Future LHC Measurements for Cosmic Ray Induced Air Shower Modelling

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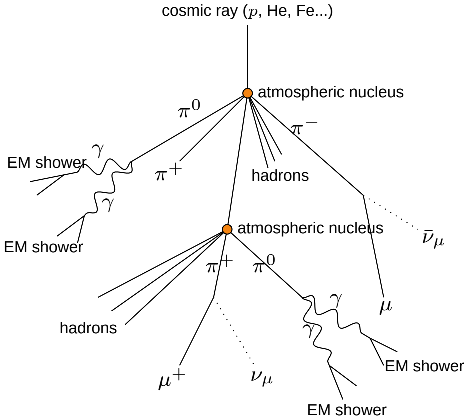
What I will cover...

- 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



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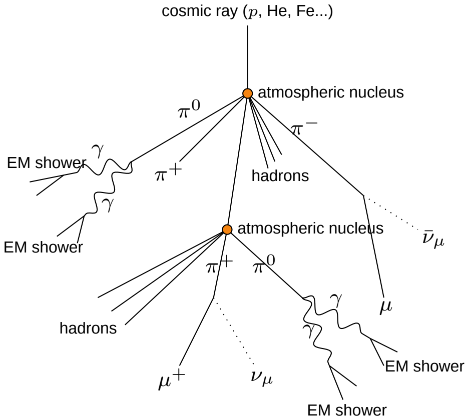
- Non-perturbative $\rightarrow$ phenomenological models



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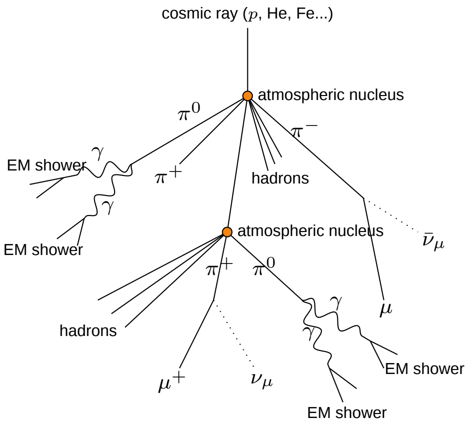

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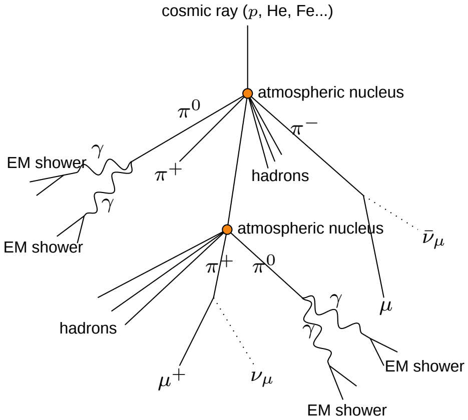

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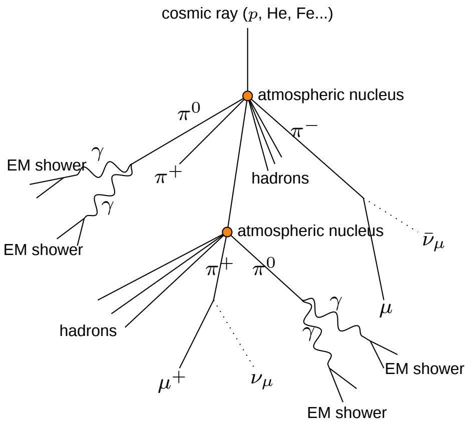
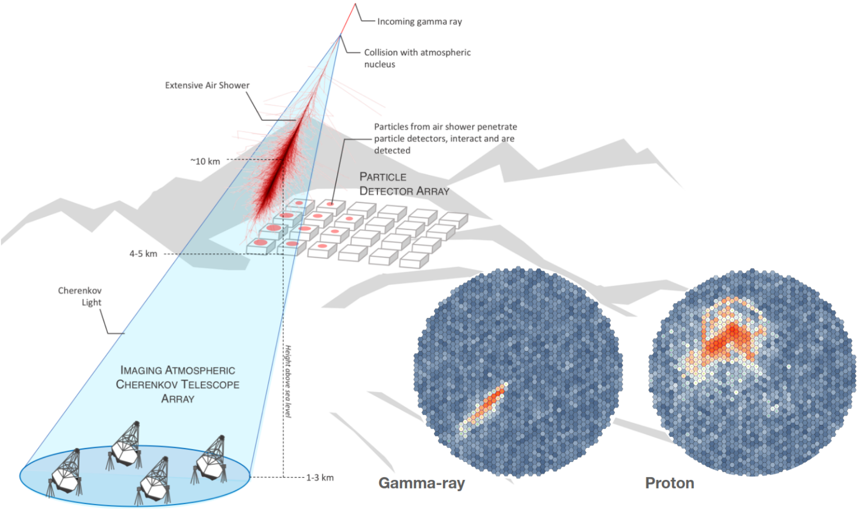


$\rightarrow$ **Tuning based on accelerator data**

$\rightarrow$ **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 γ-cuts ($\sim$ 99% rejection)

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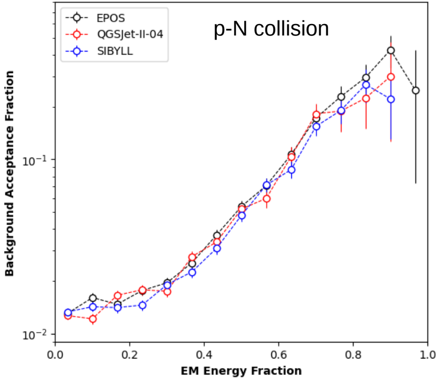

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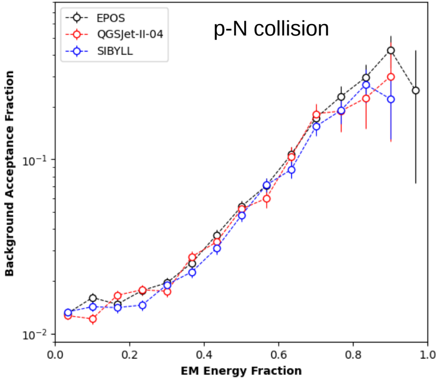

