Very forward photon production in pp and p-Pb collisions measured by the LHCf experiment

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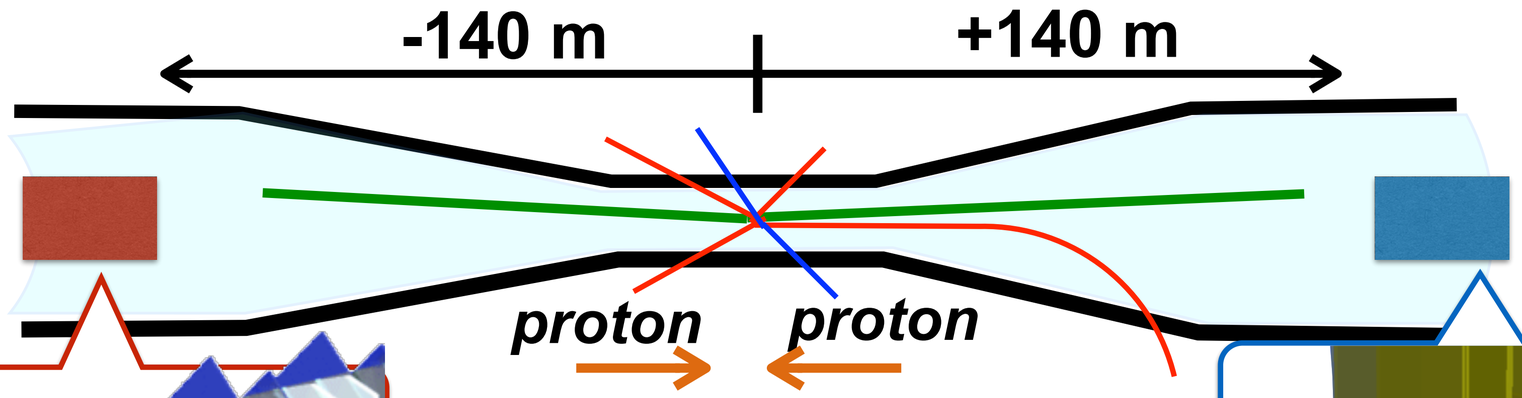
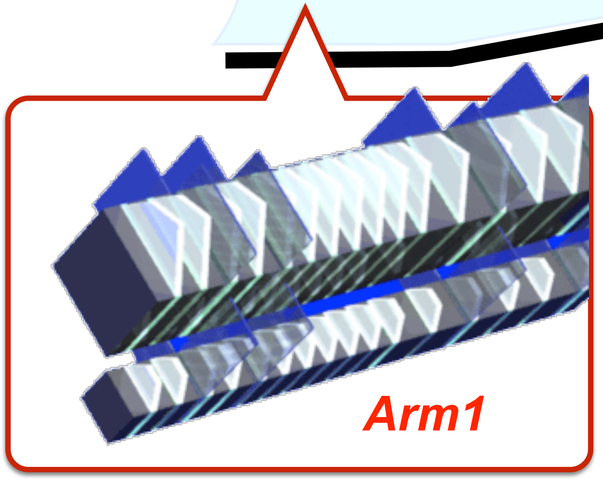
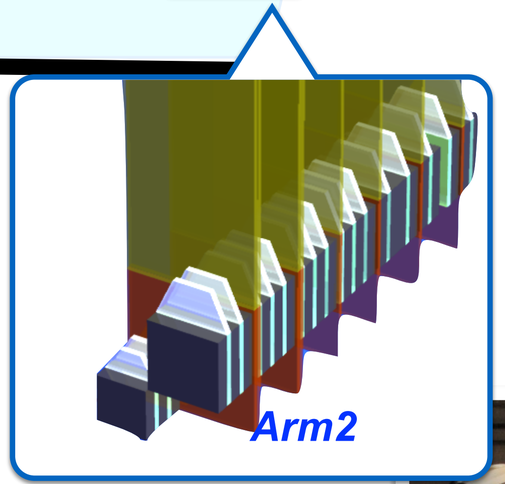
EMMI workshop: Soft photons, 26 May 2025

LHCf experiment

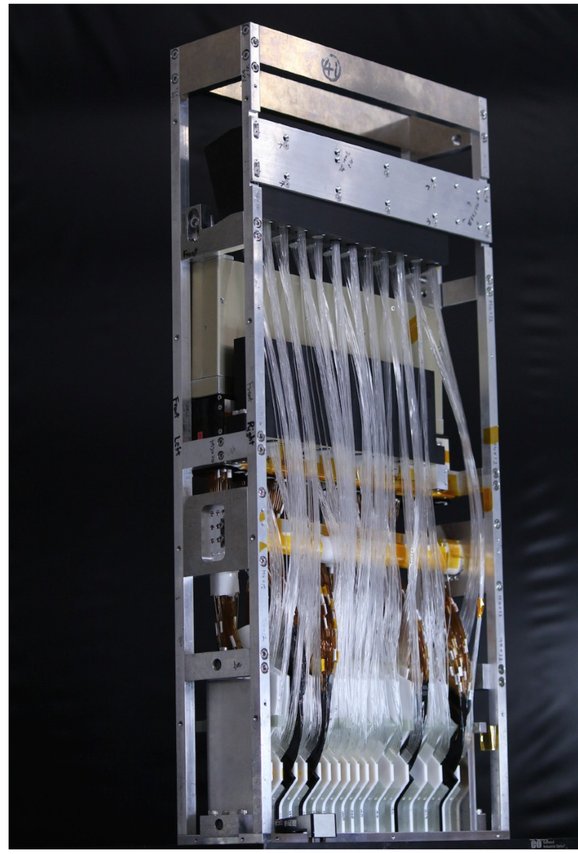






Location

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

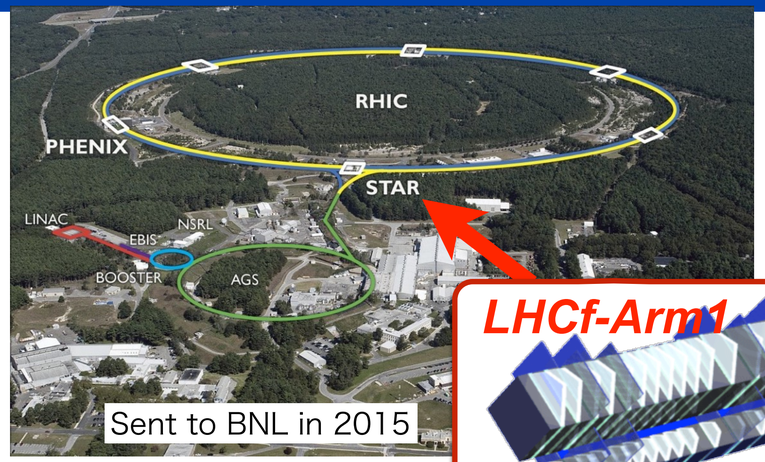


LHCf detectors

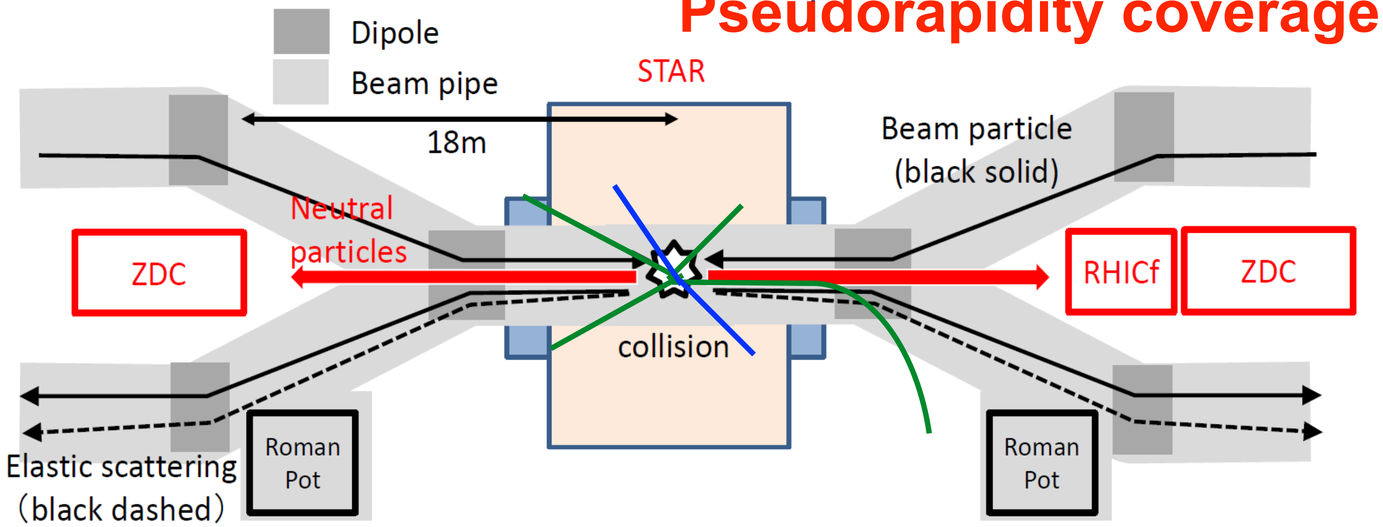
- Sampling and positioning calorimeters
- Two towers, 20x20, 40x40mm^2 (Arm1) , 25x25, 32x32mm^2(Arm2)
- Tungsten layers, 16 GSO scintillators, 4 position sensitive layers (Arm1: GSO bar hodoscopes, Arm2: Silicon strip detectors)
- Thickness: 44 r.l. and 1.7 λ

RHICf experiment

- *pp* $\sqrt{s}$= 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



High Energy Cosmic-Ray Observation

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

High energy interaction

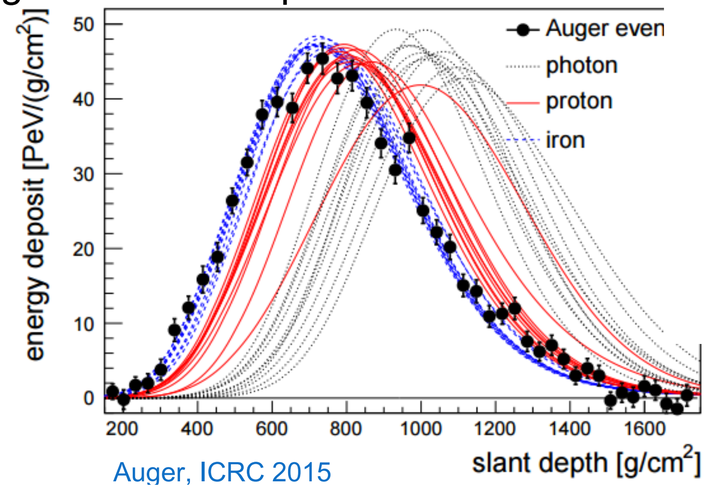
secondaries' interactions

Low energy interactions

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

Require precise understanding high energy interactions

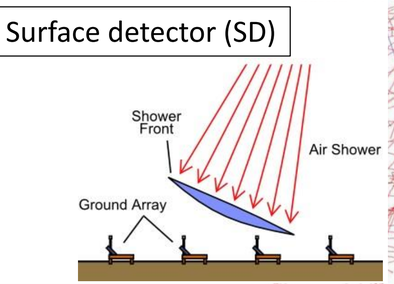
Longitudinal development of 10^{19}eV showers

