Status of the LHCf Experiment

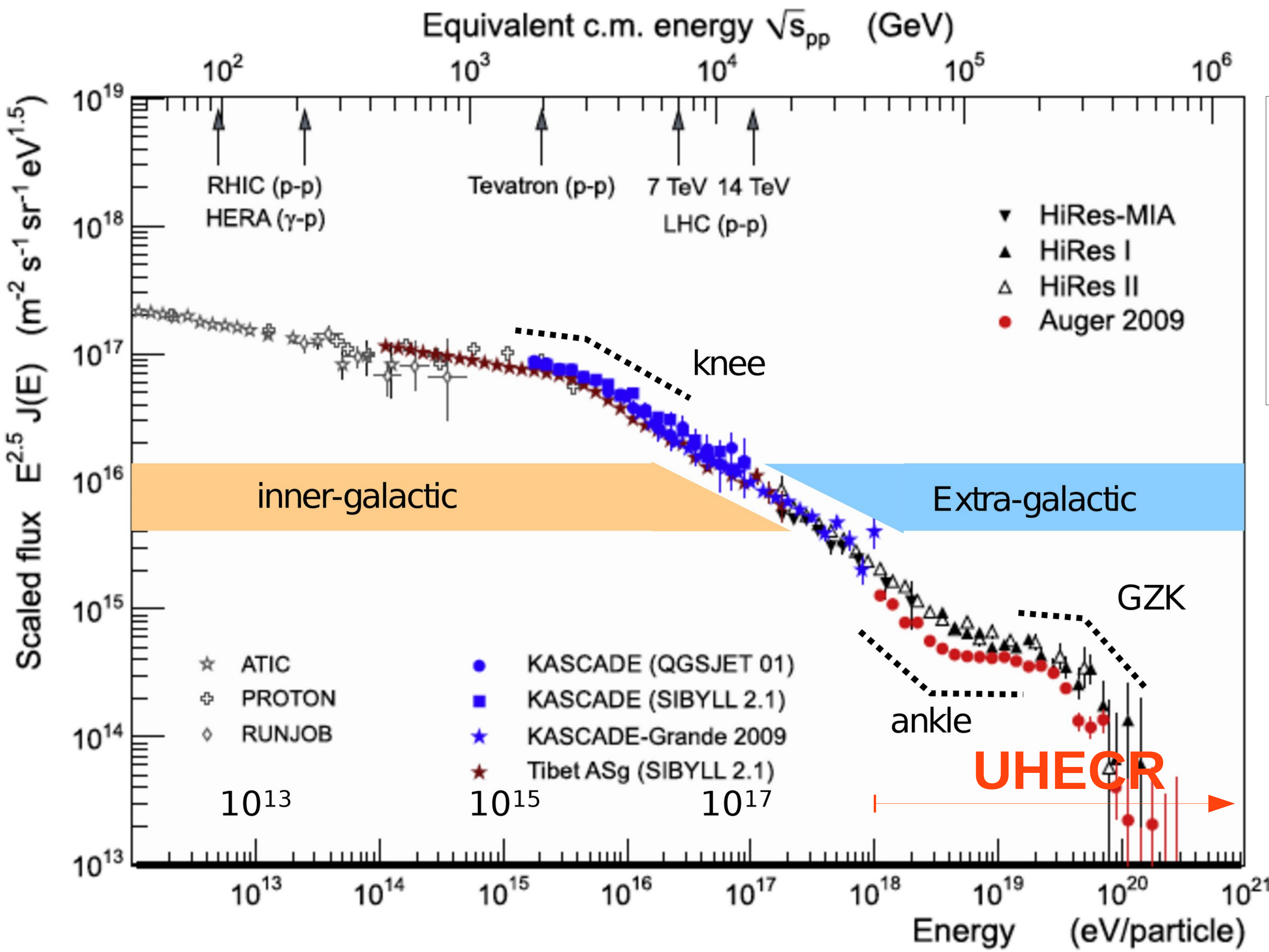
Eugenio Berti, on behalf of the LHCf collaboration

Cross Section for Cosmic Rays @ CERN

16-18 October 2024, CERN

Introduction

Ultra High Energy Cosmic Rays



Motivation
Understand mechanisms responsible for *acceleration* and *propagation*

Accurate measurements of UHECR flux and <u>composition</u> as a function of the energy

D'Enterria et al., 2011

Extensive Air Showers

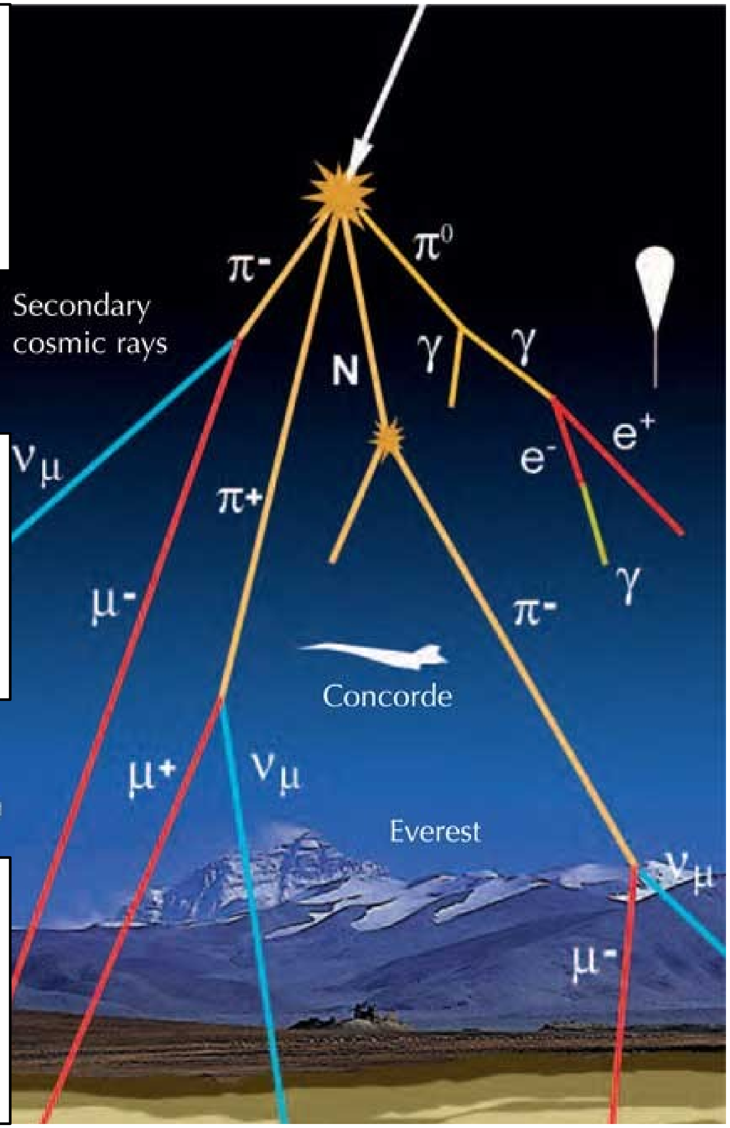
Indirect measurement of UHECR energy flux and average composition by **Extensive Air Showers**

⇩

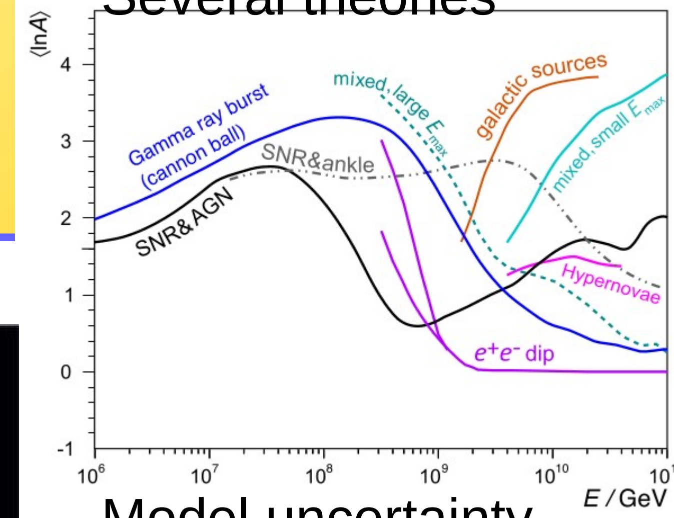
Measurement of average composition strongly relies on hadronic interaction models

⇩

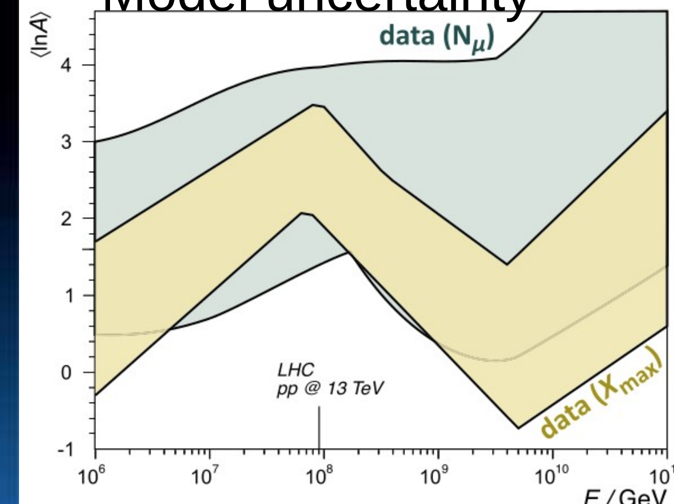
Large uncertainties in interaction models due to the lack of high energy calibration data



Several theories



Model uncertainty



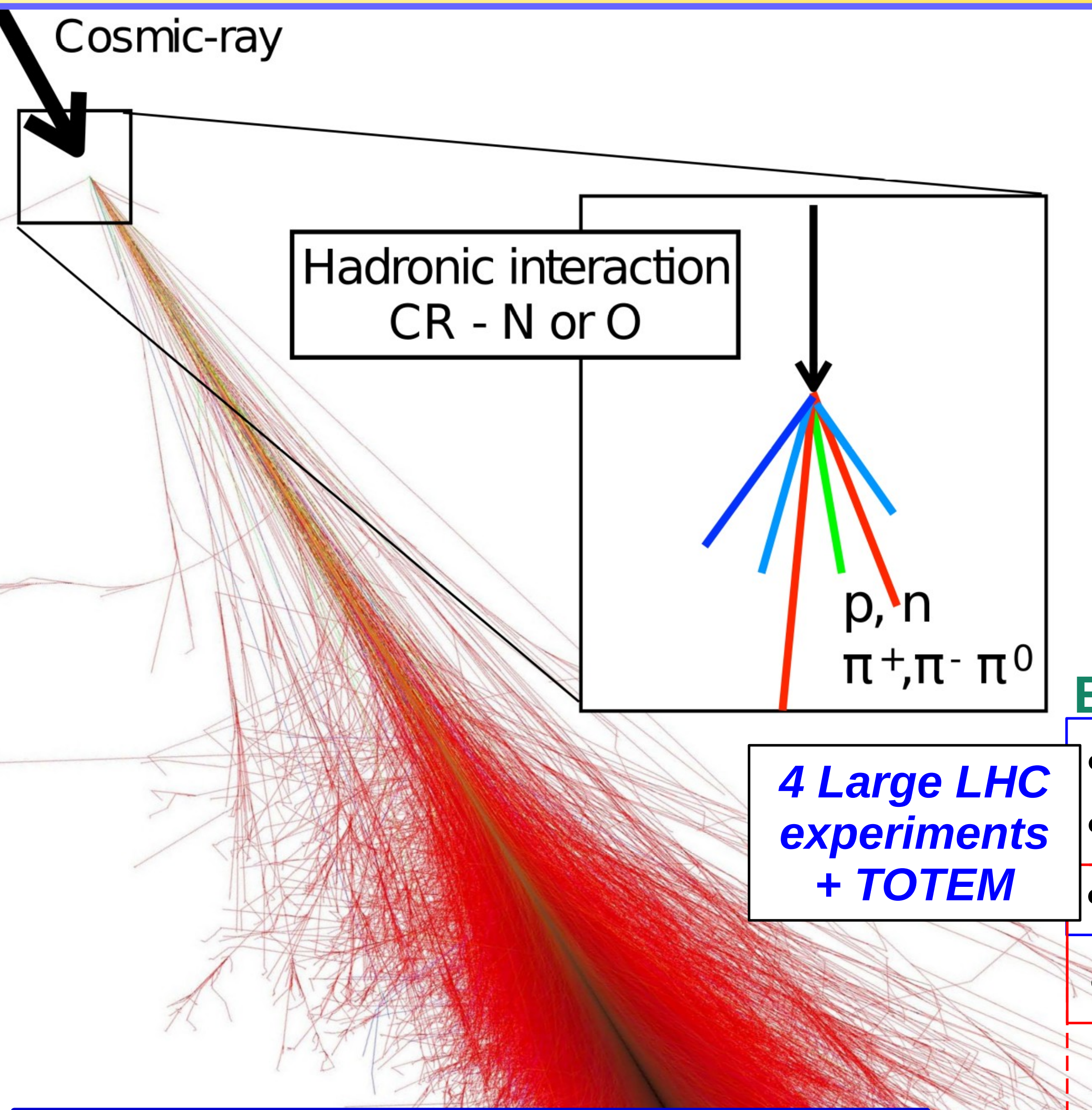
J. Albrecht et al., ASS 367, 2022

$\langle X_{max} \rangle$: Small uncertainty
$\langle N_\mu \rangle$: *Large uncertainty*

⇩

Muon Puzzle

Hadronic interaction models



4 Large LHC experiments + TOTEM

High energy calibration data are needed to properly tune hadronic interaction models

LHC is the best place where to study a system that is similar to the first CR-nucleus interaction

EAS key quantities

- Inelastic cross section
- Particle multiplicity
- E/H Ratio $R = E_\gamma / E_h$ **$\pi^0, \eta, \ldots$**
- Elasticity $k = p_{lead} / p_{beam}$ **n**

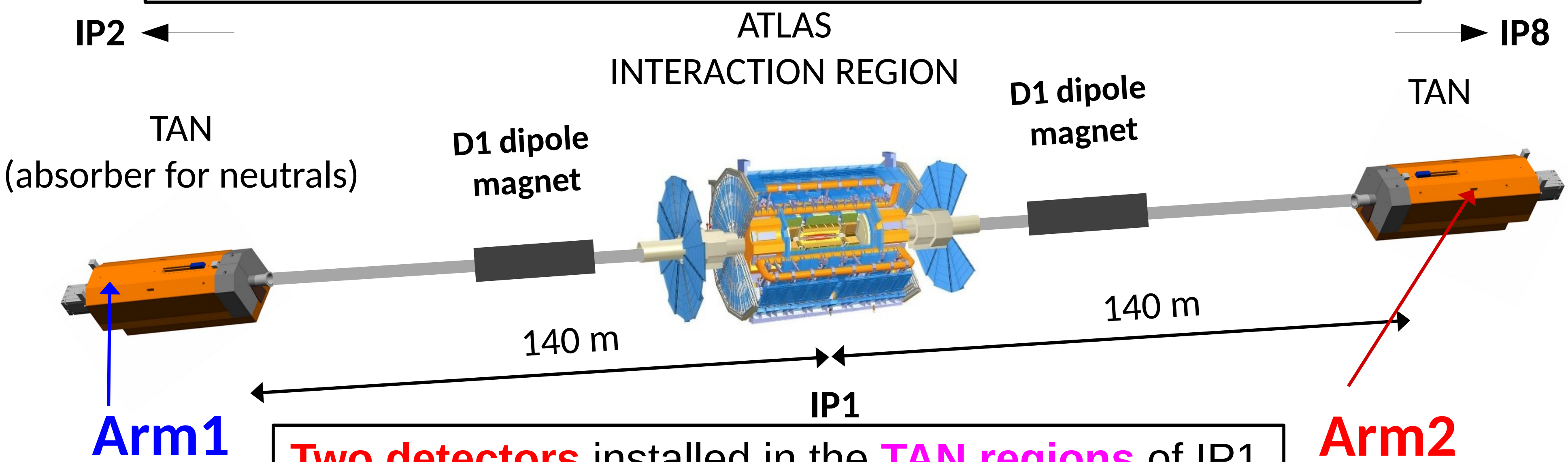
\+ *Very forward particle spectra*
- Extrapolation to $E > 10^{17}$eV
- Effect due to mass number

