Status and Prospects of the LHCf experiment

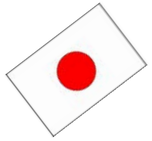
Hiroaki MENJO *ISEE, Nagoya University, Japan*
on behalf of LHCf collaborations

ISEE
Institute for
Space-Earth Environmental Research

LHCf

ISVHECRI 2024, 8-12 July 2024, Puerto Vallarta, Mexico

LHCf Collaboration



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S.Torii *Waseda University, Japan*
Y.Shimizu, T.Tamura, *Kanagawa University, Japan*
N.Sakurai *Tokushima University, Japan*
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INFN, Univ. di Firenze, Italy
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Photo @ 2022 operation

High Energy Cosmic-Ray Observation

CR primary energy:
10^9-10^{20} eV

High energy interaction

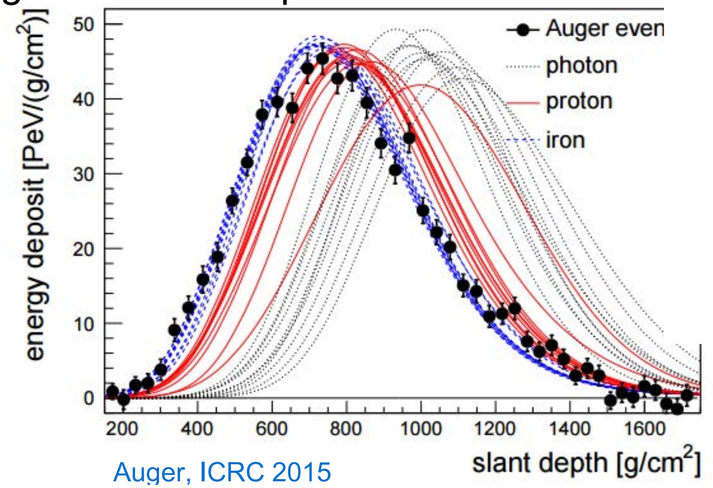
secondaries' interactions

Low energy interactions

- Reconstruct primary information from observed showers
  - Energy
  - Direction
  - Composition (particle type)

Require precise understanding high energy interactions

Longitudinal development of 10^{19}eV showers

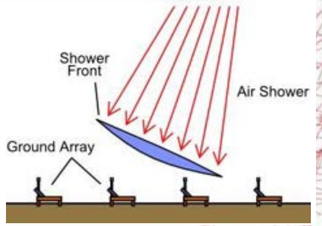


Auger, ICRC 2015

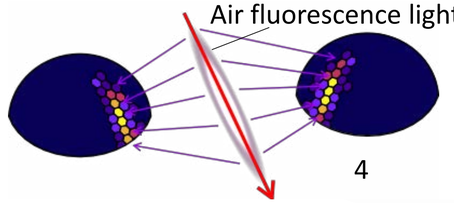
- However, current understanding is not enough
  - Diff. model prediction > experimental uncertainty
  - Muon deficit problem : 30-50% more muon in data

Sources of deficit ?
- vector mesons
- strange hadrons
- pion interactions
- nuclear effects

Surface detector (SD)



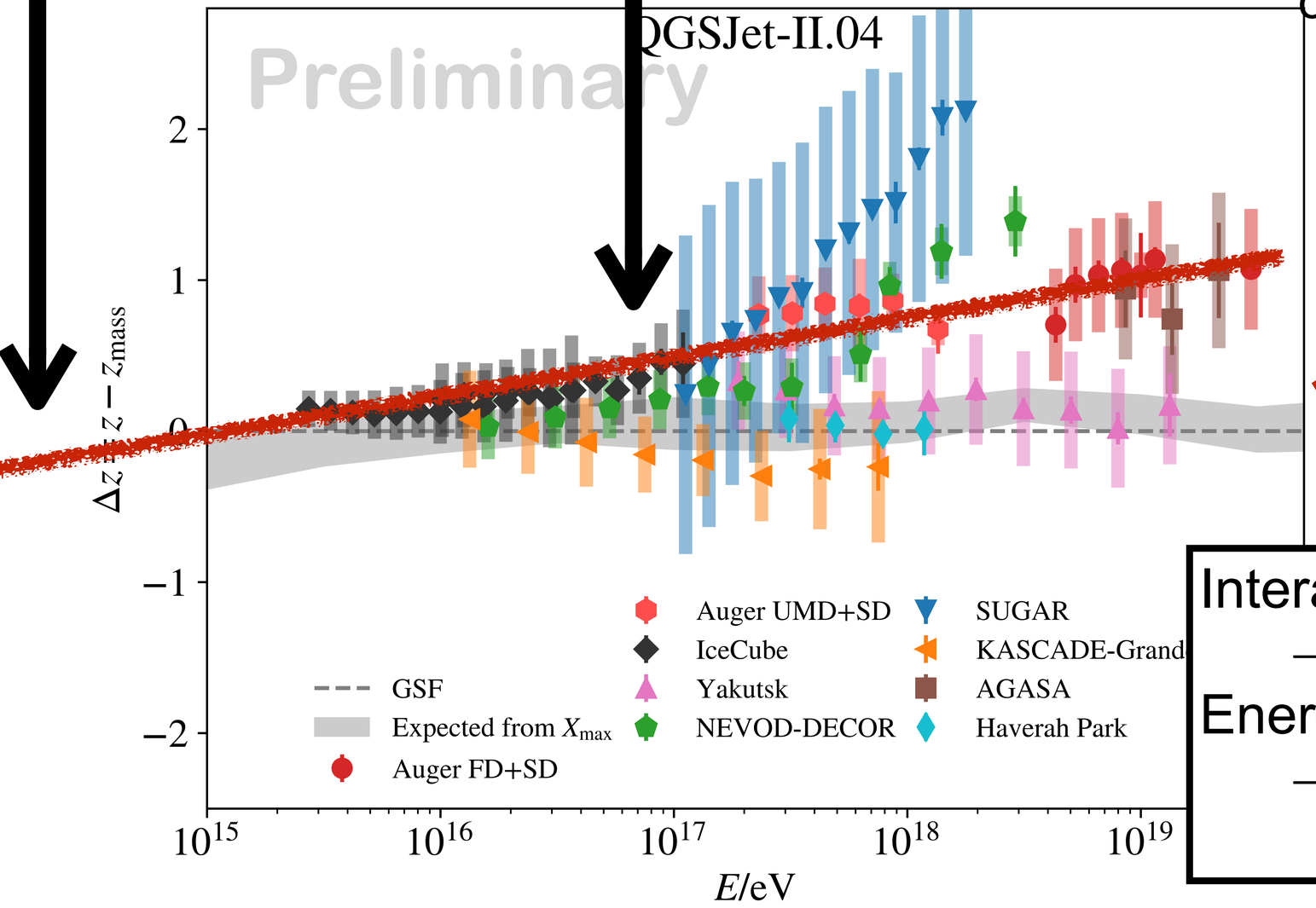
Fluorescence detector (FD)



Energy dependency of muon deficit

RHIC

LHC



Normalized muon numbers results observed by several CR experiments

$$z = \frac{\ln(N_\mu^{\rm det}) - \ln(N_{\mu p}^{\rm det})}{\ln(N_{\mu\,\rm Fe}^{\rm det}) - \ln(N_{\mu p}^{\rm det})}$$

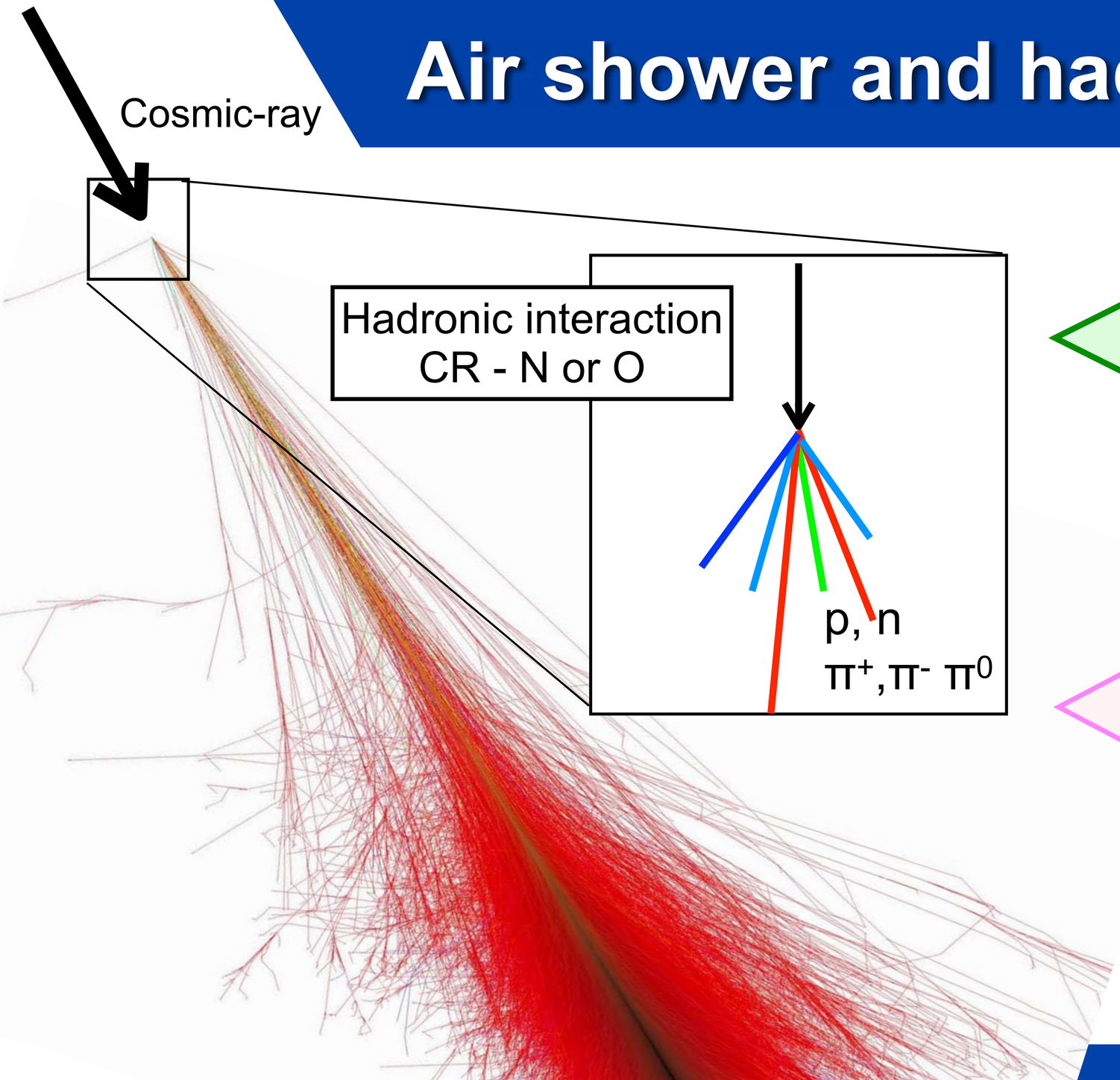
Muon deficit

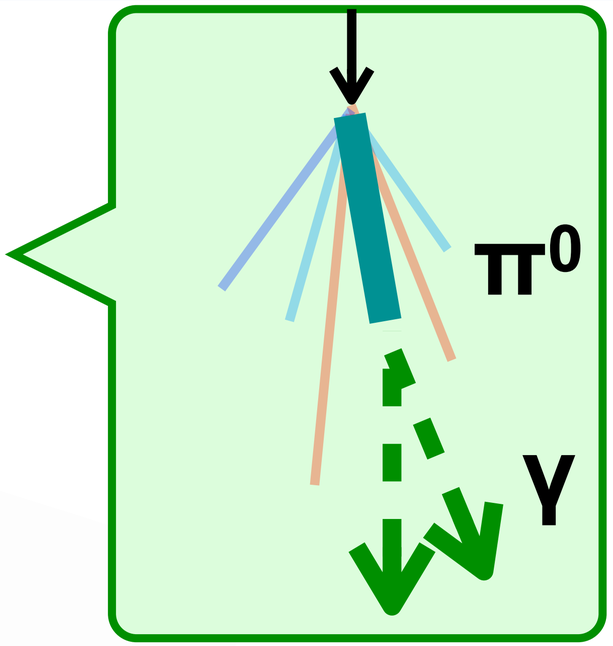
$$z_{\rm mass} \approx \frac{\langle \ln A \rangle}{\ln 56}$$

Interaction study at the highest energy
→ LHC ($\sqrt{s}$=14TeV, $E_{\rm lab} = 10^{17}$eV)
Energy dependency
→ RHIC ($\sqrt{s}$=0.5 TeV, $E_{\rm lab} = 10^{14}$eV) v.s. LHC

