

# Status and Prospects of the LHCf Experiment



Elena Gensini,  
on behalf of the LHCf collaboration

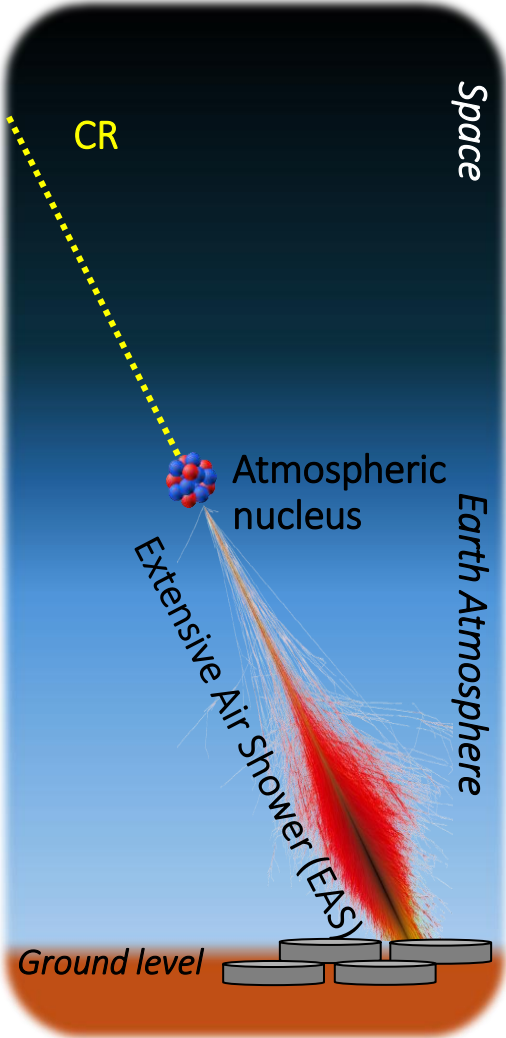


XIV International Conference  
on New Frontiers in Physics

17-31 July 2025, OAC, Kolymbari, Crete, Greece

# Physics Motivation

# Ultra High Energy Cosmic Rays



Ultra High Energy Cosmic Rays  $E > 10^{18}$  eV

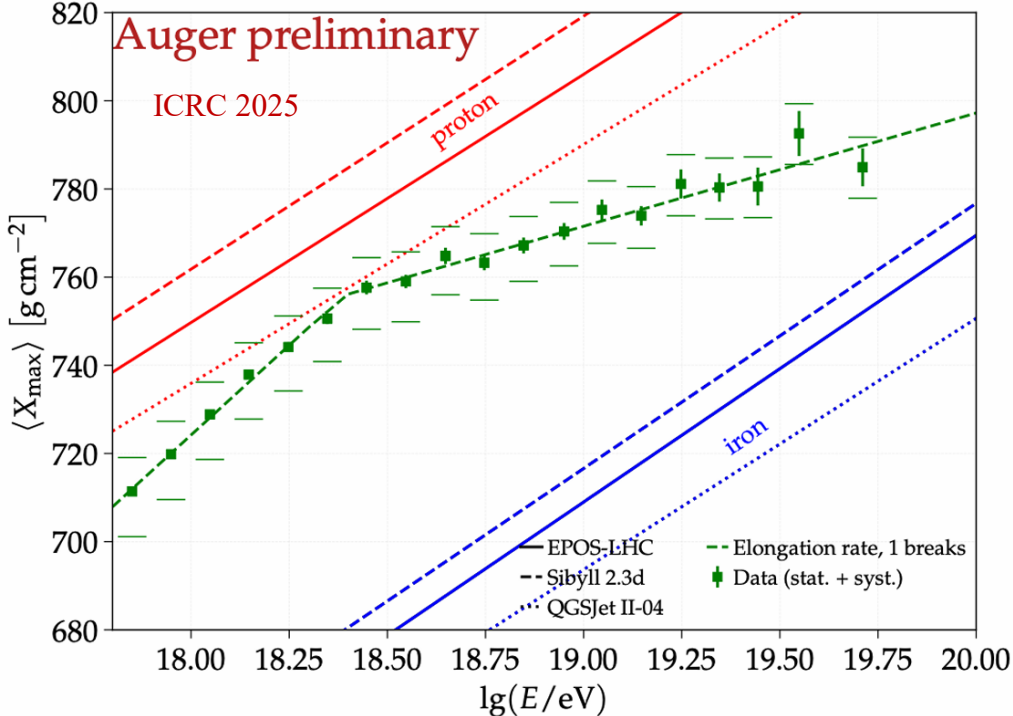
Indirect measurement of UHECR flux and **average composition** through detection of Extensive Air Shower (EAS) particles

**Main limitation**

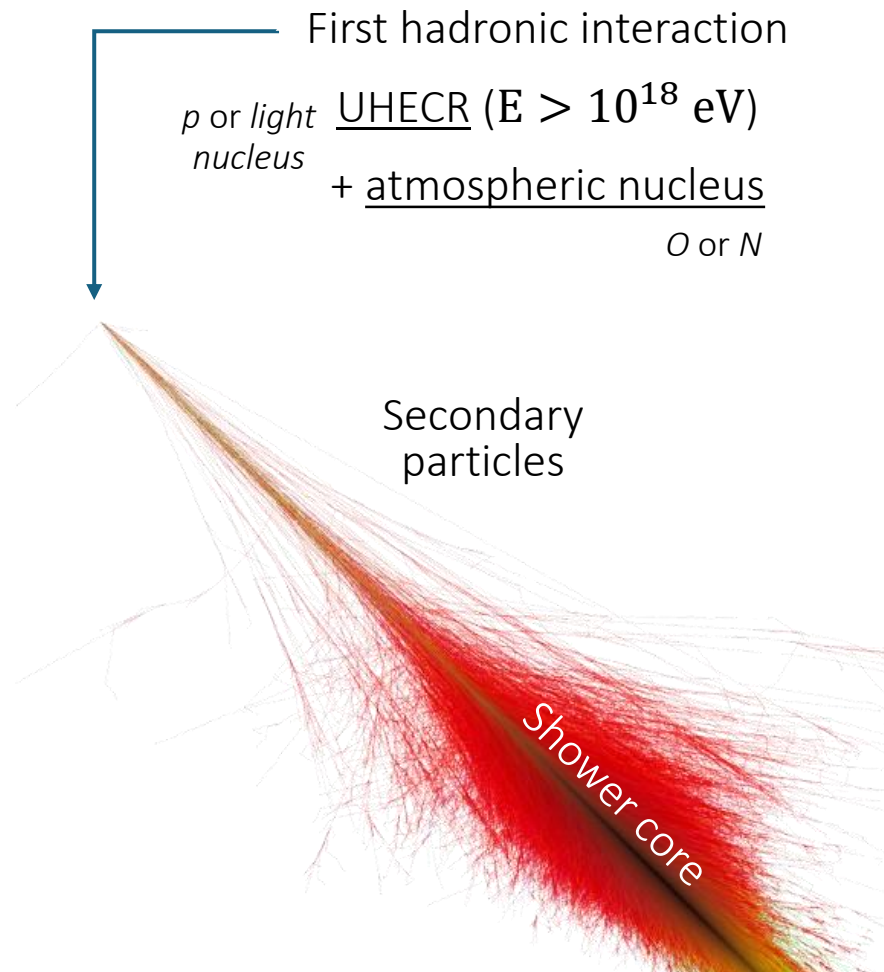
Large theoretical uncertainties in **hadronic interaction models** used for EAS simulation



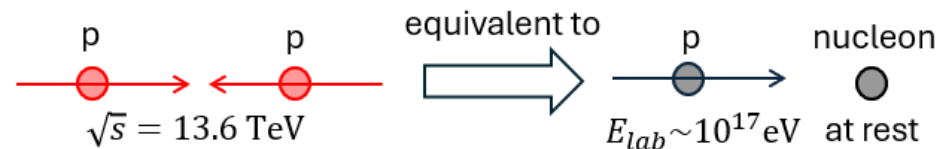
Lack of high energy calibration data



# Hadronic Interaction Models



LHC is the best place to provide high energy calibration data for the tuning of hadronic interaction model parameters



Measured quantities at LHC with an impact on the development of EAS originated by UHECRs

- Hadronic inelastic cross section,  $\sigma_{inel}$  CMS, ATLAS, TOTEM
- Particle multiplicity,  $m$
- Inelasticity  $1 - k$ , where  $k = p_{lead}/p_{beam}$
- Forward energy spectrum
- Test of scaling laws  $\rightarrow$  for extrapolation at  $E > 10^{17}$  eV
- Nuclear modification factor  $\rightarrow$  target mass number

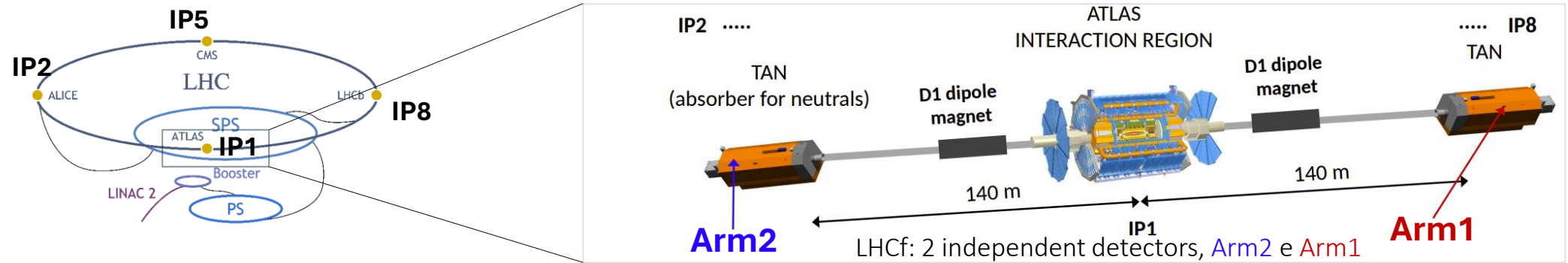


LHCf  
Experiment

# The LHCf Experiment

# The LHC-forward Experiment

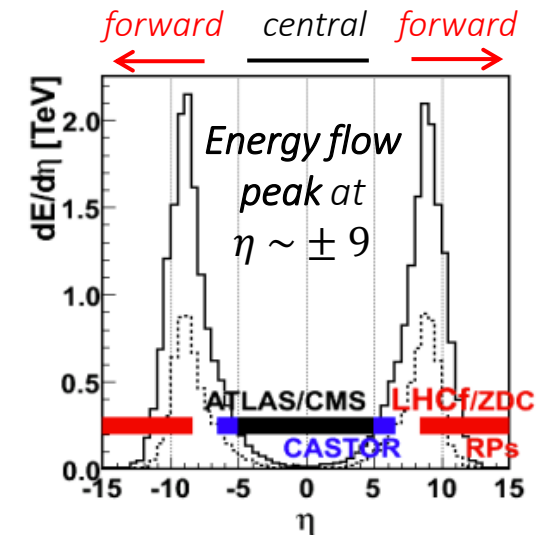
Main purpose → study of the *secondary particles* production in the very *forward* region at LHC



Detection of **neutral particles** ( $n, \gamma$ )  
having pseudorapidity  $\eta > 8.4$

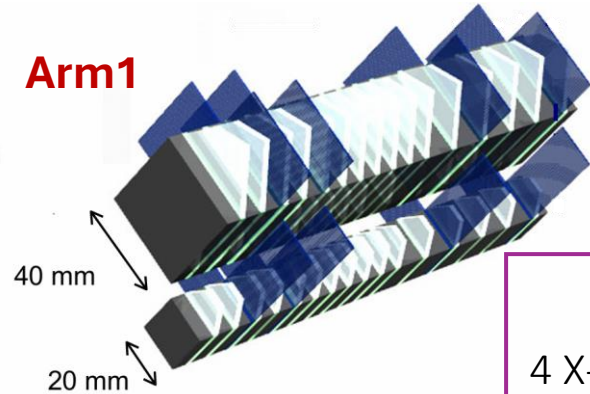
$$\eta = -\ln \left( \tan \left( \frac{\theta}{2} \right) \right)$$

No detection of charged particles:  
bended by the D1 dipole magnets



# The LHCf Experiment: Detectors

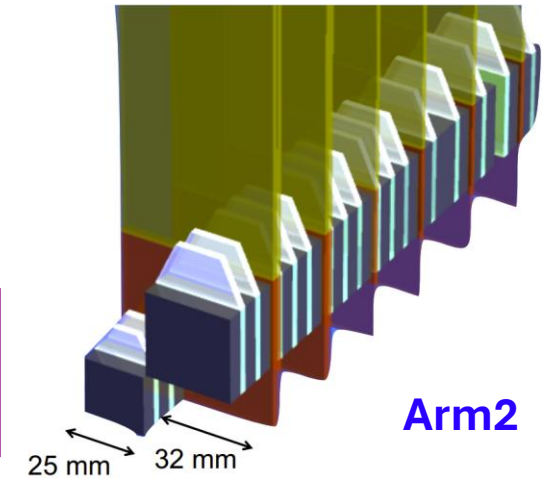
**Arm1**



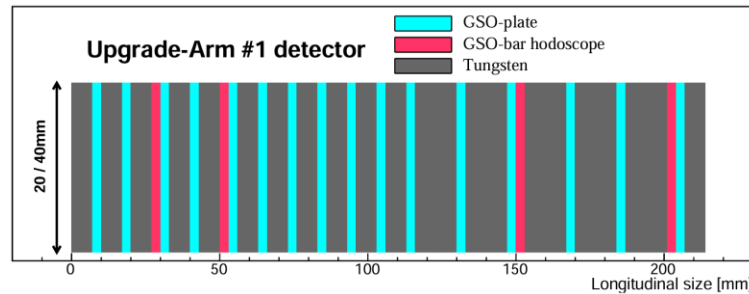
Arm1 and Arm2 are similar detectors composed by 2 **imaging** and **sampling** calorimetric towers  
Small Tower (ST) and Large Tower (LT)

