Status and prospects of the LHCf experiment

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on behalf of LHCf Collaboration

ISEE
Institute for
Space-Earth Environmental Research

LHCf

Hadronic Interaction Workshop
18-20 March 2025, Hong-Kong, China

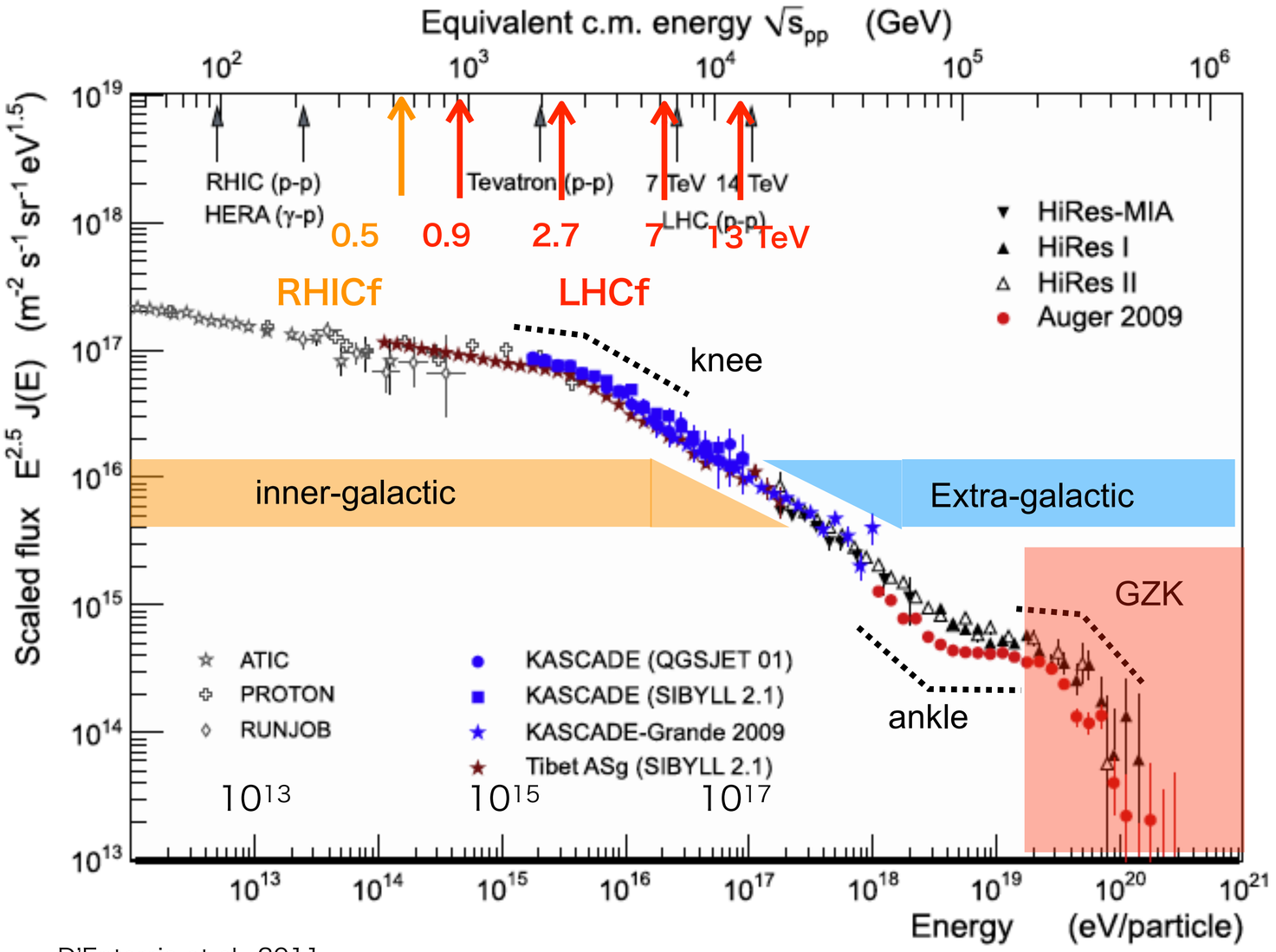
Contents

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

- Introduction : Ultra-high energy cosmic rays (UHECRs)
- LHCf and RHICf experiments
- Results
  - Very forward photon, π0, neutron measurements
  - η meson measurement
- Prospects
  - Strange particle measurements
  - Joint analyses with ATLAS
  - pO collision in 2025

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

High Energy Cosmic-rays

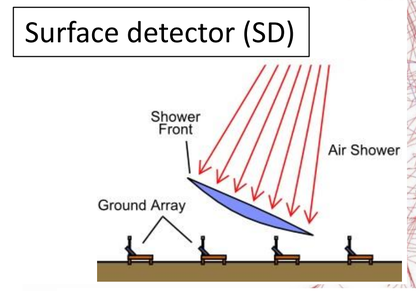


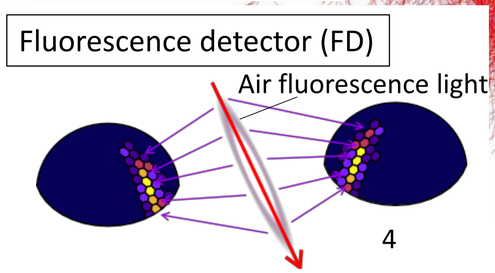
D'Enterria et al., 2011

Observation using air showers

Studying the properties of primary CR relying on MC simulation.

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





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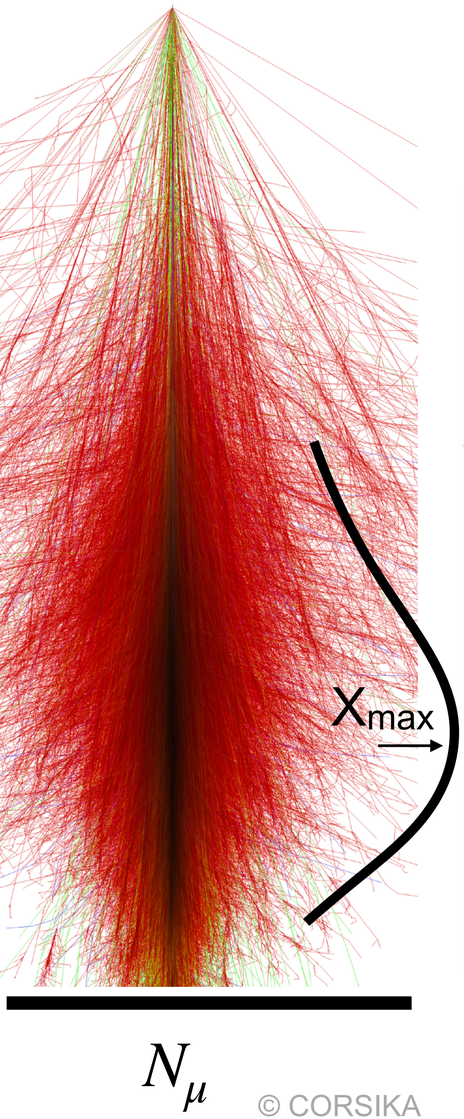
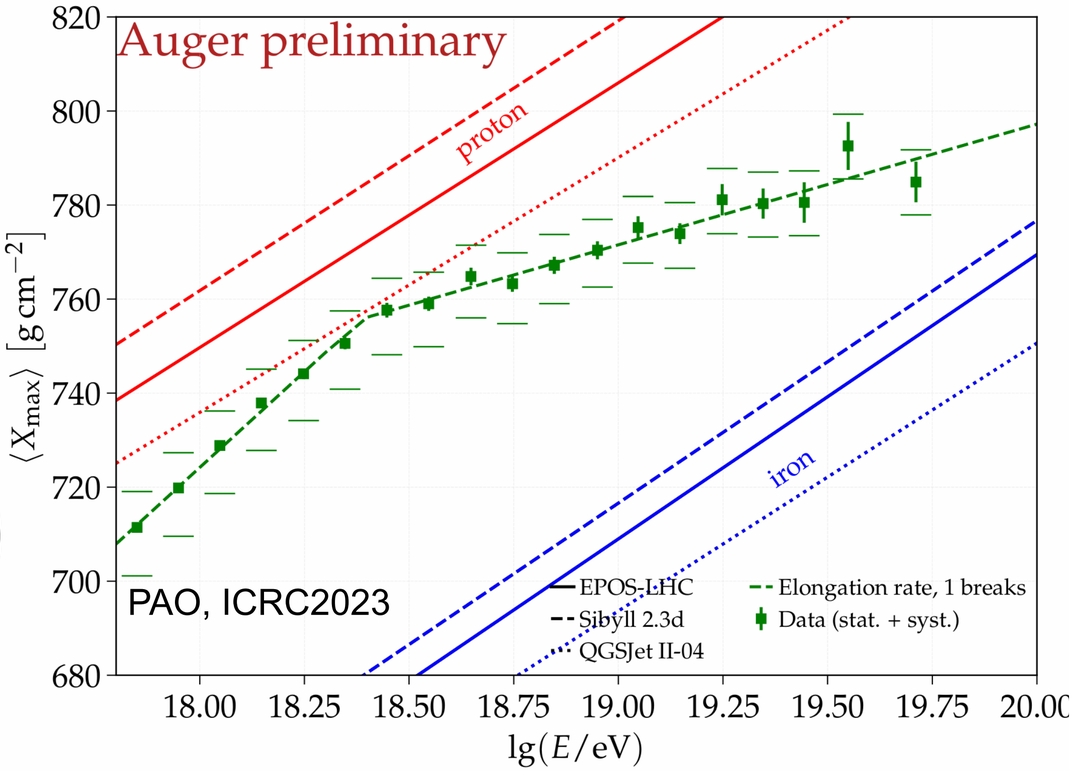
”A” measurement of UHECRs

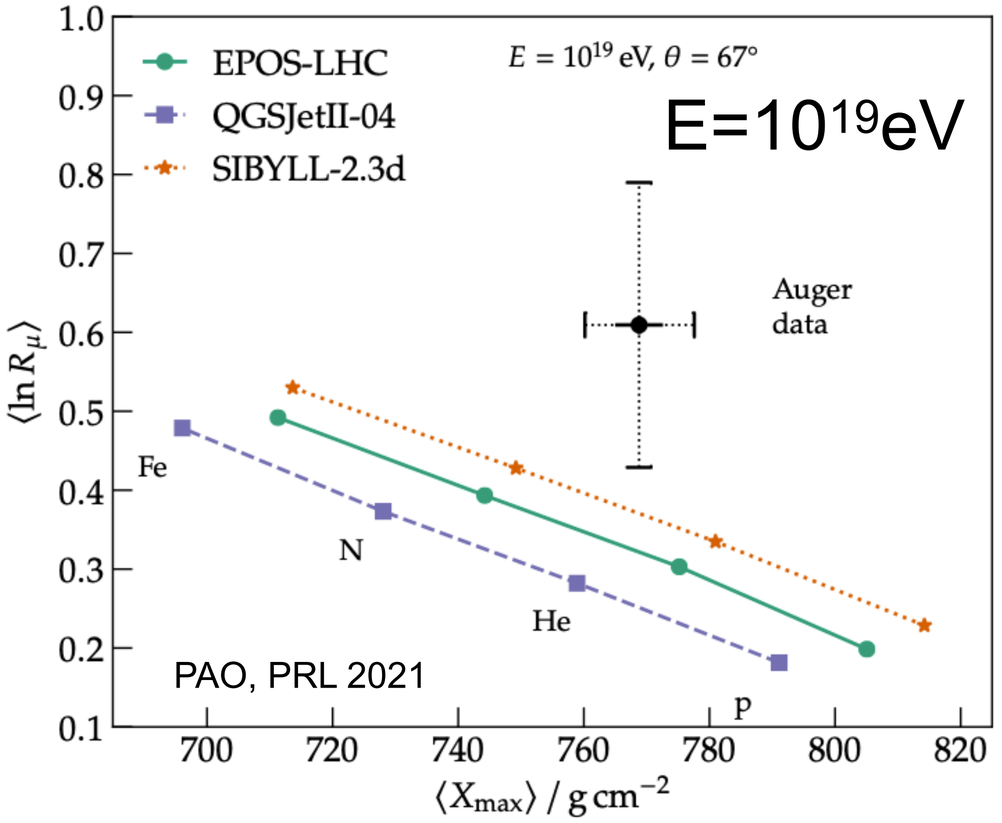


Shower Maximum Depth $< X_{MAX} >$



Interaction model uncertainty **>** Experimental uncertainty

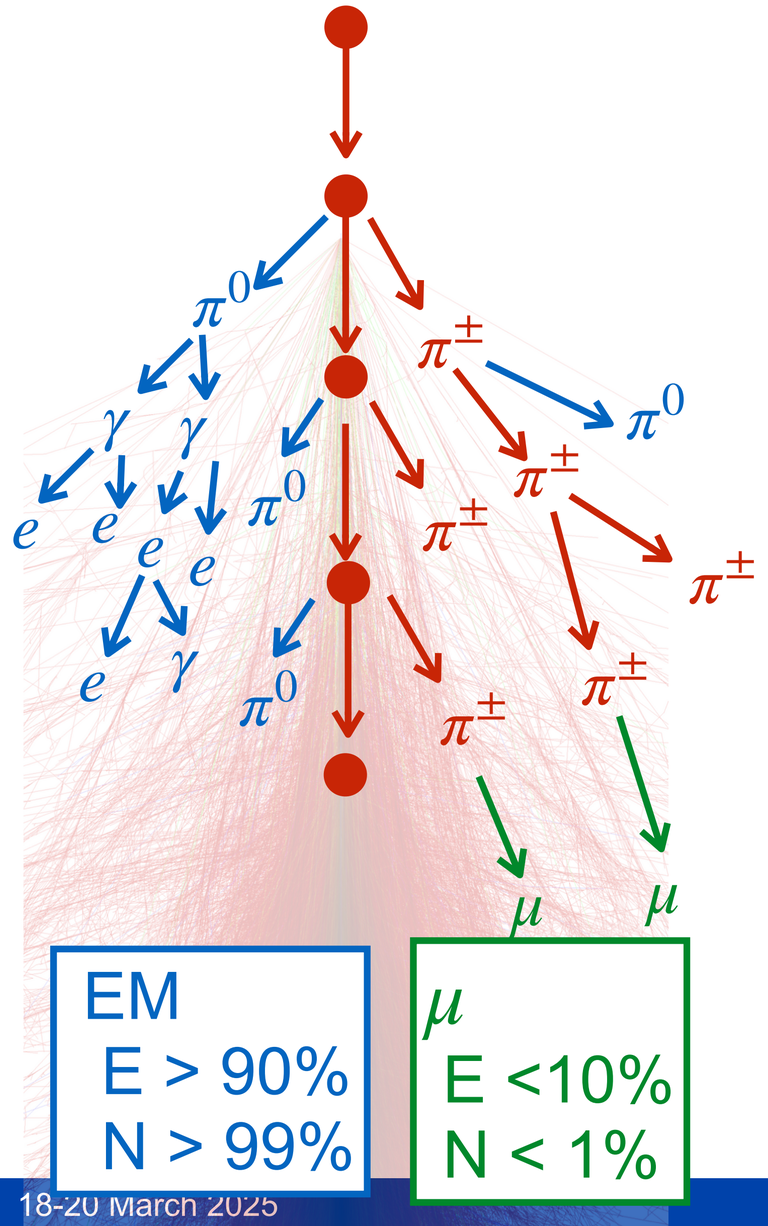
Muon Number N_μ



N_μ : Data > MC (30-50%)

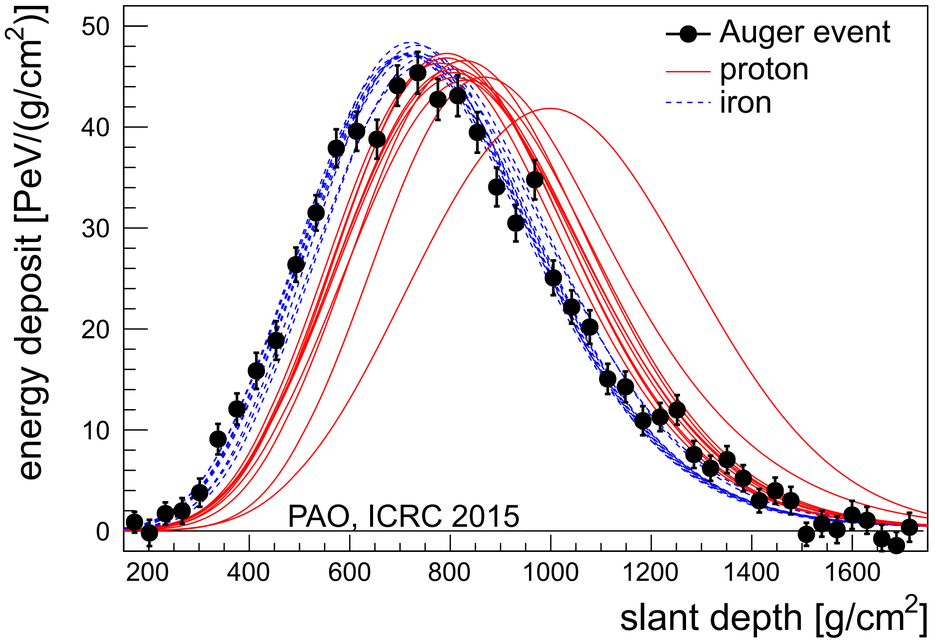
Muon puzzle

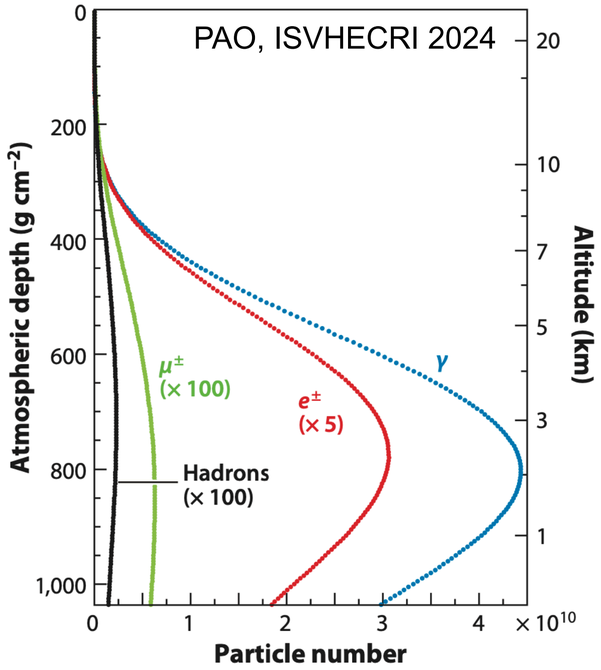
AS development v.s. Interactions



EM
E > 90%
N > 99%

μ
E <10%
N < 1%





- X_{MAX} : strong dependence on 1st interaction

  (interaction depth and particle production)

