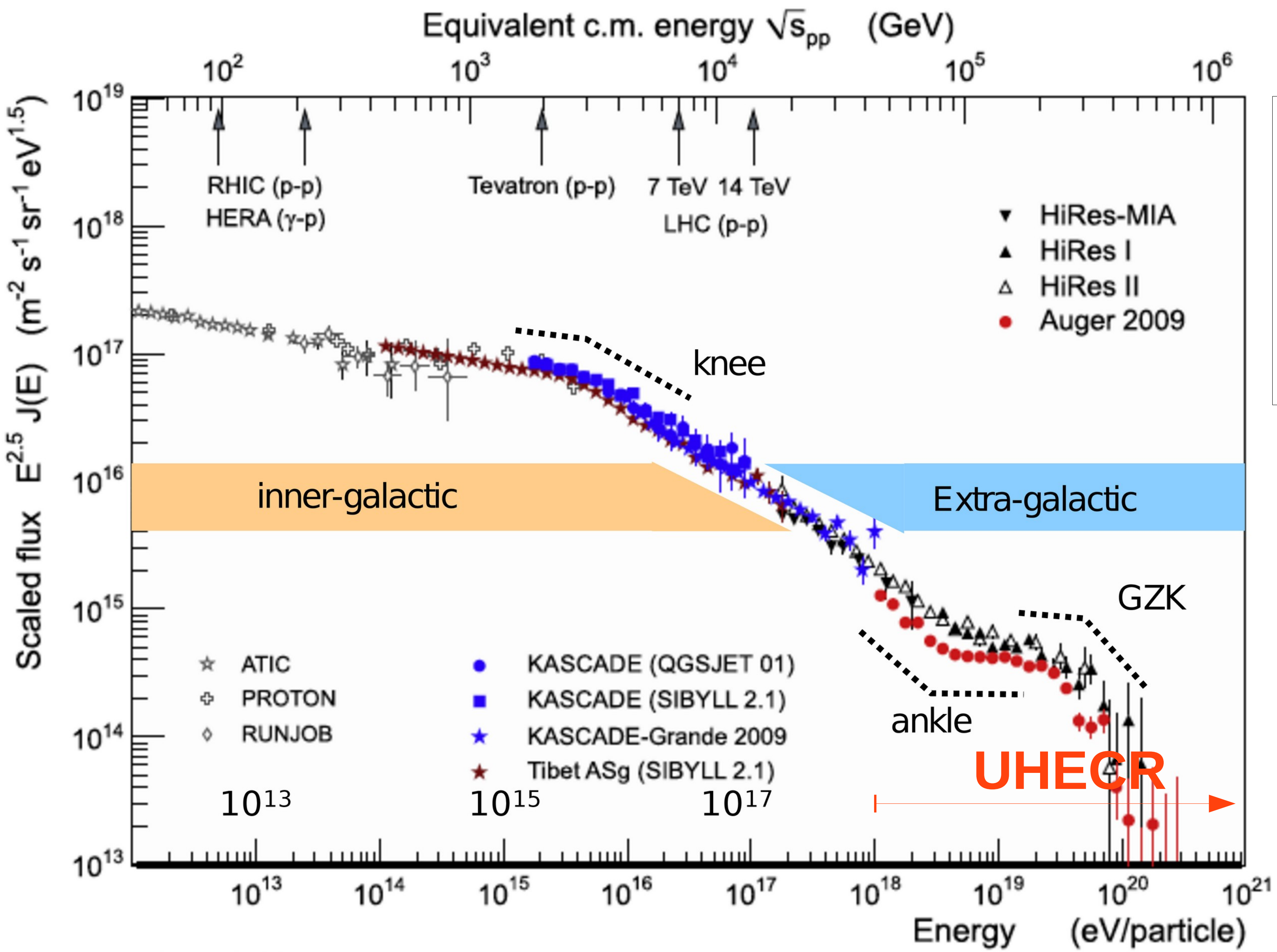
The LHCf experiment: Results and prospects for CRs physics

Eugenio Berti, on behalf of the LHCf collaboration

QCD Challenges from *pp* to *AA* collisions
February 13 – 17, 2023 Padova, Italy

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

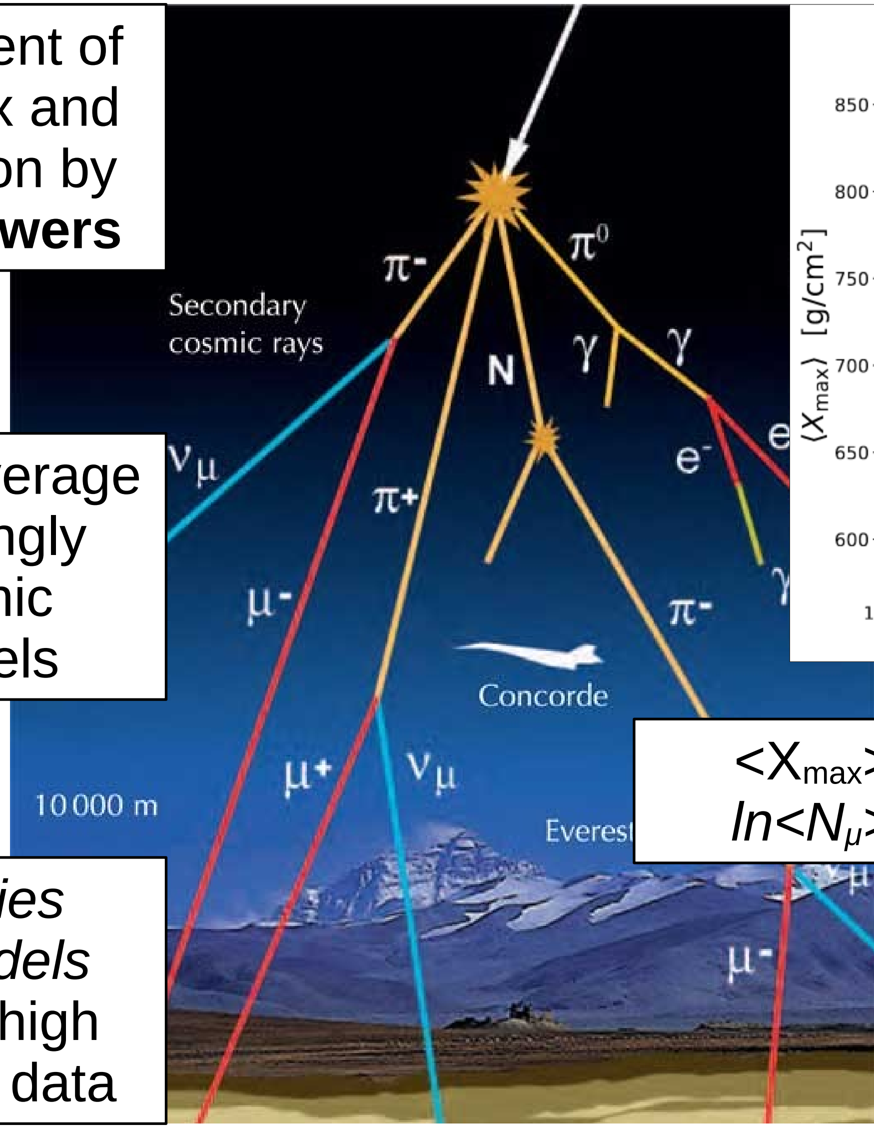
D'Enterria et al., 2011

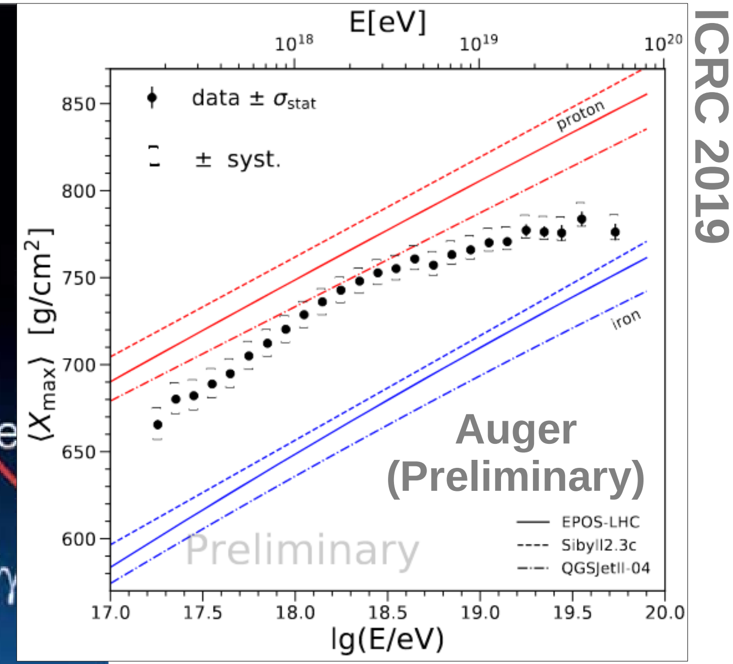
Extensive Air Showers

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



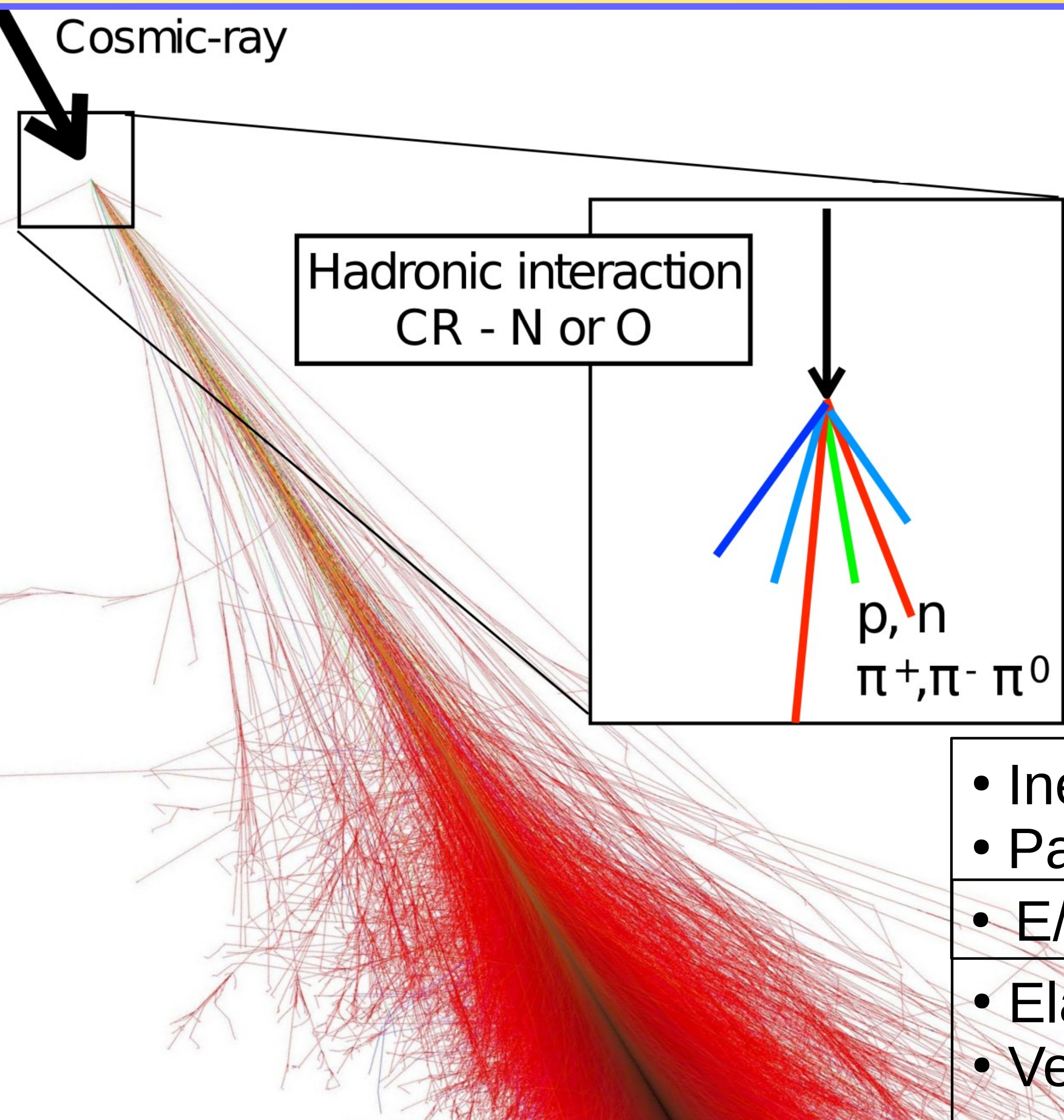


$<X_{max}>$: Small model discrepancy

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

Muon Puzzle

Hadronic interaction models



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, ...

