Sept 8-14, 2024
Hotel Tonnara Trabia (Italy)

Diffraction and Low-x

Physics of pO collisions at the LHC with proton/neutron tagging

10 September 2024

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אוניברסיטת בן-גוריון בנגב
جامعة بن غوريون في النقب
Ben-Gurion University of the Negev

Outline

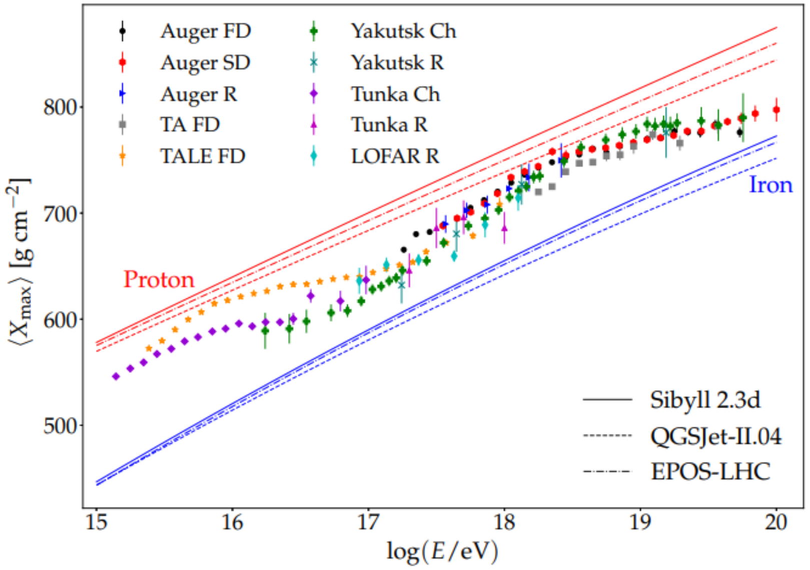
- Accelerating Oxygen ions at the LHC
- Forward proton and neutron tagging at the LHC
- Constraining models of hadronic interactions
- Determination of nuclear geometry

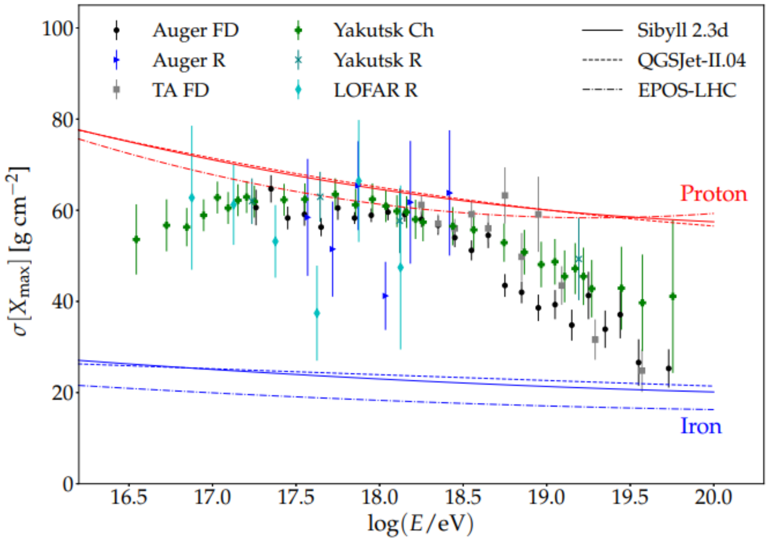
Accelerating Oxygen ions at the LHC

Motivation

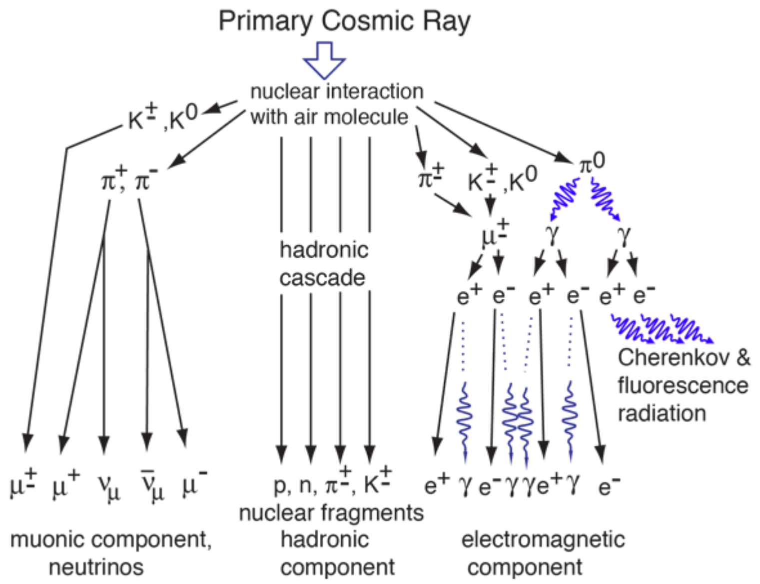
Oxygen ions at the LHC

- Oxygen ions (^{16}O) will be injected at the LHC for the first time.
- pO run is scheduled to take place in July 2025, 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]

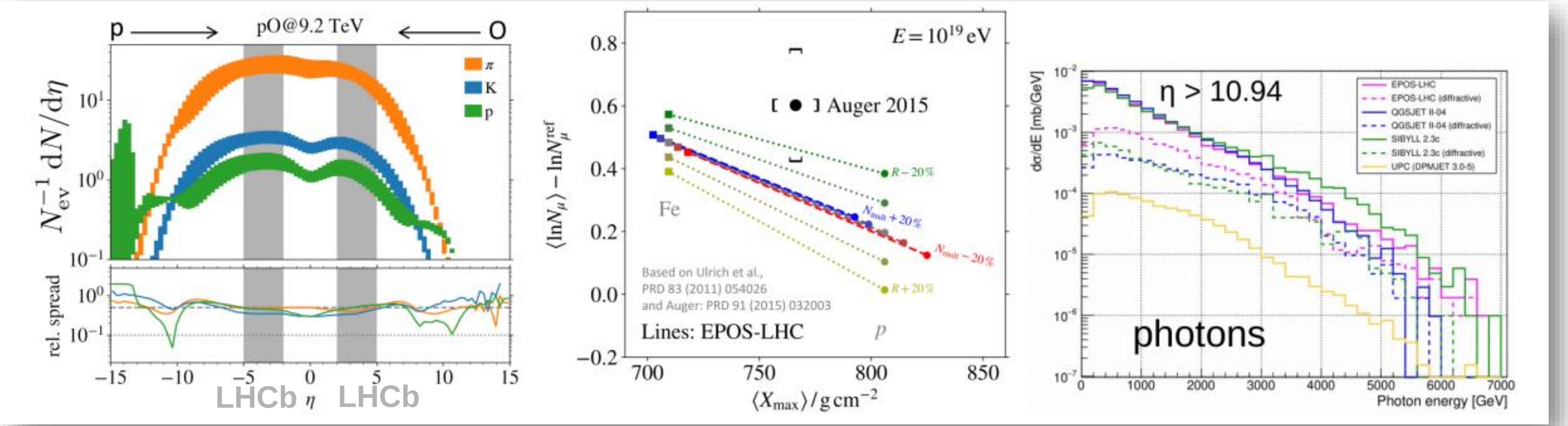


http://hyperphysics.phy-astr.gsu.edu/hbase/Astro/cosmic.html

Constrain hadronic models with pO collisions

Opportunities of OO and pO collisions at the LHC

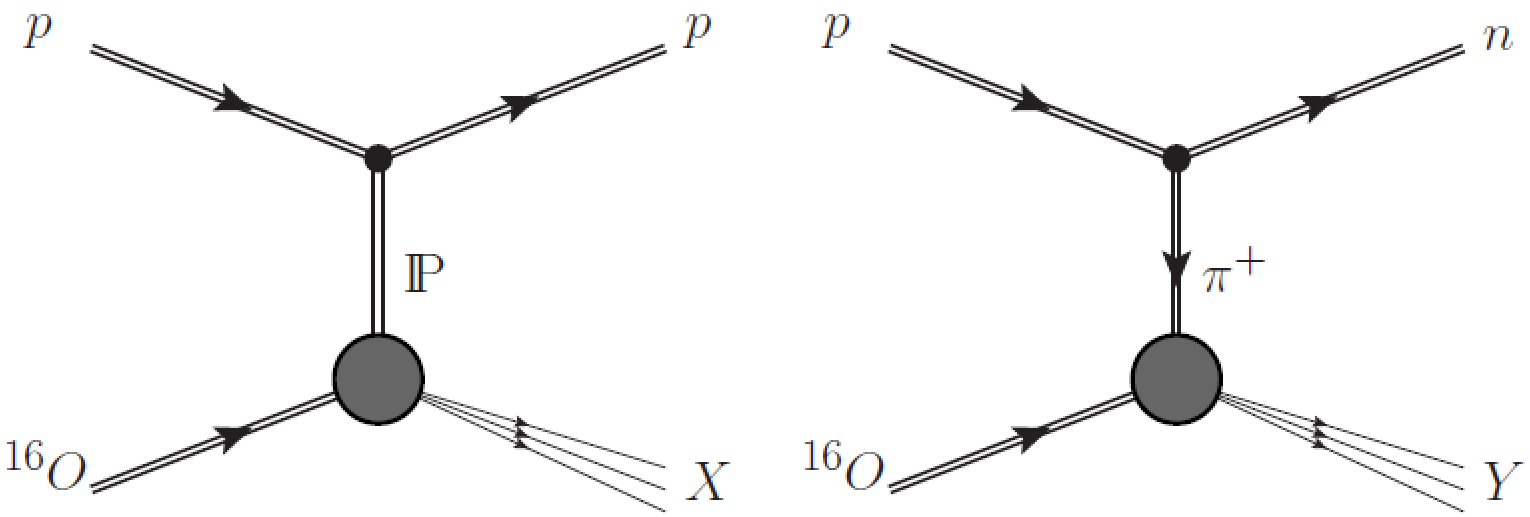
- Discussed in 2021 at a dedicated workshop at CERN (http://cern.ch/OppOatLHC)
- Summary available here 2103.01939



Constrain hadronic models with pO collisions

Extending current research program

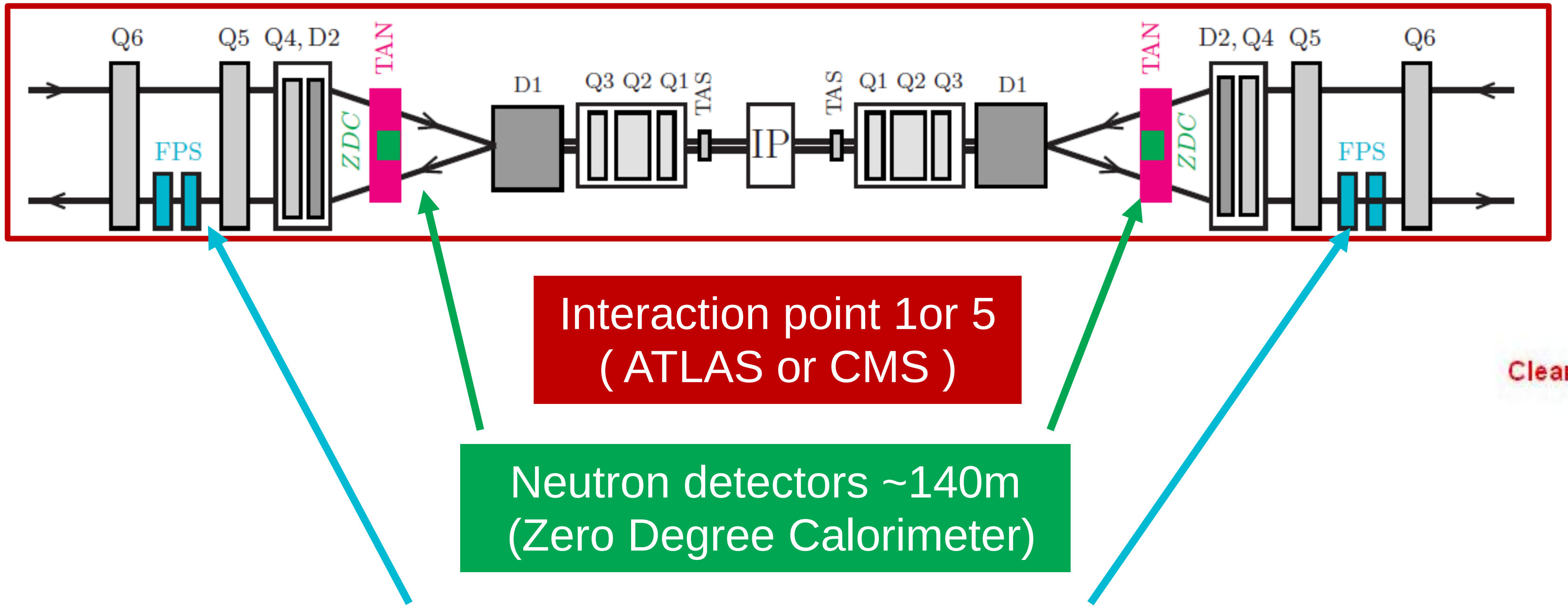
- Besides the standard research program involving pO interactions, we suggest utilizing the forward proton and forward neutron detectors to expand the probed phase-space (this talk)



Forward proton and neutron tagging at the LHC

Forward detectors at the LHC

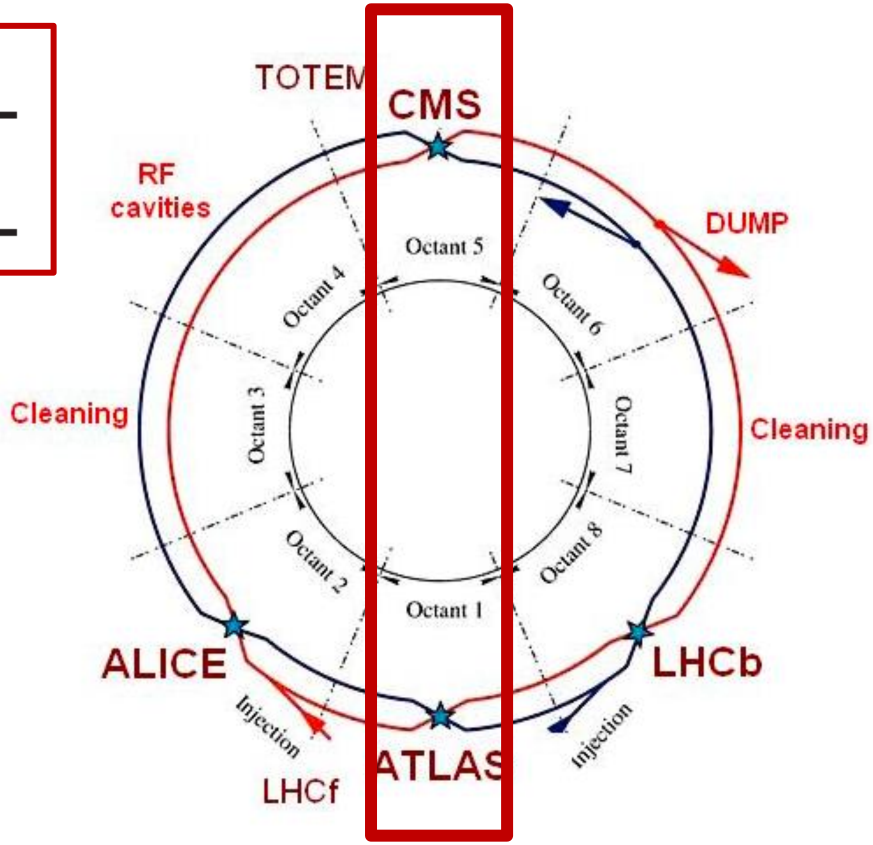
- Two interaction points (CMS / ATLAS) are equipped with both forward neutron & proton detectors at about 140 m / 220 m from the IP, respectively on both sides.