16 GSO scintillator layers + 22 W layers

**Arm1** Position sensitive layers **Arm2**  
4 X-Y GSO bars, 1 mm      4 X-Y Si strip, 160  $\mu\text{m}$

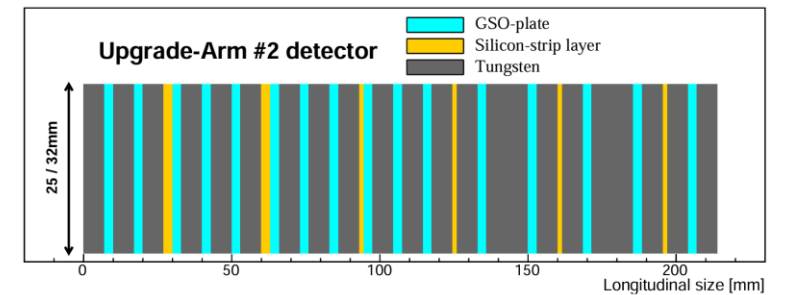


**Arm2**



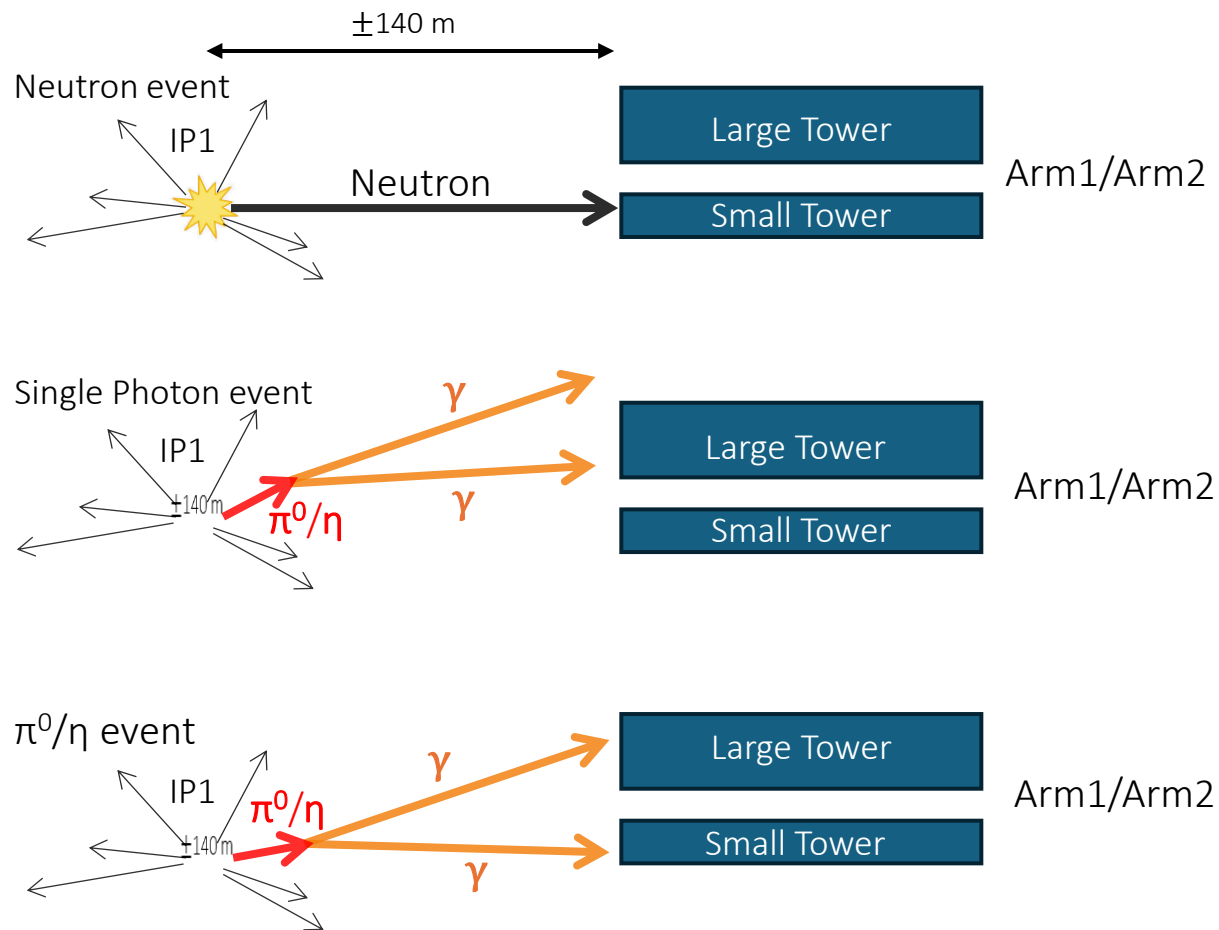
Length: 21 cm, equivalent to  
 $\sim 44 X_0$  or  $\sim 1.6 \lambda_1$

Energy Resolution  
 $< 2\%$  for  $\gamma$      $\sim 40\%$  for  $n$



Position Resolution  
**Arm1**  $< 200 \mu\text{m}$  for  $\gamma$ ,  $< 1 \text{ mm}$  for  $n$       **Arm2**  $< 40 \mu\text{m}$  for  $\gamma$ ,  $< 800 \mu\text{m}$  for  $n$

# The LHCf Experiment: Events



Hadronic interaction model  
information from LHCf data

*Information on leading baryon  
and average inelasticity*

*Information on electromagnetic  
component*

# The LHCf Experiment: Operations

		$\sqrt{s}$ or $\sqrt{s_{NN}}$	$E_{lab}$ (eV)	year	note	
LHC Run I	p+p	$\sqrt{s}=0.9$ TeV	$4.3 \times 10^{14}$	2009-2010		Focus of this presentation ↓
	p+p	$\sqrt{s}=7$ TeV	$2.6 \times 10^{16}$	2010		
	p+Pb	$\sqrt{s_{NN}}=5.02$ TeV	$1.4 \times 10^{16}$	2013	Arm2 only	
	p+p	$\sqrt{s}=2.76$ TeV	$4.1 \times 10^{15}$	2013	Arm2 only	
LHC Run II	p+p	$\sqrt{s}=13$ TeV	$9.0 \times 10^{16}$	2015		Results from Run II p+p
	p+Pb	$\sqrt{s_{NN}}=8.16$ TeV	$3.6 \times 10^{16}$	2016	Arm2 only	
RHIC	p+p (RHICf)	$\sqrt{s}=510$ GeV	$1.4 \times 10^{14}$	2017	Arm1 only	
LHC Run III	p+p	$\sqrt{s}=13.6$ TeV	$9.0 \times 10^{16}$	2022		Ongoing analysis of Run III p+p
	p+O	$\sqrt{s_{NN}}=9.6$ TeV	$5.0 \times 10^{16}$	2025	Arm2 only	Run III p+O operation

Results from Run II  
p+p at  $\sqrt{s} = 13$  TeV

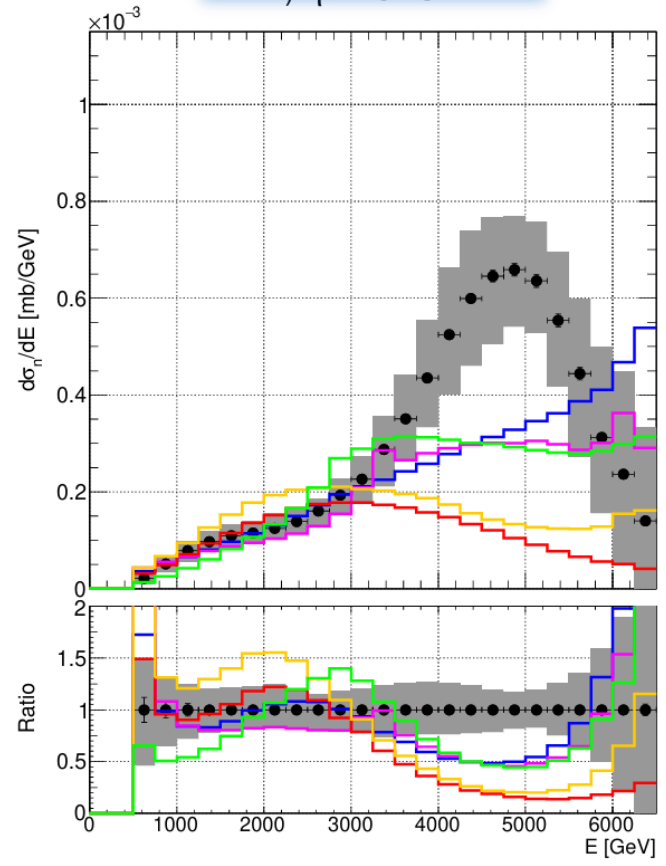
# Neutron Production Cross Section

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

$$d\sigma_n = dN_n / \int L dt$$

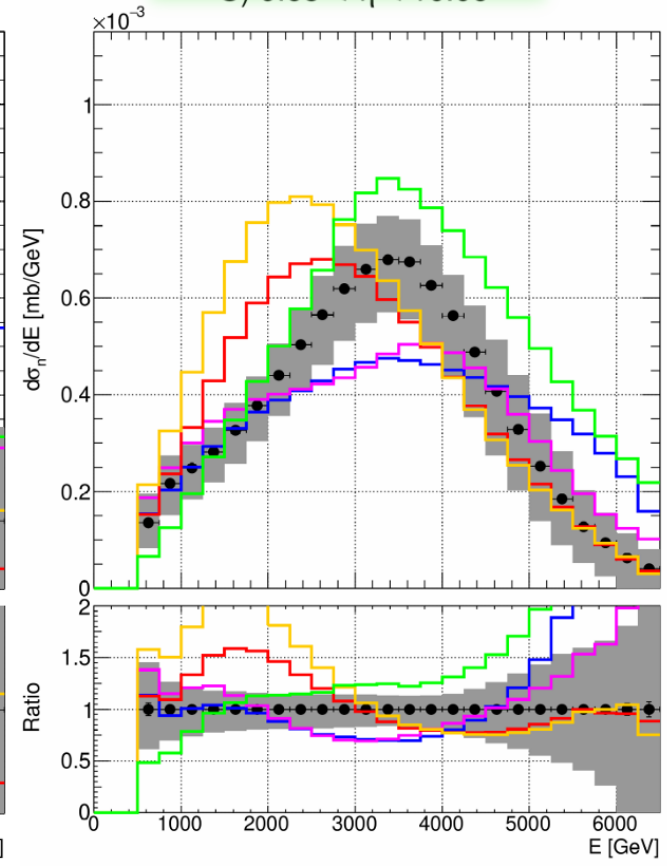
$$\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$

A)  $\eta > 10.75$



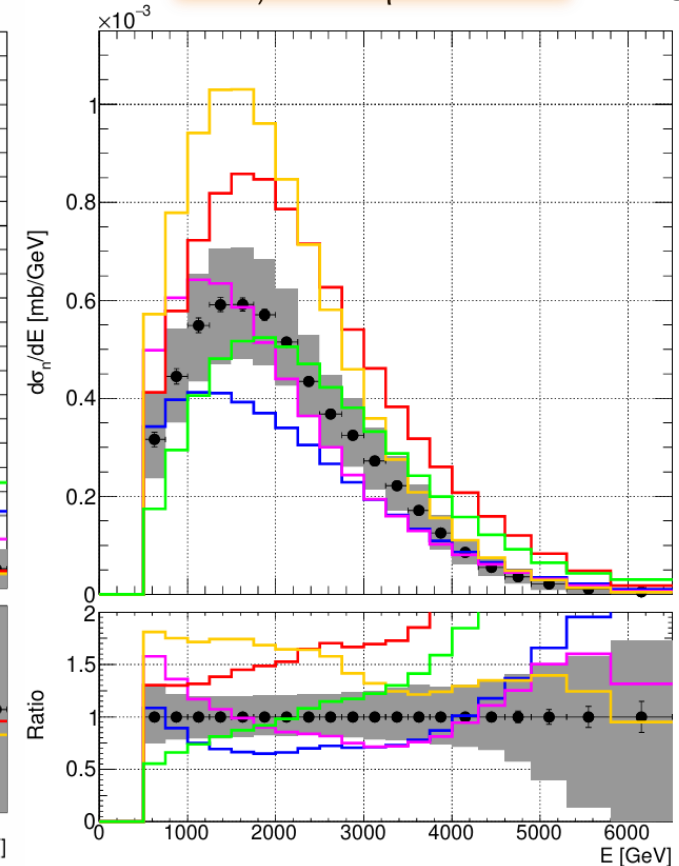
No model agrees with peak structures and production rate

C)  $9.65 < \eta < 10.06$

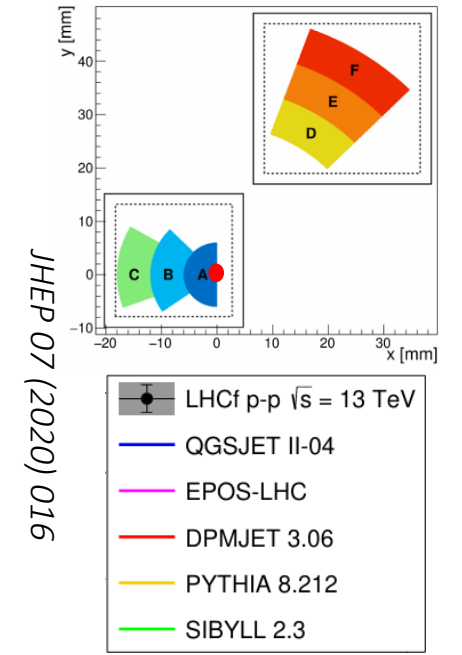


SIBYLL 2.3 and EPOS-LHC have better but not satisfactory agreement with data

E)  $8.80 < \eta < 8.99$



higher  $\eta =$  'more forward' region



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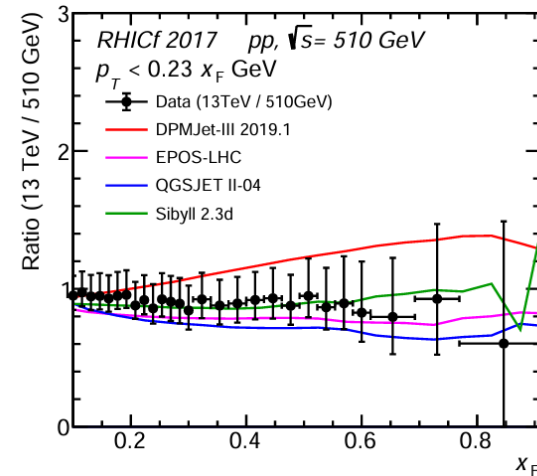
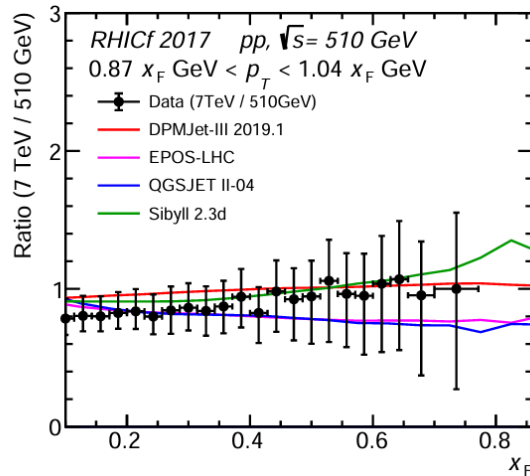
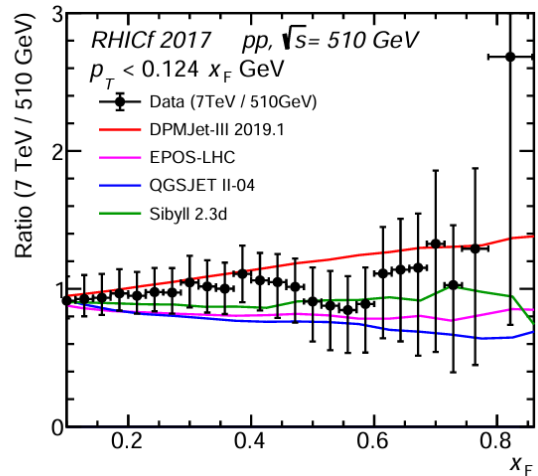
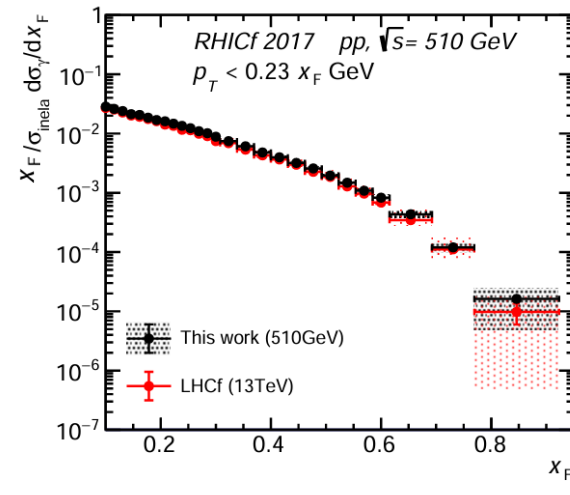
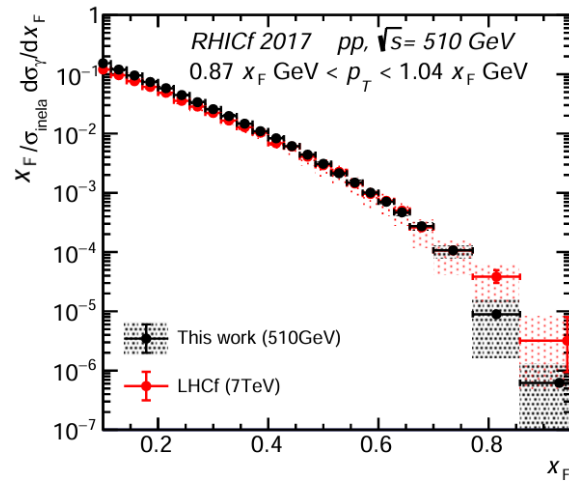
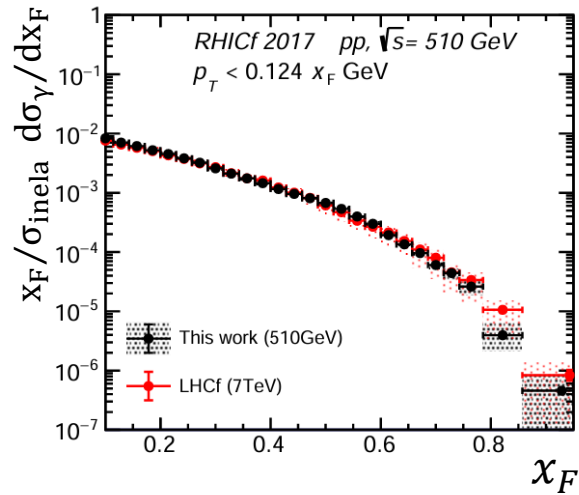
LHCf forward neutron spectra used for new EPOS, SYBILL, QGSJET versions