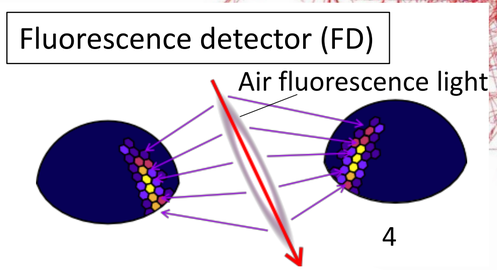


Auger, ICRC 2015

- 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





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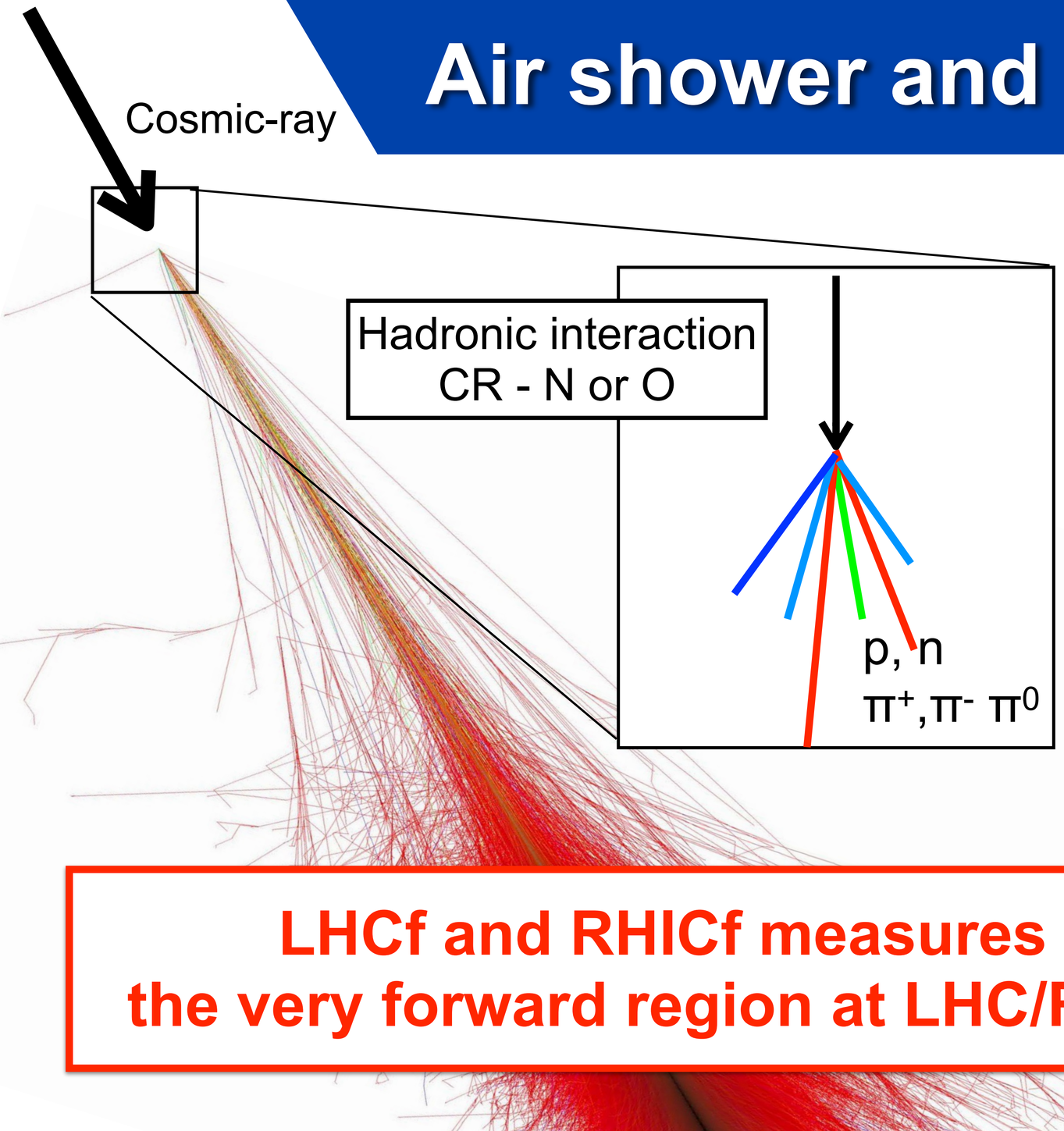
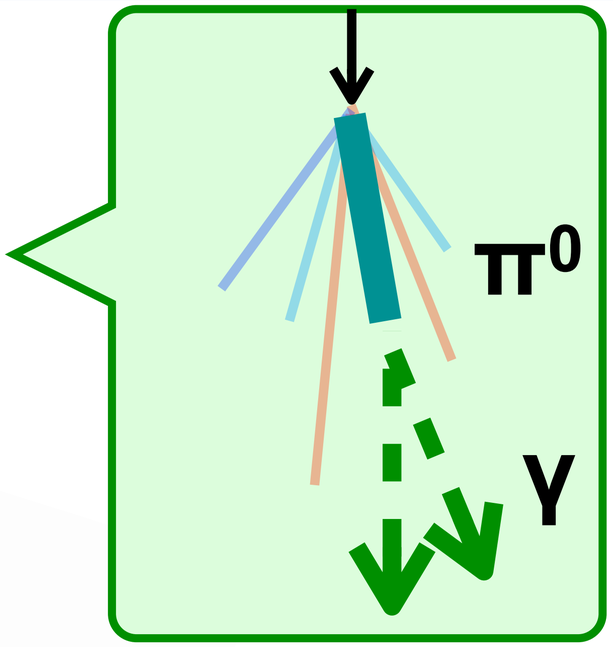
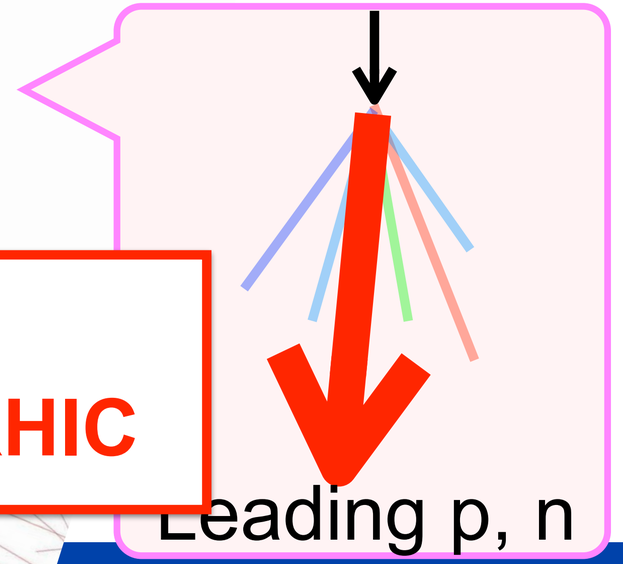
Air shower and hadronic interaction





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

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

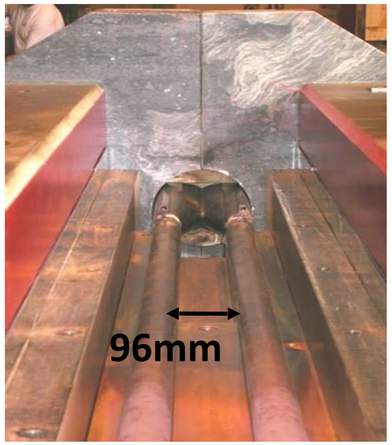
LHCf and RHICf measures the very forward region at LHC/RHIC

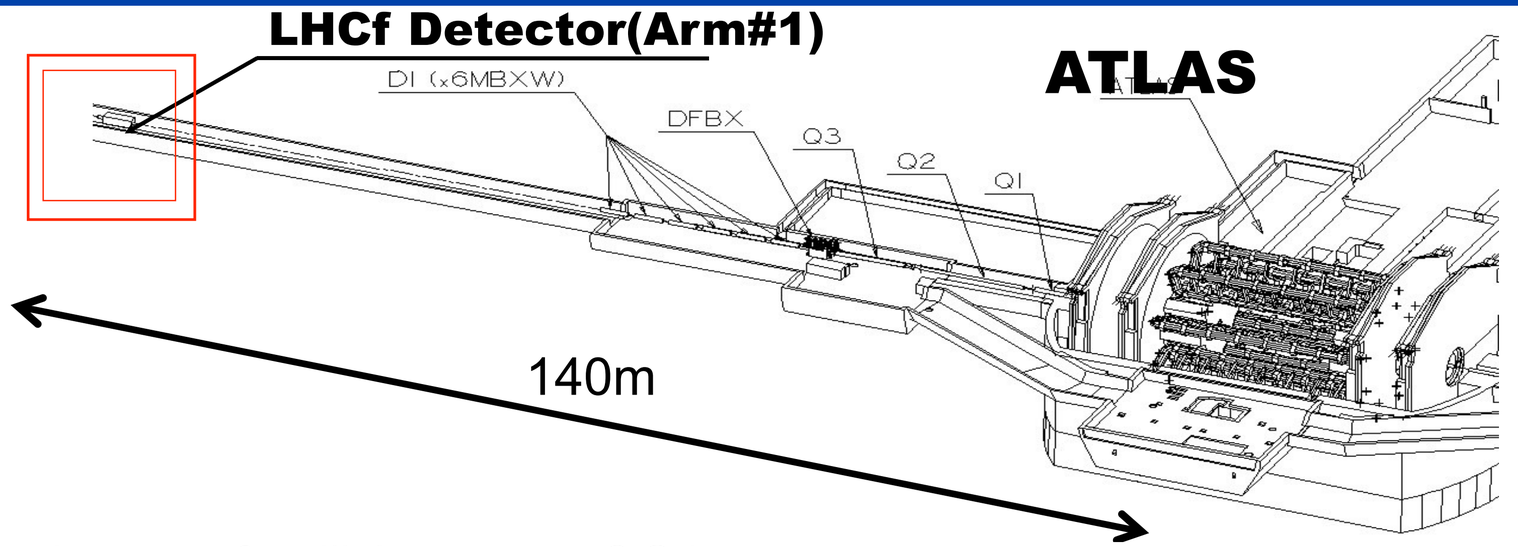
LHCf/RHICf Operations and Analyses

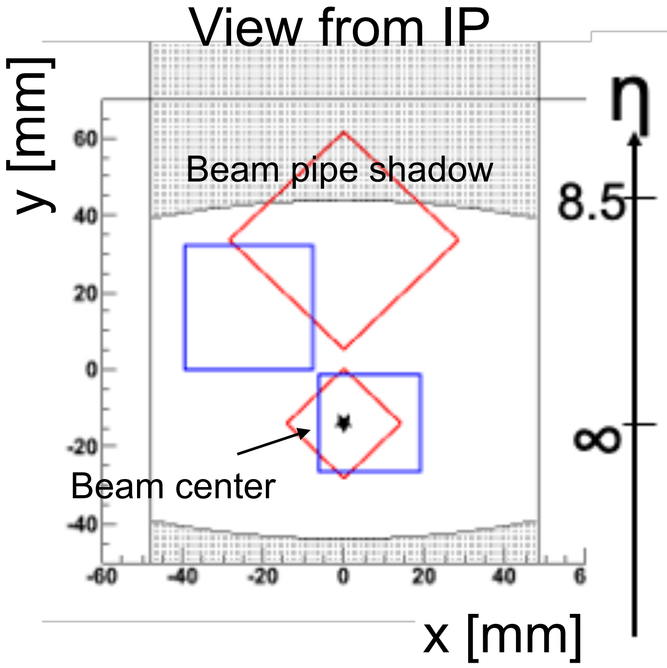
Run	E_{lab} (eV)	Photon	Neutron	π^0		LHCf-ATLAS joint analysis
p-p $\sqrt{s}$=0.9TeV (2009/2010)	4.3×10^{14}	PLB 715, 298 (2012)		-		
p-p $\sqrt{s}$=2.76TeV (2013)	4.1×10^{15}			PRC 86, 065209 (2014)	PRD 94 032007 (2016)	
p-p $\sqrt{s}$=7TeV (2010)	2.6×10^{16}	PLB 703, 128 (2011)	PLB 750 360 (2015)	PRD 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 ArX		Spin Asymmetry		R

p-O operation in the next month

Experimental setup

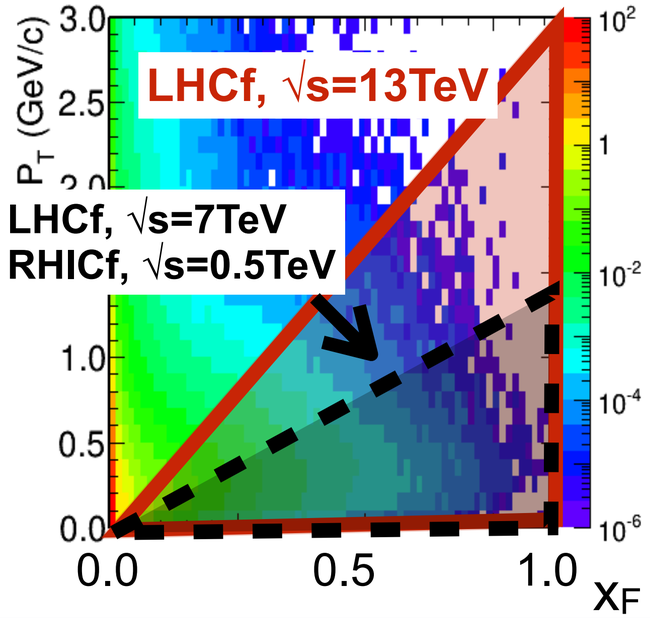






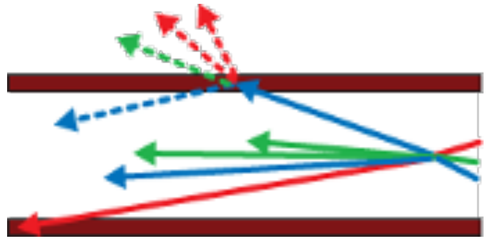
- View zero degree of collisions : $\eta > 0.84$
  - Acceptance is limited by the beam pipe btw IP and the detector.
  - Cover very low pT regions.
  - 1 r.l. beam pipe material in the front.
- Operations in low-luminosity special runs
  - Low pile up : μ = 0.01-0.04
  - Int. Luminosity : a few nb^{-1} for each run

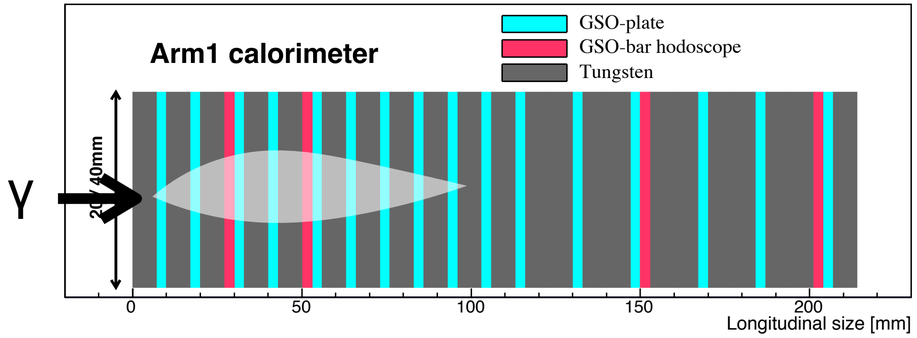
    (Exceptionally 40 nb^{-1} in 2022 run)



