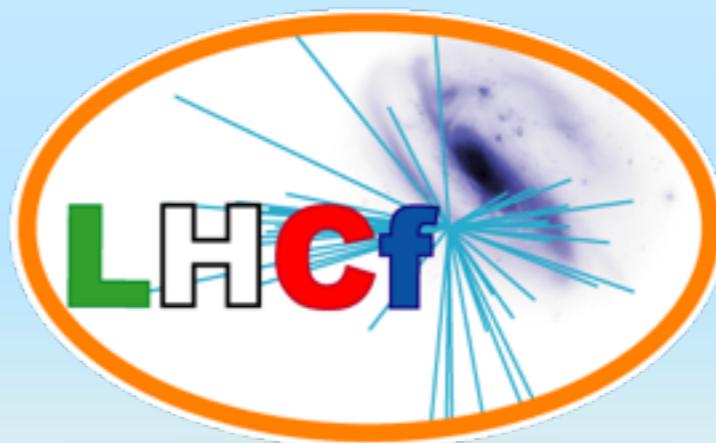


# Monte Carlo study of diffraction in p-p collisions at $\sqrt{s}=13\text{TeV}$ with the LHCf detector

Qi-Dong Zhou  
Nagoya University (JP)  
*on behalf of the LHCf collaboration*



***Low-X 2016, Gyongyos, Hungary, 6-11 Jun 2016***

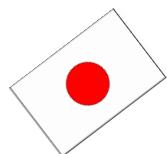
# The LHCf Collaboration

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# Outline

## ♦ Introduction

- LHCf experiment: detector, results.

## ♦ A MC study about diffractive and non-diffractive interaction contribution to the LHCf spectrum.

## ♦ ATLAS-LHCf common operation (MC study).

- Detector acceptance
- Efficiency and purity of diffraction identification by common data
- Low mass diffraction selection

## ♦ Summary

# The LHCf experiment

- ♦ Measure hadronic production cross section of neutral particles emitted in the very forward region of LHC.
- ♦ To afford the data for verifying and improving the hadronic interaction models.

LHCf and ATLAS are observing the particles from the same collisions, but different position

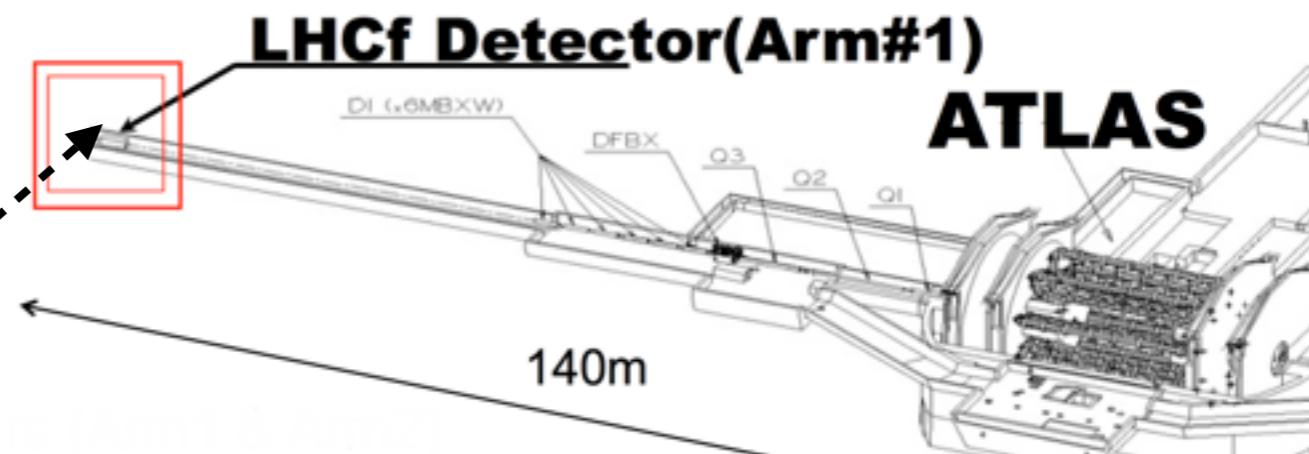


**LHCf Arm1**

**Neutron**

140m

**Collision**



**LHCf Arm2**

**Gamma**

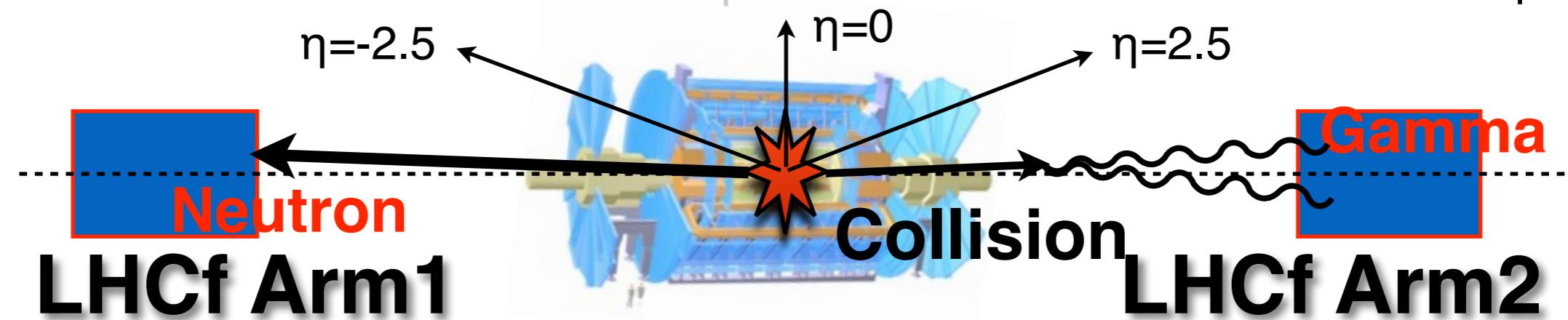
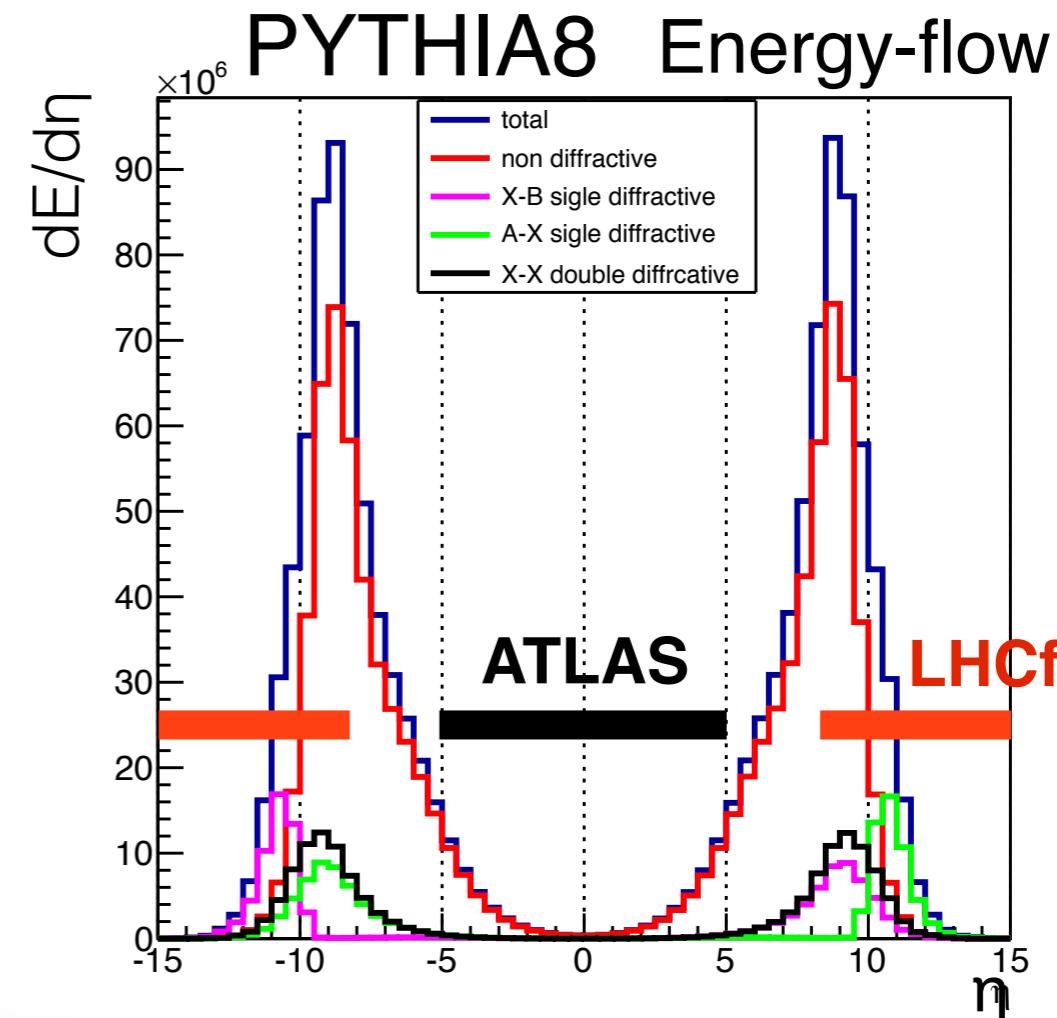
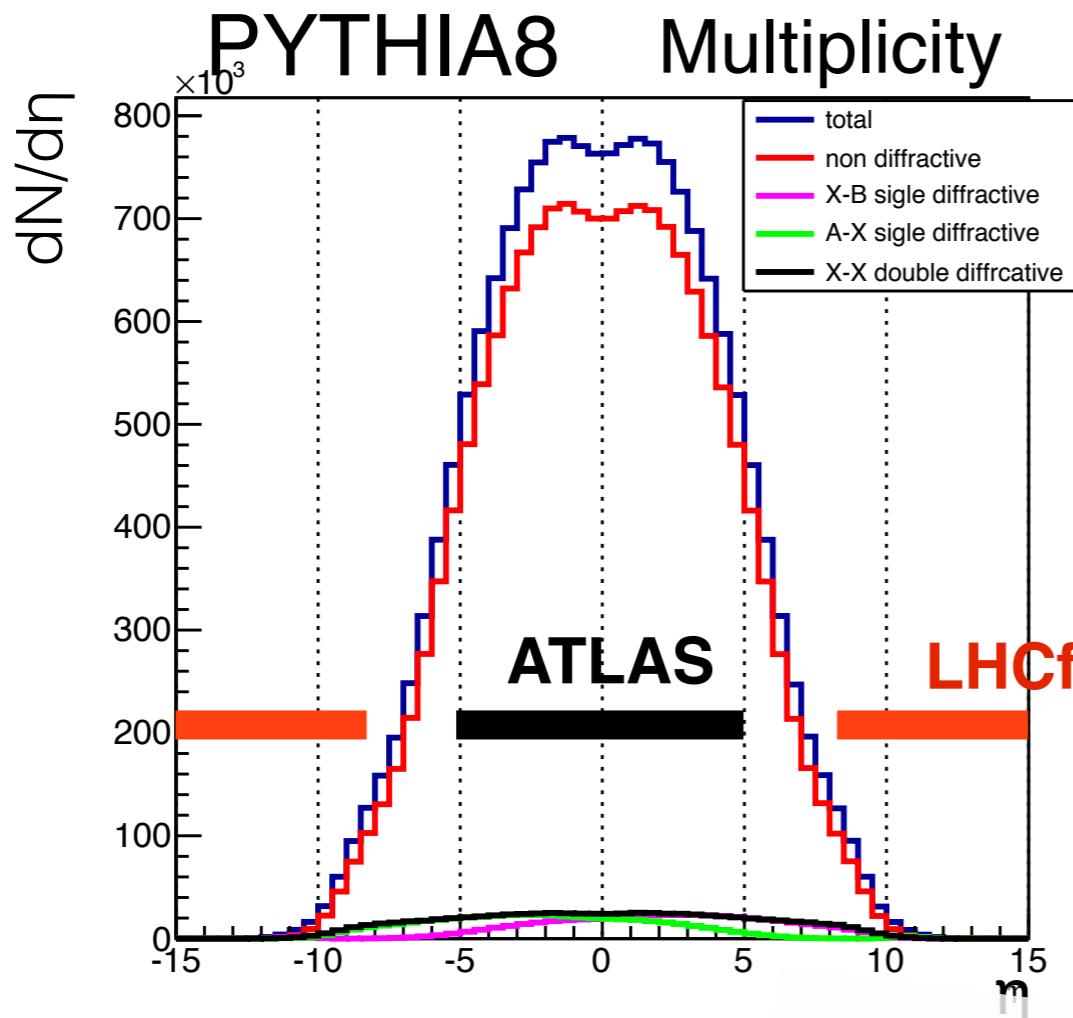
140m

LHCf detectors are sensitive to the ***soft processes***

# Particle density and energy flow at 13TeV

Most of secondary particles concentrate to the center

The most energetic secondary particles emitted to the very forward region (LHCf sensitive region)

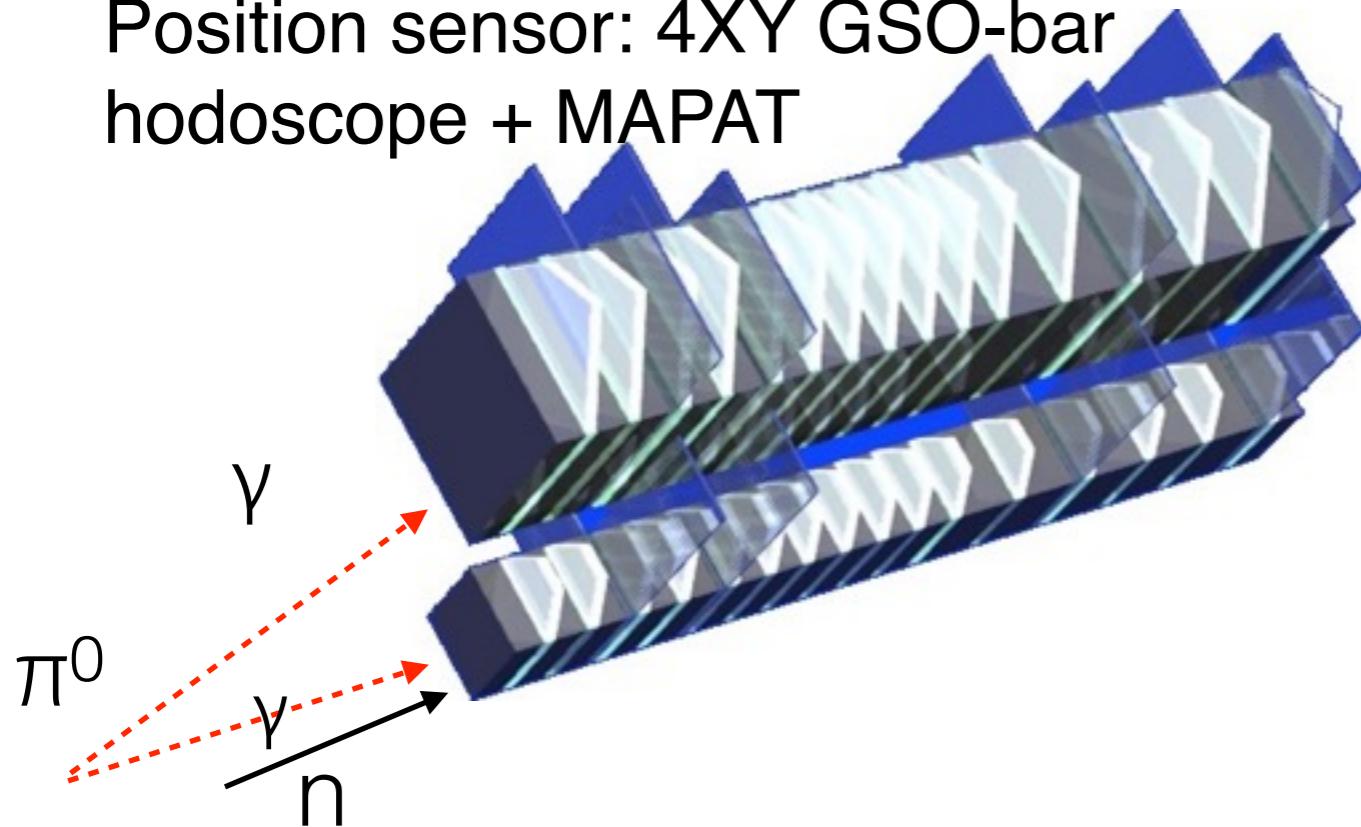


# The LHCf calorimeter

- Two imaging sampling shower calorimeters
- 44r.l. tungsten, 16 layers of GSO scintillators and 4 position sensitive layers
- The  $\eta$  coverage of the calorimeter:  $|\eta|>8.4$

Arm1 detector

Position sensor: 4XY GSO-bar  
hodoscope + MAPAT



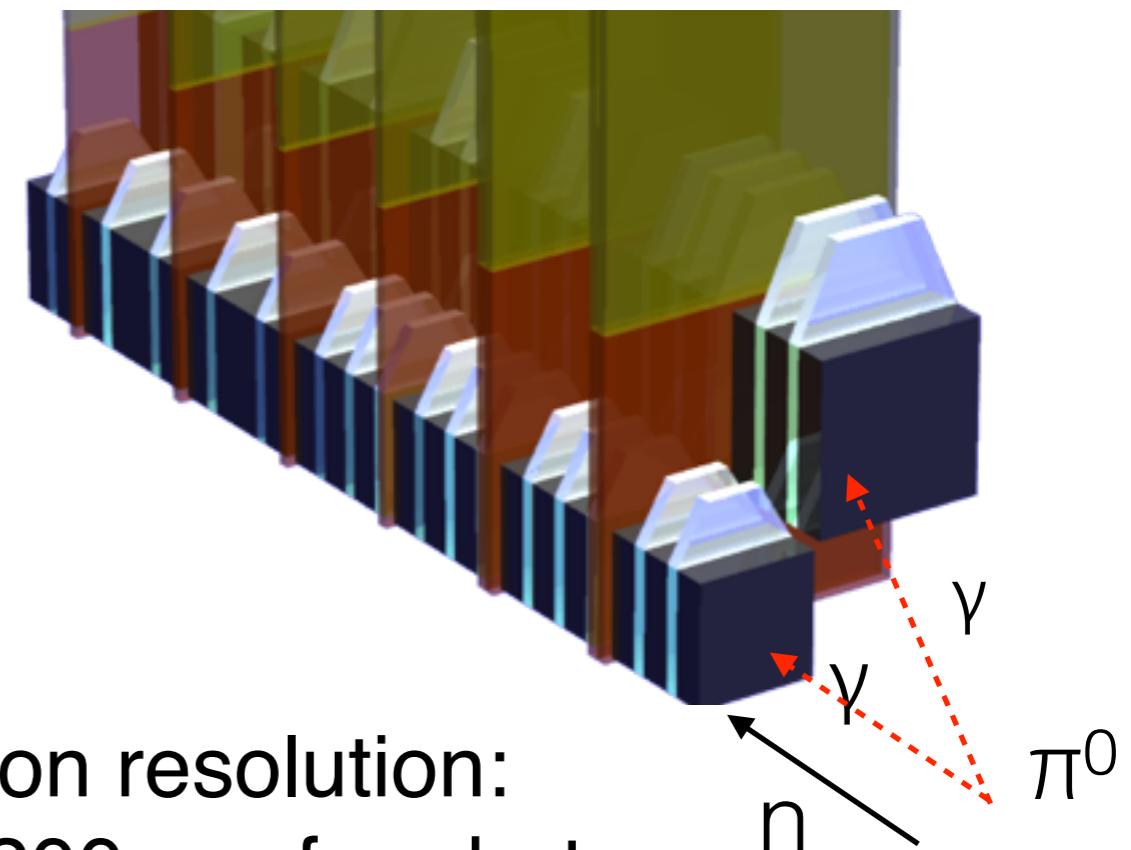
Energy resolution:(>100GeV)

<5% for photons

40% for neutrons

Arm2 detector

Position sensor:  
4XY silicon strip detectors



Position resolution:

<200 $\mu$ m for photons

<1mm for neutrons

# Operations and schedule at the LHC

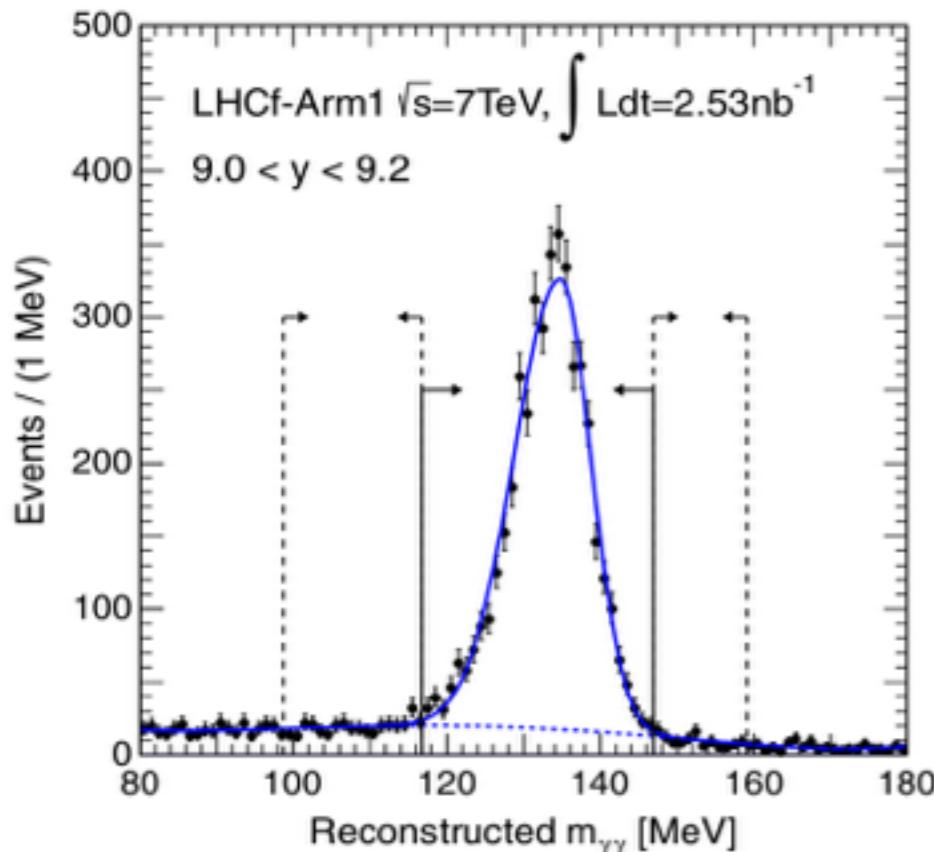
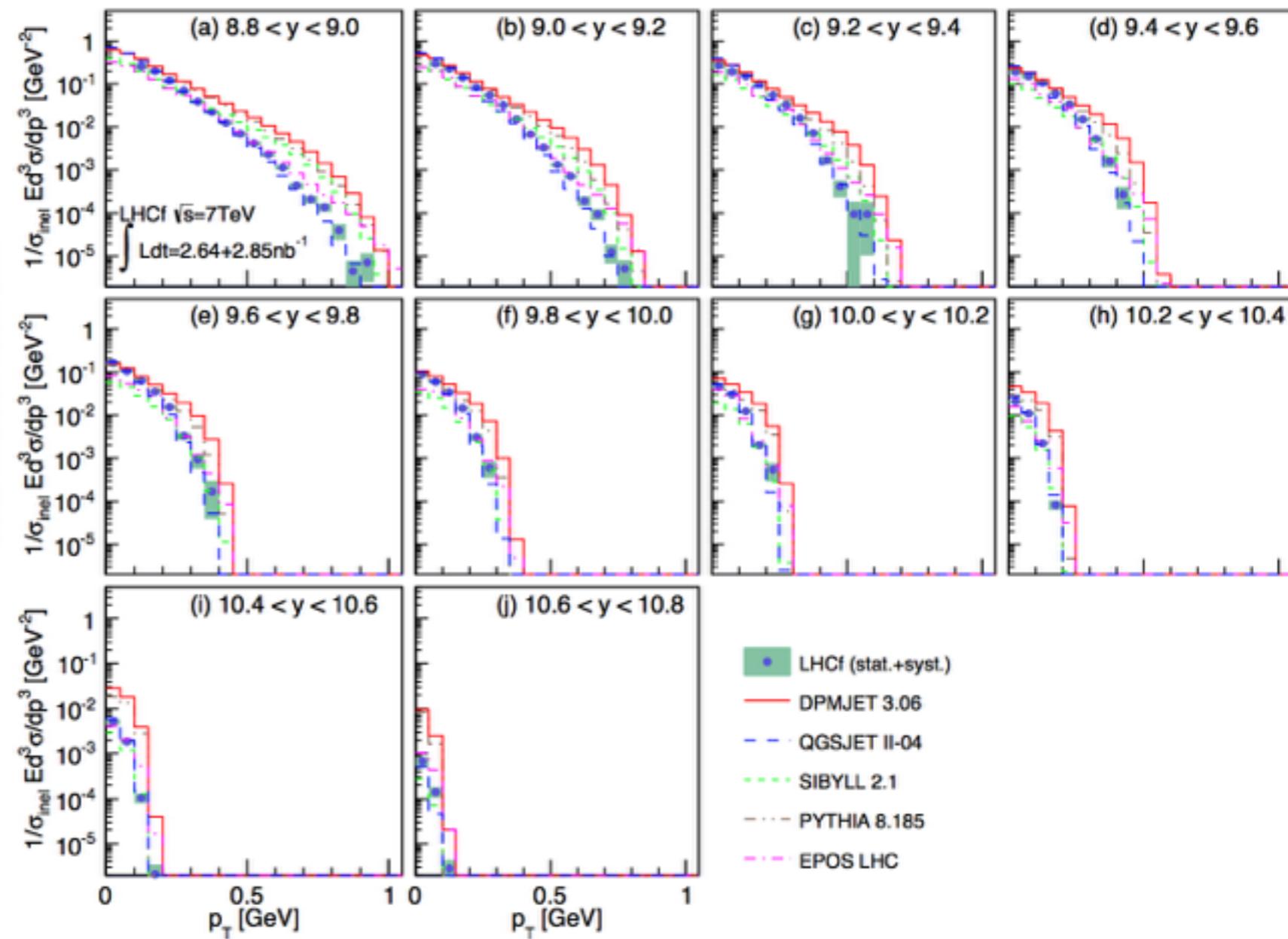
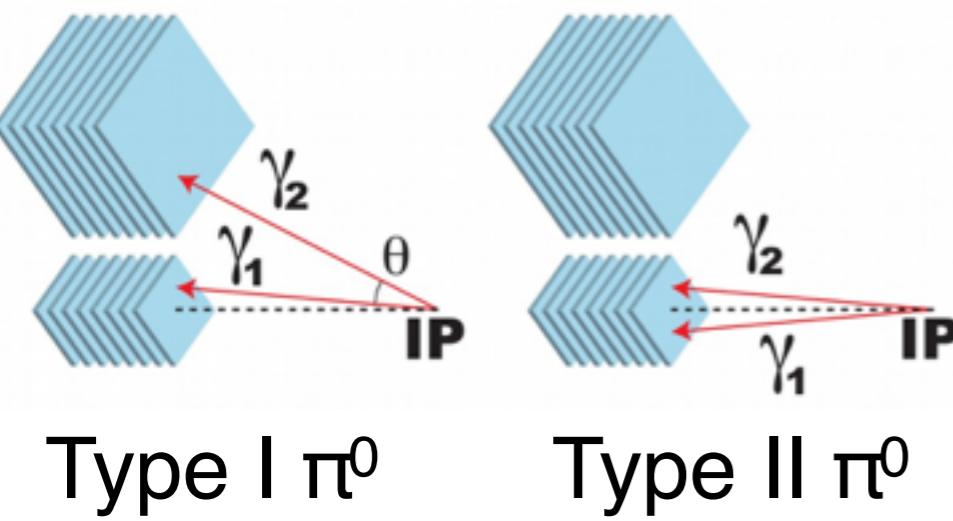
- December 2009 ~ July 2010
  - p+p @ 900GeV
  - p+p @ 7TeV
- January, February~ 2013 (only arm2)
  - p+Pb @ 5.02TeV
  - p+p @ 2.76TeV
- June 2015
  - p+p @ 13TeV
- November or December 2016
  - p+Pb @ 8.1TeV (only arm2)

# Results

	Photon	Neutron	$\pi^0$
<b>p+p 900GeV</b>	Phys. Lett. B 715, (2012)298-303		
<b>p+p 2.76TeV</b>			arXiv:1507.08764
<b>p+p 7TeV</b>	Phys. Lett. B 703, (2011)128-134	Phys. Lett. B 750, (2015)360-366	Phys. Lett. D 86, (2012) 092001 + arXiv:1507.08764
<b>p+p 13TeV</b>	Preparing	On-going	
<b>p+Pb 5.02TeV</b>			
<b>p+Pb 8.1TeV</b>			Phys. Rev. C 89, (2014) 065209

# $\pi^0$ at $\sqrt{s}=7\text{TeV}$ , p+p

$\pi^0$  was reconstructed from the two decayed  $\gamma$  observed by the LHCf

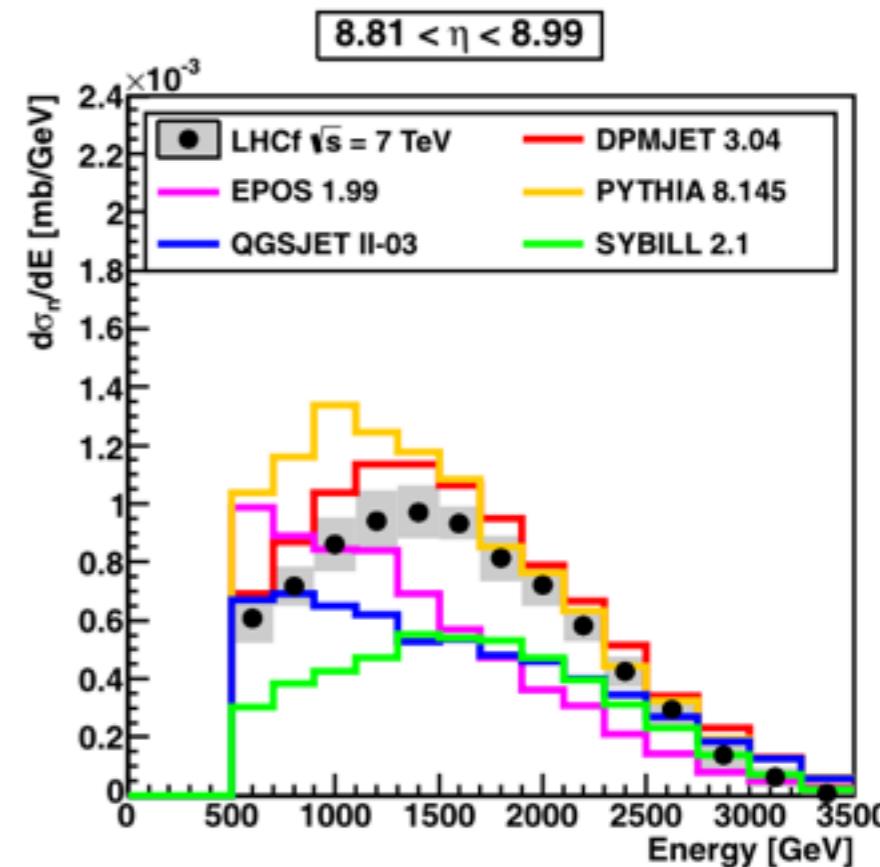
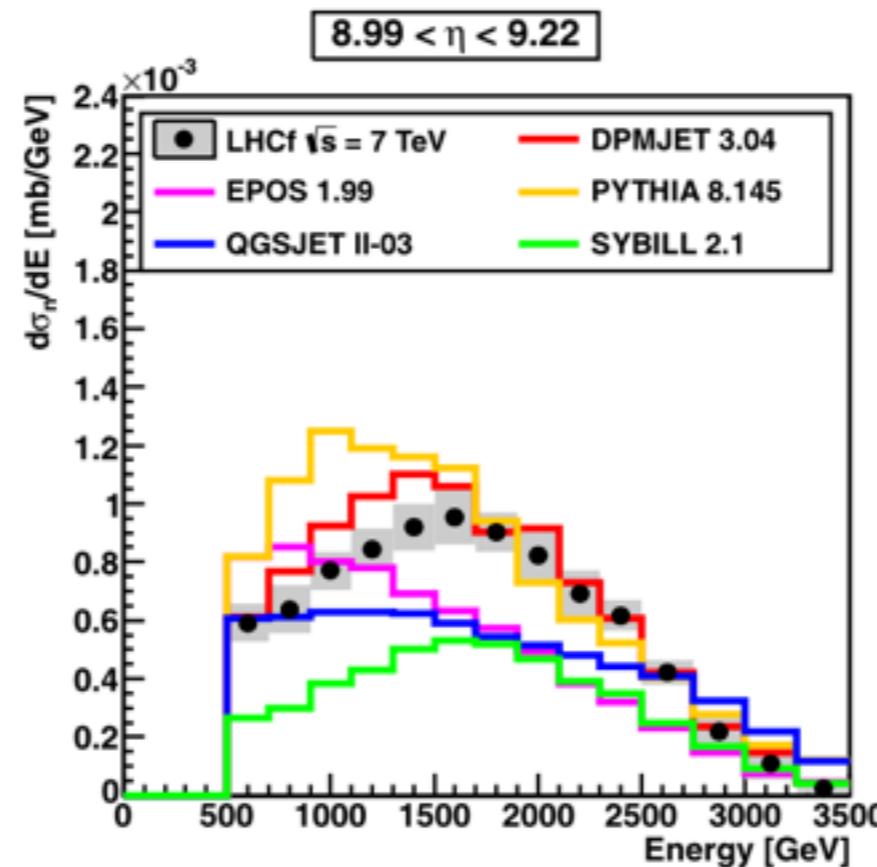
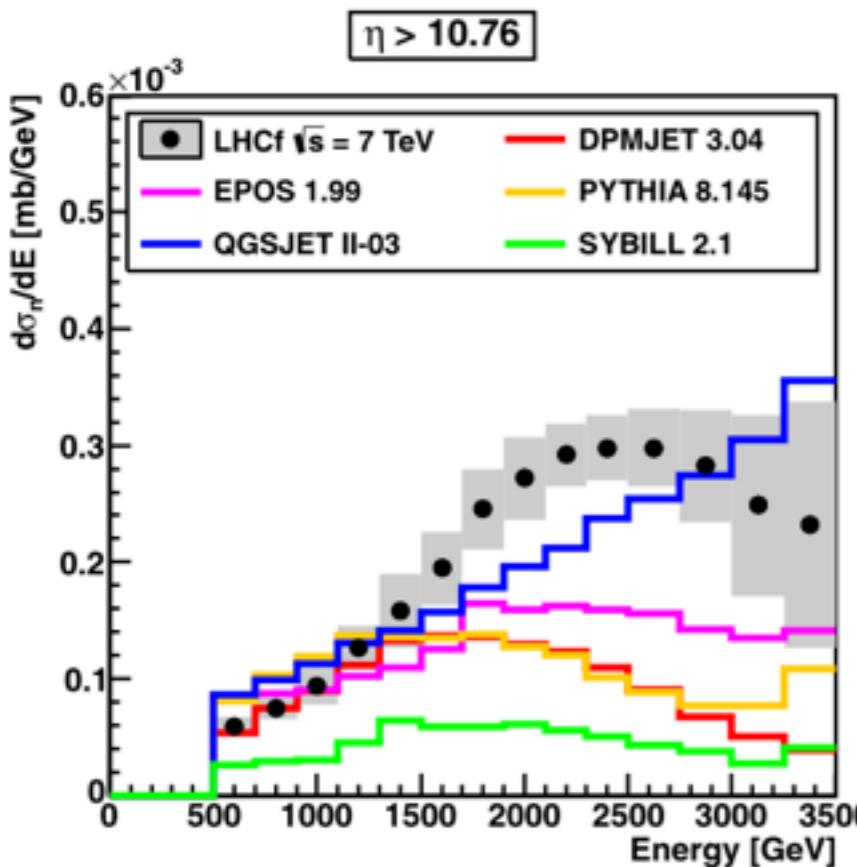
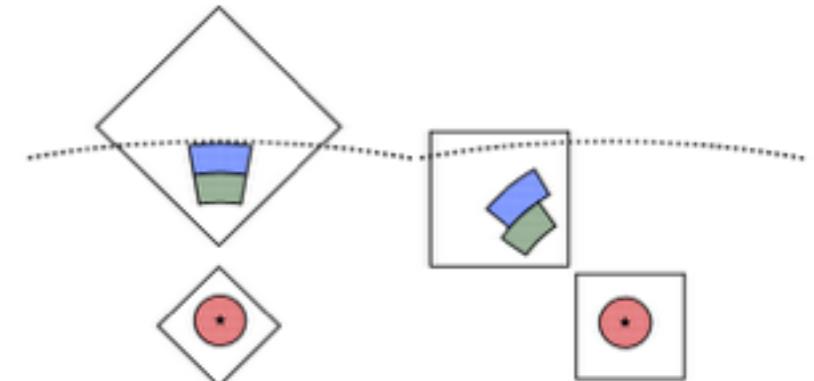


