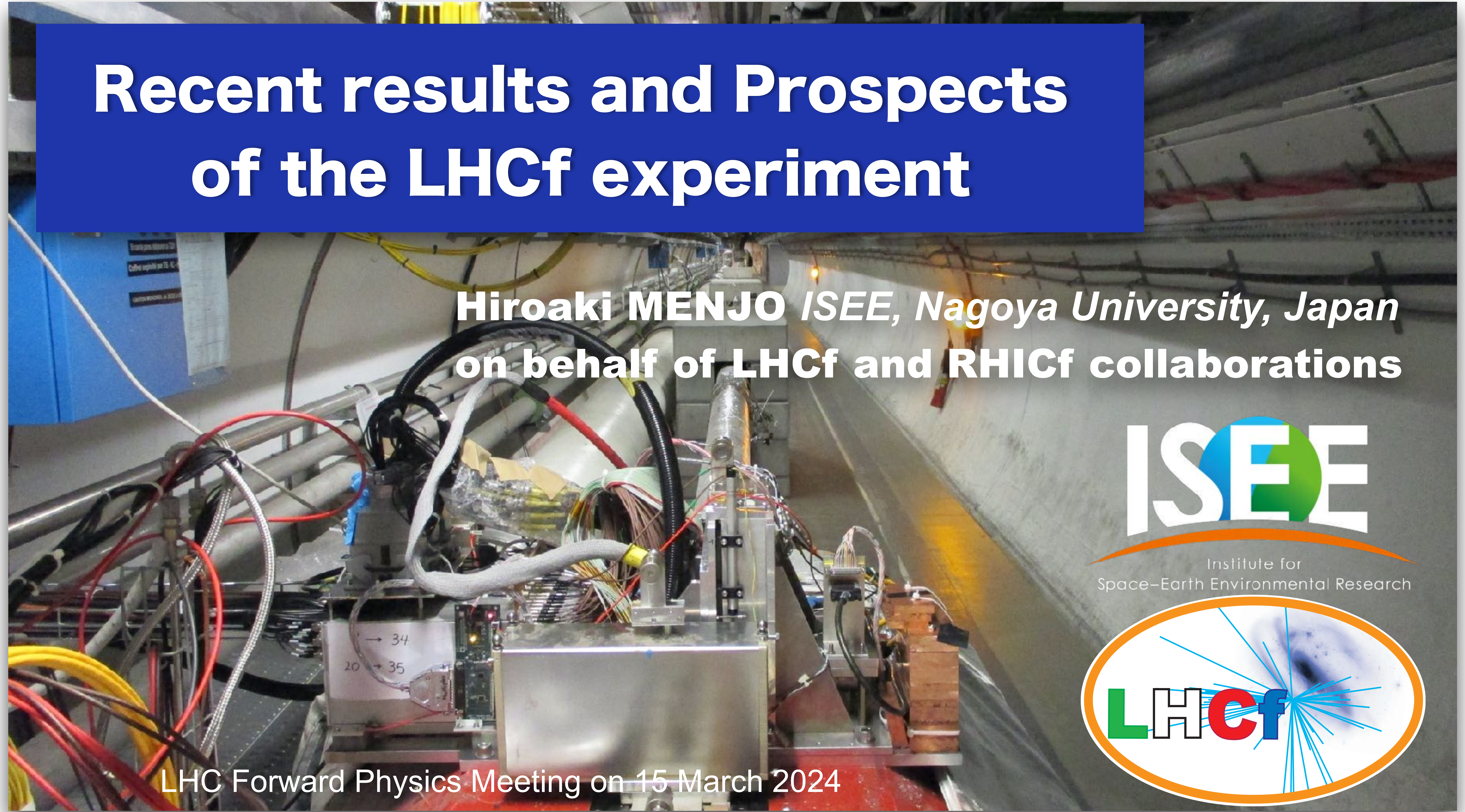
Recent results and Prospects of the LHCf experiment

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

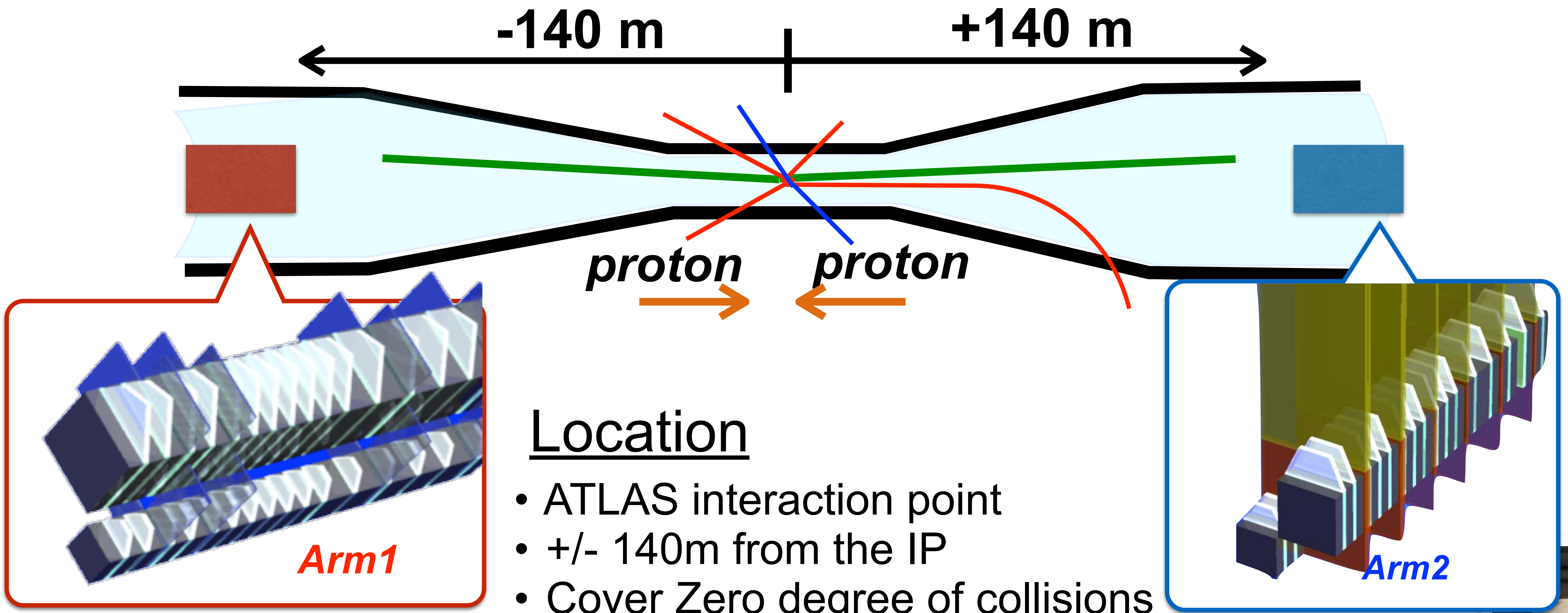


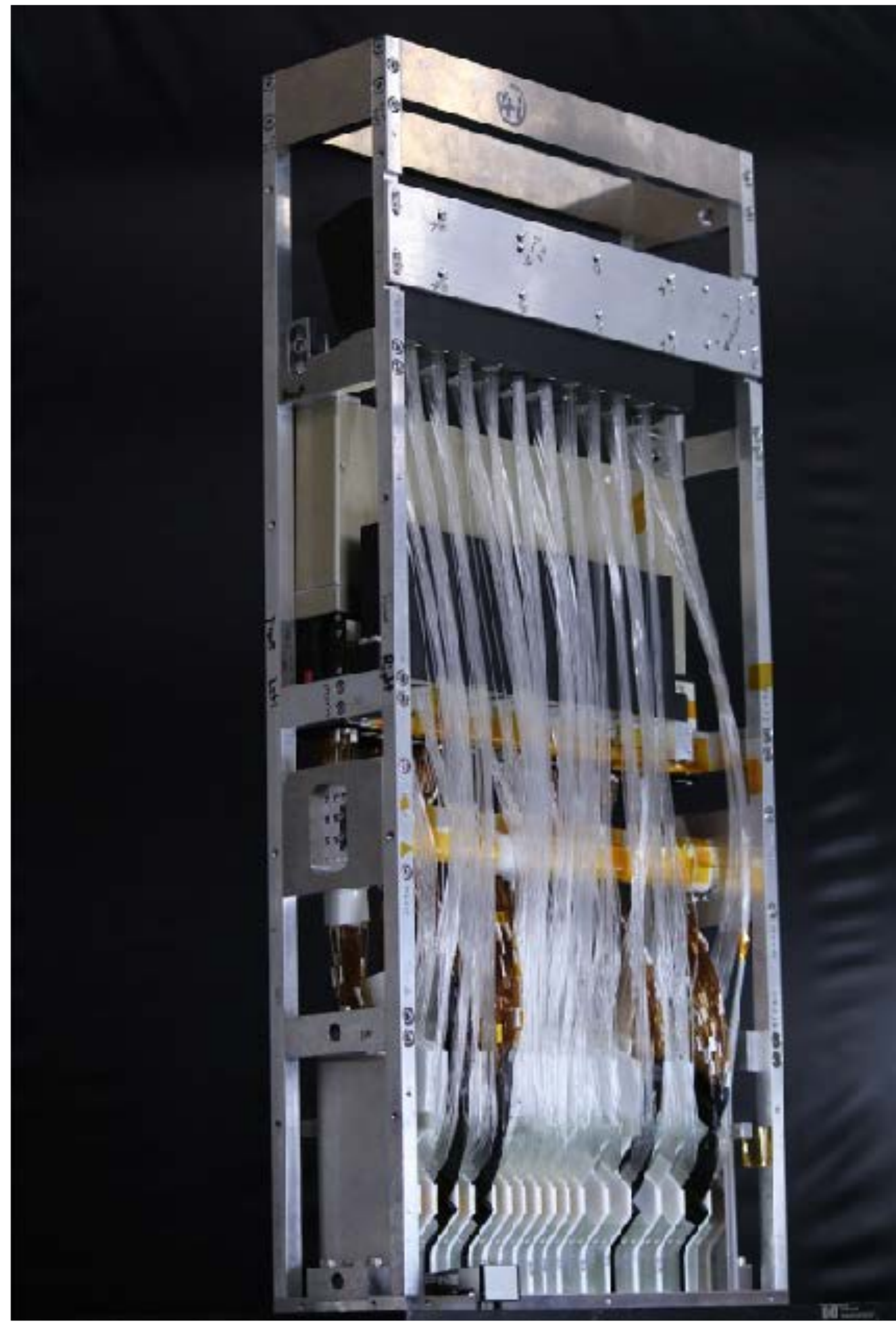
ISEE
Institute for Space–Earth Environmental Research

LHCf

LHC Forward Physics Meeting on 15 March 2024

LHCf experiment





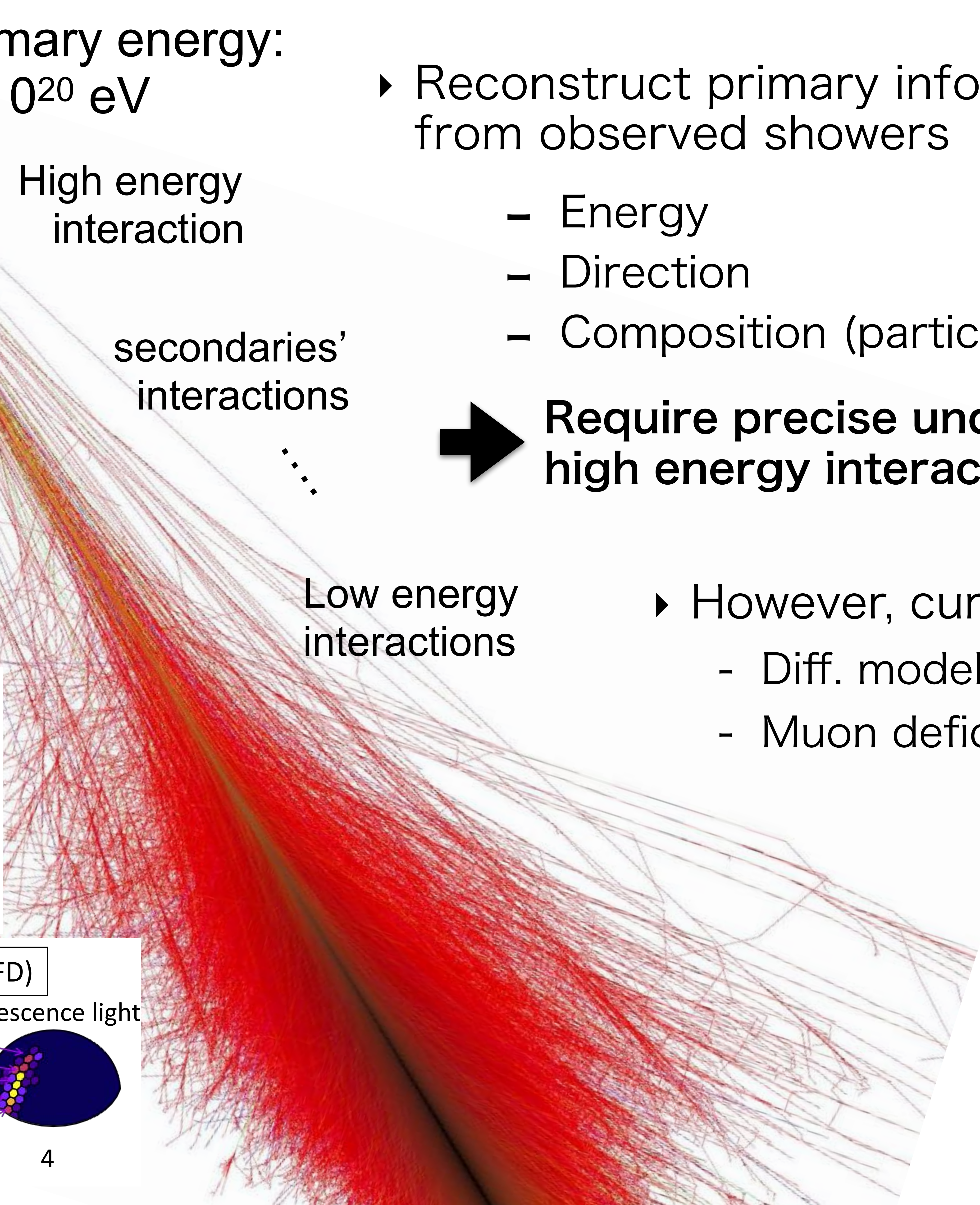
Location

- 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

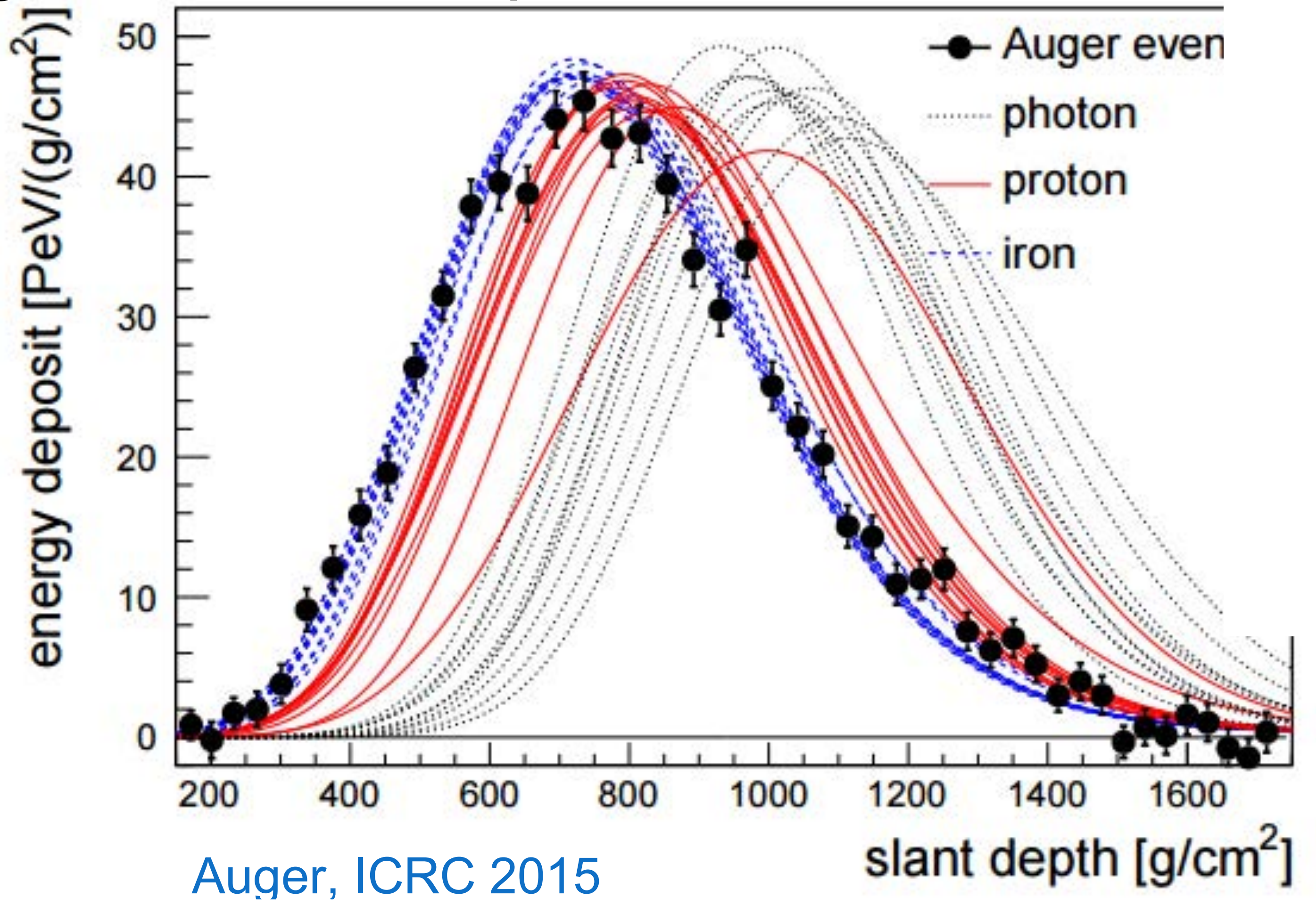
High Energy Cosmic-Ray Observation



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

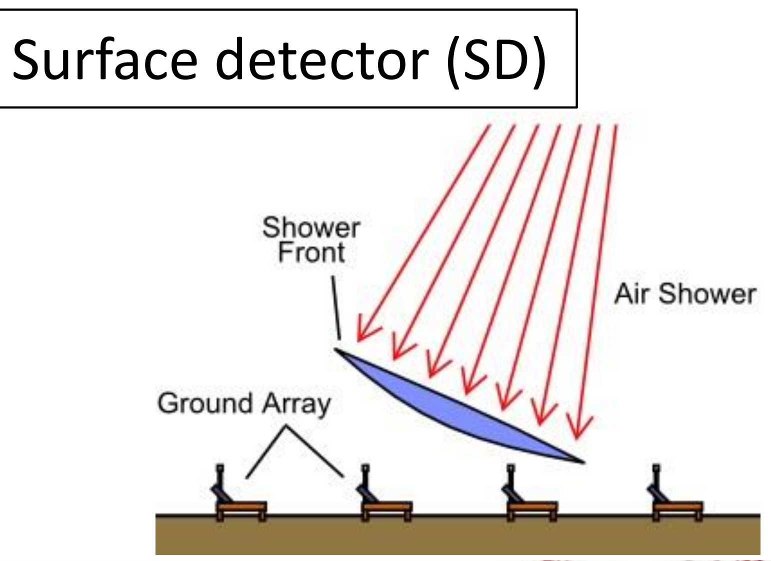
➡ **Require precise understanding high energy interactions**