J.C. Arteaga-Velmázquez ICRC2023

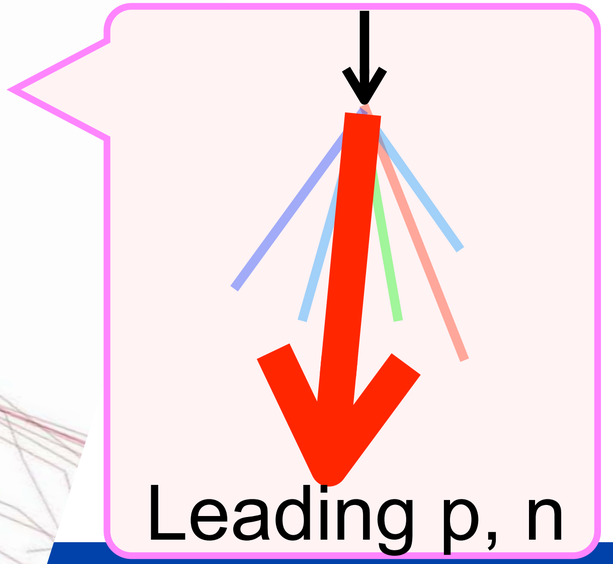
Air shower and hadronic interaction





Neutral pions

- $\pi^0 \rightarrow 2\gamma$
- Induce electromagnetic showers

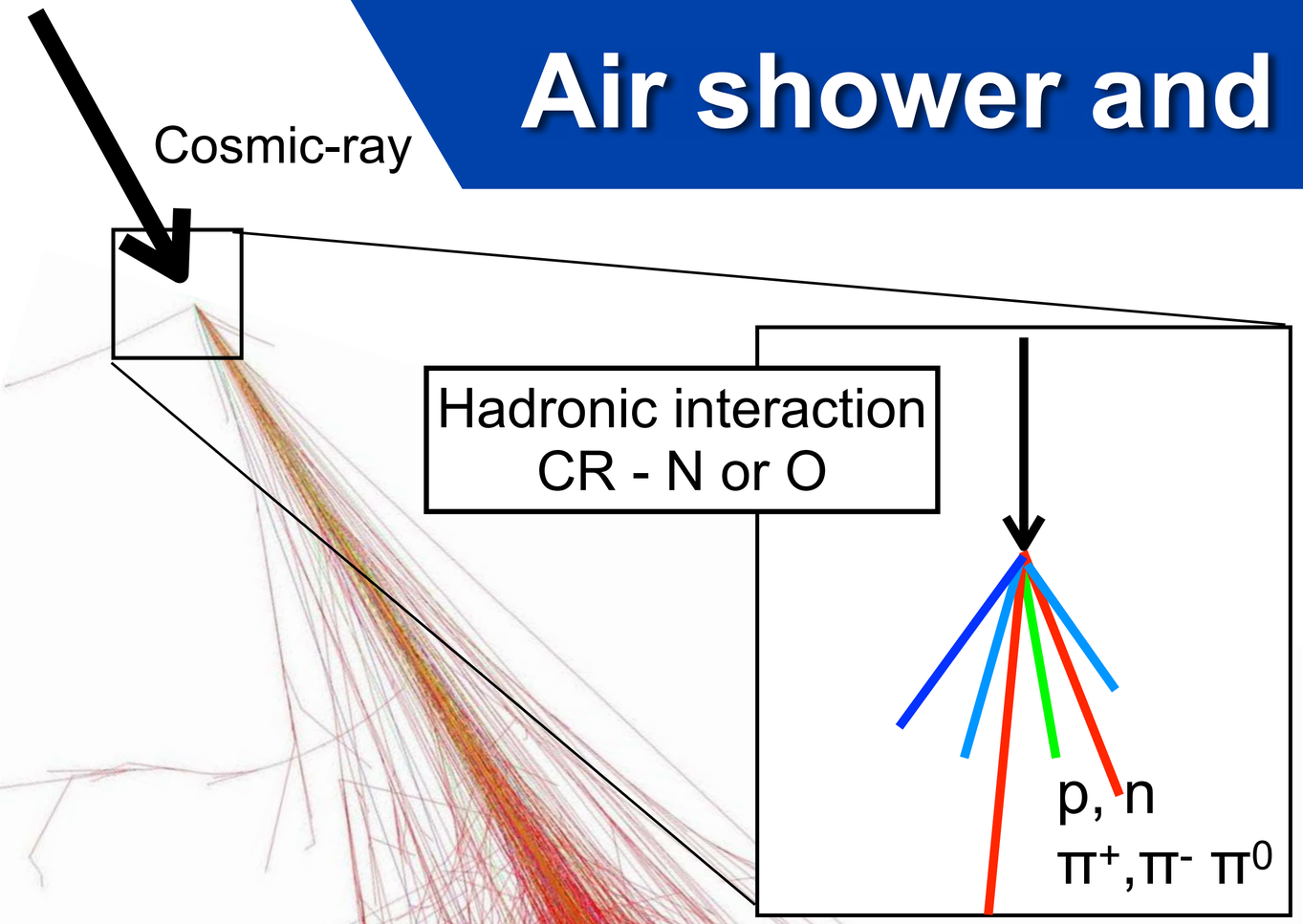


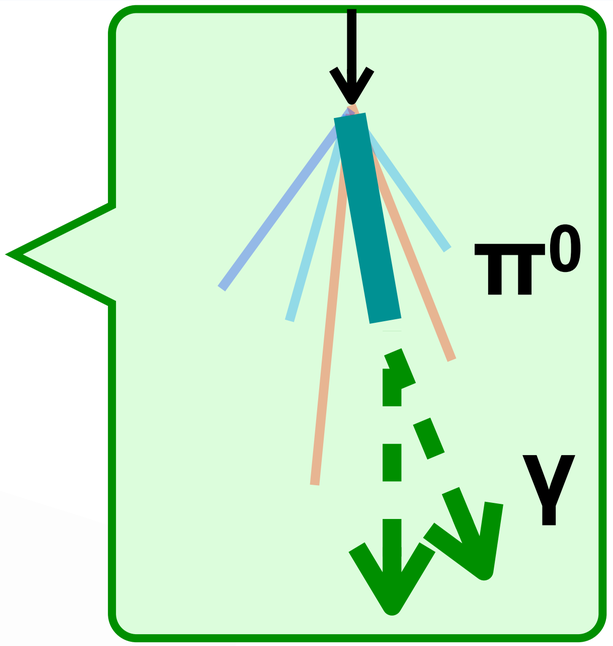
Leading baryons

- bring the energy to next collisions
- Inelasticity: fraction of energy used for particle productions

$k = 1 - E_{leading}/E_{CR}$

Air shower and hadronic interaction





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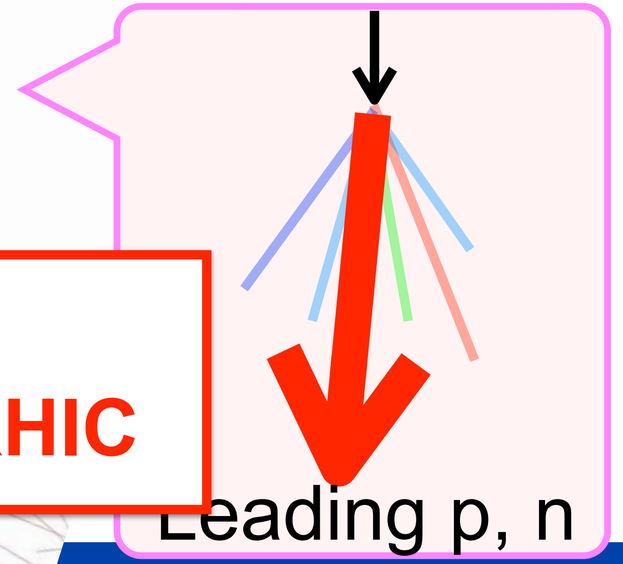

Leading baryons

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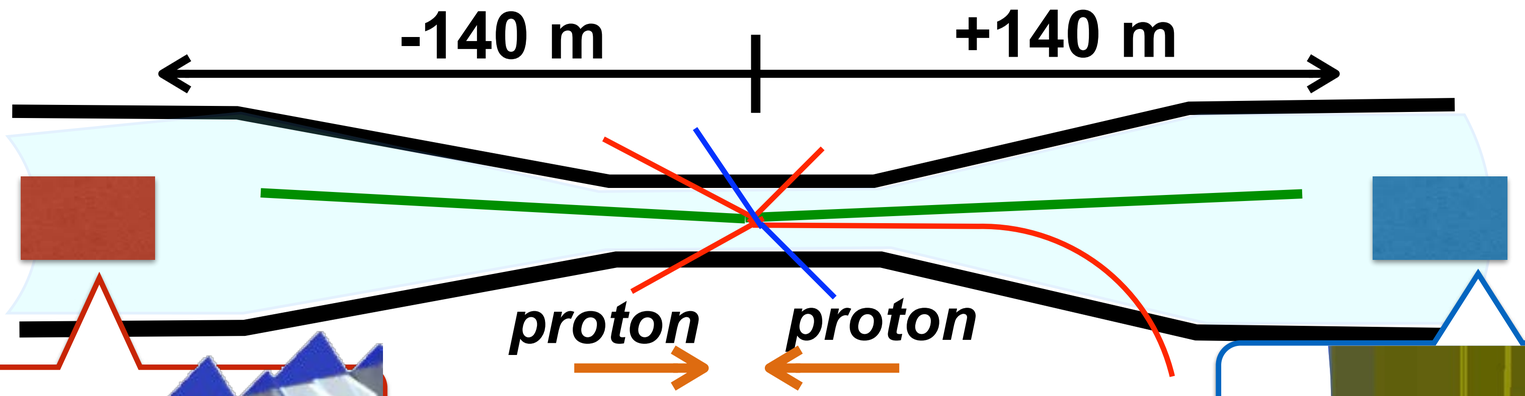
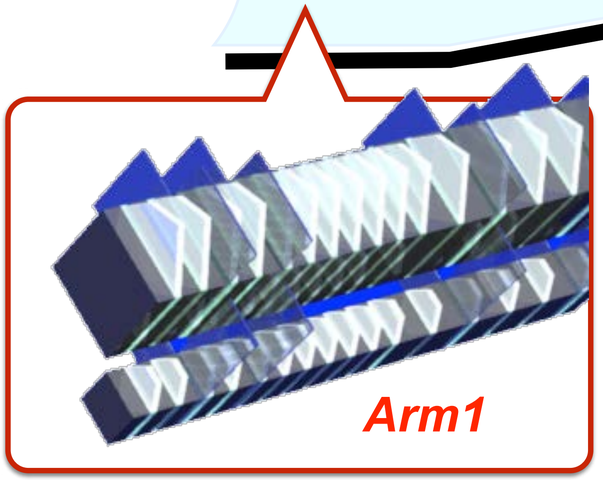
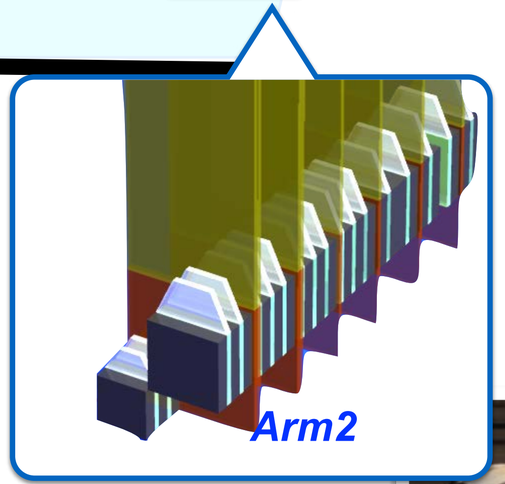
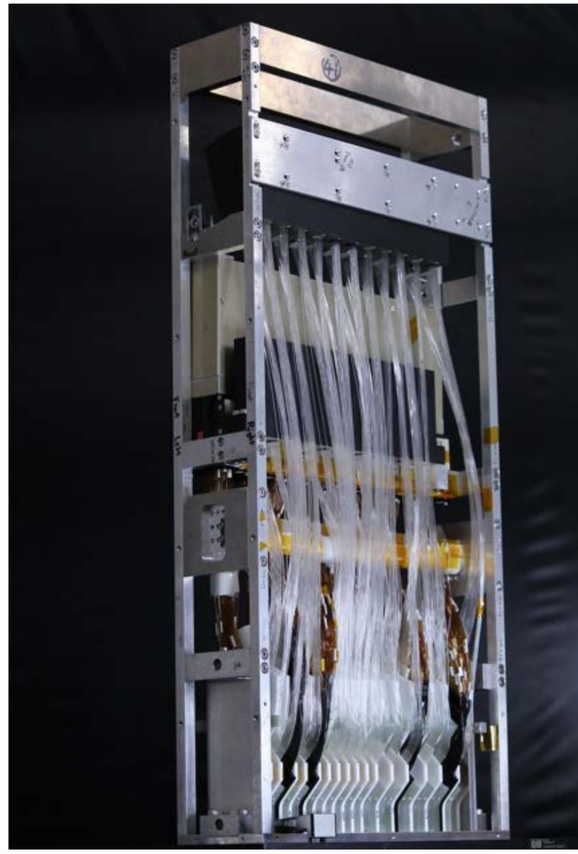
LHCf and RHICf measures the very forward region at LHC/RHIC

LHCf experiment









Location

- ATLAS interaction point
- +/- 140m from the IP
- Cover Zero degree of collisions pseudo rapidity η > 8.4

LHCf detectors

- Sampling and positioning calorimeters
- Two towers, 20x20, 40x40mm^2 (Arm1) , 25x25, 32x32mm^2(Arm2)
- Tungsten layers, 16 GSO scintillators, 4 position sensitive layers (Arm1: GSO bar hodoscopes, Arm2: Silicon strip detectors)
- Thickness: 44 r.l. and 1.7 λ

LHCf/RHICf Operations and Analyses

Run	E_{lab} (eV)	Photon	Neutron	π^0		LHCf-ATLAS joint analysis
p-p $\sqrt{s}$=0.9TeV (2009/2010)	4.3×10^{14}	PLB 715, 298 (2012)		-		
p-p $\sqrt{s}$=2.76TeV (2013)	4.1×10^{15}			PRC 86, 065209 (2014)	PRD 94 032007 (2016)	
p-p $\sqrt{s}$=7TeV (2010)	2.6×10^{16}	PLB 703, 128 (2011)	PLB 750 360 (2015)	PRD 86, 092001 (2012)		
p-p $\sqrt{s}$=13TeV (2015)	9.0×10^{16}	PLB 780, 233 (2018)	JHEP 2018, 73 (2018) JHEP 2020, 016 (2020)	preliminary		Photon in diffractive coll. Preliminary: ATLAS-CONF-2017-075 Final: under internal review
p-p $\sqrt{s}$=13.6TeV (2022)	9.0×10^{16}					
p-Pb $\sqrt{s_{NN}}$=5TeV (2013,2016)	1.4×10^{16}			PRC 86, 065209 (2014)		
p-Pb $\sqrt{s_{NN}}$=8TeV (2016)	3.6×10^{16}	prelimiary				
RHICf p-p $\sqrt{s}$=510GeV (2017)	1.4×10^{14}	Submitted ArXiv:2203.15416		Spin Asymmetry PRL 124 252501 (2021)		with STAR

LHCf/RHICf Operations and Analyses

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PRD 94 032007 (2016)

