Theory Challenges in the Precision Era of the Large Hadron Collider
Florence, September 14th, 2023

LHCf: a precision forward physics detector at LHC

Oscar Adriani
University of Florence & INFN Firenze

Where does the LHCf idea come from?

Ultra High Energy Cosmic Rays

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

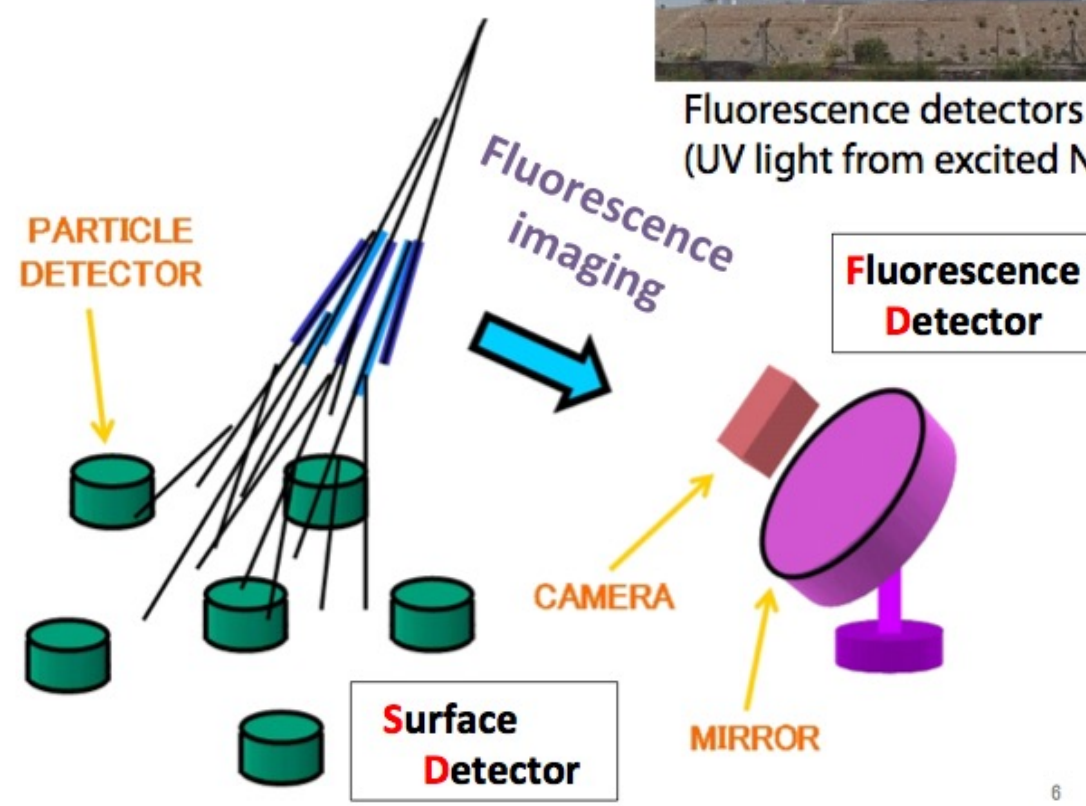
- X_{max} : depth of air shower maximum in the atmosphere
- RMS(X_{max}): fluctuations in the position of the shower maximum
- N_{μ}: number of muons in the shower at the detector level

+

MC Simulation to describe hadronic interaction with atmosphere

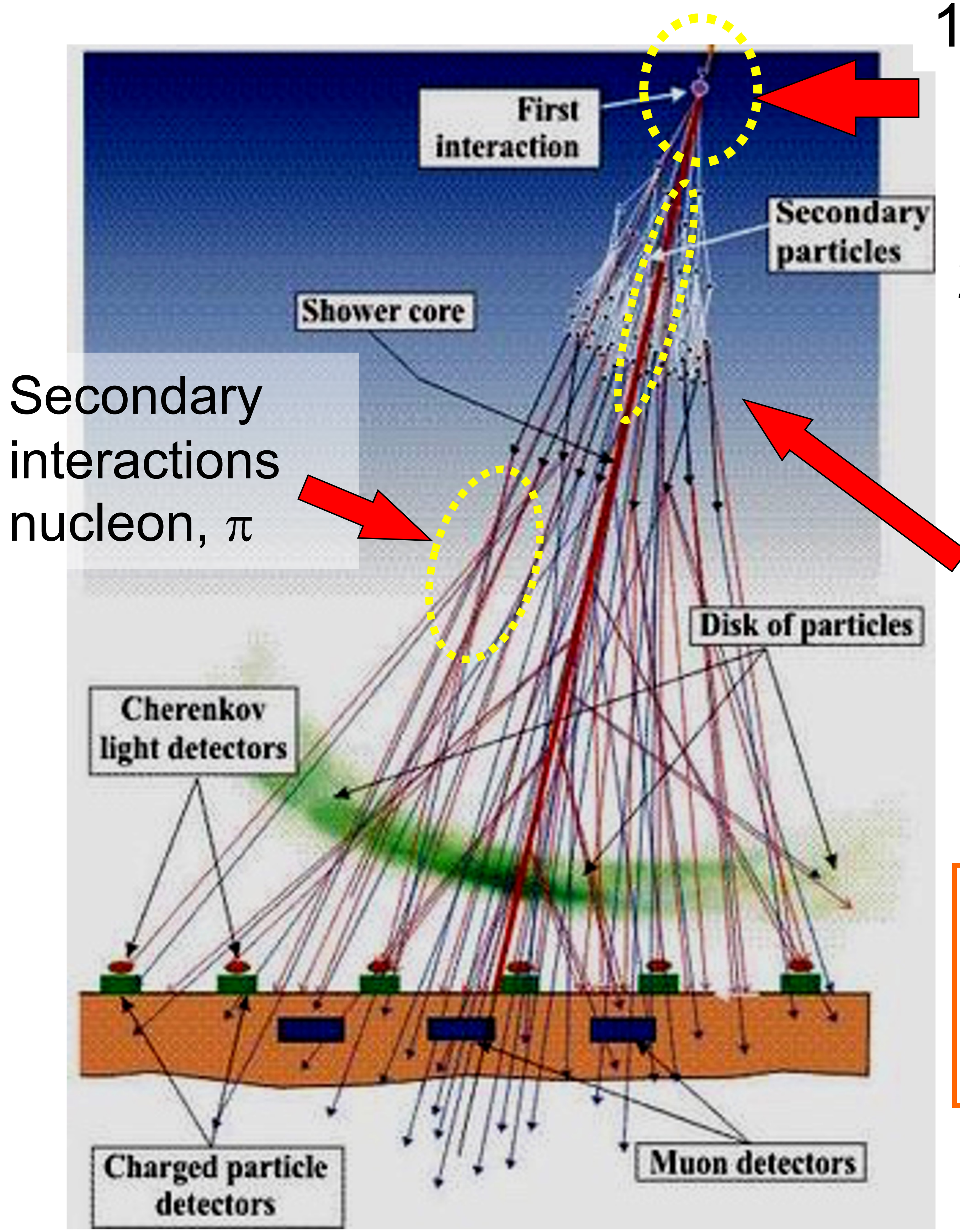
Energy, mass composition, direction
—> source of primary cosmic rays
—> origin of the universe (final goal)

Fluorescence detectors (UV light from excited N_2)



Surface detectors (charged+photon)

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

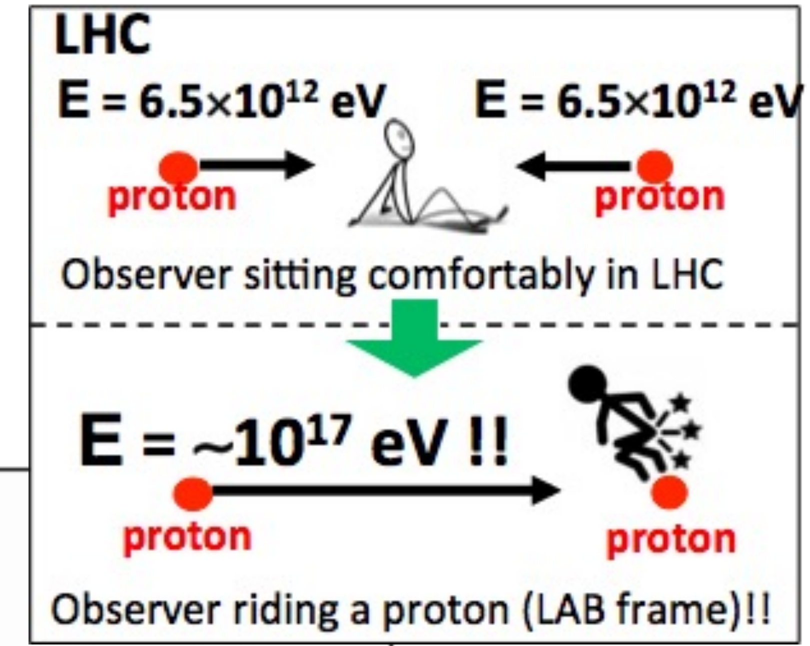
4. **Inelasticity** $k=1-E_{lead}/E_{avail}$

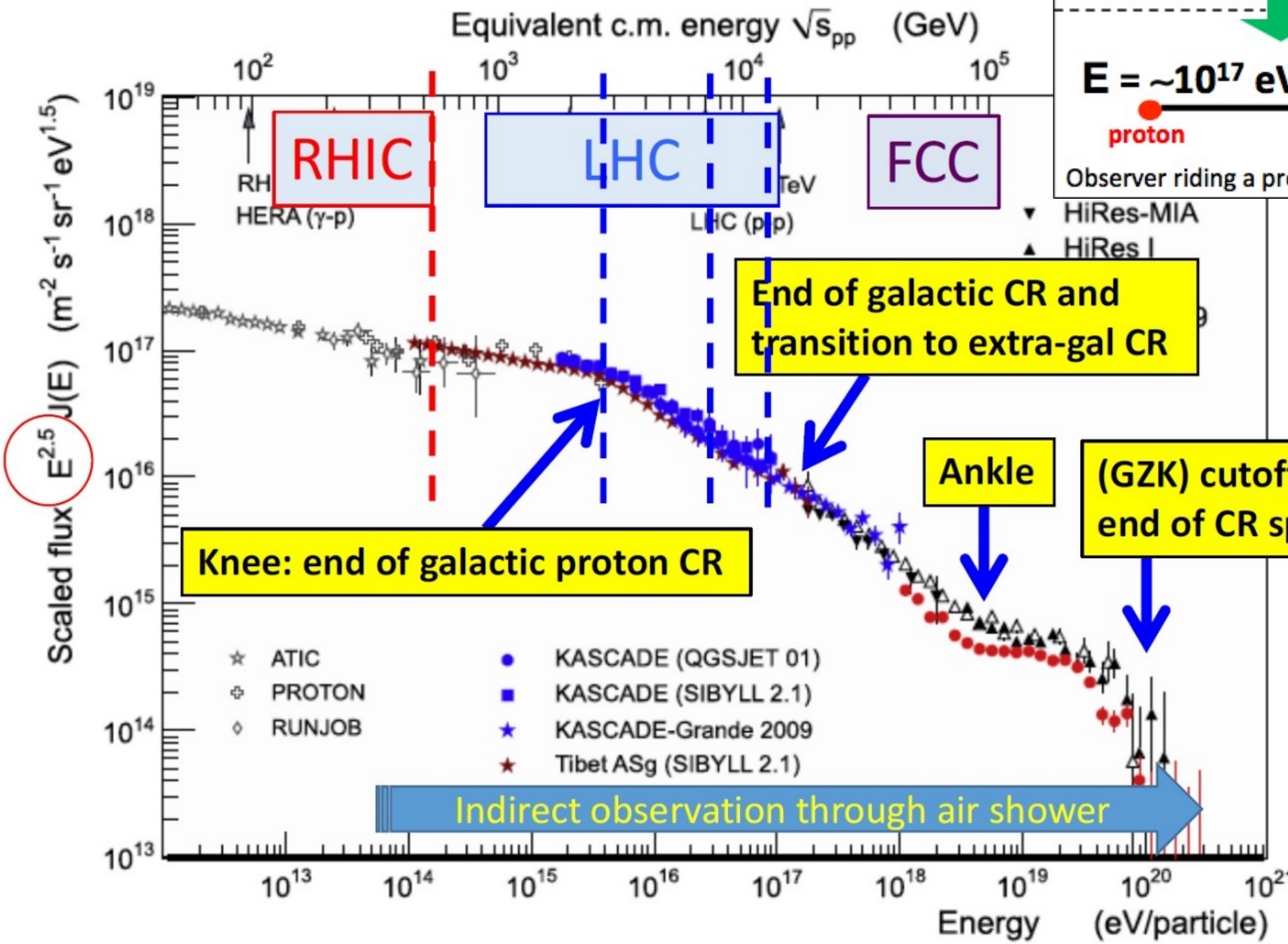
If large k (π^0s carry more energy)
rapid development
If small k (baryons carry more energy)
deep penetrating

LHCf

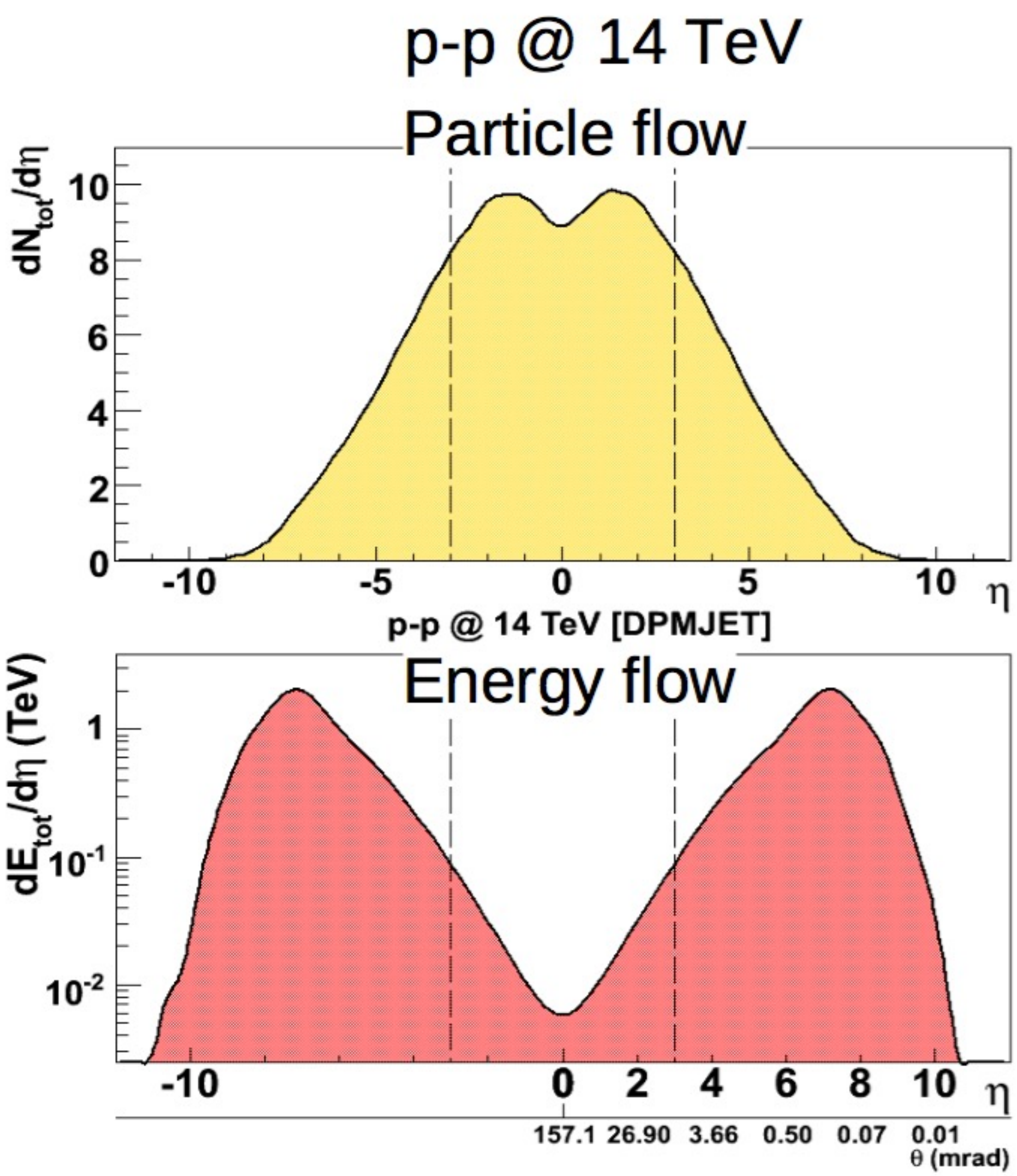
5. **Nuclear Effect (p-Nucleus)**

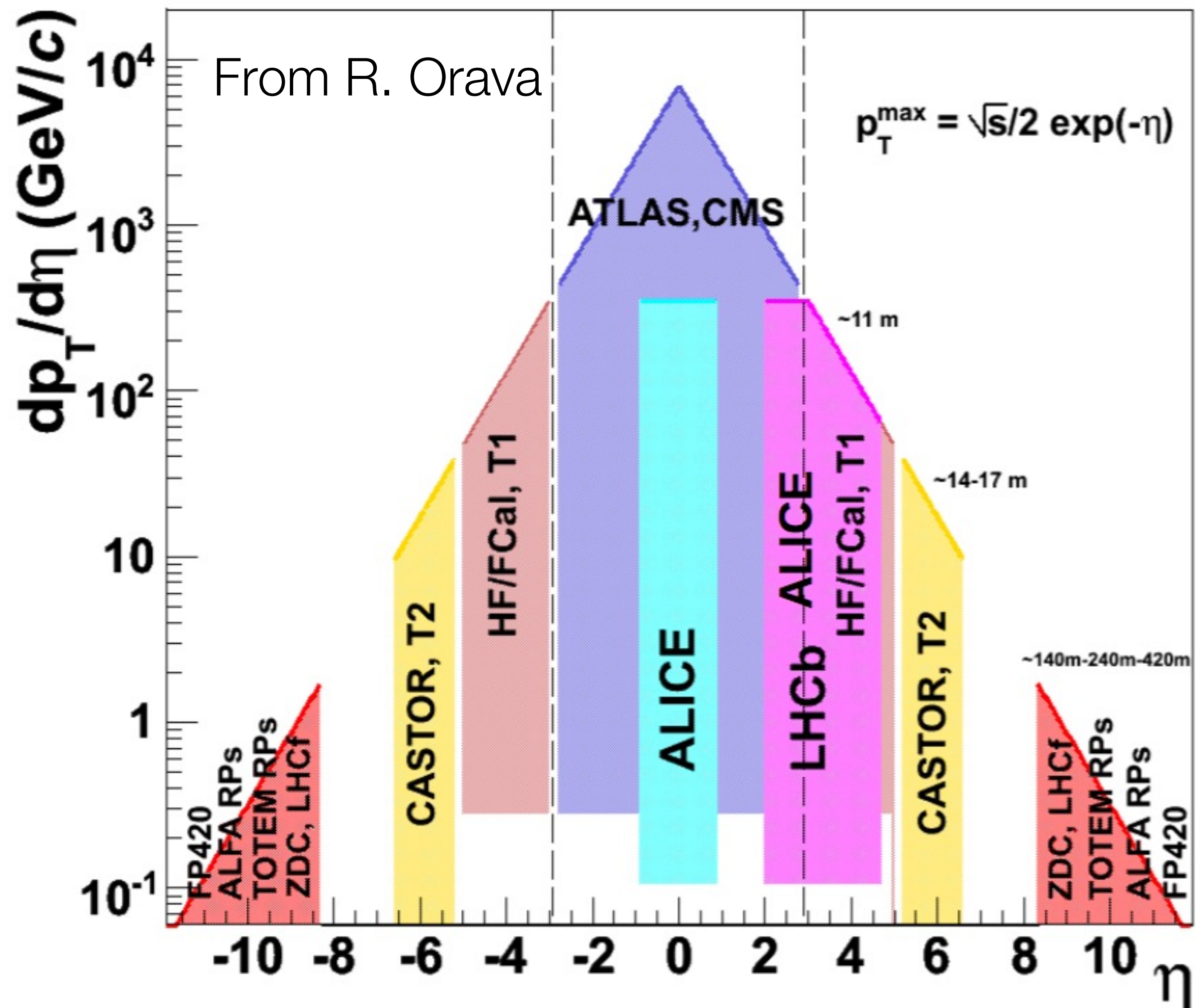
Spectrum of cosmic rays





LHC phase space coverage





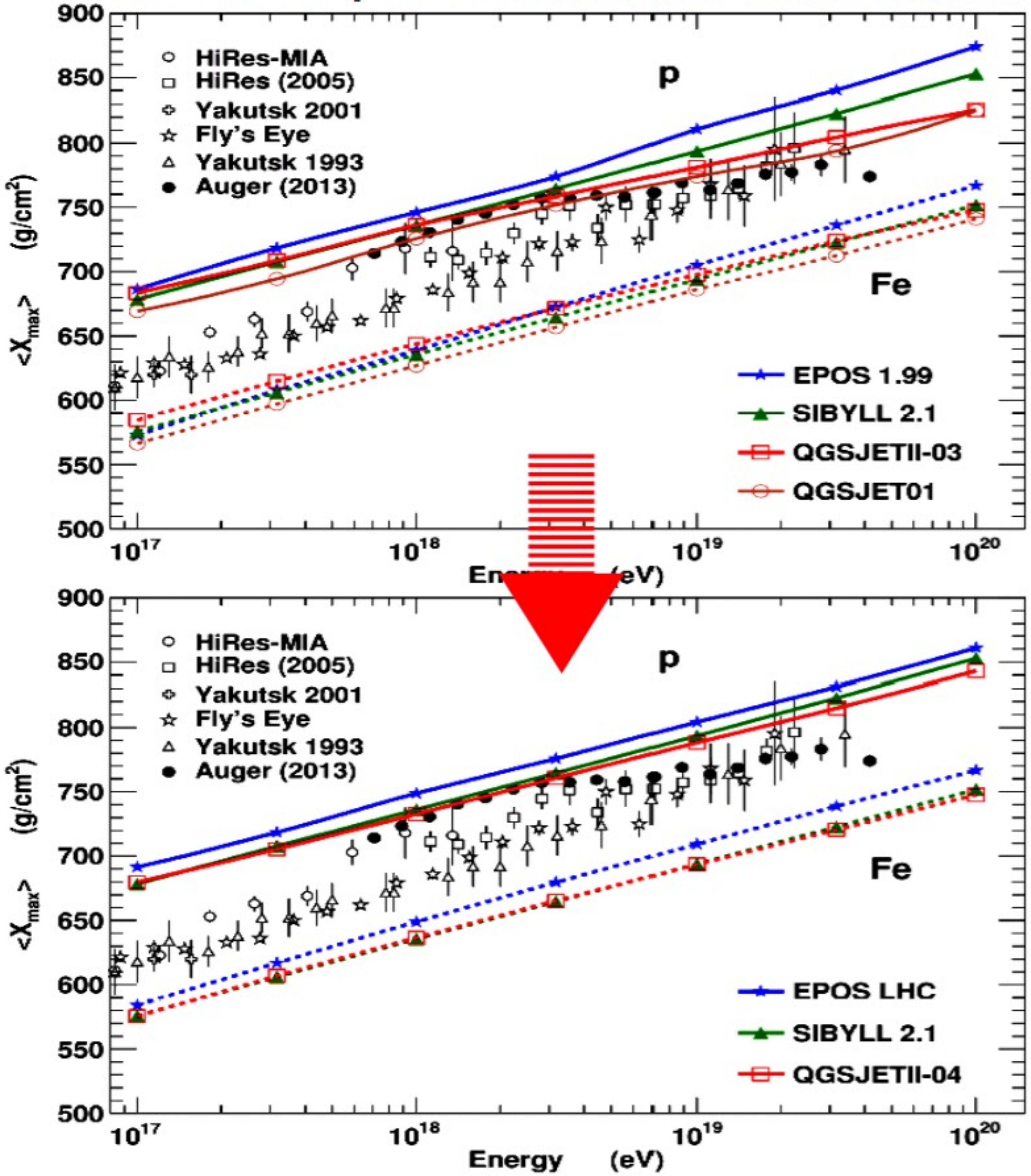
We may profit (and we are profiting) of the very broad coverage!
Dedicated forward detectors for a better measurement of the energy flow

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

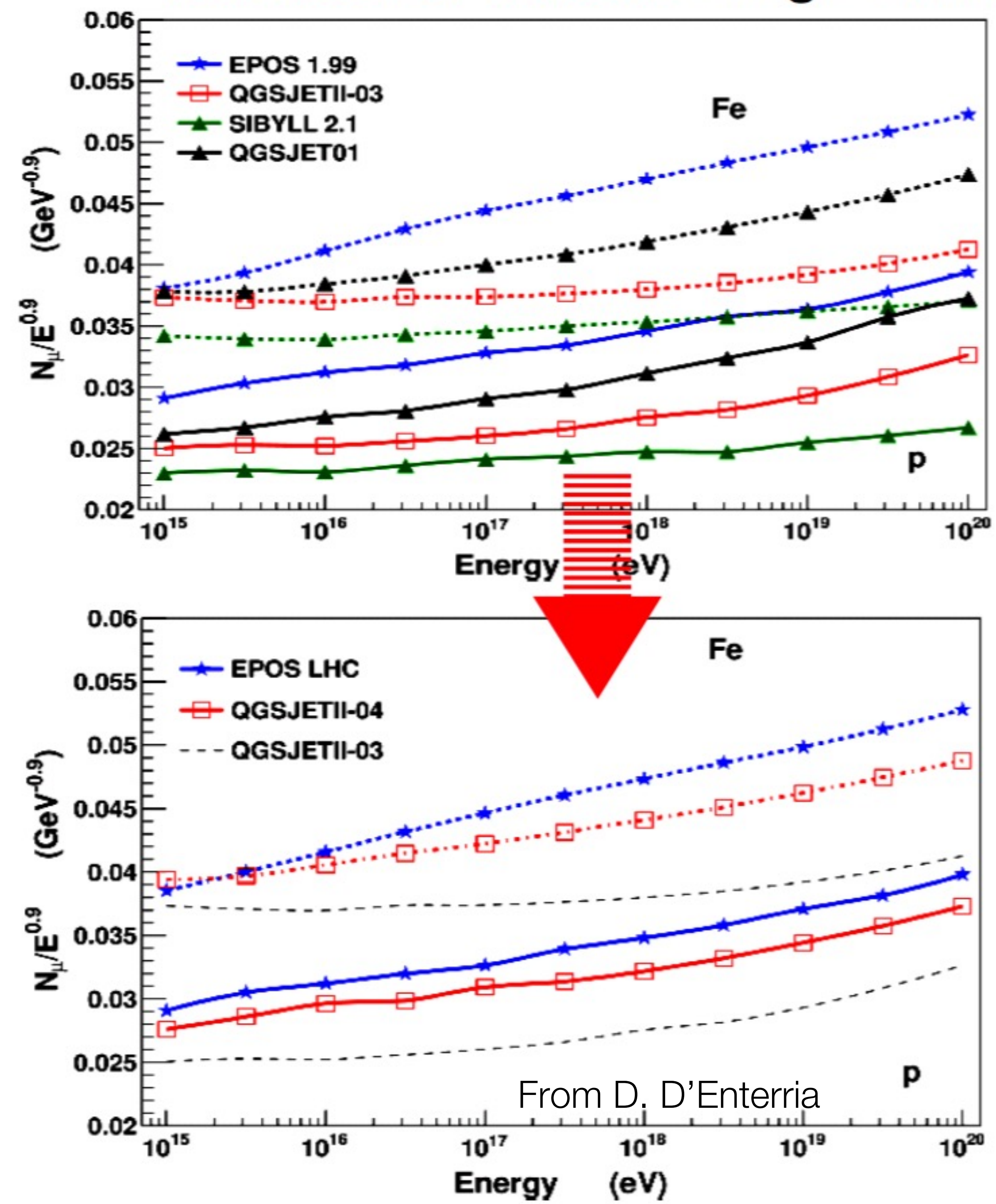
(pre-LHC)

(post-LHC)

Mean depth of **shower maximum:**



Number of muons on ground:

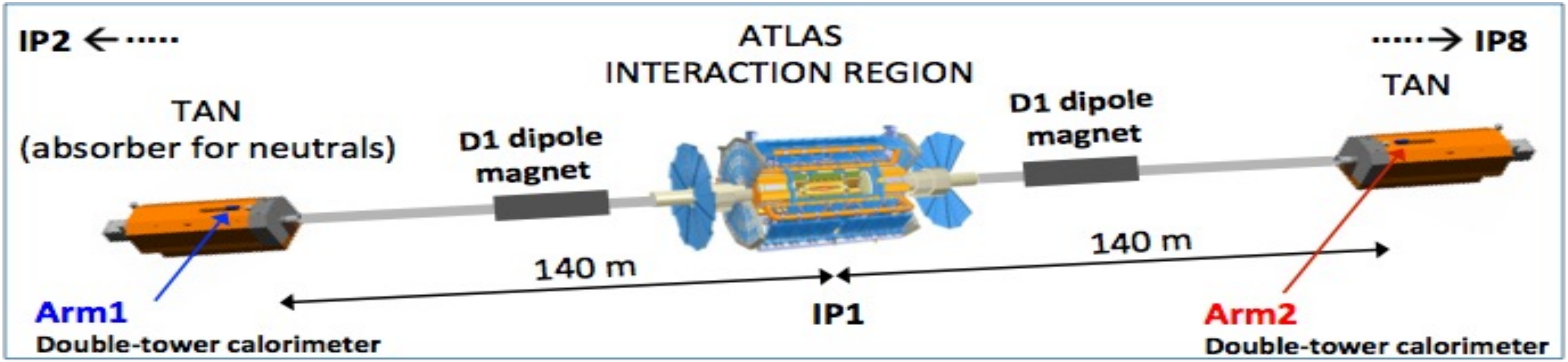


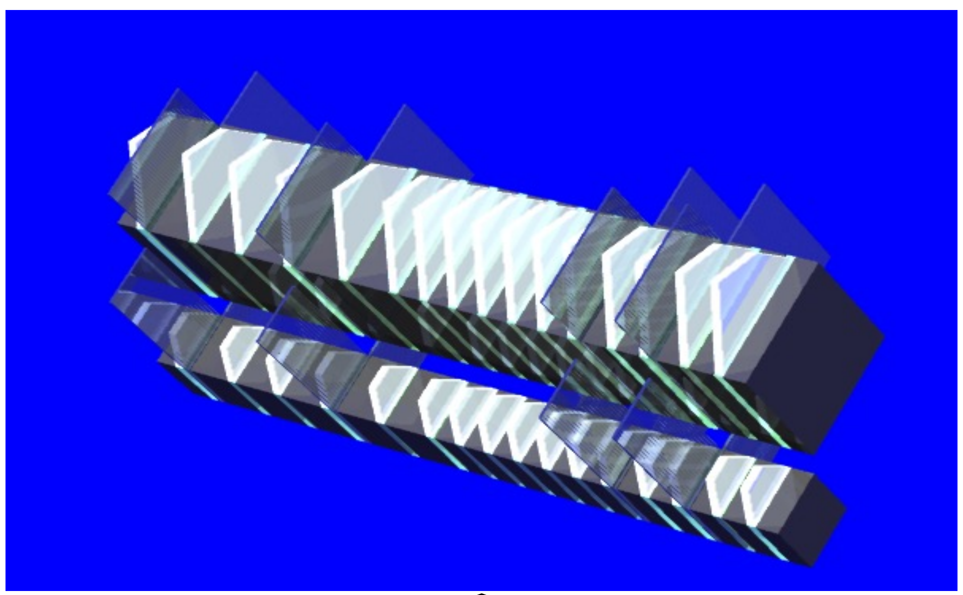
Significant reduction of differences btw different hadronic interaction models!!!

But still a lot to be done…. And… See later slides!

How LHCf is done?
What can we measure?

LHCf: location and detector layout

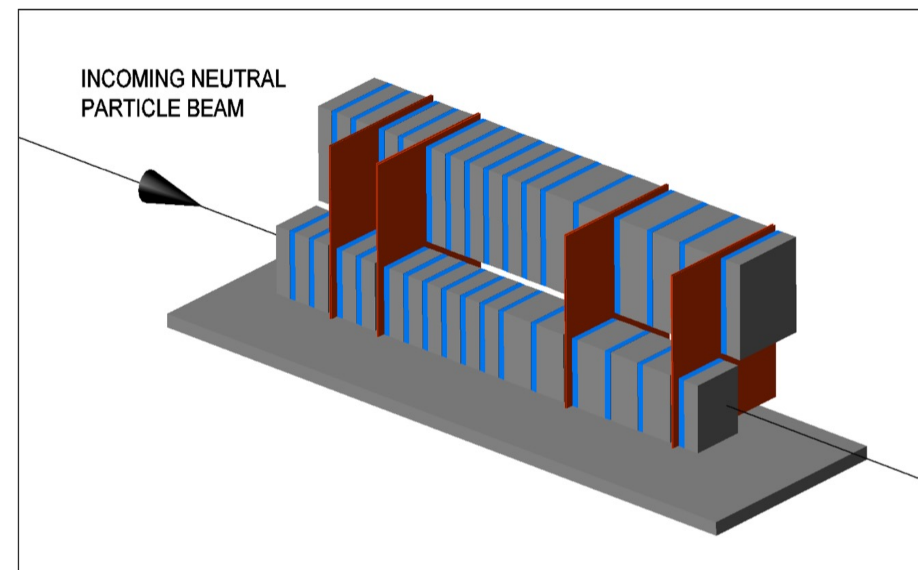




Arm#1 Detector
20mmx20mm+40mmx40mm
4 X-Y GSO Bars tracking layers

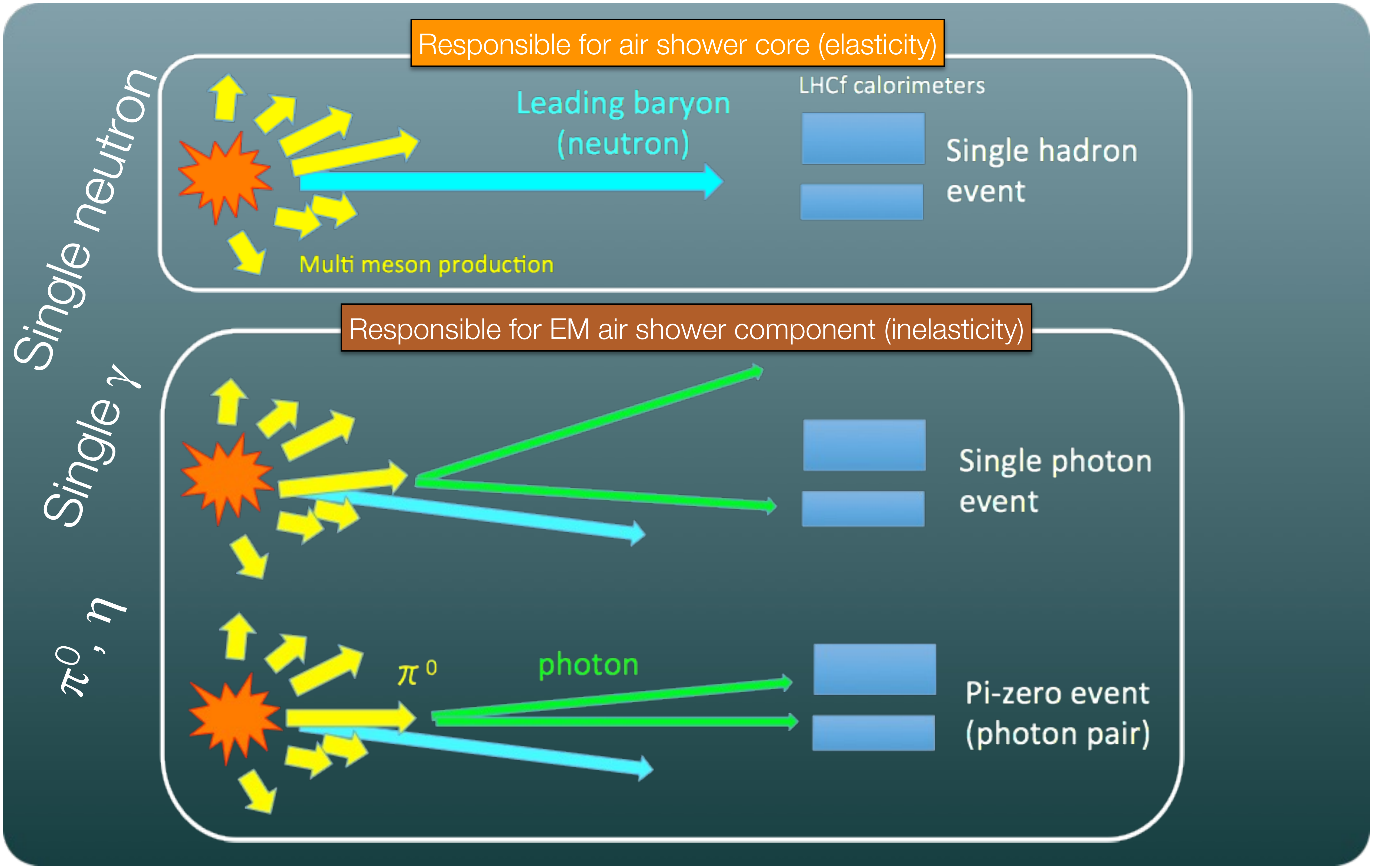
$44X_0$,
$1.6\ \lambda_{int}$

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



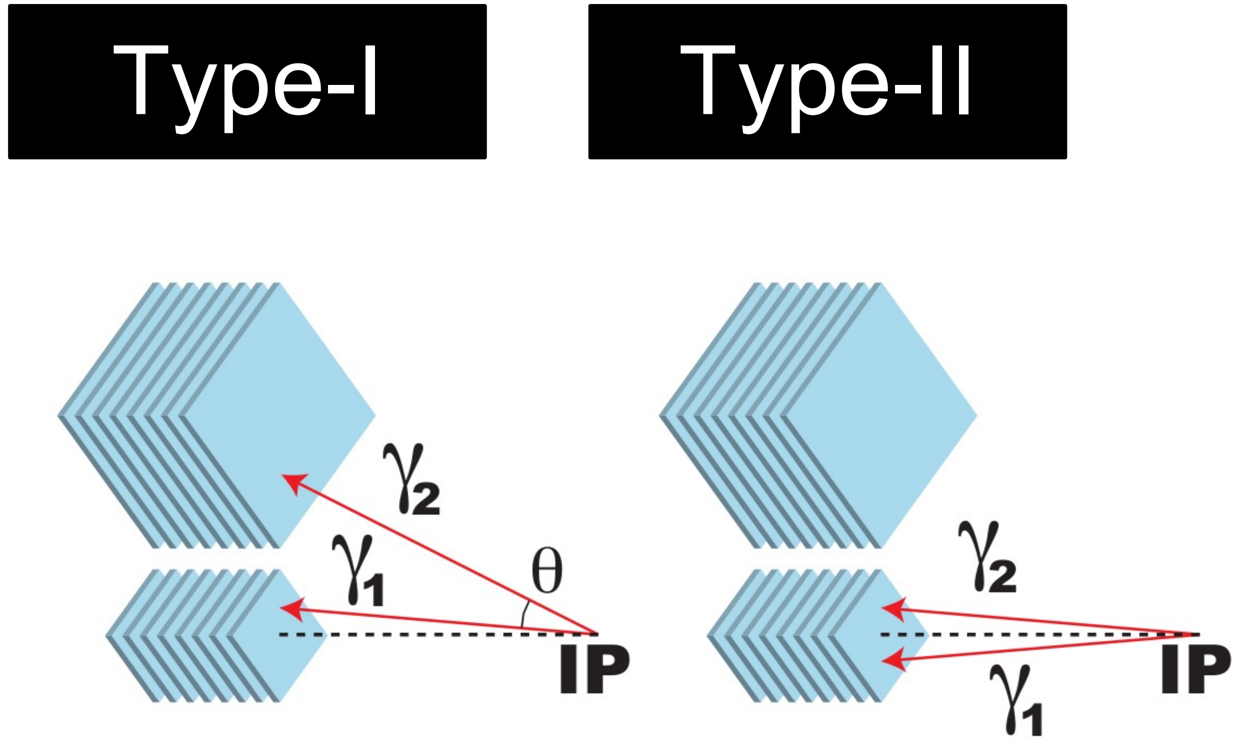
Arm#2 Detector
25mmx25mm+32mmx32mm
4 X-Y Silicon strip tracking layers

Event category in LHCf: basic measurements



What else?