Good agreement with QGSJET-II-04  
EPOS-LHC at  $P_T < 0.5$  is OK

# Neutron at $\sqrt{s}=7\text{TeV}$ , p+p

<span style="background-color: #f08080; border: 1px solid black; padding: 2px;"></span>	Small tower ( $\eta > 10.76$ )
<span style="background-color: #6b8e23; border: 1px solid black; padding: 2px;"></span>	Large tower A ( $8.99 < \eta < 9.22$ )
<span style="background-color: #4a7ebb; border: 1px solid black; padding: 2px;"></span>	Large tower B ( $8.81 < \eta < 8.99$ )
<span style="border: 1px dashed black; padding: 2px;"></span>	Beam pipe shadow
*	Beam center

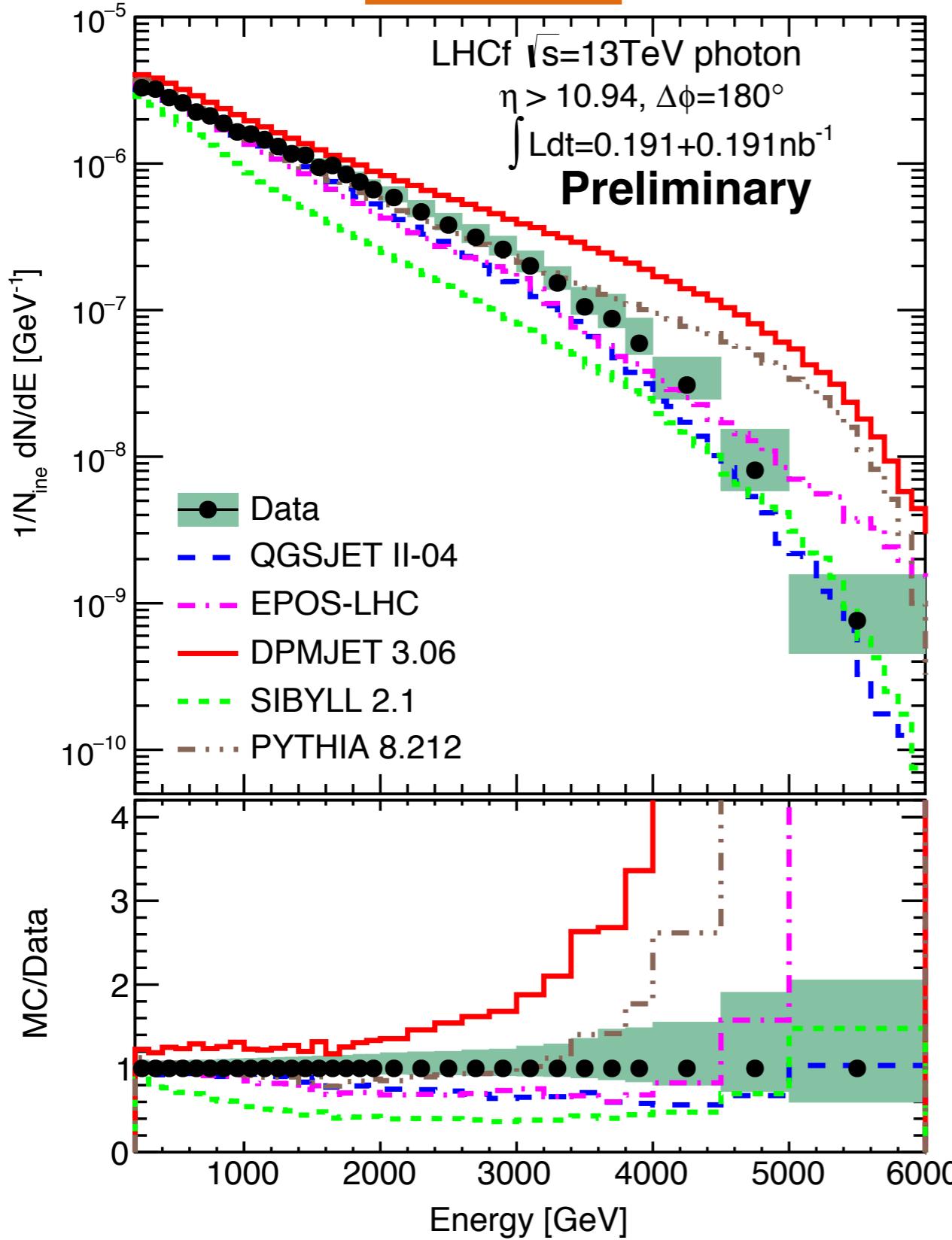
Forward neutron measurement can give constraint of forward baryon production in the models.



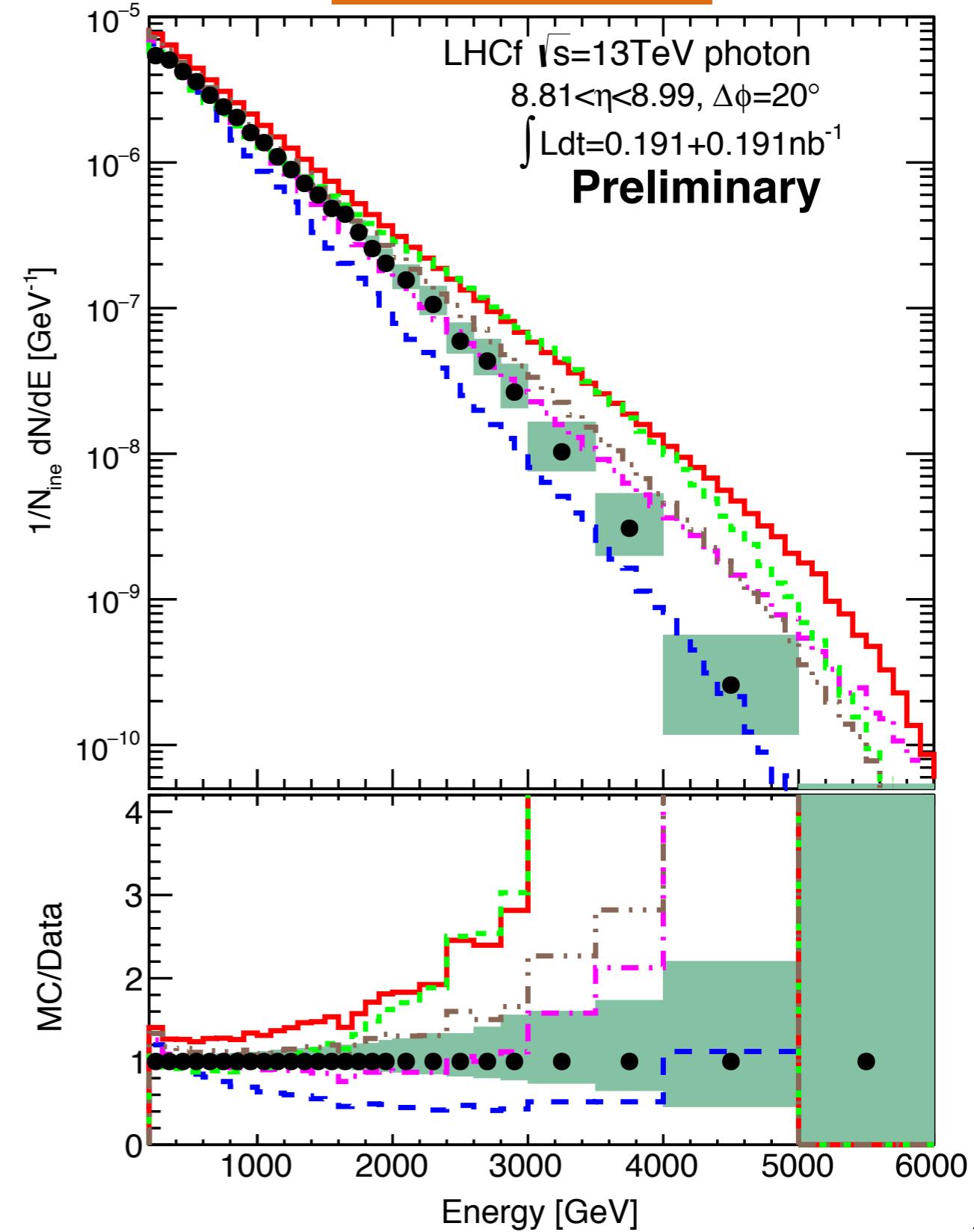
- No model can represent the data
- Models give a large discrepancy at  $\eta > 10.76$
- DPMJET3 represent the data better than the other models at  $8.81 < \eta < 9.22$

# Photon at $\sqrt{s}=13\text{TeV}$ , p-p

$\eta > 10.94$



$8.81 < \eta < 8.99$



# What's the source of the difference

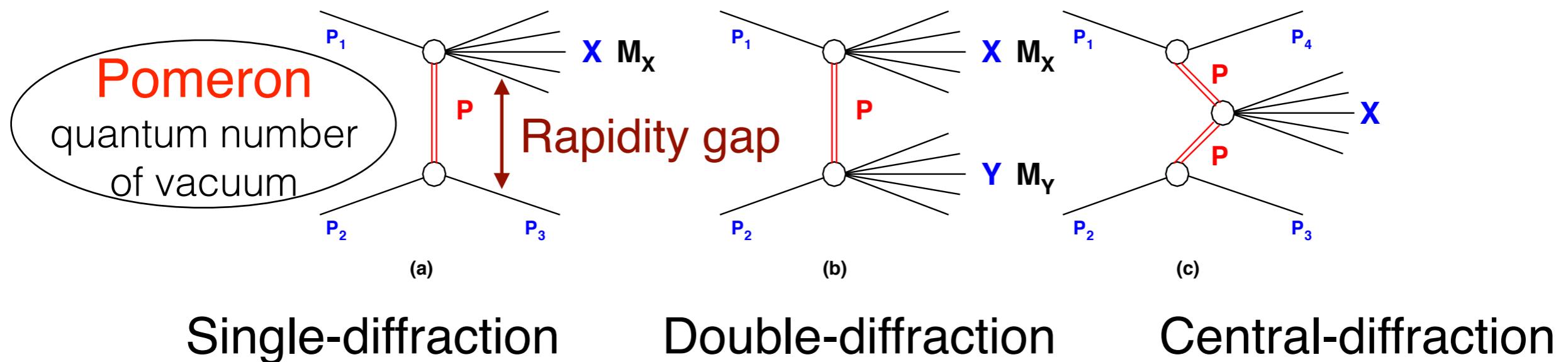
No MC simulation model can represent LHCf data perfectly

- Hard interactions can be predicted by using perturbative QCD.
- Soft interactions dominate by non-perturbative QCD,  
**phenomenological** models base on Regge theory proposed
- Diffractive dissociation belong to soft process.

Diffraction measurement is difficult issue for experiment.  
especially, low mass diffraction.

# Diffractive dissociation

Diffraction contribute 25%~30% of total cross sections.



Diffraction was described by pomeron based model, but the technic of calculation in each model is a little different

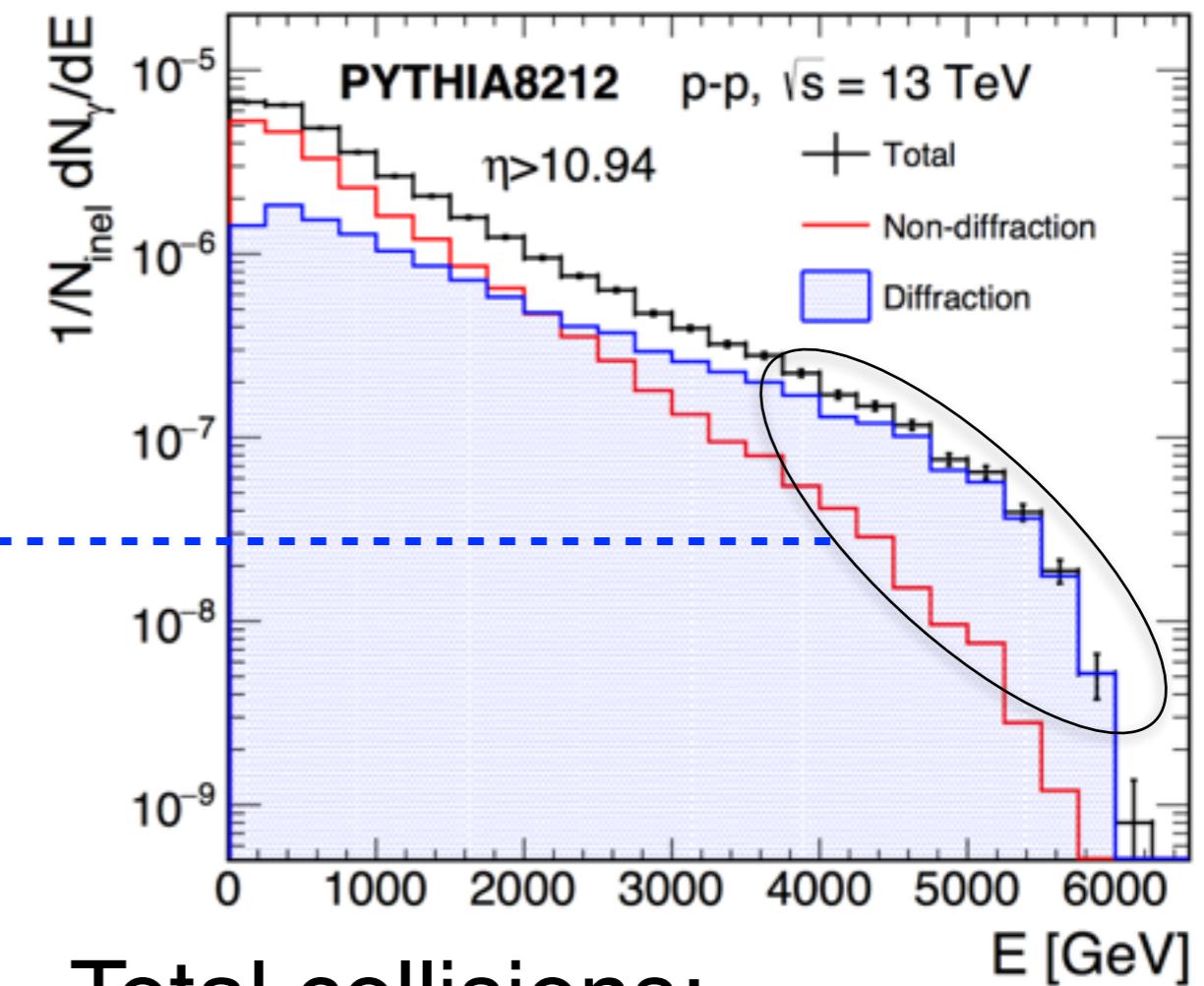
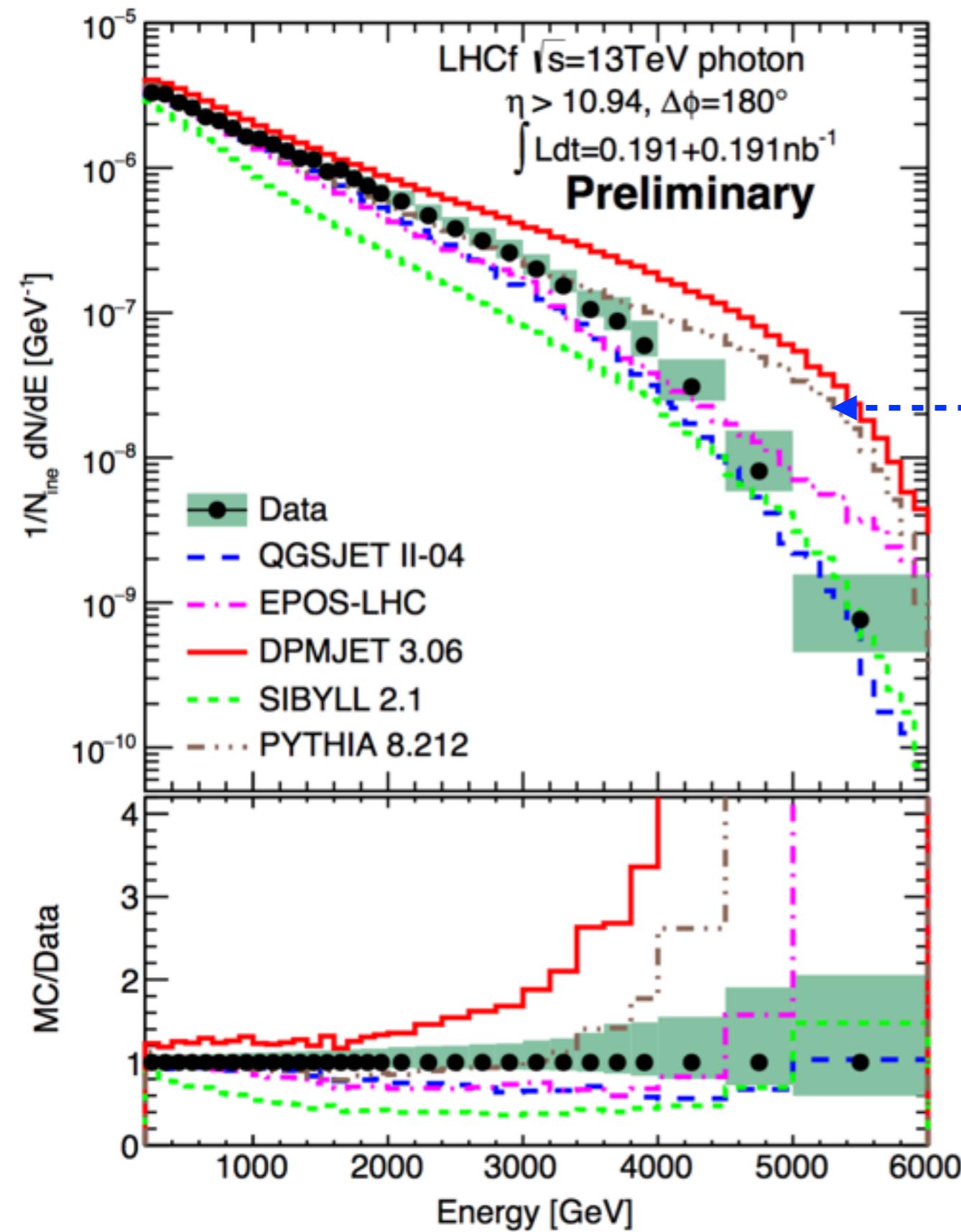
EPOS-LHC : cut diagrams (pomeron)

QGSJET-II-04: renormalized pomeron flux

SIBYLL2.1 : eikonal picture

# **Monte Carlo study about diffractive and non-diffractive interaction contribution to LHCf spectrum**

# Investigation of photon spectrum



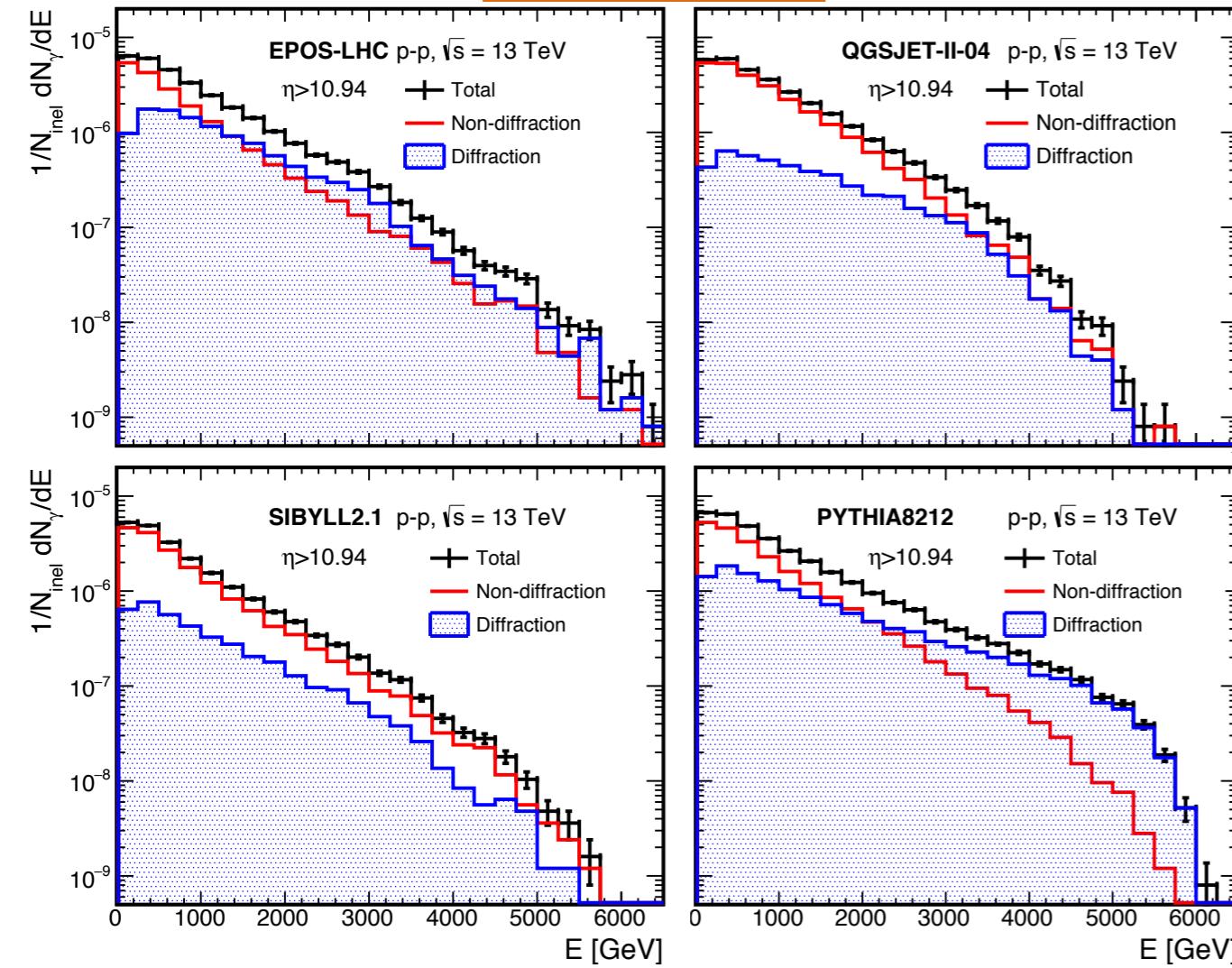
Total collisions:  
diffraction + non-diffraction

Diffraction = SD+DD+CD

The excess of PYTHIA8 at  $E>3\text{TeV}$   
due to over contribution from  
diffraction

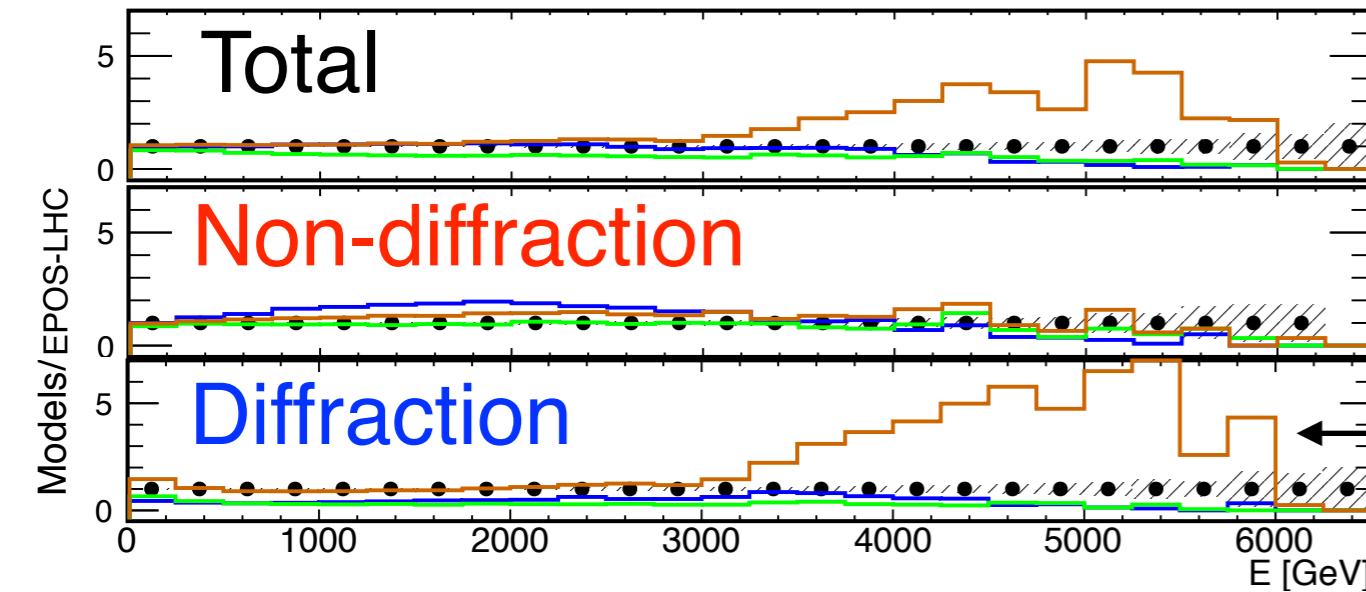
# Photon spectrum comparison

$\eta > 10.94$



Model comparison  
Total = diff. + non-diff.

EPOS-LHC	QGSJET-II-04
SIBYLL2.1	PYTHIA8212

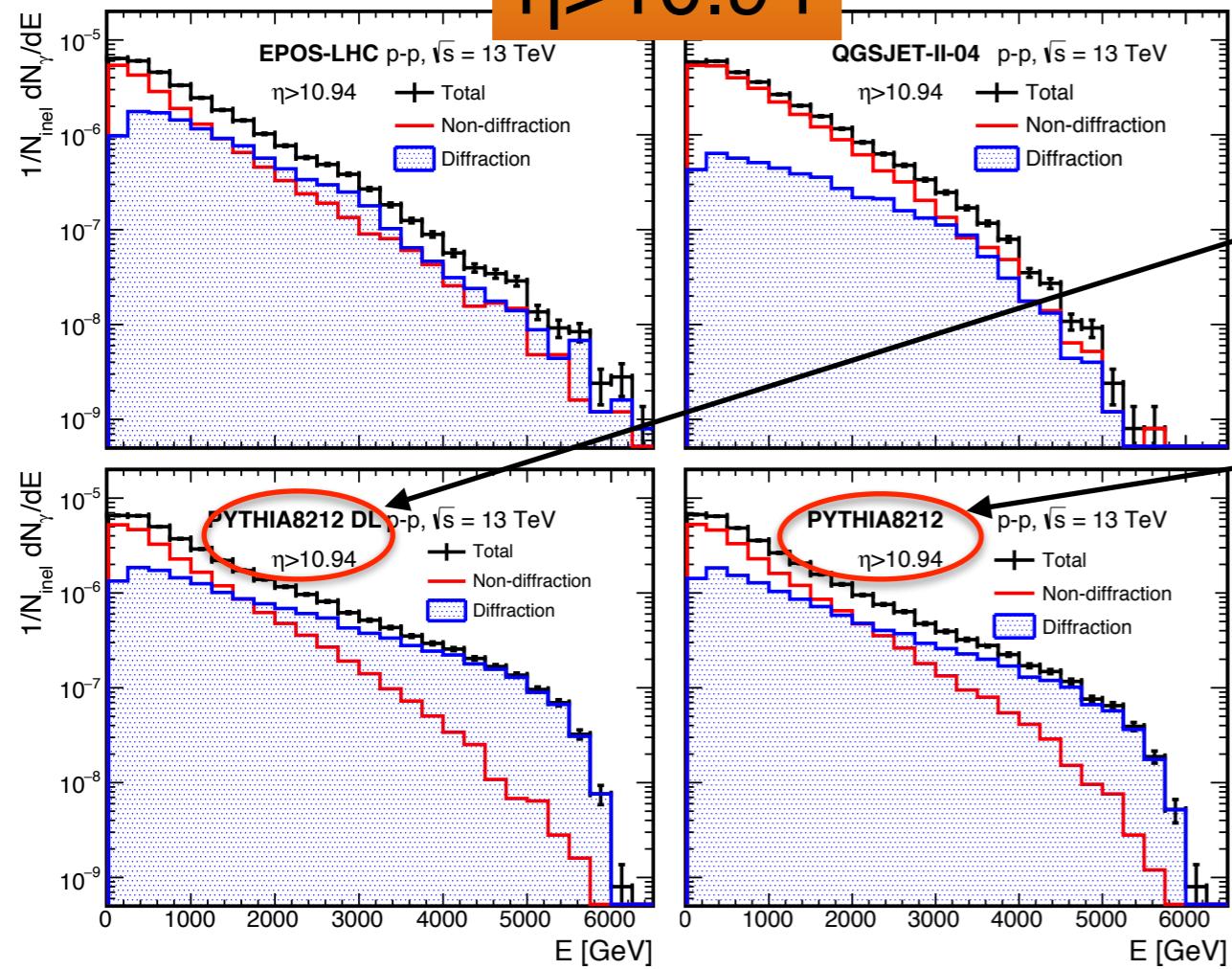


- EPOS-LHC
- QGSJET-II-04
- SIBYLL2.1
- PYTHIA8212

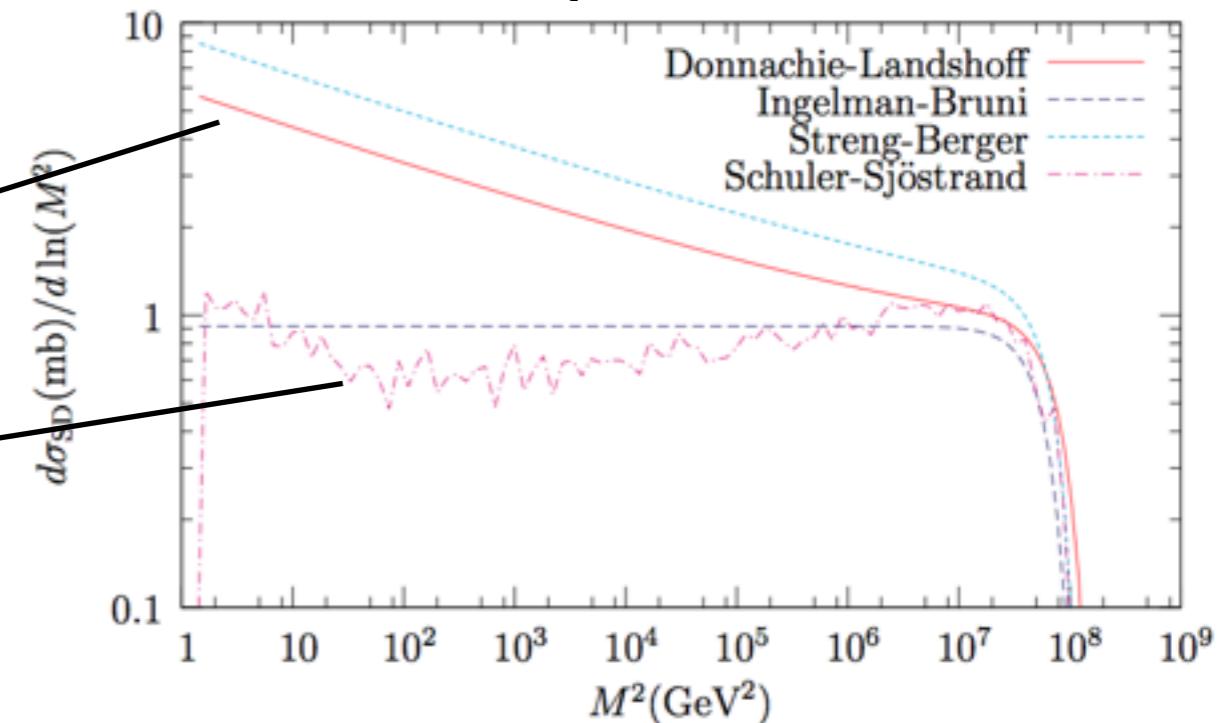
$$\frac{\text{Diffraction@PYTHIA8212}}{\text{Diffraction@EPOS - LHC}}$$

