Recent results from the LHCf experiment

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on behalf of the LHCf collaboration

The LHCf collaboration

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Introduction

Air Shower Technique

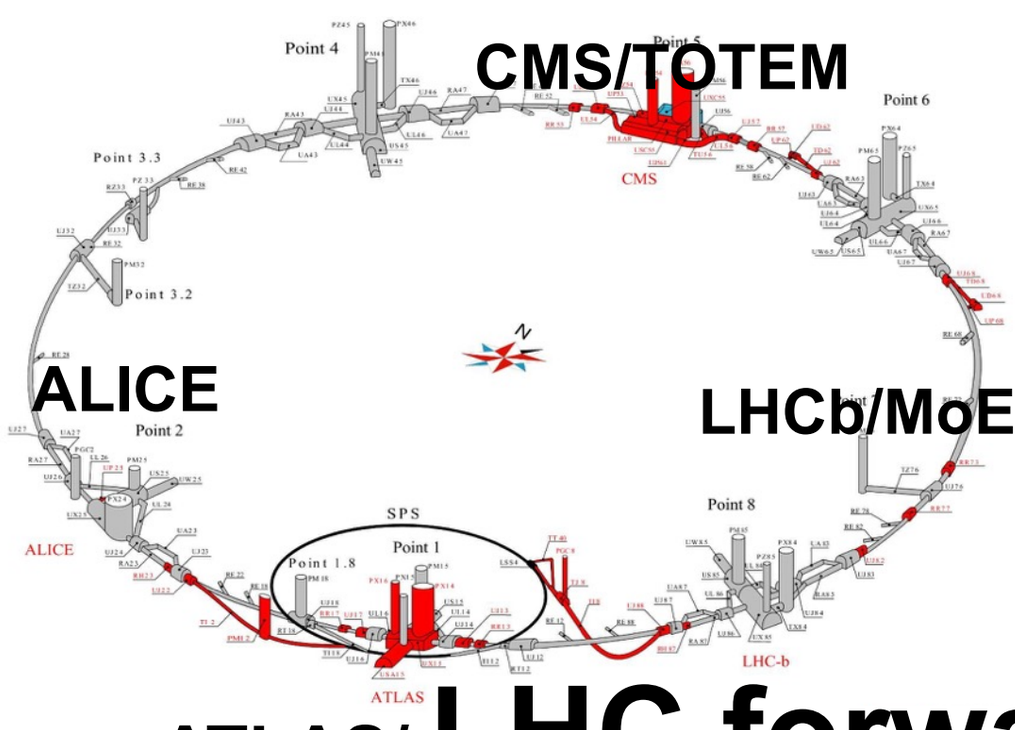
Extensive air shower observation
- longitudinal distribution
- lateral distribution
- Arrival direction

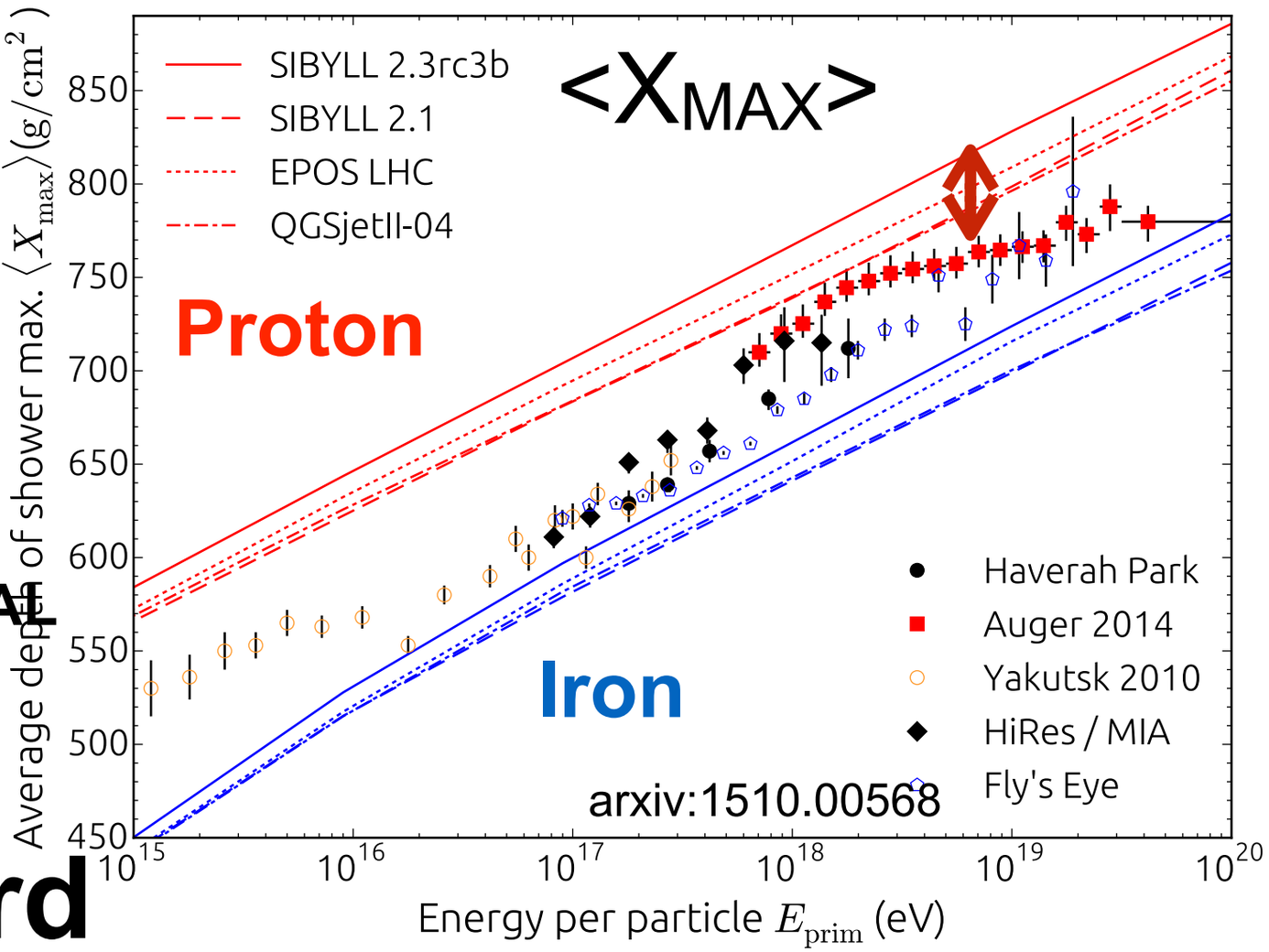
Air shower development

Astrophysical parameters
- Spectrum
- Composition
- Source distribution

LHC experiments

Test the hadronic interaction models at $\sqrt{s}$=13 TeV, E_{lab}=0.9×10^{17}eV





- **Cross section**

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

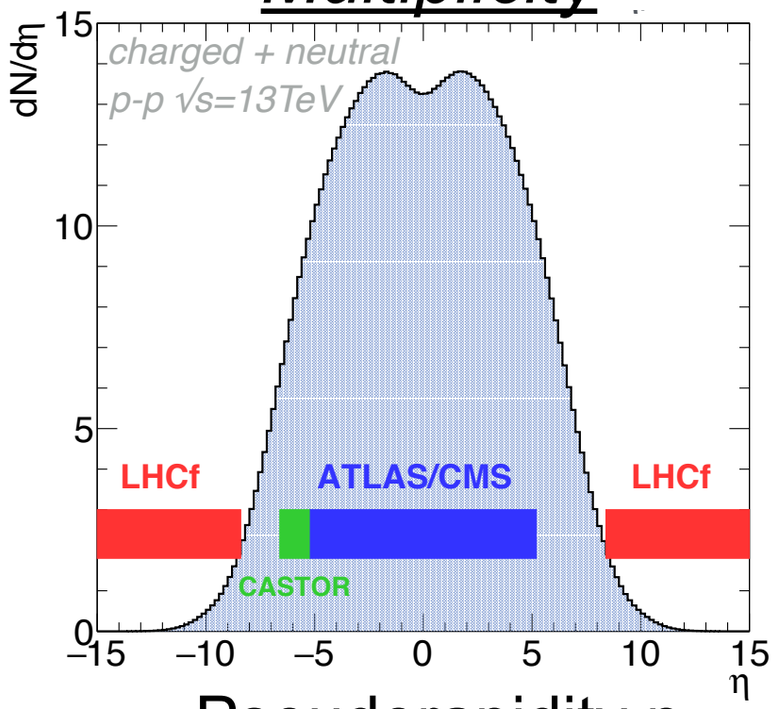
- **Very forward energy spectrum**
  - If softer shallow, development
  - If harder deep, penetrating

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

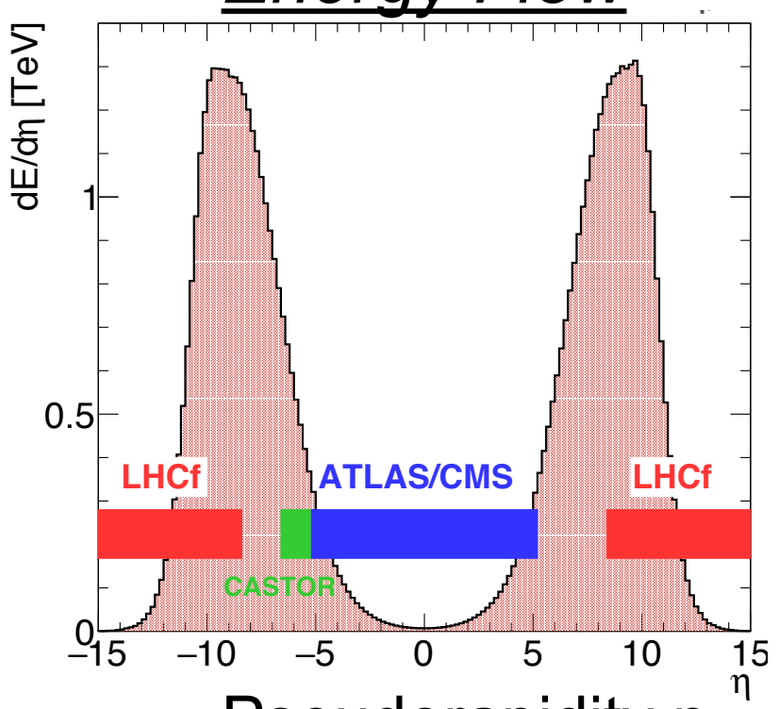
- **Elasticity** $k = \frac{E_{lead}}{E_{avail}}$
  - If small k (π^0s carry more energy): rapid development
  - If large k (baryons carry more energy): deep penetrating

- **Secondary interactions** (n, p, π)

Multiplicity

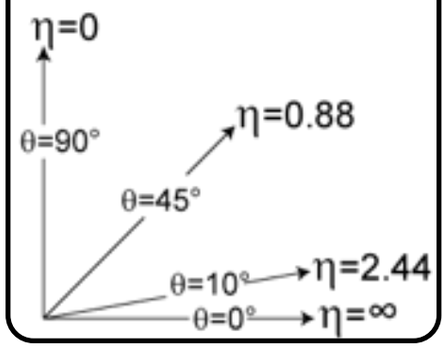


Energy Flow



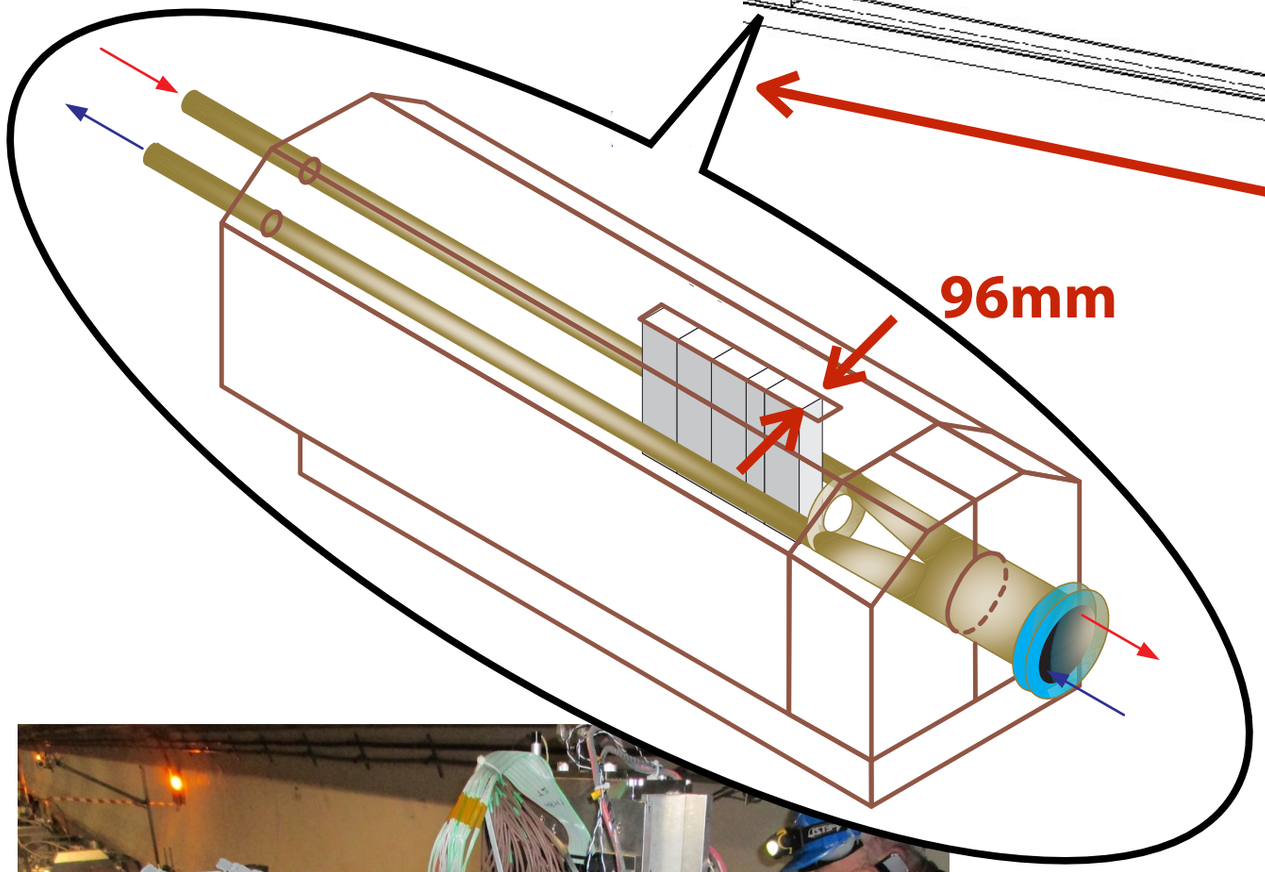
Pseudorapidity

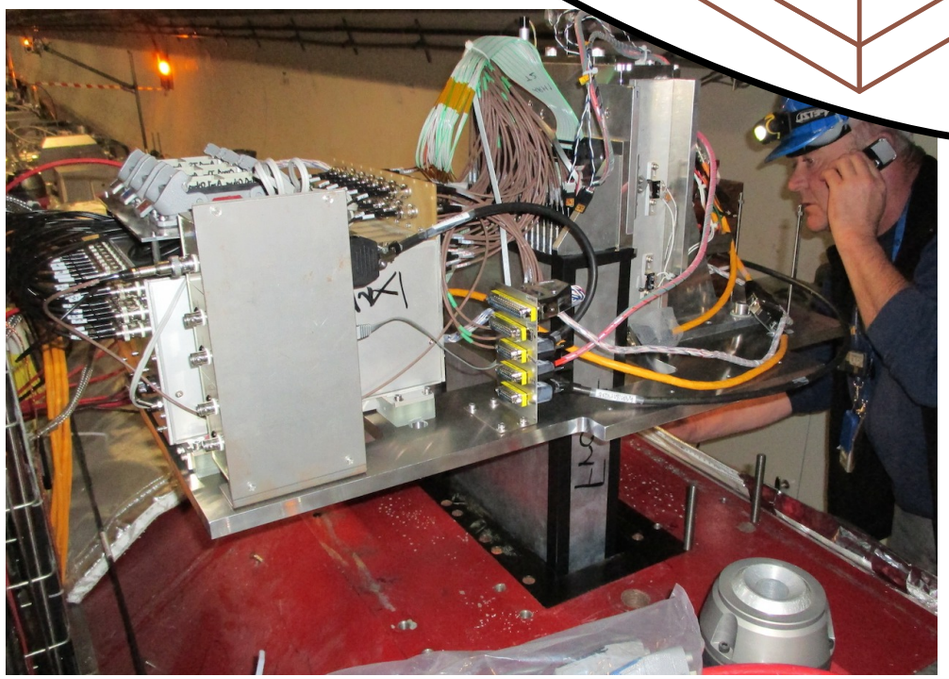
$$\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$