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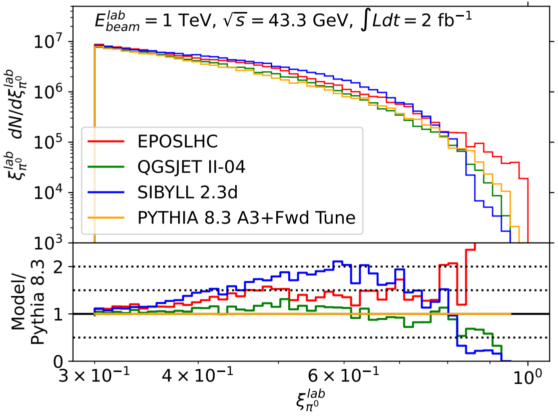
- Problem: Large uncertainties for this kind of showers!

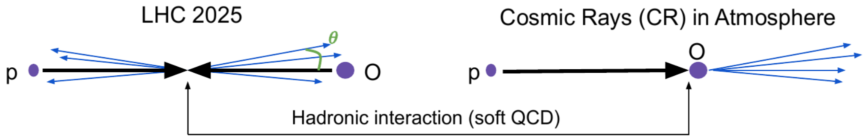
Event Generator Predictions

High-Energy π^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
- $\sim 100\%$ event generator differences in predicted π^0 energy fraction at very high energies!



Transfer: EAS vs. LHC Case



	LHC	CR-EAS with IACTs
collision	central	fixed target
typical $\sqrt{s}$	~ 13000 GeV	~ 40 GeV
particles	$p \leftrightarrow p$ $p \leftrightarrow O^{16}$ (2025!) $p \leftrightarrow Pb^{208}$	$p \rightarrow N^{14}$ $p \rightarrow O^{16}$

Transfer: EAS vs. LHC Case

Maximal Case

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

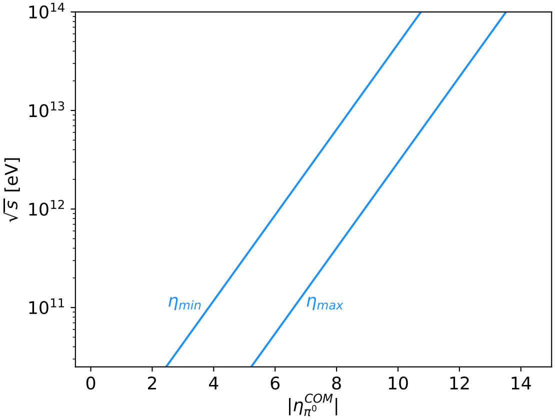
$$\eta_{\text{max}} \approx \ln\left(\frac{\sqrt{s}}{m_\pi}\right)$$

Minimal Case

π^0 inherits 70% of the beam energy:

$$\eta_{\text{min}} \approx \ln\left(\frac{0.7\,\sqrt{s}}{\sqrt{m_\pi^2 + p_{\text{T},\pi}^2}}\right)$$

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



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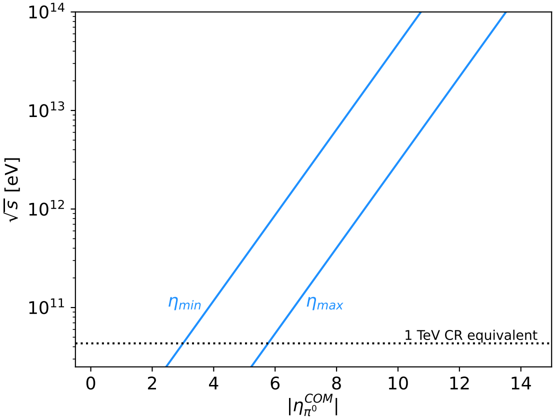

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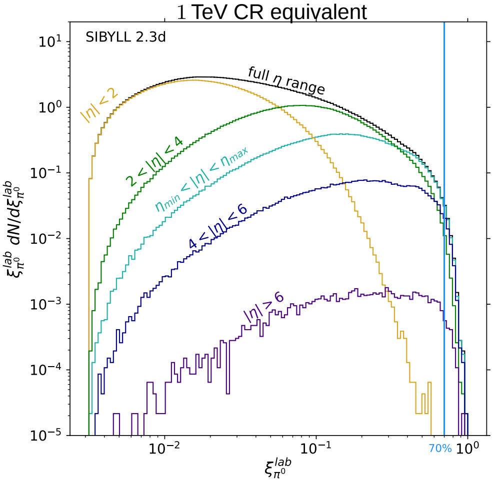

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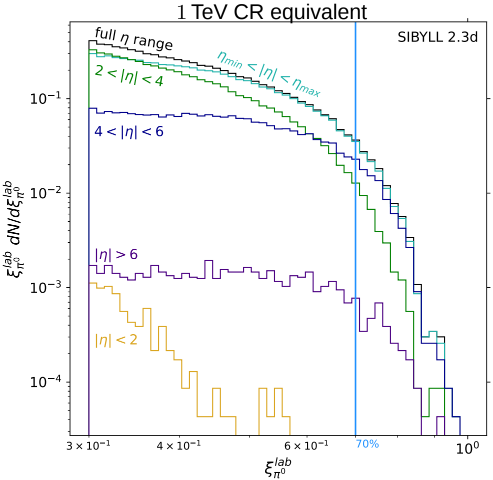

