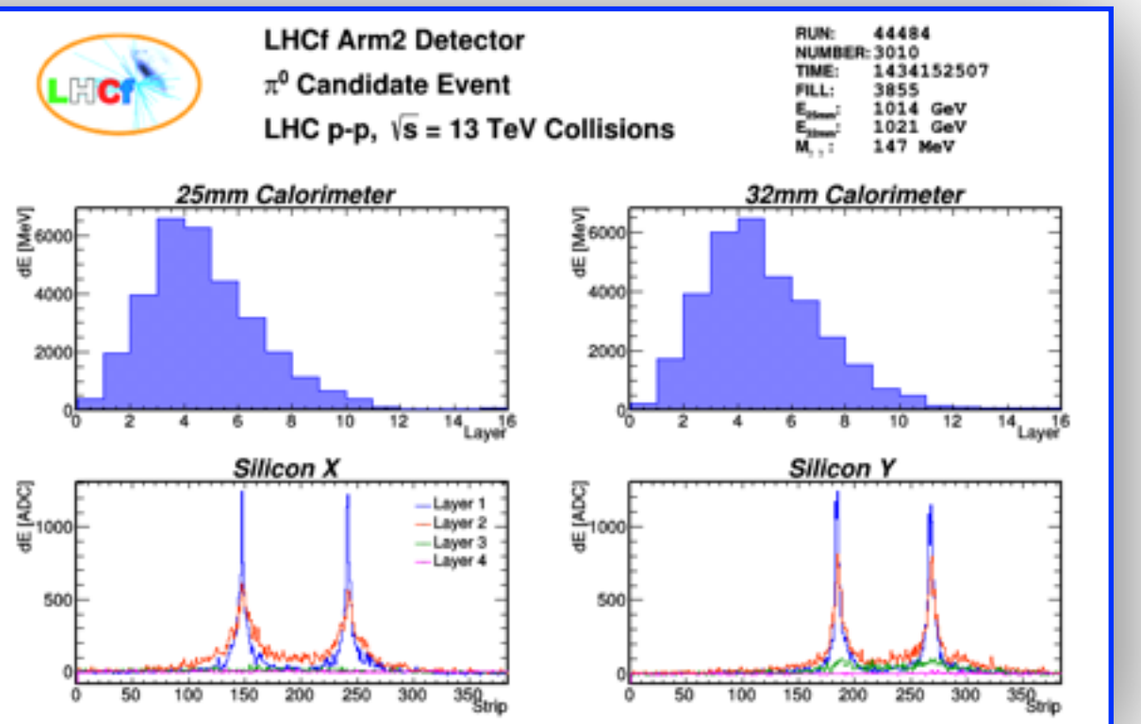




$M_{\gamma\gamma}$ mass reconstruction

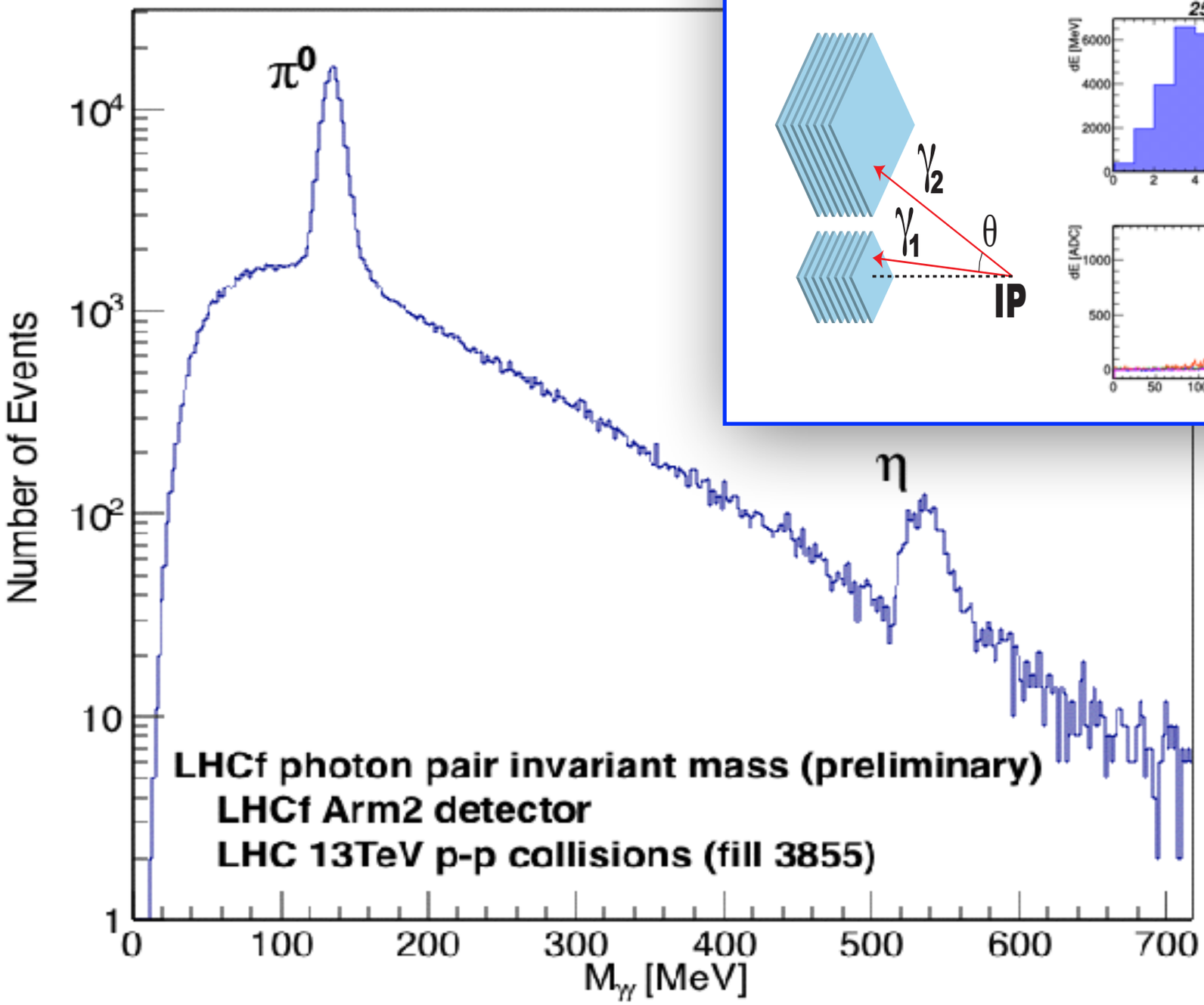


Example of π^0 candidate event

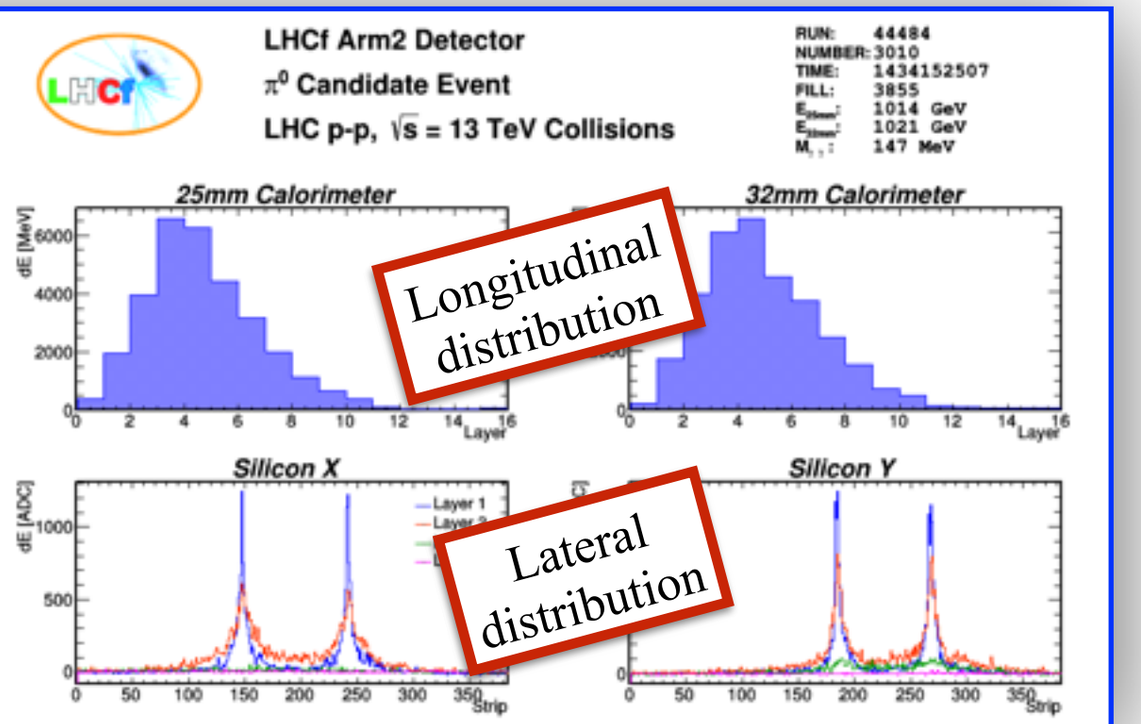


Monitor the stability of the energy scale

$M_{\gamma\gamma}$ mass reconstruction

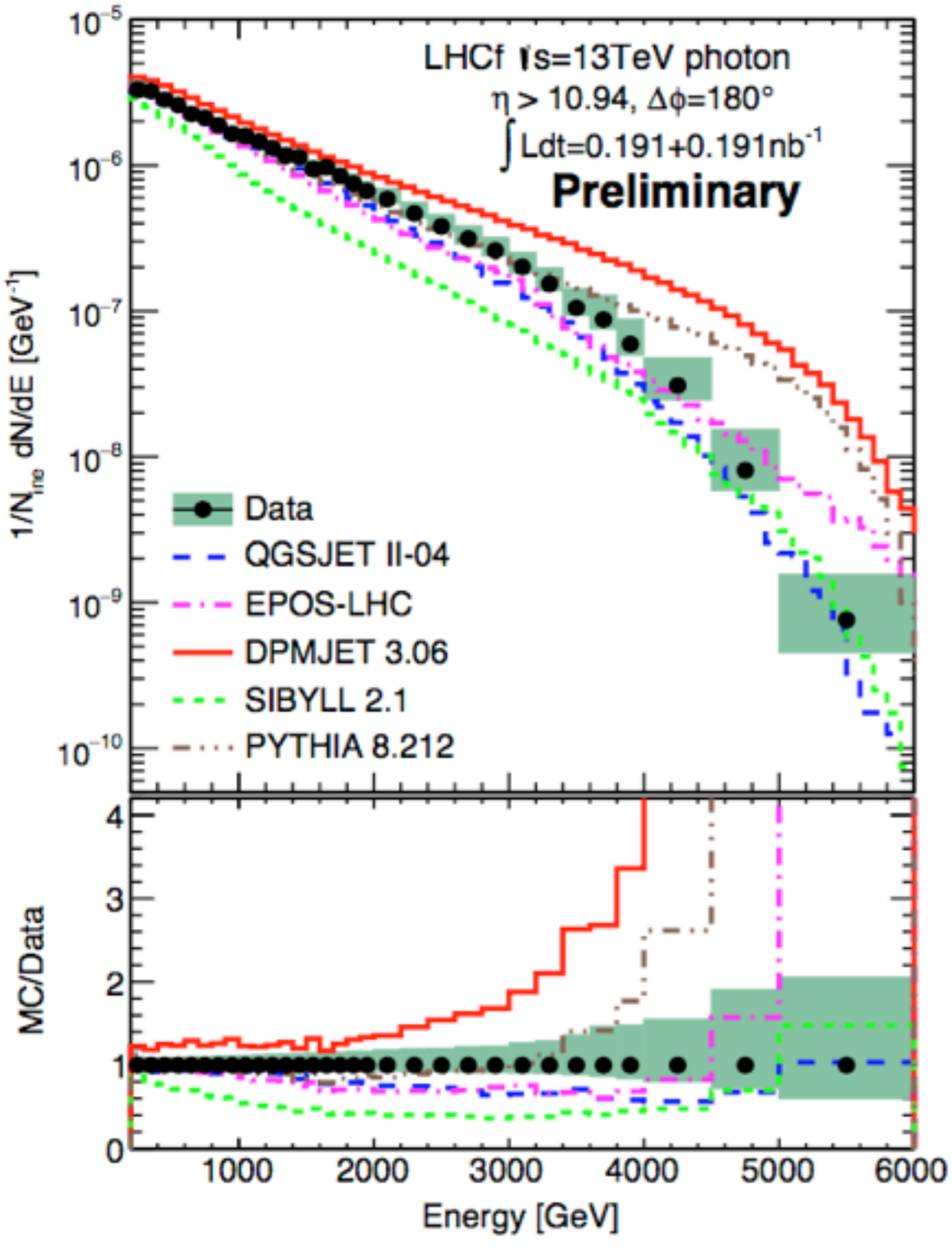


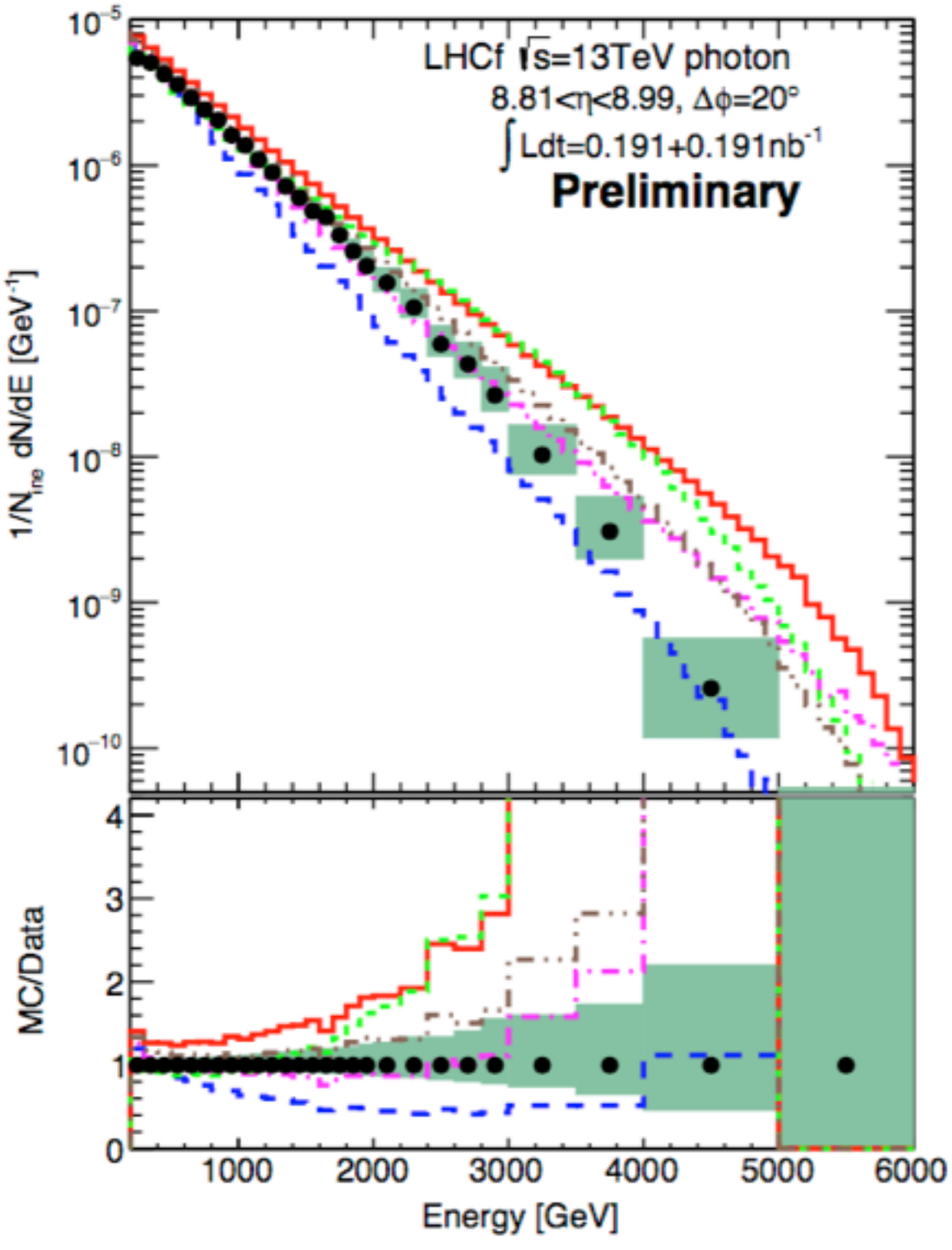
Example of π^0 candidate event



Monitor the stability of the energy scale

Photon spectrum at √s=13TeV





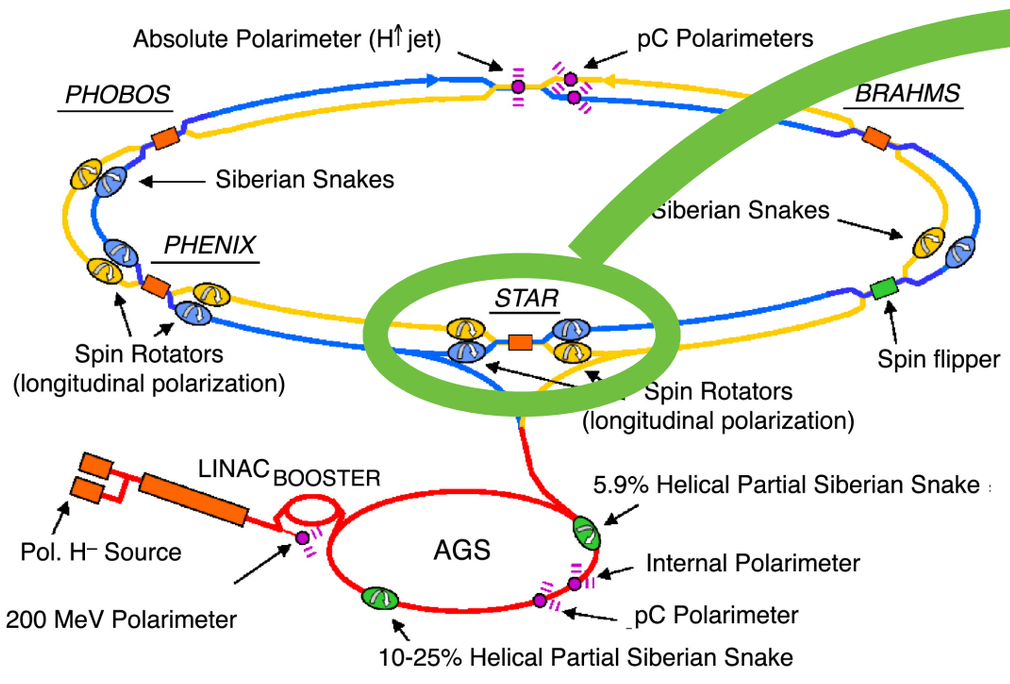
Future plan ~ LHC to RHIC ~

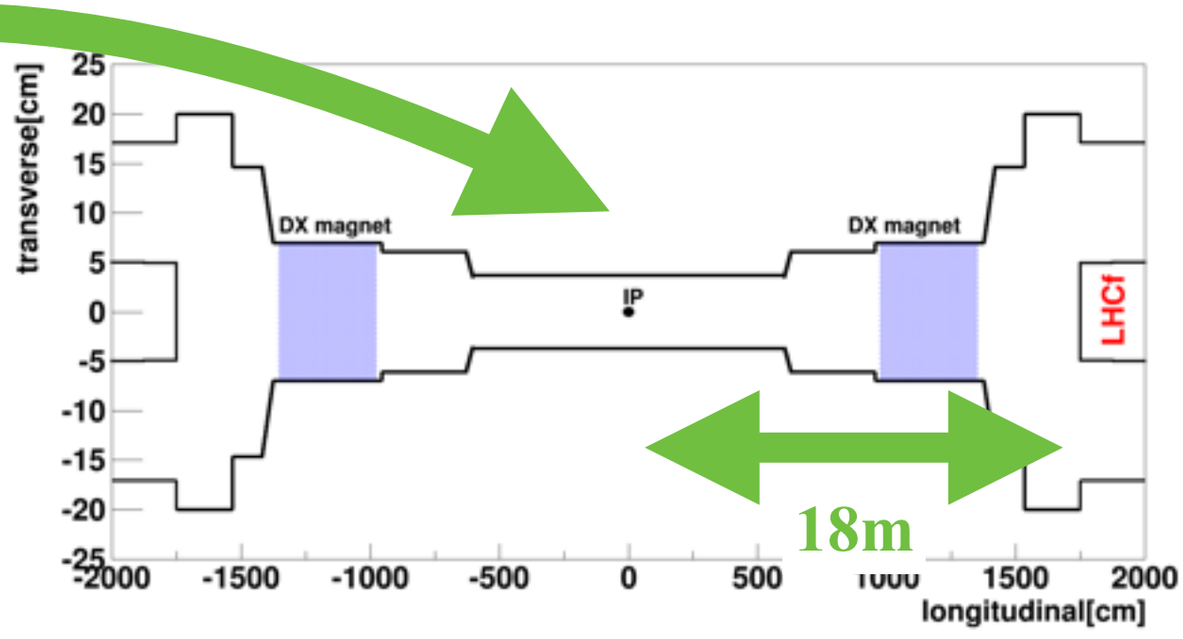
1. <u>p-Pb@$\sqrt{s_{NN}}$=8TeV</u>

