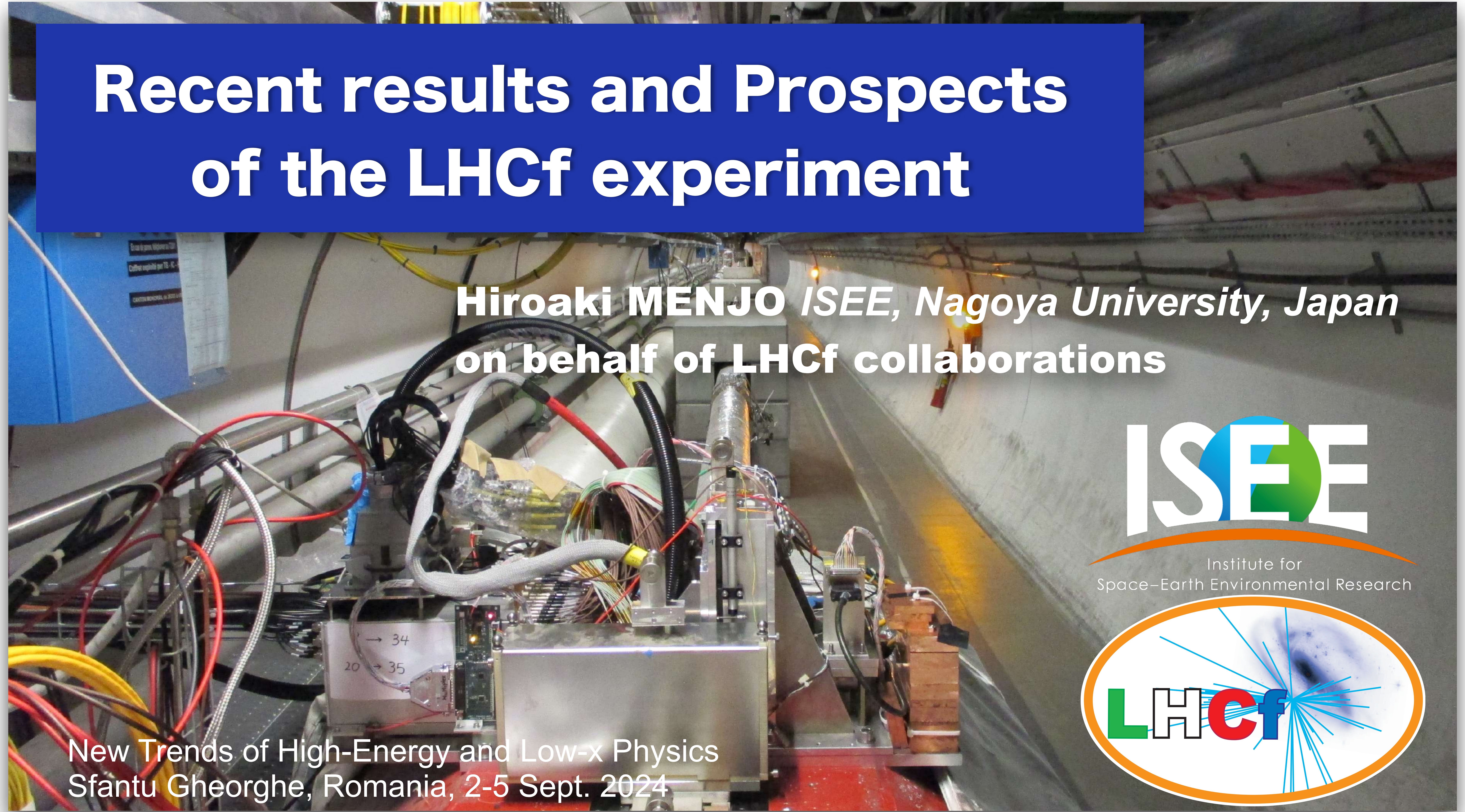
Recent results and Prospects of the LHCf experiment

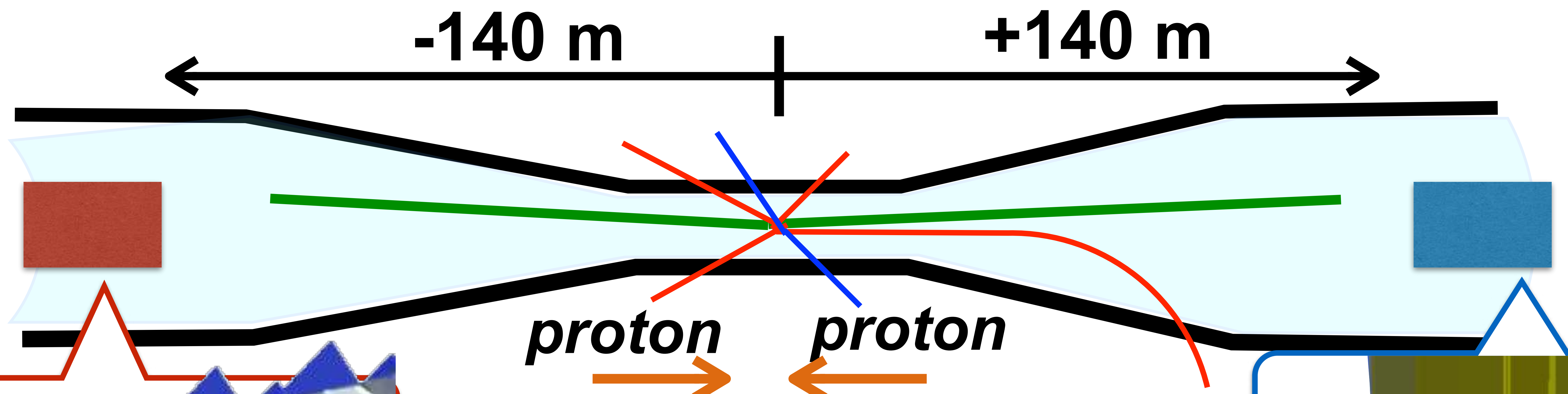
Hiroaki MENJO *ISEE, Nagoya University, Japan*
on behalf of LHCf collaborations

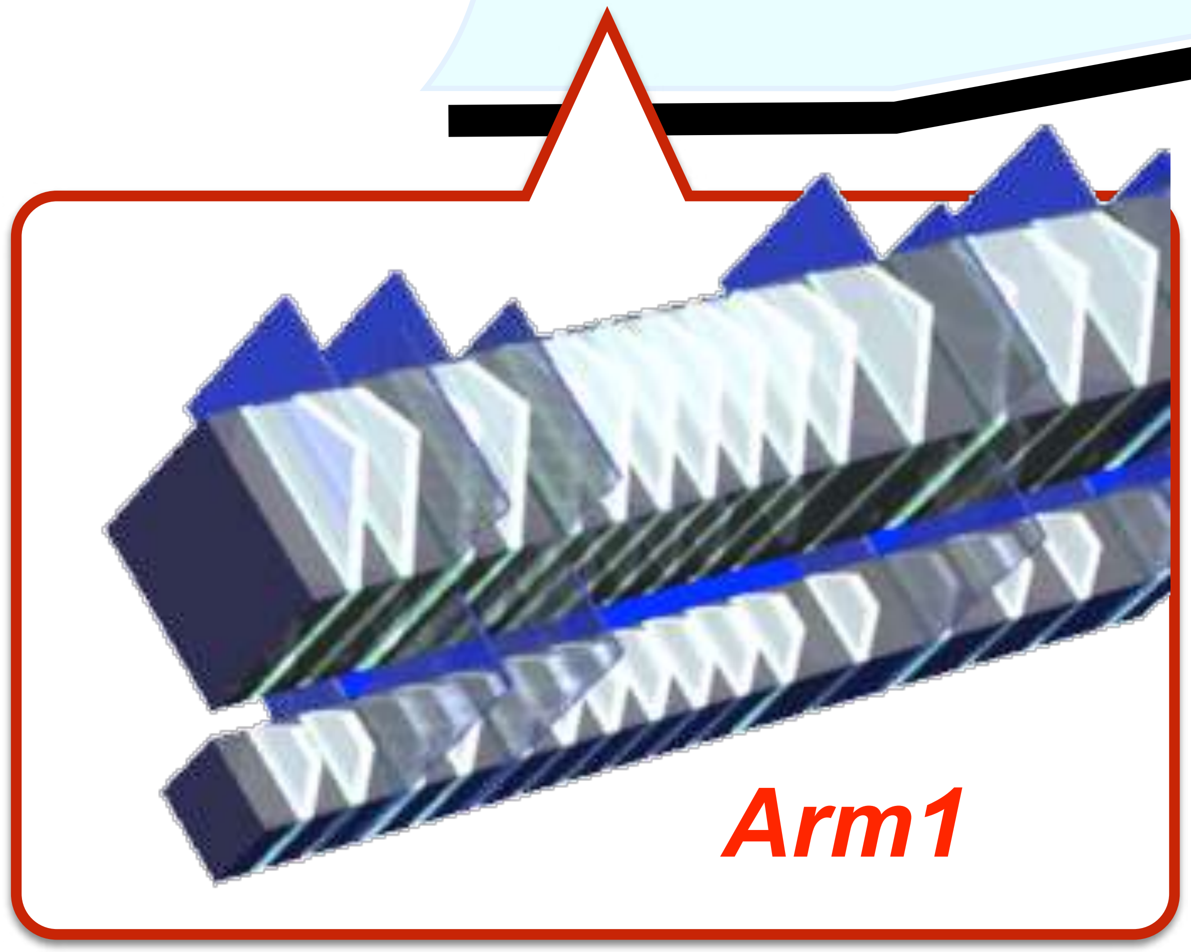


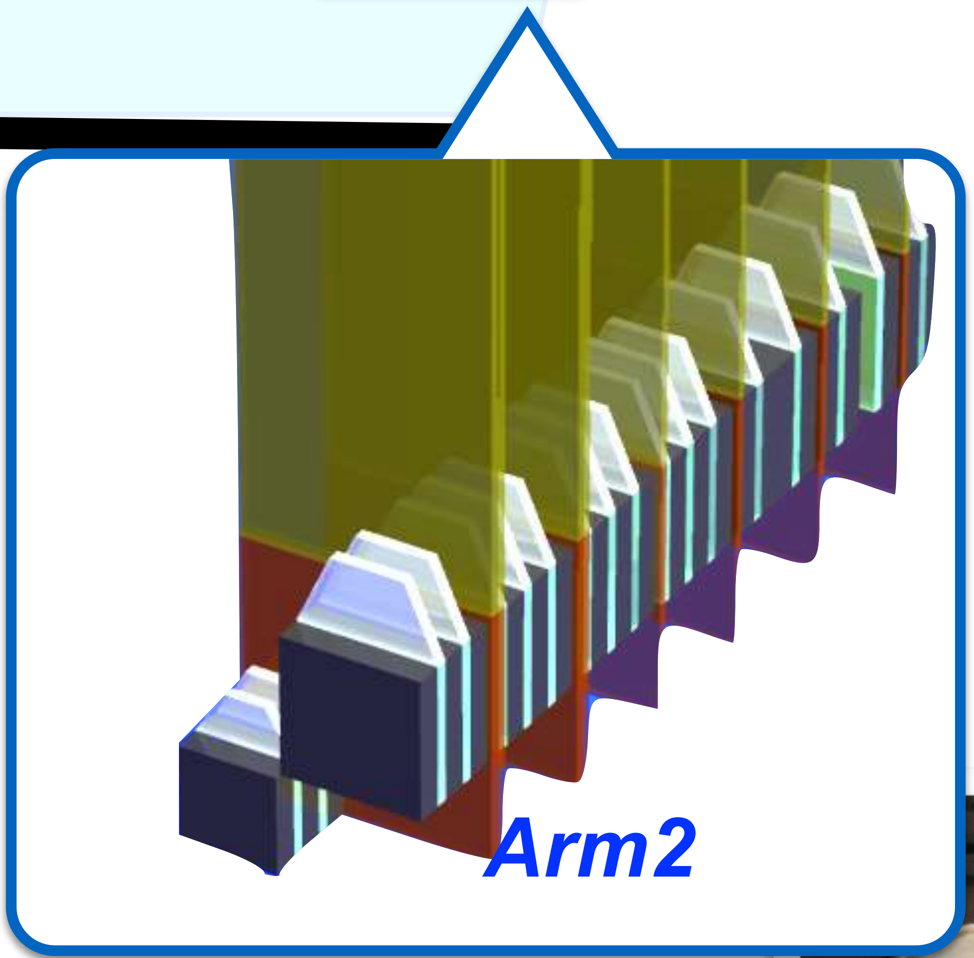
Institute for
Space-Earth Environmental Research

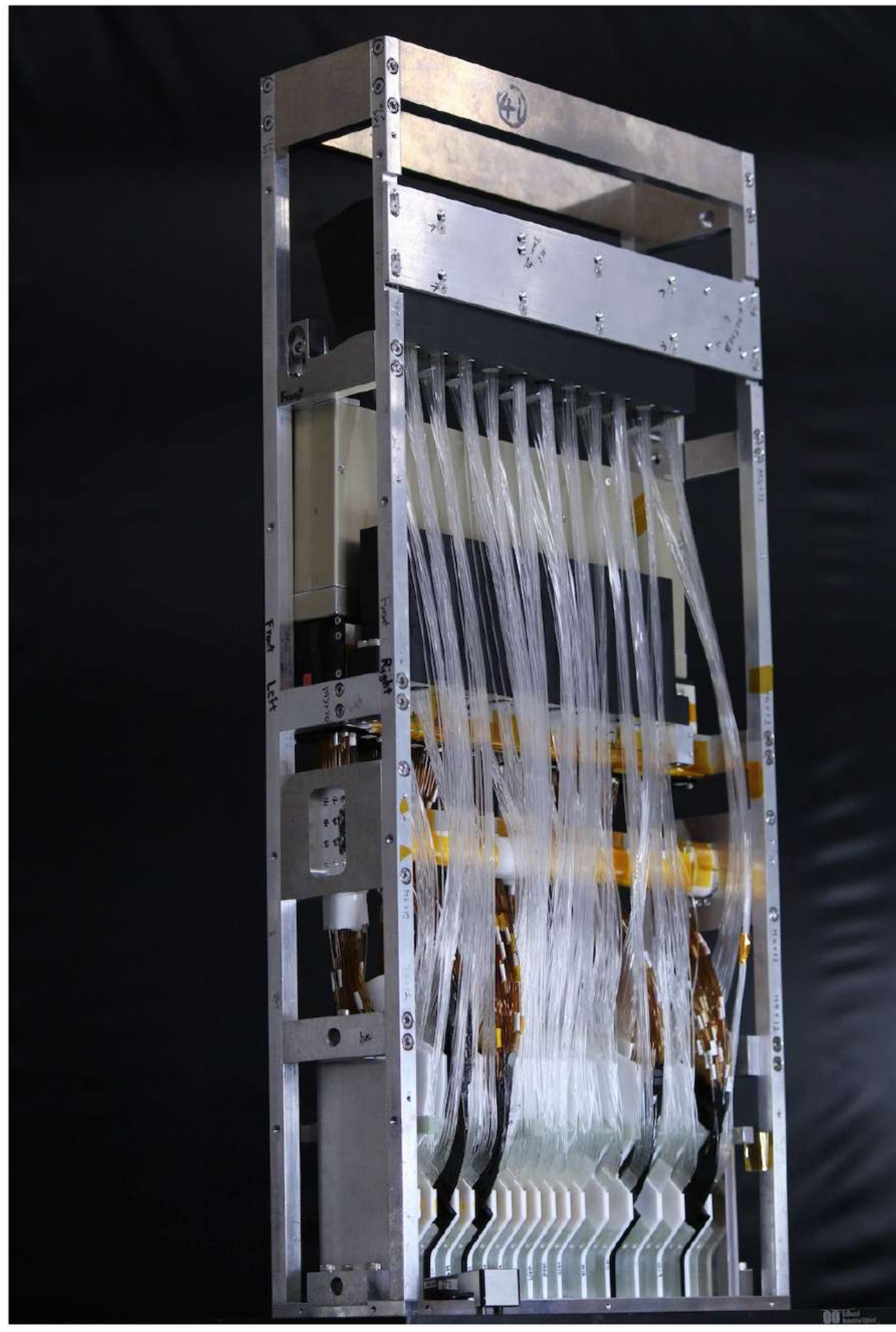
New Trends of High-Energy and Low-x Physics
Sfantu Gheorghe, Romania, 2-5 Sept. 2024

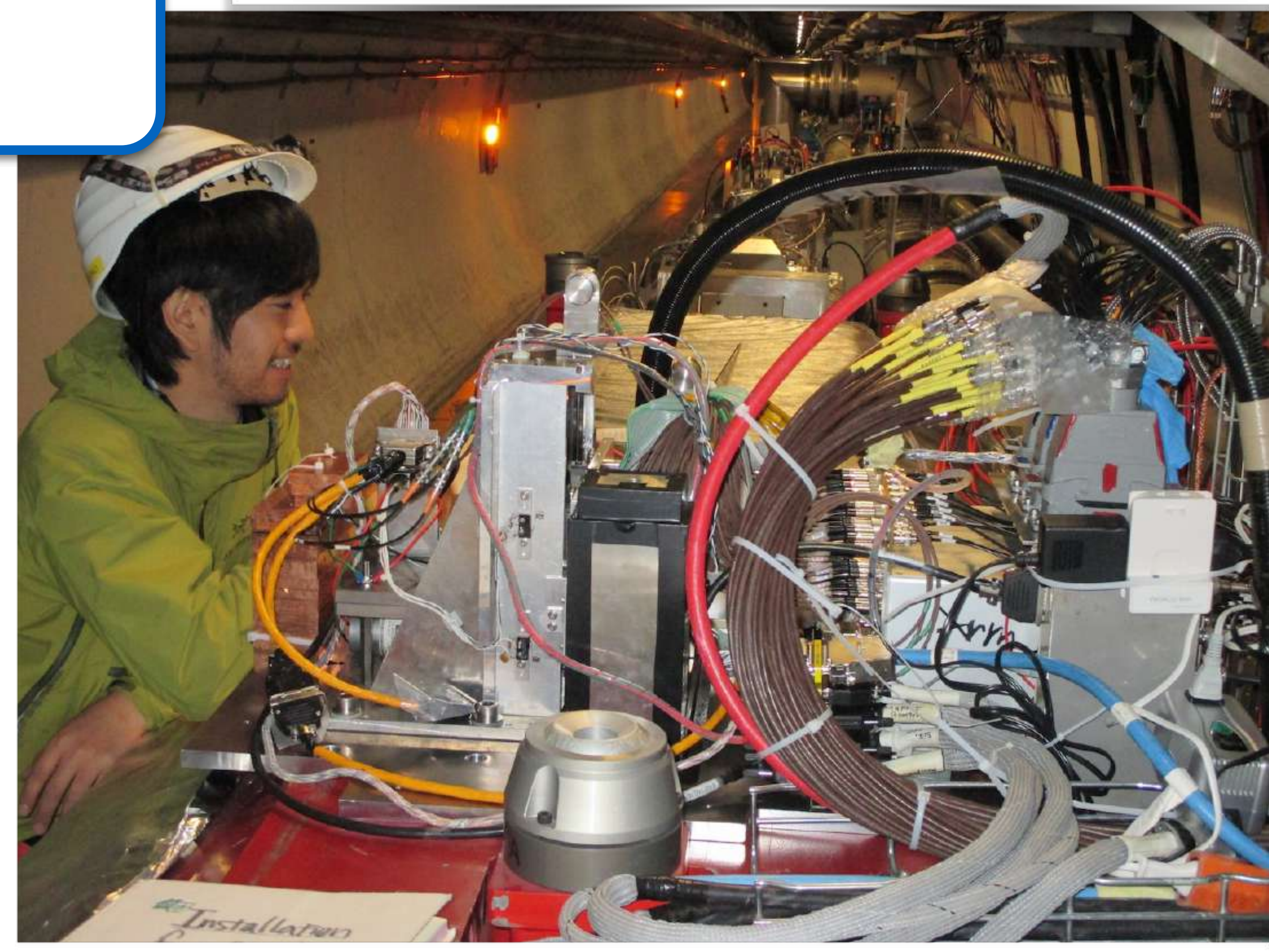
LHCf experiment











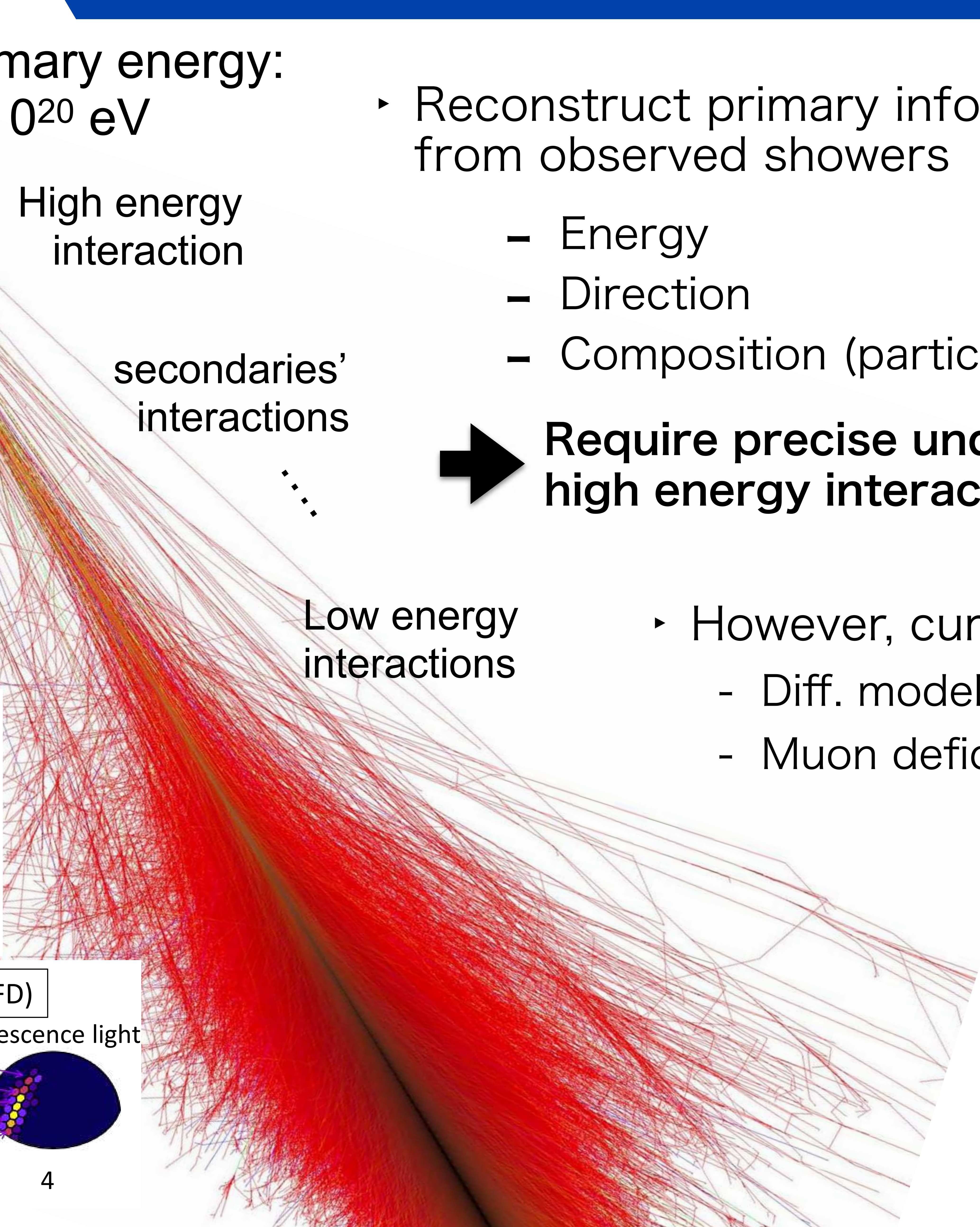
Location

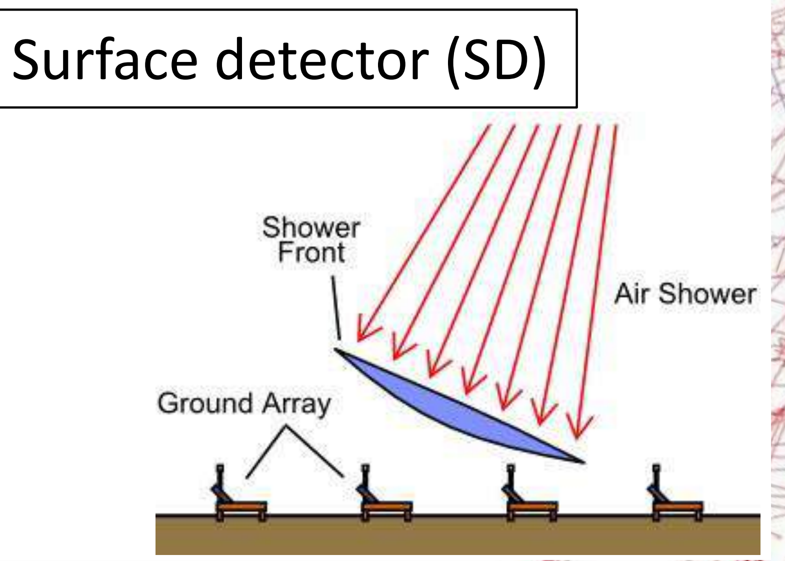
- ATLAS interaction point
- +/- 140m from the IP
- Cover Zero degree of collisions
  pseudo rapidity $\eta > 8.4$

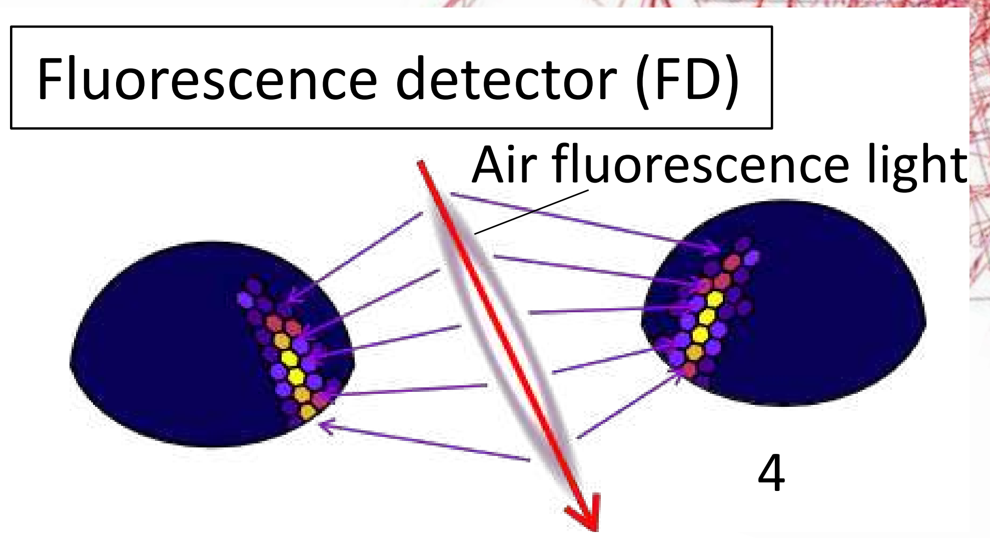
LHCf detectors

- 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

High Energy Cosmic-Ray Observation



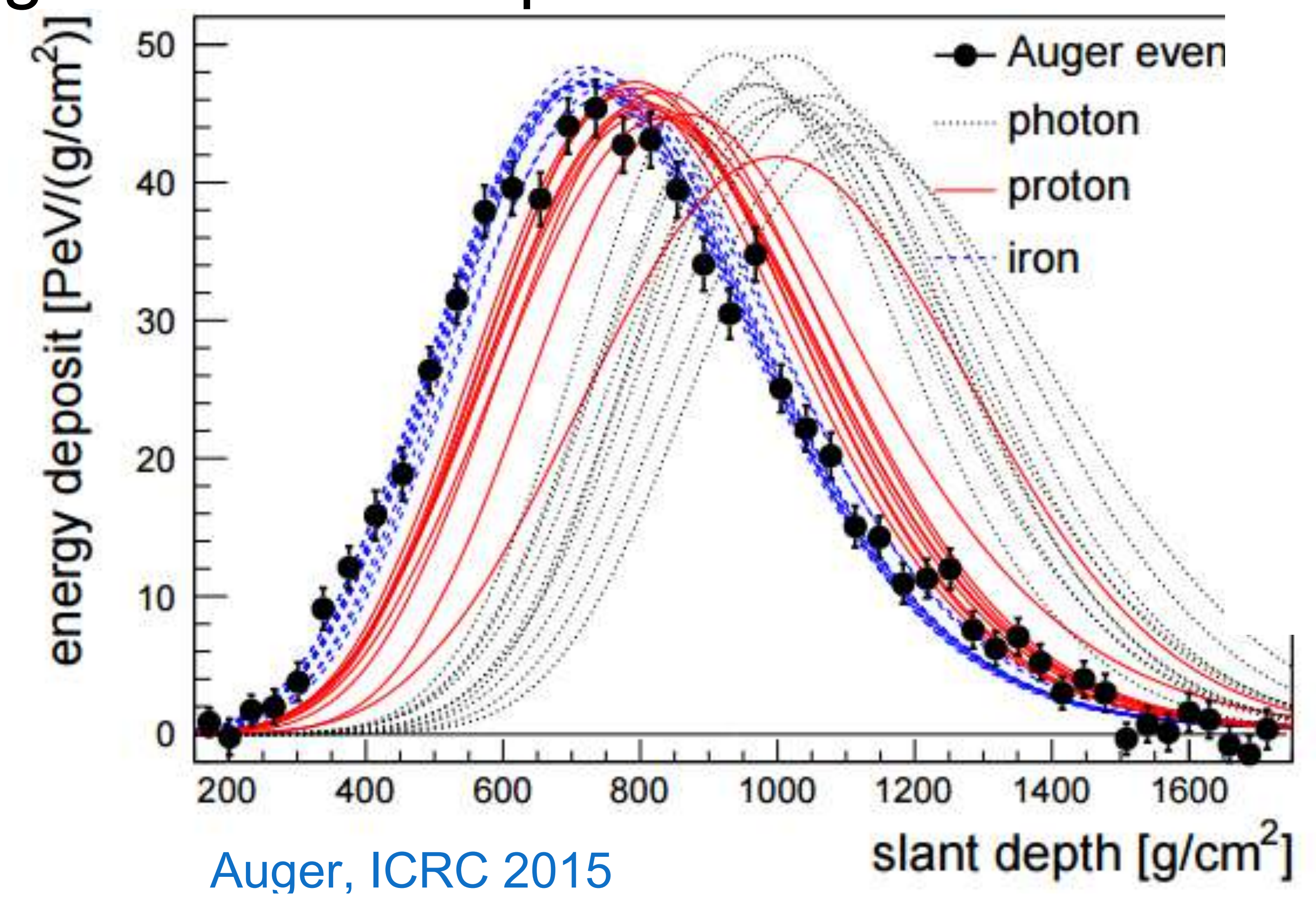




- Reconstruct primary information from observed showers
  - Energy
  - Direction
  - Composition (particle type)