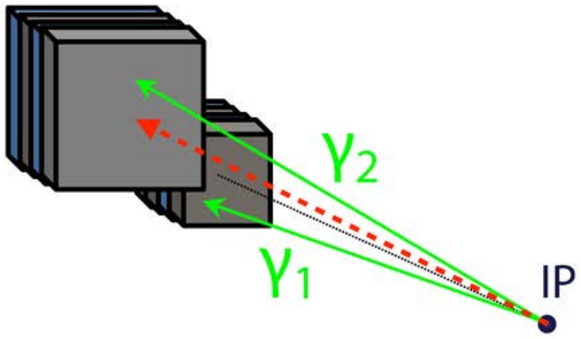
η

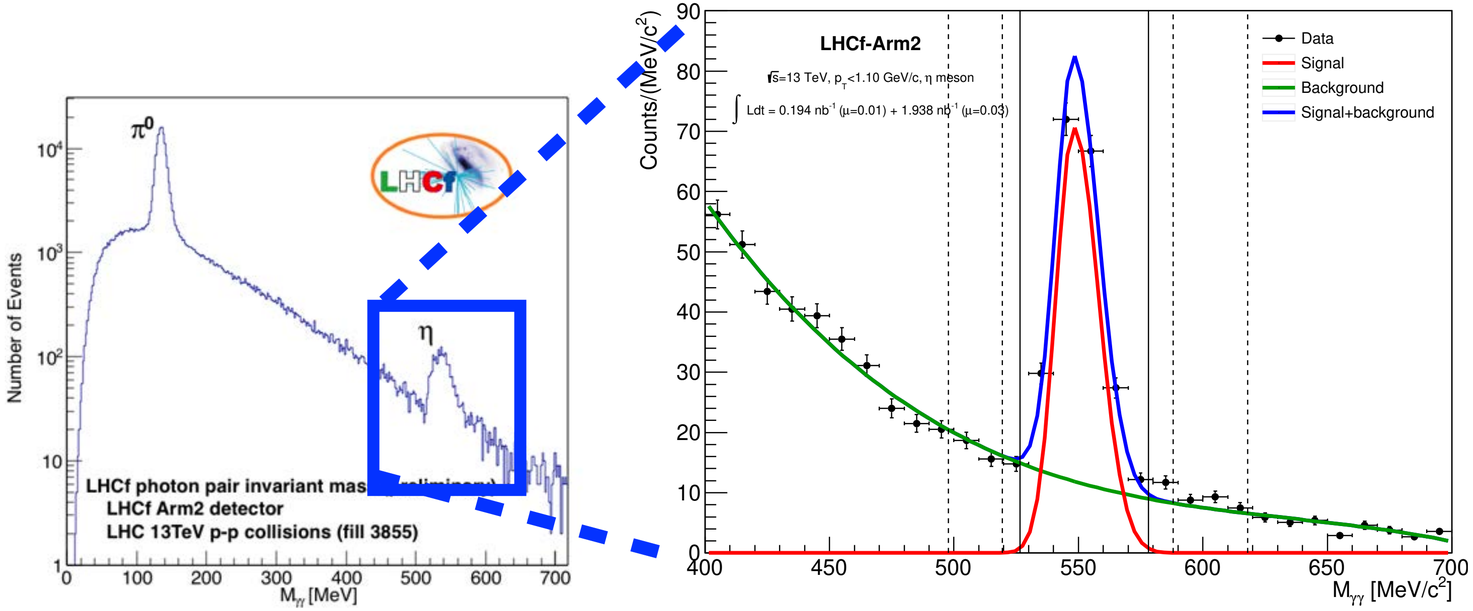
← new data

p-O operation in 2025

η meson measurement

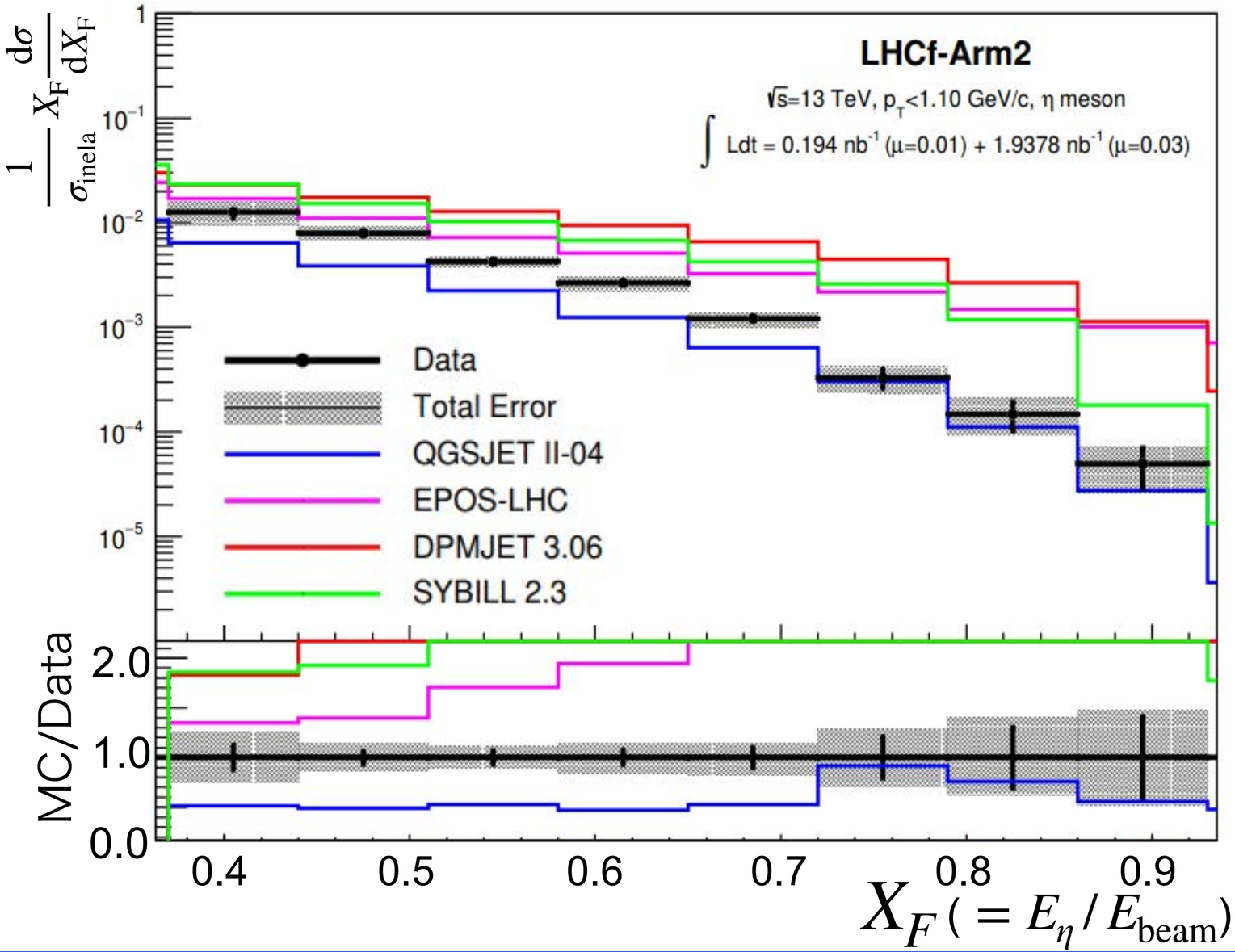
- Motivation
  - 2nd dominant source of photons (EM) in air showers.
  - Indirect probe of strange quark production.
  - Large discrepancy of predictions between models
- Data and analysis
  - pp, √s=13 TeV
  - Arm2 detector
  - Similar as Type1 π^0 analysis





O. Adriani et al., JHEP10 (2023) 169

η production diff. cross-section at *pp*, √s=13 TeV



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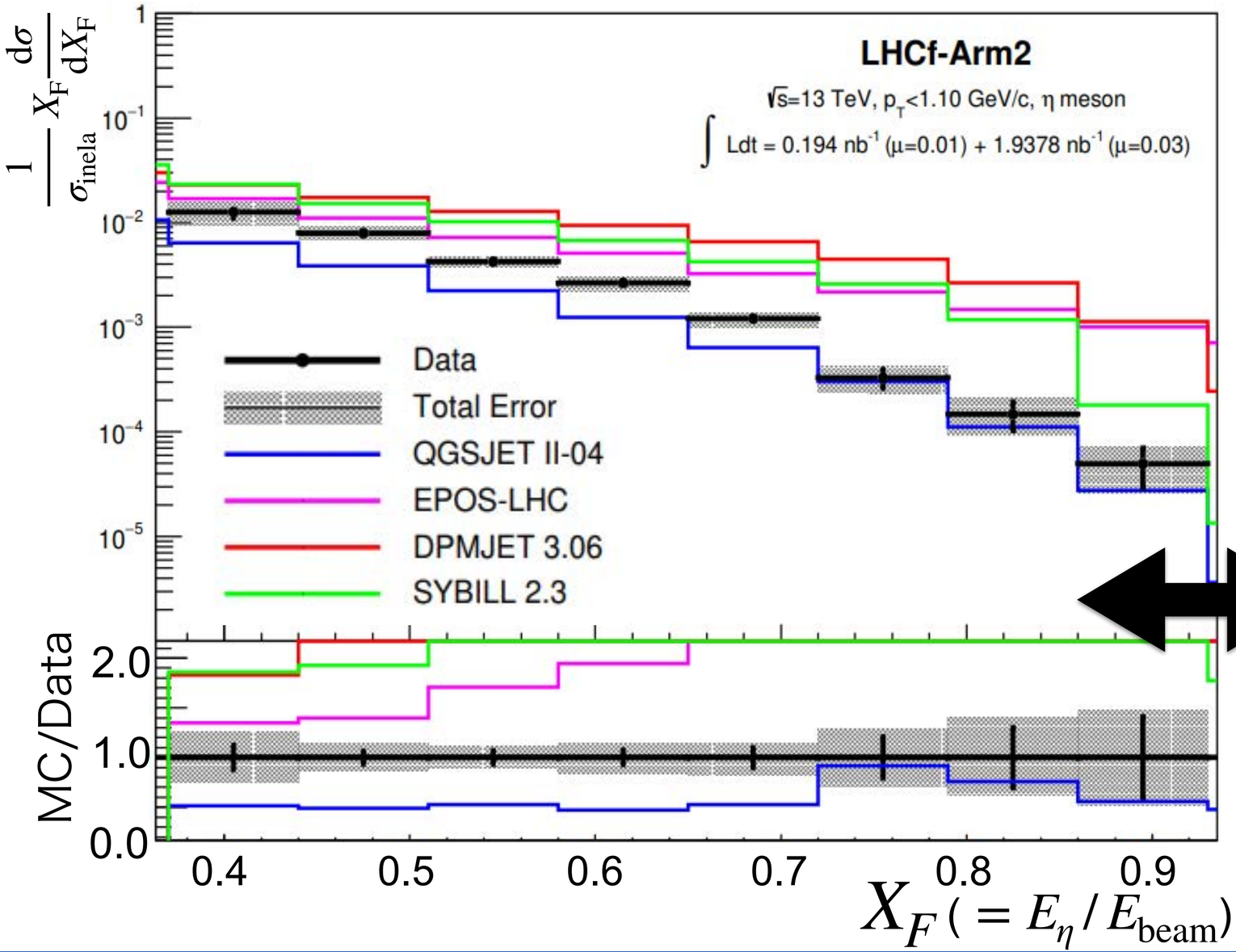
- $p_{\mathrm{T}} < 1.1\mathrm{GeV/c}$
- No model reproduce the data
- QGSJET II-04 shows good agreement in XF > 0.7, while lower σ in the others.
- EPOS-LHC, SIBYLL2.3, DPMJETIII, predict harder spectra than data.

η production diff. cross-section at *pp*, √s=13 TeV



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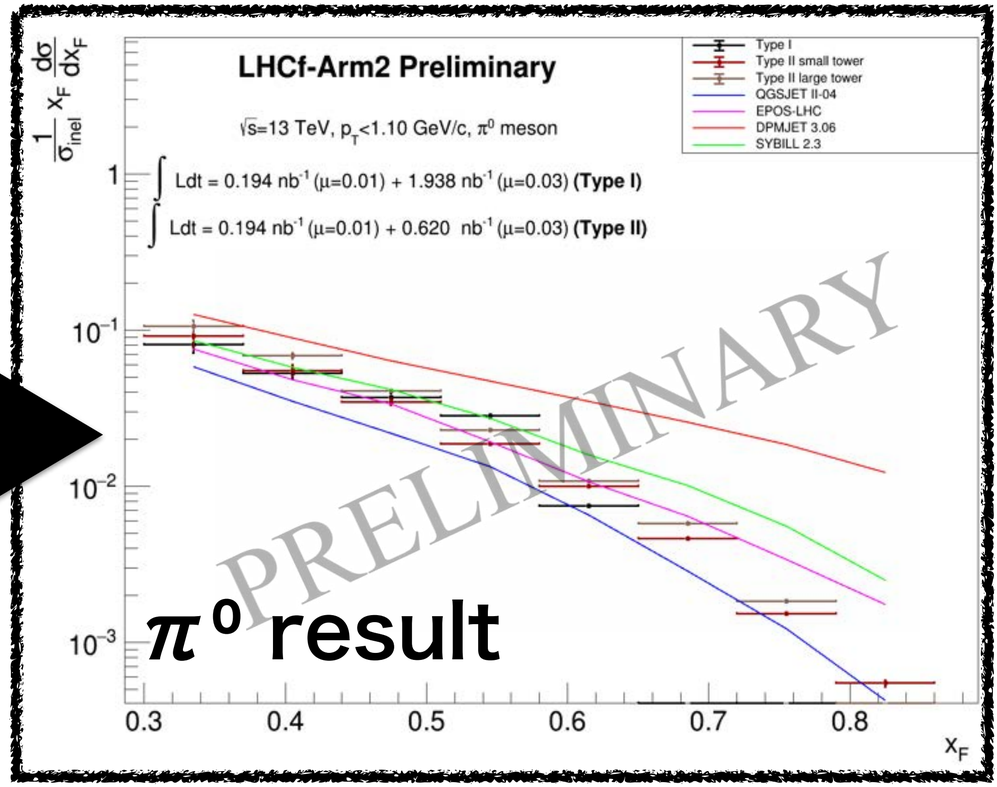
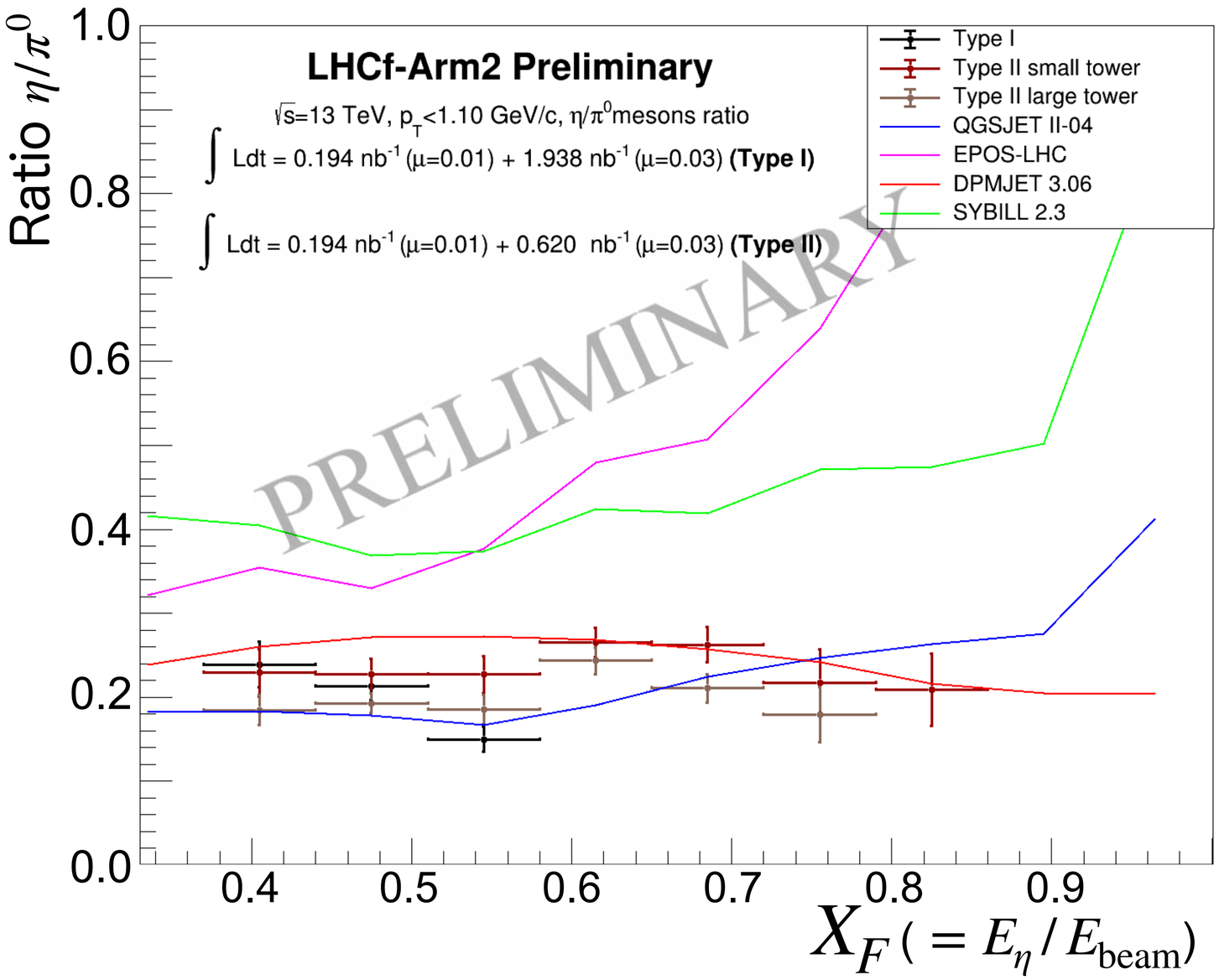


