Proton-Oxygen collisions with forward detectors

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Michael Pitt (CERN)

michael.pitt@cern.ch

Outline

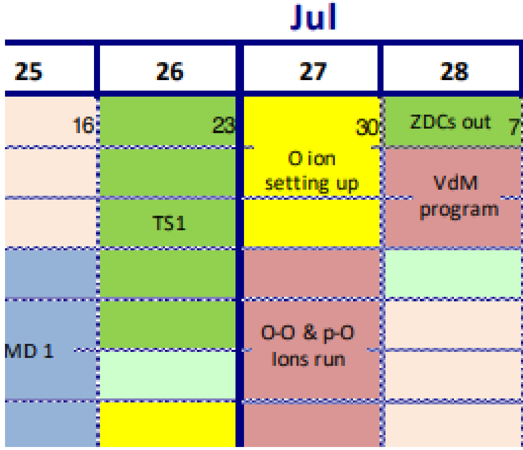
- Accelerating Oxygen ions at the LHC
- Forward proton and neutron tagging at the LHC
- Constraining models of hadronic interactions
- Determination of nuclear geometry

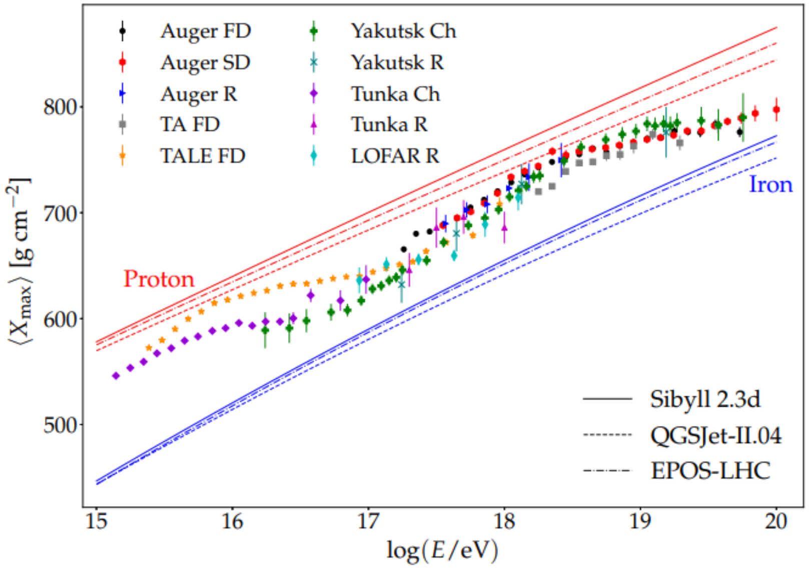
Accelerating Oxygen ions at the LHC

Motivation

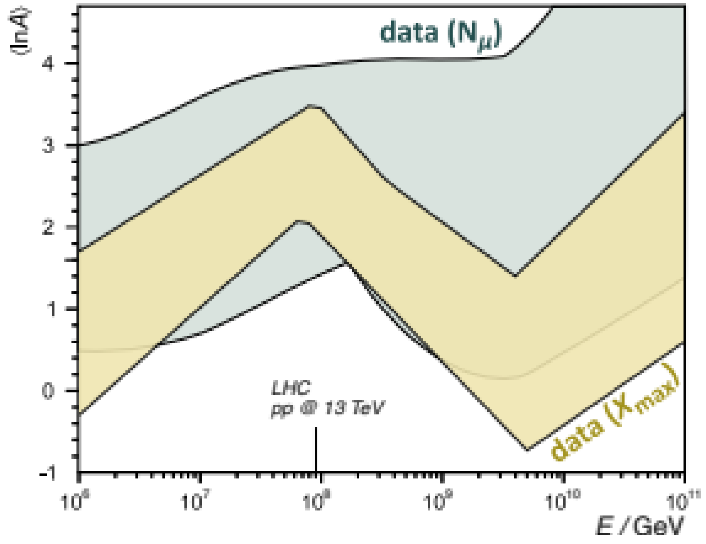
Oxygen ions at the LHC

- Oxygen ions (^{16}O) will be accelerated 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