➡ **Require precise understanding high energy interactions**

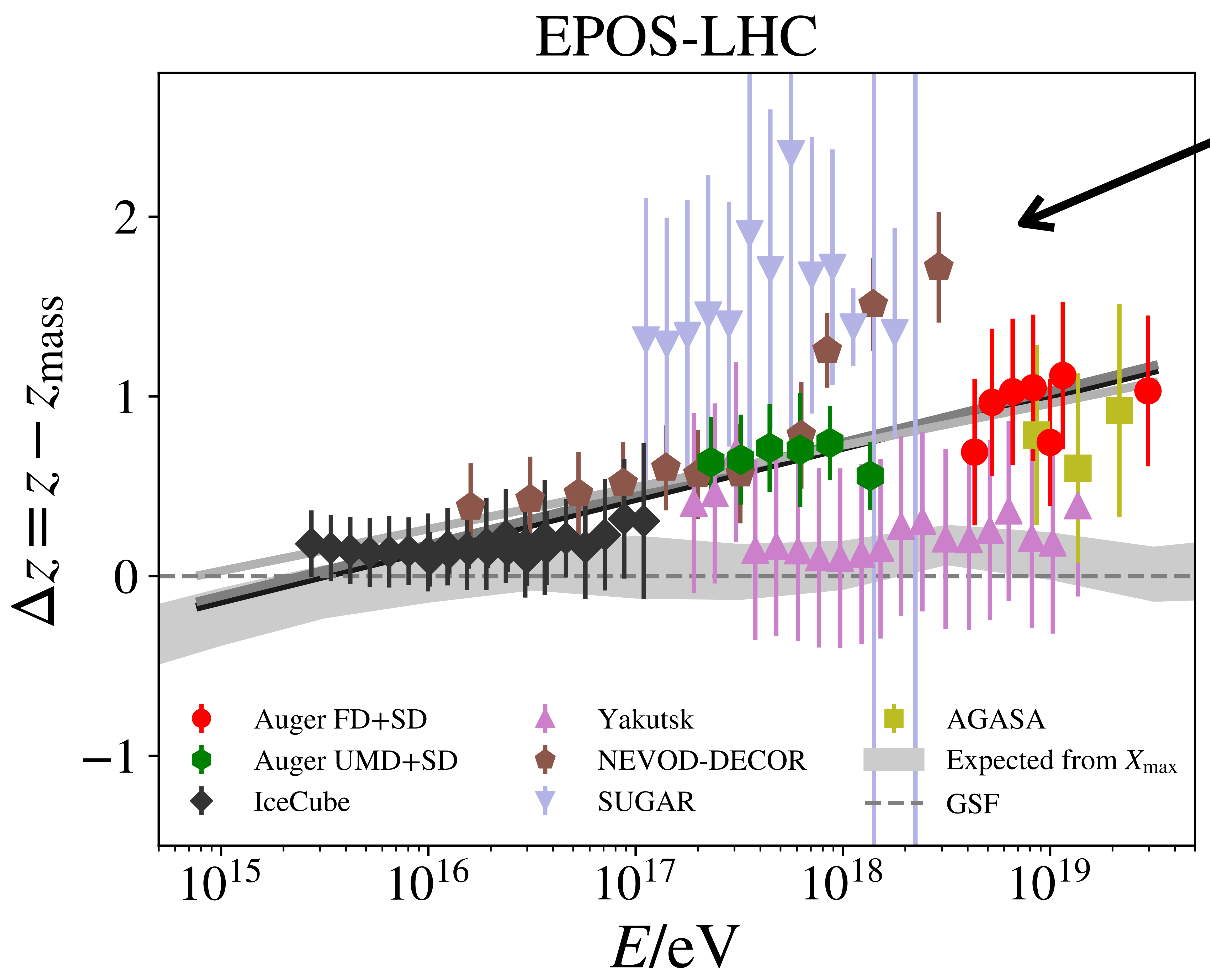
Longitudinal development of 10^{19}eV showers



- 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 (K)
- pion interactions
- nuclear effects

Energy dependency of muon excess



Normalized muon numbers results observed by several CR experiments

Muon excess

= Composition model + Air Shower MC

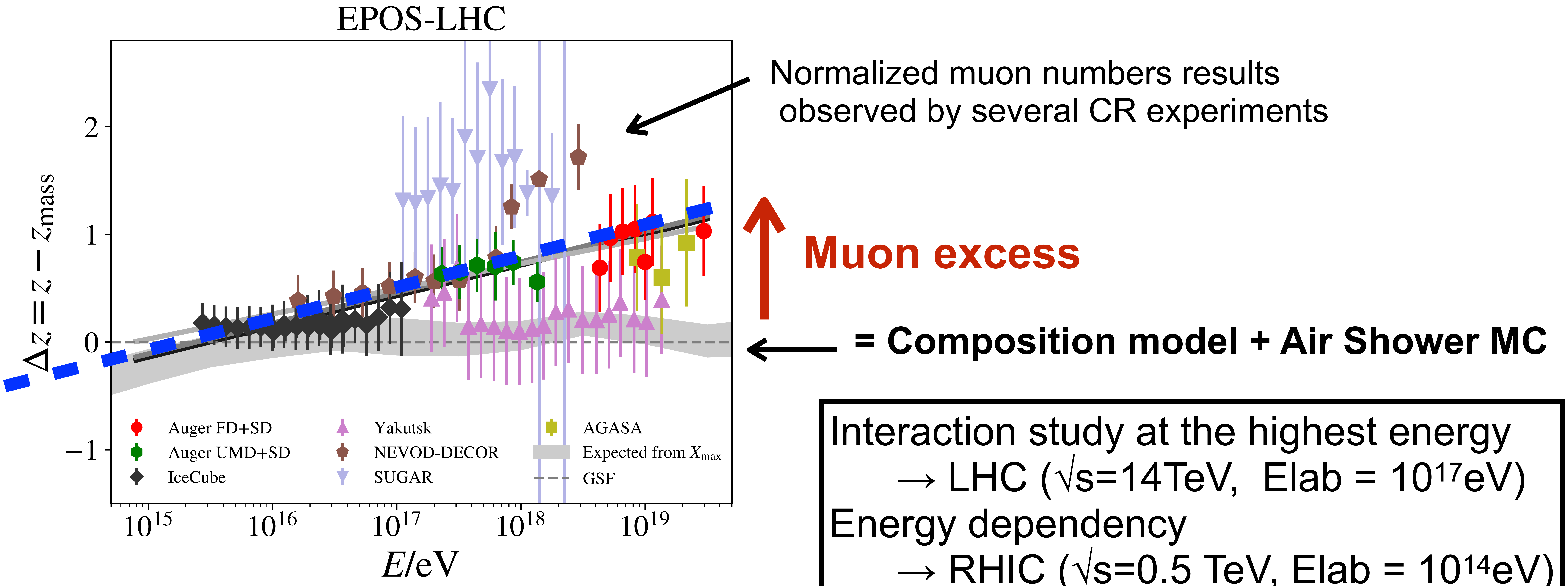
Interaction study at the highest energy
→ LHC ($\sqrt{s}$=14TeV, Elab = 10^{17}eV)
Energy dependency
→ RHIC ($\sqrt{s}$=0.5 TeV, Elab = 10^{14}eV) v.s. LHC

$$z = \frac{\ln(N_\mu^{\text{det}}) - \ln(N_{\mu_p}^{\text{det}})}{\ln(N_{\mu_{\text{Fe}}}^{\text{det}}) - \ln(N_{\mu_p}^{\text{det}})}$$

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

- Line model with slope fitted to $\Delta z = z - z_{\text{mass}}$
- Correction to $\chi^2/n_{\text{dof}} = 1$ applied to take unexplained spread into account
- Slope is 8σ (10σ) away from zero for EPOS-LHC (QGSJet-II.04)
- Onset of deviation around 40 PeV corresponds to $\sqrt{s} \sim 8$ TeV; in reach of LHC

Energy dependency of muon excess



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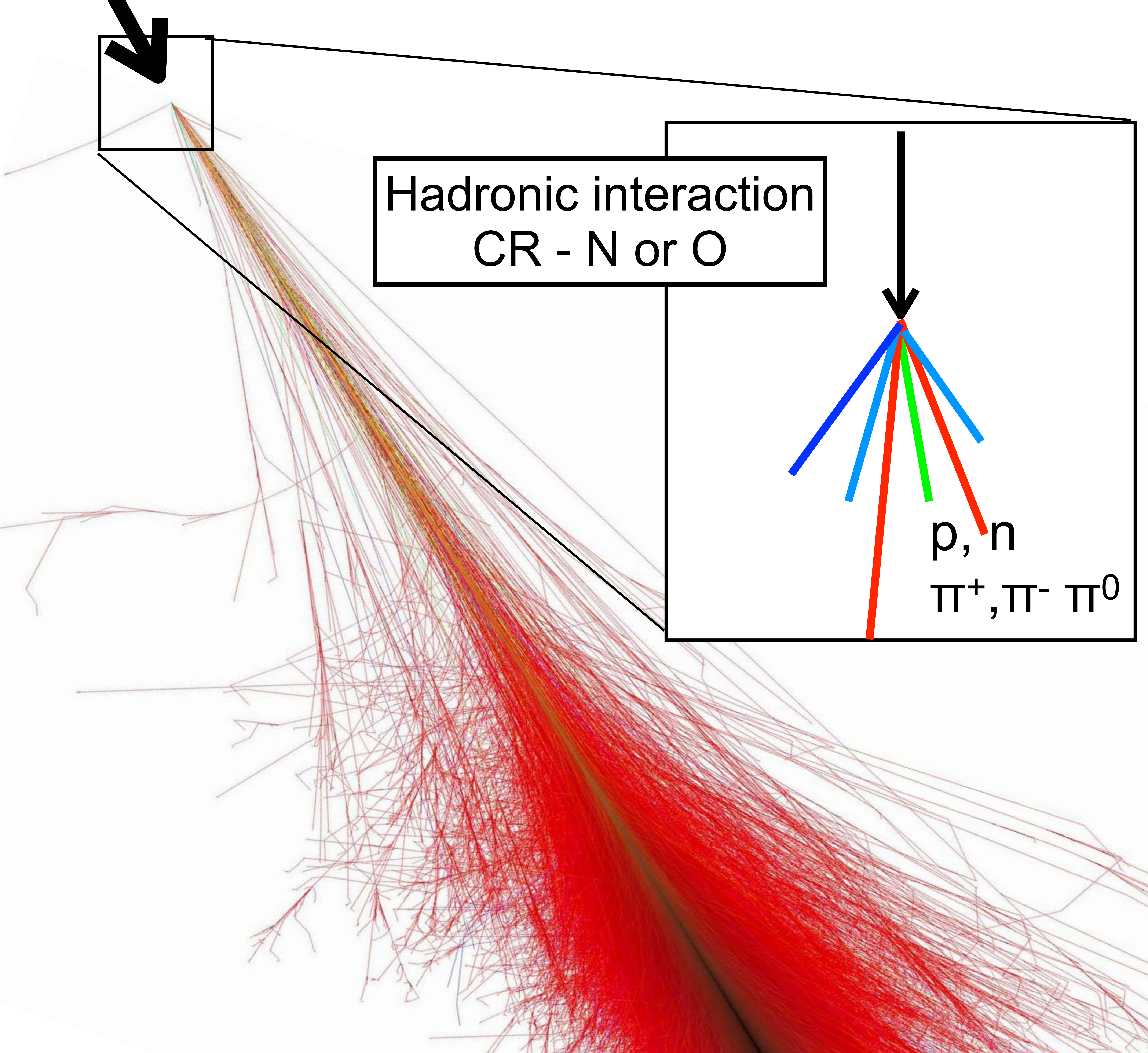
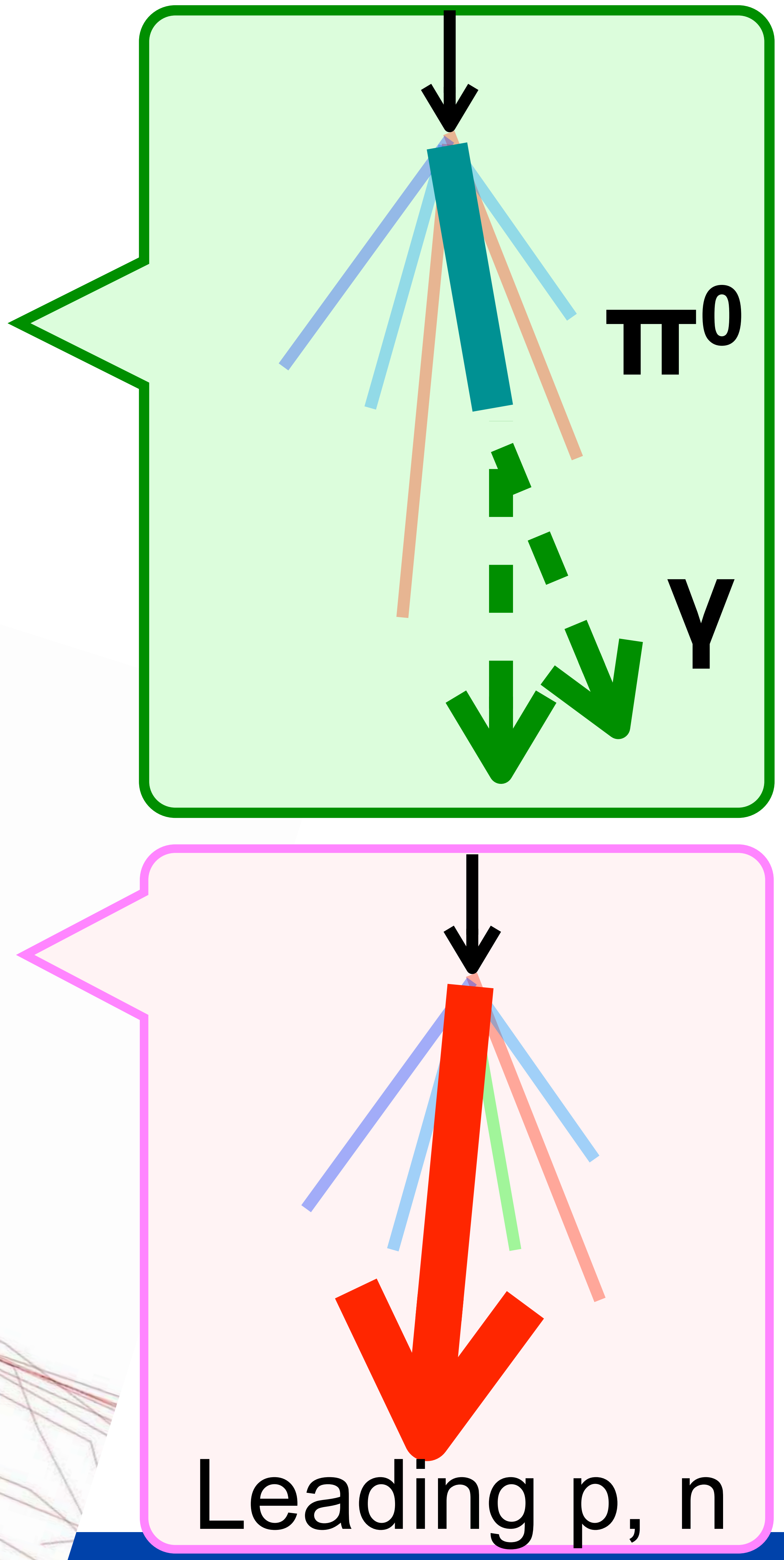
Air shower and hadronic interaction

Cosmic-ray





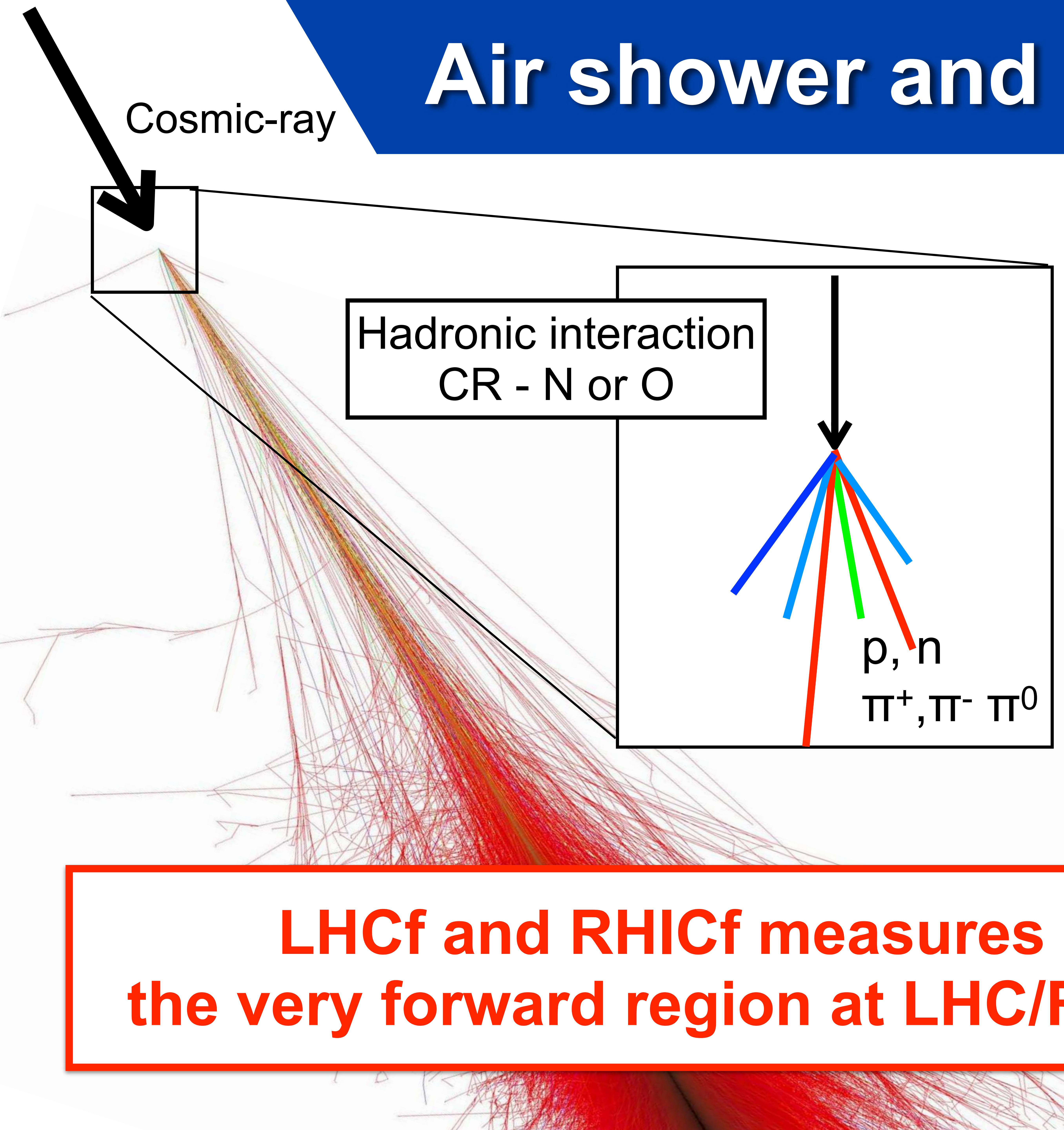
γ, π^0

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

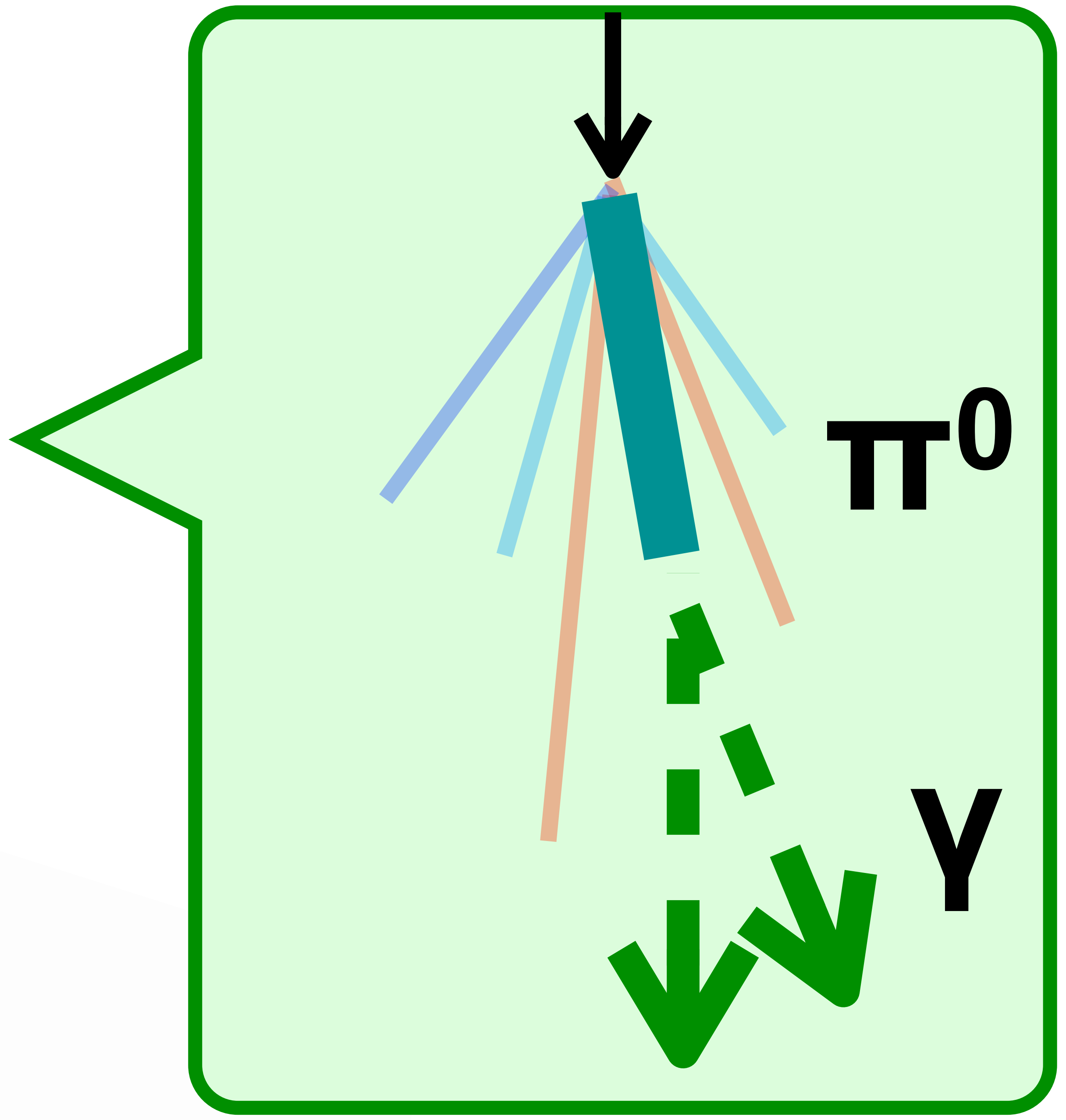
Leading baryons

- 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



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



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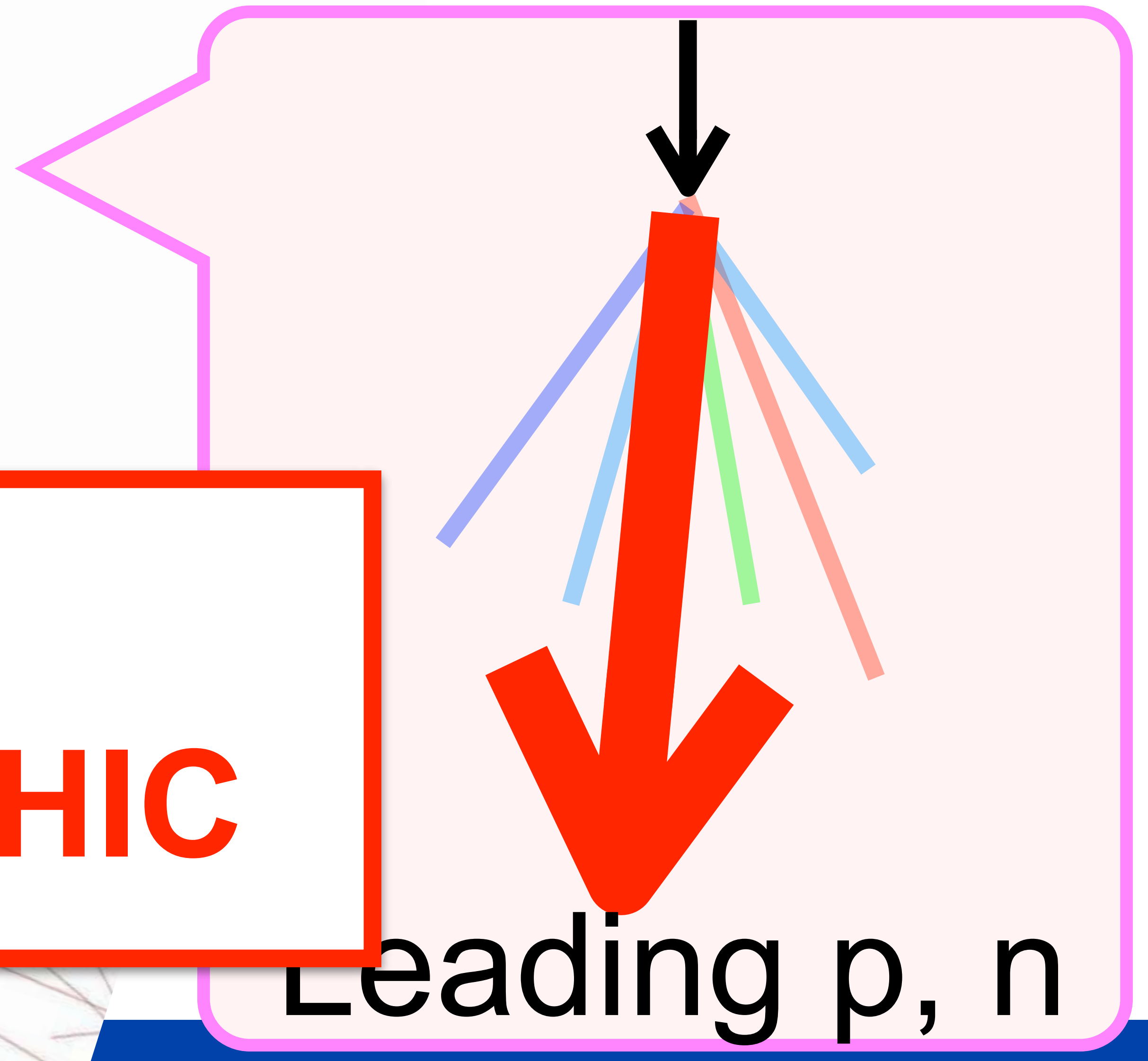

Leading baryons

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

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LHCf/RHICf Operations and Analyses

Run	E_{lab} (eV)	Photon	Neutron	π^0	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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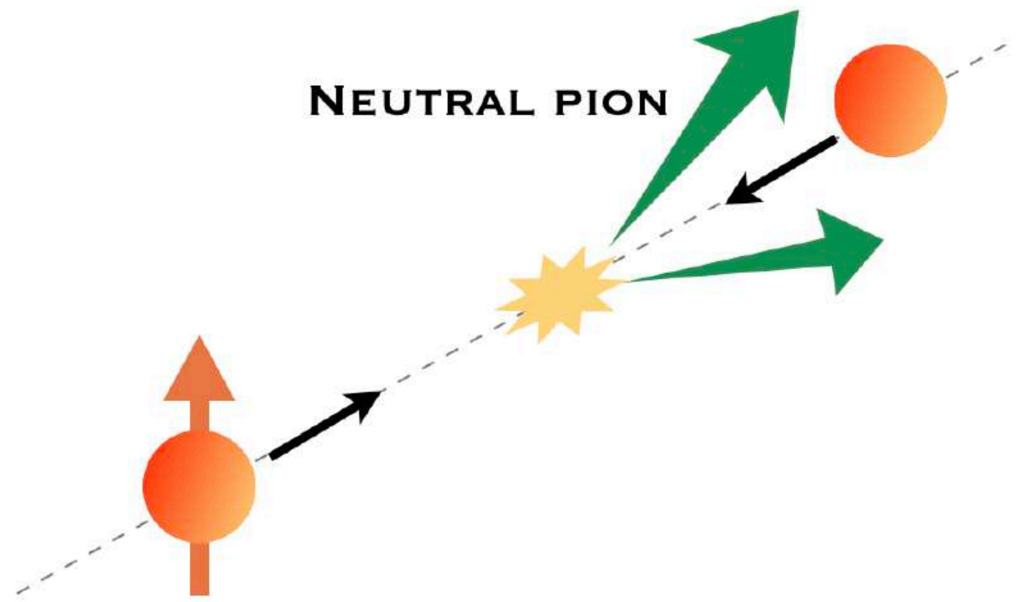
RHICf p-p √s=510GeV (2017)	1.4×10^{14}	ArXi				with STAR