# Investigation of PYTHIA8 diffraction

$\eta > 10.94$

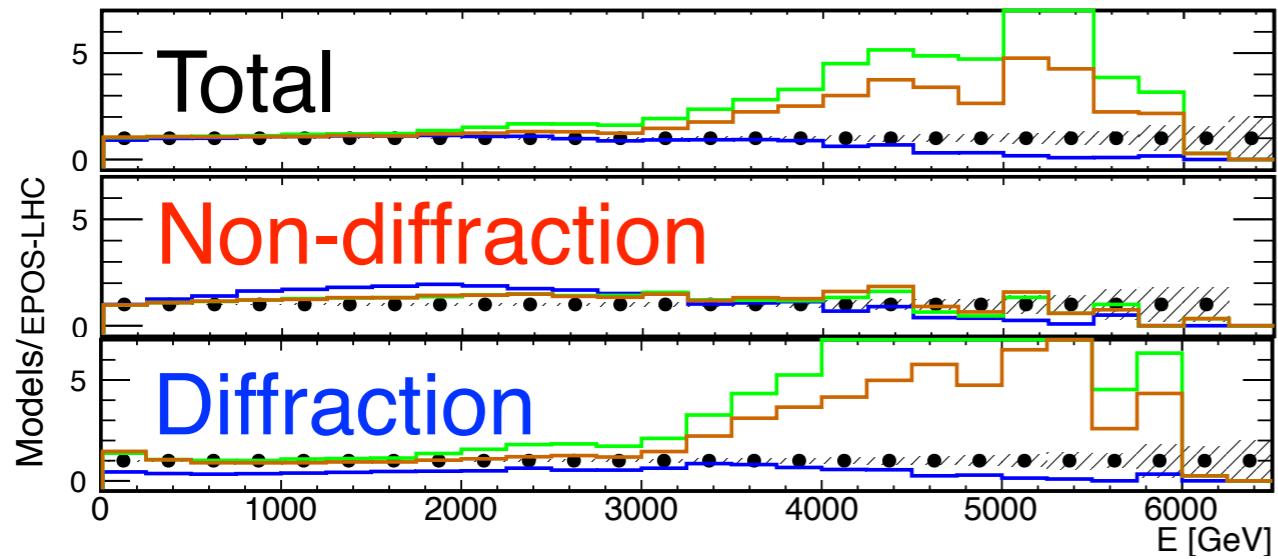


Pomeron flux options in PYTHIA



arXiv:1005.3894v1

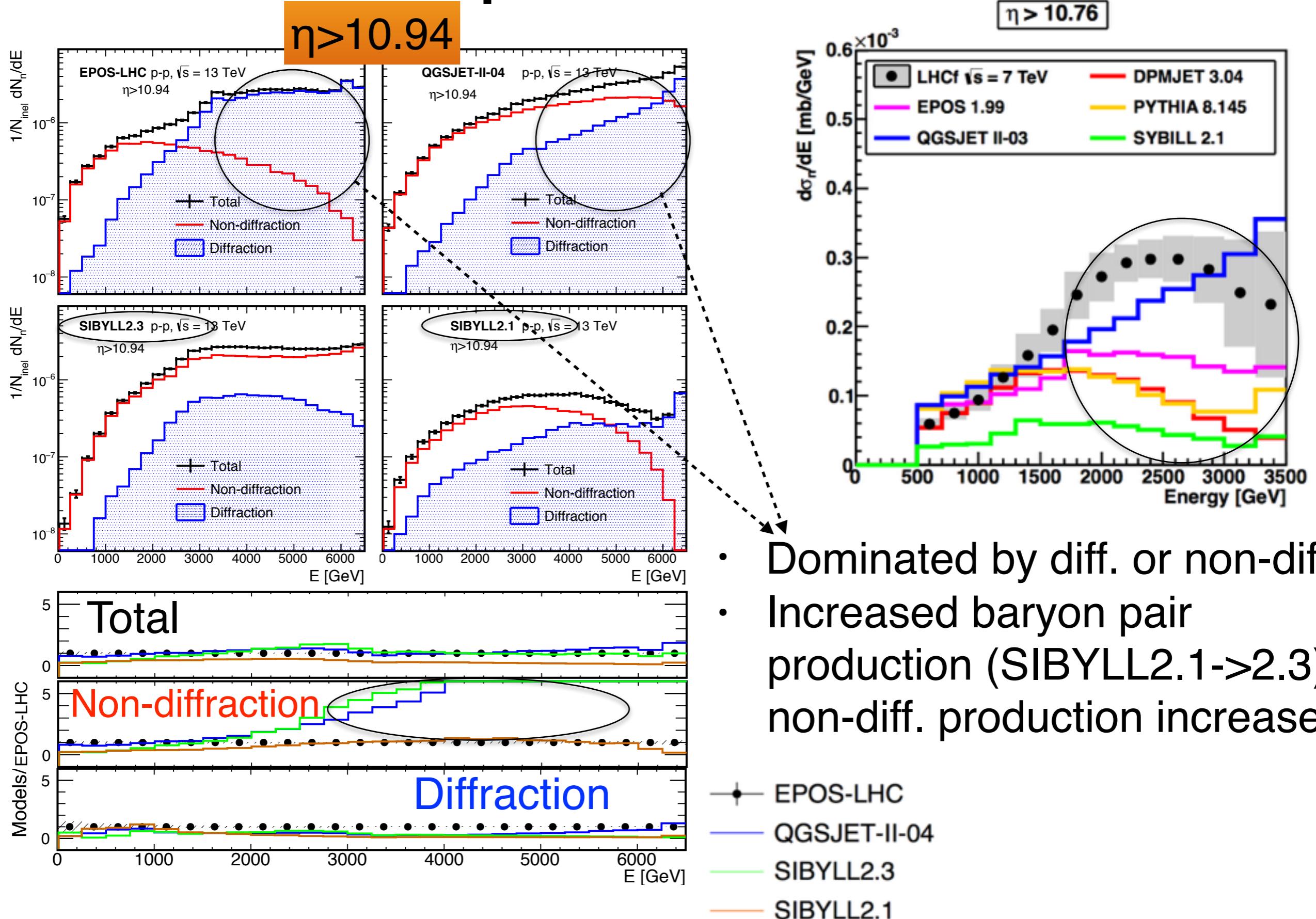
Regge trajectory:  
 $a_P(t) = 1.085 + 0.25t$  as default



- EPOS-LHC
- QGSJET-II-04
- PYTHIA8212 DL
- PYTHIA8212

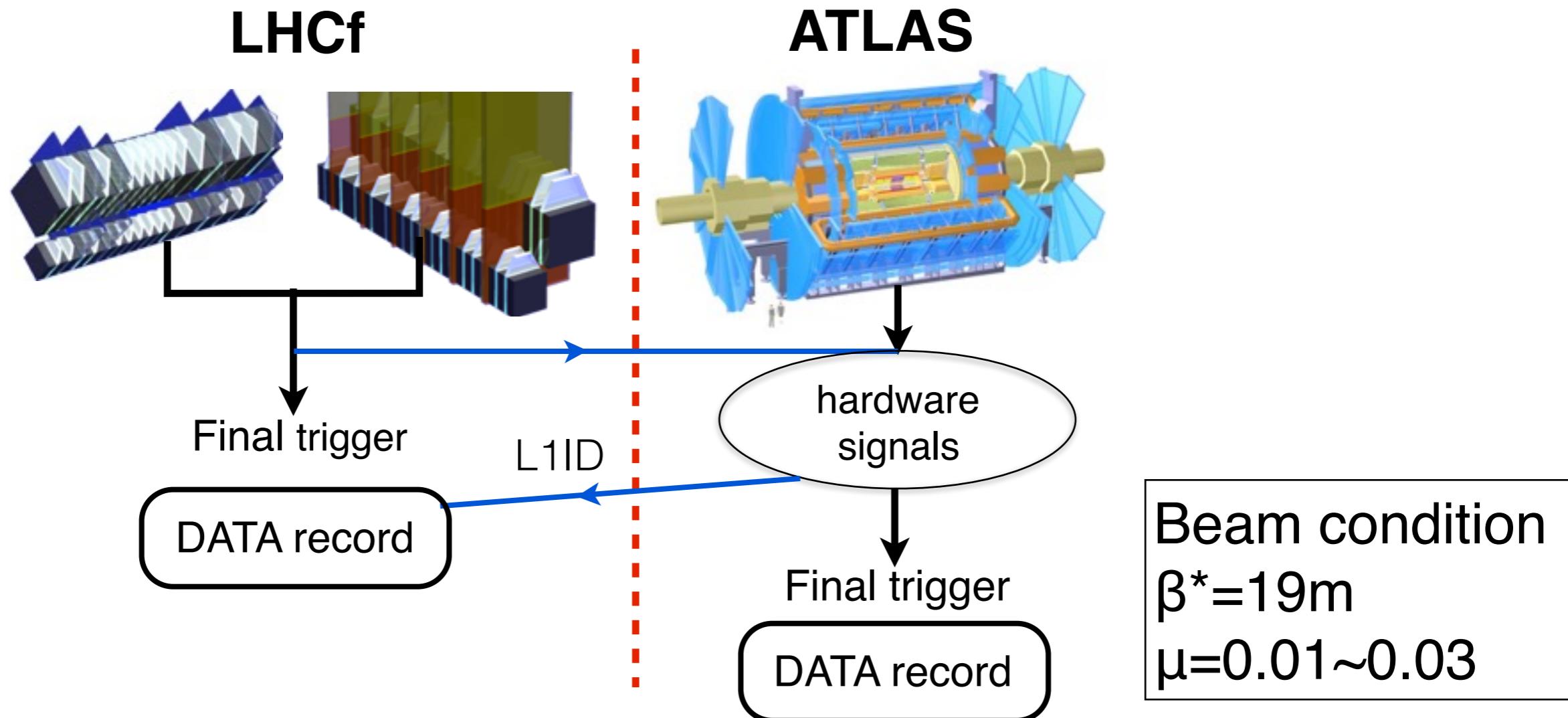
PYTHIA8DL gives better agreement to ATLAS  $n_{(\text{MBTS})}$  distribution [ATLAS-CONF-2015-038]. However, it gives too much diffraction at  $E > 3$  TeV to LHCf spectra

# Neutron spectrum comparison



# **Prospects for ATLAS-LHCf common analysis**

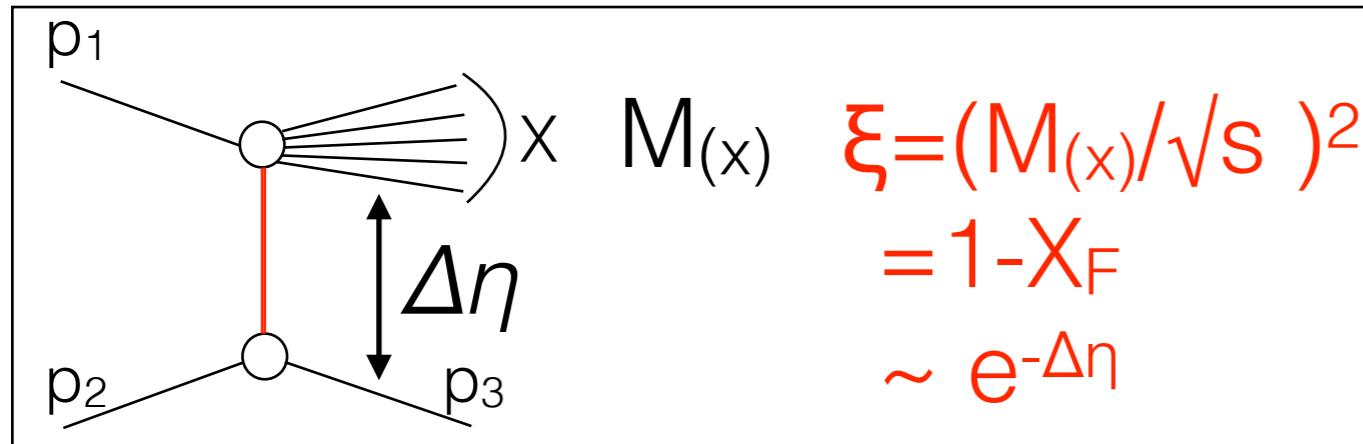
# ATLAS-LHCf common operation



- ◆ Common data acquisition for the minimum bias measurement.
- ◆ LHCf detectors were incorporated into ATLAS readout system.
- ◆ LHCf triggers ATLAS with trigger rate  $\sim 400\text{Hz}$ .
- ◆ The event matching was done offline by using ATLAS L1ID.

**Event matching succeed, data analysis on going**

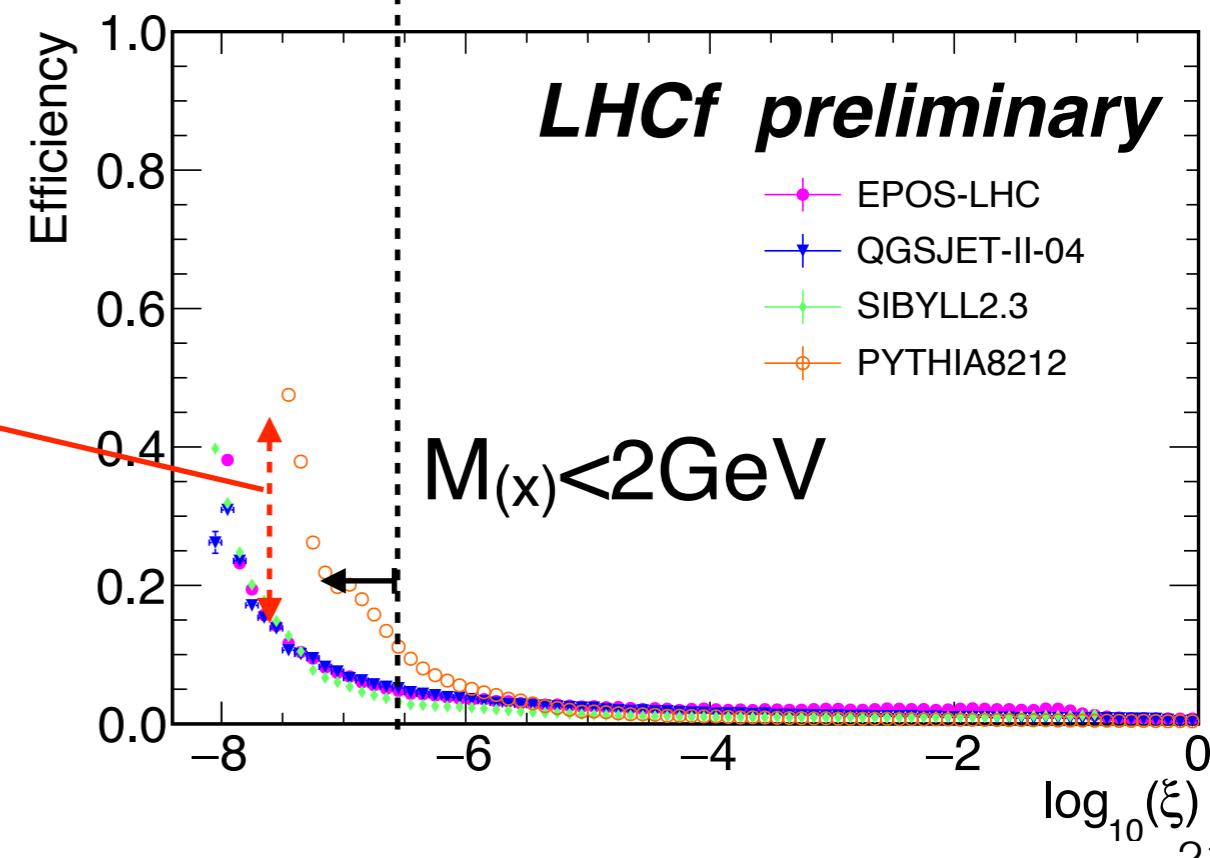
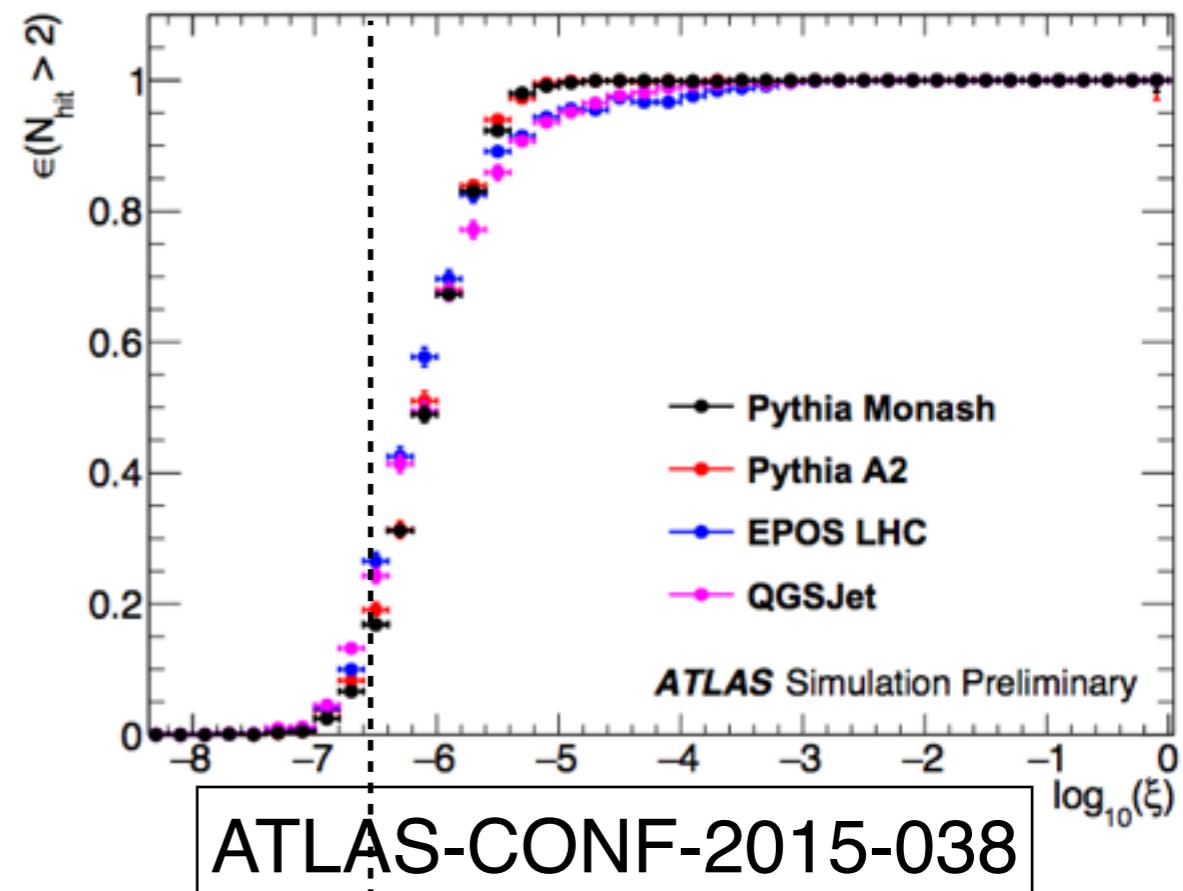
# Detector acceptance



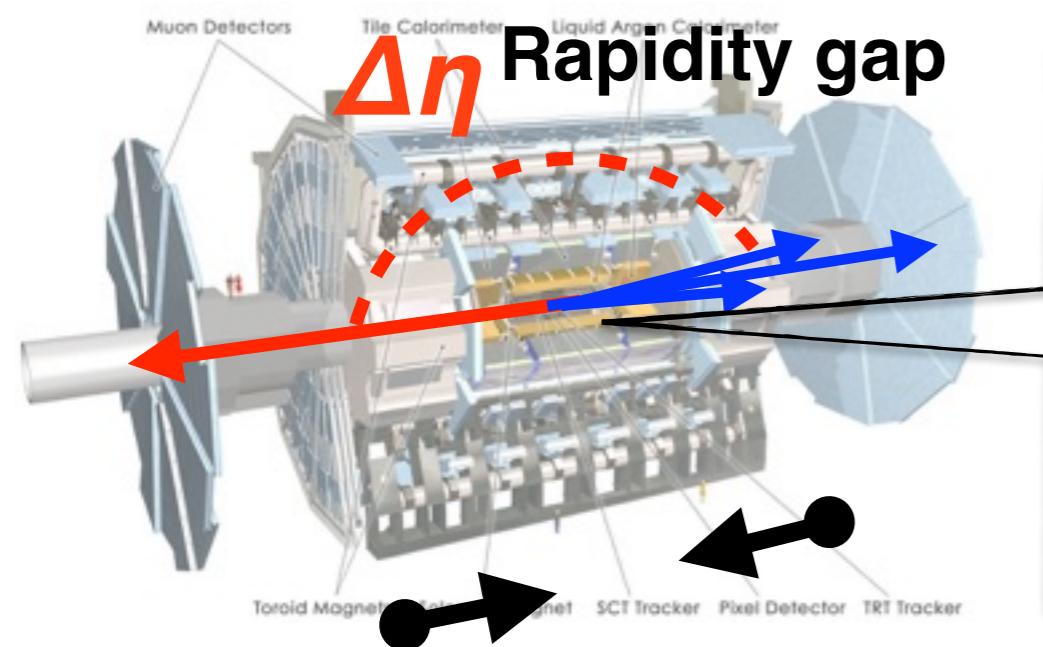
- Trigger efficiency (only with SD)
- Trigger condition of LHCf
  - Photon:  $E_\gamma > 200\text{GeV}$
  - Neutron:  $E_n > 500\text{GeV}$
- ATLAS
  - Pass track selection
  - $N_{\text{hit}} > 2$

PYTHIA has different  
fragmentation function?

LHCf and ATLAS cover different  
diffractive mass range



# LHCf event selection w/ ATLAS central trackers



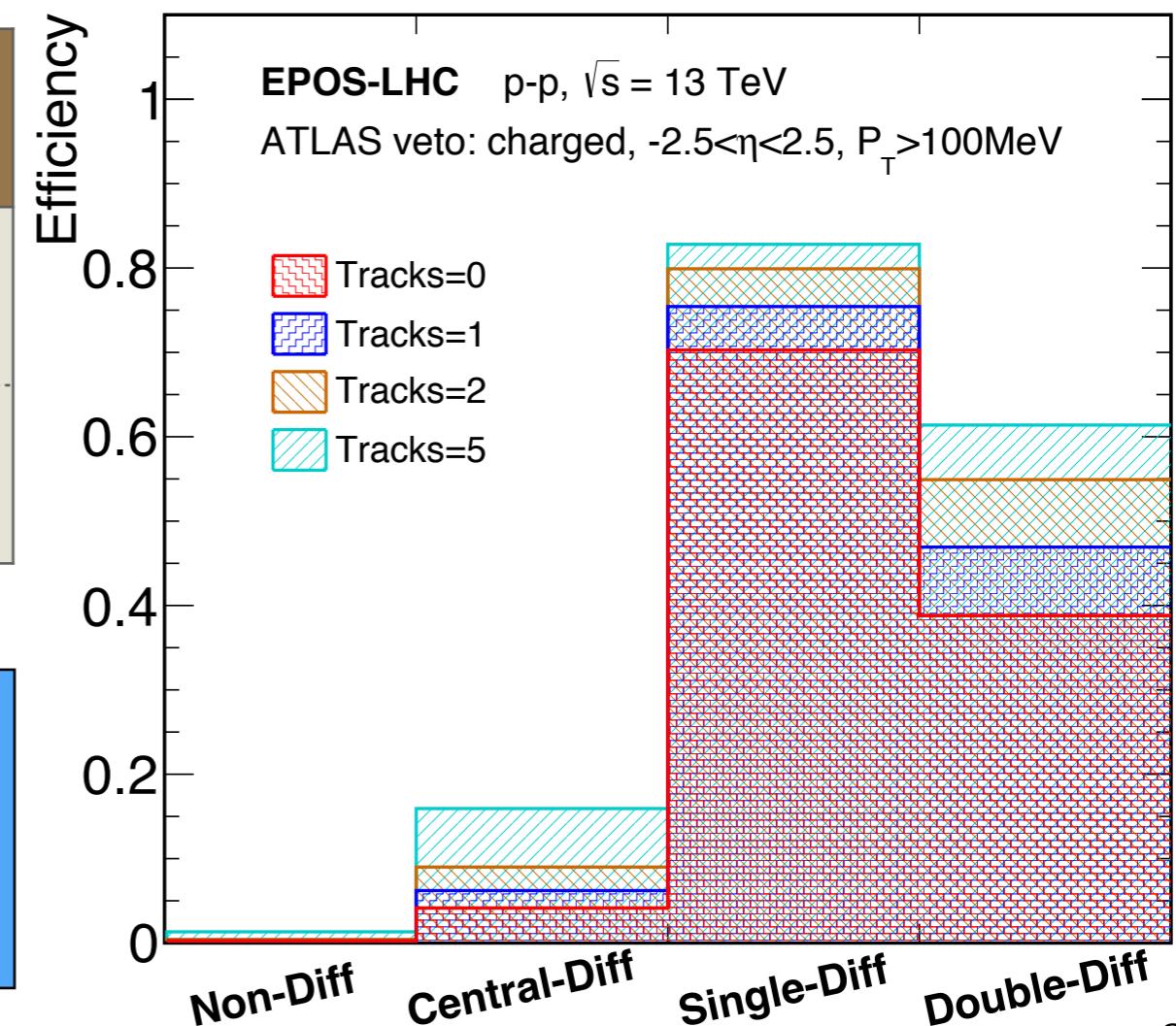
- ◆ ATLAS Inner detector (tracking system)

Condition:  
Charged particle ( $P_T > 100\text{MeV}$ ) number  
at  $|\eta| < 2.5$

→ Diffractive like (ATLAS veto)

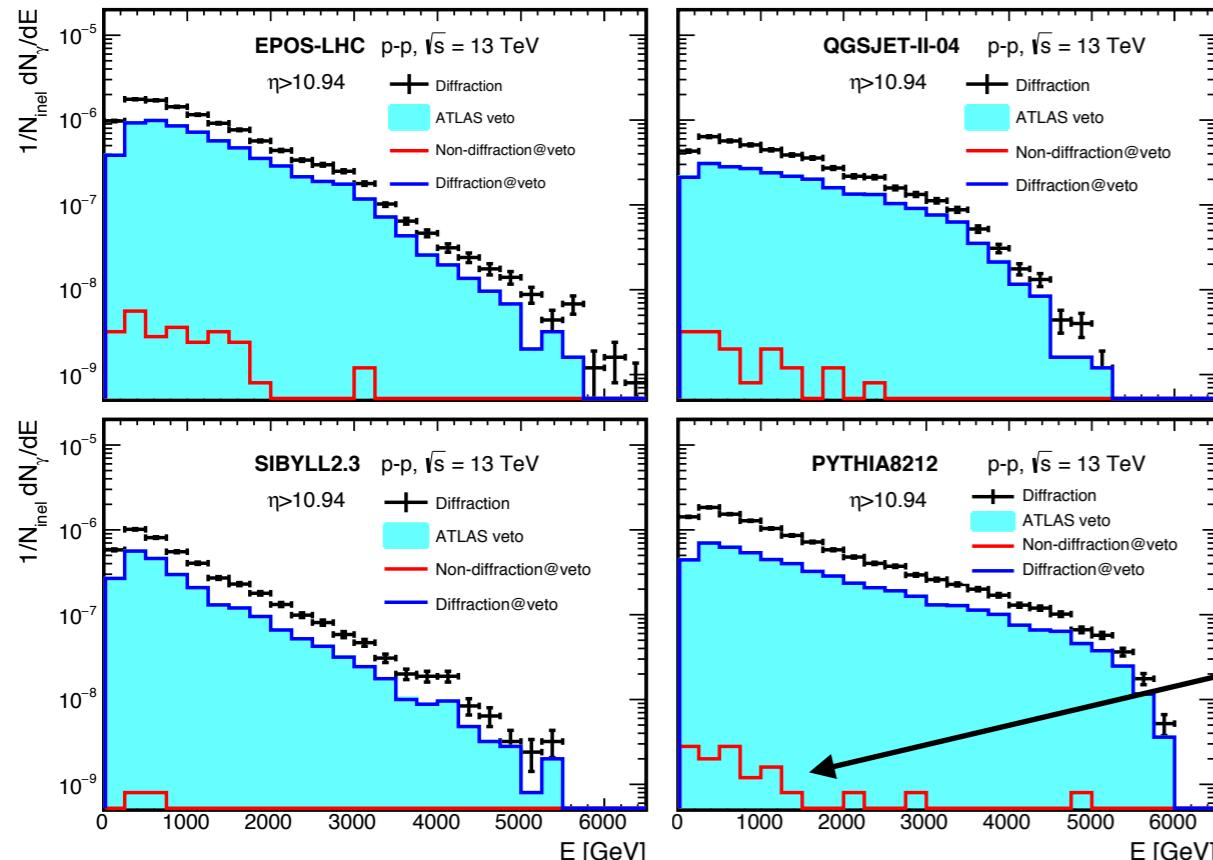
	Tracks =0	Tracks $\leq 1$	Tracks $\leq 2$	Tracks $\leq 5$
Efficiency	0.49	0.56	0.62	0.69
Purity	0.995	0.991	0.982	0.950

Diffraction identification:  
No charged particle (tracks=0) at  
 $|\eta| < 2.5$  was employed in this analysis