p-Pb measurement at LHC has been approved. The measurement will be carried with Arm2 in November 2016 and the preparation is ongoing.

2. <u>RHICf @$\sqrt{s}$=510GeV (For RUN17)</u>

We brought the Arm1 detector to BNL. The detector will be installed in front of the ZDC of the STAR experiment. The measurement will be carried in May 2017. This will allow us to confirm in the Feynman scaling in the low energy region.





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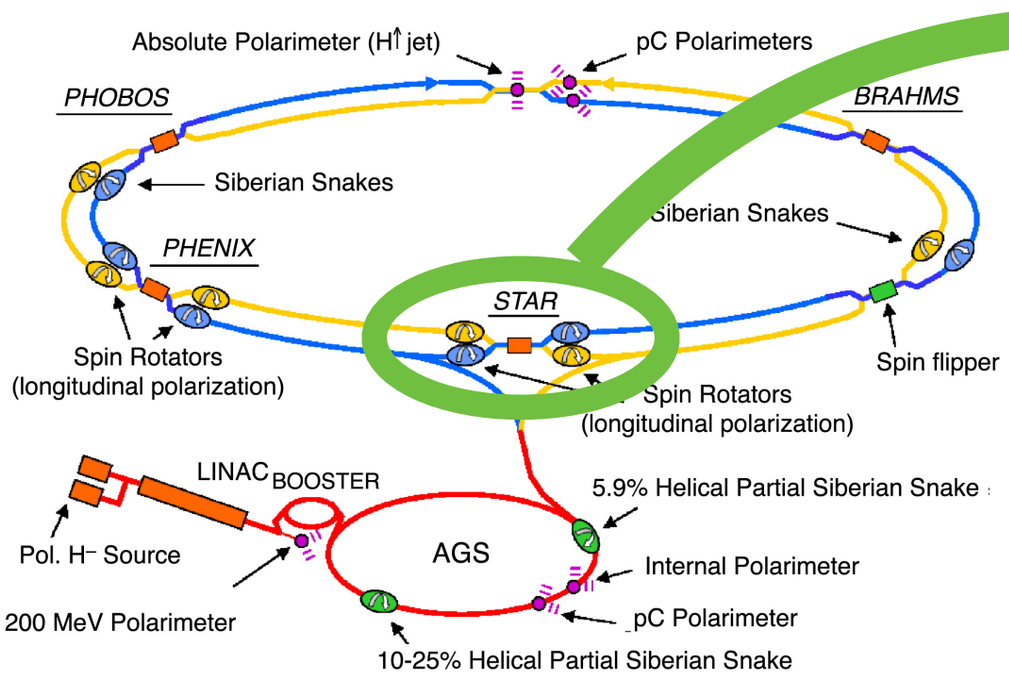
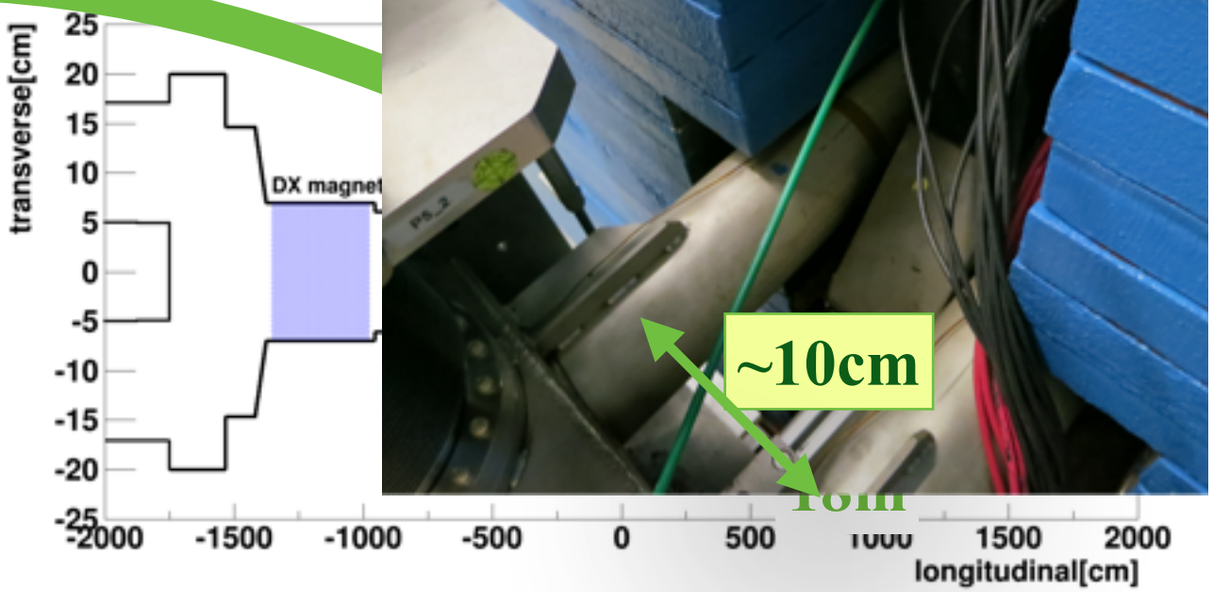




Summary

Experiments at LHC provide useful data to calibrate hadronic interaction models. LHCf is designed to measure the forward region where a large amount of energy is concentrated.

Run1 (2009 - 2013)

- LHCf has taken data in p-p and p-Pb collisions at different energies, results have been published about photon, neutron and π^0.
- No model reproduces the data perfectly, but models bracket the data well for photon and π^0. For neutron, the production rate is higher than the prediction.
- Scaling for π^0 is true at the level of 20%.

Run2 (2015)

- Dedicated run for LHCf was successful.
- LHCf + ATLAS joint analysis is ready (event matching is achieved).
- Photon inclusive energy spectra is almost completed.
- Other analysis are ongoing.

Next plan (2016 - 2017)

- p-Pb collisions at $\sqrt{s_{NN}}$=8TeV with Arm2.
- p-p collisions at $\sqrt{s}$=510 GeV with Arm1.