Interaction point 1or 5
(ATLAS or CMS)

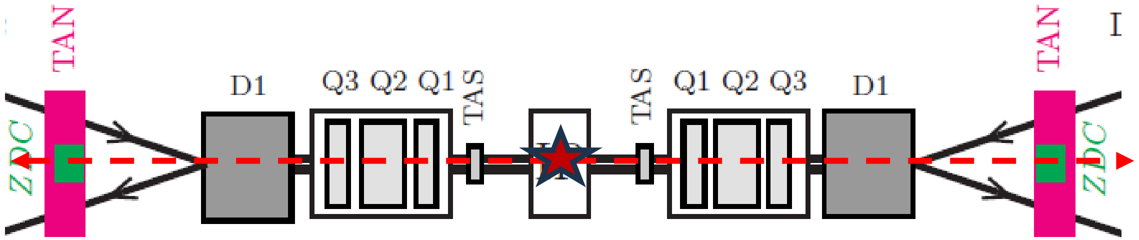
Neutron detectors ~140m
(Zero Degree Calorimeter)

Proton detectors ~220m
(AFP or PPS)



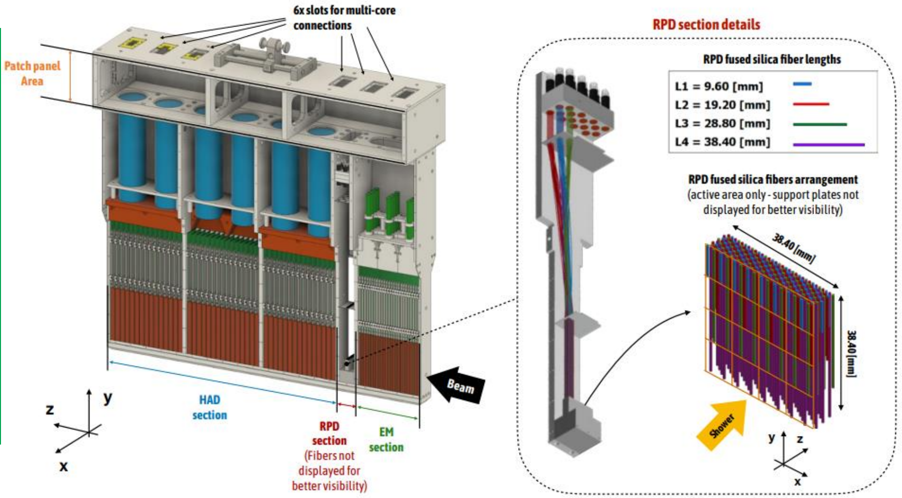
Forward neutron detector

- 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

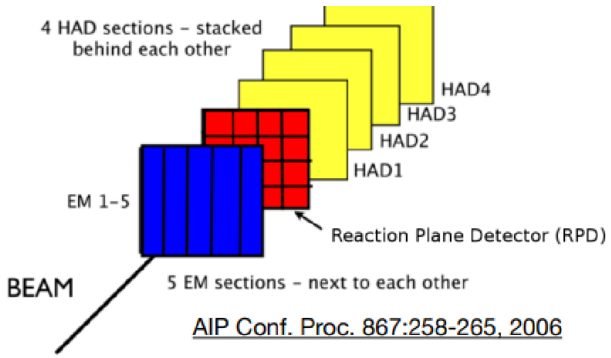


ZDC Final design (HL-LHC phase):

- 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)



CMS ZDC in Run3

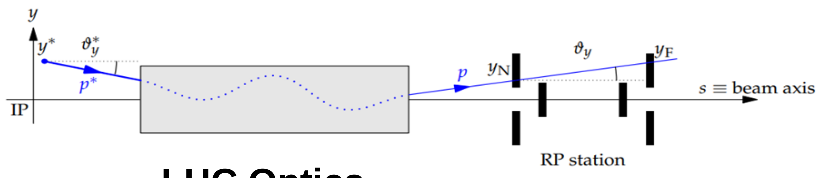


AIP Conf. Proc. 867:258-265, 2006

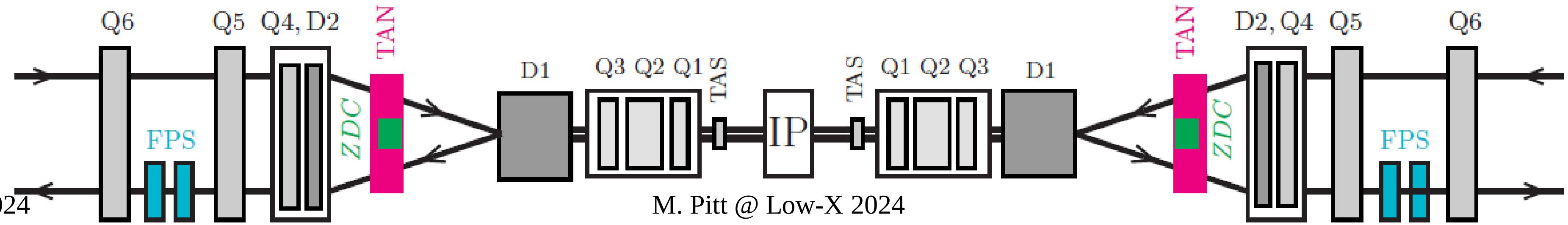
Forward proton detectors

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

$$\delta x(z) = x_D(\xi) + v_x(\xi) x^* + L_x(\xi)\theta_x^*$$
$$\delta y(z) = y_D(\xi) + v_y(\xi) y^* + L_y(\xi)\theta_y^*$$



LHC Optics



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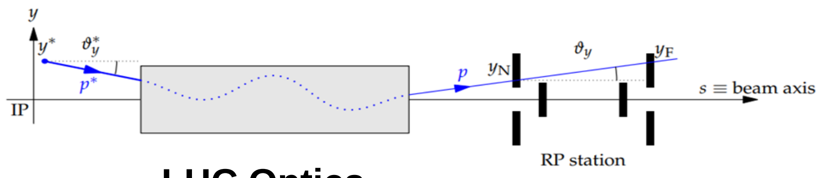

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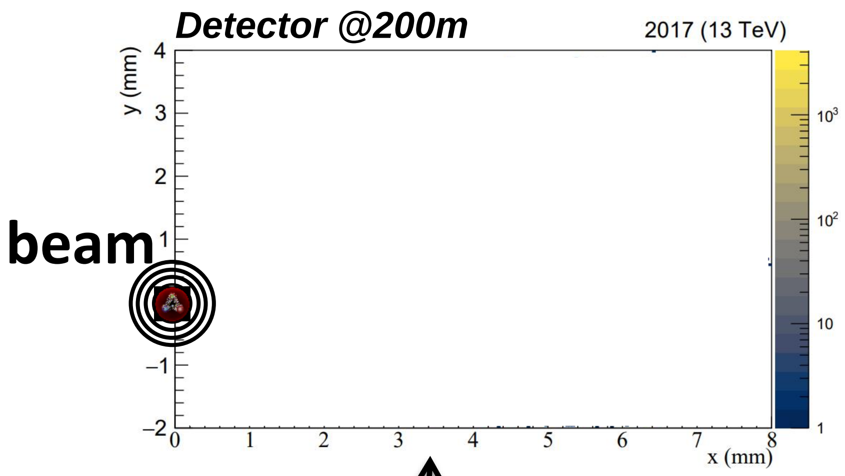

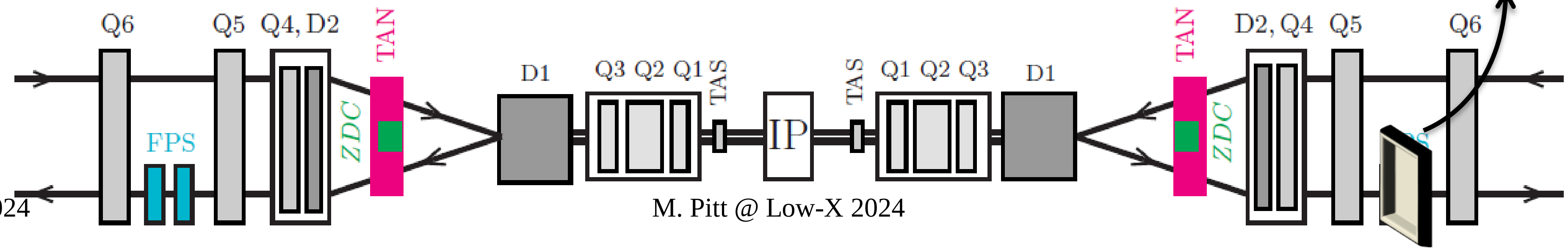

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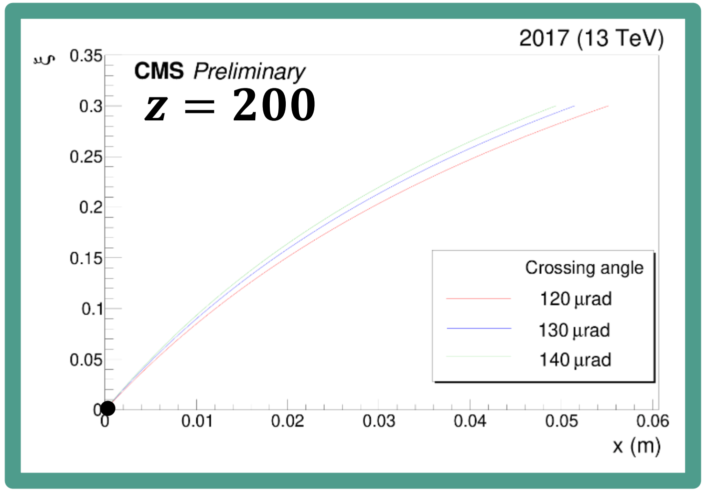

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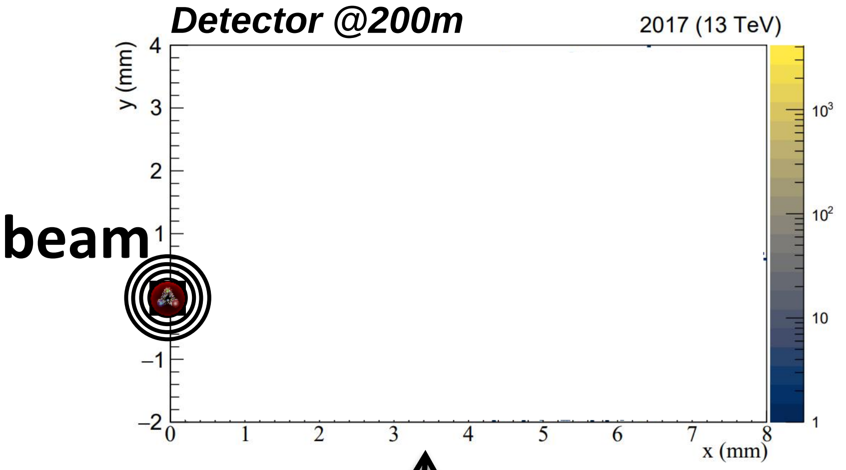

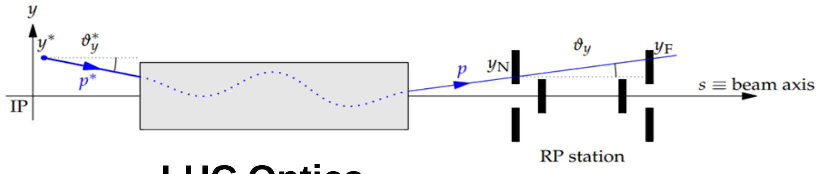

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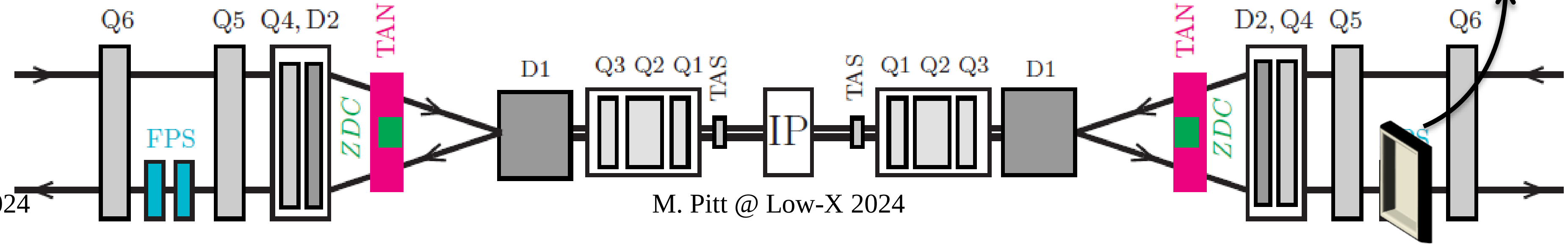

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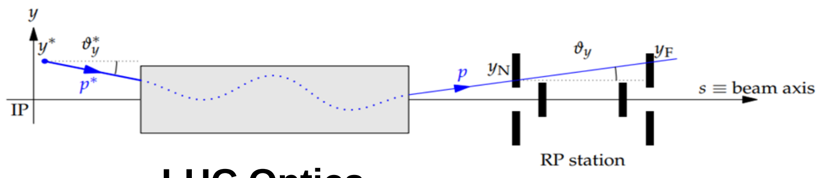
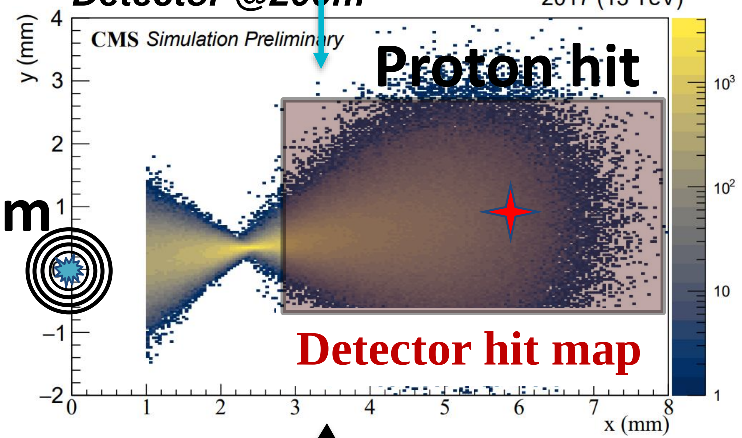


LHC Optics

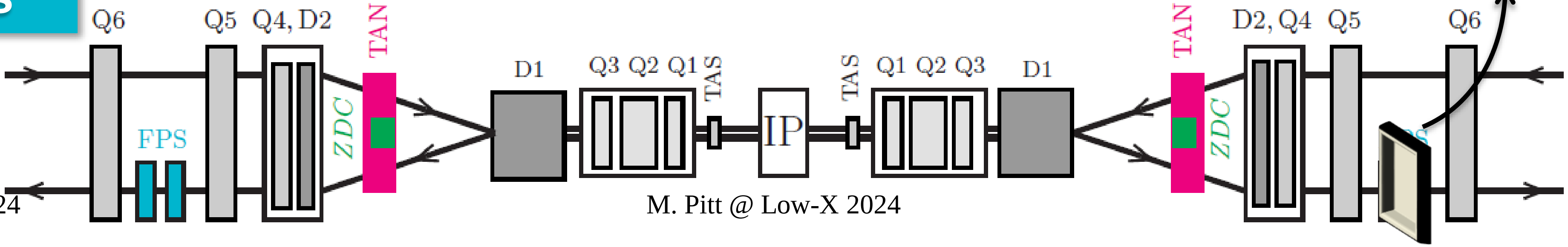
acceptance
2.5% < ξ < 15%

min distance from the beam

Collimators



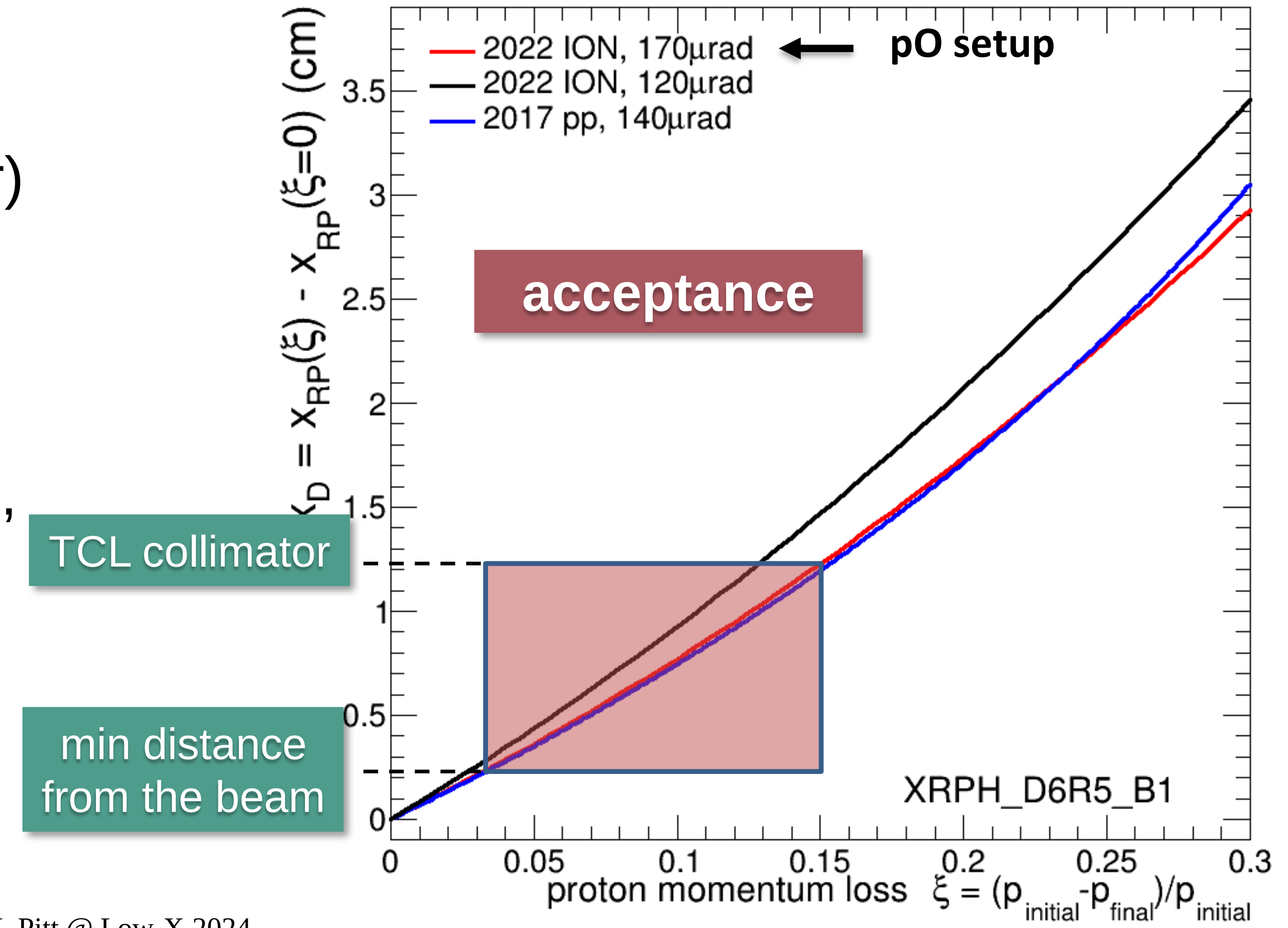
2 stations



Forward proton detectors

- Detector performance rely on different parameters:

