Forward Physics at the LHC

... and what we can learn from it

Clara Leitgeb

AP-PP Workshop 2025, DESY Zeuthen,
08.10.2025

HUMBOLDT-UNIVERSITÄT ZU BERLIN

What I will cover...

Forward detectors at the LHC

↓

Soft QCD in the forward region

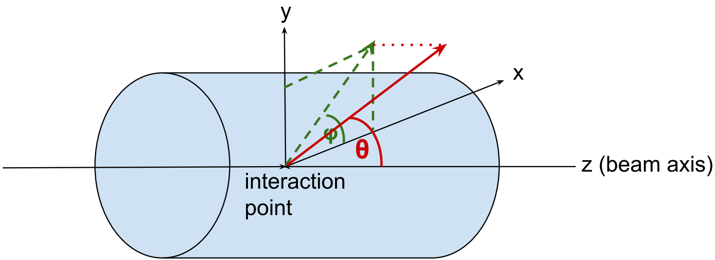
↓

Connection to cosmic ray physics

↓

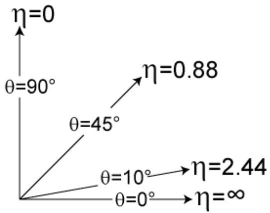
Highlight: Proton-oxygen run

What does "forward" mean?



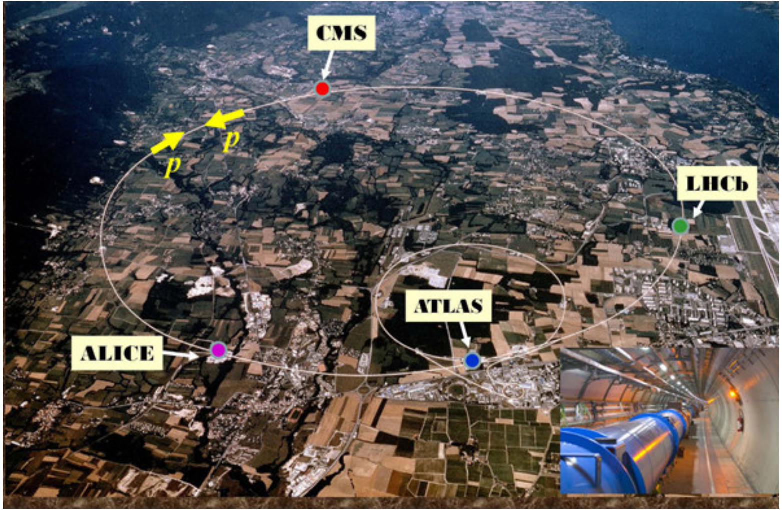
Pseudorapidity:

$$\eta = \ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

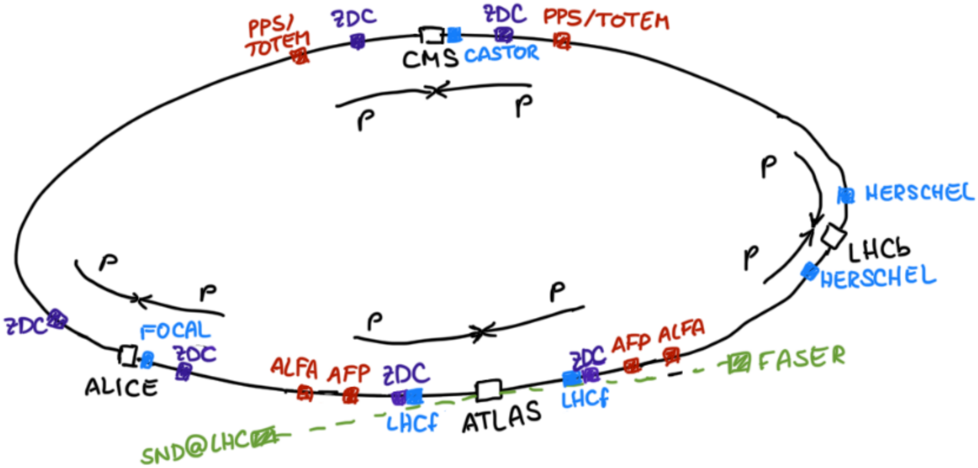


- "Central region": Around 0, e.g. $|\eta| < 2.5$
- "Forward region": Close to beam axis, at large positive or negative η, e.g. $|\eta| > 8$

The Large Hadron Collider: What you are usually shown...



The Large Hadron Collider: A (more) realistic picture



⟶ not exhaustive!

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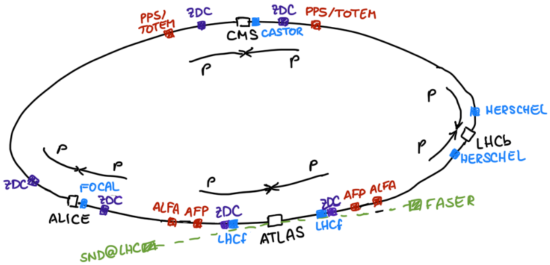
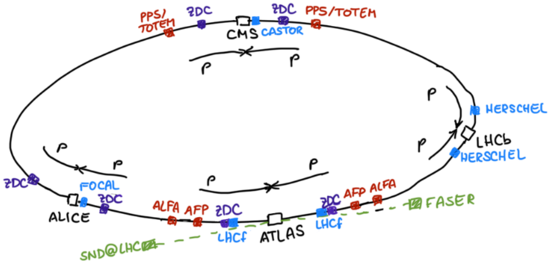


Central Detectors:

> Usually rapidity coverages of about $-2.5 < \eta < 2.5$ for tracking detectors

> Exception LHCb: $2 < \eta < 5$

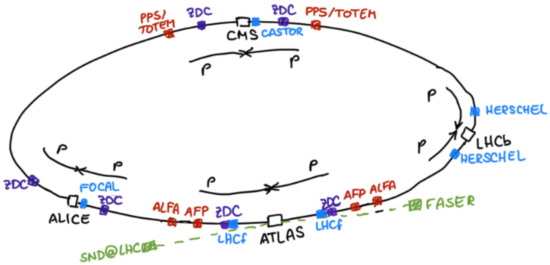
The Large Hadron Collider: A (more) realistic picture



Forward Proton Detectors:

- Measure trajectories of intact protons
- Protons with energy close to beam energy are transported along LHC beam line
- Use cases: Total cross section, diffractive cross sections, axion-like particles, τ g-2 etc.

The Large Hadron Collider: A (more) realistic picture



Forward Neutrino/LLP Detectors:

- Measure neutrinos and long lived neutral particles from interaction point
- Use cases: BSM LLPs, neutrinos from charm decays, LFU in neutrino sector etc.

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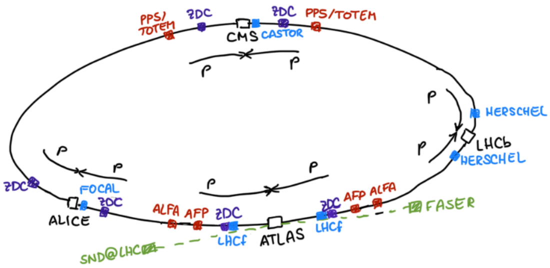
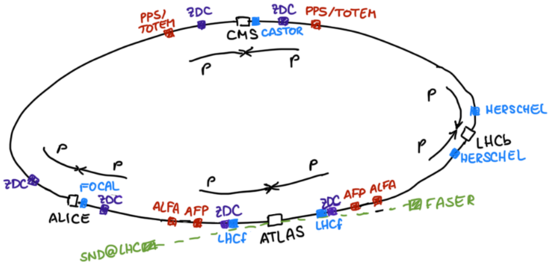


Zero Degree Calorimeters:

- Part of multiple experiments, located at beam pipe splitting
- Charged particles deflected by beam optics, only neutral particles reach ZDCs
- Number of forward neutrons as measure of collision centrality in heavy ion collisions

The Large Hadron Collider: A (more) realistic picture



Other forward detectos:

- Different physics purposes and technologies
- Example: LHCf experiment
  - Calorimeters ± 140 m from ATLAS
  - Detection of forward photons and neutrons
  - Reconstruction of forward neutral pions

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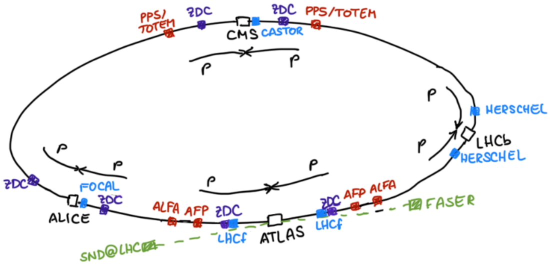

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- Example: LHCf experiment
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Rich variety of physics cases to be probed in the forward region!
$\rightarrow$ Focus of this talk: "Soft QCD"

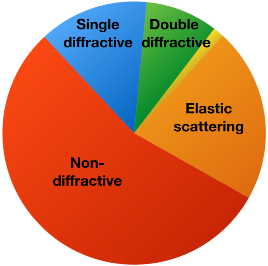
Soft QCD = small momentum transfer scattering

Why should we care?

Soft QCD = small momentum transfer scattering

Why should we care?

- Dominates LHC cross section
- Non-perturbative QCD regime, poorly modelled



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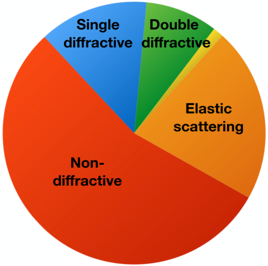

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What can we measure?

- Total cross section, elastic cross section

Soft QCD = small momentum transfer scattering

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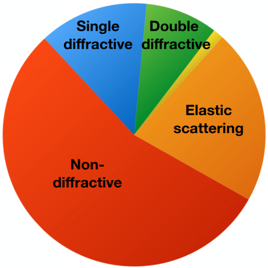
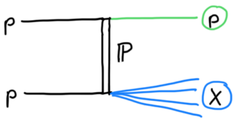
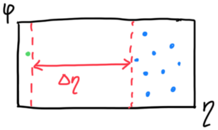
What can we measure?

> Total cross section, elastic cross section
> Diffractive cross sections, rapidity gaps
> Forward particle energy spectra
> Central-forward correlations
> ...







ATLAS+LHCf: Diffractive dissociation

ATLAS-CONF-2017-075

Event Selection:

> γ candidate inside LHCf
  - $\rightarrow$ $E(\gamma) > 200$ GeV
  - $\rightarrow$ Region A: $8.81 < \eta(\gamma) < 8.99$
  - $\rightarrow$ Region B: $\eta(\gamma) > 10.94$

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- Track reconstruction in ATLAS:
  - $\rightarrow$ $|\eta(\text{track})| < 2.5$
  - $\rightarrow$ $p_T(\text{track}) > 100$ MeV
  - $\rightarrow$ Veto such tracks! (Rapidity gap)

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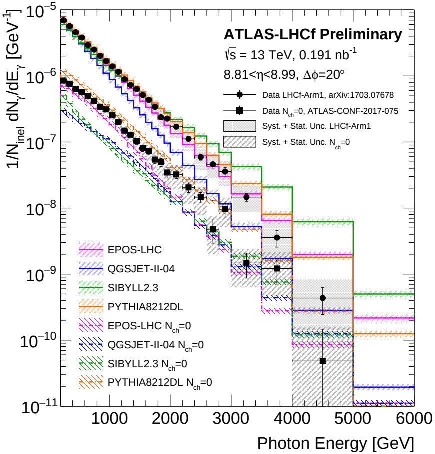

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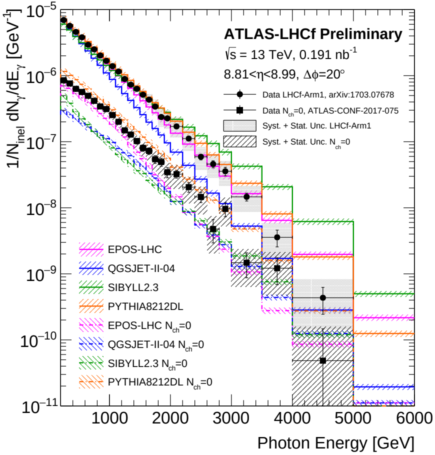
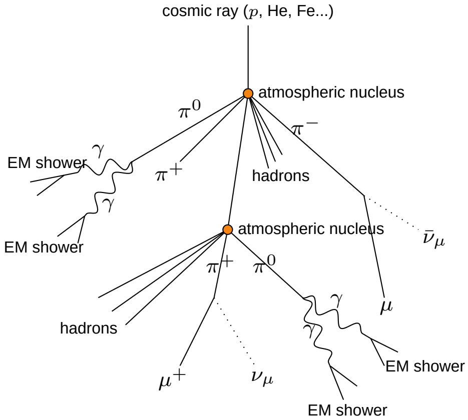
- Possible future direction: Measure intact proton in AFP! (ATL-PHYS-PUB-2023-024)



Relevance to astroparticle physics

- Hadronic interaction modeling $\rightarrow$ cosmic ray air shower reconstruction
  - Uncertainties on cosmic ray particle identification
  - Muon puzzle (high energies)
  - Background estimation for gamma-ray telescopes



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- Interdisciplinary group project of HU and DESY AP and PP groups
- Paper accepted by PRD

Probing the Cosmic Ray Background of Gamma-Ray Astronomy with Hadron Colliders

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Abstract

Hadronic cosmic particles (cosmic rays) and gamma rays are constantly absorbed in the Earth's atmosphere and result in air showers of secondary particles. Cherenkov radiation from these atmospheric events is used to measure cosmic gamma rays with ground-based telescopes. We focus here on the dominant hadronic cosmic-ray-initiated background events in the atmosphere, which give rise to gamma-ray like air showers for gamma-ray telescopes. It is shown that only a small subset of hadronic cosmic-ray interactions, those which produce a large energy neutral pion, are responsible for this background. We subsequently address how the predictions of this background vary depending on the hadronic interaction model adopted. The pseudorapidity range of the energetic pions, with respect to the shower axis produced in these background events, is shown to be large. We show that collider experiments, specifically LHCf and RHICf, probe cosmic ray interactions precisely within this pseudorapidity range. Present and future measurements with these instruments are shown to be able to test the ability for current hadronic interaction models to accurately describe these background events.