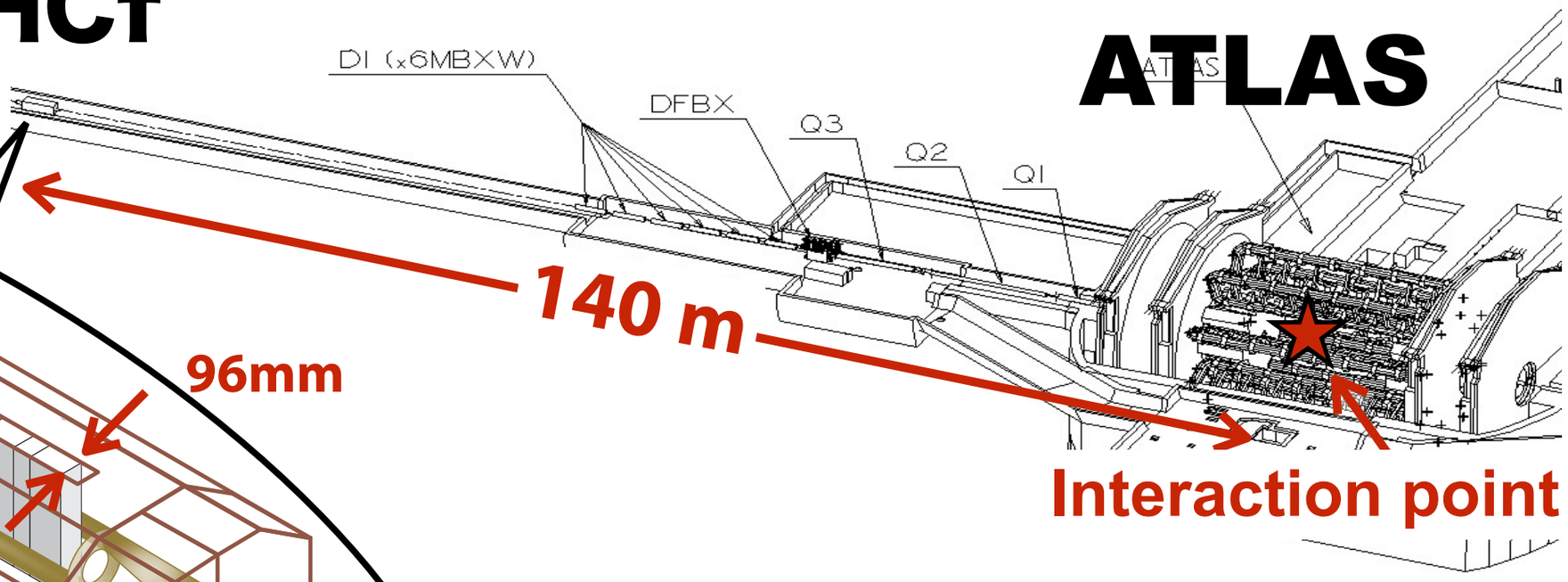
Experimental Setup

LHCf





ATLAS



- 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

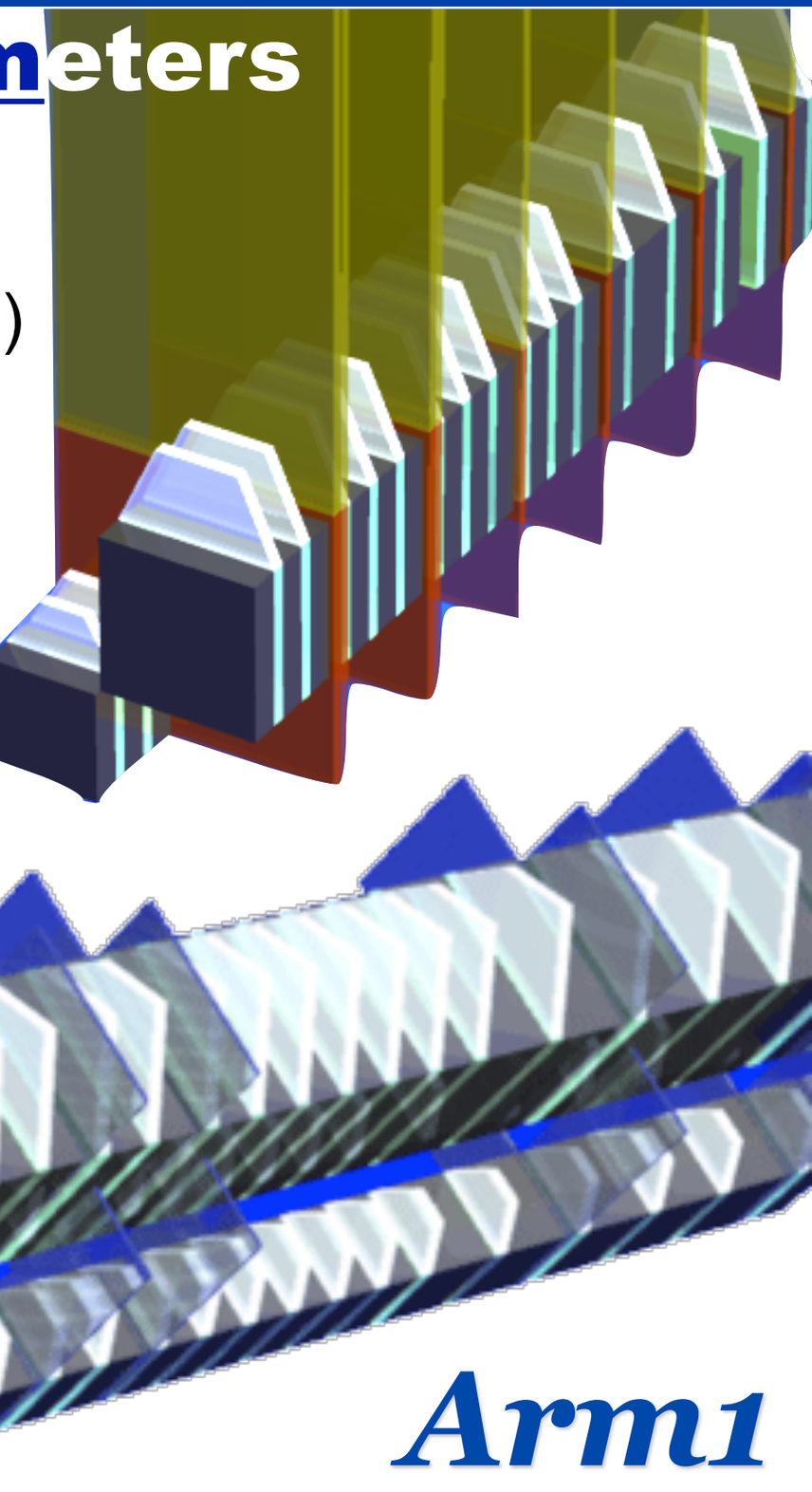
Sampling and Positioning Calorimeters

- 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**

Expected Performance
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**



Status of analysis

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

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RHICf p-p $\sqrt{s}$=510GeV (2017)	1.4×10^{14}	on-going			

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

Motivation

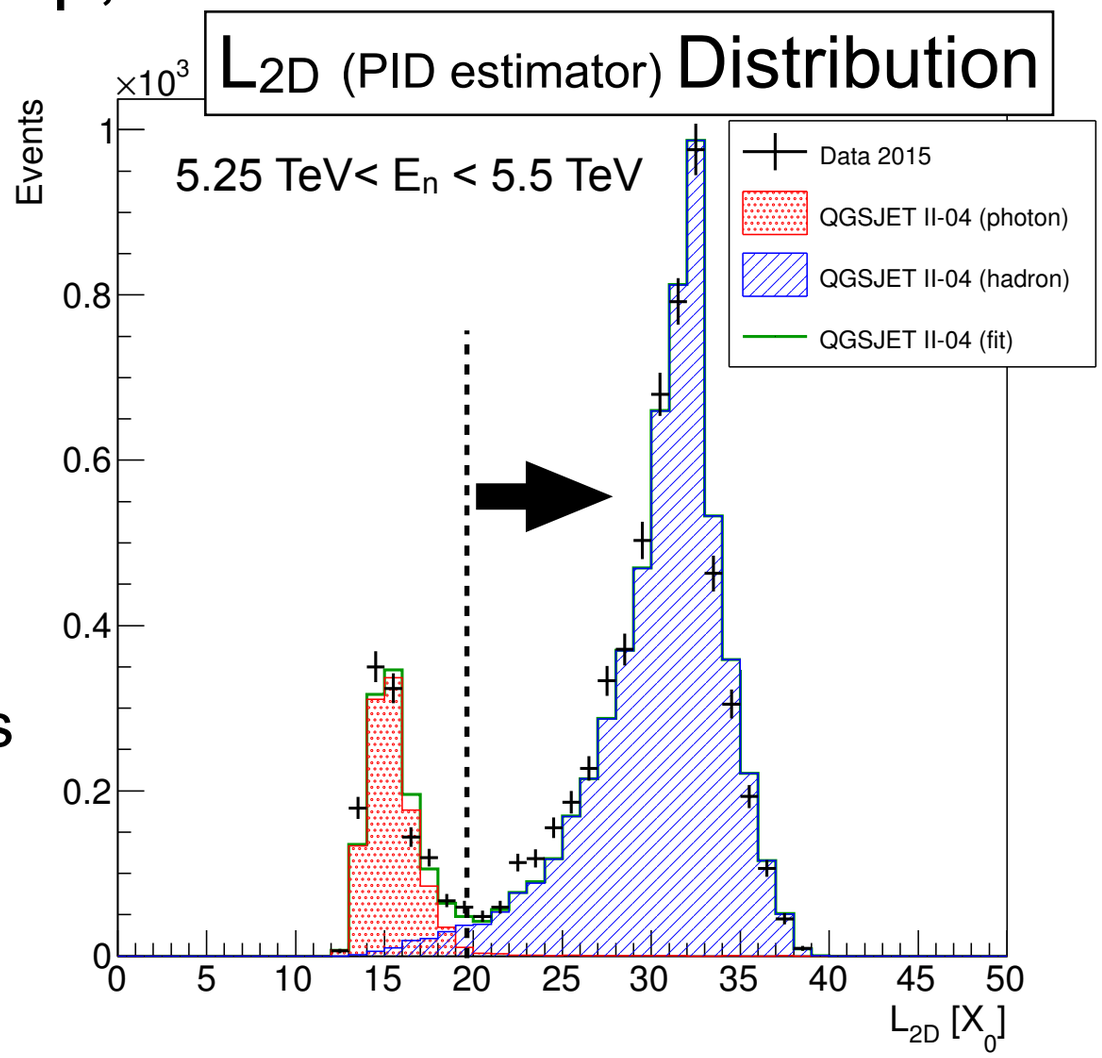
- Inelasticity measurement k_{inela}
  $k_{inela} = 1 - E_{leading}/E_{beam}$
- Large discrepancies between data and model prediction were found in the measurement at p-p, $\sqrt{s}$=7TeV

Data

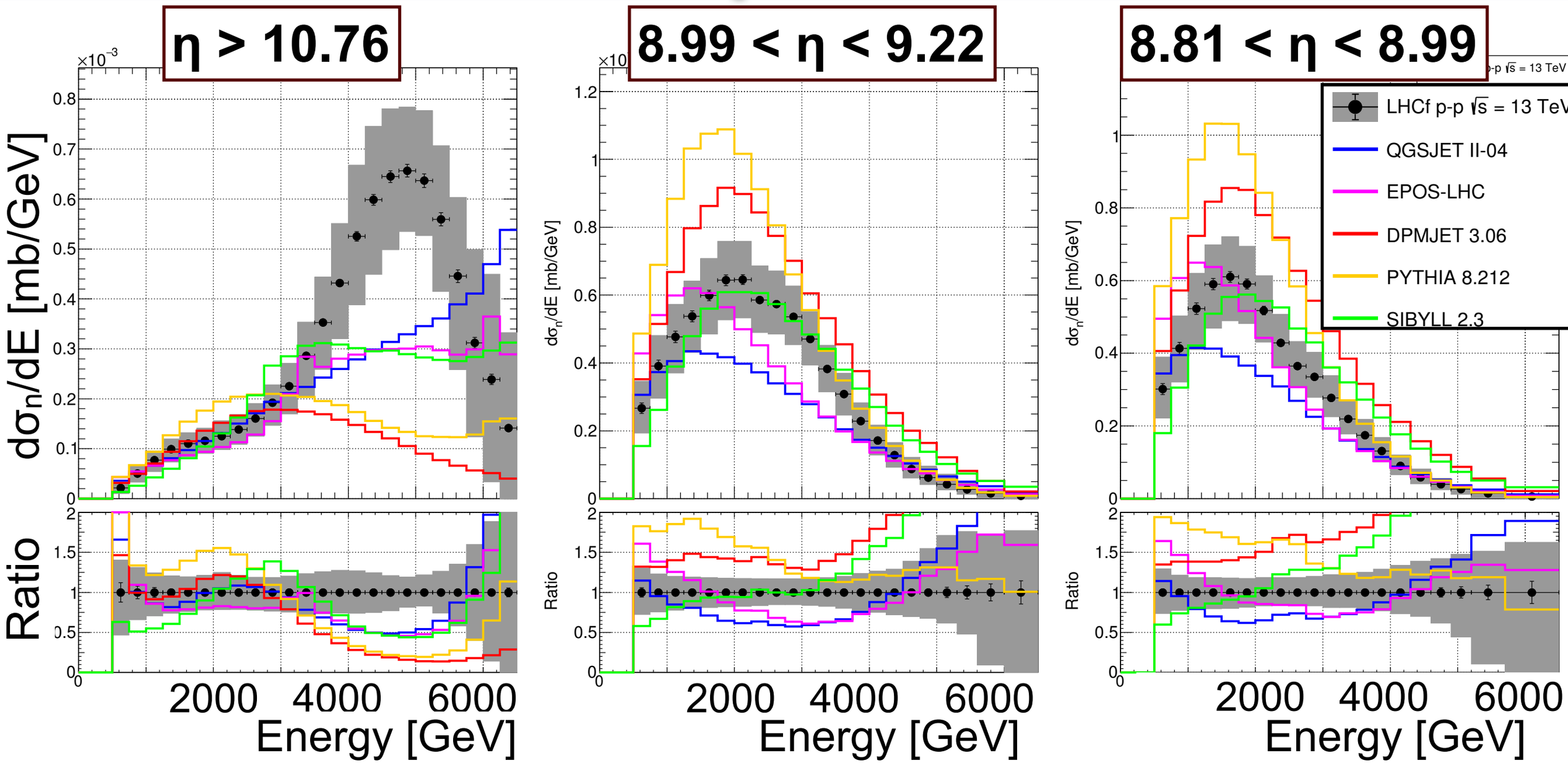
- 3 hour operation in June 2015
- Low pile-up, μ~0.01