Additionally, we are able to largely expand the π^0 phase space by detecting 2 γ in the same tower (already published)

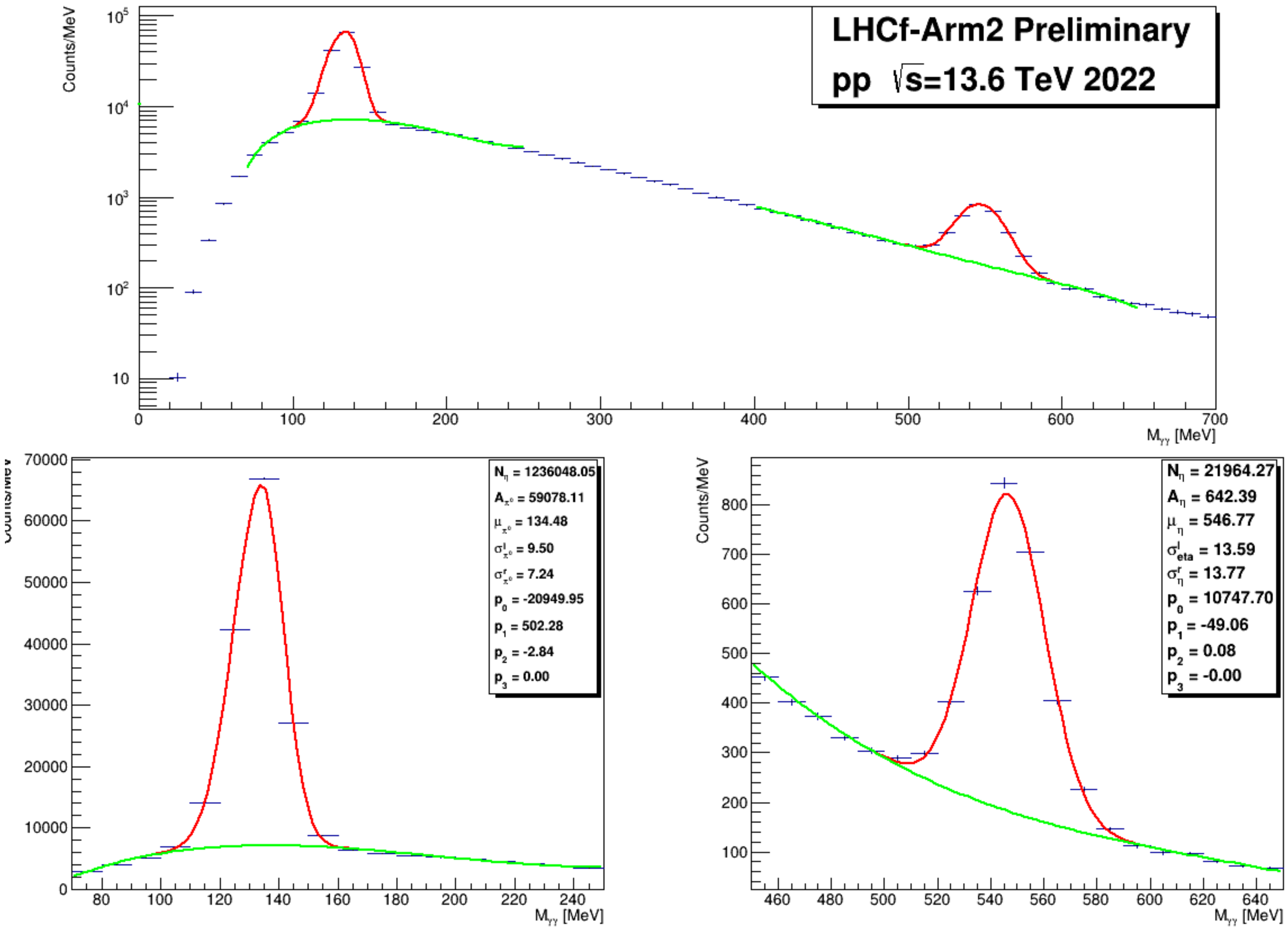


Possible future additional measurements

- 4 γ (e.g. $K^0 \rightarrow \pi^0\pi^0$)
- 1 neutron and 2 γ (e.g. $\Lambda \rightarrow n\pi^0$)

- And many possible measurements in conjunction with ATLAS
  - in the central region
  - in the very forward region (Roman Pots)

γγ invariant mass distribution



Please note the excellent resolution!

Thanks to the excellent energy AND position resolution

Very broad set of measurements

- Thanks to the strong LHCC support, LHCf have taken data in many dedicated low luminosity runs, in many different running conditions:
- p-p
  - 900 GeV
  - 2.76 TeV
  - 7 TeV
  - 13 TeV
  - 13.6 TeV
- p-Pb
  - 5.02 TeV
  - 8.1 TeV
- p-p @ RHIC (BNL in the USA) → RHICf
  - 510 GeV
- And p-O, foreseen in 2024

LHCf Data Taking and Analysis matrix

	γ	neutron	π^0	η^0
Detector Calibration	NIM A, 671, 129 (2012) JINST 12 P03023 (2017)	JINST 9 P03016 (2014)		
p+p 510 GeV (RHICf)	**submitted to PLB**		Phys. Rev. Lett. 124, 252501 (2021)	
p+p 900 GeV	Phys. Lett. B 715, 298 (2012)			
p+p 7 TeV	Phys. Lett. B 703, 128 (2011)	Phys. Lett. B 750 (2015) 360-366	Phys. Rev. D 86, 092001 (2012) Phys. Rev. D 94 032007 (2016)	
p+p 2.76 TeV			Phys. Rev. C 89, 065209 (2014) Phys. Rev. D 94 032007 (2016)	
p+Pb 5.02TeV				
p+p 13 TeV	PLB 780 (2018) 233-239	JHEP 11 (2018) 073 JHEP 07 (2020) 16	**Analysis ongoing**	**submitted to JHEP**
p+Pb 8.1TeV	Analysis ongoing			

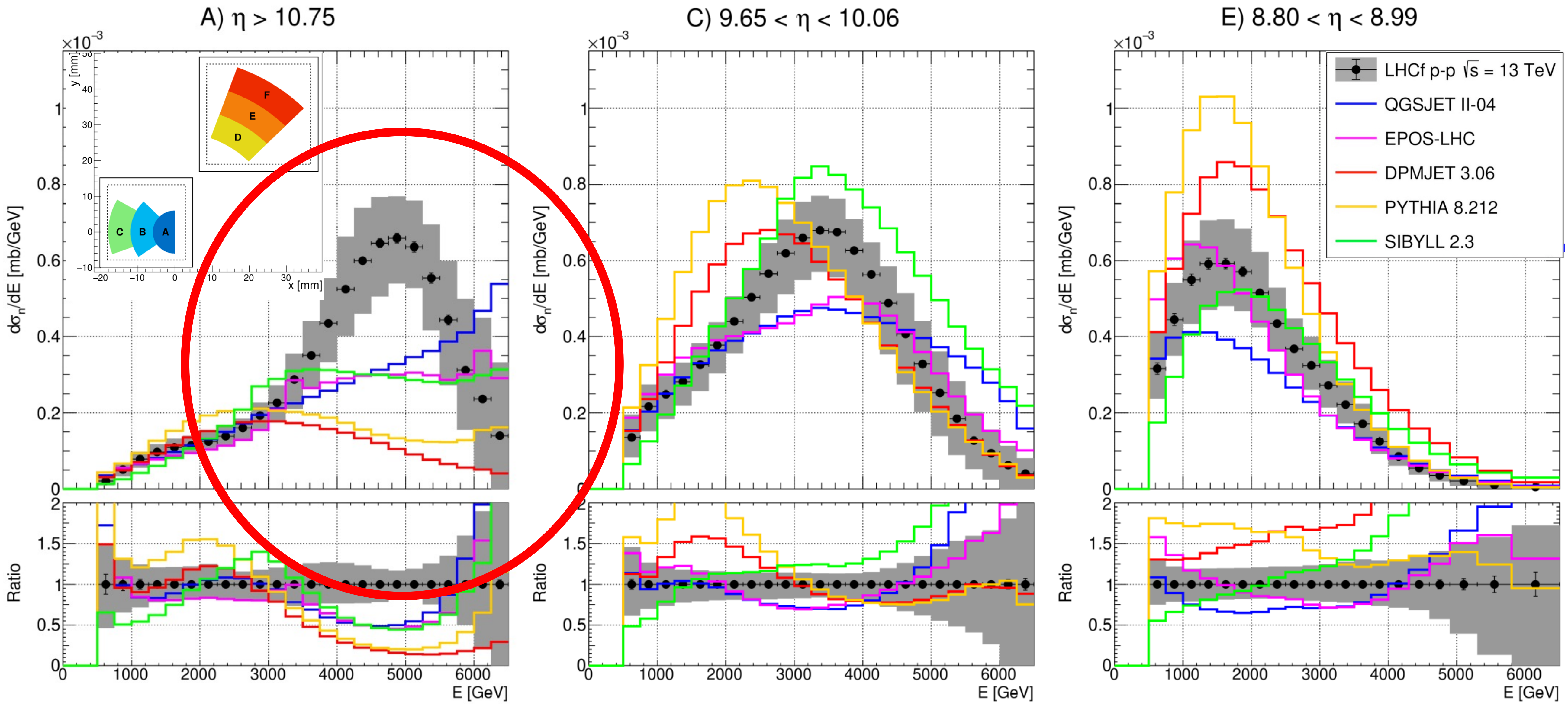
Main LHCf results

How do we quote our results?

- We measure the neutral particle spectra
  - for different particles
    - n, γ, π^o, η
  - for different rapidity bins
  - eventually in different P_t/X_F (Feynman X) regions
- We compare our spectra with the 5 most commonly used high energy hadronic interaction models
  - EPOS-LHC
  - QGSJET II-04
  - DPMJET 3
  - SYBILL 2.3
  - PYTHIA 8
  - I will show only a subset of our results, I will put all the published results in backup slides

Neutron Production Cross Section

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



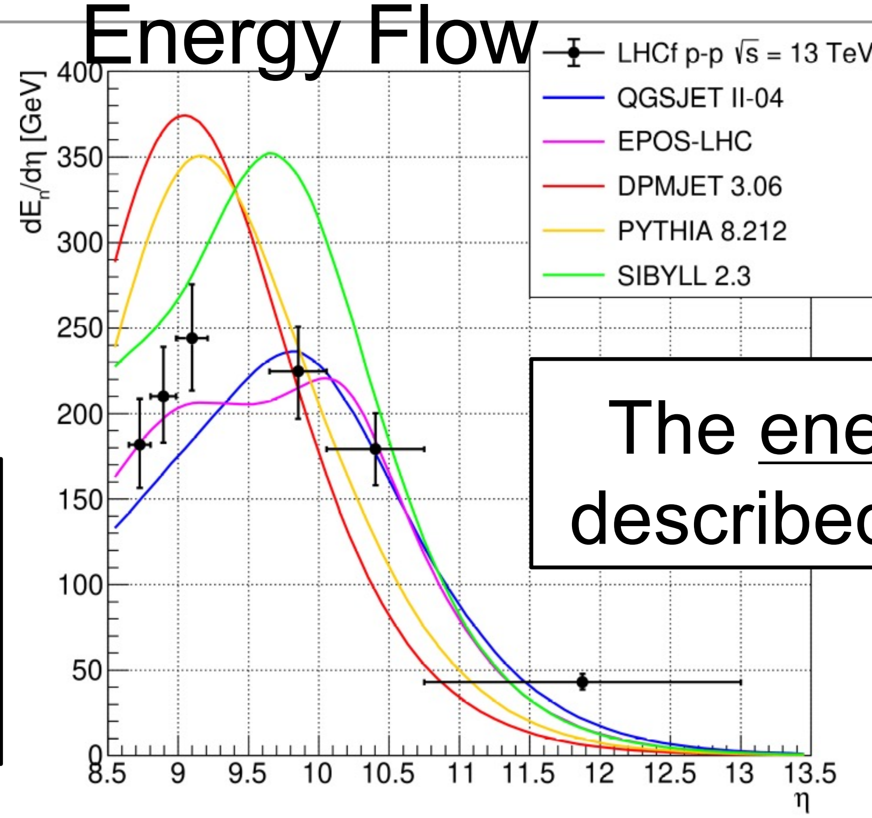
JHEP 07 (2020) 016

In η > 10.75 no model agrees with peak structure and production rate, whereas in the other regions, **SIBYLL 2.3** and **EPOS-LHC** have better but not satisfactory agreement with the experimental measurements*

Neutron Energy Flow & Inelasticity

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

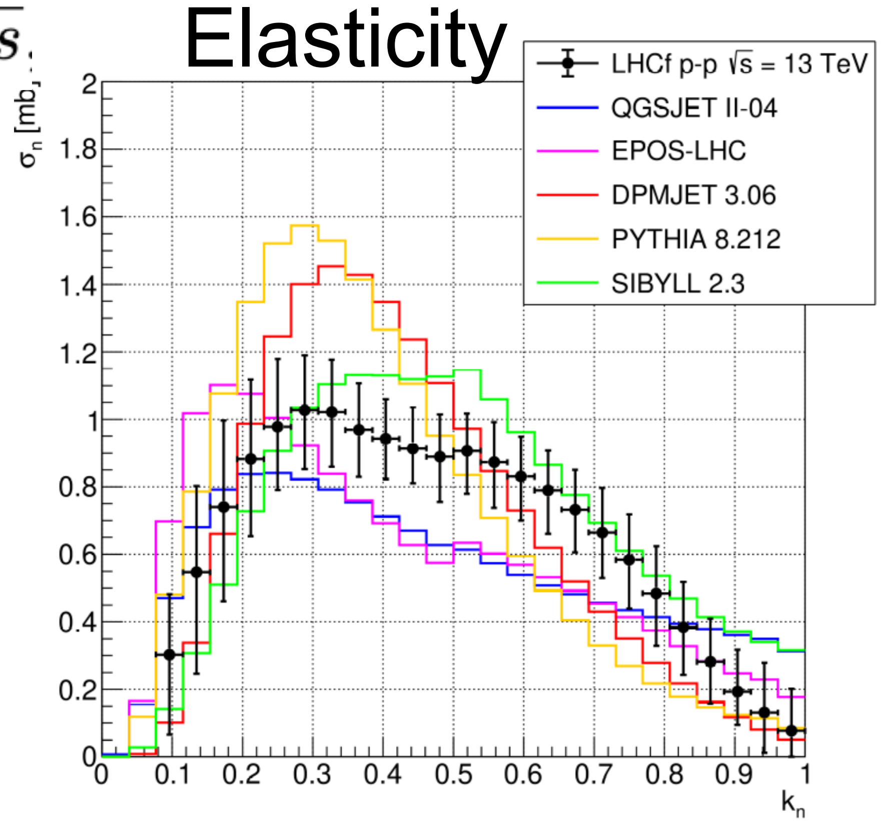
$dE_n/d\eta$

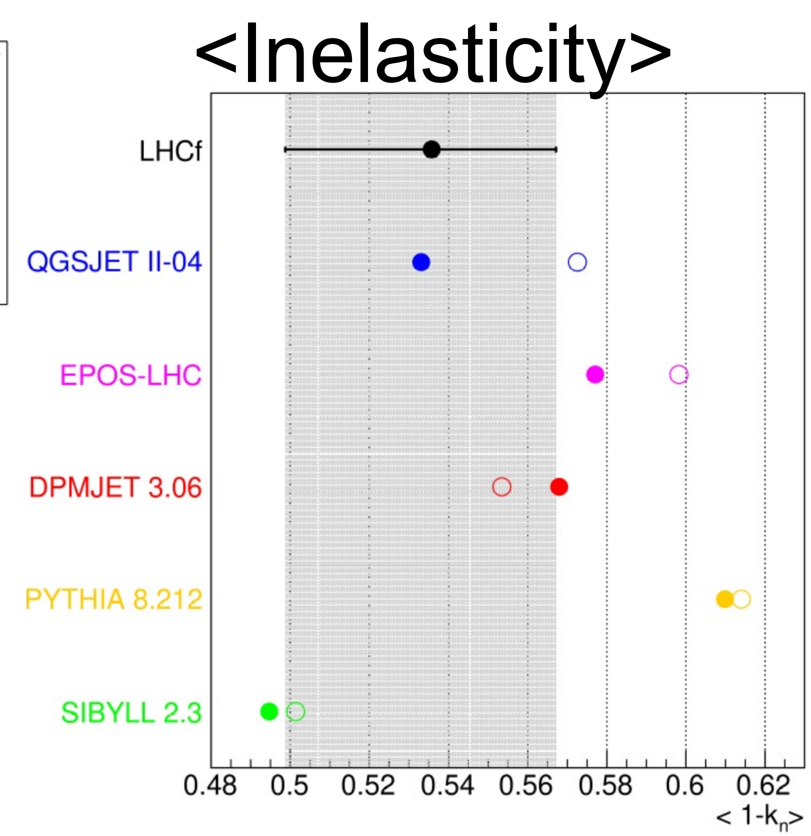


The <u>energy flow</u> is well described by **EPOS-LHC**

Most models reproduce the average inelasticity but <u>not</u> the distribution

$$k = 2E/\sqrt{s}$$

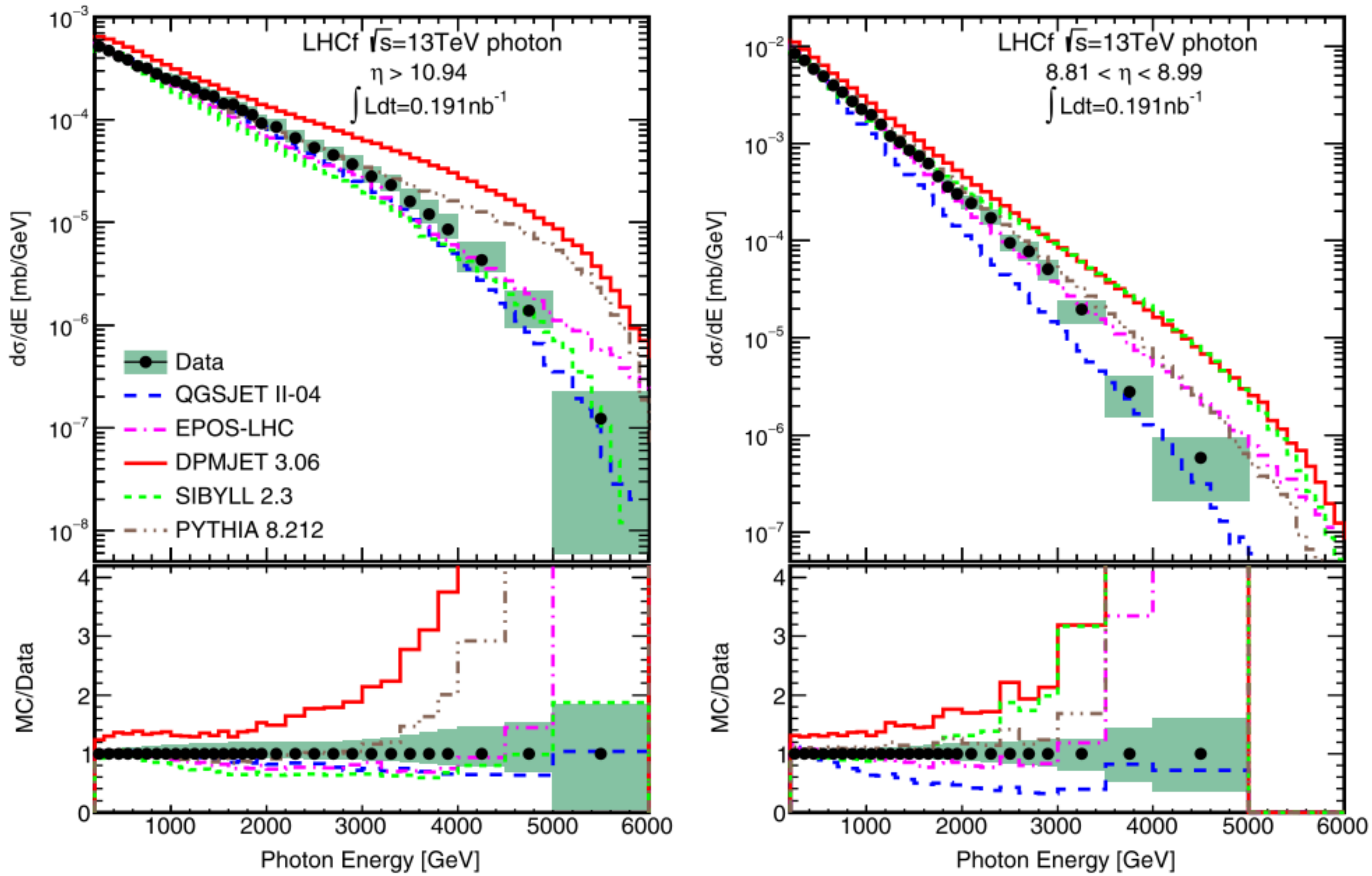




JHEP 07 (2020) 016

Photons dσ/dE

p-p √s = 13 TeV

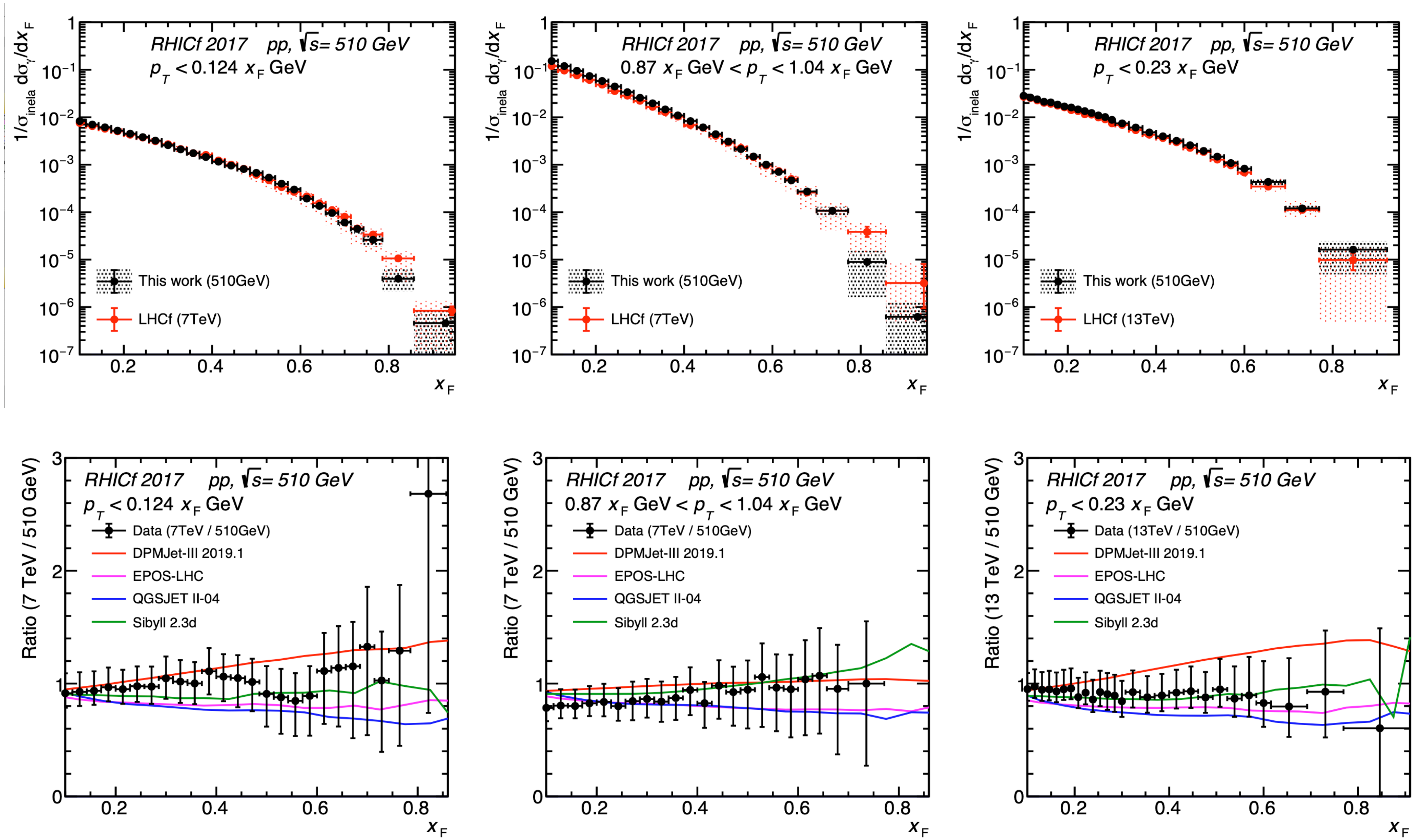


PLB 780 (2018) 233-239

QGSJET II-04 is in good agreement for η>10.94, otherwise softer
EPOS-LHC is in good agreement below 3-5 TeV, otherwise harder

Test of Feynman scaling
using forward photons

Using γ in $\sqrt{s}$=510 GeV (RHICf) and 7 or 13 TeV (LHCf)

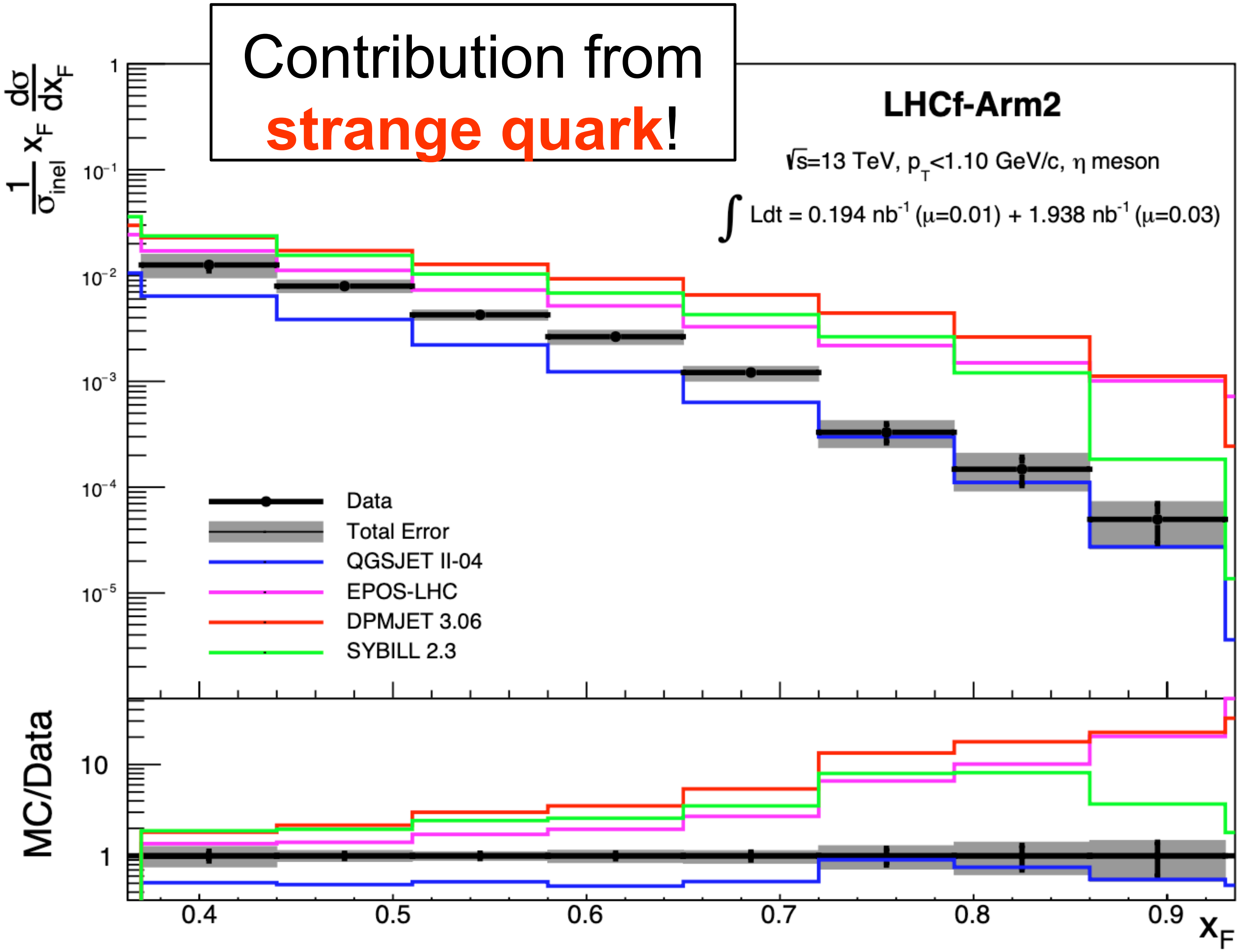


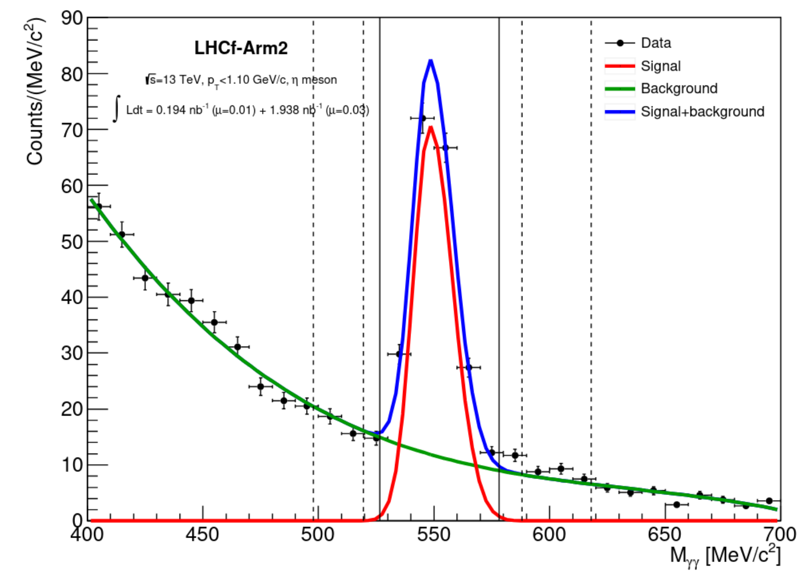
ArXiv:2203.15416
...submitted to PLB

<u>First confirmation of **Feynman scaling** using zero-degree photons</u>
but no sensitivity to small x_F dependency as in some models

η Production Rate

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





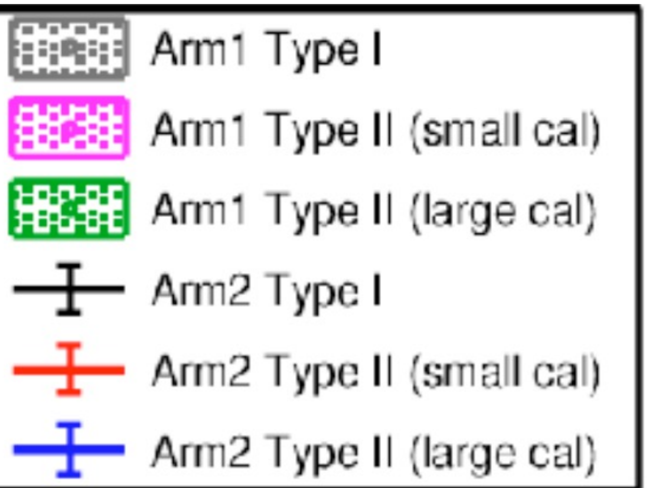
ArXiv:2305.06633

CERN-EP-2023-076

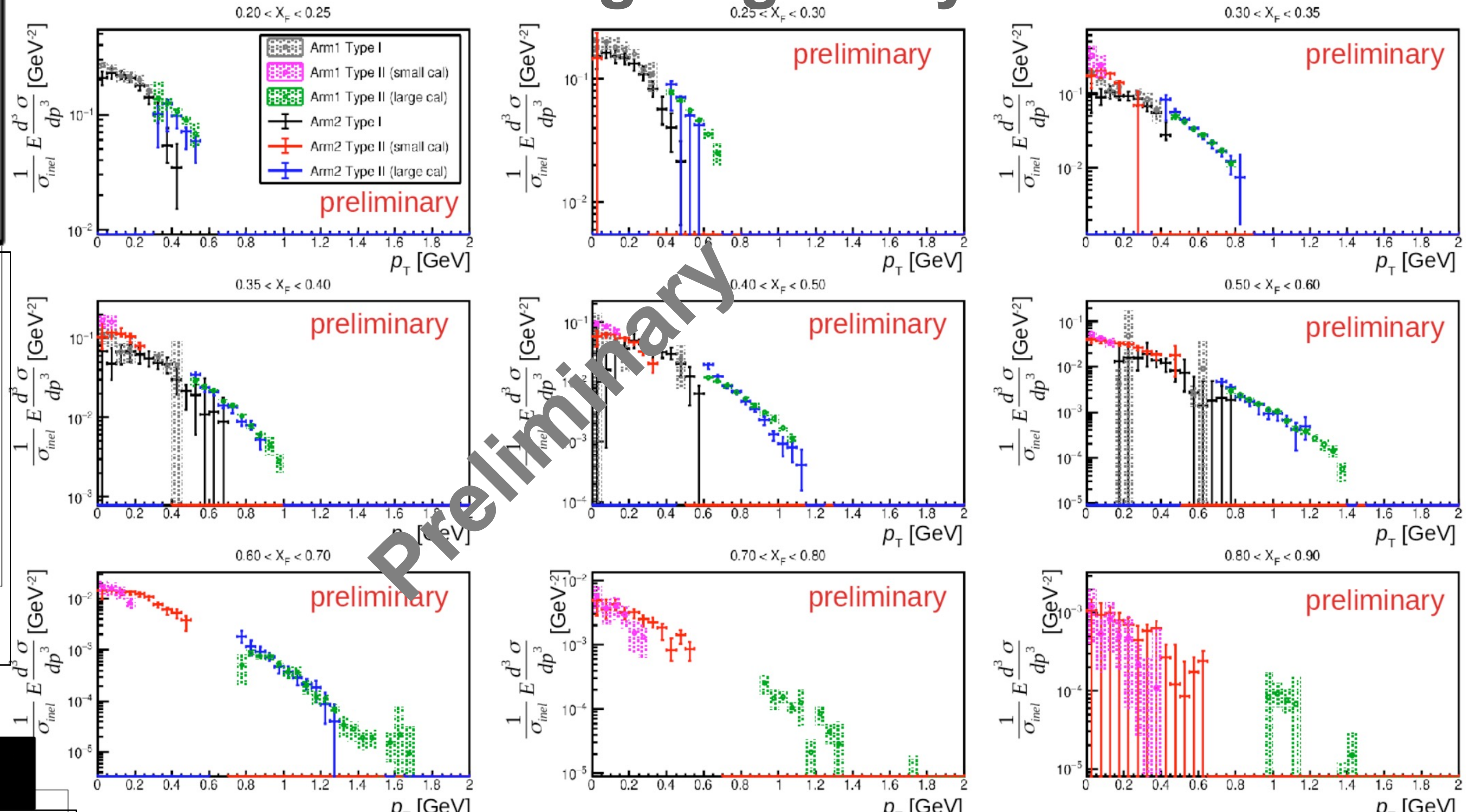
...submitted to JHEP

Among the large model variations, only **QGSJETII-04** has good but not satisfactorily agreement with the experimental measurements

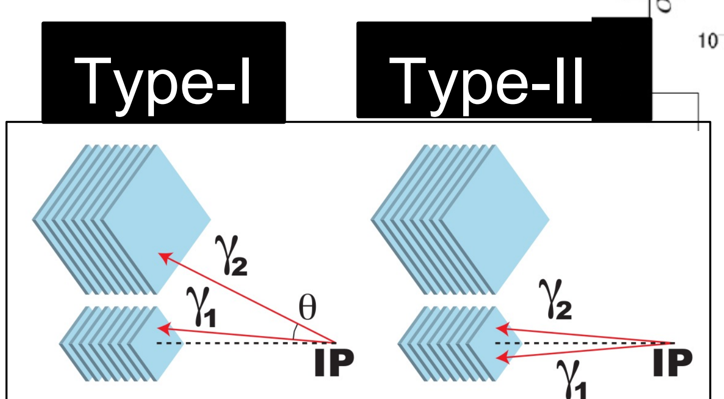
π^0 Production Rate
p-p $\sqrt{s}$ = 13 TeV



Ongoing analysis



Different Arm1 and Arm2 geometries allows for a large **p_T vs x_F coverage** with an overlap to crosscheck results



Good *agreement* between Arm1 and Arm2 data and between “Type-I” and “Type-II” events

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
  - Forward measurements vs very forward protons in AFP and RP

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

ATLAS-LHCf combined data analysis

- Operation in 2013
  - p+Pb, $\sqrt{s_{NN}}$ = 5TeV

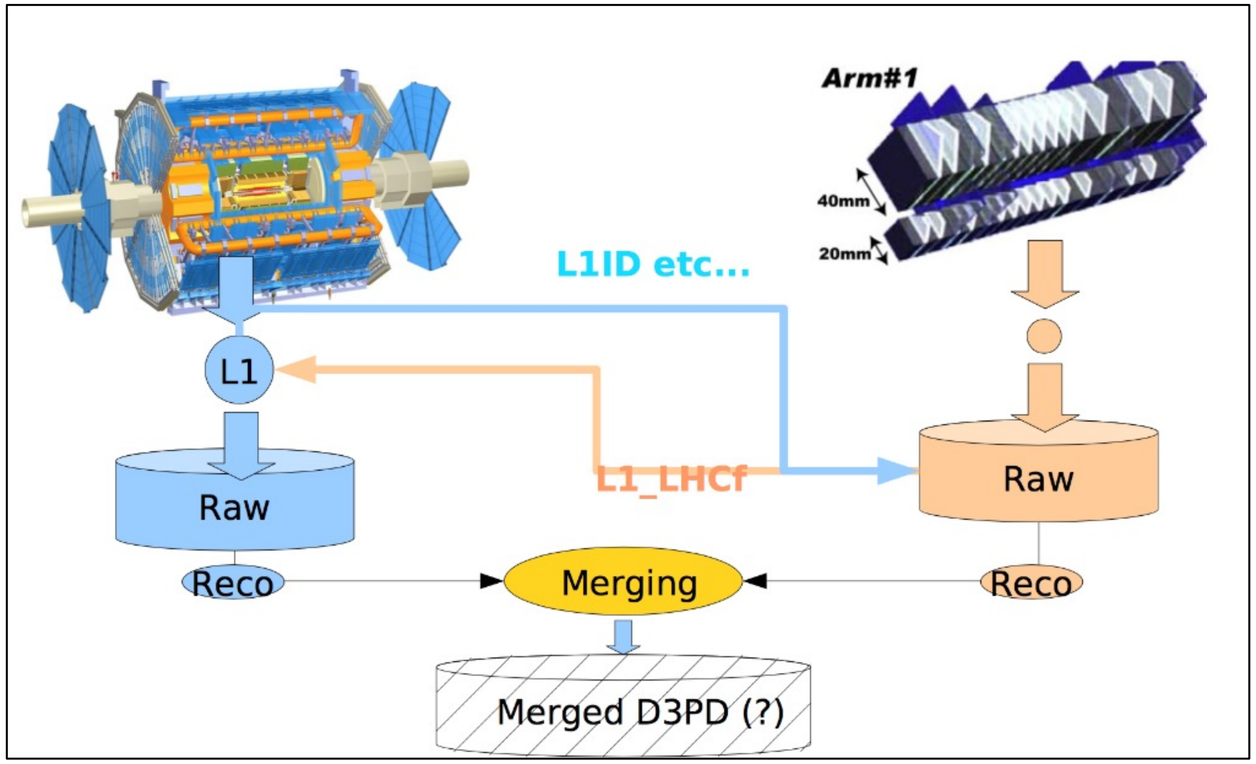
    ➔ about 10 M common events.
- Operation in 2015
  - p+p, $\sqrt{s}$ = 13TeV

    ➔ 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
- Operation in 2023
  - p+p, $\sqrt{s}$ = 13.6TeV

    ➔ about 240 M common events

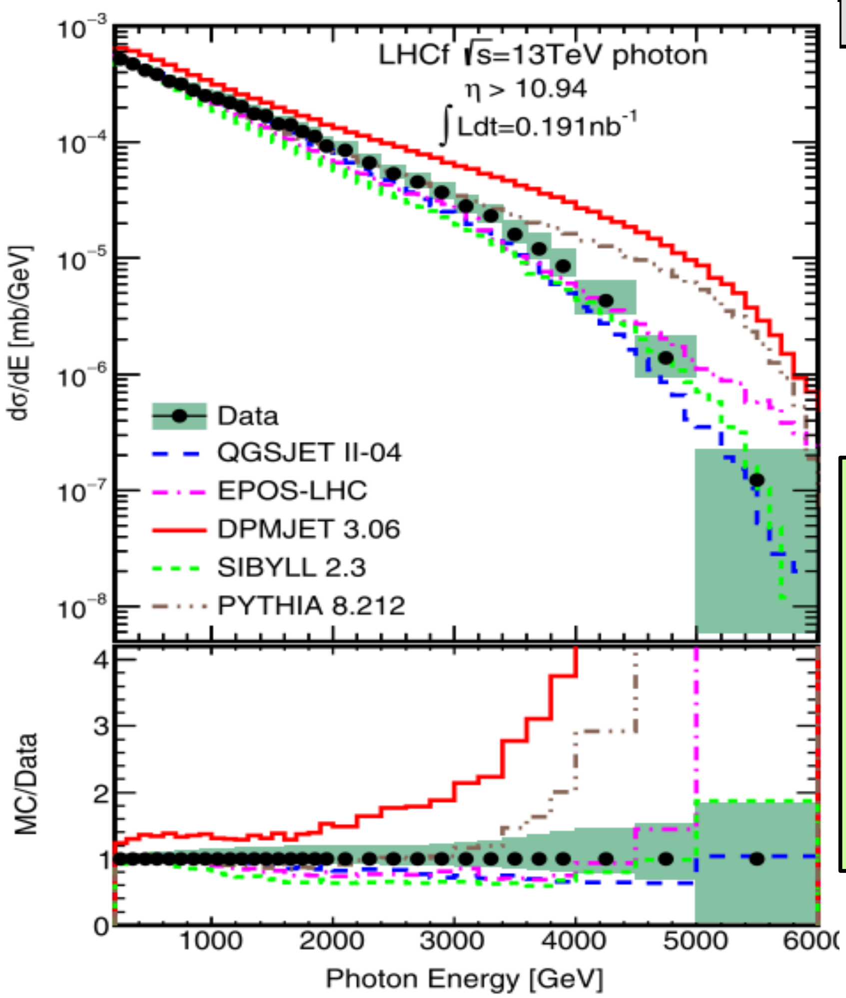


Off-line event matching

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

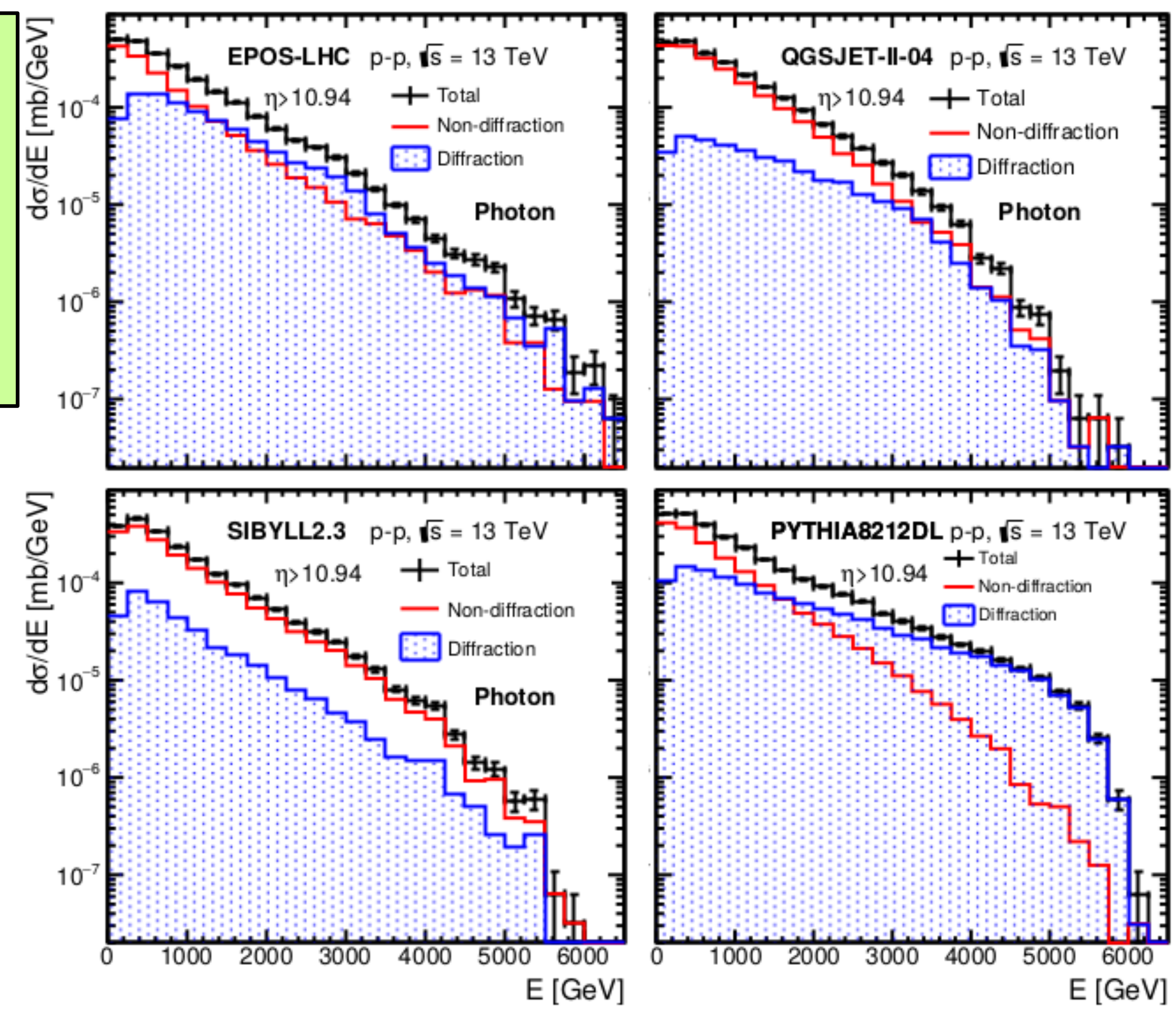
Diffractive and non-diffractive production

√s = 13 TeV - η > 10.94



Different models lead to different contributions to **diffractive** and **non-diffractive** events

How to separate diffractive and non-diffractive production?