# Test of Feynman scaling law (photons)

p+p → √s = 510 GeV (RHICf), 7 TeV, 13 TeV

$$d\sigma_\gamma = dN_\gamma / \int L dt$$

$$x_F \equiv 2p_z / \sqrt{s}$$



arXiv:2203.15416v1 [hep-ex] 29 Mar 2022 submitted to PLB

**Feynman scaling law in the forward region:**  
production cross sections of secondary particles vs  $x_F$  are independent of the incident energy in the forward region:  
$$\frac{x_F}{\sigma_{inel}} \frac{d\sigma}{dx_F} \text{ VS } x_F$$
  
independent of the center of mass energy

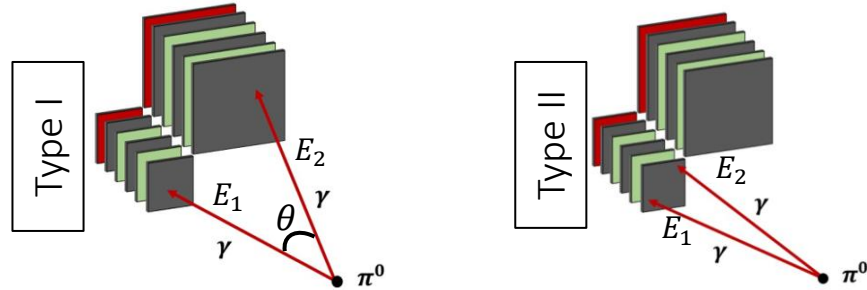
- confirmed within the error
- Precision of measurement not sufficient to discuss the weak  $x_F$  dependency predicted by certain models

# $\pi^0$ Production Rate - Preliminary

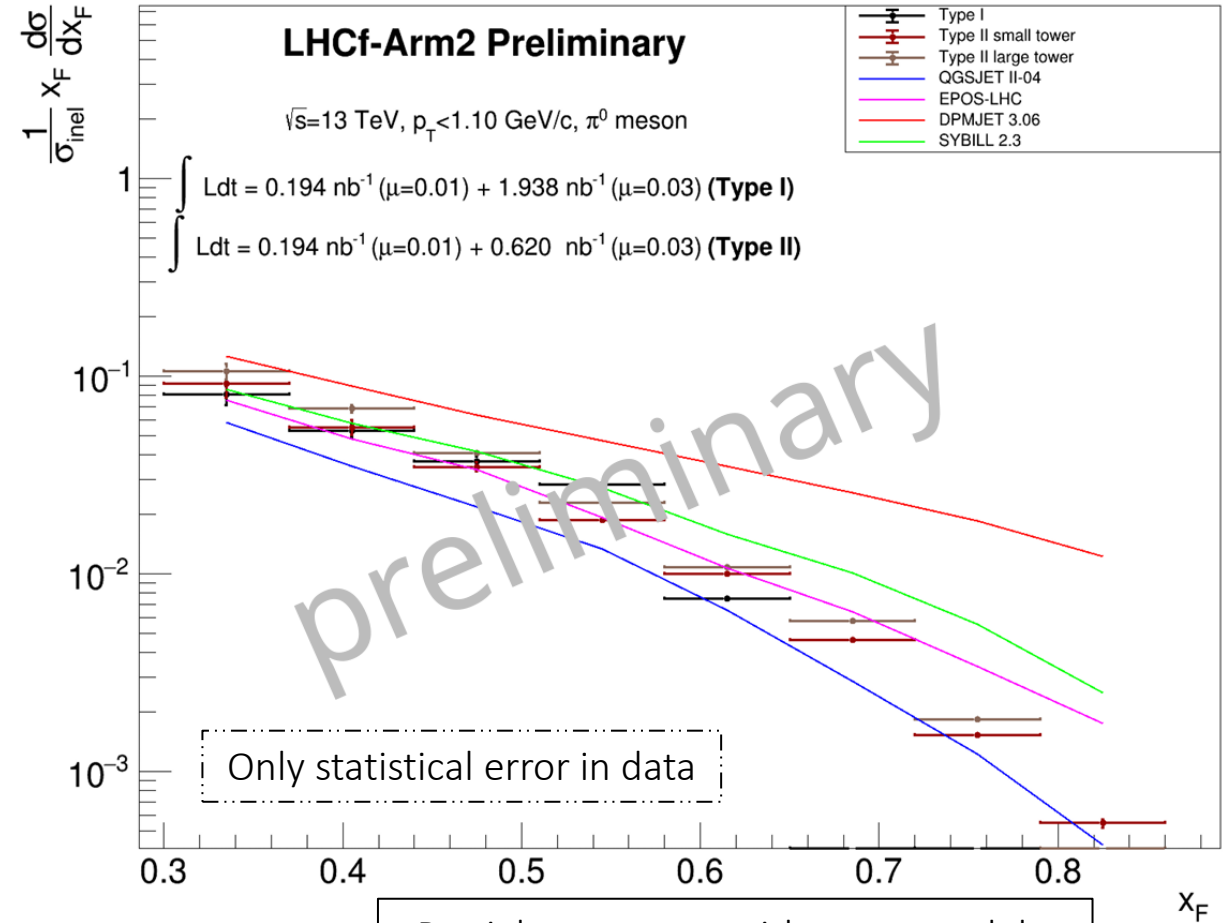
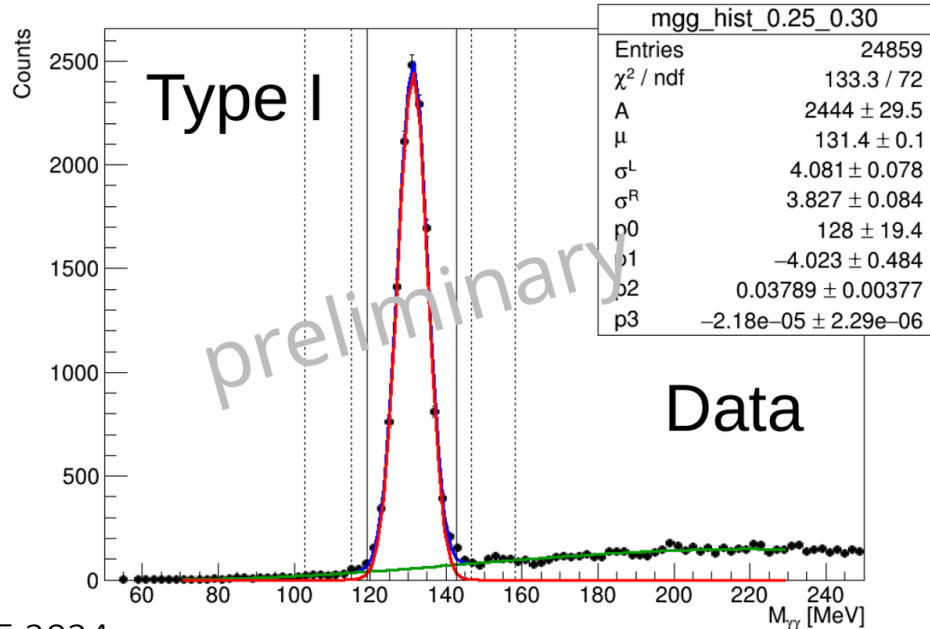
$p+p \rightarrow \sqrt{s} = 13 \text{ TeV}$

$$d\sigma = dN_{\pi^0} / \int L dt$$

$$x_F \equiv 2p_z / \sqrt{s}$$



$$M_{\gamma\gamma}^2 = (q_1 + q_2)^2 = 2E_1E_2(1 - \cos\theta)$$



Partial agreement with some models, but not across the entire range of  $x_F$

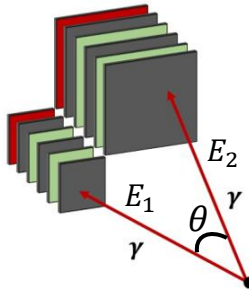
# $\eta$ Production Rate

$p+p \rightarrow \sqrt{s} = 13 \text{ TeV}$

$$d\sigma = dN_\eta / \int L dt$$

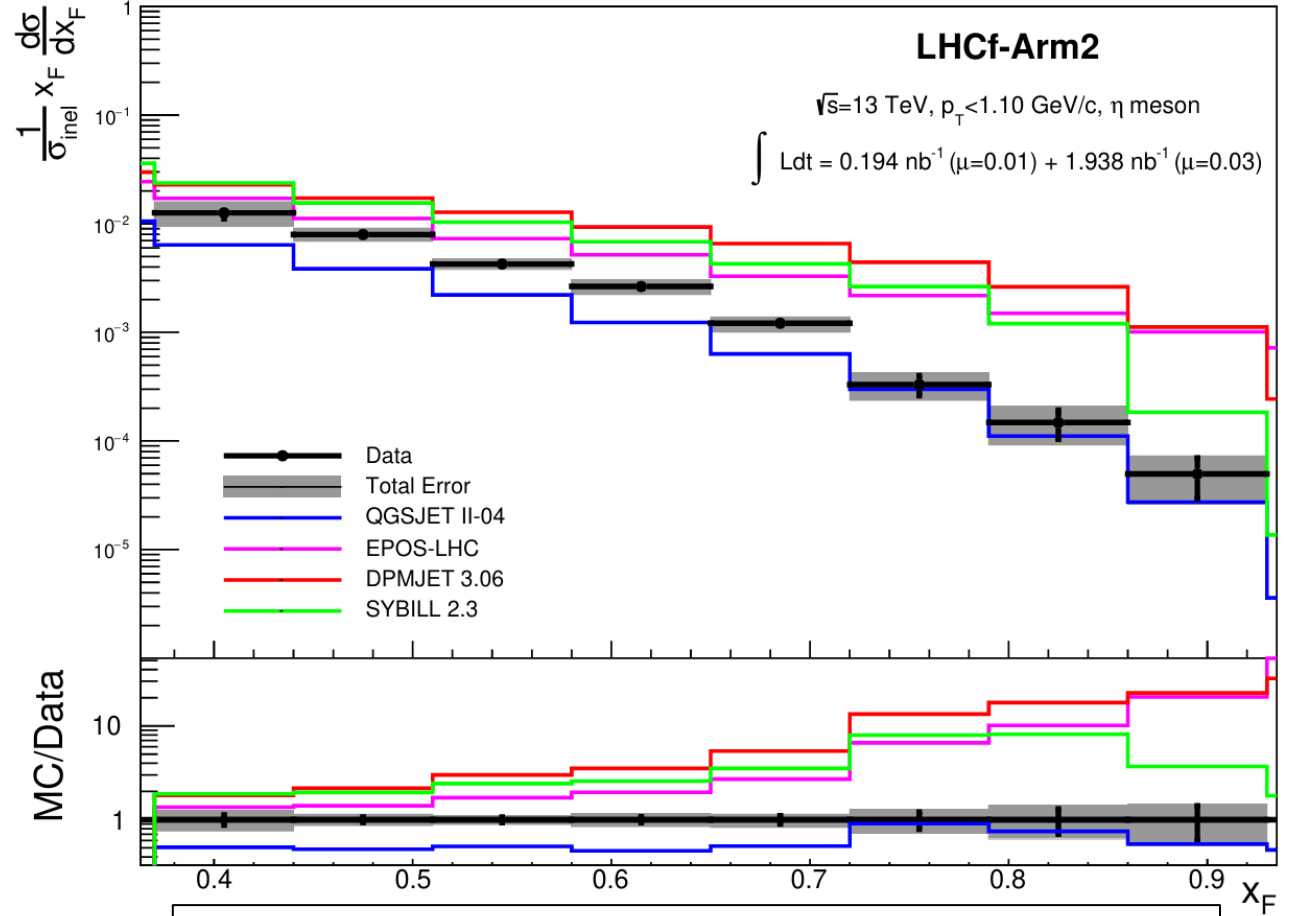
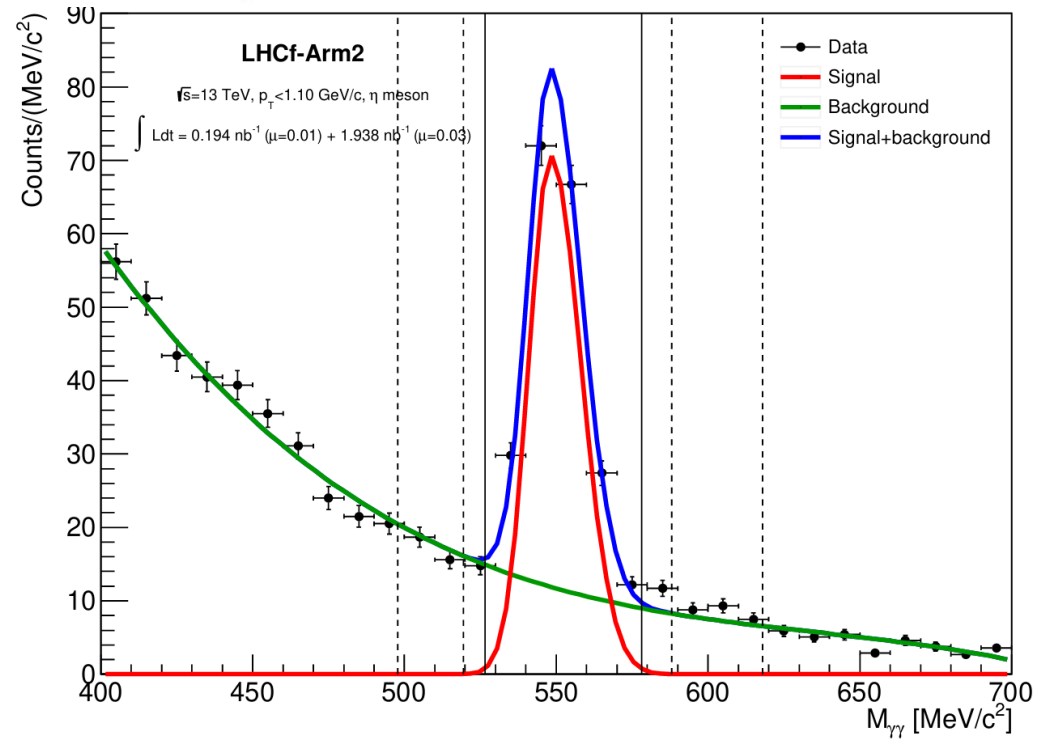
$$x_F \equiv 2p_z / \sqrt{s}$$

Type I



$\eta \rightarrow$  contribution from **strange quark**

$$M_{\gamma\gamma}^2 = (q_1 + q_2)^2 = 2E_1E_2(1 - \cos\theta)$$



- No model shows agreement across the entire  $x_F$  range
- QGSJET II-04 shows the best agreement for  $x_F > 0.7$

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# Ongoing analyses of Run III

p+p at  $\sqrt{s} = 13.6$  TeV

# p+p → √s = 13.6 TeV

Operations on September 24-26, 2022

Fill 8178 – 55 h → Longest LHC Fill ever

Fill 8179 – 2 h

For Run III operation

- Arm2 silicon DAQ upgrade: higher acquisition rate
- Optimization of LHCf trigger scheme

○ 8 times larger statistics expected with respect to Run II

○ Enlarge 2-γ event statistics (both Type I and Type II)  
→ More precise measurements of π<sup>0</sup> and η

○ Sufficient statistics of 4-γ events  
→ Possible measurement of K<sub>S</sub><sup>0</sup> → π<sup>0</sup> + π<sup>0</sup> → 4γ