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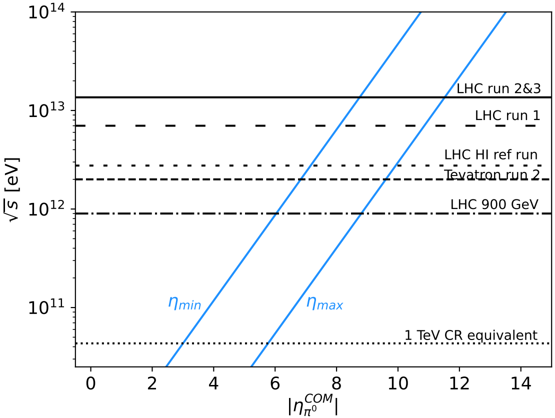
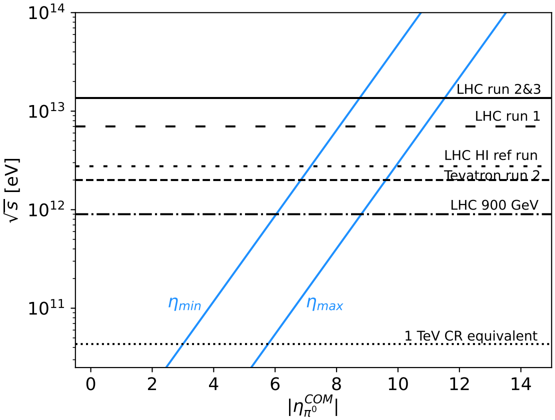


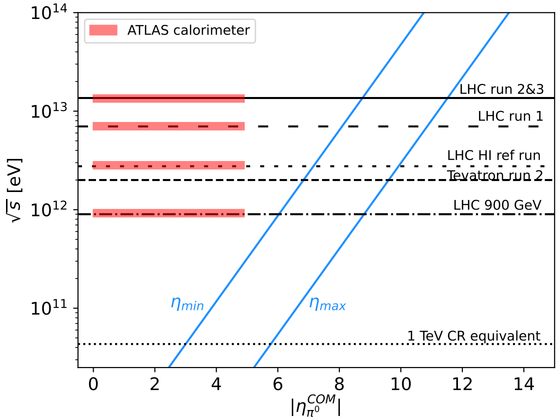
Experiments in Relevant η-Range



Experiments in Relevant η-Range

ATLAS

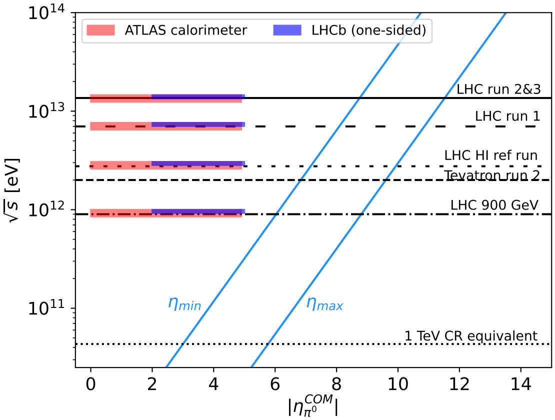
- Inner tracking detector: $|\eta| < 2.5$
- Calorimeters: $|\eta| < 4.9$
- Very similar coverage for CMS detector



Experiments in Relevant η-Range

LHCb

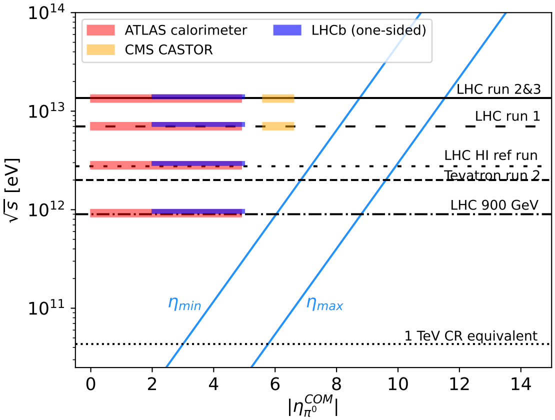
- Single arm forward detector
- Coverage: $2 < \eta < 5$



Experiments in Relevant η-Range

CMS CASTOR

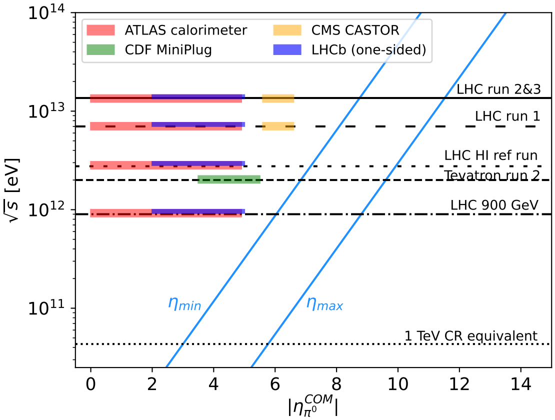
- One-sided Cherenkov calorimeter
- Coverage $-6.6 < \eta < -5.2$



Experiments in Relevant η-Range

CDF Miniplug

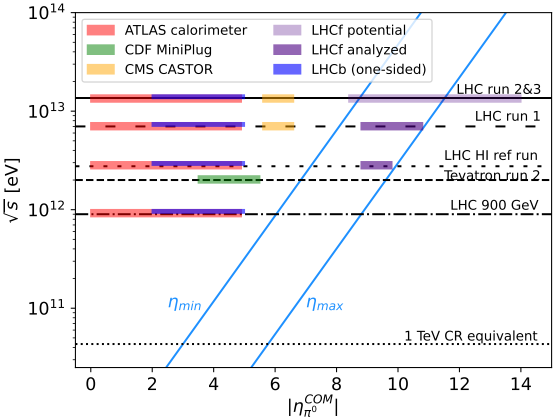
- Operated in Tevatron $p\bar{p}$ collisions at 1.96 TeV
- Coverage: $3.6 < |\eta| < 5.1$



Experiments in Relevant η-Range

LHCf Detector

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



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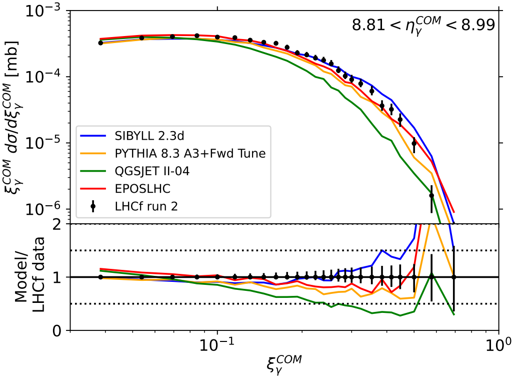