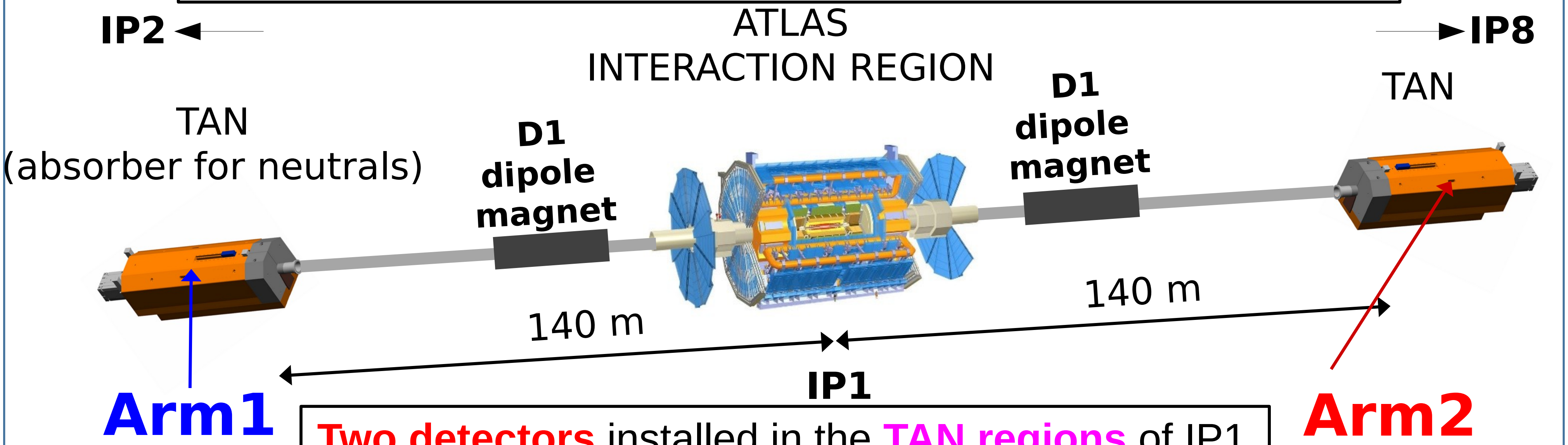
- E/H Ratio $R = E_\gamma / E_h$
- Elasticity $k = p_{lead} / p_{beam}$
- Very forward particle spectra
  - Extrapolation to $E > 10^{17}$eV
  - Nuclear modification factor

LHCf

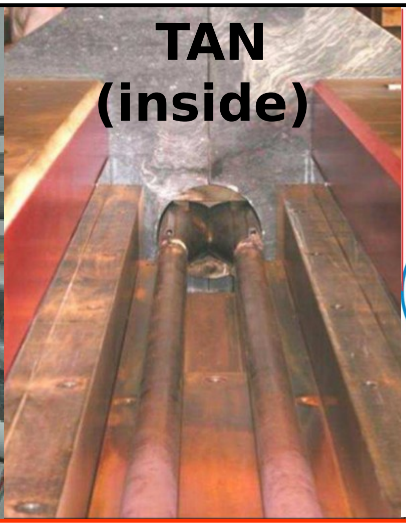
p-p at $\sqrt{s}$ = 14 TeV ⇒ $E_{LAB} = 10^{17}$ eV

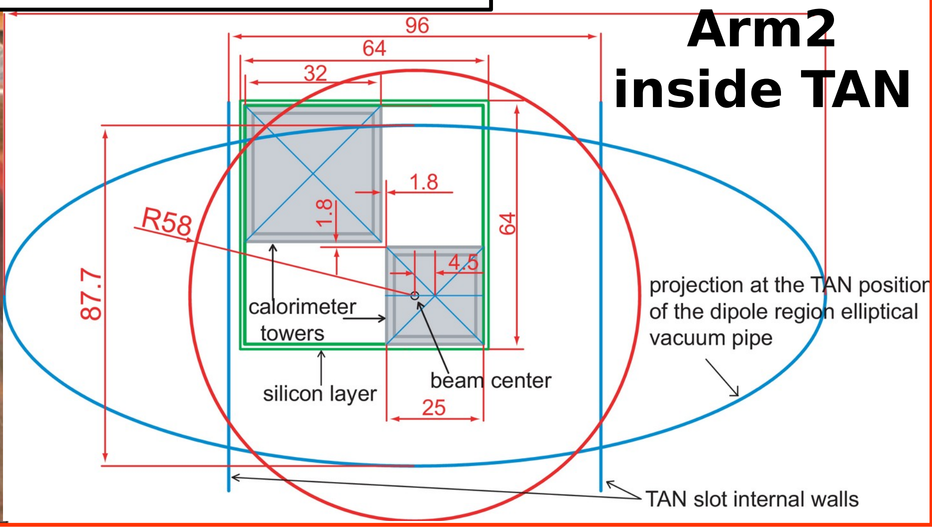
The LHCf Experiment

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



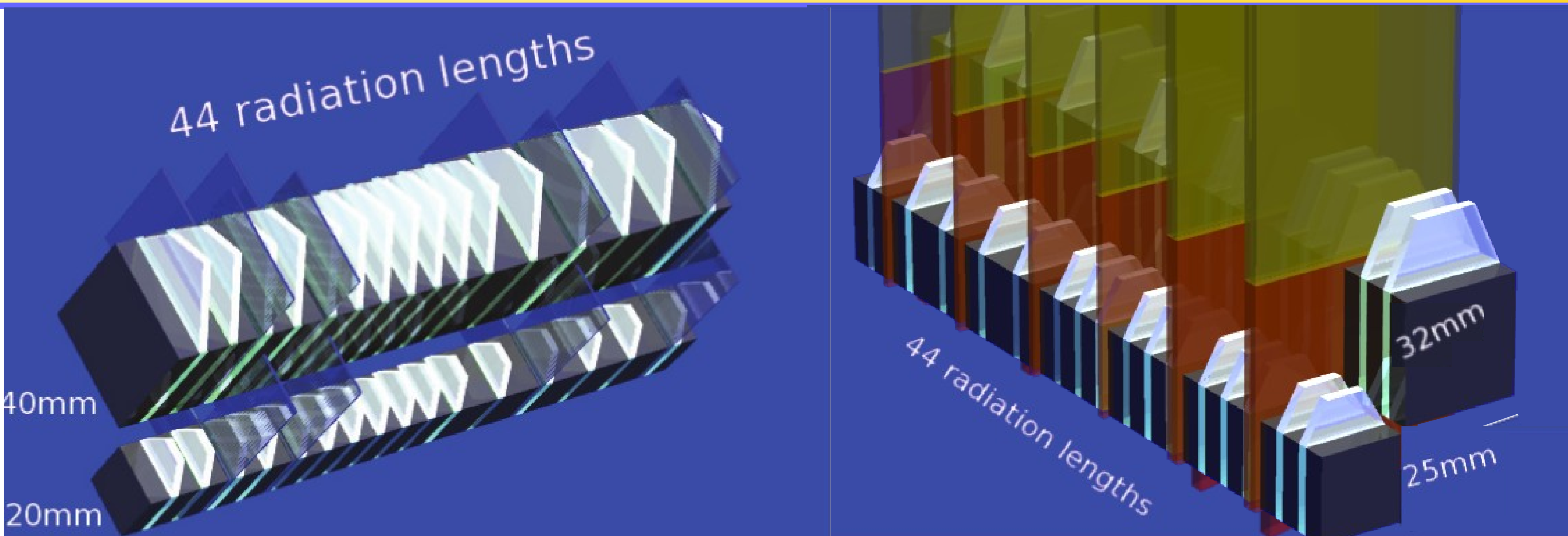
Two detectors installed in the **TAN regions** of IP1





The LHCf detectors

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)

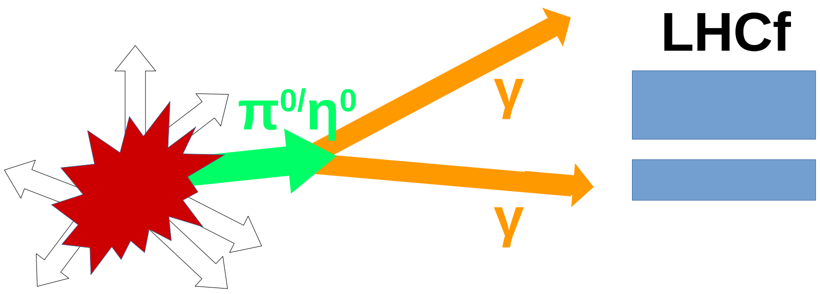
< 800 μm (hadrons)

The LHCf acceptance

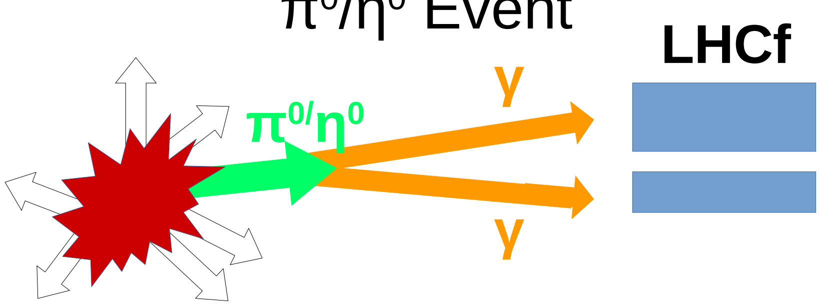
Neutron Event

Information on leading baryon and average inelasticity

Single Photon Event



π^0/η^0 Event



Information on electromagnetic component

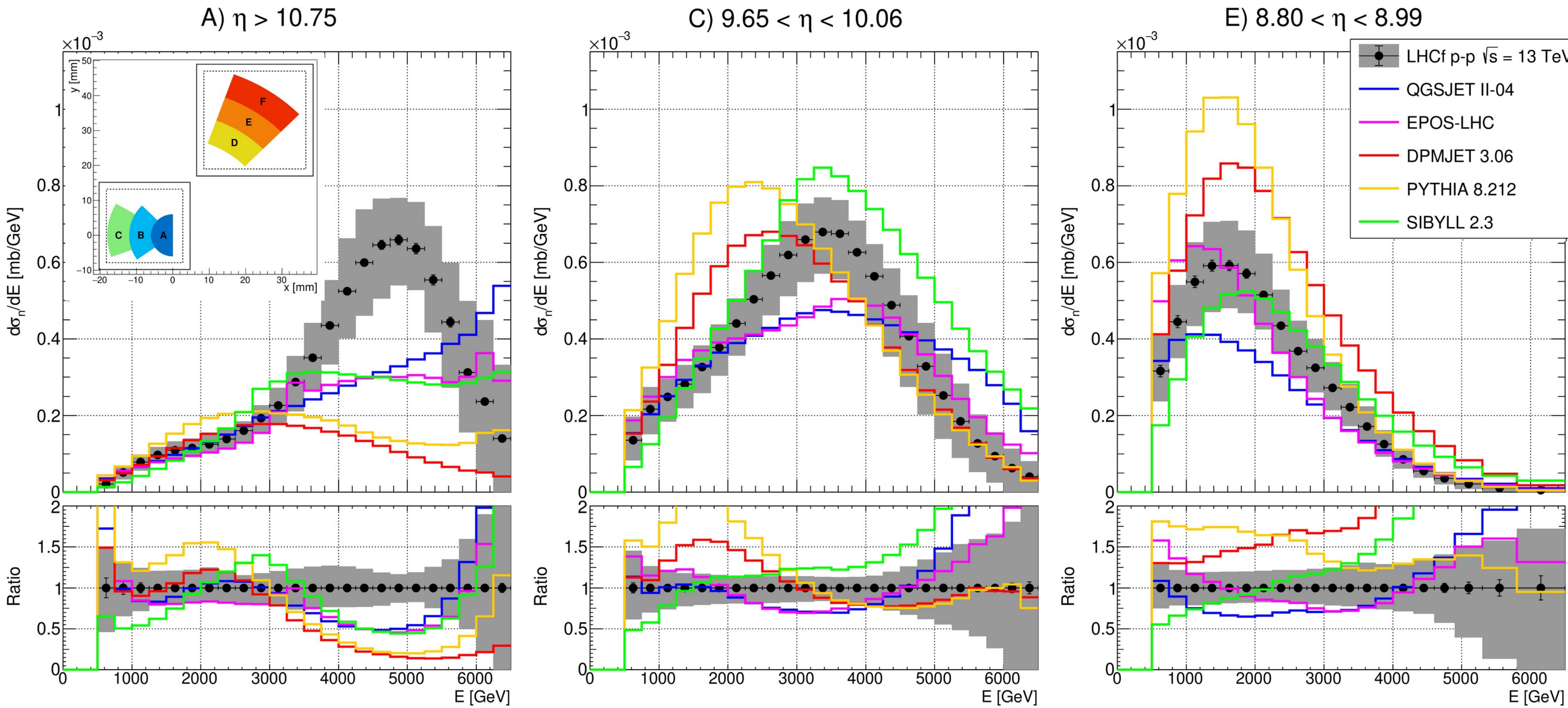
Publication table

	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**	**Almost completed**
p+Pb 8.1TeV	Analysis ongoing			

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

Neutron Production Cross Section

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



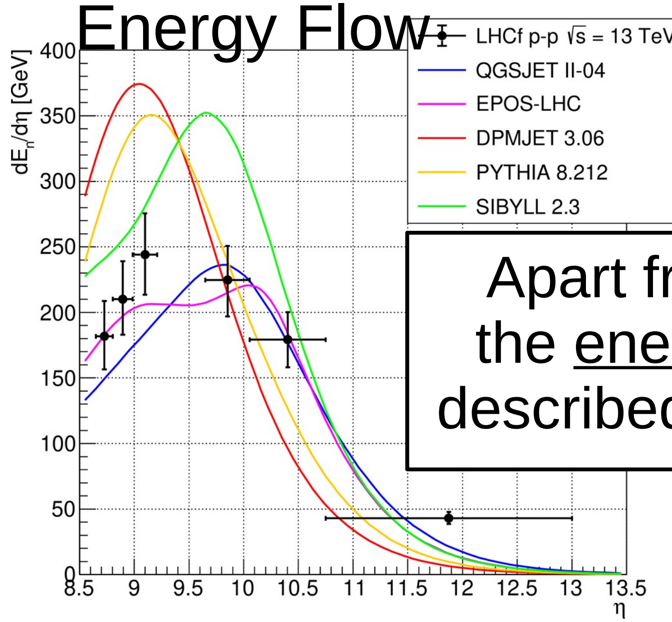
JHEP 07 (2020) 016

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 satisfactorily agreement with the experimental measurements.