LHCf measures the **total production rate** in the forward region

LHCf-ATLAS joint analysis

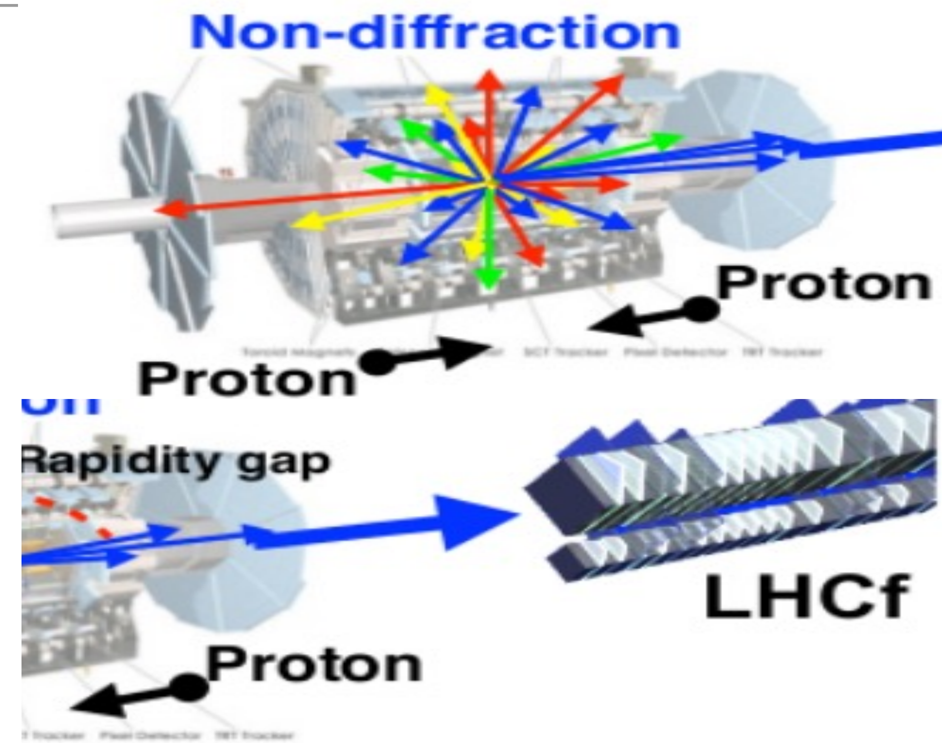
Eur. Phys. J. C (2017) 77:212

LHCf-ATLAS joint analysis

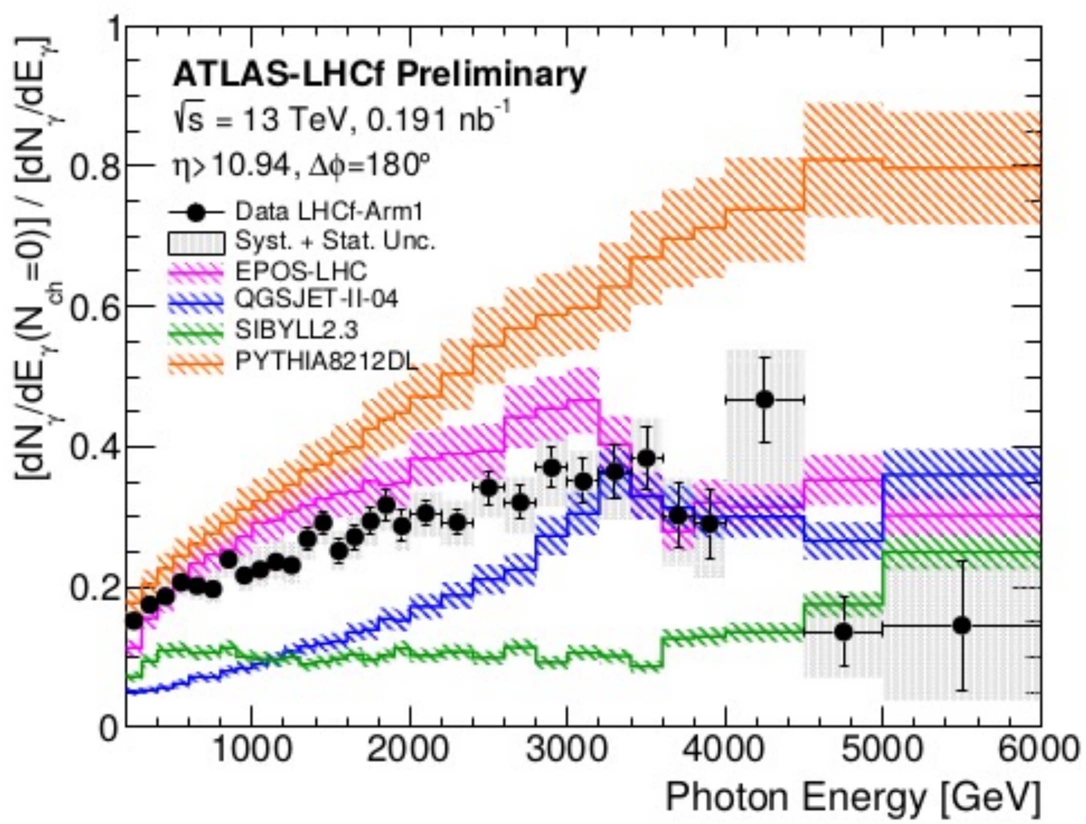
Preliminary result for photons in p-p $\sqrt{s}$ = 13 TeV

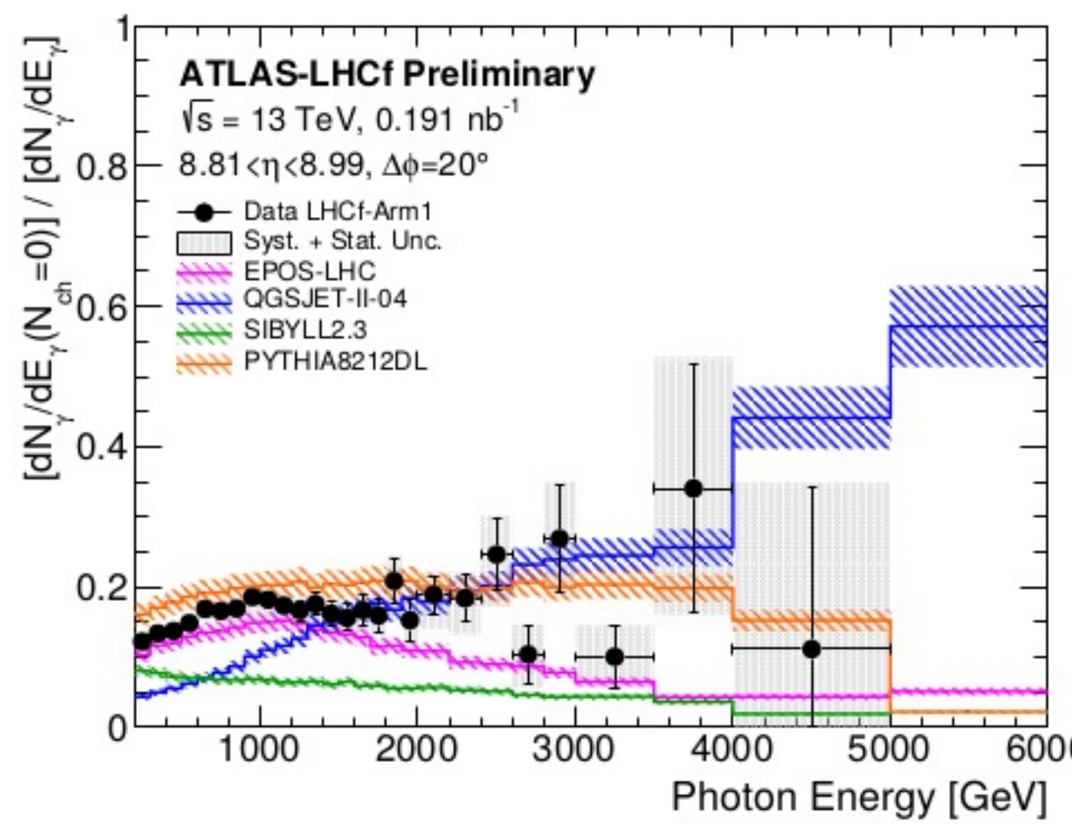
After a preliminary test in 2013,
in 2015 and 2016 LHCf and ATLAS
experiments had **common operation**.

Diffractive events can be distinguished
from non-diffractive events
by **ATLAS veto** : tracks=0 at $|\eta|<2.5$



$N_{veto}/N_{inclusive}$

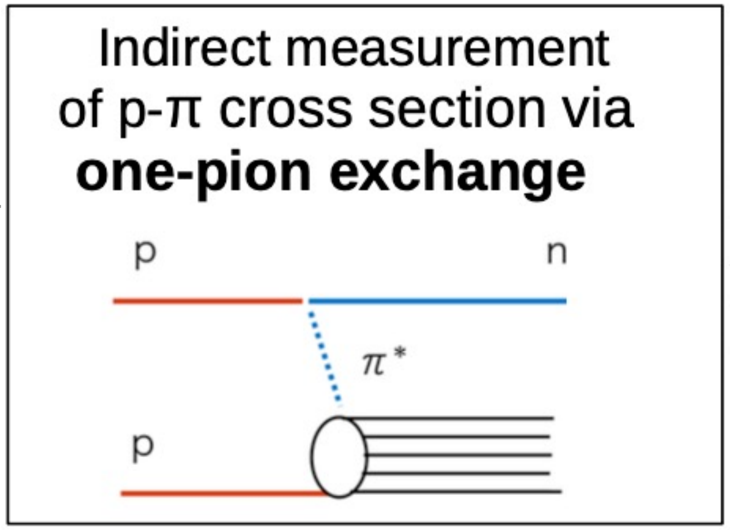


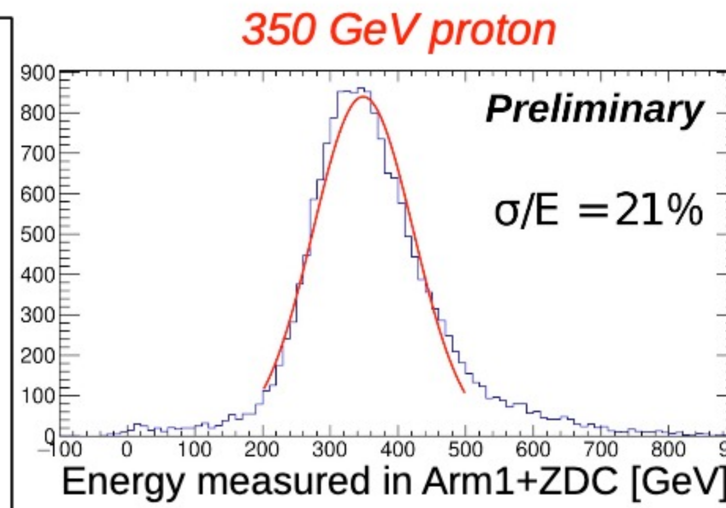


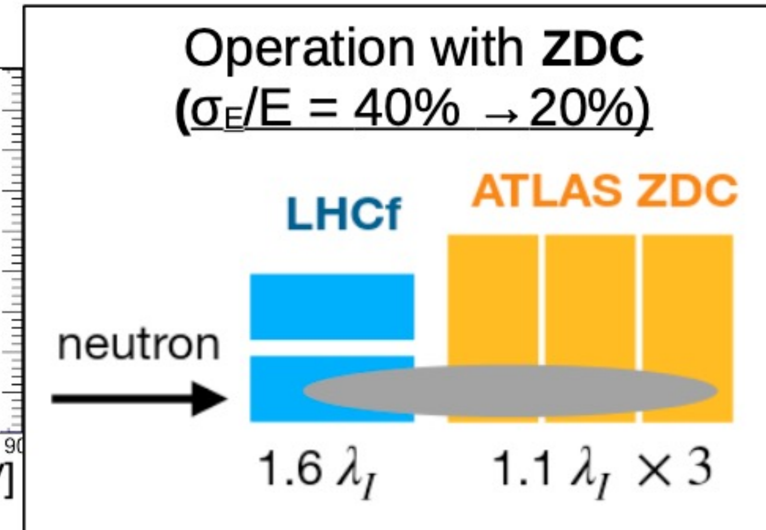
ATLAS-CONF-2017-075

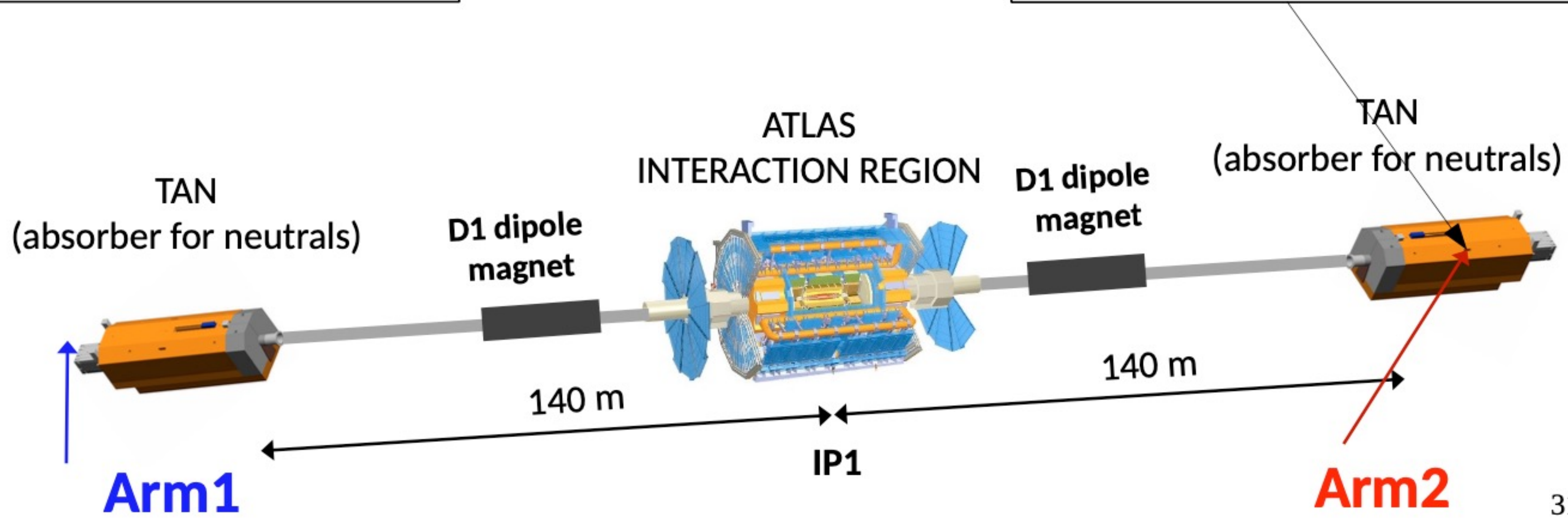
...paper in finalization

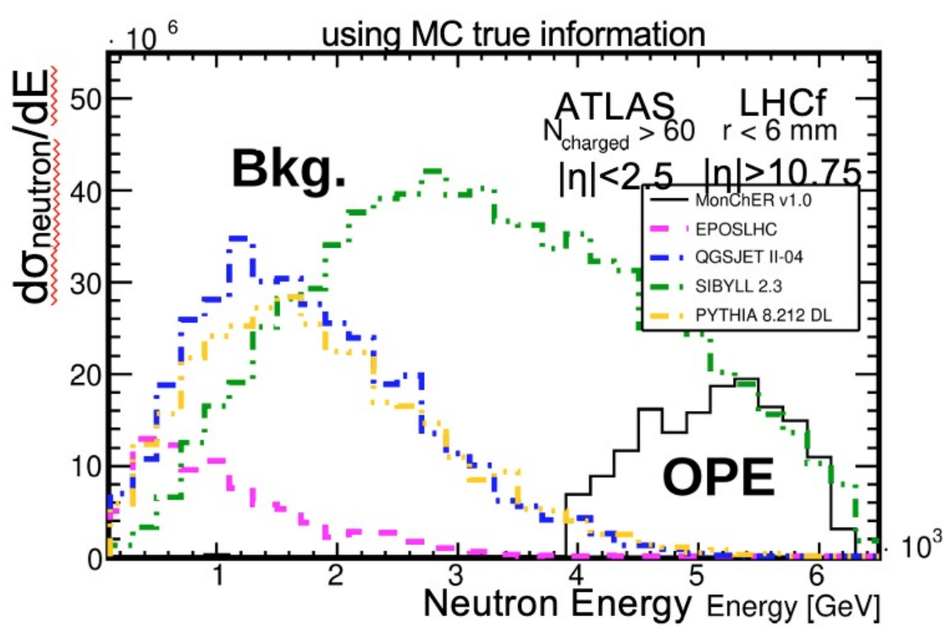
Operations with ATLAS ZDC





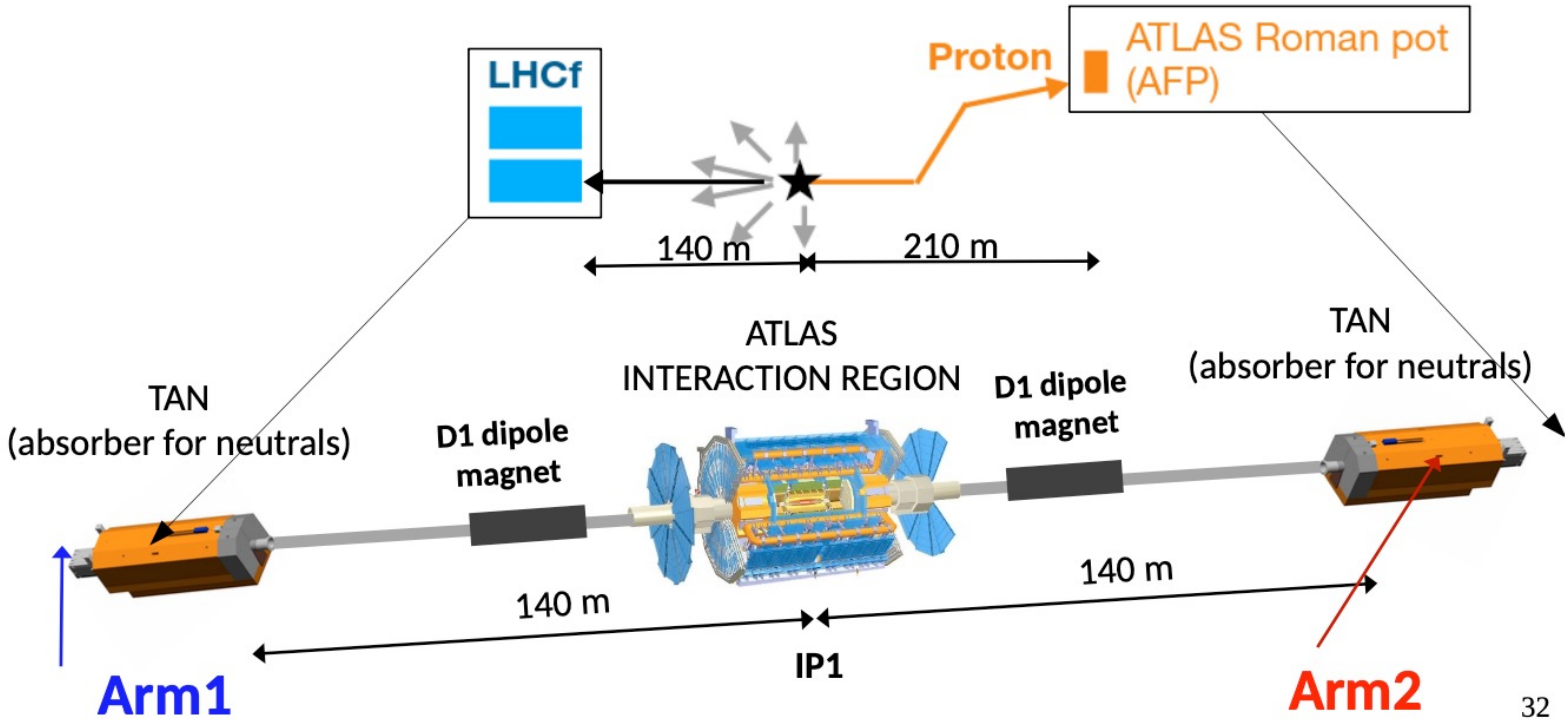






Operations with ATLAS AFP

Identification of **single diffractive events**
+ possible measurements of:
- *Δ resonance* ($p+p \rightarrow p+\Delta \rightarrow p+p+\pi^0$)
- Bremsstrahlung ($p+p \rightarrow p+p+\gamma$)



The future at LHC

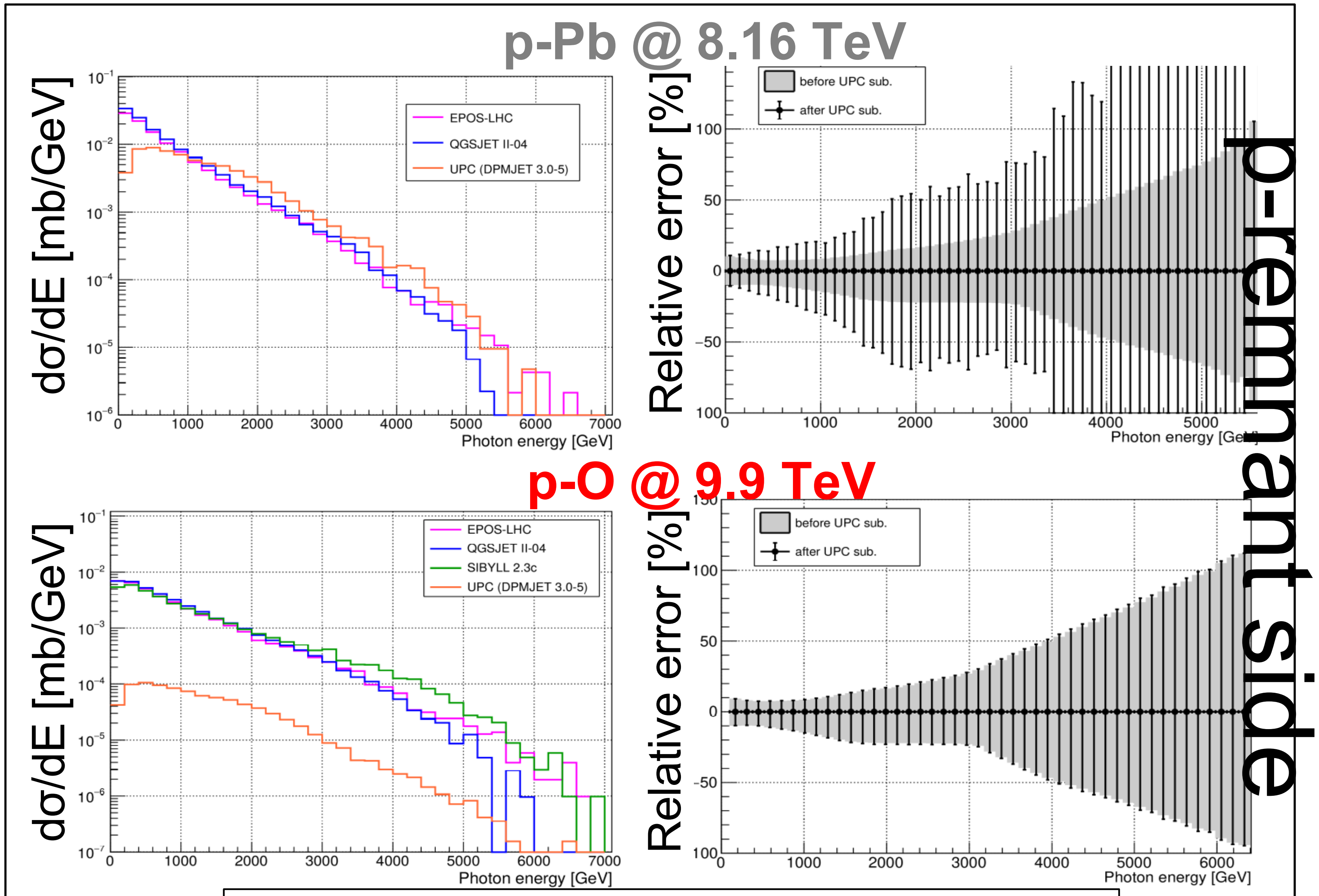
LHCf in Run III: p-O

Foreseen in 2024

Main Motivation

Both p-p and p-Pb collisions are not representative of the first interaction of a UHECR (which is a light nucleus) with an atmospheric nucleus (mainly N or O), hence *the importance of p-O (and O-O) operations to avoid large extrapolation*

In addition, the main uncertainty in forward production from p-Pb collisions is due to contribution from Ultra-Peripheral Collisions (UPC background), which is irrelevant in the EAS case



Forward photon production in η > 10.94

Run III is the **last opportunity** for LHCf!

A **week** of p-O (and possibly O-O) operations foreseen for **2024**

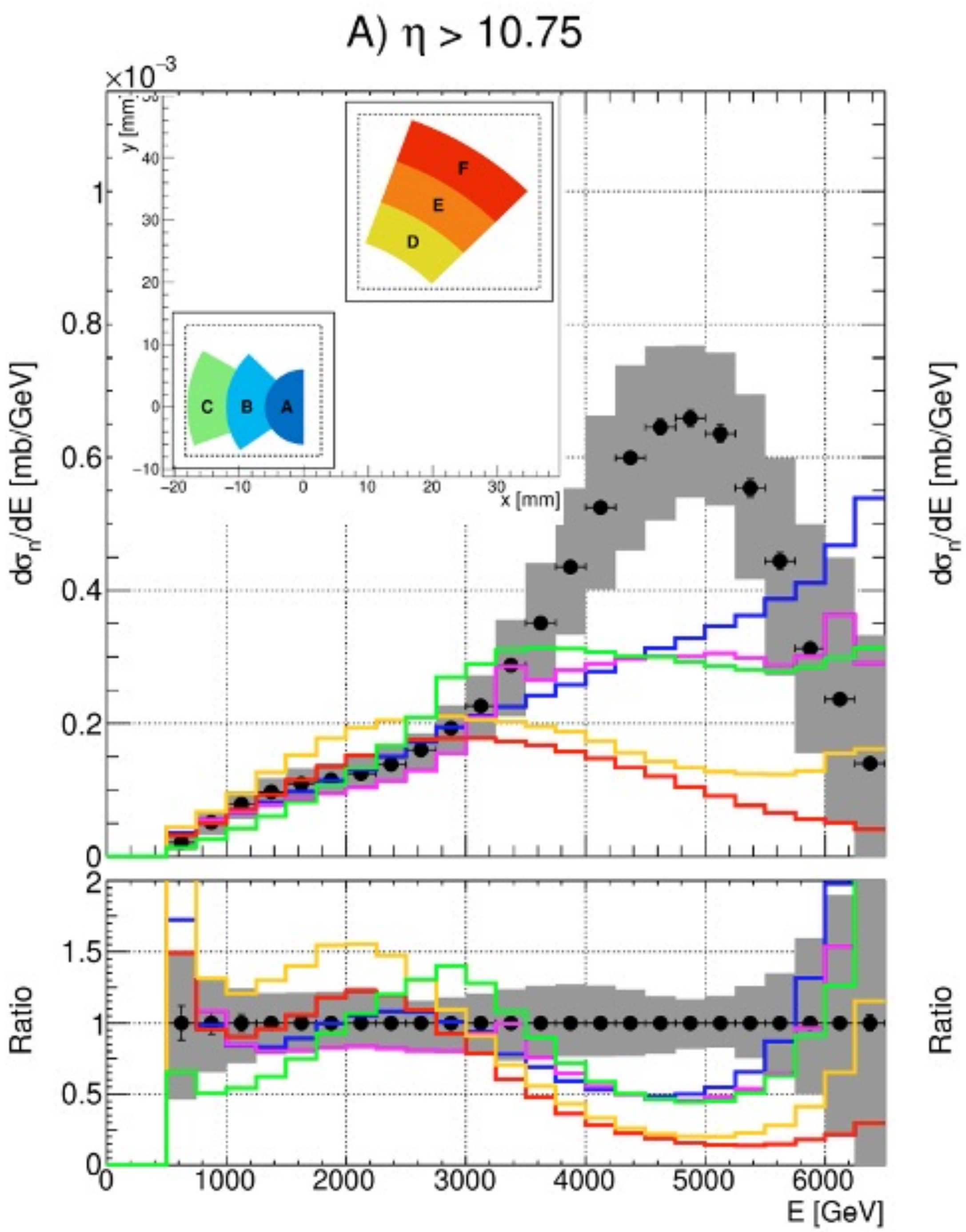
And now …. Why this talk?

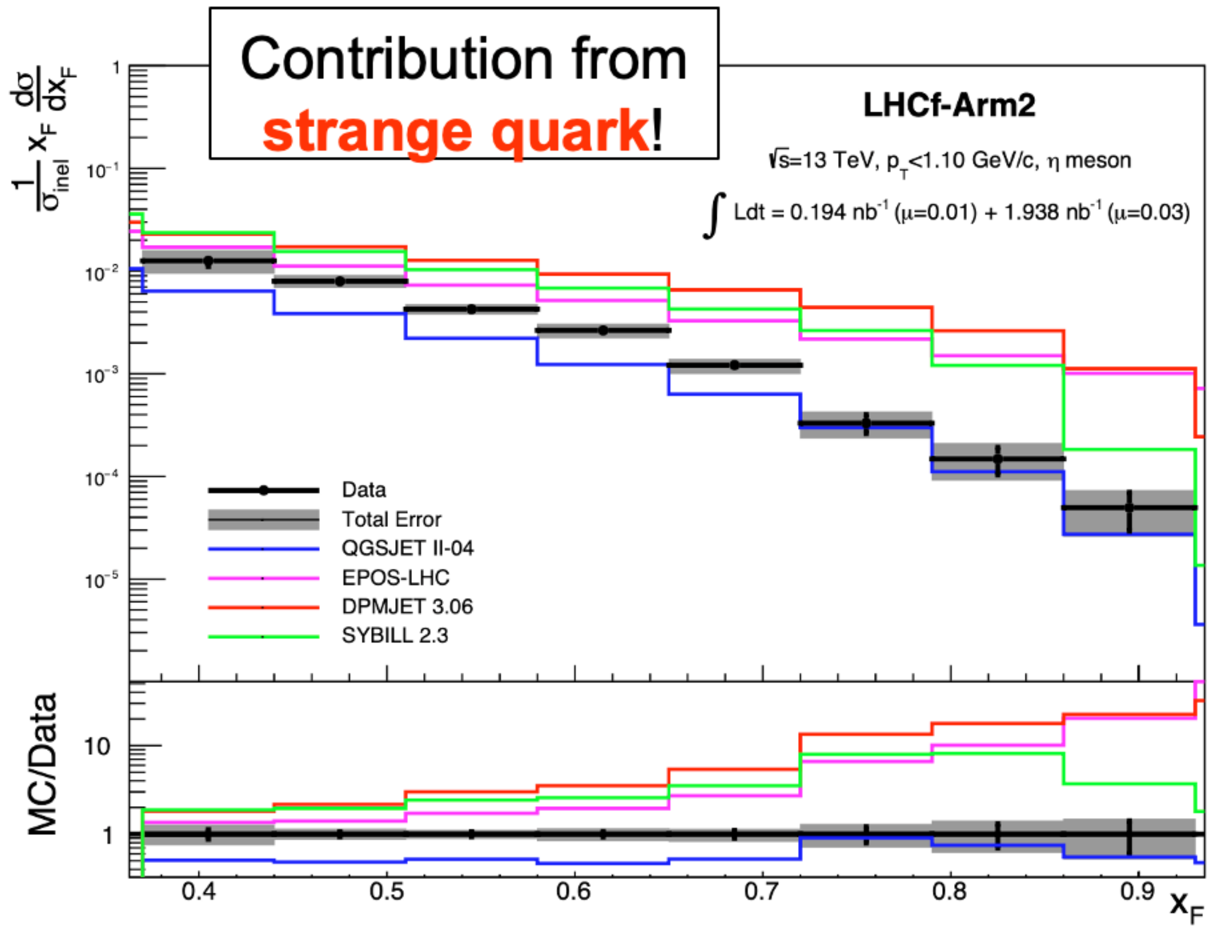
Which is the main reason of this talk?

- We demonstrated in the last 15 years that LHCf is an excellent and very precise detector
  - It is the only forward detector with such excellent performances
    - <2% γ energy resolution, ~30% neutron energy resolution
    - < 200 μm γ position resolution, <1 mm neutron position resolution
    - Able to reconstruct π^o and η
    - With <5% invariant mass resolution
    - Possibility to measure very close γ
    - Possibility to correlate LHCf and ATLAS measurements (forward and central, forward and very forward)

However….

- No significant improvements on the high energy hadronic models in the very forward region have been done in the last 15 years
- Overall very poor agreement with our data and the models expectations
  - Not 10% differences, but a factor 10 differences!!!!!!
  - Very forward neutron peak not reproduced at all by any model
- We have tried to do at our best all the measurements asked by the model developers
  - Single spectra, P_t vs X_F spectra, correlation with central region, strange quarks, etc.
- Clear difficulty for them to tune their phenomenologically models in our restricted phase space
- As a results:
  - No significant improvements in the High Energy Cosmic Rays physics
- And this is a real pity!!!!


A) η > 10.75
dσn/dE [mb/GeV]
Ratio
E [GeV]
x [mm]
y [mm]
A
B
C
D
E
F


Contribution from strange quark!
LHCf-Arm2
√s=13 TeV, pT<1.10 GeV/c, η meson
∫ Ldt = 0.194 nb⁻¹ (μ=0.01) + 1.938 nb⁻¹ (μ=0.03)
Data
Total Error
QGSJET II-04
EPOS-LHC
DPMJET 3.06
SYBILL 2.3
MC/Data
xF

A possible help from this community?

- This workshop: “Theory Challenges in the Precision Era of the Large Hadron Collider” looks to us a perfect place to ask help from this theory community
- Could you envisage some possibility to improve the theoretical expectations in the LHCf related physics?
- Could you envisage some possibility to develop new calculation methods that can help to reduce the theoretical uncertainties in the LHCf related measurements?
- Could you envisage some possibility for a theoretical collaboration with LHCf experimental peoples?

- I think it is really a pity not to exploit all the LHCf potential to improve the UHECR field and the high energy hadronic models!!!!

