LHCf/RHICf: Very forward measurements at LHC/RHIC

MENJO Hiroaki
ISEE and KMI, Nagoya University
for LHCf/RHICf collaboration





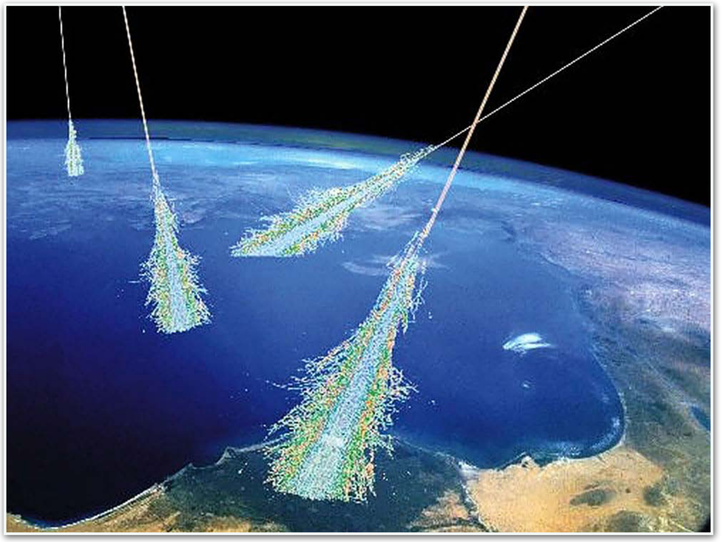
素粒子宇宙起源研究所



KMI 2026, 9-11 November 2026, Nagoya Univ.

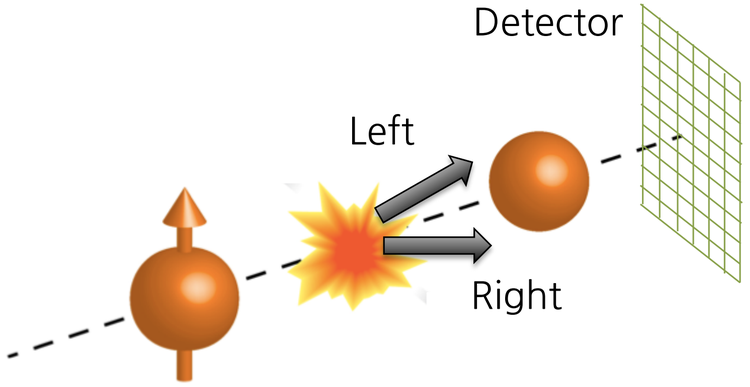
Motivation of LHCf/RHICf

Very forward region = non-pQCD regime
- pT < 1.5 GeV/c
- Beam remnant, Diffraction



Understanding of hadron production for high energy cosmic-ray physics

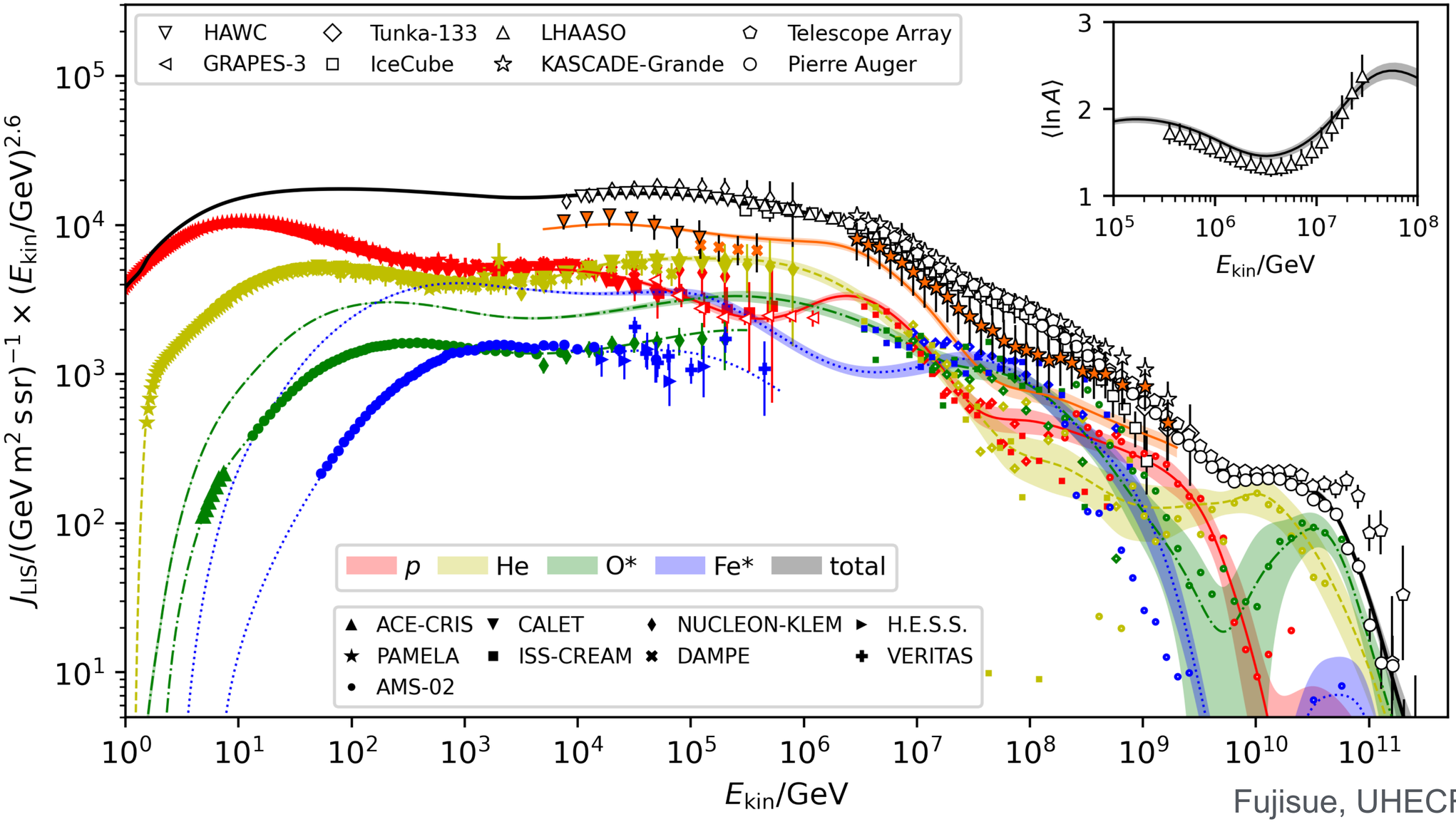
LHCf and RHICf



Measurement of Spin asymmetry at very forward region

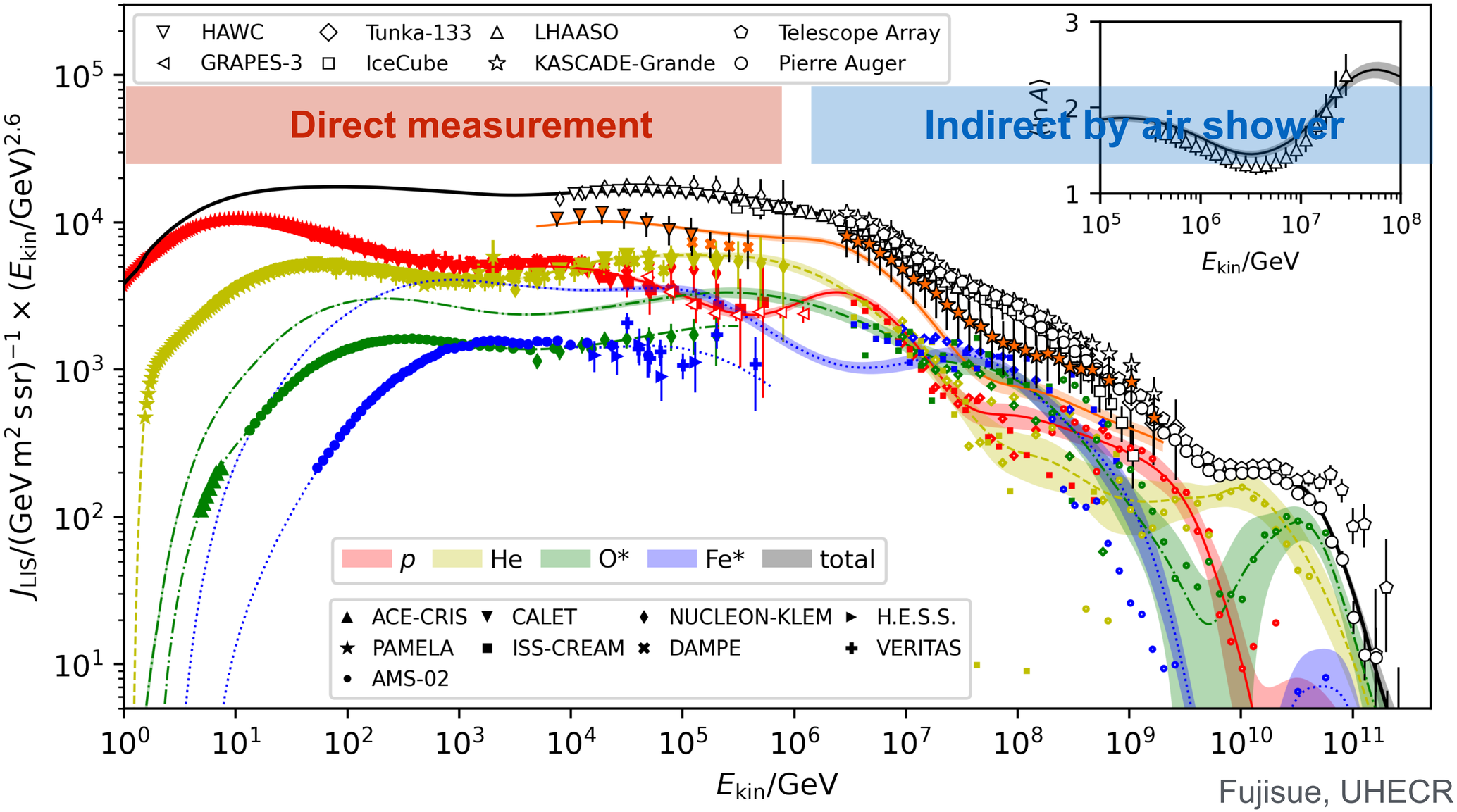
RHICf

Cosmic ray spectrum



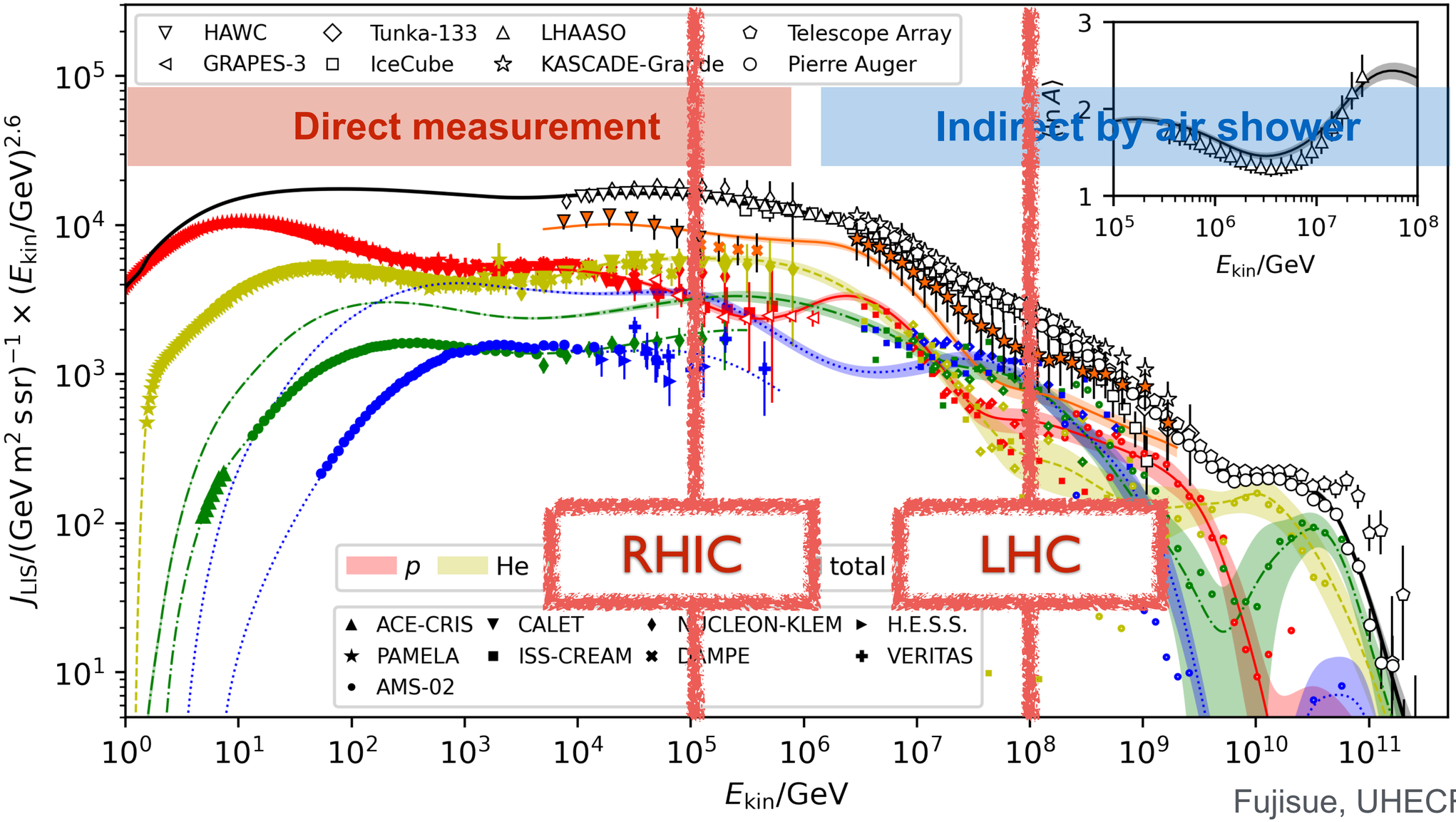
Fujisue, UHECR 2024

Cosmic ray spectrum



Fujisue, UHECR 2024

Cosmic ray spectrum



Fujisue, UHECR 2024

High Energy Cosmic-Ray Observation

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

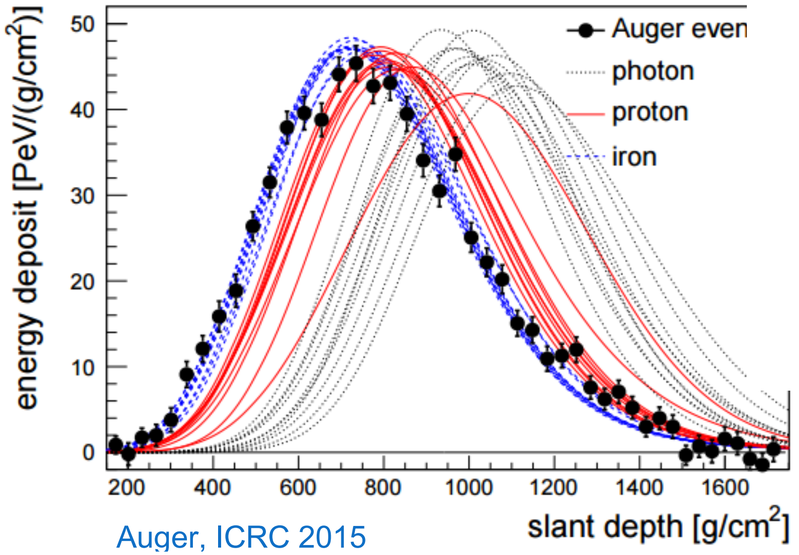
High energy interaction

secondaries' interactions

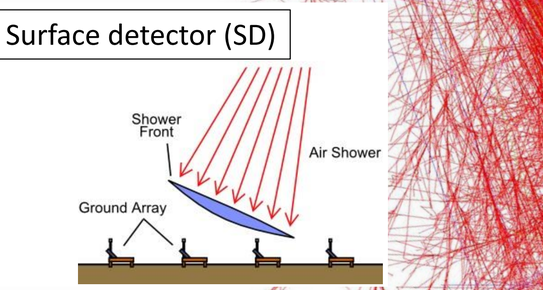
Low energy interactions

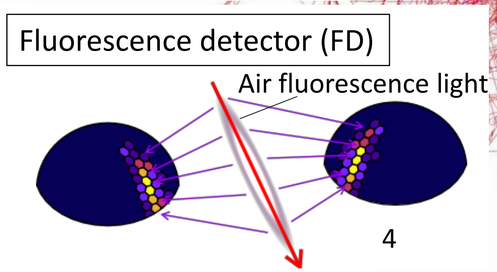
- Reconstruct primary information from observed showers
  - Energy
  - Direction
  - Composition (particle type)