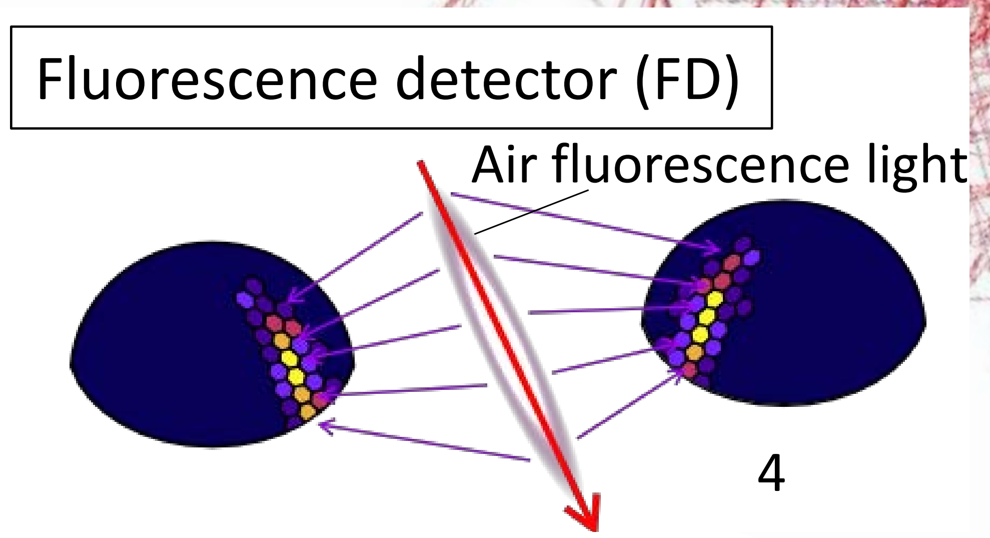
Longitudinal development of 10^{19}eV showers



- 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



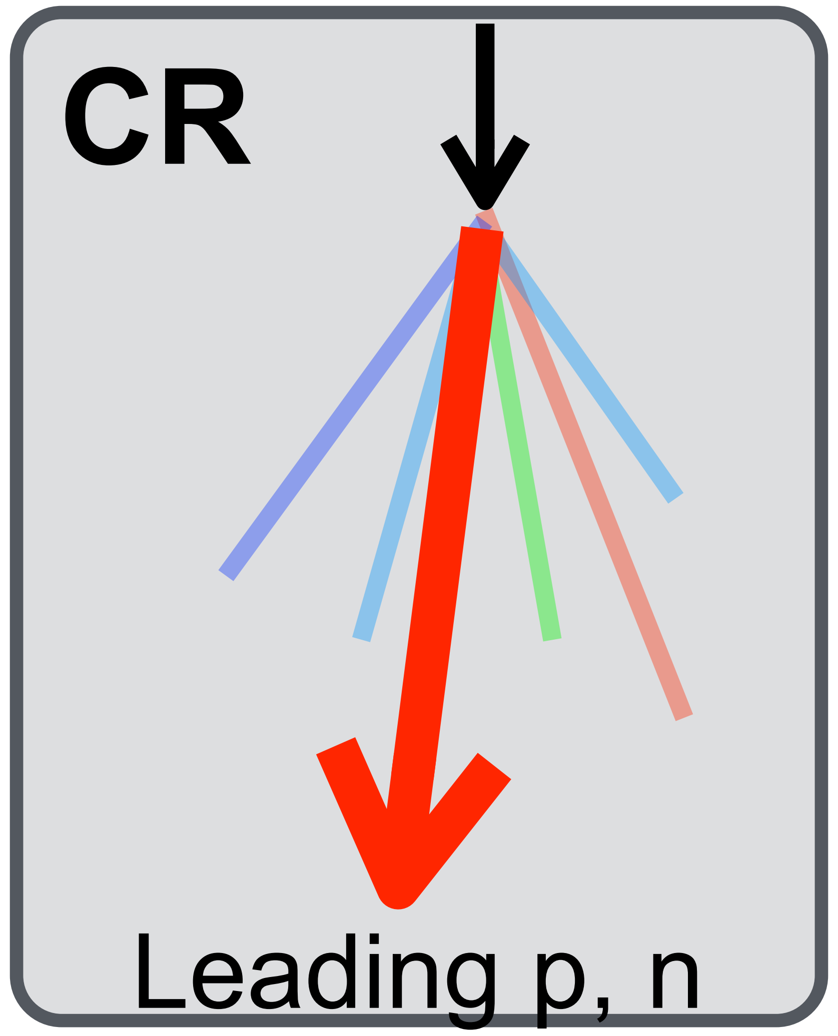


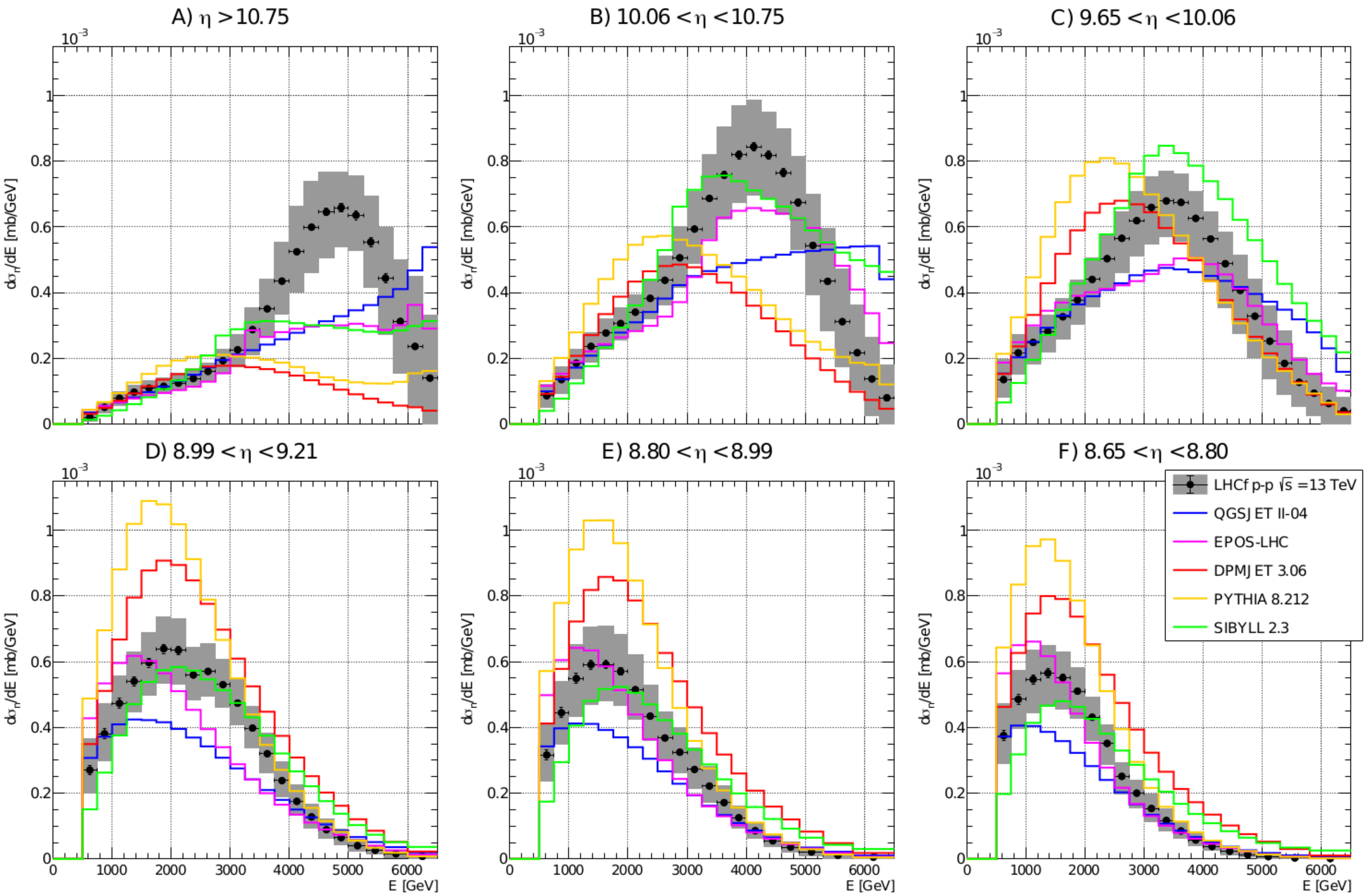
Contents

- 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
- Preparation for Oxygen run in 2025