← new data

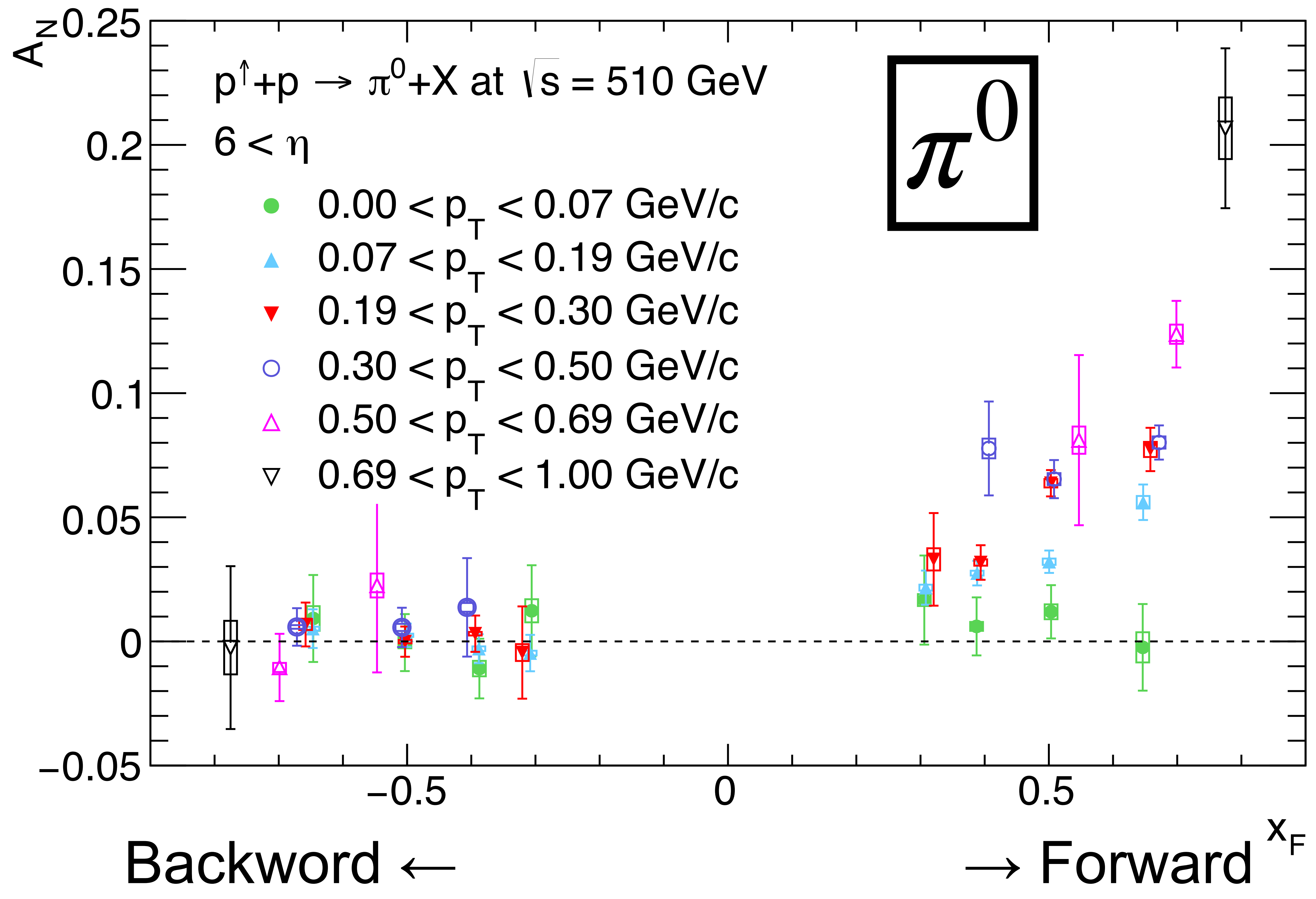
p-O operation in 2025

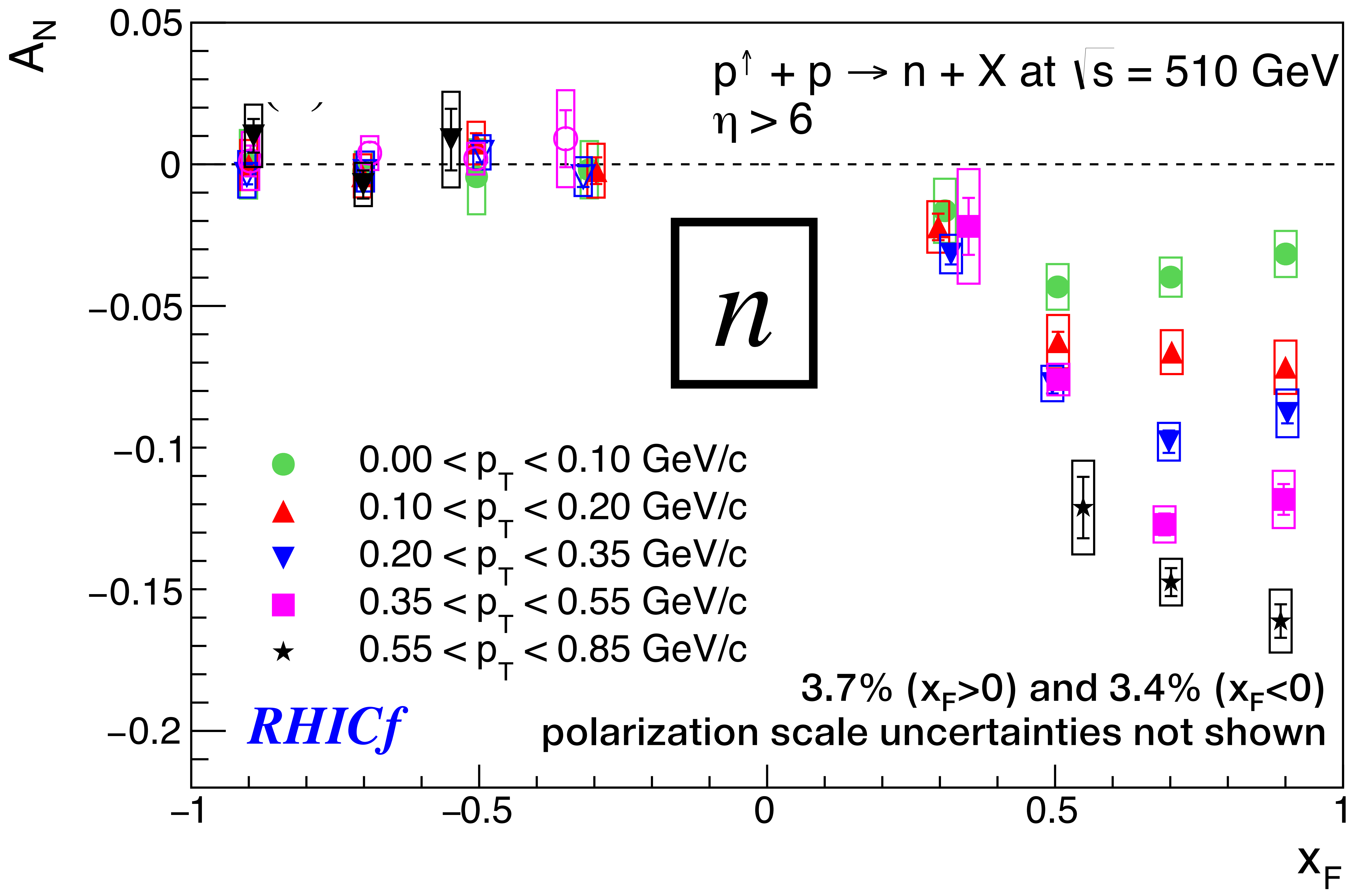
Spin Asymmetry A_N of measurements at RHIC



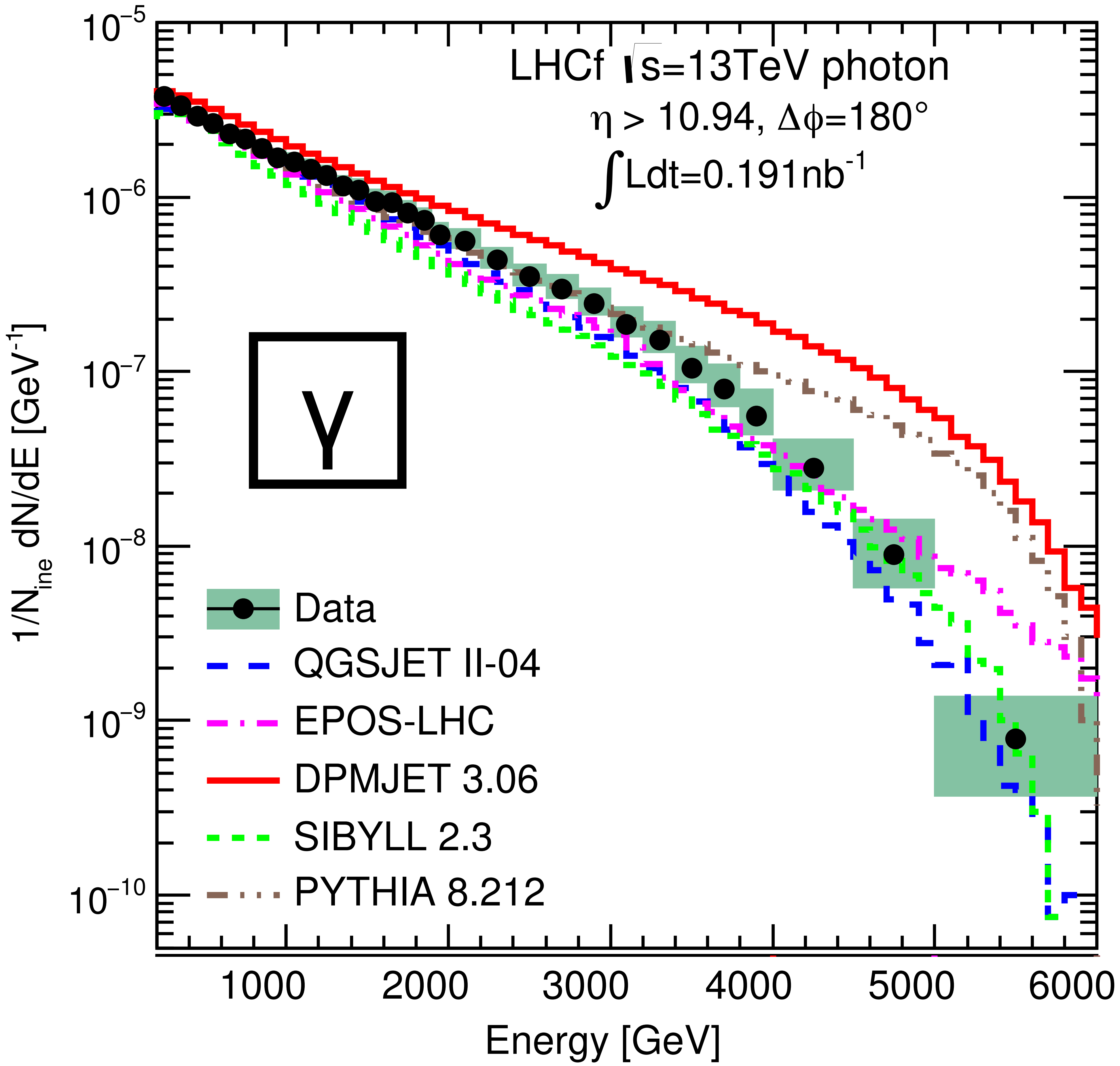
$$A_N = \frac{d\sigma_{\mathrm{left}} - d\sigma_{\mathrm{right}}}{d\sigma_{\mathrm{left}} + d\sigma_{\mathrm{right}}}$$

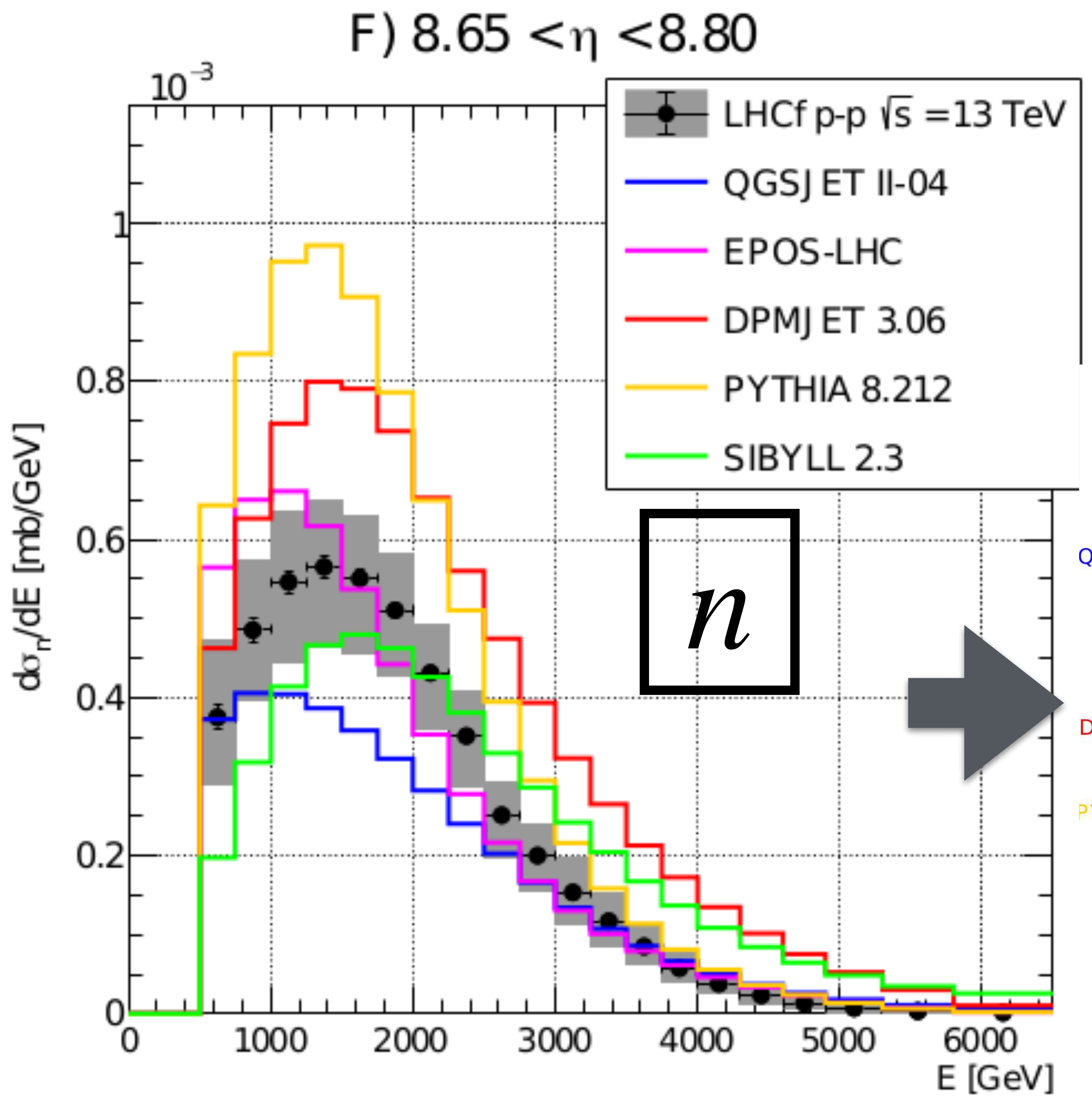
$pp, \sqrt{s} = 510$ GeV
$\eta > 6.0$



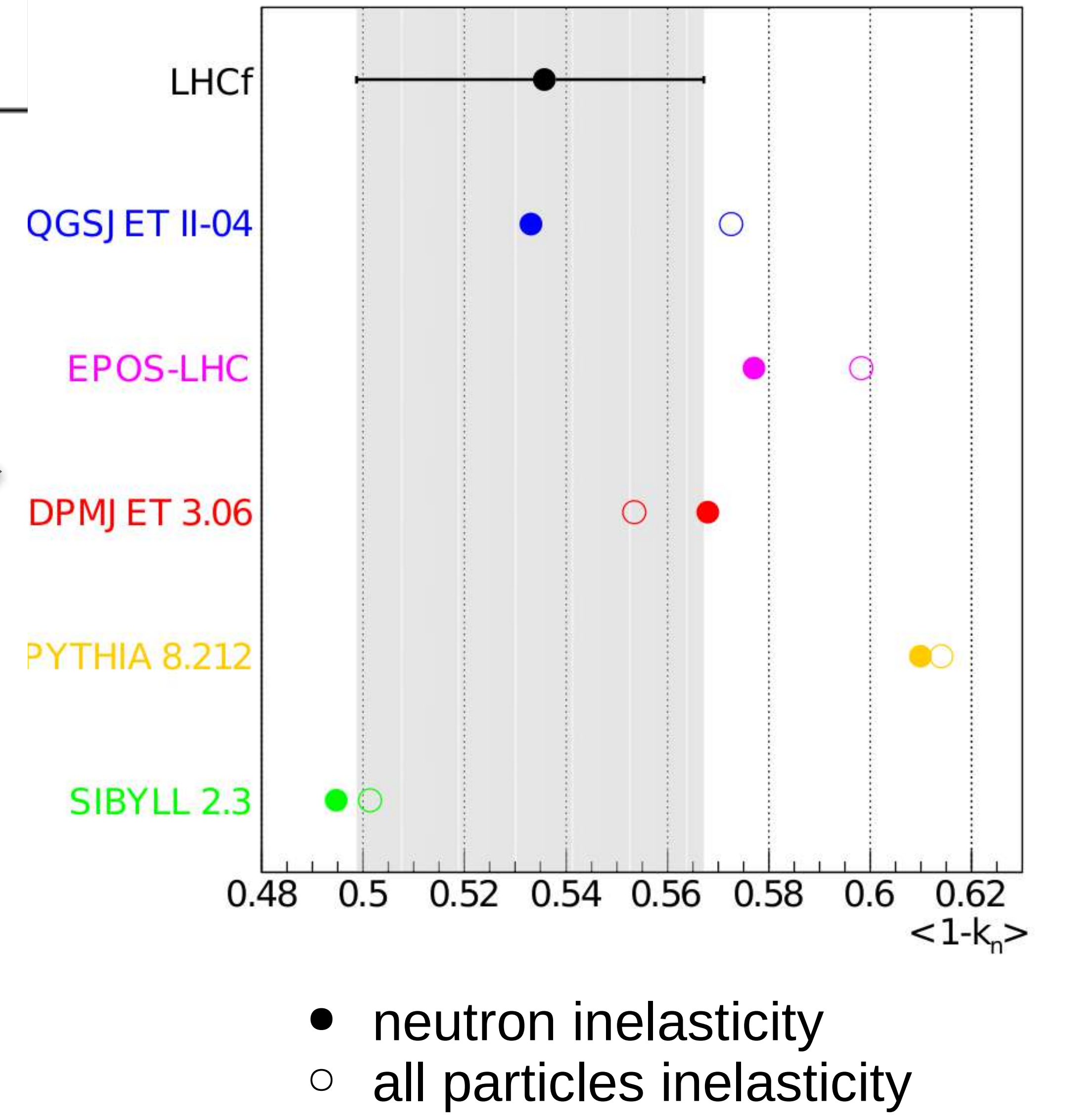


Very forward Photon & Neutron @ pp, √s=13TeV





<Inelasticity>

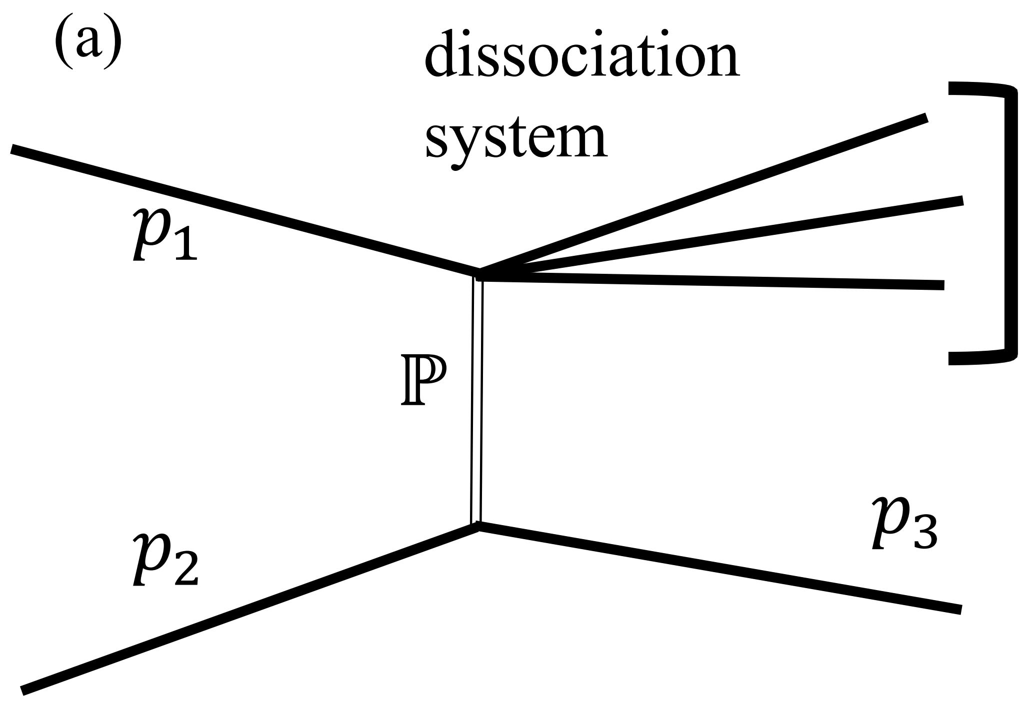


Model do not reproduce the data perfectly, but not far

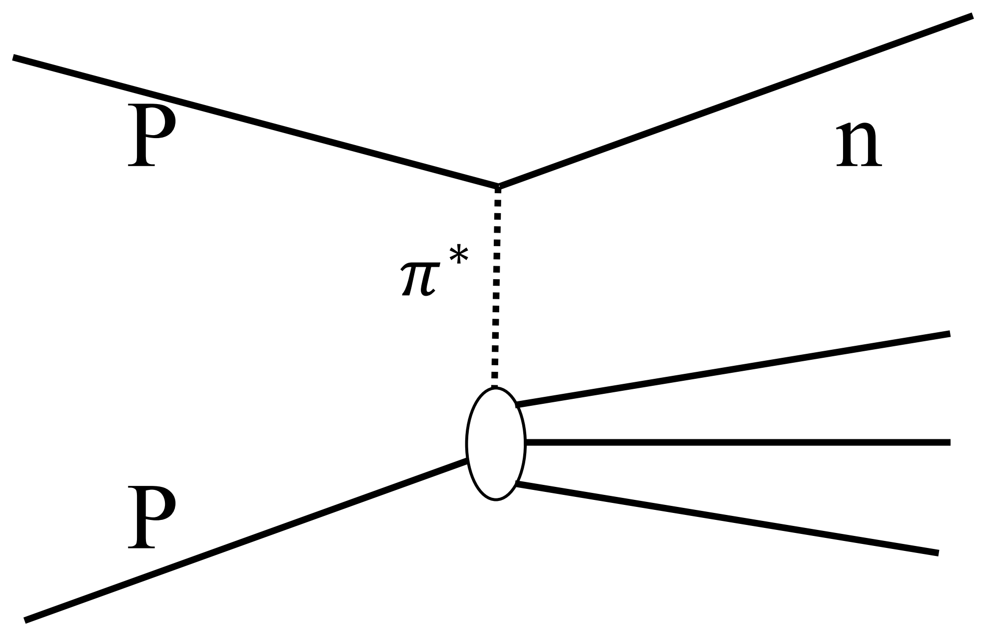
What we do in next

- Measurement of strange particles
  - Kaon contribution is one of the candidates of muon puzzle
    - Large σ_K induces more muons on the ground due to long-life time of K^0 than π^0
    - Important for production of atmospheric neutrinos also.
  - Detection with $K_s^0 \to 2\pi^0 \to 4\gamma$
- Process-based measurement with ATLAS

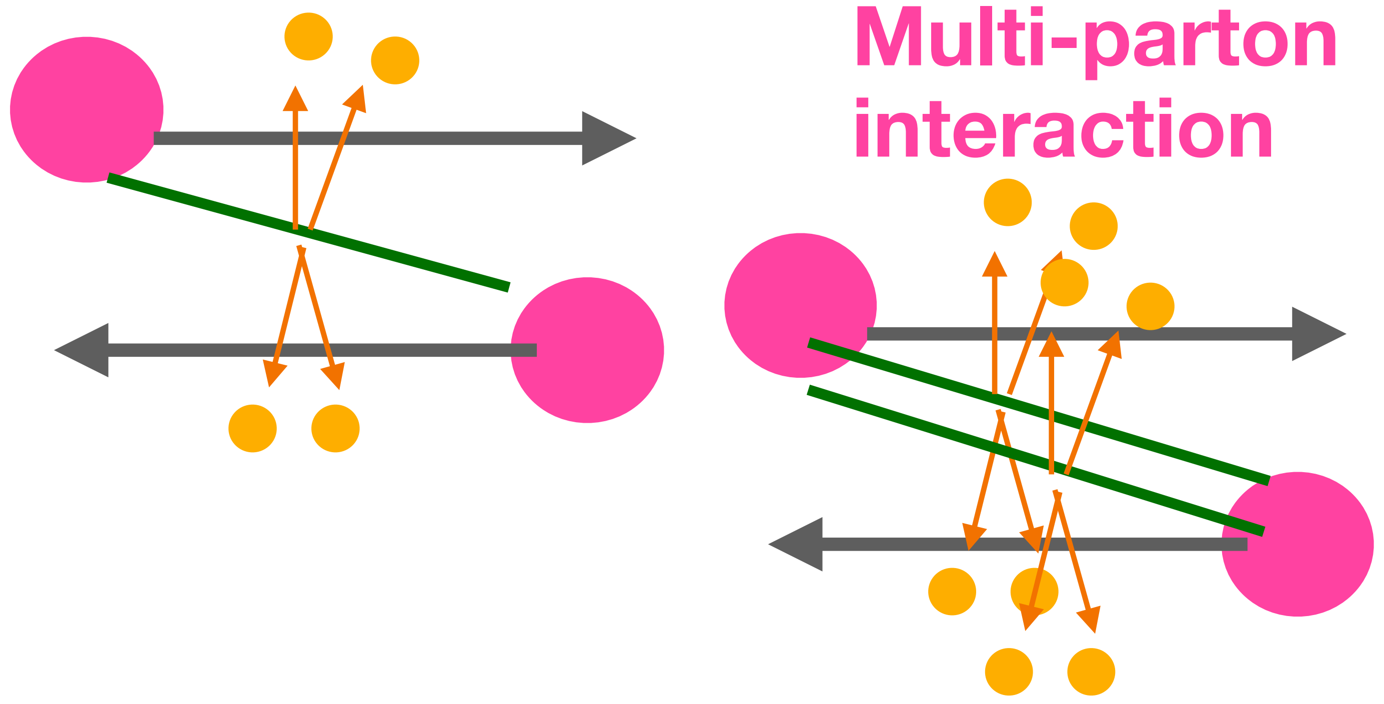
Diffractive dissociation



One pion exchange

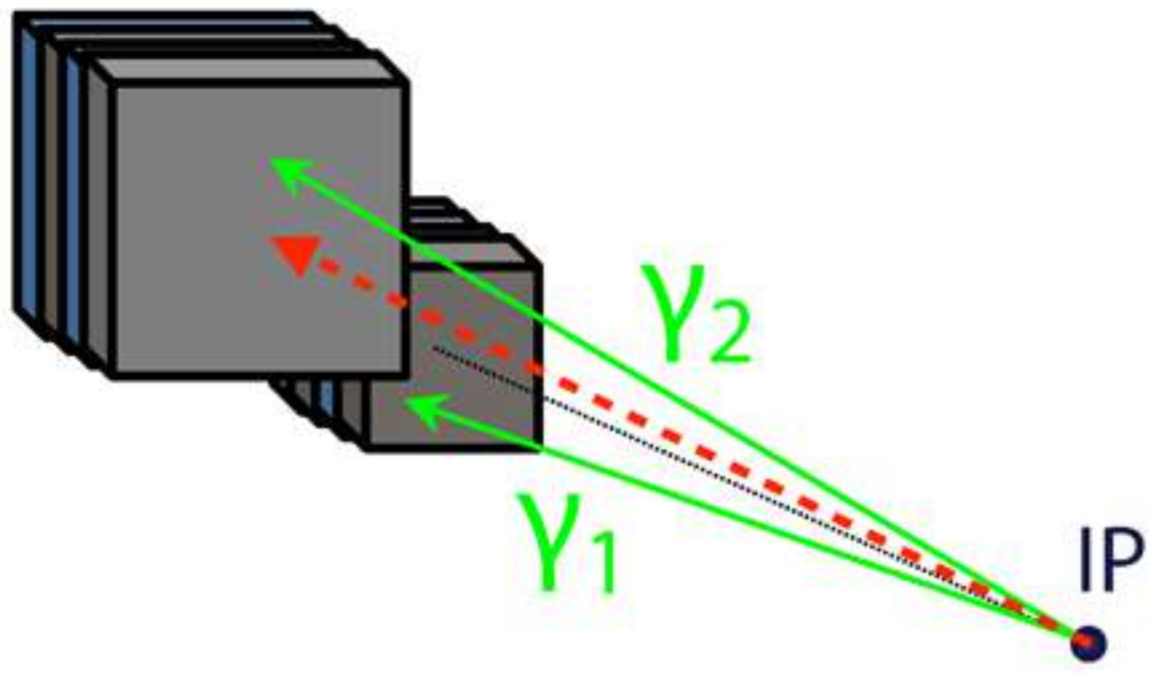


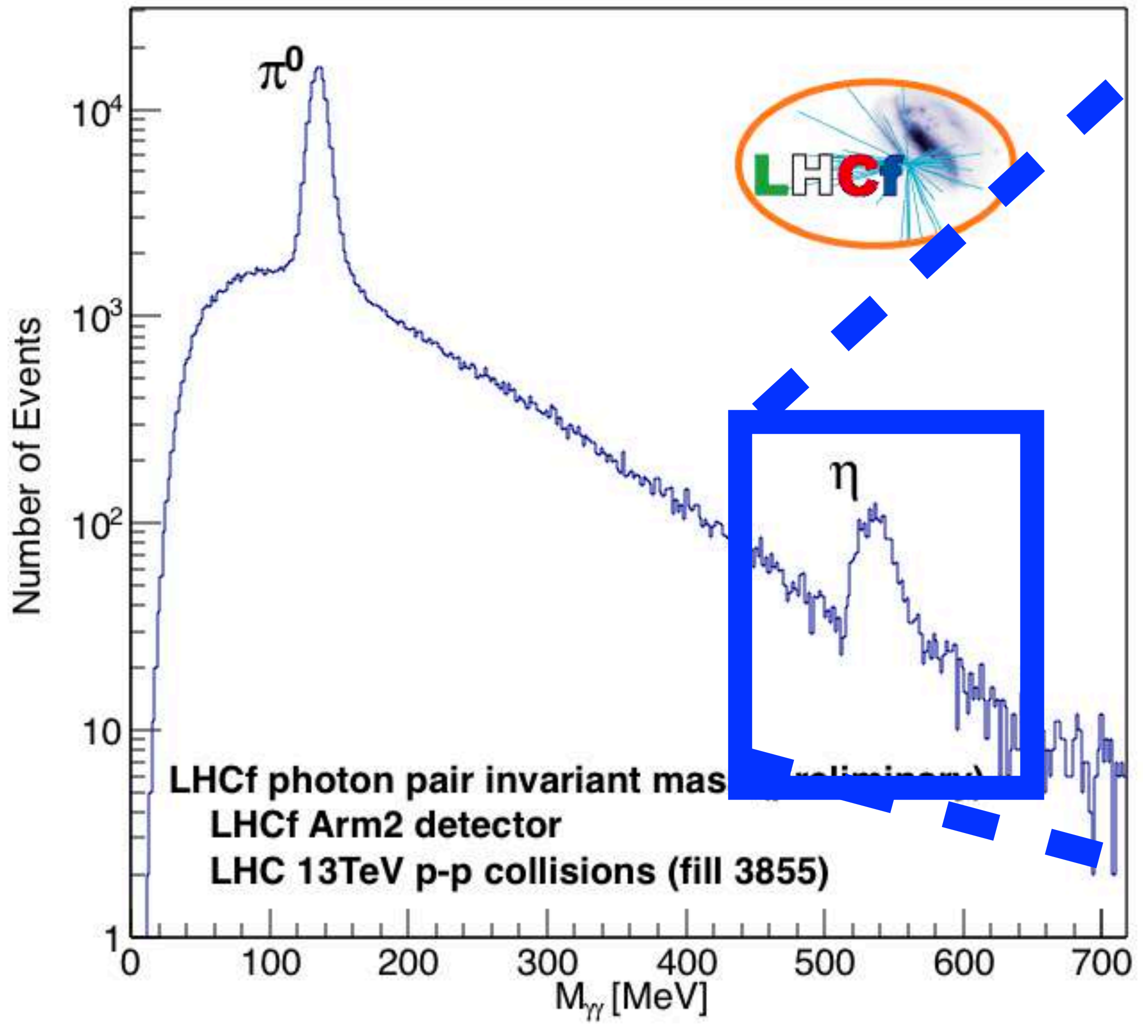
Others (Non-diffractive)

