Constraining hadronic models using pO collisions at the LHC with proton/neutron tagging

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Outline

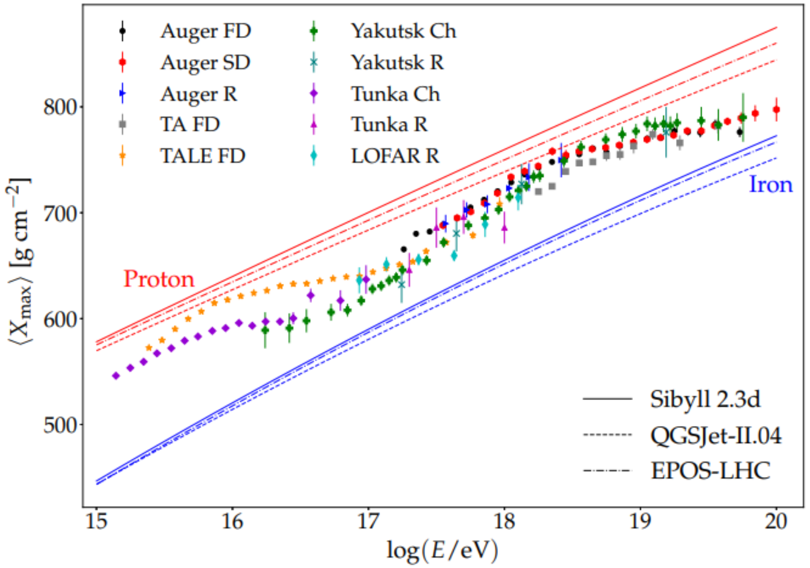
- Accelerating Oxygen ions at the LHC
- Forward proton and neutron tagging at the LHC
- Constraining models of hadronic showers using pO collisions
- Production of light isotopes on pO and OO collisions

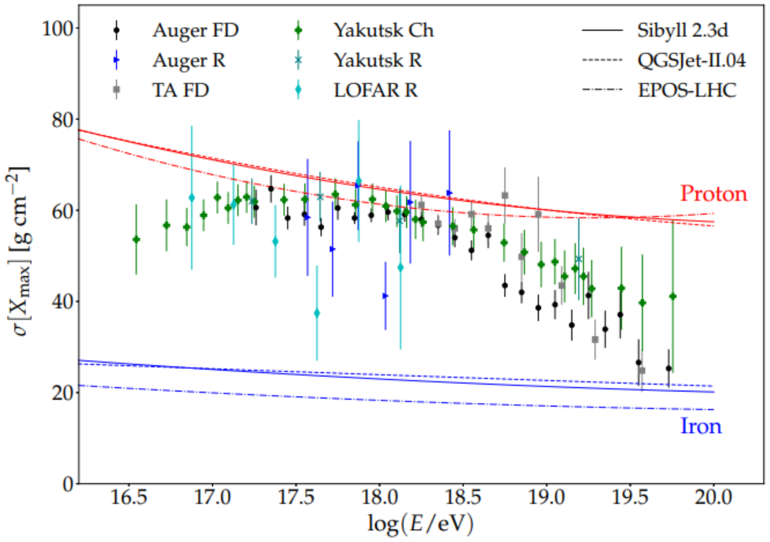
Accelerating Oxygen ions at the LHC

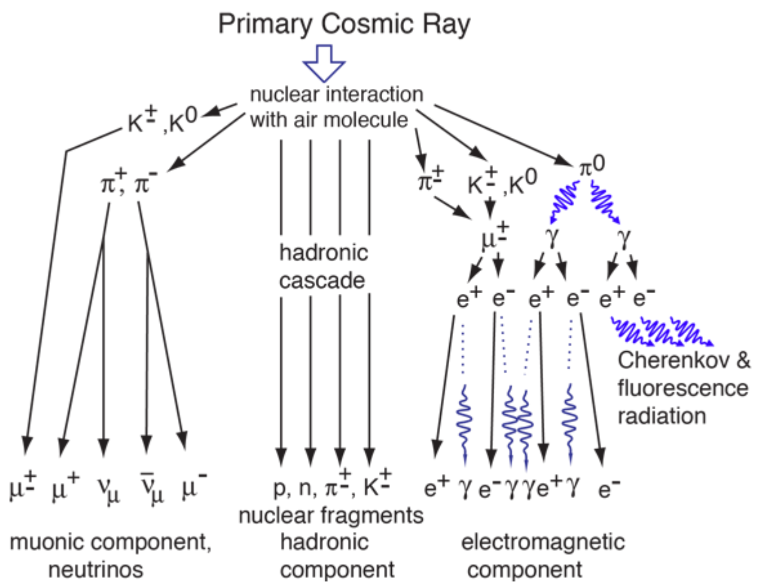
Motivation

Oxygen ions at the LHC

- Oxygen ions (^{16}O) will be injected at the LHC for the first time.
- pO run is scheduled to take place in 2024, with a run duration of a few days
- The main goal of the run is to provide input for cosmic ray modeling





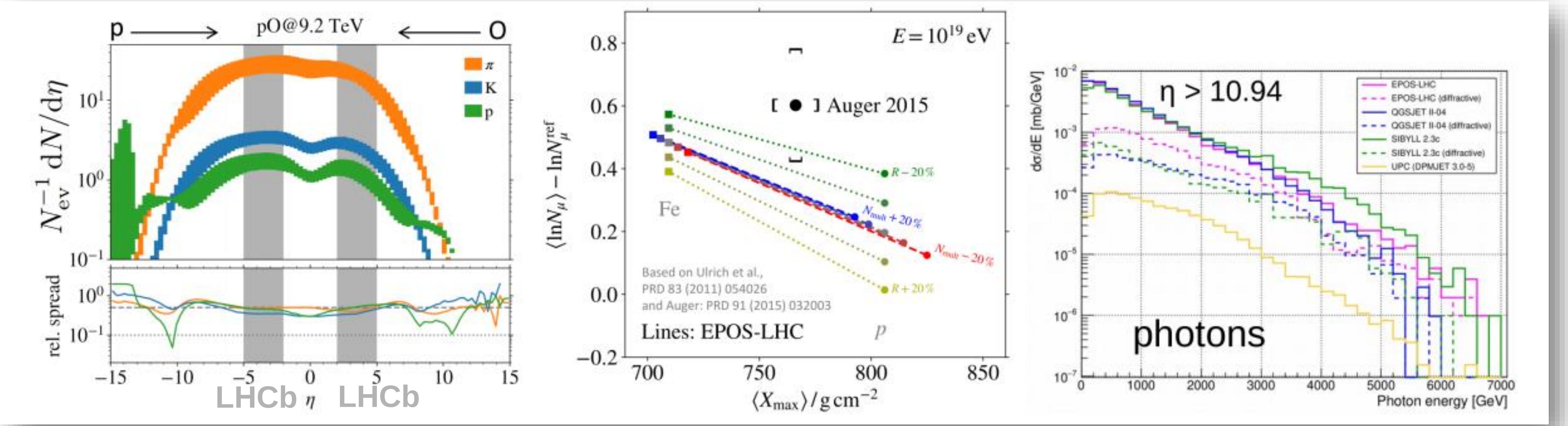


[A. D. Supanitsky Galaxies 10 (2022) 3, 75]

[http://hyperphysics.phy-astr.gsu.edu/hbase/Astro/cosmic.html]

Opportunities of OO and pO collisions at the LHC

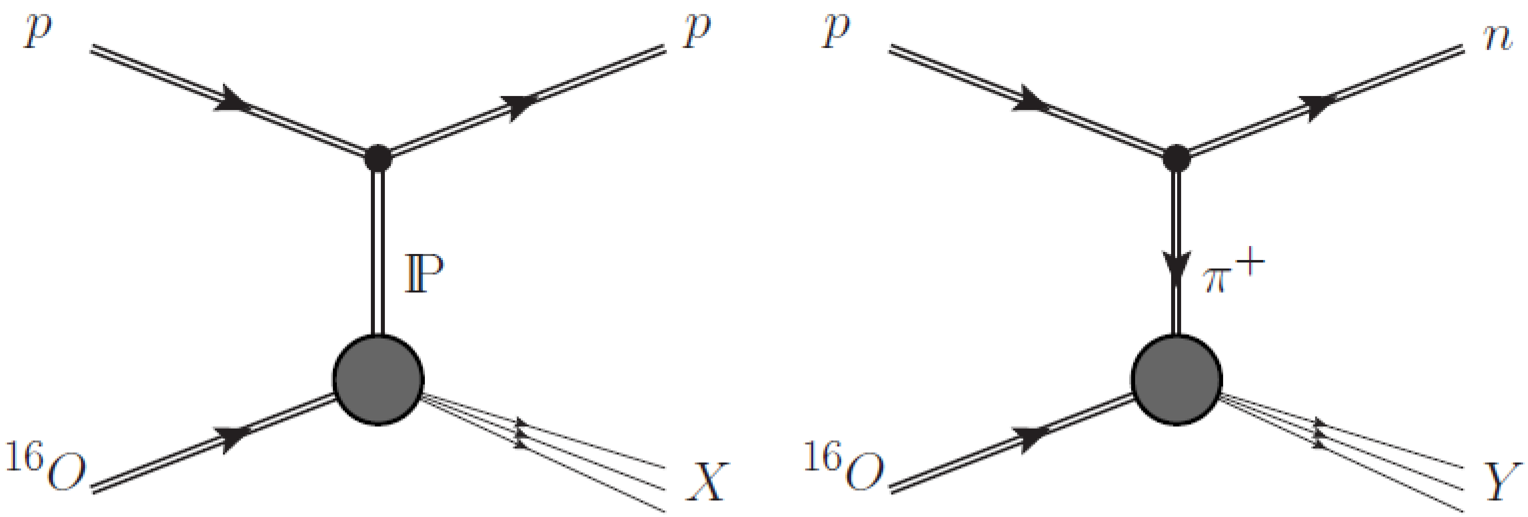
- Discussed in 2021 at a dedicated workshop at CERN (http://cern.ch/OppOatLHC)
- Summary available here 2103.01939



Constrain hadronic models with pO collisions

Extending current research program

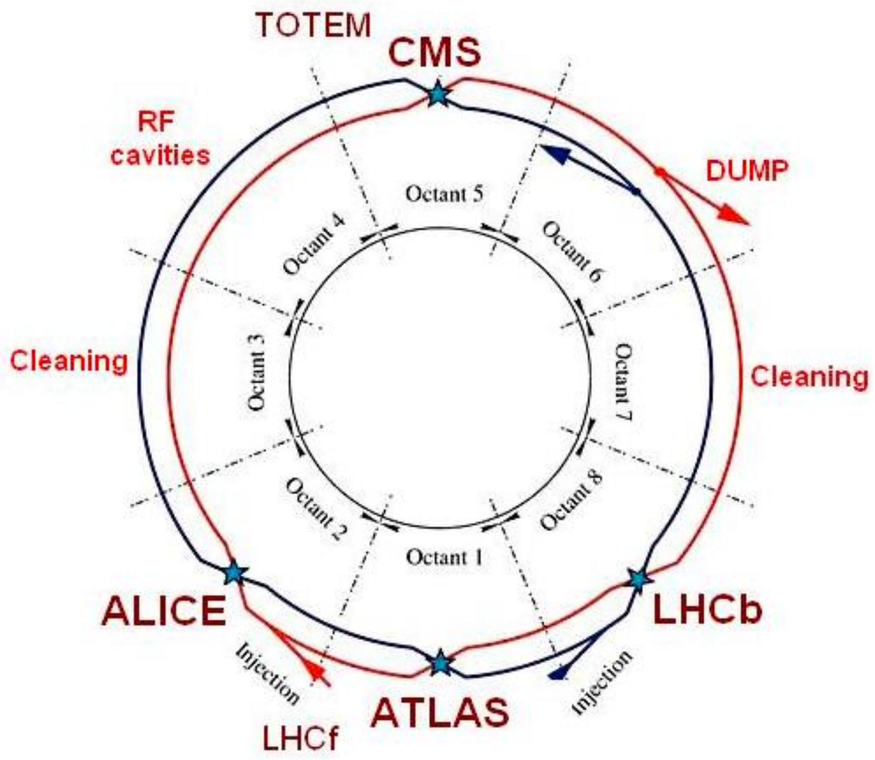
- Besides the standard research program involving pO / OO interactions, we suggest utilizing the forward proton and forward neutron detectors to expand the probed phase-space (this talk)