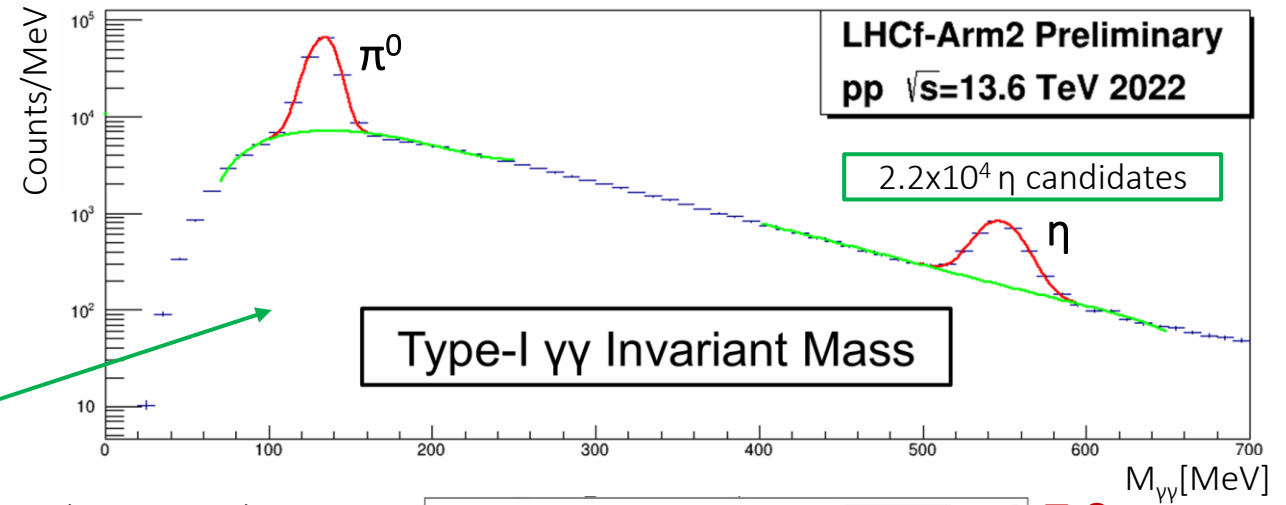
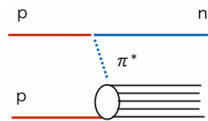
○ 40 times larger statistics of ATLAS common events with respect to Run II (ATLAS-CONF-2017-075 Run II LHCf+ATLAS data)

→ Diffractive/Non-diffractive production

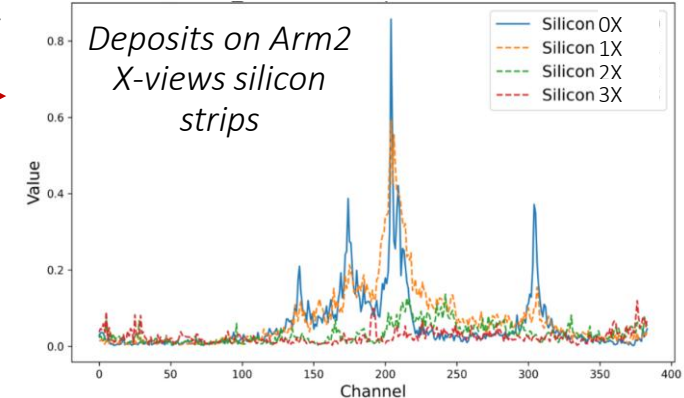
→ One-pion exchange process

→ ...

Run III LHCf+ATLAS joint analysis: H.Kobayashi ICRC2025 conference



Deep learning techniques for K<sub>S</sub><sup>0</sup> reconstruction



G. Piparo, A. Paccagnella  
EPS-HEP2025 conference

Identification of 4γ peaks on Arm2 silicon layers  
Position and energy reconstruction of each γ

Run III – p+0 operation

# p+O collisions at LHC: Physics Motivation

The LHCf experiment measures quantities directly related to **parameters of hadronic interaction models**

→ Simulation of **Extensive Air Shower** generated by collision between UHECR and atmospheric nucleus

LHCf operations Run I-II-III

*p, light nucleus*                      *N, O*

- **p+p at several center-of-mass energies**  
 $\sqrt{s} = 0.9 \text{ TeV} \div 13.6 \text{ TeV} \rightarrow E_{\text{lab}} \sim 10^{17} \text{ eV}$
- **p+Pb at nucleon-nucleon center-of-mass energies**  
 $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}, 8.16 \text{ TeV}$

→ pPb nuclear modification factor  
 (interpolation for nuclei lighter than Pb)

p+p and p+Pb are not representative of  
 UHECR+atmospheric nucleus

**Proton + Oxygen collisions at LHC, July 1-3, 2025**

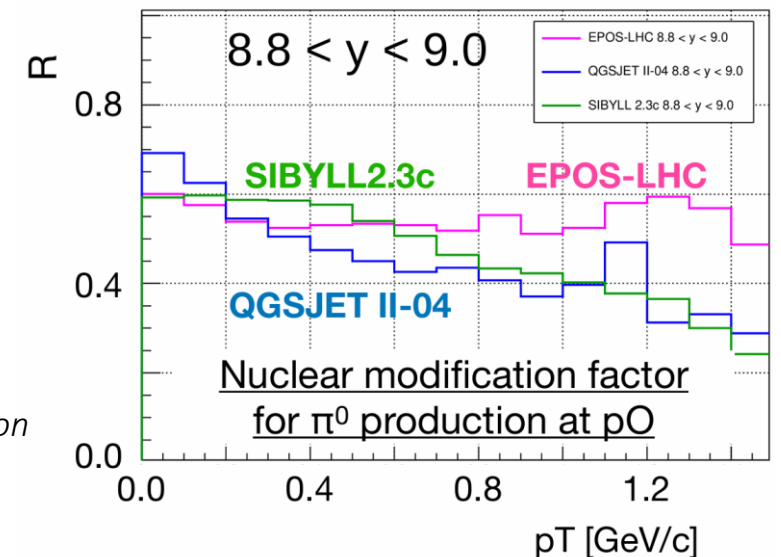
- Most important and last LHCf operation
- Reduce the uncertainties related to large extrapolation from p+p and p+Pb
- Study of nuclear effects with light nuclei

First p + light ion  
 collisions at any  
 colliders

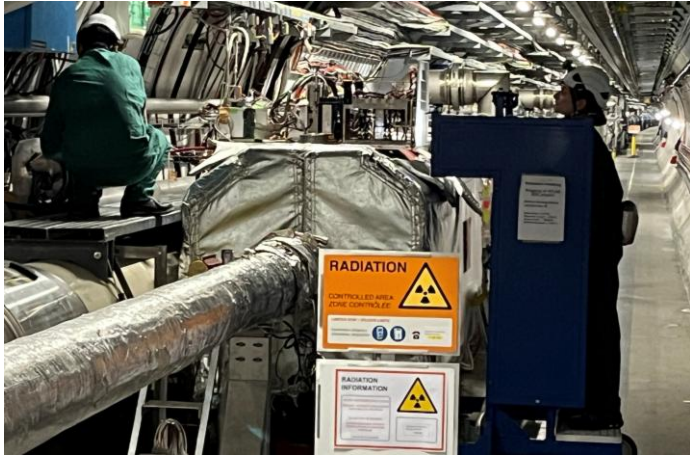
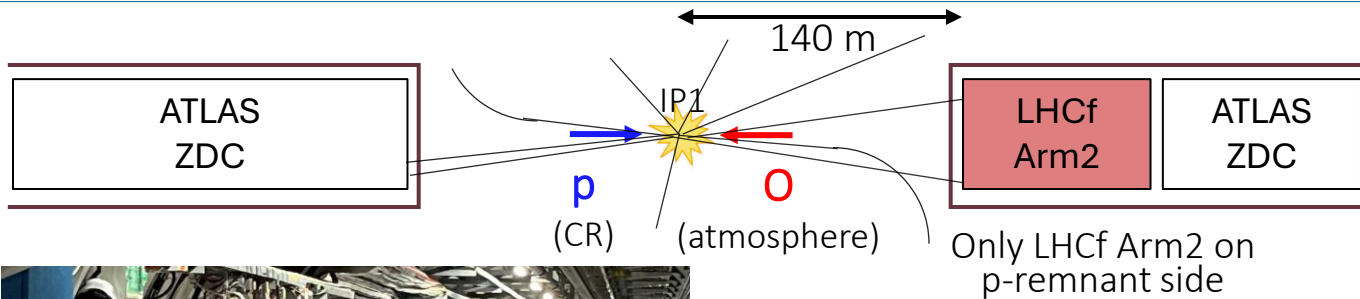
pO nuclear modification

$$R = \frac{\sigma_{pO}}{\langle N_{coll} \rangle \sigma_{pp}}$$

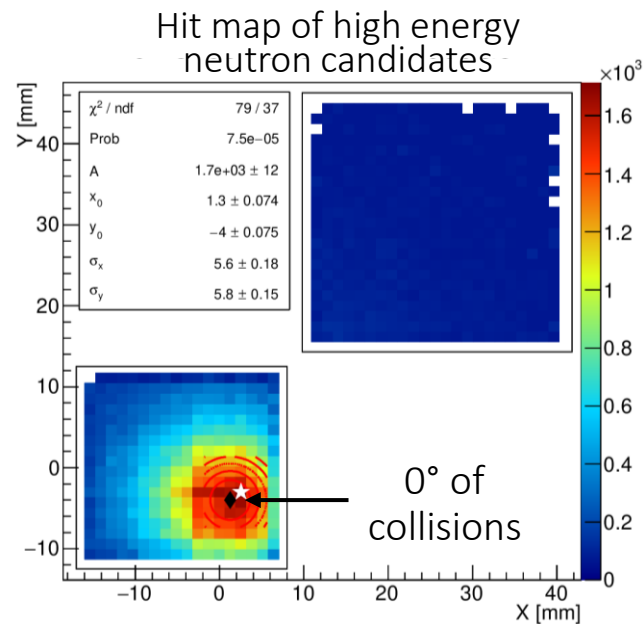
average number of nucleon-nucleon  
 collisions in a p+O collision



# p+O: Experimental setup



- Arm2 installation on 23<sup>rd</sup> of June 2025 (Technical Shutdown)
- Data taking from 1<sup>st</sup> to 3<sup>rd</sup> of July 2025
- Performed a joint operation with ATLAS  
All LHCf triggers accepted by ATLAS DAQ



Beam energies

Proton  $\rightarrow E_p = 6.8 \text{ TeV}$

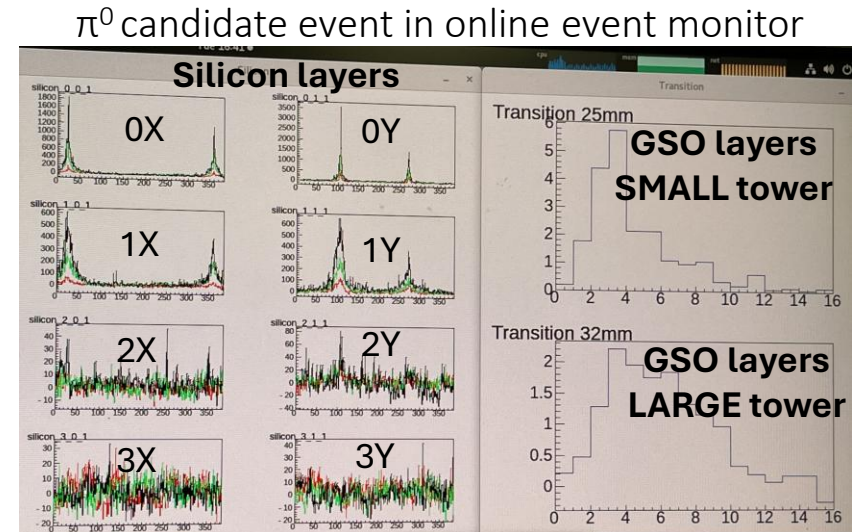
Each nucleon of Oxygen  $\rightarrow E_{nucl} = 6.8 \frac{Z}{A} \text{ TeV}$

Collision energy

$$\sqrt{s_{NN}} = 2\sqrt{E_p E_{nucl}} \sim 9.6 \text{ TeV}$$

$\downarrow$

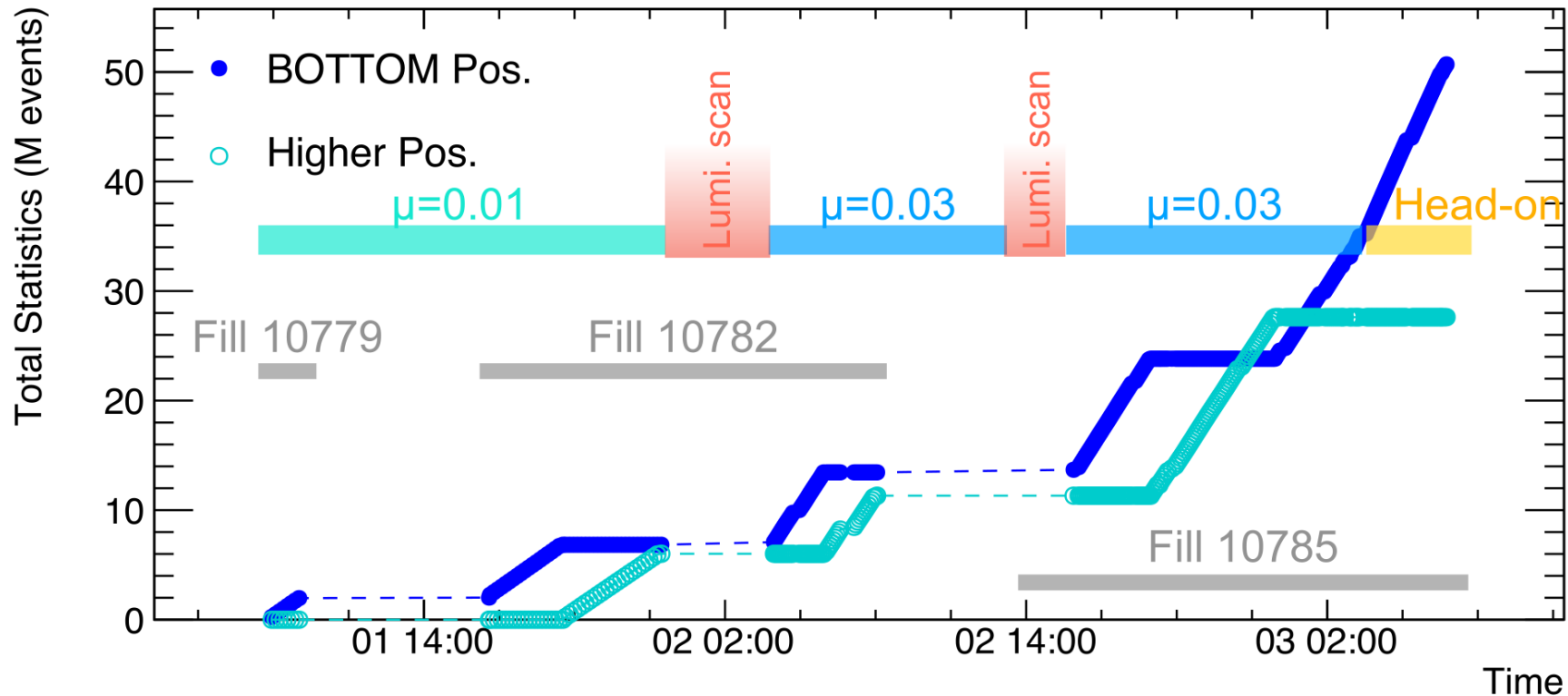
$E_{CR} = 5 \times 10^{16} \text{ eV}$



# Statistics with p+O collisions

73 M events

- 2 detector positions: BOTTOM (nominal pos.) and Higher (5 mm higher than nominal)
- 3 different luminosity conditions:  $\mu=0.01$ ,  $\mu=0.03$ , head-on collisions (higher luminosity)