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



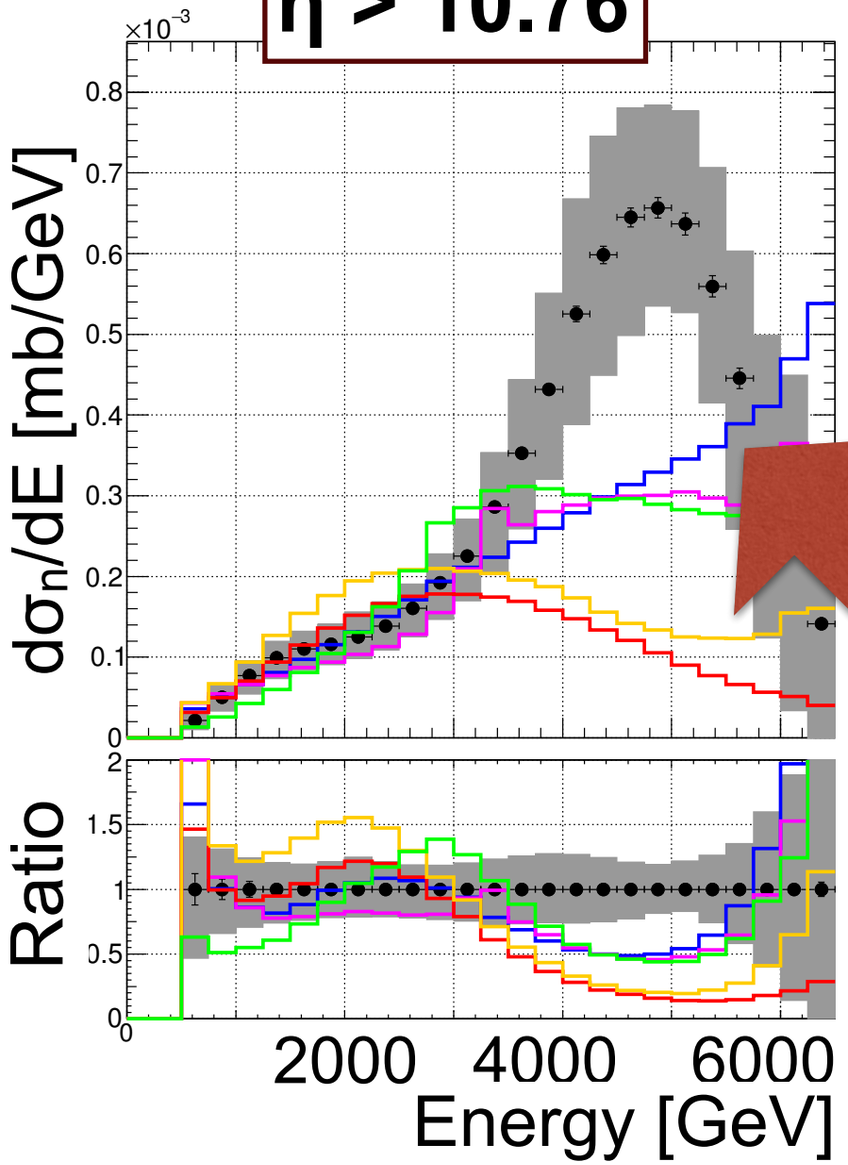
Neutron, p-p $\sqrt{s}$=13TeV Unfolded Spectra



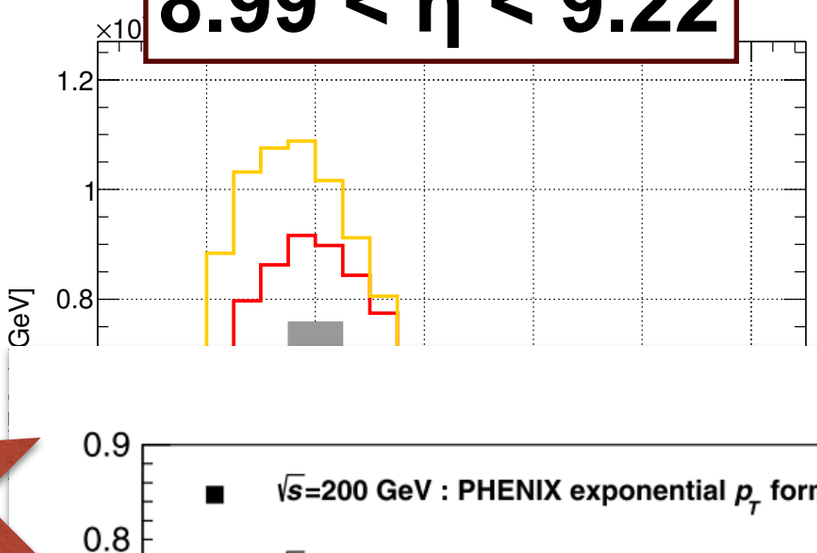
- In η > 10.76, data shows a strong increasing of neutron production in the high energy region. This behavior is not predicted by all models.
- EPOS-LHC and SIBYLL 2.3 have the best agreement in 8.99 < η < 9.22, 8.81 < η < 8.99, respectively.