# LHCf photon spectrum w/ ATLAS veto

$\eta > 10.94$



Diffraction: MC true  
ATLAS veto: tracks=0 @  $|\eta| < 2.5$

Diffraction@veto overlap ATLAS veto

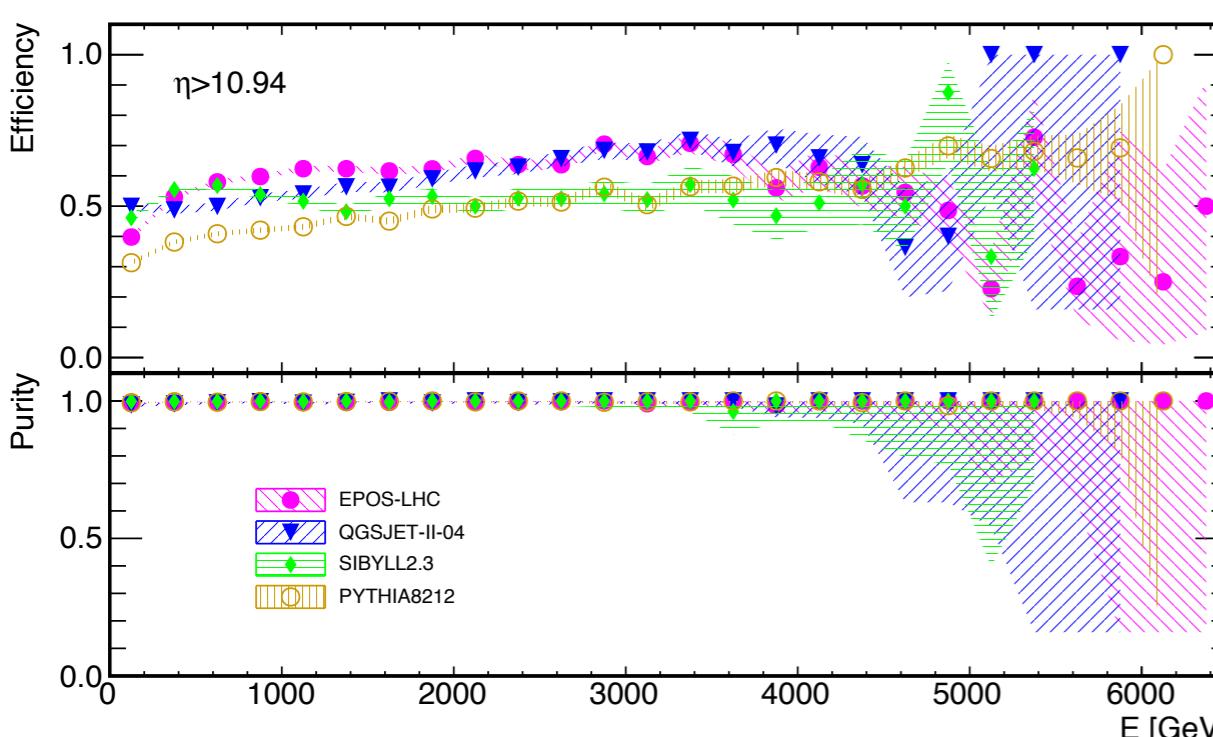
high diff. selection purity

Miss selection

$$\text{efficiency} = \frac{\text{LHCf\_event@ATLASveto}}{\text{LHCf\_Diff.}}$$

$$\text{purity} = \frac{\text{Diff.@ATLASveto}}{\text{LHCf\_event@ATLASveto}}$$

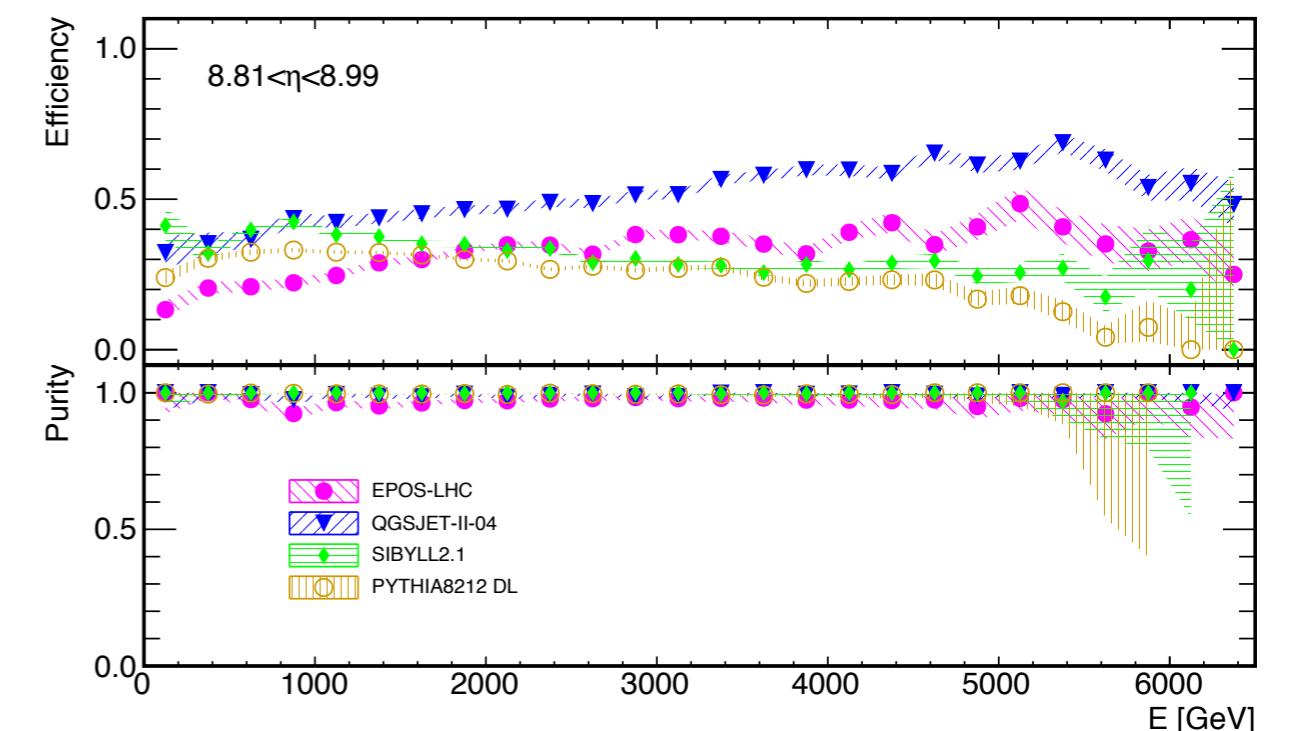
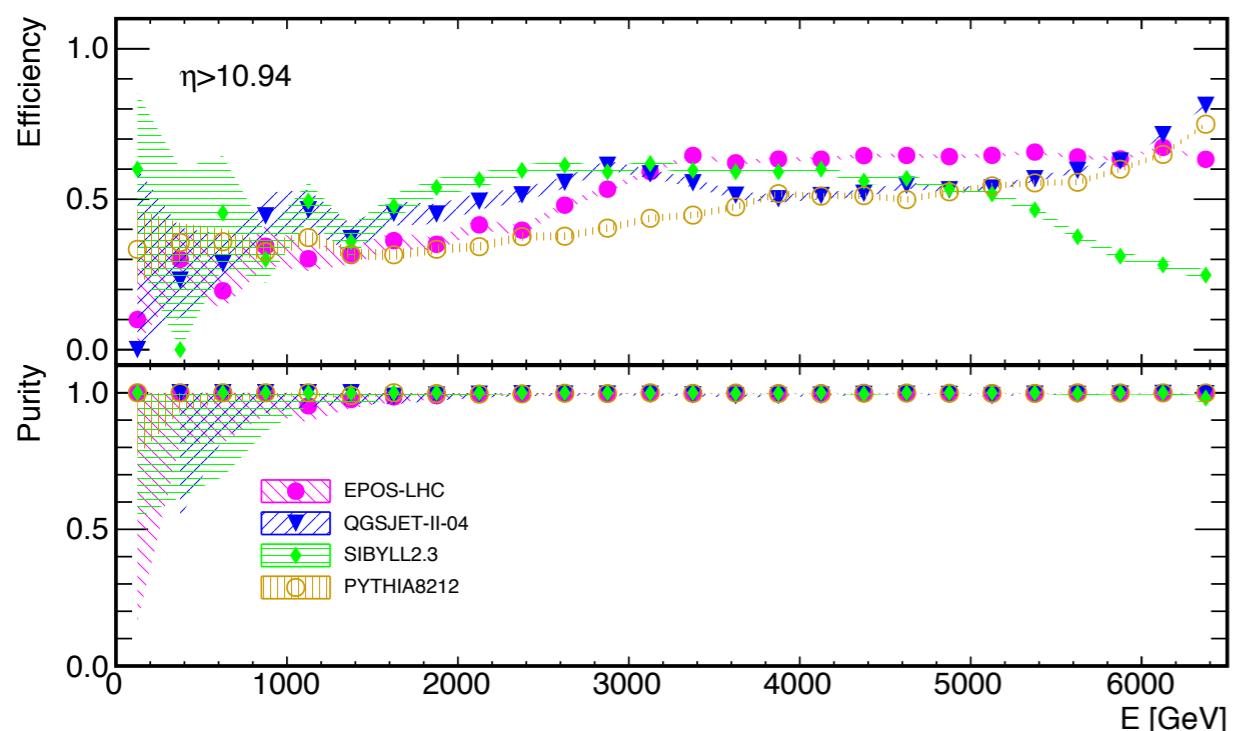
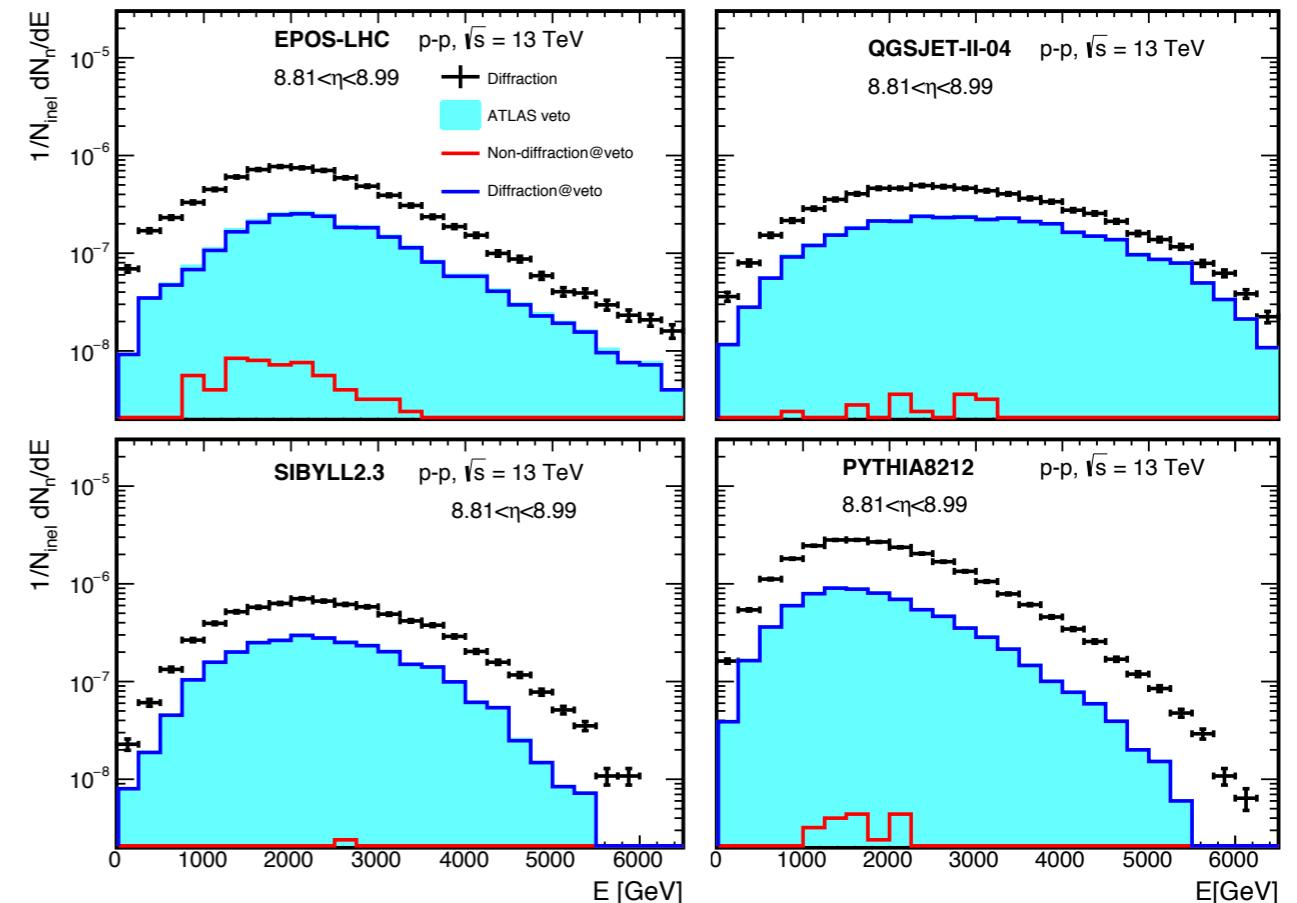
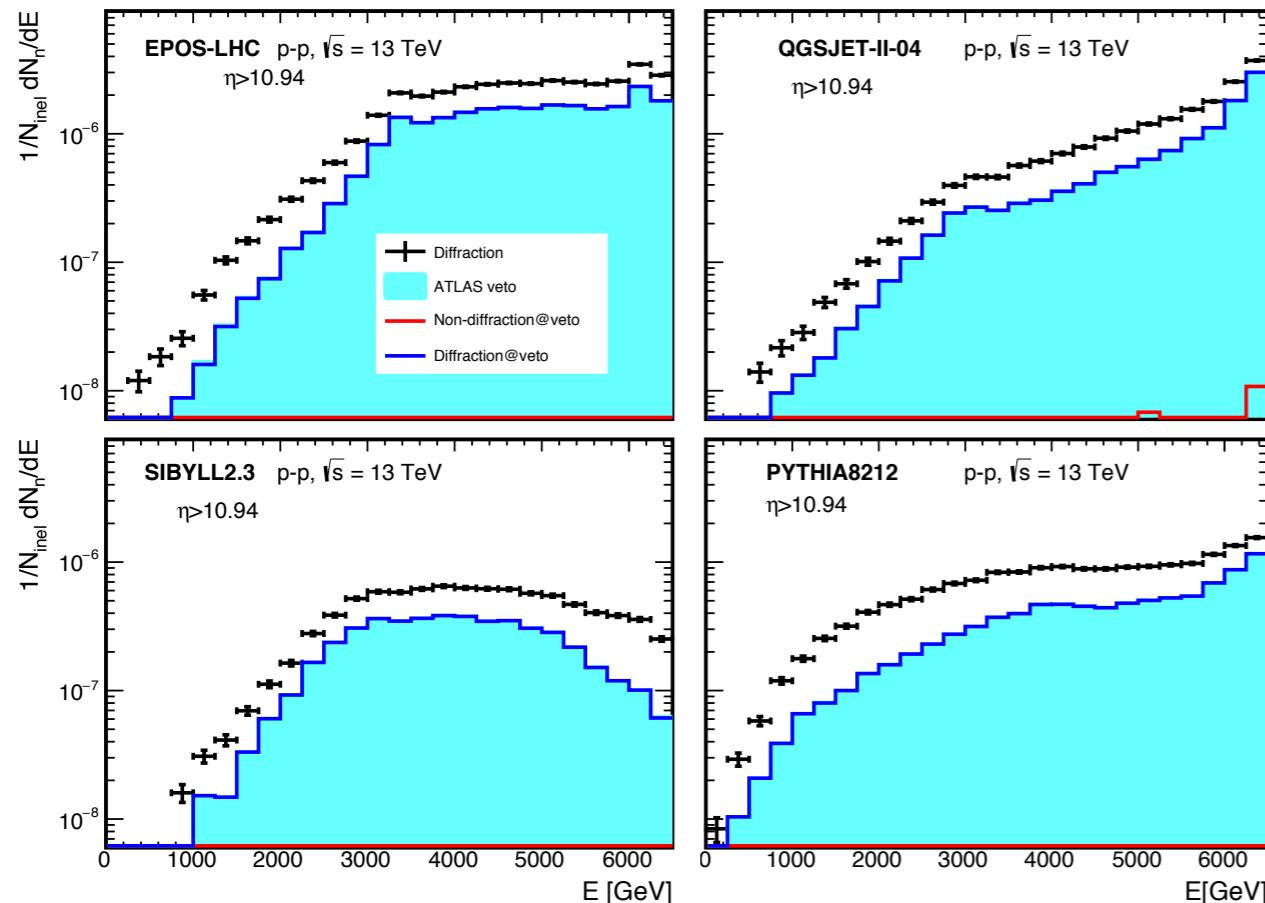
- ❖ High purity model independently.
- ❖ Efficiency ~50%, EPOS and QGSJET give almost consistent efficiency.



# LHCf neutron spectrum w/ ATLAS veto

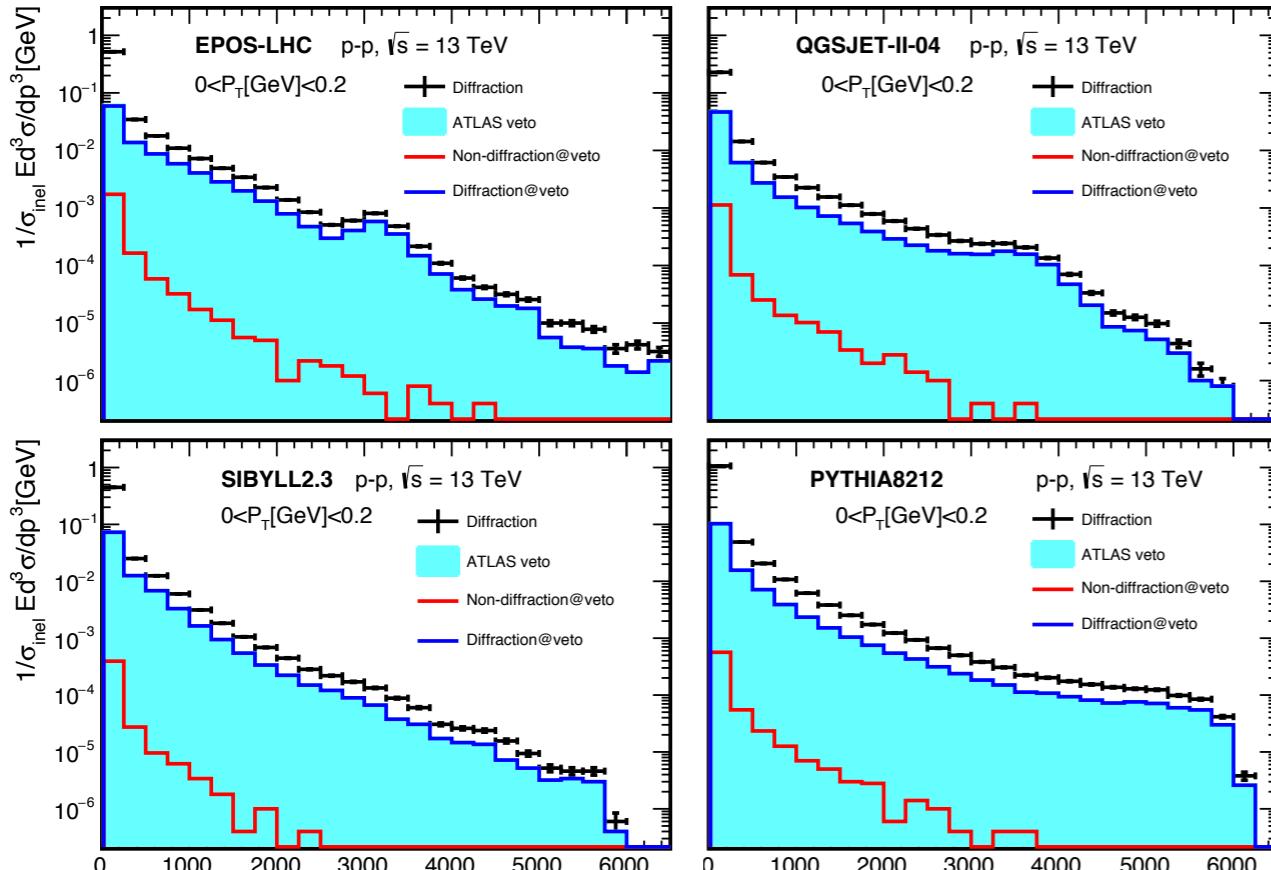
$\eta > 10.94$

$8.81 < \eta < 8.99$

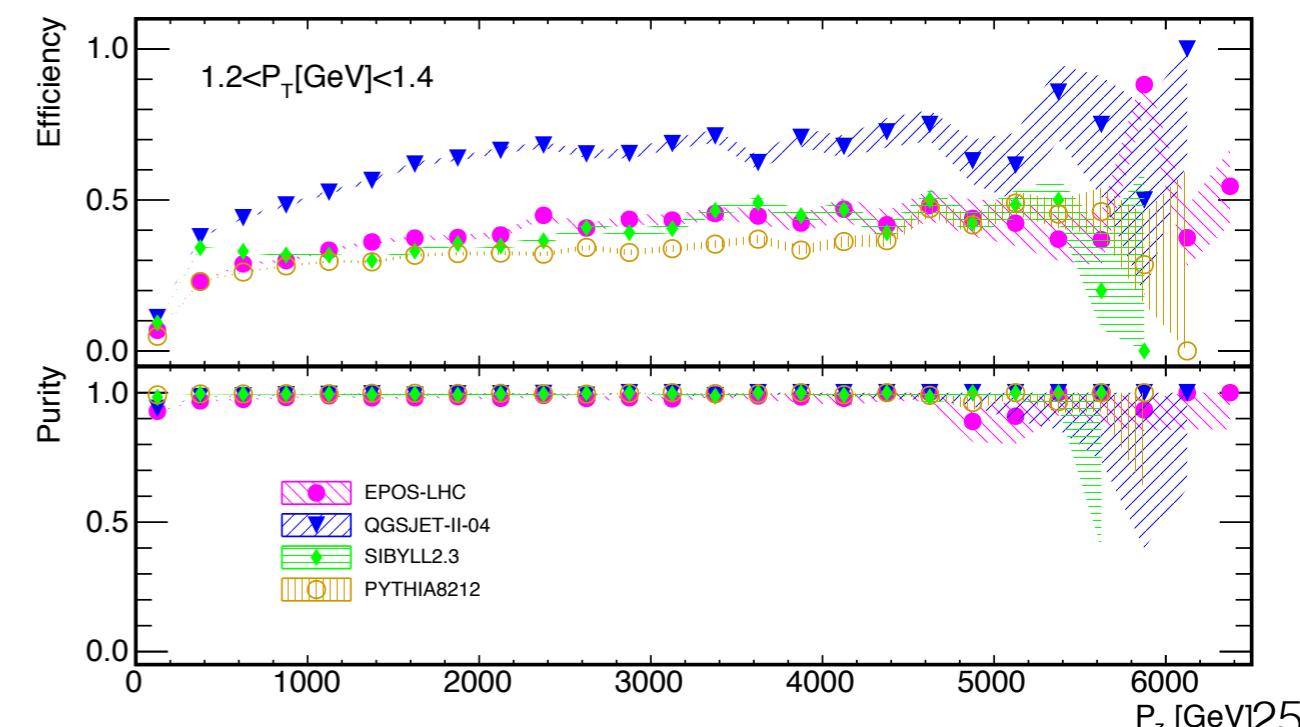
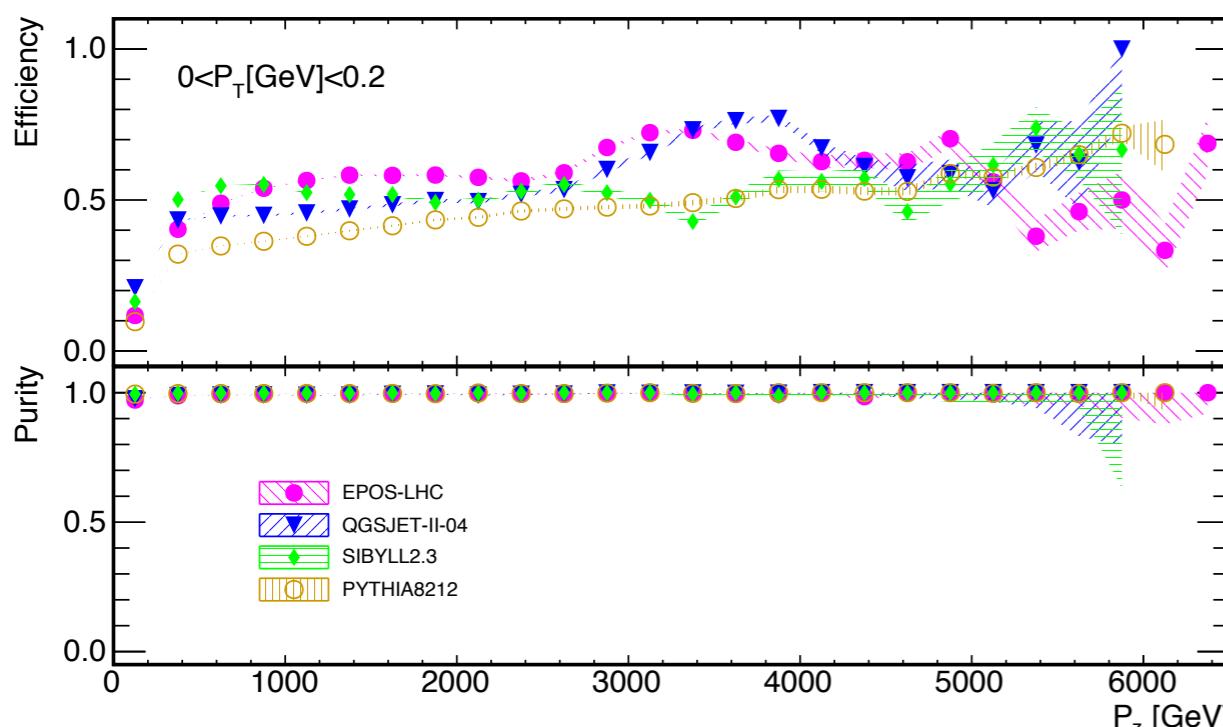
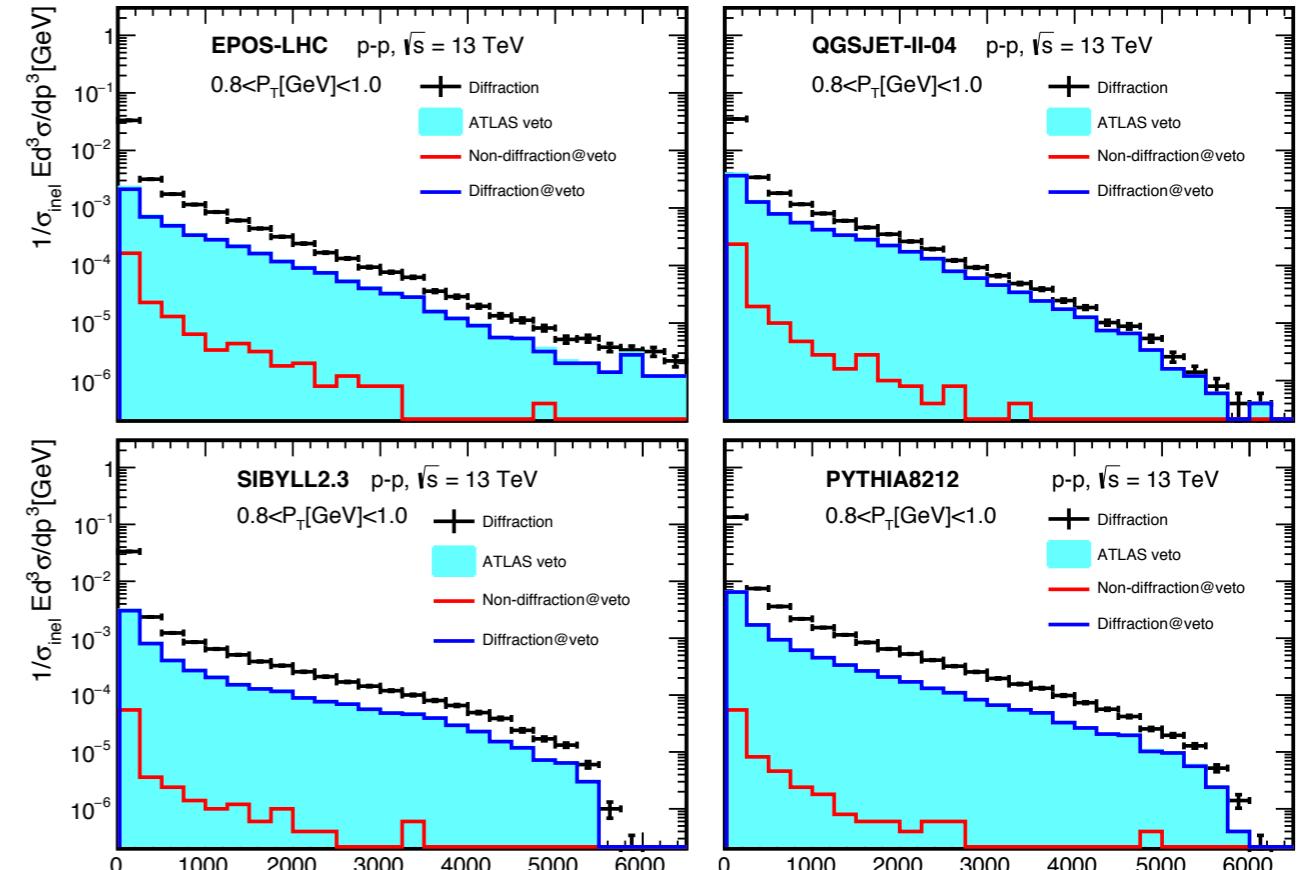


# LHCf $\pi^0$ spectrum w/ ATLAS veto

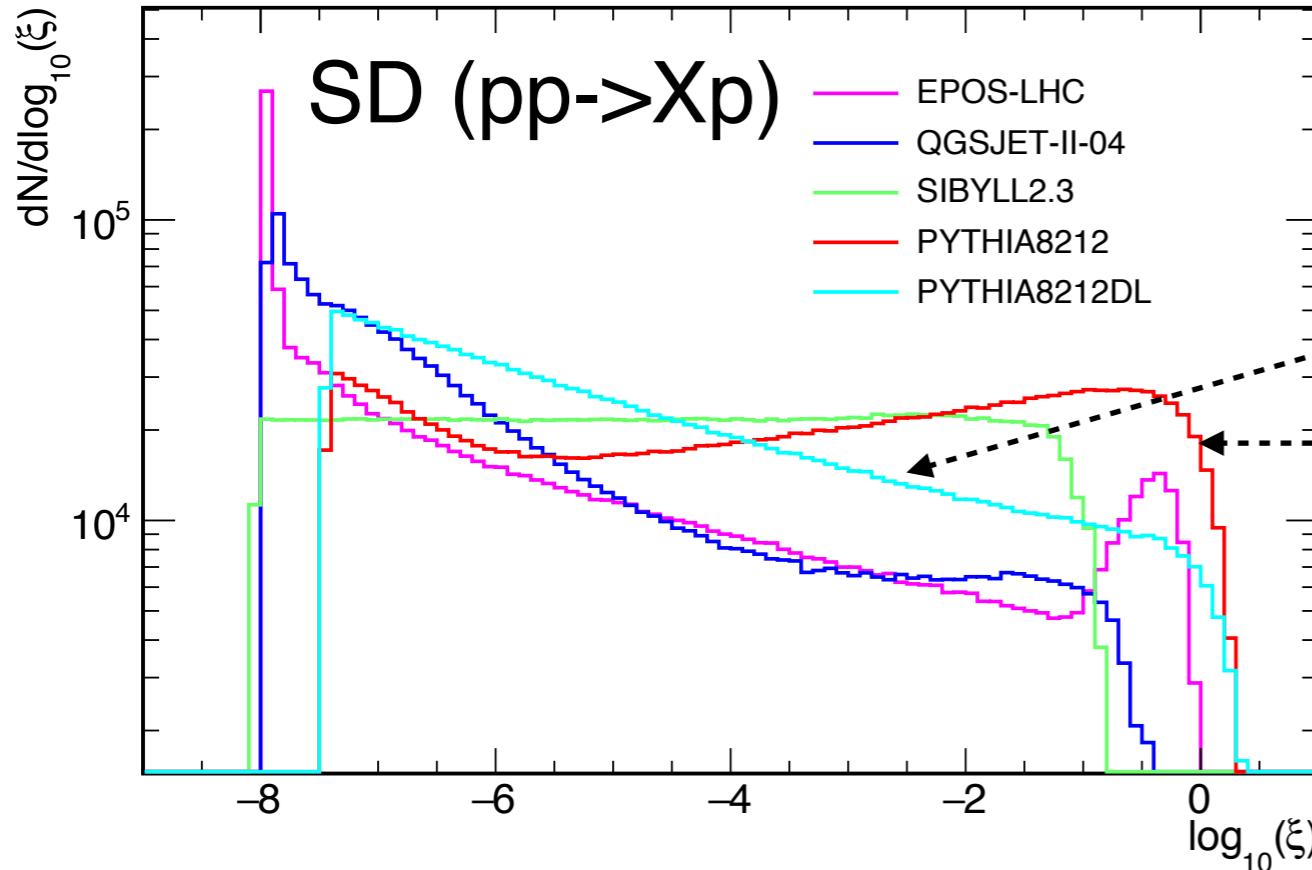
$0 < P_T [\text{GeV}] < 0.2$



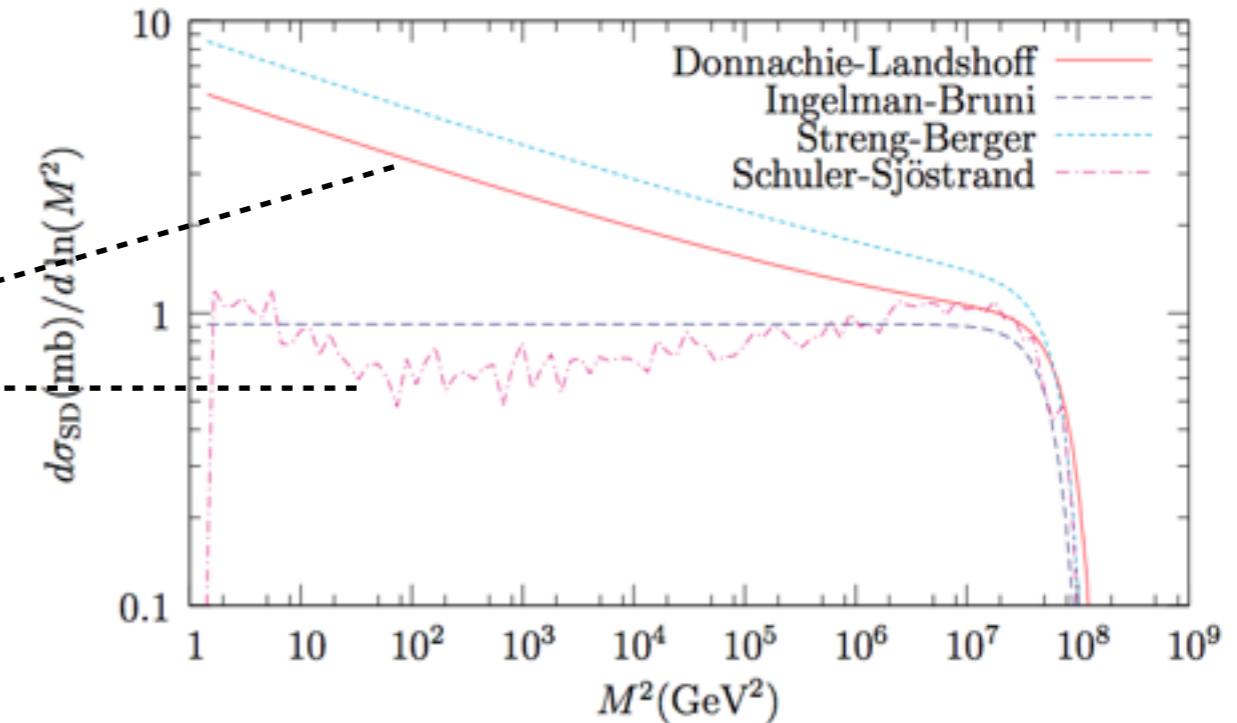
$0.8 < P_T [\text{GeV}] < 1.0$



# Diffractive mass distribution



Pomeron flux options in PYTHIA



arXiv:1005.3894v1

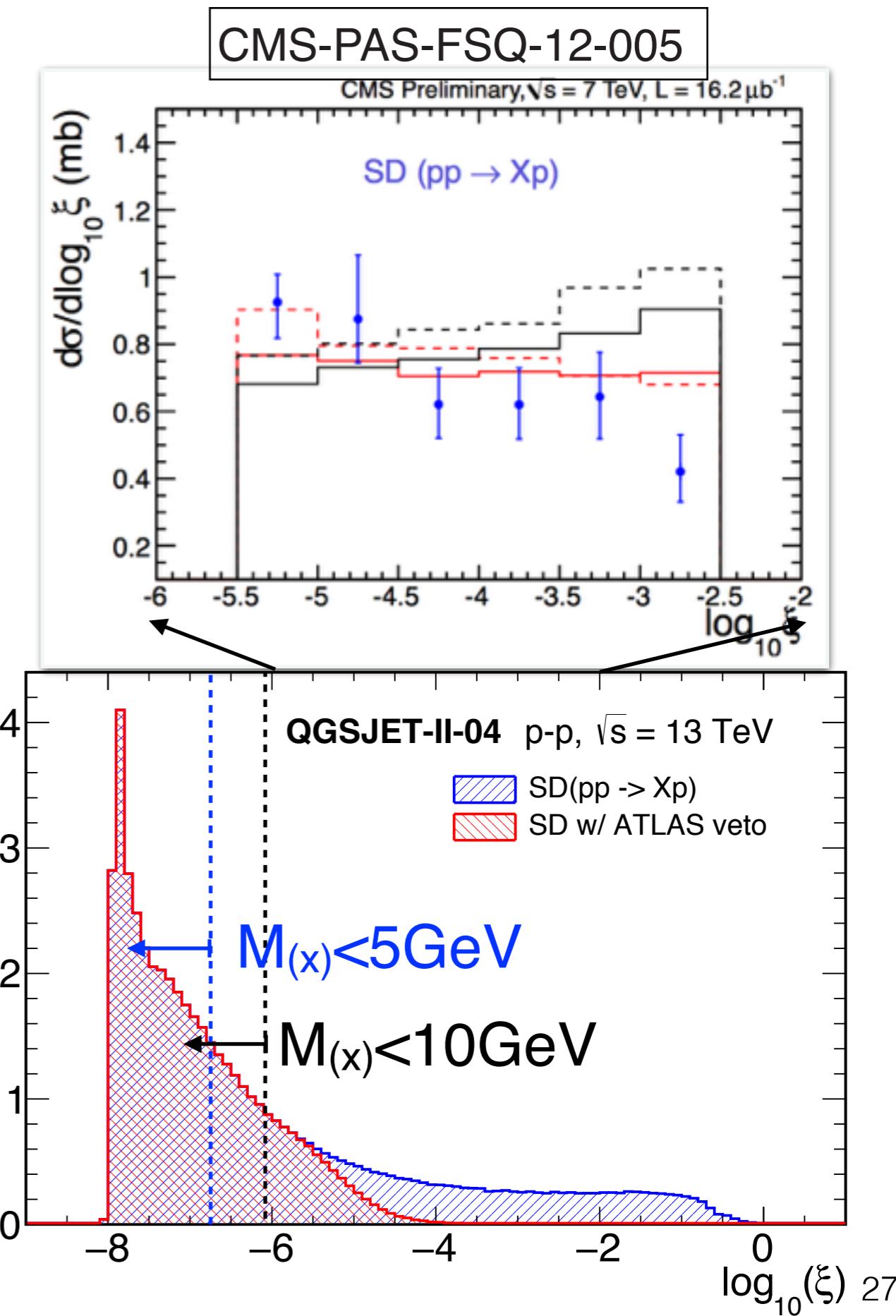
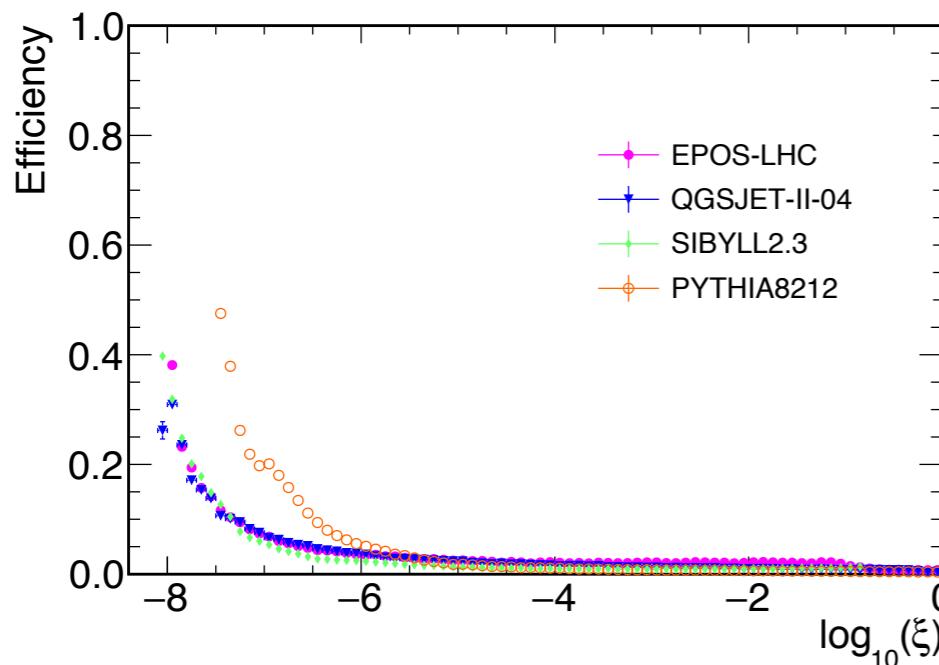
$$\begin{aligned}\xi &= (M_{(x)} / \sqrt{s})^2 \\ &= 1 - X_F \\ &\sim e^{-\Delta\eta}\end{aligned}$$

- ❖  $\log_{10}(\xi)$  distribution of SD represents the pomeron flux implemented in the model.
- ❖ Large discrepancy exists between models
- ❖ Pomeron flux is an extremely important parameter for modeling diffraction

# Low mass diffraction

- CMS
- PYTHIA version:
  - P8-MBR  $\epsilon=0.08$
  - - P8-MBR (default)  $\epsilon=0.104$
  - P8-4C
  - P6

- ❖ The inefficiency parts of ATLAS-veto are high mass diff..
- ❖ ATLAS-LHCf can access the low mass single diffraction region, with high efficiency, experimentally.



