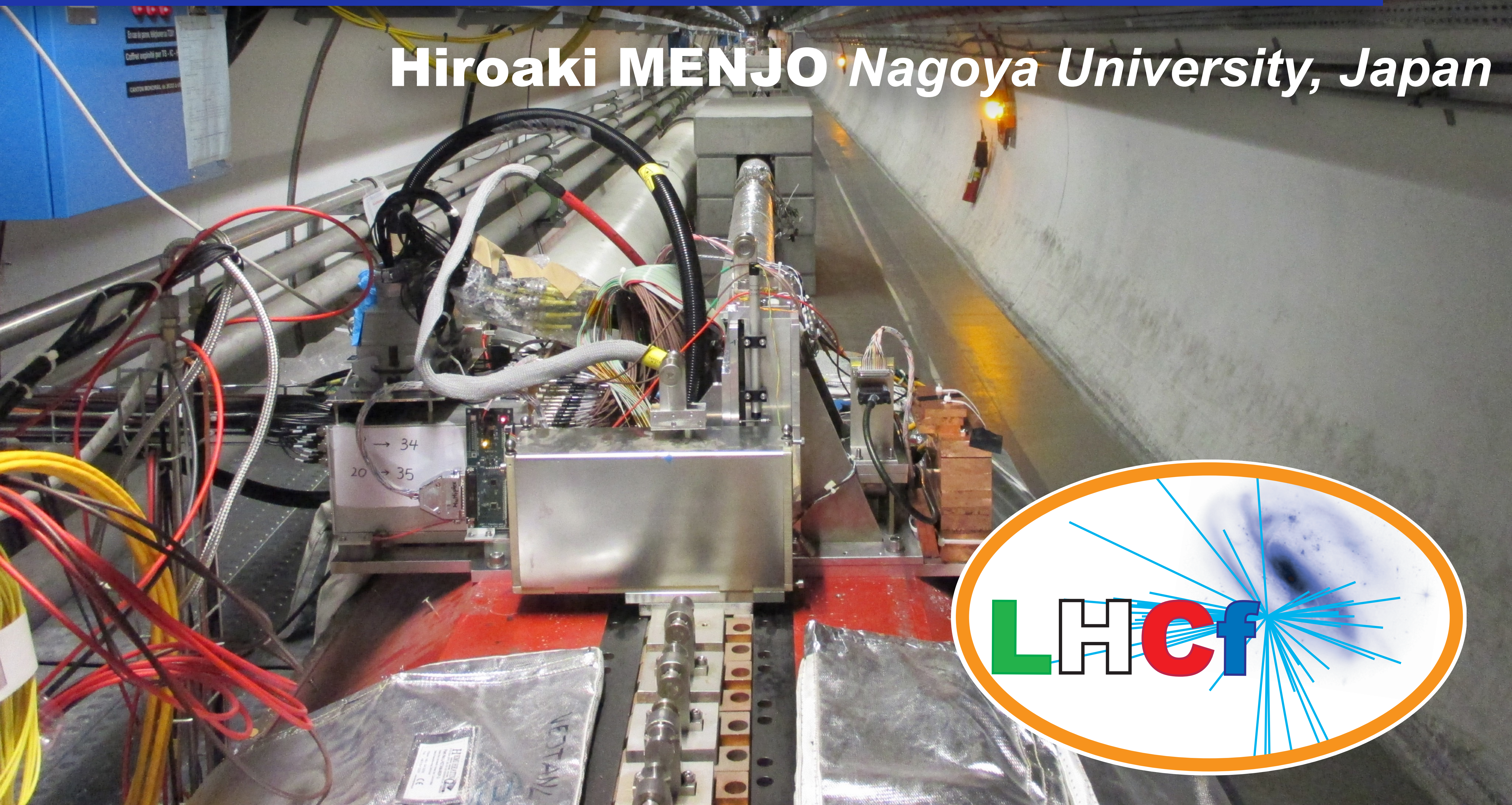
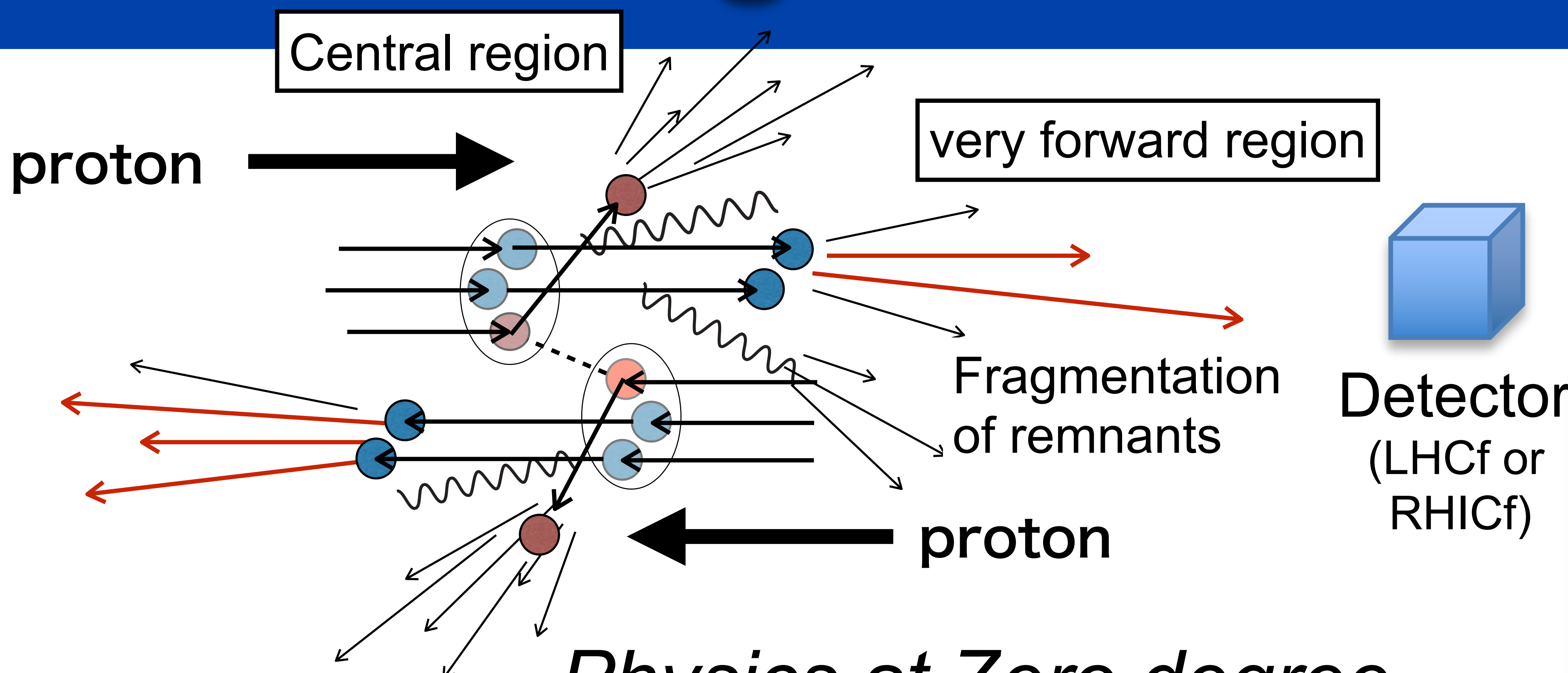
High energy hadron physics at zero-degree

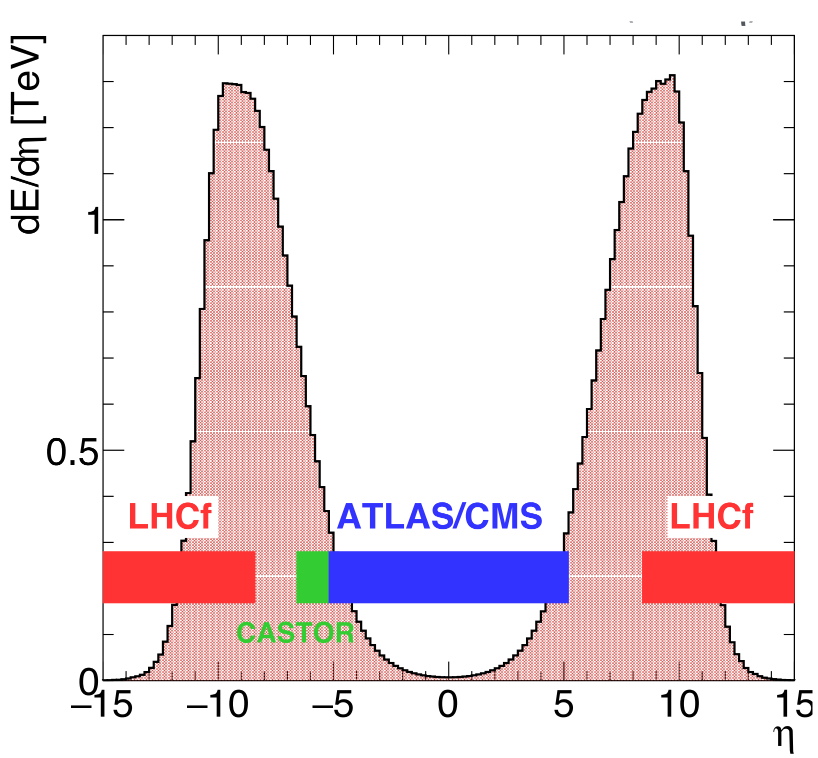
Hiroaki MENJO *Nagoya University, Japan*



Zero-degree of collisions



Physics at Zero degree

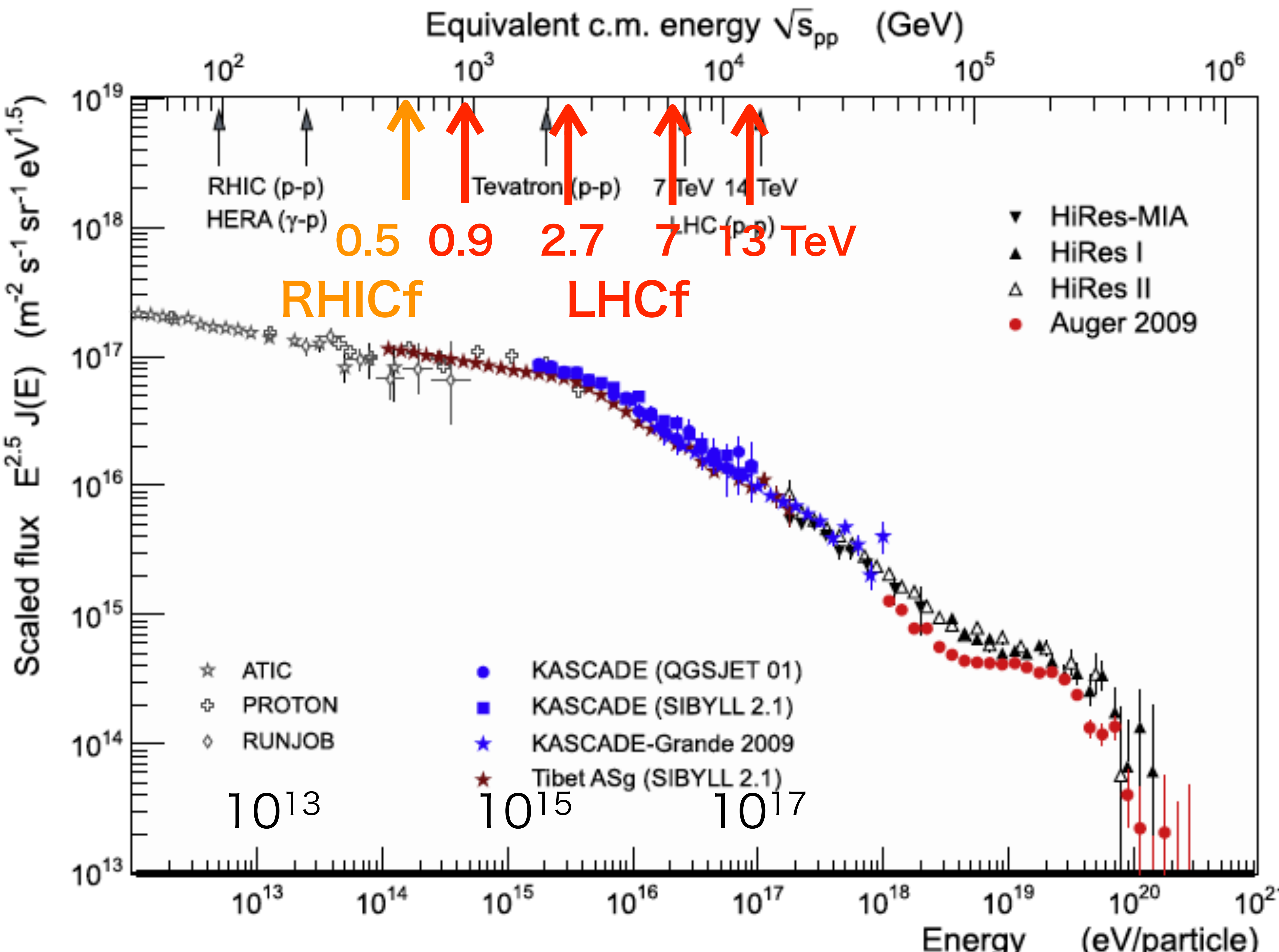


✓Soft collisions, low-pT < 1GeV
→ pQCD does not work.
→ Phenomenological model is needed

✓High energy flux
→ Most of longitudinal momentum is carried by remnants of collisions.

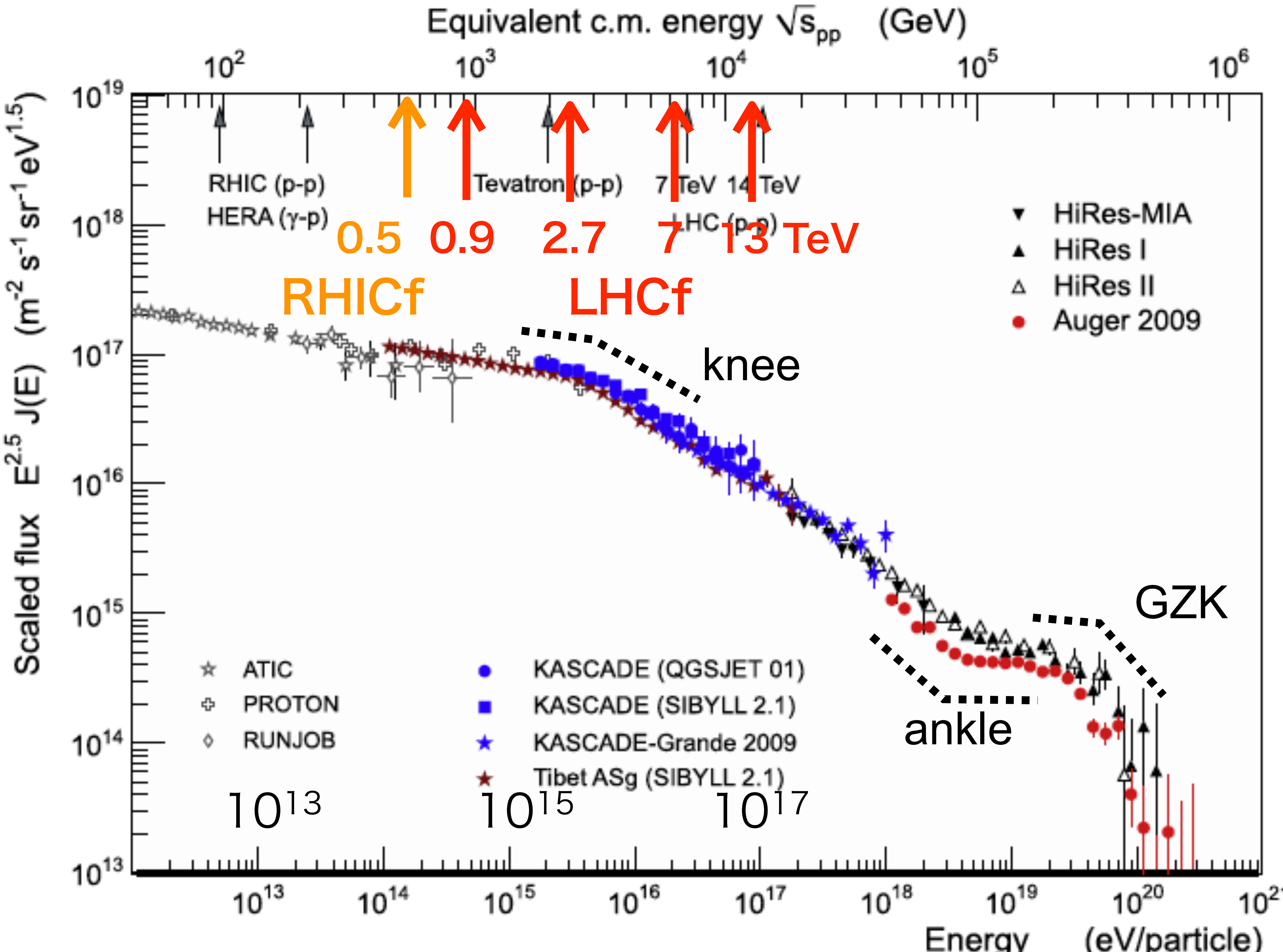
These are important for cosmic-ray physics, especially observation of ultra-high energy cosmic-rays