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%

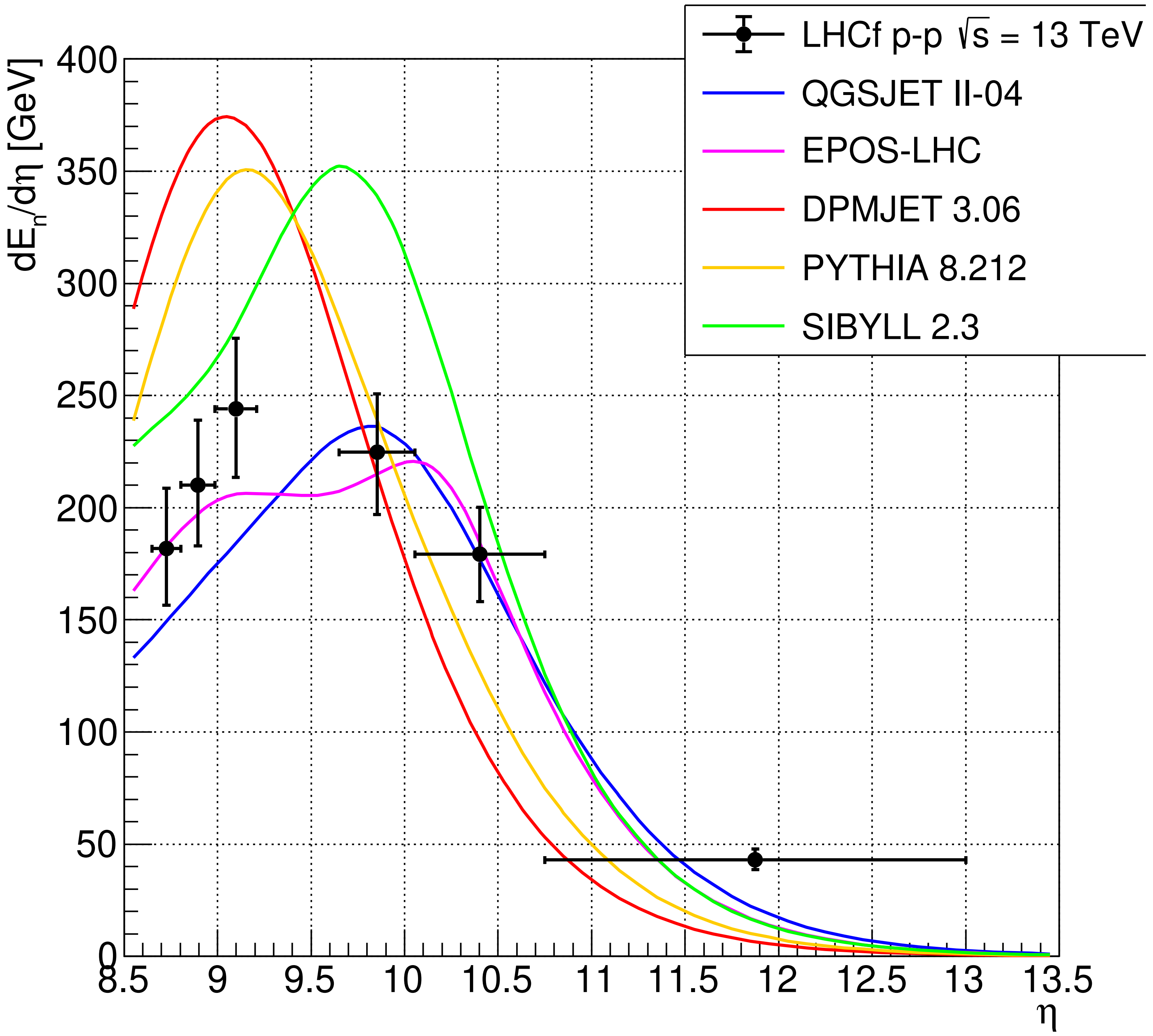




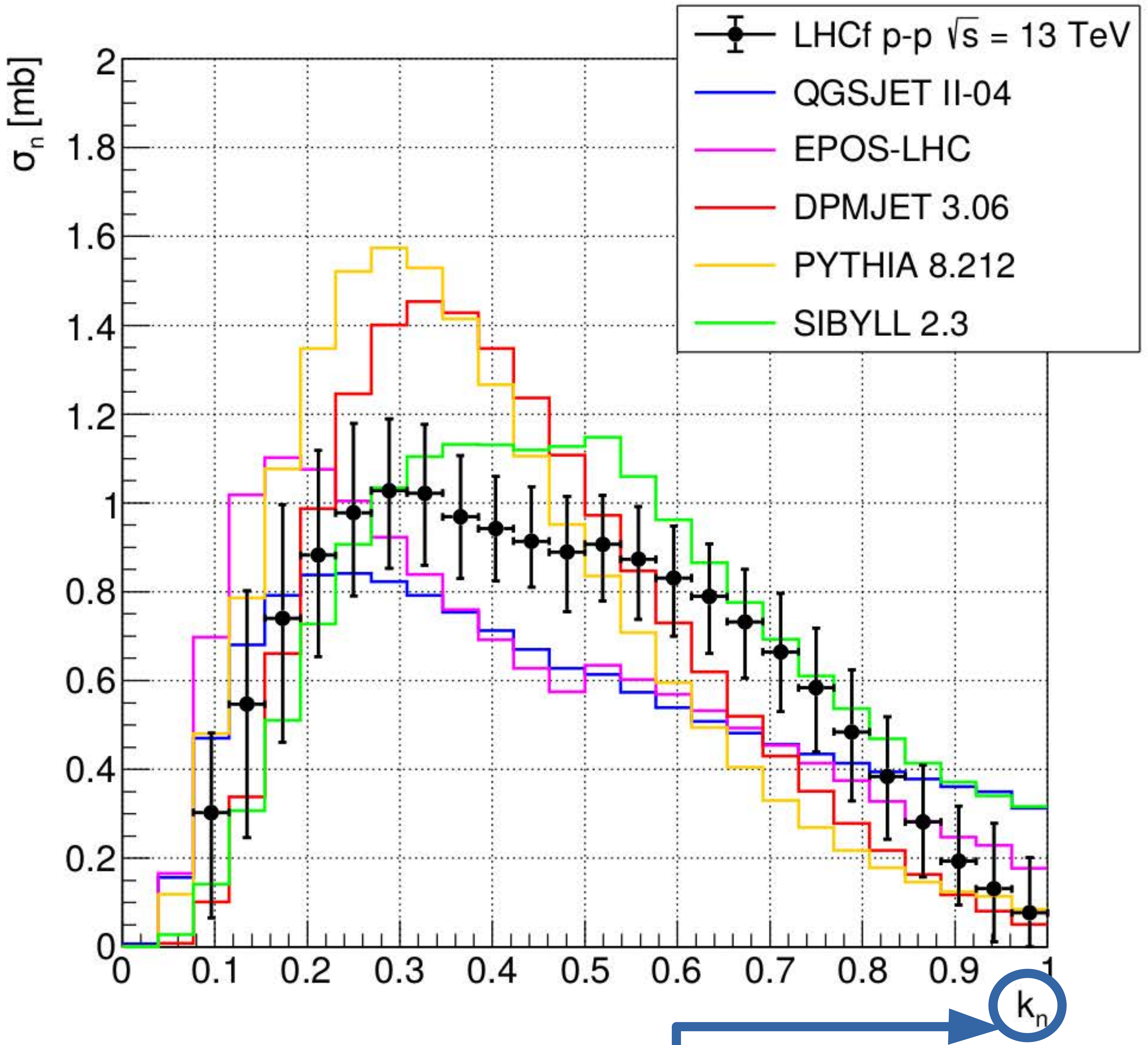
O. Adriani et al., JHEP07 (2020) 016

Inelasticity from the neutron result

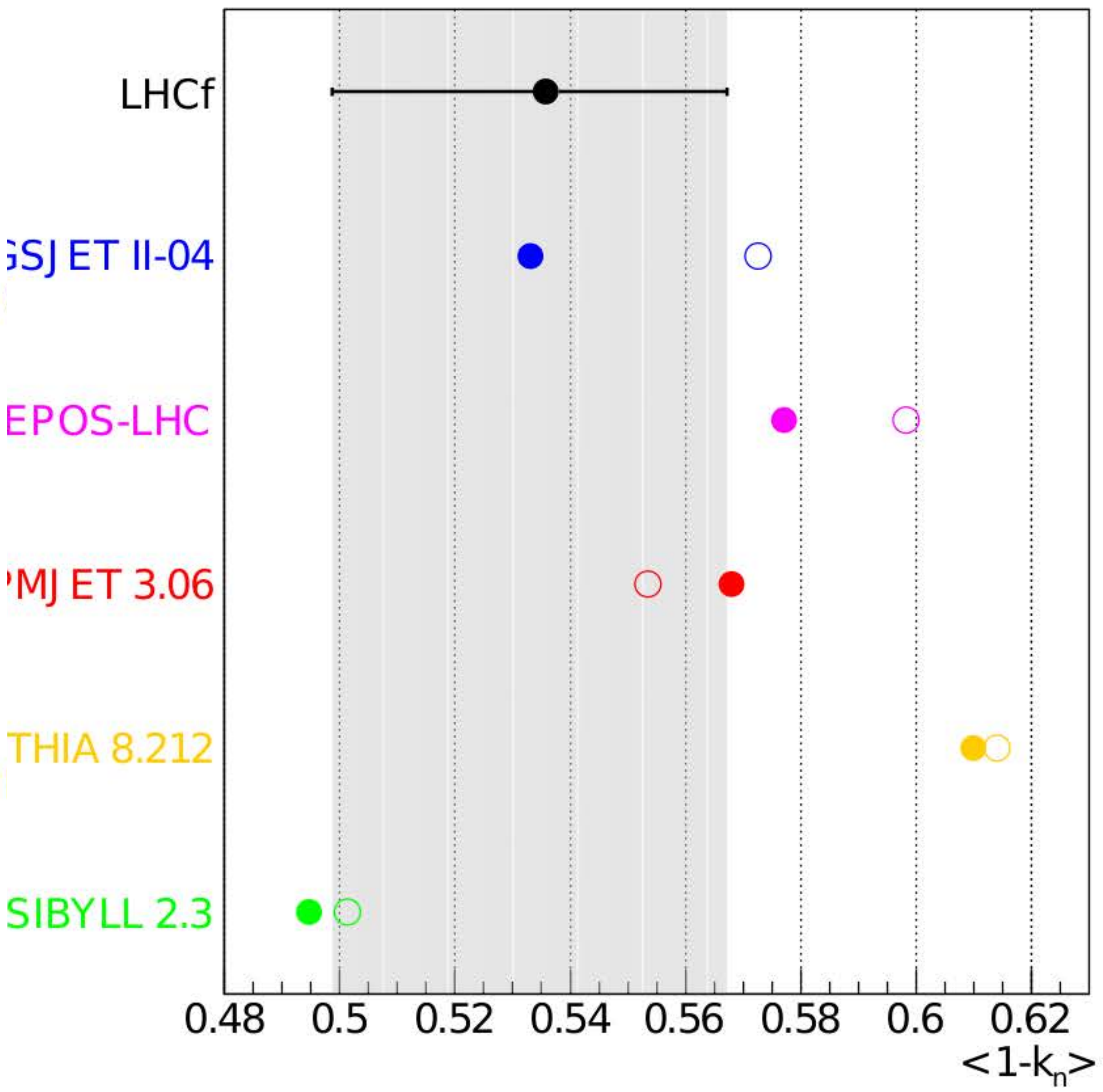
Energy flow



Elasticity distribution



<Inelasticity>



- ● neutron inelasticity
- ○ all particles inelasticity

Best agreement model

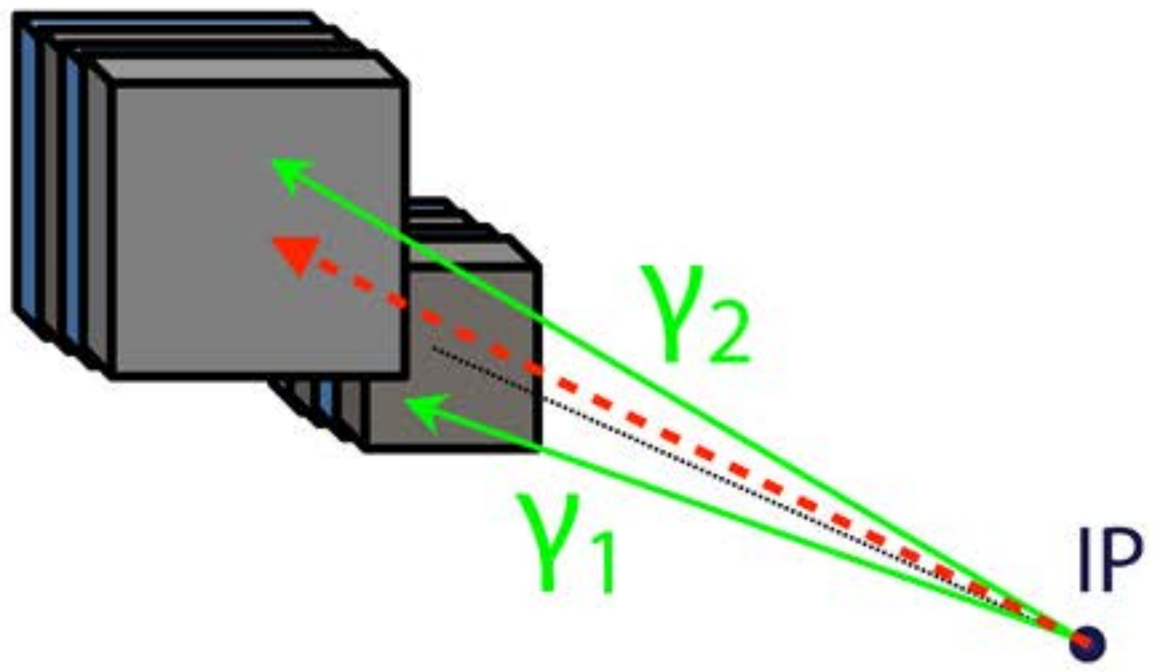
Average Inelasiticity: QGSJET II-4
Energy spectrum: EPOS, SIBYLL
Energy flow: EPOS

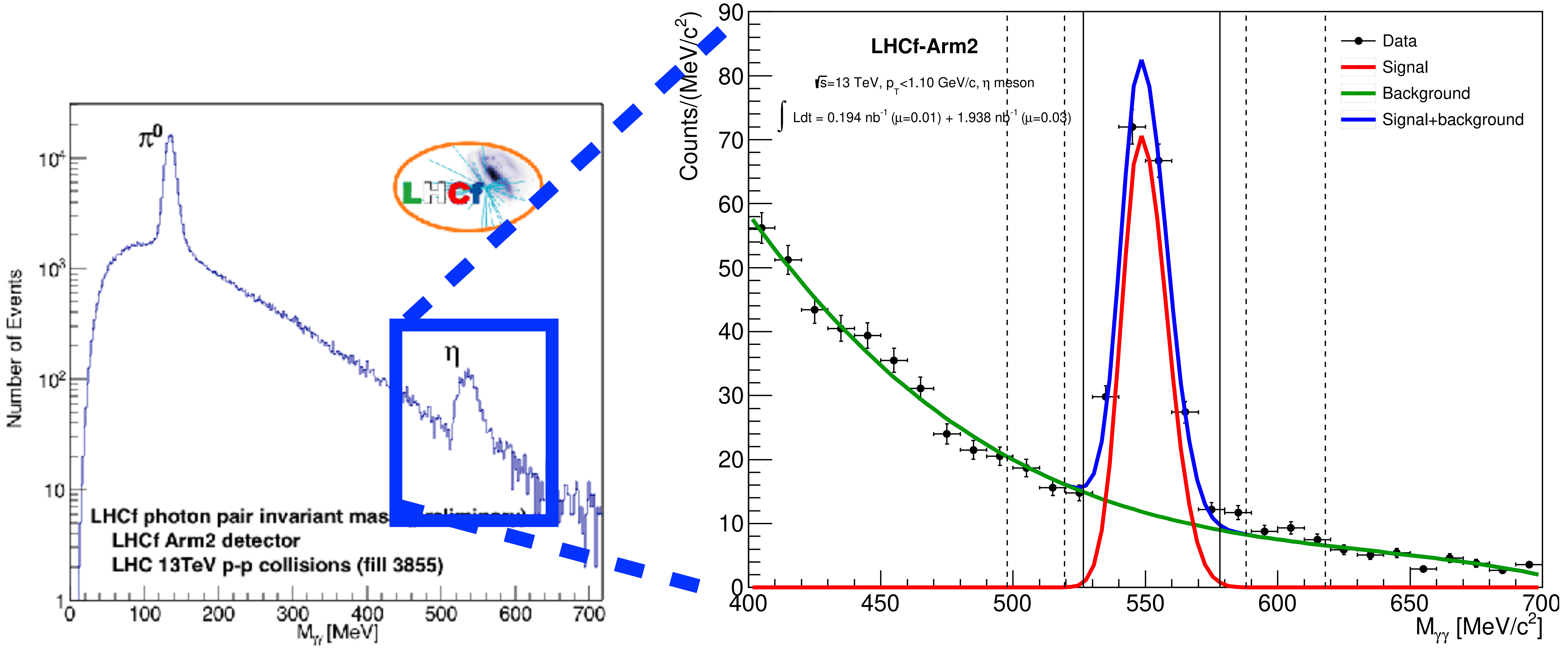
k_n ≡ elasticity in events where the leading particle is a neutron

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

η meson measurement

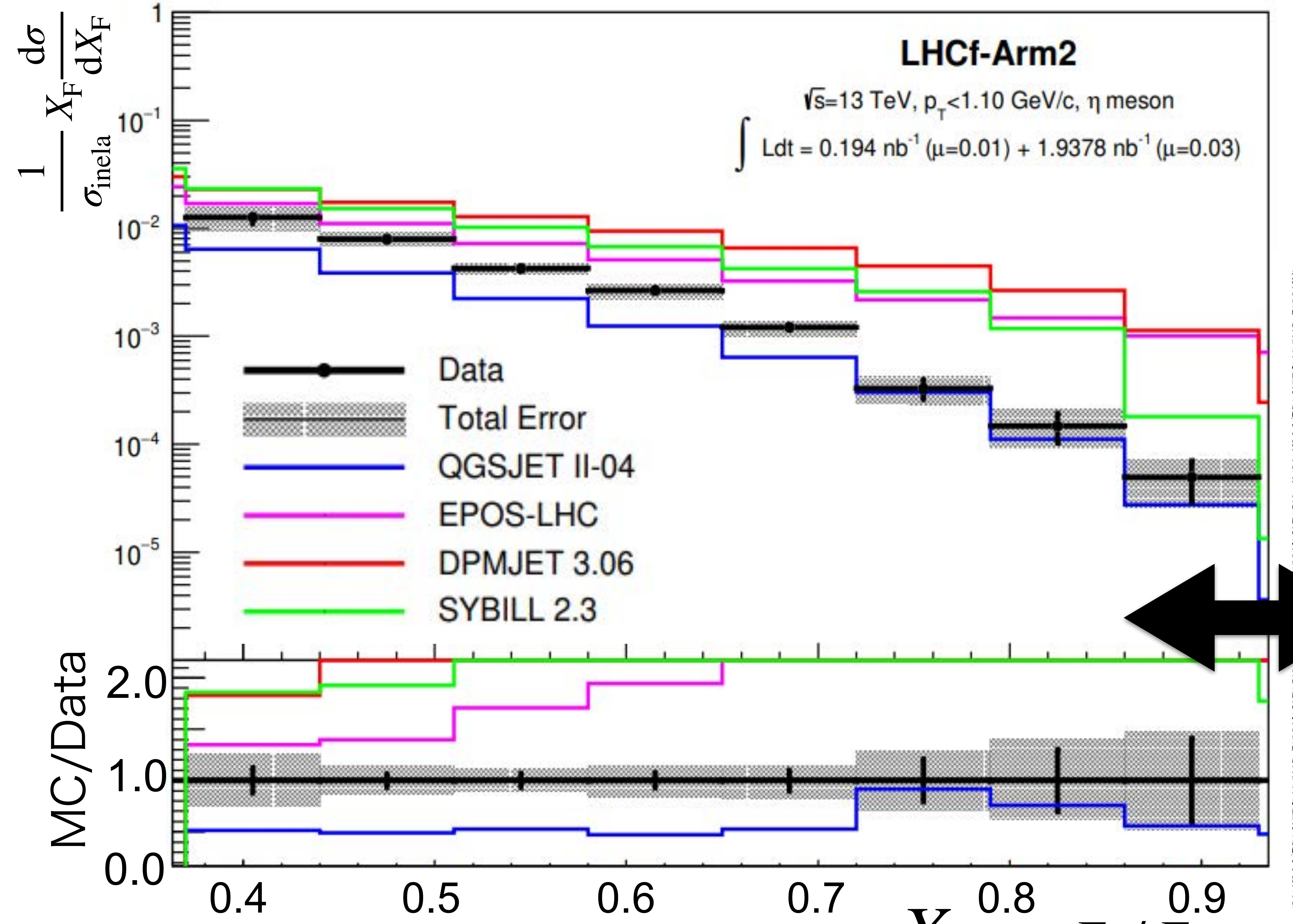
- Motivation
  - 2nd dominant source of photons (EM) in air showers.
  - Indirect probe of strange quark production.
  - Large discrepancy of predictions between models
- Data and analysis
  - pp, $\sqrt{s}$=13 TeV
  - Arm2 detector
  - Similar as Type1 π^0 analysis





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

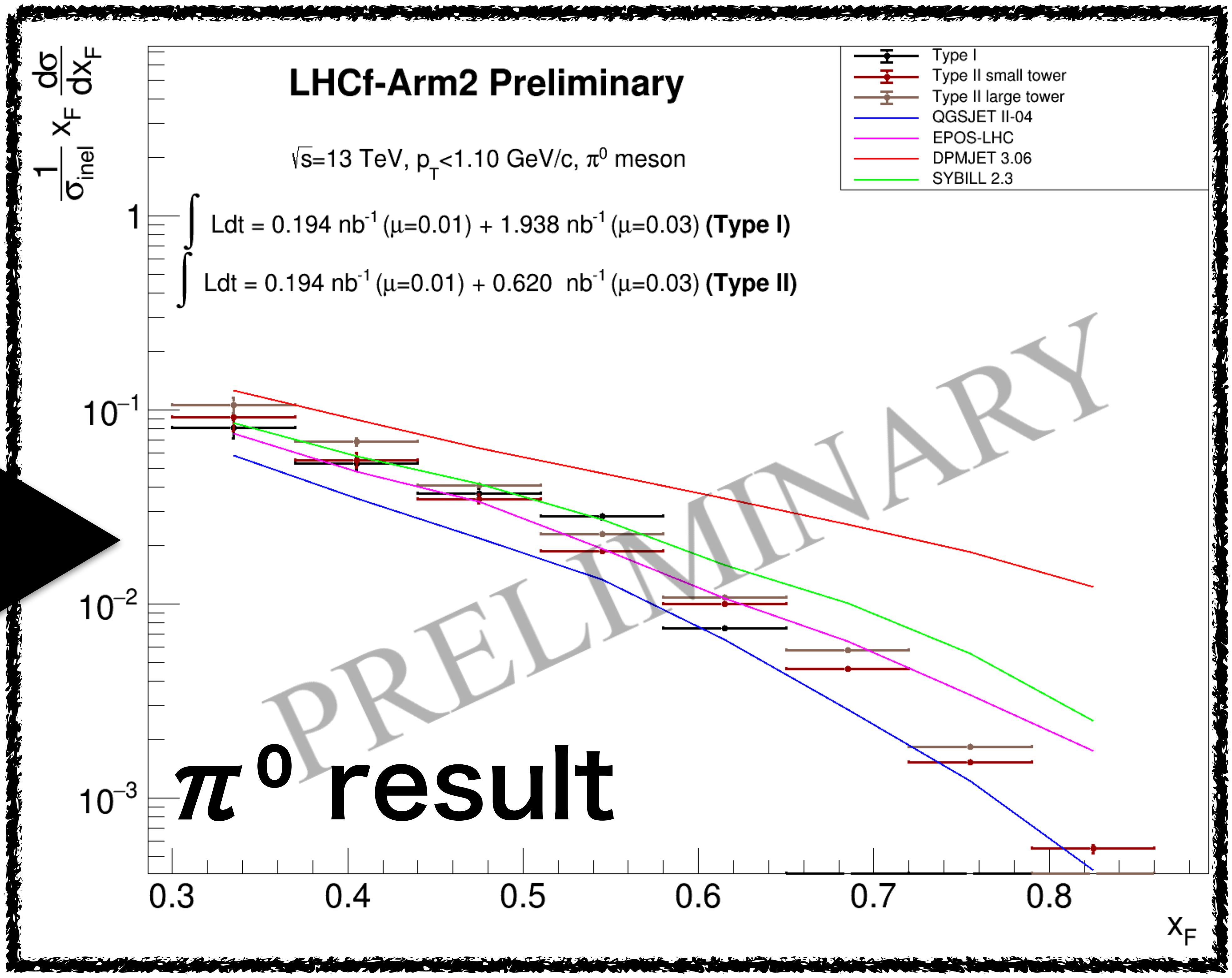
η production diff. cross-section at *pp*, √s=13 TeV