η/π^0 Ratio



- Data : constant in the whole energy range

EPOS-LHC, SIBYLL2.3

- Much larger than data

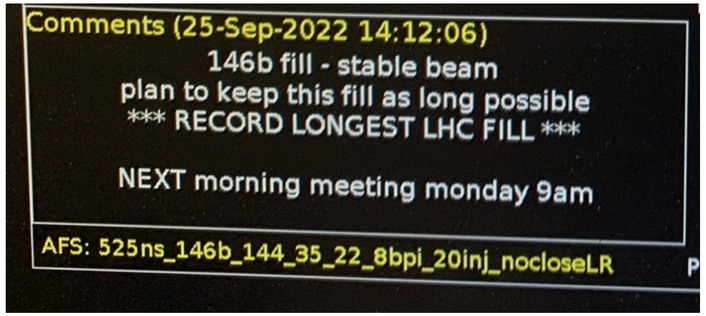
QGSJETII-04, DPMJET III

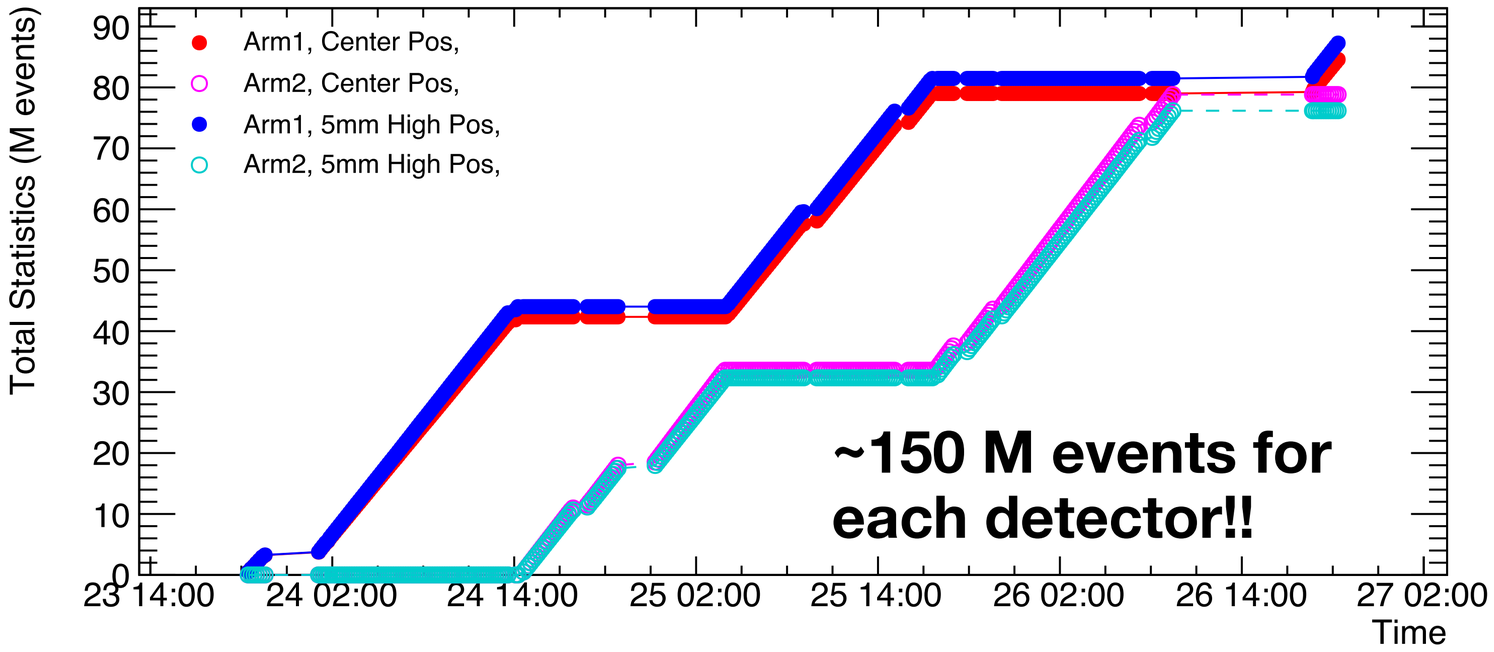
- Good agreement with data

Operation with pp, √s=13.6 TeV in 2022

- Successfully completed in Sept 2022
  - Record of the longest fill in LHC: 50 hours
  - Low luminosity special run L = 0.4 μb^{-1}/s, β^* = 19.2 m
  - 300 M events obtained in total (↔ 40 M in 2015)

    thanks to improvement of DAQ speed, higher luminosity, and optimization of trigger.



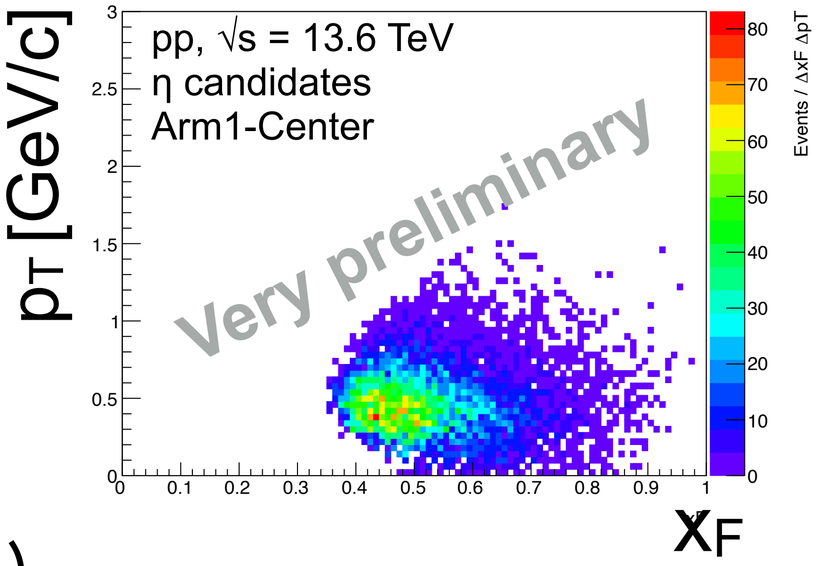


Analyses with large statistics

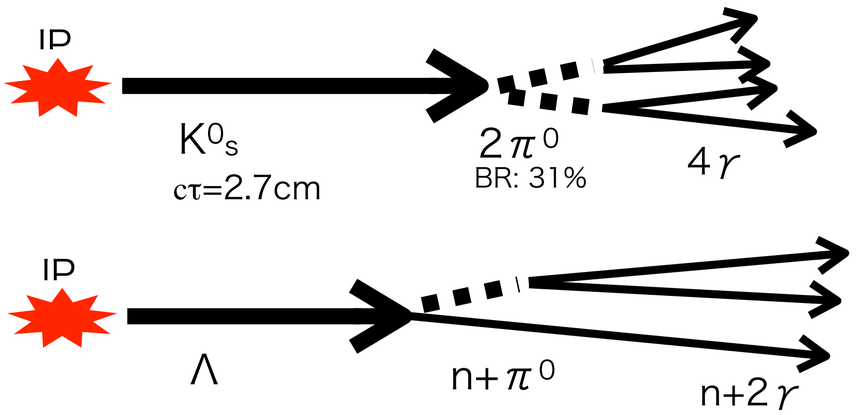
- Improvement of η and high-E π^0

  η: 2 k events (2015) → 22 k events (2022) **x10**

  → cross-section measurement in X_F-p_T bins

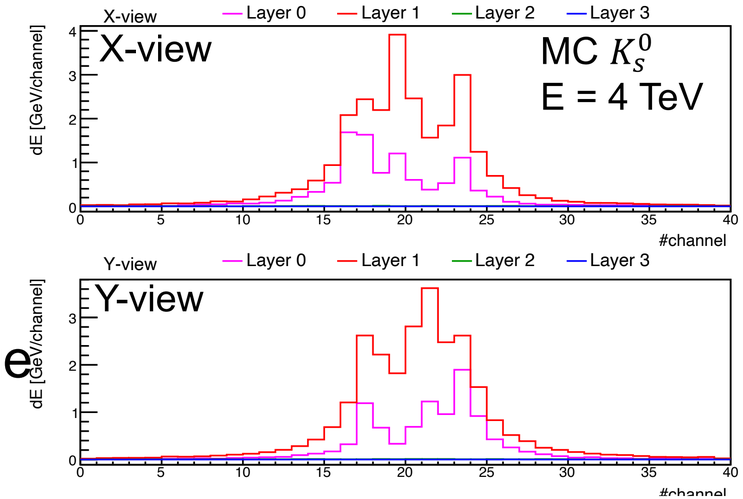


- Measurement of strange hadrons (K^0_S, Λ)



K^0_S : expect O(10^3) events

Reconstruction
of multiple hit events
→ Introducing
A machine learning technique

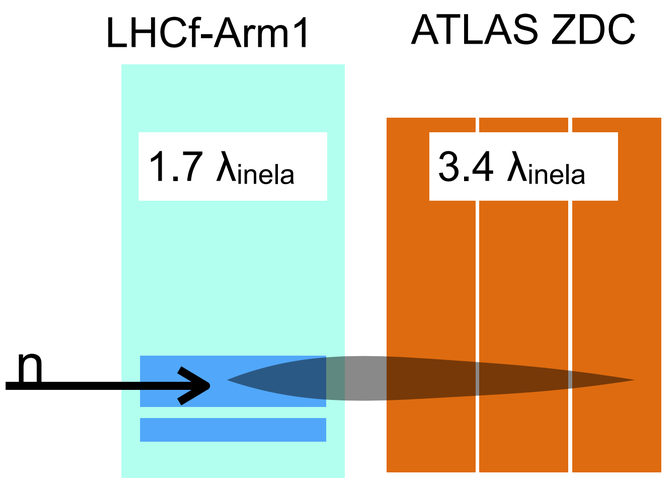


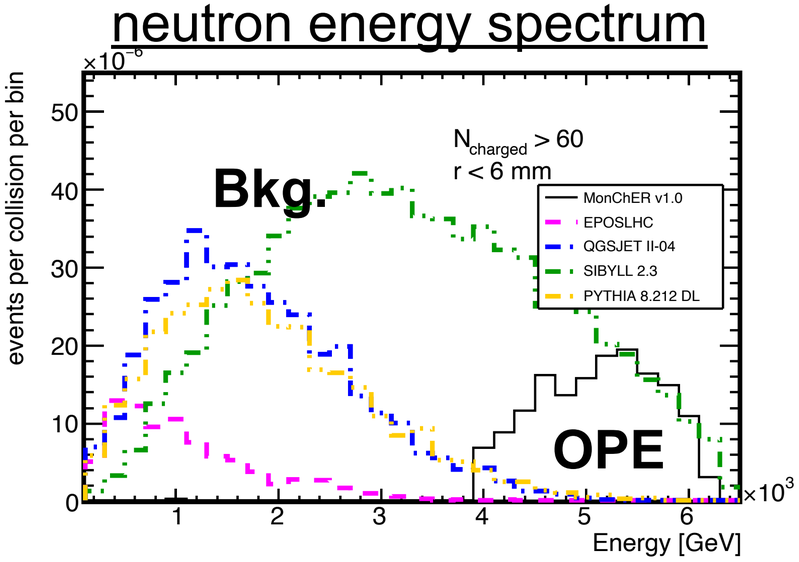
Joint operation with ATLAS

- Improvement from the last run in 2015
  - Large statistics **300** M events (↔ 6 M in 2015)
  - Participation of ATLAS ZDC and RPs
    - ZDC → Improvement of energy resolution for neutrons
    - RPs → Tagging scattered protons
- Physics Targets
  - Detailed study of single diffractive collisions
  - Measurement of proton excitation (Δ^+)
  - Measurement of Λ ($\Lambda \rightarrow n + \pi^0$)
  - p-π interaction study using OPE processes

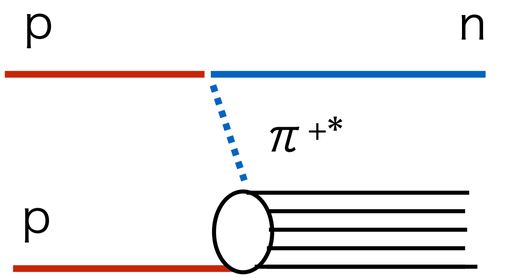
w/ RPs

w/ ZDC





One Pion Exchange (OPE)

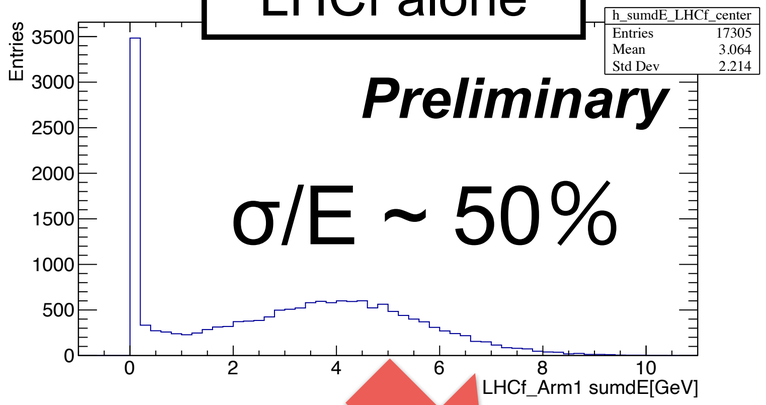


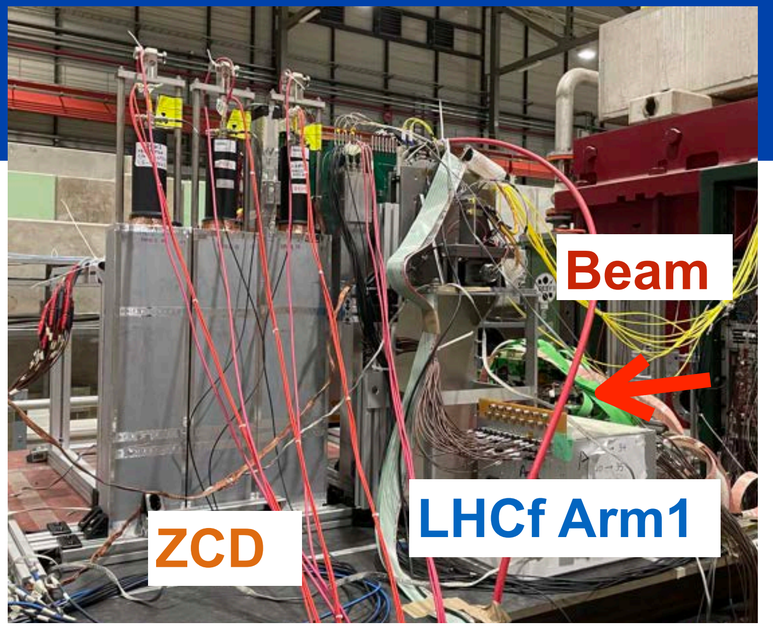
LHCf+ATLAS merged dataset is getting ready.
Start the physics analysis soon.