Cosmic-rays



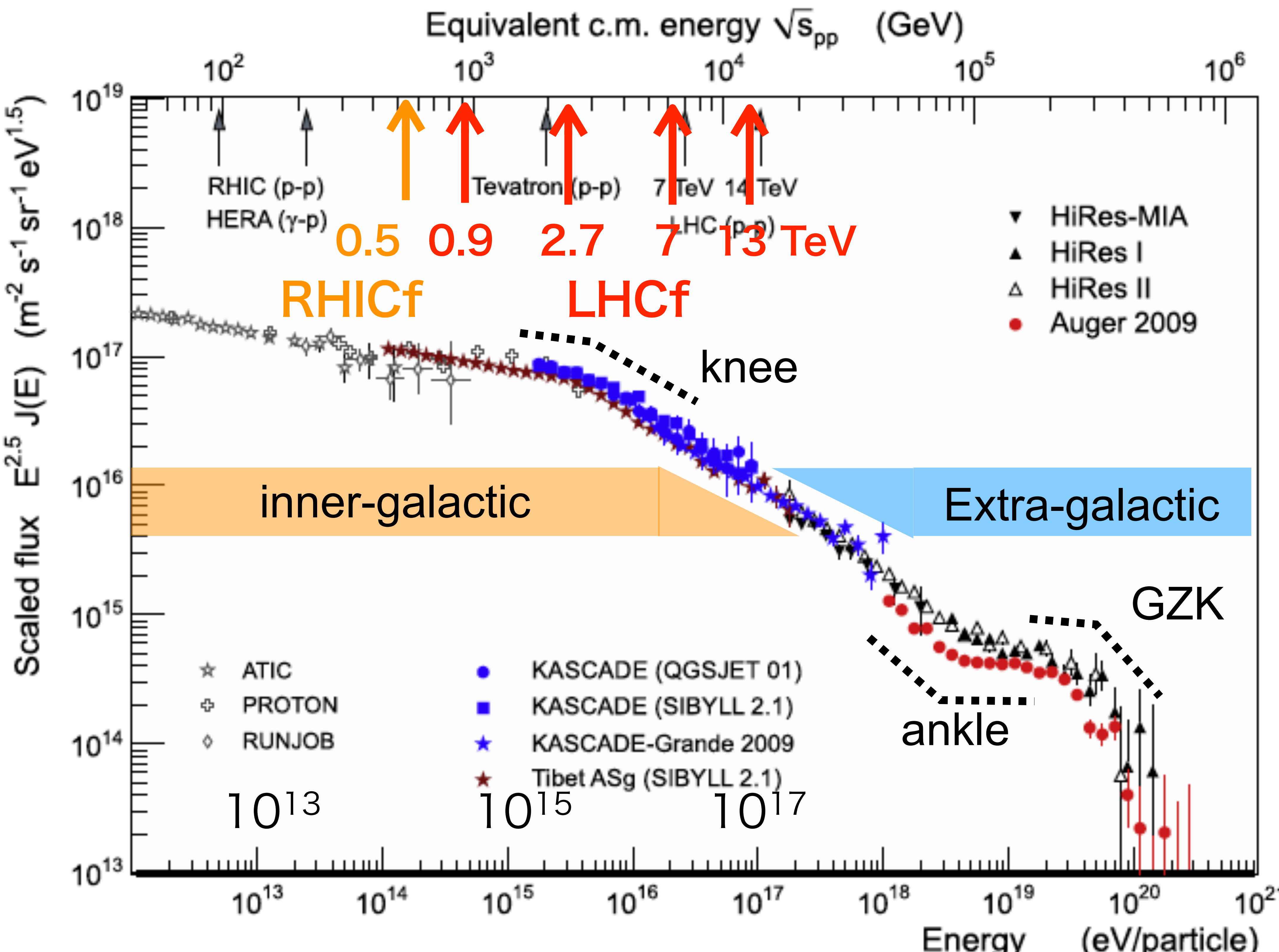
D'Enterria et al., 2011

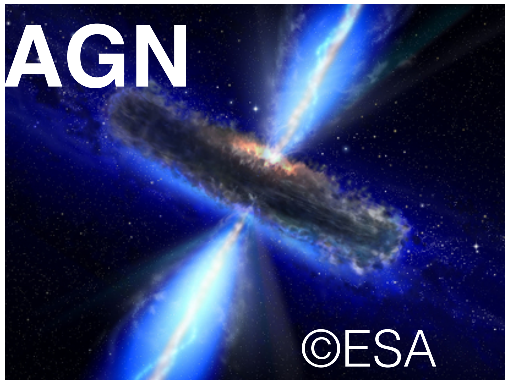
Cosmic-rays

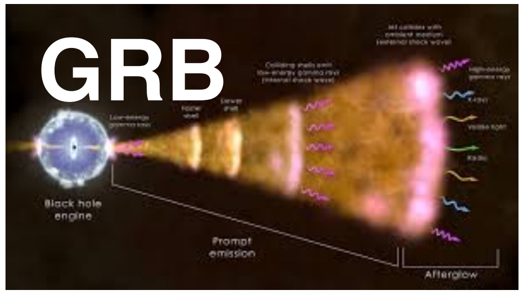


D'Enterria et al., 2011

Cosmic-rays



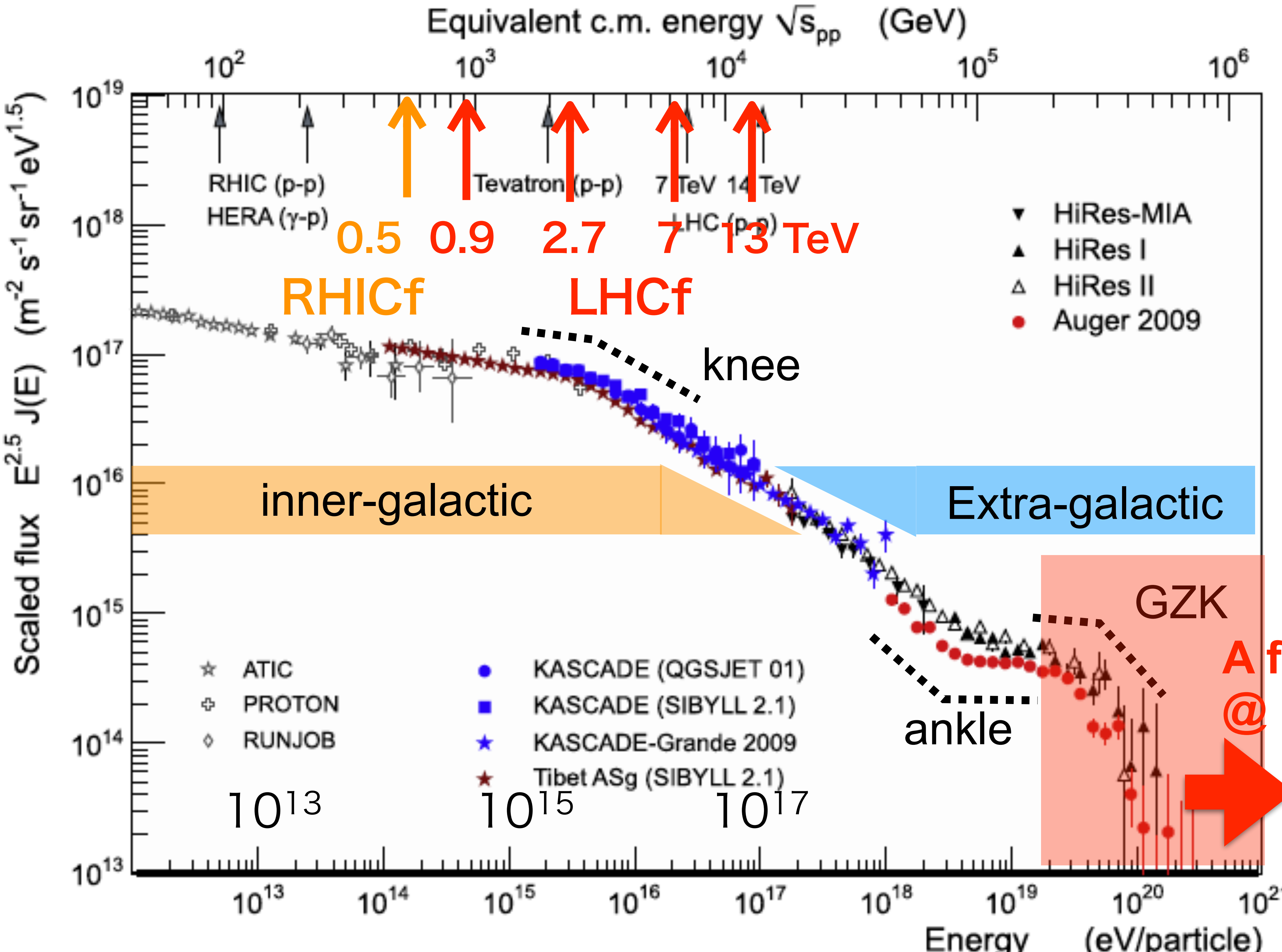


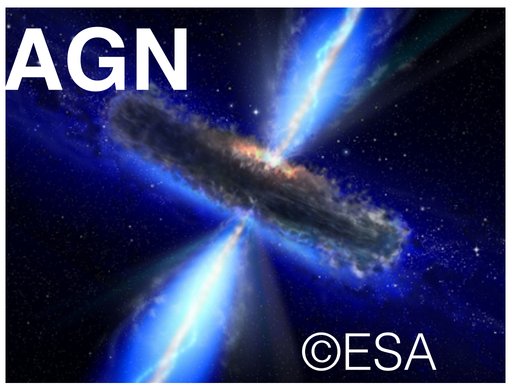


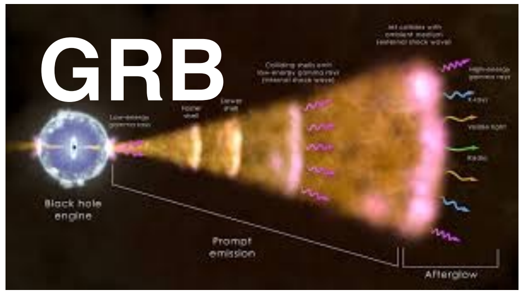
©NASA

D'Enterria et al., 2011

Cosmic-rays



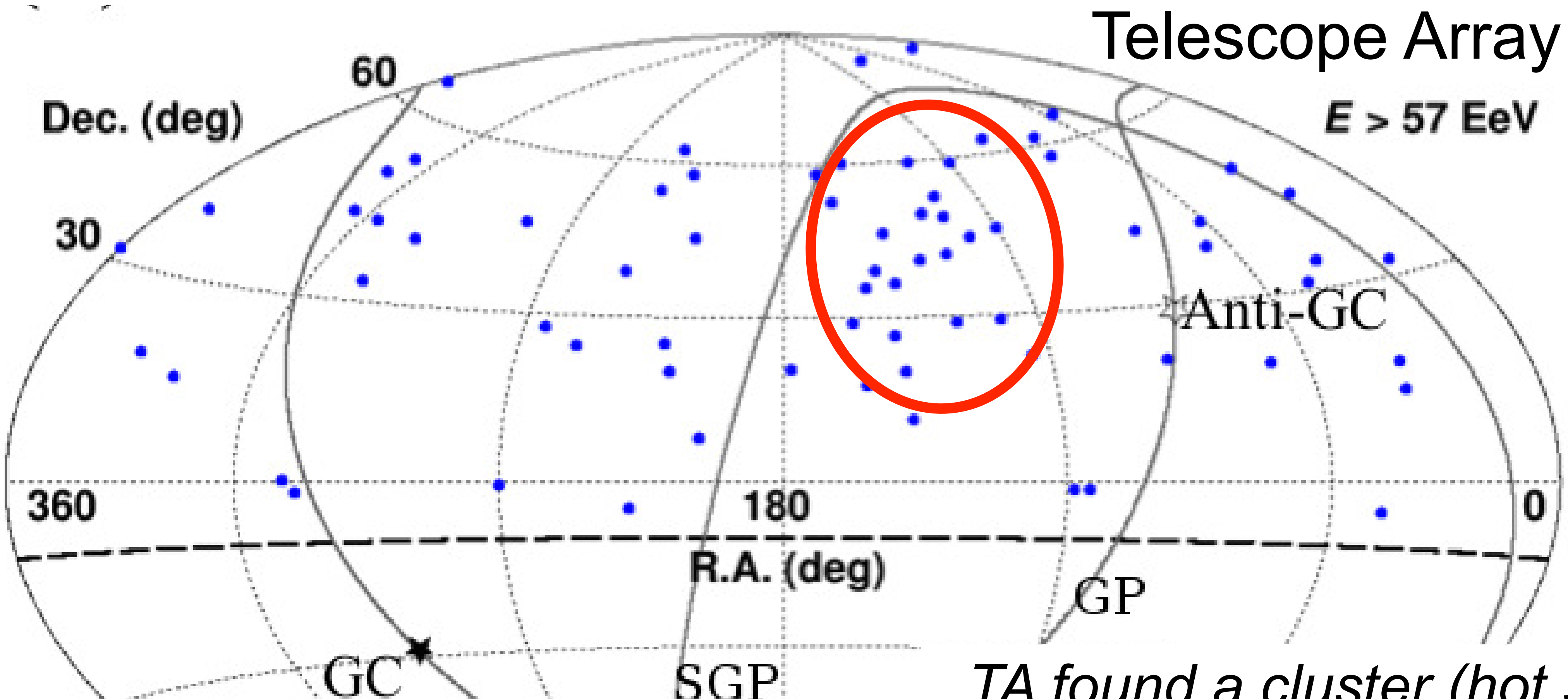


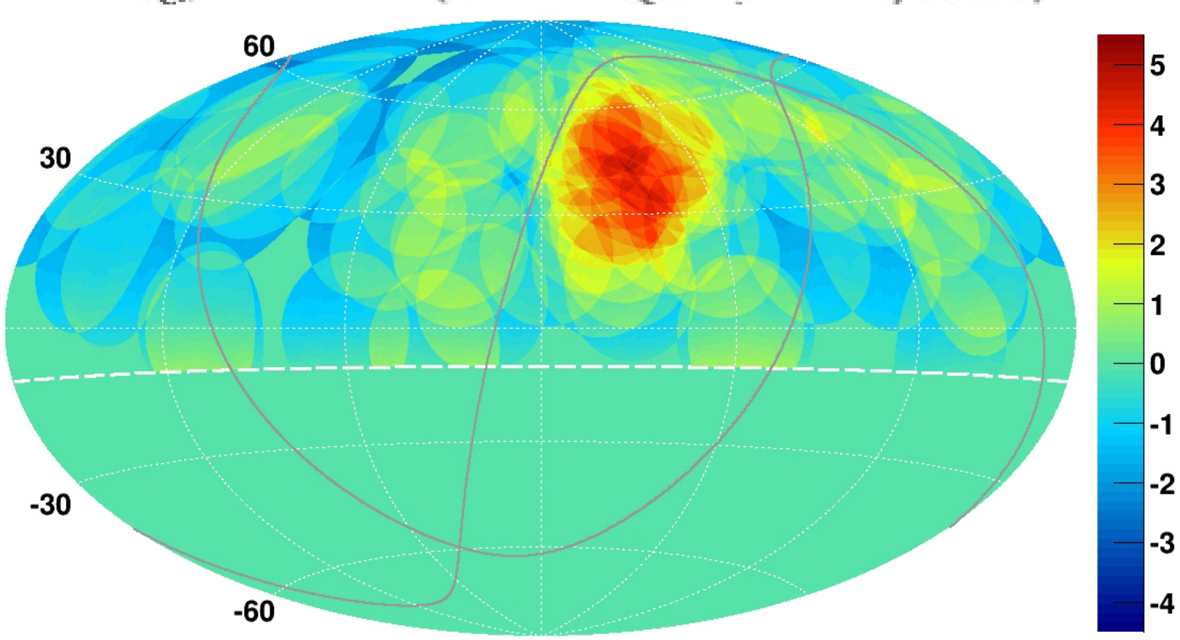


©NASA

D'Enterria et al., 2011

Arrival direction of UHECRs





TA found a cluster (hot spot.) but the distribution does not match any catalogs of energetic objects well.

- ✓Scattering angle from the source depends on the **composition**.
- ✓Mean free path of UHECRs during the propagation from the source depends on the **composition** also.

TA collaboration, ApJ 790 L21 (2014)

UHECR observations

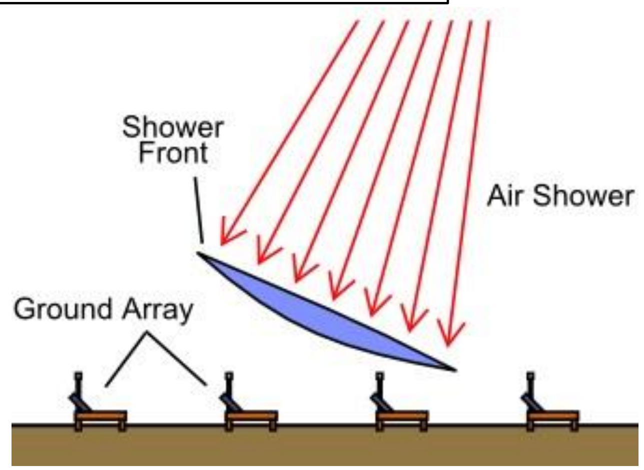
Indirect observation by using the air shower technique

😊 Easy to have Large Acceptance

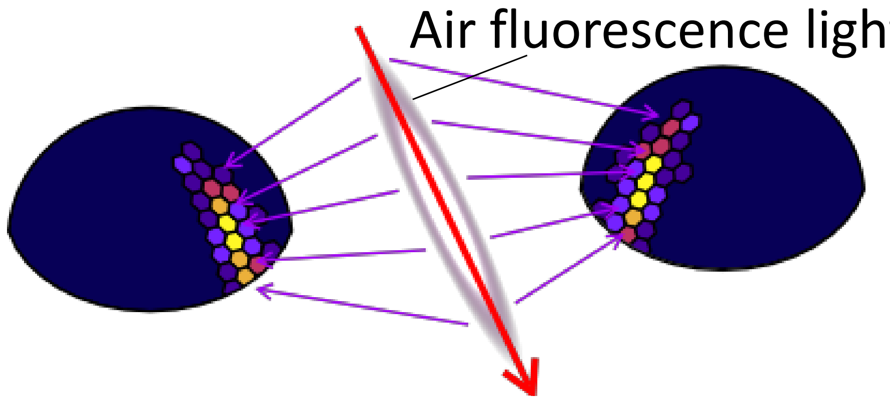
😔 Uncertainty in the reconstruction of primary CR information.

- Energy spectrum
- Anisotropy
- Chemical composition

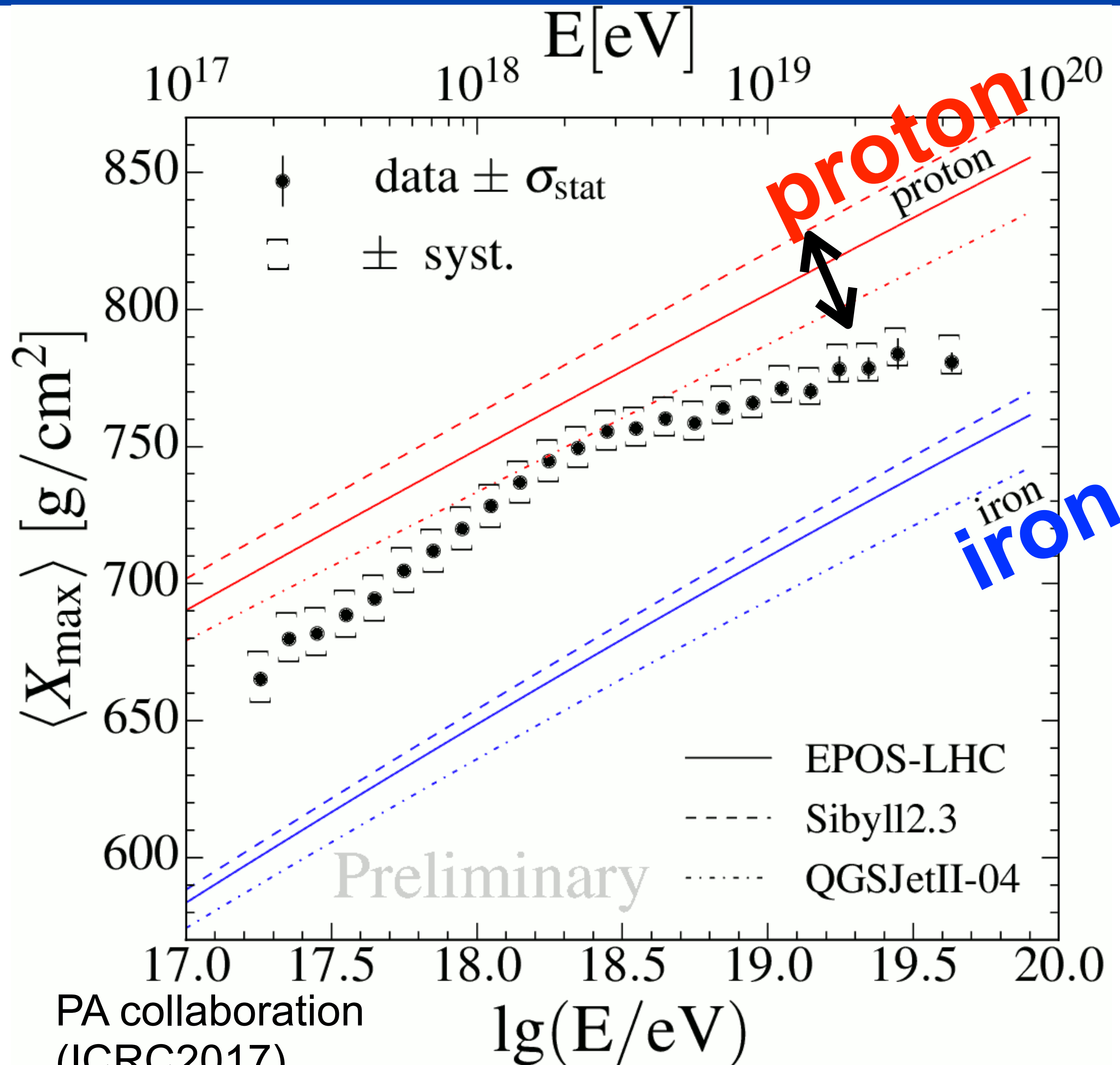
Surface detector (SD)



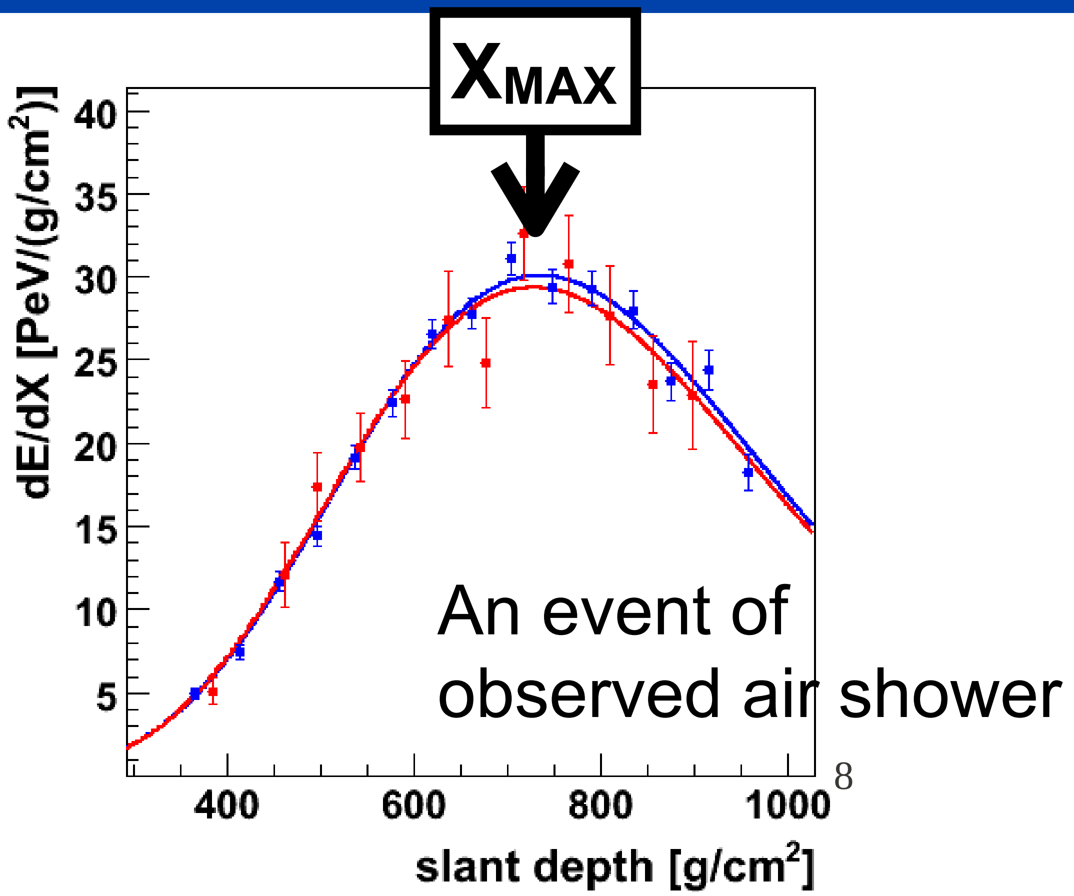
Fluorescence detector (FD)



Composition measurement



PA collaboration (ICRC2017)

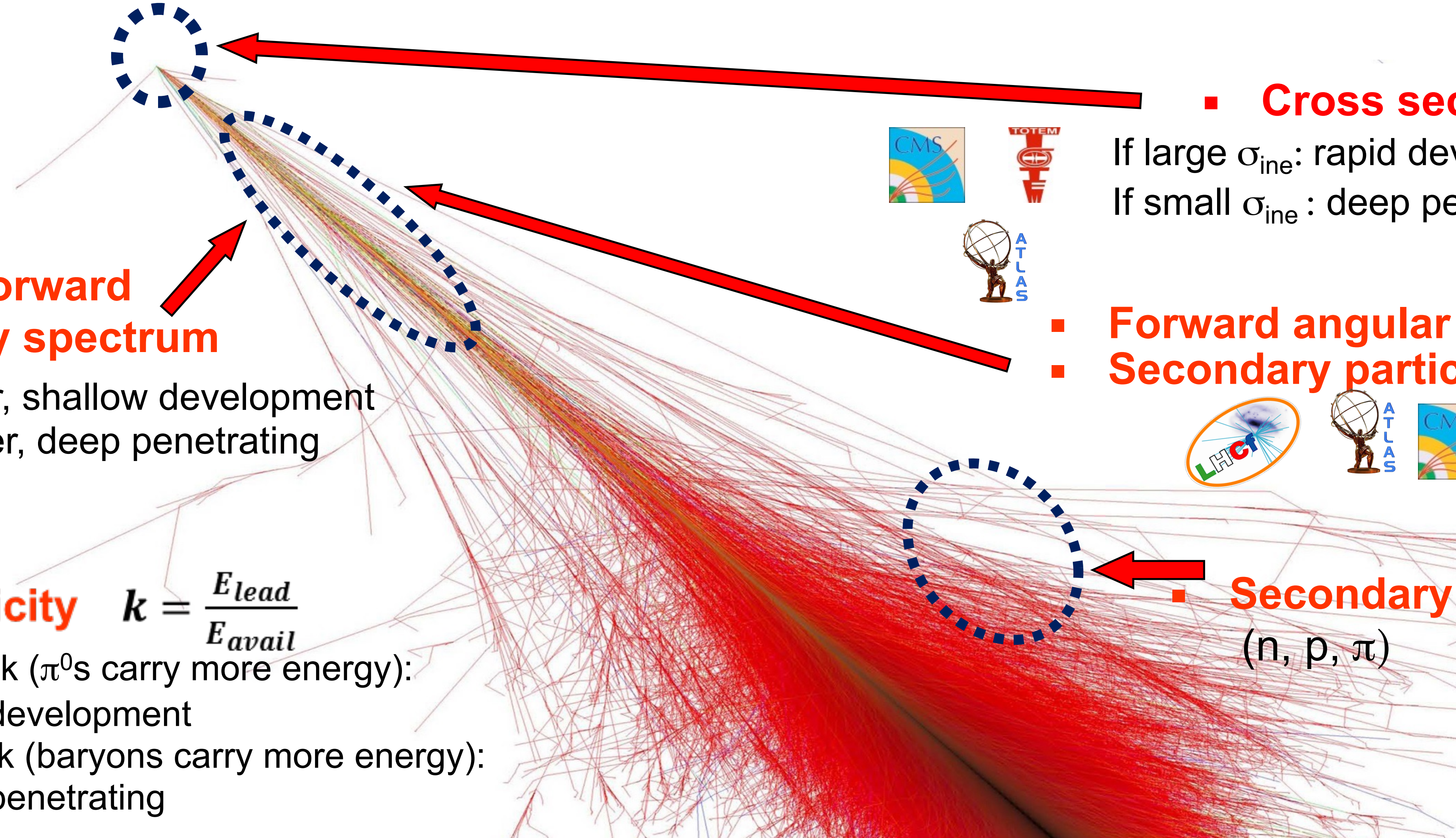


Uncertainty of hadron interaction models

V

Error of <X_{max}> measurement

- ✓ **Improvement of hadronic interaction models is one of the keys for UHECR studies.**
- ✓ **LHC provide unique opportunities to verify the models at √s=14TeV (E_{CR}=10^{17}eV)**



- **Cross section**

If large σ_{ine}: rapid development
If small σ_{ine} : deep penetrating

- **Very forward energy spectrum**

- If softer, shallow development
- If harder, deep penetrating

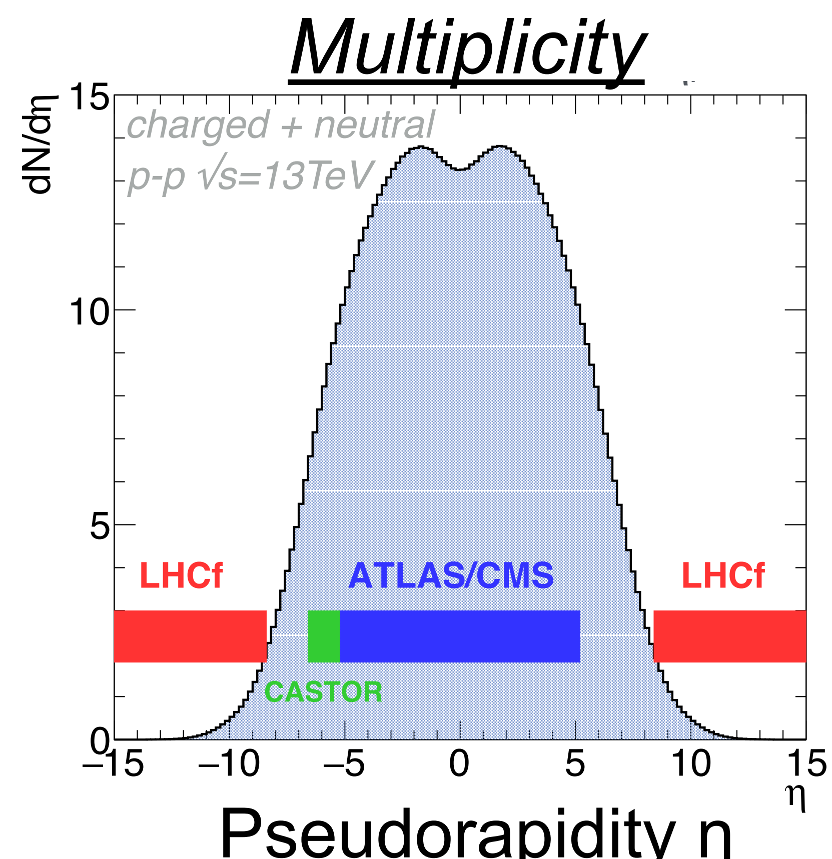
- **Forward angular emission**
- **Secondary particle multiplicity**

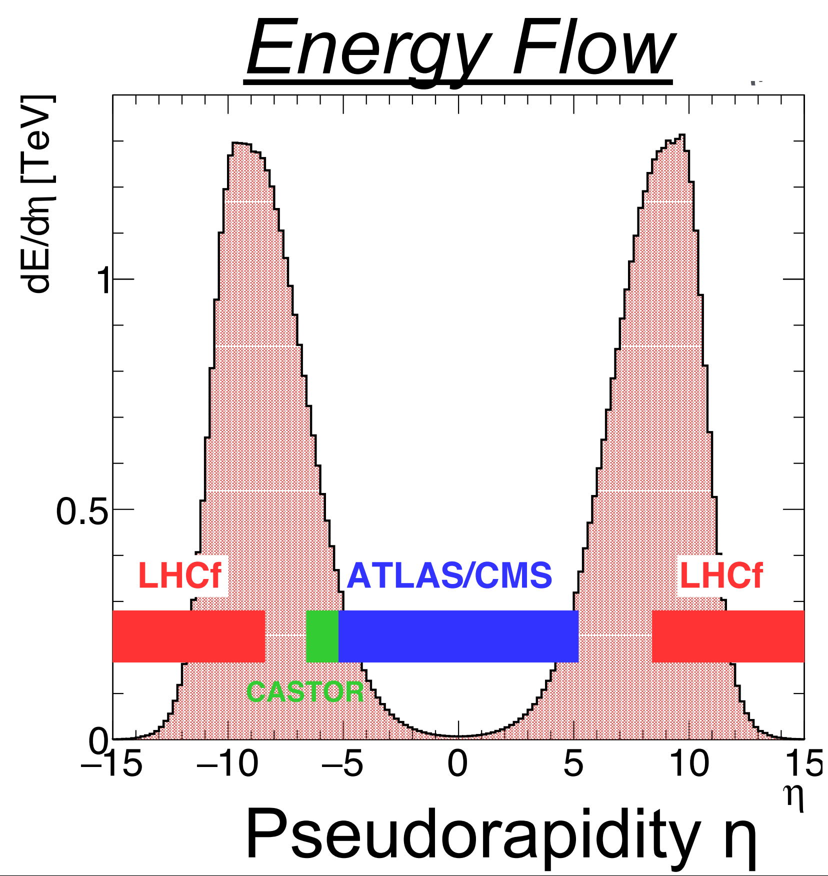
- **Elasticity** $k = \frac{E_{lead}}{E_{avail}}$

- If small k (π^0s carry more energy): rapid development
- If large k (baryons carry more energy): deep penetrating

- **Secondary interactions**

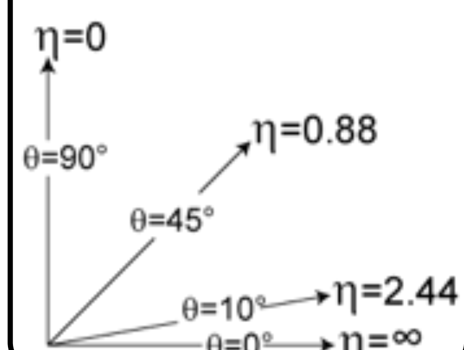
(n, p, π)





Pseudorapidity

$$\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$



The LHCf collaboration

[*,]Y.Itow, [*]Y.Makino, [*]K.Masuda, [*]Y.Matsubara, [*]E.Matsubayashi, [***]H.Menjo, [*]Y.Muraki, [*,**]T.Sako, [*]K.Sato, [*] M.Shinoda, [*]M.Ueno, [*]Q.D.Zhou**

[*]Institute for Space-Earth Environmental Research, Nagoya University, Japan
[**]Kobayashi-Maskawa Institute, Nagoya University, Japan
[***]Graduate School of Science, Nagoya University, Japan

