Low X 2019

Nicosia, Cyprus, August 29th, 2019

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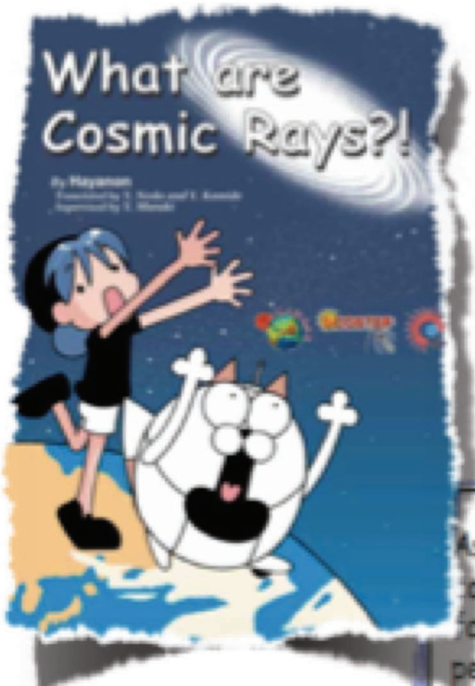
LHCf forward physics results

- Physics Motivations
- Results @ 13 TeV
- p-Pb Run
- Future perspectives

Ultra High Energy Cosmic Rays



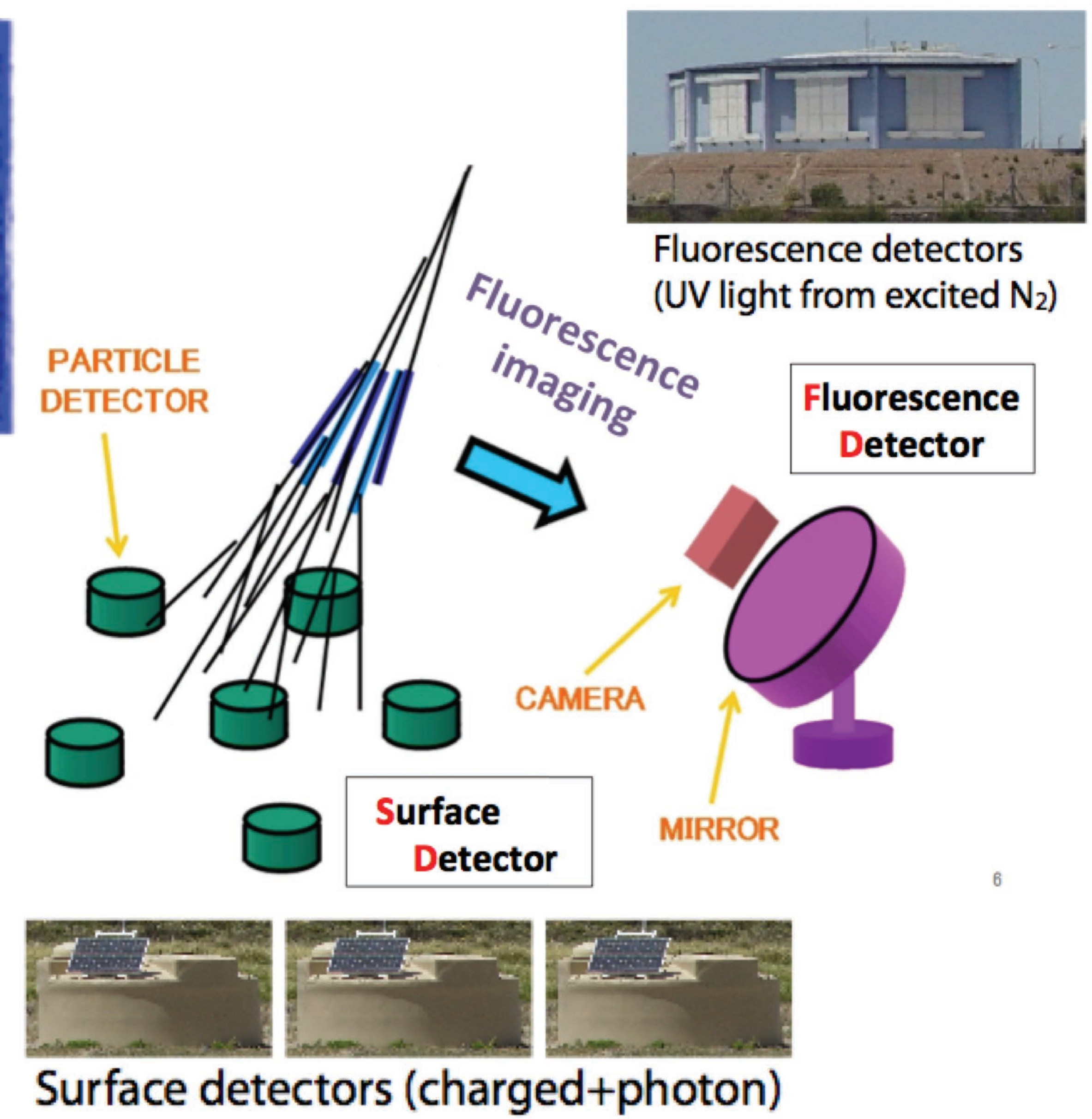
Studying the properties of primary High Energy Cosmic Rays based on observation of EAS

- X_{max} : depth of air shower maximum in 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

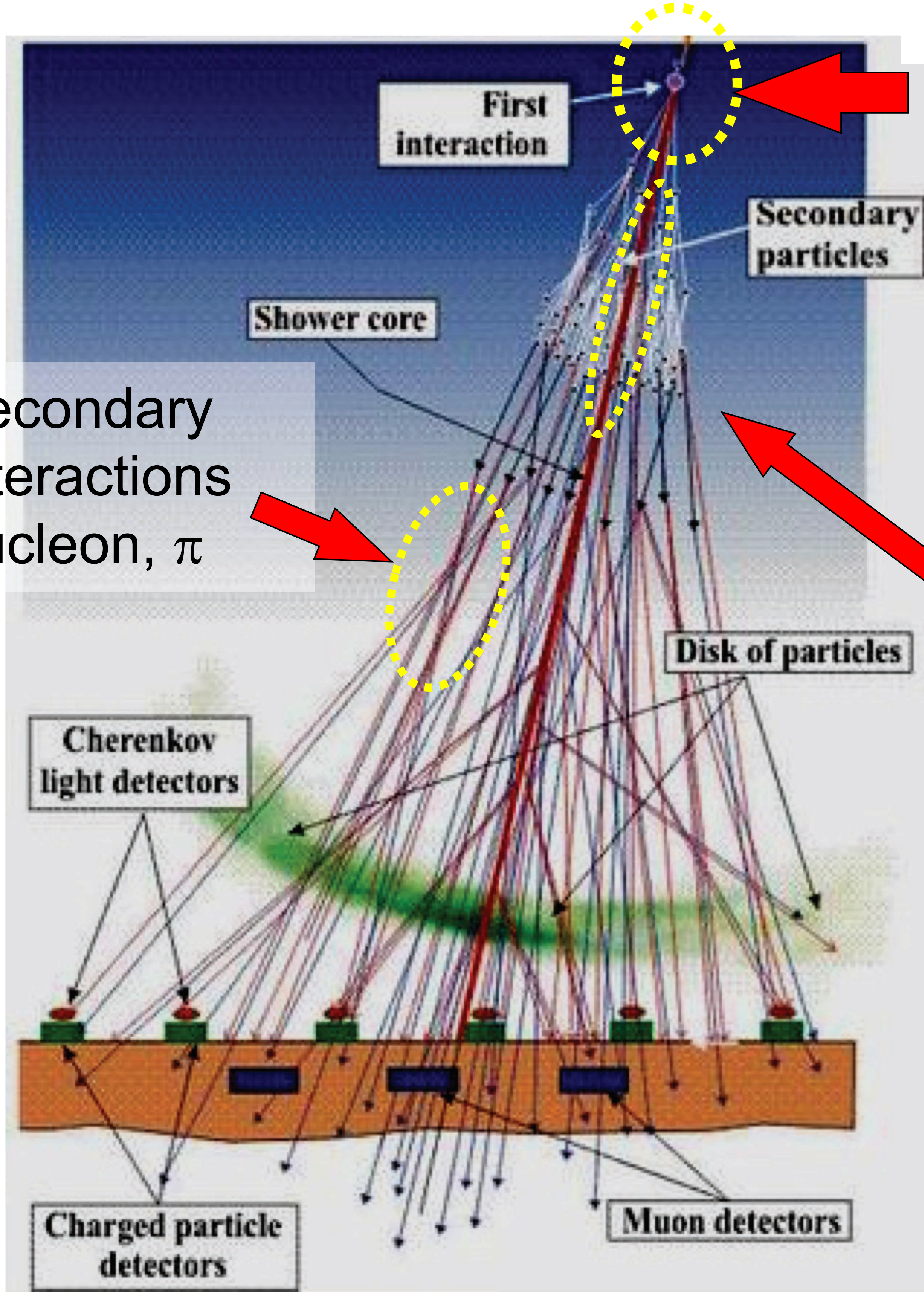
+

MC Simulation to describe hadronic interaction with atmosphere

Energy, mass composition, direction
—> source of primary cosmic rays
—> origin of the universe (final goal)



How accelerator experiments can contribute?



1. Inelastic cross section

   If large σ: rapid development
   If small σ: deep penetrating

2. Multiplicity

   If large: rapid development
   If small: deep penetrating

Totem, Atlas, CMS…

3. **Forward energy spectrum**

   If softer shallow development
   If harder deep penetrating

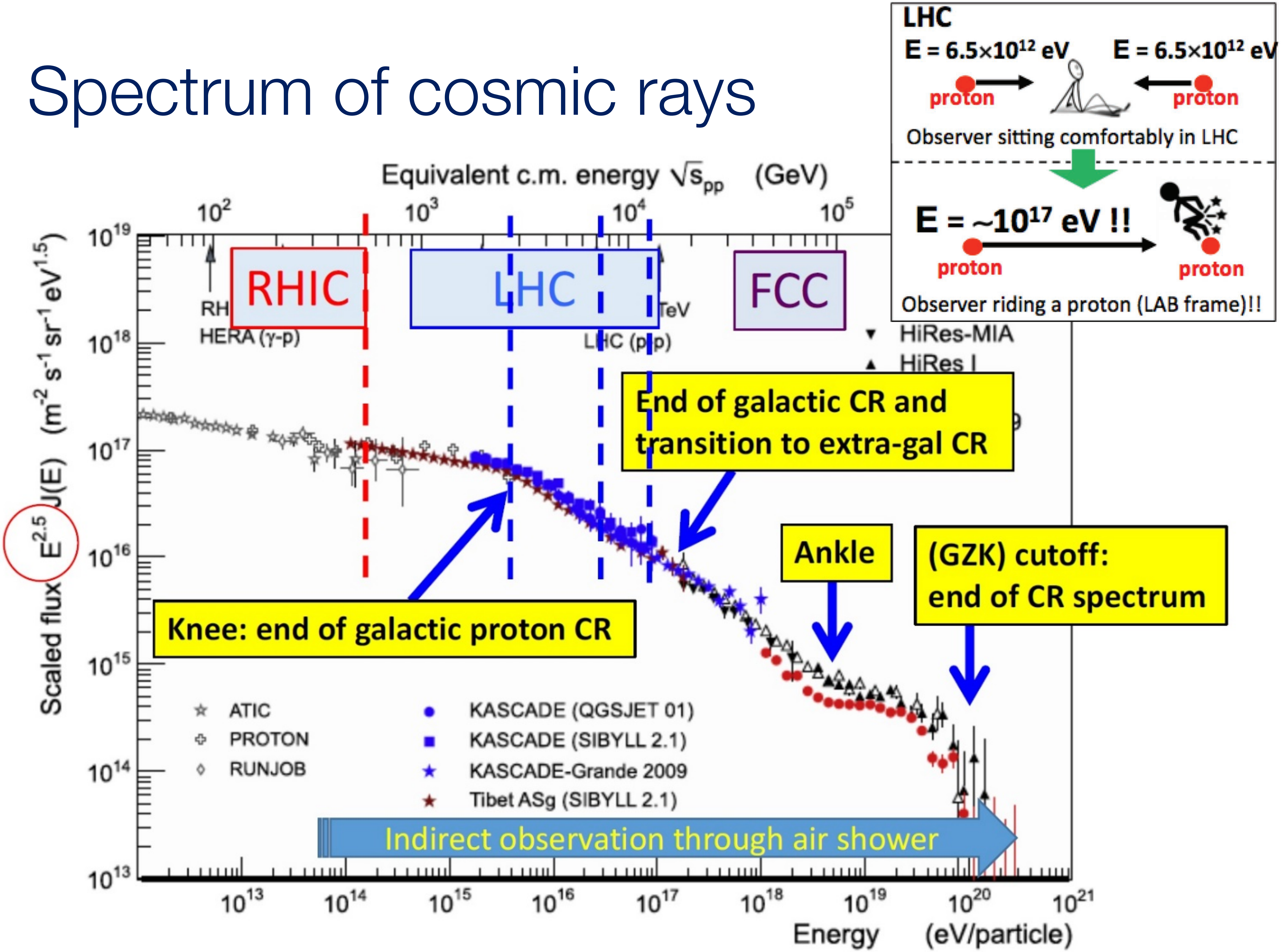
4. **Inelasticity** $k=1-E_{lead}/E_{avail}$

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

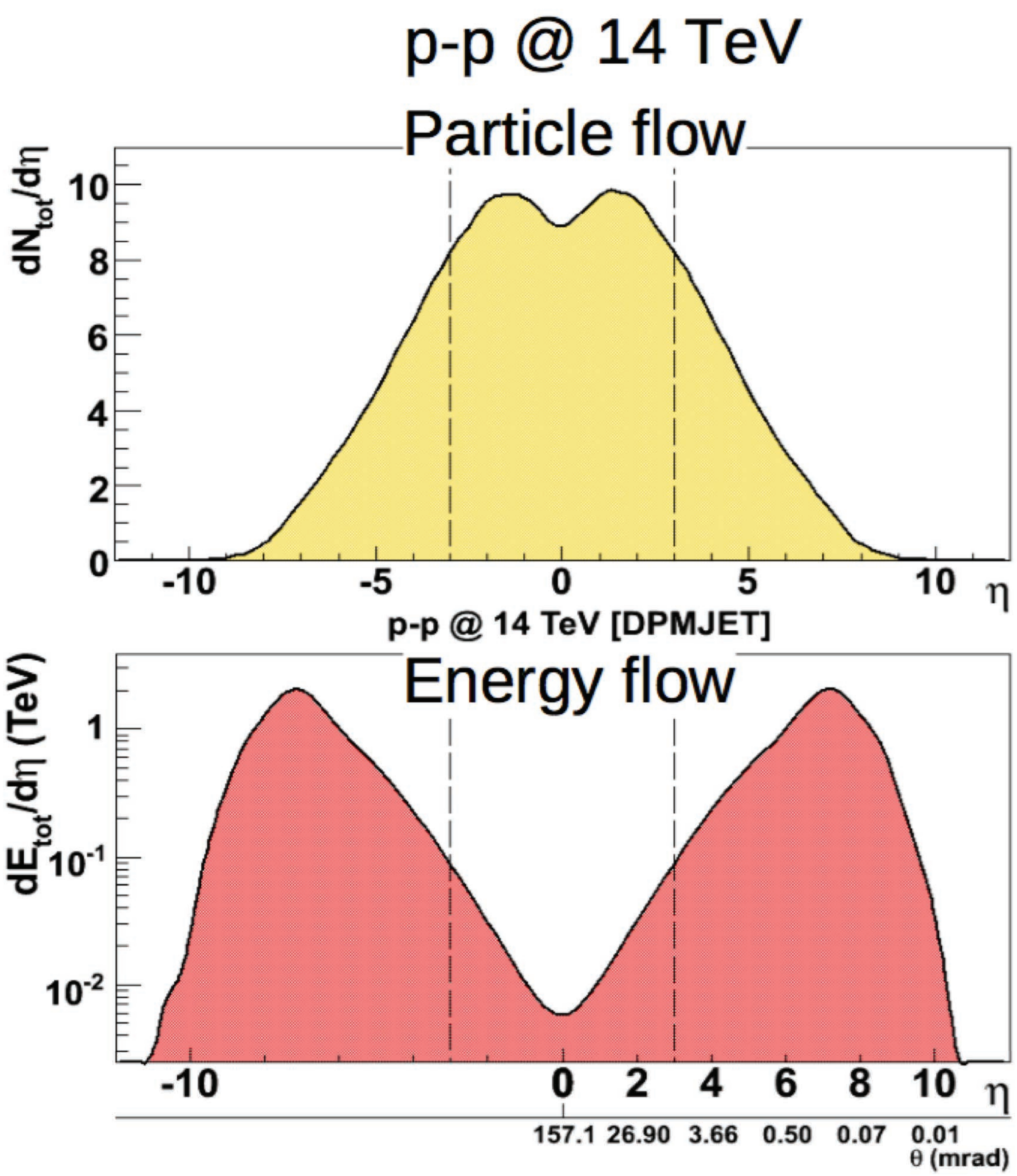
LHCf

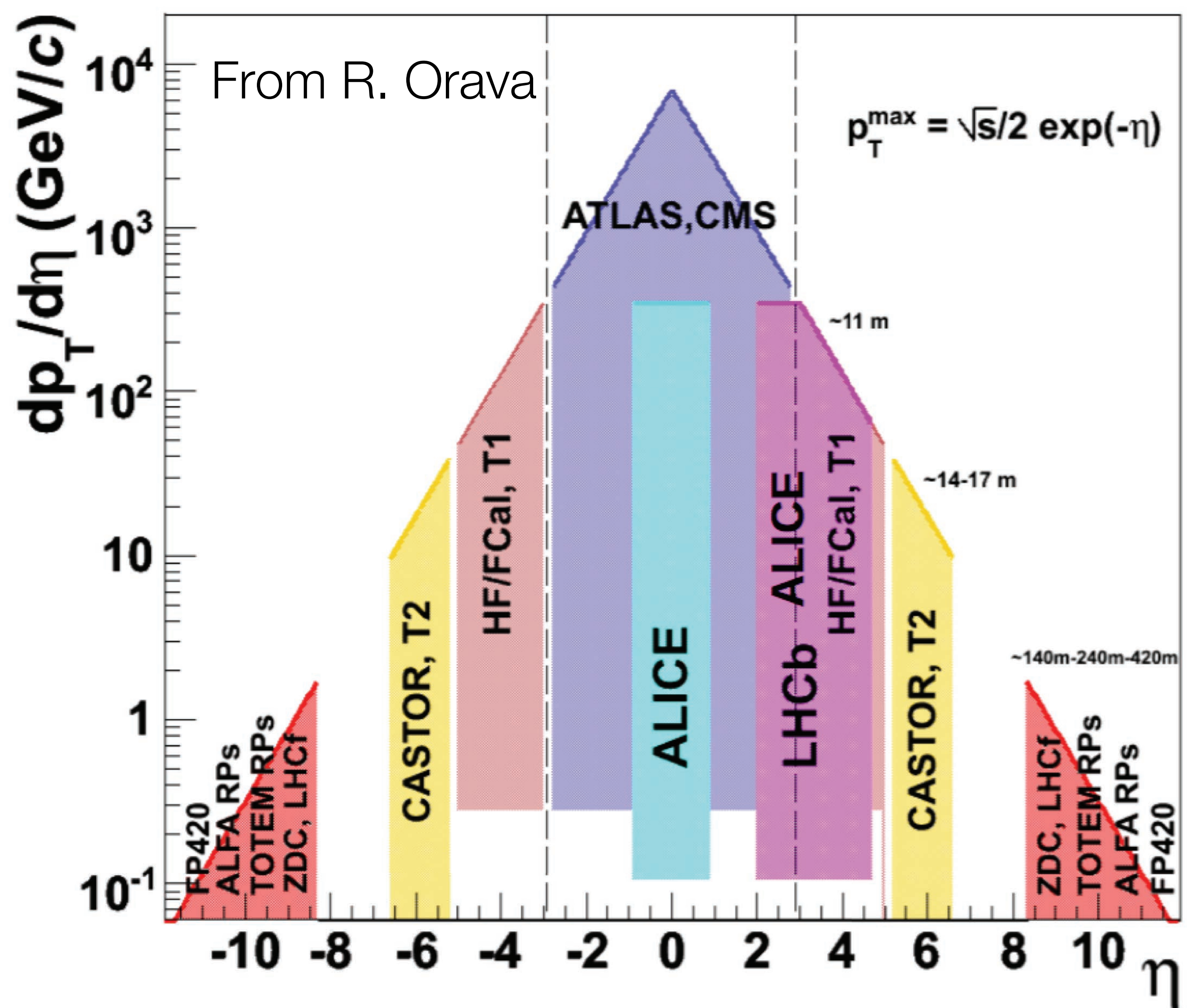
5. **Nuclear Effect (p-Nucleus)**

Spectrum of cosmic rays



LHC phase space coverage

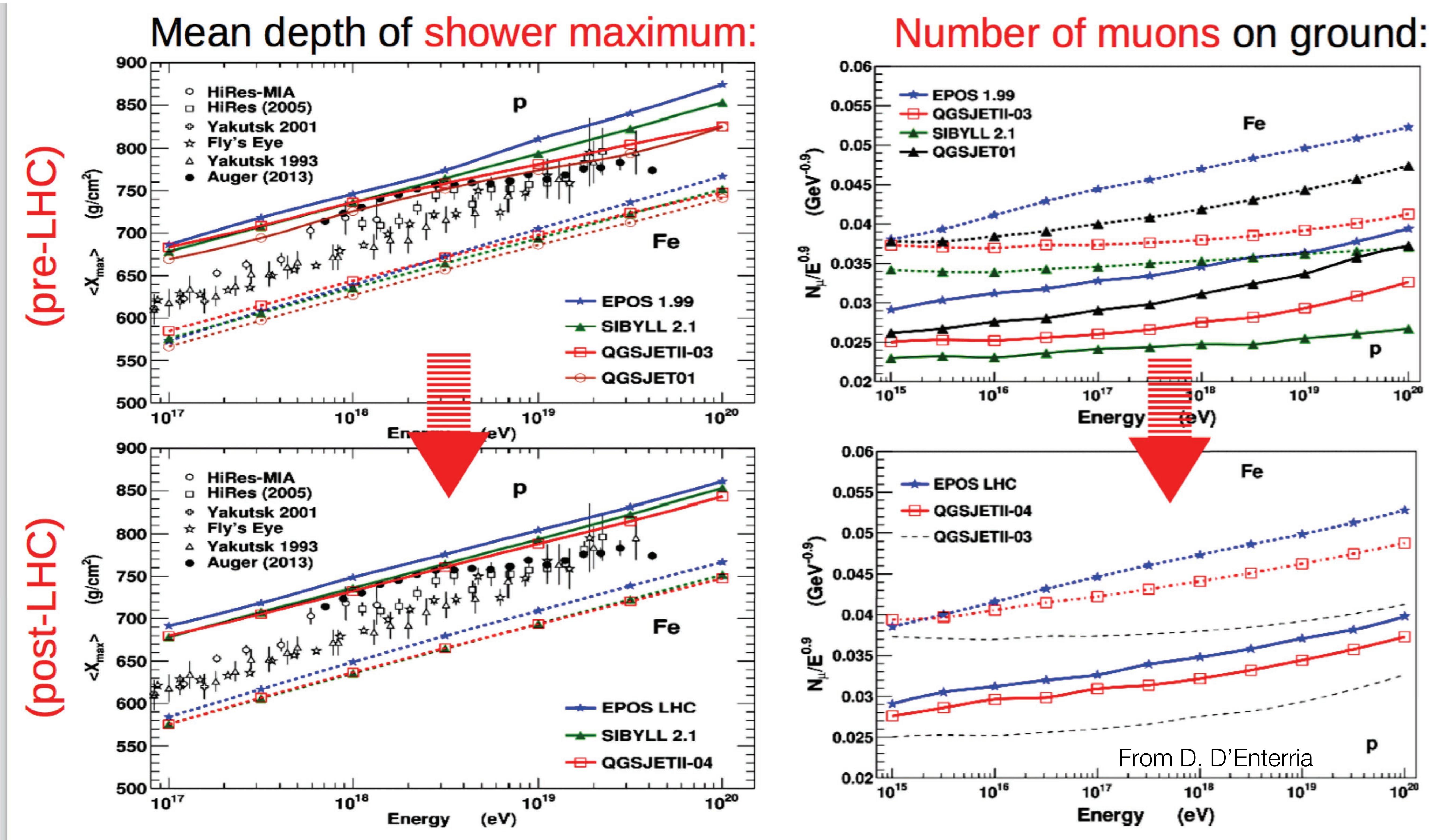




We may profit (and we are profiting) of the very broad coverage!

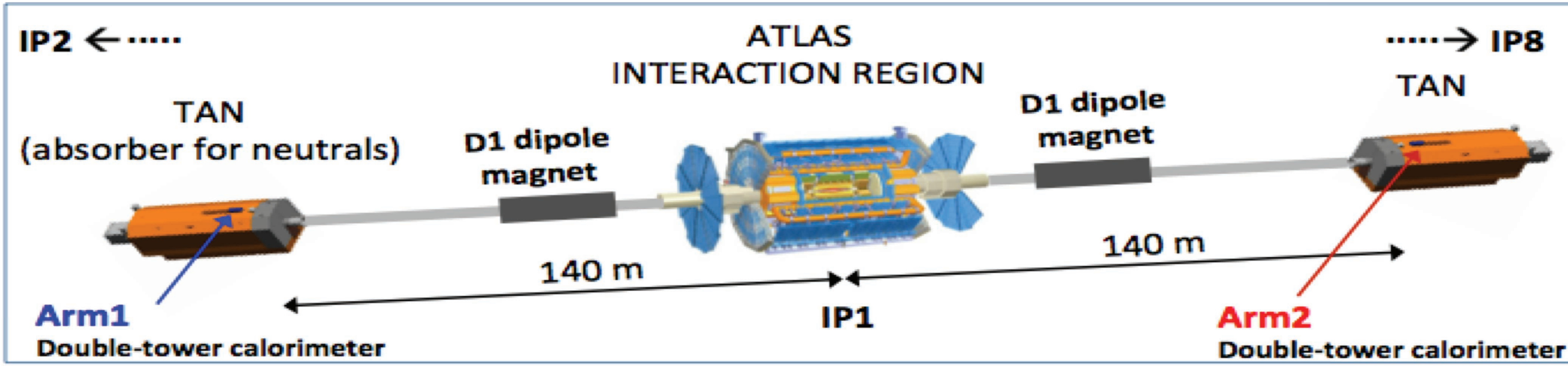
Dedicated forward detectors for a better measurement of the energy flow

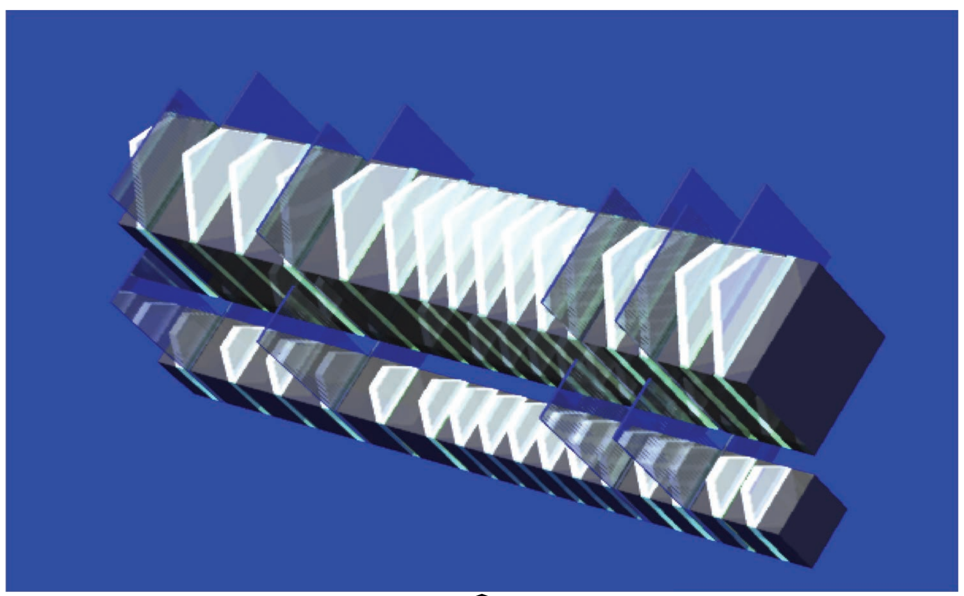
First models tuning after the first LHC data (EPOS, QGSJET and SIBYLL)



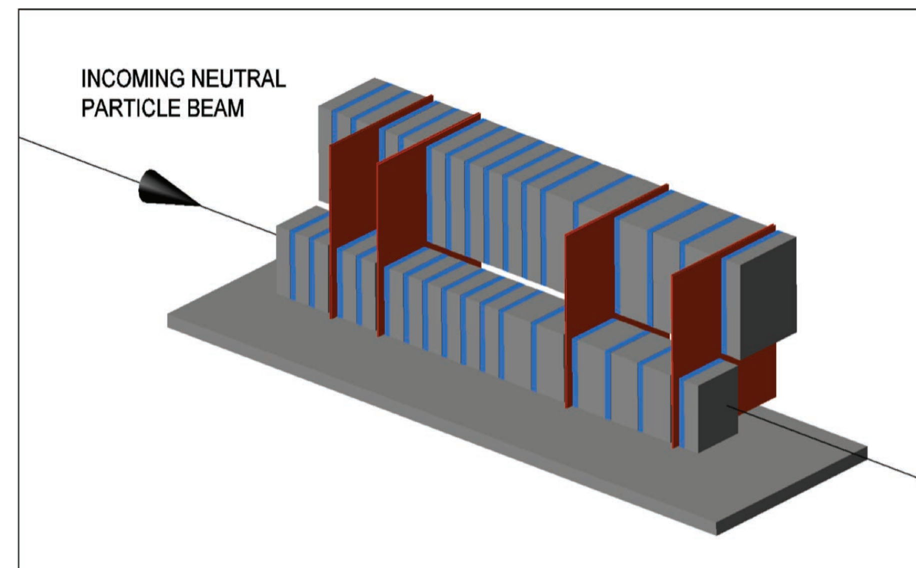
Significant reduction of differences btw different hadronic interaction models!!!
But still a lot to be done….

LHCf: location and detector layout





$44X_0$,
$1.6\ \lambda_{int}$

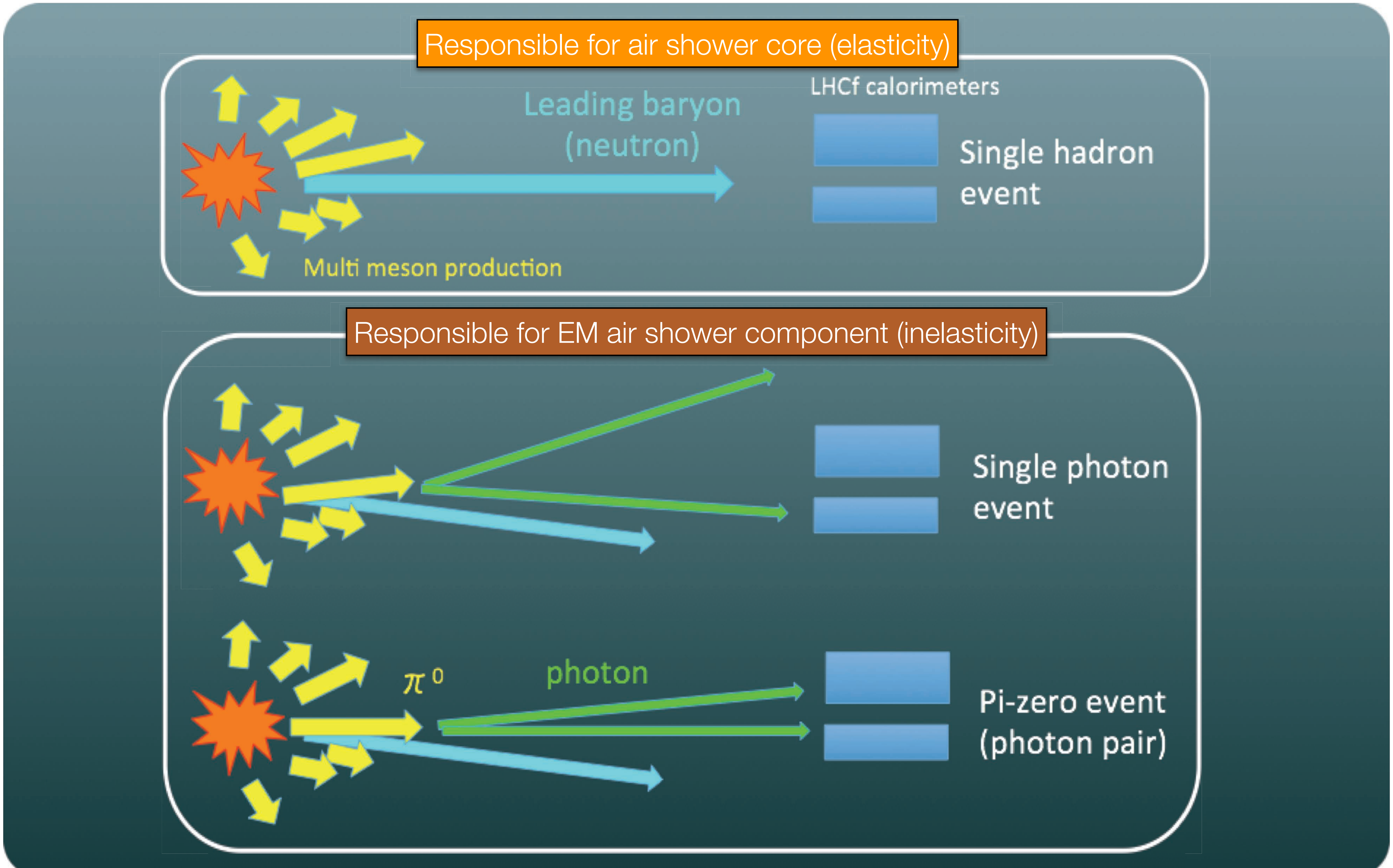


Arm#1 Detector
20mmx20mm+40mmx40mm
4 X-Y GSO Bars tracking layers

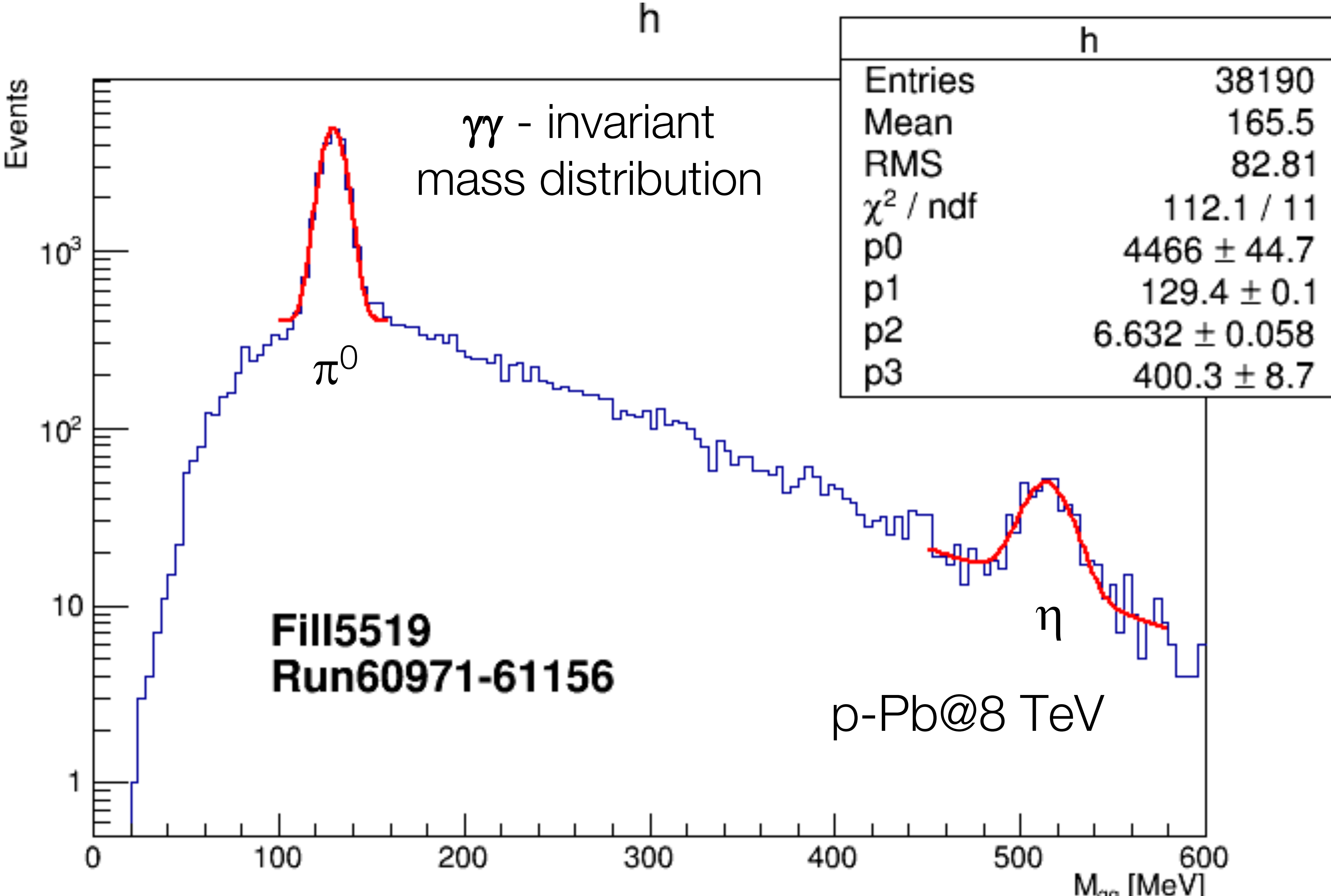
Energy resolution:
< 5% for photons
30% for neutrons
Position resolution:
< 200μm (Arm#1)
40μm (Arm#2)
Pseudo-rapidity range:
η > 8.7 @ zero Xing angle
η > 8.4 @ 140urad