Longitudinal development of 10^{19}eV showers



Auger, ICRC 2015

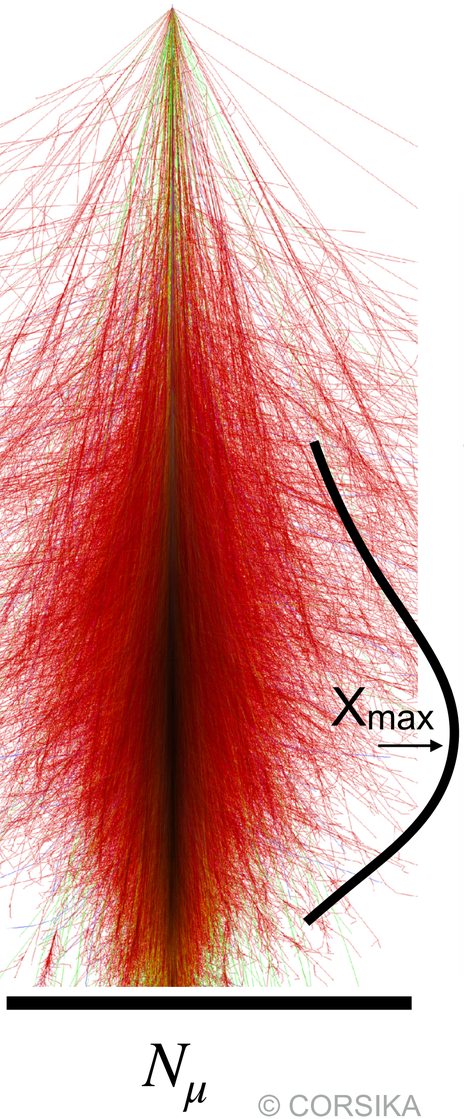




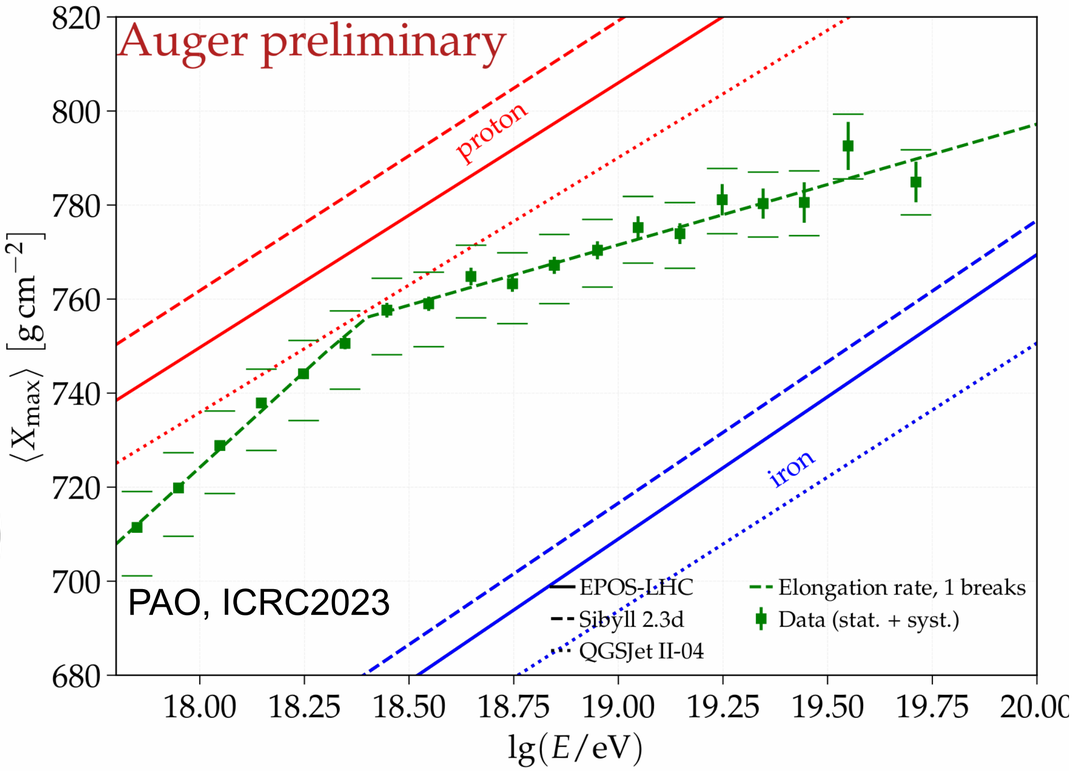
Require precise understanding air shower development, especially high energy hadronic interactions but …

4

”A” measurement of UHECRs

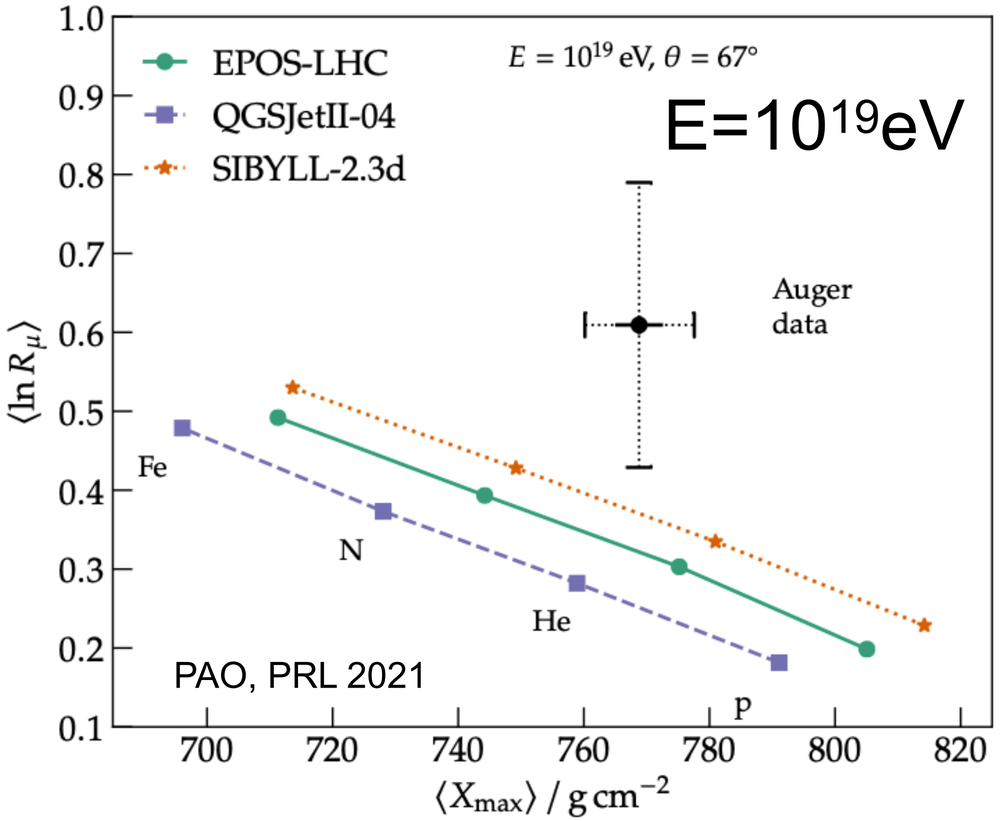


Shower Maximum Depth $< X_{MAX} >$



Interaction model uncertainty **>** Experimental uncertainty

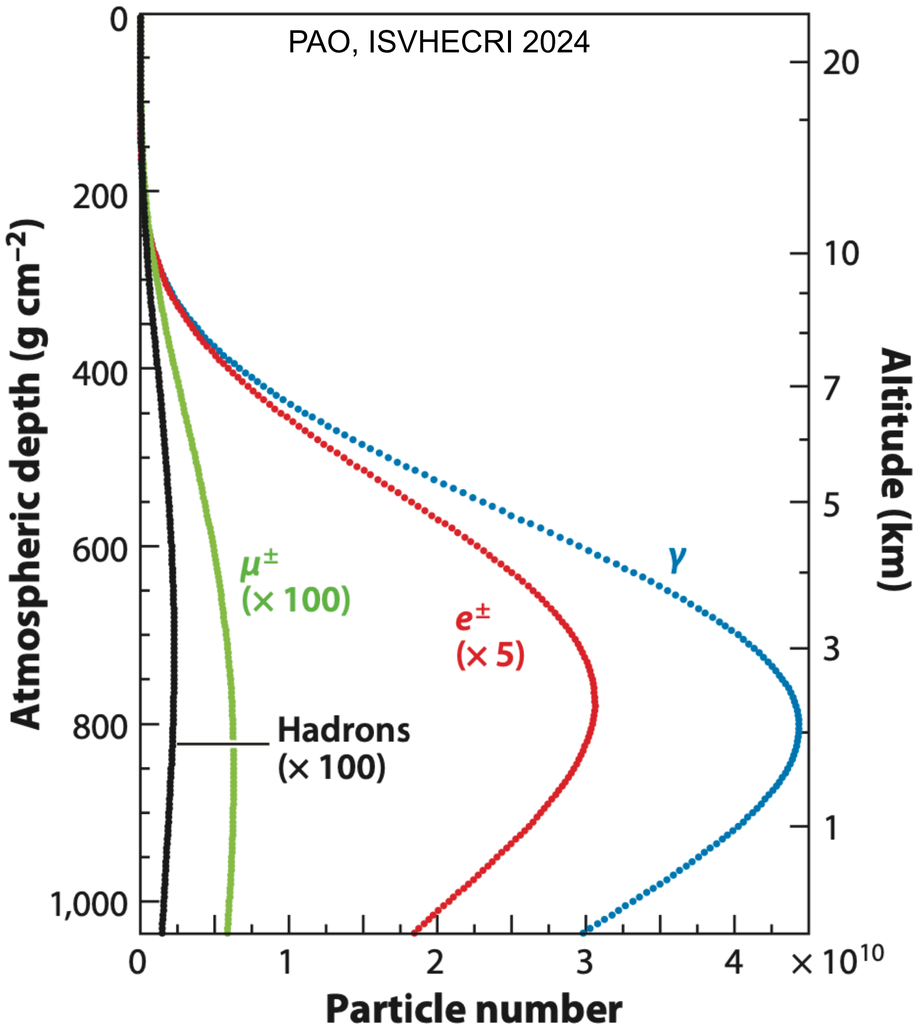
Muon Number N_μ

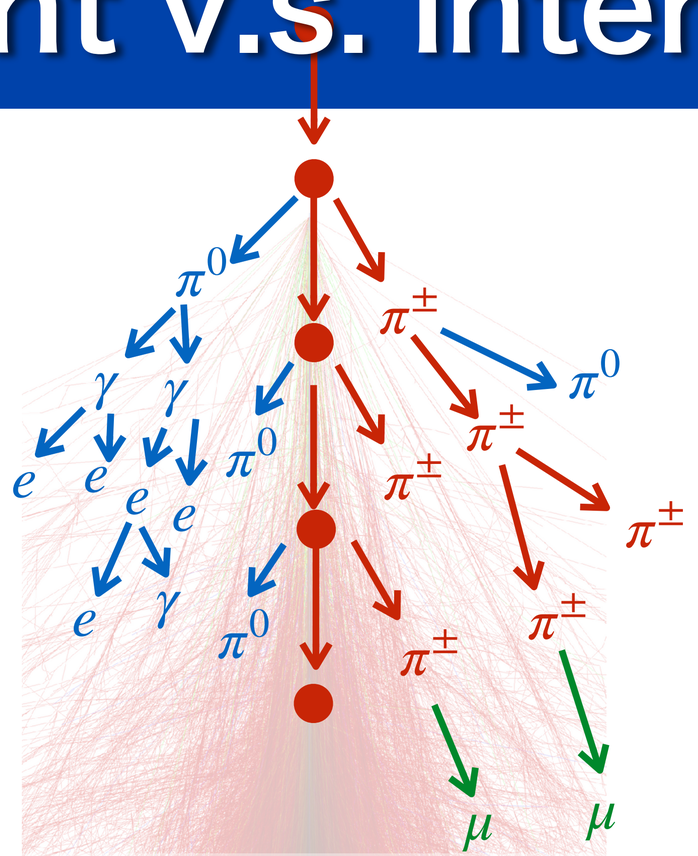


N_μ : Data > MC (30-50%)

Muon puzzle

AS development v.s. Interactions





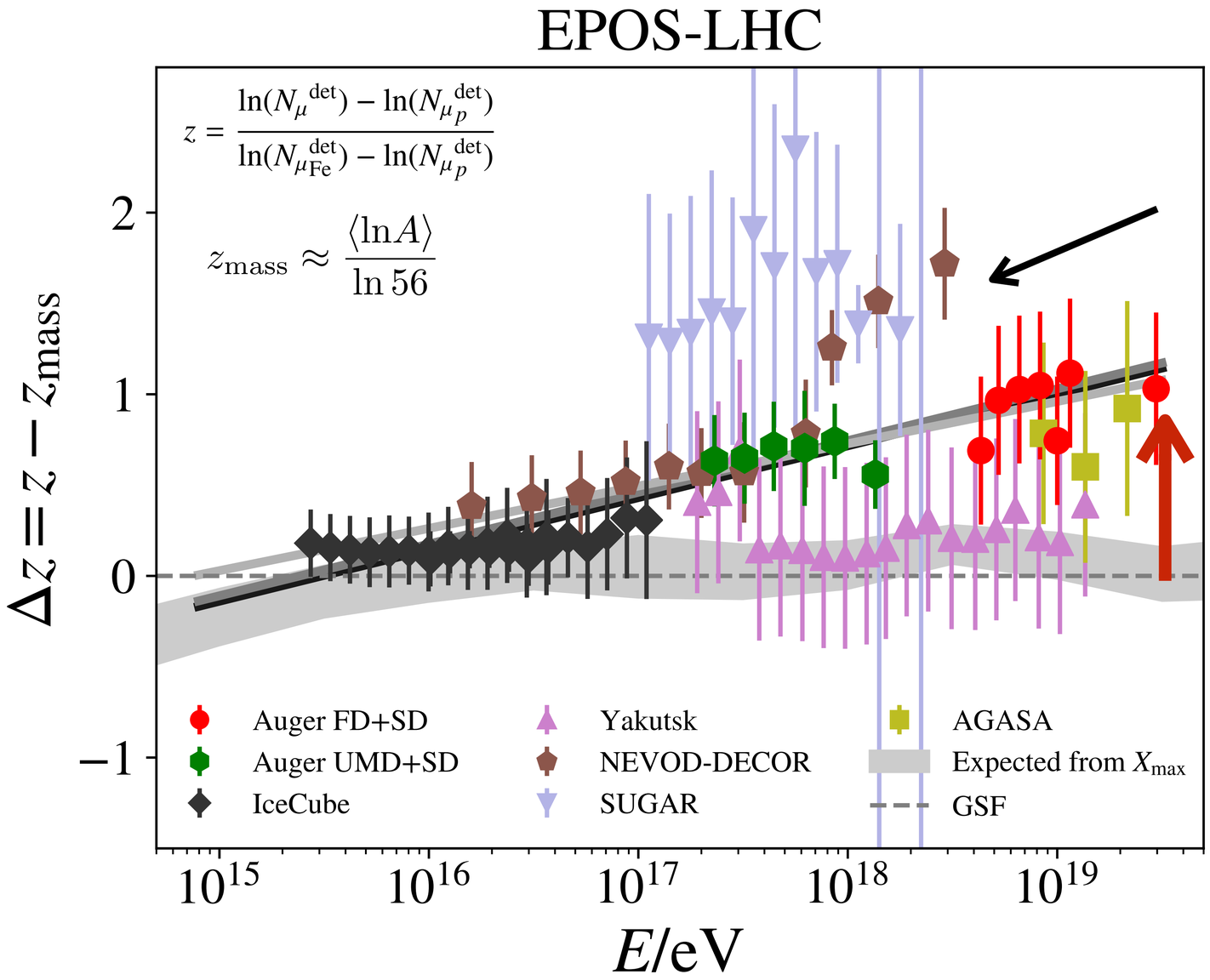
EM
E > 90%
N > 99%

μ
E <10%
N < 1%

- X_{MAX} : strong dependence on 1st interaction (interaction depth and particle production)
- N_μ : $\sum E_{had.}^{end} = E_{CR} \prod (1 - R_{EM}^{i-th})$