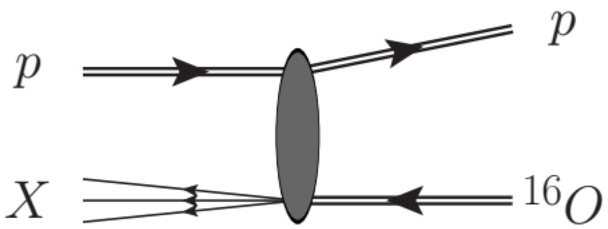
  - Crossing angle (the less the better)
  - Collimation scheme
  - Intensity (if super low then the verticals detectors can be inserted, but then need to adjust β*)
  - Minimal distance to the beam

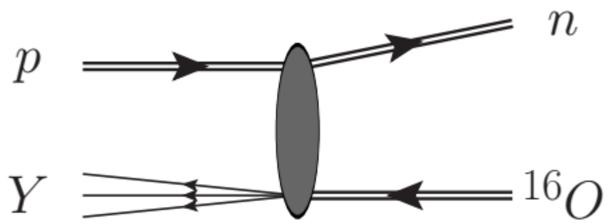


Constraining models of hadronic showers using pO collisions

Forward protons / neutrons in p-O collisions

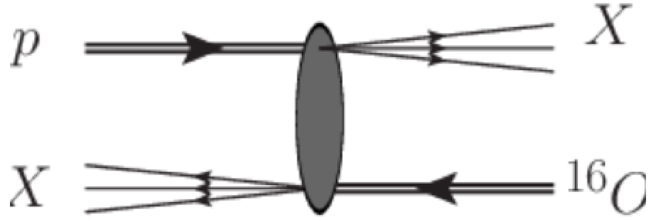
- High energy protons and neutrons emerge from p-O interactions
- By measuring the production rates, and event kinematics one can constrain their modeling

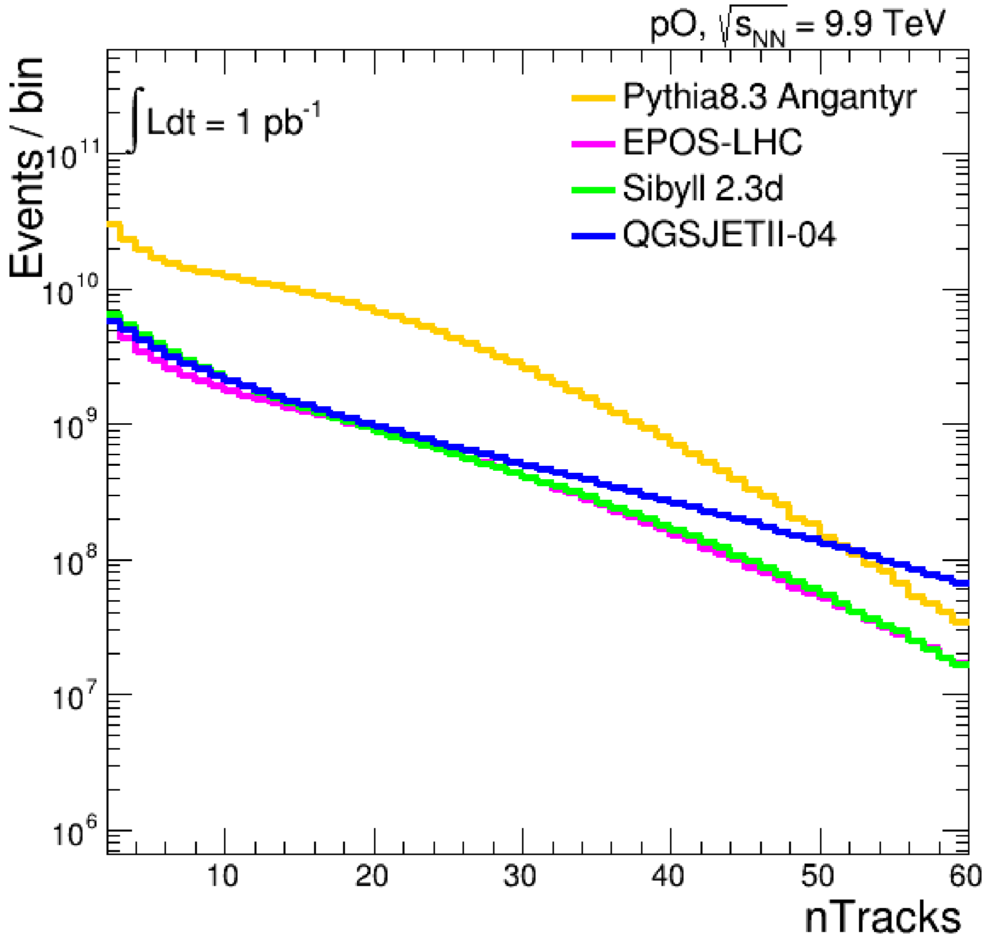




Forward protons in p-O collisions

- Event kinematics (like track multiplicity) constrain hadronic models

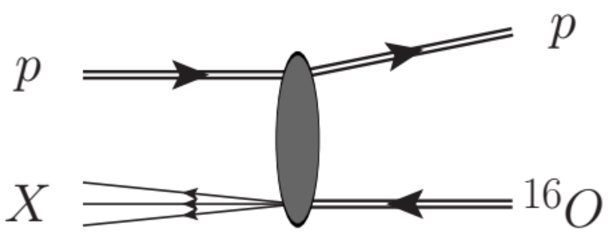


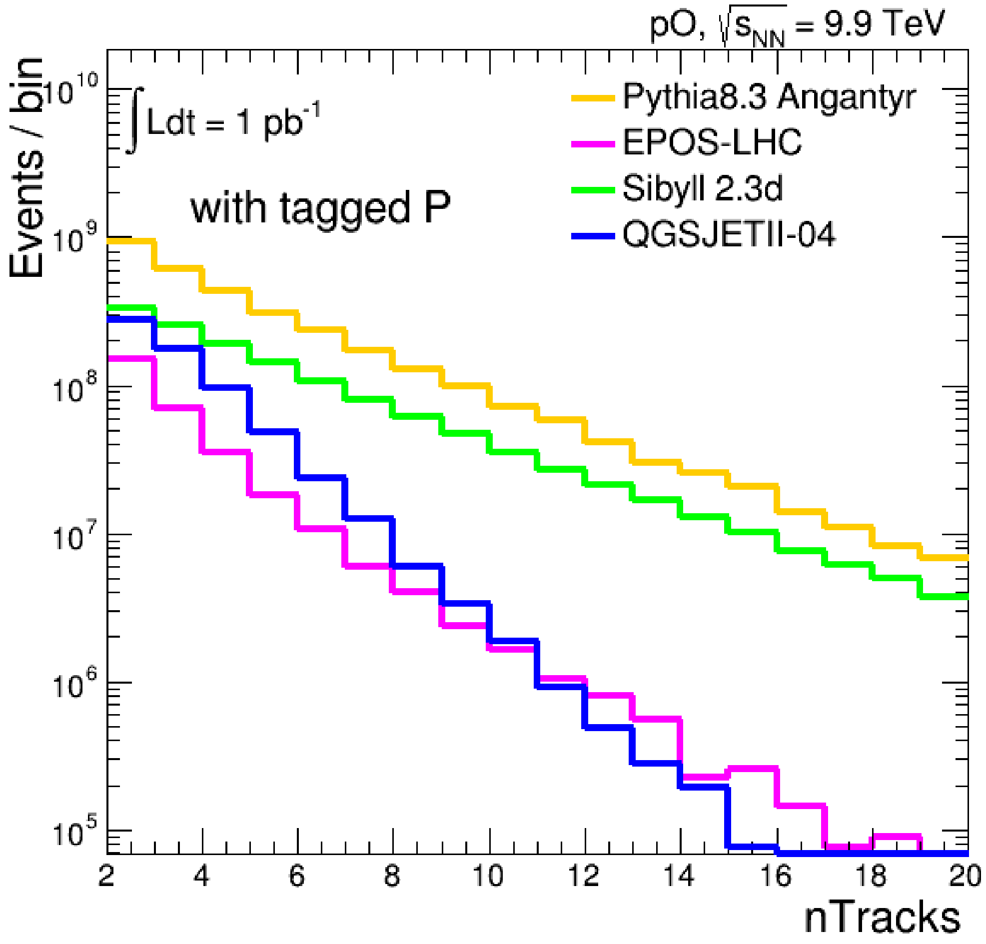


nTracks = charged particles with pT>1GeV and |η|<2.5

Forward protons in p-O collisions

- Event kinematics (like track multiplicity) constrain hadronic models
- Diffractive events, ~20%, (with forward protons) often lacks large central activity:





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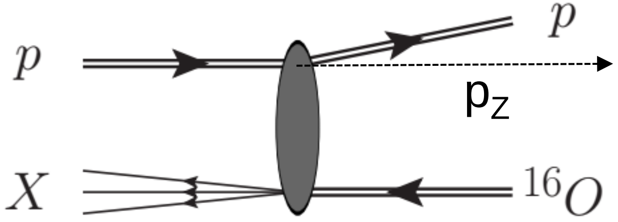
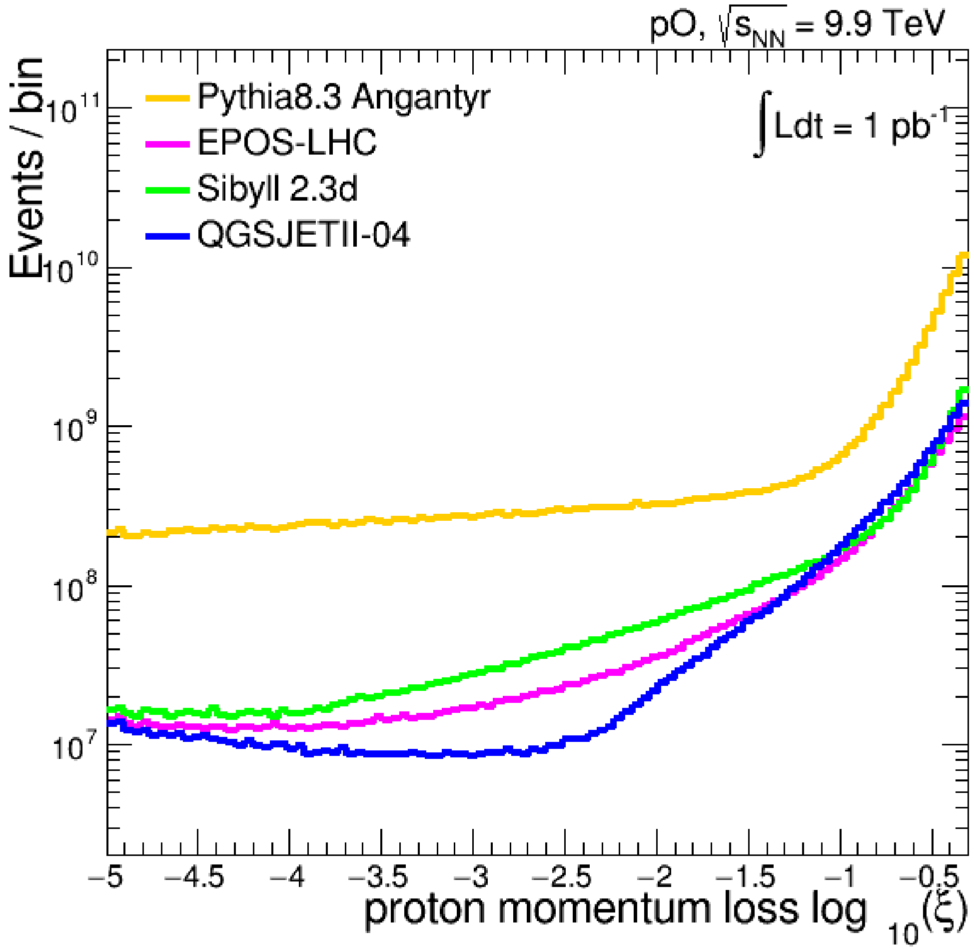
- Proton kinematics are weakly constrained in hadronic models

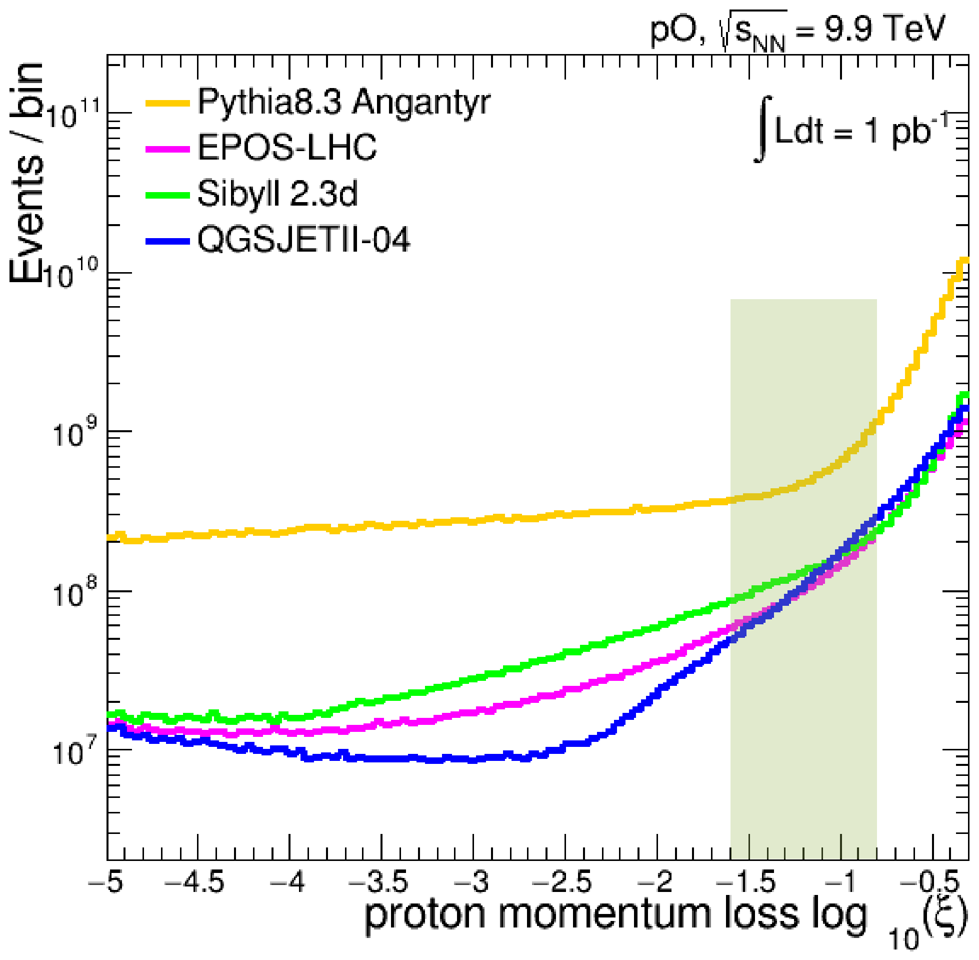




Forward protons in p-O collisions

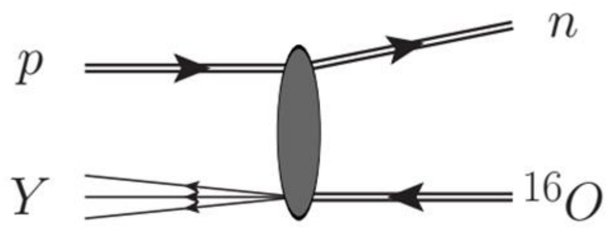
- Event kinematics (like track multiplicity) constrain hadronic models
- Diffractive events, ~20%, (with forward protons) often lacks large central activity:
- Proton kinematics are weakly constrained in hadronic models
- Even with small fiducial region (2.5%<ξ<15%), sizable differences in acceptance:

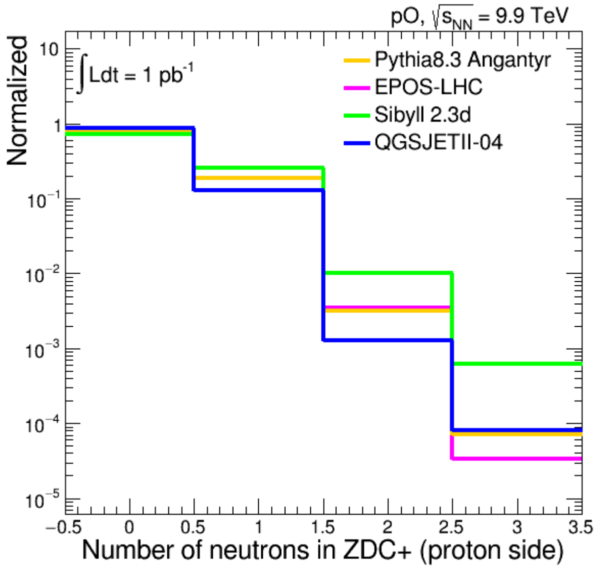
Generator	acc.	σ[mb]
EPOS-LHC	2.24%	75.63
Pythia8	1.40%	498.0
Sibyll	2.90%	76.66
QGSJETII-04	2.60%	77.03

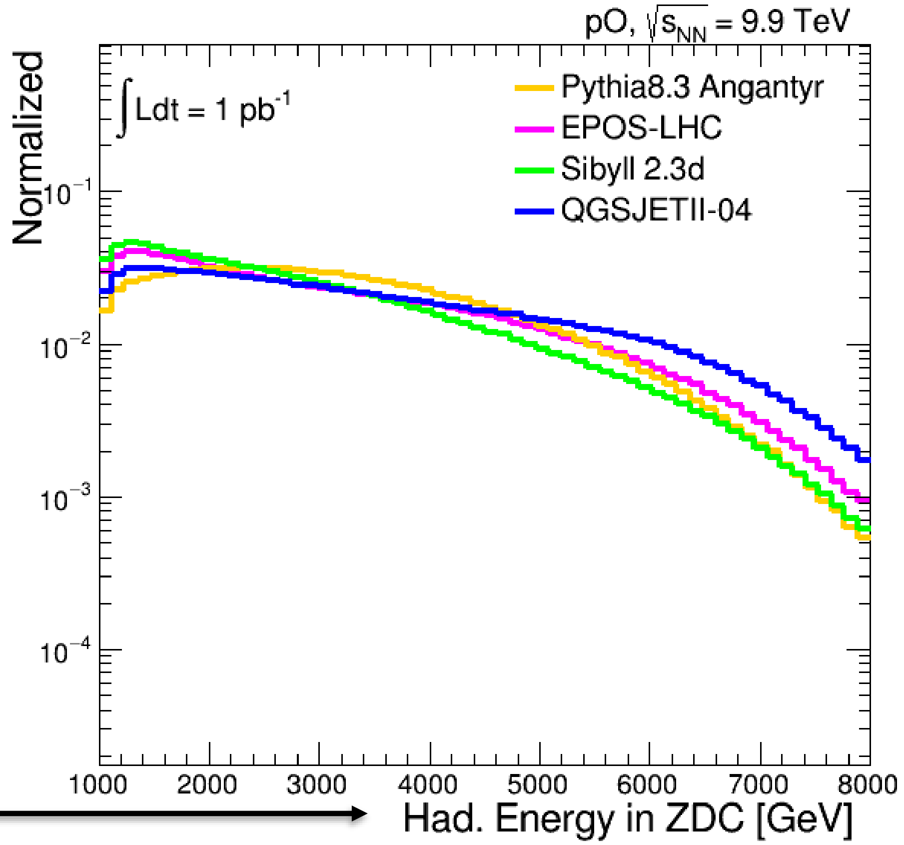


Forward neutrons in p-O collisions

- Neutrons can also be produced via pion exchange
- Forward neutron distributions in ZDC is an additional observable to study hadronic interactions







Neutron energy smearing of 15% is applied →

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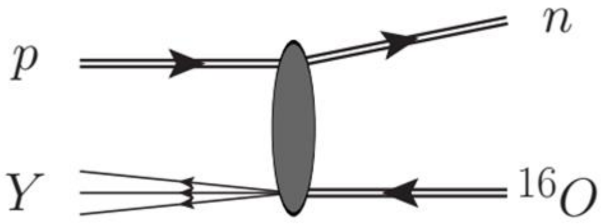
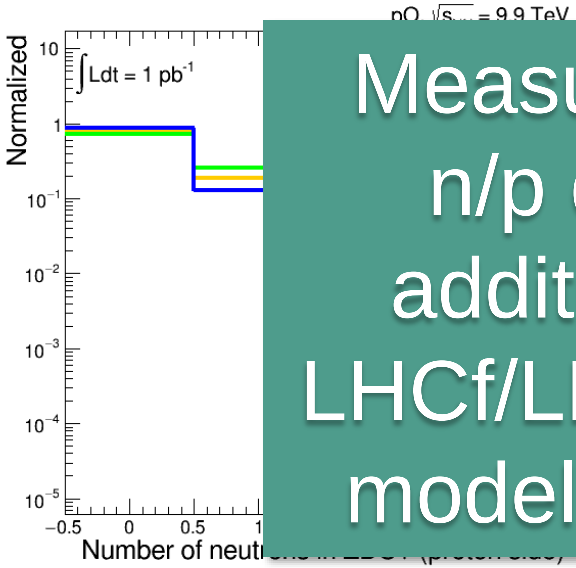
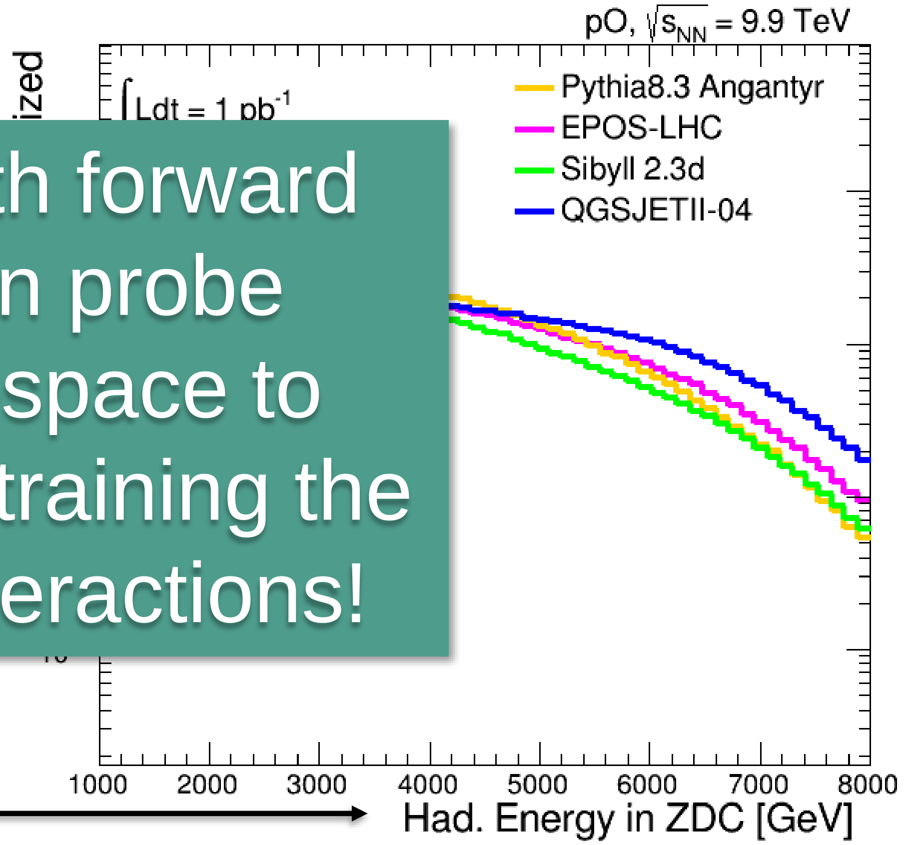






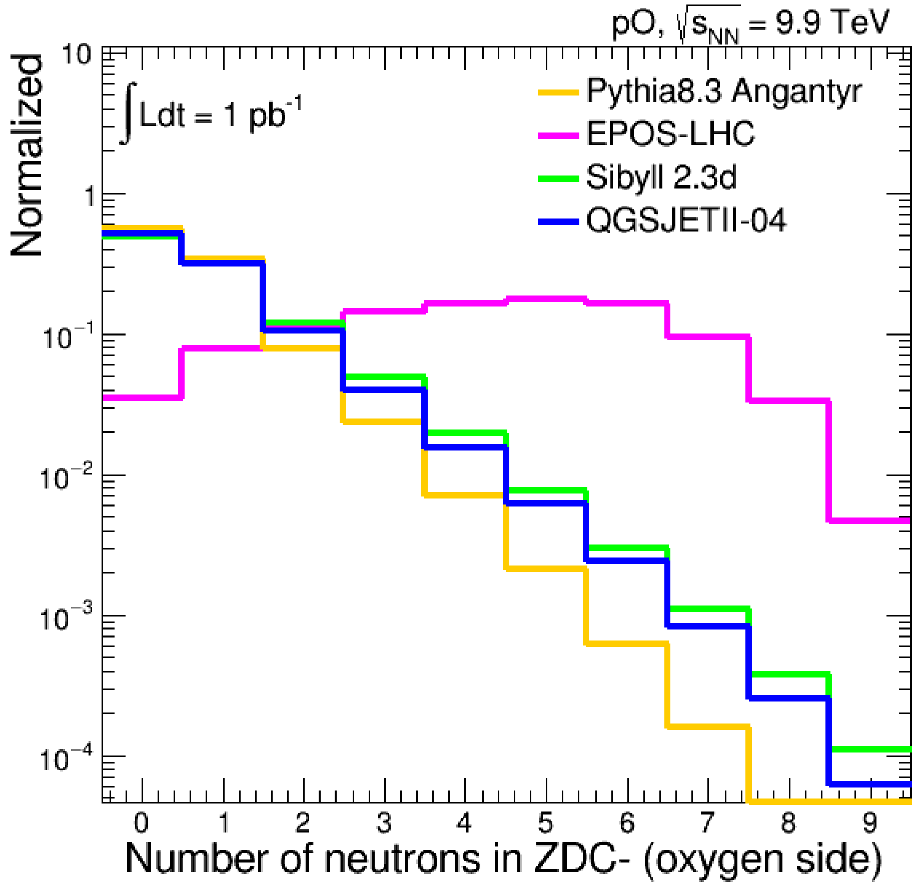
Measurements with forward n/p detectors can probe additional phase-space to LHCf/LHCb in constraining the modeling of pO interactions!

Neutron energy smearing of 15% is applied →

Constraining ion geometry through its fragments

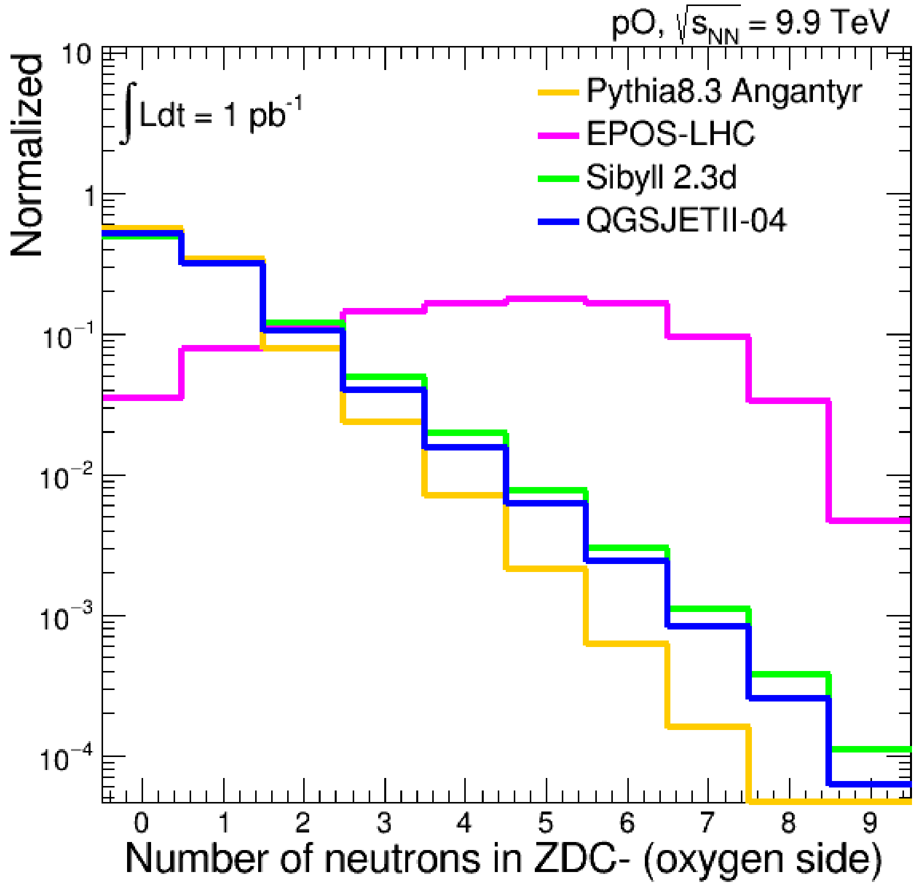
Oxygen side - neutron tagging

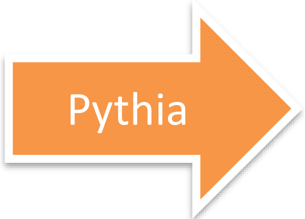
- Neutrons can be tagged also in the oxygen side