Arm#2 Detector
25mmx25mm+32mmx32mm
4 X-Y Silicon strip tracking layers

Event category in LHCf



γγ invariant mass distribution



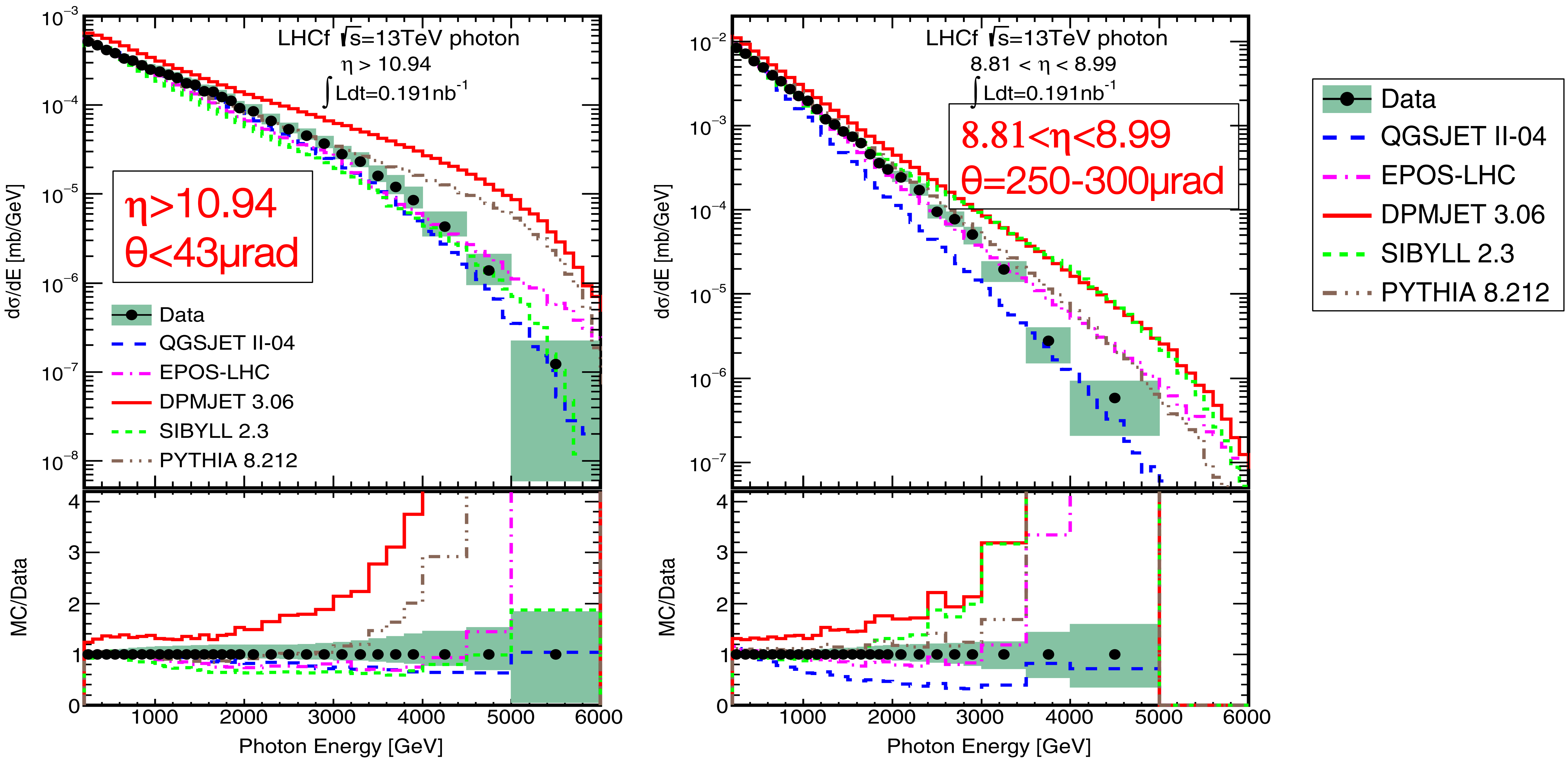
LHCf Data Taking and Analysis matrix

RUN	Proton E_{LAB} (eV)	γ	n	π^0 limited acceptance	π^0 full acceptance	LHCf - ATLAS	Performance
SPS test beam		NIM A 671 (2012) 129	JINST 9 (2014) P03016				
p+p 900 GeV	4.3×10^{14}	PLB 715 (2012) 298-303		Not accessible.			IJIMPA 28 (2013) 1330036
p+p 7 TeV	2.6×10^{16}	PLB 703 (2011) 128-134	PLB 750 (2015) 360-366	PRD 86 (2012) 092001	PRD 94 (2016) 032007		
p+p 2.76 TeV	4.1×10^{15}			PRC 89 (2014) **065209**			
p+Pb 5 TeV	1.4×10^{16}						
p+p 13 TeV	9.0×10^{16}	PLB 780 (2018) 233–239 On-going: ATLAS-LHCf	Arm1: on-going Arm2: JHEP11 (2018) 073	Preliminary		Conf. Note: ATLAS-CONF-2017-075	
p+Pb 8.1 TeV	3.6×10^{16}	Prelim.					

γ Spectra in p-p

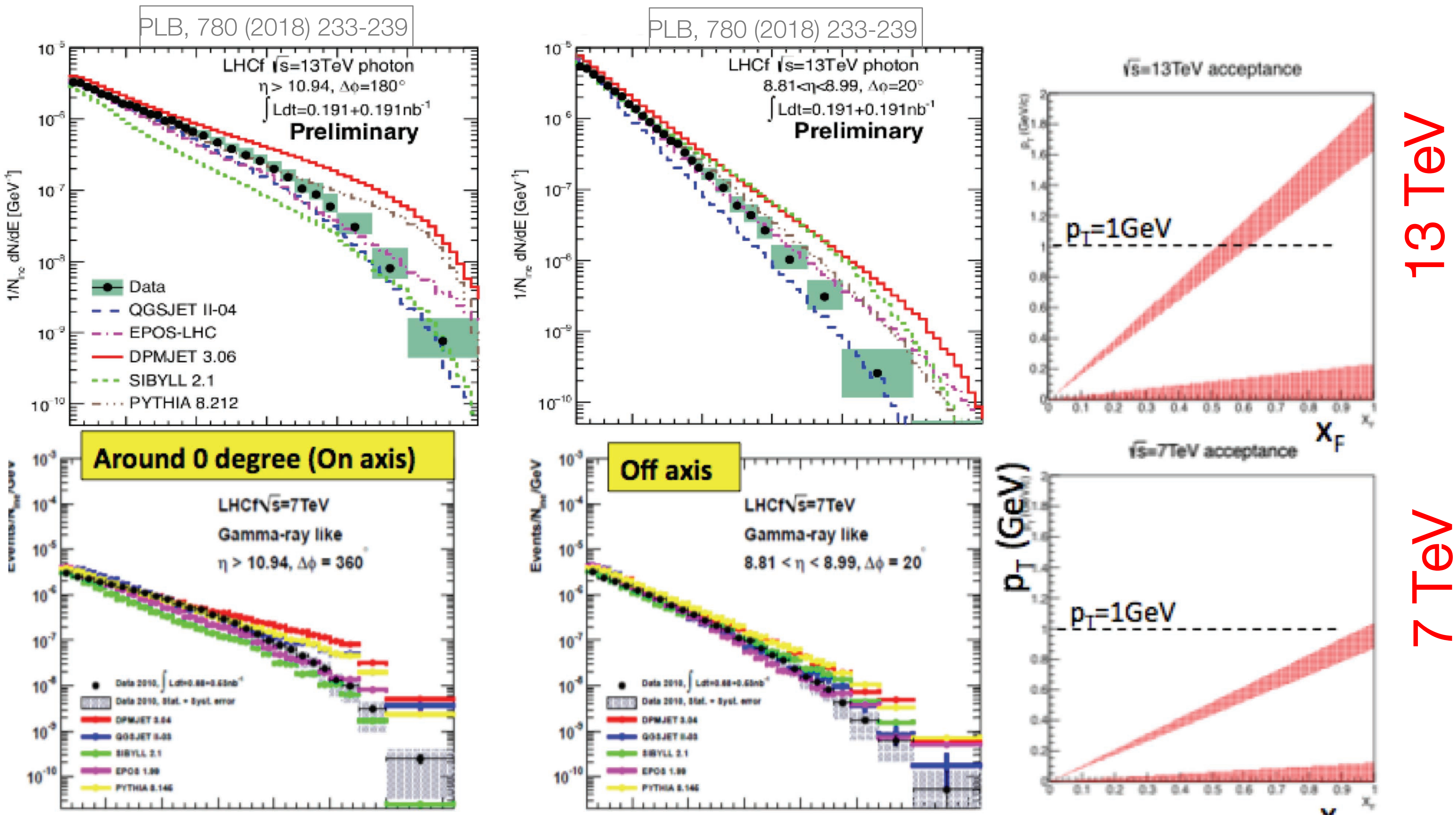
Photon production cross section in LHC 13TeV p-p collision

PLB, 780 (2018) 233-239



- PYTHIA8, DPMJET3 overestimate
- SIBYLL2.3 under(over) estimates at small (large) angle
- QGSJET II-04 underestimates
- EPOS-LHC shows best agreement (slight overestimate near maximum energy)

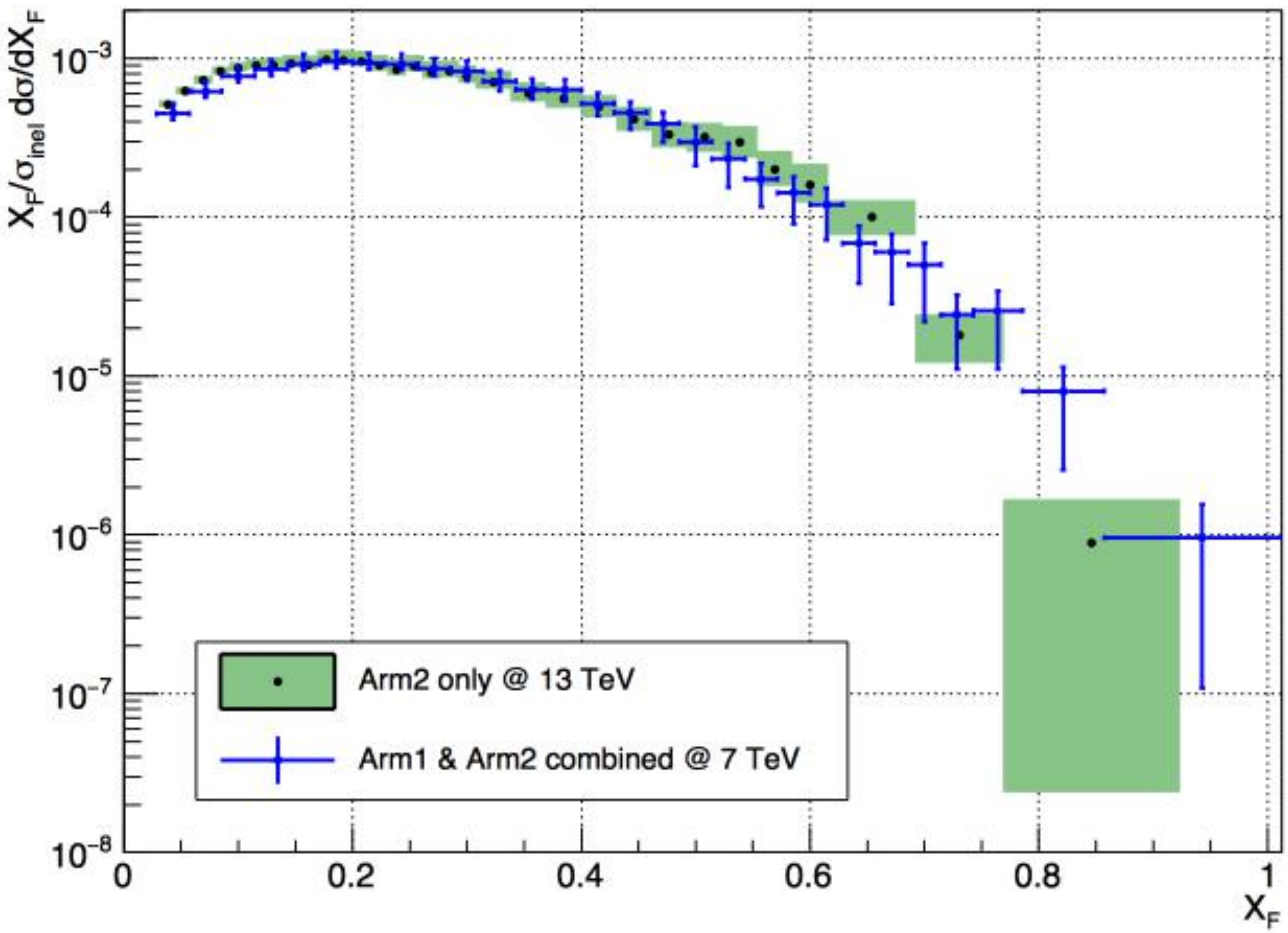
γ energy spectra 7 vs 13 TeV



High energy data covers up to larger p_T

Similar trend in 7TeV and 13TeV, but differences look enhanced in 13TeV results

Photon spectra – Feynman Scaling (7 TeV vs 13 TeV)

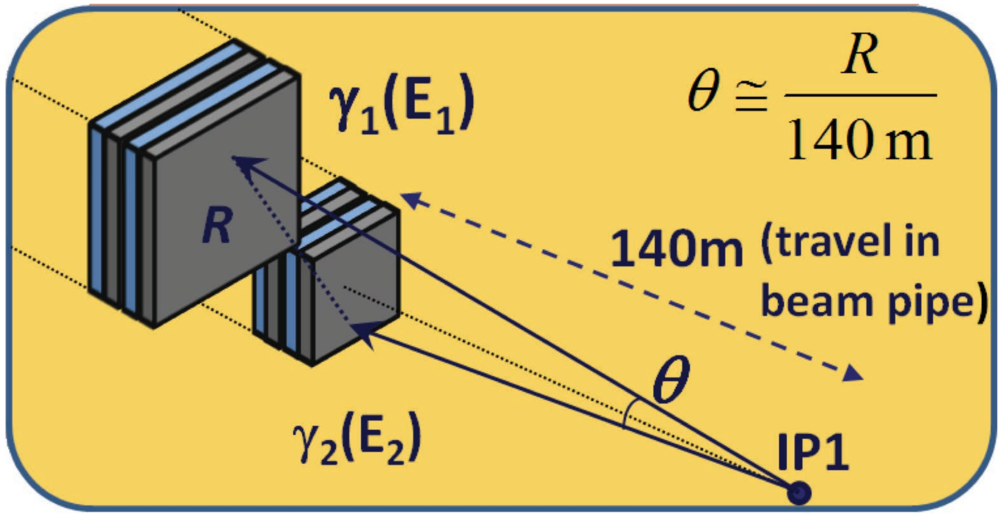


Feynman scaling: differential cross section as a function of X_F independent of $\sqrt{s}$ for X_F

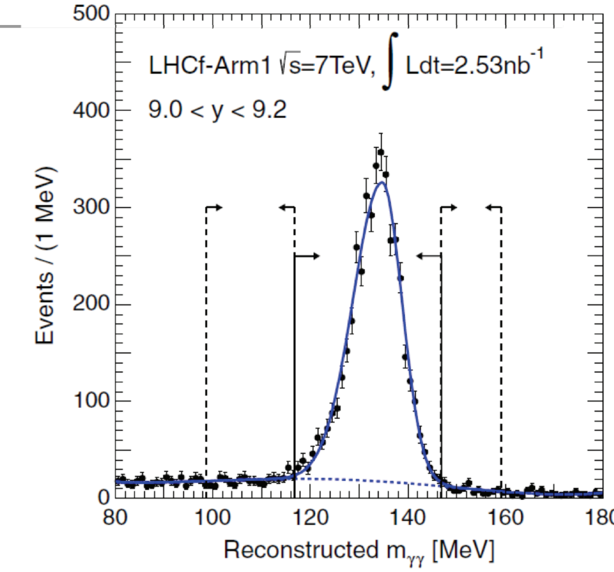
Feynman scaling holds within systematic uncertainties

π^0 spectra in p-p

LHCf results: π^0 p_T for different η in p+p @ 7 TeV

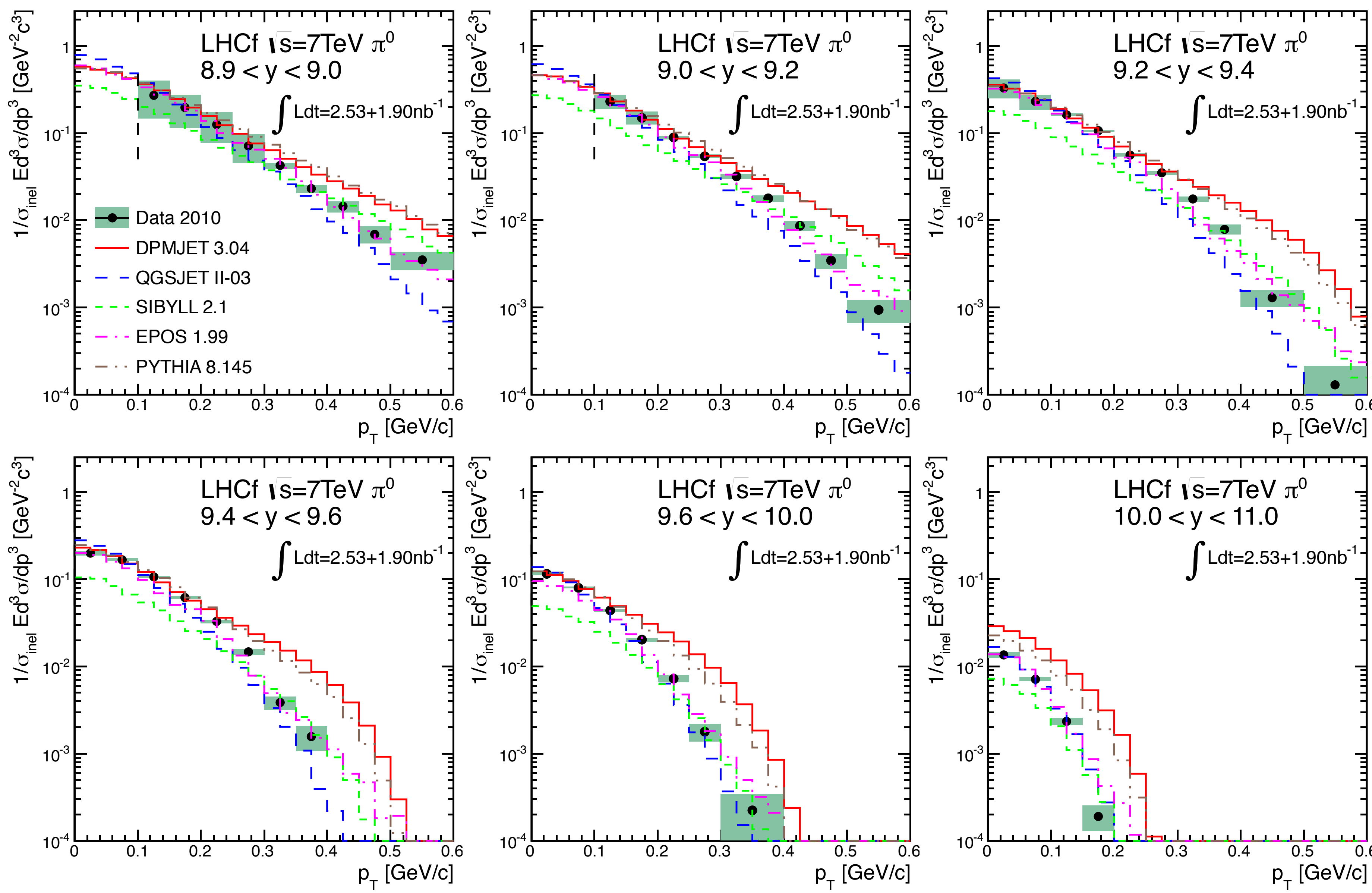


Reconstruction of the invariant mass of two-photon events



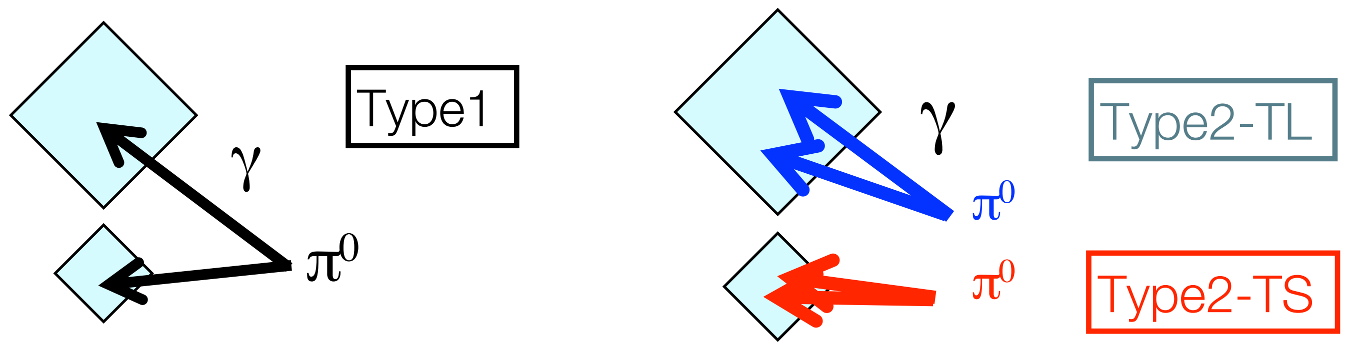
7 TeV pp, π^0

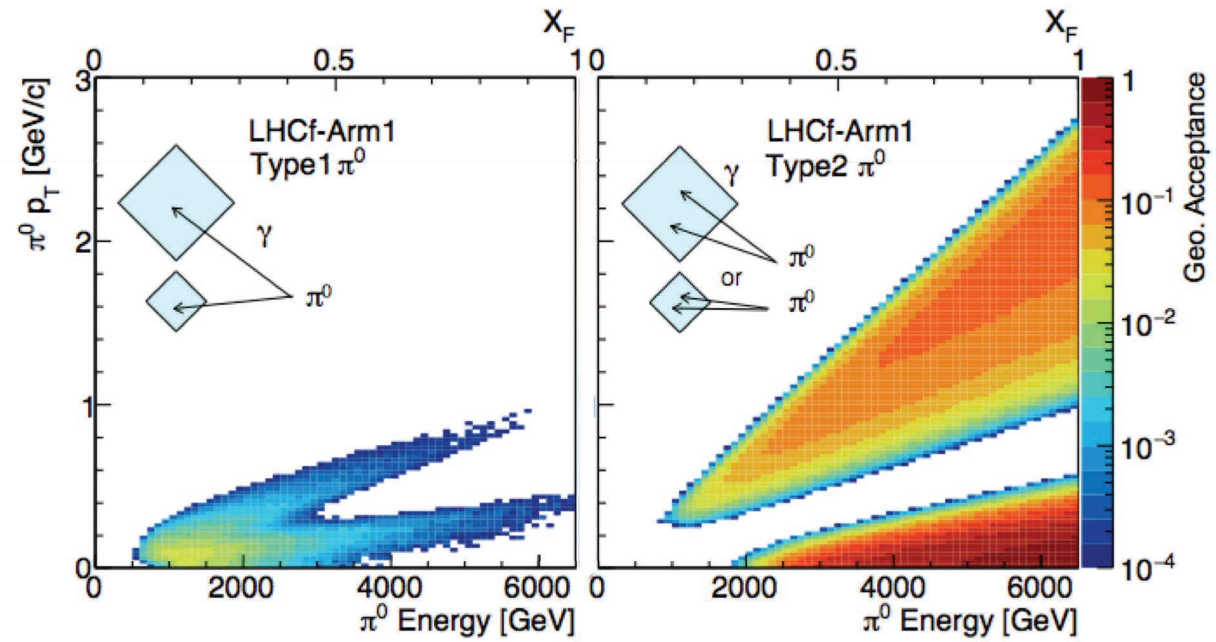
Identification of events with two particles hitting the two towers

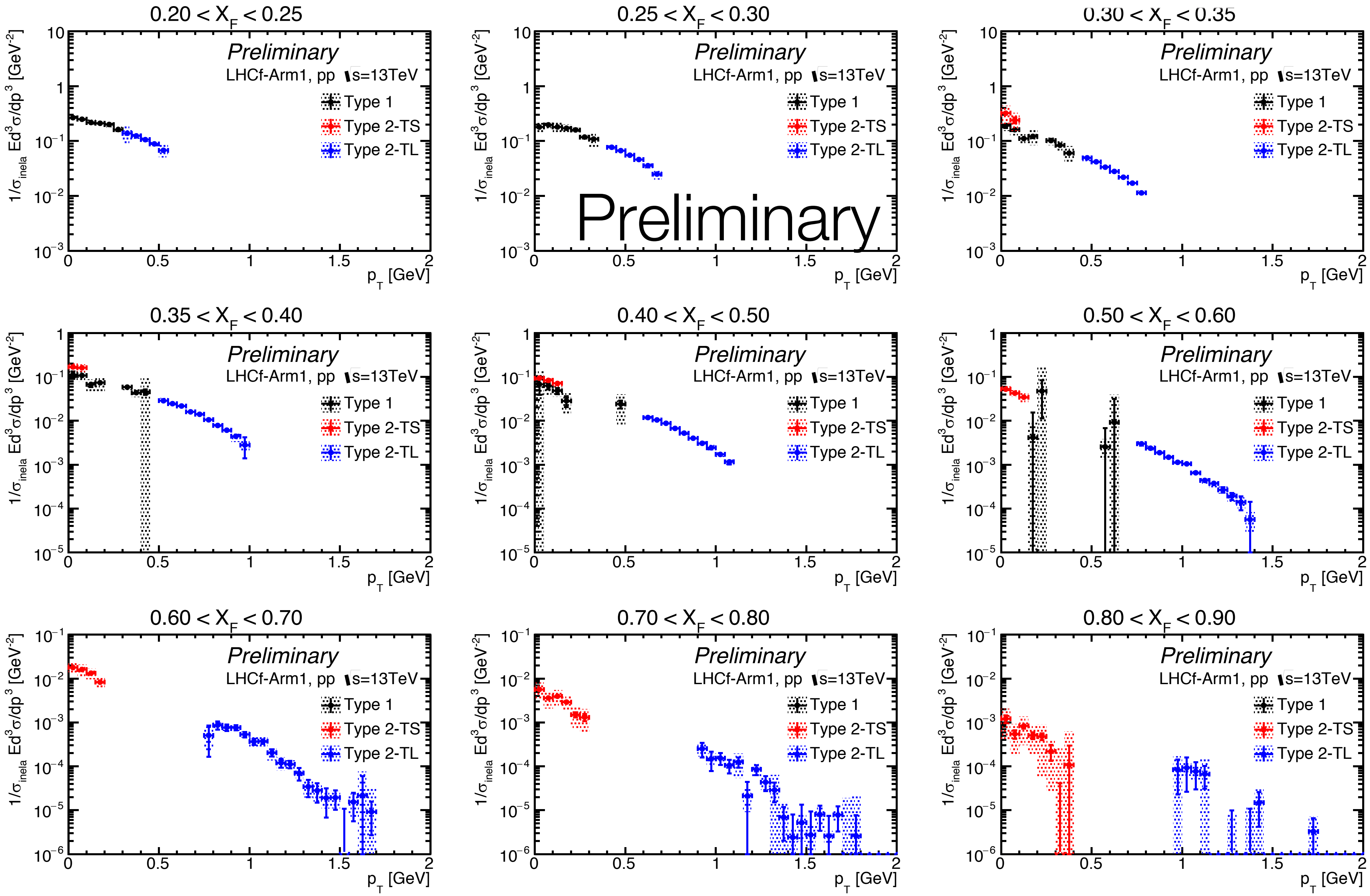


- **EPOS1.99** show the best agreement with data in the models.
- **DPMJET** and **PYTHIA** have harder spectra than data ("popcorn model")
- **QGSJET** has softer spectrum than data (only one quark exchange is allowed)

π^0 in p+p @ 13 TeV



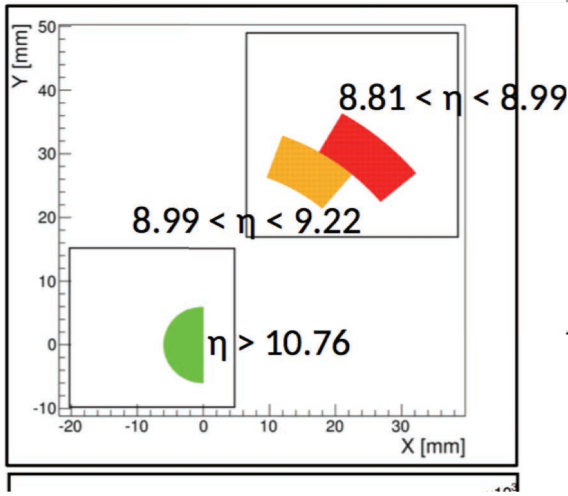




- Smooth connection of 3 spectra
- Wide transverse momentum coverage
- The gaps will be covered by Arm2 and other detector position data.

Hadron spectra (~neutrons) in p-p

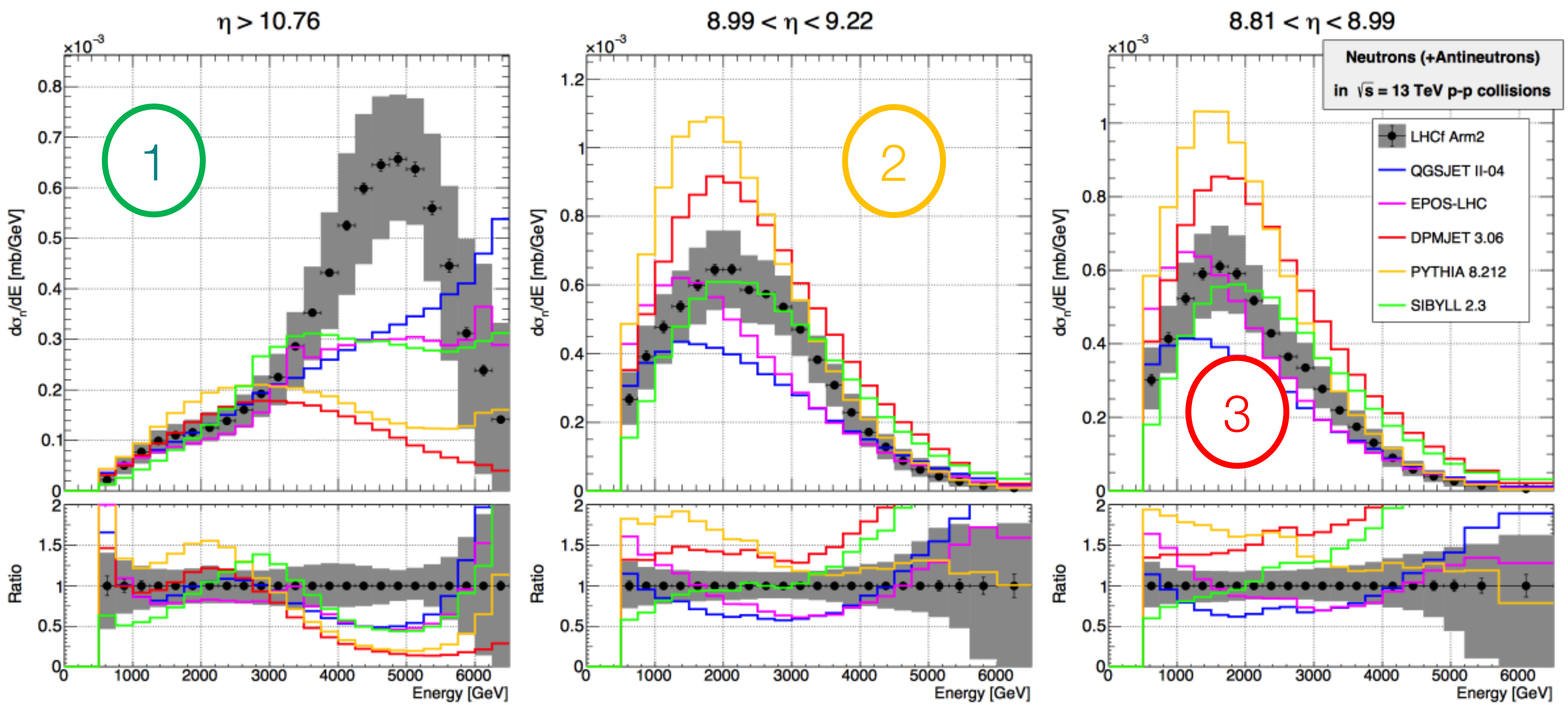
ARM2 unfolded neutron spectra



Differential production cross section

$$d\sigma_n/dE = \frac{dN(\Delta\eta,\Delta E)}{E}\frac{1}{L}\times\frac{2\pi}{d\varphi}$$

Unfolding is very important (40% energy resolution)

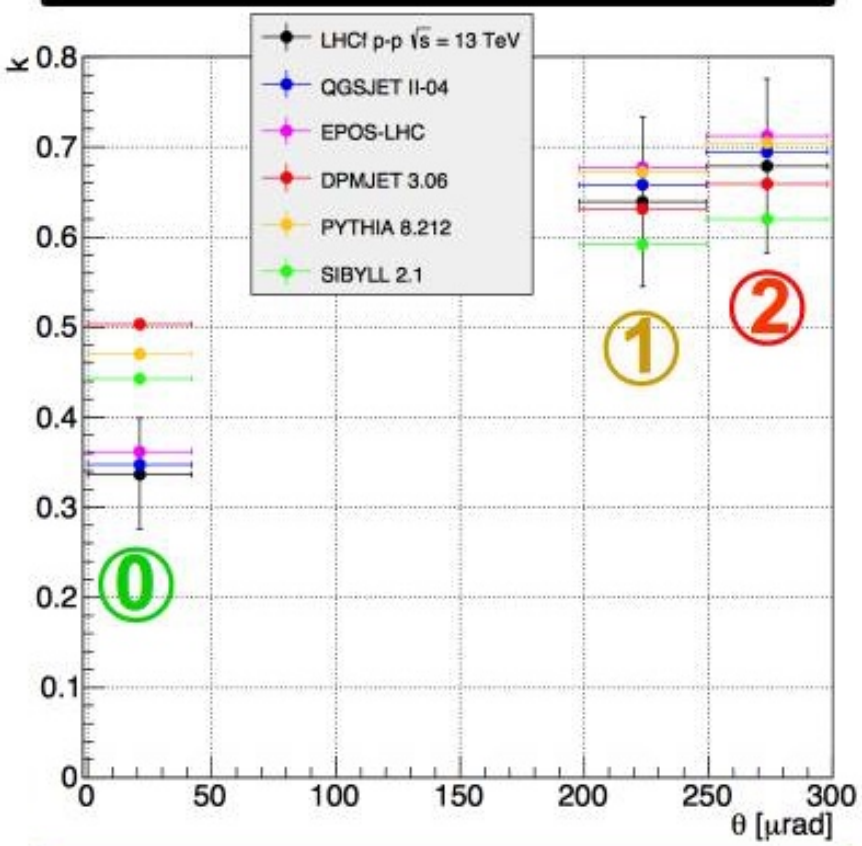


JHEP 1811 (2018) 073

In η > 10.76 no model agrees with peak structure and production rate. Among all models, **SIBYLL 2.3** and **EPOS-LHC** have the best overall agreement in 8.99 < η < 9.22 and 8.81 < η < 8.99, respectively.