R_{EM} = energy fraction of EM components

Energy dependency of muon excess

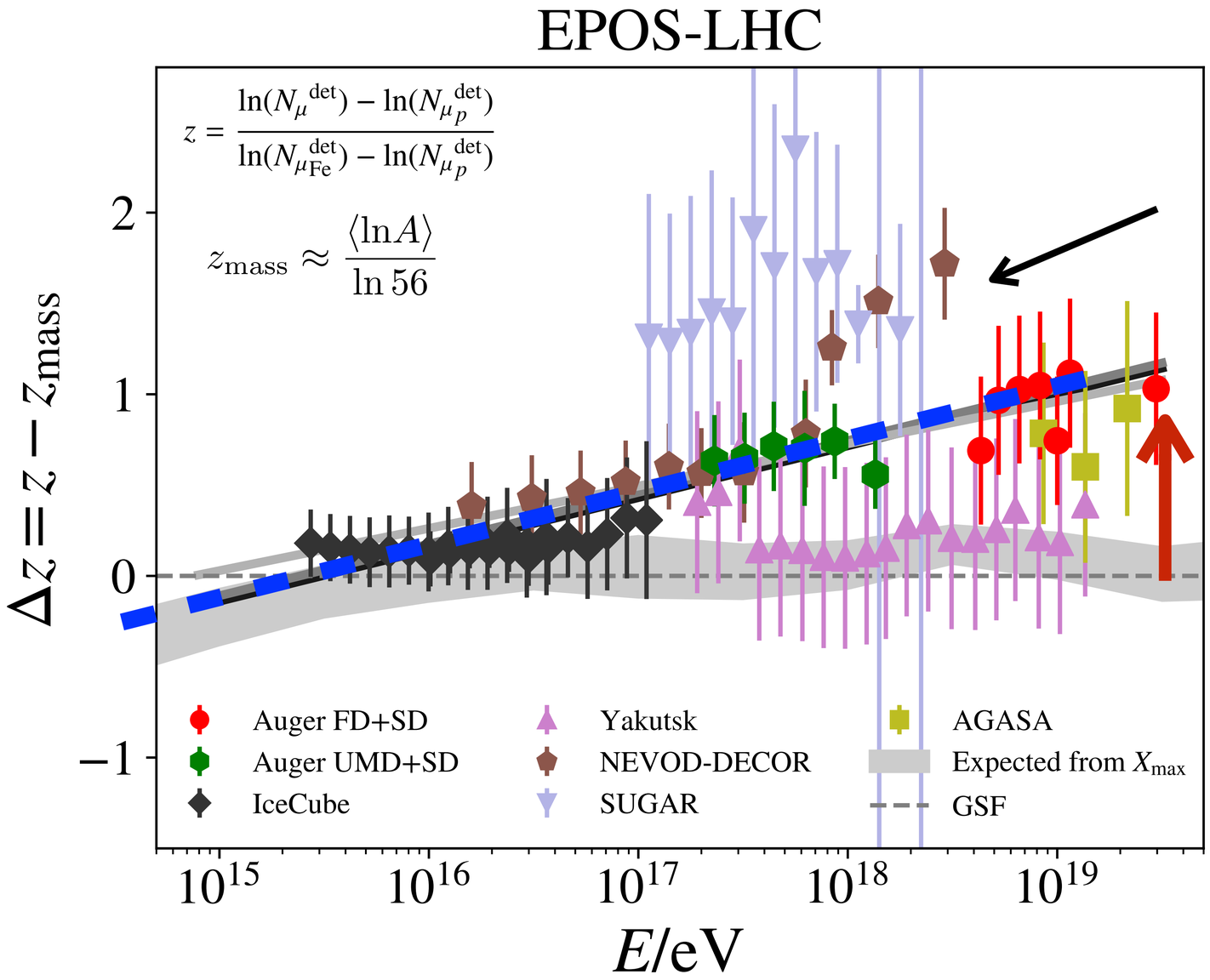


Normalized muon numbers results observed by several CR experiments

Muon excess

Composition model + Air Shower MC

Energy dependency of muon excess

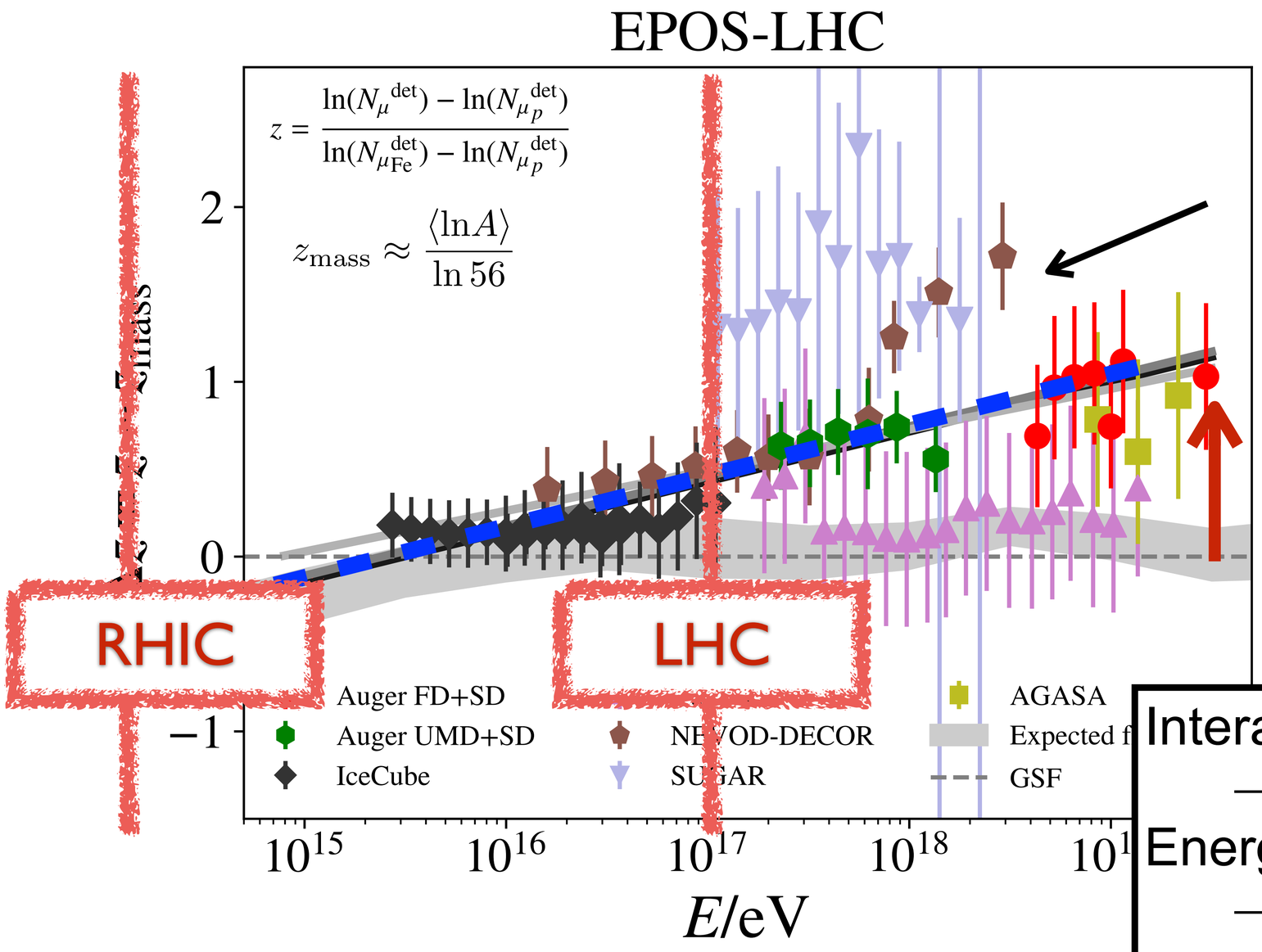


Normalized muon numbers results observed by several CR experiments

Muon excess

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Energy dependency of muon excess



Normalized muon numbers results observed by several CR experiments

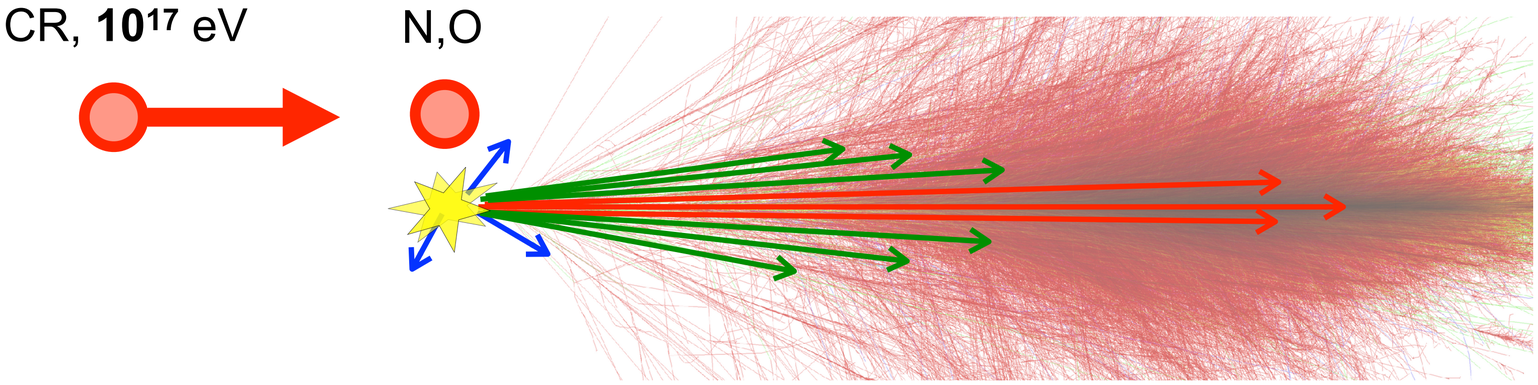
Muon excess

← **Composition model + Air Shower MC**

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

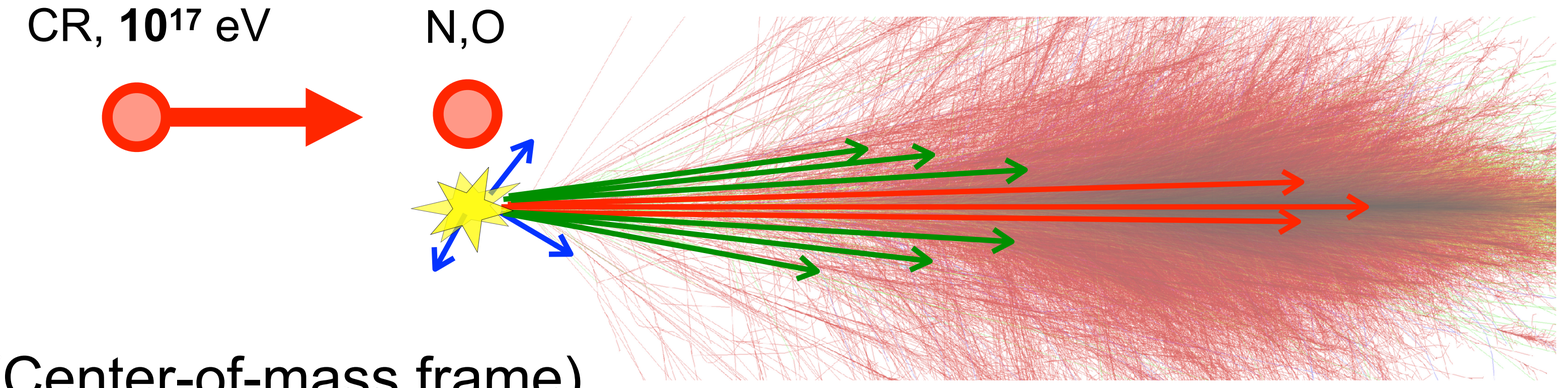
Interaction studies at LHC

Cosmic-ray (target-rest frame)

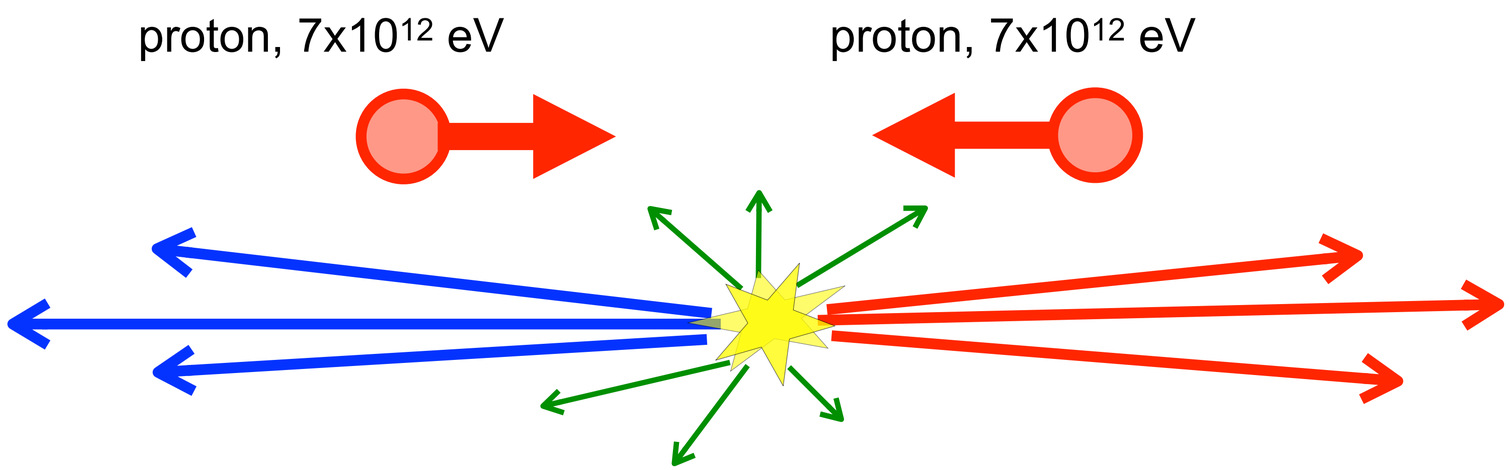


Interaction studies at LHC

Cosmic-ray (target-rest frame)



LHC (Center-of-mass frame)

