# Hadron Collider Measurements for IACT Background Modelling


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Kenneth Ragan (McGill U.),
David Berge (HU Berlin & DESY),
Cigdem Issever (HU Berlin & DESY)



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# Particle Physics - Astroparticle Physics Crossover

## Particle Physics Group

- Cigdem Issever (DESY/HU)
- Clara Leitgeb (HU)


## Astroparticle Group

- Dan Parsons (HU)
- Andrew Taylor (DESY)
- Ken Ragan (McGill U.)
- David Berge (DESY/HU)






- Results presented at Diffraction & Low-x 2024 (proceedings)
- Paper submitted to PRD

# What I will cover...

Atmospheric Air Showers with IACTs

↓

Event Generator Predictions for Cosmic Ray Backgrounds

↓

Connections to LHC Case

↓

Existing Datasets and Analyses

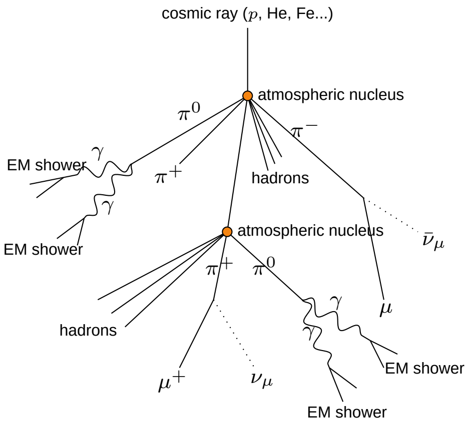
↓

Possibilities for Analyses in Near and Far Future

# Introduction

## Soft QCD in Air Showers

- Cosmic proton hits atmospheric nucleus
  $\rightarrow$ Particle shower
- Soft QCD: Hadronic interaction with low momentum transfer
- Non-perturbative $\rightarrow$ phenomenological models



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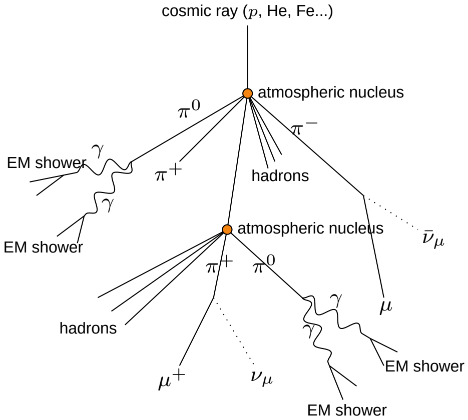

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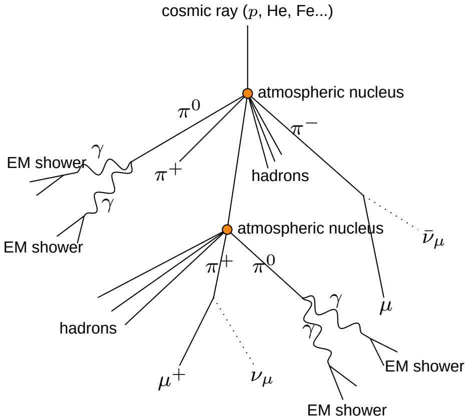

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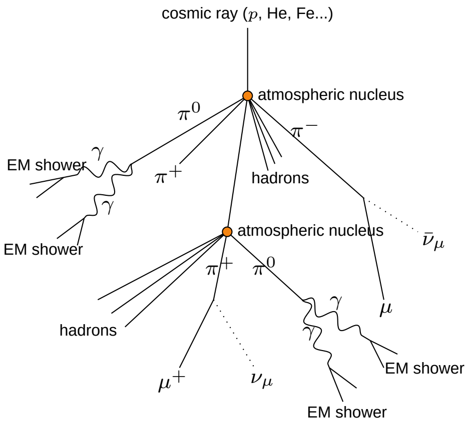

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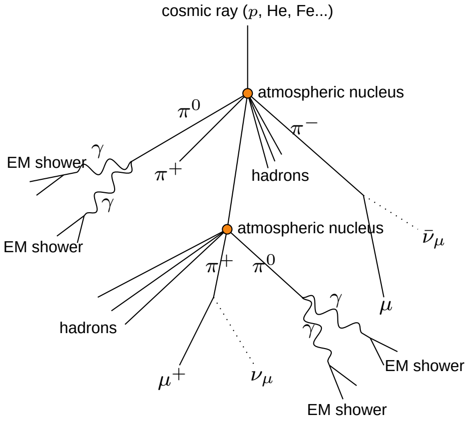
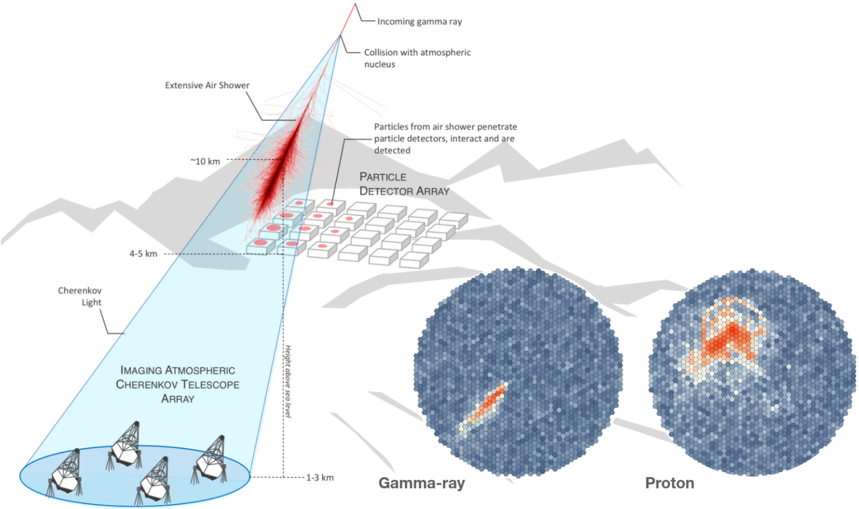



$\rightarrow$ **Tuning based on accelerator data**

$\rightarrow$ **But which data?**

# Imaging Atmospheric Cherenkov Telescopes (IACTs)




(c) Richard White

# Backgrounds for Cosmic Gamma Rays with IACTs

## Proton CR Rejection

- Problem for big and diffuse sources
  - $\rightarrow$ No side-band estimation possible
  - $\rightarrow$ Dependent on event generator predictions
- MVA discrimination based on image shapes
- Small fraction of proton CR events passes $\gamma$-cuts ($\sim$ 99% rejection)

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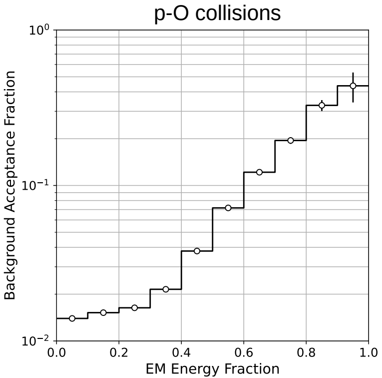