# Summary

- ◆ LHCf has taken data in p-p and p-Pb collisions at different energies, results have been published about photon, neutron and  $\pi^0$   

**No models represent the data perfectly**
- ◆ The identification of diffraction can verify and improve the hadronic interaction models.
- ◆ The efficiency and purity of diffractive event identification by ATLAS-LHCf common operation were estimated.
  - The efficiency of diffraction identification is approximately 50%, with 99% purity.
- ◆ LHCf detectors have high sensitivity at  $\log_{10}(\xi) < -6$
- ◆ Application of ATLAS veto to the LHCf data purifies low mass diffraction event samples

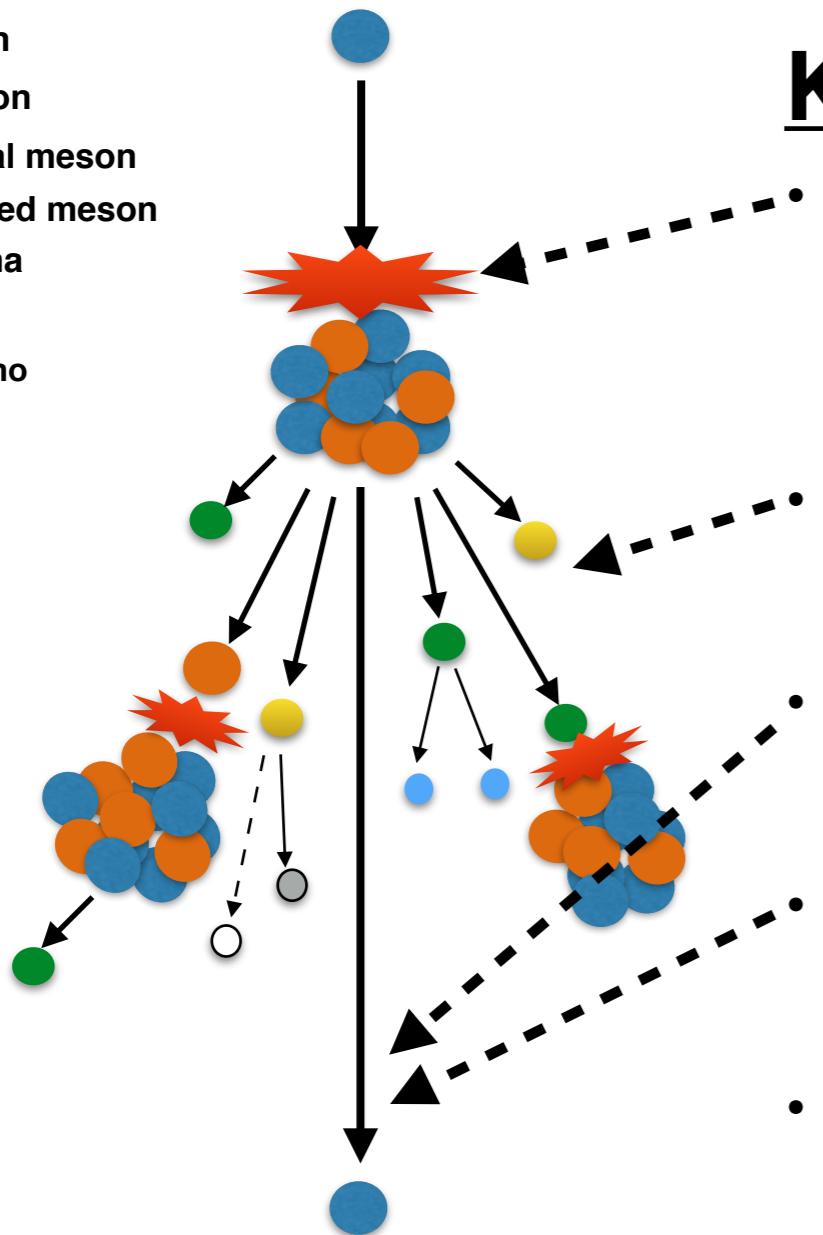
***Stay Tuned***

# *Backup*

# What to be calibrated by accelerators

Hard interactions can be predicted by using perturbative QCD.  
Soft interactions dominate by non-perturbative QCD,  
Phenomenological models base on Regge theory proposed

- Proton
- Neutron
- Neutral meson
- Charged meson
- Gamma
- Muon
- Neutrino

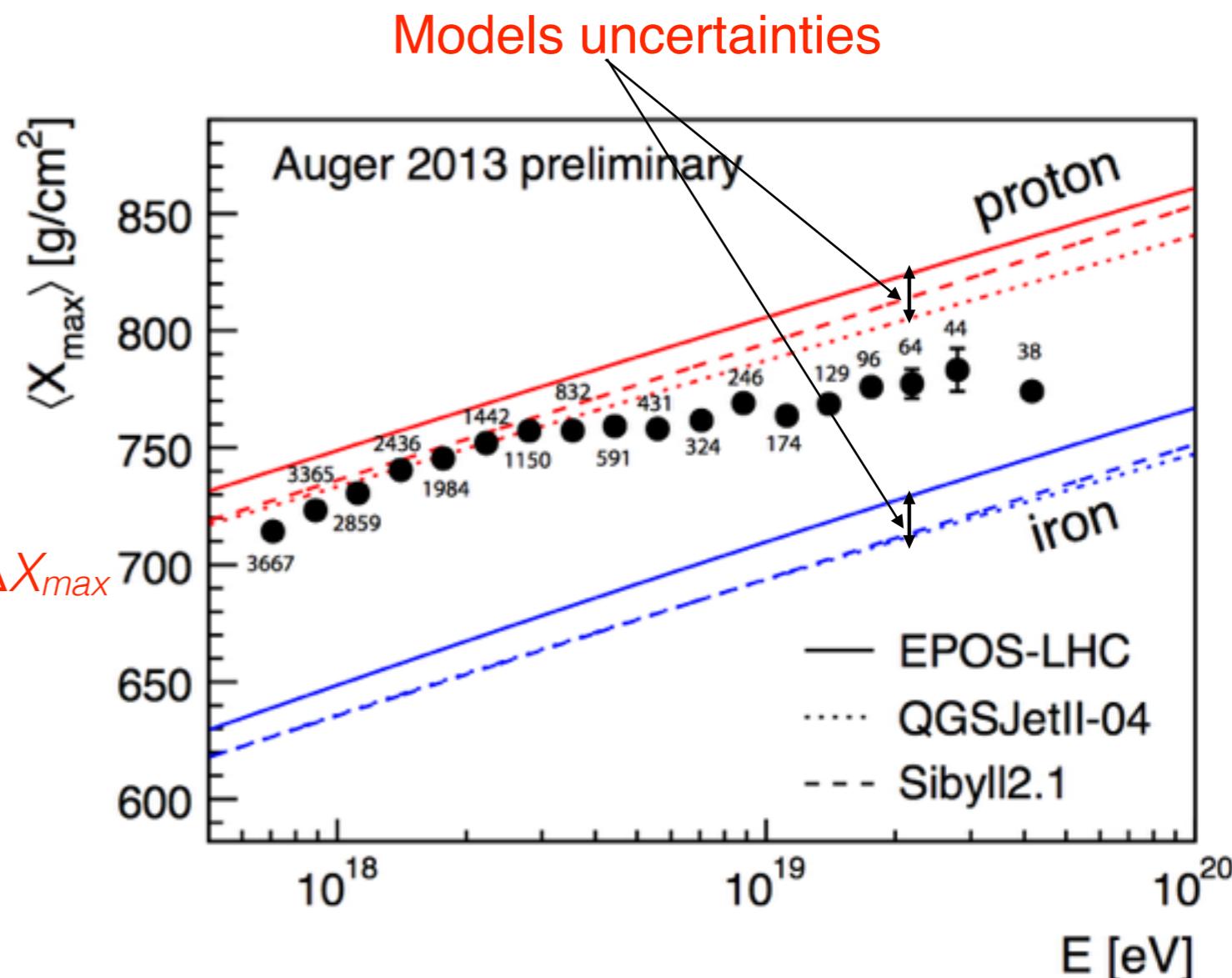
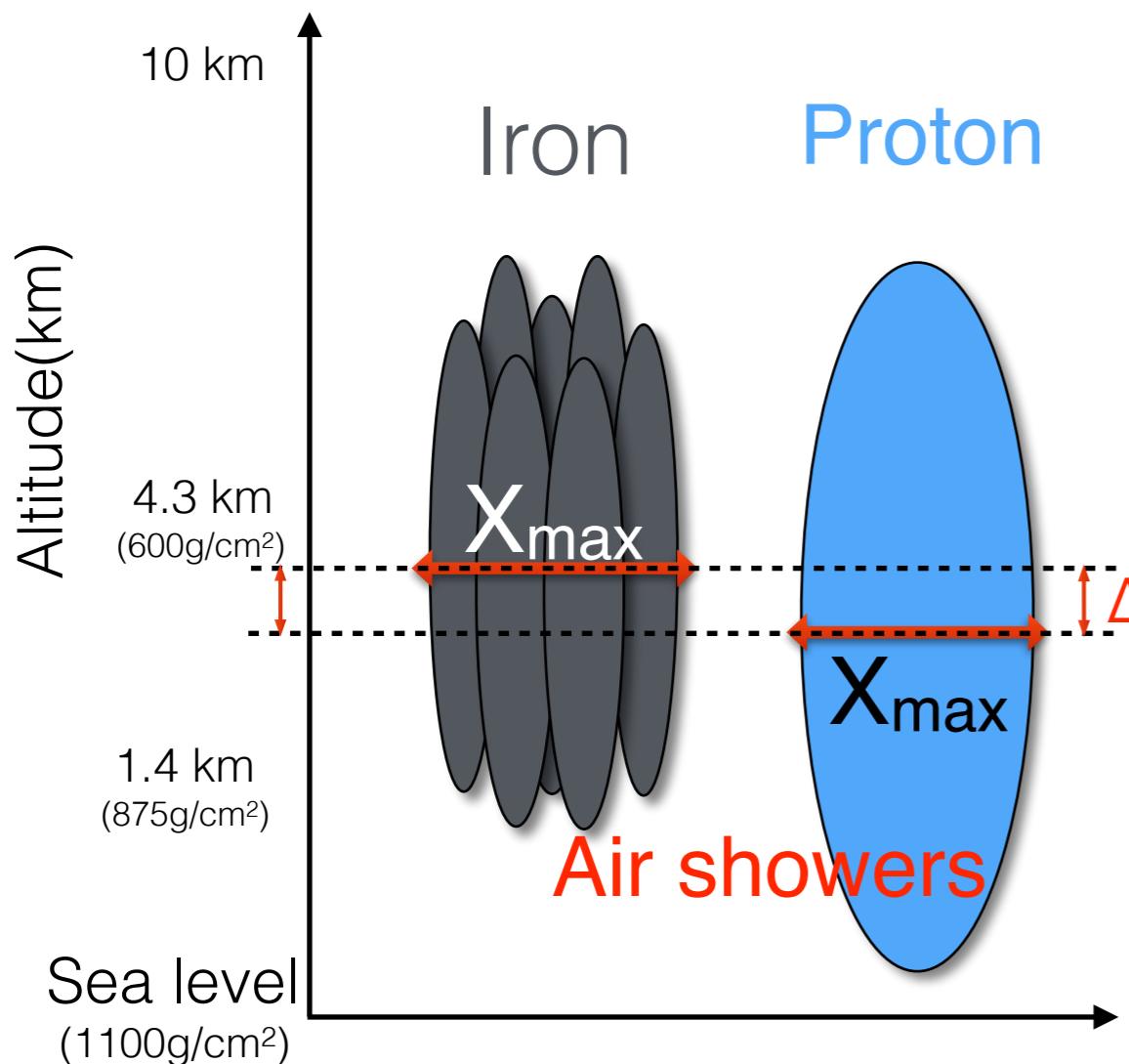


## Key parameters

- Inelastic cross section(interaction mean free path)  
TOTEM, ATLAS, CMS etc.
- Multiplicity  
Central detector
- Inelasticity ( $k = 1 - P_{\text{lead}}/P_{\text{beam}}$ )  
LHCf, ZDC, etc.
- Forward energy spectrum  
LHCf, ZDC, etc.
- Nuclear effect  
LHCf, ALICE, etc.

# Hadronic interaction models

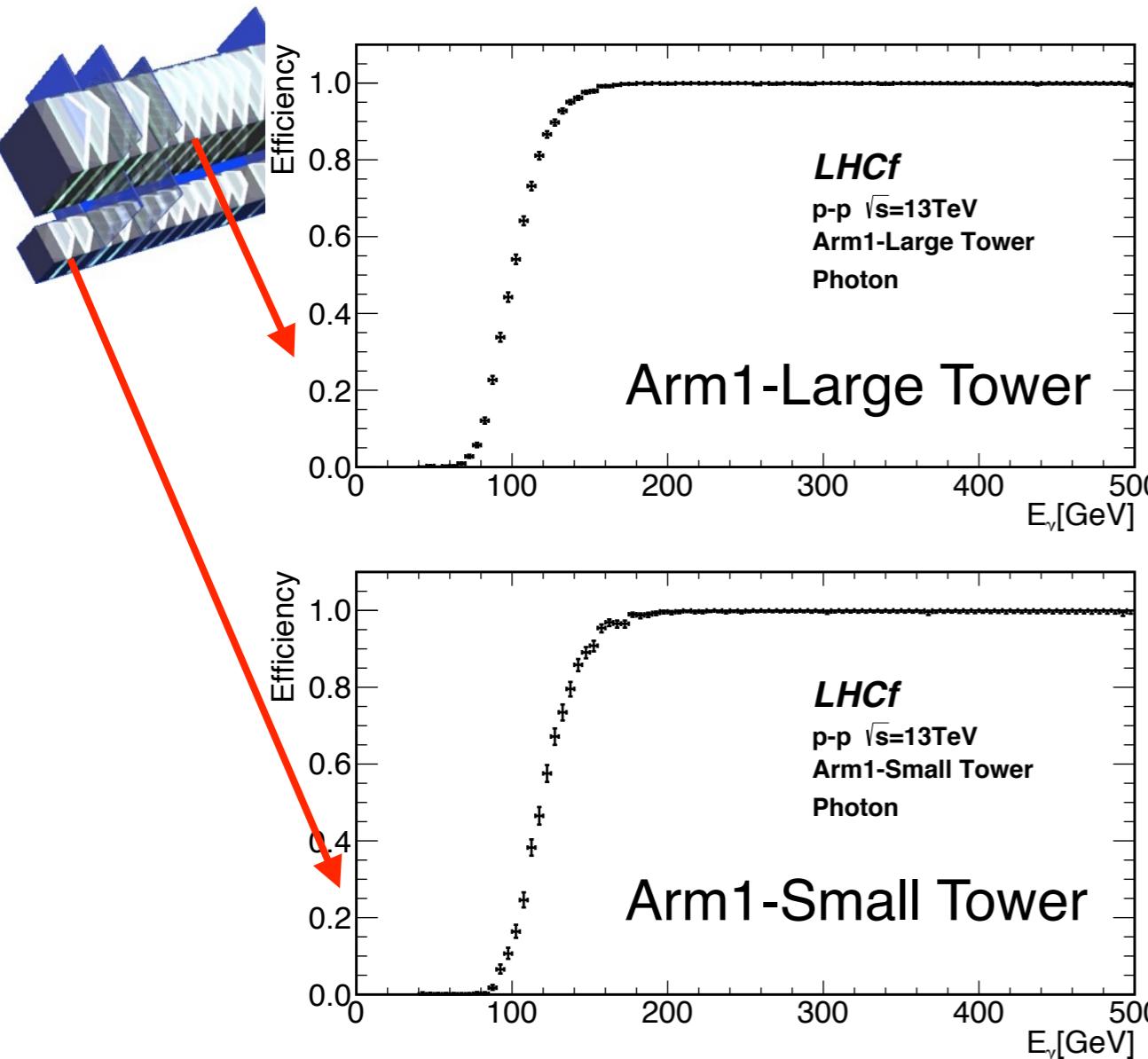
$\Delta X_{\max}$  indicates the different primary mass composition



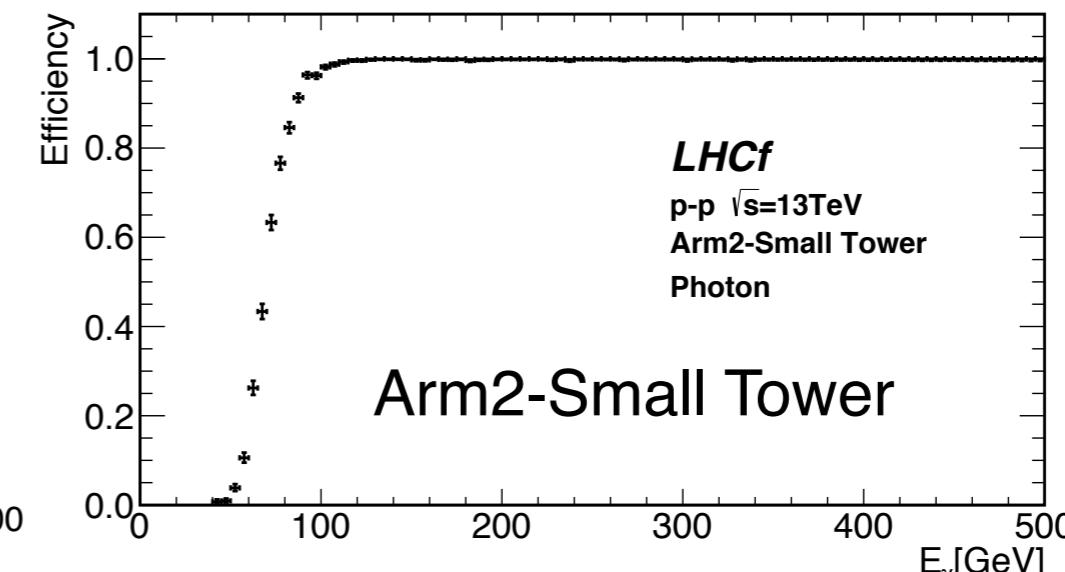
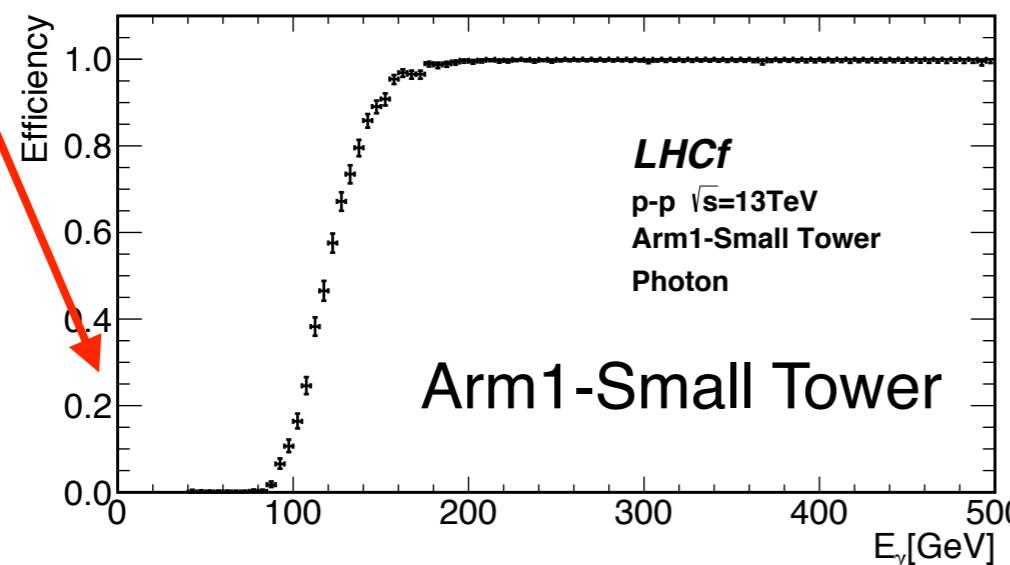
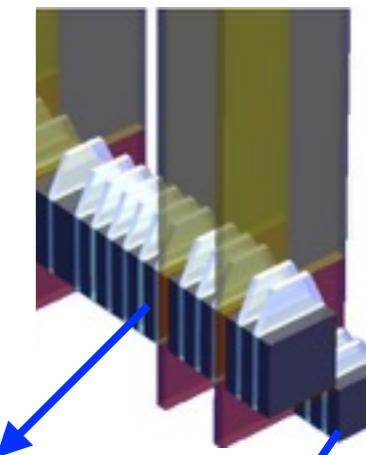
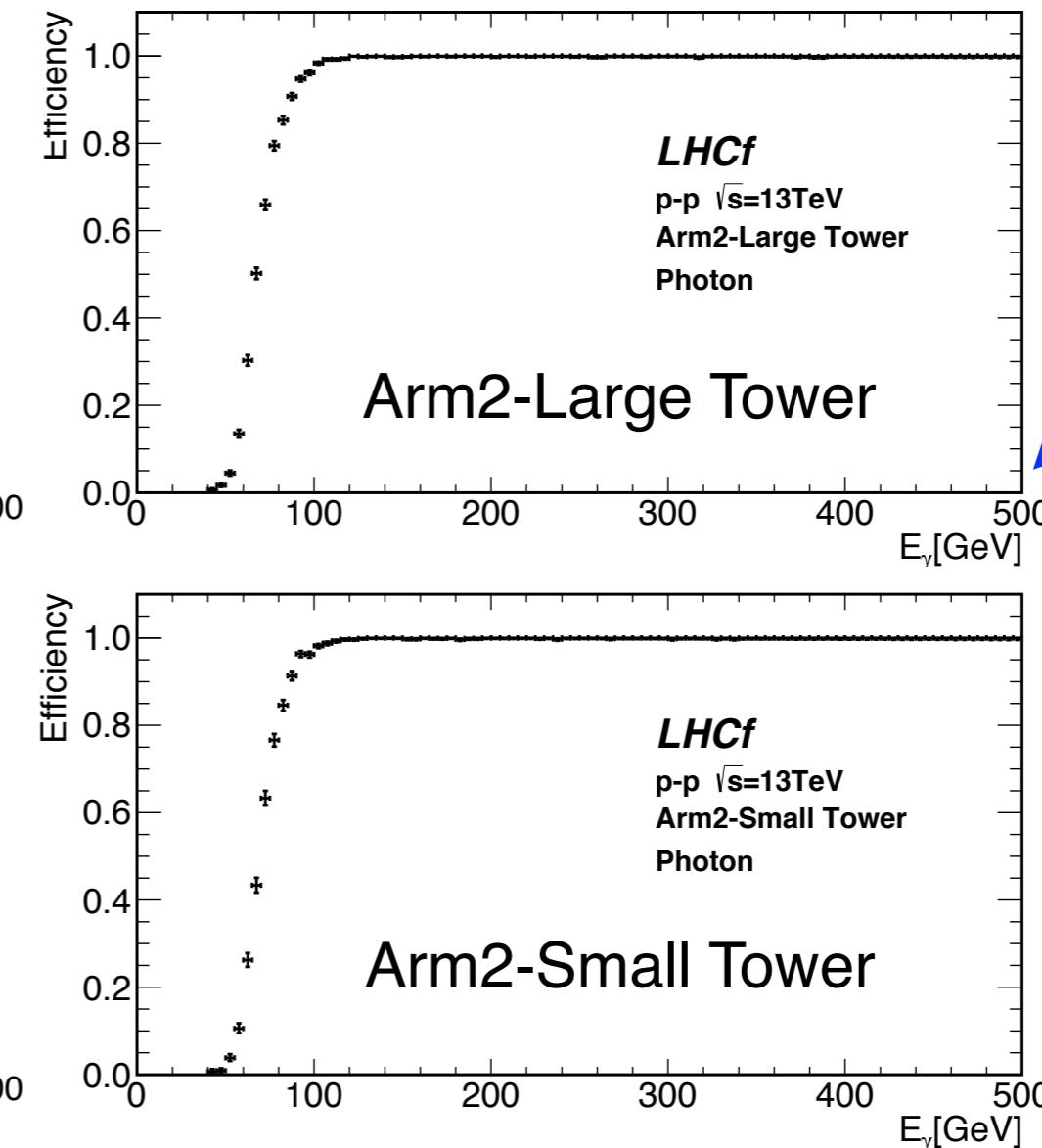
The issue to interpret the air shower data:  
The limitations in modeling of hadronic interactions in  
air shower and largely unknown model uncertainties.

# Detection efficiency of photon

LHCf#Arm1



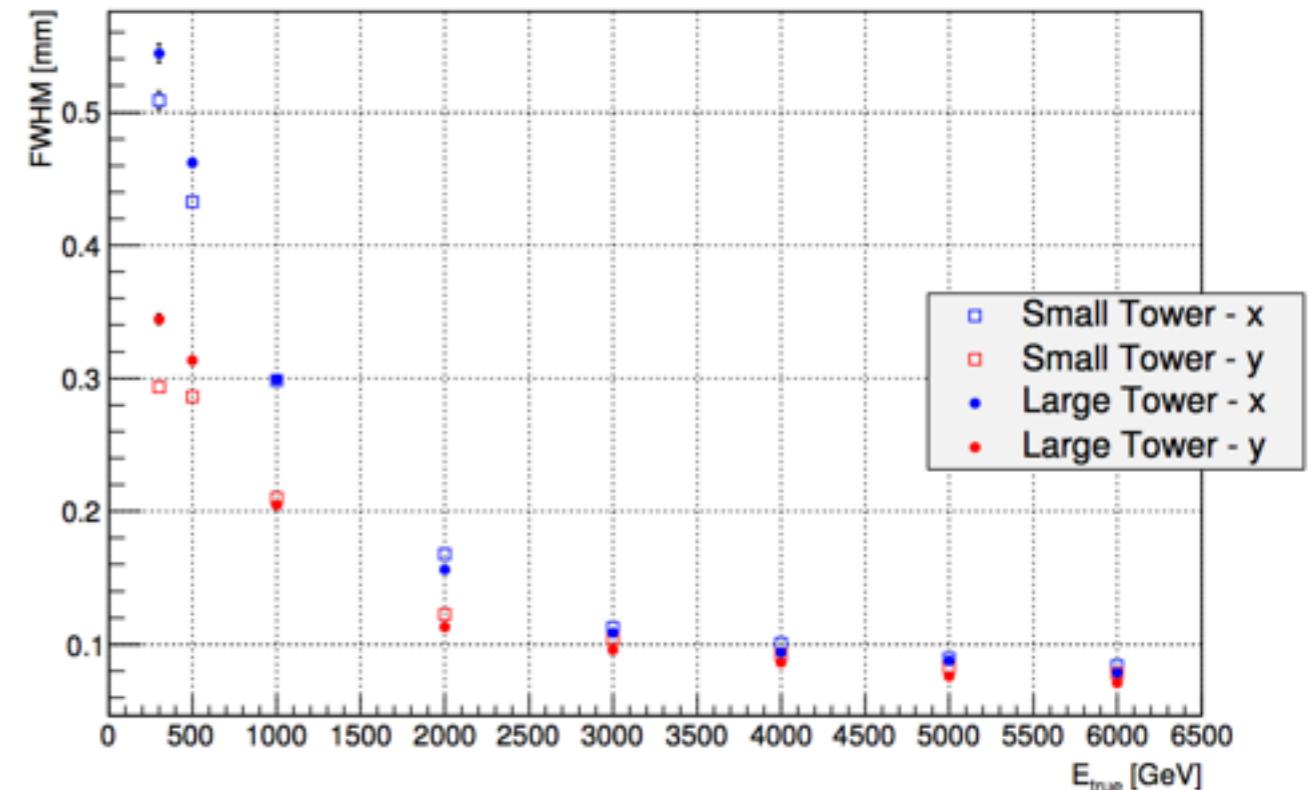
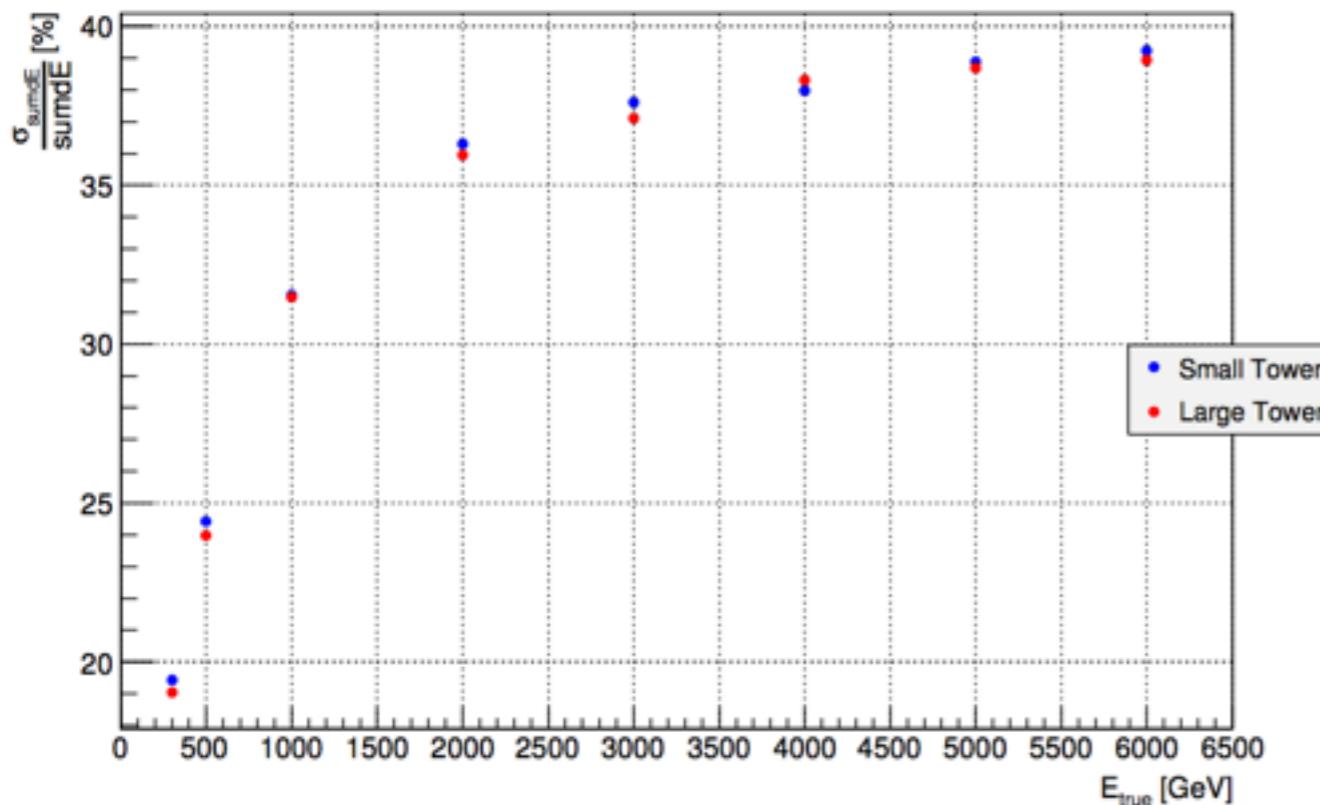
LHCf#Arm2



- ◆ Threshold for Arm1 small tower and large tower are 176, 152GeV, respectively.
- ◆ Threshold for Arm2 small tower and large tower are 100 and 101GeV.

# LHCf detector performance (Arm2)

## Neutron



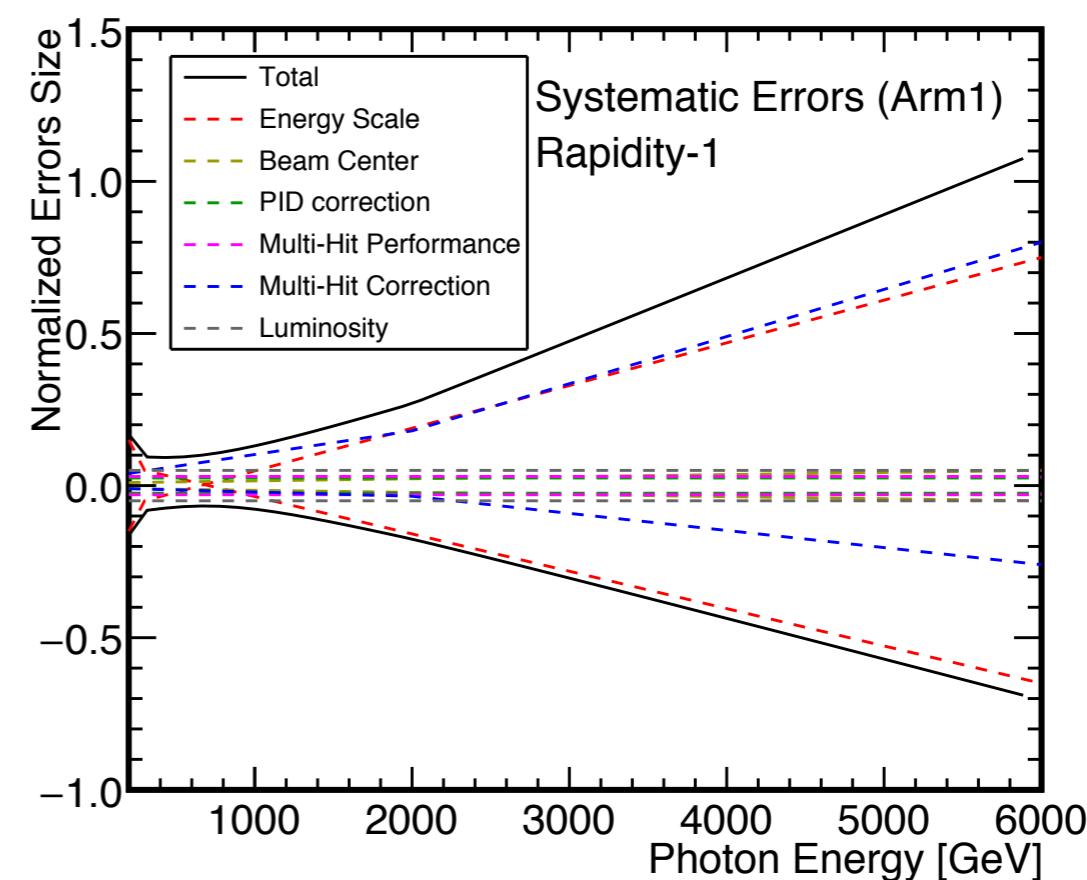
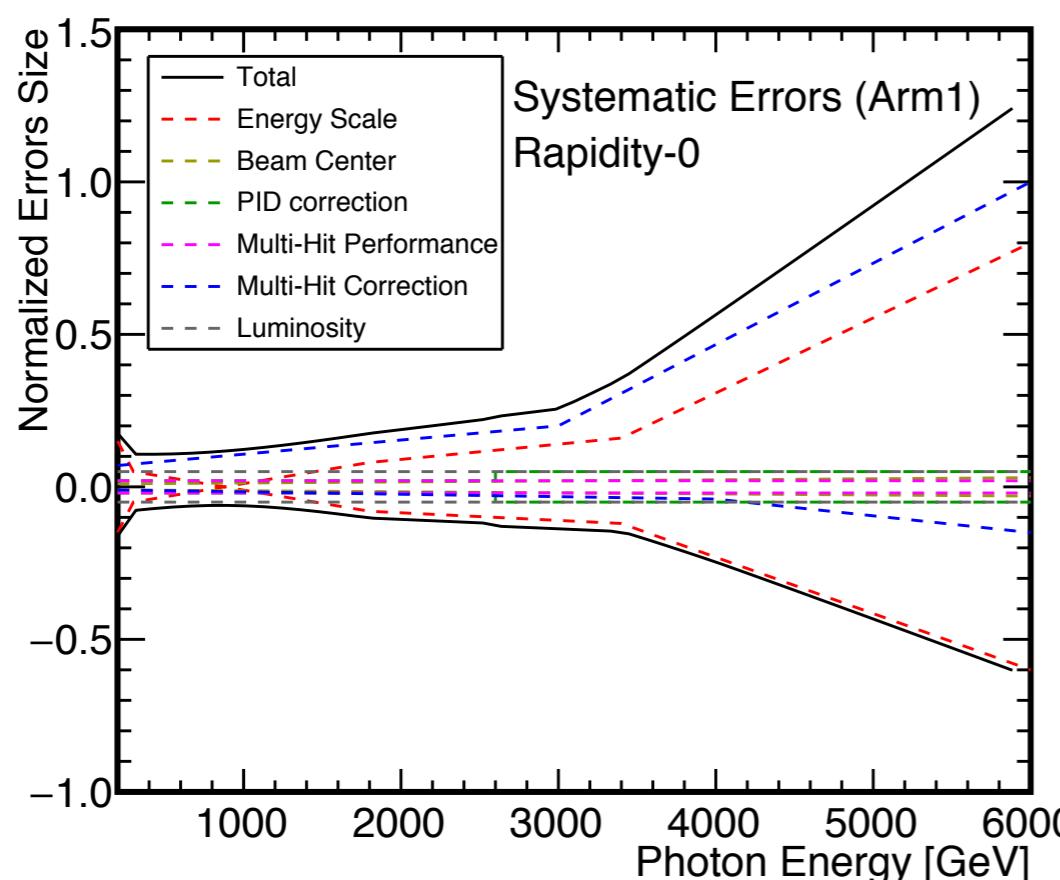
Energy resolution of 13TeV

Position resolution of 13TeV

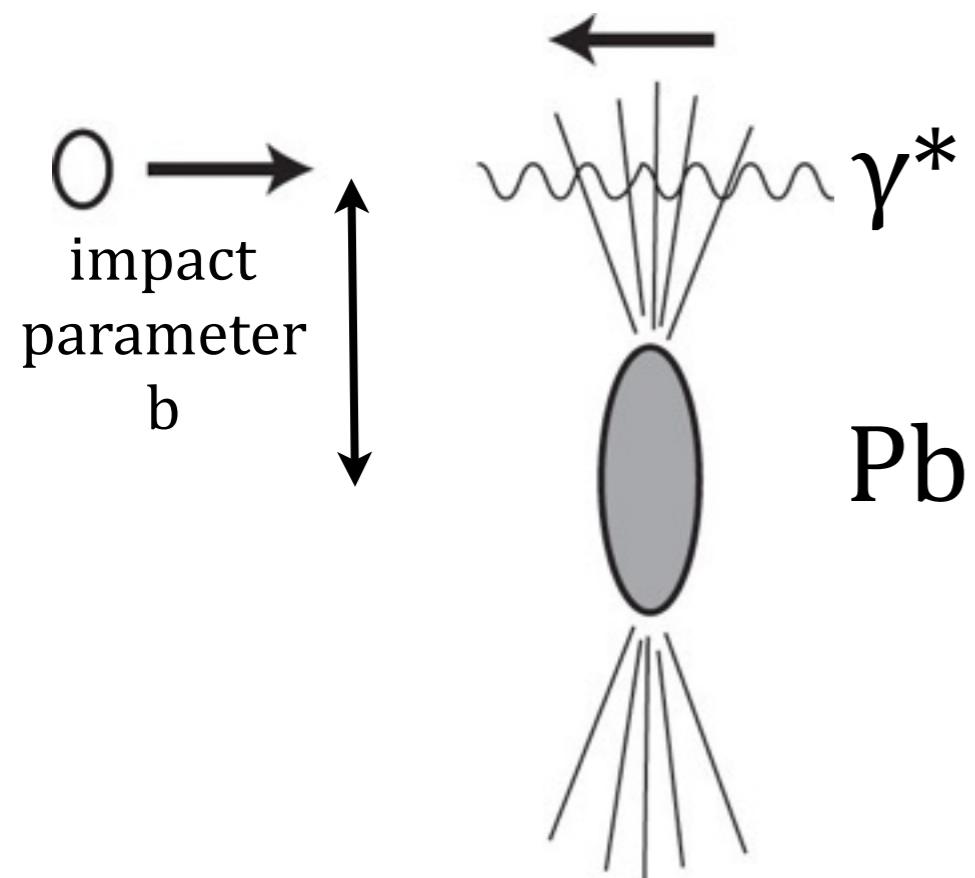
# Systematic uncertainties (*preliminary*)

p-p@13TeV

Items	Arm1 $ \eta  < 10.94$	Arm1 $8.99 < \eta < 1.81$
Energy scale	-11%, +14%	-28%, +23%
PID correction	$\pm 5\%$	$\pm 2.5\%$
Beam center	$\pm 2\%$	$\pm 3\%$
Multi hit performance	$\pm 2\%$	$\pm 3\%$
Multi hit correction	-3%, +20%	-9%, +34%
Luminosity	$\pm 5\%$	$\pm 5\%$