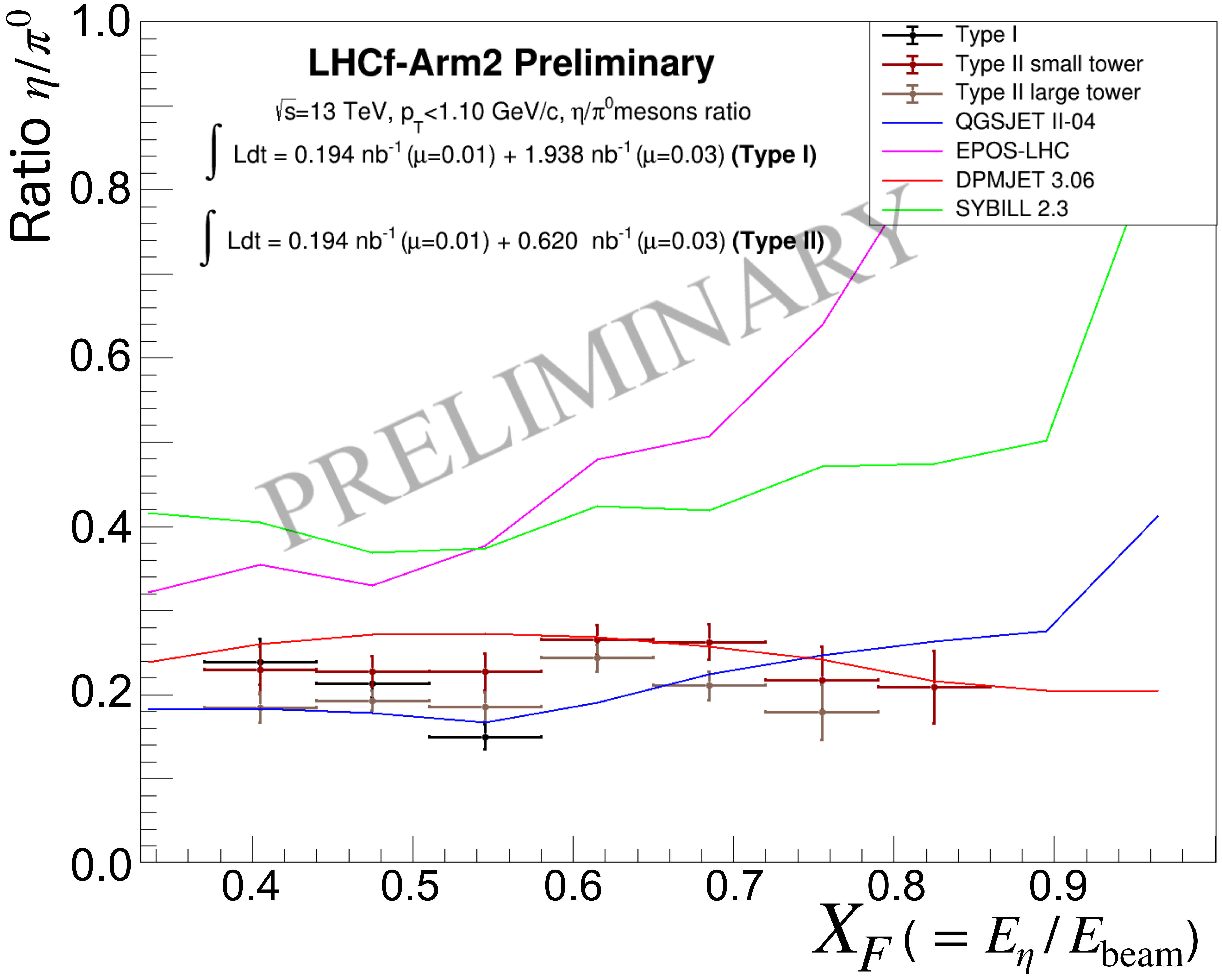
$X_F(=E_\eta/E_{\mathrm{beam}})$

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

- $p_T < 1.1\mathrm{GeV/c}$
- No model reproduce the data



η/π^0 Ratio



- Data : constant in the whole energy range

EPOS-LHC, SIBYLL2.3

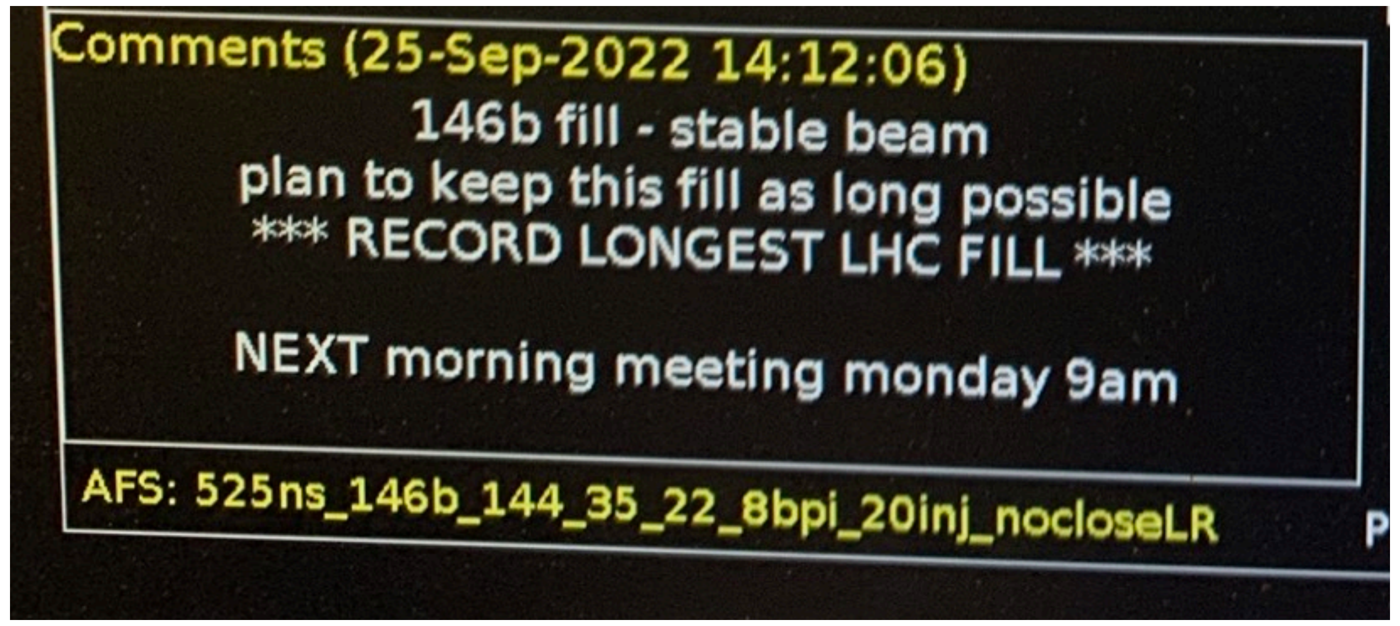
- Much larger than data
- These models cares low-mass resonance productions.
  → contribution from these decays

QGSJETII-04, DPMJET III

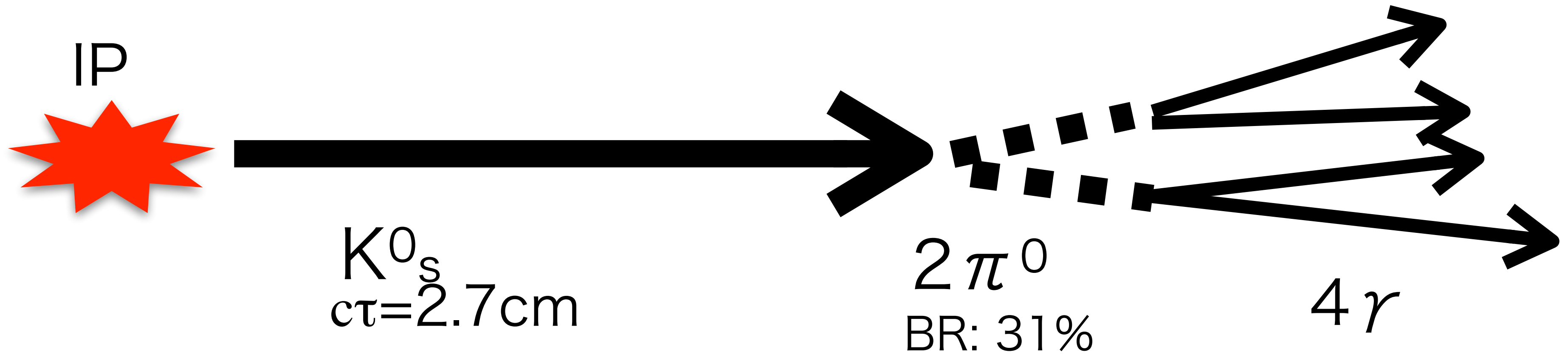
- Good agreement with data
- Less care about resonances.
  → flat ratio

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 $\mu b^{-1}/s$, 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.



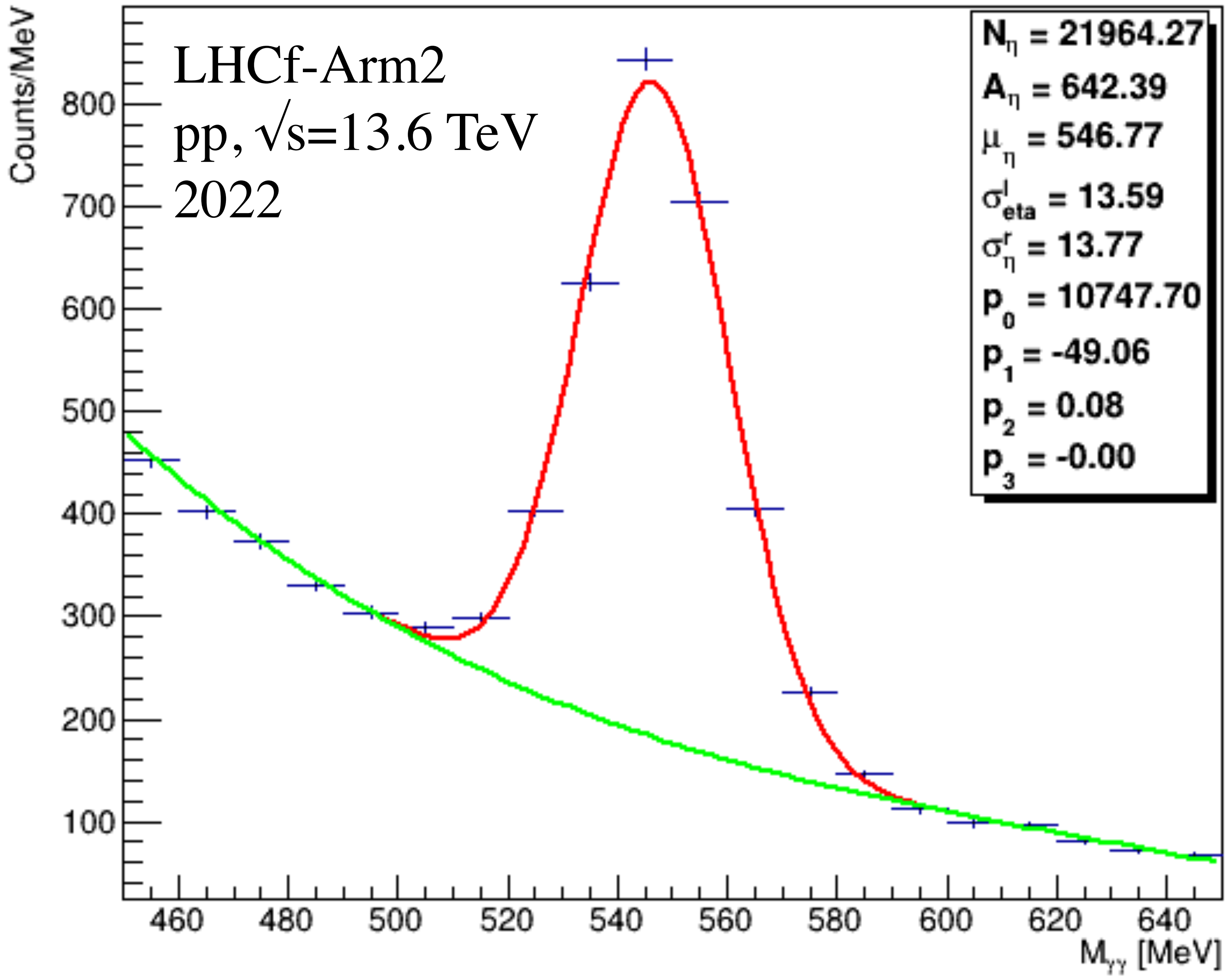
- Physics targets
  - Increase statistics of η and high-energy π^0
    η: 2 k events (2015) → 22 k events (2022) **x10**
    → cross-section measurement in X_F-p_T bins
  - Measurement of strange hadrons (K^0_S, Λ)



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

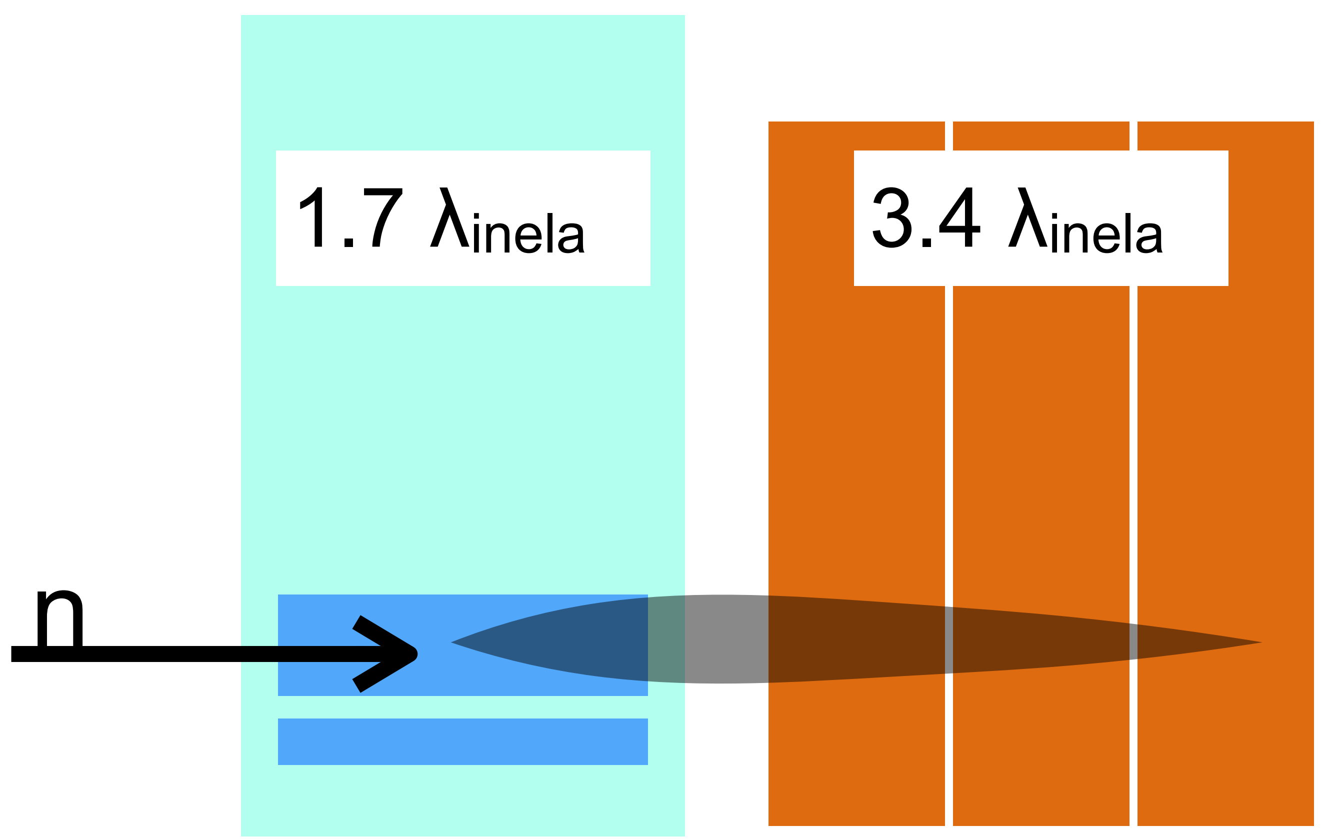
These analyses are on-going

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

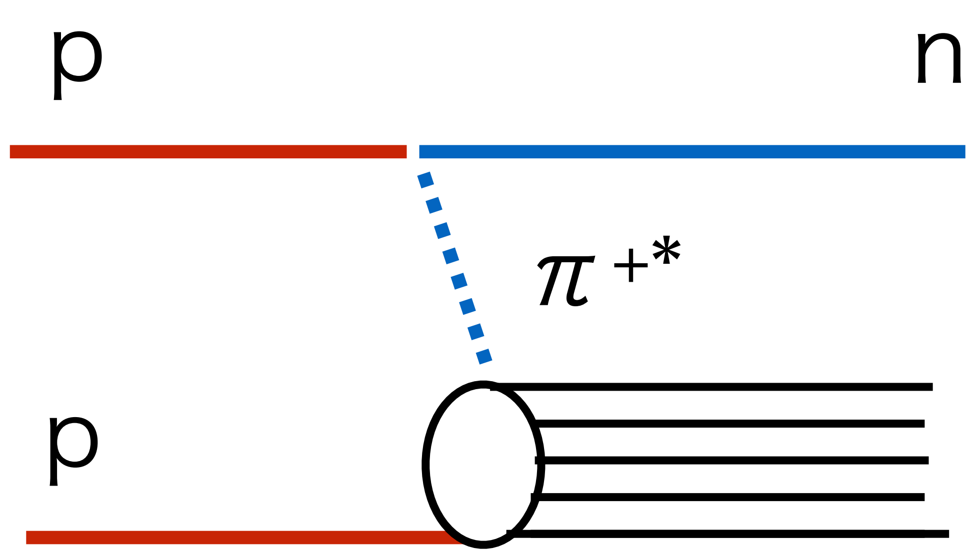


- Physics Targets
  - Detailed study of single diffractive collisions
  - Measurement of proton excitation (Δ^+)
  - Measurement of Λ ($\Lambda \rightarrow n + \pi^0$)
  - p-π interaction study using OPE processes