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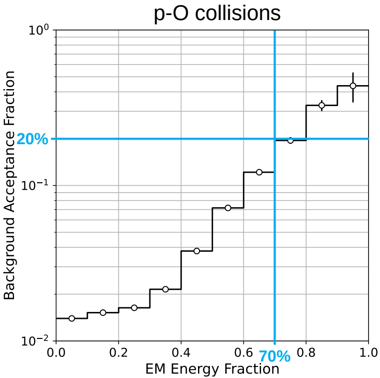


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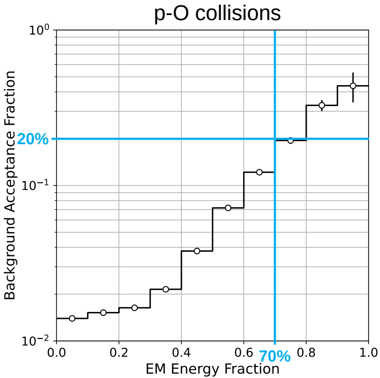


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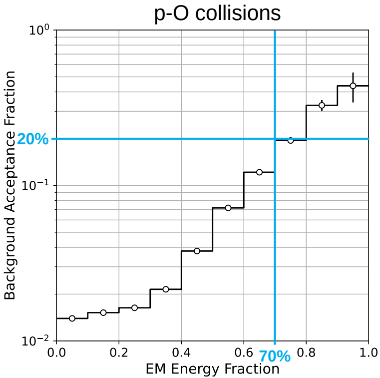
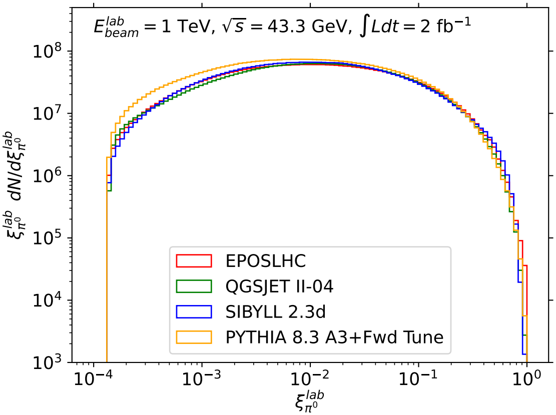



- But: Typically $\#p\,/\,\#\gamma \sim 10^3$ - $10^4$!
- Source: Production of high energy $\pi^0 \rightarrow$ EM-shower development
- Problem: Large uncertainties for this kind of showers!

# Event Generator Predictions

## High-Energy $\pi^0$ production in $pp$ collisions

- Dominant source for $p$-CR backgrounds
- $\xi_{\pi^0} = \frac{E_{\pi^0}}{E_{\text{beam}}}$
- Lab frame in this example:
  $1$ TeV proton $\rightarrow$ resting proton



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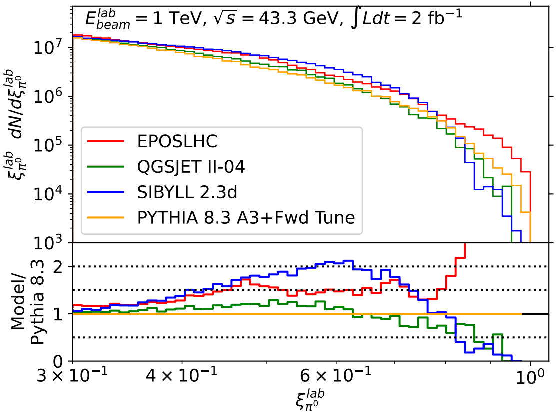
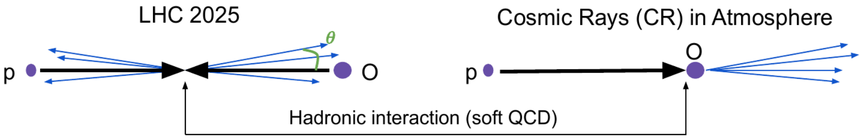
  $1$ TeV proton $\rightarrow$ resting proton
- $\sim 100\%$ event generator differences in predicted $\pi^0$ energy fraction at very high energies!



# Transfer: EAS vs. LHC Case




| | LHC | CR-EAS with IACTs | Transfer |
|---|---|---|---|
| | | | |

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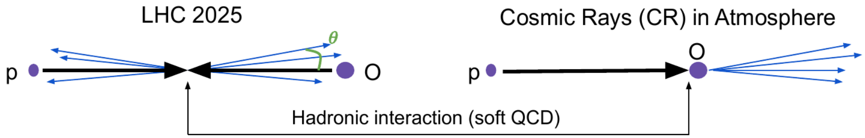


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| | | | |

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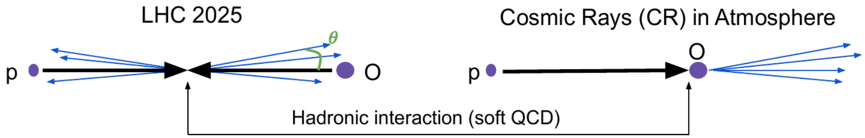


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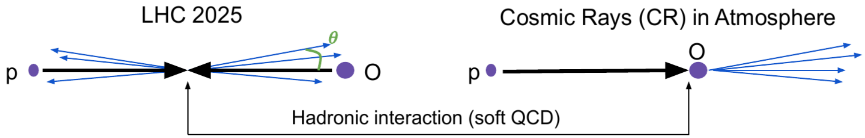


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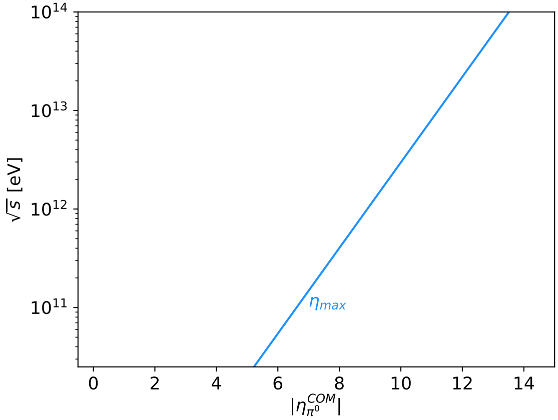
| typical $\sqrt{s}$ | $\sim 13000$ GeV | $\sim 40$ GeV | **scaling law** |