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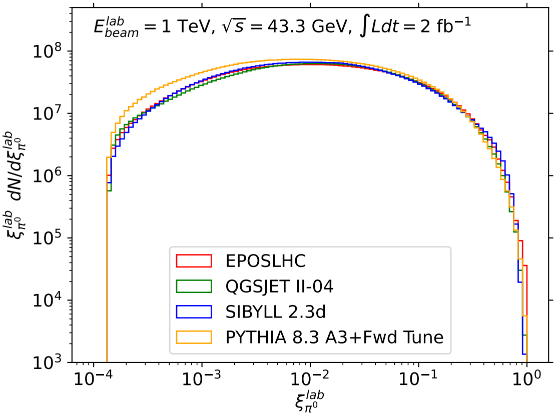
Event generator predictions

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



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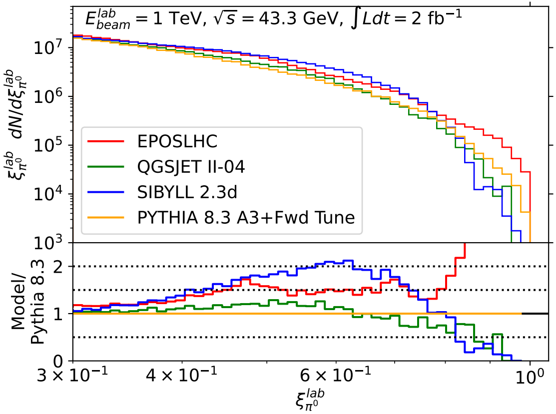
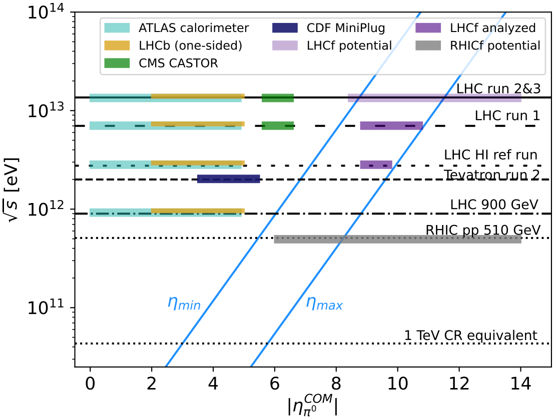
- $\sim 100\%$ event generator differences in predicted π^0 energy fraction at very high energies!



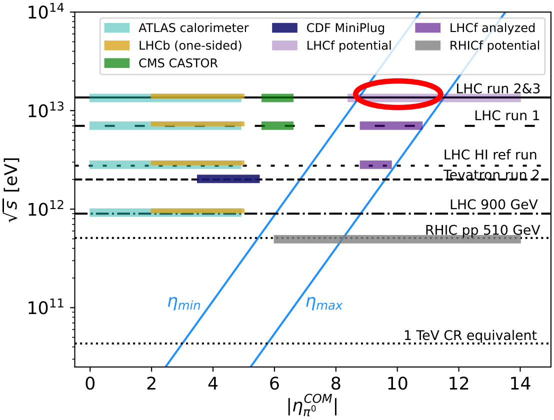
"Wish list" for future analyses



"Wish list" for future analyses

> LHCf run 2 and/or run 3 π^0 energy spectrum in bins of η

$\rightarrow$ Datasets available! :)



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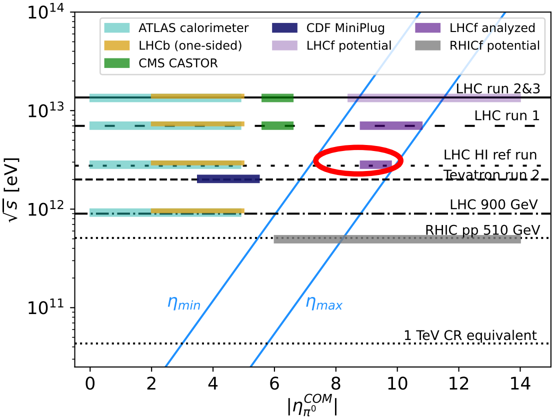
- LHCf HI ref run measurement of π^0 energy spectrum in bins of η (so far only p_T)



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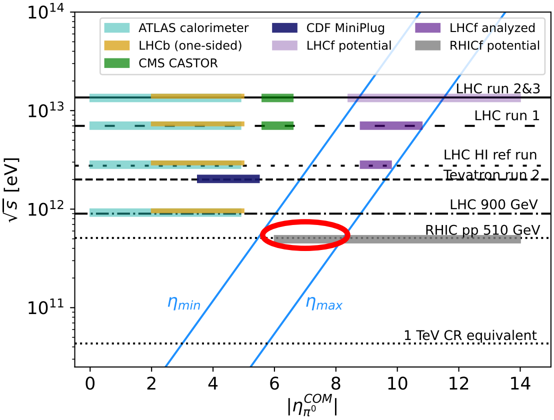

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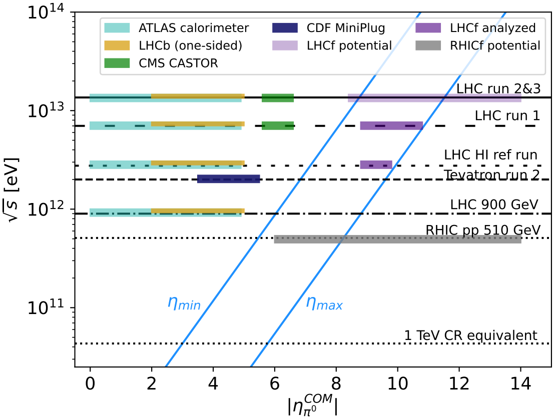
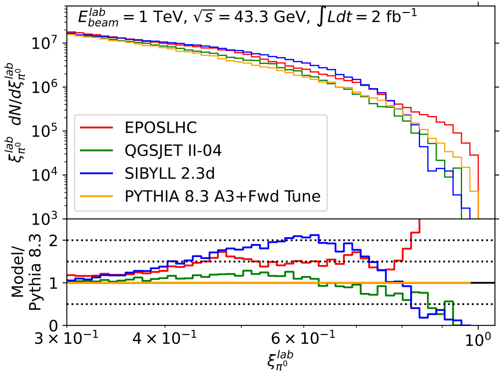
Proton-oxygen collision run at LHC!

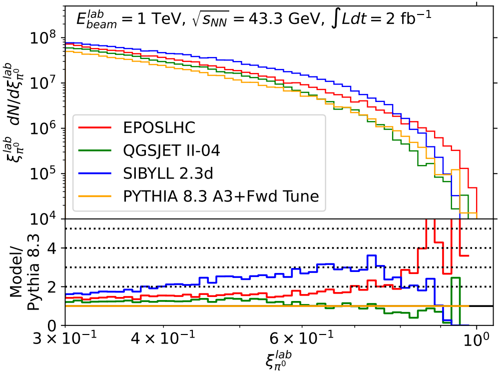


Generator predicitons for proton-oxygen

1 TeV p $\longrightarrow$ resting p:



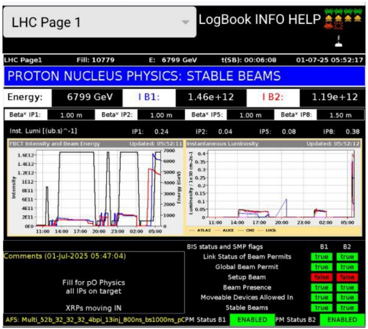
1 TeV p $\longrightarrow$ resting O^{16}:

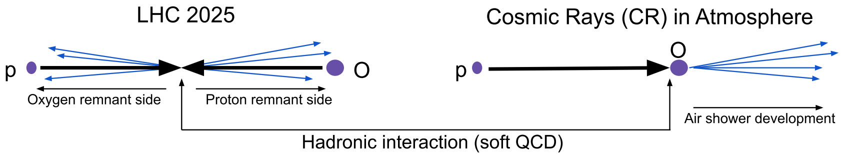


$\Rightarrow$ Even bigger discrepancies in pO!

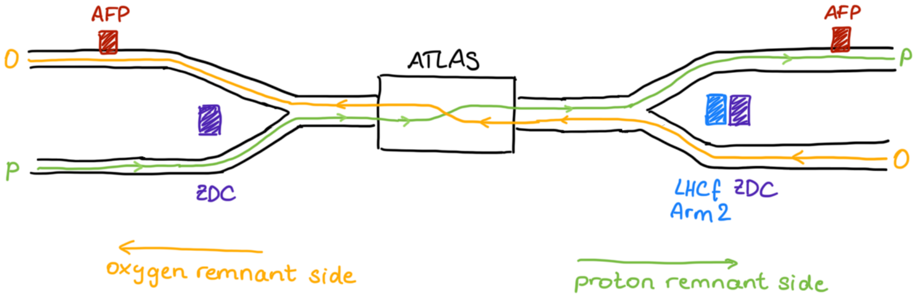
Light ions at the LHC

- LHC premiere: proton-oxygen, oxygen-oxygen, neon-neon collisions
- Special run period in July 2025
- Challenging run for LHC machine experts
- Smooth running → luminosity targets for all experiments surpassed!
- Proton-oxygen was long requested by AP community
- Recent LHC seminar





Proton-oxygen run at ATLAS



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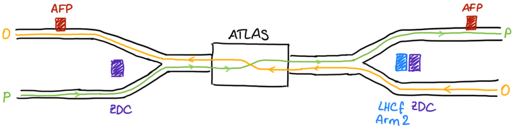
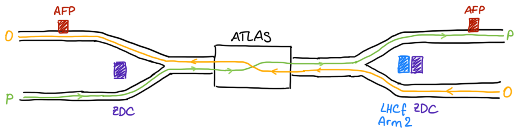


ATLAS:

- Central track analysis
- Combinations with forward detector data
- Important input for event generator tuning!