Neutron EnergyFlow & Inelasticity

p-p √s = 13 TeV

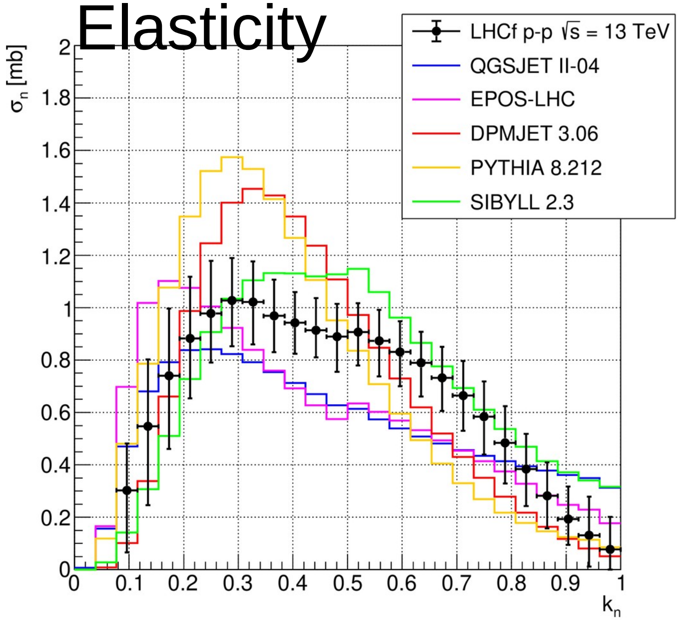
Energy Flow



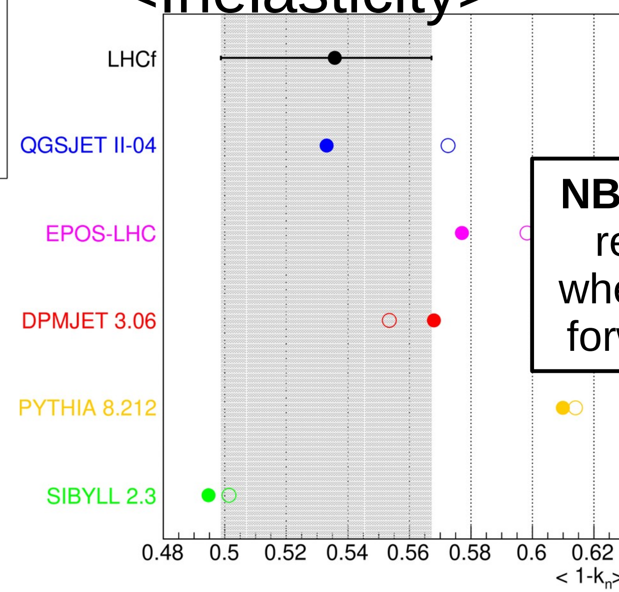
Apart from η > 10.75, the energy flow is well described by **EPOS-LHC**

Most models reproduce the average inelasticity but not the distribution

Elasticity



<Inelasticity>



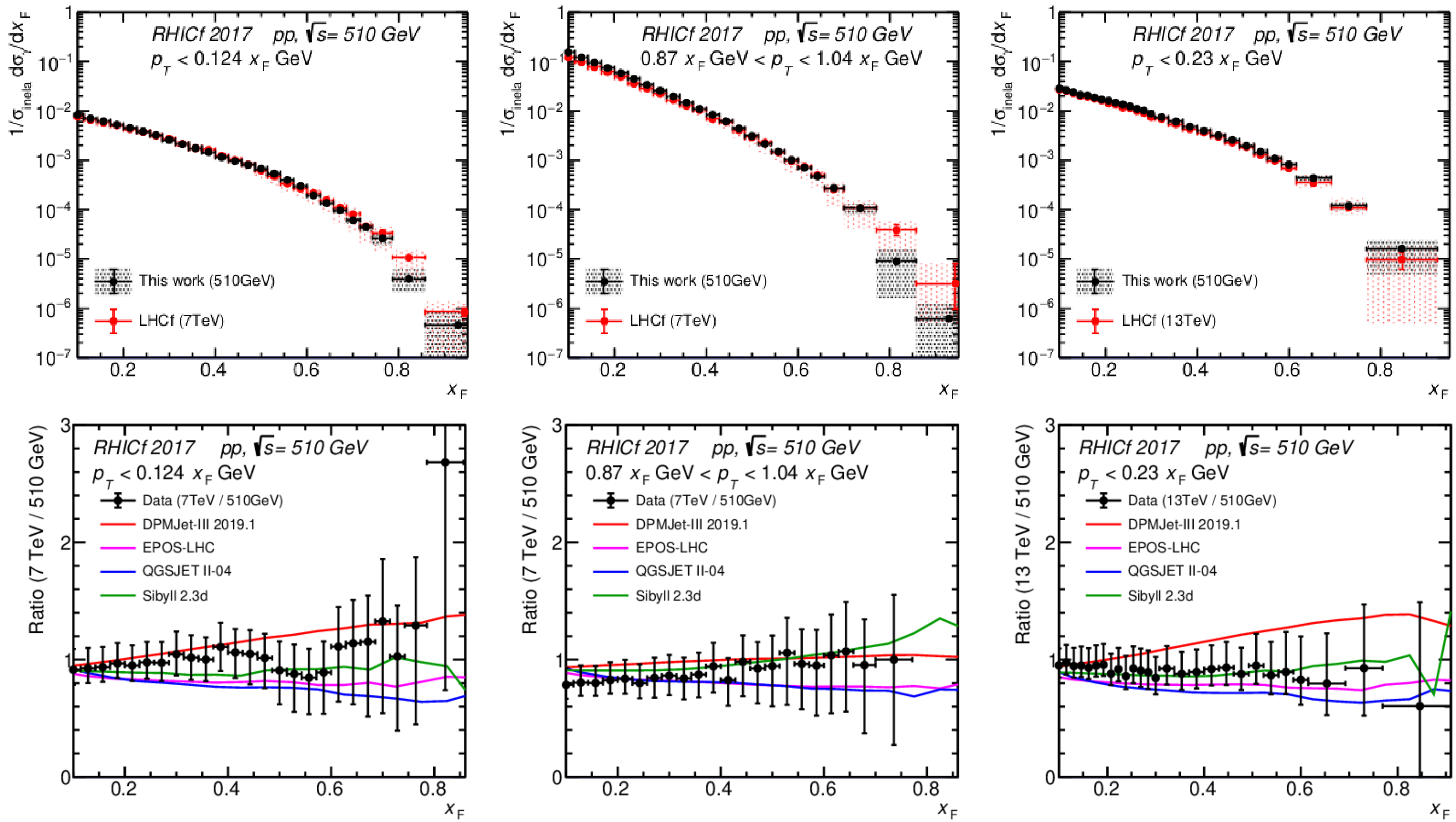
NB Elasticity/Inelasticity refers only to events where the neutron is the forward leading particle

JHEP 07 (2020) 016

Test of Feynman scaling

using forward photons

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



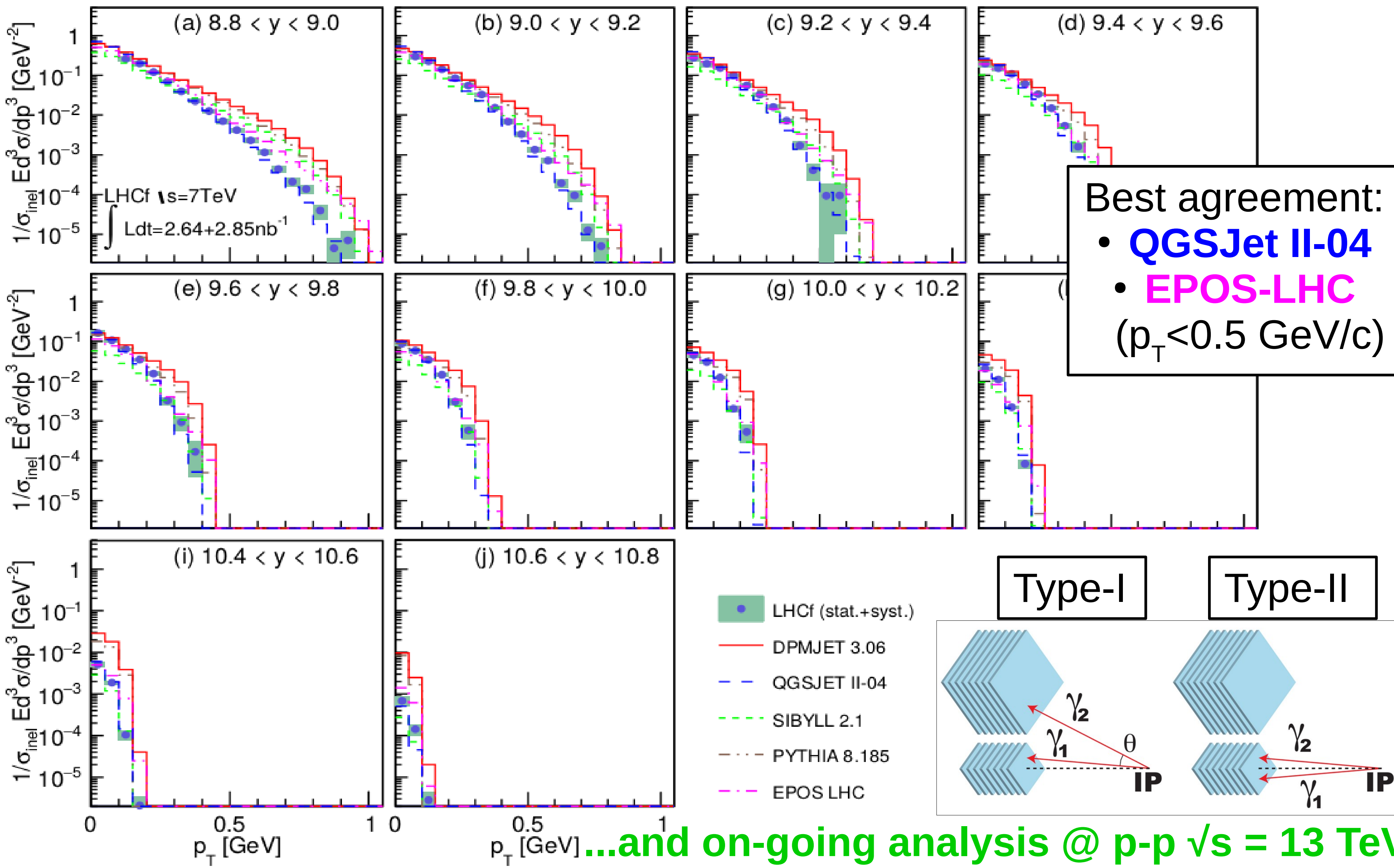
ArXiv:2203.15416

…submitted to PLB

<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 Cross Section

p-p $\sqrt{s}$ = 7 TeV



Best agreement:

- **QGSJet II-04**
- **EPOS-LHC**

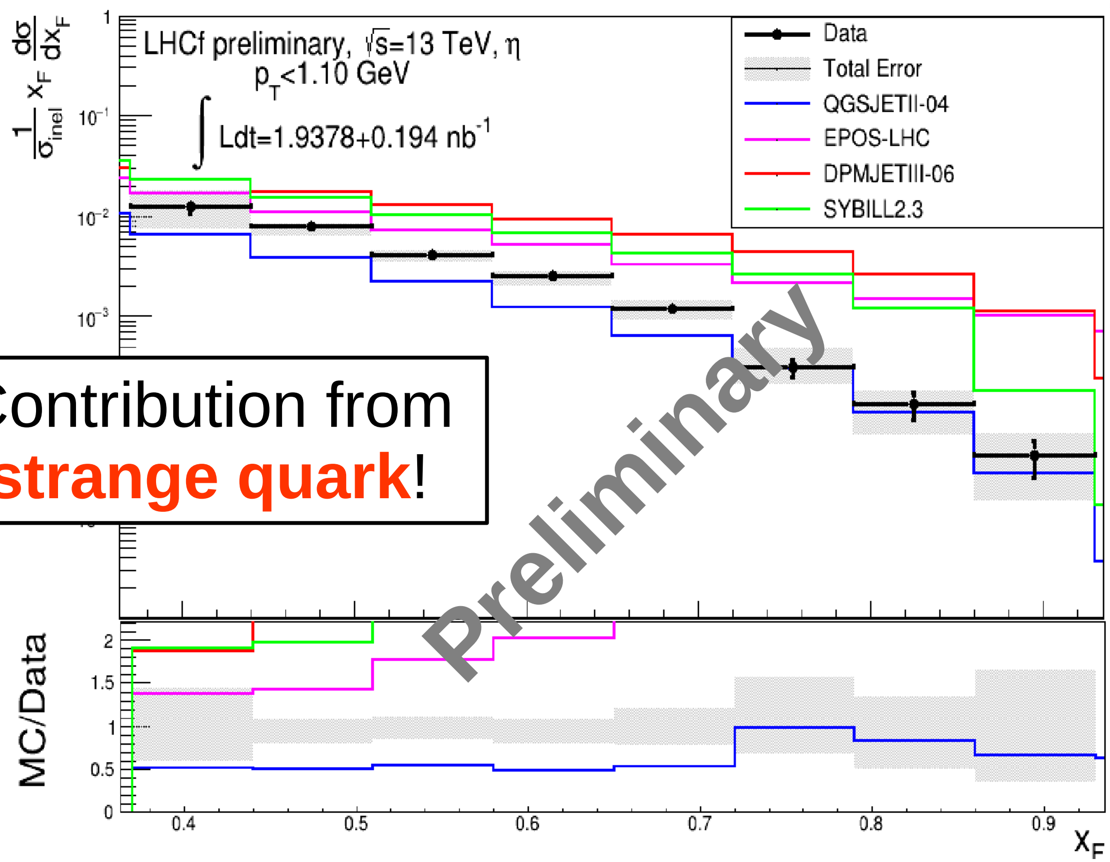
(p_T<0.5 GeV/c)

PRD 64 (2016), 032007

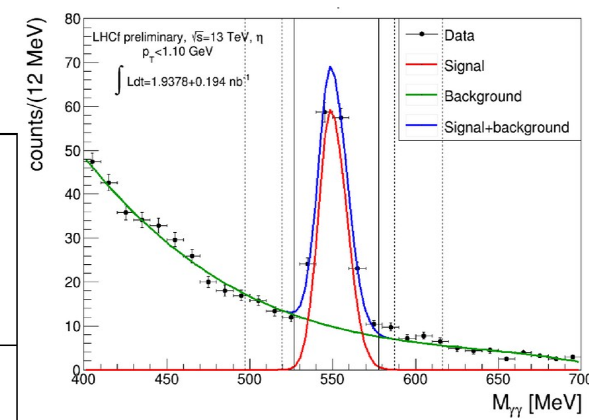
...and on-going analysis @ p-p √s = 13 TeV

η^0 Production Cross Section

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



Contribution from **strange quark**!



...almost completed

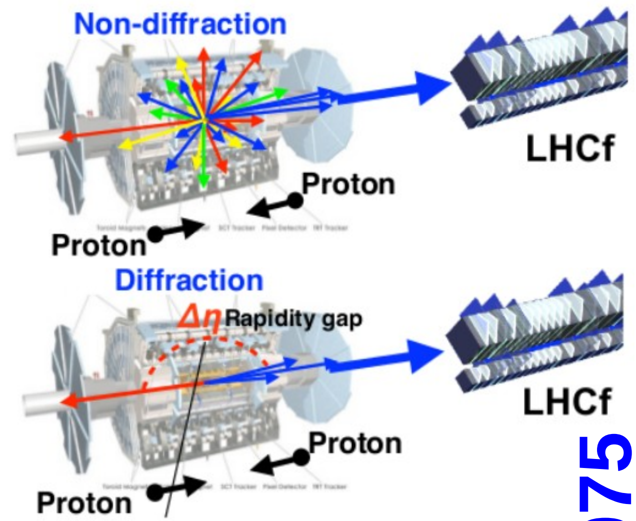
Among the large model variations, only **QGSJETII-04** has good but not satisfactorily agreement with the experimental measurements.