K.Yoshida *Shibaura Institute of Technology, Japan*

T.Iwata, K.Kasahara, T.Suzuki, S.Torii
Waseda University, Japan

Y.Shimizu, T.Tamura *Kanagawa University, Japan*

N.Sakurai *Tokushima University, Japan*

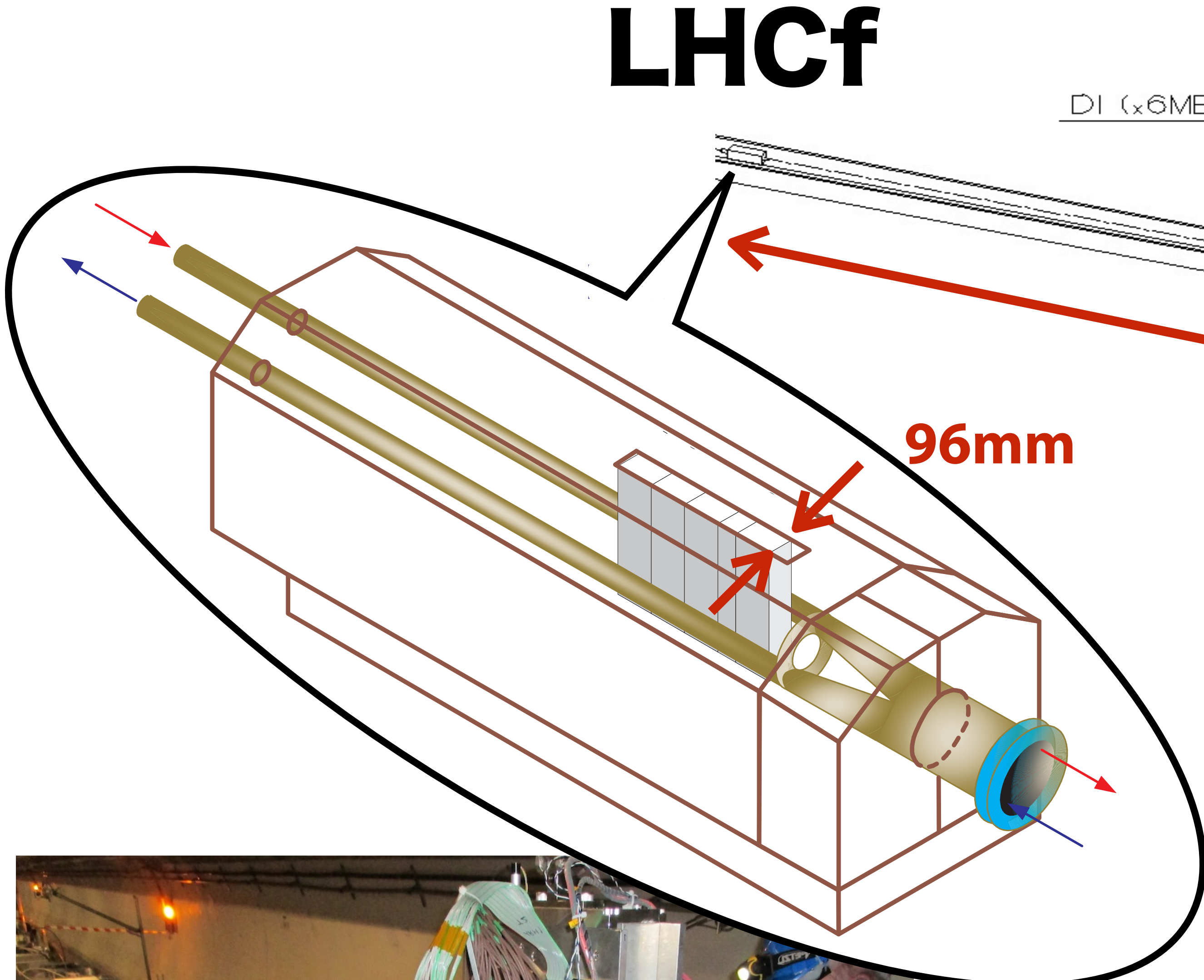
M.Haguenauer *Ecole Polytechnique, France*

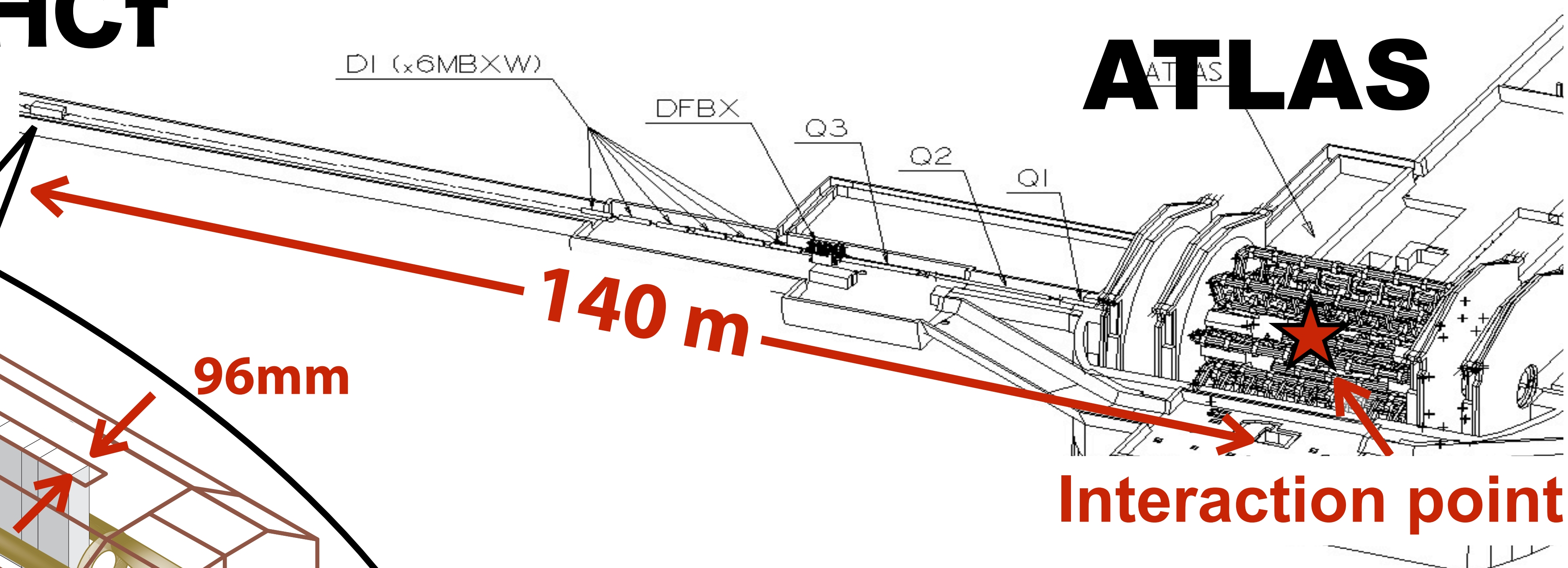
W.C.Turner *LBNL, Berkeley, USA*

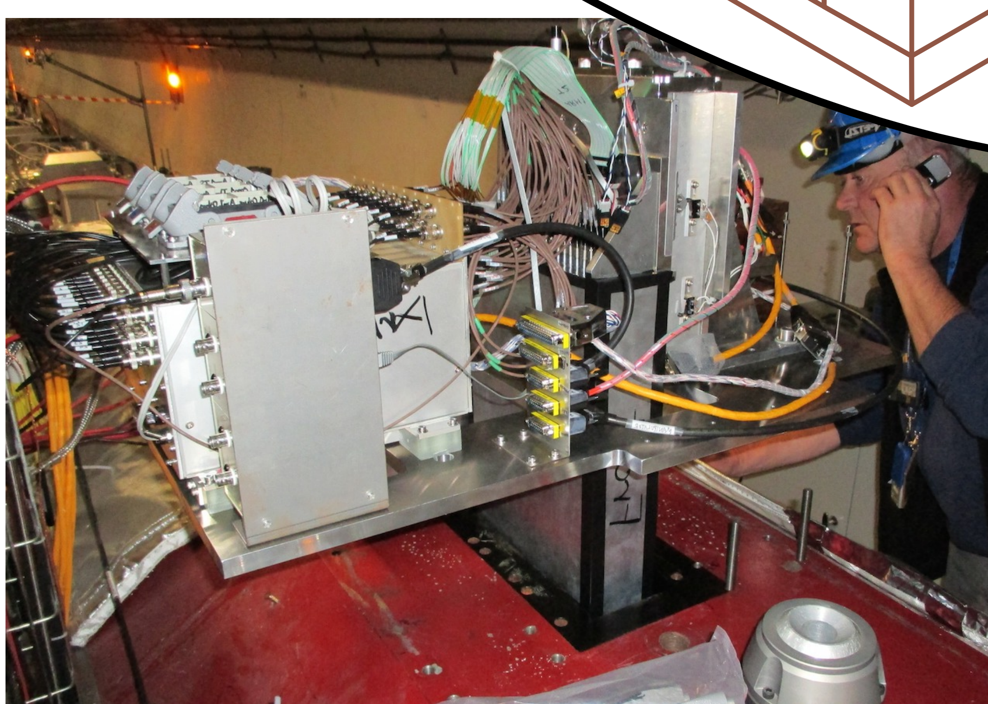
O.Adriani, E.Berti, L.Bonechi, M.Bongi, R.D'Alessandro, P.Papini, S.Ricciarini, A.Tiberio
INFN, Univ. di Firenze, Italy

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

Experimental Setup







- Two independent detectors: **Arm1 and Arm2** in both sides of ATLAS interaction points
- pseudorapidity coverage: **$\eta > 8.4$**
- Measure neutral particles **Photon, Neutrons and π^0**
  Charged particles are swept out by the magnetic field of the dipole magnets

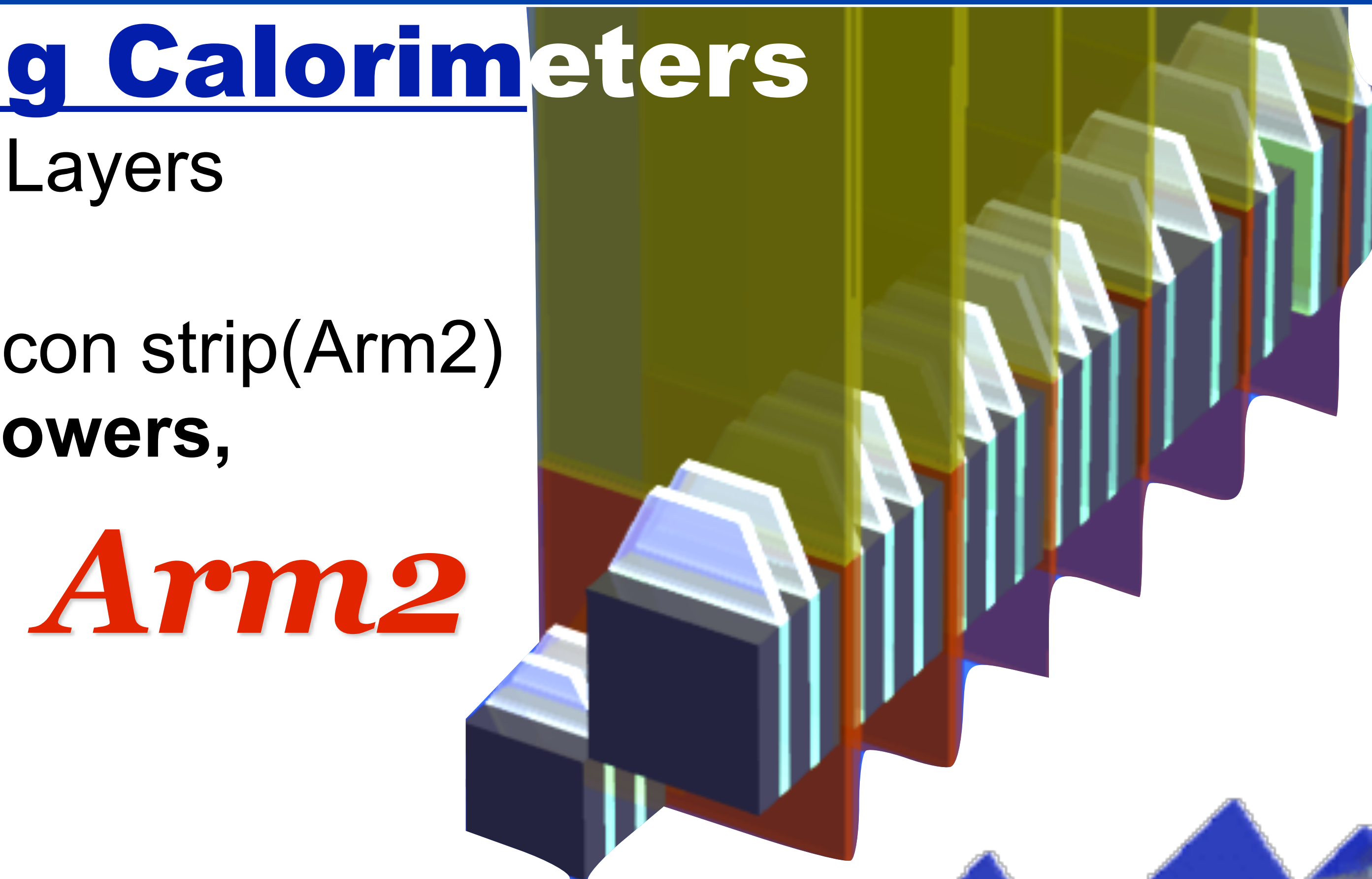
The LHCf detectors

Sampling and Positioning Calorimeters

- W (44 r.l , 1.7λ_I) and Scintillator x 16 Layers
- Four positioning sensitive layers
  XY-Scintillator bars (Arm1) and XY-Silicon strip(Arm2)
- **Each detector has two calorimeter towers, which allow to reconstruct π^0**

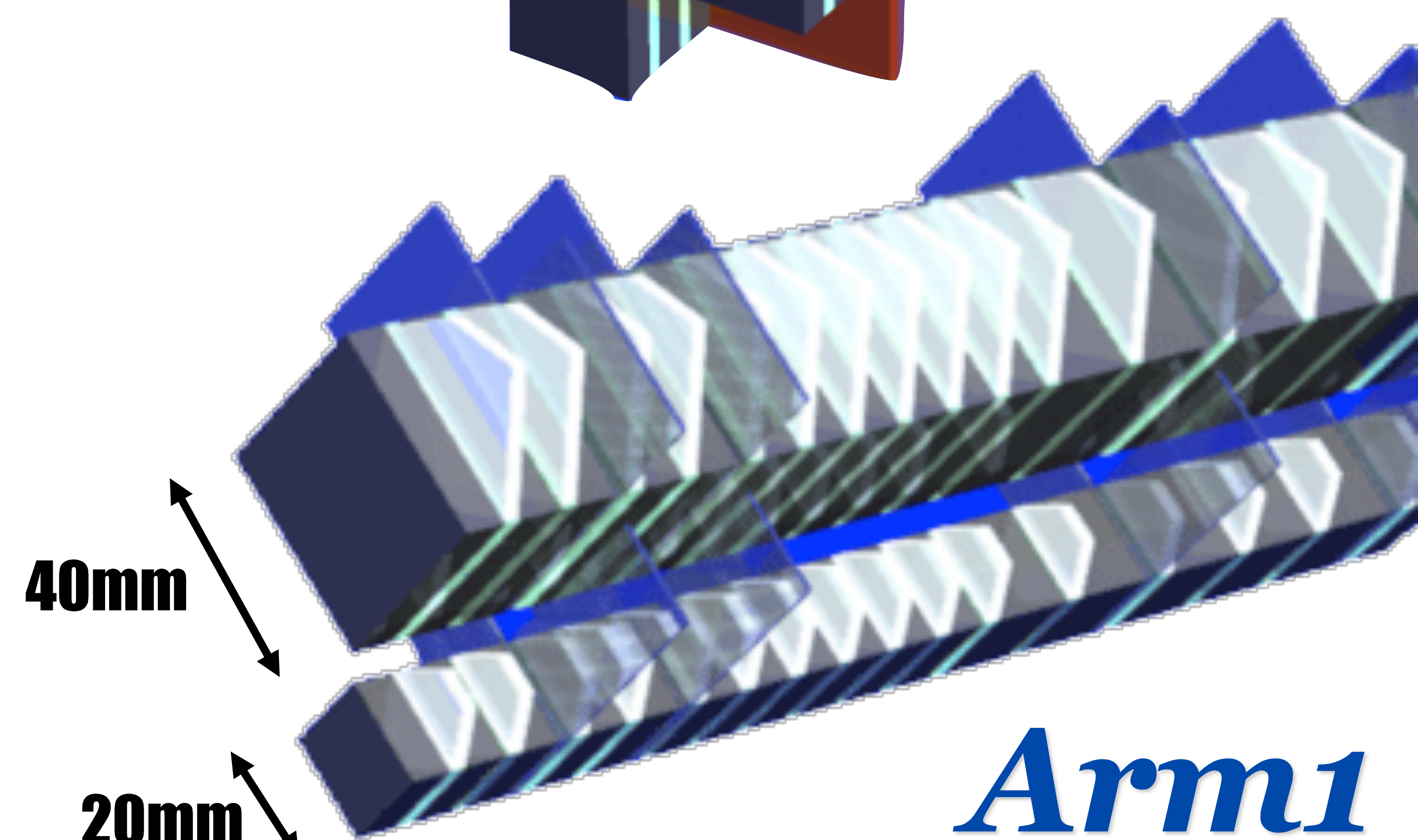
<u>Expected Performance</u>

Energy resolution (> 100GeV)
< 5% for Photons
40% for Neutrons
Position resolution
< 200μm for Photons
a few mm for Neutrons

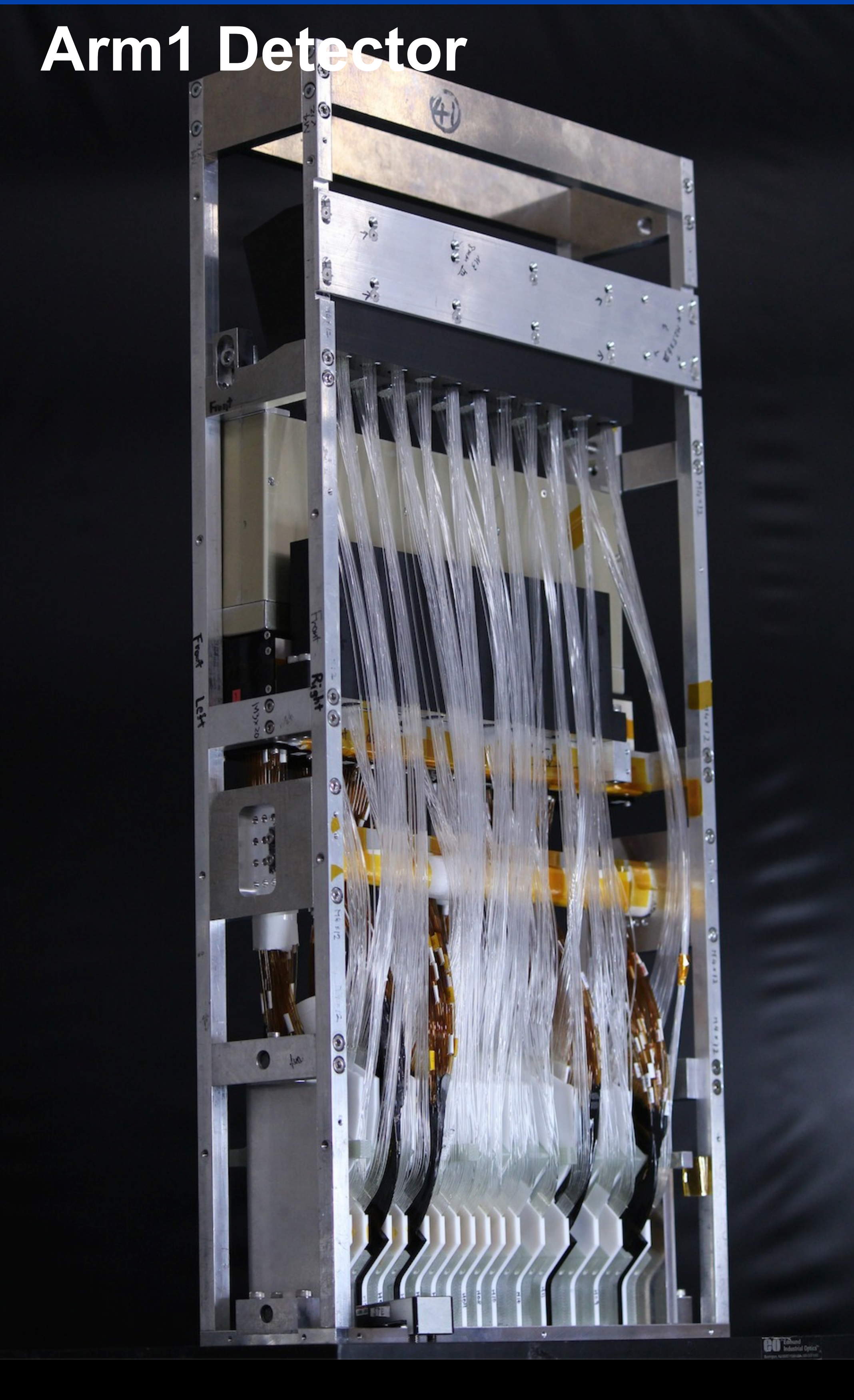


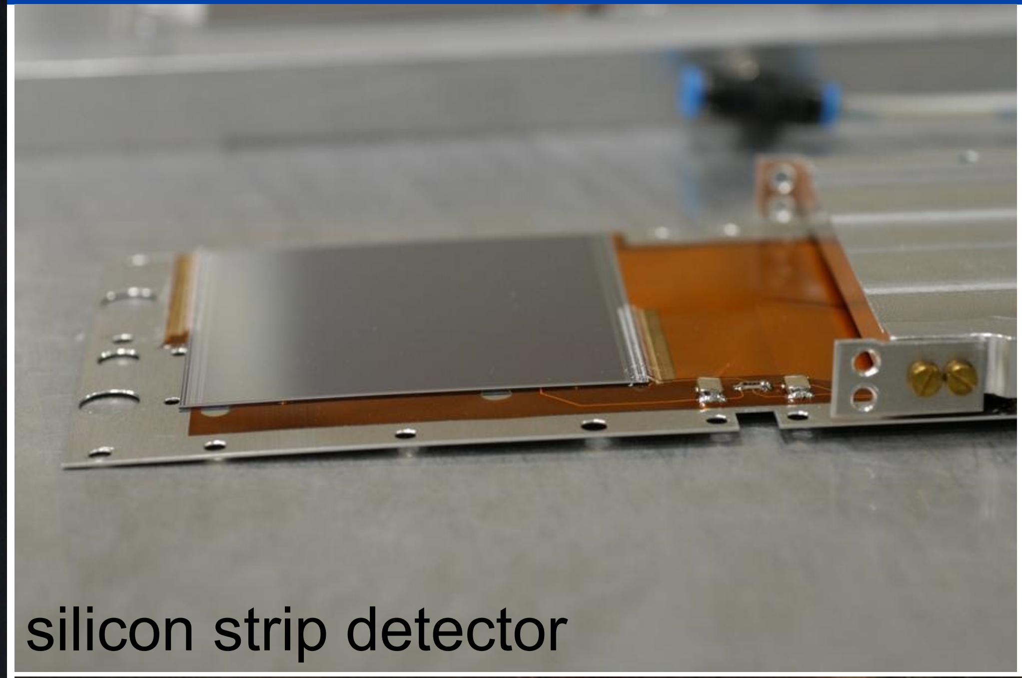
Front Counter

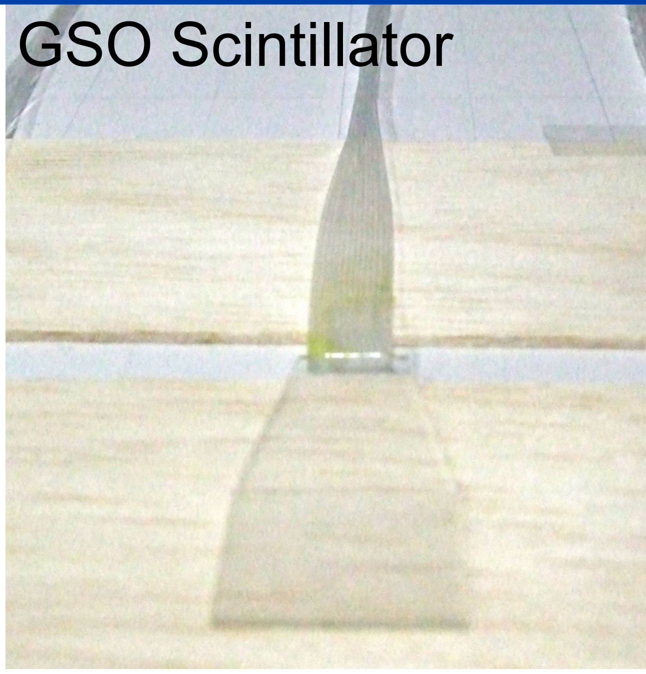
- thin scintillators with 80x80mm^2
- **To monitor beam condition.**
- **For background rejection of beam-residual gas collisions by coincidence analysis**



