LHCf: Very forward measurement at LHC

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on behalf of LHCf collaboration

Institute for
Space-Earth Environmental Research

2nd International workshop on Forward Physics and
Forward Calorimeter Upgrade in ALICE,
Tukuba Univ., 13-15 Mar 2023

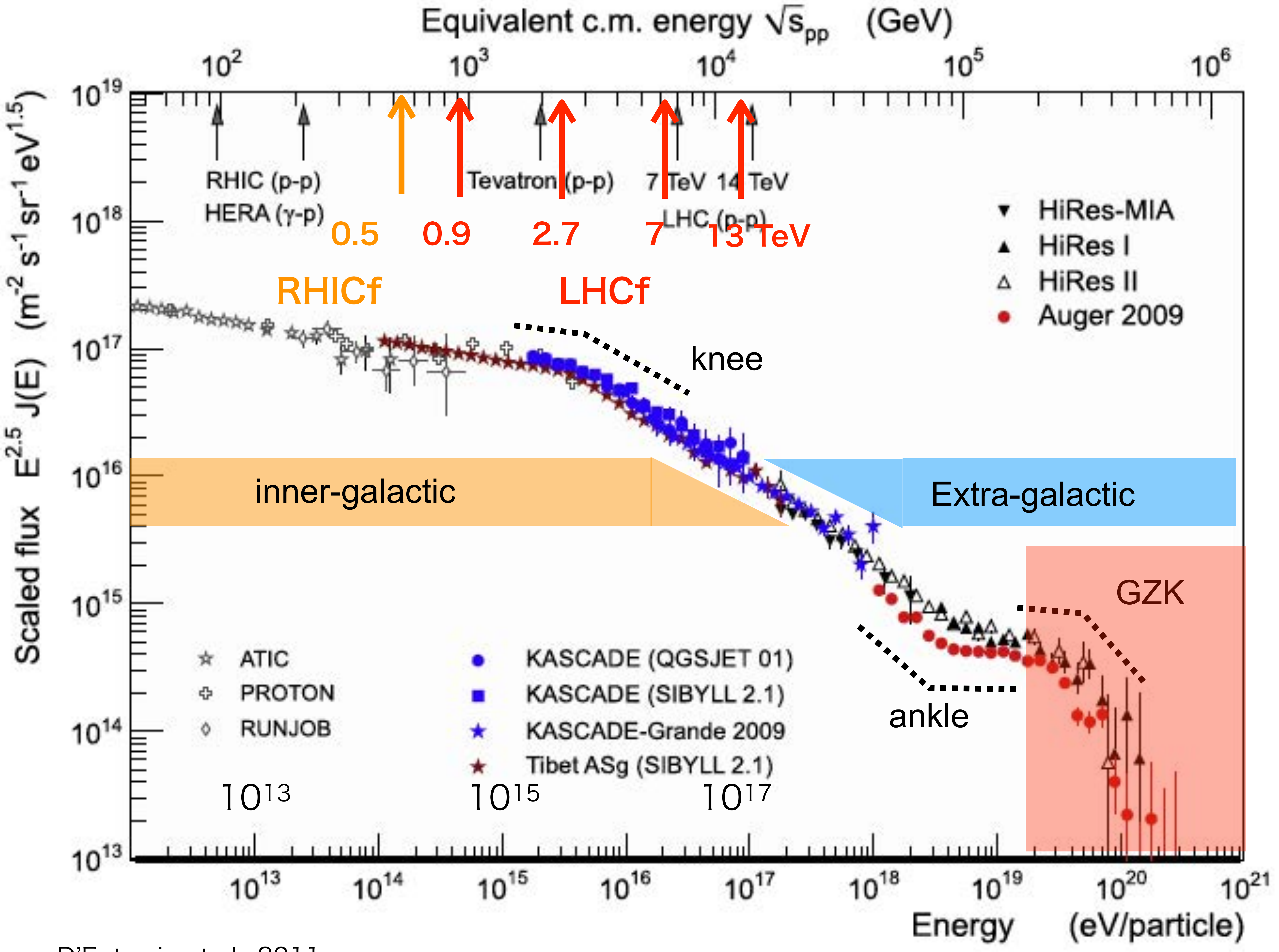
Contents

LHCf: Very Forward experiment at LHC
→ production of most energetic particles
→ Motivated for high-energy cosmic ray physics

- Introduction : Ultra-high energy cosmic rays (UHECRs)
- LHCf experiments
- Recent results
  - η meson measurement by LHCf
  - Status of LHCf-ATLAS joint analysis
- LHC-Run3 operations
  - pp $\sqrt{s}$=13.6 TeV in 2022
  - pO collision in 2024

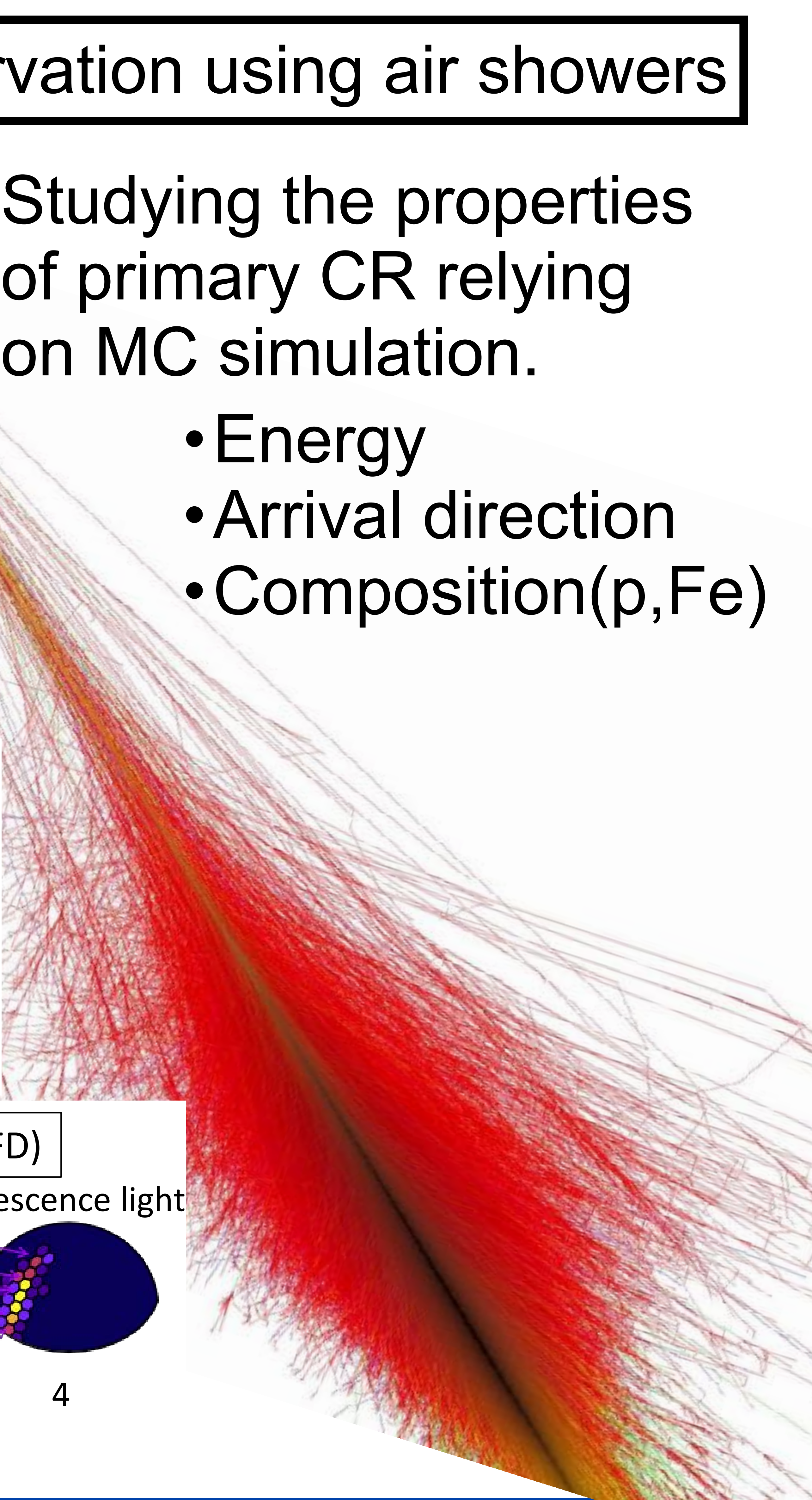
Photo @ 2022 operation
Members from Nagoya Univ., INFN(Italy)

Ultra-High Energy Cosmic-rays (UHECRs)



D'Enterria et al., 2011

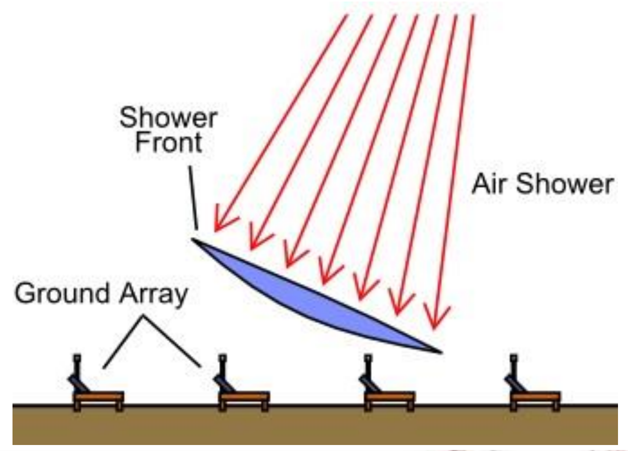
Observation using air showers



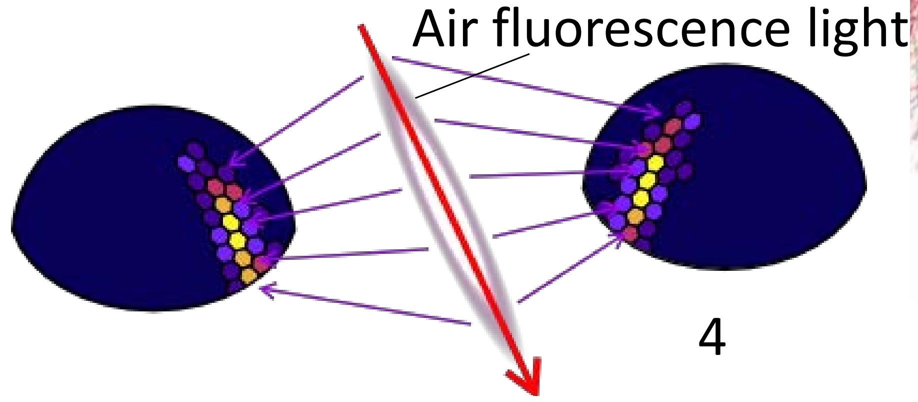
Studying the properties of primary CR relying on MC simulation.

- Energy
- Arrival direction
- Composition(p,Fe)

Surface detector (SD)

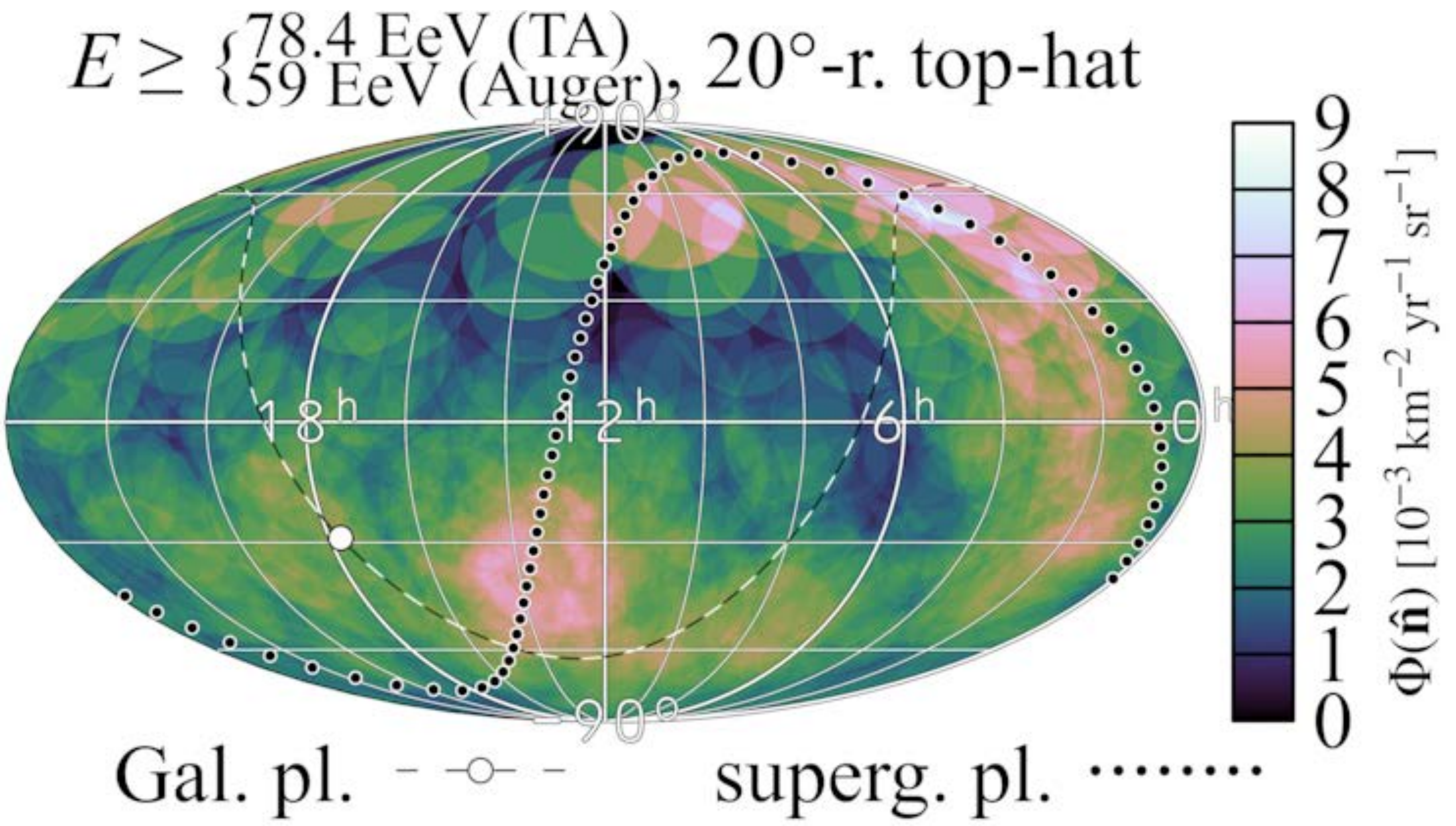


Fluorescence detector (FD)



Arrival direction for UHECRs

Combined result of Auger and TA with 20 degree smearing



PAO and TA, ICRC 2021

✓ A few hotspots

✓ Not point like

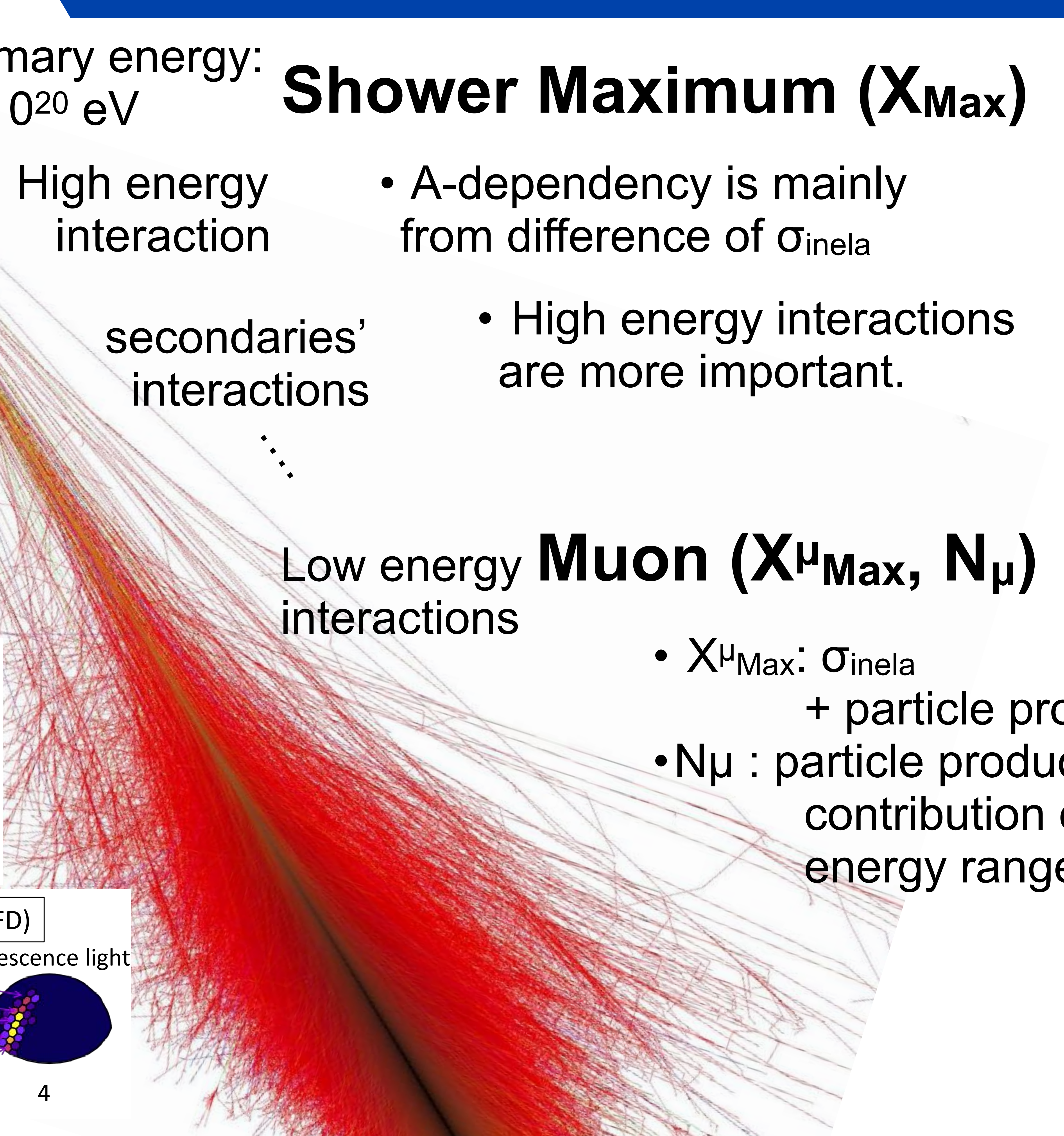
Why ?

Bend by Magnetic field

proton → only a few degrees

- **Source distribution ?**
- **Magnetic field uncertainty ?**
- **Composition (p, Fe)**

Estimators of Composition



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

High energy interaction

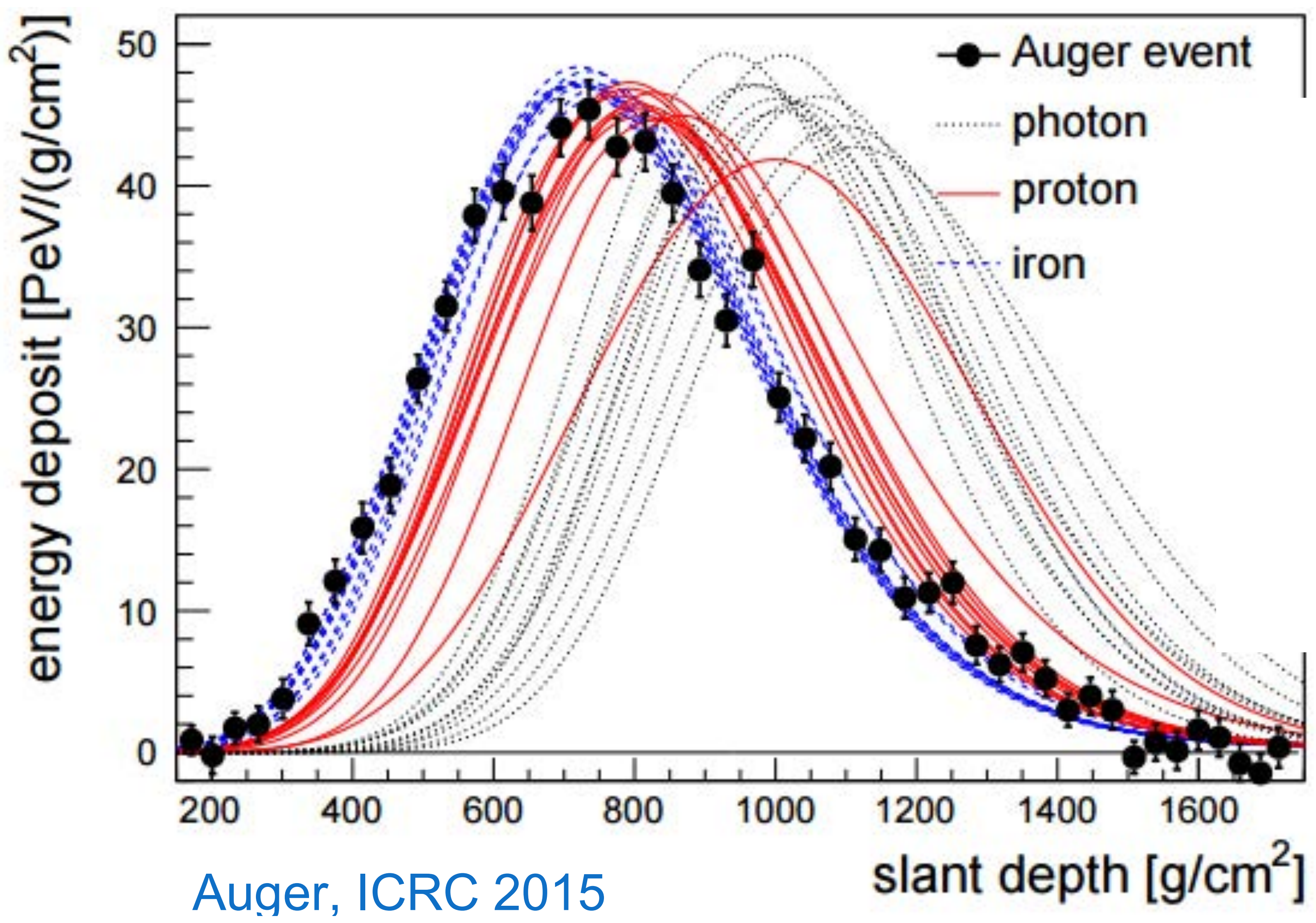
secondaries' interactions

....

Low energy interactions

Shower Maximum (X_{Max})

- A-dependency is mainly from difference of σ_{inela}
- High energy interactions are more important.

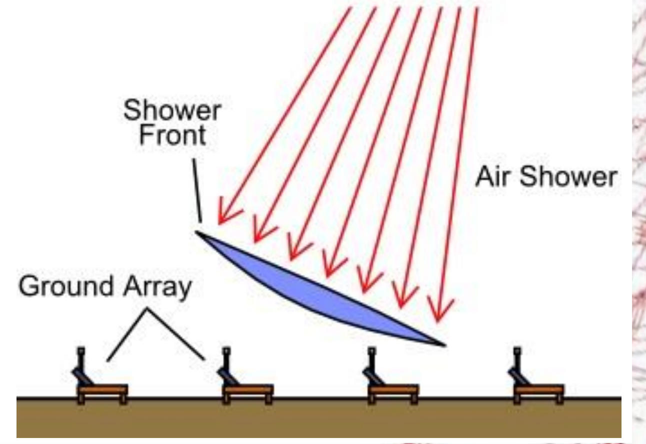


Auger, ICRC 2015

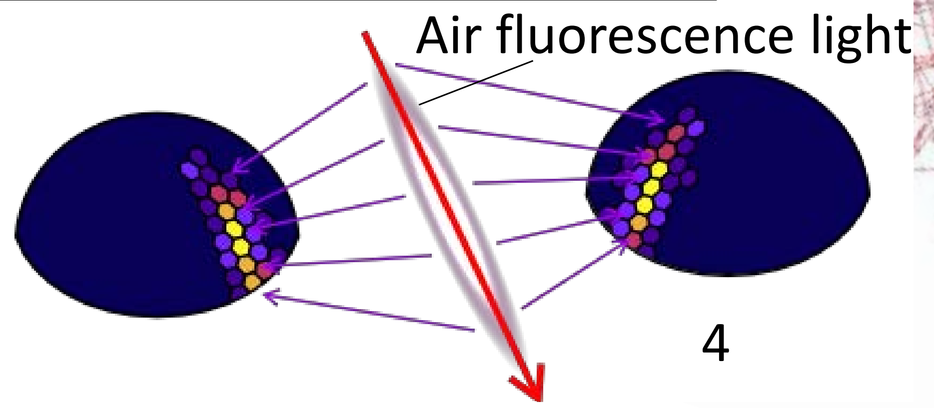
Muon (X^{μ}_{Max}, N_{μ})

- X^{μ}_{Max}: σ_{inela} + particle production
- N_{μ} : particle production contribution of wide energy ranges

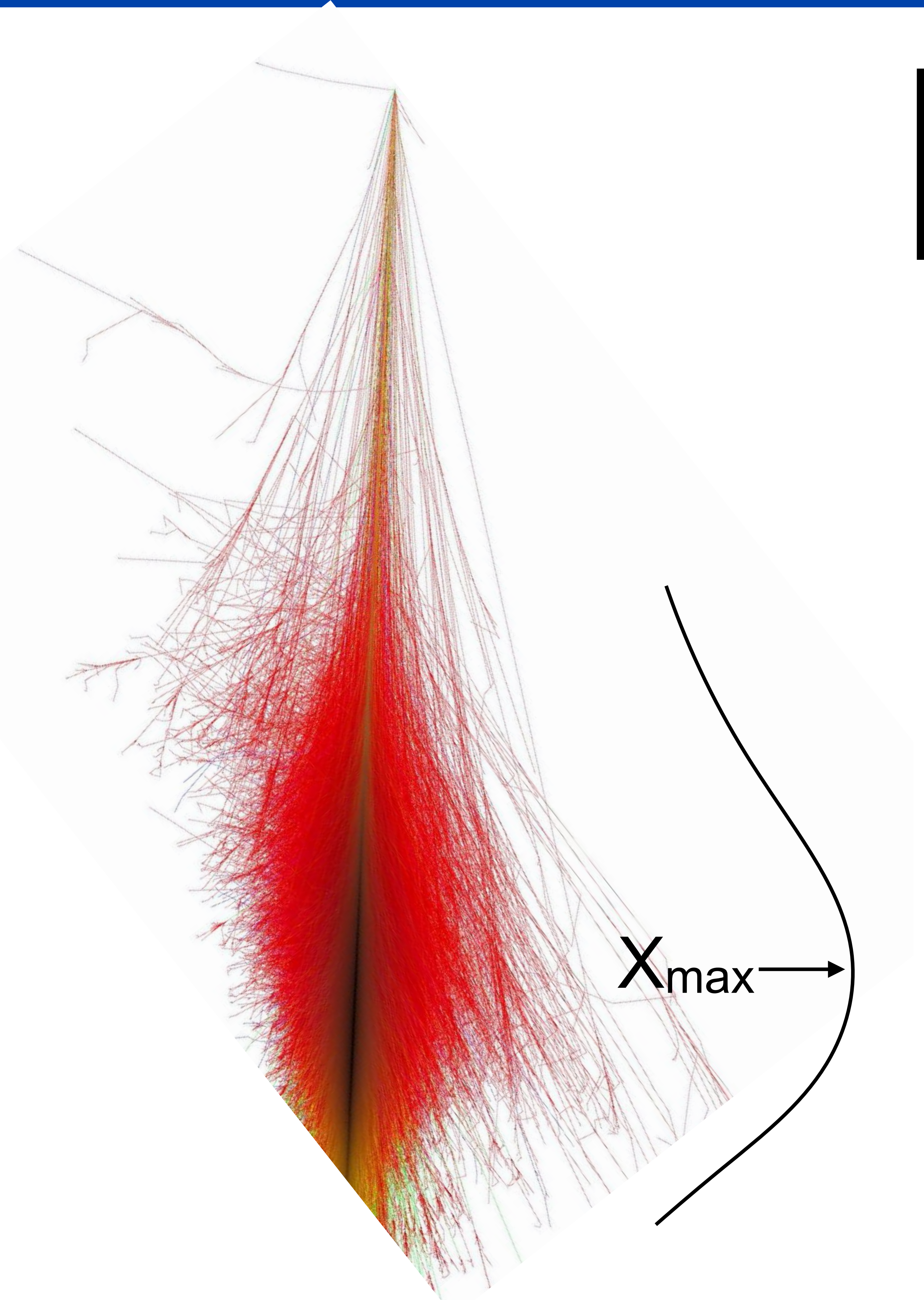
Surface detector (SD)