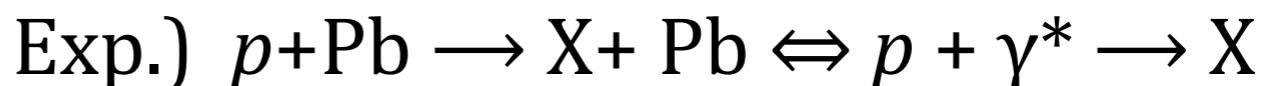


# UPC process at p-Pb



## Ultra Peripheral Collisions (UPCs)

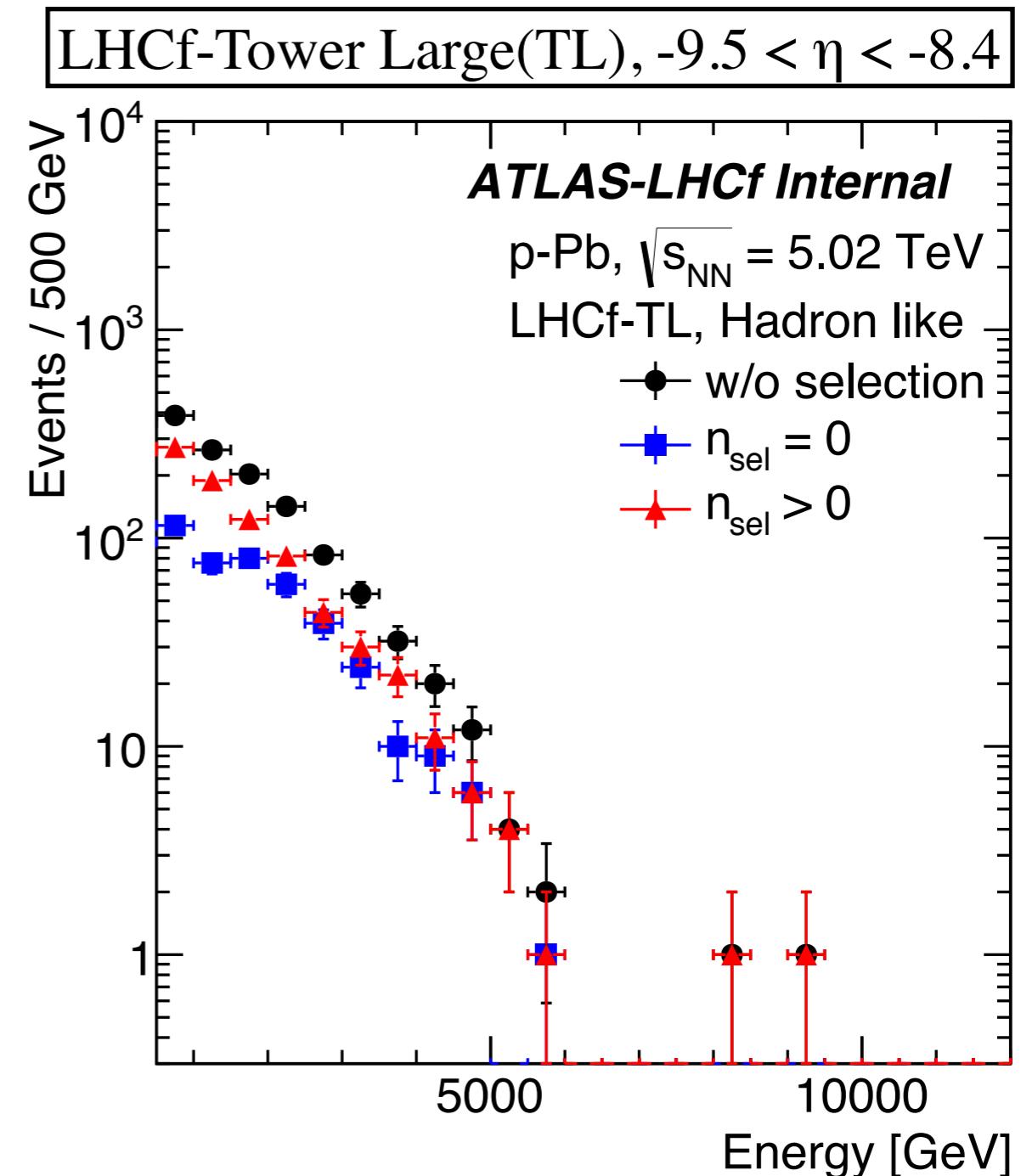
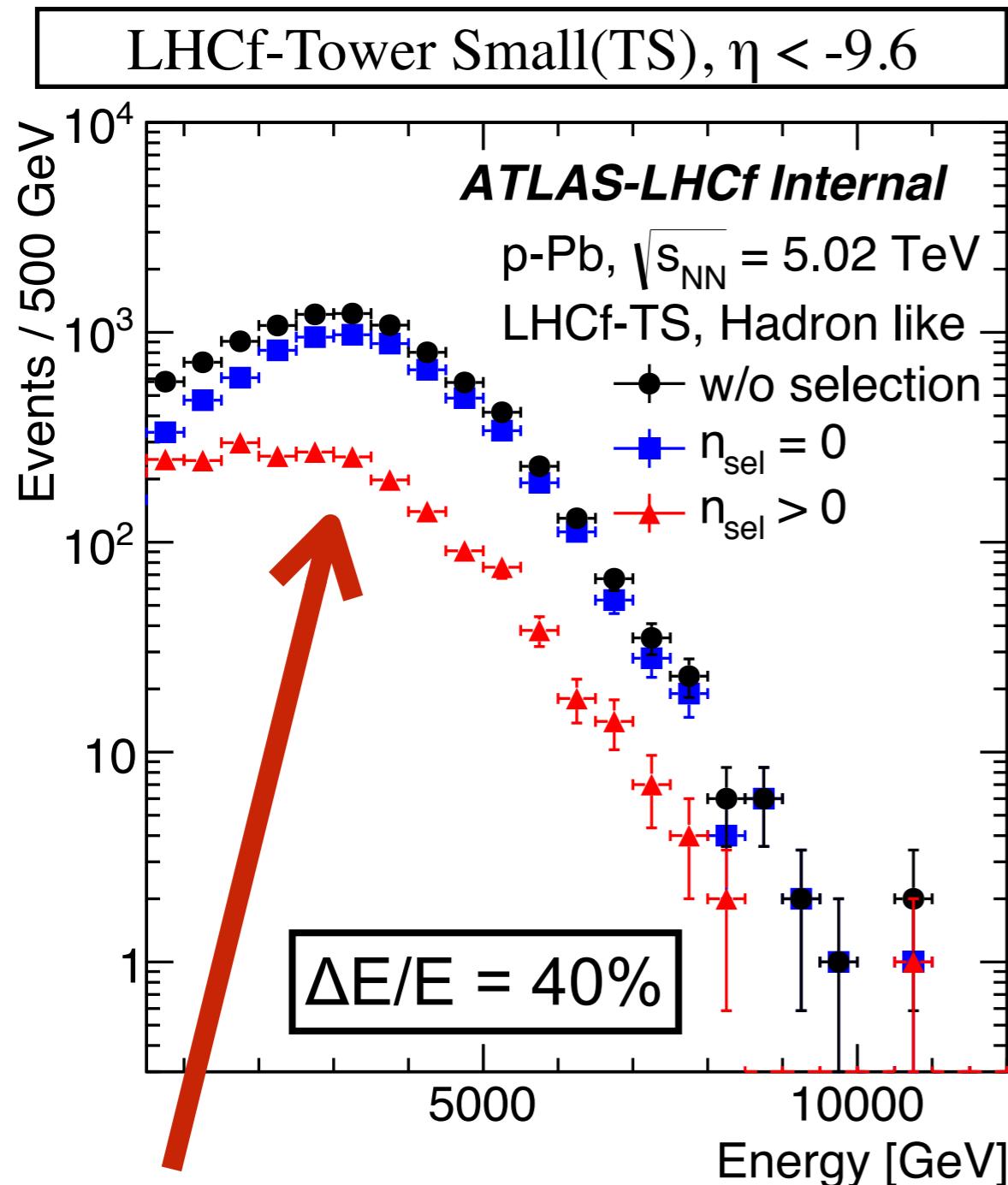
If  $b > R_p + R_{Pb}$ , hadron interaction is strongly suppressed and proton collides with electromagnetic field of Pb, of which strength is proportional to  $Z^2$ . The EM interaction can be described as a collision between proton and quasi-photon.



***In UPCs, what can we see at zero degree of collision ?  
= in LHCf***

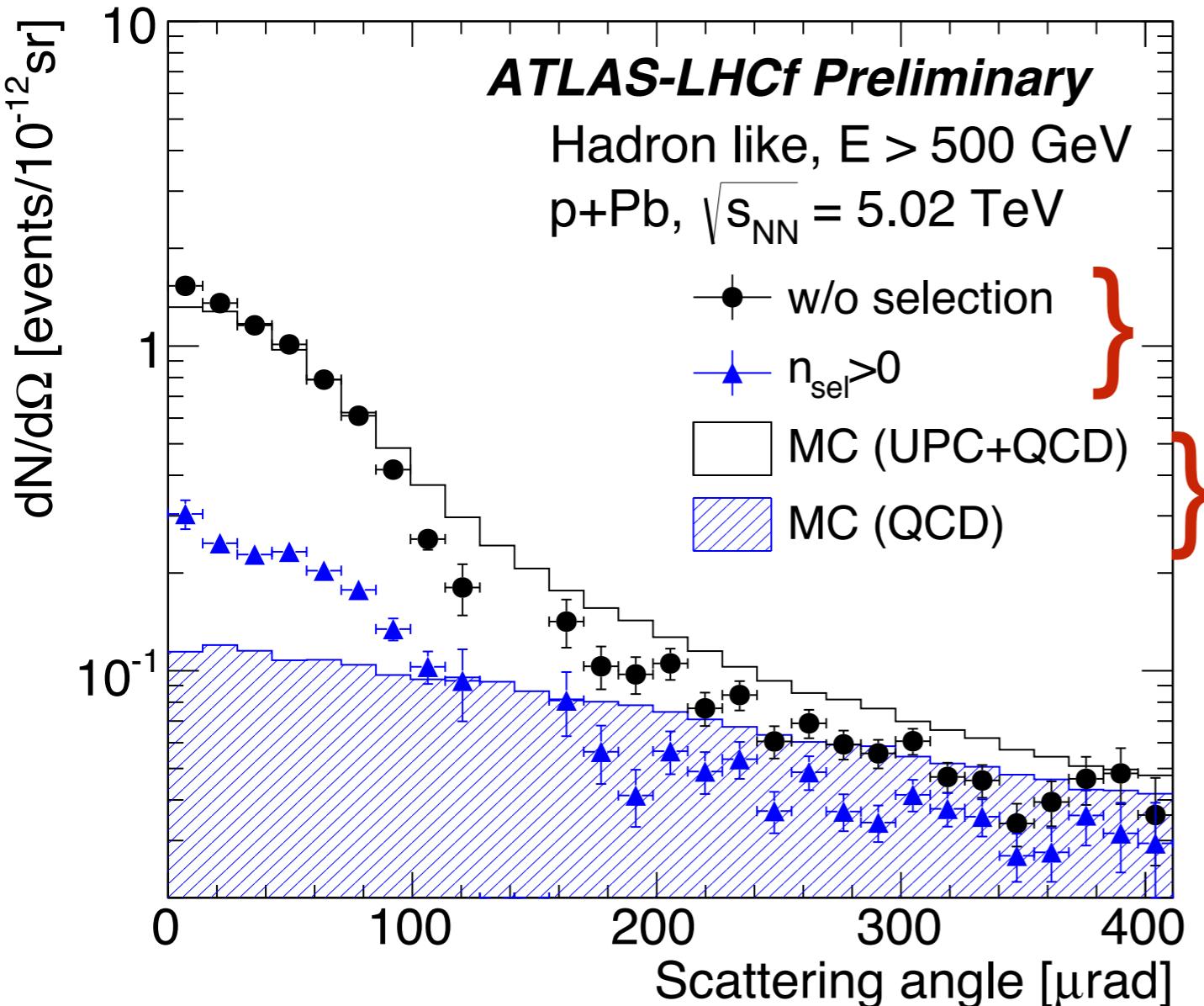
LHCf had operations with  $p + \text{Pb}$  collisions of  $\sqrt{s_{NN}} = 5.02 \text{ TeV}$  in 2013  
LHCf measured the energy spectra of  $\gamma$ ,  $\pi^0$ , neutron inclusively.

# Energy Spectra - Hadron like -(neutron)



Clear difference between spectra of  $n_{sel}=0$  and of  $n_{sel}>0$ .  
 Harder spectrum of  $n_{sel}=0$  due to contribution of  $\Delta$  resonance at UPCs

# Scattering angle distribution



Data with the event selection by number of tracks in ATLAS;  $n_{sel}$

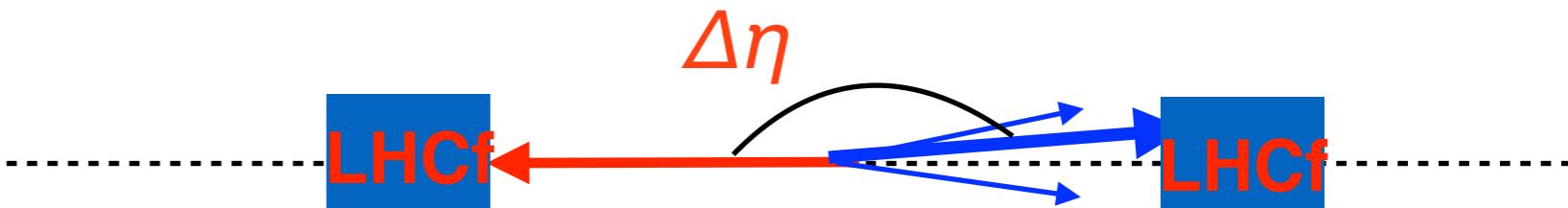
MC with the selection by process

- ✓ Clear concentration at zero degree with events of  $n_{sel}=0$ .
- ✓ Similar distribution of  $n_{sel}>0$  as one of MC (QCD)

Note) The sum of UPC and QCD simulations was normalized to all data in the range from 0  $\mu$ rad to 120  $\mu$ rad.

- The joint analysis clearly helps to study the forward particle production with categorizing the type of interaction.

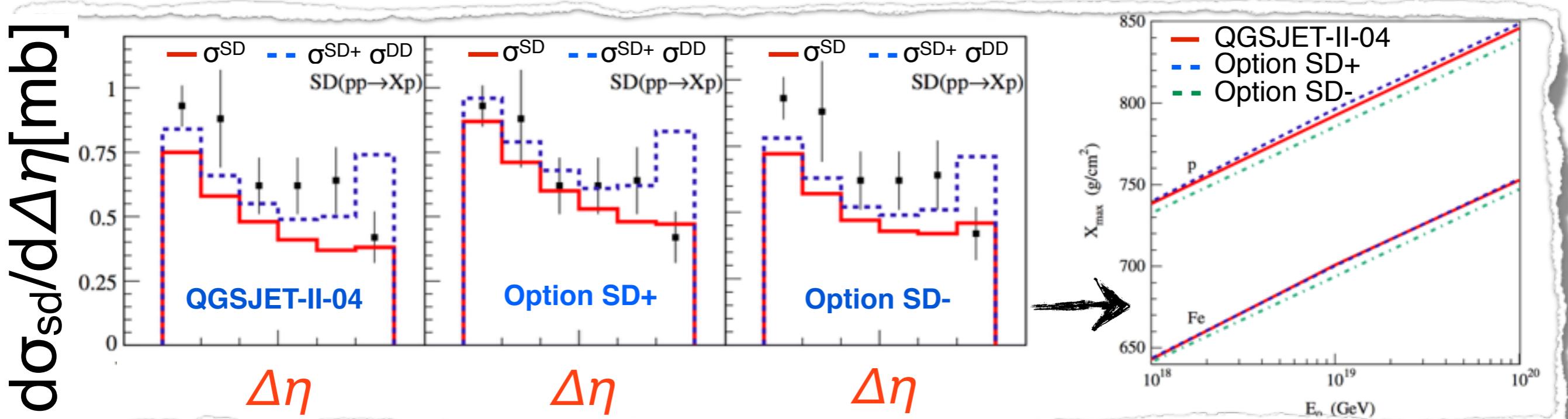
# Impact of diffraction collisions to $X_{max}$



## Diffraction

- ♦  $K_{inel} = \Delta E/E_0 = \exp(-\Delta\eta) \ll 1$  (inelasticity)  
( $\Delta E$ : the energy loss of the leading secondary nucleon).
- diffraction collision is related to the  $X_{max}$
- ♦ The higher rate of Diffractive collision, the deeper  $X_{max}$

S. Ostapchenko, et al., Phy. Rev. D 89, 074009 (2014)

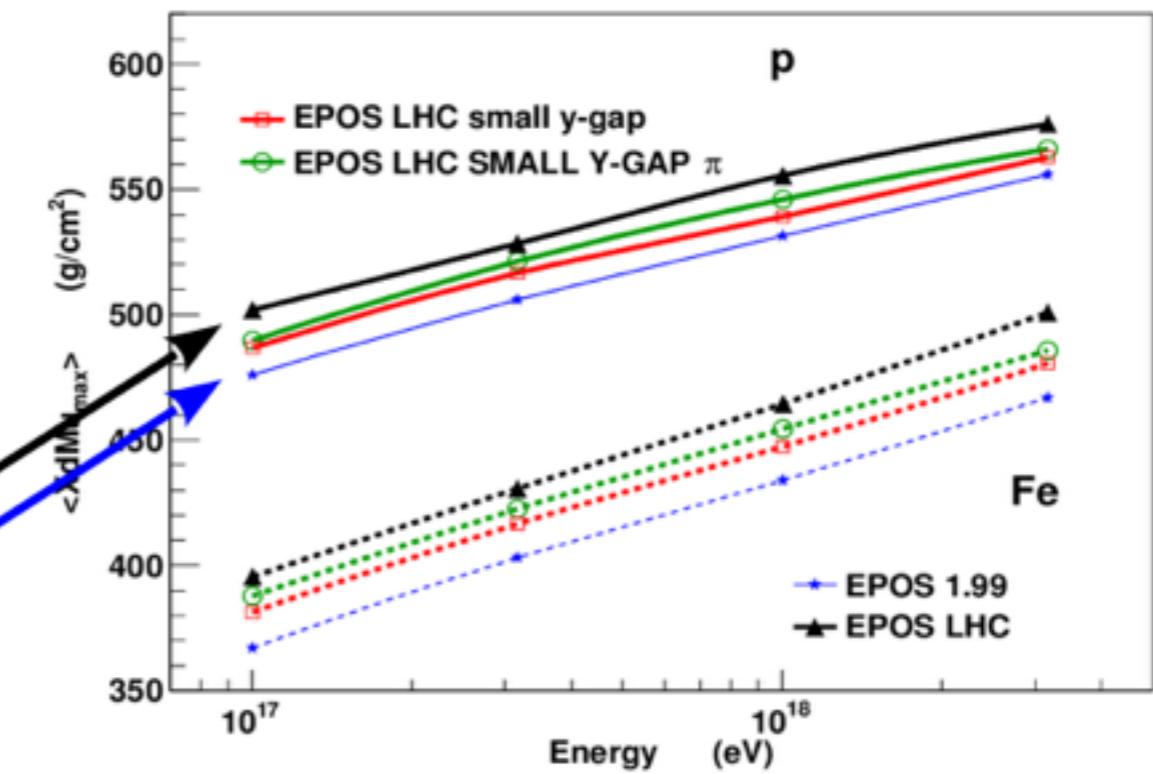
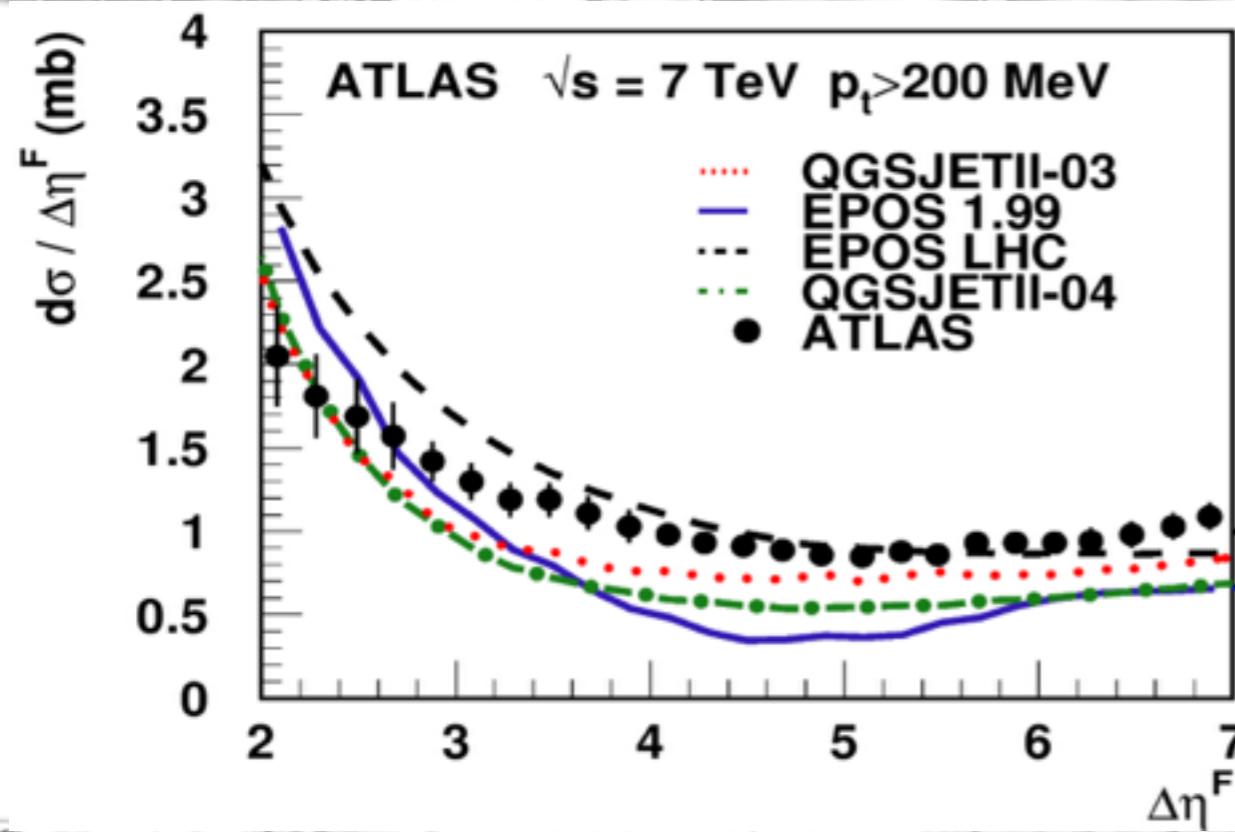


# Impact of diffraction collisions to $X^u_{\max}$

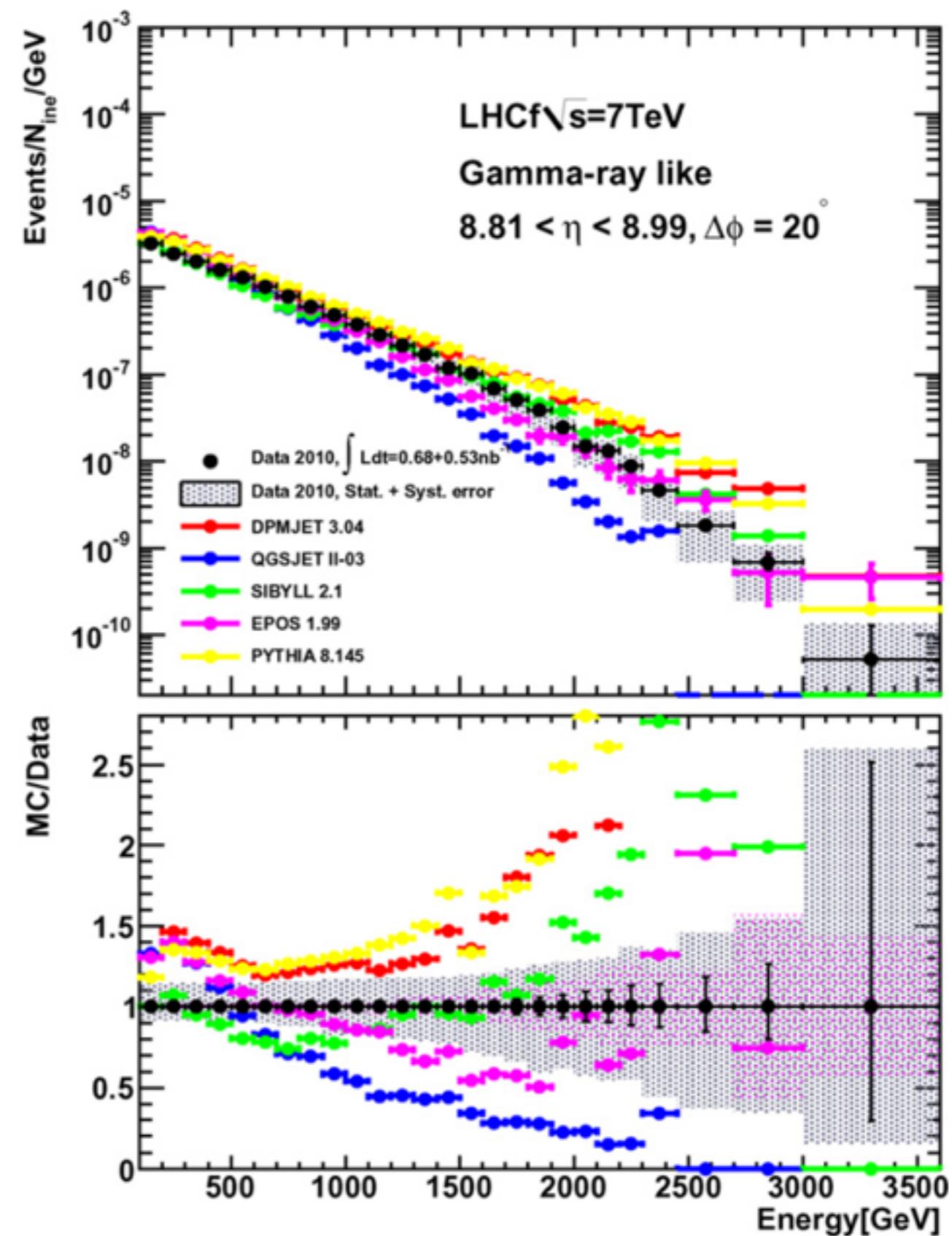
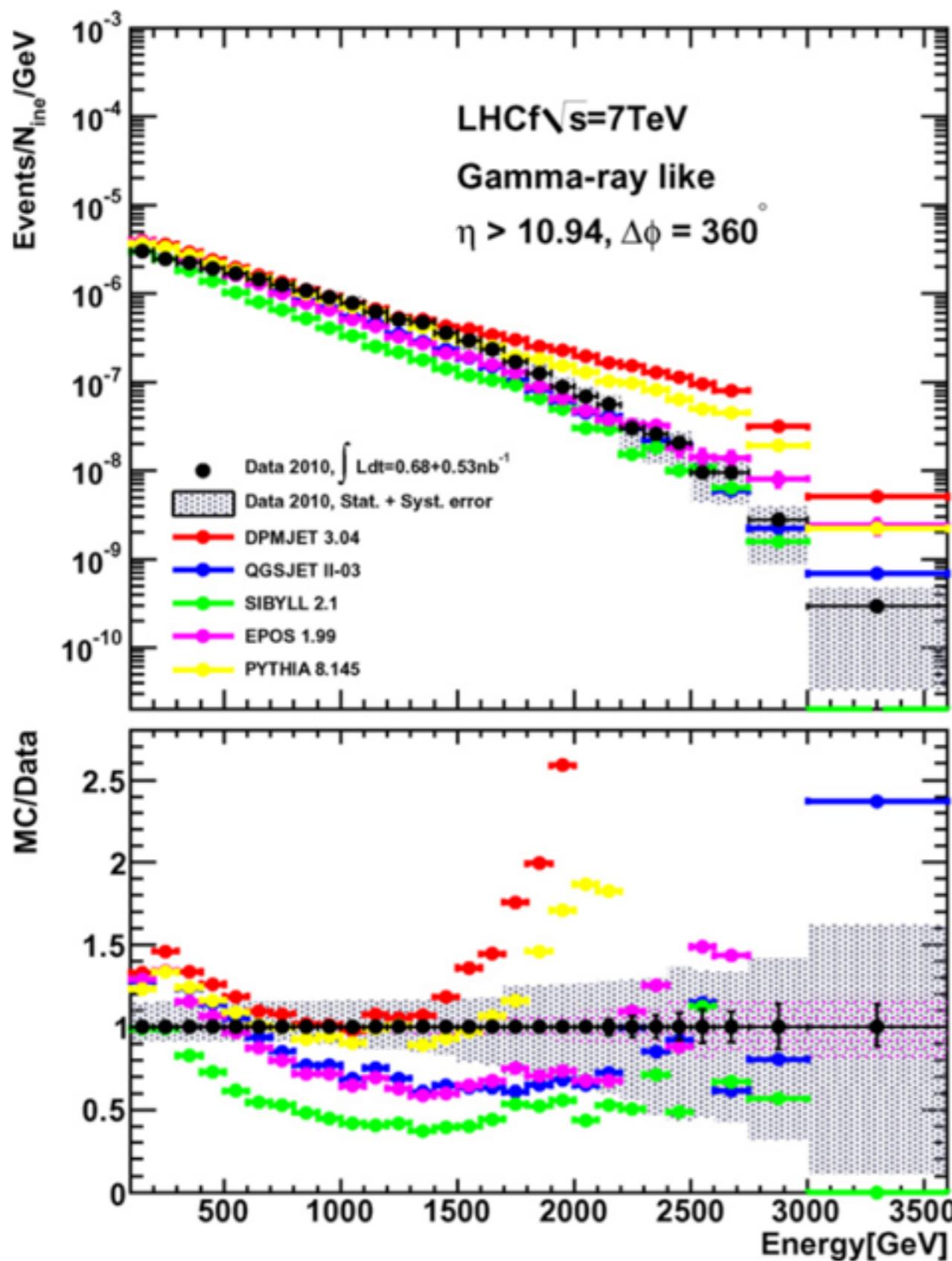


- ♦ Weak influence on EM Xmas
- ♦ Cumulative effect for  $X^u_{\max}$
- ♦ Neutron (baryon) and gamma (pair production from  $\pi$  meson) are detectable for LHCf detectors