Thank you

Backup

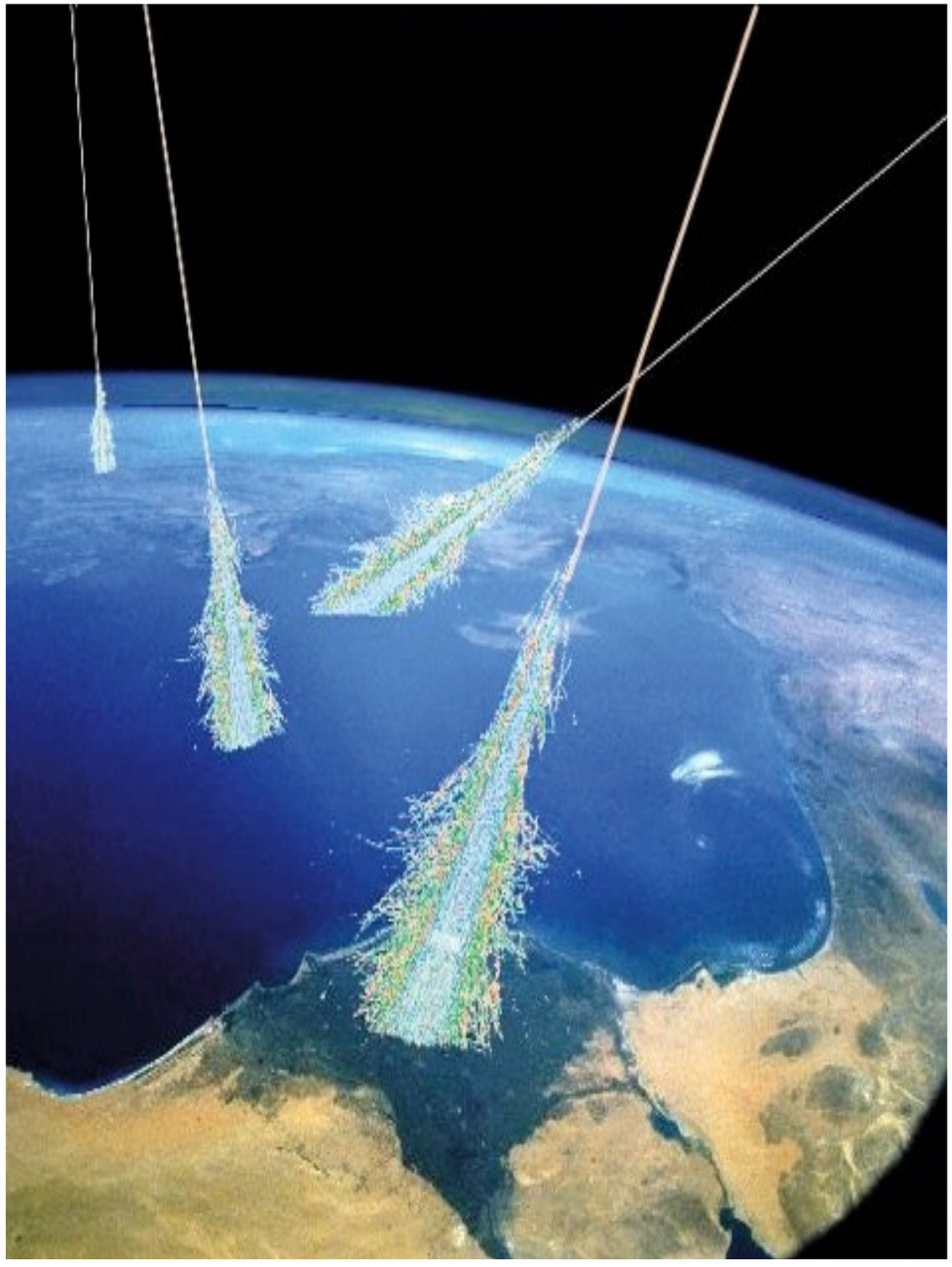
Air shower and observables

X_{max}: depth of air shower maximum from the top of the atmosphere

RMS(X_{max}): fluctuations in the position of the shower maximum

N_{μ}: number of muons in the shower at the detector level

To go from these observables to the CR composition and energy determination passing through the hadronic interaction models is mandatory

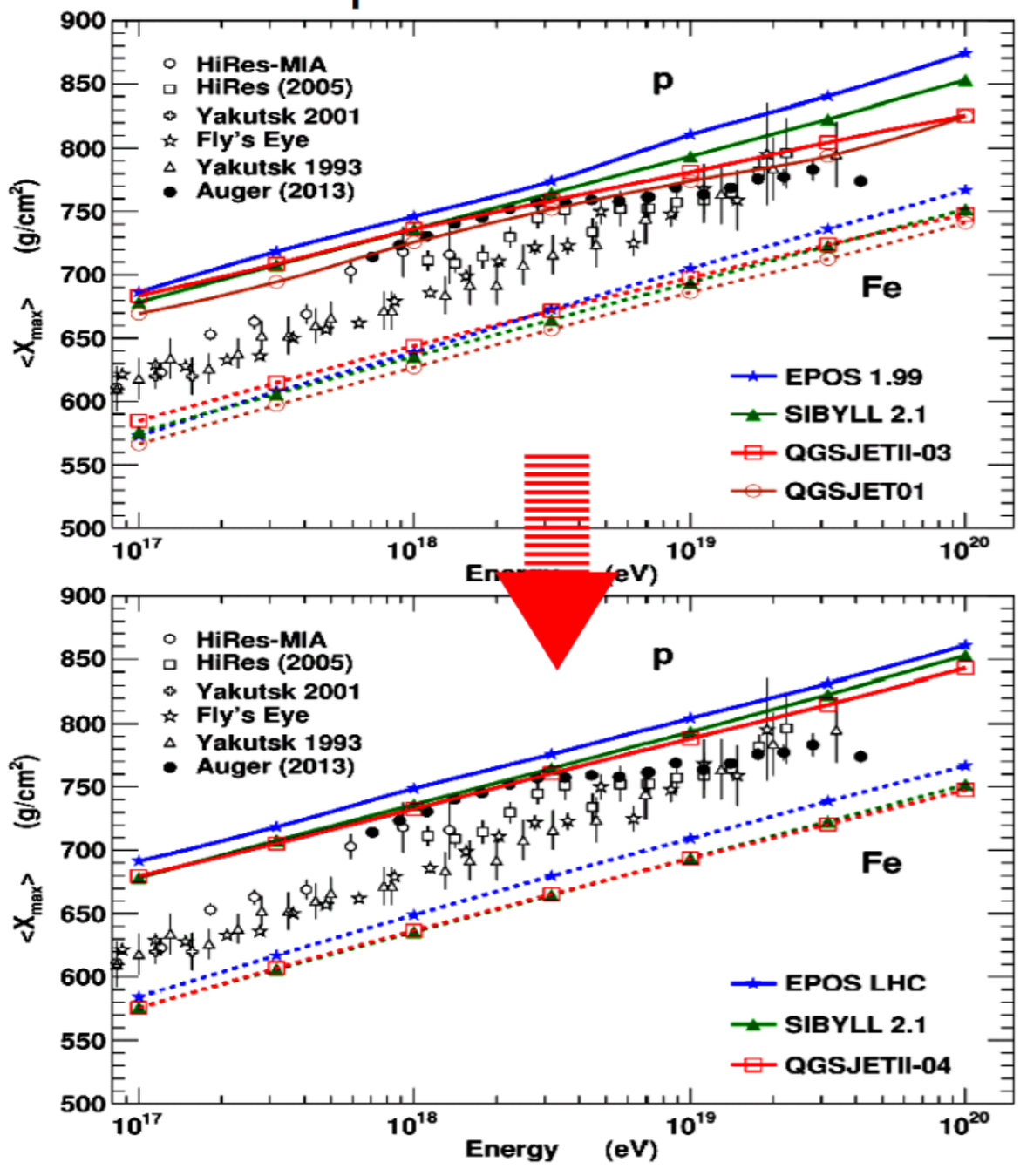


Model tuning after LHC Run1 (EPOS and QGSJET2)

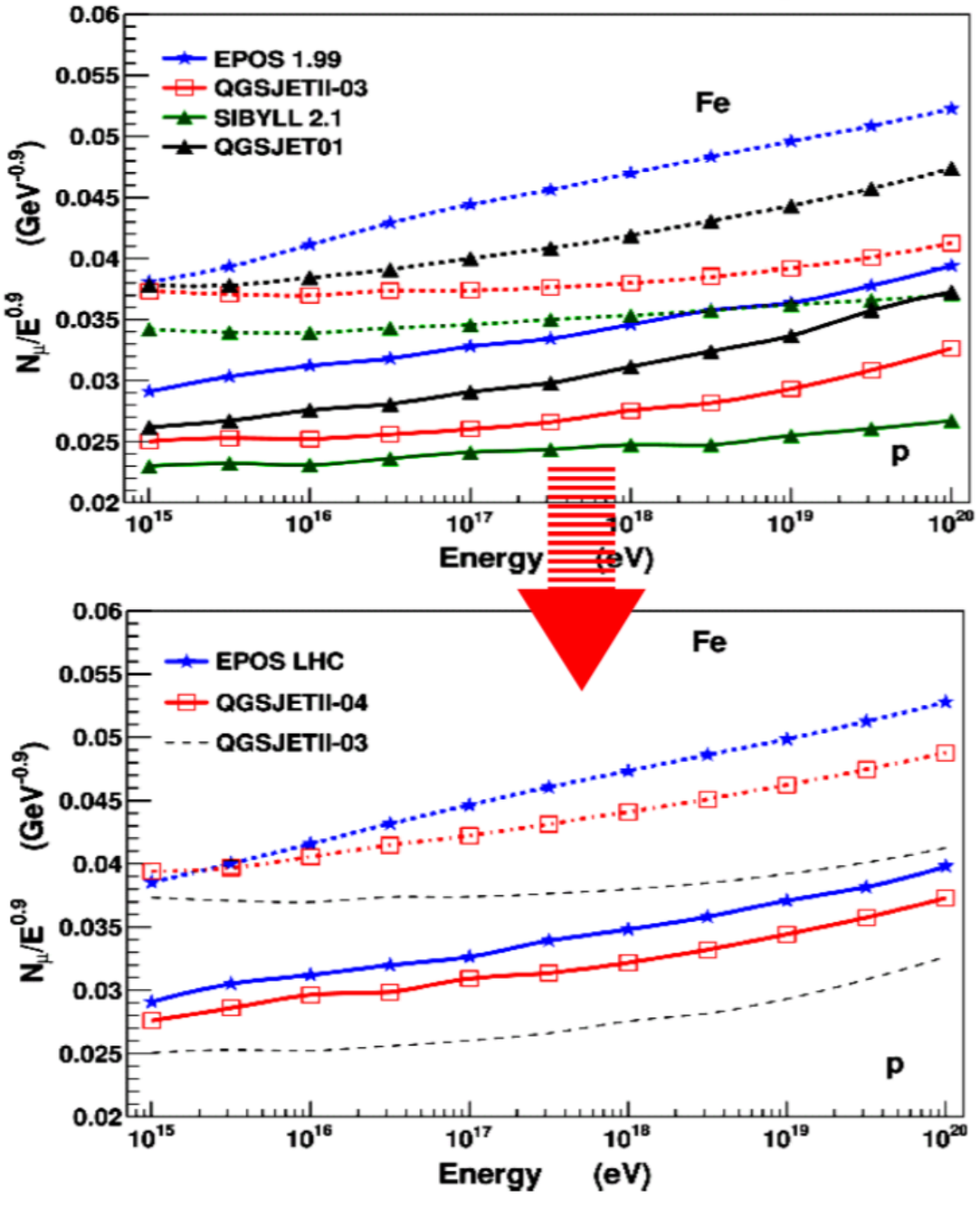
(pre-LHC)