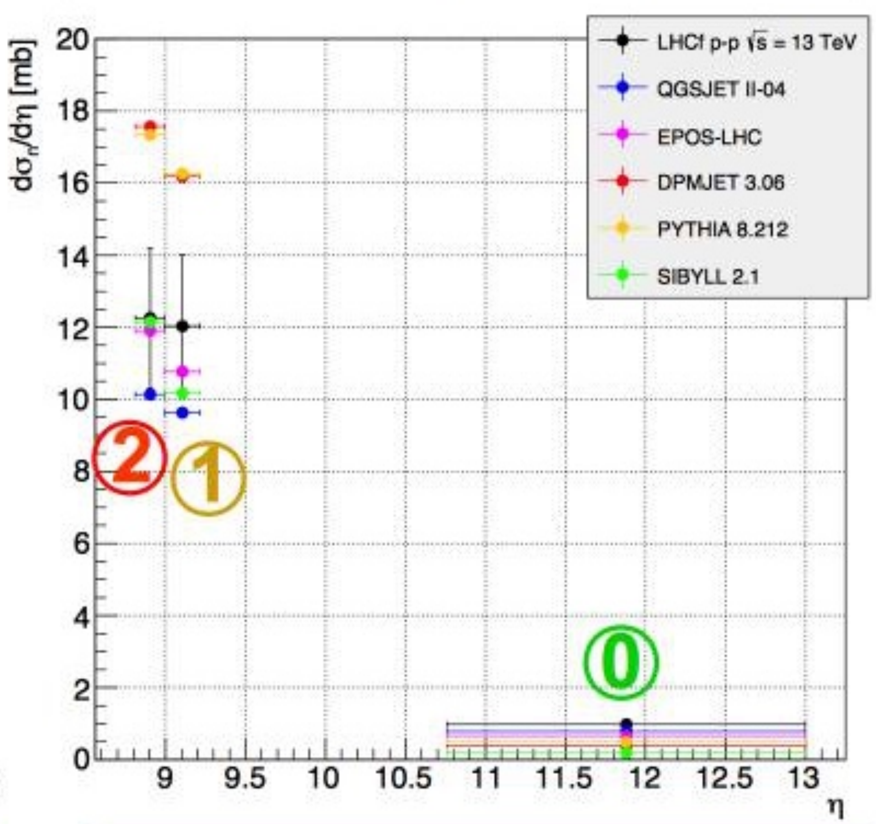
Measurement of interesting quantities for CR Physics

Inelasticity VS θ



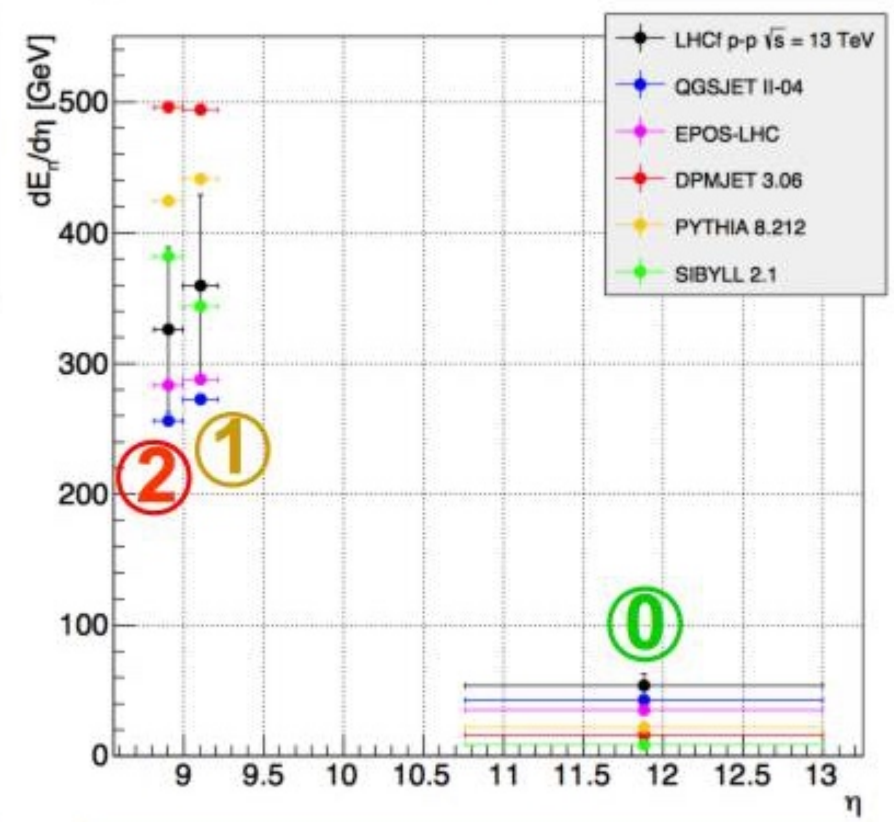
All models overestimate inelasticity in the most forward region even if **QGSJET II-04** and **EPOS-LHC** are consistent within the error bars

dσ/dη VS η



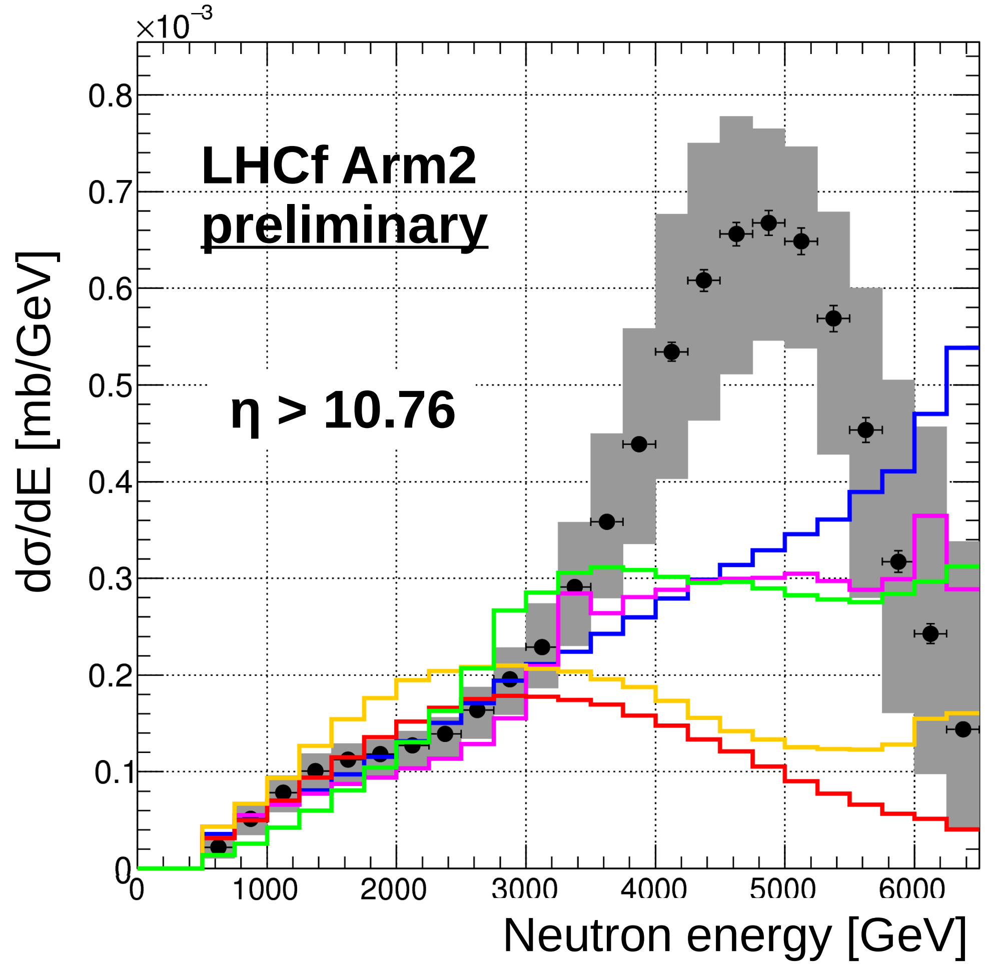
EPOS-LHC and **SIBYLL 2.1** reproduce enough well the measured total differential cross section except in the most forward region

dE/dη VS η

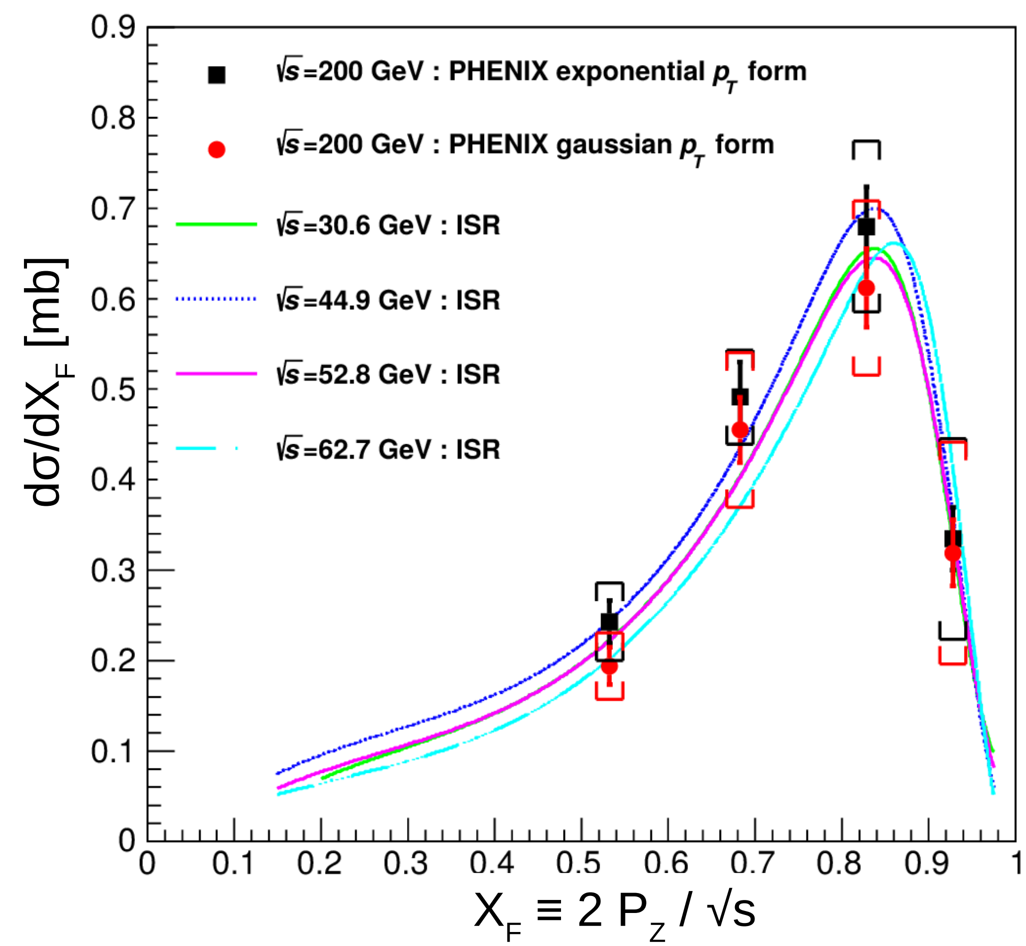


Where the energy flux is high, the agreement between experimental measurements and **SIBYLL 2.1**/**EPOS-LHC** is quite good

√s scaling; Neutron @ zero degree



0 < P_T < 0.28 X_F GeV/c



0 < P_T < 0.11 X_F GeV/c

Different P_T coverage!

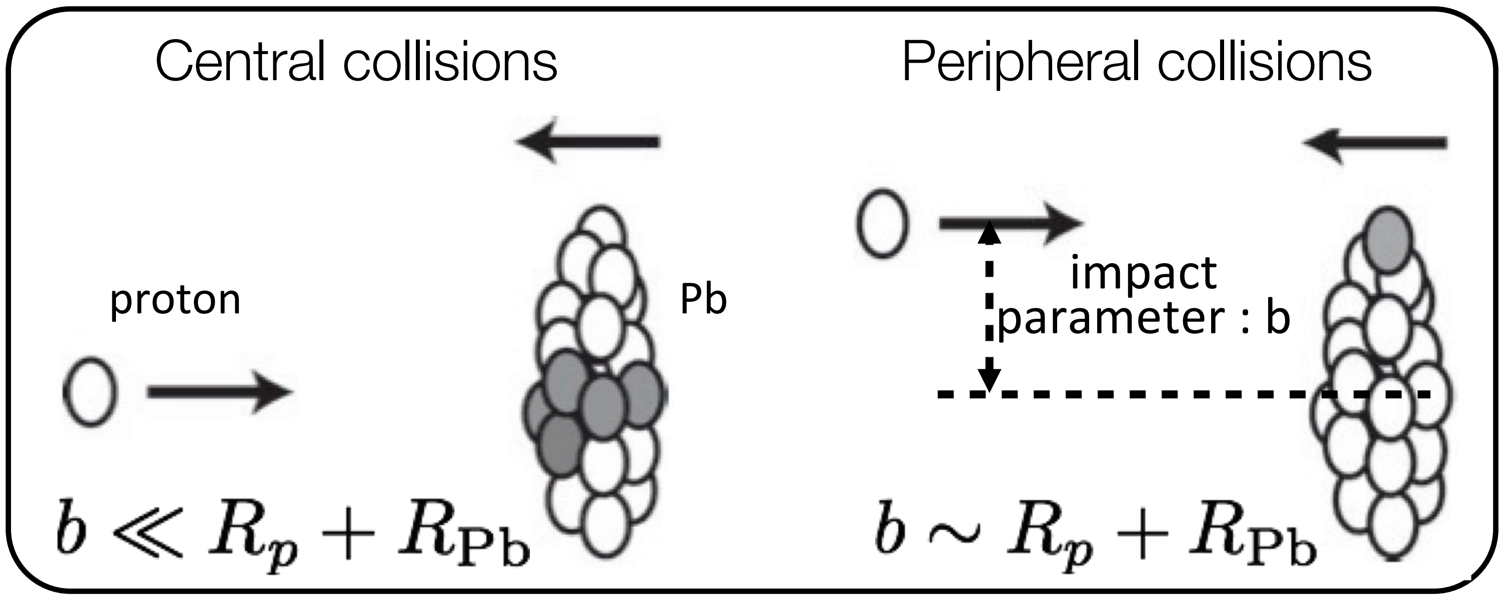
Same structure observed by PHENIX and ISR (qualitatively)

Analysis to be performed adding 900 GeV 2.76 TeV and RHICf data

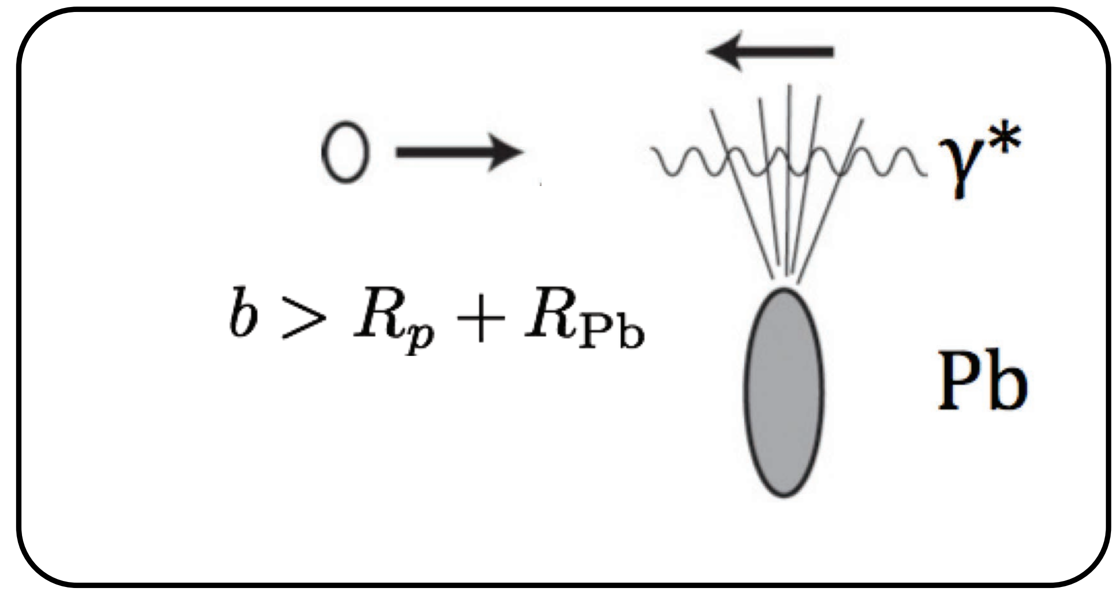
p-Pb results

LHCf @ pPb 5.02 TeV and 8.16 TeV

(Soft) QCD :
central and peripheral collisions



Ultra peripheral collisions :
virtual photons from rel. Pb collides a proton



proton rest frame

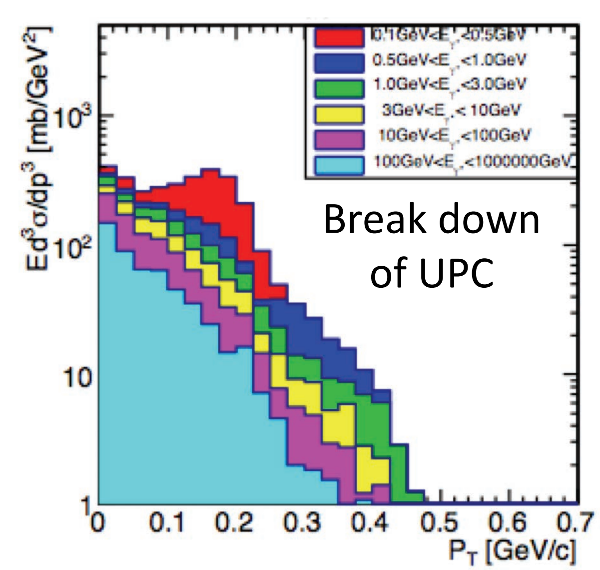
Momentum distribution of the UPC induced secondary particles is estimated as

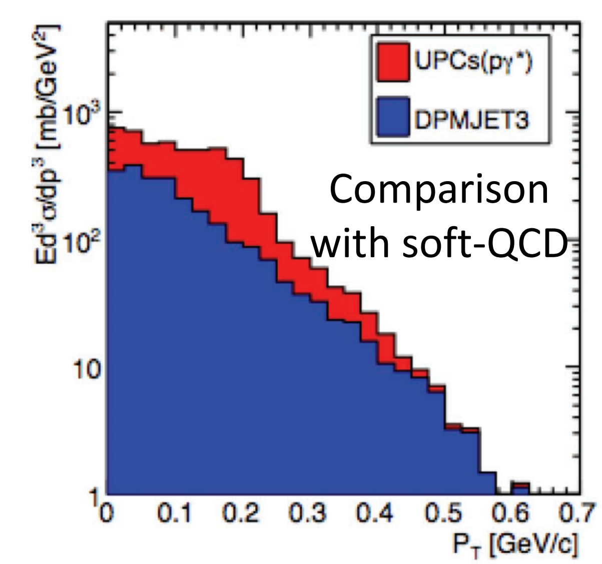
1. energy distribution of virtual photons is estimated by the Weizsacker Williams approximation.
2. photon-proton collisions are simulated by the SOPHIA model (E_γ > pion threshold).
3. produced mesons and baryons by γ-p collisions are boosted along the proton beam.

Dominant channel to forward π^0 is

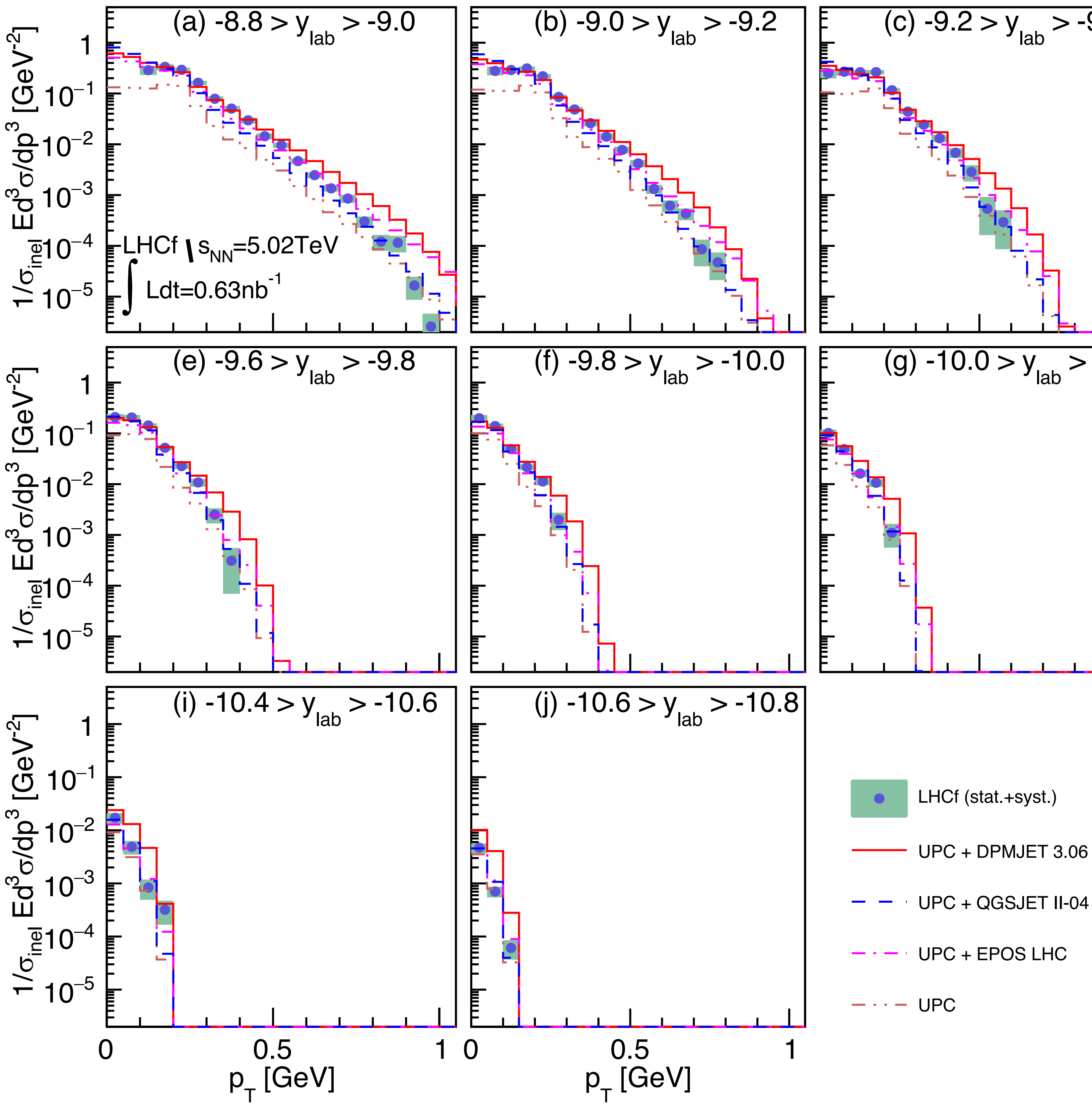
$$\gamma + p \rightarrow \Delta(1232) \rightarrow p + \pi^0$$

About half of the observed π^0 may originate in UPC, another half is from soft-QCD.



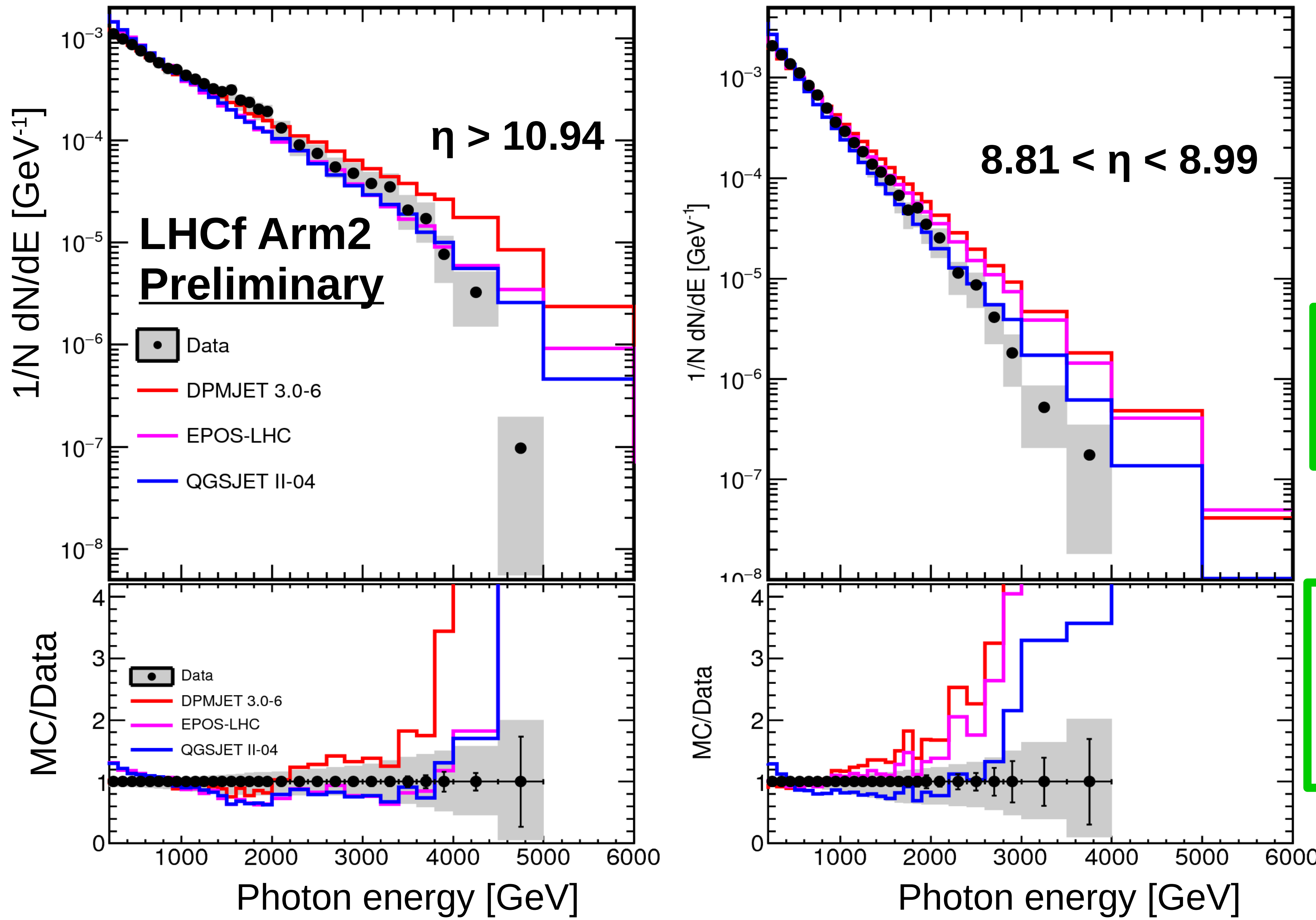


LHCf @ pPb 5.02 TeV: π^0 p_T spectra as function of η



- QGSJETII-04 and EPOS-LHC: similar, good agreement for pT>0.4 GeV
- DPMJET: good agreement for –8.8 > ylab > –10.0 and p_T < 0.3 GeV

Photon spectra in pPb @ 8.16 TeV



UPC added to MC simulations

All spectra normalized to their integral

Only "shape" comparison (not cross section)

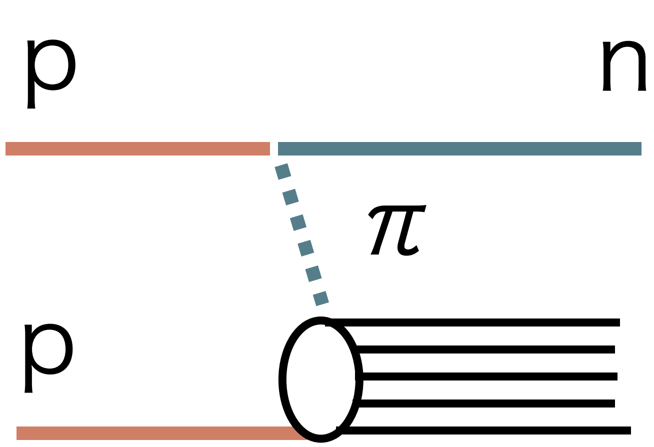
- η > 10.94: good agreement of **EPOS-LHC** and **QGSJET II-04**
- 8.81 < η < 8.99: all models predict an harder spectrum

Combining forward and central info

Physics cases with ATLAS joint taken data

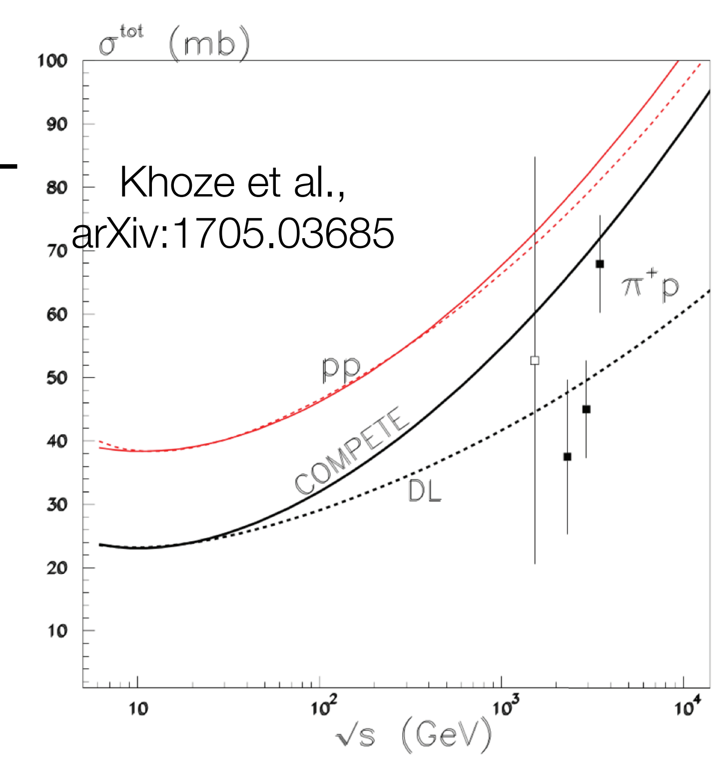
- In p+p collisions
  - Forward spectra of Diffractive/ Non-diffractive events
  - Measurement of proton-π collisions
  - Forward hadron vs central activity correlation

All are important for precise-understanding of CR air shower development



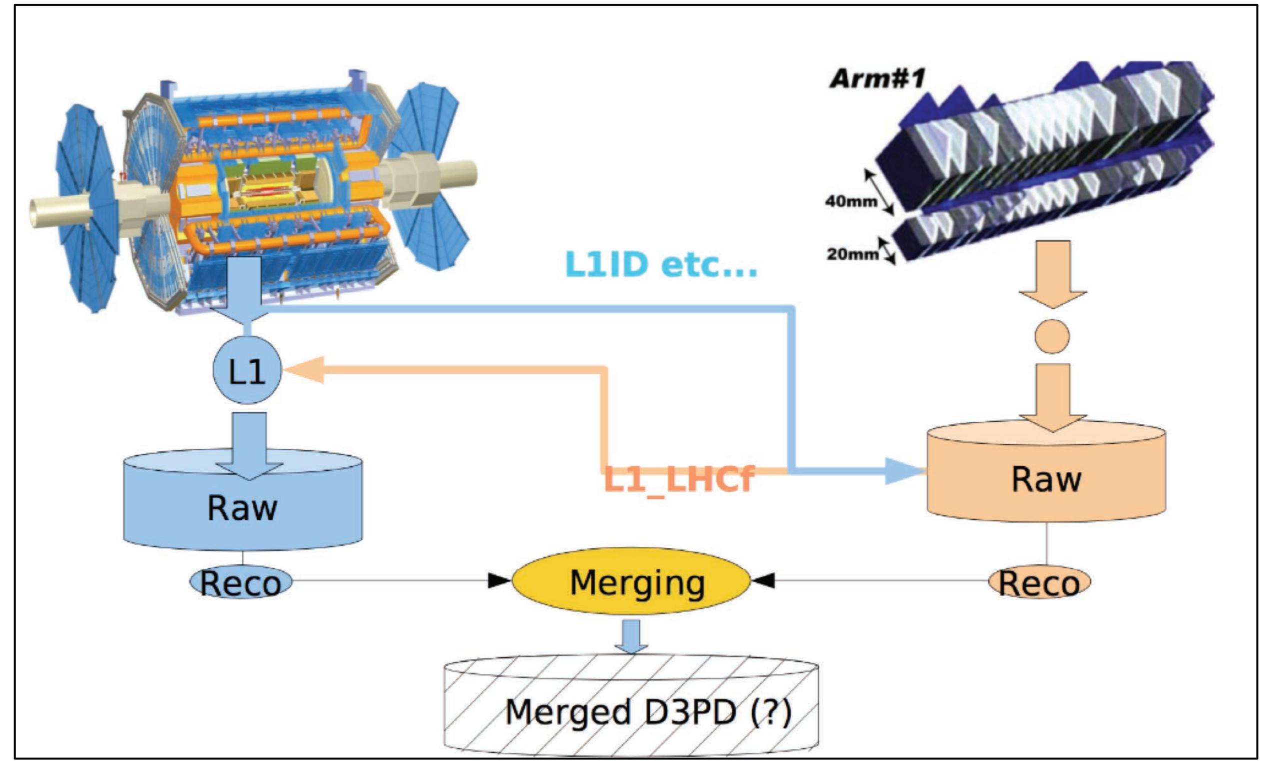
p-π measurement at LHC

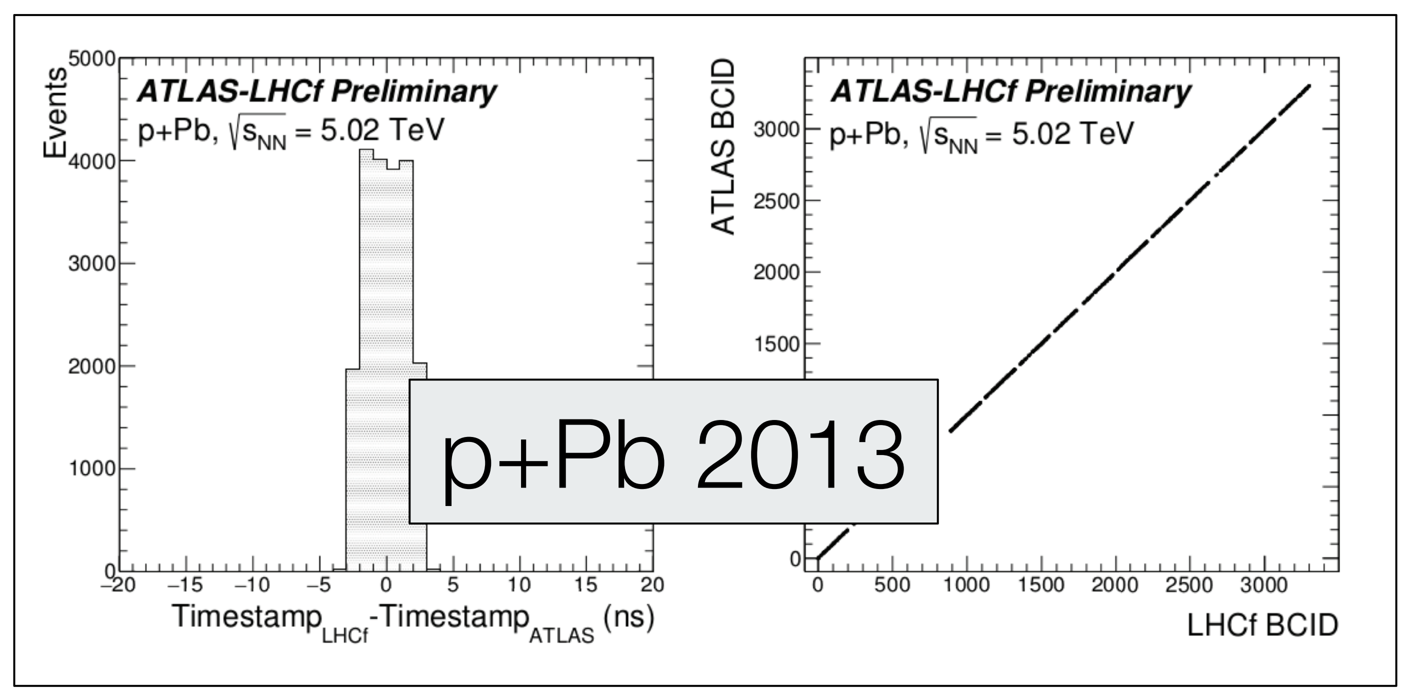
Leading neutron can be tagged by LHCf detectors
-> total cross section
    multiplicity measurement



ATLAS-LHCf combined data analysis

- Operation in 2013
  - p+Pb, $\sqrt{s_{NN}}$ = 5TeV
    - ➔ about 10 M common events.
- Operation in 2015
  - p+p, $\sqrt{s}$ = 13TeV
    - ➔ about 6 M common events.
- Operation in 2016
  - p+Pb, $\sqrt{s_{NN}}$ = 5TeV
    - ➔ about 26 M common events
  - p+Pb, $\sqrt{s_{NN}}$ = 8TeV
    - ➔ about 16 M common events