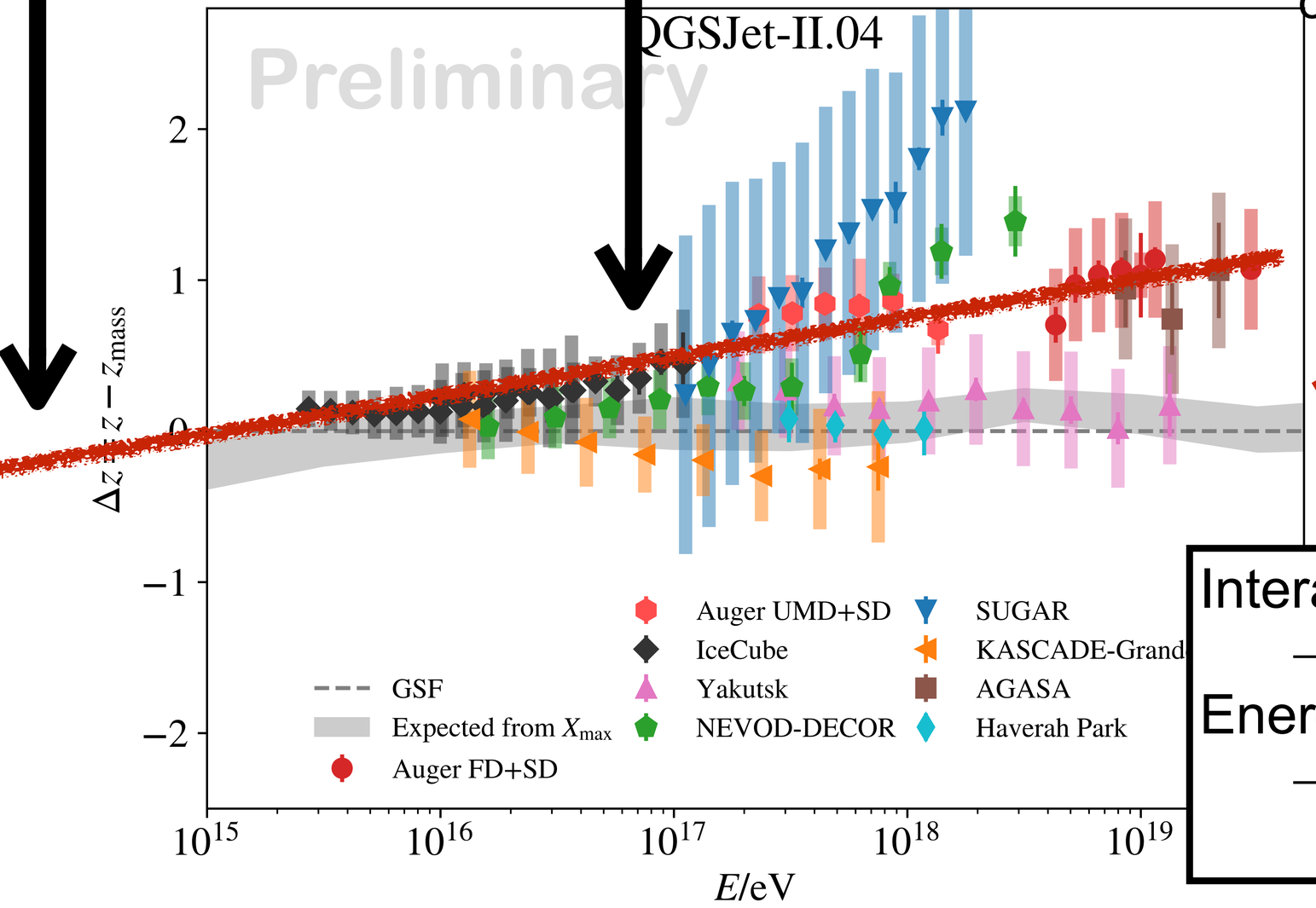
- N_μ : $\sum E_{had.}^{end} = E_{CR} \prod (1 - R_{EM}^{i-th})$

  R_{EM} = energy fraction of EM components

Energy dependency of muon deficit

RHIC

LHC



Normalized muon numbers results observed by several CR experiments

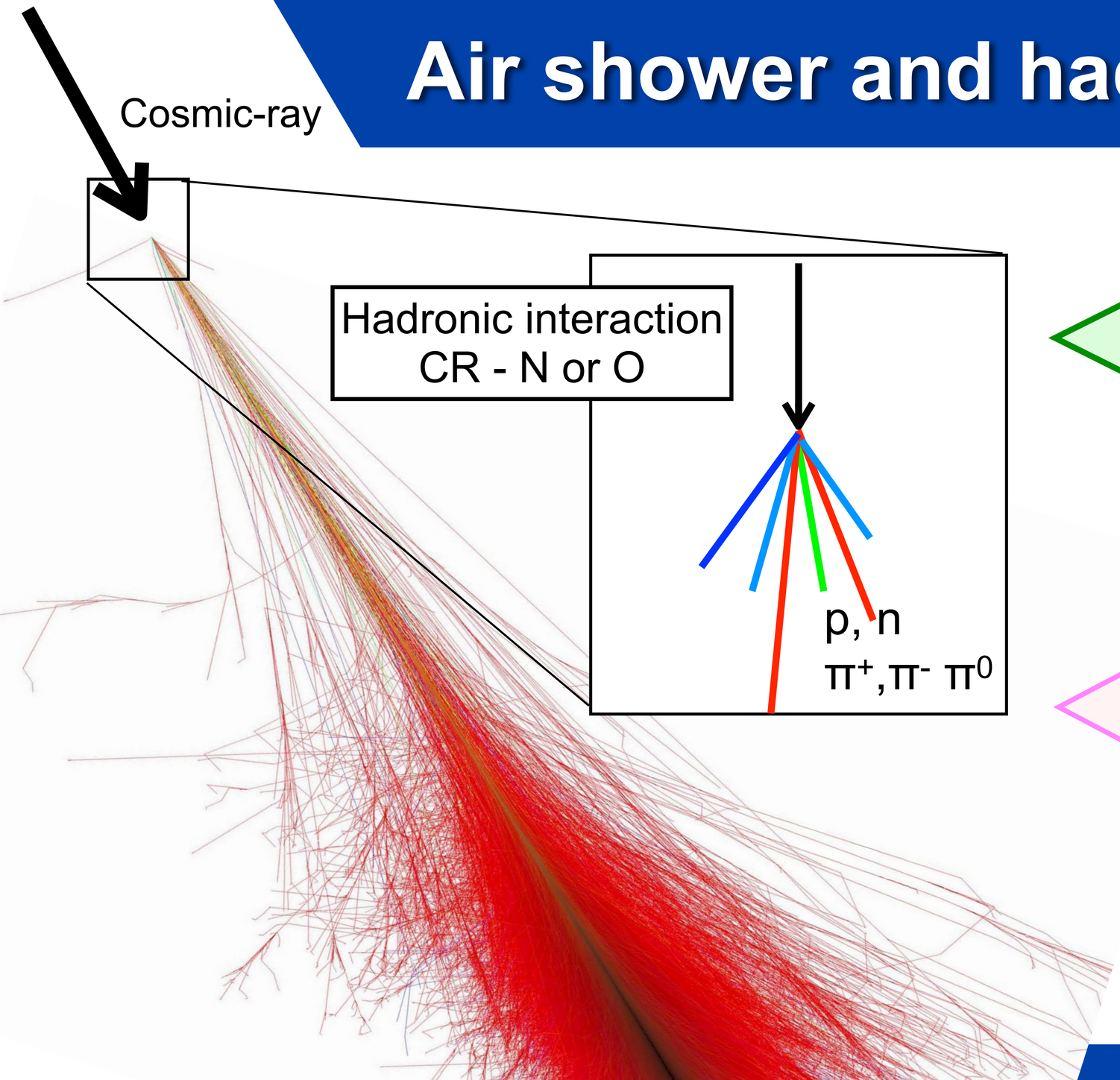
$$z = \frac{\ln(N_\mu{}^{\rm det}) - \ln(N_{\mu\,p}{}^{\rm det})}{\ln(N_{\mu\,{\rm Fe}}{}^{\rm det}) - \ln(N_{\mu\,p}{}^{\rm det})}$$

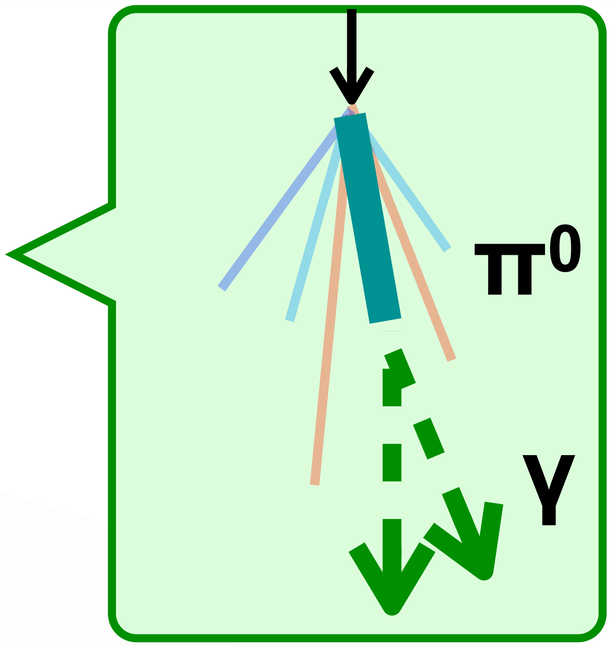
Muon deficit

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

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

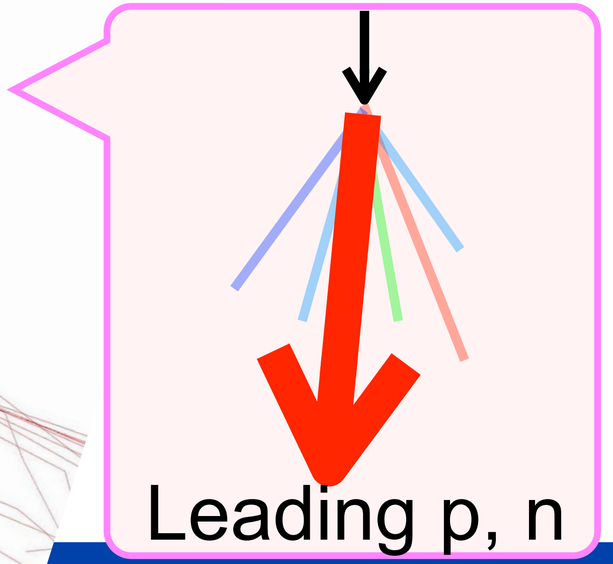
Air shower and hadronic interaction





γ, π^0

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

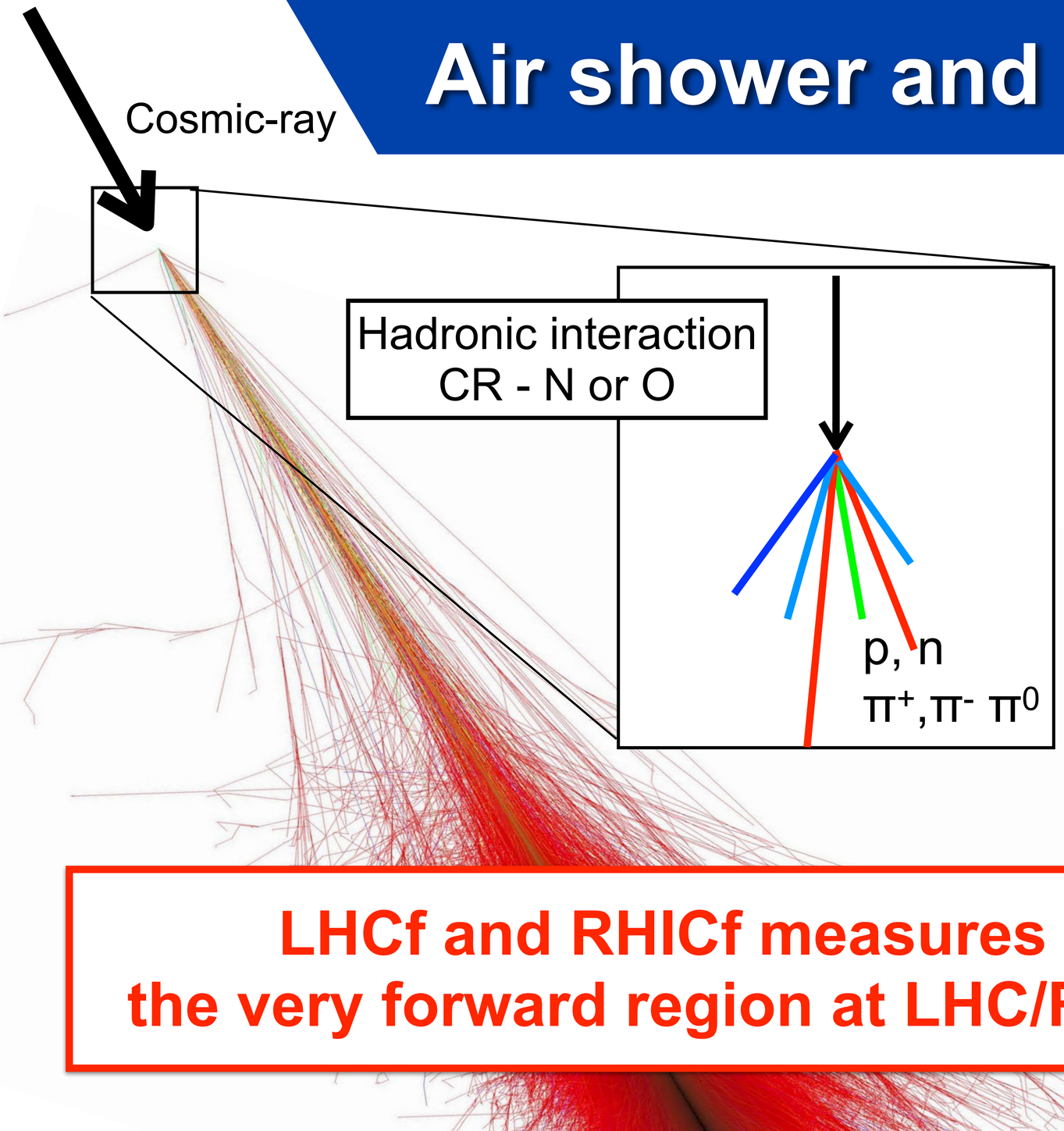


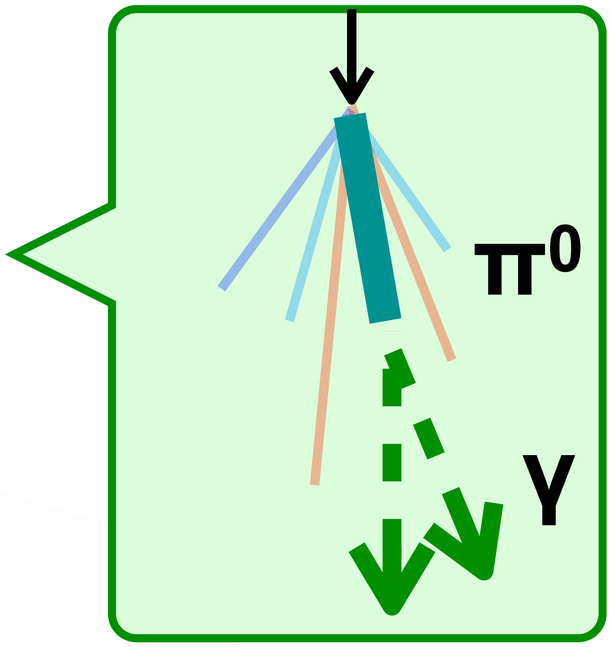
Leading baryons

- 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





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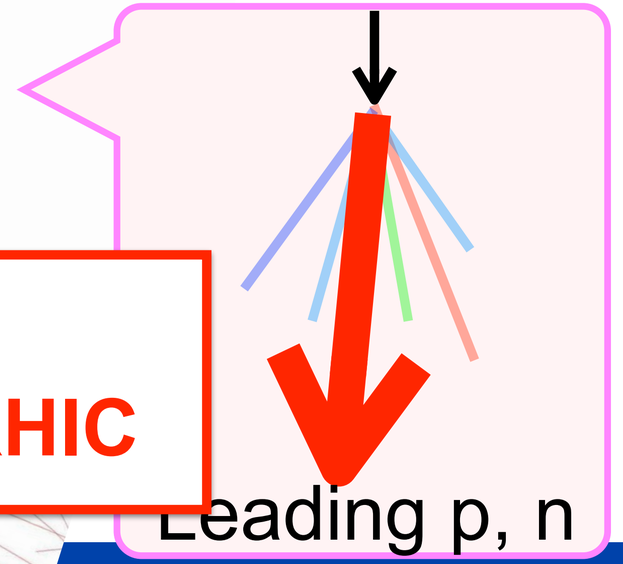

Leading baryons

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

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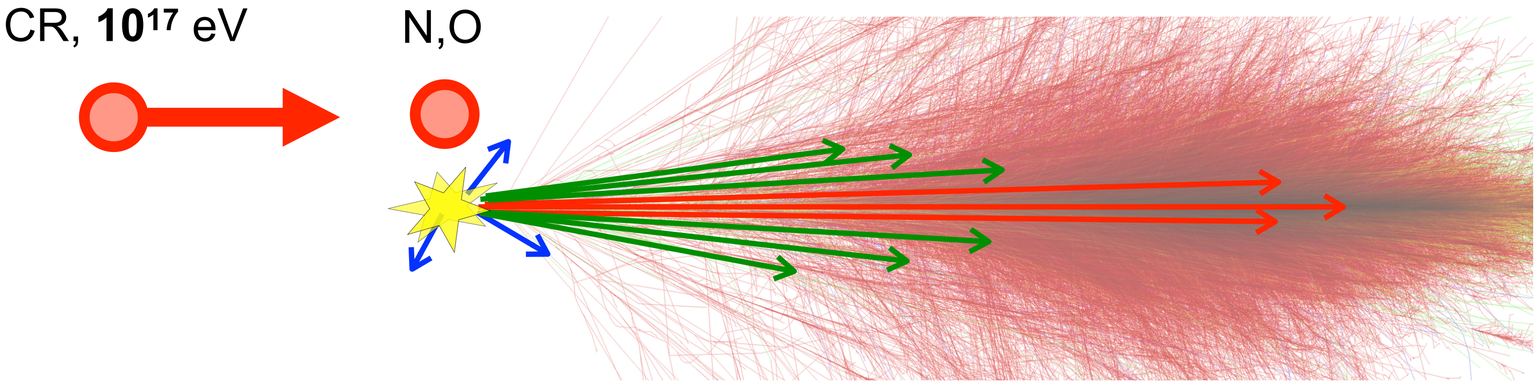
LHCf and RHICf measures the very forward region at LHC/RHIC

