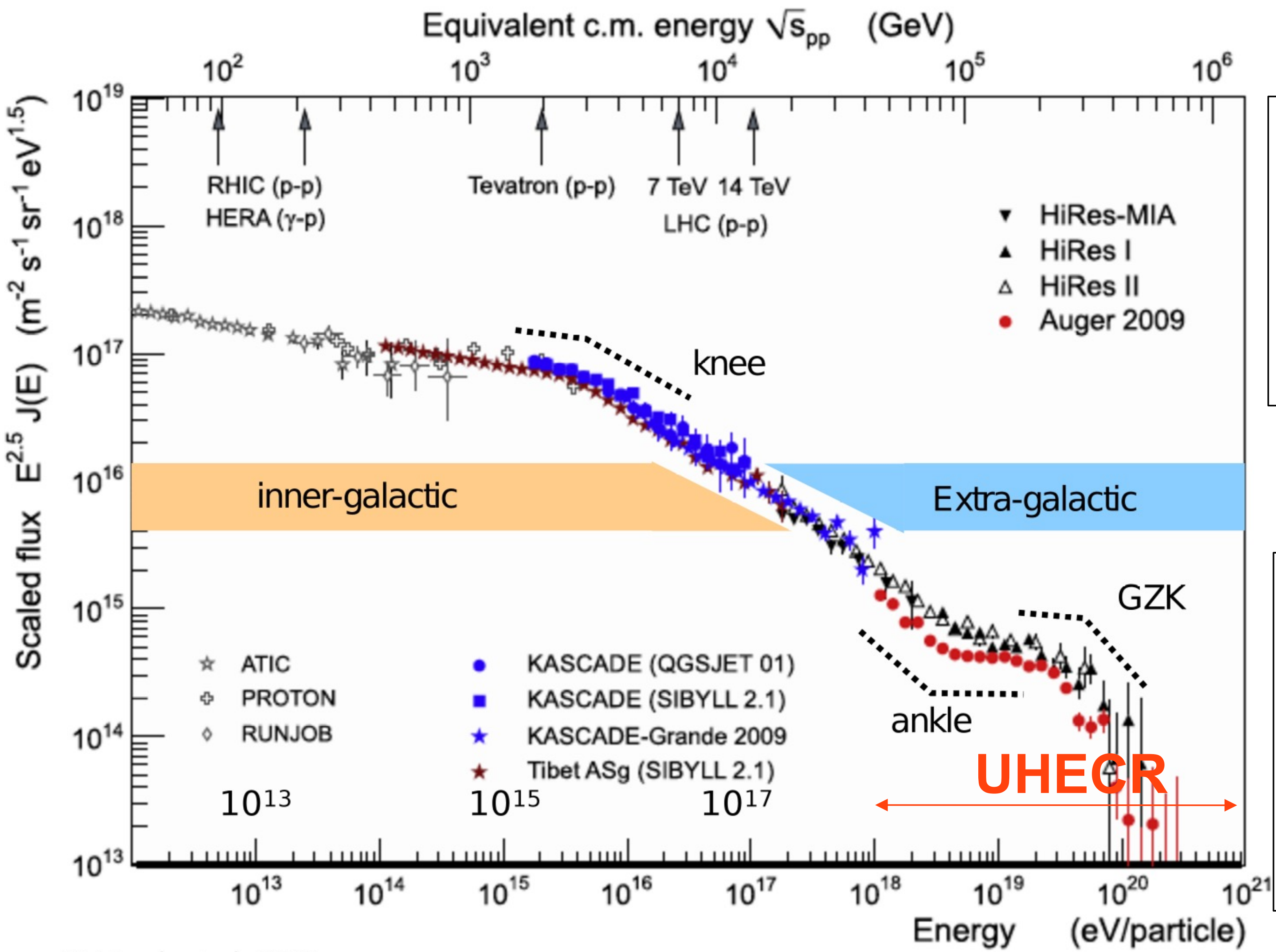
LHCf Status Report

Oscar Adriani, on behalf of the LHCf collaboration
154th LHCC Meeting - OPEN Session
7 June 2023, CERN

Introduction

Ultra High Energy Cosmic Rays



D'Enterria et al., 2011

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

Accurate measurements of UHECR flux and composition as a function of the energy

Extensive Air Showers

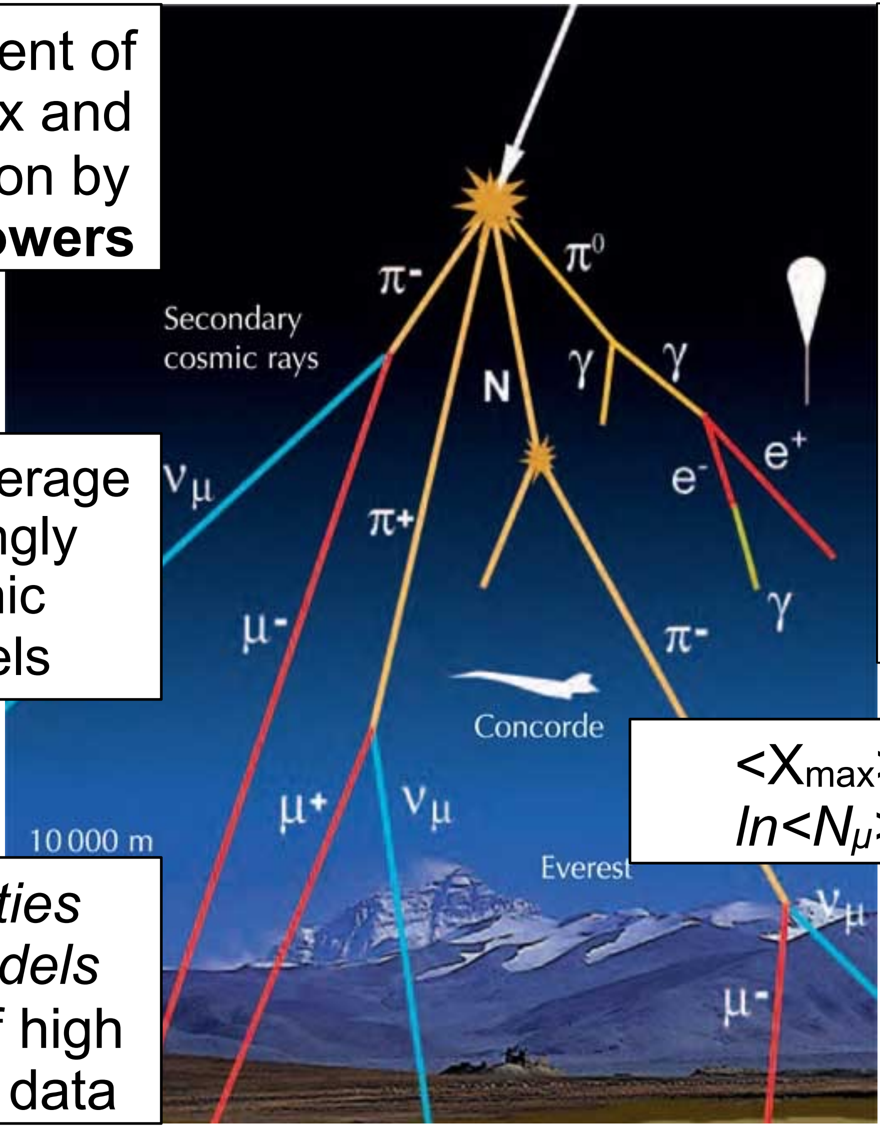
Indirect measurement of UHECR energy flux and average composition by **Extensive Air Showers**

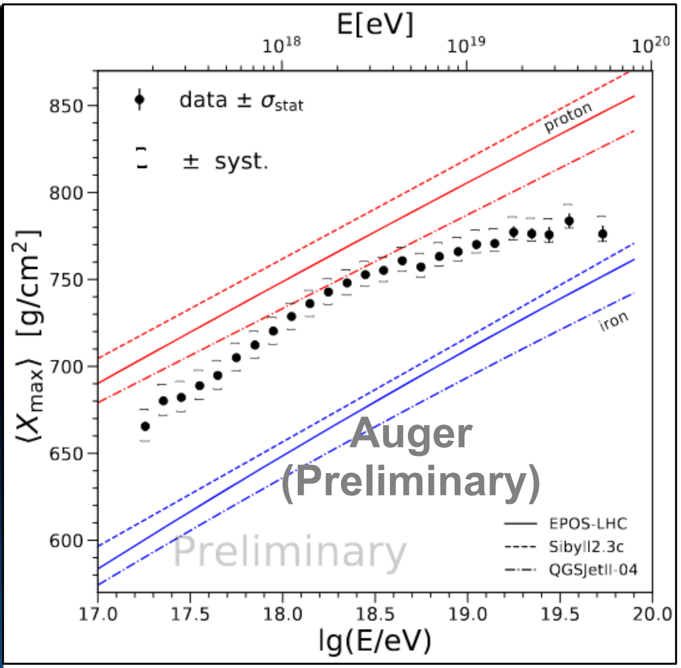
⇩

Measurement of average composition strongly relies on hadronic interaction models

⇩

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





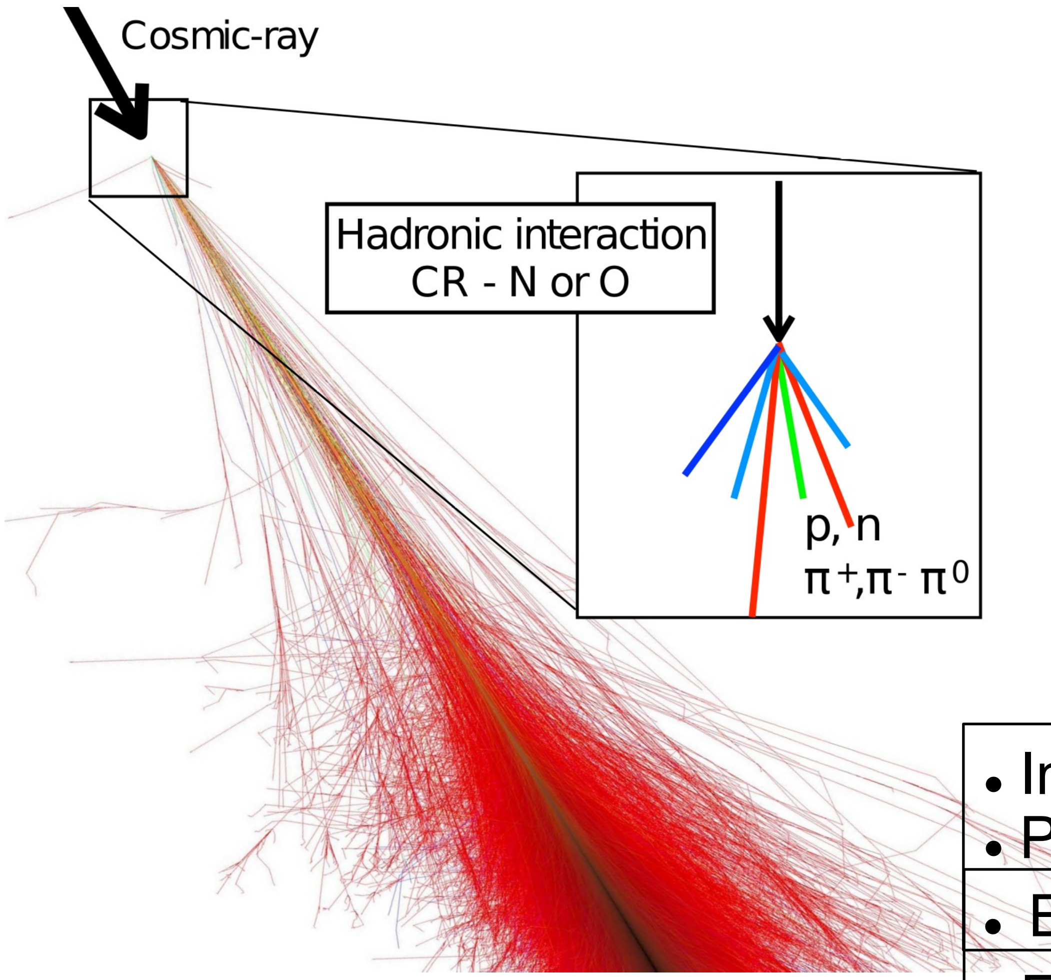
ICRC 2019

$<X_{max}>$: Small model discrepancy
$ln<N_\mu>$: Large model discrepancy

⇩

Muon Puzzle

Hadronic interaction models



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

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

- Inelastic cross section
- Particle multiplicity

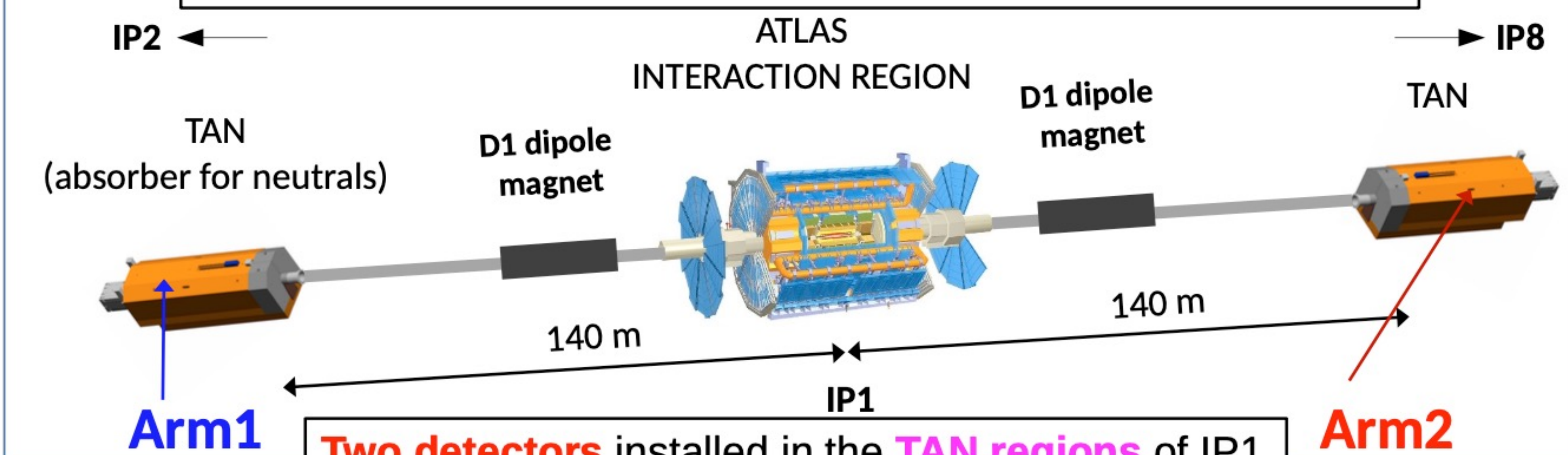
TOTEM, ATLAS, CMS, ...