The LHCf detectors







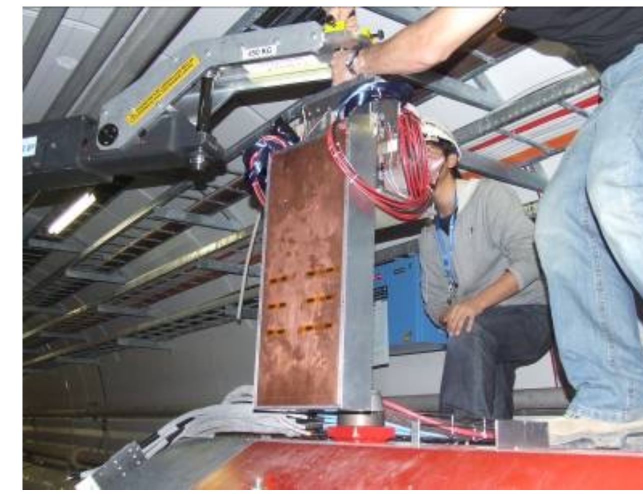
The LHCf history

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

Jul 2006
construction

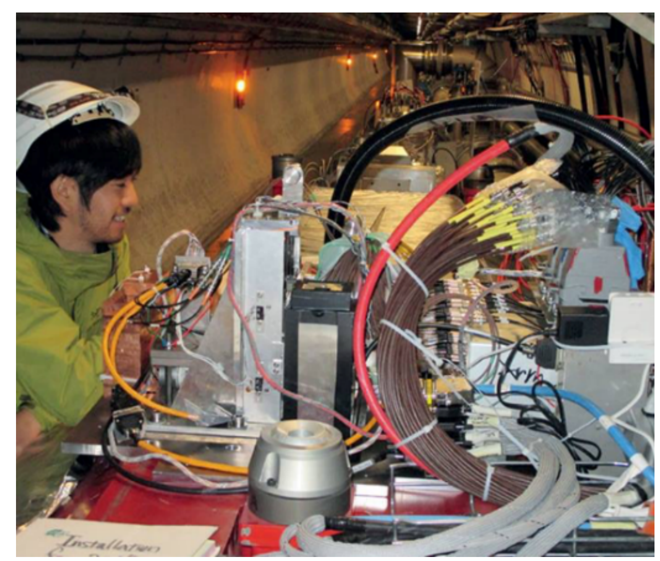
Aug 2007
SPS beam test

Jan 2008
Installation
Sep
1st LHC beam

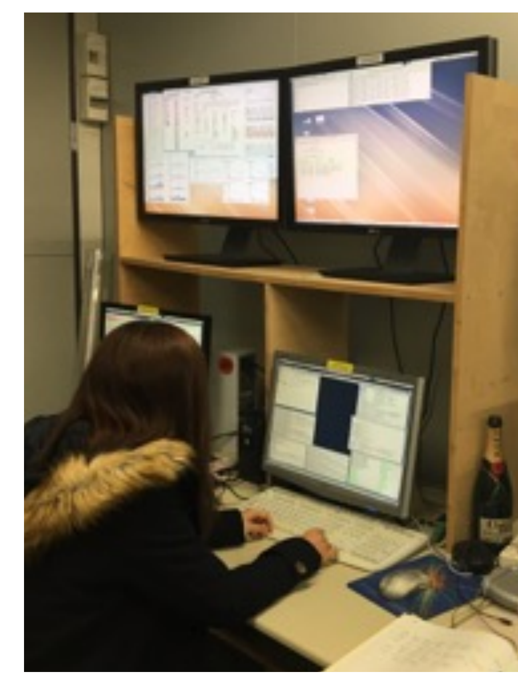


Dec 2009 - Jul 2010
0.9TeV & 7TeV p-p
(detector removal)

Dec 2012- Feb 2013
5TeV/n p-Pb, 2.76TeV p-p
Arm2 only
(detector removal and <u>upgrade</u>)



May-June 2015
13 TeV dedicated p-p
(detector removal)

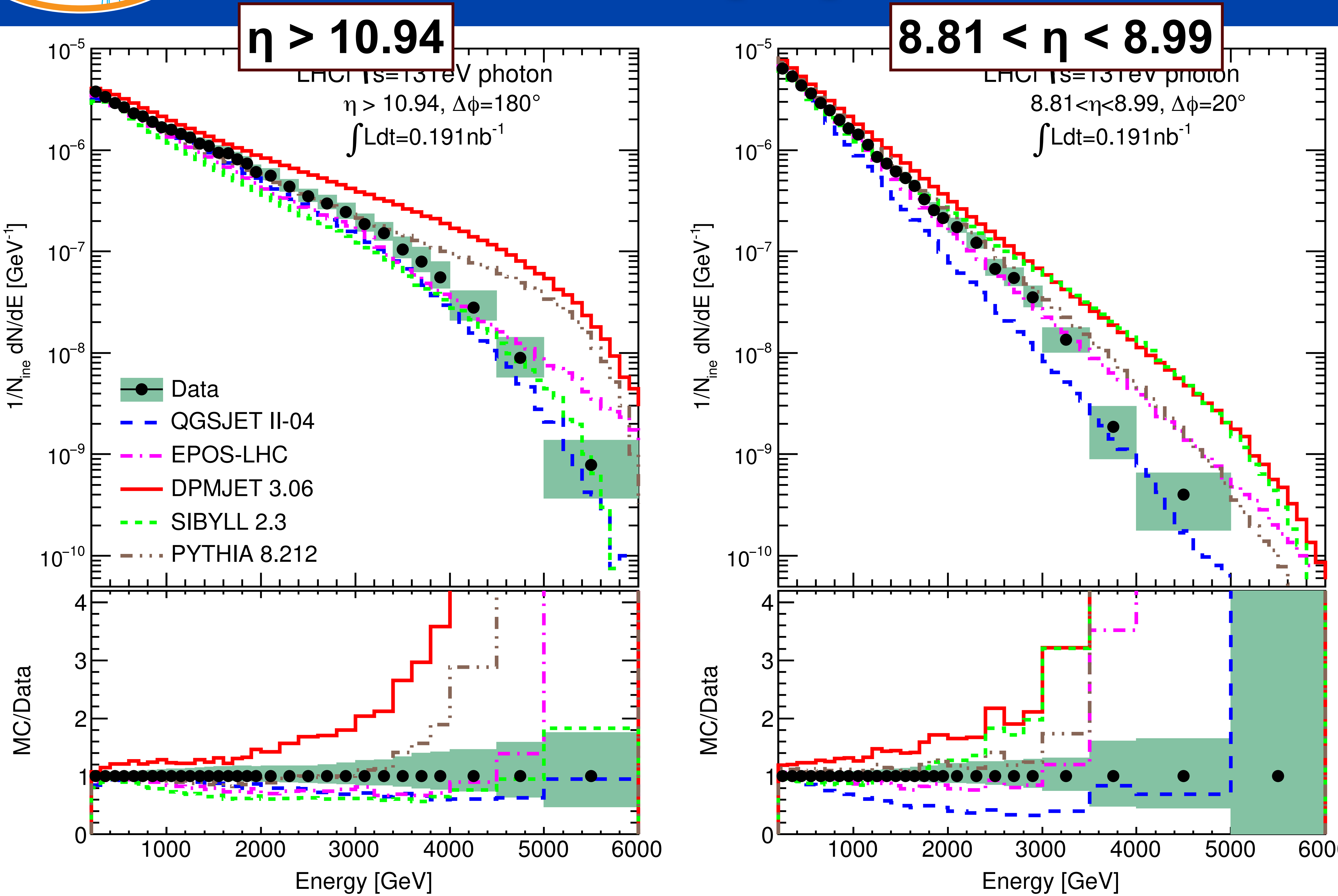


Nov. 2016
5TeV/n & 8TeV/n p+Pb
Arm2 only
(detector removal)

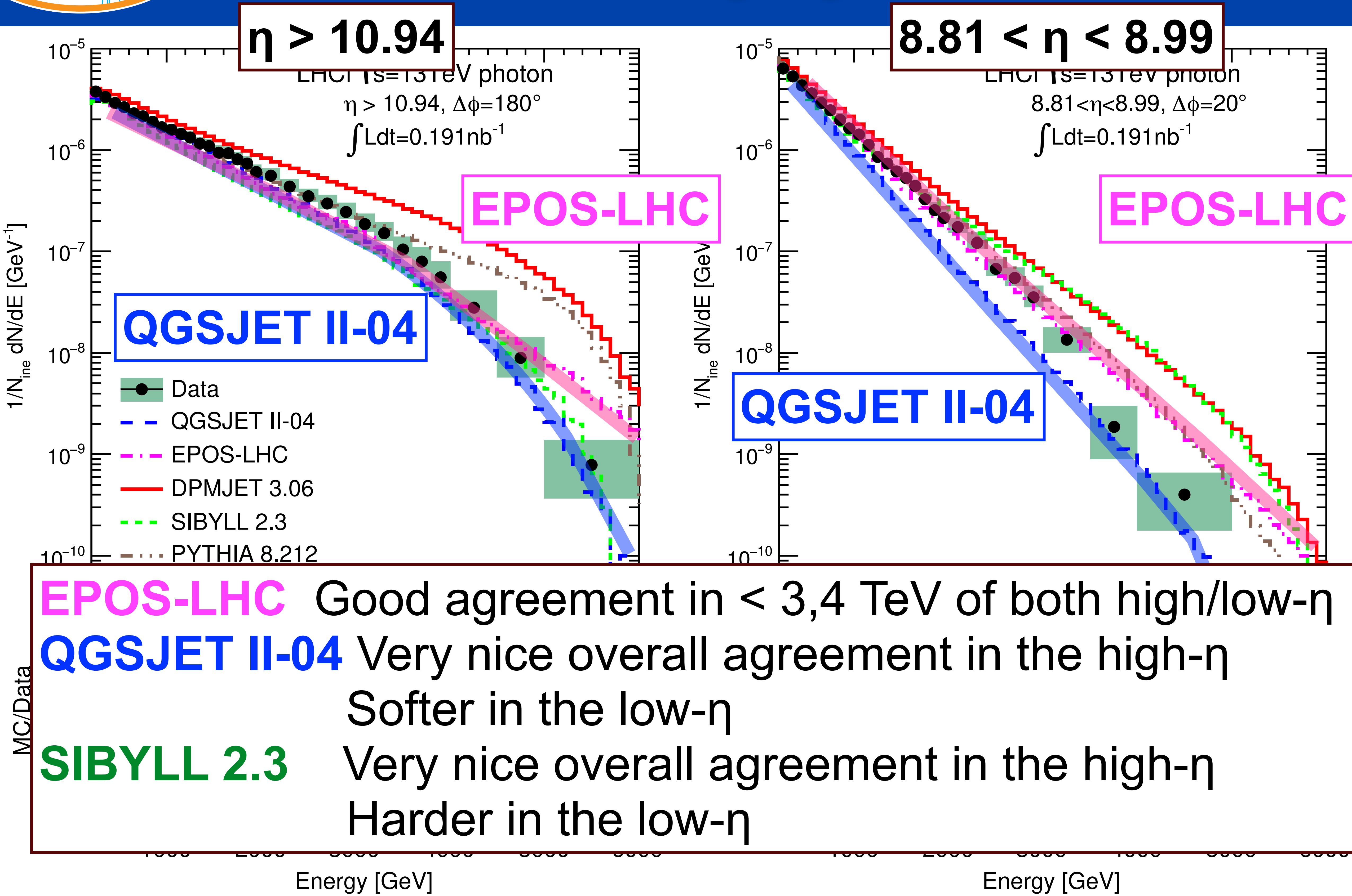
LHCf operations and results

<table>
<tr><th>Run</th><th>E_{lab} (eV)</th><th>Photon</th><th>Neutron</th><th colspan="2">π^0</th></tr>
<tr><td>p-p $\sqrt{s}$=0.9TeV
(2009/2010)</td><td>4.3×10^{14}</td><td>PLB 715, 298
(2012)</td><td></td><td colspan="2">-</td></tr>
<tr><td>p-p $\sqrt{s}$=2.76TeV
(2013)</td><td>4.1×10^{15}</td><td></td><td></td><td>PRC 86, 065209
(2014)</td><td rowspan="2">PRD 94
032007
(2016)</td></tr>
<tr><td>p-p $\sqrt{s}$=7TeV
(2010)</td><td>2.6×10^{16}</td><td>PLB 703, 128
(2011)</td><td>PLB 750
360 (2015)</td><td>PRD 86, 092001
(2012)</td></tr>
<tr><td>p-p $\sqrt{s}$=13TeV
(2015)</td><td>9.0×10^{16}</td><td>PLB 780, 233
(2018)</td><td>JHEP, 2018, 73
(2018)</td><td colspan="2">on-going</td></tr>
<tr><td>p-Pb $\sqrt{s_{NN}}$=5TeV
(2013,2016)</td><td>1.4×10^{16}</td><td></td><td></td><td>PRC 86, 065209
(2014)</td><td></td></tr>
<tr><td>p-Pb $\sqrt{s_{NN}}$=8TeV
(2016)</td><td>3.6×10^{16}</td><td>Preliminary</td><td></td><td colspan="2"></td></tr>
<tr><td>RHICf
p-p $\sqrt{s}$=510GeV
(2017)</td><td>1.4×10^{14}</td><td colspan="4">on-going</td></tr>
</table>

Photon at p-p, 13TeV



Photon at p-p, 13TeV



EPOS-LHC Good agreement in < 3,4 TeV of both high/low-η

QGSJET II-04 Very nice overall agreement in the high-η
Softer in the low-η

SIBYLL 2.3 Very nice overall agreement in the high-η
Harder in the low-η

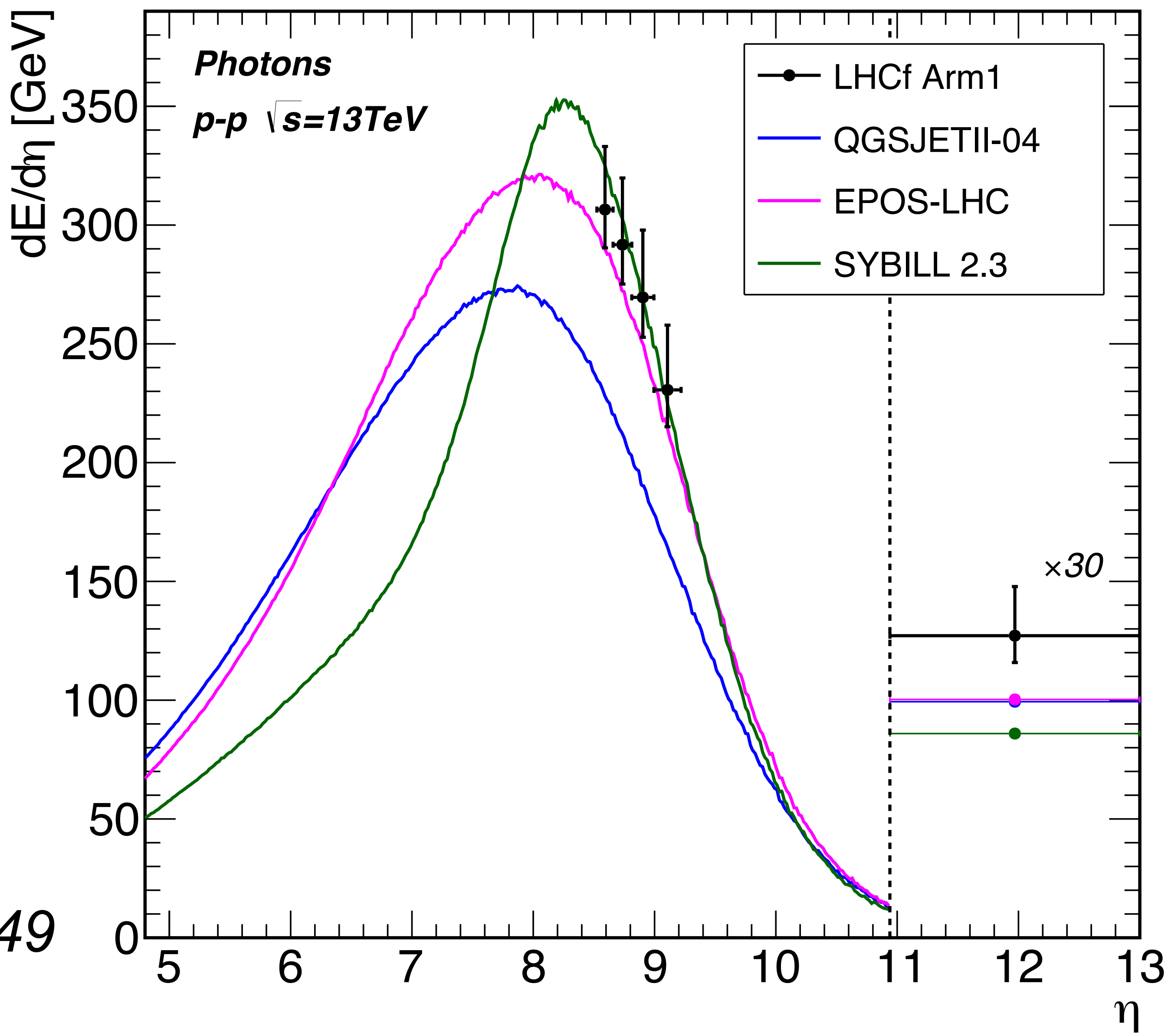
Photon Energy Flow

<u>*Energy Flow Calculation:*</u>

$$\frac{dE}{d\eta} = C_{thr}\frac{1}{\Delta\eta}\sum_{E_j > 200GeV} E_j F(E_j)$$

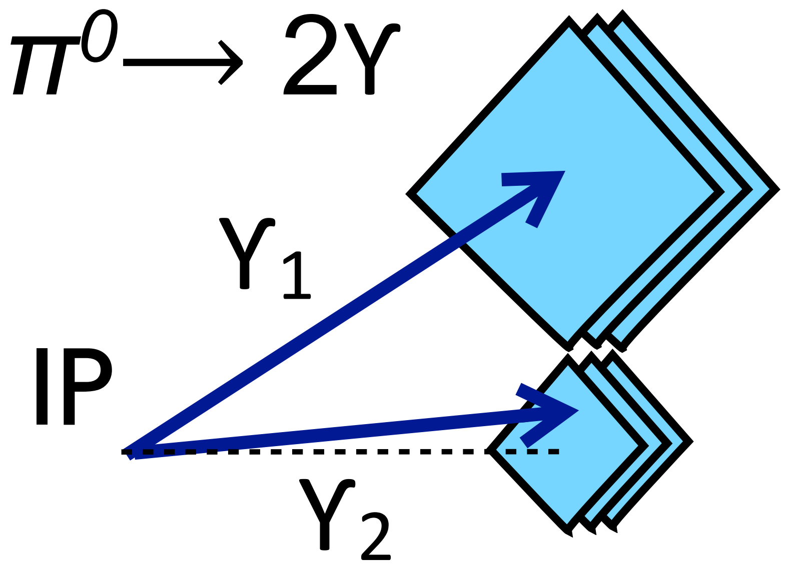
F(Ej) : Measured differential cross-section
Δη : The pseudo-rapidity range
C_{thr} : Correction factor for the threshold 200 GeV→ 0 GeV.

Ref: Y. Makino CERN-THESIS-2017-049

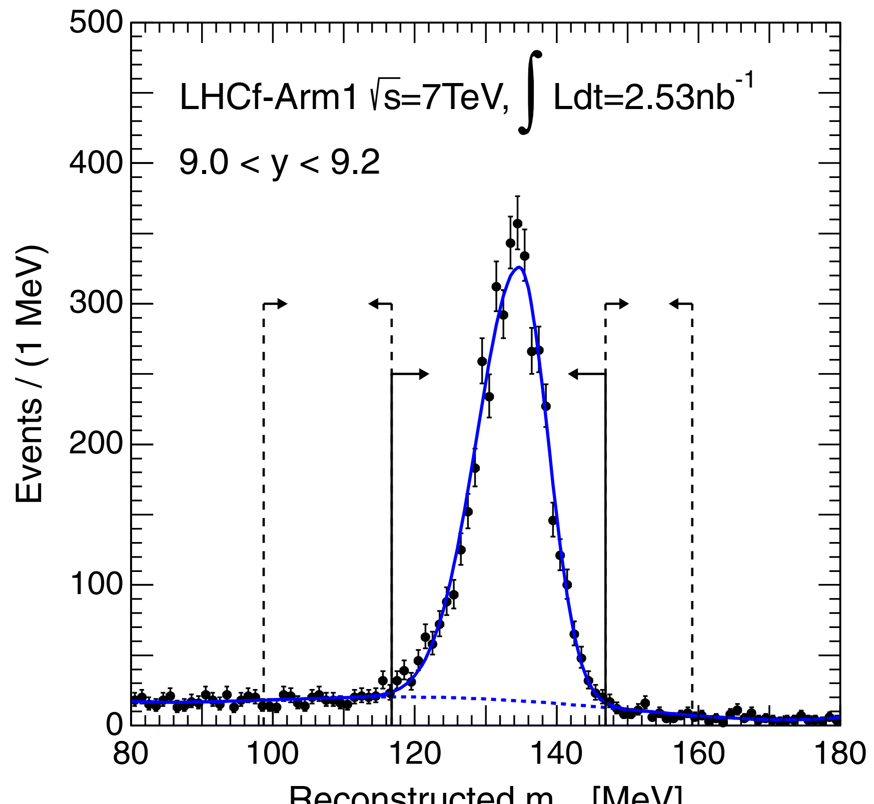


EPOS-LHC, SIBYLL2.3 Good agreement
QGSJET II-04 ~ 30% lower than data

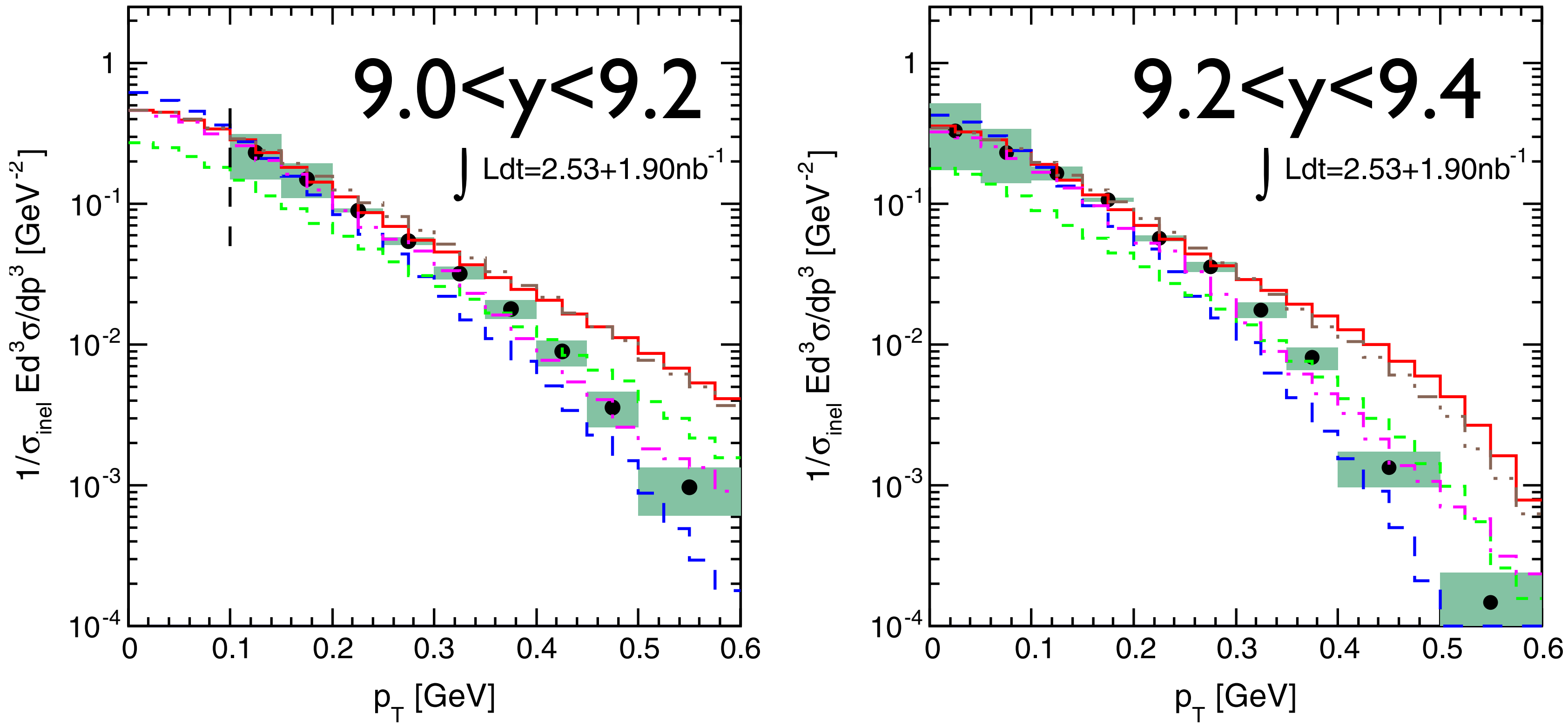
Neutral Pions at 7TeV p-p



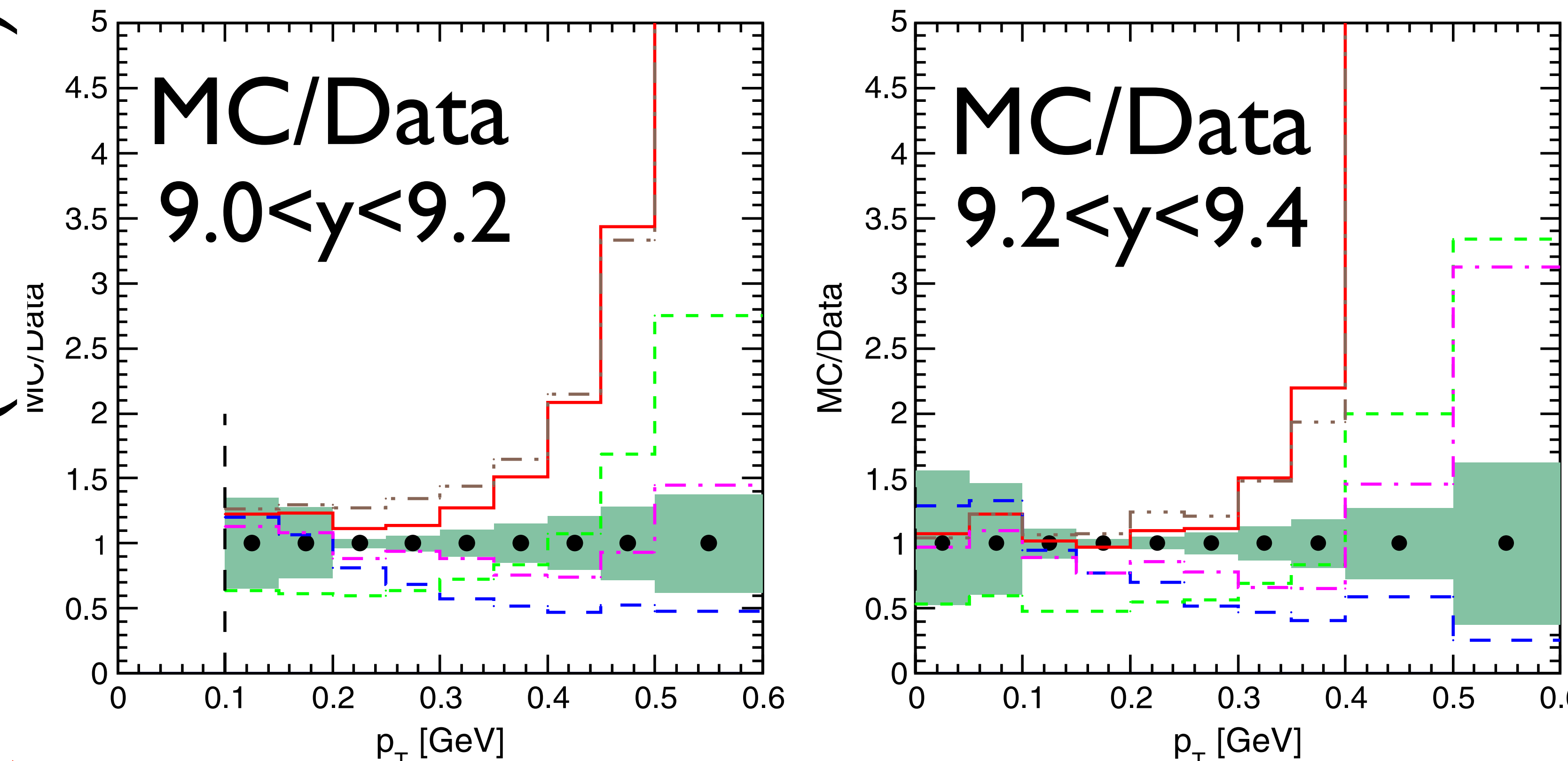
Reconstructed Mass



P_T spectra



Ratio (MC/Data)