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

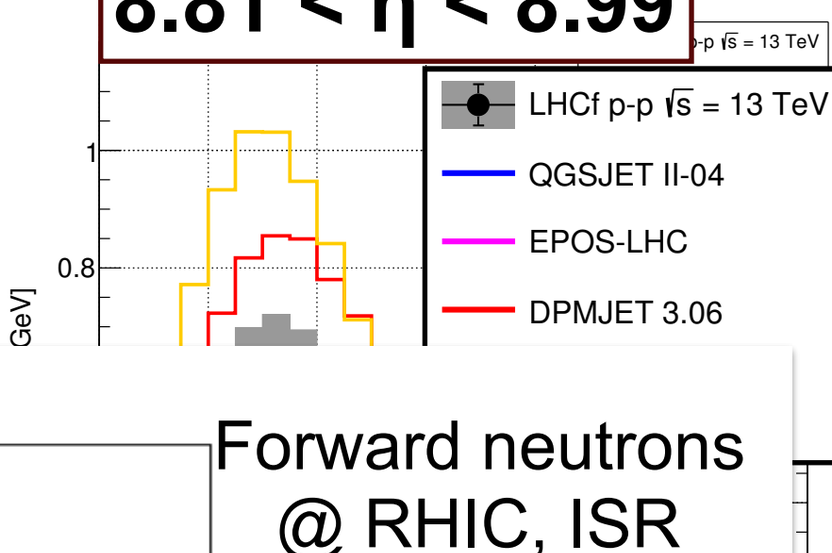
$\eta > 10.76$



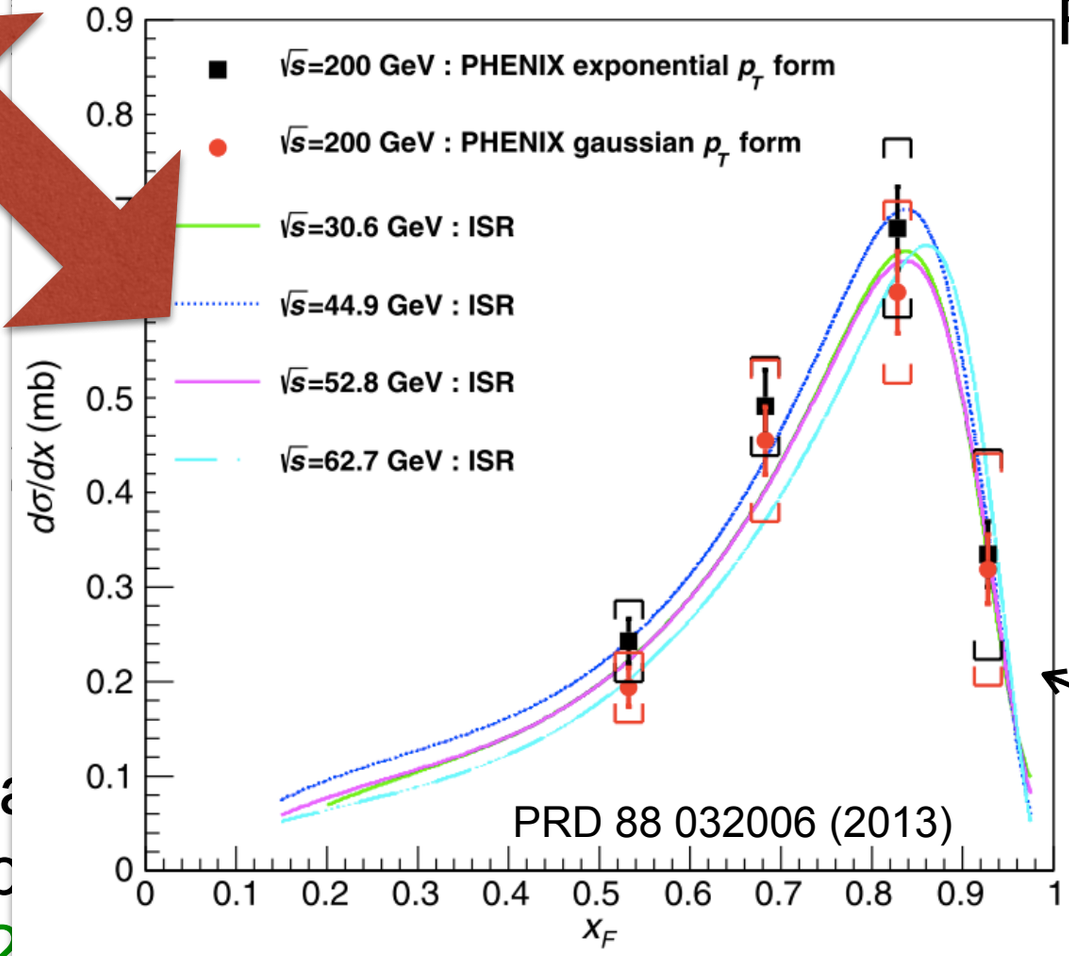
$8.99 < \eta < 9.22$



$8.81 < \eta < 8.99$



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



Forward neutrons @ RHIC, ISR

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

Detailed comparison is needed

$p_T < 0.11\ X_F$

⇕

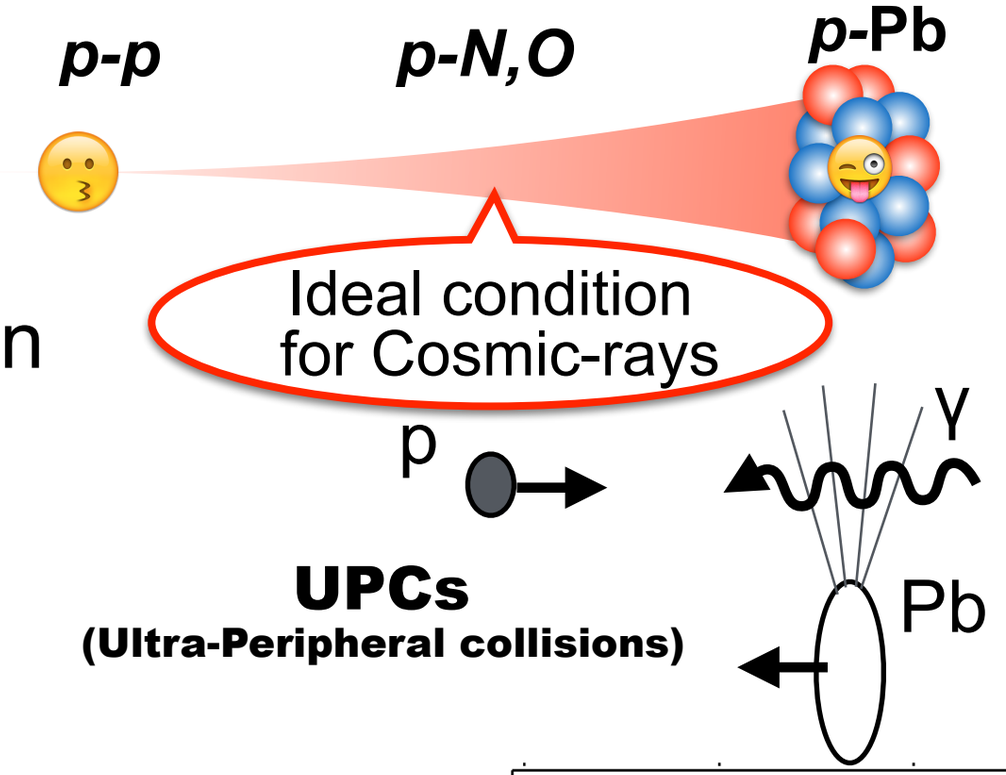
$p_T < 0.28\ X_F$

@ η>10.76, 13TeV

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

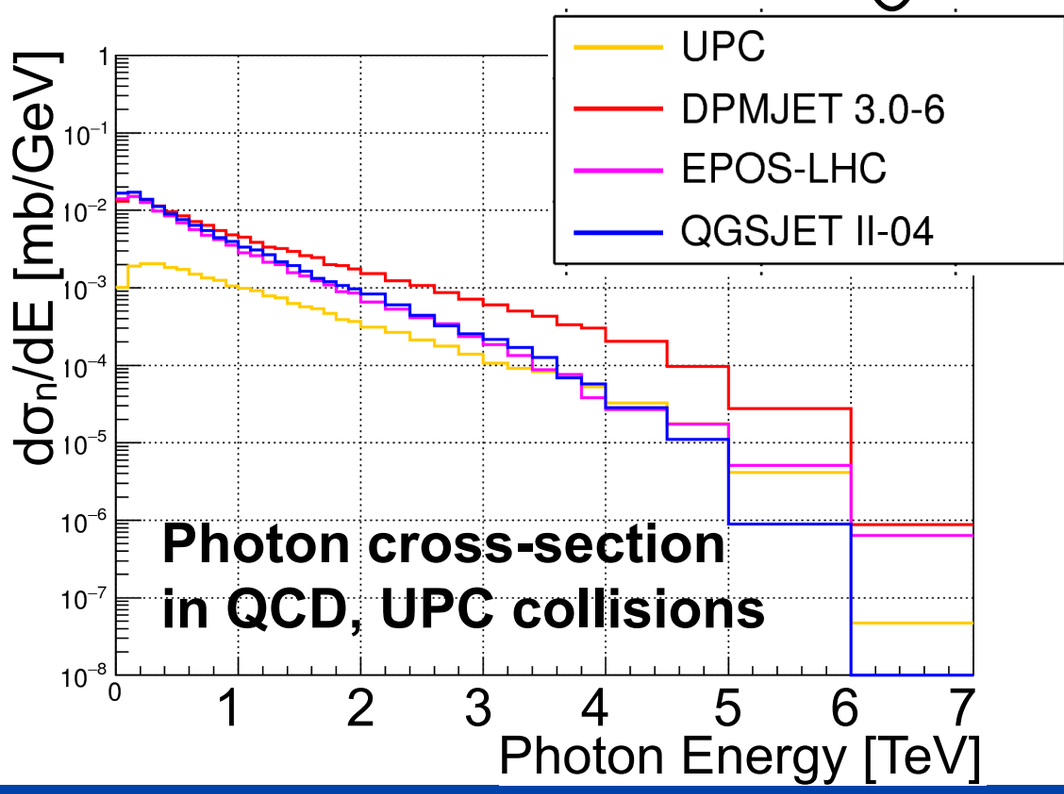


Data

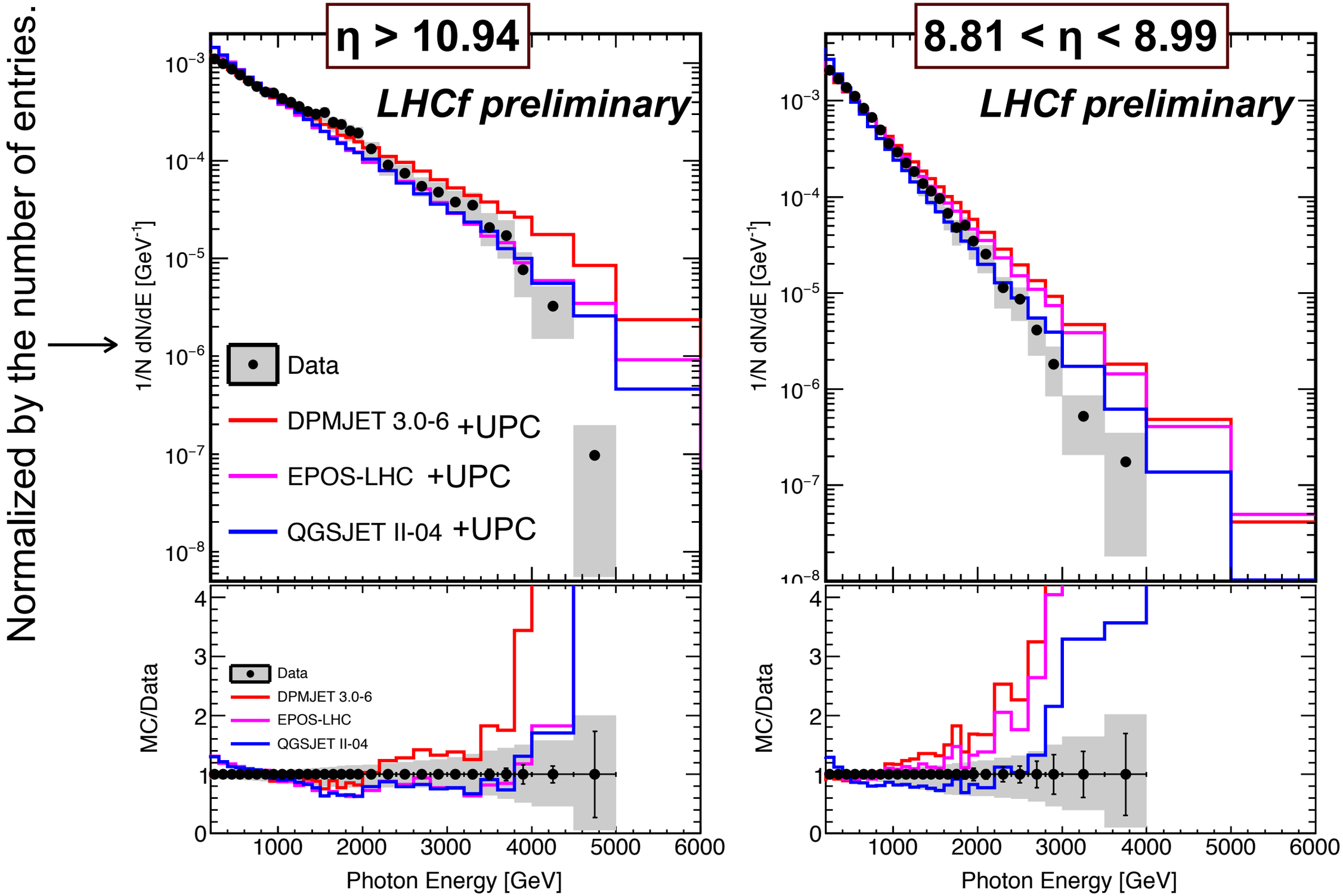
- 2 hour operation in November 2016
- Low pile-up, μ~0.01

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

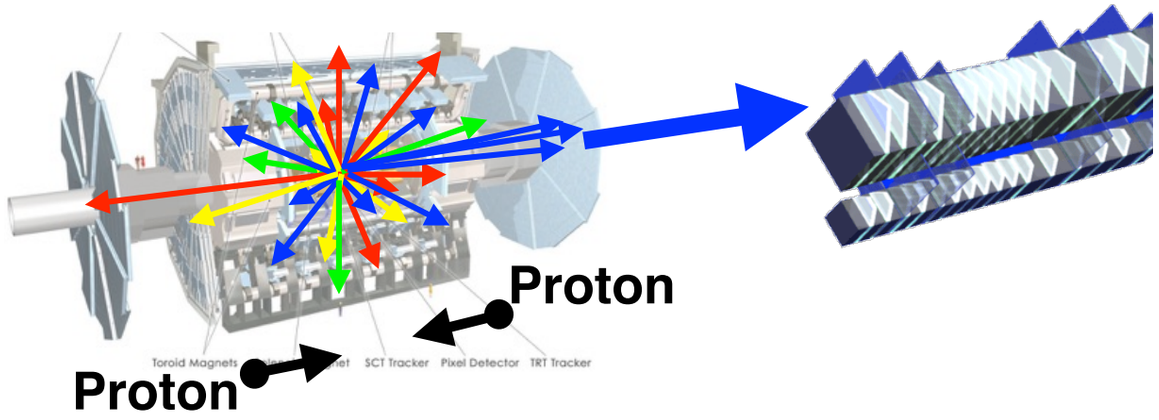


Photon, p-Pb $\sqrt{s_{NN}}$=8TeV



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 ⟷ x10^3 ⟷ LHC 10^{17}eV ⋯⋯ x10^3 ⋯⋯▶ UHECR ~10^{20}eV

Diffractive processes

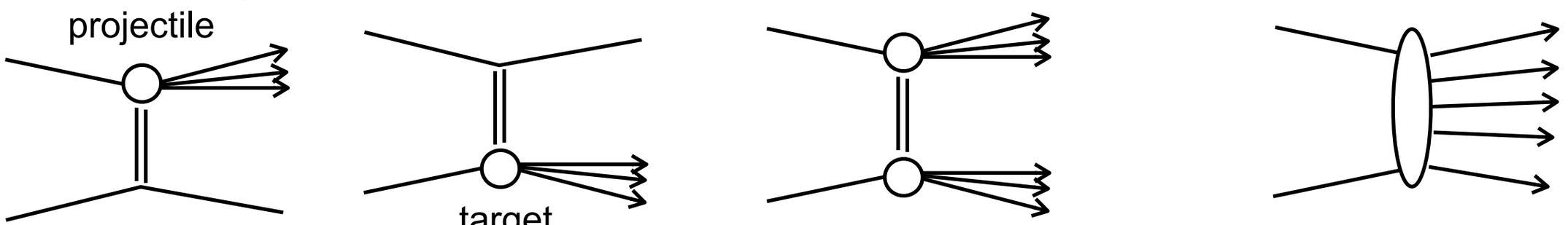
Inelastic processes

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

Identification of diffractive events by ATLAS

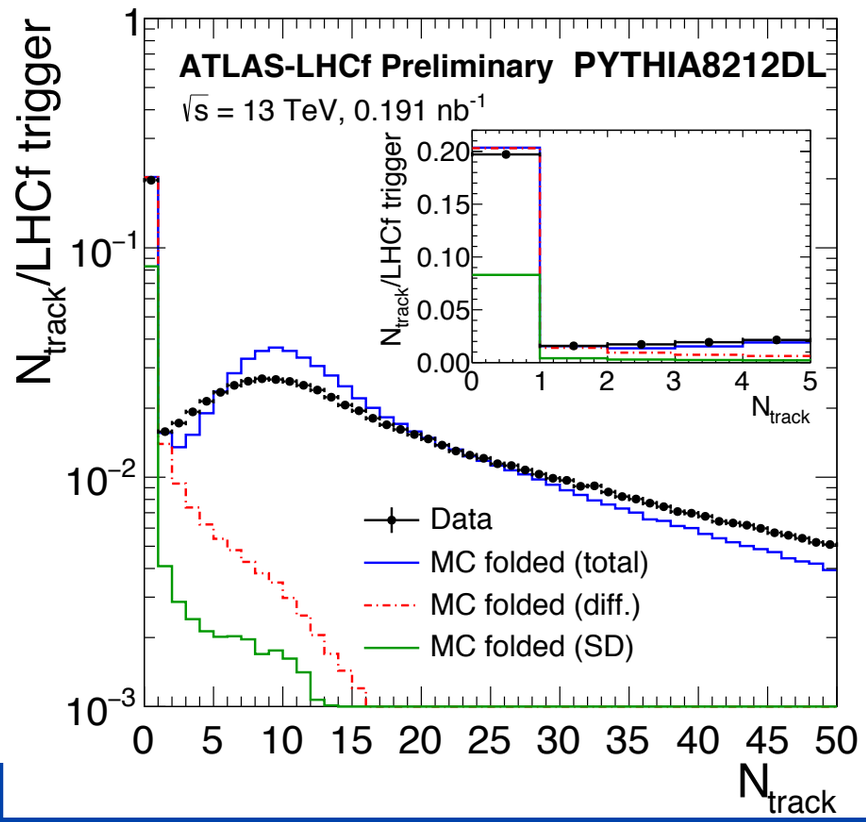
Method

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

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

→ Selecting pure samples of proton dissociations.
→ Sensitive to only low-mass dissociations $M_X \lesssim 50$ GeV

ATLAS-CONF-2017-075

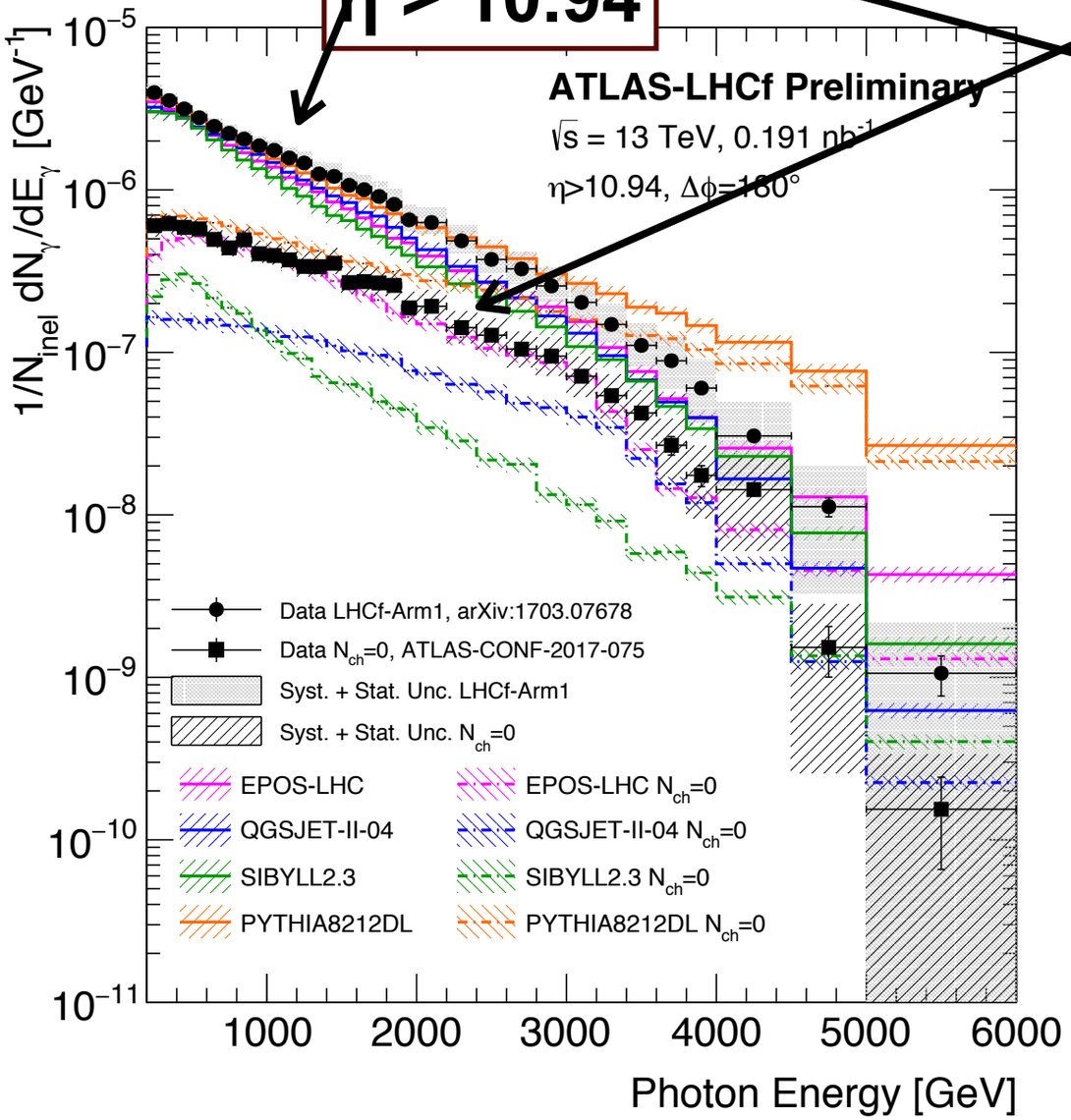


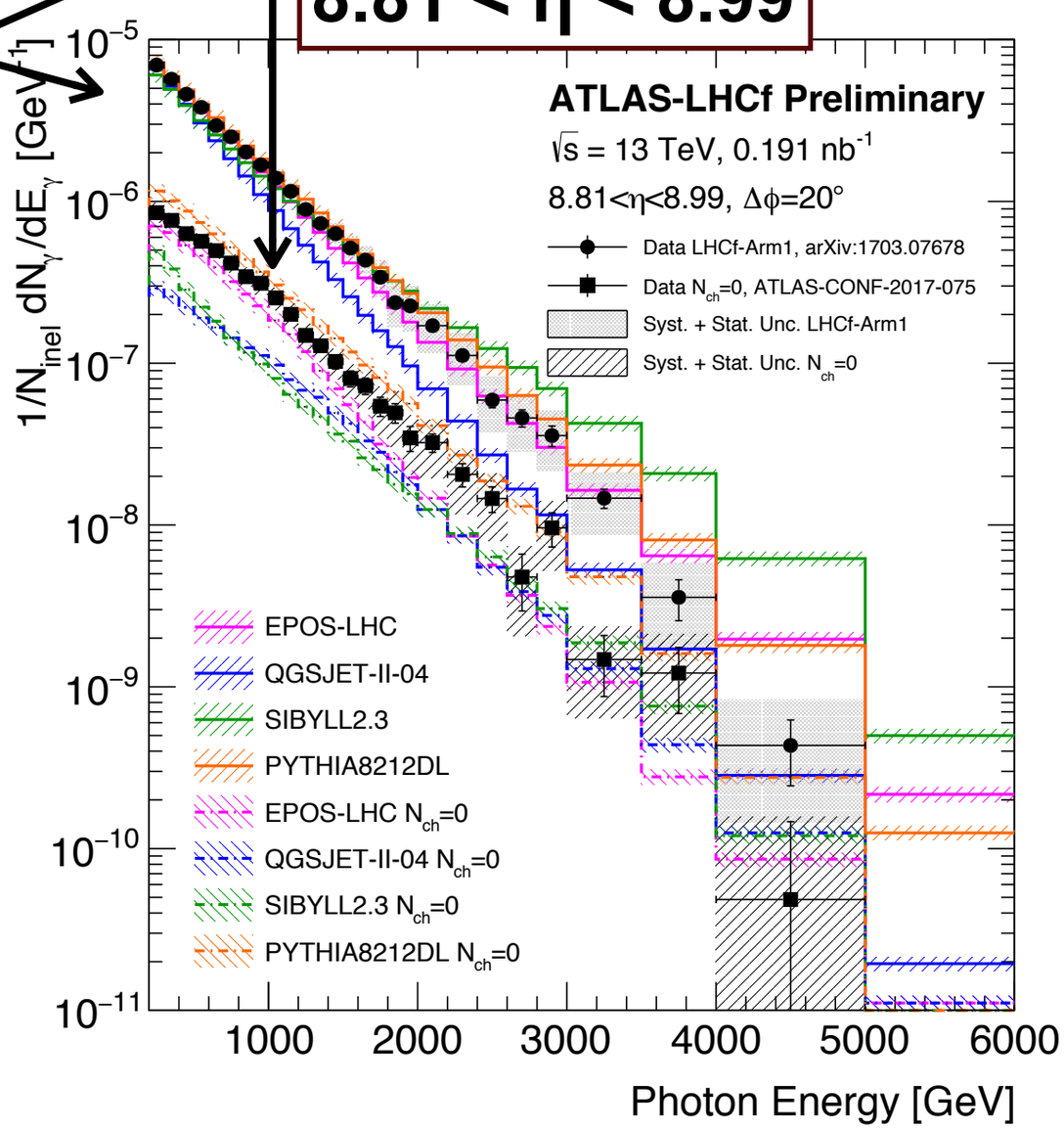
Measurement of contributions of diffractive processes to forward photon spectra in *pp* collisions at $\sqrt{s}$ = 13 TeV