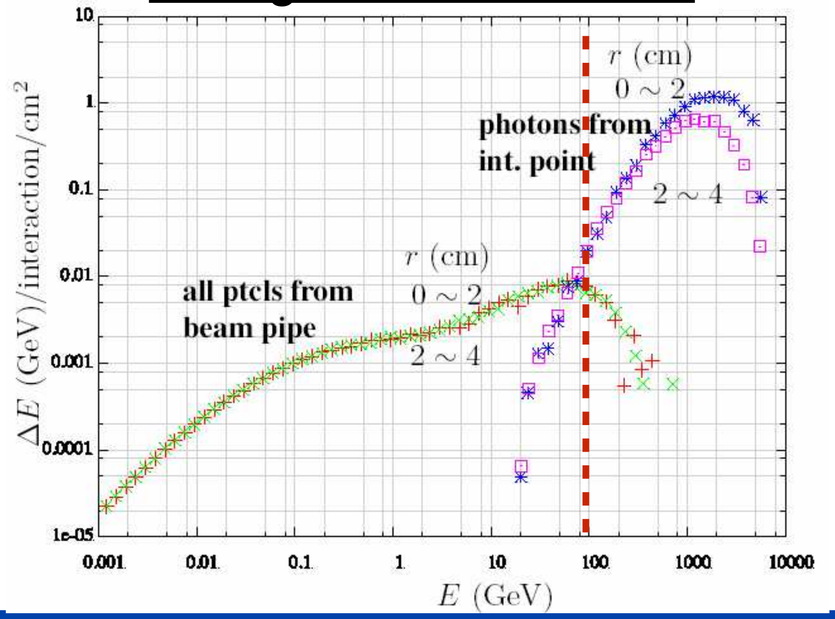
Trigger efficiency for photons

- Trigger condition
  - Any three successive layers with dE > $dE_{thr.}$
  - The threshold was optimized to avoid low-energy background contamination due to secondaries-beam pipe interactions

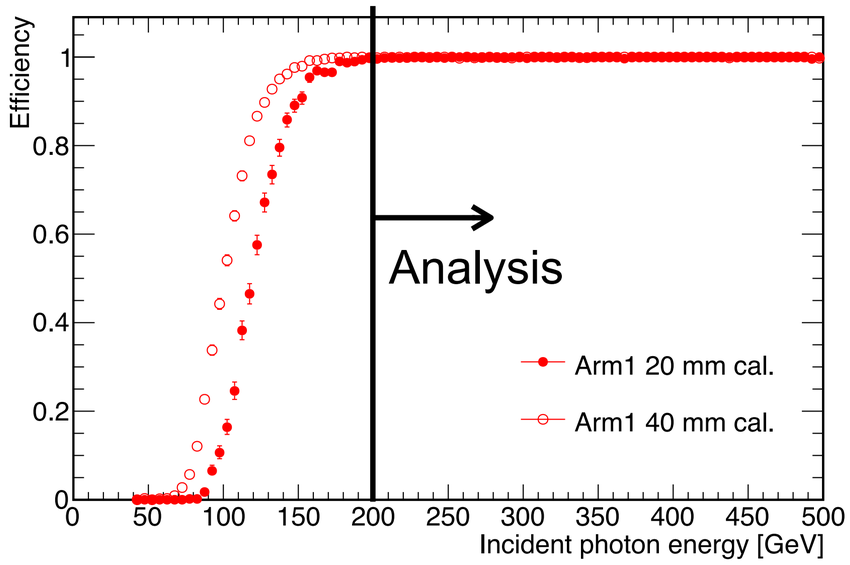




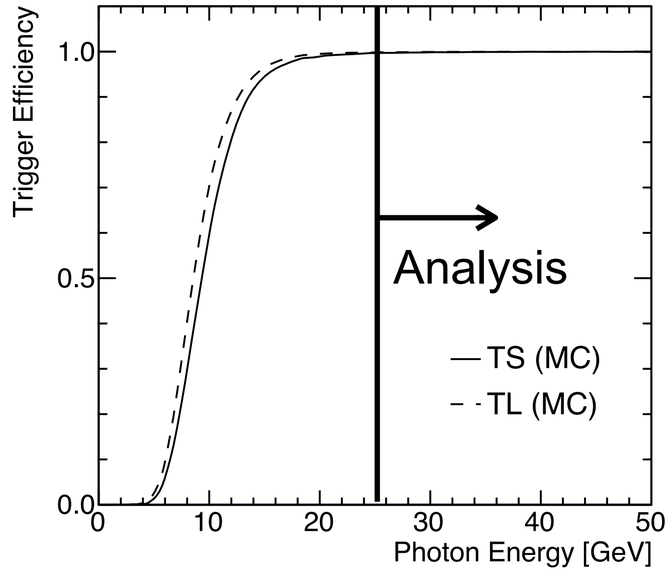
Background estimation



Trigger efficiency at LHCf pp, 13TeV

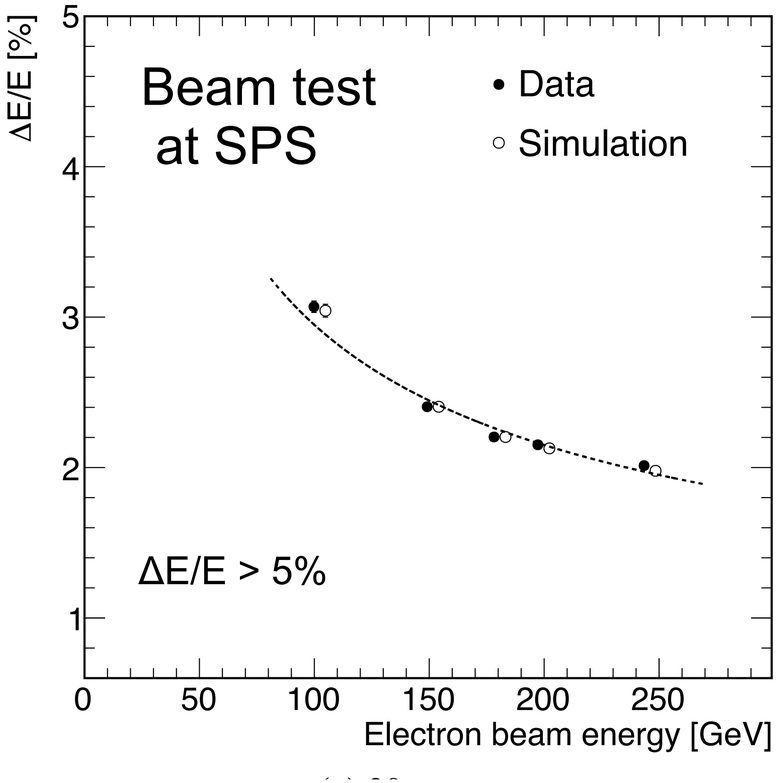


RHICf pp, 0.5TeV

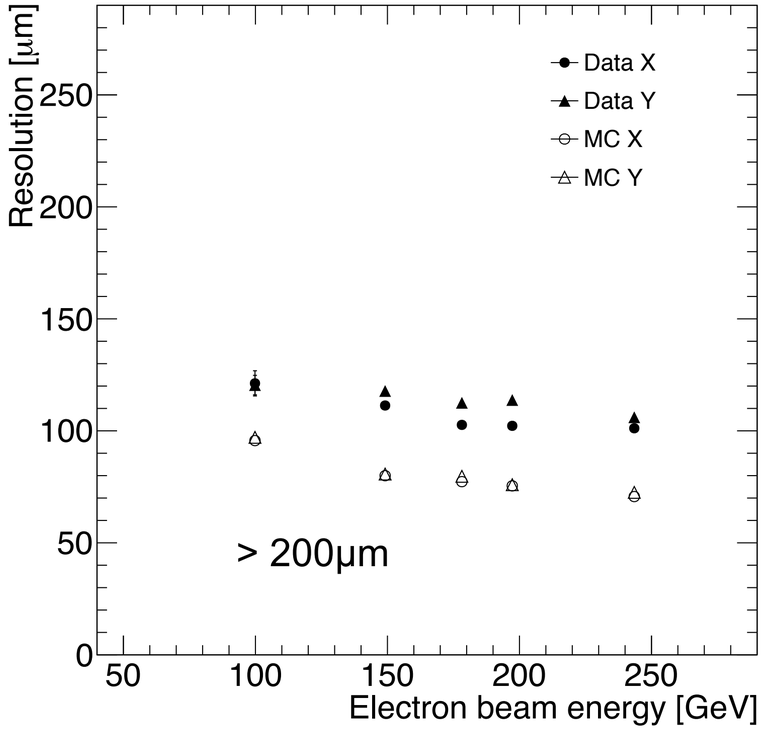


Performance for EM showers

Energy resolution

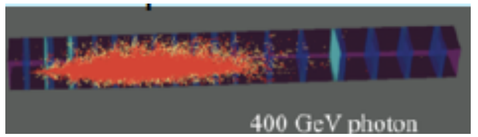


Position resolution

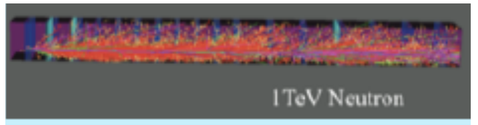


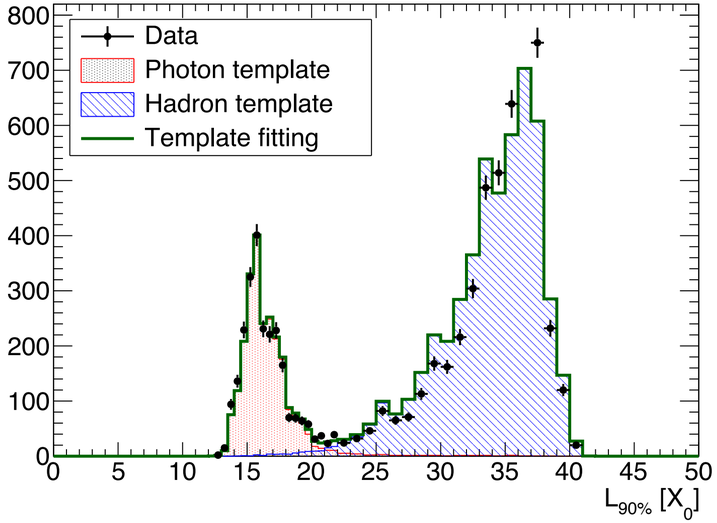
PID

400 GeV photon



1TeV Neutron

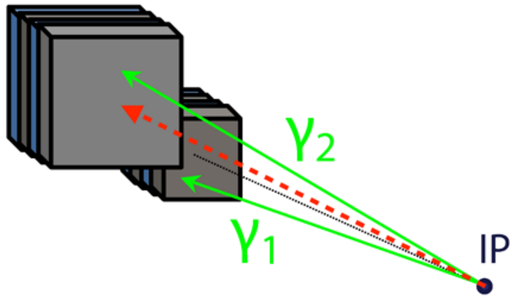




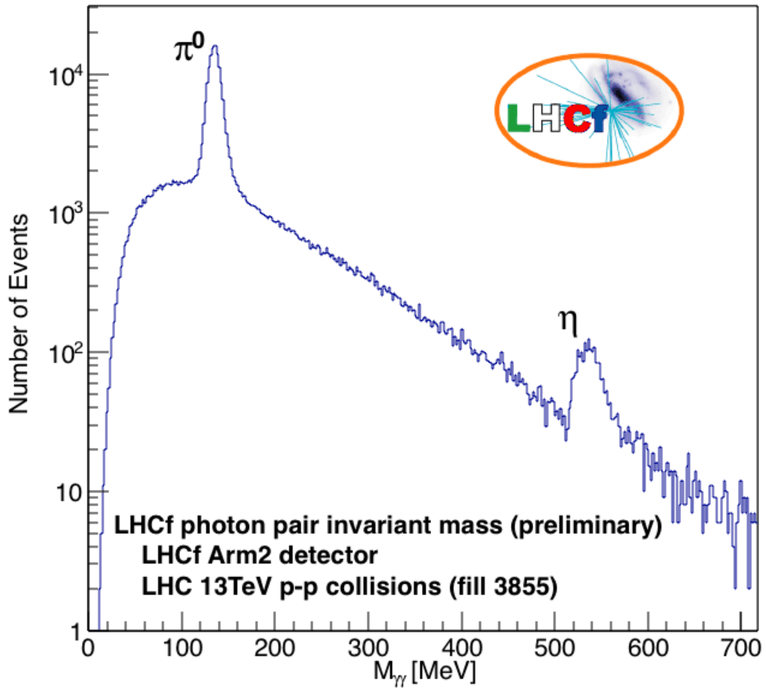
Parameterized the longitudinal shape of showers.

Photon measurements by LHCf/RHICf

- Inclusive measurement
  - Measured photons are expected to be
    - ~90% from π^0 decays
    - ~9% from η decays
    - ~1% from others (K^0 decay and etc.)
- Analysis criteria:
  - Require only one photon in a calorimeter.
    - ~5% are events with multiple particle incidents, which were identified by lateral distributions
    - These contributions are estimated by MC and are corrected.