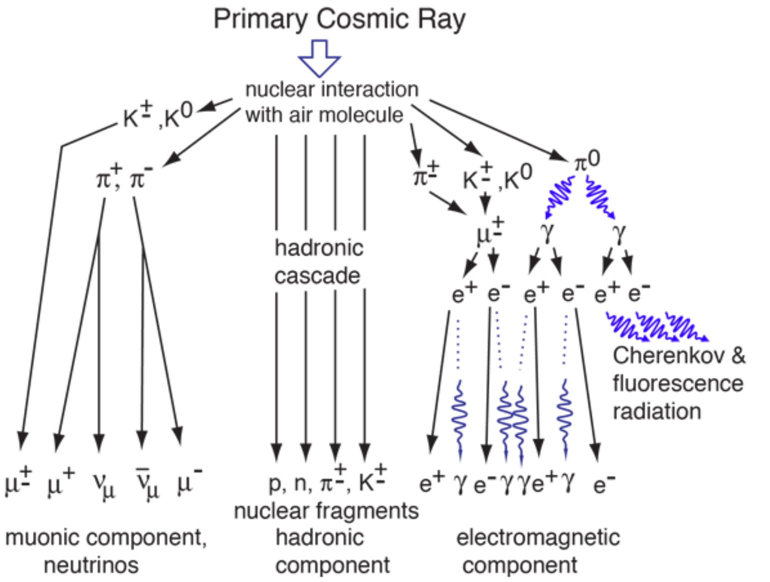




A. D. Supanitsky Galaxies 10 (2022) 3, 75



J. Albrecht et al. ASS 367 (2022) 3, 27

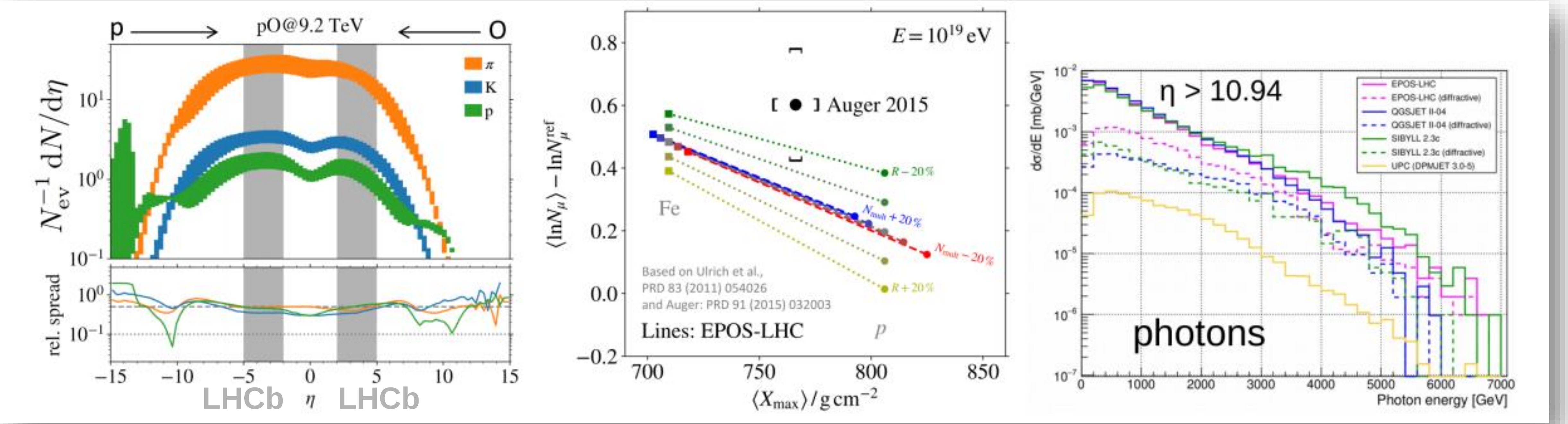


http://hyperphysics.phy-astr.gsu.edu/hbase/Astro/cosmic.html

Constrain hadronic models with pO collisions

Opportunities of OO and pO collisions at the LHC

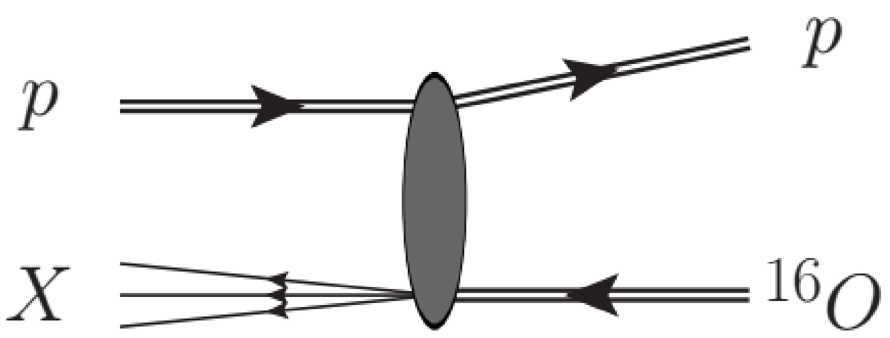
- Discussed in 2021 at a dedicated workshop at CERN (http://cern.ch/OppOatLHC)
- Summary available here 2103.01939
- The main interest for p-O collisions comes from LHCb and LHCf.