Fluorescence detector (FD)

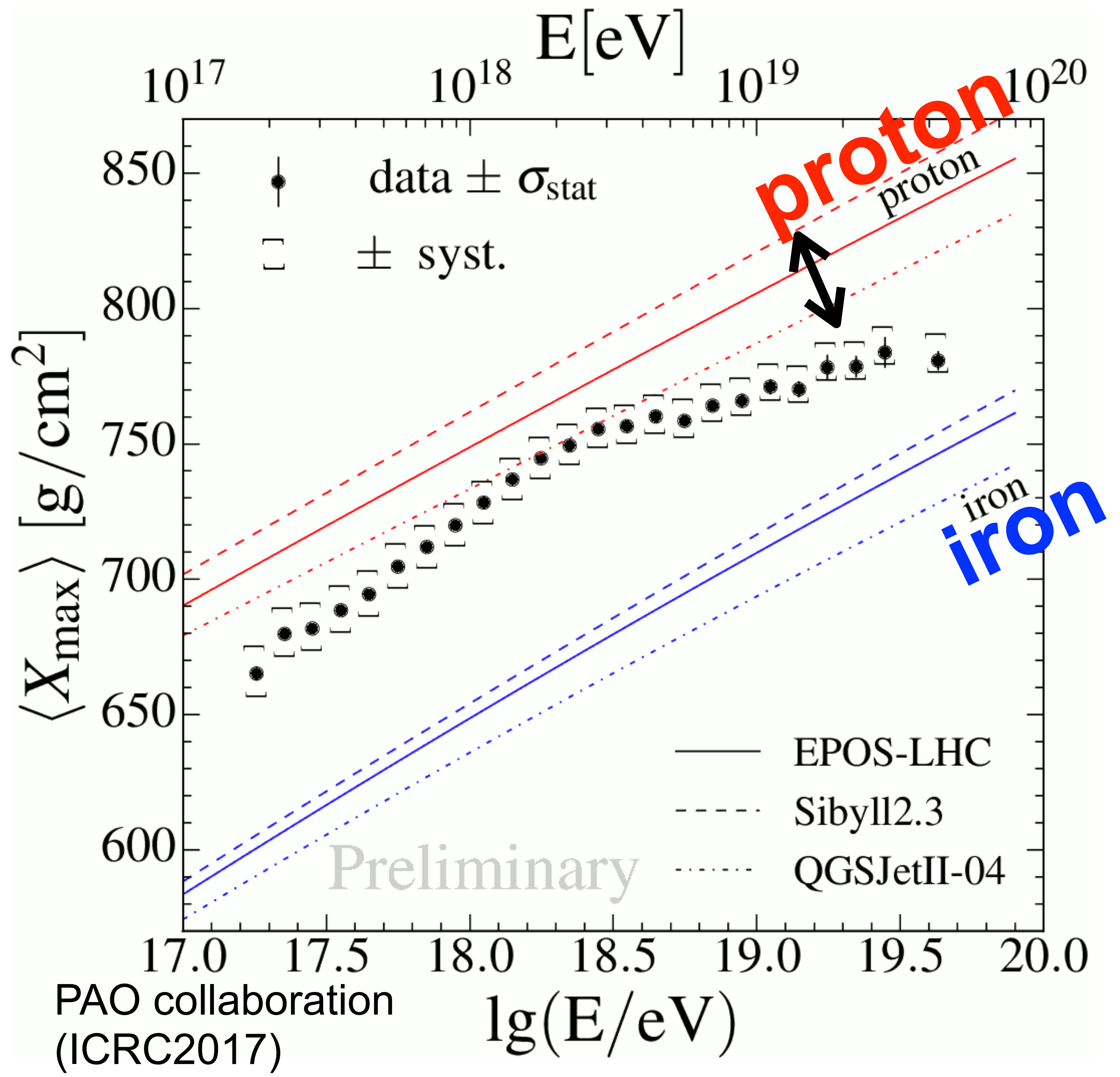


Estimators of Mass Composition



N^{μ}: Number of muons on the ground

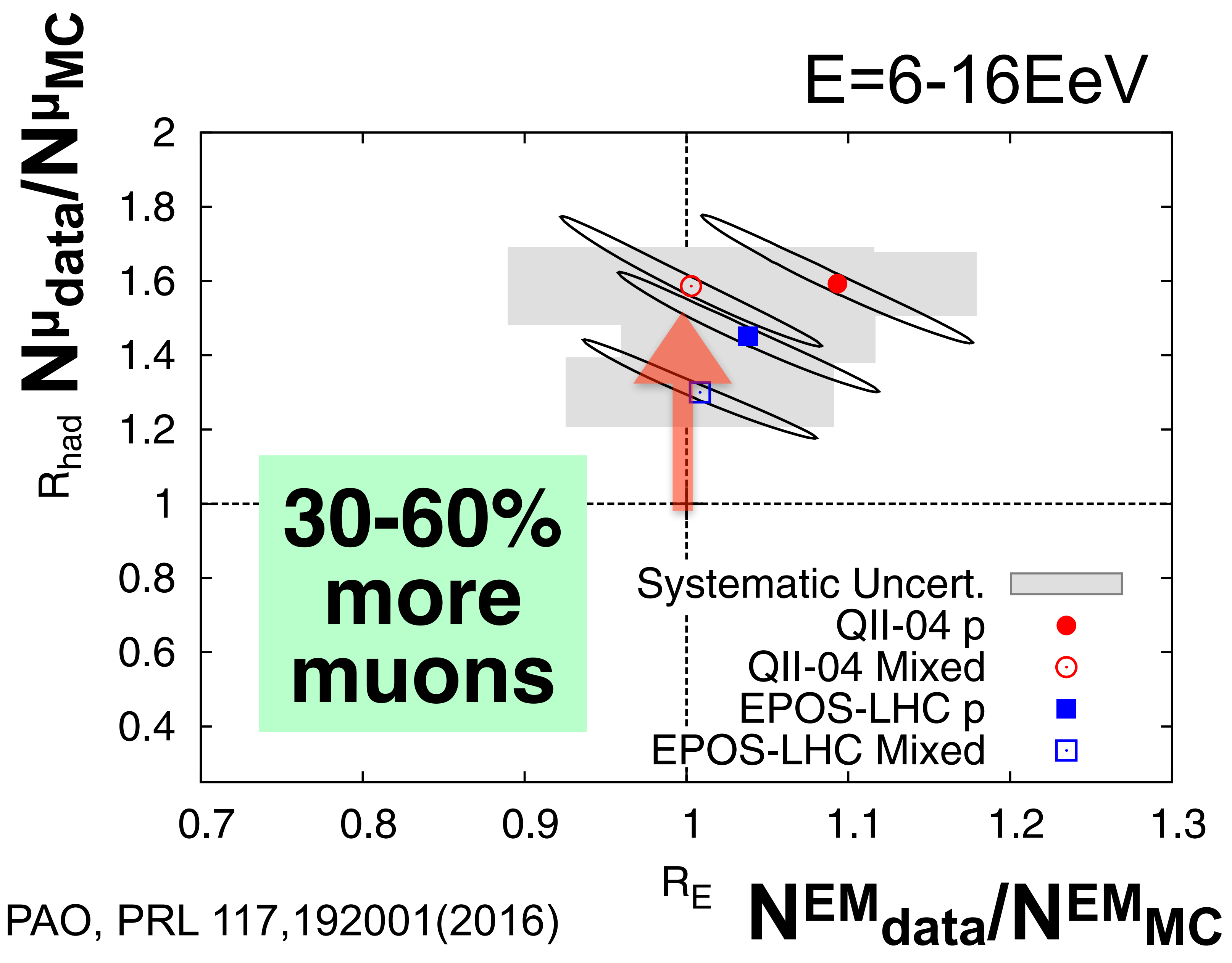
Large model dependency of UHECR composition measurement



PAO collaboration (ICRC2017)

Interaction model uncertainty > Experimental uncertainty

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



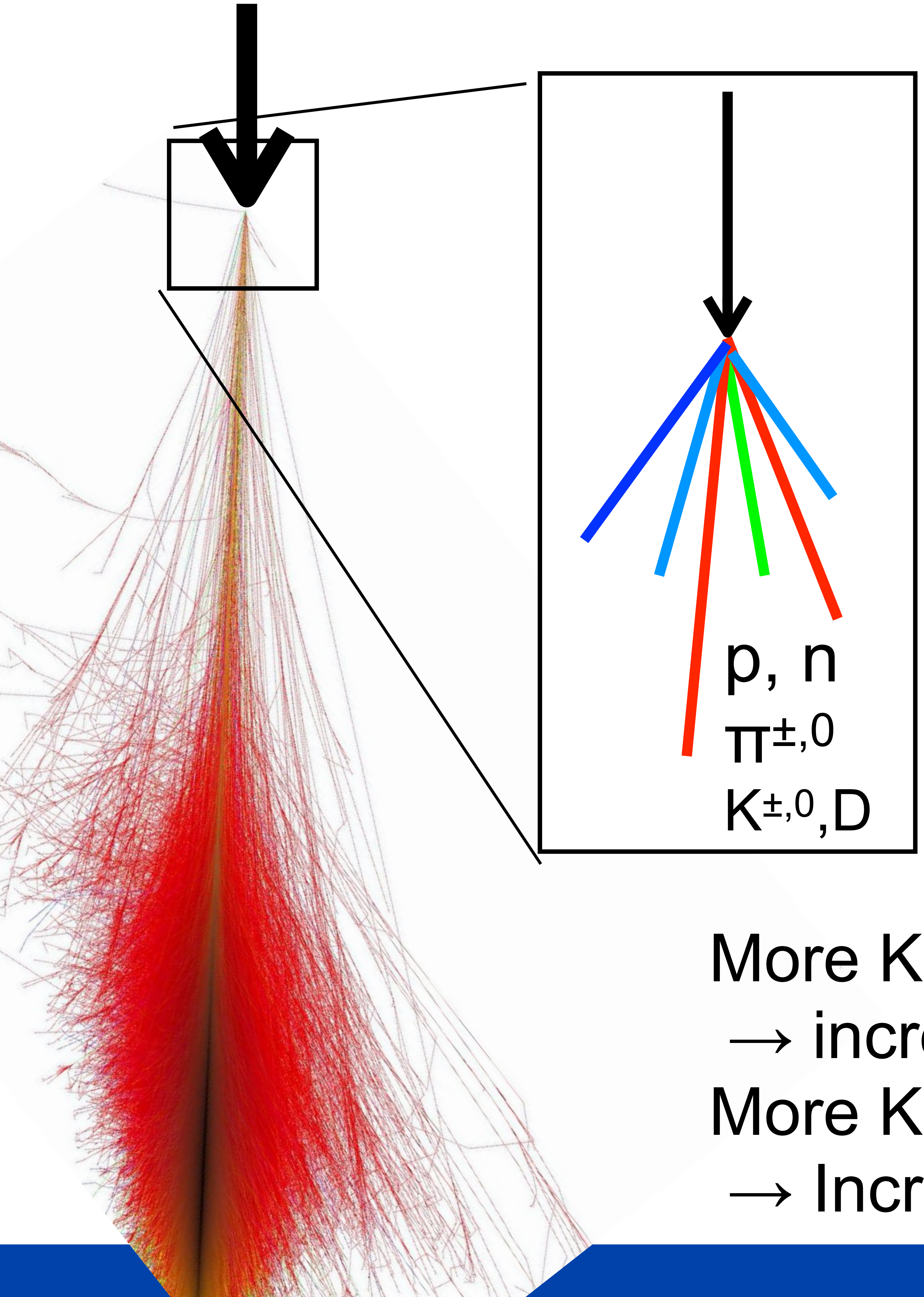
PAO, PRL 117,192001(2016)

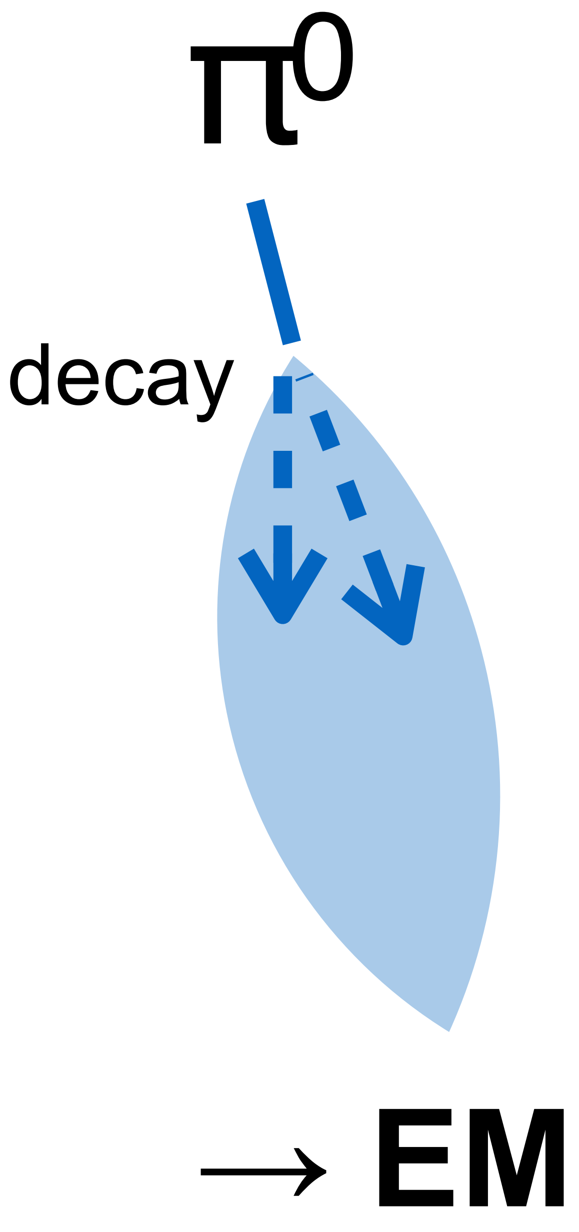
Sensitive $E^{\pi 0}/E^{had}$ for a collision

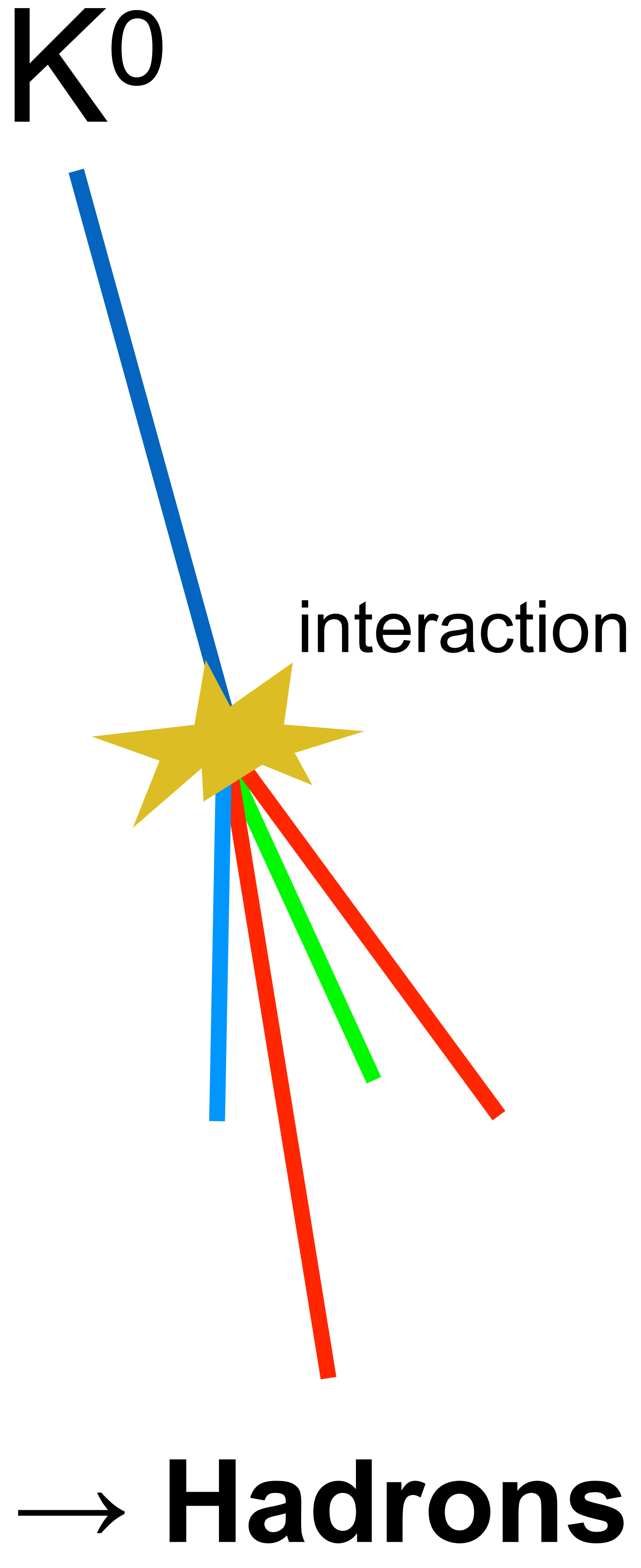
Possibility
- Strangeness enhancement
- Vector meson
- p-π interaction etc.

Contribution of strange particles in air shower

Cosmic-ray

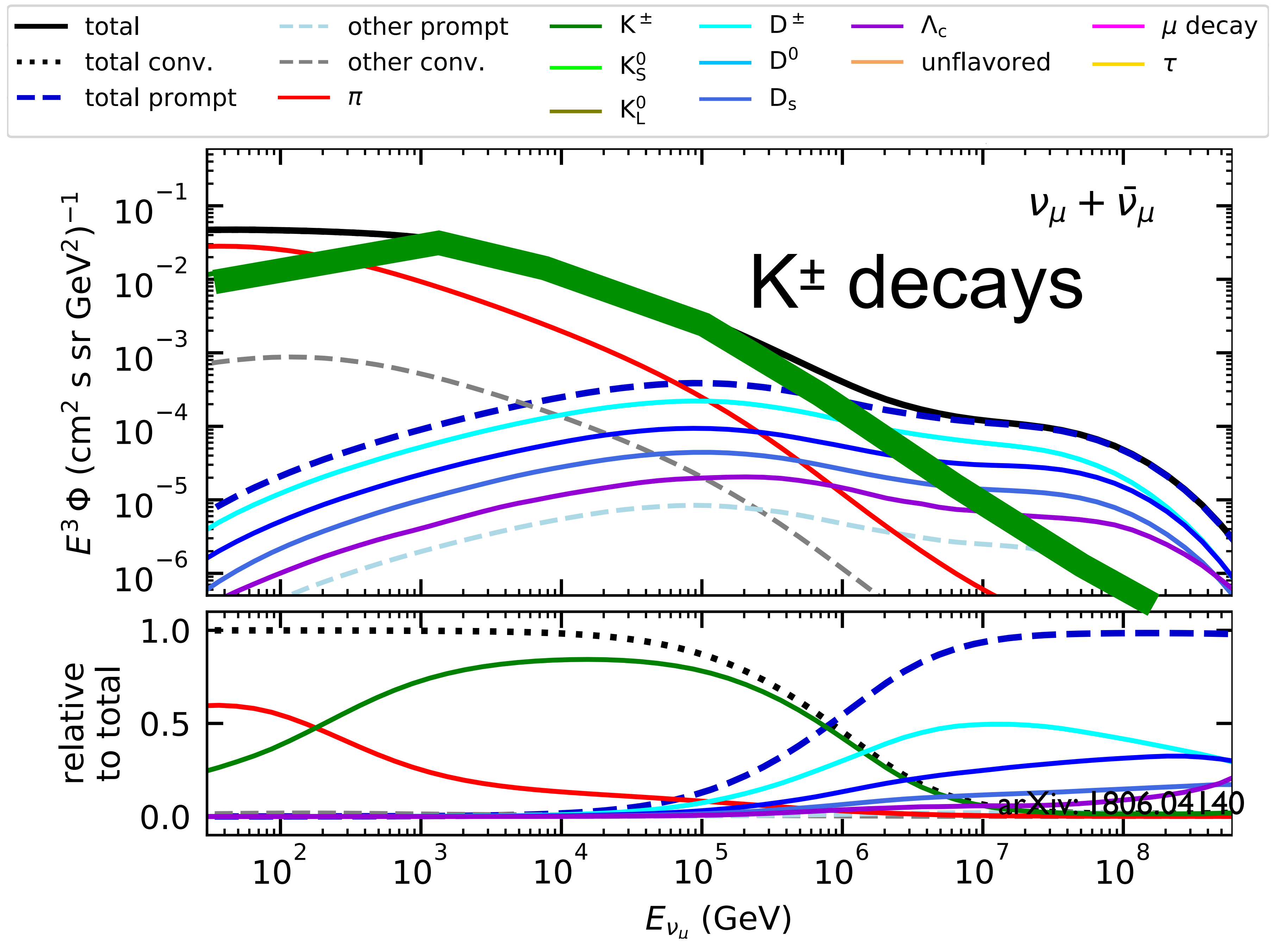






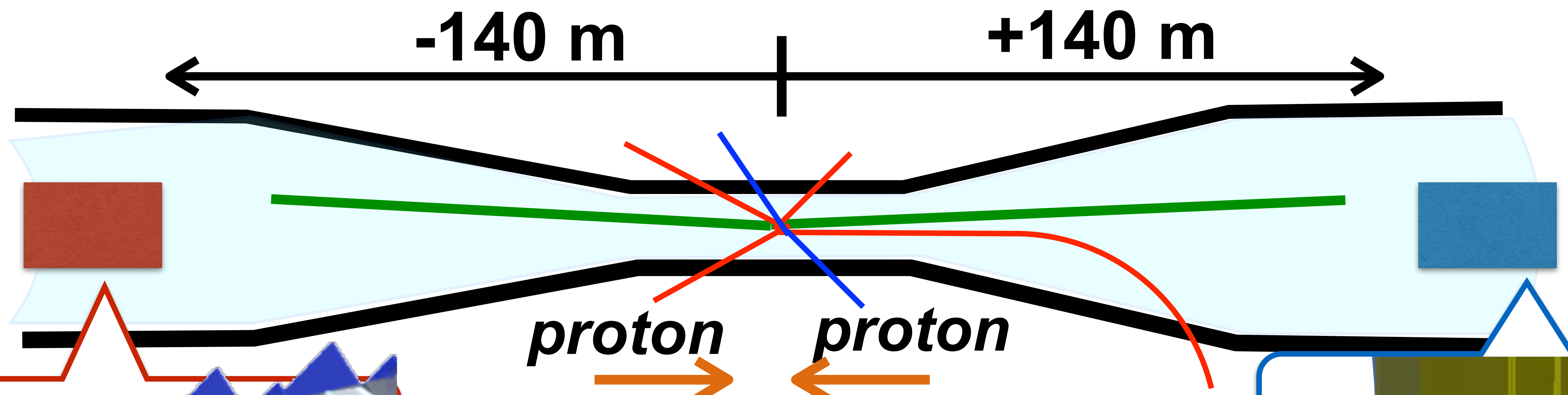
More K^0
→ increase #muons
More $K^{\pm}$
→ Increase $\#\nu_{e,\mu}$

Source of Atmospheric neutrino production

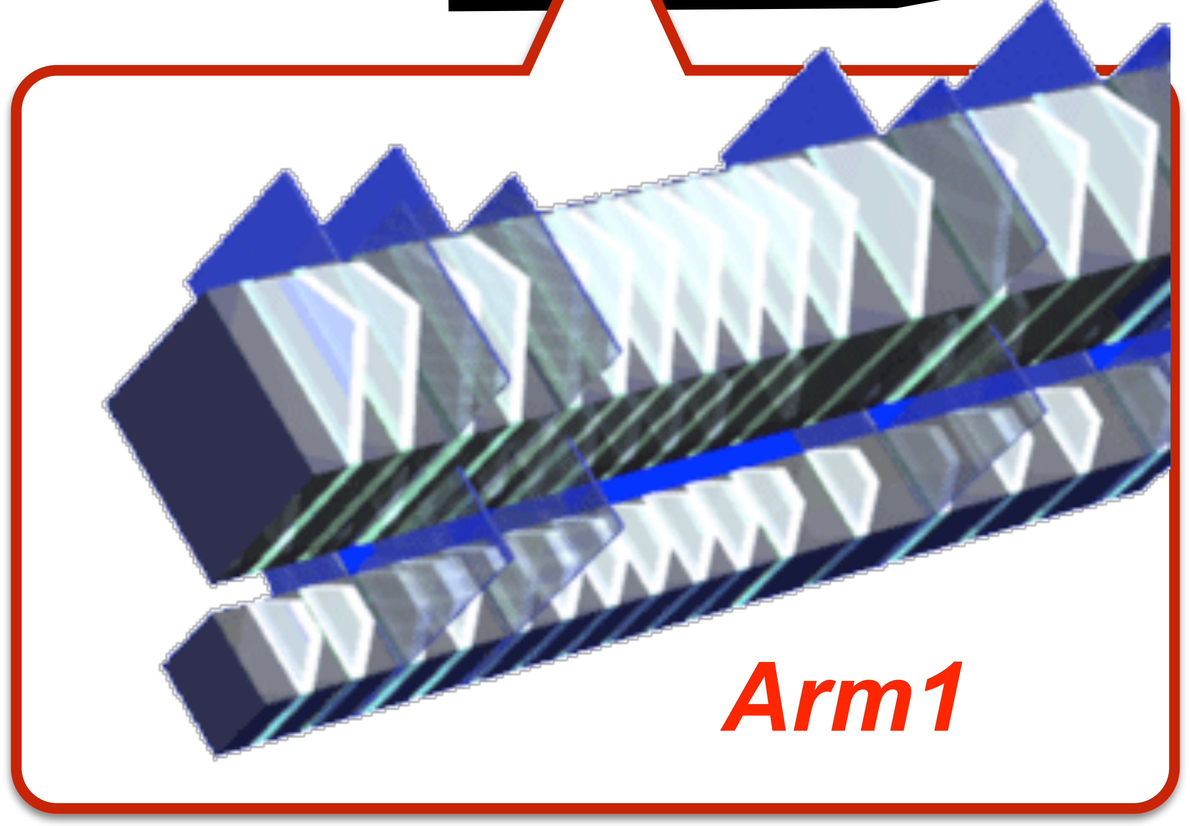


High energy atm. ν are backgrounds of astronomical neutrino search by IceCube.