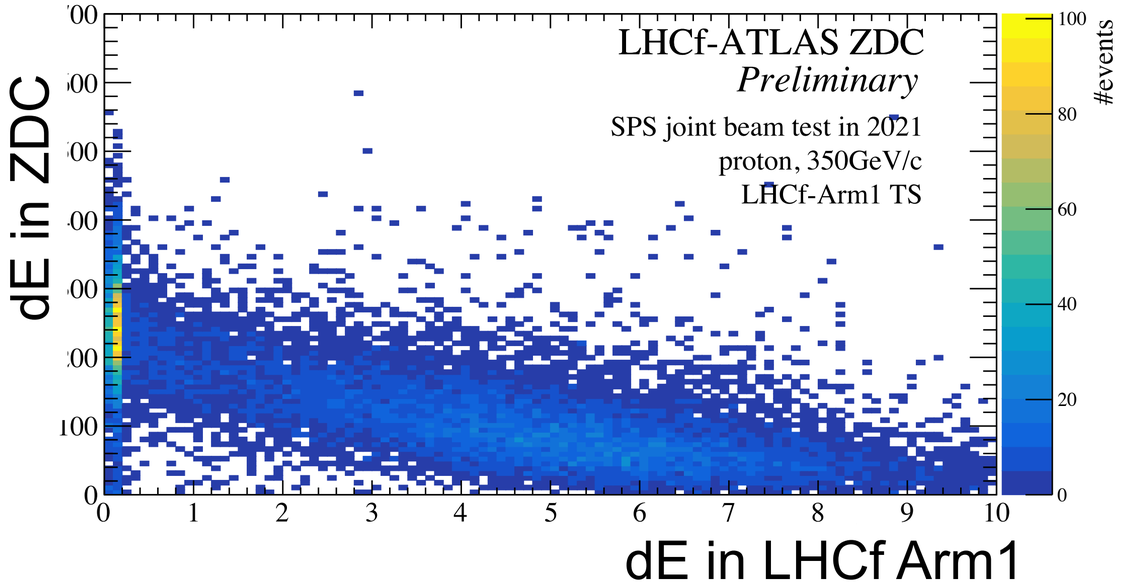
LHCf+ZDC beam test at SPS

- CERN SPS H4 beam line
- 1 week in Sept. 2021
- Proton 350 GeV/c beams
- obtained 650 k events in total

LHCf alone

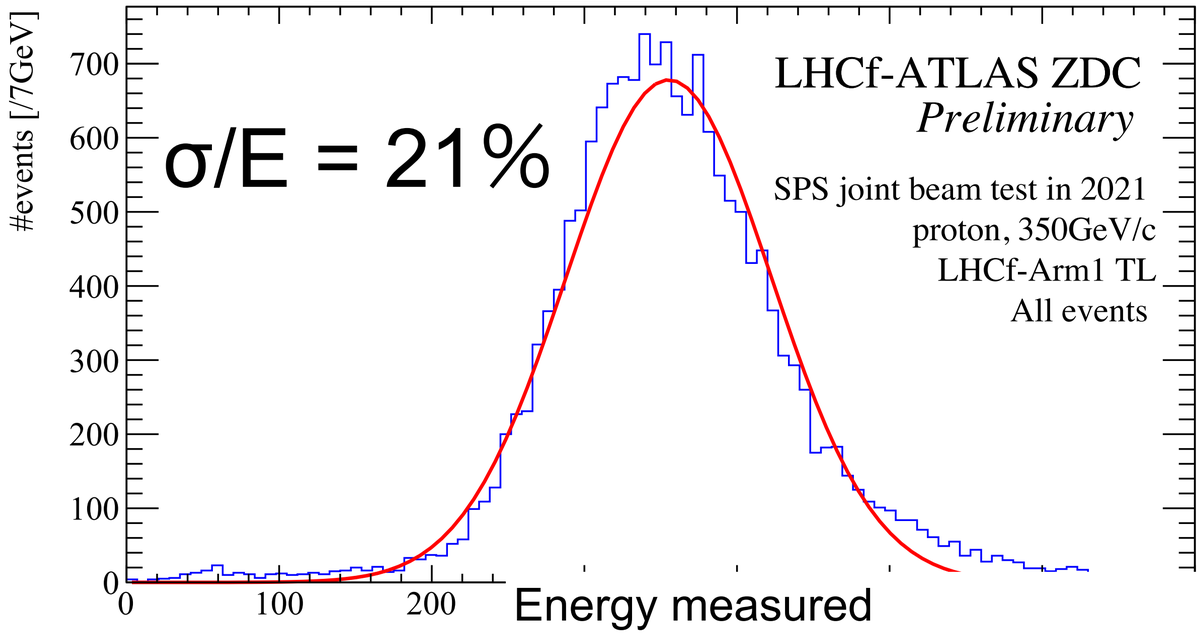






Confirmed improvement of energy resolution to 21%

LHCf + ZDC

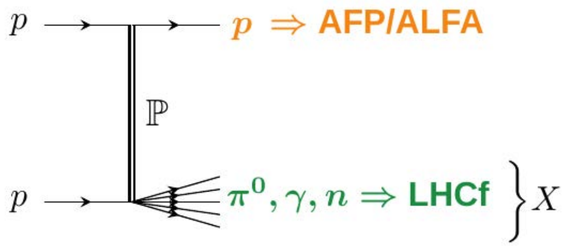


Joint operation with ATLAS RPs

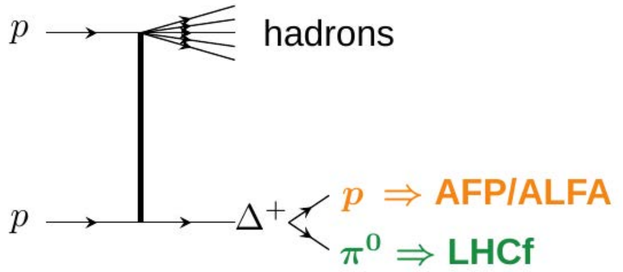
- Physics targets:
  - Detailed study of single diffractive collisions,
  - Measurement of proton excitation (very low-mass diff.)

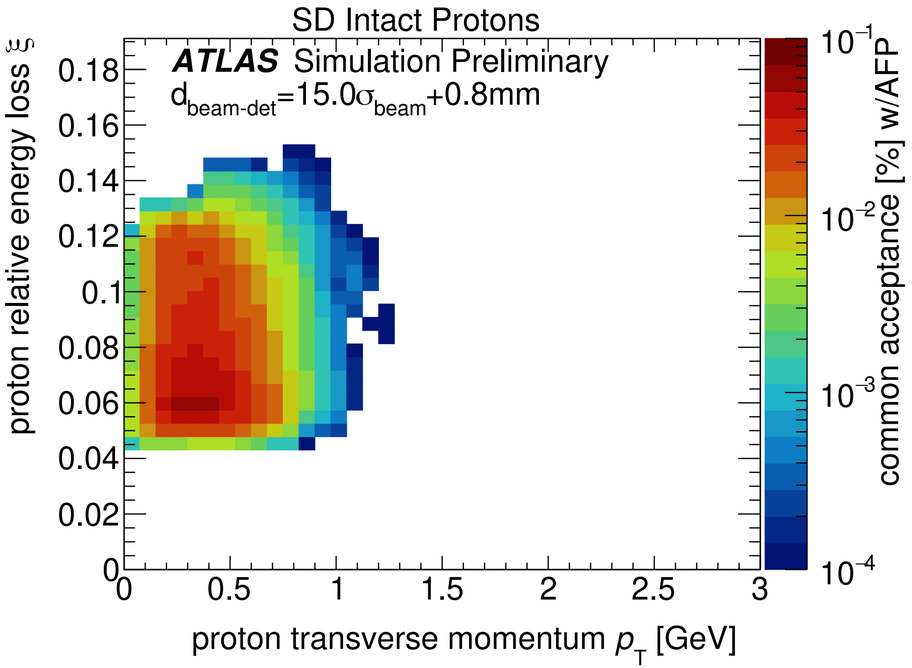
Fusibility study using MC
ATL-PHYS-PUB-2023-024

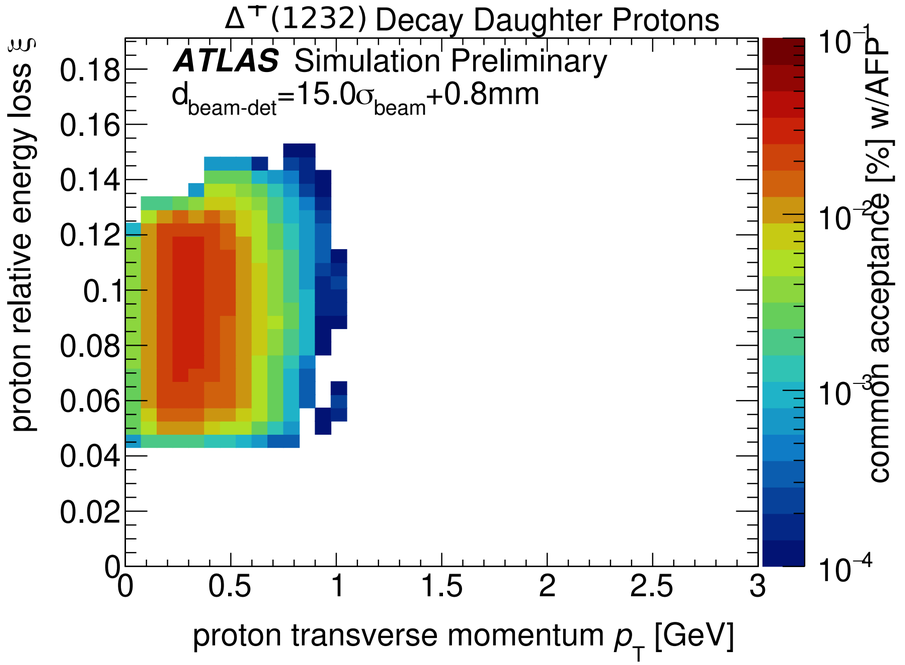
Single diffractive



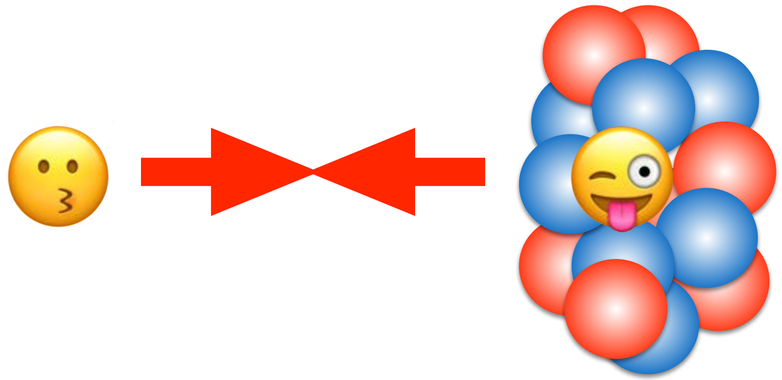
$\Delta^+(1232)$





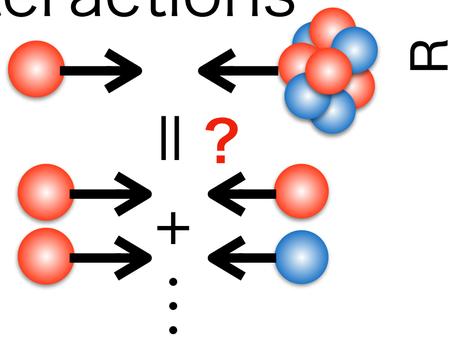


p-O measurement in 2025



Motivation

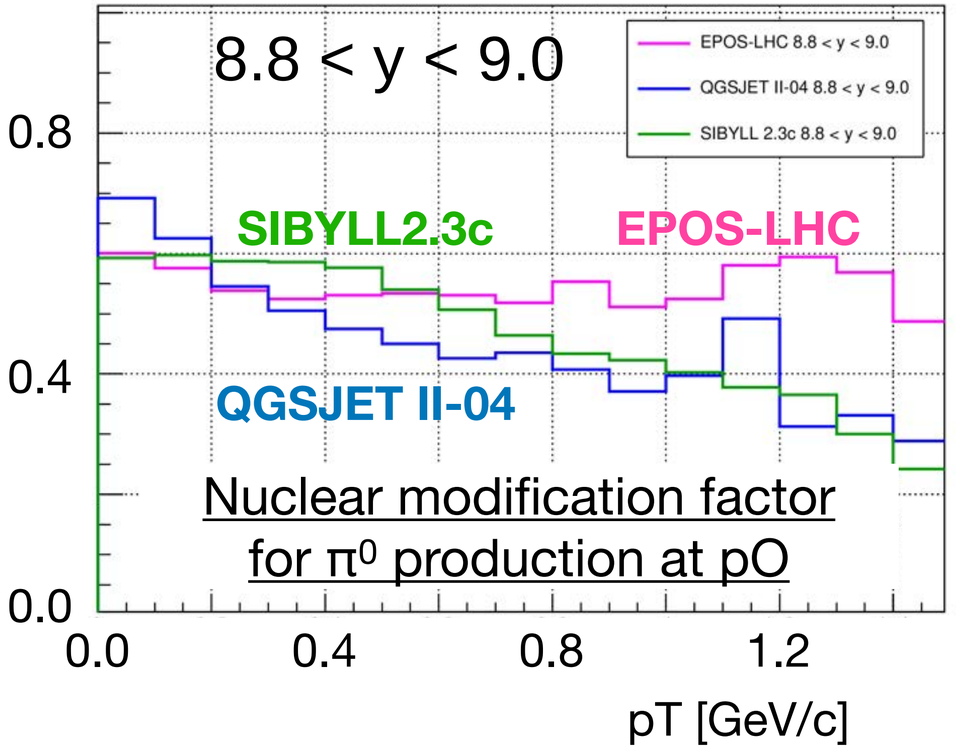
- Ideal condition of CR-Air interaction study
  - First proton-“light ion” collisions at colliders
  - Different modeling of nuclear effect induces difference predictions among models.
  - Negligible contribution of Ultra Peripheral Collisions (UPCs)
- Nucleus(nucleon)-Nucleus interactions
  - **Glauber theory**
    describe as superposition
    of nucleon collisions
  - **Nuclear effect**
    - Nuclear shadowing
    - Limiting Fragmentation
    - QGP (core-corona)



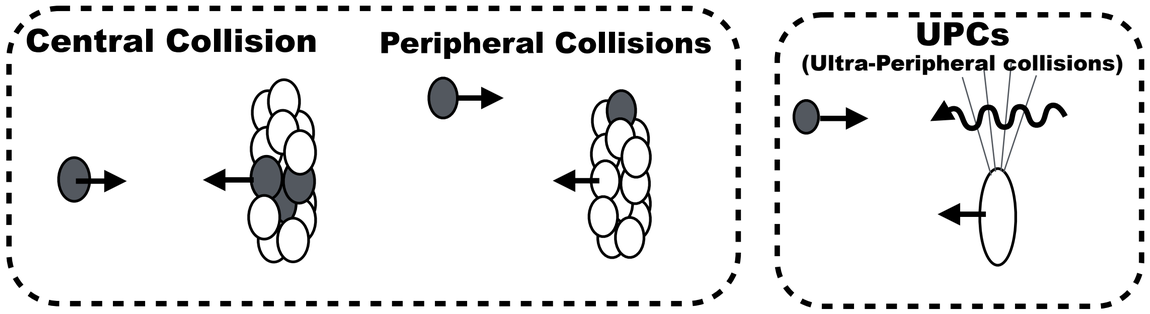
Nuclear Modification Factor

$$R = \frac{\sigma_{pO}}{A\,\sigma_{pp}}$$

A: average number of nucleon collision



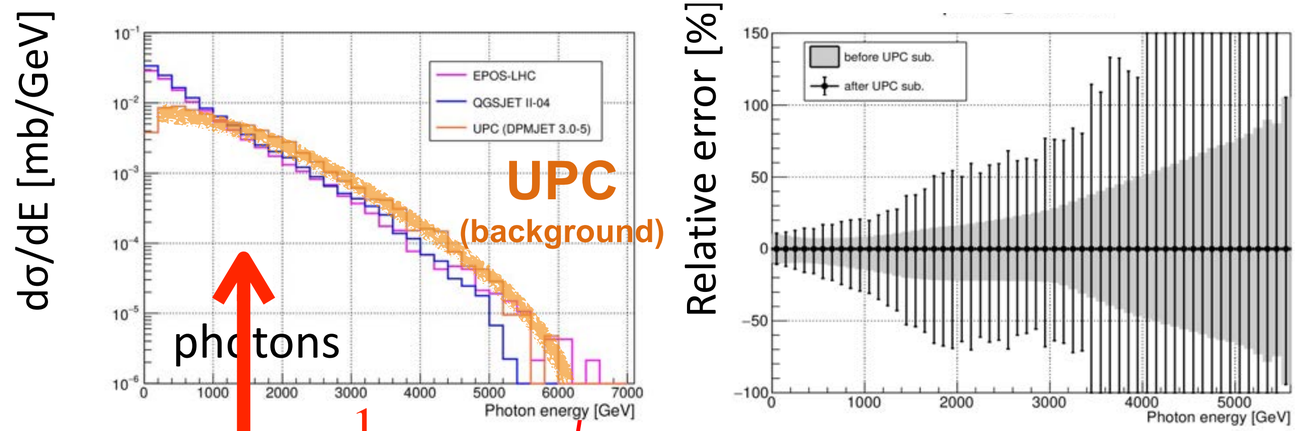
Effect of the Ultra Peripheral Collisions (UPCs)



- UPCs are background
  - Air : Oxygen atom (neutral)
  - LHC Beam : Oxygen nucleus (+8e)
- $\sigma_{UPC} \propto Z^2$
  - p-Pb : QCD ~ UPC
  - p-O : QCD >> UPC