LHCf

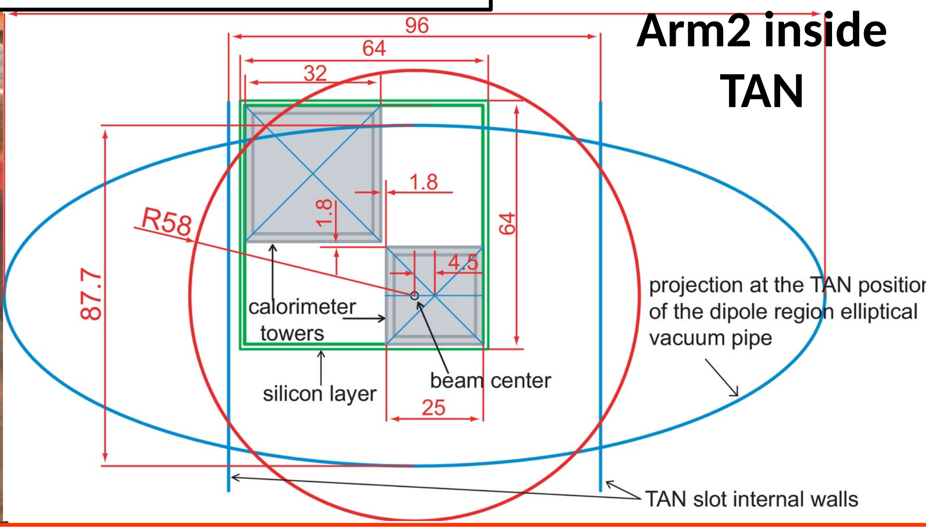
p-p at $\sqrt{s}$ = 14 TeV ⇒ $E_{LAB} = 10^{17}$ eV

The LHCf Experiment

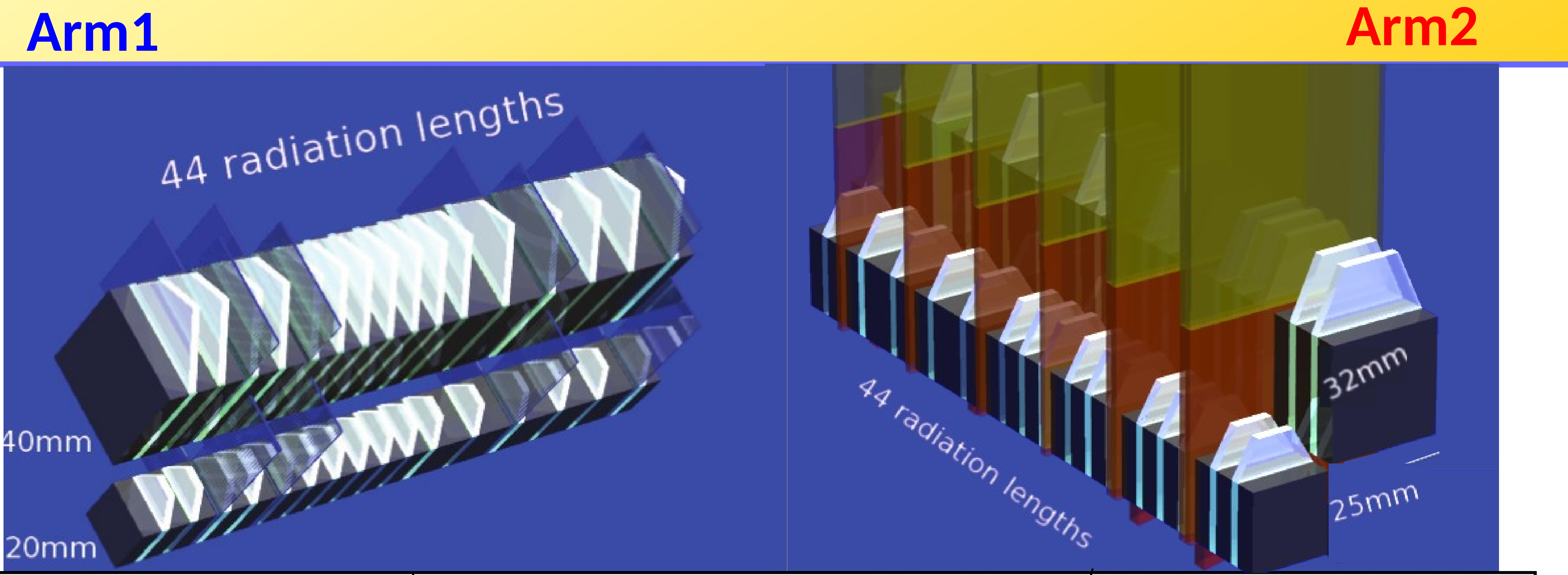
Detection of **neutral particles** having **pseudorapidity η > 8.4**



Two detectors installed in the **TAN regions** of IP1



The LHCf detectors



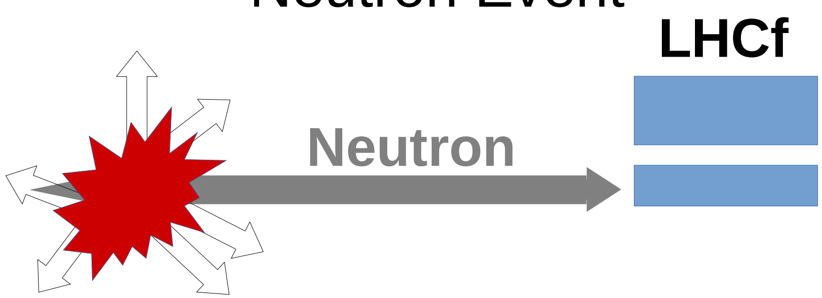
Tower Size:
20 x 20 and 40 x 40 mm^2
Imaging layers:
4 x-y 1mm GSO bars
Position resolution:
< 200 μm (photons)
< 1 mm (hadrons)

Two sampling calorimeters
Two towers: 22 tungsten and 16 GSO scintillators layers
Depth: 21 cm, 44 X_0, 1.6 λ_I
Energy resolution:
< 2% (photons)
~ 40% (hadrons)

Tower Size:
25 x 25 and 32 x 32 mm^2
Imaging layers:
4 x-y 160μm Si microstrip
Position resolution:
< 40 μm (photons)
< 800 μm (hadrons)

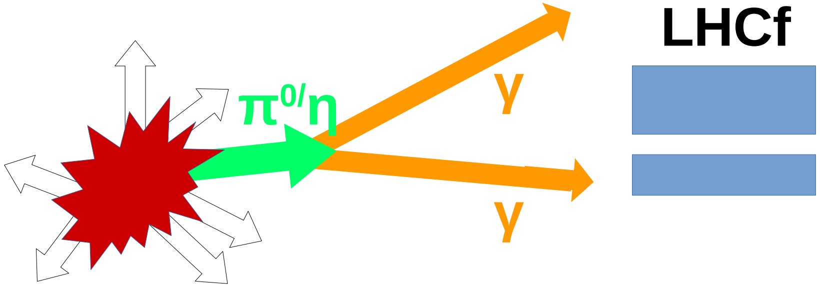
The LHCf acceptance

Neutron Event

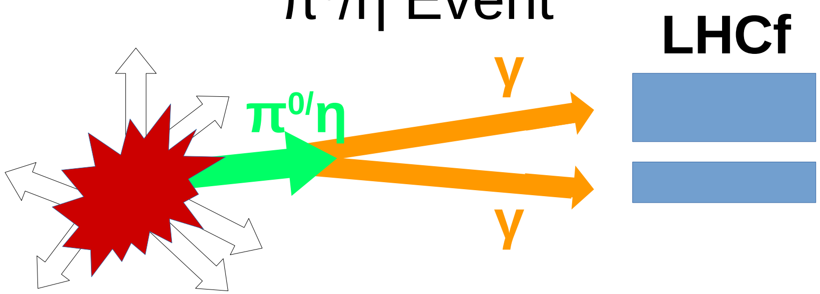


Information on leading baryon and average inelasticity

Single Photon Event



π^0/η Event

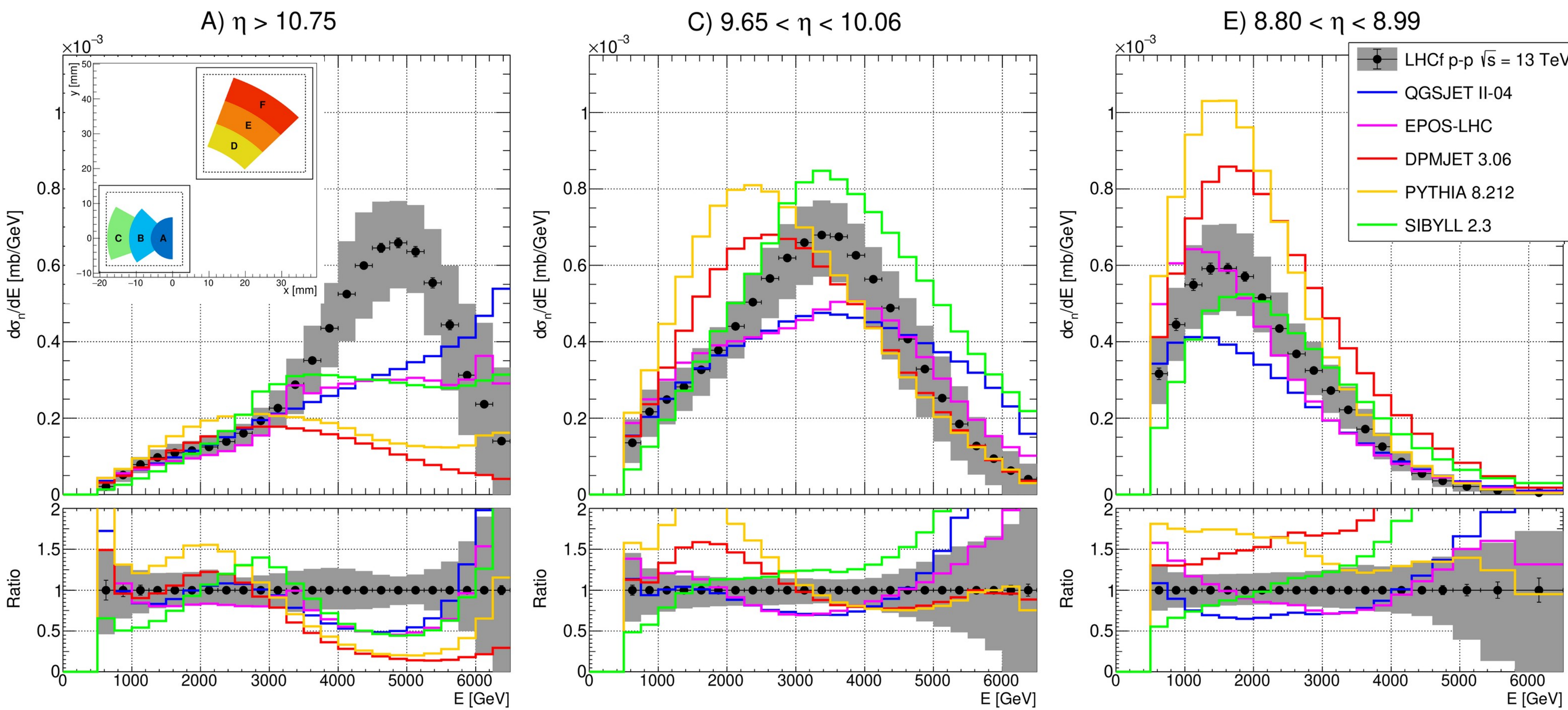


Information on electromagnetic component

Results from Run II

Neutron Production Cross Section

p-p √s = 13 TeV



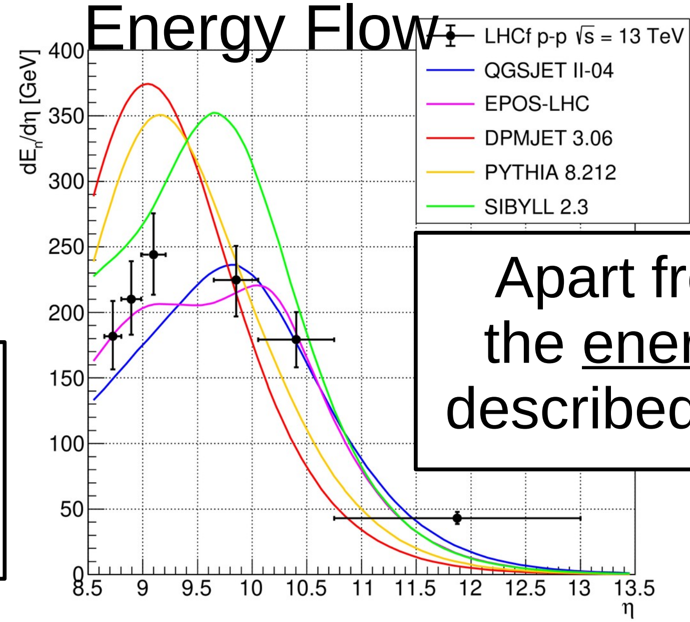
JHEP 07 (2020) 016

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 satisfactorily agreement with the experimental measurements

Neutron Energy Flow & Inelasticity

p-p √s = 13 TeV

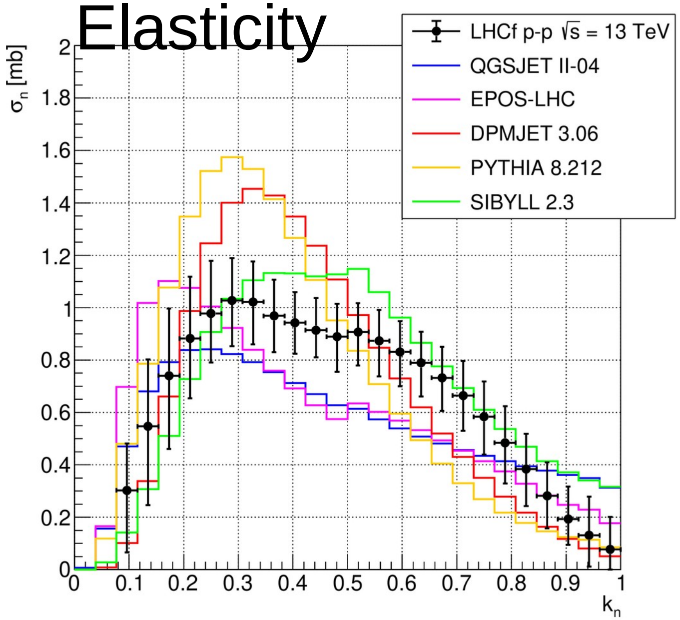
Energy Flow



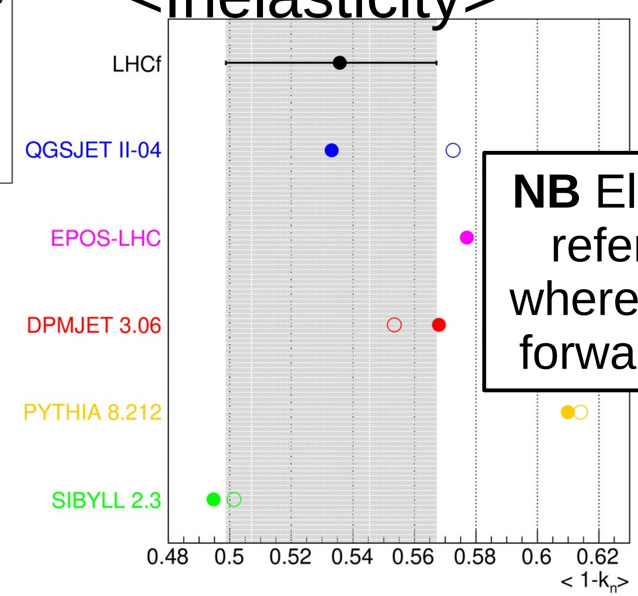
Apart from η > 10.75, the <u>energy flow</u> is well described by **EPOS-LHC**