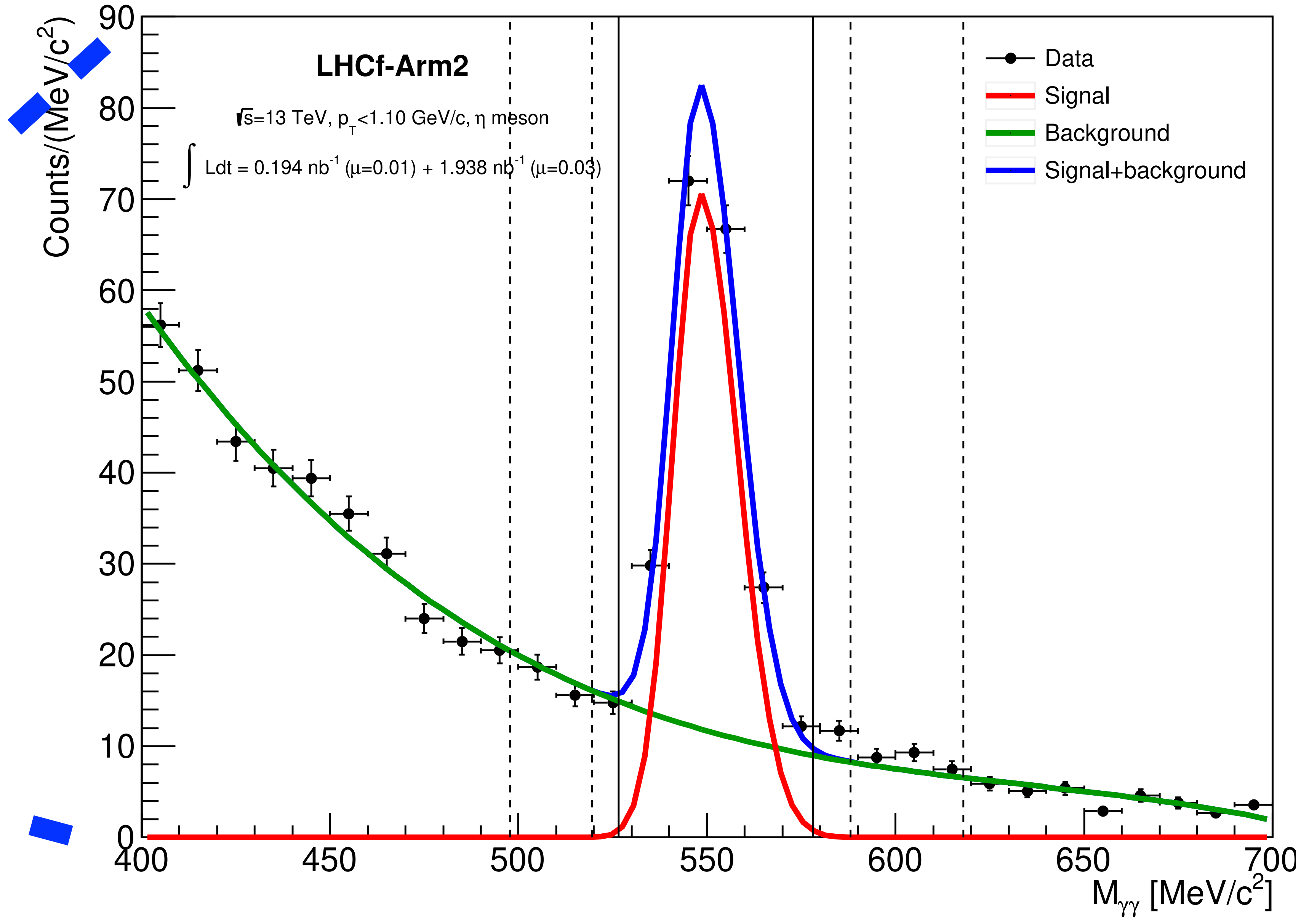


η meson measurement

- 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, $\sqrt{s}$=13 TeV
  - Arm2 detector
  - Similar as Type1 π^0 analysis

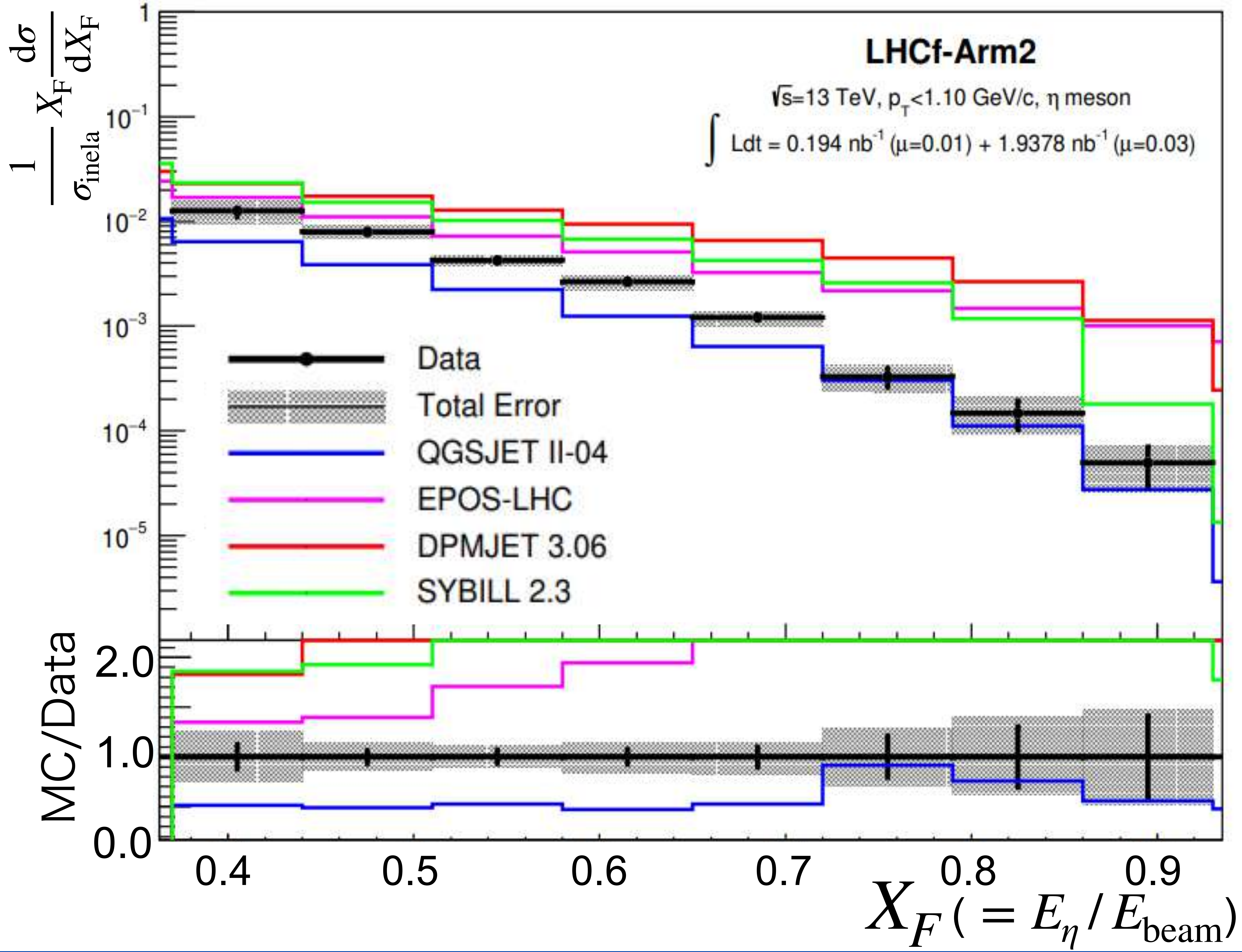






O. Adriani et al., JHEP10 (2023) 169

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



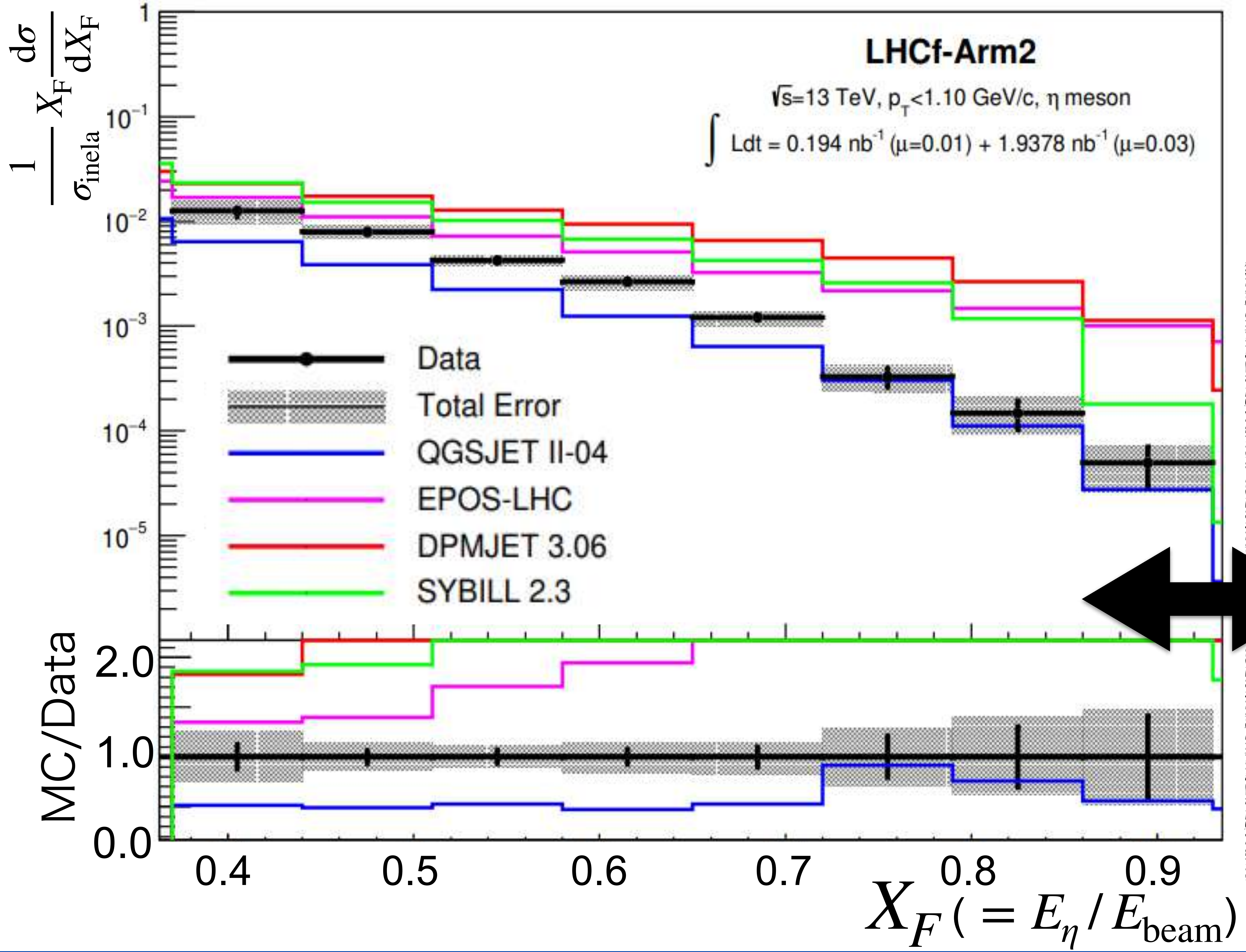
$$\frac{1}{\sigma_{\mathrm{inela}}} X_F \frac{d\sigma}{dX_F}$$

$$X_F (= E_\eta / E_{\mathrm{beam}})$$

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

- $p_T < 1.1\mathrm{GeV/c}$
- 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



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

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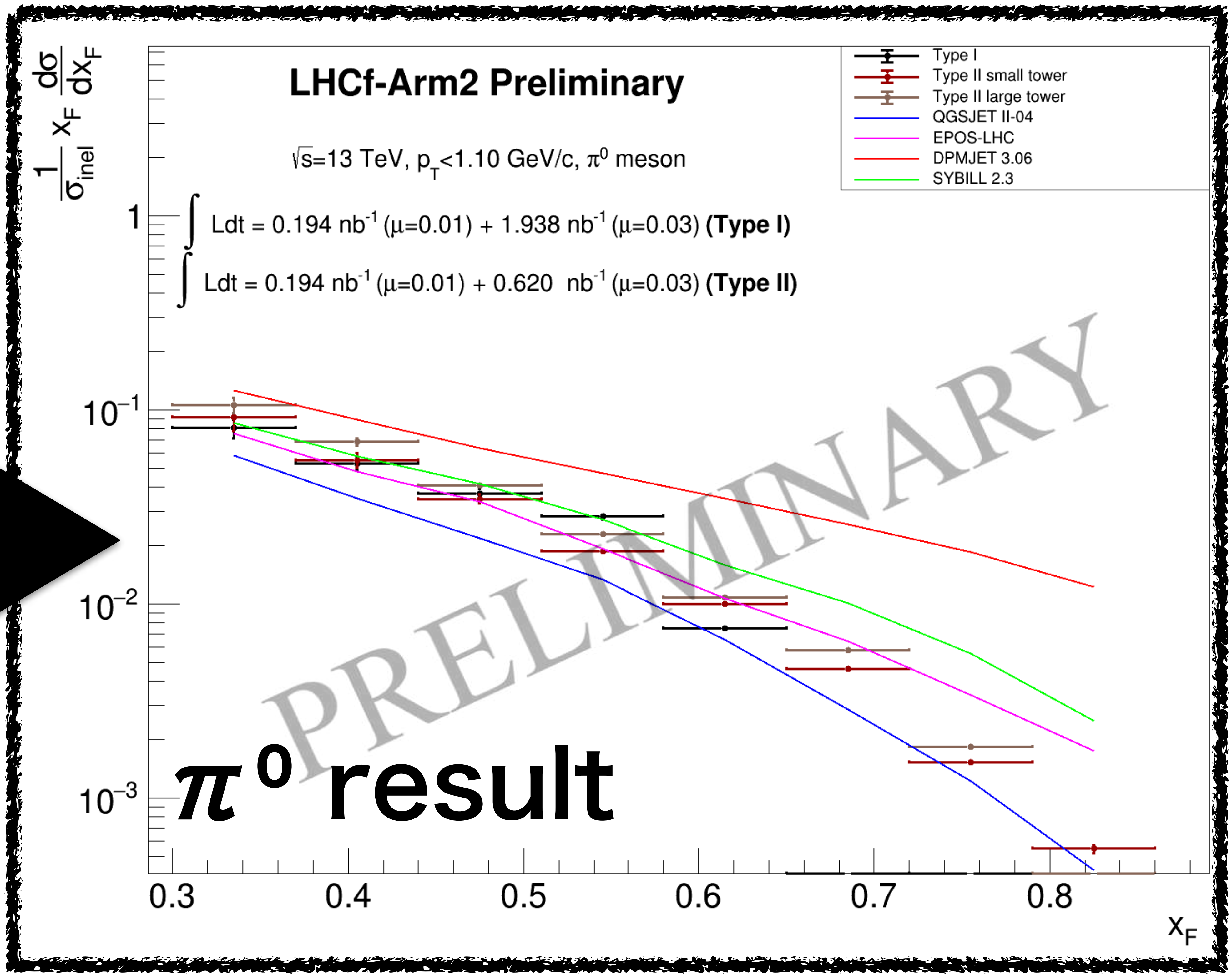
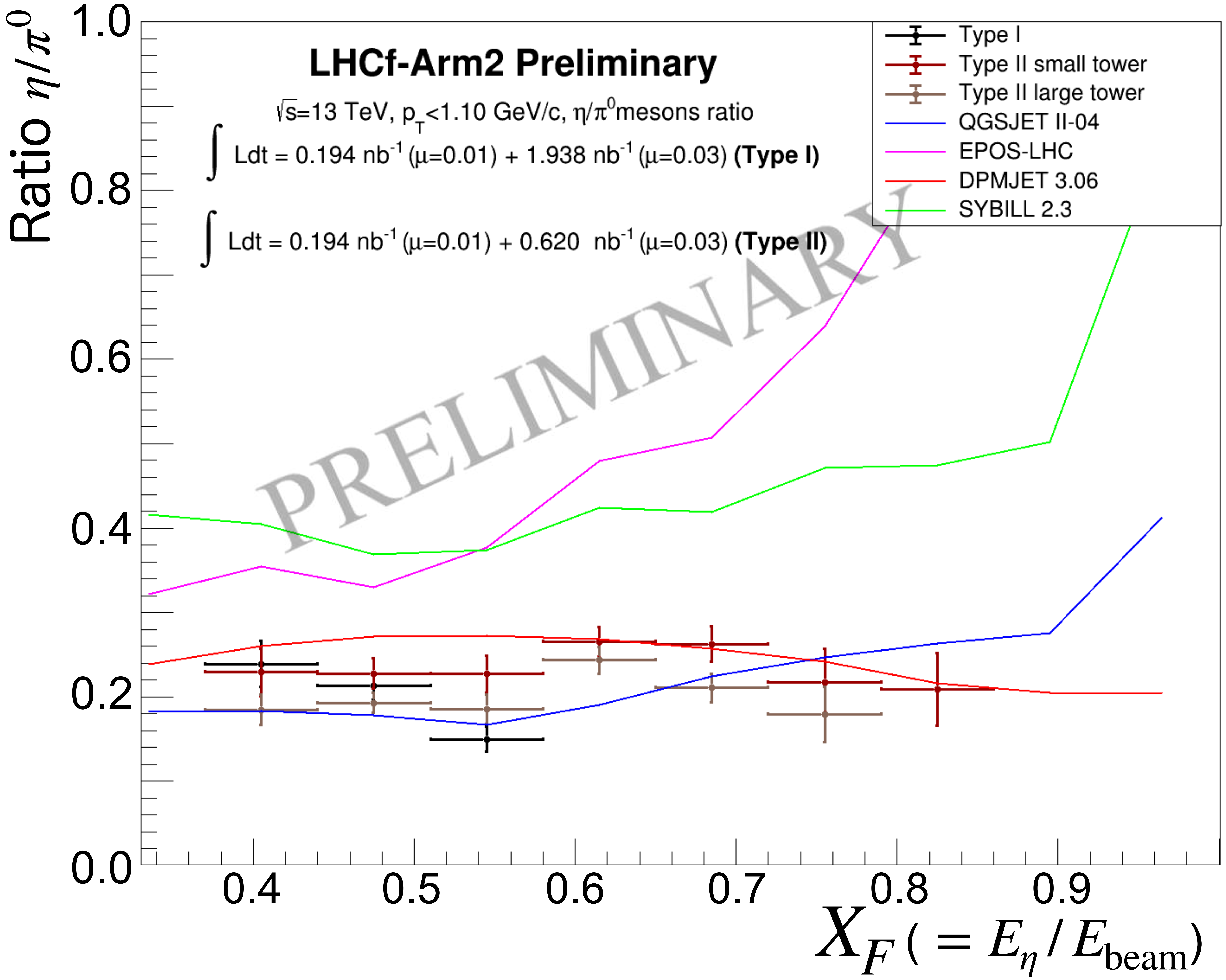


η/π^0 Ratio



- Data : constant in the whole energy range

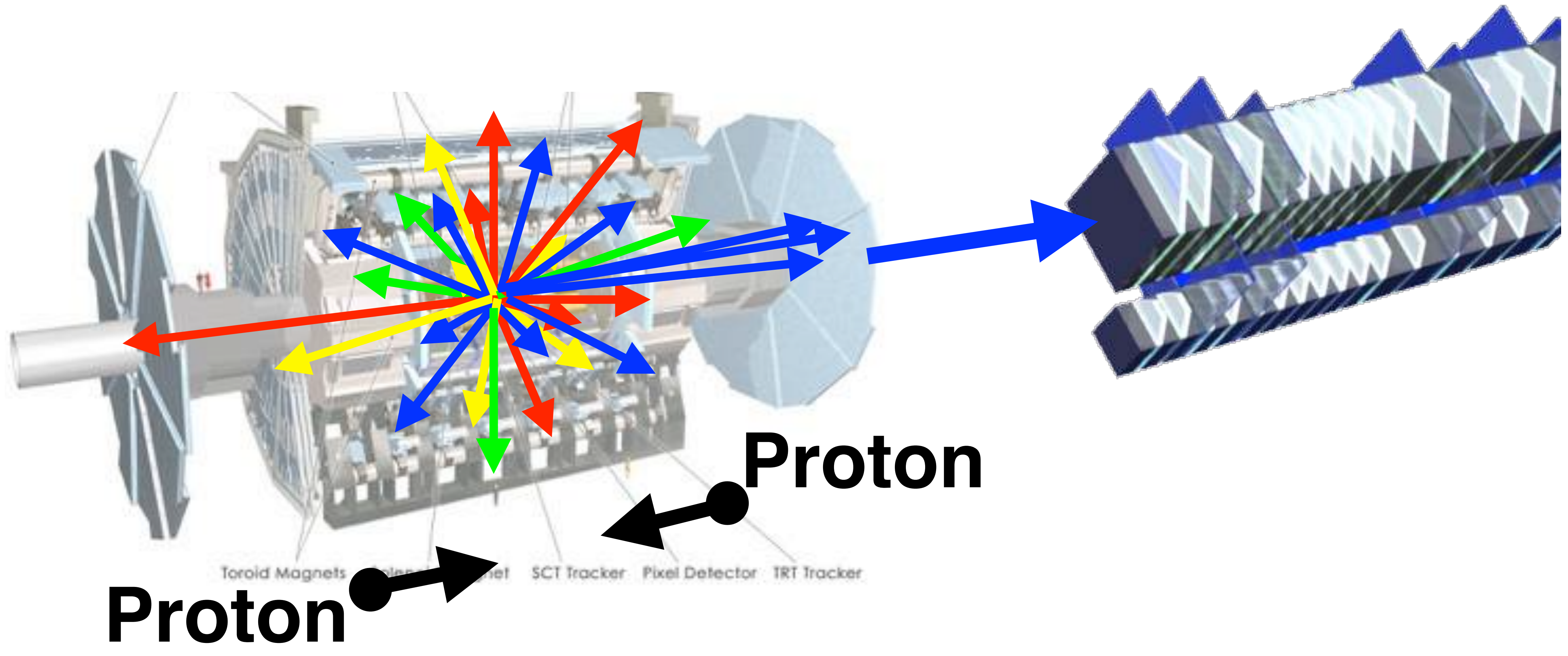
EPOS-LHC, SIBYLL2.3

- Much larger than data
- These models cares low-mass resonance productions.
  → contribution from these decays

QGSJETII-04, DPMJET III

- Good agreement with data
- Less care about resonances.
  → flat ratio

Measurement of diffractive contribution



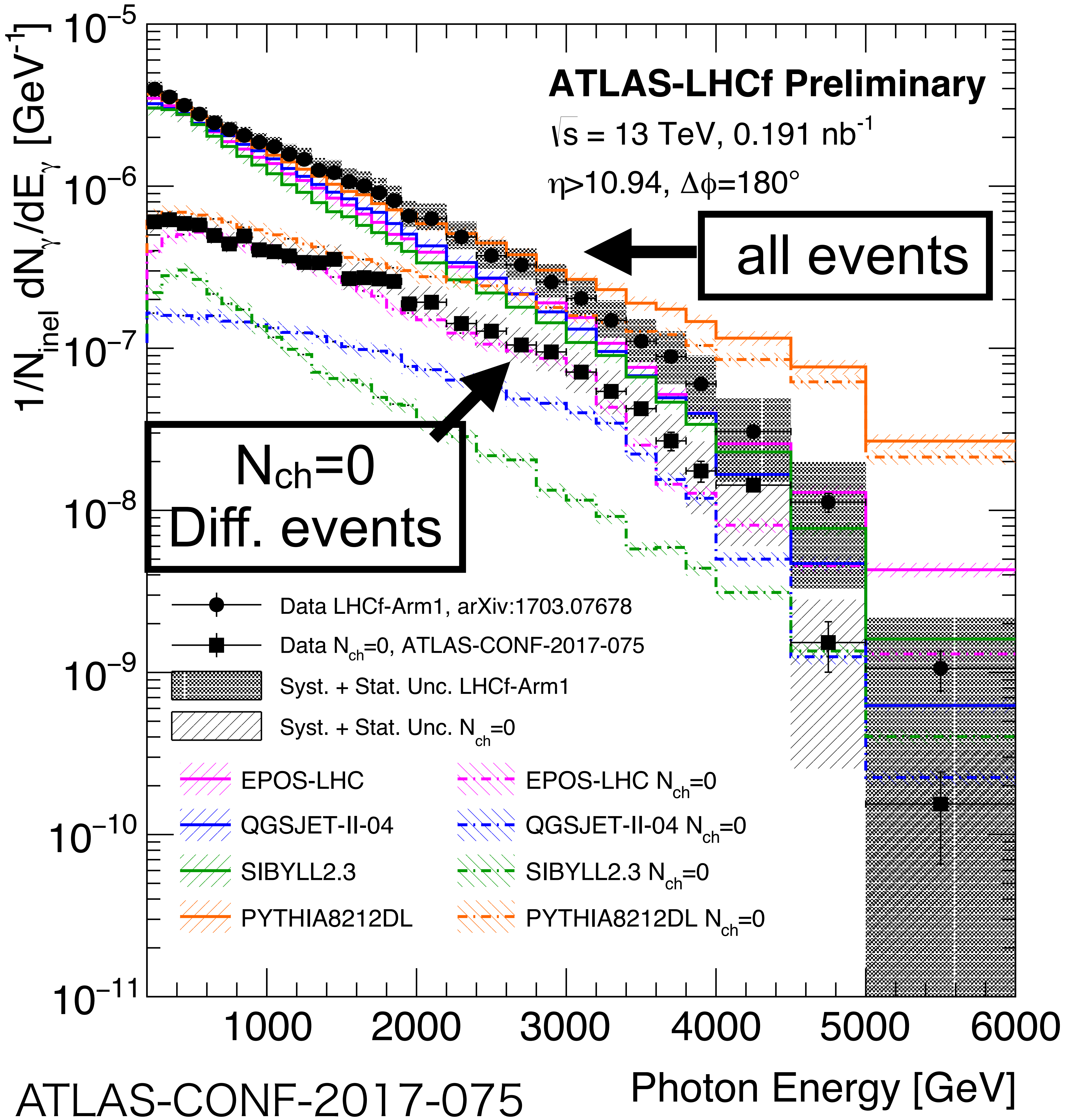
Identification of diffractive events by ATLAS

Method

- Event selection by $N_{tracks}=0$ ⇔ Large rapidity gap $\Delta\eta > 5$

  N_{tracks}: the number of tracks detected **by ATLAS inner trackers** ($|\eta|<2.5$, $p_T > 100$ MeV)

→ Selecting pure samples of proton dissociations.
→ Sensitive to only low-mass dissociations $M_X \lesssim 50$ GeV

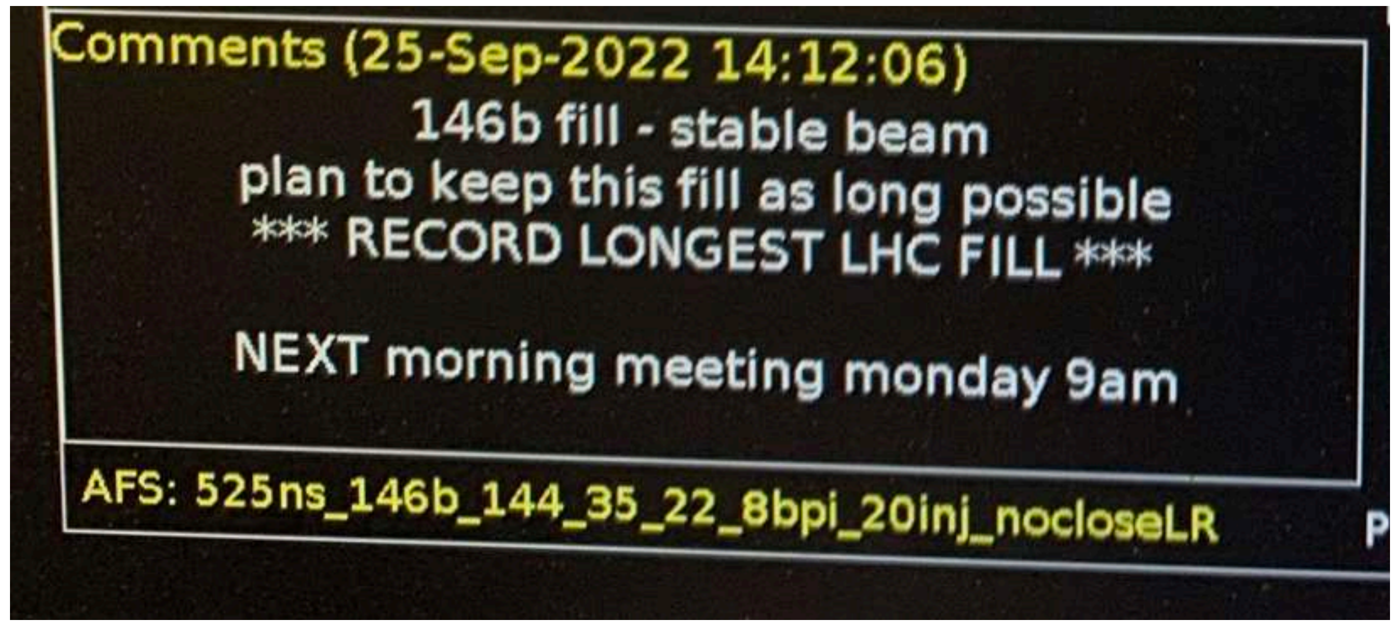


ATLAS-CONF-2017-075

Operation with pp, $\sqrt{s}$=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 $\mu b^{-1}/s$, β^* = 19.2 m
  - 300 M events obtained in total (↔ 40 M in 2015)

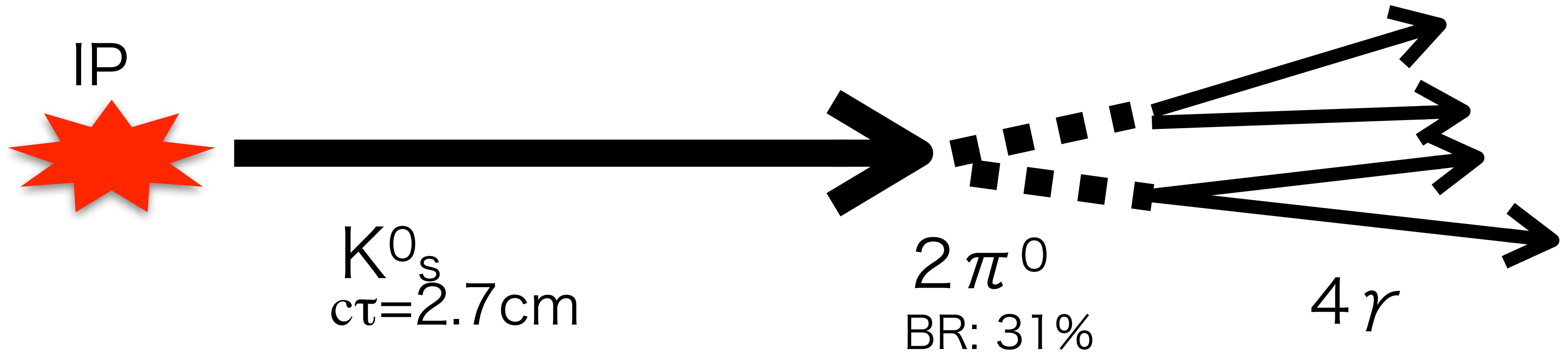
    thanks to improvement of DAQ speed, higher luminosity, and optimization of trigger.