LHCf experiment

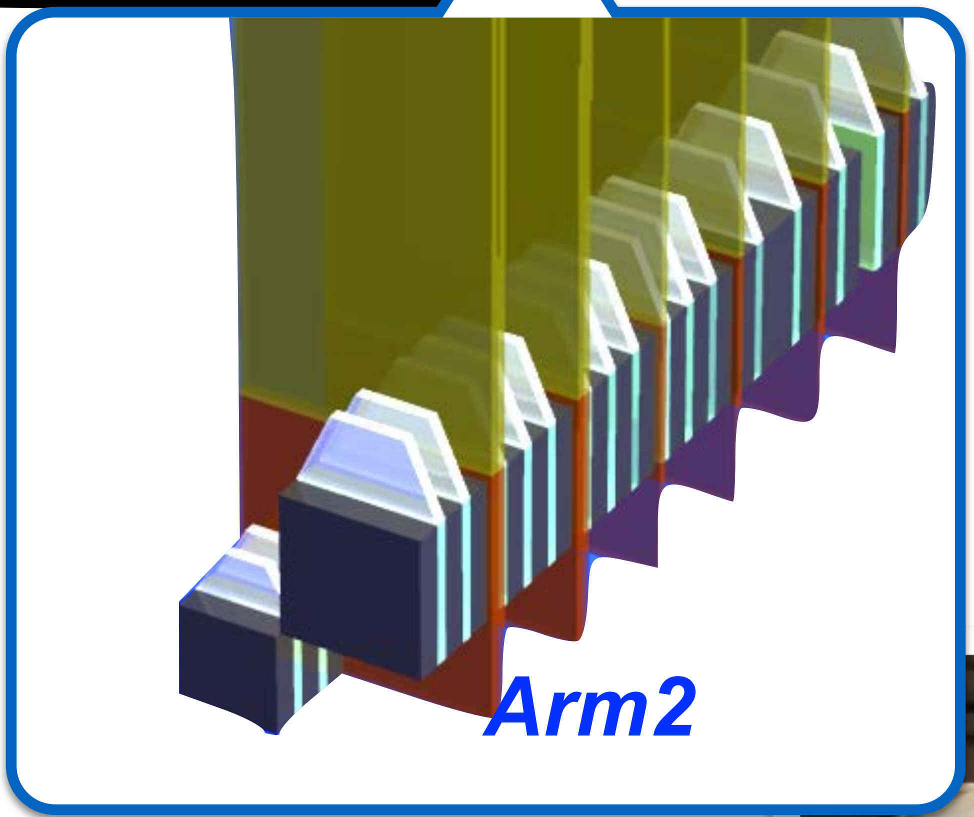


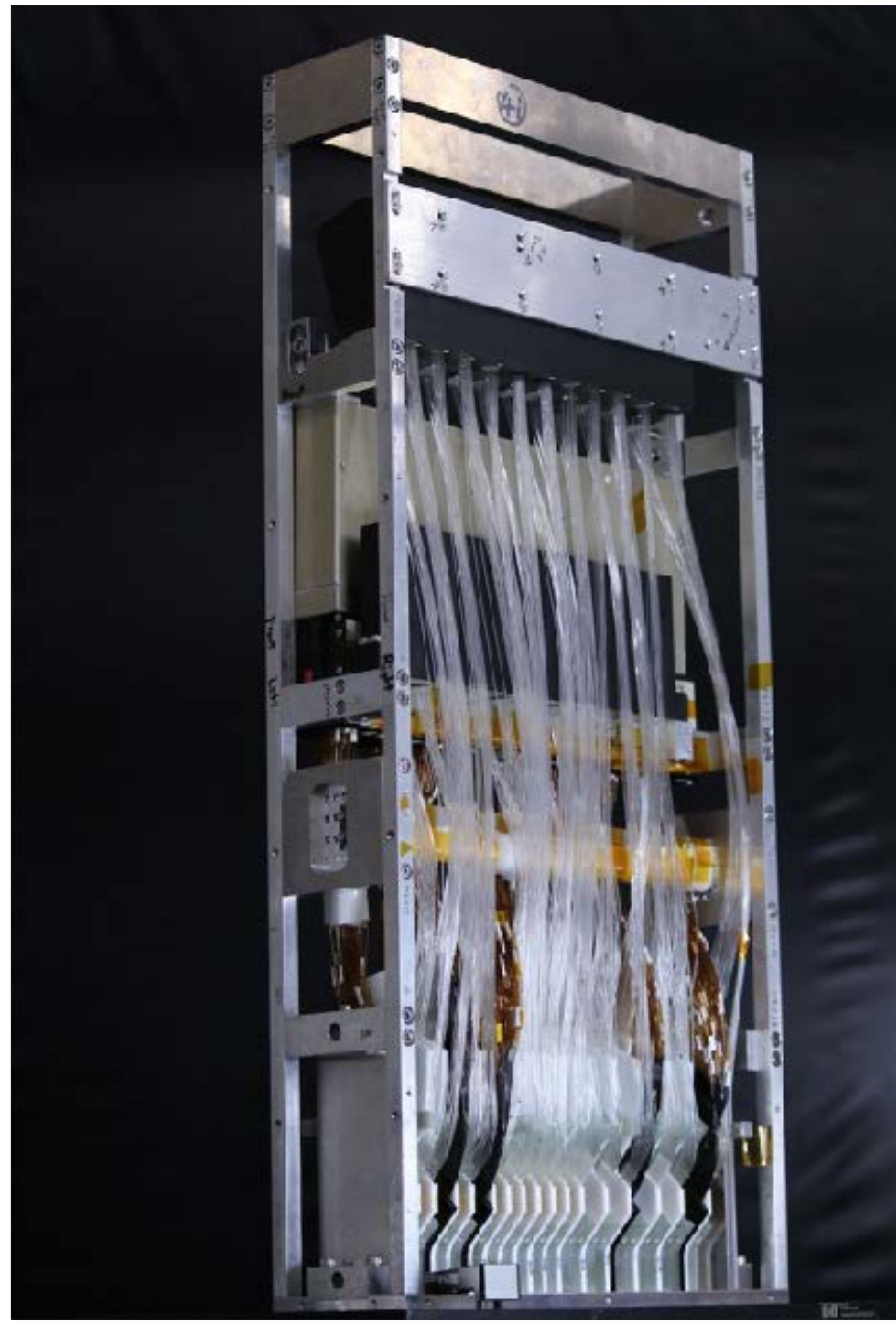
$\sqrt{s}=14\text{TeV} \rightarrow E_{lab} = 10^{17}\text{eV}$



Location

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





LHCf detectors

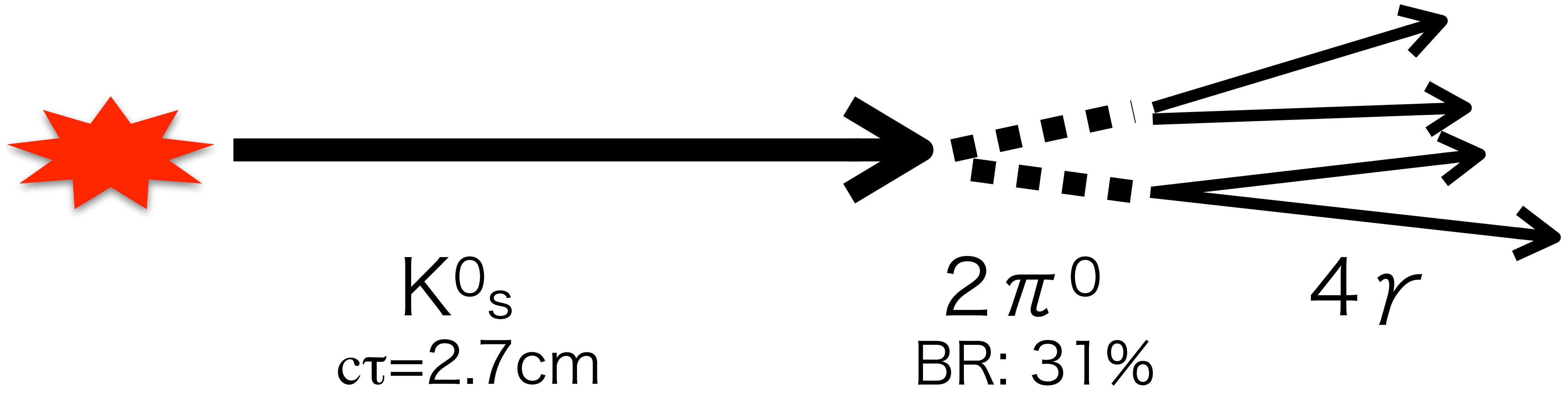
- Sampling and positioning calorimeters
- Two towers, 20x20, 40x40mm^2 (Arm1) , 25x25, 32x32mm^2(Arm2)
- Tungsten layers, 16 GSO scintillators, 4 position sensitive layers
  (Arm1: GSO bar hodoscopes, Arm2: Silicon strip detectors)
- Thickness: 44 r.l. and 1.7 λ

LHCf/RHICf Operations and Analyses

<table>
<tr><th>Run</th><th>E_{lab} (eV)</th><th>Photon</th><th>Neutron</th><th colspan="2">π^0</th><th>LHCf-ATLAS joint analysis</th></tr>
<tr><td>p-p $\sqrt{s}$=0.9TeV (2009/2010)</td><td>4.3x10^{14}</td><td>PLB 715, 298 (2012)</td><td></td><td colspan="2">-</td><td></td></tr>
<tr><td>p-p $\sqrt{s}$=2.76TeV (2013)</td><td>4.1x10^{15}</td><td></td><td></td><td>PRC 86, 065209 (2014)</td><td rowspan="2">PRD 94 032007 (2016)</td><td></td></tr>
<tr><td>p-p $\sqrt{s}$=7TeV (2010)</td><td>2.6x10^{16}</td><td>PLB 703, 128 (2011)</td><td>PLB 750 360 (2015)</td><td>PRD 86, 092001 (2012)</td><td></td></tr>
<tr><td>p-p $\sqrt{s}$=13TeV (2015)</td><td>9.0x10^{16}</td><td>PLB 780, 233 (2018)</td><td>JHEP 2018, 73 (2018)
JHEP 2020, 016 (2020)</td><td colspan="2">preliminary</td><td>Photon in diffractive coll.
Preliminary: ATLAS-CONF-2017-075
Final: under internal review</td></tr>
<tr><td>p-Pb $\sqrt{s_{NN}}$=5TeV (2013,2016)</td><td>1.4x10^{16}</td><td></td><td></td><td colspan="2">PRC 86, 065209 (2014)</td><td></td></tr>
<tr><td>p-Pb $\sqrt{s_{NN}}$=8TeV (2016)</td><td>3.6x10^{16}</td><td>prelimiary</td><td></td><td colspan="2"></td><td></td></tr>
<tr><td>RHICf p-p $\sqrt{s}$=510GeV (2017)</td><td>1.4x10^{14}</td><td>Submitted ArXiv:2203.15416</td><td></td><td colspan="2">Spin Asymmetry PRL 124 252501 (2021)</td><td>with STAR</td></tr>
</table>

How to measure strange particles by LHCf

$K^{\pm}$ ❌ Swept out by D1 magnetic field

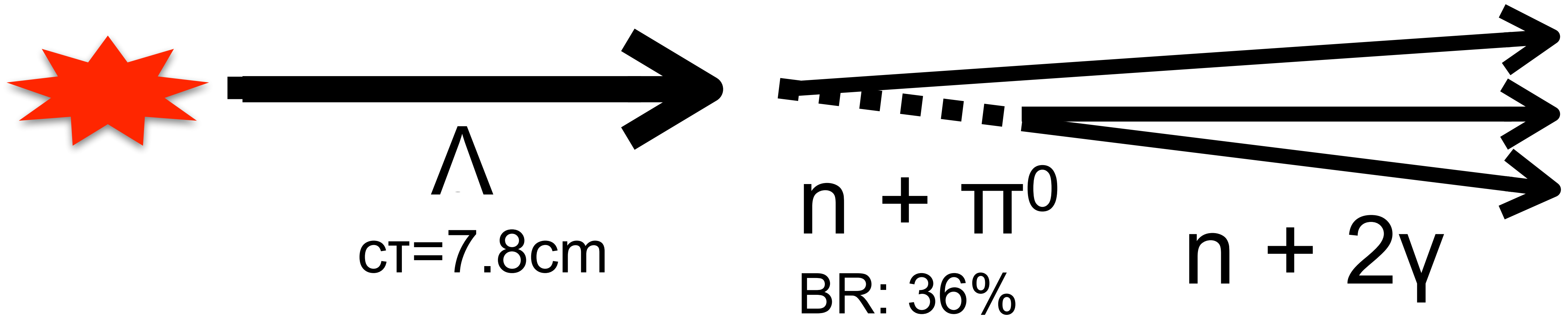


K^0

K^0_s decays between IP and detectors.
$K^0_s \rightarrow 2\pi^0 \rightarrow 4\gamma$

Poor acceptance
Challenging of reconstruction 4 photos

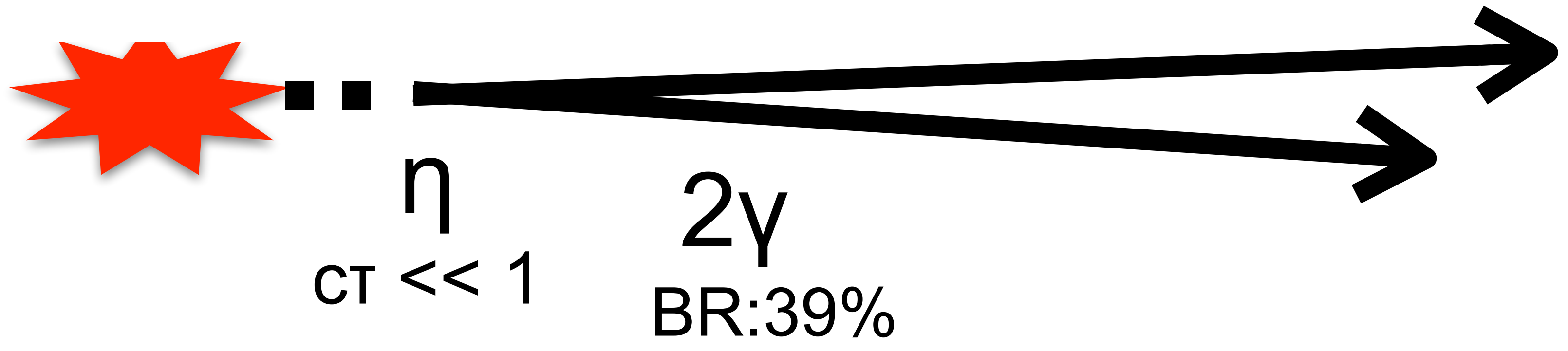
Other channels



Λ (uds)

Decays between IP and detectors.
$\Lambda \rightarrow n+\pi^0 \rightarrow n+2\gamma$

Challenging of reconstruction for mix of hadronic and EM showers

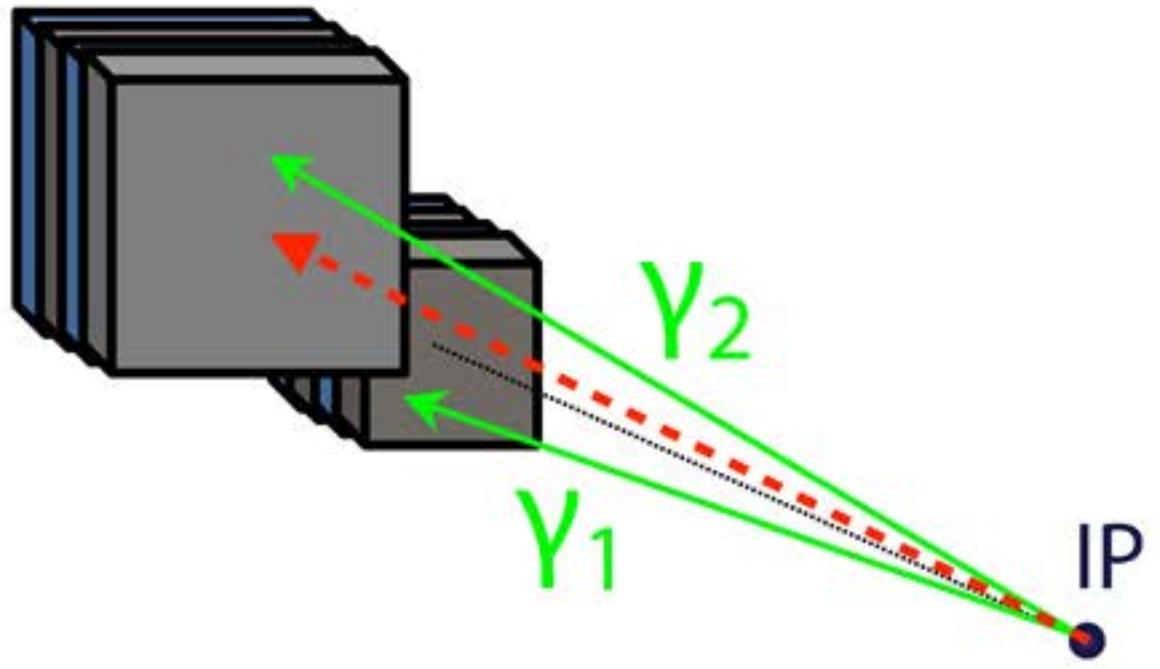


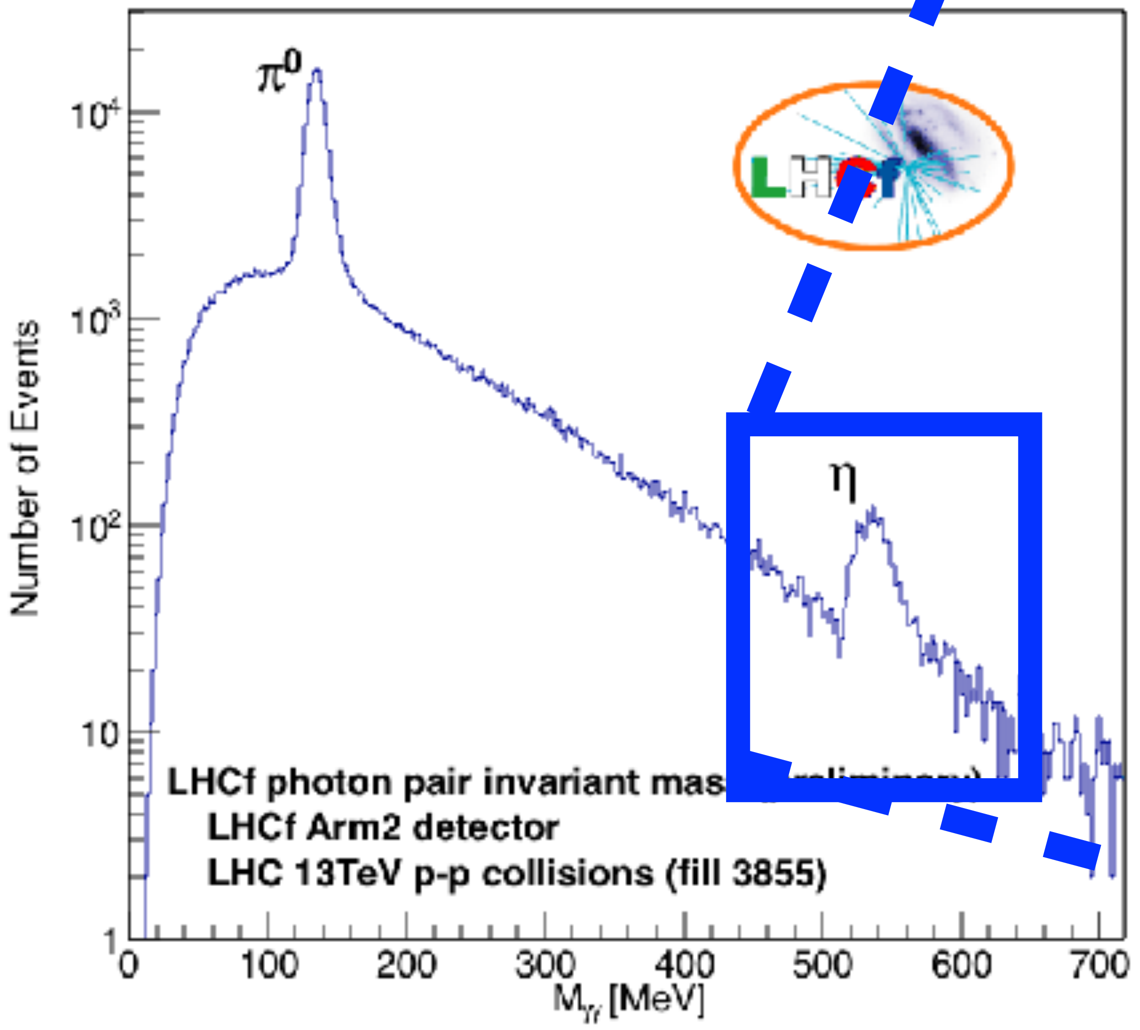
η $(u\bar{u}+d\bar{d}+s\bar{s})$

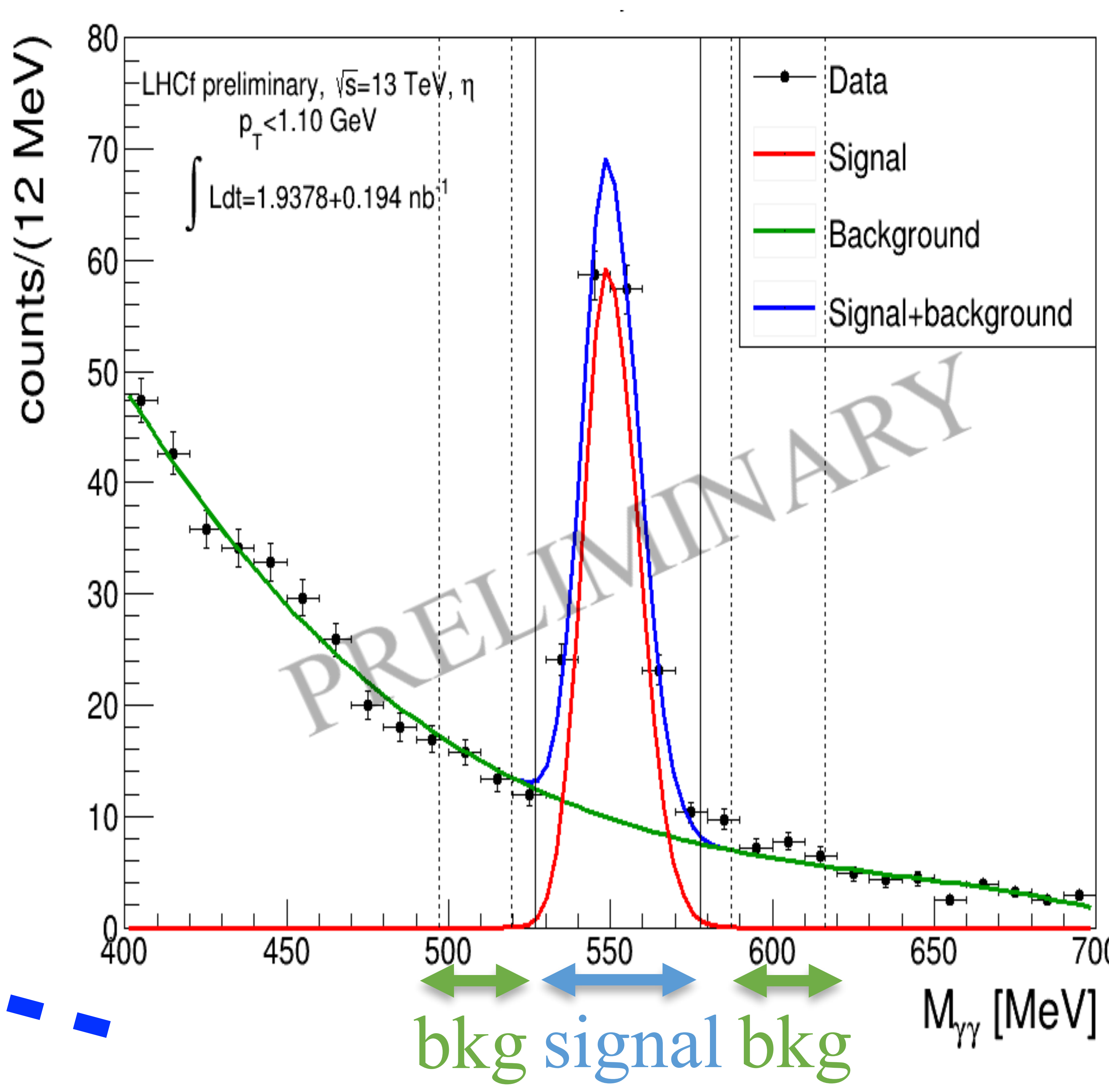
Reconstruction method is well established
(= method for π^0)