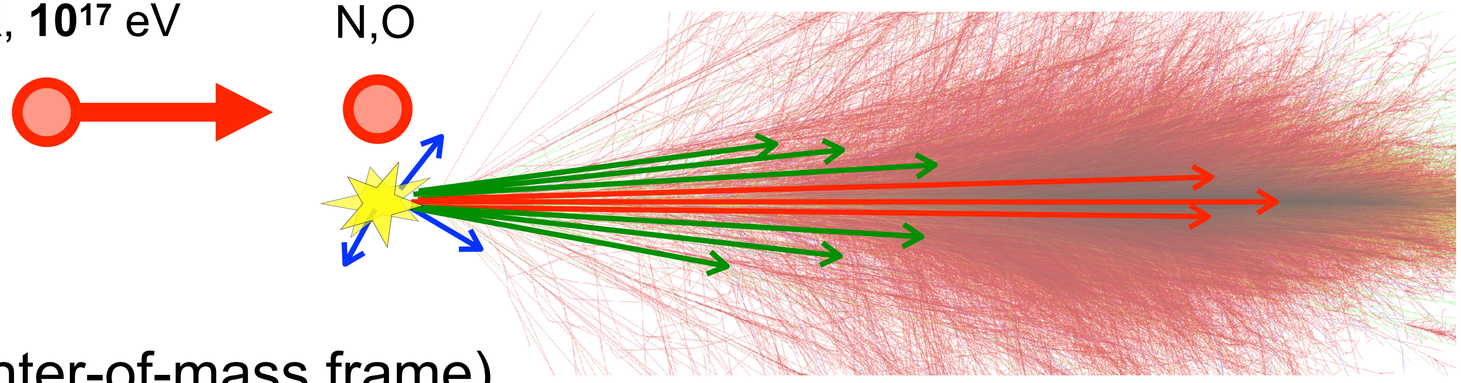


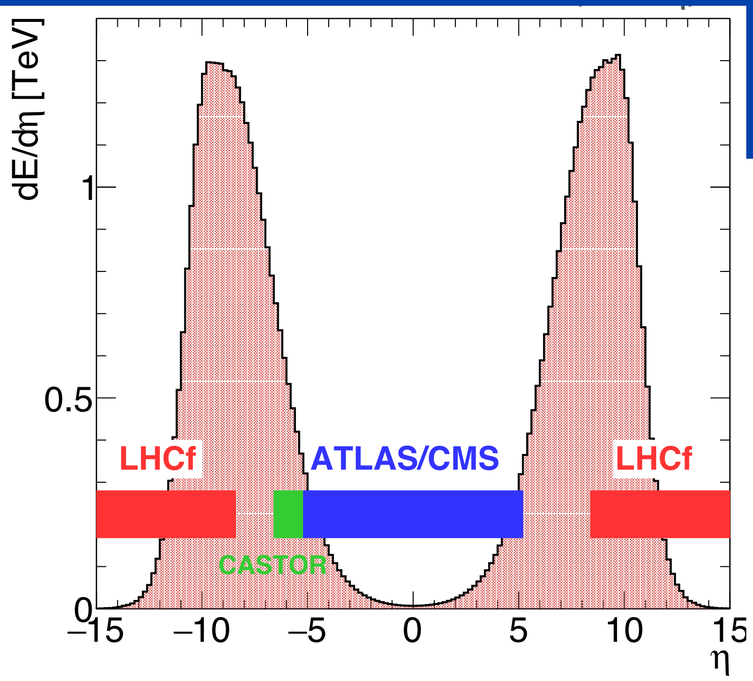
Interaction studies at LHC

Cosmic-ray (target-rest frame)

CR, **10^{17}** eV

N,O

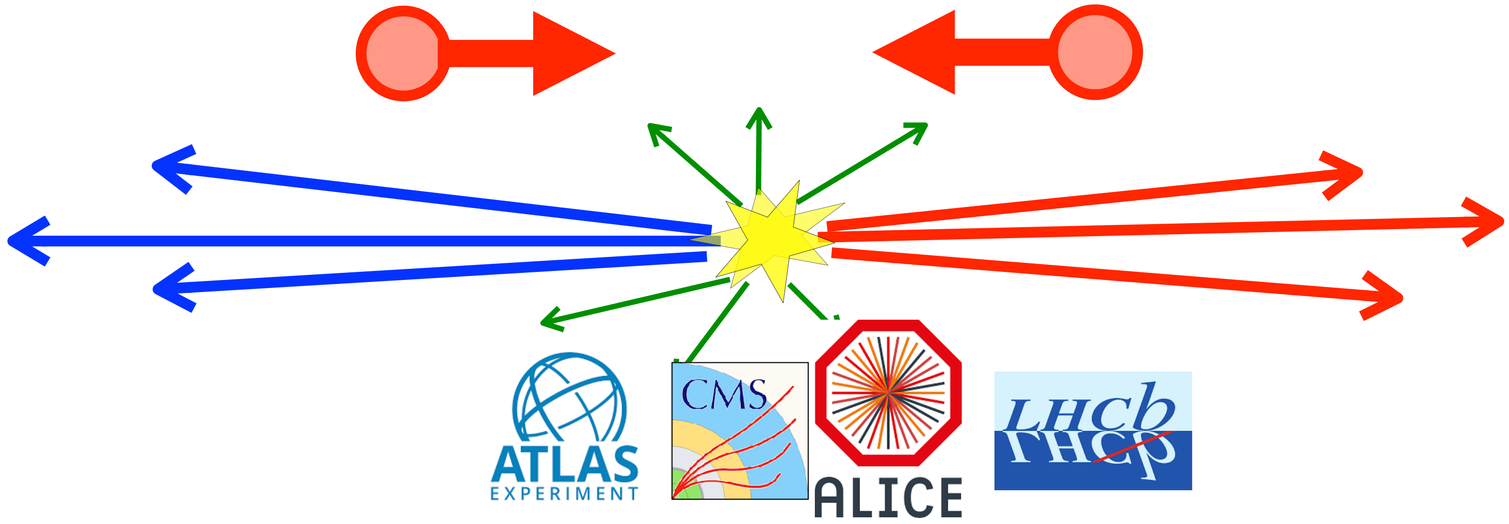




LHC (Center-of-mass frame)

proton, 7x10^{12} eV

proton, 7x10^{12} eV



Scattered proton

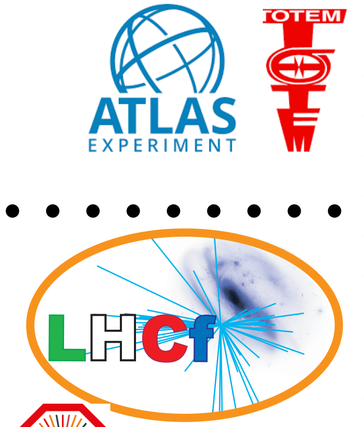
$\rightarrow \sigma_{total}$

γ, π^0, n

$\rightarrow k$

$\nu_{e,\mu,\tau}$

$\rightarrow K/\pi$



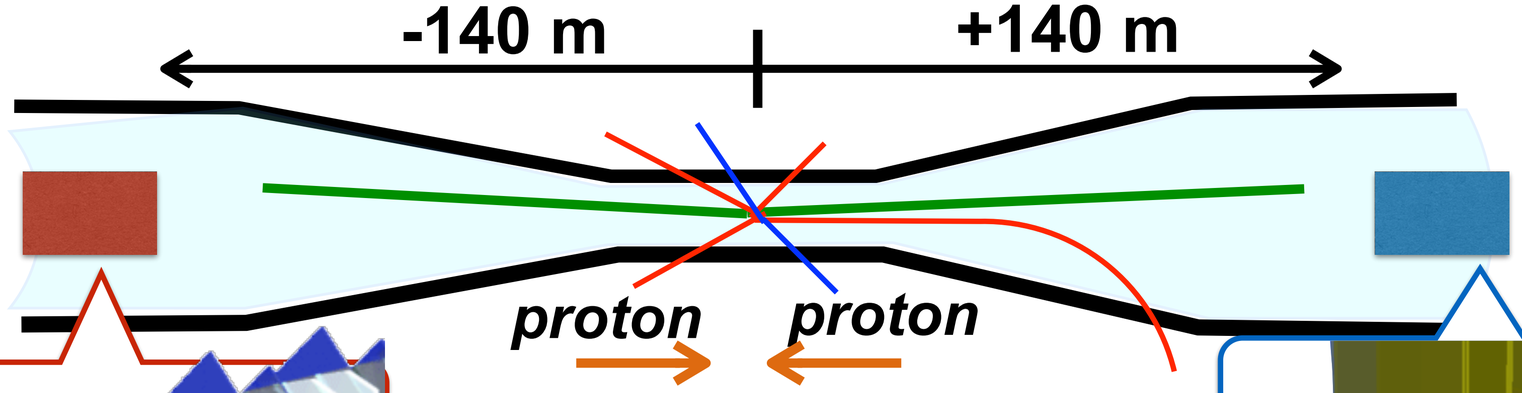
(ATLAS EXPERIMENT CMS ALICE for AA collisions)

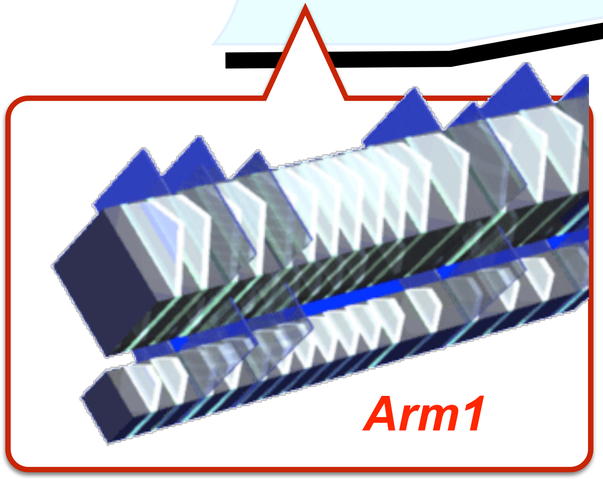
FASER

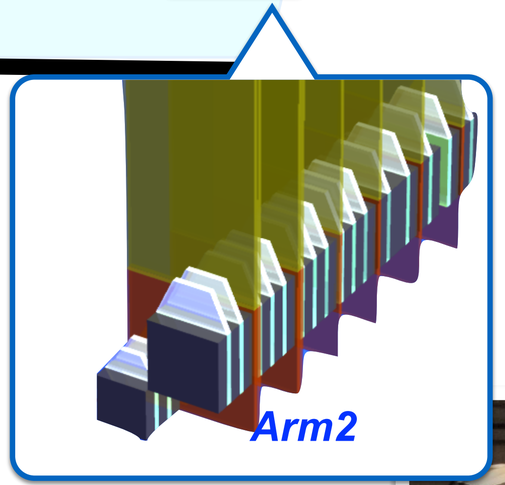
LHC

Scattering and Neutrino Detector at the LHC

LHCf experiment

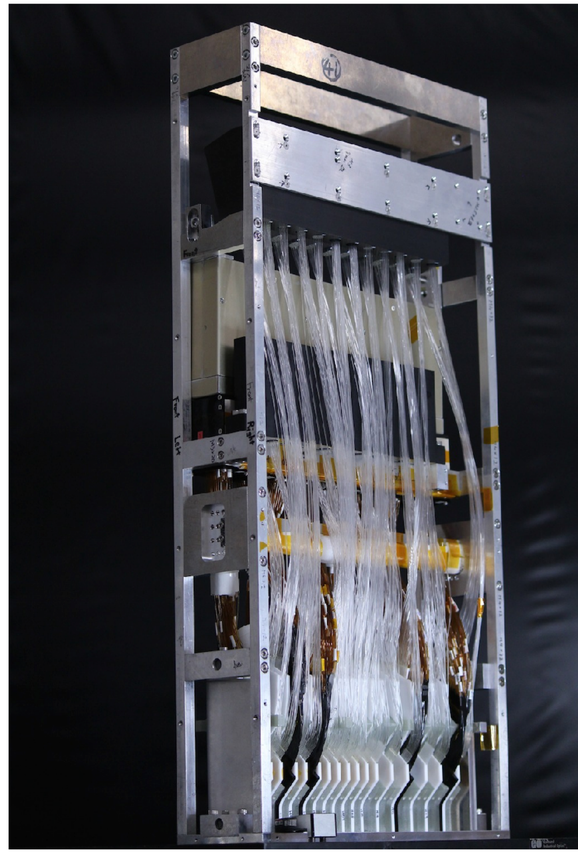






Location

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



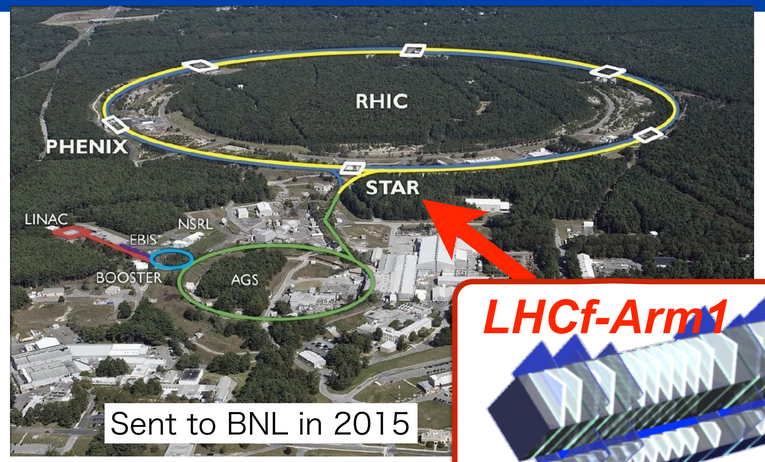


LHCf detectors

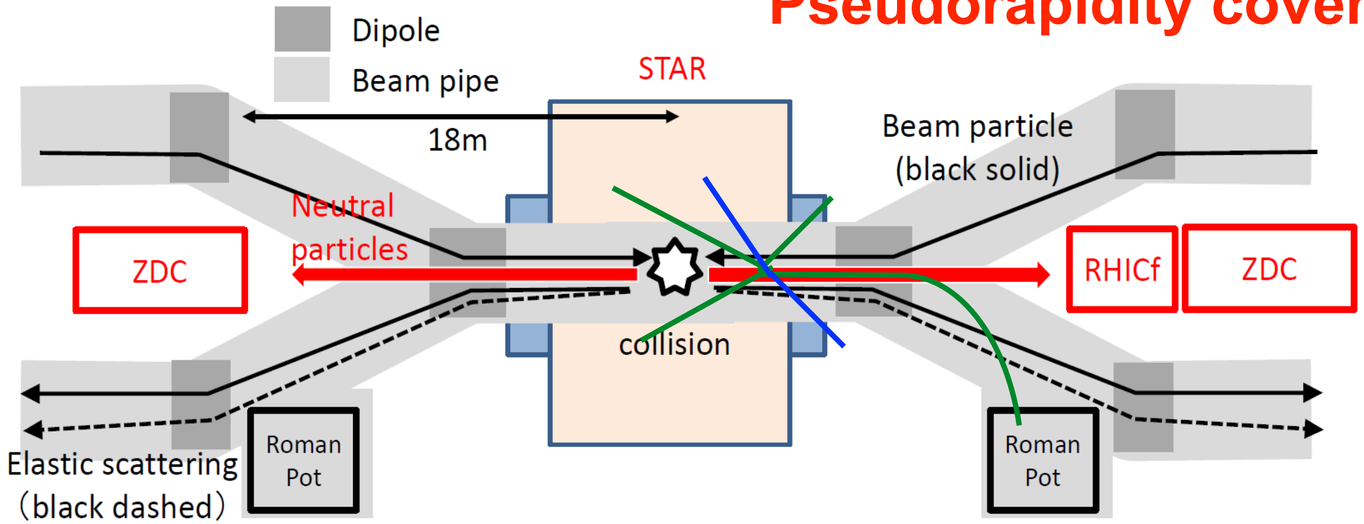
- Sampling and positioning calorimeters
- Two towers, 20x20, 40x40mm^2 (Arm1) , 25x25, 32x32mm^2(Arm2)
- Tungsten layers, 16 GSO scintillators, 4 position sensitive layers (Arm1: GSO bar hodoscopes, Arm2: Silicon strip detectors)
- Thickness: 44 r.l. and 1.7 λ

RHICf experiment

- *pp* $\sqrt{s}$= 510 GeV (polarized beam)
  - Equivalent to E_{lab} = 1.4x10^{14}eV
  - Test of energy scaling with the wide p_T range
  - Single spin asymmetry measurement
  - The operation was successfully completed in 2017
  - Common operation with STAR