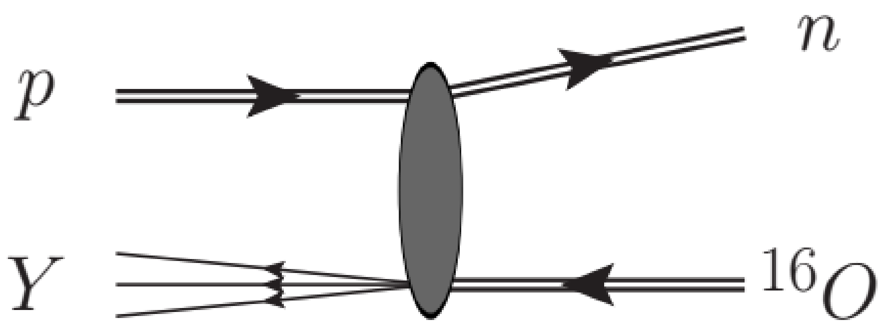


Constrain hadronic models with pO collisions

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

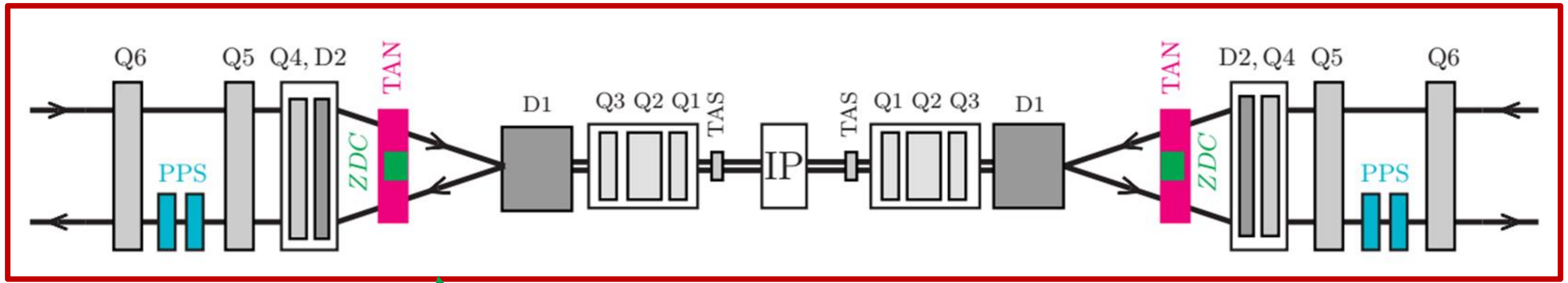




Forward proton and neutron tagging at the LHC

Forward detectors at the LHC

- CMS experiment is equipped with both forward neutron & proton detectors at about 140 m / 220 m from the IP, respectively on both sides.



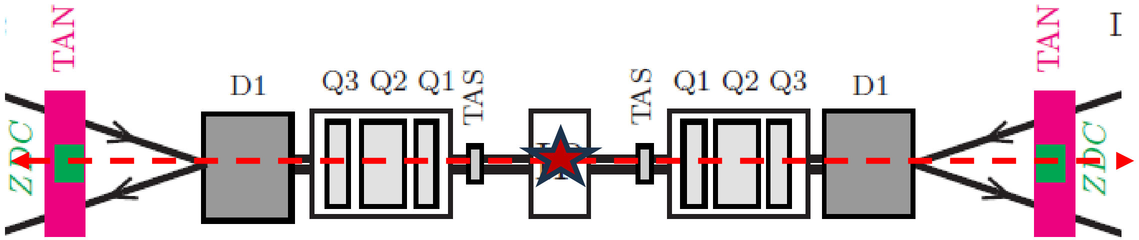
Interaction point

Neutron detectors ~140m
(Zero Degree Calorimeter)

Proton detectors ~220m
(PPS)