η meson measurement

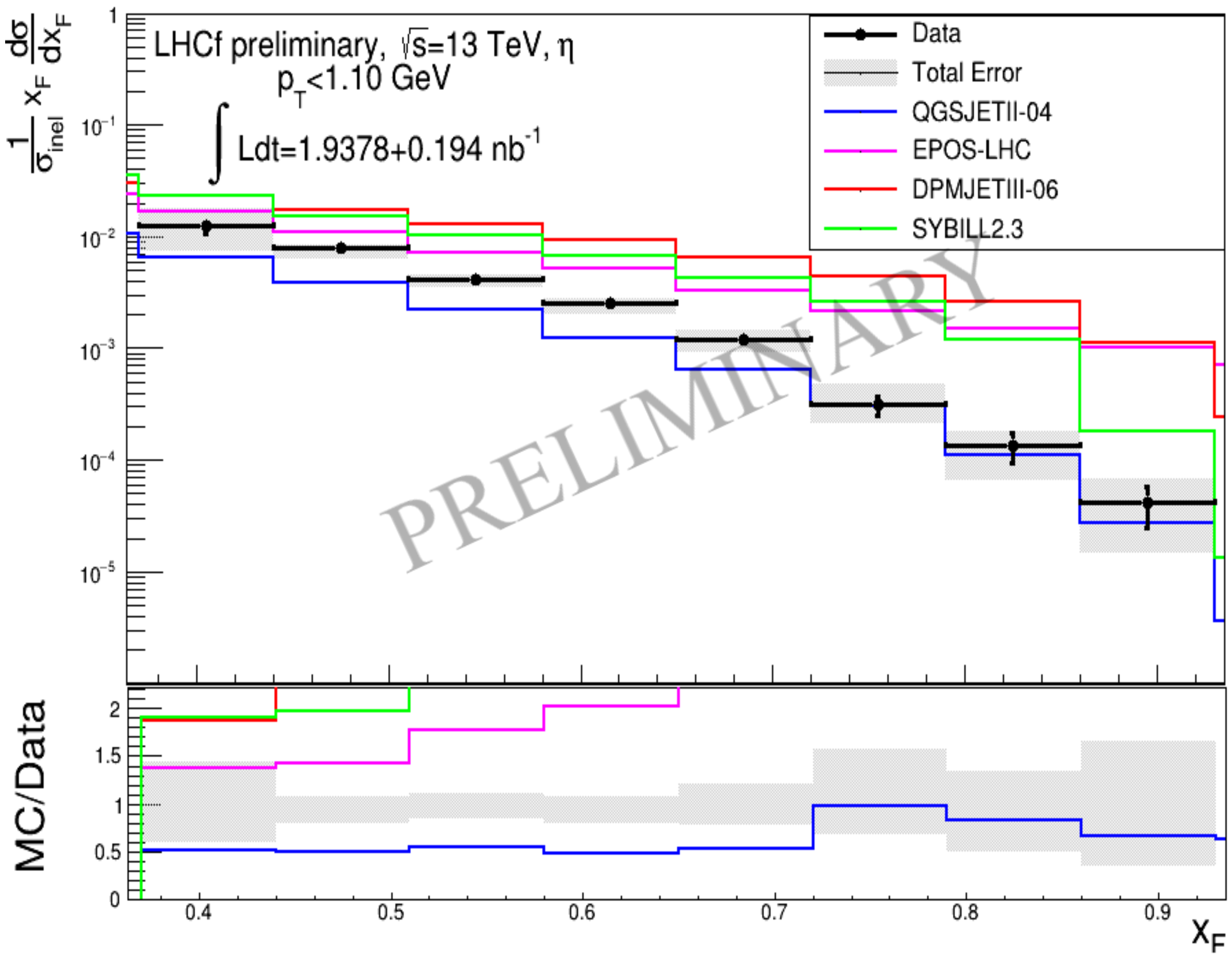
- Motivation
  - 2nd dominant source of photons (EM) in air showers.
  - Contribution of strange quark
  - Large discrepancy of predictions between models
- Data and analysis
  - pp, √s=13 TeV
  - Arm2 detector
  - Similar as Type1 π^0 analysis







η spectrum at pp, $\sqrt{s}$=13TeV

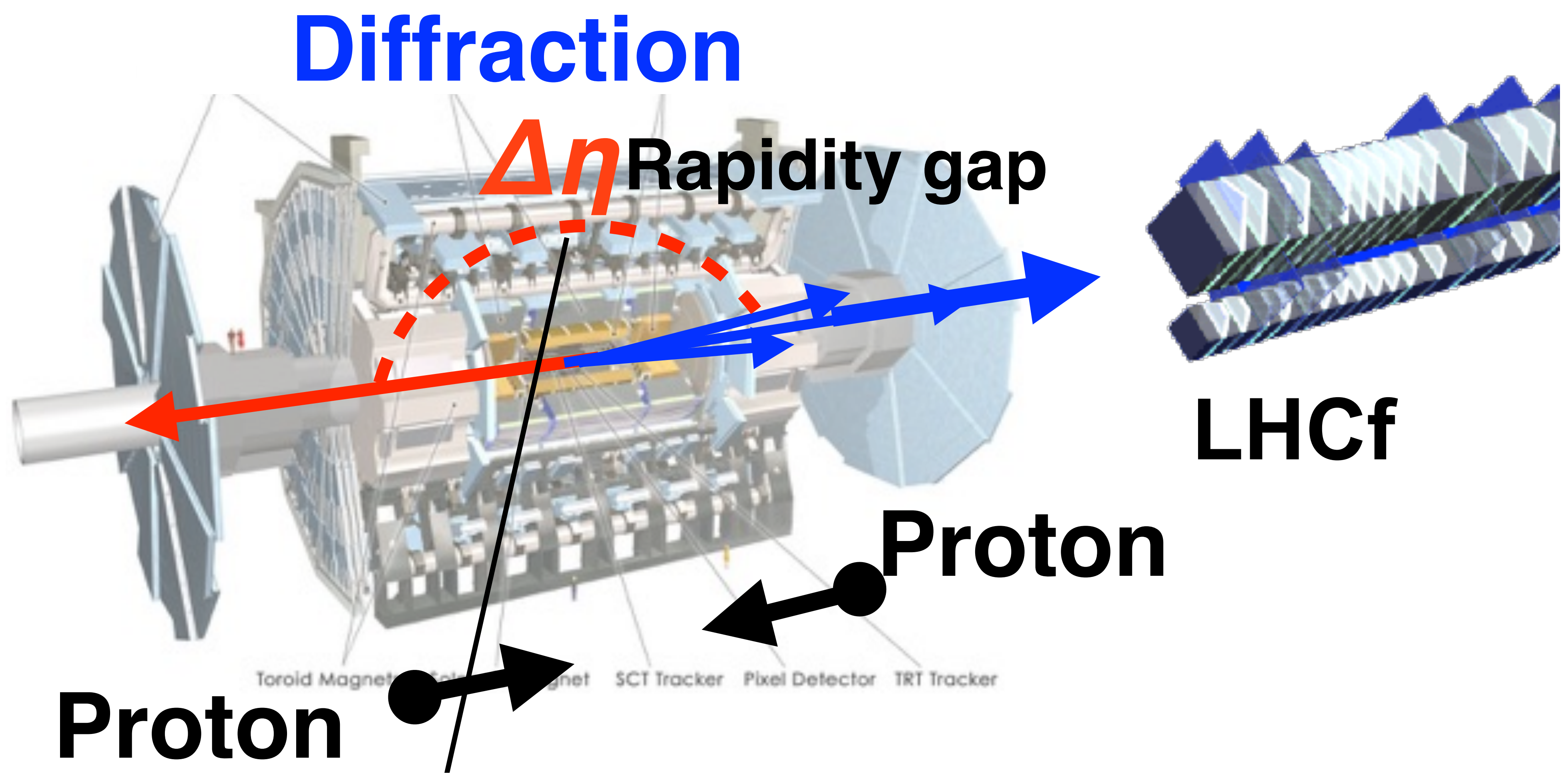


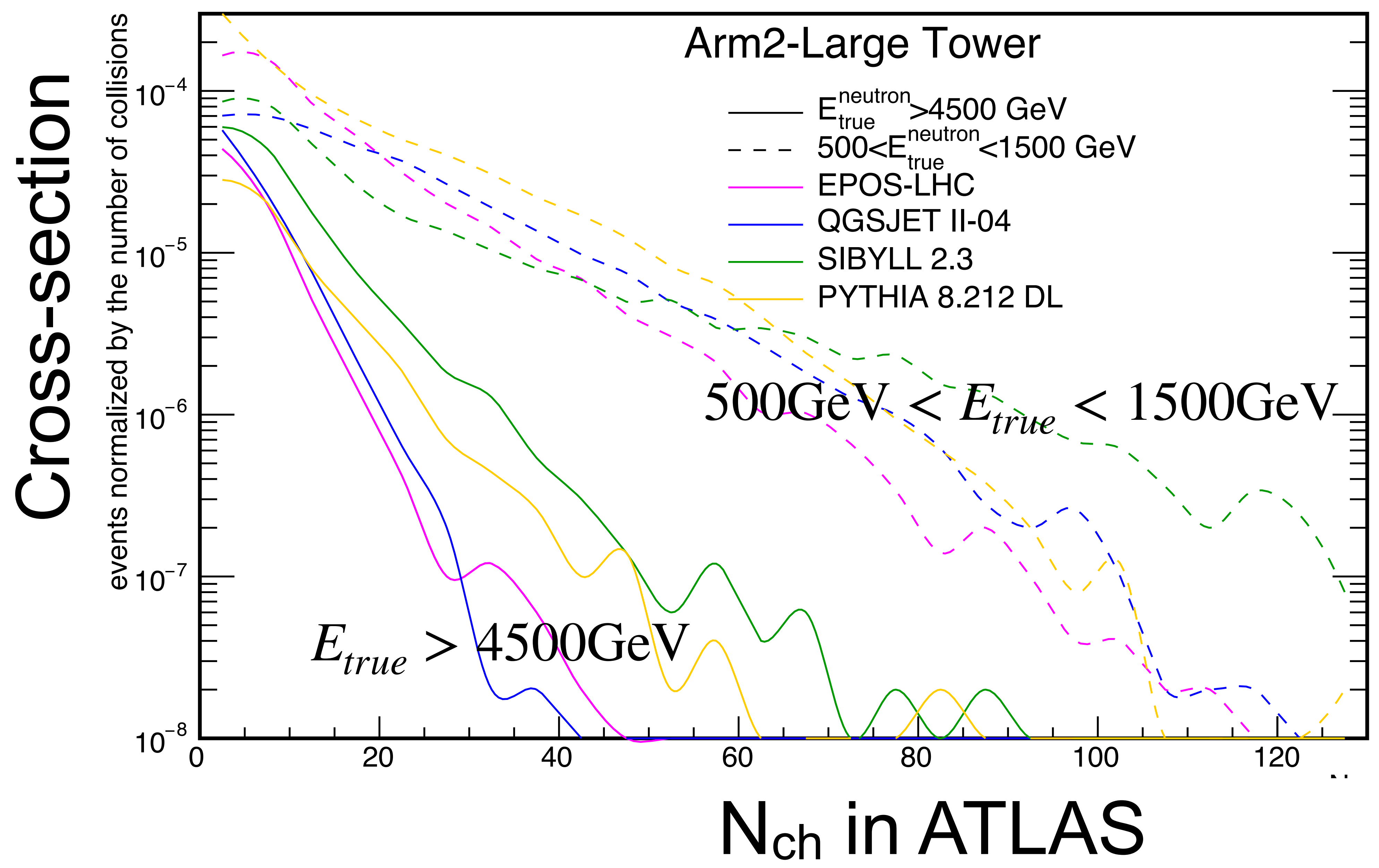
Piparo, LHCP 2022

- No model can reproduce the data perfectly
- QGSJET II-04 shows a best agreement among the models.

→ Poor statistics of eta events (~ 100) affect on the systematic uncertainties; background subtraction etc.
It will be improved with analysis of Run3 data.

On-going Joint analyses with ATLAS





- Study of diffractive collisions
  - Photon spectra with N_{ch}=0 in ATLAS (p_T>0.1GeV, |η| < 2.5)
- Study of MPI
  - Correlation between forward neutron and N_{ch} in ATLAS
  - Good test of modeling for total energy budget for MPIs

    Superposition of single API: MPI ↗ Forward neutron energy ↘

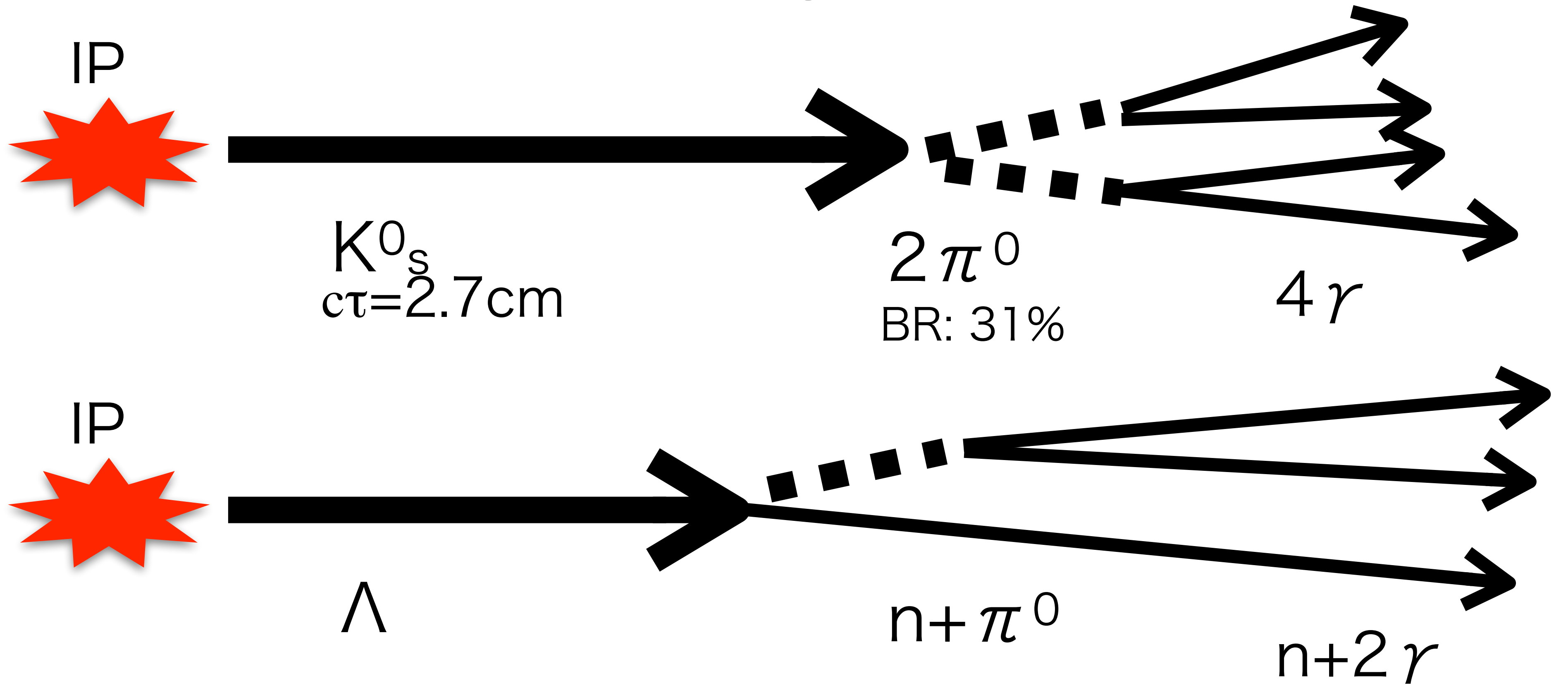
    Kinematic overlap : MPI ↗ Forward neutron energy →

LHCf Run3 operations

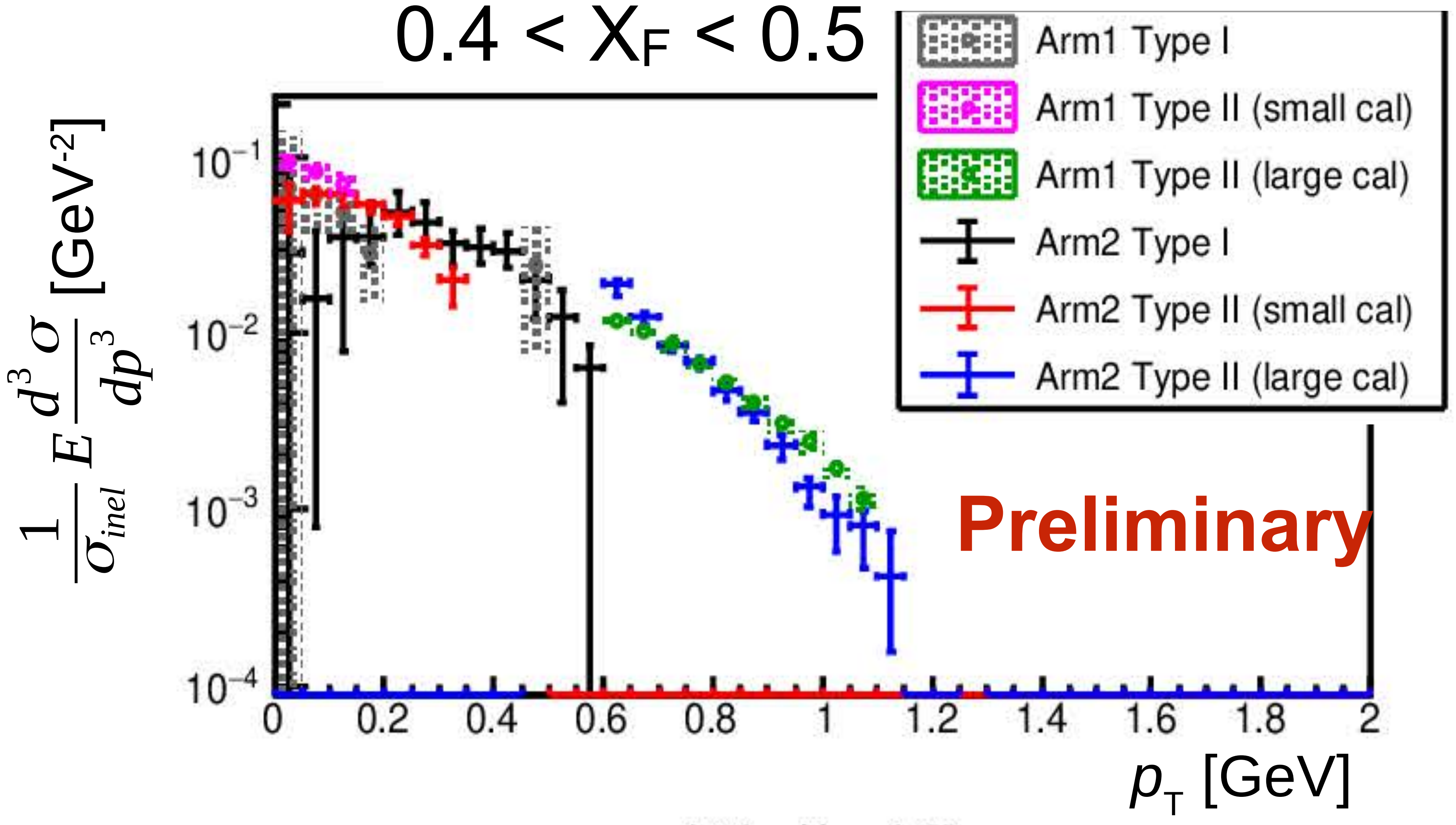
- pp, $\sqrt{s}$=13.6TeV in Sept. 2022
- p-Oxygen collisions in 2024

proton-proton collisions in 2022

- Motivations
  - Increase statistics of π^0 and η
  - Measurement of strange hadrons (K^0_S, Λ)



π0 measurement
at pp, √s=13 TeV (2015)



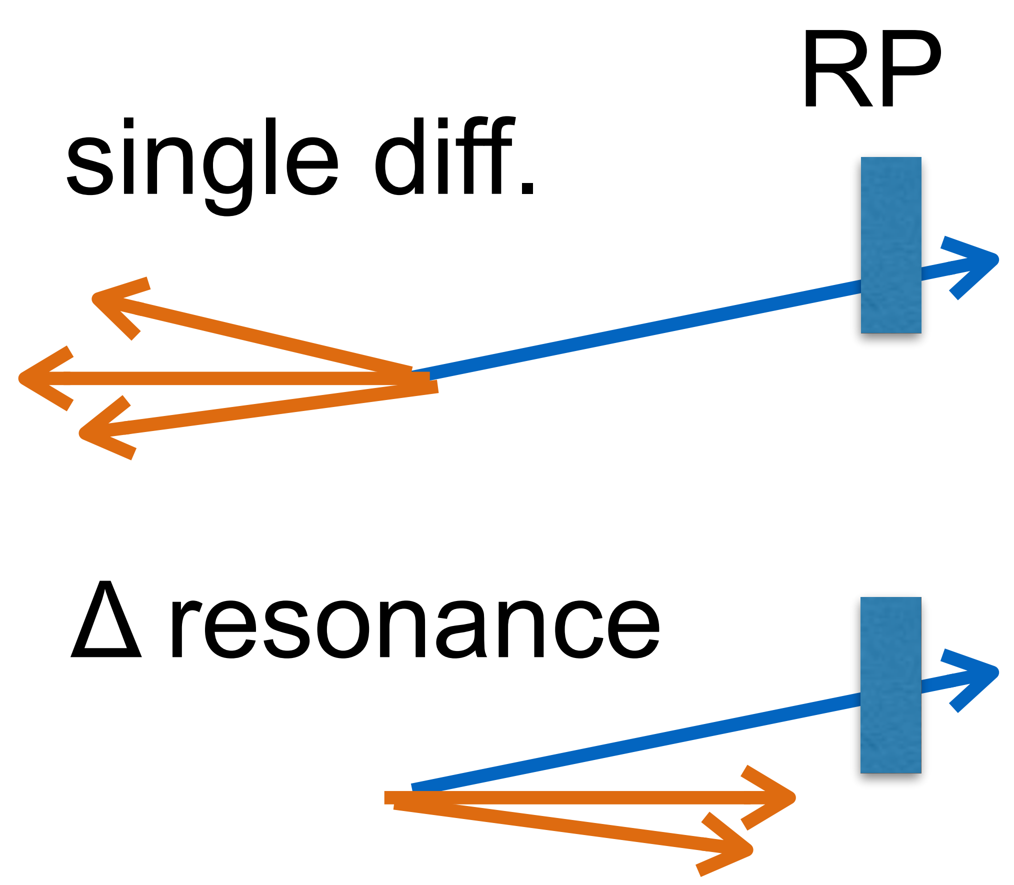
- Requirement
  - Integral Luminosity = 40 nb^{-1} (~ **x10** larger than last operation)
    @ Luminosity ~ 10^{30} $cm^{-2}s^{-1}$ (~ **x10** higher)

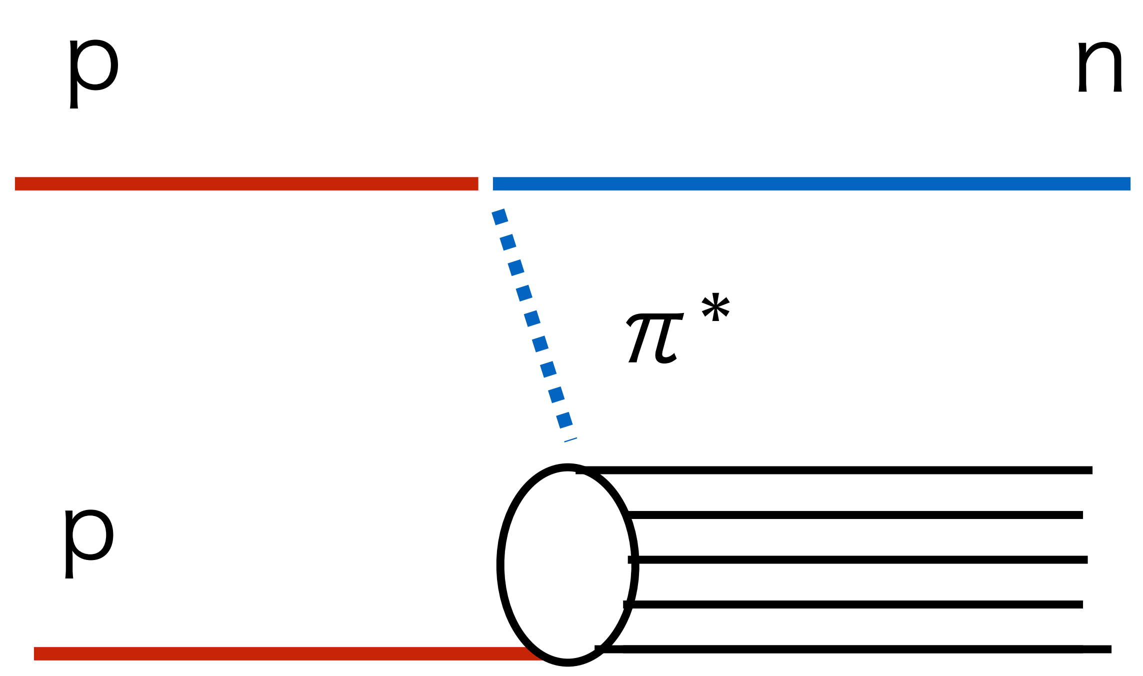
Hardware upgrade

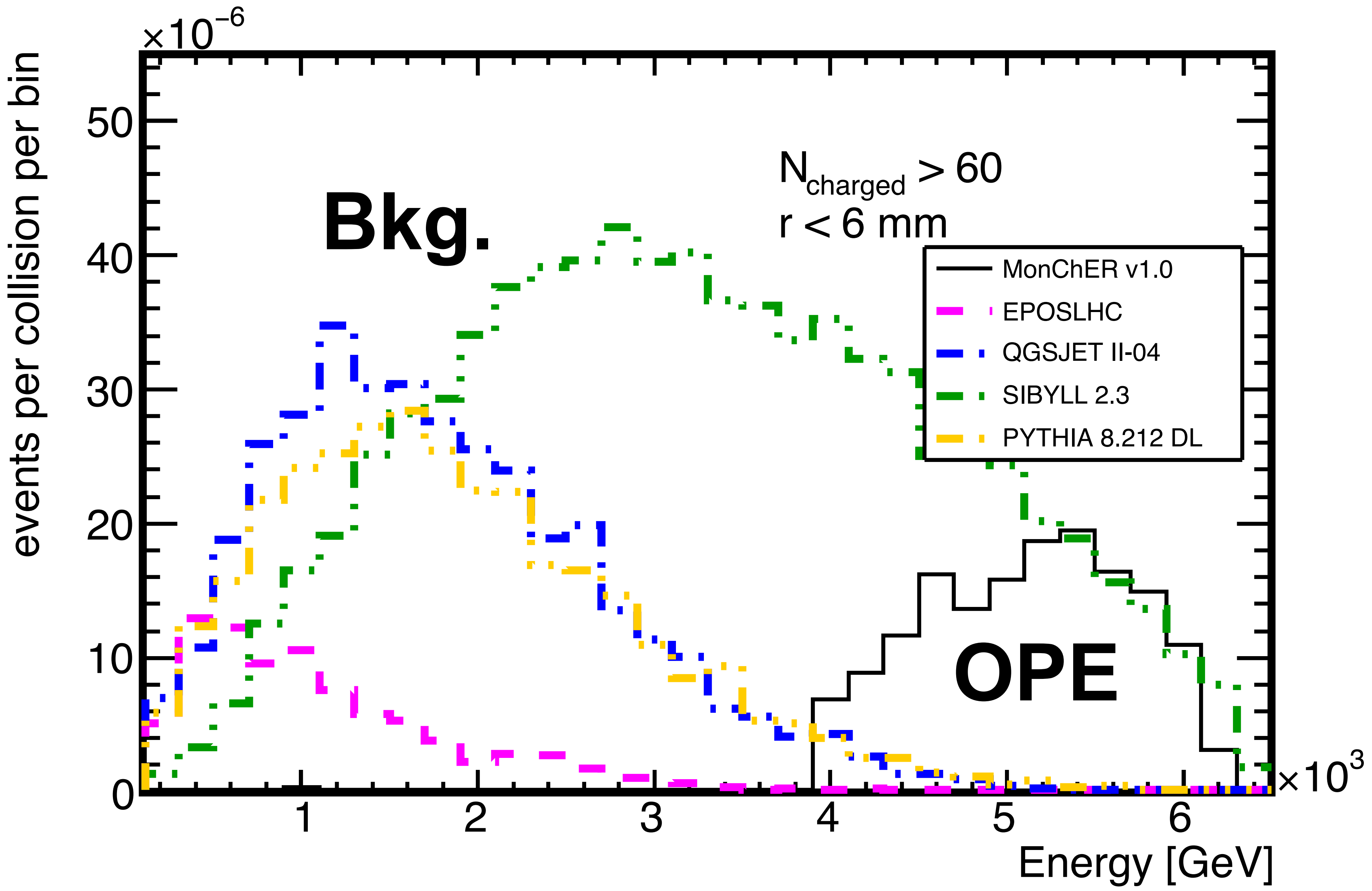
✓ Improve readout speed of silicon DAQ
✓ New trigger for high energy π^0, η, K^0_S