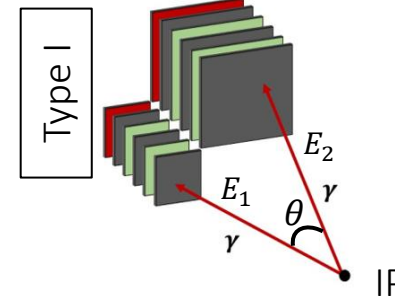
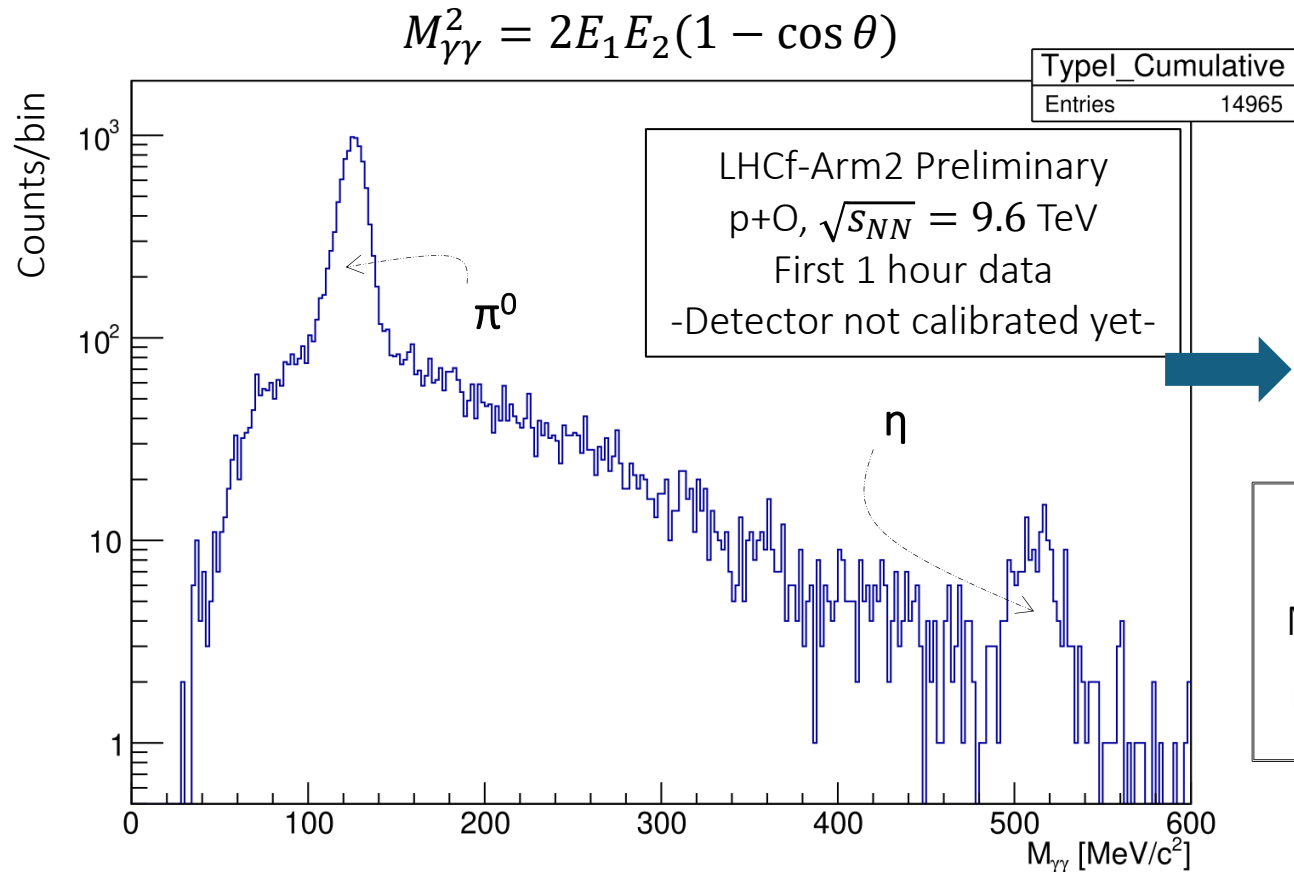
$\mu$  is the average number of collisions per bunch crossing

Example:

$\mu=0.01 \rightarrow 1\%$  pile-up probability

# $\gamma\gamma$ invariant mass distribution in p+O

- Run 81537-81544, first 1 hour of data taking
- Only **Type I** events



- Clear peaks of  $\pi^0$  and  $\eta$
- Good statistics obtained for  $\pi^0$  and  $\eta$  analyses

p+O Run successfully completed

Most relevant LHCf operation for the UHECR Physics

Last LHCf operation after almost 20 years of activity

# Summary

## LHCf operations at LHC

- ✓ p+p and p+Pb collisions at several center-of-mass energy
- ✓ LHCf neutral forward particle spectra → calibration data for **hadronic interaction models**

Run II p+p at  $\sqrt{s} = 13$  TeV  $\rightarrow E_{lab} = 9.0 \times 10^{16}$  eV

- Neutron production cross section
- Photon production rate ( $\sqrt{s} = 13$  TeV, 7 TeV, 510 GeV) *Test of Feynman scaling law*
- $\pi^0$  production rate
- $\eta$  production rate *Contribution from strange quark*

Info on leading baryon and average inelasticity

Info on electromagnetic component

Run III p+p at  $\sqrt{s} = 13.6$  TeV  $\rightarrow$  8 times statistics wrt Run II (many ongoing analyses)

- More precise analyses of  $\pi^0$  and  $\eta$
- Development of deep learning techniques for  $K_S^0$  reconstruction *Contribution from strange quark*
- LHCf+ATLAS joint analysis *Diffraction/Non-diffractive events, OPE process, ...*

Run III p+O at  $\sqrt{s_{NN}} = 9.6$  TeV  $\rightarrow E_{lab} = 5 \times 10^{16}$  eV *pO Nuclear modification factor*

- Most important LHCf operation successfully completed in July 1-3, 2025
- Detector calibration test beam at SPS in September/October 2025

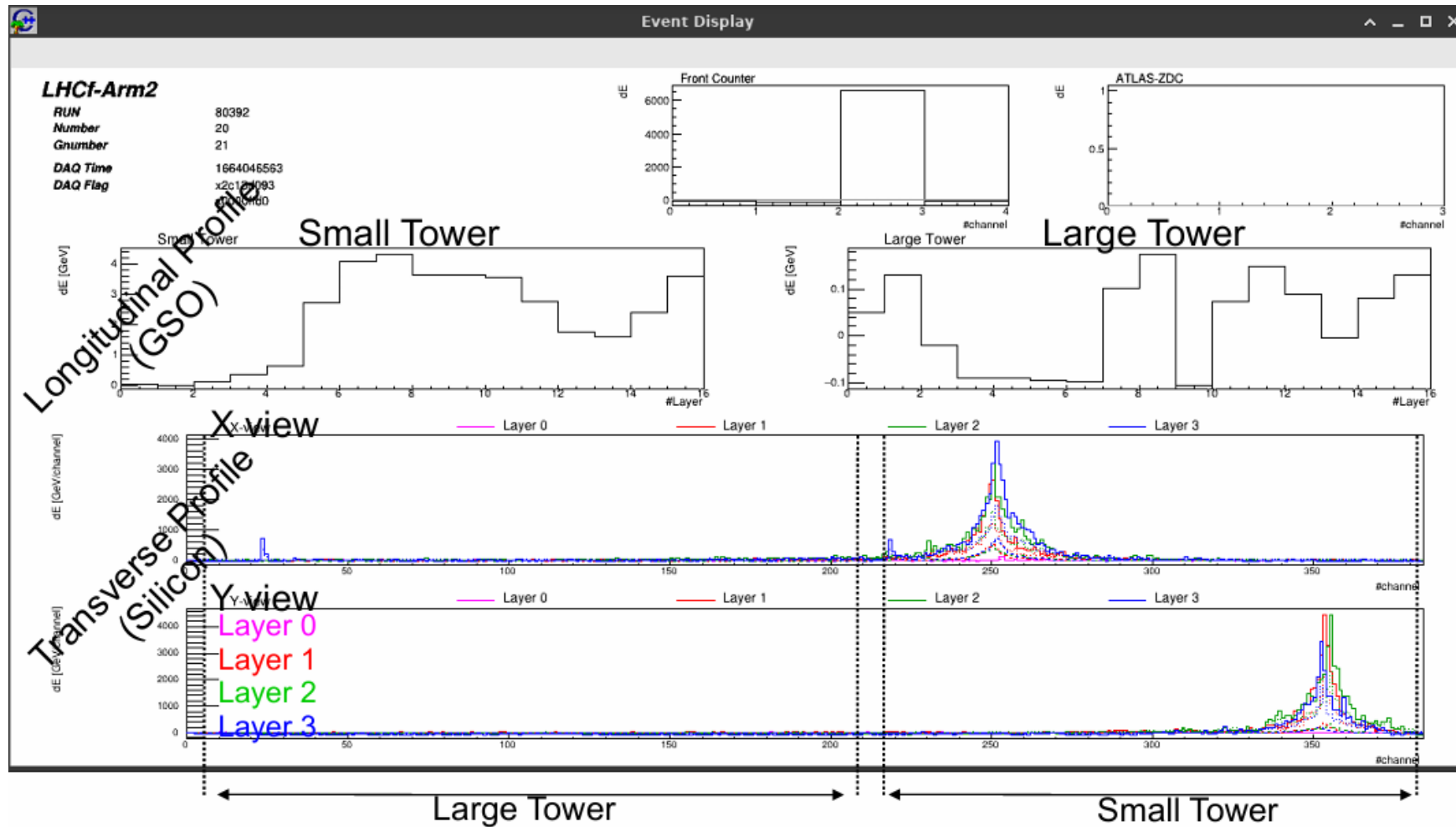
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# *Backup slides*

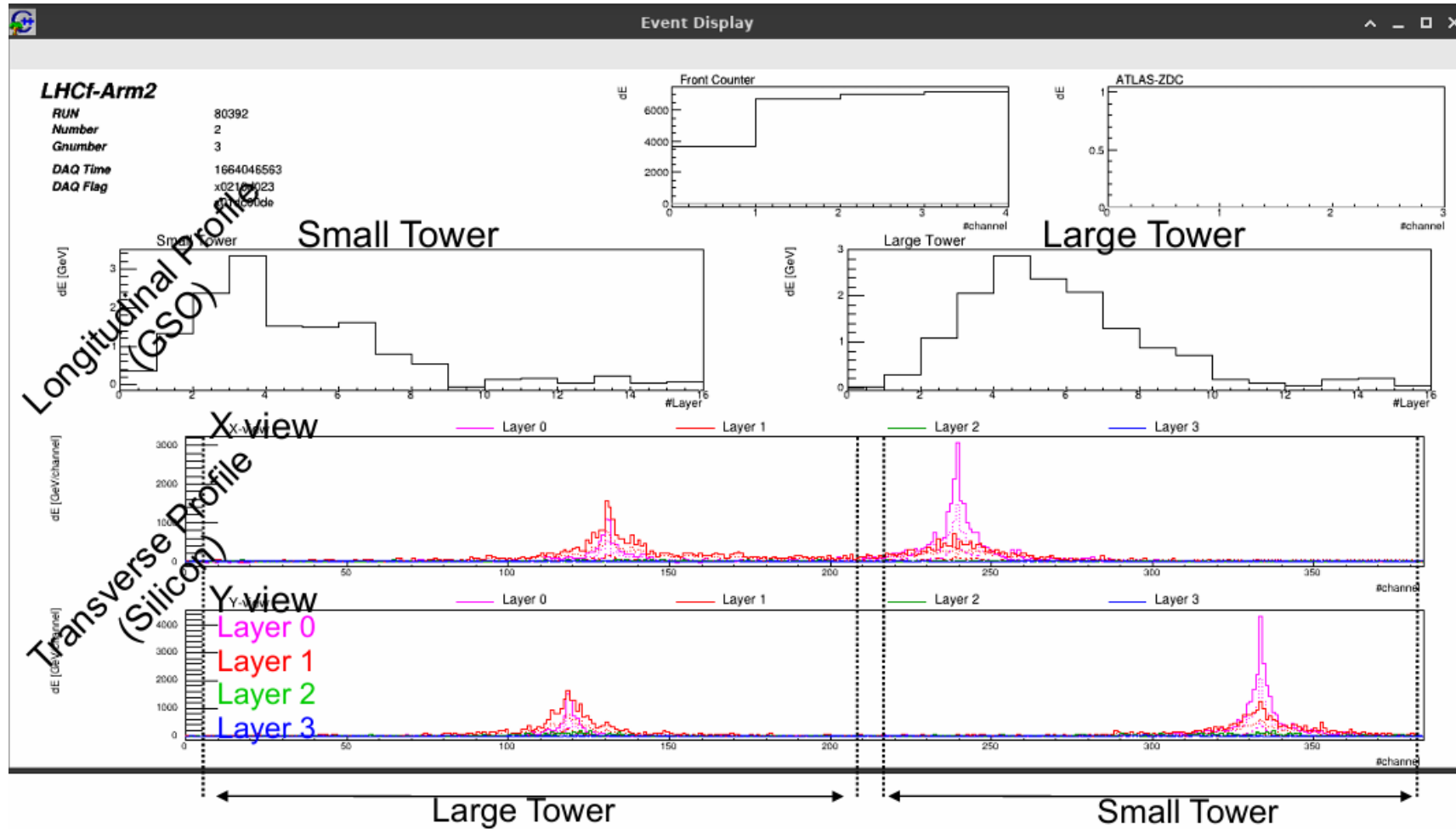
# The LHCf Experiment: Operations Published Results and Ongoing Analysis

Run	$E_{\text{lab}}$ (eV)	Photon	Neutron	$\pi^0$	$\eta$	w/ ATLAS
p+p $\sqrt{s}=0.9$ TeV (2009-2010)	$4.3 \times 10^{14}$	PLB 715, 298 (2012)				
p+p $\sqrt{s}=2.76$ TeV (2013)	$4.1 \times 10^{15}$			•		
p+p $\sqrt{s}=7$ TeV (2010)	$2.6 \times 10^{16}$	PLB 703, 128 (2011) •	PLB 750 360 (2015)	PRD 86, 092001 (2012) PRD 94, 032007 (2016) = •		
p+p $\sqrt{s}=13$ TeV (2015)	$9.0 \times 10^{16}$	PLB 780, 233 (2018) •	JHEP 2018, 73 (2018) JHEP 2020, 016 (2020)	preliminary	JHEP 2023,169 (2023)	ATLAS-CONF-2017-075
p+p $\sqrt{s}=13.6$ TeV (2022)	$9.0 \times 10^{16}$					
p+Pb $\sqrt{s_{\text{NN}}}=5.02$ TeV (2013,2016)	$1.4 \times 10^{16}$		PRC 86, 065209 (2014)	PRC 86, 065209 (2014) •		
p+Pb $\sqrt{s_{\text{NN}}}=8.16$ TeV (2016)	$3.6 \times 10^{16}$	preliminary				
RHICf p+p $\sqrt{s}=510$ GeV (2017)	$1.4 \times 10^{14}$	ArXiv:2203.15416 submitted to PLB = •				
p+O $\sqrt{s_{\text{NN}}}=9.6$ TeV (2025)	$5.0 \times 10^{16}$					