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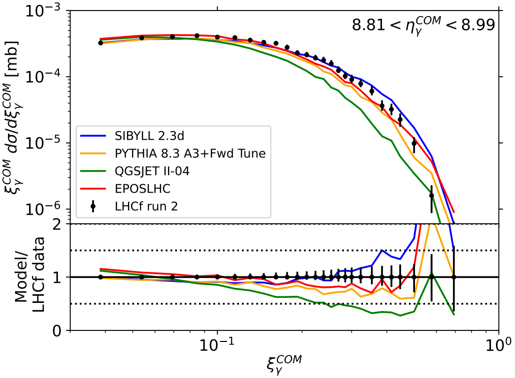

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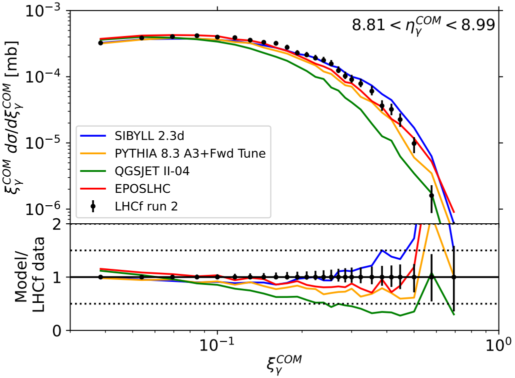
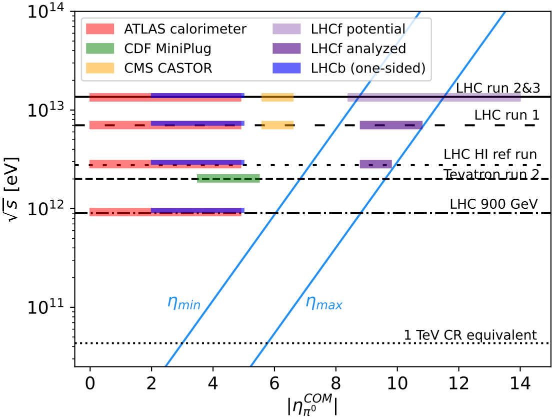


"Whish List" for Future Analyses



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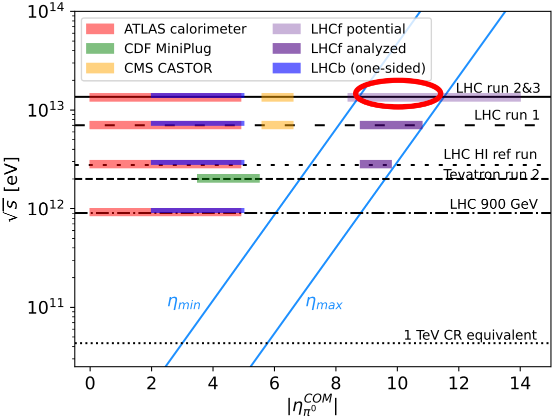

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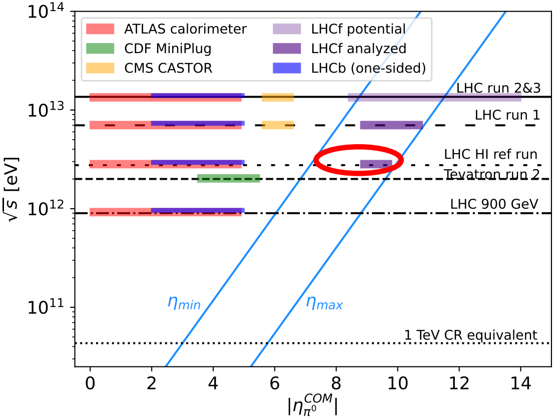

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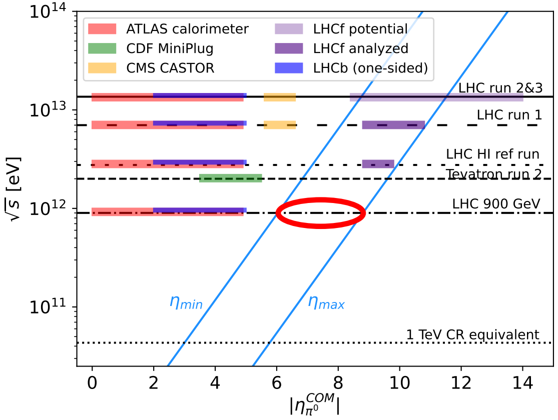

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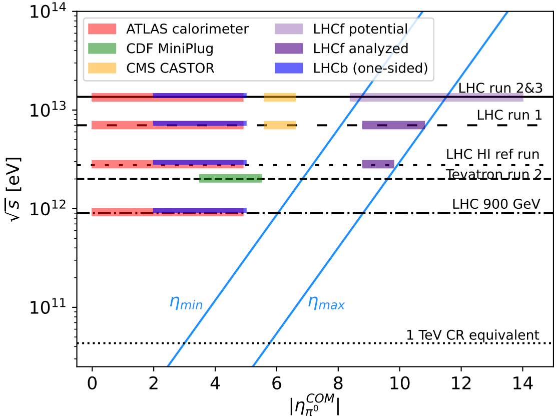
(LHCf + ATLAS-ZDC on p-remnant side)



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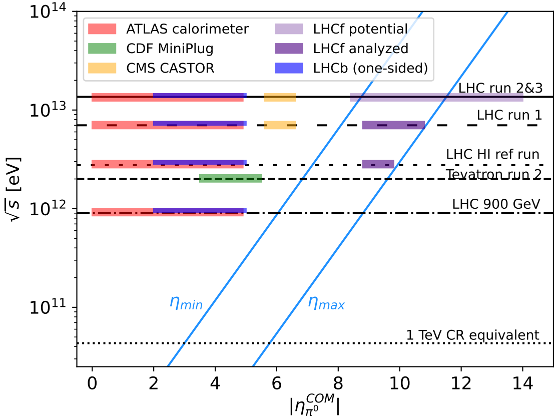