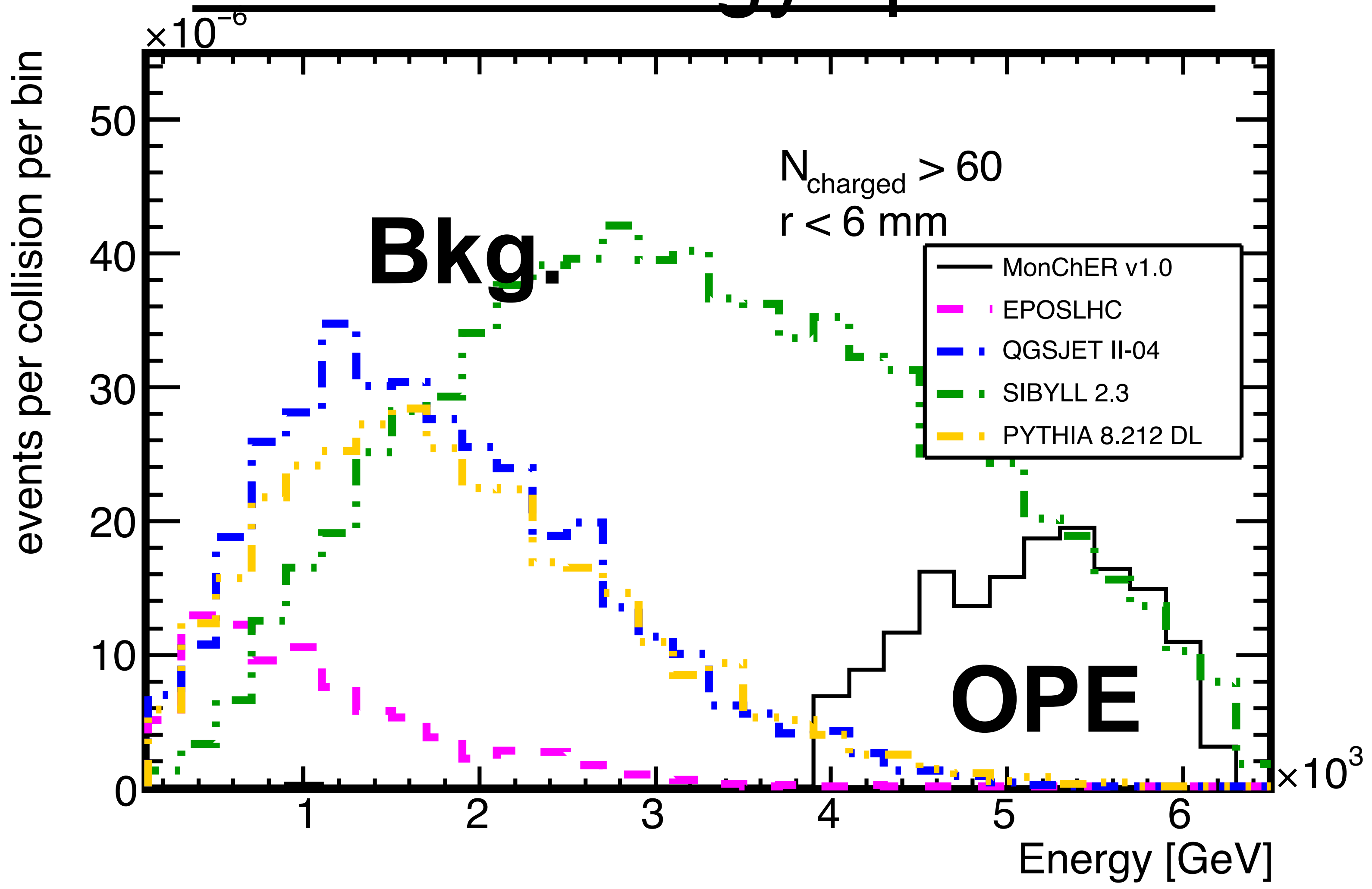
w/ RPs

w/ ZDC

One Pion Exchange (OPE)



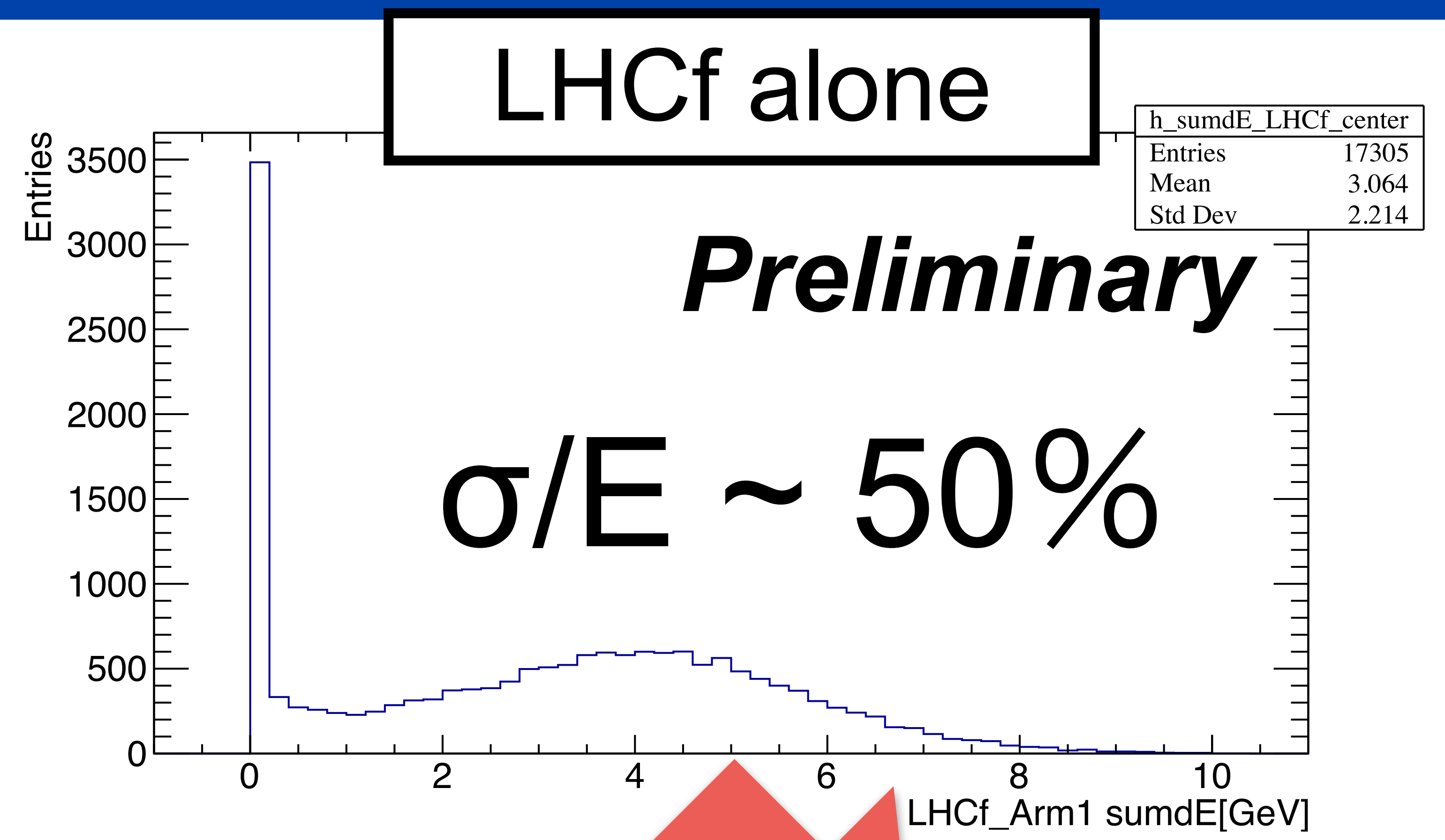
neutron energy spectrum

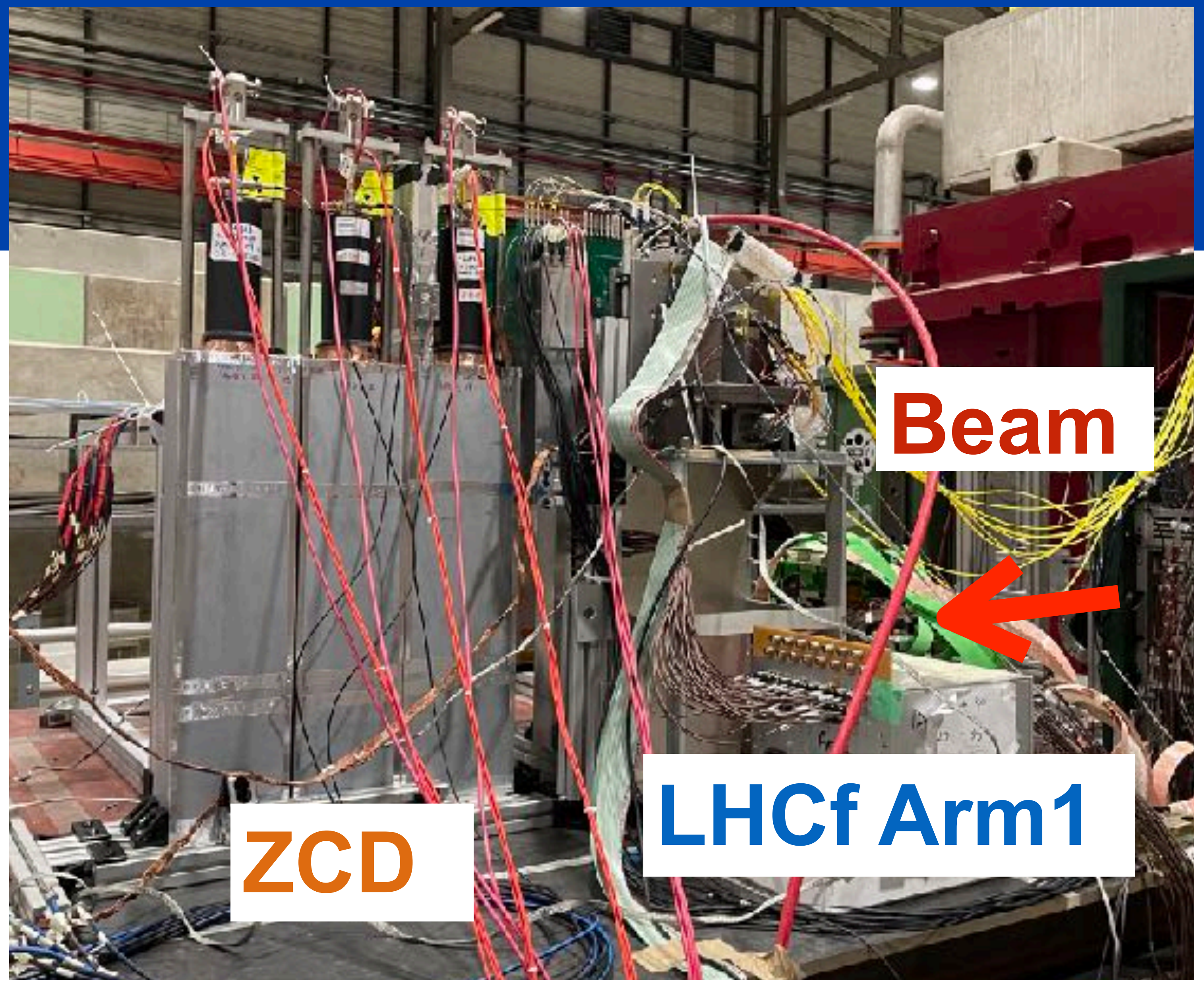


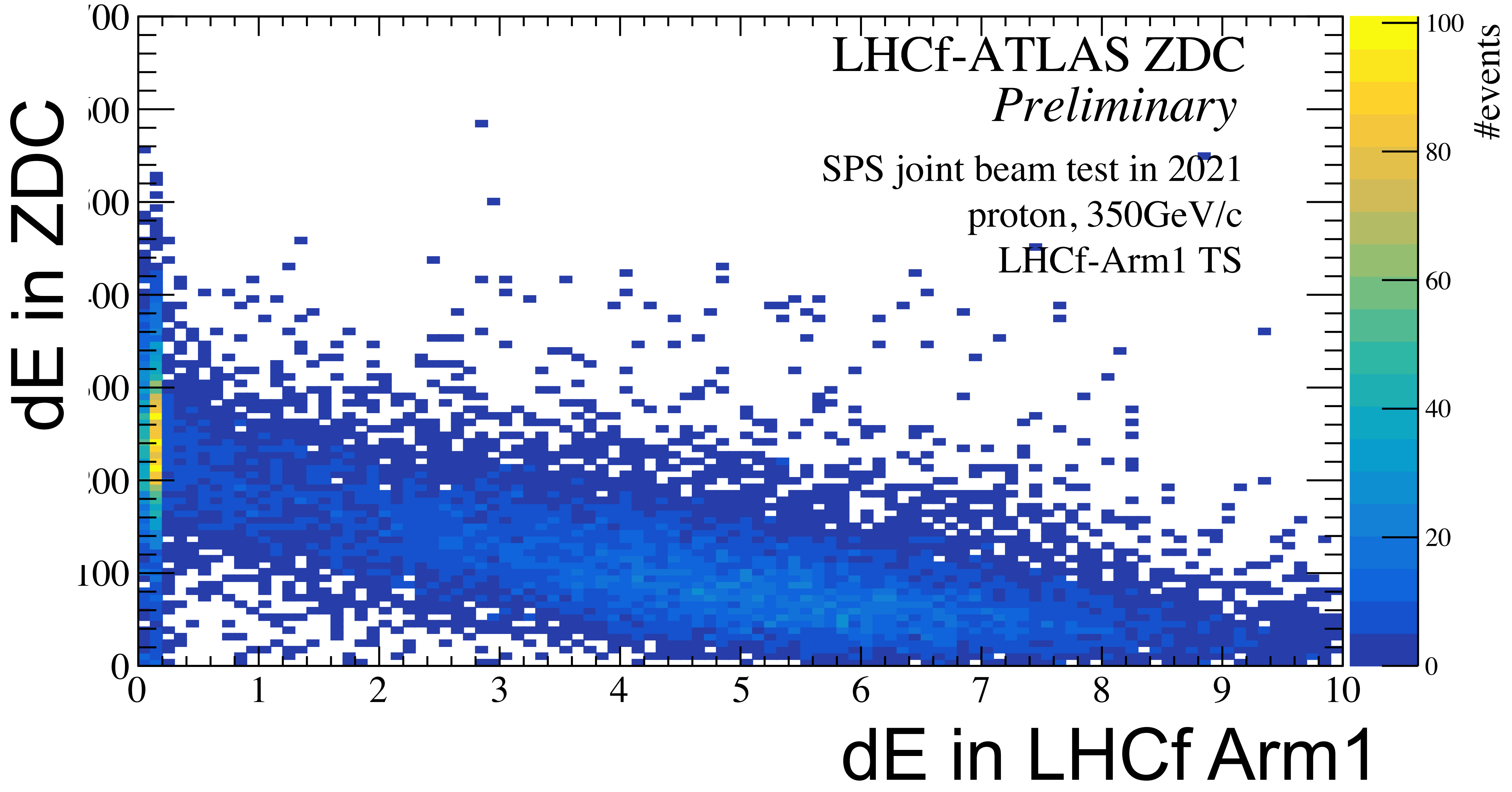
LHCf+ATLAS merged dataset is getting ready.
Start the physics analysis soon.