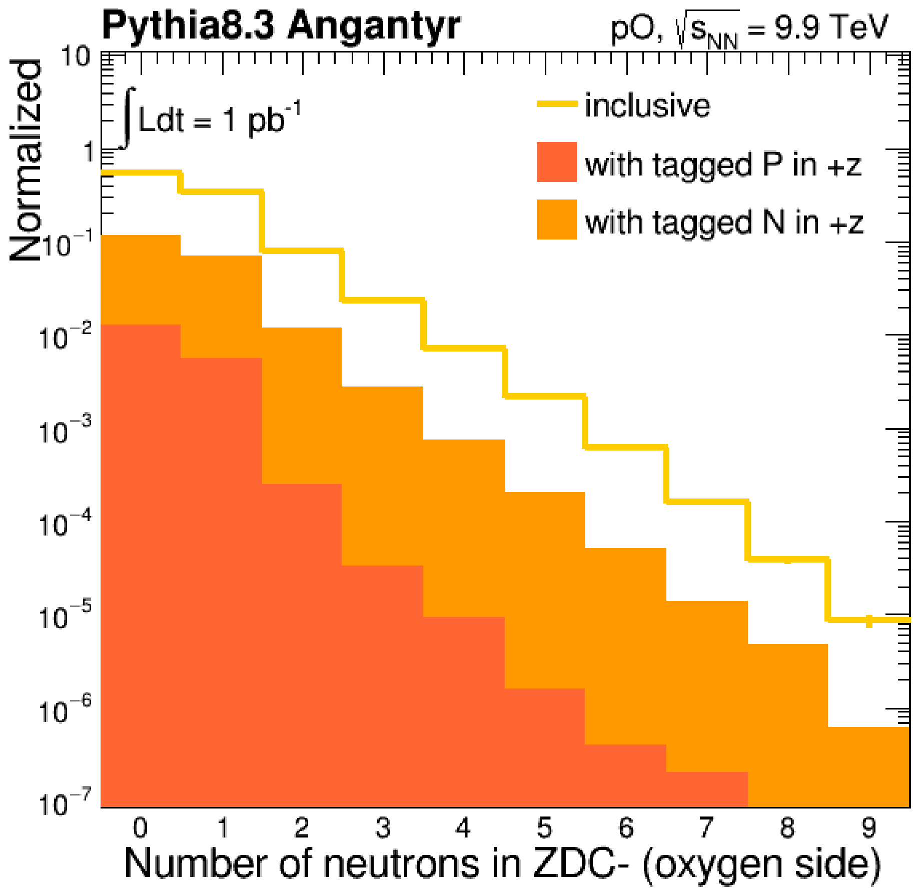


Oxygen side – neutron tagging

- Neutrons can be tagged also in the oxygen side
- Different ZDC energy spectra for diffractive and non diffractive events







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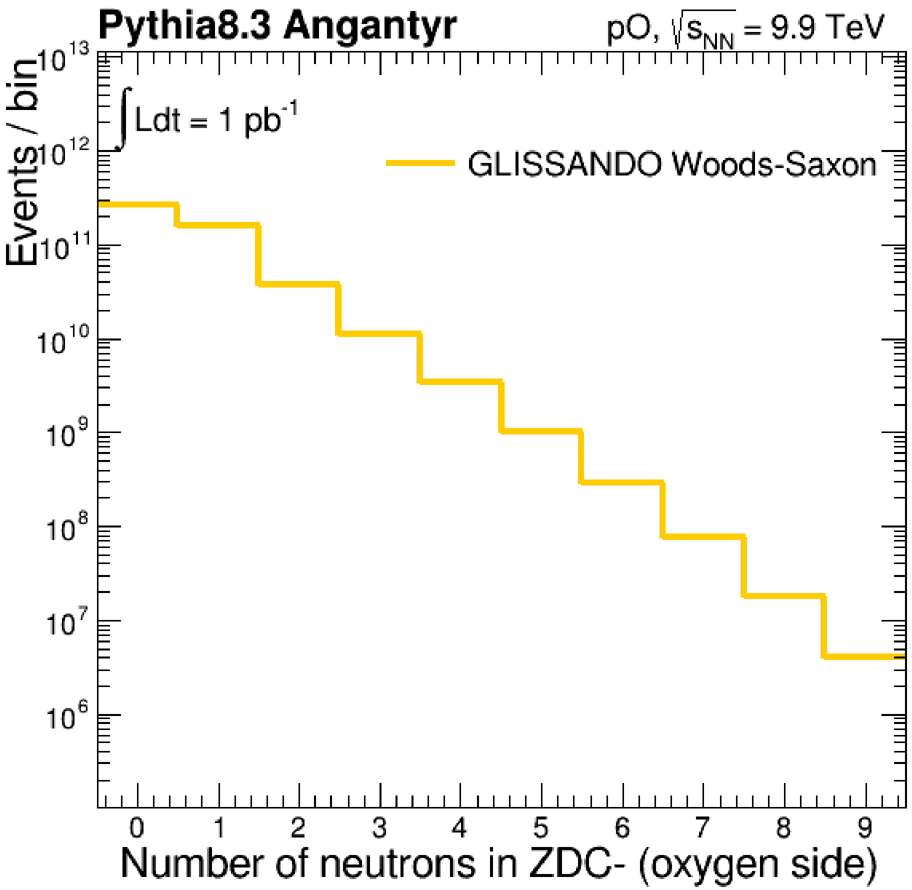

Nucleus Models - the nuclear geometry

- GLISSANDO Woods-Saxon (0710.5731, 1310.5475):

$\rho(r) = \frac{\rho_0}{1+e^{\frac{r-R}{a}}}$ with a=0.54fm, R=1.1A^(1/3) - 0.656 A^(-1/3)

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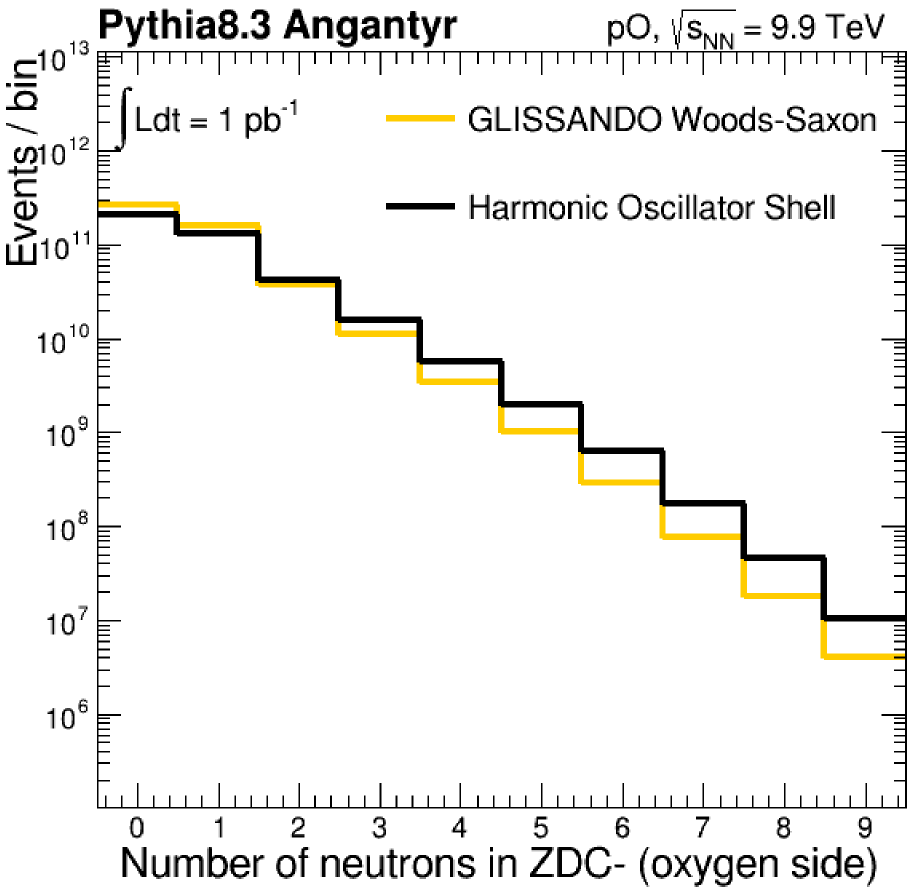

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- Harmonic Ocsilator shell

$\rho(r) = \frac{4}{\pi^{\frac{3}{2}} C^3}\left(1 + \frac{(A-4)r^2}{6C^2}\right) e^{-\frac{r^2}{C^2}}$ with $C = \left(\frac{5}{2} - \frac{4}{A}\right)^{-1} \left(\langle r^2\rangle_A - \langle r^2\rangle_p\right)$, $\langle r^2\rangle_A = 0.77\text{fm}^2$

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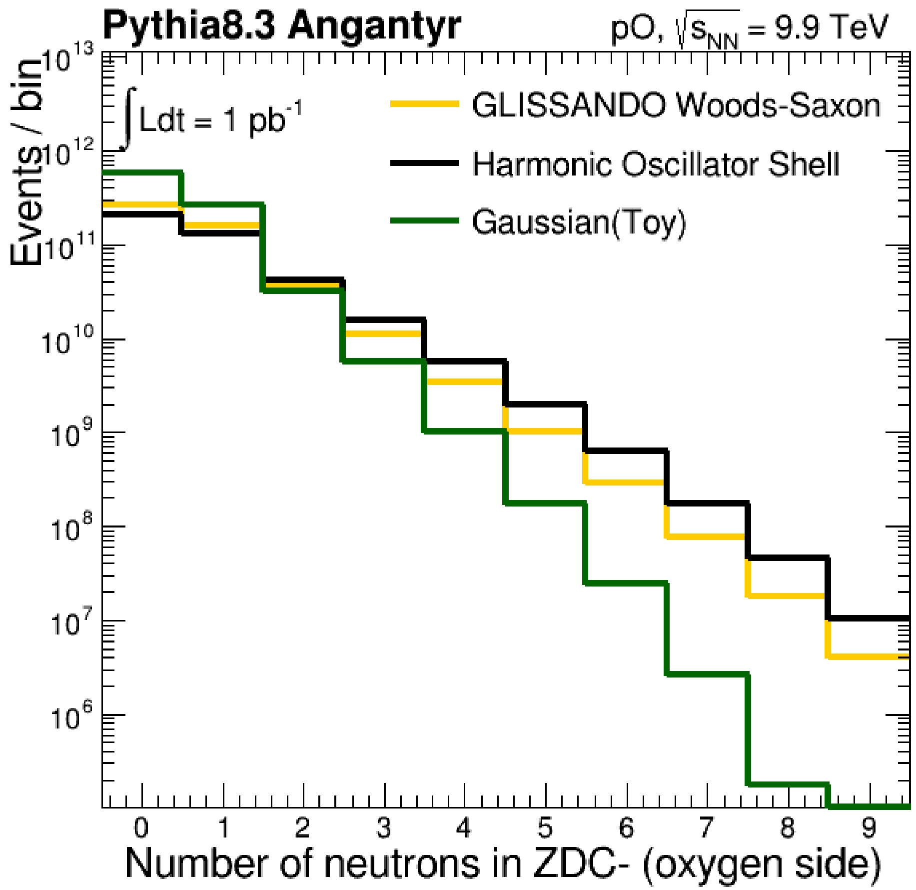

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- Gaussian model

The Gaussian model parametrizes the nuclear radial density as a Gaussian distribution with Charge radius of 7.7fm (reasonable for O16)

Oxygen side - neutron tagging

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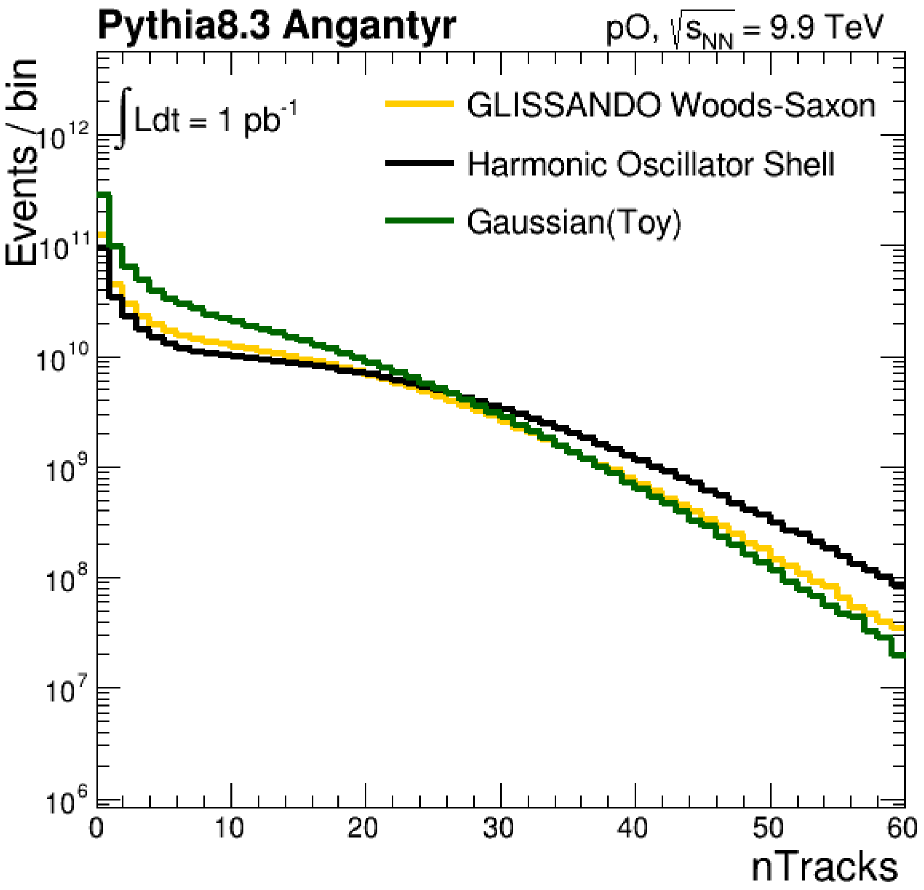
Many observables are sensitive to nuclear geometry



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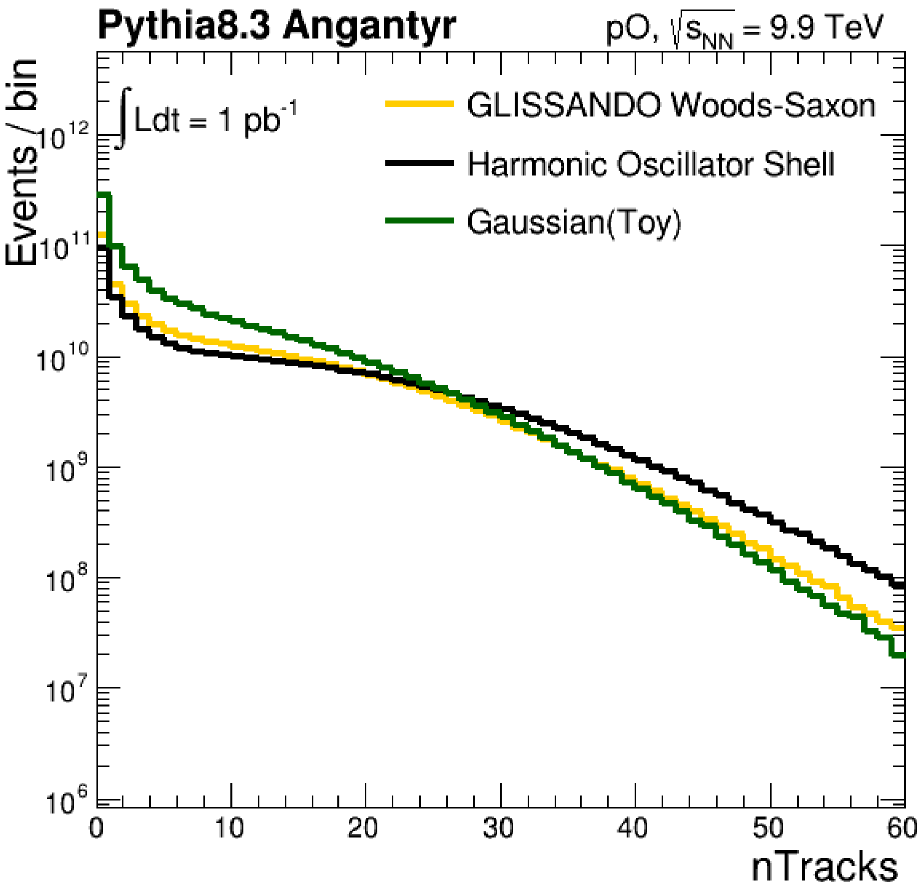