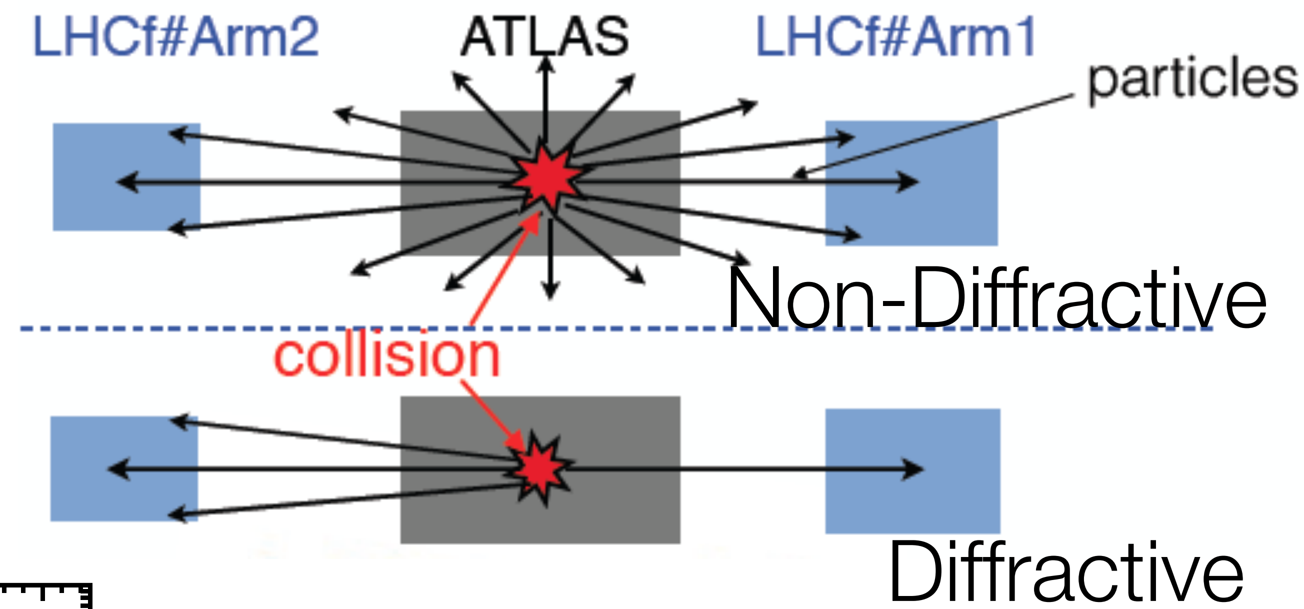
Off-line event matching

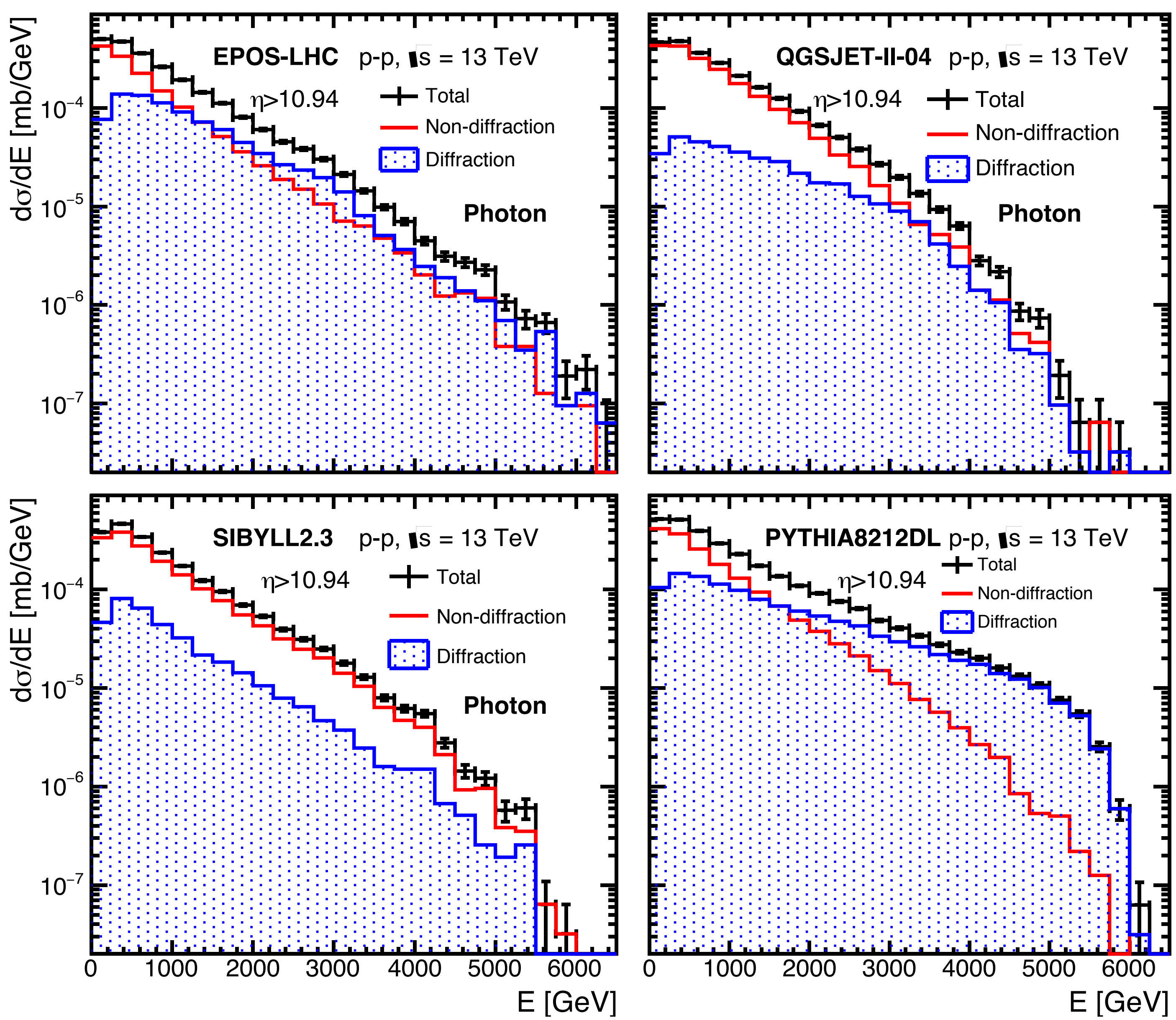
Important to separate the contributions due to diffractive and non-diffractive collisions

WG active meeting every 2 weeks

Diffractive studies

- MC studies
  - Contributions on forward photon/neutron spectra from diffractive/non-diffractive collisions.
  - Event-selection by the central particle production to separate these events





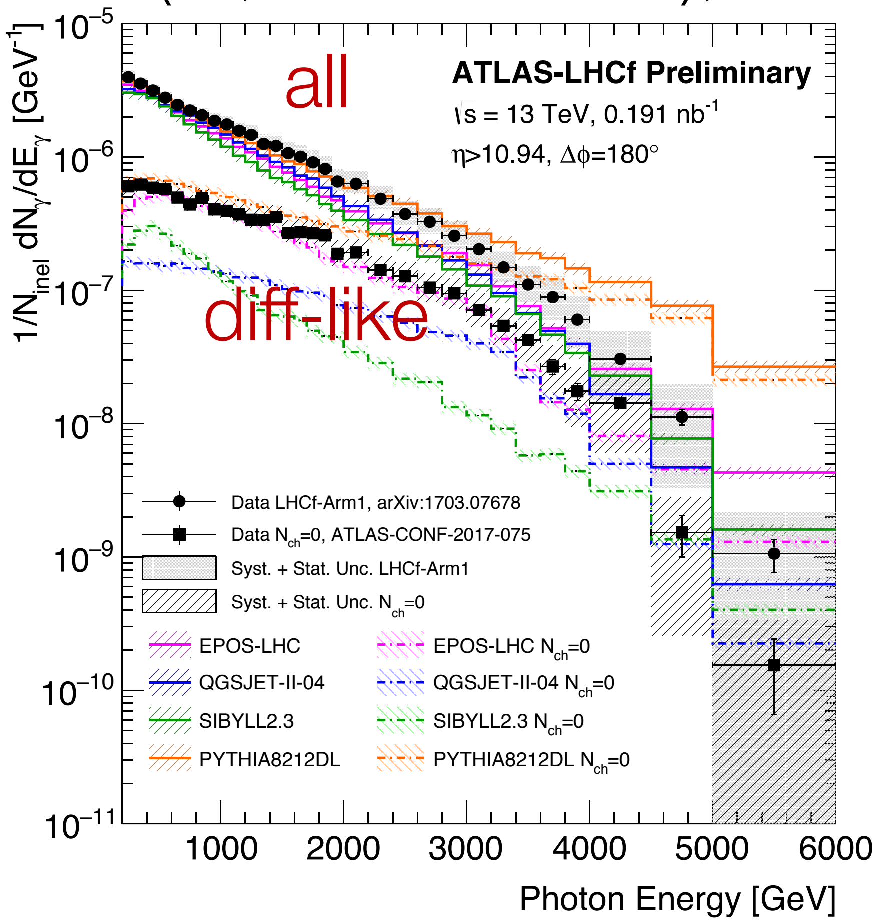
Very forward photon energy spectra predicted by four models with total/diffractive/non-diffractive

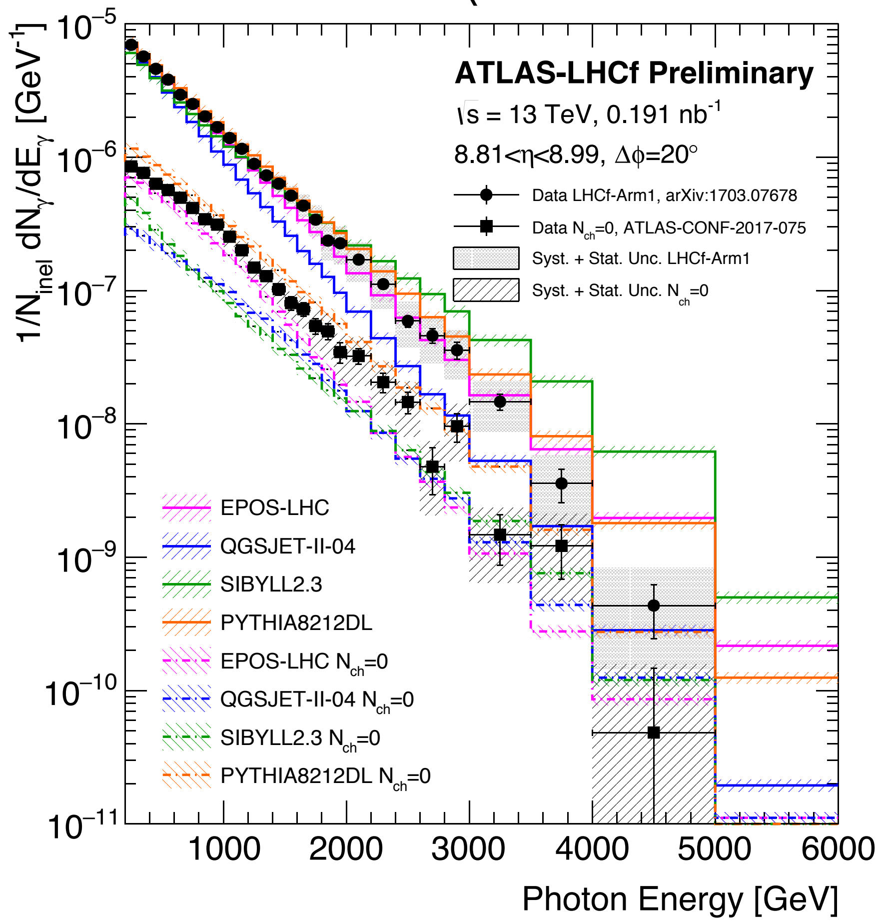
- Total: Quite similar spectra in EPOS,QGSJET and SIBYLL (LHCf alone)
- Diffractive/Non-diffractive: Very big difference between models (ATLAS-LHCf)

- ATLAS inner tracker enables to categorize events in diffractive-like and non-diffractive-like

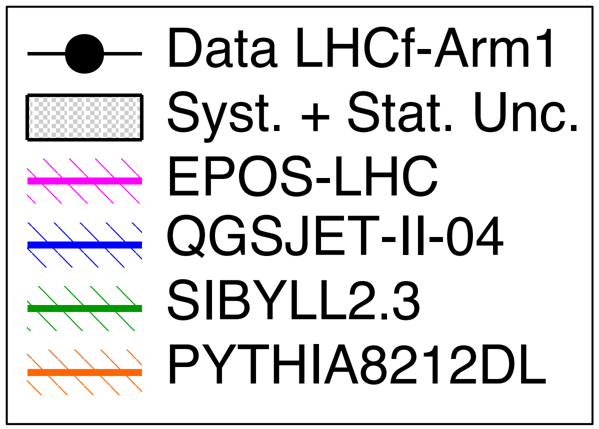
ATLAS-LHCf joint analysis for diffraction

LHCf (all; ●+solid lines), LHCf diffractive-like (■+dashed lines)

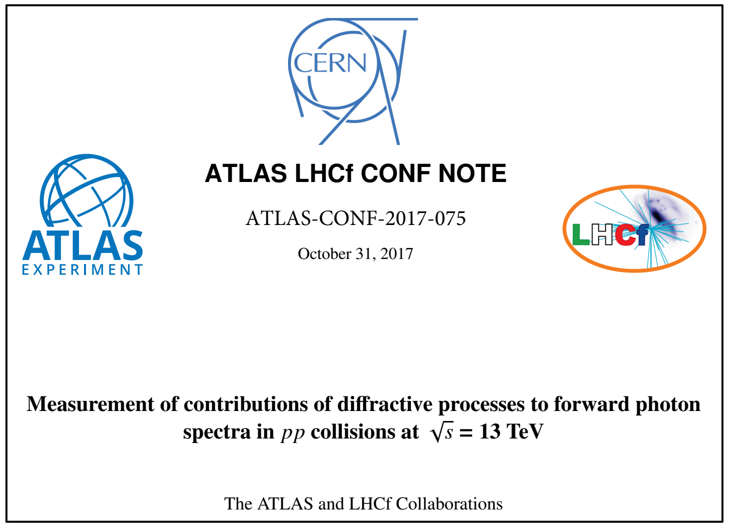




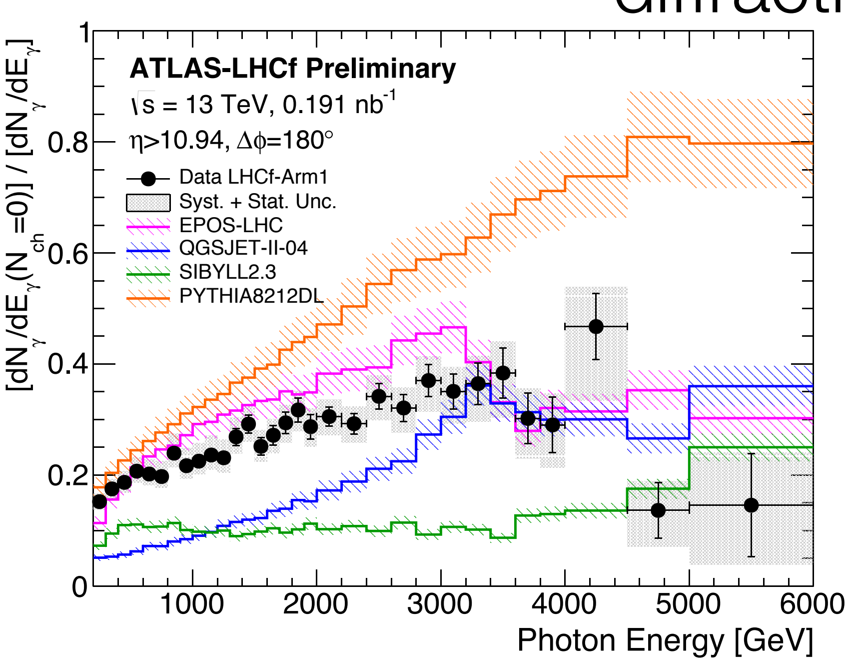
- Use ATLAS N_{ch}=0 to define diffractive-like events
- Applied to LHCf photon cross sections

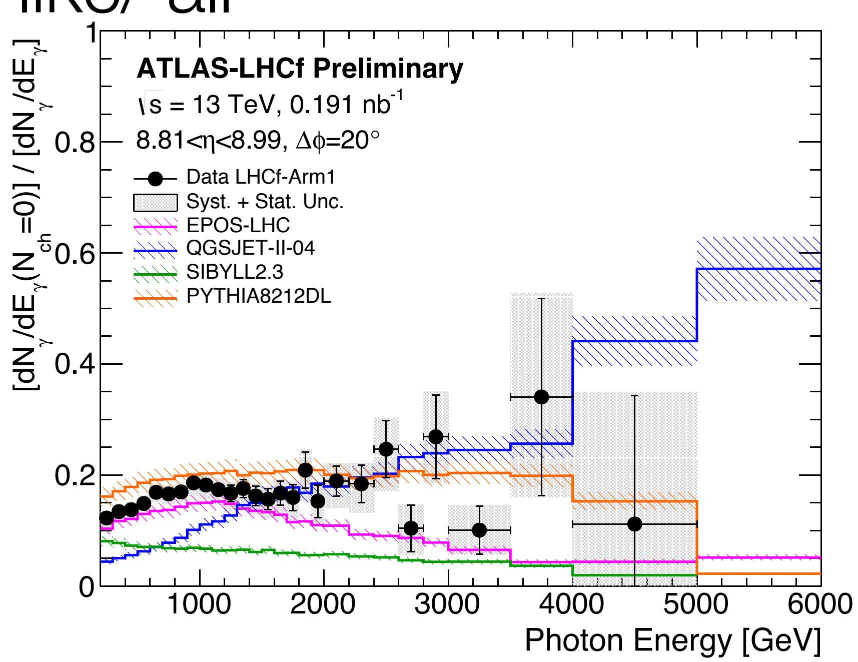


ATLAS-CONF-2017-075



diffractive-like/ all





Central-forward neutron correlation

Constraining high energy interaction mechanisms by studying forward hadron production at the LHC

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July 30, 2018

Abstract

We demonstrate that underlying assumptions concerning the structure of constituent parton Fock states in hadrons make a strong impact on the predictions of hadronic interaction models for forward hadron spectra and for long-range correlations between central and forward hadron production. Our analysis shows that combined studies of proton-proton collisions at the Large Hadron Collider by central and forward-looking detectors have a rich potential for discriminating between the main model approaches.

PRD 94 (114026) 2016

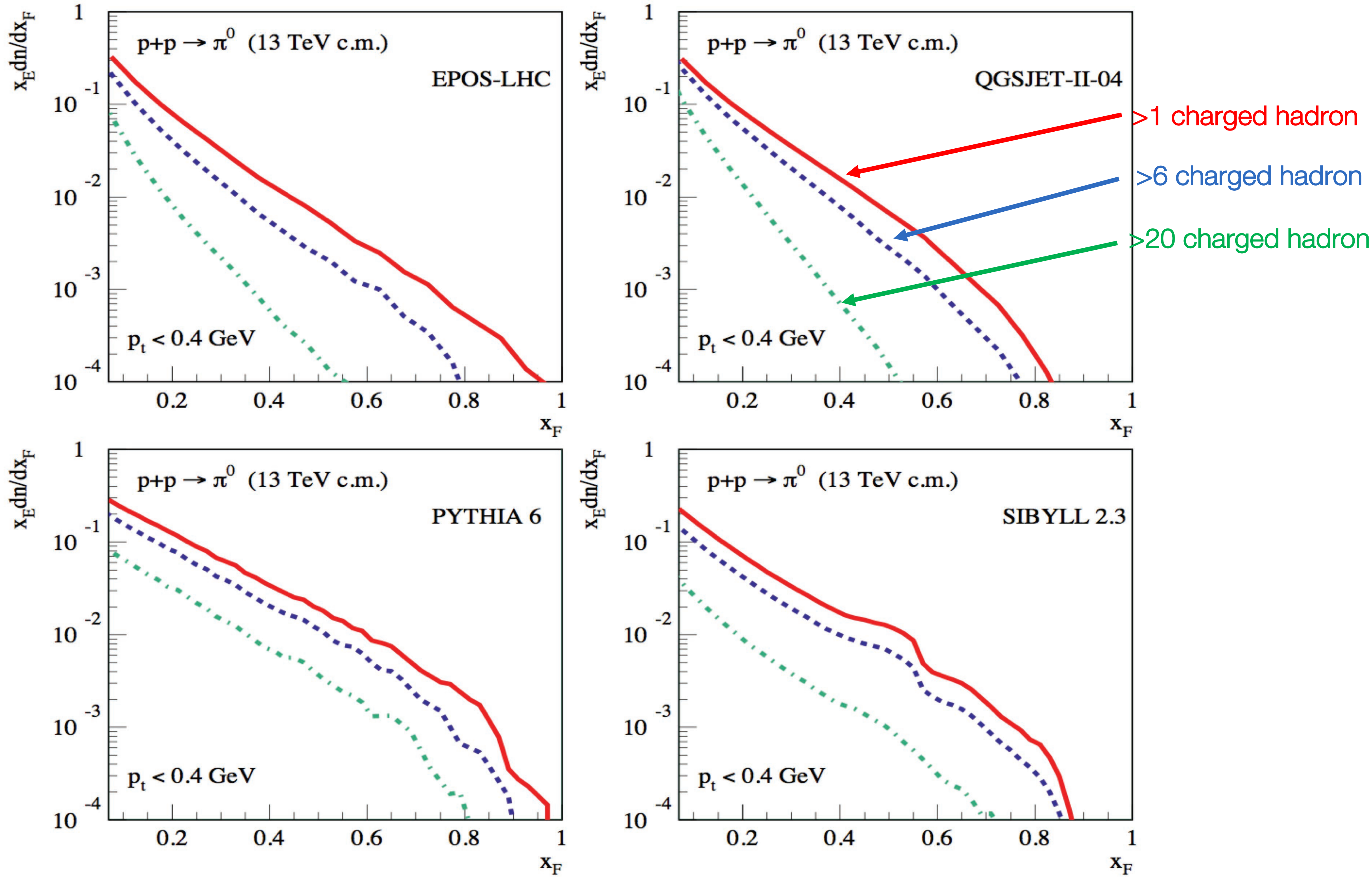
The experimental measurement of:

- Forward π^0 spectra vs central multiplicity
- Forward hadron spectra vs central multiplicity

could be very useful to determine the best model approach for high energy interactions

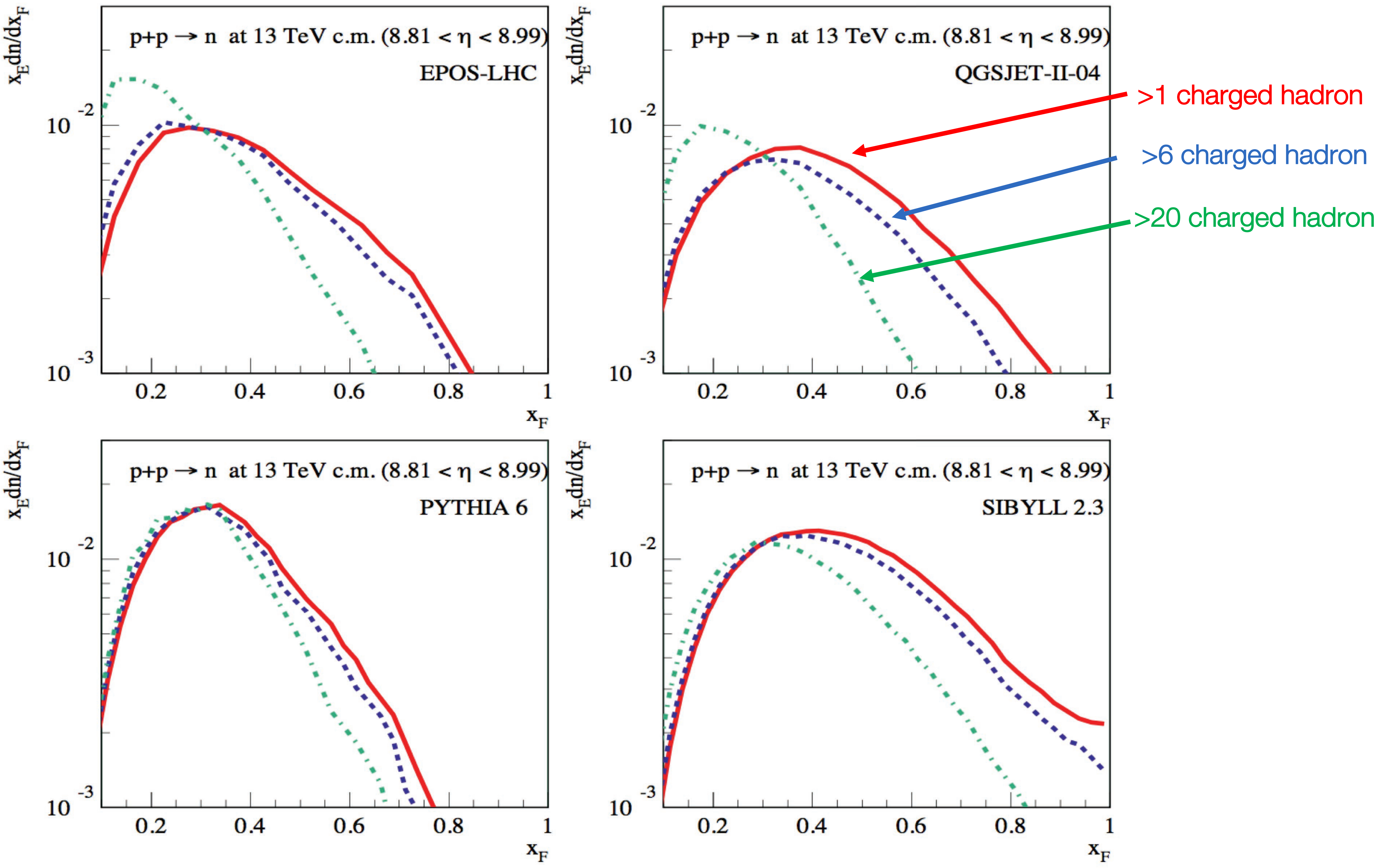
π^0 forward spectra vs central multiplicity

PRD 94 (114026) 2016



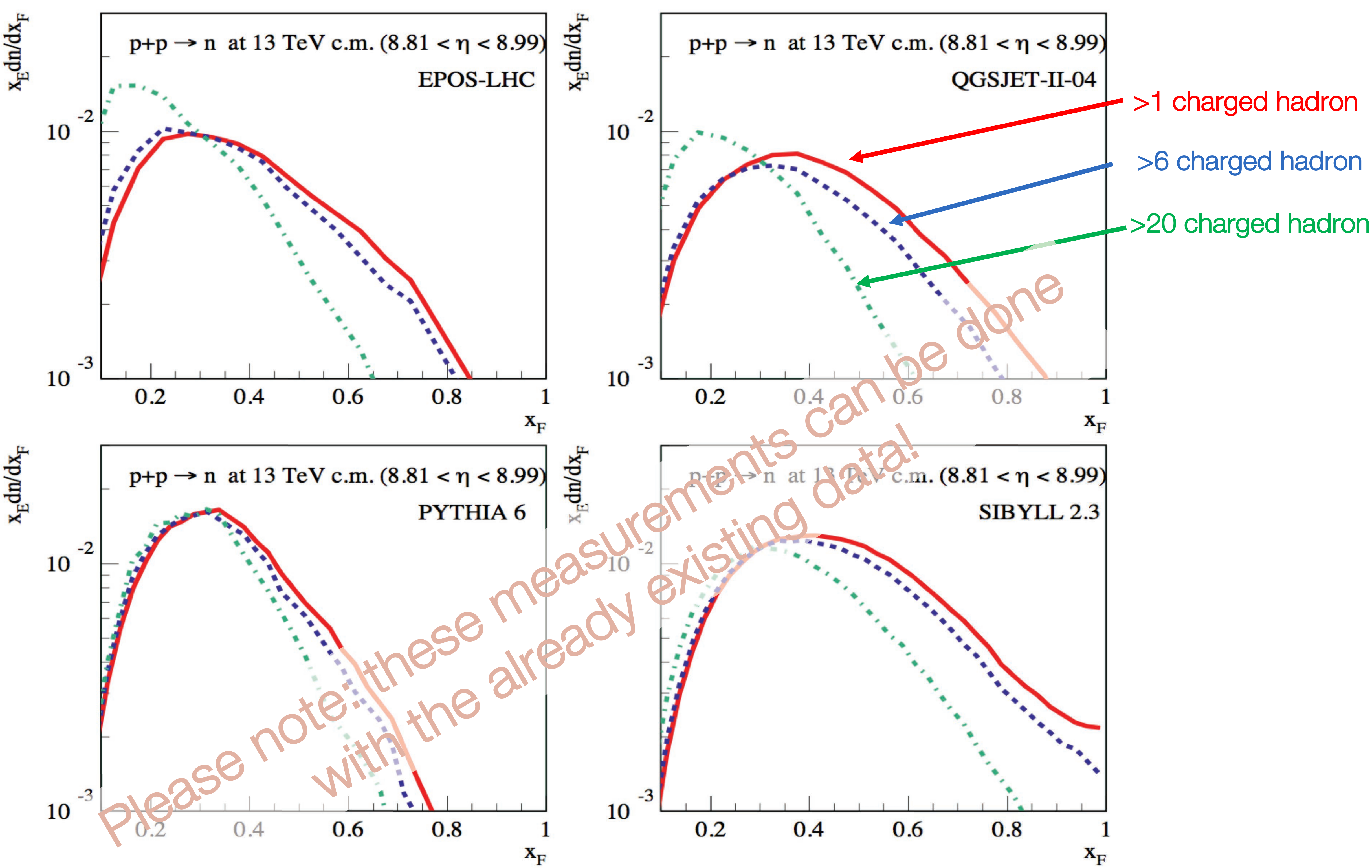
Neutrons forward spectra vs central multiplicity

PRD 94 (114026) 2016



Neutrons forward spectra vs central multiplicity

PRD 94 (114026) 2016



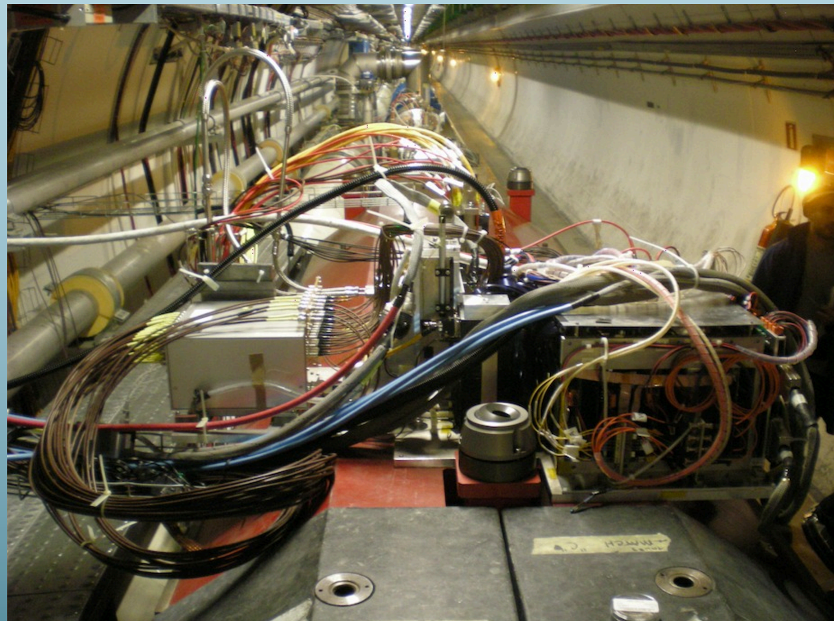
Please note: these measurements can be done with the already existing data!

From LHC to RHIC

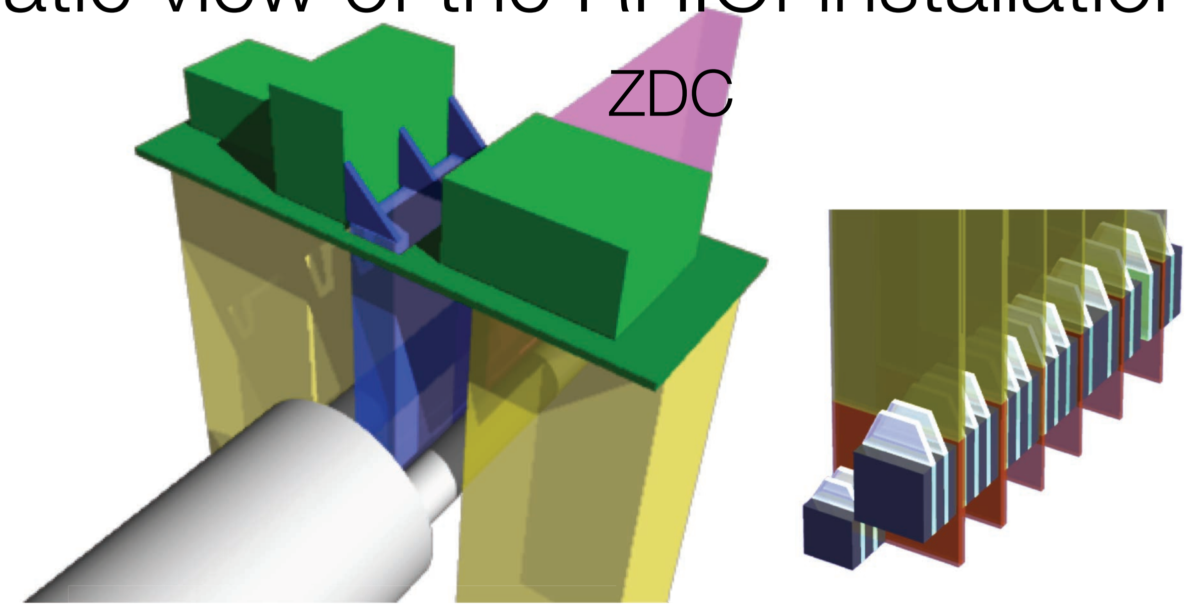
From the LHC to RHIC

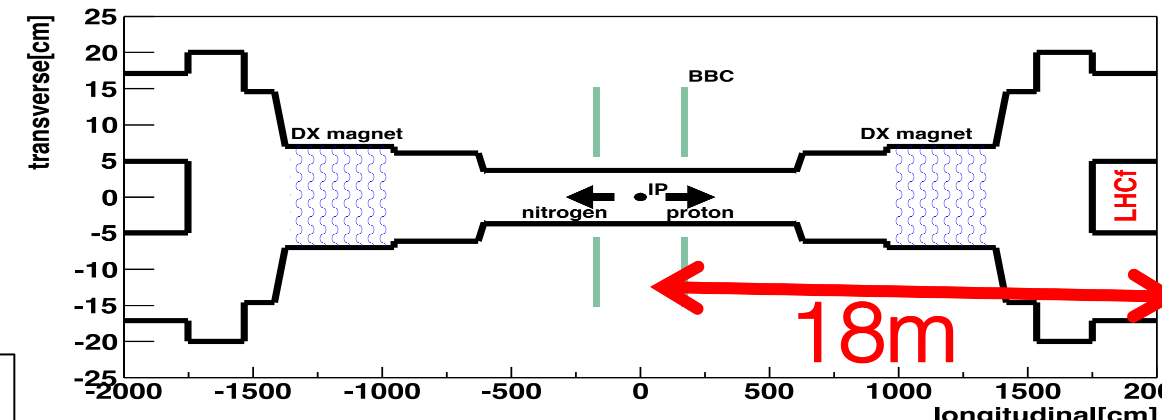
√s scaling, or breaking?