Forward proton and neutron tagging at the LHC

The Large Hadron Collider

- The most powerful particle accelerator and the largest CERN accelerator complex.
- Designed to accelerate hadrons (protons/heavy ions) up to 7 TeV per proton beam
- 4 Interaction points in the center of 4 detectors (ATLAS, ALICE, CMS, LHCb)



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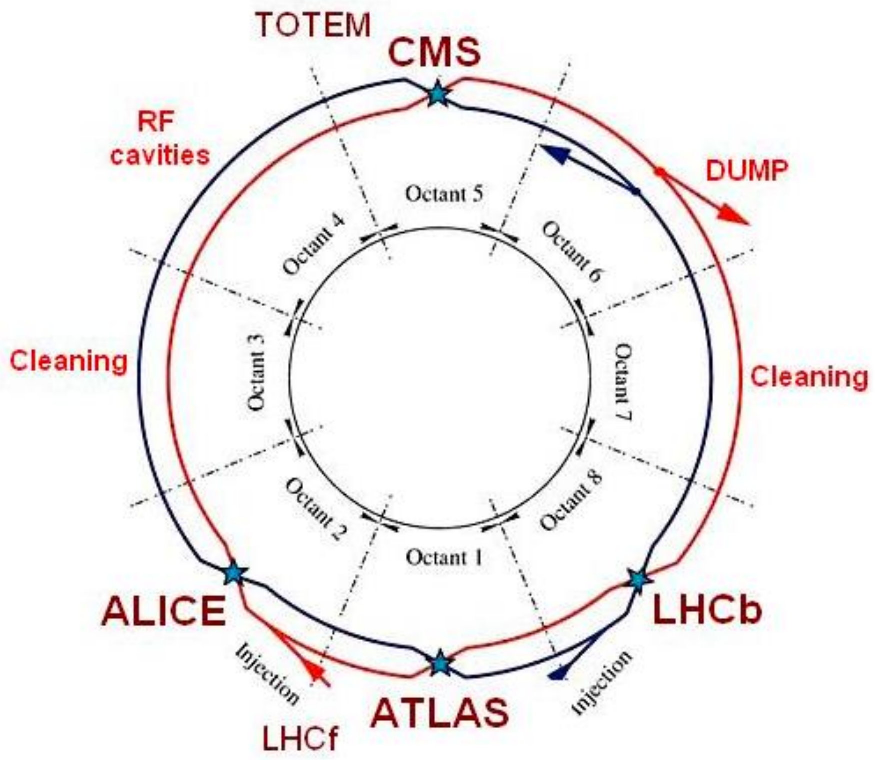
- In practice LHC comprise more than 4 experiments
- Example: neutrino physics (see Neutrino physics and astrophysics parallel session)
  - SND@LHC (M. Güler's talk on Monday)
  - FASER (Y. Takubo's talk on Monday)



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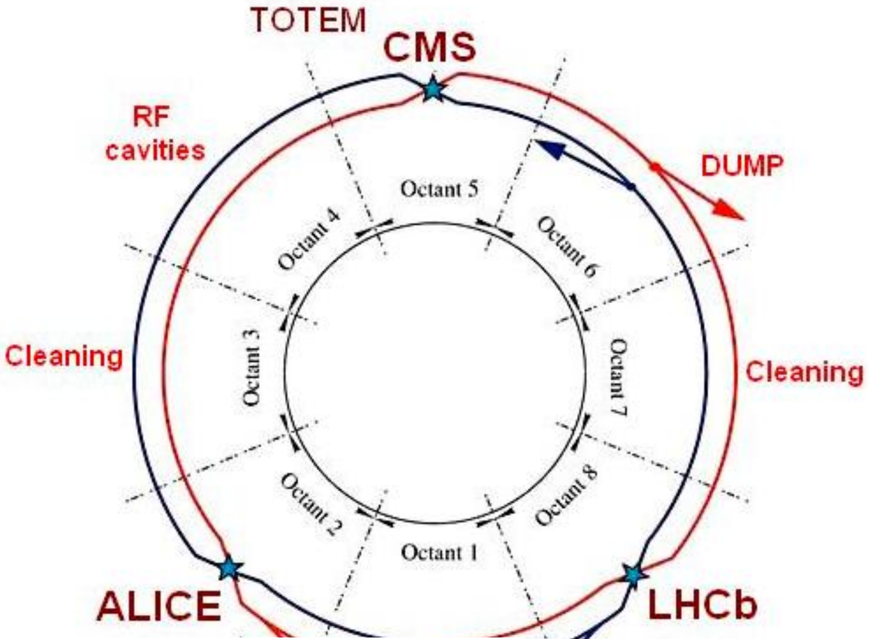

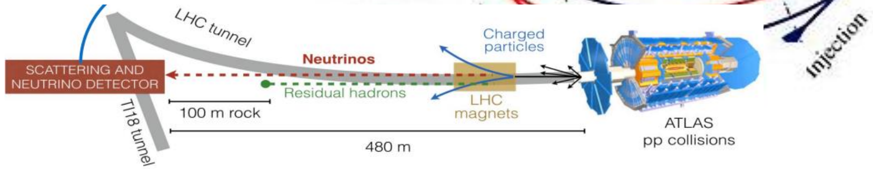

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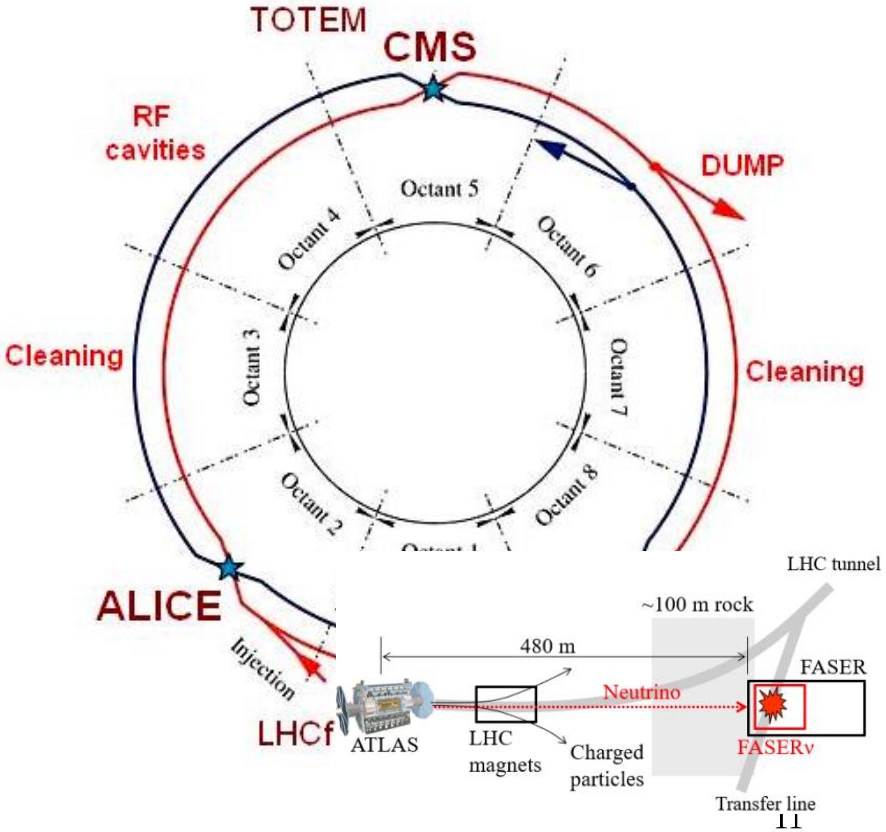
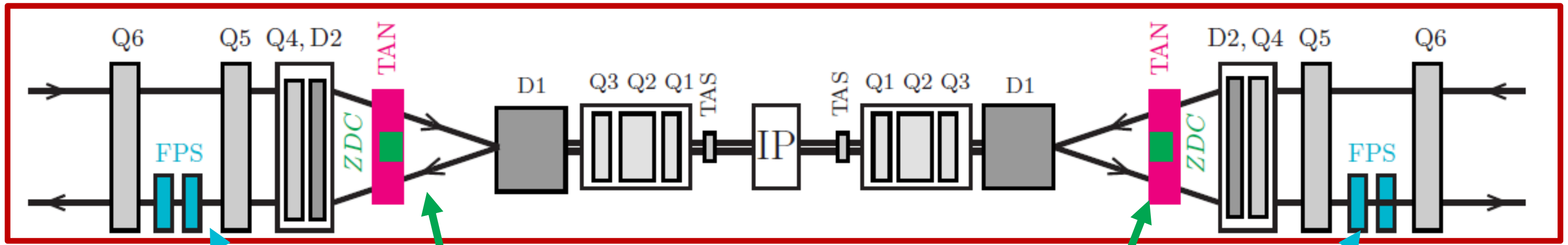


Forward detectors at the LHC

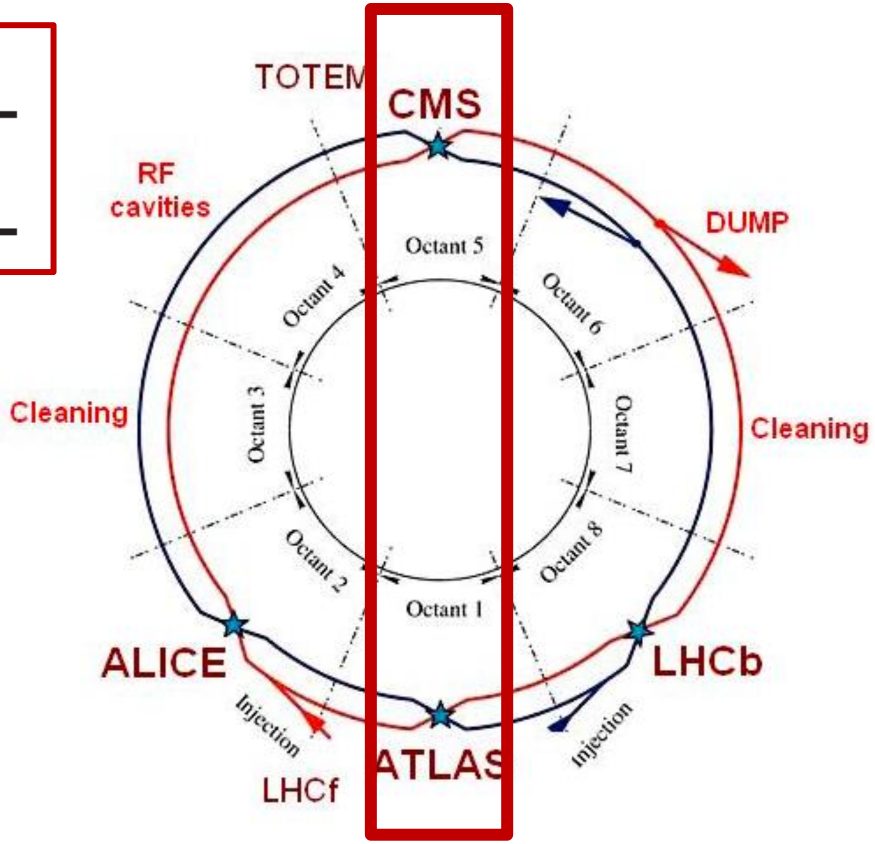
- Two interaction points (CMS / ATLAS) are equipped with forward neutron / proton detectors at about 140 m / 220 m from the IP, respectively on both sides.