- Physics targets
  - Increase statistics of η and high-energy π^0

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

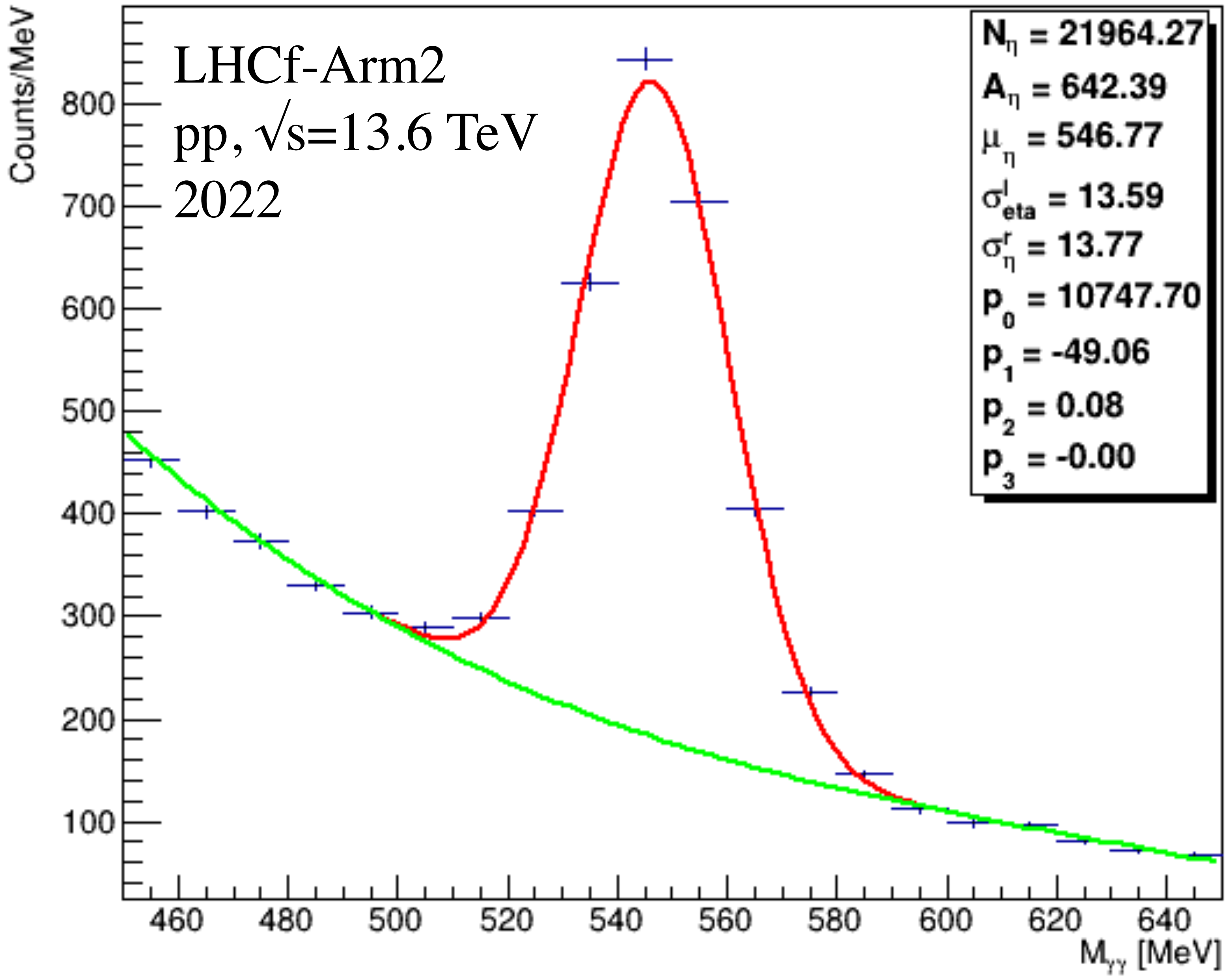
    → cross-section measurement in X_F-p_T bins
  - Measurement of strange hadrons (K^0_s, Λ)



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

These analyses are on-going

Reconstructed $M_{\gamma\gamma}$ distribution

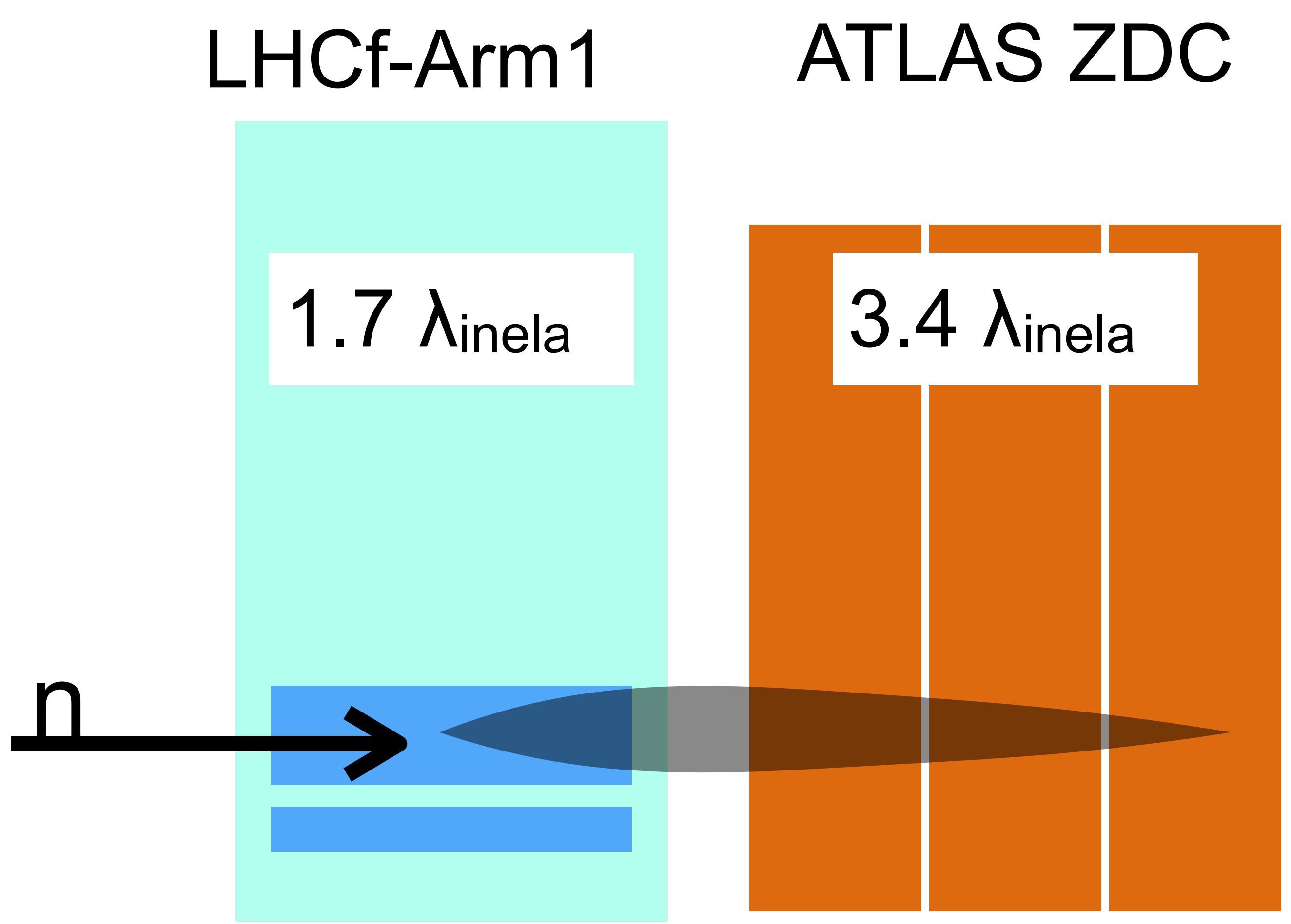


Joint operation with ATLAS

- 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

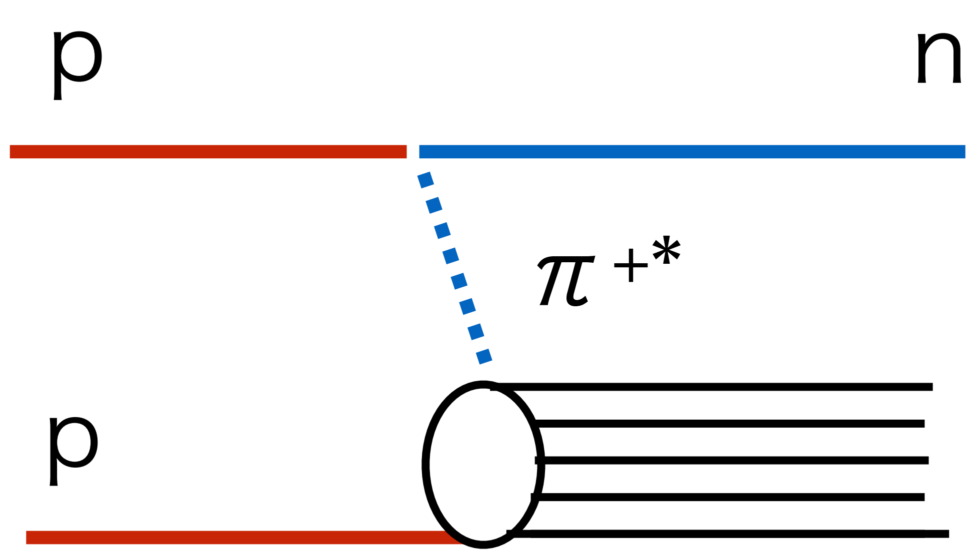


- Physics Targets
  - Detailed study of single diffractive collisions
  - Measurement of proton excitation (Δ^+)
  - Measurement of Λ ($\Lambda \rightarrow n + \pi^0$)
  - p-π interaction study using OPE processes

w/ RPs

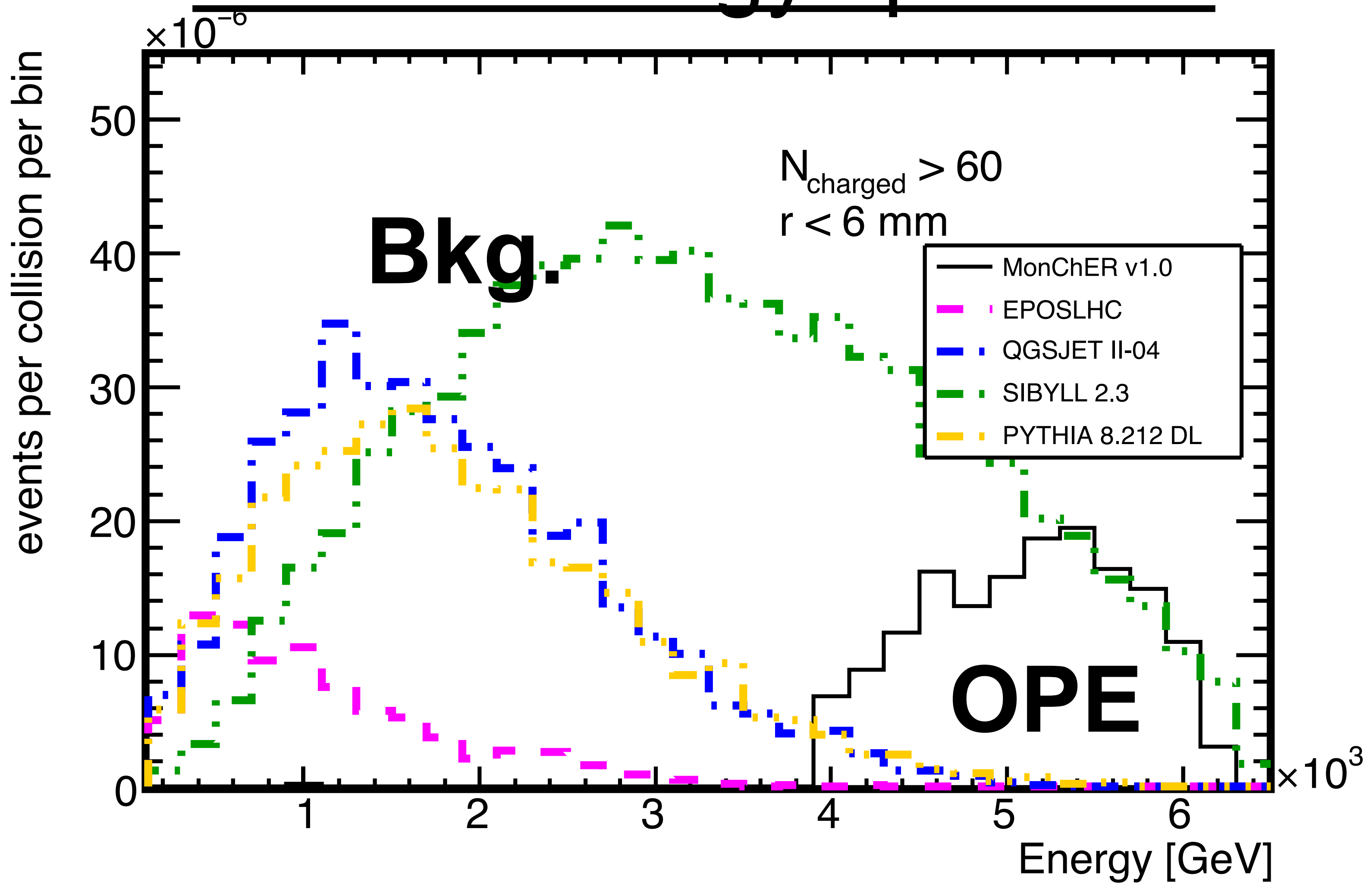
w/ ZDC

One Pion Exchange (OPE)



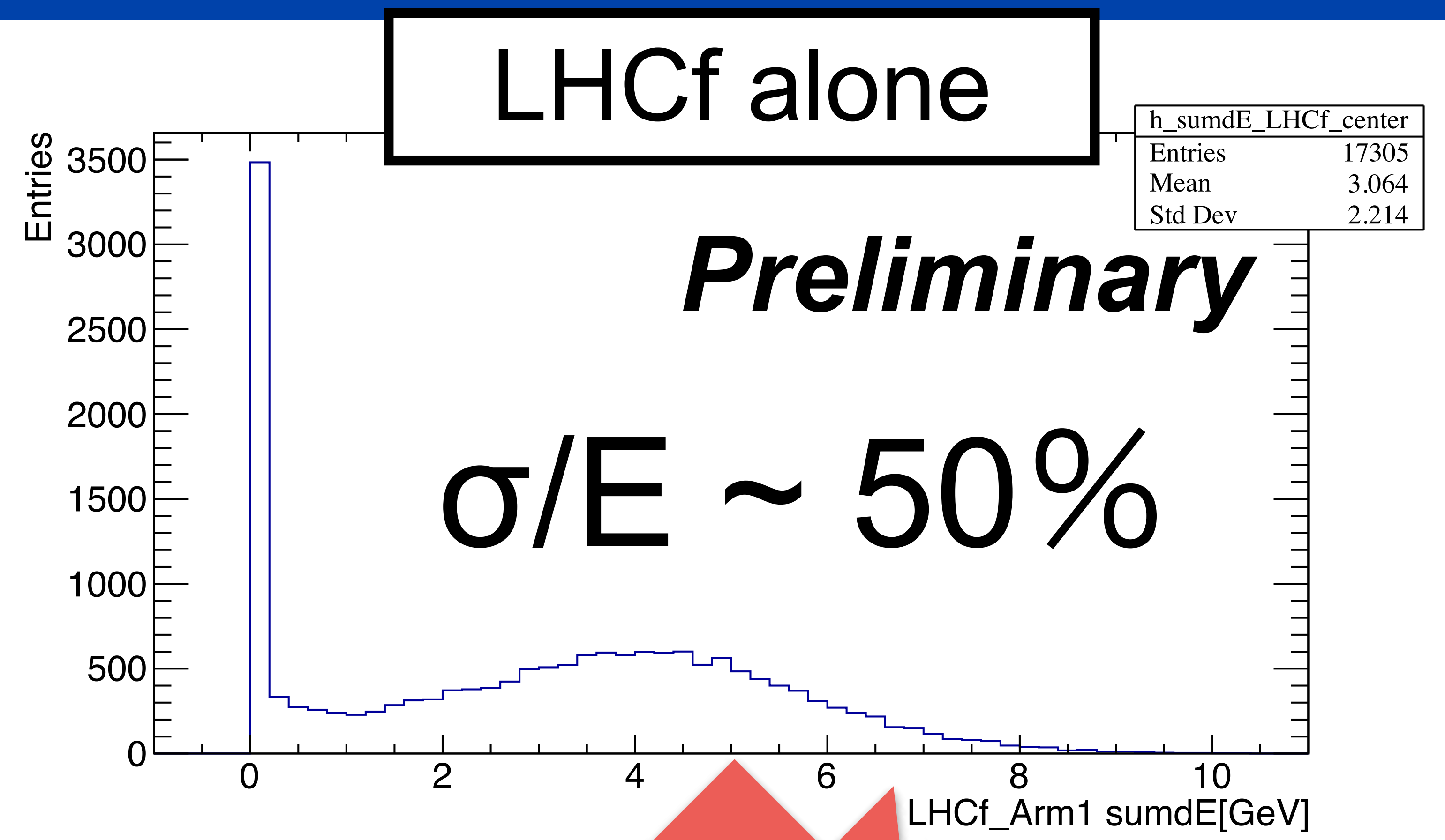
LHCf+ATLAS merged dataset is getting ready.
Start the physics analysis soon.