# Transfer: EAS vs. LHC Case - Scaling Law

## Maximal Case

$\pi^0$ inherits $\sim$ all energy from beam:

$$\eta_{\text{max}} \approx \ln\left(\frac{\sqrt{s}}{m_\pi}\right)$$



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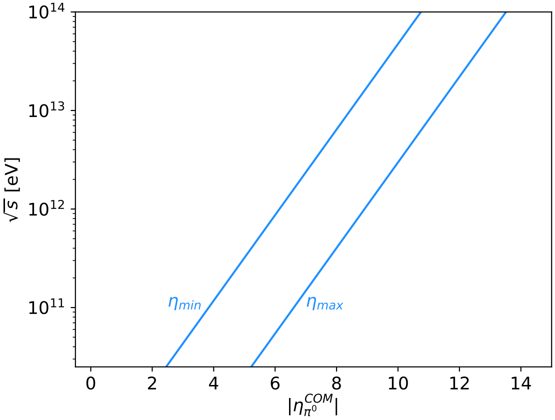
From simulations: $p_{\text{T},\pi} \lesssim 1.5\,\text{GeV}$



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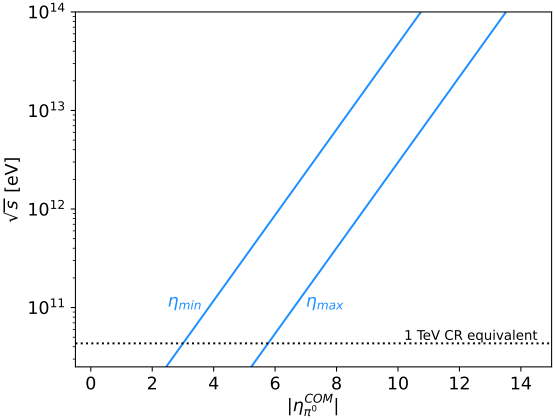

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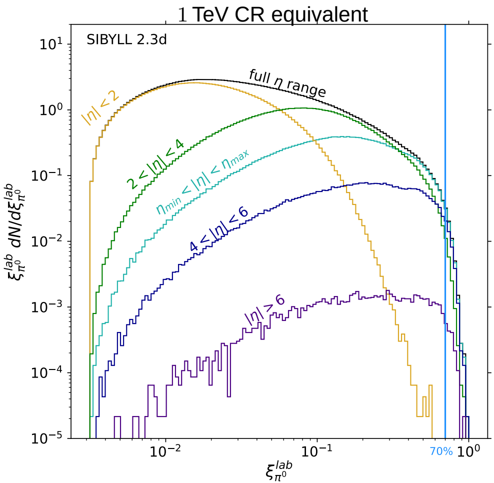

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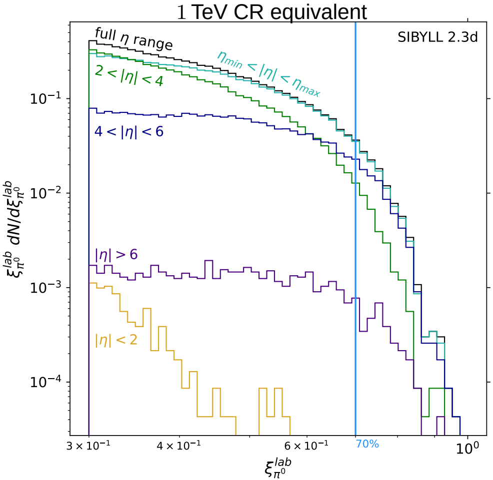

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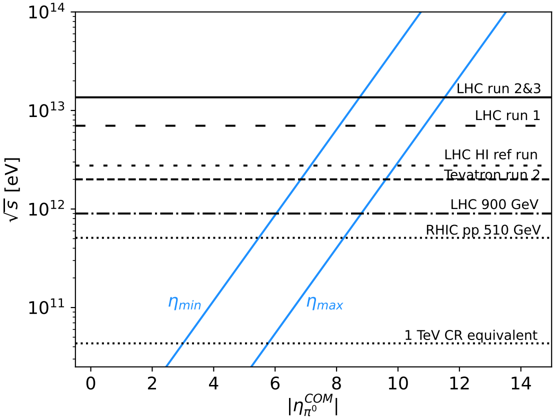
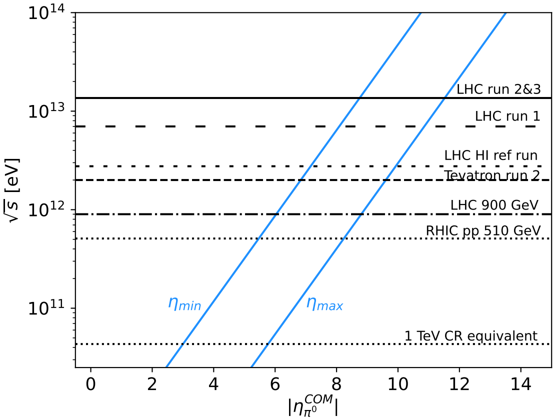


# Experiments in Relevant $\eta$-Range



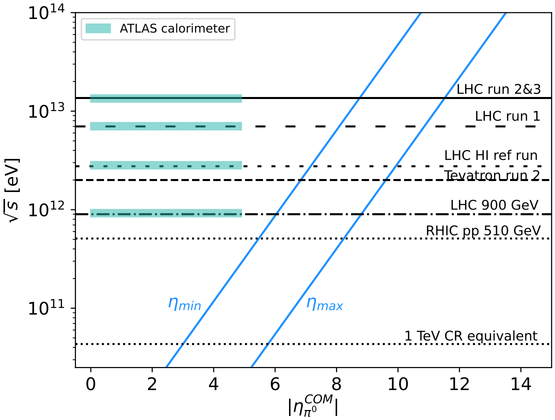
# Experiments in Relevant $\eta$-Range

## ATLAS

> Inner tracking detector: $|\eta| < 2.5$

> Calorimeters: $|\eta| < 4.9$

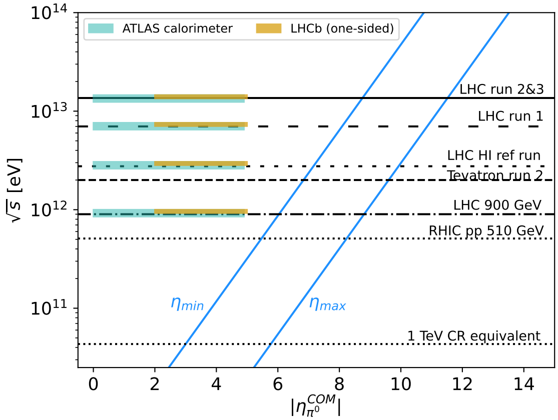
> Very similar coverage for CMS detector