Interaction point 1or 5
(ATLAS or CMS)

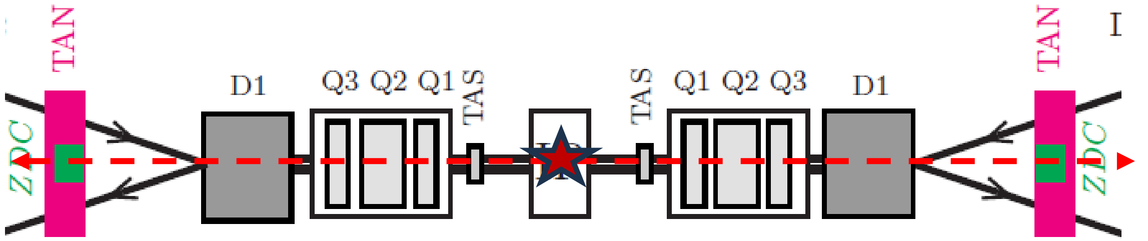
Neutron detectors ~140m
(Zero Degree Calorimeter)

Proton detectors ~220m
(Forward Proton Spectrometer)



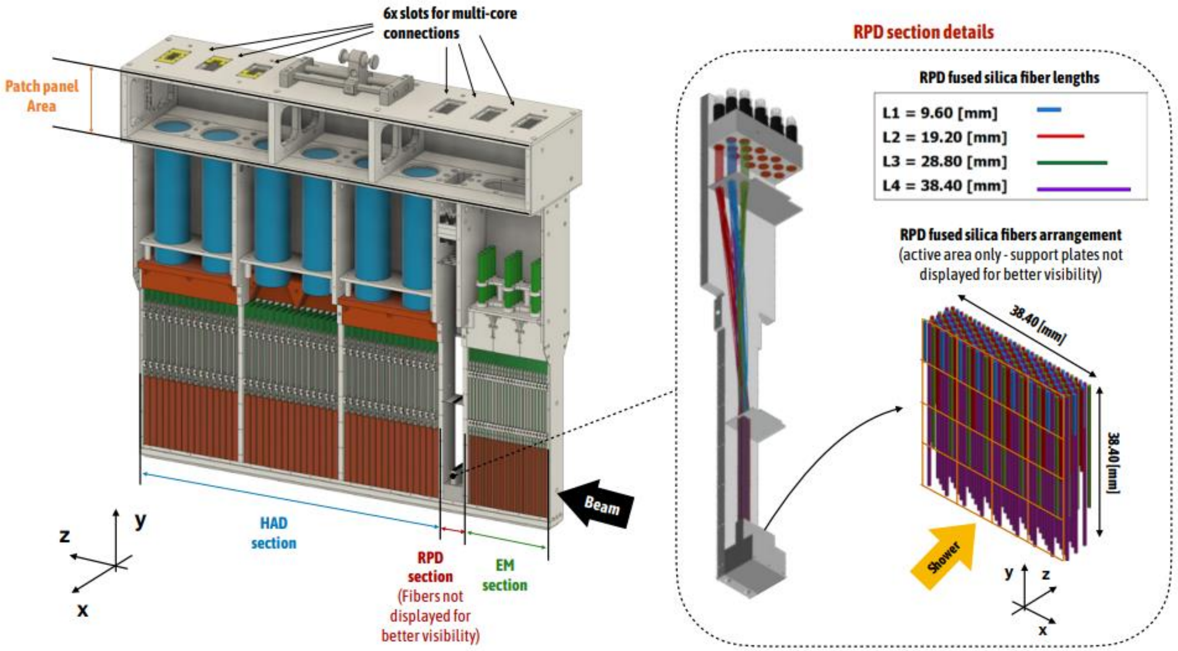
Forward neutron detectors

- The Zero Degree Calorimeter (ZDC) aims to detect forward neutral particles produced during heavy ion (AA or pA) collisions
- Located in the Target Absorber for Neutrals (TAN) ~ 140 m from the IP



ZDC Final design:

- EM section – photons, ~30 rad. length
- Reaction Plane Detector (RPD) – transverse profile of neutron showers
- Had section – neutrons (3 modules each ~1.15 int. length)



Forward proton detectors

○ Forward Proton Spectrometers (AFP/PPS):

- Intact protons lose a fraction of momentum ($\boldsymbol{\xi = \Delta p_Z/p}$) and are scattered at small angles ($\boldsymbol{\theta_x^*, \theta_y^*}$) $\rightarrow$ they are deflected away from the beam and measured by the spectrometers

$$\delta x(z) = x_D(\xi) + v_x(\xi)x^* + L_x(\xi)\theta_x^*$$
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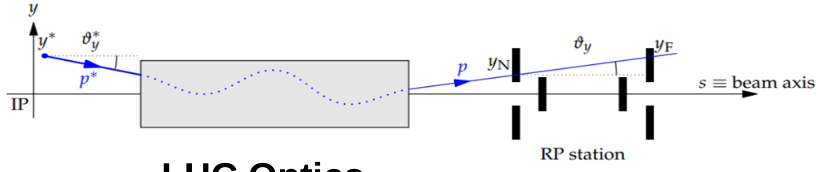
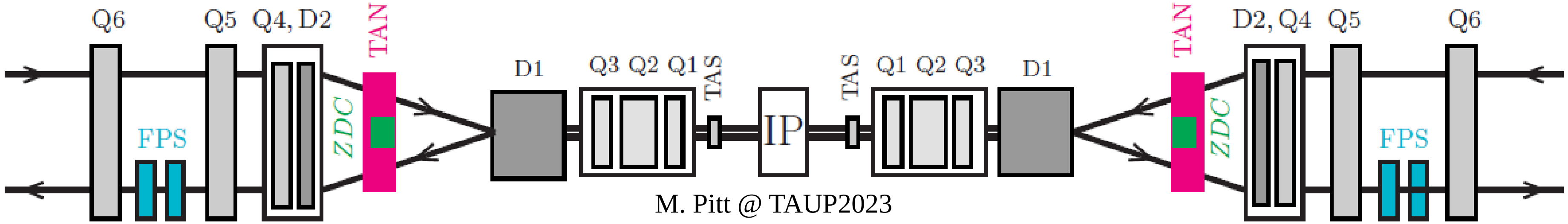


LHC Optics



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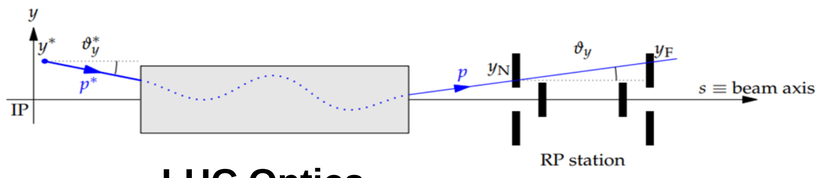

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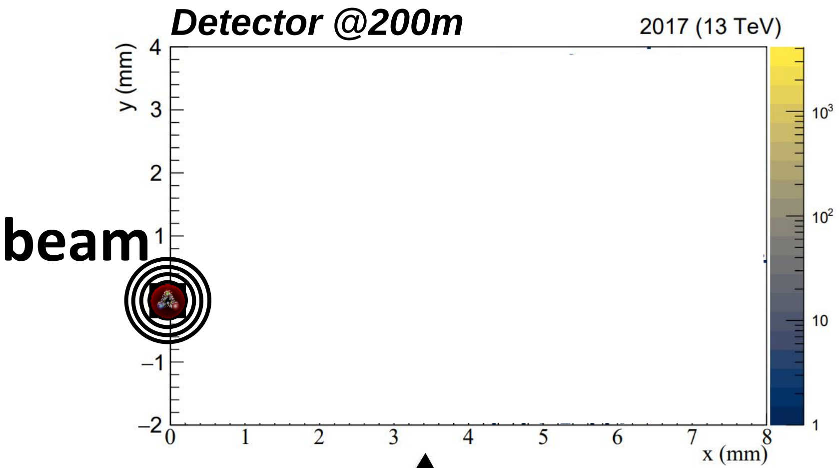

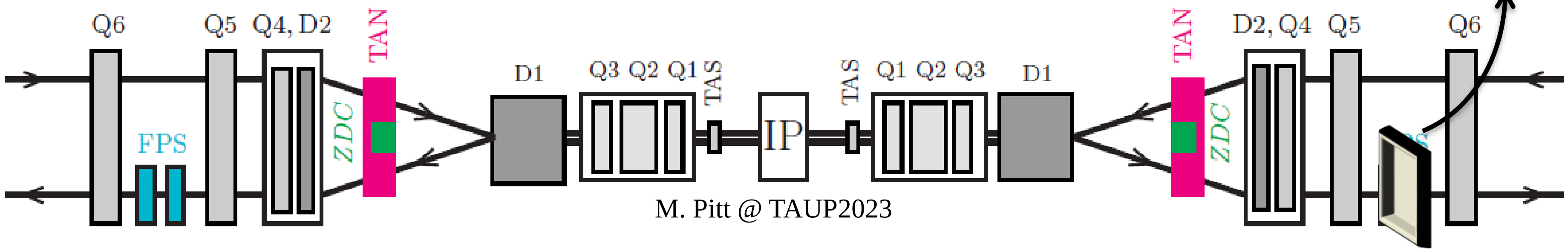

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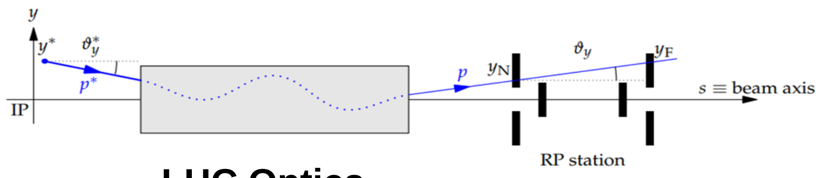

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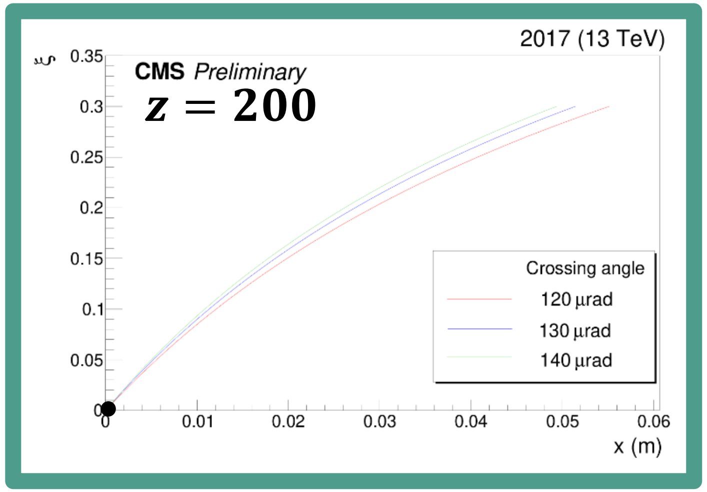

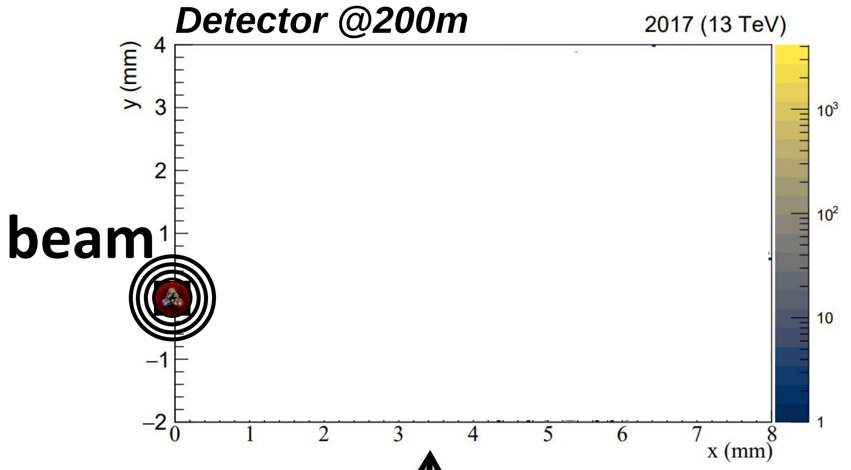

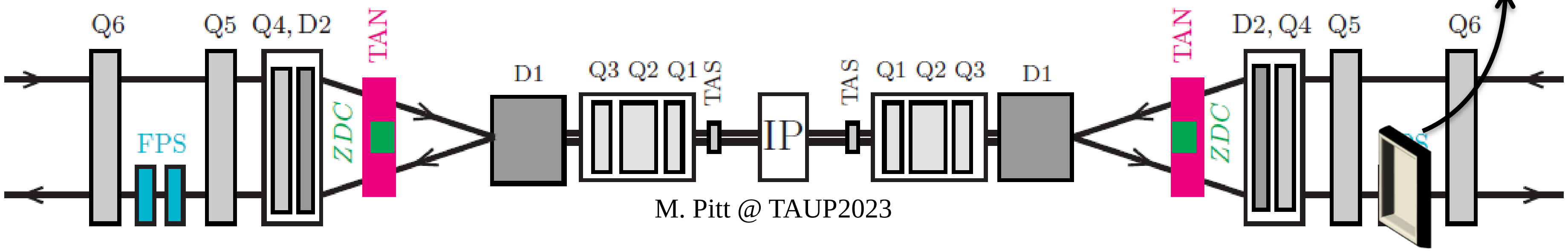

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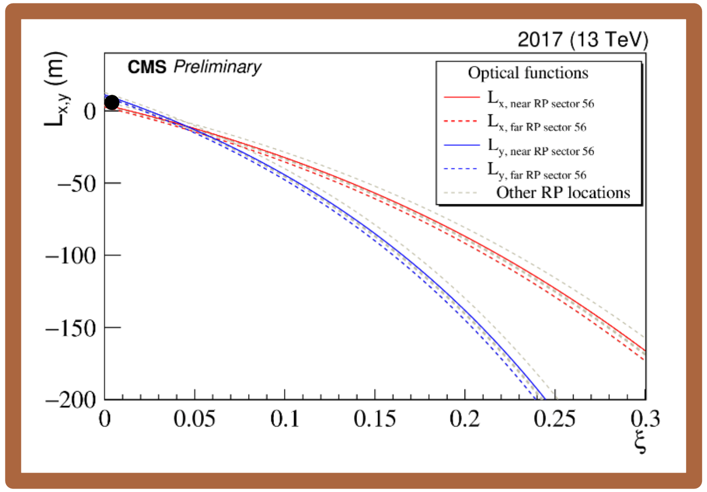

