STATUS AND PROSPECTS OF THE LHCF EXPERIMENT

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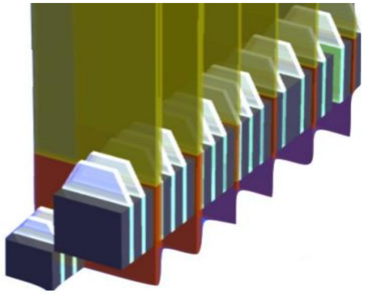
- **Preparation for p-O collisions data-taking in 2025:**

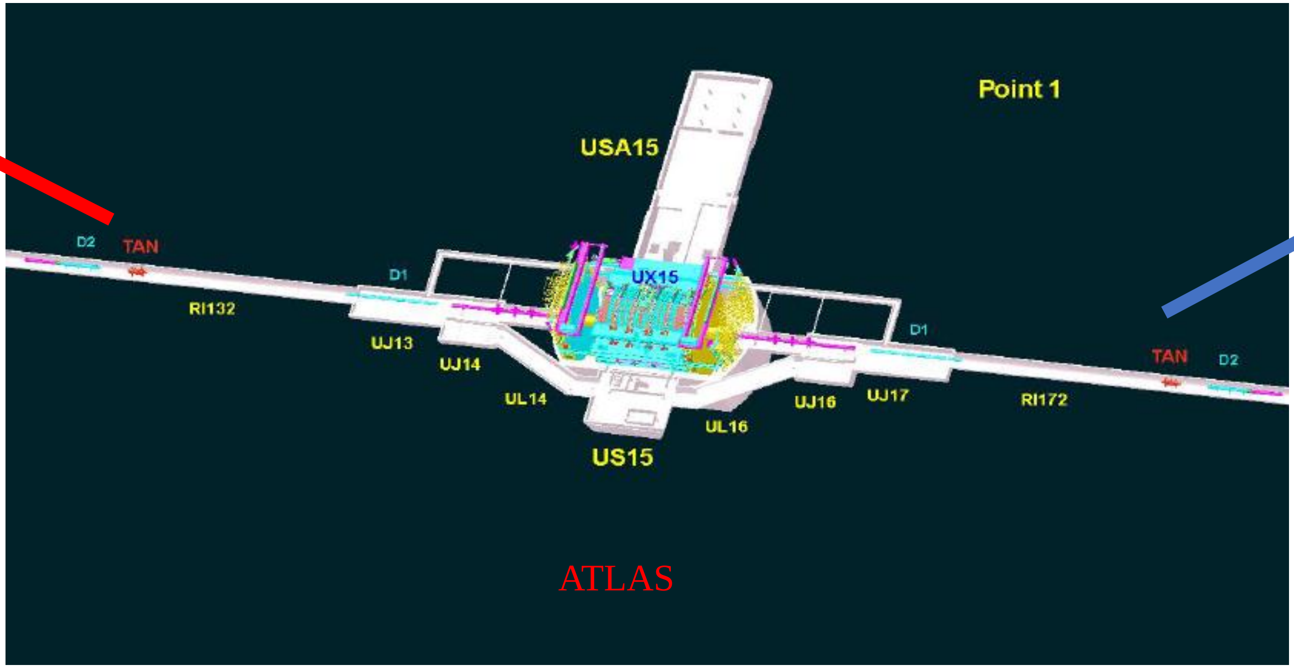
INTRODUCTION TO THE LHCF EXPERIMENT

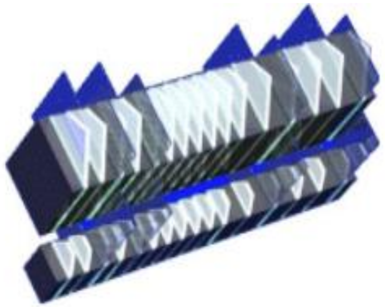
The LHCf experiment

- A **unique experiment** designed to measure neutral particle production in the **very forward pseudorapidity region**.
- Composed by two **sampling** and calorimeters (ARM1 & ARM2), located at about ± 141 m from the LHC Interaction Point 1 (IP1).
- LHCf aims to provide experimental data needful to tune and calibrate **hadronic interaction models** widely used by ground-based cosmic ray experiments.



LHCF-ARM2





LHCF-ARM1

The LHCf detectors

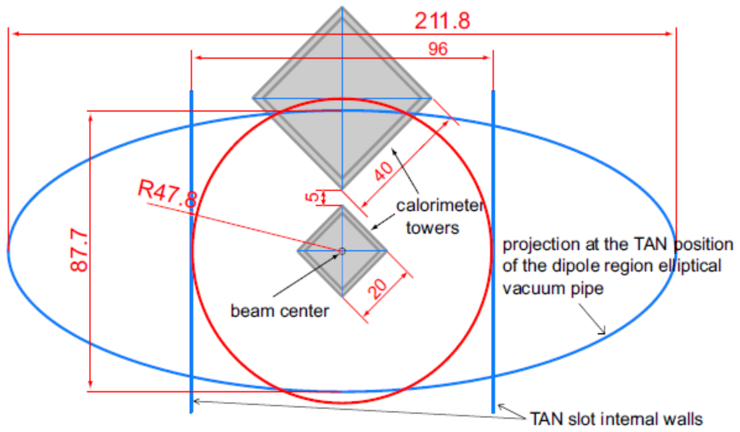
ARM1

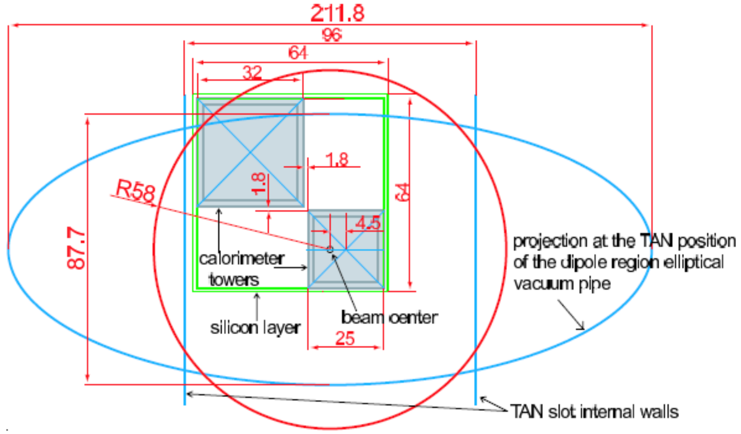
- **Energy resolution** <5% for photons and 35-40% for neutrons.
- Tracking with 4 GSO scintilating layers.
- **Position resolution** $\approx 200\ \mu m$.

ARM2

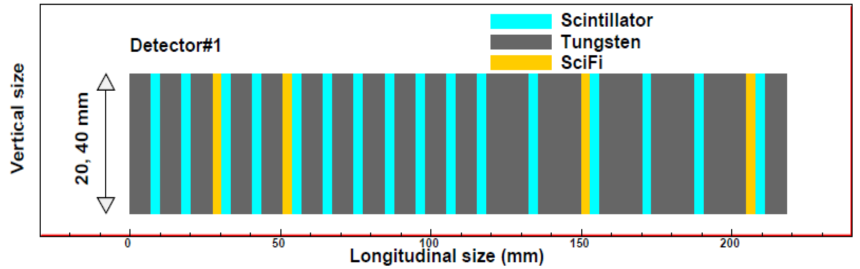
- Same Energy resoultion as ARM1.
- Tracking with 4 XY **silicon microstrips** layers.
- **Position resolution** $\approx 40\ \mu m$.

Transversal view

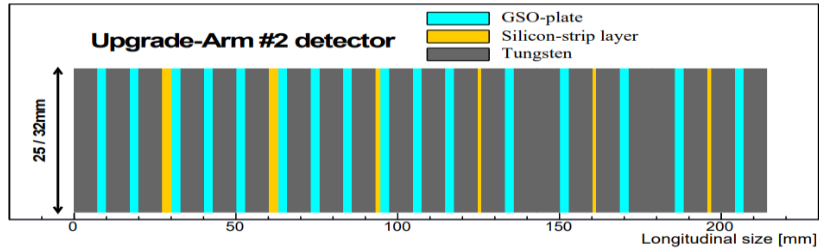




Longitudinal view

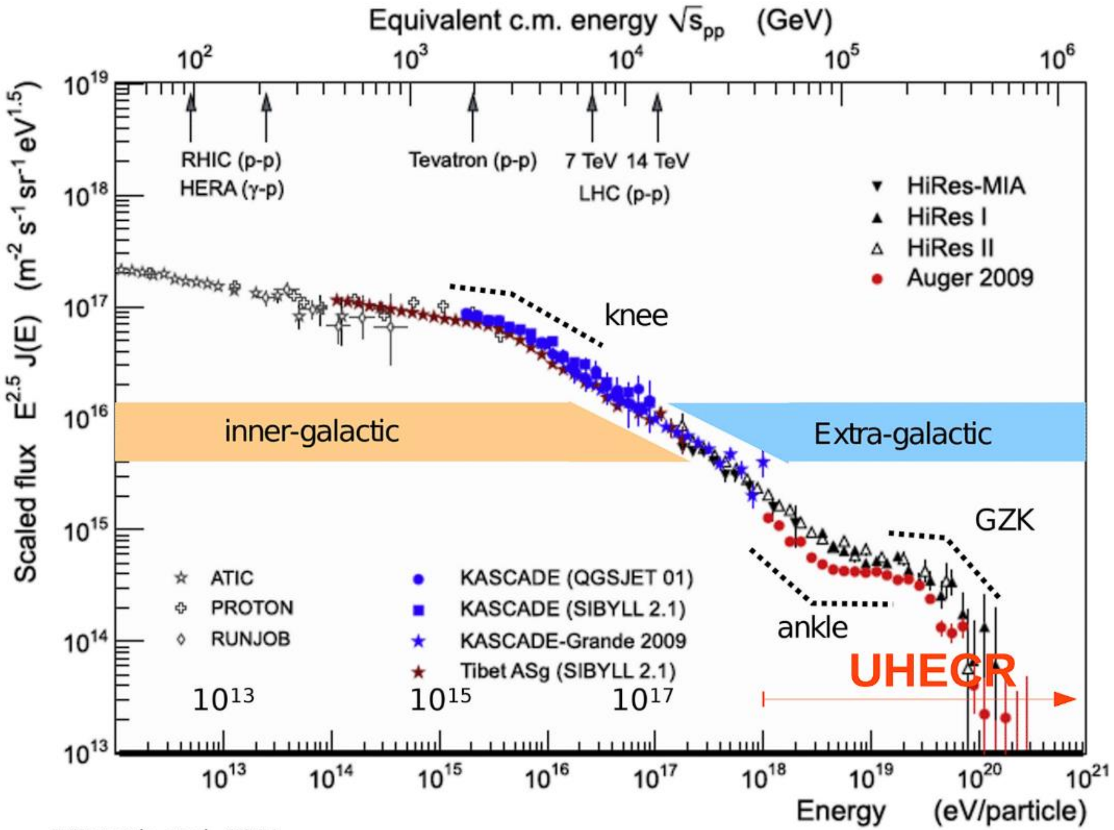


44 X_0 and 1.6 λ_I deep



Experimental purpose

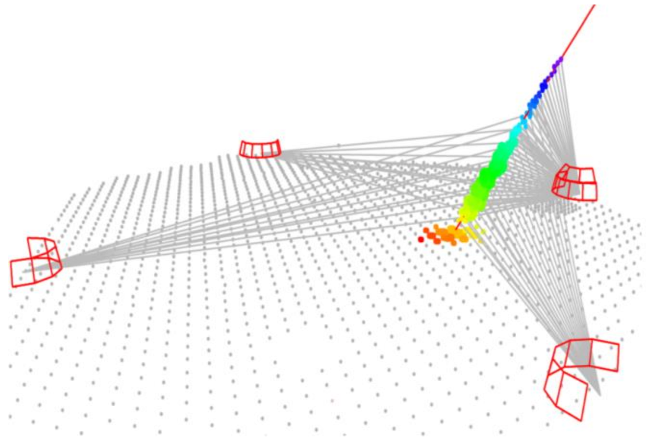
Ultra High Energy Cosmic Rays (UHECR)