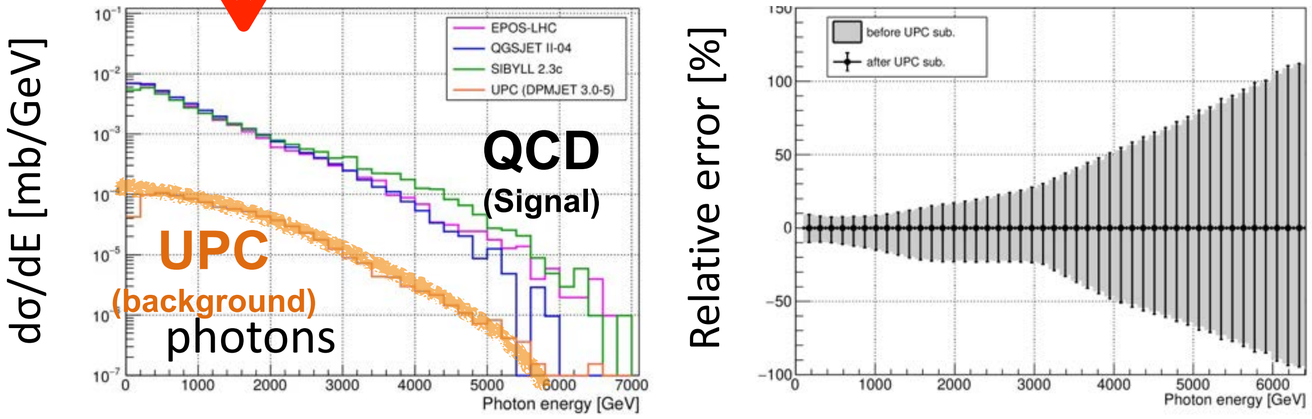
UPC contribution is negligible for "inclusive" measurement

p-Pb at $\sqrt{s_{NN}}$ = 8.2 TeV



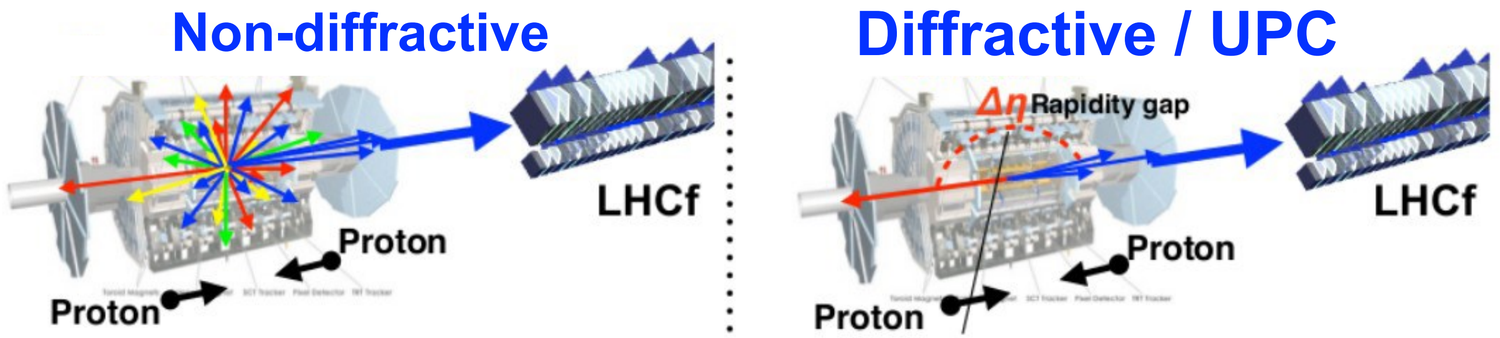
$\times \frac{1}{100}$

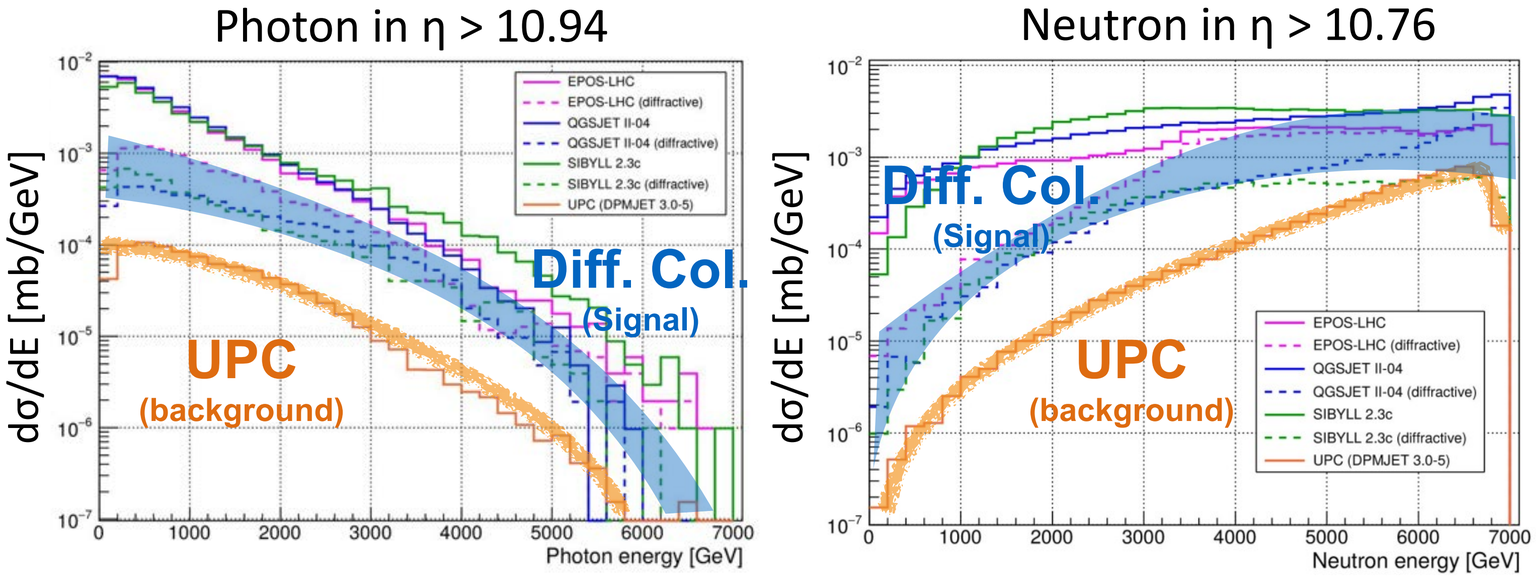
p-O at $\sqrt{s_{NN}}$ = 10 TeV



Impact on LHCf-ATLAS joint analysis

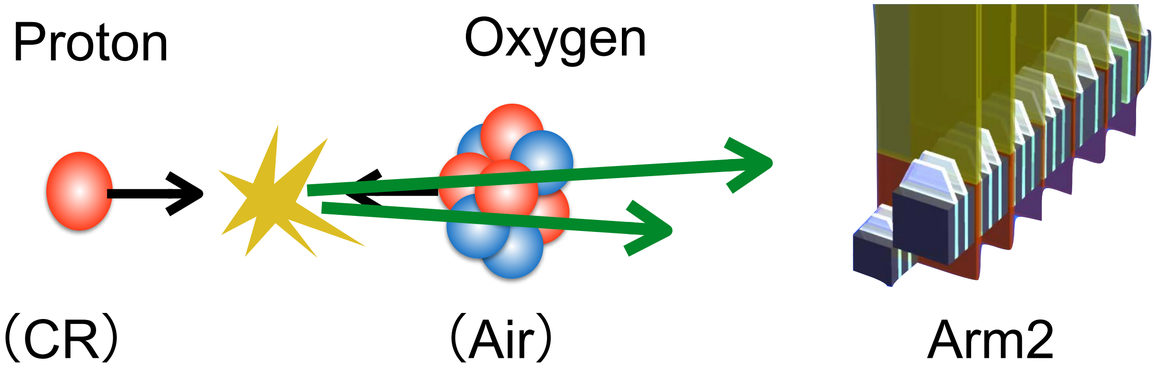
- Need to be careful in the central-forward correlation analyses with ATLAS.
- In single diffractive study.
  - Little central activity in both low-mass diffractive and UPC events.
    → No way to separate these events experimentally.
  - The UPC contribution is still a controllable level.





Operation strategy

- Setup
  - Only Arm2 detector is installed in p-remnant side.
    too-high multiplicity (<#Hits> > 5) in O-remnant side
  - Joint operation with ATLAS



- Oxygen run in July 2025
  - 1 week special run (p-O and O-O)
  - Install the detector during TS1
  - Beam commissioning (4 day)
  - **p-O collisions (2 days) ← LHCf Operation**
    - - - - - Remove the detector from LHC - - - - -
  - O-O collisions (2 days) ← too high multiplicity

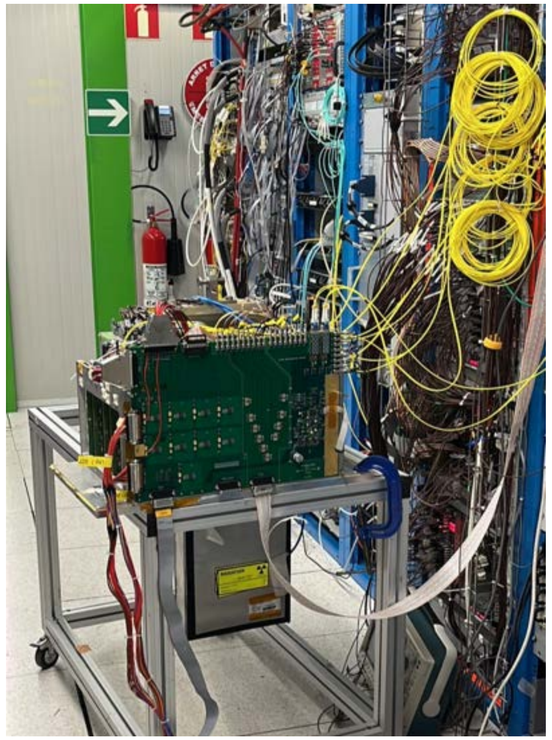
*) This schedule might be changed

Preparation status

- DAQ system already prepared in USA15 (ATLAS counting room)
- DAQ speed improvement : Max. rate 1.6 kHz (2022)→ 3.3 kHz
  → increase #events of photons and neutrons

- Schedule in the next one year.
  - This winter
    - Test of DAQ with the full system
    - Test of LHCf + ATLAS common operation
    - Setup onsite quick analysis system.
  - Operation in July
    - Final test of detector, DAQ etc just before the run.
  - Beam test at SPS
    - Energy calibration using e^- and p beams

Test of the Arm2 detector in USA15 in Feb 2024



Summary

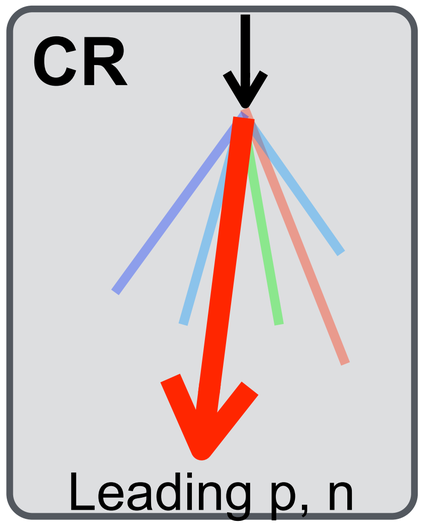
- LHCf measures the very forward neutral particles, which are motivated for cosmic ray physics.
- Presented results from Run 2 data
  - η meson diff. cross-section
- Many analyses are on-going
  - η, π^0 with high statistics data, K^0_S measurement
  - Joint analyses with ATLAS including ZDC, RPs
    (Joint analysis using Run 2 data is on-going, also)
- pO operation will be in 2025
  - Ideal condition for studying CR-Air interactions.
  - Mostly ready for the operation.

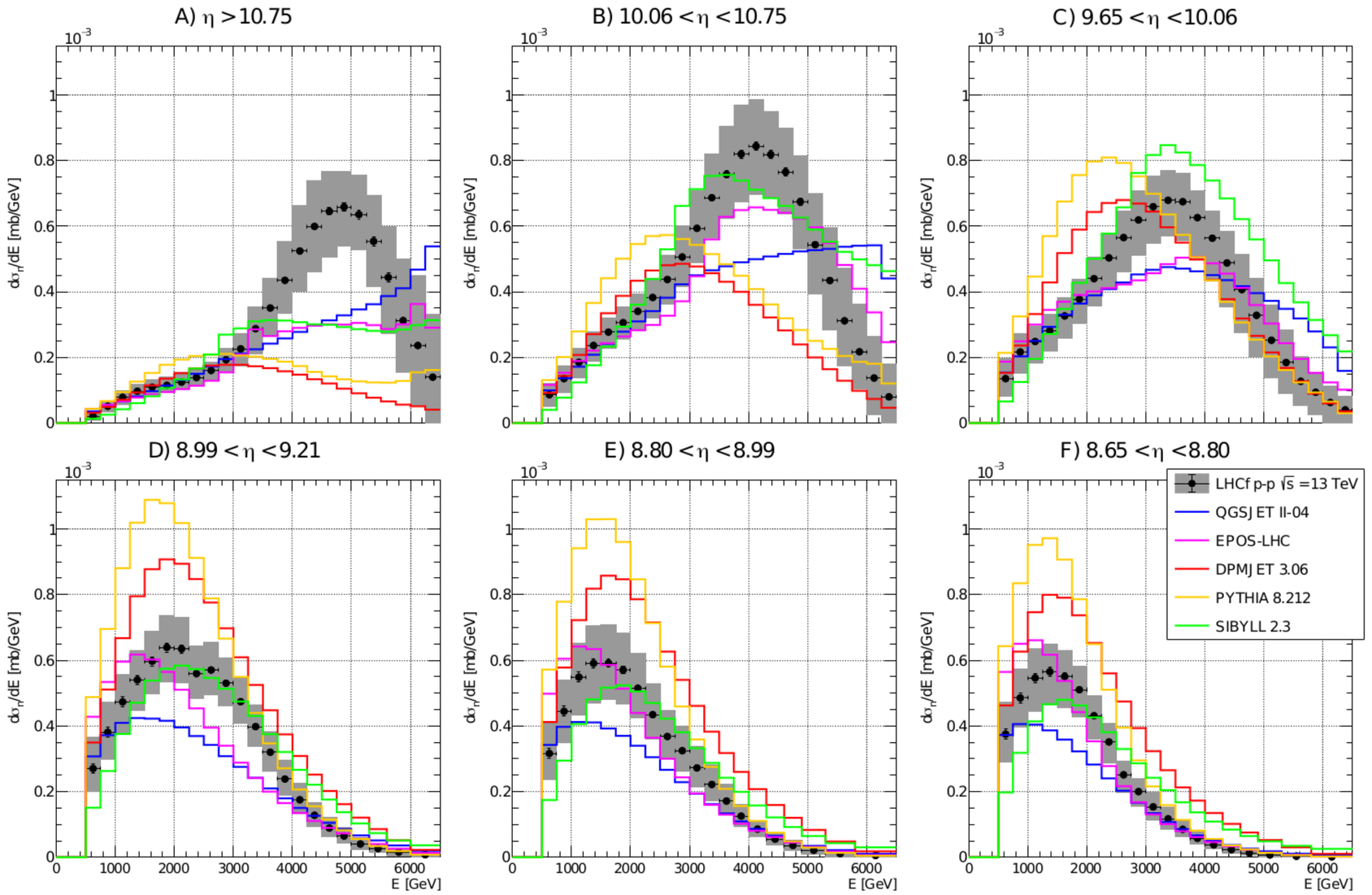
Thank you very much !!