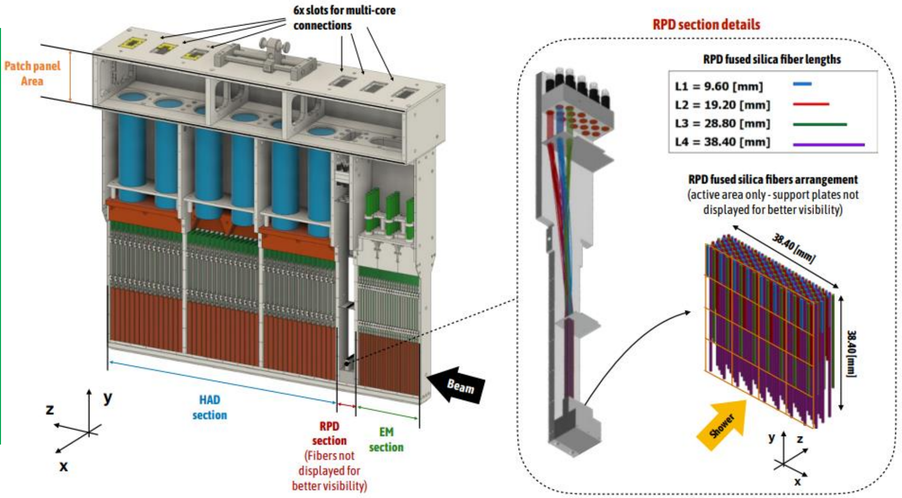
Forward neutron detector

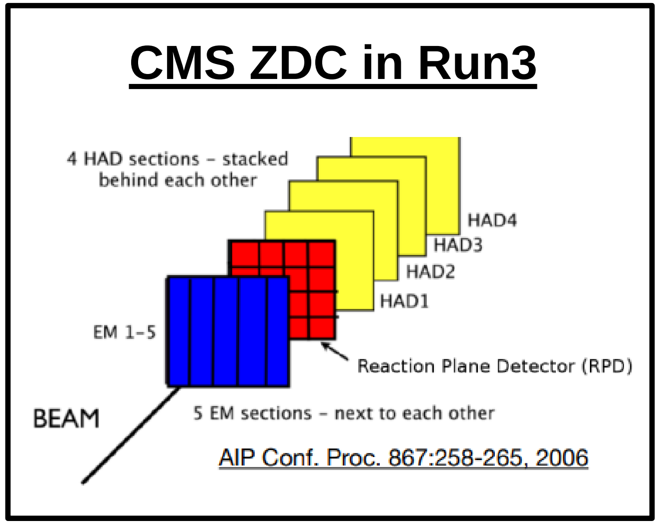
- The Zero Degree Calorimeter (ZDC) aims to detect forward neutral particles produced during heavy ion (AA or pA) collisions
- Located in the Target Absorber for Neutrals (TAN) ~ 140 m from the IP



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)





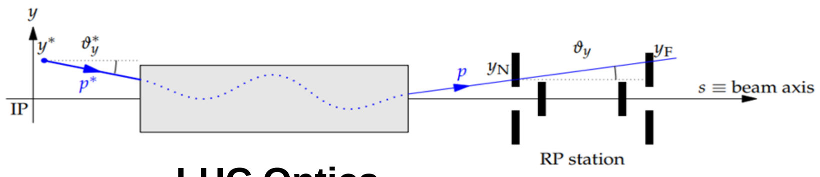
Granularity of the ECAL section will be reduced after Run3 (due to available space)

Forward proton detectors

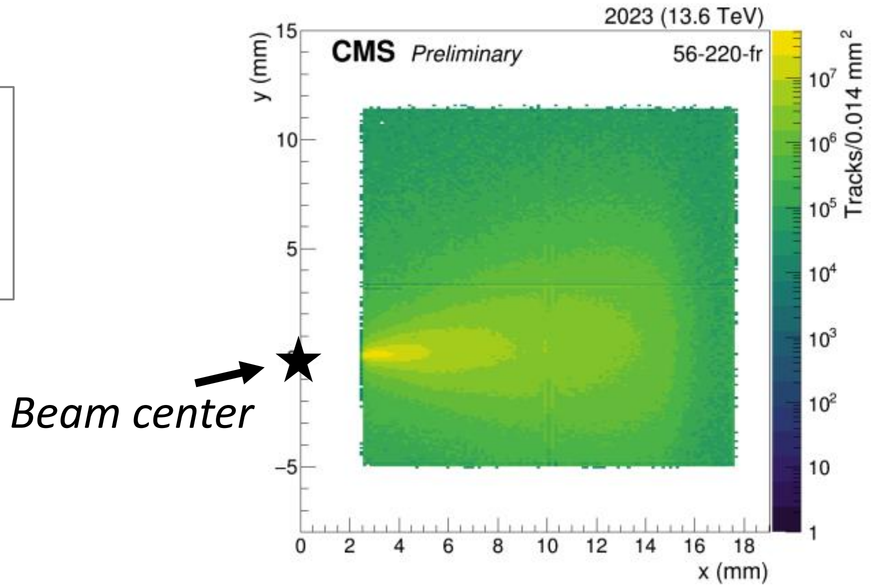
○ Precision Proton Spectrometers (PPS):

- 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

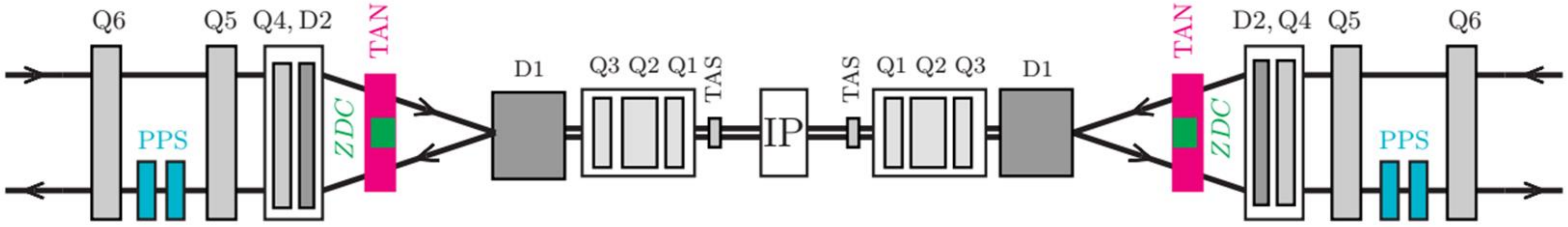
$$\delta x(z) = x_D(\xi) + v_x(\xi)x^* + L_x(\xi)\theta_x^*$$
$$\delta y(z) = y_D(\xi) + v_y(\xi)y^* + L_y(\xi)\theta_y^*$$