LHCf Arm2 detector in the LHC tunnel

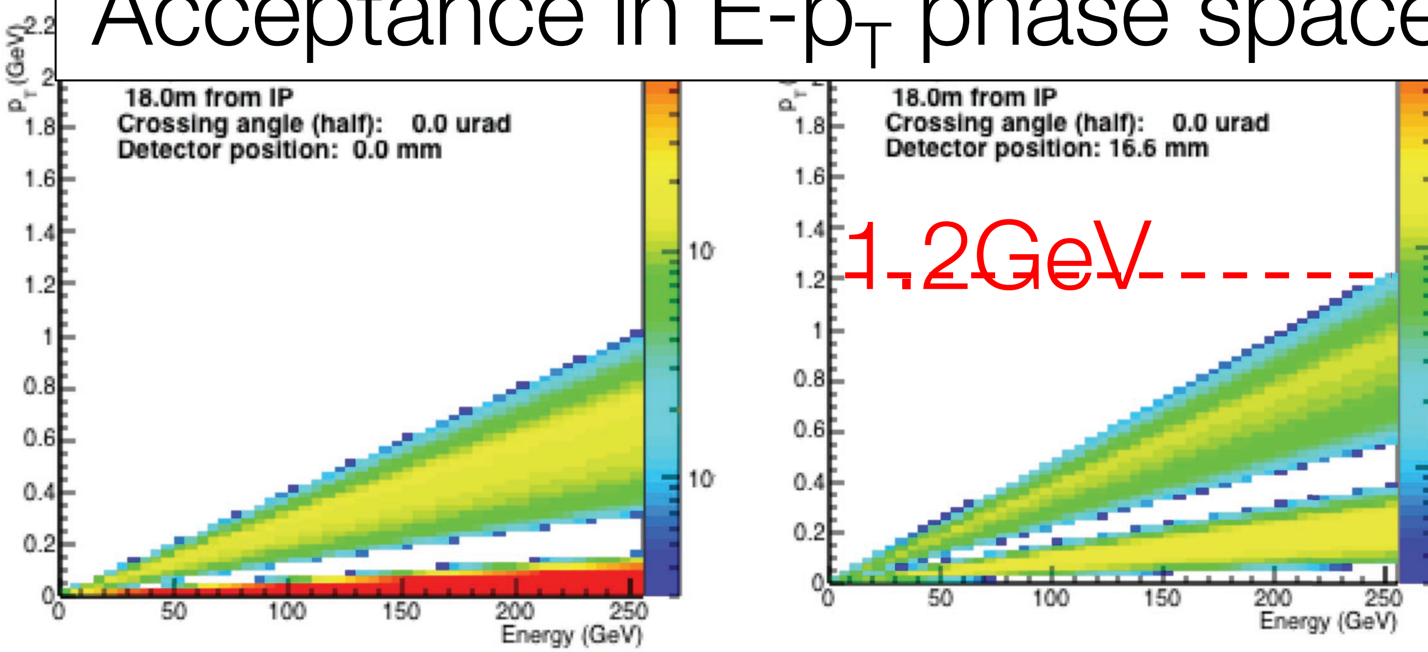


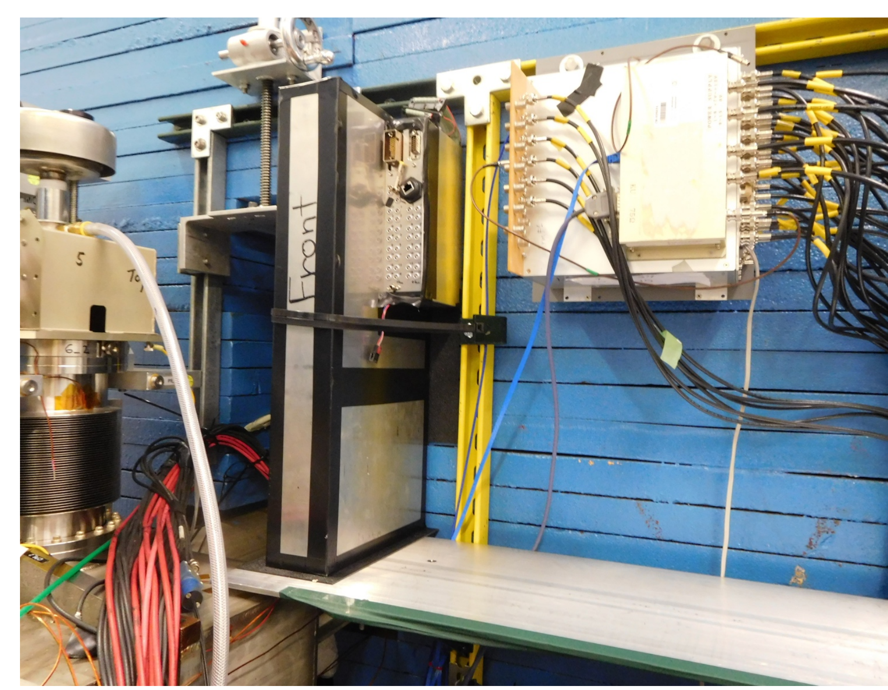
Schematic view of the RHICf installation



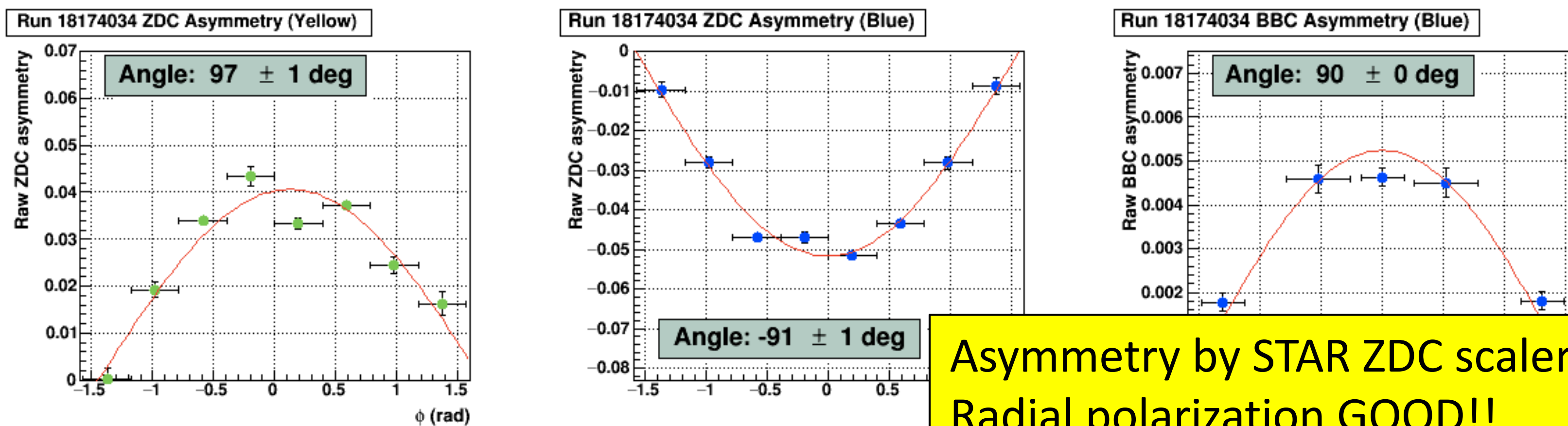


Acceptance in E-p_T phase space





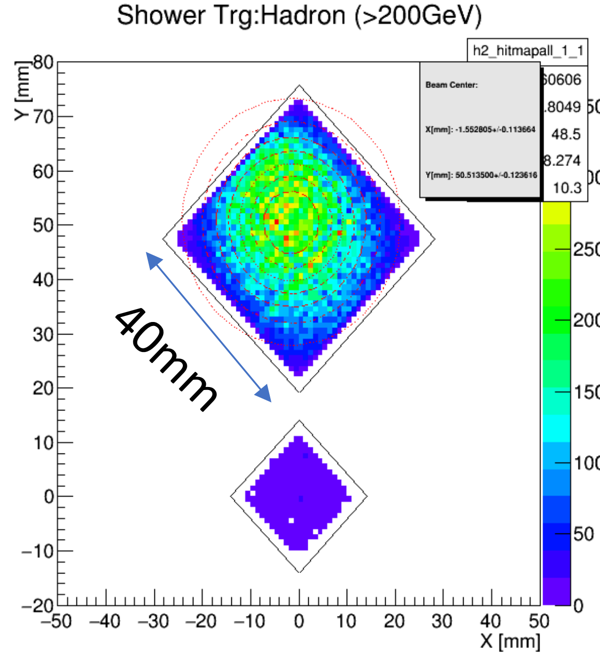
Very rough overview of the 2017 RHICf run

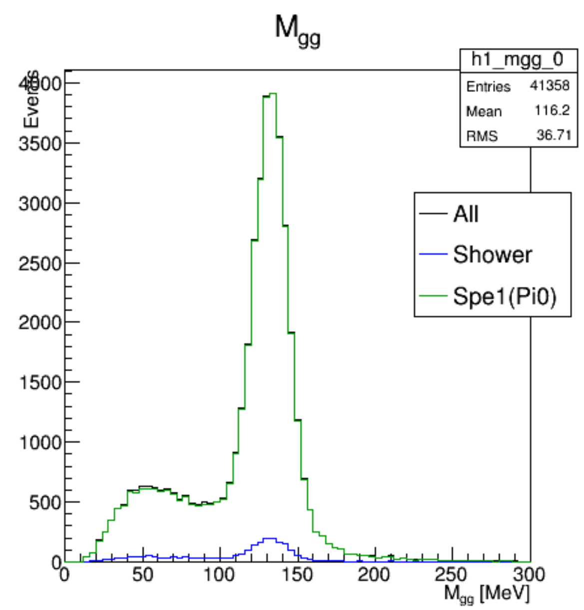


June 2017

Asymmetry by STAR ZDC scaler
Radial polarization GOOD!!

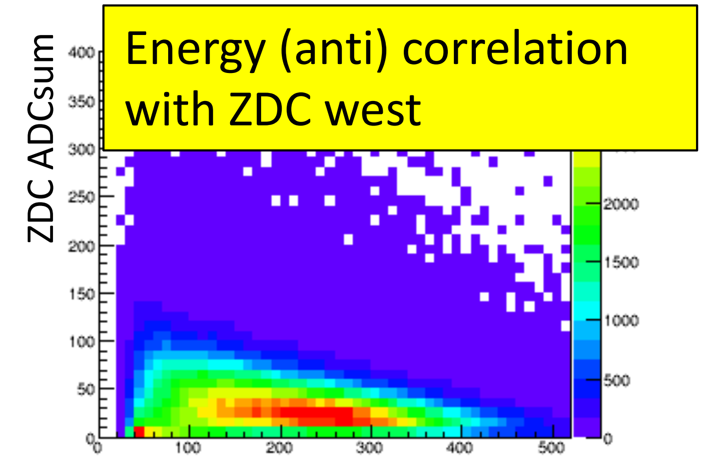
Hadron shower hitmap
0 degree well defined!

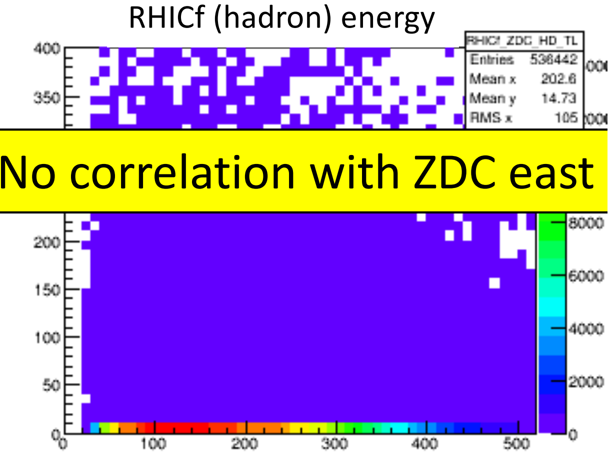




Invariant mass of 2γ
Peak by π^0 !!

Energy (anti) correlation
with ZDC west





No correlation with ZDC east

First analysis priority: transverse spin asymmetry of very forward π^0 in polarized pp collisions at 510 GeV c.m. energy

The future at LHC

Proposal for LHCf operation in LHC Run3

1. **Low luminosity run for p+p at 14 TeV (2021?)**

LHCf was originally approved for this run

Motivations:

- Slightly higher energy → slightly higher boost
- Dedicated trigger for «rare» events (~1000 η, some K^0 expected in one day)
- Increase of γ, n and π^0 statistics wrt 13 TeV
- Combined data taking with ATLAS, ALFA Roman Pot and hopefully hadronic ZDC modules

2. **Low luminosity p+O (or O+O) run or other light ions at the highest achievable energy (2023?)**

Motivations:

- Optimal collisions to simulate the interactions with the atmosphere
- Negligible background from UPC
- First forward measurement at high energy with light ions
- Combined data taking LHCf-ATLAS-ALFA-ZDC might give useful info on the generation of CR shower in the fwd and central regions at the same time
- Possibility to take data also in the ion remnant side: direct study of nuclear effects in the generation and development of atmospheric showers

Physics cases and related upgrade of the DAQ system are summarized in a detailed Technical Report submitted this year to LHCC (CERN-LHCC-2019-008) → Accepted!!!!

Summary

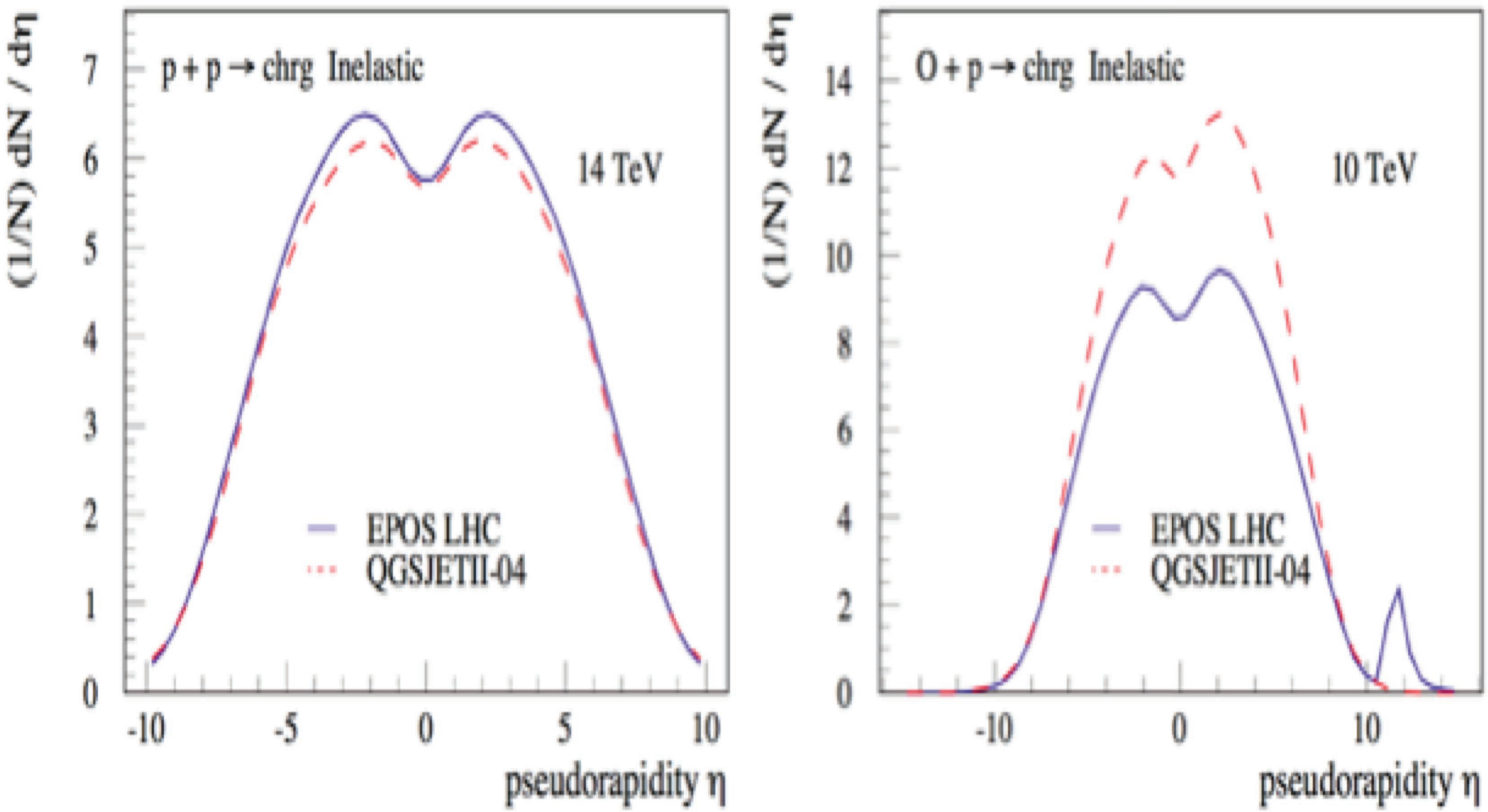
LHCf zero degree results are significantly contributing to improve our knowledge of hadronic interaction model for HECR Physics

- We have precisely measured γ, π^0 and n spectra in many different experimental conditions
  - p-p from 900 GeV up to 13 TeV c.m. energy
  - p-Pb at 5.02 and 8.16 TeV c.m. energy
- We are finalizing the analysis to correlate forward and central activity (LHCf/ATLAS)
- We have taken data with 510 GeV p-p polarized beam at RHIC
- We have been approved for LHC RUN3 operations with upgraded detectors
  - Low luminosity p-p 14 TeV
  - p-O run

- Still a lot of results will come in the next years…
- So… stay tuned!!!!

Back-up Slides

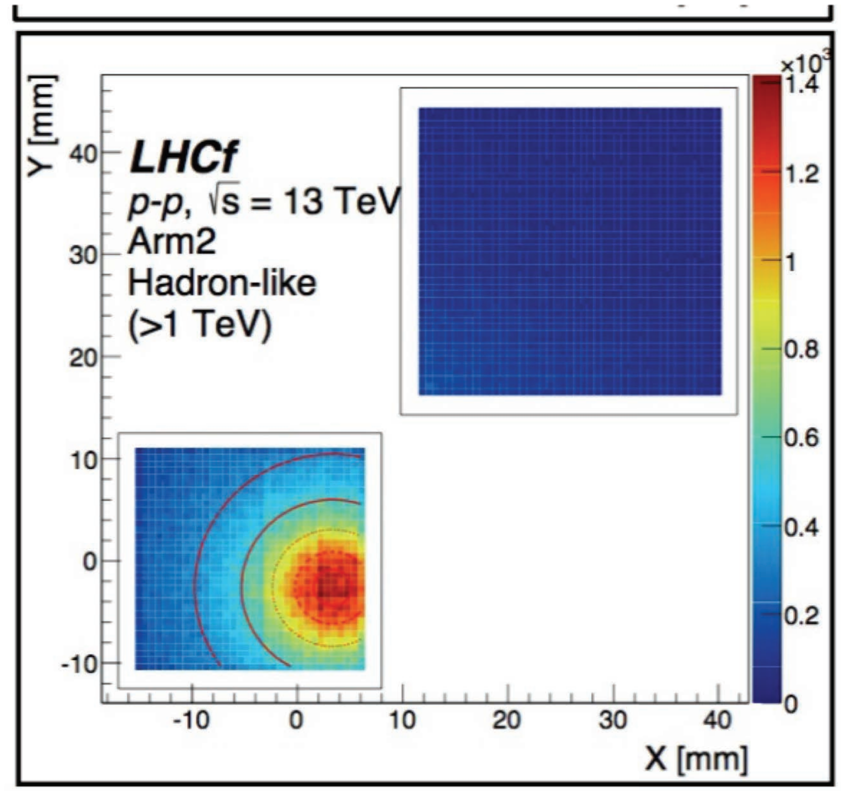
p-O collisions



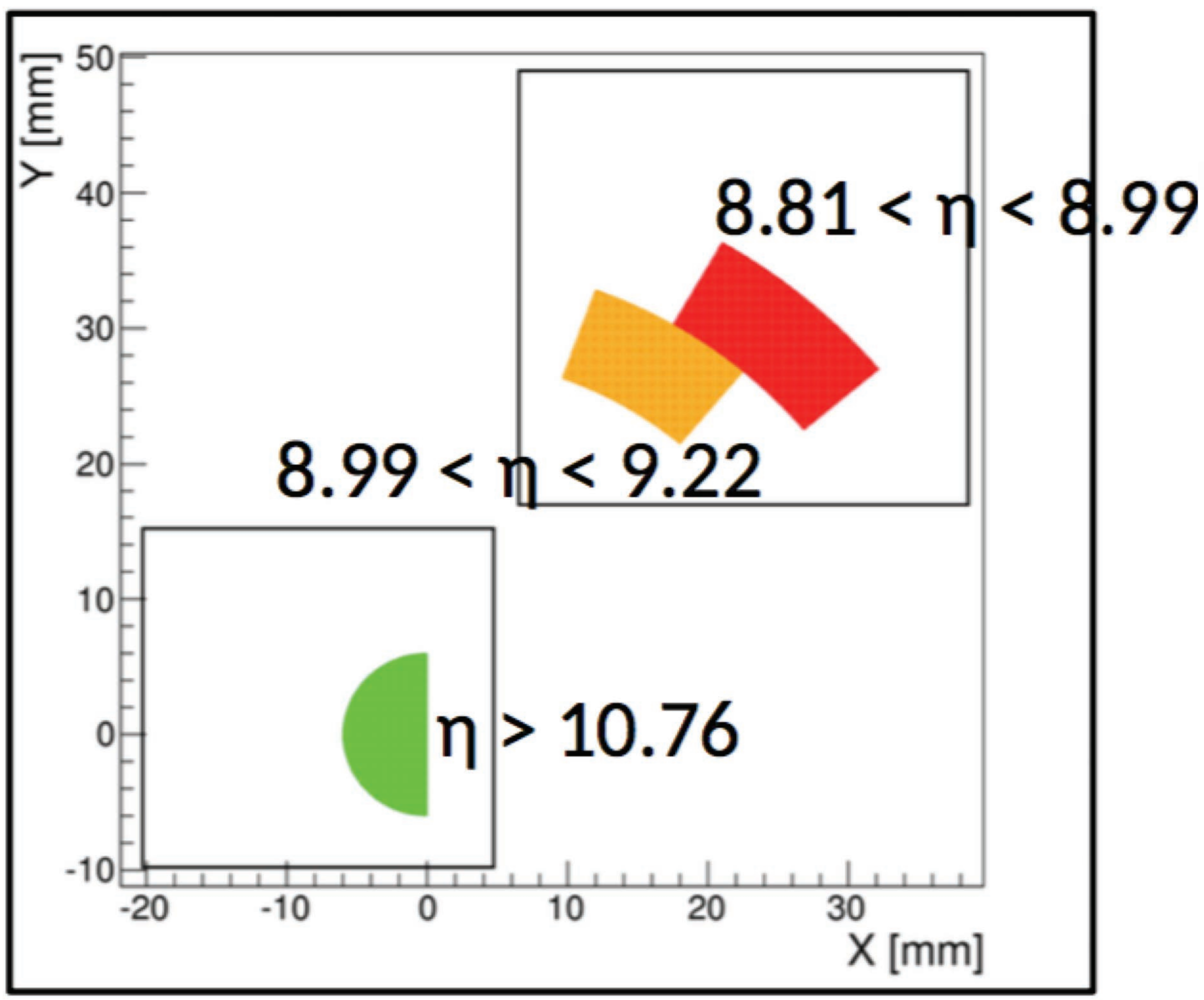
Analysis of hadron production in p-p collisions at 13 TeV

Data set

12 July 2015, 22:32-1:30 (3 hours)
Fill # 3855
$\mu = 0.01$
$\int L dt = 0.19\ nb^{-1}$
$\sigma_{ine} = 78.53$ mb



Beam Center
Estimated using 2D fit on high energy ha dron hitmap distribu tion



Same as 7 TeV analysis
PLB 750 (2015) 360-366

Event selection criteria:

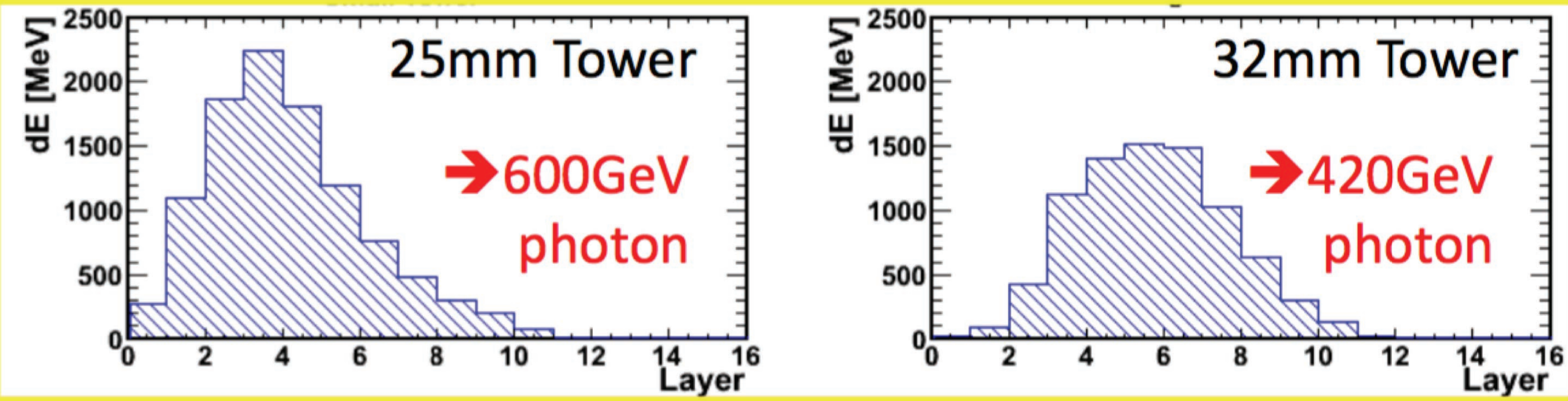
software trigger
at least 3 consecutive layers with deposit above threshold $dE > dE^{thr}$

PID selection
$L_{2D} > L_{2D}^{thr}$ where L_{2D} is a variable related to shower longitudinal profile

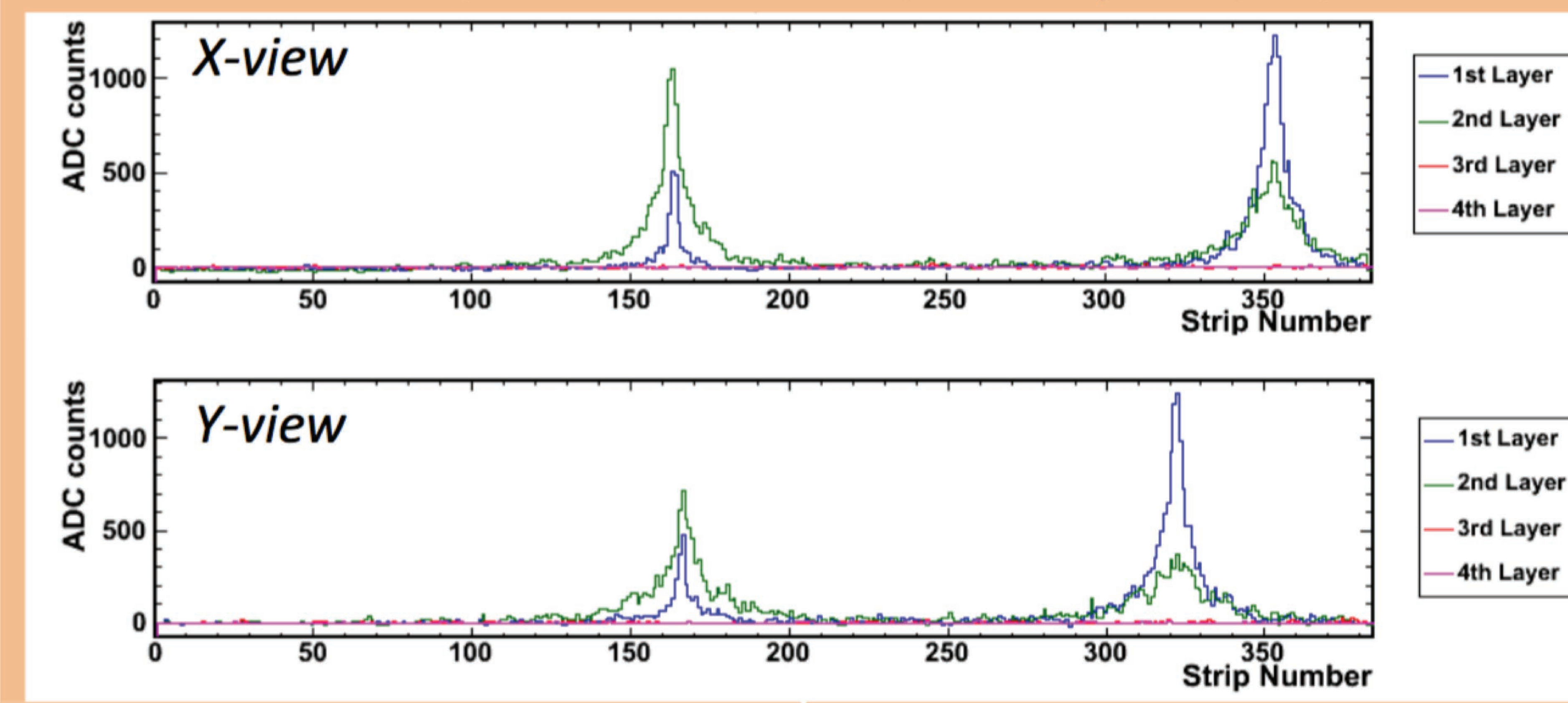
pseudorapidity acceptance
3 different pseudorapidity regions

π^0 reconstruction

Longitudinal development measured by scintillator layers



Transverse profile measured by silicon μ–strip layers



Determination of **energy** from total energy release

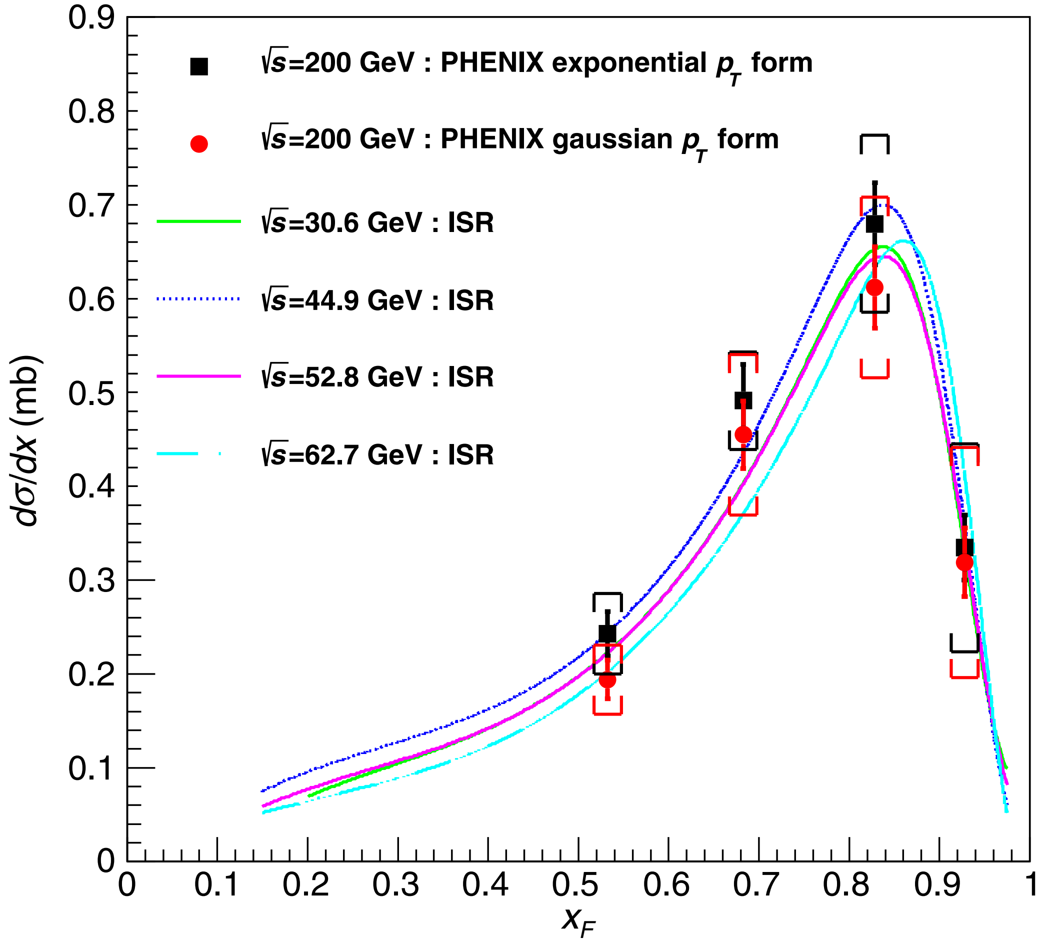
PID from shape

Determination of the **impact point**

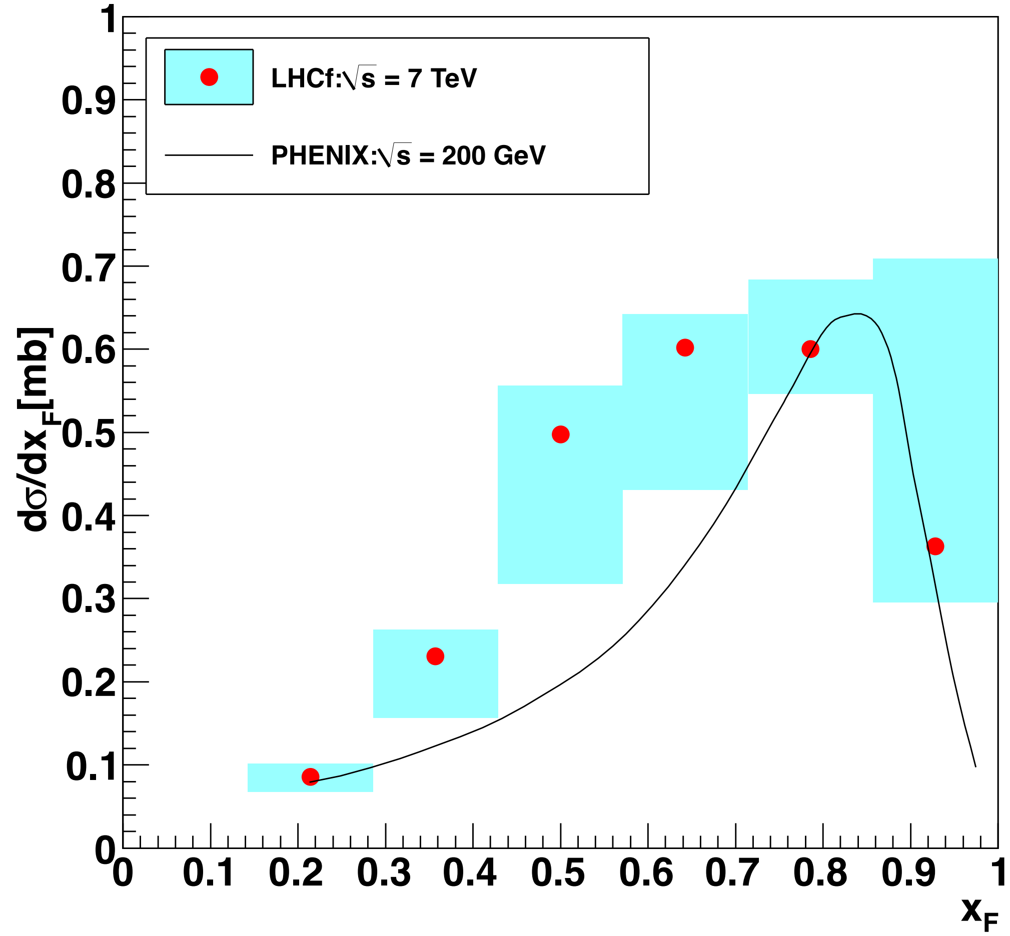
Measurement of the **opening angle** of gamma pairs

Identification of **multiple hit**

√s scaling; Neutron @ zero degree



PHENIX, PRD, 88, 032006 (2013)



LHCf, K.Kawade, PhD thesis, CERN-THESIS-2014-315

$p_T < 0.11\ x_F$ GeV/c

$\sqrt{s}$ = 30-60 GeV @ISR

$\sqrt{s}$ = 200 GeV @RHIC

$p_T < 0.11\ x_F$ GeV/c

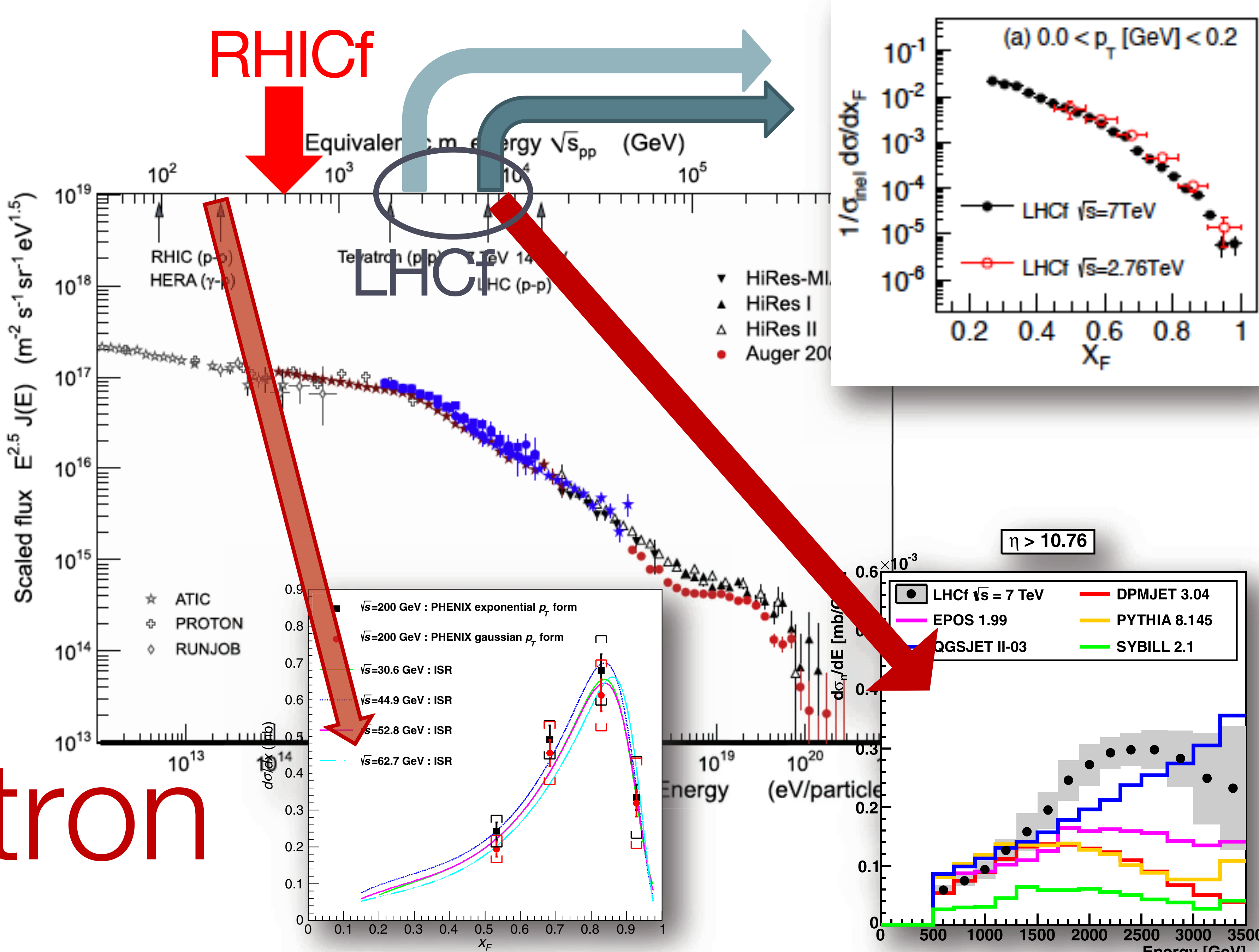
$\sqrt{s}$ = 7000 GeV @LHC

Narrower angle than the published result to compare with the previous works

- Excellent scaling at $\sqrt{s}$ = 30-200GeV
- $\sqrt{s}$ = 7TeV result agrees in a peak structure, but slightly soft??