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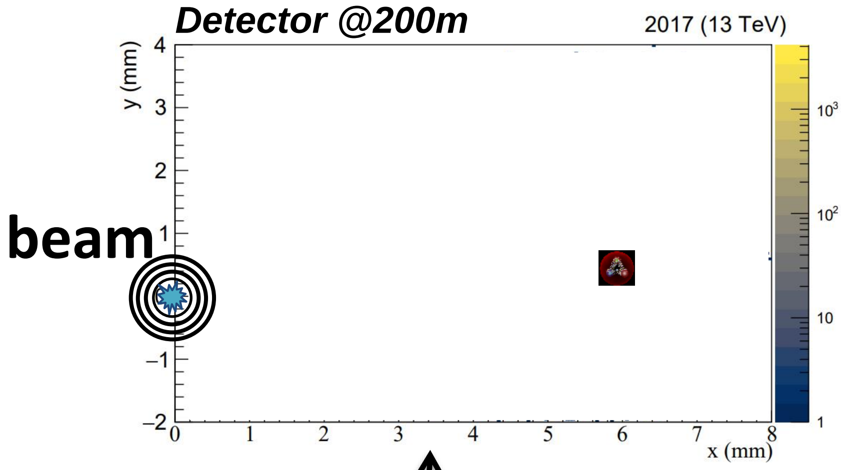

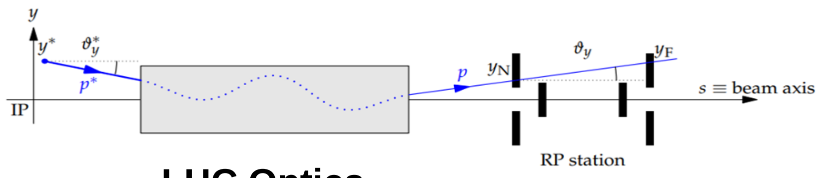

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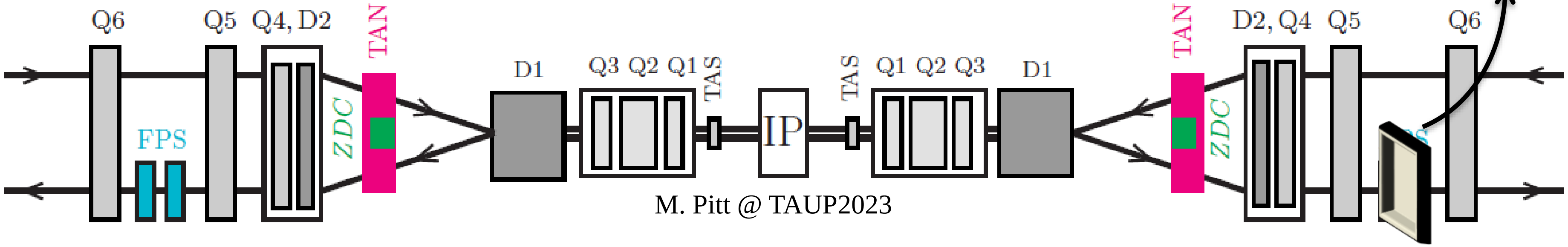

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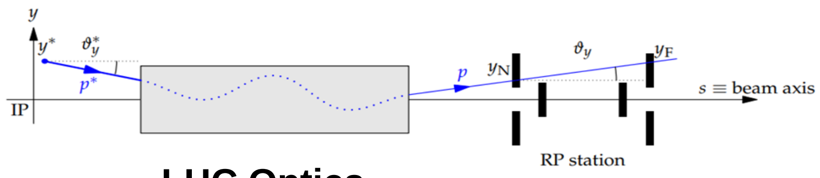
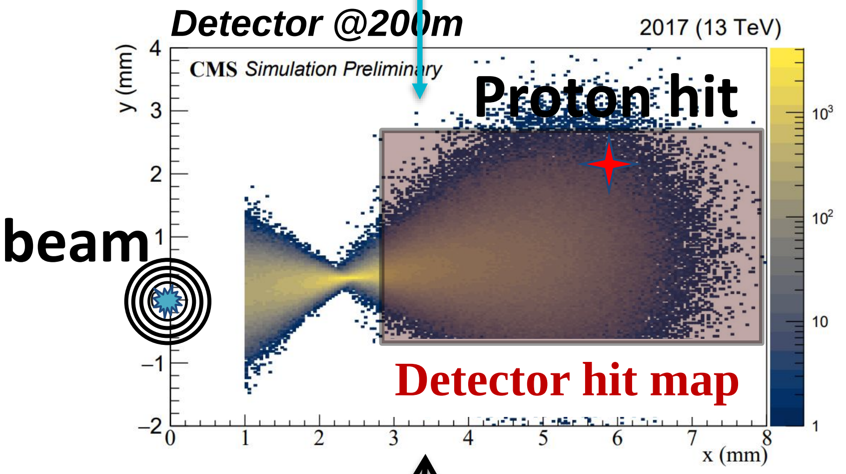


LHC Optics

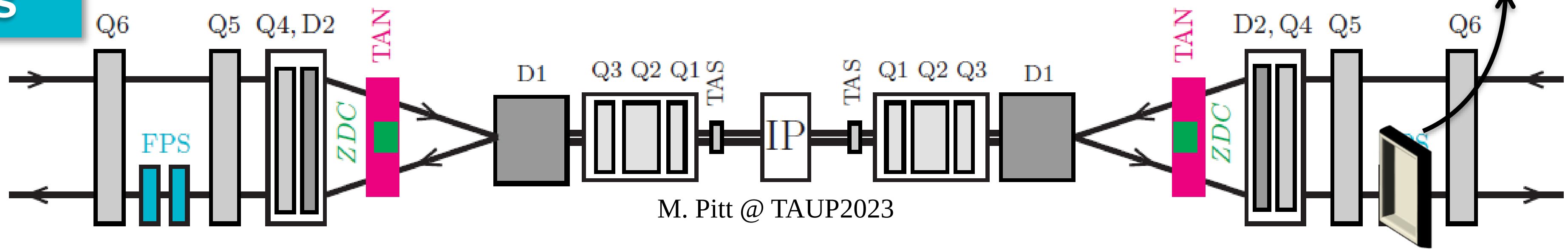
acceptance
2.5% < ξ < 15%

min distance from the beam

Collimators



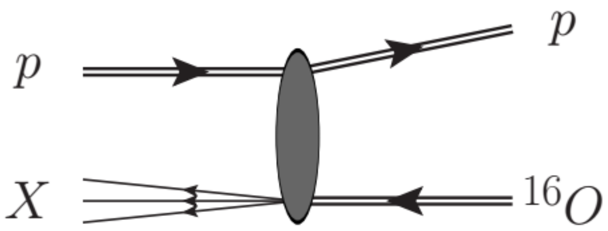
2 stations

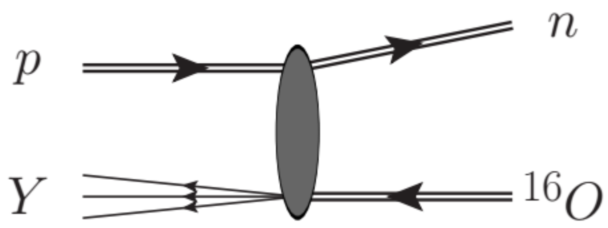


Constraining models of hadronic showers using pO collisions

Forward protons / neutrons in p-O collisions

- High energy protons and neutrons emerge from p-O interactions
- By measuring the production rates, and event kinematics one can constrain their modeling





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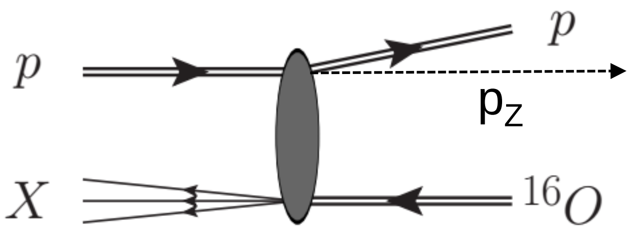