Nucl

- Gl

$\rho(r) =$

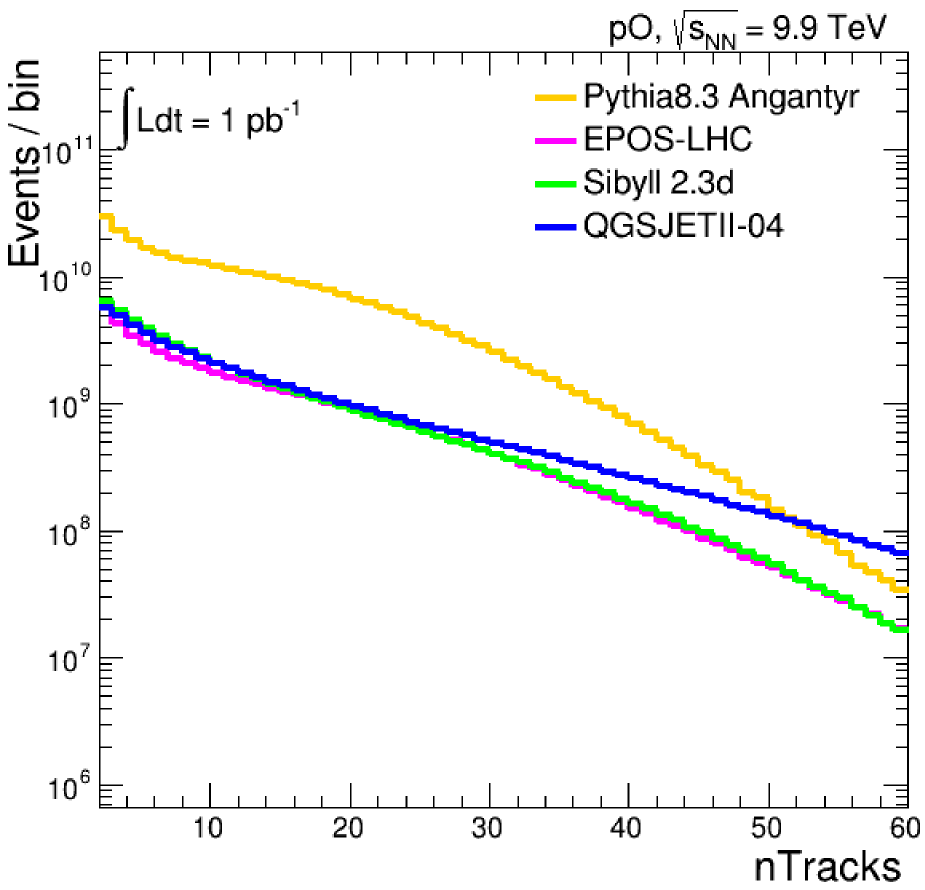
- Ha

$\rho(r) =$

- Ga

The Ga

with Ch



310.5475):

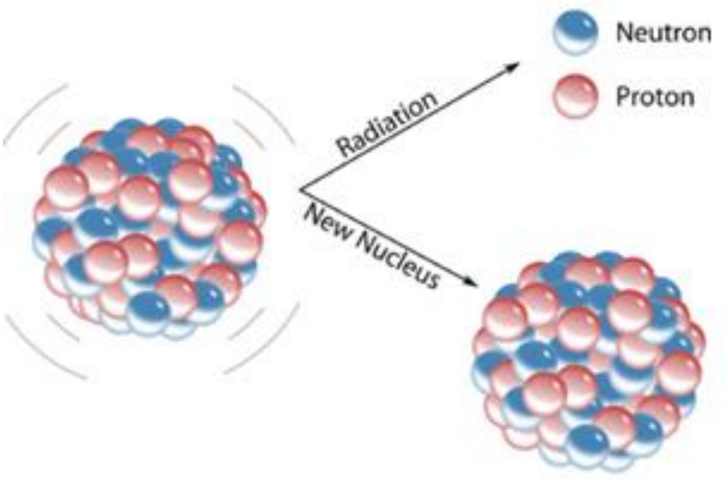
$r^2\rangle_A = 0.77\text{fm}^2$

Gaussian distribution

How distinguish differences between hadronic interactions and nuclear geometry?

Ion tagging at the LHC

- Calculations has been made for Oxygen case but can be extended to any other ion species.
- Ion tagging was discussed in the past ([1903.09498](), [1405.4555]())
- In pO collisions Oxygen ion breakup into protons, neutrons and nuclei fragments



All neutrons are measured in the ZDC

No protons will reach proton detector (xL~50%)

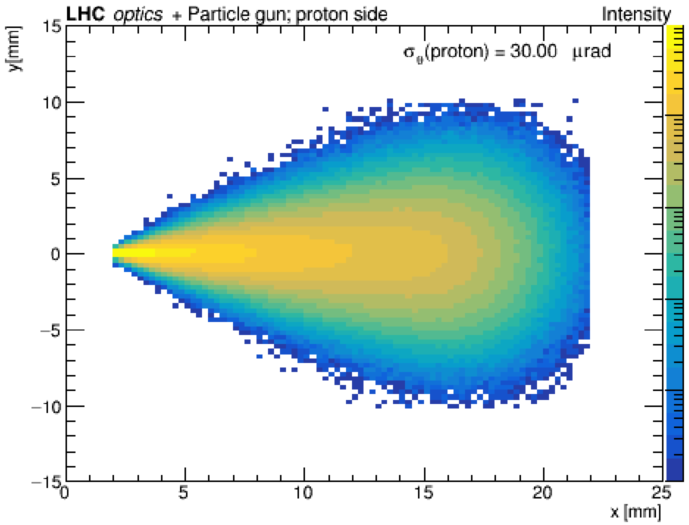
Ions with (A,Z) will be deflected from the beam center as beam particles with ~50(A/Z)% momentum w.r.t. steering magnets.

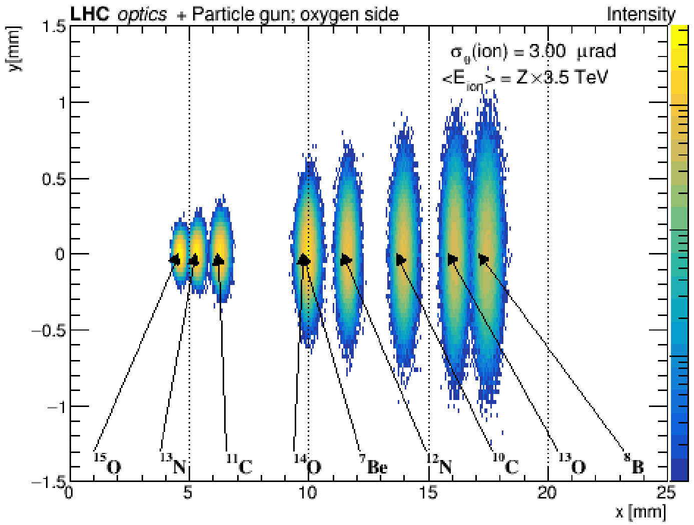
QCD interactions with proton tagging

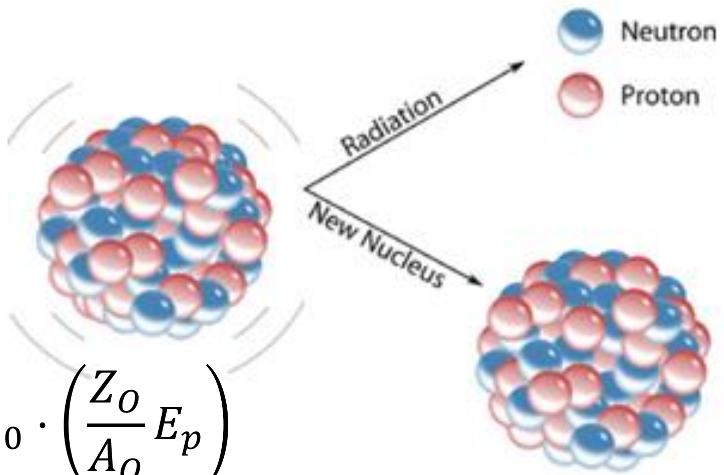
Ion tagging in pO events

- Pomeron and pion exchange can be tagged by **proton / neutron** detectors
- 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.

$$\xi_{RP} = 1 - \left(\frac{Z_O}{A_O}\right)\left(\frac{A_1}{Z_1}\right)$$







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

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Proton detectors

Ion tagging in pO events

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- Adding fermi motion (**exaggerated**)

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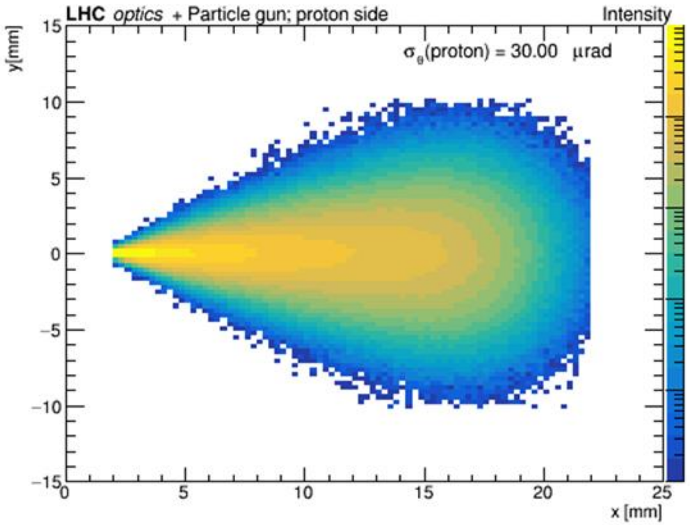

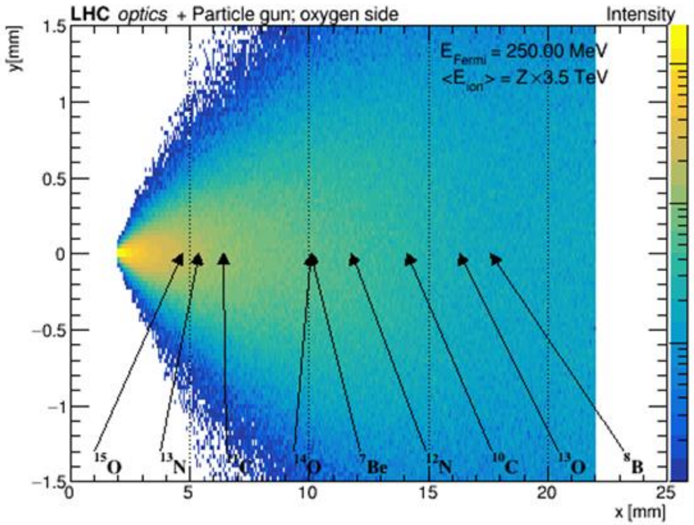

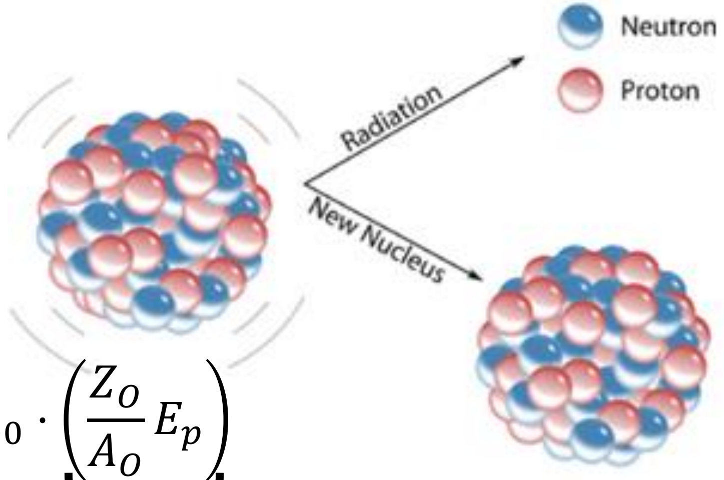

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Proton detectors

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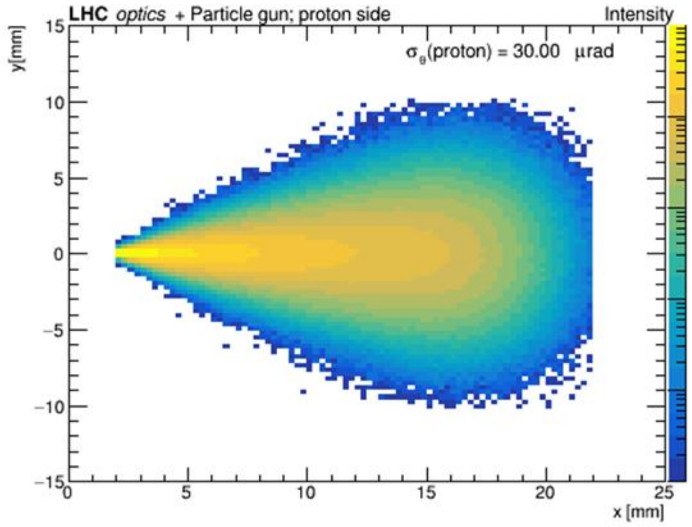

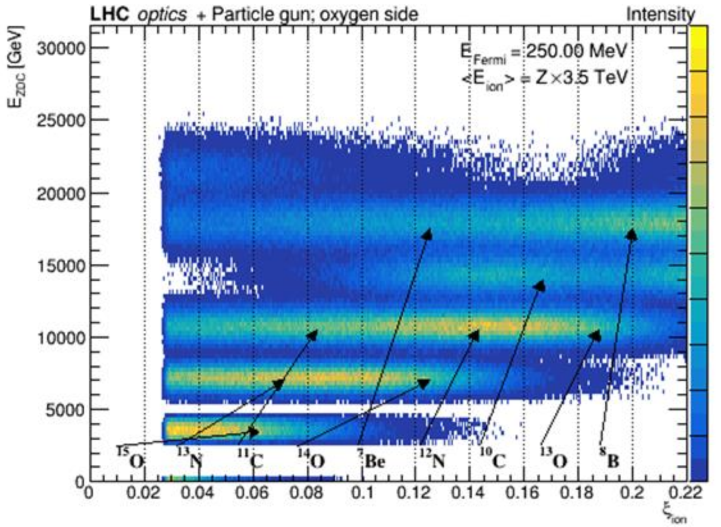

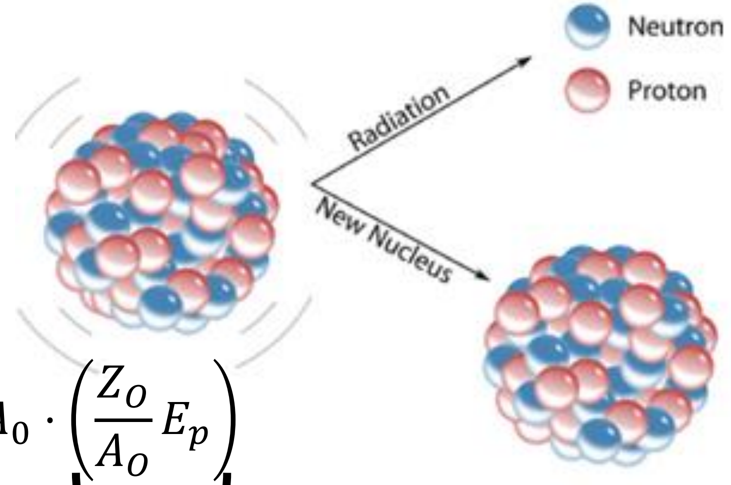

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Proton detectors

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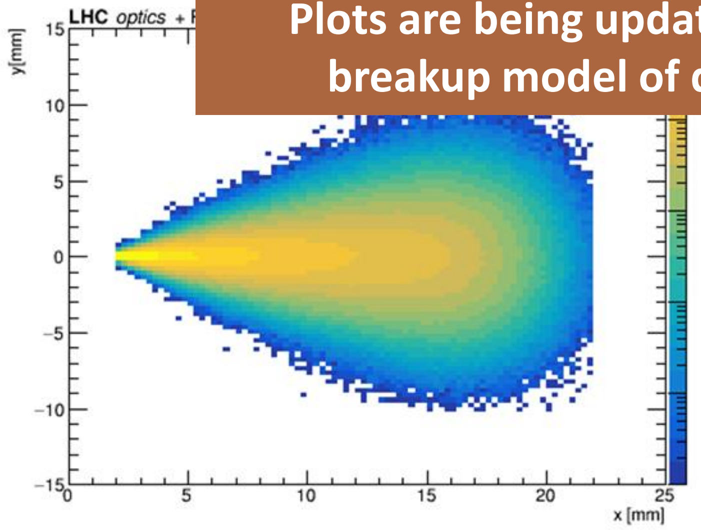
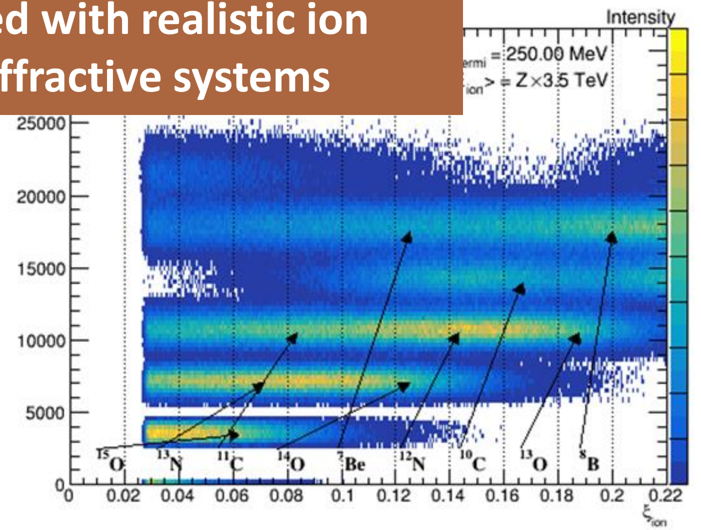
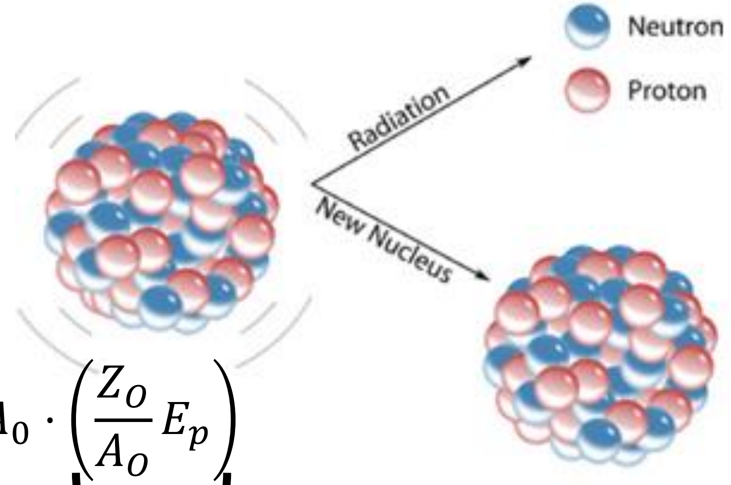
Plots are being updated with realistic ion breakup model of diffractive systems