√s scaling, or breaking?

LHCf 2.76TeV and 7TeV data shows scaling of forward π^0

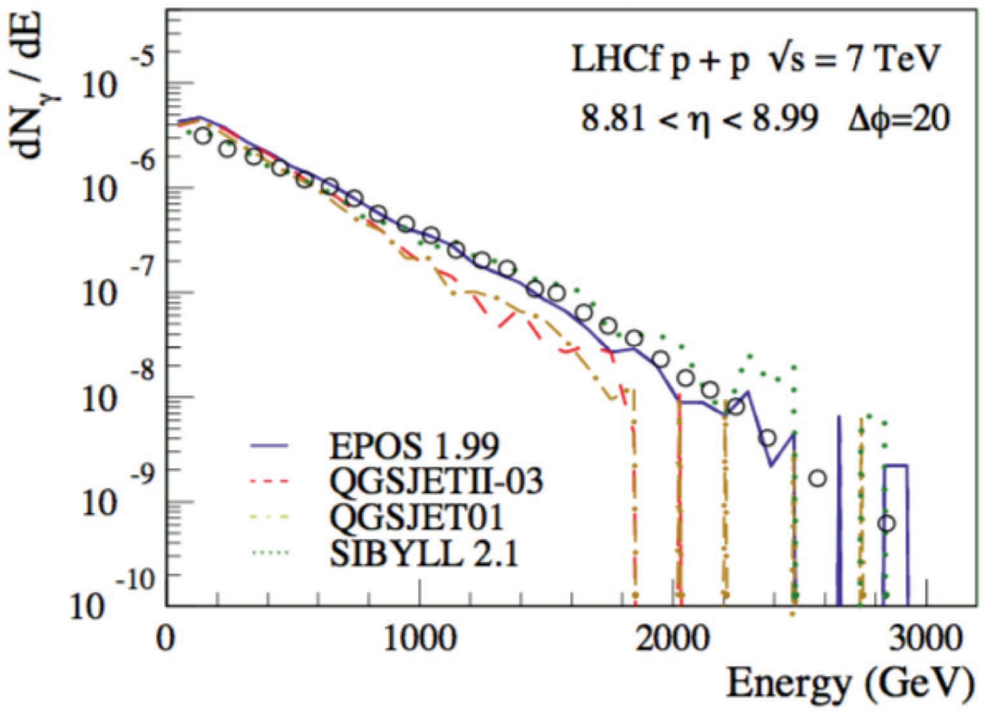


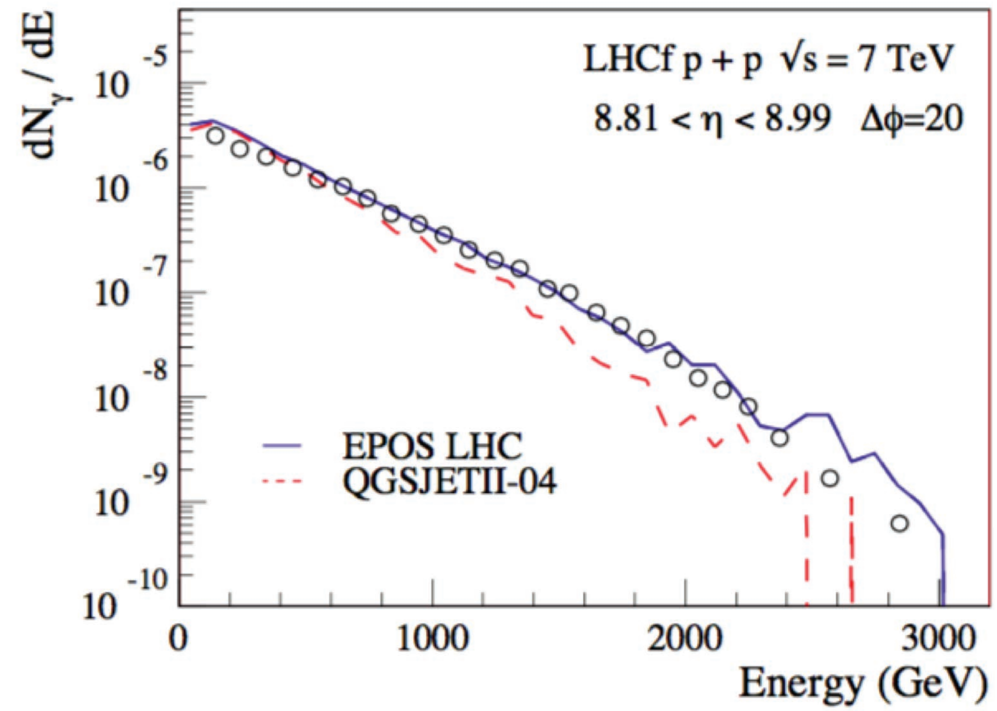
π^0

neutron

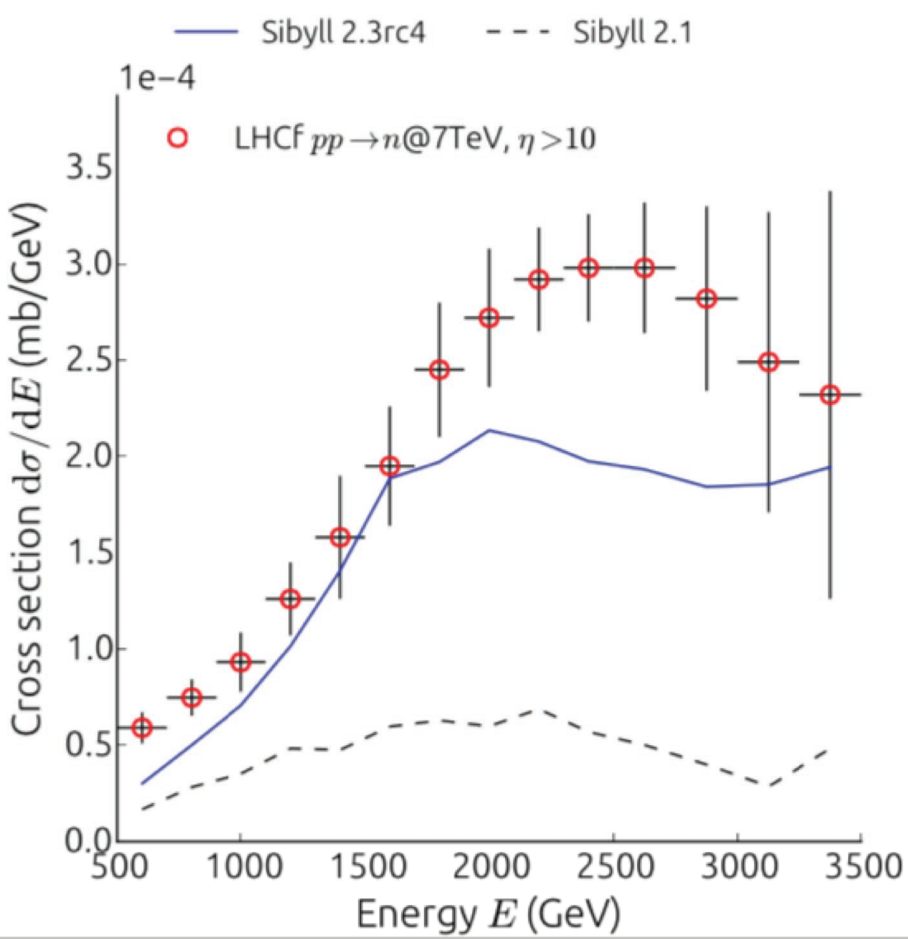
ISR (30-60GeV), PHENIX (200GeV) and LHCf (7TeV) data indicate scaling *breaking* of forward neutrons????

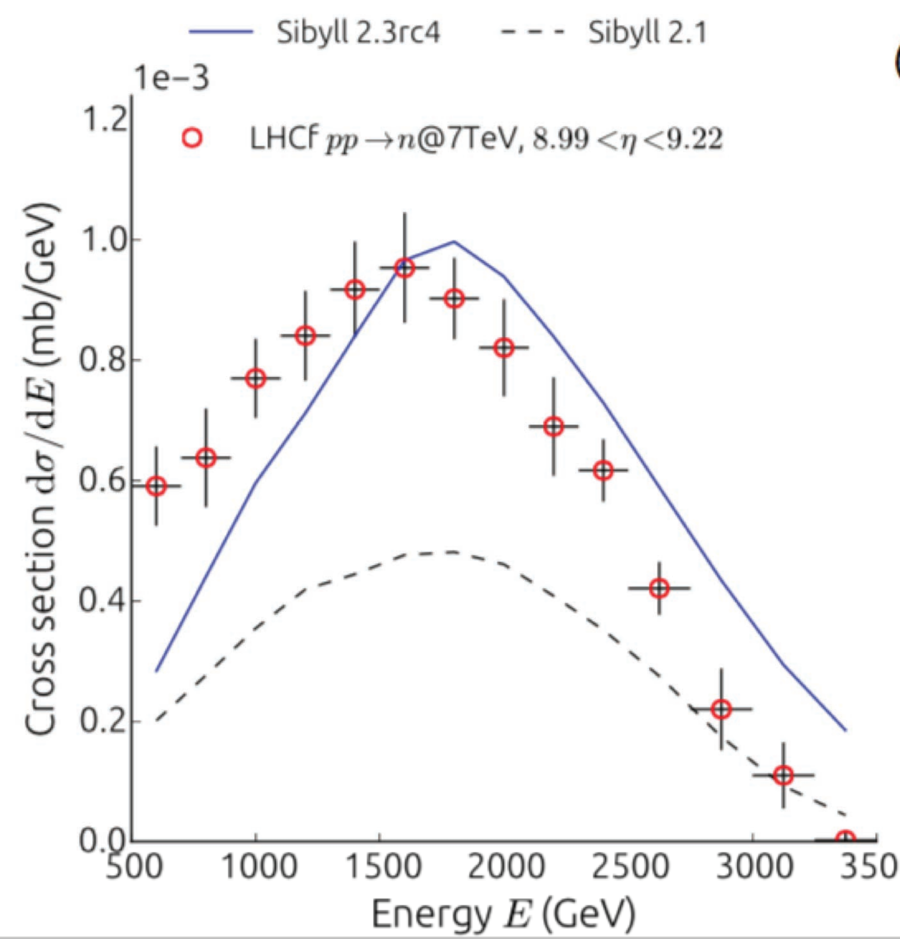
But not everything is perfect….





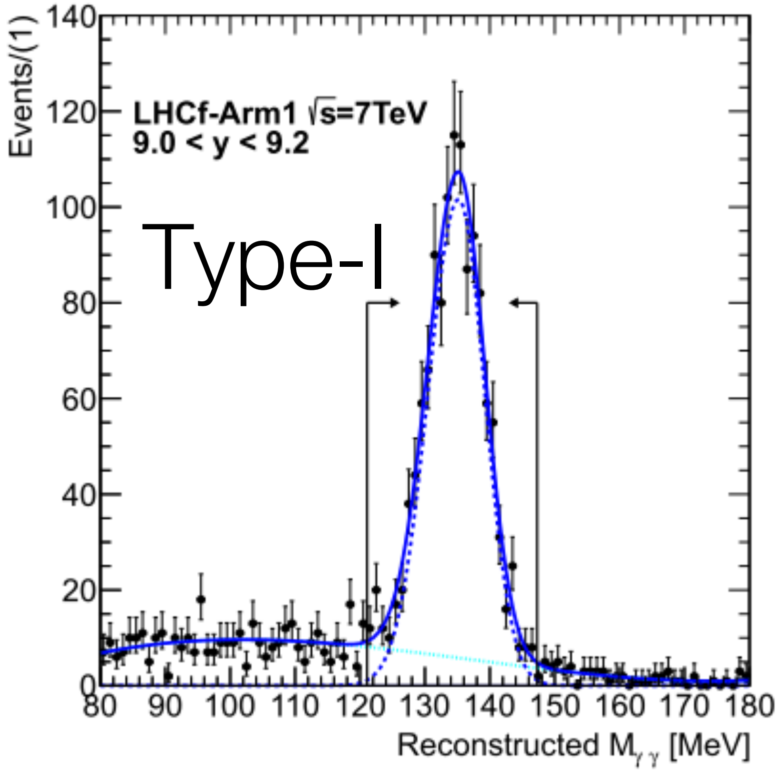
(Pierog 2014)

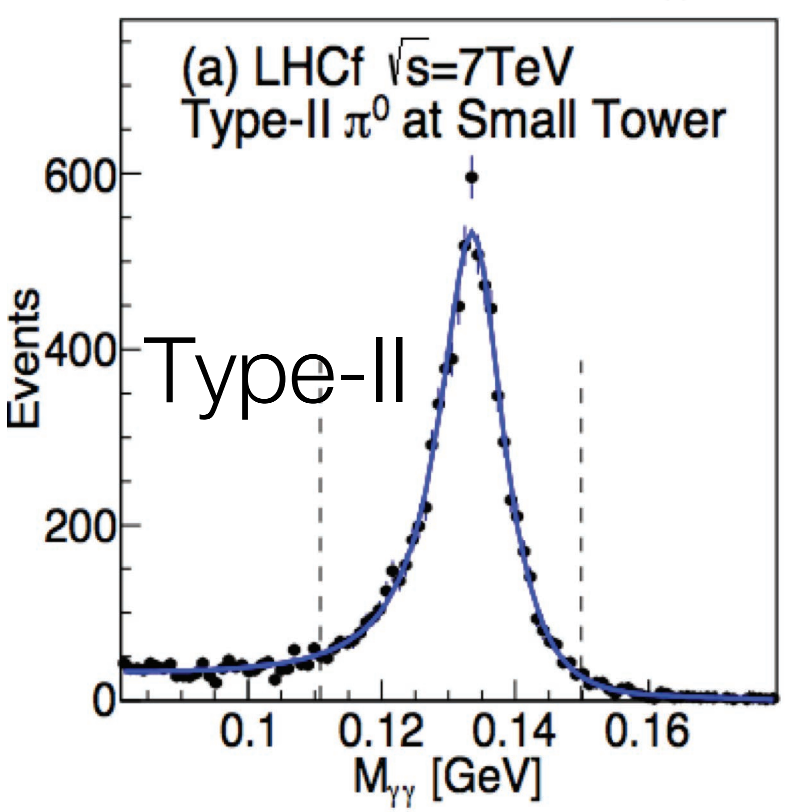


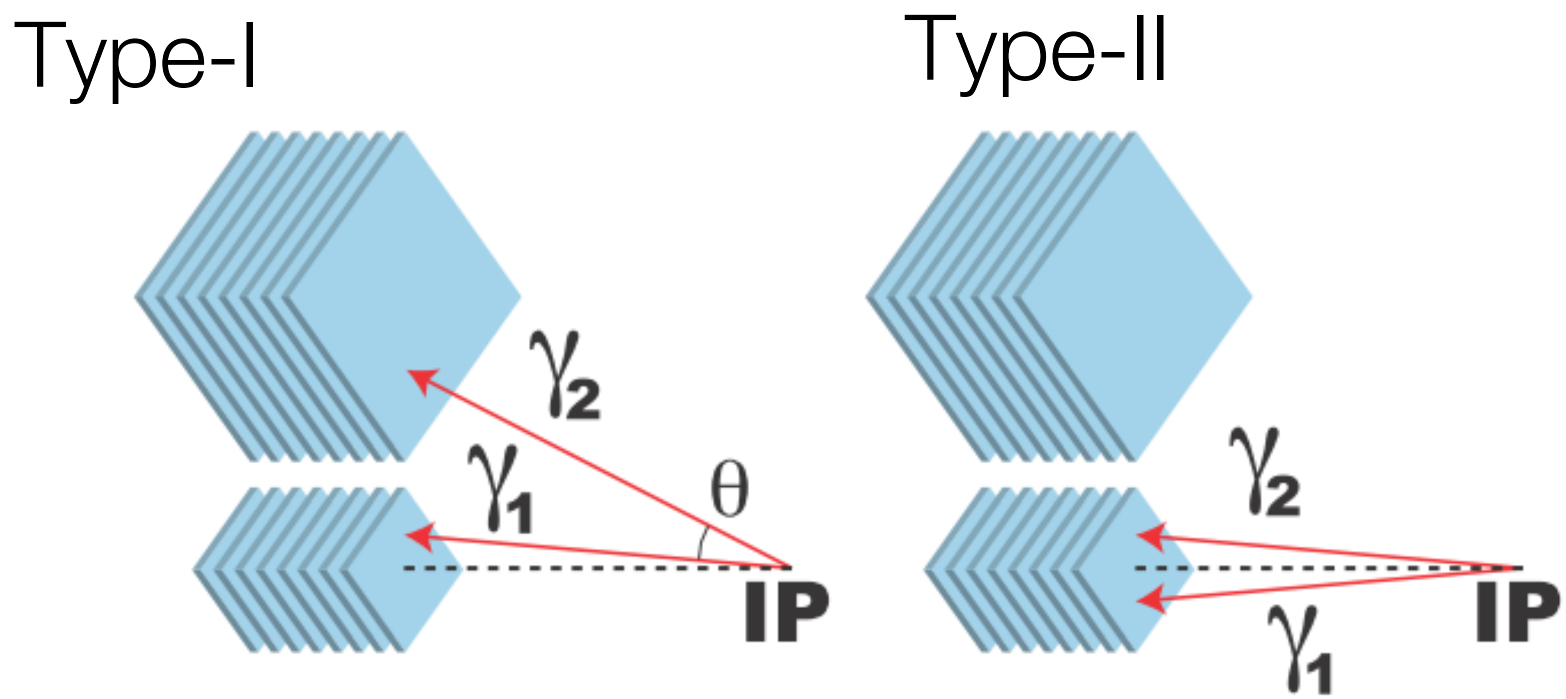


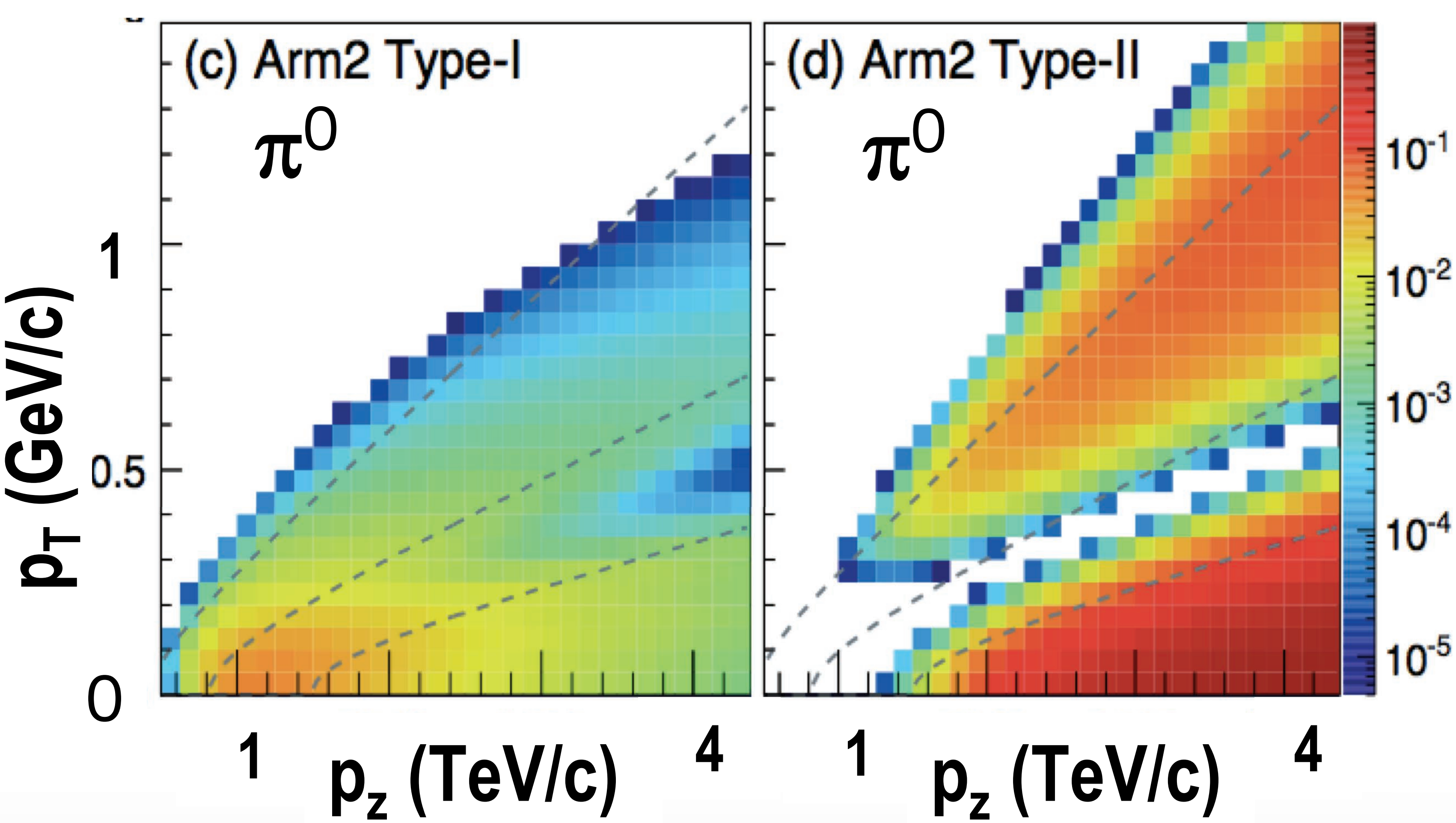
(Riehn 2015)

LHCf π^0 results: improvement @ 7 TeV

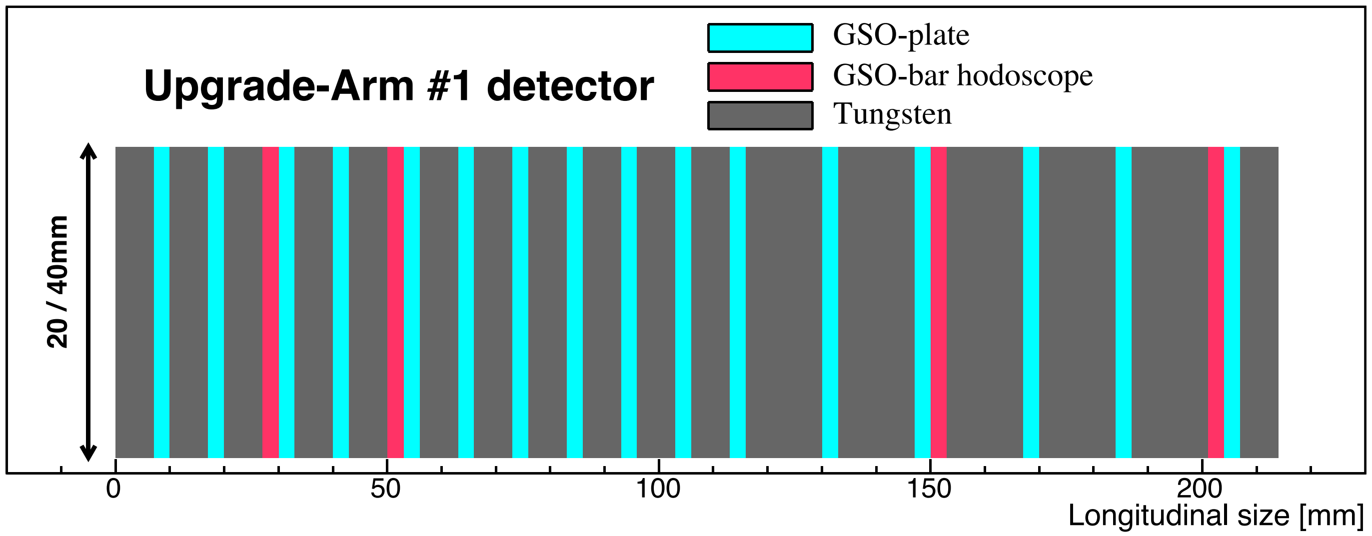




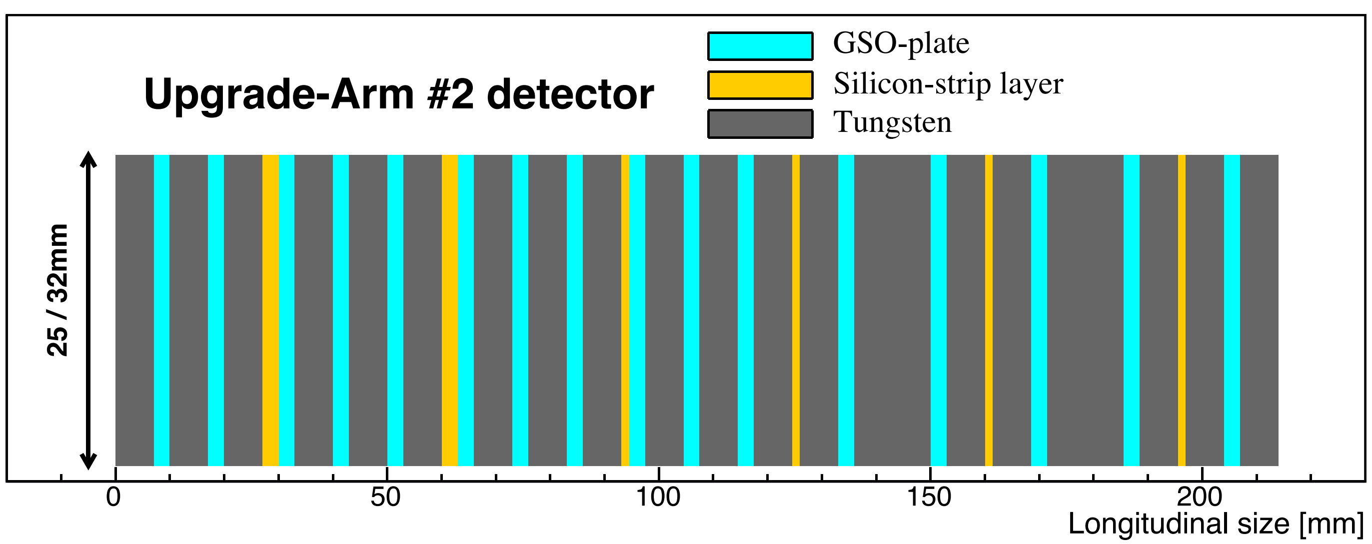




LHCf @ 13 TeV



(a) Arm1

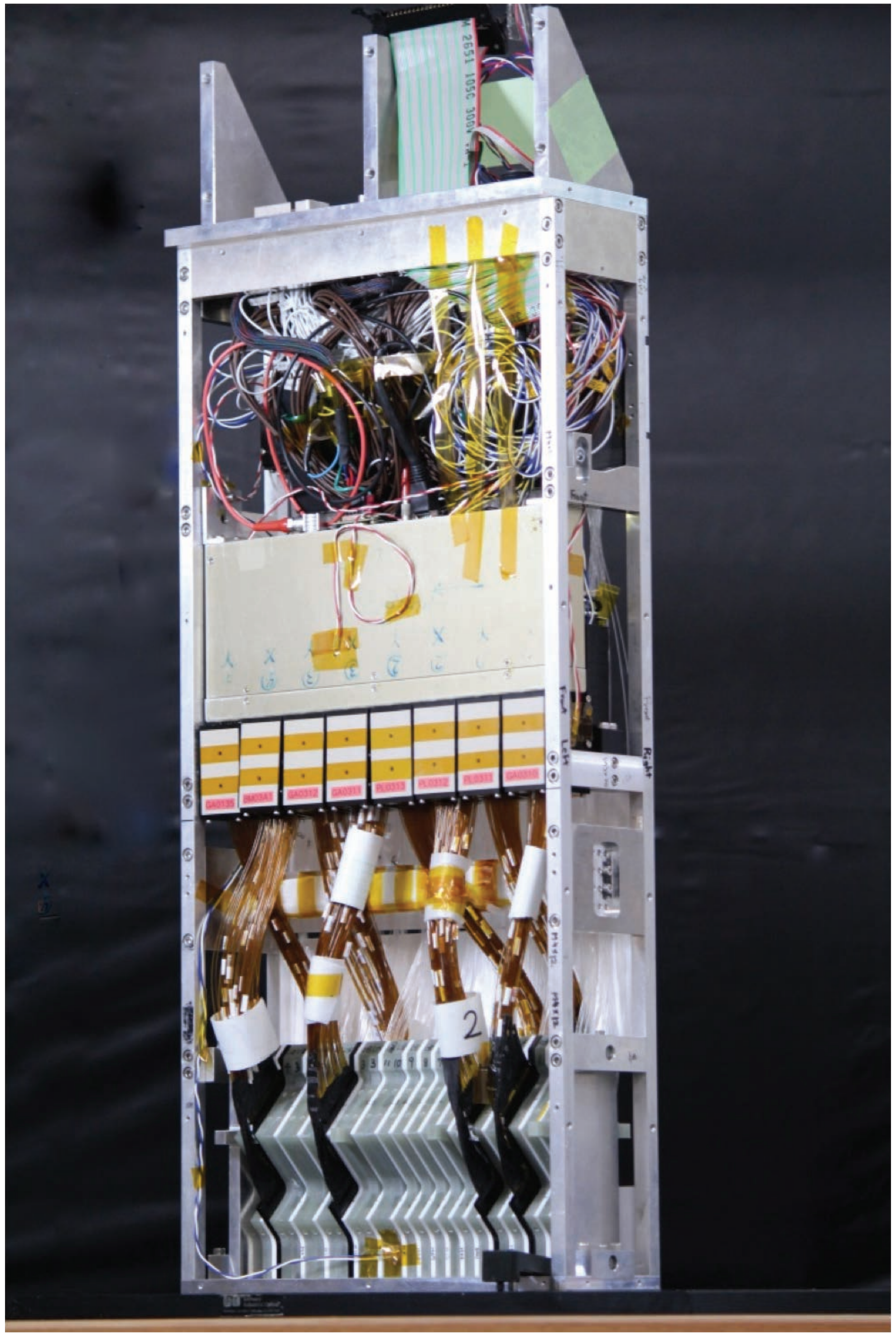


(b) Arm2

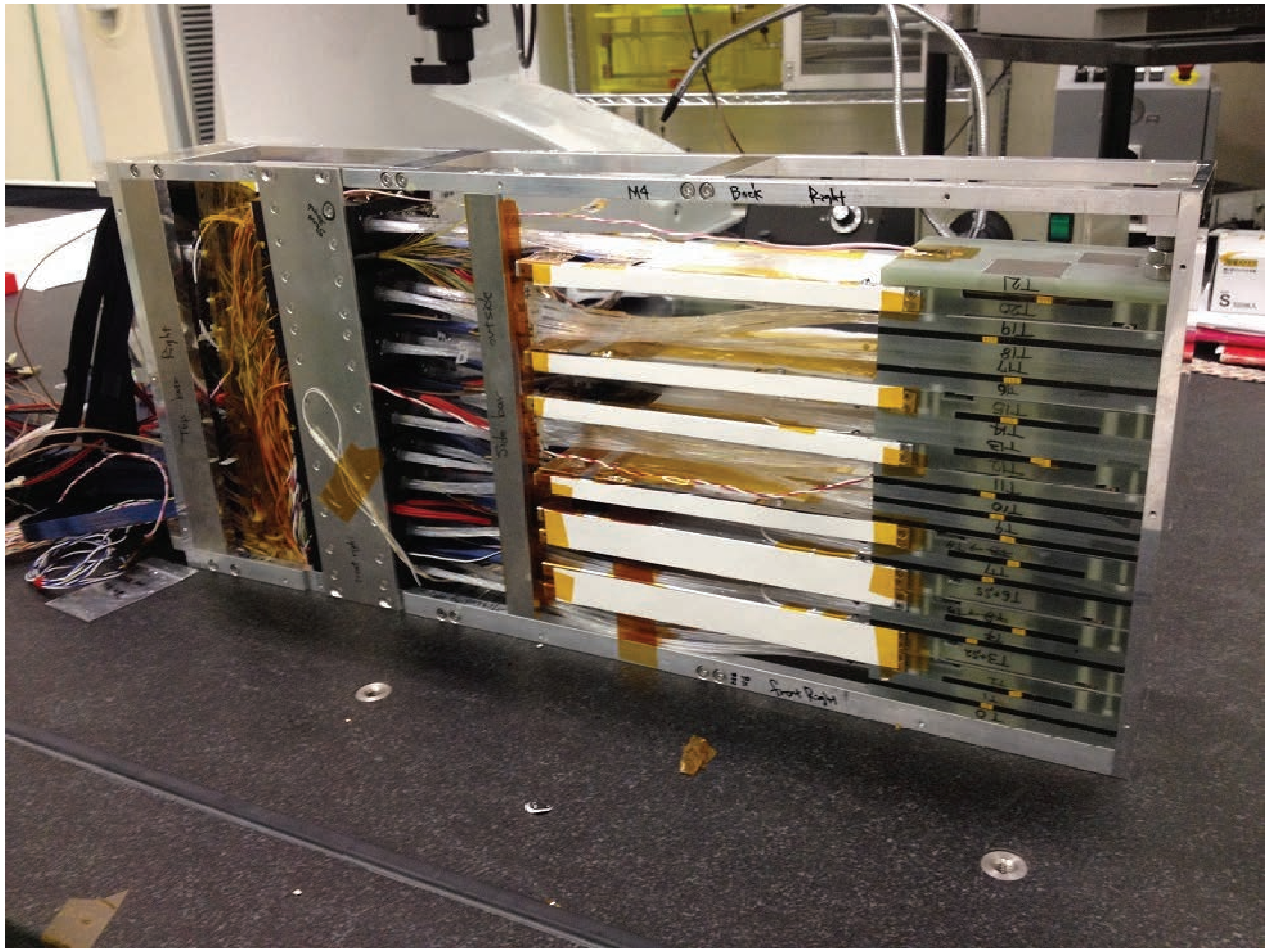
- Sampling layers
  - EJ-260 is replaced with GSO
  - 3mm (EJ-260) -> 1mm (GSO)
- Position sensitive layers
  - Arm1
    - SciFi is replaced with GSO-bar hodoscope
  - Arm2
    - Longitudinal configuration is changed
    - Grounding for not-used strips