D'Enterria et al., 2011

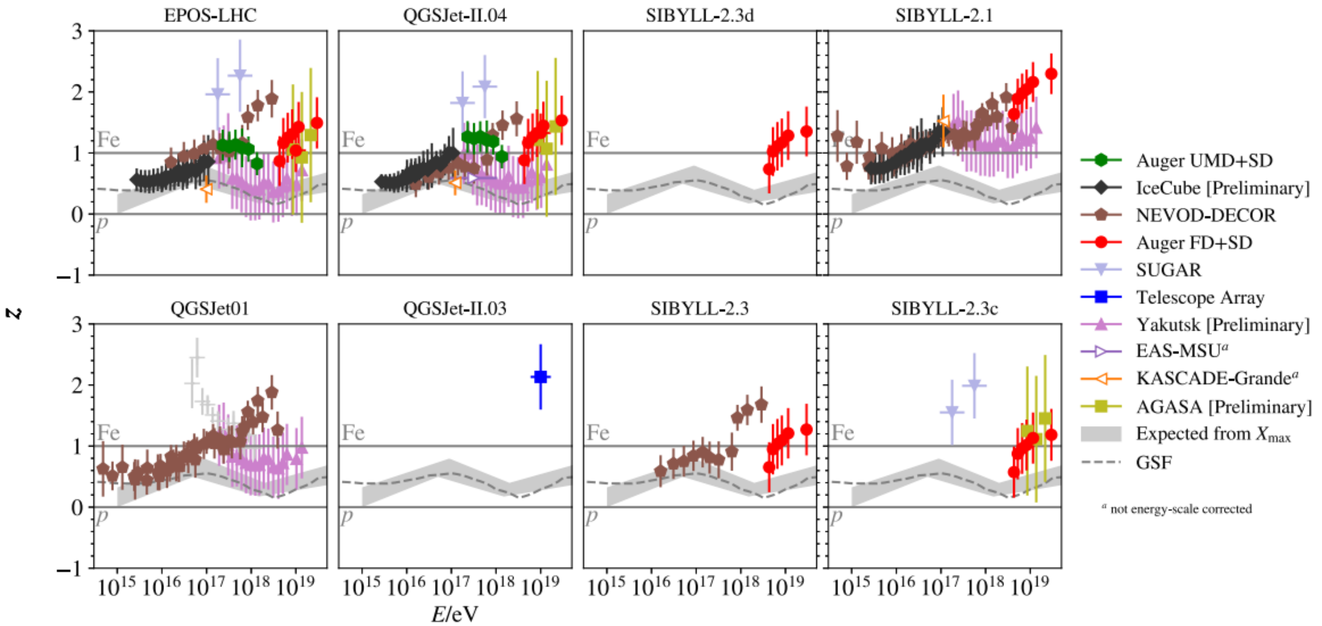
- **Motivation:** Understand mechanisms responsible for acceleration and propagation.
- The accurate measurements of UHECR flux and **composition** as a function of the energy.

Indirect measurements of energy flux and average composition by **Extensive Air Showers**.



Experimental purpose

The Muon Puzzle in UHECR composition measurements



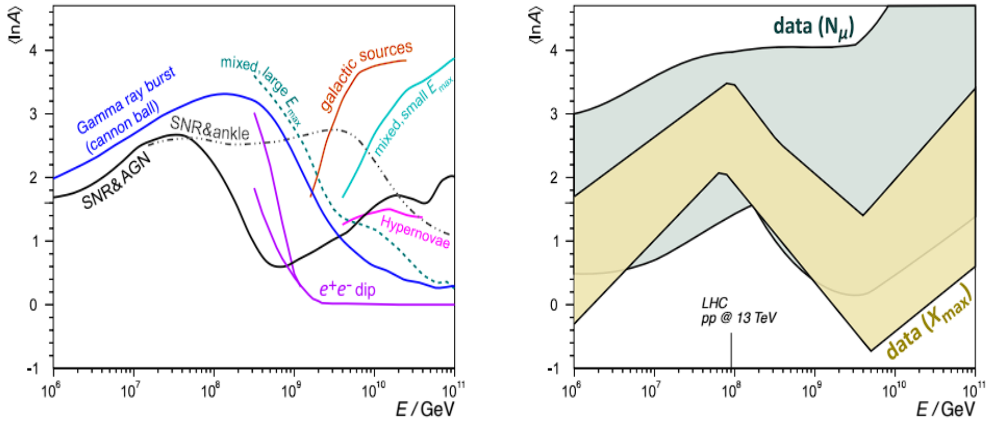
Normalized muon numbers results observed by several CR experiments

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

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

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

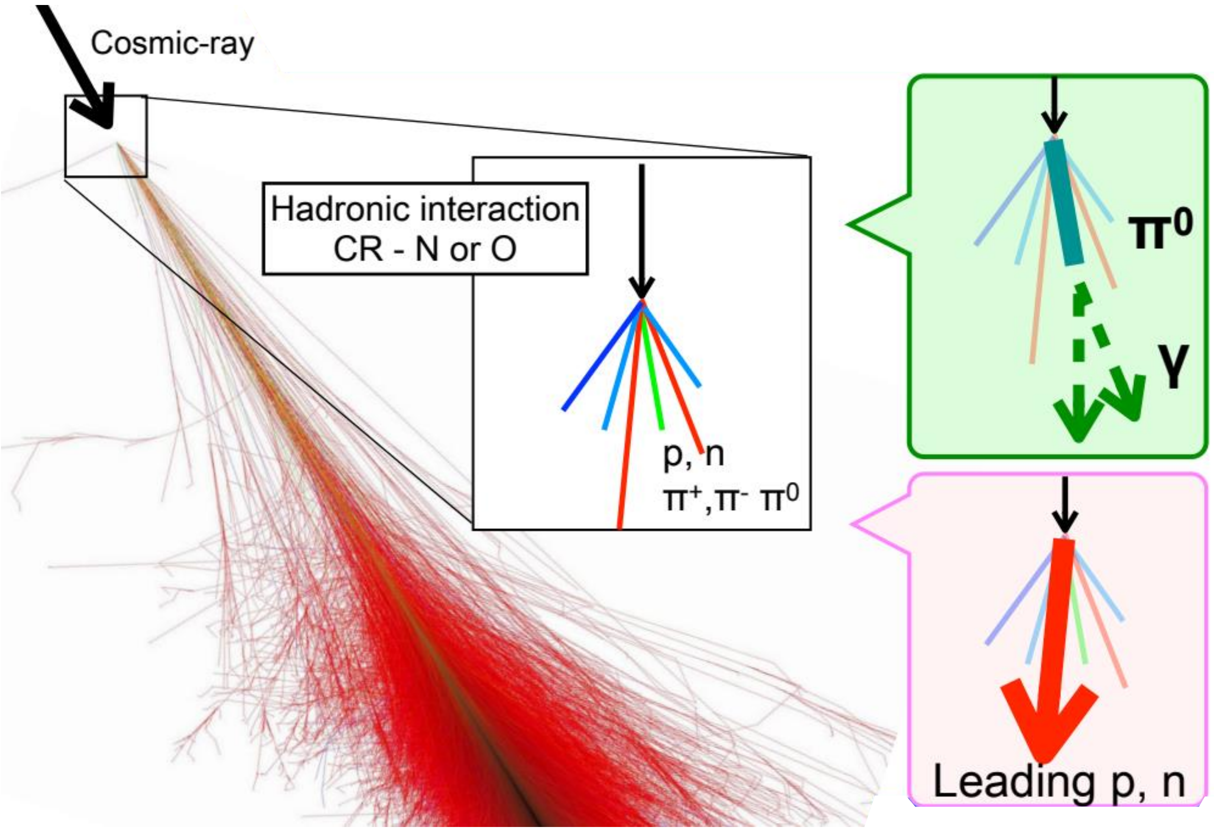
- **A muon excess in Hadronic Interaction Models (HIM) predictions is observed by several experiments.**
- This is reflected in **large uncertainties** induced in the composition results of the ground-based CR experiments.
- Reducing measurement uncertainties is crucial for discriminating between **cosmic ray production/acceleration models.**



J. Albrecht et al., ASS 367, 2022

Experimental purpose

Extensive Air Showers (EAS)



NEUTRAL PIONS

- $\pi^0 \rightarrow \gamma\gamma$.
- Induce electromagnetic showers.
- The fraction of π^0 is a fundamental input for HIM.

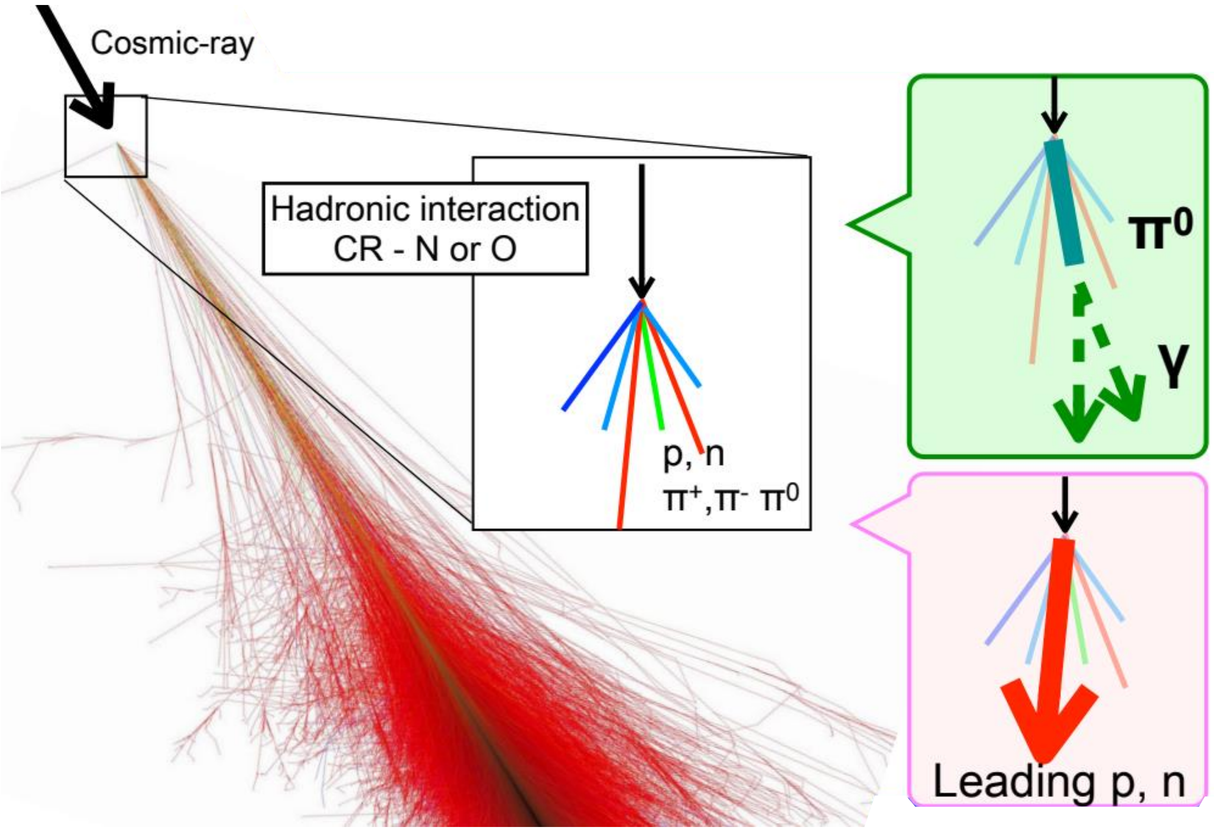
LEADING BARYONS

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

$k = 1 - E_{leading} / E_{CR}$.

Experimental purpose

Extensive Air Showers (EAS)