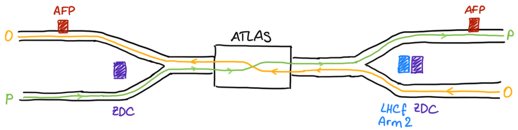
Proton-oxygen run at ATLAS



AFP:

- Installed on both proton- and oxygen-remnant side
- Forward proton spectra
- Forward oxygen-fragment reconstruction

Proton-oxygen run at ATLAS

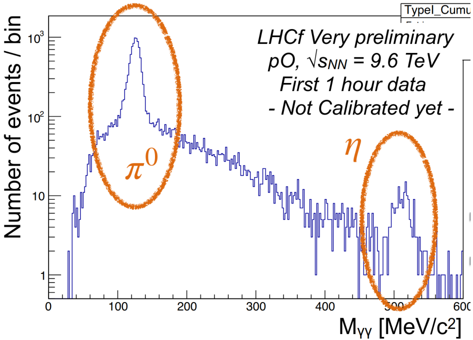


LHCf+ZDC:

- Covering forward region of proton-remnant side
- Oxygen-remnant side not possible (too high radiation)
- Forward photon and pion spectra
- Installed together with ZDC $\rightarrow$ improved neutron reconstruction

LHCf in proton-oxygen

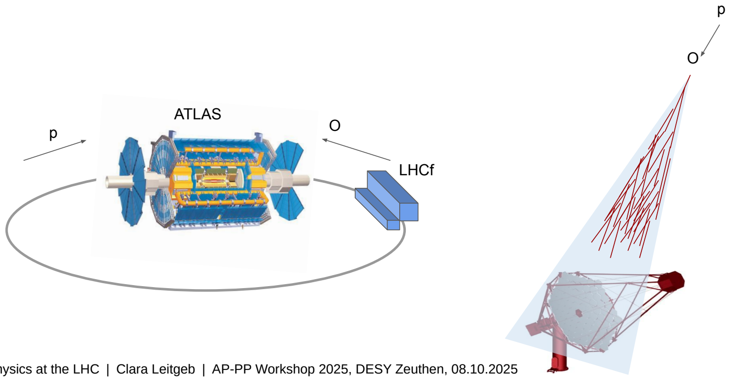
- Arm 2 detector installed with ZDC on proton remnant side
- Total of 73M events recorded by LHCf
- All LHCf triggers were accepted by ATLAS DAQ
- Clear peaks of π^0 and η visible, good statistics for analyses



M.Hiroaki's slides at ICRC

Conclusion

- Rich forward physics program at LHC
- Data in forward region important for hadronic interaction modelling
- Conncetion to cosmic ray induced air shower modelling
- Valuable data taken in proton-oxygen collisions at LHC in central and forward region



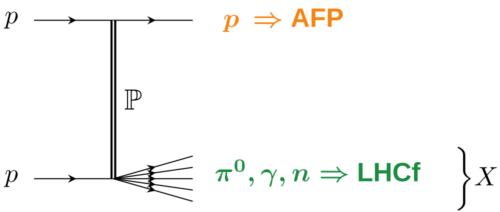
Backup

LHCf+AFP: Diffractive dissociation

ATL-PHYS-PUB-2023-024

Event Selection Strategy:

- $\geq 1\,\gamma$ or $= 1$ neutron in LHCf
- $E_{\gamma,n} > 200\,\text{GeV}$
- Proton in AFP (opposite side)



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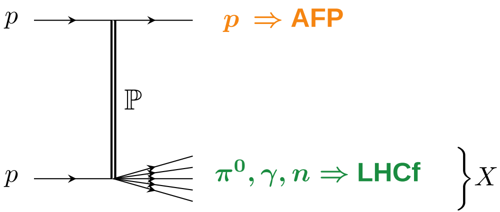

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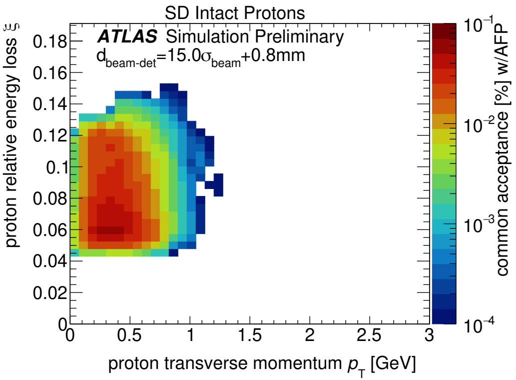
Advantages wrt single-detector analysis:

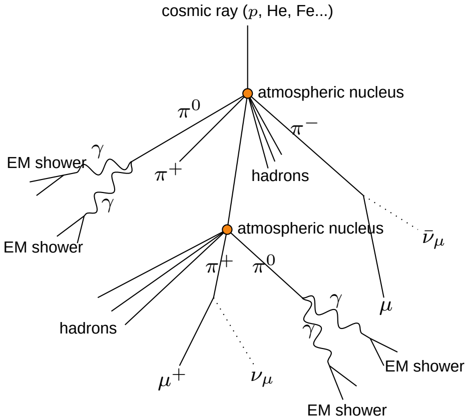
- Improved discrimination against other processes
- Better kinematic reconstruction



Motivation

Soft QCD in Air Showers

> Cosmic proton hits atmospheric nucleus
> $\rightarrow$ Particle shower



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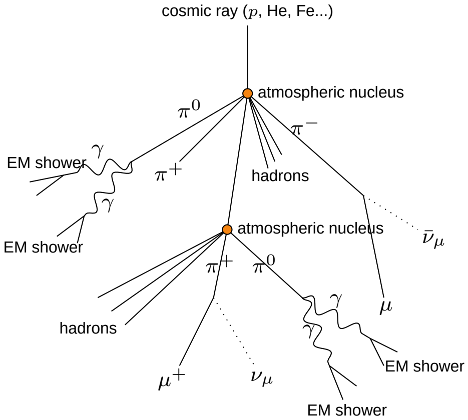
- Soft QCD: Hadronic interaction with low momentum transfer
- Non-perturbative $\rightarrow$ phenomenological models



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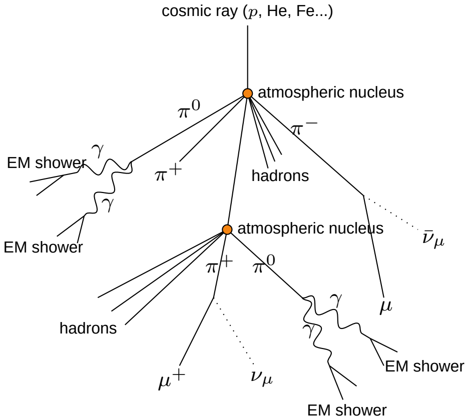
  - Position of shower maximum
  - Particle multiplicities



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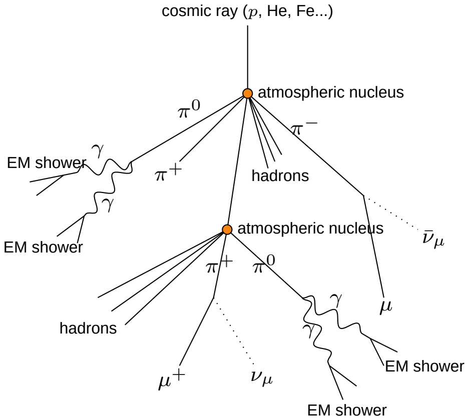
- Identification of initial cosmic particle:
  Large uncertainties



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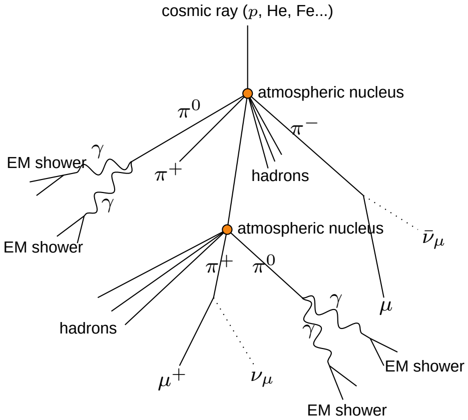
$\Rightarrow$ Tuning based on accelerator data



Backgrounds for cosmic gamma rays with Cherenkov telescopes

Proton Cosmic Ray 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)

Backgrounds for cosmic gamma rays with Cherenkov telescopes

Proton Cosmic Ray Rejection

- Problem for big and diffuse sources
  - $\rightarrow$ No side-band estimation possible
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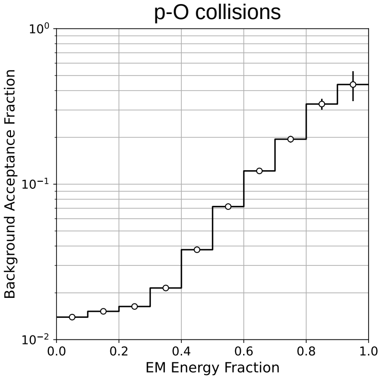

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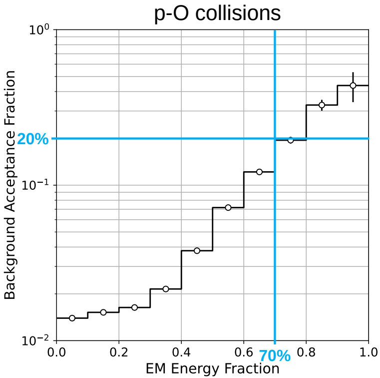

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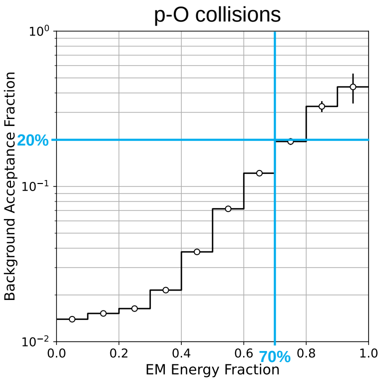

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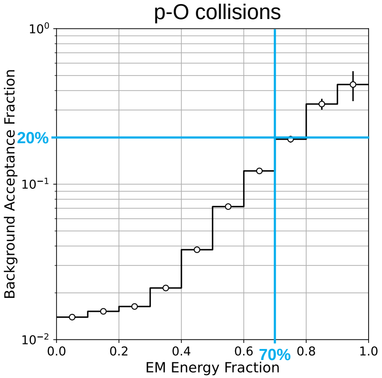
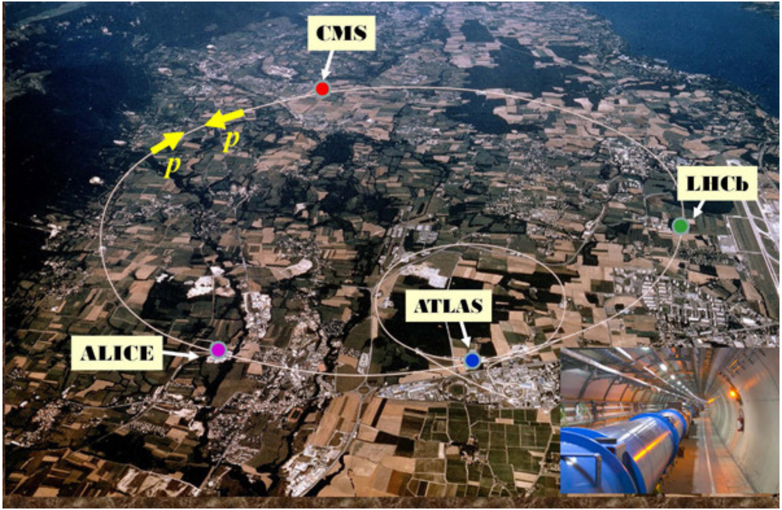


- But: Typically $\#p\,/\,\#\gamma \sim 10^3$ - 10^4!
- Source: Production of high energy $\pi^0 \rightarrow$ EM-shower development
- Problem: Large uncertainties for this kind of showers!

The Large Hadron Collider



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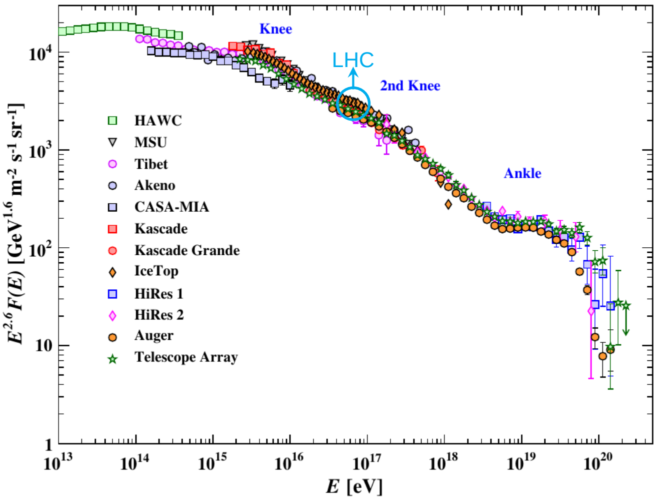
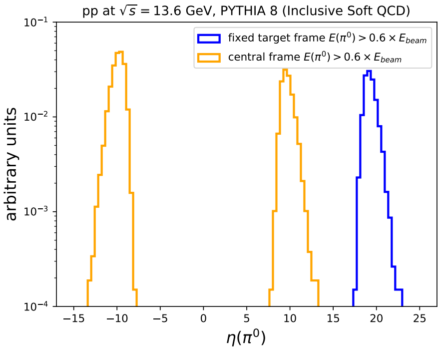