- E/H Ratio $R = E_\gamma / E_h$
- Elasticity $k = p_{lead} / p_{beam}$
- Very forward particle spectra
  - Extrapolation to E > 10^{17}eV
  - Nuclear modification factor

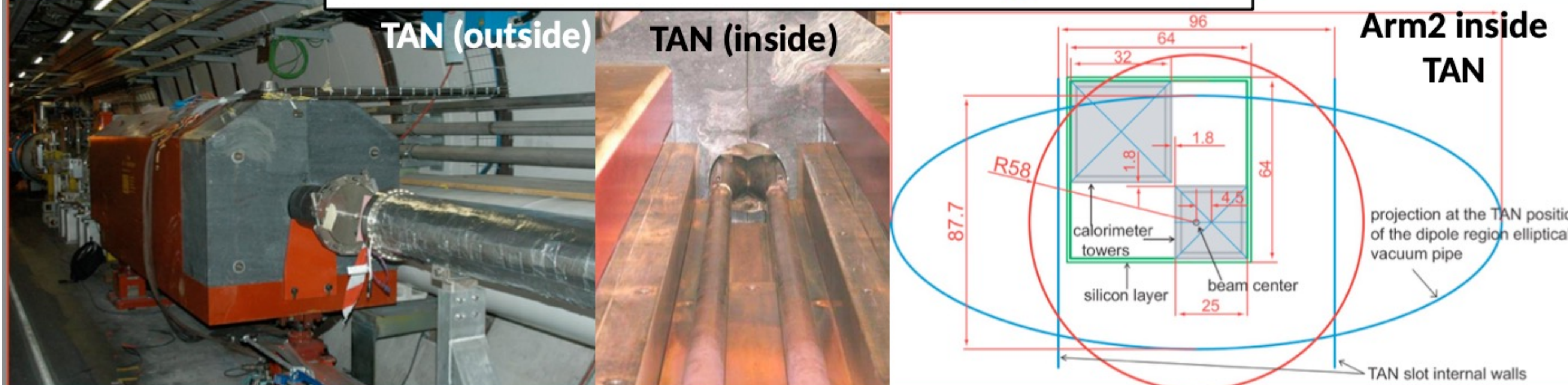
LHCf

The LHCf experiment

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

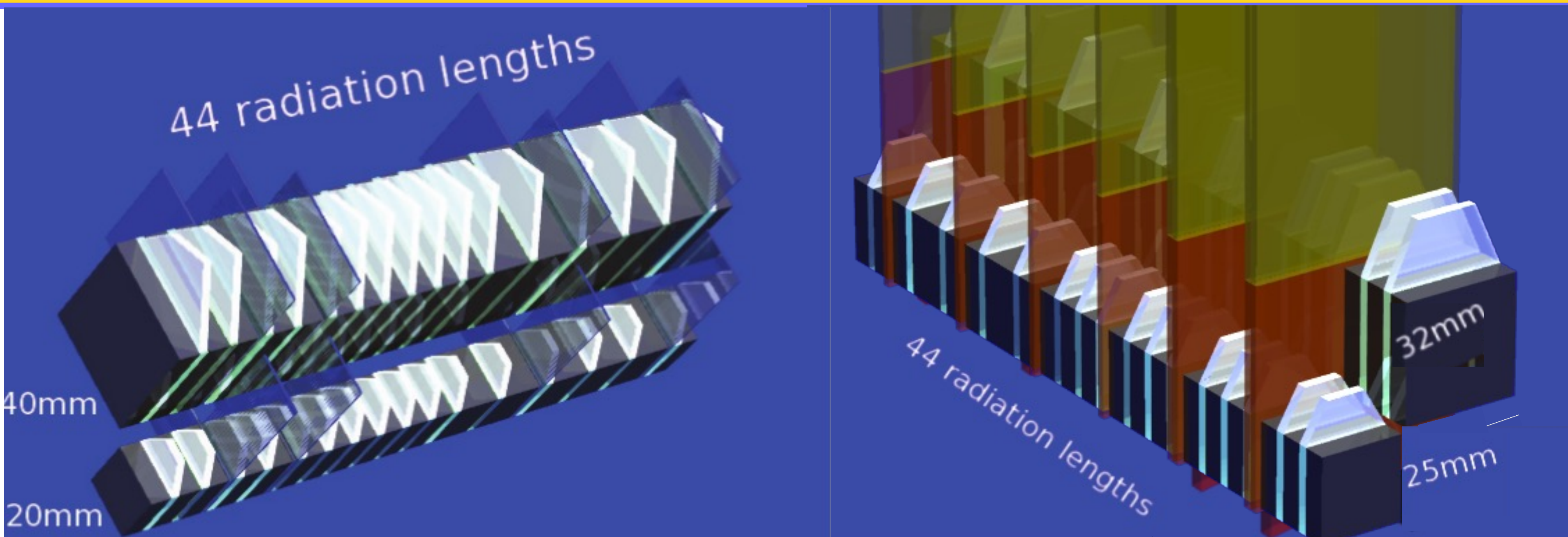


Two detectors installed in the **TAN regions** of IP1



The LHCf detectors

Arm1 **Arm2**



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)

Arm1

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)

Arm2

Tower Size:

25 x 25 and 32 x 32 mm^2

Imaging layers:

4 x-y 160μm Si microstrip

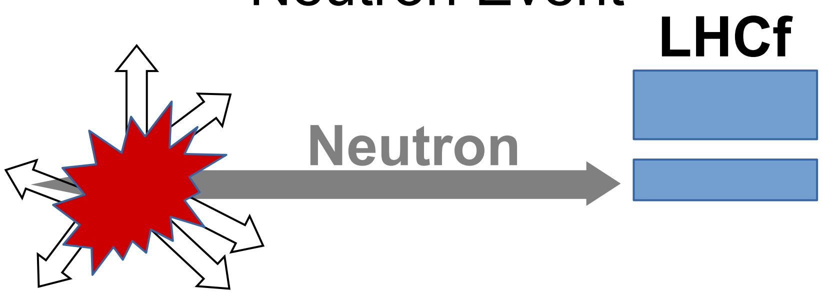
Position resolution:

< 40 μm (photons)

< 800 μm (hadrons)

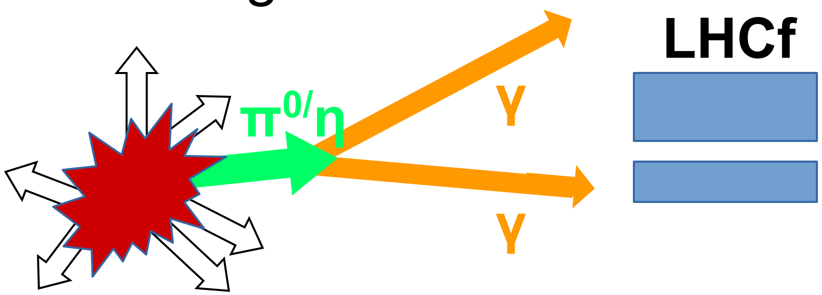
The LHCf acceptance

Neutron Event

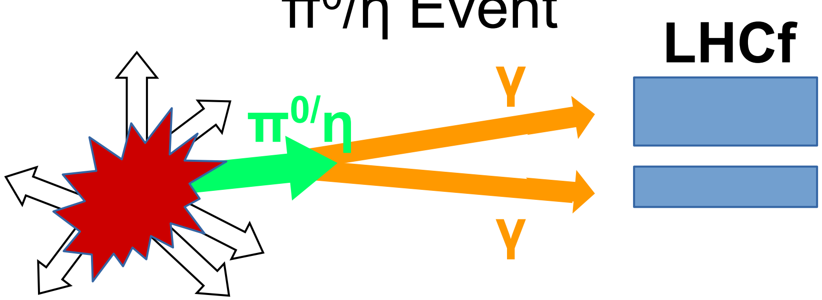


Information on leading baryon and average inelasticity

Single Photon Event



π^0/η Event

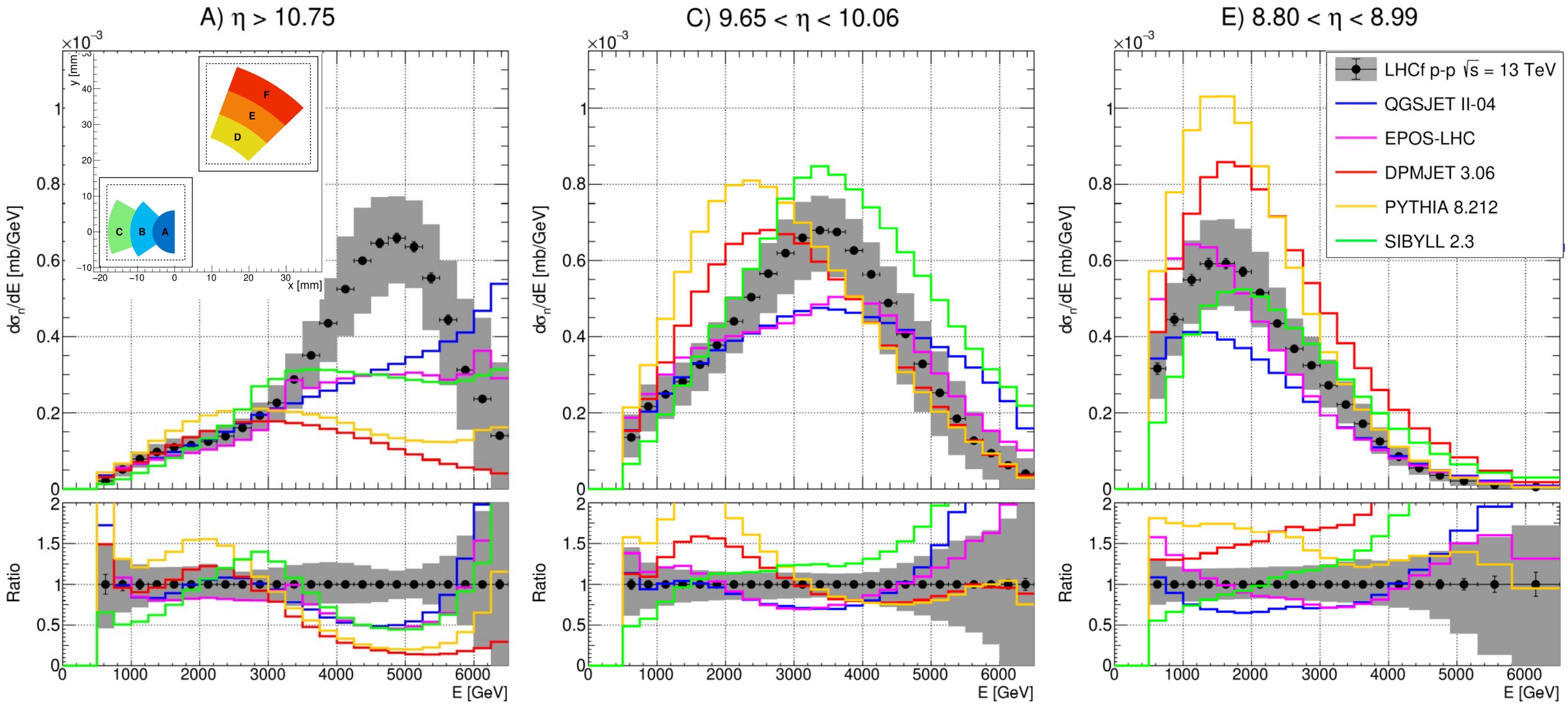


Information on electromagnetic component

Results from Run II

Neutron Production Cross Section

p-p $\sqrt{s}$ = 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*

*:LHCf forward neutron spectra will be used for the next EPOS version!

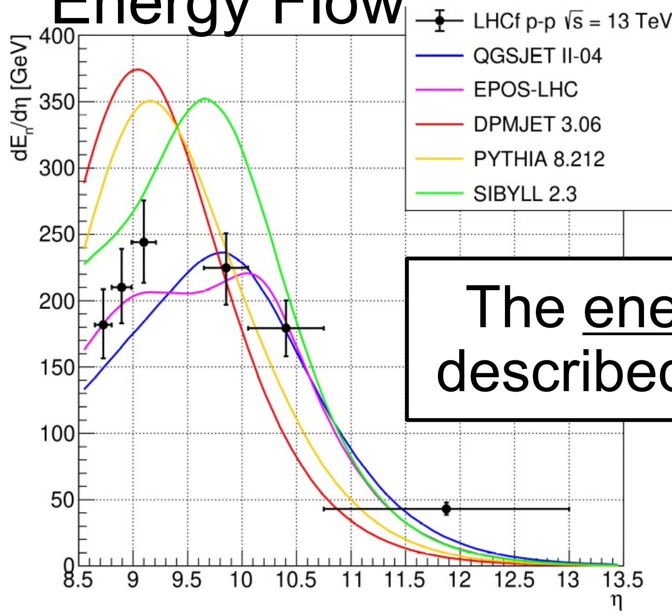
Neutron Energy Flow & Inelasticity

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

JHEP 07 (2020) 016

Energy Flow

$dE_n/d\eta$

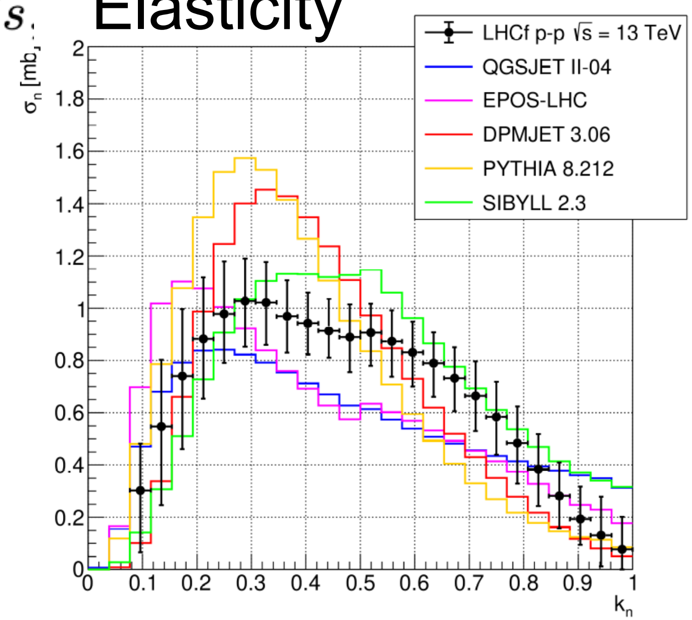


The energy flow is well described by **EPOS-LHC**

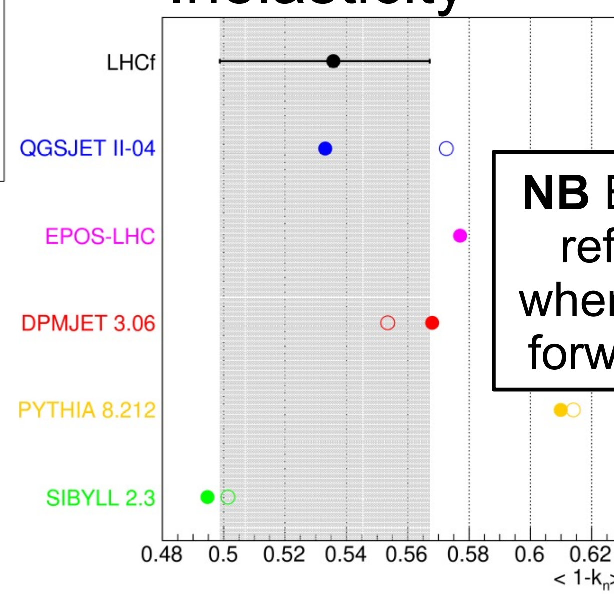
Most models reproduce the average inelasticity but not the distribution