Pseudorapidity coverage: η > 6



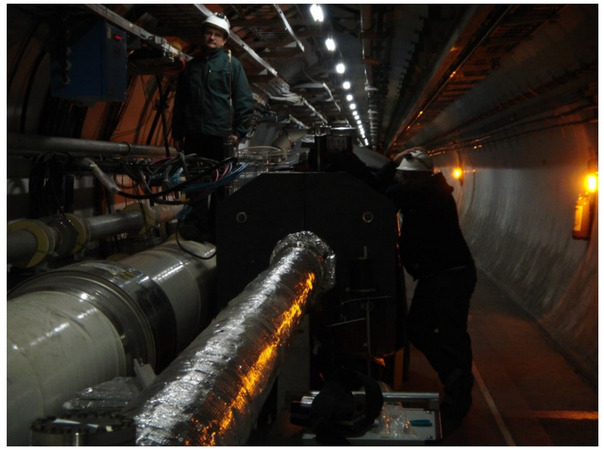


LHCf/RHICf History

2006: SPS (CERN Courier)



2008: 1st installation



2014: test SPS

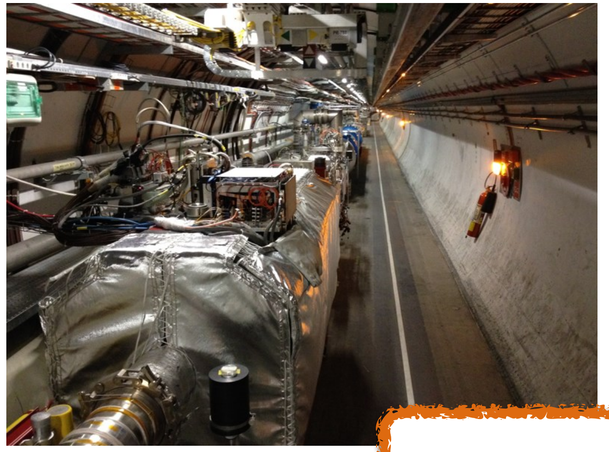


2015: LHCf team

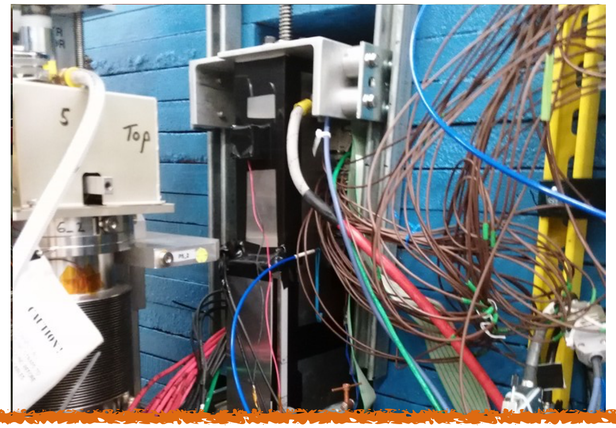


2025 : run p+O

2016: run p+Pb



2017: RHICf run (p+p, 0.5 TeV)



2022: run p+p 13.6 TeV



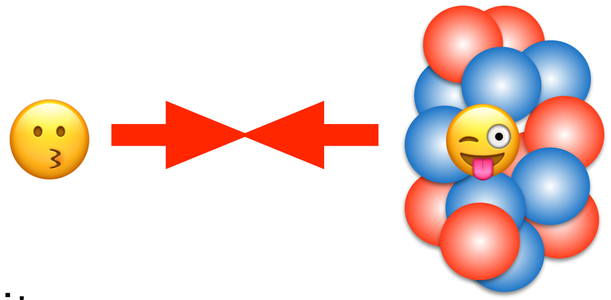


Biggest and last milestone achieved in 2025

pO collision and Nuclear Effect

- Proton - Oxygen collisions at LHC
  - First proton - “light ion” collisions at any colliders
  - Ideal condition for studying CR-Air interaction

    Note) Choice of Oxygen is due to easier beam preparation than Nitrogen.

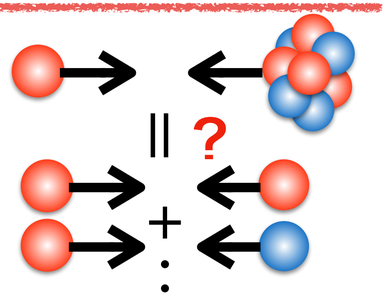


- Nucleus(nucleon)-Nucleus interactions
  - **Glauber theory**

    describe as superposition

    of ”nucleon” collisions
  - **Nuclear effect**

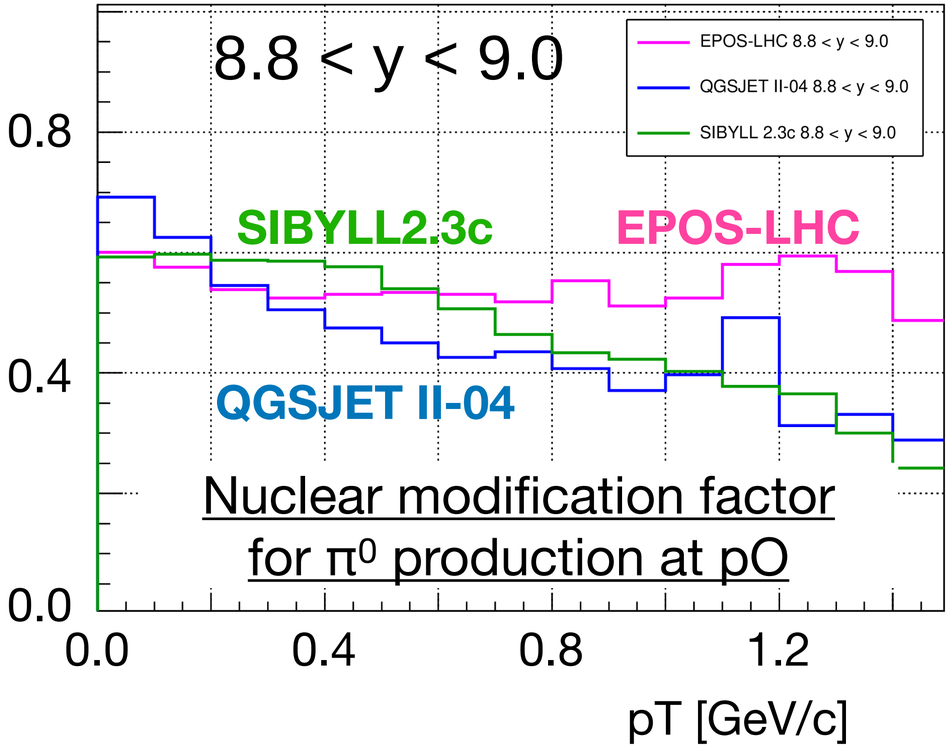
    - Nuclear shadowing
    - Limiting Fragmentation
    - QGP (core-corona)



Nuclear Modification Factor

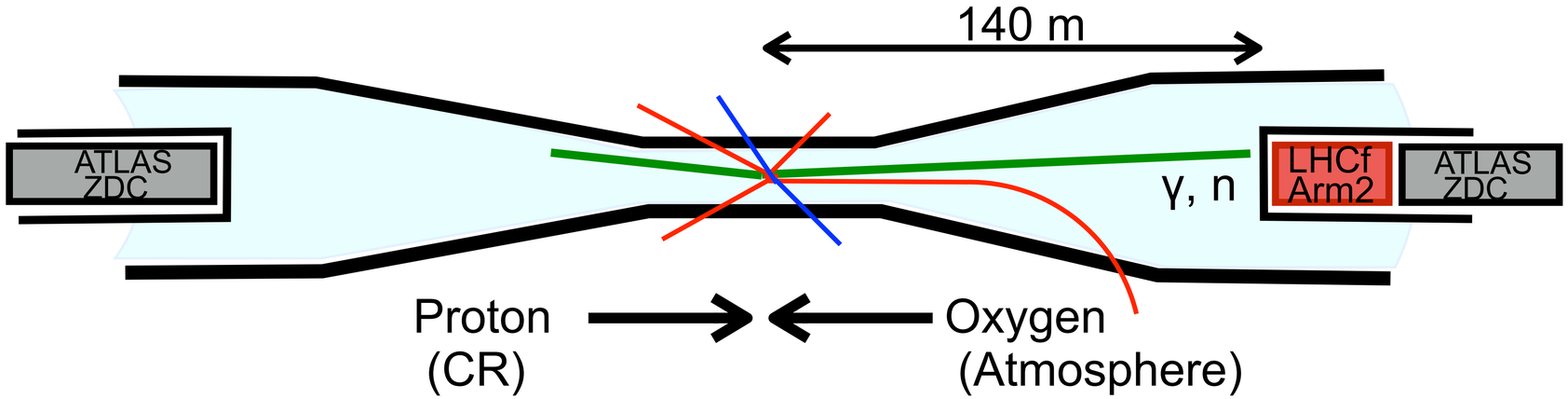
$$R = \frac{\sigma_{pO}}{A\,\sigma_{pp}}$$

A: average number of nucleon collision



Nuclear modification factor for π^0 production at pO

Experimental Setup



Beam energies

Proton : 6.8 TeV

Oxygen : 3.4 A TeV

Collision energy

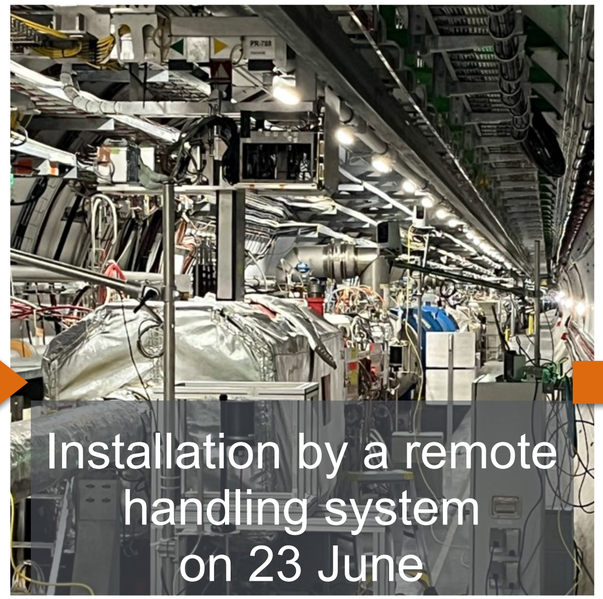
$$\sqrt{s_{NN}} = 9.6 \text{ TeV}$$

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

Operation in the proton beam side

- Only Arm2 detector was used.
- Installation was done just before the Oxygen special run

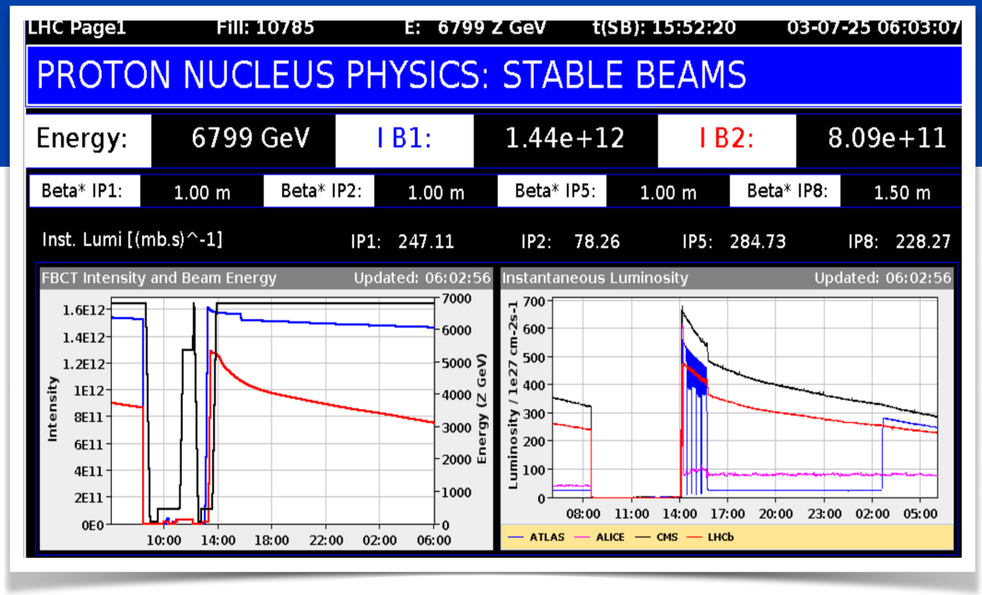

Got ready for installation photo at 20 June


Installation by a remote handling system on 23 June

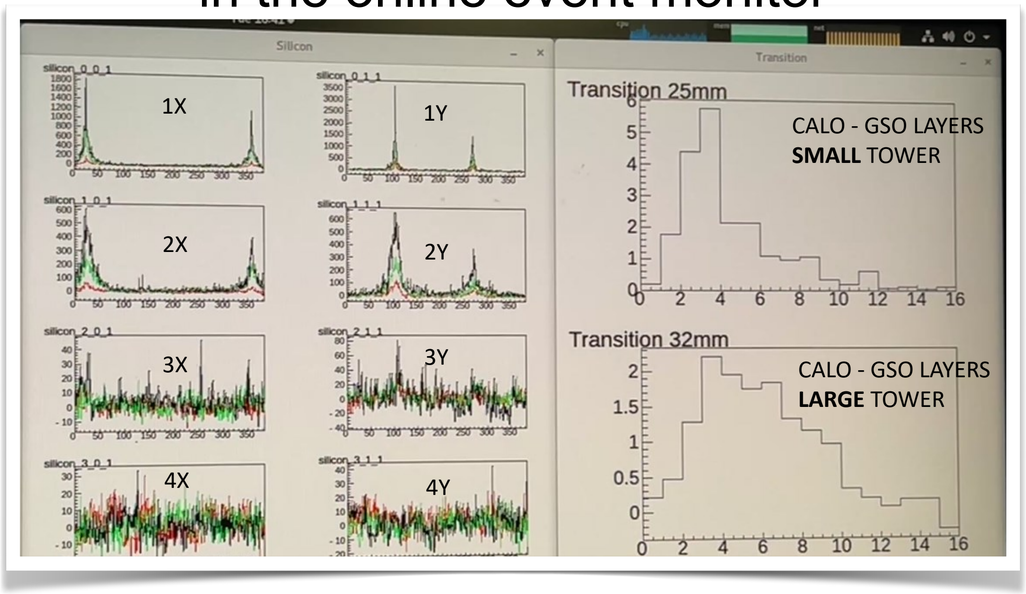

Ready for the data taking !!