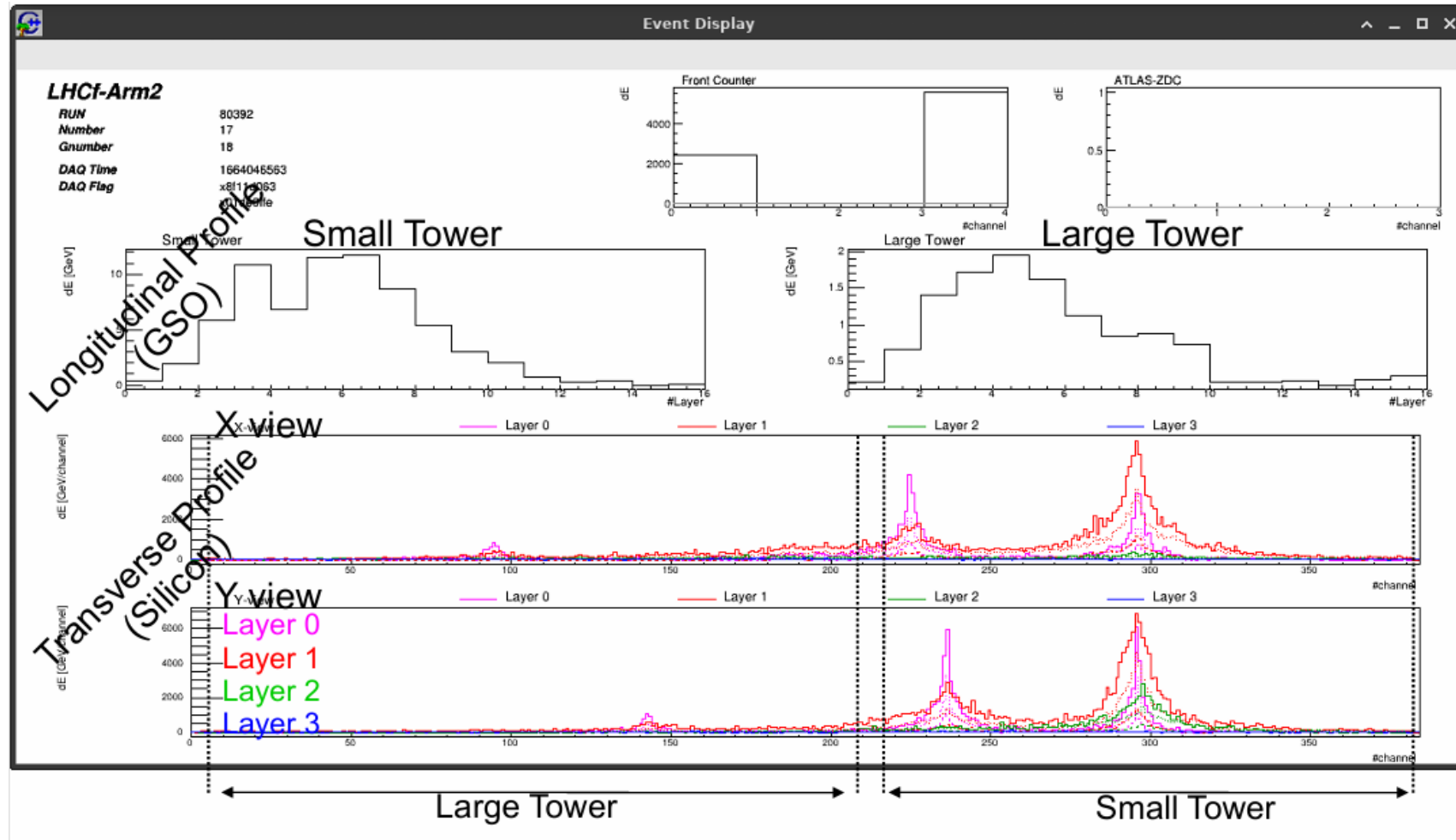
# Neutron event in Arm2



# $\pi^0$ Type I event in Arm2



# $\pi^0$ Type II event in Arm2

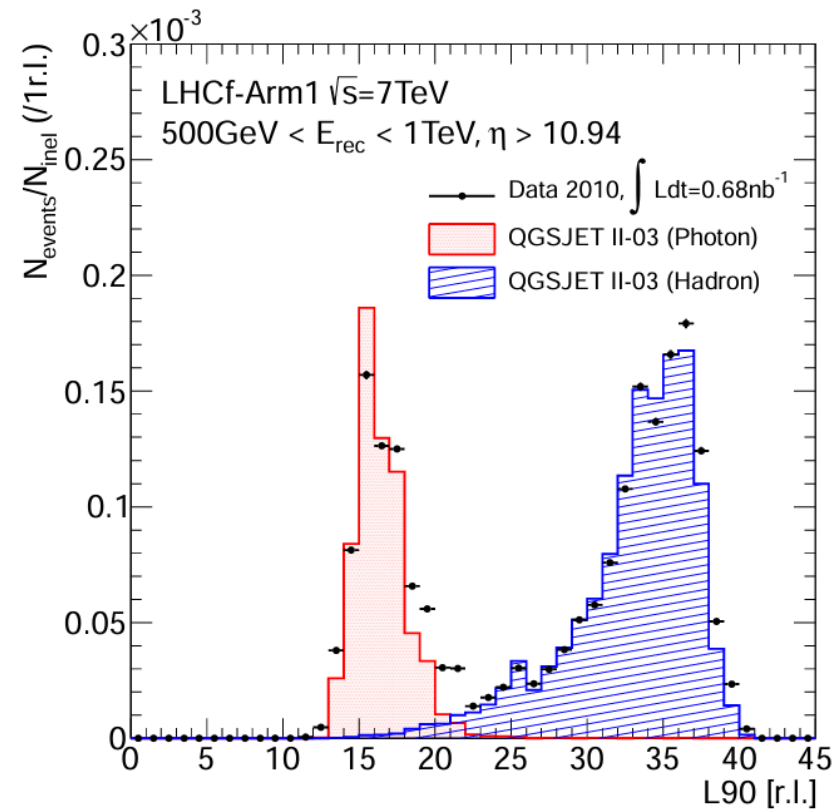


# Photon/Hadron discrimination

$L_{90\%}$  is the longitudinal distance, in units of radiation length, measured from the 1st tungsten layer of a calorimeter to the position where the energy deposition integral reaches 90% of the total shower energy deposition.

$L_{90\%} < 20 X_0 \rightarrow$  photon

$L_{90\%} > 20 X_0 \rightarrow$  hadron



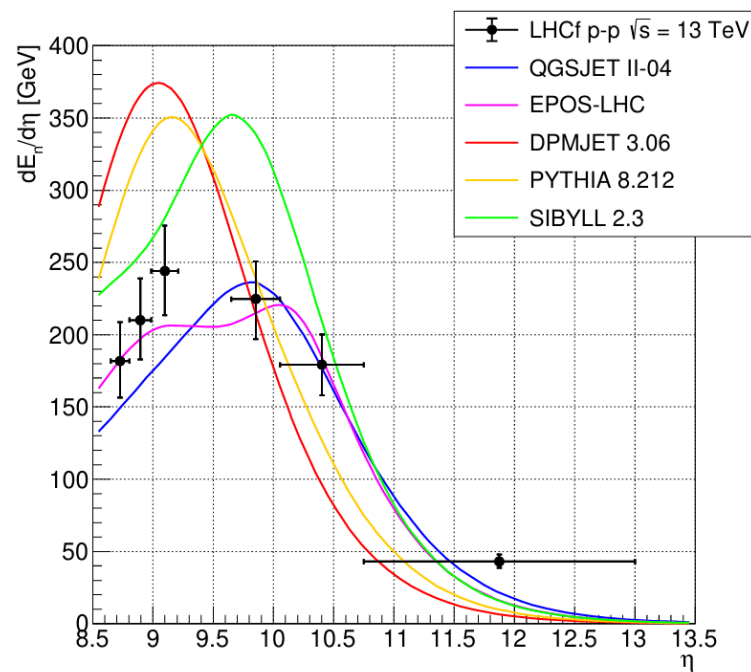
# Neutron Energy Flow and Inelasticity

p+p → √s = 13 TeV

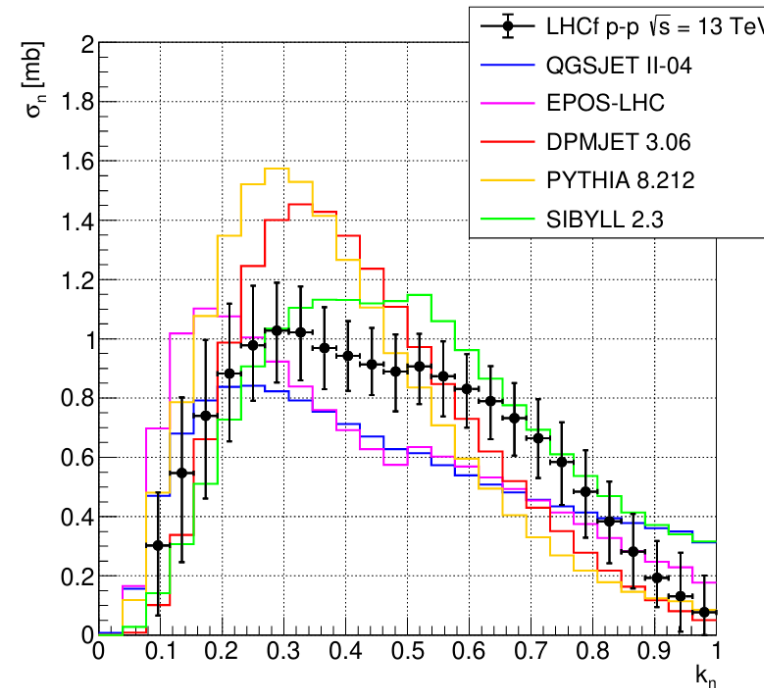
$$d\sigma = dN_n / \int L dt$$

$$\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$

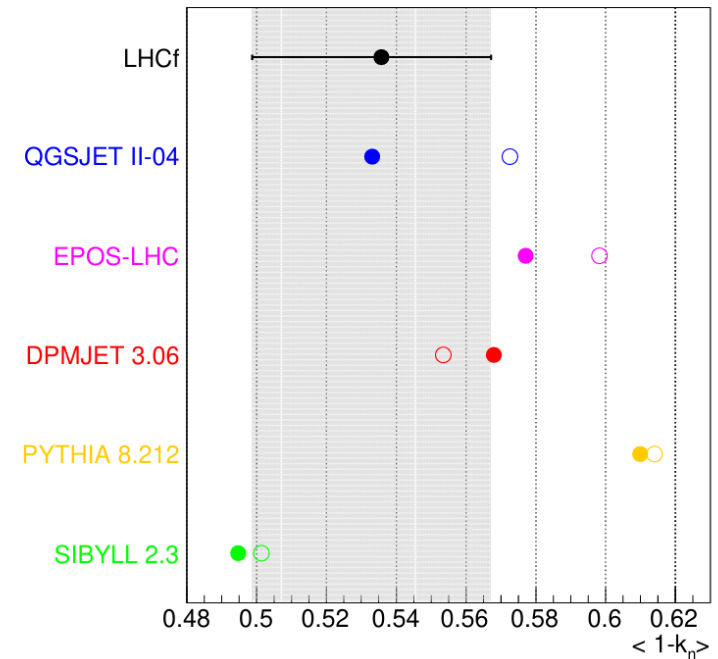
higher  $\eta$  = 'more forward' region



Neutron energy flow



Inclusive production cross section vs elasticity  $k_n = 2E_n/\sqrt{s}$



Average inelasticity  $1-k_n$

JHEP 07 (2020) 016

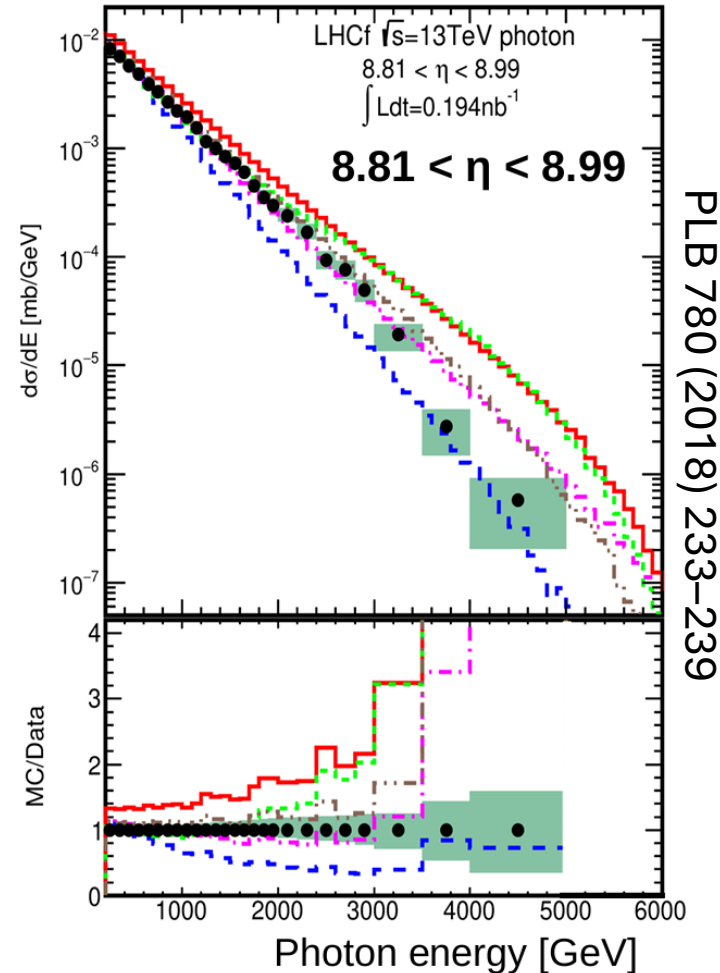
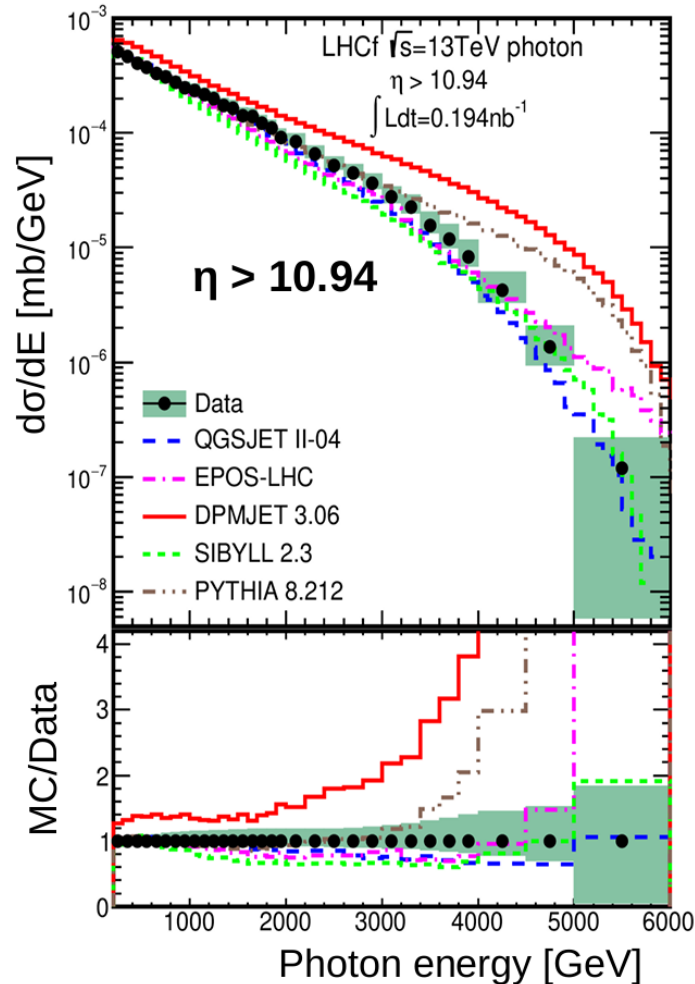
# Photon Production Cross Section

$p+p \rightarrow \sqrt{s} = 13 \text{ TeV}$

$$d\sigma = dN_\gamma / \int L dt$$

$$\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$

higher  $\eta$  = 'more forward' region



EPOS-LHC

good agreement for  $E < 3\text{-}4 \text{ TeV}$  in both pseudorapidity regions

QGSJET II-04

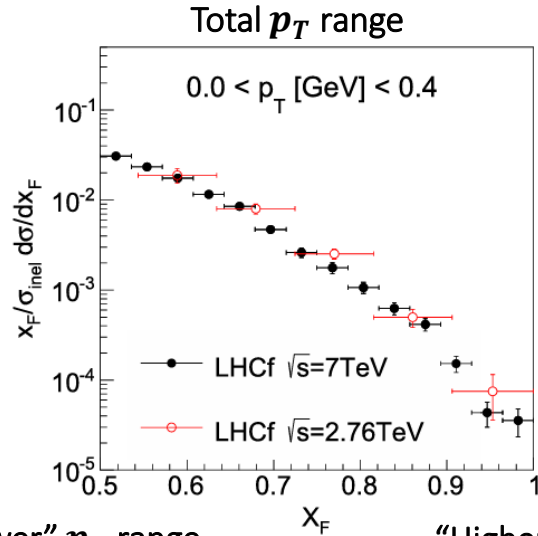
good overall agreement for high- $\eta$ , softer spectrum in low- $\eta$