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

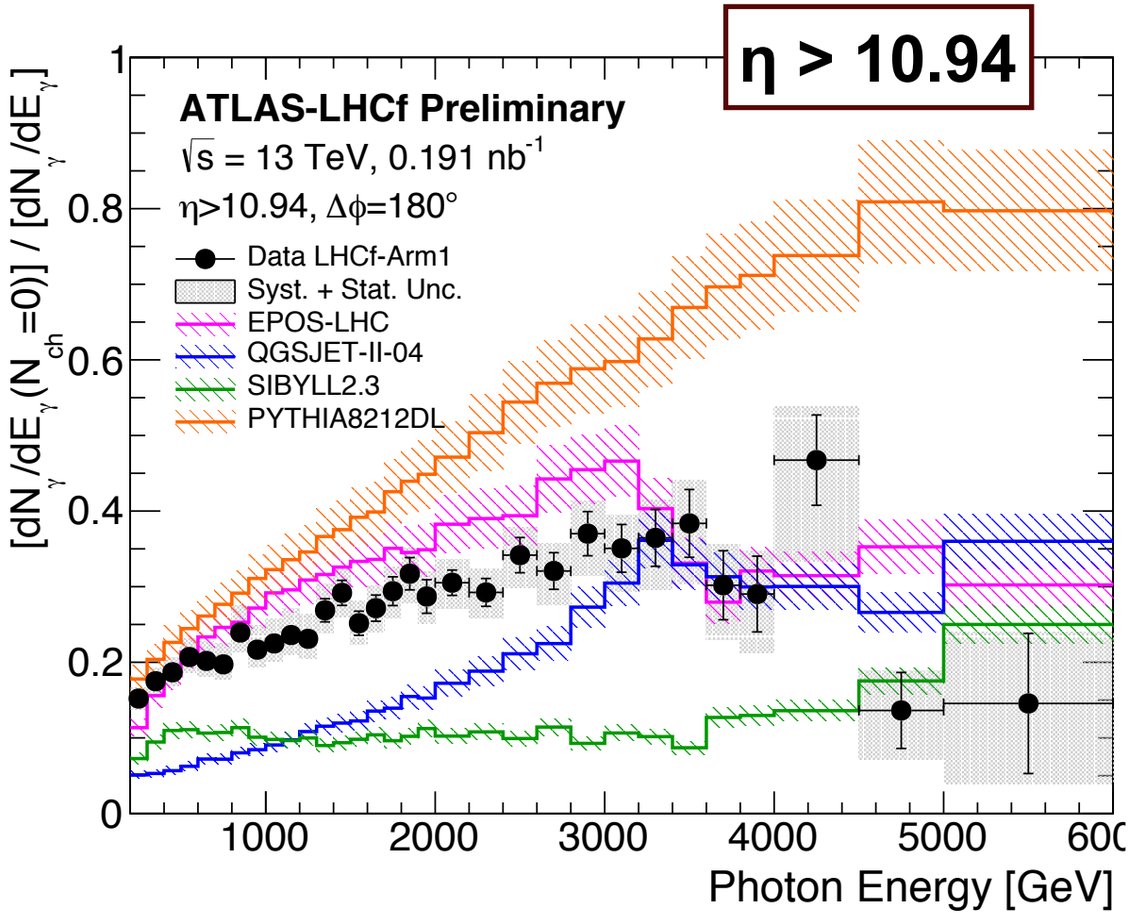


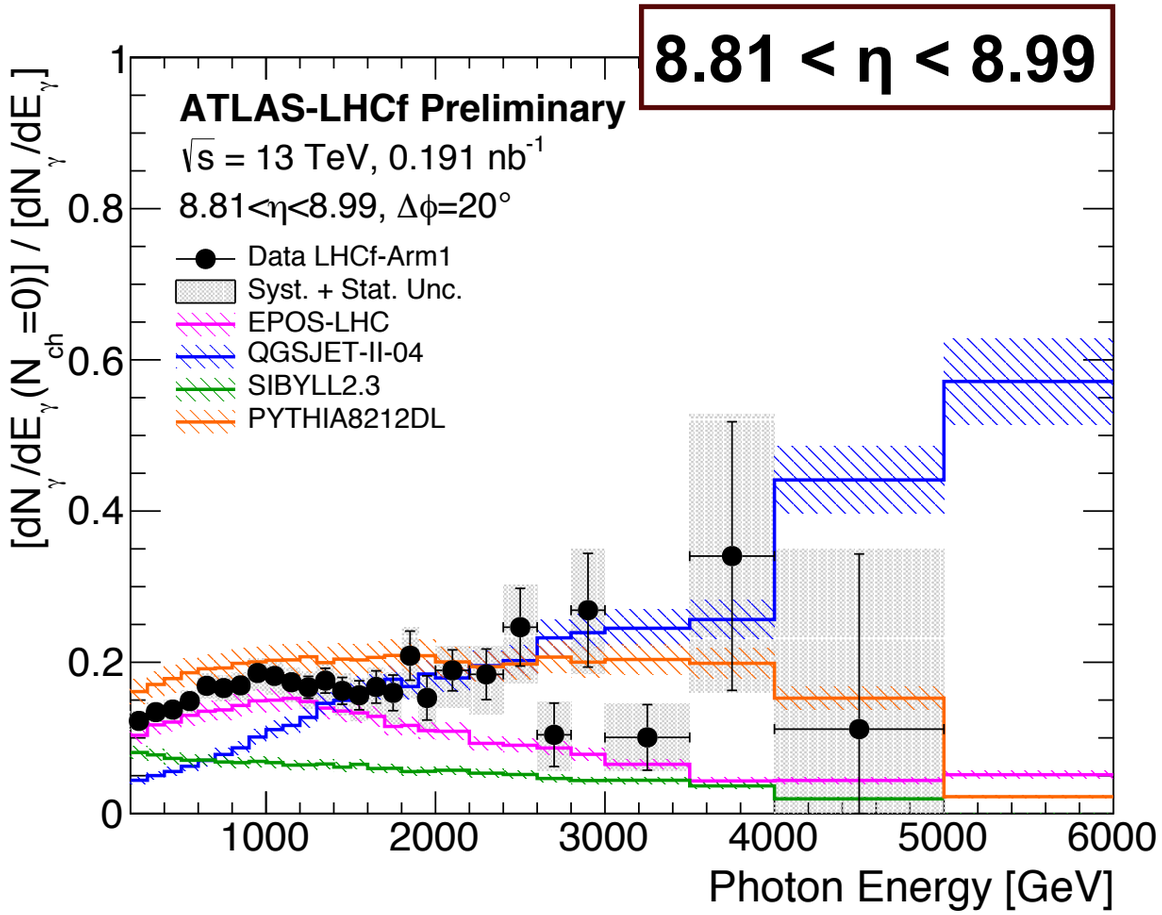


Measurement of contributions of diffractive processes to forward photon spectra in *pp* collisions at √s = 13 TeV

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

ATLAS-CONF-2017-075

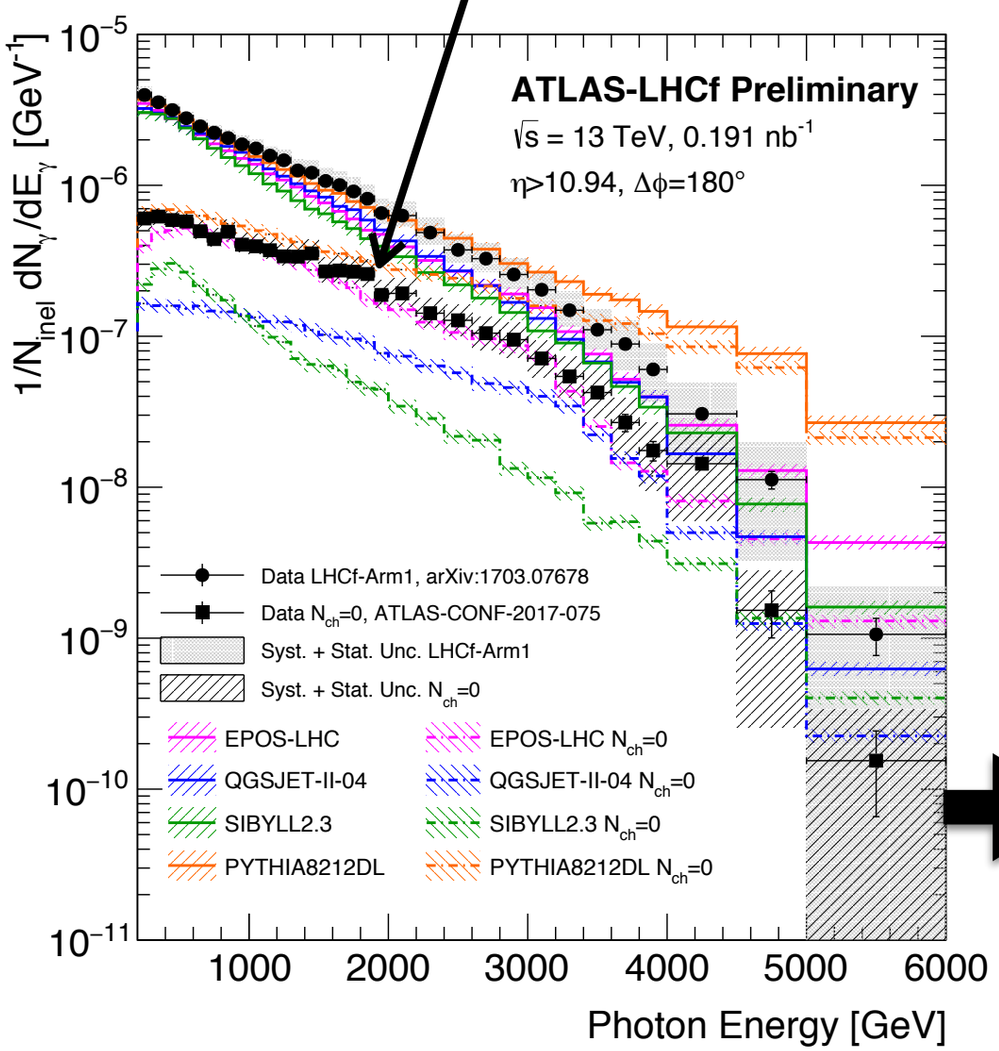




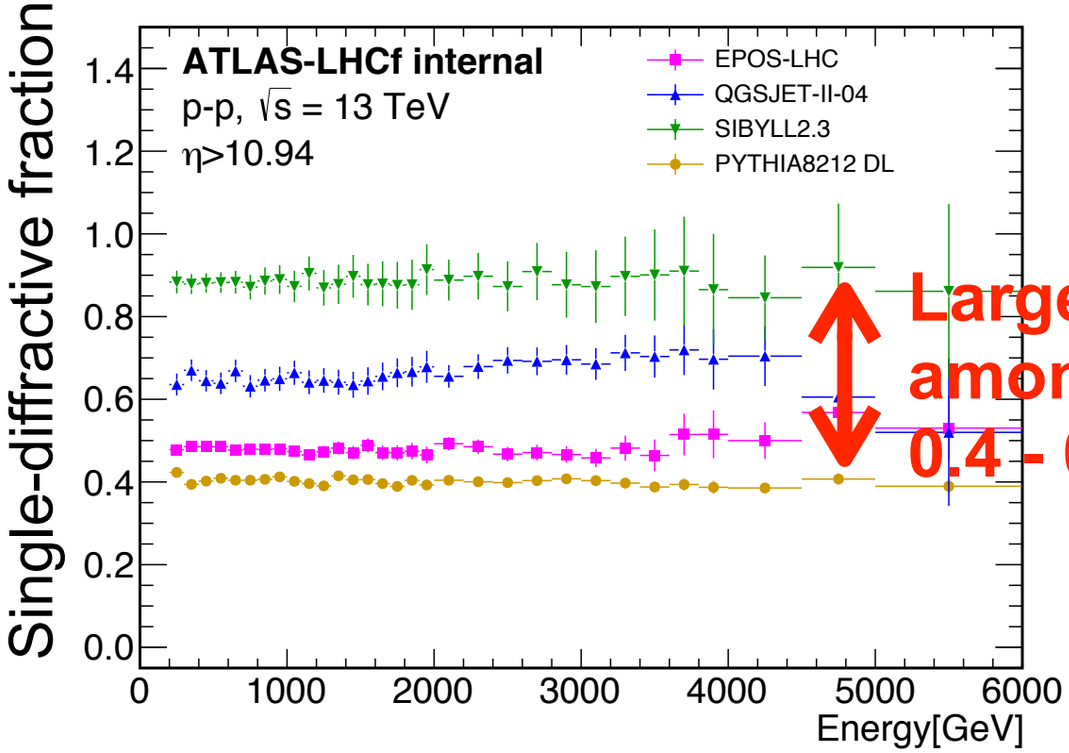
- At η>10.94, the ratio of data increased from 0.15 to 0.4. with increasing of the photon energy up to 4TeV.
- PYTHIA8212DL predicts higher fraction at higher energies.
- SIBYLL2.3 show small fraction compare with data at η>10.94.
- At 8.81 < η < 8.99, the ratio of data keep almost constant as 0.17.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

Update plan of the joint analysis

Diffractive (=Single+Double)

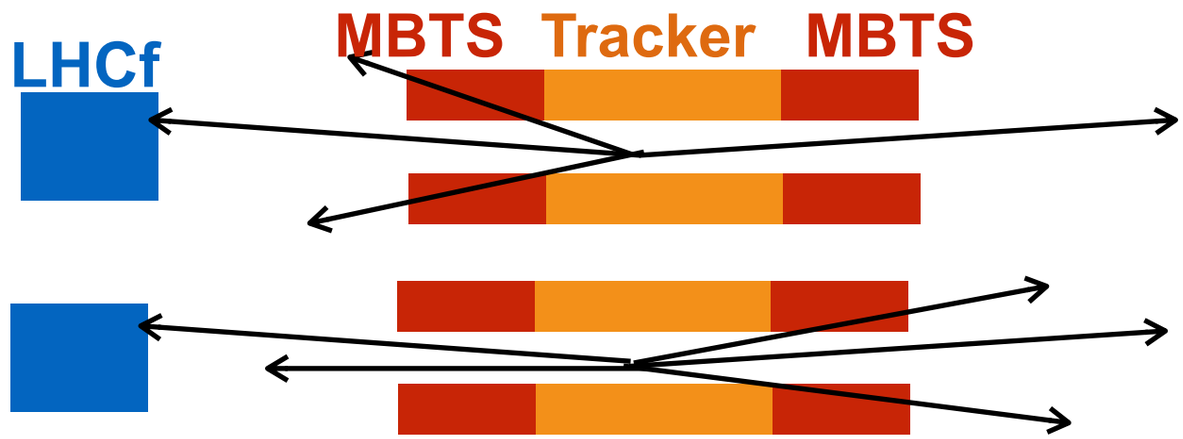


How much fraction of single diffractive in the selected events ?