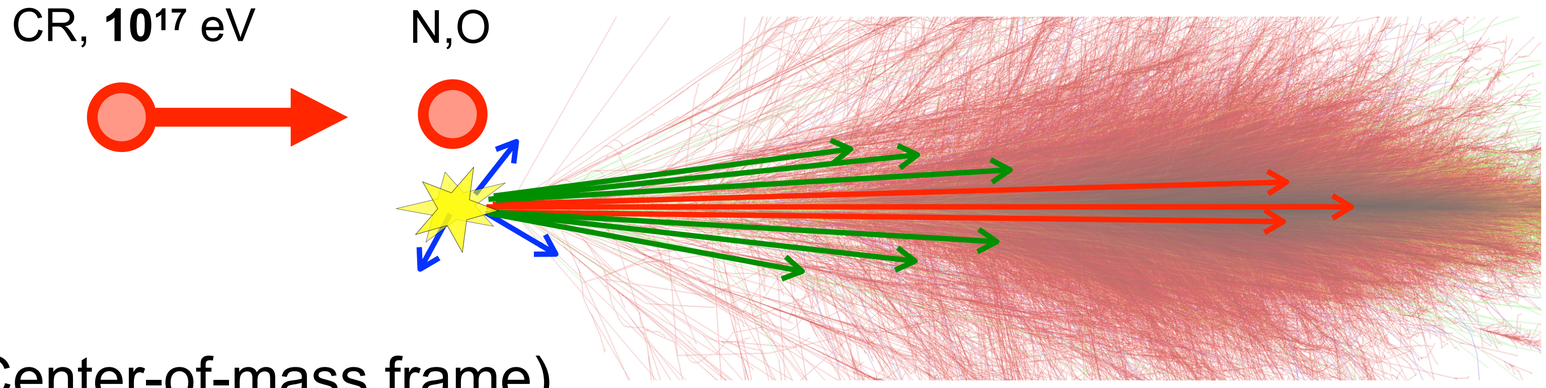
Interaction studies at LHC

Cosmic-ray (target-rest frame)

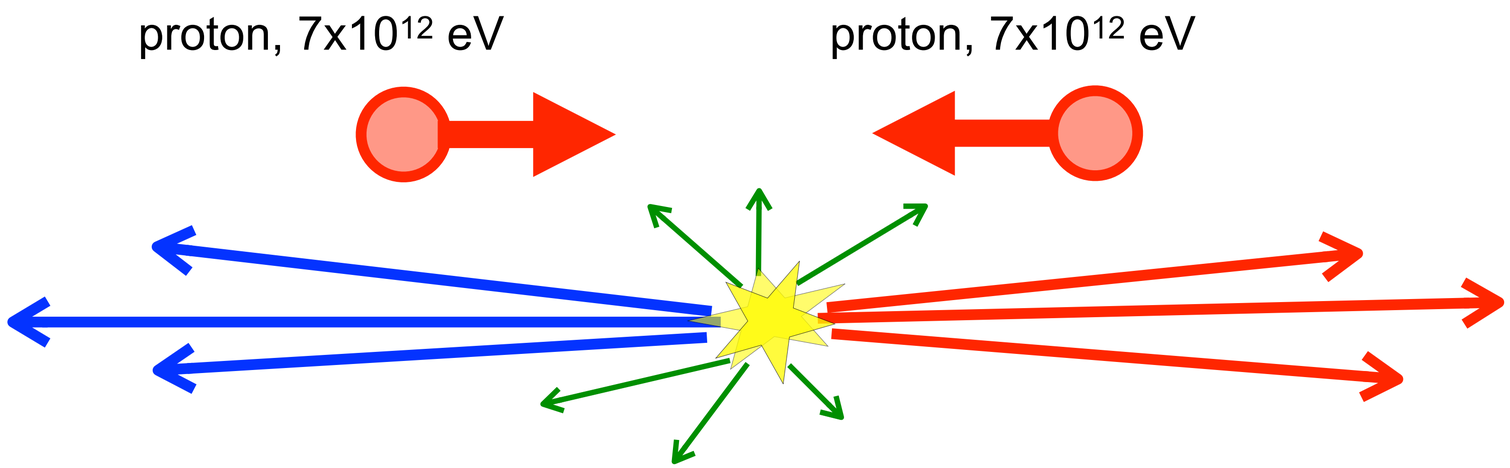


Interaction studies at LHC

Cosmic-ray (target-rest frame)

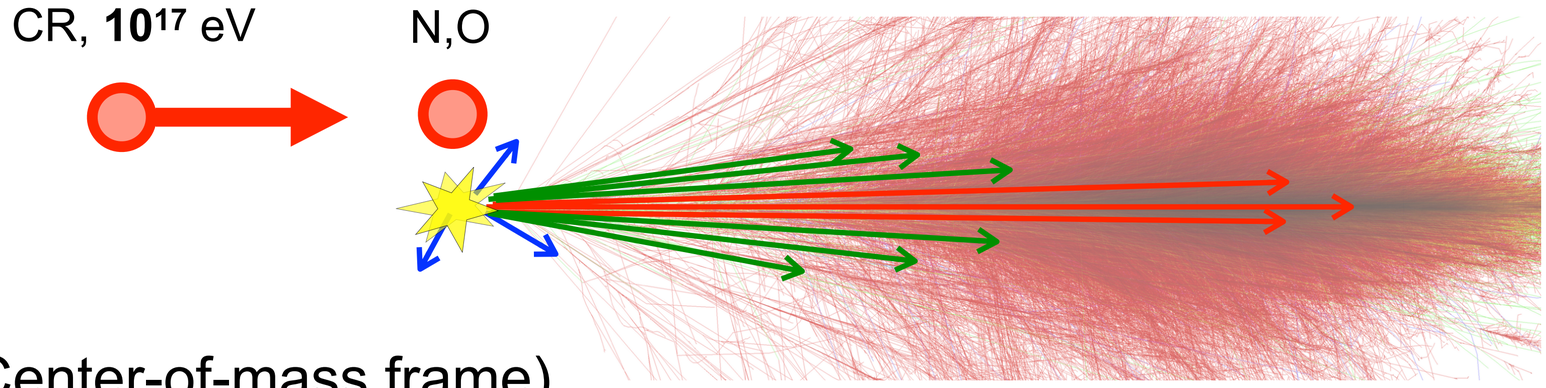


LHC(Center-of-mass frame)



Interaction studies at LHC

Cosmic-ray (target-rest frame)



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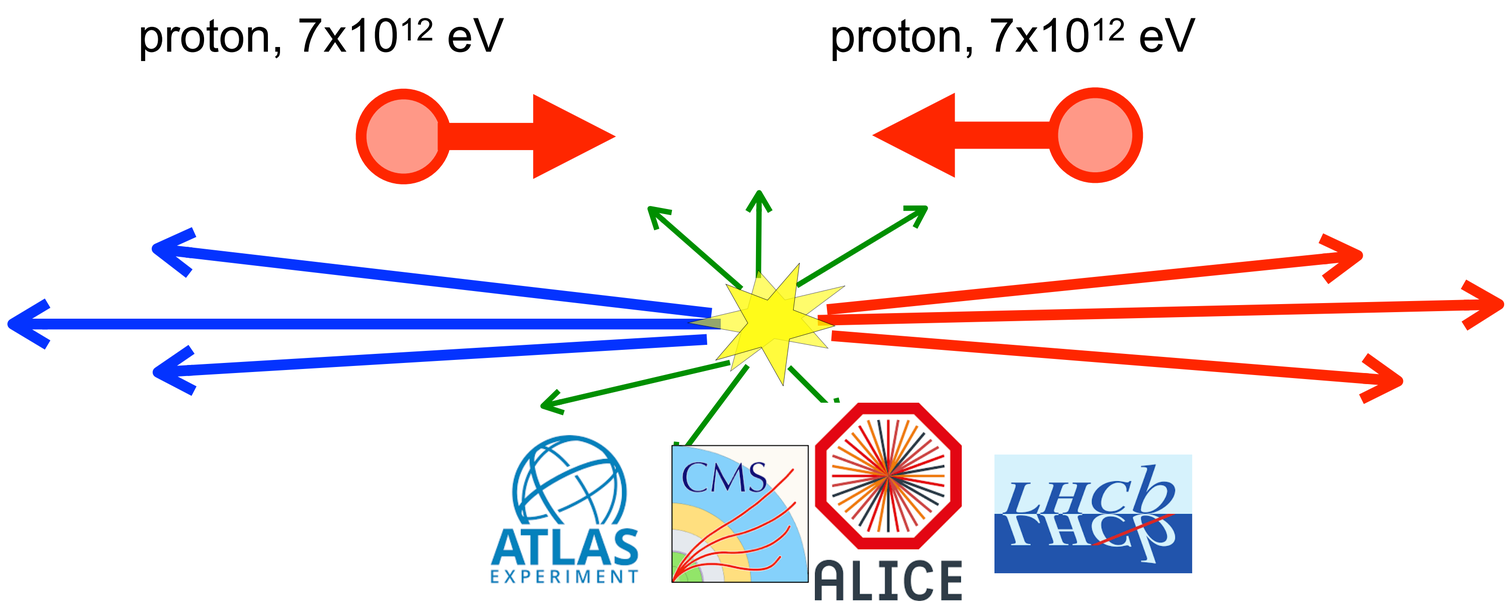
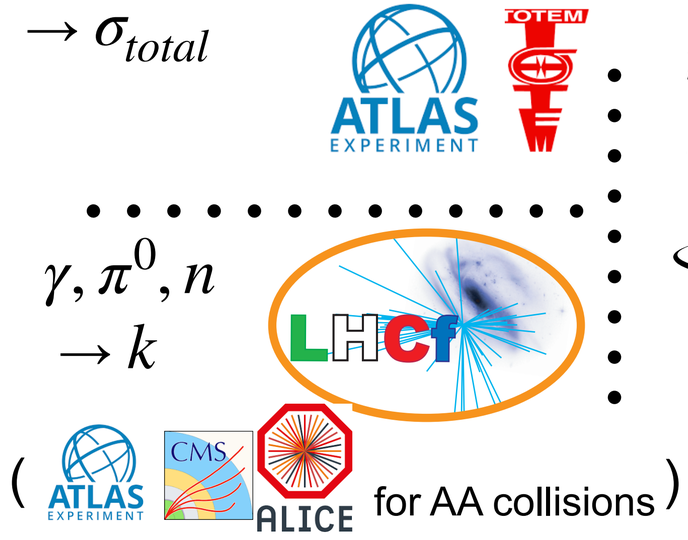
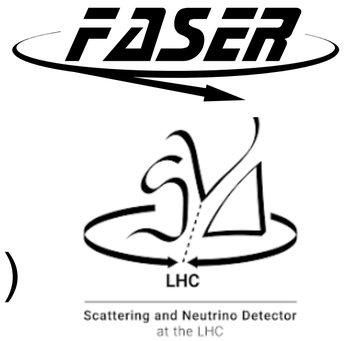


Scattered proton

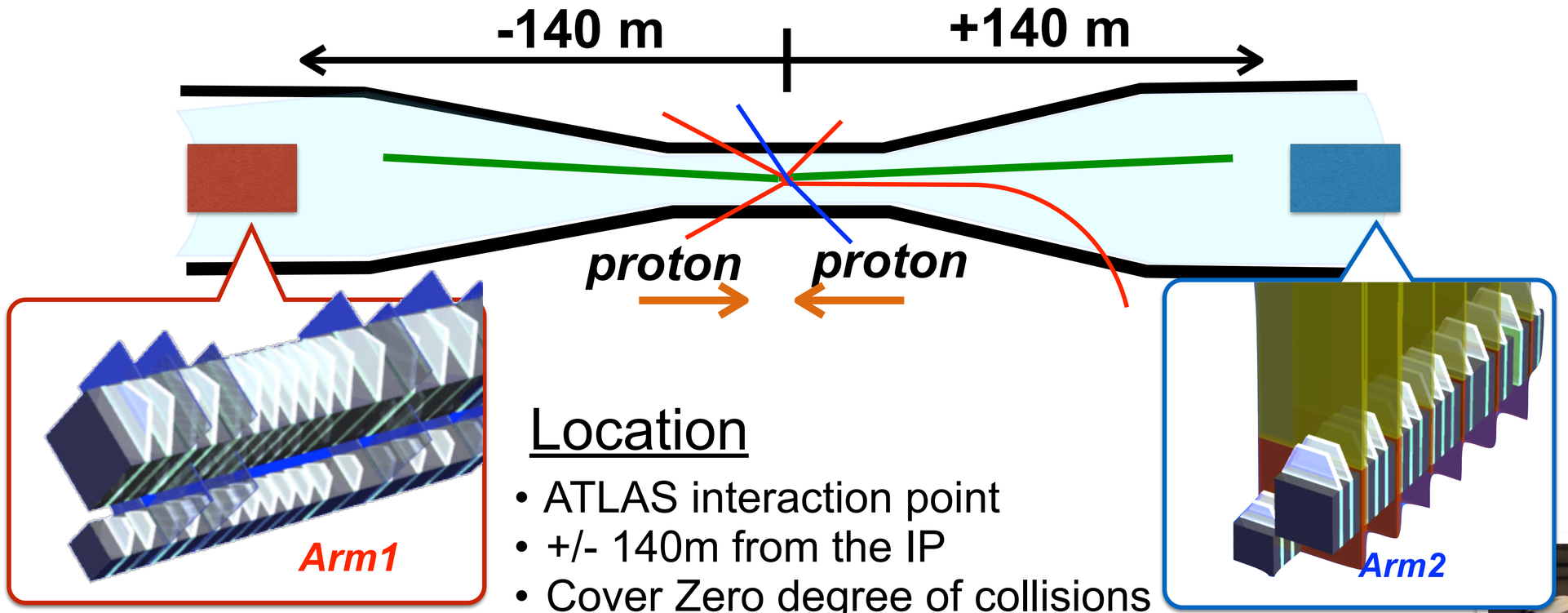
$\rightarrow \sigma_{total}$

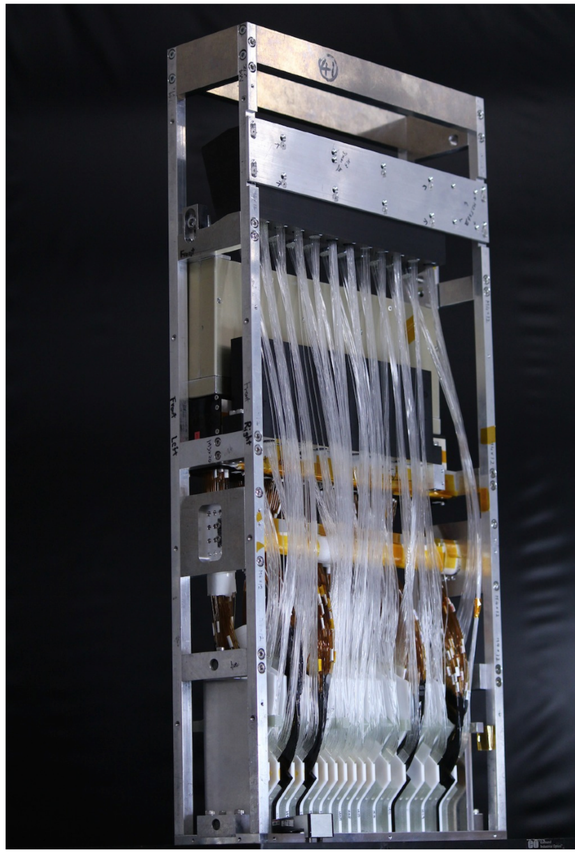


$\nu_{e,\mu,\tau}$
$\rightarrow K/\pi$



LHCf experiment





Location

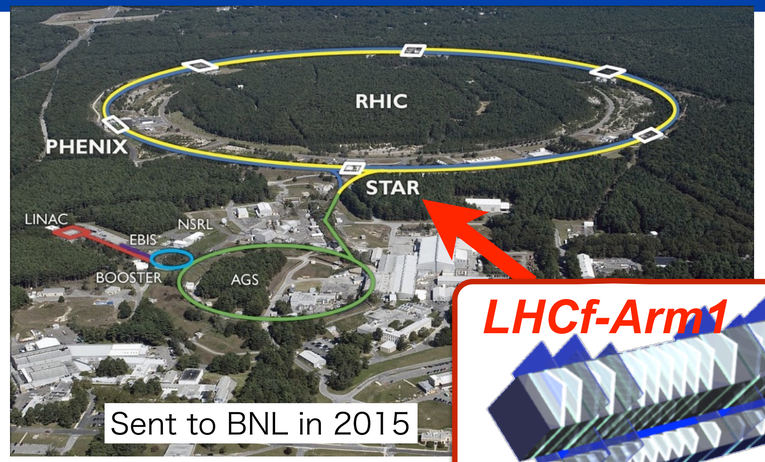
- ATLAS interaction point
- +/- 140m from the IP
- Cover Zero degree of collisions pseudo rapidity η > 8.4

LHCf detectors

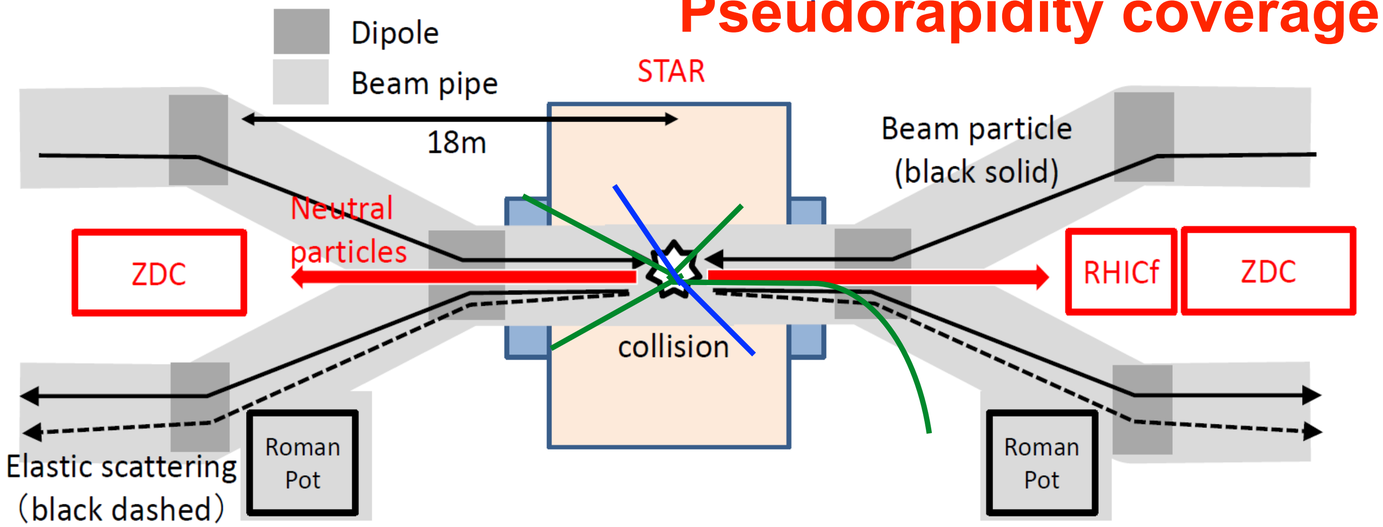
- Sampling and positioning calorimeters
- Two towers, 20x20, 40x40mm^2 (Arm1) , 25x25, 32x32mm^2(Arm2)
- Tungsten layers, 16 GSO scintillators, 4 position sensitive layers (Arm1: GSO bar hodoscopes, Arm2: Silicon strip detectors)
- Thickness: 44 r.l. and 1.7 λ

RHICf experiment

- *pp* √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 Operations and Analyses