# Experiments in Relevant $\eta$-Range

## LHCb

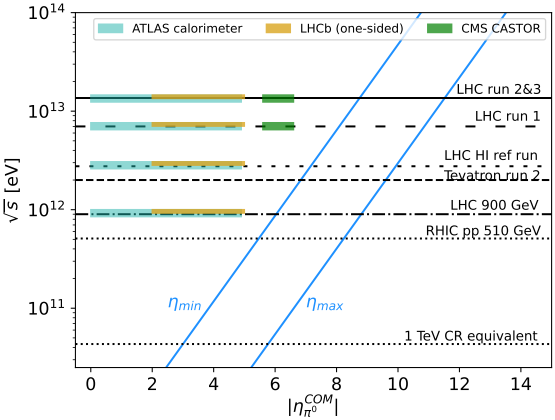
- Single arm forward detector
- Coverage: $2 < \eta < 5$



# Experiments in Relevant $\eta$-Range

## CMS CASTOR

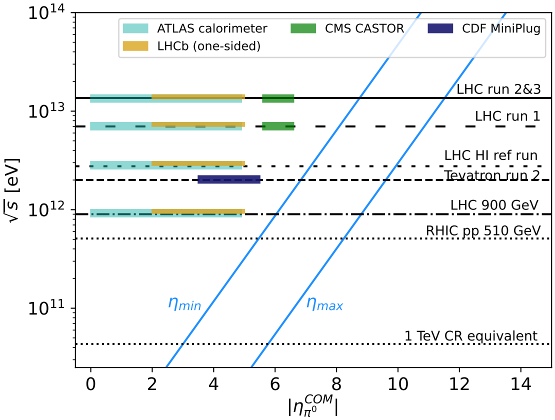
- One-sided Cherenkov calorimeter
- Coverage $-6.6 < \eta < -5.2$



# Experiments in Relevant $\eta$-Range

## CDF Miniplug

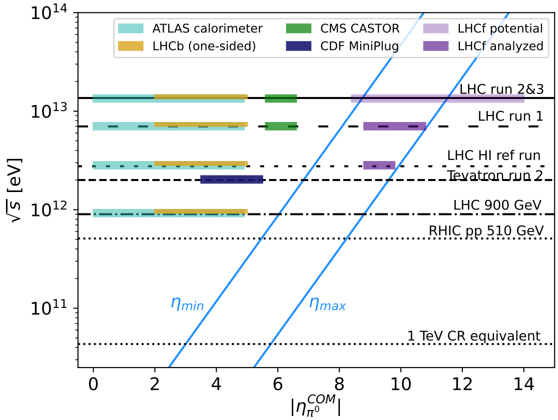
- Operated in Tevatron $p\bar{p}$ collisions at $1.96$ TeV
- Coverage: $3.6 < |\eta| < 5.1$



# Experiments in Relevant $\eta$-Range

## LHCf Detector

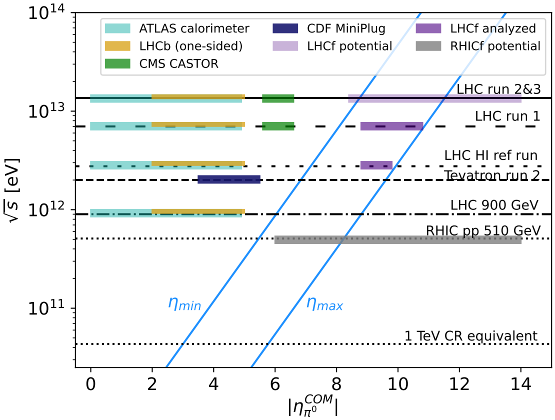
- Two armed neutral particle detector at $\pm 140$ m from IP 1
- Coverage: $|\eta| > 8.4$



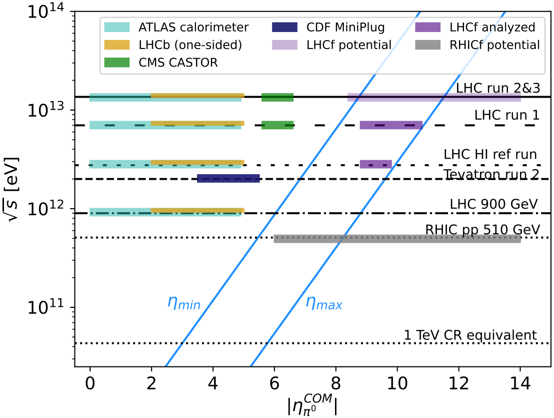
# Experiments in Relevant $\eta$-Range

## RHICf Detector

- One arm neutral particle detector at $18\,$m from STAR IP
- Coverage: $\eta > 6$



# "Wish List" for Future Analyses



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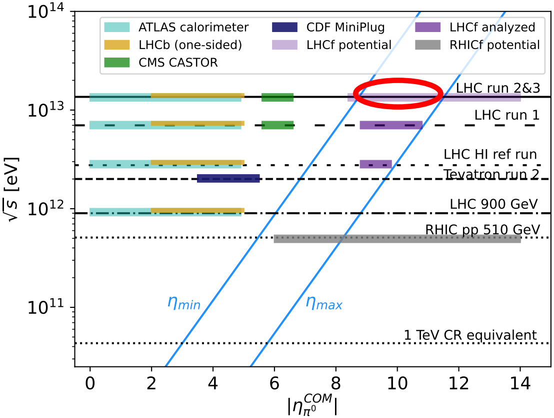
- LHCf run 2 and/or run 3 $\pi^0$ energy spectrum in bins of $\eta$
  - $\rightarrow$ Datasets available! :)



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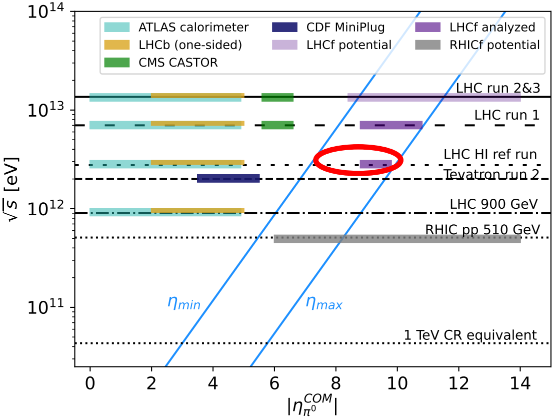

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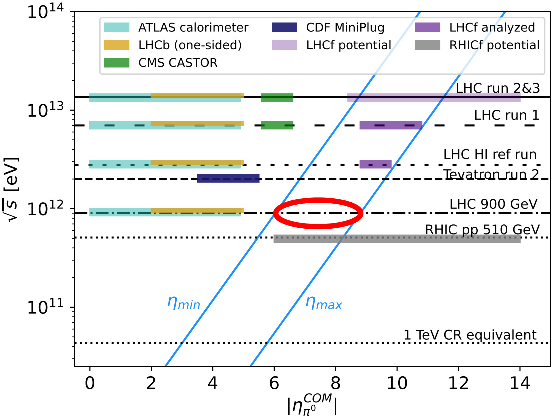