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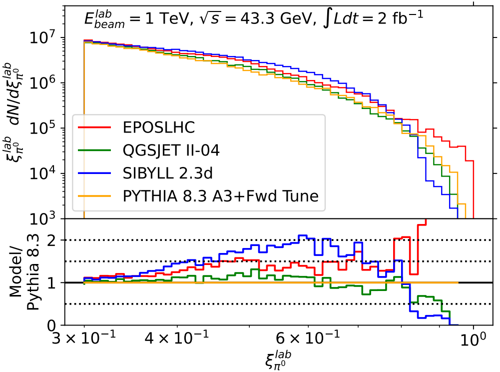
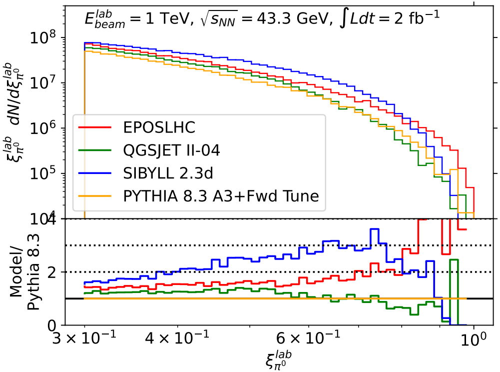
Remark: LHCf discontinued after Run 3!

Generator Predicitons for Proton-Oxygen

1 TeV p $\longrightarrow$ resting p:

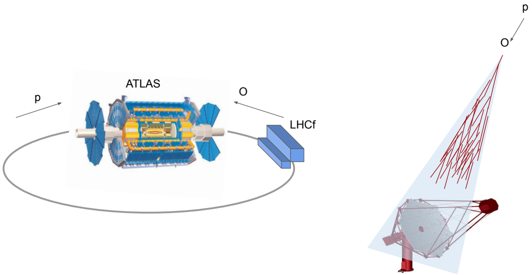


1 TeV p $\longrightarrow$ resting O^{16}:



$\Rightarrow$ Even bigger discrepancies in pO!

Conclusion



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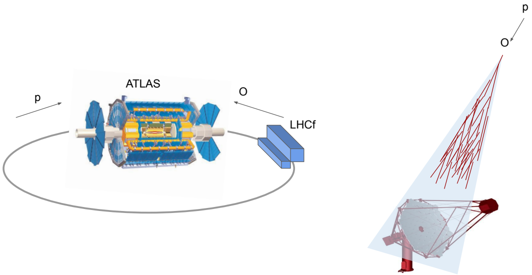

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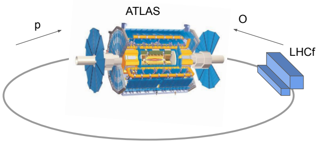

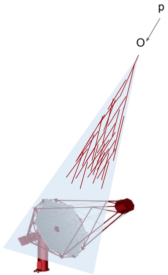

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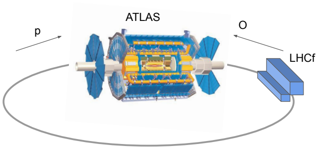

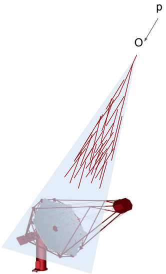

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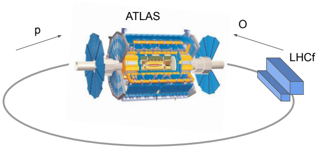

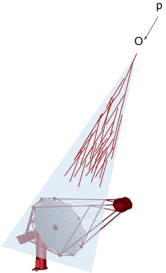

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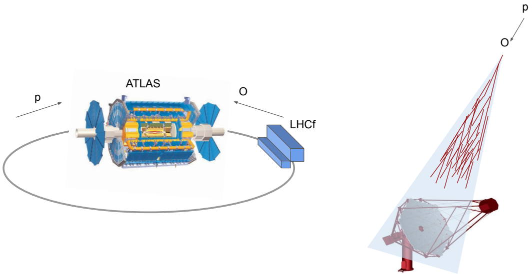

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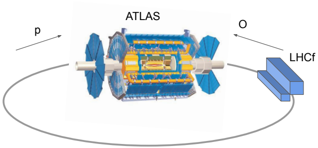
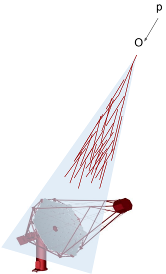
$\rightarrow$ Need π^0 energy spectra for high η bins at different $\sqrt{s}$!

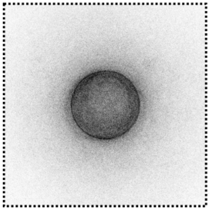


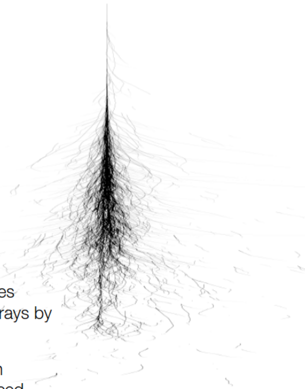


Backup

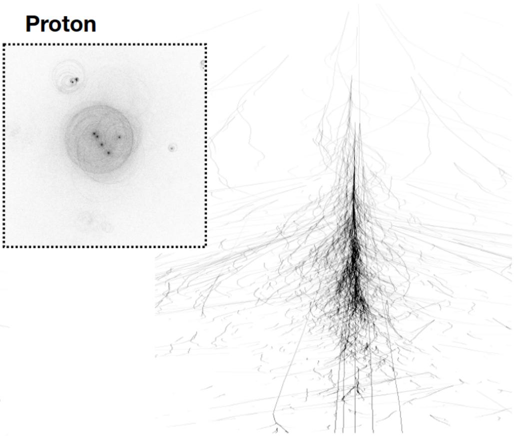
Backgrounds for Cosmic Gamma Rays with IACTs