LHCf at 13 TeV

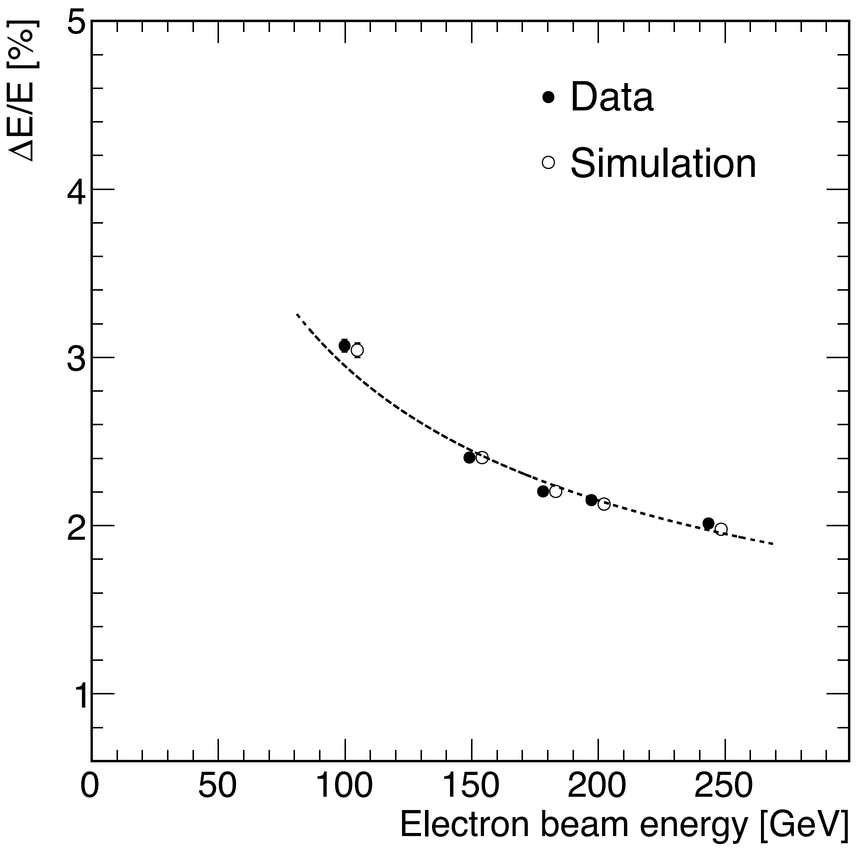
Arm1



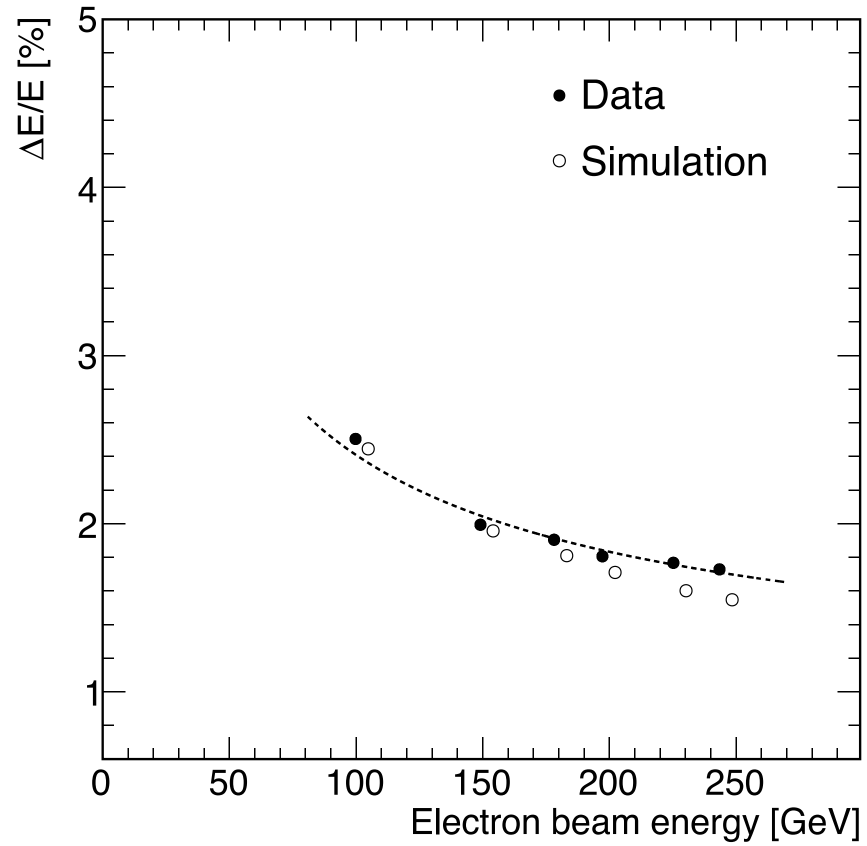
Arm2



Performance of the upgraded detector

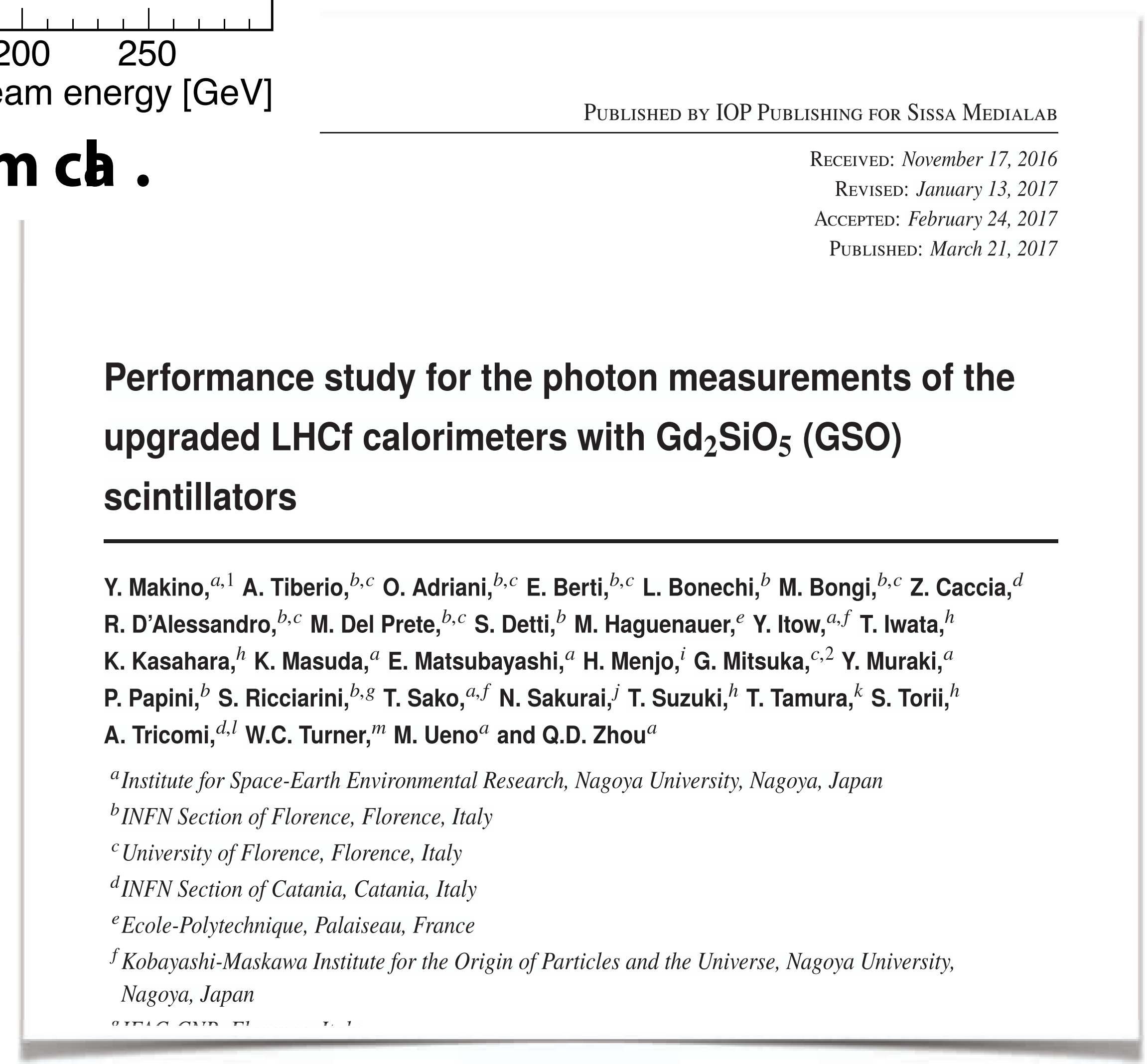


Arm1 20mm cal.



Arm2 25mm cal.

JN ST 12 P030023 (2017)



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Performance study for the photon measurements of the upgraded LHCf calorimeters with Gd_2SiO_5 (GSO) scintillators

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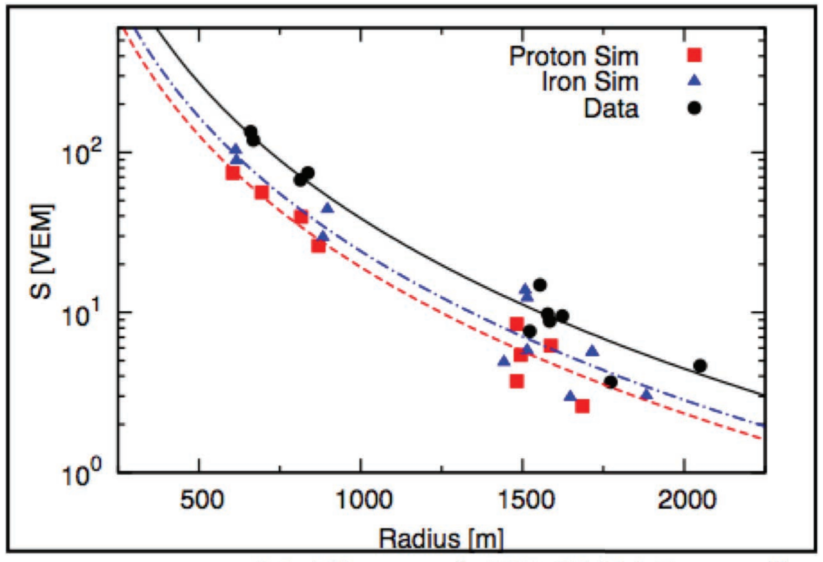
[f] *Kobayashi-Maskawa Institute for the Origin of Particles and the Universe, Nagoya University, Nagoya, Japan*

LHCf neutron analysis: motivations

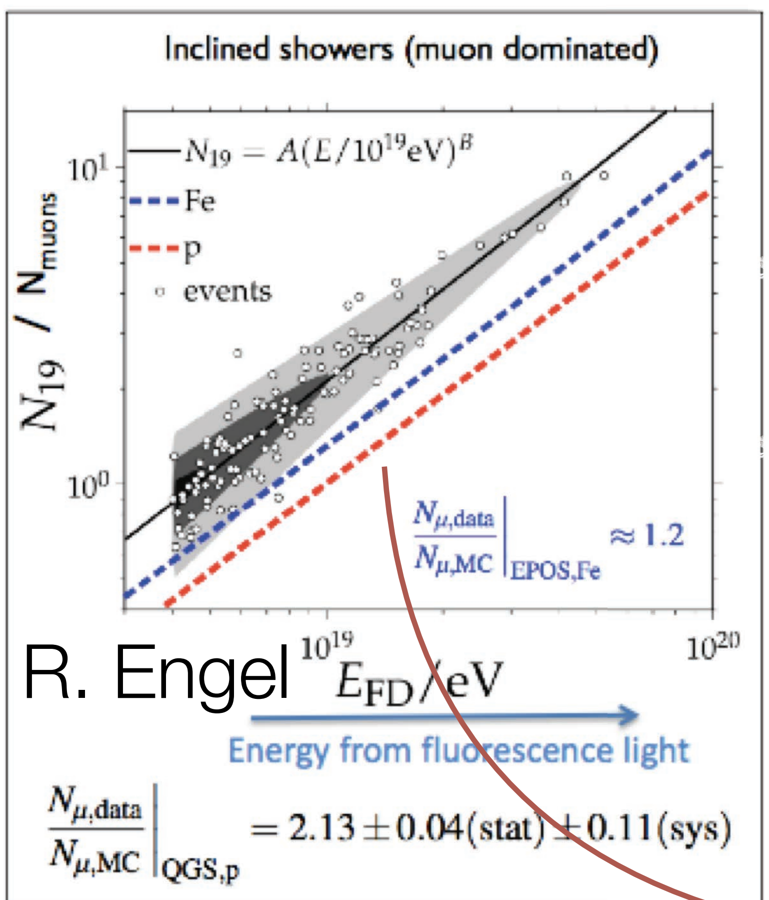
Inelasticity measurement $k=1-p_{leading}/p_{beam}$

Muon excess at Pierre Auger Observatory

- cosmic rays experiment measure PCR energy from muon number at ground and florescence light
- 20-100% more muons than expected have been observed



[J.Allen, et al. ICRC2011 Proceedings]

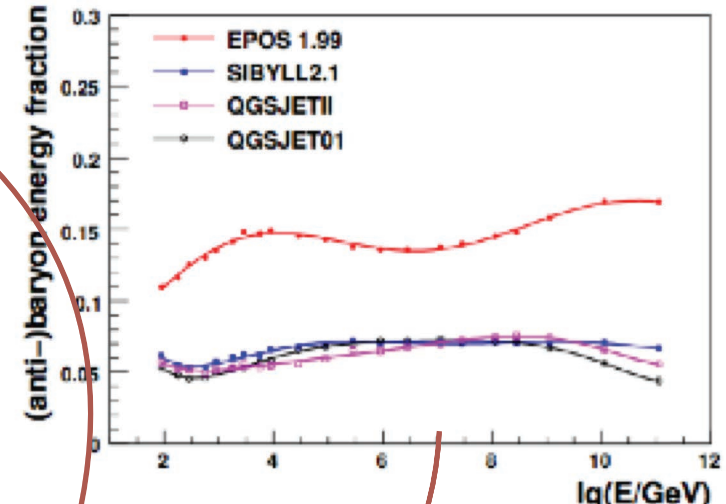


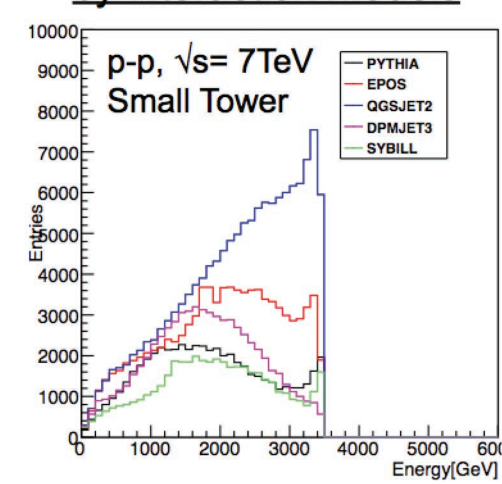
R. Engel

Number of muons depends on the energy fraction of produced hadron

Muon excess in data even for Fe primary MC

EPOS predicts more muon due to larger baryon production

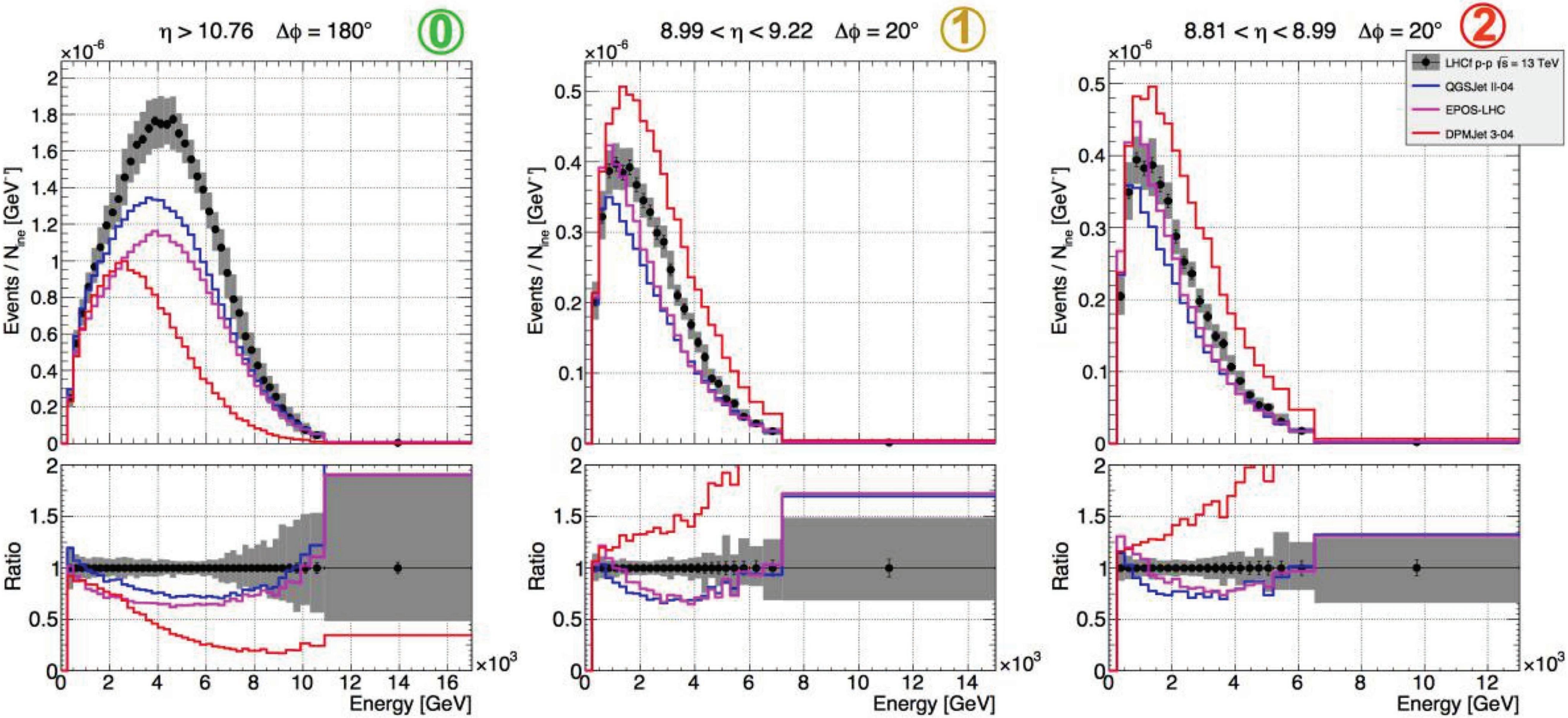




importance of baryon measurement

Reconstructed ARM2 hadron energy spectra

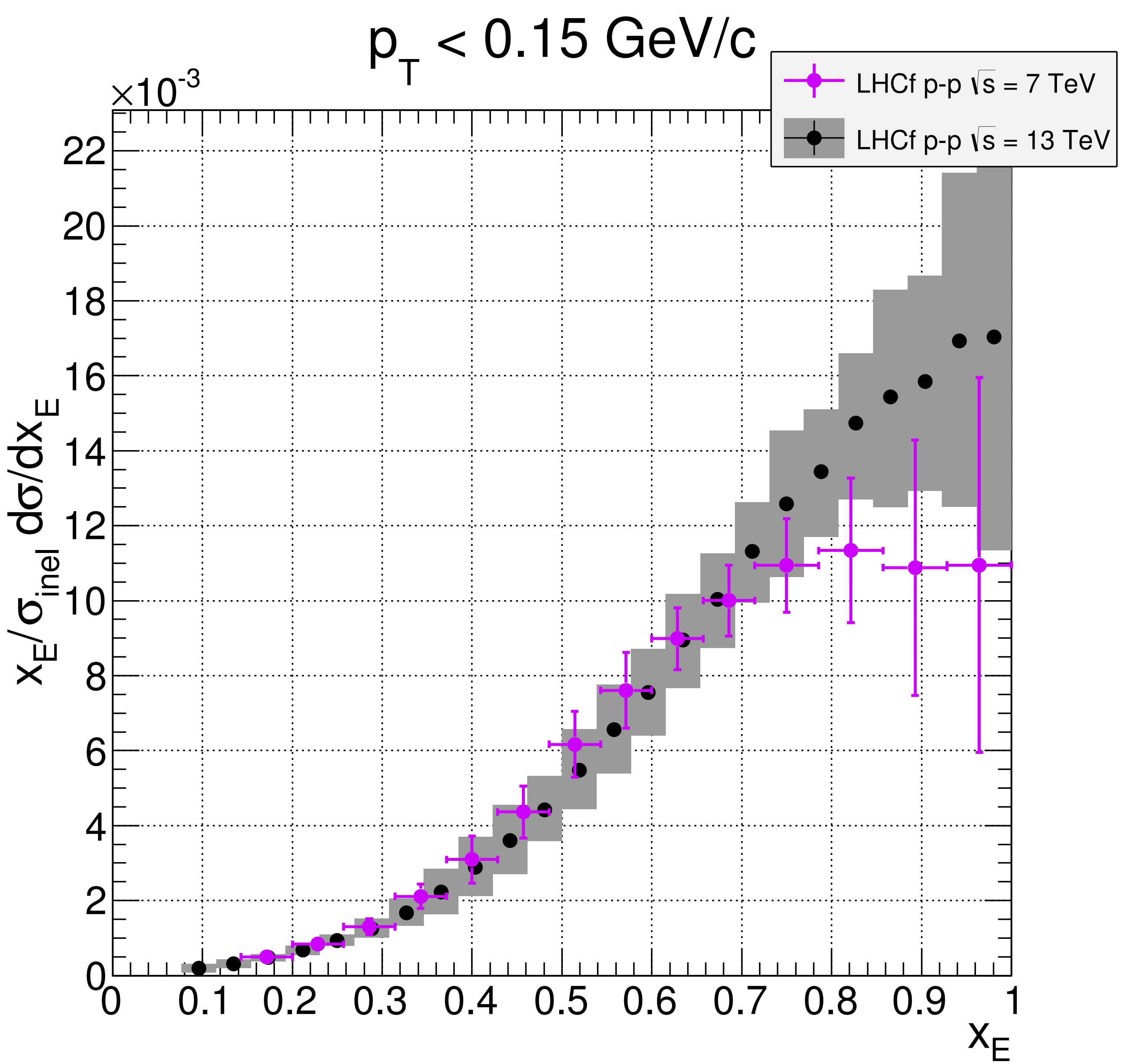
Events / N_{ine} / dE



QGSJET II-04 and **EPOS-LHC** have similar shape but lower yield

DPMJET 3.04 have very different shape and yield

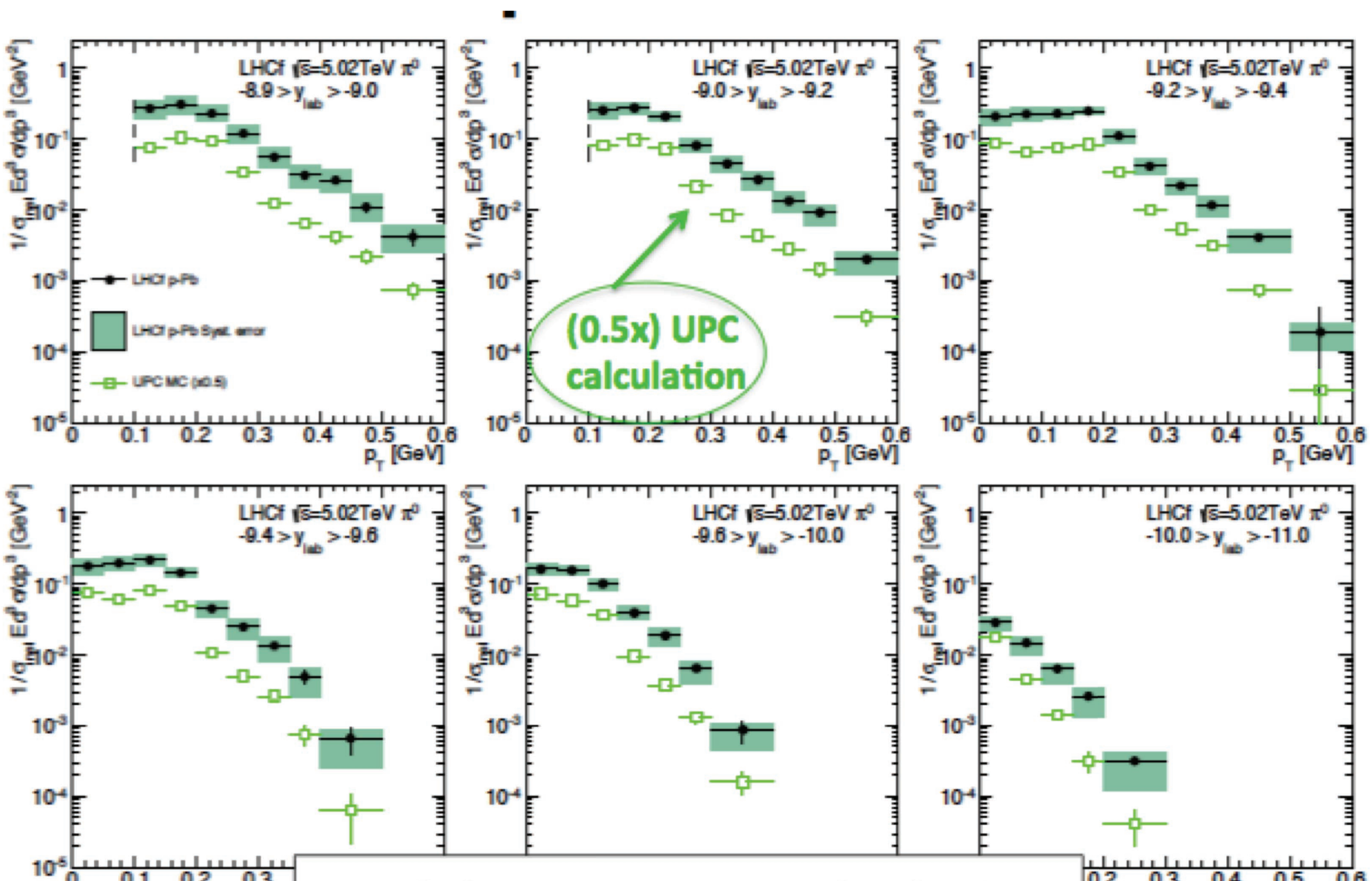
Feynman scaling in neutron production cross-section



Feynman scaling hypothesis holds within the error bars

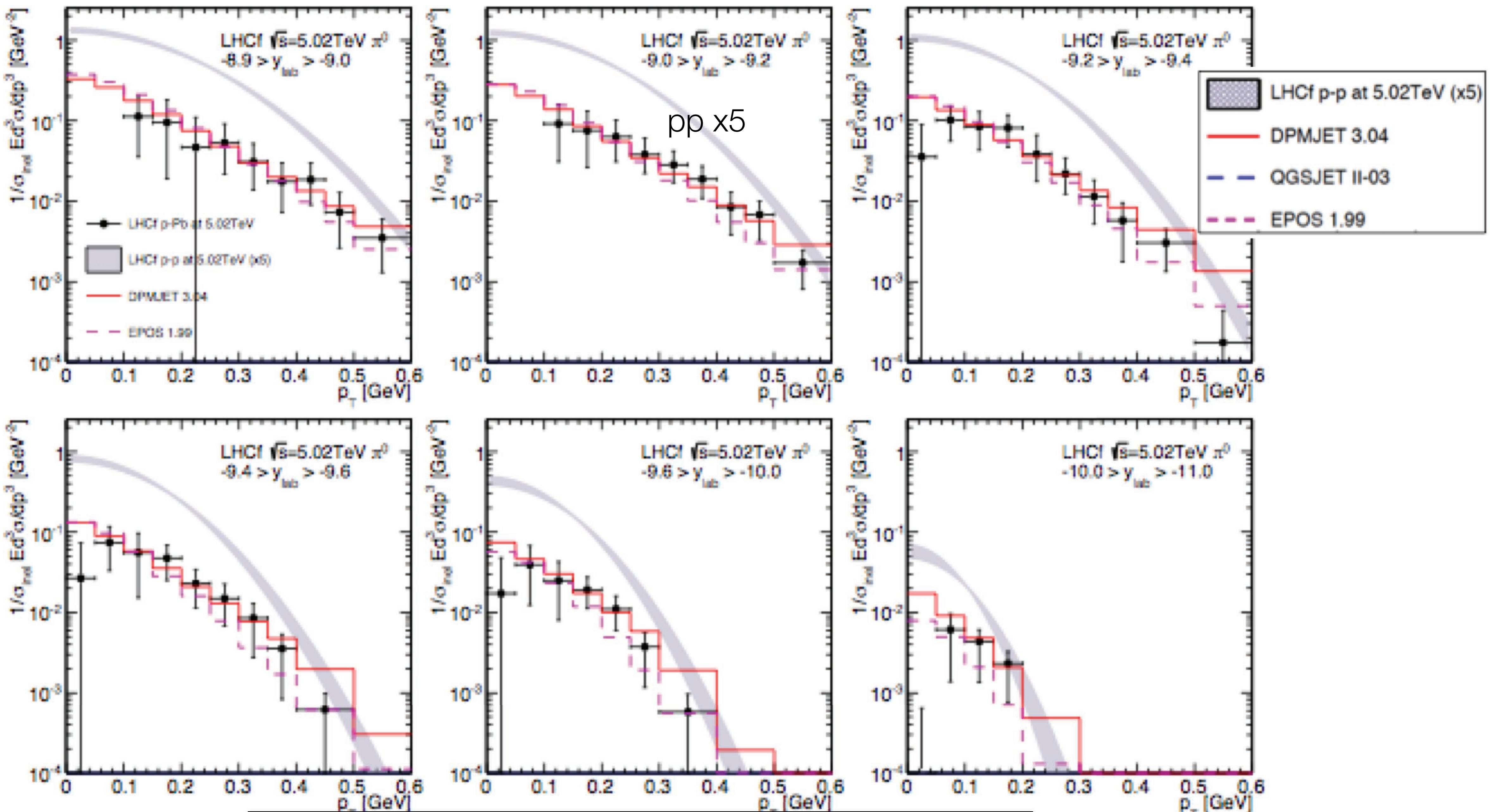
Consistency is good especially in the region $0.2 < x_F < 0.75$

LHCf @ pPb 5.02 TeV: π^0 spectra @ p-remnant side



LHCf data vs. UPC calculation

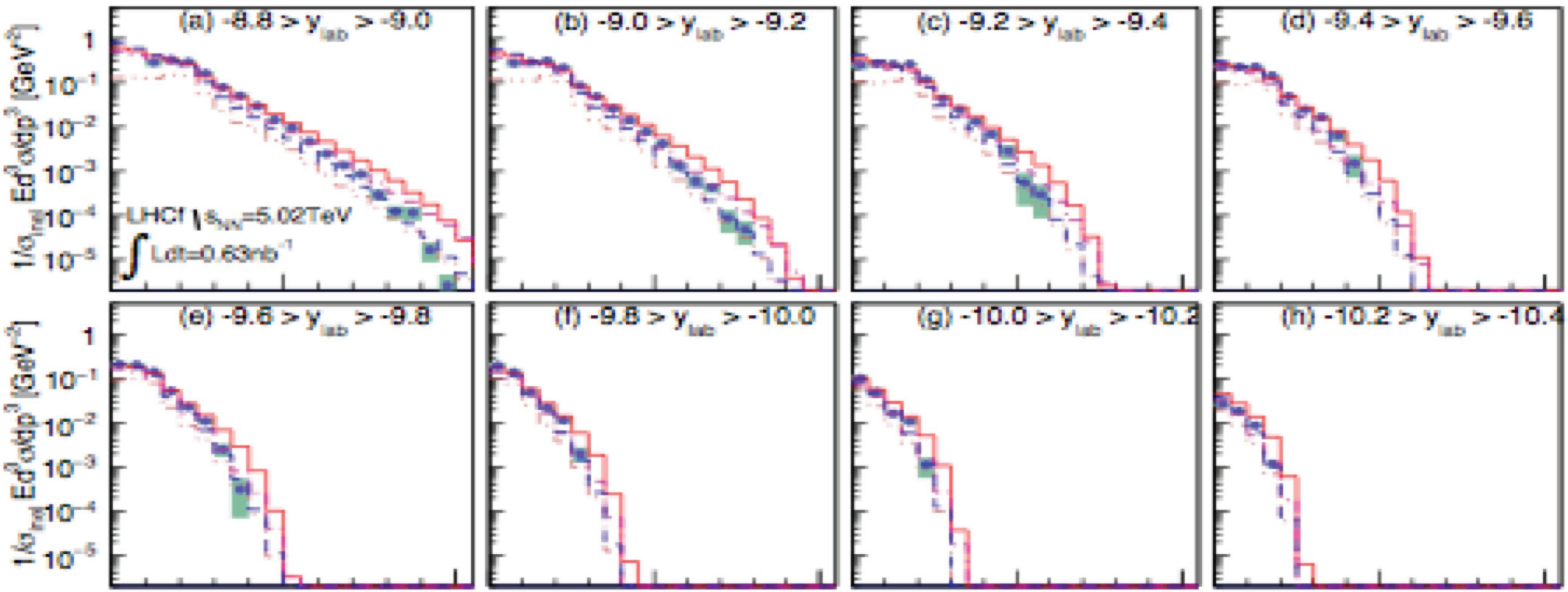
LHCf @ pPb 5.02 TeV: π^0 spectra @ p-remnant side

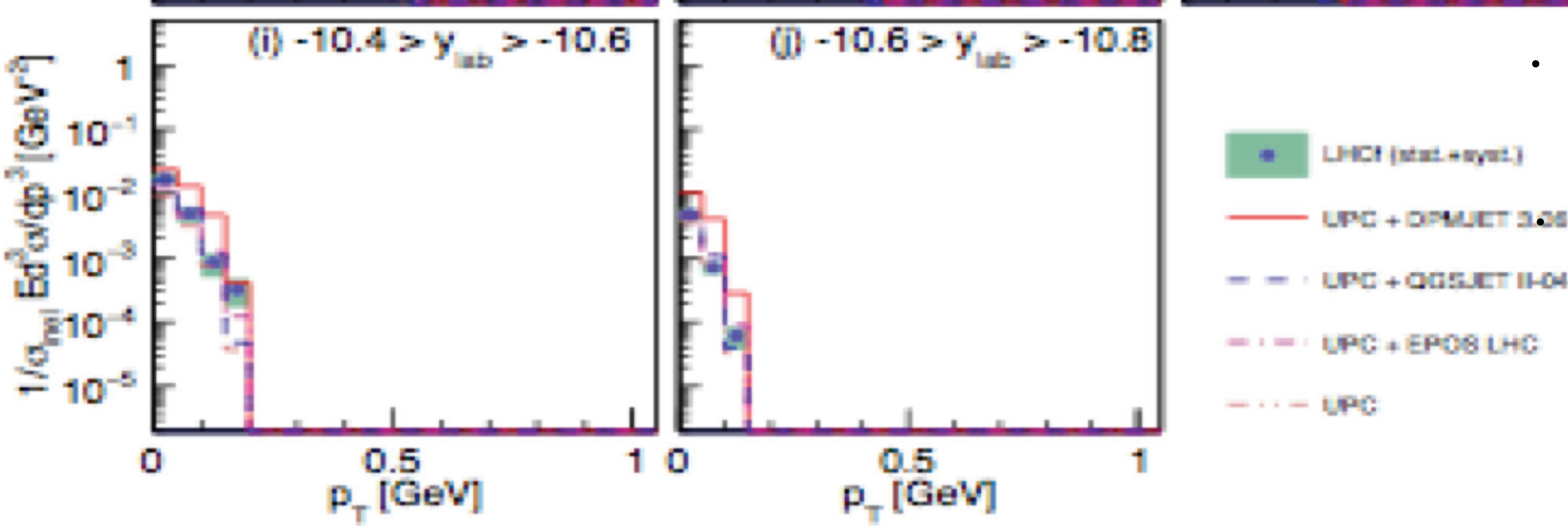


LHCf Data (UPC subtracted) vs Models

- The LHCf results in p-Pb (filled circles) show good agreement with DPMJET and EPOS.
- The LHCf results in p-Pb are clearly harder than the LHCf results in p-p at 5.02TeV (shaded area) which are interpolated from the results at 2.76TeV and 7TeV.