(post-LHC)

Mean depth of shower maximum:



Number of muons on ground:

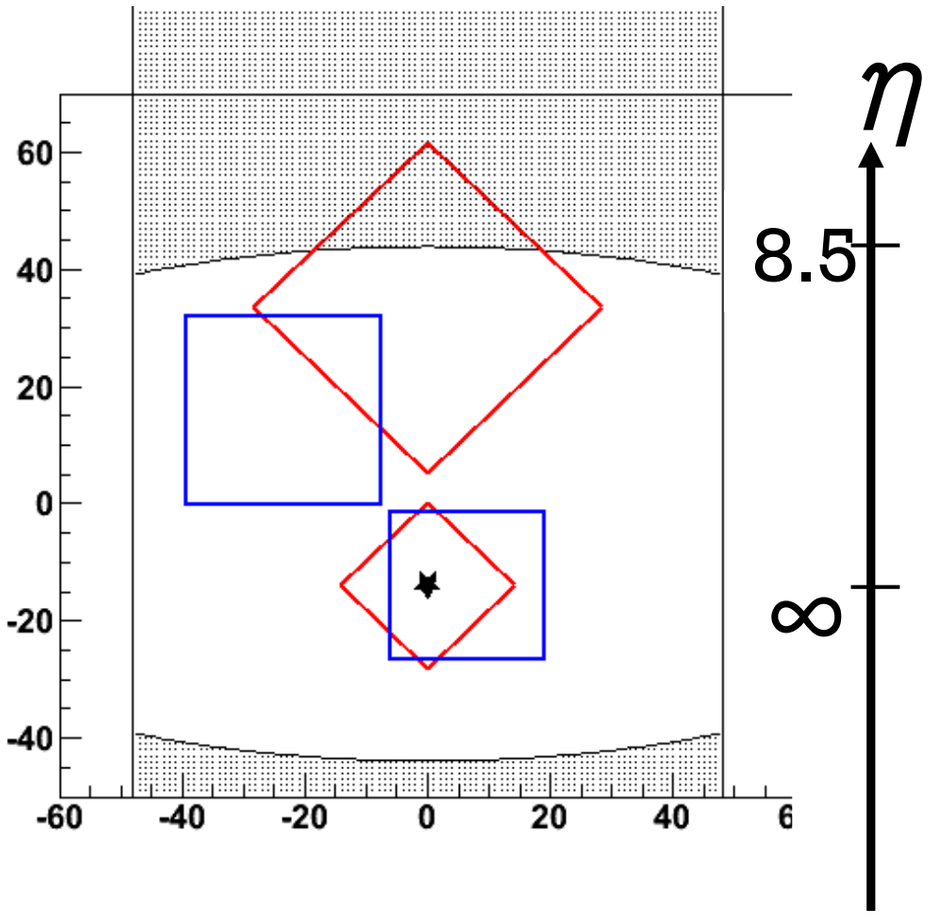


LHCf measurement

Energy spectra and Transverse momentum distribution of

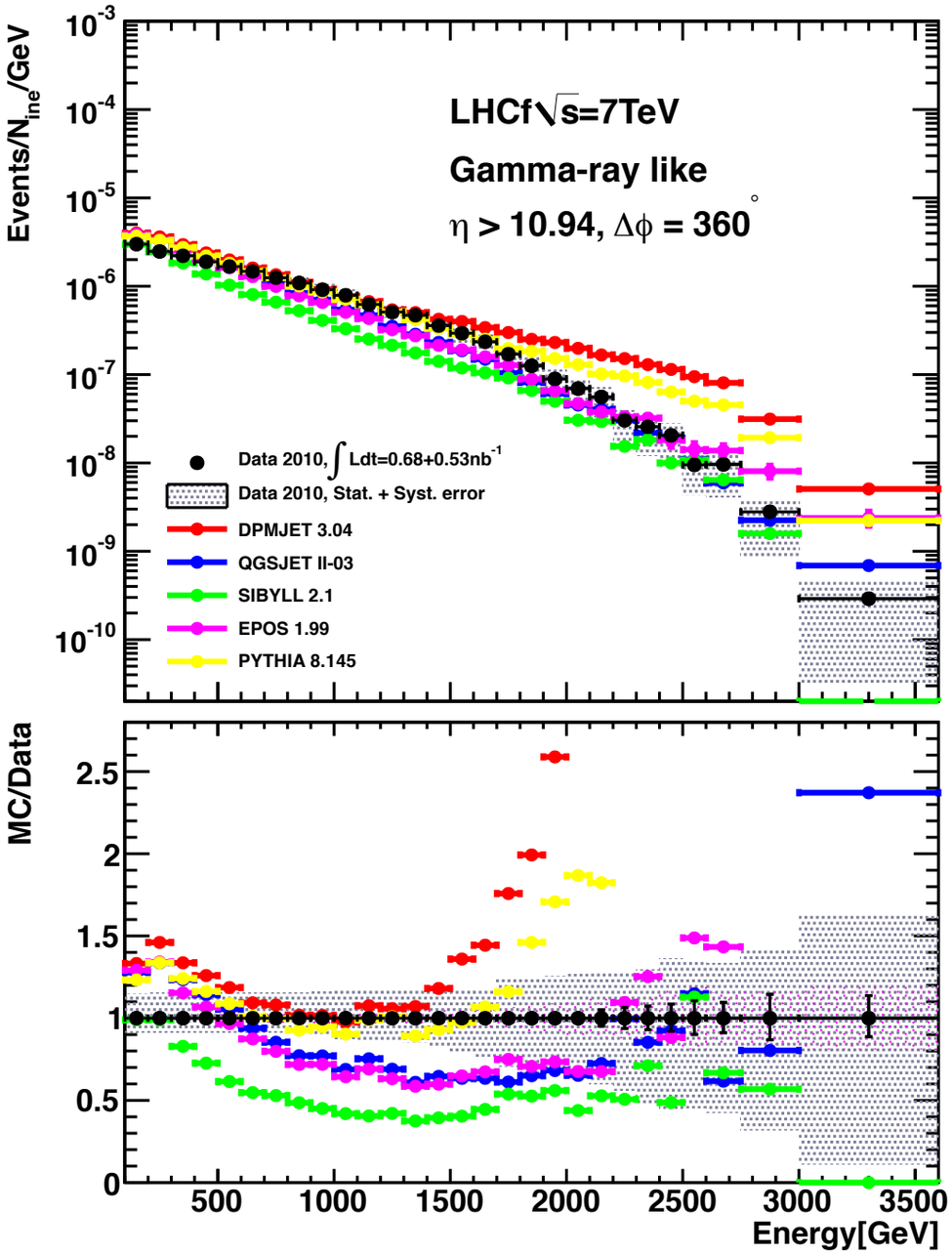
- Photons
  - ✦ E>100GeV with dE/E<5%
- Neutral Hadrons
  - E>a few 100 GeV with dE/E~40%
- π^0
  - E>600GeV with dE/E<3%