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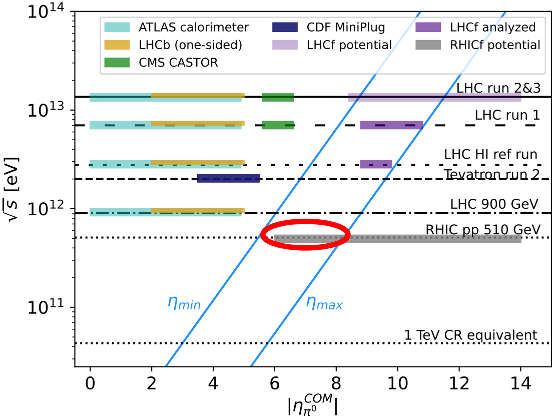
  - RHICf dataset available! :)



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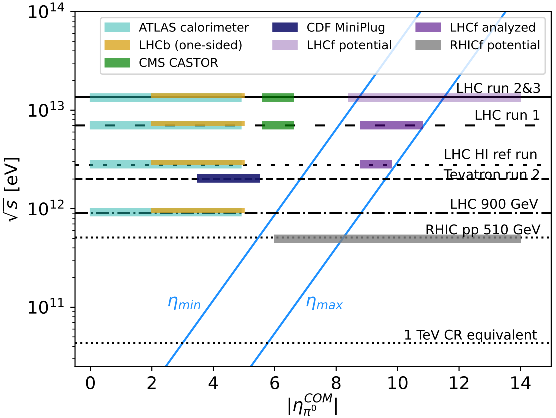
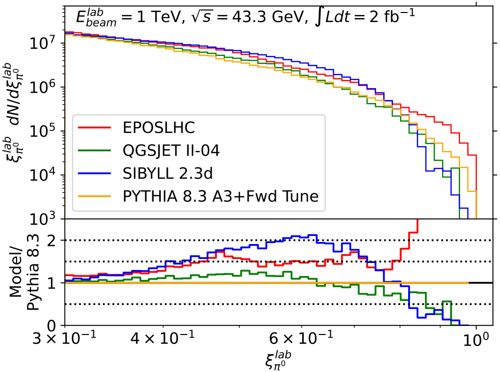
**In addition:**
Proton-Oxygen collisions in 2025!
(LHCf + ATLAS-ZDC on $p$-remnant side)

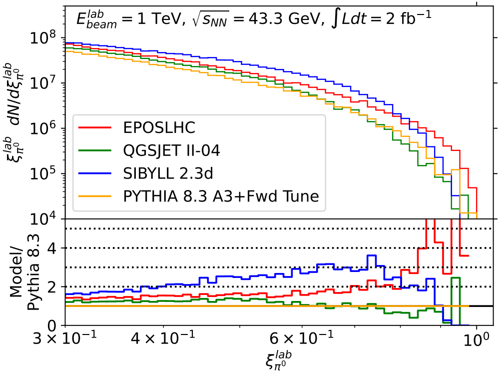


# Generator Predicitons for Proton-Oxygen

$1$ TeV p $\longrightarrow$ resting p:




$1$ TeV p $\longrightarrow$ resting O$^{16}$:



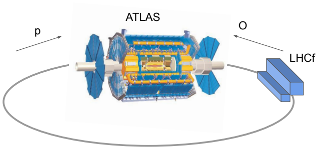

$\Rightarrow$ Even bigger discrepancies in pO!

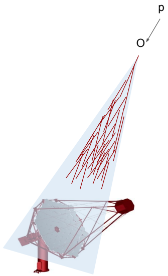
# Conclusion

- Proton CRs important backgrounds for IACT analyses
- Dominant source: Production of highly energetic $\pi^0$ in primary collision
- Large model discrepancies explicitly in high energy end of $\pi^0$ spectrum
- Models need to be tuned on data in analogous $\sqrt{s} - \eta$ region

$\rightarrow$ Only LHCf and RHICf are taking data in right region but no corresponding public results so far

$\rightarrow$ Need $\pi^0$ energy spectra for high $\eta$ bins at different $\sqrt{s}$!

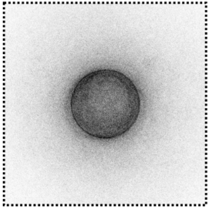


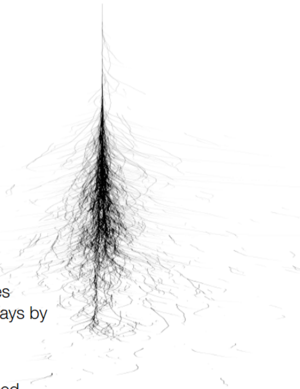



# Backup

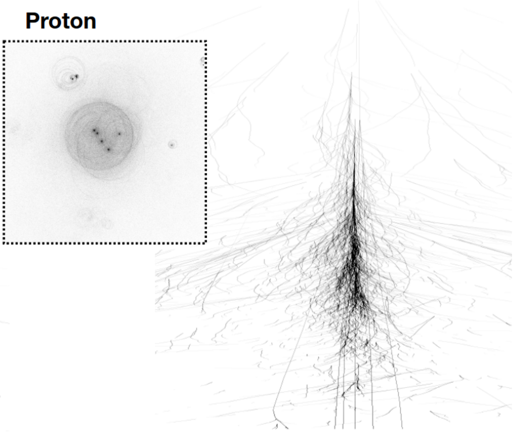
# Backgrounds for Cosmic Gamma Rays with IACTs

**Gamma-ray**





**Proton**

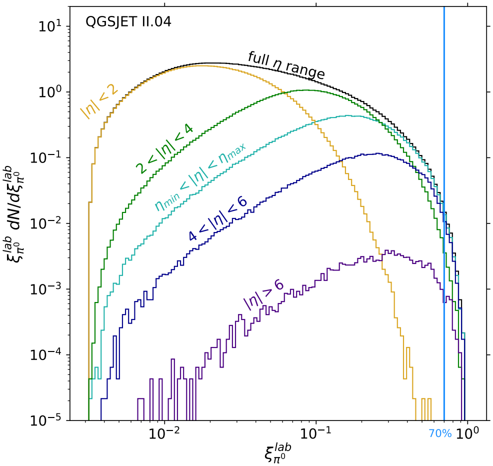


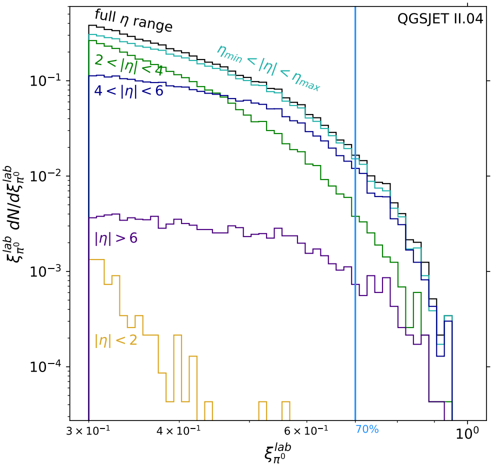
Even for the strongest sources protons outnumber gamma-rays by a factor $10^4$