Operation with pO

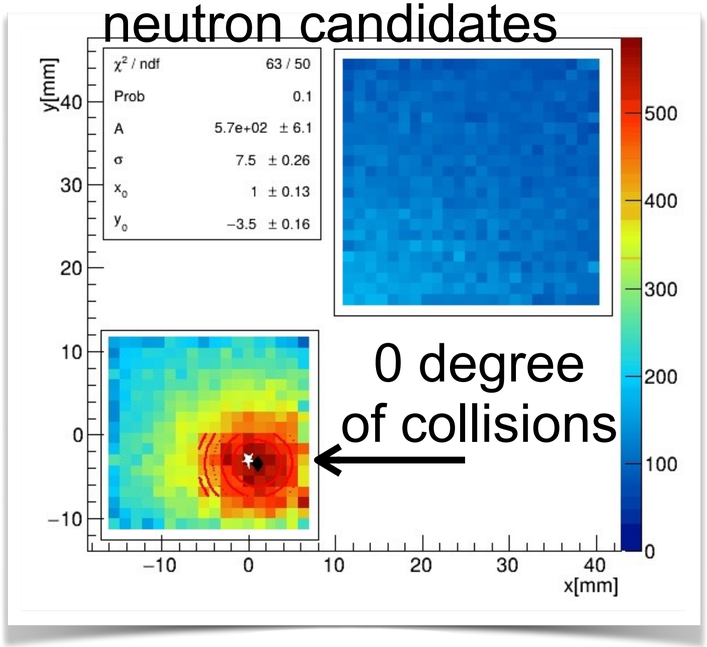
- **Successfully completed !!**
  - Data taking from 1st until 3rd July
  - Low luminosity operation ~ 10^{28} $cm^{-2}s^{-1}$
  - Preformed a joint operation with ATLAS
    - *All LHCf triggers were accepted by ATLAS DAQ*



First π^0 candidate events found in the online event monitor



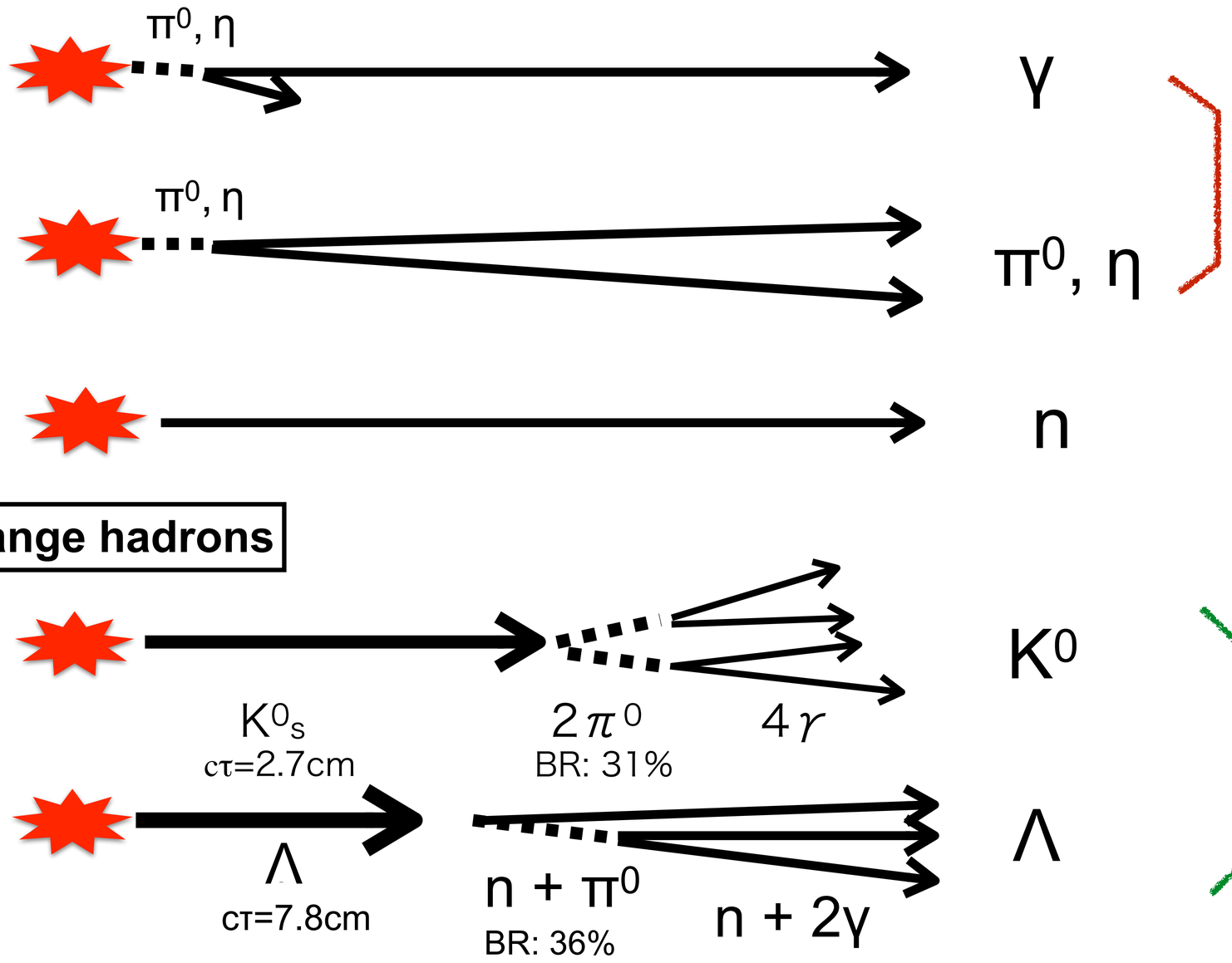
Hit map of high energy neutron candidates





Operation in the control room

Analyses



Sources of EM components in the air showers

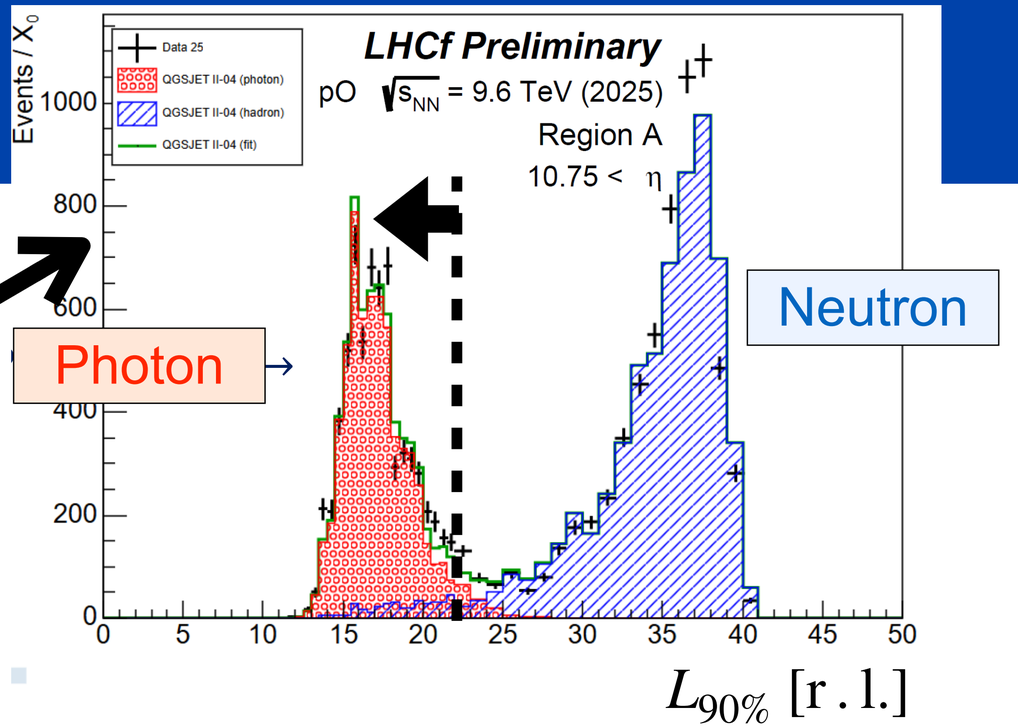
Estimations of inelasticity
(E_{beam} - $E_{leading}$ ~ $E_{hadrons}$)

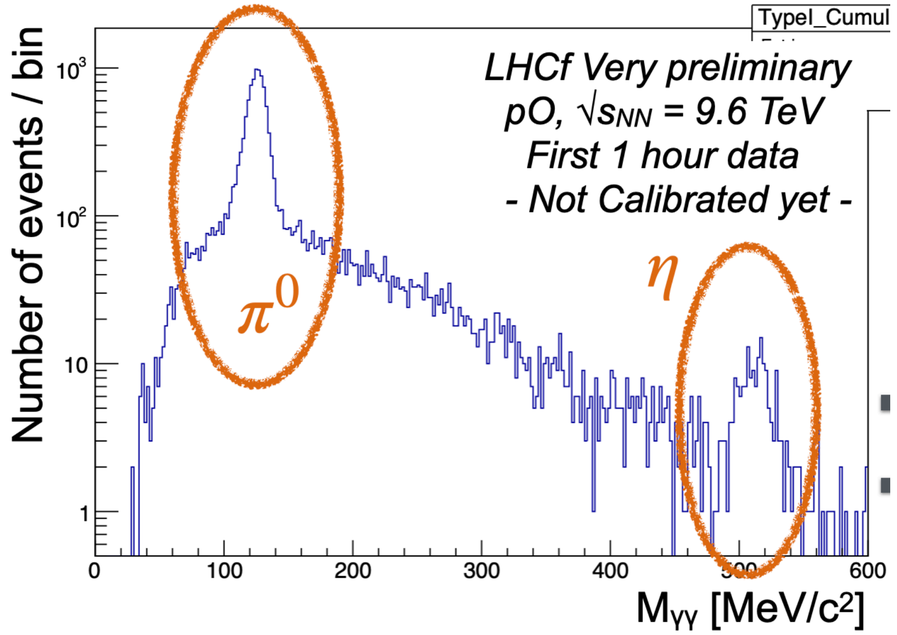
Challenging
- Small acceptance
- Difficult reconstruction
but important for muon puzzle

Photon analysis

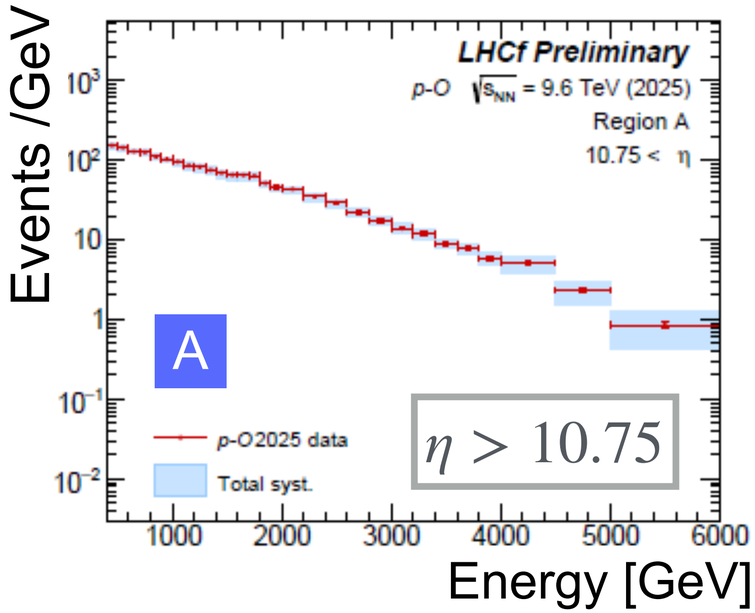
- Data set
  - 3 hours, nominal detector position

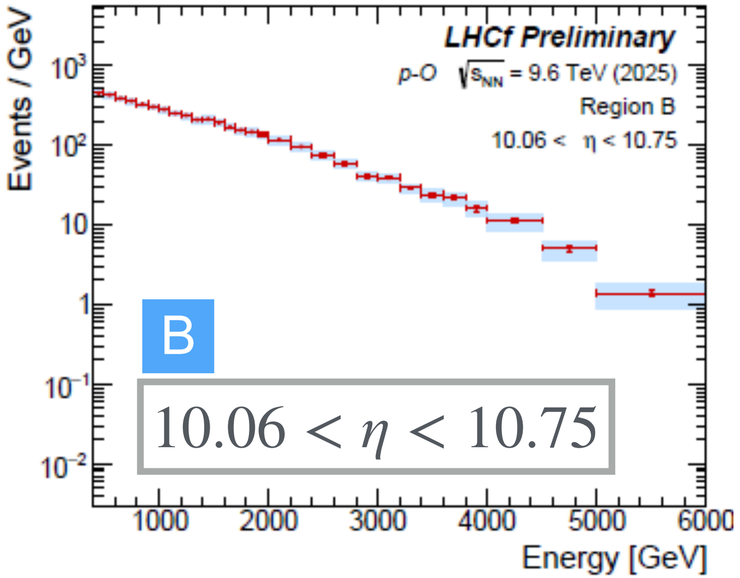
- Analysis Method
  - **PID selection**
    - Parameterize the shower tail position as $L_{90\%}$
  - **Energy cut** $E_\gamma > 400\,\mathrm{GeV}$
    - Ensure the 100% trigger efficiency
  - **Energy calibration using π^0 mass**
  - **Pseudo-rapidity η selections**
    - Define the six analysis areas corresponding to the η regions