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

Elasticity



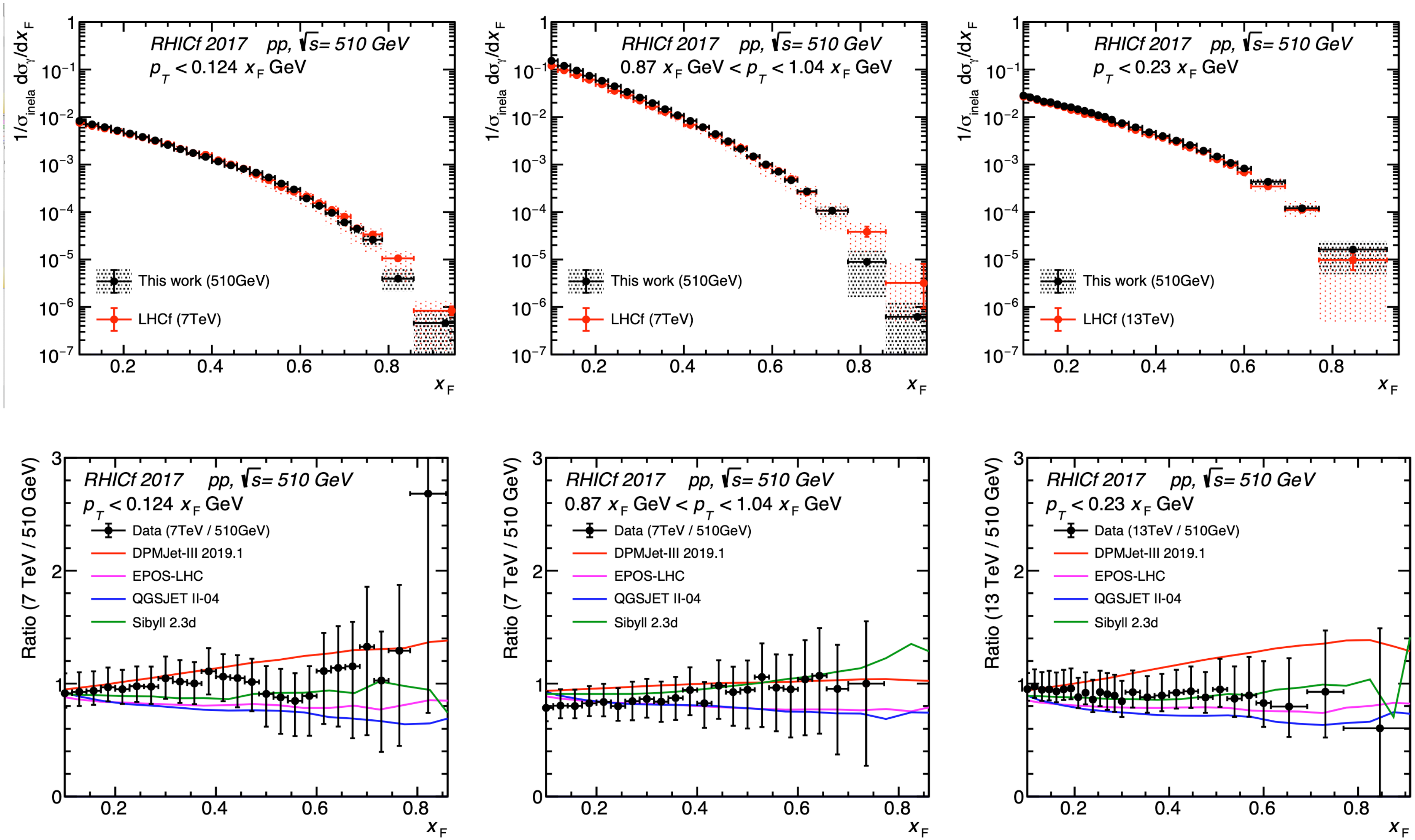
<Inelasticity>



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

Test of Feynman scaling
using forward photons

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



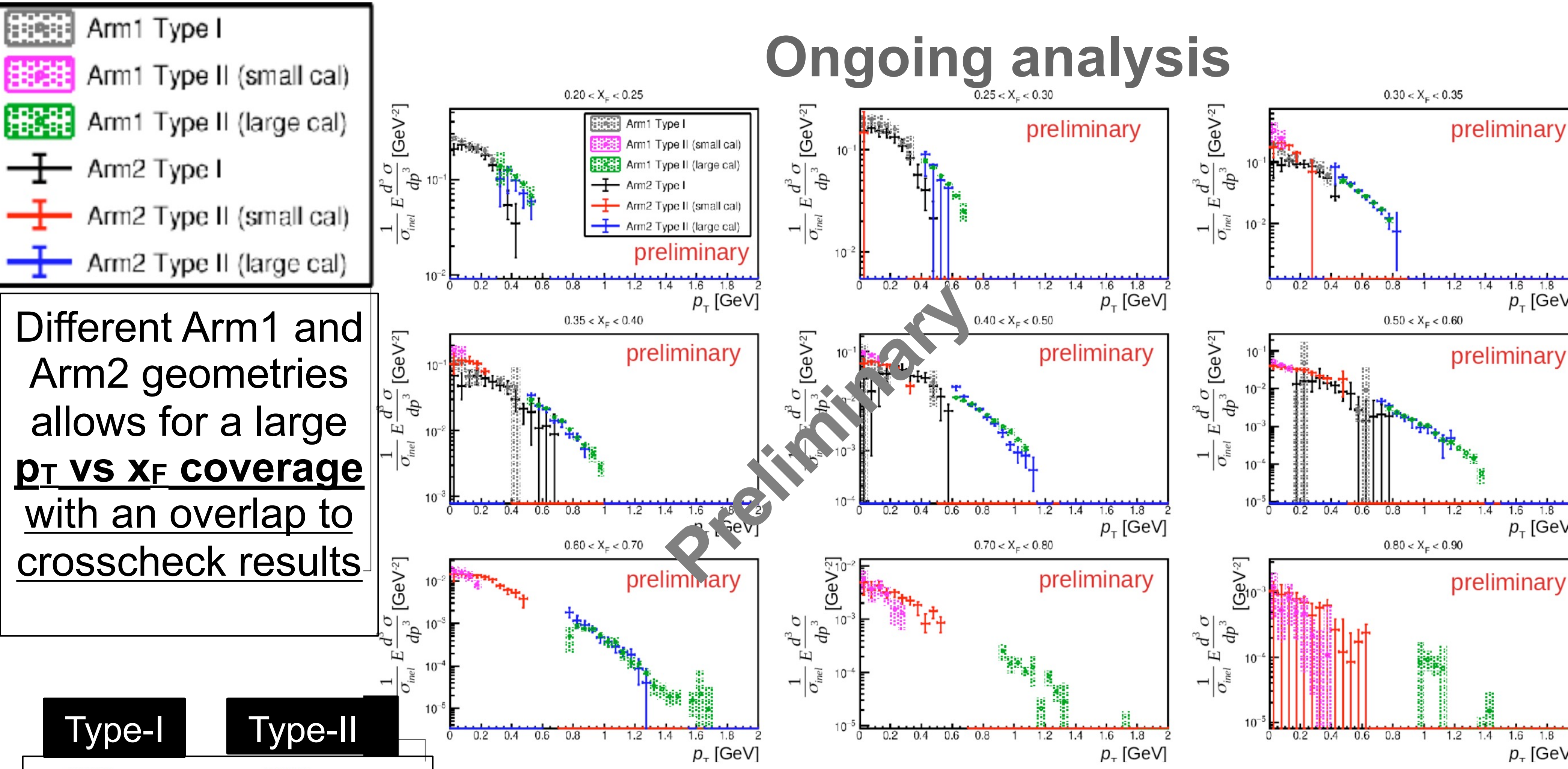
ArXiv:2203.15416
...submitted to PLB

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

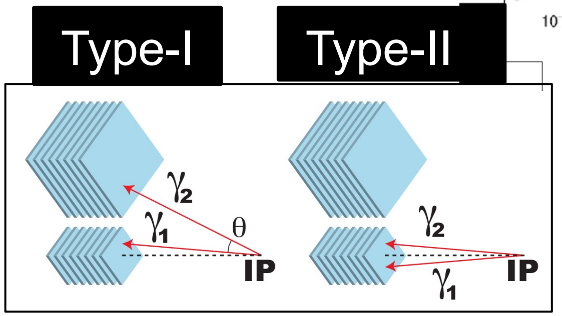
π^0 Production Rate

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

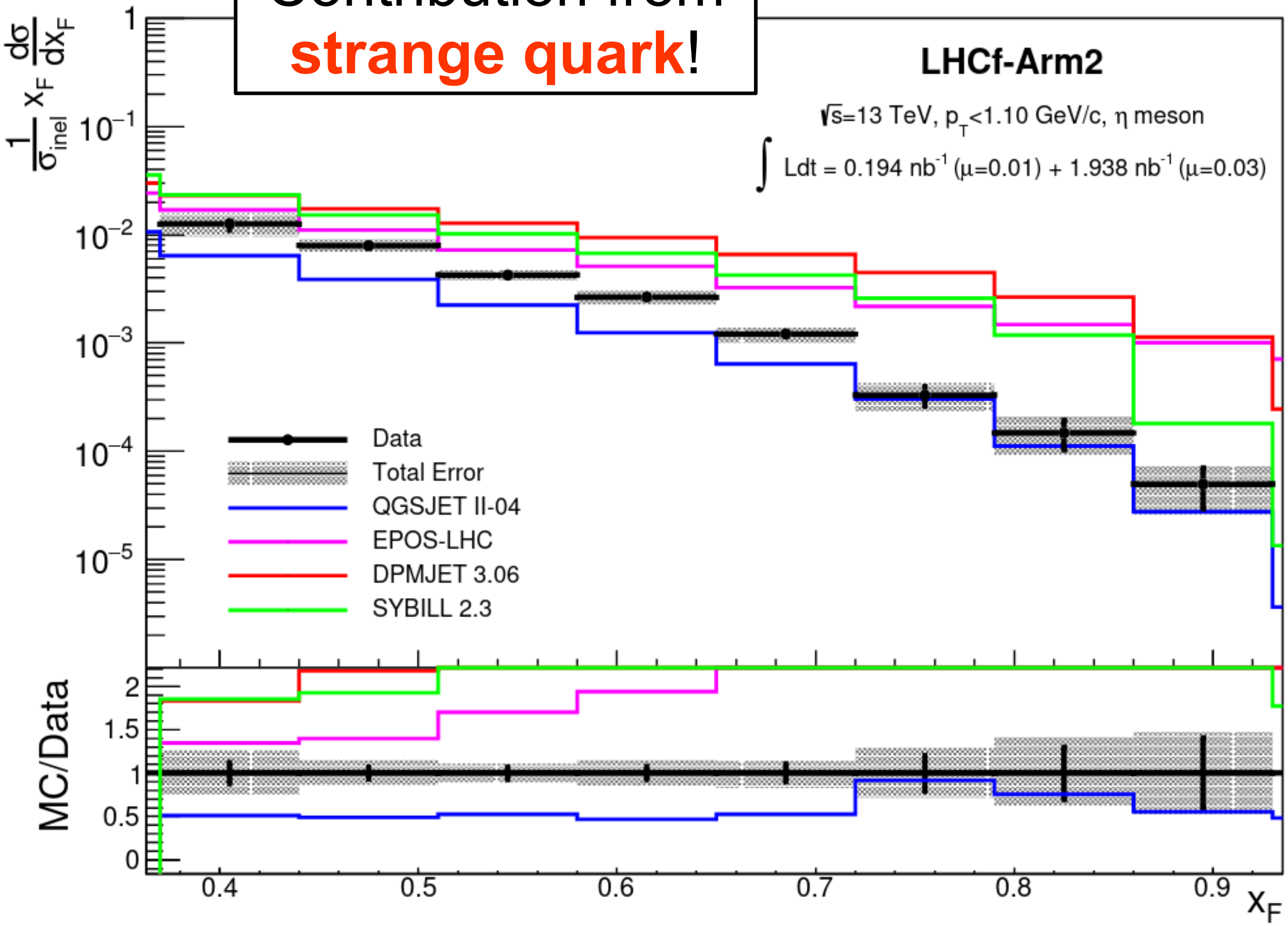


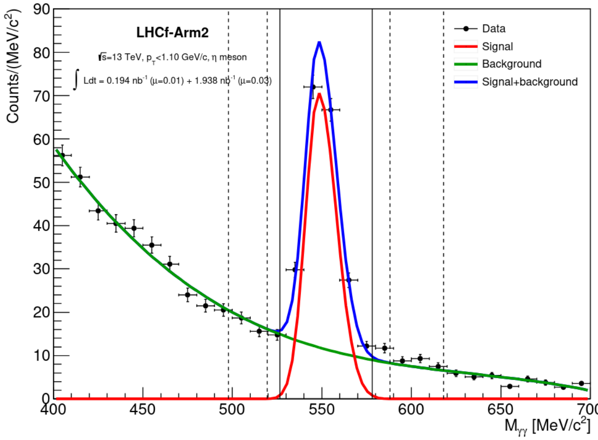
Good *agreement* between Arm1 and Arm2 data and between "Type-I" and "Type-II" events

η Production Rate

p-p √s = 13 TeV

Contribution from **strange quark**!





ArXiv:2305.06633
CERN-EP-2023-076
…submitted to JHEP

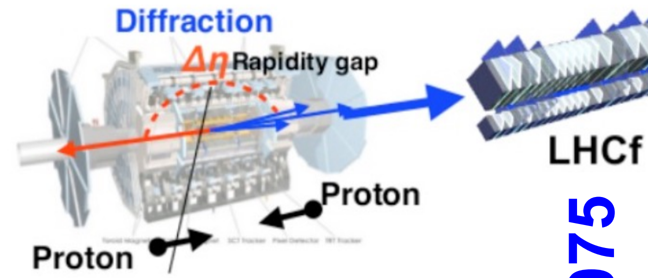
Among the large model variations, only **QGSJETII-04** has good but not satisfactorily agreement with the experimental measurements

LHCf-ATLAS joint analysis

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

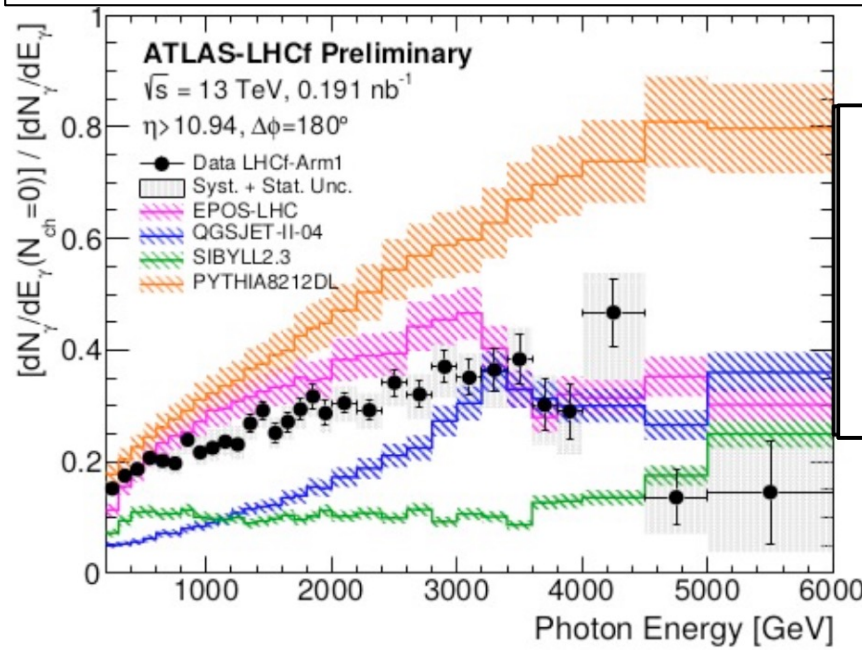
The LHCf-ATLAS common operations leads to a much **higher degree of information** on *processes responsible for forward production*, allowing for accurate measurements of:

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



Forward photon production in η > 10.94

$N_{veto}/N_{inclusive}$



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 √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 (possibly) K^0_S

Longest LHC Fill ever!