Obvious differences between proton and gamma-ray induced showers

(c) Konrad Bernlöhr

# $\eta$-Range of Interest for $1$ TeV CR collision equivalent in $pp$



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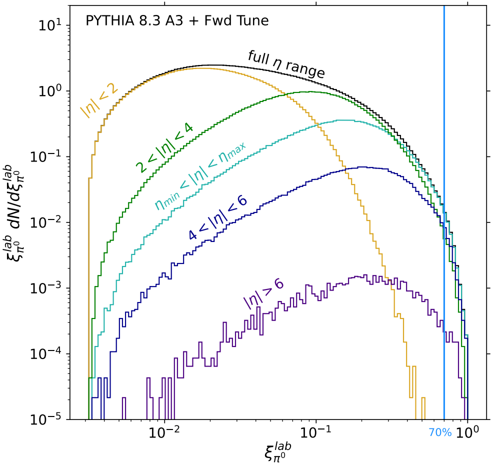


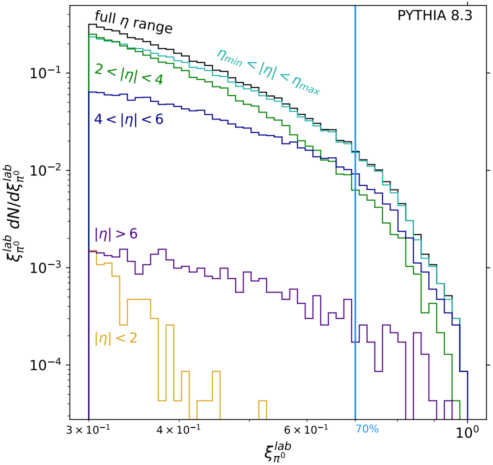

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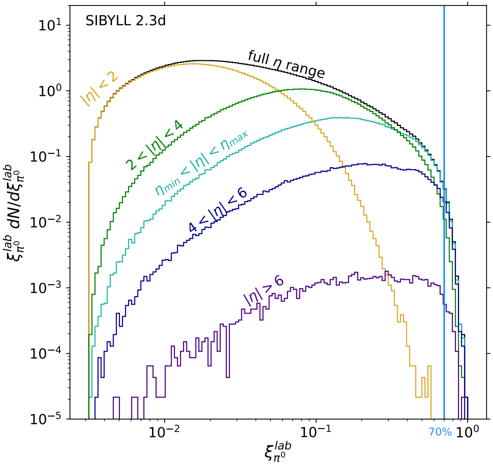


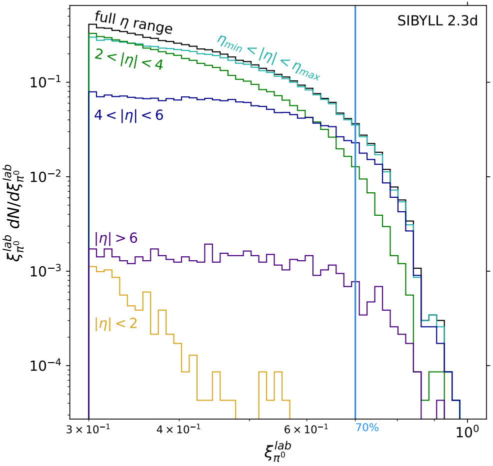

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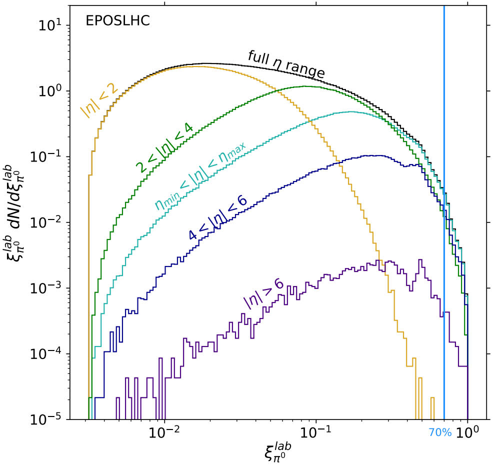
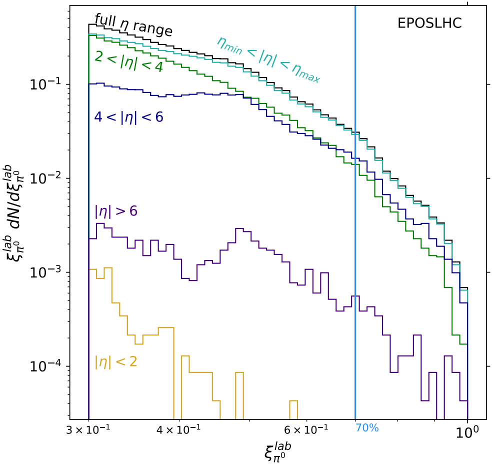
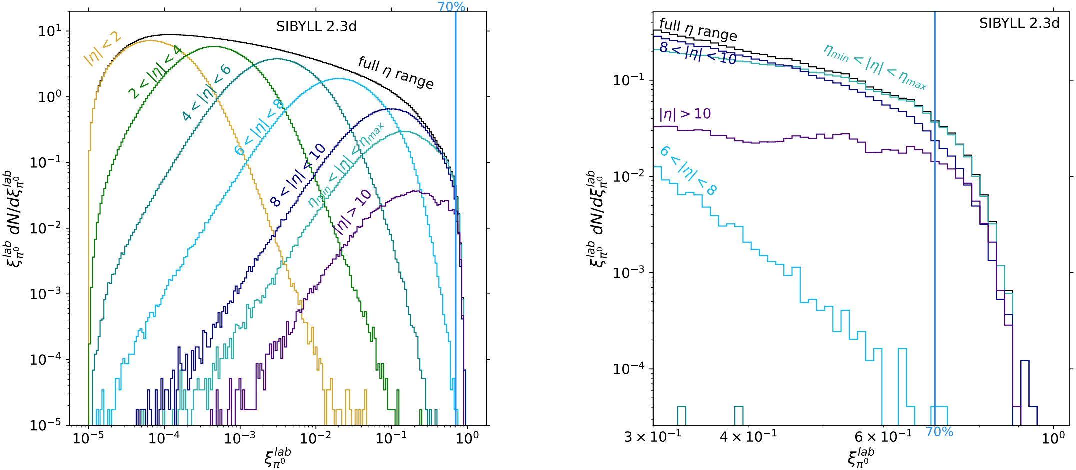