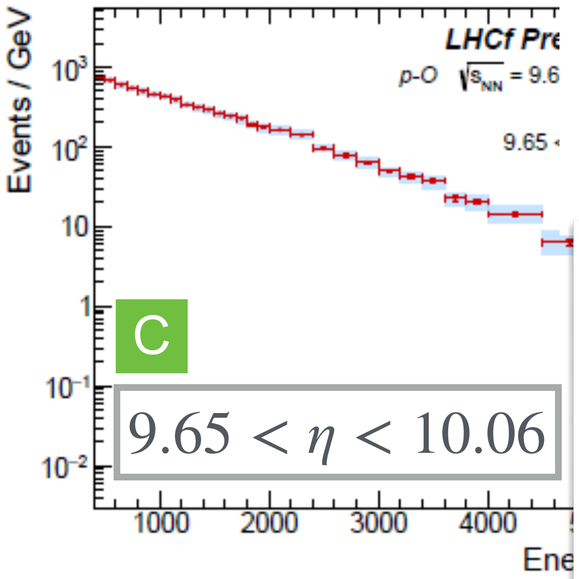


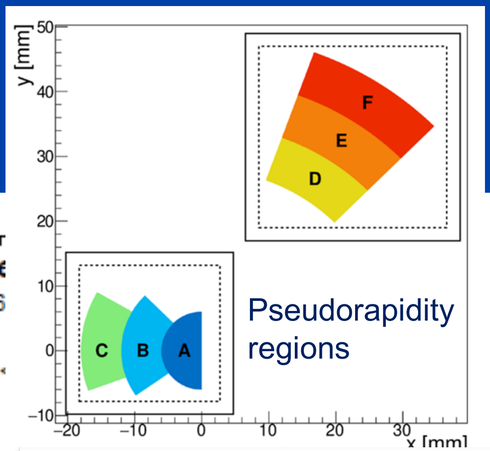


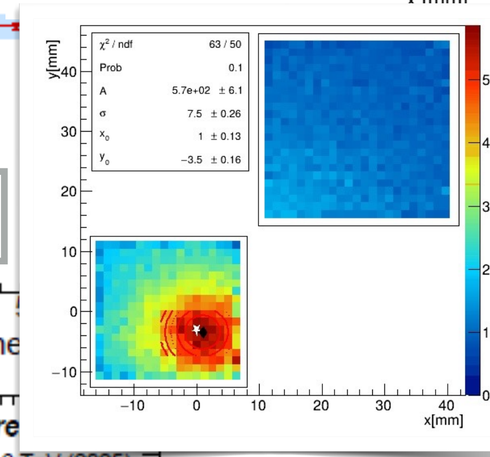
Preliminary results

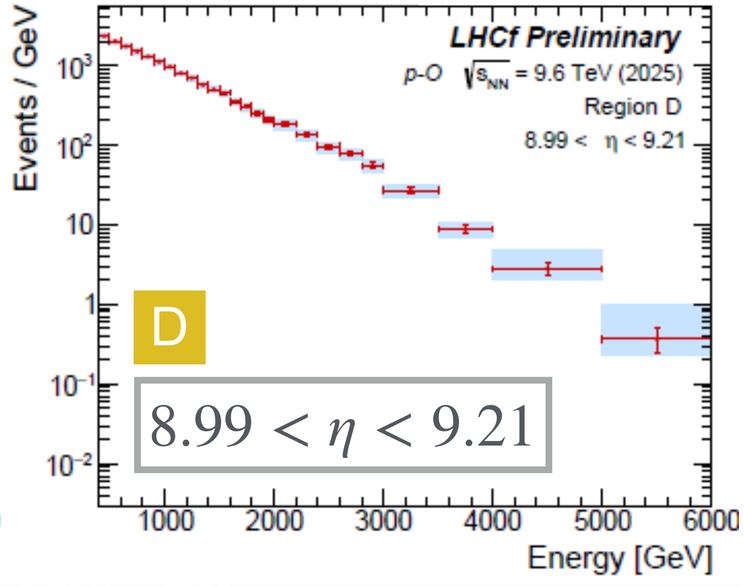


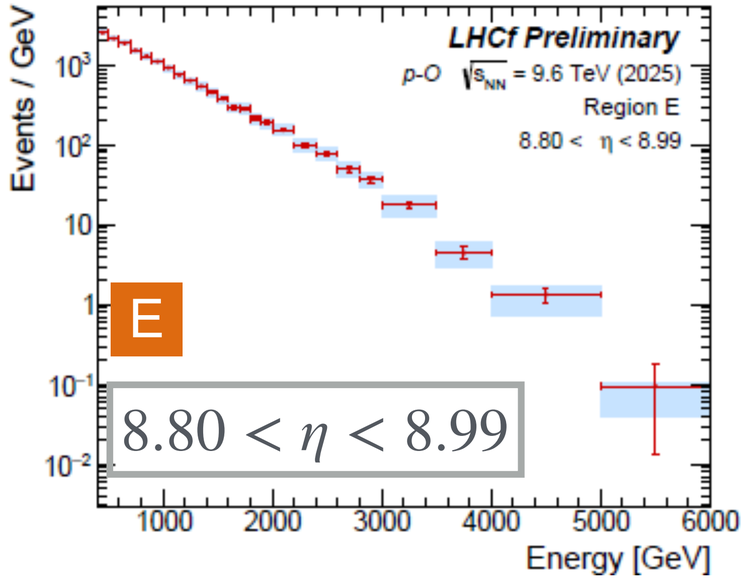


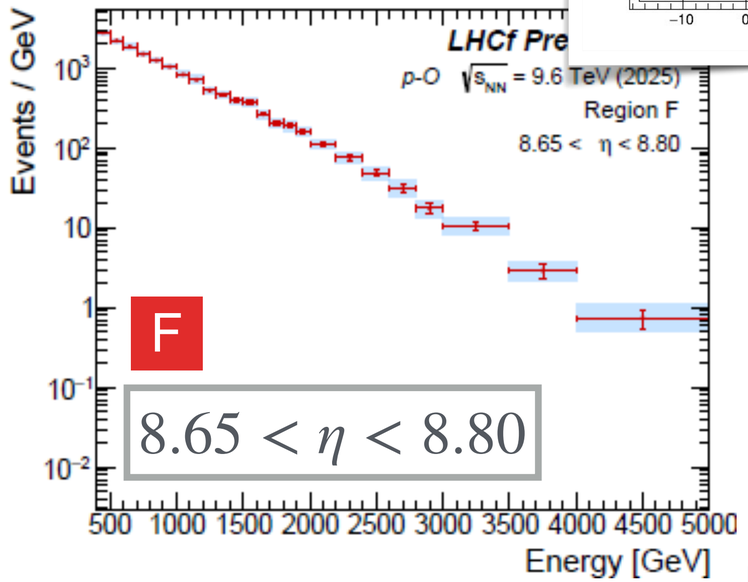




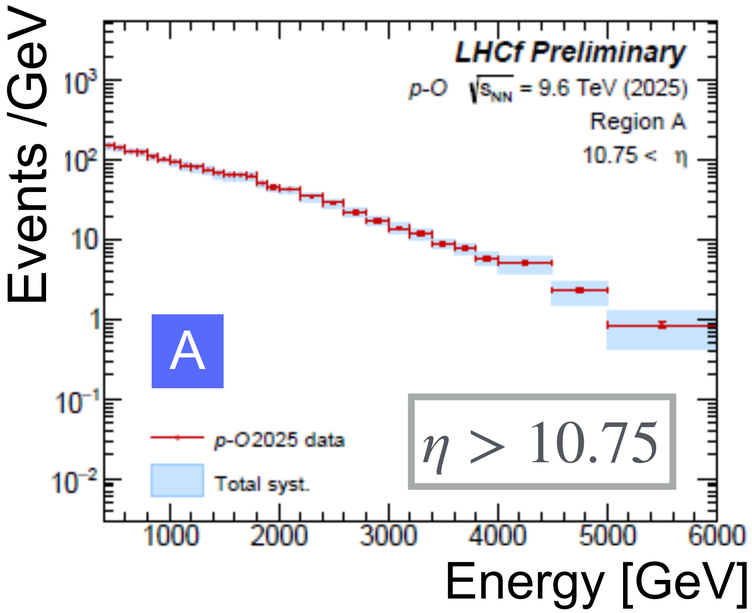


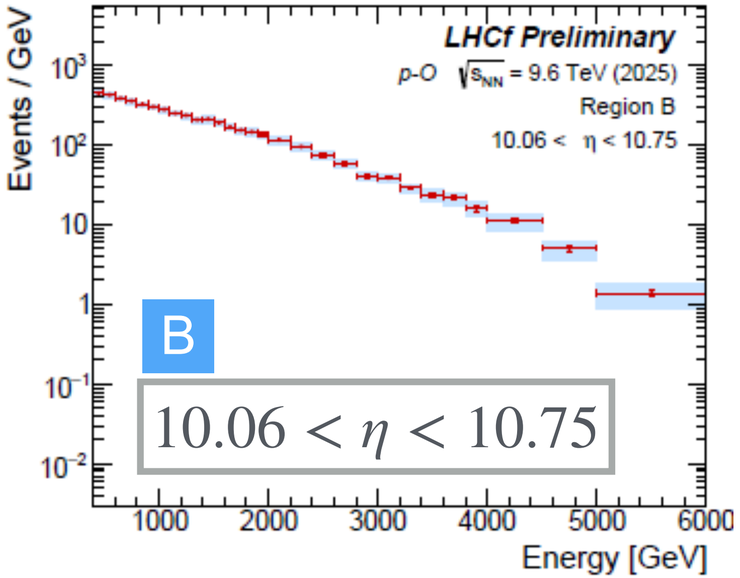


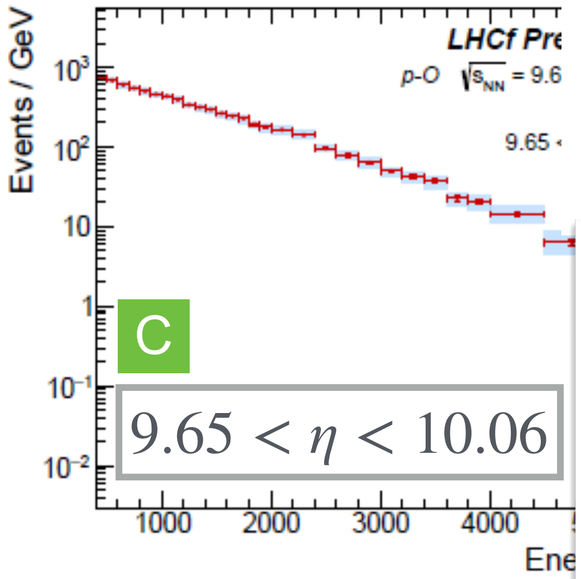


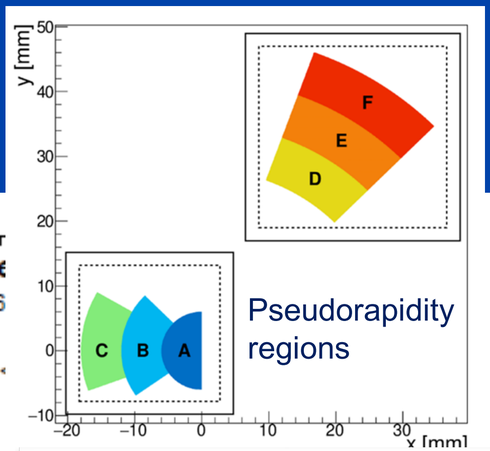


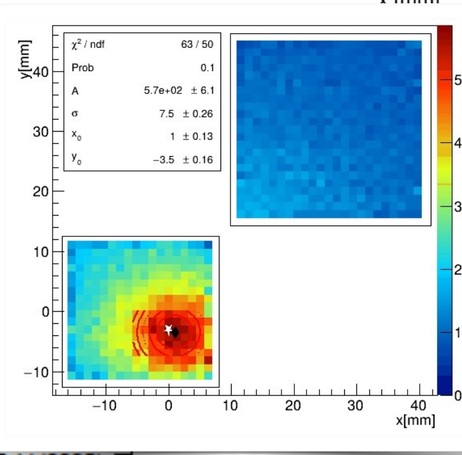
Preliminary results

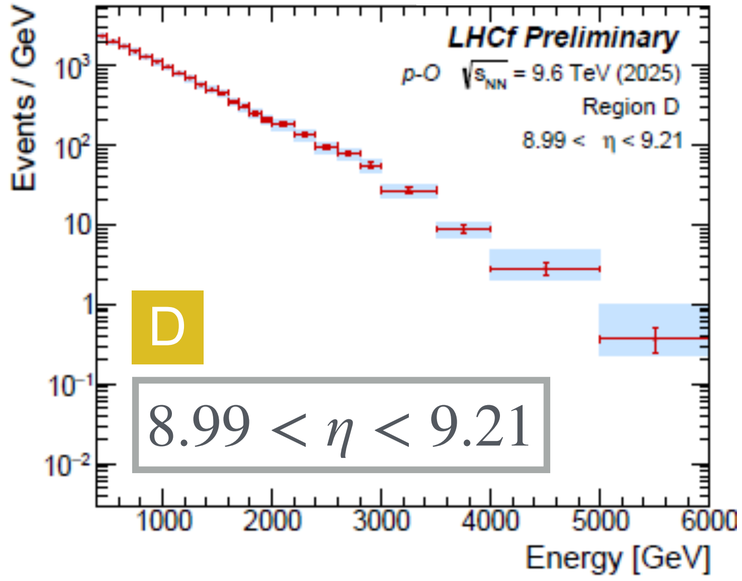


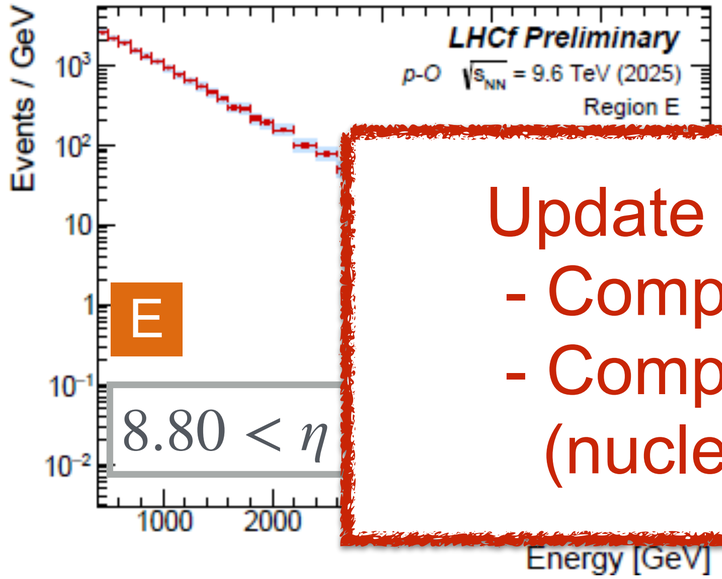


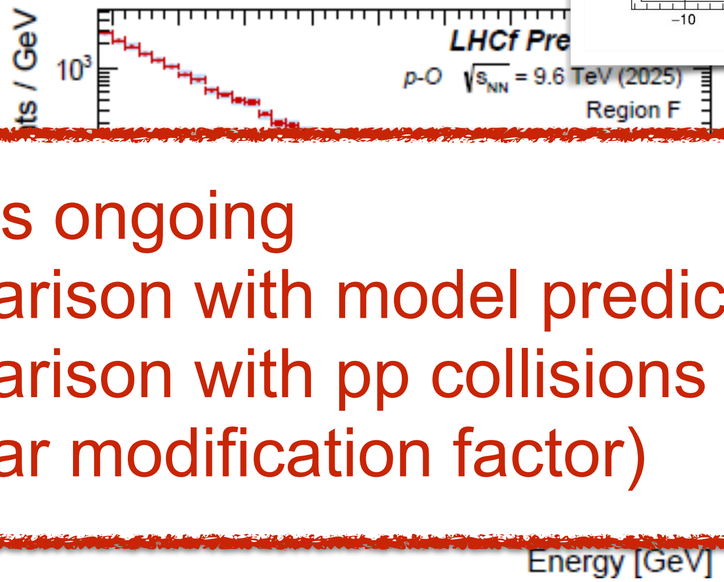






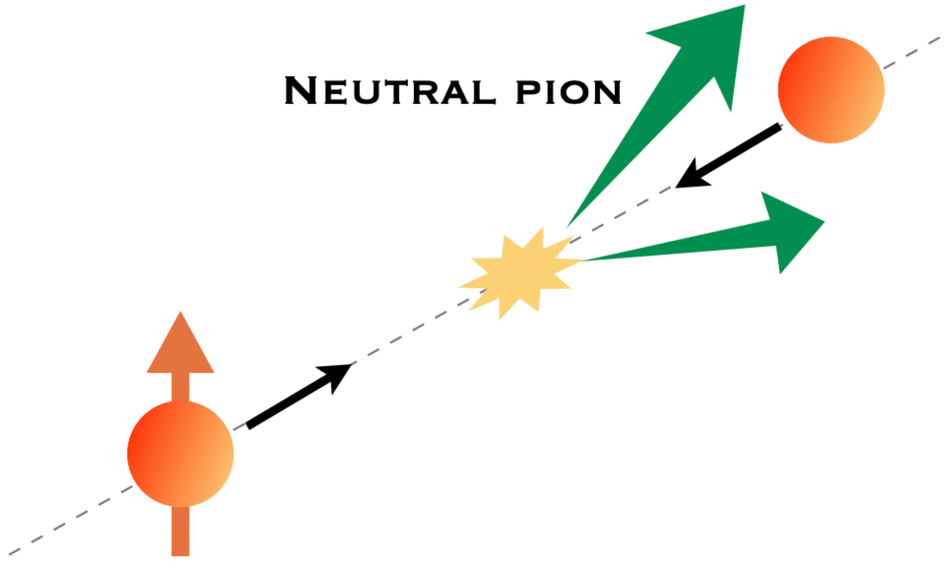




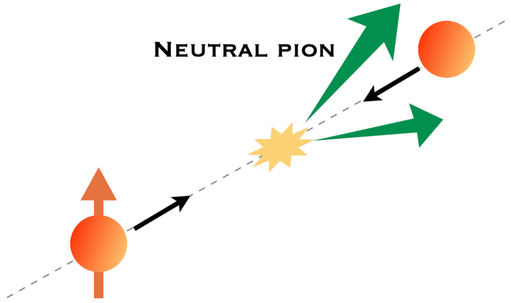


Update is ongoing
- Comparison with model predictions
- Comparison with pp collisions (nuclear modification factor)

