Forward Physics at the LHC

... and how it can benefit Astroparticle Physics

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HUMBOLDT-UNIVERSITÄT ZU BERLIN

ATLAS EXPERIMENT

Astroparticle Physics Seminar, DESY
Zeuthen, 26.1.2024

What I will cover...

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Connecting EAS and LHC

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Connecting EAS and LHC

Forward physics at ATLAS

- Detectors
- Combining detectors
- Physics cases
- Outlook on Run 3 data

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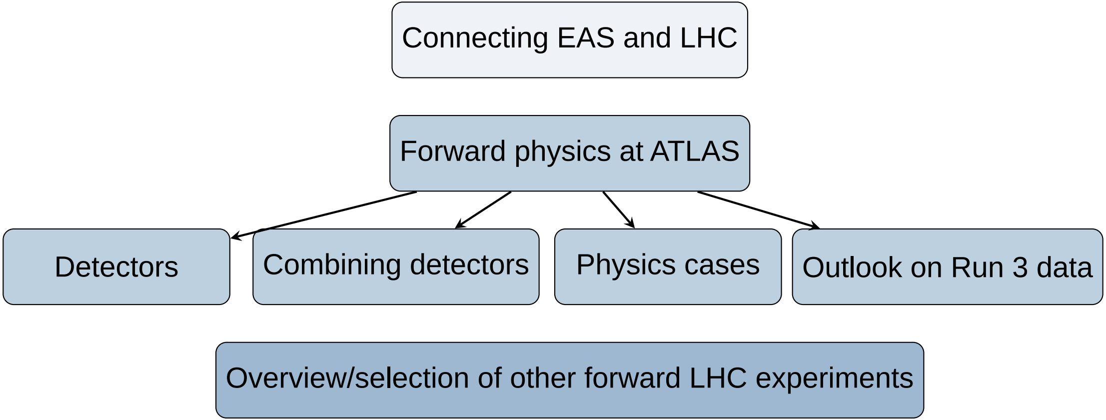
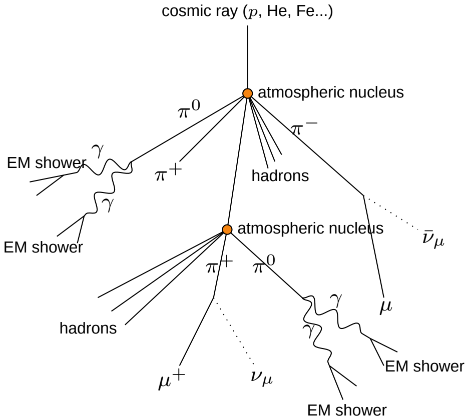


Motivation

Soft QCD in Air Showers

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



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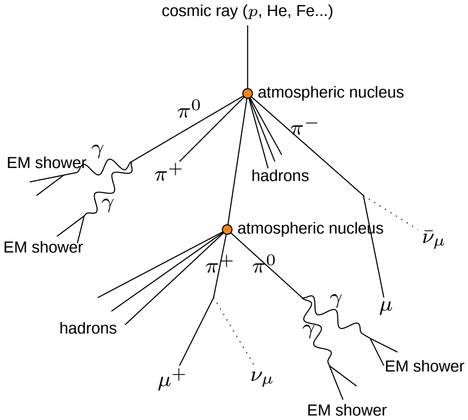
- Soft QCD: Hadronic interaction with low momentum transfer
- Non-perturbative $\rightarrow$ phenomenological models



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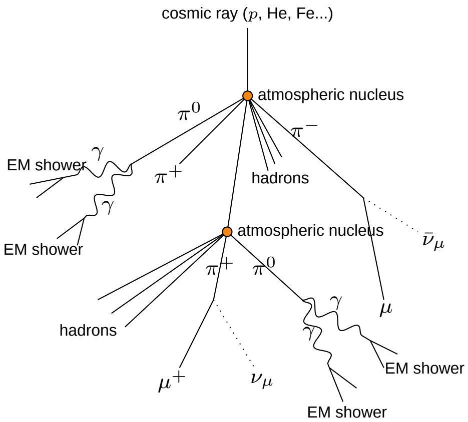
  - Particle multiplicities



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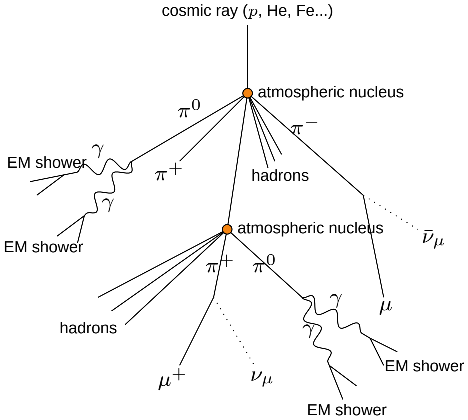

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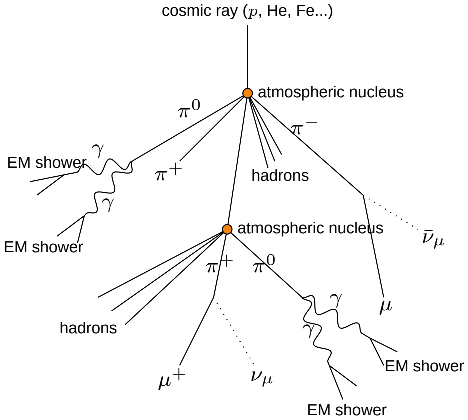
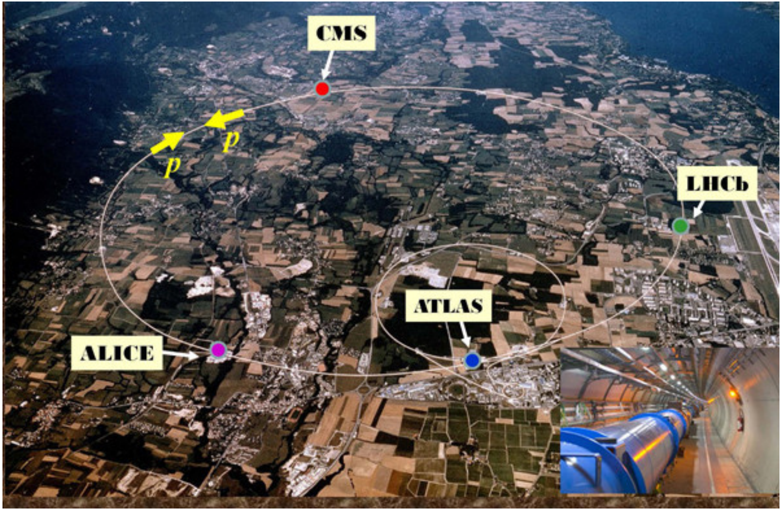
$\Rightarrow$ Tuning based on accelerator data



The Large Hadron Collider



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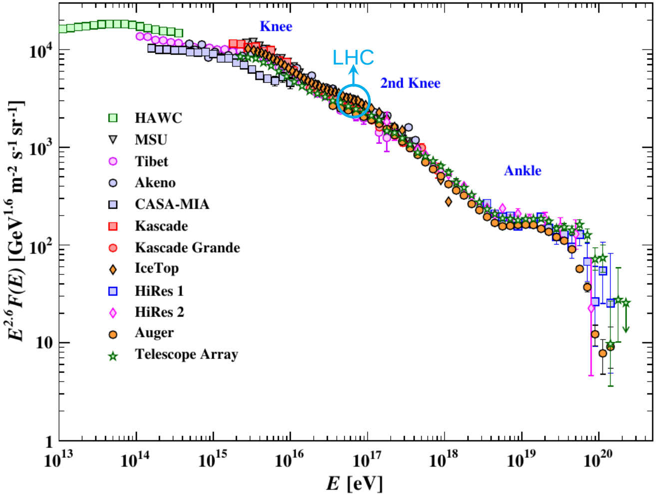

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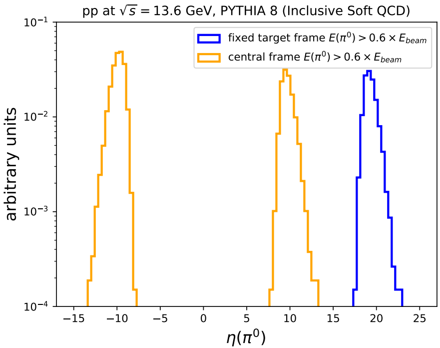
Soft QCD at the LHC

> Low momentum transfer scattering
  → Particles in forward region



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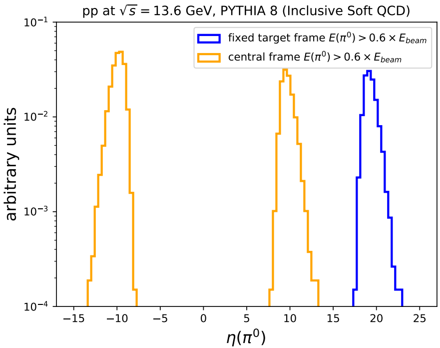
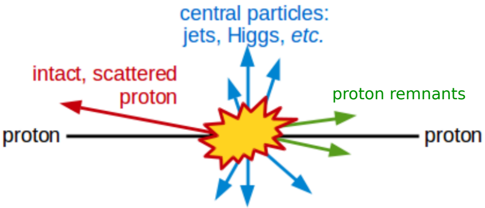
  - $\rightarrow$ Experiments at high $|\eta| = \left| -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)\right|$





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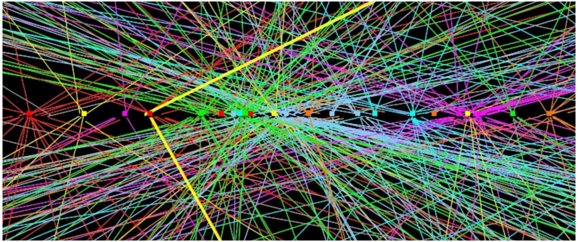
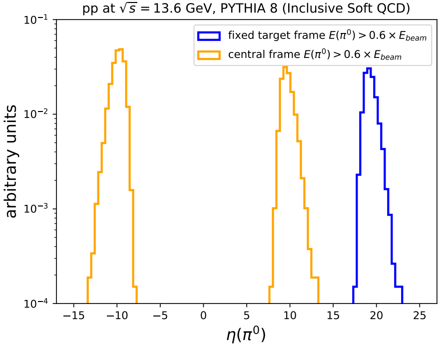
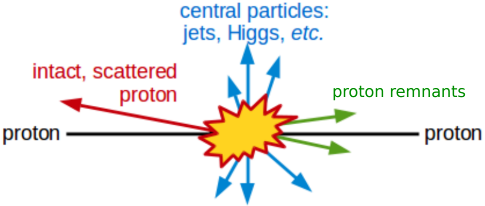
Soft QCD at the LHC