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

Elasticity



<Inelasticity>



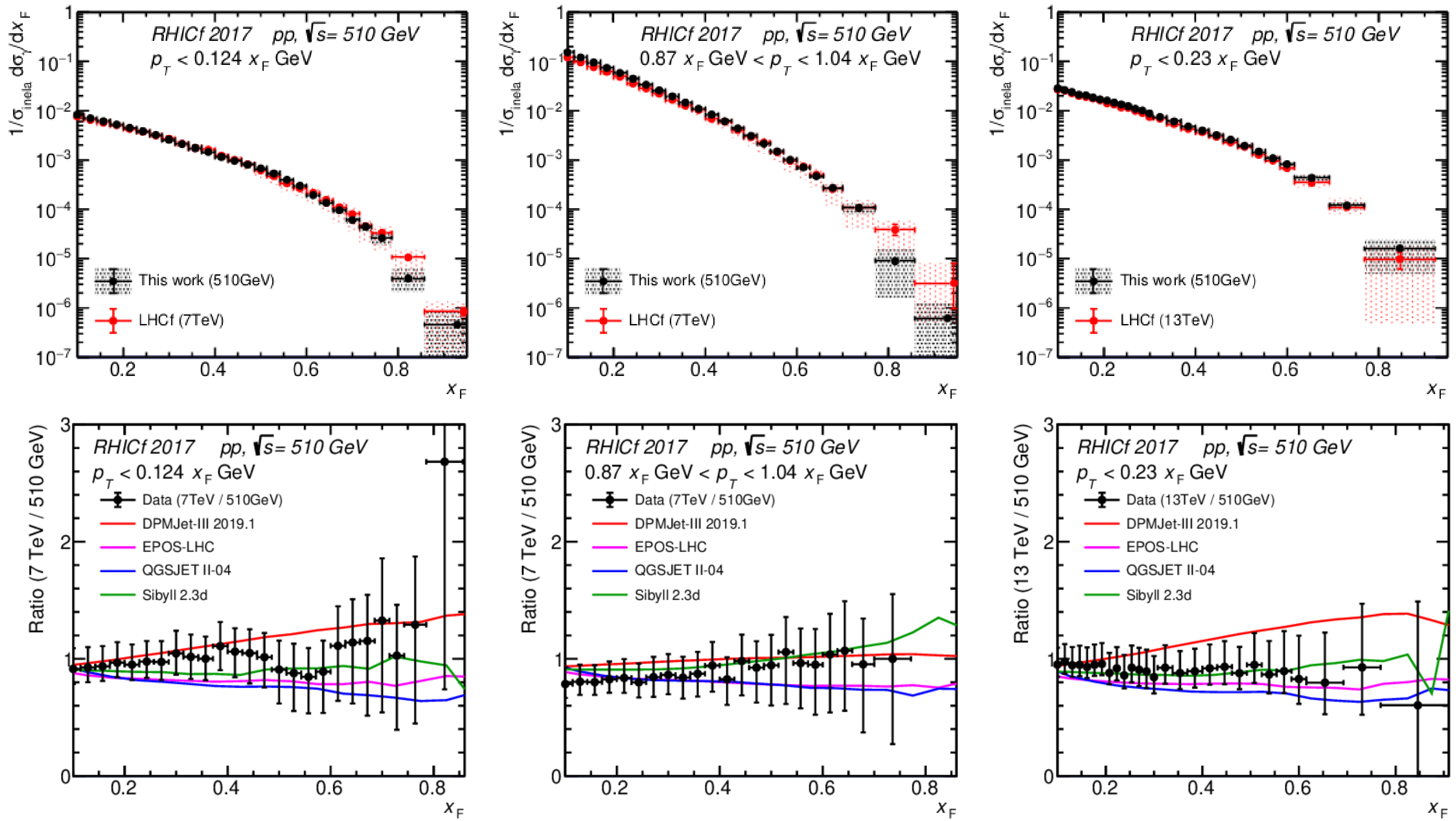
NB Elasticity/Inelasticity refers only to events where the neutron is the forward leading particle

JHEP 07 (2020) 016

Test of Feynman scaling

using forward photons

Using γ in √s=510 GeV (RHICf) and 7 or 13 TeV (LHCf)



ArXiv:2203.15416

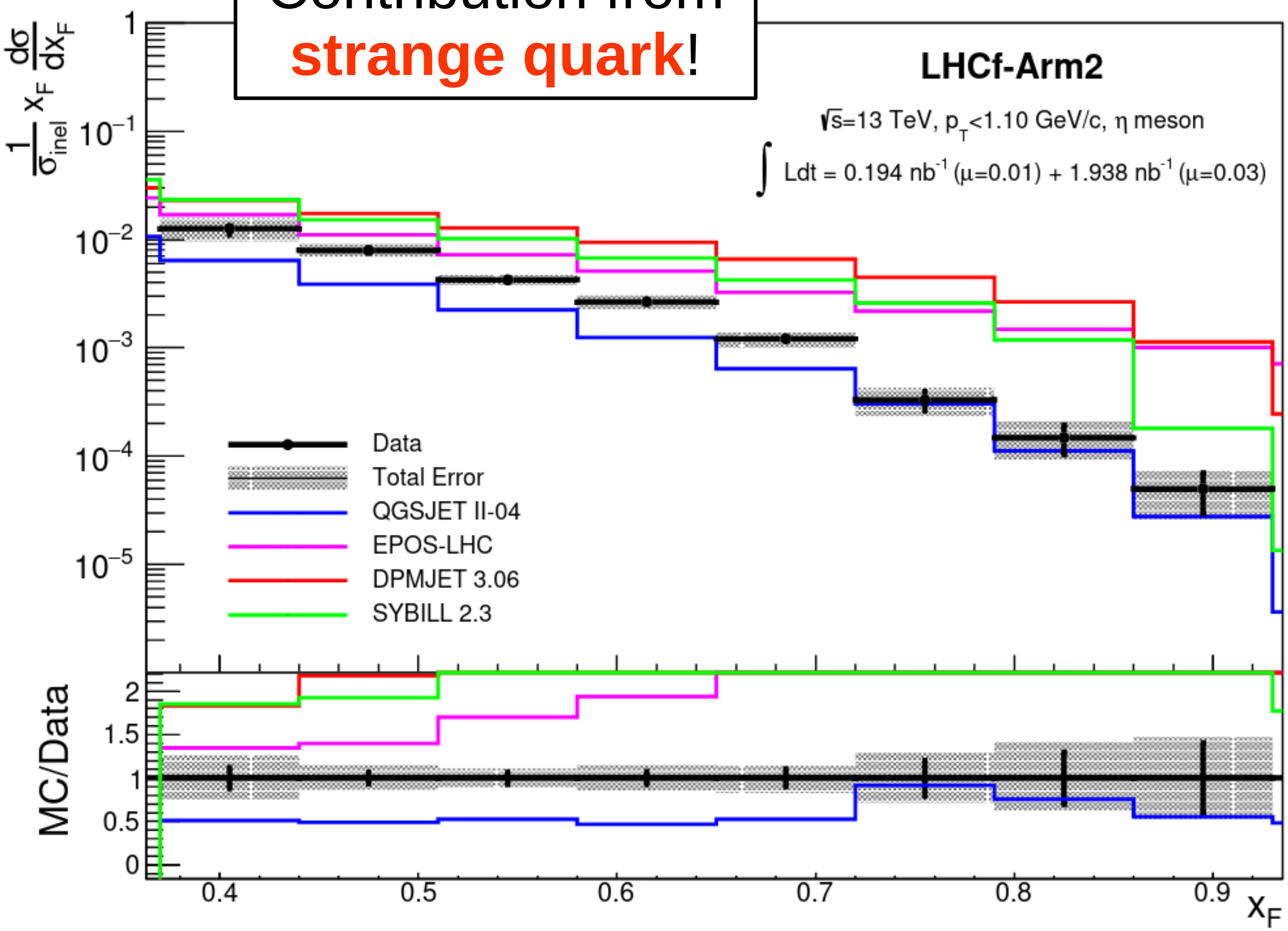
…submitted to PLB

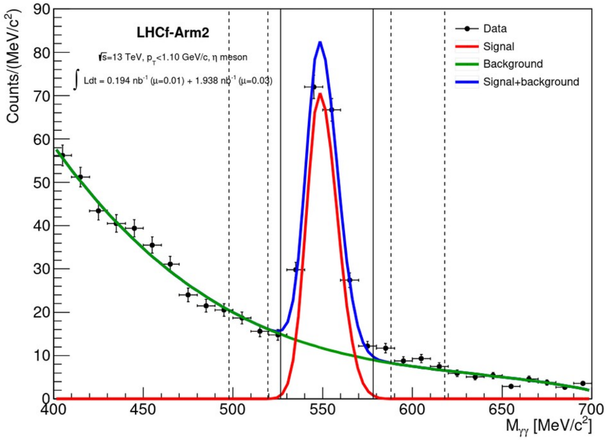
First confirmation of **Feynman scaling** using zero-degree photons
but no sensitivity to small x_F dependency as in some models

η Production Rate

p-p √s = 13 TeV

Contribution from **strange quark**!





JHEP 10 (2023) 169

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

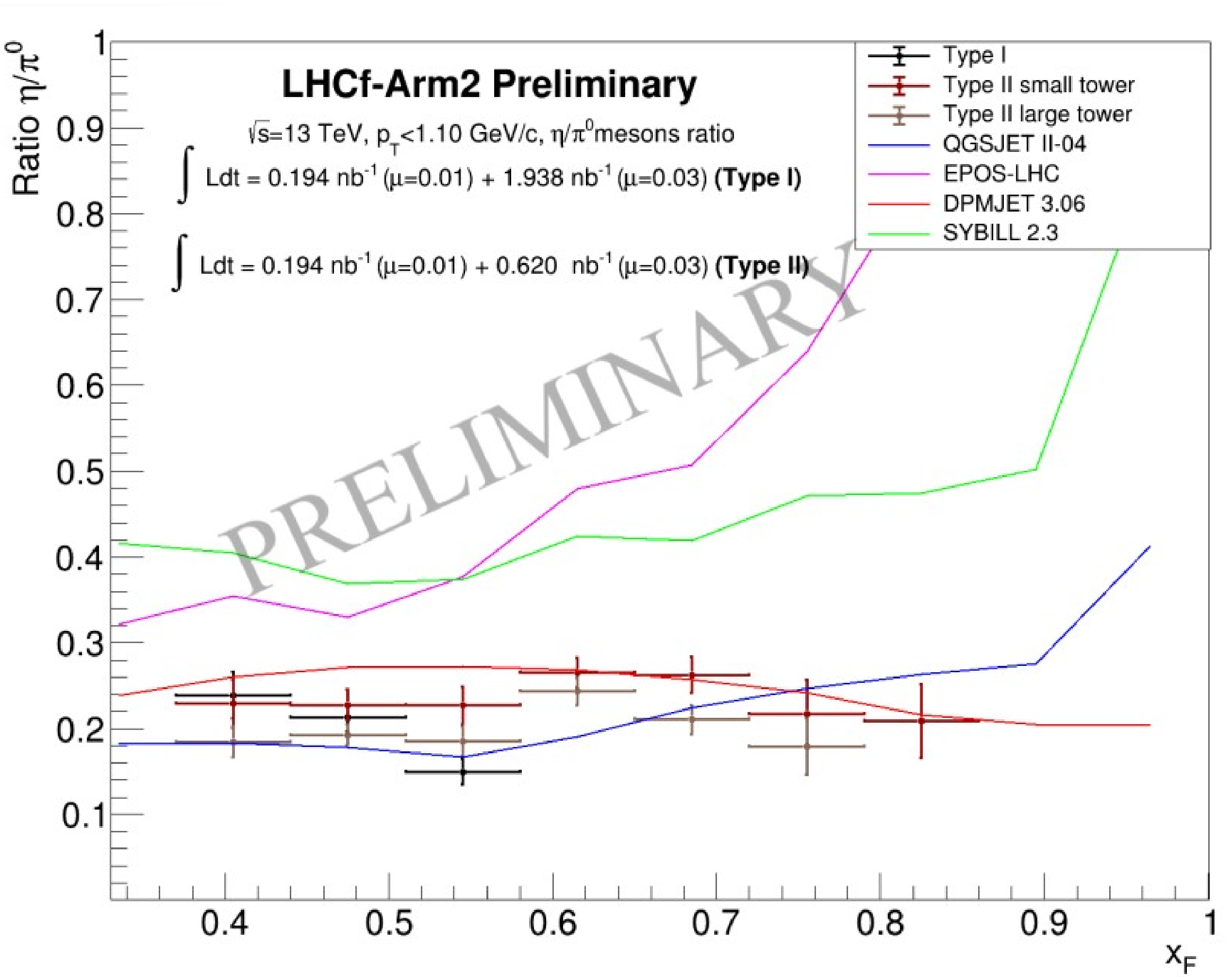
η/π^0 Production Rate

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

π^0 analysis has been repeated with exactly the same methodology of η analysis and ratio has been computed

SIBYLL 2.3, **EPOS-LHC** have discrepancies (impact of low-mass resonance production?)

QGSJETII-04, **DPMJET 3** has a flat trend that is more compatible with the experimental one

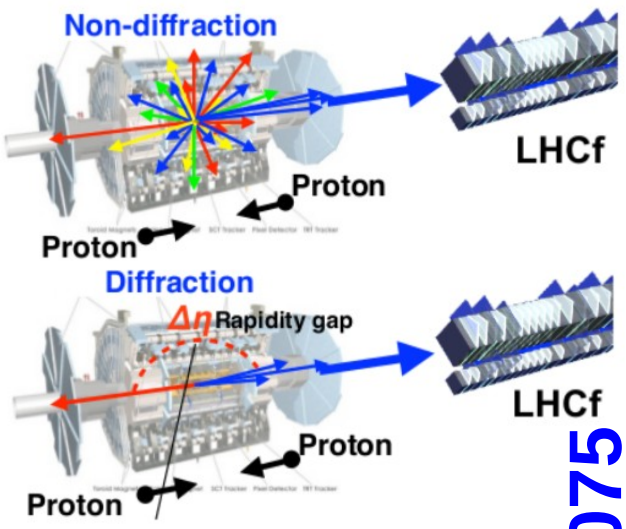


LHCf-ATLAS joint analysis

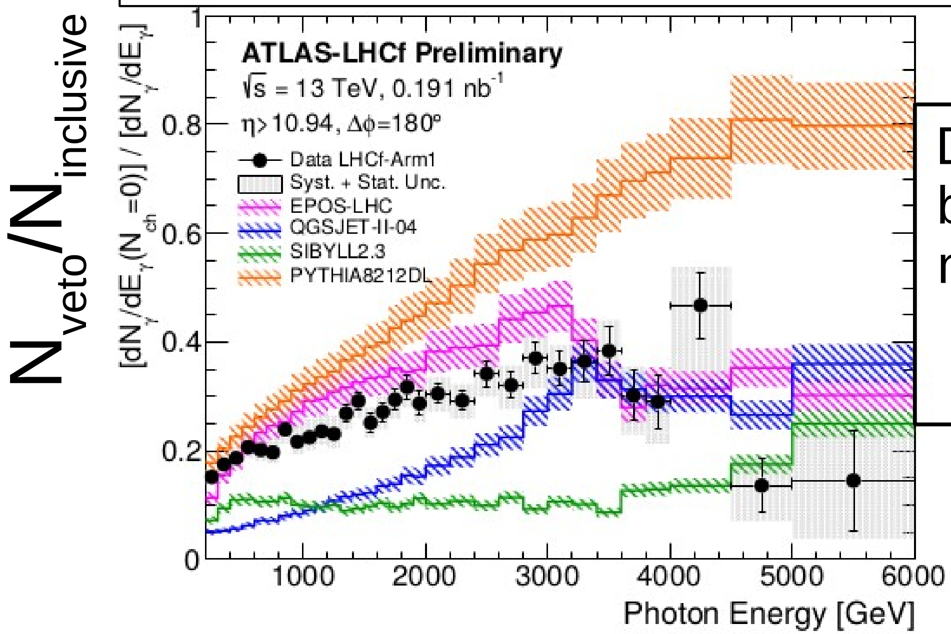
p-p √s = 13 TeV

The LHCf-ATLAS common operations leads to a much **higher degree of information** on *processes responsible for forward production*, allowing for accurate measurements of:

- Diffractive/Non-Diffractive production
- Multi-parton interaction process
- One-pion exchange process
- …



Forward photon production in η > 10.94



Diffractive events can be distinguished from non-diffractive events by **ATLAS veto** : Tracks=0 at |η|<2.5

ATLAS-CONF-2017-075

…paper in finalization

Operations in Run III

p-p $\sqrt{s}$ = 13.6 TeV
Operations on September 24-26, 2022

Main Motivation
Thanks to the silicon DAQ upgrade and optimization of trigger scheme, significantly **enlarge the double-γ event statistics** for more precise measurements of the production of π^0, η and (under study) K^0_S

Longest LHC Fill ever!