Motivation

Soft QCD at the LHC

> Low momentum transfer scattering

→ Particles in forward region



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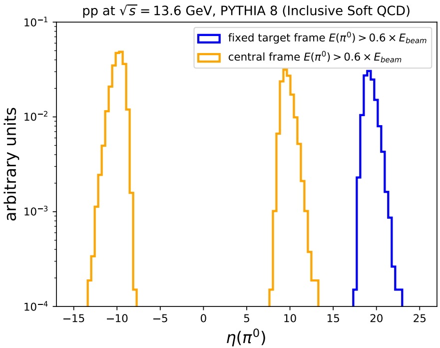
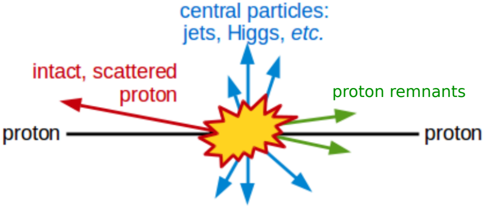
  - $\rightarrow$ Experiments at high $|\eta| = \left| -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)\right|$

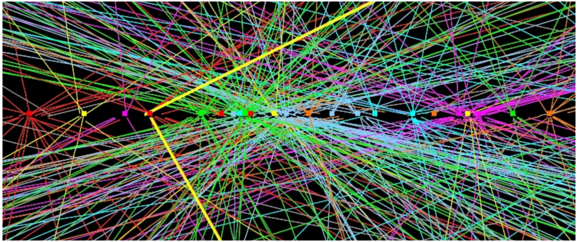


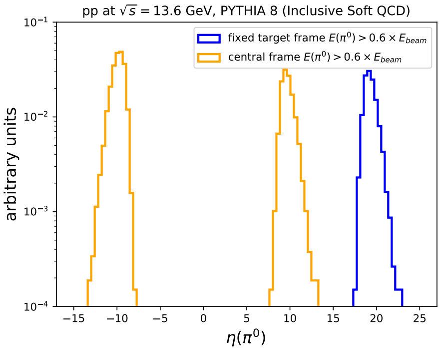


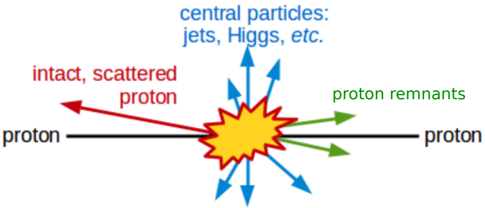
Motivation

Soft QCD at the LHC

- Low momentum transfer scattering
  - $\rightarrow$ Particles in forward region
  - $\rightarrow$ Experiments at high $|\eta| = \left| -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)\right|$
- Large fraction of the total pp cross section
- High relevance for pileup modelling
  (pileup = # of interactions per bunch crossing)







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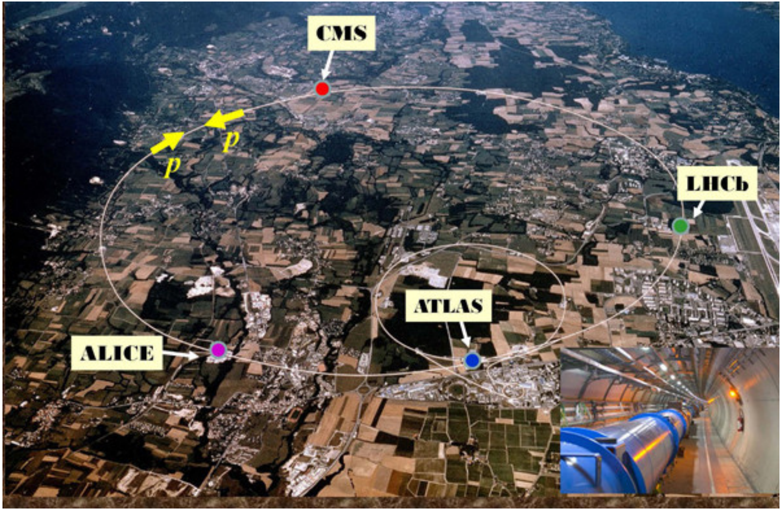

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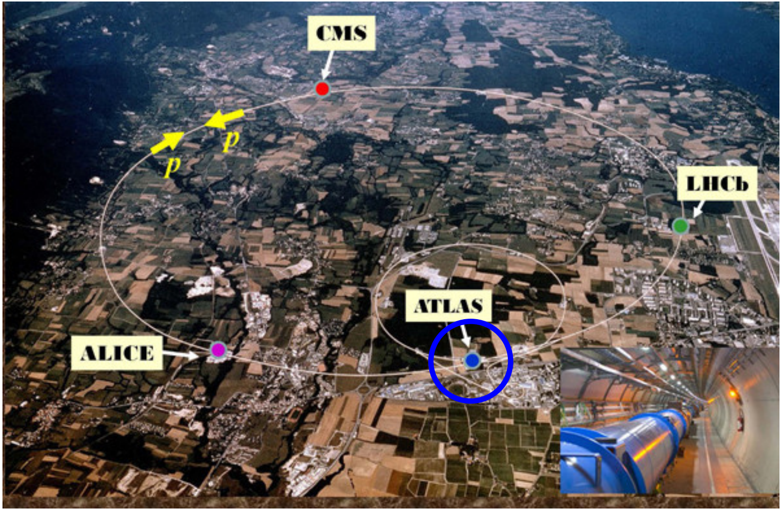
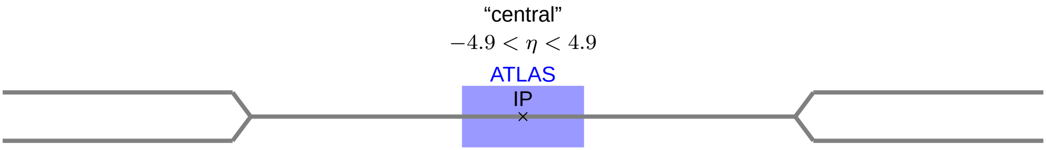


Overview of Forward Experiments



- Multi-purpose detector: ATLAS

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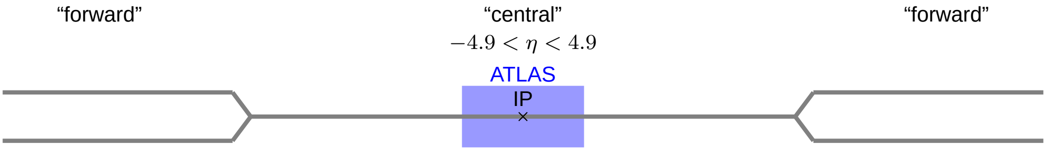

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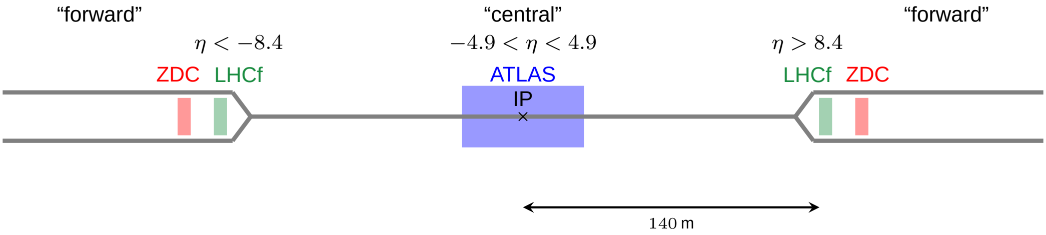

- Multi-purpose detector: ATLAS
- Calorimeters: LHCf, ZDC

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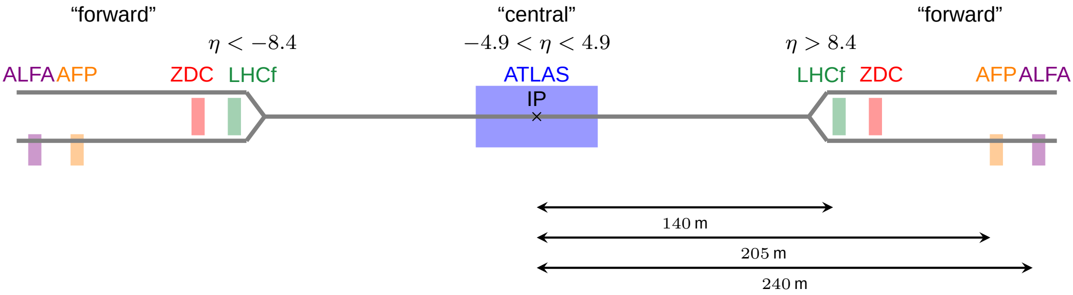
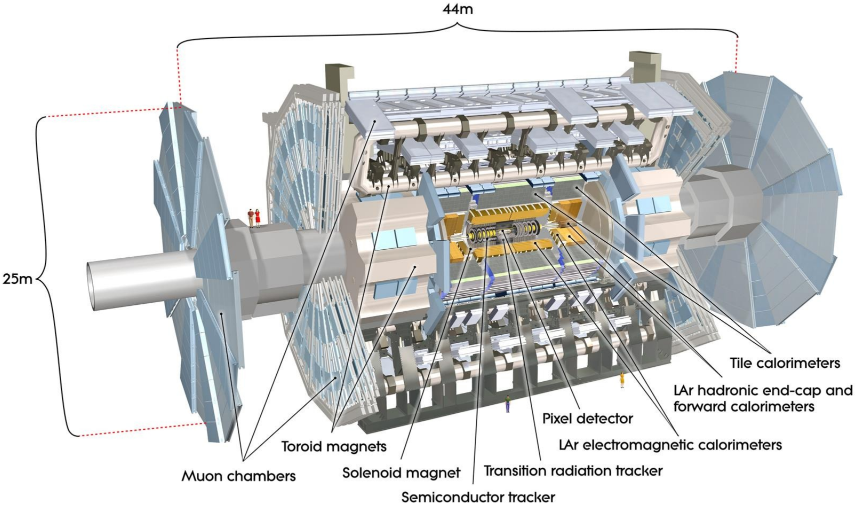


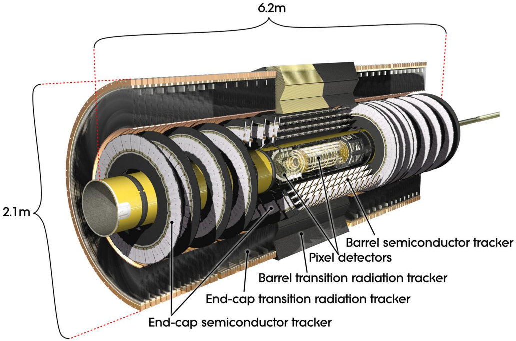
> Multi-purpose detector: ATLAS
> Calorimeters: LHCf, ZDC
> Proton detectors: AFP, ALFA

ATLAS Detector



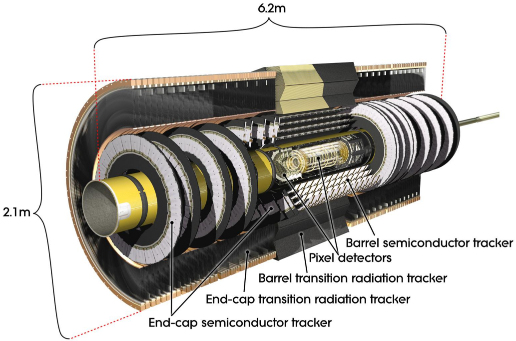
ATLAS: Inner Tracking Detector

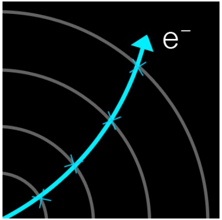
- Covers central rapidities ($|\eta| < 2.5$)
- Different sensor systems to detect charged particles
- Inside solenoid magnet



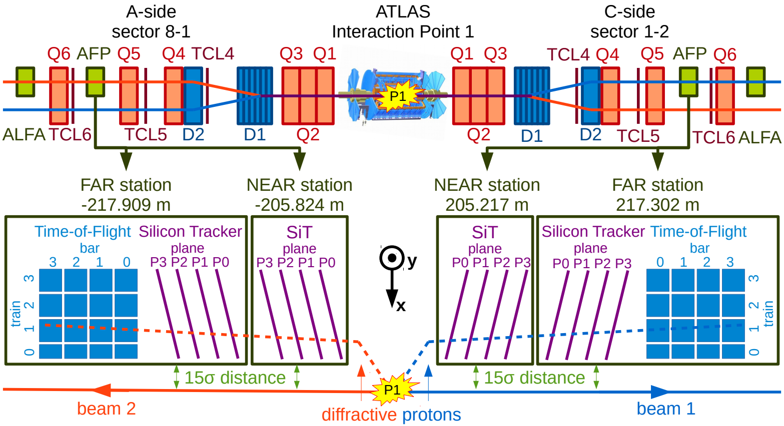
ATLAS: Inner Tracking Detector

- Covers central rapidities ($|\eta| < 2.5$)
- Different sensor systems to detect charged particles
- Inside solenoid magnet
- Reconstruct:
  - Hits $\Rightarrow$ tracks
  - Deflection in B-field
    $\Rightarrow$ charge, momentum
  - ≥ 2 tracks
    $\Rightarrow$ primary interaction vertex