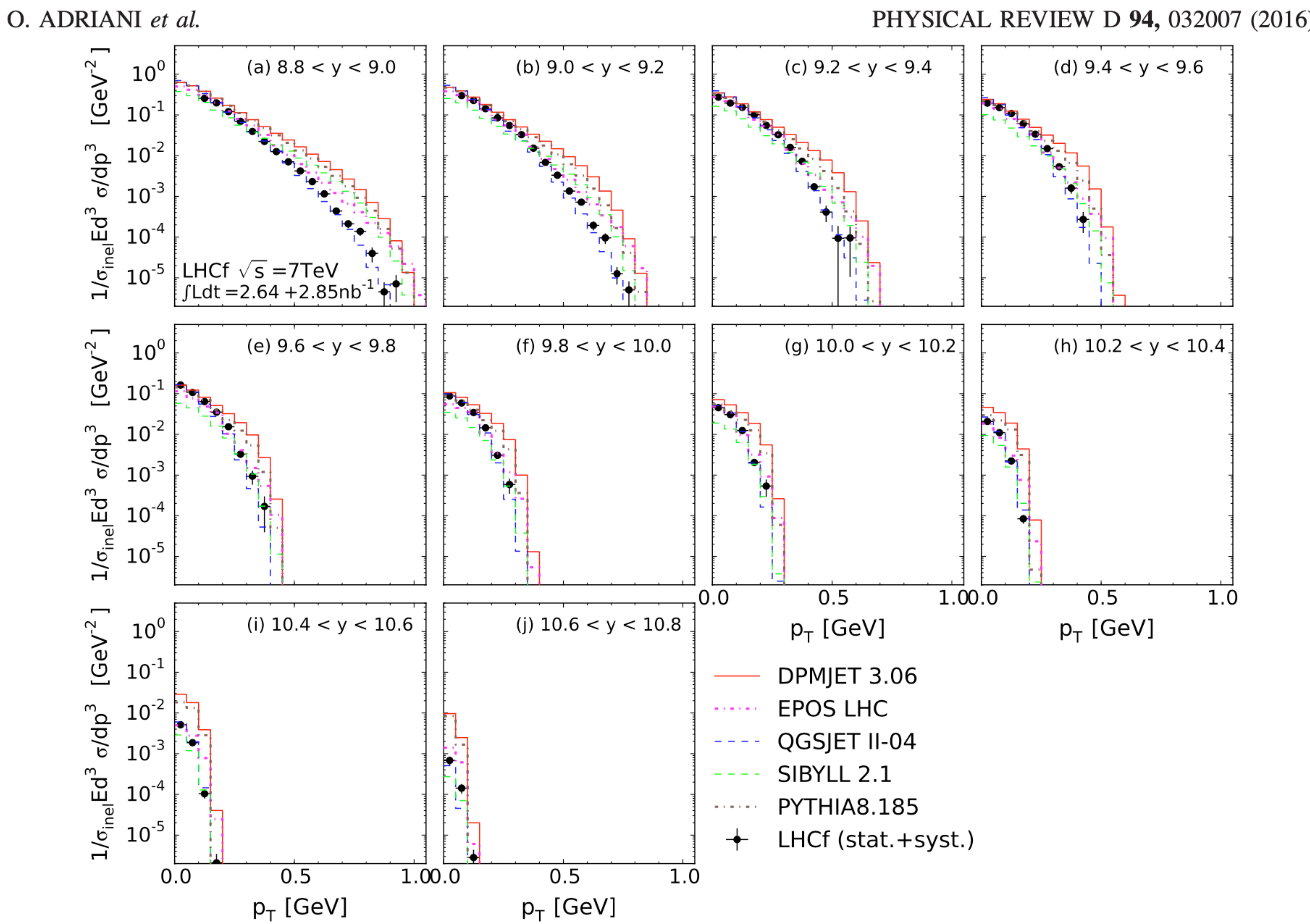
Thanks!!!

Compilation of all LHCf/RHICf published results

π^0

π^0@7 TeV: P_T vs η

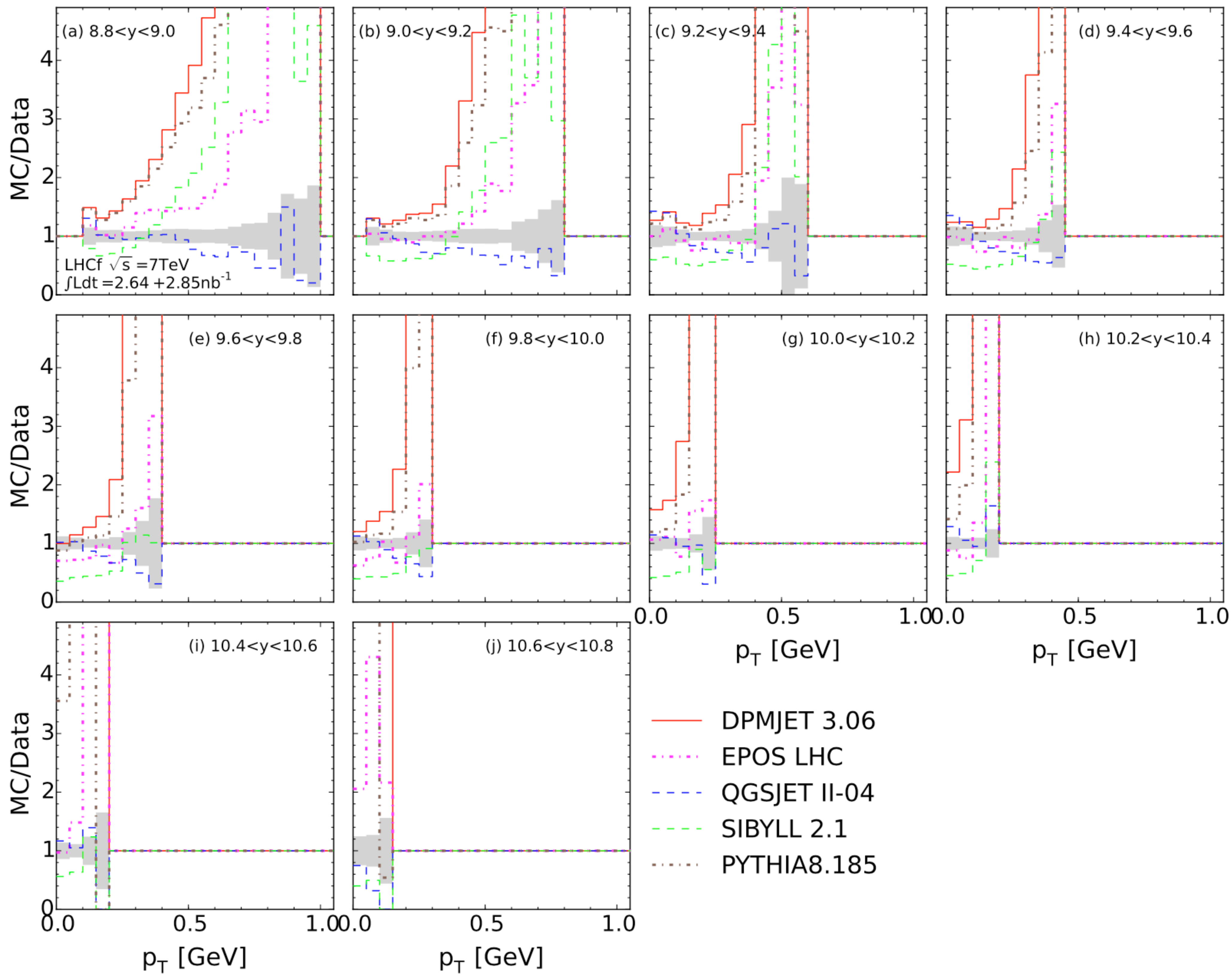
PhysRevD.94.032007



π^0@7 TeV: P_T vs η MC/Data

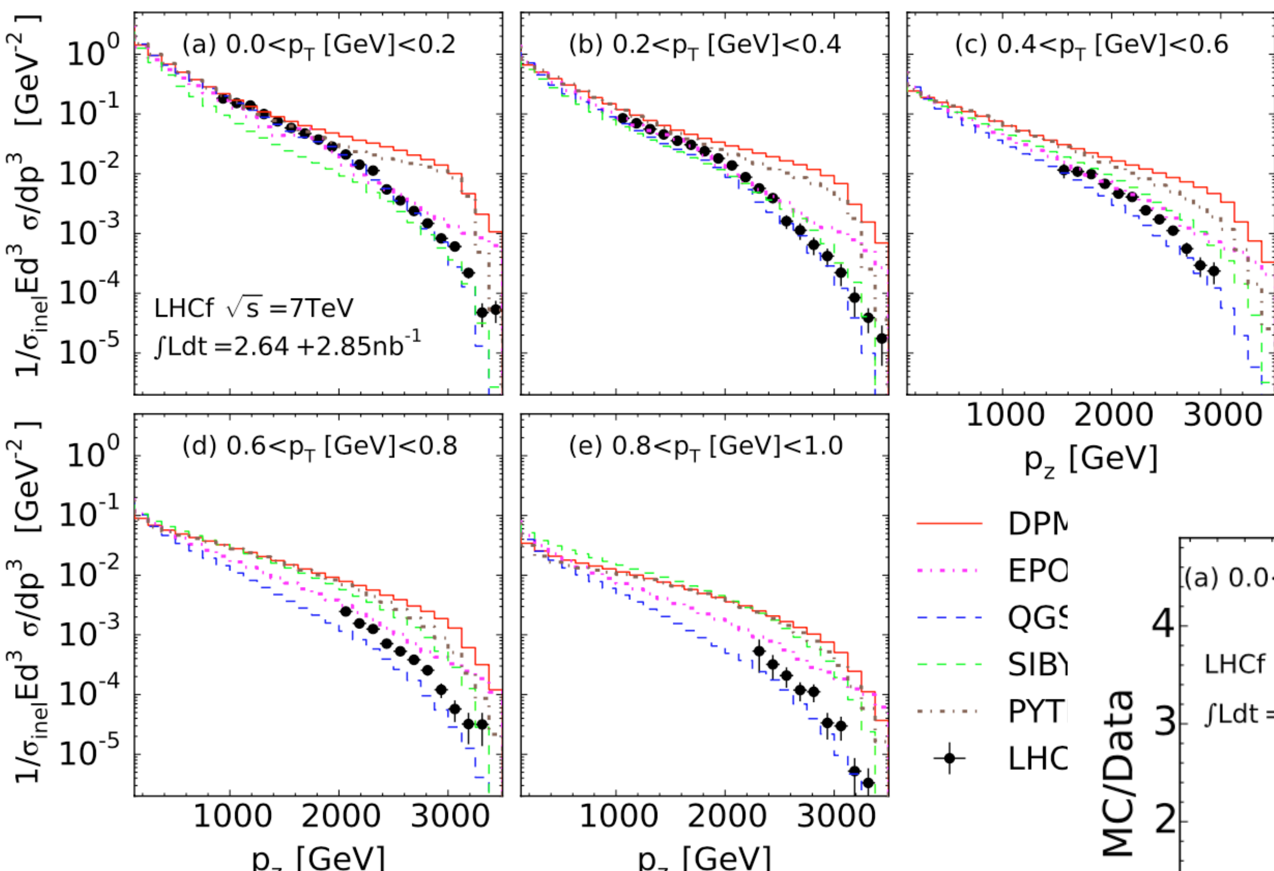
PhysRevD.94.032007

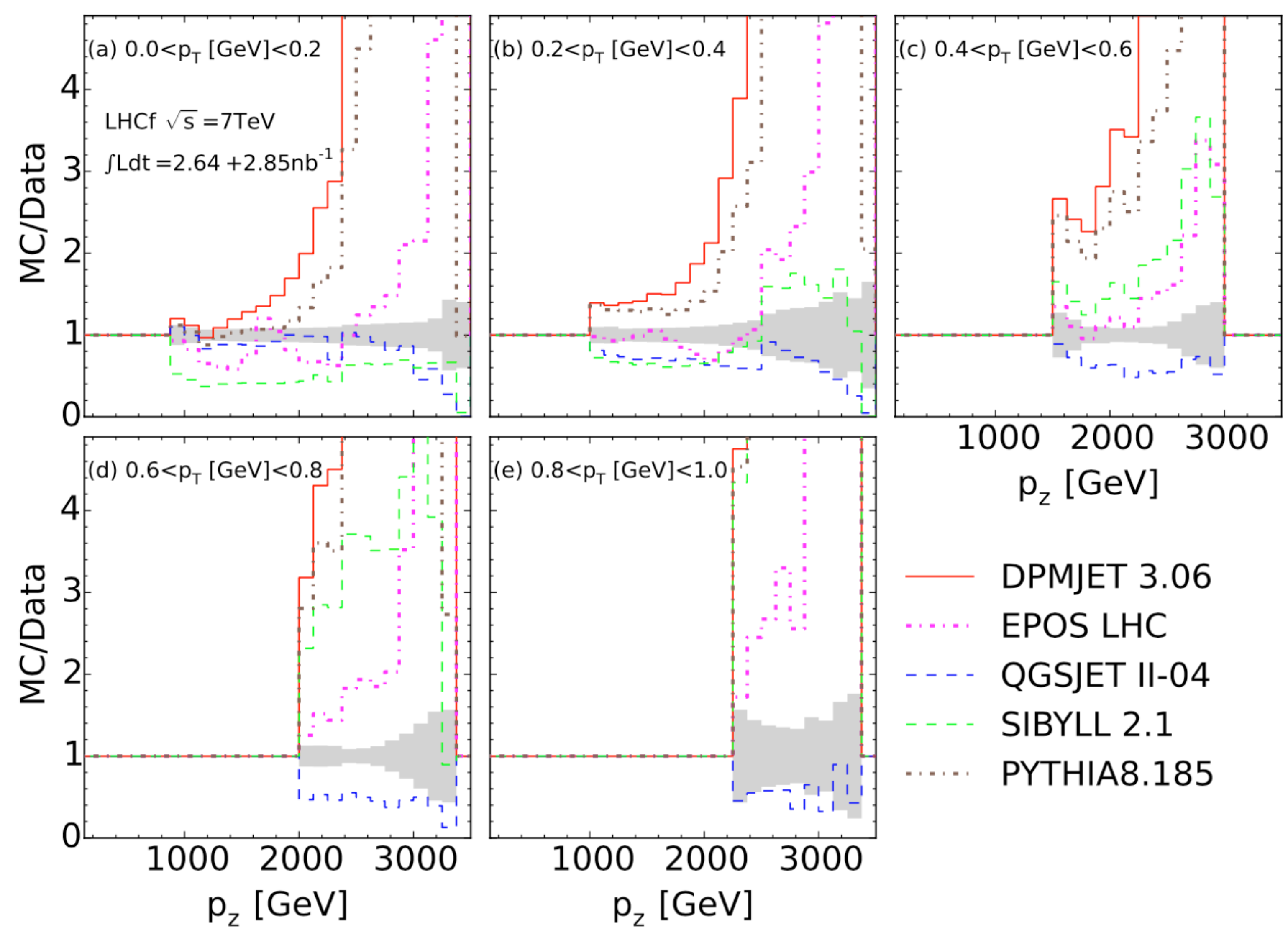
MEASUREMENTS OF LONGITUDINAL AND TRANSVERSE … PHYSICAL REVIEW D **94,** 032007 (2016)



π^0@7 TeV: P_Z vs P_T PhysRevD.94.032007

PHYSICAL REVIEW D **94,** 032007 (2016)

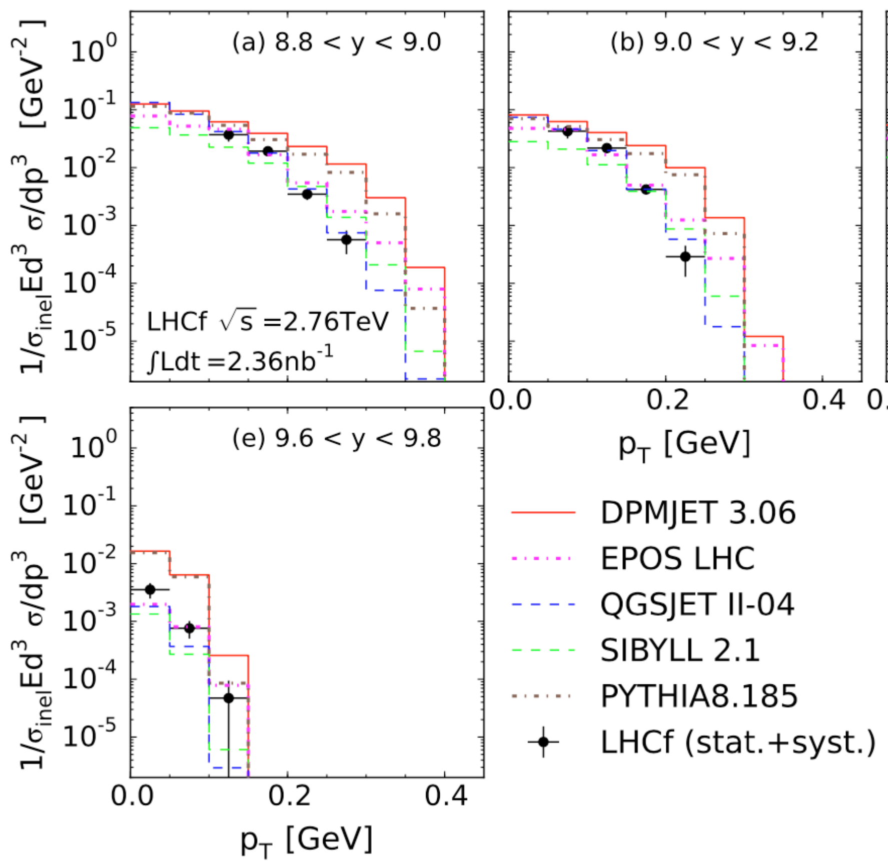


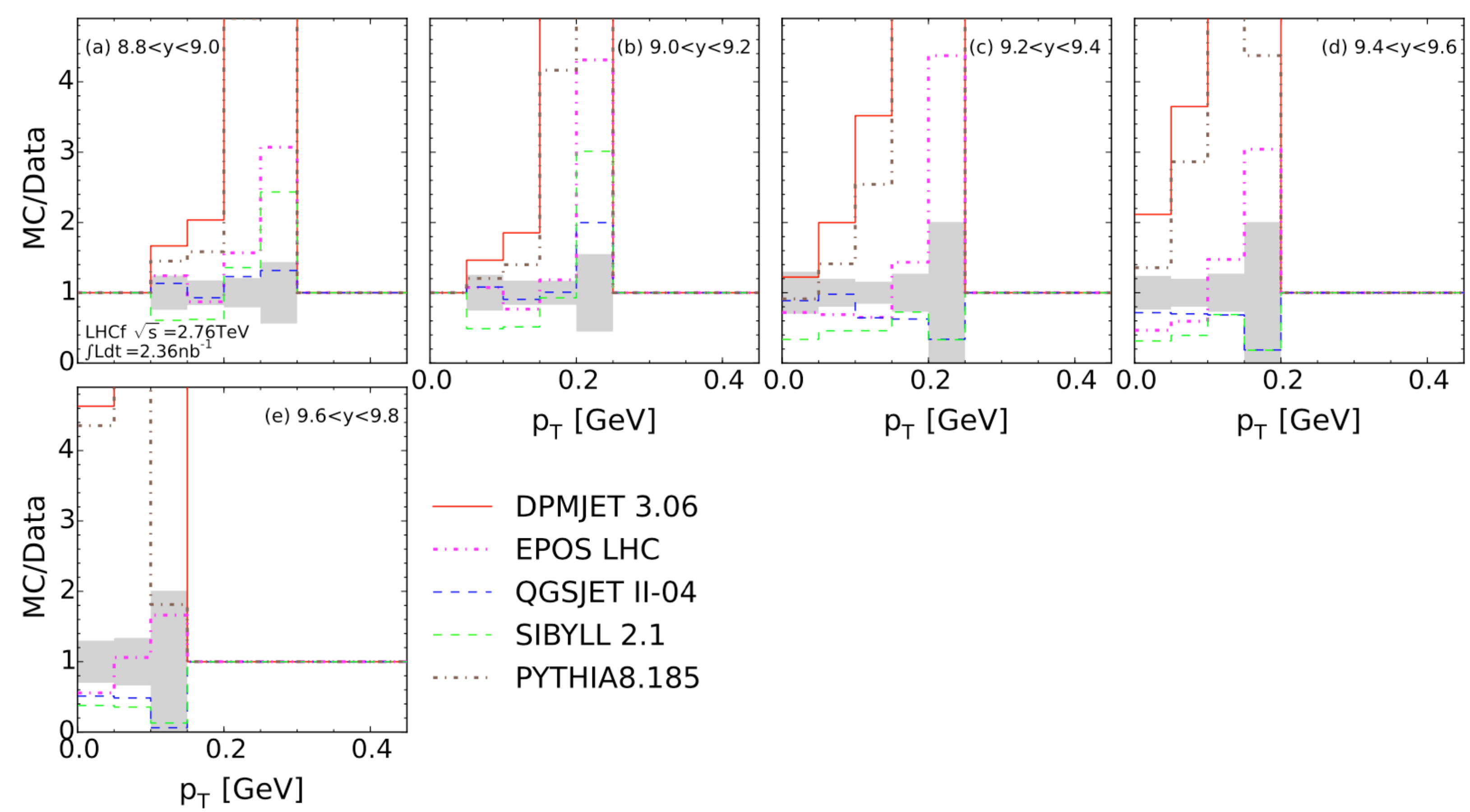


π^0@2.76 TeV: P_T vs η

PhysRevD.94.032007

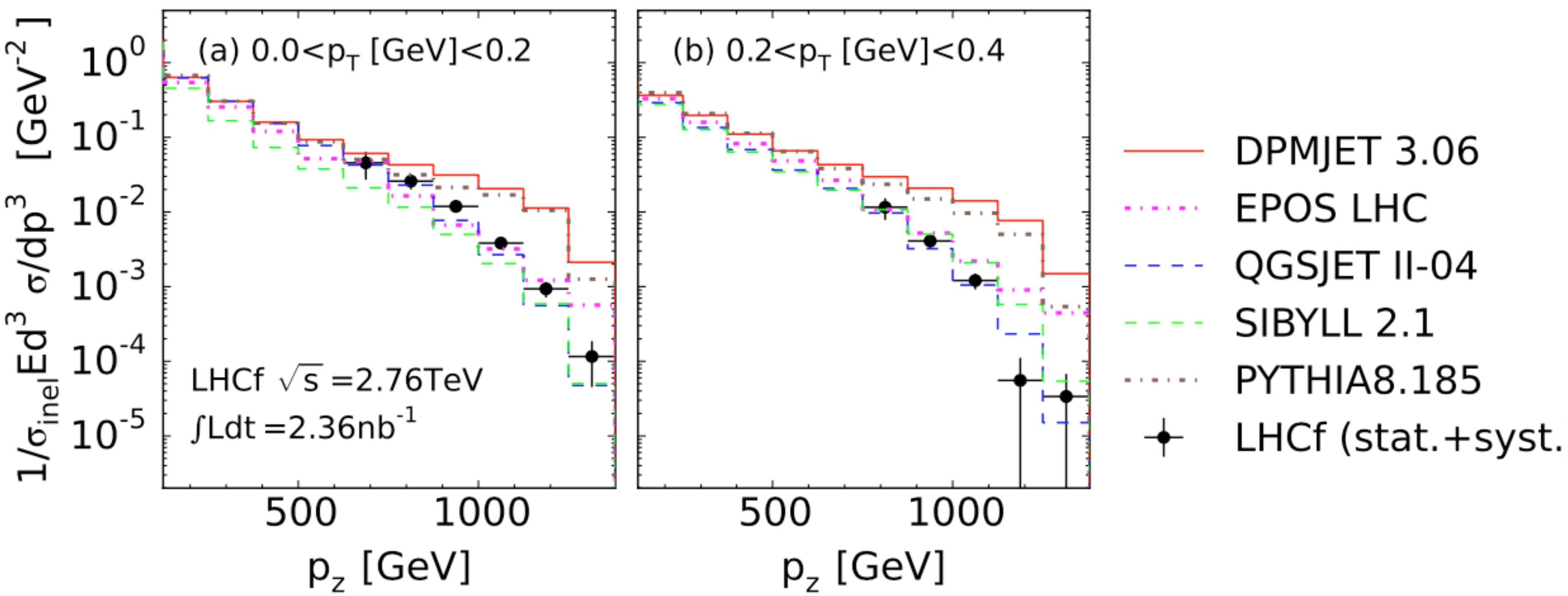
MEASUREMENTS OF LONGITUDINAL AND TRANSVERSE … PHYSICAL REVIEW D **94,** 032007 (2016)

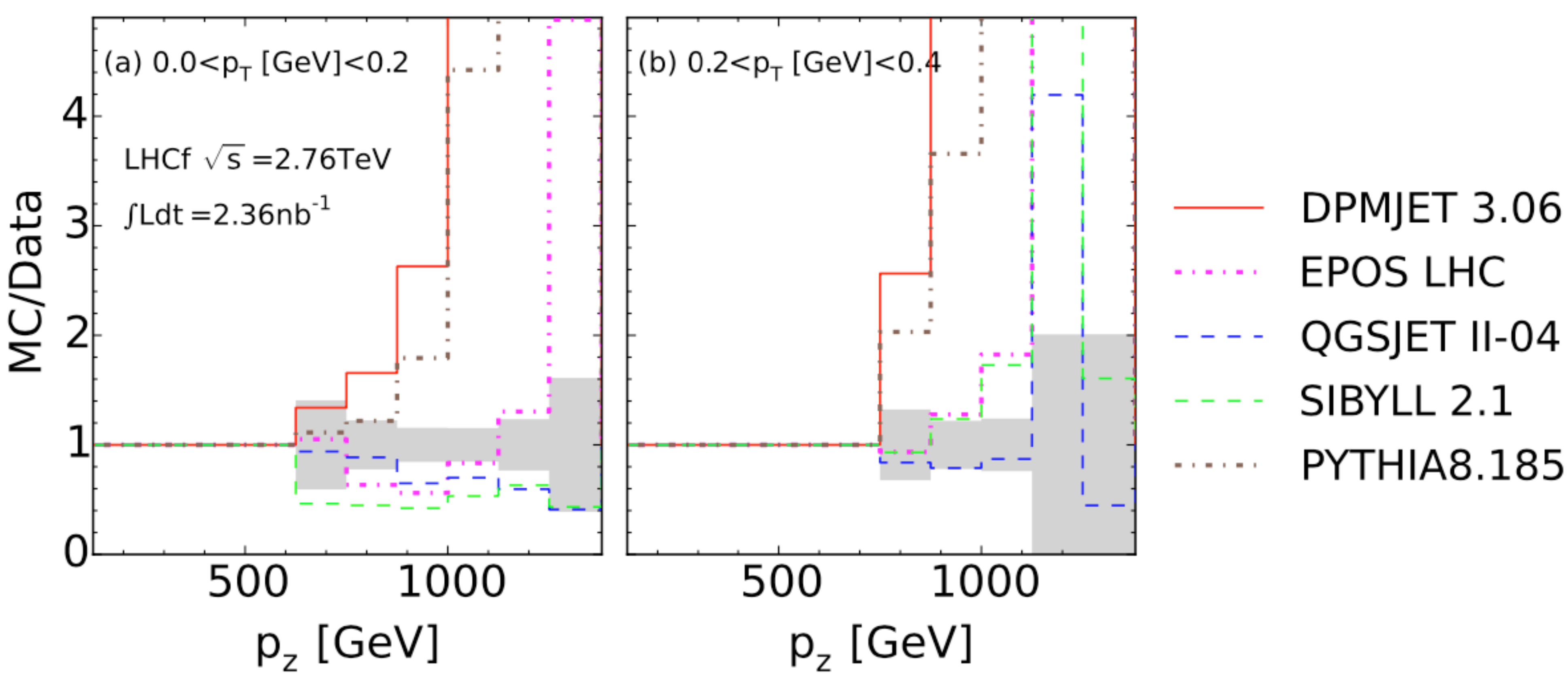




π^0@2.76 TeV: P_Z vs P_T PhysRevD.94.032007

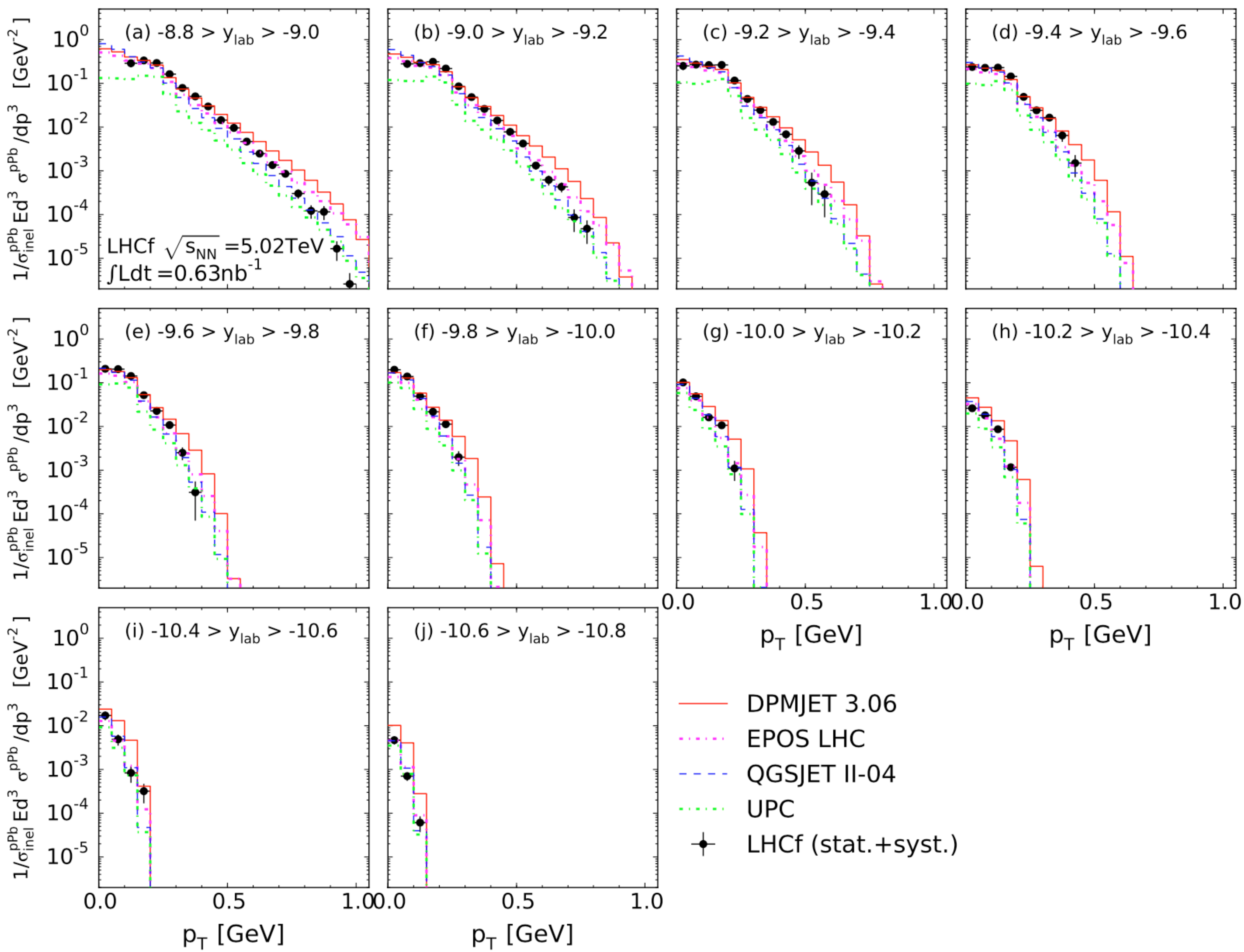
PHYSICAL REVIEW D **94,** 032007 (2016)



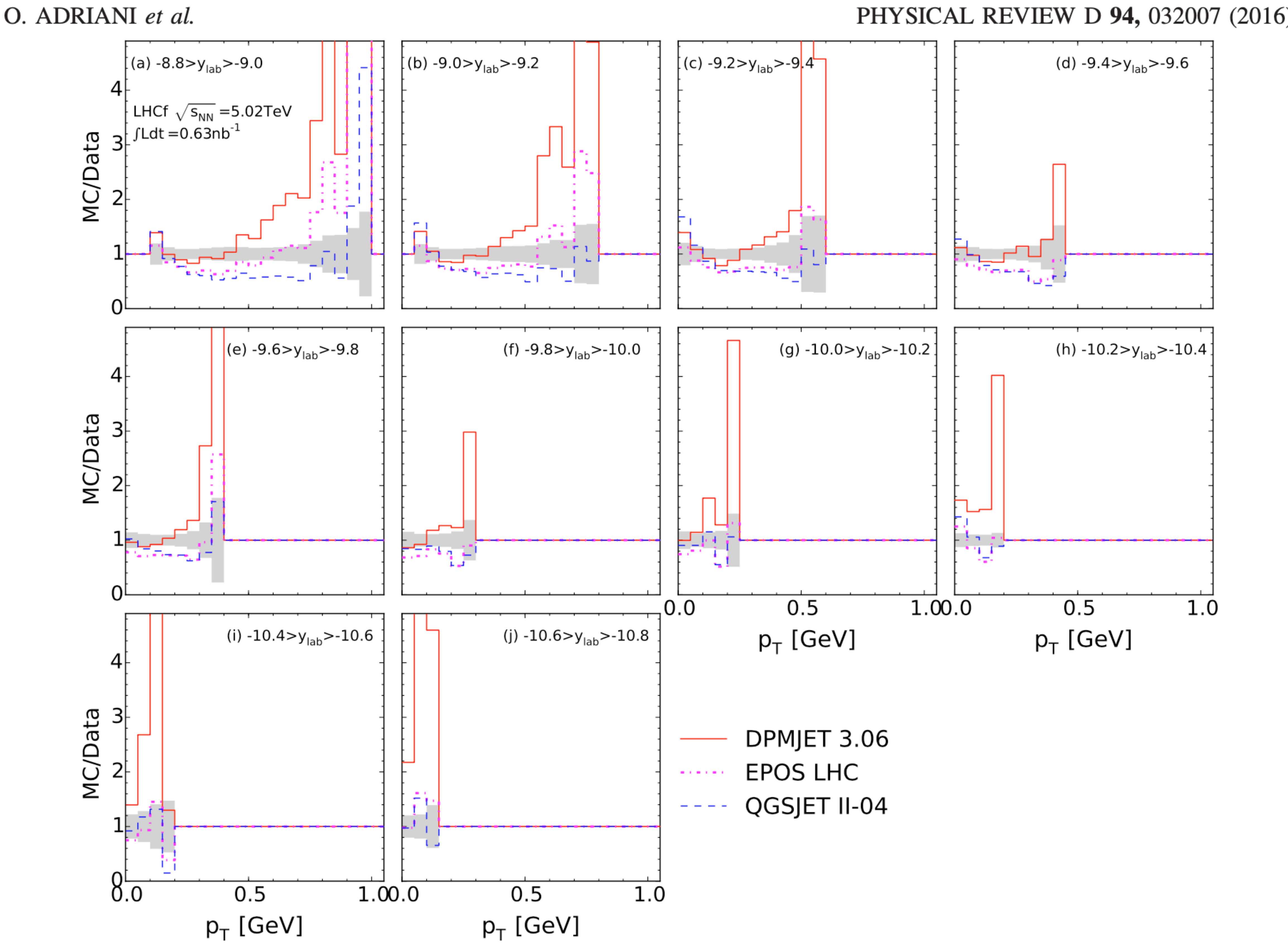


π^0@5.02 TeV p-Pb: P_T vs η PhysRevD.94.032007

MEASUREMENTS OF LONGITUDINAL AND TRANSVERSE … PHYSICAL REVIEW D **94,** 032007 (2016)



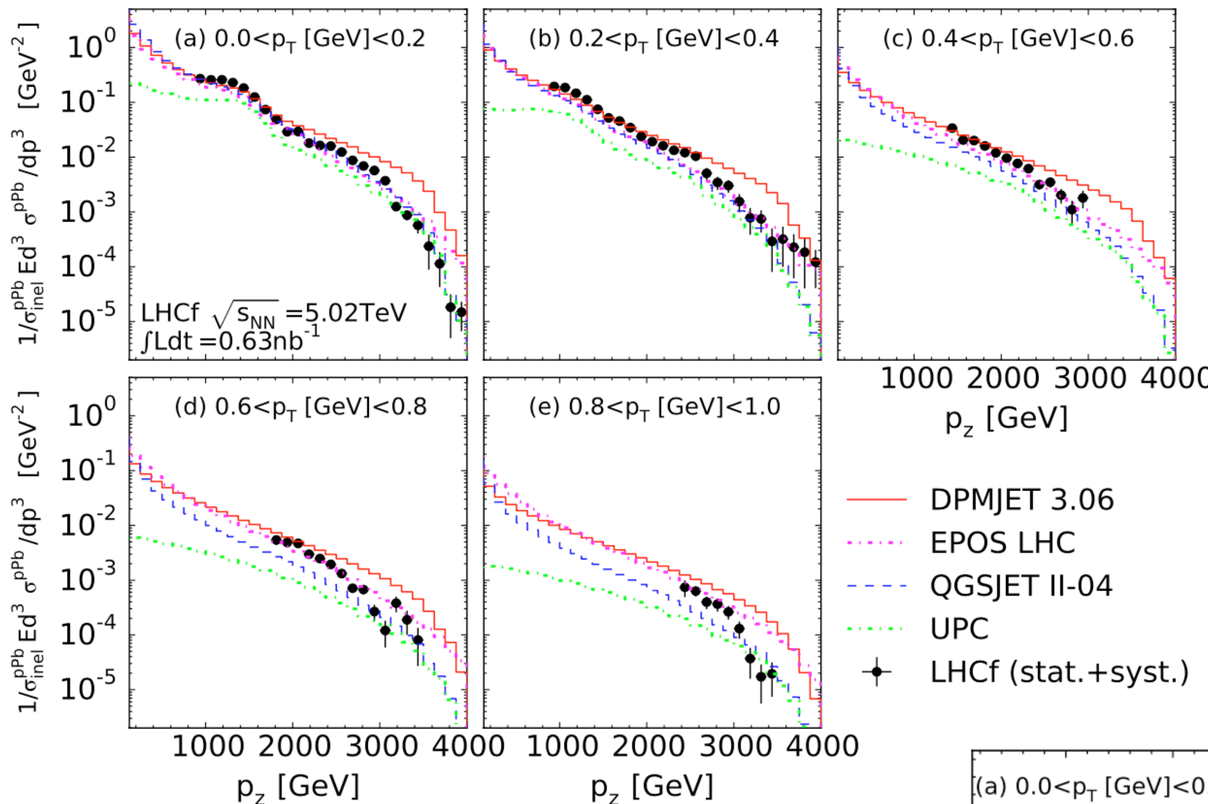
π^0@5.02 TeV p-Pb: P_T vs η PhysRevD.94.032007