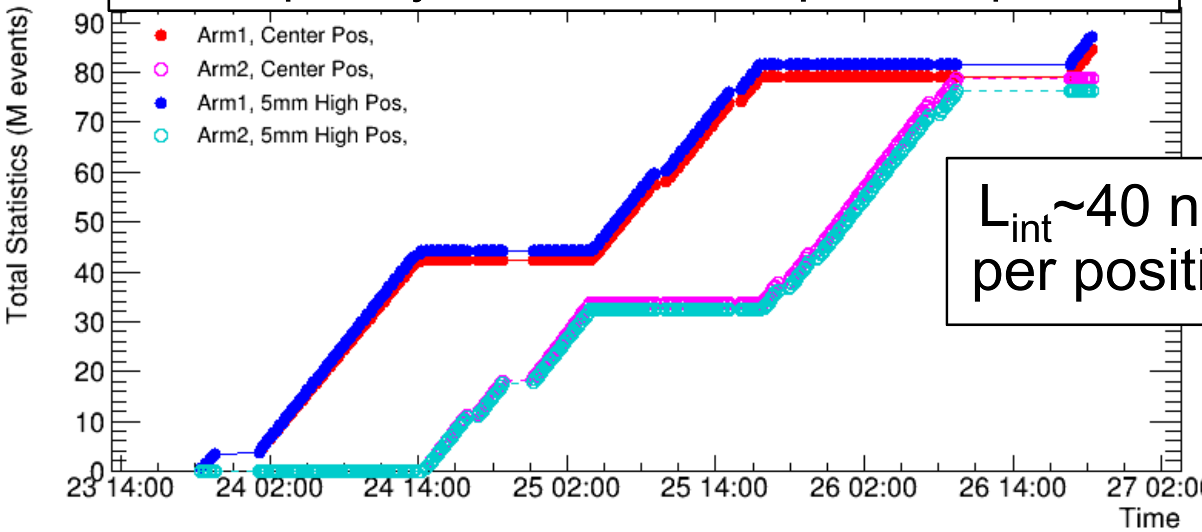
September 24-26:
Fill 8178 - 55h
Fill 8179 - 2h

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

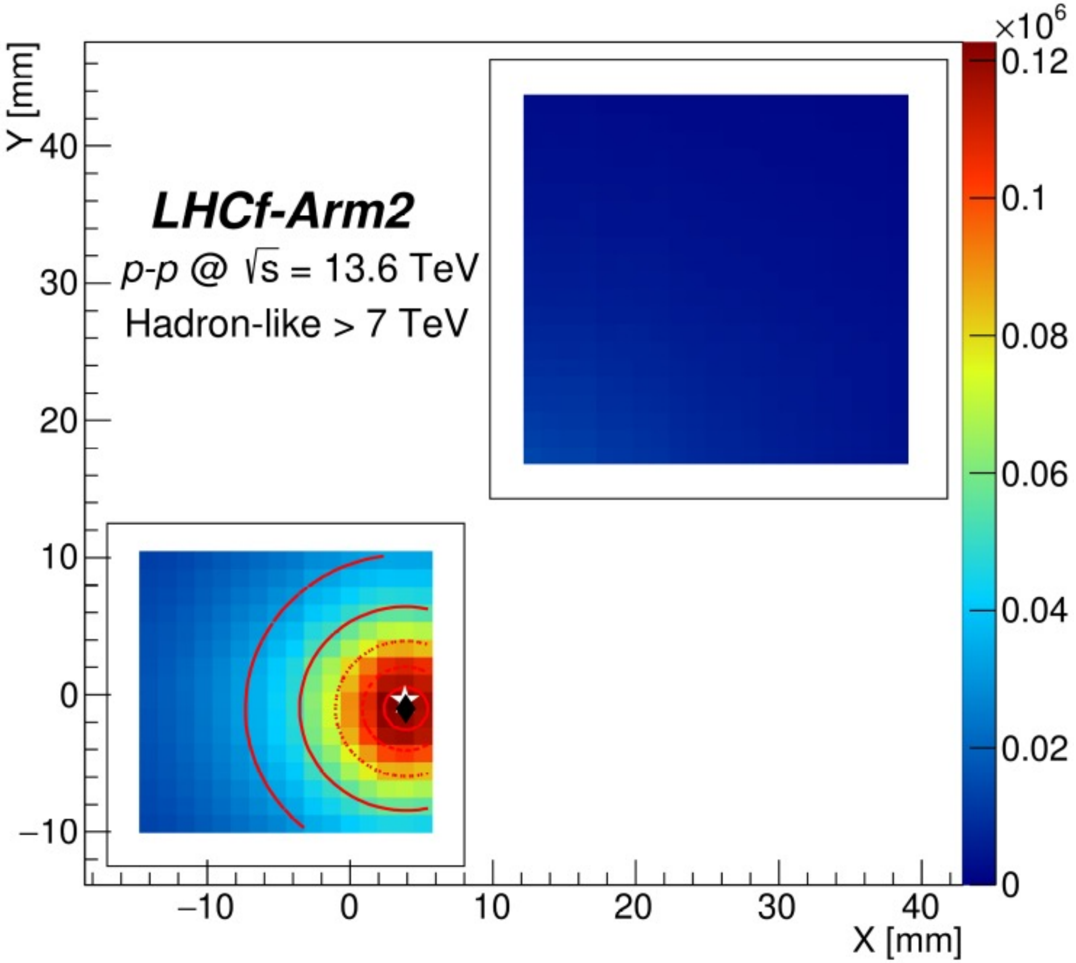


L_{int}~40 nb^{-1} per position

We expect *a few thousands of η events* and *a few hundreds of K^0_S events*

Preliminary studies
Beam Center

While the calibration of the detector is not yet completed,
we started to make some preliminary check of the acquired data



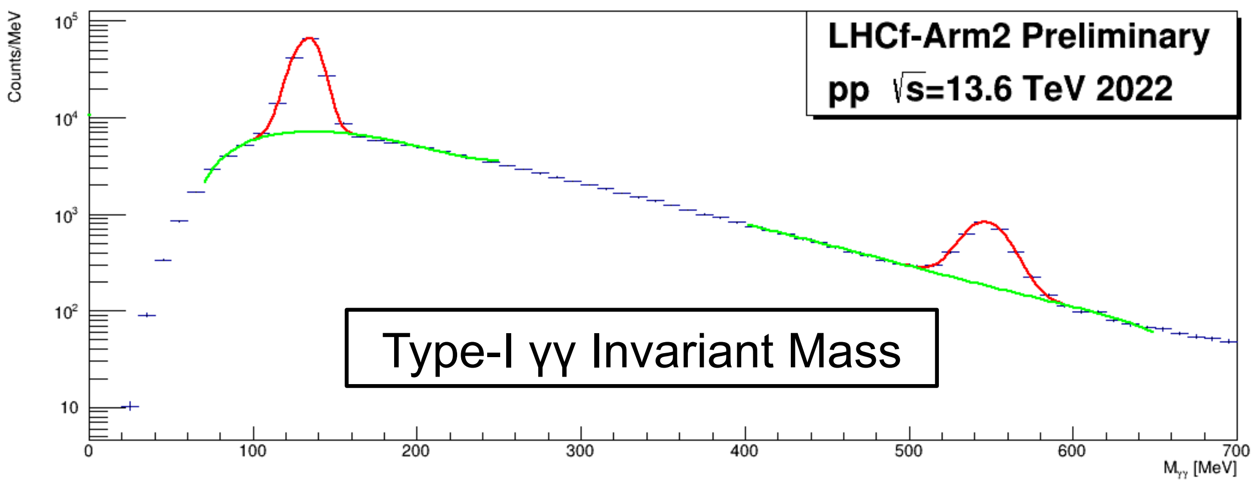
✓ Accurate estimation of the *projection of the beam center* on the detector plane using hadron-like event hitmap reconstructed with the Arm2 silicon microstrip detector

Data quality confirmed that the hardware was performing nicely; the hardware will be used as it is in the oxygen run (with the Arm2 detector only)

Preliminary studies

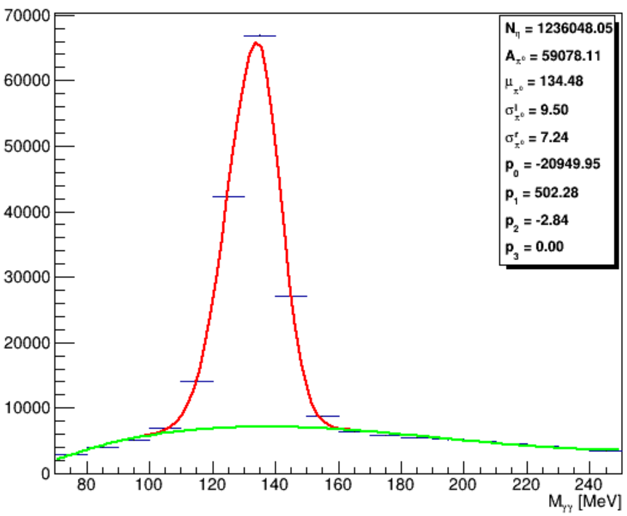
Collected statistics

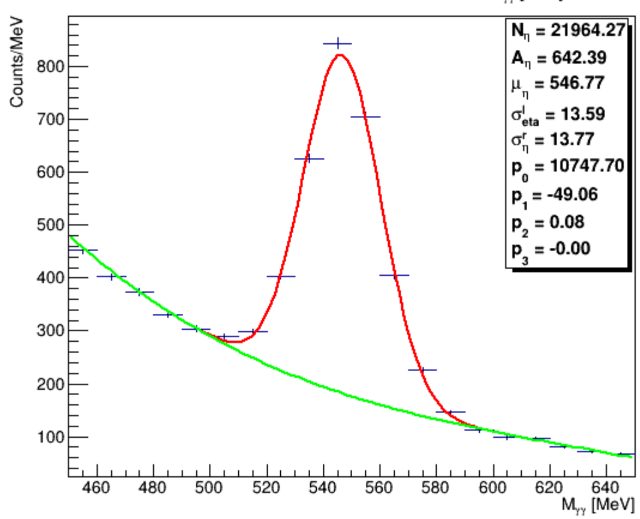
While the calibration of the detector is not yet completed,
we started to make some preliminary check of the acquired data



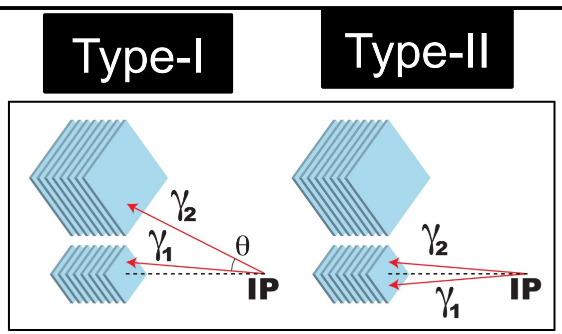
✓ Confirmation of the large *increase in η statistics* with respect to Run II data by roughly a **factor 10**:

- 2.2×10^4 η candidates





Type-II events will greatly improve the statistics thanks to dedicated trigger



Run III Data Analysis Plan

The large γγ event statistics collected in Run III allows for a precise measurement of forward π^0 and η production with fine p_T-x_F binning

	LHCf Standalone analysis	ATLAS-LHCf joint analysis
Short term goals	Complete the calibration of Arm1 and Arm2 detectors	Check the event alignment and the overall data quality
	Check preliminary spectra of *forward γ production*	Calibrate **LHCf+ZDC** to reconstruct hadronic showers
Medium term goals	Repeat the measurement of forward π^0 and η production with much larger statistics	
Long term goals	Measure forward production of **K^0_s meson** (using the decay $K^0_s \to 2\ \pi^0 \to 4\ \gamma$)	Measure the contribution of one pion exchange to forward neutron production

Differently from Run II, the presence of the ATLAS ZDC hadronic modules allows for an improvement of the LHCf energy resolutions to about 20%, which is necessary to accurately measure one pion exchange contribution

Other interesting physics items, made possible by the jointly data taking with ATLAS, will be investigated on a longer time scale

LHCf in Run III: p-O

Hopefully foreseen in 2024

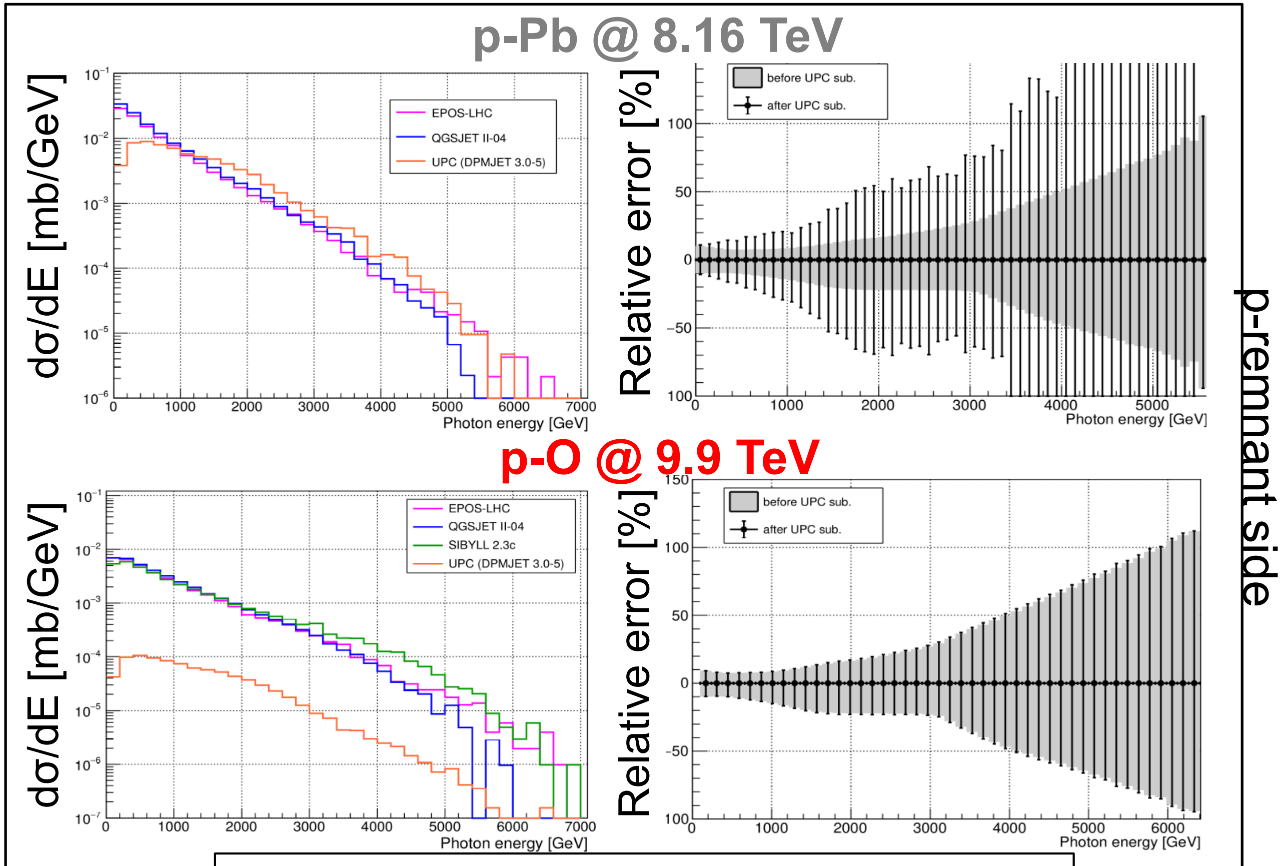
Main Motivation

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

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

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



Forward photon production in η > 10.94

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 event 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 2024:

Run III is the last chance for LHCf experiment to take this data!

Thank you
for the attention!