Gamma-ray





Proton

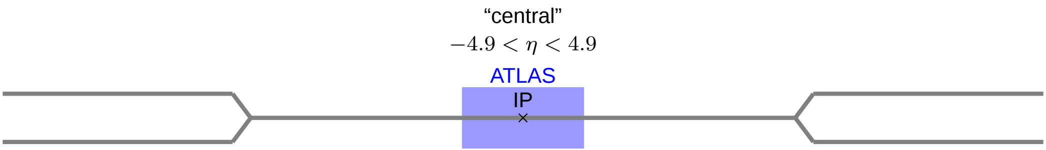


Even for the strongest sources protons outnumber gamma-rays by a factor 10^4

Obvious differences between proton and gamma-ray induced showers

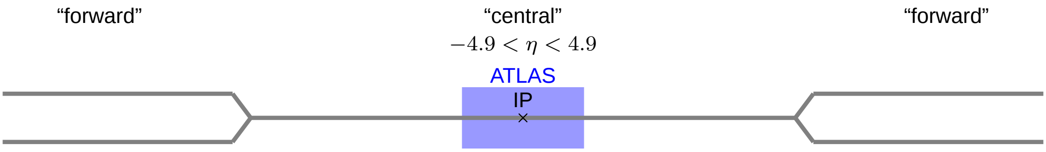
(c) Konrad Bernlöhr

Overview of Forward Experiments Near ATLAS IP



- Multi-purpose detector: ATLAS

Overview of Forward Experiments Near ATLAS IP



> Multi-purpose detector: ATLAS

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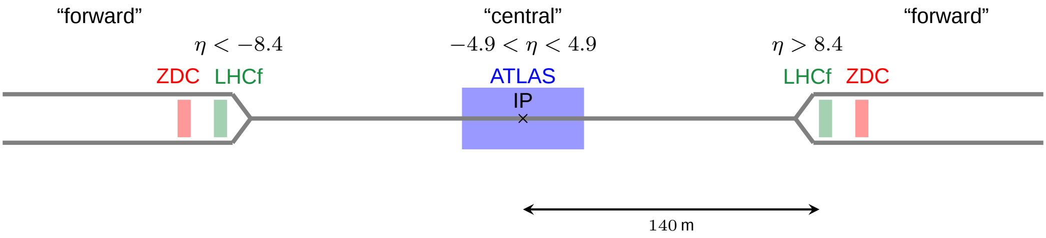
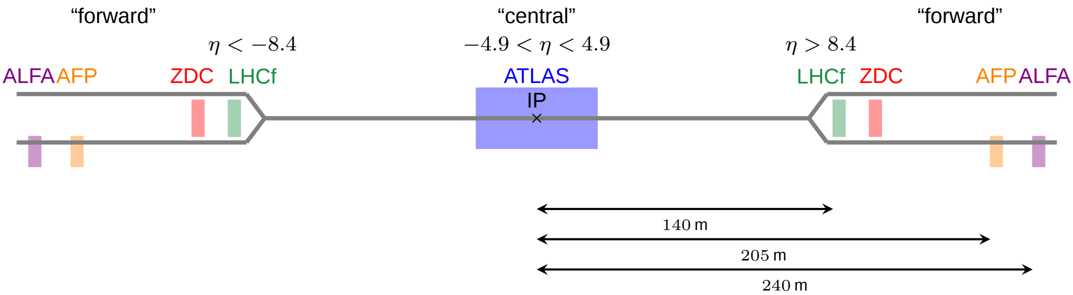


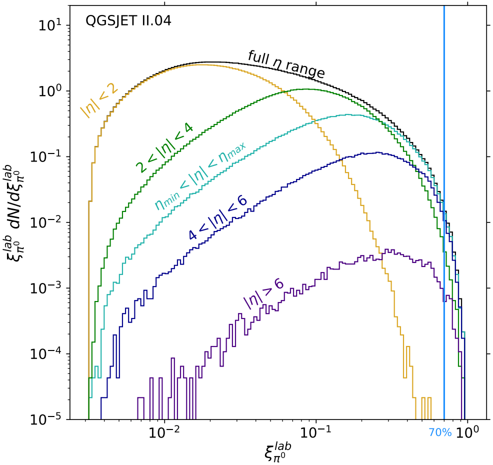
- Multi-purpose detector: ATLAS
- Forward neutral particle calorimeters: LHCf, ZDC

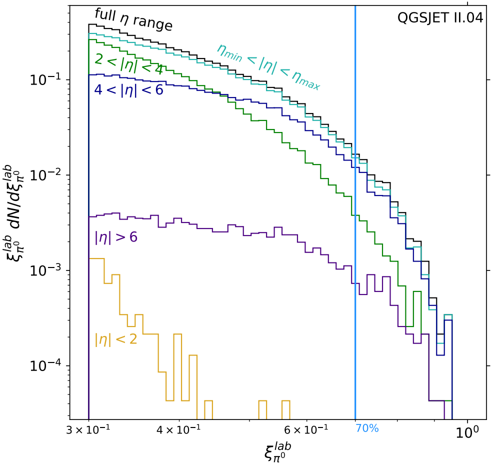
Overview of Forward Experiments Near ATLAS IP



- Multi-purpose detector: ATLAS
- Forward neutral particle calorimeters: LHCf, ZDC
- Forward proton detectors: AFP, ALFA