- 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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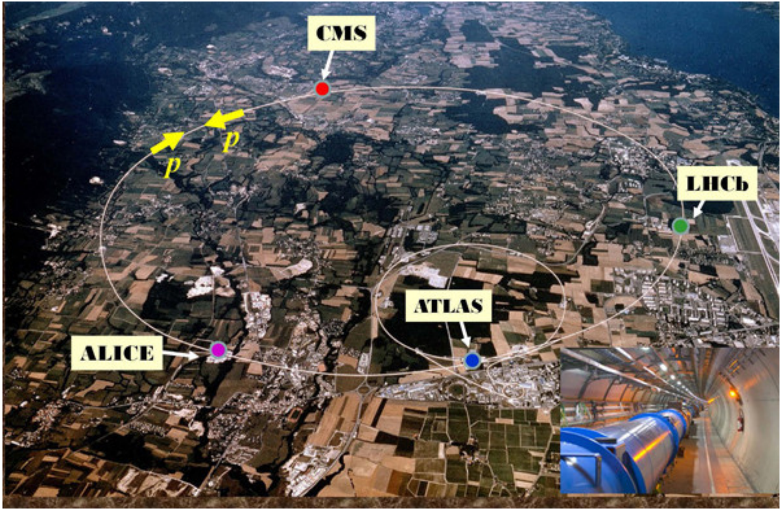

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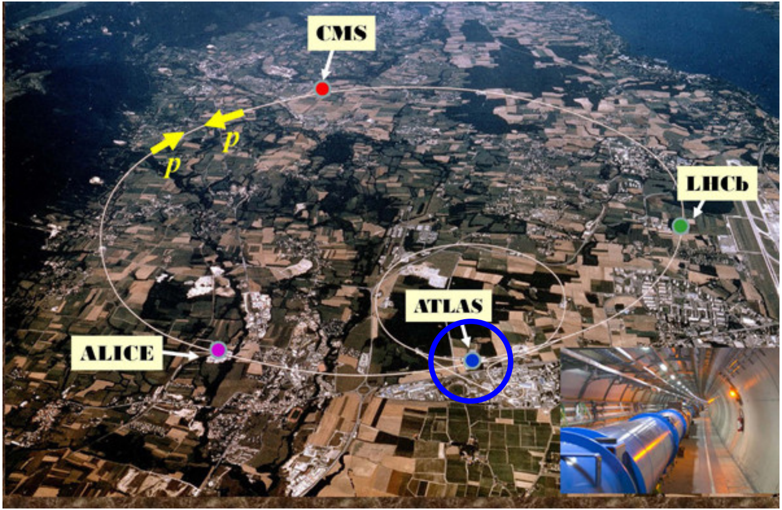
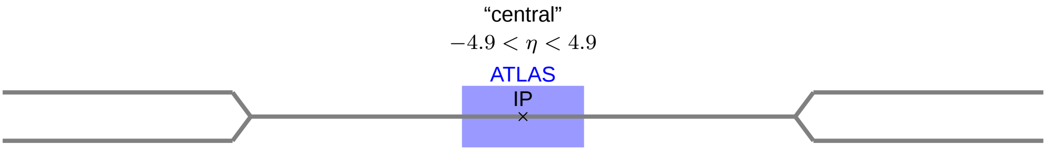


Overview of Forward Experiments



- Multi-purpose detector: ATLAS

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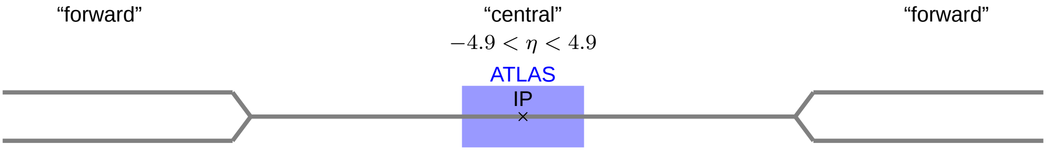

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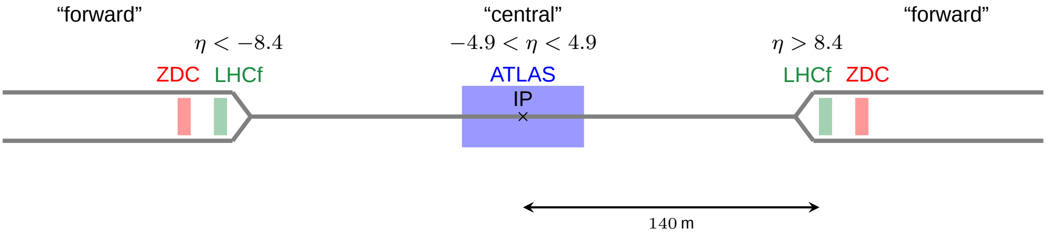

> Multi-purpose detector: ATLAS
> Calorimeters: LHCf, ZDC

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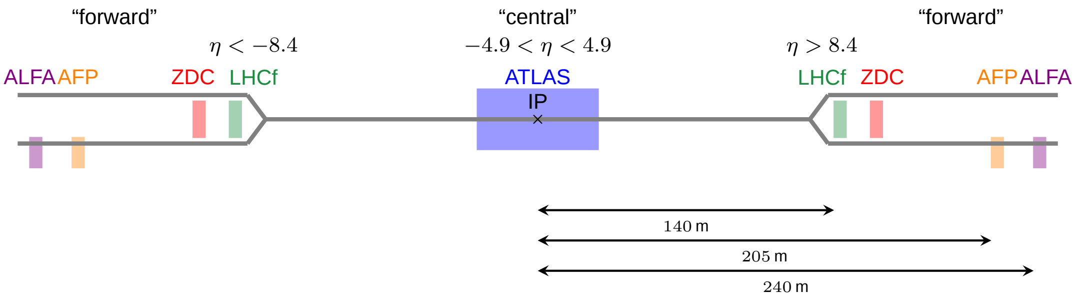
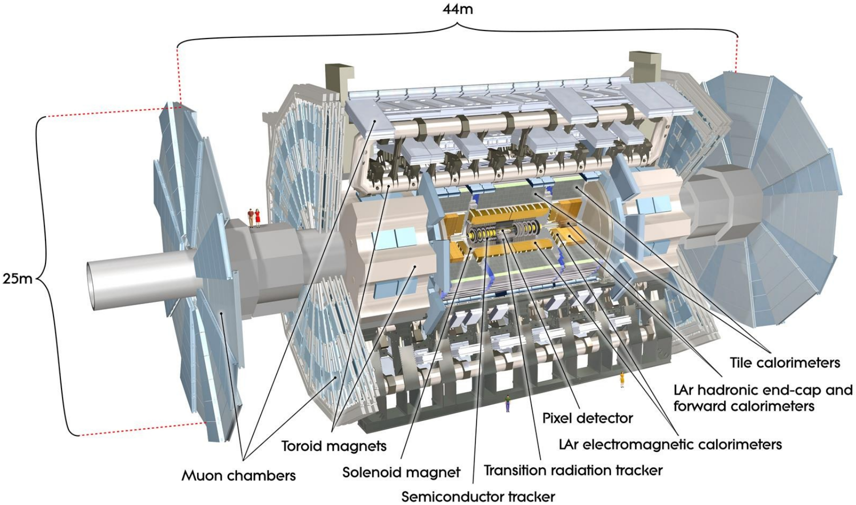


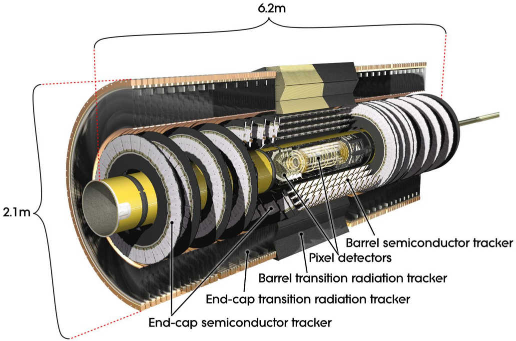
- Multi-purpose detector: ATLAS
- Calorimeters: LHCf, ZDC
- Proton detectors: AFP, ALFA

ATLAS Detector



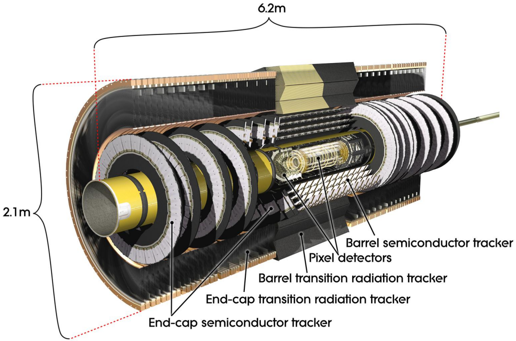
ATLAS: Inner Tracking Detector

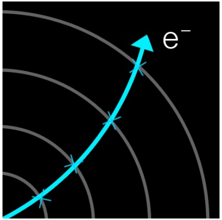
- Covers central rapidities ($|\eta| < 2.5$)
- Different sensor systems to detect charged particles
- Inside solenoid magnet