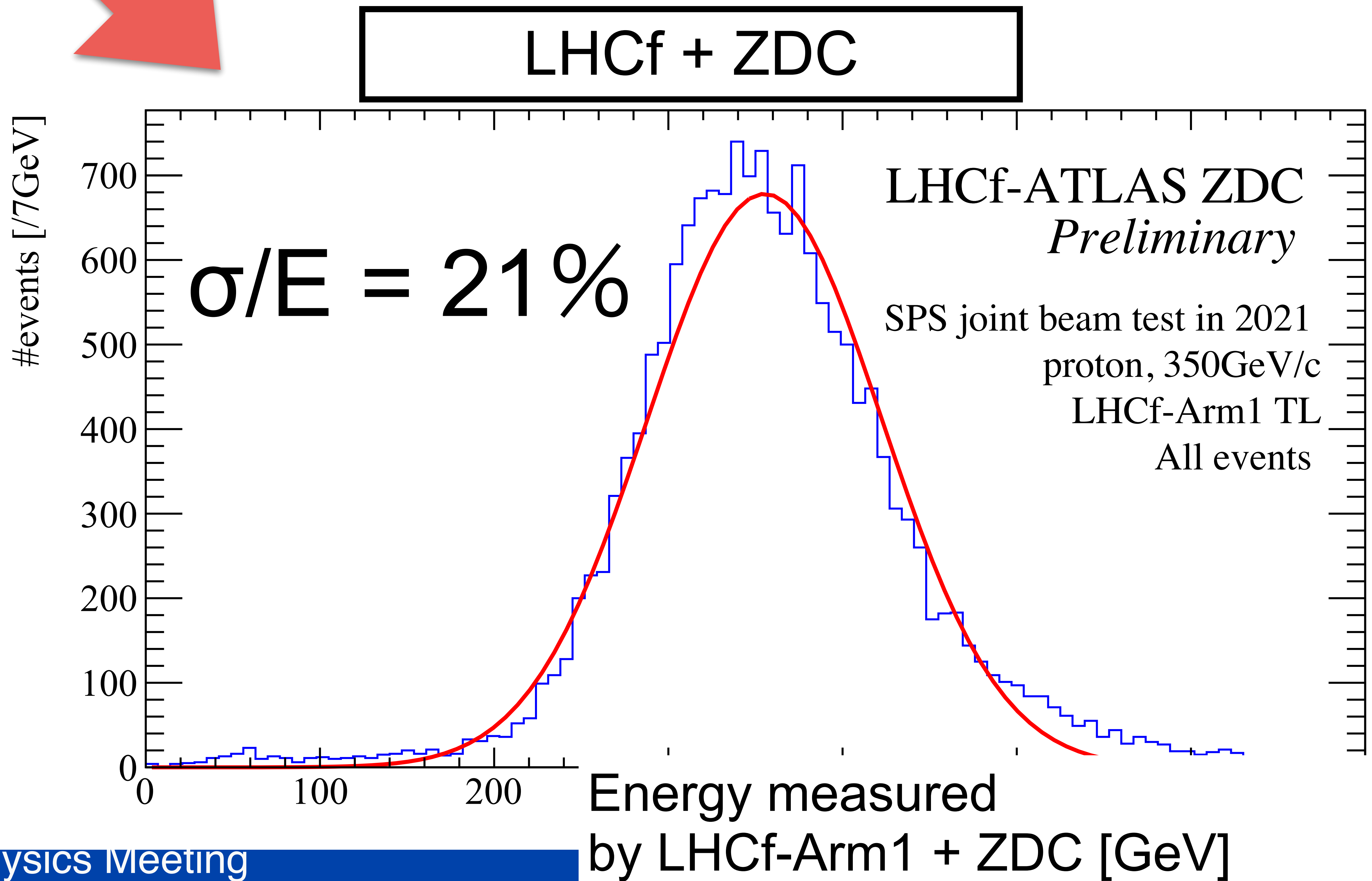
LHCf+ZDC beam test at SPS

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









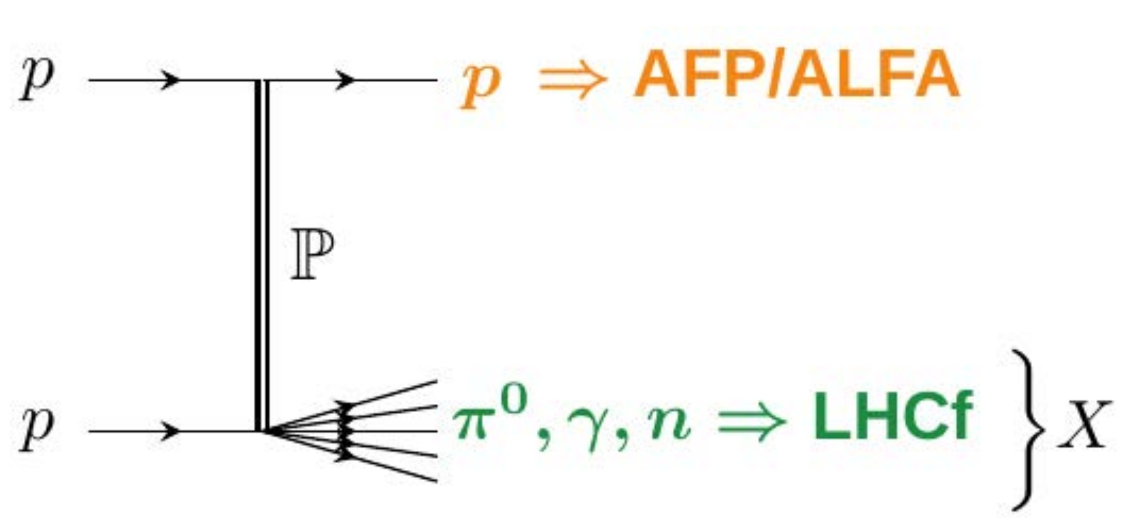
Confirmed improvement of energy resolution to 21%

Joint operation with ATLAS RPs

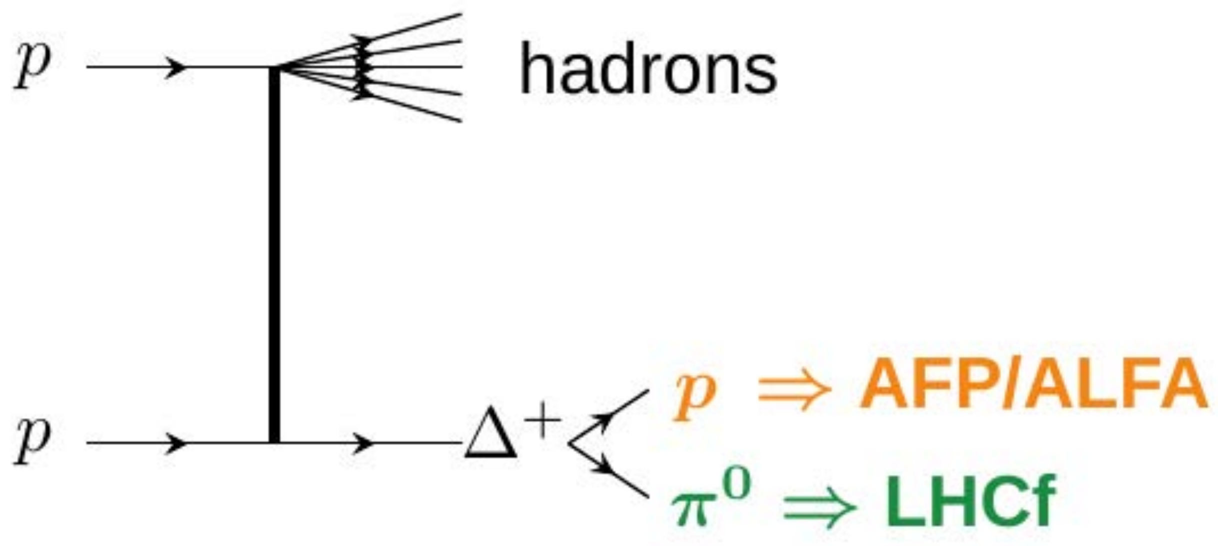
- Physics targets:
  - Detailed study of single diffractive collisions,
  - Measurement of proton excitation (very low-mass diff.)

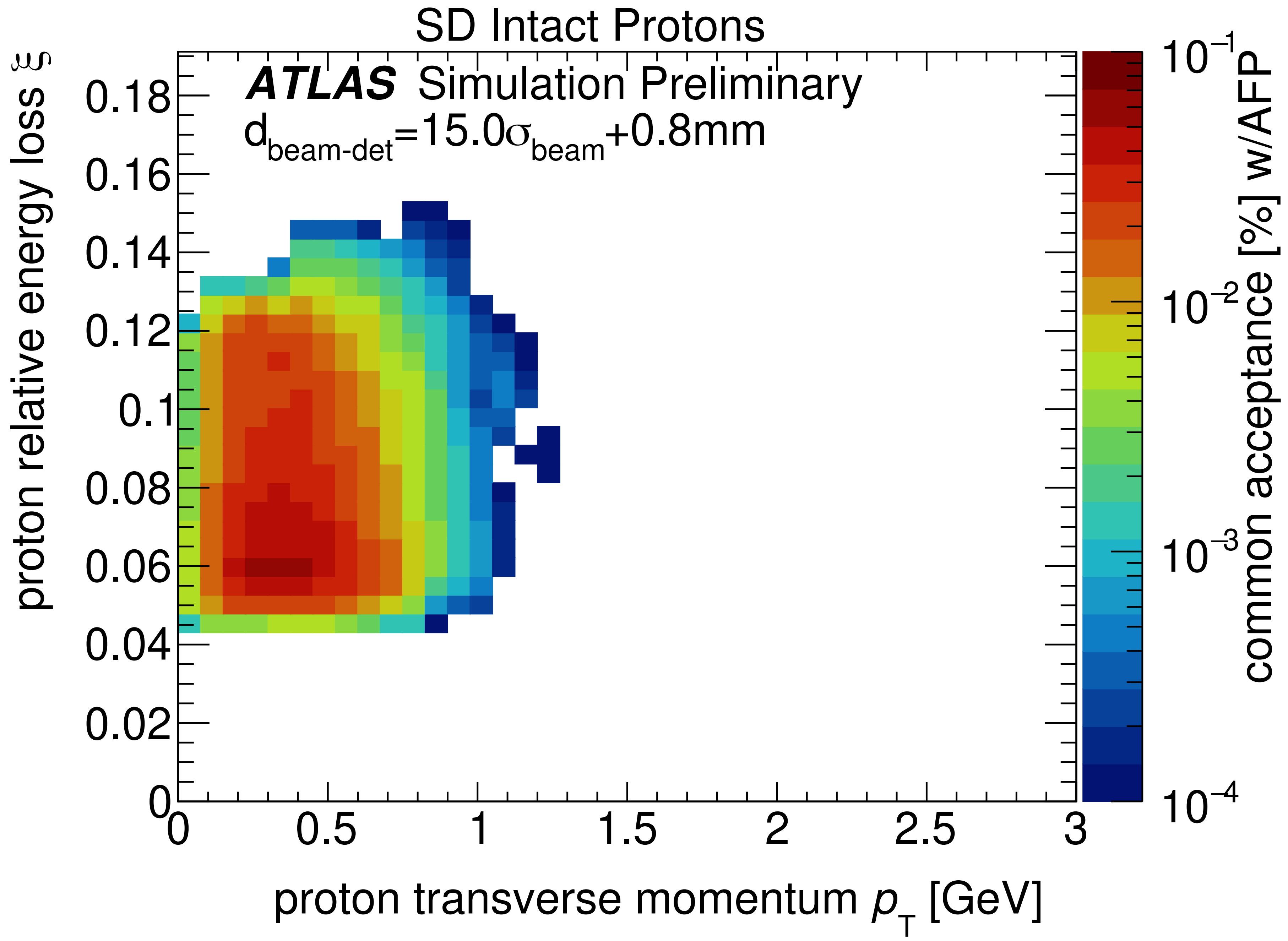
Fusibility study using MC
ATL-PHYS-PUB-2023-024

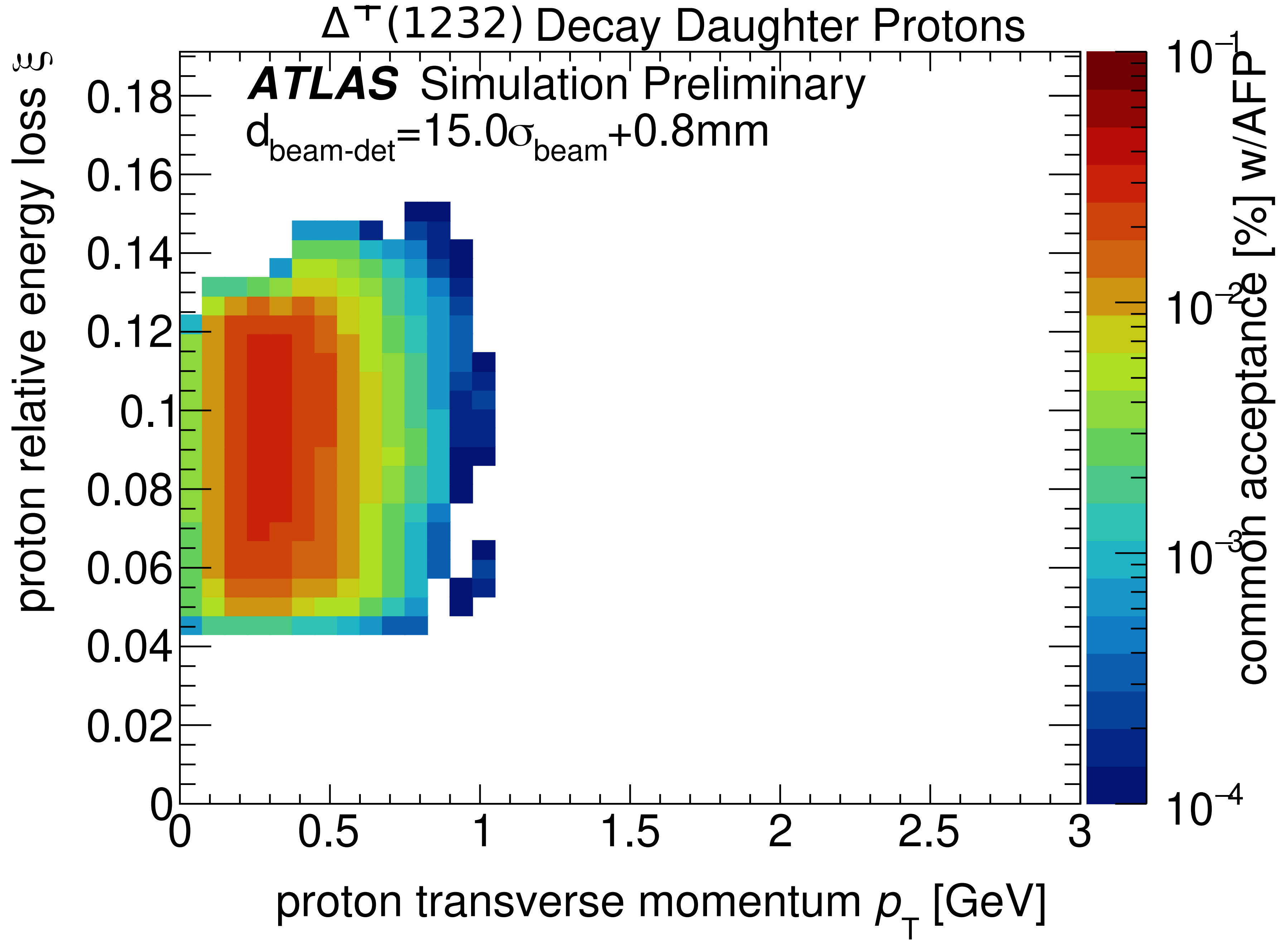
Single diffractive



Δ⁺(1232)