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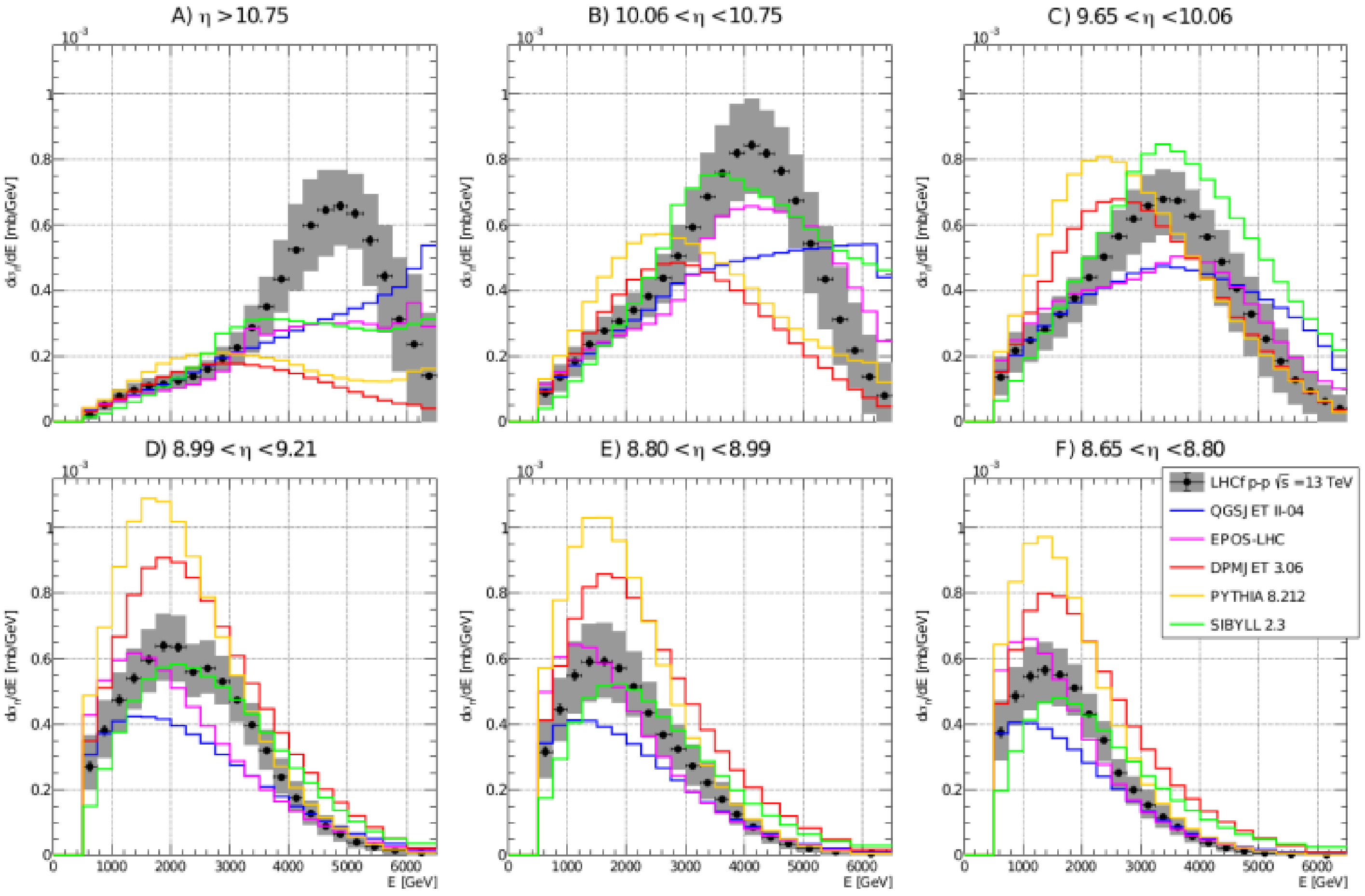
LHCf can measure them at LHC to solve the Muon Puzzle and mitigate the uncertainties in the CR mass composition measurements

RESULTS FROM LHC-RUN II DATA

Neutron measurement in p-p at $\sqrt{s}$= 13 TeV

- **Inelasticity (k = 1 - $E_{leading}$/ E_{CR})** is an important parameter for understanding cosmic ray (CR) air shower development.
- Models fail to reproduce **the peak structure at η > 10.75** and underestimate the total cross-section.
- **For 8.65 < η < 10.75**, either **EPOS-LHC** or **SIBYLL 2.3** agrees best with data, depending on the pseudorapidity region.



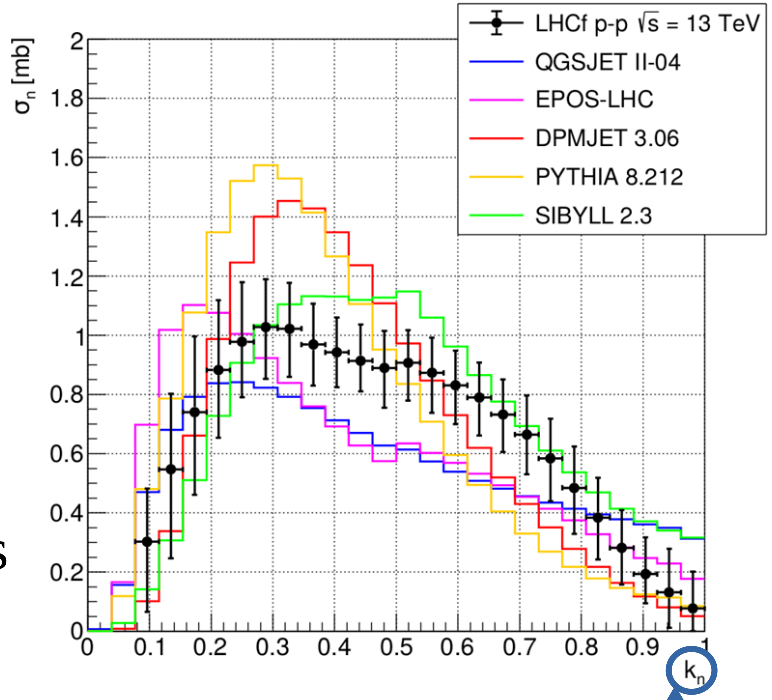
O. Adriani et al., JHEP07 (2020) 016

Inelasticity in p-p at $\sqrt{s}$= 13 TeV

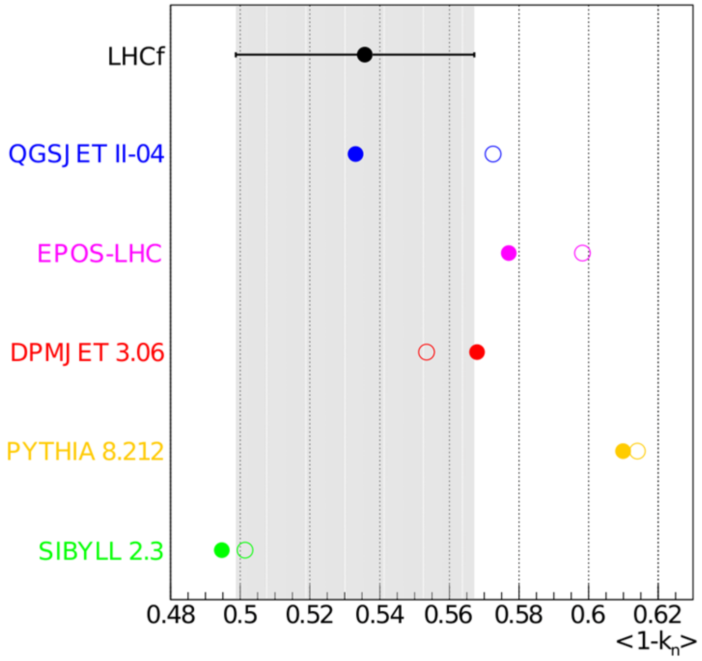
- **Inelasticity (k = 1 - $E_{leading}/E_{CR}$) is** an important parameter for understanding cosmic ray (CR) air shower development.

- **Neutron elasticity** distribution is not well reproduced by any model l, though **SIBYLL 2.3** performs better than others

- **Average neutron inelasticity** is accurately reproduced by **QGSJET II-04** and is close to predictions from other models, except for PYTHIA 8.212.



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

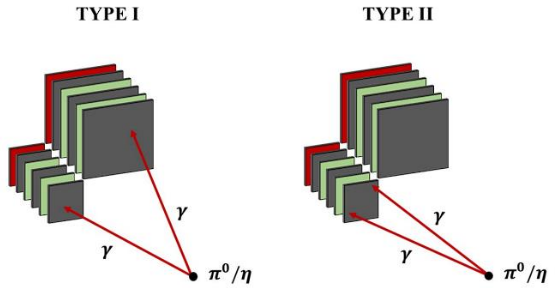


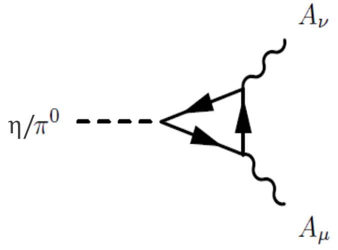
•neutron inelasticity
∘all particles inelasticity

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

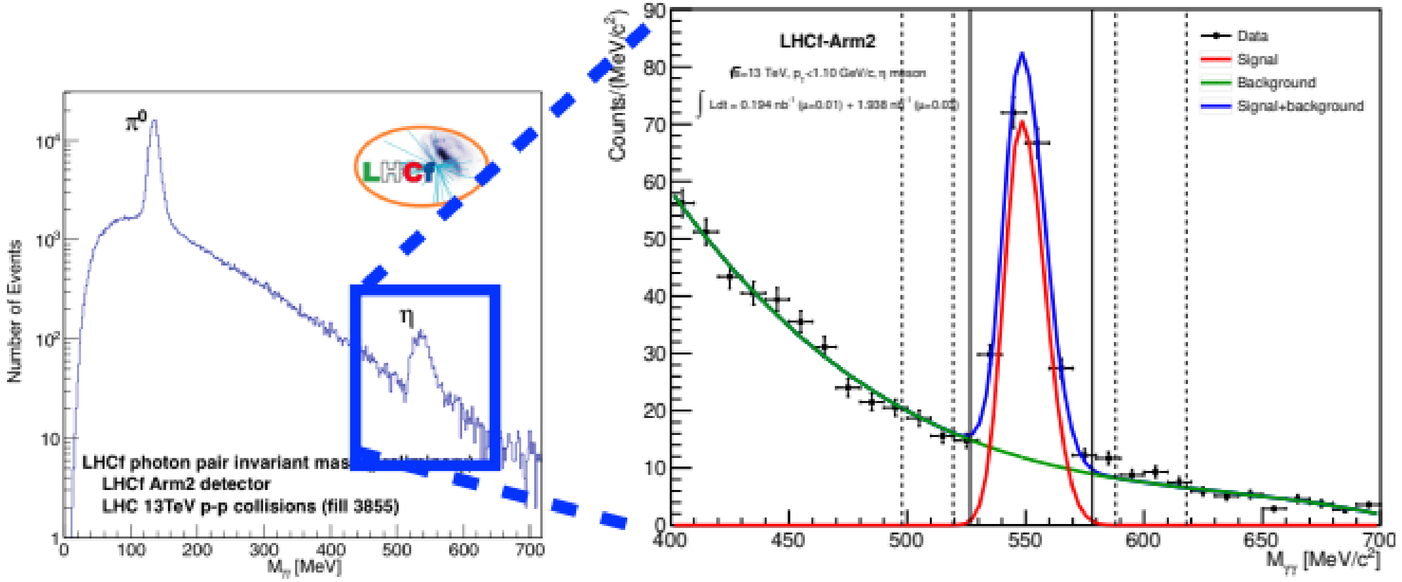
η meson measurement in p-p at $\sqrt{s}$= 13 TeV

- **The first η meson measurement by LHCf.**
- Motivation of the measurement:
  - Eta mesons are the **second largest source of photons** (EM) in air showers.
  - indirect probe for **strange quark** production.
  - **Strong discrepancies** in model predictions.
- Analysis performed using LHCf-Arm2 only for **Type I events**.