AFP Detectors



> Goal: Reconstruct scattered proton trajectories close to the beam

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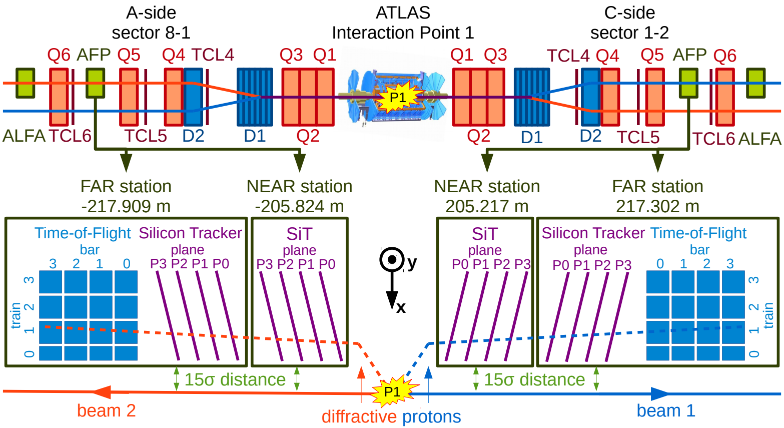
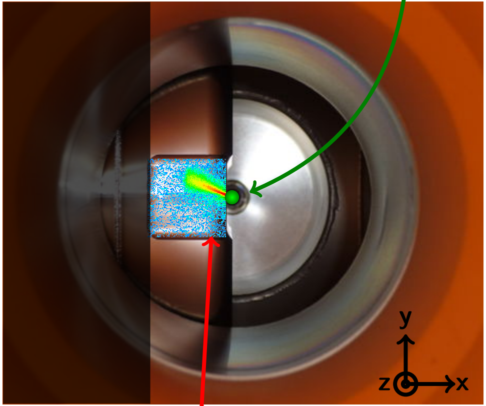


> Goal: Reconstruct scattered proton trajectories close to the beam

> Roman Pot stations can be inserted directly into the beam pipe

shadow of TCL4 and TCL5 collimators

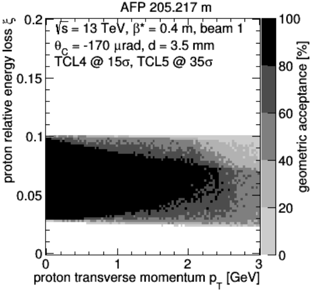
LHC beam



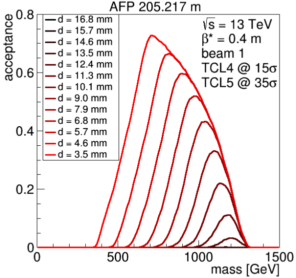
diffractive protons

thin window and floor (300 μm)

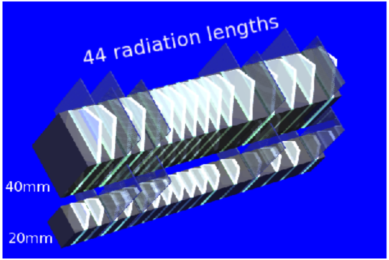
Geometric acceptance:

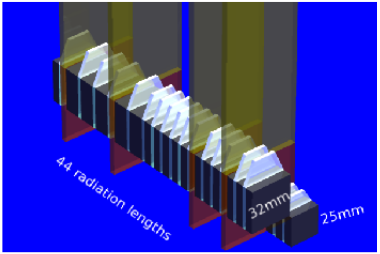


Mass acceptance:



LHCf Detectors





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

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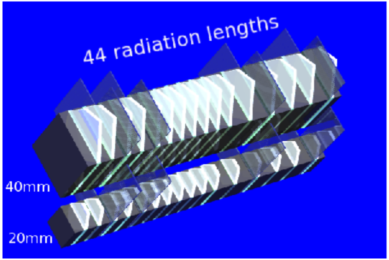

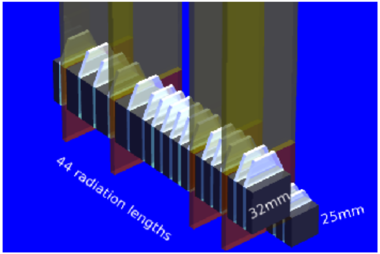

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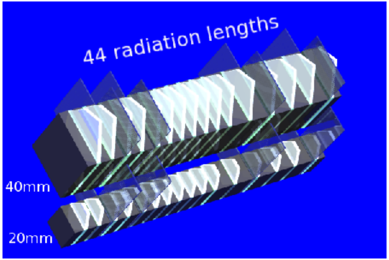

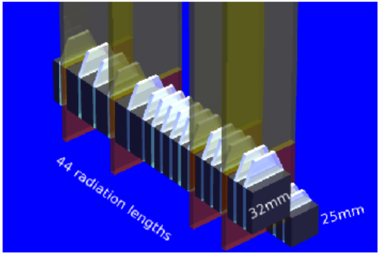

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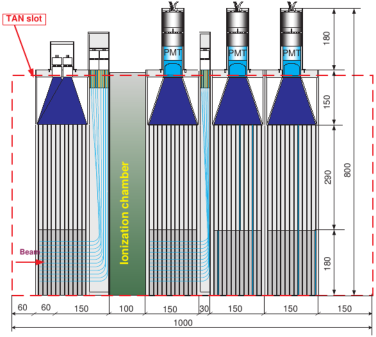
- Tungsten absorber, plastic scintillators + position sensitive layers per tower
- Only reached by neutral particles: n, γ, $\pi^0 \rightarrow \gamma\gamma$, $\eta^0 \rightarrow \gamma\gamma$...
- Energy resolution: < 3% (photons), ~ 40% (neutrons)

ATLAS ZDC Detectors



- Two calorimeter systems on each side of ATLAS
- Each consists of 1 EM module and 3 hadronic modules
- Usually operational during heavy ion runs

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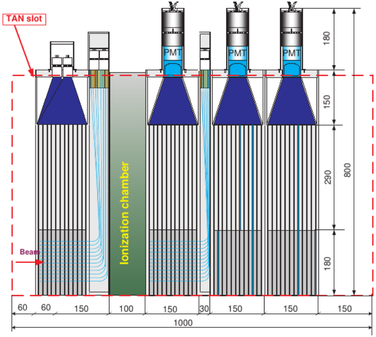

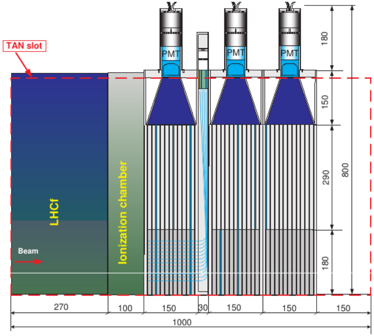

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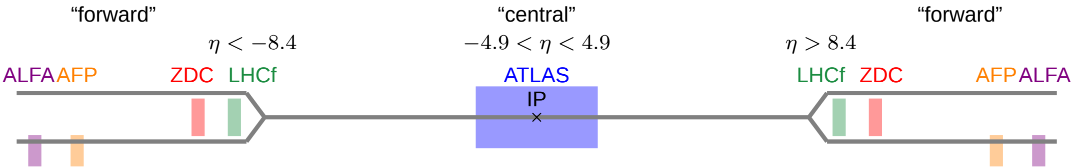
- Each consists of 1 EM module and 3 hadronic modules
- Usually operational during heavy ion runs
- Combination with LHCf: EM module replaced by LHCf

$\rightarrow$ Improve neutron energy resolution: $40\% \rightarrow 20\%$

Combination of Multiple Detectors



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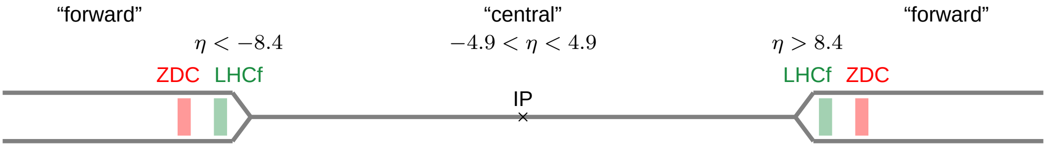

- LHCf + ZDC: Improve neutron energy resolution

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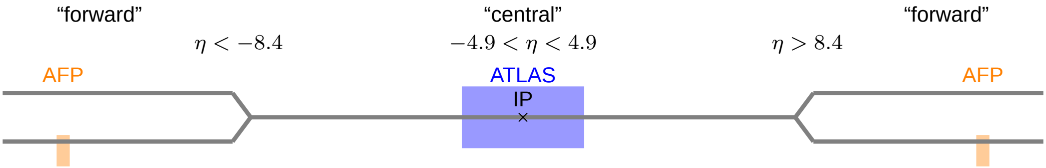

- LHCf + ZDC: Improve neutron energy resolution
- AFP + ATLAS: Diffractive dissociation, exclusive processes

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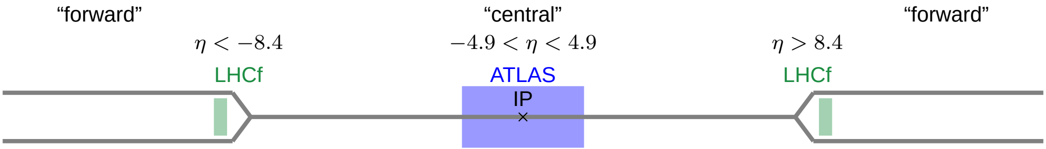

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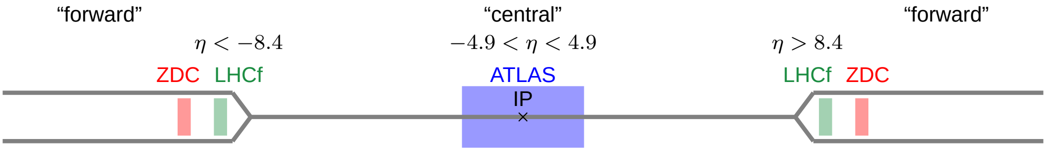

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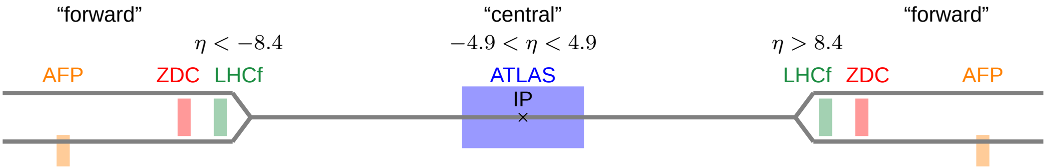

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- LHCf + AFP (+ ZDC + ATLAS): Single diffractive dissociation, proton excitations

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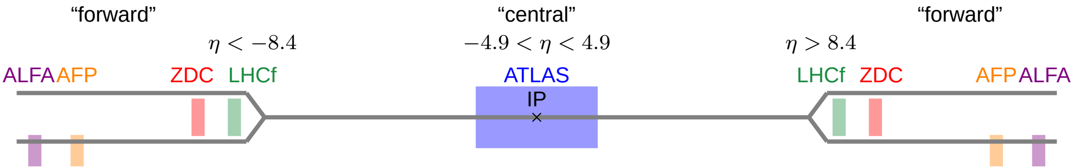

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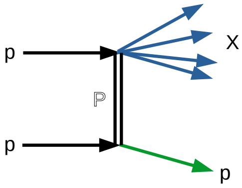
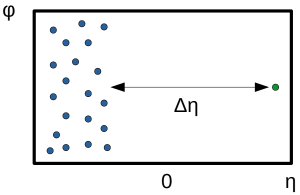
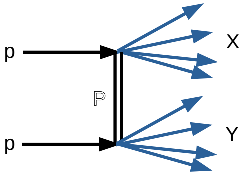
ATLAS+LHCf: Diffractive Dissociation

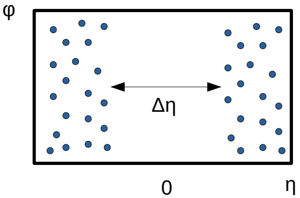
Single Diffractive Dissociation





Double Diffractive Dissociation





ATLAS+LHCf: Diffractive Dissociation

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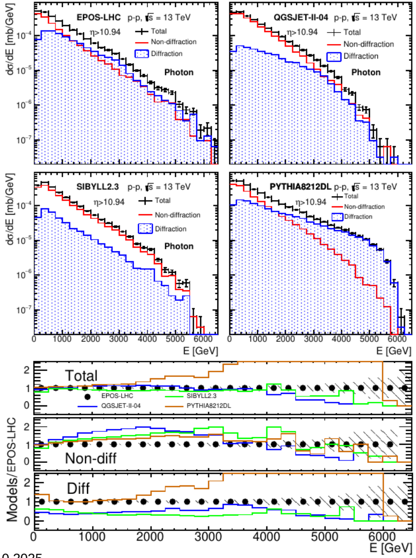