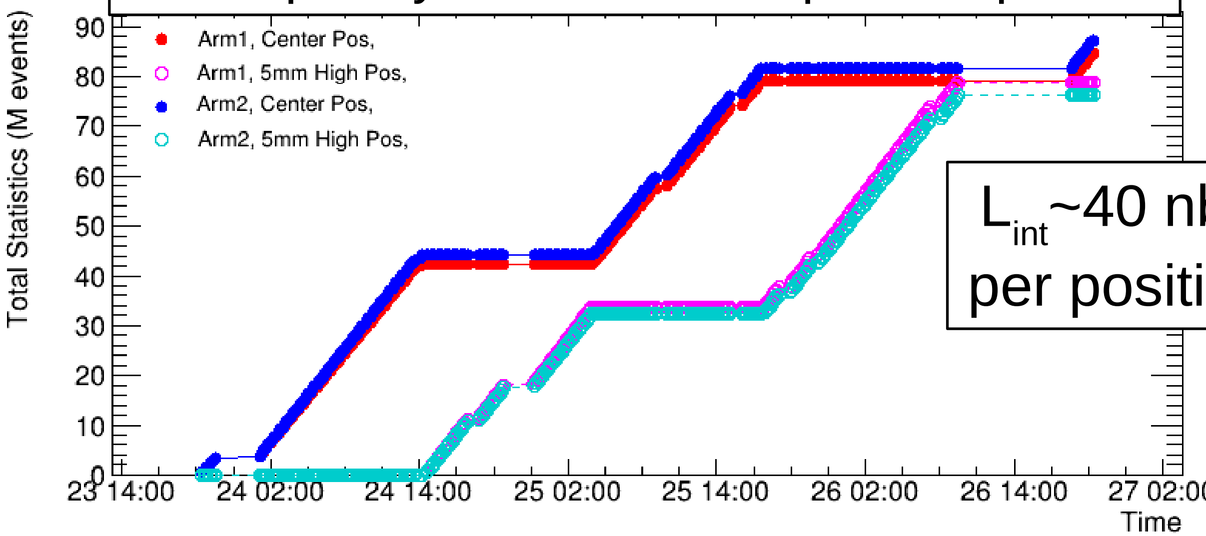
September 24-26:
Fill 8178 - 55h
Fill 8179 - 2h

8 times larger statistics with respect to Run II

Much larger increase for the **double-γ events** (Type-I and Type-II)

40 times larger statistics of **ATLAS common events** with respect to Run II

Data acquired in two different positions to completely cover the acceptance η>8.4

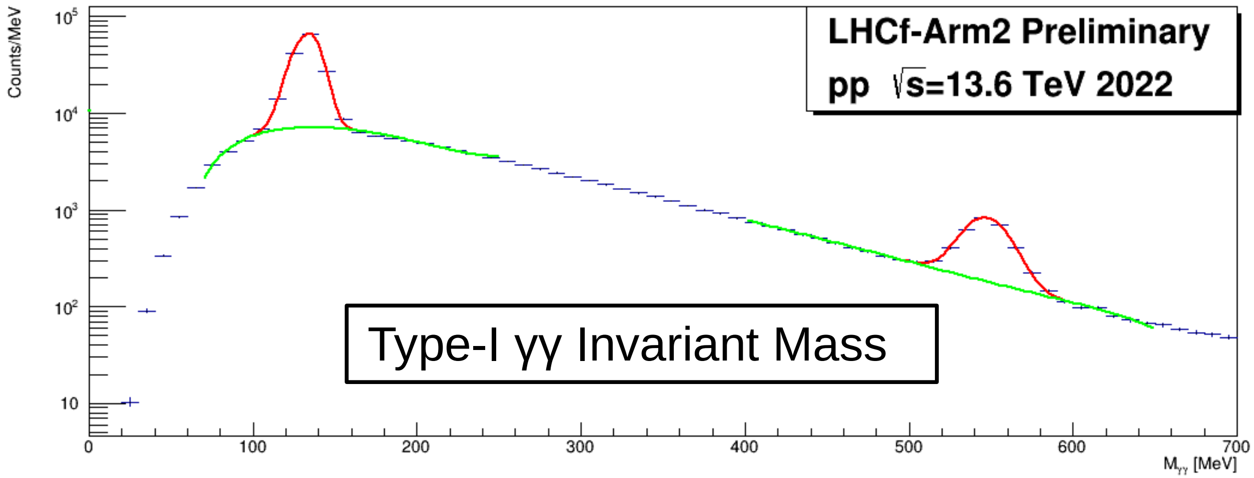


L_{int}~40 nb^{-1} per position

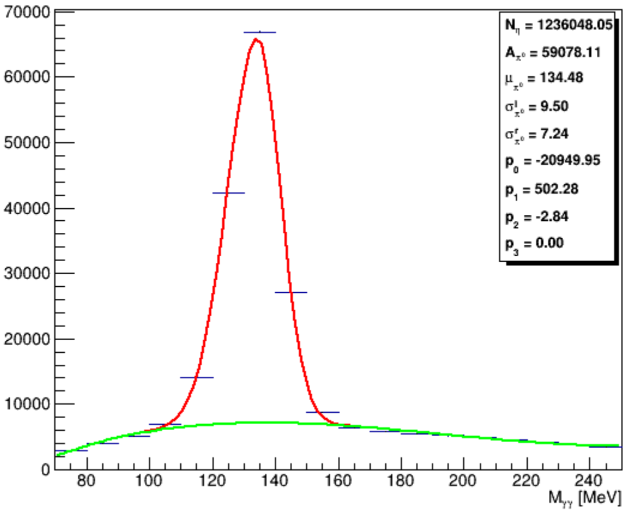
Physics targets

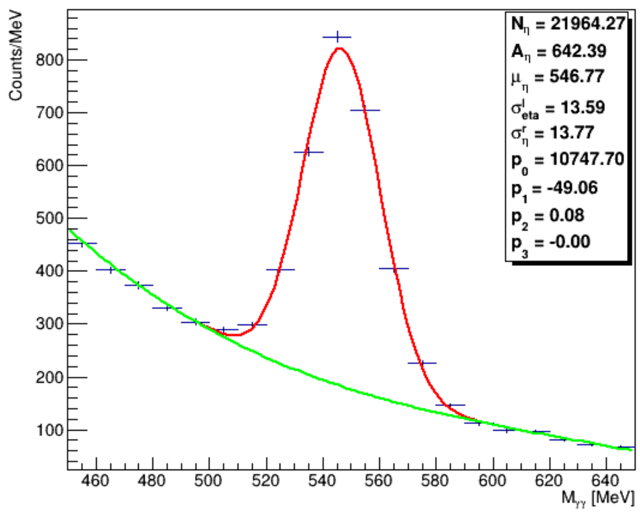
π^0 and η measurements

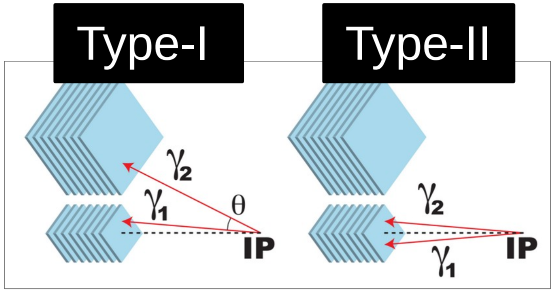
Large *increase in π^0 and η statistics* with respect to Run II data sample by roughly a **factor 10**!



➔ Decrease the term of statistical uncertainty
➔ Extend measurements to a larger x_F-p_T interval



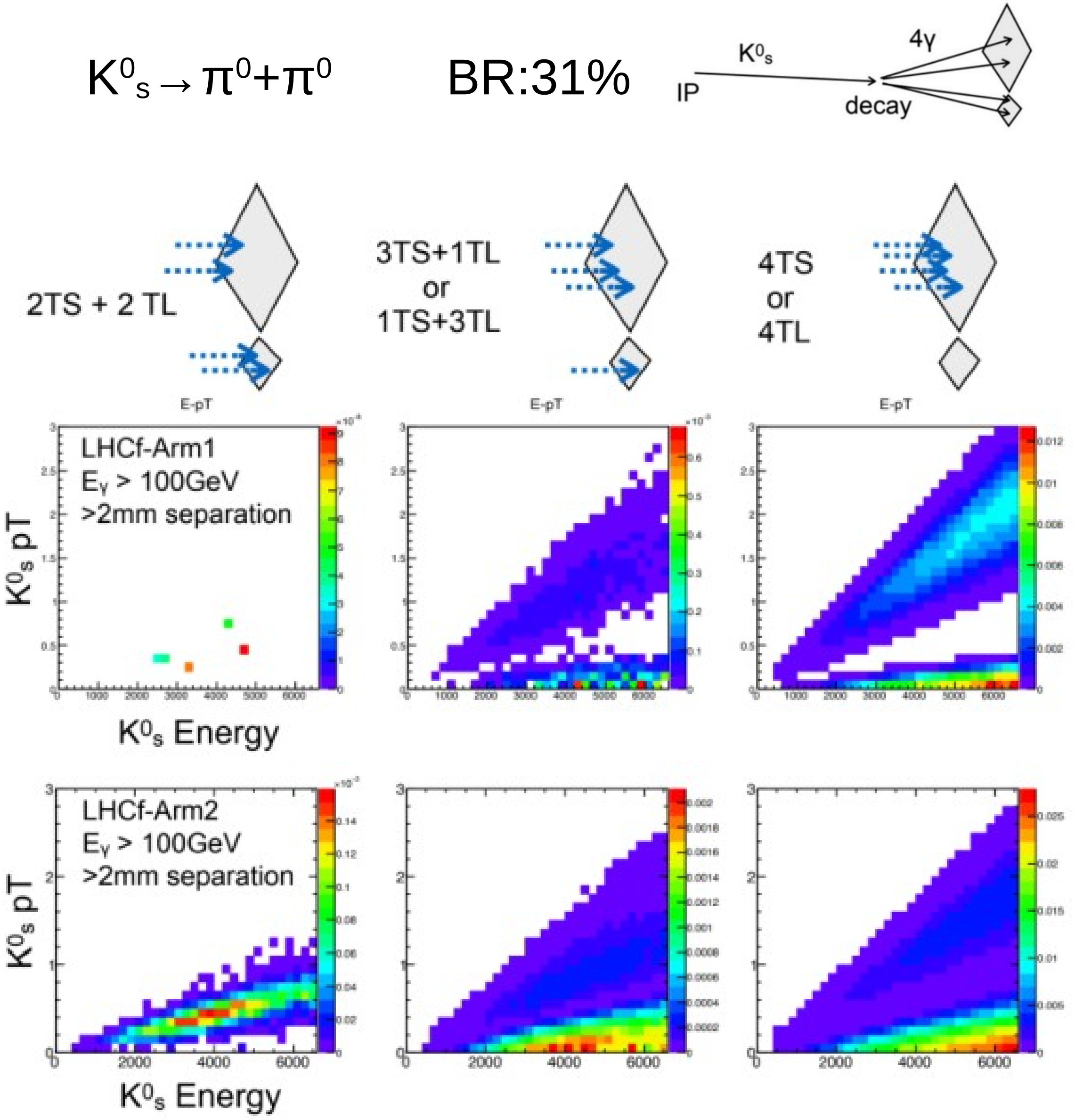




Physics targets
K^0_s measurement

Expected **O(10^3)** candidate events for K^0s (4γ), Λ^0 (2γ+n)!

$K^0_s \rightarrow \pi^0 + \pi^0$ BR:31%



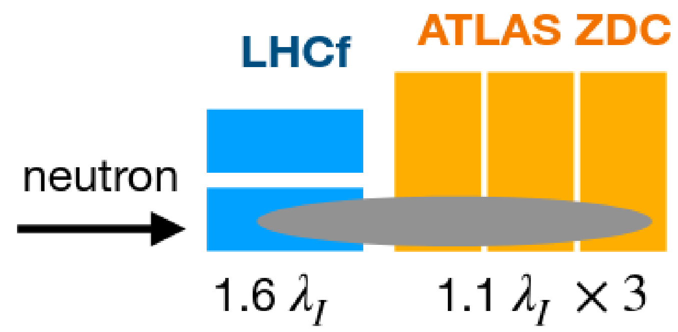
- ➔ Information on strangeness (and baryon) production in the very forward region
- ✗ Challenging multiparticle reconstruction method: ML techniques are in study

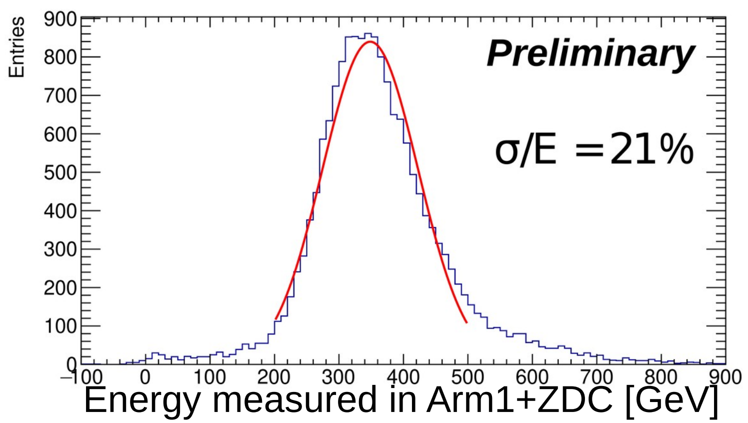
Physics targets LHCf+ATLAS

One pion exchange measurement

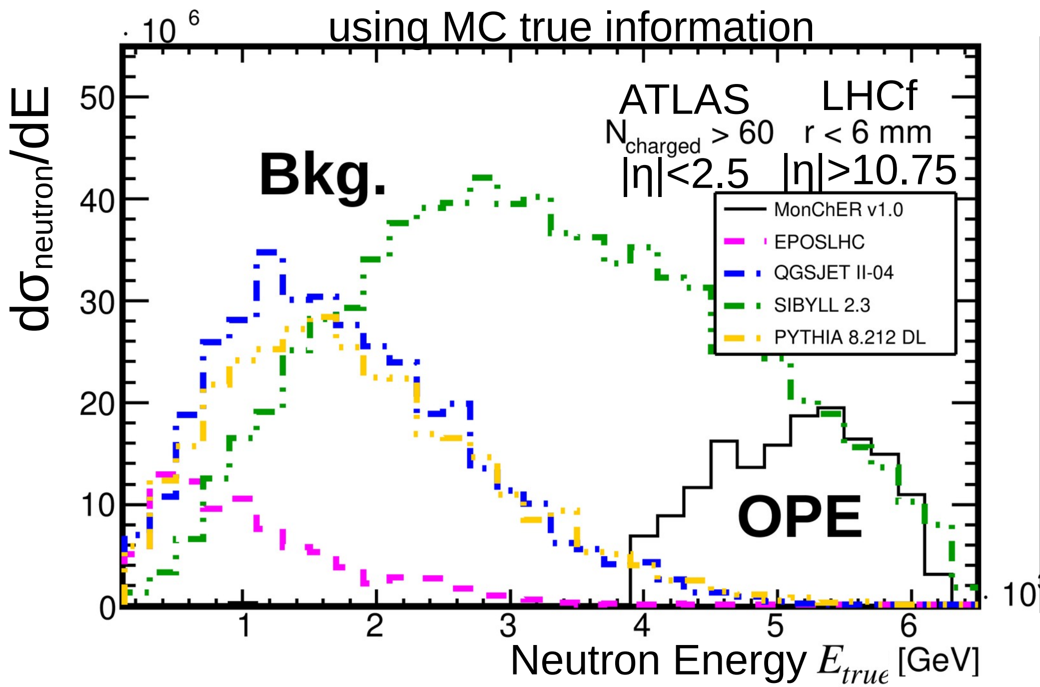
Improvement of hadronic energy resolution thanks to LHCf+ZDC system

Operation with **ZDC**
(σ_E/E = 40% → 20%)

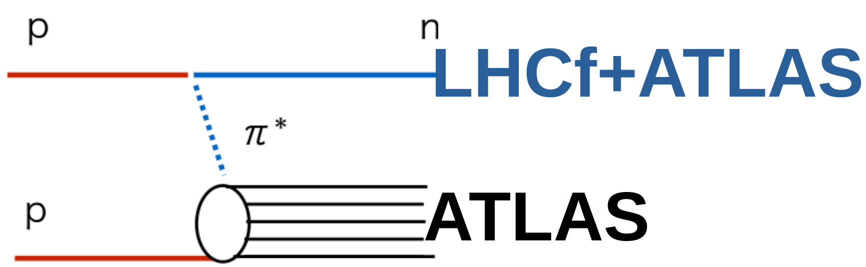




using MC true information



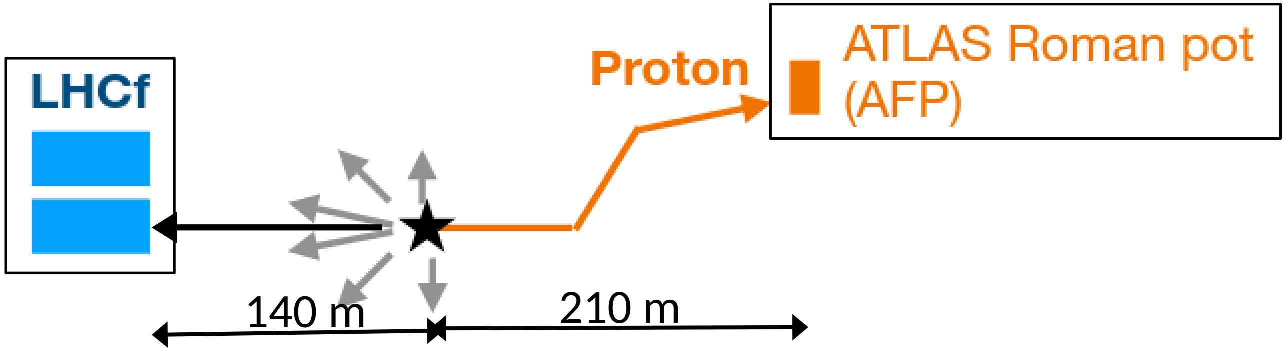
The information of multiplicity in the central region (ATLAS), energy (ATLAS+LHCf) and pseudorapidity (LHCf) of forward neutrons allows to get indirect estimation of p-π cross section from one-pion exchange process