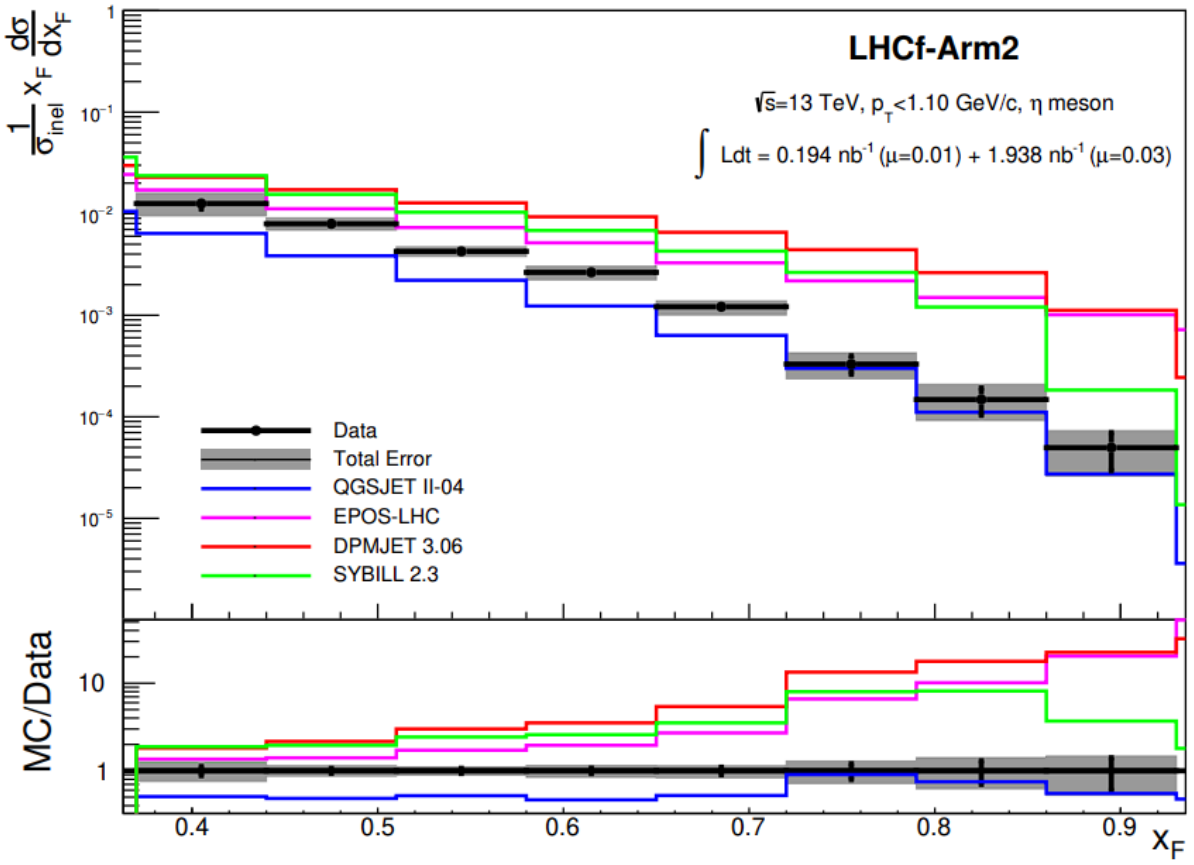


η → $\gamma\gamma$ (only Type I)
B.R. 39.36%



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

Forward η production rate

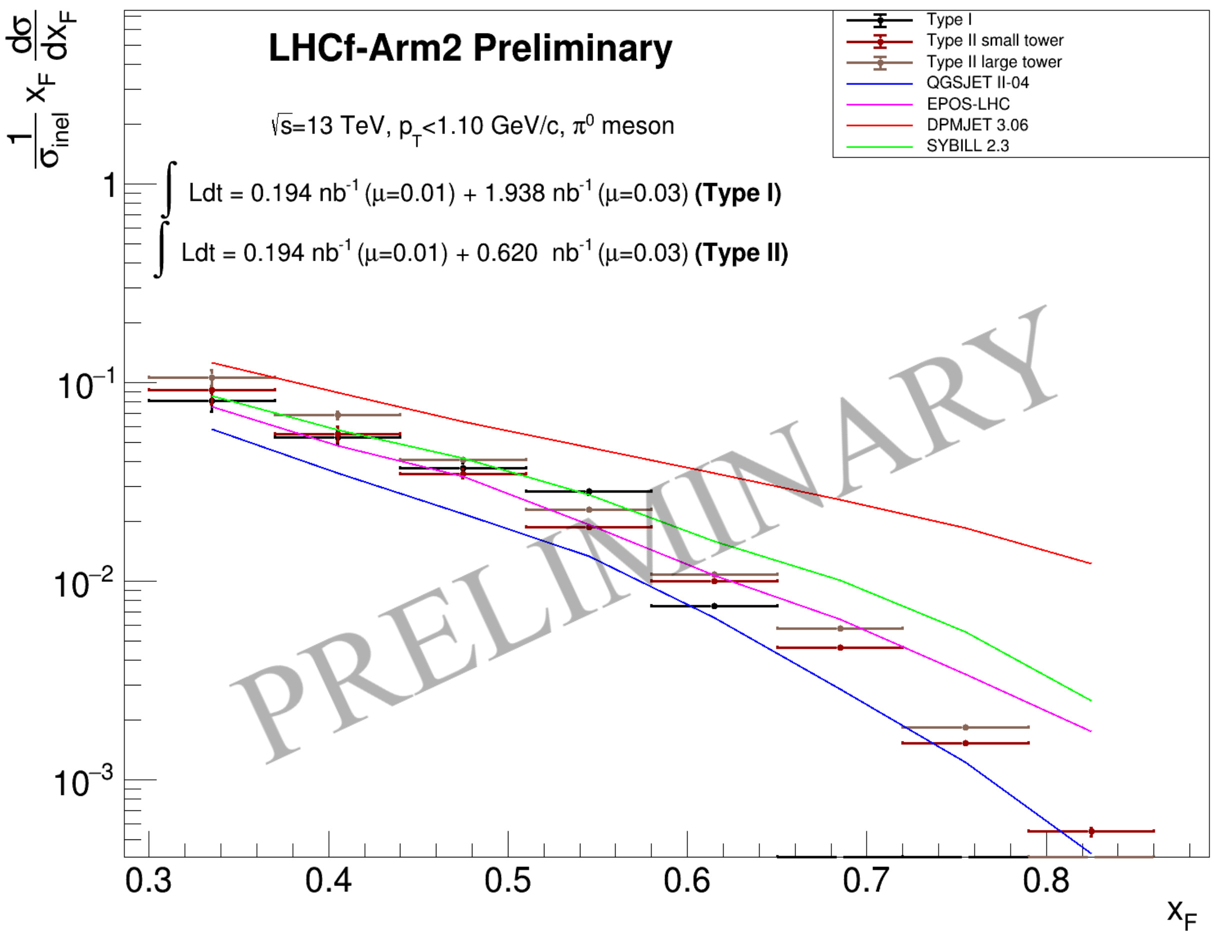


O. Adriani et al., JHEP10 (2023) 169

- η meson production rate measured with LHCf-Arm2 at √s = 13 TeV in p_T< 1.1 GeV/c.
- Compared to **QGSJETII-04**, **EPOS-LHC**, **DPMJET 3.06**, and **SIBYLL 2.3**.
- **None of the models reproduce the full x_F range accurately**. **QGSJETII-04** fits best at high x_F > 0.7, while others predict harder spectra.

Forward η/π^0 production ratio

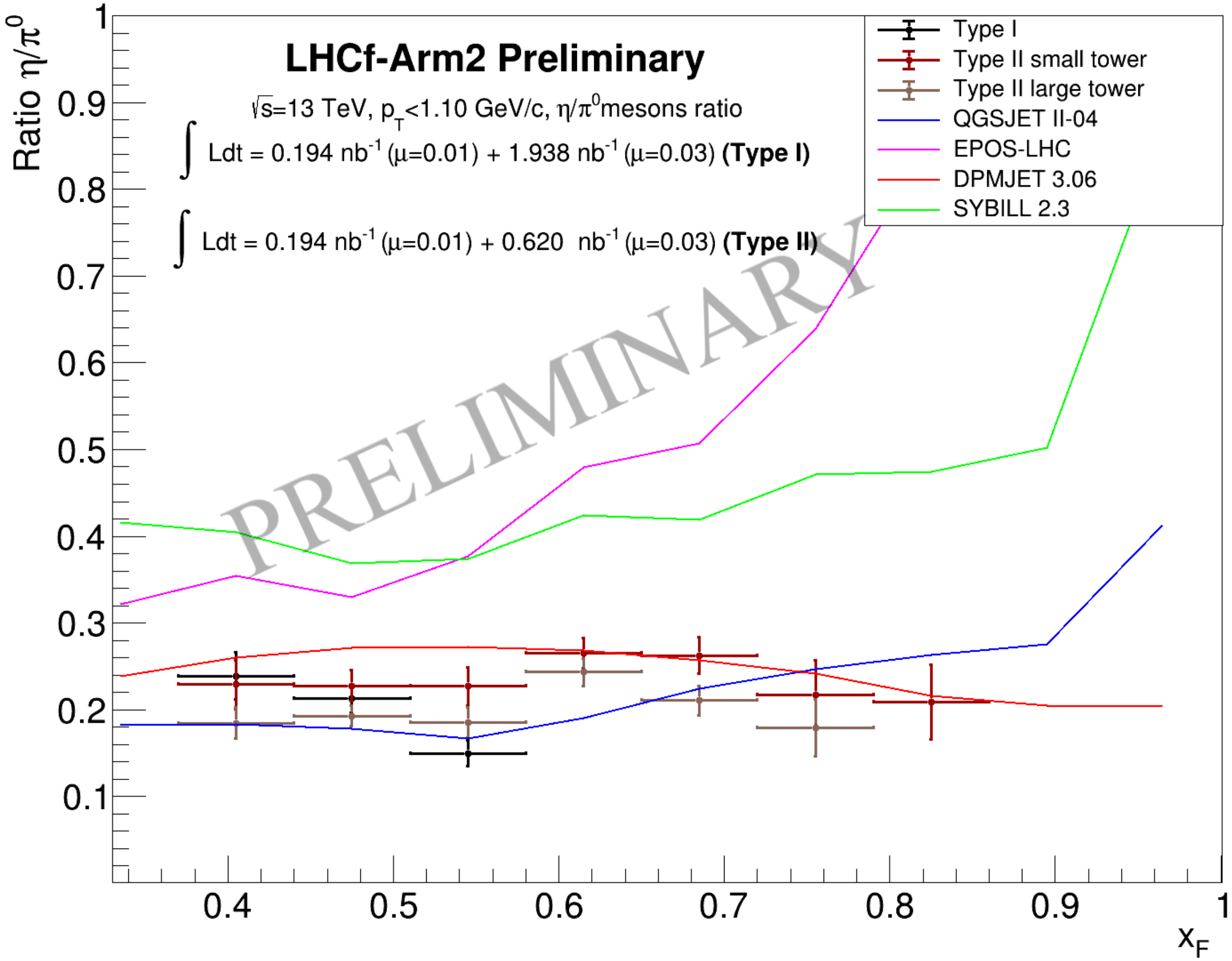
- The inclusive π^0 production rate was calculated using **the same methodology and conditions** of η mesons with minor differences to calculate the ratio between productions.



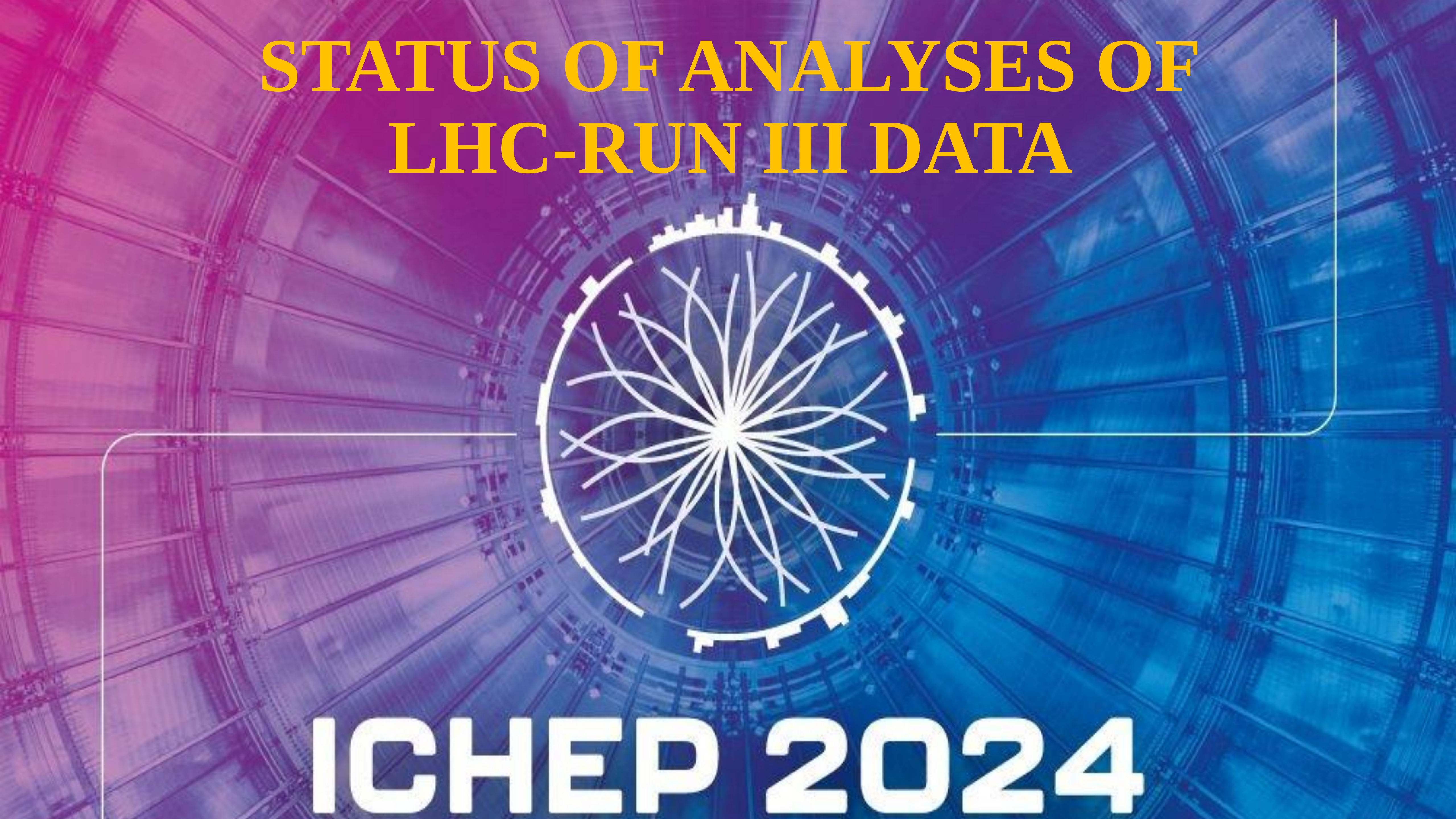
Forward η/π^0 production ratio

- The inclusive π^0 production rate was calculated using **the same methodology and conditions** of η mesons with minor differences to calculate the ratio between productions.

- **EPOS-LHC** and **SIBYLL 2.3** :
  - Predictions much larger than data.
  - Focus on low-mass resonance production, contributing to discrepancies.
- **QGSJETII-04** and **DPMJET 3.06** :
  - Show good agreement with data.
  - Less emphasis on resonances, resulting in a flat ratio.