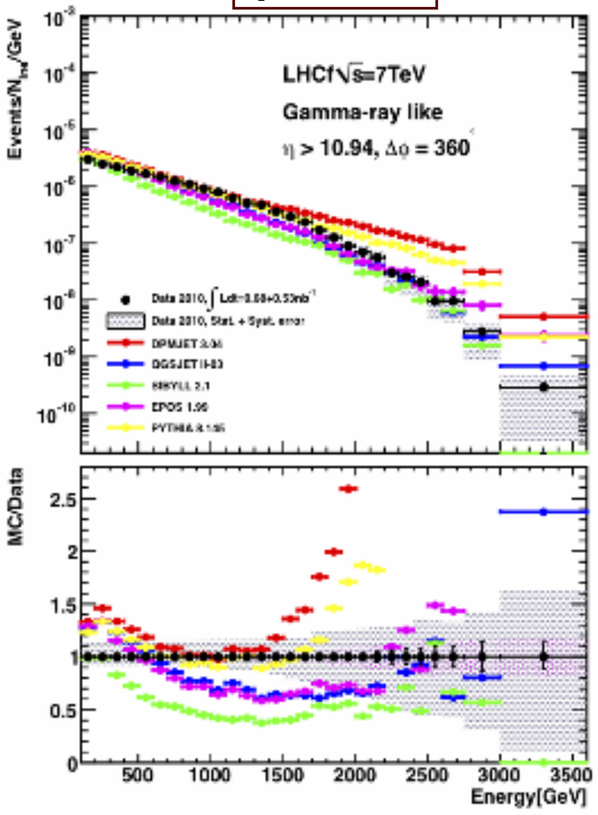
Reconstructed mass distribution from two-photon hit events



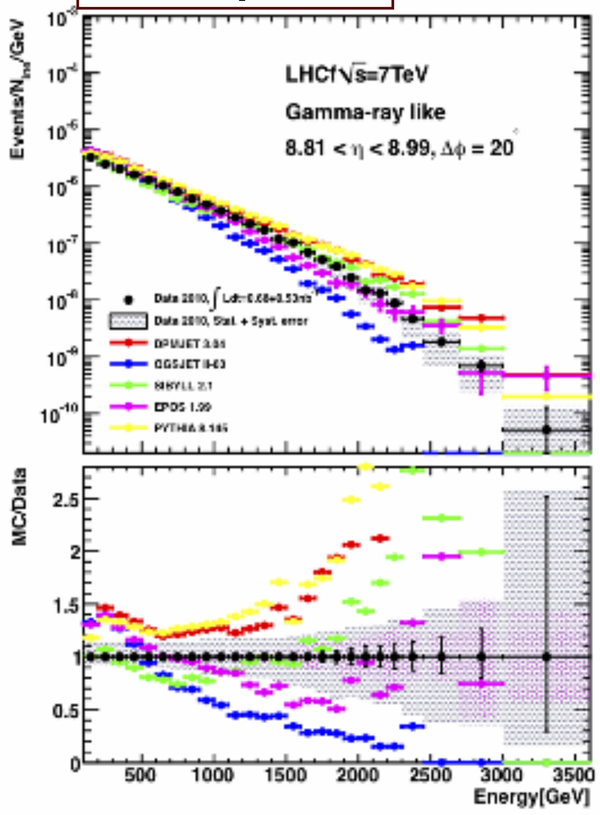
LHCf at pp, √s=7 TeV and 13 TeV

pp, √s=7 TeV

η > 10.94



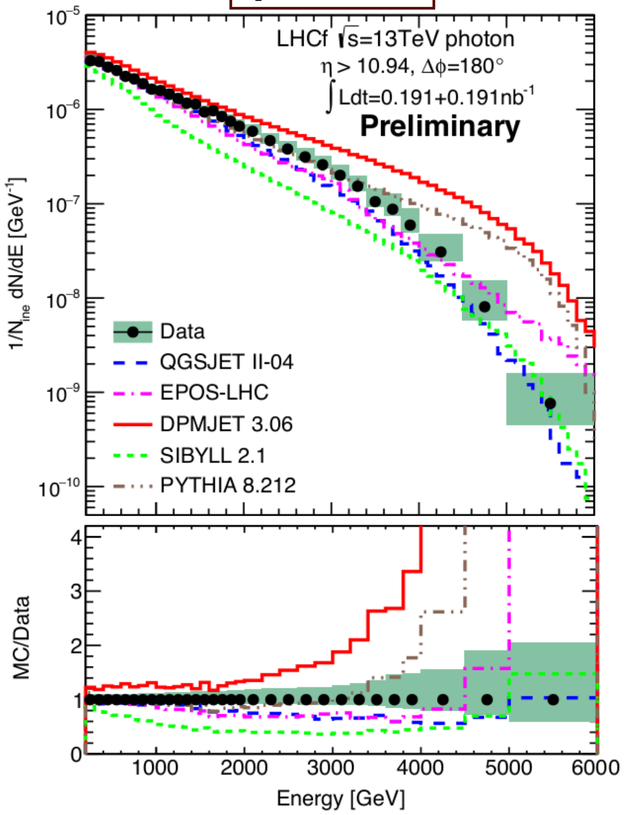
8.81 < η < 8.99



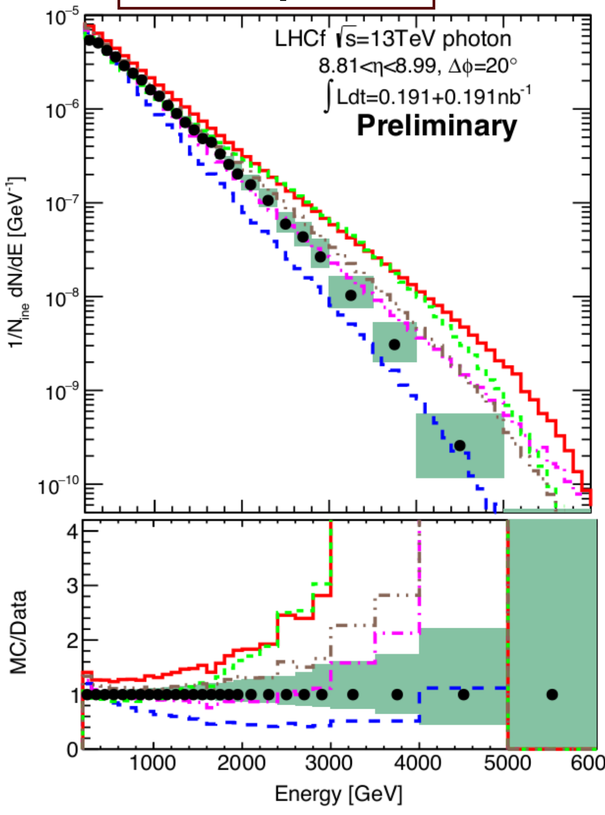
PLB 703, 128 (2011)

pp, √s=13 TeV

η > 10.94

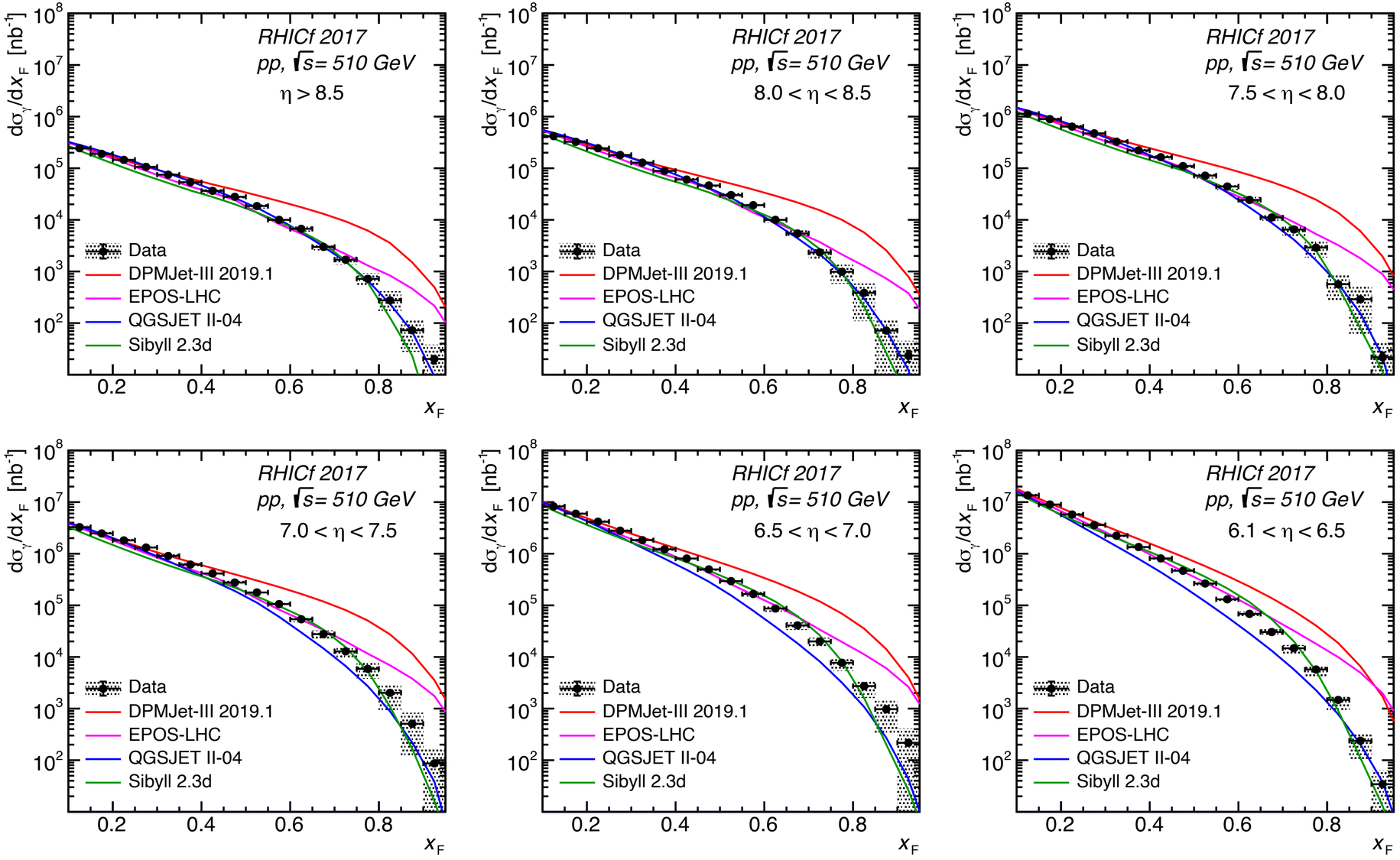


8.81 < η < 8.99



PLB 780, 233 (2018)

RHICf at pp, √s=0.5 TeV

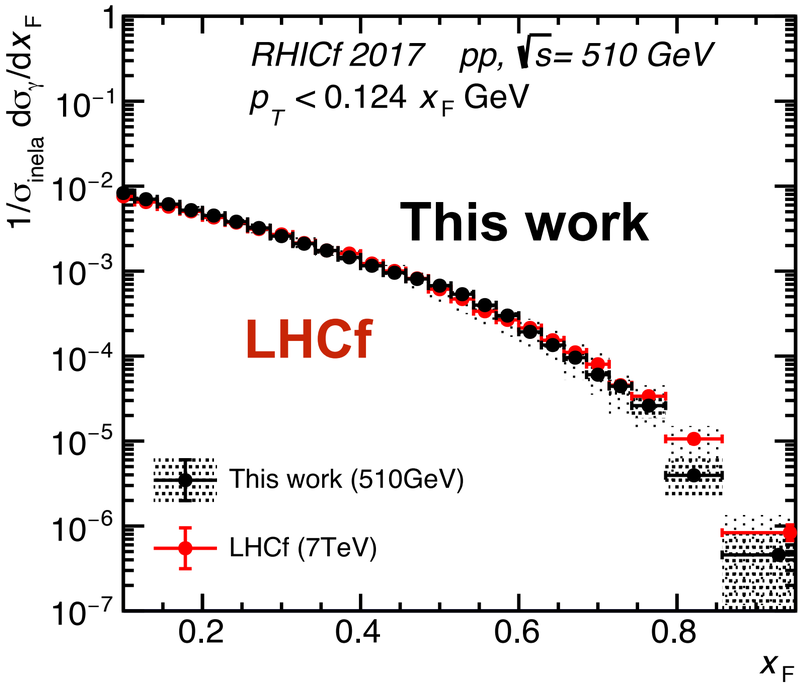


ArXiv: 2203.15416

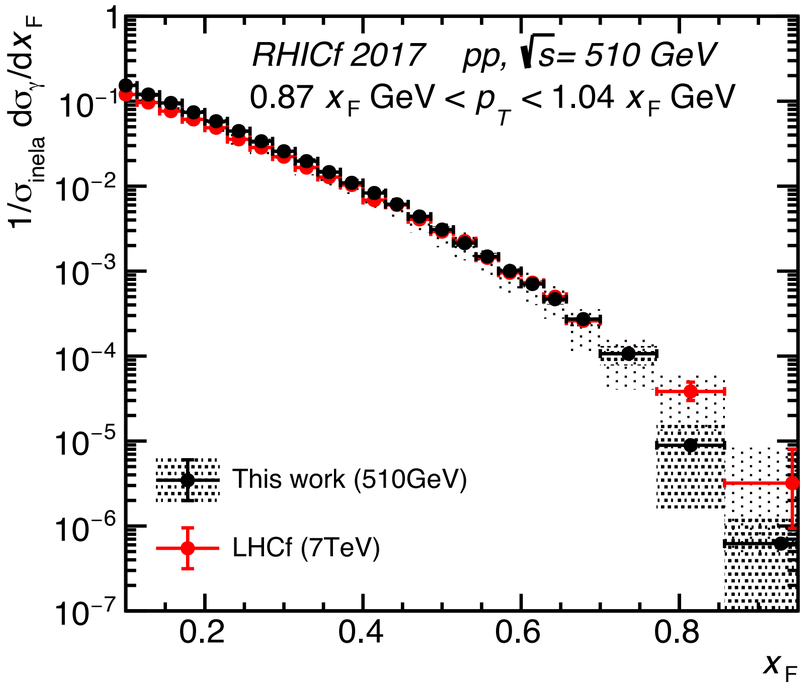
Collision energy scaling test by LHCf v.s. RHICf

- 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)