Large difference among models 0.4 - 0.9

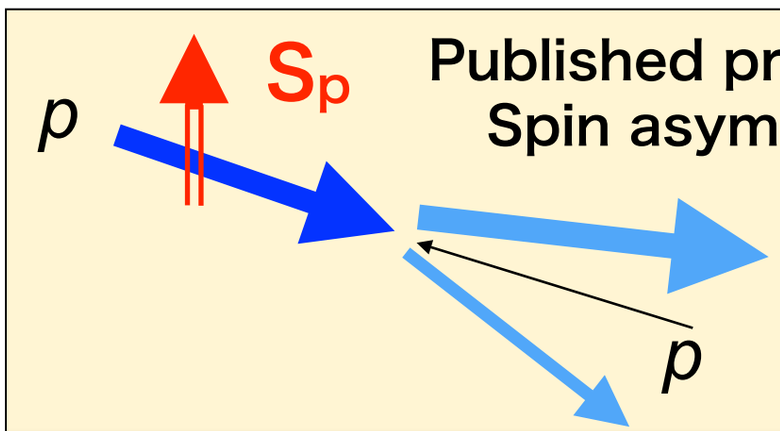
Going to measure the fraction by using ATLAS-**MBTS** (2.08 < |η| < 3.86)



RHICf experiment

RHIC at BNL

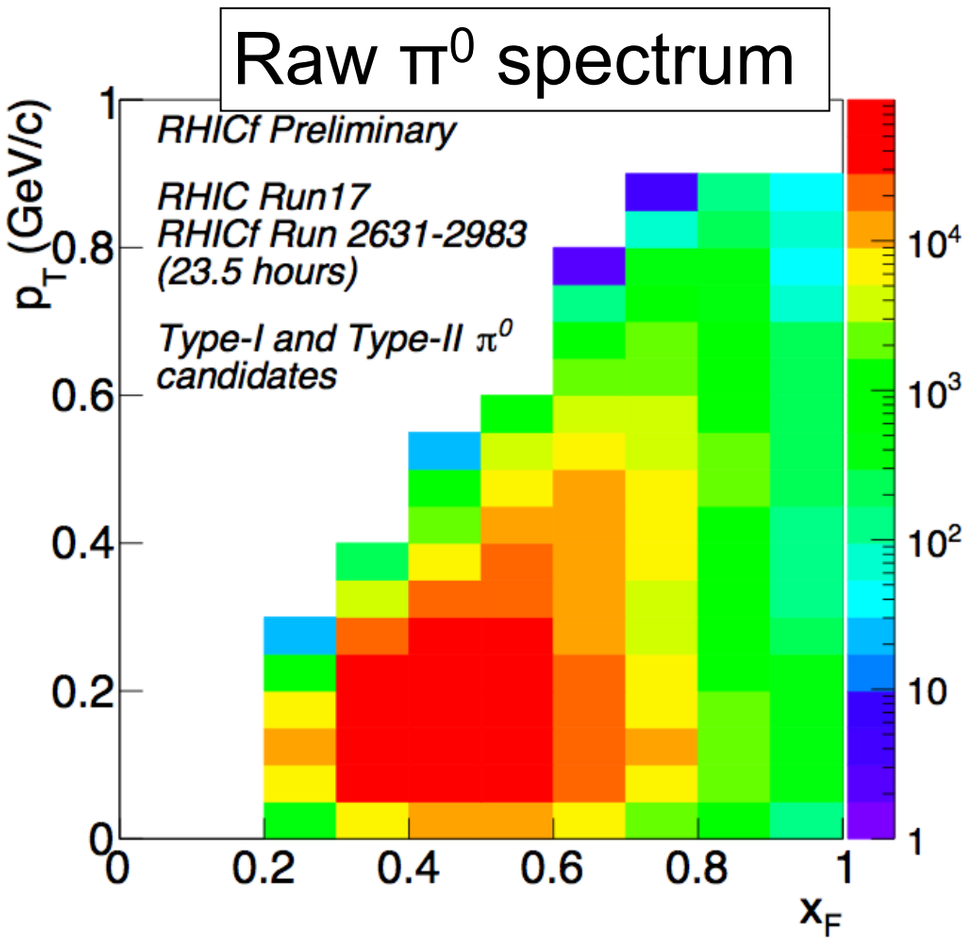
- **p+p $\sqrt{s}$ = 510 GeV**
  (polarized beam)
- Operation in June 2017.
- Test of energy scaling with the wide p_T range.
  (The X_F-pT coverage is almost same as LHCf @ p+p $\sqrt{s}$=7TeV)
- Common operation with STAR



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

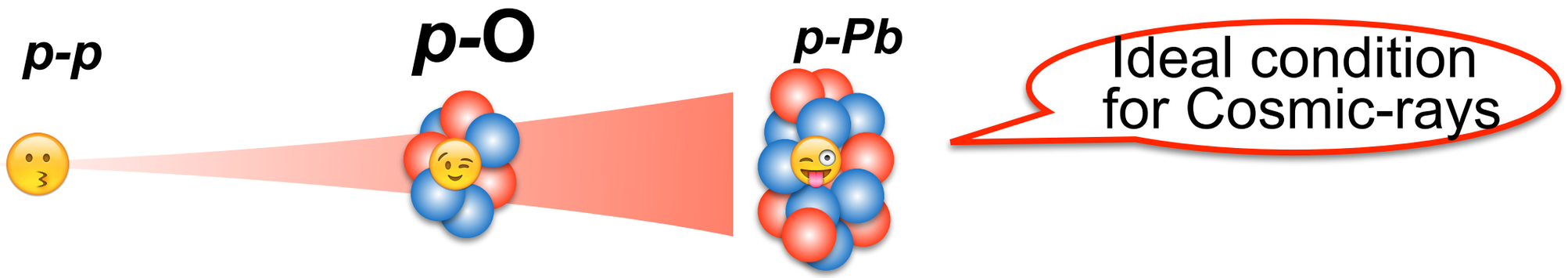
$$A_N = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$

Analysis for π^0 production cross-section measurement is on-going.



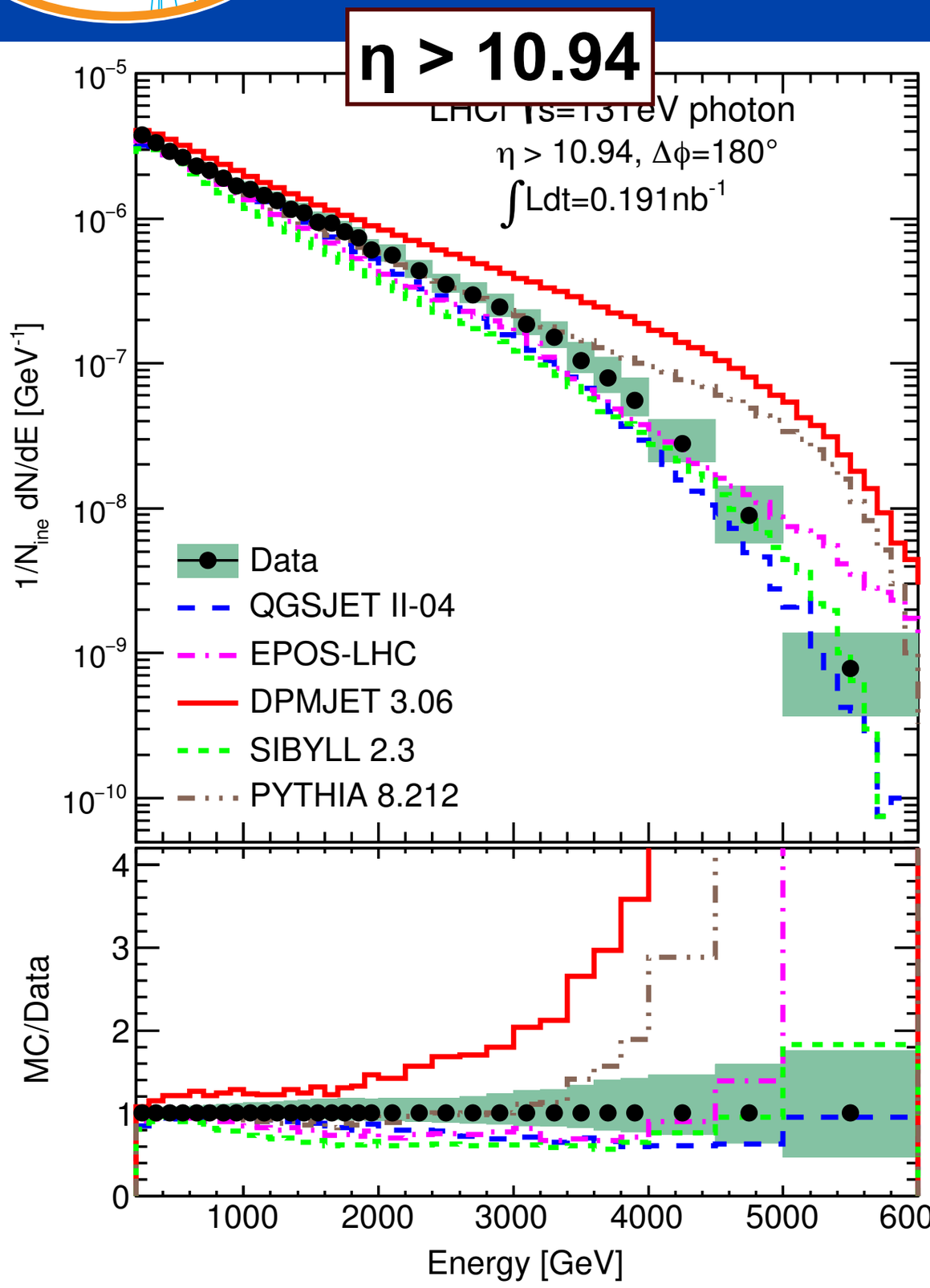
Summary

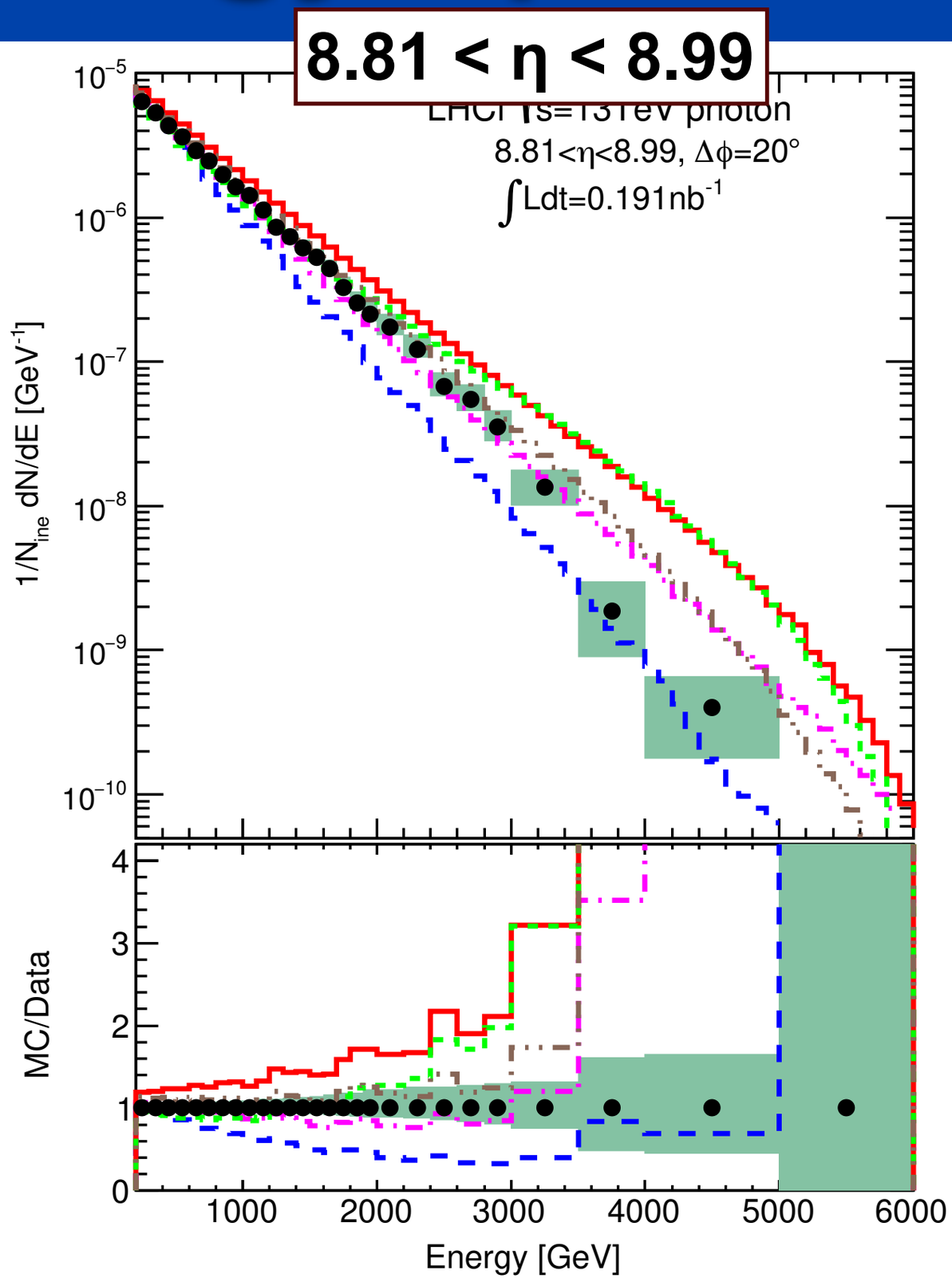
- Final/Preliminary results were shown.
  - Forward neutron cross-sections at p-p, $\sqrt{s}$ = 13 TeV
  - Forward photon energy spectra at p-Pb, $\sqrt{s}$ = 13 TeV
- On-going analyses
  - Diffractive contribution on forward photon production at p-p, $\sqrt{s}$ = 13 TeV from ATLAS-LHCf joint analysis.
  - Measurement of π^0 at p-p, $\sqrt{s}$ = 0.5TeV with RHICf
- Future plan
  - Operation with p-O collisions at LHC