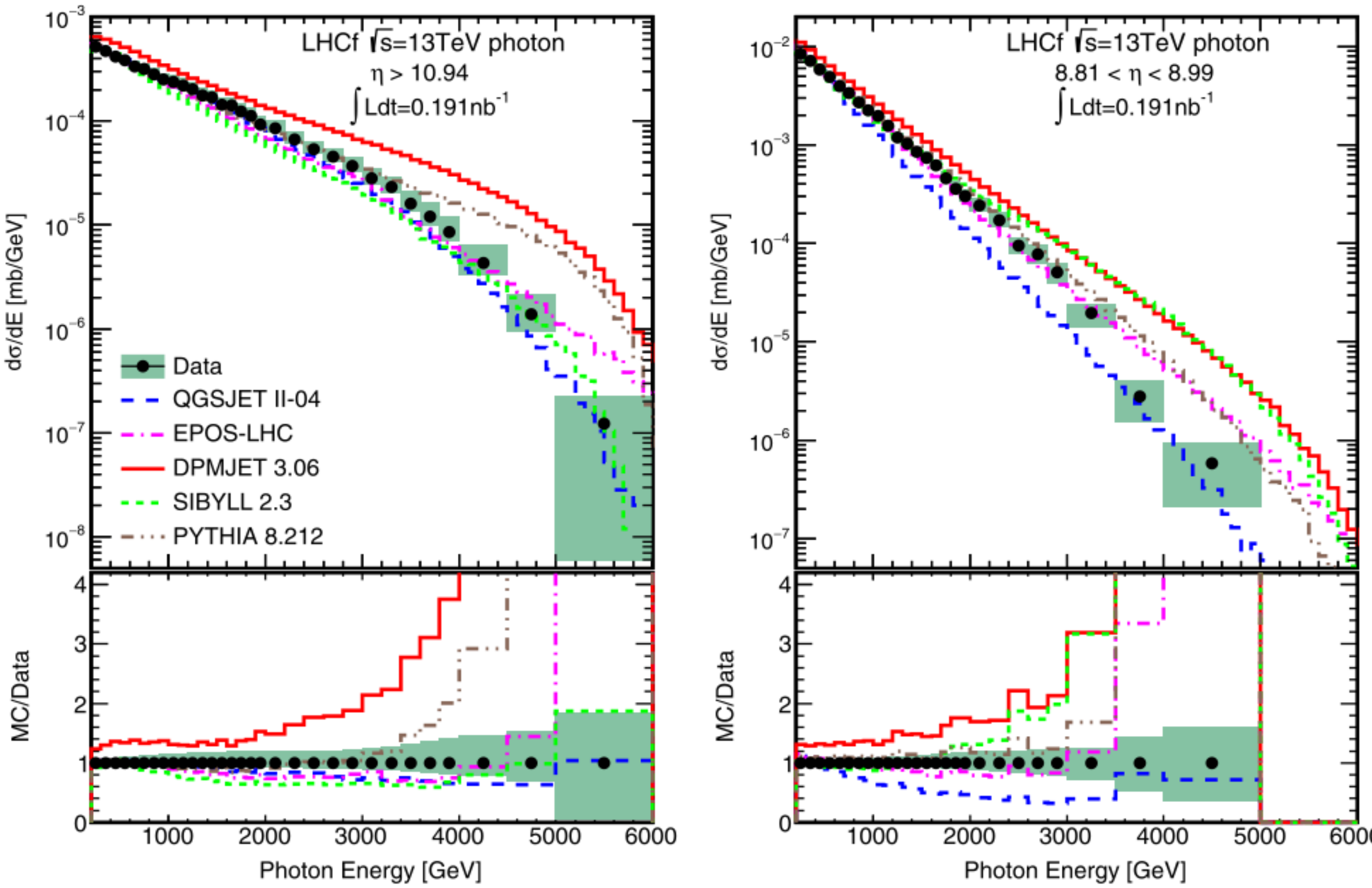
Publication table

	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			

Focus of this presentation (p+p 13 TeV row)

Photons dσ/dE

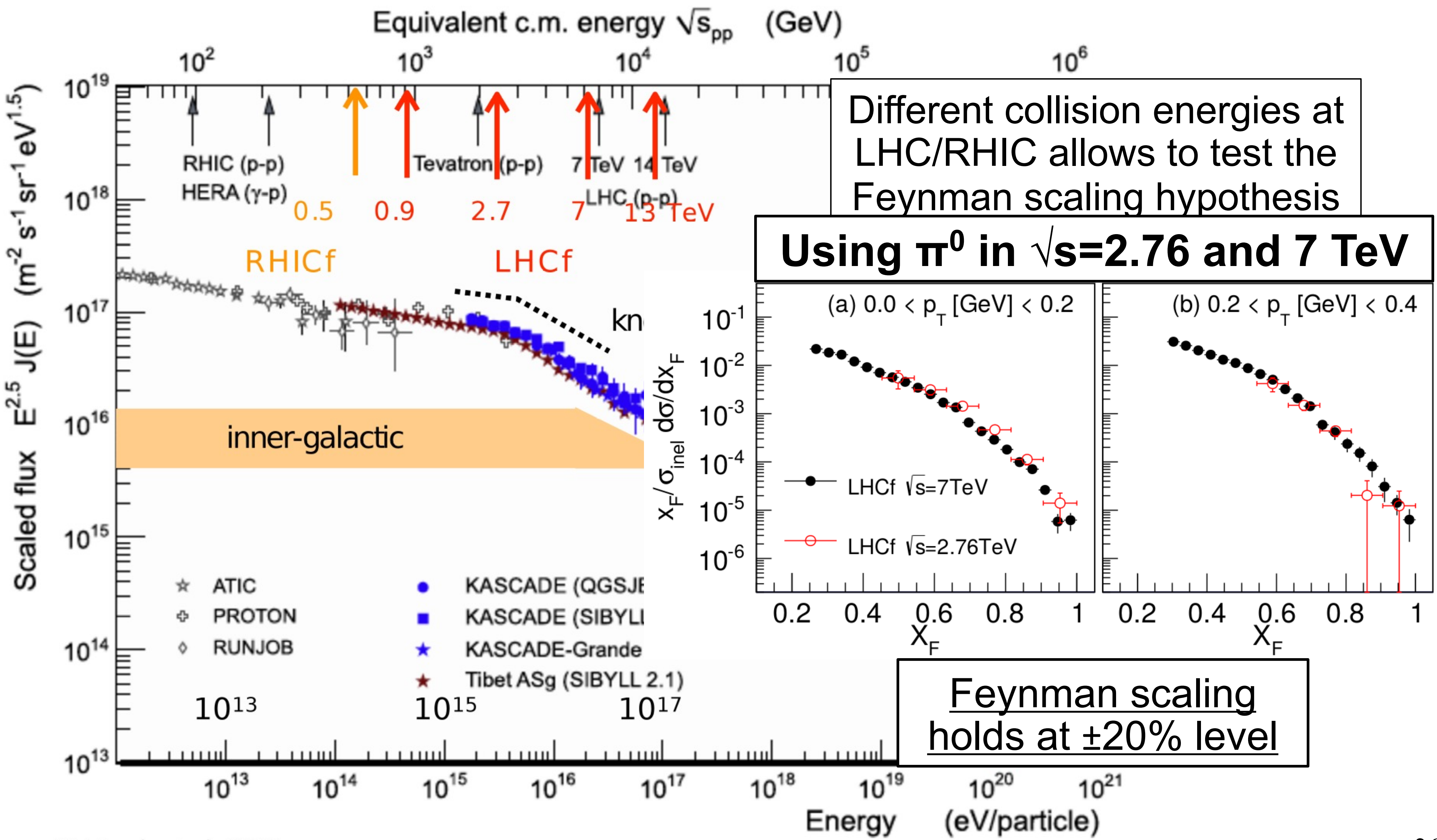
p-p √s = 13 TeV



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

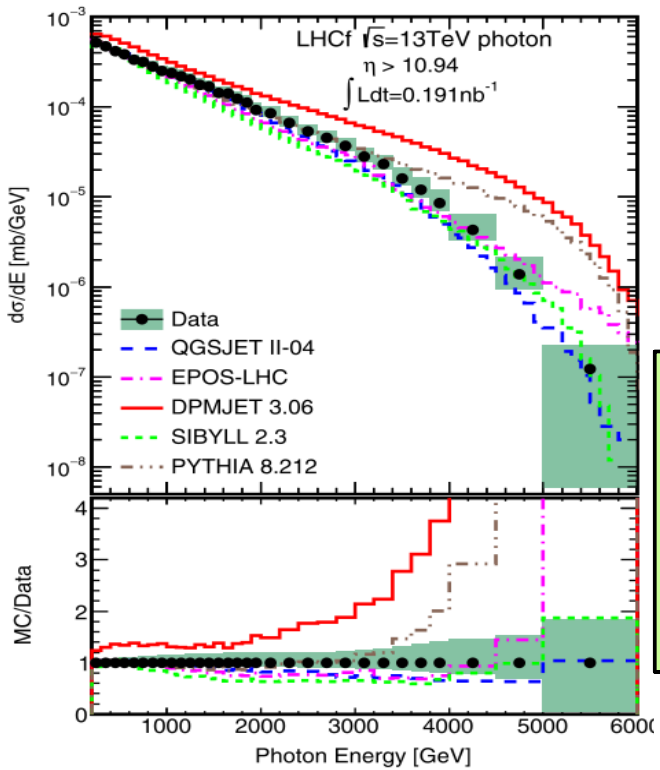
Using π^0 in $\sqrt{s}$=2.76 and 7 TeV

Feynman scaling holds at ±20% level

D'Enterria et al., 2011

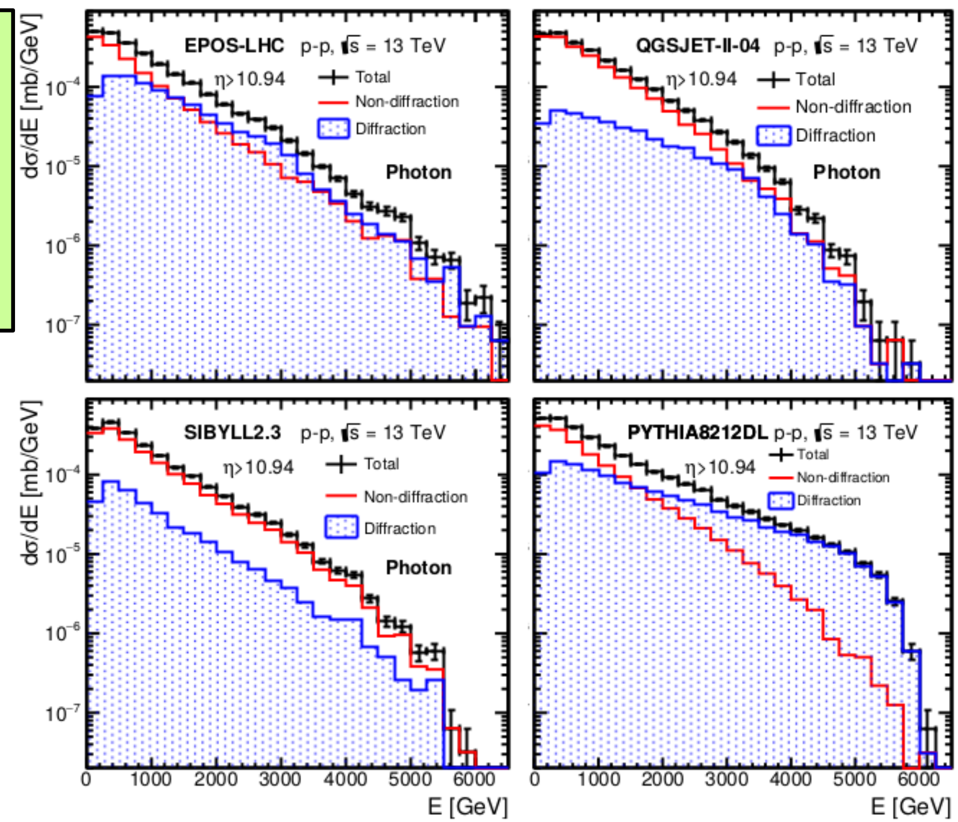
Diffractive and non-diffractive production

√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

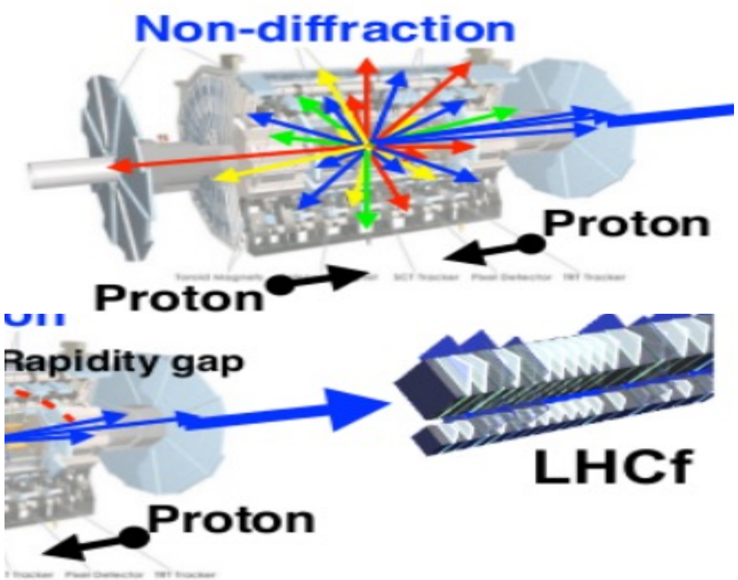
LHCf-ATLAS joint analysis

LHCf-ATLAS joint analysis

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

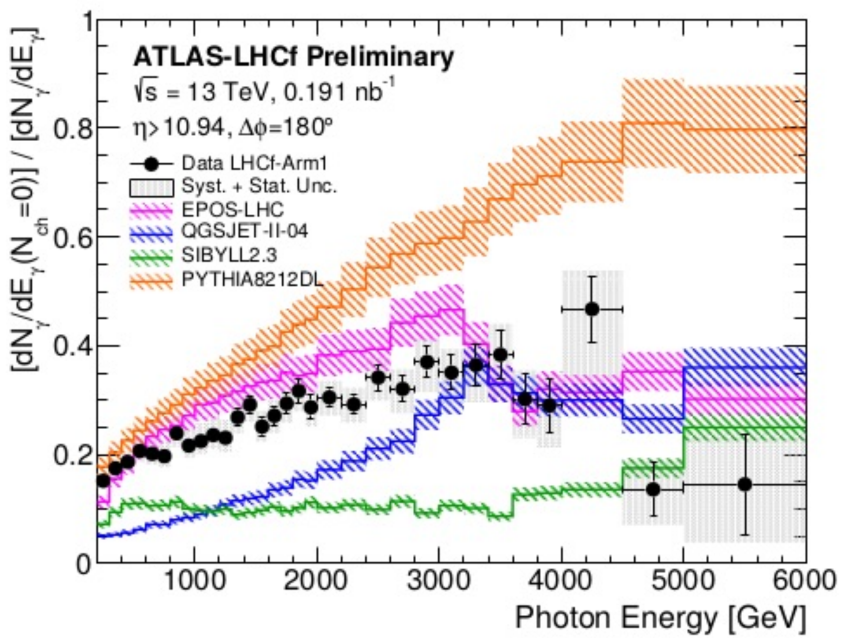
After a preliminary test in 2013, in 2015 and 2016 LHCf and ATLAS experiments had **common operation**.