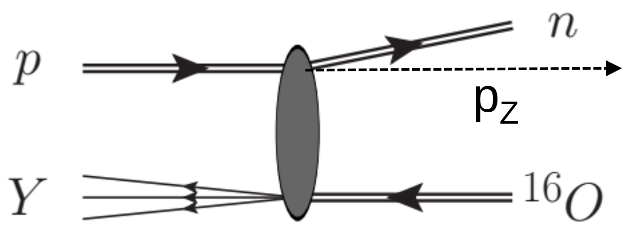

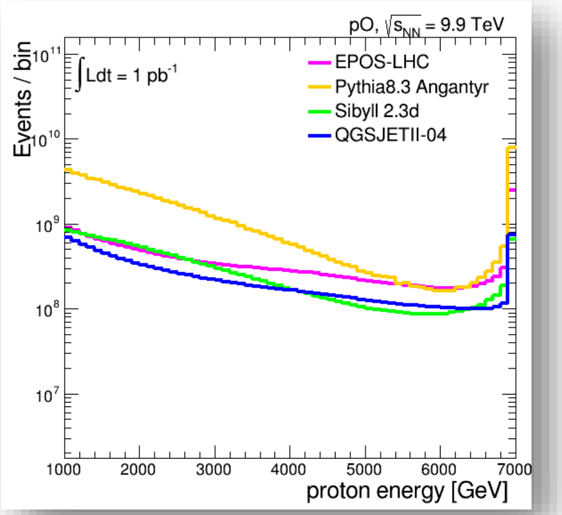

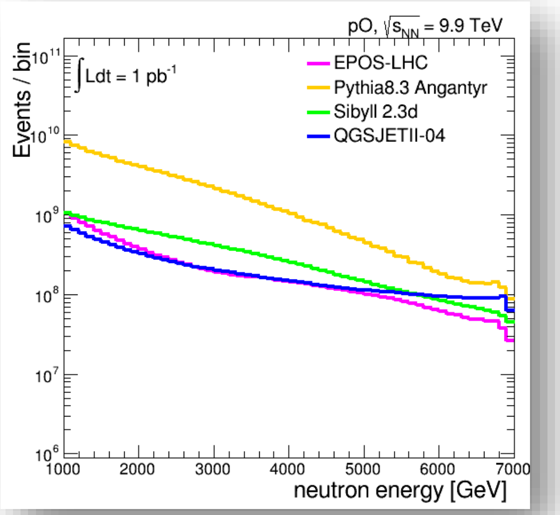

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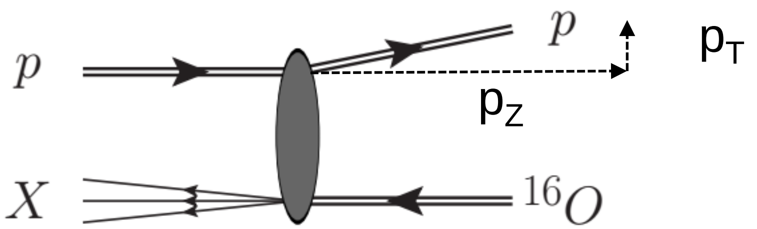
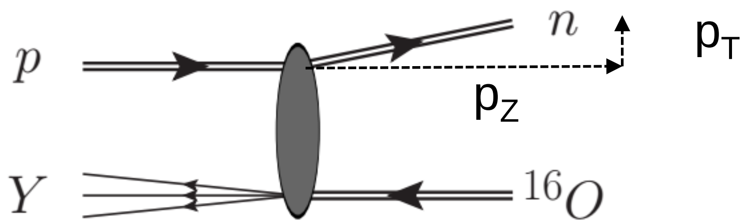
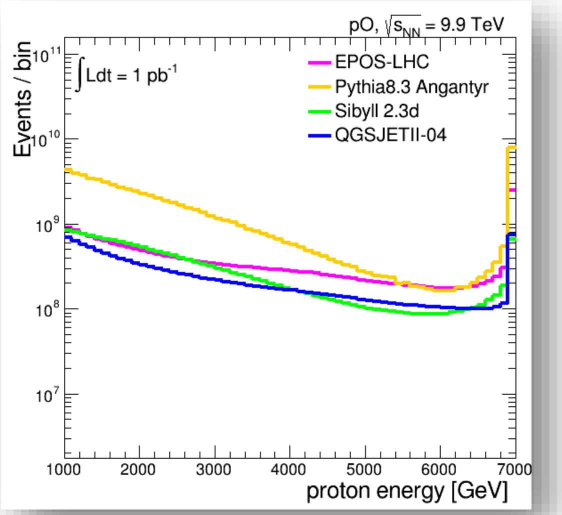
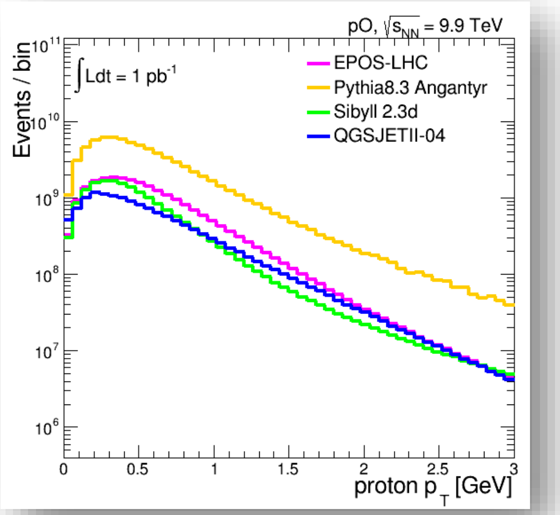
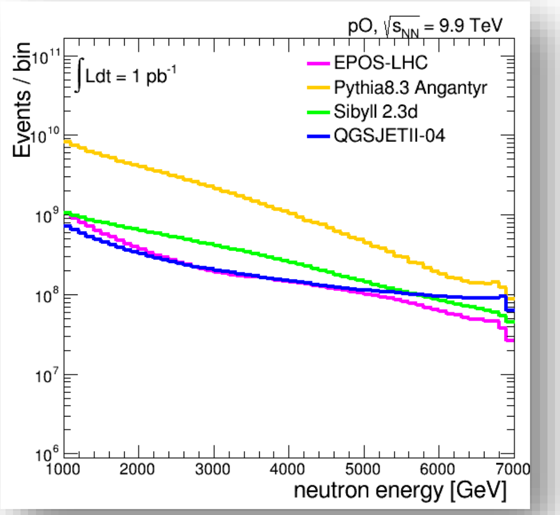
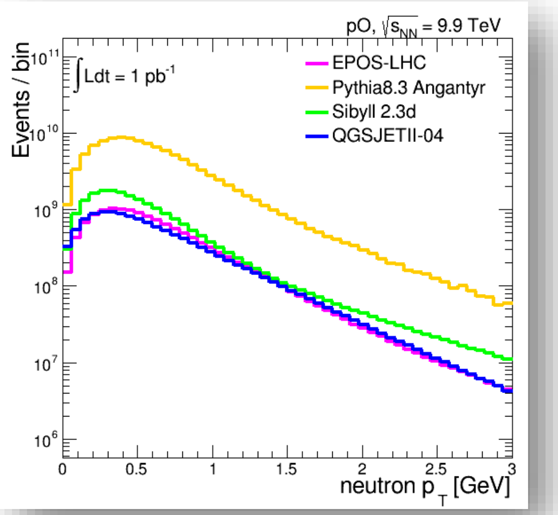




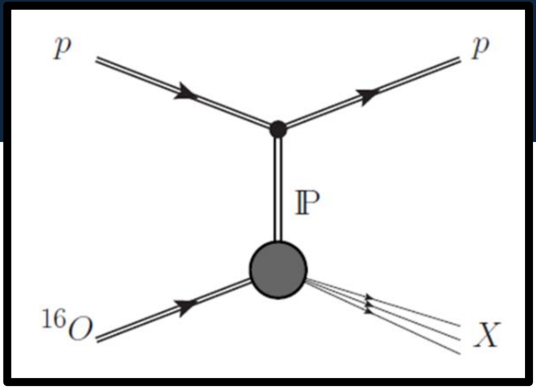




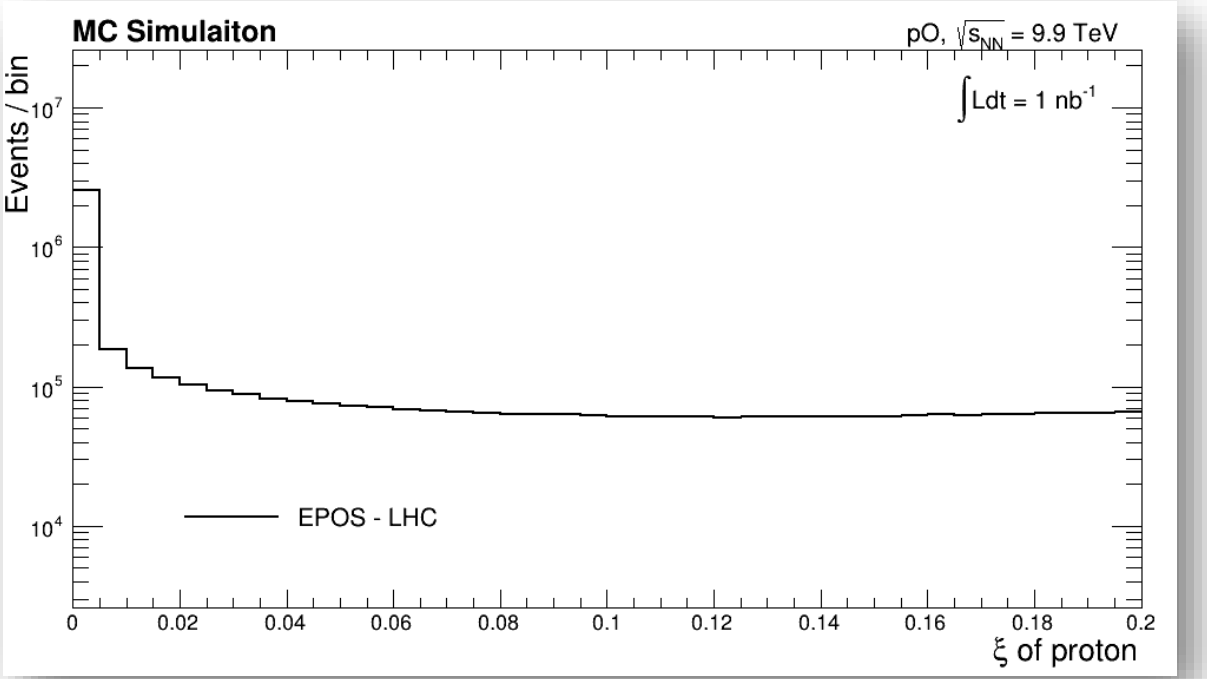


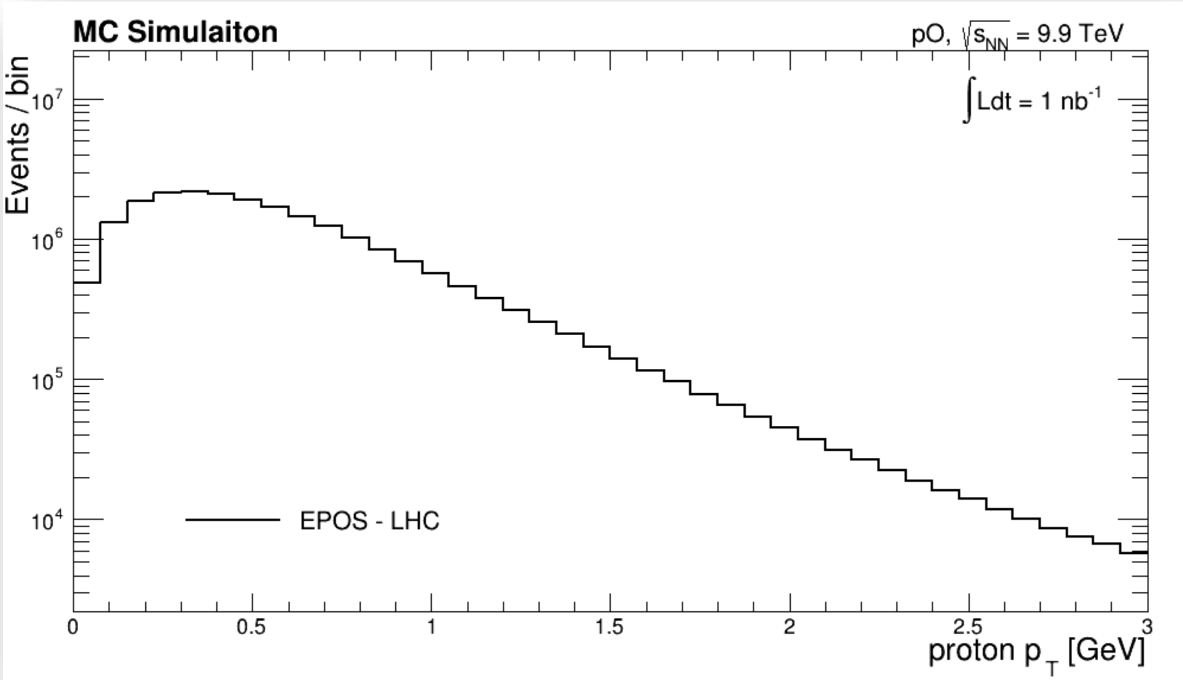


Proton kinematics



- About ~20% of p-O interactions will have an intact proton (ξ ~ inelasticity K)





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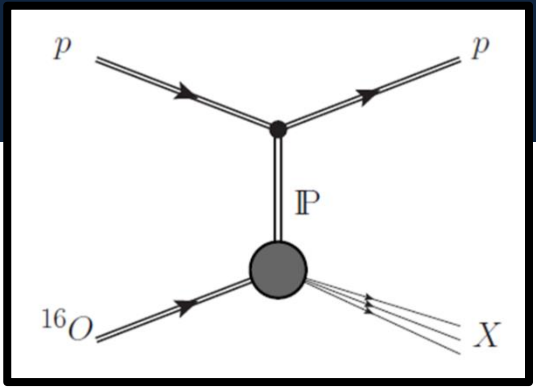