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

LHCf/RHICf Operations and Analyses

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)		-		
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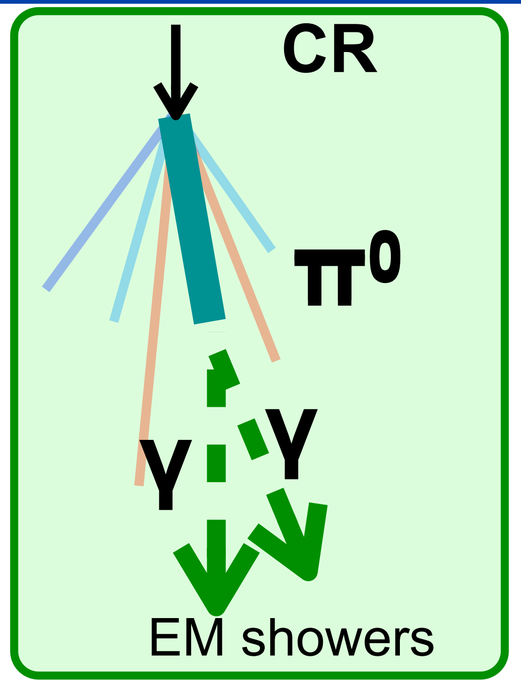
RHICf p-p $\sqrt{s}$=510GeV (2017)	1.4×10^{14}	Submitted ArXiv		Submitted		with STAR

← new data

p-O operation in 2025

Photon (π^0) measurement at *pp*

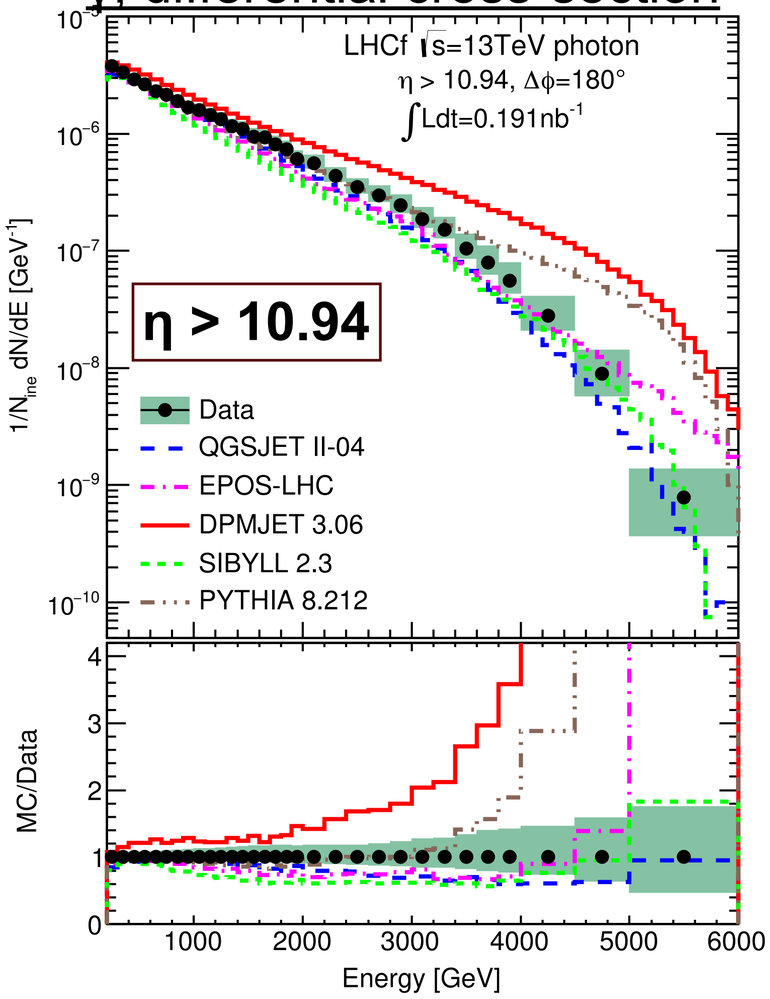


- Source of EM components in CR-air showers
- γ's originate from π^0 and η decays
- LHCf covers high energy photons X_F >~ 0.1

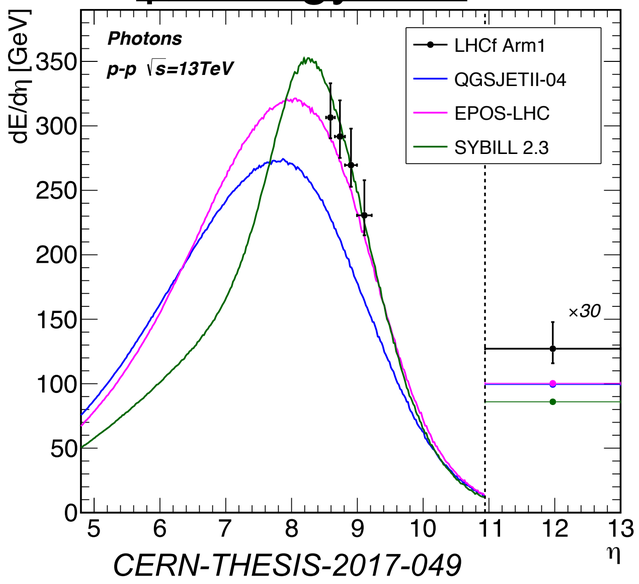
Comparison with model predictions

EPOS-LHC shows the best agreement
QGSJETII-04 reproduces spectrum shape well
SIBYLL reproduces energy flow well.

γ, differential cross-section

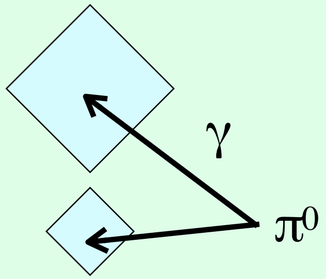


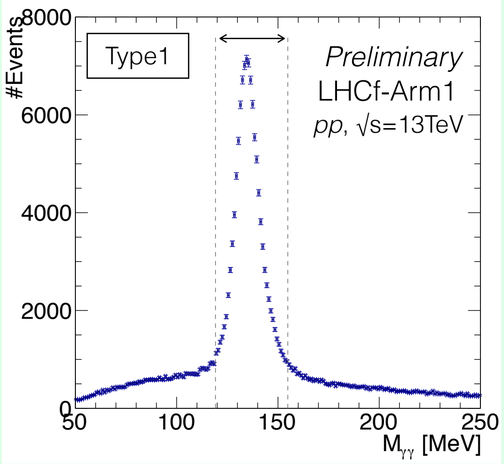
γ, energy flow



π^0 measurement

simultaneous detection
2γ from π^0 decays

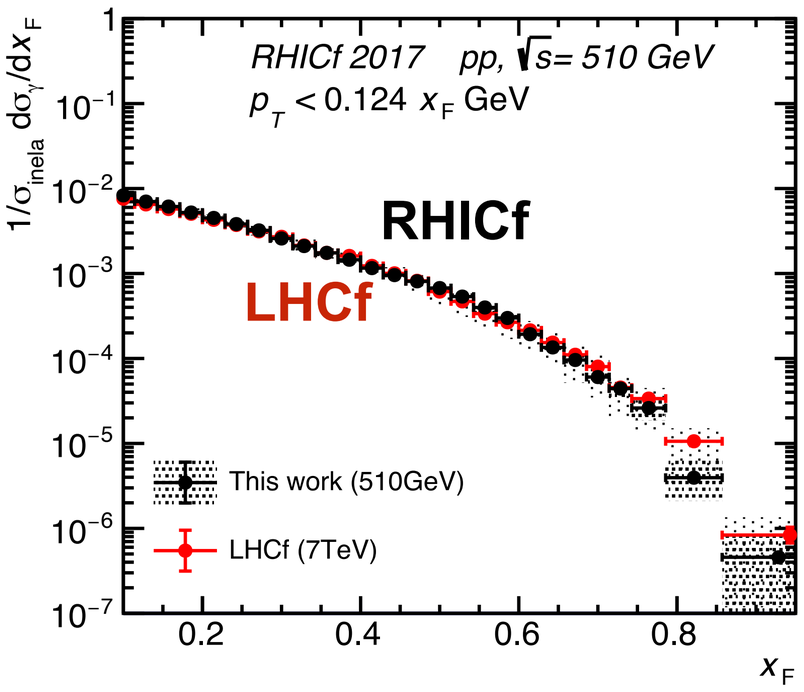




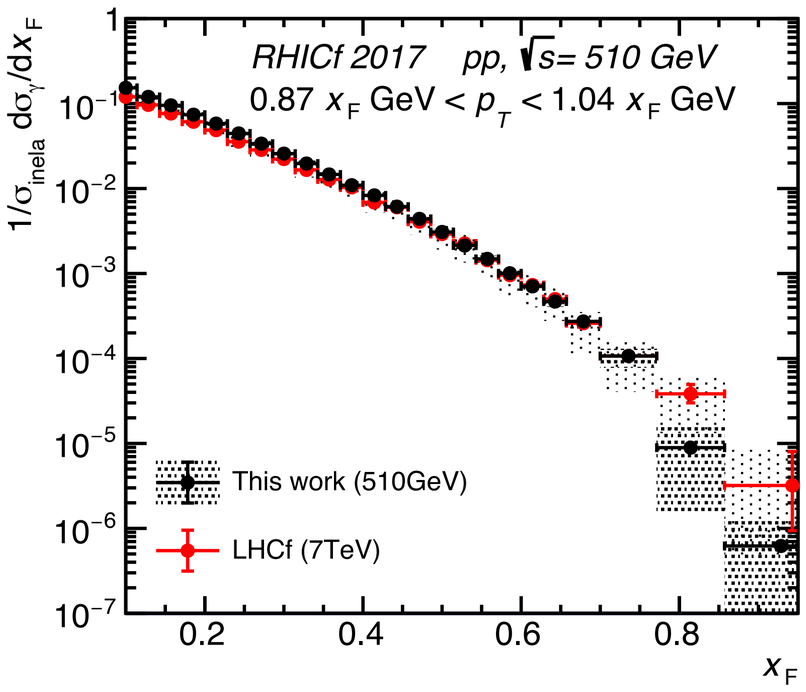
Photon: RHICf v.s. LHCf

- Test of Feynman Scaling with RHICf (√s=510GeV) and LHCf (√s=7,13 TeV)
- 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)