LHCf-ATLAS joint analysis

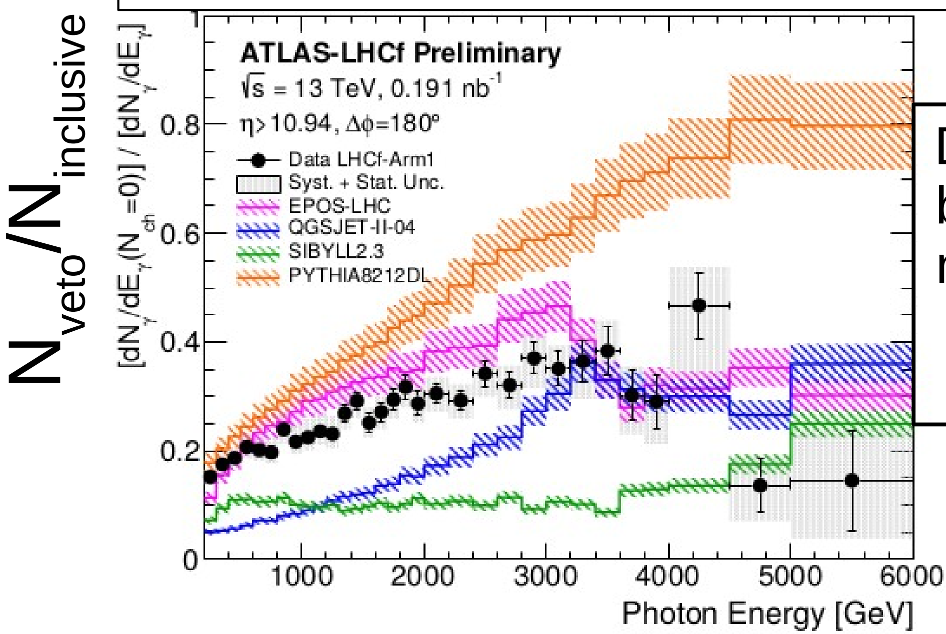
p-p √s = 13 TeV

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

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



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

LHCf 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^0 and (possibly) K^0_S

Longest LHC Fill ever!

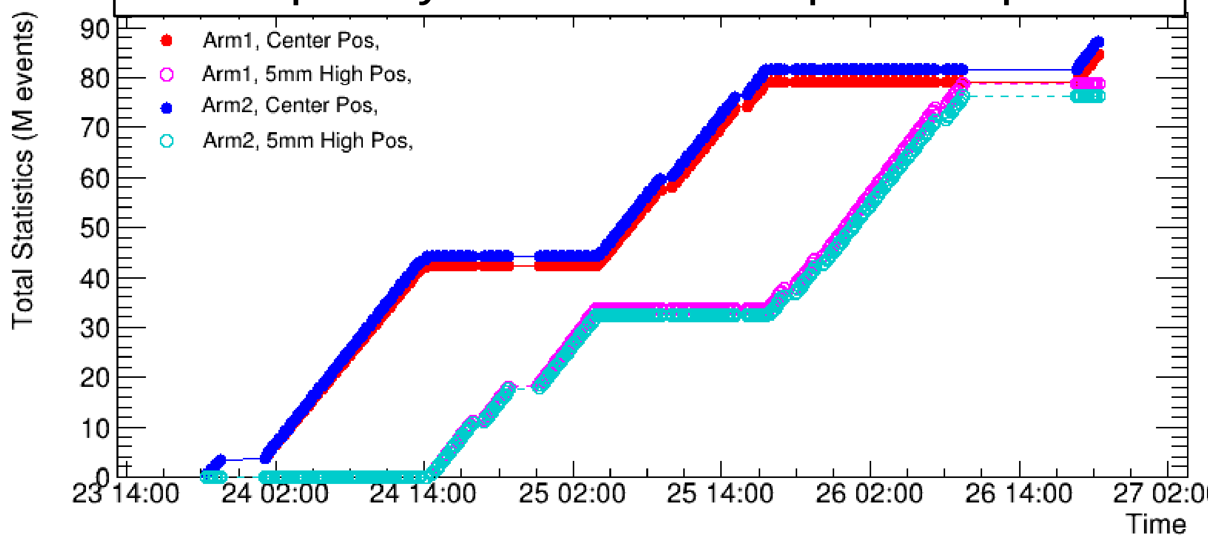
September 24-26:
Fill 8178 - 55h
Fill 8179 - 2h

8 times larger statistics with respect to Run II

Much larger increase for the **double γ events**

For each detector position
L_{int} ~ 40 nb^{-1}

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



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

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

Foreseen in 2024

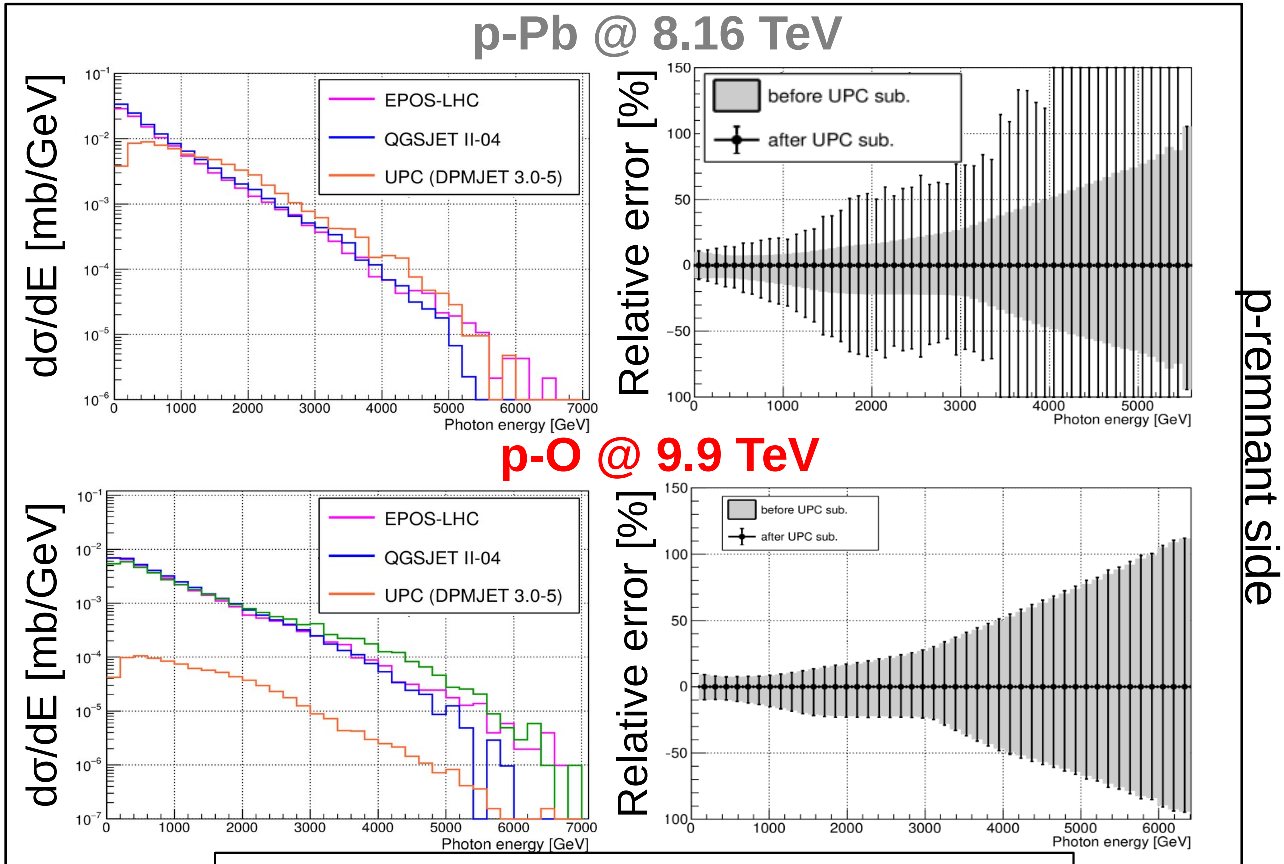
Main Motivation

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

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

A **week** of p-O and 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:

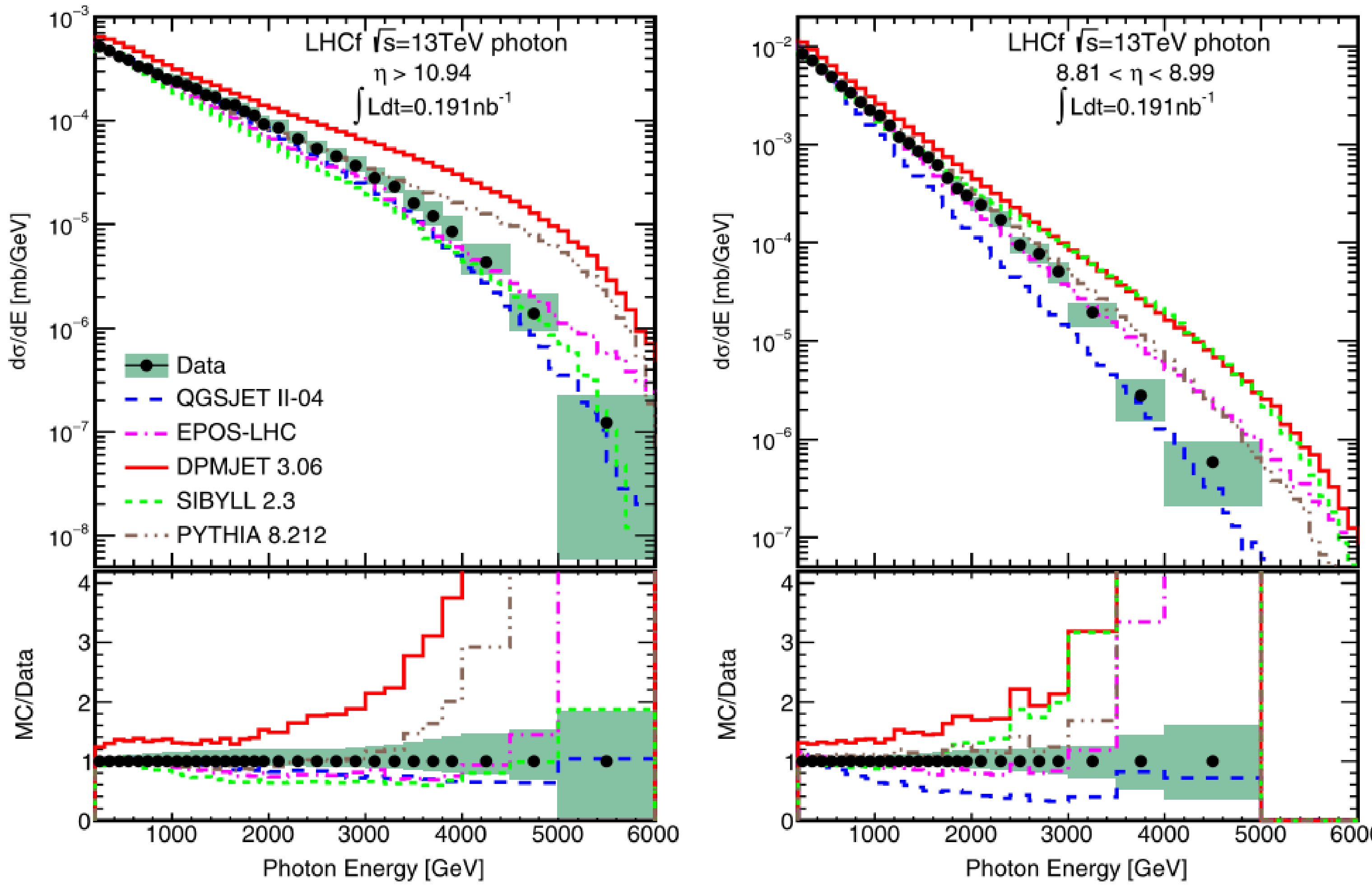
- High precision measurement on *forward π^0 and η^0 production*
- First event measurement of *K^0_s production* in the forward region
- Insight into different production mechanisms (*LHCf-ATLAS*)

Of fundamental importance for CR are **p-O and O-O runs** in 2024 and 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



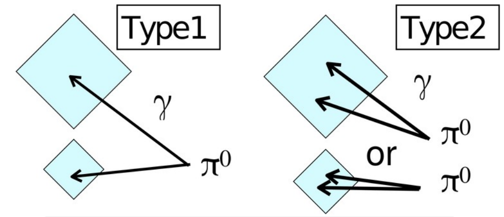
PLB 780 (2018) 233-239

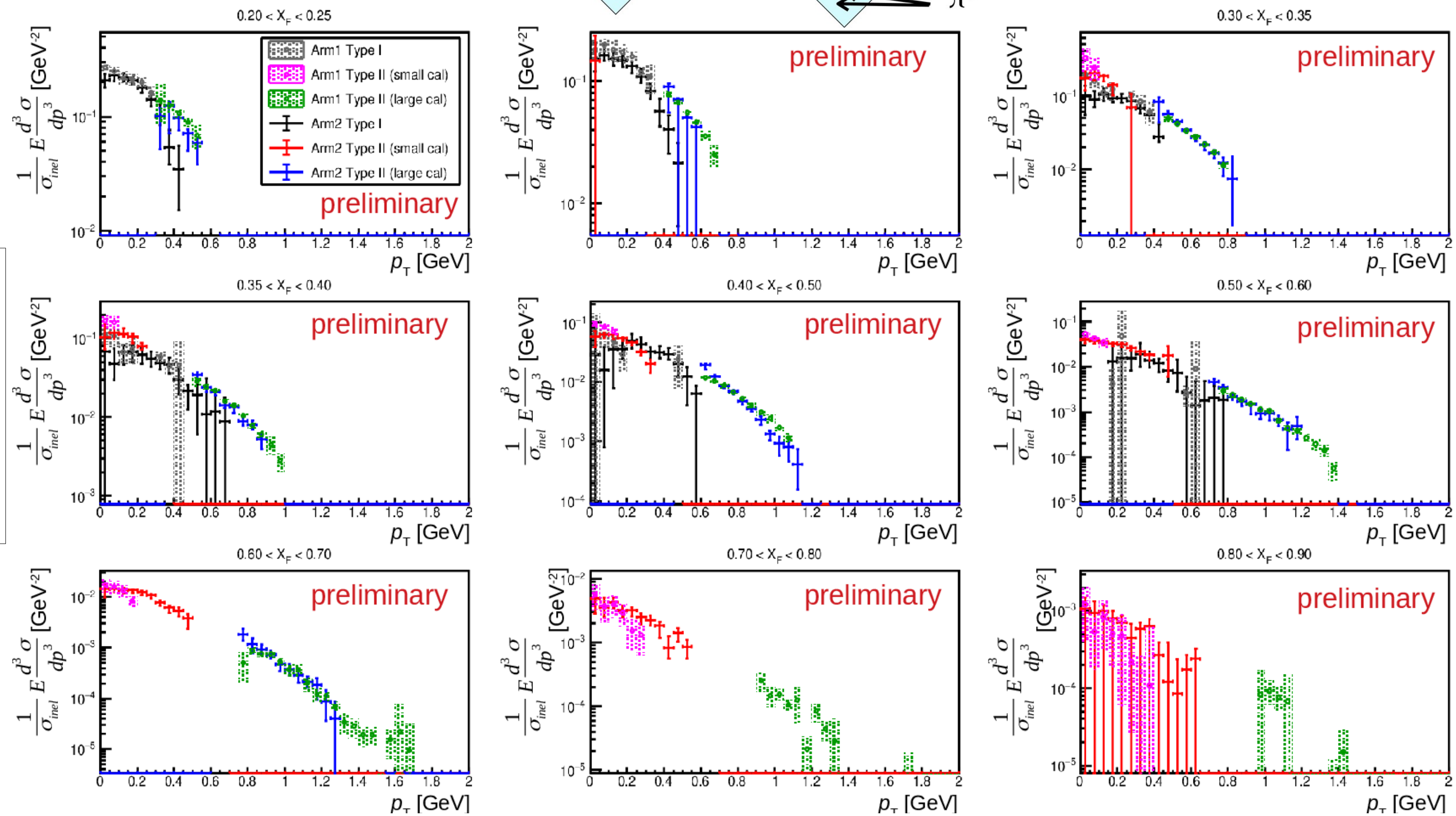
QGSJET II-04 is in good agreement for η>10.94, otherwise softer
EPOS-LHC is in good agreement below 3-5 TeV, otherwise harder