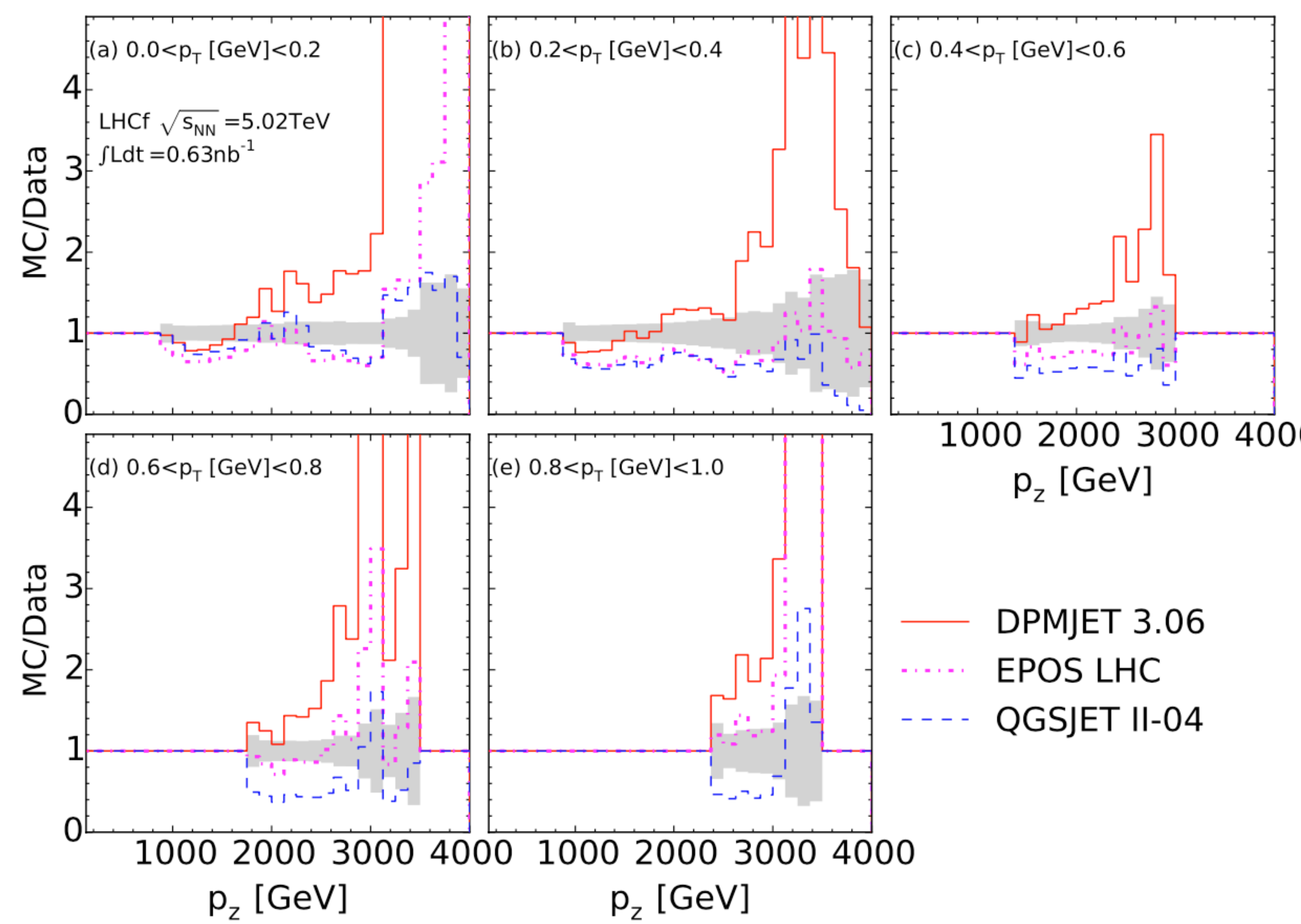


π^0@5.02 TeV p-Pb: P_Z vs P_T

PhysRevD.94.032007

MEASUREMENTS OF LONGITUDINAL AND TRANSVERSE … PHYSICAL REVIEW D **94,** 032007 (2016)

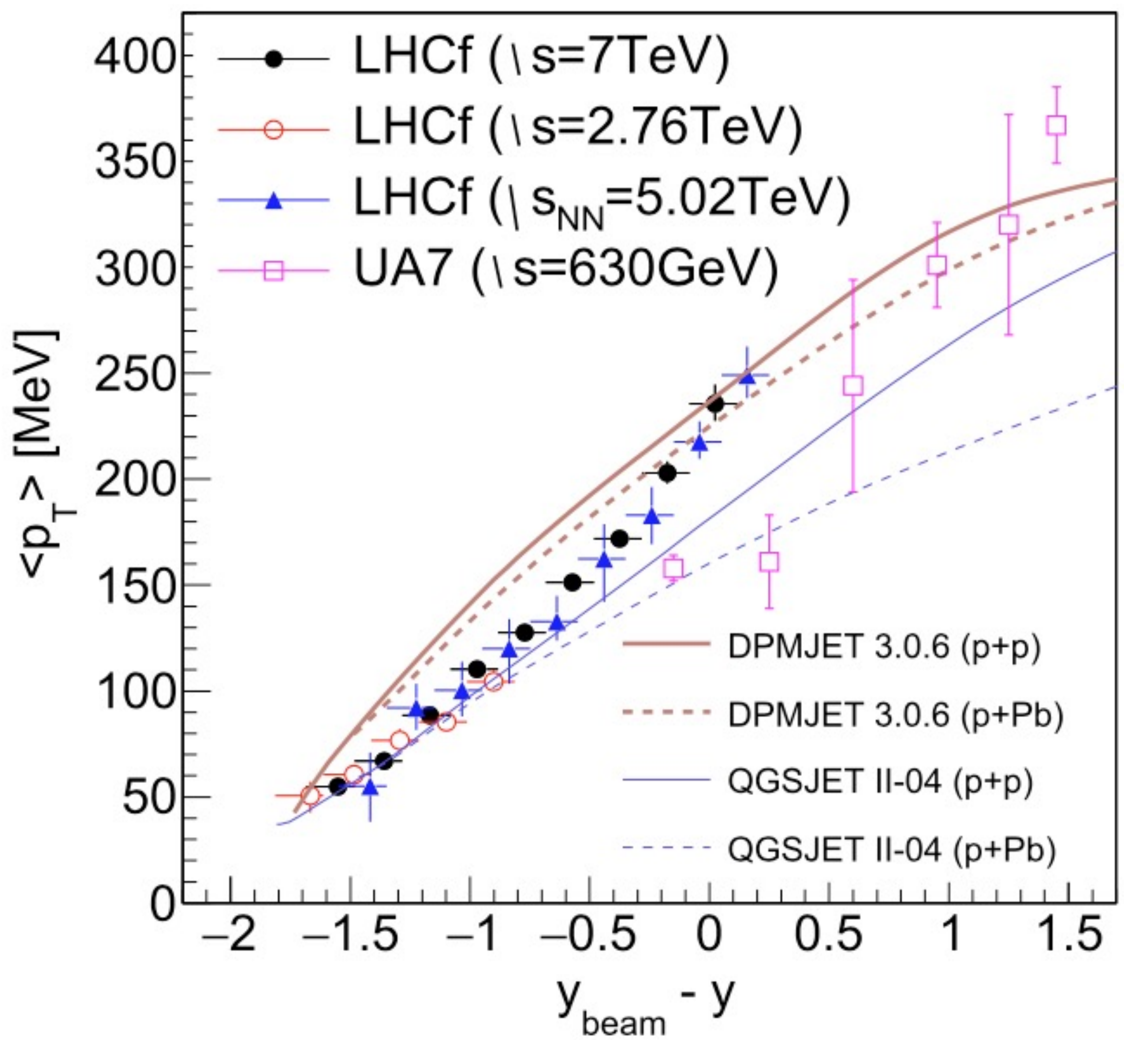




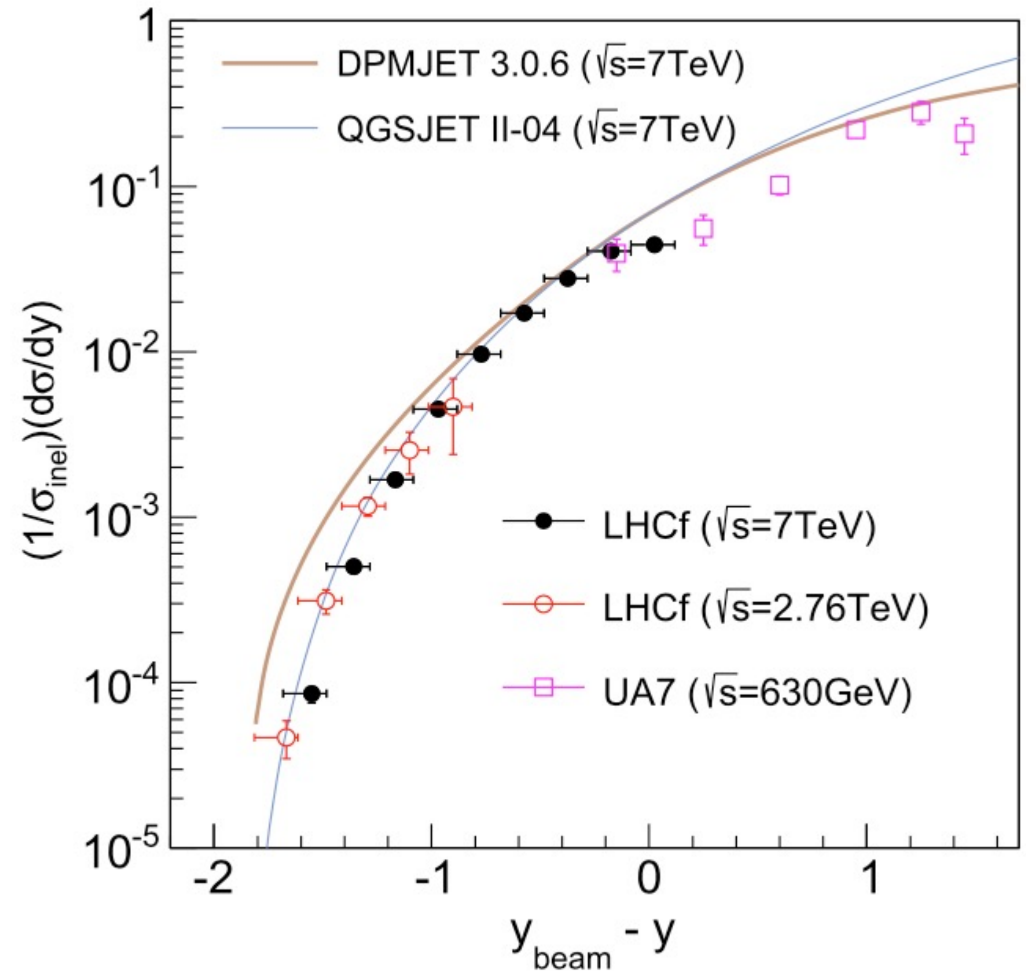
π^0 : <P_T> and $d\sigma/d\eta$

PhysRevD.94.032007

PHYSICAL REVIEW D **94,** 032007 (2016)

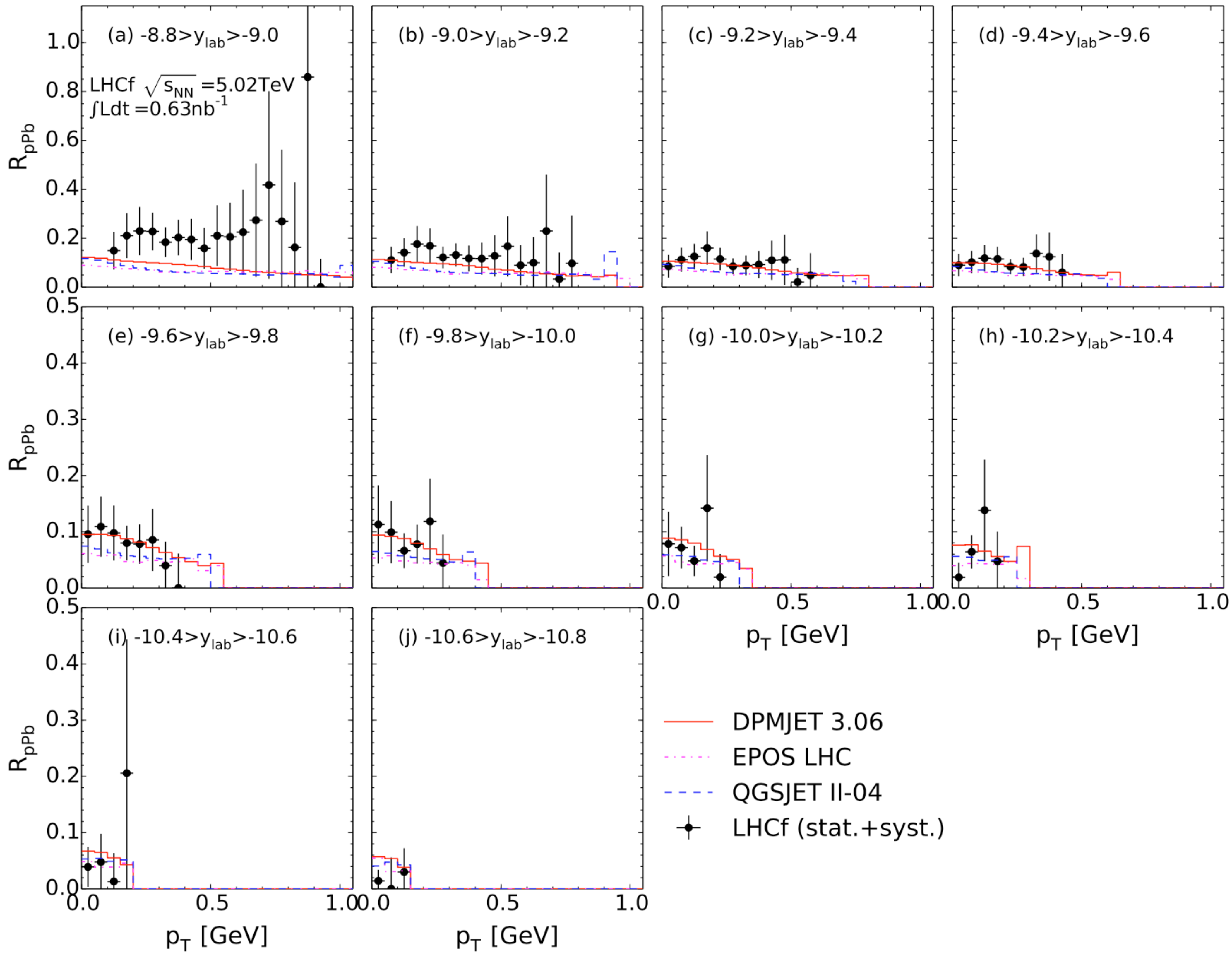


PHYSICAL REVIEW D **94,** 032007 (2016)



π^0@5.02 TeV p-Pb: Nuclear Modification Factor

PhysRevD.94.032007



π^0@7 TeV: P_T vs η

PhysRevD.86.092001

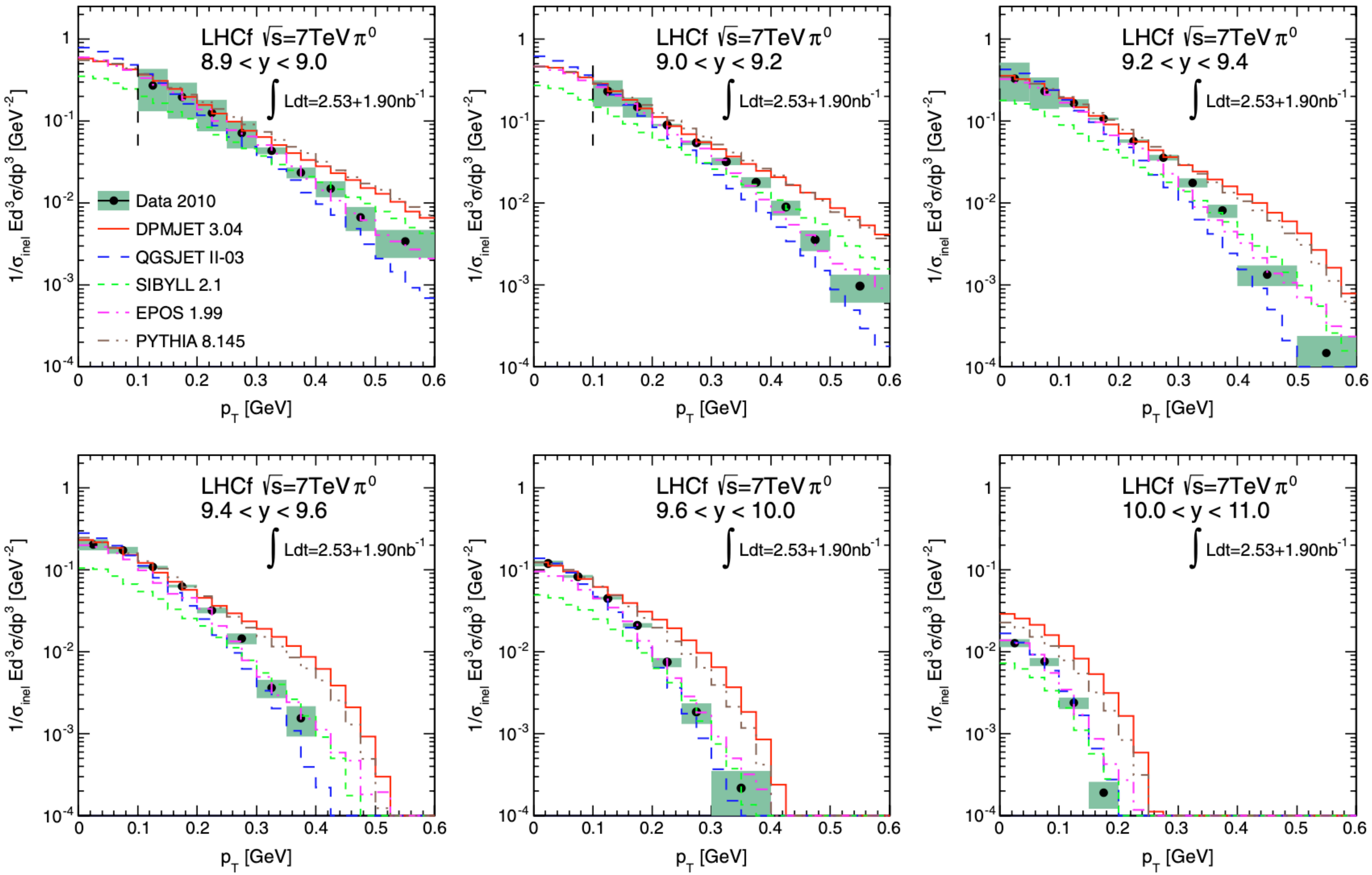


FIG. 7 (color online). Combined p_T spectra of the Arm1 and Arm2 detectors (black dots) and the total uncertainties (shaded rectangles) compared with the predicted spectra by hadronic interaction models.

π^0@7 TeV: P_T vs η MC/Data   PhysRevD.86.092001

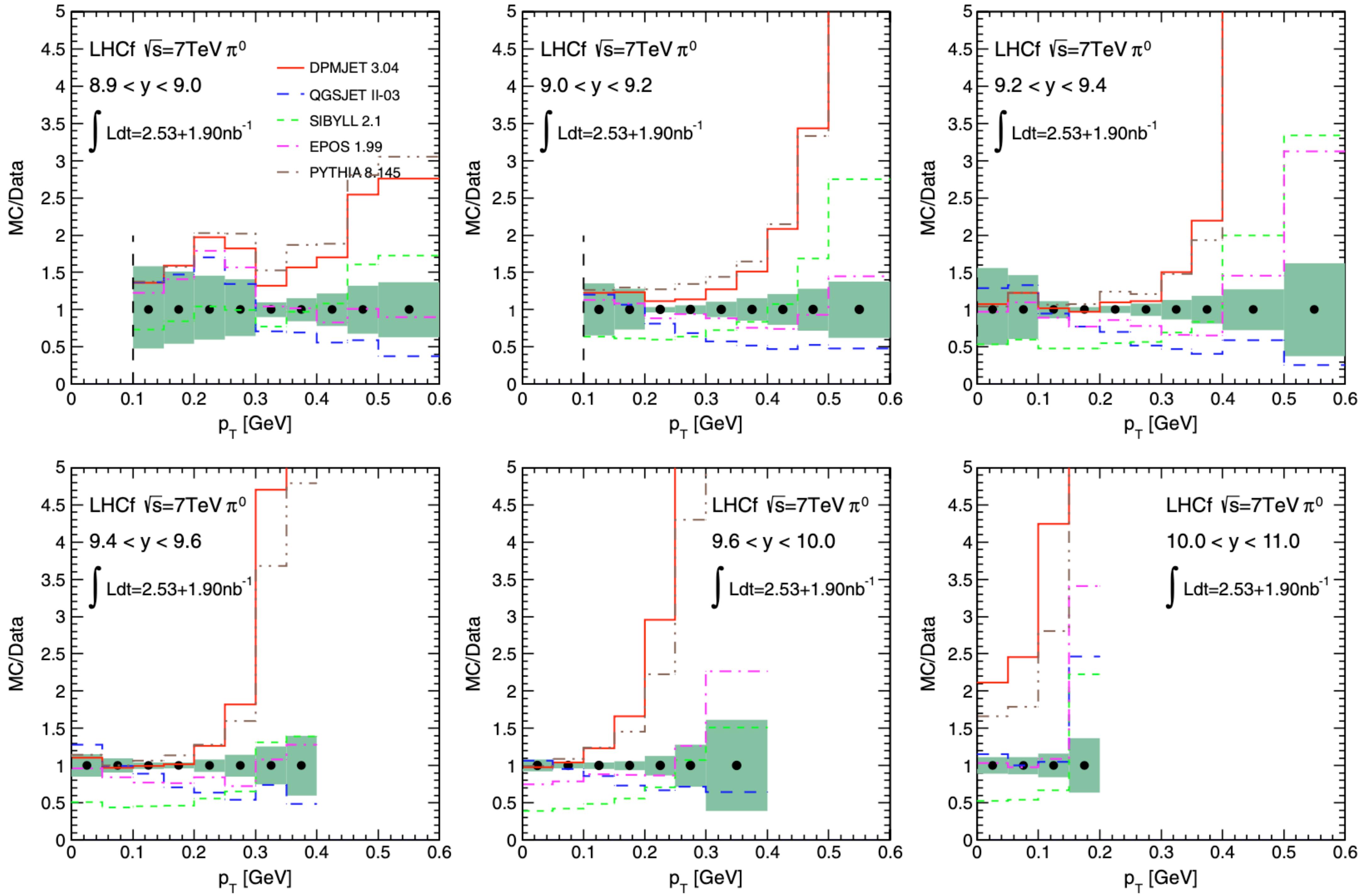


FIG. 8 (color online). Ratio of the combined p_T spectra of the Arm1 and Arm2 detectors to the predicted p_T spectra by hadronic interaction models. Shaded areas indicate the range of total uncertainties of the combined p_T spectra.

π^0@5.02 TeV p-Pb: P_T vs η PhysRevC.89.065209

O. ADRIANI *et al.* PHYSICAL REVIEW C **89**, 065209 (2014)

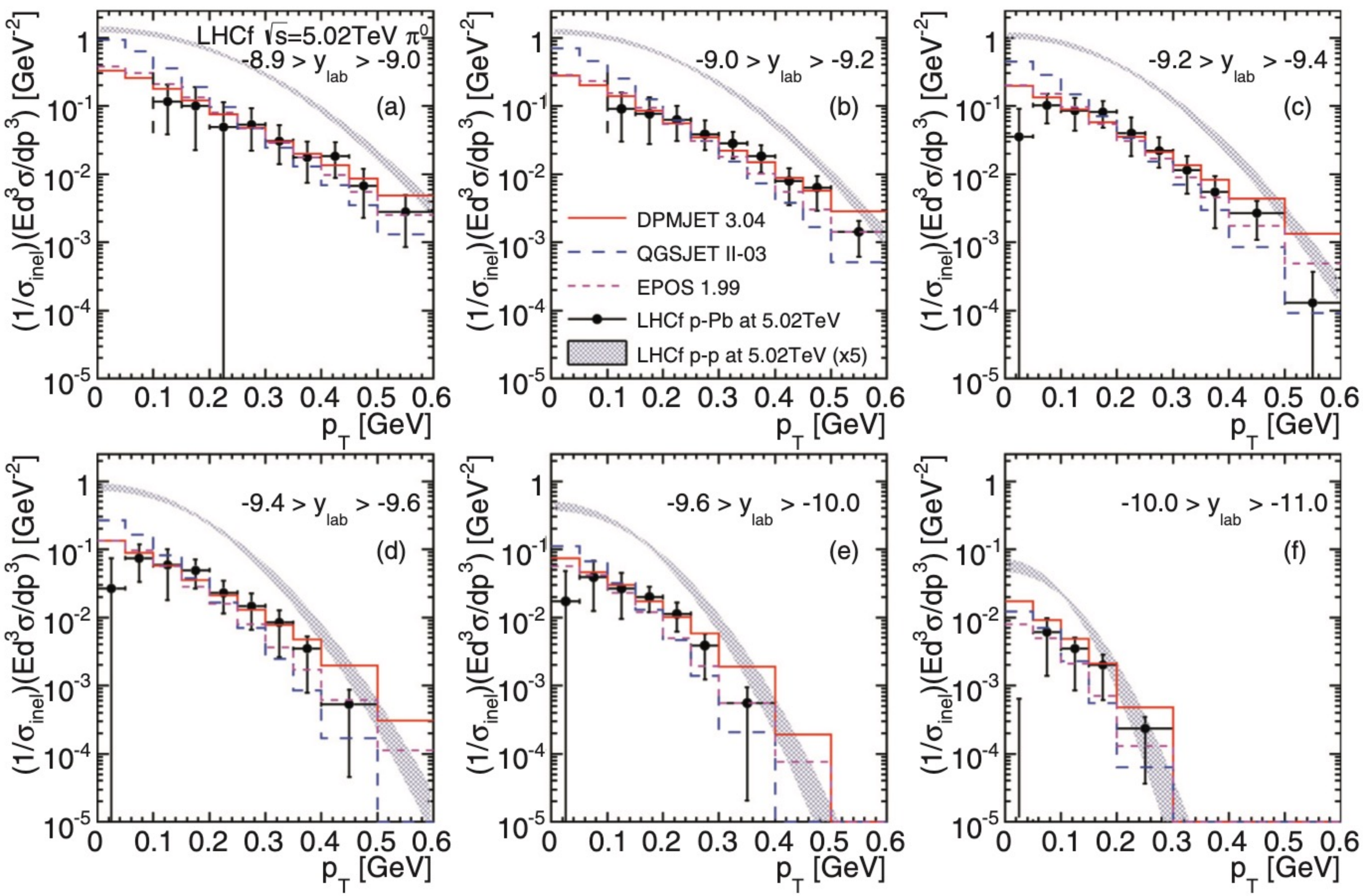


FIG. 3. (Color online) Experimental p_T spectra measured by LHCf after the subtraction of the UPC component (filled circles). Error bars indicate the total uncertainties incorporating both statistical and systematic uncertainties. Hadronic interaction models predictions and derived spectra for p-p collisions at 5.02 TeV are also shown (see text for details).

π^0@5.02 TeV p-Pb: P_T vs η MC/Data

PhysRevC.89.065209

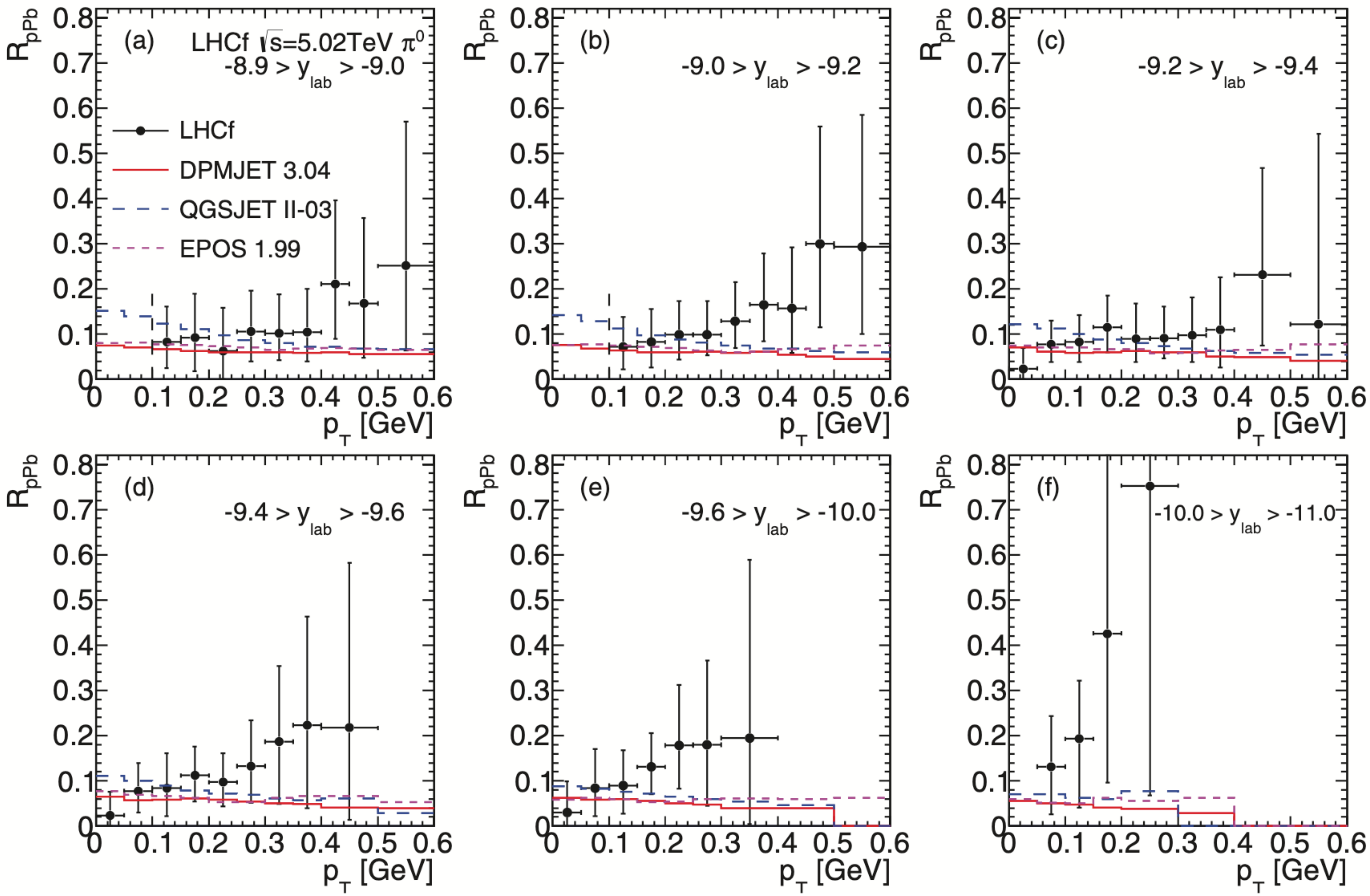


FIG. 6. (Color online) Nuclear modification factor for π^0's. Filled circles indicate the factors obtained by the LHCf measurements. Error bars indicate the total uncertainties incorporating both statistical and systematic uncertainties. Other lines are the predictions by hadronic interaction models (see text for details.)

π^0@510 GeV polarized p-p (RHICf): Neutron Asymmetry

PRL124_2020_252501

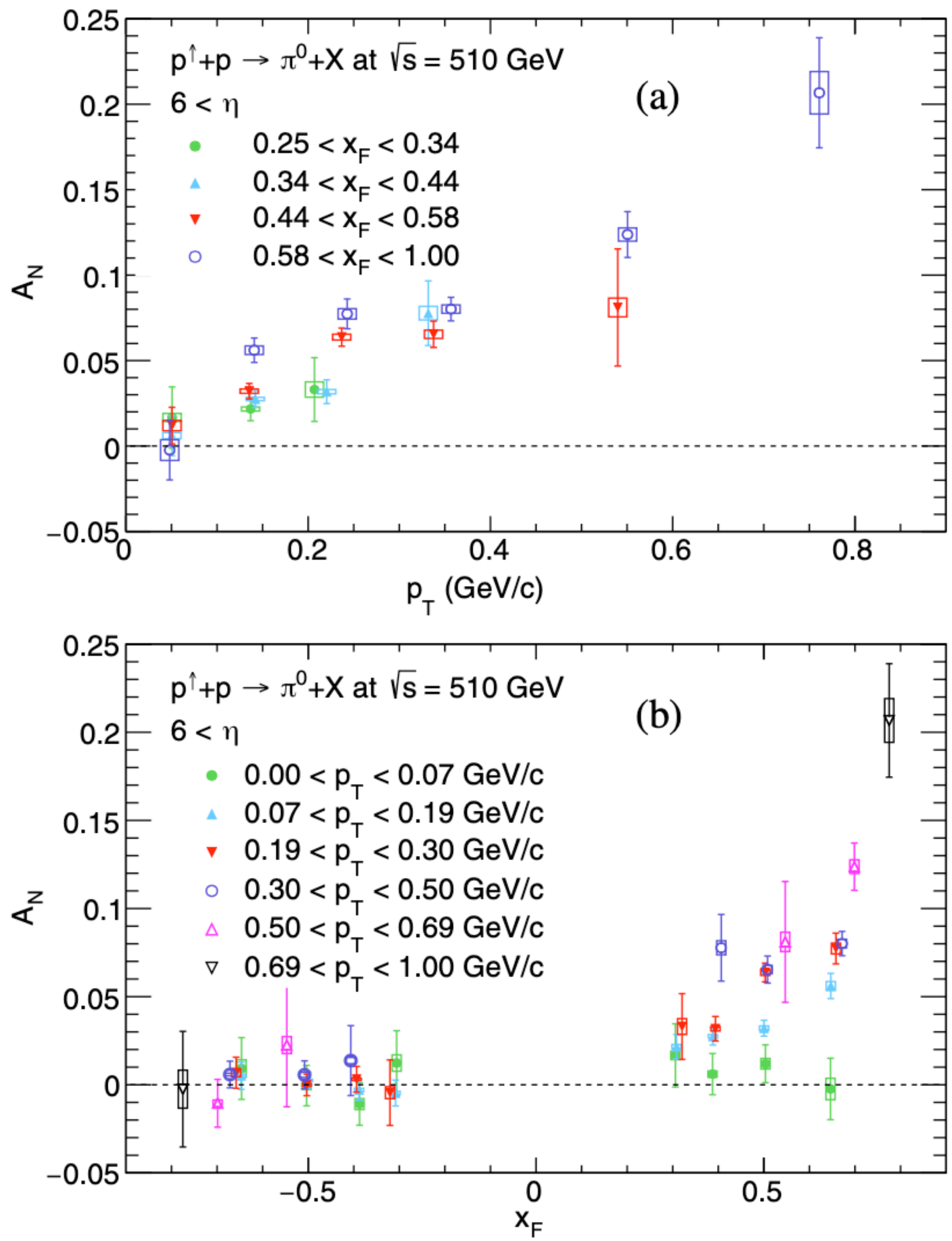
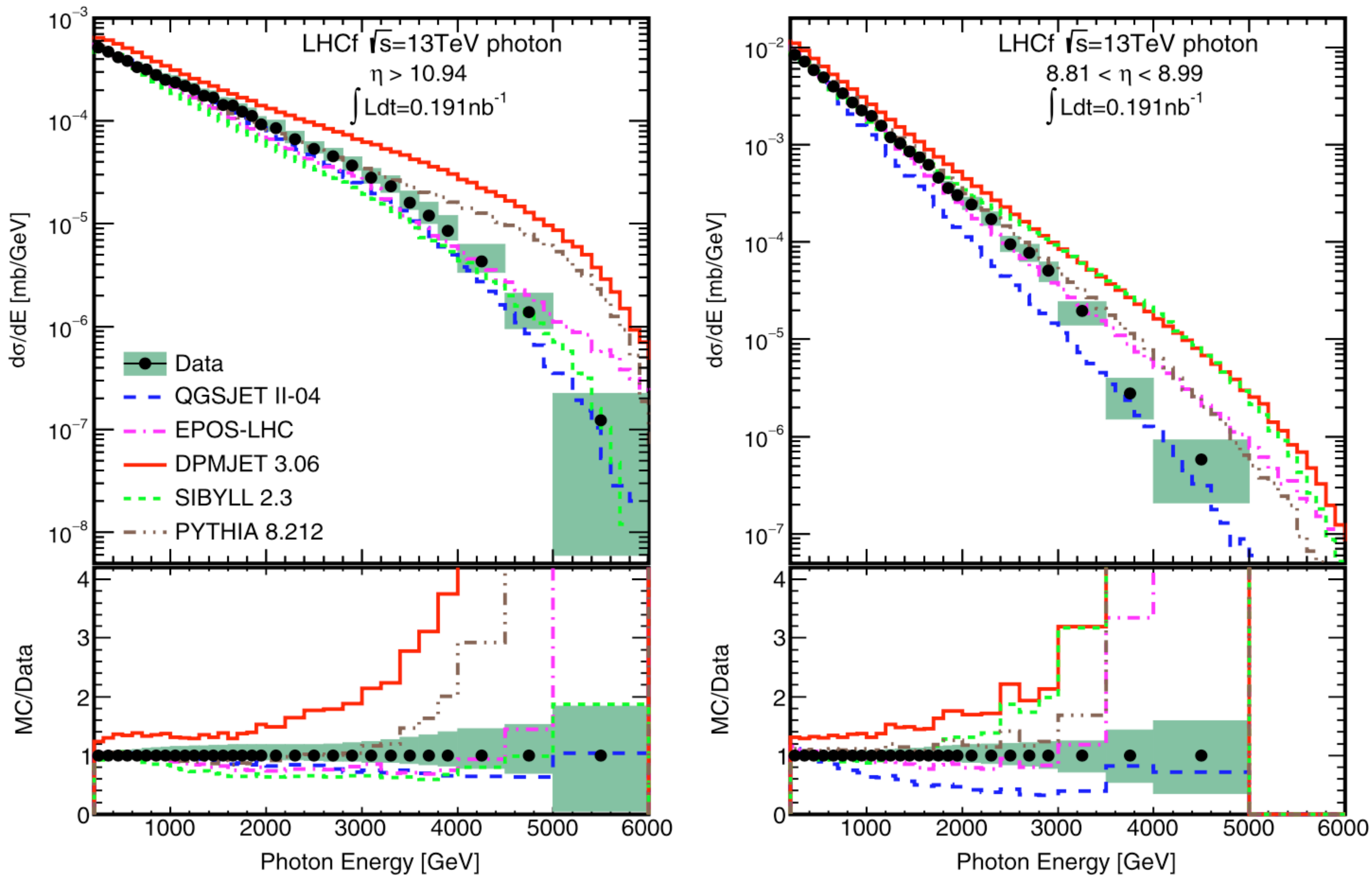


FIG. 3. A_N of the very forward π^0's as functions of (a) p_T for several x_F ranges and (b) x_F for several p_T ranges. Only forward A_N was presented in (a). Error bars represent the statistical uncertainties, and the boxes represent the systematic uncertainties.