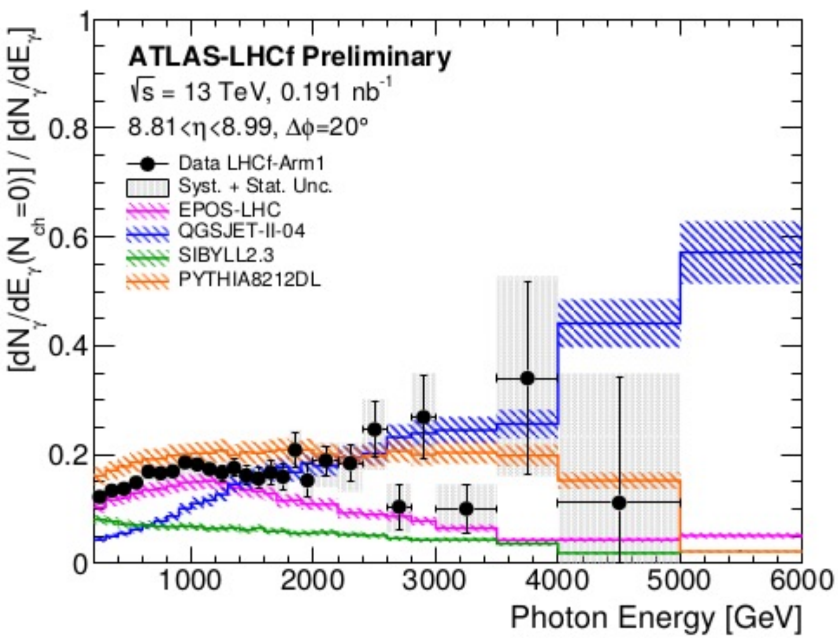
Diffractive events can be distinguished from non-diffractive events by **ATLAS veto** : tracks=0 at |η|<2.5



ATLAS-CONF-2017-075
…paper in finalization

$N_{veto}/N_{inclusive}$

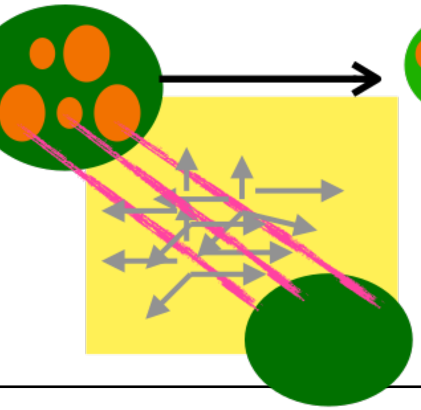




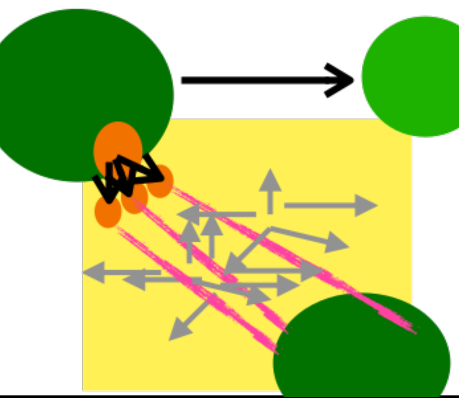
LHCf-ATLAS joint analysis

On-going analysis

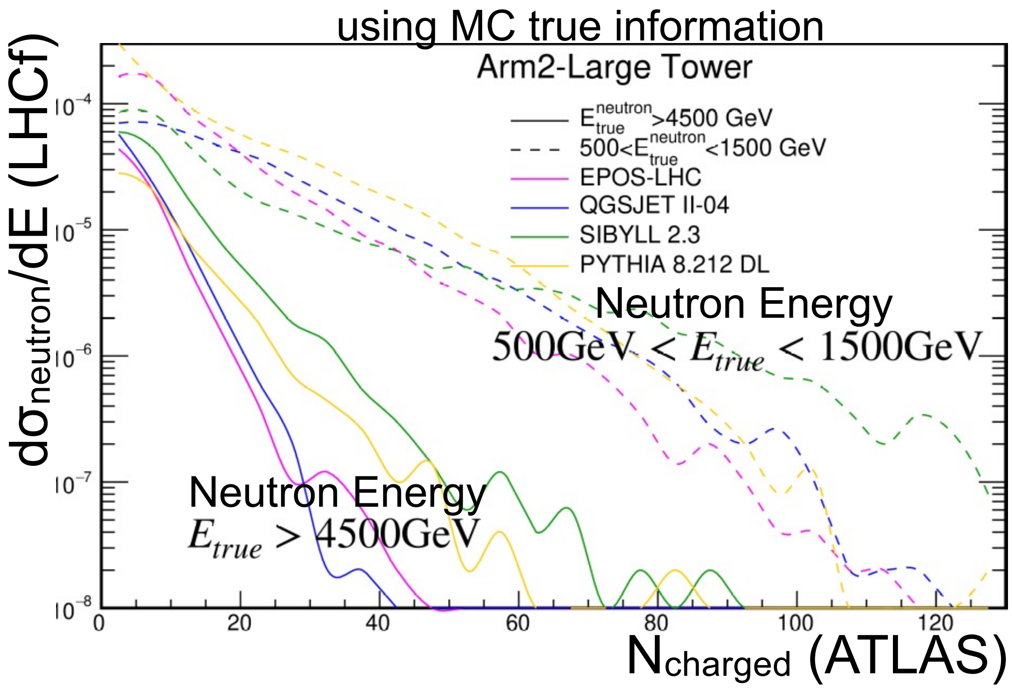
Study of **mechanism of multiparton interaction** using neutron events in LHCf as proposed by S. Ostapchenko et al., Phys. Rev. D 94, 114026



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-ATLAS joint analysis

Foreseen analysis with Run III data

GOAL: Increase the statistics for LHCf-ATLAS common analyses

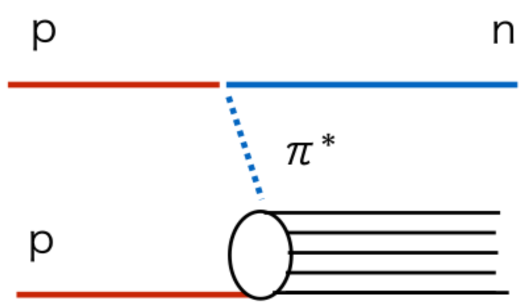
GOAL: Identification of single diffractive events + measurements of:

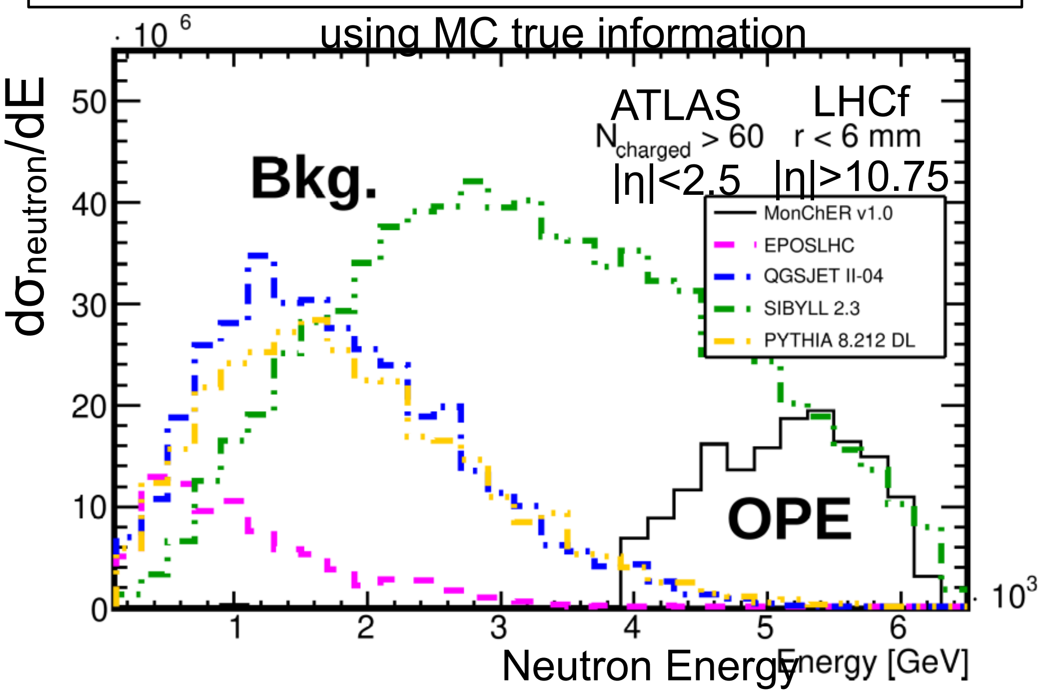
- *Δ resonance* (p+p→p+Δ→p+p+π⁰)
- Bremsstrahlung (p+p→p+p+γ)

← Operation with **ALFA+AFP roman pots**

GOAL: Indirect measurement of p-π cross section via the contribution from one-pion exchange (OPE) with better hadron energy resolution

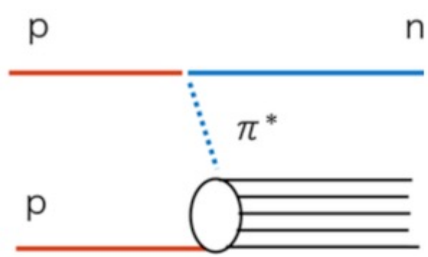
← Operation with **ZDC** (σ_E/E = 40% →20%)

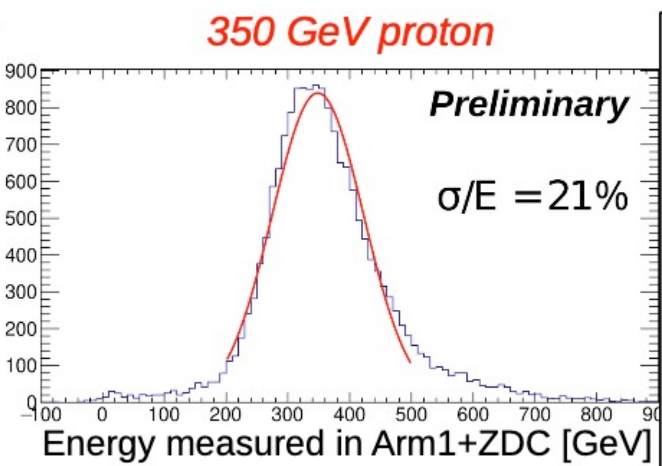




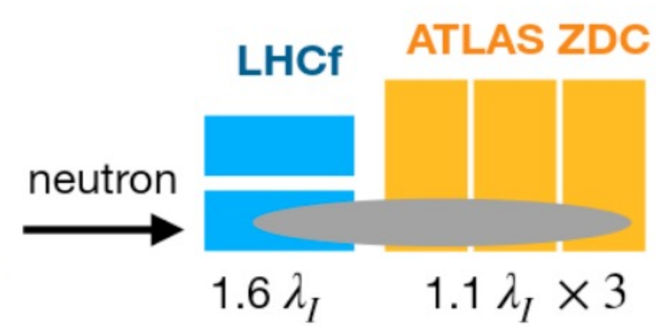
Additional motivations for Run III: Operations with ATLAS ZDC

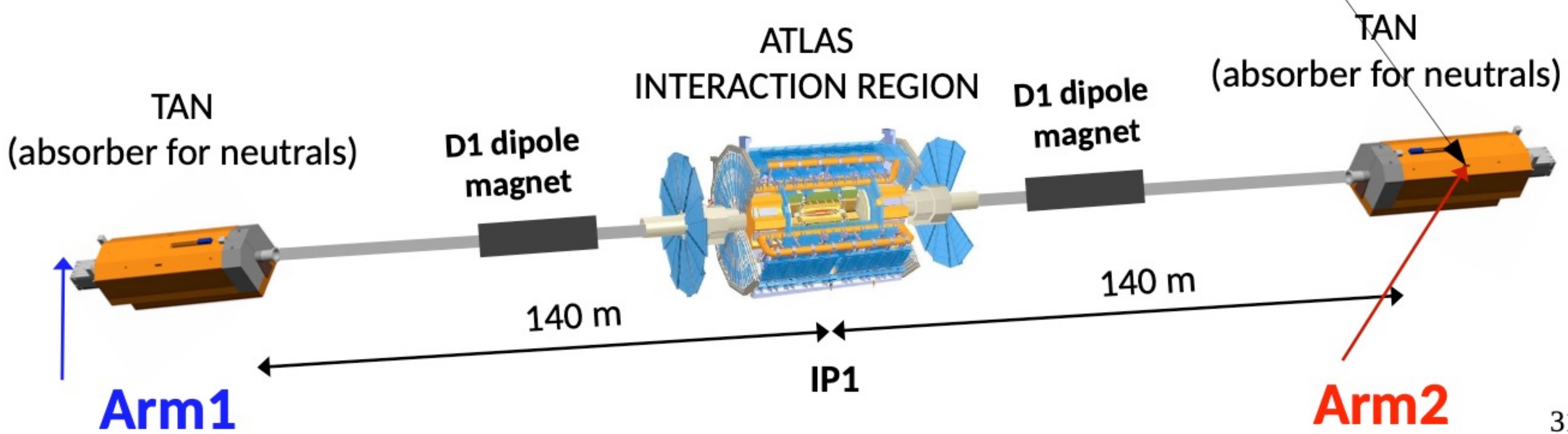
Indirect measurement of p-π cross section via **one-pion exchange**





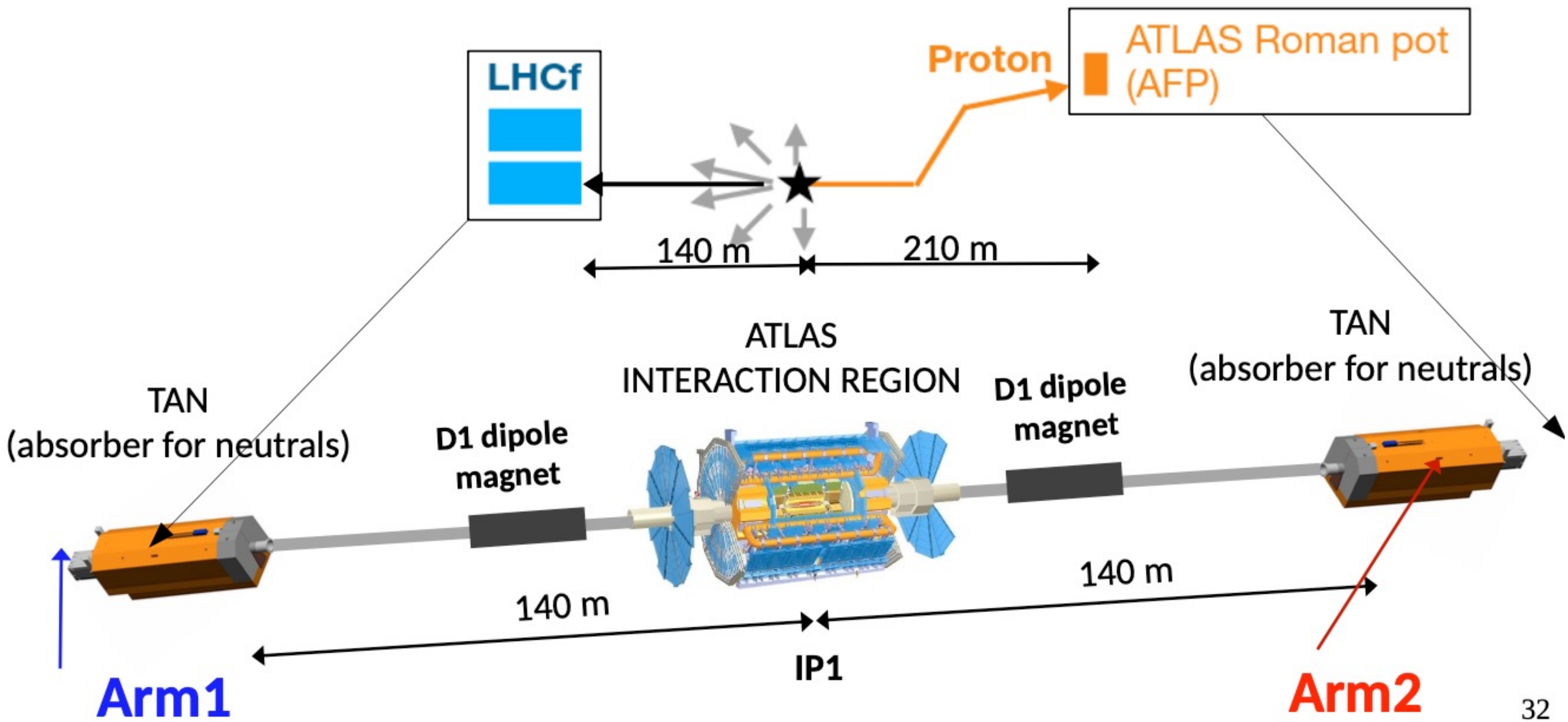
Operation with **ZDC**
(σ_E/E = 40% → 20%**)**