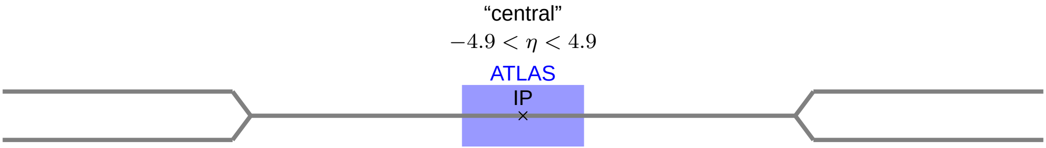



# $\eta$-Range of Interest for $pp$ collisions at $13.6$ TeV (LHC run 3)



# The LHCf Detector

# Overview of Forward Experiments Near ATLAS IP




> Multi-purpose detector: ATLAS

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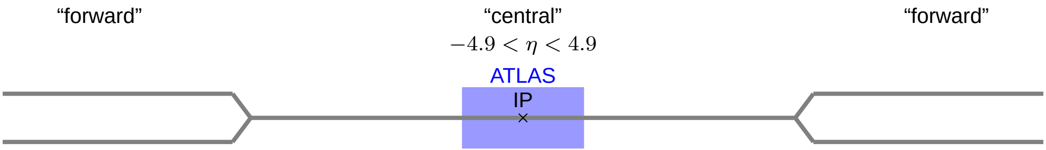


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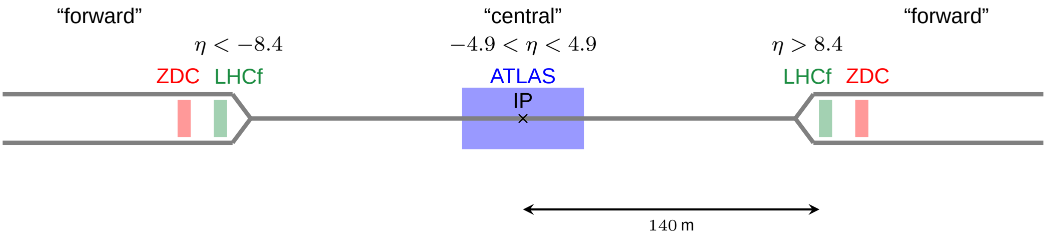


- Multi-purpose detector: ATLAS
- Forward neutral particle calorimeters: LHCf, ZDC

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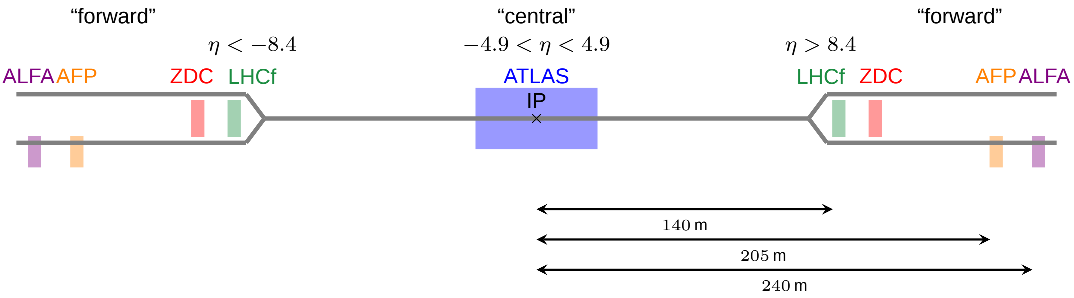


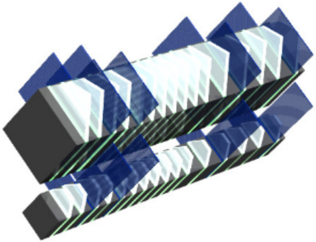

> Multi-purpose detector: ATLAS

> Forward neutral particle calorimeters: LHCf, ZDC

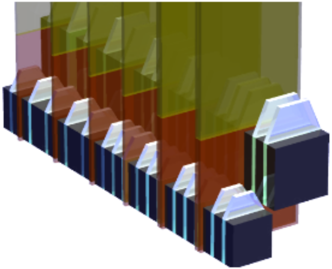
> Forward proton detectors: AFP, ALFA

# LHCf Detectors

Arm 1



Arm 2



(c) LHCf

- Two calorimeter towers on each side of ATLAS
- Different geometric orientations
- Tungsten absorber, plastic scintillators + position sensitive layers per tower

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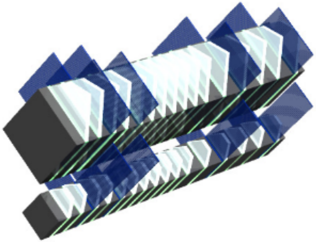

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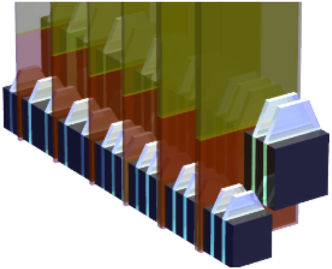

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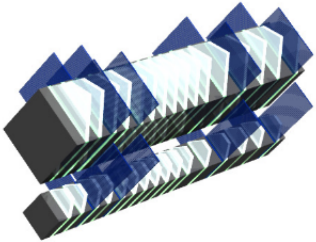

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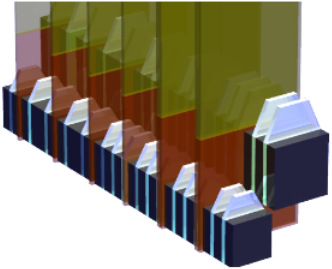

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- Tungsten absorber, plastic scintillators + position sensitive layers per tower
- Only reached by neutral particles: $n$, $\gamma$, $\pi^0 \to \gamma\gamma$, $\eta^0 \to \gamma\gamma$...
- Energy resolution: $< 3\%$ (photons), $\sim 40\%$ (neutrons)

# LHCf Analyses

## Forward Photons in Run 2

- No public reconstructed $\pi^0$ energy spectra for run 2 or run 3 from LHCf yet

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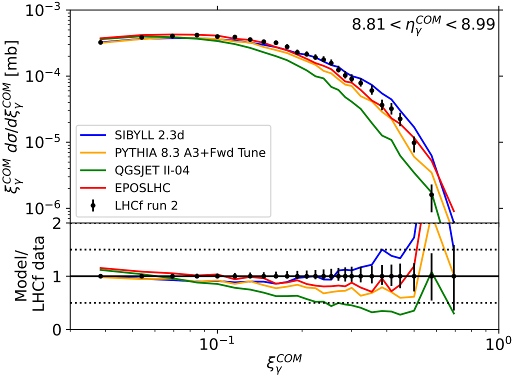