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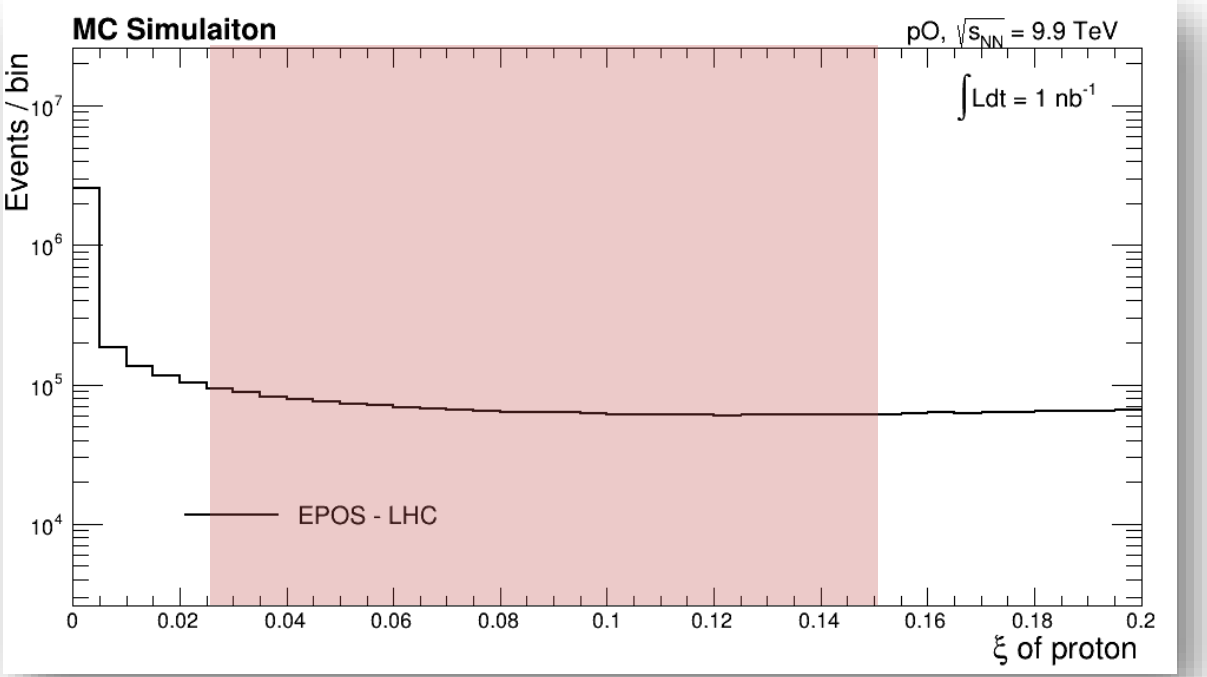
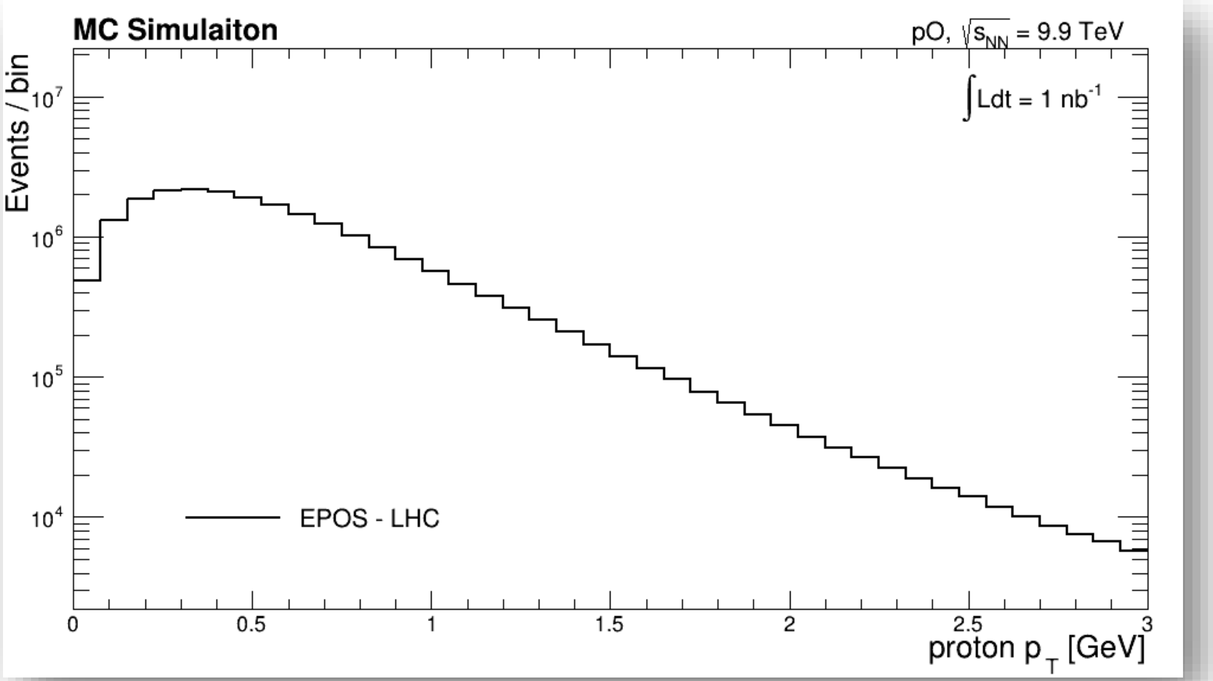
- In 2-4% of <u>all events</u> proton momentum loss is within 2.5% < ξ < 15%





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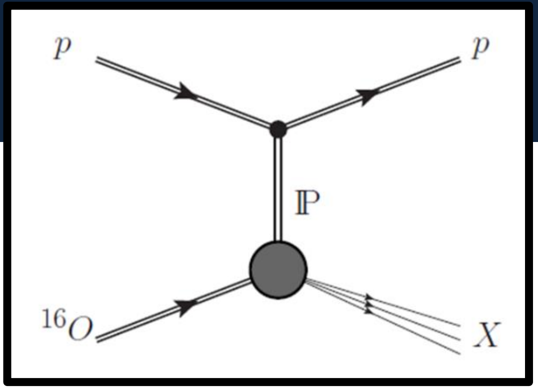

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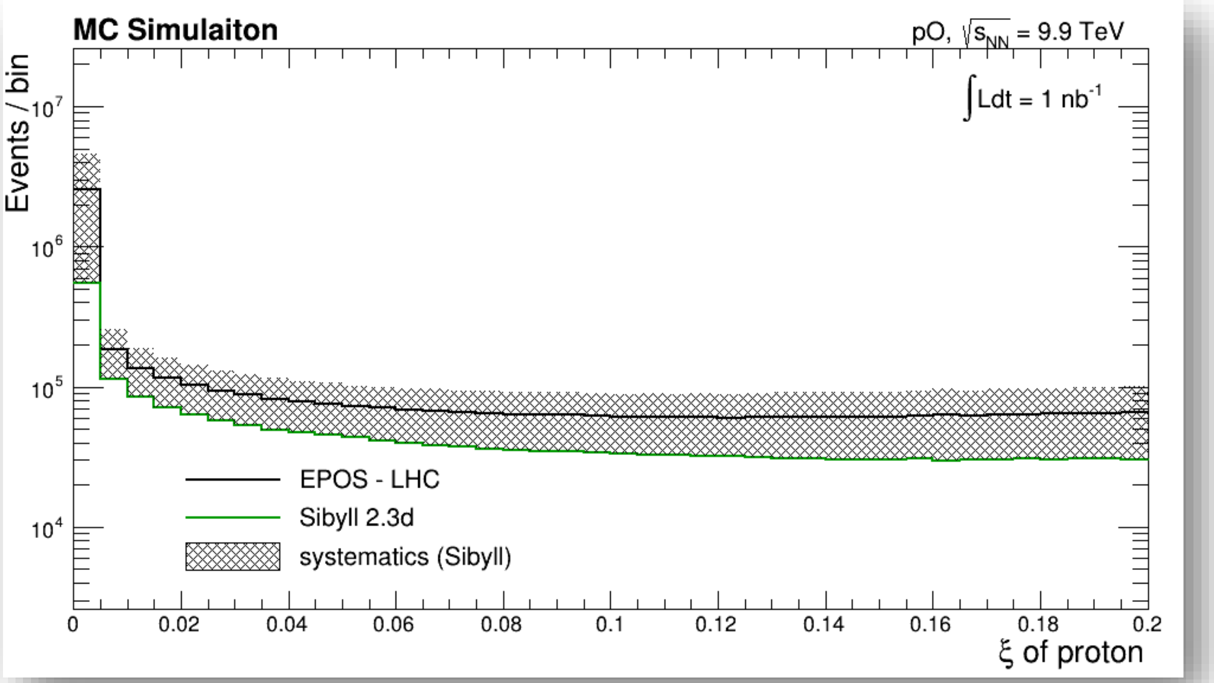
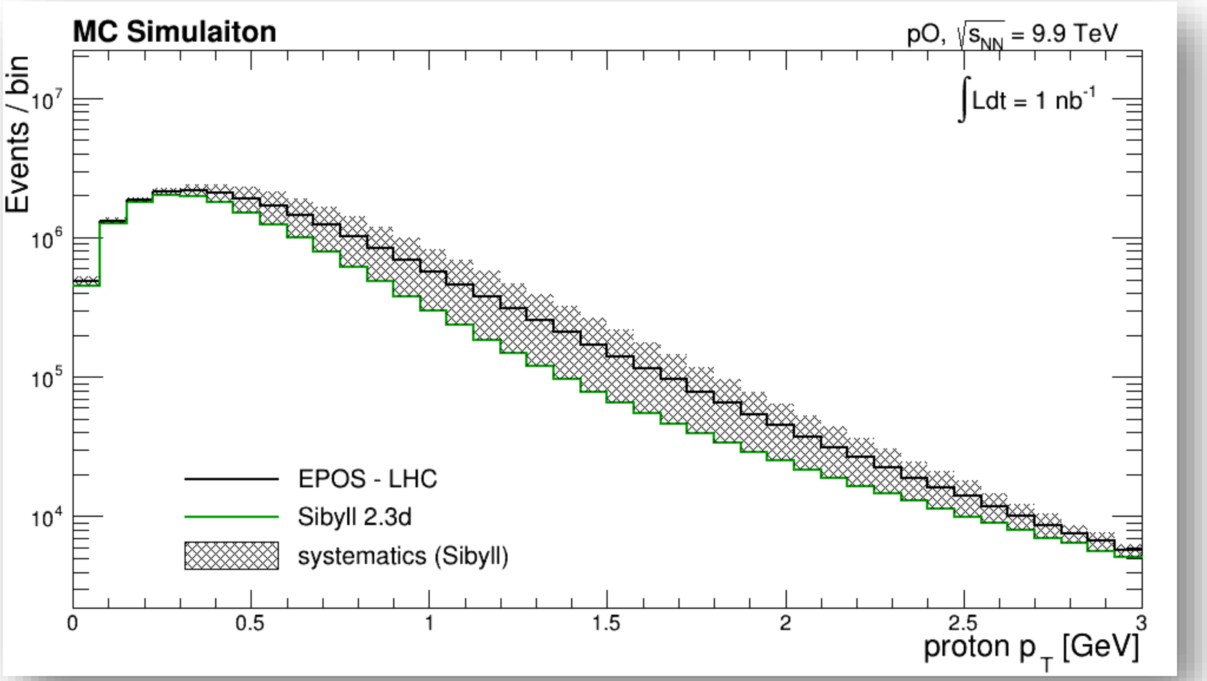
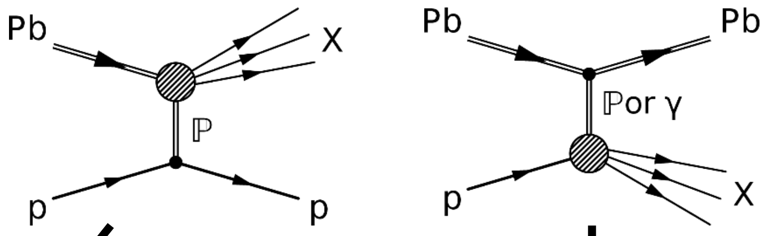
- Comparison between EPOS-LHC and Sibyll2.3d – some difference between the generators