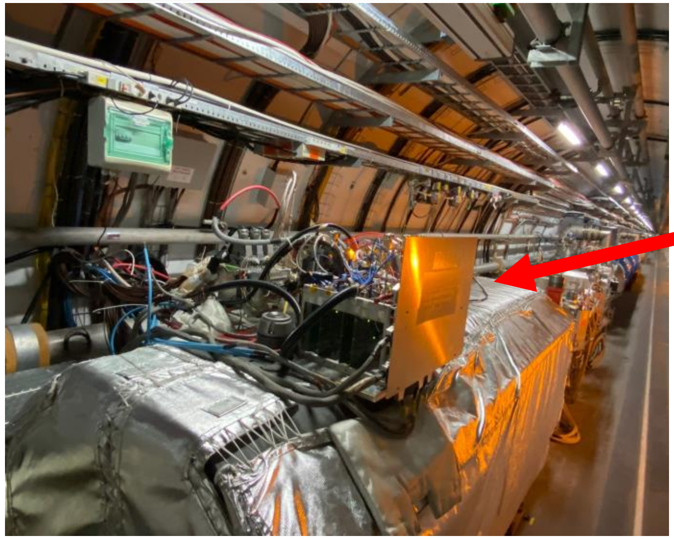
STATUS OF ANALYSES OF LHC-RUN III DATA



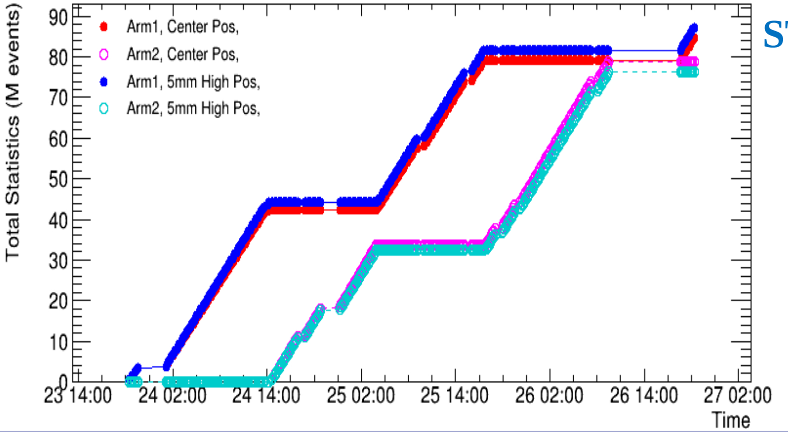
Run III operations in p-p at $\sqrt{s}$ =13.6 TeV

LHCf data-taking successfully performed in Sept 2022:

- Special run with **low luminosity** L = 0.4 μb^{-1}/s, β^* = 19.2 m.
- Improvement of DAQ speed, higher luminosity, and optimization of trigger.
- **300 M events** acquired vs **40 M** in 2015.



LHCf-Arm2 detector installed inside the LHC tunnel at TAN position

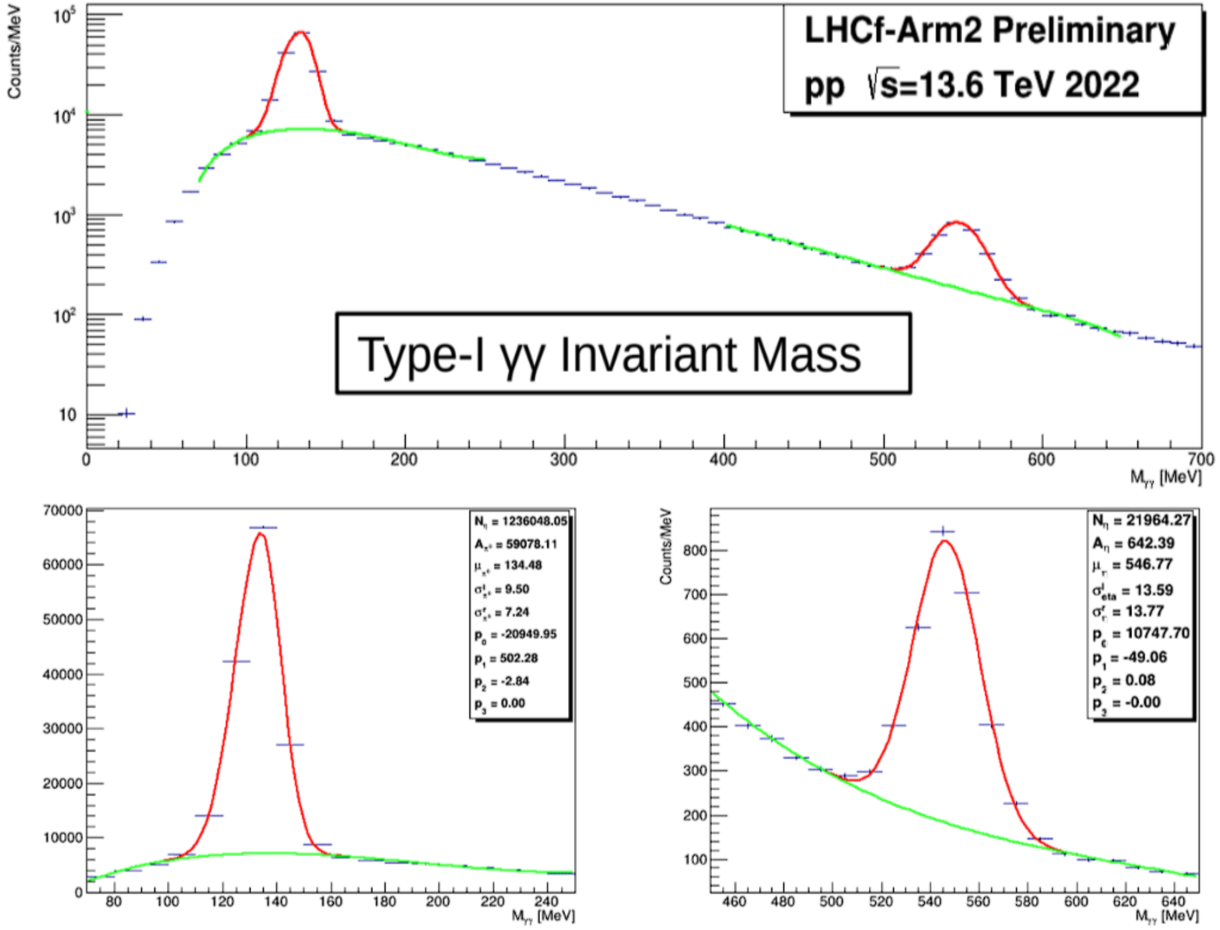


STATISTICS INCREASED BY ROUGHLY A FACTOR OF 10 W.R.T. THE PREVIOUS DATA-TAKING

Physics targets

- **Increase statistics of η and high-energy π^0:**
  - Confirmed the increase of **a factor ~10**.
  - 22k η events vs 2k in 2015.
  - **Reduction of uncertainties** on single spectra and ratio.
  - Possibility of cross-sections and ratio measurement **in several X_F-p_T bins**.

Reconstructed di-photon invariant mass distribution (Type I events)



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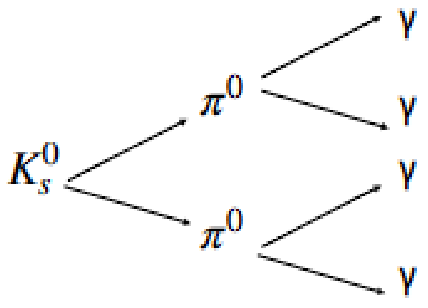
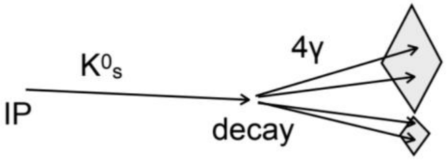
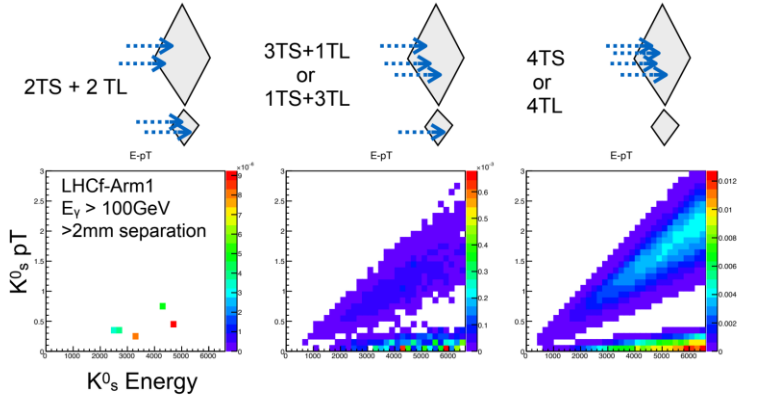
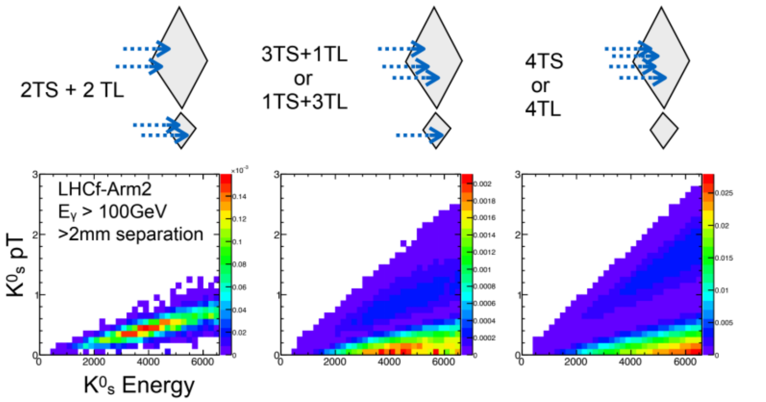
- **Measurement of strange hadrons:**
  - K_s^0: requires the identification of four photons in the final state.





Acceptance of K_s^0 in the LHCf detectors





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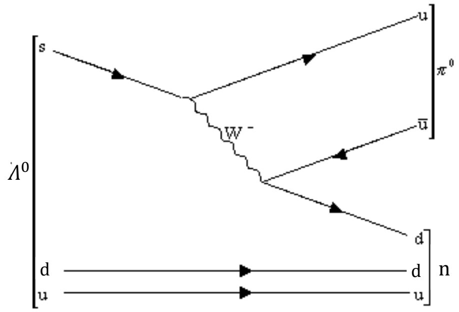
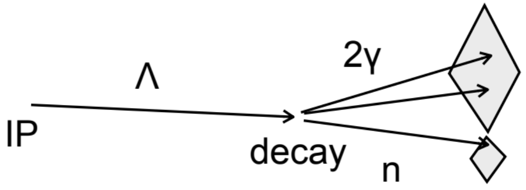


- **Measurement of strange hadrons:**
  - K^0_s: requires the identification of four photons in the final state.
  - Λ^0: requires the identification of two photons and one neutron.
  - Expected O(10^3) events for both particles.
  - **New reconstruction methods** are required for multi-hits events.