π^0 Production Cross Section

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

Ongoing analysis



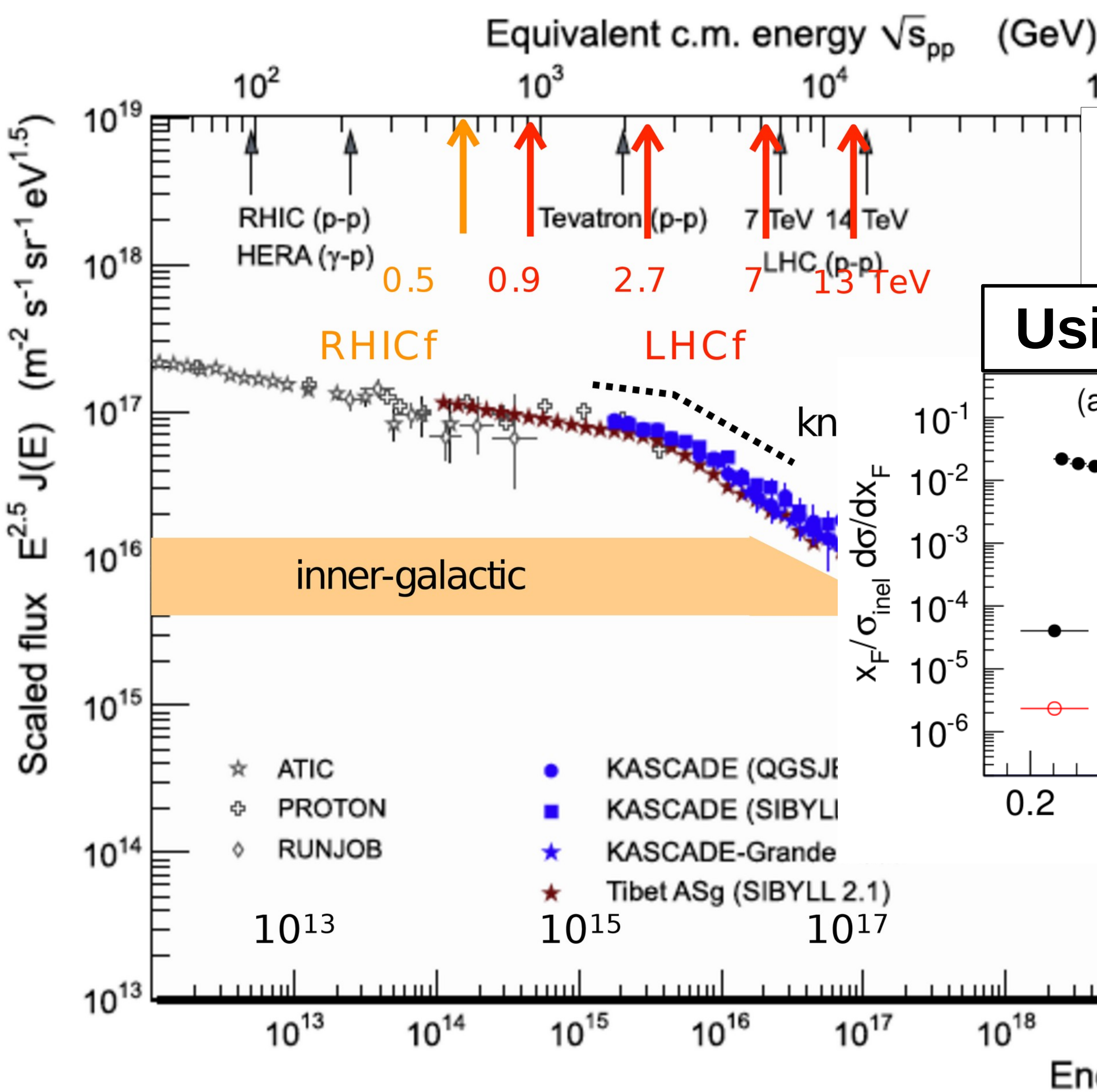


Arm2 acceptance extends to low-p_T

Arm1 acceptance extends to high-p_T

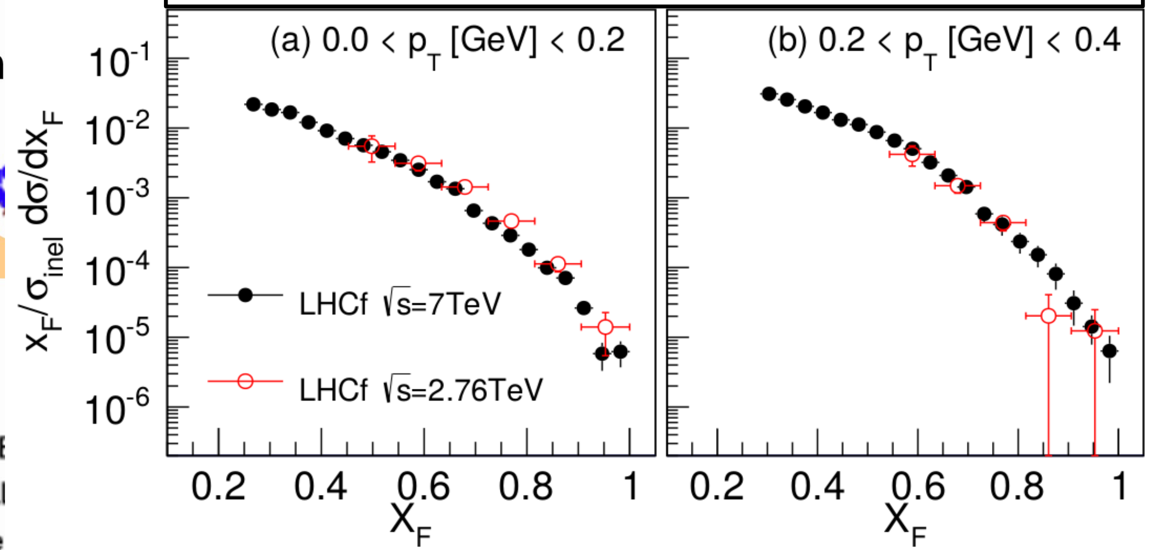
Good agreement between Arm1 and Arm2 data and between “Type-I” and “Type-II” events

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

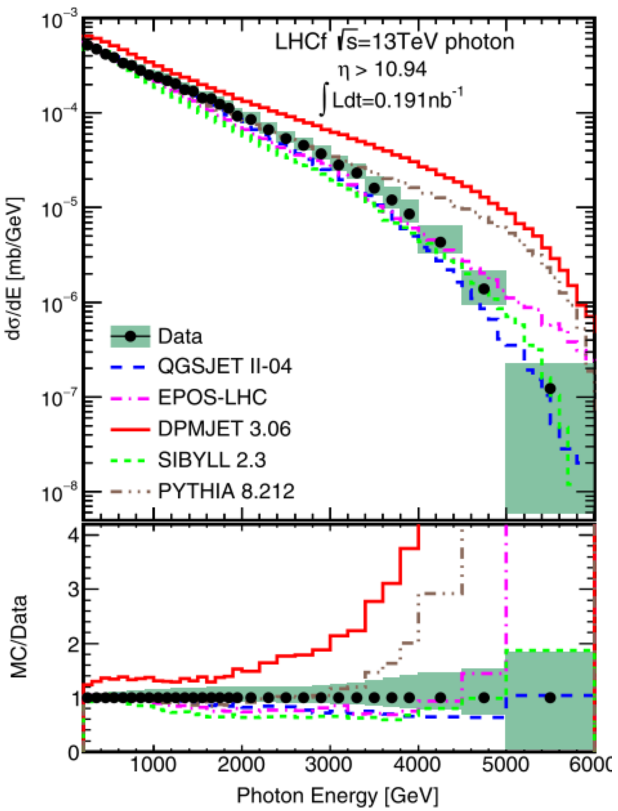


<u>Feynman scaling holds at ±20% level</u>

D'Enterria et al., 2011

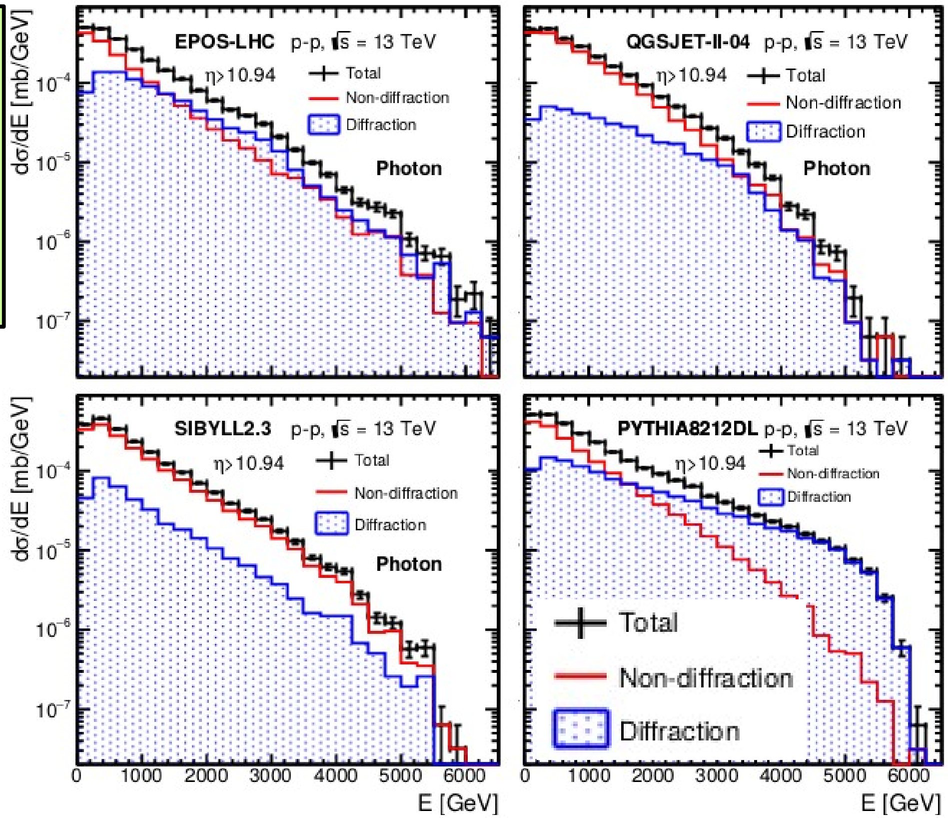
Diffractive and non-diffractive production

√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?



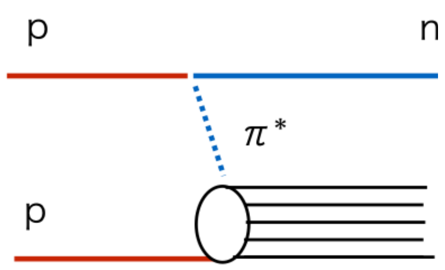
LHCf measures the **total production rate** in the forward region

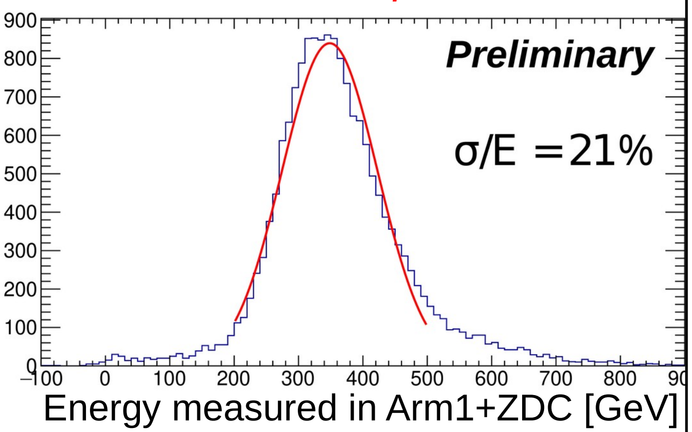
LHCf-ATLAS joint analysis

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

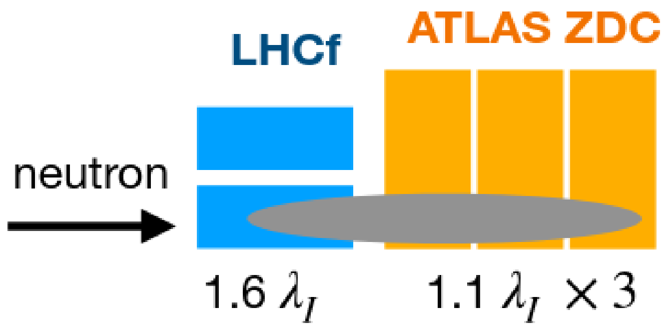
Additional motivations for Run III:
Operations with ATLAS ZDC