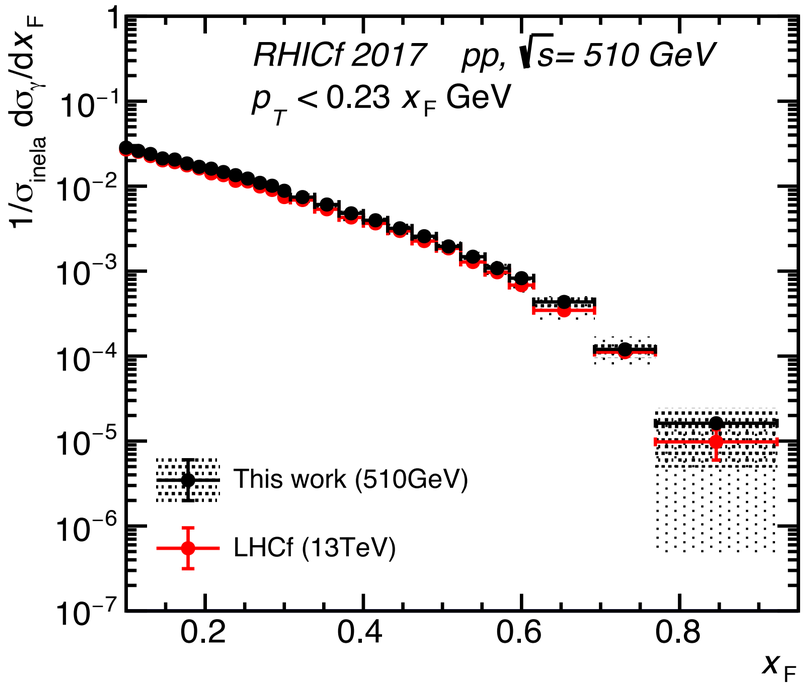
v.s. LHCf 7TeV η > 10.94



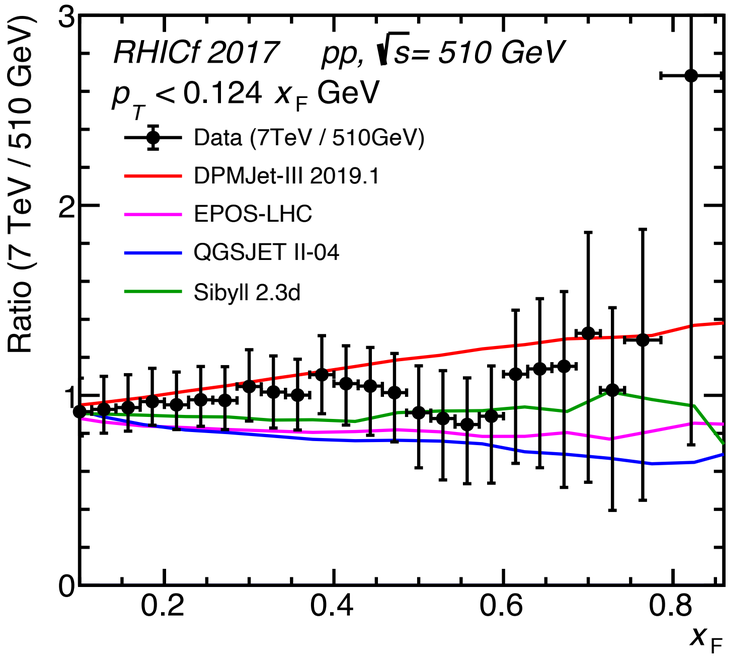
v.s. LHCf 7TeV 8.81 < η < 8.99

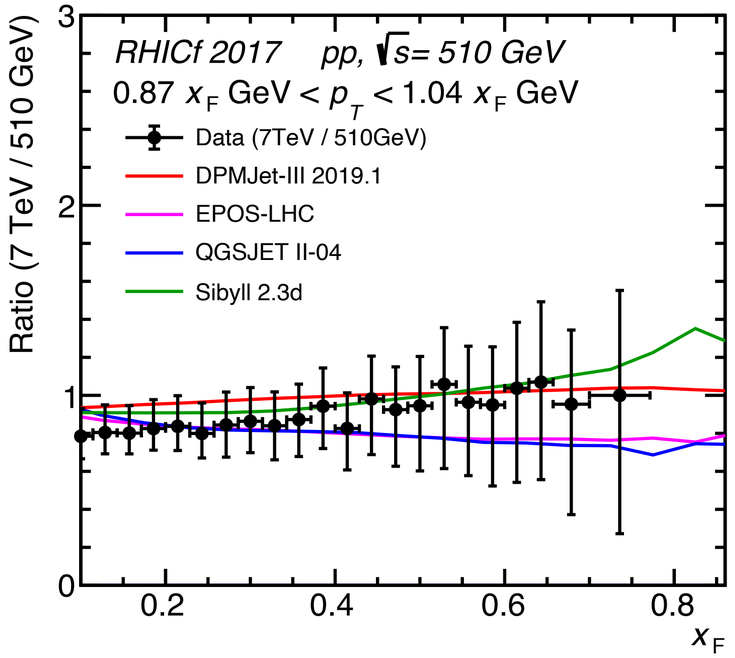


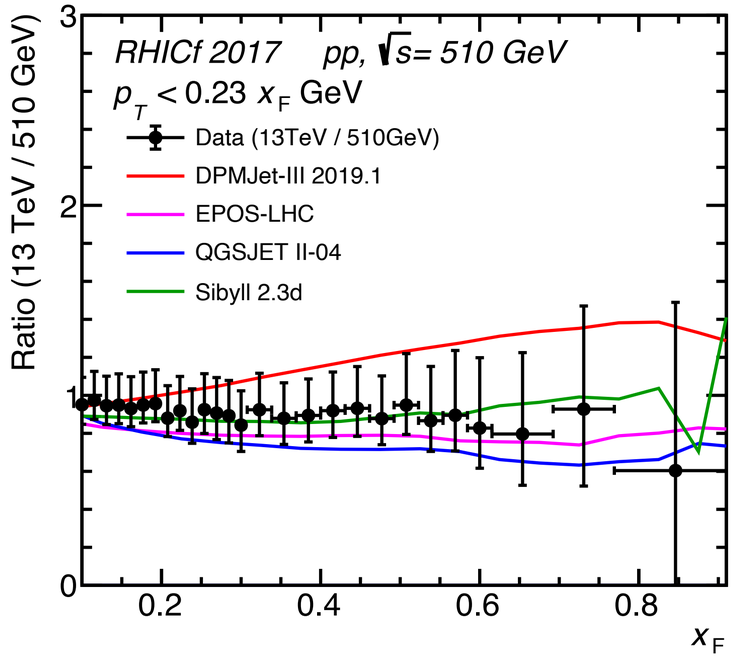
v.s. LHCf 13TeV η > 10.94



Ratio (7TeV or 13TeV/ 510GeV)



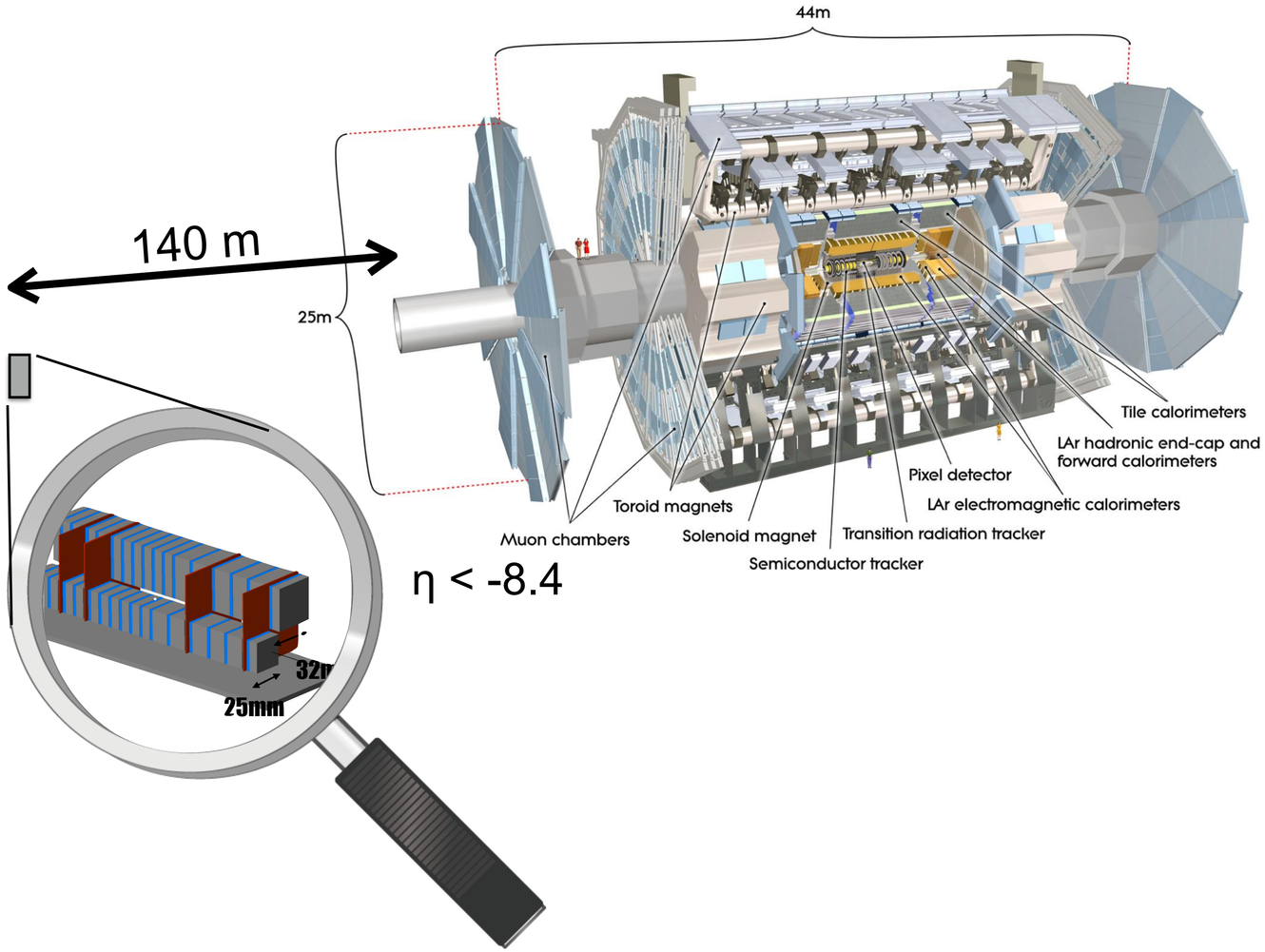




First confirmation of collision-energy scaling at zero degree photons.

- 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

Joint analysis with ATLAS



Measurement of diffractive contribution

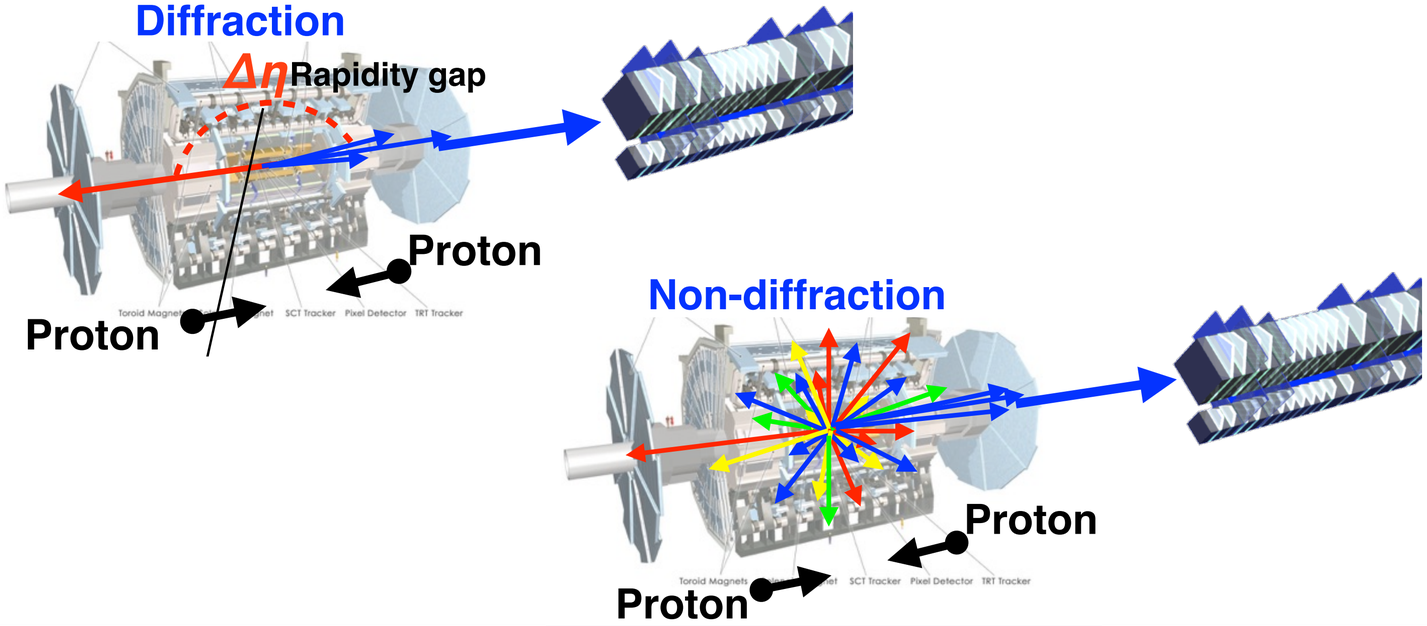
Identification of diffractive events by ATLAS