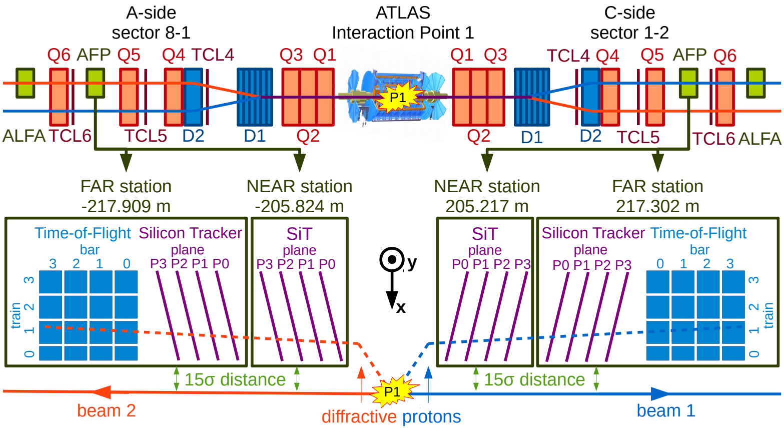
ATLAS: Inner Tracking Detector

- 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



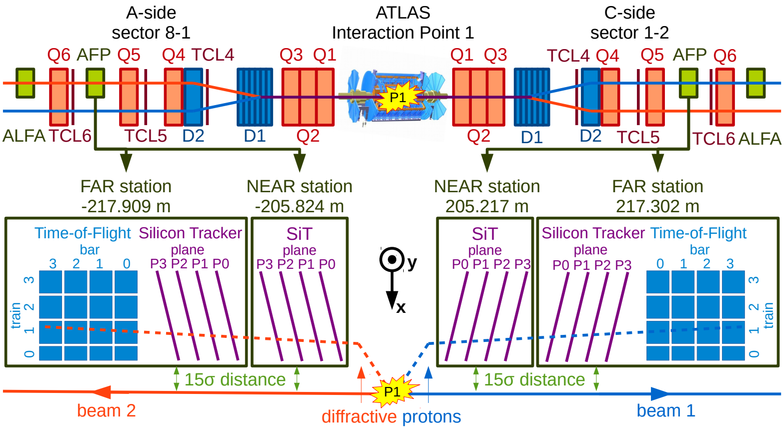


AFP Detectors



> Goal: Reconstruct scattered proton trajectories close to the beam

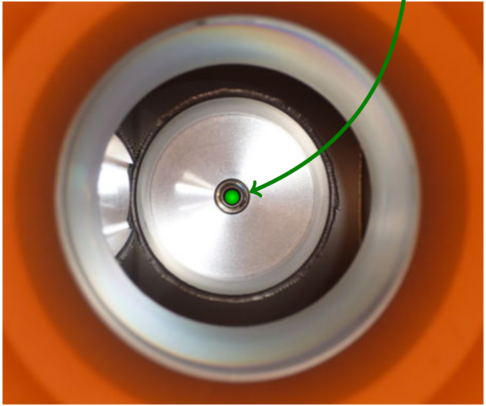
AFP Detectors

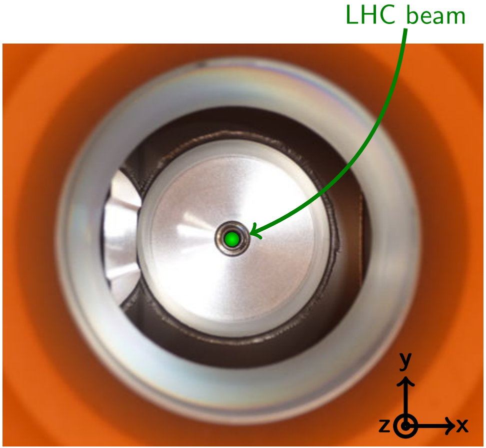


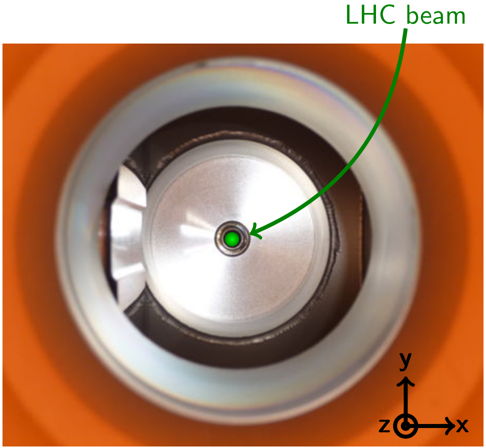
> Goal: Reconstruct scattered proton trajectories close to the beam

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

Advantages of Roman Pot Technology


LHC beam


LHC beam
y
z
x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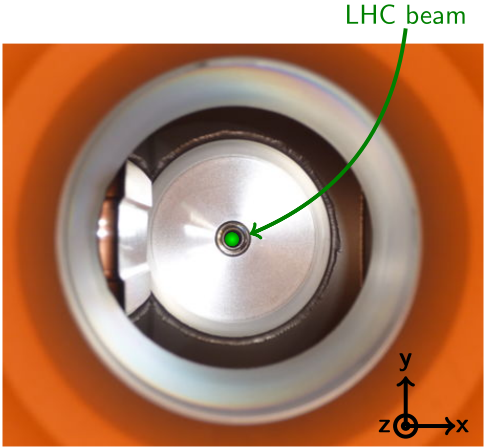
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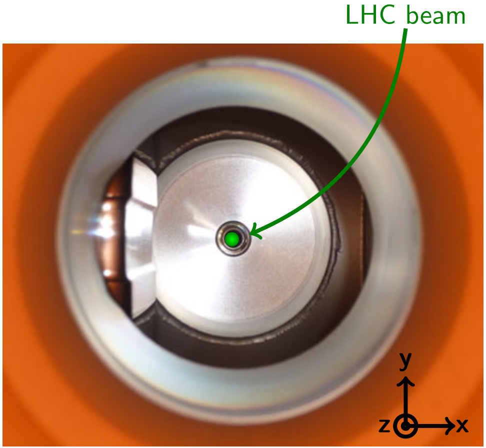
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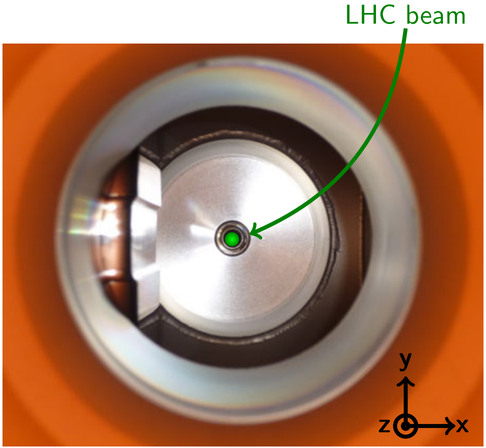
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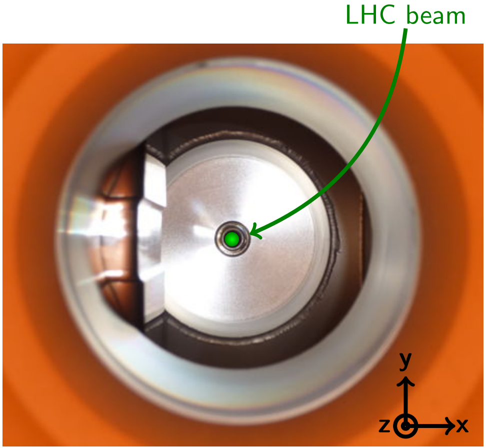

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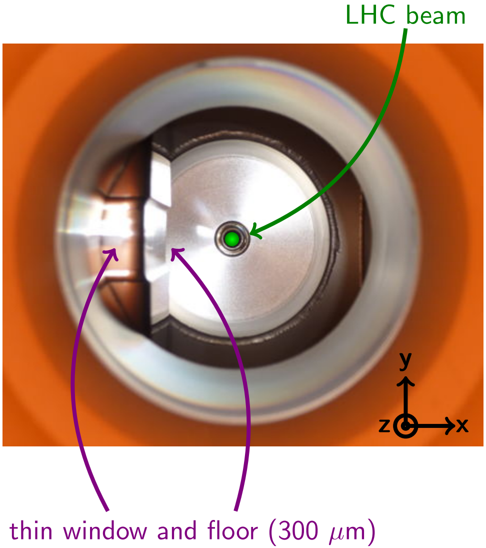
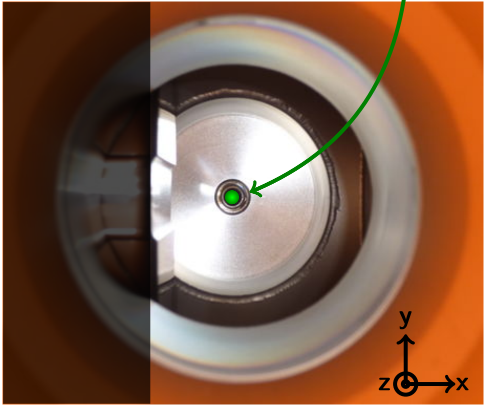


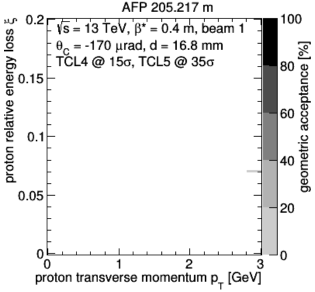
shadow of TCL4 and TCL5 collimators

LHC beam



thin window and floor (300 μm)

Geometric acceptance:



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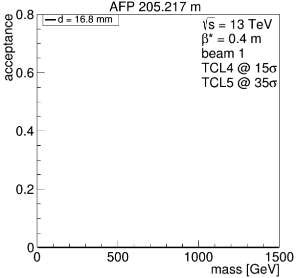

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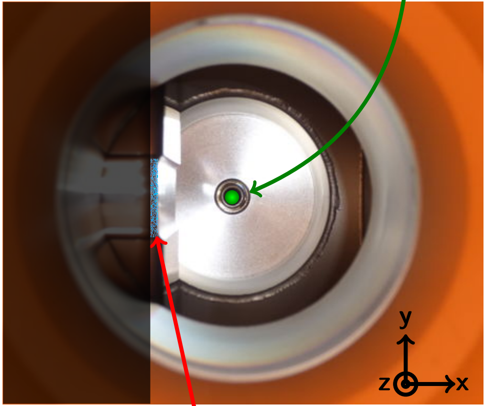

diffractive protons

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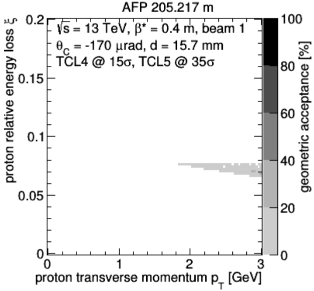