Backup

Forward Neutron at *pp*, √s=13 TeV

- Inelasiticity measurement (k = 1- $E_{leading}/E_{CR}$),
  → important parameters for understanding CR-air shower development.
- Update of the past result with extension of fiducial regions
- Energy resolution : 40%

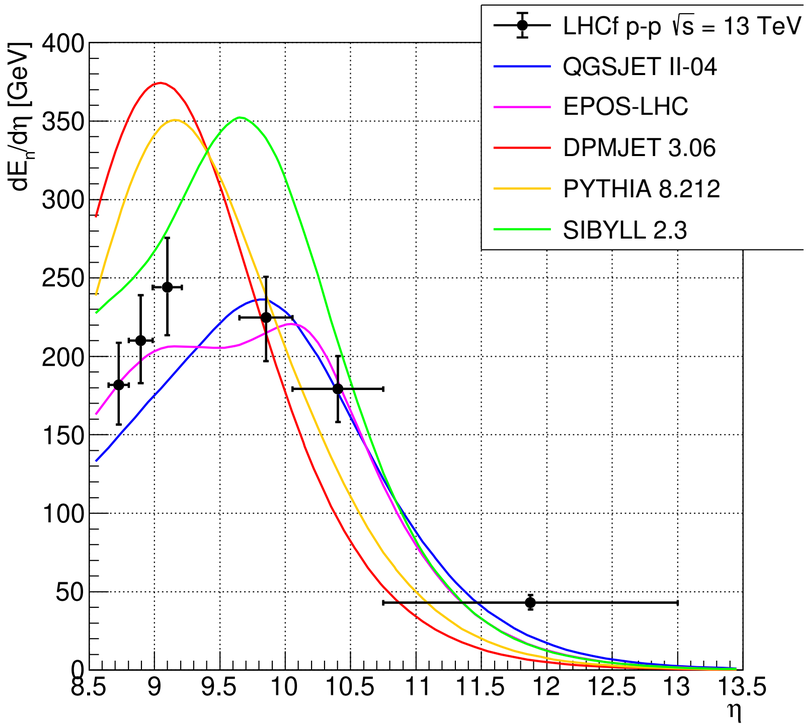




O. Adriani et al., JHEP07 (2020) 016

Inelasticity from the neutron result

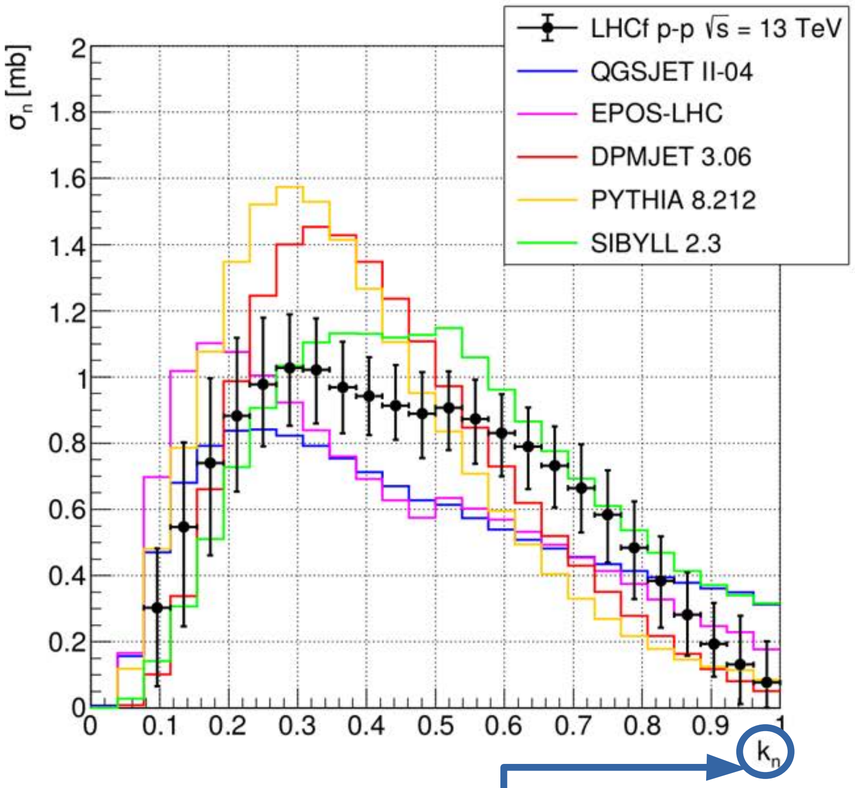
Energy flow



Best agreement model

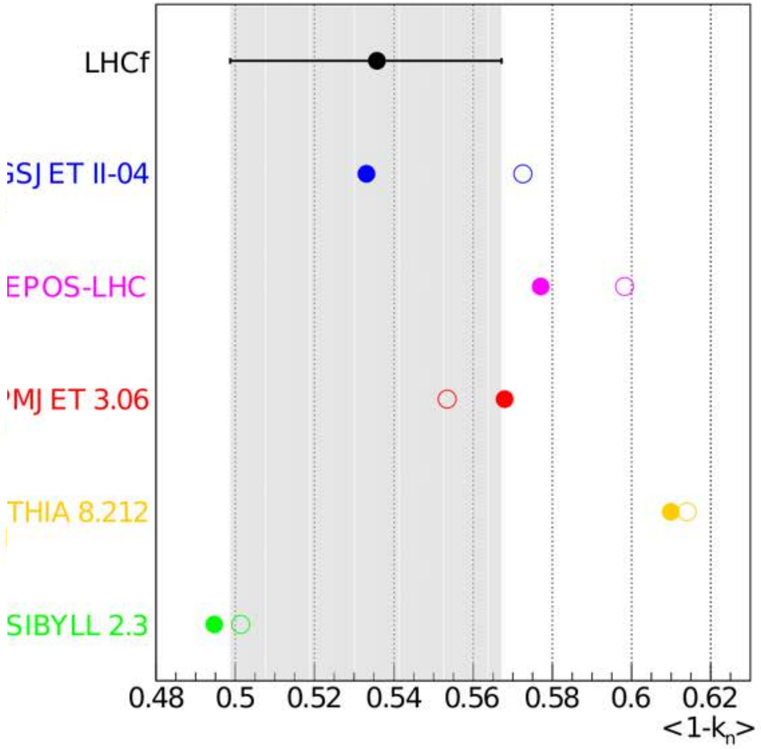
Average Inelasiticity: QGSJET II-4
Energy spectrum: EPOS, SIBYLL
Energy flow: EPOS

Elasticity distribution



k_n ≡ elasticity in events where the leading particle is a neutron

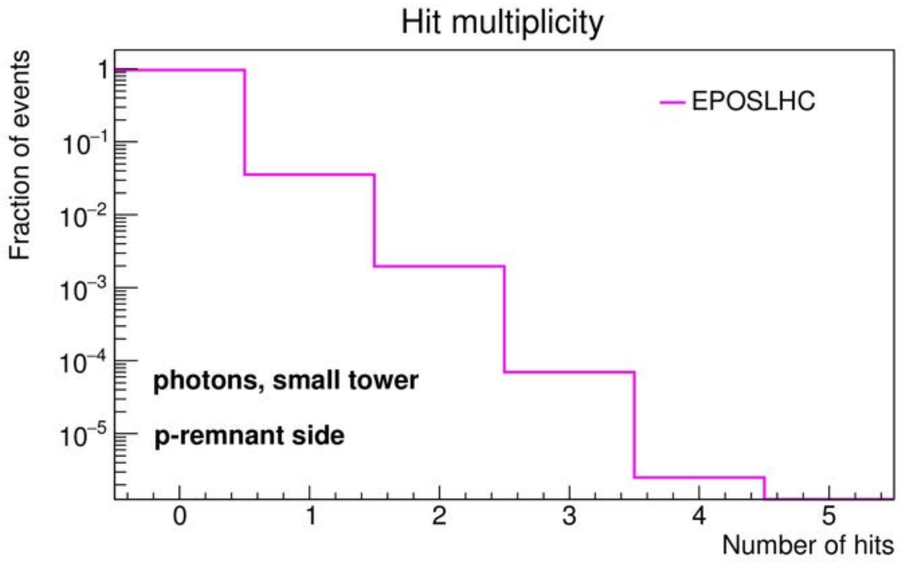
<Inelasticity>

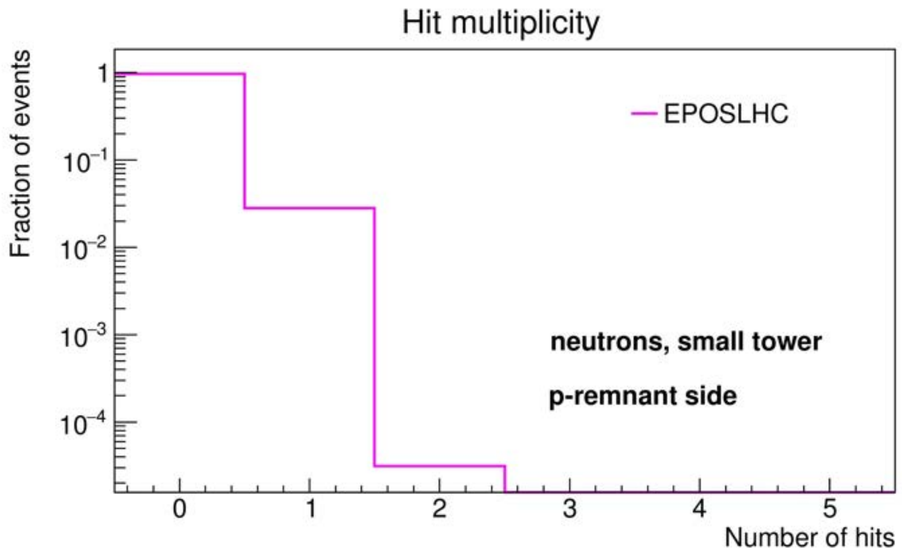


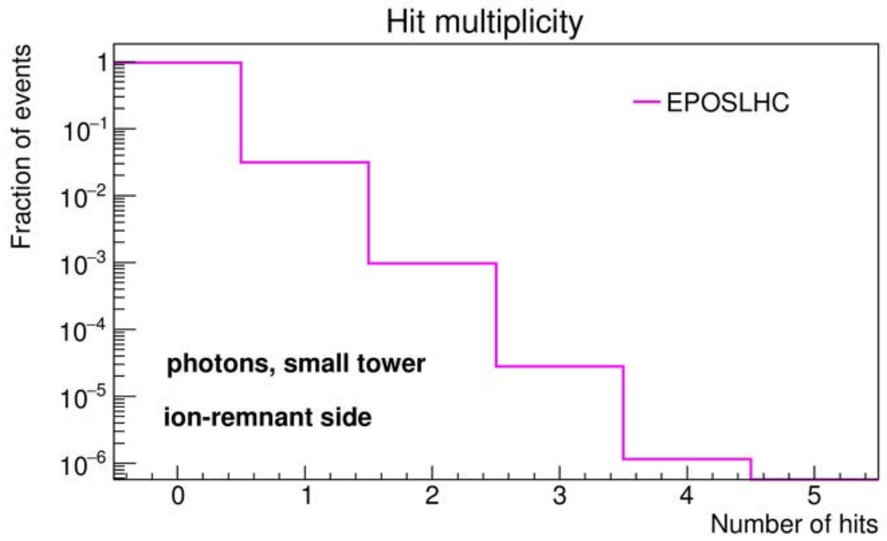
- ● neutron inelasticity
- ○ all particles inelasticity