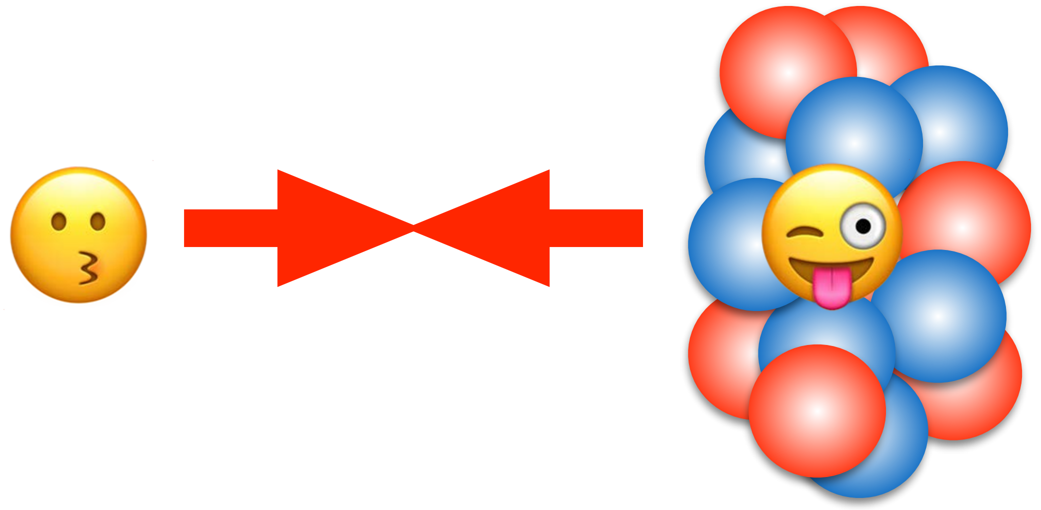




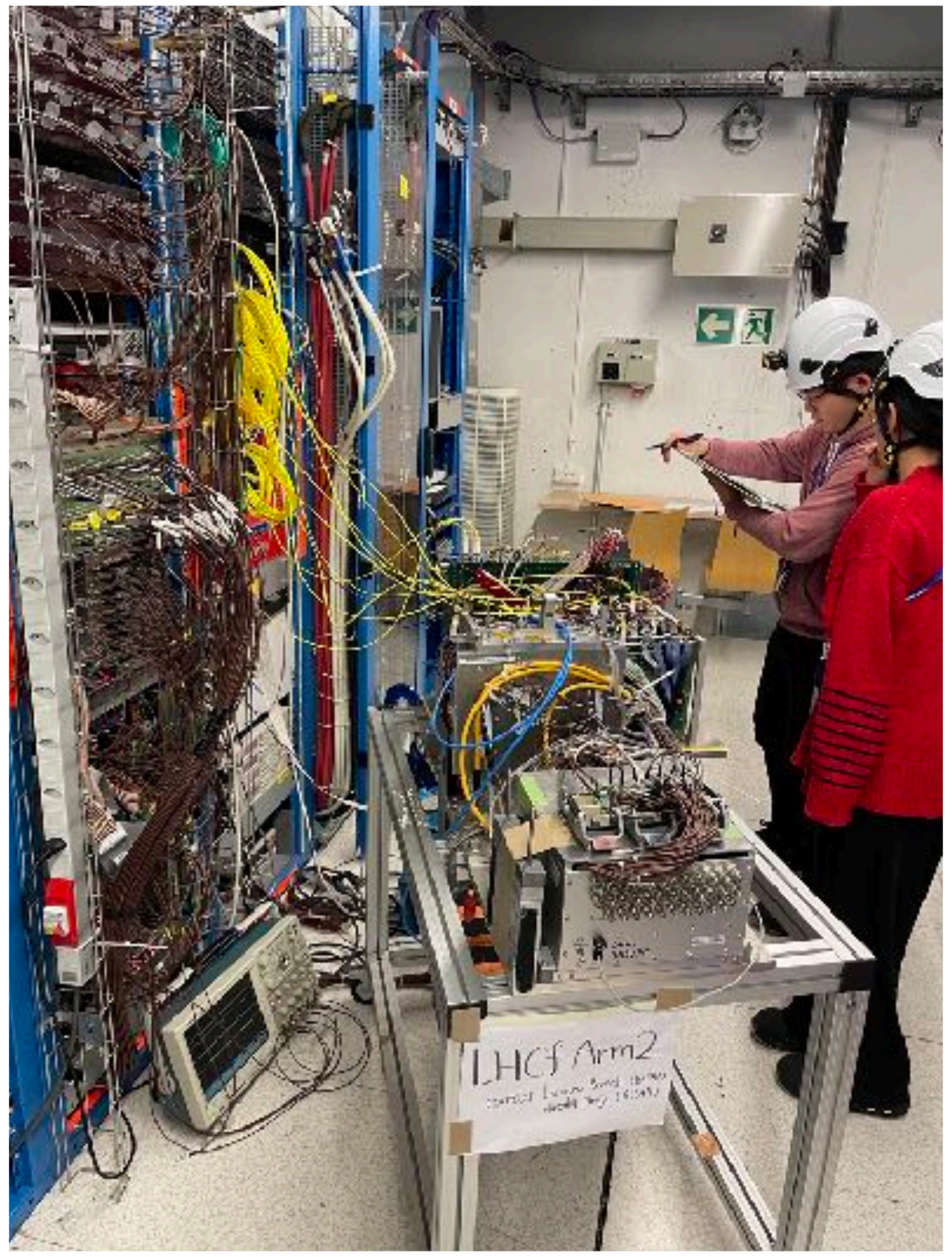


pO collisions in 2025

- Ideal for studying the cosmic-ray interactions of CR-Air
  - Long story for requesting this p-light ion collisions at LHC.
  - Run3 is a last opportunity of LHCf operations
    - Due to change of the TAN structure in Run4, LHCf detectors cannot fit the slot anymore.
      (the experimental slot width :10 cm -> 5 cm)



- Oxygen run in 2025
  - Currently the special run is scheduled for 1 week just after TS1 in 2025.
  - LHCf Arm2 will be installed in the proton-remnant side of pO.
    The detector will be removed before OO (replaced with ATLAS ZDC-EM)
- Preparation status
  - Setup work of the DAQ system was completed in Jan-Feb.
  - Improving the DAQ speed to maximize the statistics.
  - A commissioning with ATLAS is planed during the next YETS.



Summary

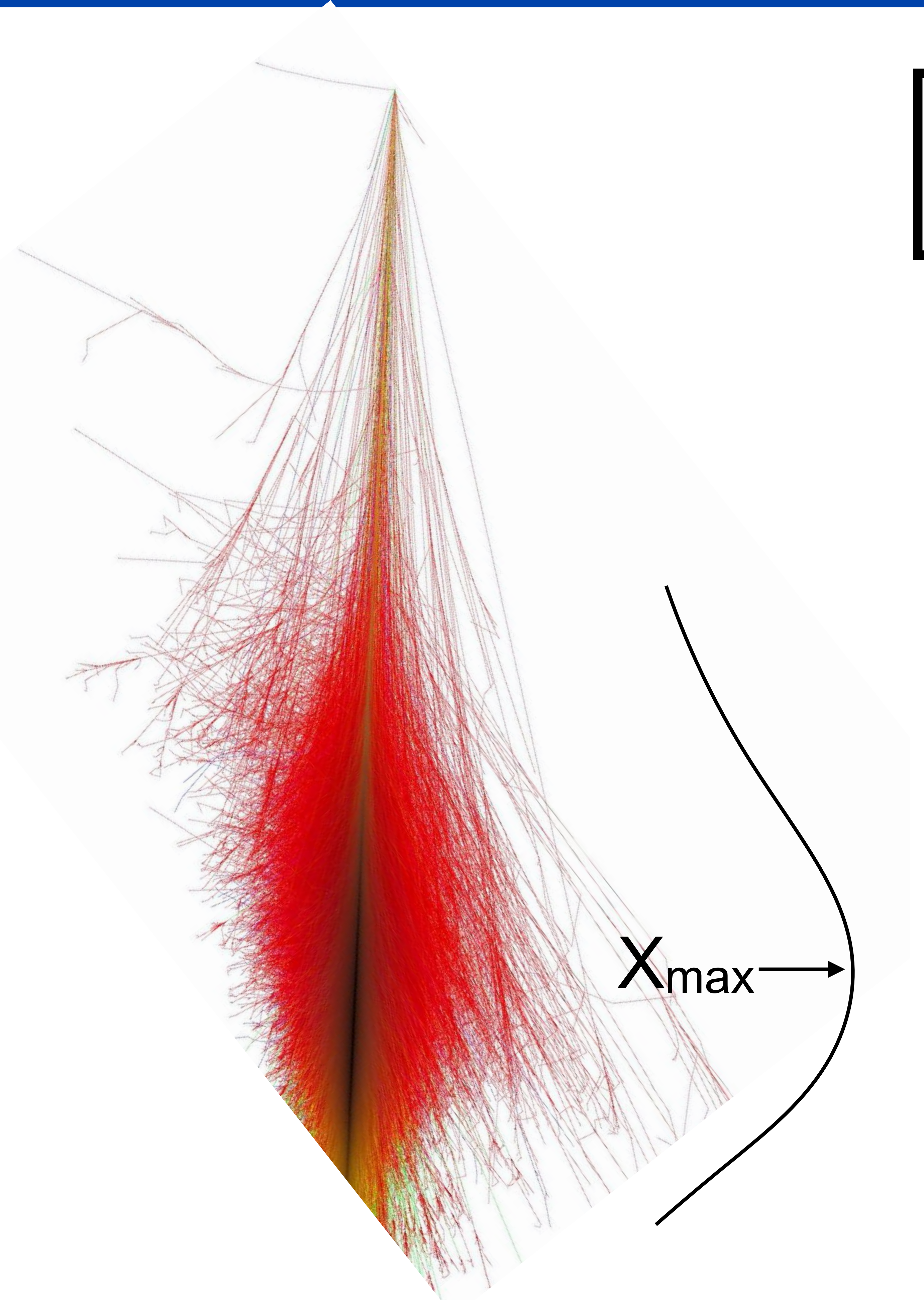
- LHCf measures the very forward neutral particles, which are motivated for cosmic ray physics.
- Presented results from Run 2 data
  - Updated neutron results → inelasticity measurement.
  - η meson diff. cross-section
- Many analyses are on-going
  - η, π^0 with high statistics data, K^0_s measurement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

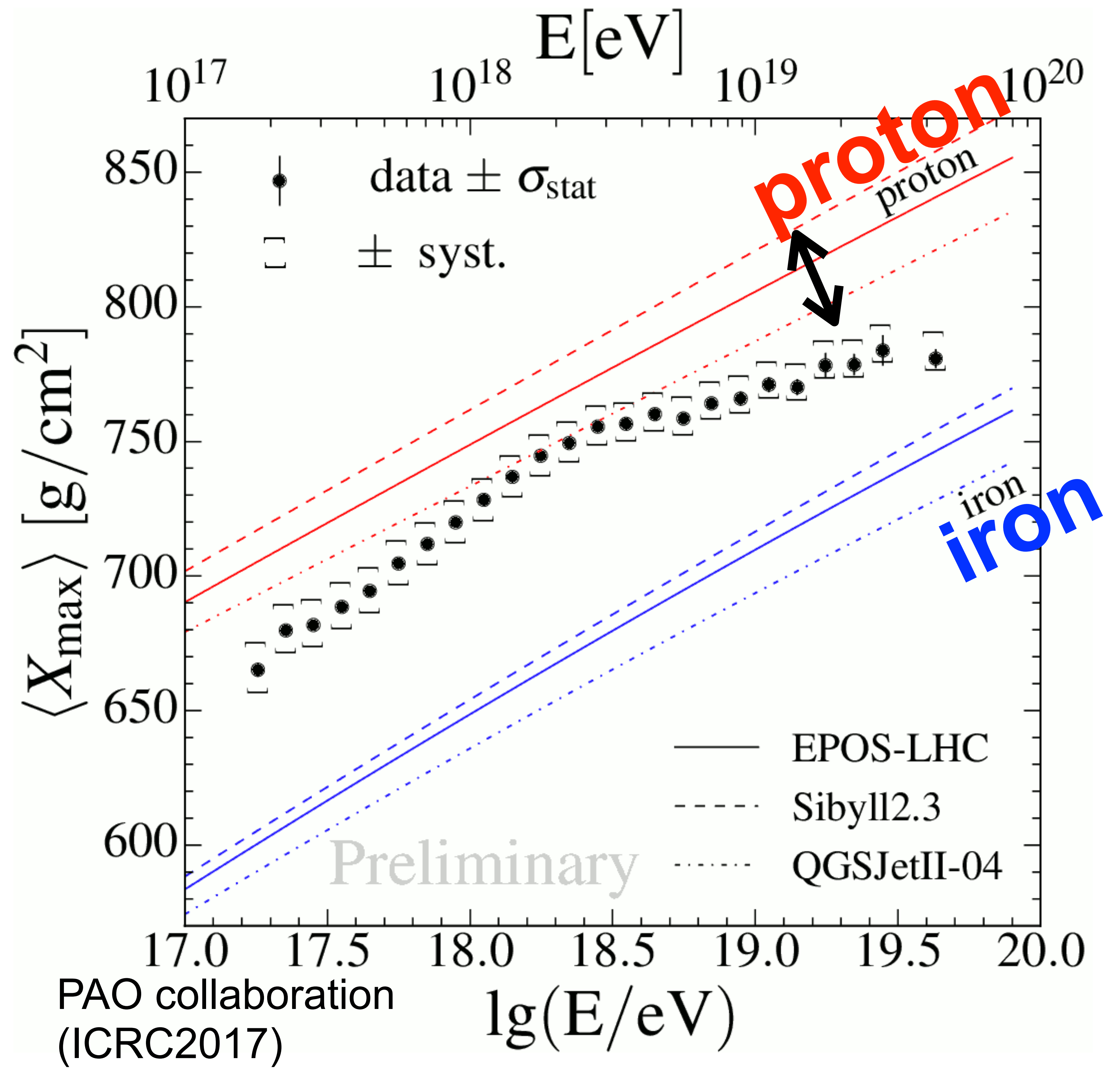
Backup

Estimators of Mass Composition



N^{μ}: Number of muons on the ground

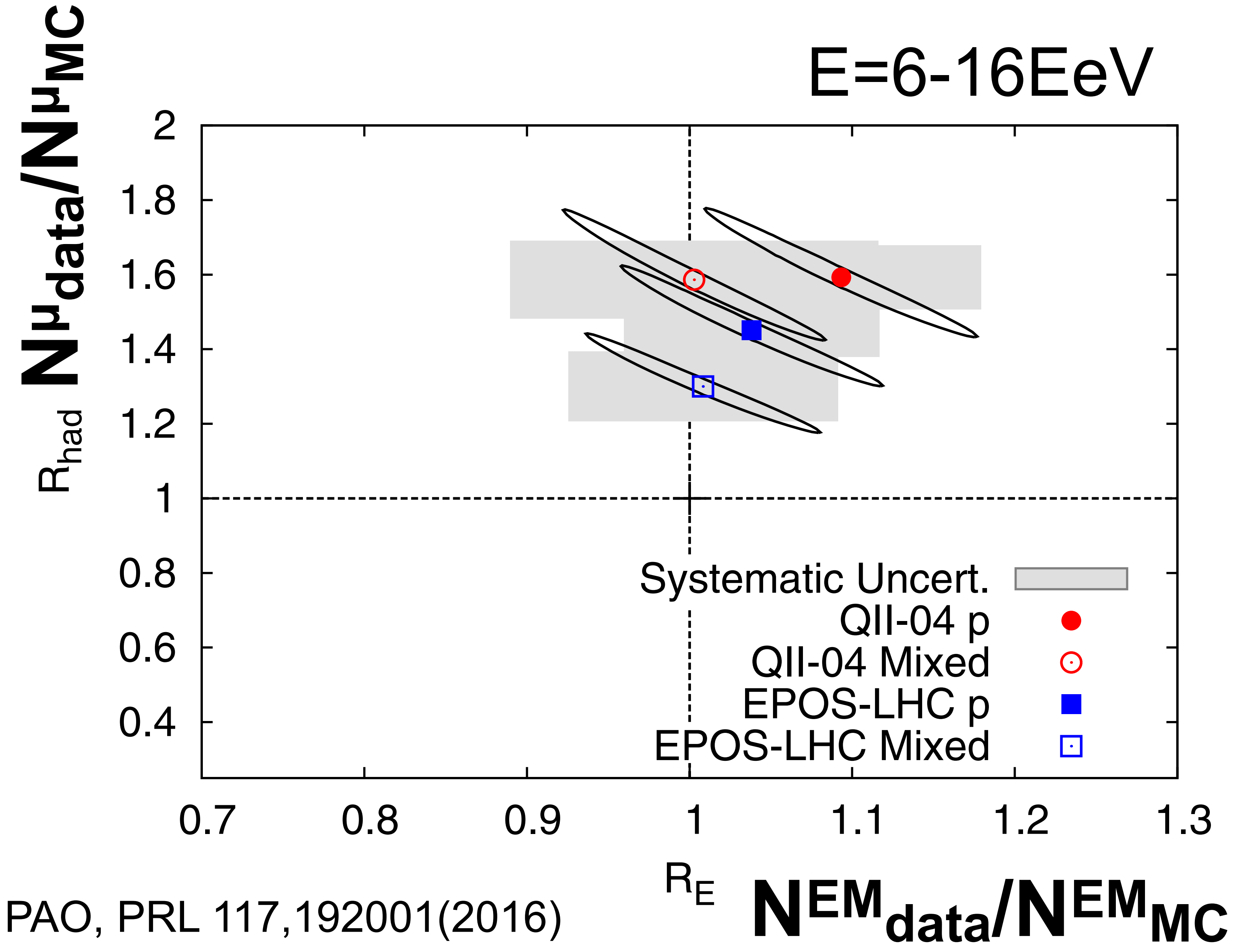
Large model dependency of UHECR composition measurement



PAO collaboration (ICRC2017)

Interaction model uncertainty > Experimental uncertainty

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



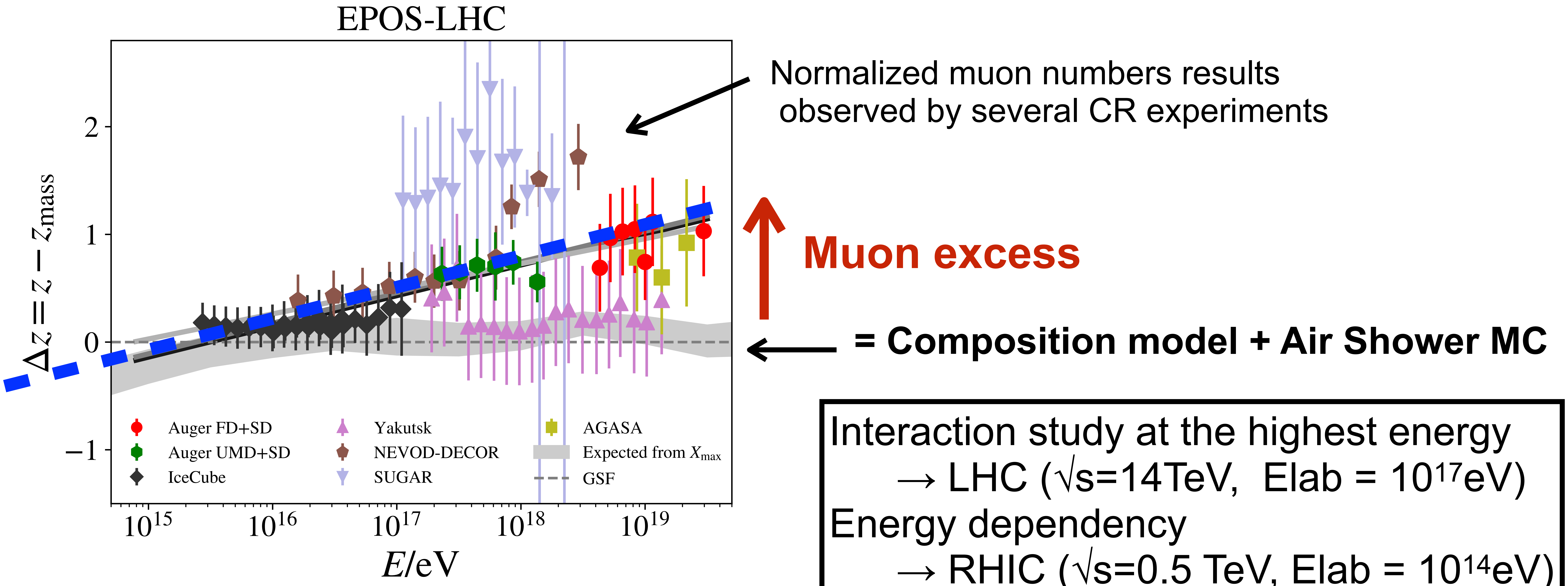
PAO, PRL 117,192001(2016)