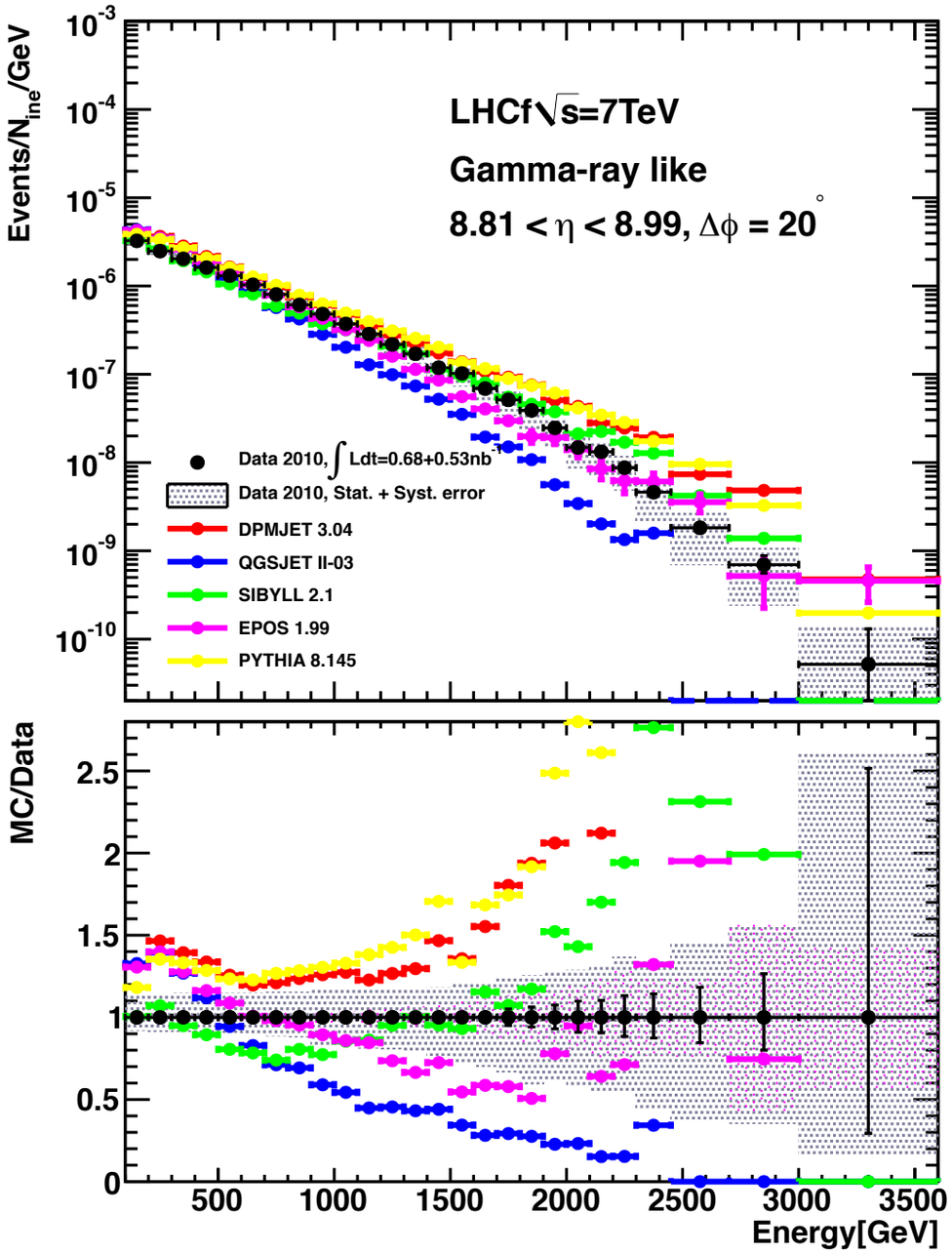
Front view of calorimeters
@ 100μrad crossing angle