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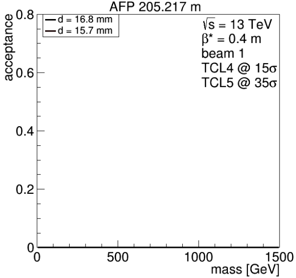

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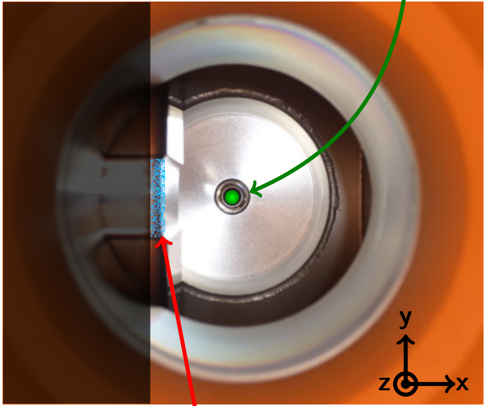

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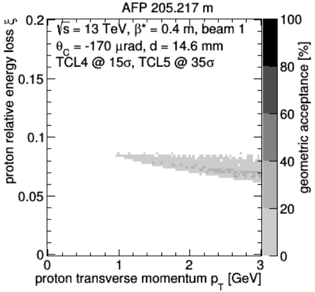

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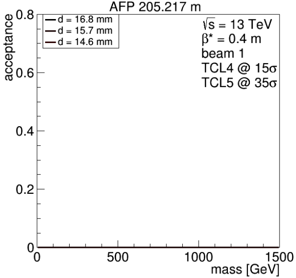

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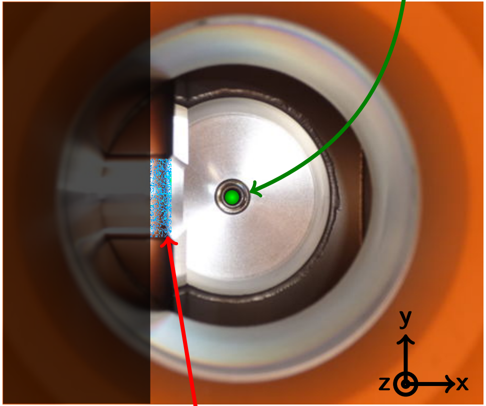

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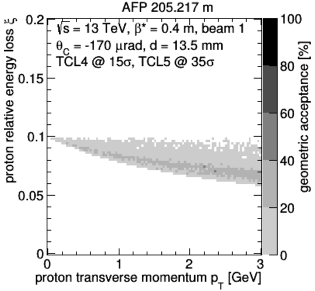

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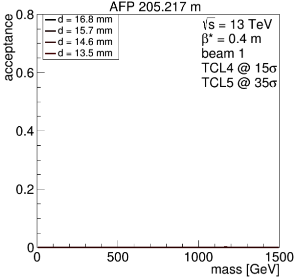

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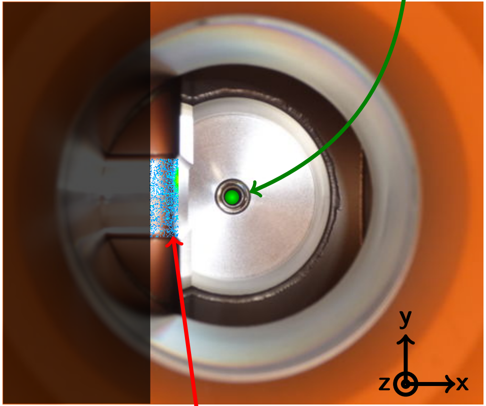

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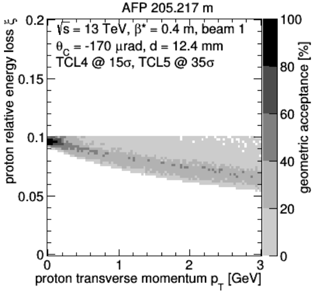

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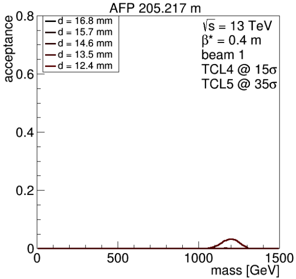

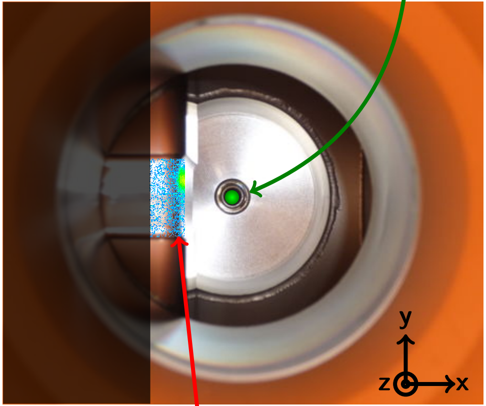

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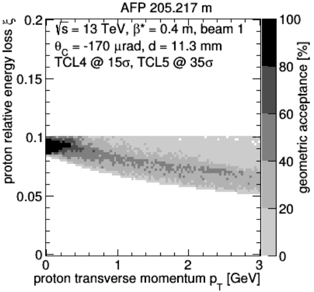

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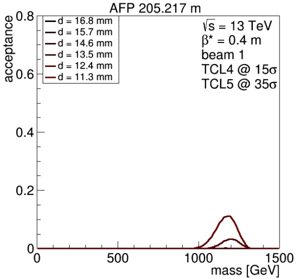

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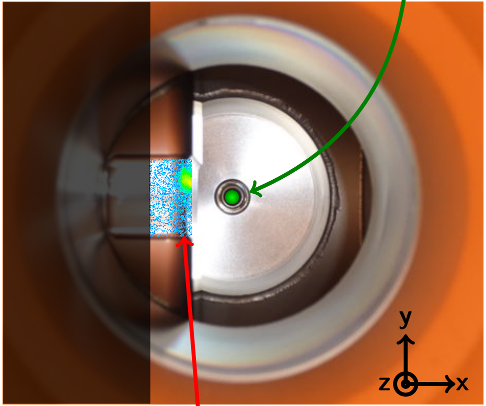

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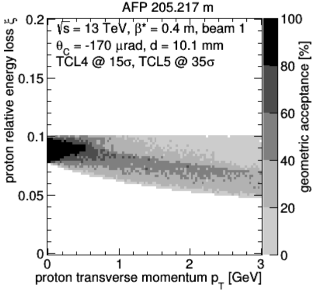

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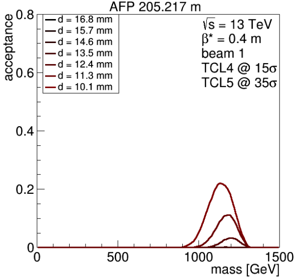

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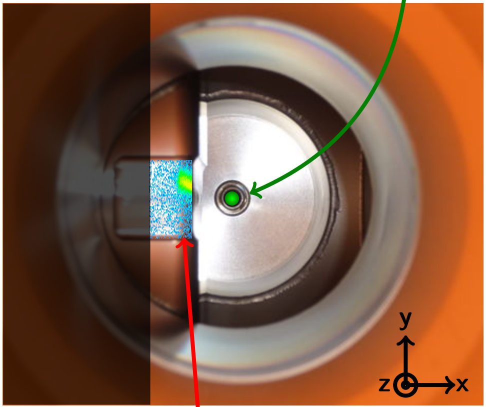

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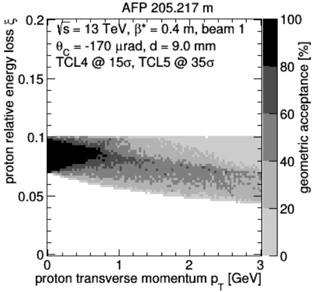

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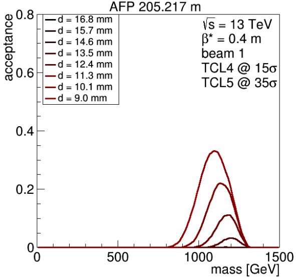

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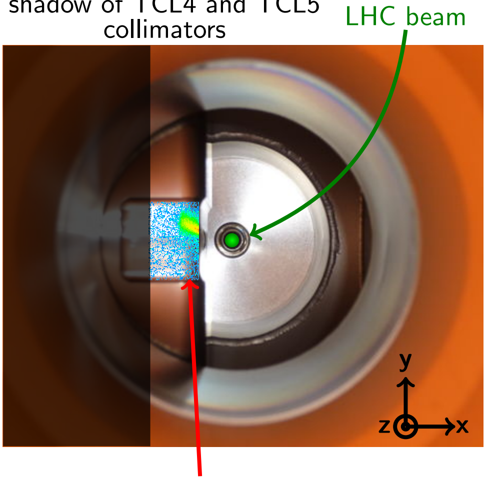

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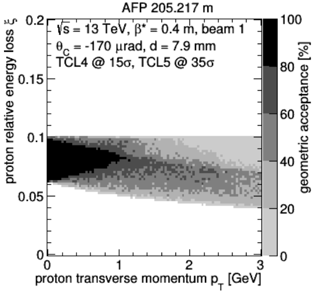

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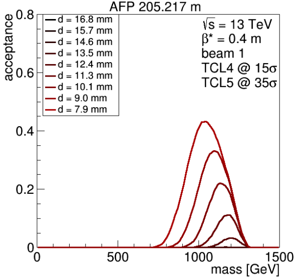