Spin Asymmetry Measurements from RHICf



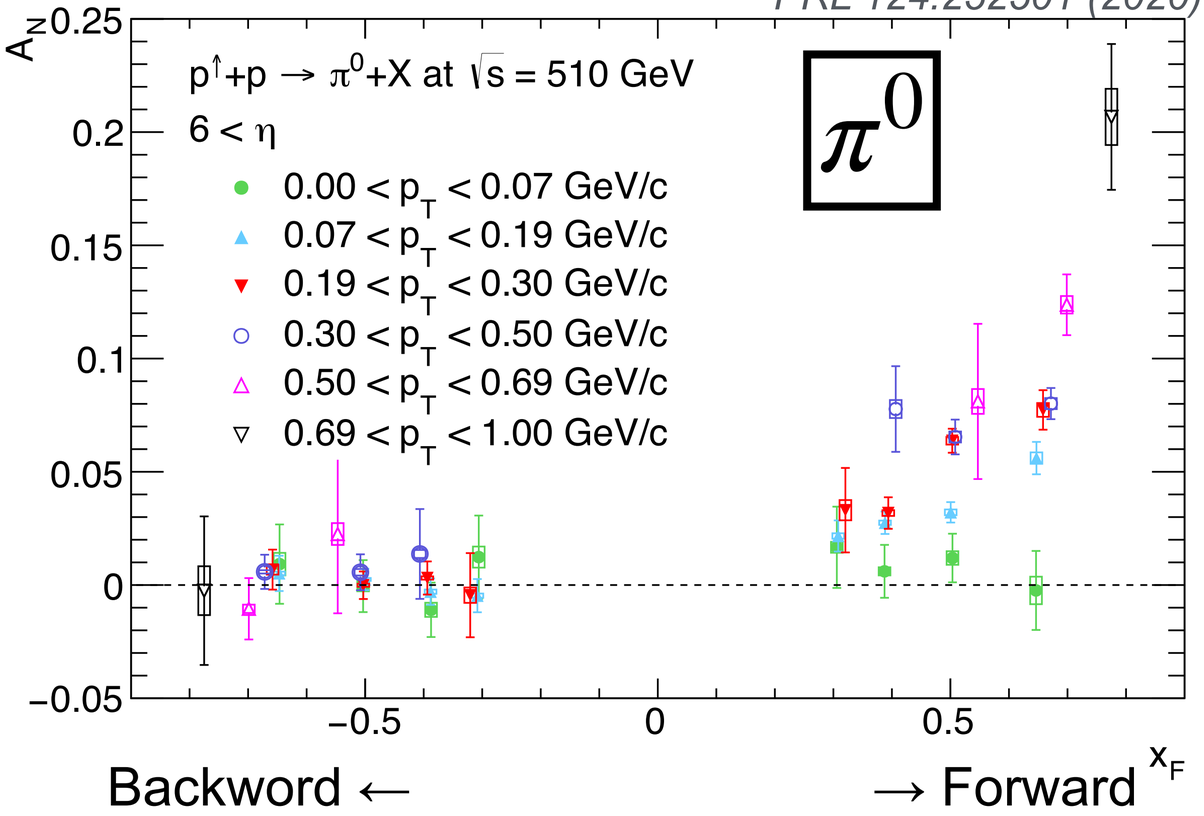
Results of Spin Asymmetry A_N



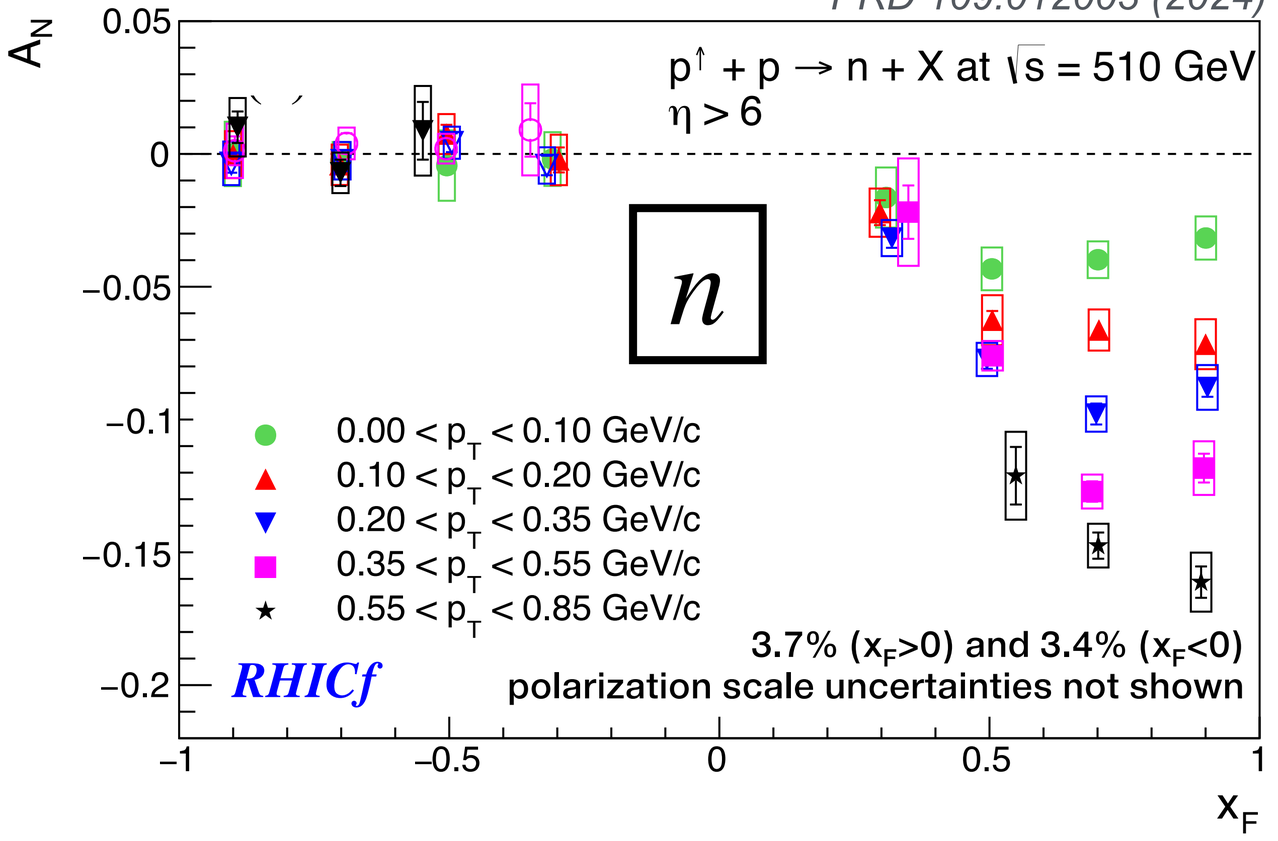
$$A_N = \frac{d\sigma_{\text{left}} - d\sigma_{\text{right}}}{d\sigma_{\text{left}} + d\sigma_{\text{right}}}$$

$pp, \sqrt{s} = 510$ GeV
$\eta > 6.0$

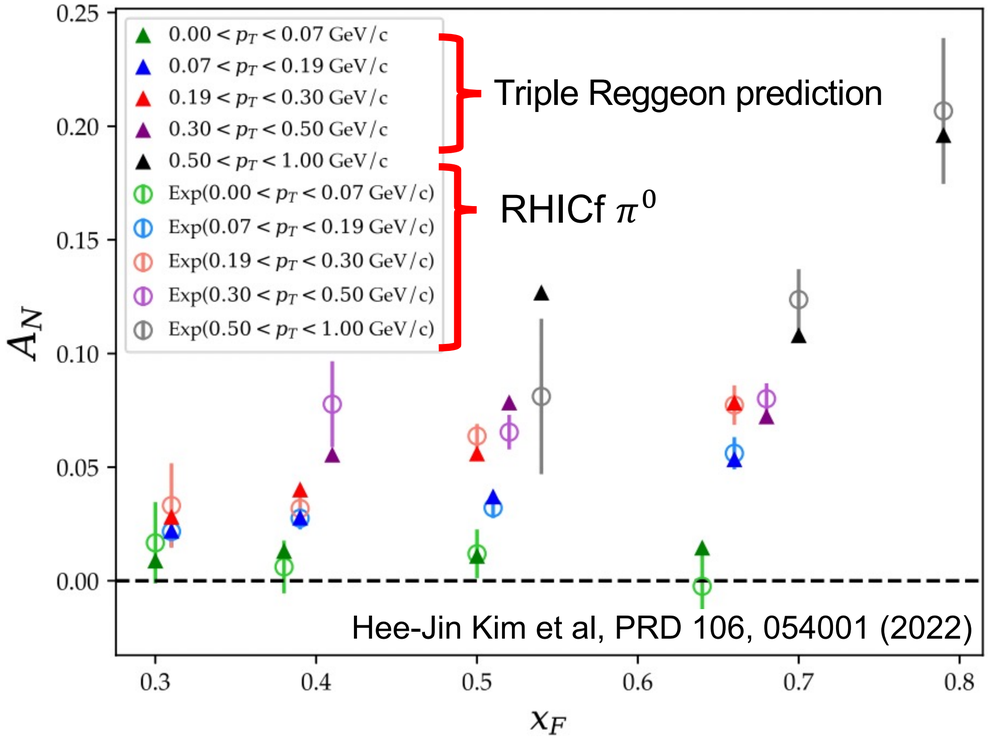
PRL 124:252501 (2020)



PRD 109:012003 (2024)

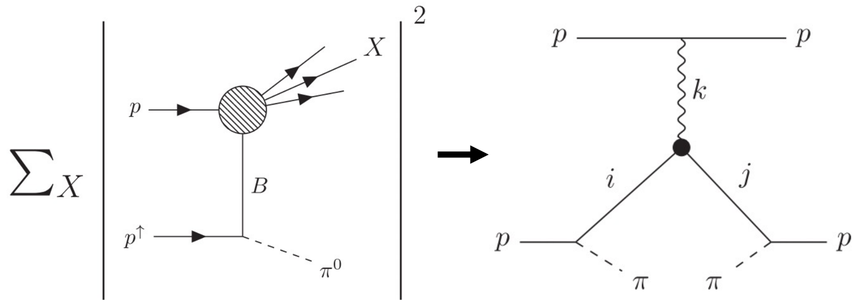


Why large A_N ?

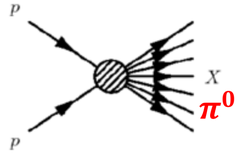


One explanation is based on the triple Reggeon approach

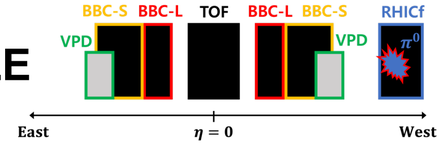
Triple Reggeon diagram

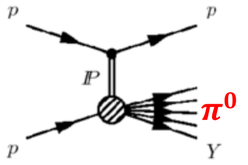


Large A_N may baryonic triple regge exchange (especially ΔΔ*, NN*)

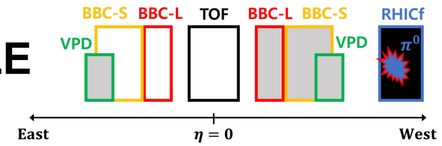


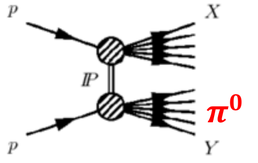
Non Diff. ⟷ **NDLE**



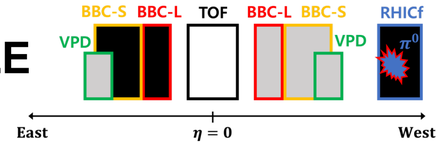


Single Diff. ⟷ **SDLE**





Double Diff. ⟷ **DDLE**



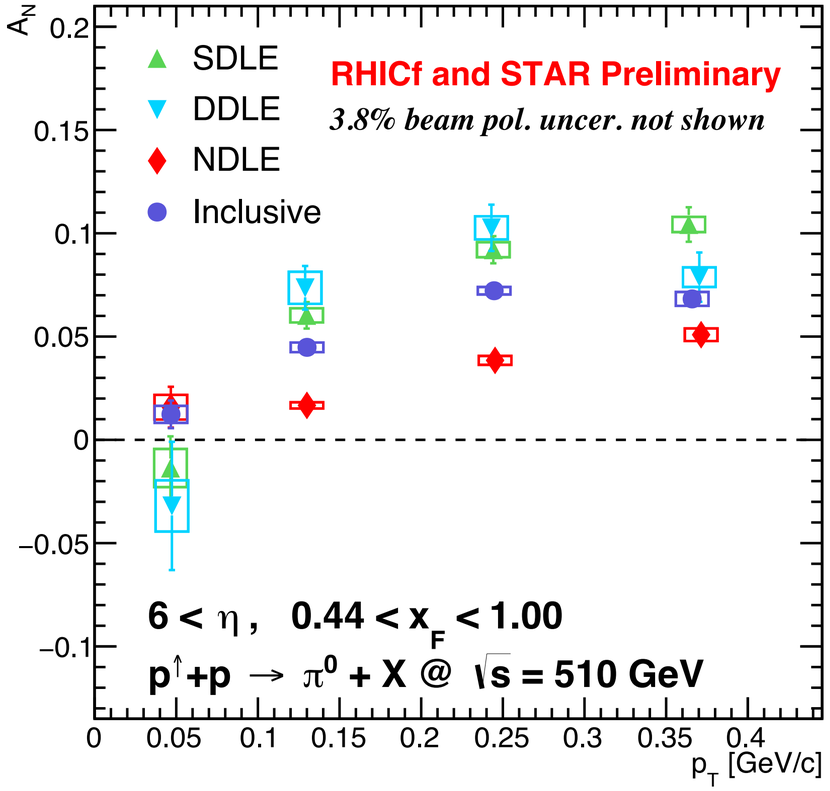
Legend:

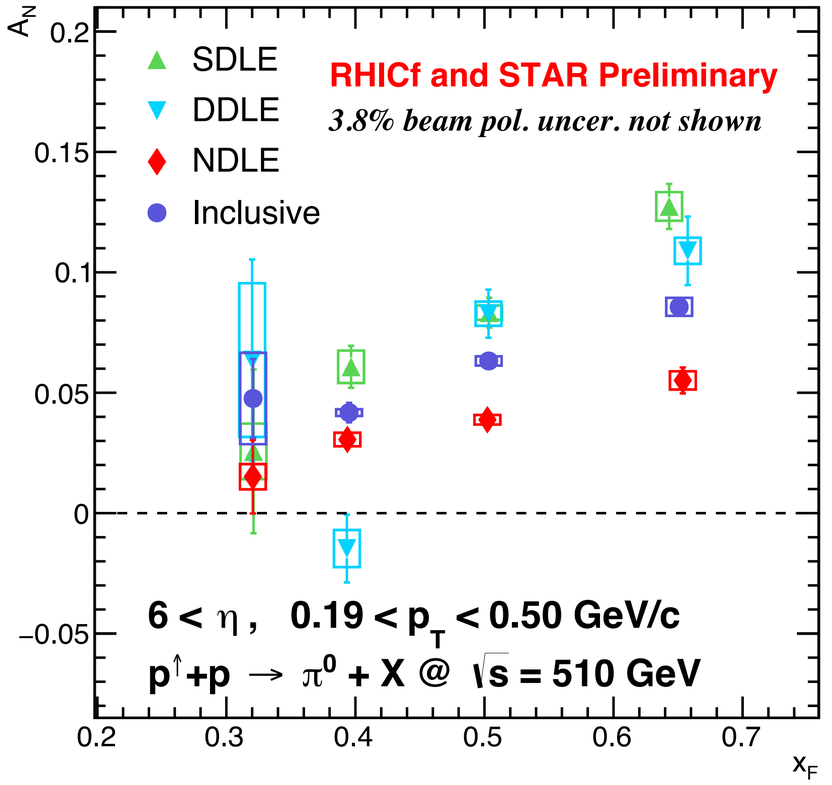
- Always signal
- signal or not
- No signal

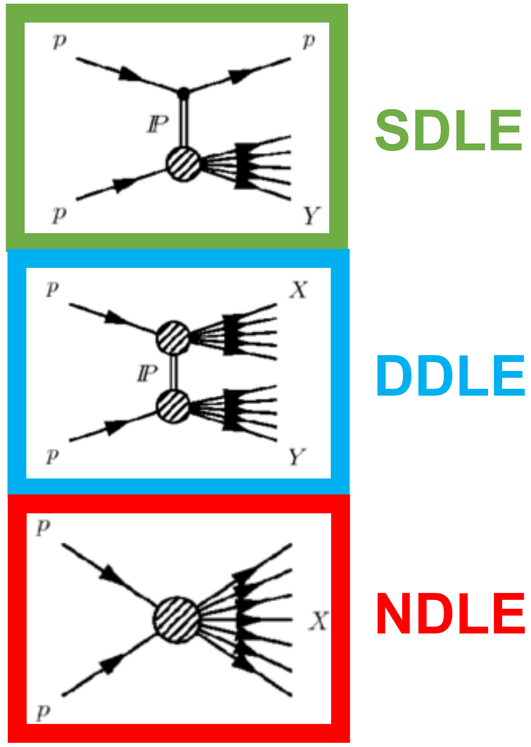
Test with RHICf+STAR

- Categorize the events with central activities measured by STAR detectors

Preliminary result of A_N







- Clear dependency of AN on the event category was observed.
  SDLE and DDLE ↗ NDLE ↘

RHICf+STAR works further understanding of interactions

Summary

- LHCf and RHICf have completed all operations successfully !!
  - The last LHCf operation was performed with pO collisions, which is an ideal configuration for studying CR-atmospheric nucleus interactions
- Many analyses are on-going and results will come in next years
  - Results from pO collision data
    Especially nuclear modification factor measurements w/ comparing pp
  - Strange hadron measurements, K^0 and Λ
    Developing reconstruction methods
  - Joint analyses, LHCf+ATLAS, RHICf + STAR
    Deep understanding the interaction using central-forward correlations

Backup

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}	S ArXi				with STAR

p-O operation in 2025