LHC Optics



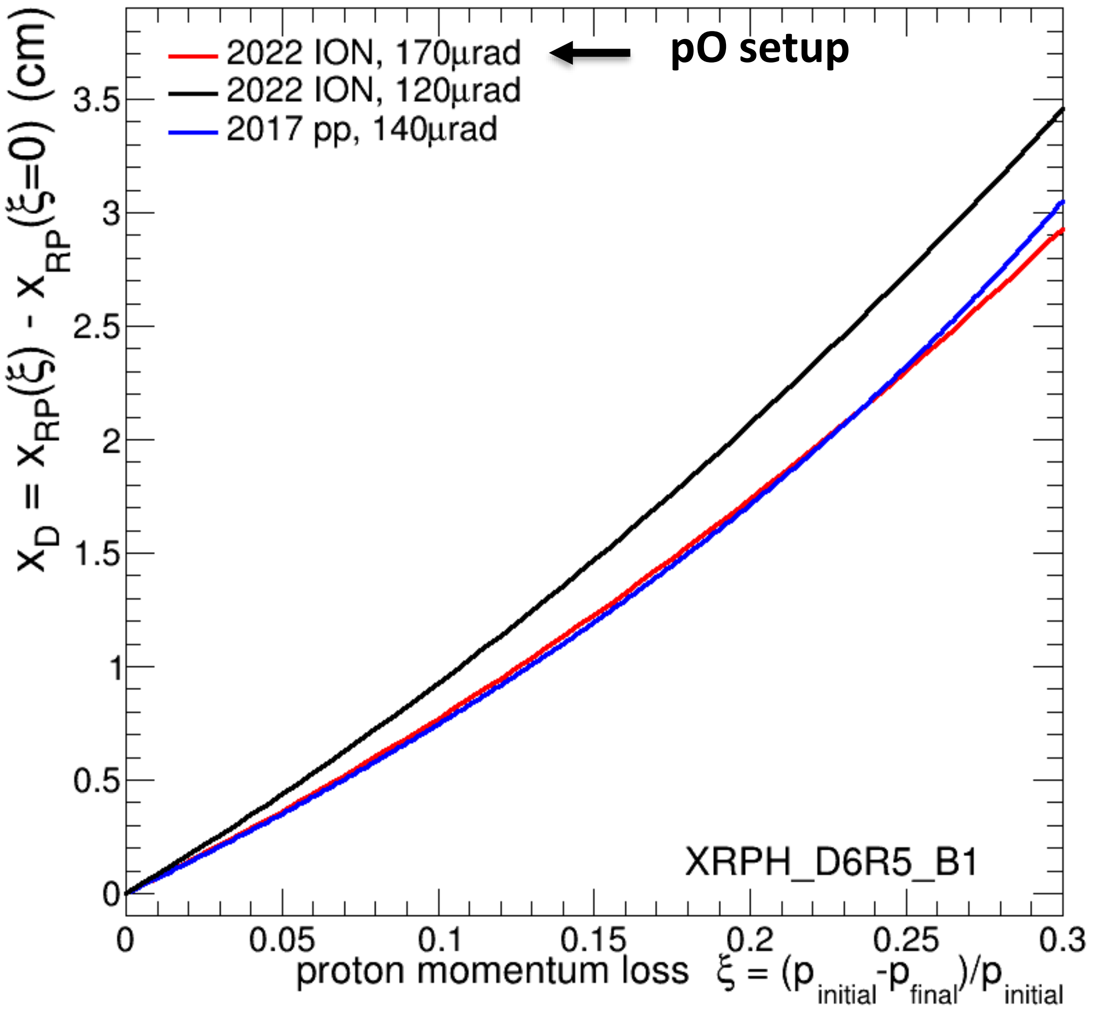
CMS-DP-2024-008



Forward proton detectors

- Detector performance rely on different parameters:

  - Crossing angle (the less the better)