- Contribution of diffractive vs. non-diffractive very different for each event generator!
- Central veto helps disentangle diffractive and non-diffractive

ATLAS+LHCf: Diffractive Dissociation

ATLAS-CONF-2017-075

Event Selection

- γ candidate inside LHCf
  - $\rightarrow$ $E(\gamma) > 200$ GeV
  - $\rightarrow$ Region A: $8.81 < \eta(\gamma) < 8.99$
  - $\rightarrow$ Region B: $\eta(\gamma) > 10.94$

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ATLAS-CONF-2017-075

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- Track reconstruction in ATLAS:
  - $\rightarrow$ $|\eta(\text{track})| < 2.5$
  - $\rightarrow$ $p_T(\text{track}) > 100\,$MeV
  - $\rightarrow$ Veto such tracks! (Rapidity gap)

ATLAS+LHCf: Diffractive Dissociation

ATLAS-CONF-2017-075

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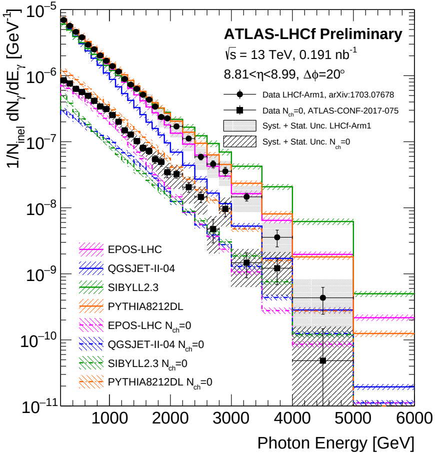
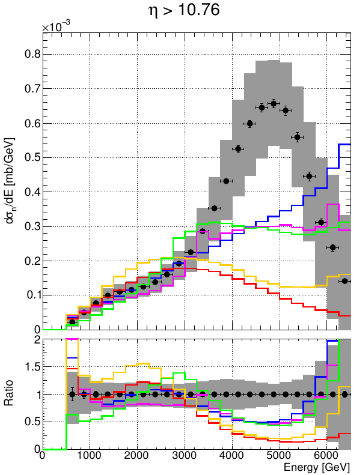


ATLAS+LHCf+ZDC: One-Pion-Exchange

LHCf (“alone”) measured neutron energy spectrum (JHEP11(2018)073):

- Large differences between data and event generator predictions



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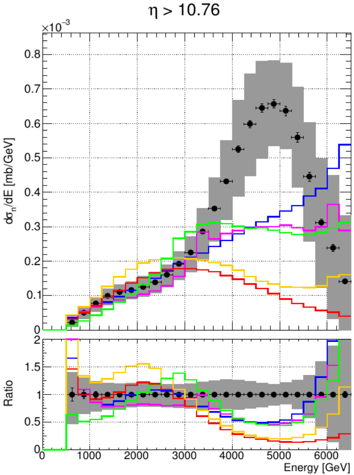

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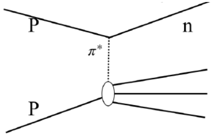
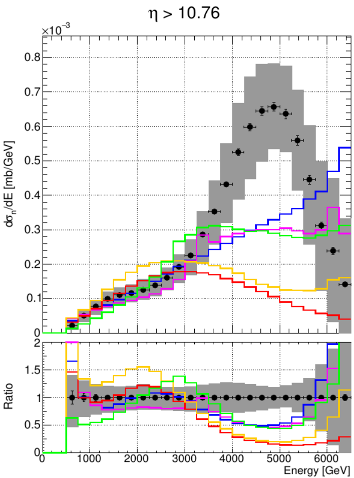
- Could be from...
  - ... Diffractive dissociation mismodelling
  - ... Mismodelling of non-diffractive processes
  - ... Generators don't take pion exchange into account





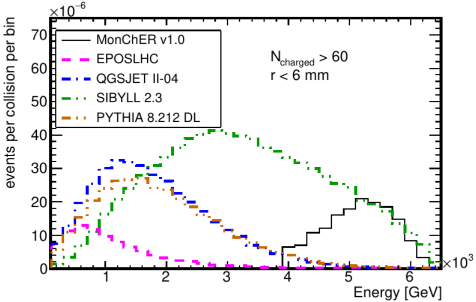
$\rightarrow$ How disentangle these contributions?

ATLAS+LHCf+ZDC: One-Pion-Exchange

K. Ohashi at ICRC 2021

Event Selection Strategy

- Diffractive veto:
  - ATLAS tracks with $|\eta| < 2.5$ and $p_T > 100$ MeV
  - $N(\text{tracks}) > 10$



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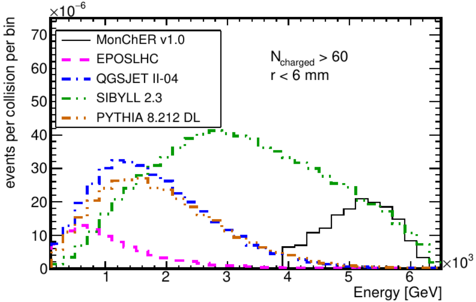
  - Neutron in LHCf with $E(n) > 3500$ GeV and $\eta > 10.76$
  - Additionally $N(\text{tracks}) > 60$



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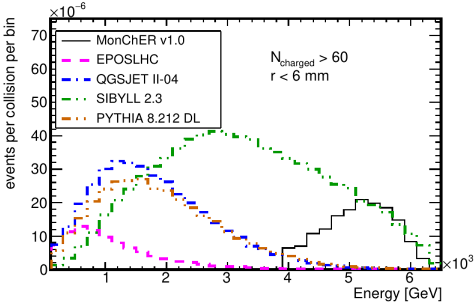

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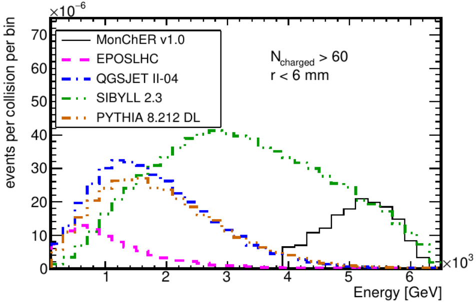


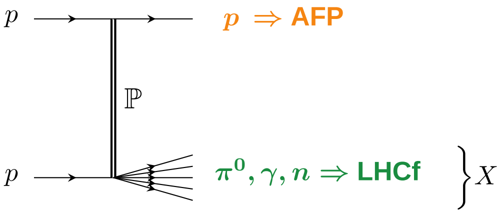
$\rightarrow$ To be studied with new LHC run 3 data!

LHCf+AFP: Diffractive Dissociation

ATL-PHYS-PUB-2023-024

Event Selection Strategy

- $\geq 1\,\gamma$ or $= 1$ neutron in LHCf
- $E_{\gamma,n} > 200\,$GeV
- Proton in AFP (opposite side)



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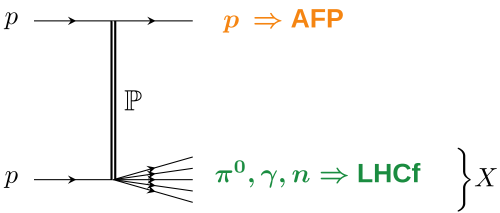

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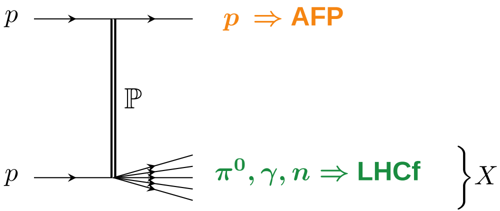


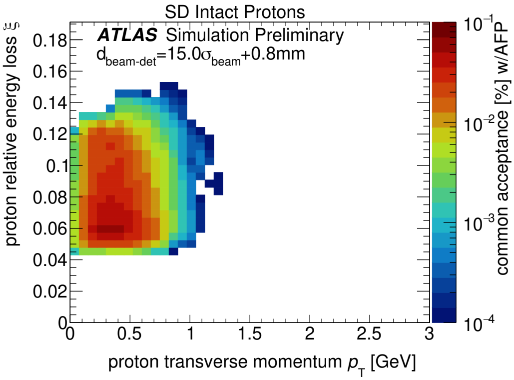
Advantages

- Improved discrimination against other processes
- Better kinematic reconstruction

LHCf+AFP: Diffractive Dissociation

- Checked combined acceptance of LHCf+AFP
- As function of p_T and energy loss ξ

$$\xi = \frac{E_{\text{beam}} - E_{\text{proton}}}{E_{\text{beam}}}$$



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> Checked combined acceptance of LHCf+AFP

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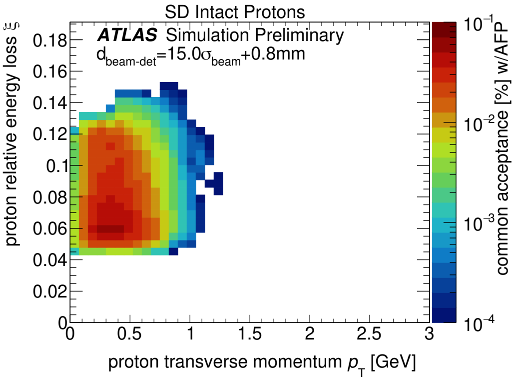
> Expected ~ 10 million events with run 3 data

$\rightarrow$ Ongoing efforts!



Run 3 Data: Special Run for LHCf

- $23^{\text{rd}} - 26^{\text{th}}$ September 2022
- $\sim$ 2.5 days of data taking
- Record: Longest LHC fill ever!
- Low pileup conditions: $\langle\mu\rangle \approx 0.02$
- Simultaneous data taking by ATLAS, LHCf, ZDC and AFP

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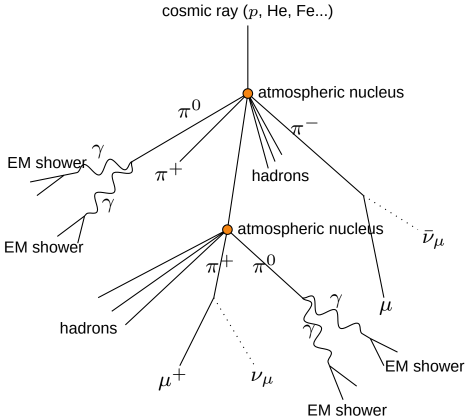
  - Generate common simulations
    - Common detector simulation of LHCf+ZDC
    - Simulation of proton transportation to AFP under special beam conditions

Outlook: Proton-Oxygen at the LHC

Proton-Oxygen collisions at the LHC for the first time in 2025!

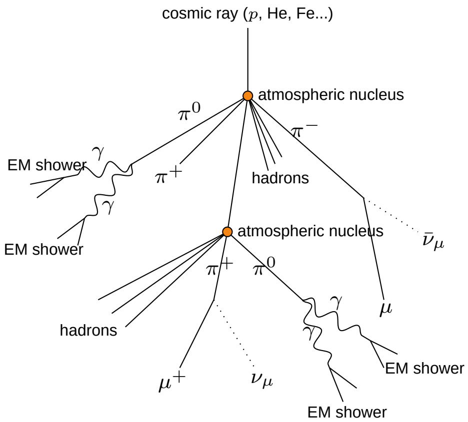


Outlook: Proton-Oxygen at the LHC

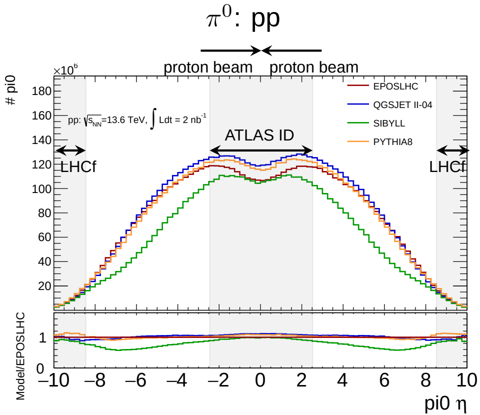
Proton-Oxygen collisions at the LHC for the first time in 2025!