→ Similar as Photon results

Neutron, p-p $\sqrt{s}$=13TeV

Motivation

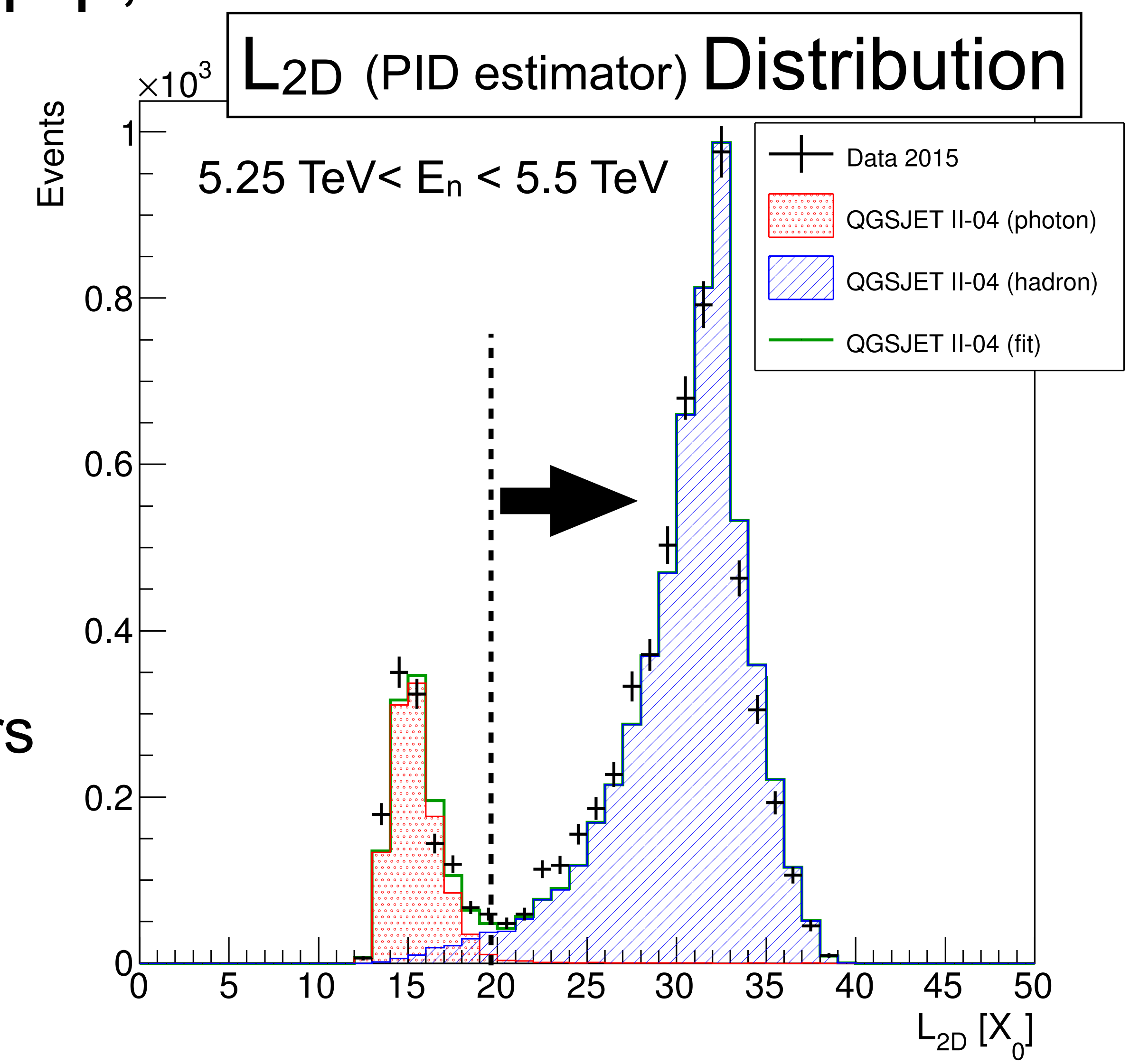
- Inelasticity measurement k_{inela}
  $k_{inela} = 1 - E_{leading}/E_{beam}$
- Large discrepancies between data and model prediction were found in the measurement at p-p, $\sqrt{s}$=7TeV

Data

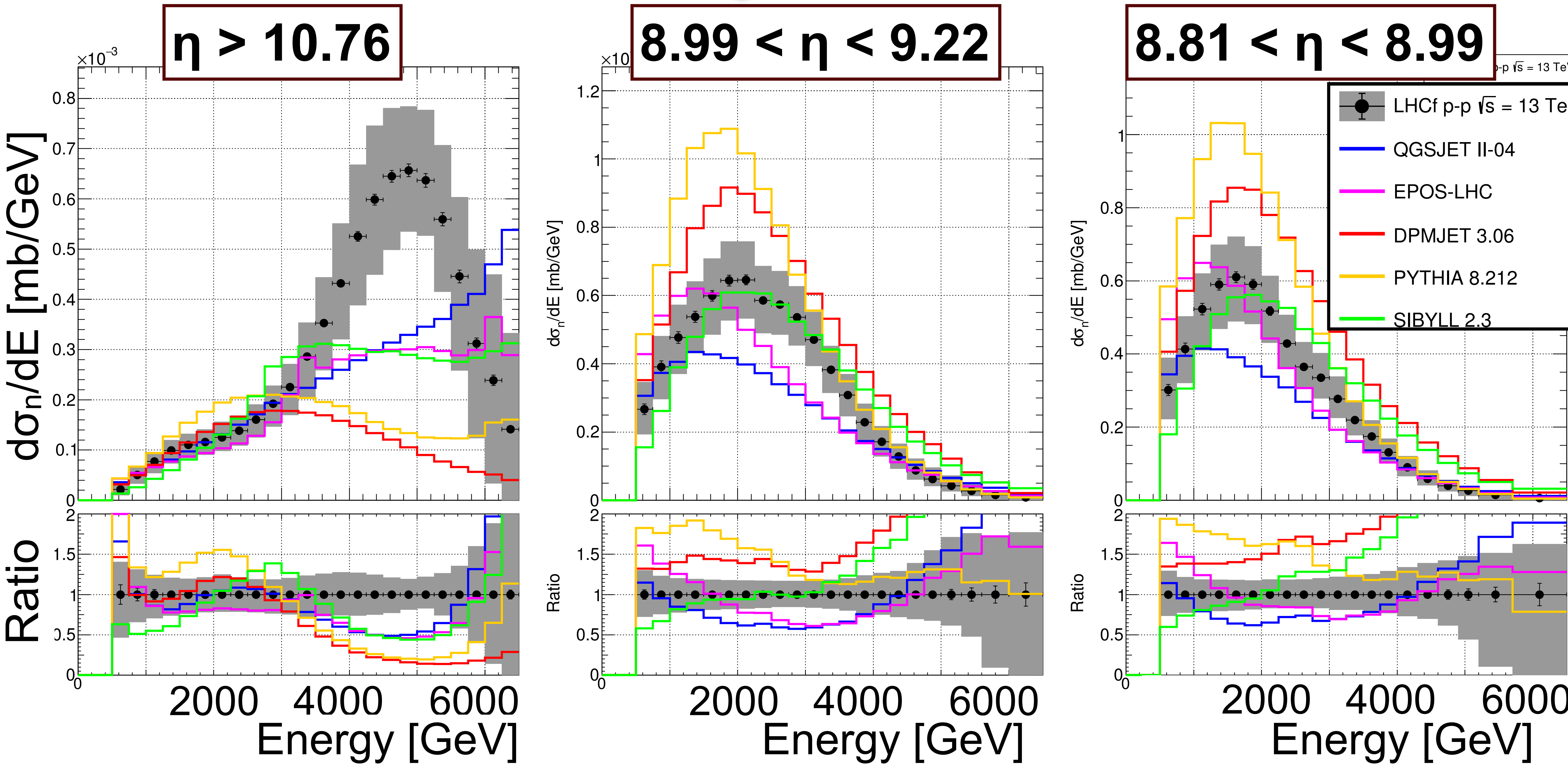
- 3 hour operation in June 2015
- Low pile-up, μ~0.01

Analysis

- Particle Identification
  EM shower → develop in shallow layers
  Hadronic showers → develop in deep layers
- Energy resolution of 40%
- Contamination of Δ^0, K^0



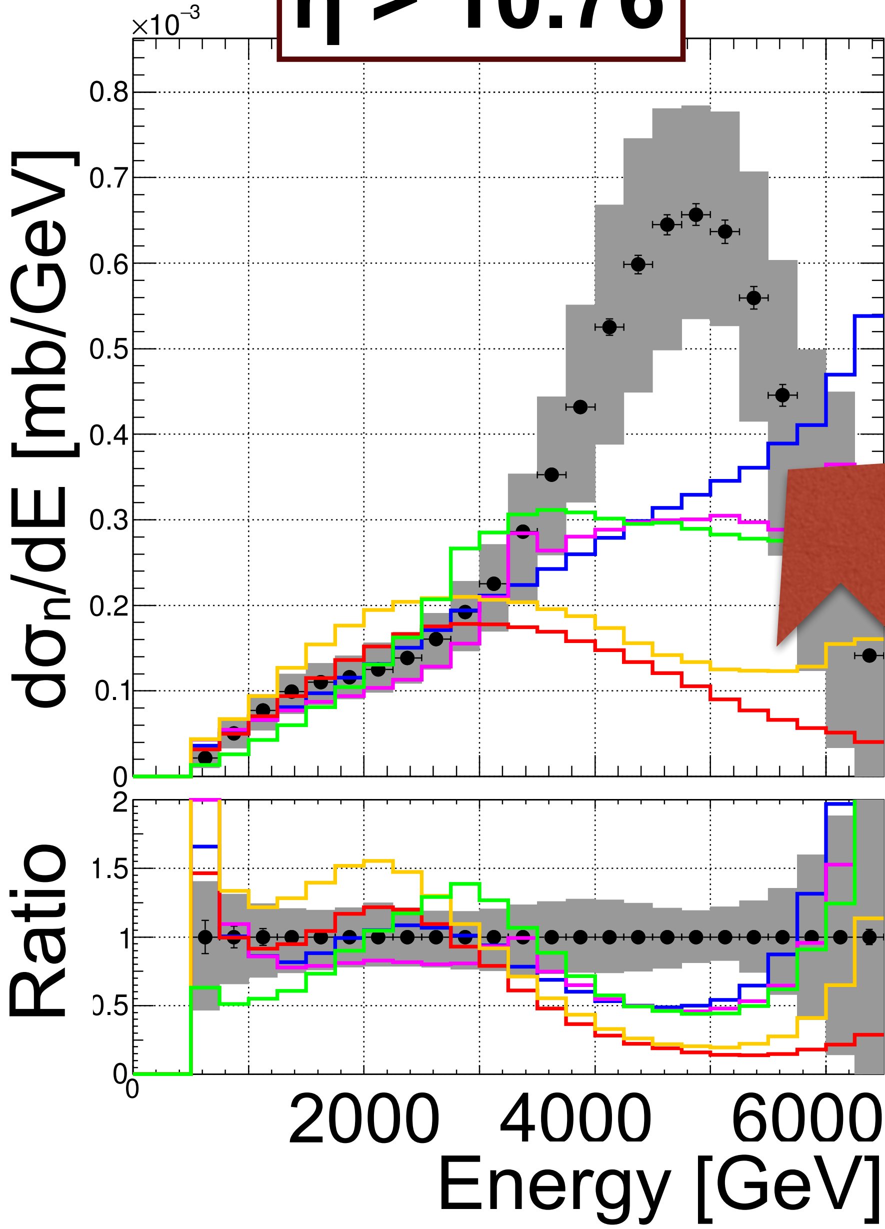
Neutron, p-p √s=13TeV Unfolded Spectra

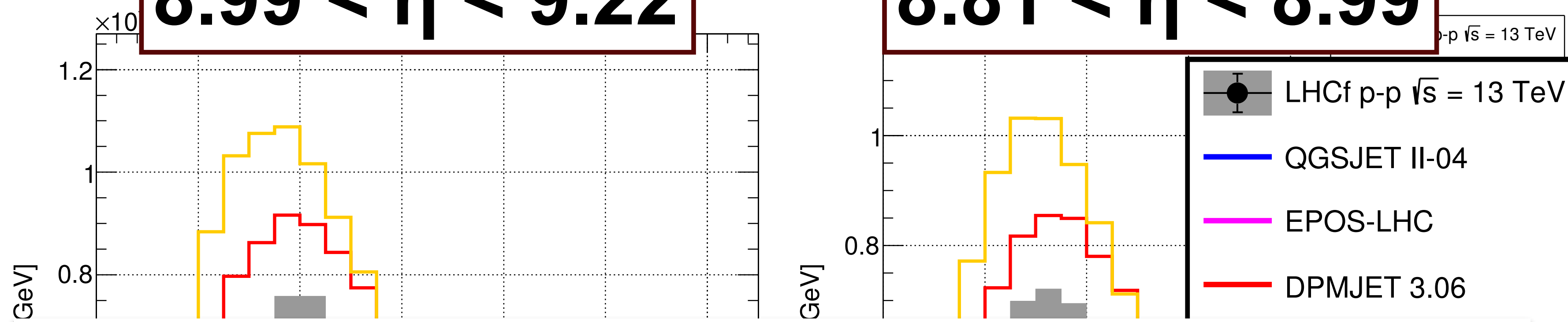


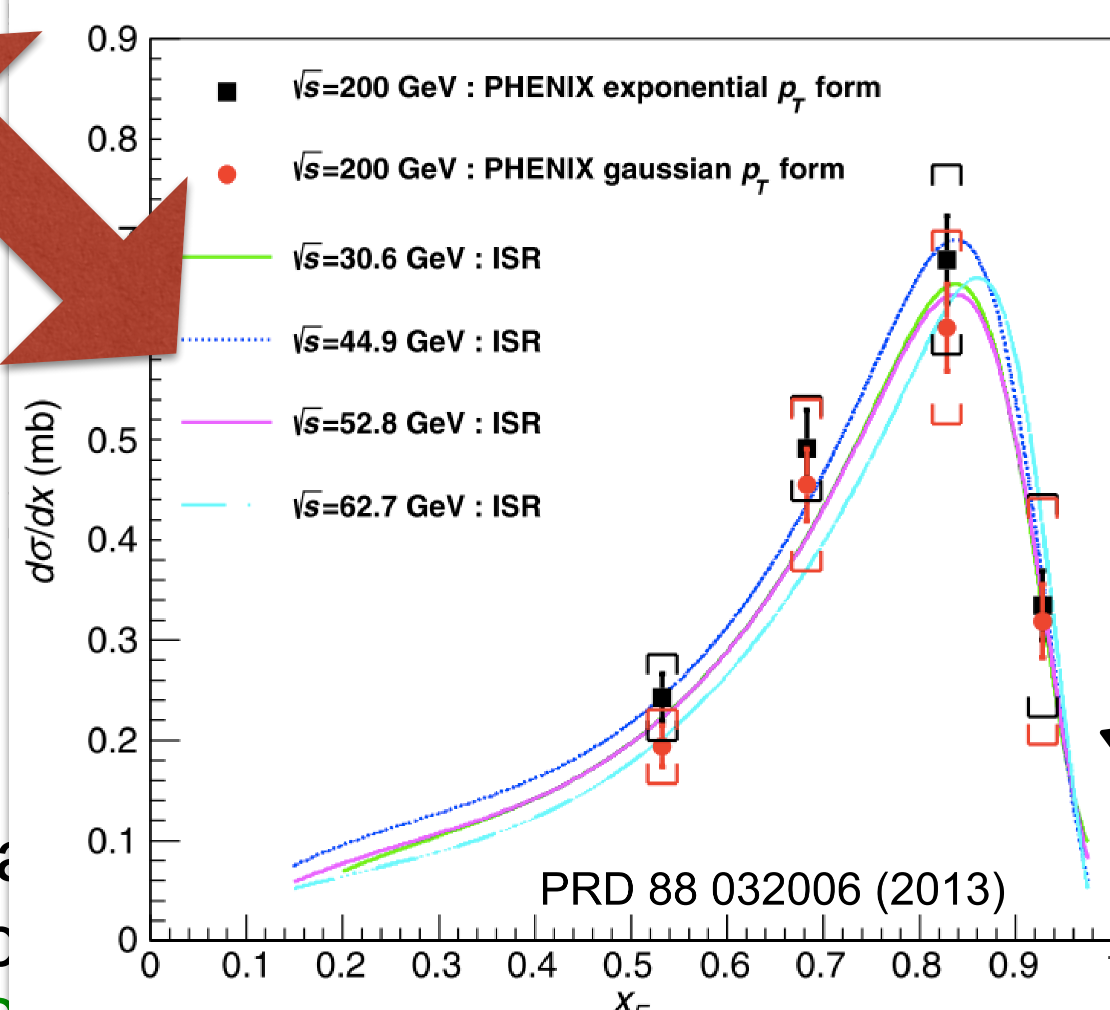
- In η > 10.76, data shows a strong increasing of neutron production in the high energy region. This behavior is not predicted by all models.
- EPOS-LHC and SIBYLL 2.3 have the best agreement in 8.99 < η < 9.22, 8.81 < η < 8.99, respectively.

Neutron, p-p $\sqrt{s}$=13TeV Unfolded Spectra

η > 10.76 **8.99 < η < 9.22** **8.81 < η < 8.99**







Forward neutrons @ RHIC, ISR

The peaked spectra are explained by a one-pion exchange model.

Detailed comparison is needed

$p_T < 0.11\ X_F$

⇳

$p_T < 0.28\ X_F$

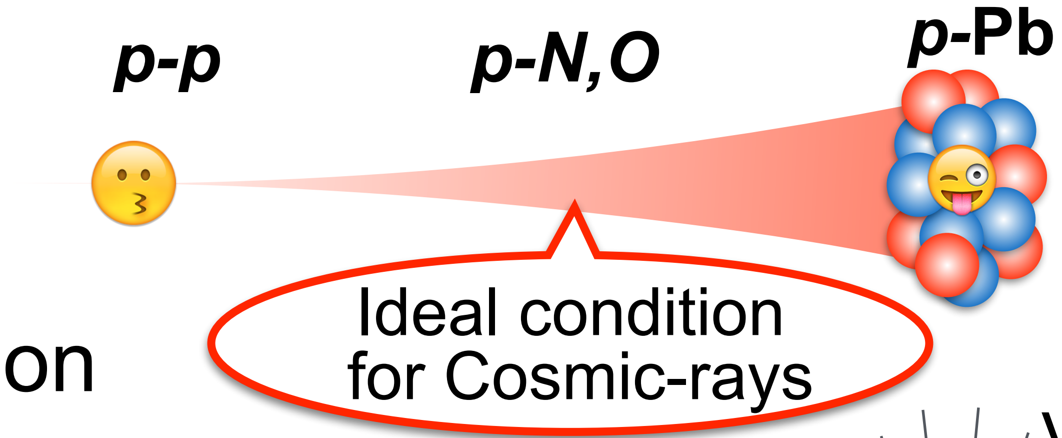
@ η>10.76, 13TeV

- In η > 10.76, data shows a high energy region. This b
- EPOS-LHC and SIBYLL 2 8.81 < η < 8.99, respectively.

Photon, p-Pb $\sqrt{s_{NN}}$=8TeV

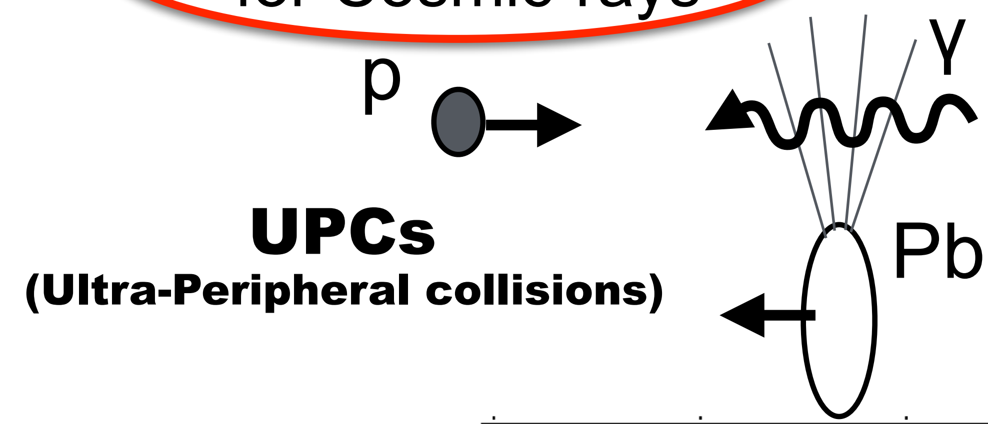
Motivation

- Measurement of the nuclear effect
  CR interaction (p-N,O) ≠ p-p
- Large suppression of forward π^0 production was measured at p-Pb, $\sqrt{s_{NN}}$=5TeV