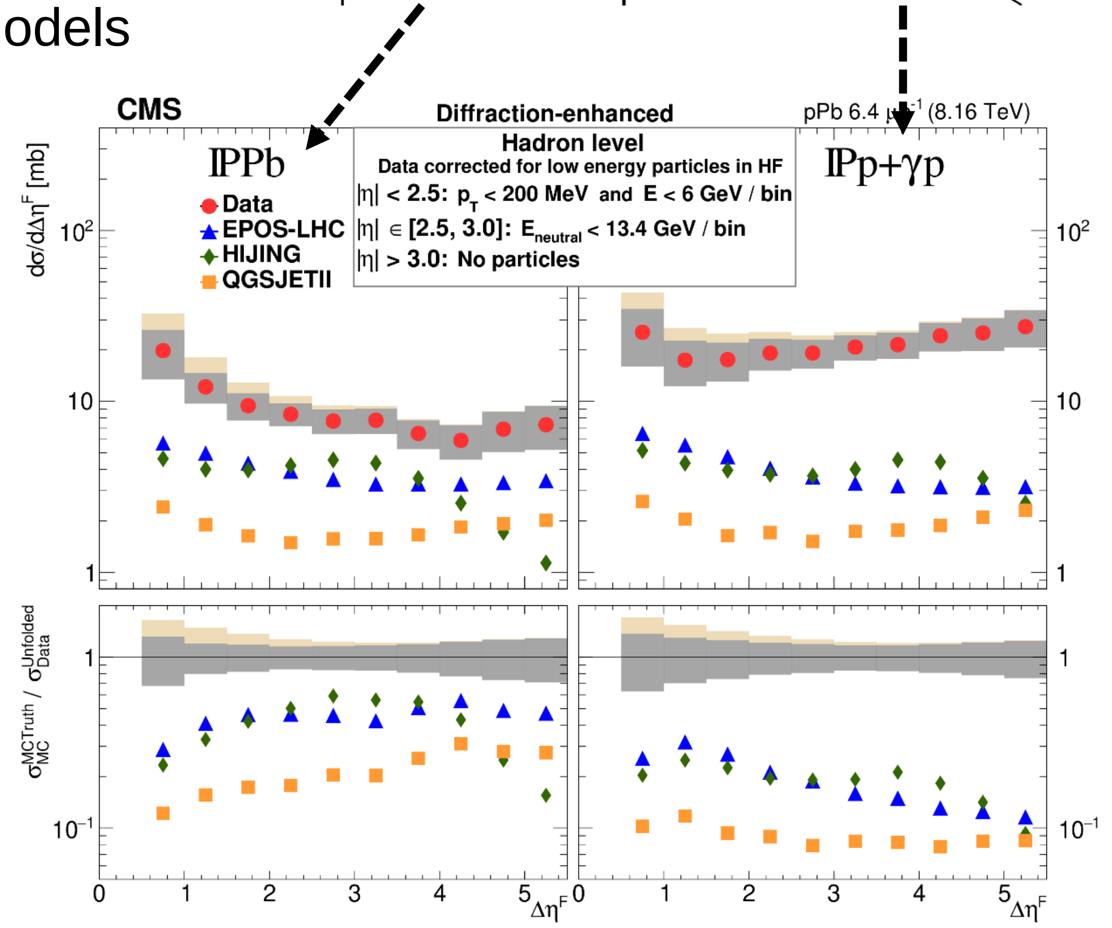


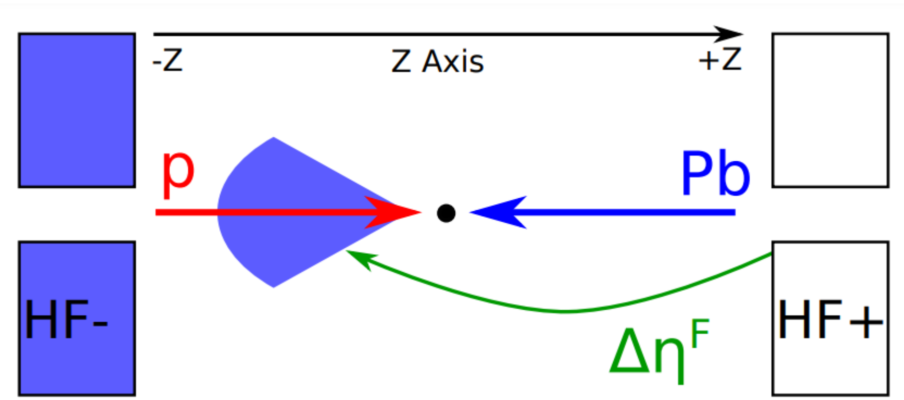


Rapidity gaps in color neutral exchange

- Events with a diffractive proton are characterized by the presence of large Rapidity Gaps (RG) (~ relative to the shower width)
- This component is weakly constrained in the current models (example from CMS pPb data arXiv:2301.07630)







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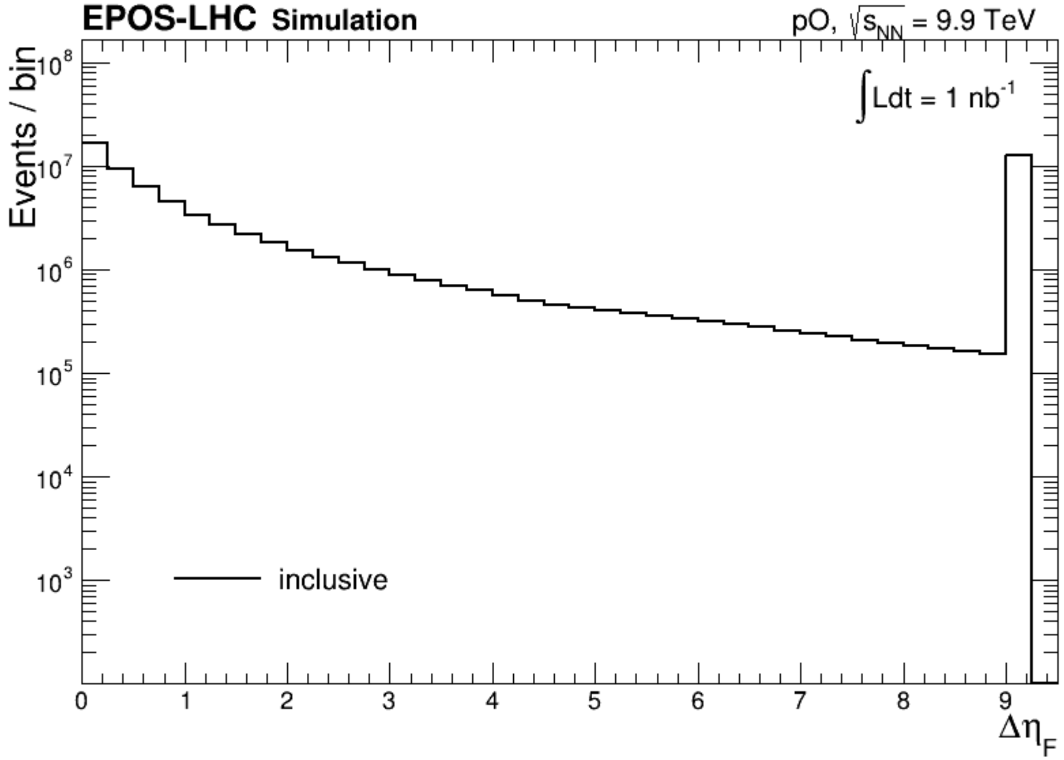
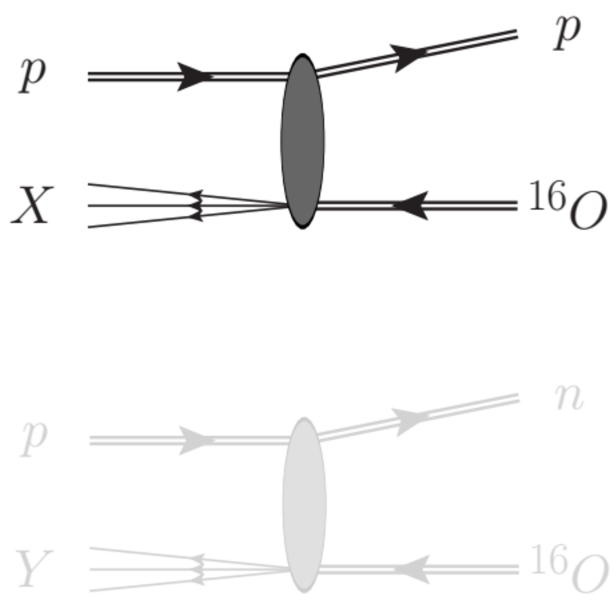
- Using the RG, some diffractive events escape detection

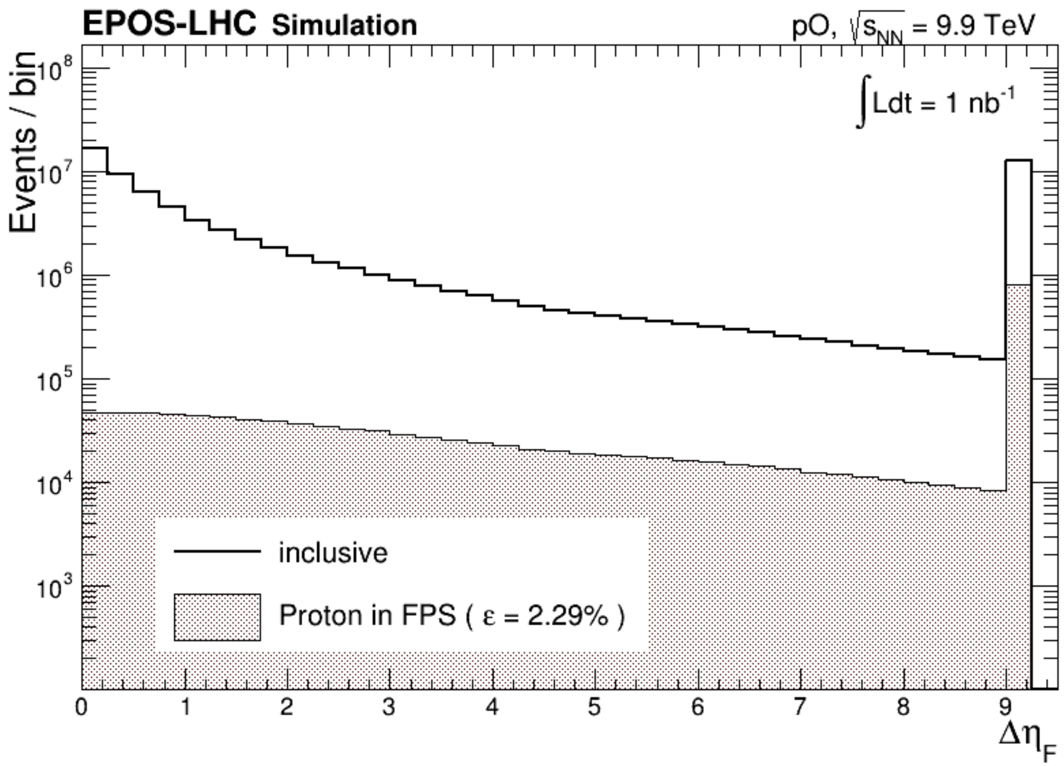


GAP := $P_T > 1$ GeV, with $|\eta|<4.5$

Rapidity gaps in color neutral exchange

- Events with a diffractive proton are characterized by the presence of large Rapidity Gaps (RG)
- Using the RG, some diffractive events escape detection, but can be recovered using proton tag





GAP := P_T > 1 GeV, with |η|<4.5

Rapidity gaps in color neutral exchange

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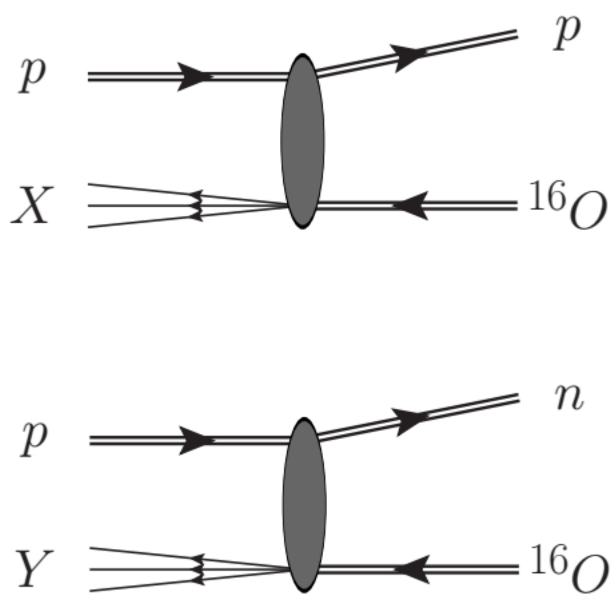

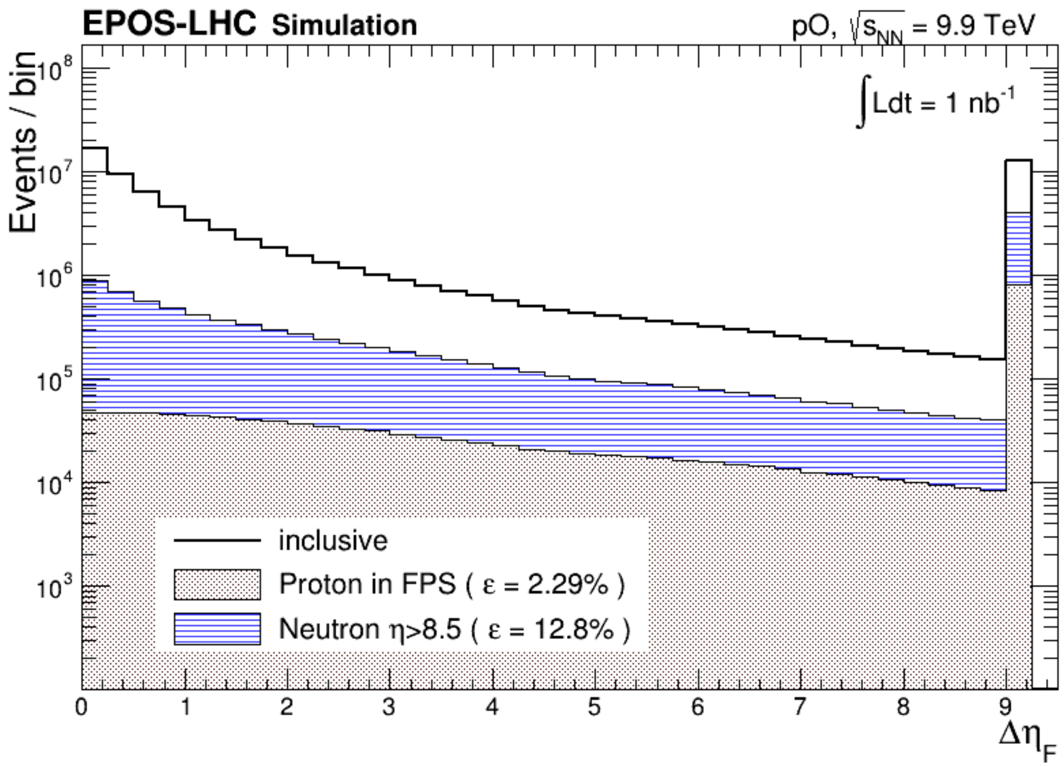

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Rapidity gaps in color neutral exchange