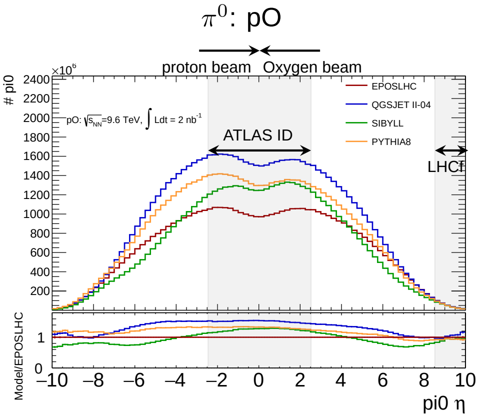
> Again, the entire set of detectors will join the run:
  $\rightarrow$ ATLAS, LHCf, ZDC and AFP

$\Rightarrow$ Preparatory and feasibility studies ongoing!



Generator Predictions for pO



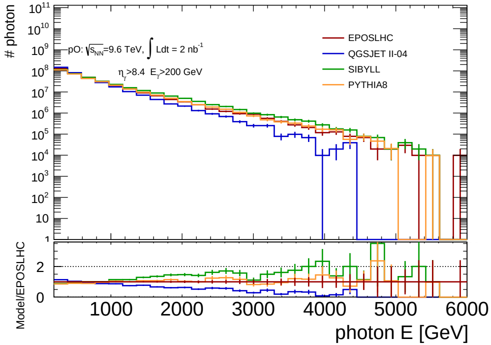


$\rightarrow$ models show similar behaviour in central region (have been tuned there)

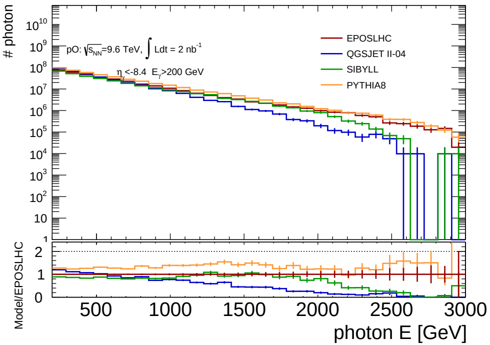
$\rightarrow$ Huge differences between models in the entire η-spectrum

Generator Predictions for pO

Proton remnant side:



Oxygen remnant side:

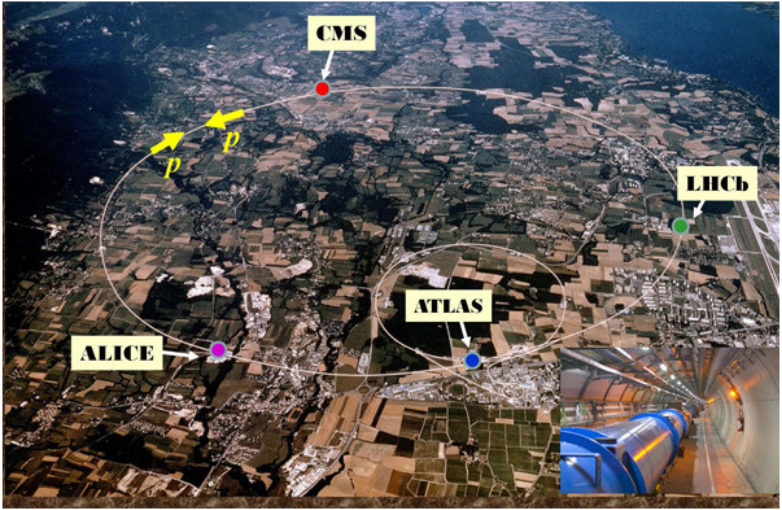


> Large disagreements between generators, especially at high photon energies

> Differences on both sides (→ data should be taken on both sides!)

What about other LHC experiments?

The Large Hadron Collider



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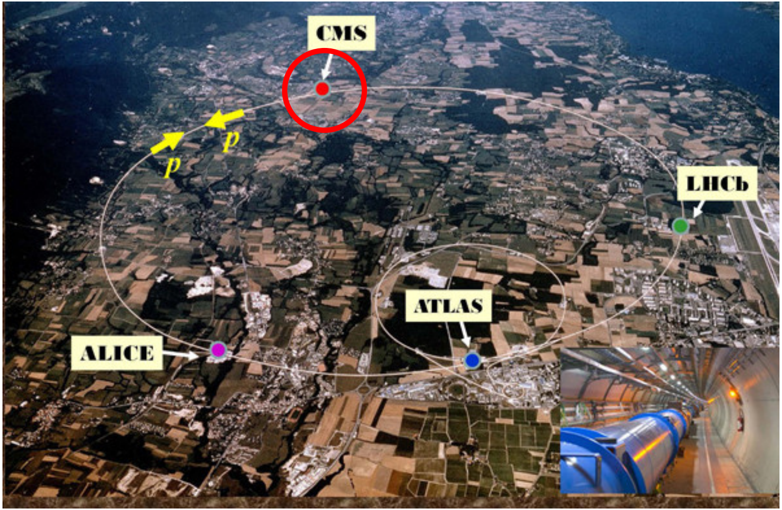
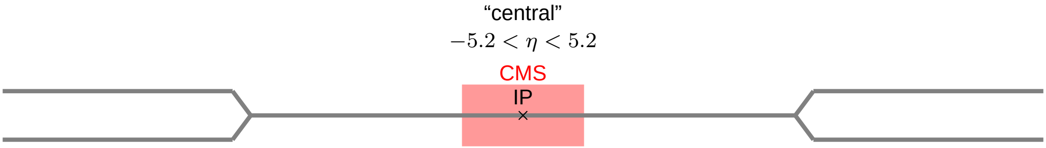


Forward Experiments around CMS



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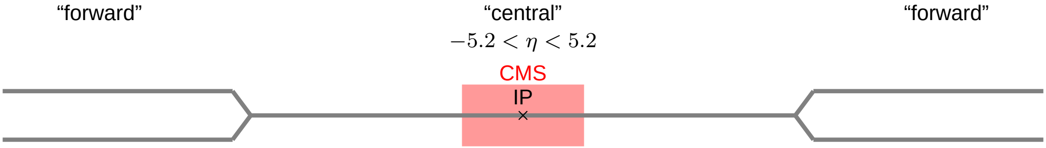

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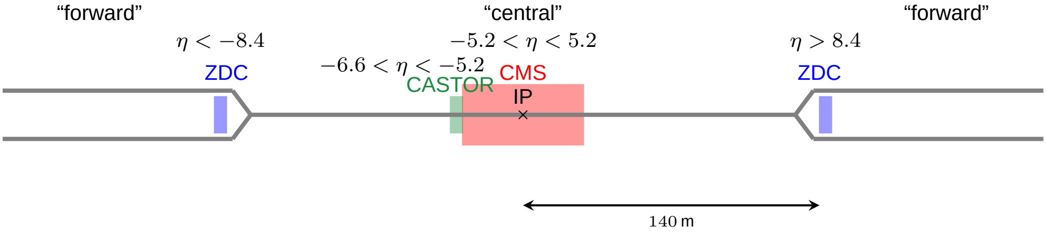

- Calorimeters: CASTOR, ZDC

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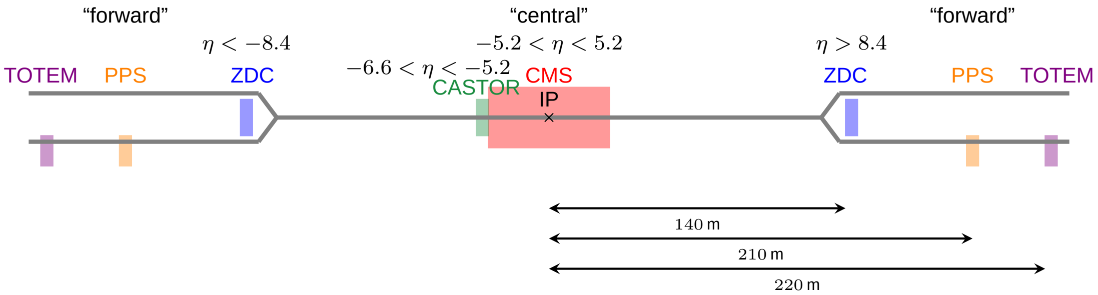
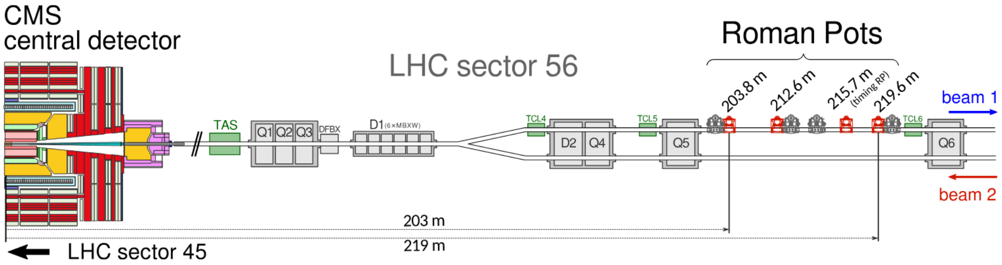


> Calorimeters: CASTOR, ZDC

> Proton detectors: PPS, TOTEM

CMS PPS: Precision Proton Spectrometer



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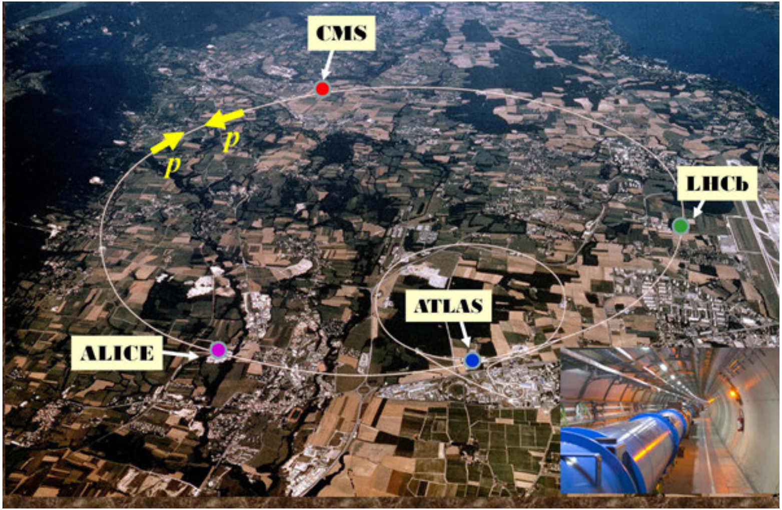

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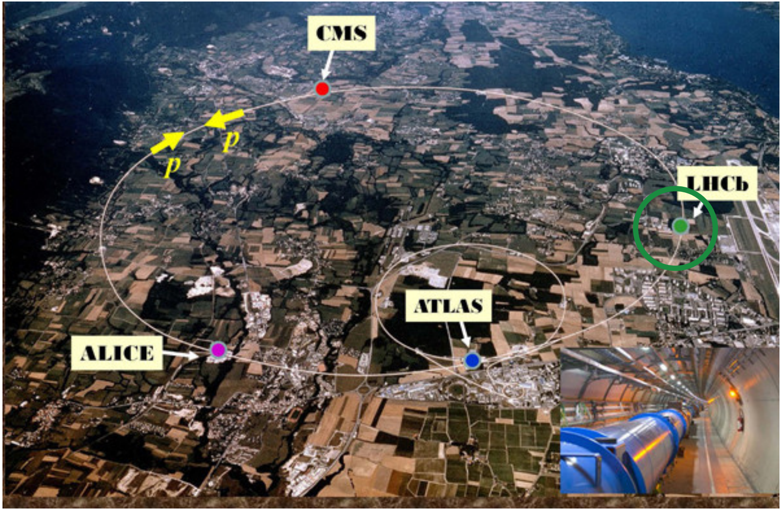
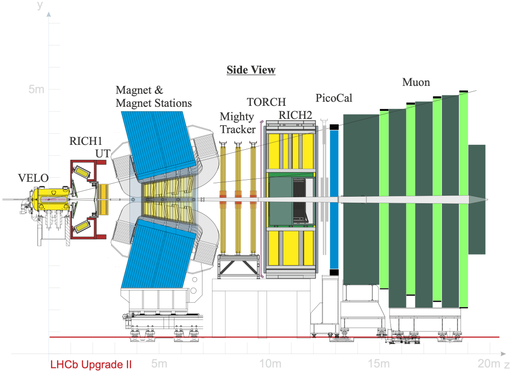


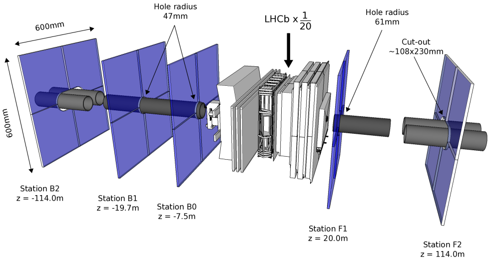
LHCb Detector

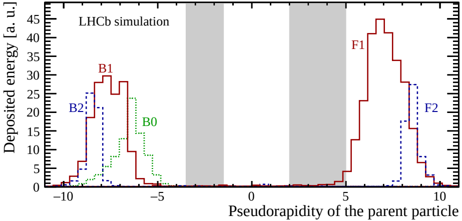
- Dedicated to measurements in the forward region
- Coverage: $2 < \eta < 5$
- Main interest in flavour physics, CP violation etc.
- Soft QCD program: particle multiplicities, inelastic cross section...
- Fixed target configuration possible (noble gas injection)