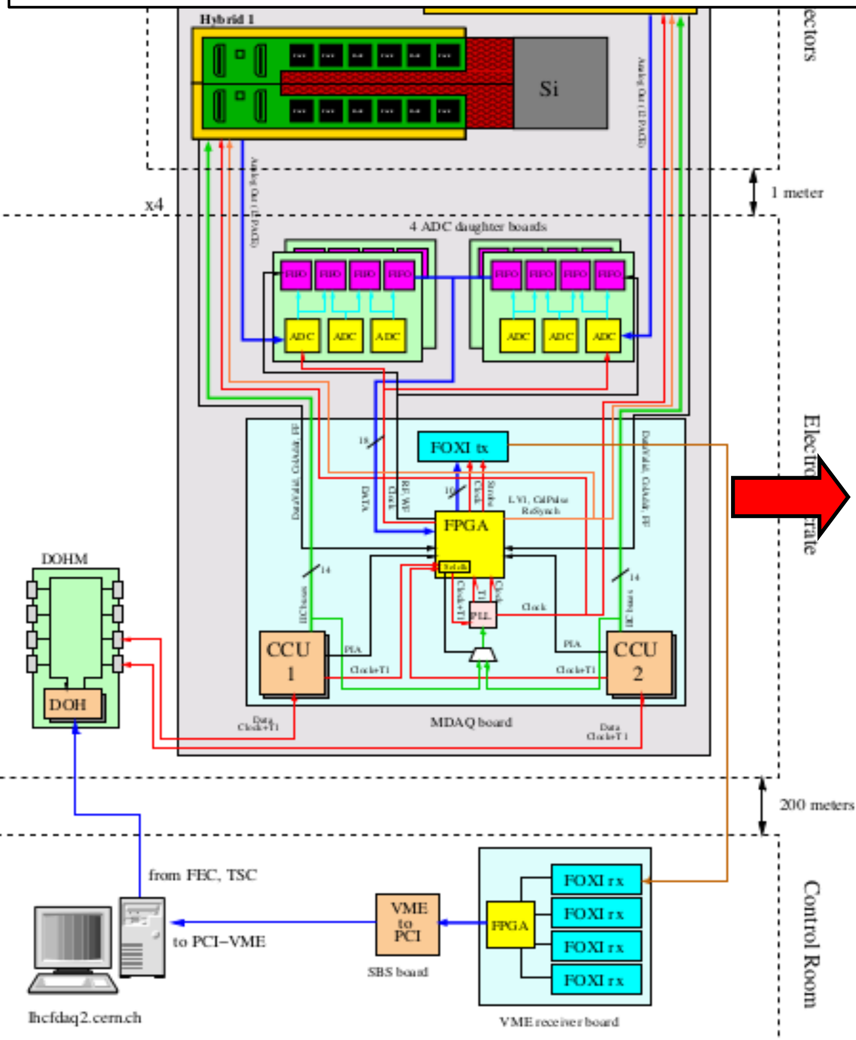
Additional motivations for Run III: Operations with ATLAS AFP

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



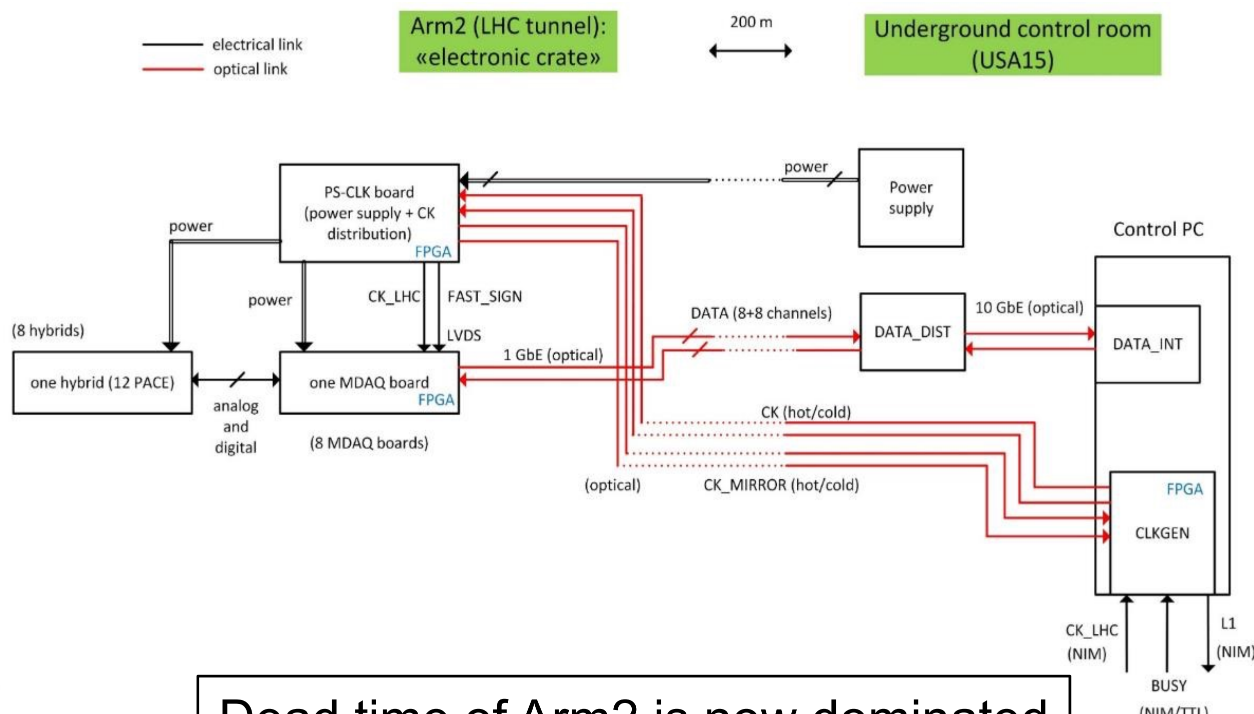
Upgrade for Run III operations:
Upgrade of the silicon microstrip DAQ

Old electronics based on 100 Mbit/s Fiber Optical Transmitter/Receiver Interface (FOXI) transmitters



New electronics based on **1 Gbit/s fast optical links**

The time necessary for readout+transmission of silicon data reduces from 370 μs to 200 μs

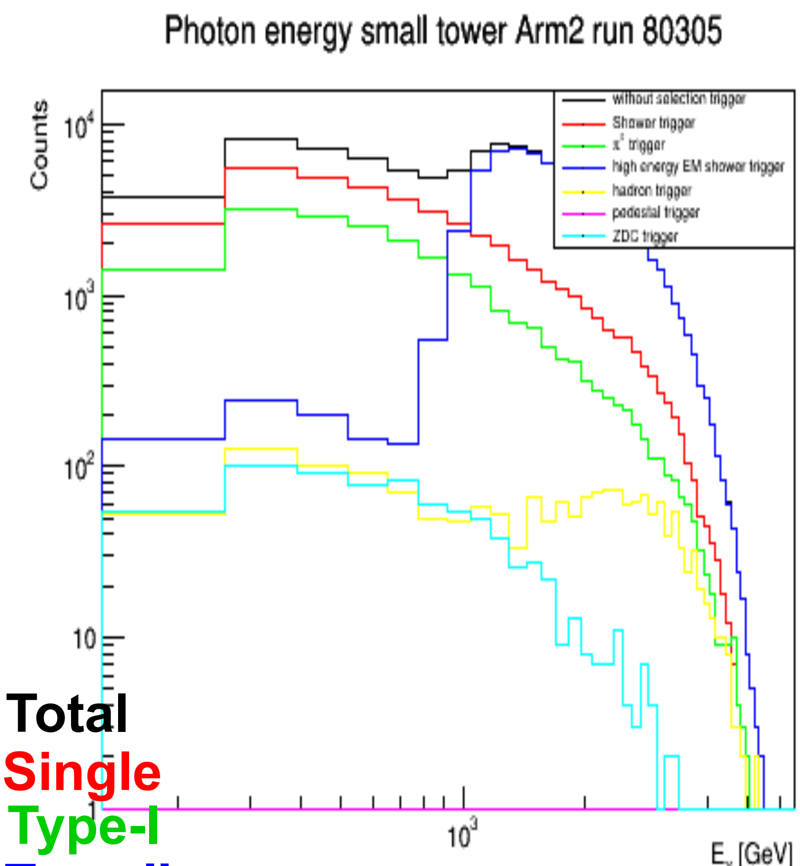


<u>Dead time of Arm2 is now dominated by VME to read out GSO scintillators</u>

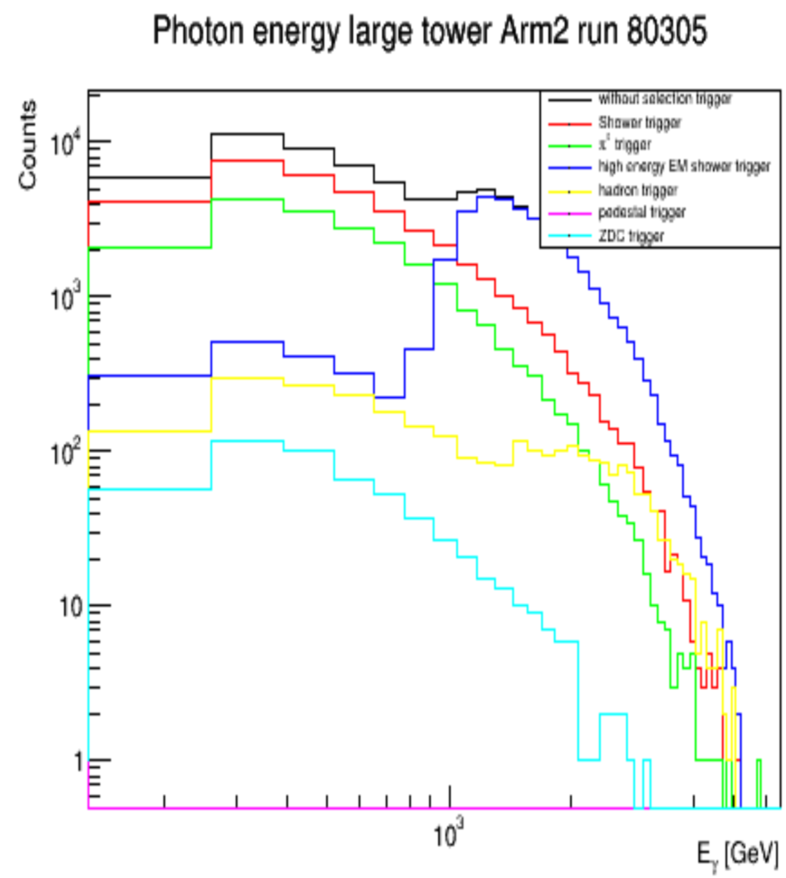
In Run III, the maximum DAQ speed of the Arm2 detector increased from 0.5 to **1.5 kHz**

Upgrade for Run III operations:
Optimization of the trigger scheme

Small Tower



Large Tower

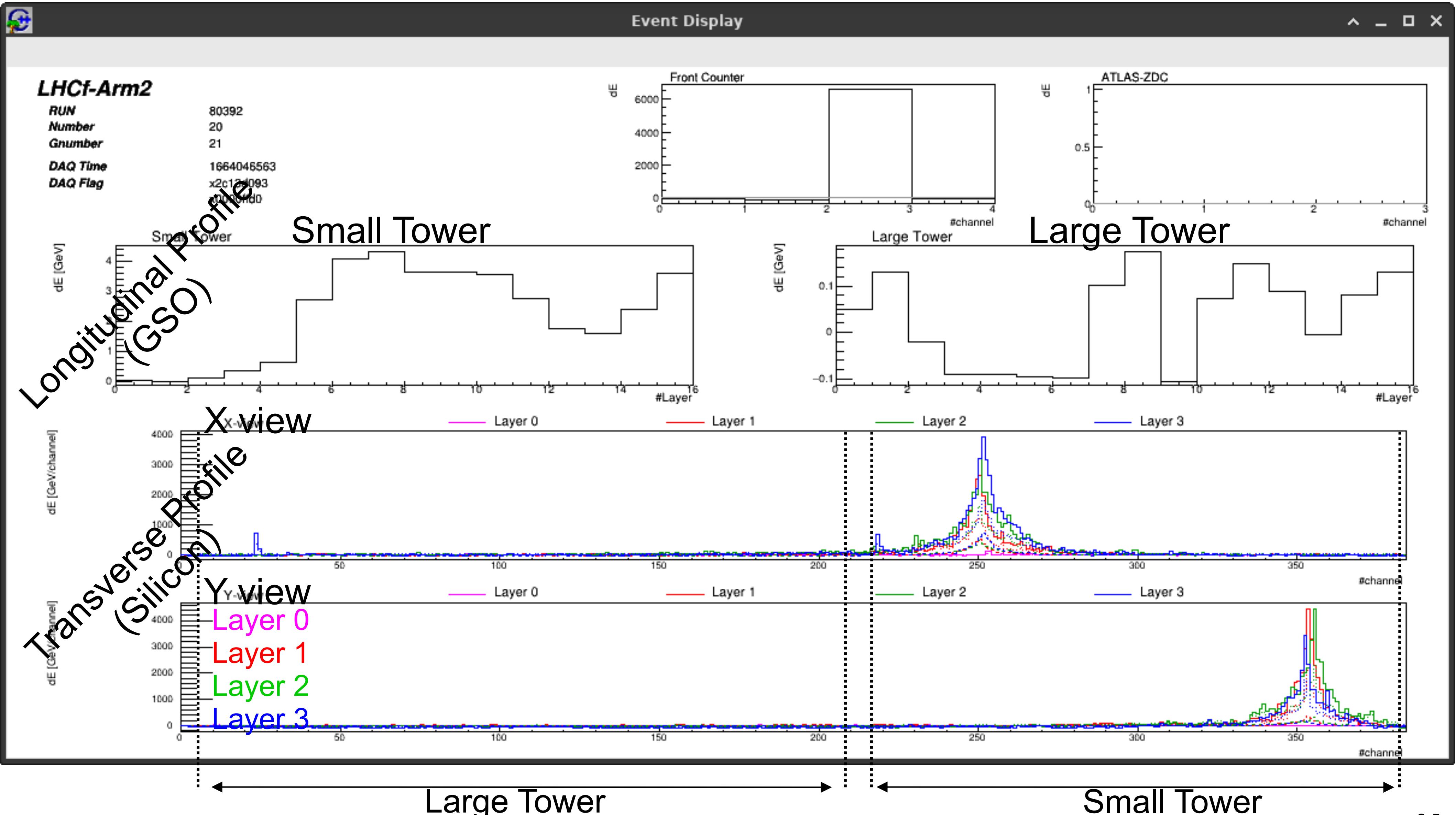


Trigger schemes

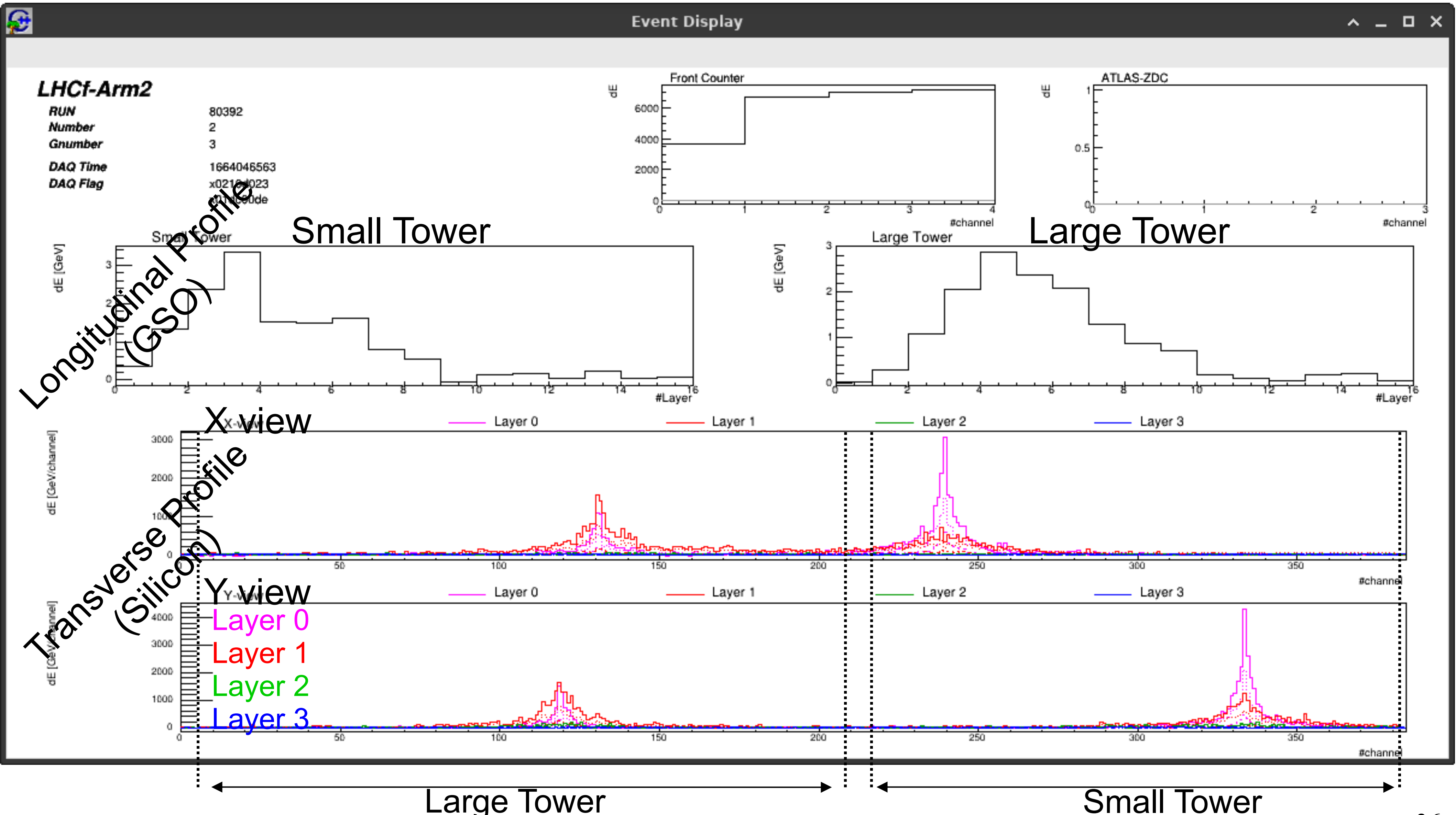
Total
Single
Type-I
Type-II
Hadron
ZDC
Pedestal