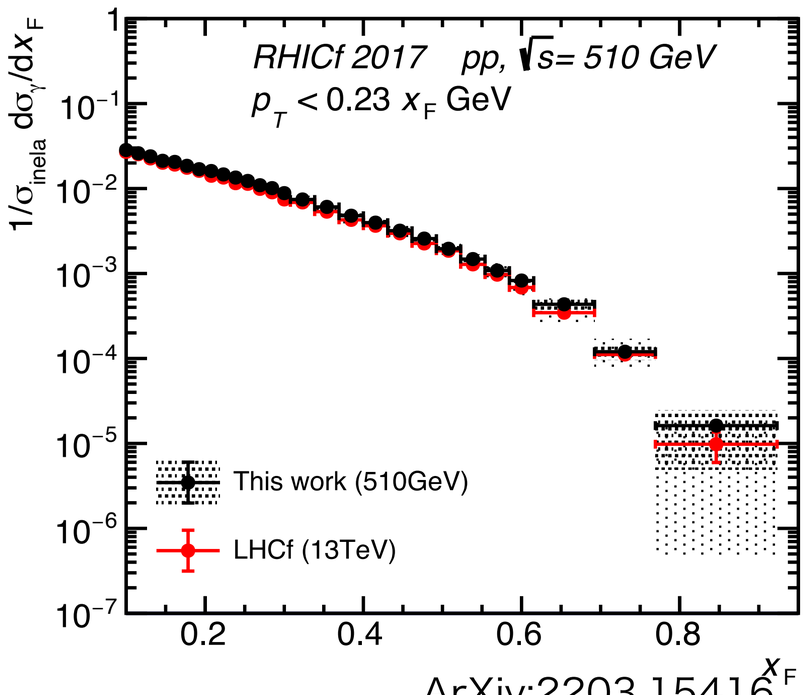
510 GeV v.s. 7TeV
n > 10.94



510 GeV v.s. 7TeV
8.81 < n < 8.99



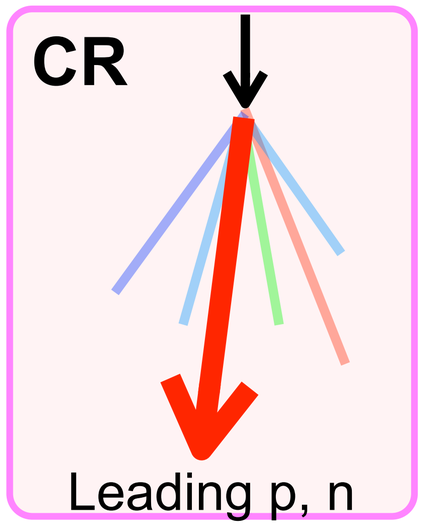
510 GeV v.s. 13TeV
n > 10.94

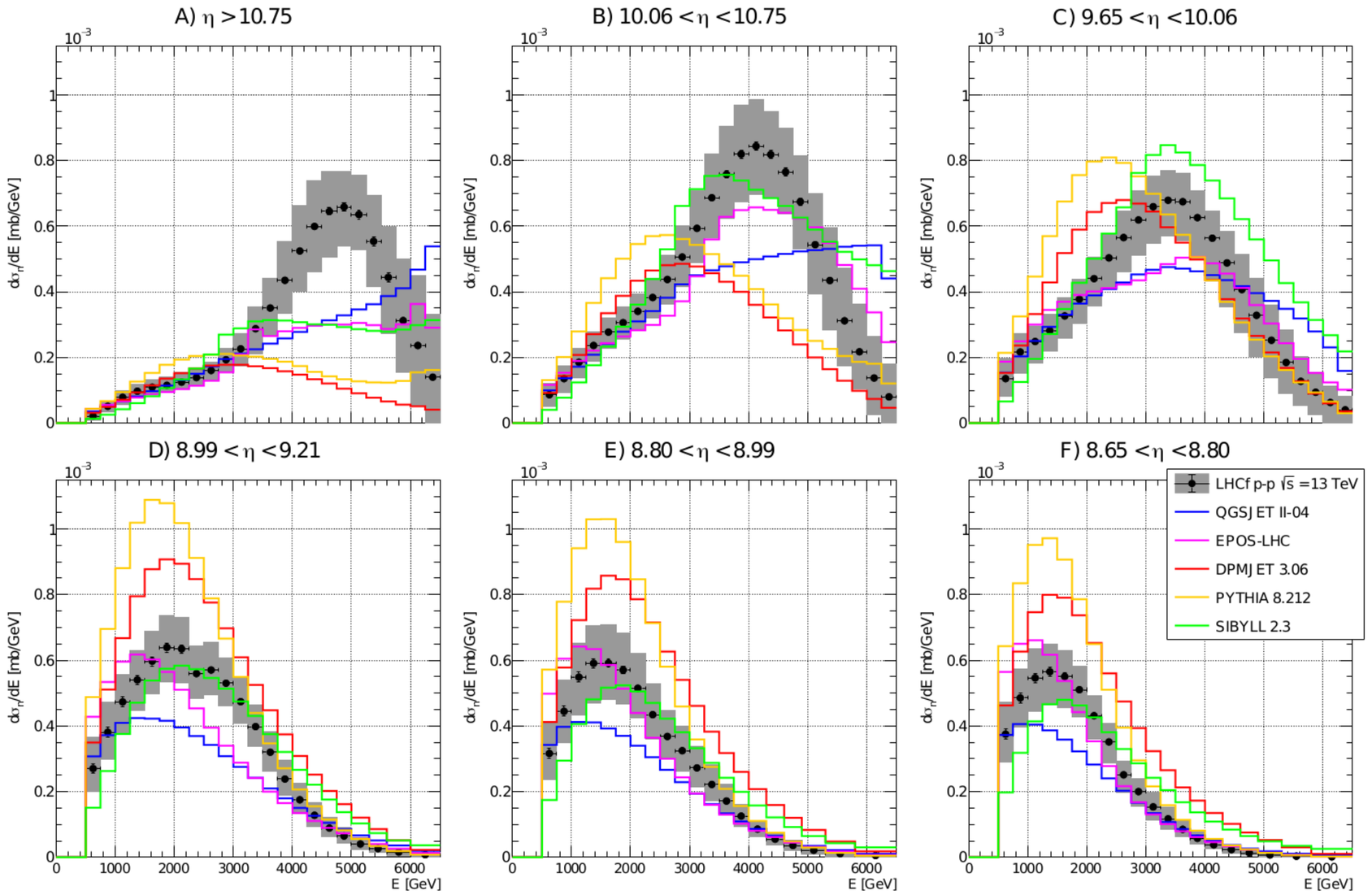


ArXiv:2203.15416

Forward Neutron at *pp*, √s=13 TeV

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

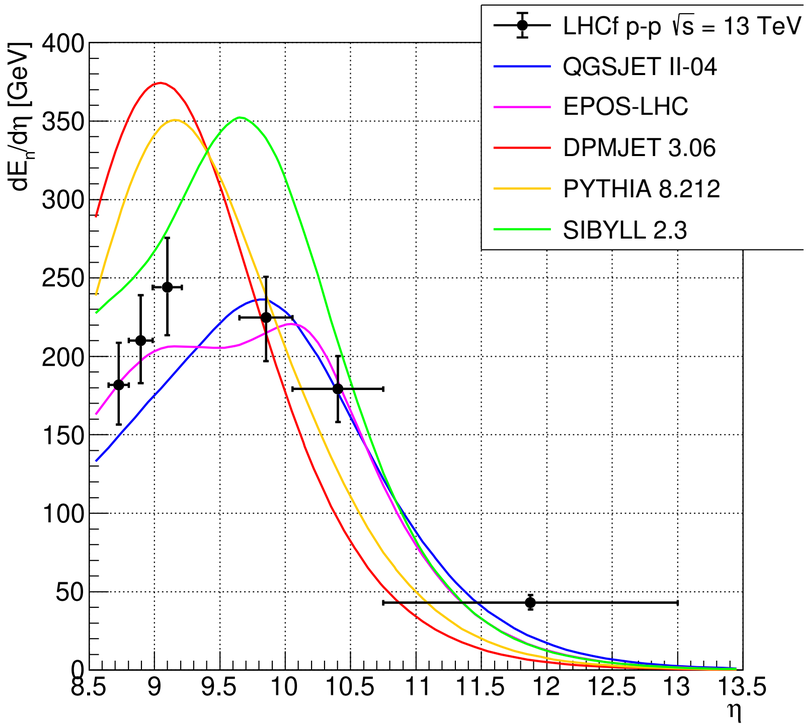




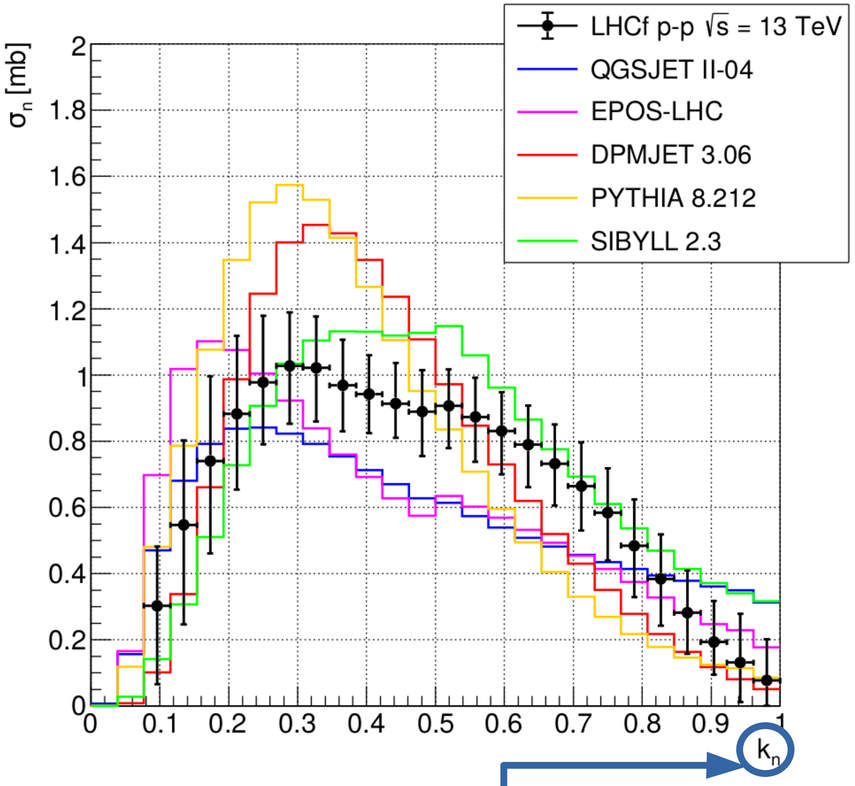
O. Adriani et al., JHEP07 (2020) 016

Inelasticity from the neutron result

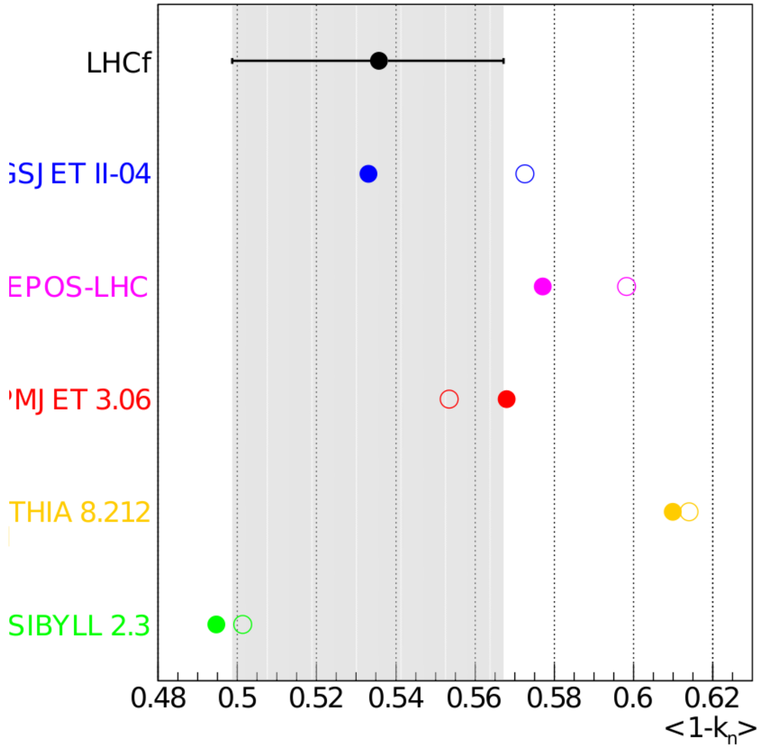
Energy flow



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

Muon puzzle solved ??

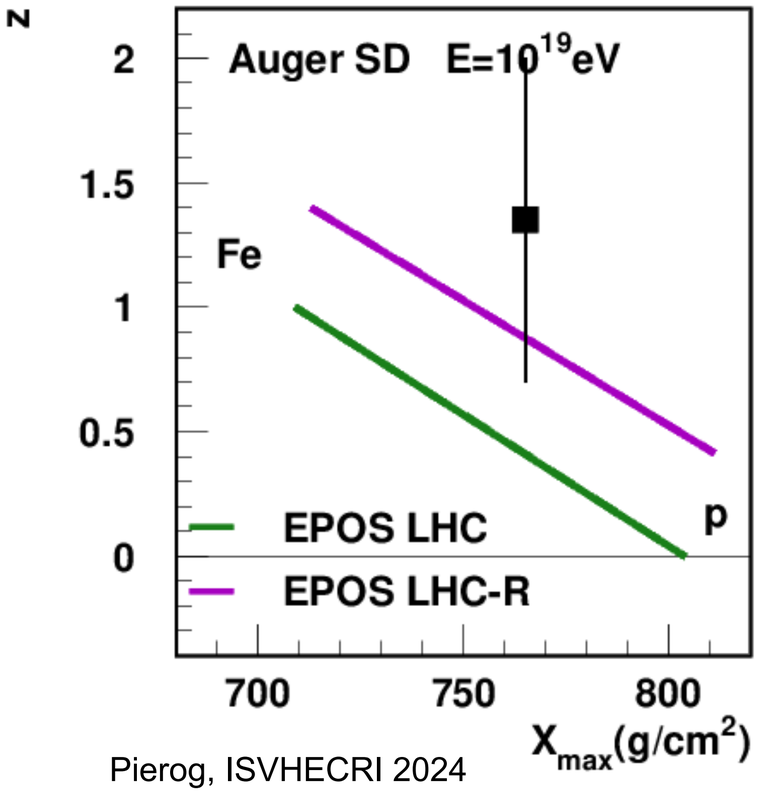
- Inclusive γ, π^0, n results
  - Data on the middle of model predictions.

- Model updates

pre-LHC	post-LHC (~2010)	Recent
EPOS 1.99	EPOS LHC	EPOS LHC-R
QGSJET 01/II-03	QGSJET II-04	QGSJET III
SIBYLL 2.1	SIBYLL 2.3	SIBYLL 2.3d

7TeV results
N_{ch}, σ_{inela}

LHCf results
+ other 13TeV results

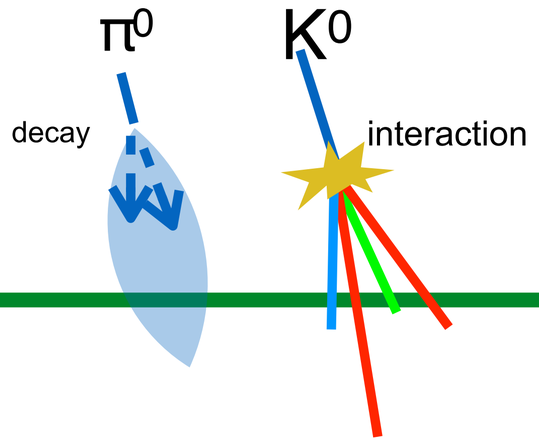


Pierog, ISVHECRI 2024

What we can do in the next.

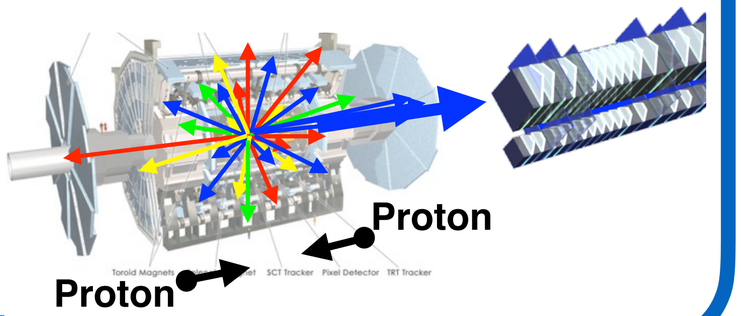
Strange particle measurement

- One of candidates for muon puzzle
- Large production induce more muons



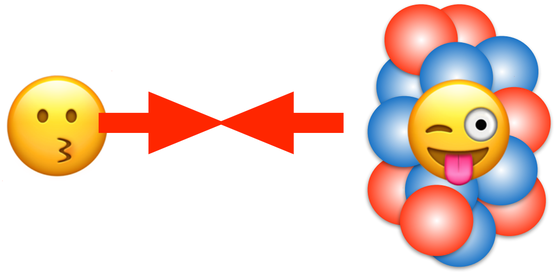
Joint analysis with ATLAS

- Process based analysis
- p-π interaction study

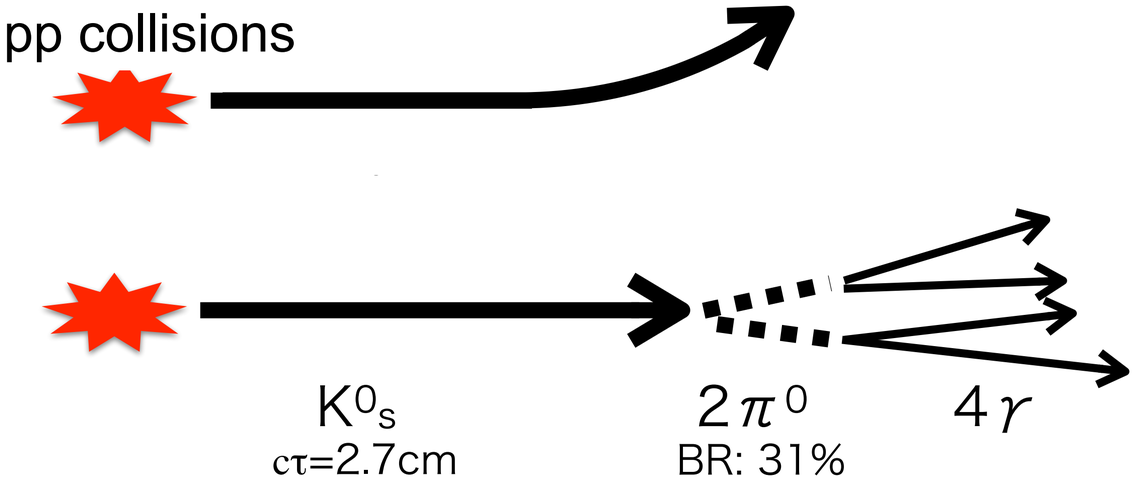


proton-Oxygen collisions

- Ideal condition for CR interaction study



How to measure strange particles in LHCf

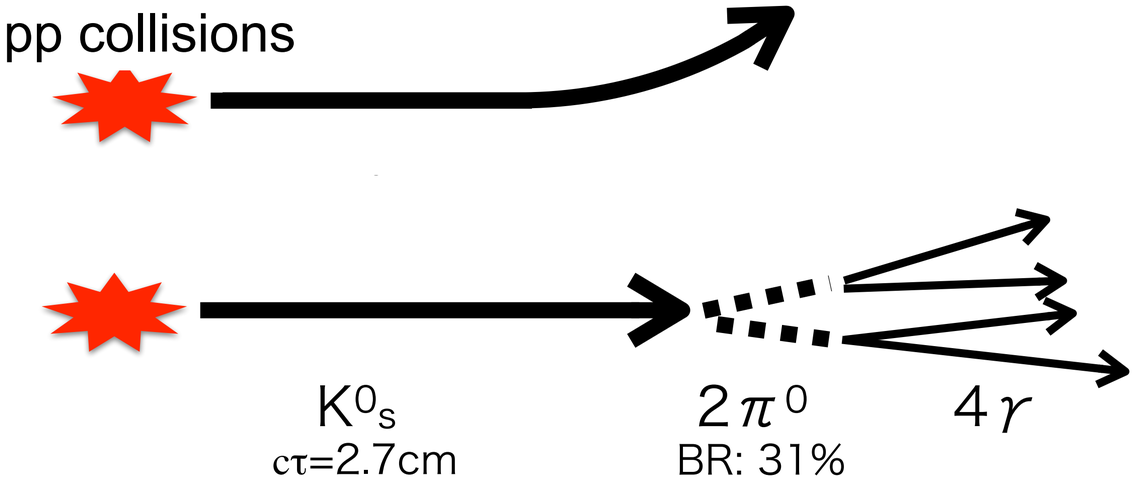


$K^{\pm}$ ✗ Swept out by D1 magnetic field

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

How to measure strange particles in LHCf



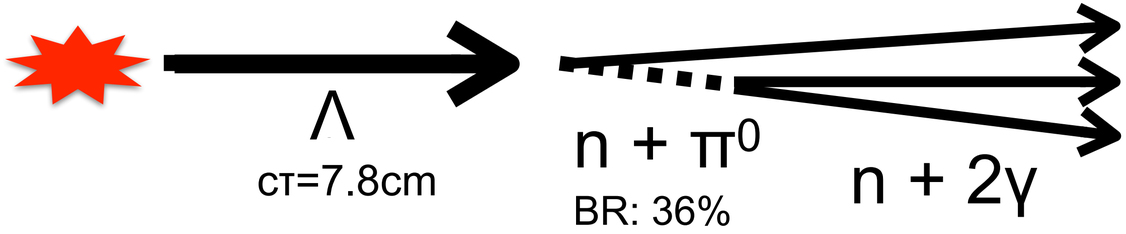
$K^\pm$ ✗ Swept out by D1 magnetic field

K^0

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

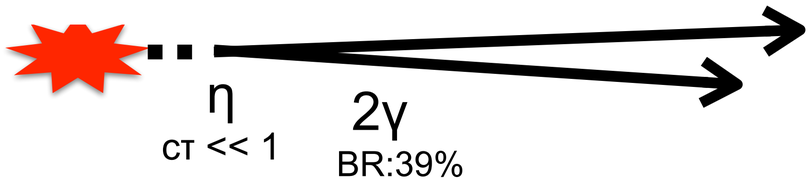
Poor acceptance
Challenging of reconstruction 4 photos

Other channels



Λ
(uds)

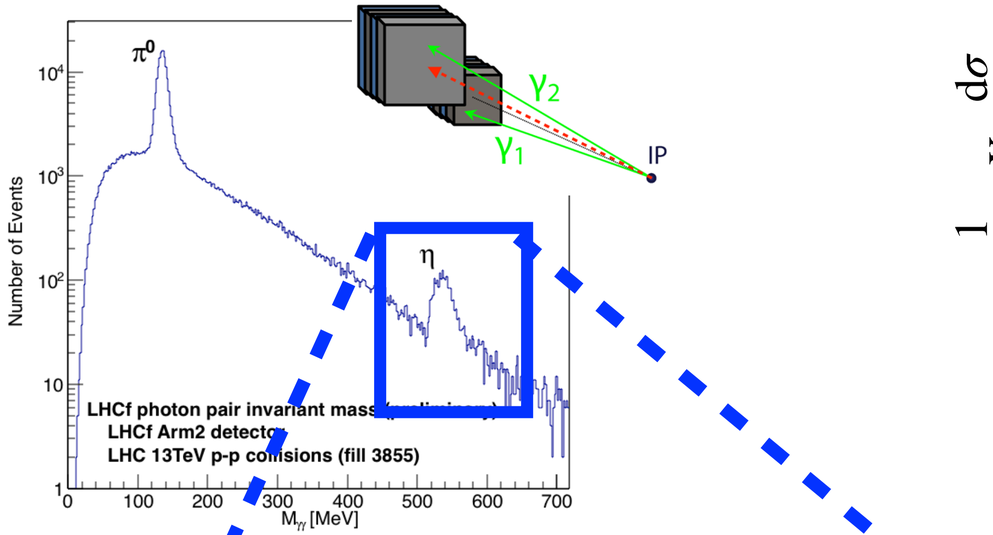
Decays between IP and detectors.
$\Lambda \rightarrow n+\pi^0 \rightarrow n+2\gamma$
Challenging of reconstruction for mix of hadronic and EM showers



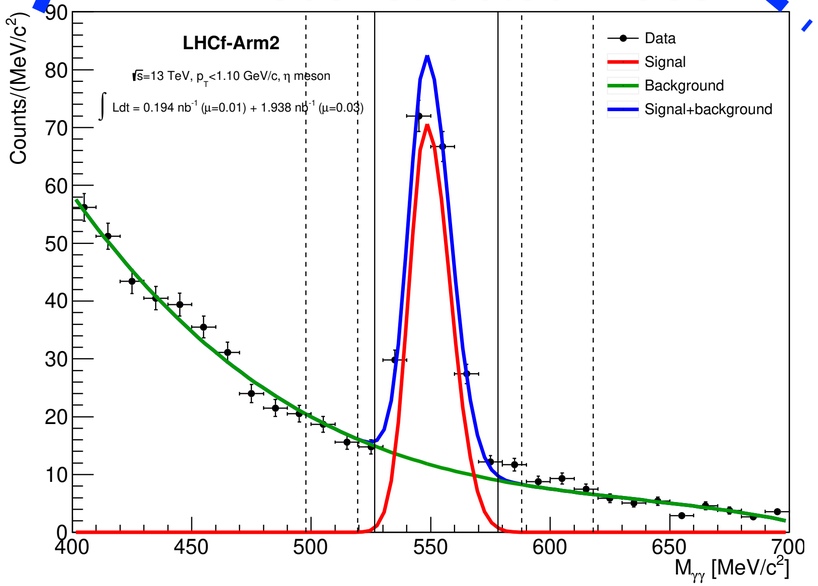
η
$(u\bar{u}+d\bar{d}+s\bar{s})$

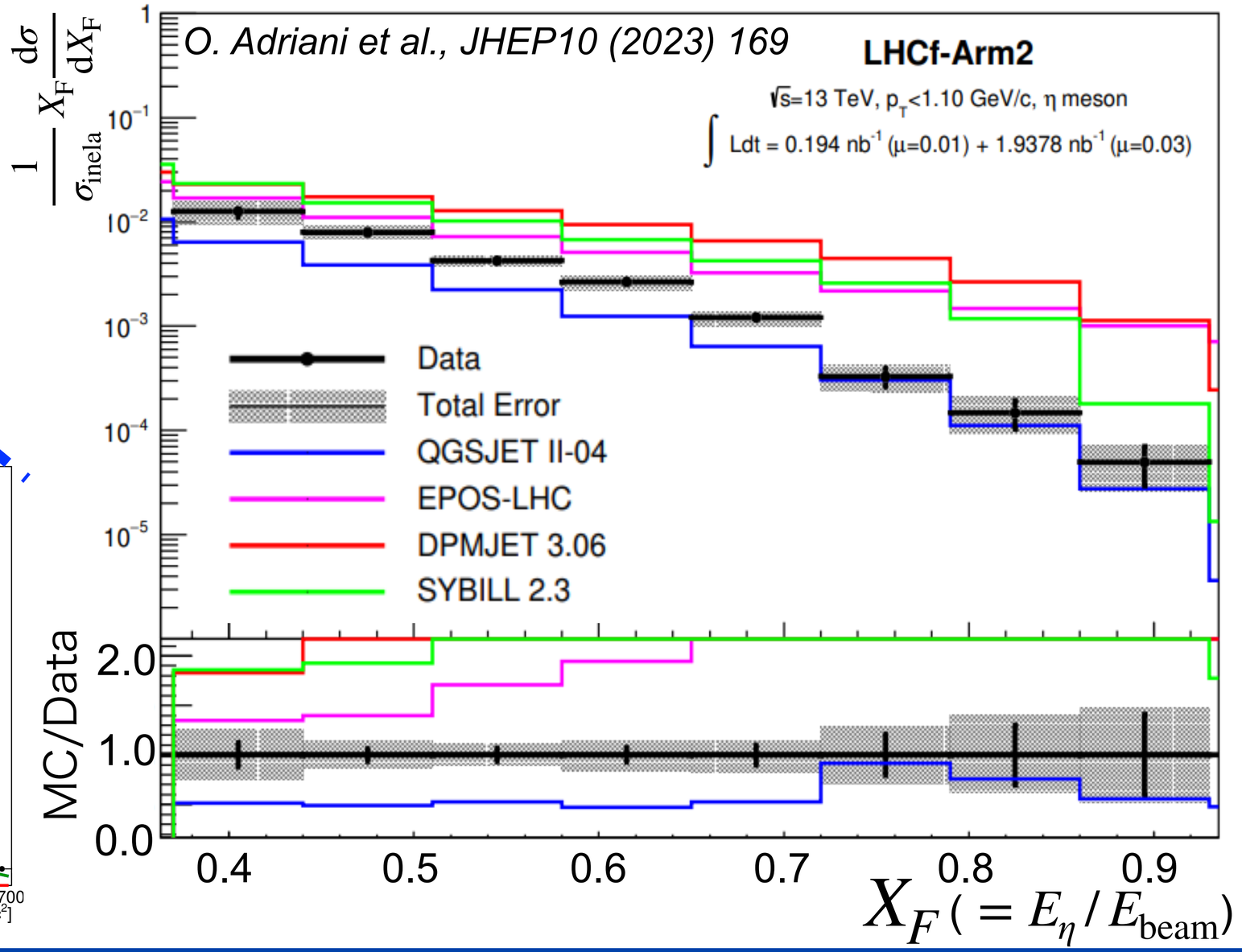
Reconstruction method is well established (= method for π^0)