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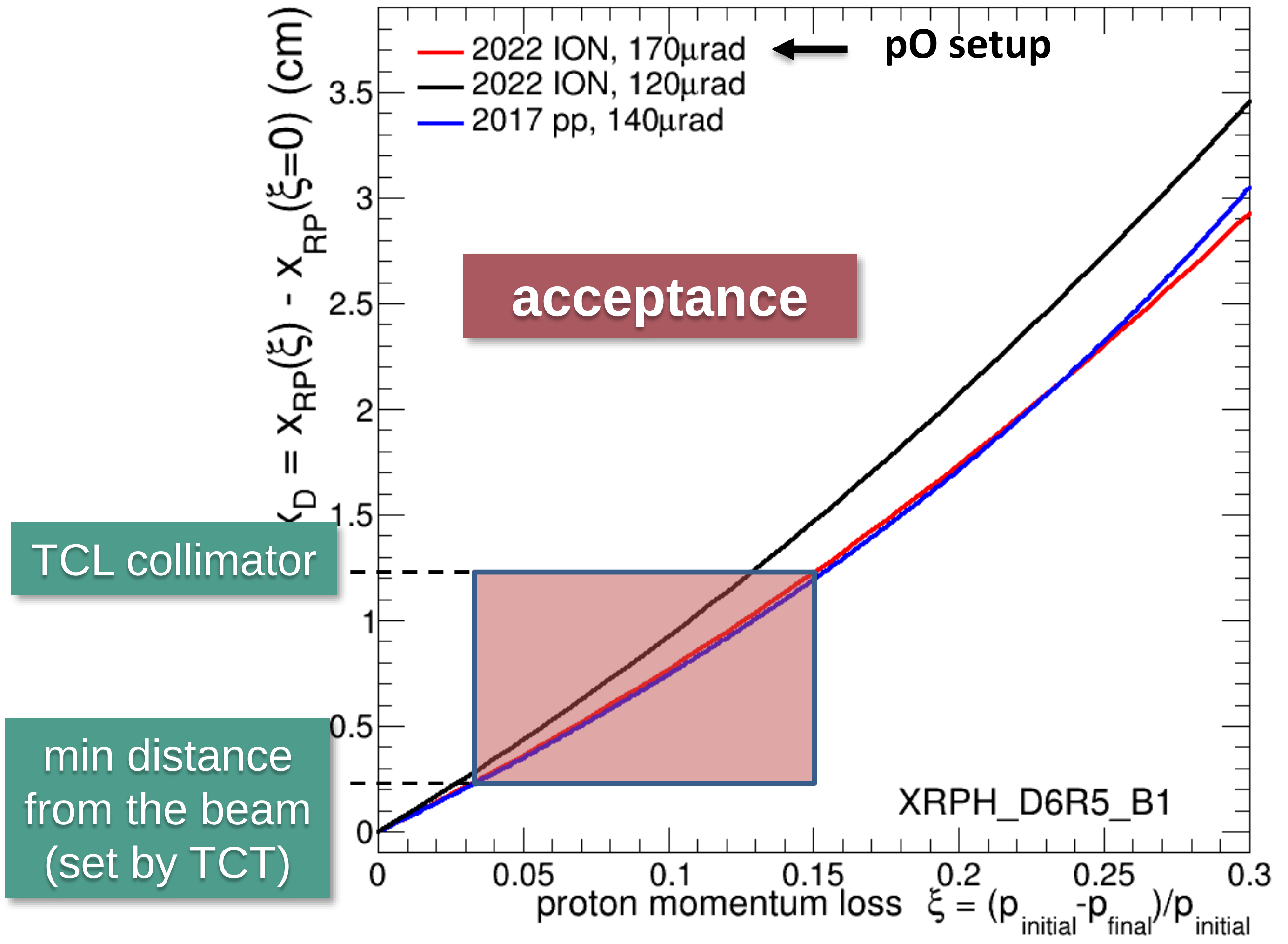
➢ Crossing angle (the less the better)

➢ Collimation scheme

  ➢ TCL (open/closed)