The different trigger schemes enhance different event categories

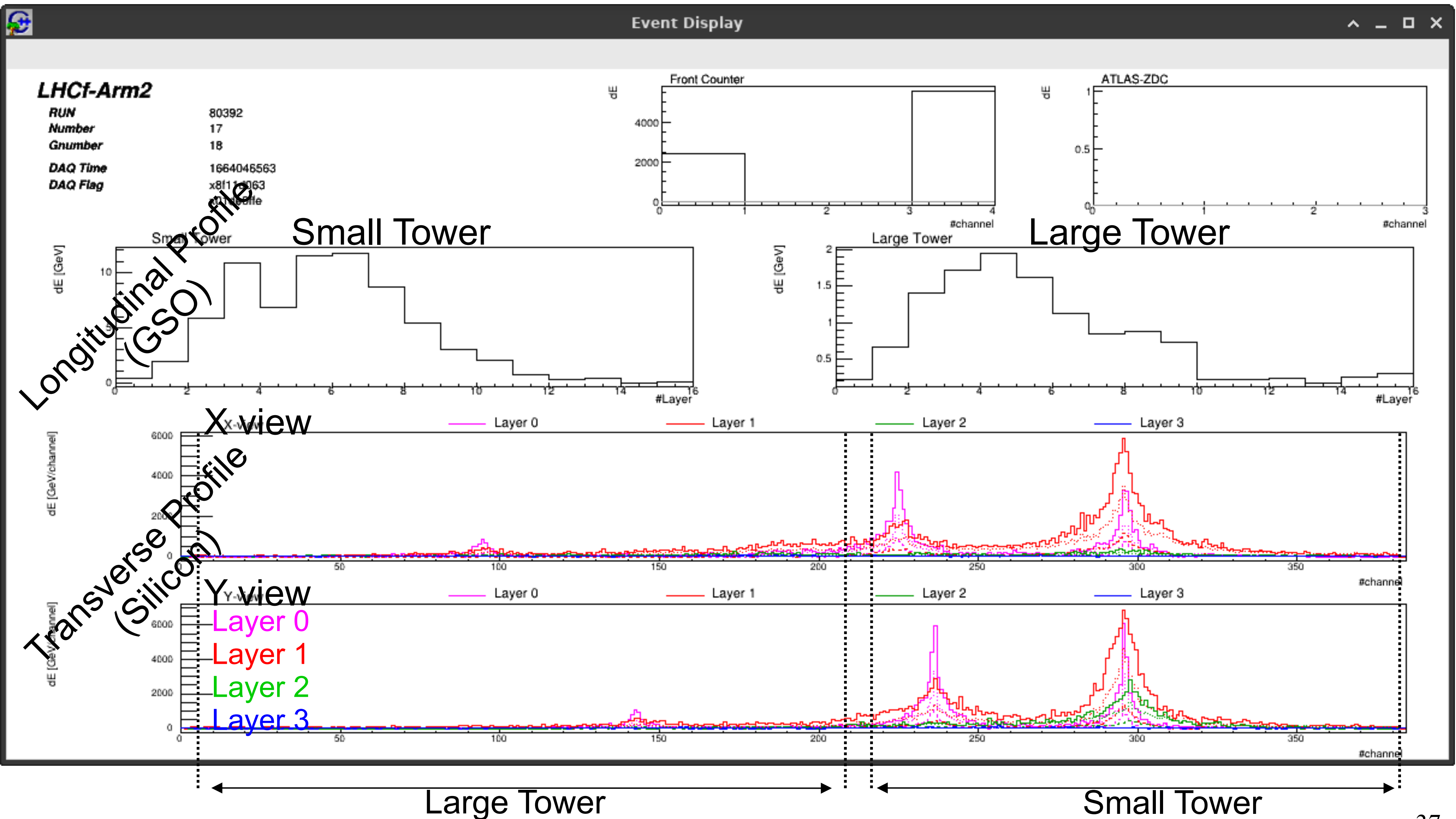
p-p √s = 13.6 TeV:
Hadron-like candidate in Small Tower



p-p √s = 13.6 TeV:
Type-I candidate



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

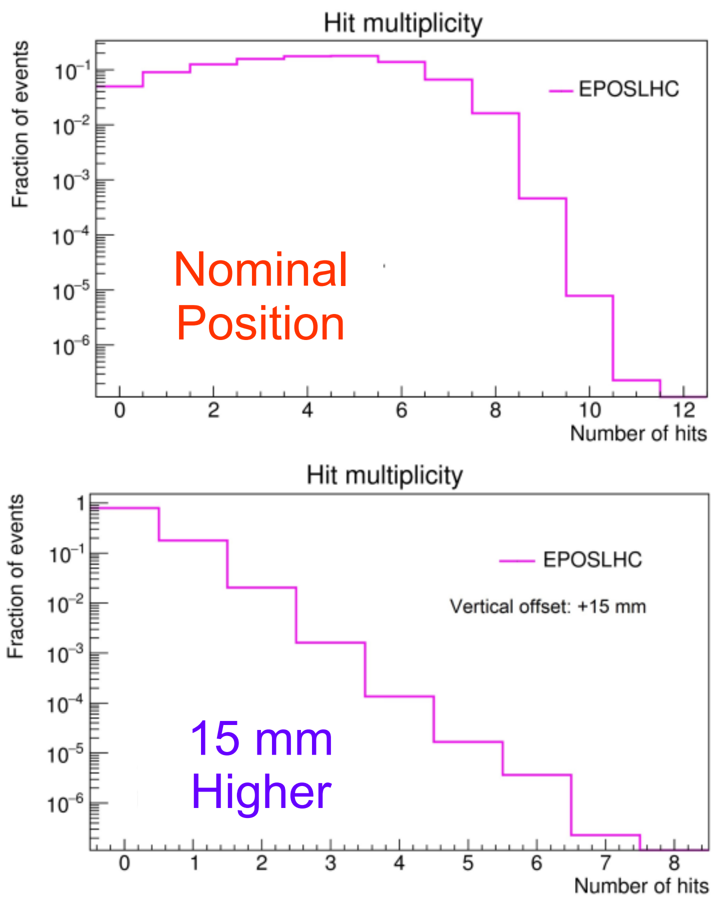


LHCf in Run III: p-O and O-O

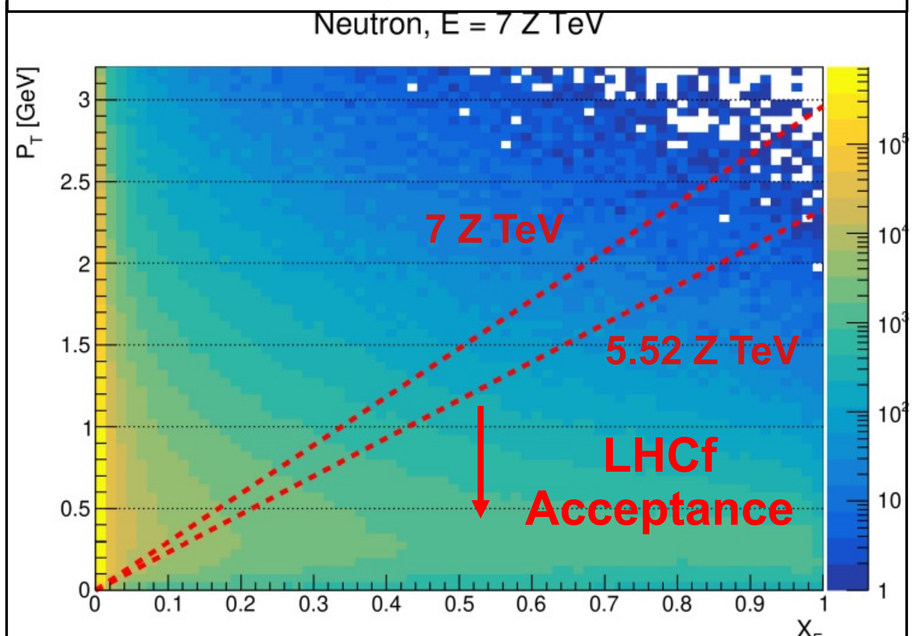
Operation conditions

Expected luminosity
L_{int}~1.4 nb^{-1} for p-O
L_{int}~0.7 nb^{-1} for O-O

Neutron Multiplicity in one Tower
<u>O-O</u>



<u>Higher collision energy</u> is preferred because of larger LHCf acceptance



Due to large multiplicity we will operate:
- p-O: with Arm2 on the **proton-remnant side**
- O-O: with Arm2 @ 15 mm higher than nominal

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
$L_{int} \sim 40\ nb^{-1}$

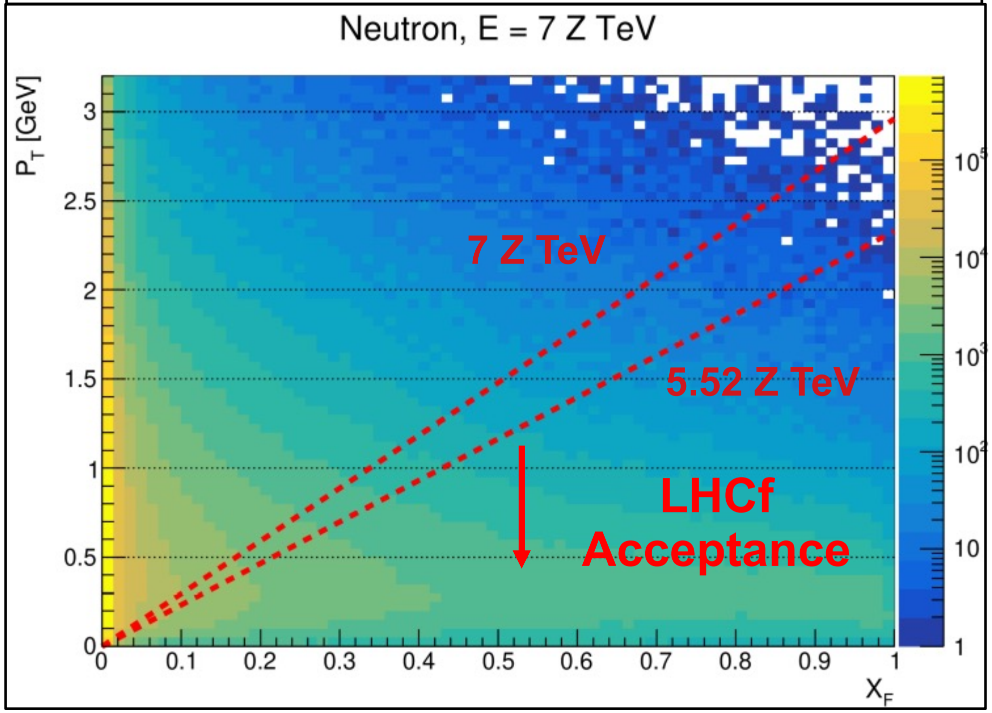
Ideal conditions for
p-O @ 9.9 TeV:

- 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)

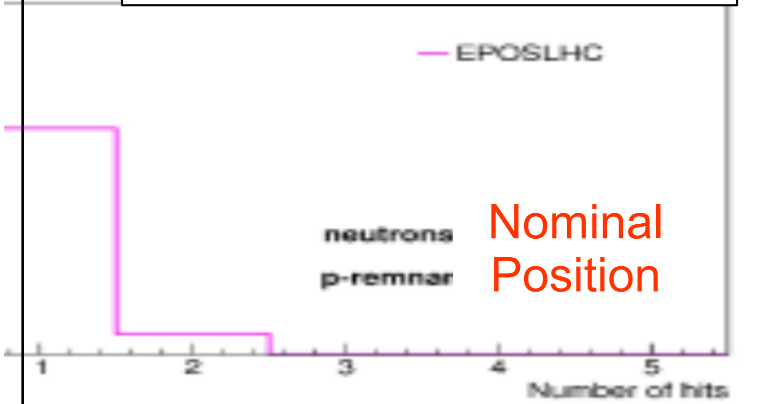
L_{int}~0.7 nb^{-1} for p-O nominal position
L_{int}~0.7 nb^{-1} for p-O +5 mm higher position
L_{int}~0.7 nb^{-1} for O-O

Higher collisions energy increases the LHCf detector acceptance



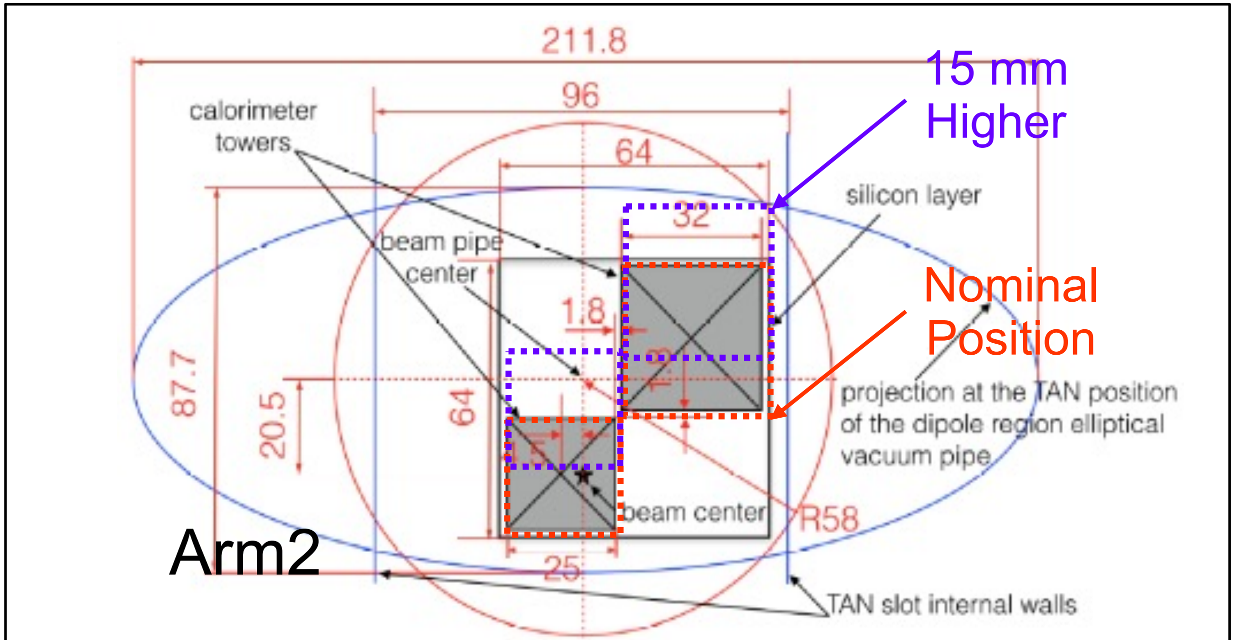
p-O and O-O operations:
Main experimental challenge

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 (η<11)



Neutron Multiplicity in Small Tower
Oxygen remnant side