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

Several ideas to solve it

- Strange particles
- Vector meson productions
- QGP

Energy dependency of muon excess



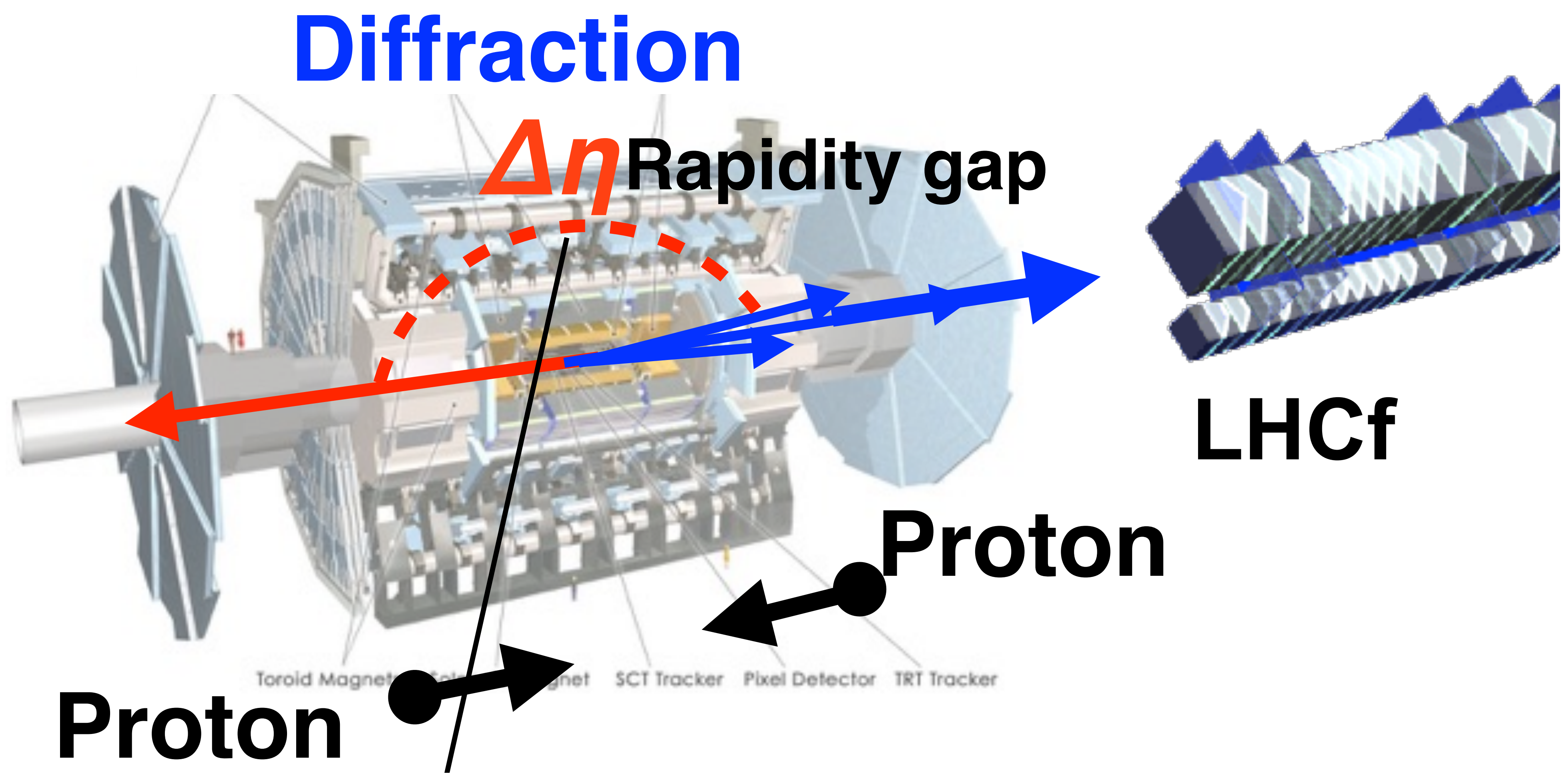
Interaction study at the highest energy
→ LHC ($\sqrt{s}$=14TeV, Elab = 10^{17}eV)
Energy dependency
→ RHIC ($\sqrt{s}$=0.5 TeV, Elab = 10^{14}eV)
v.s. LHC

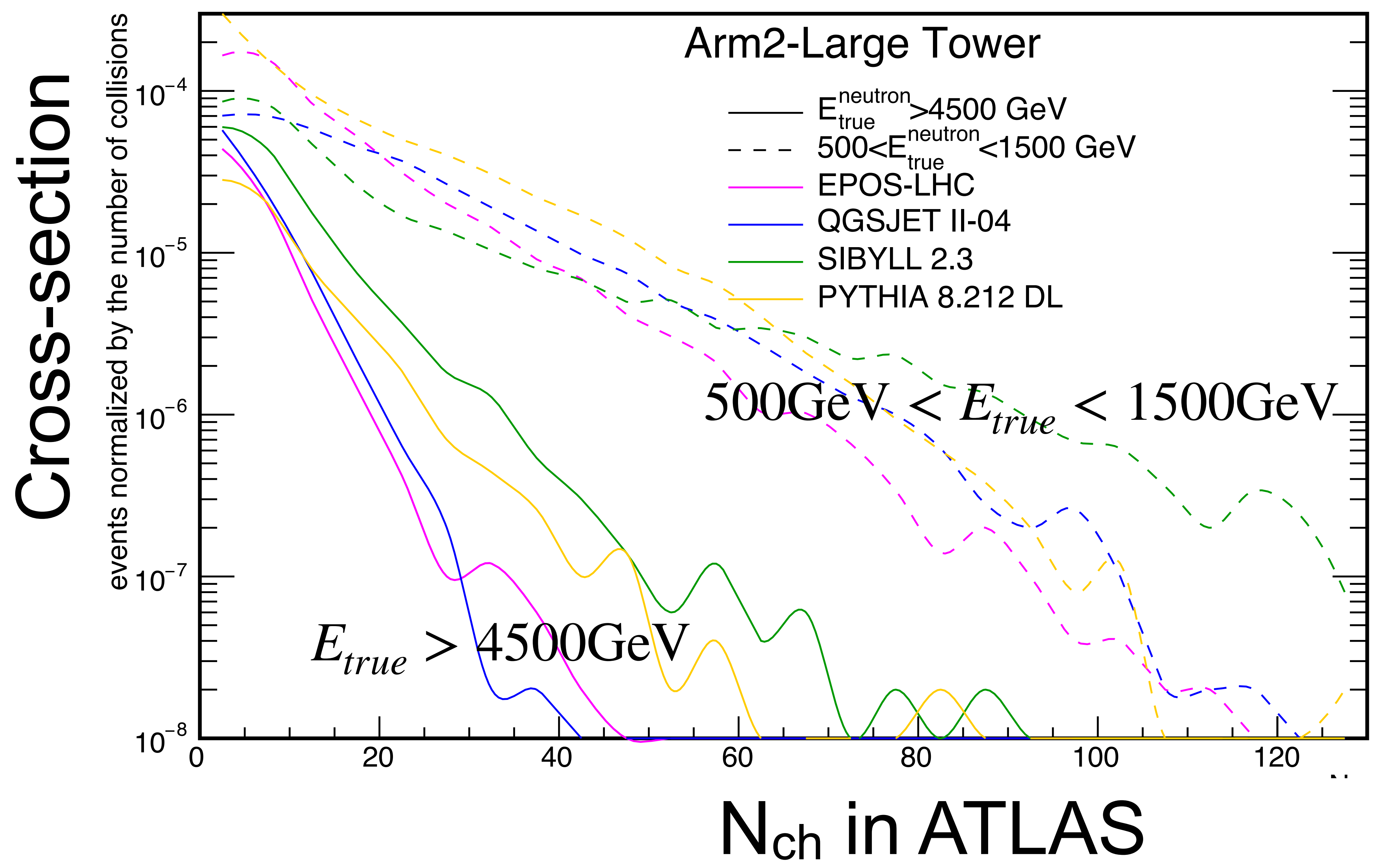
$$z = \frac{\ln(N_\mu{}^{\mathrm{det}}) - \ln(N_{\mu_p}{}^{\mathrm{det}})}{\ln(N_{\mu_{\mathrm{Fe}}}{}^{\mathrm{det}}) - \ln(N_{\mu_p}{}^{\mathrm{det}})}$$

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

- Line model with slope fitted to $\Delta z = z - z_{\mathrm{mass}}$
- Correction to $\chi^2/n_{\mathrm{dof}} = 1$ 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

On-going Joint analyses with ATLAS



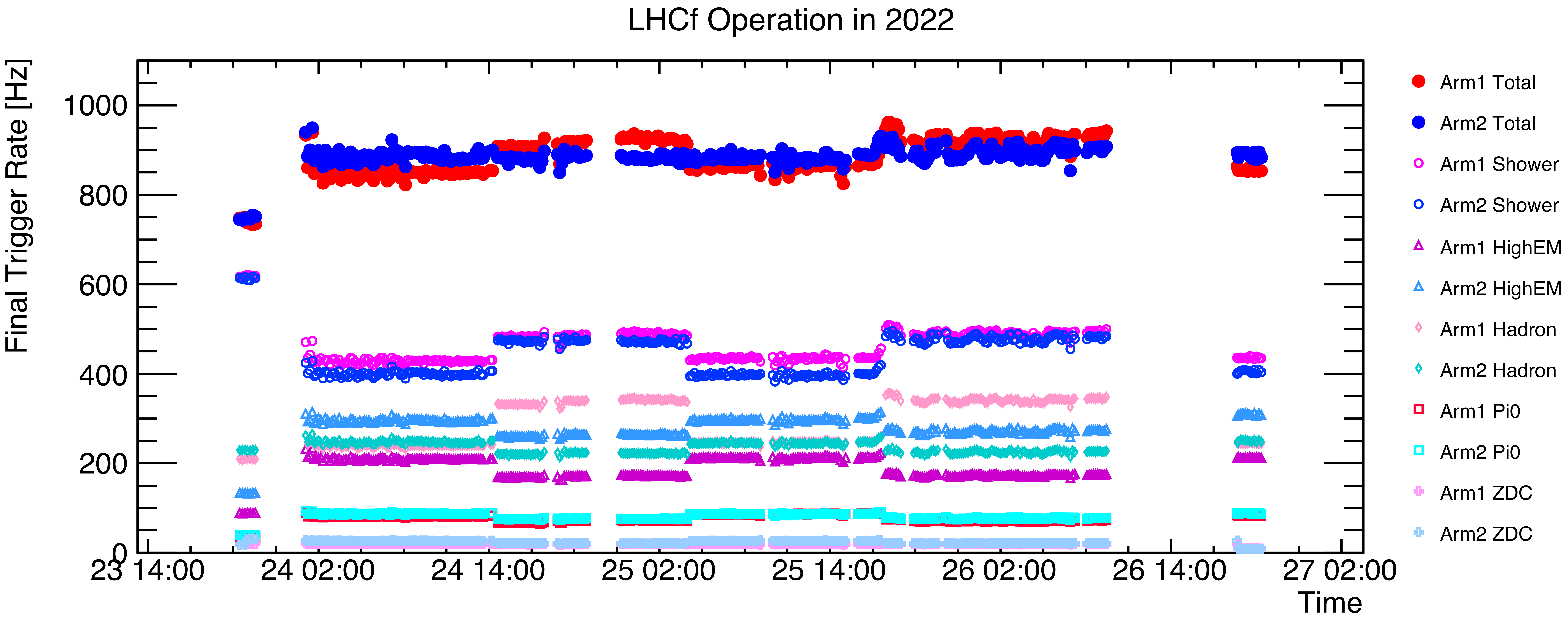


- Study of diffractive collisions
  - Photon spectra with N_{ch}=0 in ATLAS (p_T>0.1GeV, $|\eta| < 2.5$)
- Study of MPI
  - Correlation between forward neutron and N_{ch} in ATLAS

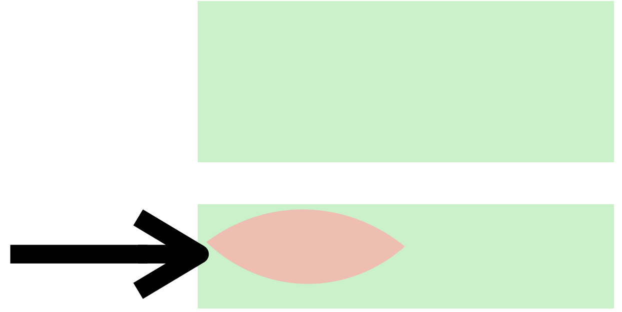
Superposition of single API: MPI ↗ Forward neutron energy ↘

Kinematic overlap : MPI ↗ Forward neutron energy →

6 Trigger modes



Shower Trg.



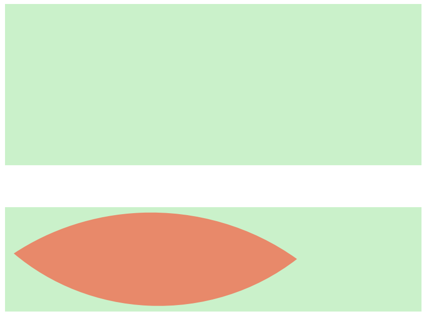
Baseline trigger
Any showers

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

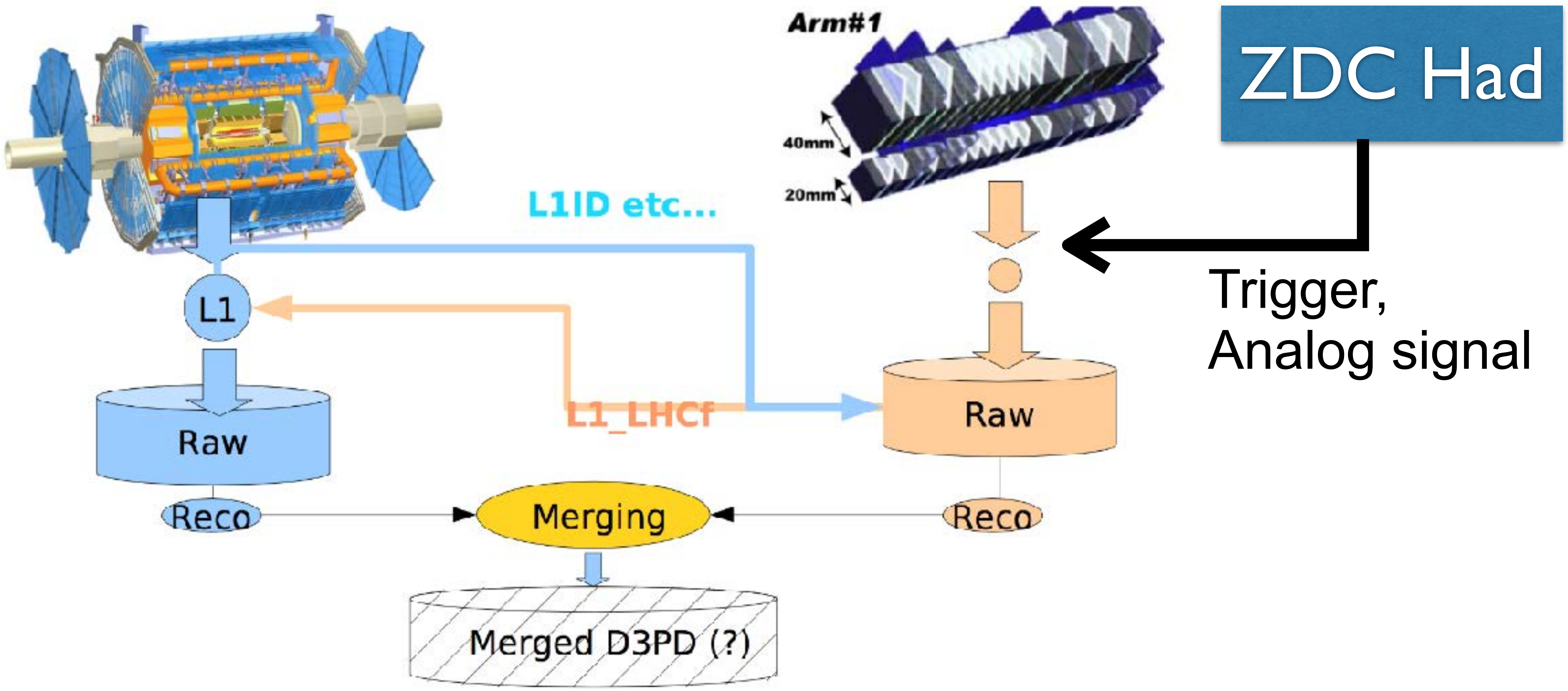
Pedestal Trg.

= 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

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)