Backup

Photon Energy Spectra





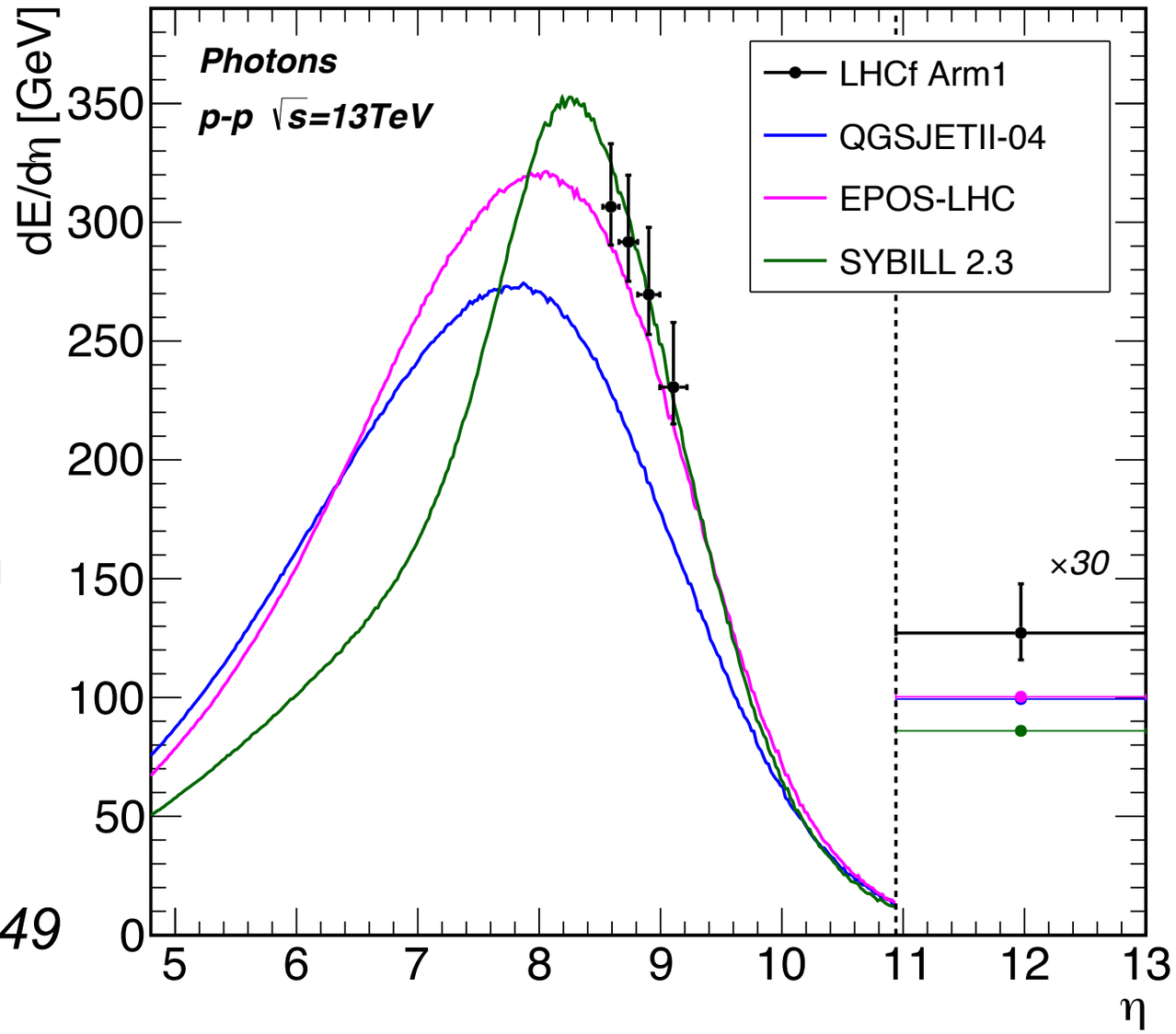
Photon Energy Flow

Energy Flow Calculation:

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

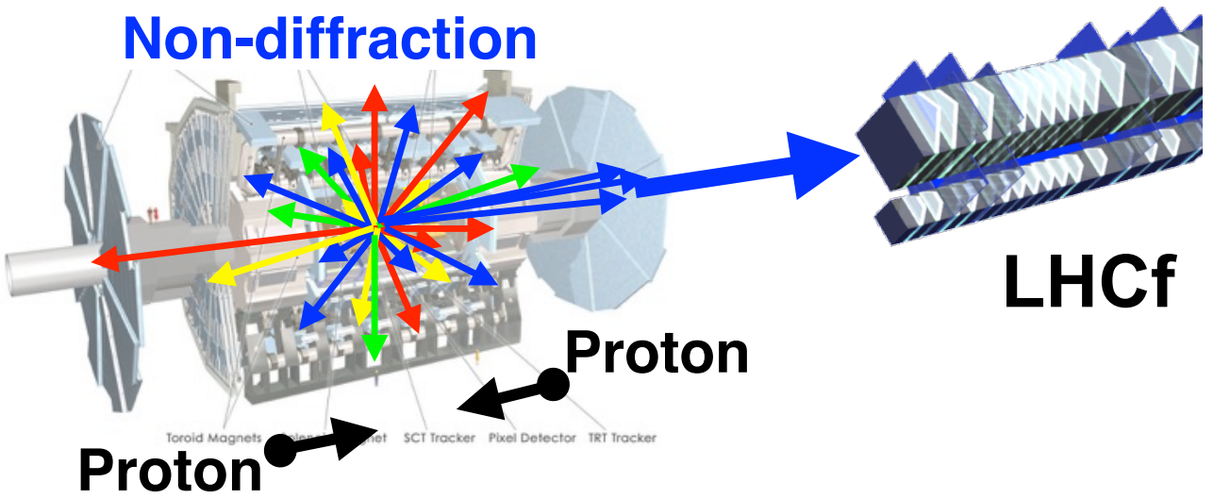
F(Ej) : Measured differential cross-section
Δη : The pseudo-rapidity range
C_{thr} : Correction factor for the threshold
200 GeV→ 0 GeV.

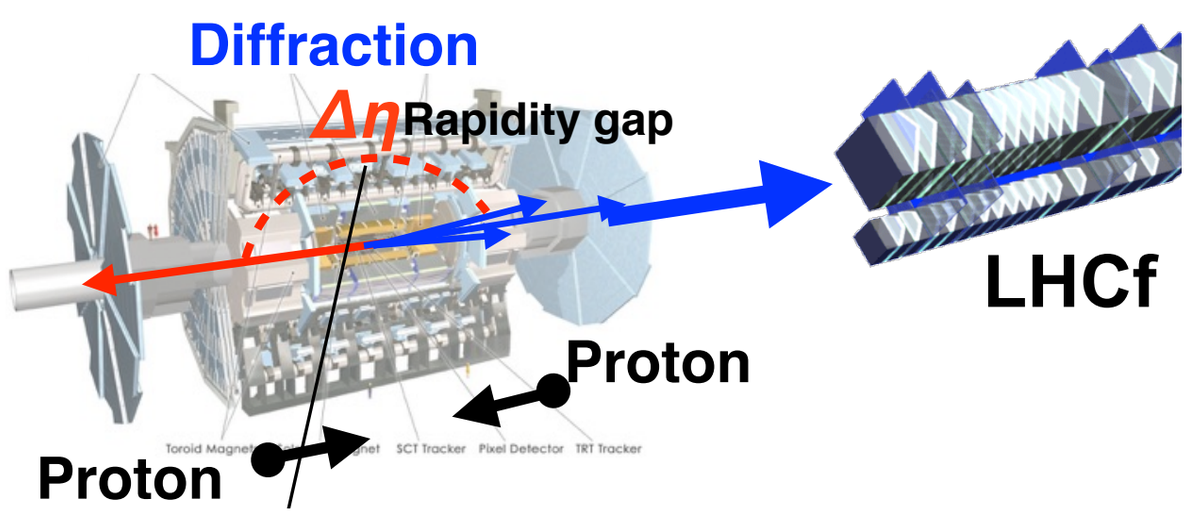
Ref: Y. Makino CERN-THESIS-2017-049

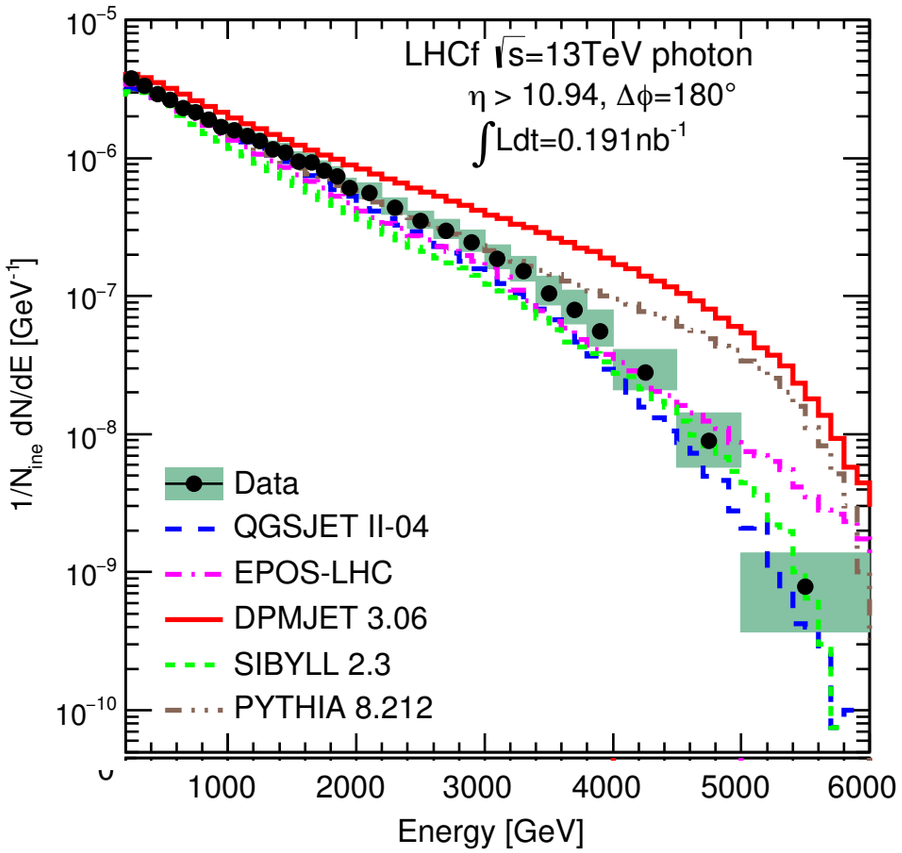


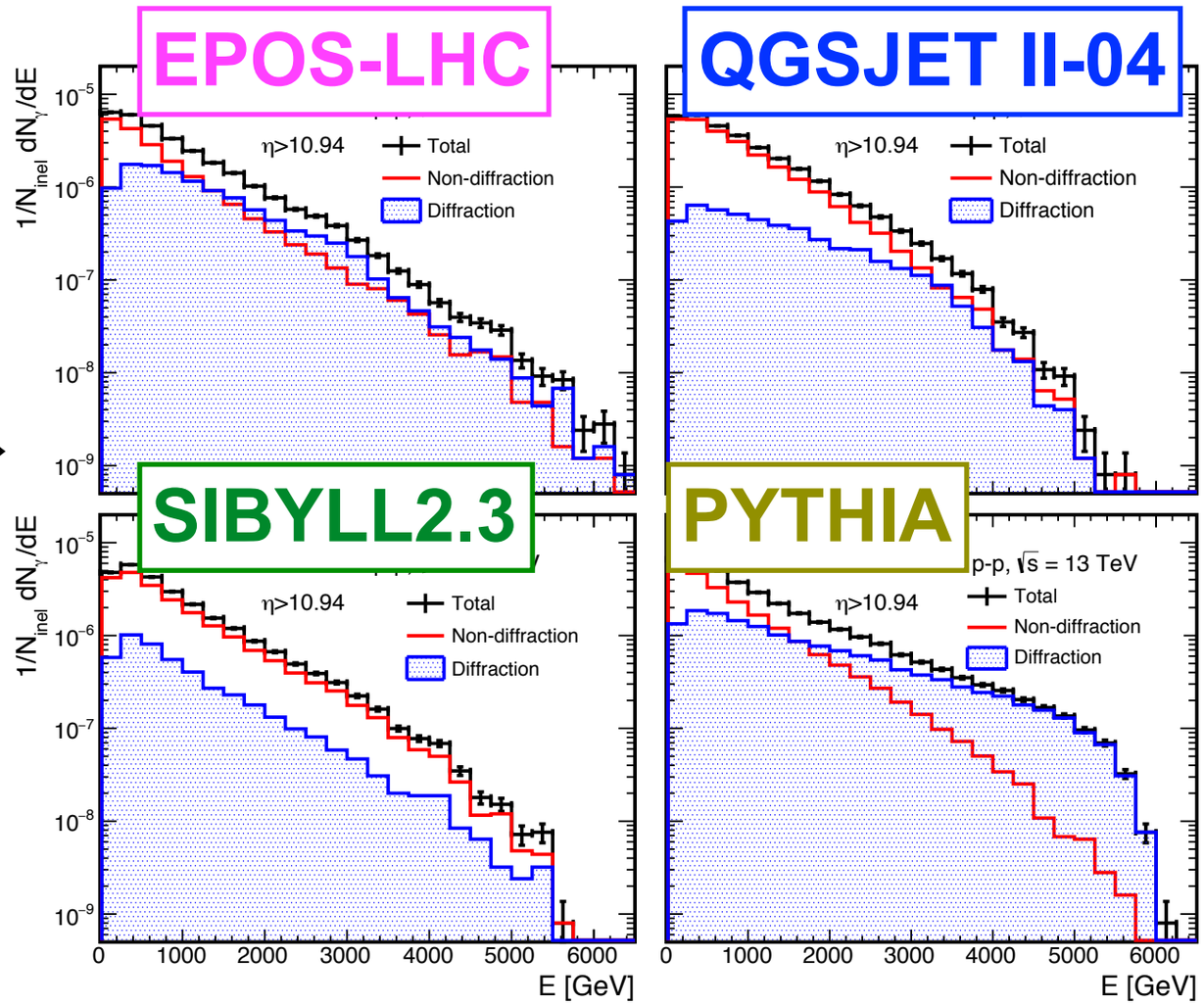
EPOS-LHC, SIBYLL2.3 Good agreement
QGSJET II-04 ~ 30% lower than data