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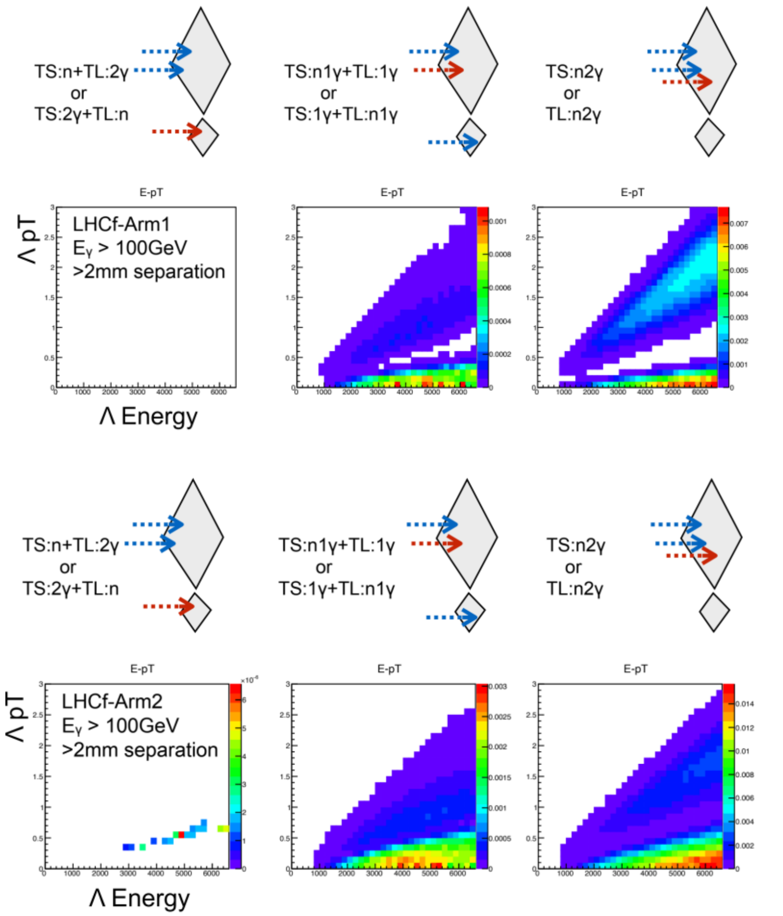
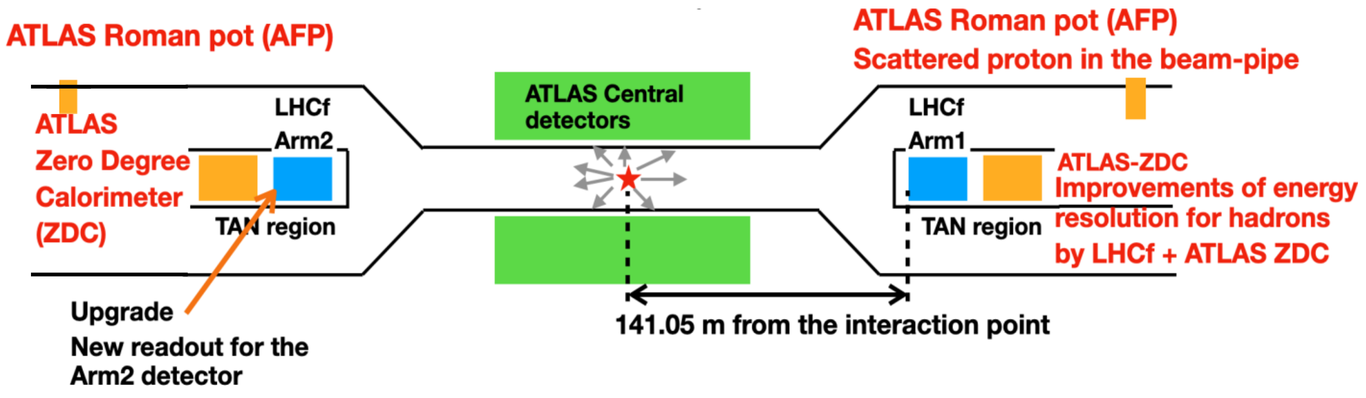


Joint operation with ATLAS

- Improvements from the last run in 2015:
  - Large statistics of **300 M events** vs 6 M in 2015.
  - Partecipation of **ATLAS subdetectors:**
    - ZDC to improve **energy resolution for neutrons.**
    - Roman Pots to tag **scattered protons**.

LHCf-ATLAS joint operation setup



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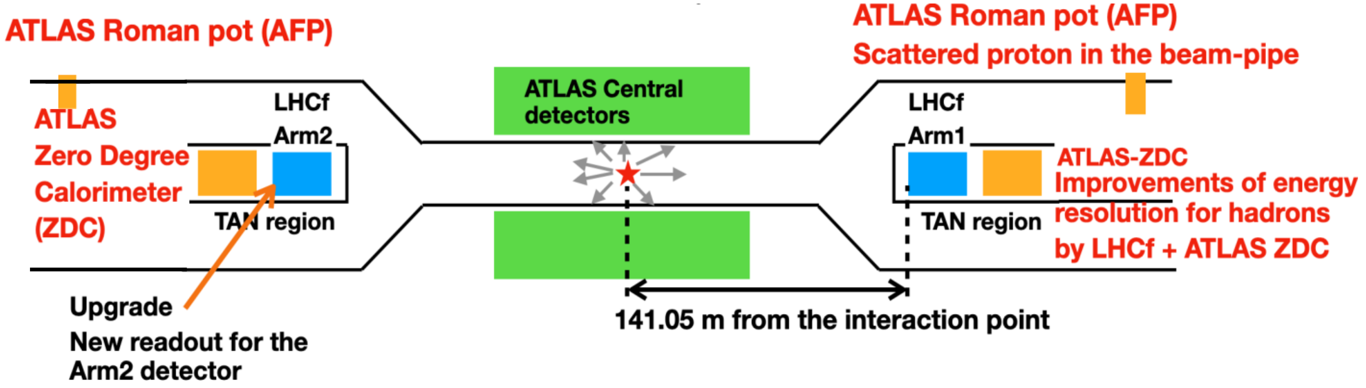
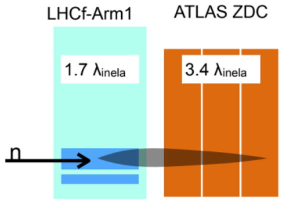
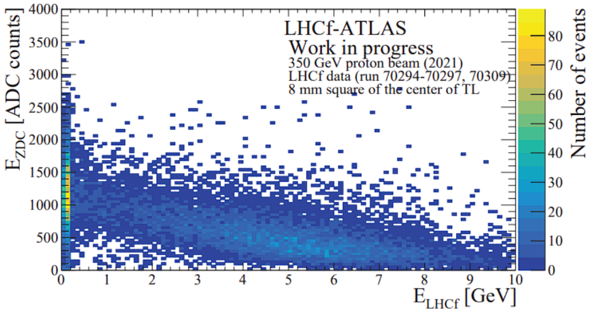
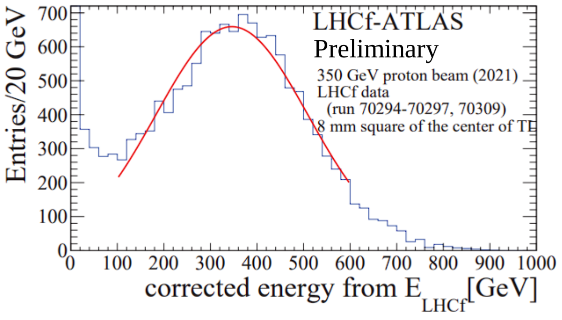




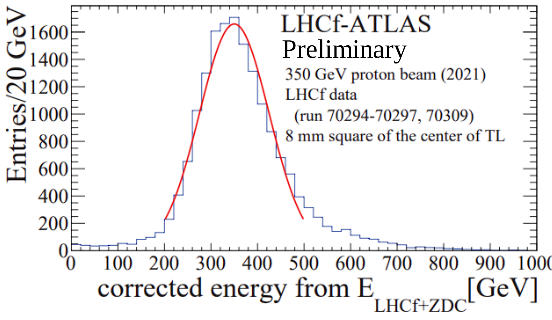


Confirmed improvement of energy resolution with LHCf+ZDC reconstruction (Combined beam test at SPS, Sept 2021)

LHCf only $\sigma/E \sim 46\%$



LHCf+ZDC $\sigma/E \sim 21\%$



EPJ Web of Conferences , 05012 (2023)

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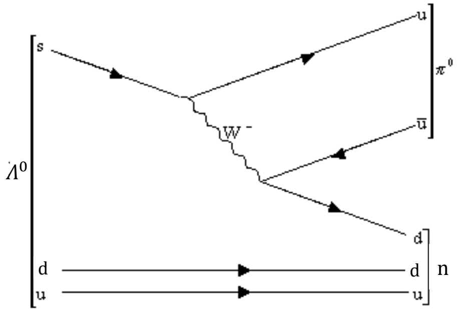
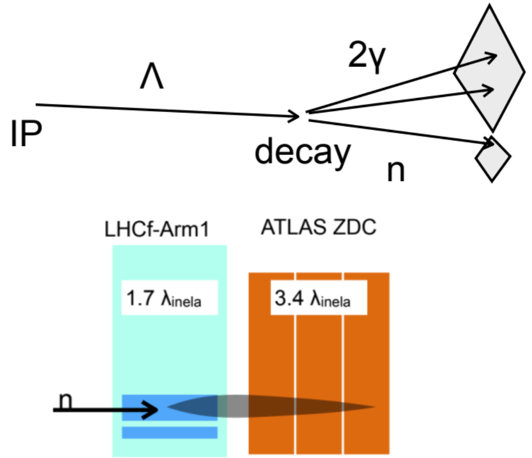
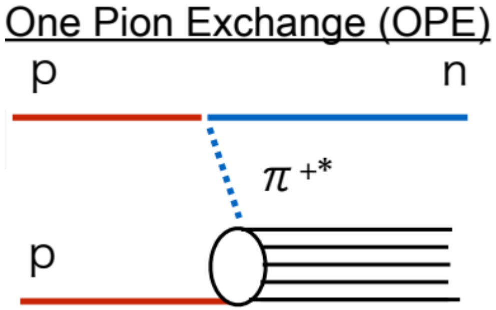
- **Phyisics Targets with ZDC:**
  - Measurement of Λ^0.
  - p-π interaction study using OPE processes.

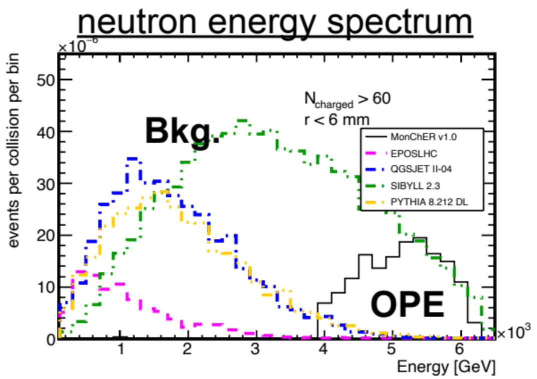
Improvement of the neutron energy resolution for Λ^0 measurement





Improvement of the neutron energy resolution for OPE studies





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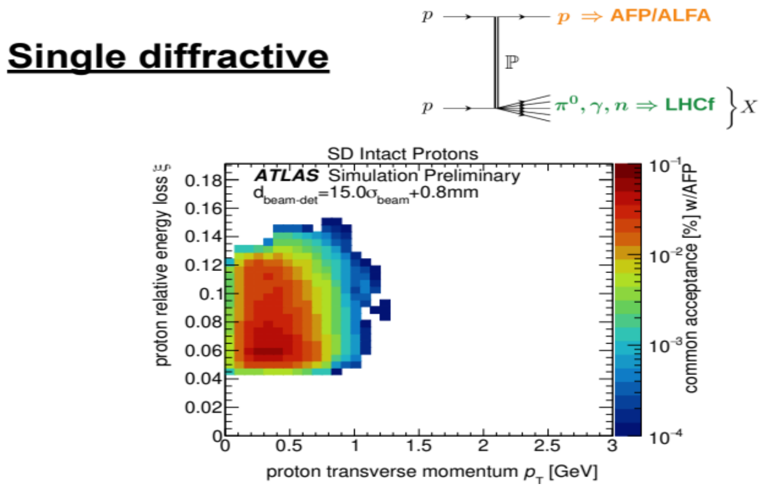
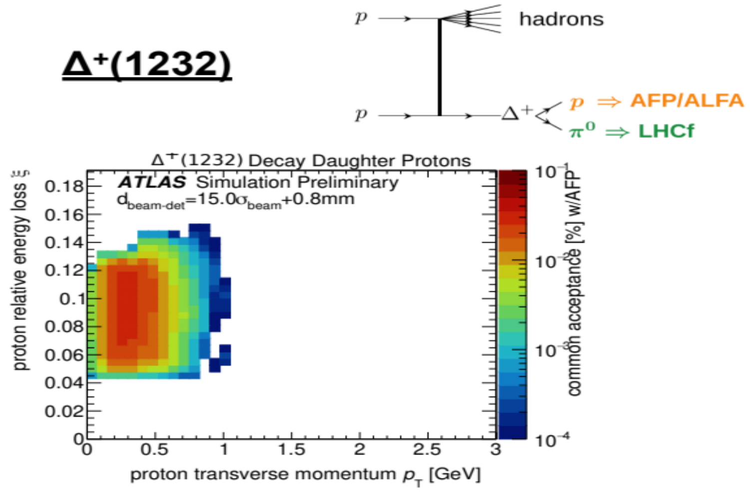
- **Phyisics Targets with ZDC:**
  - Measurement of Λ^0.
  - p-π interaction study using OPE processes.
- **Phyisics Targets with RPs:**
  - Detailed study of single diffractive collisions.
  - Measurement of proton excitation (Δ^+).