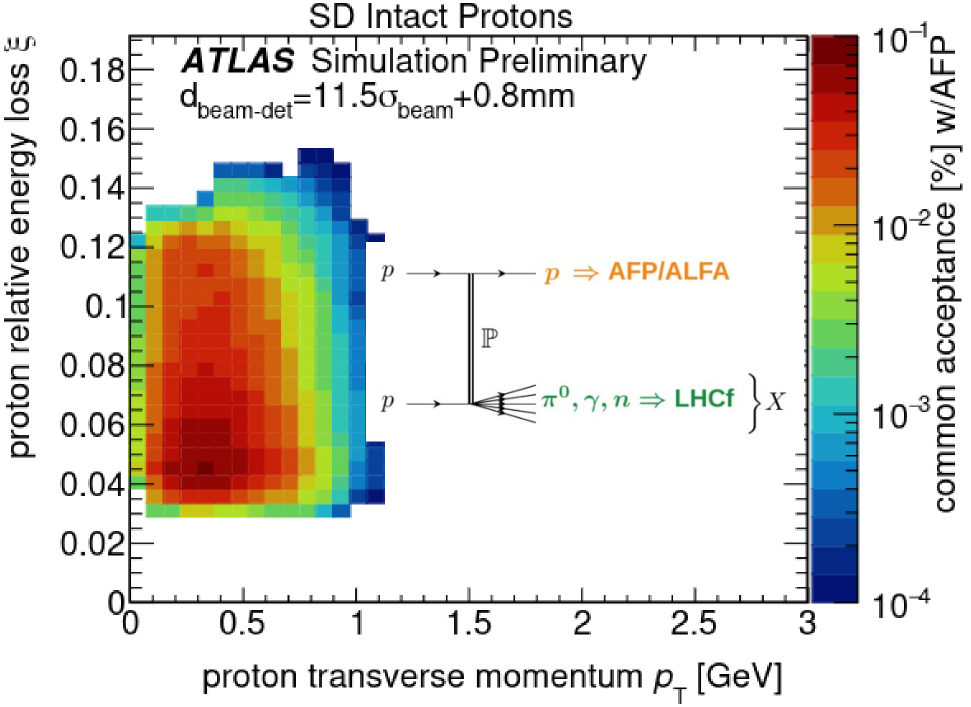
Physics targets LHCf+ATLAS

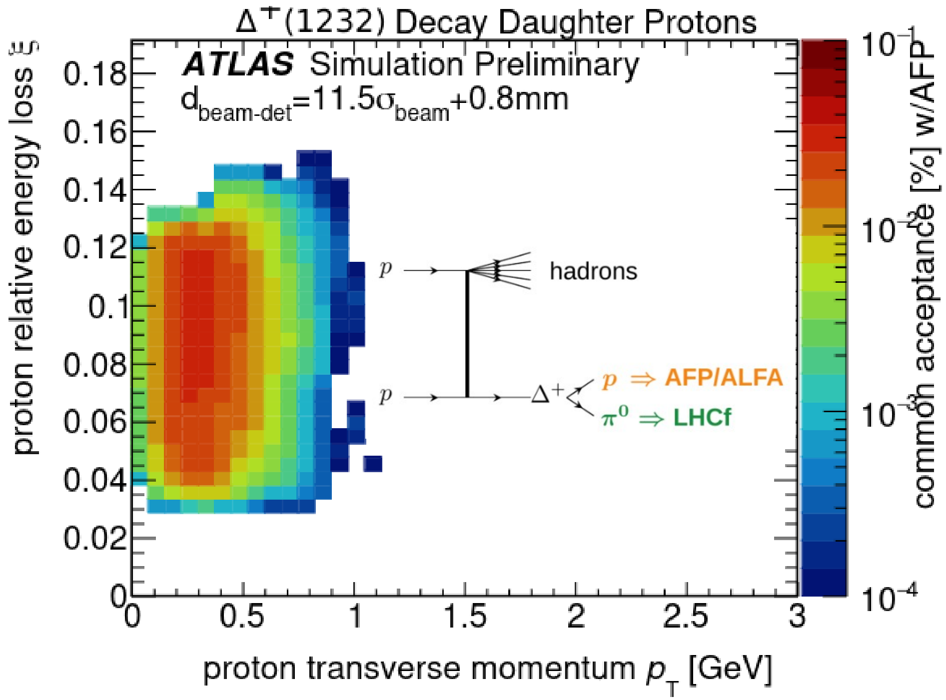
Diffraction process measurement

Improvement of information thanks to LHCf+ARP(ALFA+AFP) system



Measurement of **single diffractive** and *Δ resonance* contributions to production in the very forward region

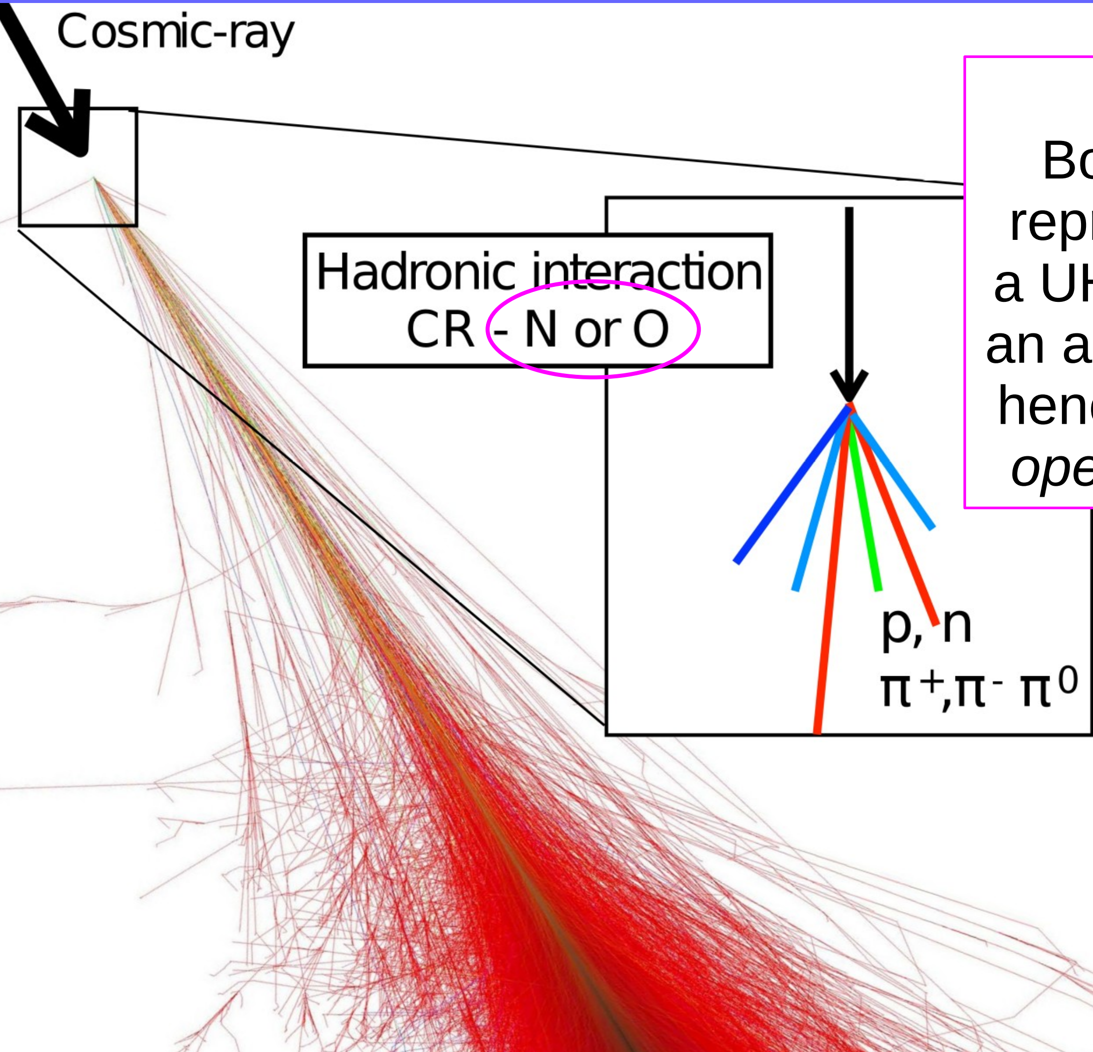




ATLAS-PHYS-PUB-2023-024

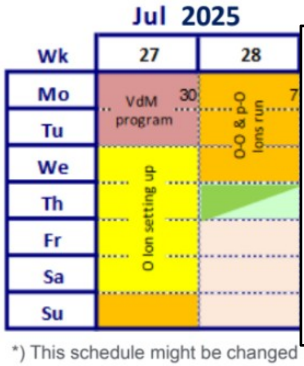
LHCf in Run III: p-O

Foreseen in July 2025



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 <u>avoid large interpolation</u>*



One week of oxygen run (p-O and O-O) in 2025:

- 1-2 days of data taking
- L_{int} = 1.4 nb^{-1} for p-O

[unlikely O-O with LHCf]

Additional motivations wrt p-Pb collisions:

- Ultra Peripheral background negligible
- LHCf-ATLAS analysis possible (no UPC)

Summary

The LHCf experiment highlighted *significant deviations* in forward production with respect to the current model expectations.

The data acquired in **p-p $\sqrt{s}$ = 13.6 TeV** will improve our knowledge:

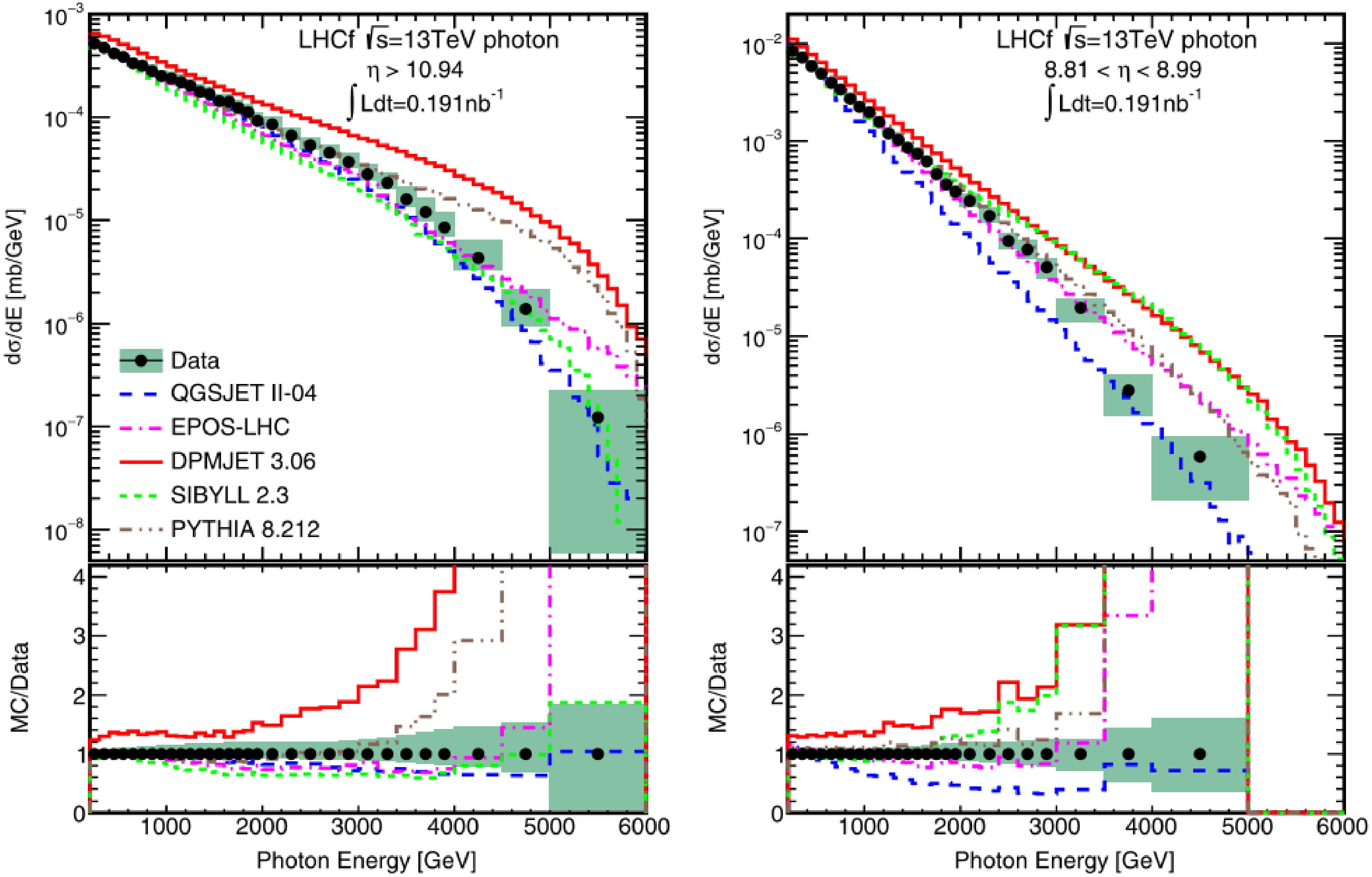
- High precision measurement on *forward π^0 and η production*
- First ever measurement of *K^0_s production* in the forward region
- Insight into different production mechanisms (*LHCf-ATLAS*)

Of fundamental importance for CR are **p-O runs** in 2025:
Run III is the last chance for LHCf experiment to take this data!

Thank you
for the attention!

Photons dσ/dE

p-p √s = 13 TeV

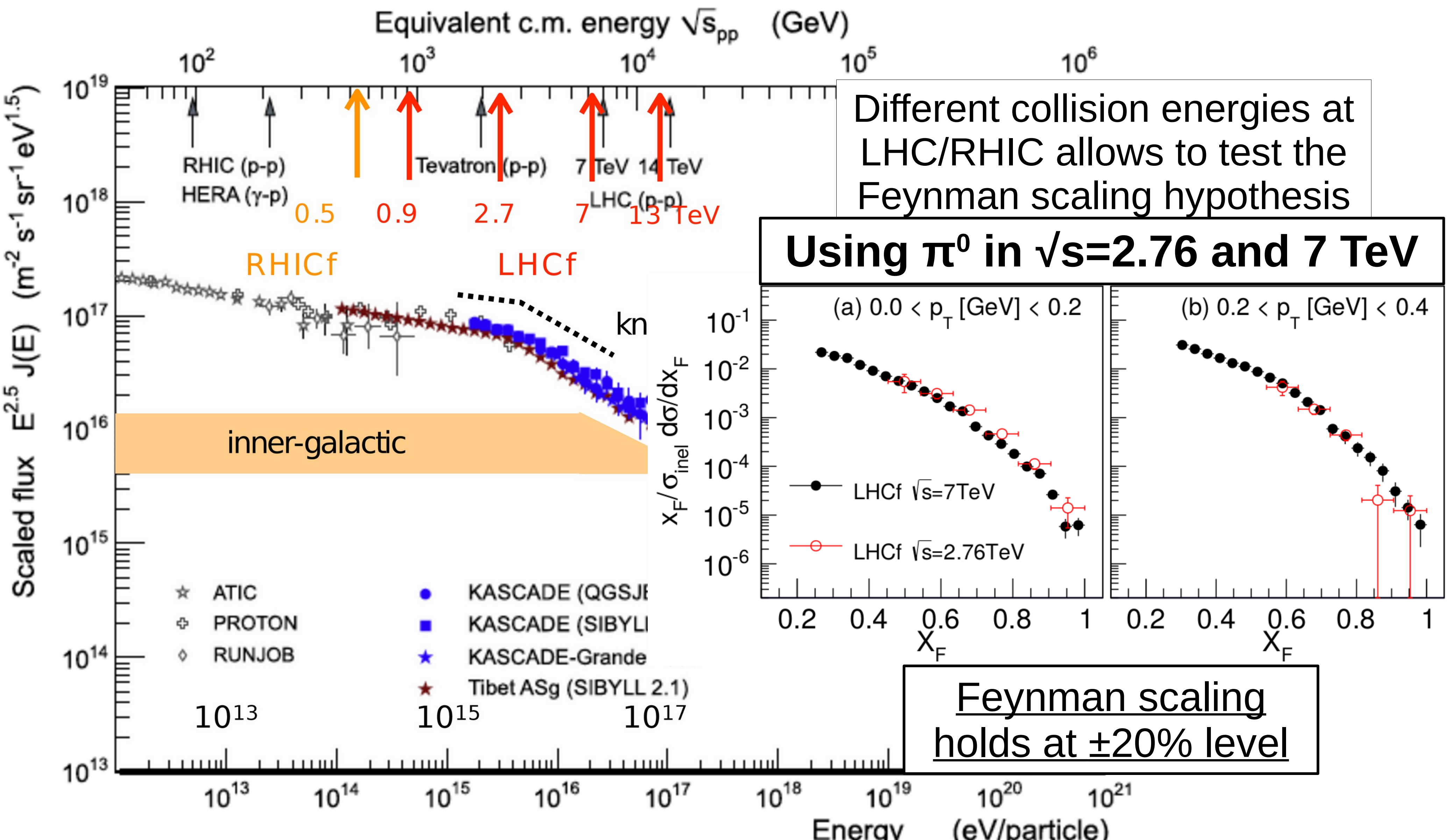


PLB 780 (2018) 233-239

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 π^0



Different collision energies at LHC/RHIC allows to test the Feynman scaling hypothesis