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

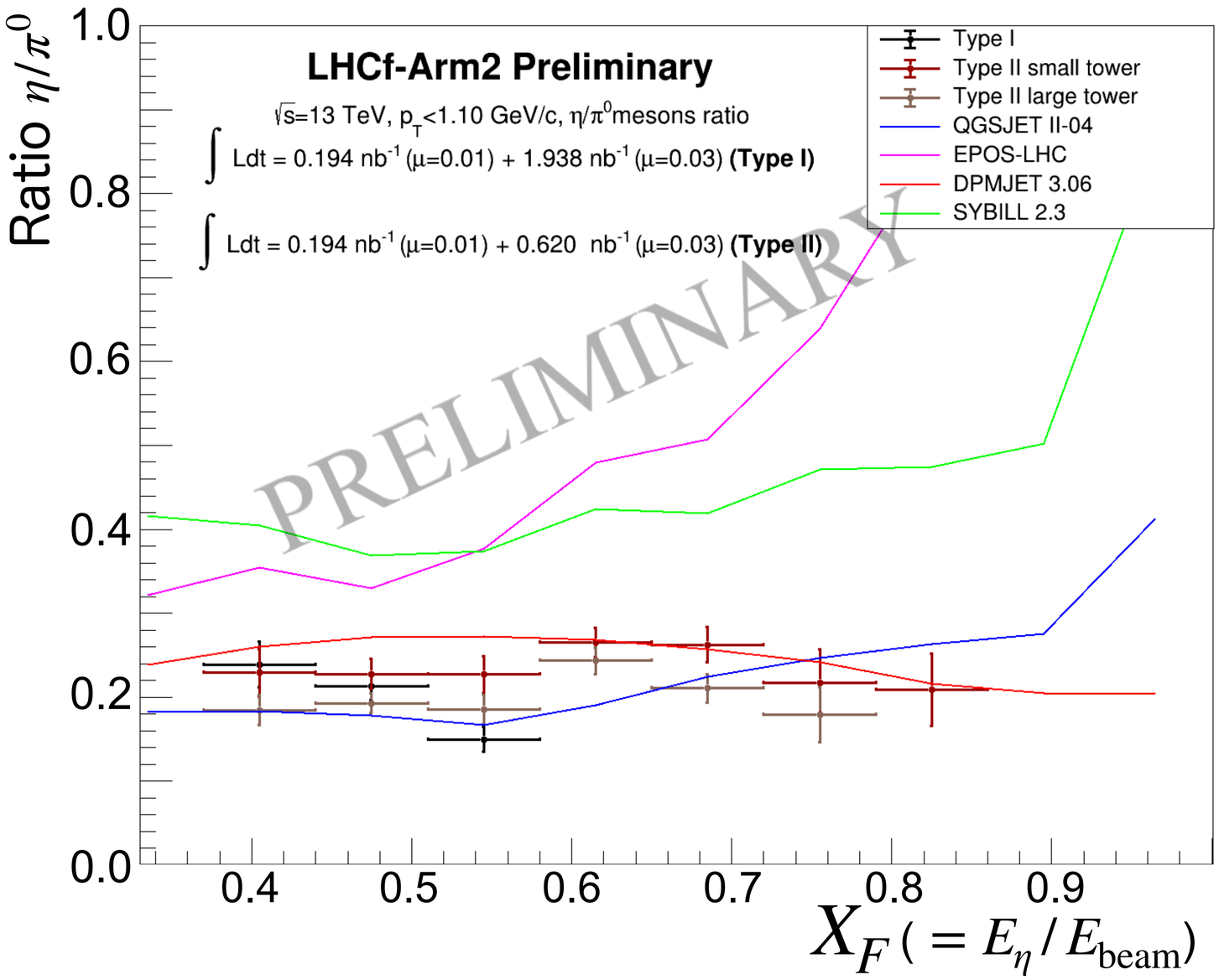


Reconstructed mass





η/π⁰ Ratio



- Data : constant in the whole energy range

EPOS-LHC, SIBYLL2.3

- Much larger than data

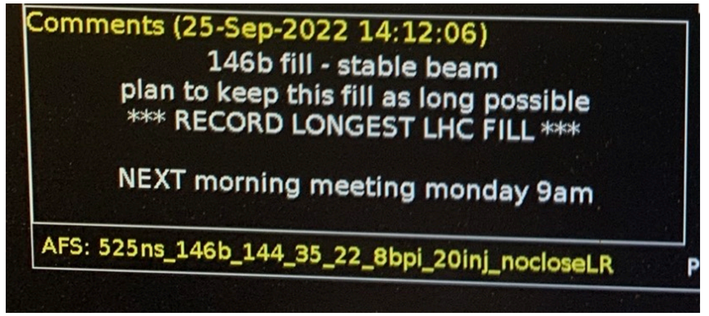
QGSJETII-04, DPMJET III

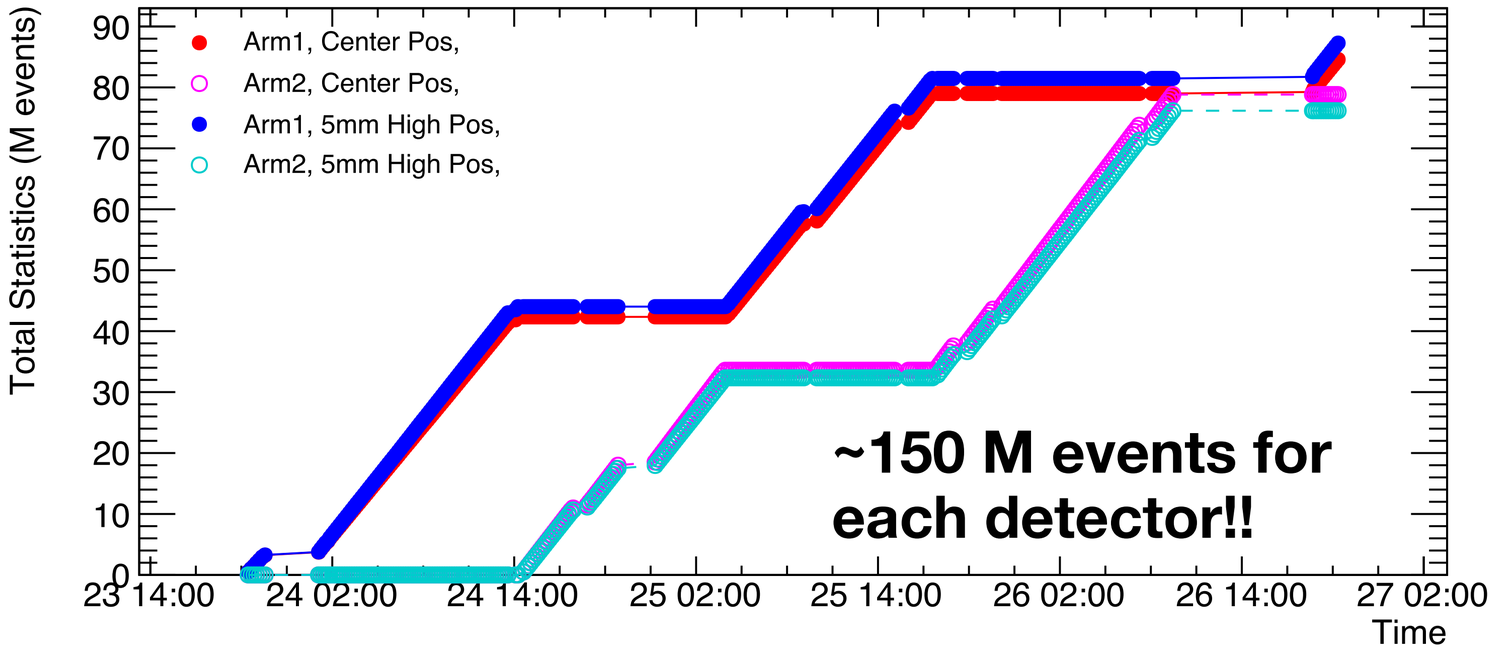
- Good agreement with data

Operation with pp, √s=13.6 TeV in 2022

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

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



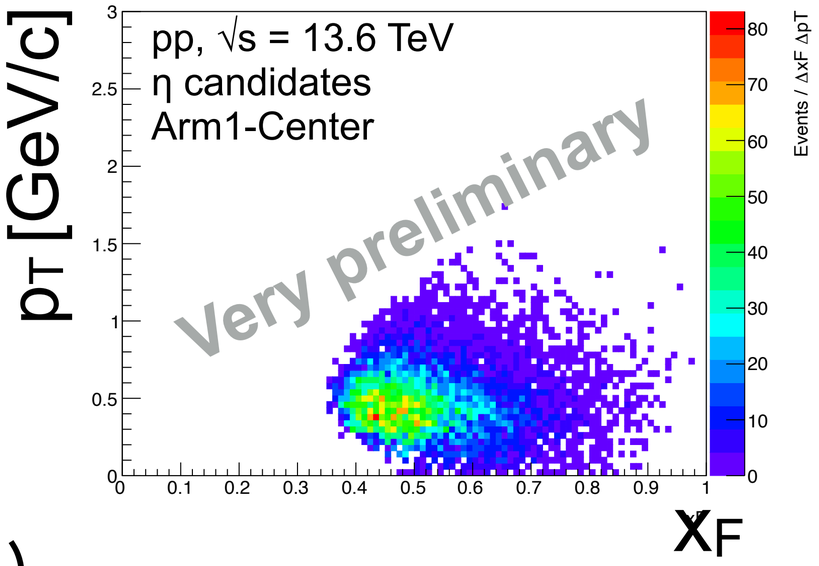


Analyses with large statistics

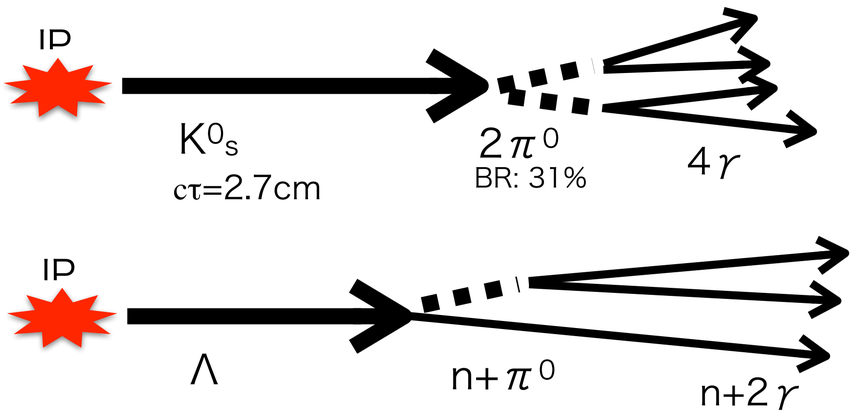
- Improvement of η and high-E π^0

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

  → cross-section measurement in X_F-p_T bins

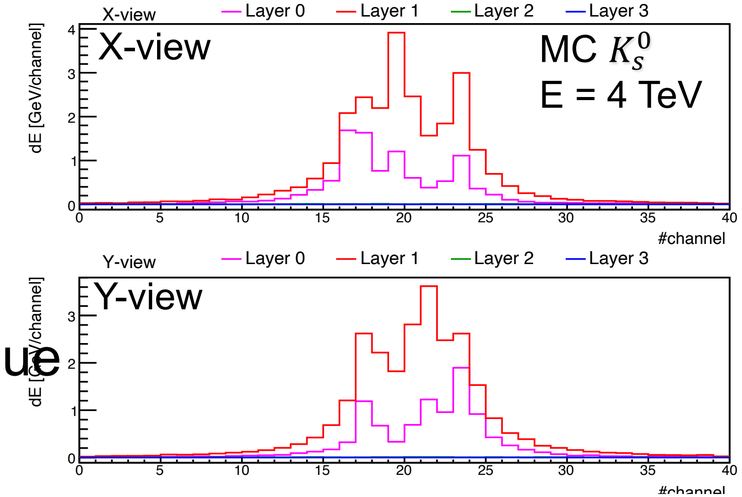


- Measurement of strange hadrons (K^0_S, Λ)



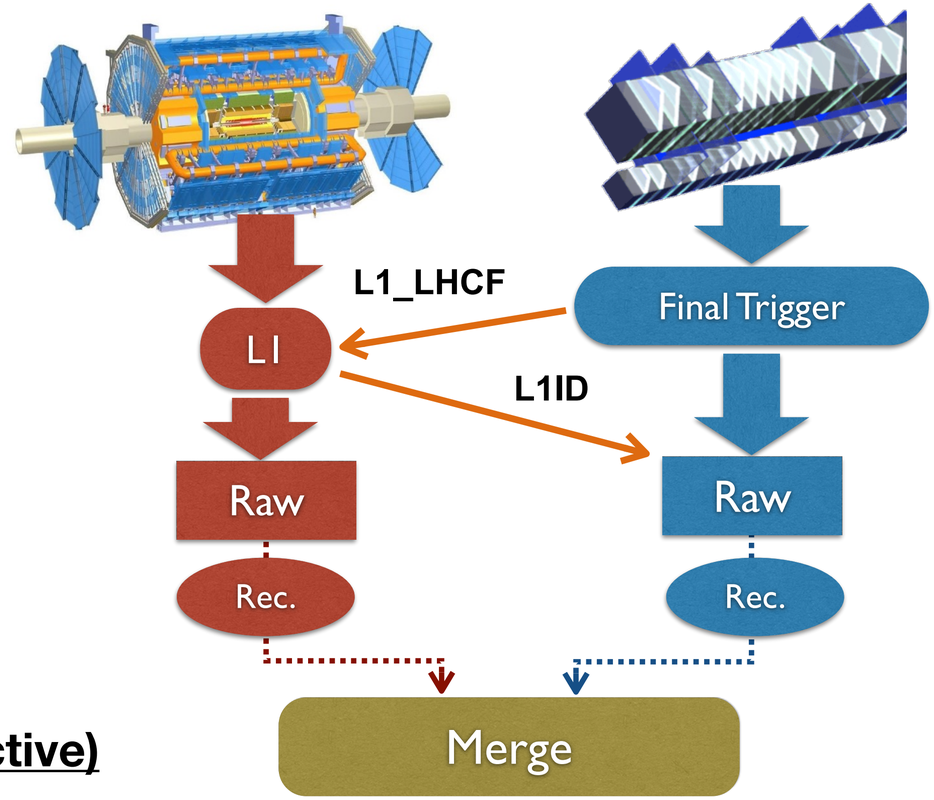
K^0_S : expect O(10^3) events

Reconstruction
of multiple hit events
→ Introducing
a machine learning technique

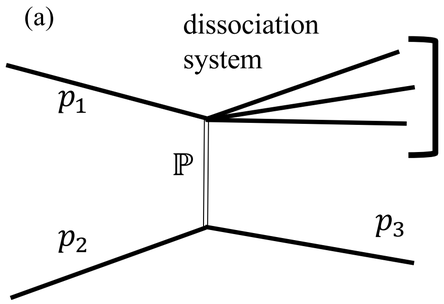


Joint operation with ATLAS

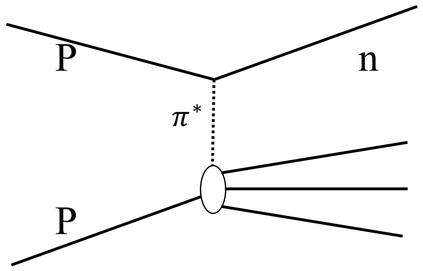
- Process-based analyses
  - Detail understanding of interaction
  - Forward-Central correlation
  - Forward(LHCf)-Forward(ATLAS-ZDC, RP)
- Trigger exchange btw. LHCf and ATLAS
  - merge reconstructed data with event-matching



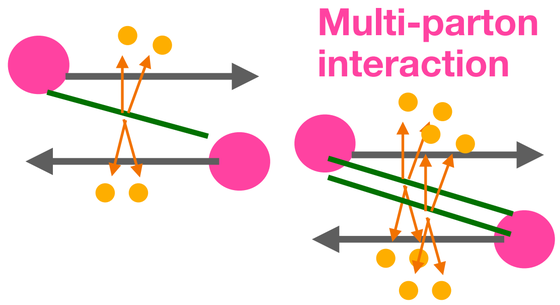
Diffractive dissociation



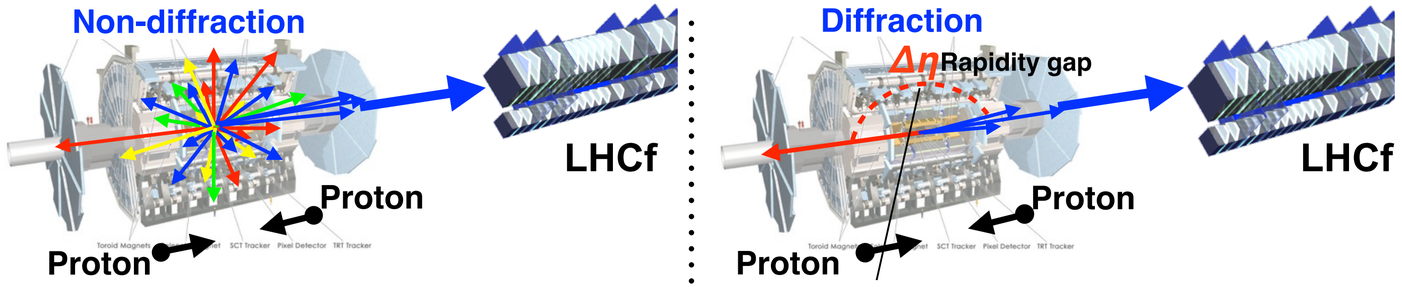
One pion exchange



Others (Non-diffractive)