Photons

Photons@13 TeV: spectra

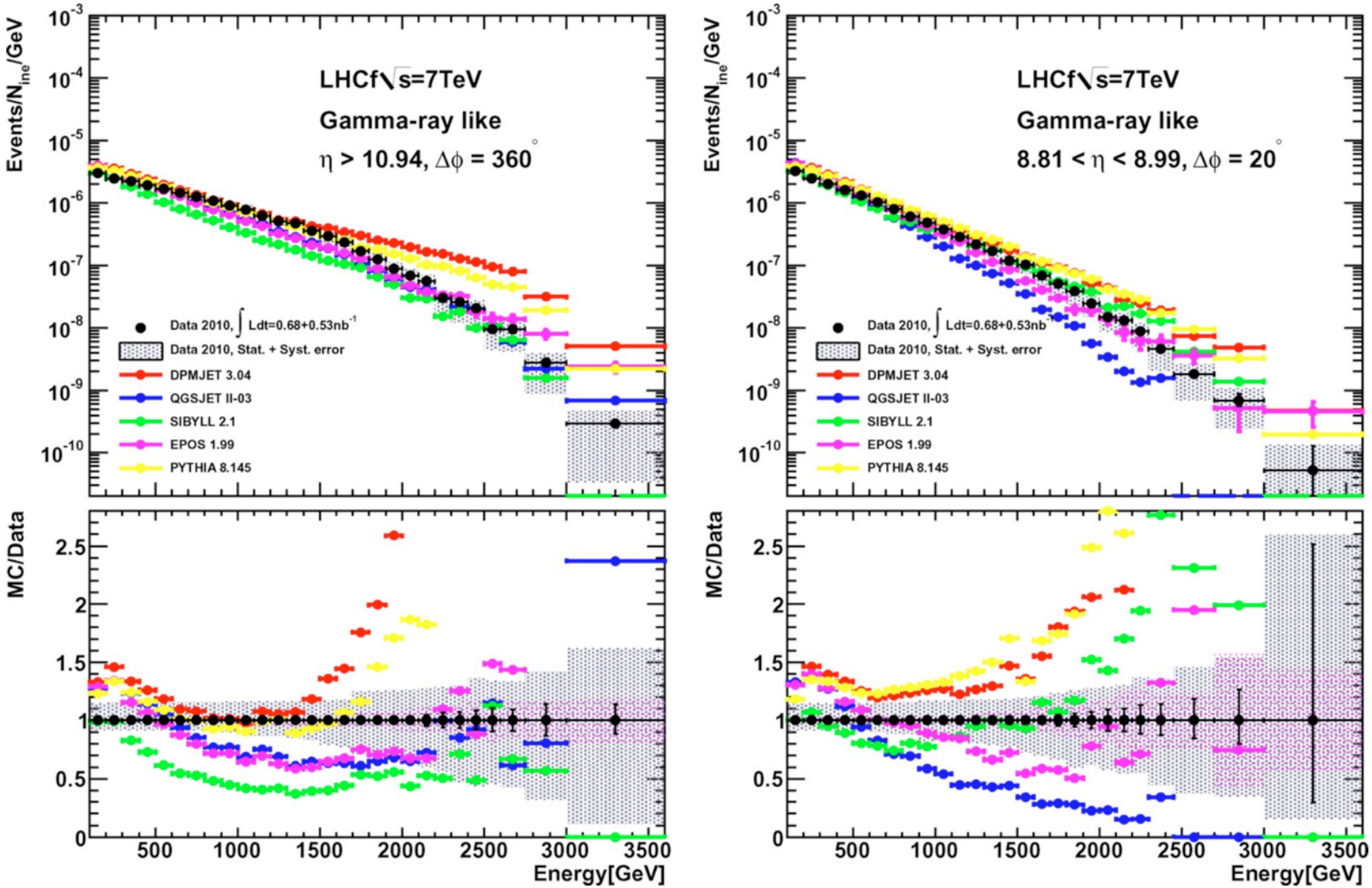
PLB780_2018_233



Photons@7 TeV: spectra

PLB703_2011_128

LHCf Collaboration / Physics Letters B 703 (2011) 128–134



Photons@900 GeV: spectra

PLB715_2012_298

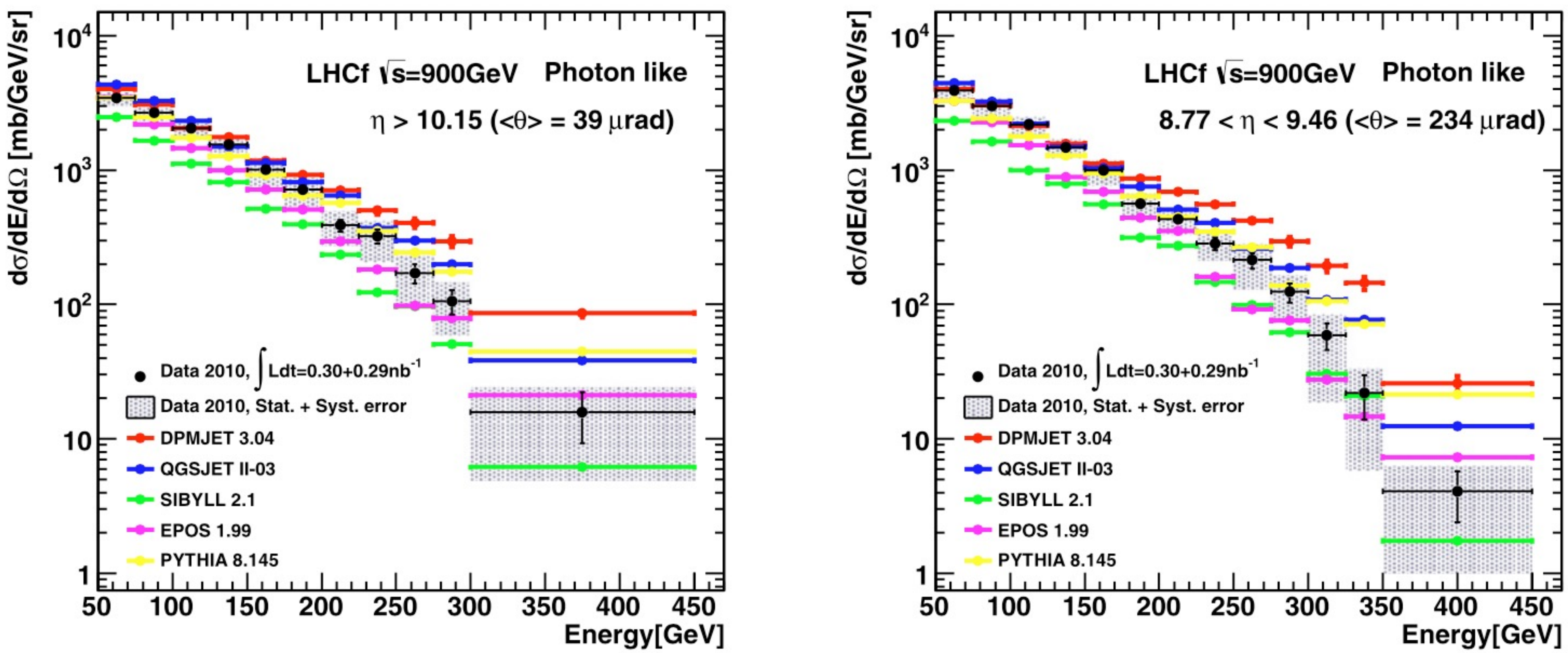
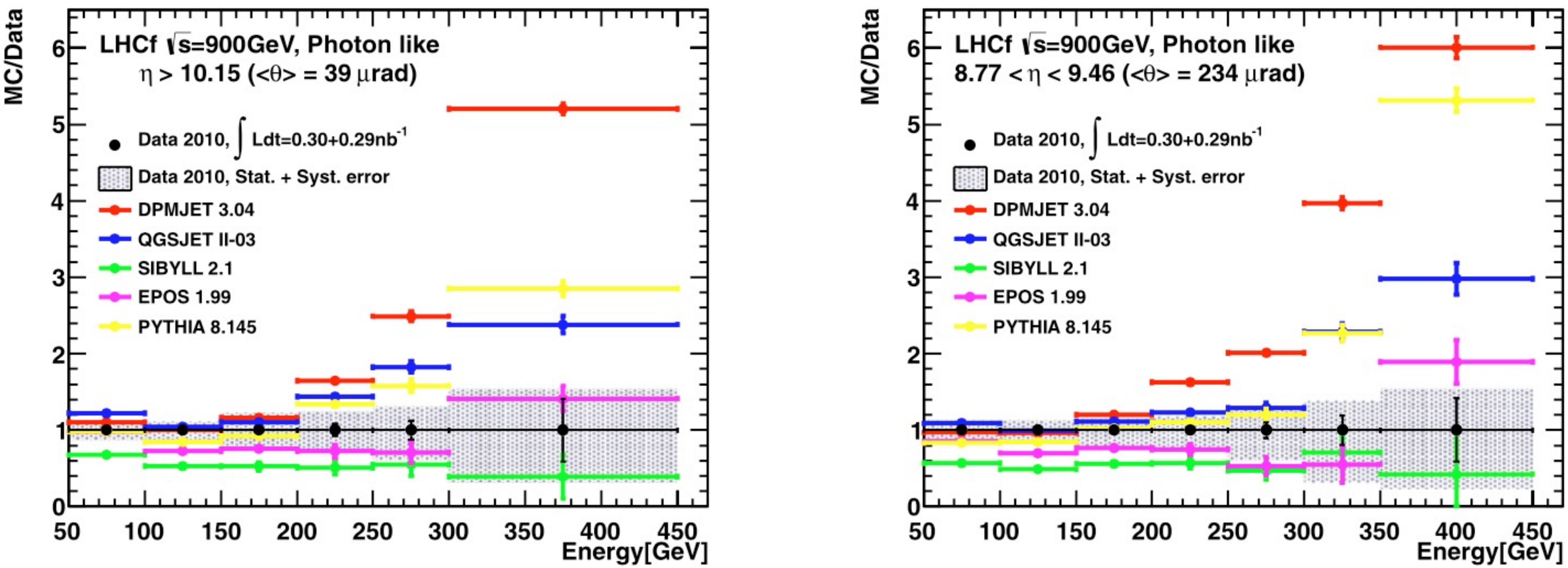


Fig. 4. Combined Arm1 and Arm2 photon energy spectra compared with MC predictions. The data from Arm1 and Arm2 correspond to the integral luminosities of 0.30 and 0.29 nb^{-1}, respectively. The left and the right panels are the results of the small ($\eta > 10.15$) and the large ($8.77 < \eta < 9.46$) towers, respectively. The black points indicate the experimental data with the statistical uncertainty (error bars) and the total uncertainty, quadratical summation of the statistical and the systematic errors (black hatches). The systematic uncertainty of the luminosity determination (±21%) is not taken into account in the errors. The colored points indicate the results of MC predictions, QGSJET II-03 (blue), PYTHIA 8.145 (yellow), SIBYLL 2.1 (green), EPOS 1.99 (magenta) and DPMJET 3.04 (red). Only the statistical uncertainty of DPMJET 3.04 is shown by the error bars as representative of the models.

Photons@900 GeV: MC/Data

PLB715_2012_298

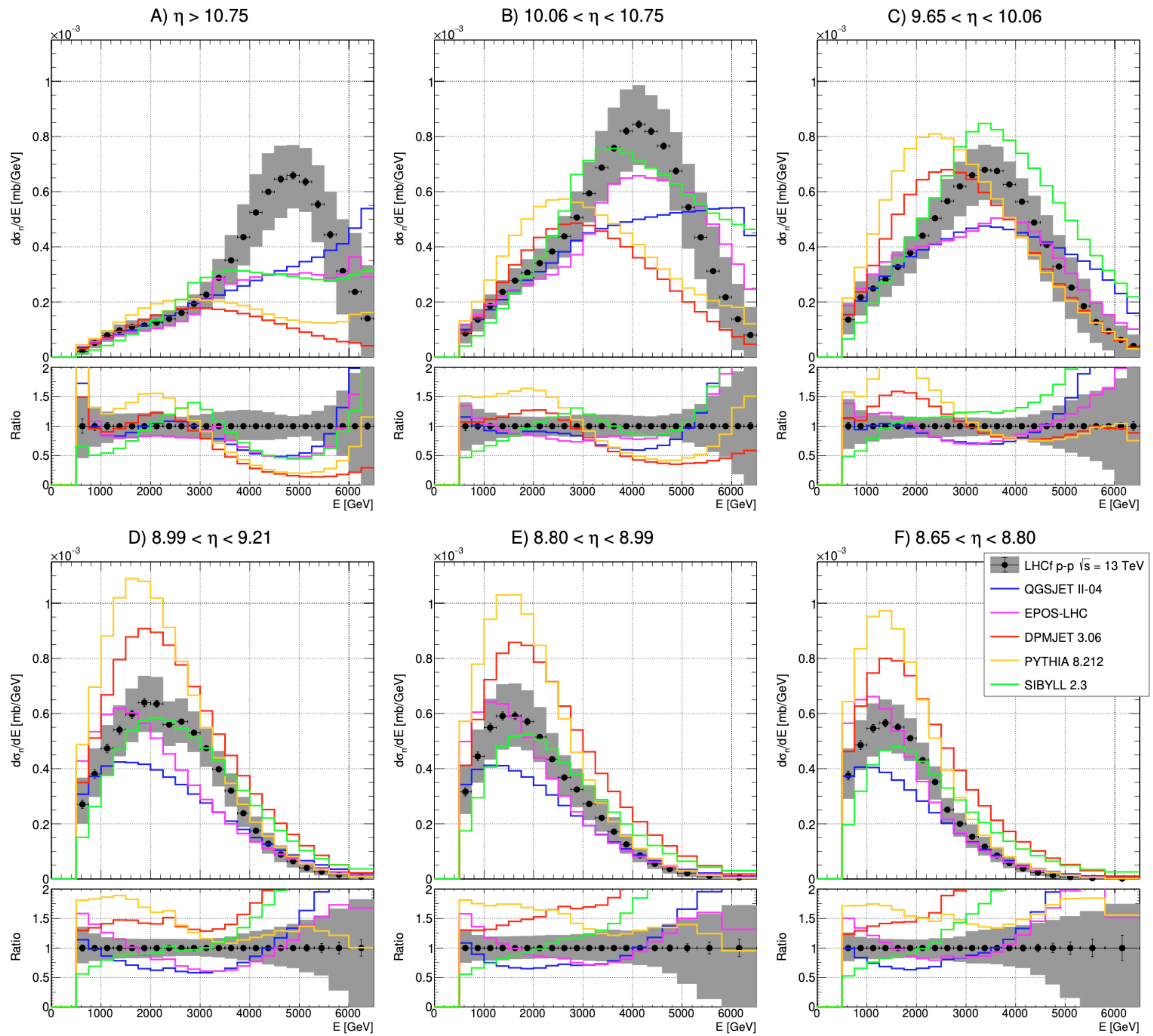
O. Adriani et al. / Physics Letters B 715 (2012) 298–303



Neutrons

Neutrons@13 TeV: spectra

JHEP07(2020)016



Neutrons@13 TeV: Energy Flow

JHEP07(2020)016

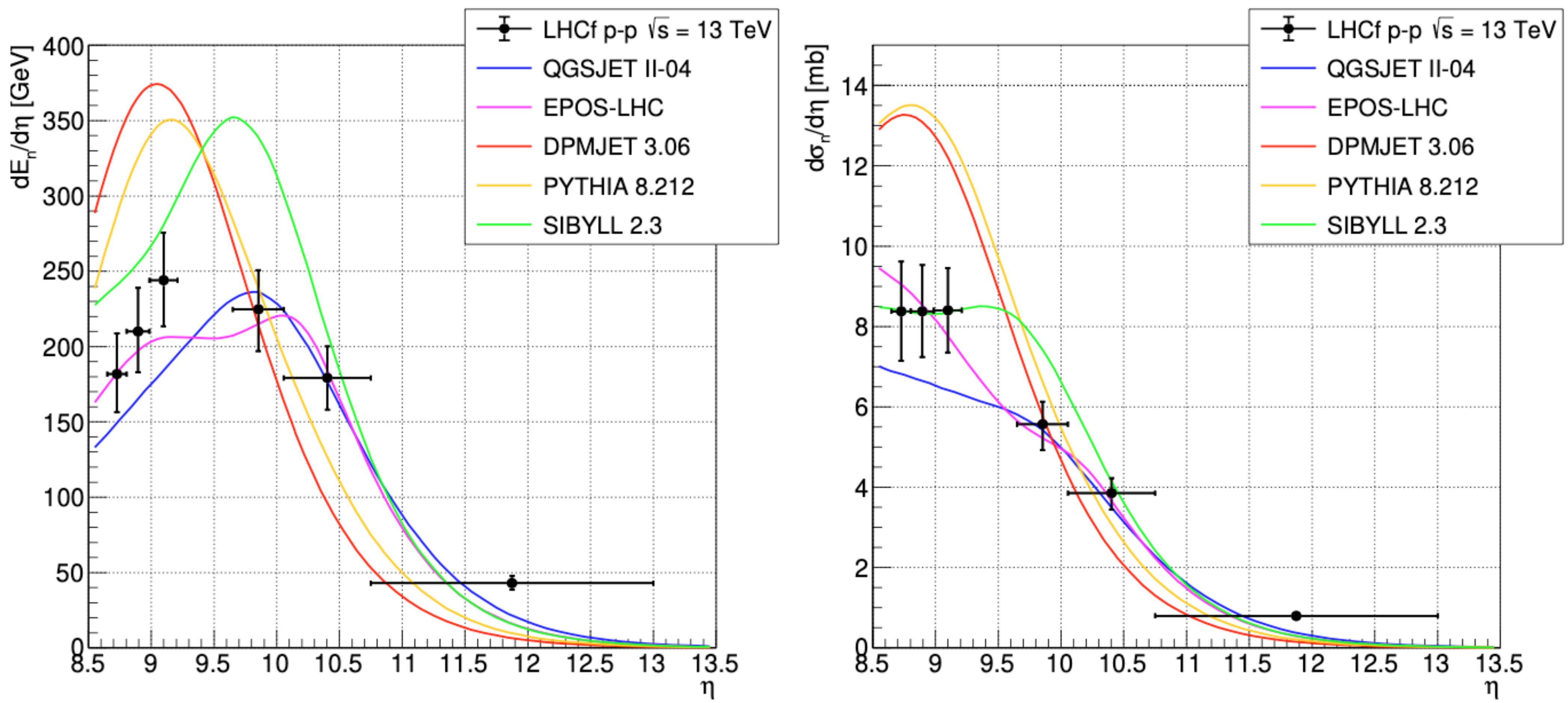


Figure 3. Differential energy flow $\mathrm{d}E_\mathrm{n}/\mathrm{d}\eta$ (left) and differential cross section $\mathrm{d}\sigma_\mathrm{n}/\mathrm{d}\eta$ (right) of neutrons produced in p-p collisions at $\sqrt{s} = 13\,\mathrm{TeV}$, measured using the LHCf Arm2 detector. Black markers represent the experimental data with statistical and systematic uncertainties, whereas colored lines refer to model predictions at the generator level.

Neutrons@13 TeV: Elasticity

JHEP07(2020)016

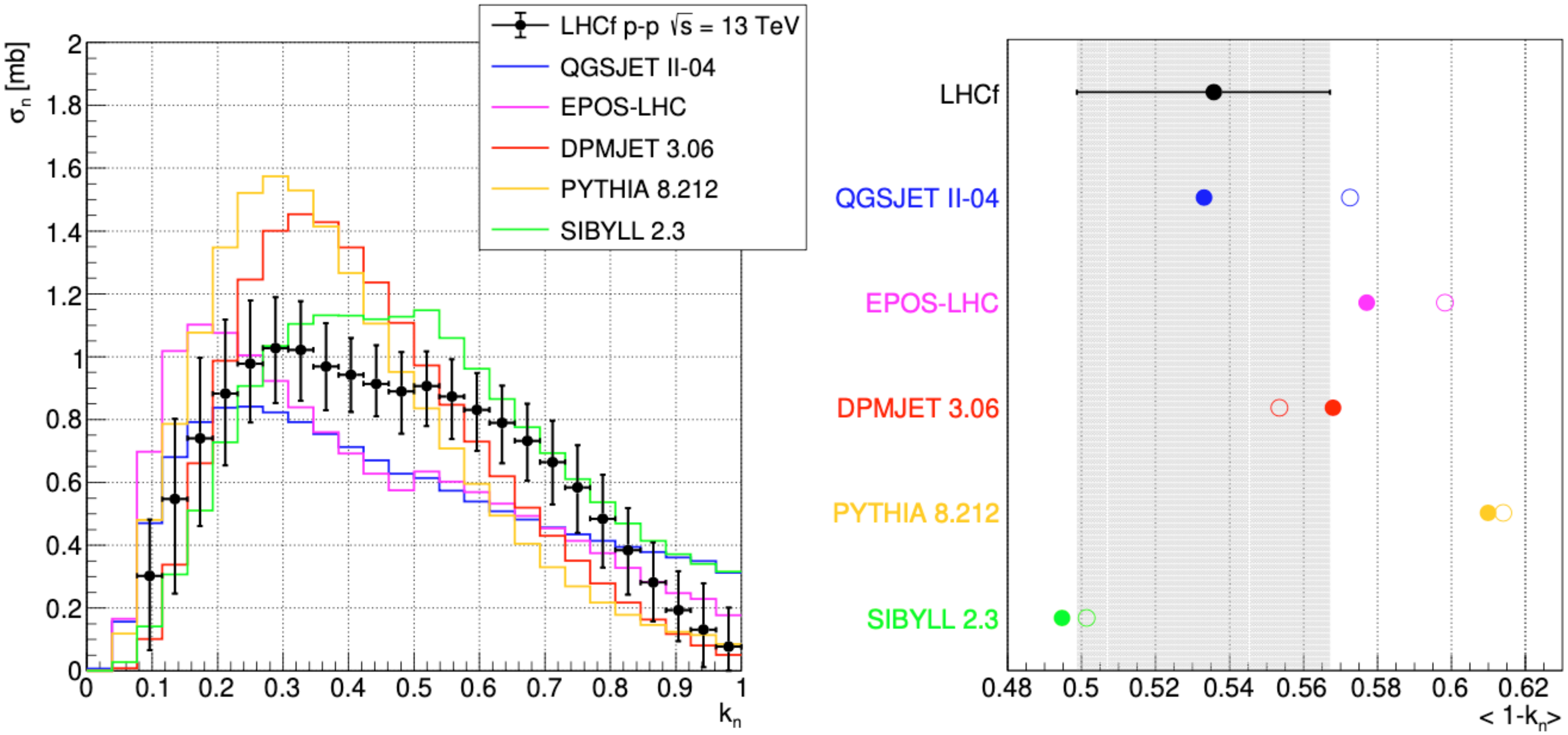


Figure 4. Inclusive production cross section as a function of elasticity k_n (left) and average inelasticity $\langle 1-k_\mathrm{n}\rangle$ extracted from that distribution (right), relative to p-p collisions at $\sqrt{s} = 13$ TeV. These quantities, measured using the LHCf Arm2 detector, are only relative to the events where the leading particle is a neutron. Black markers represent the experimental data with the quadratic sum of statistical and systematic uncertainties. Solid lines (left) and full circles (right) refer to model predictions at the generator level, obtained using only the events where the leading particle is a neutron. In order to compare this approach to the general case, $\langle 1-k\rangle$, the average inelasticity obtained using all the events independently of the nature of the leading particle, is also reported as open circles in the right figure.

Neutrons@13 TeV: spectra

JHEP11(2018)073

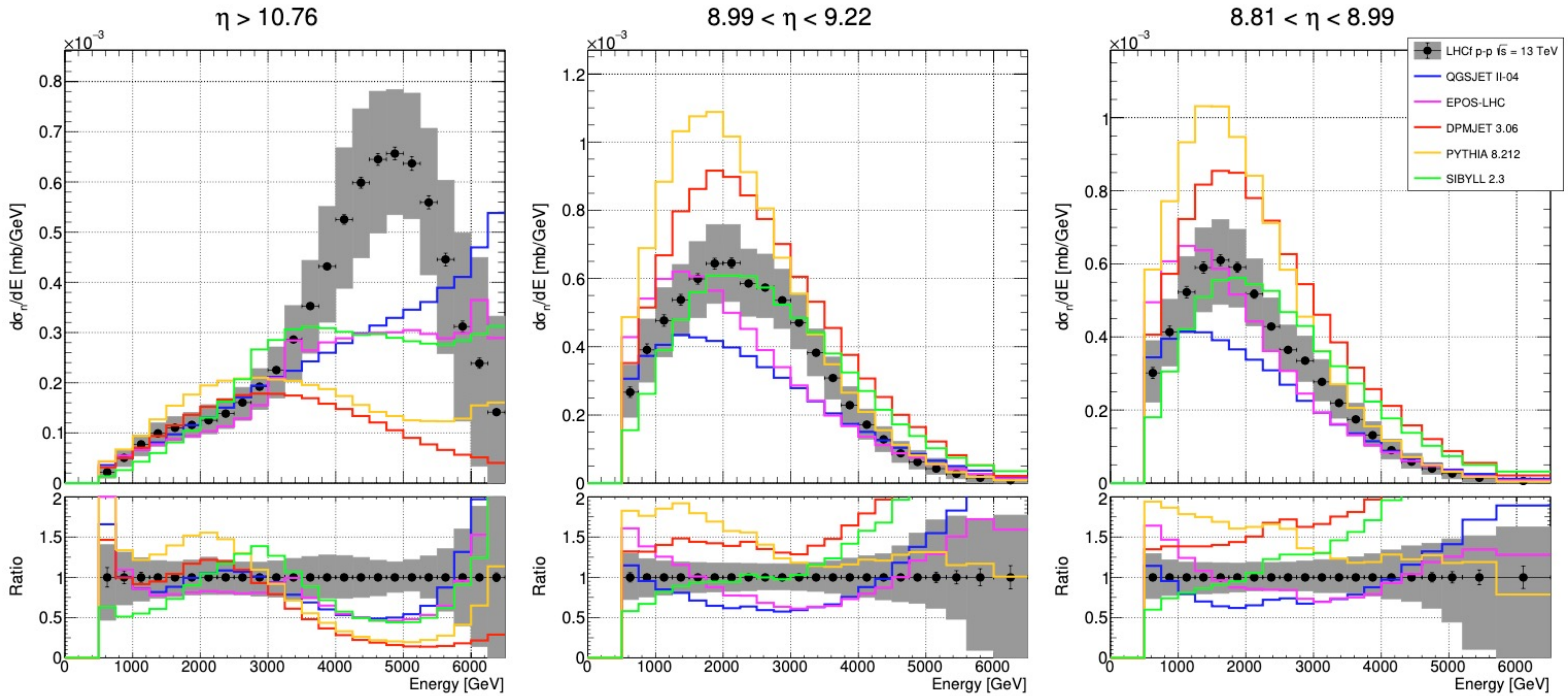


Figure 6. Unfolded differential neutron production cross section for p-p collisions at $\sqrt{s} = 13\,\mathrm{TeV}$, measured using the LHCf Arm2 detector. Black markers represent the experimental data with statistical errors, whereas gray bands represent the quadratic sum of statistical and systematic uncertainties. Colored histograms refer to models predictions at the generator level. The top plot shows the energy distributions expressed as $\mathrm{d}\sigma_\mathrm{n}/\mathrm{dE}$ and the bottom one the ratios of these distributions to the experimental data points.

Neutrons@7 TeV: spectra   PLB750_2015_360

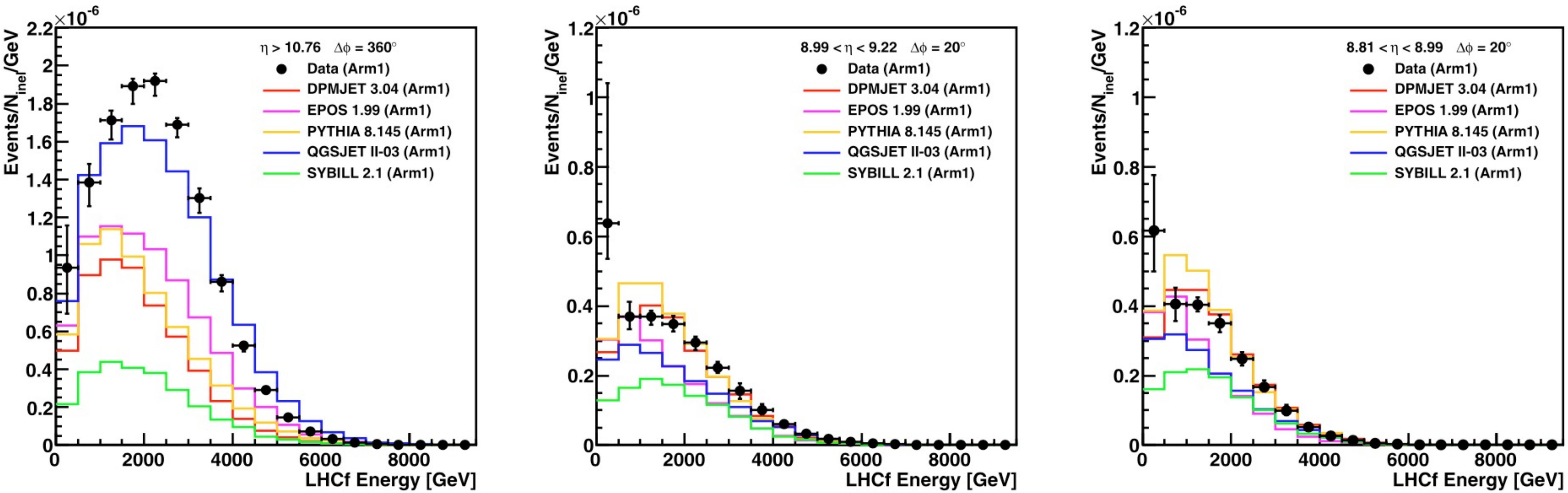


Fig. 4. Measured Arm1 energy spectra of neutron-like events together with MC predictions. The left panel shows the results for the small tower, and the center and right panels show the results for the large tower. The vertical bars represent the statistical uncertainties (which are very small) and systematic uncertainties (excluding the energy scale and luminosity uncertainties). Colored lines indicate MC predictions by EPOS 1.99 (magenta), QGSJET II-03 (blue), SYBILL 2.1 (green), DPMJET 3.04 (red), and PYTHIA 8.145 (yellow). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Neutrons@7 TeV: spectra PLB750_2015_360

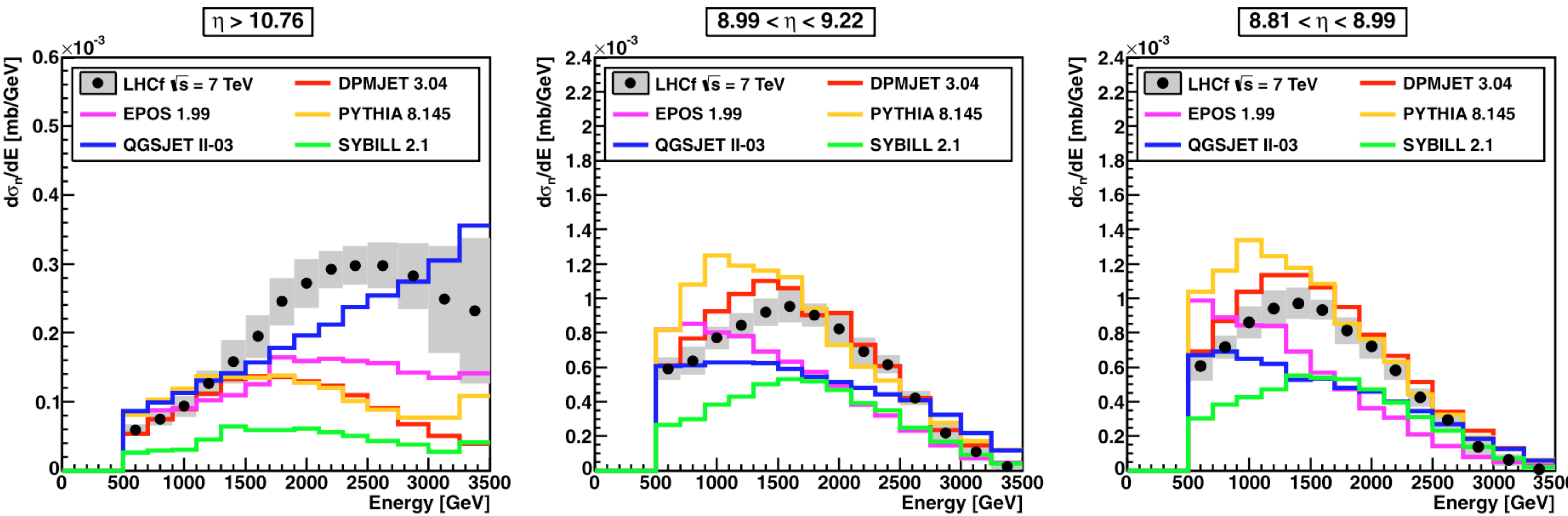
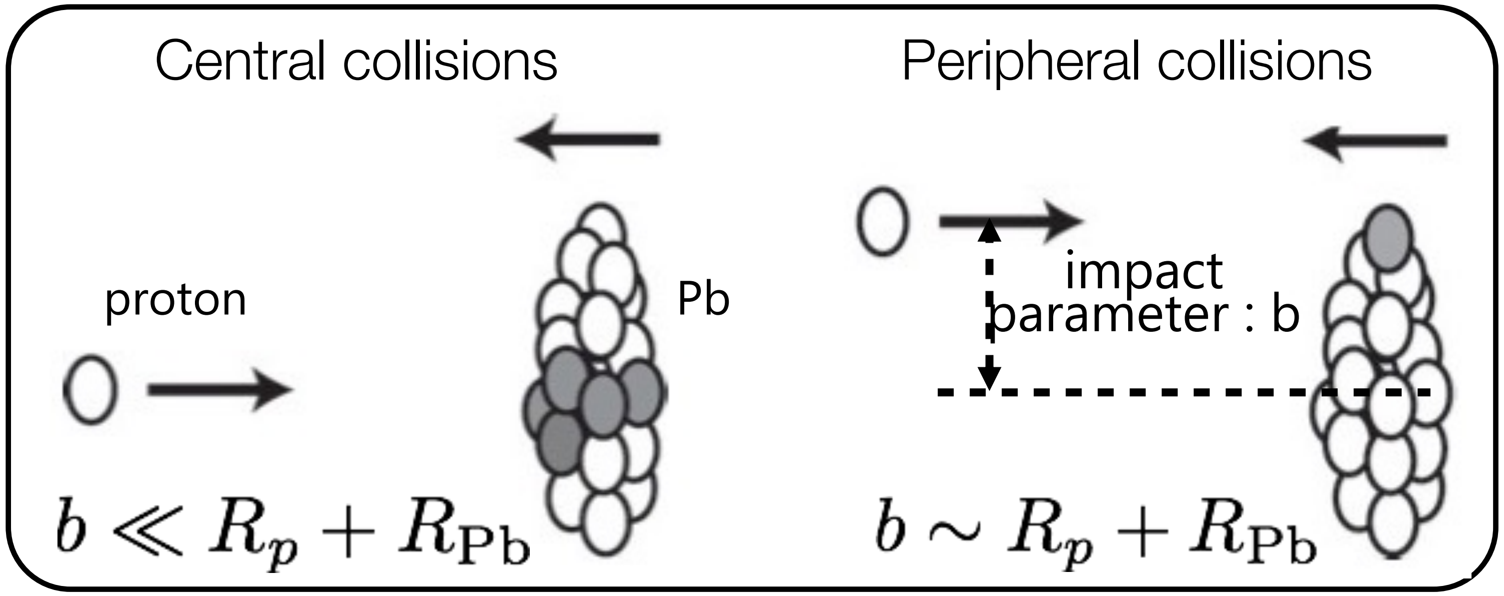


Fig. 7. Comparison of the LHCf results with model predictions at the small tower ($\eta > 10.76$) and large towers ($8.99 < \eta < 9.22$ and $8.81 < \eta < 8.99$). The black markers and gray shaded areas show the combined results of the LHCf Arm1 and Arm2 detectors and the systematic errors, respectively. (For interpretation of the colors in this figure, the reader is referred to the web version of this article.)

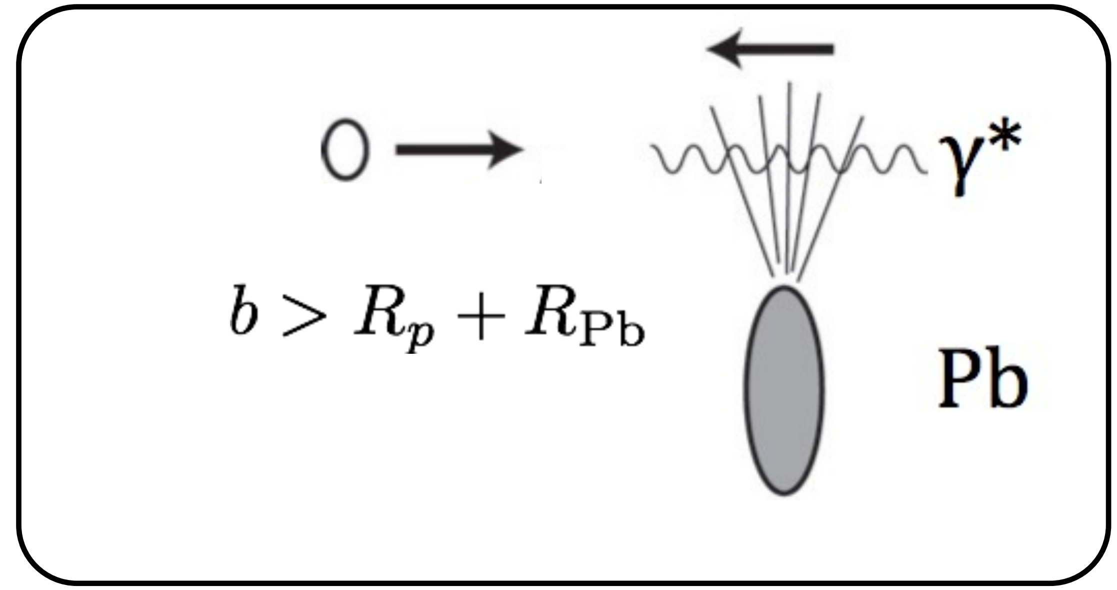
Backup

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



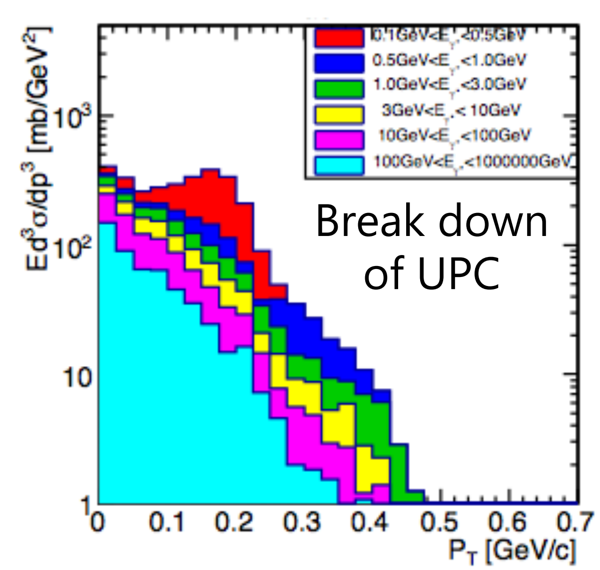
proton rest frame

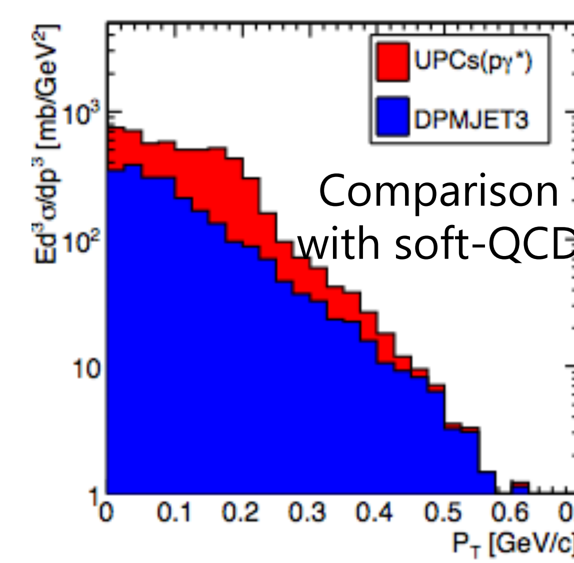
Momentum distribution of the UPC induced secondary particles is estimated as
1. energy distribution of virtual photons is estimated by the Weizsacker Williams approximation.
2. photon-proton collisions are simulated by the SOPHIA model (E_γ > pion threshold).
3. produced mesons and baryons by γ-p collisions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

Dominant channel to forward π^0 is

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

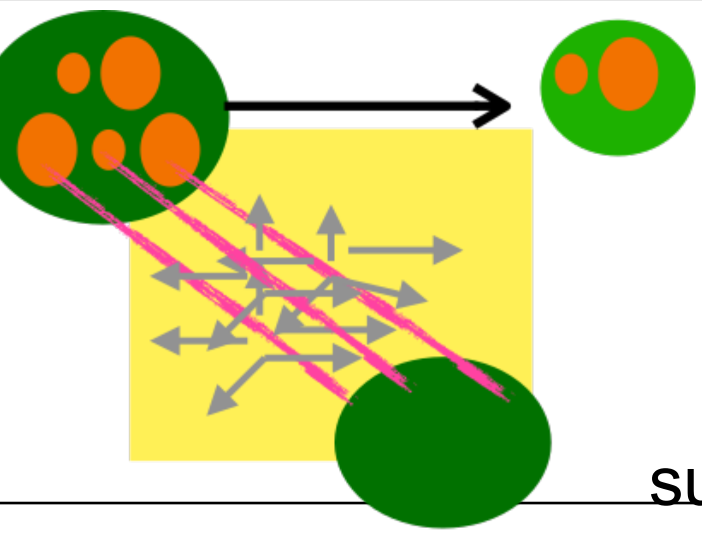
About half of the observed π^0 may originate in UPC, another half is from soft-QCD.