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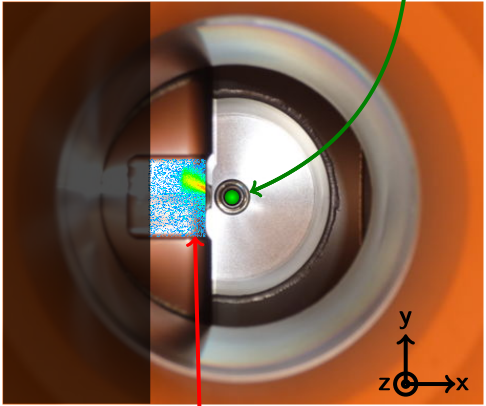

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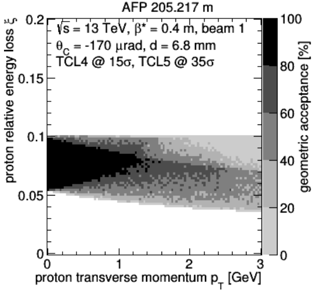

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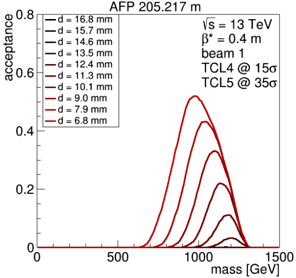
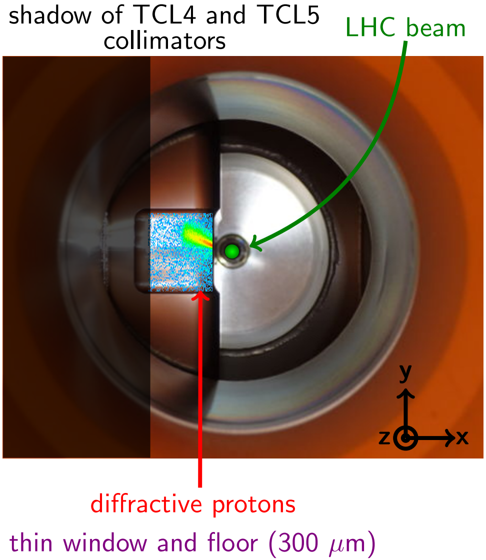
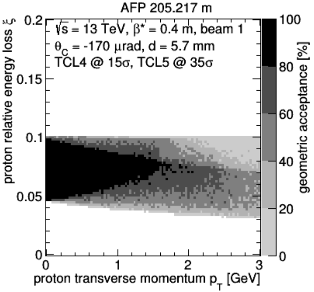
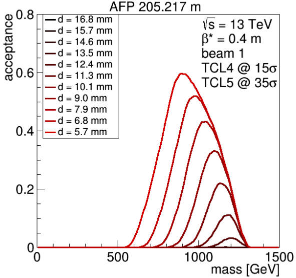




Geometric acceptance:

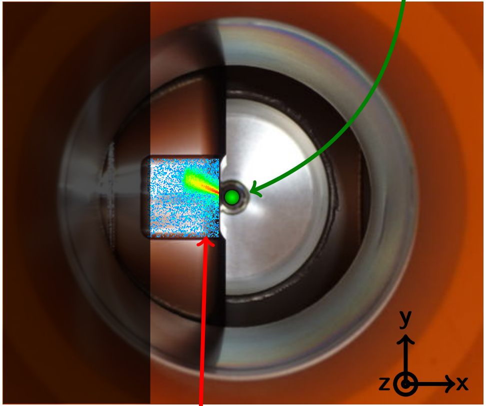


Mass acceptance:



shadow of TCL4 and TCL5 collimators

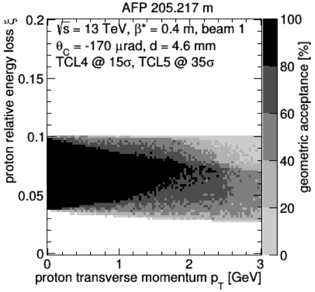
LHC beam



diffractive protons

thin window and floor (300 μm)

Geometric acceptance:



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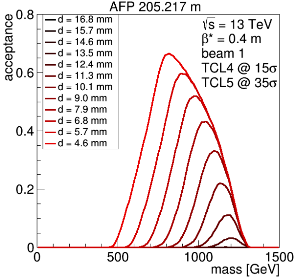

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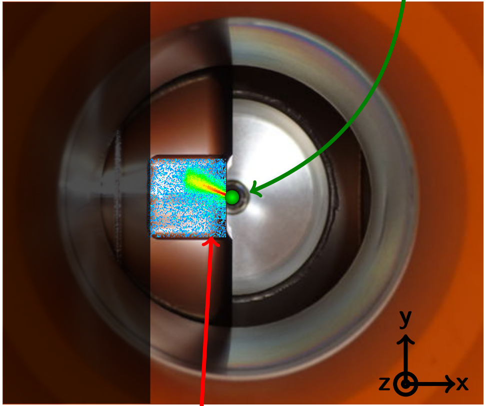

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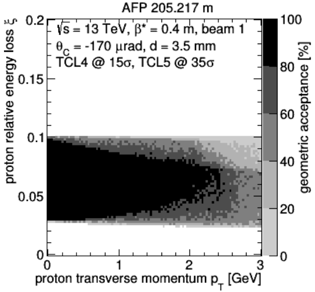

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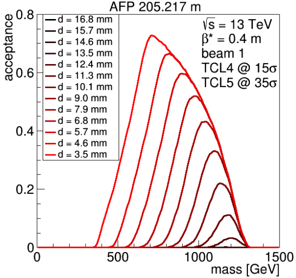
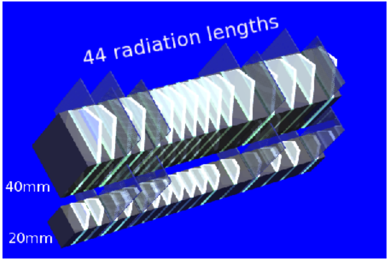
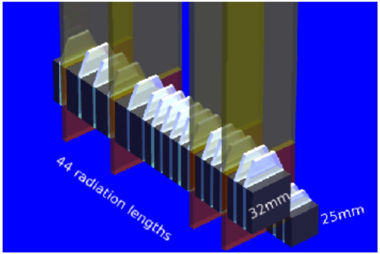


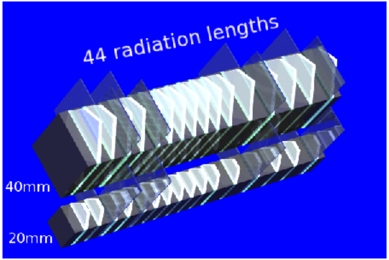
LHCf Detectors

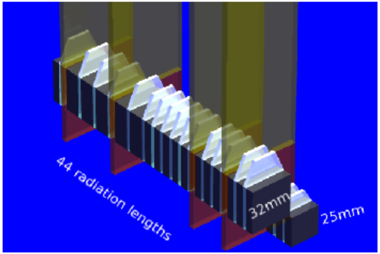




- Two calorimeter towers on each side of ATLAS
- Different geometric orientations
- Tungsten absorber, plastic scintillators + position sensitive layers per tower

LHCf Detectors





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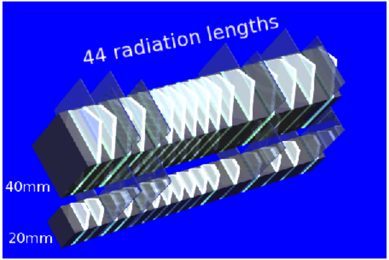

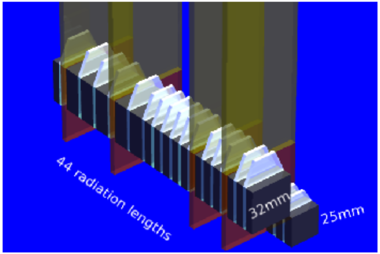

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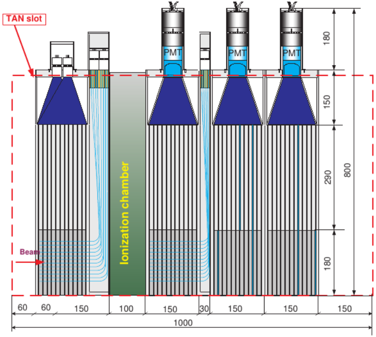
- Tungsten absorber, plastic scintillators + position sensitive layers per tower
- Only reached by neutral particles: n, γ, $\pi^0 \to \gamma\gamma$, $\eta^0 \to \gamma\gamma$...
- Energy resolution: $< 3\%$ (photons), $\sim 40\%$ (neutrons)

ATLAS ZDC Detectors



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- Each consists of 1 EM module and 3 hadronic modules
- Usually operational during heavy ion runs

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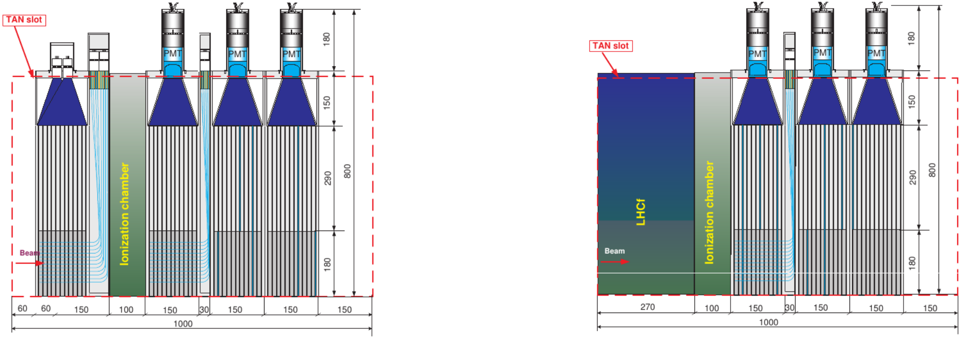
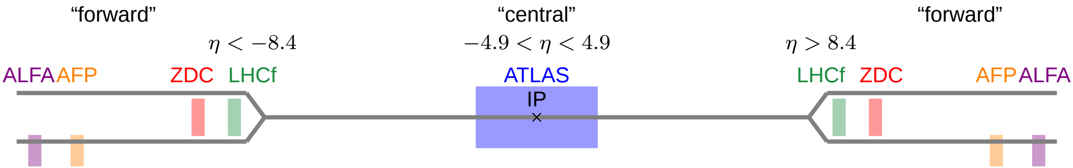