η-Range of Interest for 1 TeV CR collision equivalent in pp





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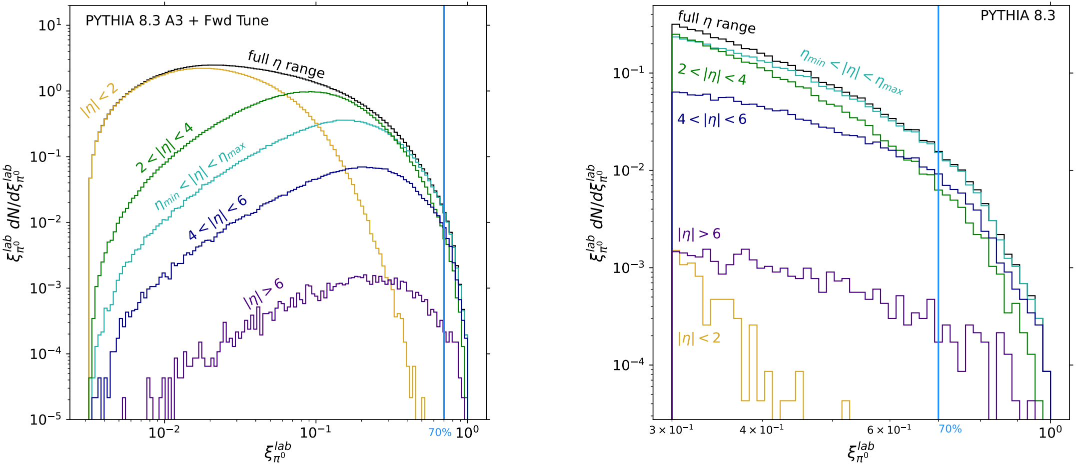

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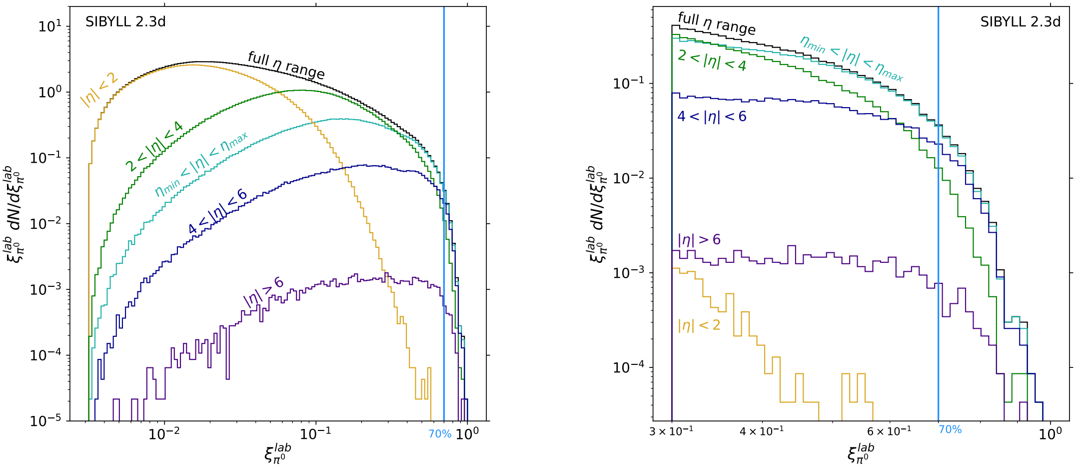

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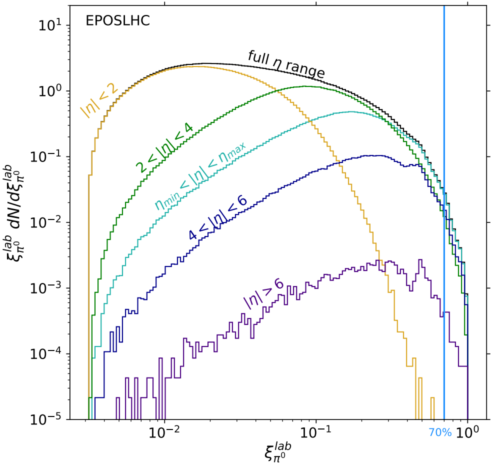
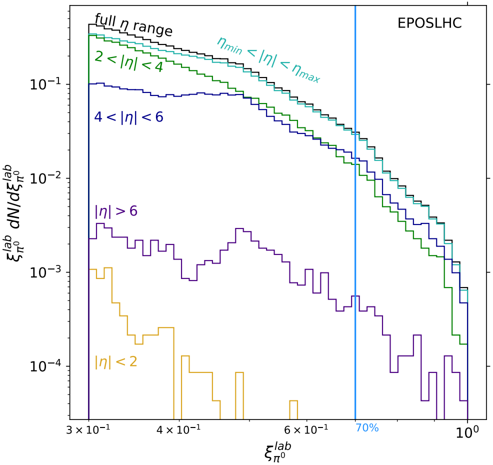
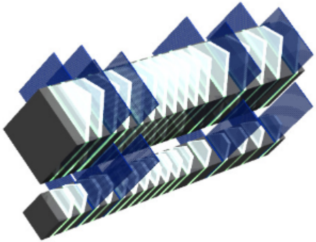


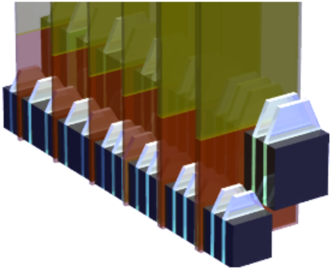


LHCf Detectors

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

LHCf Detectors

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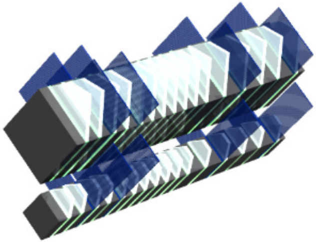
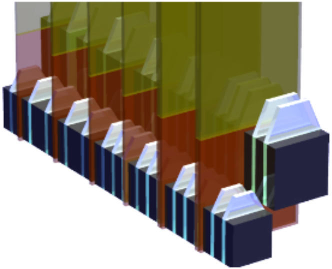


Arm 2



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- Different geometric orientations
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LHCf Detectors