- **LHCf+ATLAS merged dataset is getting ready. The physics analysis will start soon**

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



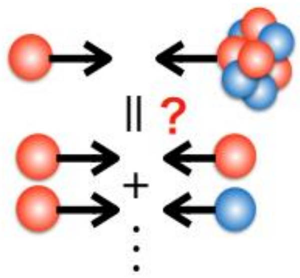


PREPARATION FOR p-O COLLISIONS DATA-TAKING IN 2025

Motivations

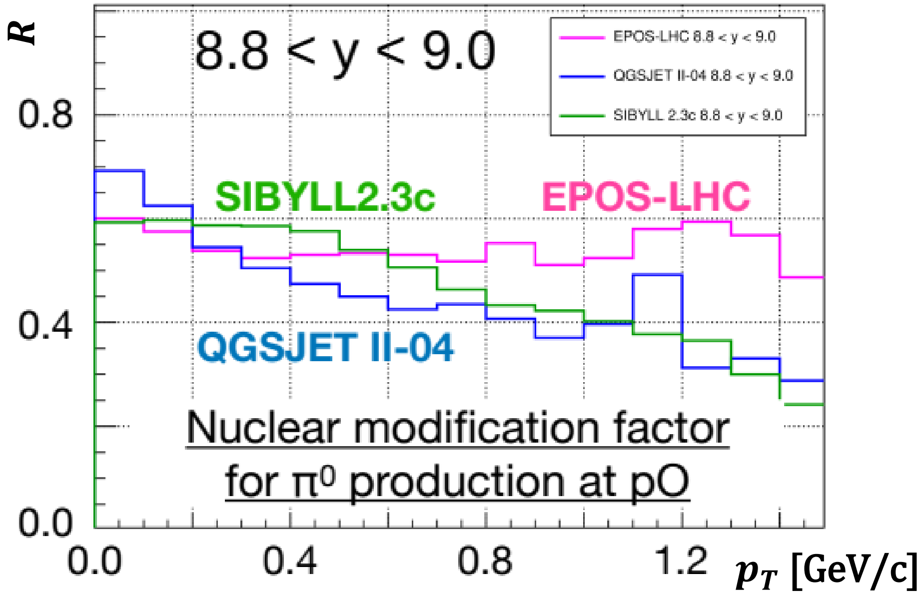
- **Ideal conditions for studying CR-air interactions:**
  - **First proton-"light ion" collisions at colliders.**
  - Different nuclear effects modeling leads to varying predictions among models.
  - Negligible contribution **from Ultra Peripheral Collisions (UPCs)**.
- **Study of Nucleus(nucleon)-Nucleus interactions:**
  - Described as a superposition of nucleon collisions by **Glauber theory.**
  - **Nuclear effects:**
    - Nuclear shadowing.
    - Limiting Fragmentation.
    - QGP formation.

Nuclear modification factor



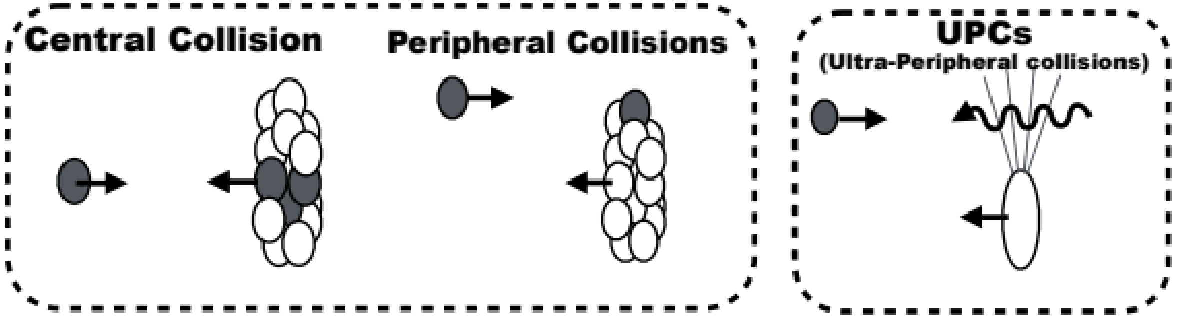
$$R = \frac{\sigma_{pO}}{A\,\sigma_{pp}}$$

A: average number of nucleon collision

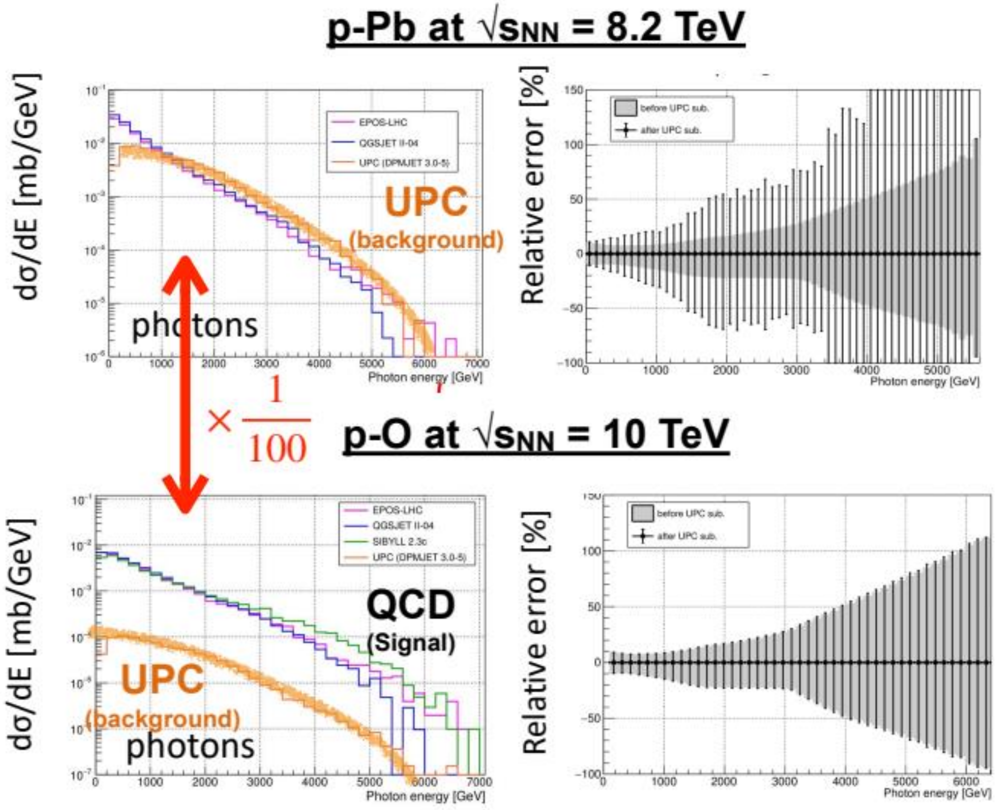


Nuclear modification factor for π^0 production at pO

Effect of the Ultra Peripheral Collisions (UPCs)



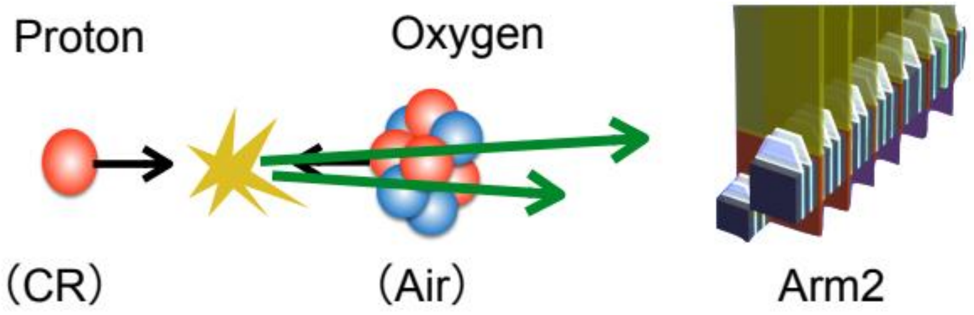
- **Strong background from UPCs:**
  - **Air** : Oxygen atom (neutral)
  - **LHC Beam** : Oxygen nucleus
- $\sigma_{UPC} \propto Z^2$:
  - For p-Pb collisions **QCD** ~ **UPC**
  - For p-Pb collisions **QCD** ≫ **UPC**

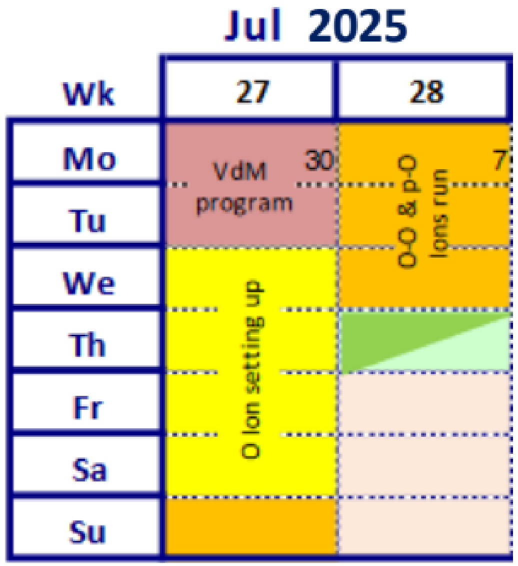


UPC contribution in negligible for inclusive measurements

Operation strategy

- Setup**:**
  - **Only LHCf-Arm2** detector will be installed in p-remnant side (too-high multiplicity 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) .
  - **LHCf operation in p-O collisions (2 days).**
  - Remove the detector from LHC for O-O collisions (too high multiplicity).





*) This schedule might be changed

Preparation status

- **DAQ system already prepared** in USA15 (ATLAS counting room).
- **DAQ speed improvement**: Max. rate 1.6 kHz (2022) → 3.3 kHz

- **Schedule in the next one year:**
  - This winter:
    - Test of **DAQ**.
    - 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

Summary

- **LHCf measures very forward neutral particle productions, which are crucial for understanding UHECRs production and acceleration.**
- **Results from Run II Data:**
  - Neutron production and inelasticity.
  - η meson spectra and η/π^0 ratio.
- **Many analyses are on-going and foreseen:**
  - π^0 and η with high statistics, first measurements of very forward K_s^0 and Λ^0.
  - Joint analyses with ATLAS detectors.
- **p-O data-taking in 2025:**
  - Ideal condition for studying CR – Air interactions.
  - Preparation is in an advanced state.

THANK YOU FOR THE ATTENTION!

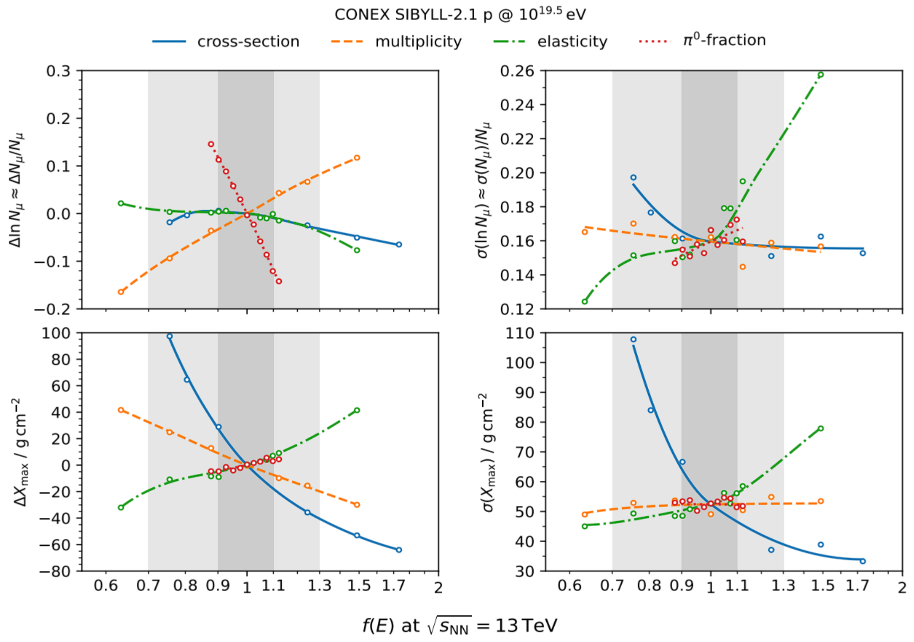
Giuseppe Piparo[1,2], on behalf of the LHCf collaboration

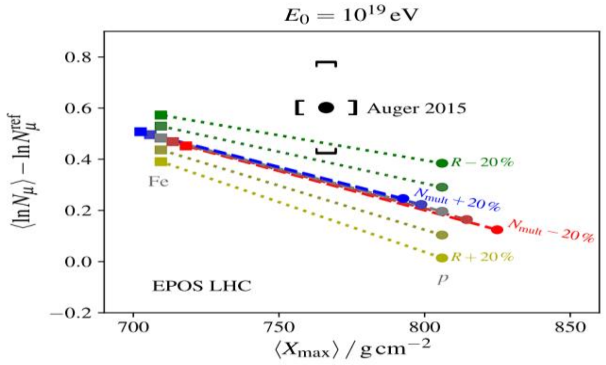
1. Istituto Nazionale di Fisica Nucleare (INFN), Catania section
2. University of Catania, Department of Physics and Astronomy