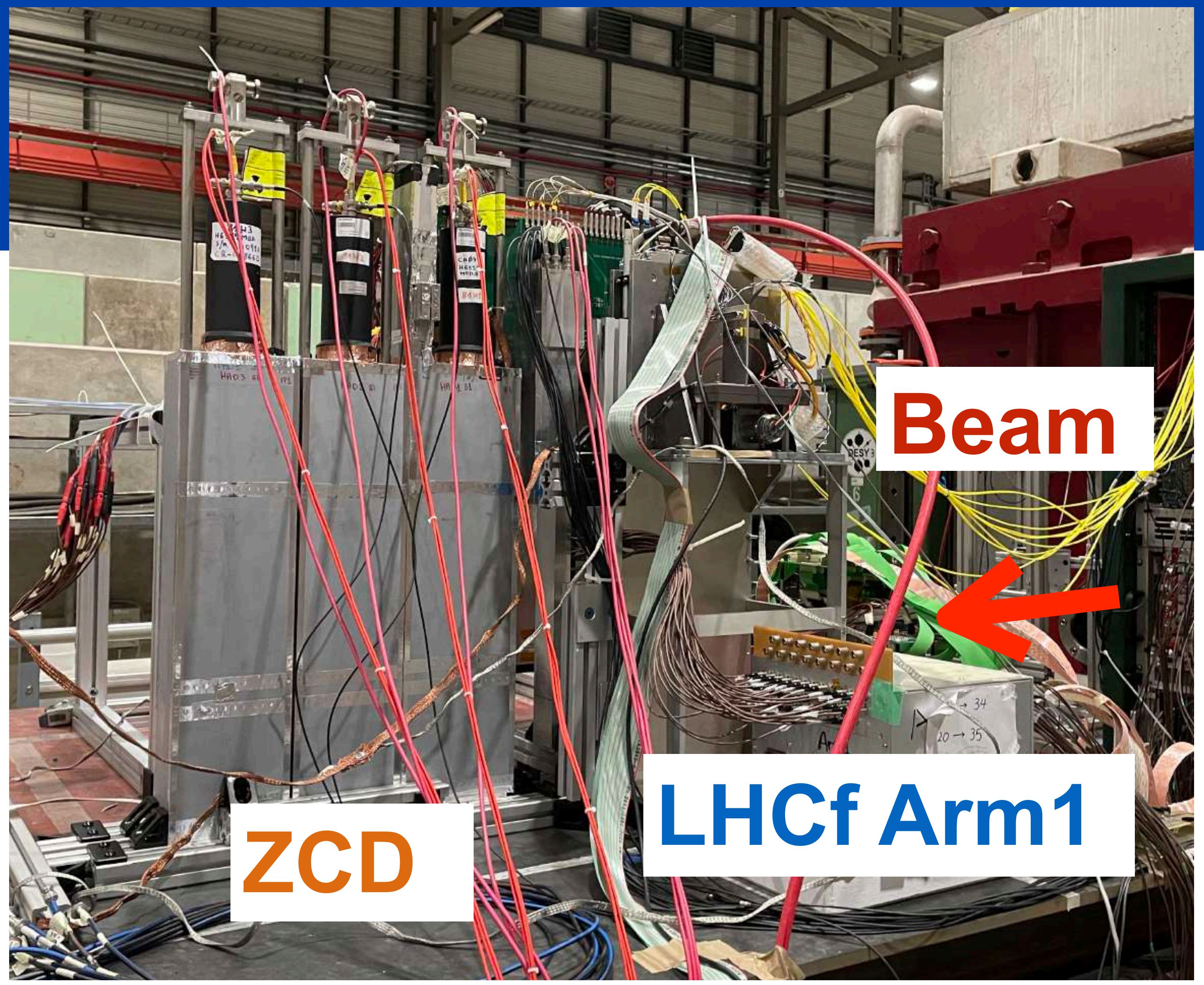
neutron energy spectrum

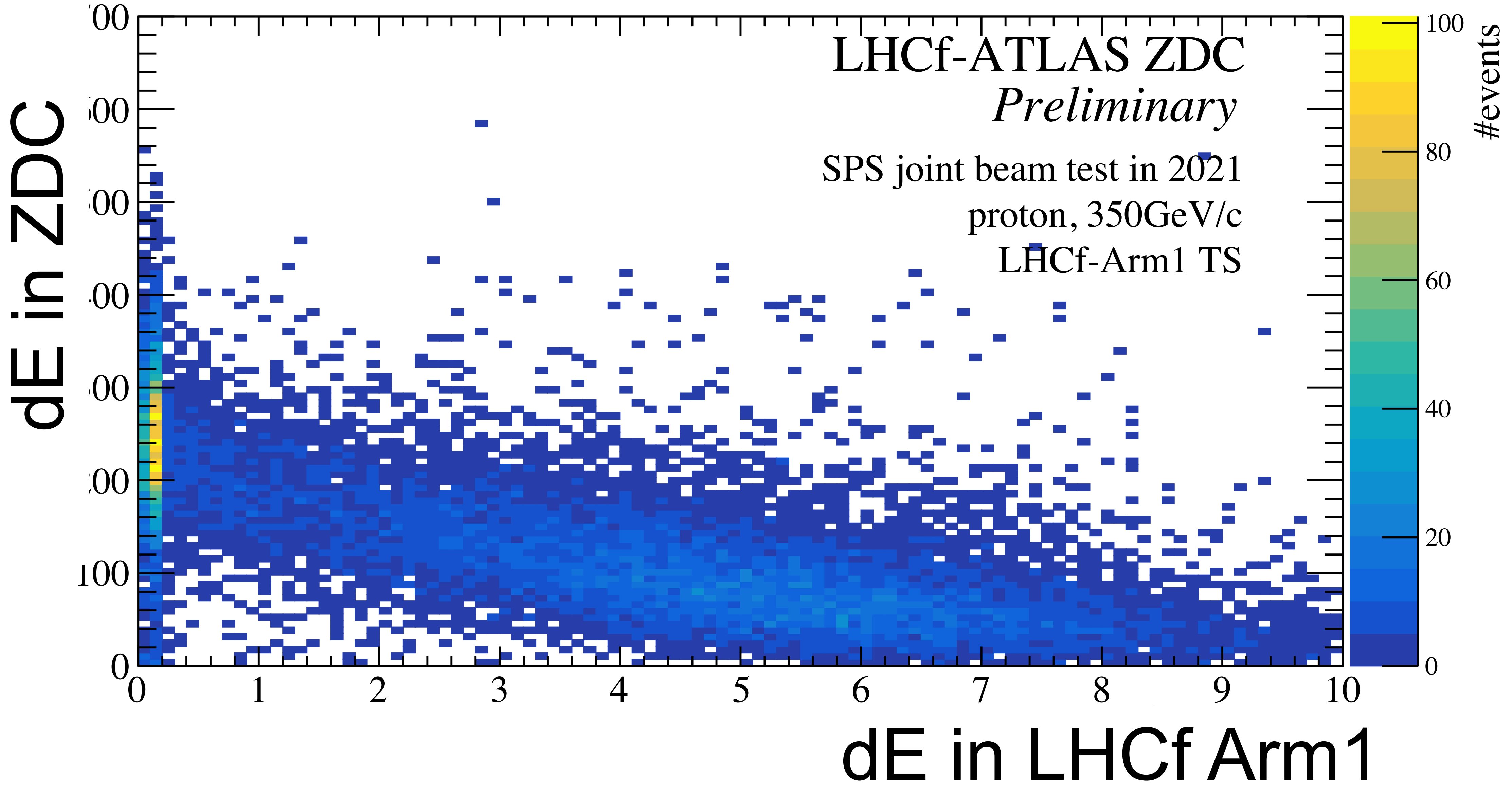


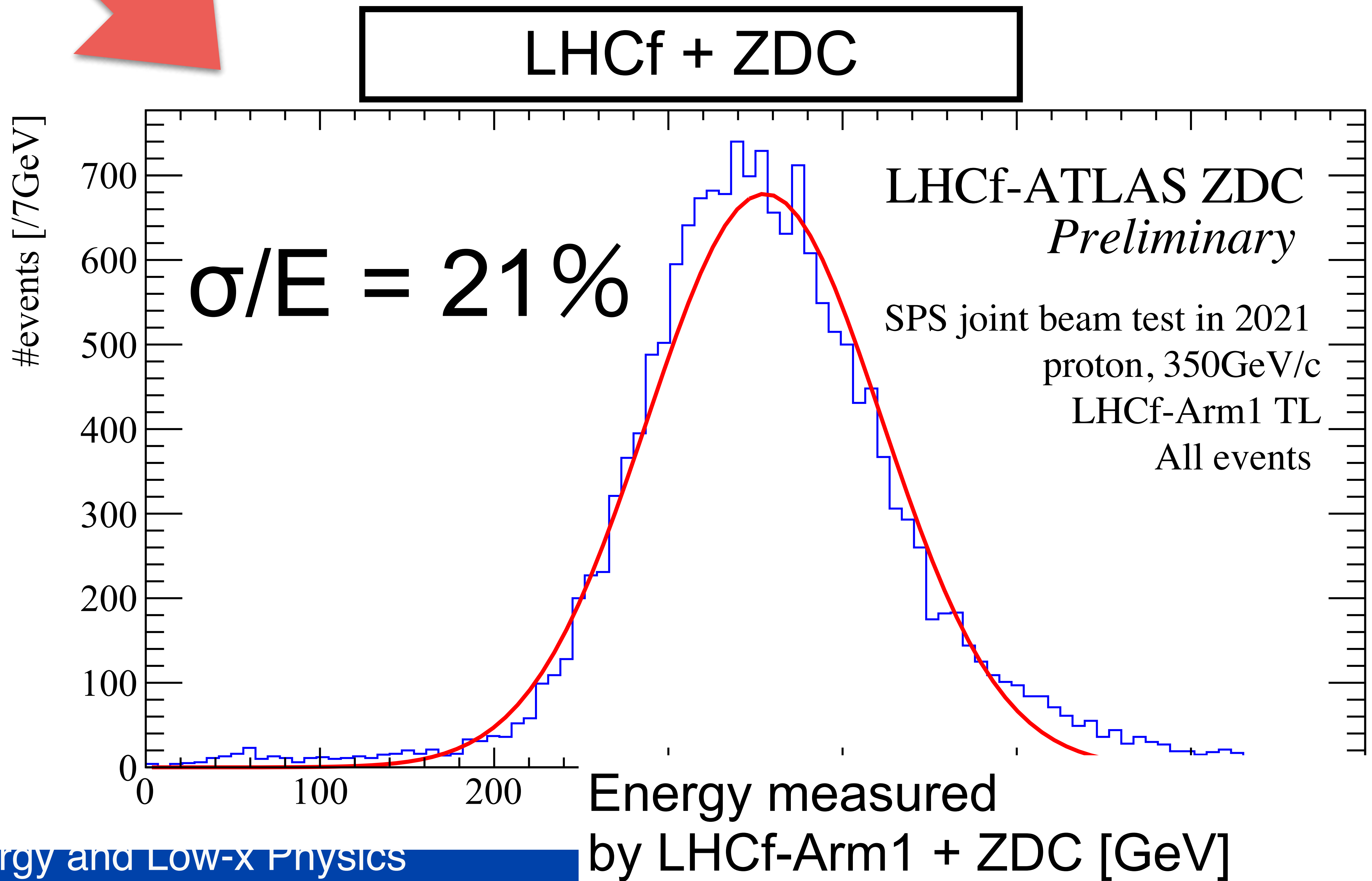
LHCf+ZDC beam test at SPS

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









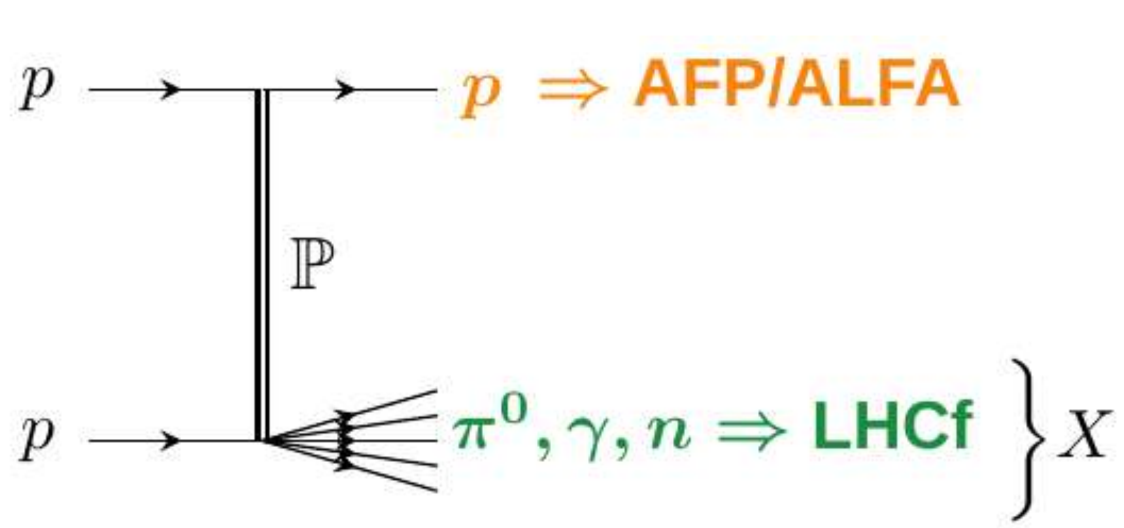
Confirmed improvement of energy resolution to 21%

Joint operation with ATLAS RPs

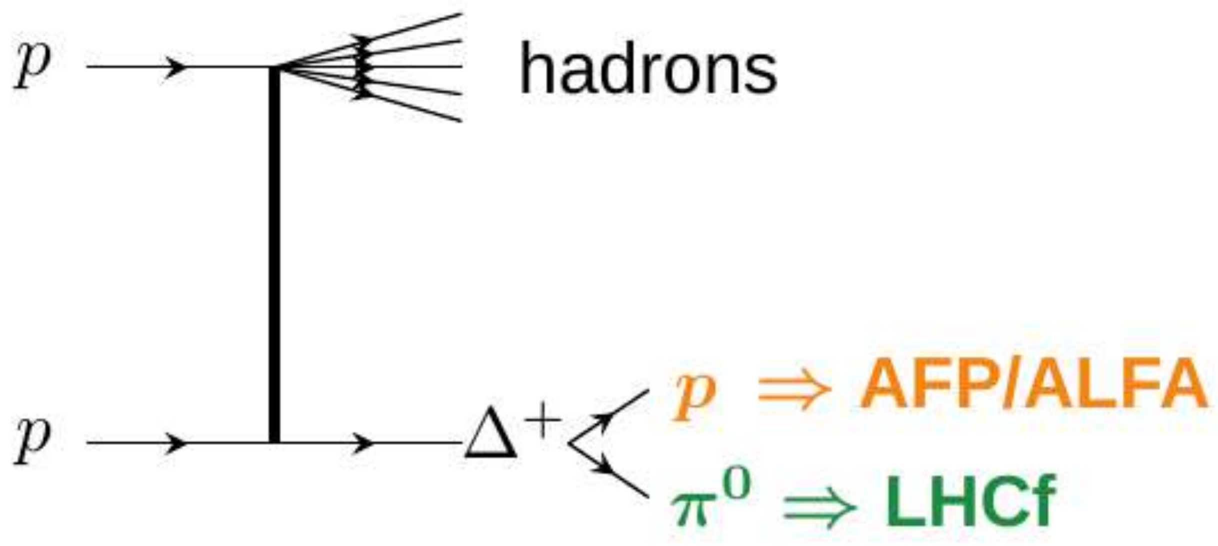
- Physics targets:
  - Detailed study of single diffractive collisions,
  - Measurement of proton excitation (very low-mass diff.)

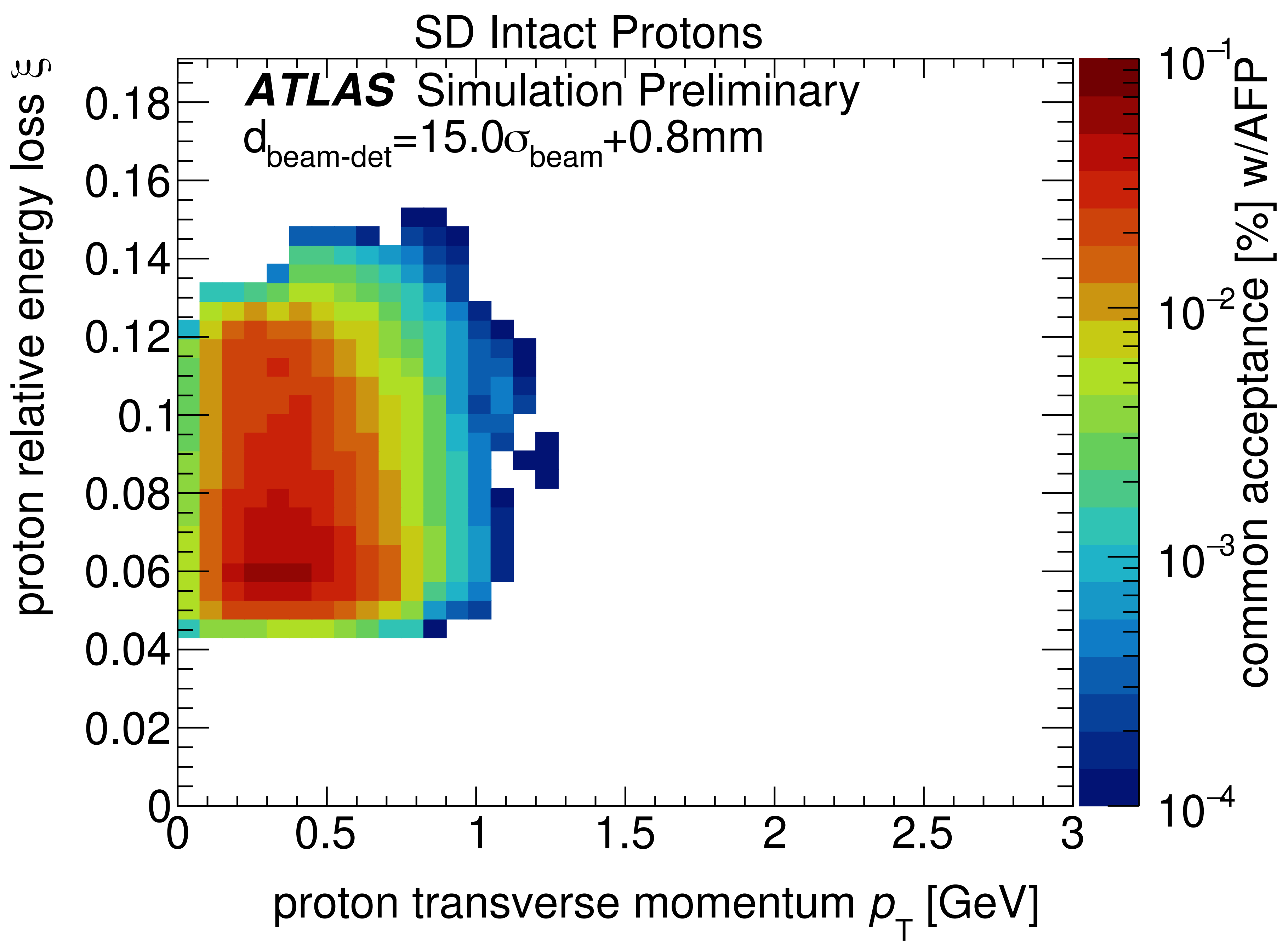
Fusibility study using MC
ATL-PHYS-PUB-2023-024

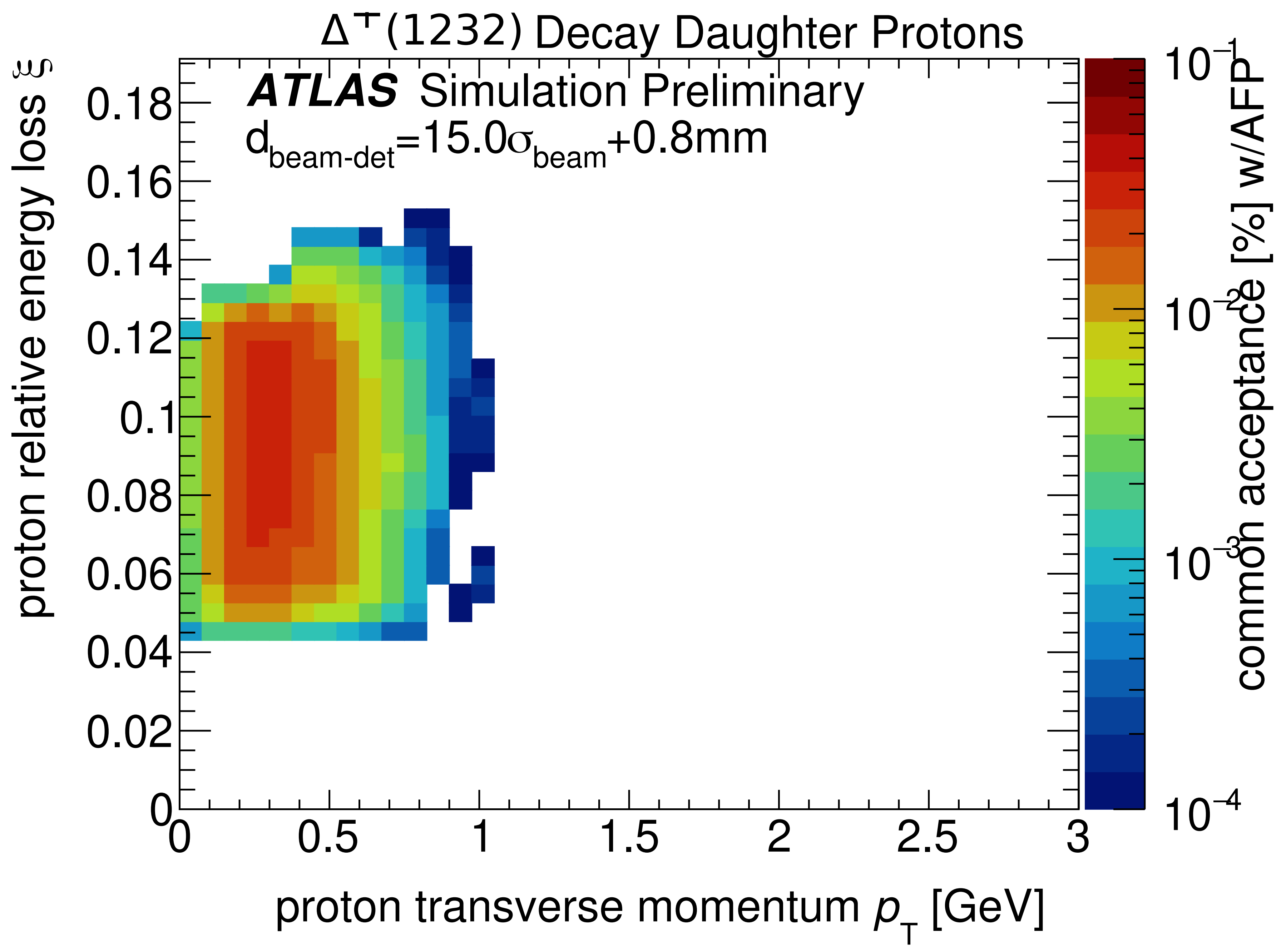
Single diffractive



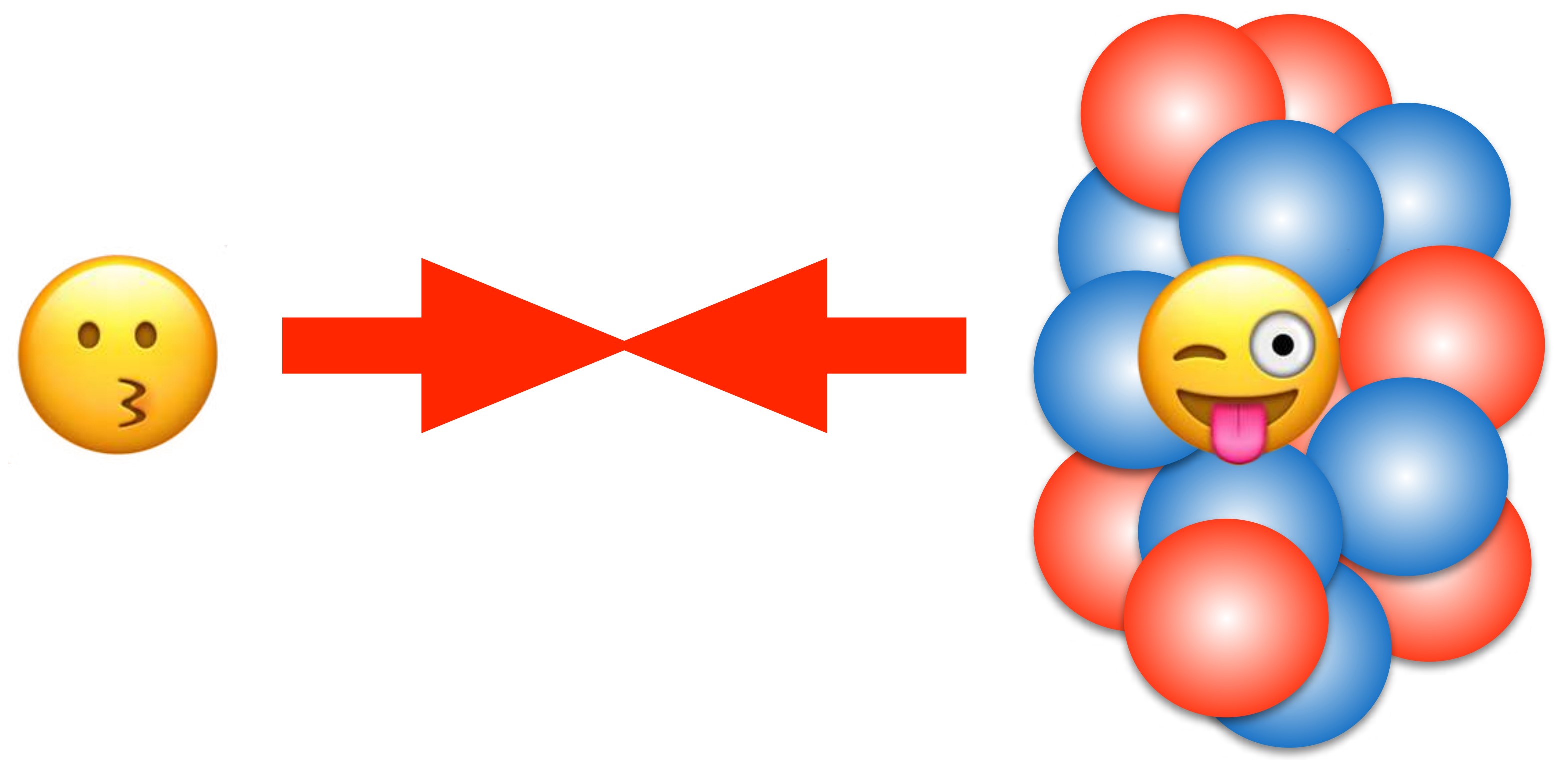
Δ⁺(1232)





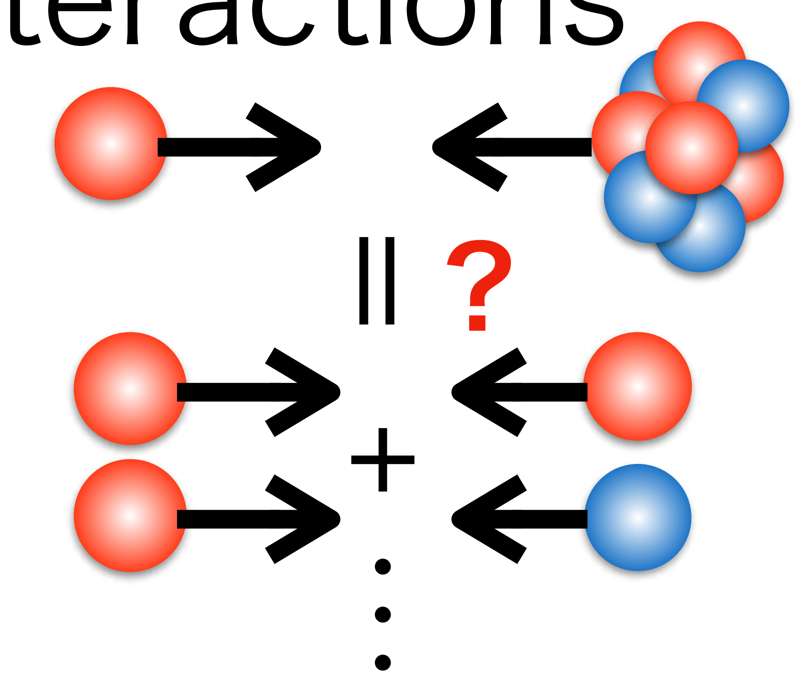


p-O measurement in 2025



Motivation

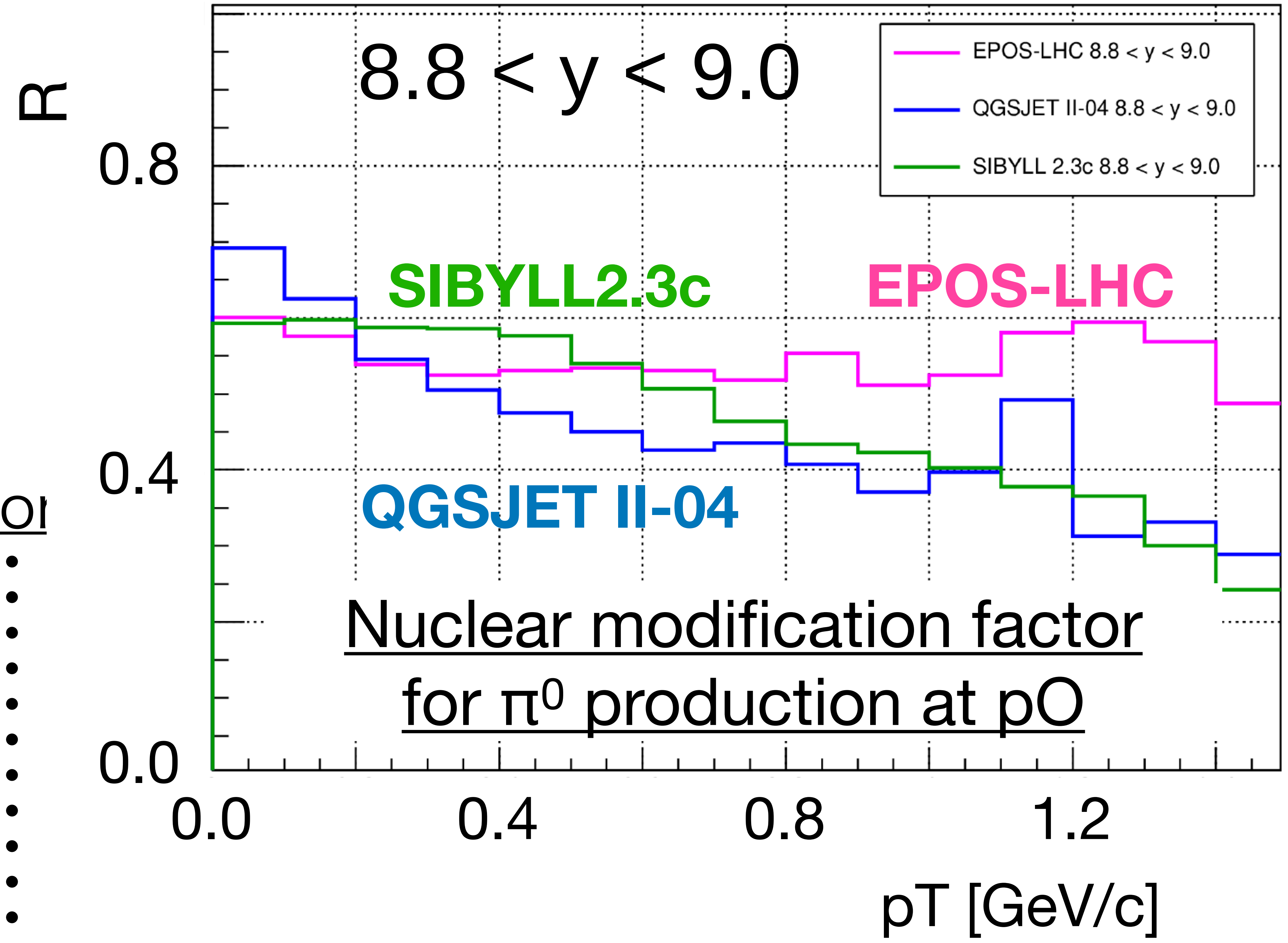
- Ideal condition of CR-Air interaction study
  - First proton-“light ion” collisions at colliders
  - Different modeling of nuclear effect induces difference predictions among models.
  - Negligible contribution of Ultra Peripheral Collisions (UPCs)
- Nucleus(nucleon)-Nucleus interactions
  - **Glauber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



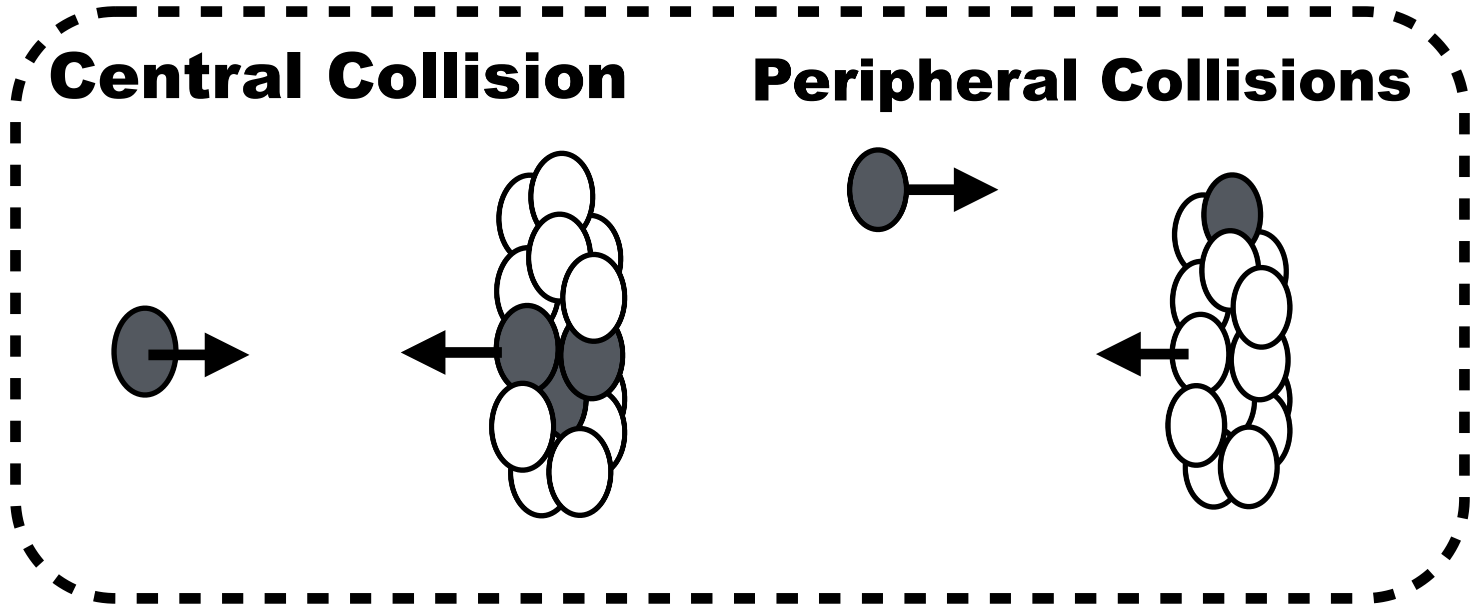
Nuclear Modification Factor

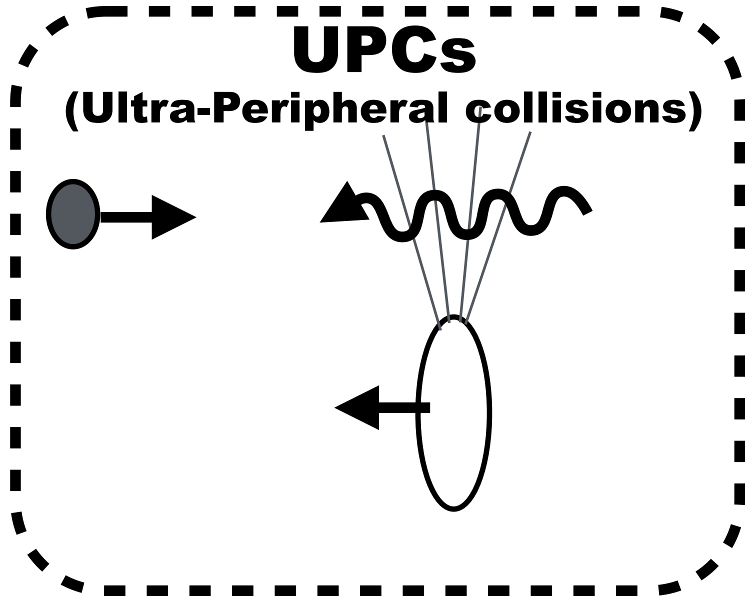
$$R = \frac{\sigma_{pO}}{A\,\sigma_{pp}}$$

A: average number of nucleon collision



Effect of the Ultra Peripheral Collisions (UPCs)