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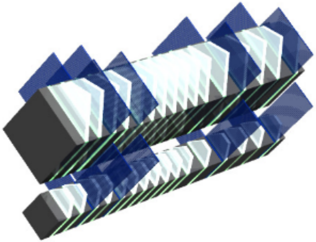
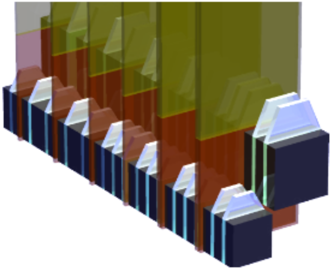


Arm 2



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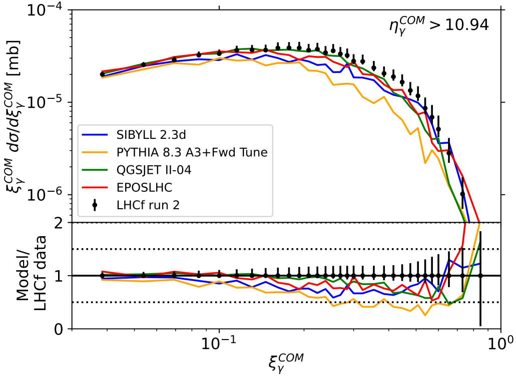
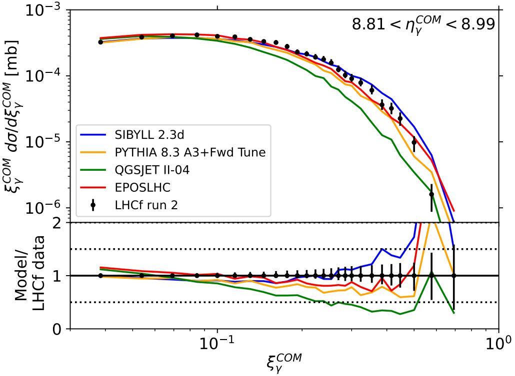
- Two calorimeter towers on each side of ATLAS
- Different geometric orientations
- Tungsten absorber, plastic scintillators + position sensitive layers per tower
- Only reached by neutral particles: n, γ, $\pi^0 \rightarrow \gamma\gamma$, $\eta^0 \rightarrow \gamma\gamma$...
- Energy resolution: $< 3\%$ (photons), $\sim 40\%$ (neutrons)

LHCf Analyses

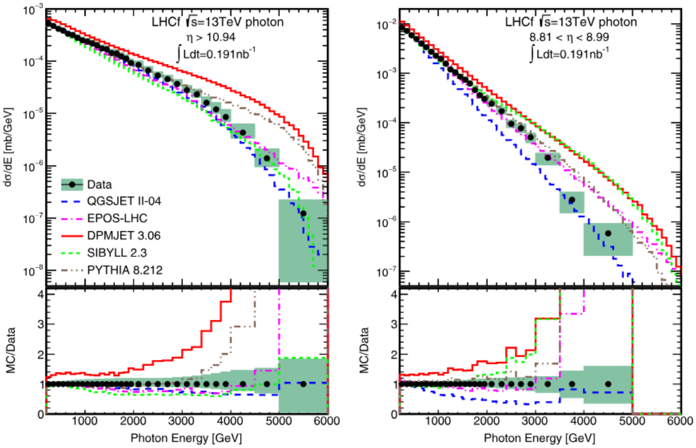
Data from Phys. Let. B 780 (2018)



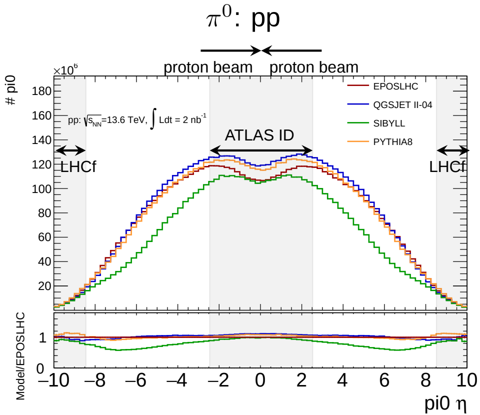


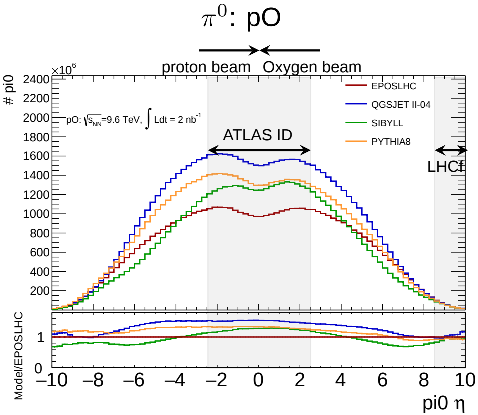
LHCf Analyses

Plots from Phys. Let. B 780 (2018)



Generator Predictions for pO



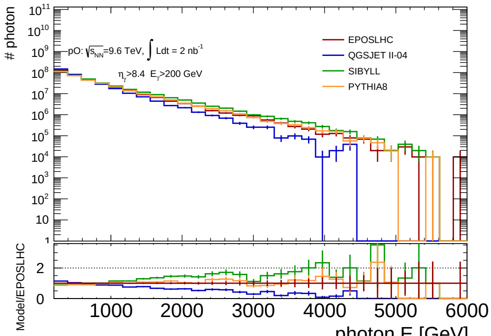


$\rightarrow$ models show similar behaviour in central region (have been tuned there)

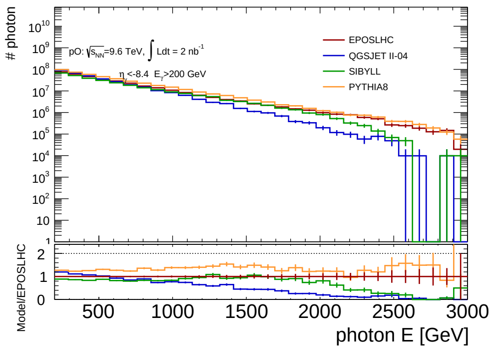
$\rightarrow$ Huge differences between models in the entire η-spectrum

Generator Predictions for pO

Proton remnant side:



Oxygen remnant side:



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

Cosmic Ray Spectrum