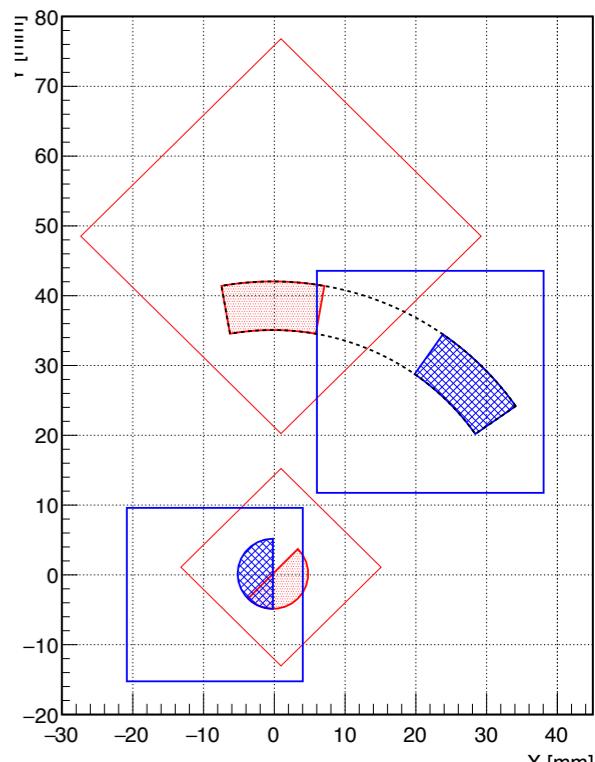
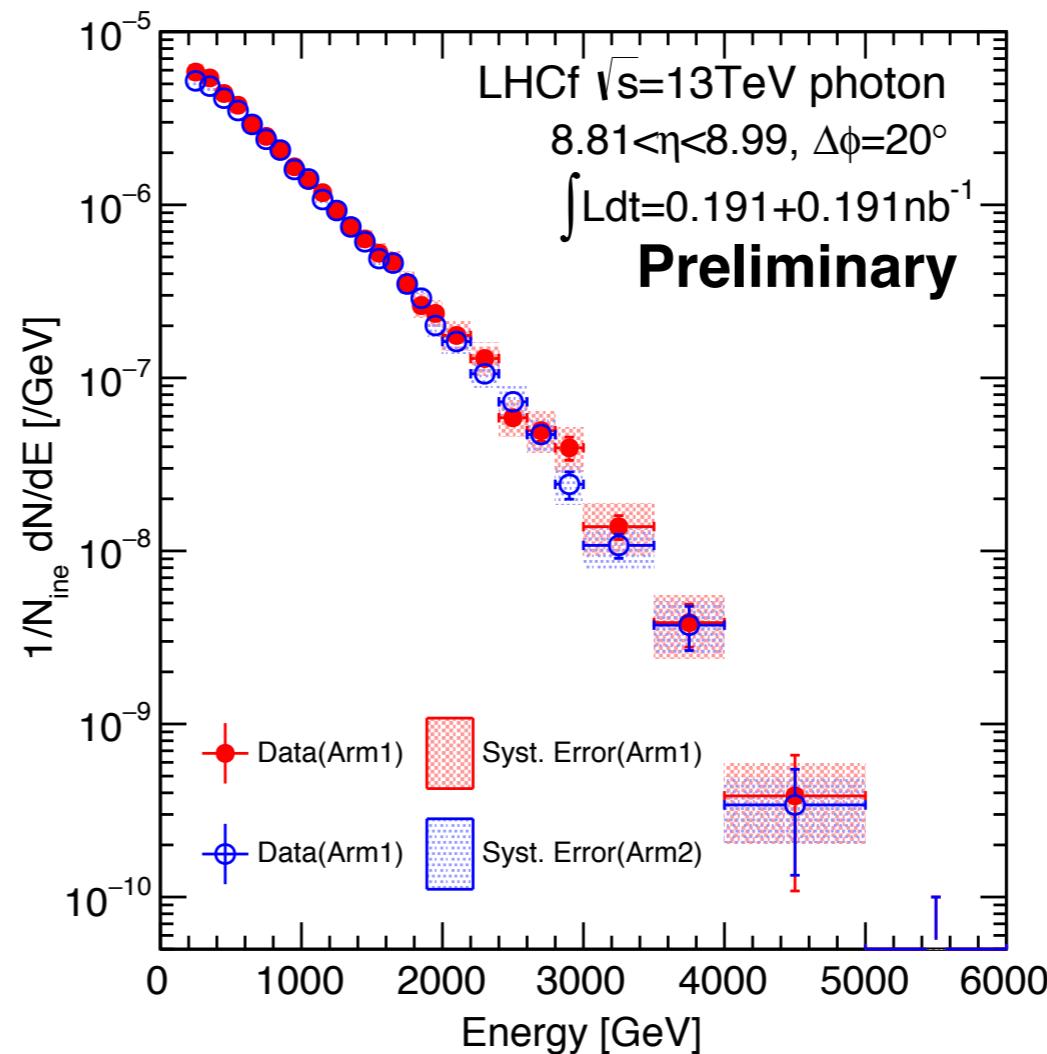
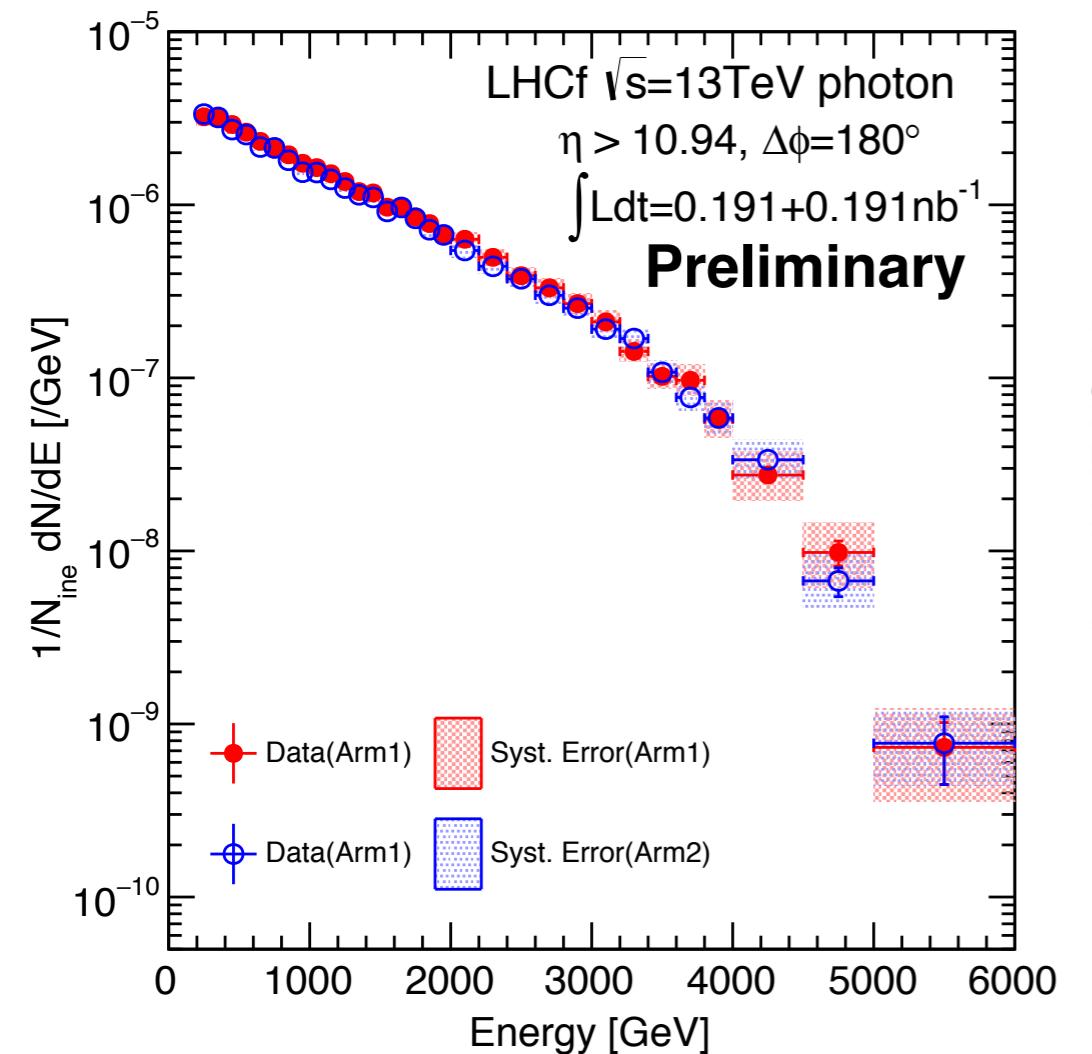
T. Pieorg, HESZ 2015



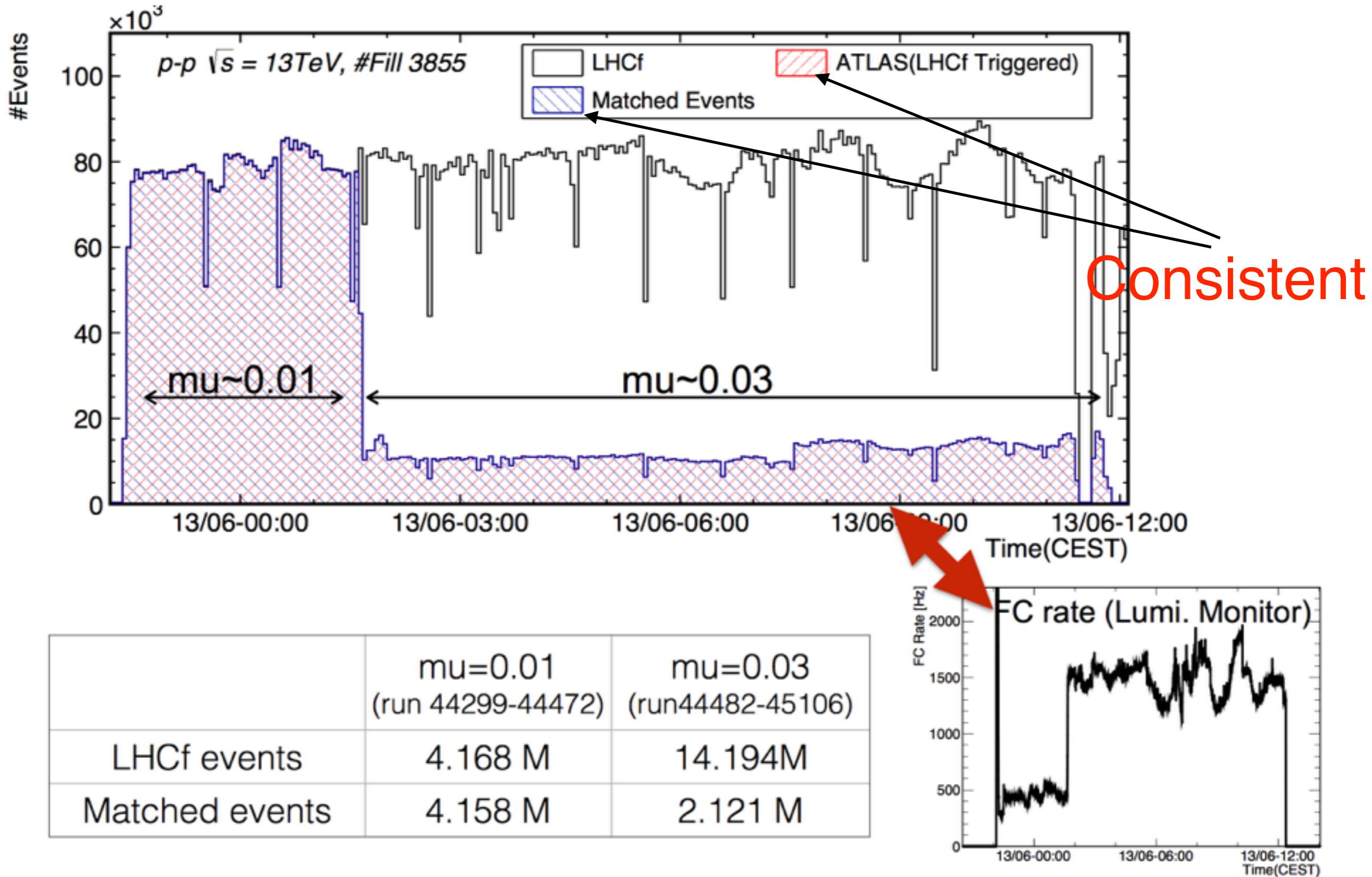
# Photon at $\sqrt{s}=7\text{TeV}$ , p+p



# Consistency of Arm1 and Arm2

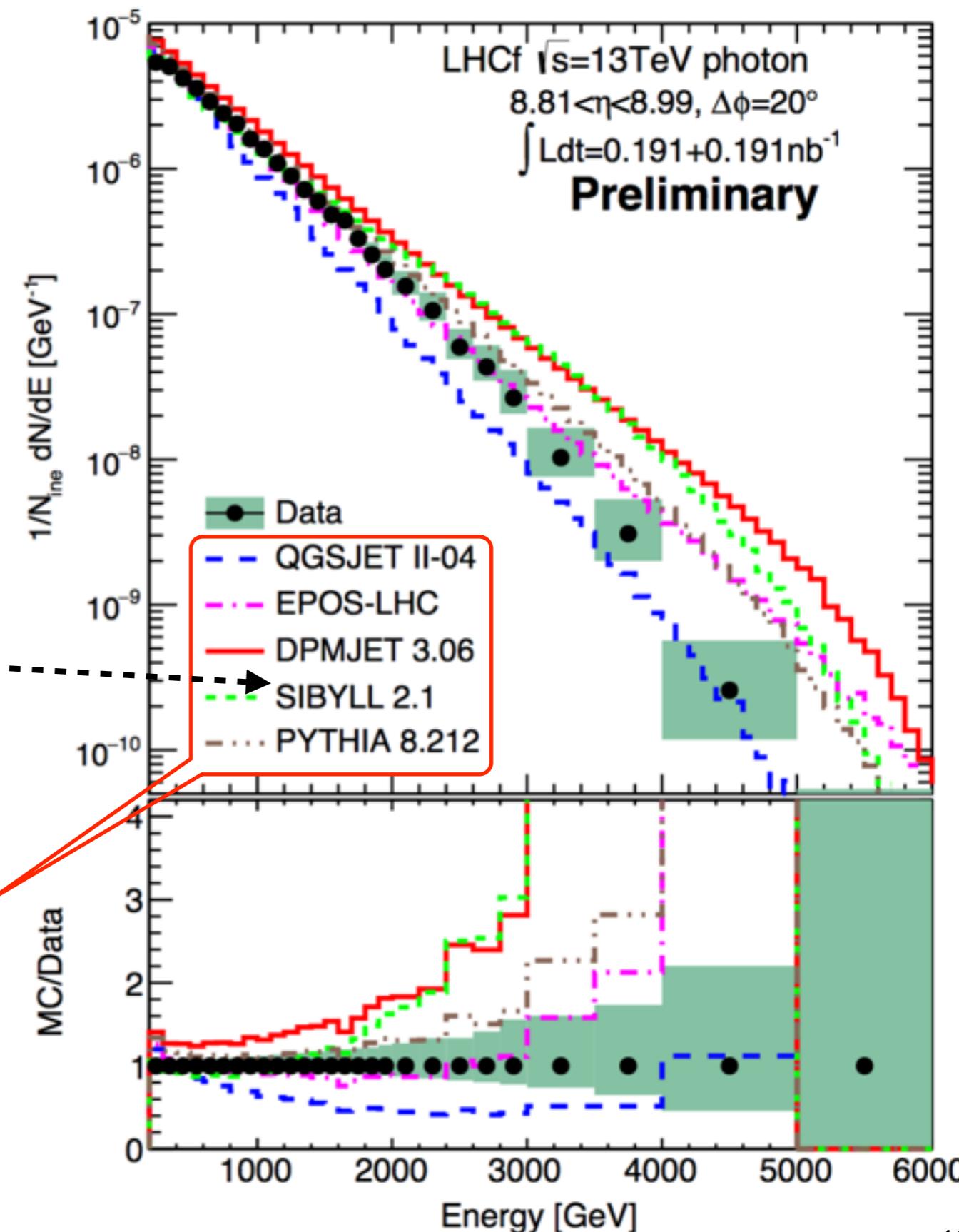
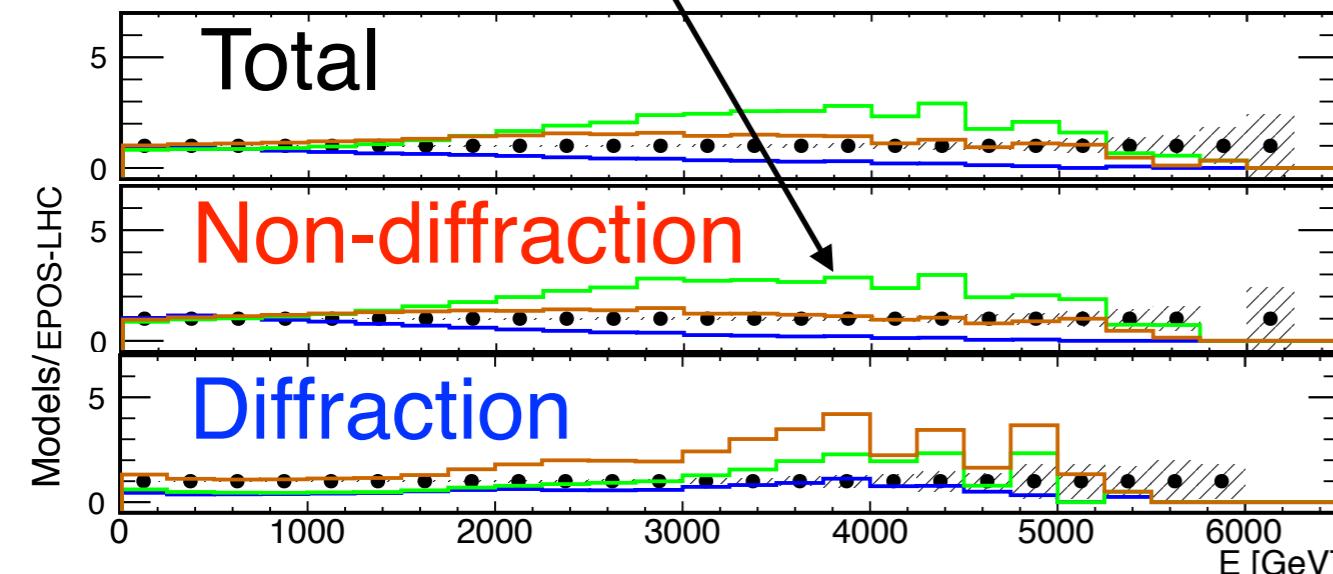
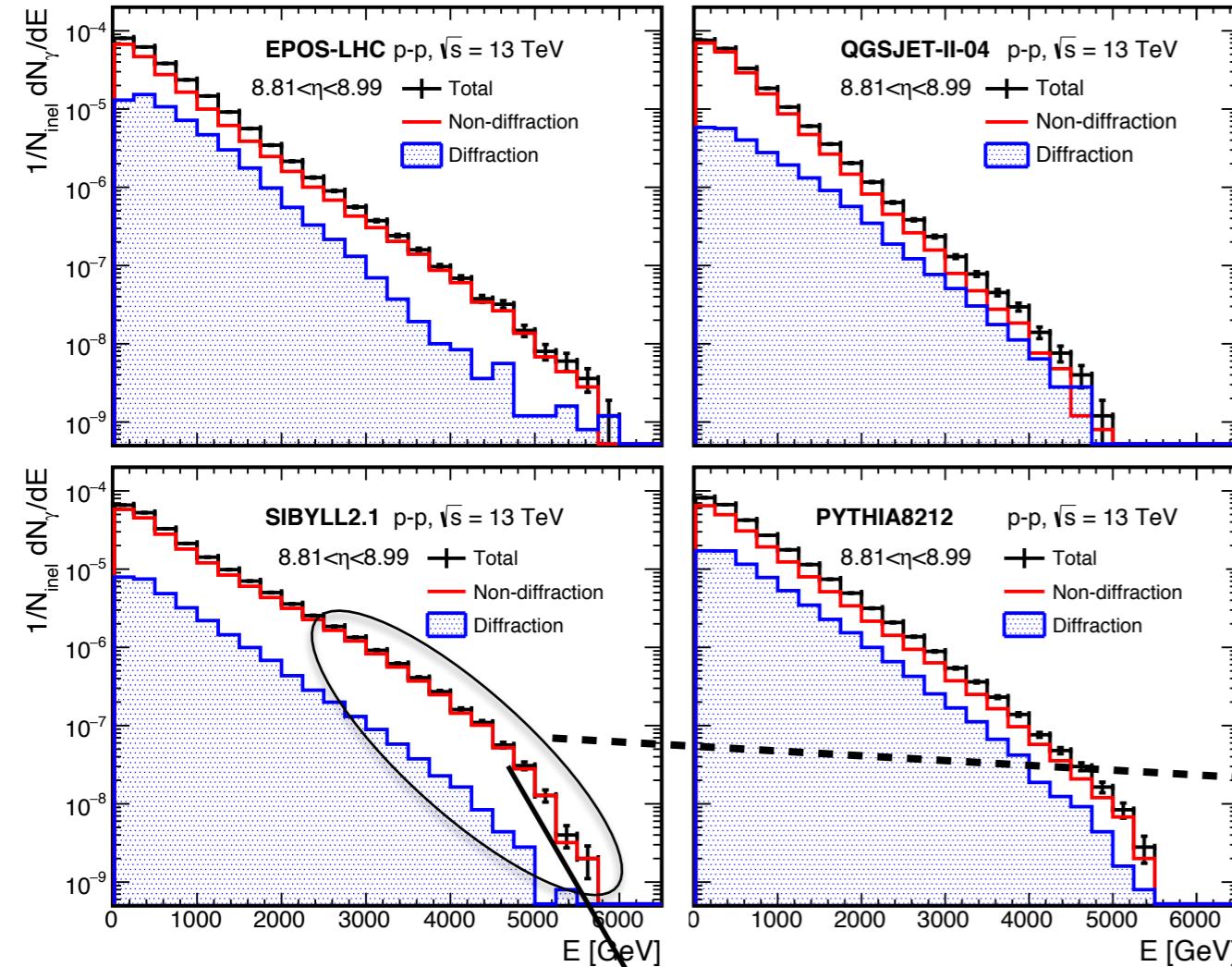


# LHCf-ATLAS Event matching



# Photon spectrum comparison II

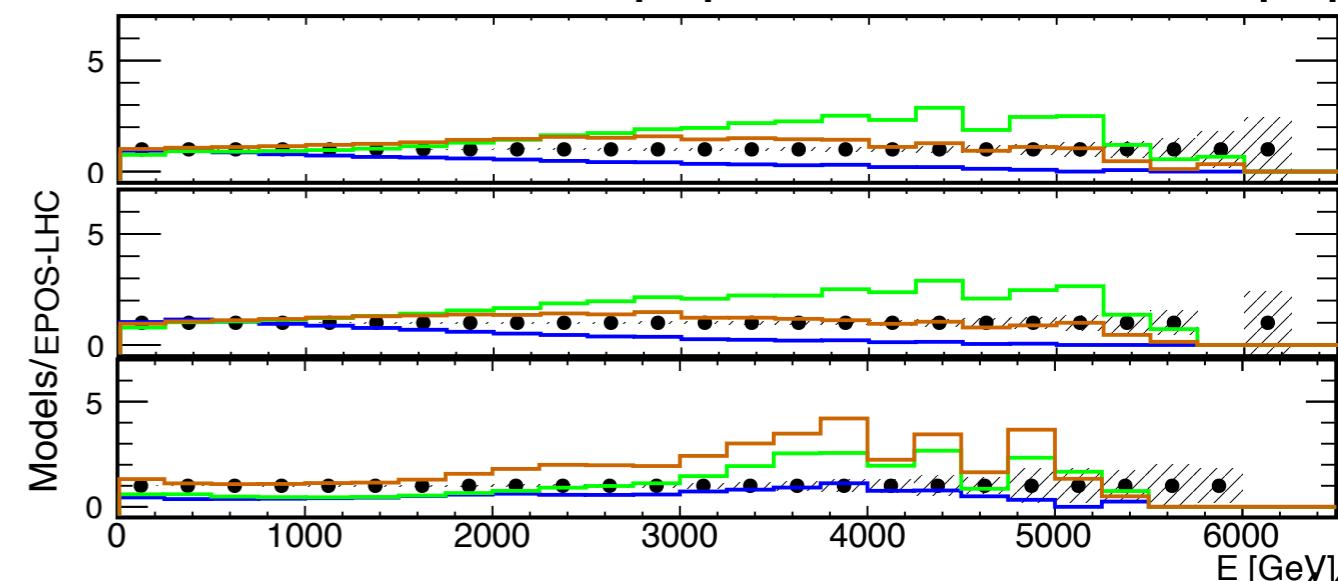
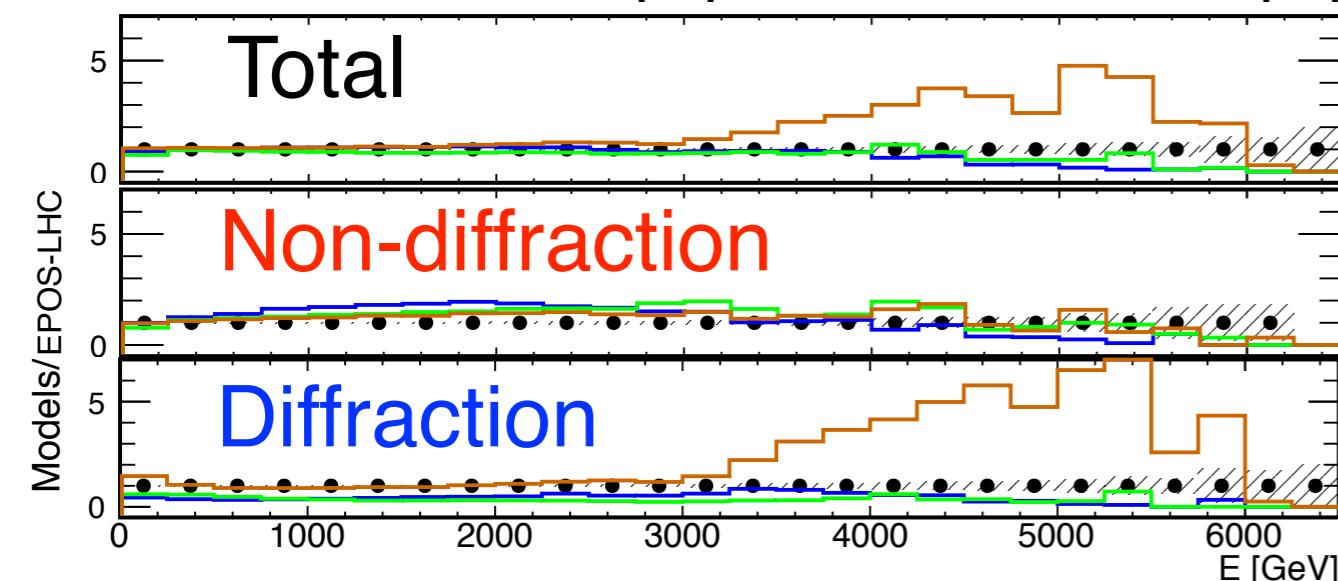
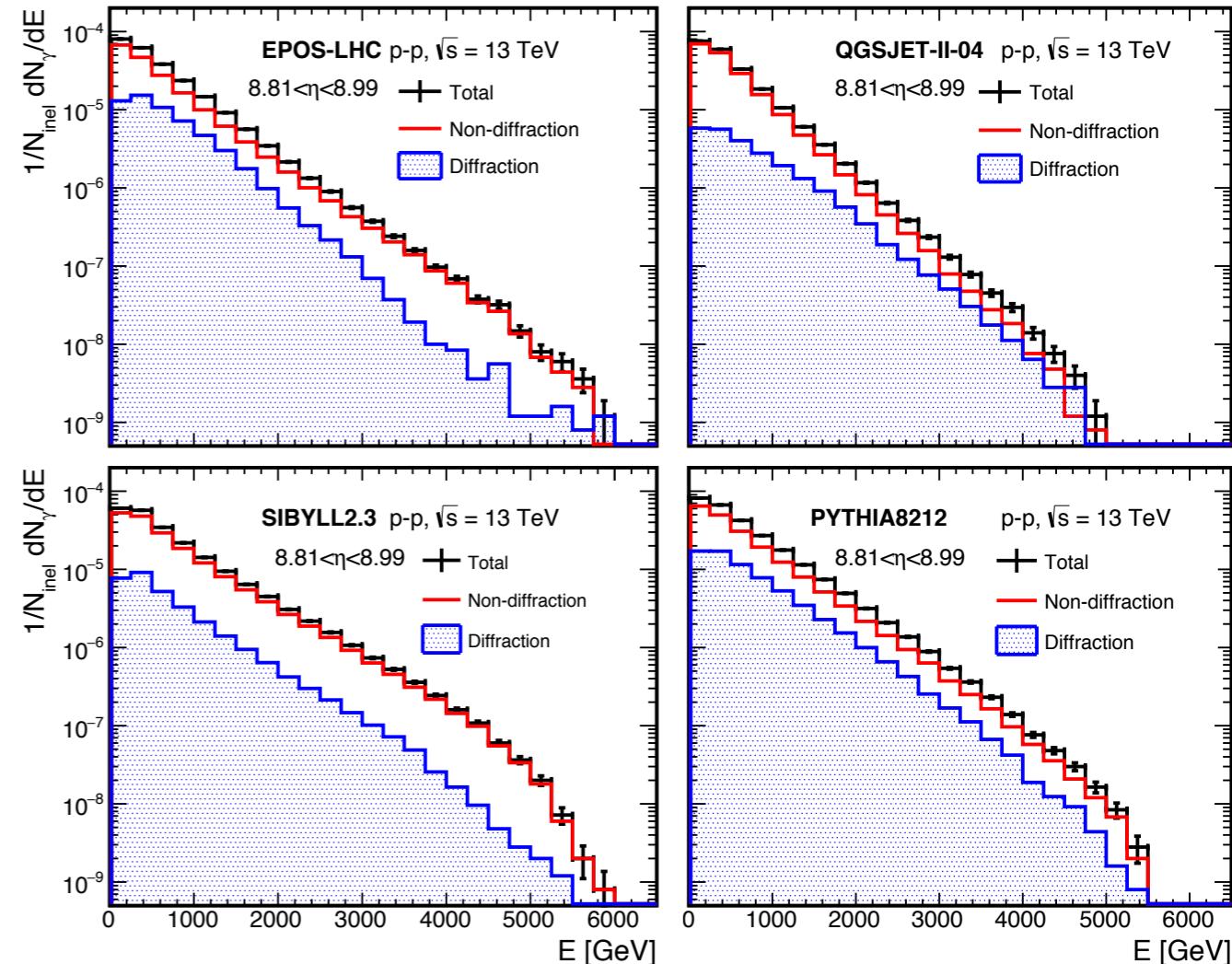
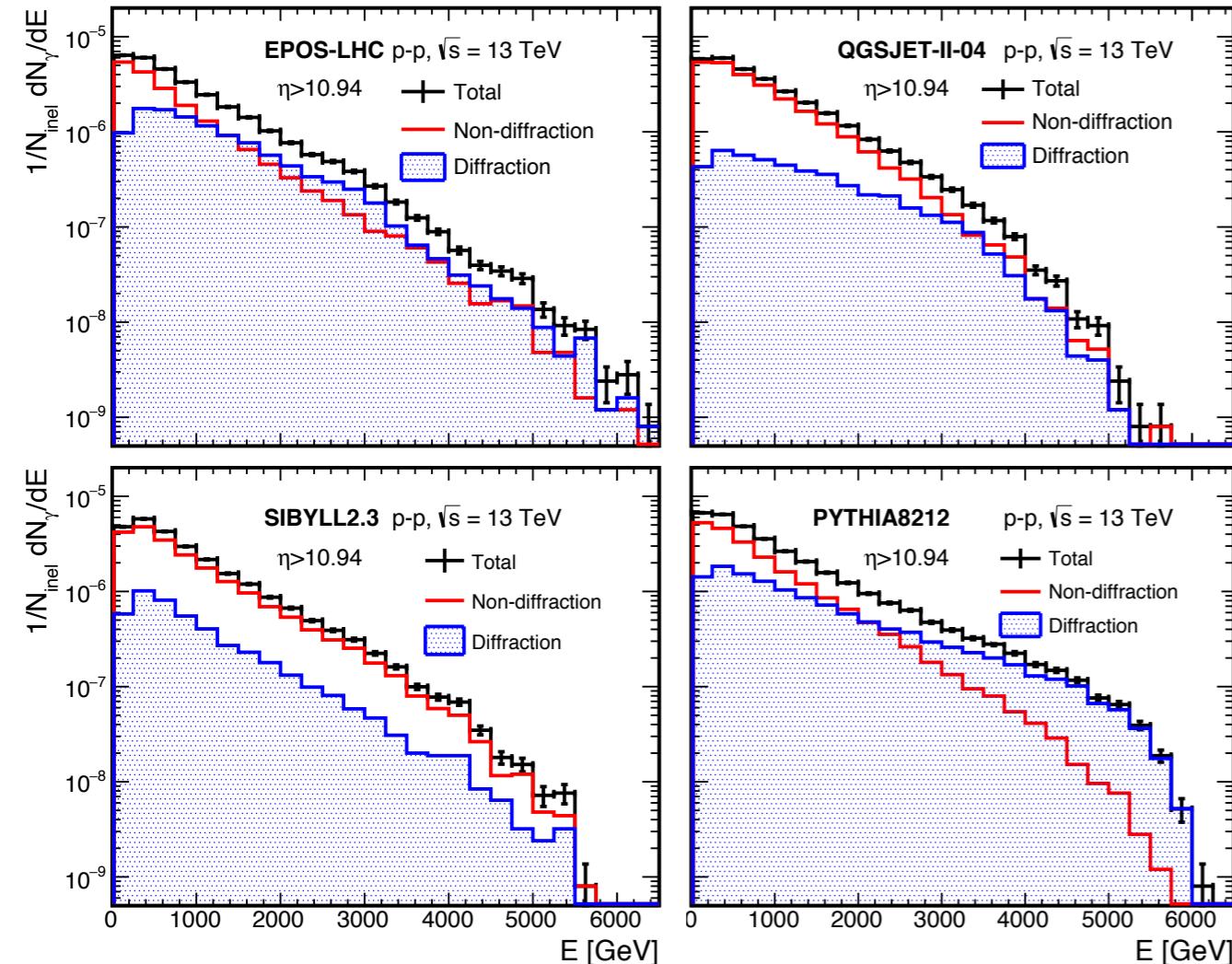
$8.81 < \eta < 8.99$