Joint operation with ATLAS

- Increase the statistics of common events
  → Improve the results of current joint analyses
- Operation with RPs (ALFA and AFP)
  - Study of hadronization at single diffractive events
  - Measurement of Δ resonance (→ p + π^0)
- Joint operation with ATLAS ZDC
  - Improvement of energy resolution for hadronic showers with thicker detectors: LHCf (1.7 λ) + ZDC (4.5 λ)
    → from 40% to 20 %
  - p-π cross section measurement via one-pion exchange (OPE) process



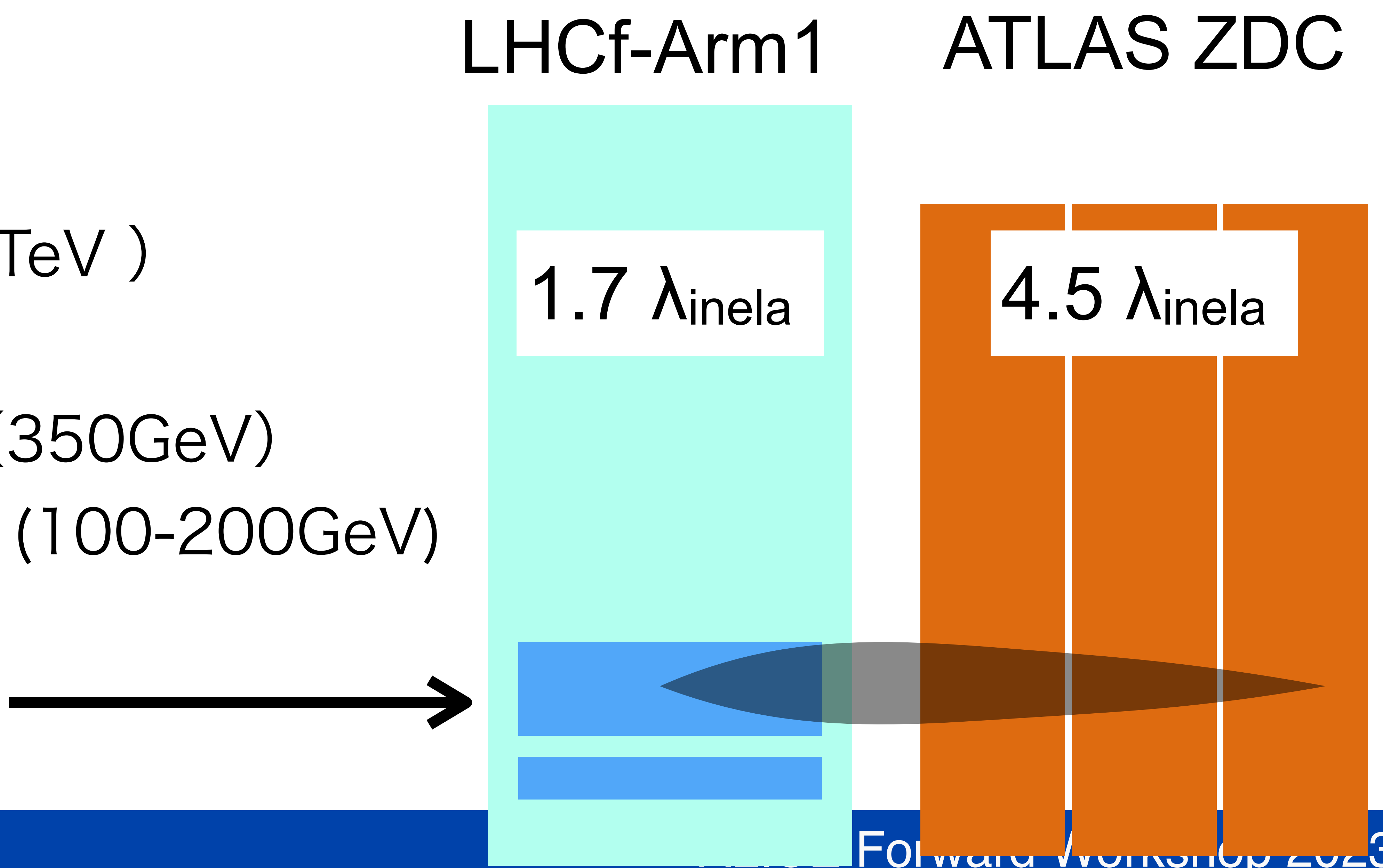


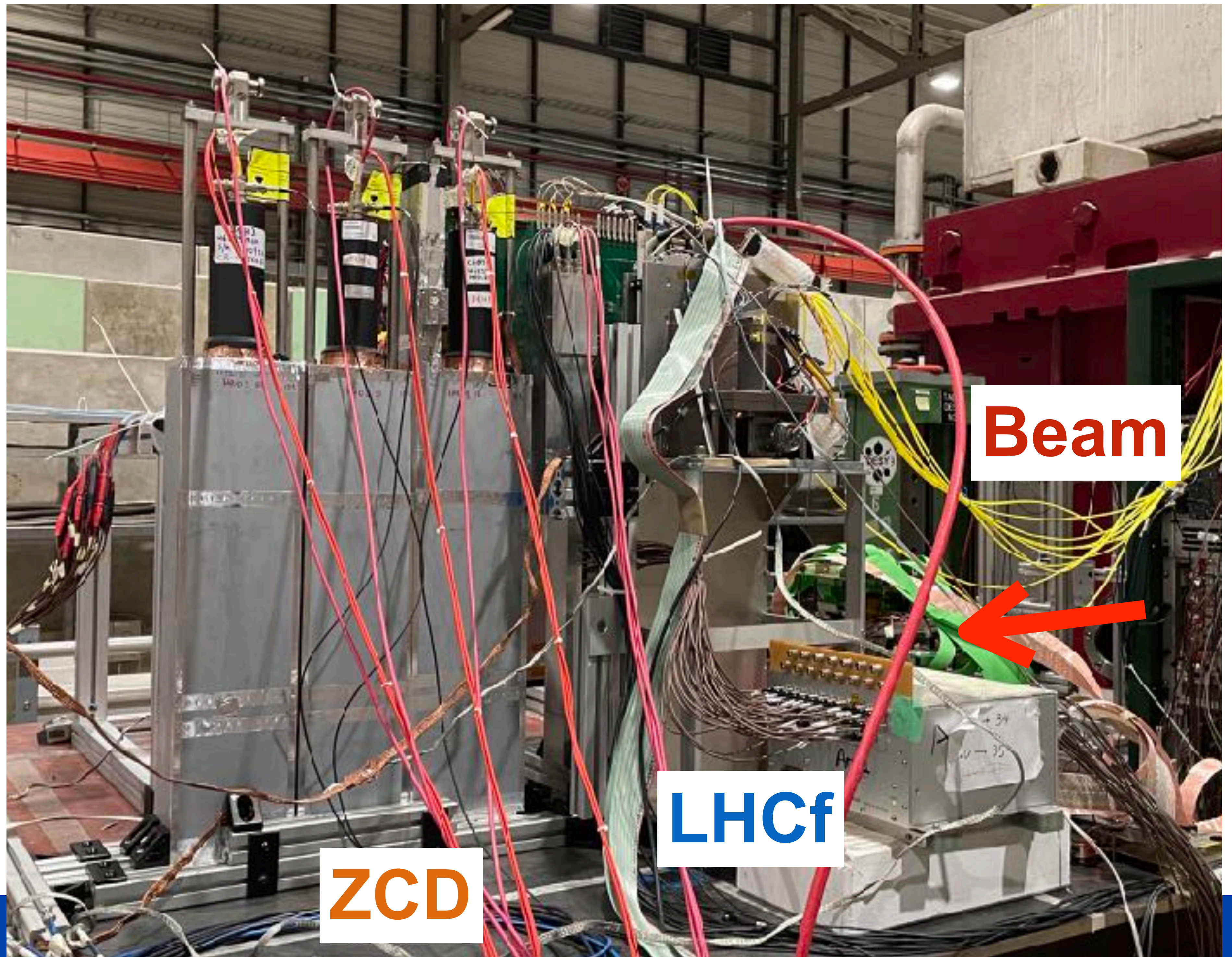


Beam test in 2021

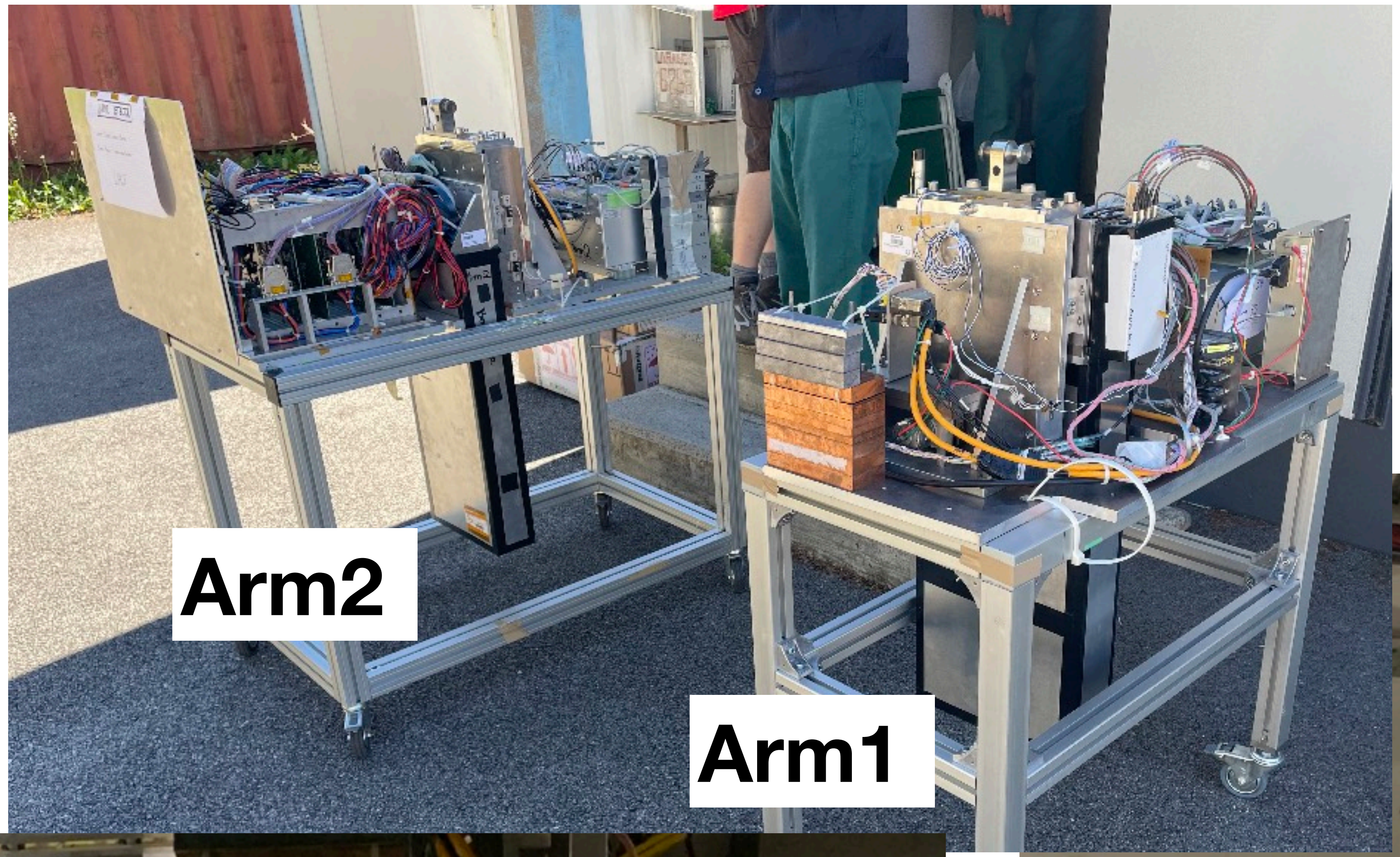
- Beam test @ CERN-SPS H4 line
  - Test of the upgraded DAQ system
    → Confirmed the improvement of readout speed.
    Arm2 Max DAQ: 0.8 kHz ➡ 2 kHz
  - Joint beam test with ATLAS ZDC
    → Confirmed energy resolution for hadronic showers
    40% (LHCf alone) → 21% (LHCf+ZDC)

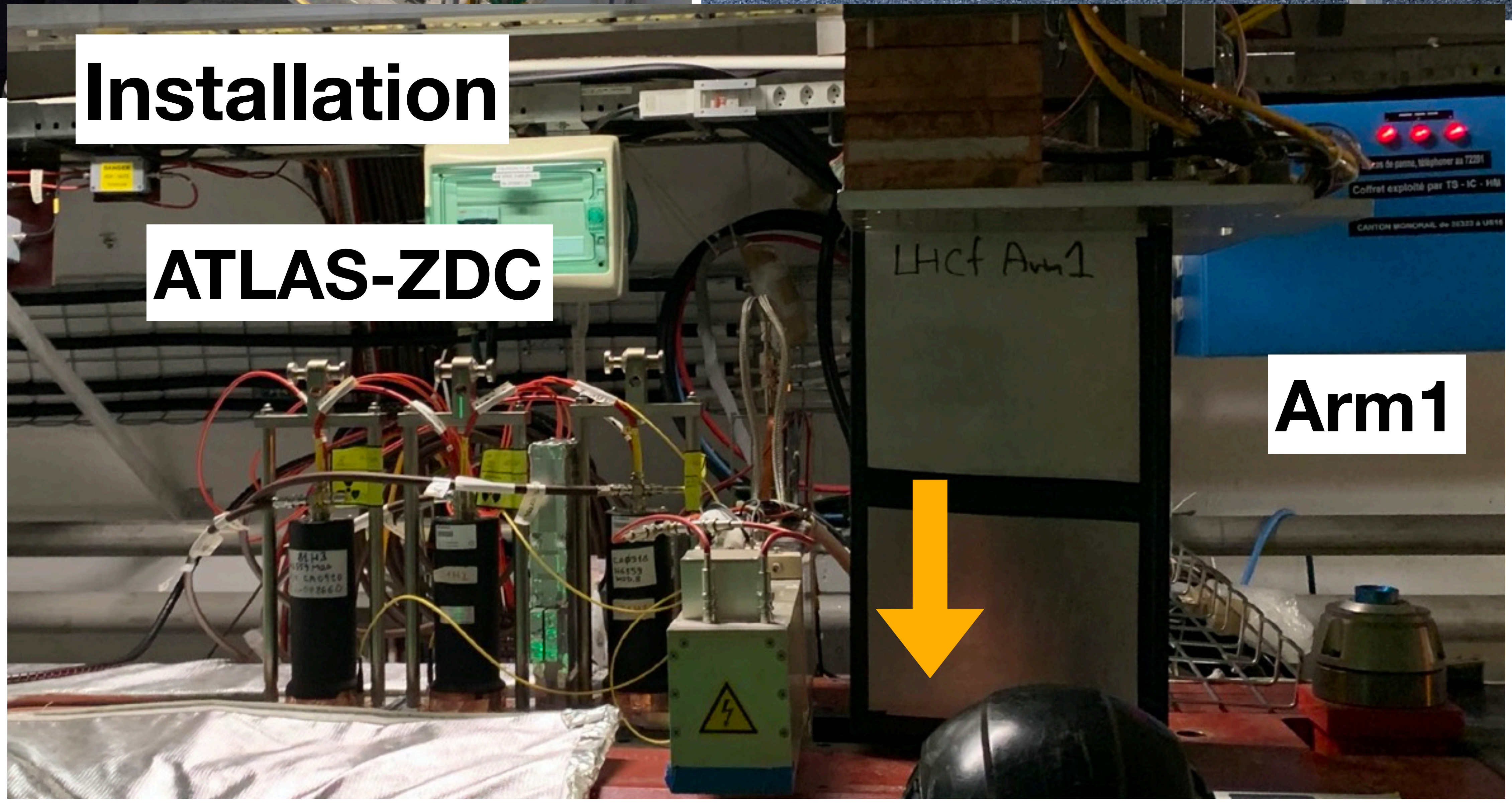
@LHC：
Neutron（E<7 TeV）
@Beam Test：
Proton beam（350GeV)
Electron beam (100-200GeV)



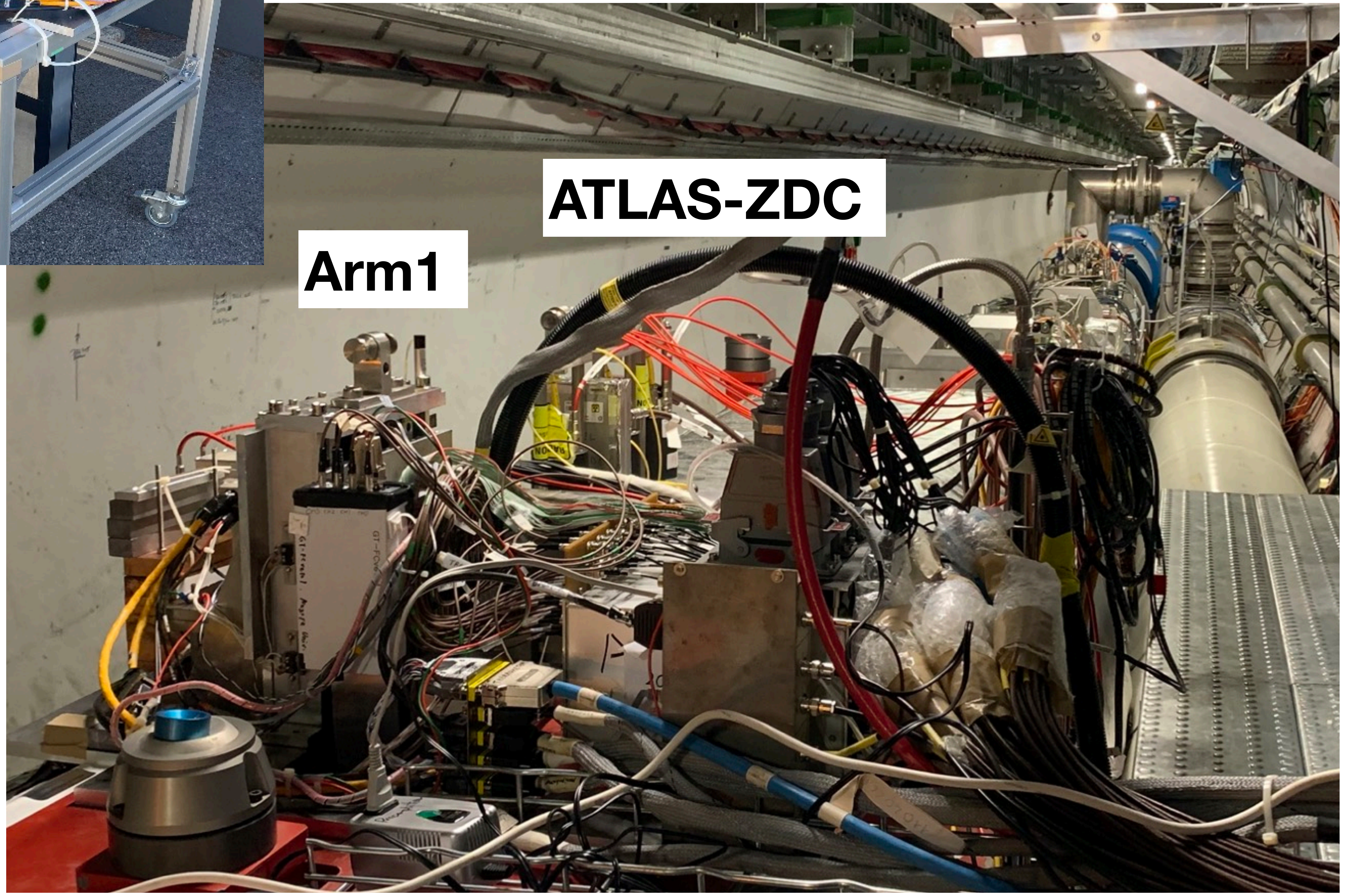


Preparation / installation

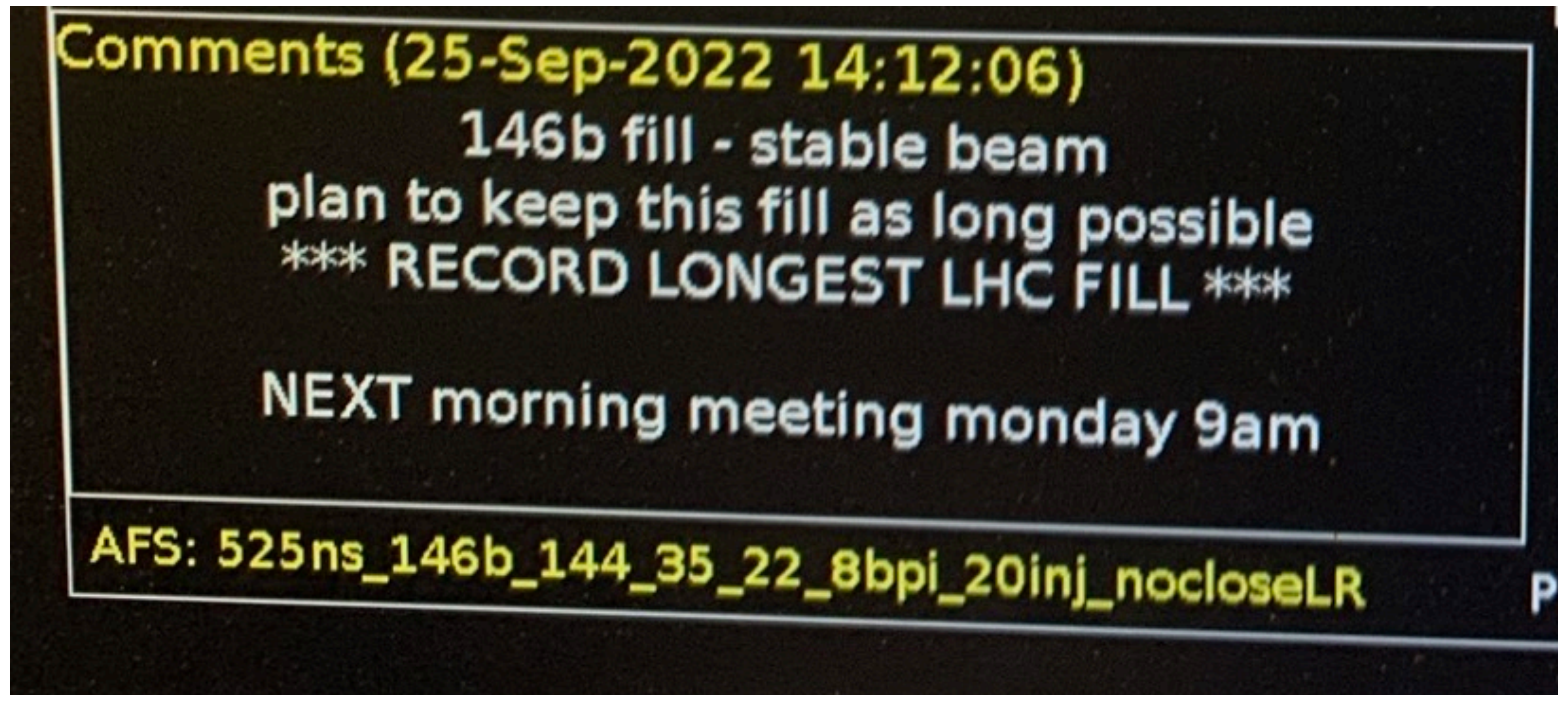




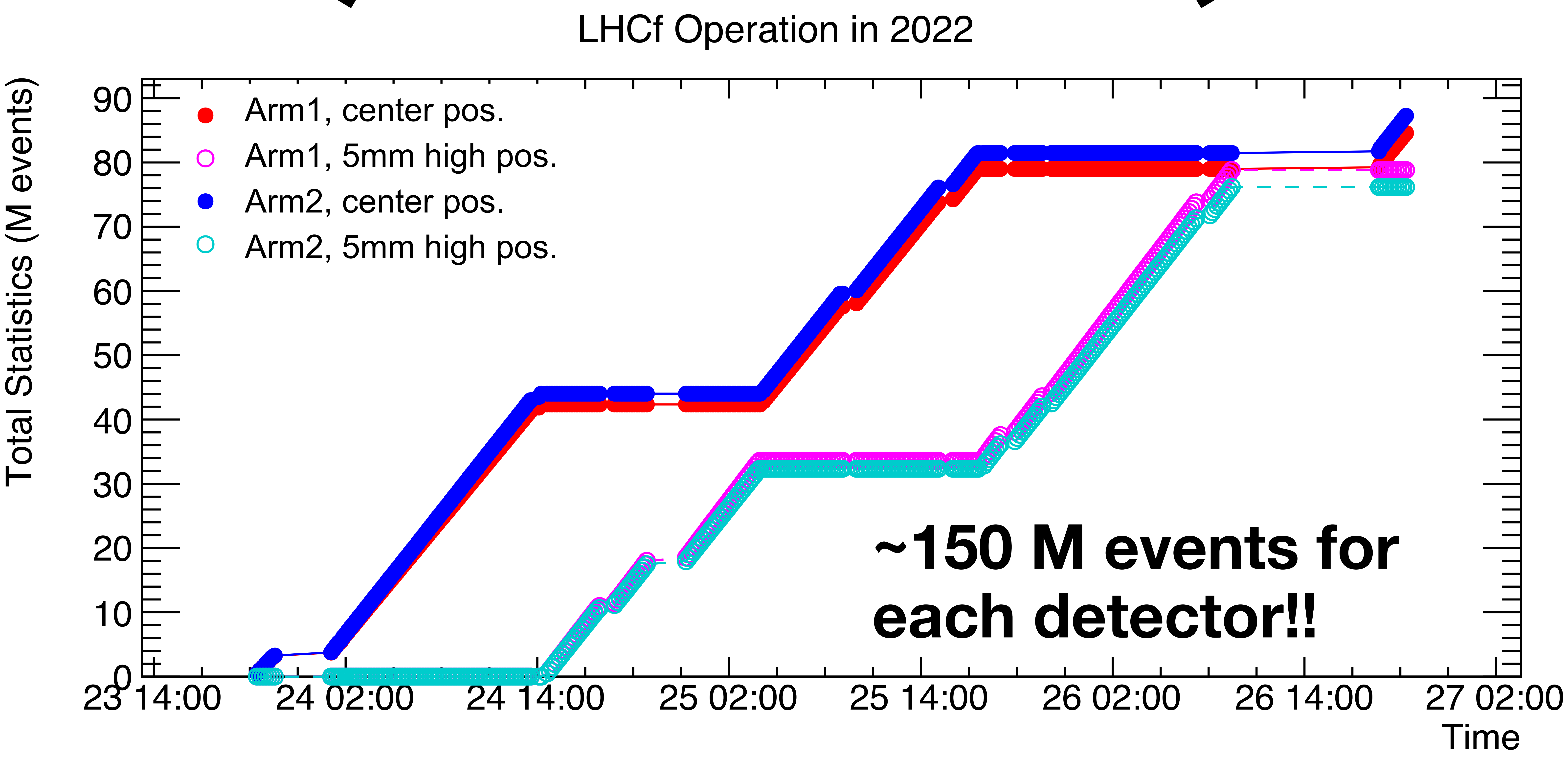
Install/Remove at each operation to avoid the radiation damage.