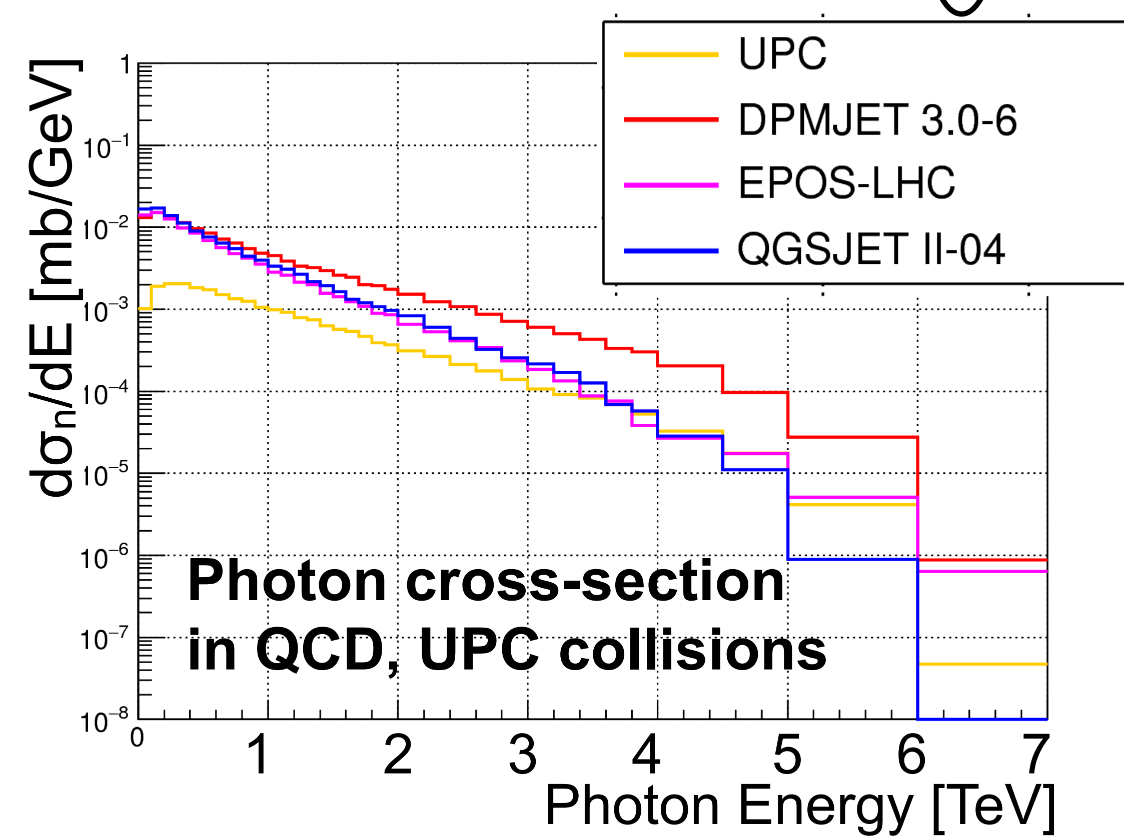
Data

- 2 hour operation in November 2016
- Low pile-up, μ~0.01



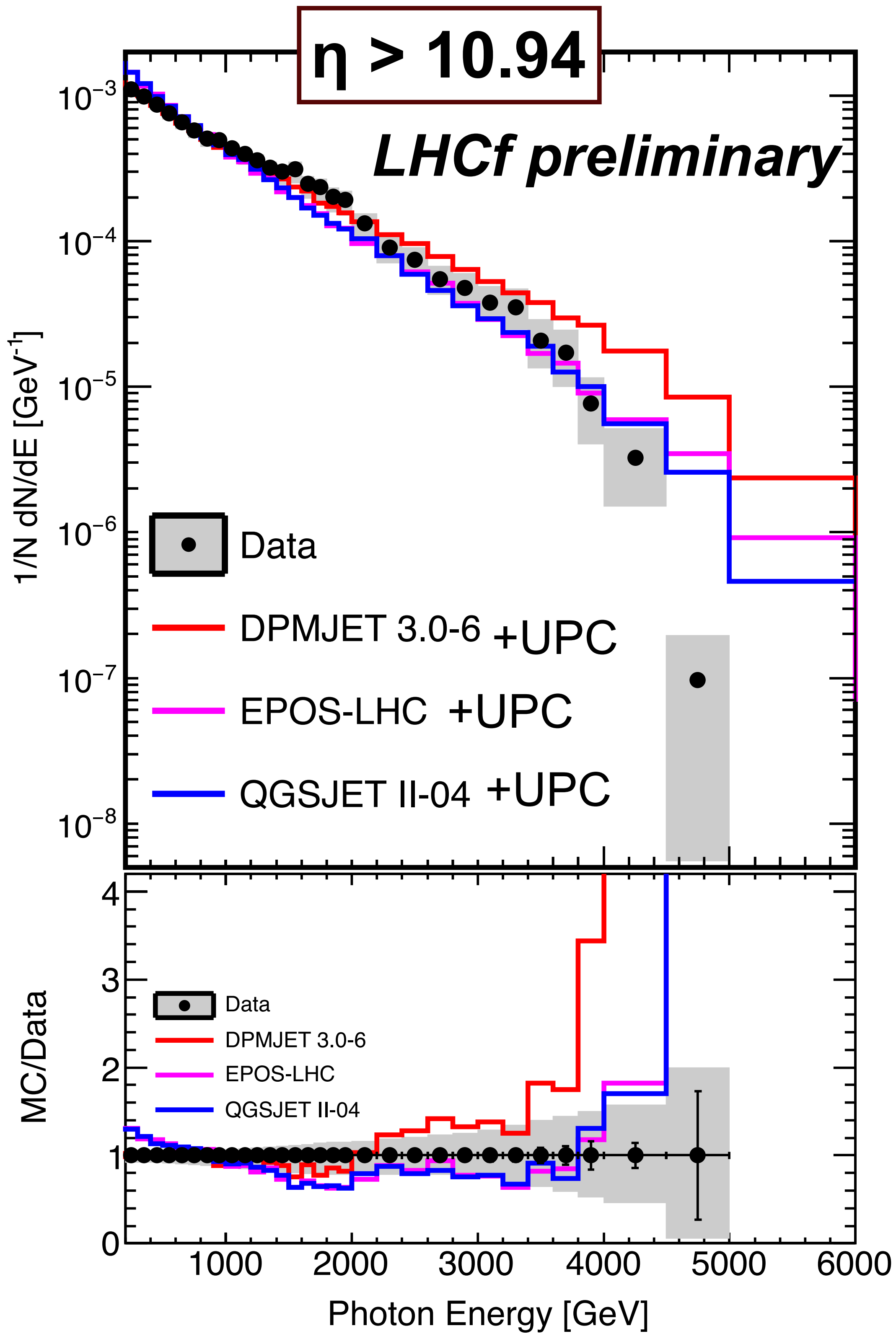
Analysis

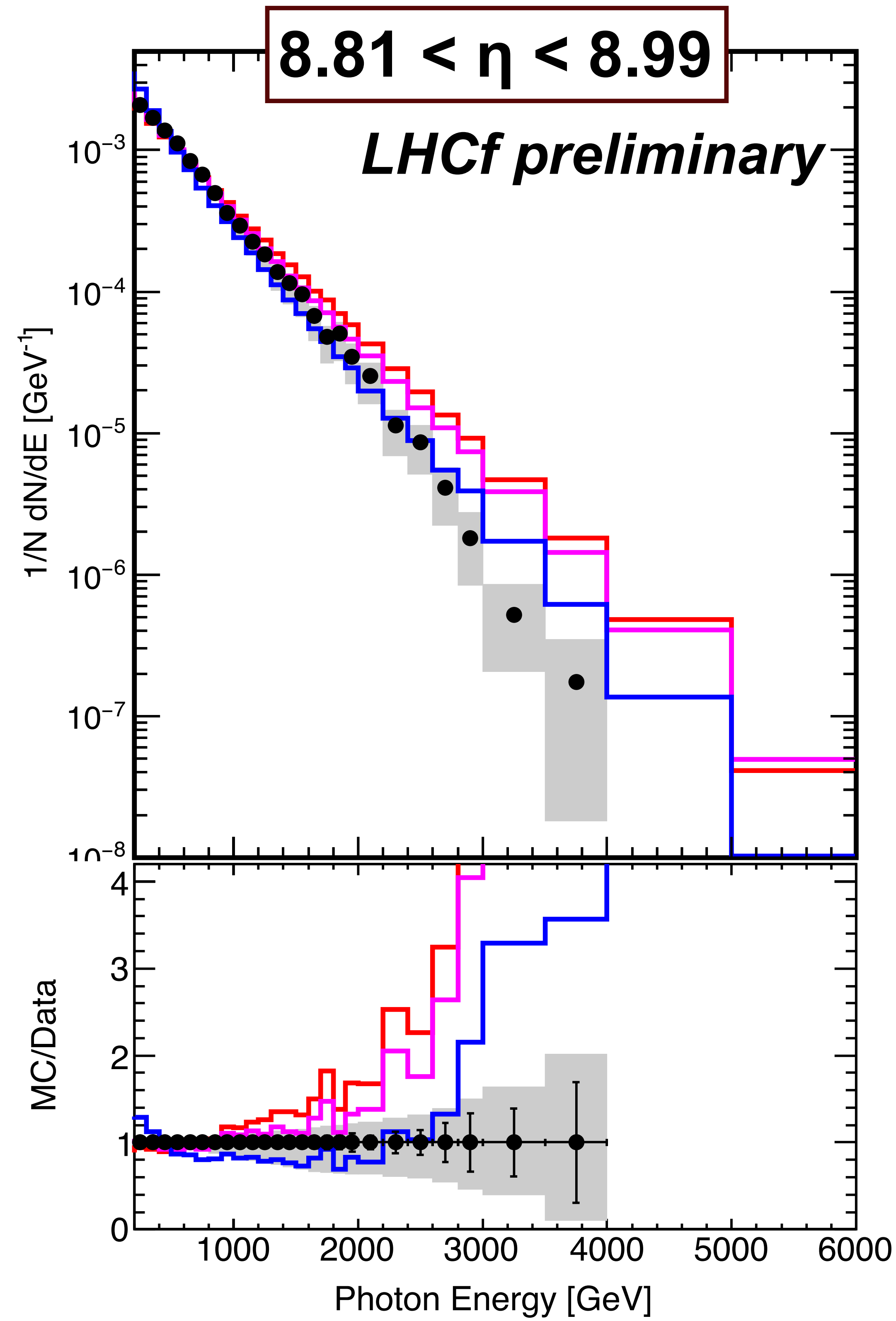
- Use the well-developed method for photon analysis at p-p,13TeV
- Contribution of UPC collisions
  20 - 50 % of total photon events
  Estimated by the STARLIGHT simulator



Photon, p-Pb $\sqrt{s_{NN}}$=8TeV

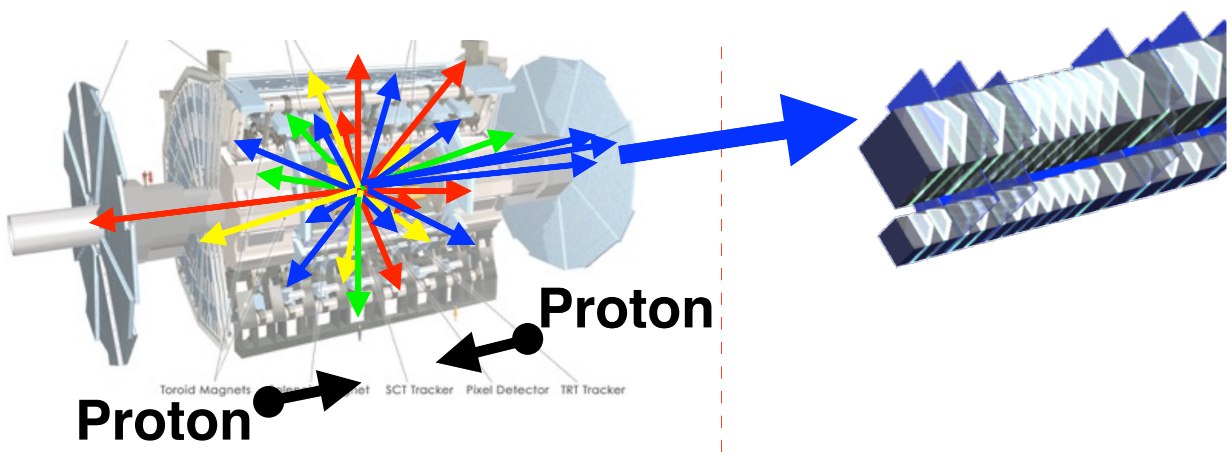
Normalized by the number of entries. →





What's next ?

- Complete the analysis for inclusive γ,π^0,n.
- Additionally,
  - Process-based measurement
    For understanding the sources of discrepancy between data and models
    ⇒ **LHCf+ATLAS joint analysis**



First target:
Measurement of contribution of diffractive processes to the forward particle production

  - Collision-energy dependence (Feynman Scaling)
    For improving the predictive power in > E_{LHC}
    ⇒ **RHIC forward (RHICf) at pp, $\sqrt{s}$=0.5TeV**

RHIC 10^{14}eV	⟷ $\times10^3$	LHC 10^{17}eV	⇢ $\times10^3$	UHECR $\sim10^{20}$eV

Diffractive processes

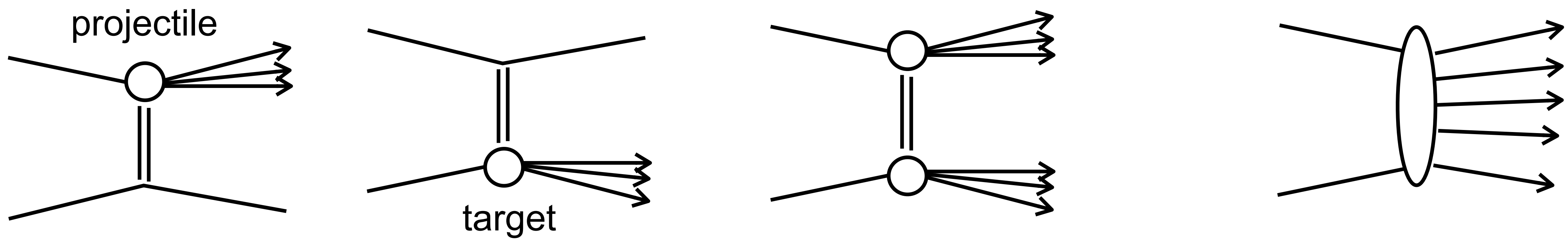
Inelastic processes

Diffractive (20%)

Non-diffractive (80%)

Single diffractive

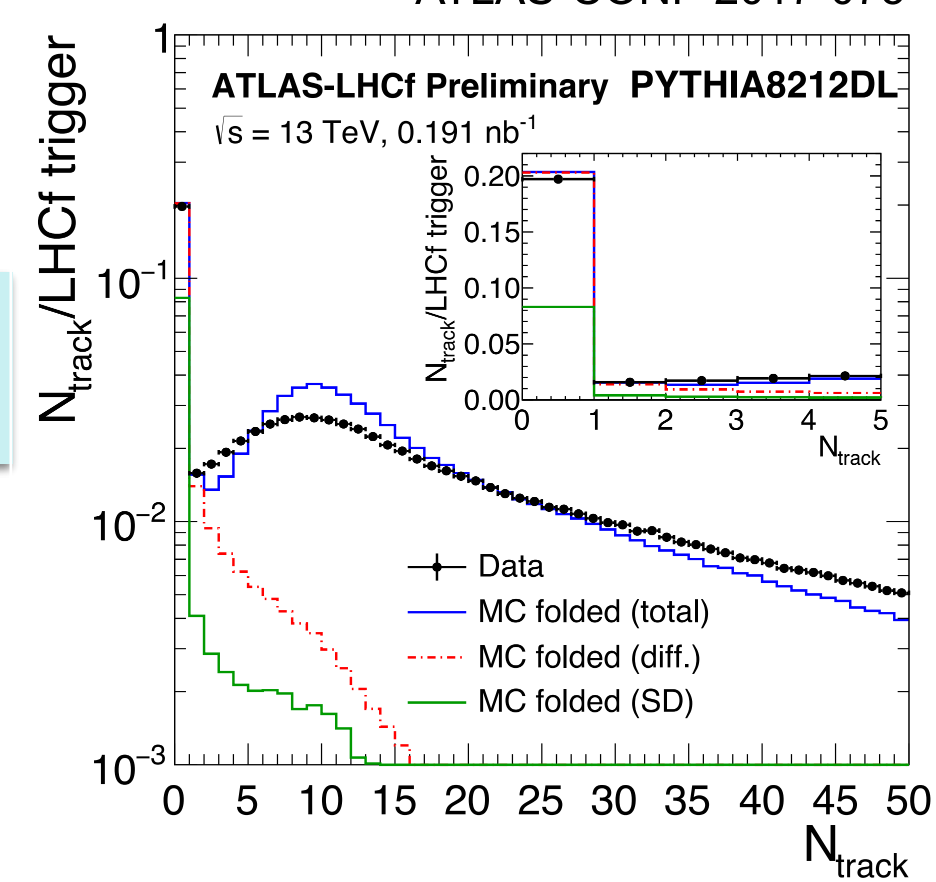
Double diffractive



K_{el}=0.55 K_{el}=0.99 K_{el}=0.54 K_{el}=0.45

K_{el} : Elasticity @ pp,√s=13TeV

ATLAS-CONF-2017-075



Identification of diffractive events by ATLAS

Method

- Event selection by N_{tracks}=0 ⇔ Large rapidity gap $\Delta\eta > 5$

N_{tracks}: the number of tracks detected **by ATLAS inner trackers** (|η|<2.5, p_T > 100 MeV)

→ Selecting pure samples of proton dissociations.

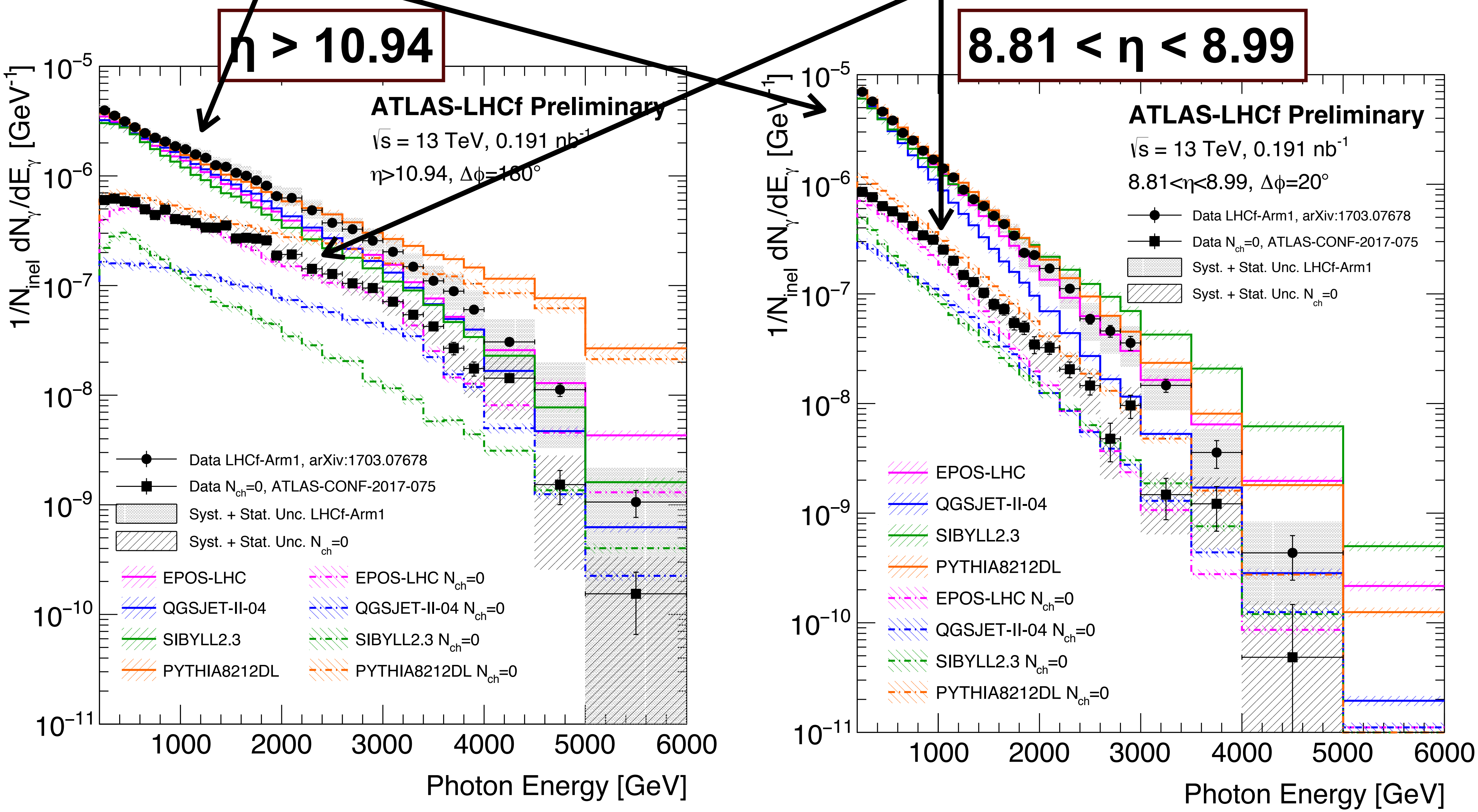
→ Sensitive to only low-mass dissociations $M_X \lesssim 50$ GeV

Measurement of contributions of diffractive processes to forward photon spectra in *pp* collisions at √s = 13 TeV

Preliminary result of the measurement for forward photons is published in a conference-note; ATLAS-CONF-2017-075

Inclusive photon spectra

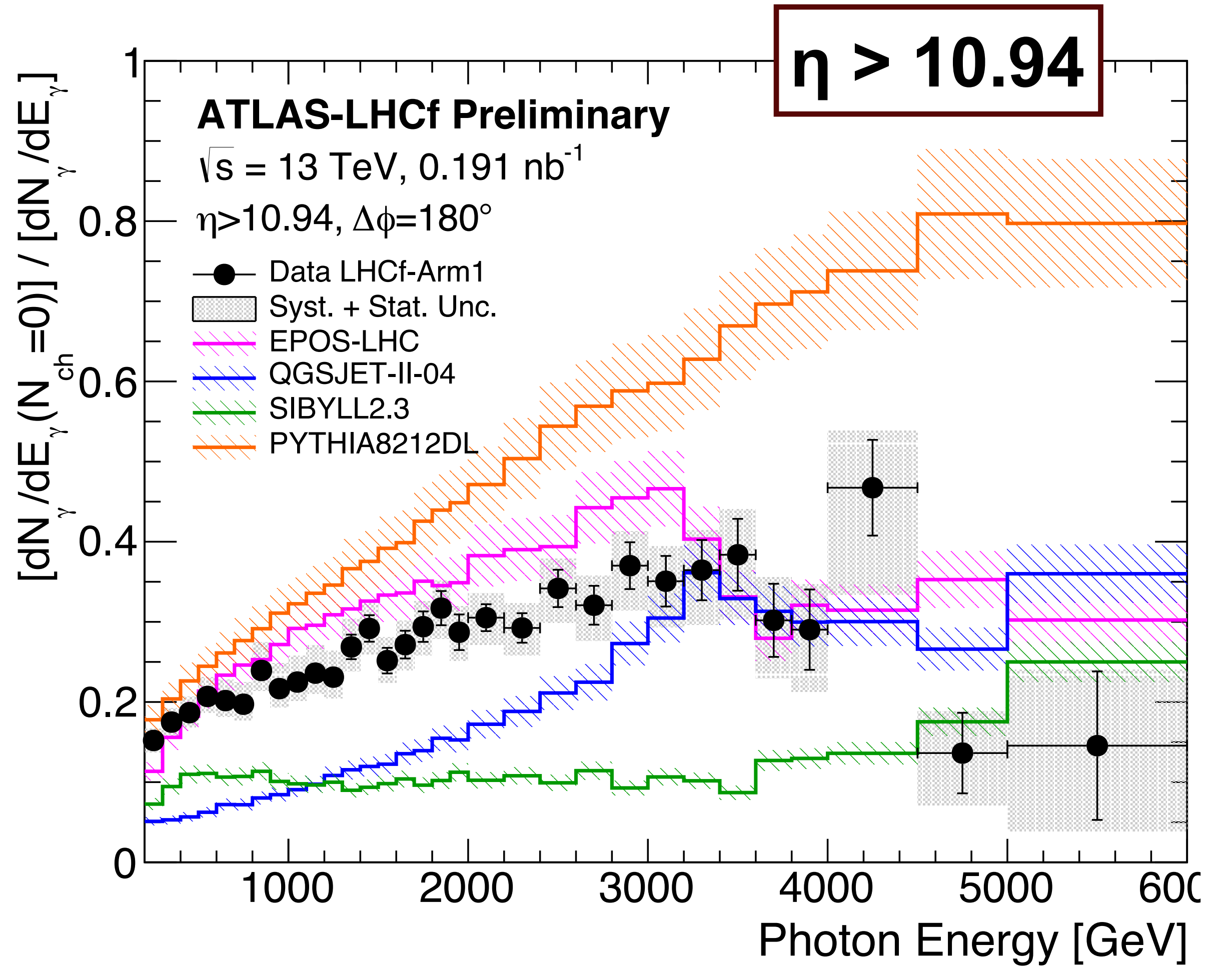
Photon spectra w/ N_{ch} = 0 selection

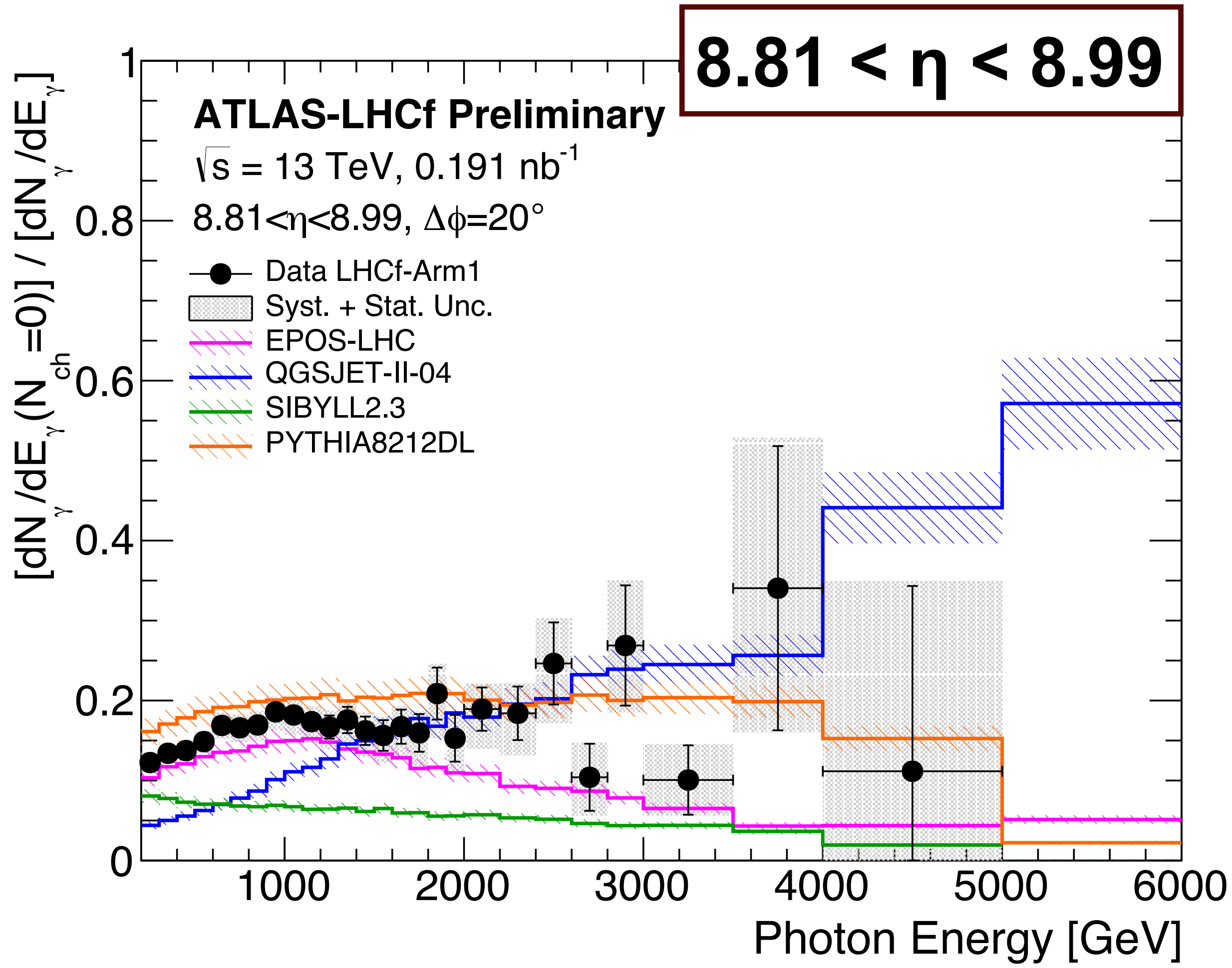


Measurement of contributions of diffractive processes to forward photon spectra in *pp* collisions at √s = 13 TeV

Ratio ($N_{ch=0}$/Inclusive)