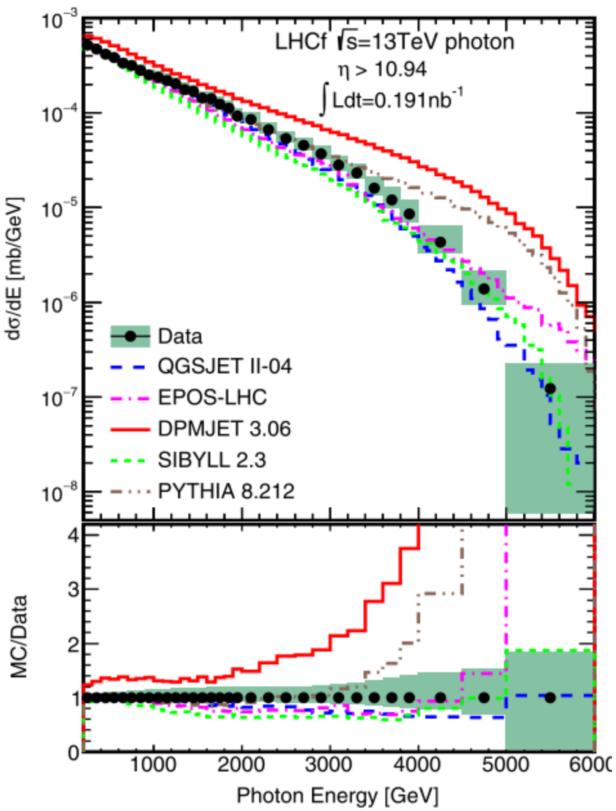
Using π^0 in $\sqrt{s}$=2.76 and 7 TeV

Feynman scaling holds at ±20% level

D'Enterria et al., 2011

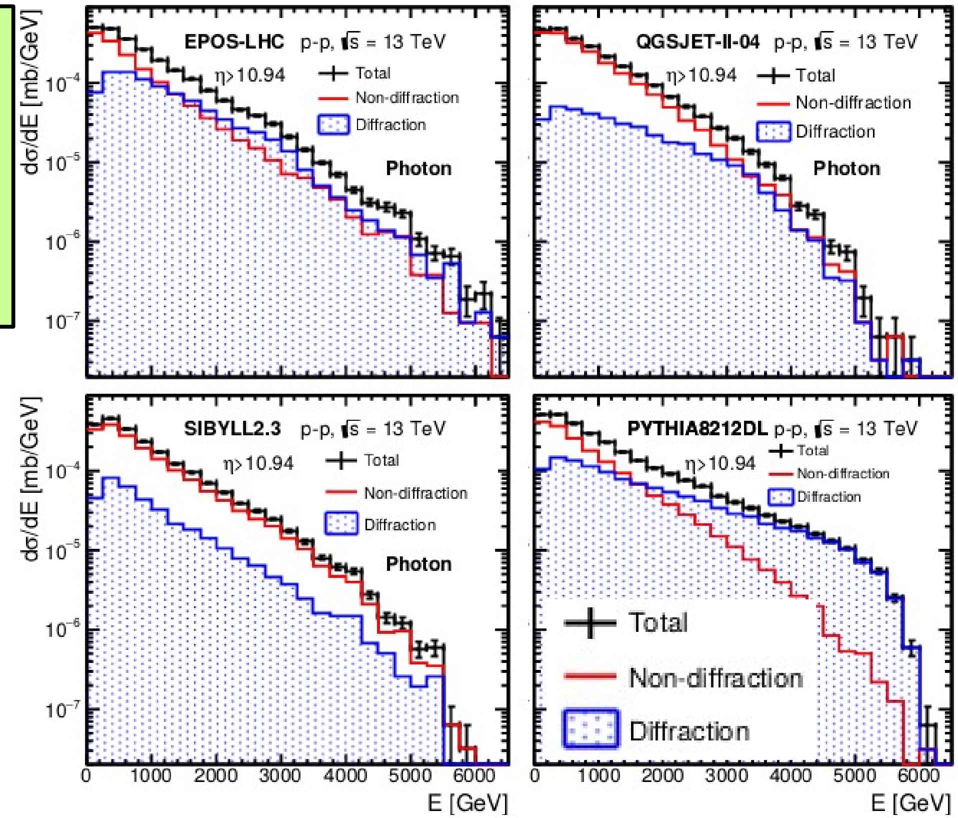
Diffractive and non-diffractive production

√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?



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

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

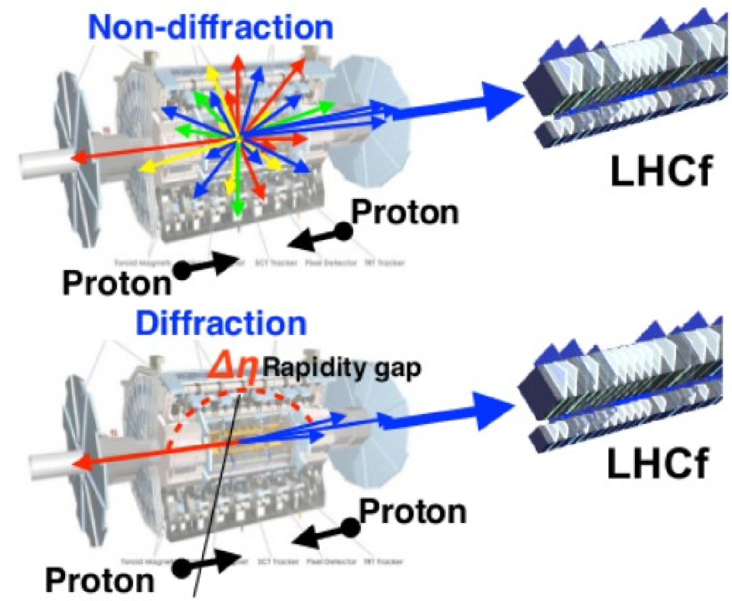
LHCf-ATLAS joint analysis

LHCf-ATLAS joint analysis

Preliminary result for photons in p-p √s = 13 TeV

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

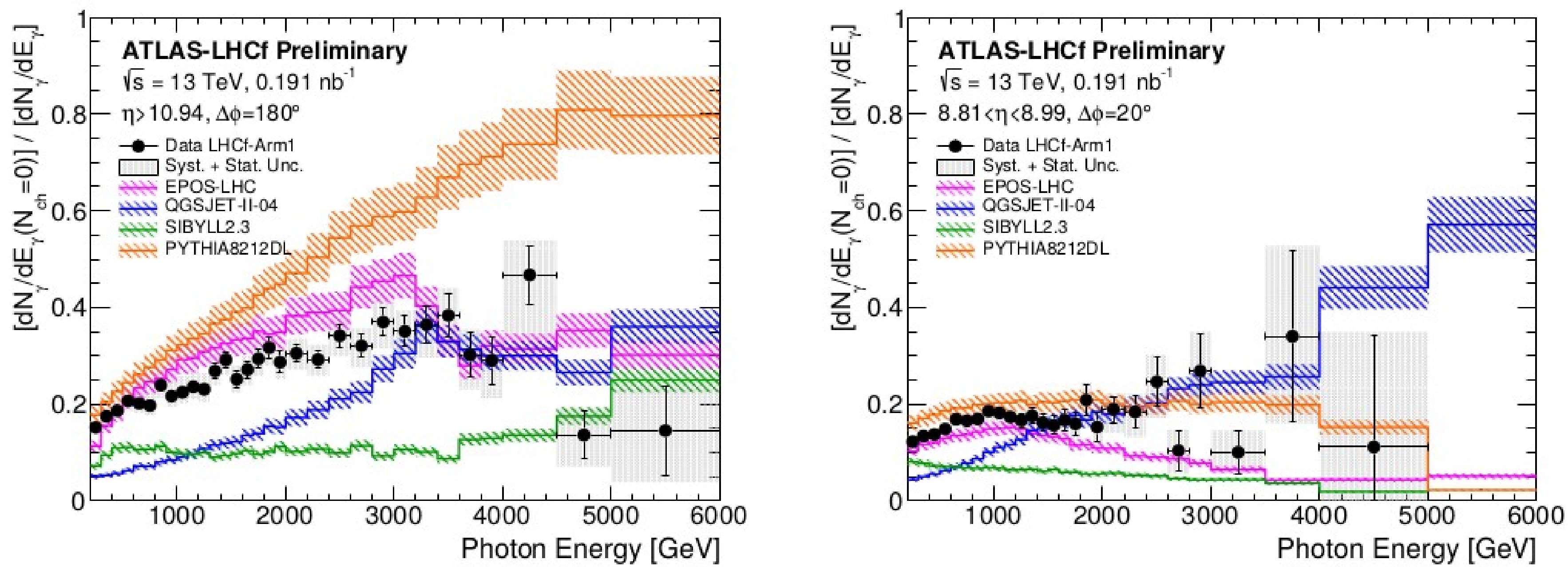
Diffractive events can be distinguished from non-diffractive events by **ATLAS veto** : tracks=0 at |η|<2.5



ATLAS-CONF-2017-075

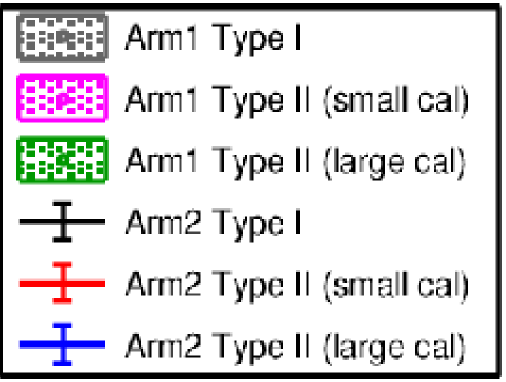
…paper in finalization

$N_{veto}/N_{inclusive}$

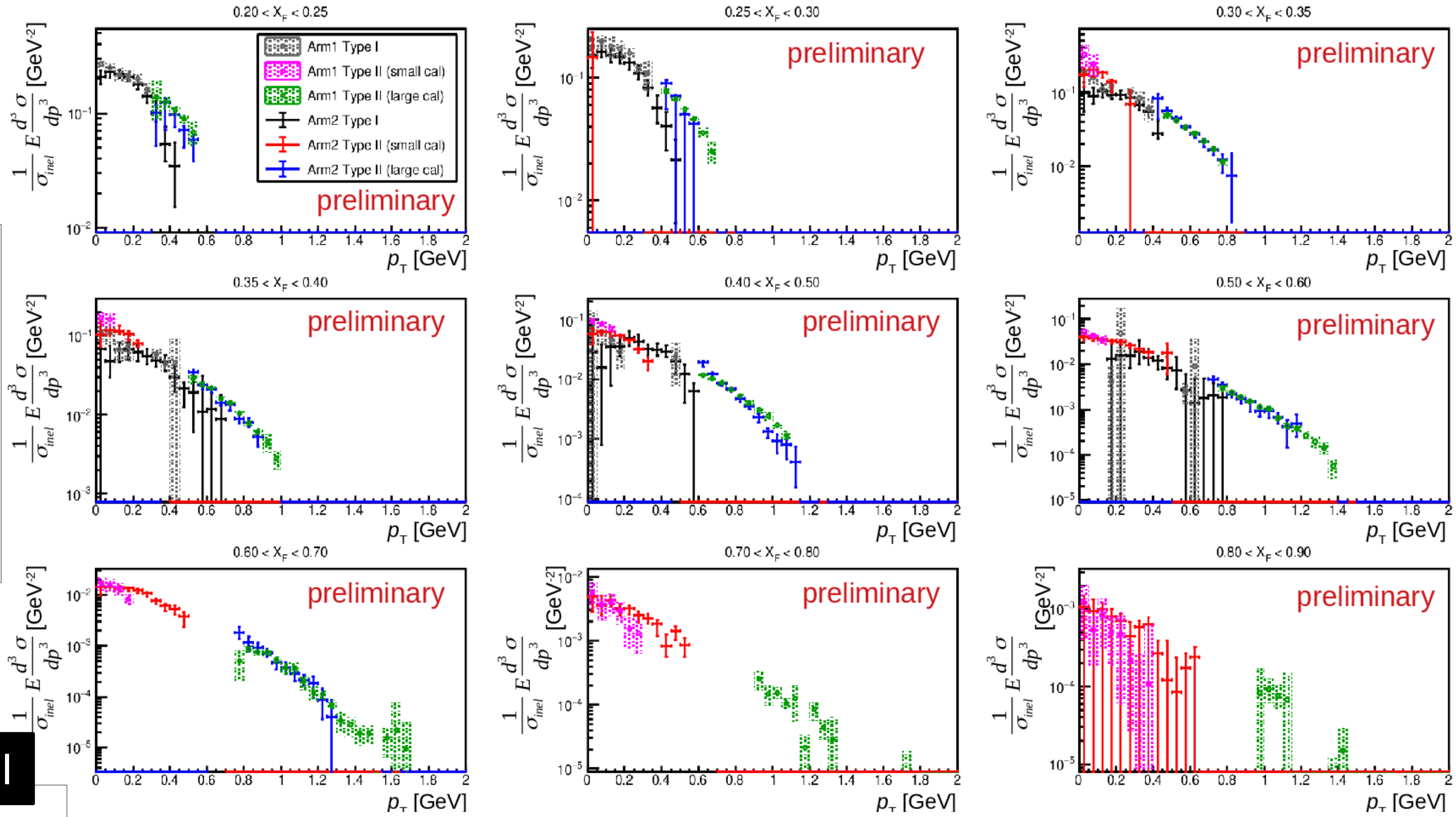


π^0 Production Rate

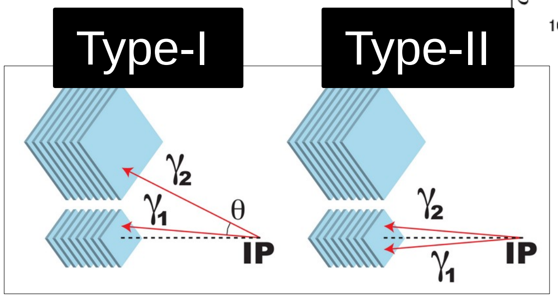
p-p √s = 13 TeV



Ongoing analysis

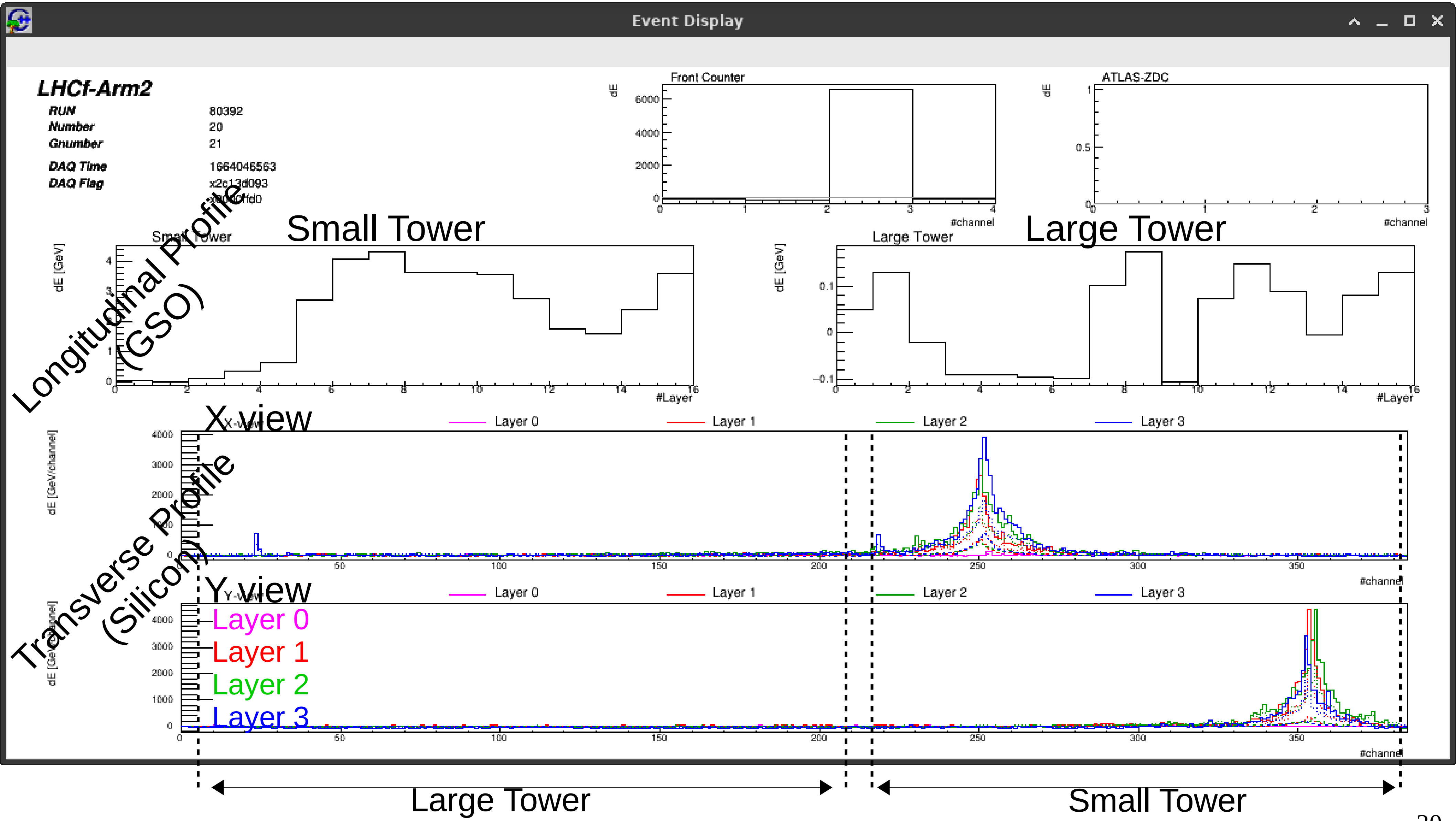


Different Arm1 and Arm2 geometries allows for a large **<u>p_T vs x_F coverage</u>** <u>with an overlap to crosscheck results</u>