Operation in 24-27 September

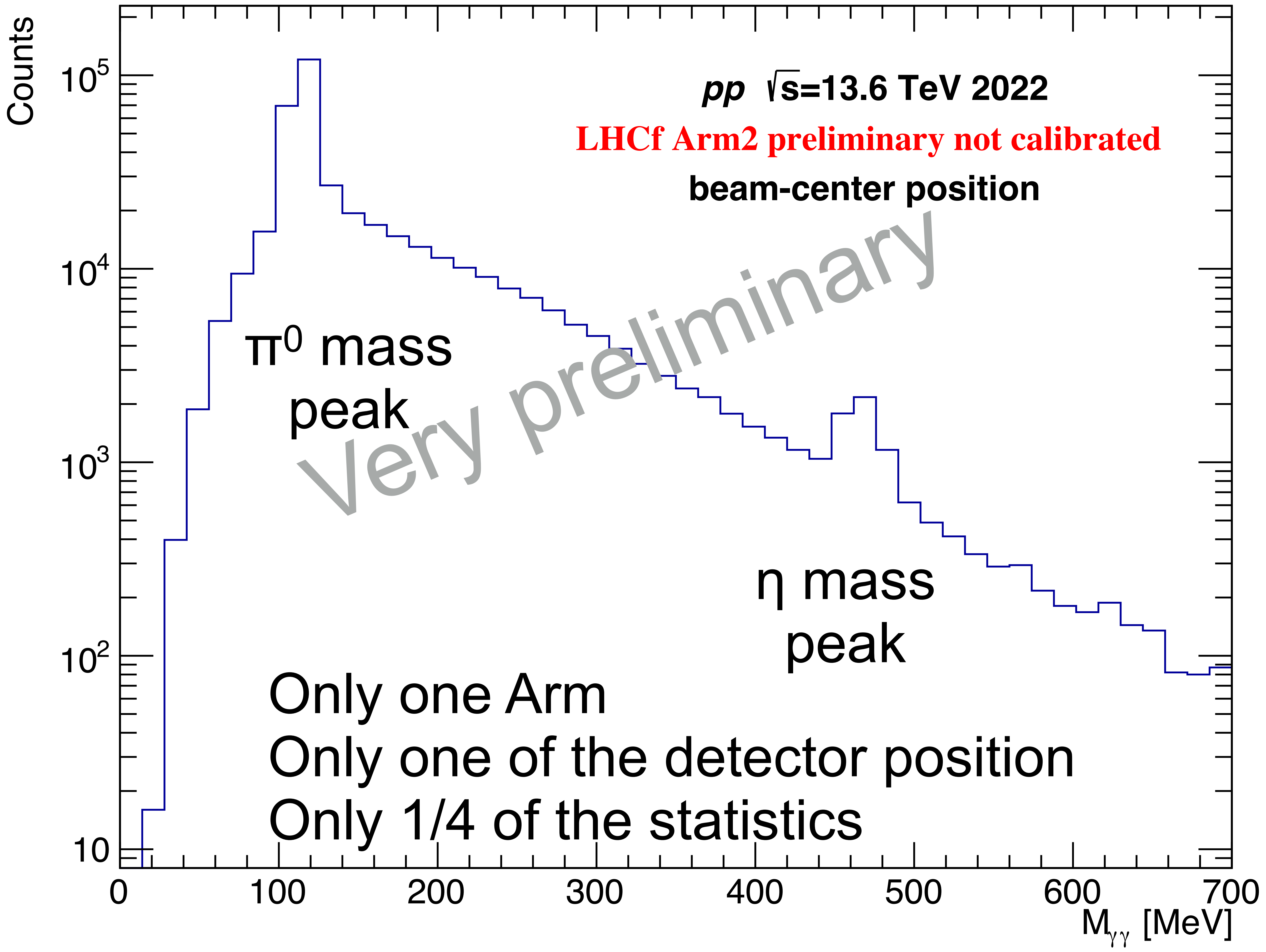


Stable beams for more than 57 hours
(Record the Longest LHC Fill)

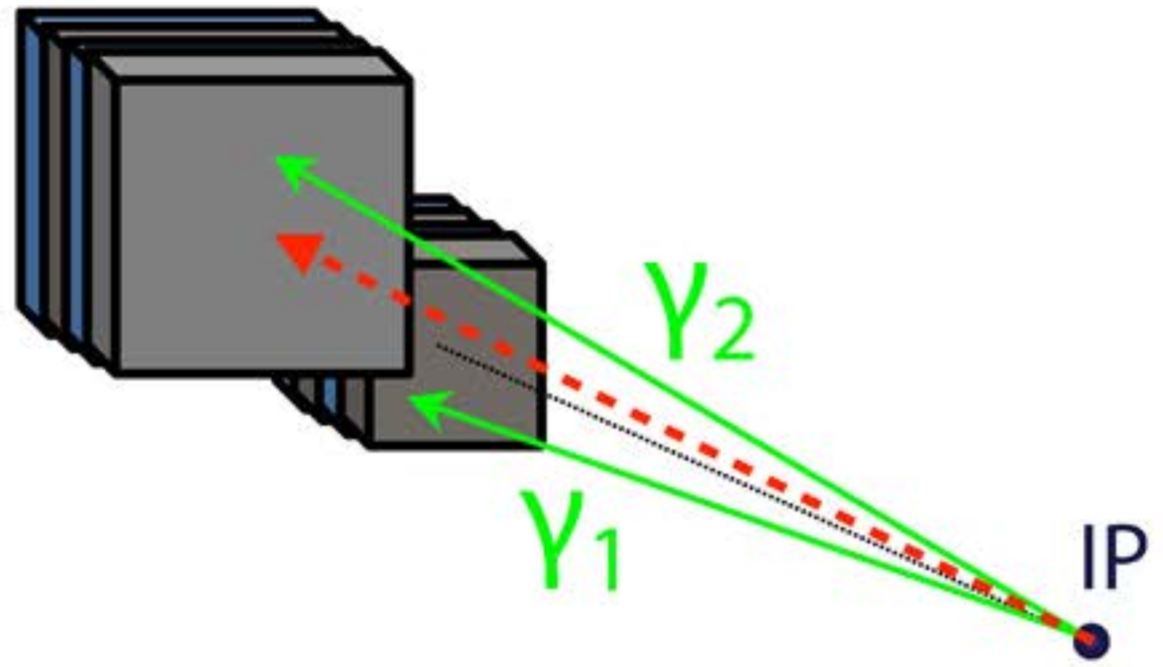


Sent LHCf triggers to ATLAS DAQ and recoded all events in their disk,

Obtained Data



Reconstructed mass from di-photon events



LHCf events:

Obtained η events: ~ 1500 events x 4

⇔ ~ 100 events in 2015 data set.

LHCf-ATLAS common events:

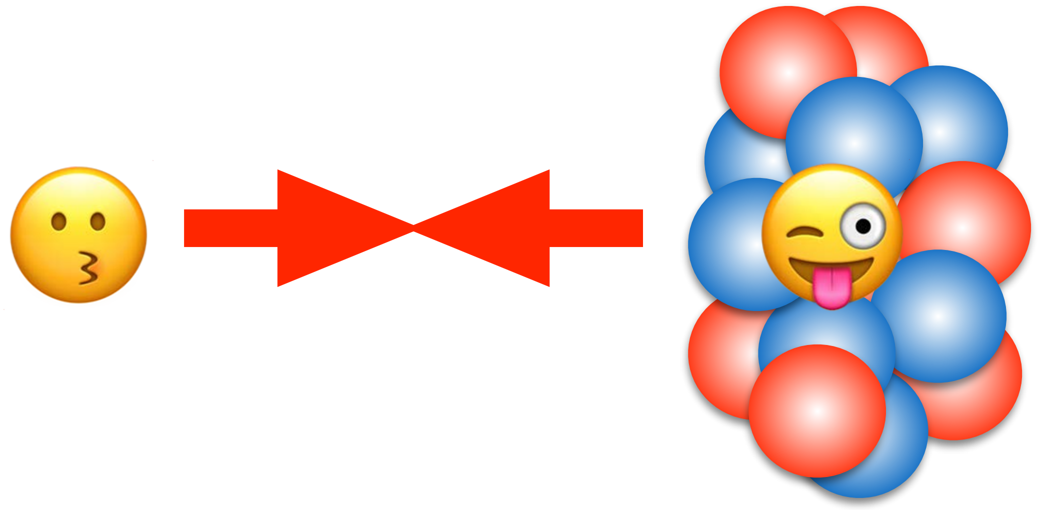
~300 M events ⇔ ~7 M events in 2015.

x ~ 50 increases

➡ **Improve/open many analysis channels with high statistics including K^0_s and Λ measurements**

pO (+OO) collisions in 2024

- 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
    - Change of the beam line configuration after Run3 to improve radiation protection
      Therefore no possibility of installation of LHCf detectors in Run 4 and later



- LHC schedule pO, OO collision in 2024
  - LHCf and other experiments requested it continuously since LHC start.
  - Dense discussions and reviews about pO+OO in 2021
    OO + pO Workshop in February https://indico.cern.ch/event/975877/overview
- Details of operation condition are under discussions
  - Requesting pO with the highest beam energy (E_{proton}=7TeV, $\sqrt{s_{NN}}$=10TeV)
  - About 7 days for pO + OO including the beam setup

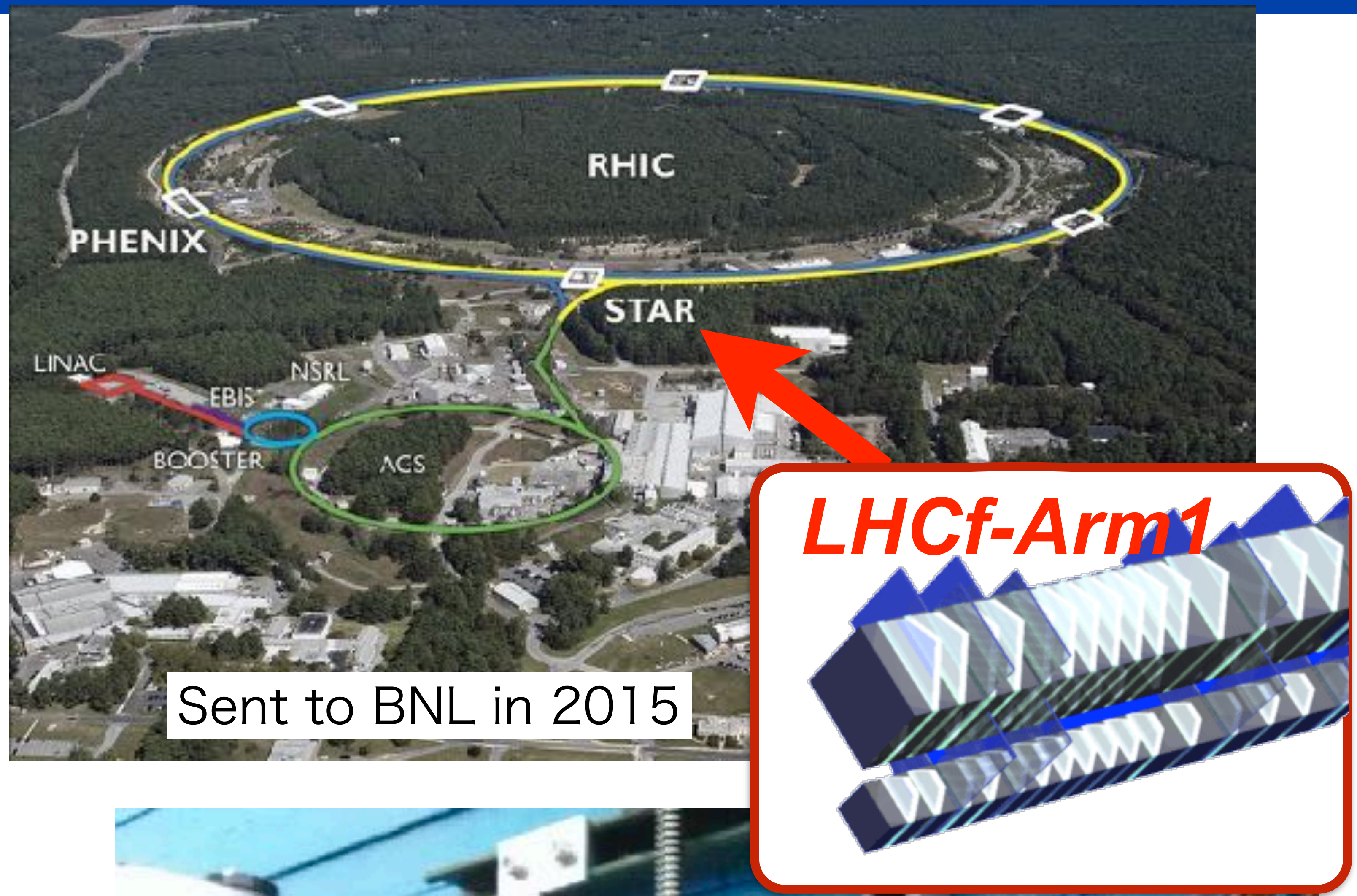
Summary

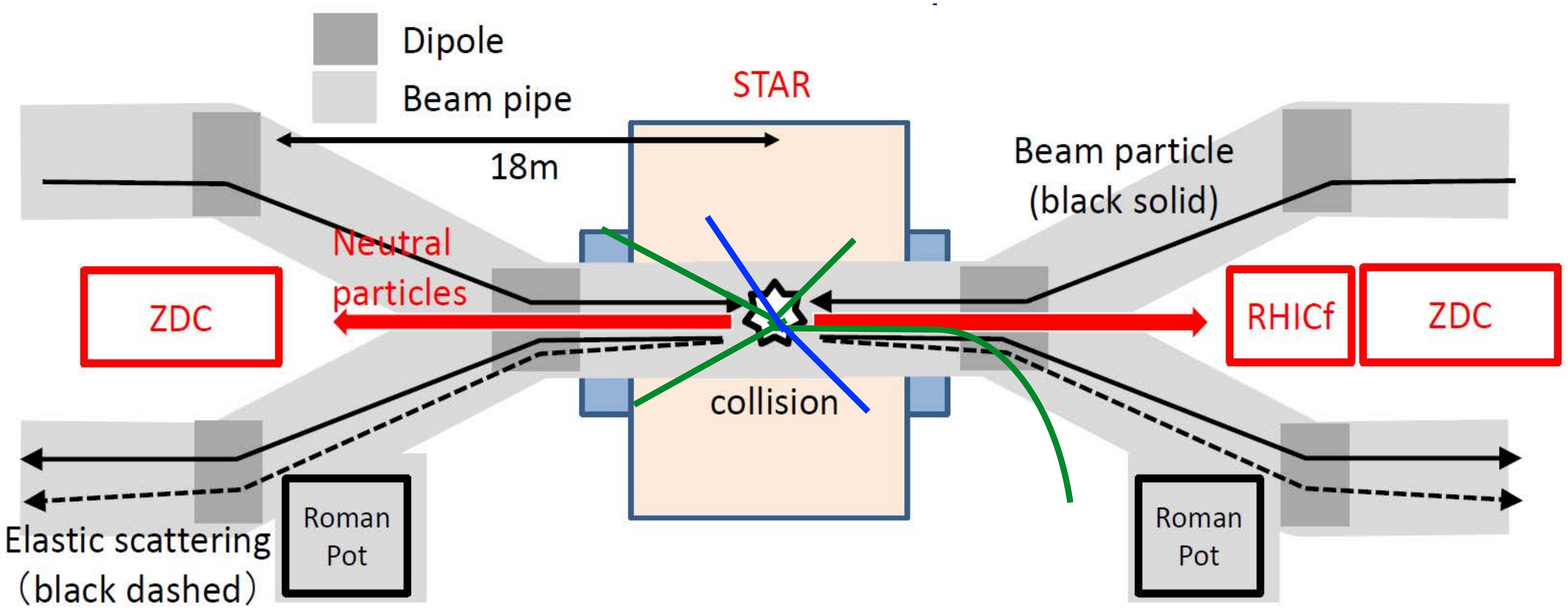
- LHCf measured forward neutral particles at LHC to study hadronic interaction for cosmic-ray air showers.
- Analyses are on-going
  - Eta measurement
  - Joint analyses with ATLAS are on-going
- LHC Run3 operations
  - LHCf pp in 2022
    - Successfully completed in September during a low-luminosity run
    - Obtained total 300 M events, enough to measure η, K^0_S
    - Joint operation with ATLAS including ZDC and RPs
  - LHCf pO + OO in 2024

Backup

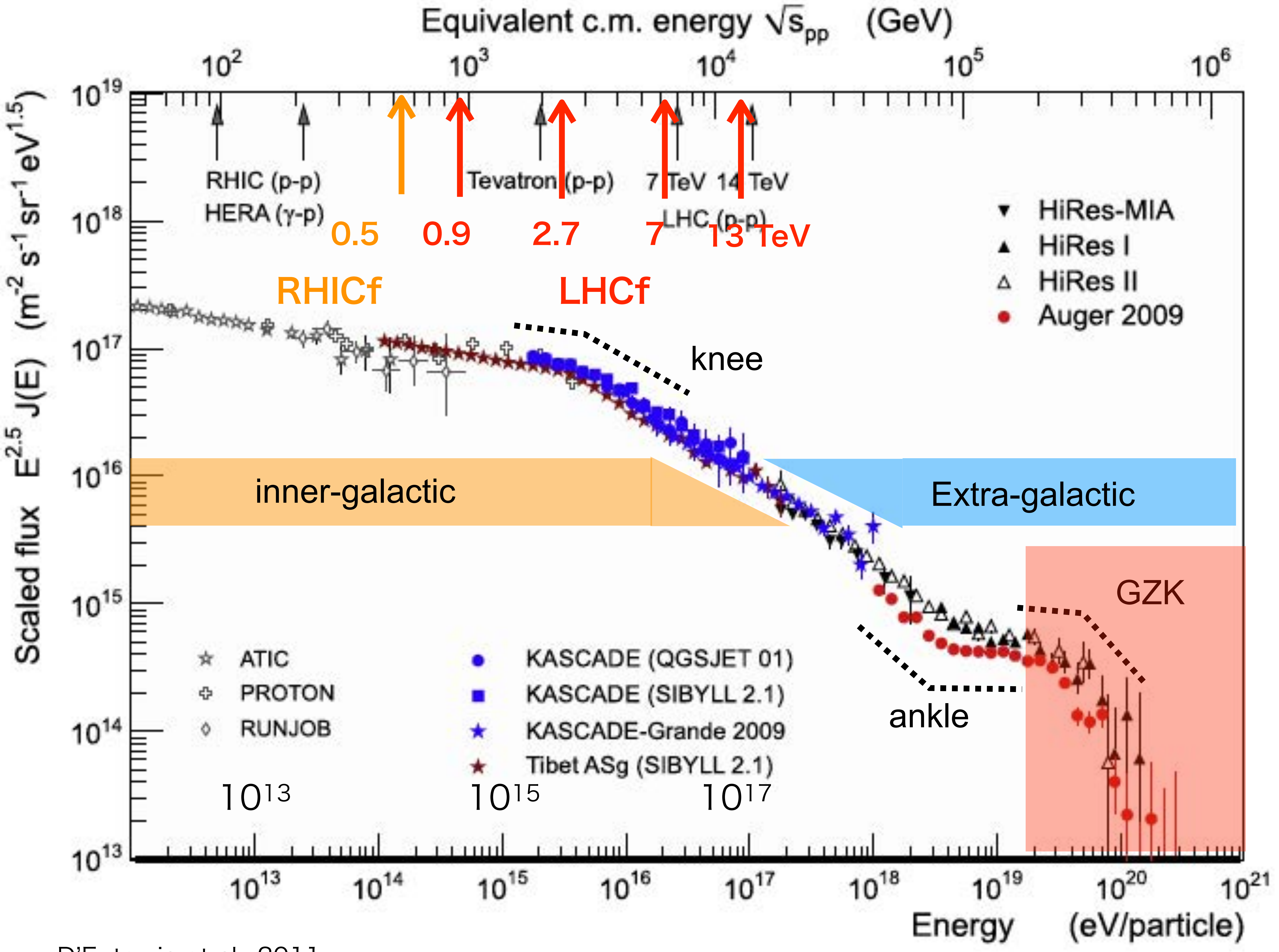
RHICf experiment

- *pp* $\sqrt{s}$= 510 GeV (polarized beam)
  - Equivalent to E_{lab} = 1.4×10^{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





Collision energy scaling

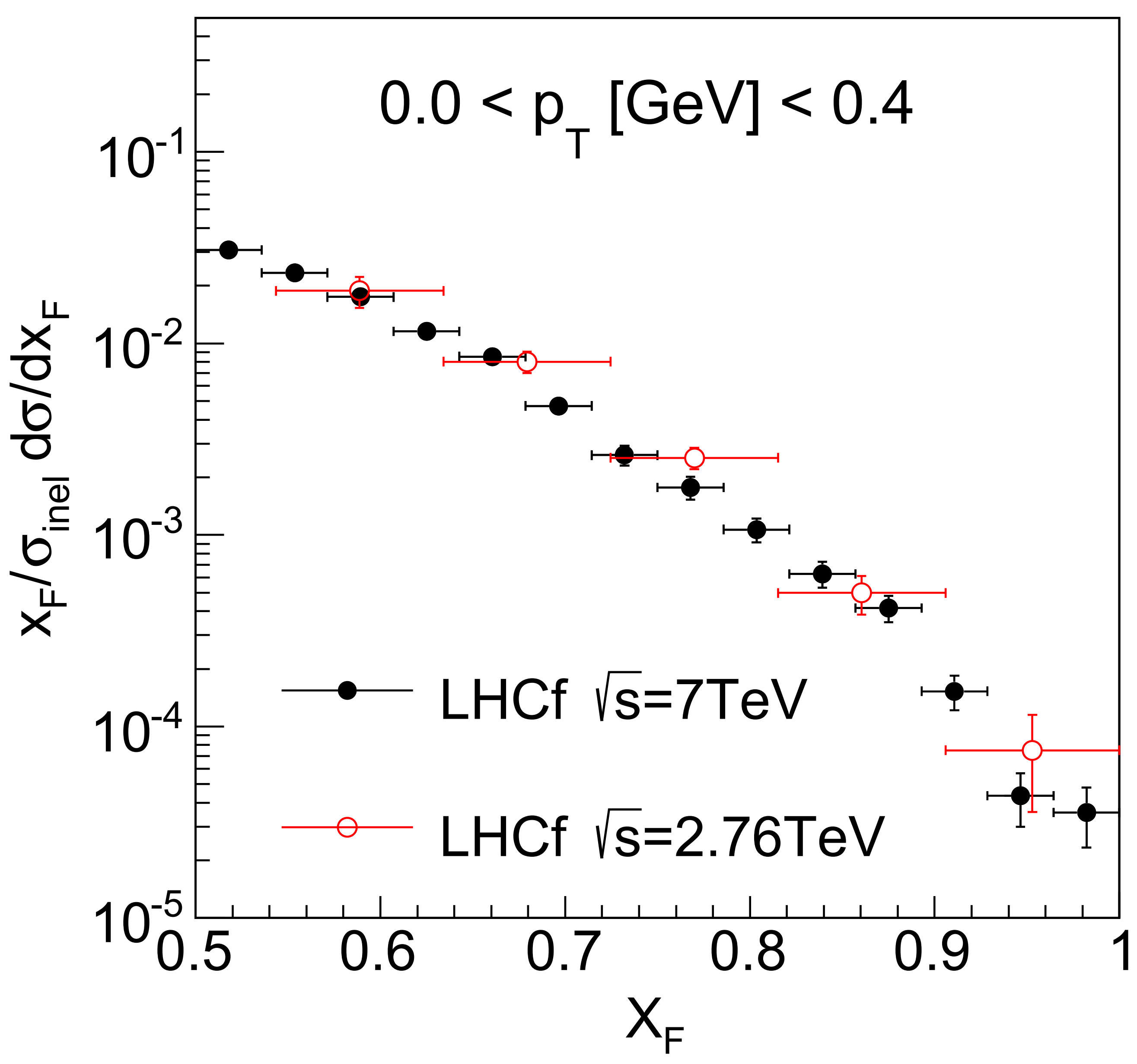


D'Enterria et al., 2011

- Wide energy range of CRs
- Continuous collision in Air shower

Important to test collision energy scaling known as Feynman scaling

LHCf ⇔ RHICf provide the test from 0.5 to 13 TeV (x 20)