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Proton detectors

Physics with Ion tagging – α clusters

- Can we tag alphas? $\xi_{RP,\alpha} = 1 - \left(\frac{Z_O}{A_O}\right)\left(\frac{A_\alpha}{Z_\alpha}\right) = 0$
- Several channels exists, one example:
  - 16O → 11C + 3n + 2p
  - 16O → 11C + 1n + α

(11C has half-life 20 min, ξ~8.3%)

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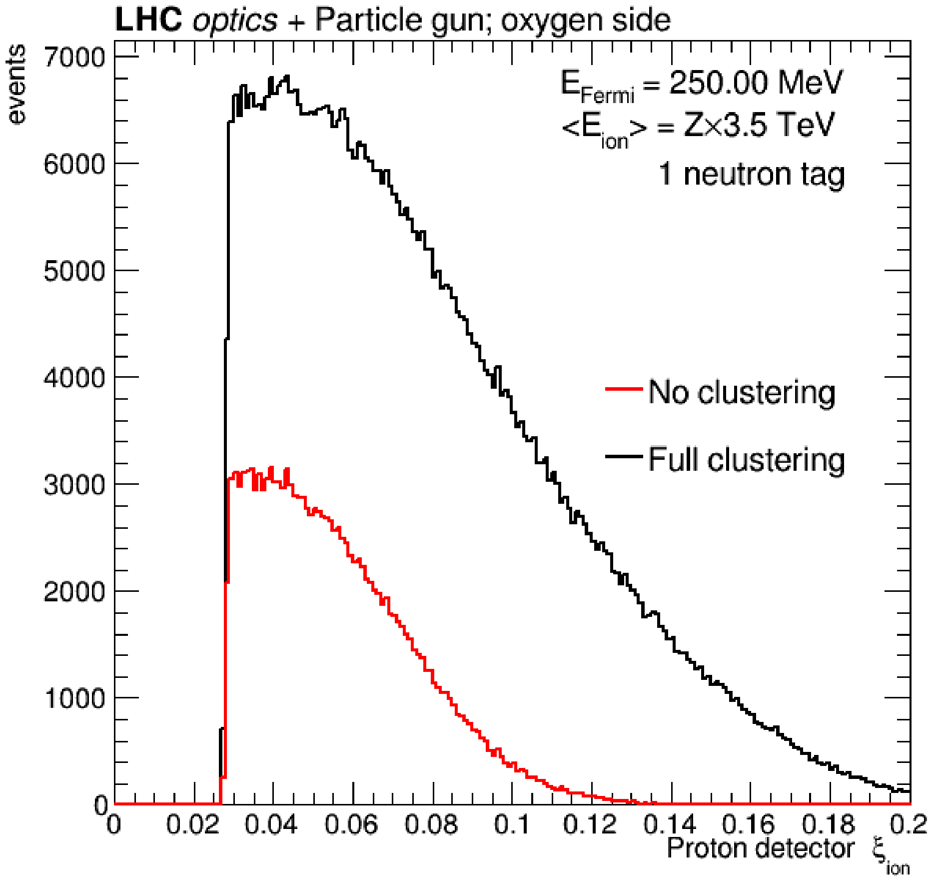

In 1n channel, when alphas are emitted more isotopes with 1n detected

QCD interactions with proton tagging

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Fermi energy is exaggerated to accommodate various detector/condition effects
High spectator multiplicity included

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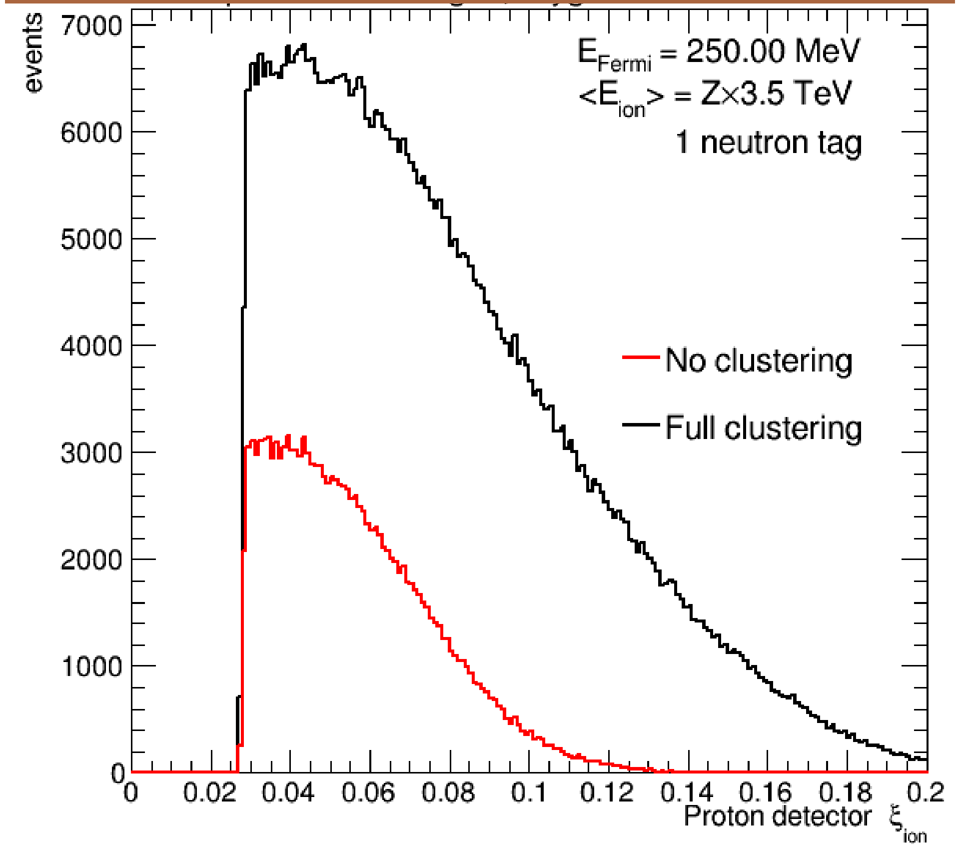

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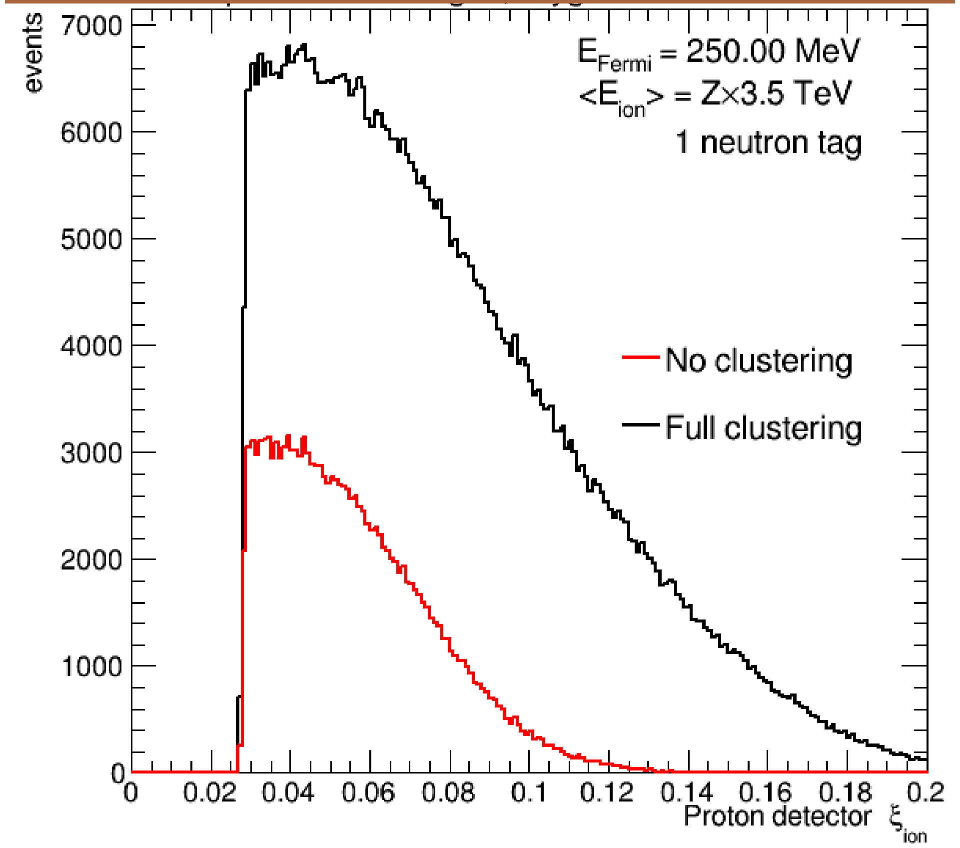


In 1n chann … n detected

Physics results can be delivered

Summary

Proton/Neutron tagging

- Participation of forward proton/neutron detectors in p-O / O-O collisions improves modeling of (in)elasticity in proton – Air collisions
- Proton/Neutron tagging in pO covers a complementary phase-space to the standard program (diffraction, pion exchange, …)

Probing nuclear geometry through ion tagging

- Forward proton detectors are sensitive to ion remnants.
- Can a combined measurement of forward proton/neutron shade light on ion disintegration?
- Challenges – tracking with high Q, multiple scattering, have the LHC with the right settings

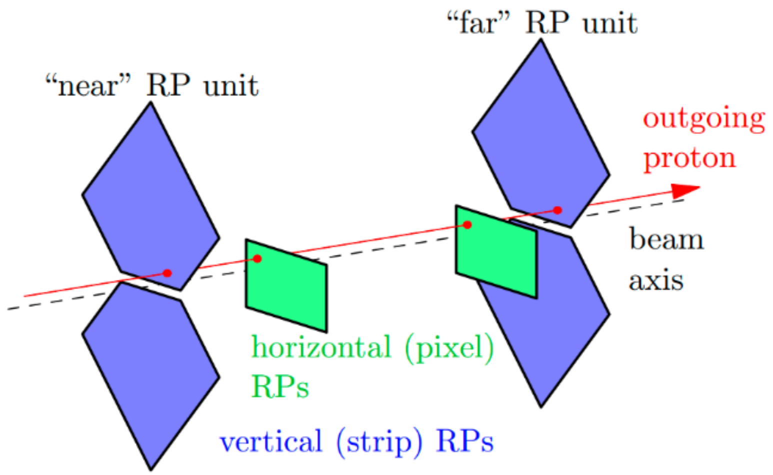
Feedback is welcomed: feel free to contact michael.pitt@cern.ch

Backup

Forward detectors – commissioning

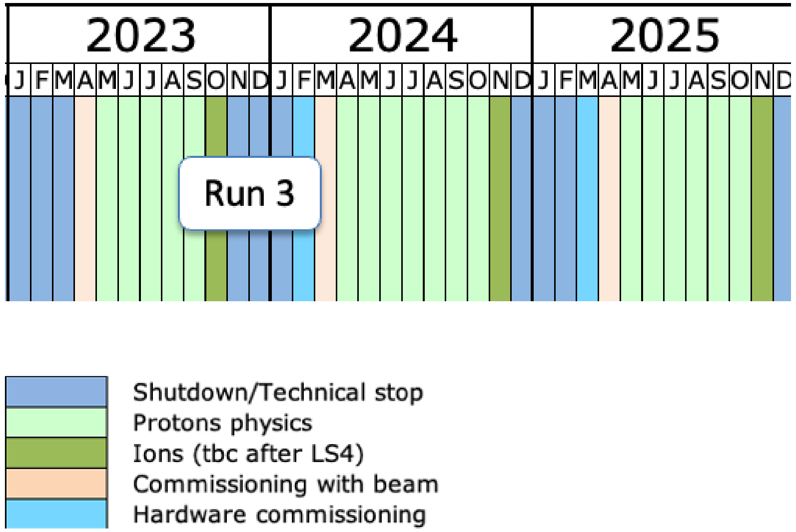
Precision Proton Spectrometer

- **<u>Only if LHC optics changes</u>** (e.g. high beta*), a special alignment run is required (2-3 bunches / beam) to approximately 12h, where vertical detectors are used with horizontal to measure the beam center



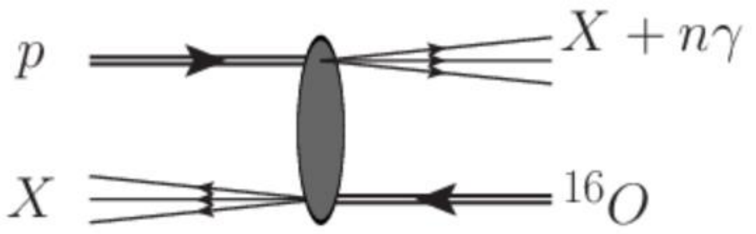
Zero Degree Calorimeter

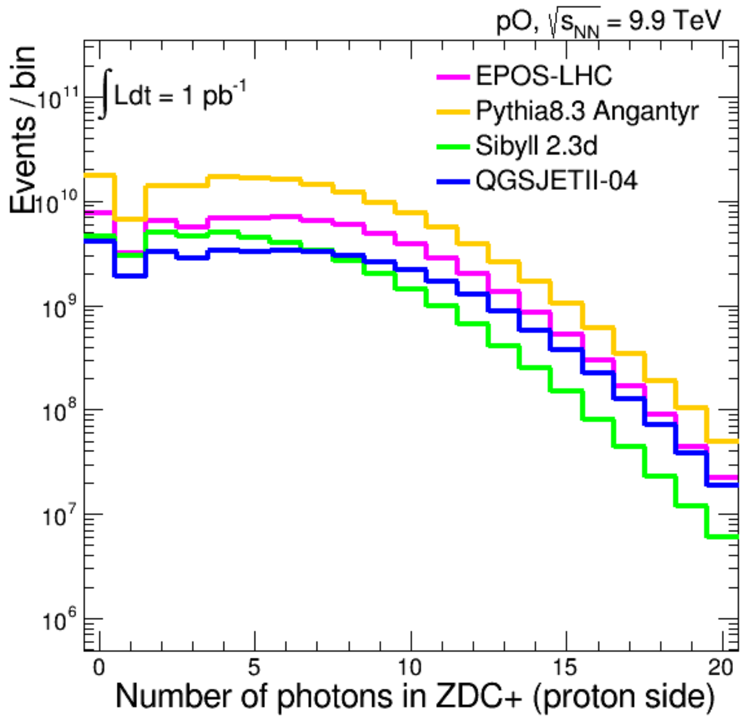
- ZDC is not installed during standard pp runs
- Before data taking: Need access, installation often takes ~ 1 day (usually after MD/TS)
- After data taking – access is needed to deinstall the detectors (offer done during the YETS)