  ➢ Minimal distance to the beam



Forward proton detectors

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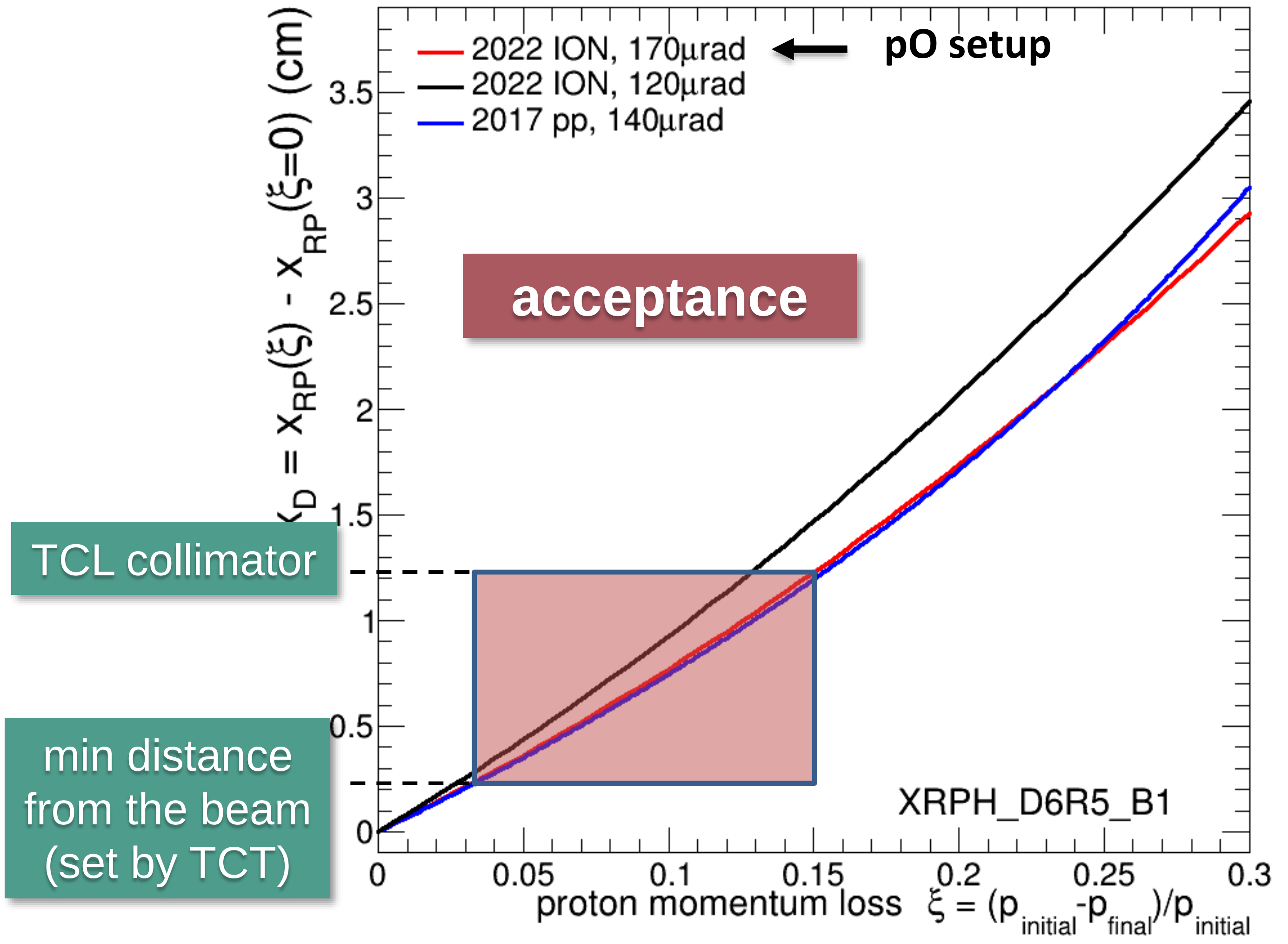
  - Intensity (LHCf requires mu~0.01 and >2us bunch spacing, L~nb^{-1})