ATLAS-CONF-2017-075

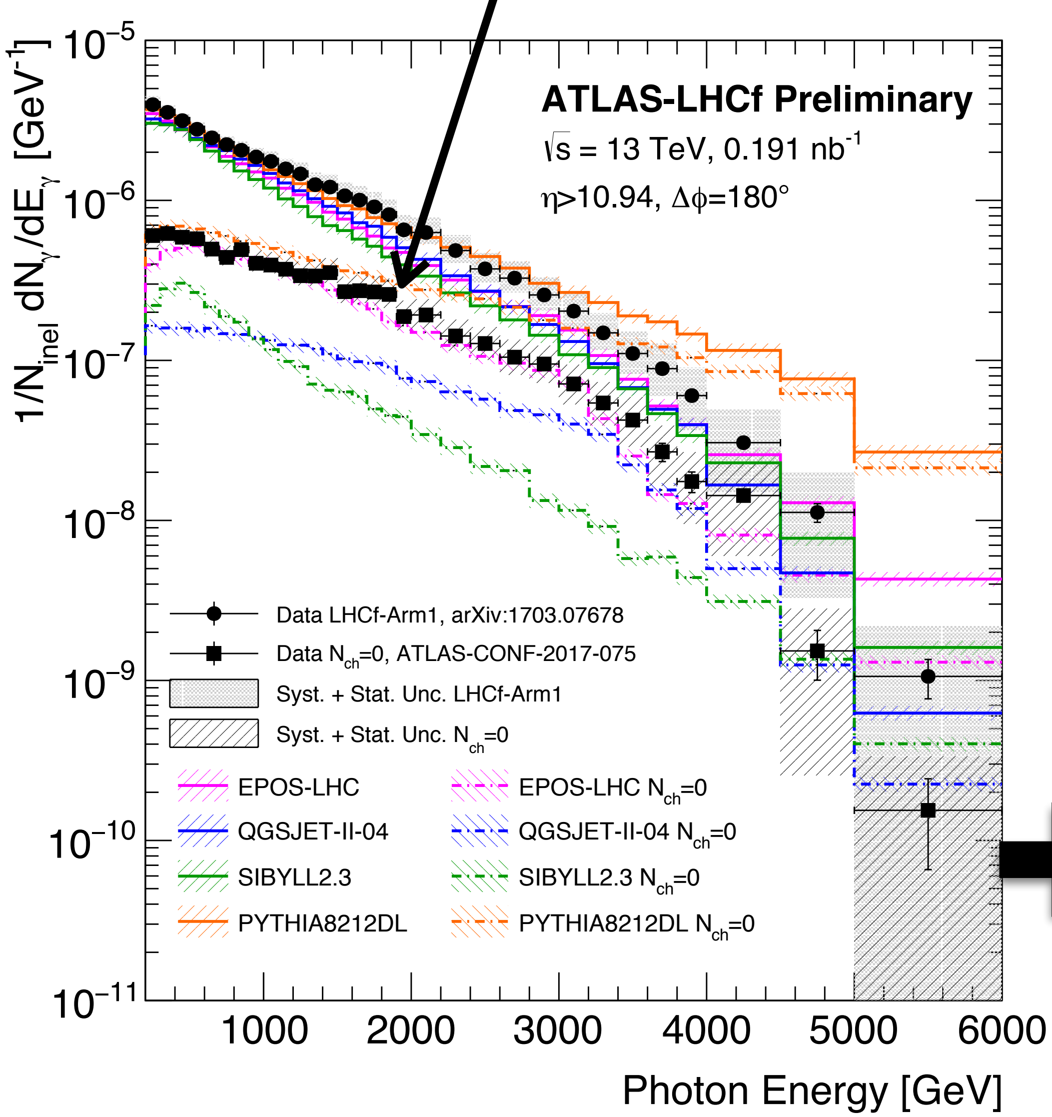




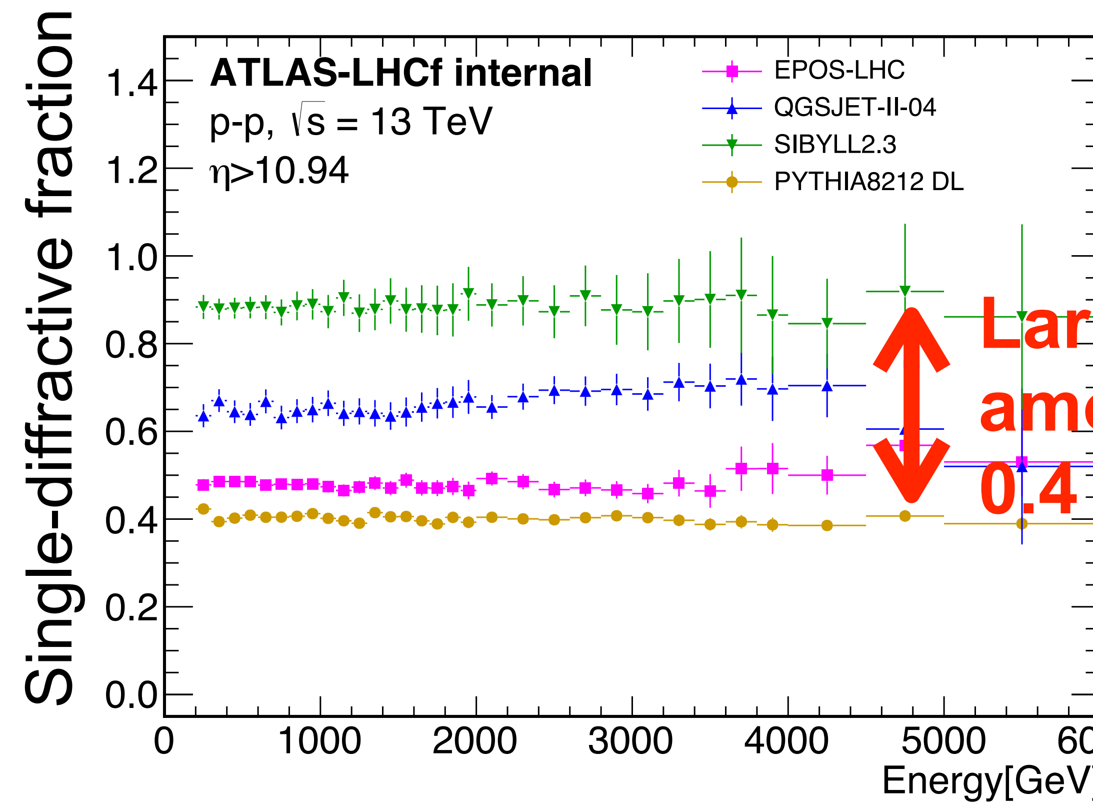
- At η>10.94, the ratio of data increased from 0.15 to 0.4. with increasing of the photon energy up to 4TeV.
- PYTHIA8212DL predicts higher fraction at higher energies.
- SIBYLL2.3 show small fraction compare with data at η>10.94.
- At 8.81 < η < 8.99, the ratio of data keep almost constant as 0.17.
- EPOS-LHC and PYTHIA8212DL show good agreement with data at 8.81 < η < 8.99.

Update plan of the joint analysis

Diffractive (=Single+Double)

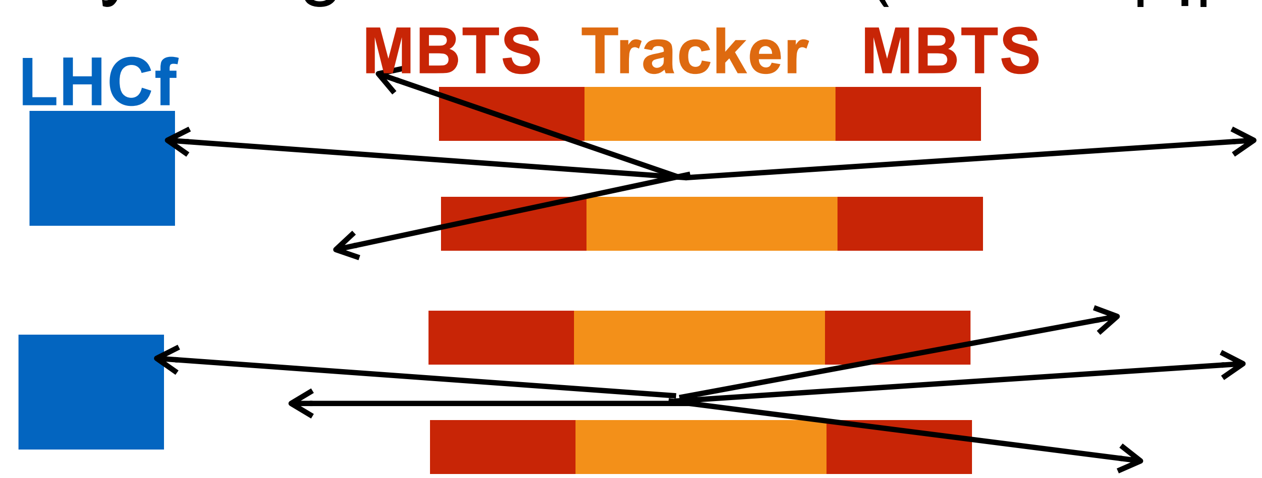


How much fraction of single diffractive in the selected events ?



Large difference among models 0.4 - 0.9

Going to measure the fraction by using ATLAS-**MBTS** (2.08 < |η| < 3.86)



RHICf experiment

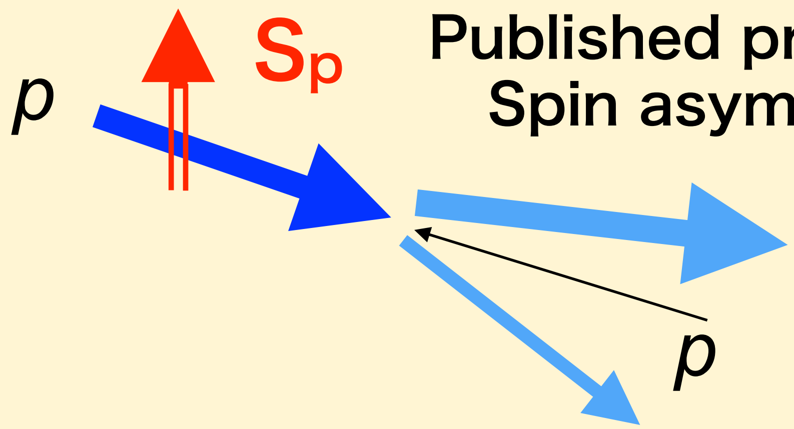
RHIC at BNL

- **p+p √s = 510 GeV**
  (polarized beam)
- Test of energy scaling with the wide p_T range.
  (The X_F-pT coverage is almost same as LHCf @ p+p √s=7TeV)
- The operation was successfully completed in June 2017
- Common operation with STAR

Arm1 detector in RHIC tunnel

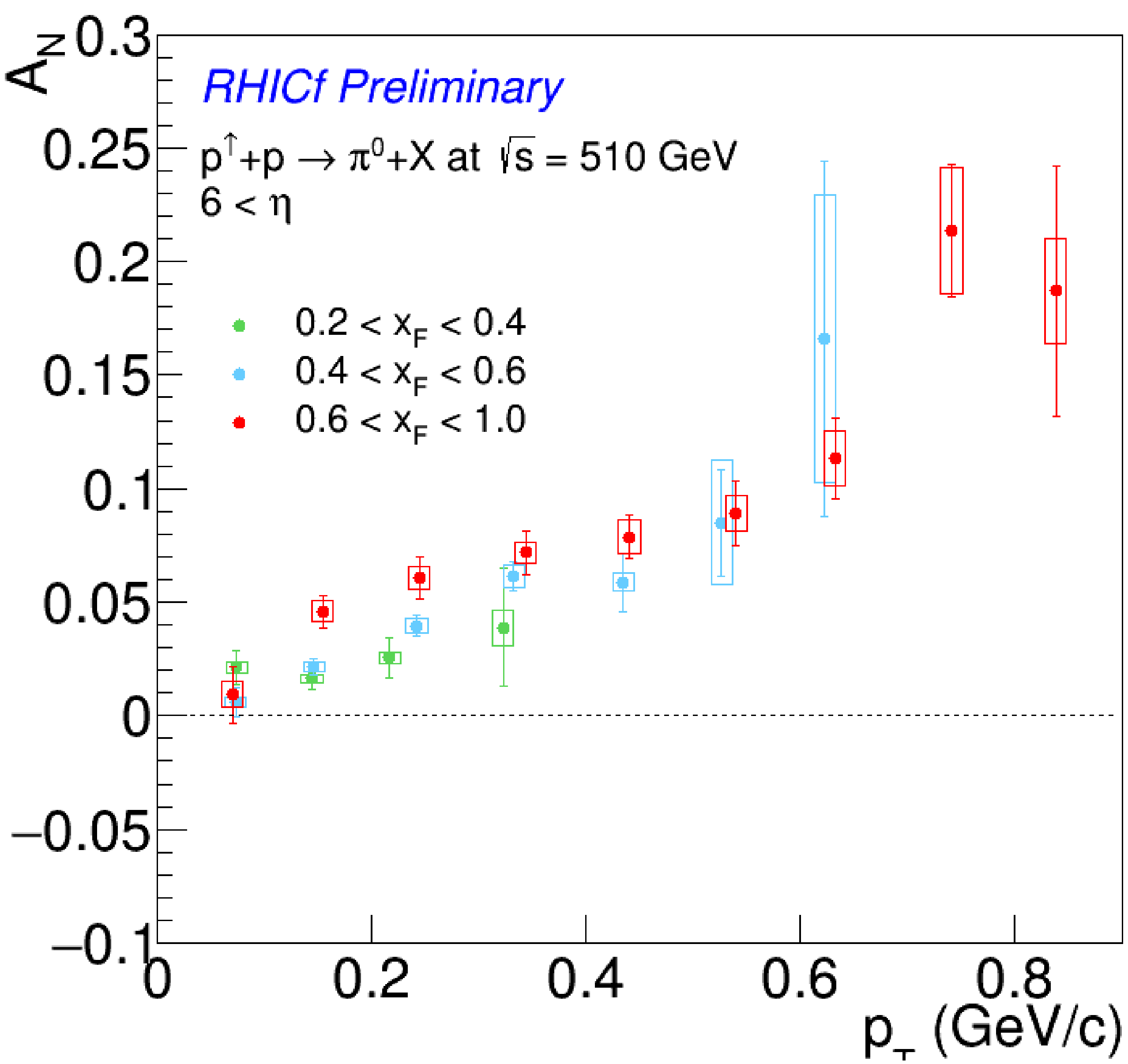
Photo in the operation room

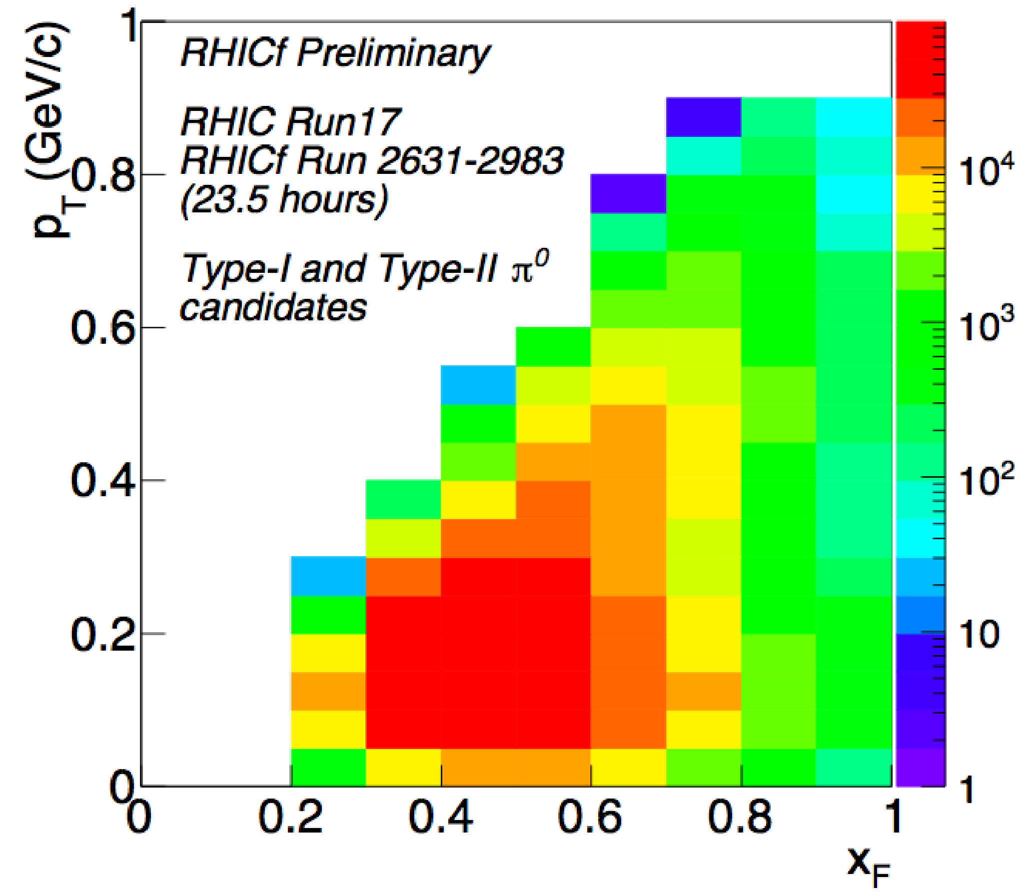
First physics result from RHICf



Published preliminary results of Spin asymmetry (A_N) for π^0

$$A_N = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$

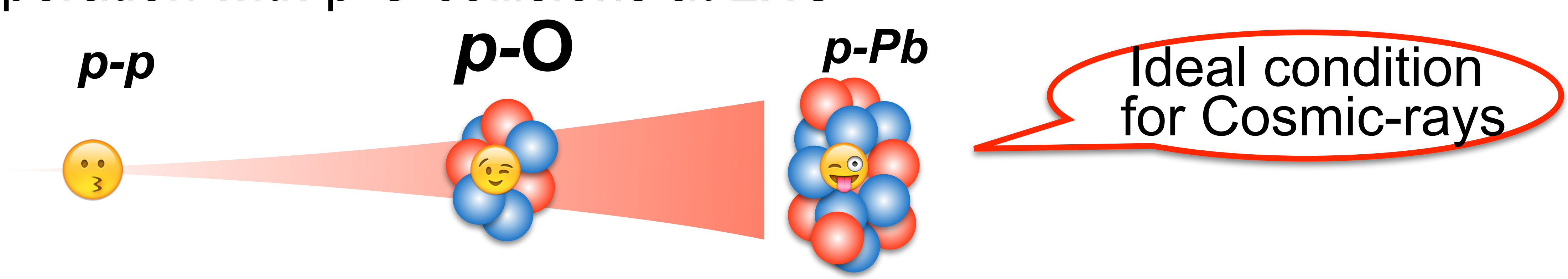




- ✓ Large spin asymmetry was found in very forward π^0 production.
- ✓ Detailed analysis is on-going.
- ✓ Cross-section measurements for forward photons, π^0, and neutrons are on-going.

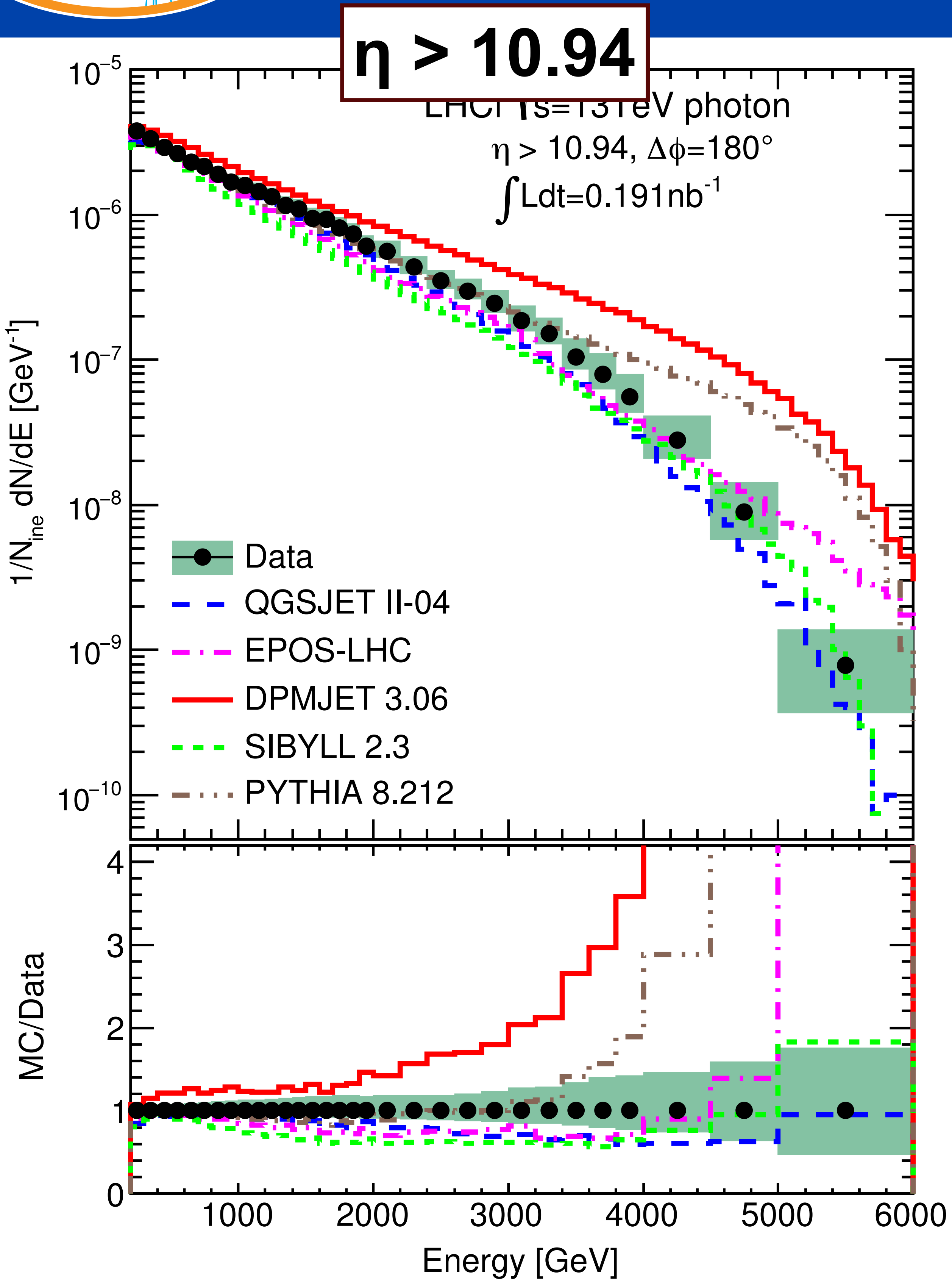
Summary

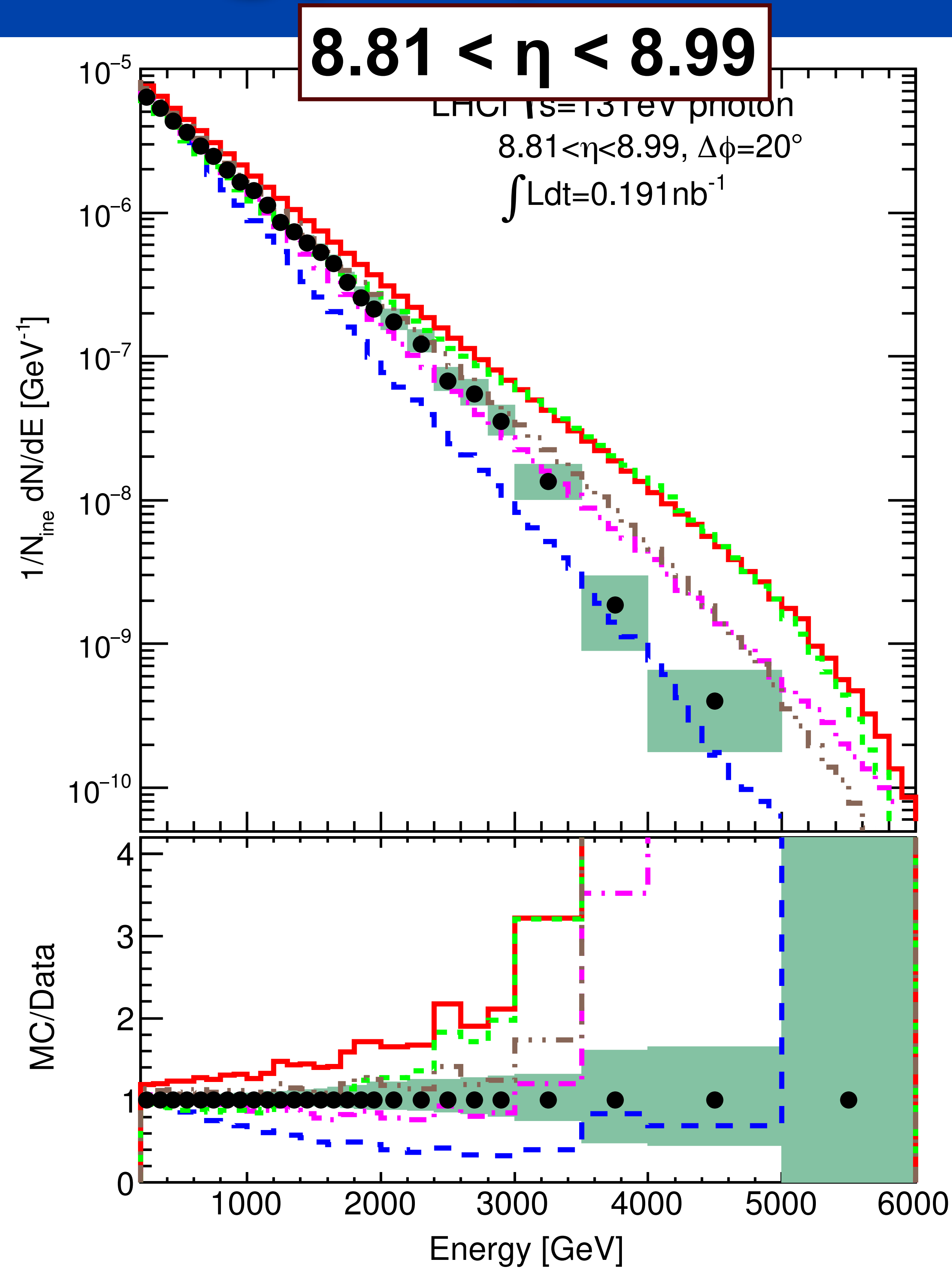
- LHCf measures the energy spectra of neutral particles, γ, π^0, n in the very forward regions of collisions ($\eta > 8.4$), which is important for understanding air-shower developments.
- Operations have successfully completed for
  p-p: $\sqrt{s}$ = 0.9, 2.76, 7, 13 TeV and
  p-Pb: $\sqrt{s_{NN}}$ = 5, 8 TeV.
- Combine analysis with ATLAS and the measurement at RHIC are also proceeded to understand the hadronic interaction better.
- Future plan
  - Operation with p-O collisions at LHC