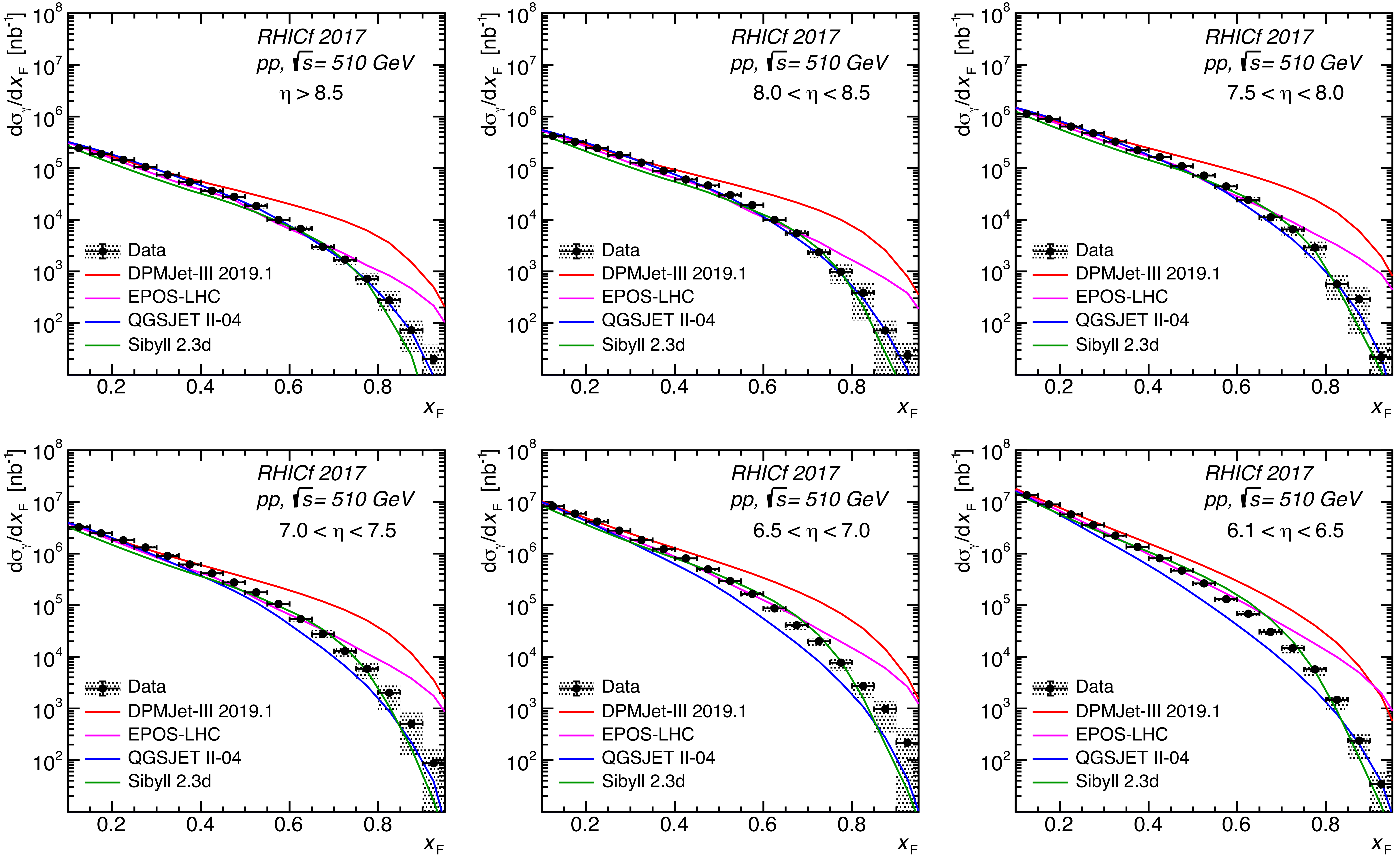


RHICf photon analysis

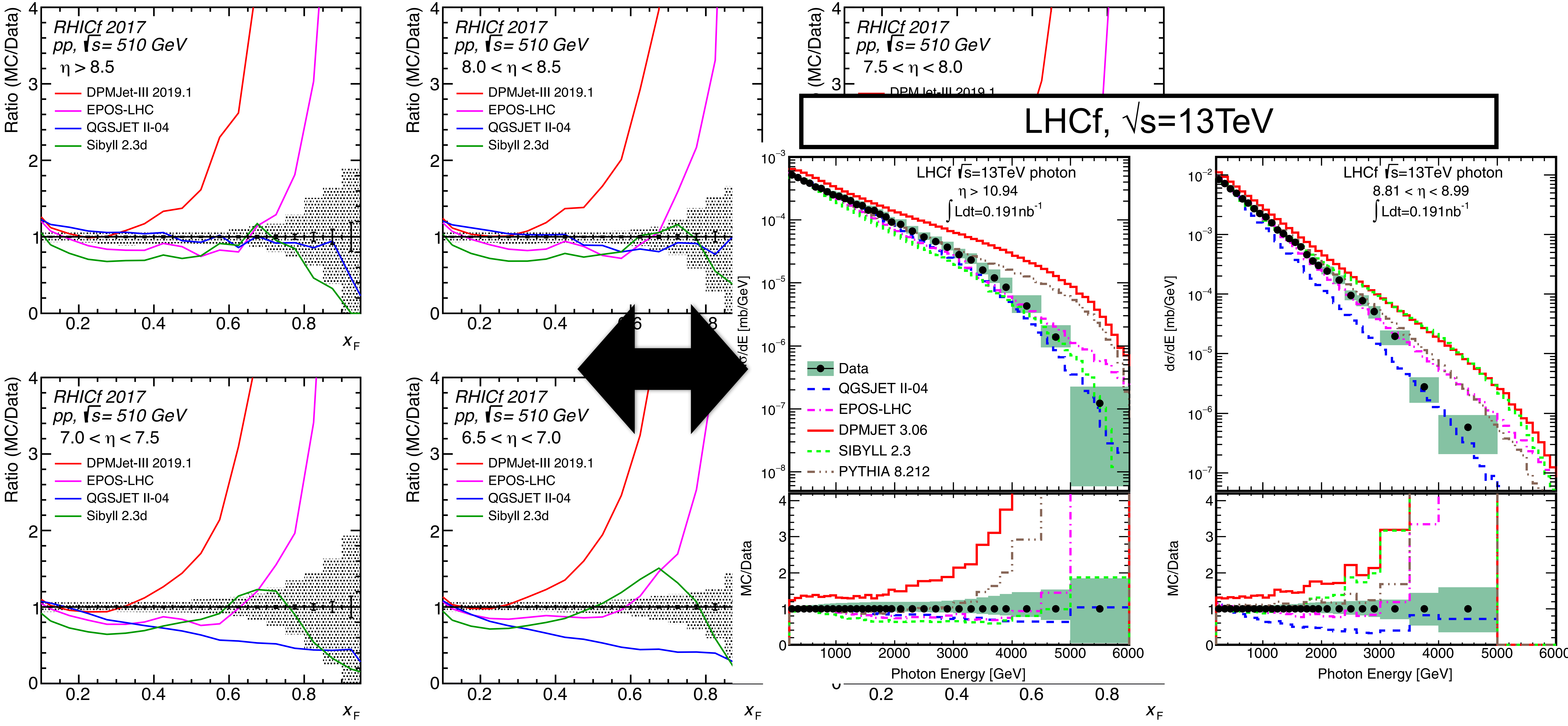
- Data
  - pp, √s = 0.51 TeV

Results of production cross-section measurement

Inclusive production cross-section



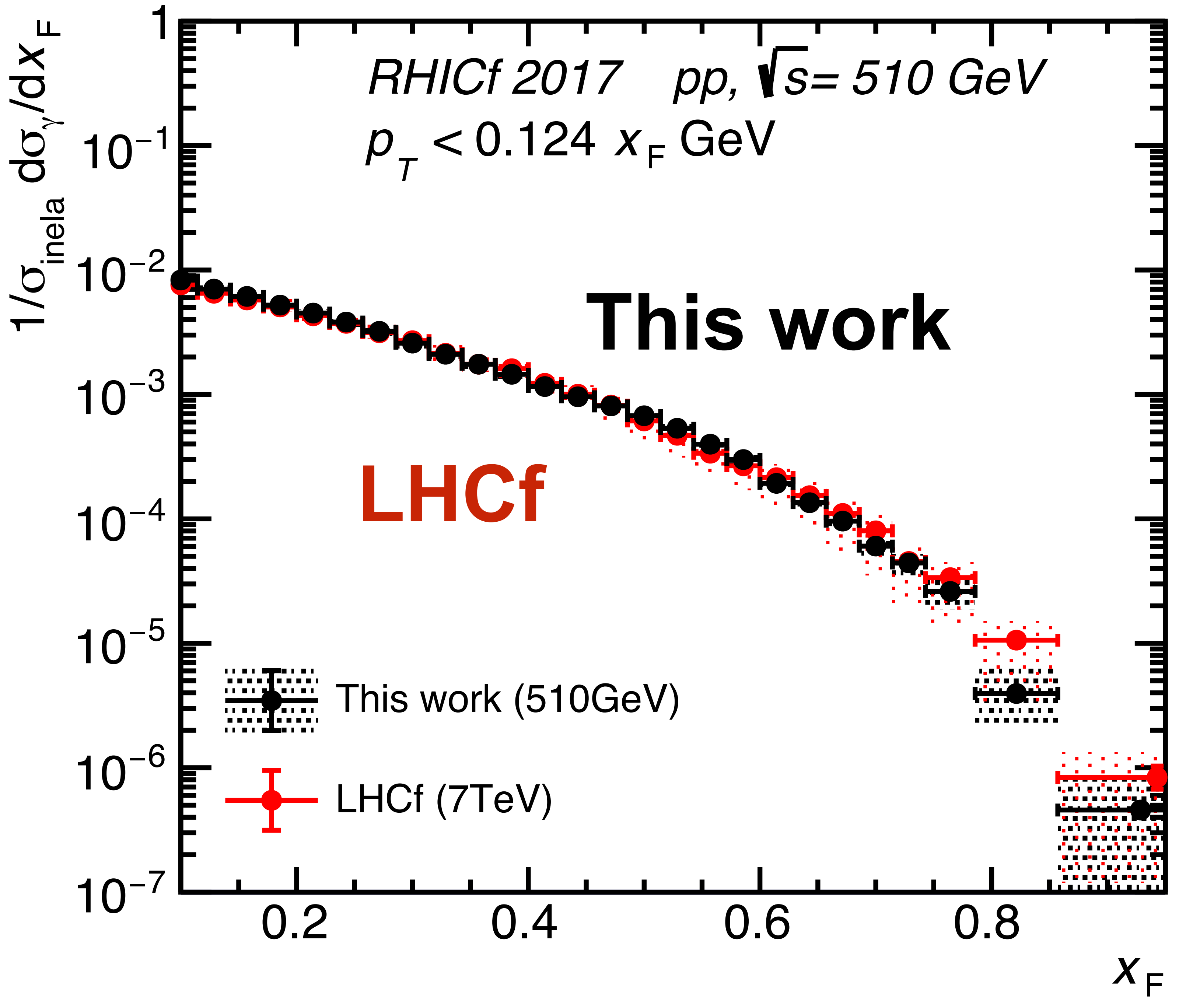
Ratio (MC/Data)



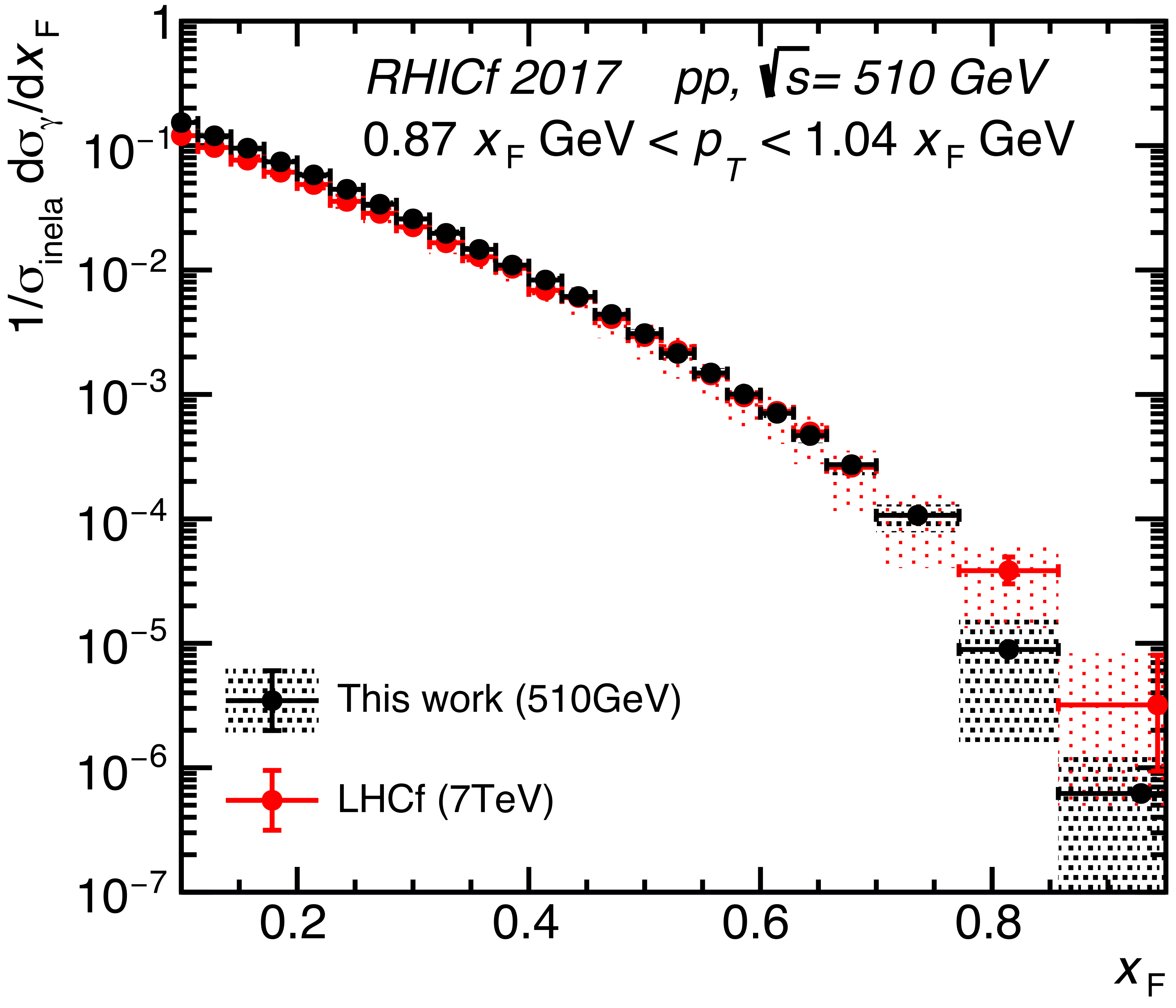
Test of collision energy scaling

- Comparison with LHCf ($\sqrt{s}$ = 7 and 13 TeV) photon results.
- Selected same X_F-p_T phase space coverage as those results
- Normalized by $\sigma_{inela.}$ (σ_{inela} = 48.3, 72.9, 79.5 mb for 0.5, 7, 13 TeV)

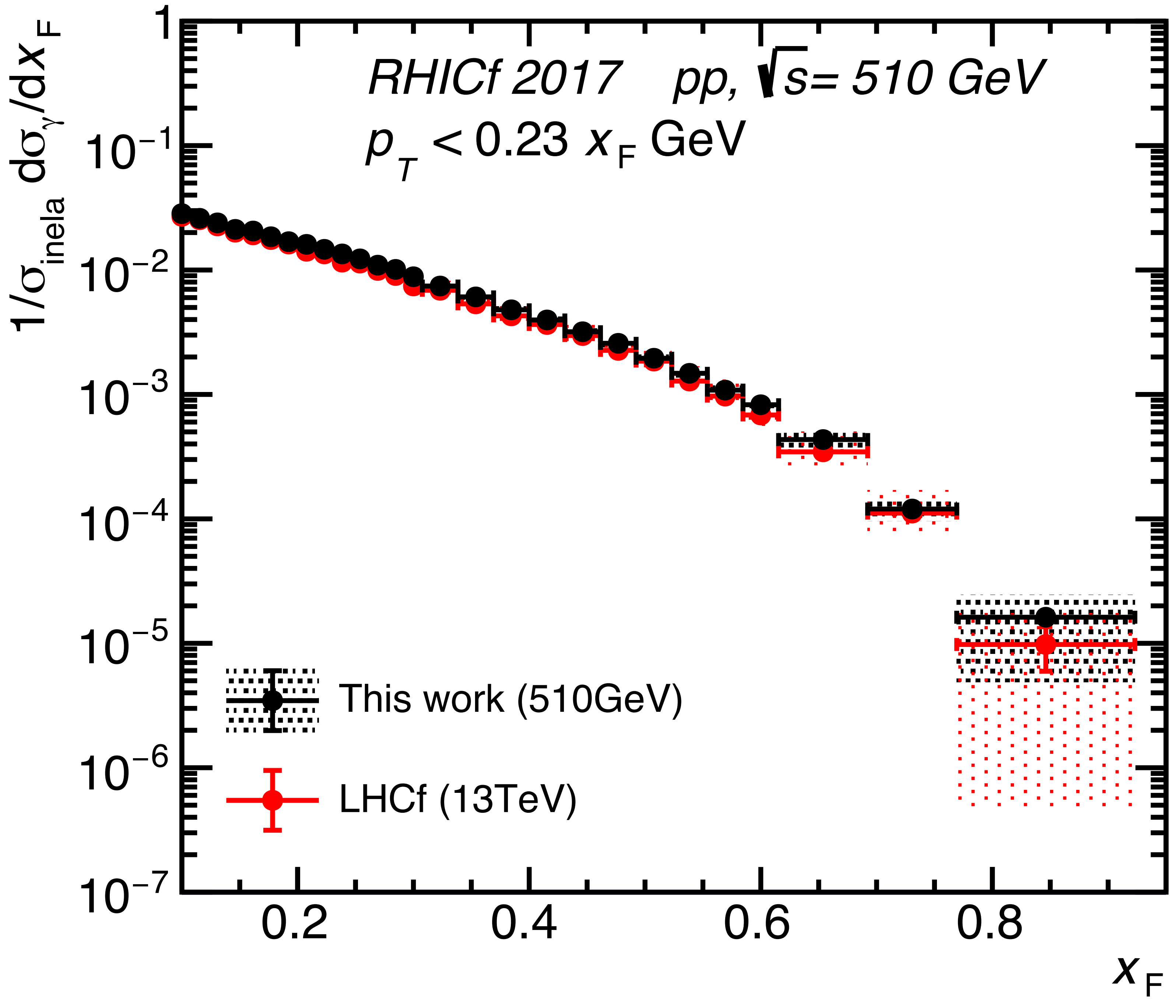
v.s. LHCf 7TeV η > 10.94



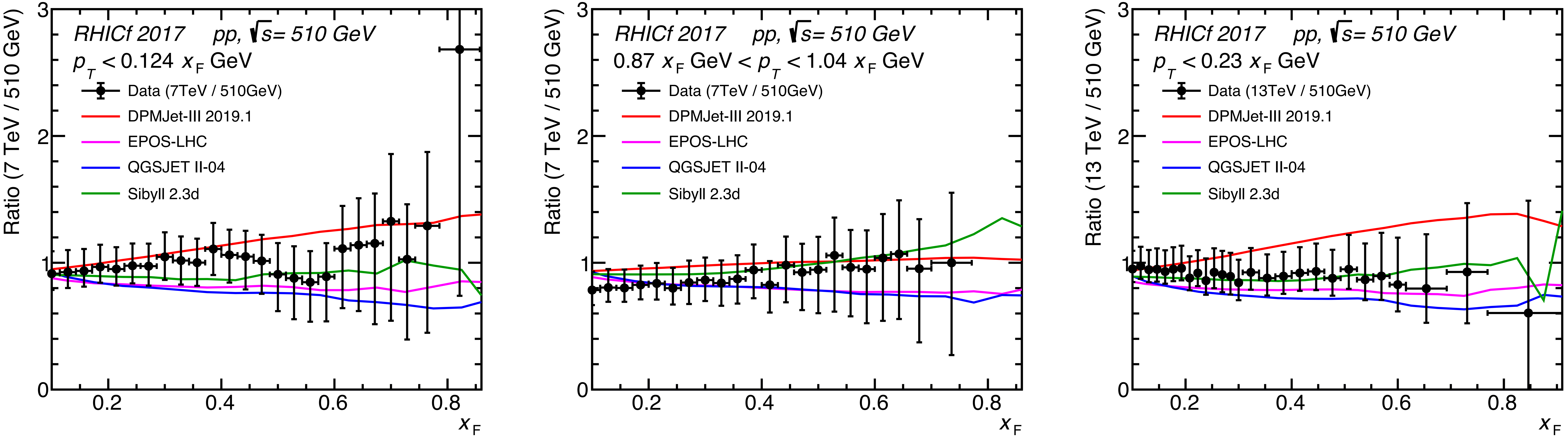
v.s. LHCf 7TeV 8.81 < η < 8.99



v.s. LHCf 13TeV η > 10.94



Ratio (7TeV or 13TeV/ 510GeV)



First confirmation of collision-energy scaling at zero degree photons.

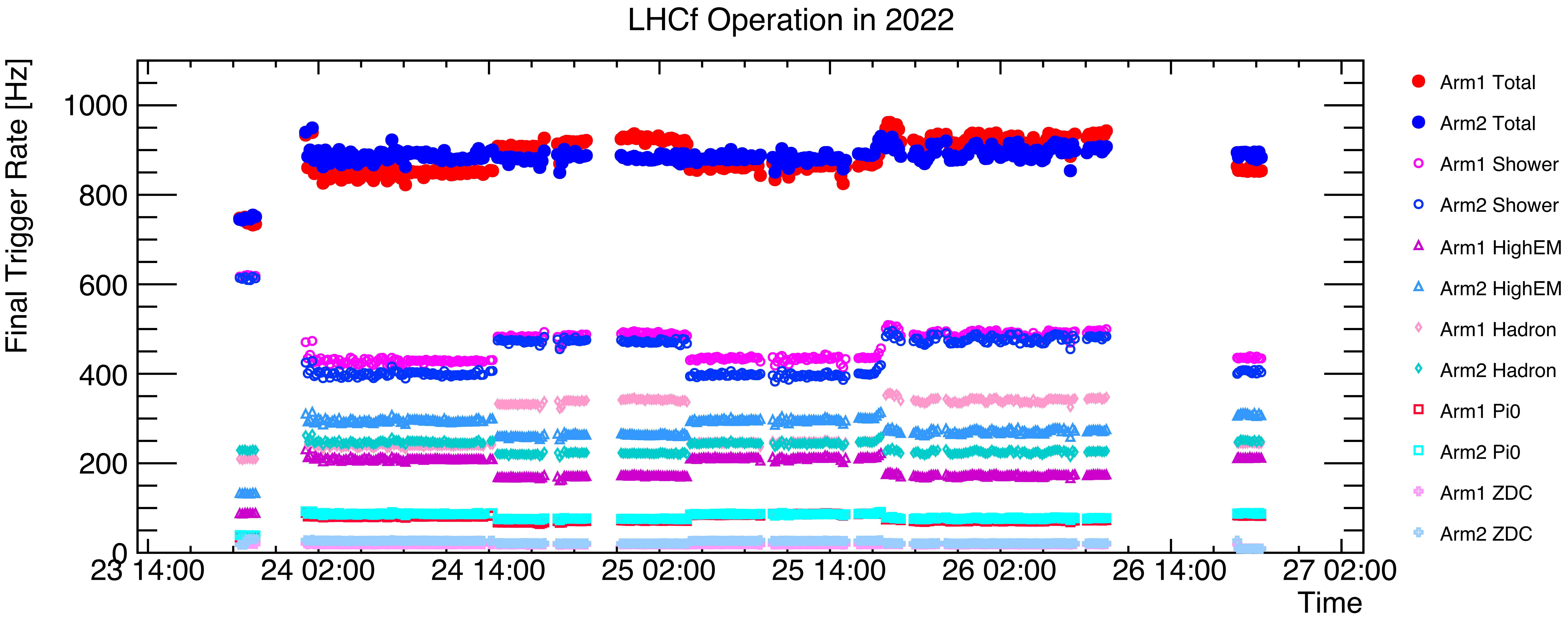
- Consistent with the scaling within the errors

  Lower ratio at X_F<0.4 of the middle plot can be explained by the difference of method with LHCf 7TeV paper.

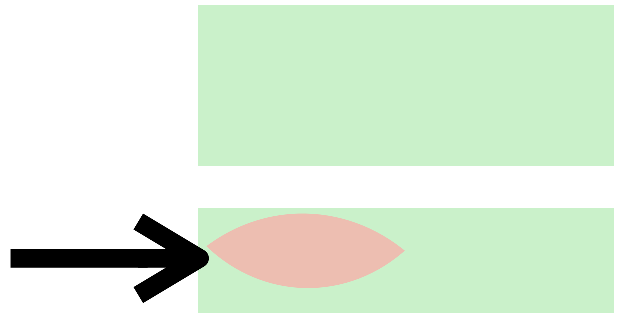
- No sensitivity to test weak X_F dependency predicted by some models.

  → Need an effort to reduce the errors in both LHCf and RHICf

6 Trigger modes



Shower Trg.



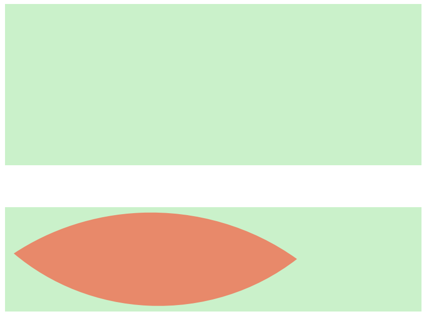
Baseline trigger
Any showers

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)

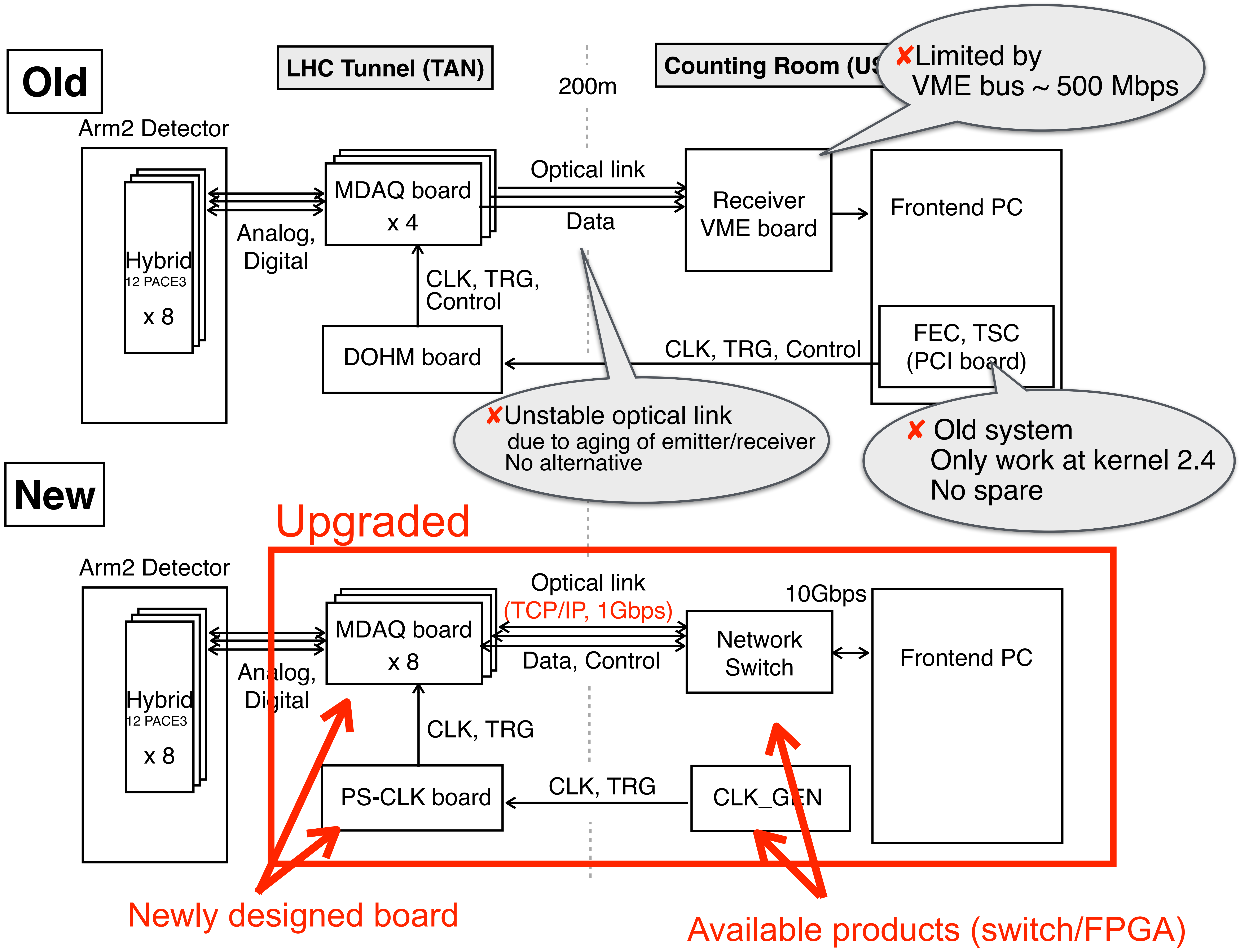
ZDC Trg.