- Two calorimeter systems on each side of ATLAS
- Each consists of 1 EM module and 3 hadronic modules
- Usually operational during heavy ion runs
- Combination with LHCf: EM module replaced by LHCf

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

Combination of Multiple Detectors



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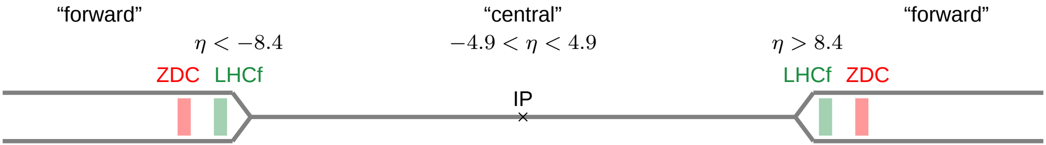

> LHCf + ZDC: Improve neutron energy resolution

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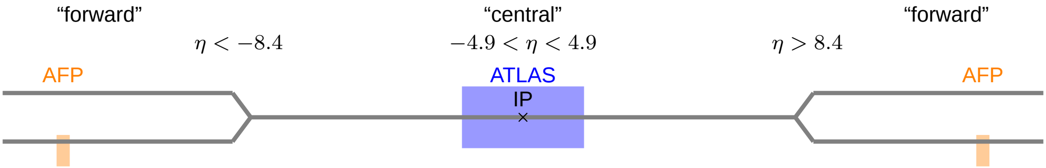

- LHCf + ZDC: Improve neutron energy resolution
- AFP + ATLAS: Diffractive dissociation, exclusive processes

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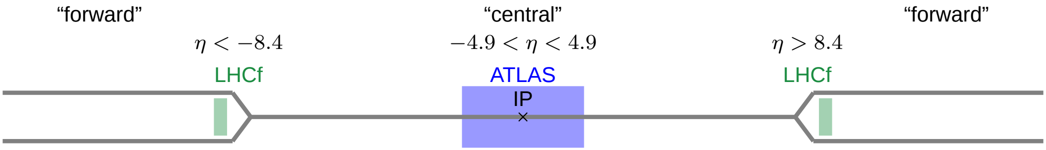

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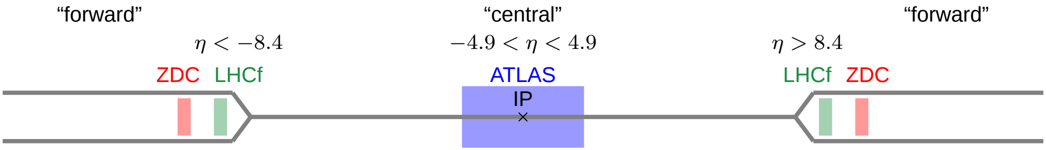

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- LHCf + ZDC + ATLAS: One-pion-exchange process

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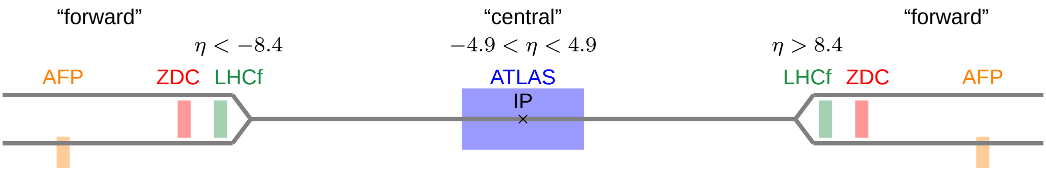

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- LHCf + AFP (+ ZDC + ATLAS): Single diffractive dissociation, proton excitations

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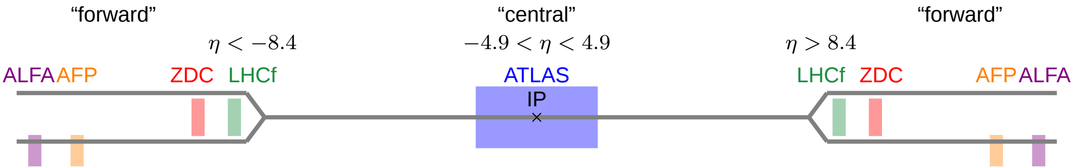

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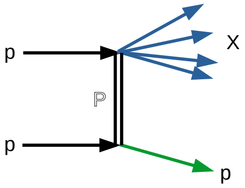
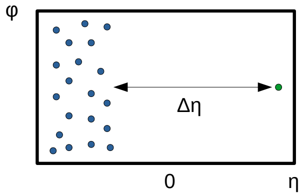
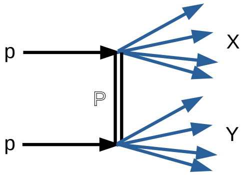
ATLAS+LHCf: Diffractive Dissociation

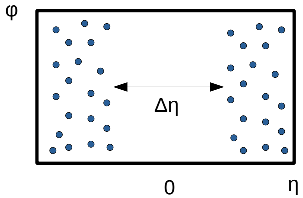
Single Diffractive Dissociation





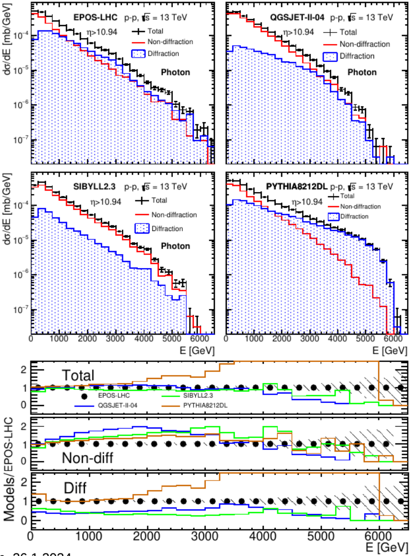
Double Diffractive Dissociation





ATLAS+LHCf: Diffractive Dissociation

Eur. Phys. J. C77 no. 4, (2017) 212



- 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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- Track reconstruction in ATLAS:
  - $\rightarrow$ $|\eta(\text{track})| < 2.5$
  - $\rightarrow$ $p_T(\text{track}) > 100$ MeV
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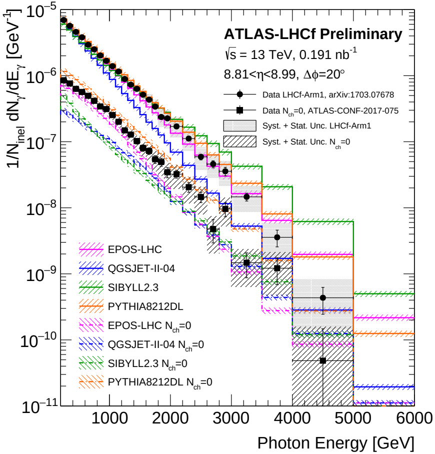
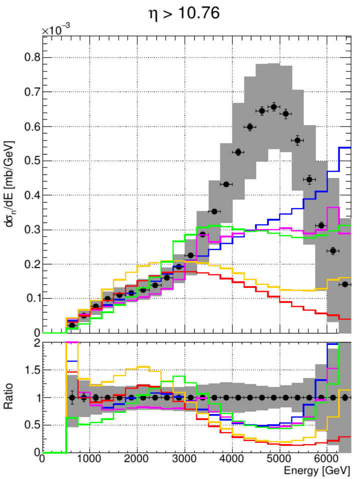


ATLAS+LHCf+ZDC: One-Pion-Exchange

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

- Large differences between data and event generator predictions



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  - ... Diffractive dissociation mismodelling
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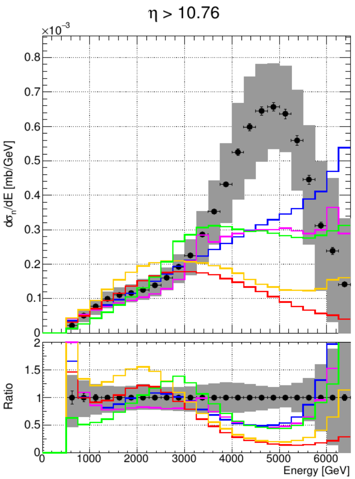

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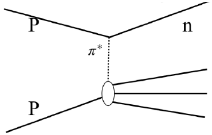
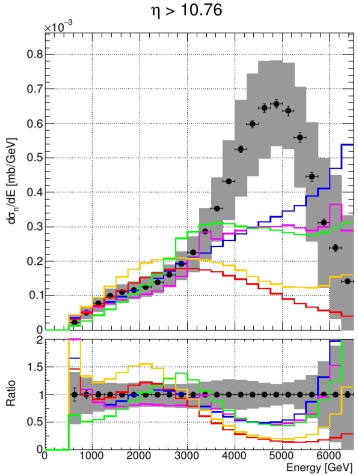
  - ... Mismodelling of non-diffractive processes
  - ... Generators don’t take pion exchange into account





$\rightarrow$ 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
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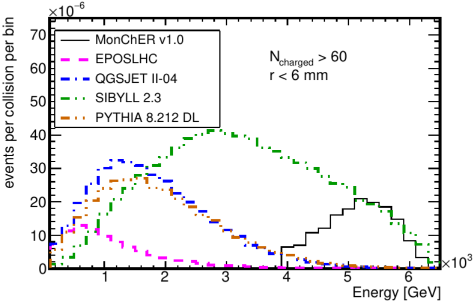

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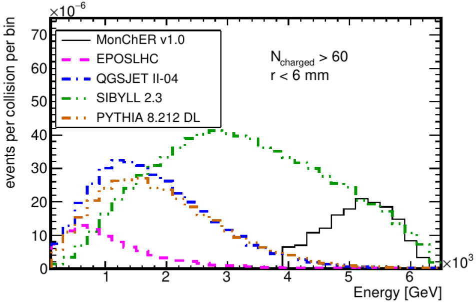
  - Neutron in LHCf with $E(n) > 3500$ GeV and $\eta > 10.76$
  - Additionally $N(\text{tracks}) > 60$



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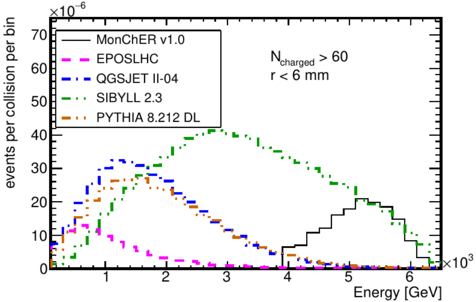

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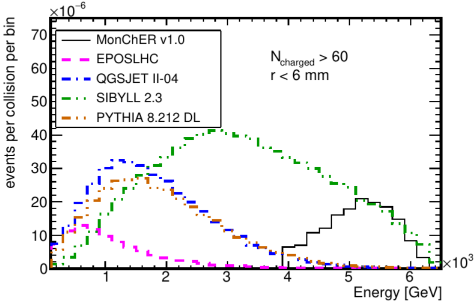


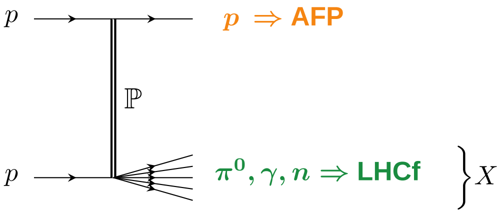
$\rightarrow$ To be studied with new LHC run 3 data!