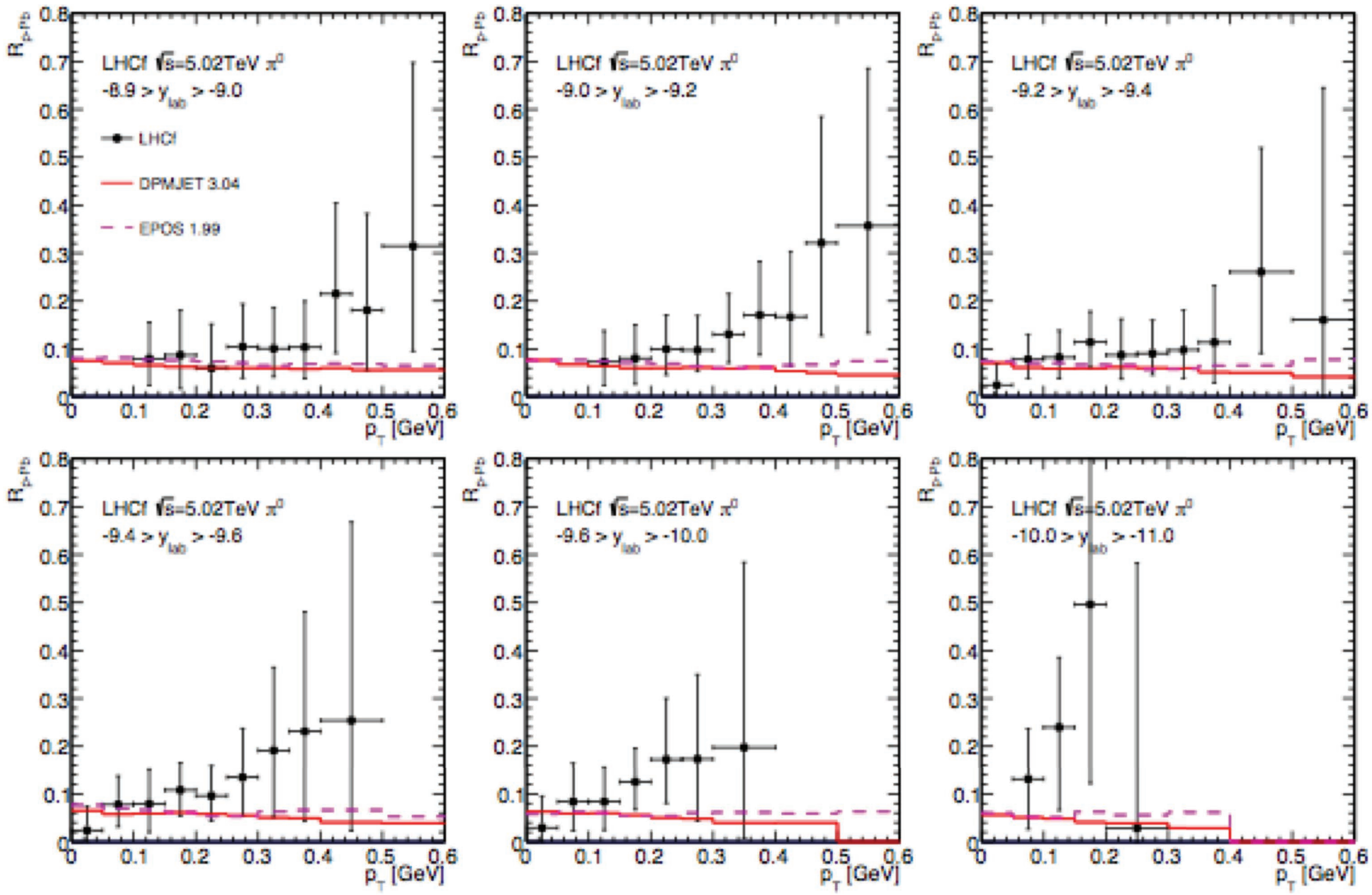
LHCf @ pPb 5.02 TeV: π^0 p_T spectra





- QGSJETII-04 and EPOS-LHC: similar, good agrement for pT>0.4 GeV
- DPMJET: good agreement for –8.8 > ylab > –10.0 and p_T < 0.3 GeV
- Characteristic bump at y > –9.6 and p_T ~ 0.2GeV: Ultra Peripheral Collisions

LHCf @ pPb 5.02 TeV:
Nuclear modification factor



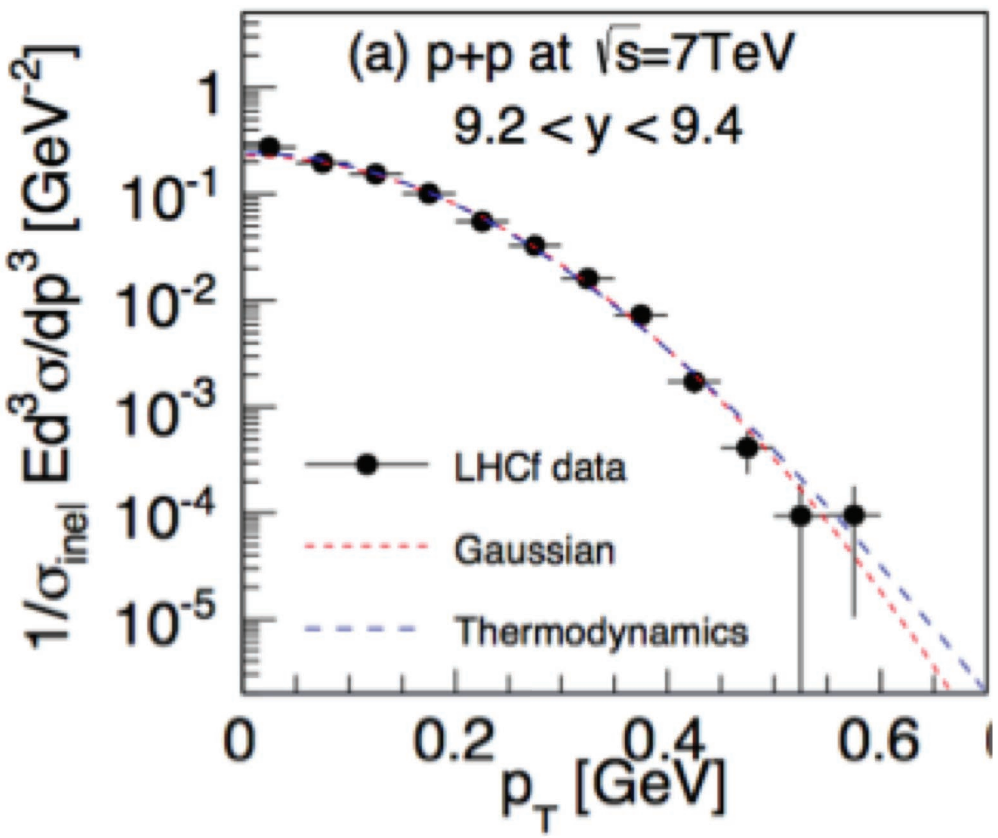
$$R_{\rm pPb}(p_{\rm T}) \equiv \frac{d^2N^{\rm pPb}_{\pi^0}/dydp_{\rm T}}{\langle N_{\rm coll}\rangle d^2N^{\rm pp}_{\pi^0}/dydp_{\rm T}}$$

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

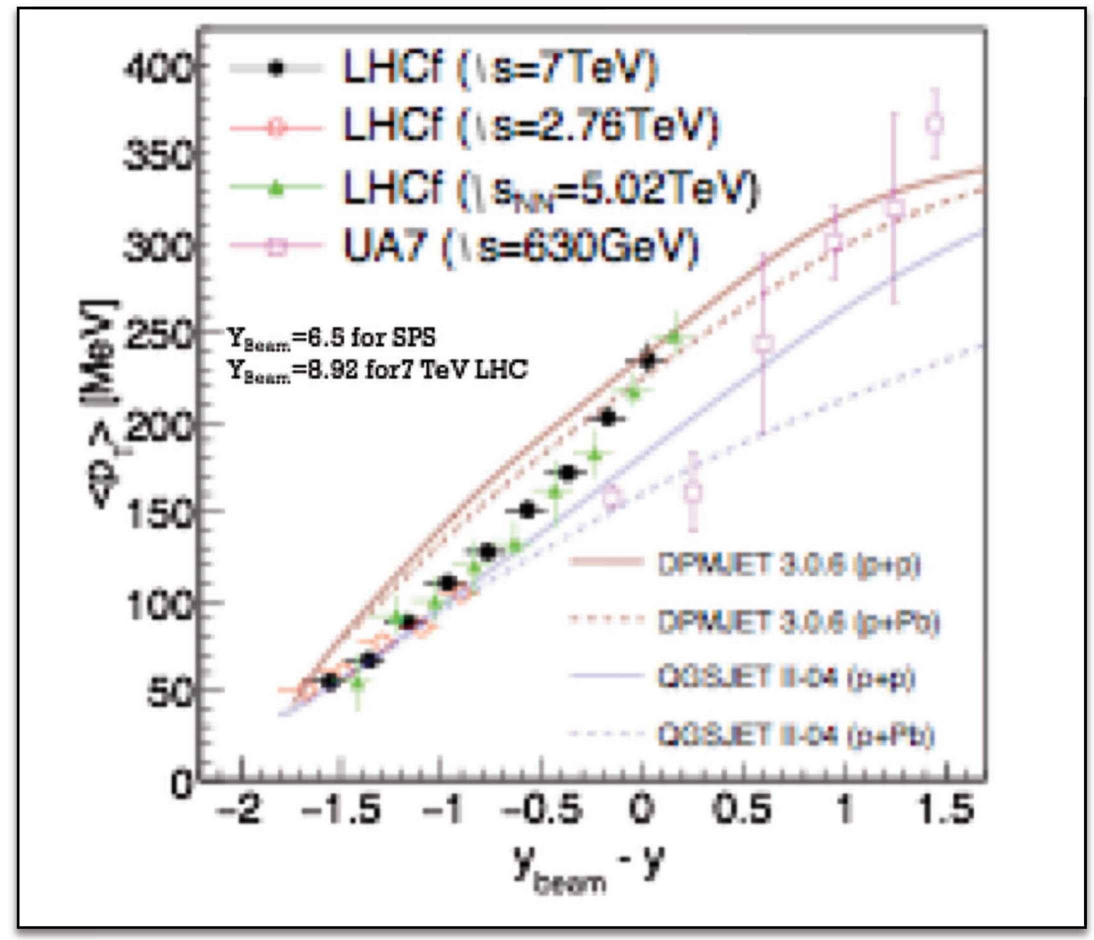
Both LHCf and MCs show strong suppression
But LHCf grows as increasing p_T, understood by the softer p_T spectra in p-p at 5TeV than those in p-Pb.

π^0 average p_T for different cm energies

p_T spectra vs best-fit function



Average p_T vs y_{lab}



$<p_T>$ is inferred in 3 ways:

1. Thermodynamical approach
2. Gaussian distribution fit
3. Numerical integration up to the histogram upper bound

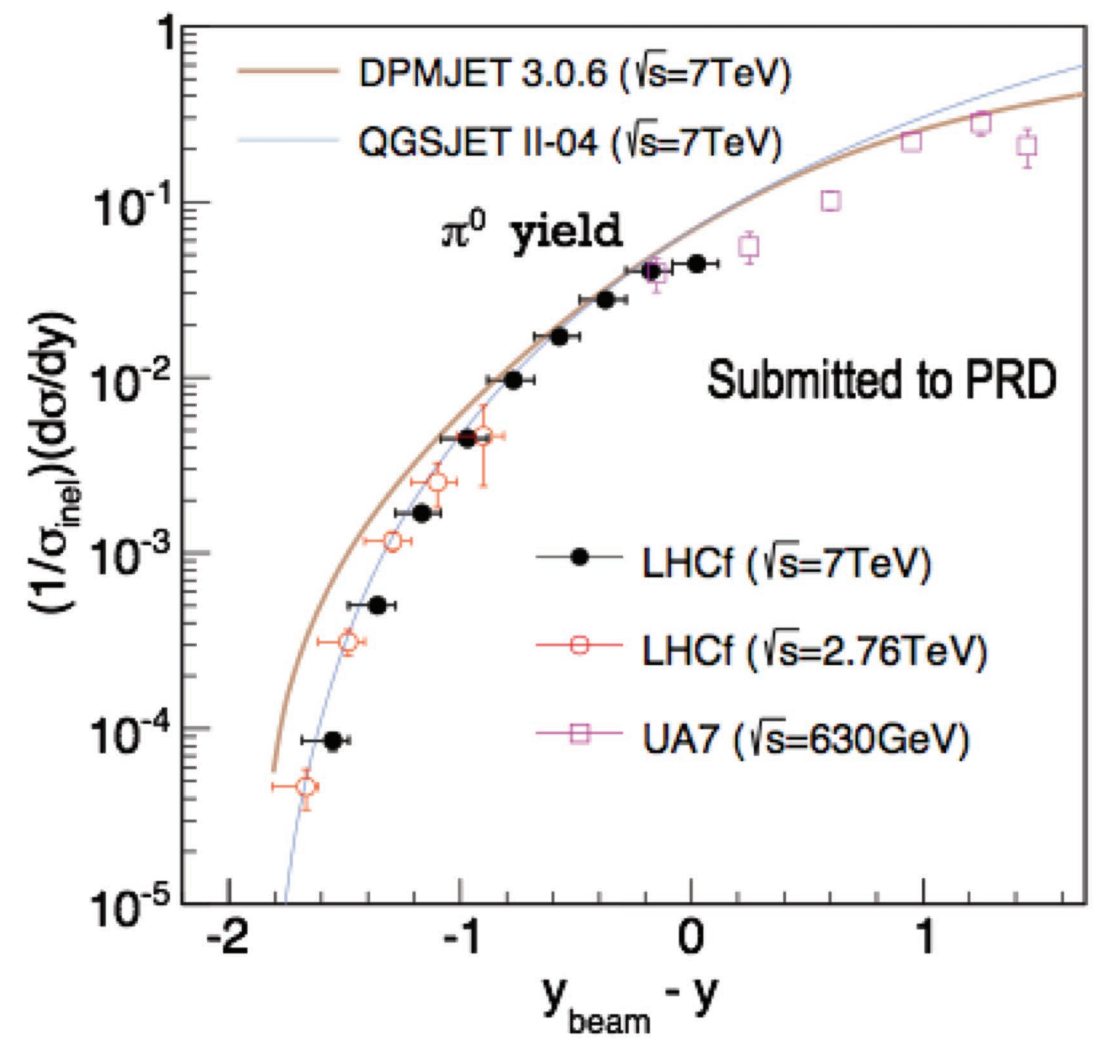
From scaling considerations (projectile fragmentation region) we can expect that $<p_T>$ vs rapidity loss should be independent from the c.m. energy

Reasonable scaling can be inferred from the data

Limiting fragmentation in forward π^0 production

Limiting fragmentation hypothesis: rapidity distribution of the secondary particles in the forward rapidity region (target's fragment) should be independent of the center-of-mass energy.

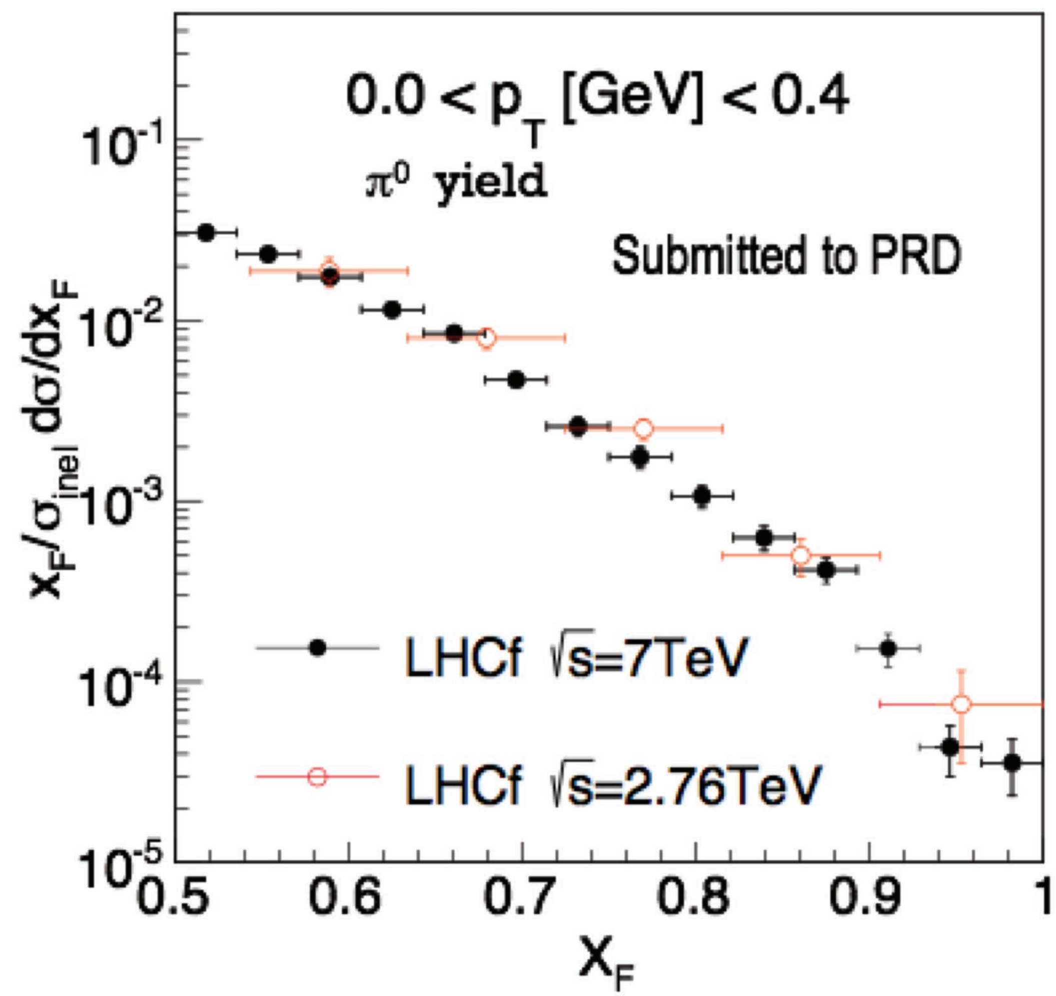
This hypothesis for π^0 is true at the level of ±15%



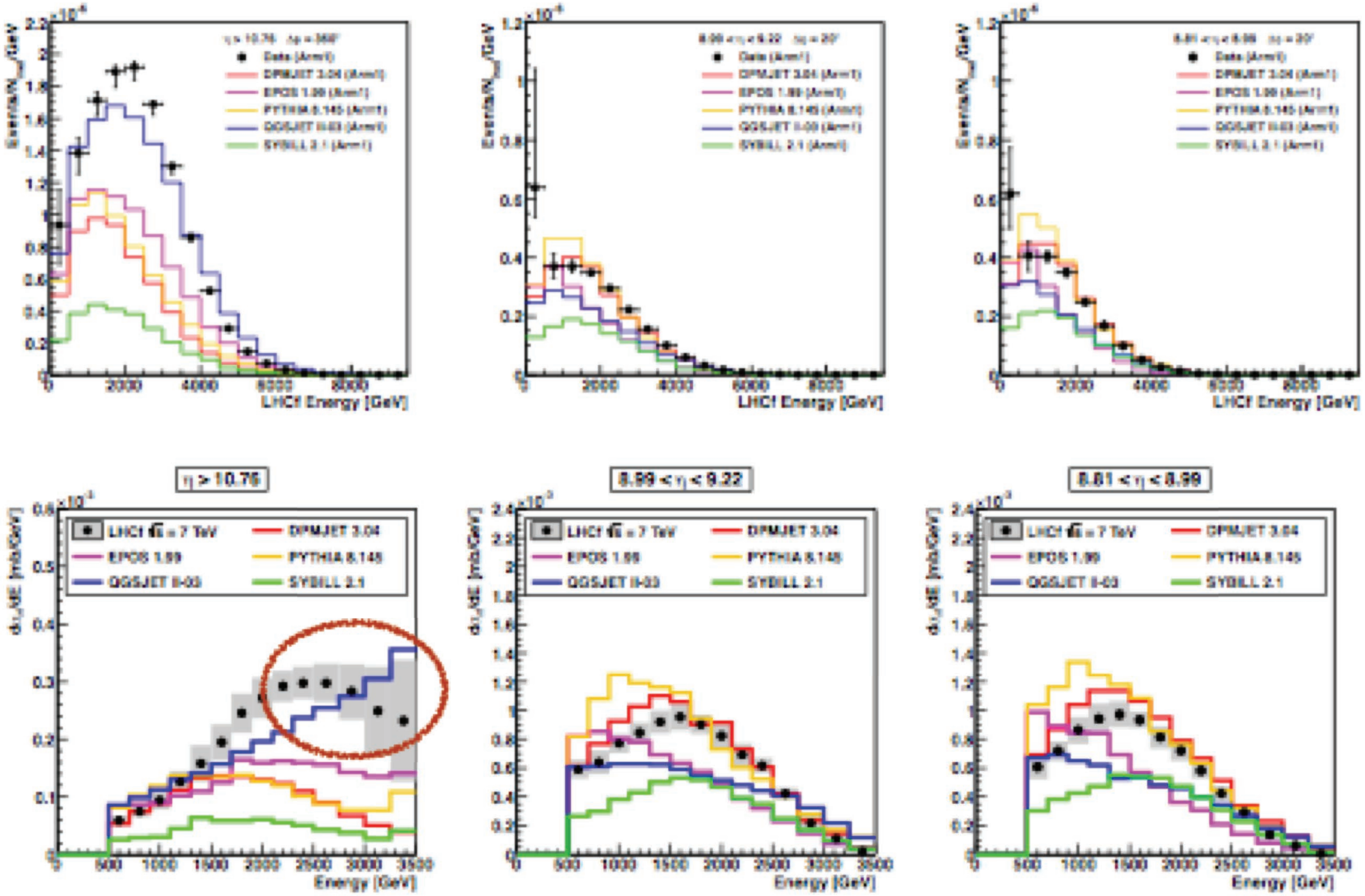
Feynman scaling in forward π^0 production

Feynman scaling hypothesis:
cross sections of secondary particles as a function of $x_F \equiv 2p_z/\sqrt{s}$ are independent from the incident energy in the forward region ($x_F > 0.2$).

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



LHCf @ pp 7 TeV: neutron spectra



n/γ ratio

Data (η>10.76)	3.05±0.19
DPMJET3.04	1.05
EPOS 1.99	1.80
PYTHIA 8.145	1.27
QGSJET II-03	2.34
SYBILL 2.1	0.88

Data (8.99<η<9.22)	1.26±0.08
DPMJET3.04	0.76
EPOS 1.99	0.69
PYTHIA 8.145	0.82
QGSJET II-03	0.65
SYBILL 2.1	0.57

- LHCf Arm1 and Arm2 agree with each other within systematic error, in which the energy scale uncertainty dominates.
- In η>10.76 huge amount of neutron exists. Only QGSJET2 reproduces the LHCf result.
- In other rapidity regions, the LHCf results are enclosed by the variation of models.

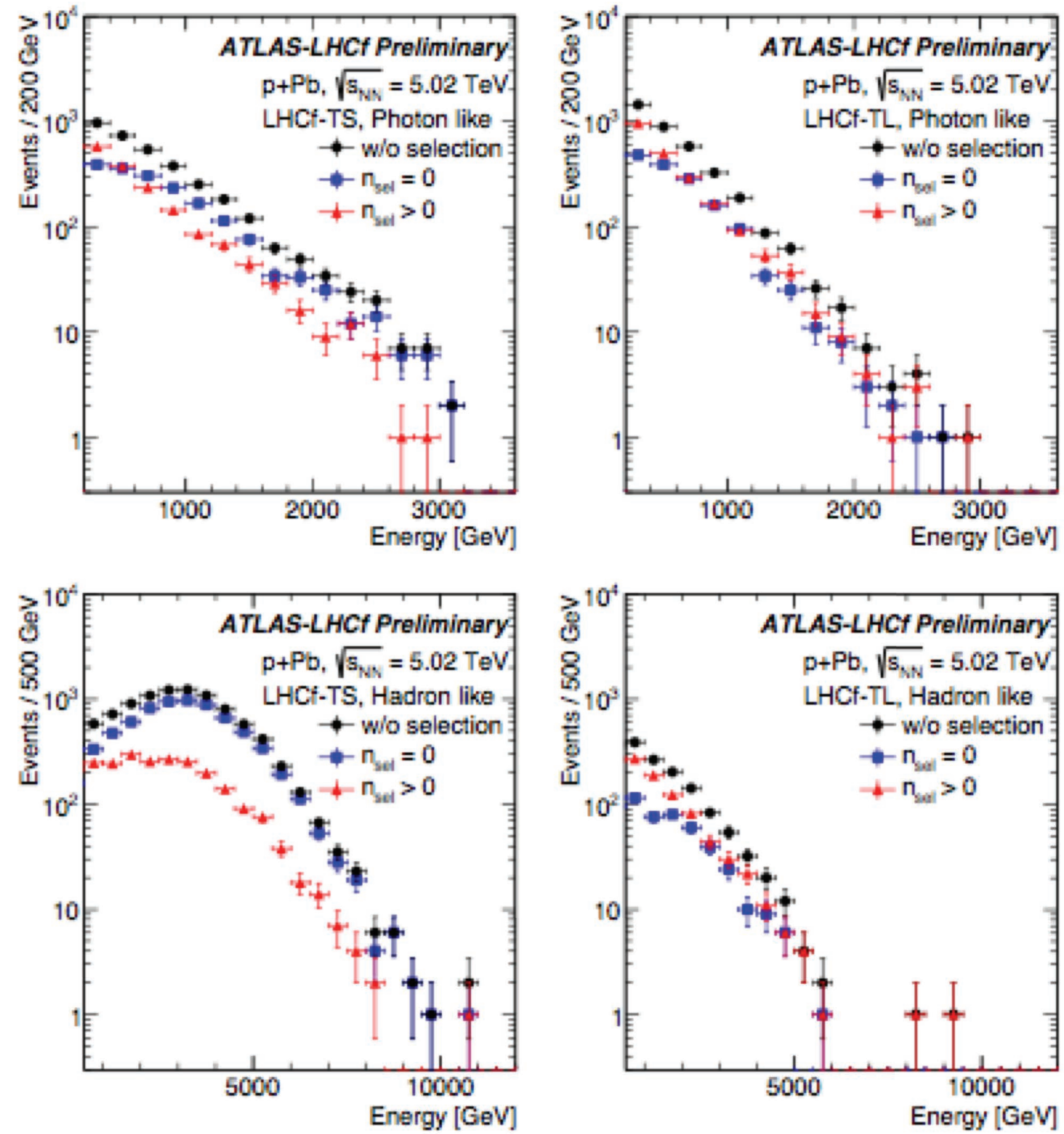
LHCf spectra in p-Pb collisions with Atlas tagging on tracks

Nsel:

number of good charged ATLAS tracks

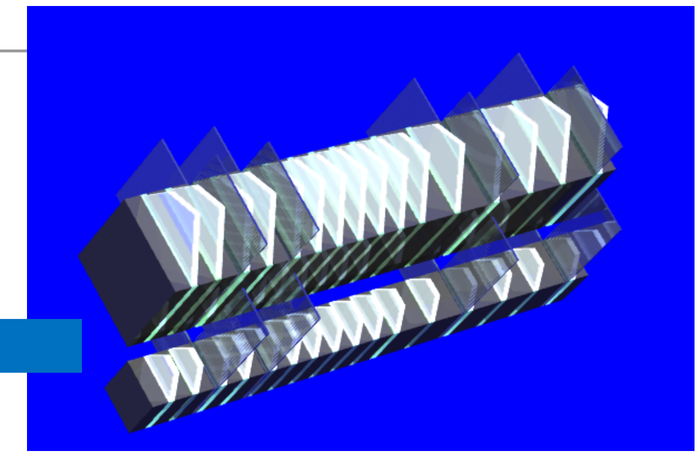
- $p_T > 100$ MeV
- vertex matching
- $|\eta| < 2.5$.

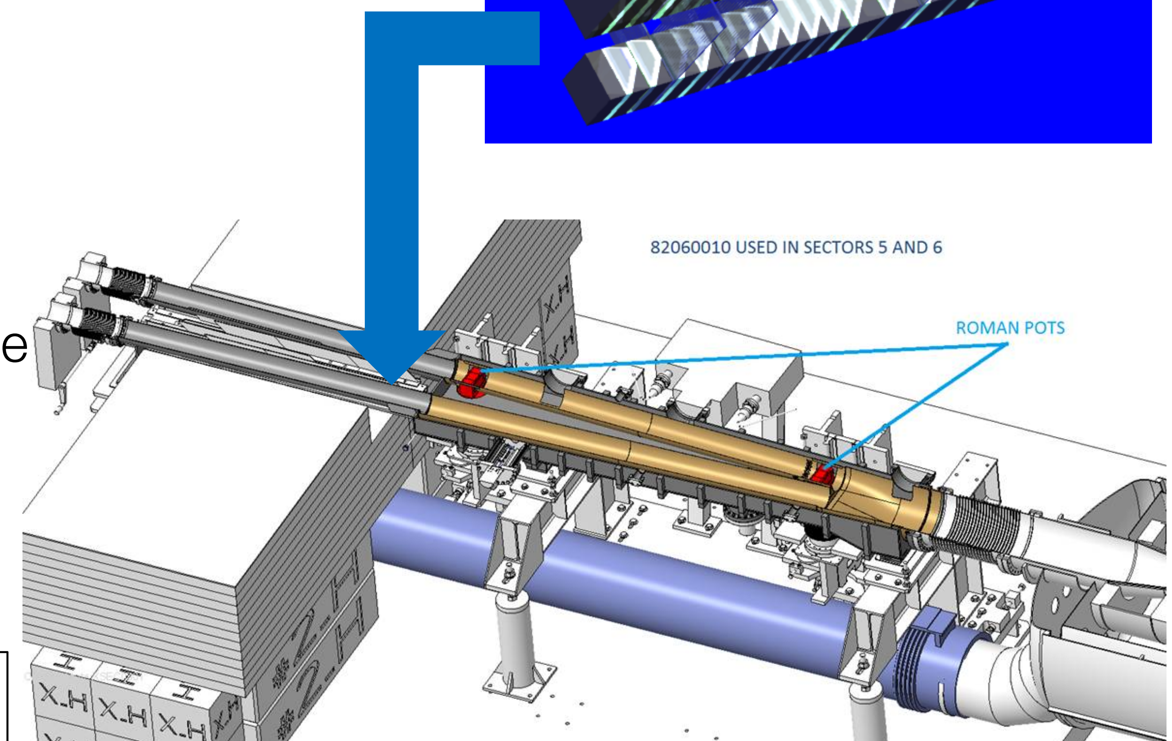
Significant UPC contribution in the very forward region with $N_{sel}=0$



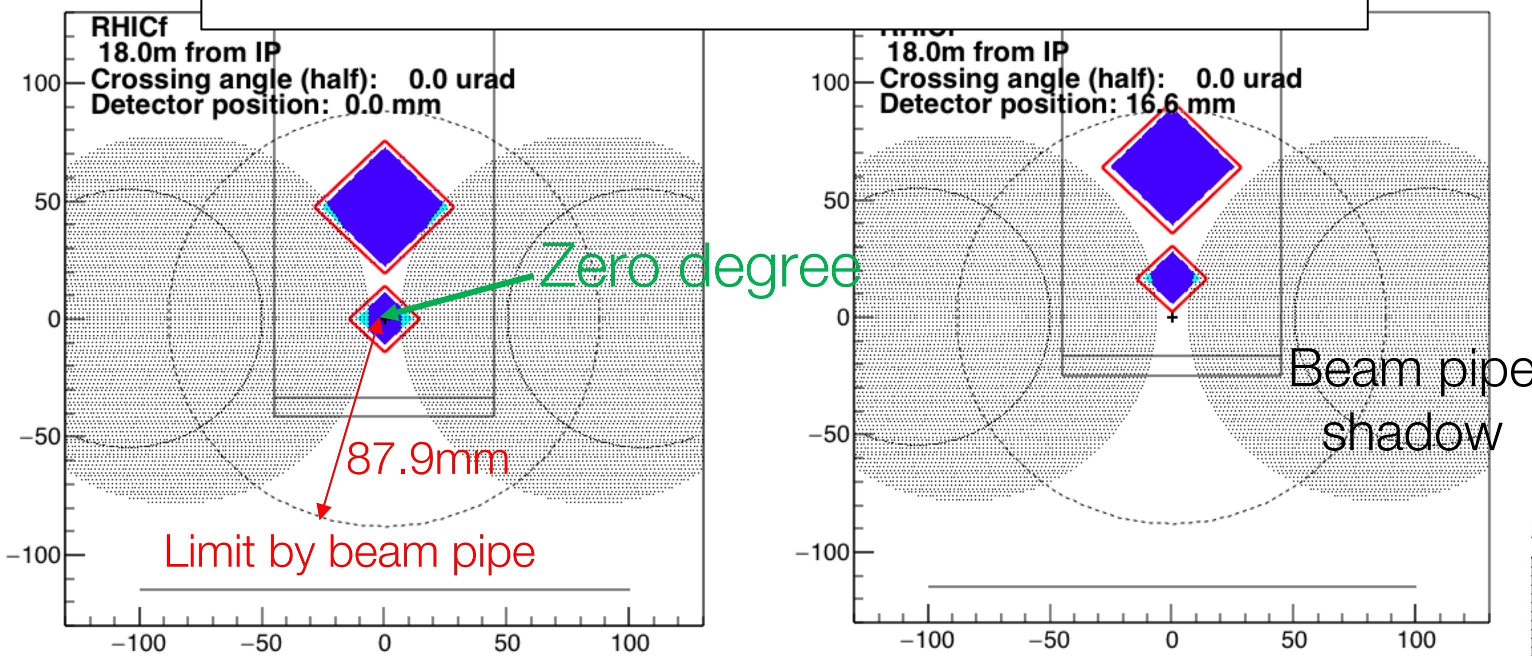
RHICf detector acceptance

Compact double calorimeters
(20mmx20mm and 40mmx40mm)

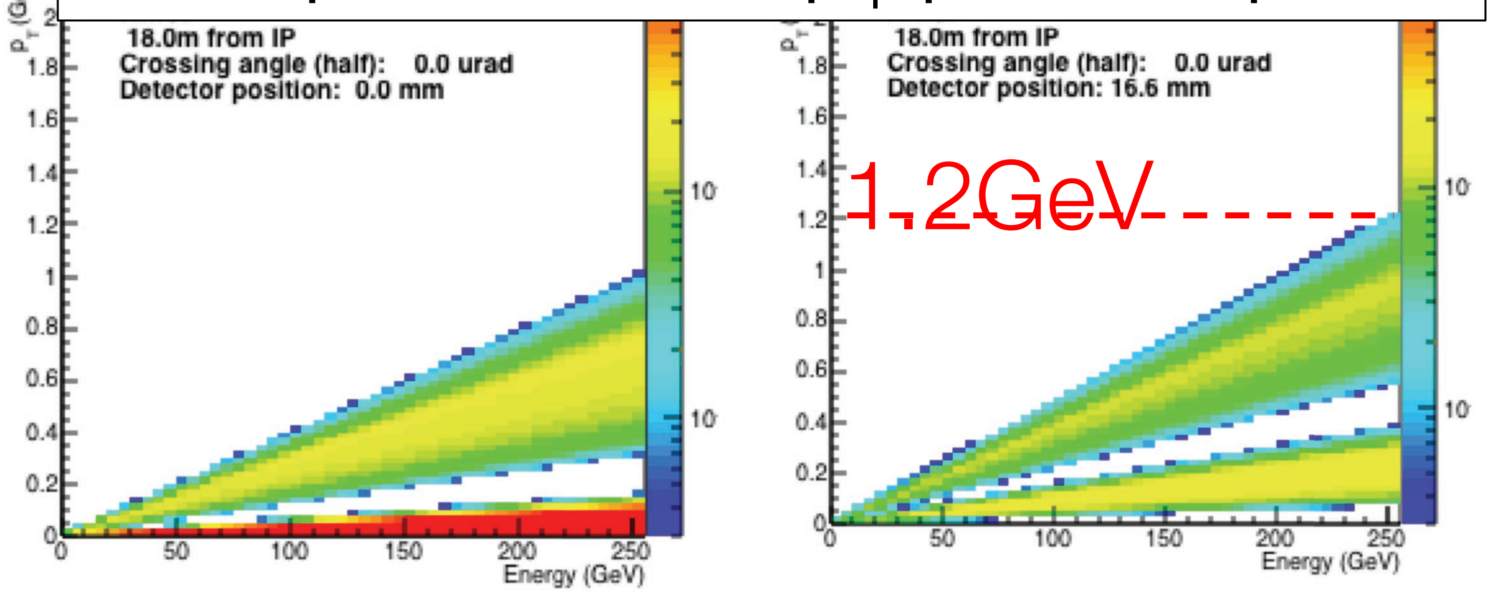




Cross section view from IP

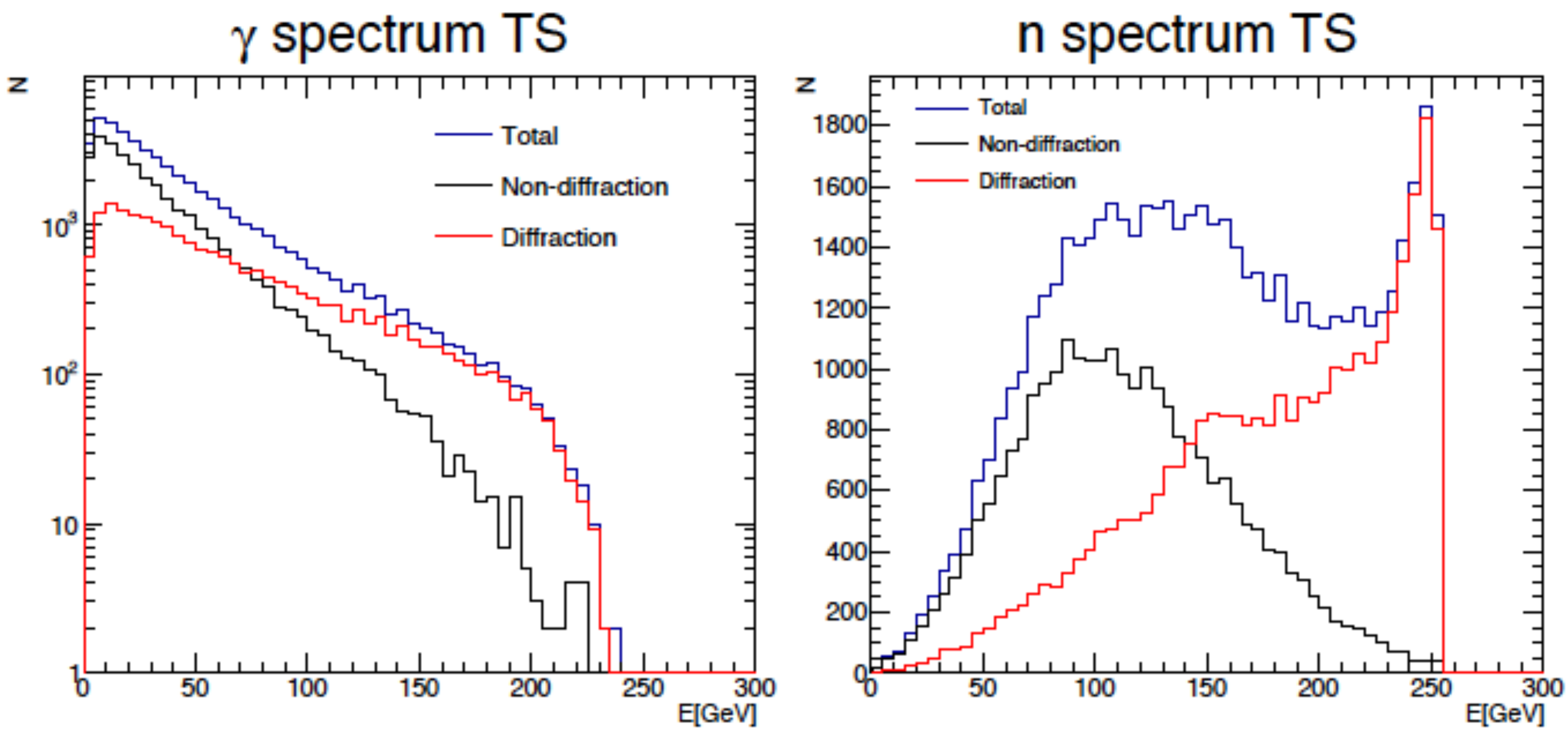


Acceptance in E-p_T phase space



- ✓ Widest and gapless p_T coverage is realized by moving the vertical detector position.
- ✓ Beam pipes obscure photons but not neutrons.

Diffractive vs. non diffractive at η>8.2 with √s=510GeV p+p collisions



PYTHIA 8 simulation

BLUE: inclusive spectra expected by RHICf only

RED: diffractive only (“RHICf + no central track in STAR” will be similar => TBC)

BLACK: non diffractive (“RHICf + >=1 central track in STAR” => TBC)