Trigger from ZDC

Pedestal Trg.

= zero bias trigger

Upgrade of Silicon readout system



- Readout speed of silicon data for 3k channels, 14 kB/event

  Old system: 0.8 msec / event
  → New system: 0.1 msec / event

- Readout speed of all data including other data

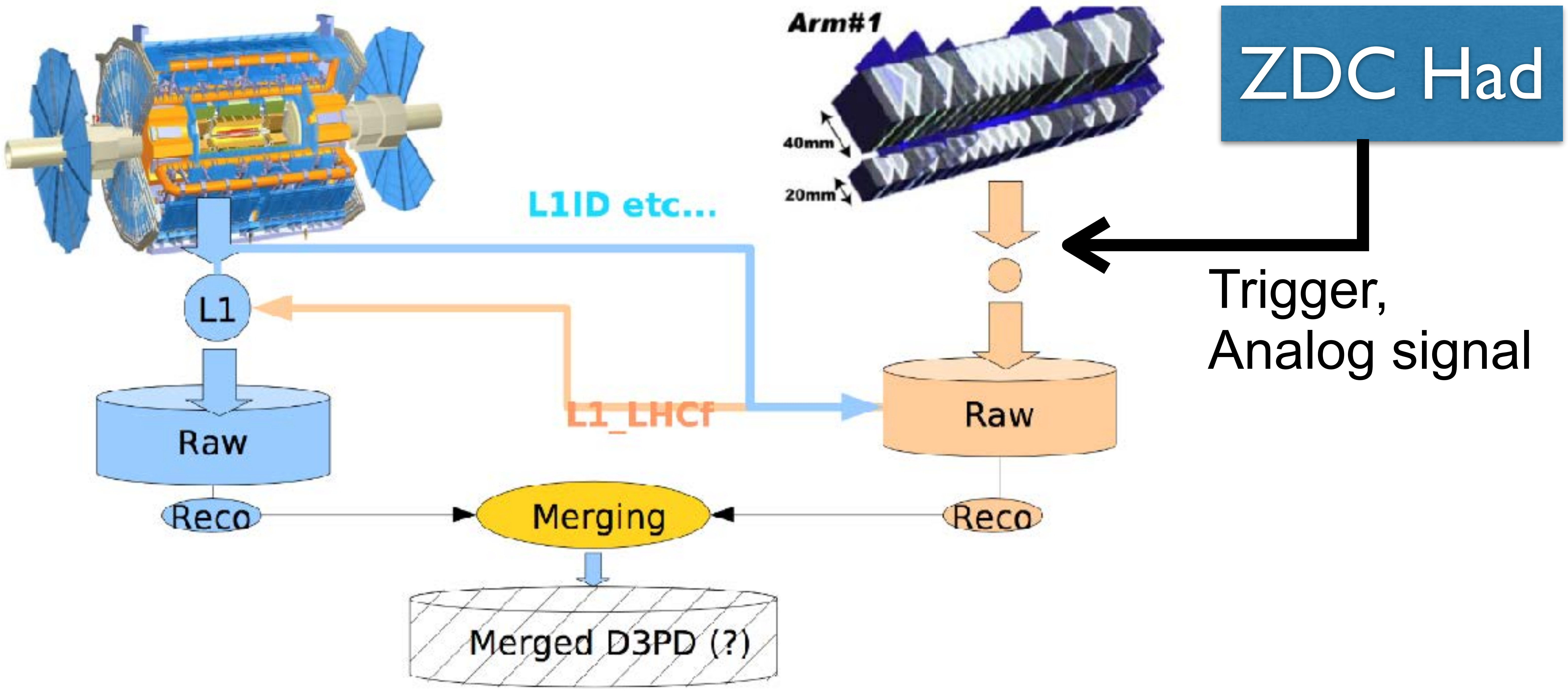
  Old system: 1.2 msec
  → New system: ~ 0.4 msec 1/3

New MDAQ board

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

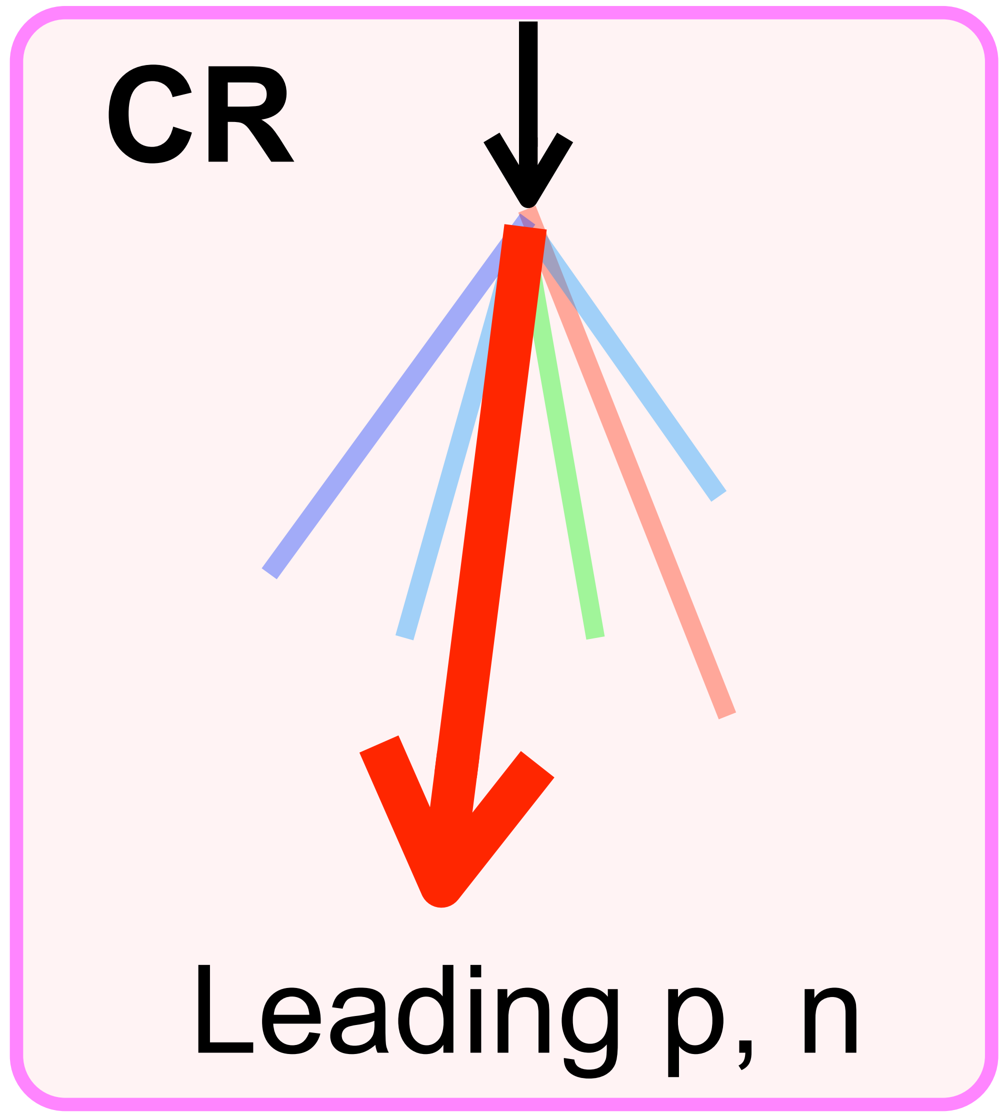


Improvement from 2015 run

- 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)

Inelasticity measurement at pp



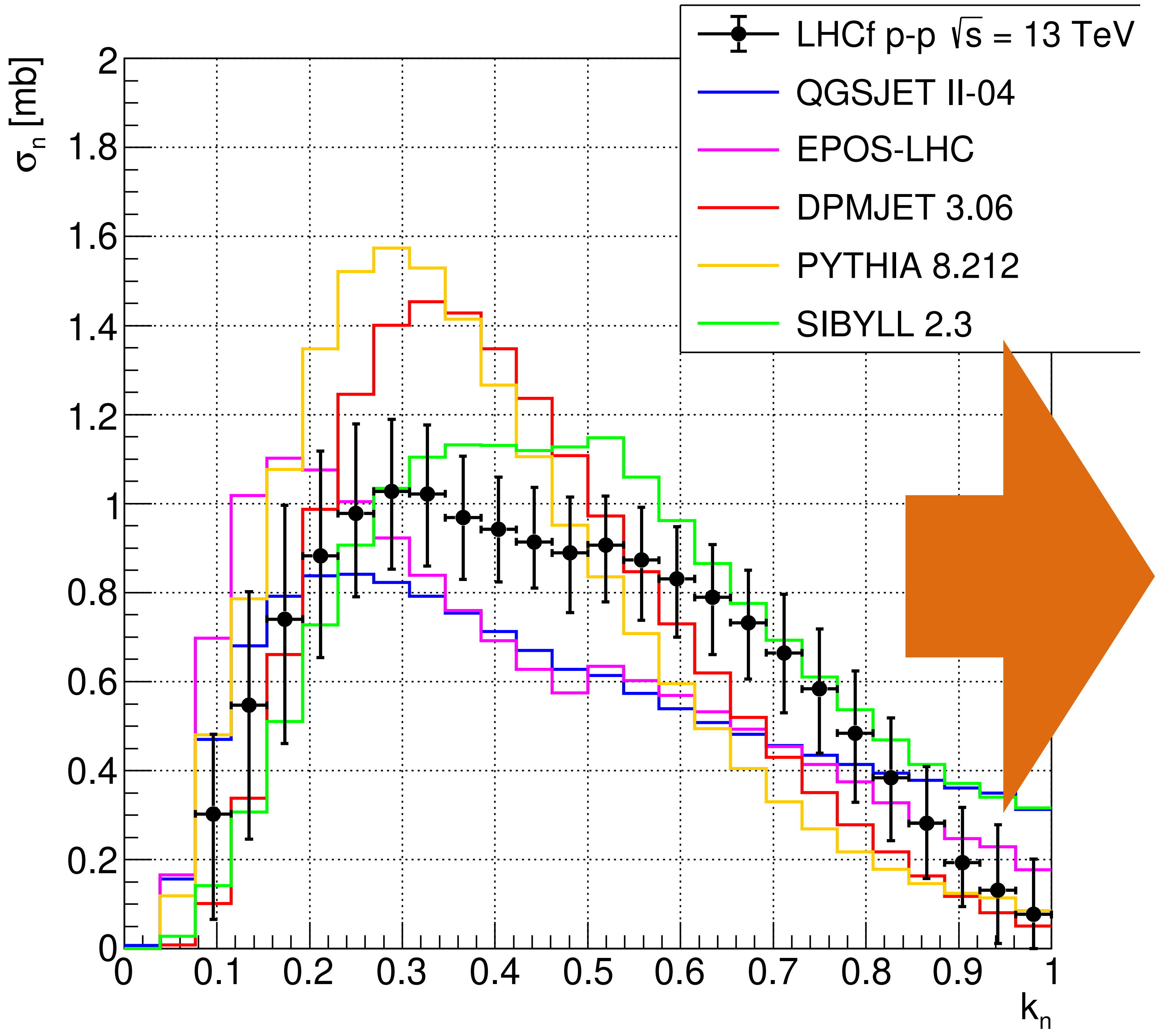
- Inelasiticity (k = 1- $E_{\mathrm{leading}}/E_{\mathrm{CR}}$), energy fraction used for particle productions, is one of the most important parameters for understanding CR-air shower development.
- LHCf measures high energy neutrons, which can be leading baryons.
- 40% energy resolution for neutrons. ~ 10% contamination of K_0, Λ

Best agreement model

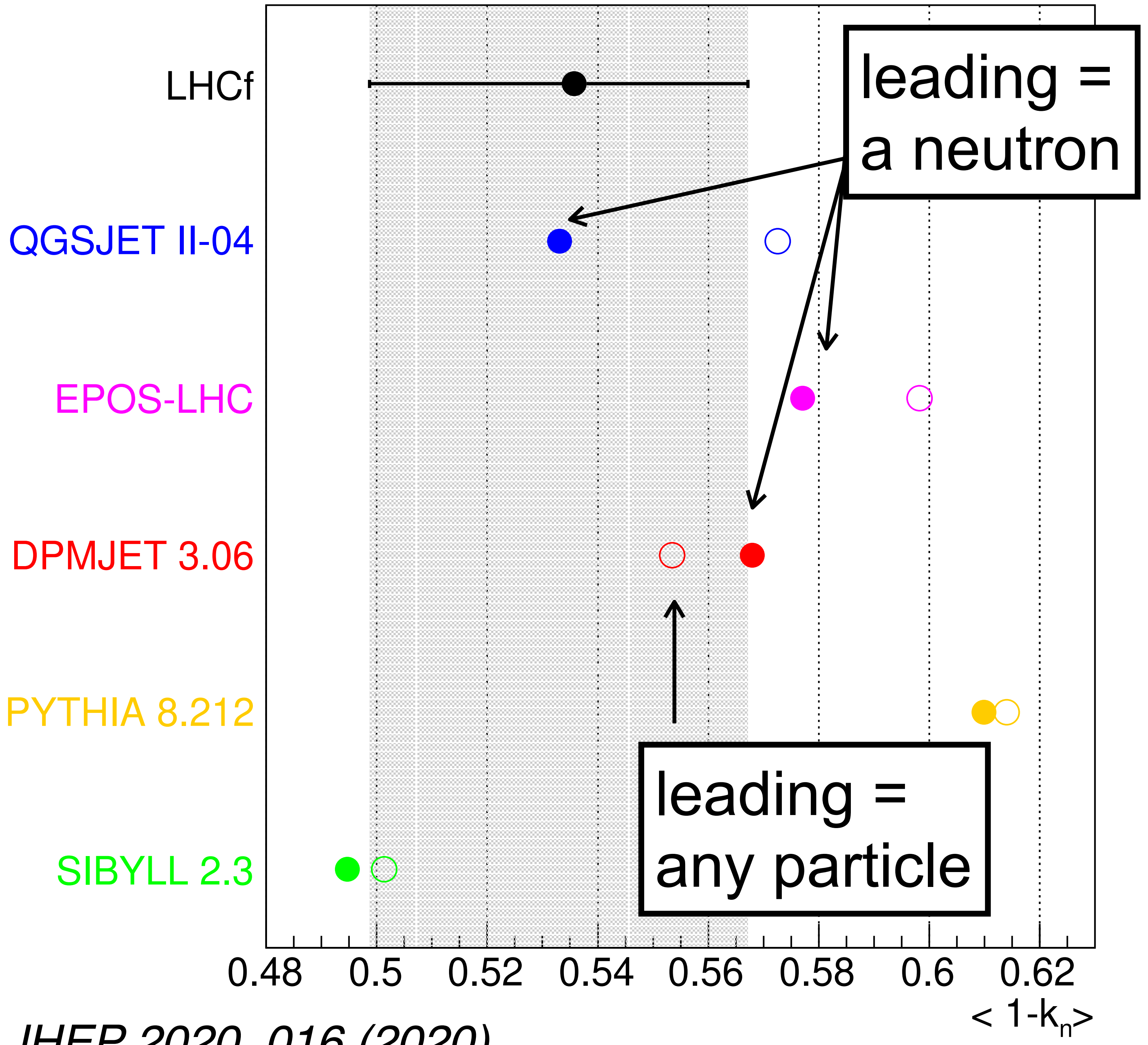
Average Inelasiticity: QGSJET II-4
Energy spectrum: EPOS, SIBYLL
Energy flow: EPOS

LHCf-ATLAS joint analysis is on-going with LHCf-neutron samples.

n, differential cross-section

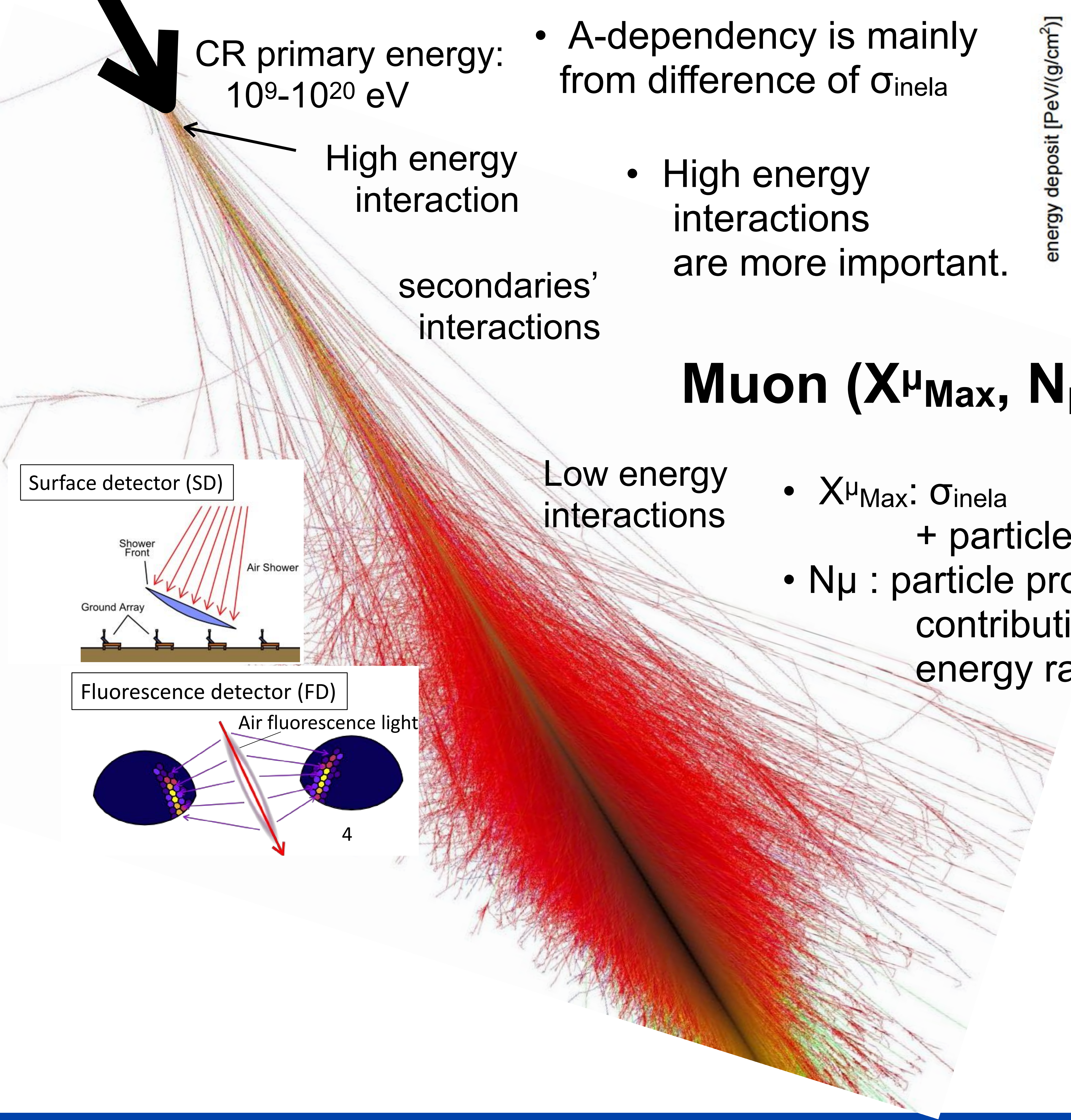


Average Inelasticity



JHEP 2020, 016 (2020)

Composition measurement of UHECRs



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

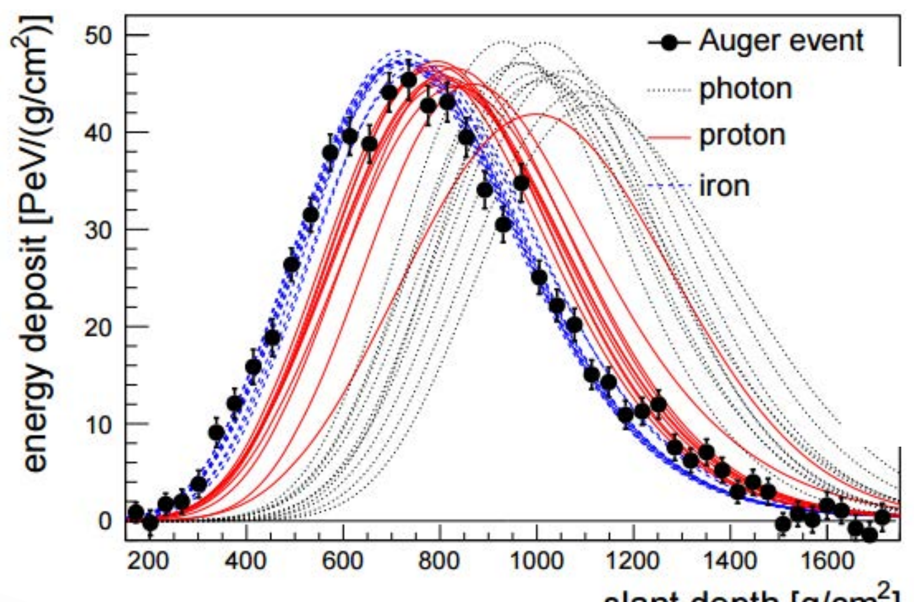
High energy interaction

secondaries' interactions

Low energy interactions

Shower Maximum (X_{Max})

- A-dependency is mainly from difference of σ_{inela}
- High energy interactions are more important.

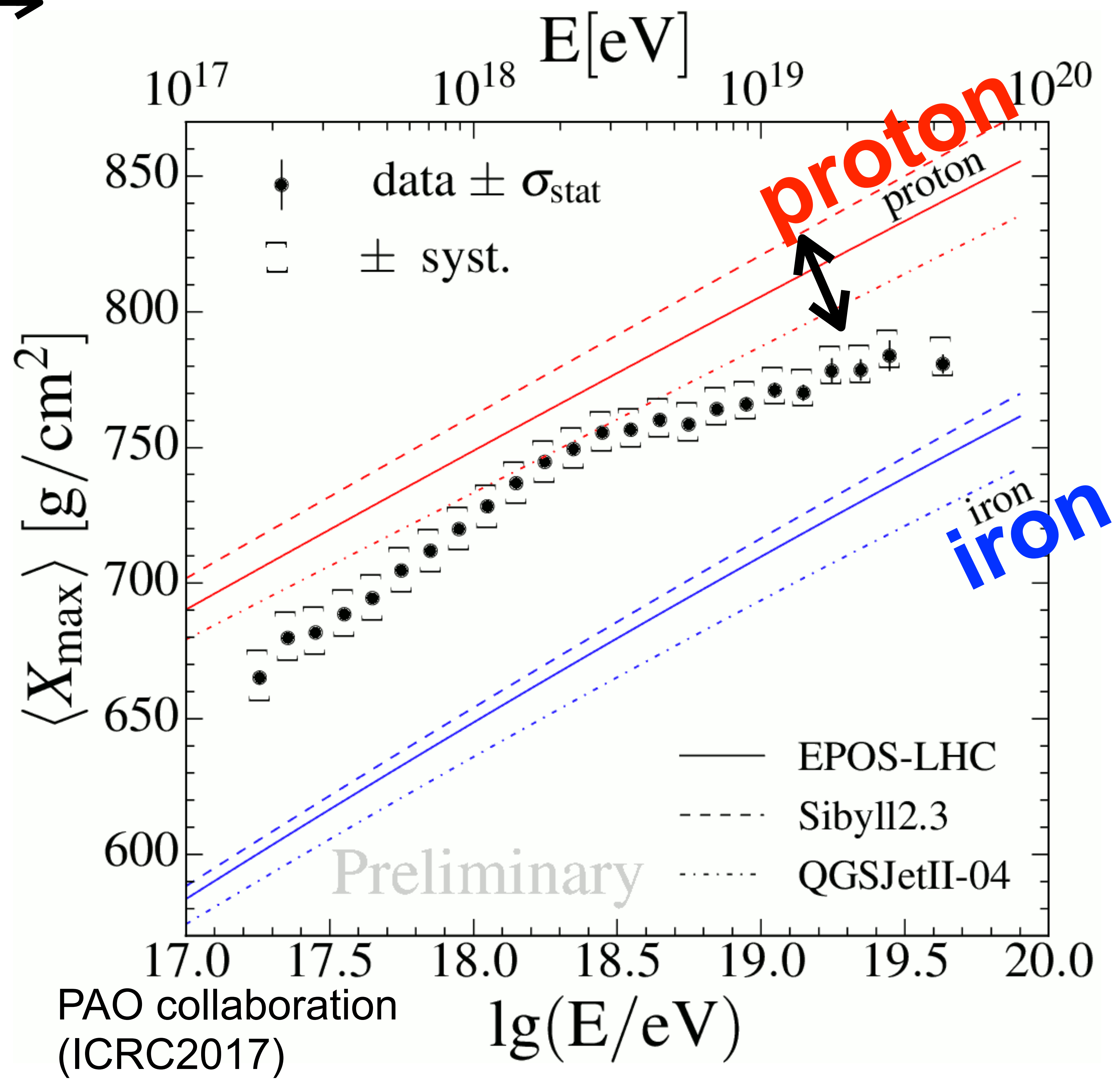


Auger, ICRC 2015

Muon (X^{μ}_{Max}, N_{μ})

- X^{μ}_{Max}: σ_{inela} + particle production
- N_{μ} : particle production contribution of wide energy ranges

Results of X_{MAX} measurement



PAO collaboration (ICRC2017)

Interaction model uncertainty > Experimental uncertainty