BACKUP

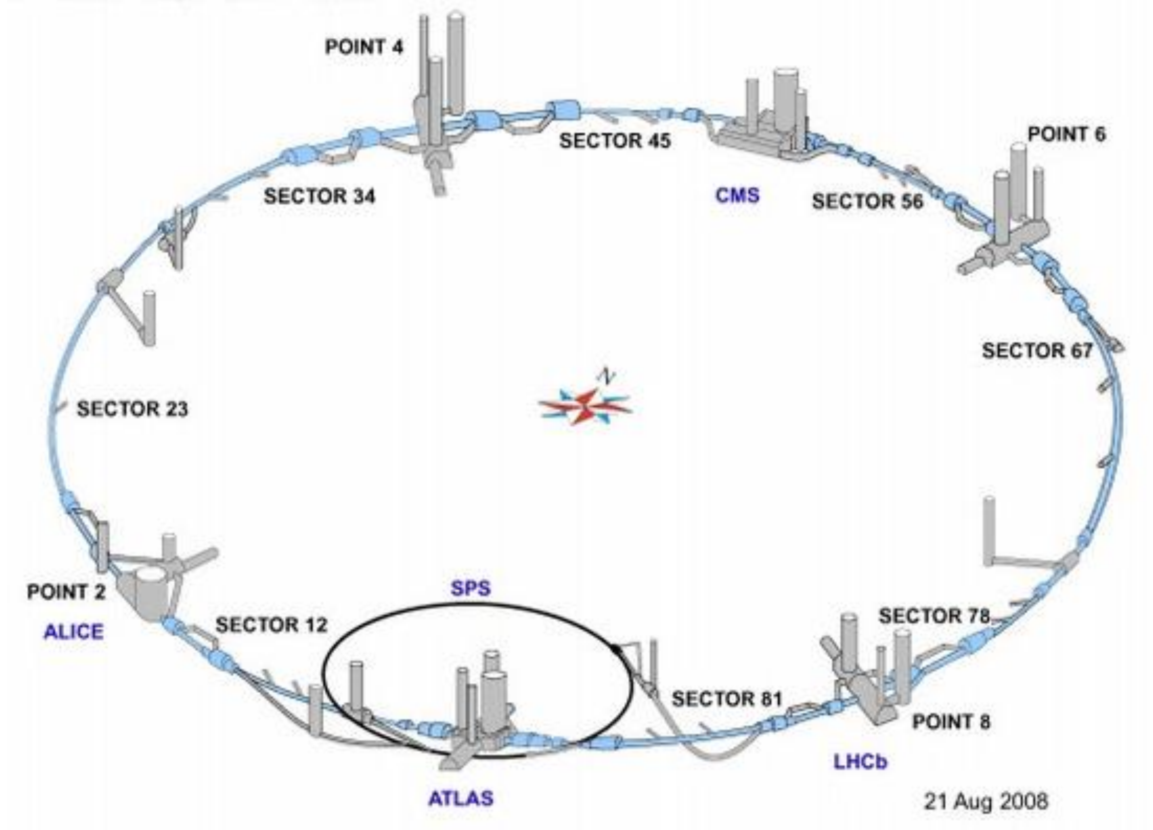
HIM parameters tuning

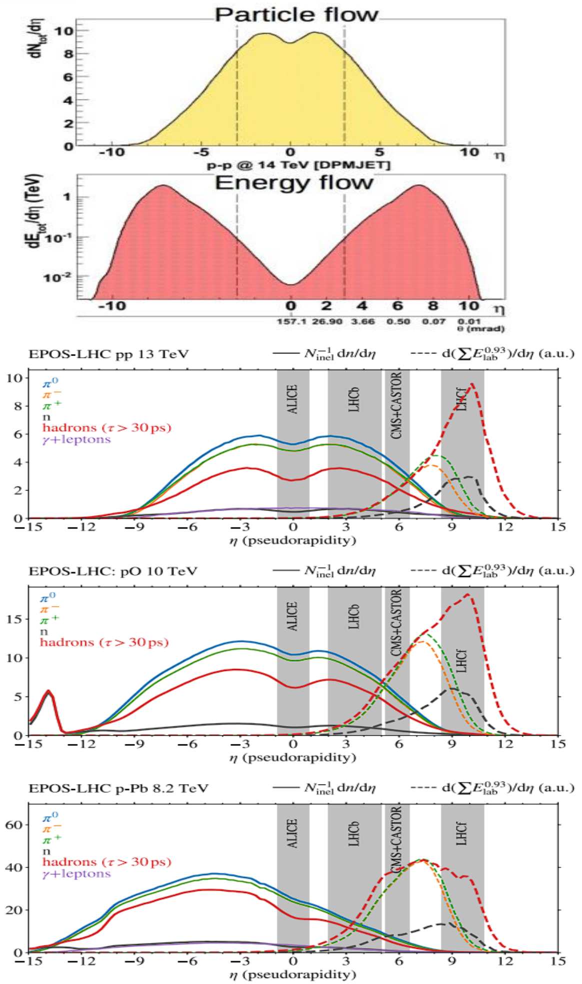
- **The number of muons produced in an air shower is sensitive to various parameters:**
  - The inelastic cross section.
  - The hadron multiplicity.
  - The elasticity (energy fraction carried by the most energetic particle).
  - The fraction of neutral pions produced.
- To increase Nμ in simulations one has **to increase the hadron multiplicity** and/or decrease **the fraction of neutral pions produced**.
- In addition, **an increase in the hadron multiplicity** changes Xmax in such a way that the discrepancy cannot be resolved.
- **A reduction in the neutral pion fraction** is, therefore, **the most plausible scenario**, possibly accommodated by a moderate change in the hadron multiplicity.

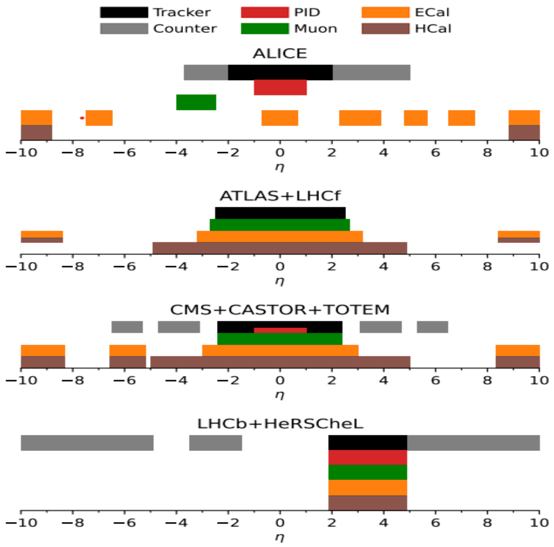




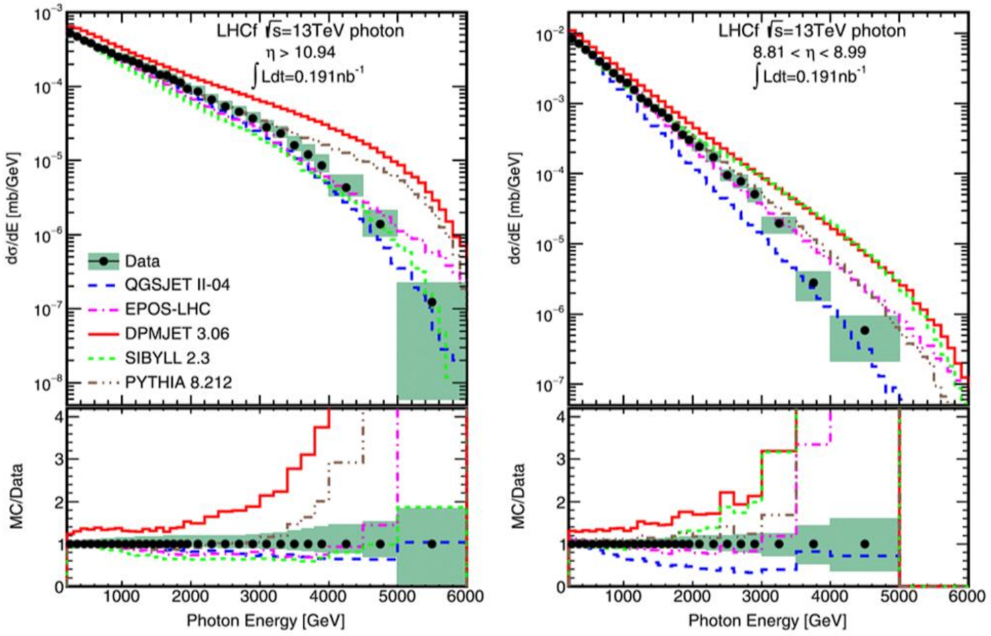
Overview of LHC experiments pseudorapidity coverage







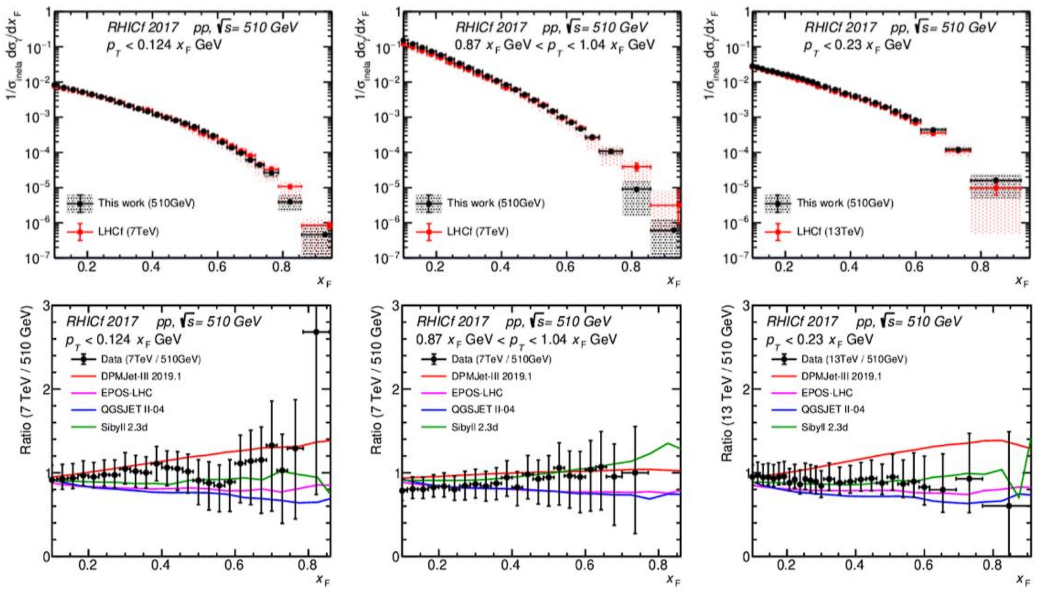
Very forward photon spectra and Feynman scaling



PLB 780 (2018) 233-239

QGSJET II-04 is in good agreement for η>10.94, otherwise softer
EPOS-LHC is in good agreement below 3-5 TeV, otherwise harder

Using γ in √s=510 GeV (RHICf) and 7 or 13 TeV (LHCf)



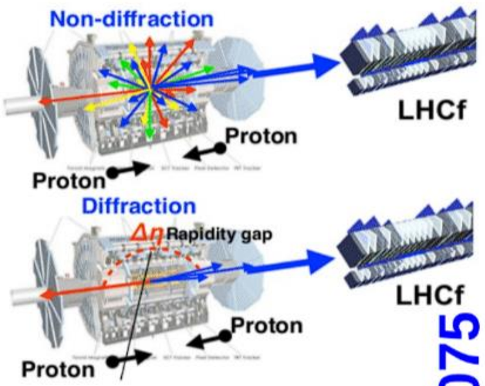
ArXiv:2203.15416

First confirmation of **Feynman scaling** using zero-degree photons but no sensitivity to small x_F dependency as in some models

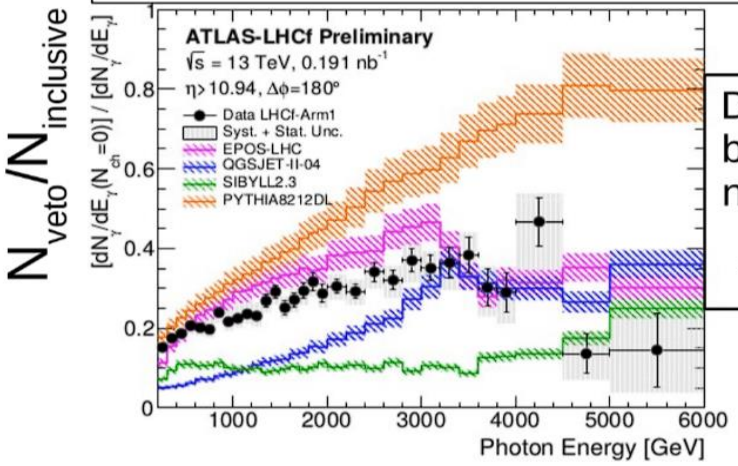
LHCf-ATLAS common photon analysis

The LHCf-ATLAS common operations leads to a much **higher degree of information** on *processes responsible for forward production*, allowing for accurate measurements of:

- Diffractive/Non-Diffractive production
- Multi-parton interaction process
- One-pion exchange process
- …



Forward photon production in η > 10.94



Diffractive events can be distinguished from non-diffractive events by **ATLAS veto** : Tracks=0 at |η|<2.5

ATLAS-CONF-2017-075

…paper in finalization

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