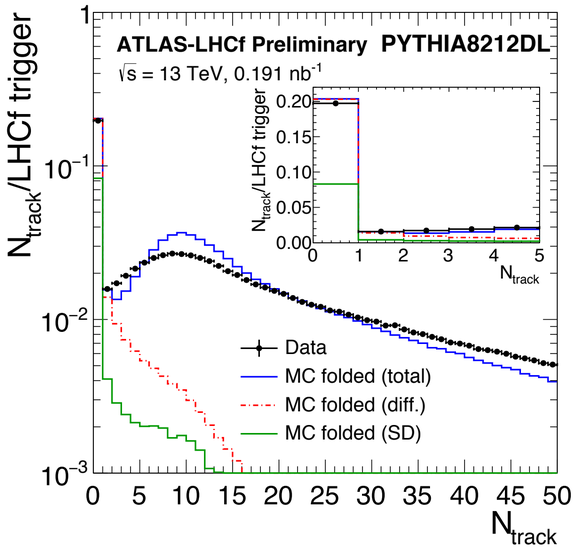
Method

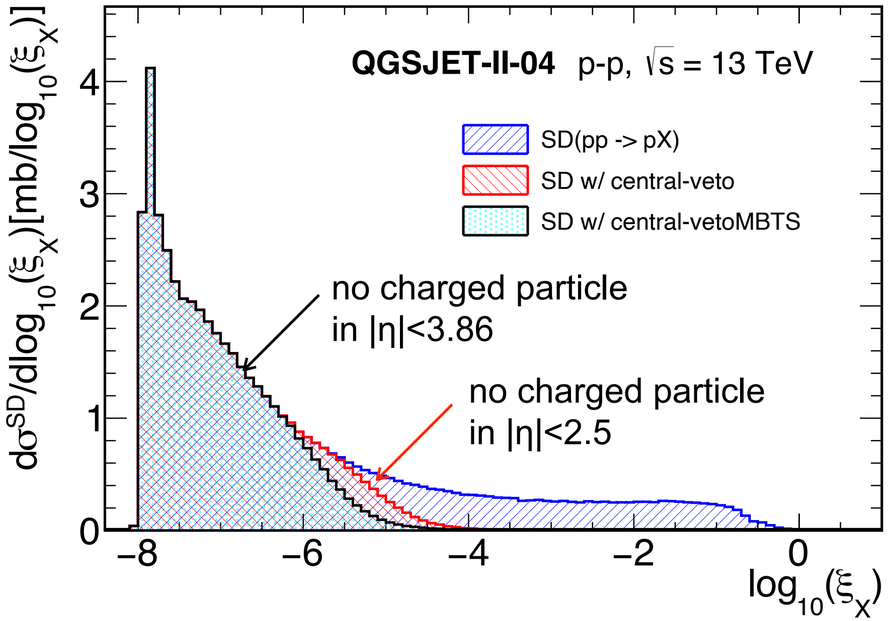
- Event selection by N_{tracks}=0 ⇔ Large rapidity gap $\Delta\eta > 5$

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

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



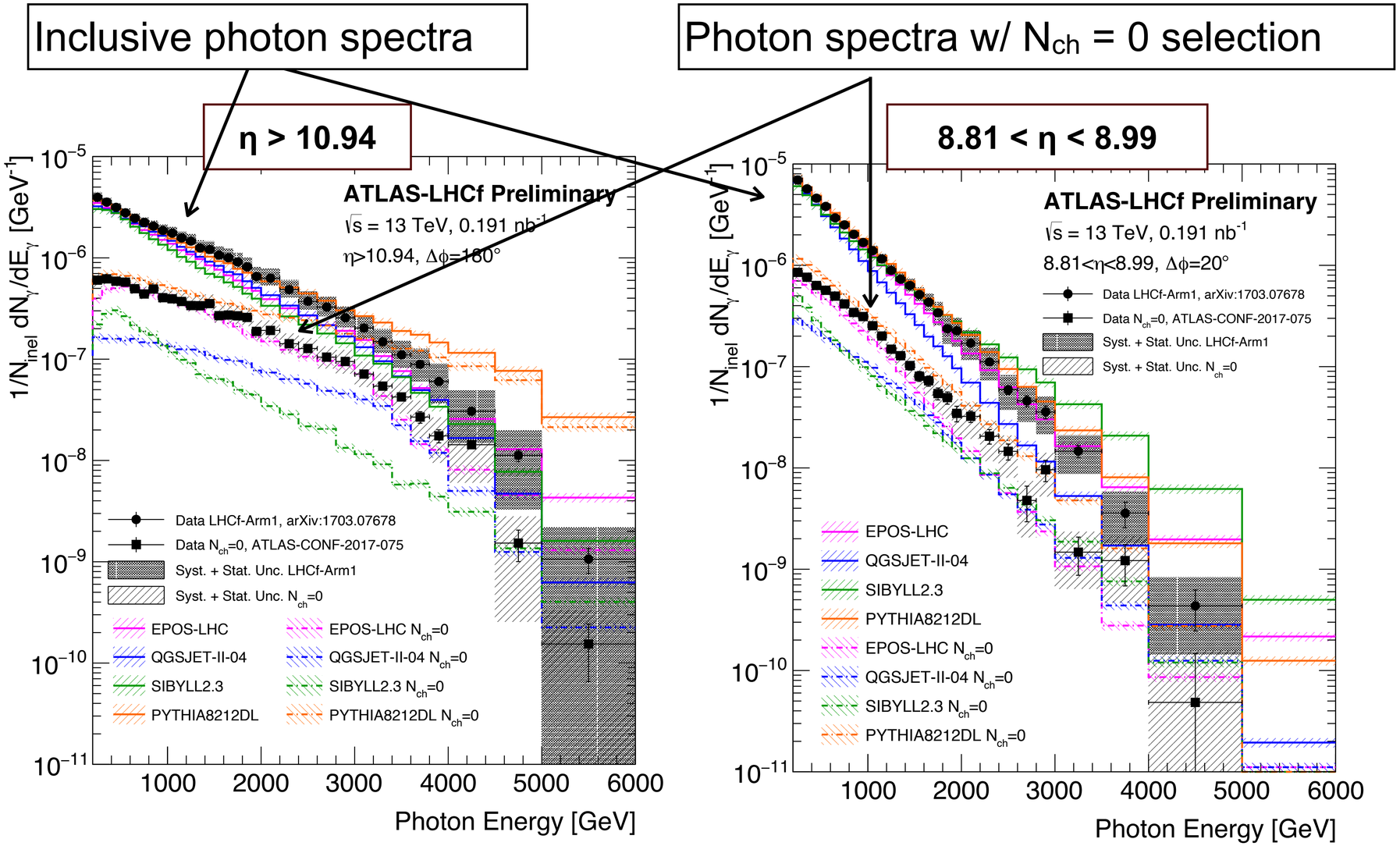




Measurement for photons

Inclusive photon spectra

Photon spectra w/ N_{ch} = 0 selection



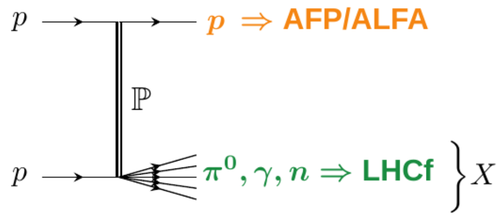
ATLAS-CONF-2017-075

Fisbility study of LHCf+ATLAS RPs

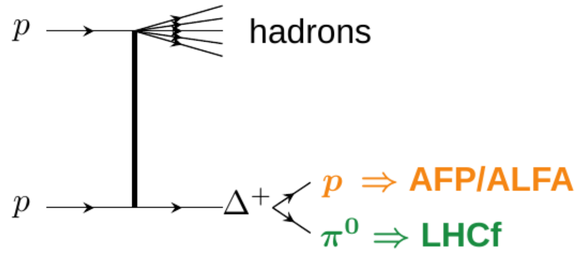
- ATLAS AFP joined the LHCf run in 2022 with pp, √s=13.6 TeV
  Joint analysis is on-going !!
- Physics targets:
  - Detailed study of single diffractive collisions,
  - Measurement of proton excitation (very low-mass diff.)

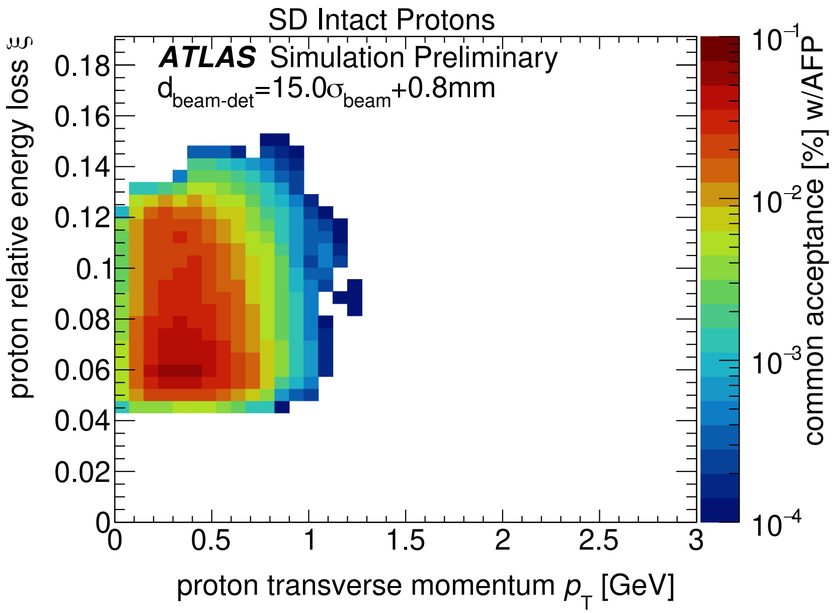
Feasibility study by MC
ATL-PHYS-PUB-2023-024

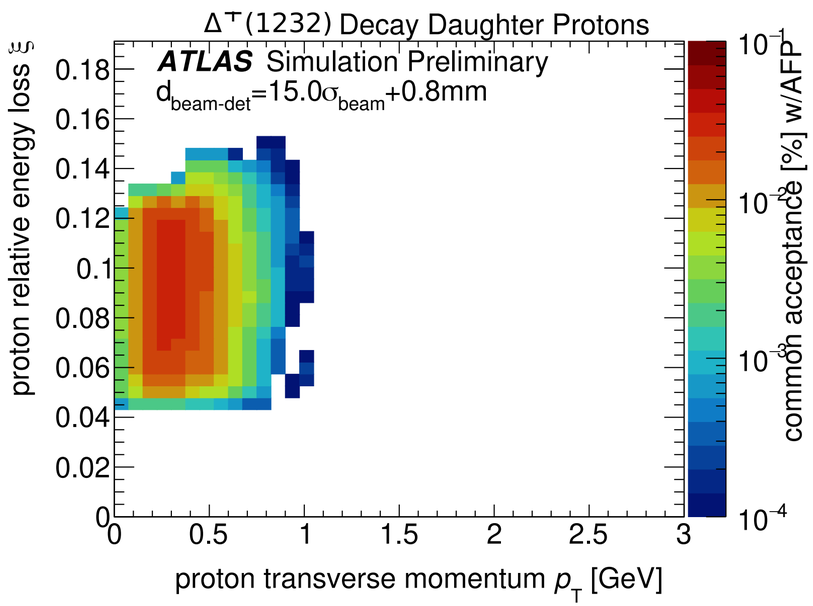
Single diffractive



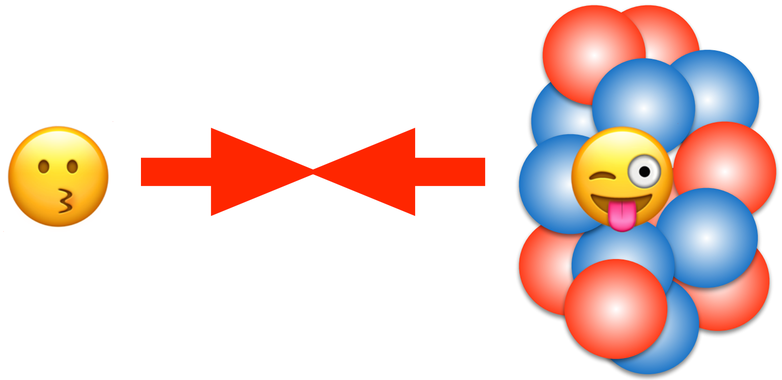
$\Delta^+(1232)$





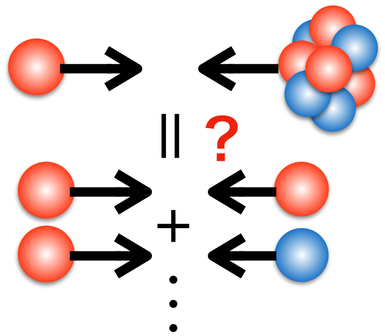


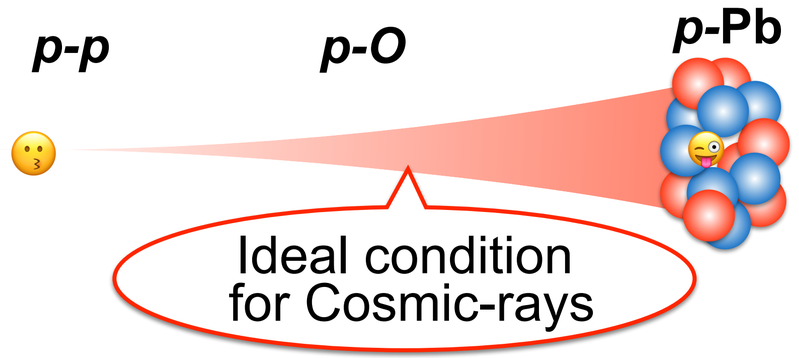
Photon measurements at p-A

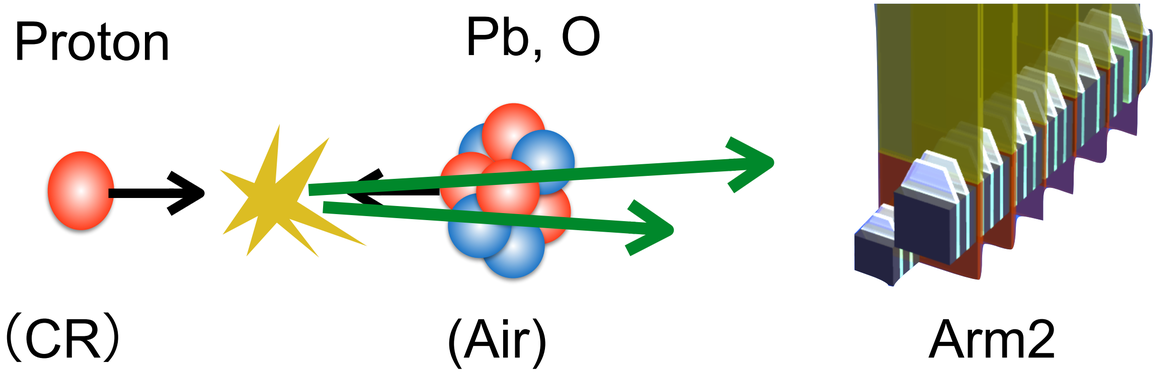


p-Pb and p-O measurement by LHCf

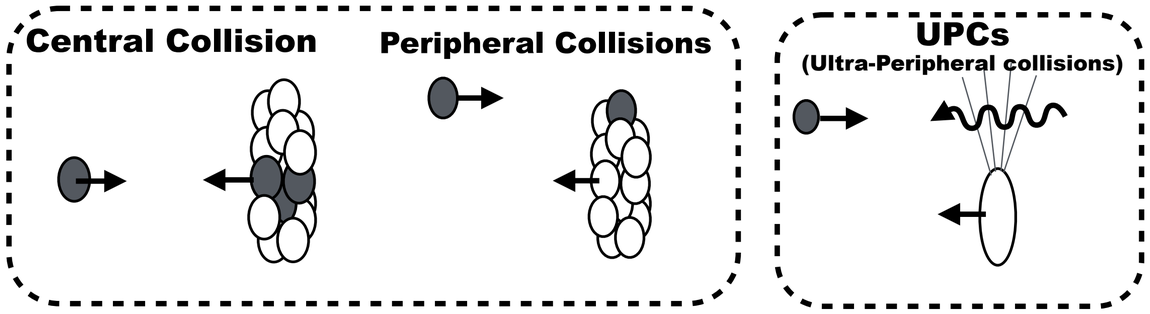
- Motivation
  - Measurement of the nuclear effect on the forward particle production.
- Operation
  - p-Pb, $\sqrt{s_{NN}}$=5TeV in 2013
  - p-Pb, $\sqrt{s_{NN}}$=8TeV in 2016
  - **p-O, $\sqrt{s_{NN}}$=10 TeV in the next month !!**
- Experimental setup
  - Arm2 detector is installed in the p-remnant side.
    Too high multiplicity at A side due to spectator neutrons