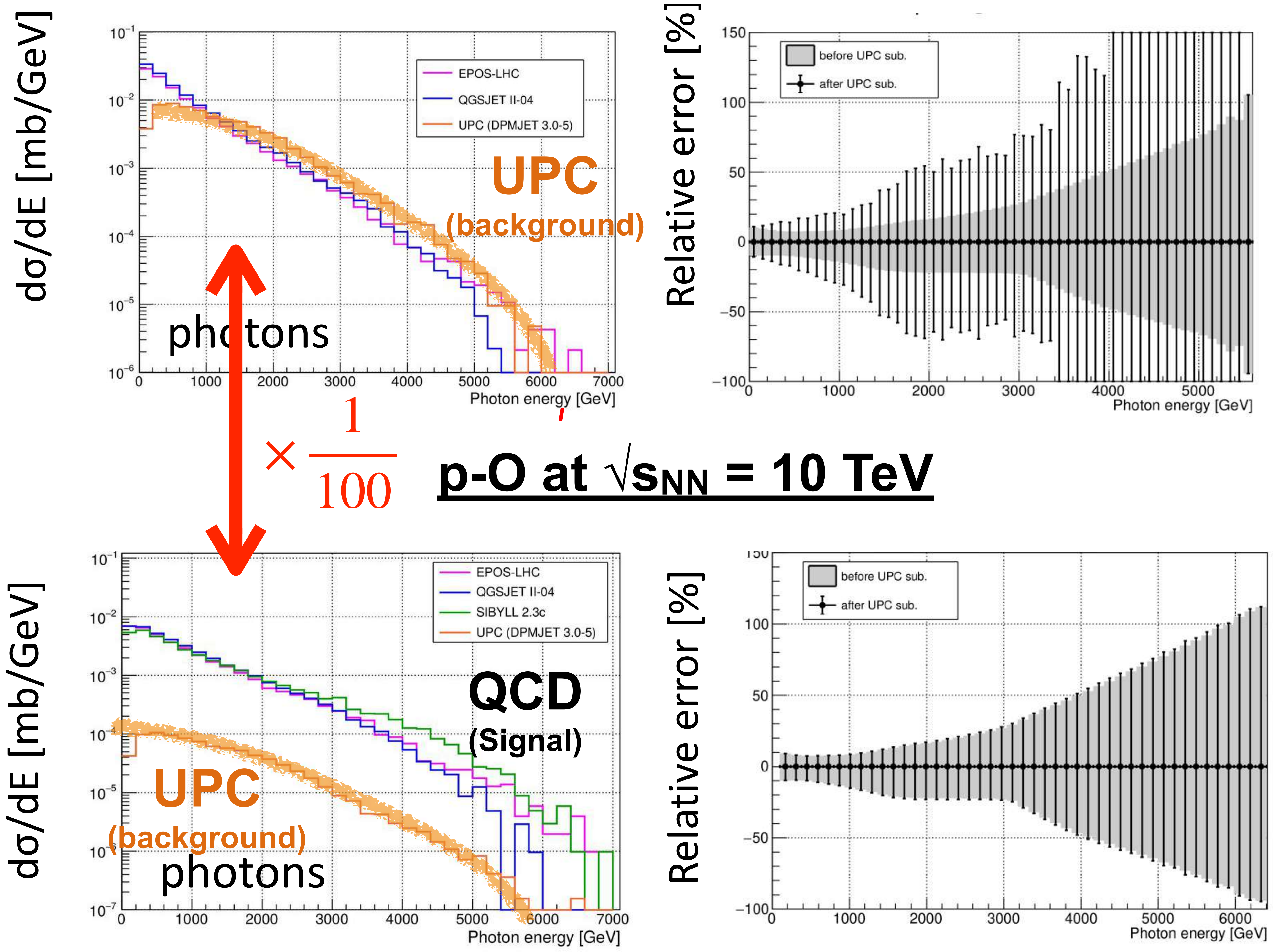




- UPCs are background
  - Air : Oxygen atom (neutral)
  - LHC Beam : Oxygen nucleus (+8e)
- $\sigma_{\mathrm{UPC}} \propto Z^2$
  - p-Pb : QCD ~ UPC
  - p-O : QCD >> UPC

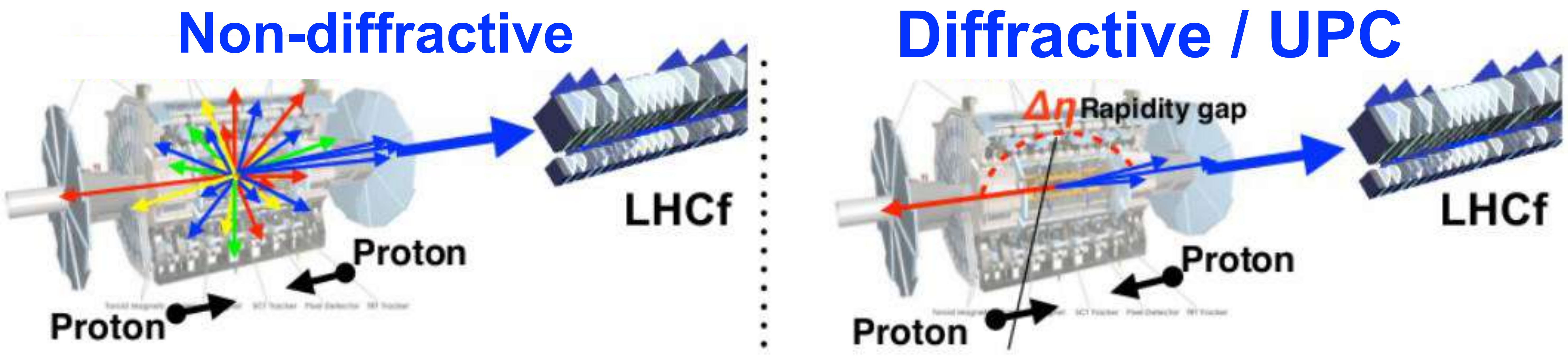
UPC contribution is negligible for "inclusive" measurement

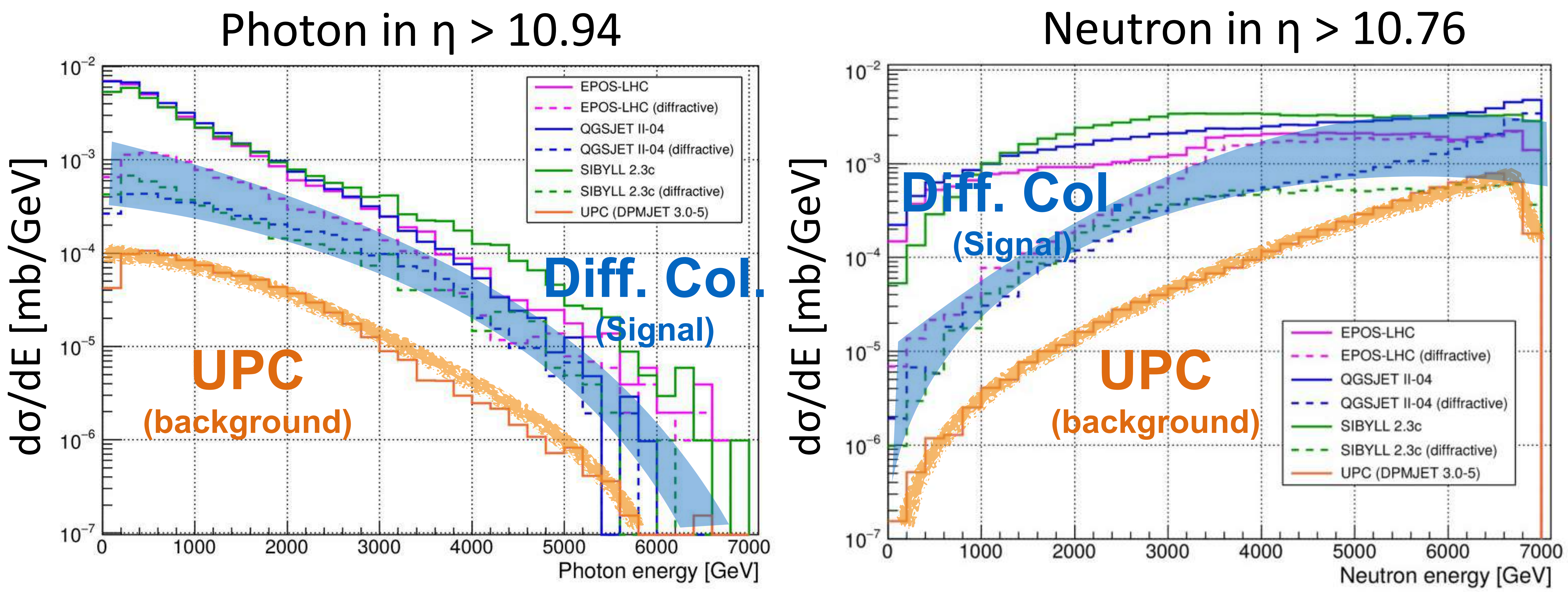
p-Pb at $\sqrt{s_{NN}}$ = 8.2 TeV



Impact on LHCf-ATLAS joint analysis

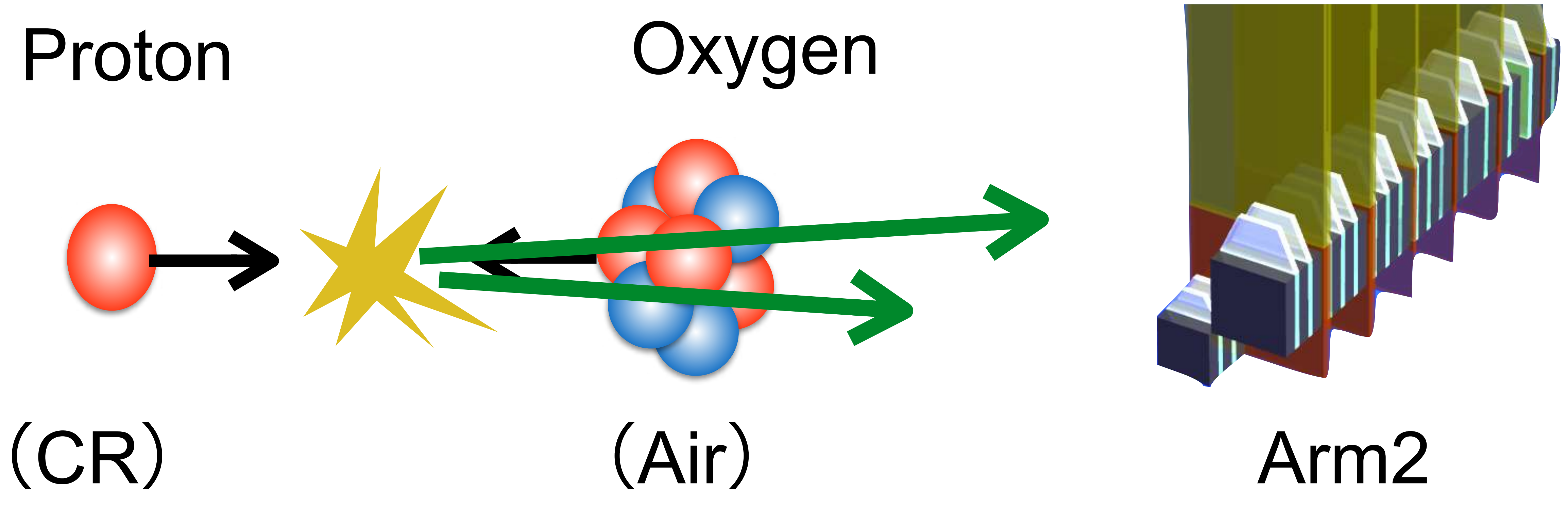
- Need to be careful in the central-forward correlation analyses with ATLAS.
- In single diffractive study.
  - Little central activity in both low-mass diffractive and UPC events.
    → No way to separate these events experimentally.
  - The UPC contribution is still a controllable level.





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

Summary

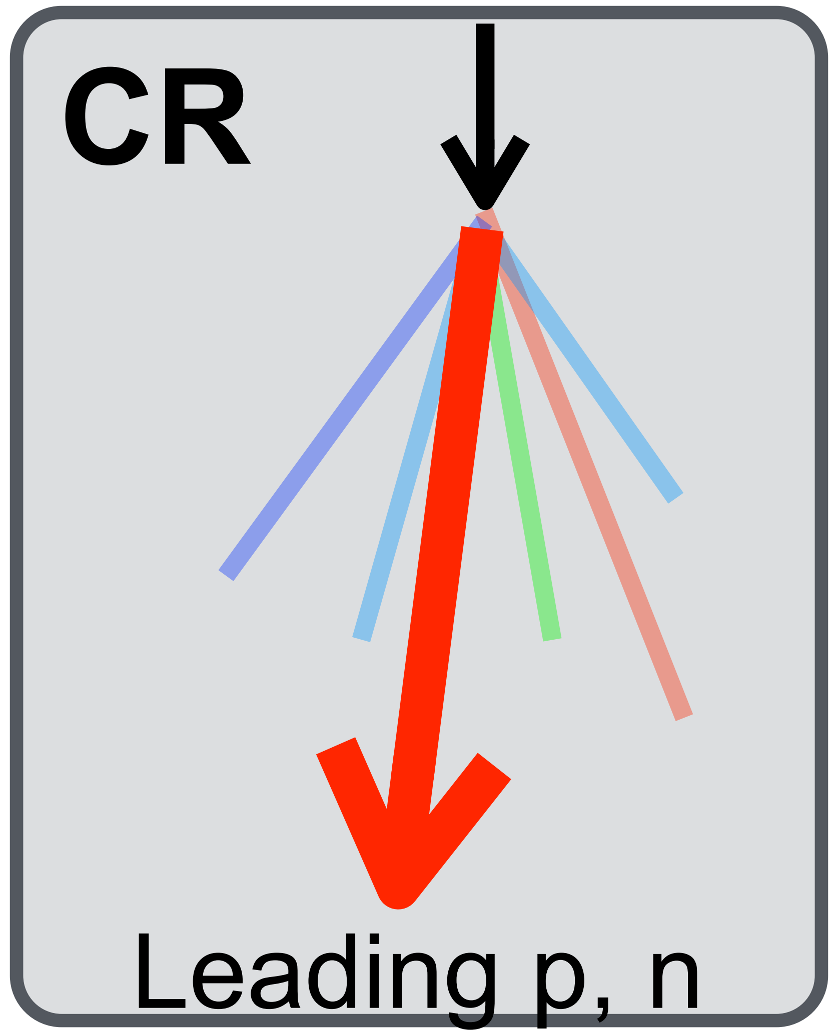
- LHCf measures the very forward neutral particles, which are motivated for cosmic ray physics.
- Presented results from Run 2 data
  - Updated neutron results → inelasticity measurement.
  - η meson diff. cross-section
- Many analyses are on-going
  - η, π^0 with high statistics data, K^0_s measurement
  - 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.

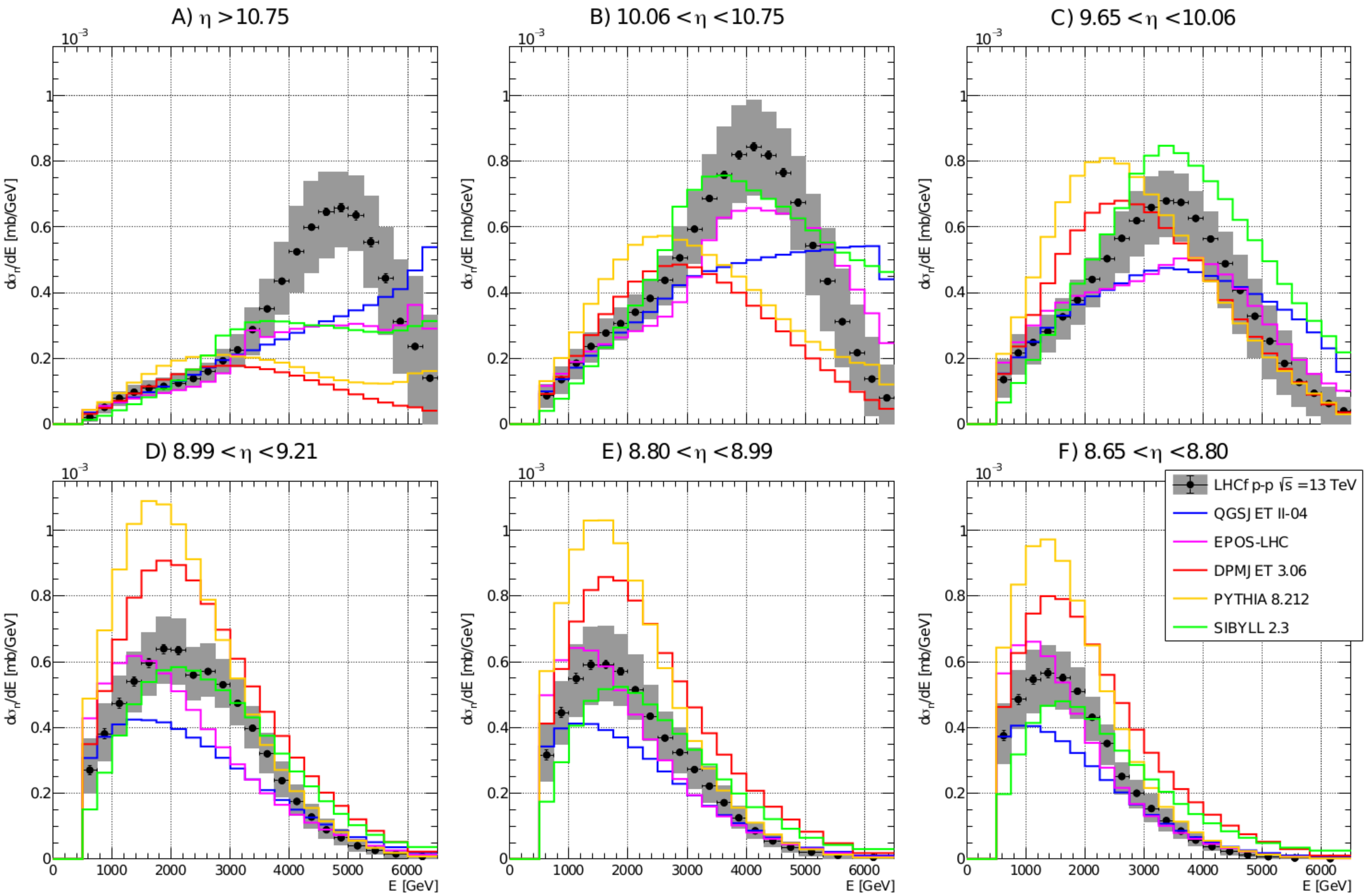
Thank you very much !!