# Test of Feynman scaling law ( $\pi^0$ )

$p+p \rightarrow \sqrt{s} = 2.76 \text{ TeV}, 7 \text{ TeV}$

$$d\sigma_\gamma = dN_\gamma / \int L dt$$

$$x_F \equiv 2p_z / \sqrt{s}$$



Feynman scaling law in the forward region:  
 production cross sections of secondary particles vs  $x_F$  are independent of the incident energy in the forward region:

$$\frac{x_F}{\sigma_{inel}} \frac{d\sigma}{dx_F} \text{ VS } x_F$$

independent of the center of mass energy

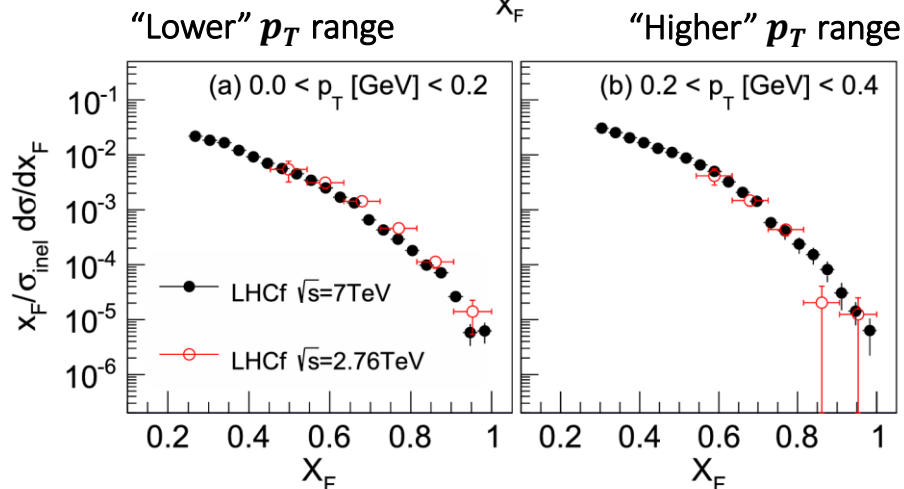
Total  $p_T$  range

distributions are compatible with each other at the  $\pm 20\%$  level

Reduced  $p_T$  range

all  $x_F$  bins are consistent within their uncertainties, except for two bins

- one in “lower”  $p_T$  : 30% deviation
- one in “higher”  $p_T$  : 40% deviation



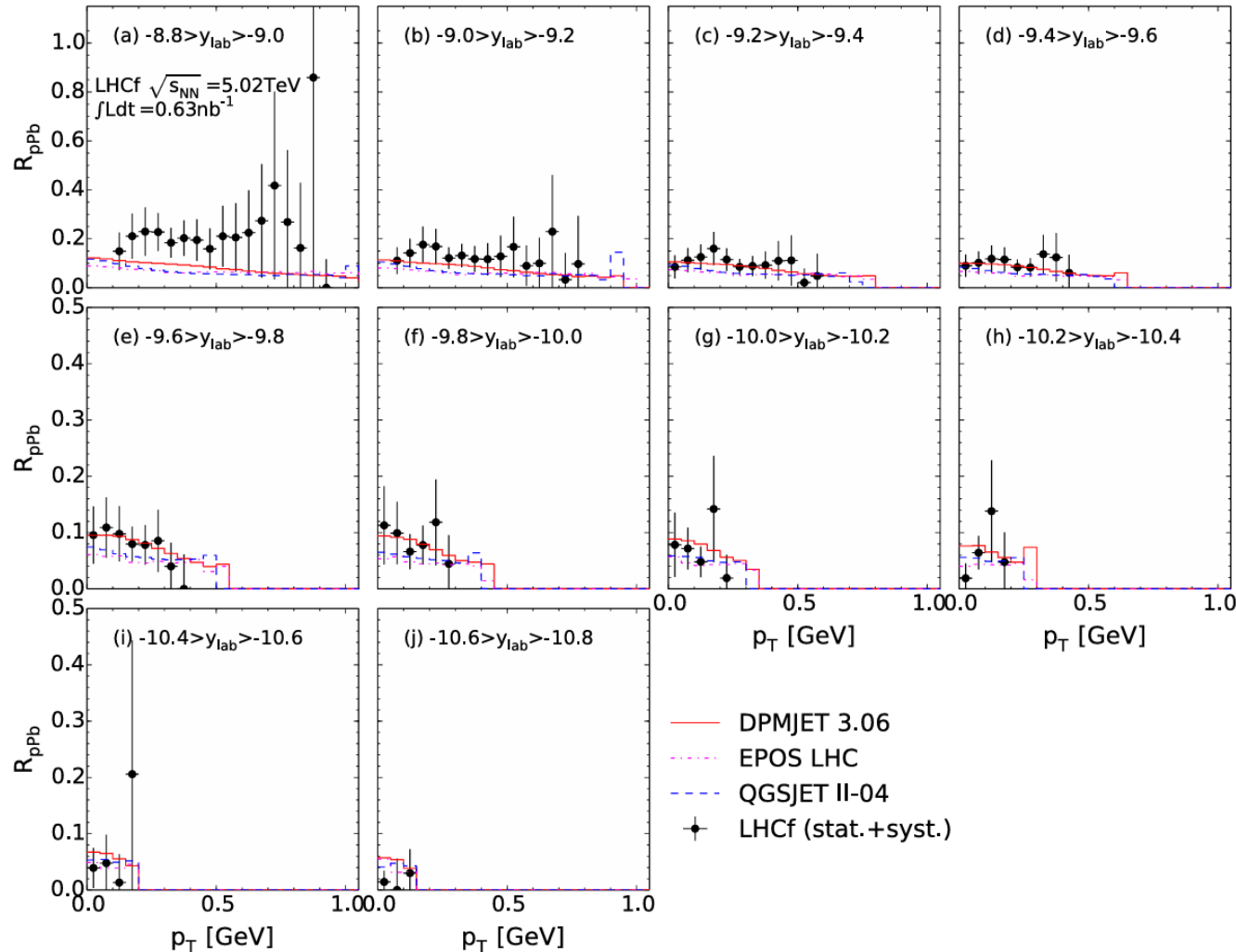
The  $x_F$  distributions at  $\sqrt{s} = 2.76 \text{ TeV}, 7 \text{ TeV}$  indicate that Feynman scaling holds at the 20% level at these center-of-mass energies in the very forward region.

PHYSICALREVIEWD94,032007(2016)

# pPb nuclear modification factor

$$p+\text{Pb} \rightarrow \sqrt{s_{NN}} = 5.02 \text{ TeV}$$

$$d\sigma = dN_n / \int L dt$$



$$R_{\text{pPb}} \equiv \frac{\sigma_{\text{inel}}^{\text{pp}}}{\langle N_{\text{coll}} \rangle \sigma_{\text{inel}}^{\text{pPb}}} \frac{Ed^3\sigma^{\text{pPb}}/dp^3}{Ed^3\sigma^{\text{pp}}/dp^3}$$

PHYSICALREVIEWD94,032007(2016)

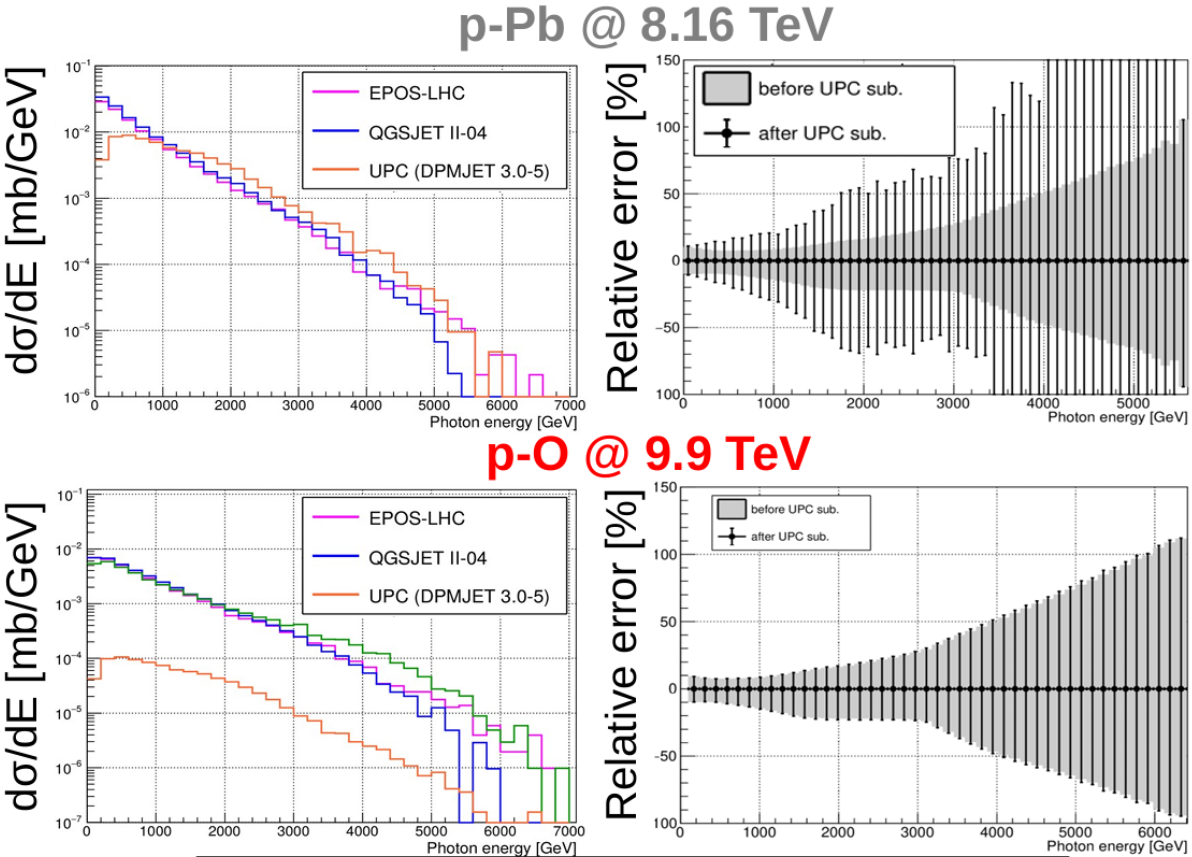
Inclusive cross section of  $\pi^0$  production

$$Ed^3\sigma^{\text{pp}}/dp^3 \quad p+\text{Pb collisions at } \sqrt{s_{NN}} = 5.02 \text{ TeV}$$

$$Ed^3\sigma^{\text{pPb}}/dp^3 \quad p+p collisions at } \sqrt{s} = 5.02 \text{ TeV}$$

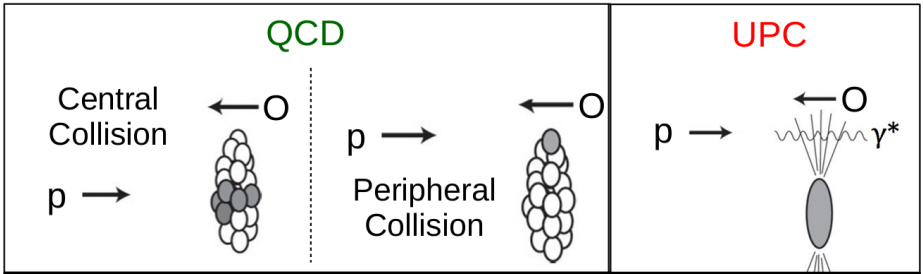
Hadronic models shows an overall agreement with  $R_{\text{pPb}}$  estimated from LHCf data

# Ultra Peripheral Collisions



**Forward photon production in  $\eta > 10.94$**

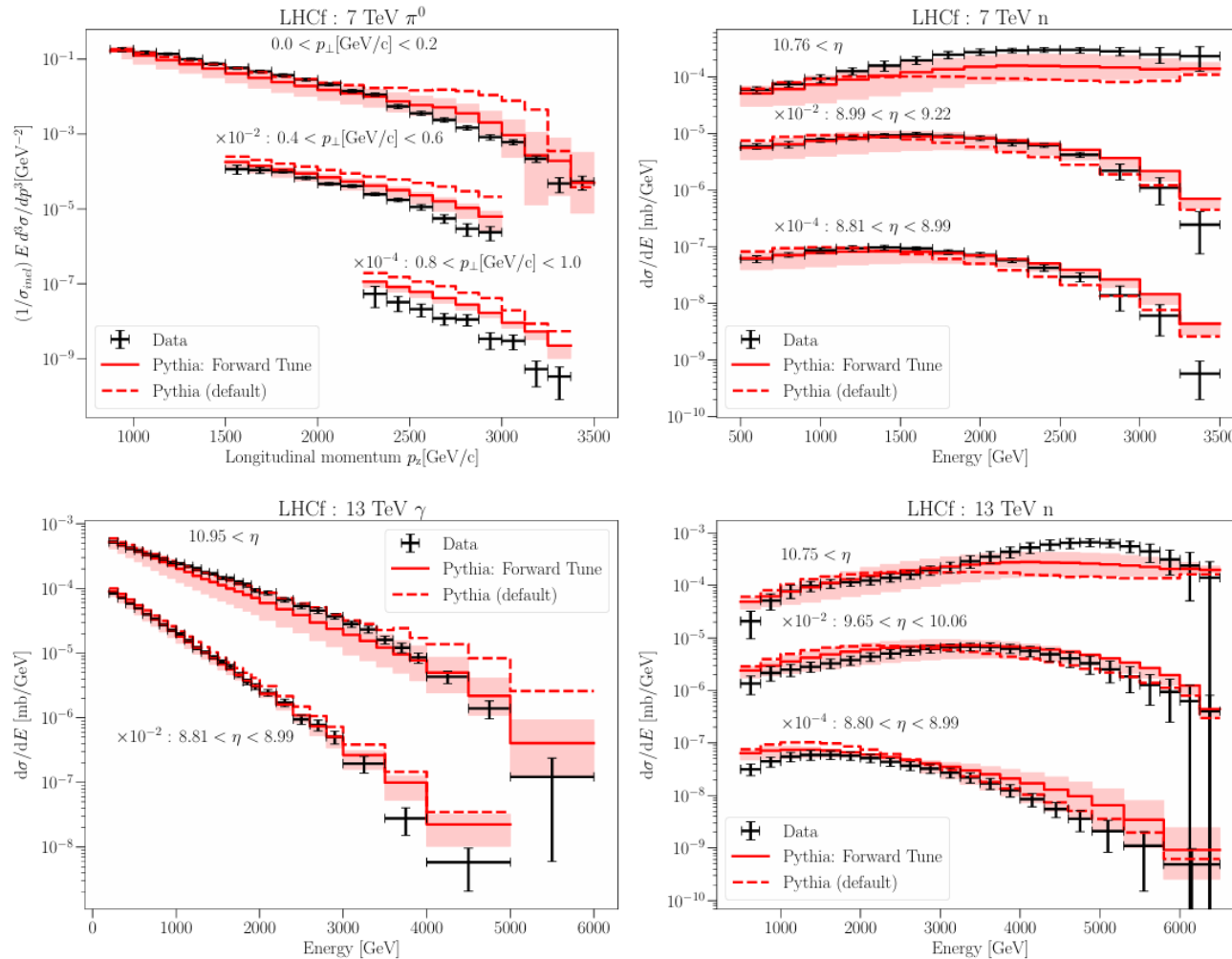
p-premnannt side



UPC (Coulombian interaction)

- Source of background in LHCf measurements
- Systematic from the estimation of the UPC contribution (10%-50%) to be subtracted from data