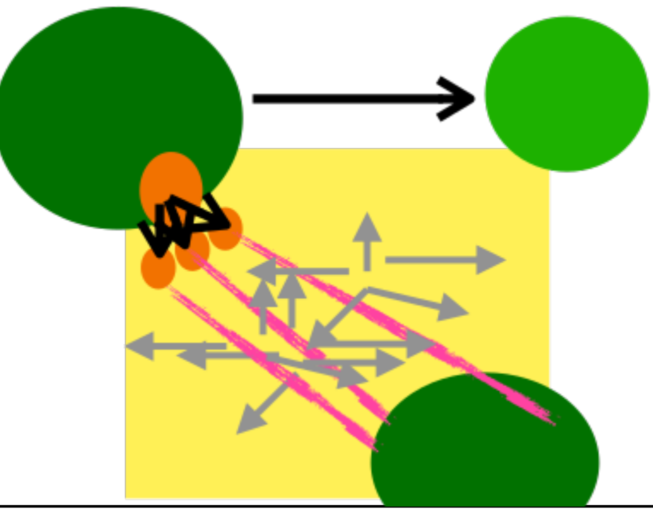


LHCf-ATLAS joint analysis
On-going analysis

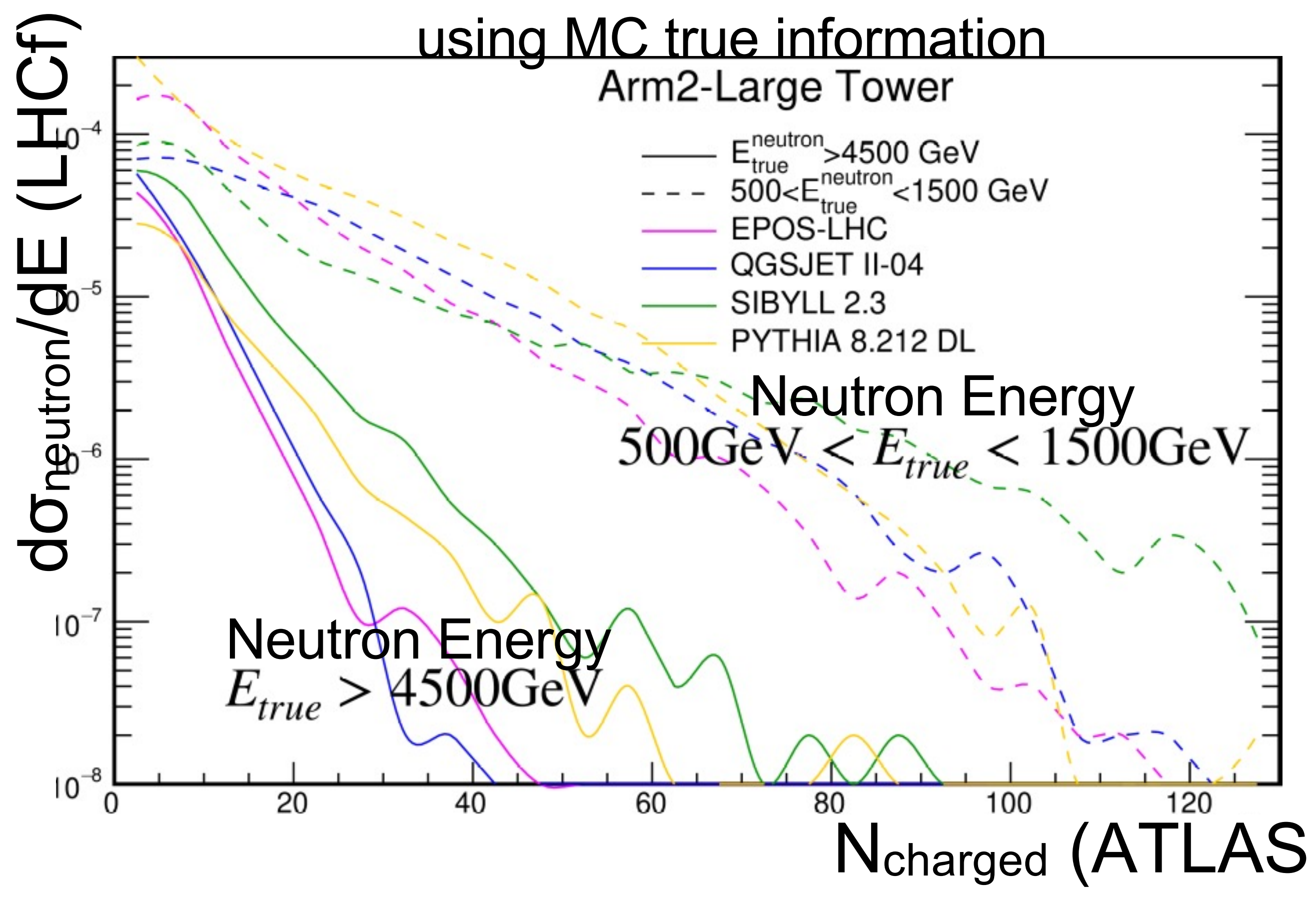
Study of **mechanism of multiparton interaction** using neutron events in LHCf as proposed by S. Ostapchenko et al., Phys. Rev. D 94, 114026



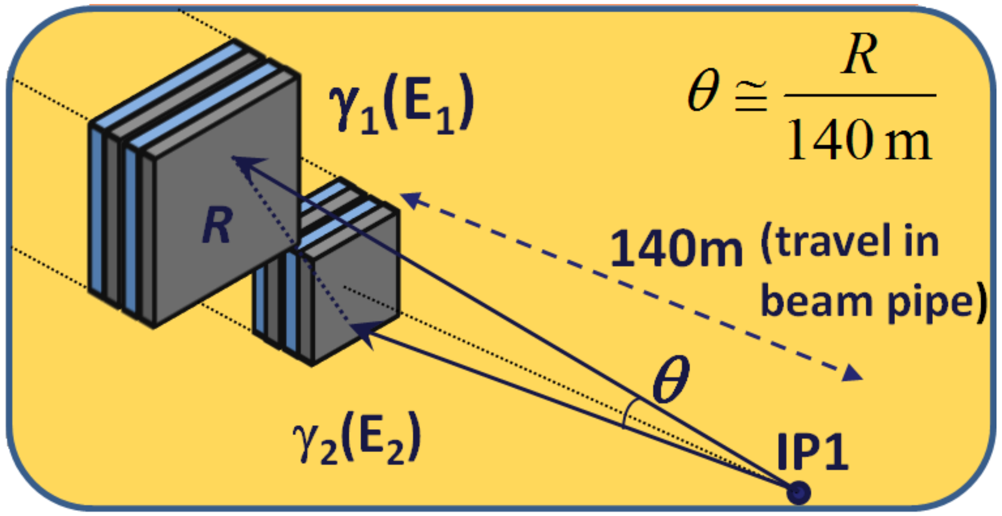
Strong central-forward correlation (QGSJET, EPOS)
Initial part of parton cascade modeled as superposition of partons



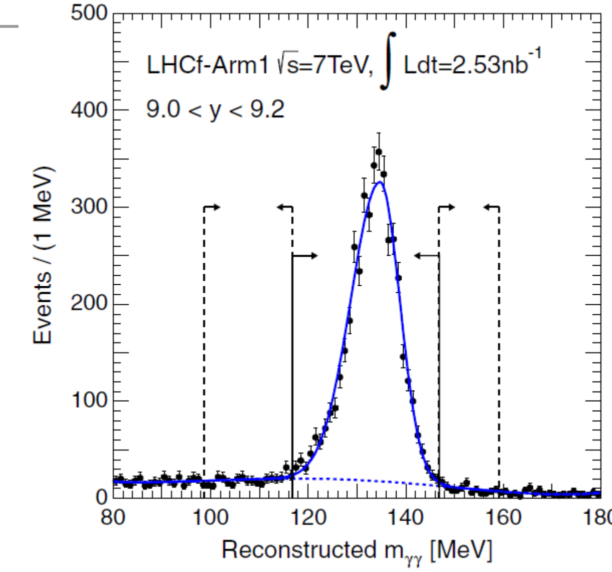
Weak central-forward correlation (SIBYLL, PYTHIA)
Initial part of parton cascade modeled as universal state



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



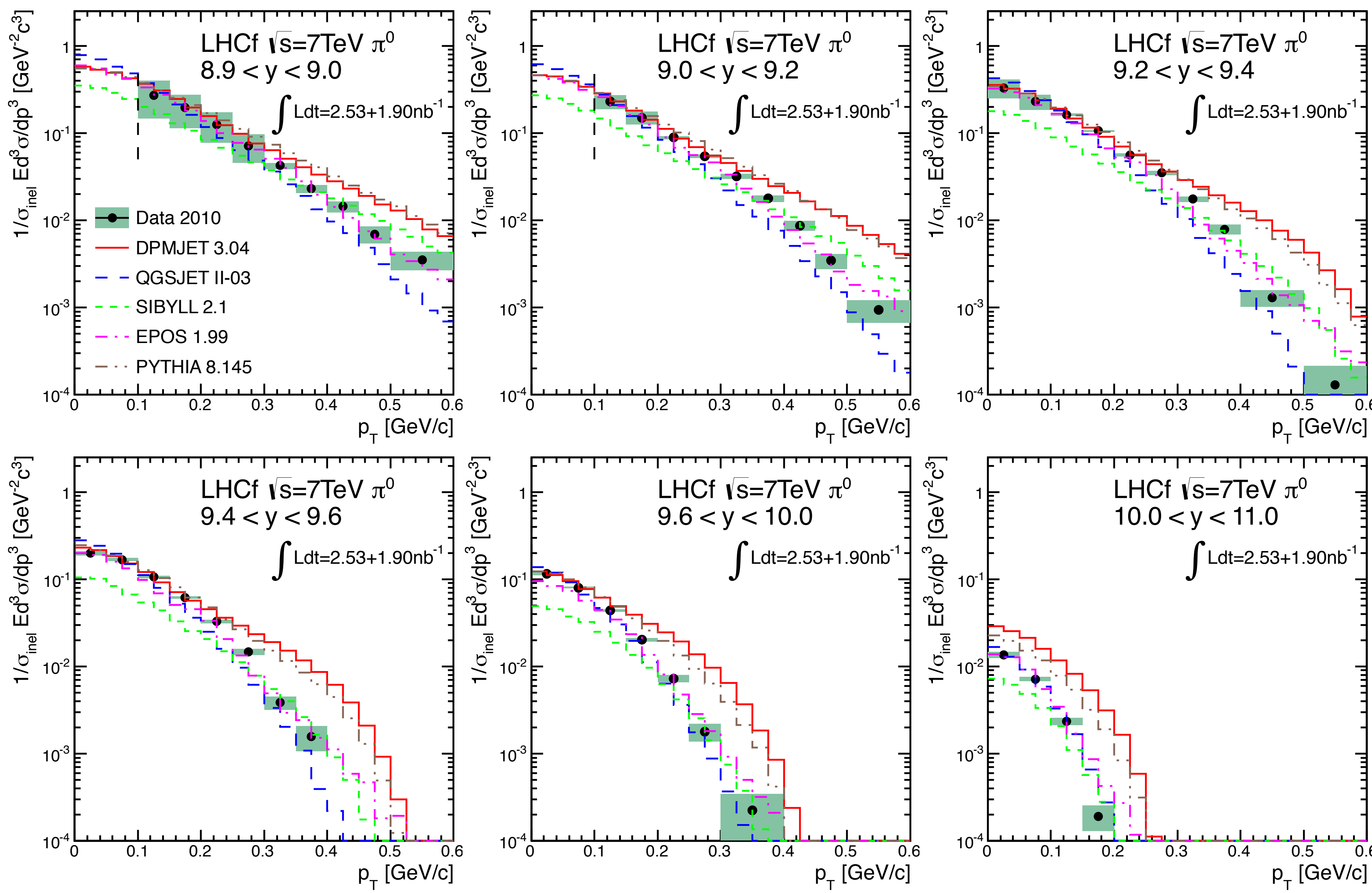
Reconstruction of the invariant mass of two-photon events



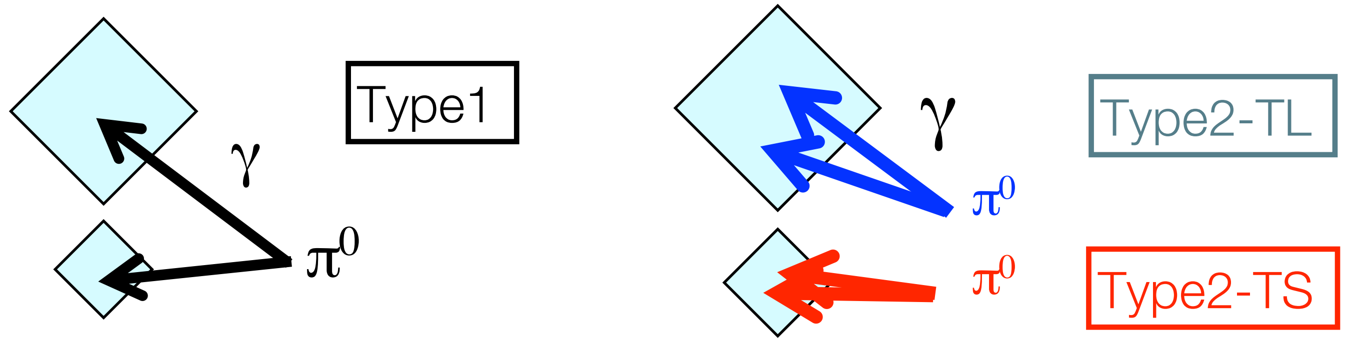
7 TeV pp, π^0

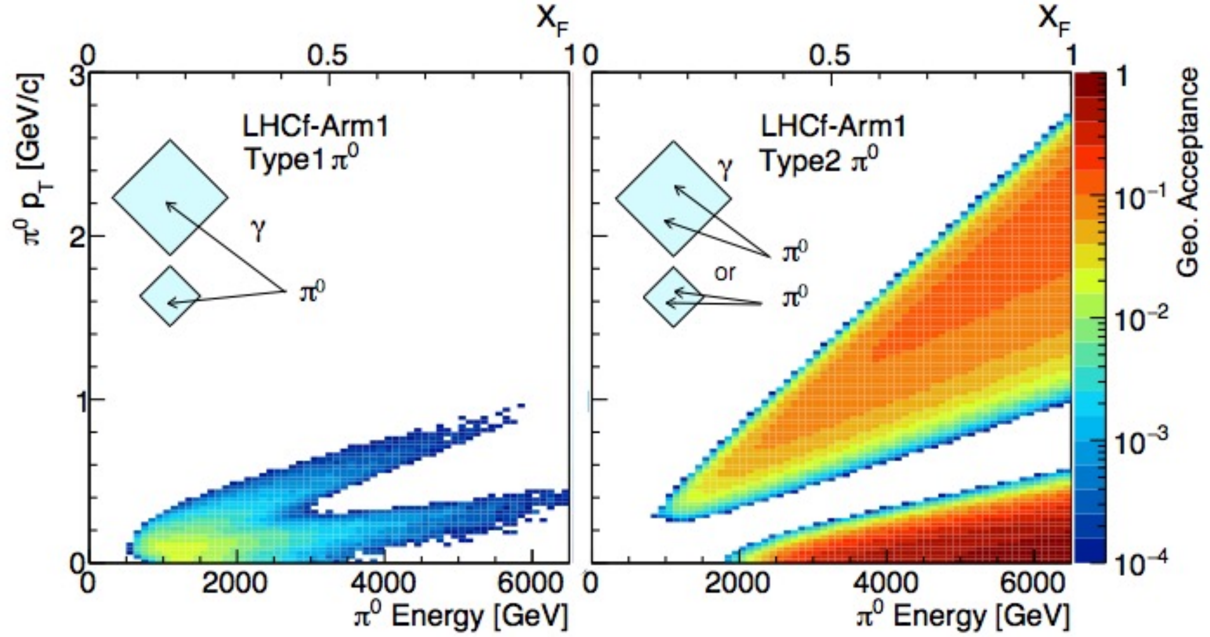
Identification of events with two particles hitting the two towers

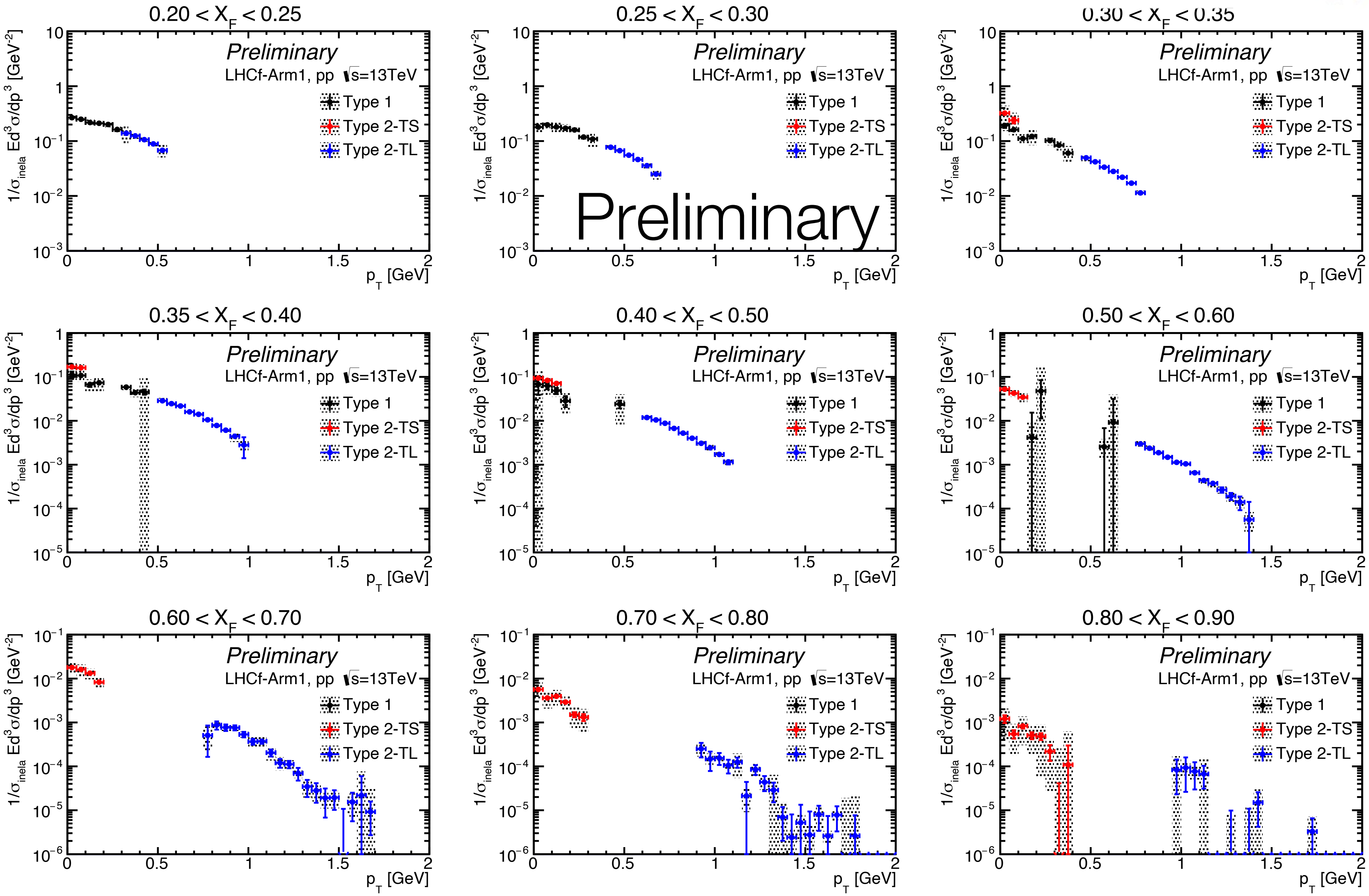
- **EPOS1.99** show the best agreement with data in the models.
- **DPMJET** and **PYTHIA** have harder spectra than data ("popcorn model")
- **QGSJET** has softer spectrum than data (only one quark exchange is allowed)



π^0 in p+p @ 13 TeV



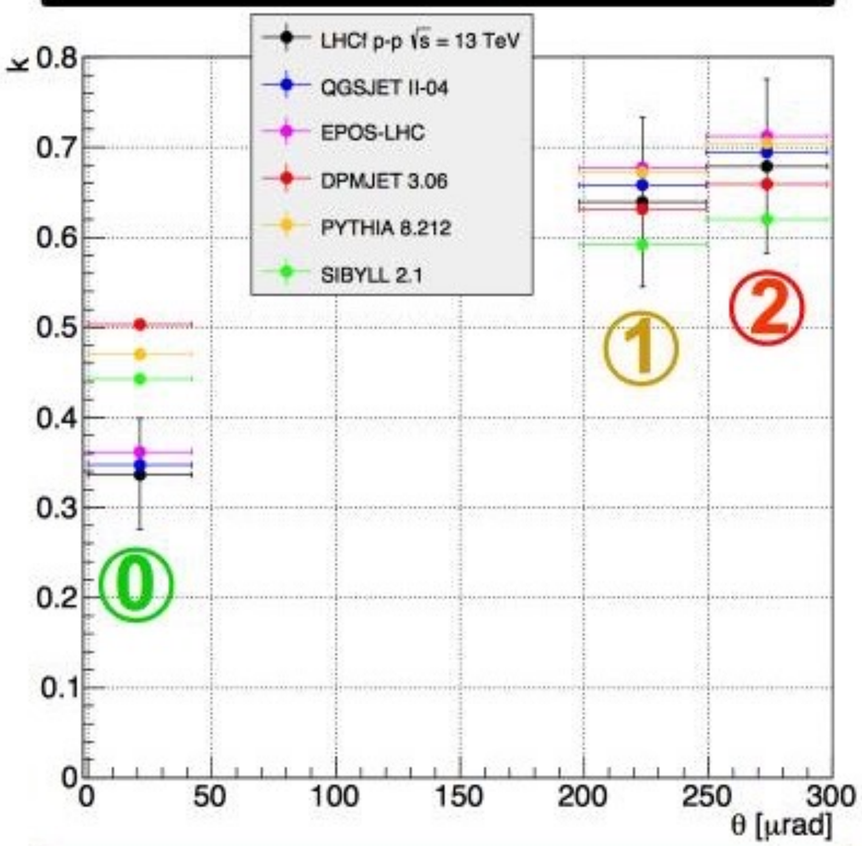




- Smooth connection of 3 spectra
- Wide transverse momentum coverage
- The gaps will be covered by Arm2 and other detector position data.

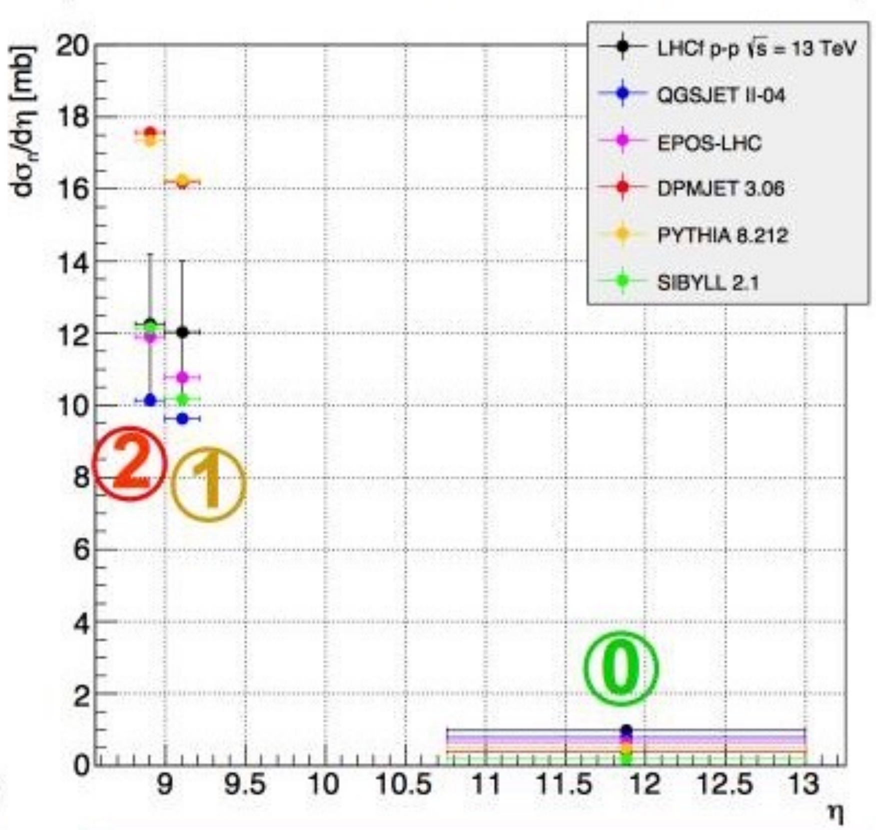
Measurement of interesting quantities for CR Physics

Inelasticity VS θ



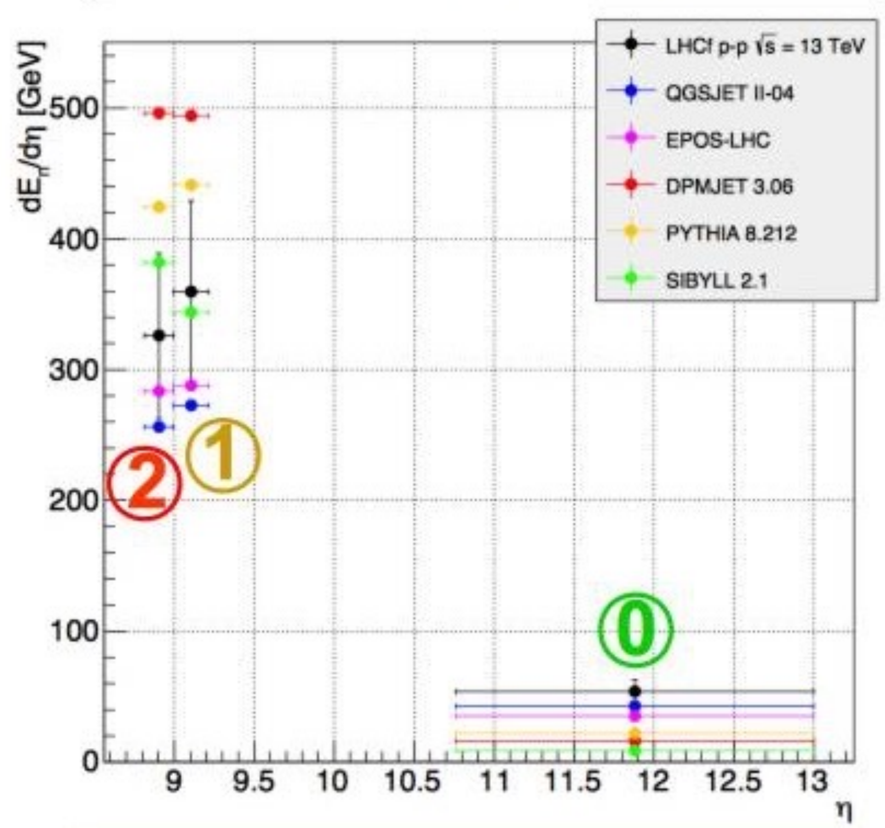
All models overestimate inelasticity in the most forward region even if **QGSJET II-04** and **EPOS-LHC** are consistent within the error bars

dσ/dη VS η



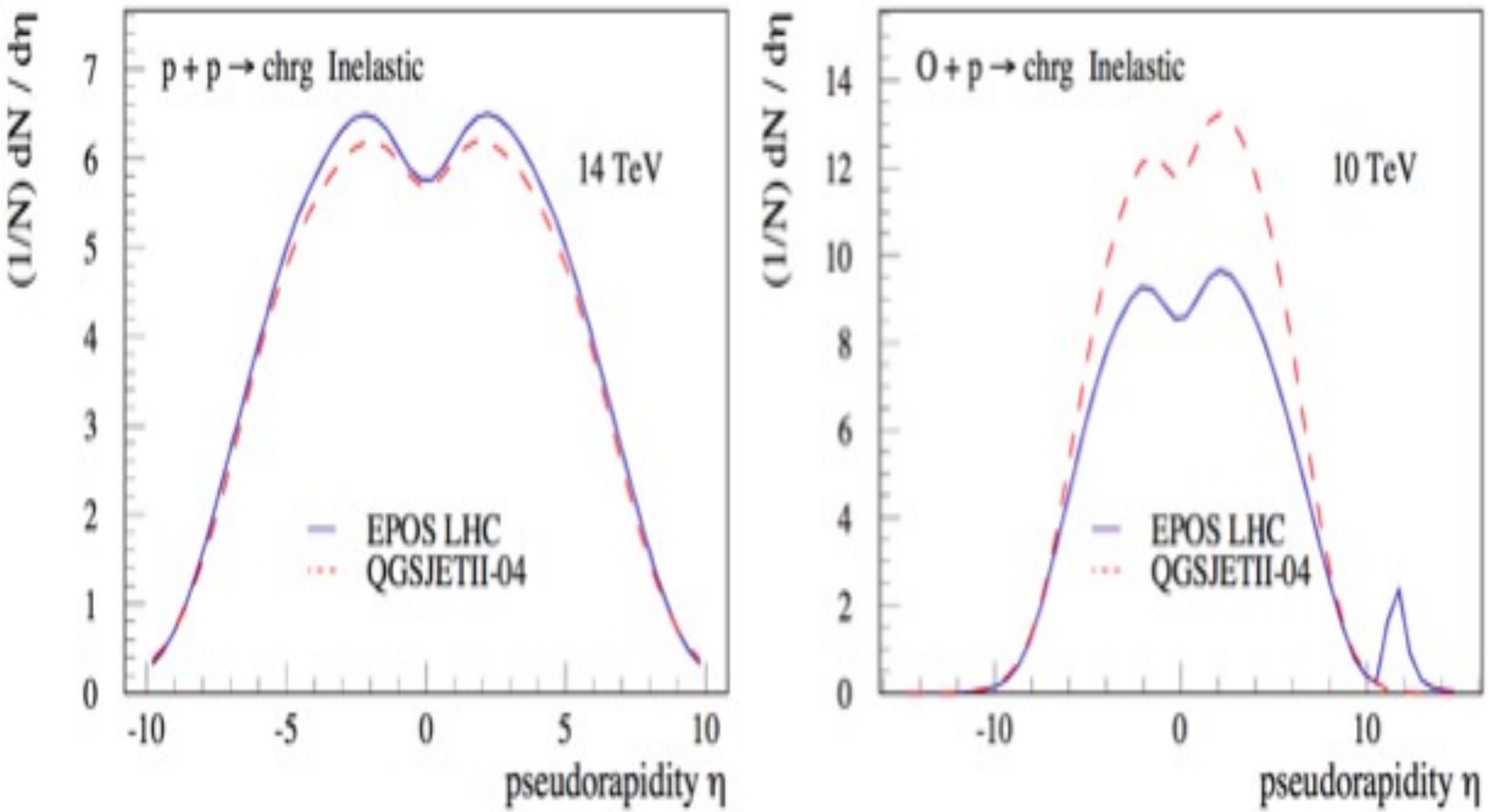
EPOS-LHC and **SIBYLL 2.1** reproduce enough well the measured total differential cross section except in the most forward region

dE/dη VS η



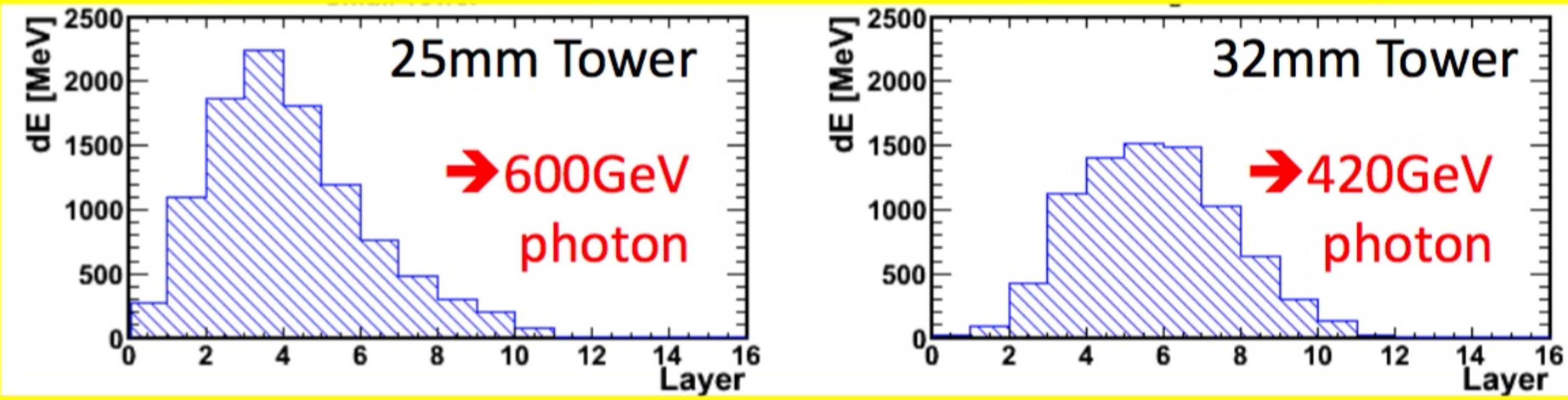
Where the energy flux is high, the agreement between experimental measurements and **SIBYLL 2.1**/**EPOS-LHC** is quite good

p-O collisions



π^0 reconstruction

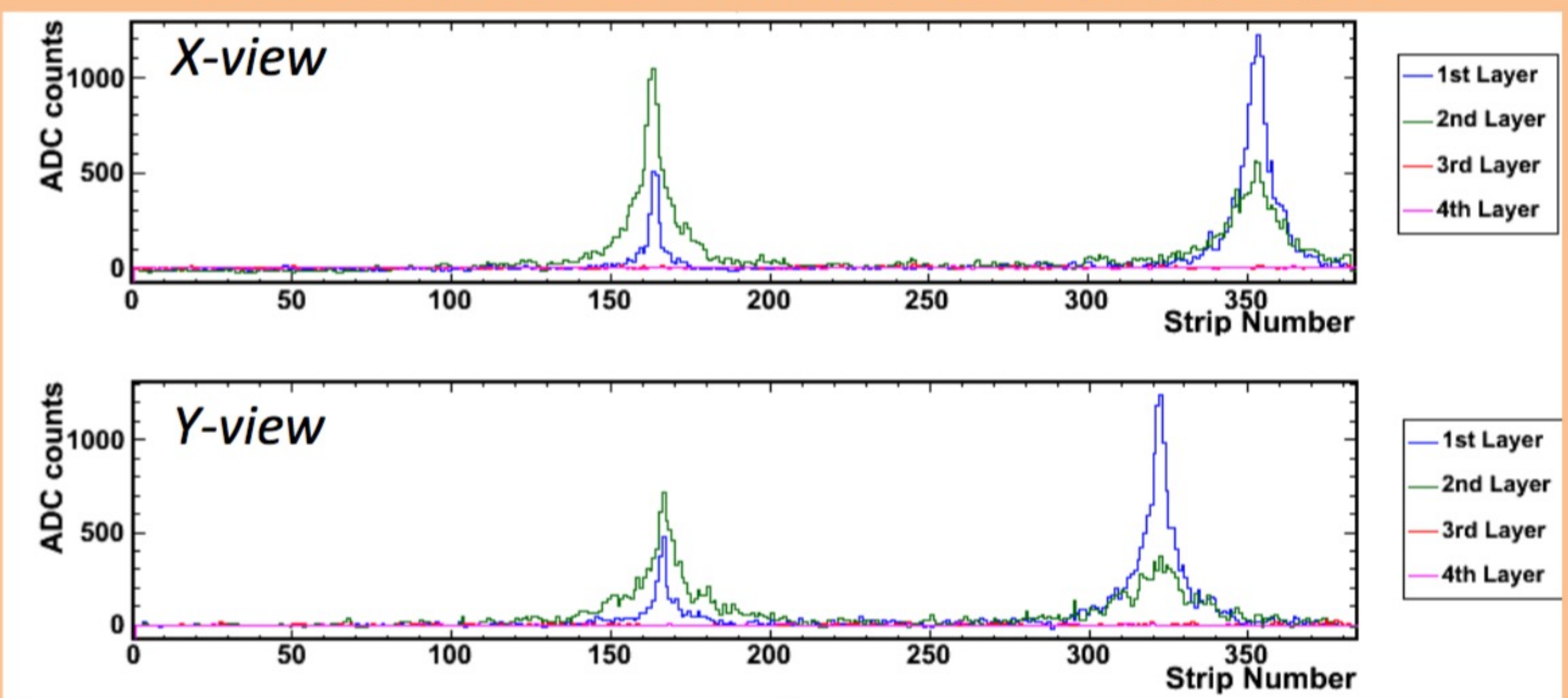
Longitudinal development measured by scintillator layers



Determination of **energy** from total energy release

PID from shape

Transverse profile measured by silicon μ–strip layers

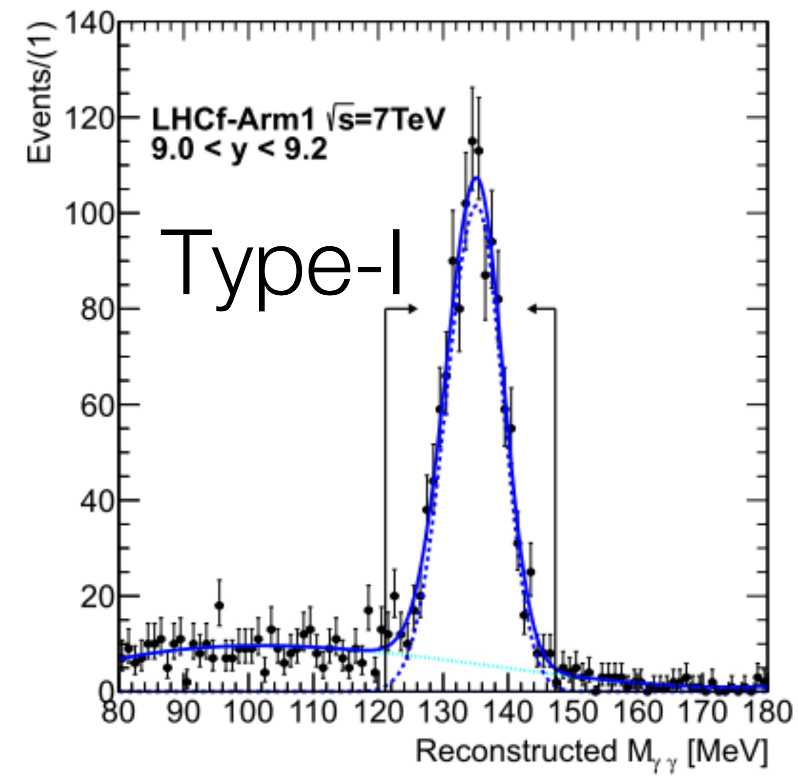


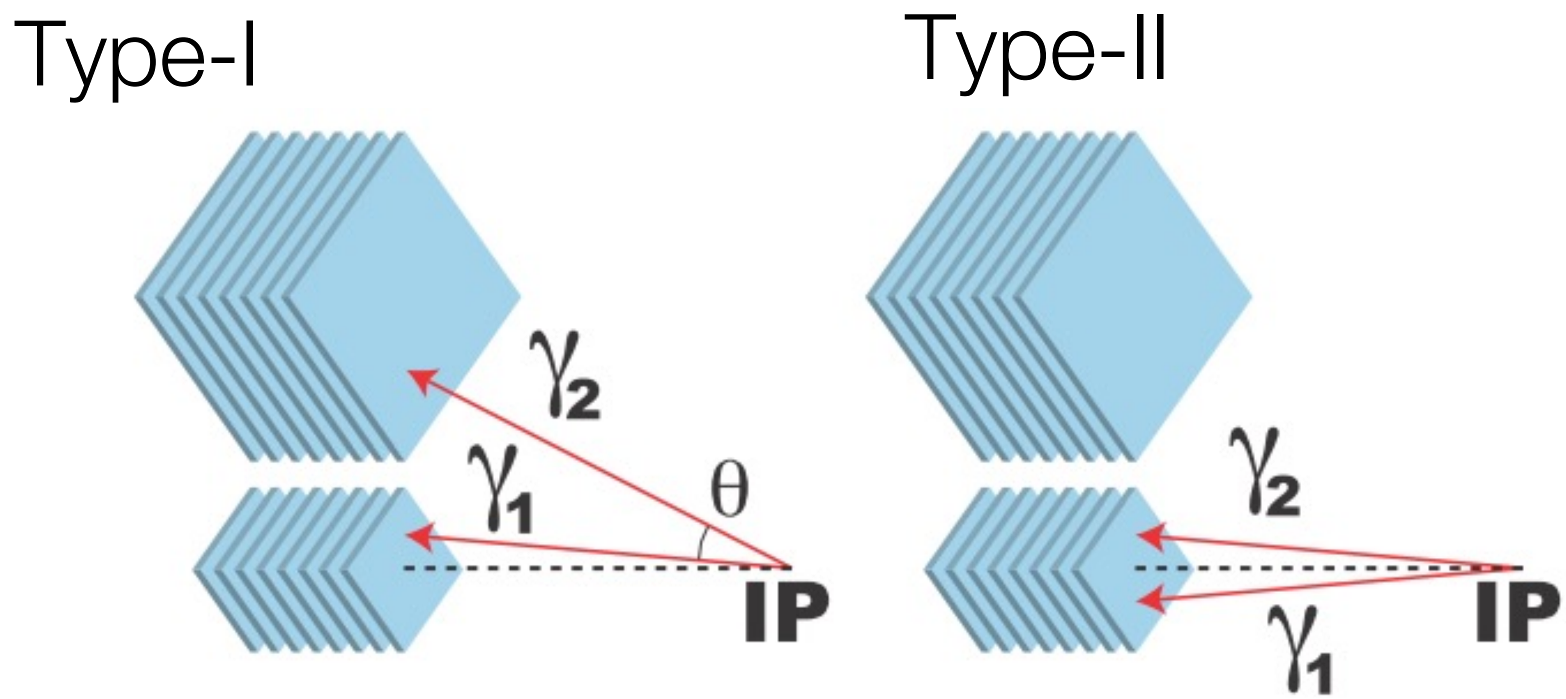
Determination of the **impact point**

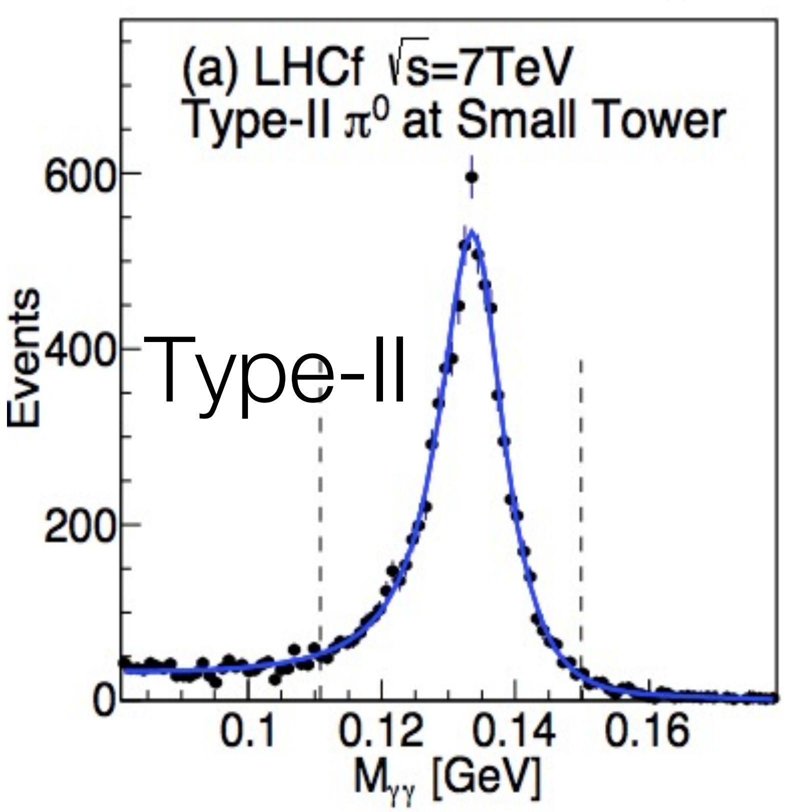
Measurement of the **opening angle** of gamma pairs