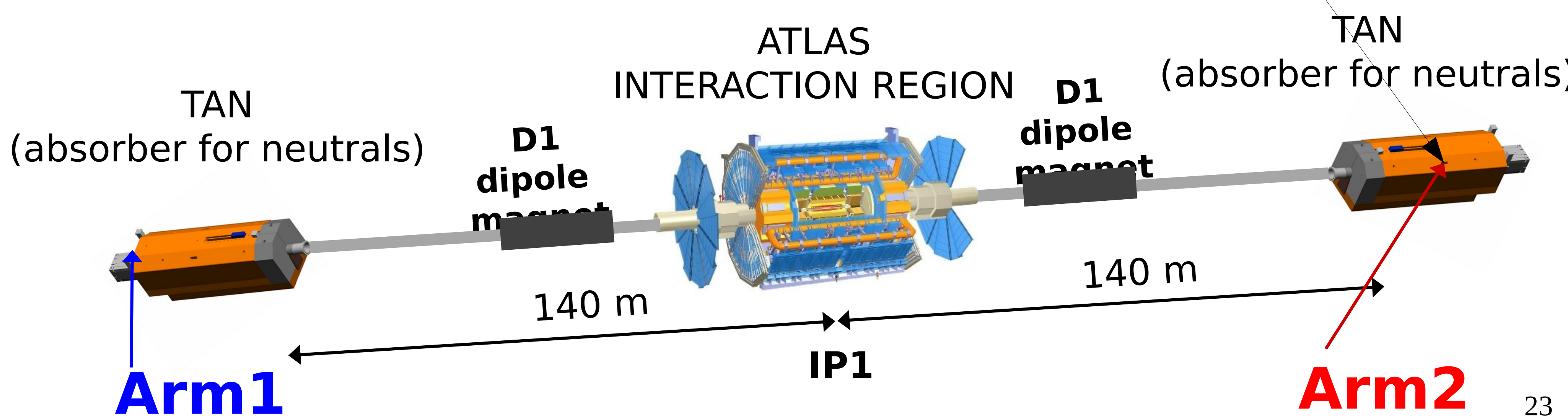
Indirect measurement of p-π cross section via **one-pion exchange**





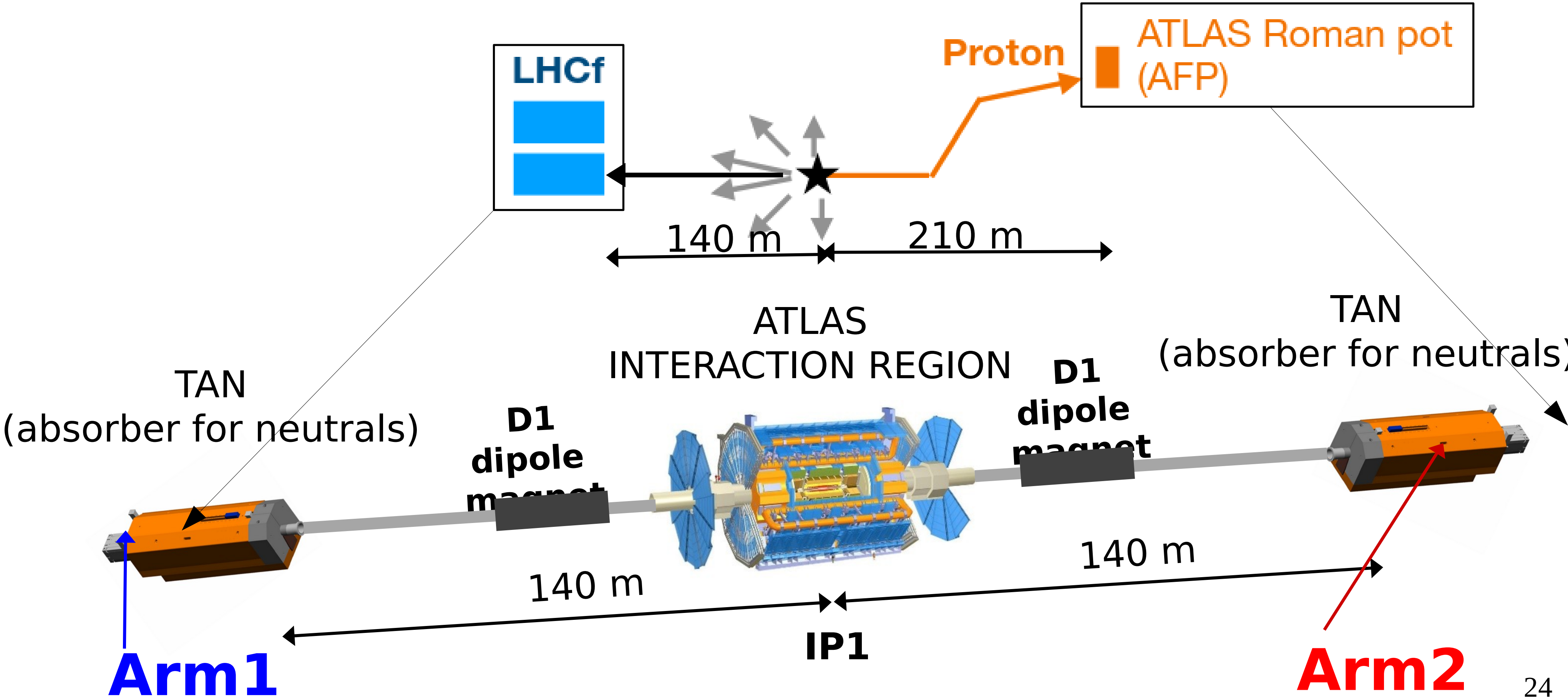
Operation with **ZDC**
(σ$_E$/E = 40% → 20%**)**





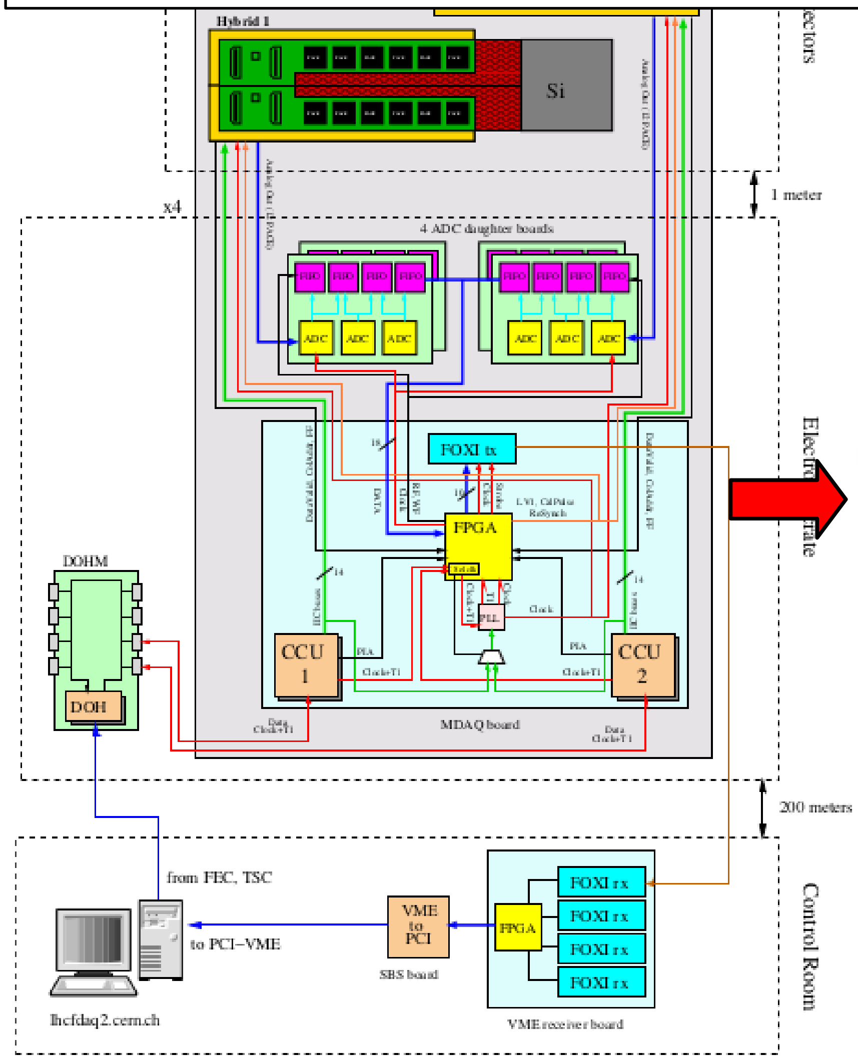
Additional motivations for Run III:
Operations with ATLAS AFP

Identification of **single diffractive events**
+ possible measurements of:
- *Δ resonance* (p+p → p+Δ → p+p+π^0)
- Bremsstrahlung (p+p → p+p+γ)



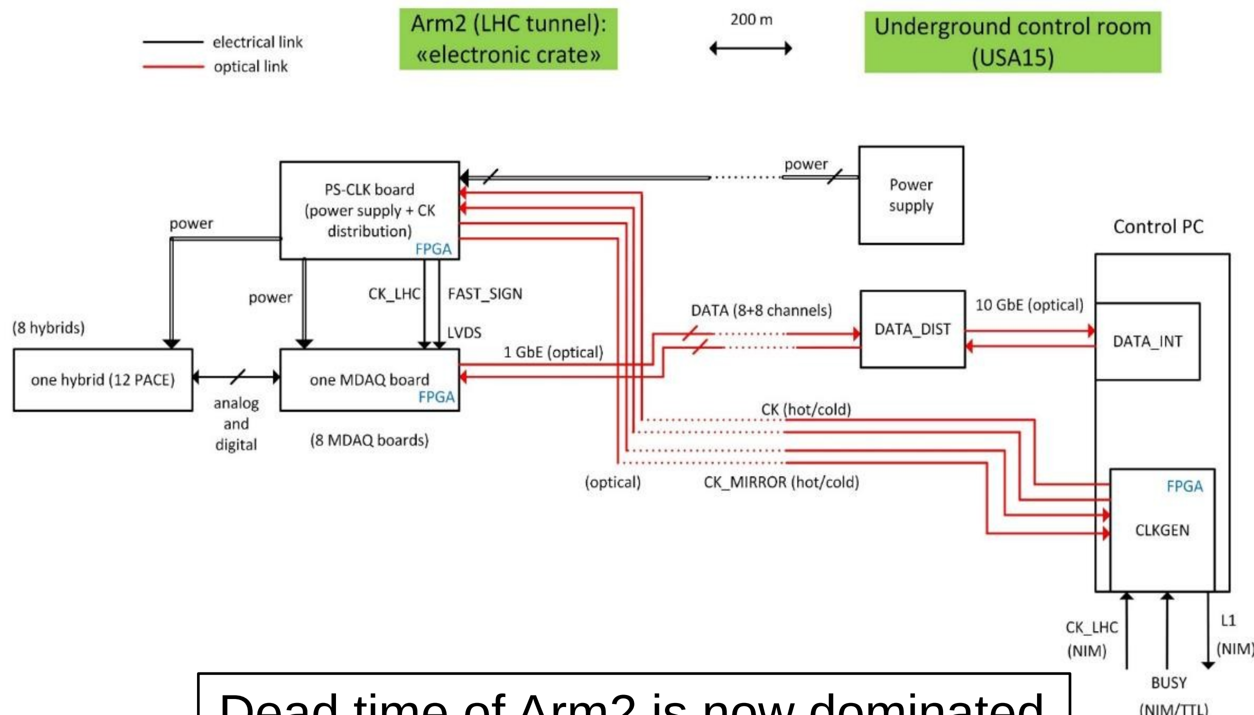
Upgrade for Run III operations:
Upgrade of the silicon microstrip DAQ

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

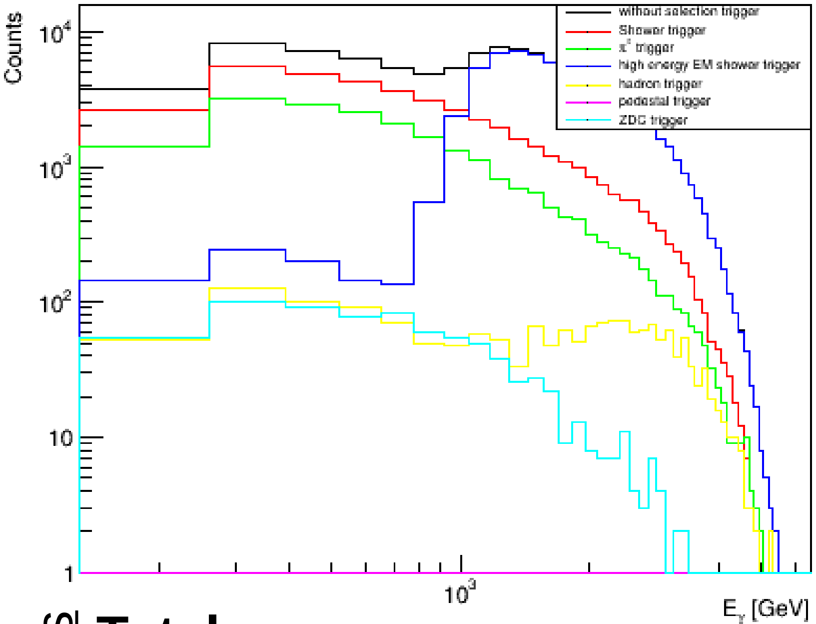


<u>Dead time of Arm2 is now dominated by VME to read out GSO scintillators</u>

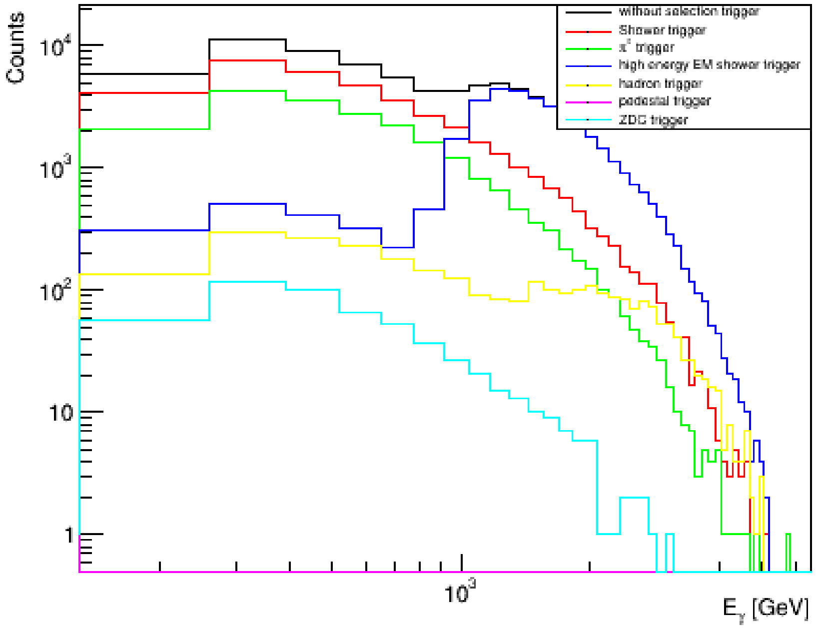
In Run III, the maximum DAQ speed of the Arm2 detector increased from 0.5 to **1.5 kHz**