Ultra Peripheral Collisions (UPCs)



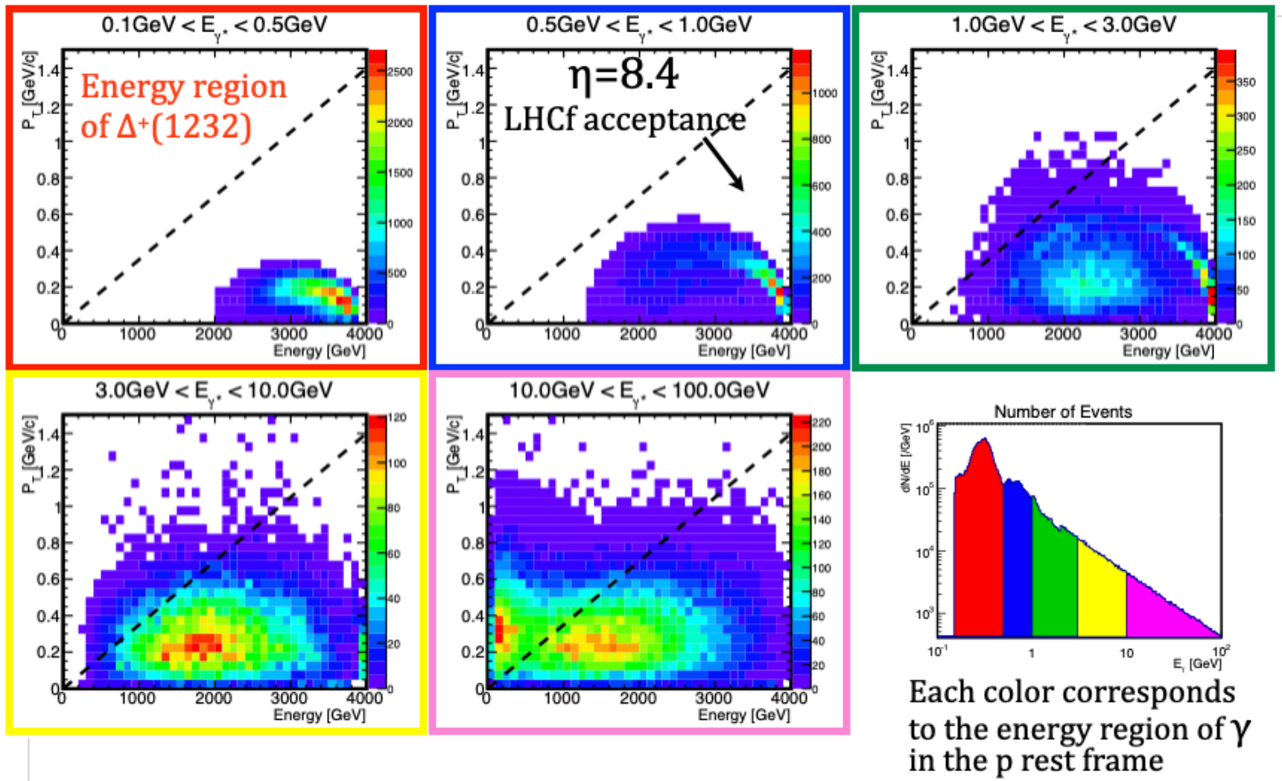
- Many photon from UPCs

  Example:

$$p + \gamma^* \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases}$$

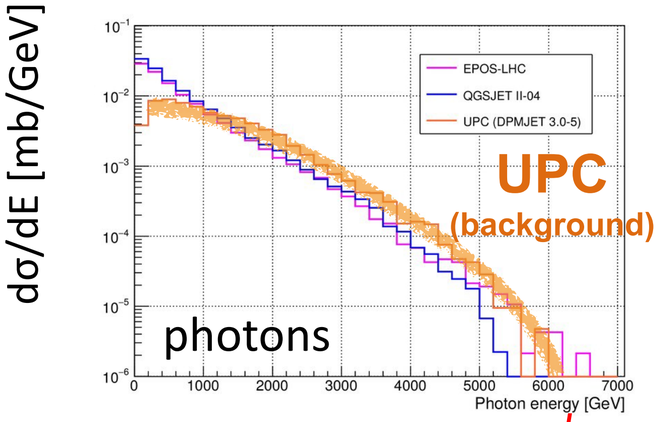
- $\sigma_{UPC} \propto Z^2$
  - p-Pb : QCD ~ UPC
  - p-O : QCD >> UPC

MC prediction of Photons from UPC at pPb, $\sqrt{s_{NN}}$=5TeV

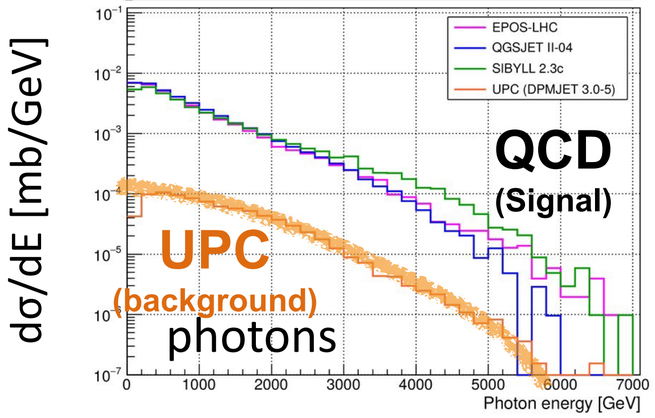


Each color corresponds to the energy region of γ in the p rest frame

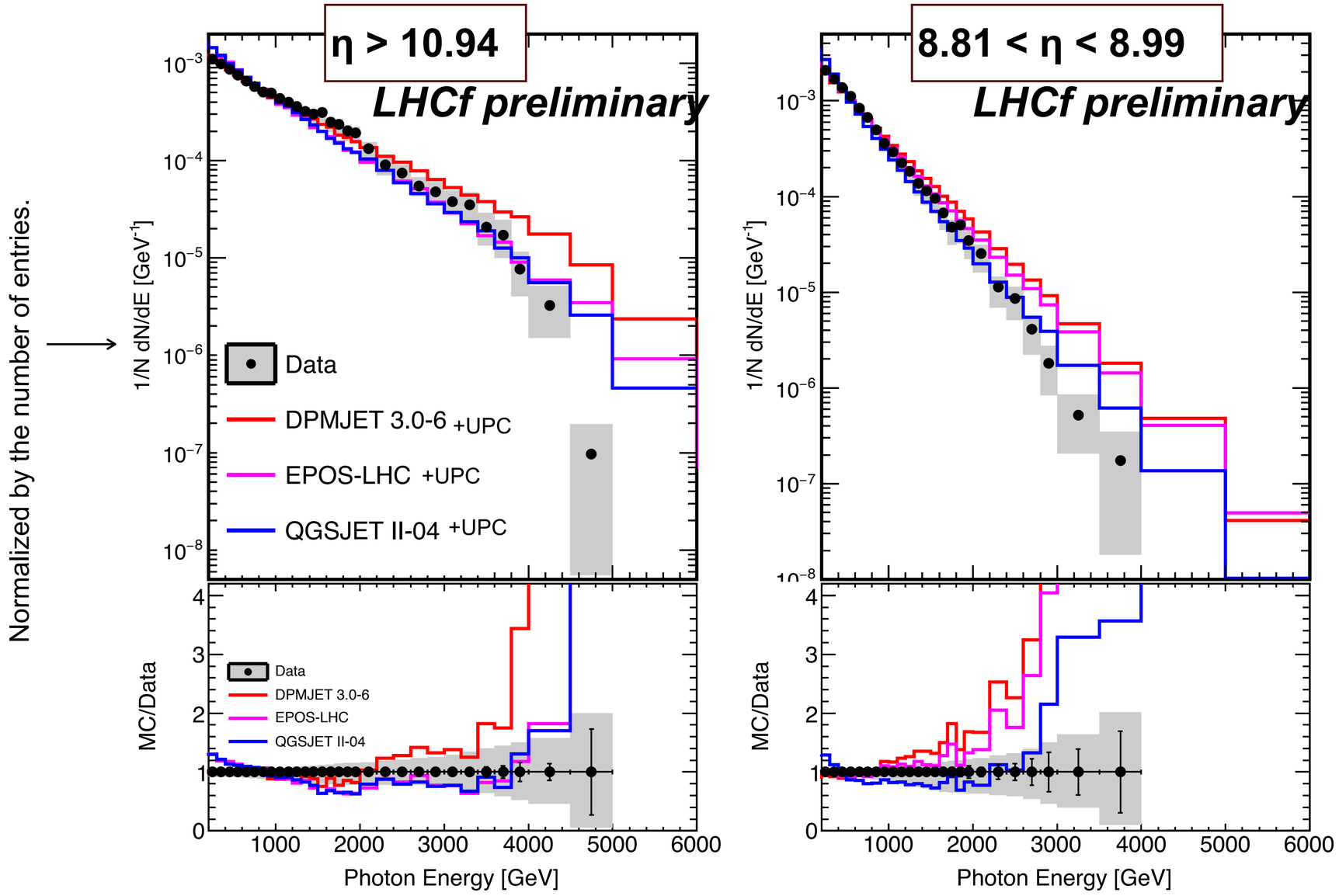
p-Pb at $\sqrt{s_{NN}}$ = 8.2 TeV



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



Photon measurement at pP, $\sqrt{s_{NN}}$=8TeV



UPC/QCD separation by LHCf+ATLAS

- Simple event selection :
  - Ntrack = 0: UPCs and low-mass diffractive collisions
  - Ntrack > 0: Non-diffractive collisions