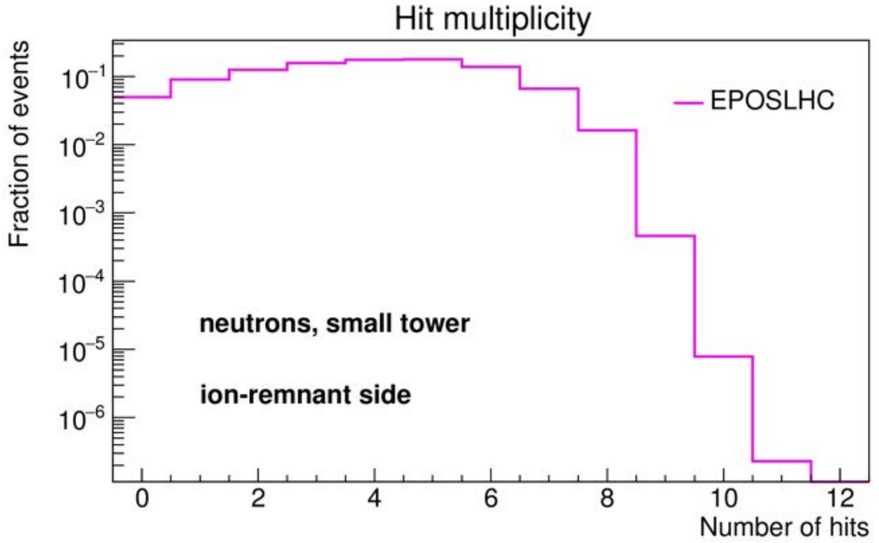
O. Adriani et al., JHEP07 (2020) 016

Hit Multiplicity in pO

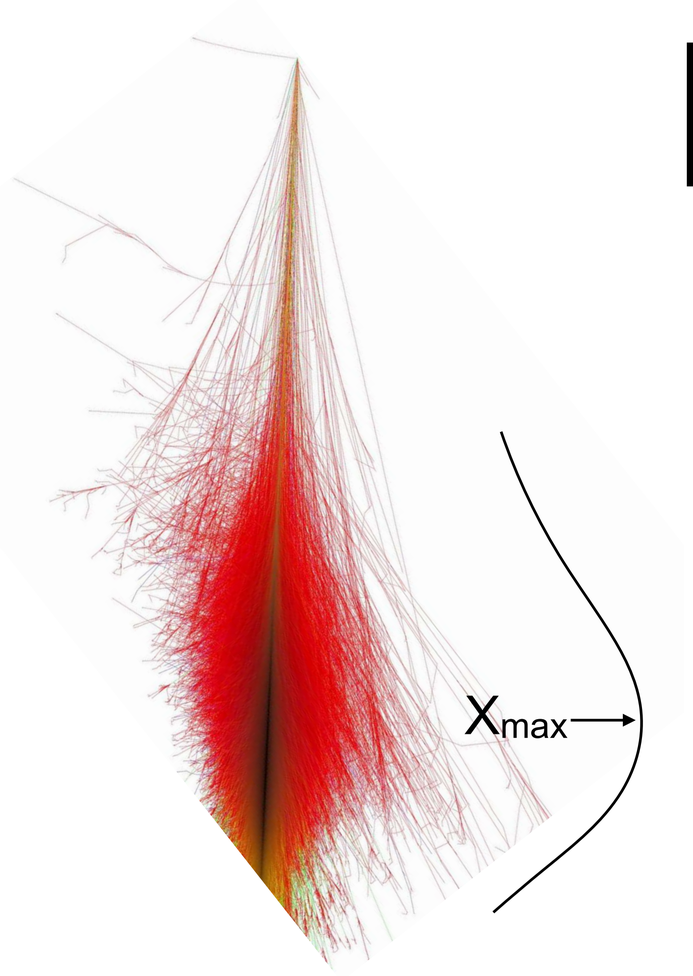






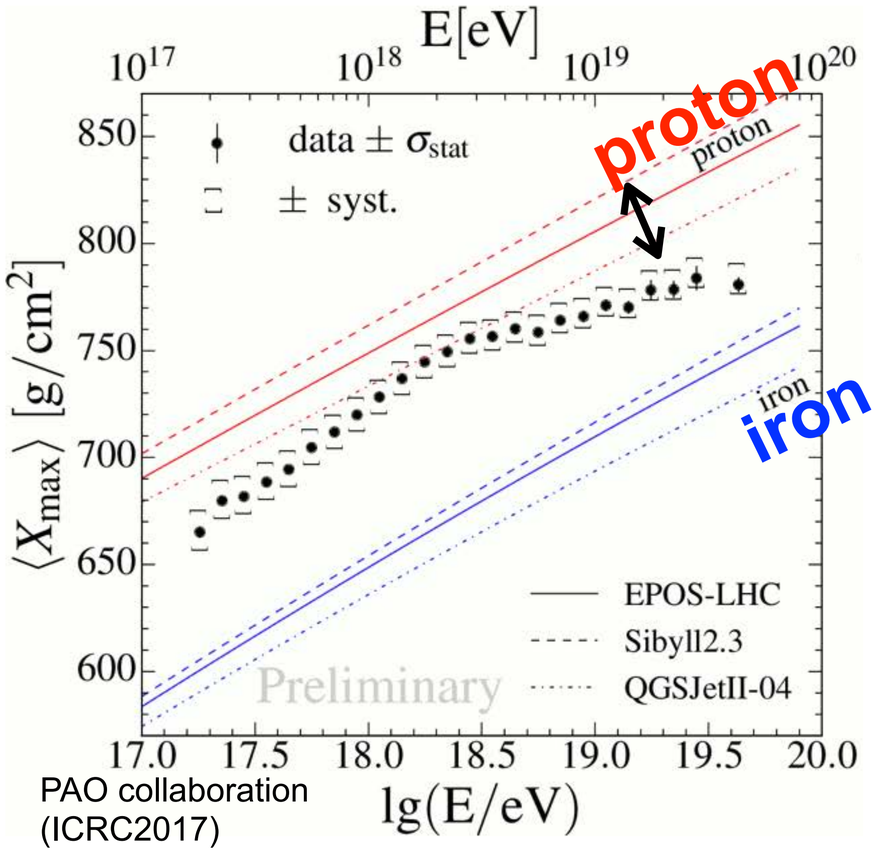


Estimators of Mass Composition



N^{μ}: Number of muons on the ground

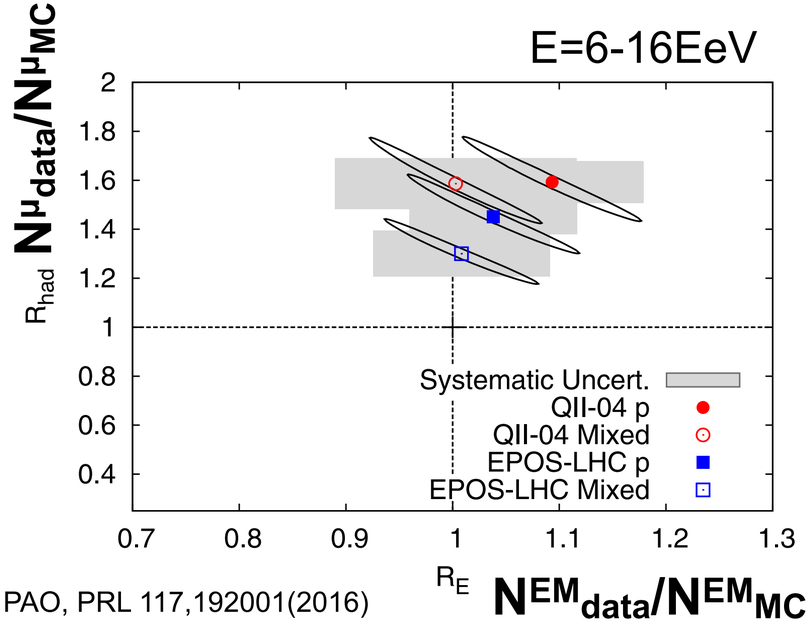
Large model dependency of UHECR composition measurement



PAO collaboration (ICRC2017)

Interaction model uncertainty **>** Experimental uncertainty

Muon excess $N^{\mu}_{data} > N^{\mu}_{MC}$



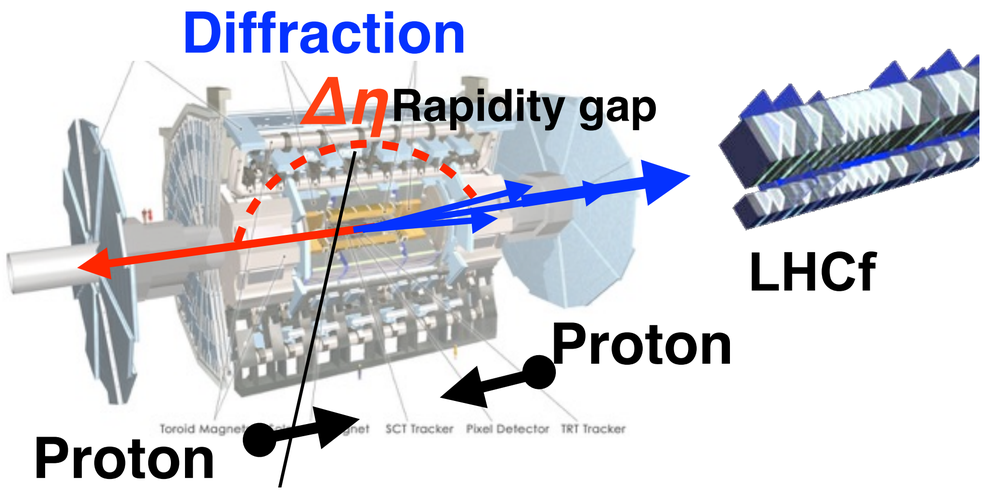
PAO, PRL 117,192001(2016)

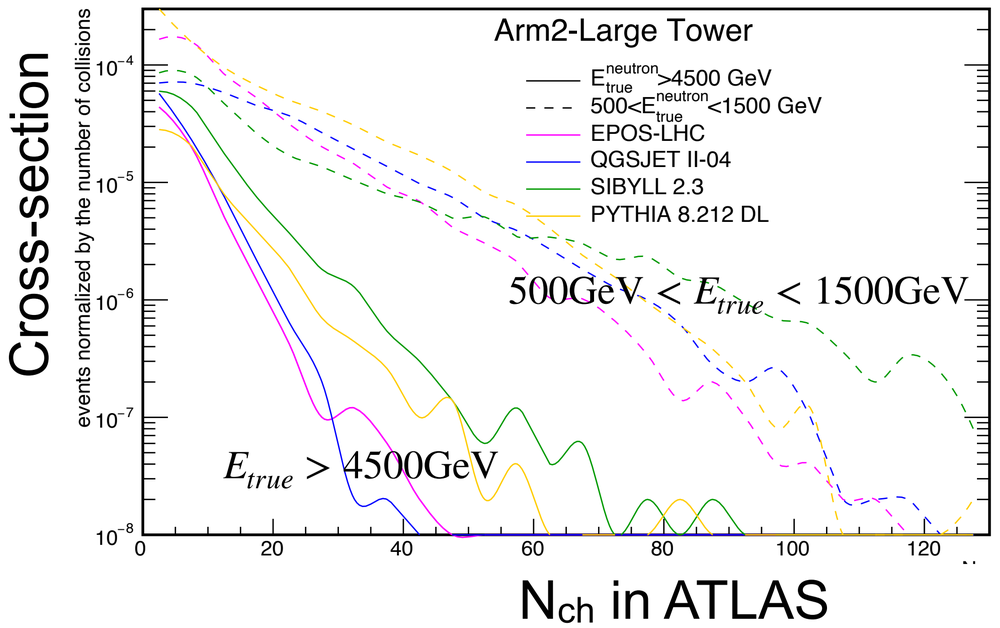
Sensitive $E^{\pi 0}/E^{had}$ for a collision

Several ideas to solve it

- Strange particles
- Vector meson productions
- QGP

On-going Joint analyses with ATLAS



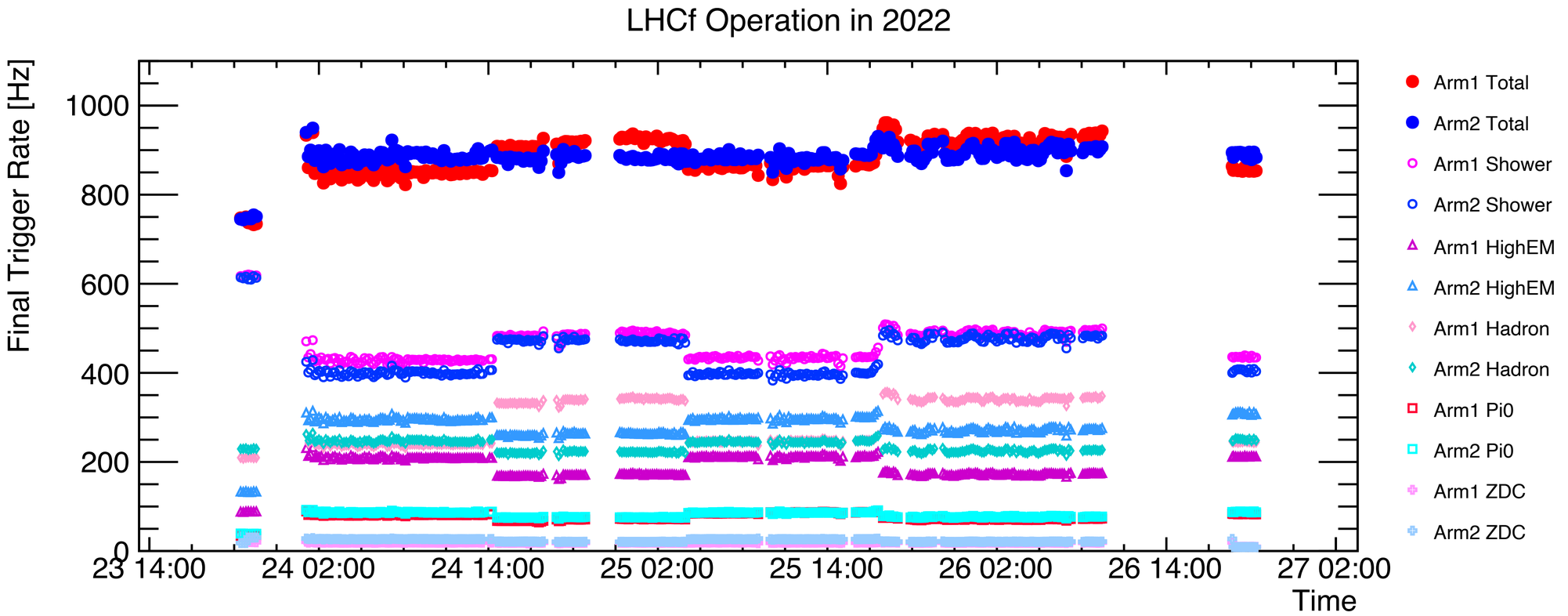


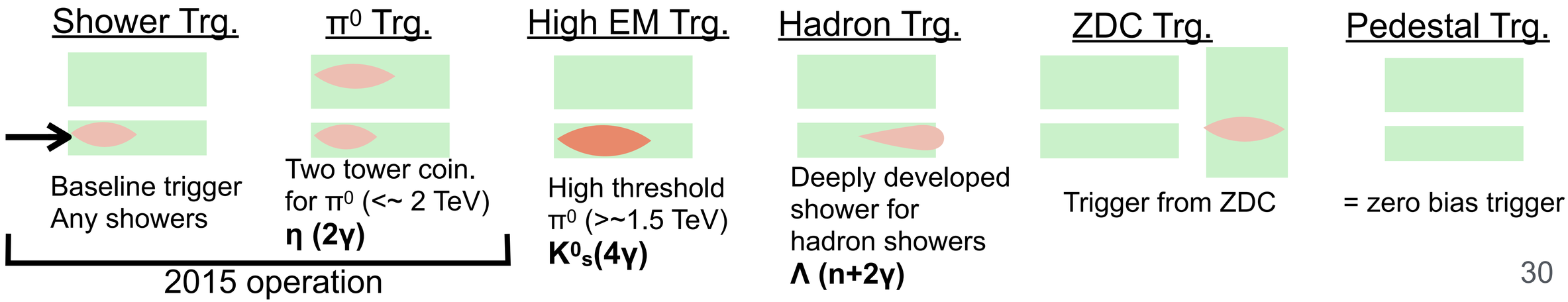
- Study of diffractive collisions
  - Photon spectra with N_{ch}=0 in ATLAS (p_T>0.1GeV, $|\eta| < 2.5$)
- Study of MPI
  - Correlation between forward neutron and N_{ch} in ATLAS

Superposition of single API: MPI ↗ Forward neutron energy ↘

Kinematic overlap : MPI ↗ Forward neutron energy →

6 Trigger modes

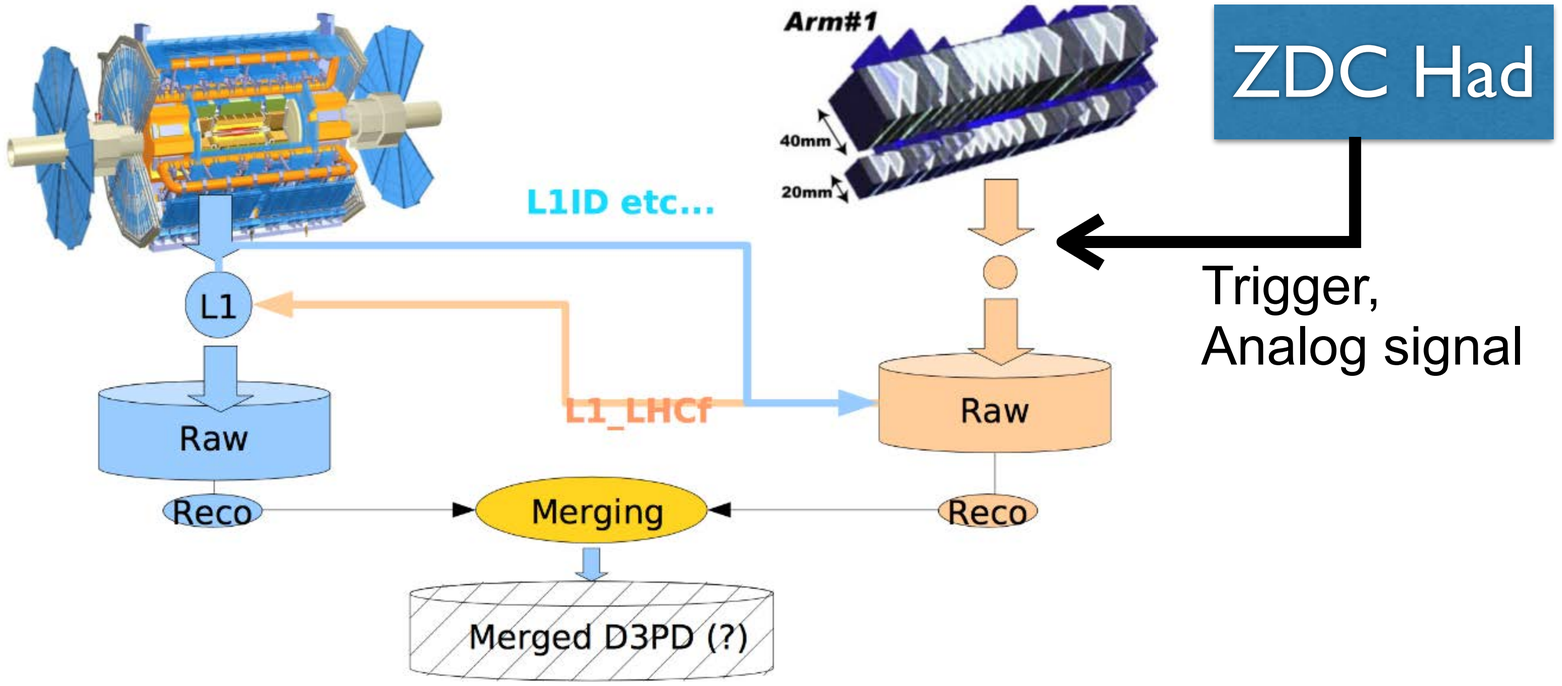




Run3 LHCf+ATLAS joint operation

- Many physics cases
  - Detailed study of diffractive interaction using RPs
  - MPI modeling study using very forward neutron
  - One-pion-exchange measurement for p-π^+ collision study

DAQ scheme



Improvement from 2015 run

- Presence of ZDC, RPs
  - 3 ZDC-HAD modules were installed for LHCf runs
  - AFP worked in the full period partially with ALFA
- No pre-scaling of LHCf triggers in ATLAS

  → **All 300M events recorded**
  (⇔ 6 M events in 2015)