Backup

Forward Neutron at *pp*, √s=13 TeV

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

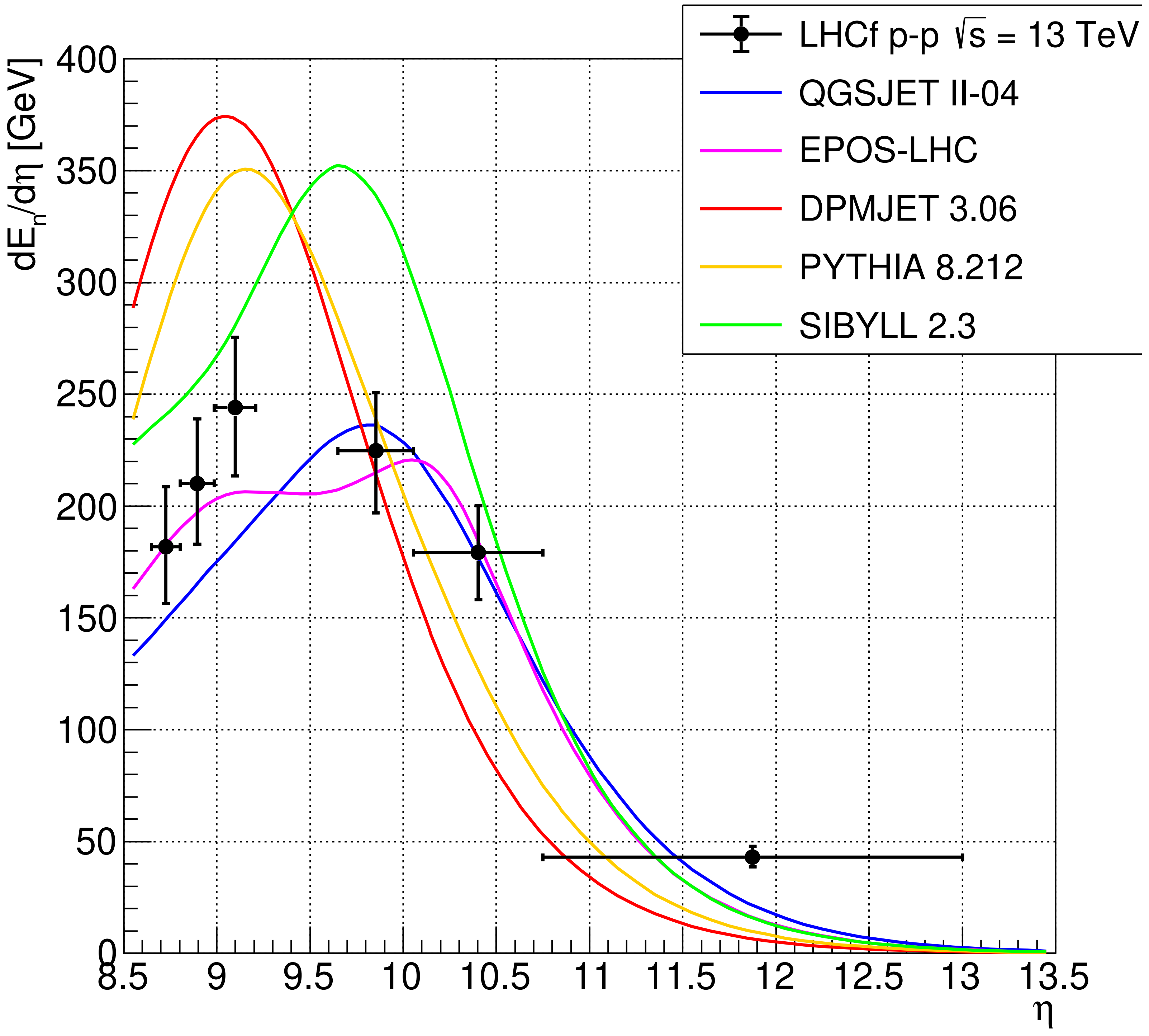




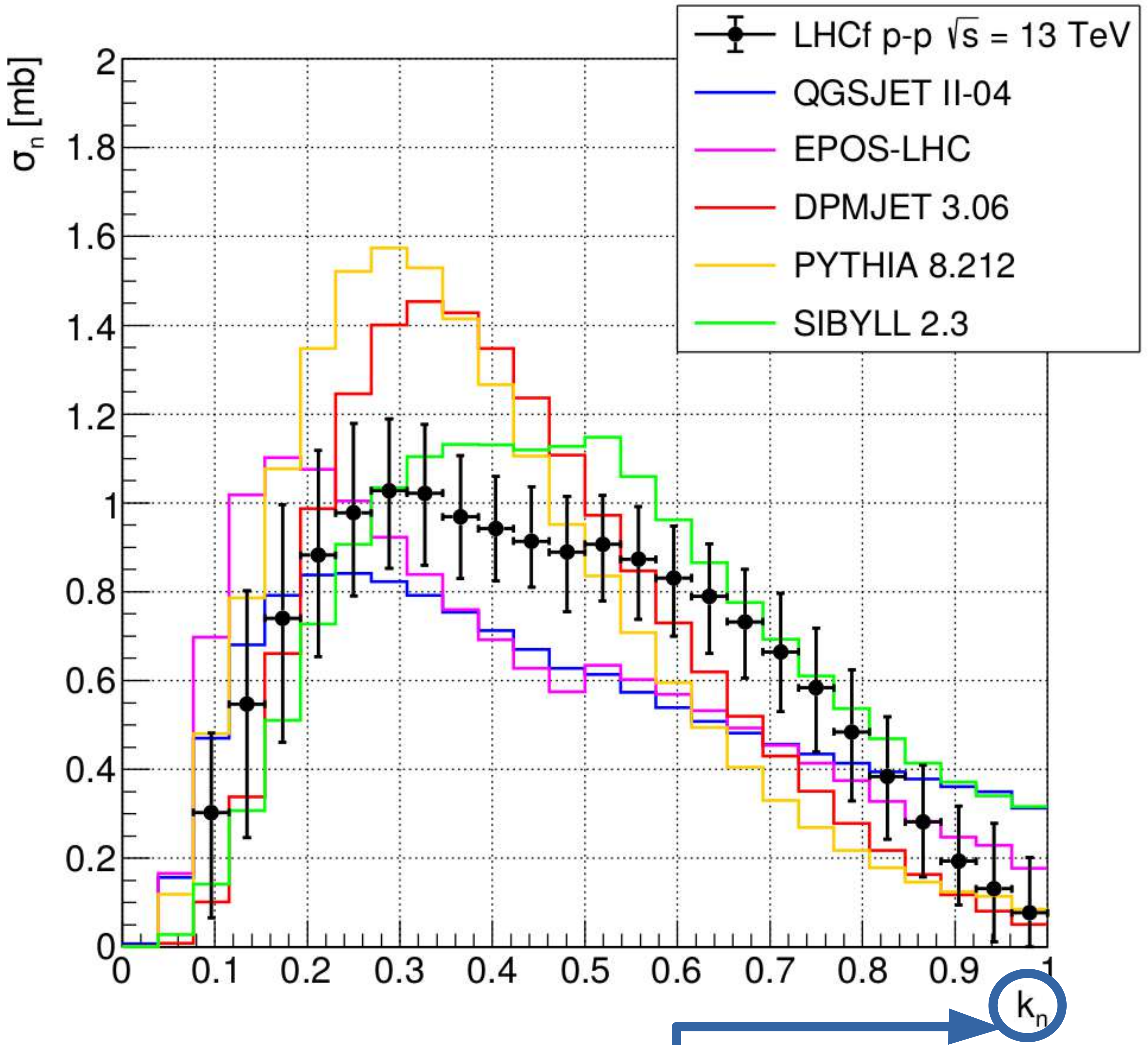
O. Adriani et al., JHEP07 (2020) 016

Inelasticity from the neutron result

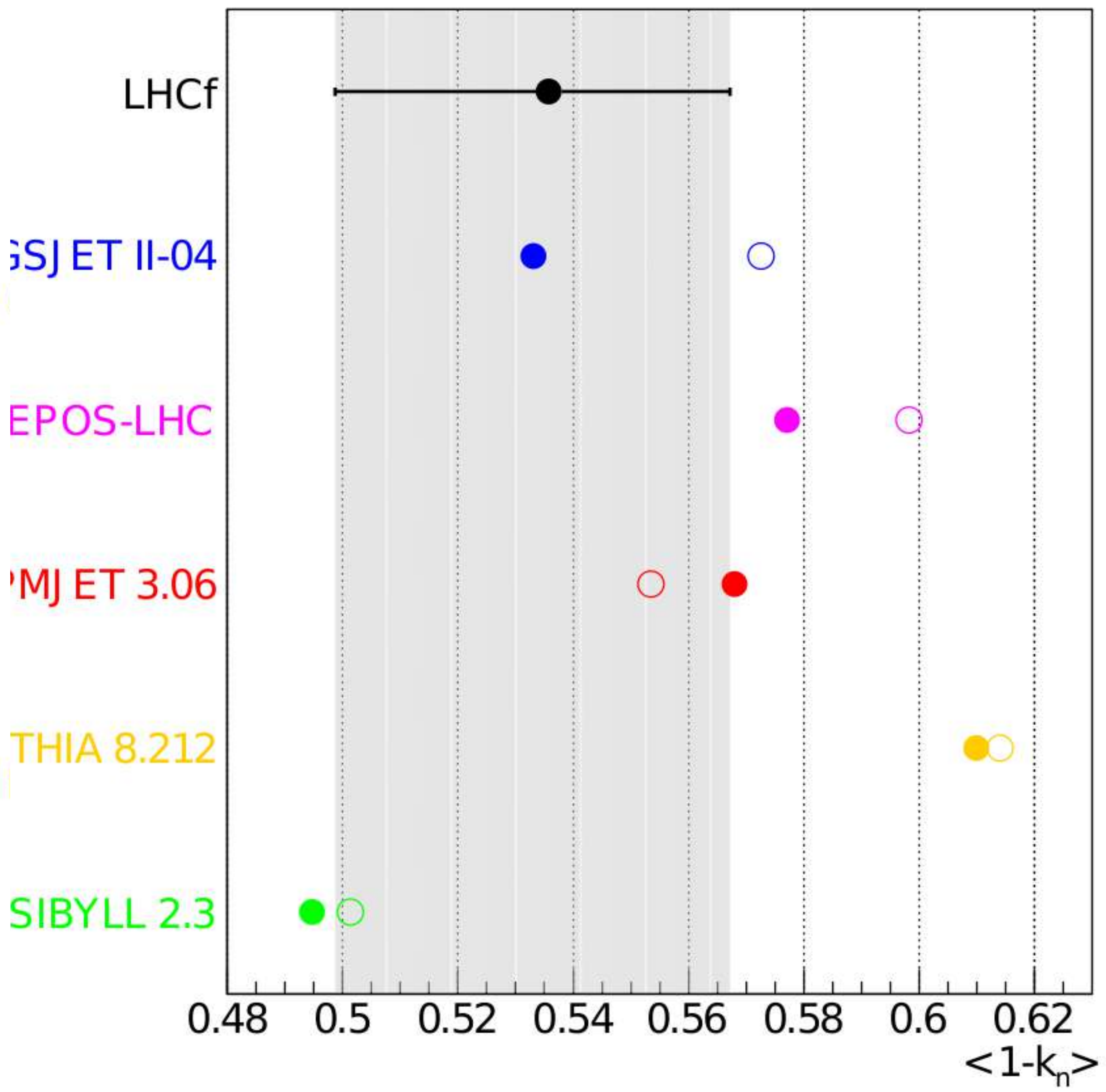
Energy flow



Elasticity distribution



<Inelasticity>



- ● neutron inelasticity
- ○ all particles inelasticity

Best agreement model

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

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

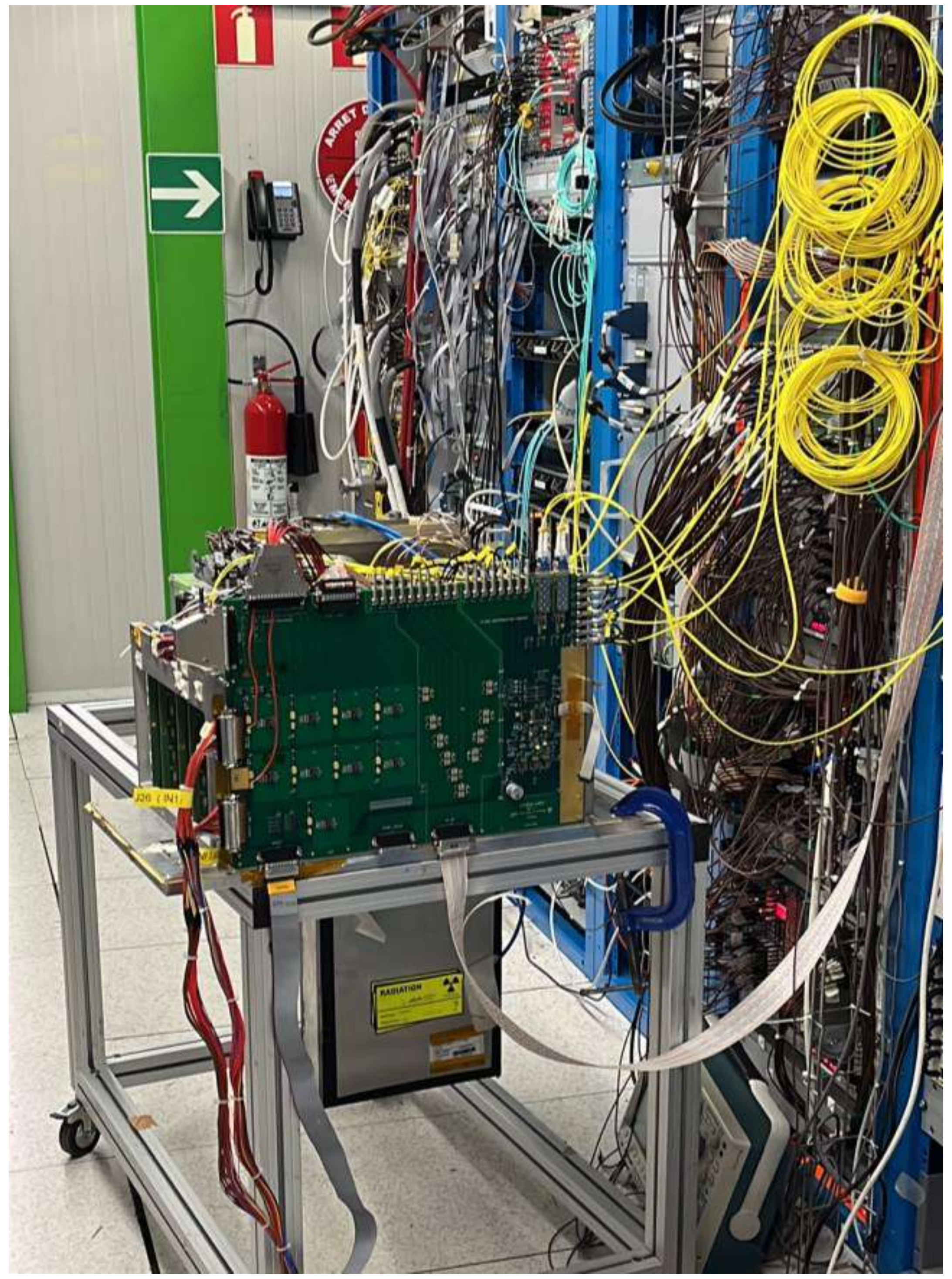
O. Adriani et al., JHEP07 (2020) 016

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

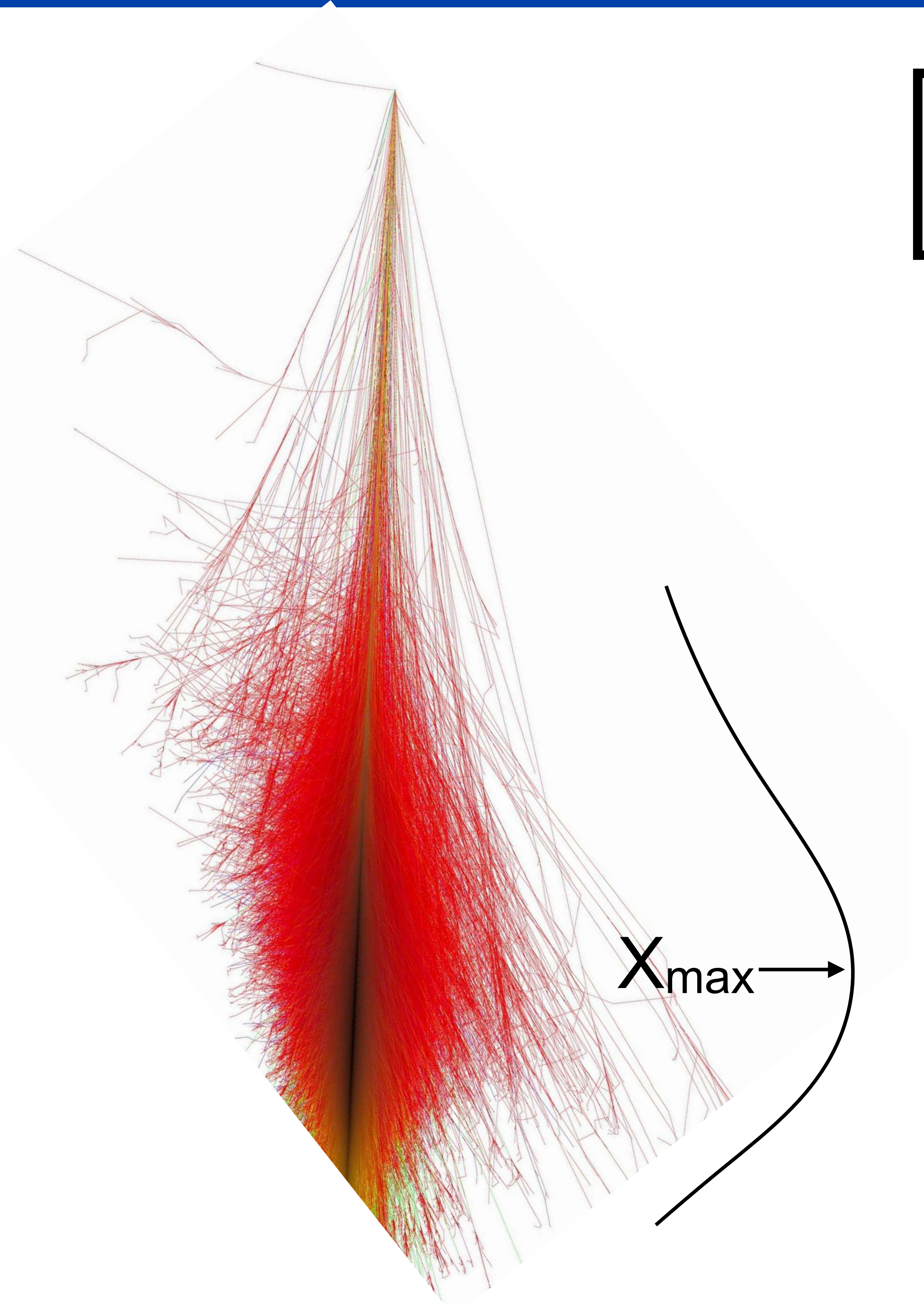
Test of the Arm2 detector in USA15 in Feb 2024



Contents

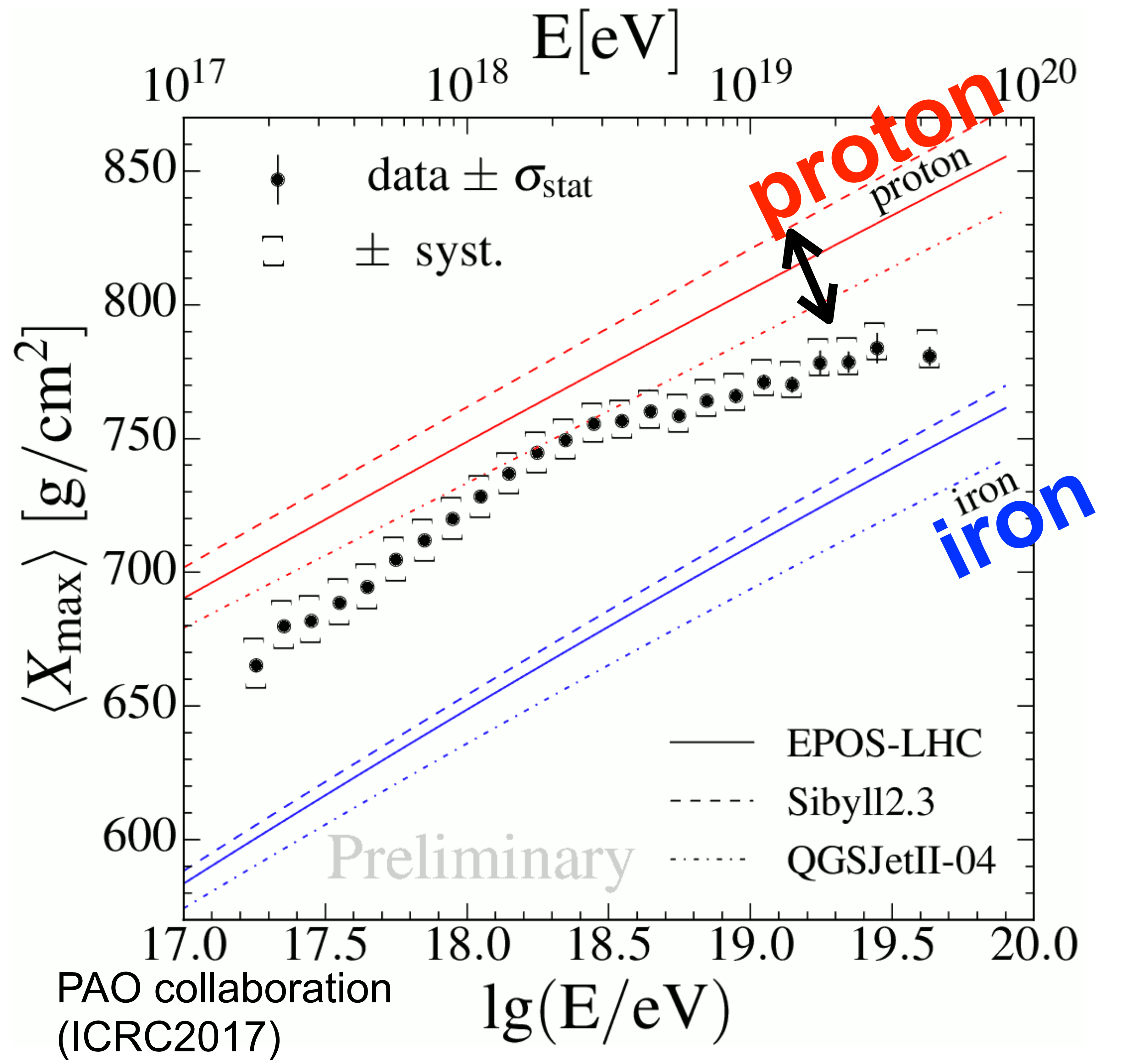
- Results from Run 2 data (pp, $\sqrt{s}$=13 TeV in 2015)
  - inelasticity measurement using forward neutron
  - η meson production cross-section
- Status of analyses with Run 3 data (pp, $\sqrt{s}$=13.6 TeV in 2024)
  - Physics targets
  - Joint operation with ATLAS
- Oxygen run in 2025

Estimators of Mass Composition



N^{μ}: Number of muons on the ground

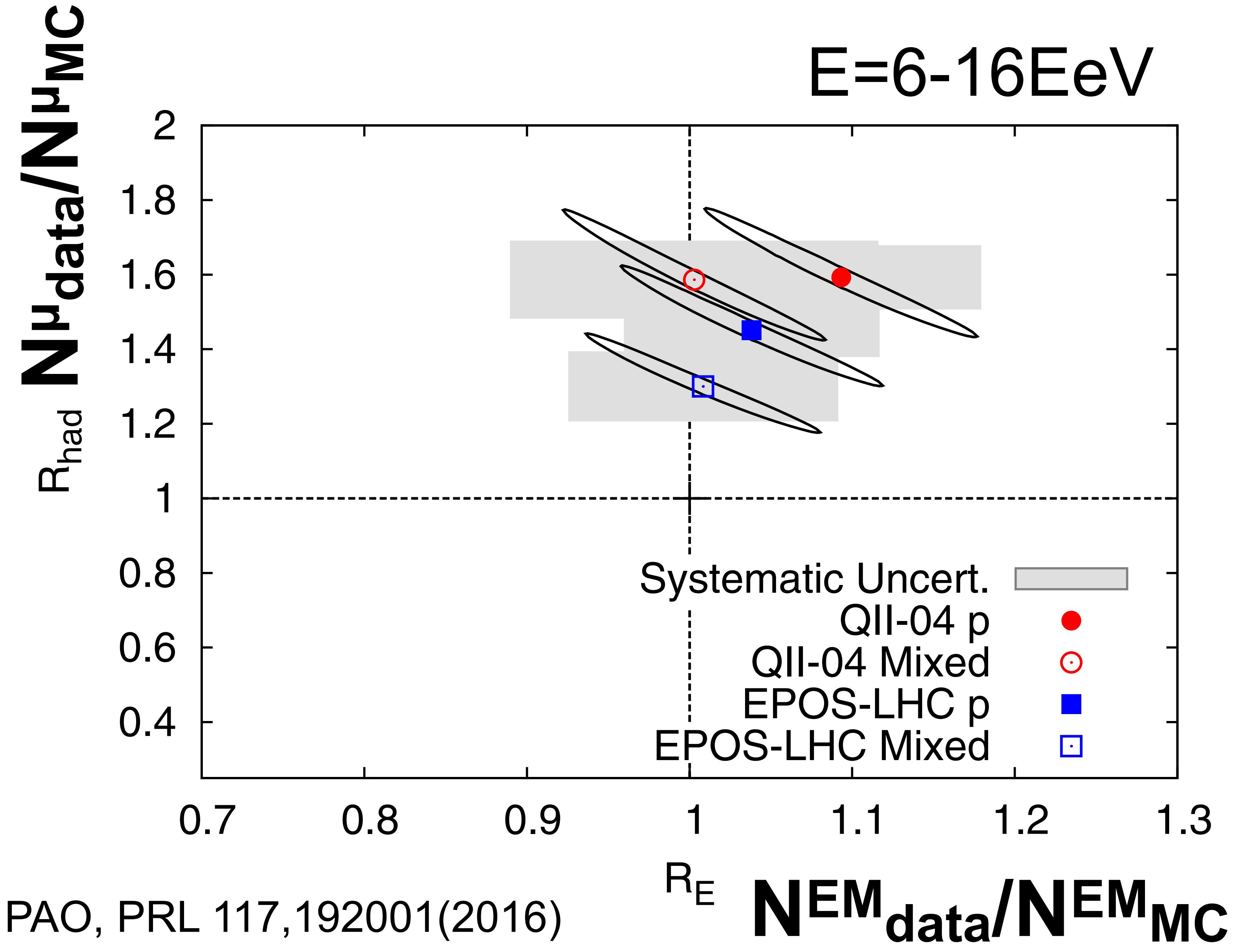
Large model dependency of UHECR composition measurement



PAO collaboration (ICRC2017)

Interaction model uncertainty > Experimental uncertainty

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



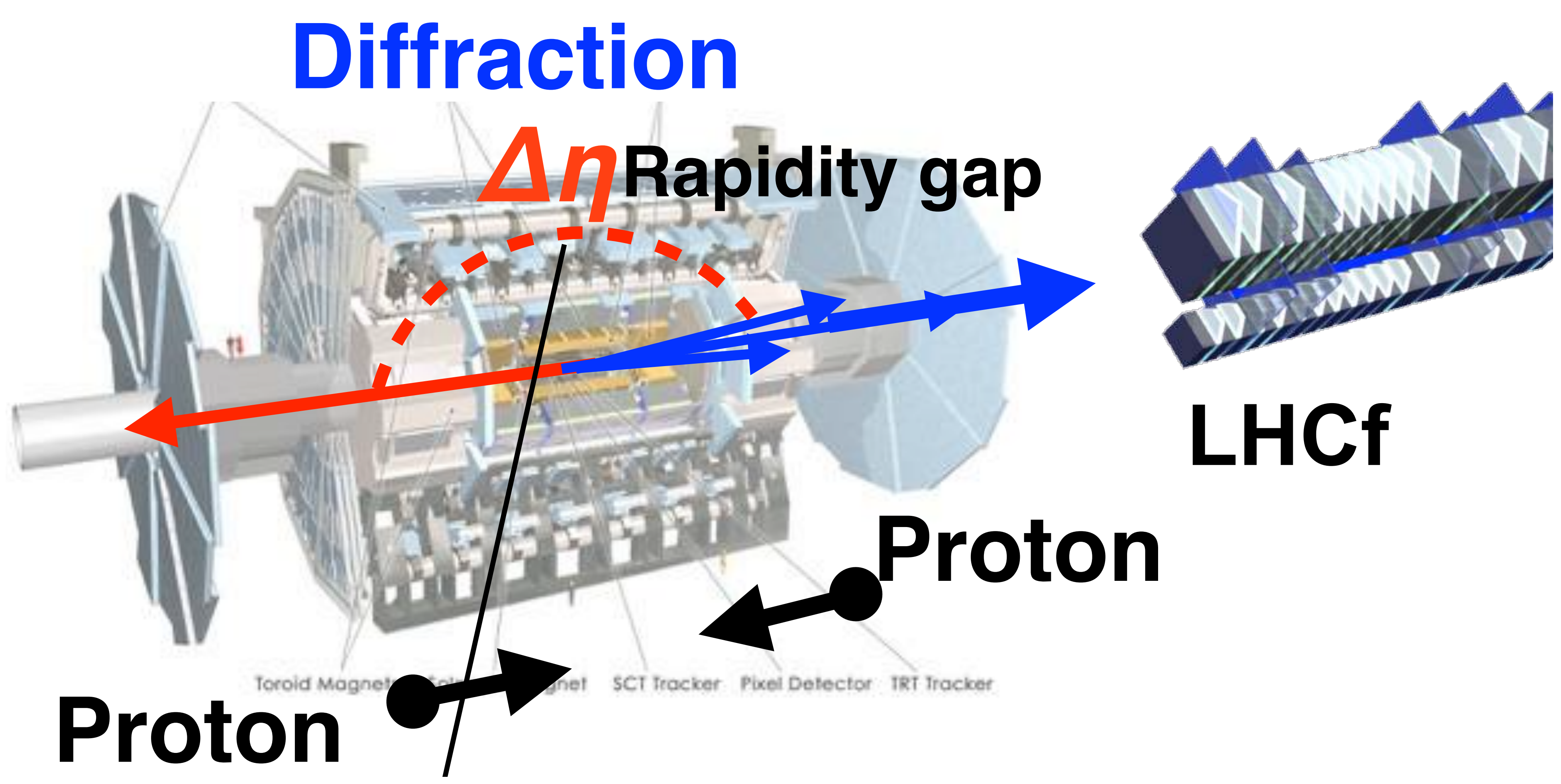
PAO, PRL 117,192001(2016)

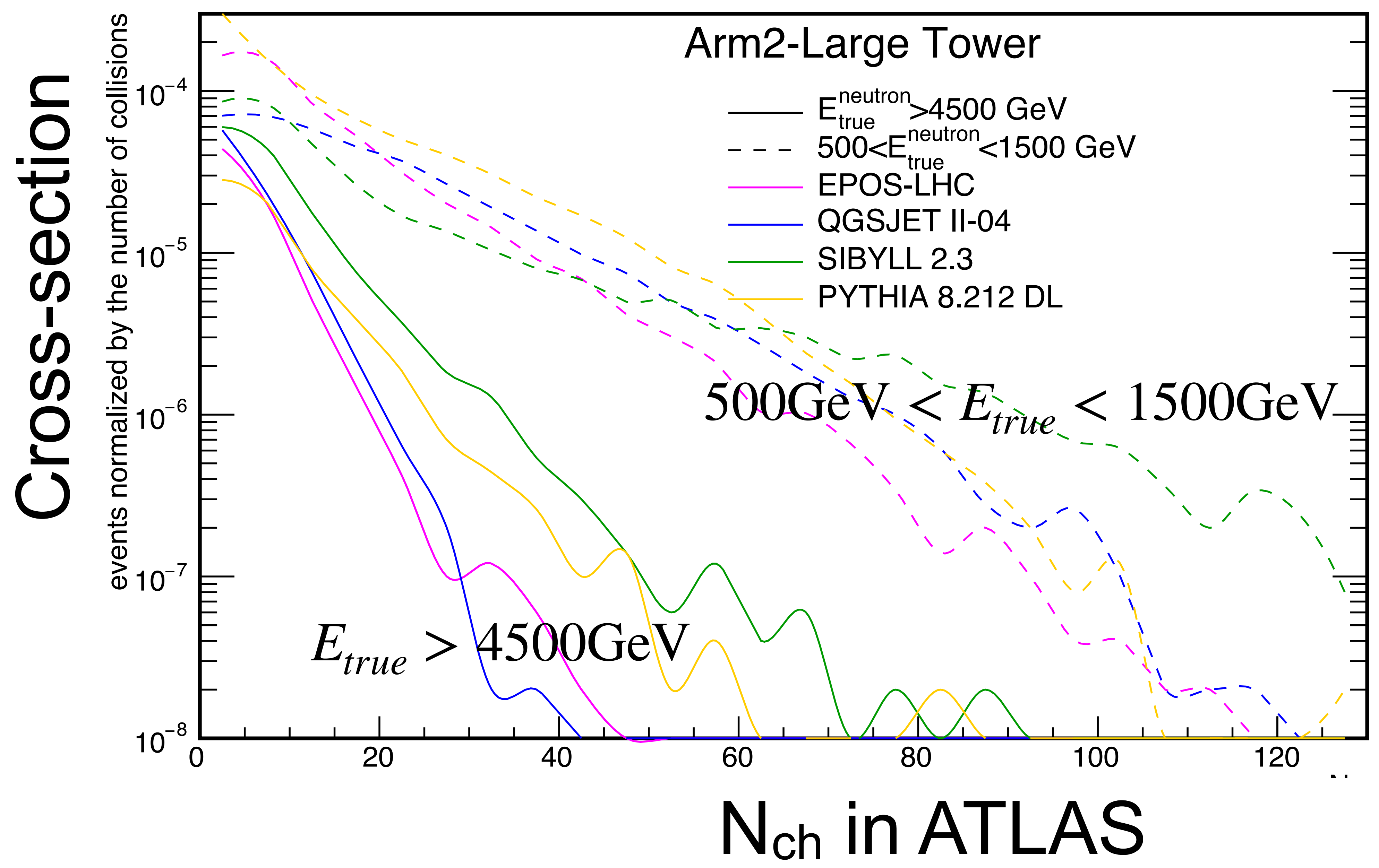
Sensitive $E^{\pi 0}/E^{had}$ for a collision

Several ideas to solve it

- Strange particles
- Vector meson productions
- QGP

On-going Joint analyses with ATLAS



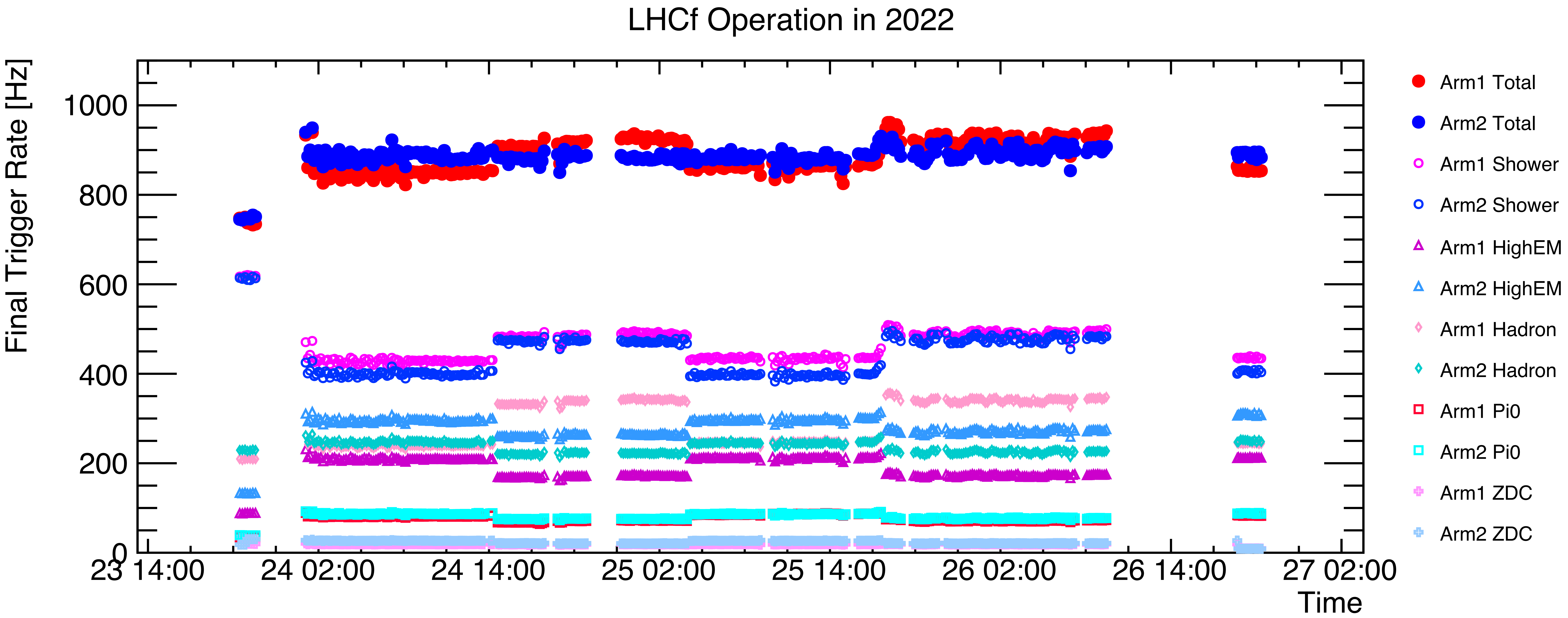


- Study of diffractive collisions
  - Photon spectra with N_{ch}=0 in ATLAS (p_T>0.1GeV, $|\eta| < 2.5$)
- Study of MPI
  - Correlation between forward neutron and N_{ch} in ATLAS

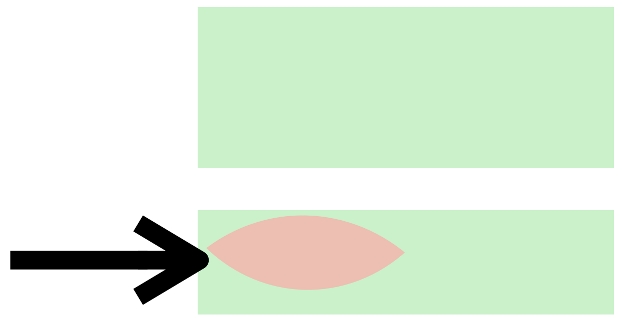
Superposition of single API: MPI ↗ Forward neutron energy ↘

Kinematic overlap : MPI ↗ Forward neutron energy →

6 Trigger modes



Shower Trg.



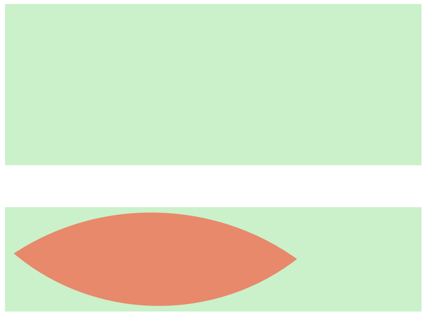
Baseline trigger
Any showers

π^0 Trg.

Two tower coin.
for π^0 (<~ 2 TeV)
η (2γ)

2015 operation

High EM Trg.



High threshold
π^0 (>~1.5 TeV)
K^0_s(4γ)

Hadron Trg.

Deeply developed
shower for
hadron showers
Λ (n+2γ)

ZDC Trg.

Trigger from ZDC

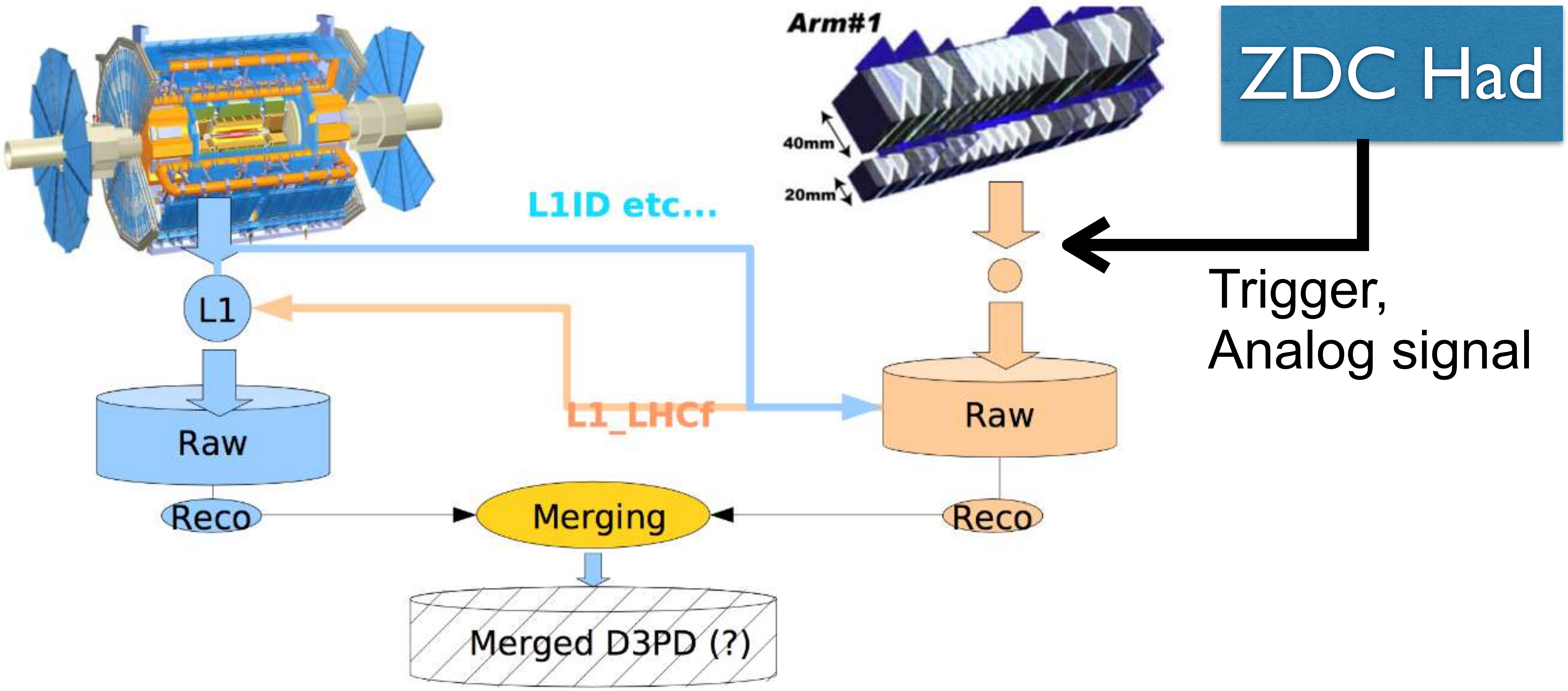
Pedestal Trg.

= zero bias trigger

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

<u>DAQ scheme</u>



<u>Improvement from 2015 run</u>

- 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)