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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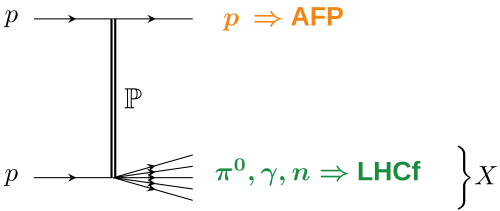
- (+ ZDC information)



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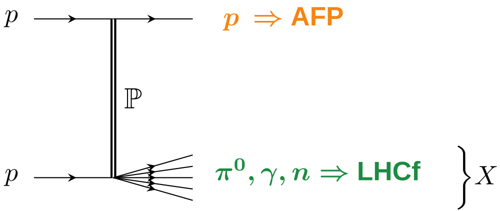


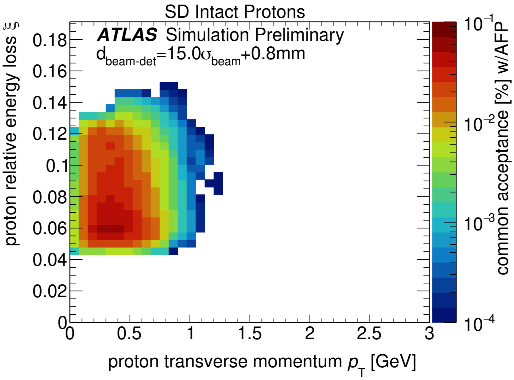
Advantages

- 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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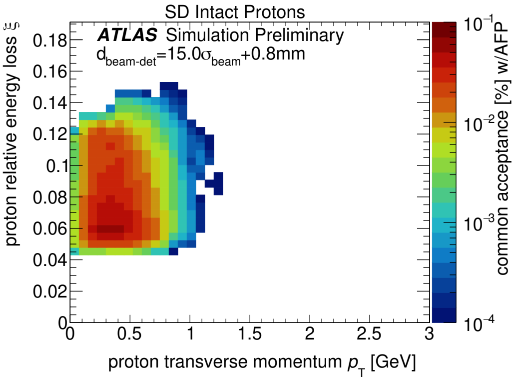
- Expected ~ 10 million events with run 3 data

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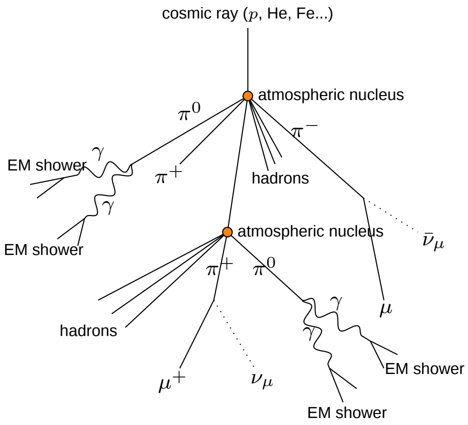
  - Generate common simulations
    - Common detector simulation of LHCf+ZDC
    - Simulation of proton transportation to AFP under special beam conditions

Outlook: Proton-Oxygen at the LHC

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

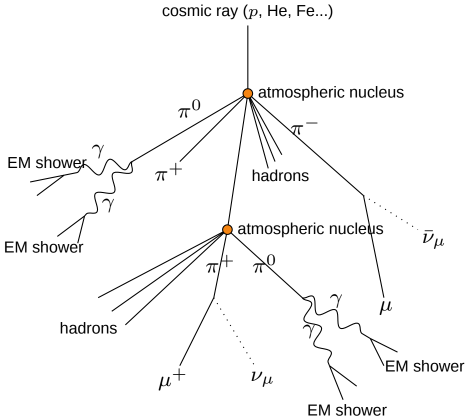


Outlook: Proton-Oxygen at the LHC

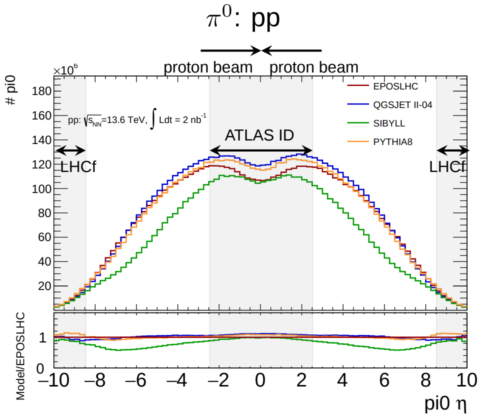
Proton-Oxygen collisions at the LHC for the first time in 2025!

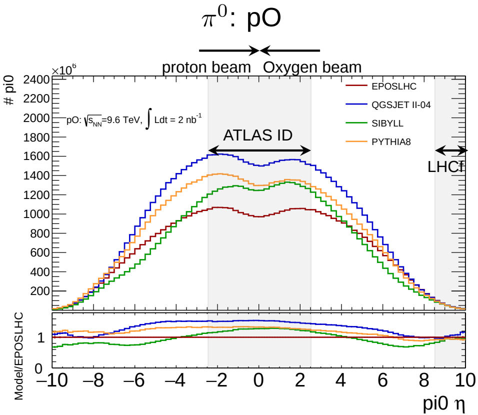
- Again, the entire set of detectors will join the run:
  - $\rightarrow$ ATLAS, LHCf, ZDC and AFP

$\Rightarrow$ Preparatory and feasibility studies ongoing!



Generator Predictions for pO



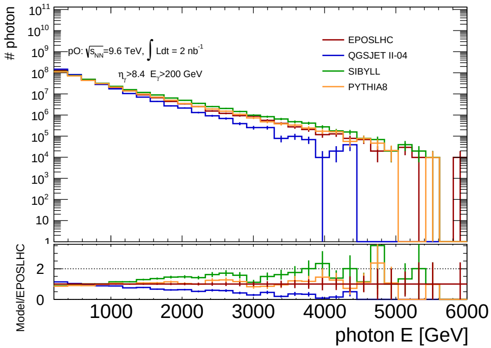


→ models show similar behaviour in central region (have been tuned there)

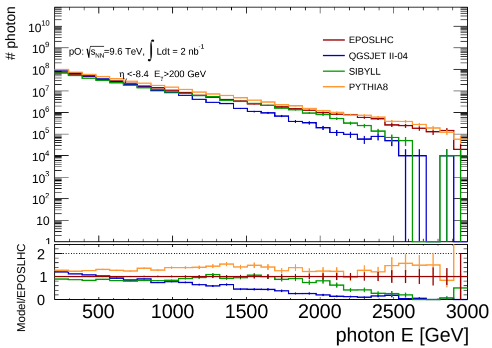
→ Huge differences between models in the entire η-spectrum

Generator Predictions for pO

Proton remnant side:



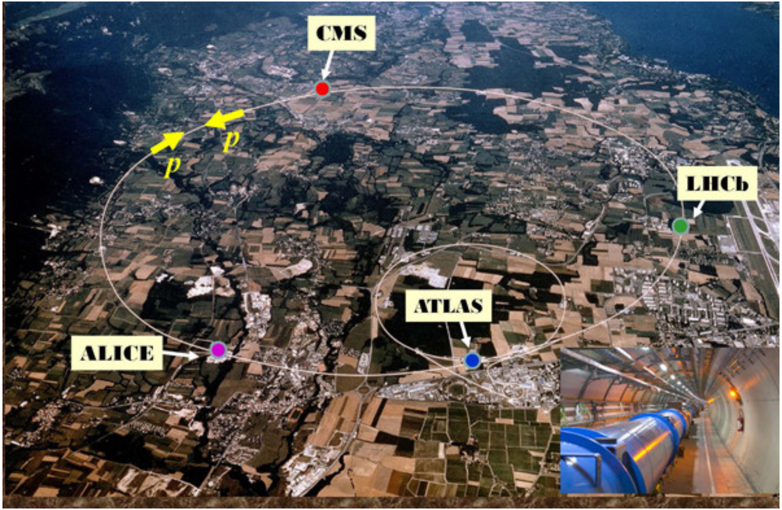
Oxygen remnant side:



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

What about other LHC experiments?