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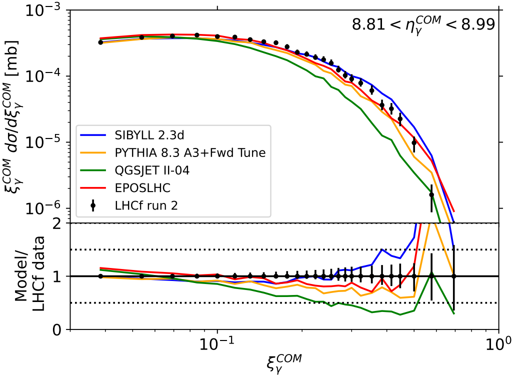
- Pythia 8: Using forward tune (based on other LHCf measurements than this one)



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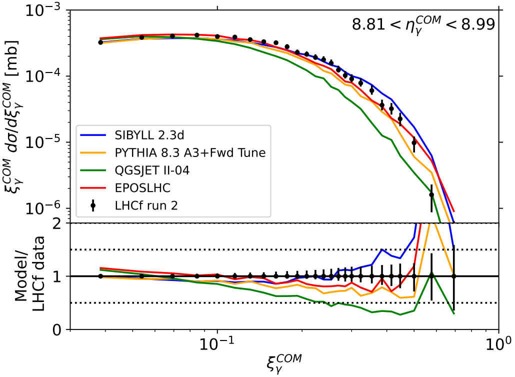
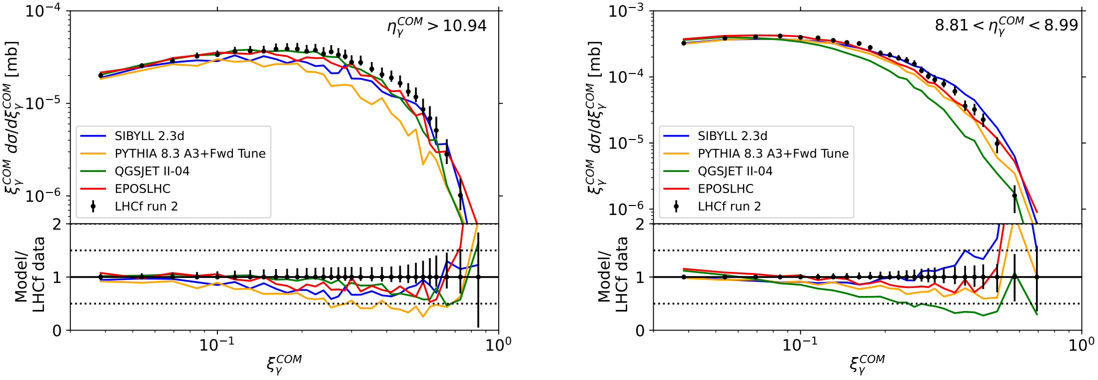
- Pythia 8: Using forward tune (based on other LHCf measurements than this one)
- Model discrepancies especially large at high energies



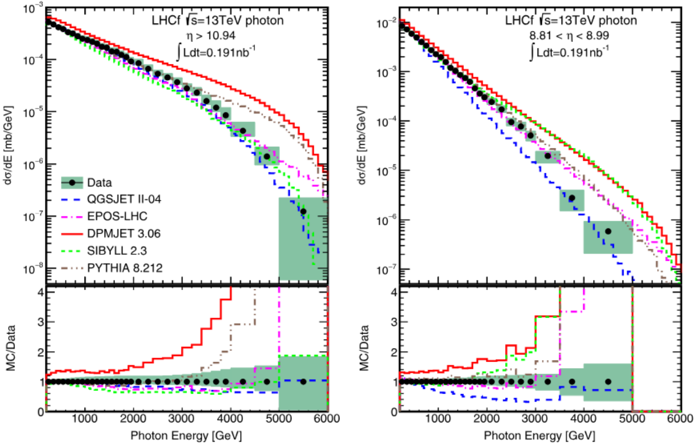
# LHCf Analyses

Data from Phys. Let. B 780 (2018)

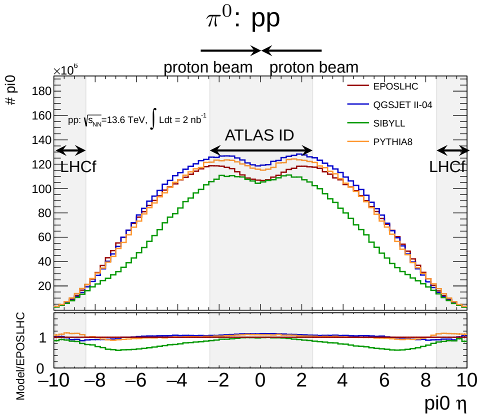


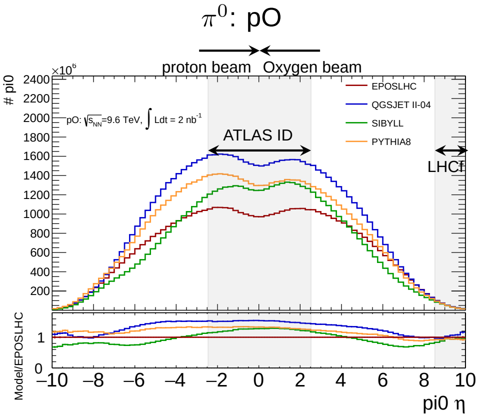
# LHCf Analyses

Plots from Phys. Let. B 780 (2018)



# Generator Predictions for pO



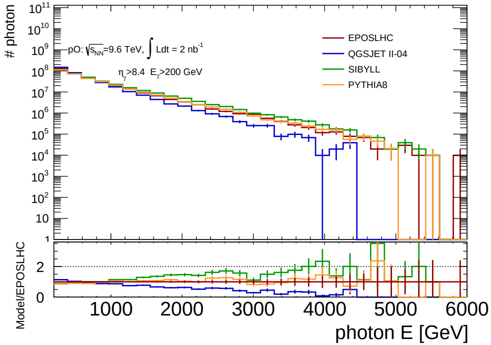




→ models show similar behaviour in central region (have been tuned there)

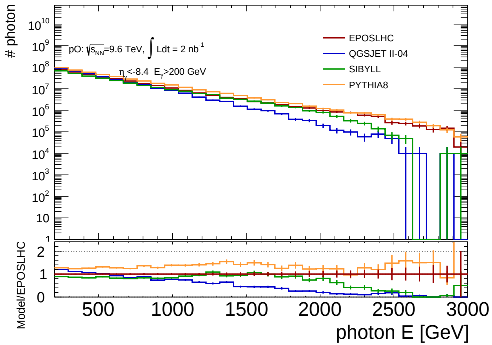
→ Huge differences between models in the entire $\eta$-spectrum

# Generator Predictions for pO

Proton remnant side:




Oxygen remnant side:




- Large disagreements between generators, especially at high photon energies
- Differences on both sides (→ data should be taken on both sides!)