Backup

Photon Energy Spectra





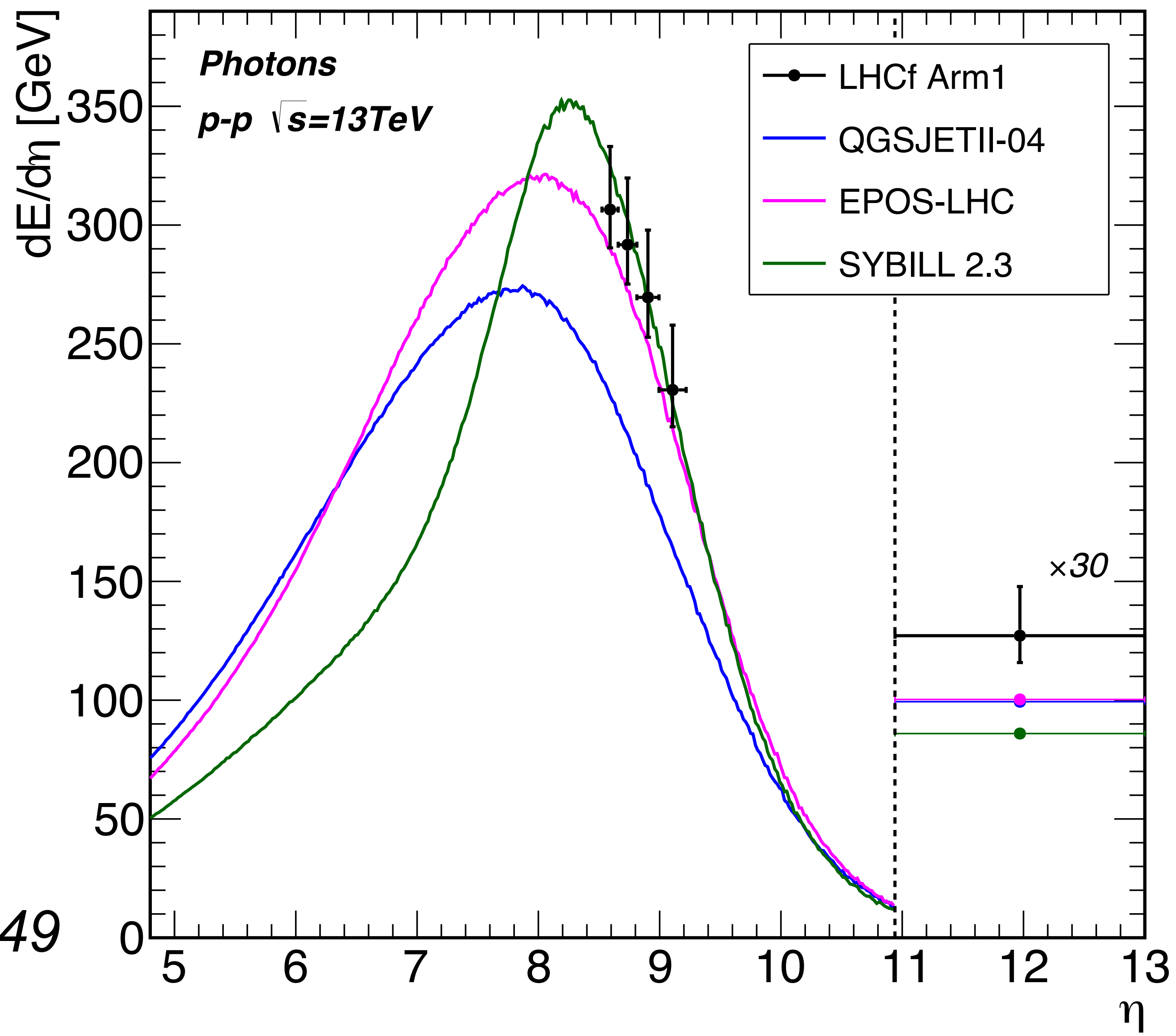
Photon Energy Flow

<u>*Energy Flow Calculation:*</u>

$$\frac{dE}{d\eta} = C_{thr}\frac{1}{\Delta\eta}\sum_{E_j>200GeV} E_j F(E_j)$$

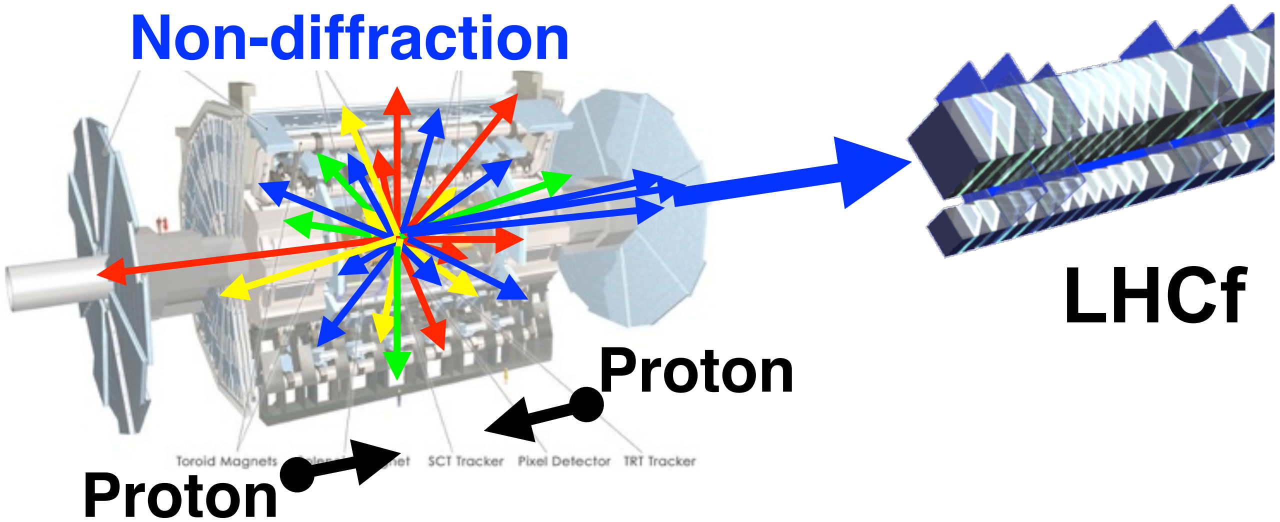
F(Ej) : Measured differential cross-section
Δη : The pseudo-rapidity range
C_{thr} : Correction factor for the threshold 200 GeV→ 0 GeV.

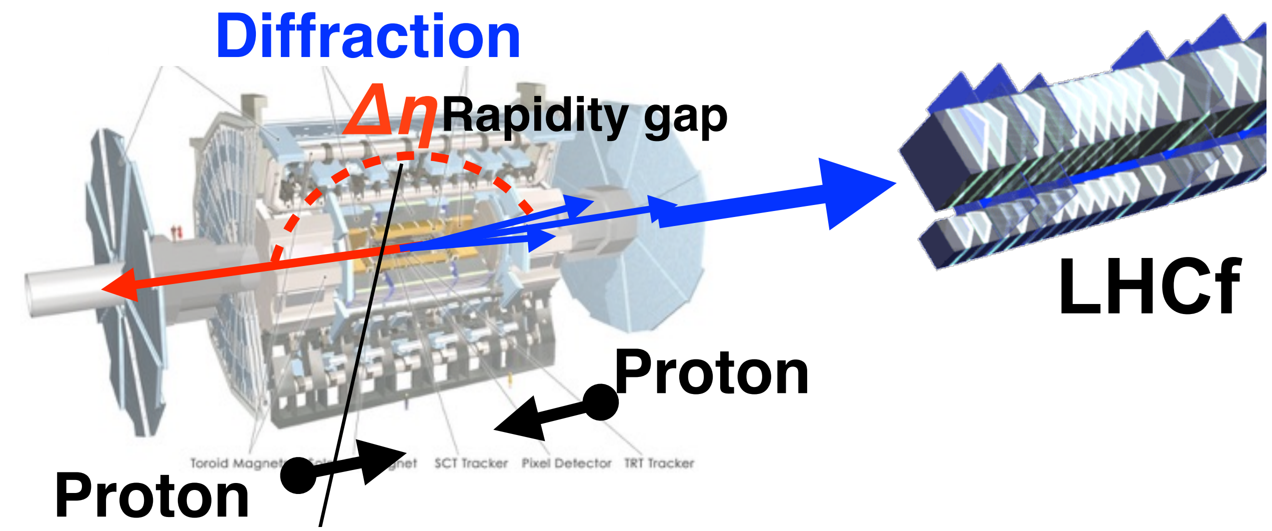
Ref: Y. Makino CERN-THESIS-2017-049

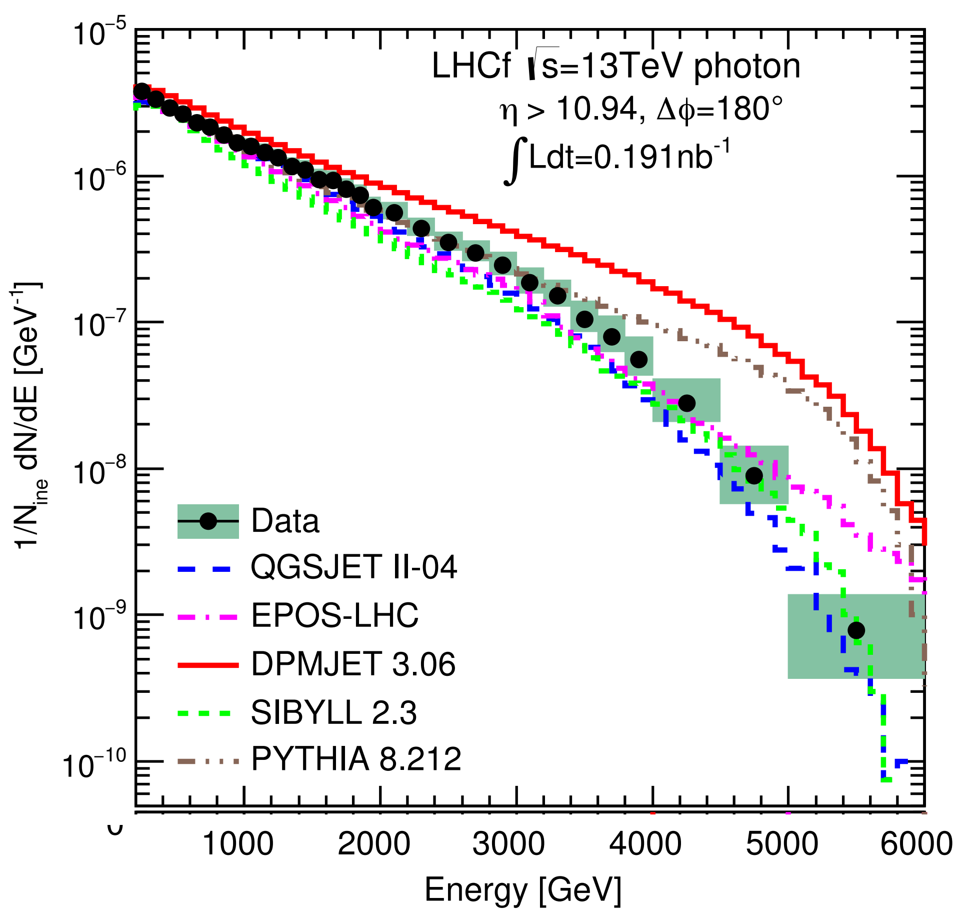


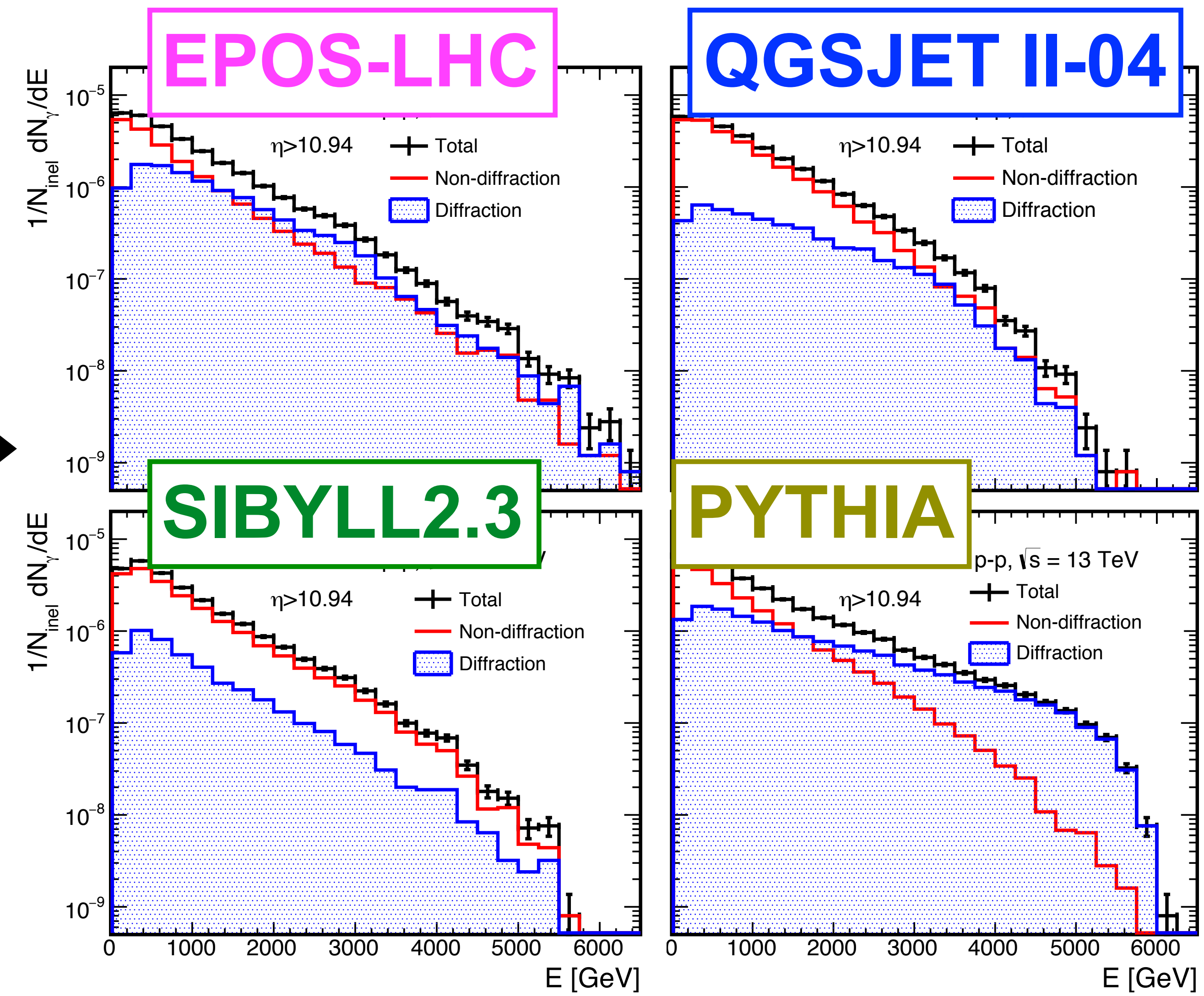
EPOS-LHC, SIBYLL2.3 Good agreement
QGSJET II-04 ~ 30% lower than data

Joint Analysis with ATLAS - Selection of Diffractive interactions -



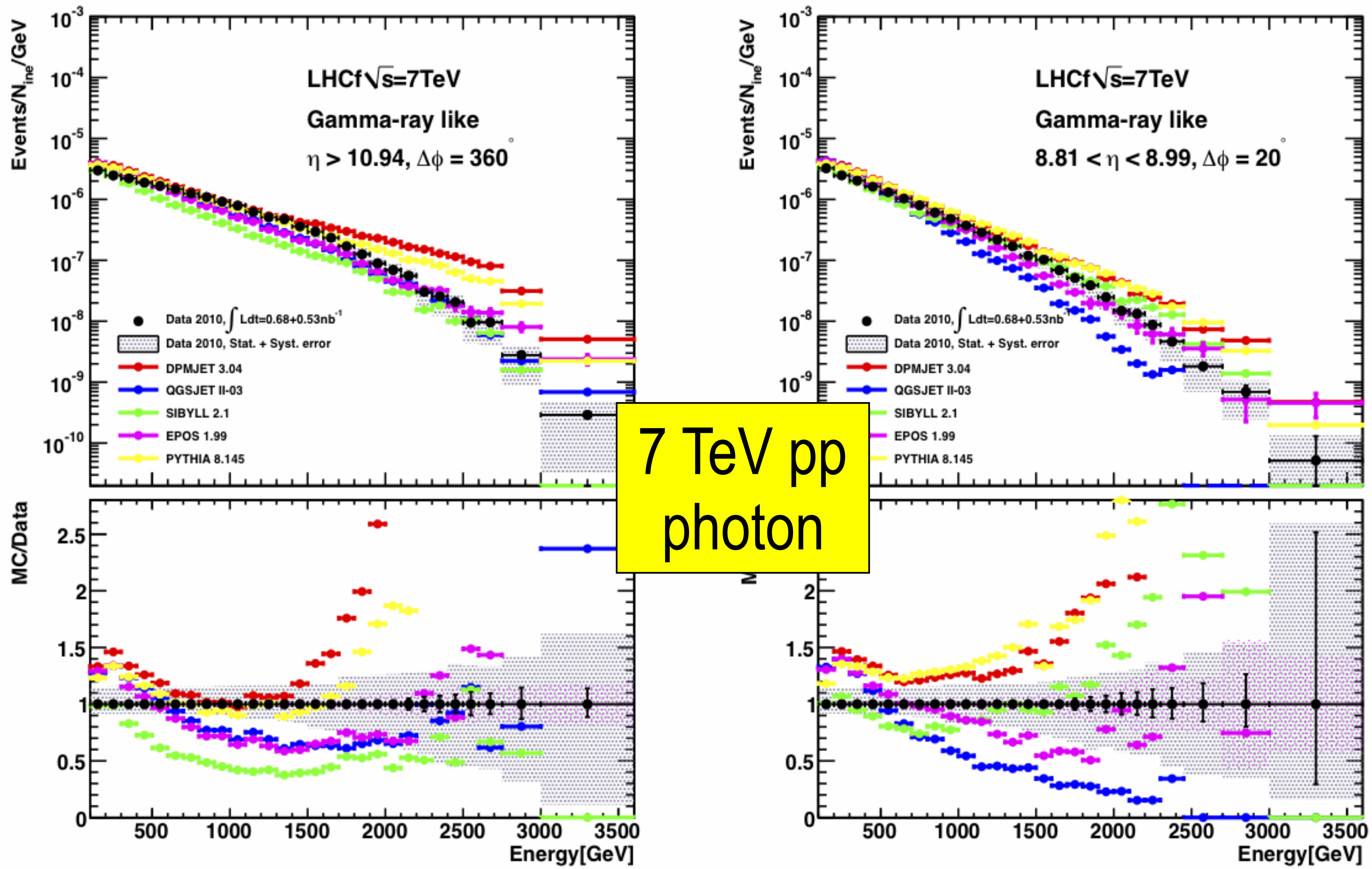




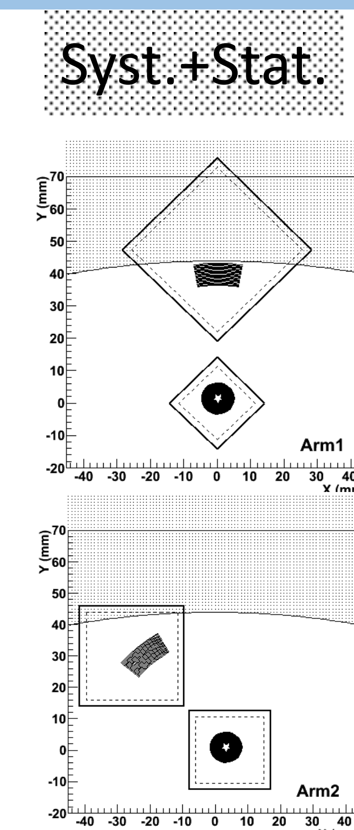


Poster by Q.Zhou; CRD131

LHCf results: single γ energy - p+p @ 7 TeV

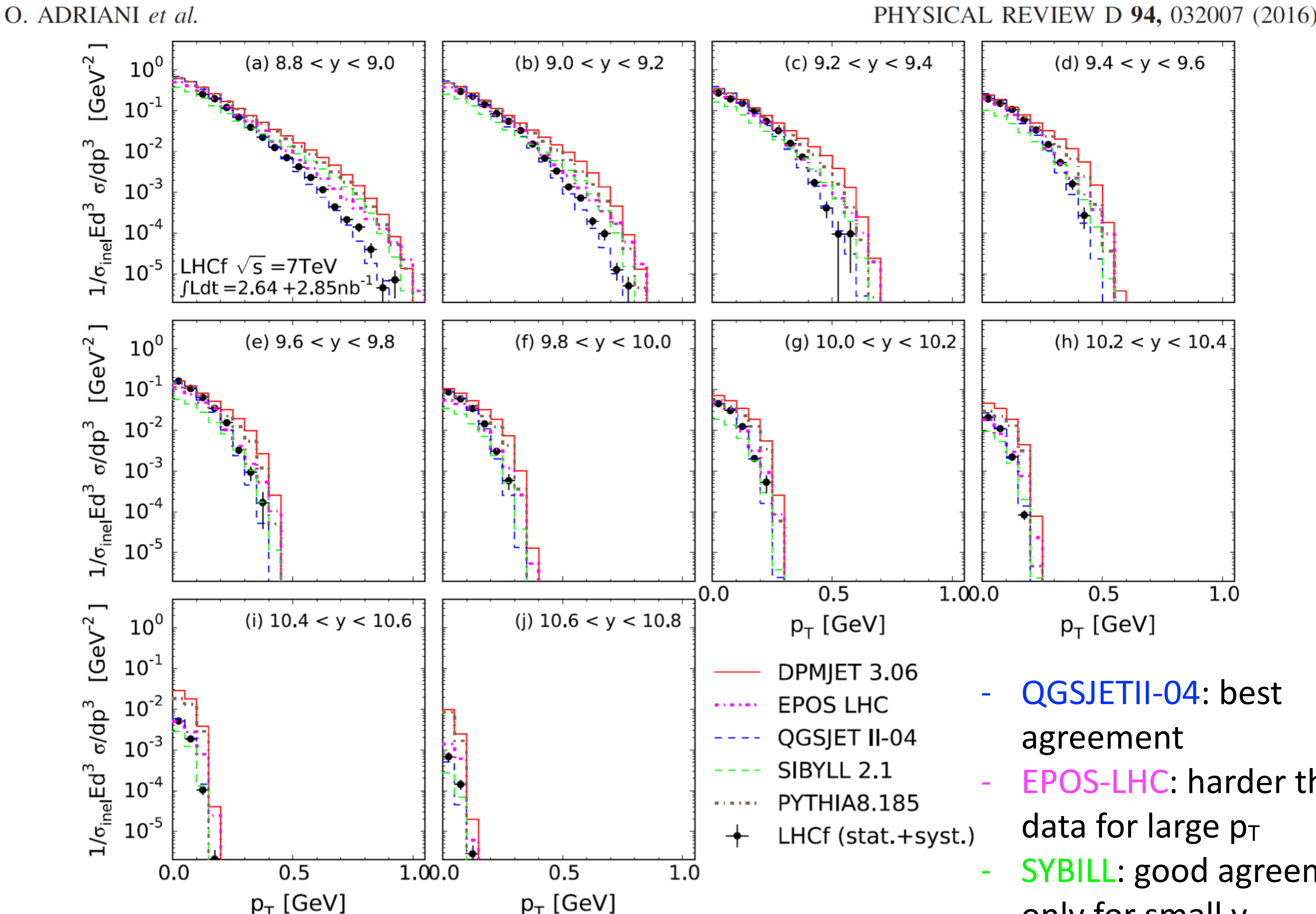


DATA
DPMJET 3.04
QGSJET II-03
SIBYLL 2.1
EPOS 1.99
PYTHIA 8.145



- No model can reproduce the **LHCf data** perfectly.
- DPMJET and PYTHIA are in good agreement at high-η for 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.

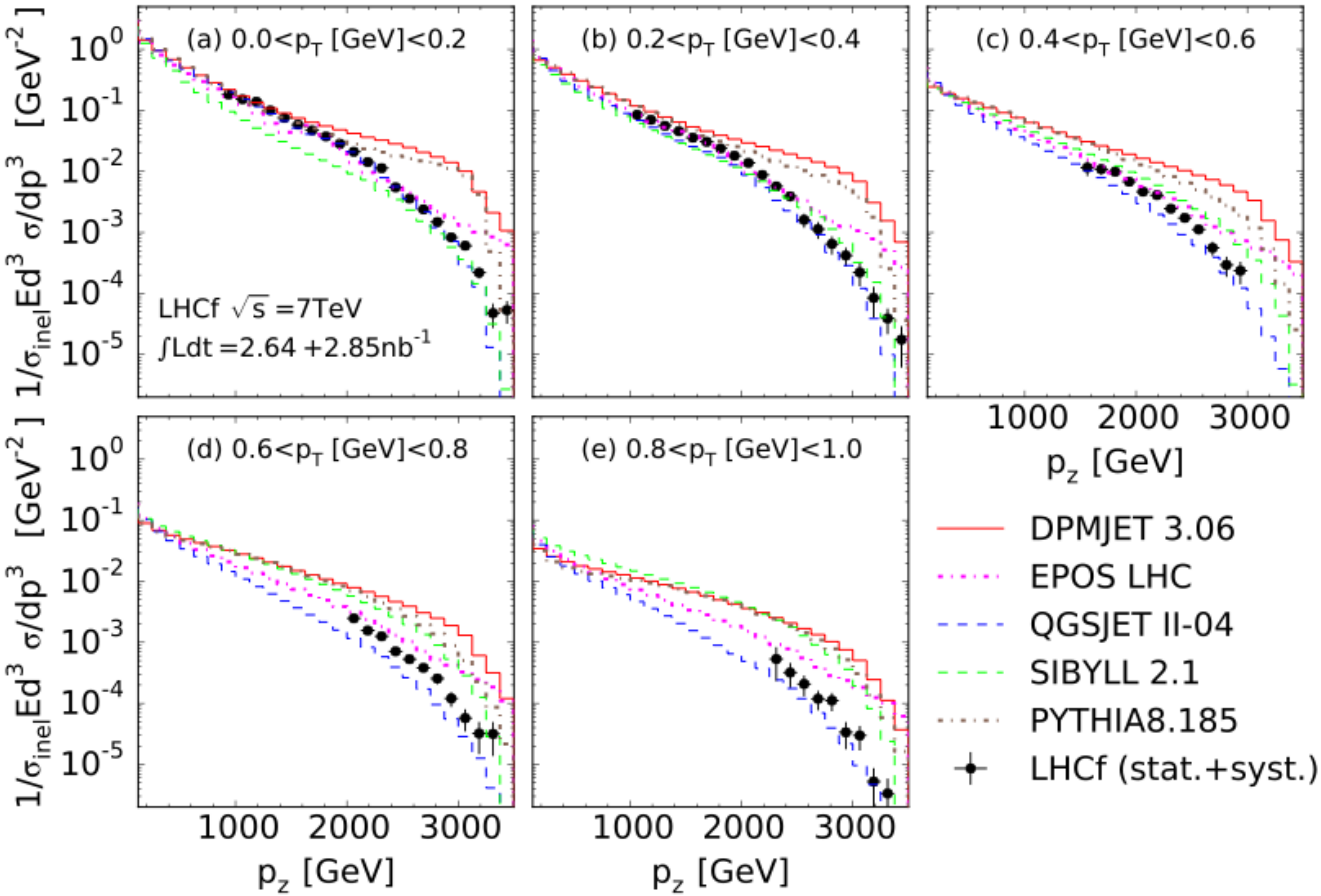
π^0 p_T spectra at p+p,7TeV



- QGSJETII-04: best agreement
- EPOS-LHC: harder than data for large p_T
- SYBILL: good agreement only for small y

π^0 p_Z (~E) spectra at p+p,7TeV

PRD 94 (2016) 032007



DPMJET and Pythia overestimate over all E-p_T range