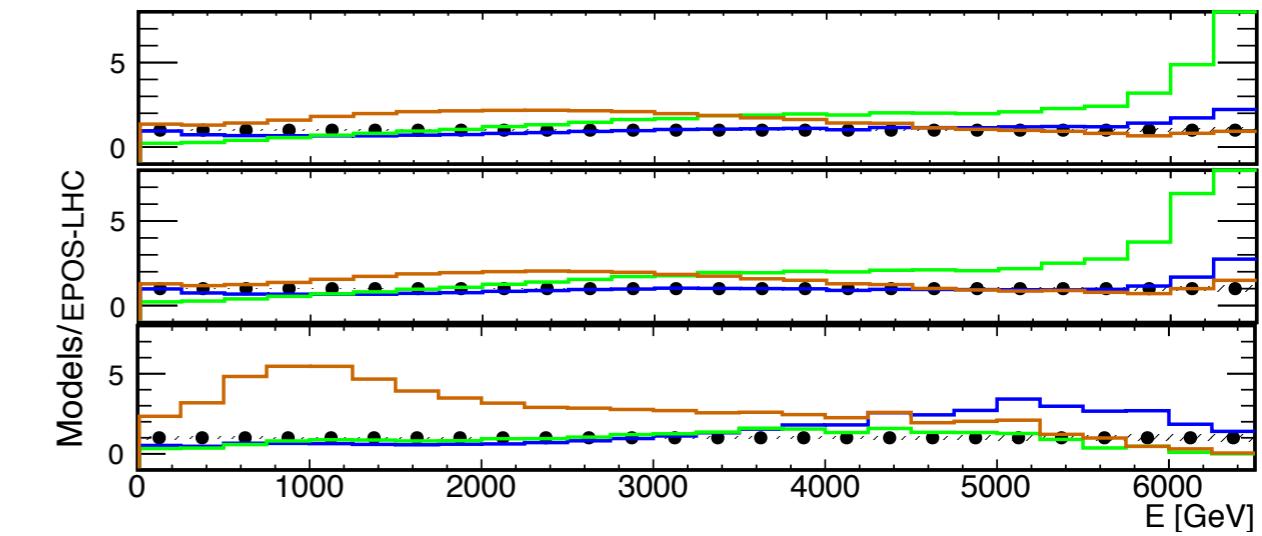
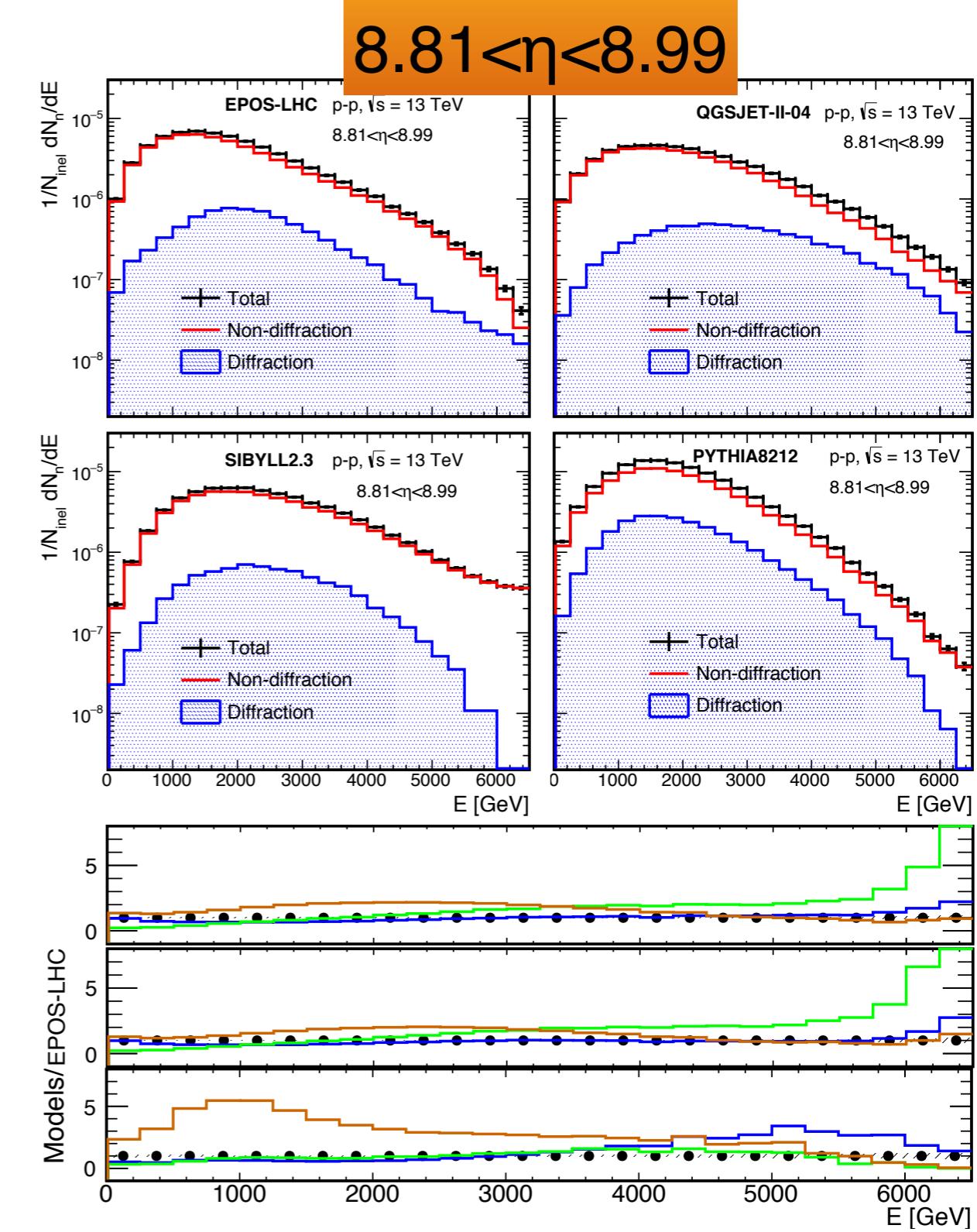
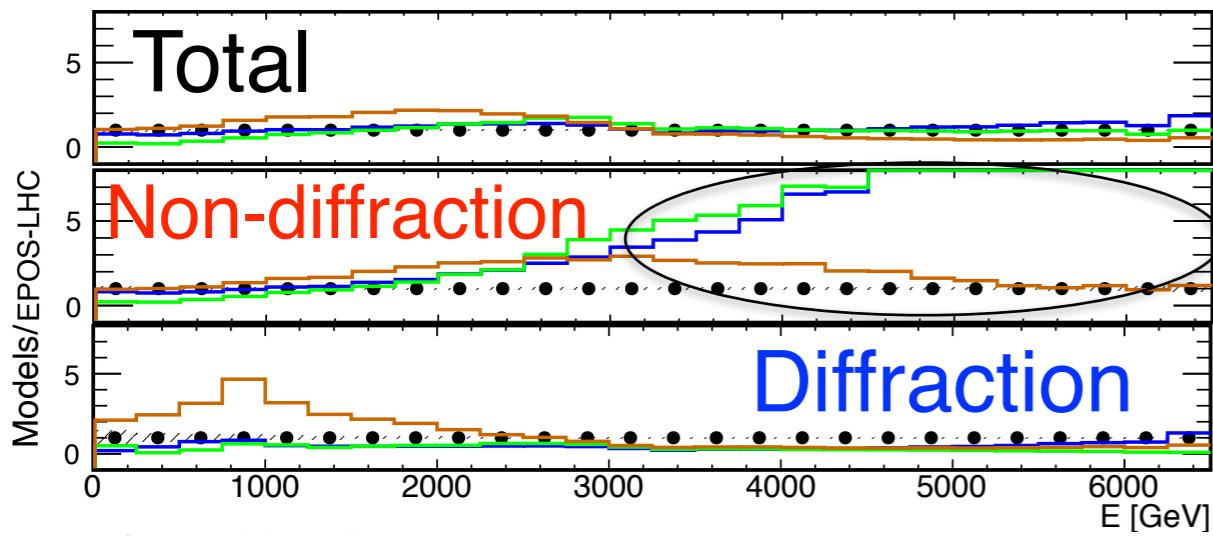
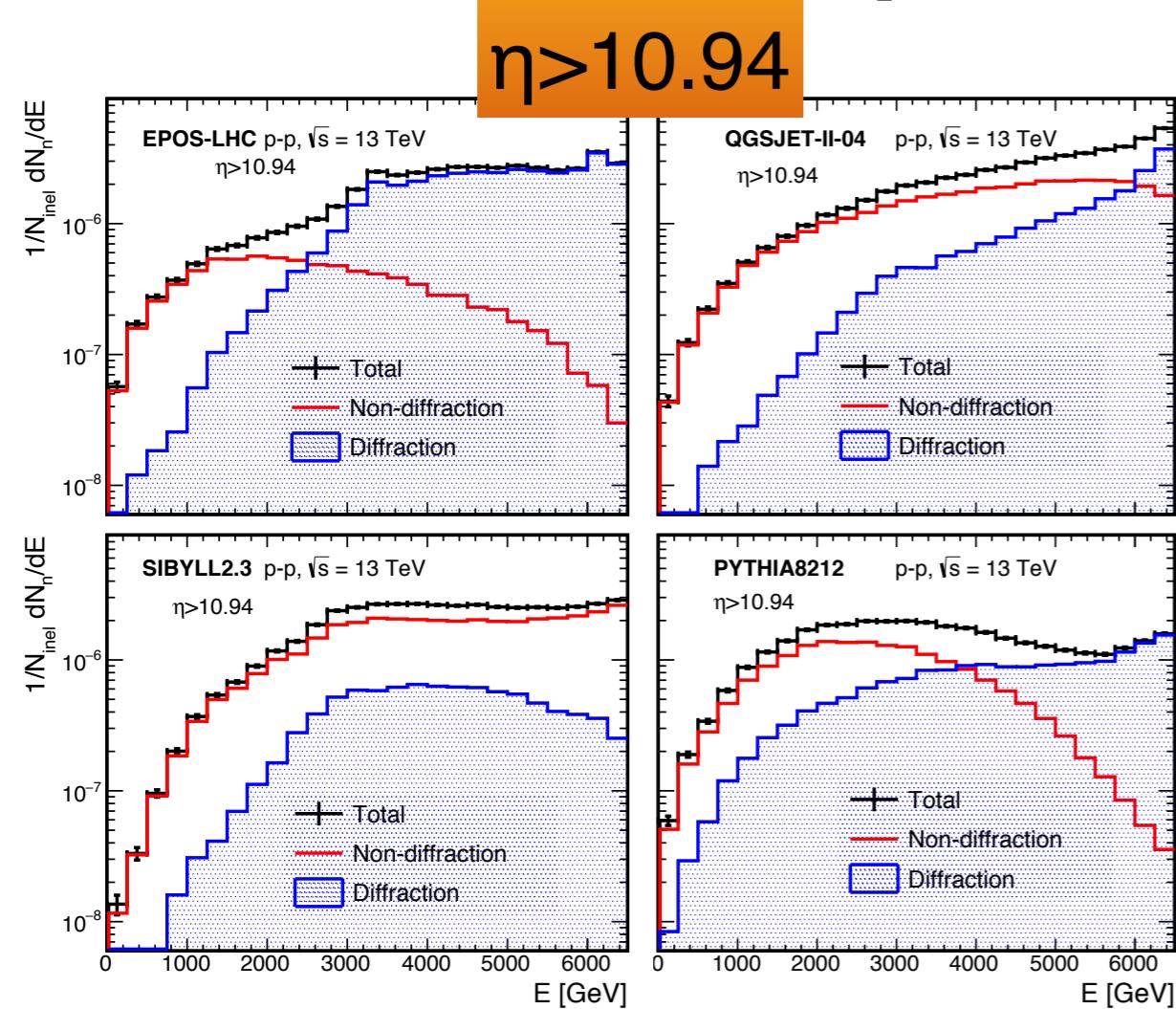
# Photon spectrum comparison

$\eta > 10.94$

$8.81 < \eta < 8.99$



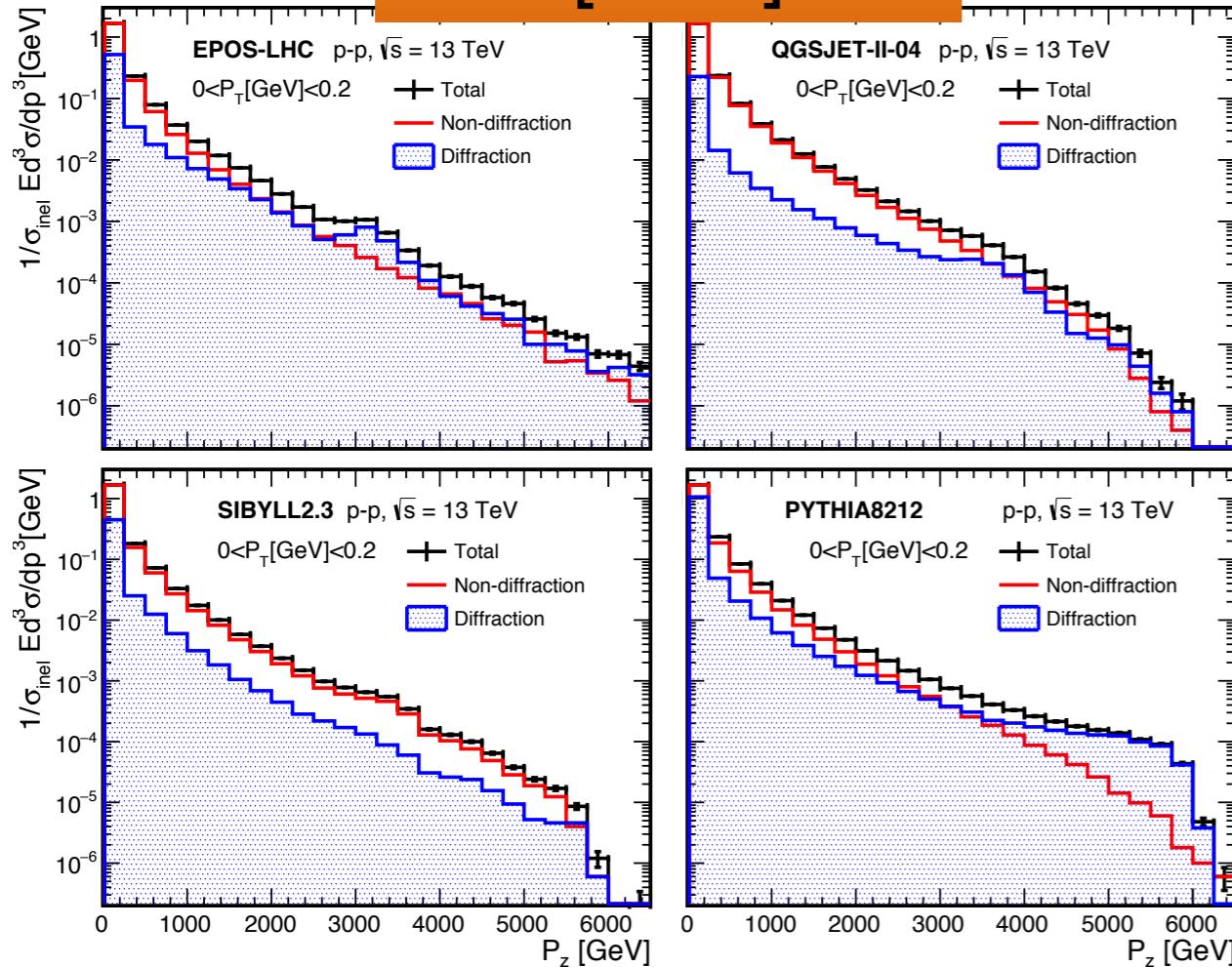
# Neutron spectrum comparison



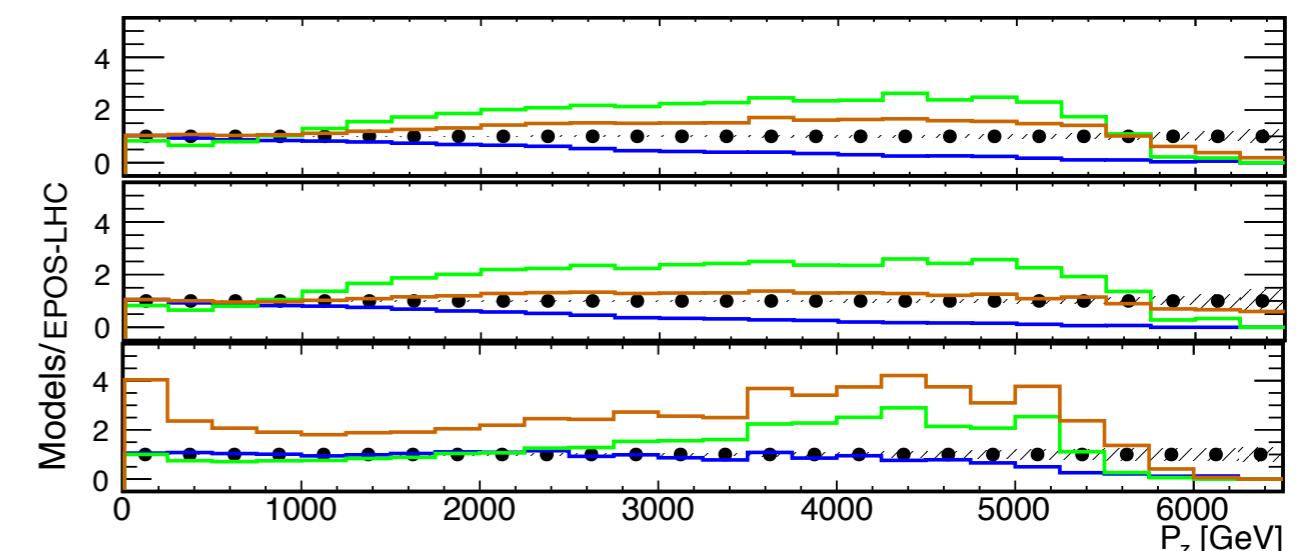
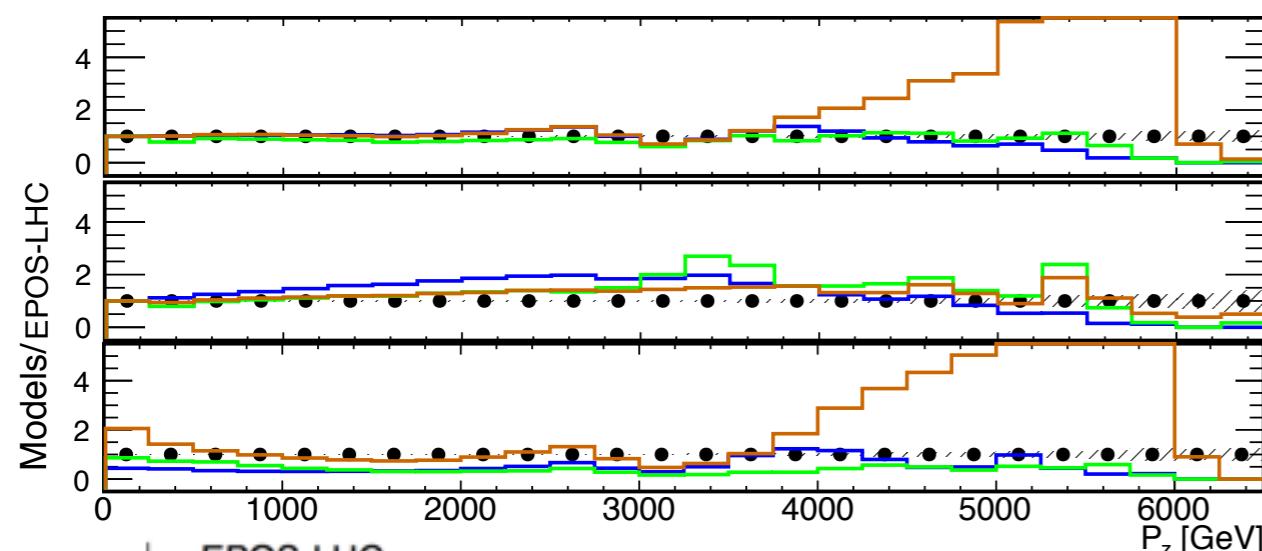
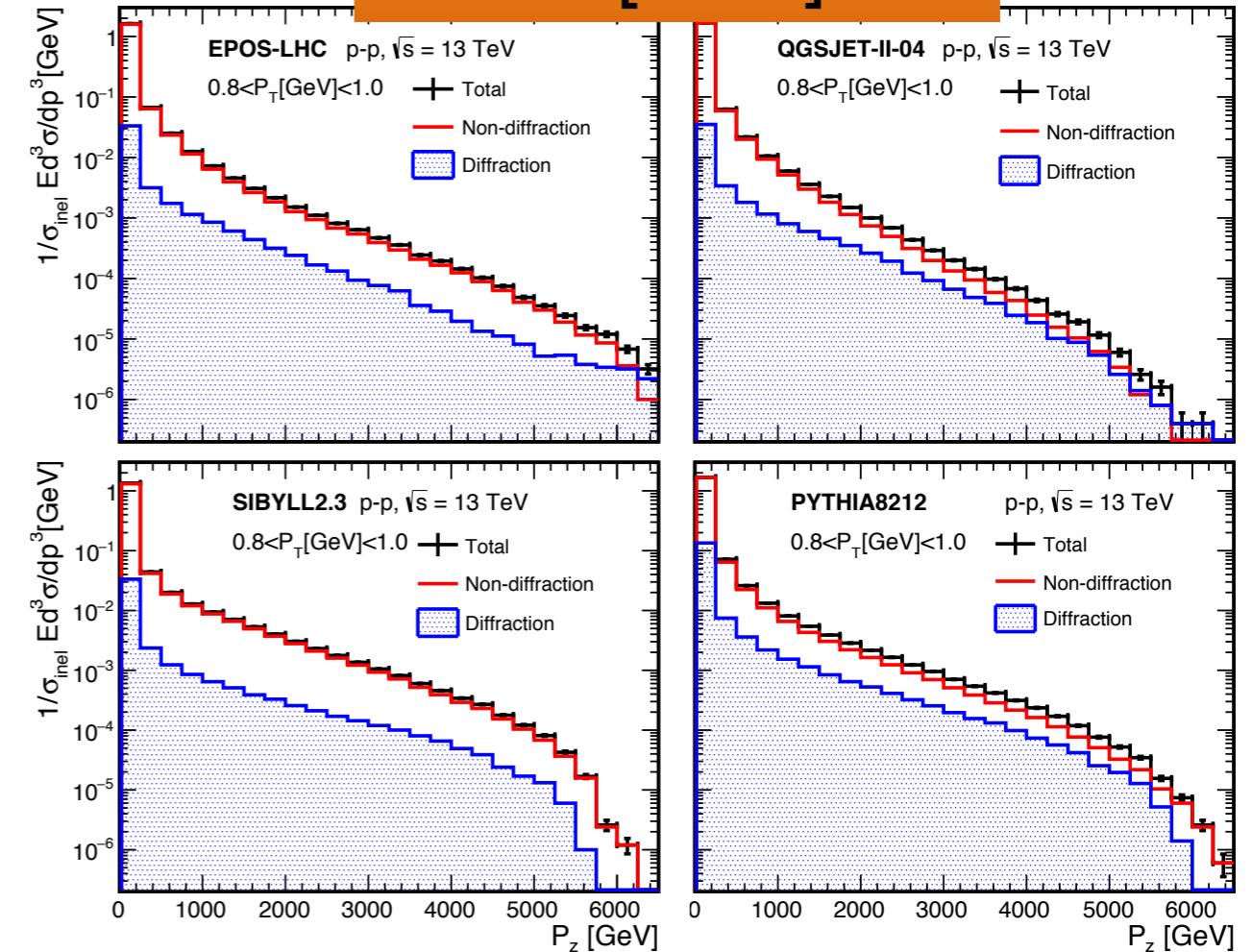
- EPOS-LHC
- QGSJET-II-04
- SIBYLL2.3
- PYTHIA8212

# $\pi^0$ spectrum comparison

$0 < P_T [\text{GeV}] < 0.2$

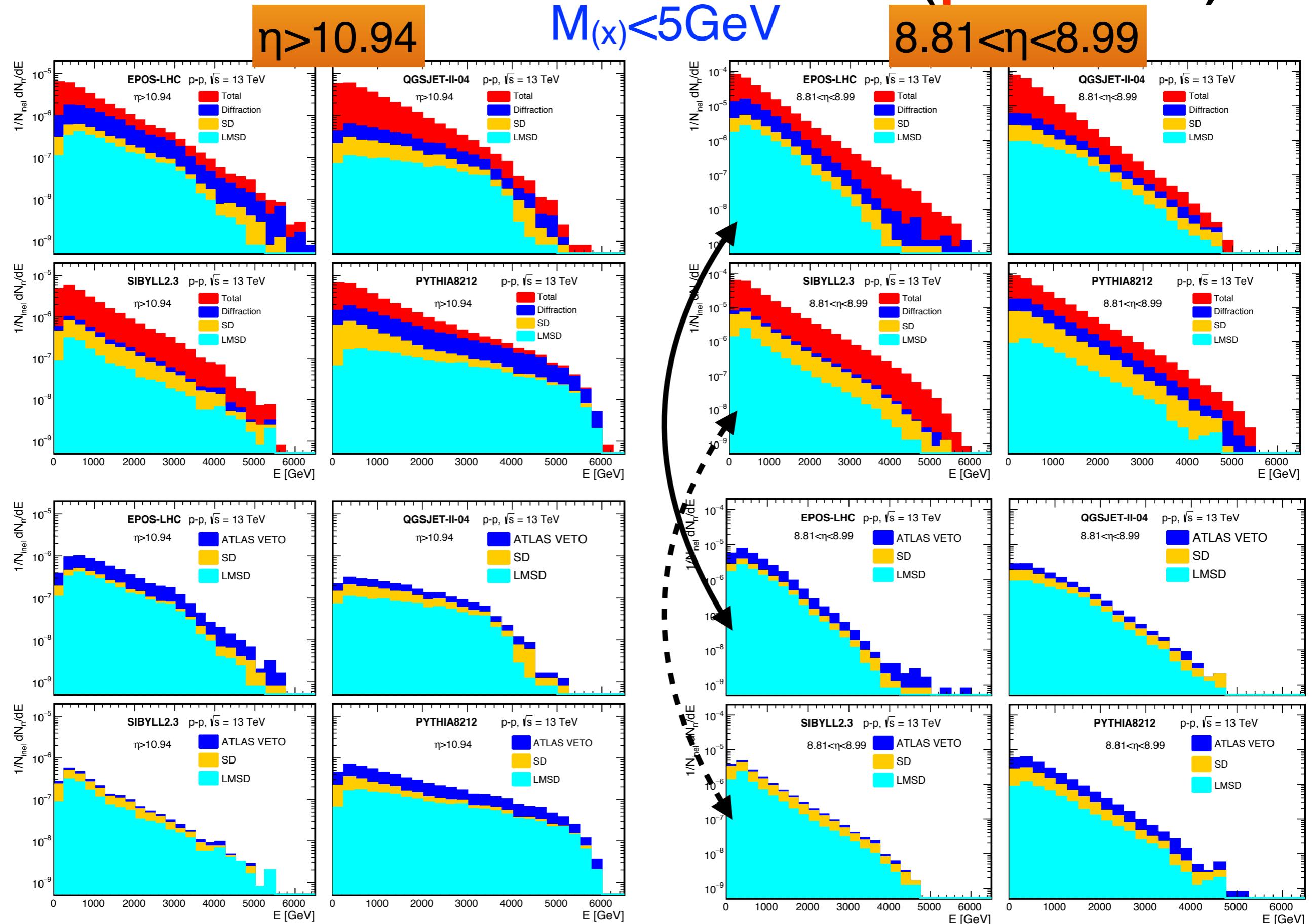


$0.8 < P_T [\text{GeV}] < 1.0$



• EPOS-LHC  
— QGSJET-II-04  
— SIBYLL2.3  
— PYTHIA8212

# Low mass diffraction (photon)

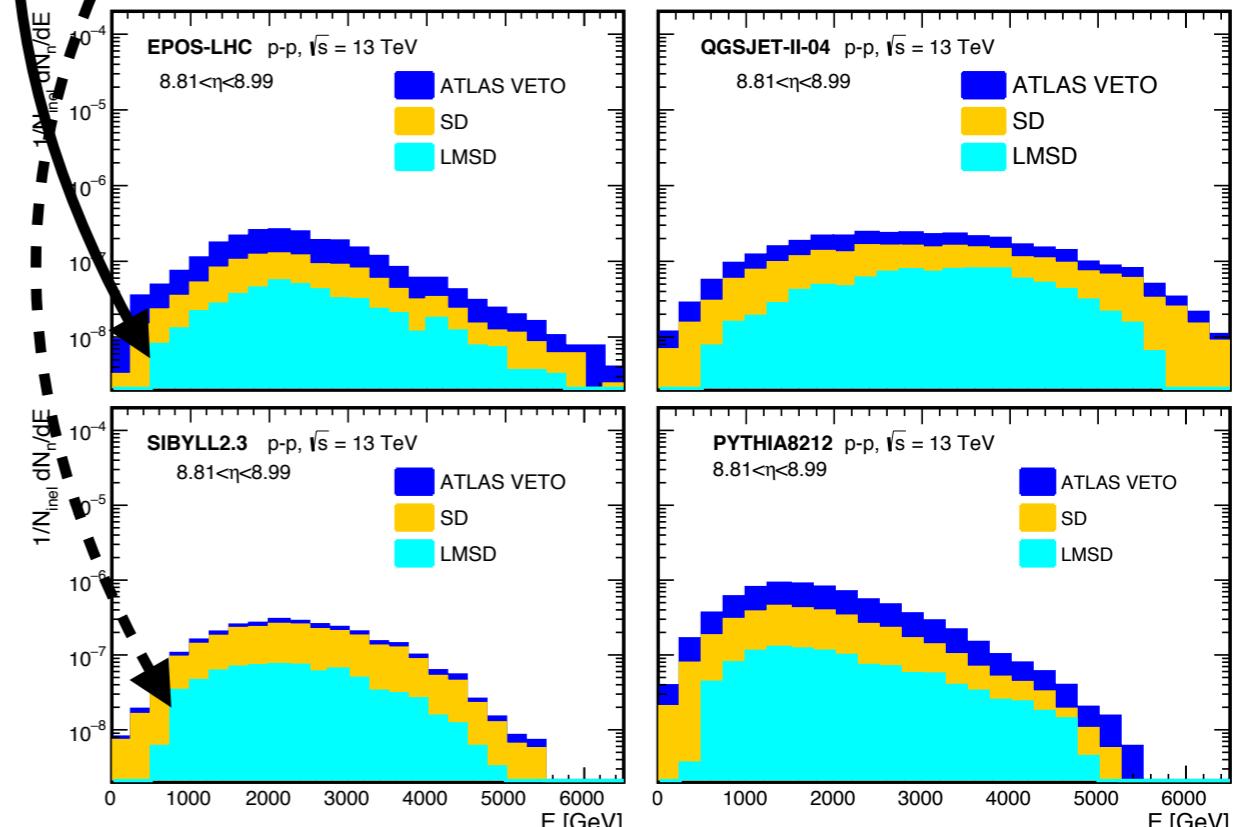
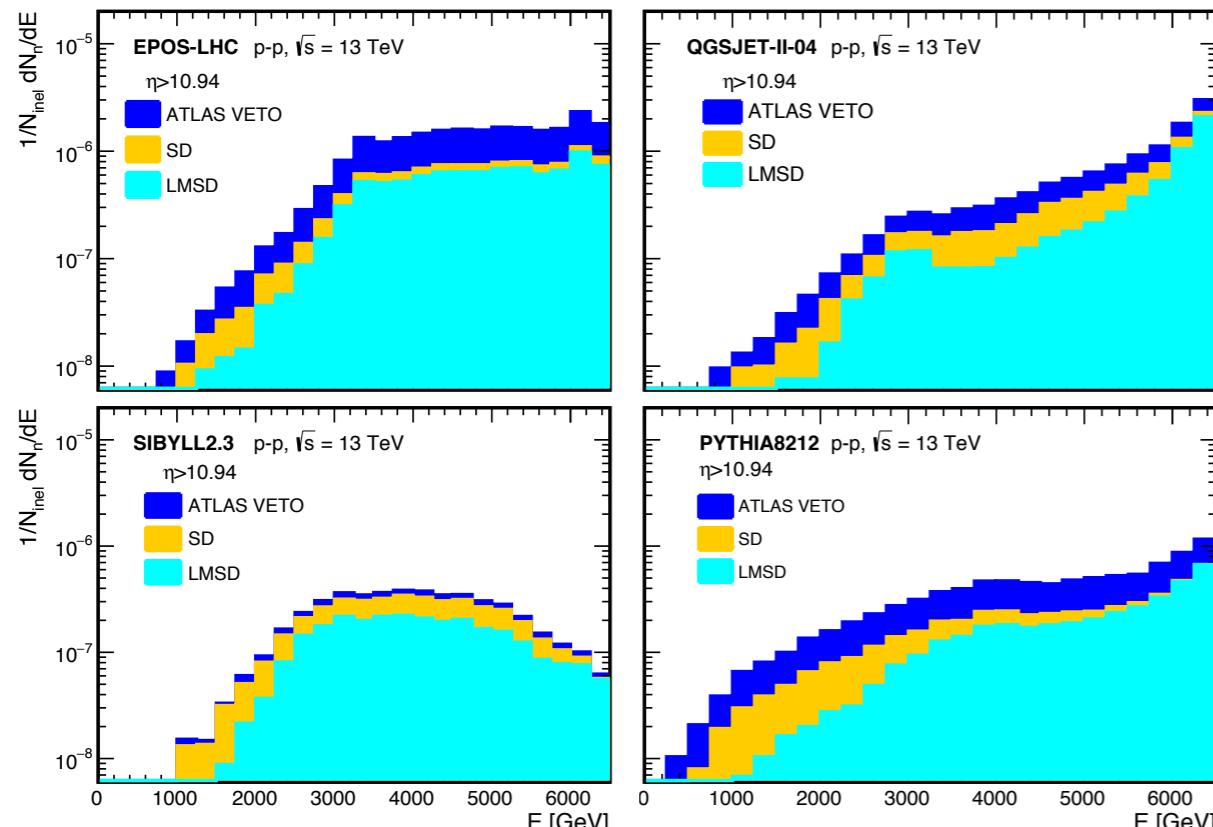
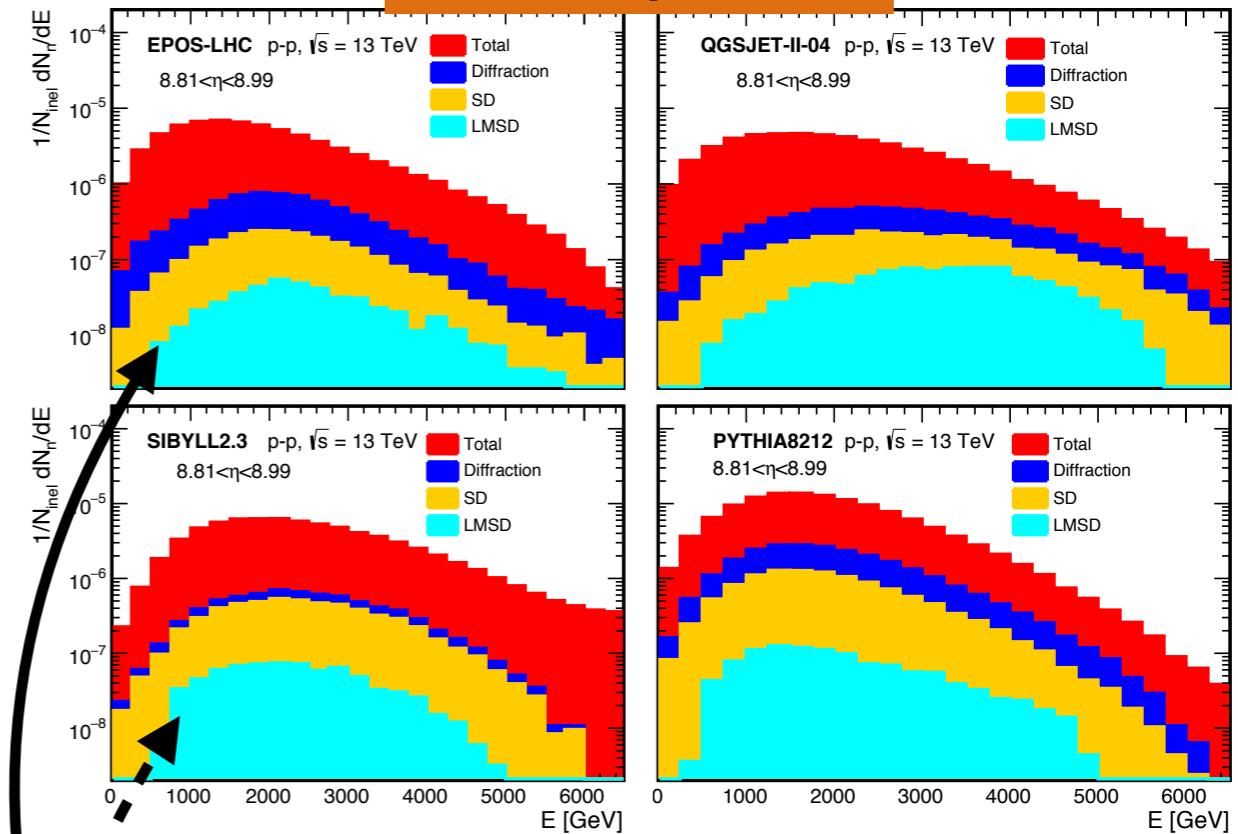
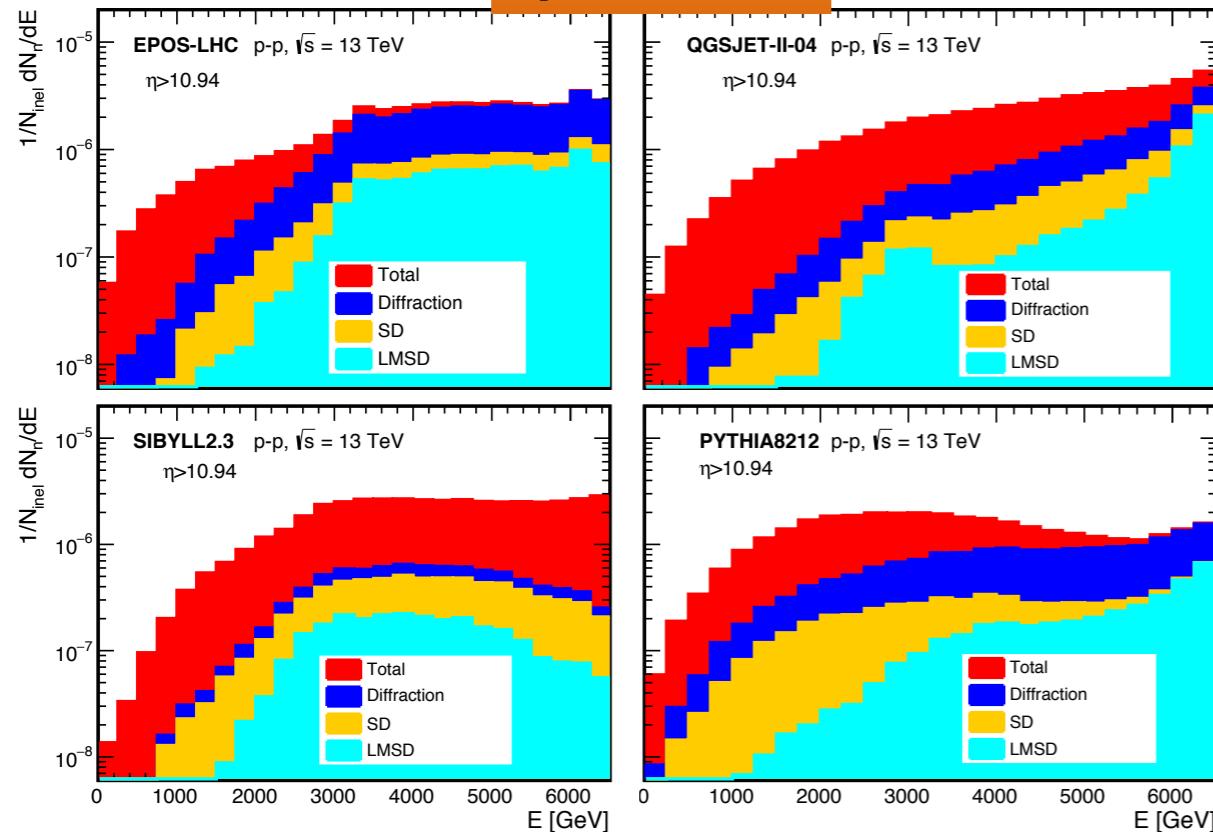


# Low mass diffraction (neutron)

$\eta > 10.94$

$M(x) < 5 \text{ GeV}$

$8.81 < \eta < 8.99$



# Low mass diffraction ( $\pi^0$ )

$0 < P_T [\text{GeV}] < 0.2$

$M(x) < 5 \text{ GeV}$

$0.8 < P_T [\text{GeV}] < 1.0$