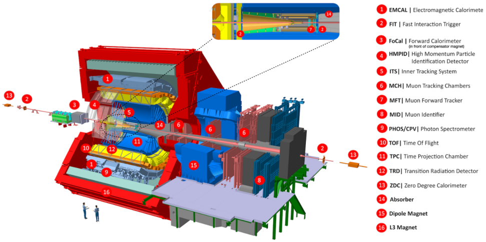
LHCb Detector and HeRSCHeL

LHCB-DP-2016-003

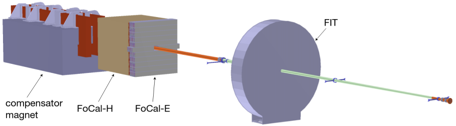




ALICE Detector and FoCal



ALICE-TDR-022



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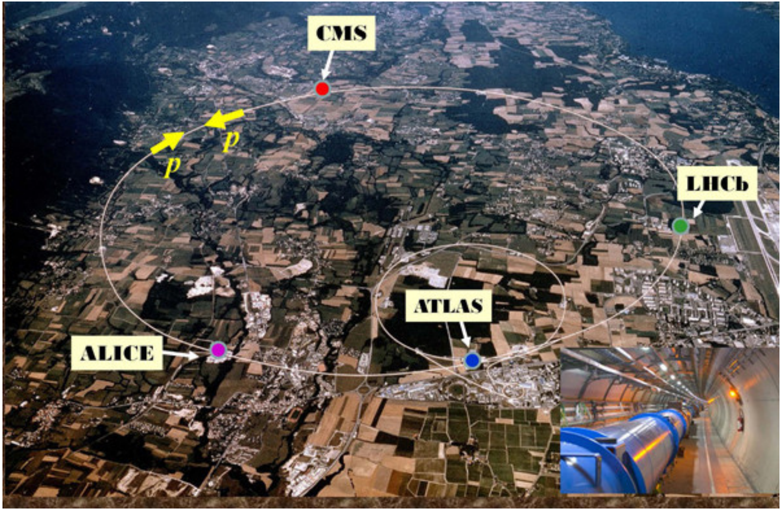

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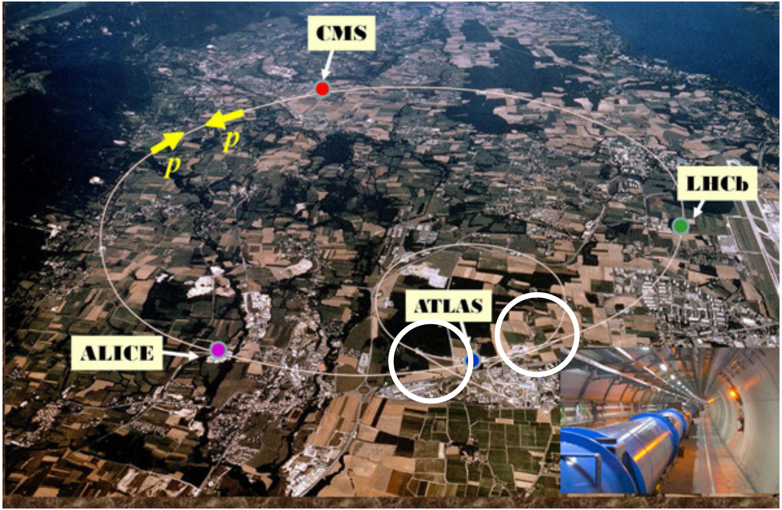

Forward Neutrinos

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FASER & FASERν

- New LHC experiment
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- $480\,$m downstream of the ATLAS IP
- On beam axis ($\eta > 9.1$)
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Successor experiments will be part of the Forward Physics Facility during HL-LHC!

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Short answer: We don't really know...

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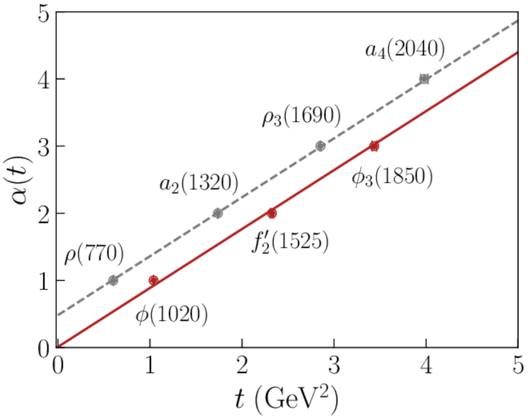

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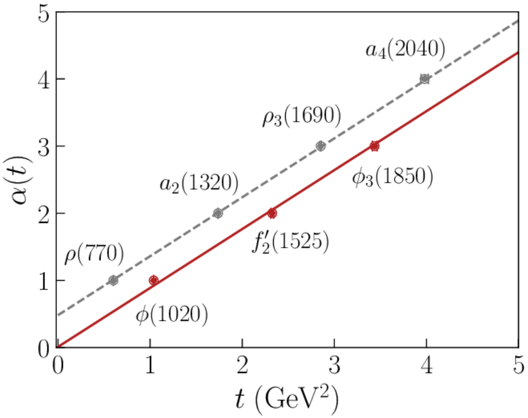
$\rightarrow$ Regge trajectories $\alpha(t)$
(Mandelstam t: squared momentum exchange)



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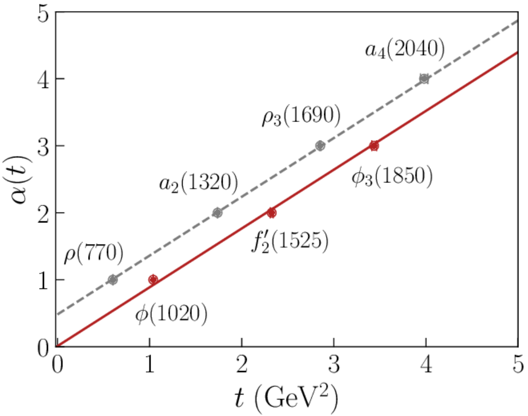
Energy dependence of total hadron-hadron cross sections



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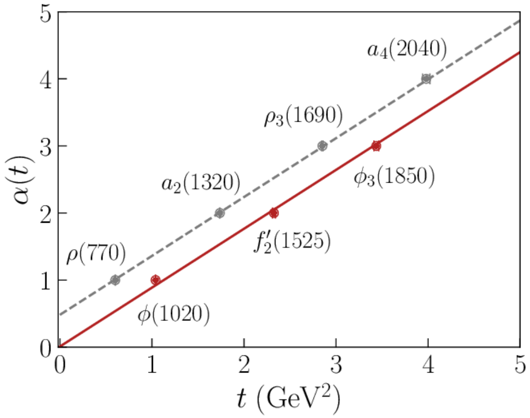

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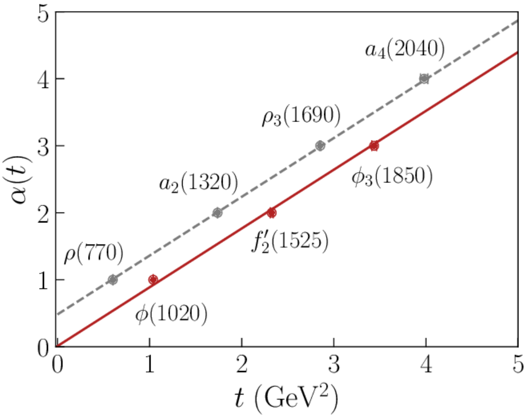

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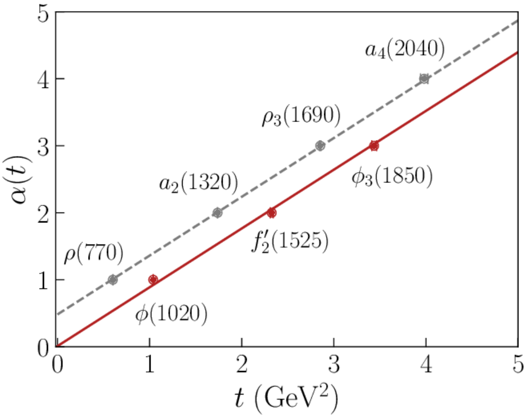

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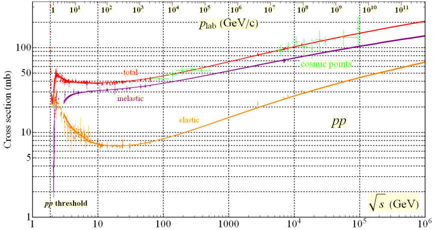
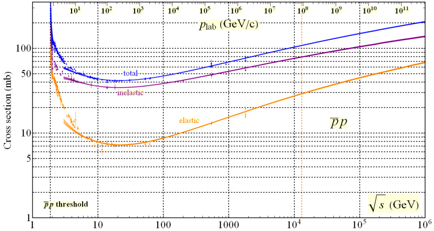
- Observation: $\sigma_{\text{total}} \sim$ constant with high energy with slight logarithmic rise





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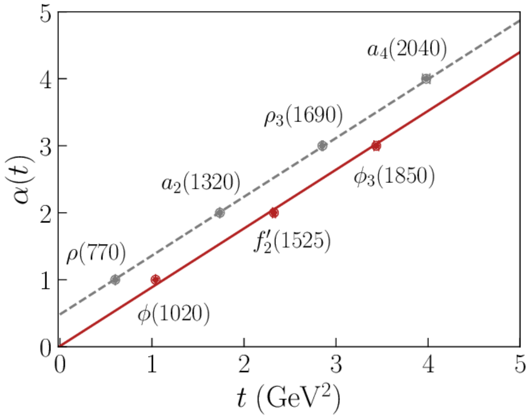

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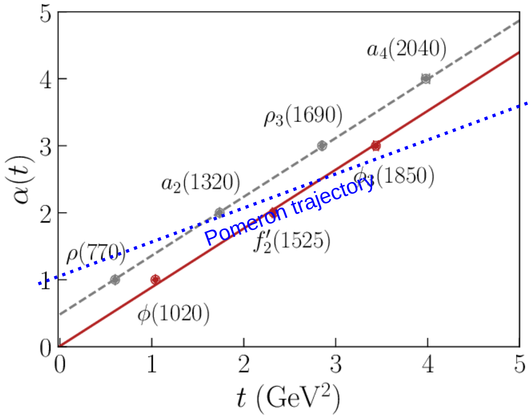
→ Expectation: σ_{total} decreases with s at small t

- Observation: $\sigma_{\text{total}} \sim$ constant with high energy with slight logarithmic rise
- Idea: There exists another trajectory with $\alpha(0) \gtrsim 1$ that dominates strong interactions at small t

→ Pomeron!

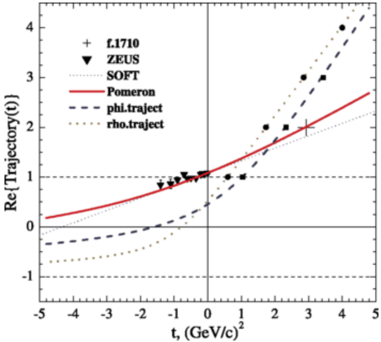


Open Questions

Did it work? What about QCD?

- Concept fairly successful
- But: Up to now no confirmed particles on the Pomeron trajectory
- Pomeron definition only valid for low $t =$ non-perturbative regime of QCD

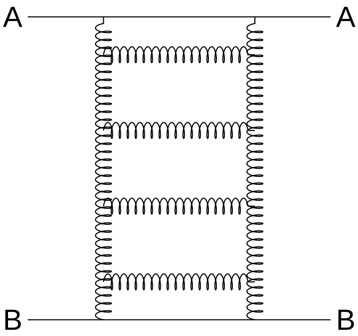
$\rightarrow$ What is the Pomeron in QCD?



Open Questions

QCD Pomeron?

- Properties of Regge Pomeron: Quantum numbers of the vacuum, C-even
- BFKL equation: Pomeron analogous to exchange of two (or a higher even number) gluons in QCD
- Represented by “ladder” operator



Open Questions

Pomeron Resonances?

- No known particles on Pomeron trajectory known yet
- Candidates: Tensor (spin 2) glueballs
  - Purely gluonic bound states allowed by QCD
  - Haven’t been identified as well so far