Joint Analysis with ATLAS
- Selection of Diffractive interactions -



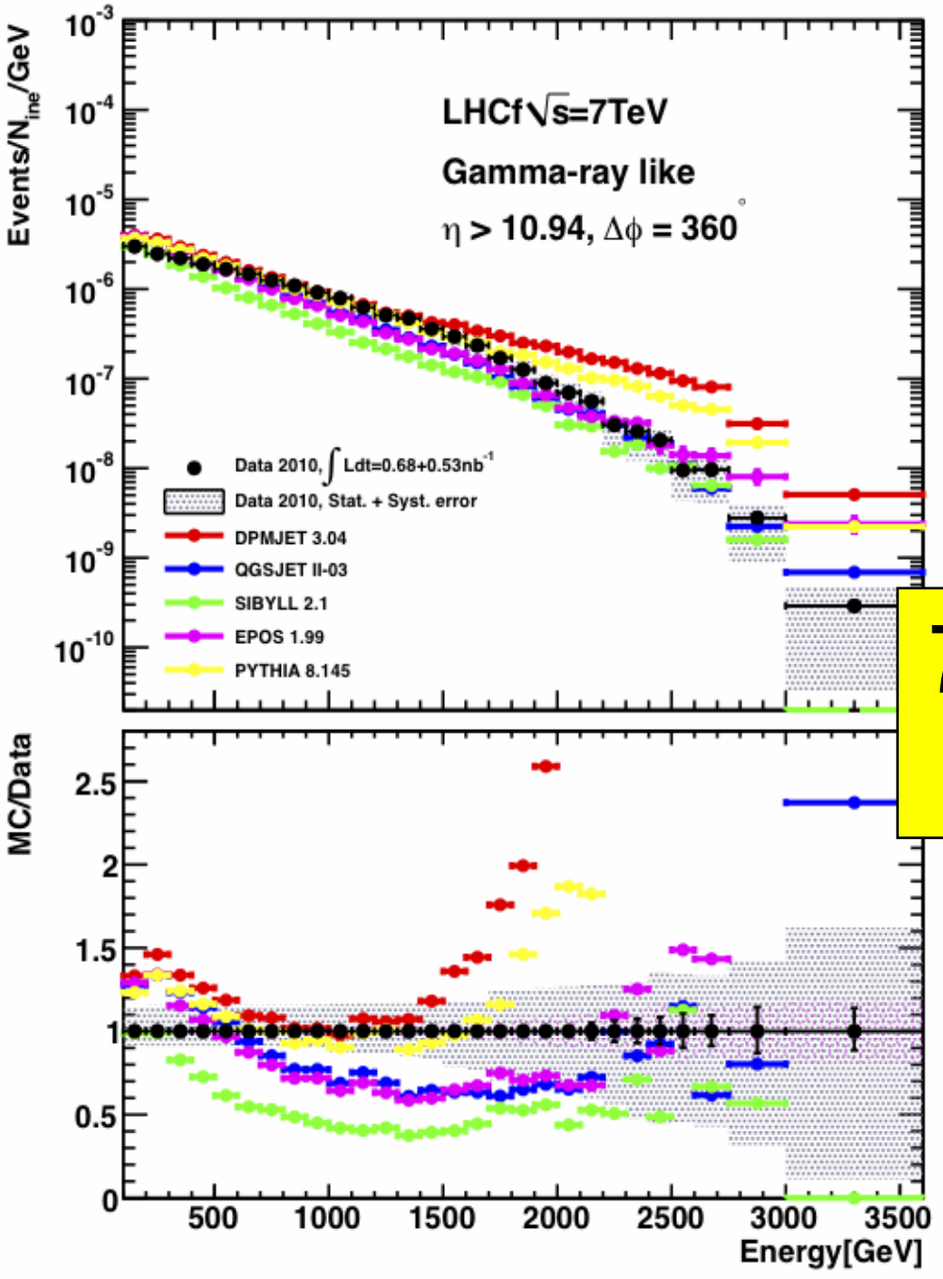


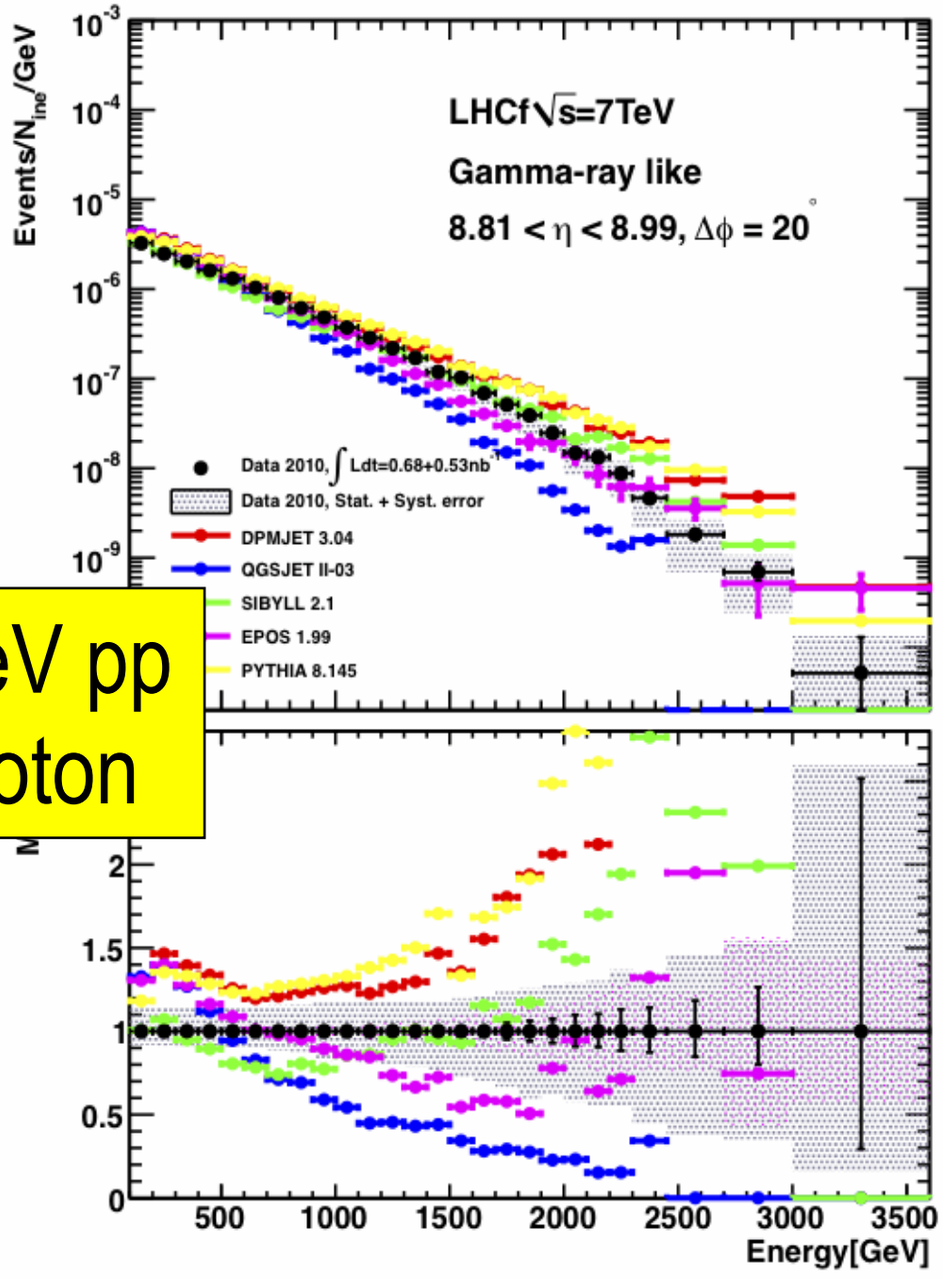




Poster by Q.Zhou; CRD131

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

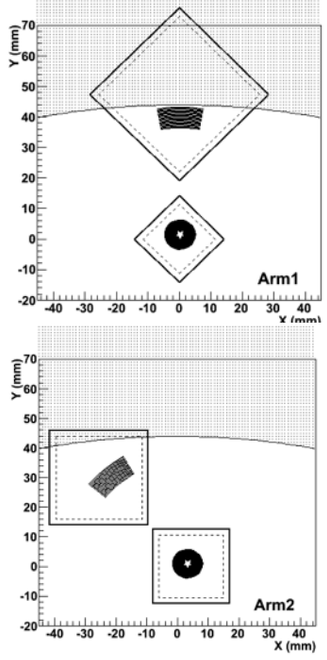




7 TeV pp photon

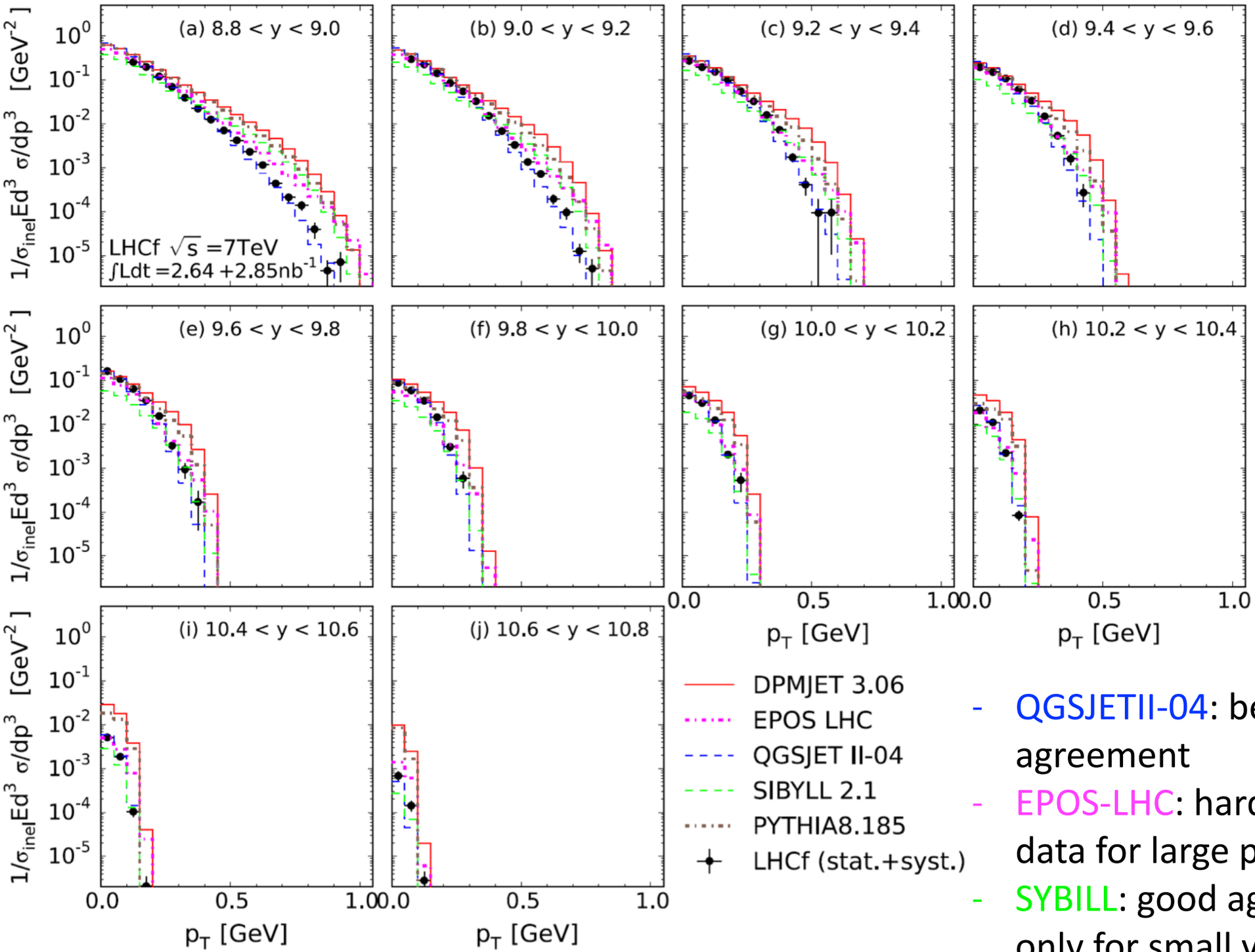
DATA
DPMJET 3.04
QGSJET II-03
SIBYLL 2.1
EPOS 1.99
PYTHIA 8.145

Syst.+Stat.



- 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

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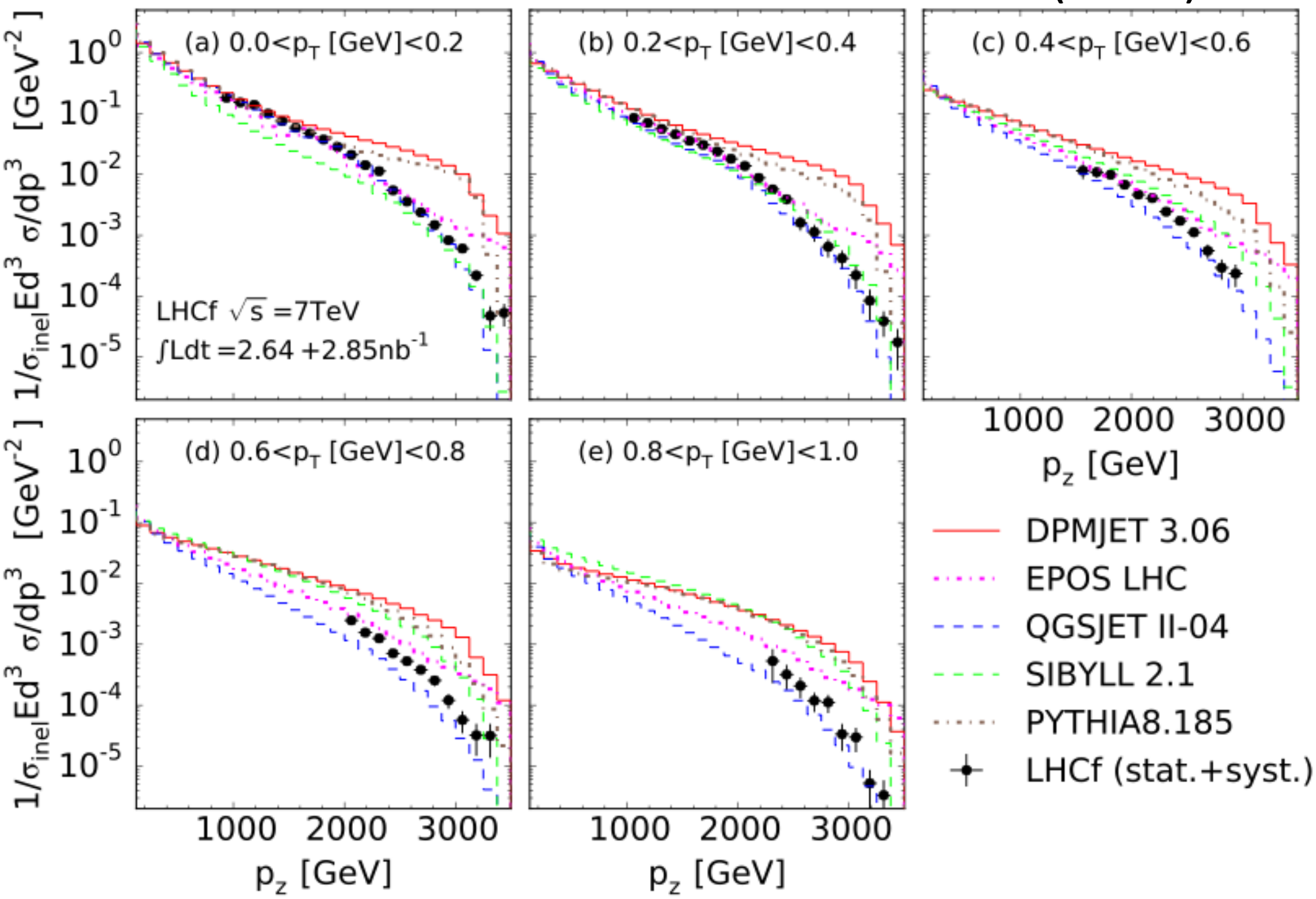

DPMJET and Pythia overestimate over all E-p_T range