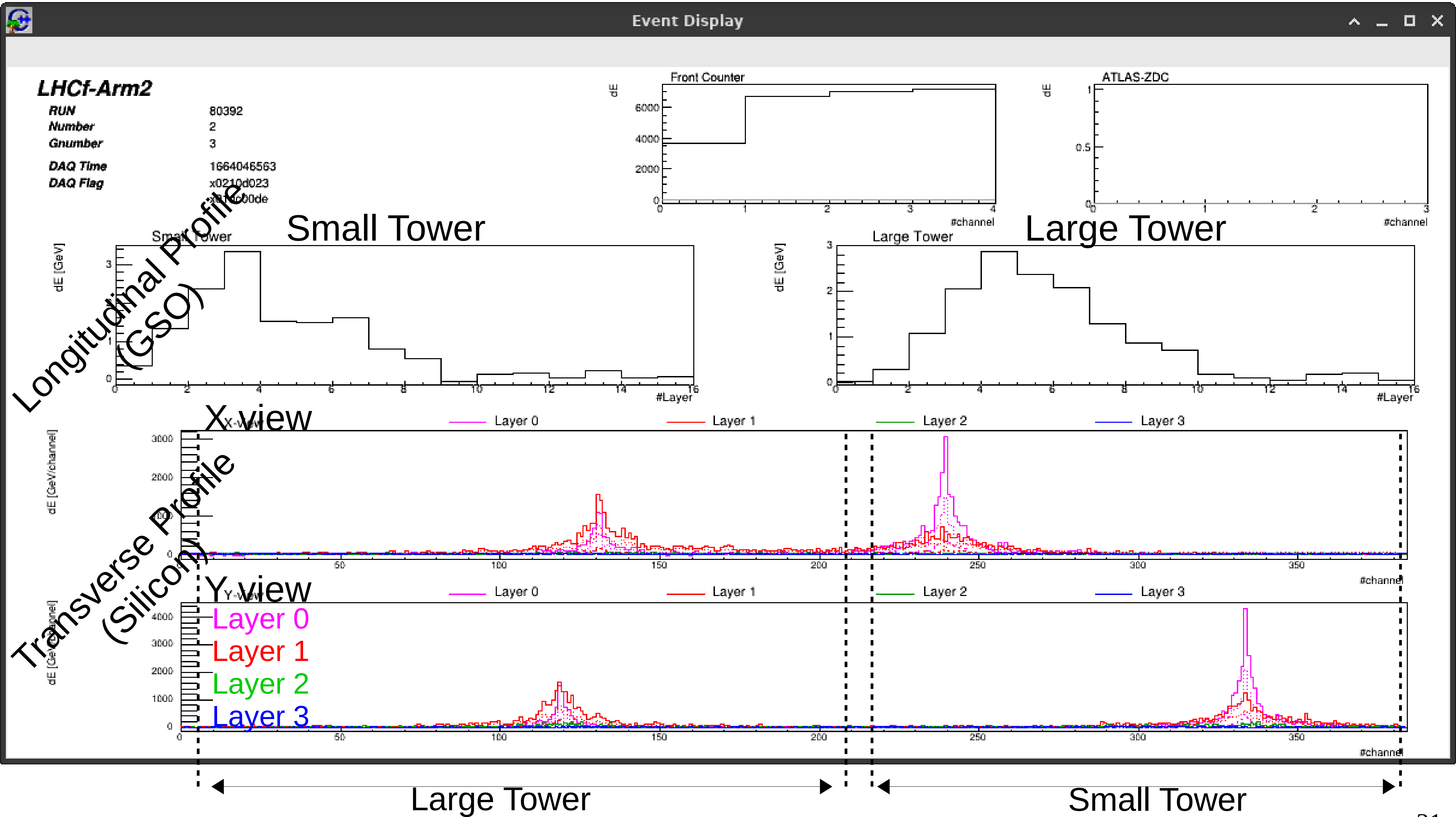


Good *agreement* between Arm1 and Arm2 data and between "Type-I" and "Type-II" events

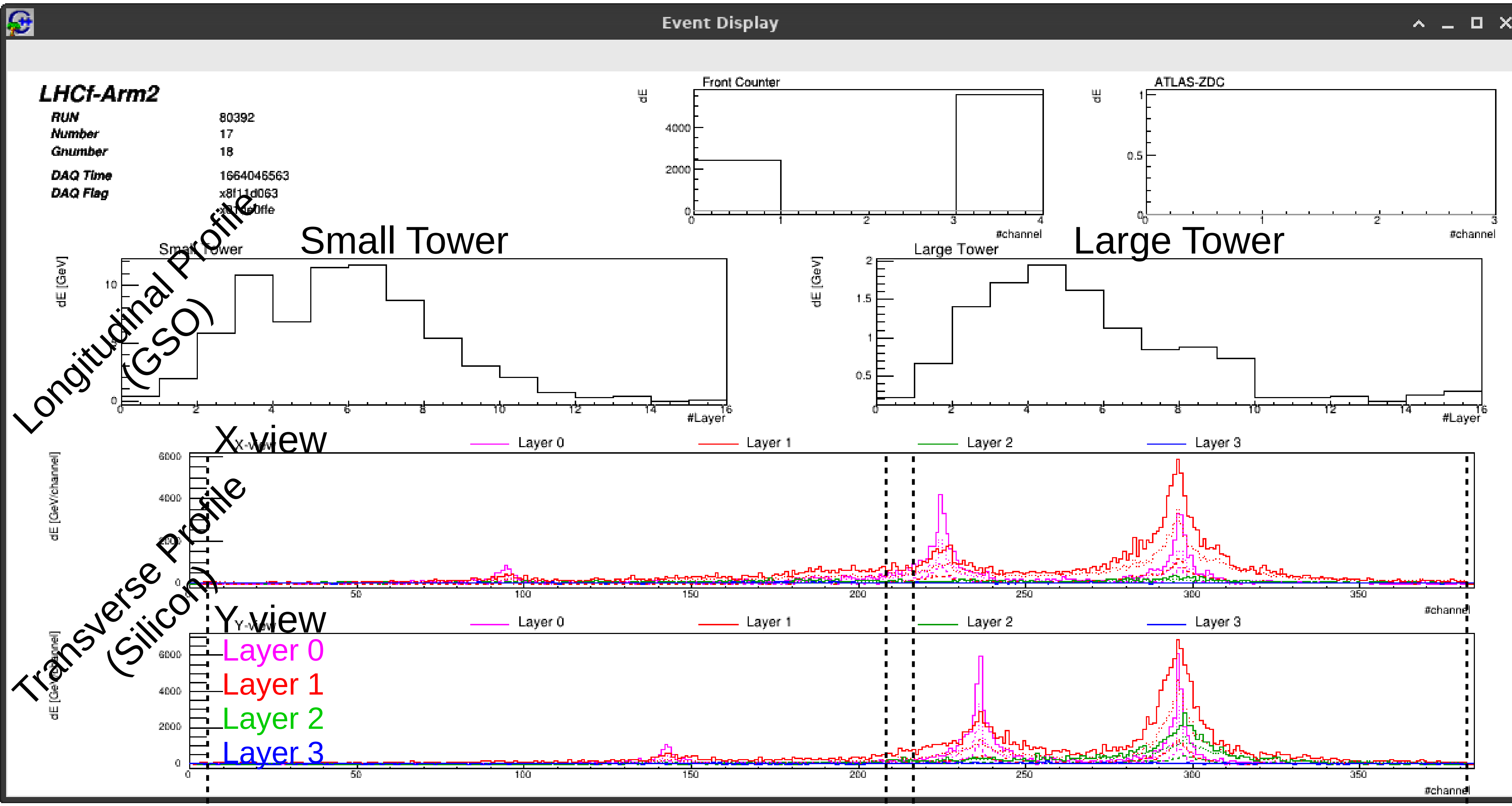
p-p √s = 13.6 TeV:
Hadron-like candidate in Small Tower



p-p √s = 13.6 TeV:
Type-I candidate



p-p √s = 13.6 TeV:
Type-II candidate in Small Tower



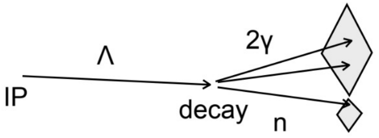
Large Tower

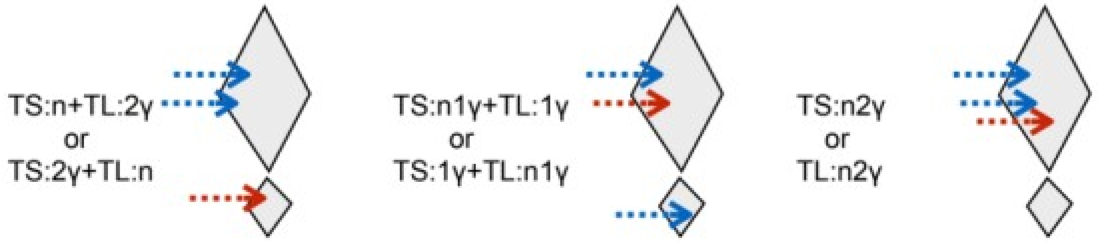
Small Tower

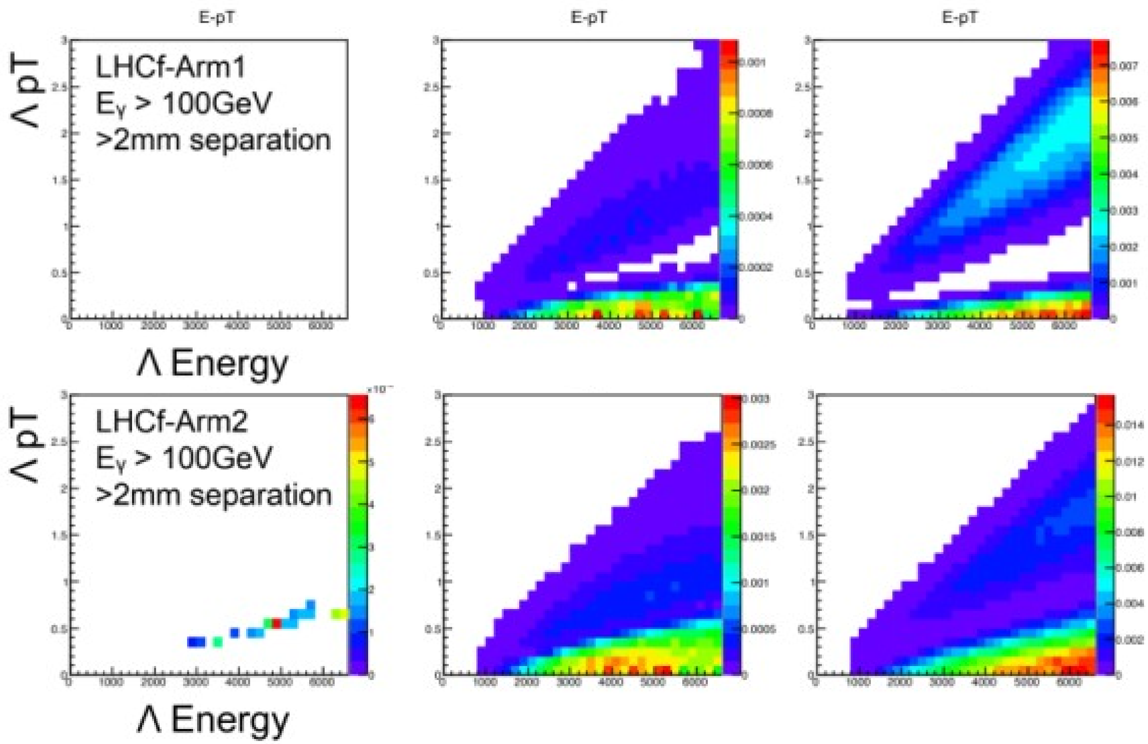
Physics targets
Λ^0 measurement

Expected **O(10³)** candidate events for K^0s (4γ), Λ^0 (2γ+n)!

$\Lambda^0 \rightarrow n+\pi^0$ BR:36%





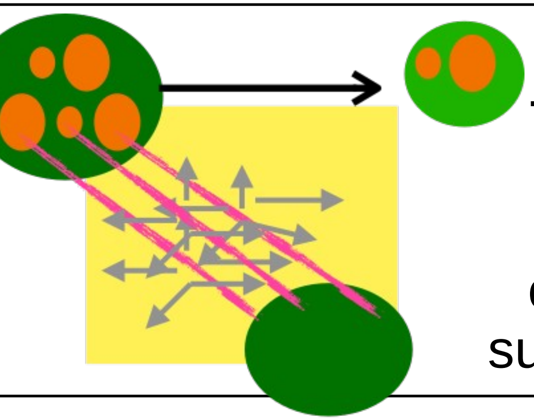


- ➔Information on strangeness (and baryon) production in the very forward region
- ✗ Challenging multiparticle reconstruction method: ML techniques are in study

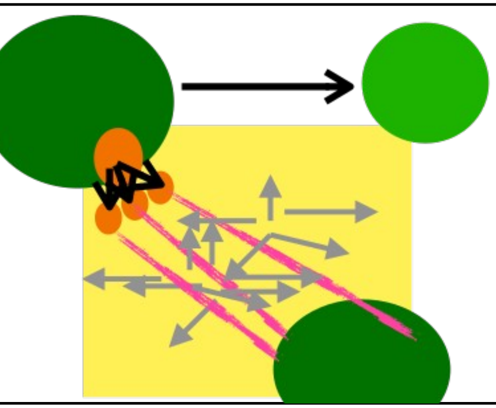
LHCf-ATLAS joint analysis

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

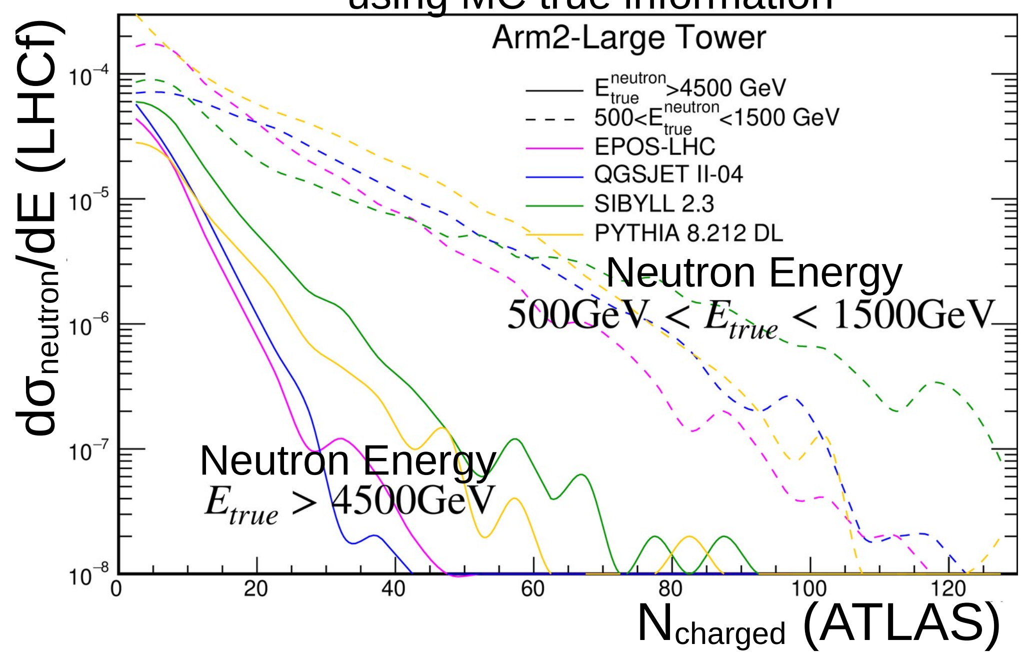


Strong central-forward correlation (QGSJET, EPOS)
Initial part of parton cascade modeled as superposition of partons