Upgrade for Run III operations:
Optimization of the trigger scheme

Small Tower



Large Tower

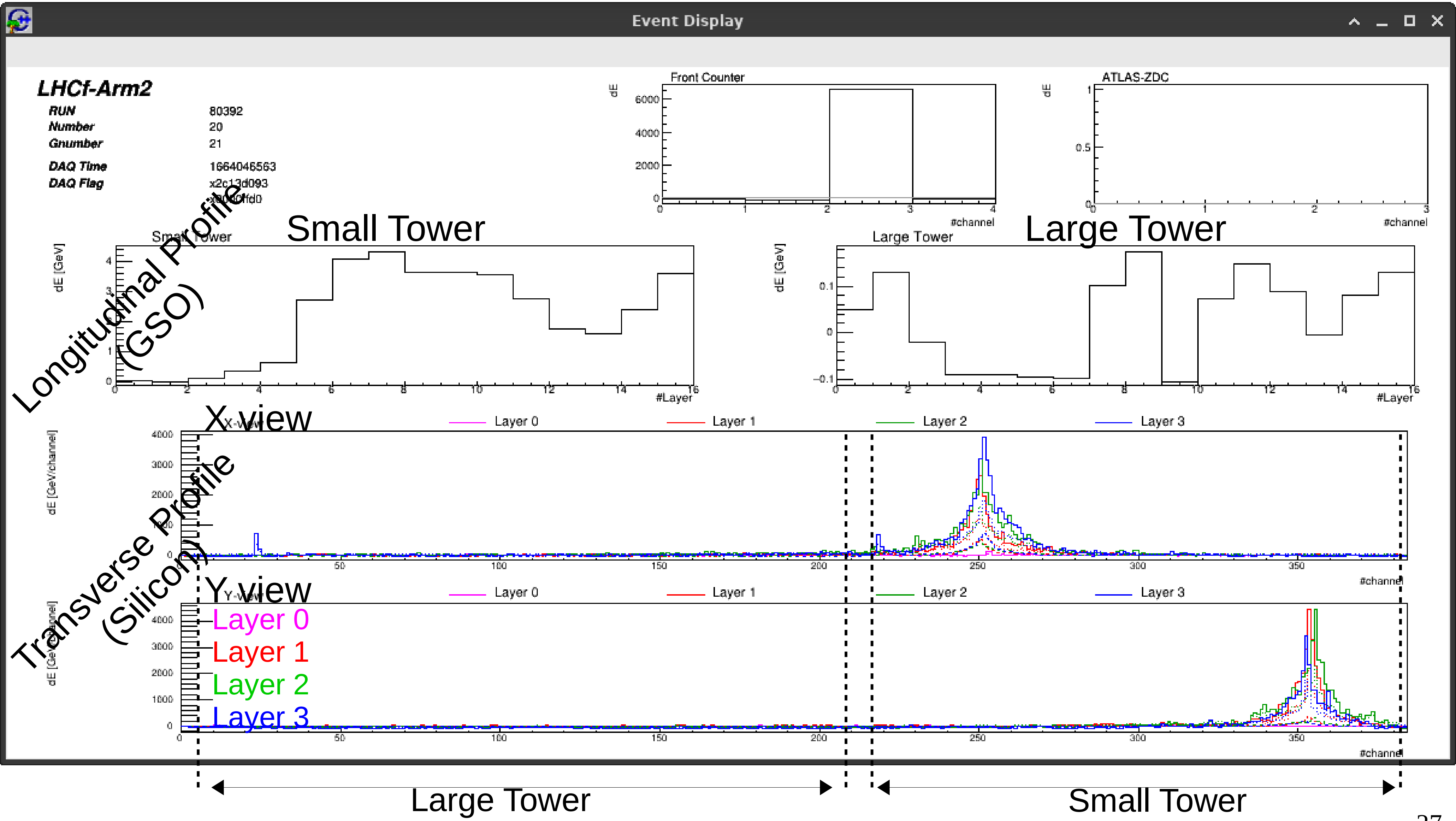


Trigger schemes

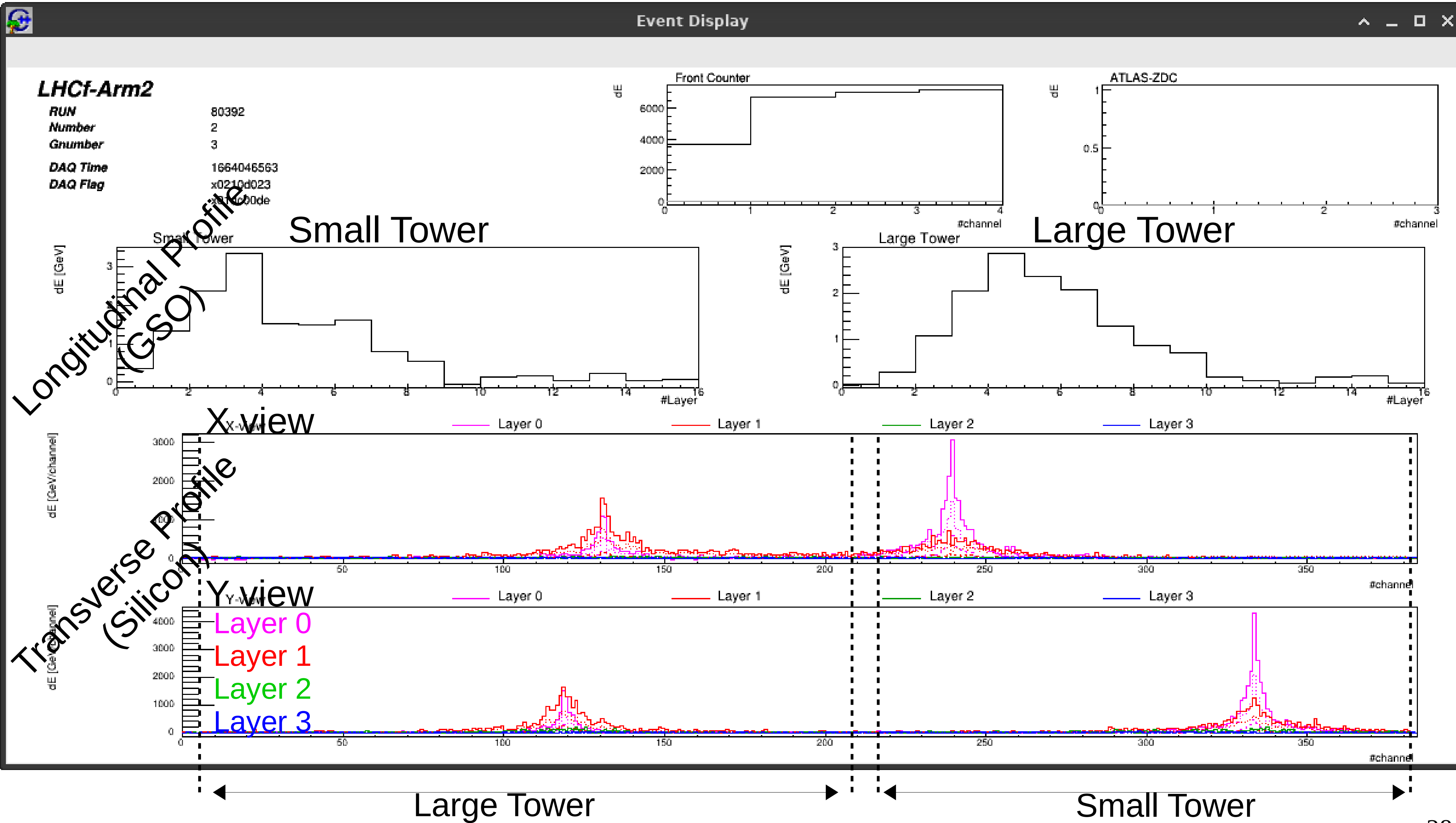
Total
Single
Type-I
Type-II
Hadron
ZDC
Pedestal

The different trigger schemes enhance different event categories

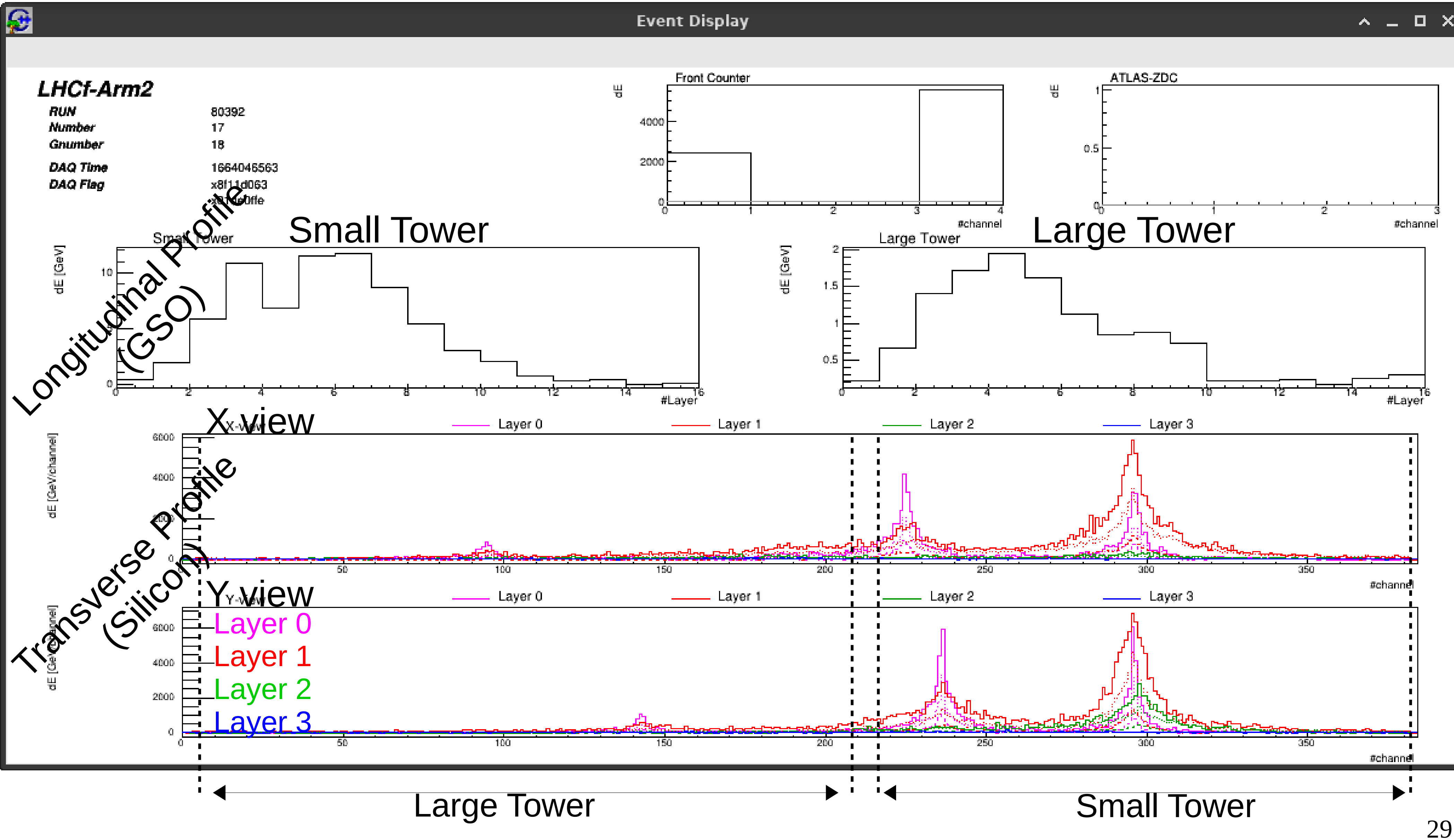
p-p √s = 13.6 TeV:
Hadron-like candidate in Small Tower



p-p √s = 13.6 TeV:
Type-I candidate



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



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

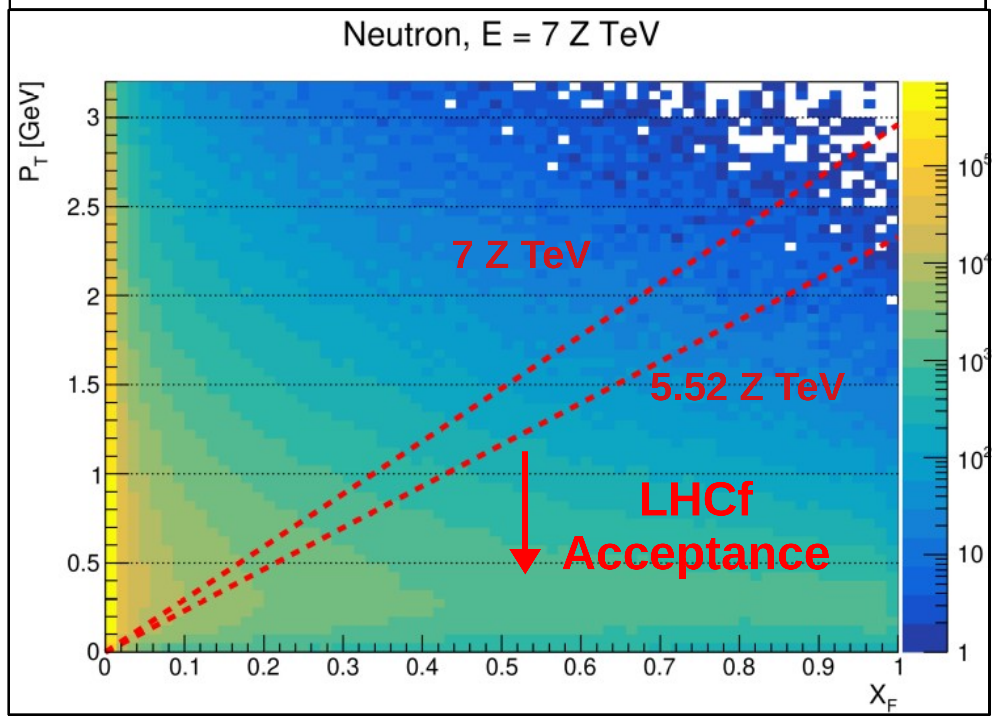
For each detector position
L_{int} ~ 40 nb^{-1}

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)

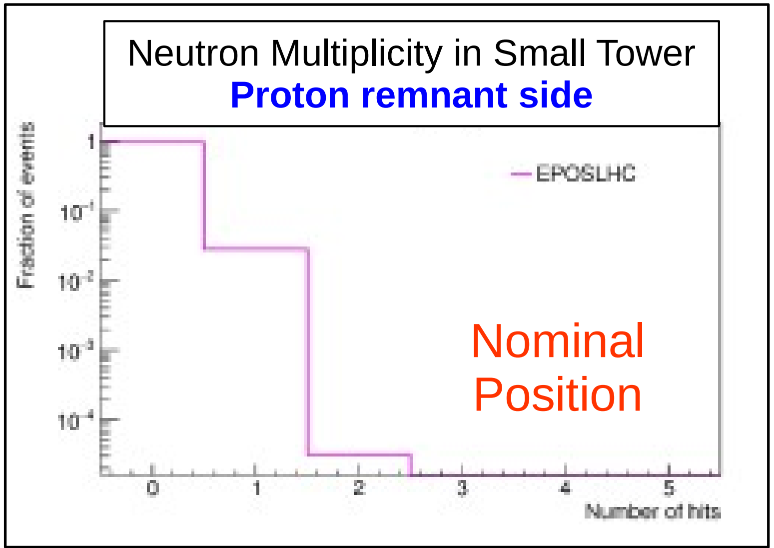
L_{int}~1.4 nb^{-1} for p-O
L_{int}~0.7 nb^{-1} for O-O