# Pythia tuning with LHCf data



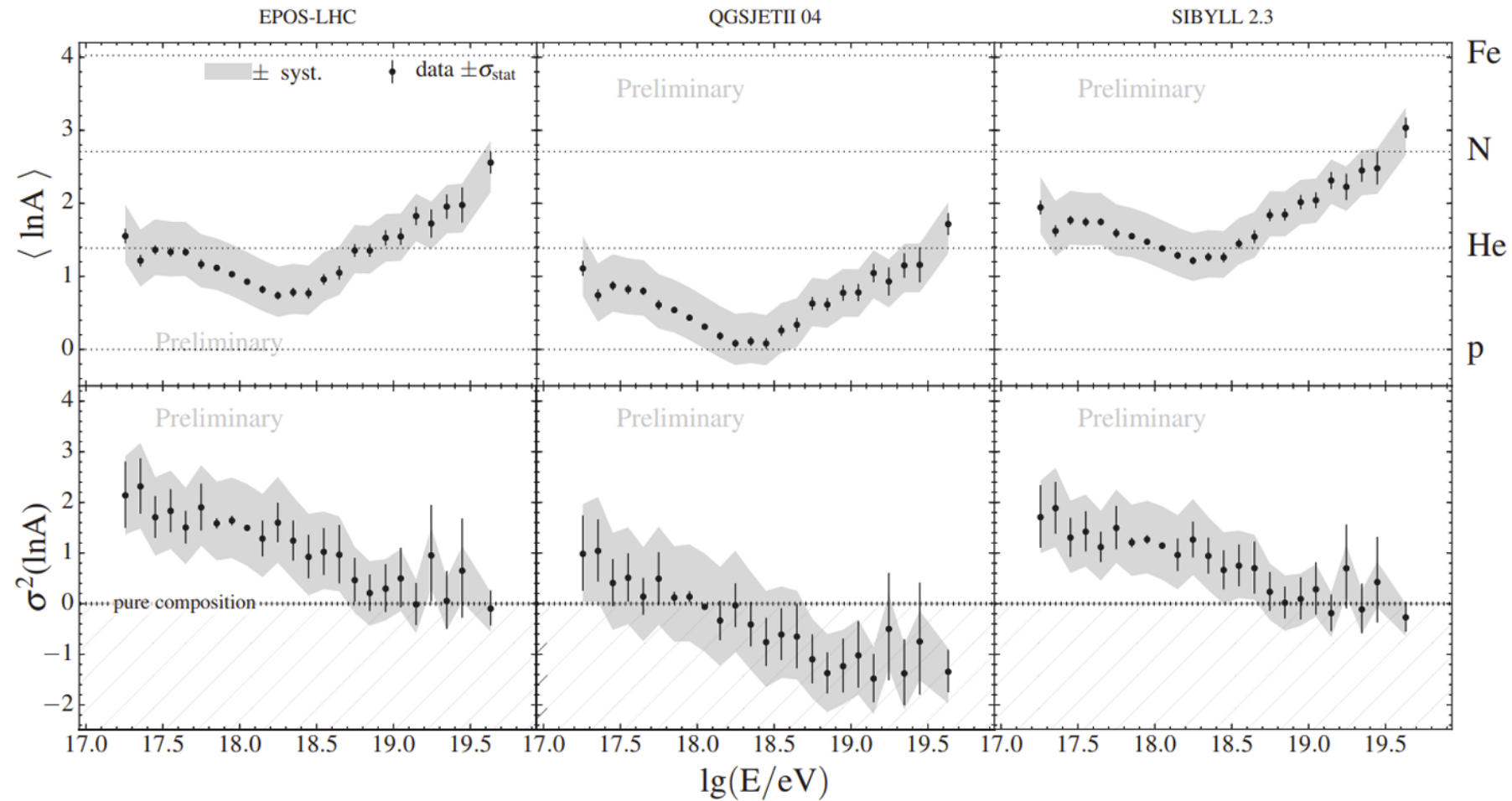
PHYSICAL REVIEW D 109, 016010 (2024)

# Hadronic Interaction Models

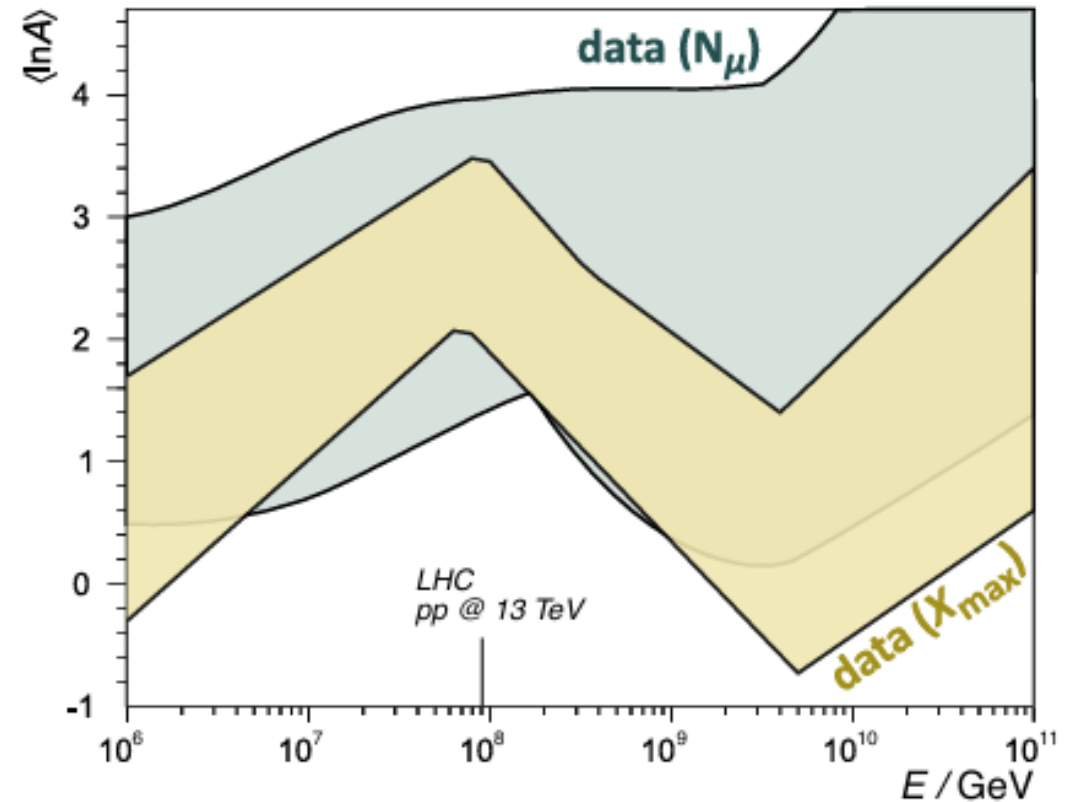
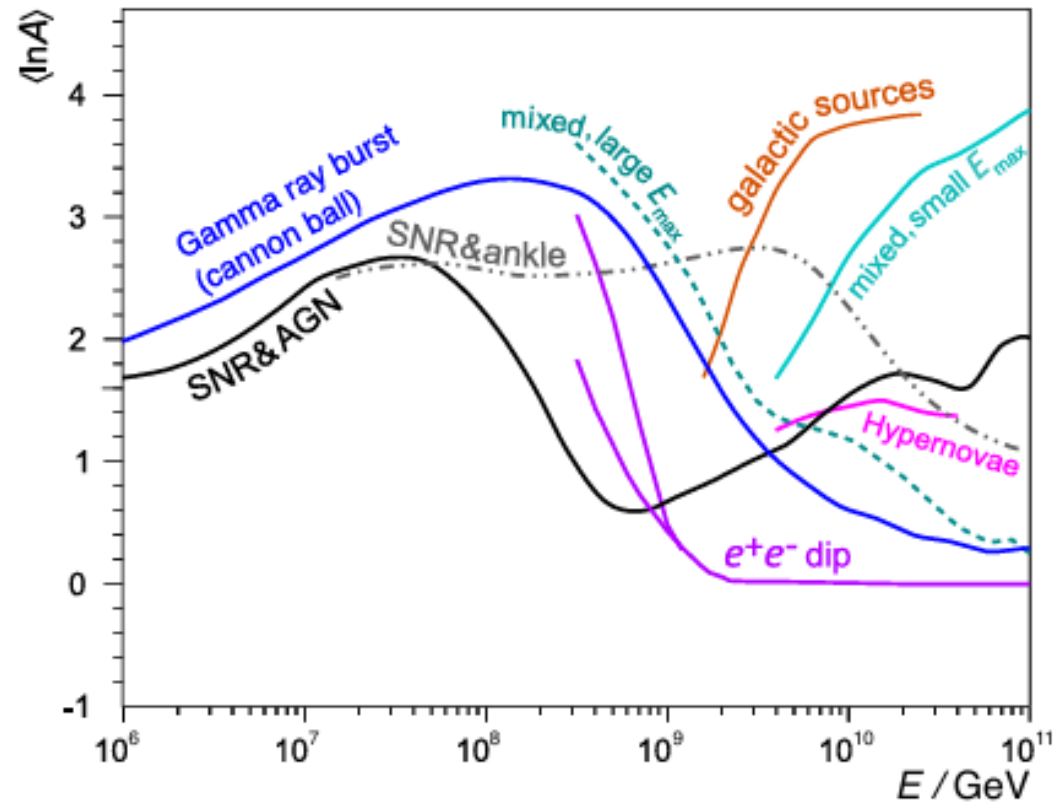
**Table 2** Comparison of the theoretical approaches in commonly used hadronic interaction models.

	DPMJET-III.19-1	EPOS-LHC	QGSJETII-04	SIBYLL2.3d	PYTHIA 8
Domain	EAS, HEP	EAS, HIC	EAS	EAS	HEP
Theoretical basis	GRFT + minijet	GRFT + energy sharing	GRFT + resummation	GRFT + minijet	parton model
Nuclear collisions	Glauber	extended GRFT	extended GRFT	extended superposition	Glauber via Argantyr
Pomeron	soft+hard	semi-hard	semi-hard	soft+hard	soft+hard
Energy evolution of parton densities	via $Q_0(s)$ cut	parameterised	Higher-order Pomeron graphs	via $Q_0(s)$ cut	via $Q_0(s)$ cut
Energy evolution of elasticity	constant	falling	falling	constant	—
Parton distributions	CT14	custom	custom	GRV	various
Non-diffractive remnant	—	multi-quark exchange (low to high mass)	one-quark exchange (low mass)	one-quark exchange (low mass)	low mass
Diffractive dissociation (low mass)	2-channel eikonal	diffractive Pomeron	3-channel eikonal	2-channel eikonal	Pomeron emission
Diffractive dissociation (high mass)	cut enhanced graphs	Pomeron exchange	cut enhanced graphs	Pomeron exchange	Pomeron exchange
String fragmentation (fitted data)	Lund ( $e^+e^-$ )	area law ( $e^+e^-$ )	custom ( $p$ - $p$ )	Lund ( $p$ - $p$ )	Lund ( $e^+e^-$ )
Forward-central correlation	weak	strong	strong	weak	strong
Charm production	pQCD (incomplete)	—	—	parameterised + intrinsic	pQCD
Collective effects	string fusion	core-corona (parameterised)	—	—	colour reconnection, rope hadronization, string shoving

# UHECR Composition: Model discrepancies

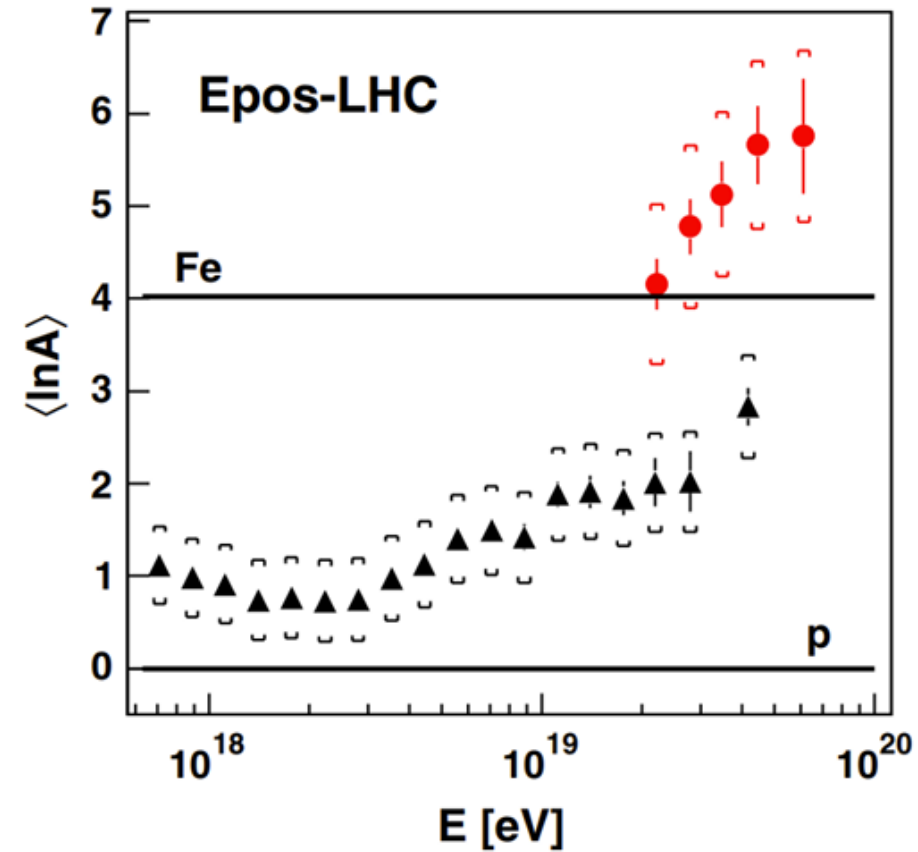
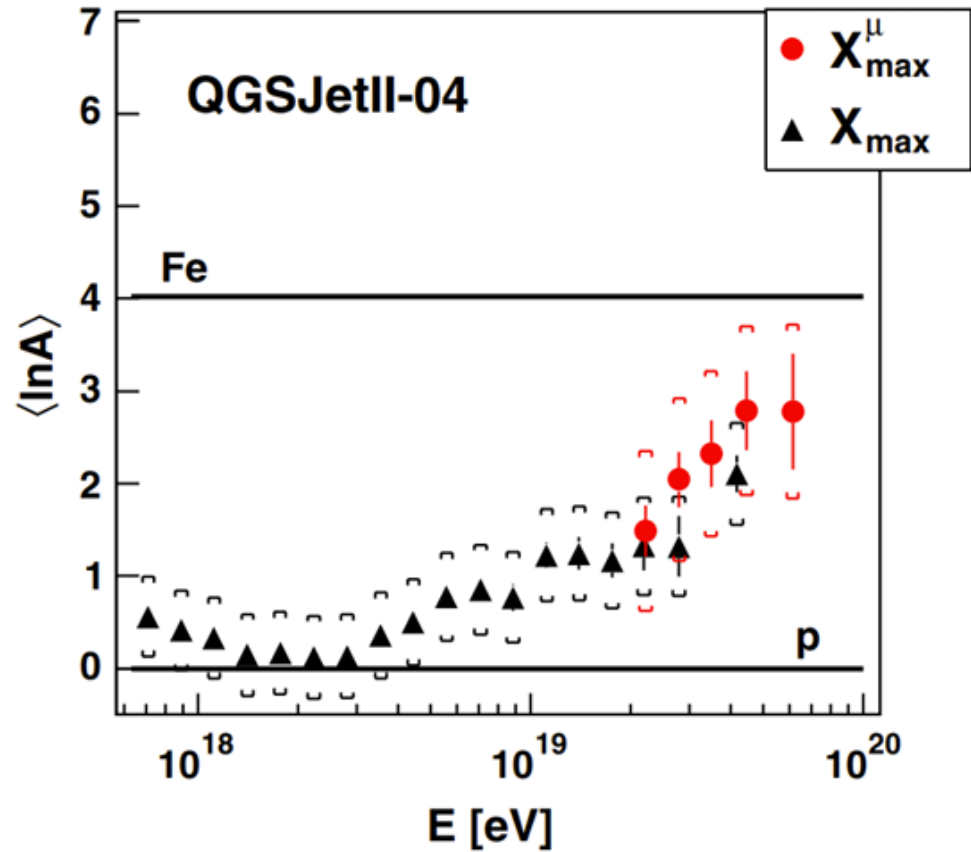


# UHECR Composition: Model discrepancies



Kampert, K.-H., Unger, M.: Astropart. Phys. 35, 660 (2012)

# UHECR Composition: Model discrepancies



# Muon Puzzle

Muon Puzzle:

- Number of muons predicted by hadronic interaction models in EAS are underestimate with respect to experimental observations
- Hypothesis: overestimation of E/H ratio in hadronic interaction models

E/H increases if QGP process occurs in p-light nucleus, light nucleus-light nucleus interactions at very high energy in the very forward region

Signature of QGP state: enhancement of baryonic production and strangeness

Measurement of strange particles and baryons in hadronic collisions at very high energy in the forward regions

QGP evidences are predicted in p-p collisions at  $\sqrt{s} = 13\text{TeV}$  for  $\eta \approx 6.5$

arXiv:2105.06148v2 [astro-ph.HE] 4 Apr 2022

Results from ALICE in the central region