Measurement of diffractive contribution



$N_{ch} >> 1$ $N_{ch} \sim 0$

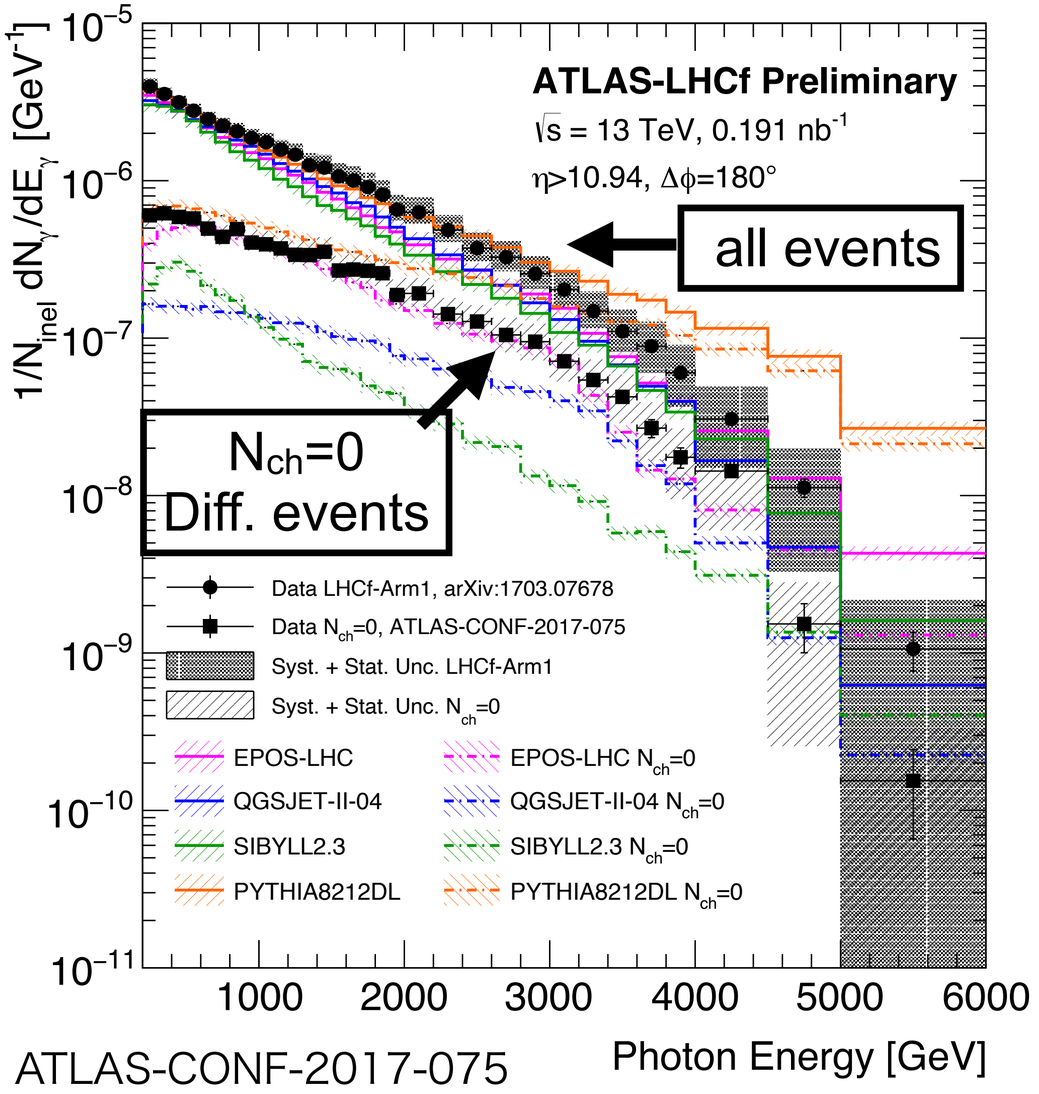
Identification of diffractive events by ATLAS

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)

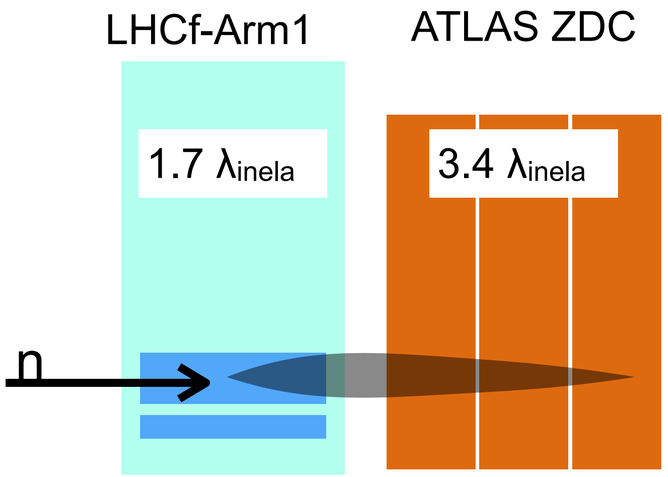
→ Selecting pure samples of proton dissociations.
→ Sensitive to only low-mass dissociations $M_X \lesssim 50$ GeV



ATLAS-CONF-2017-075

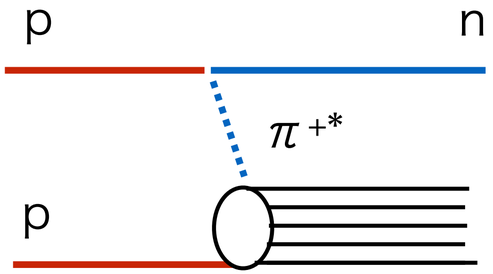
Joint operation in 2022

- 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**



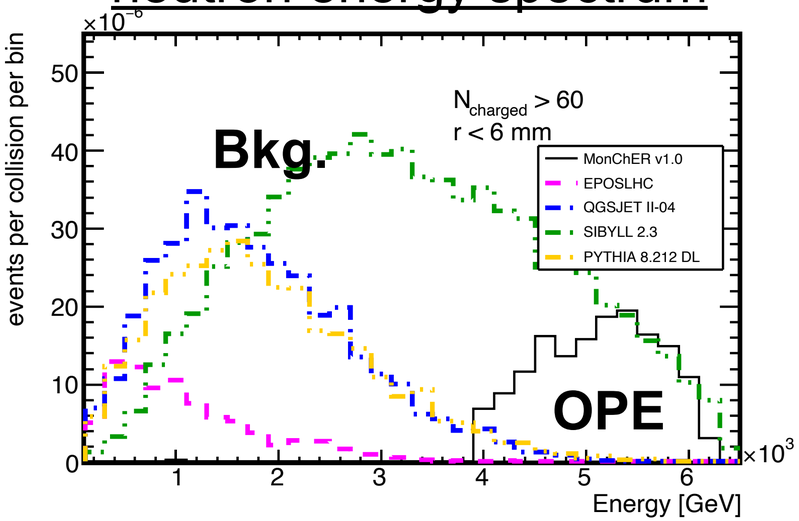
w/ RPs

w/ ZDC



One Pion Exchange (OPE)

neutron energy spectrum

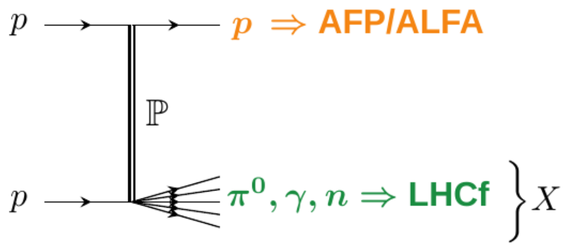


Joint operation with ATLAS RPs

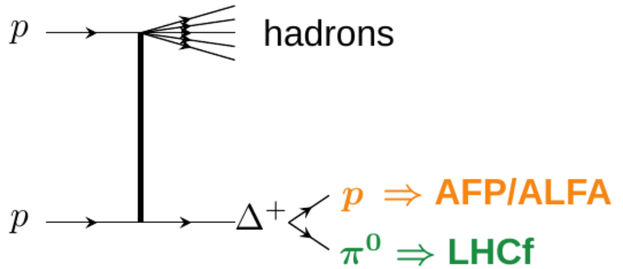
- Physics targets:
  - Detailed study of single diffractive collisions,
  - Measurement of proton excitation (very low-mass diff.)

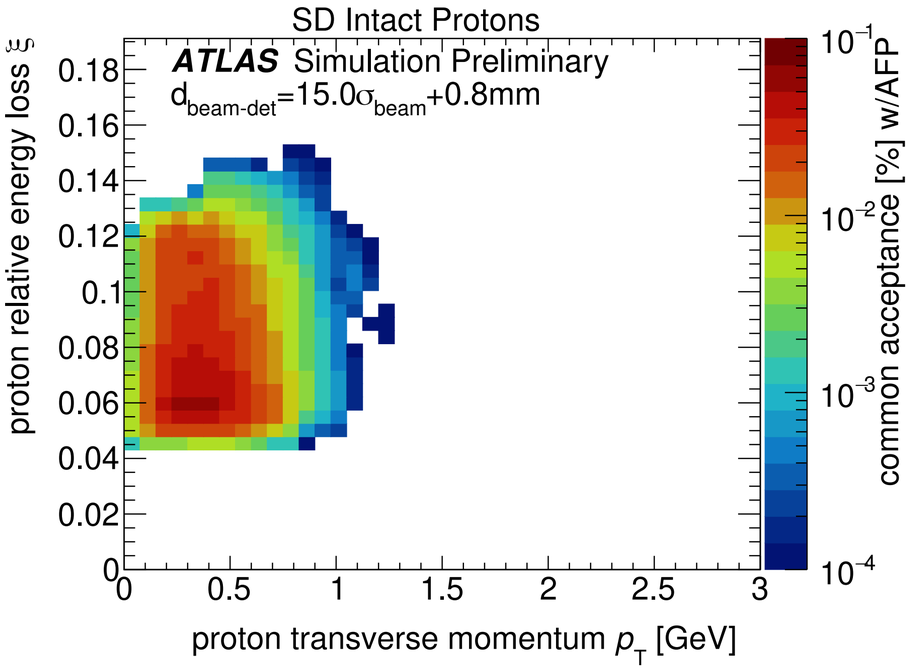
Fusibility study using MC
ATL-PHYS-PUB-2023-024

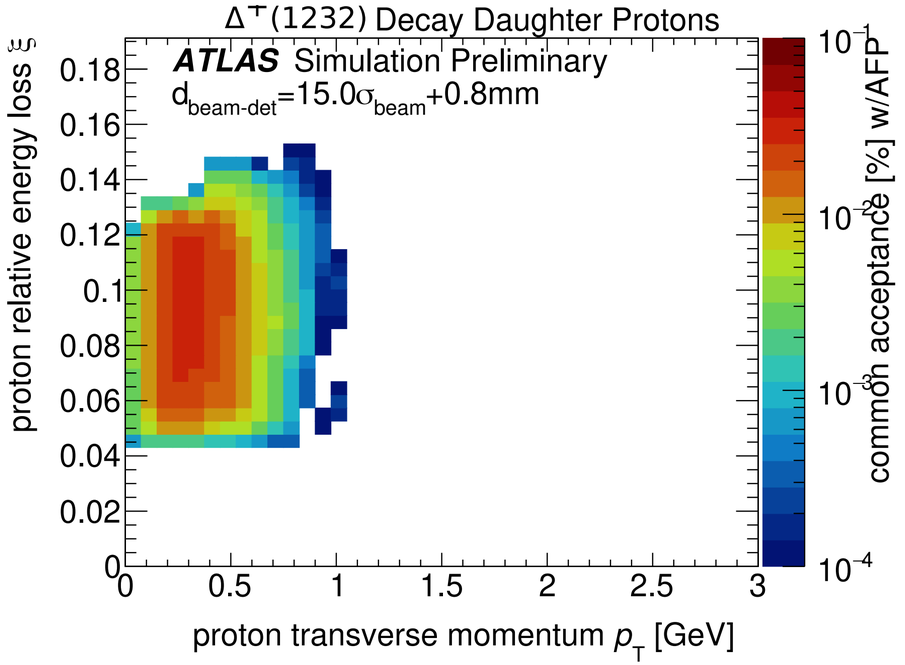
Single diffractive



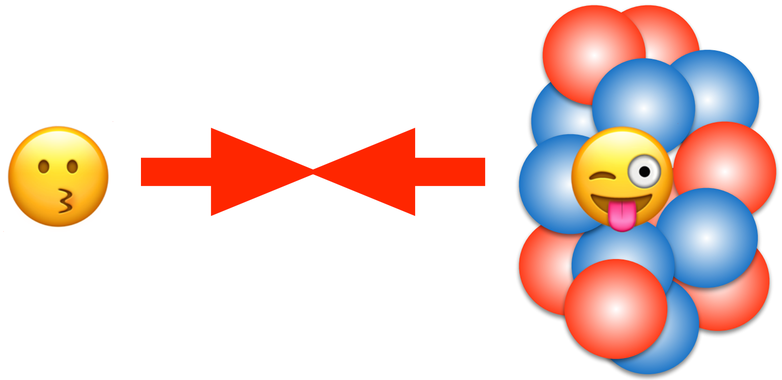
$\Delta^+(1232)$





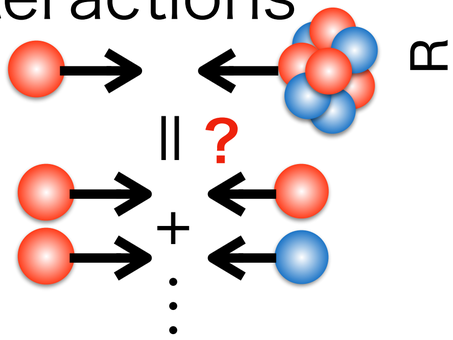


p-O measurement in 2025



Motivation

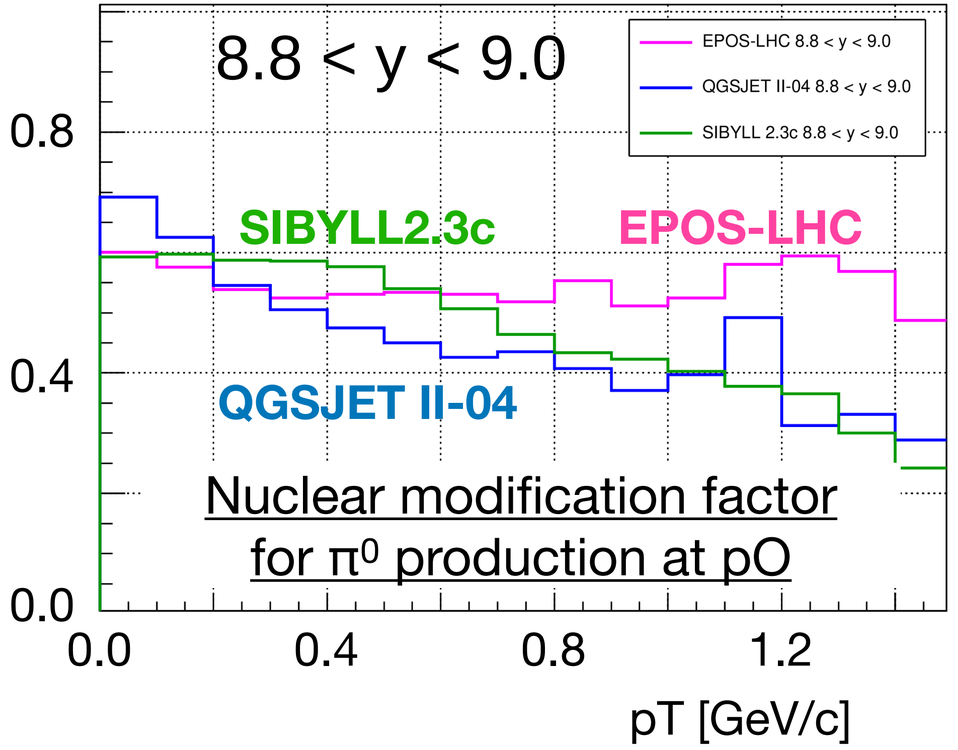
- **Ideal condition of CR-Air interaction study**
  - First proton-“light ion” collisions at colliders
  - Different modeling of nuclear effect induces difference predictions among models.
  - Negligible contribution of Ultra Peripheral Collisions (UPCs)
- Nucleus(nucleon)-Nucleus interactions
  - **Glauber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



Nuclear Modification Factor

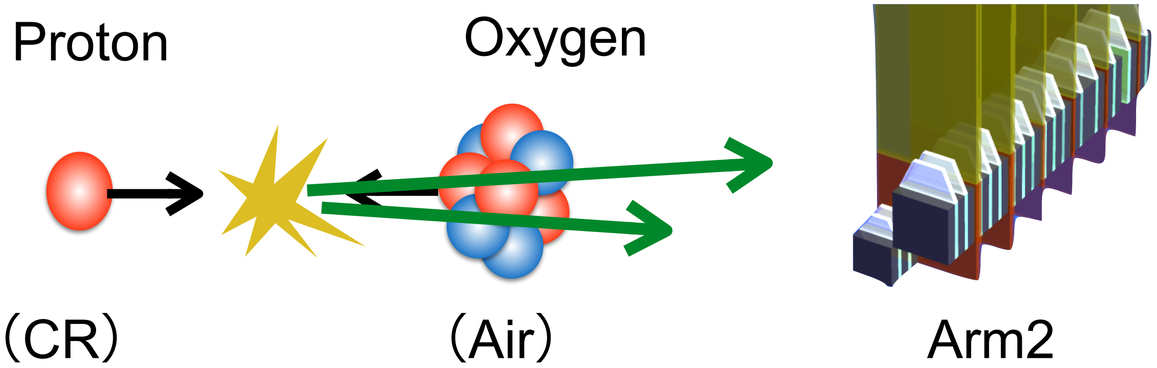
$$R = \frac{\sigma_{pO}}{A\,\sigma_{pp}}$$