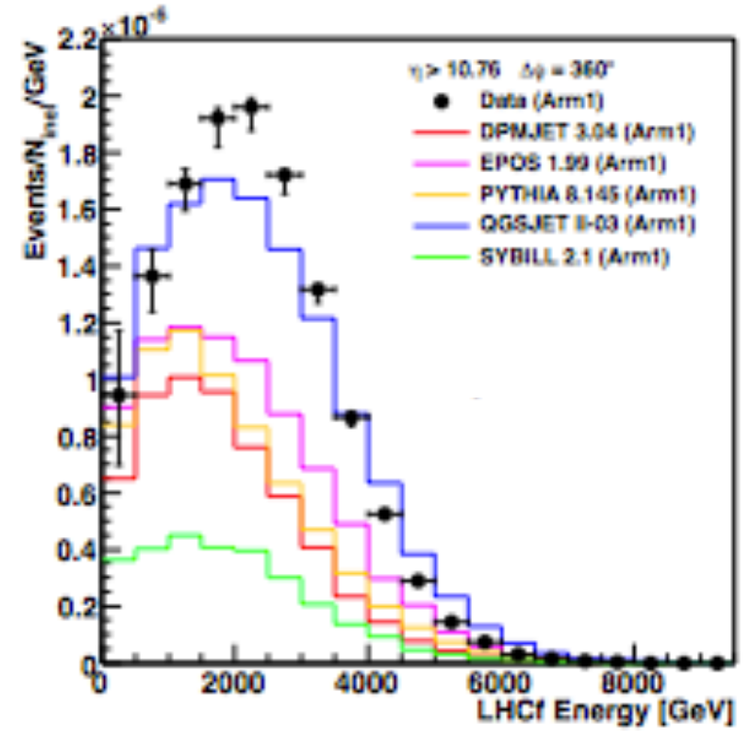
Acceptance η>8.4

Photon inclusive energy specterum @√s=7TeV

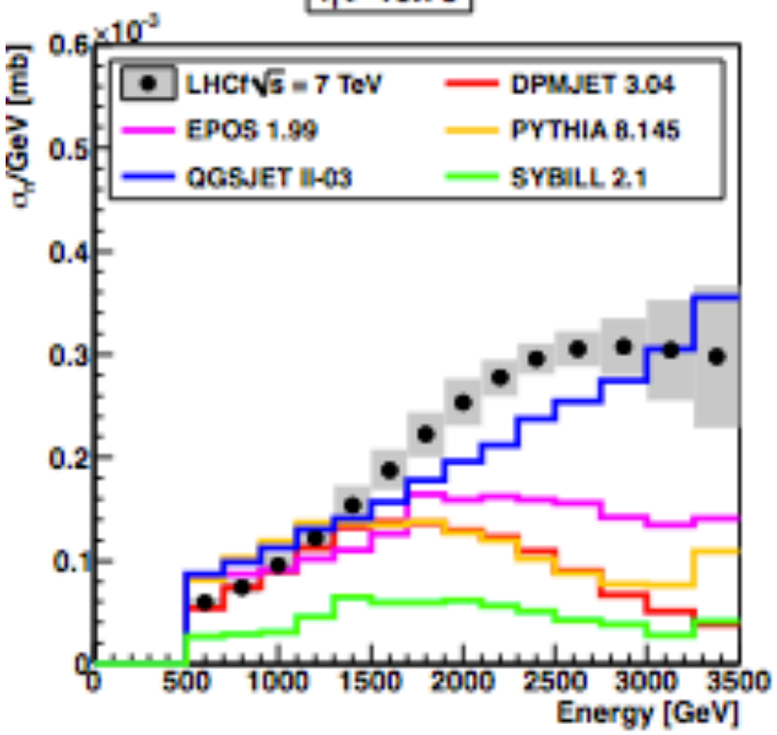


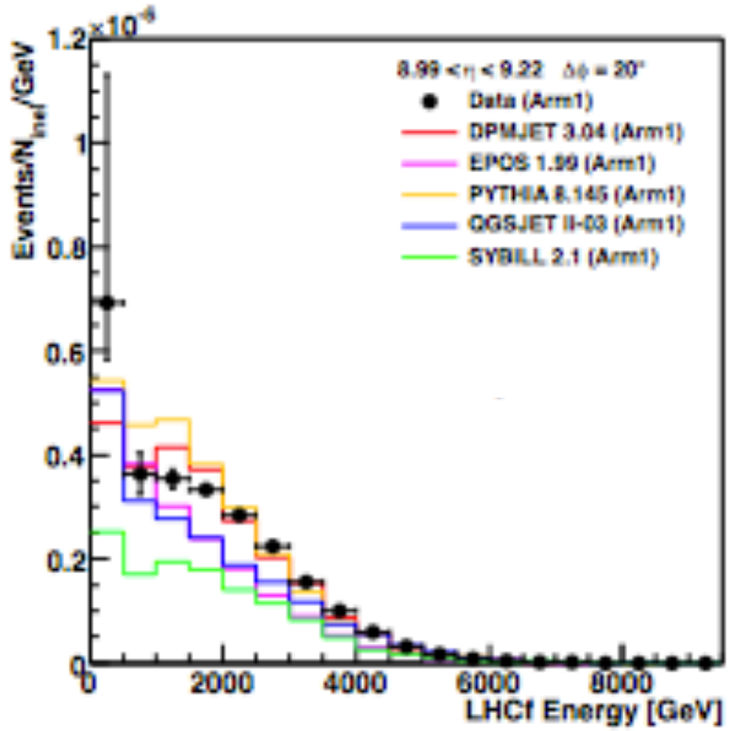


Neutron inclusive energy specterum @√s=7TeV

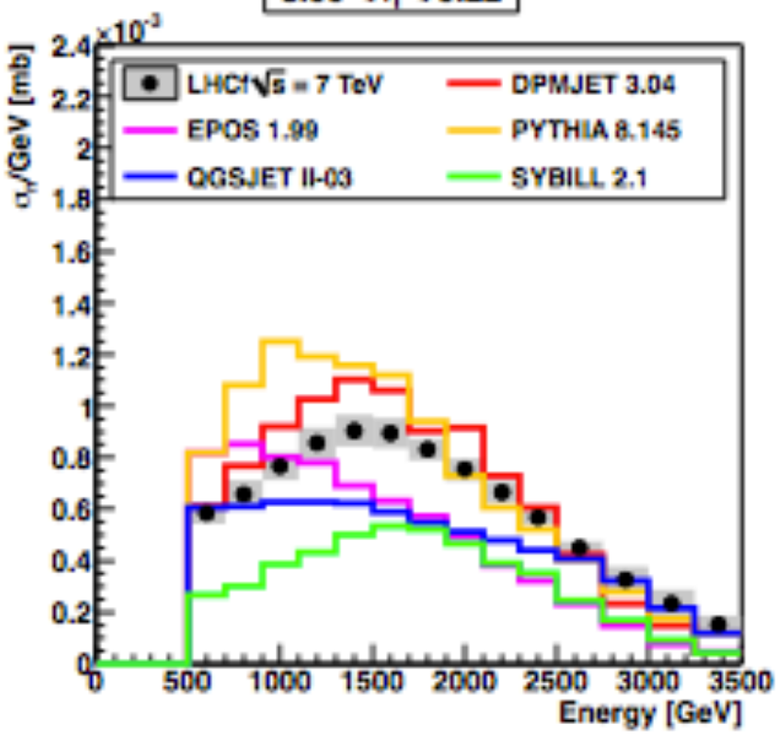


η > 10.76





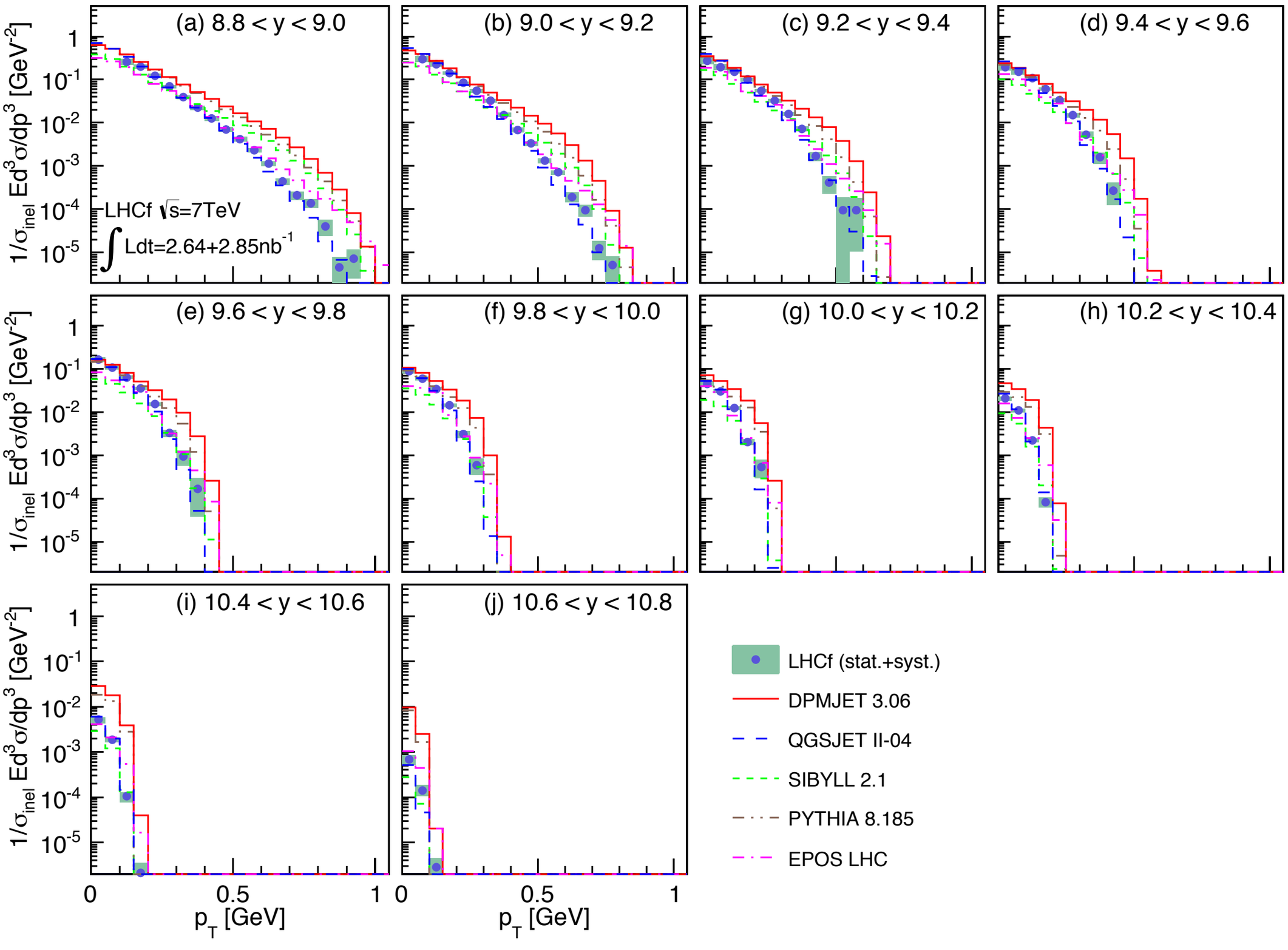
8.99 < η < 9.22



Data (η>10.76)	3.05±0.19
DPMJET3.04	1.05
EPOS1.99	1.80
PYTHIA8.148	1.27
QGSJETII-03	2.34
SYBILL2.1	0.88

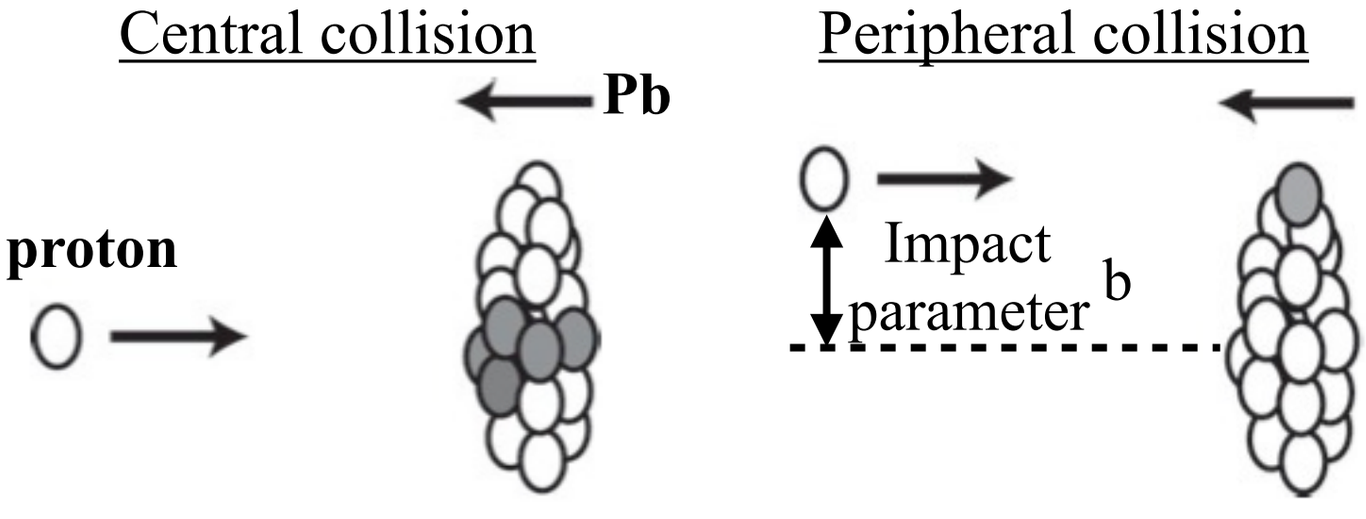
Data (8.99η>10.76)	1.26±0.08
DPMJET3.04	0.76
EPOS1.99	0.69
PYTHIA8.148	0.82
QGSJETII-03	0.65
SYBILL2.1	0.57

π^0 P_T spectrum @$\sqrt{s}$=7TeV

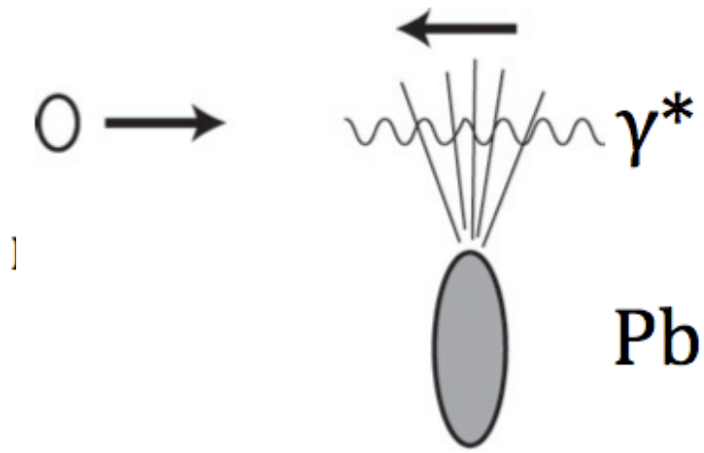


Analysis of p-Pb@$\sqrt{s_{NN}}$=5.02TeV

Soft QCD



Ultra peripheral

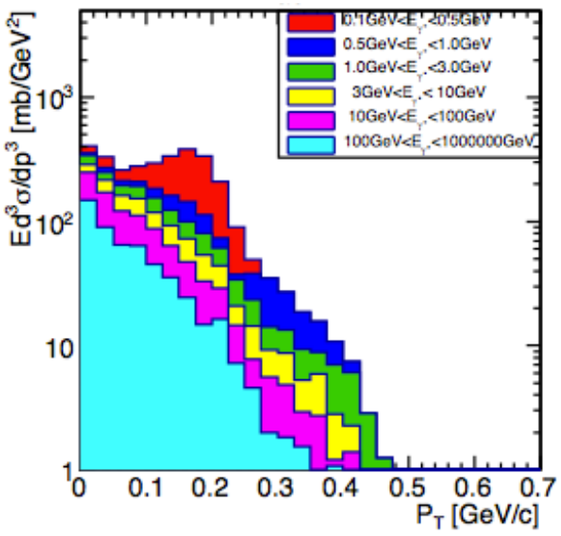


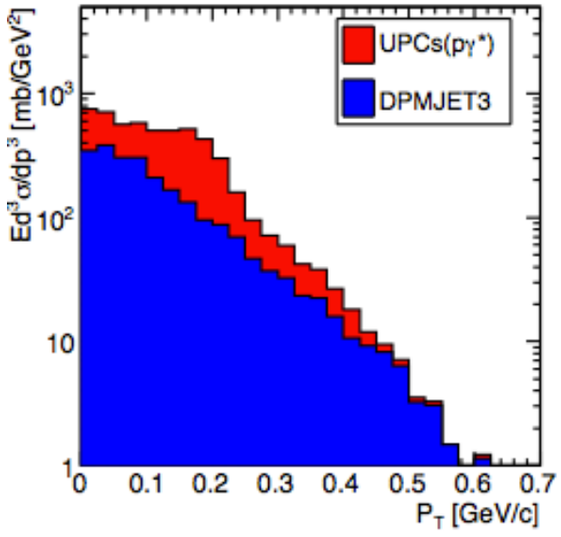
Estimation of momentum distribution of the UPC induced secondary particles (Lab frame+Boost):
1. energy distribution of virtual photons is estimated by the Weizsacker Williams approximation
2. photon-proton collisions are simulated by the SOPHIA model (E_γ > pion threshold)