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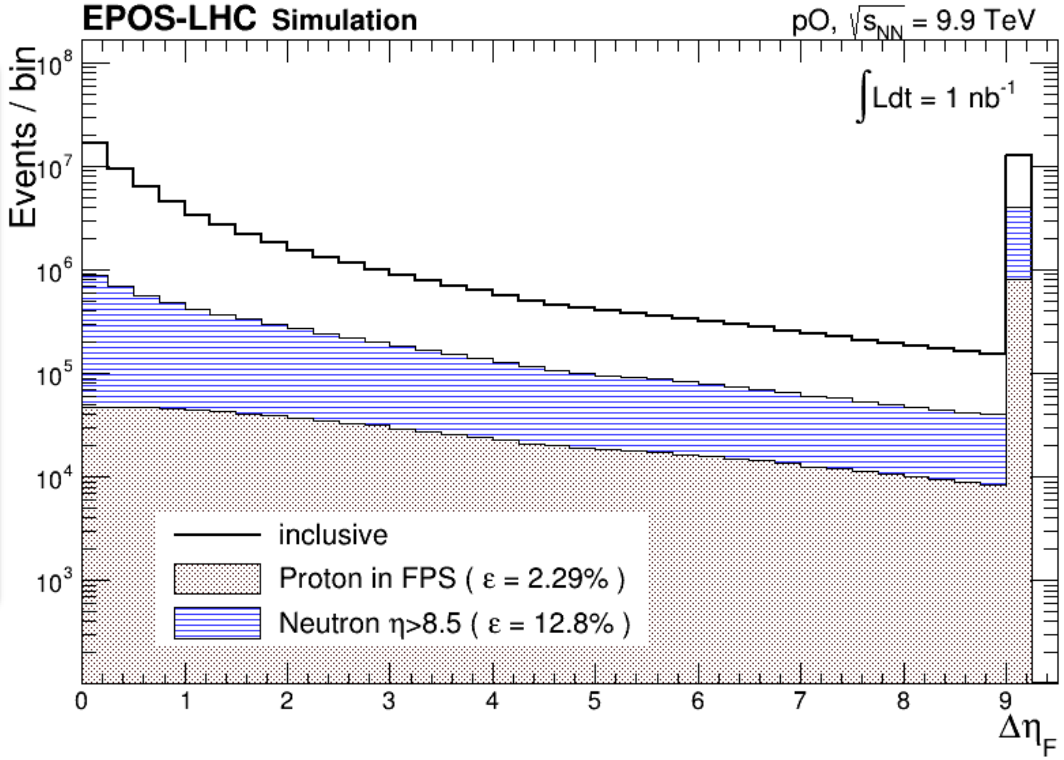
Measurements with forward n/p detectors can probe additional phase-space to LHCf/LHCb in constraining the modeling of pO interactions!



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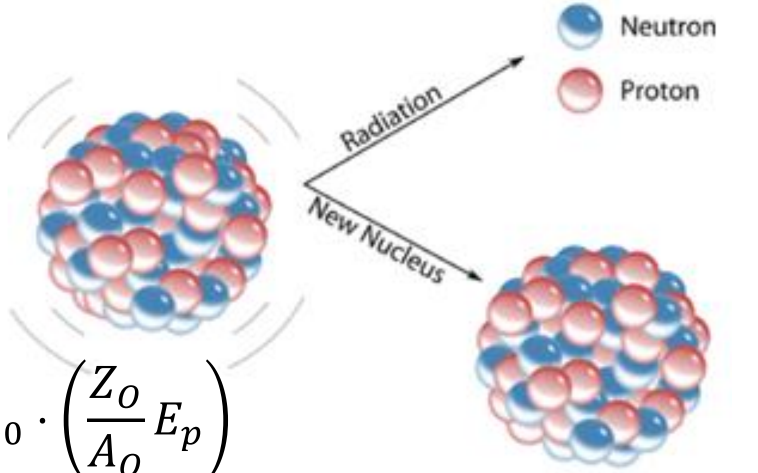
Production of light isotopes on pO and OO collisions

Ion tagging at the LHC

- On the ion side, oxygen ions will disintegrate, protons and neutrons will carry half of the beam momentum and ion remnants can form various isotopes.
- While neutrons can be measured with ZDC, protons have very low momentum (0.5 the nominal) to reach the FPS.
- Yet, some lighter ions with different kinematics can reach the FPS

$$E_N = 1 \cdot \left(\frac{Z_O}{A_O} E_p\right) = \frac{1}{2} E_p$$



$$E_{A_0} = A_0 \cdot \underbrace{\left(\frac{Z_O}{A_O} E_p\right)}_{\text{Energy / nucleon}}$$

$$E_{A_1} = A_1 \cdot \left(\frac{Z_O}{A_O} E_p\right)$$

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- While neutrons can be measured with ZDC, protons have very low momentum (0.5 the nominal) to reach the FPS.
- Yet, some lighter ions with different kinematics can reach the FPS
- **Proton detector as ion "mass" (A/Z) spectrometer!**

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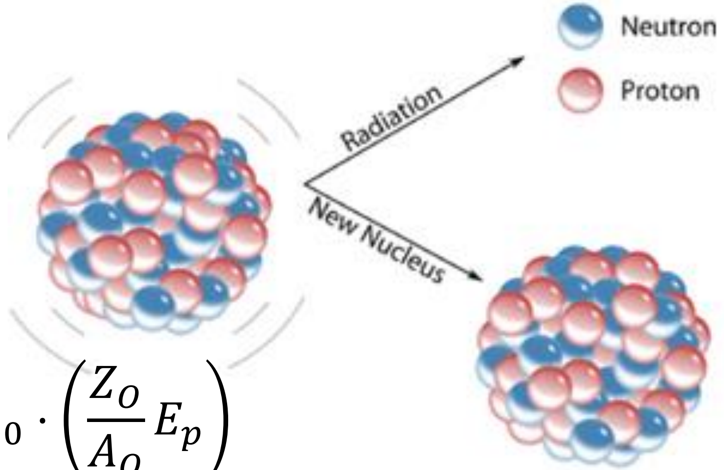

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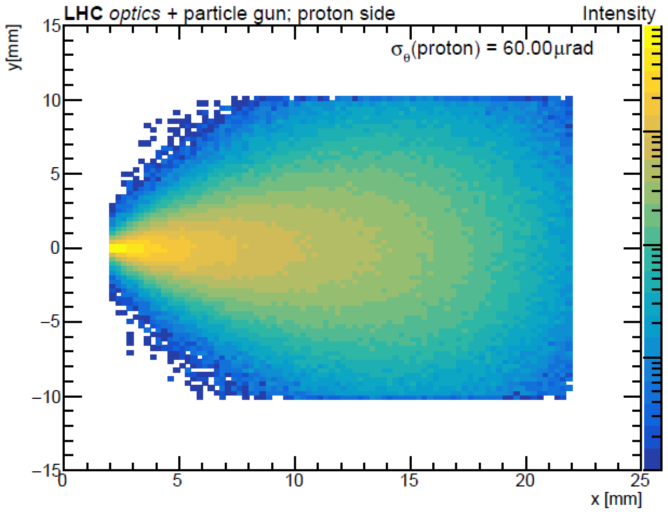
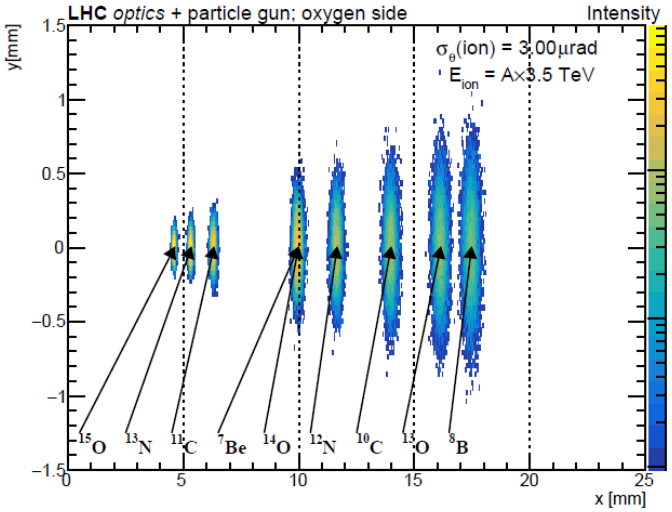




Low energy nuclear physics

Summary

Proton/Neutron tagging

- Participation of ZDC/FPS detectors in p-O / O-O collisions are currently investigated
- Improved modeling of (in)elasticity in proton – Air collisions
- Proton/Neutron tagging in pO covers a complementary phase-space to the standard program.
- As a by-product, we can commission proton spectrometers for any future pA LHC Runs

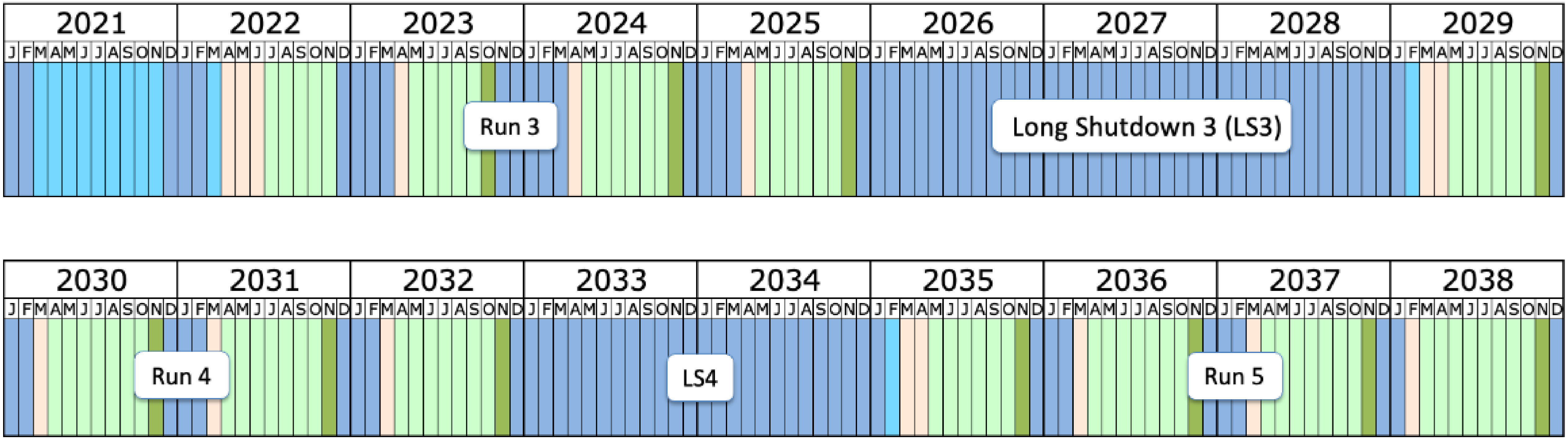
Ion tagging

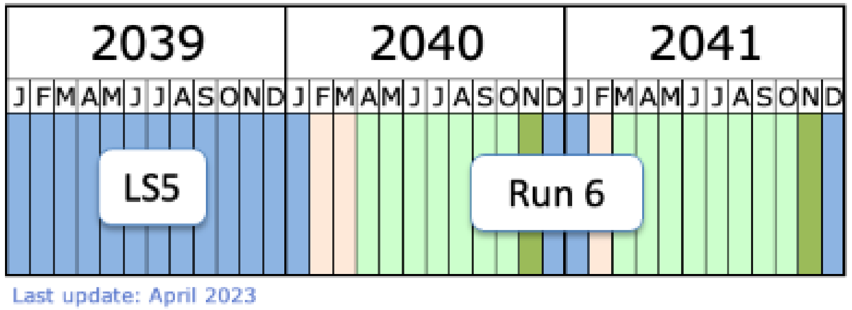
- Forward spectrometers sensitive to a few ions -> systematic measurements of ion disintegration.
- Can a combined measurement of forward spectrometer + ZCD shade light on ion disintegration?
- Challenges – tracking with high Q, multiple scattering, kinematic ranges, Fermi motion

Feedback is welcomed: feel free to contact michael.pitt@cern.ch

Backup

LHC Run schedule





https://lhc-commissioning.web.cern.ch/schedule/LHC-long-term.htm