The Large Hadron Collider



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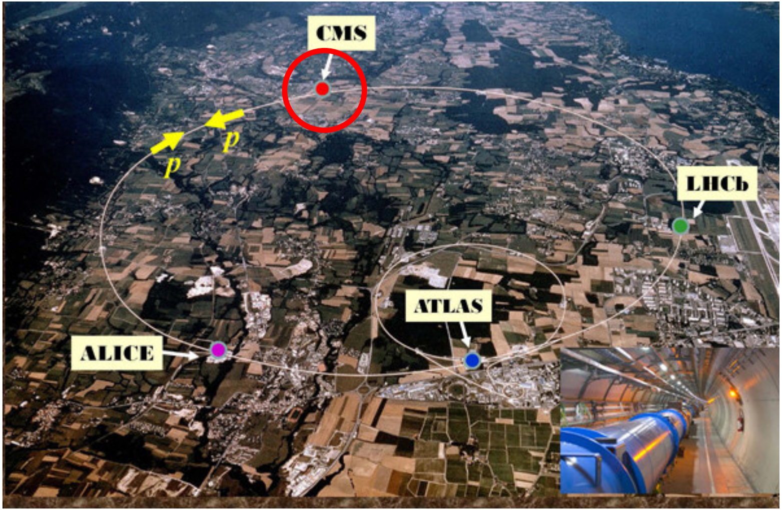
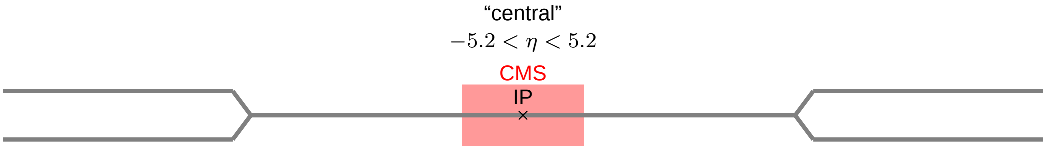


Forward Experiments around CMS



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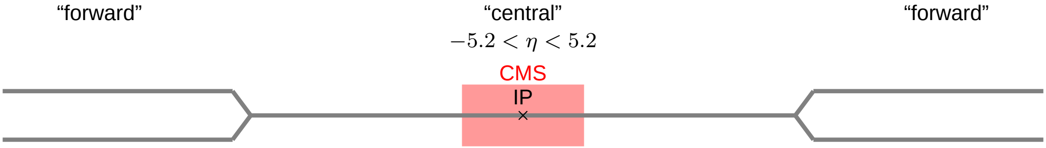

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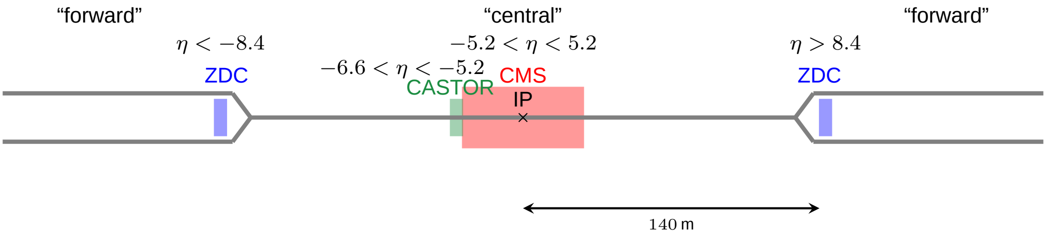

- Calorimeters: CASTOR, ZDC

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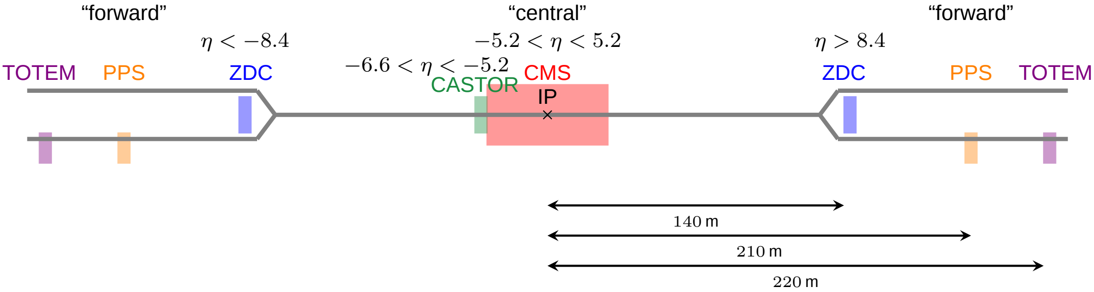

- Calorimeters: CASTOR, ZDC
- Proton detectors: PPS, TOTEM

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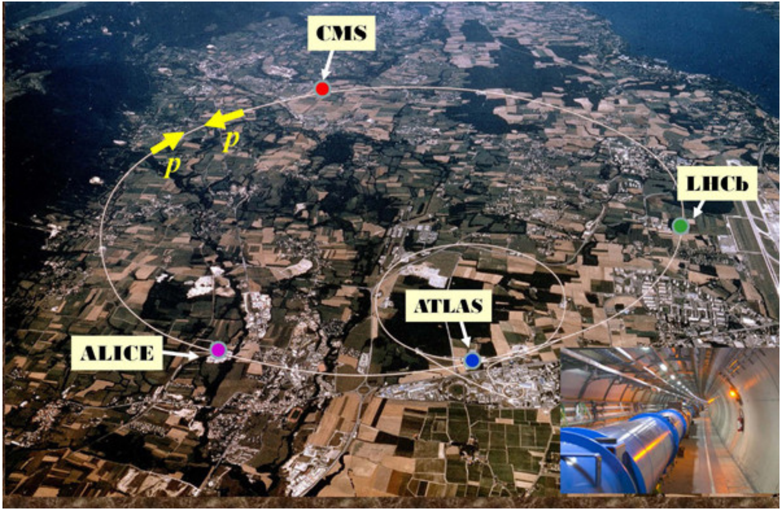

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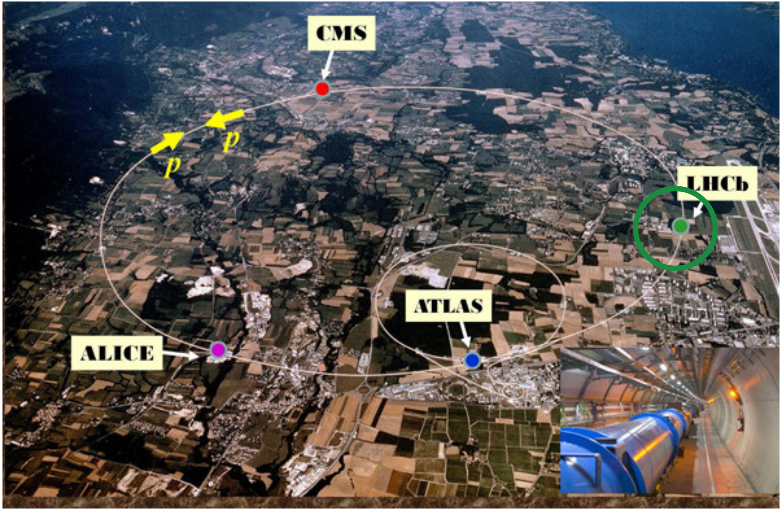
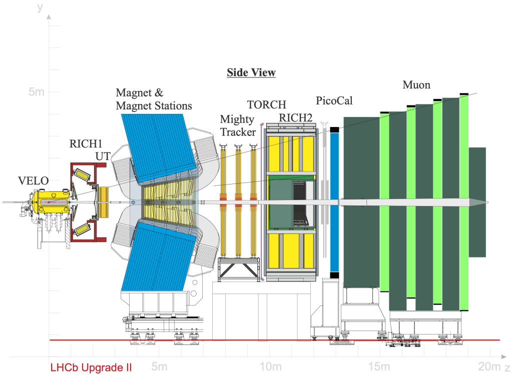


LHCb Detector

- 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)



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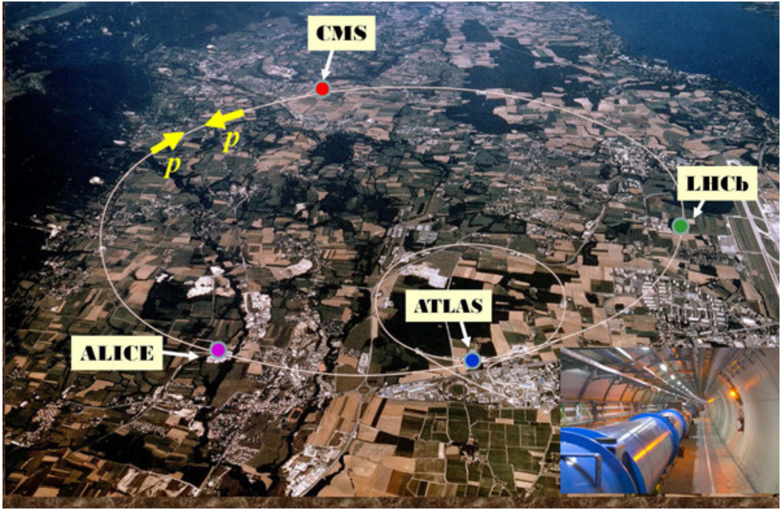

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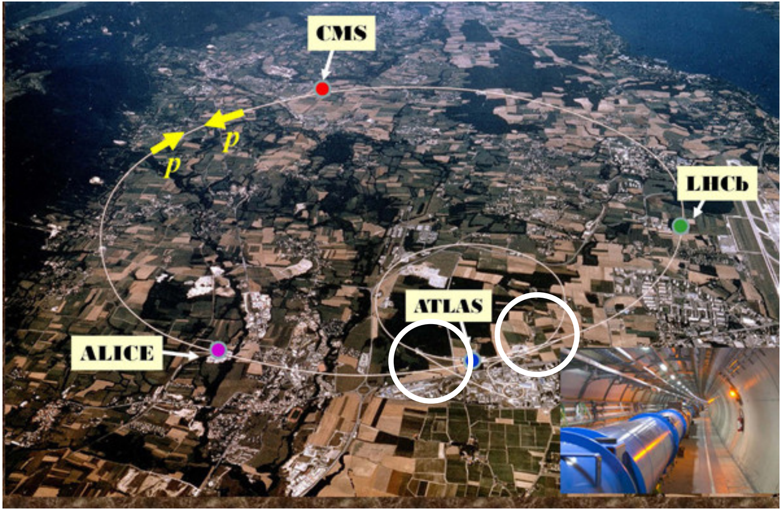

Forward Neutrinos

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FASER & FASERν

- New LHC experiment
  $\rightarrow$ first data in 2022
- 480 m downstream of the ATLAS IP
- On beam axis ($\eta > 9.1$)
- Long lived light particle searches & forward TeV neutrinos (+ flavour info)

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Successor experiments will be part of the Forward Physics Facility during HL-LHC!

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- Lot's of starting and ongoing work $\rightarrow$ **Stay tuned!**