A: average number of nucleon collision



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

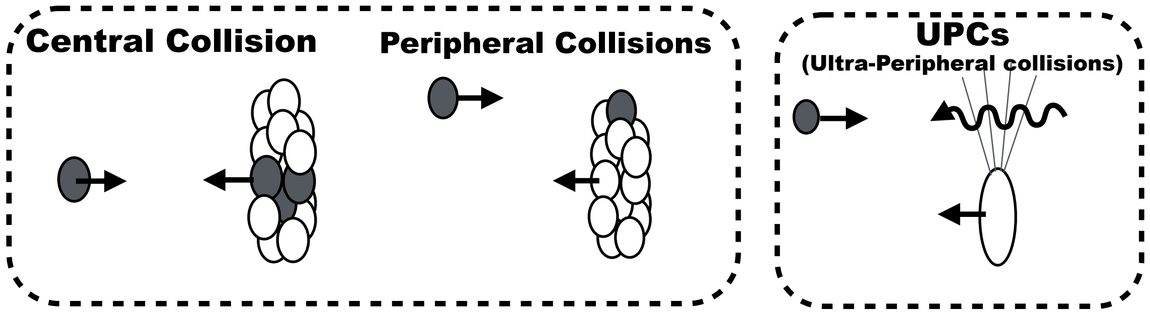
Summary

- 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

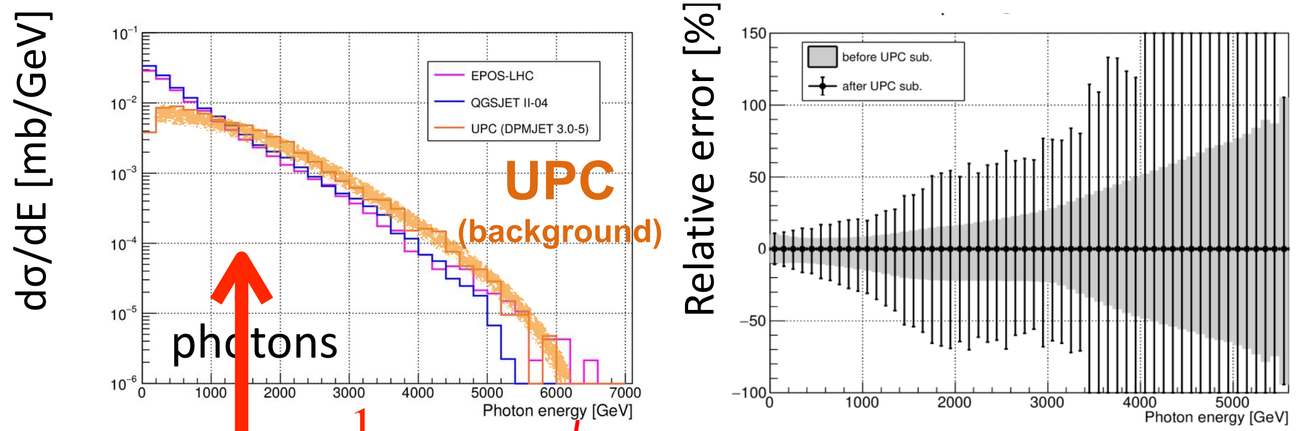
Effect of the Ultra Peripheral Collisions (UPCs)



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

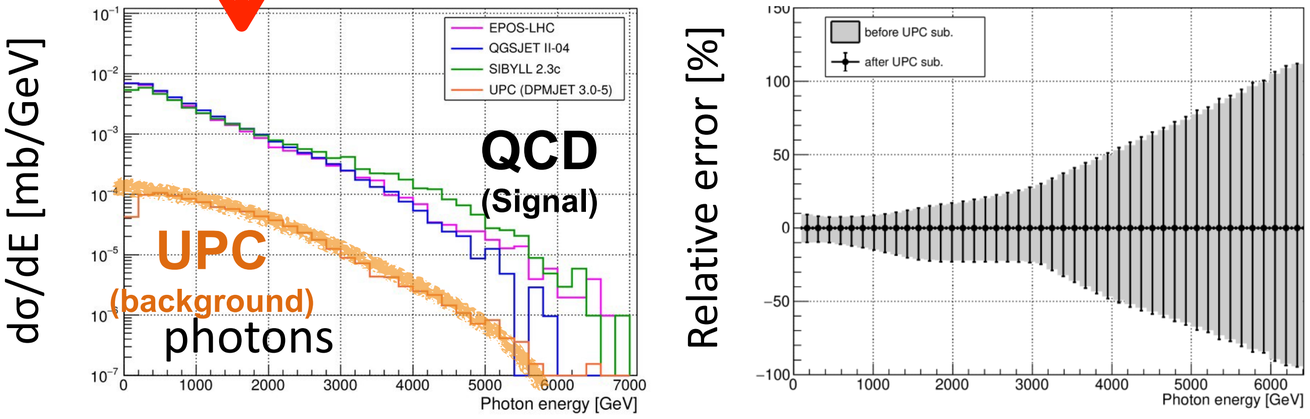
UPC contribution is negligible for "inclusive" measurement

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



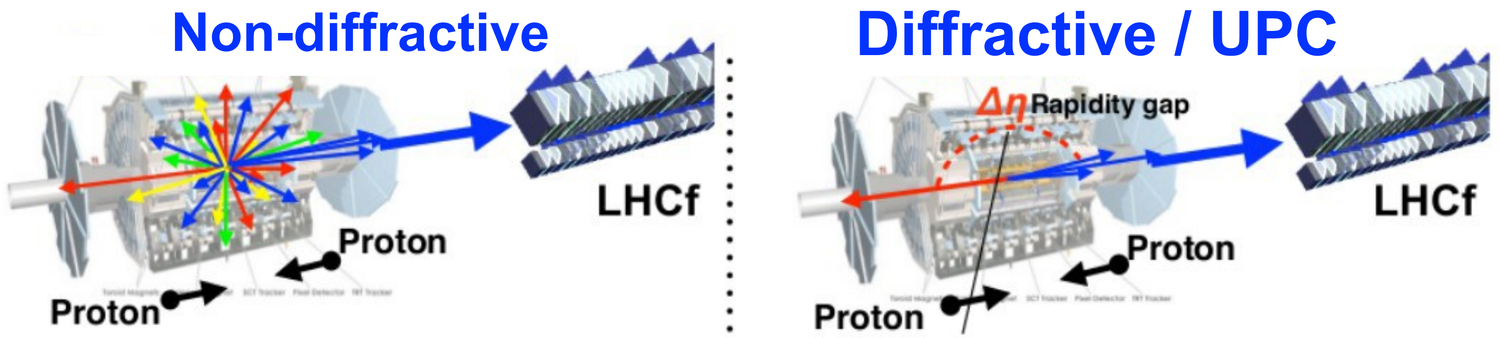
$\times \frac{1}{100}$

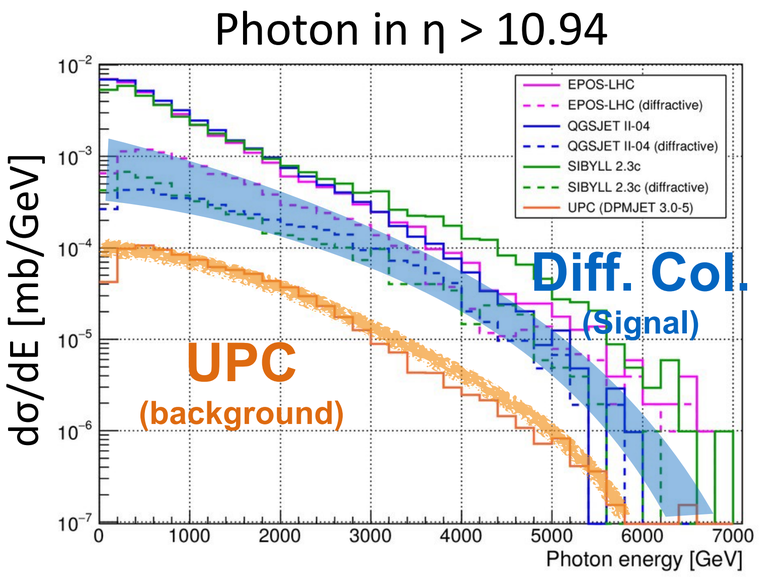
p-O at $\sqrt{s_{NN}}$ = 10 TeV

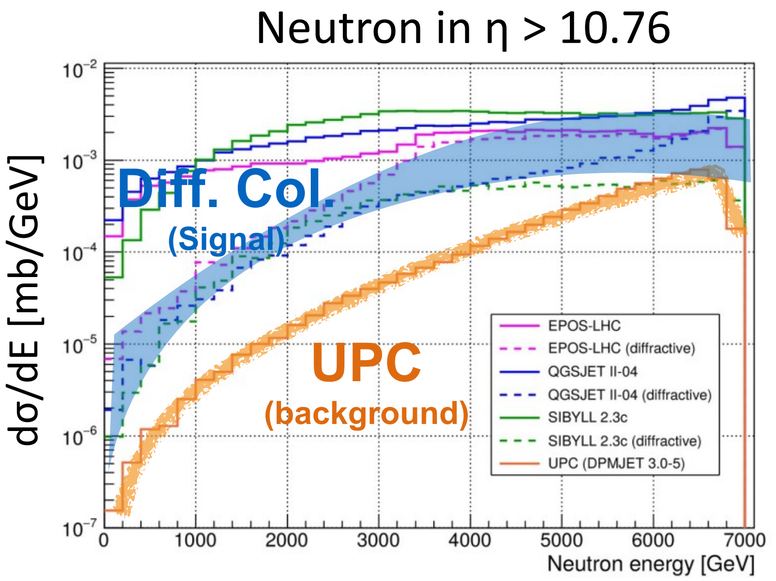


Impact on LHCf-ATLAS joint analysis

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

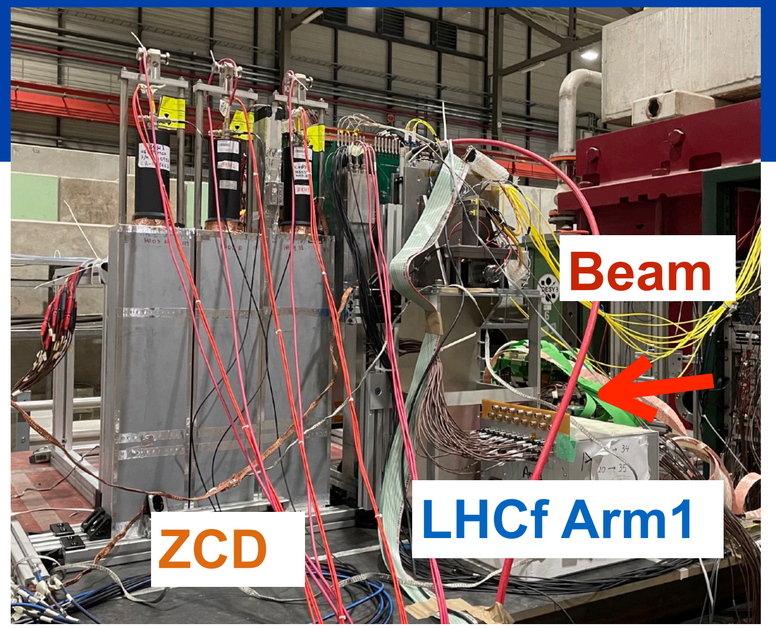




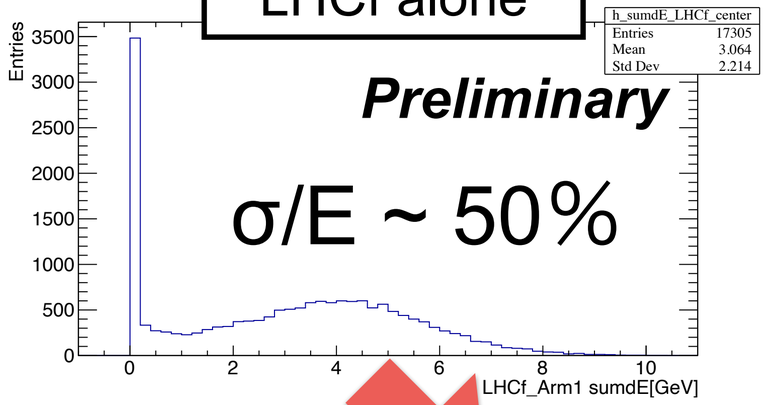


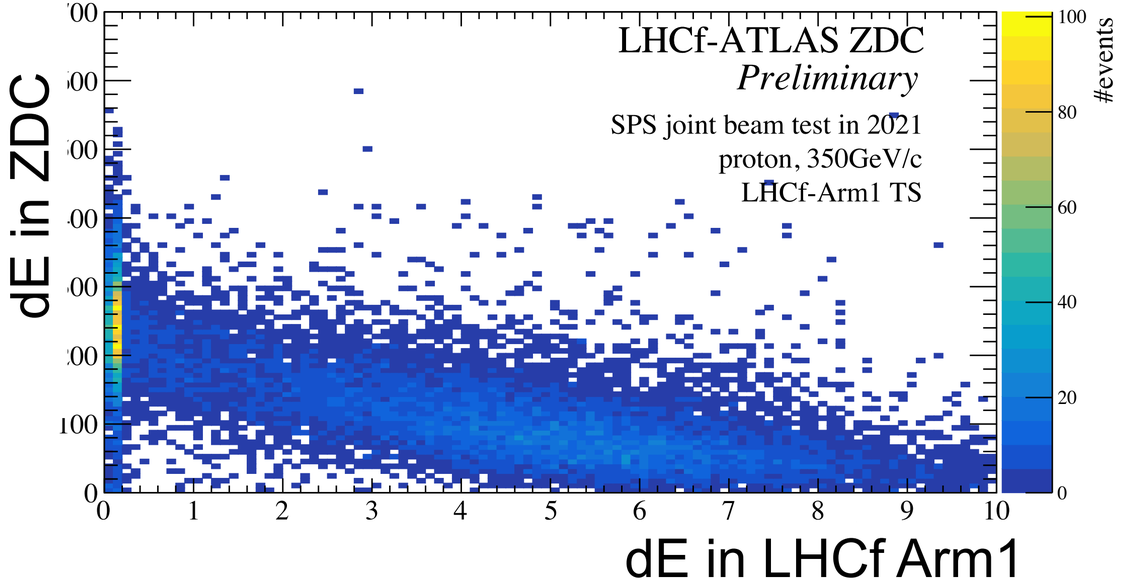
LHCf+ZDC beam test at SPS

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



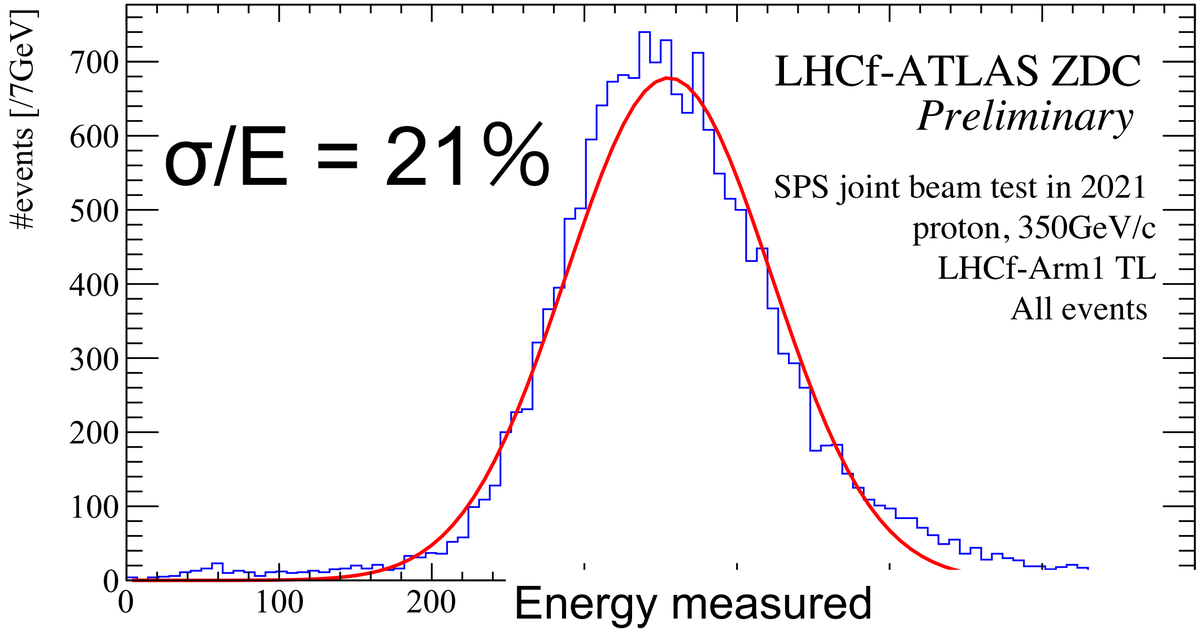
LHCf alone



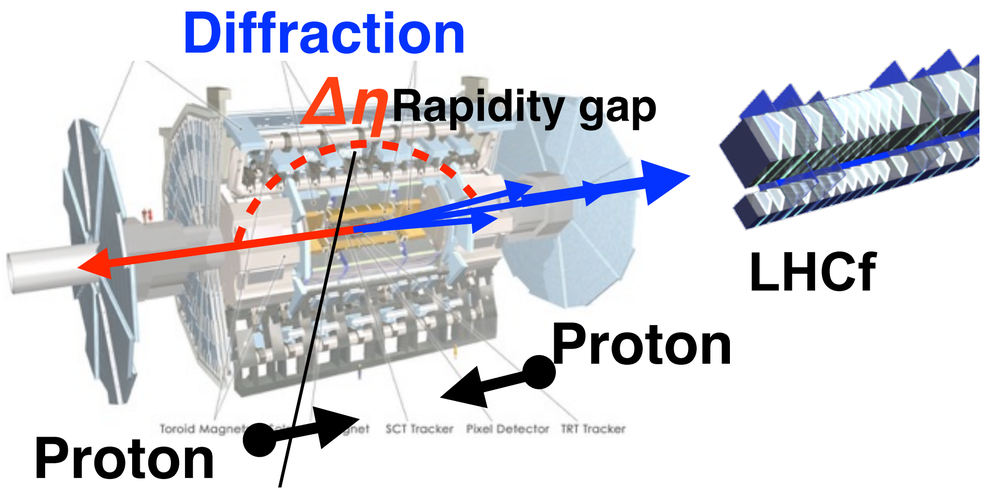


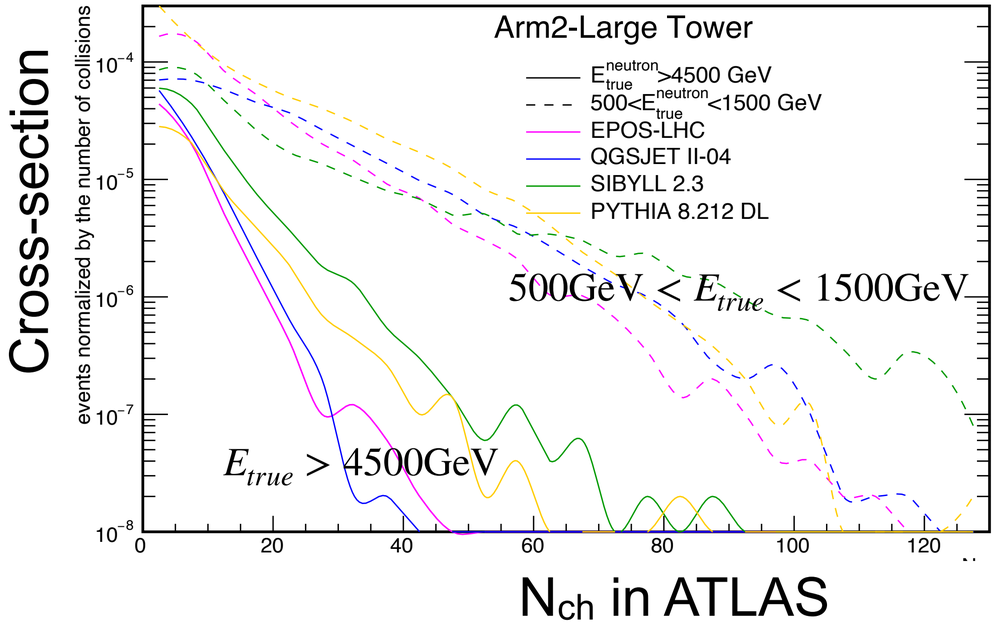
Confirmed improvement of energy resolution to 21%

LHCf + ZDC



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 →