Dominant channel to forward π^0 is

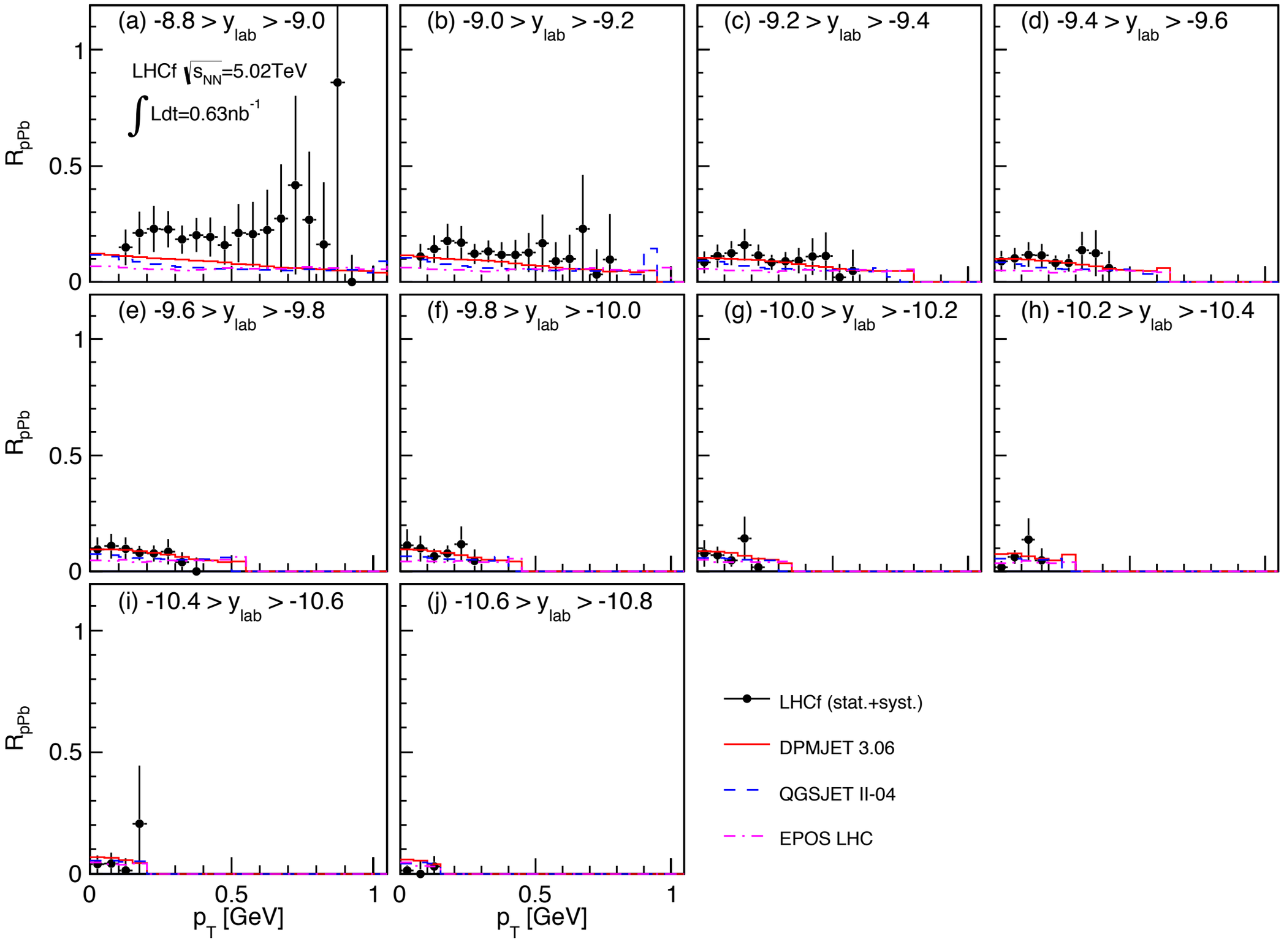
$$\gamma + p \rightarrow \Delta(1232) \rightarrow p + \pi^0$$

About half of the observed π^0 originate from UPC
About half is from soft-QCD
Need to subtract UPC component



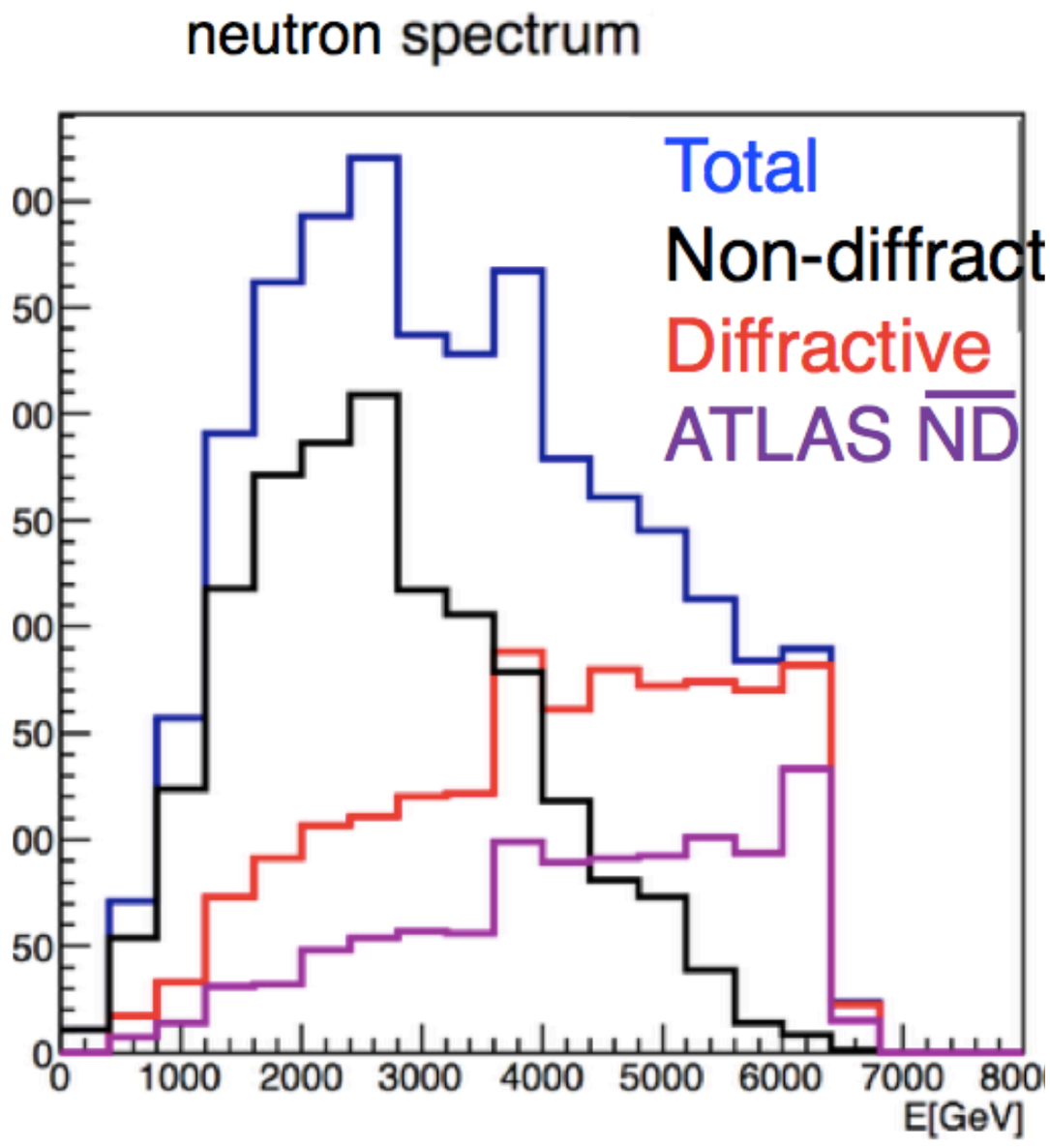


Nuclear modification facetor of p-Pb@$\sqrt{s_{NN}}$=5.02TeV



LHCf-ATLAS combine analysis

- Non-diffraction tagging by
  N_{trk}>=2 in ATLAS |η|<2
  (P_T>100 MeV/c)
- Diffraction : 10 % of LHCf data



A commonly triggered event

ATL-PHYS-PUB-2015-038
30 August 2015