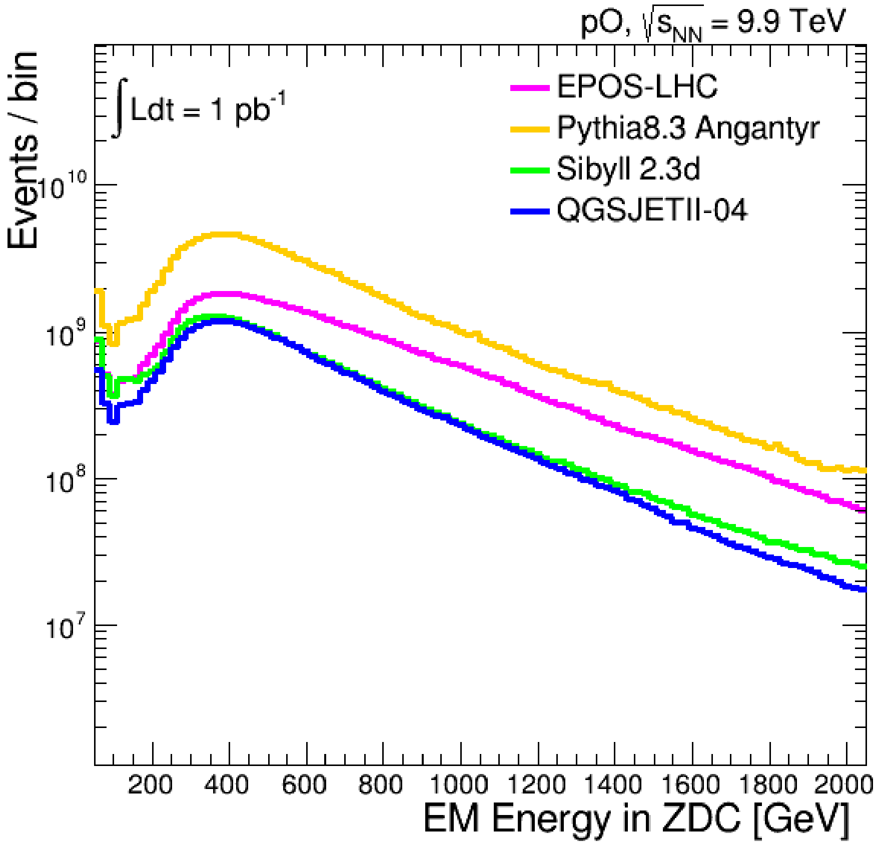


Forward neutrons in p-O collisions

- Photons can be produced in non-diffractive events
- Forward photon distributions in ZDC is additional observable to study hadronic interactions

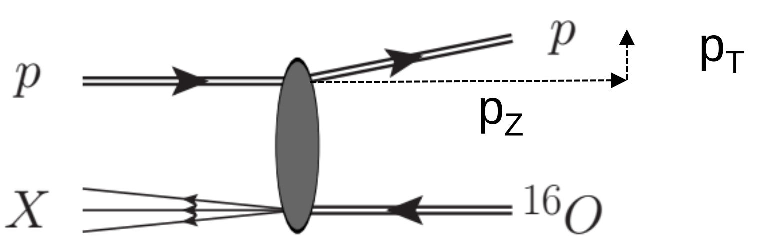


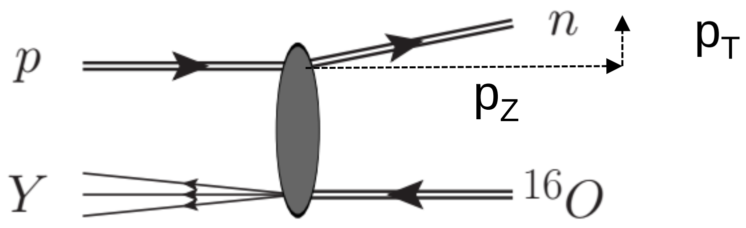


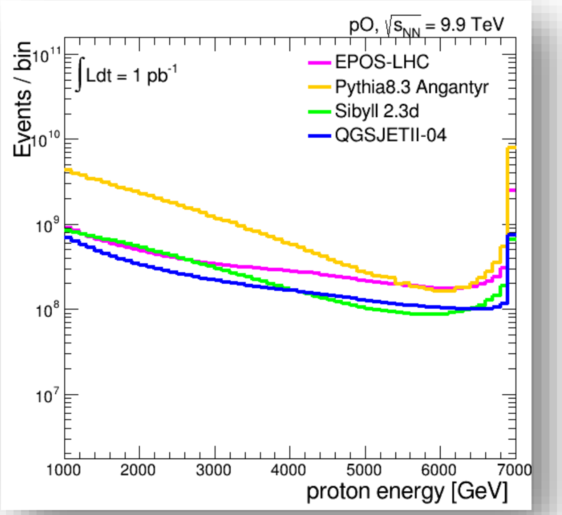


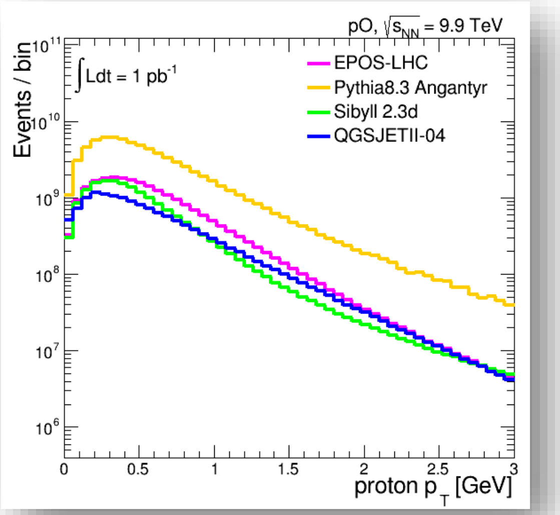
Forward protons / neutrons in p-O collisions

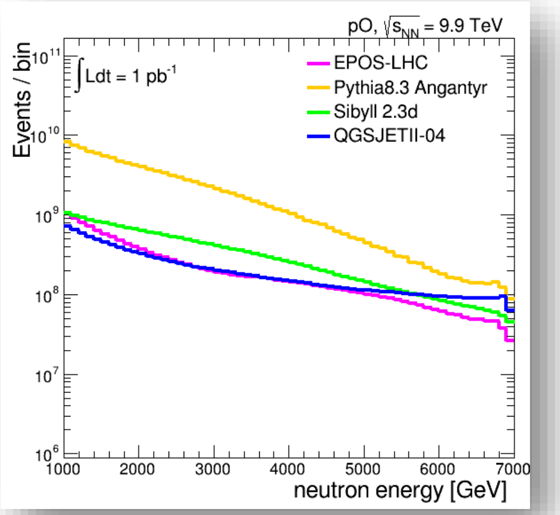
- High energy protons and neutrons emerge from p-O interactions
- By measuring the production rates, and event kinematics one can constrain their modeling

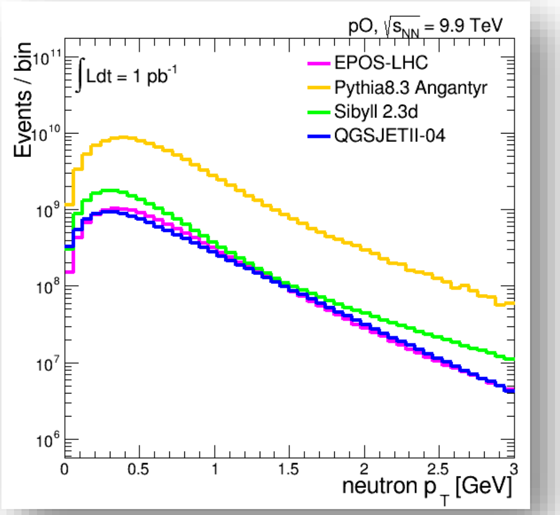










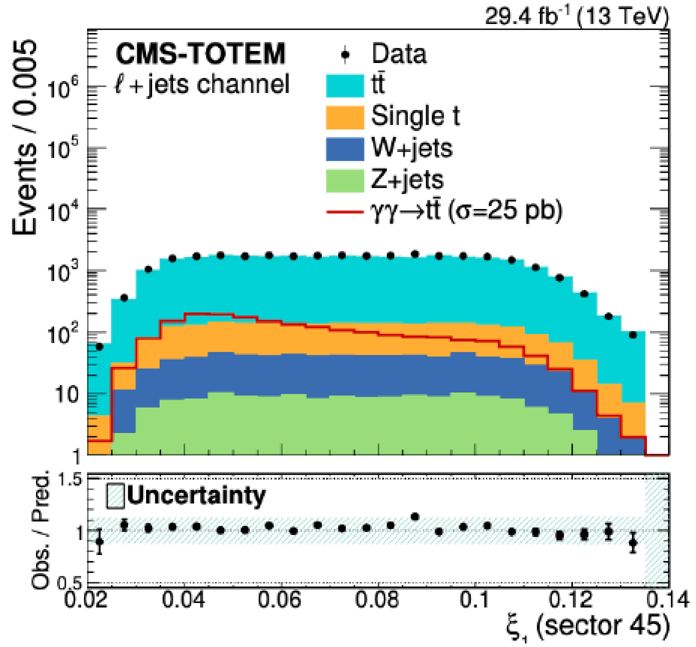


Example of forward detectors performance

Proton Detectors (PPS)

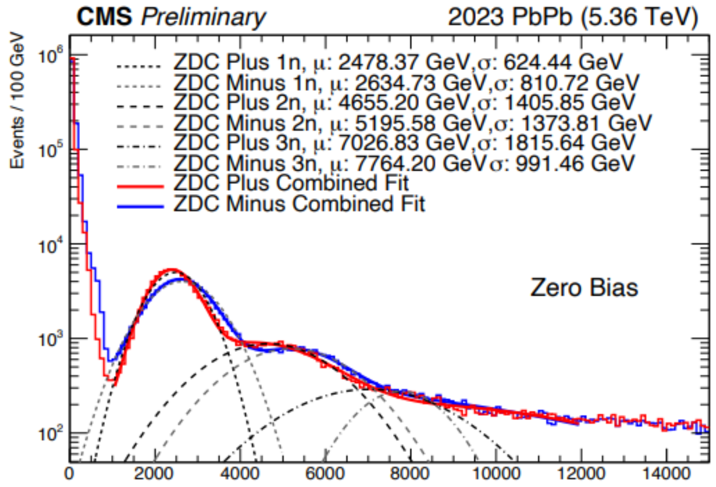
See more in A. Solano's talk

- Operated during standard *pp* runs (high PU)
  - Measured proton momentum loss ($\xi = \Delta p_Z/p$) in range between 2.5% - 15% with unprecedented resolution
- In CMS, an additional vertical detectors can be inserted at very low PU, and mostly efficient for high β* LHC optics ($\xi \sim 0$)



Zero Degree Calorimeter

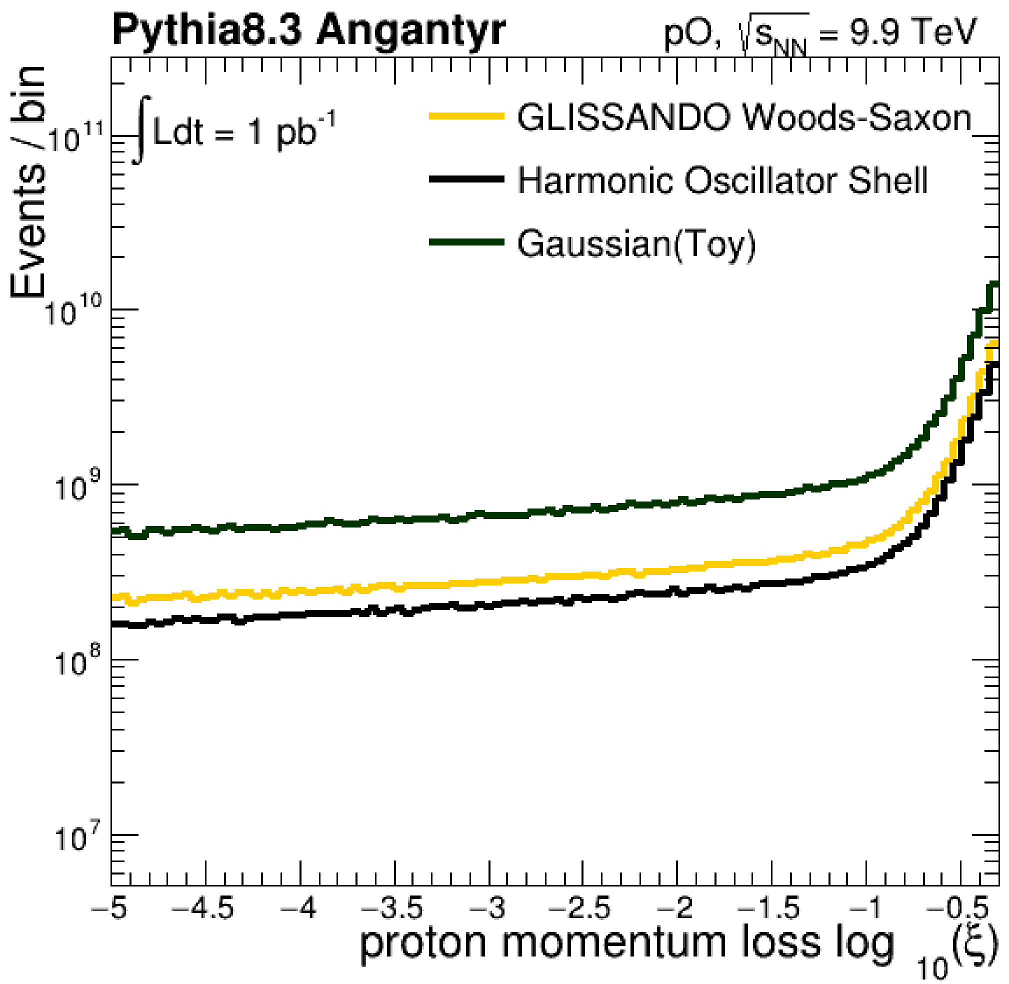
- Operated at very low pileup – can sustain integrated luminosity up to ~ 1fb^{-1} and *at pileup rate up to μ ~ several*
  - *Measures* neutral particles with |η|>8.3 (can resolve single neutrons)
  - Neutron peaks are fitted with 28% width (res. + smearing)
  - EM has 5 horizontal divisions (can be up to 3 in Run 4)



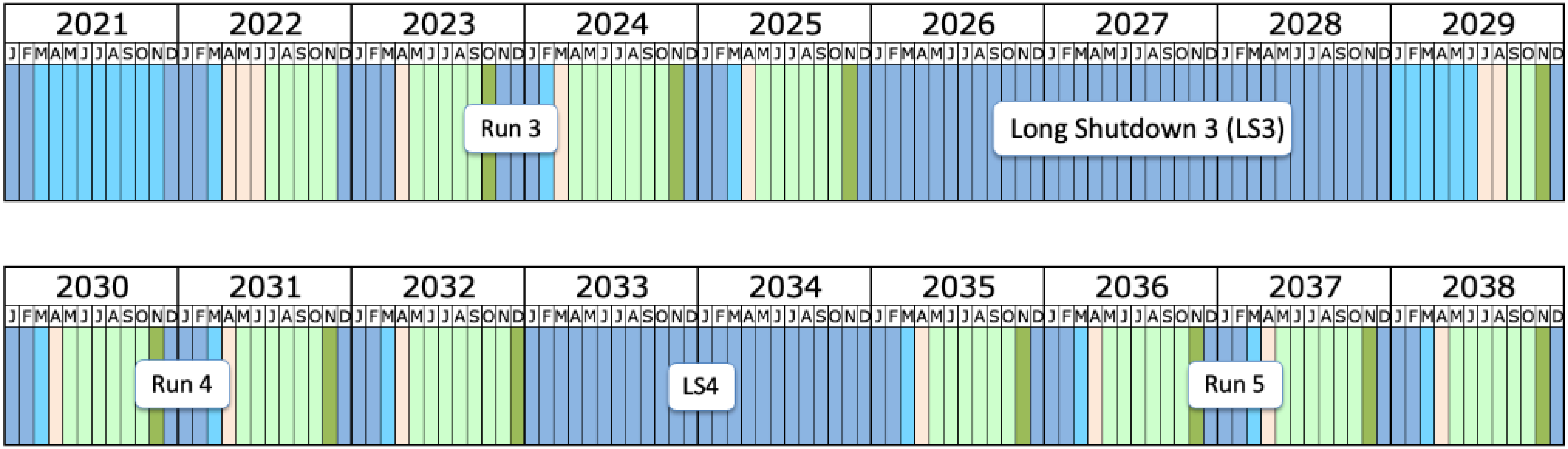
CMS DP–2024/002

Protons vs geometry

- Diffraction and ion geometry – we can tag diffractive protons in pO collisions and to look at event kinematics or oxygen remnants
- From the simulation it seems that diffraction is similarly modeled with respect to different geometries



LHC Run schedule



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