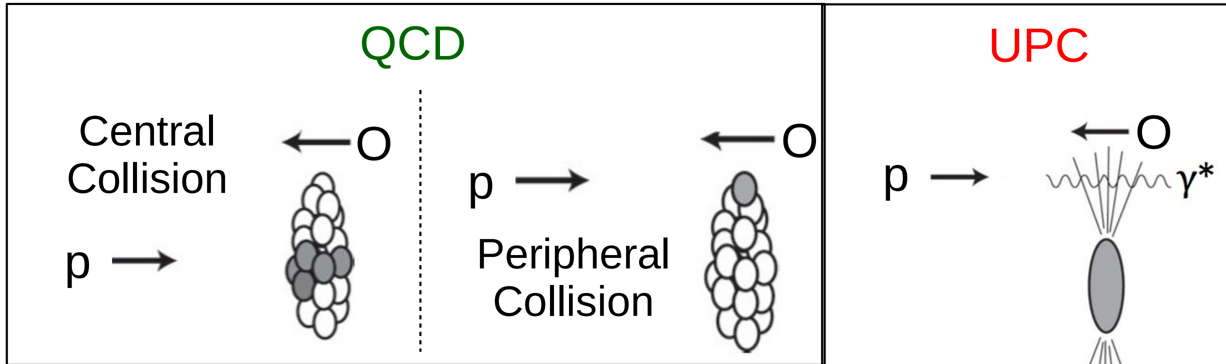
Weak central-forward correlation (SIBYLL, PYTHIA)
Initial part of parton cascade modeled as universal state

using MC true information

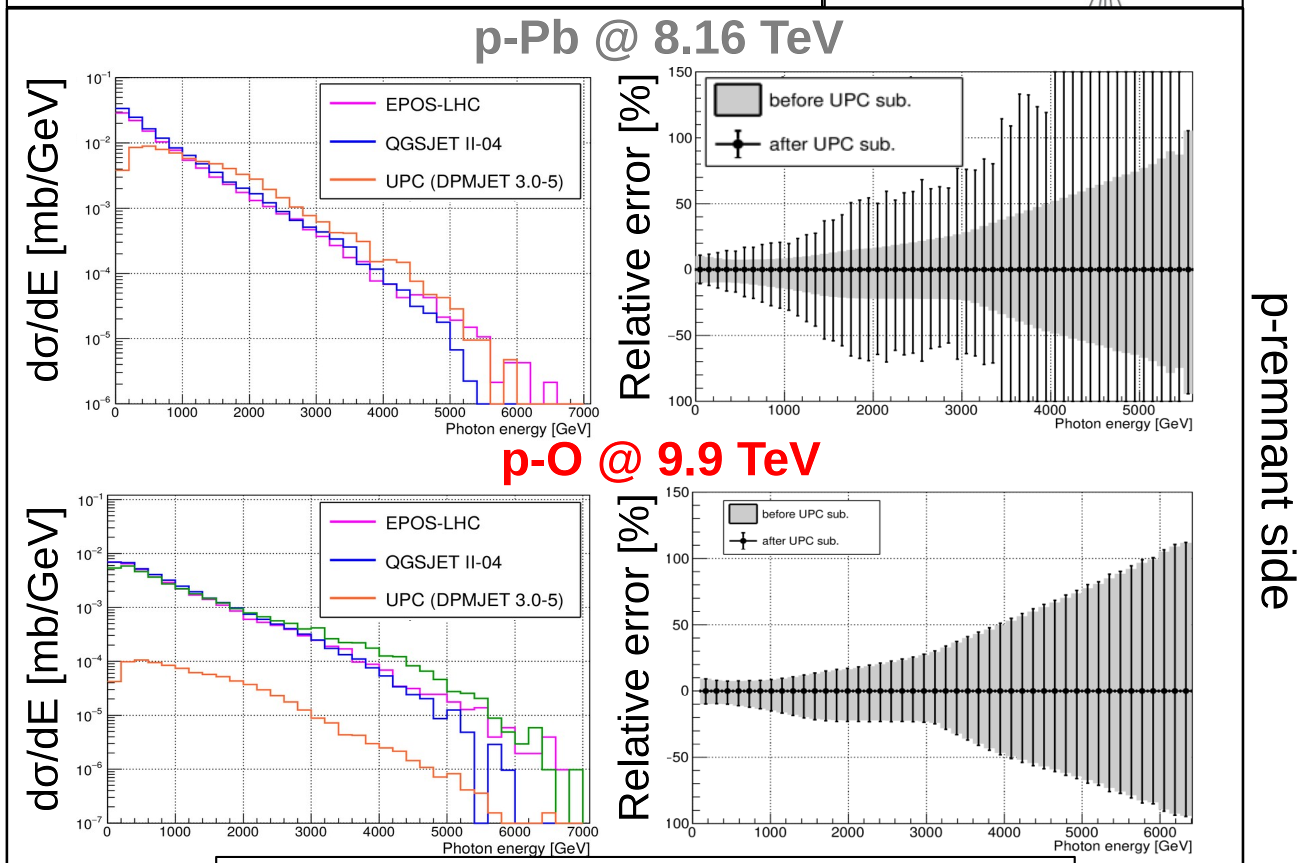


p-O and O-O operations:
Ultra Peripheral Collisions

In the case of EAS interaction, forward production is dominated by **soft QCD processes**.



Forward production measured in **p-Pb collisions** was affected by a large contribution from **Ultra Peripheral Collision** (Coulombian interaction) that constitutes a significant source of <u>background for measurements</u>: the uncertainty is dominated by the systematic from the estimation of the UPC contribution (10-50%) to be subtracted from data

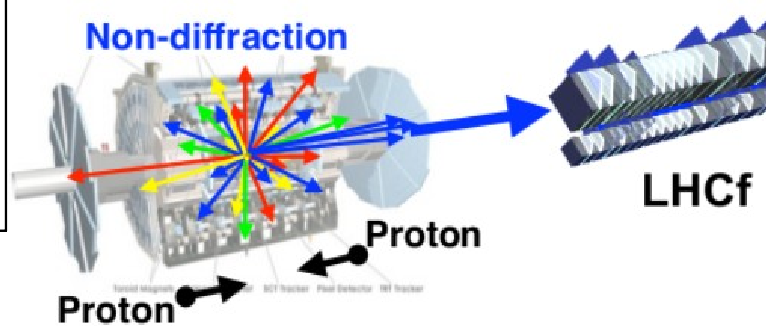


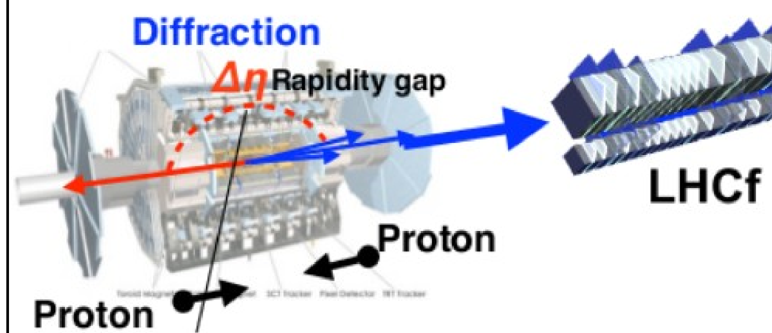
In **p-O collisions**, UPC background is negligible and does not contribute to the final error!

Forward photon production in η > 10.94

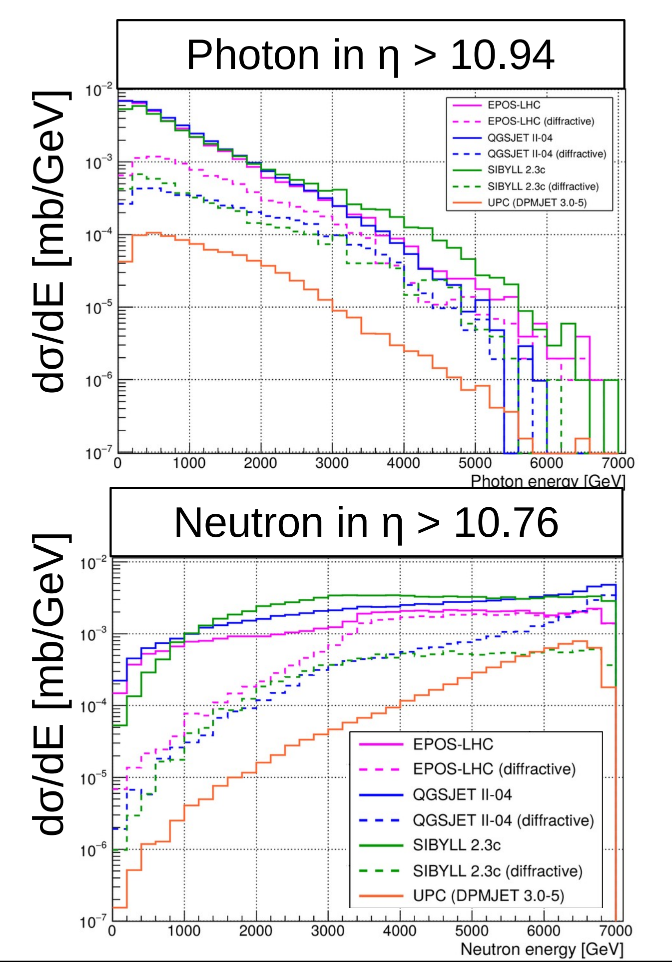
LHCf-ATLAS Joint Analysis

The **LHCf-ATLAS joint analysis** proved to be a very powerful tool to study forward production from different contributions, non-diffractive and diffractive (M_X<50GeV), by looking at the activity in the central region.





ATLAS-CONF-2017-075



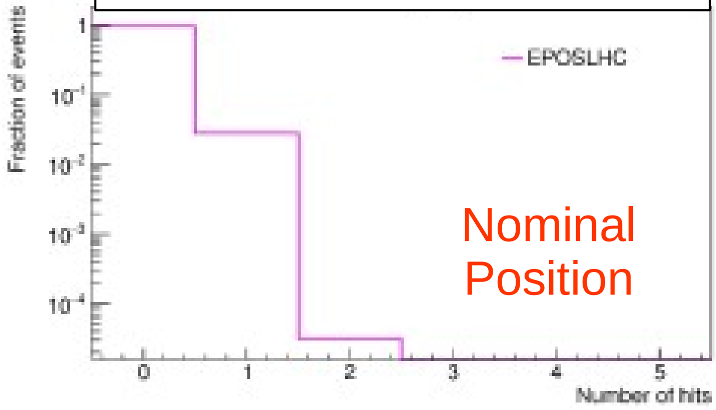
Because of the large UPC contribution, which (having no activity in central region) mimics a diffractive event, the LHCf-ATLAS joint analysis was not effective in **p-Pb collisions**.

In **p-O collisions**, the UPC contribution is negligible respect to diffraction contribution, so that the LHCf-ATLAS joint analysis can be successfully extended to investigate forward production in p-ion collisions.

p-O and O-O operations:

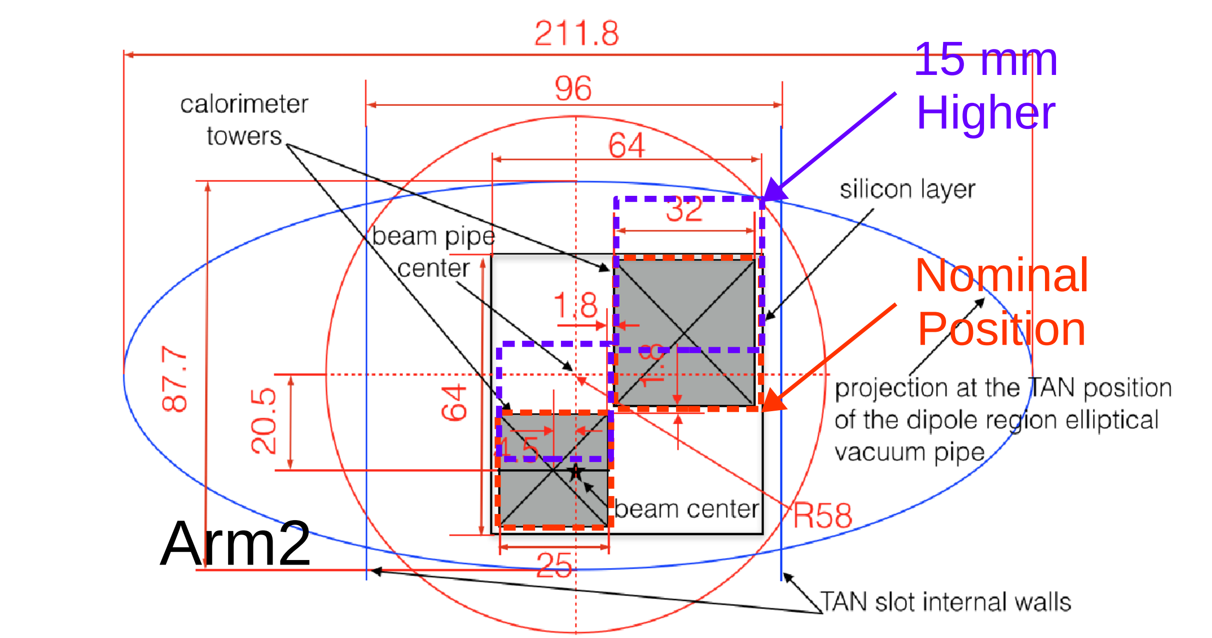
Main experimental challenge

Neutron Multiplicity in Small Tower
Proton remnant side

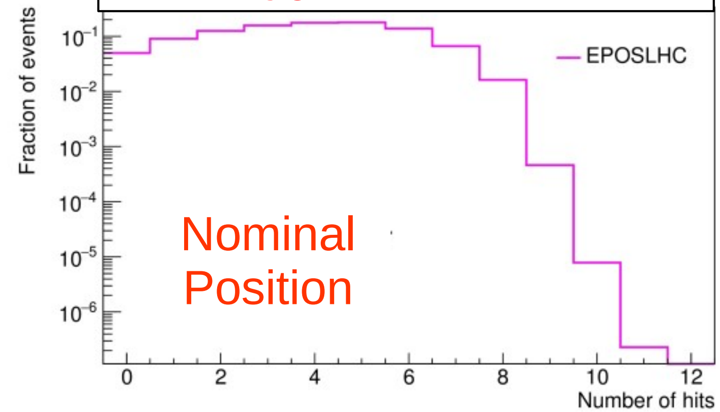


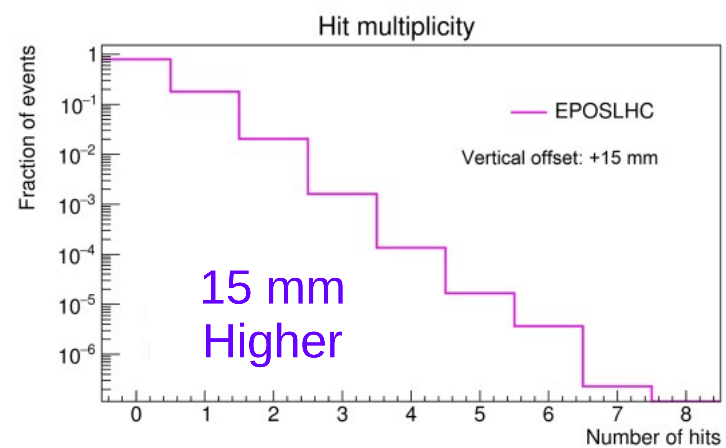
LHCf can safely operate on proton-remnant side since it can separately reconstruct two particles in same tower and less than 10% of events have more than a particle

Due to high multiplicity, LHCf can operate on oxygen remnant side only 15 mm higher ($\eta<11$)



Neutron Multiplicity in Small Tower
Oxygen remnant side





p-O and O-O operations:
Collision conditions

2022 conditions for **p-p @ 13.6 TeV**:
- N_{bunch} = 144/500
- Δt_{bunch} = 525 ns
- $L < 10^{30}\ cm^{-2}s^{-1}$
- $\theta_{crossing}$ = 290 μrad
- μ = 0.01-0.02
- β^{*} = 19.2 m

For each detector position
$\mathbf{L_{int} \sim 40\ nb^{-1}}$

Ideal conditions for **p-O @ 9.9 TeV**:
- N_{bunch} = 24/43
- Δt_{bunch} = 2 μs
- $L < 10^{29}\ cm^{-2}s^{-1}$
- $\theta_{crossing}$ = 290 μrad
- μ = 0.01-0.02
- β^{*} = 10 m

(Expected)

$\mathbf{L_{int} \sim 1.4\ nb^{-1}}$ for p-O
$\mathbf{L_{int} \sim 0.7\ nb^{-1}}$ for O-O

Higher collisions energy increases the LHCf detector acceptance