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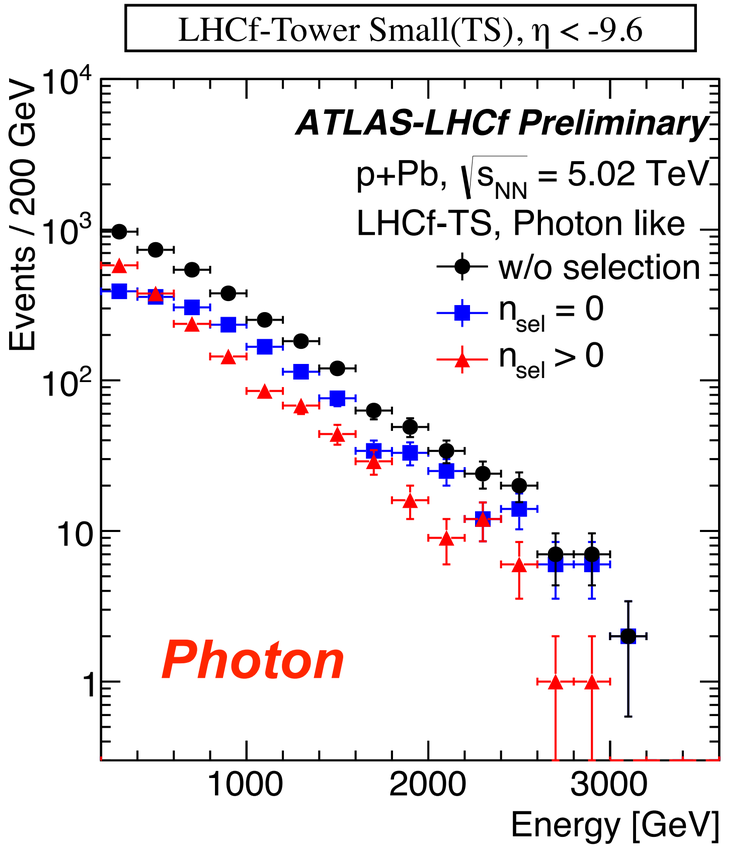
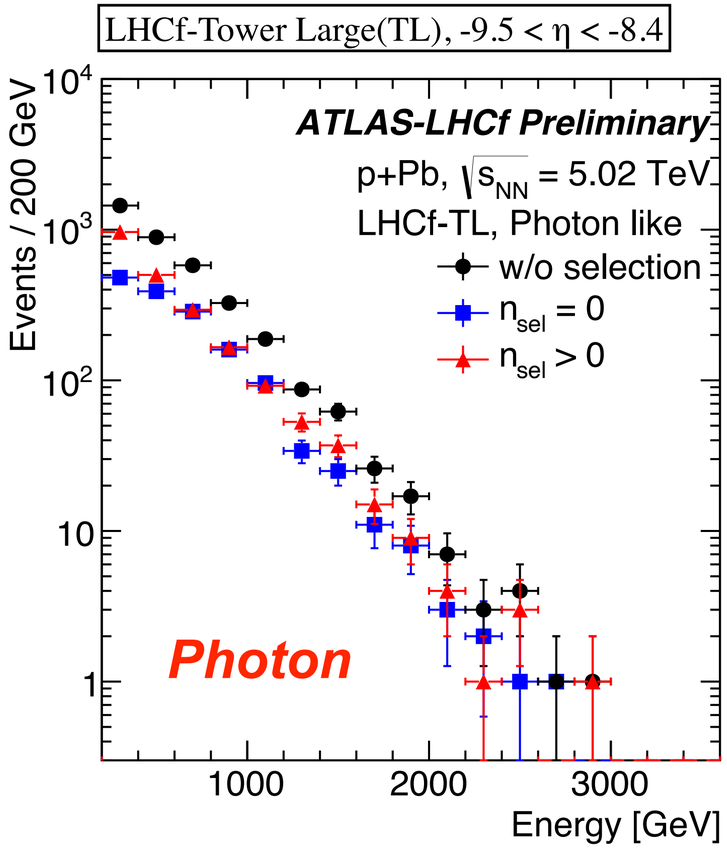
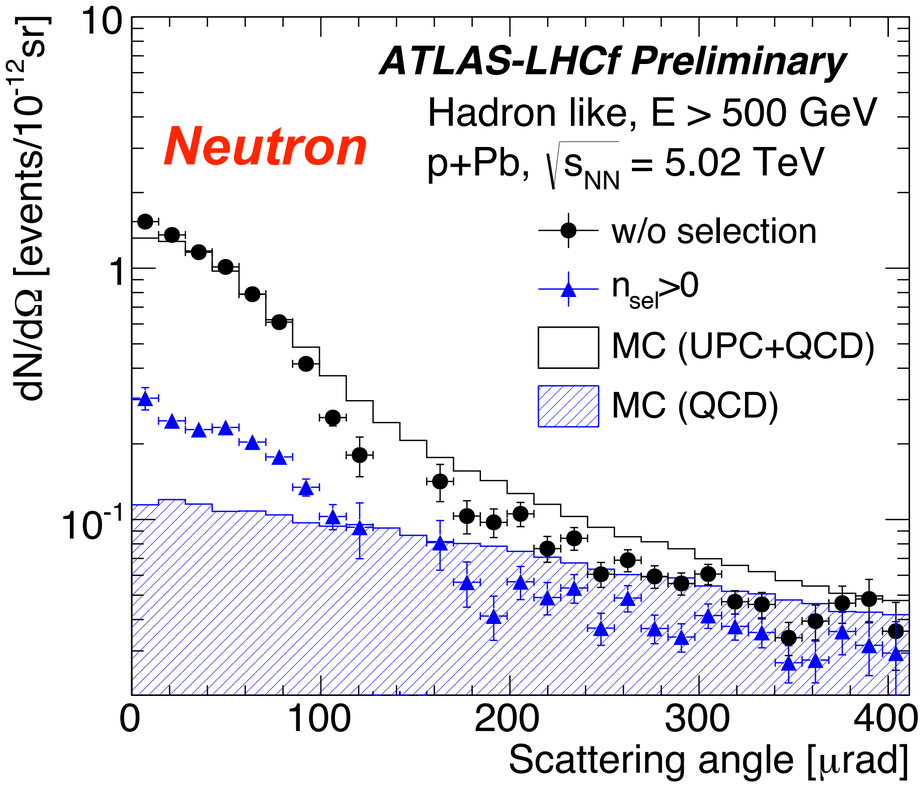






Summary

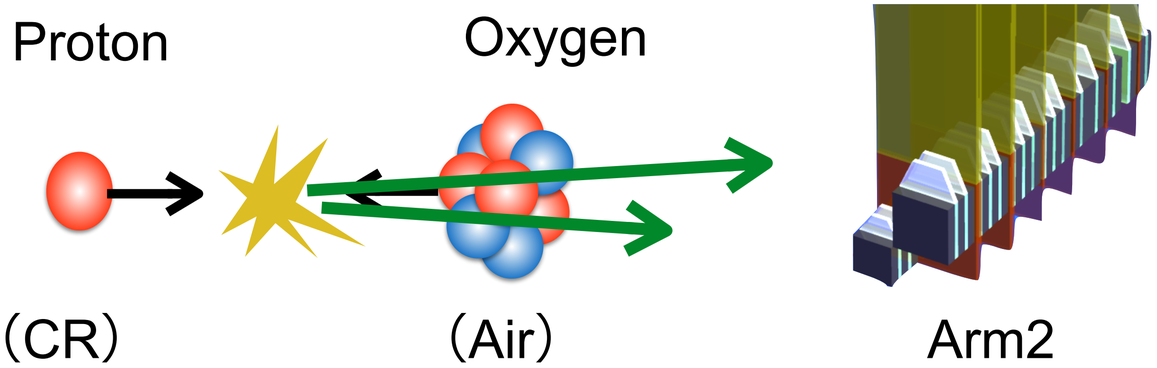
- LHCf/RHICf measured inclusive differential cross-section of very forward photons to improve the cosmic-ray interaction models.
- Phase-space coverages are pT < 1-2 GeV/c and xF > 0.05-0.1, which are limited by the beam pipe configuration and backgrounds.
- Currently no interaction models reproduce the LHCf/RHICf data perfectly while the data is on the prediction bands.
- Photons from UPCs were large background at p-Pb collisions, while it will be negligible at the coming pO run.

Thank you very much !!

Backup

Operation strategy

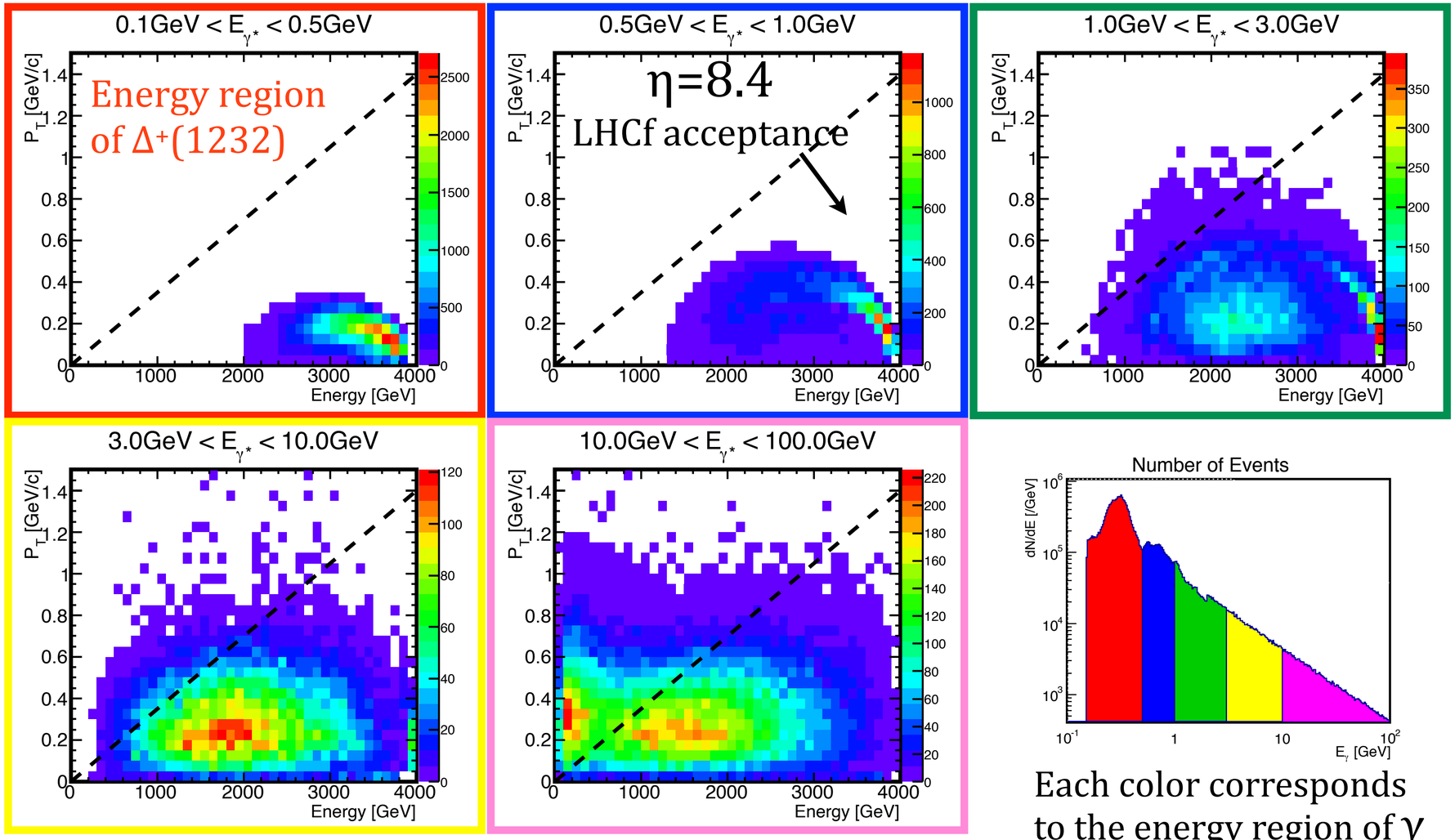
- Setup
  - Only Arm2 detector is installed in p-remnant side.
    too-high multiplicity (<#Hits> > 5) in O-remnant side
  - Joint operation with ATLAS



- Oxygen run in July 2025
  - 1 week special run (p-O and O-O)
  - Install the detector during TS1
  - Beam commissioning (3 day)
  - **p-O collisions (2 days) ← LHCf Operation**
    - - - - - Remove the detector from LHC - - - - -
  - O-O collisions (1 days) ← too high multiplicity

*) This schedule might be changed

Energy vs. p_T : p + γ* → n + X

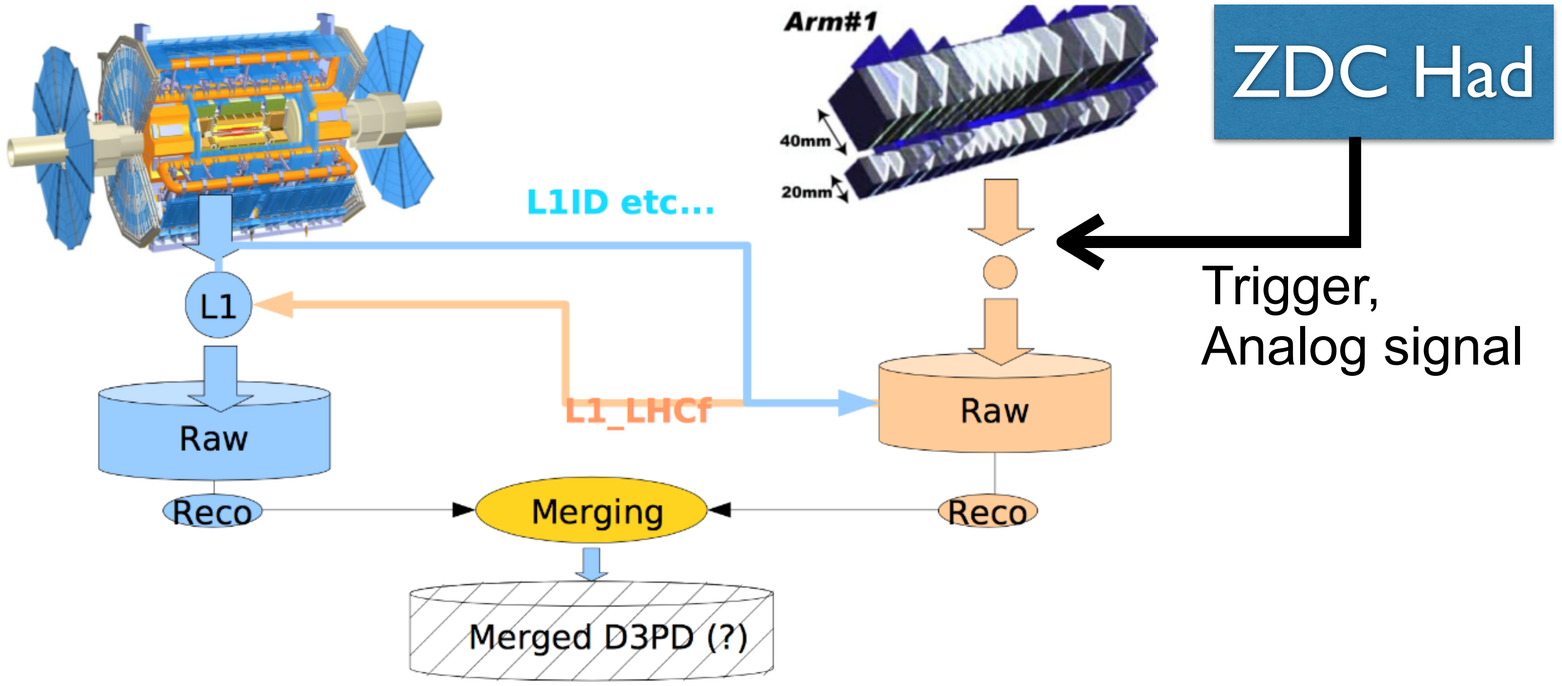


Each color corresponds to the energy region of γ in the p rest frame

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)