Higher collisions energy increases the LHCf detector acceptance



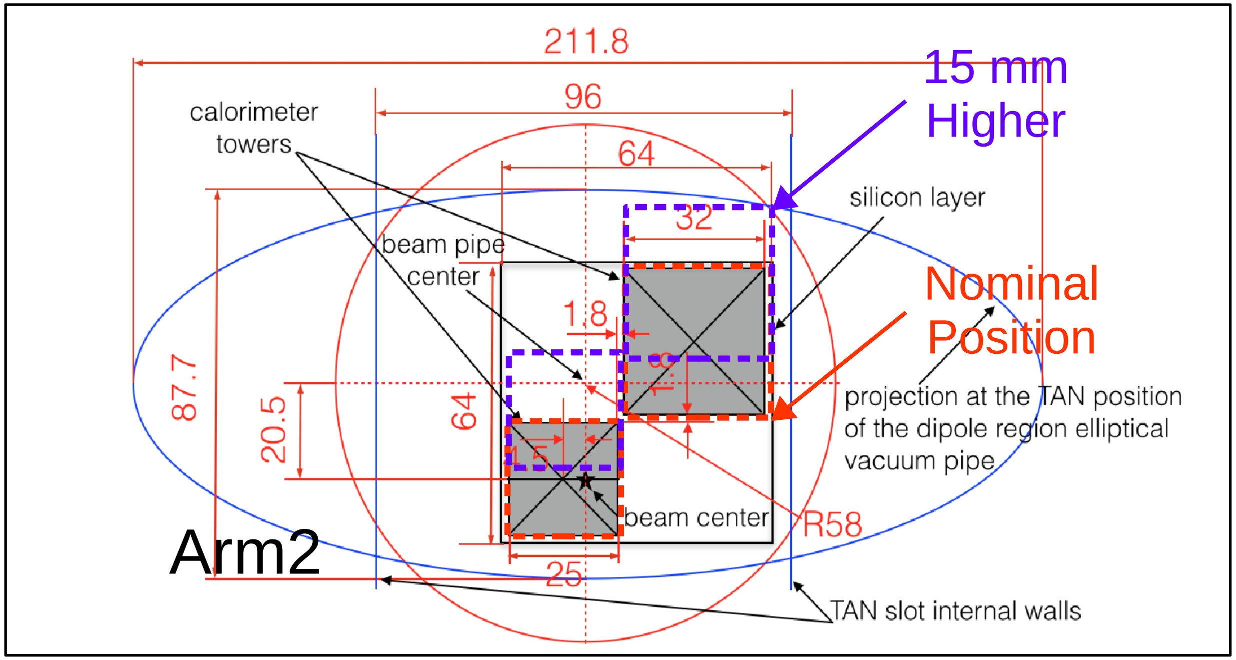
p-O and O-O operations:

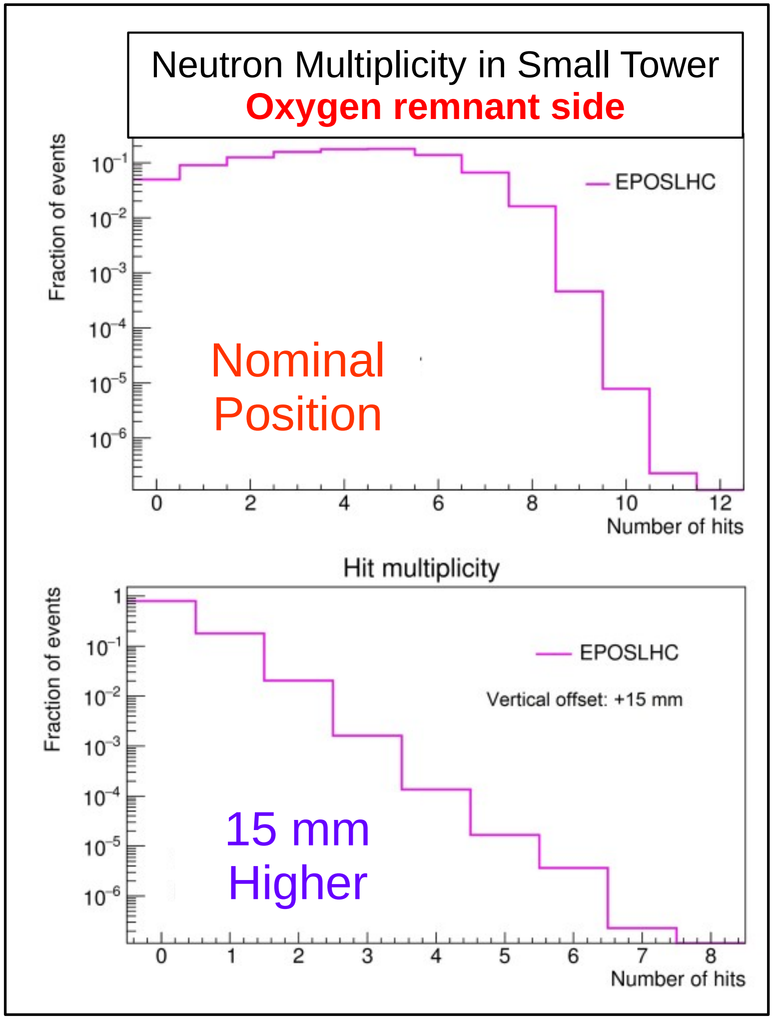
Main experimental challenge



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)



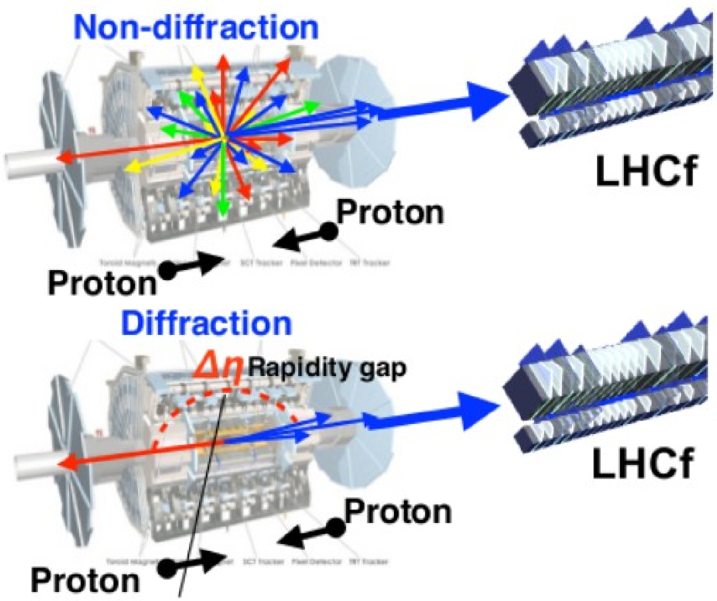


LHCf-ATLAS joint analysis

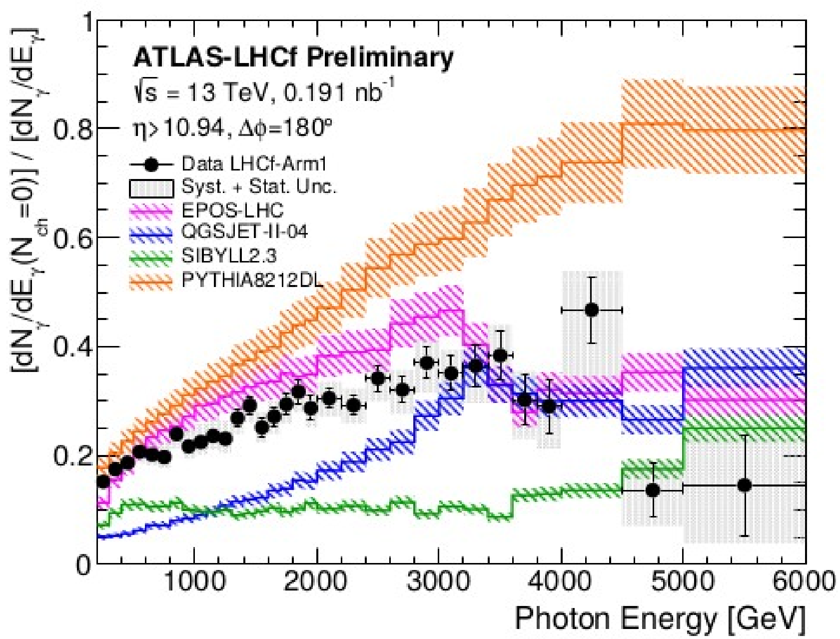
Preliminary result for photons in p-p √s = 13 TeV

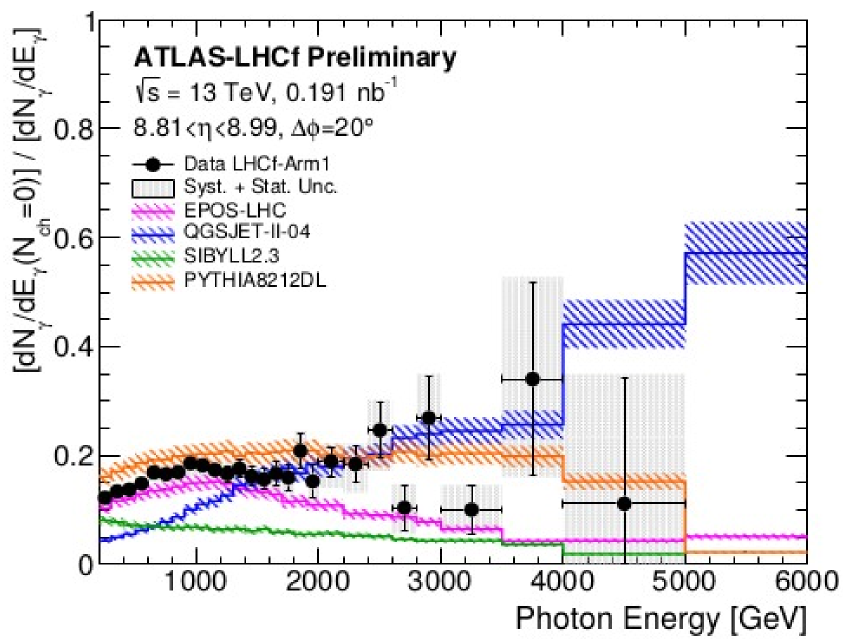
After a preliminary test in 2013, in 2015 and 2016 LHCf and ATLAS experiments had **common operation**.

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



$N_{veto}/N_{inclusive}$





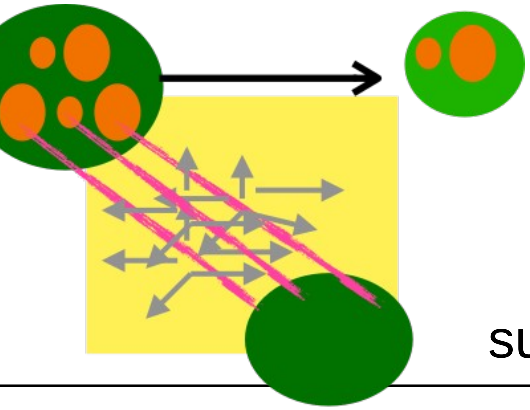
ATLAS-CONF-2017-075

...paper in finalization

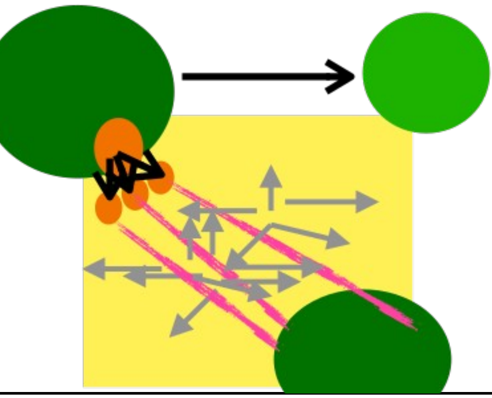
LHCf-ATLAS joint analysis

On-going analysis

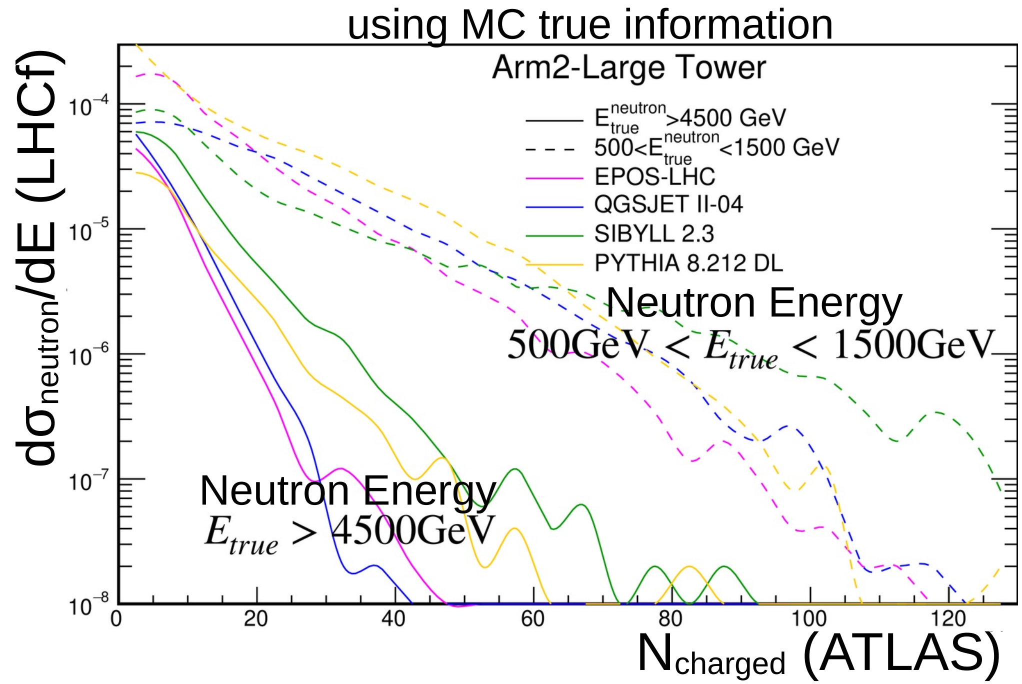
Study of **mechanism of multiparton interaction** using neutron events in LHCf as proposed by S. Ostapchenko et al., Phys. Rev. D 94, 114026



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+π^0)
- 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%)