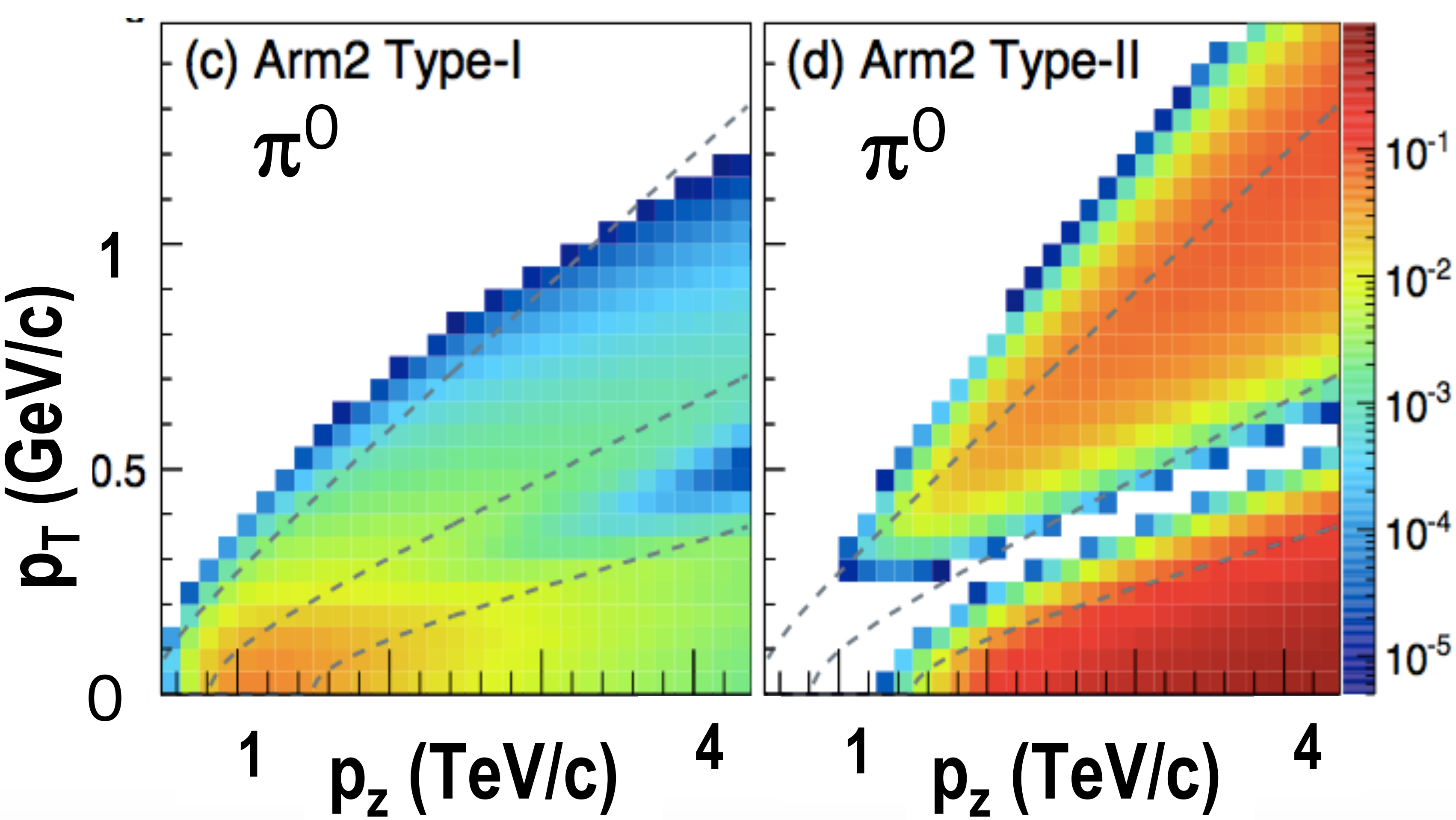
Identification of **multiple hit**

LHCf π^0 results: improvement @ 7 TeV







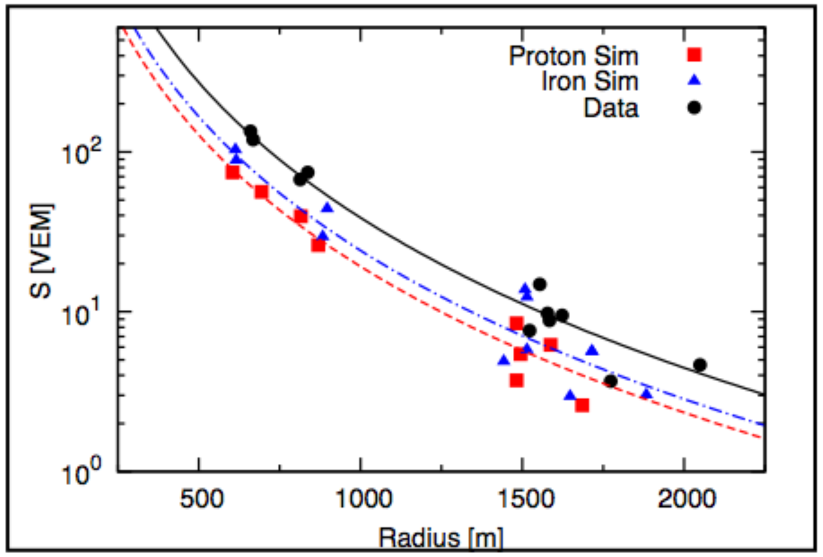


LHCf neutron analysis: motivations

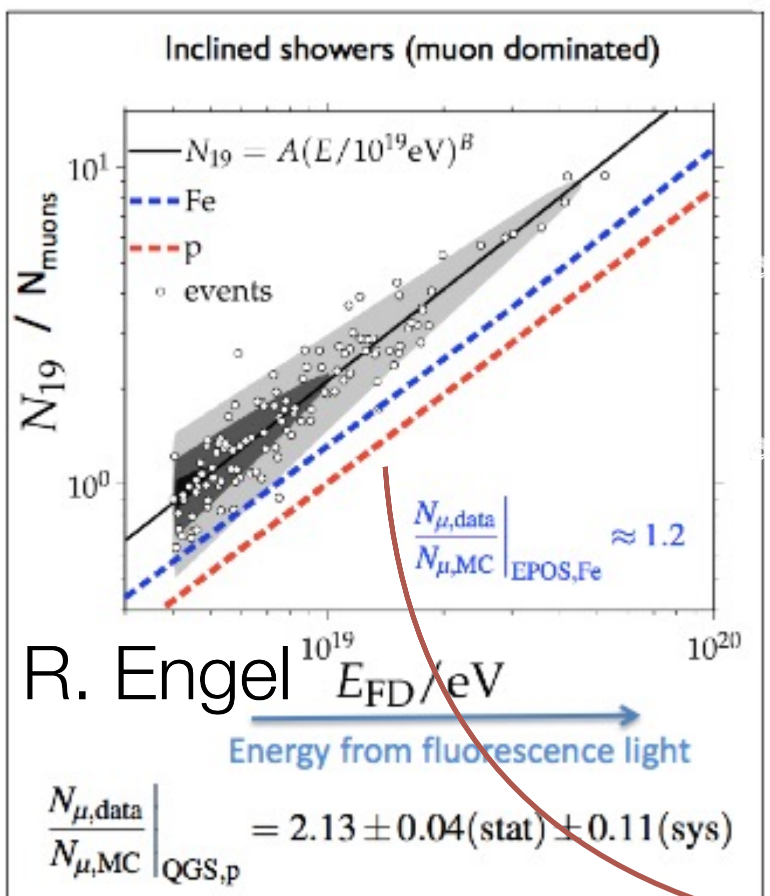
Inelasticity measurement $k=1-p_{leading}/p_{beam}$

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]

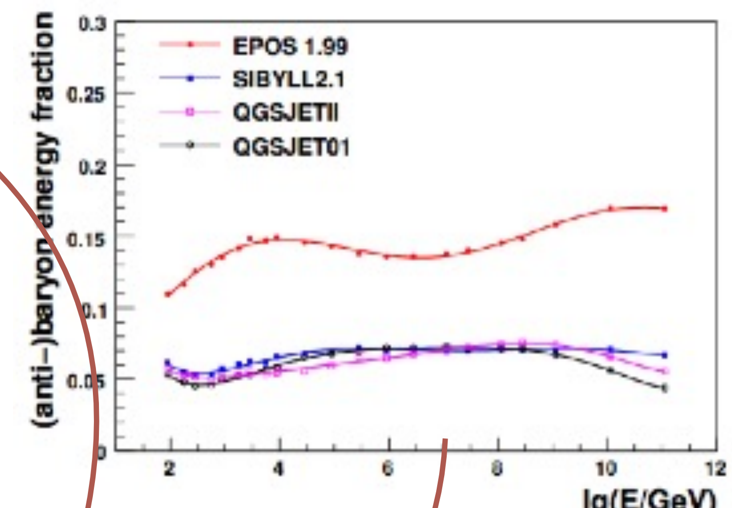


R. Engel

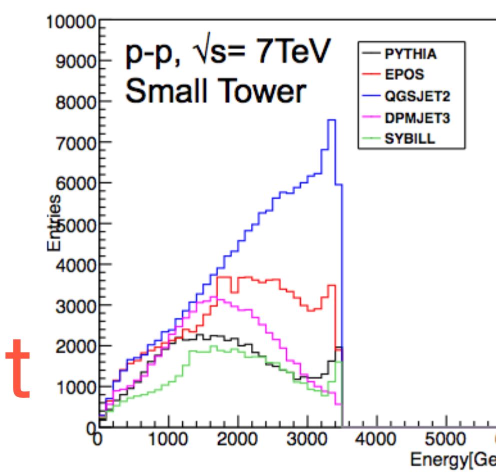
Number of muons depends on the energy fraction of produced hadron

Muon excess in data even for Fe primary MC

EPOS predicts more muon due to larger baryon production



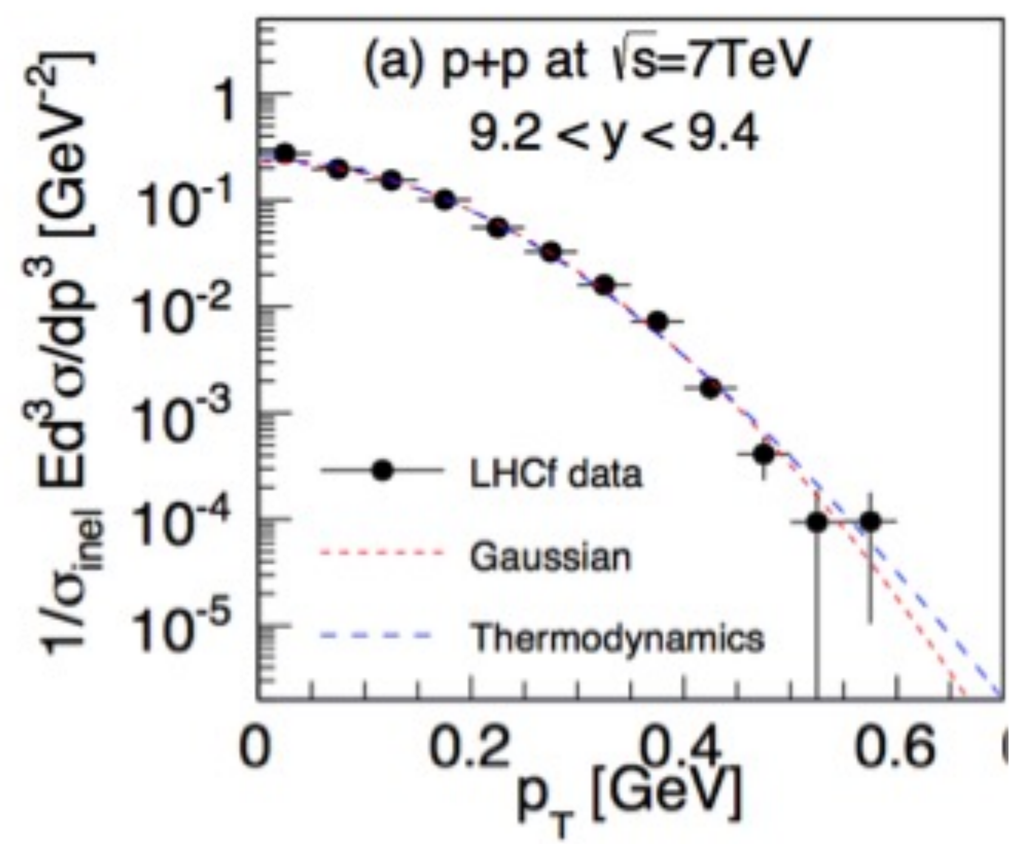
Neutron spectra predicted by interaction models



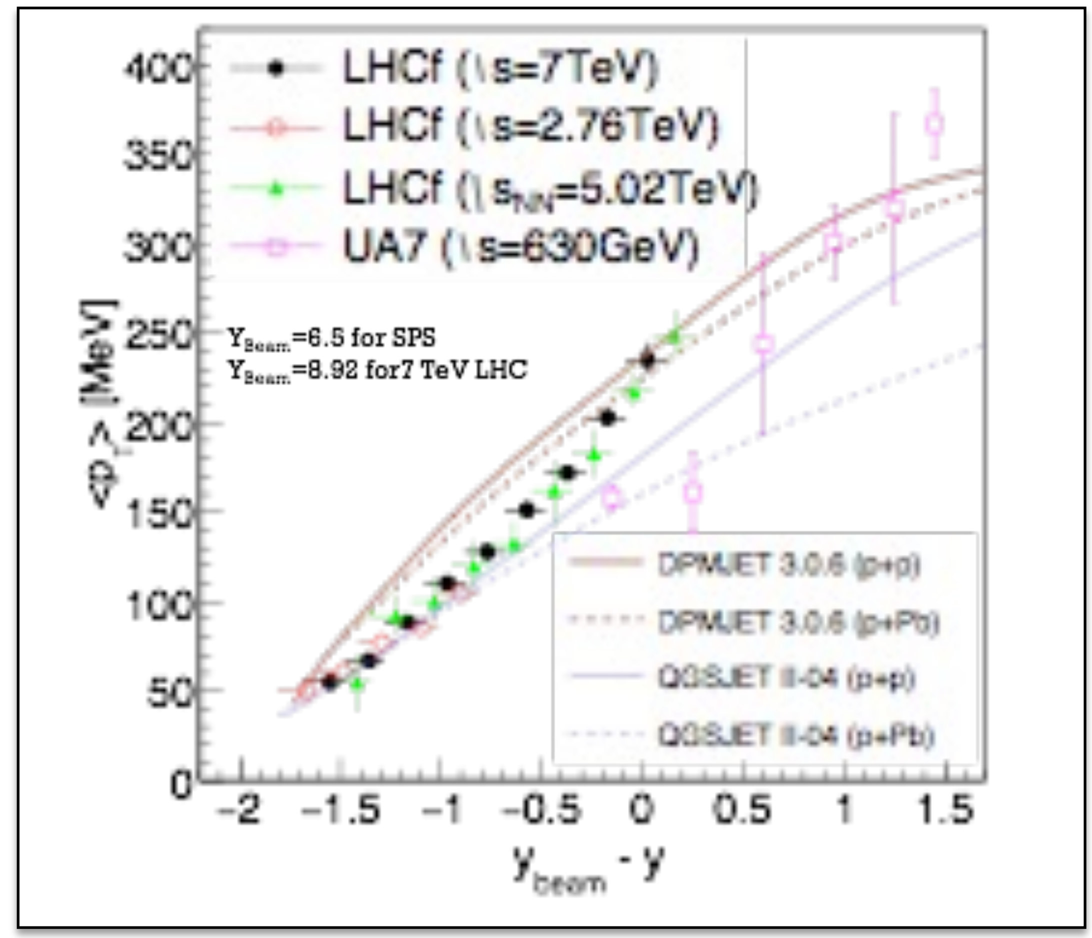
importance of baryon measurement

π^0 average p_T for different cm energies

p_T spectra vs best-fit function



Average p_T vs y_{lab}



$\langle p_T \rangle$ is inferred in 3 ways:

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

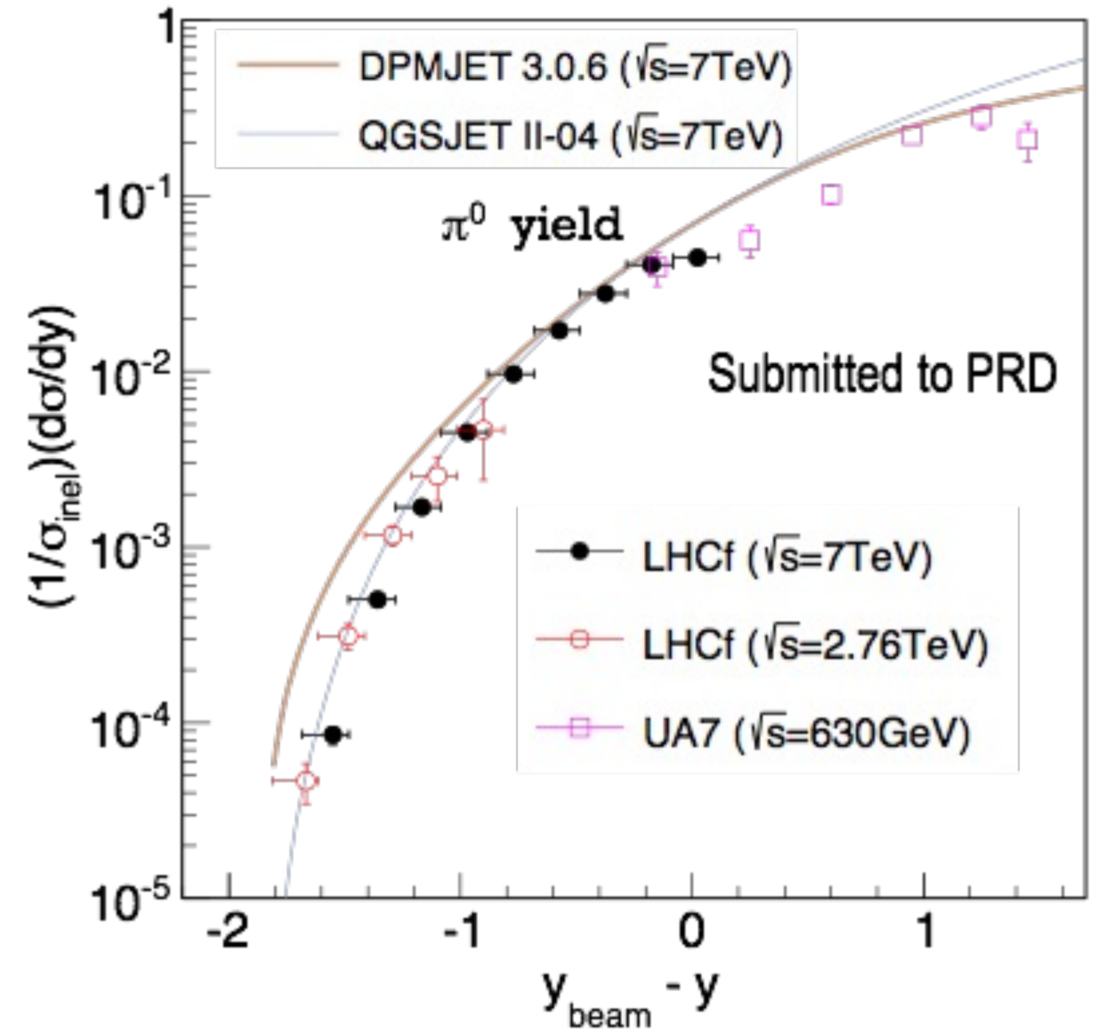
From scaling considerations (projectile fragmentation region) we can expect that $\langle p_T \rangle$ vs rapidity loss should be independent from the c.m. energy

Reasonable scaling can be inferred from the data

Limiting fragmentation in forward π^0 production

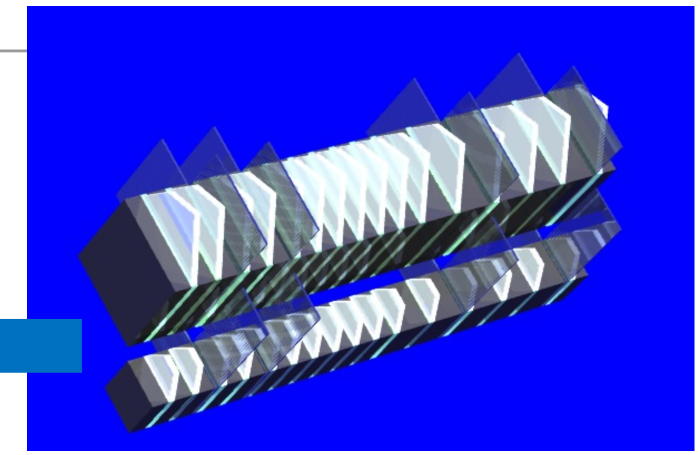
Limiting fragmentation hypothesis: rapidity distribution of the secondary particles in the forward rapidity region (target's fragment) should be independent of the center-of-mass energy.

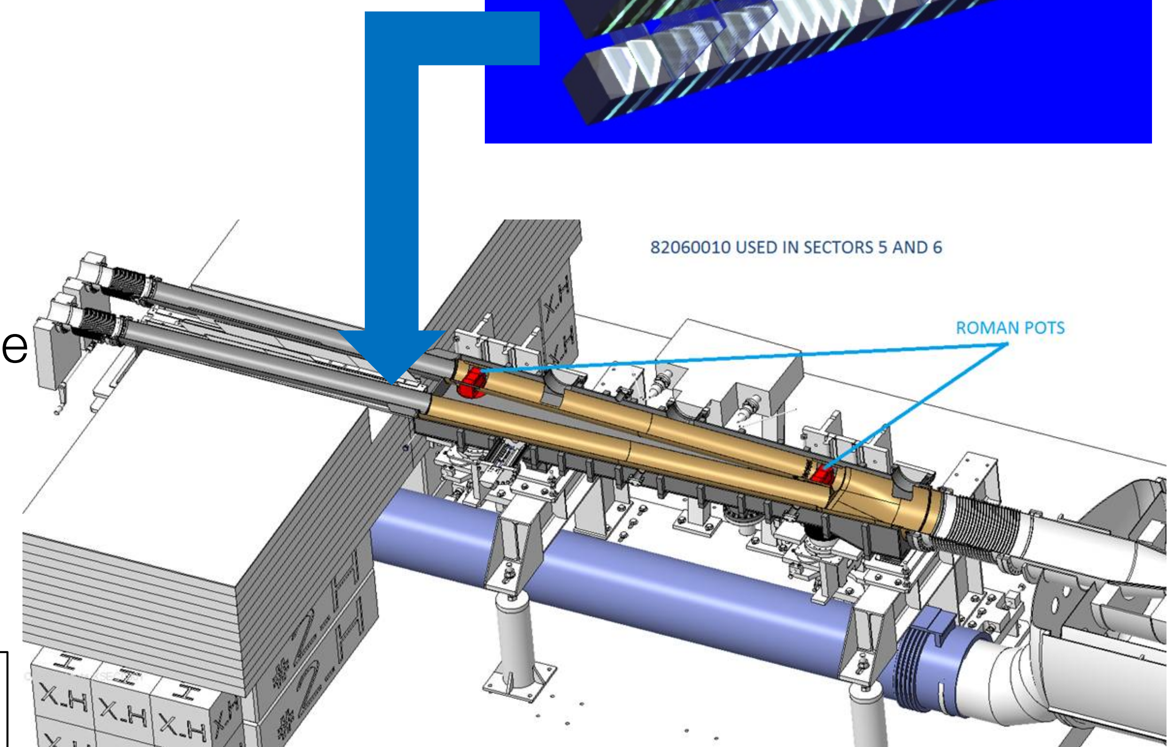
This hypothesis for π^0 is true at the level of ±15%



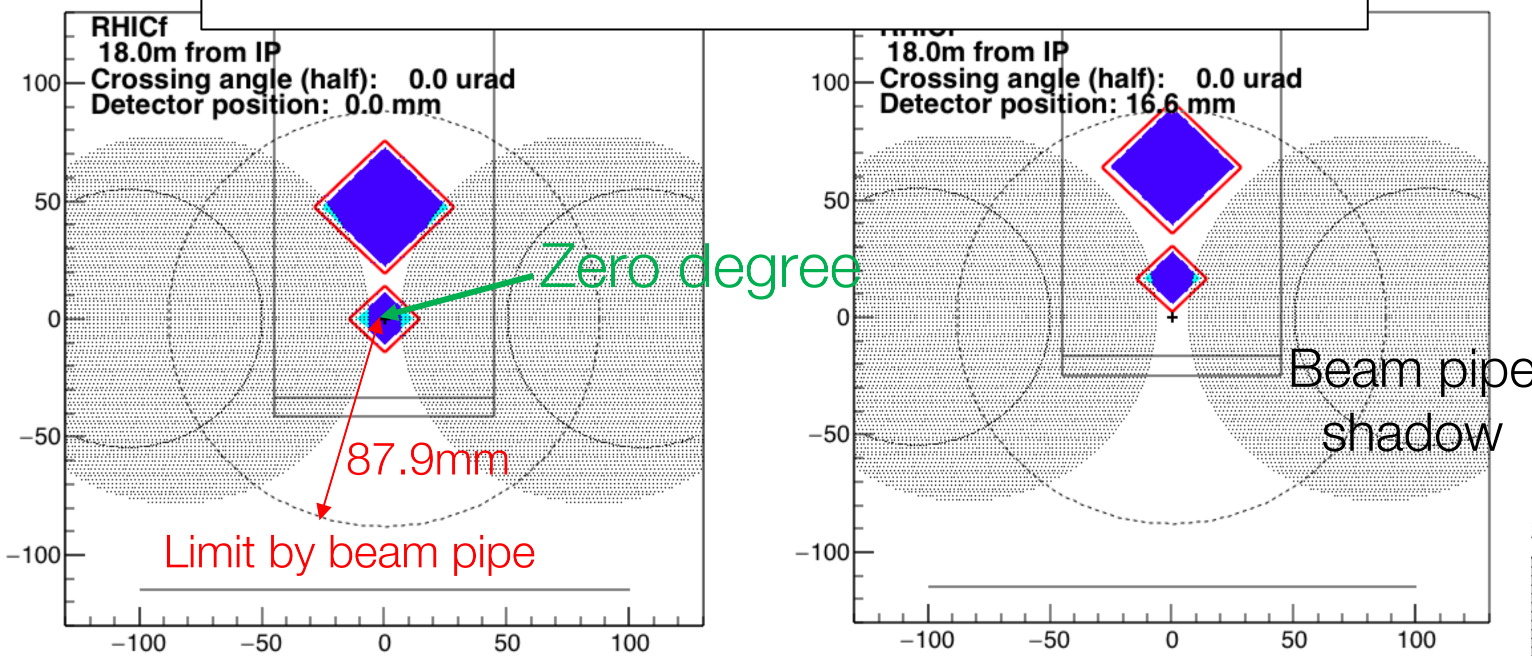
RHICf detector acceptance

Compact double calorimeters (20mmx20mm and 40mmx40mm)

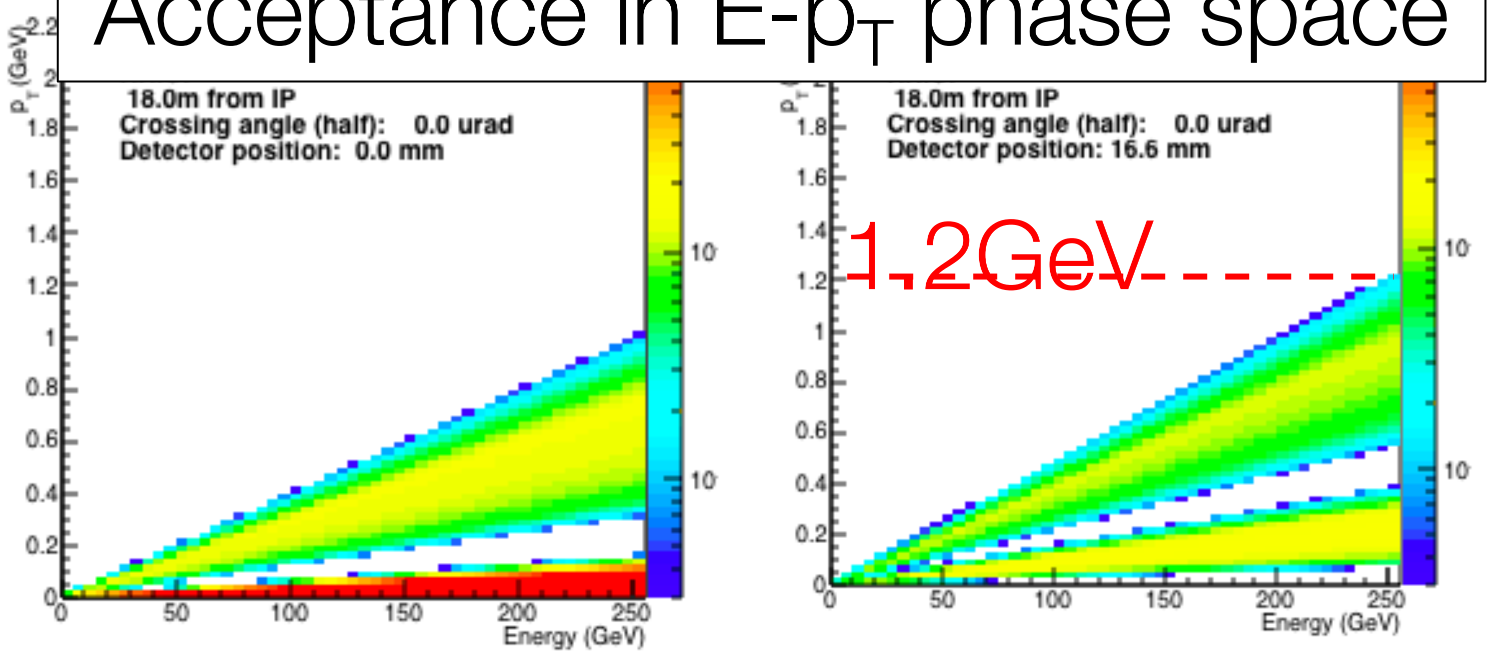




Cross section view from IP



Acceptance in E-p_T phase space

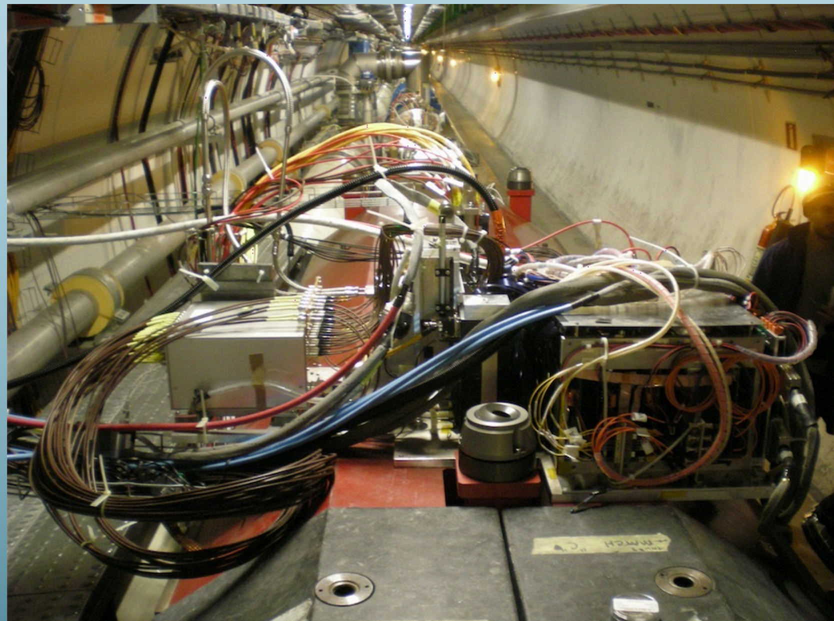


- ✓ Widest and gapless p_T coverage is realized by moving the vertical detector position.
- ✓ Beam pipes obscure photons but not neutrons.

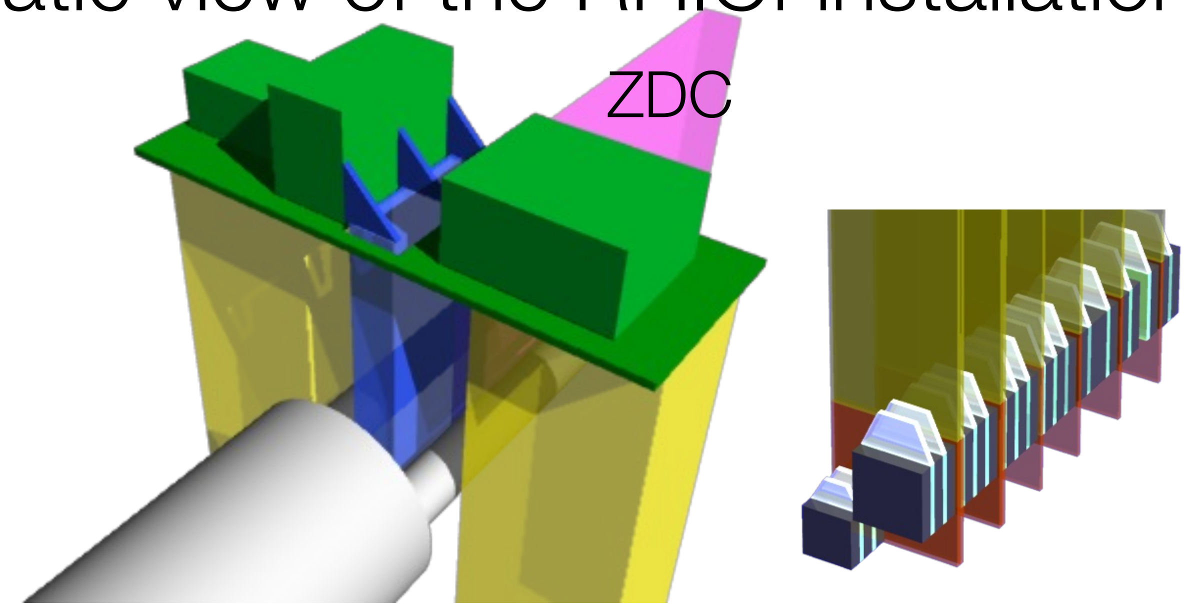
From the LHC to RHIC

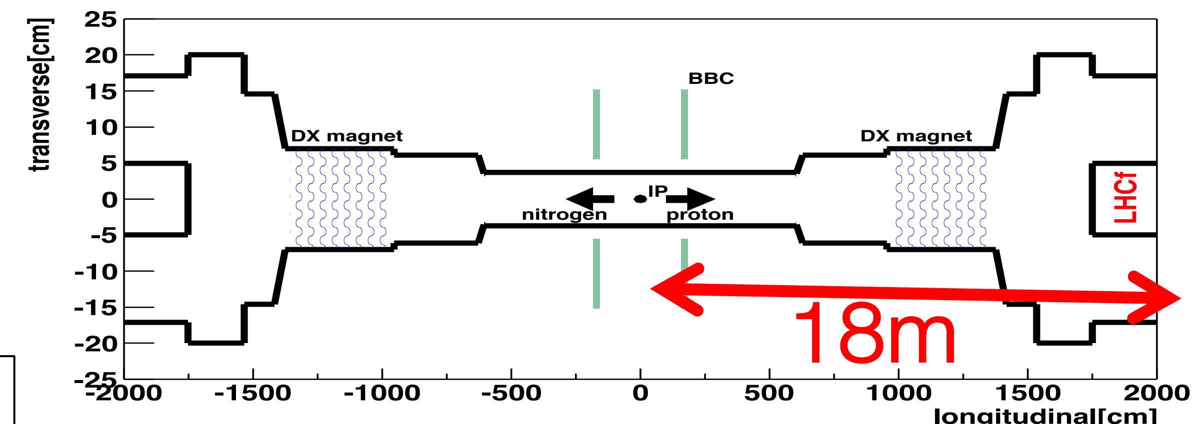
√s scaling, or breaking?

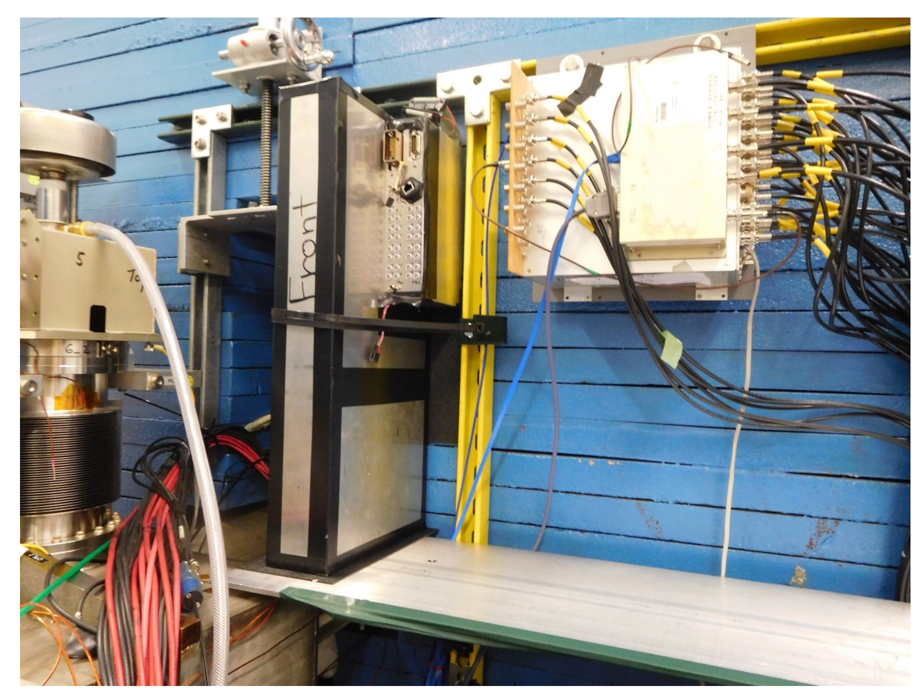
LHCf Arm2 detector in the LHC tunnel



Schematic view of the RHICf installation







Acceptance in E-p_T phase space