Forward proton detectors

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Can be as low as we want

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- ➢ Collimation scheme
  - ➢ TCL (open/closed)
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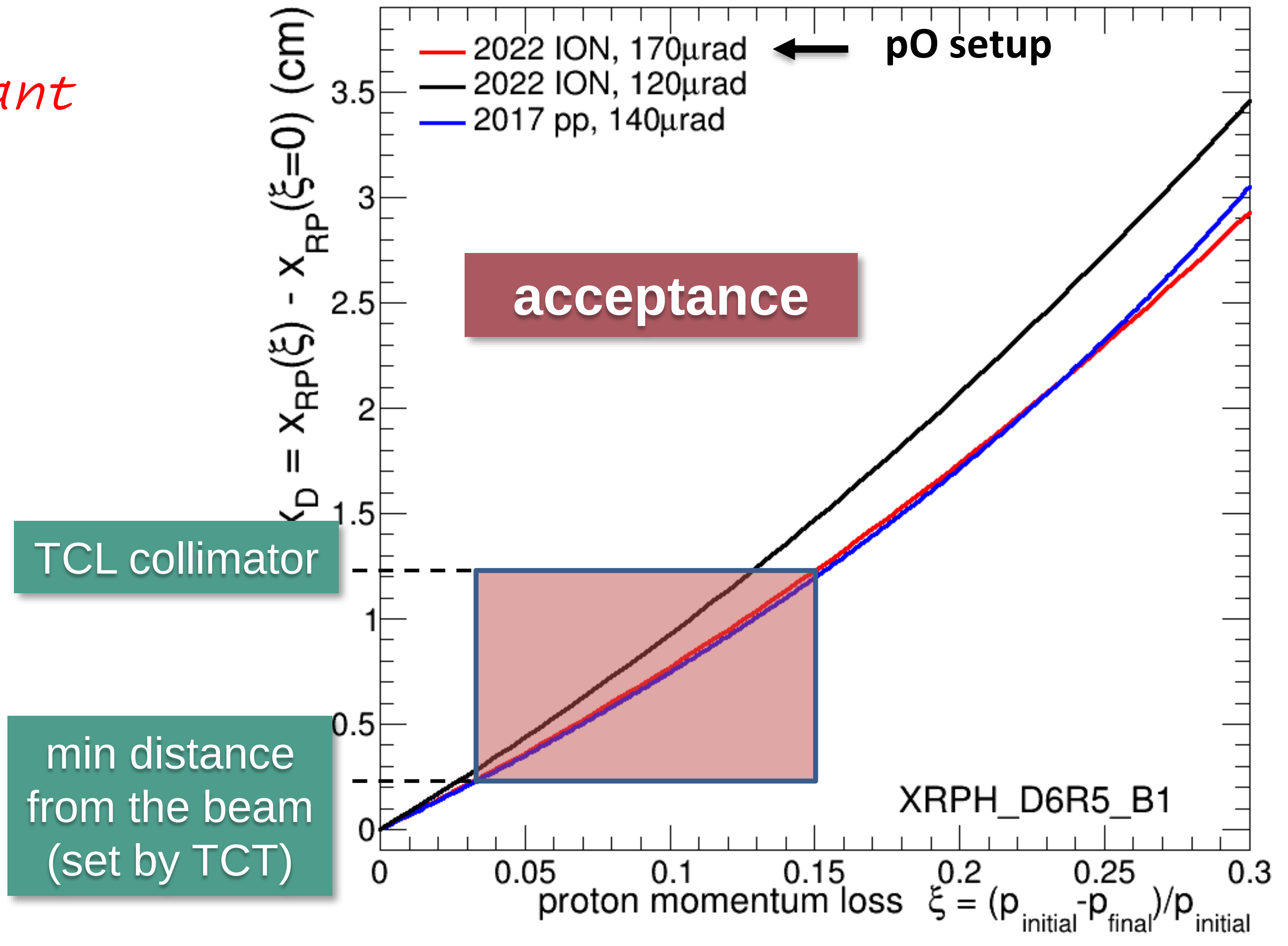
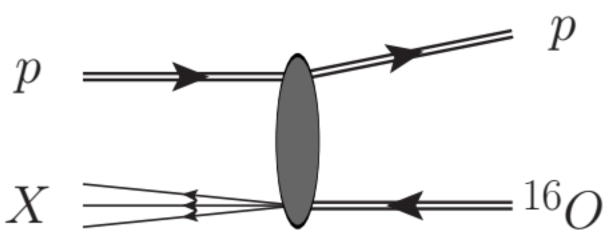


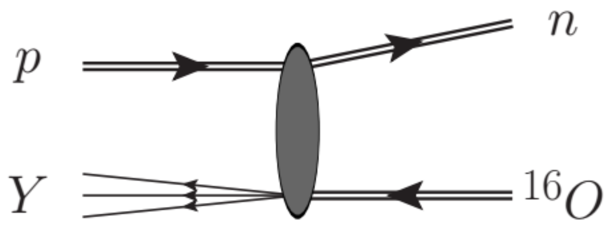
- *Pileup is determined by LHCf*
- *So far, the verticals are not considered*

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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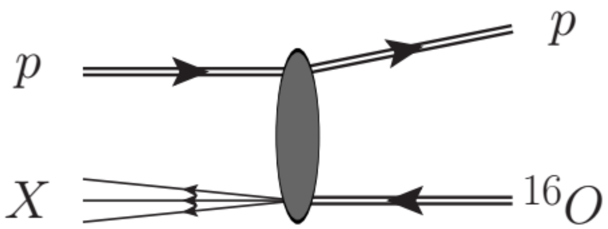
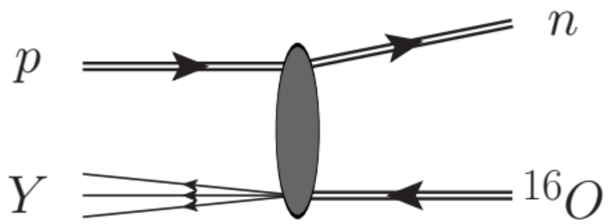


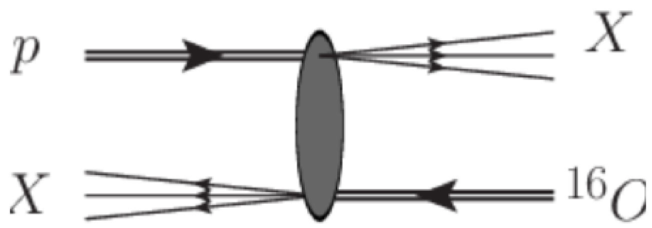


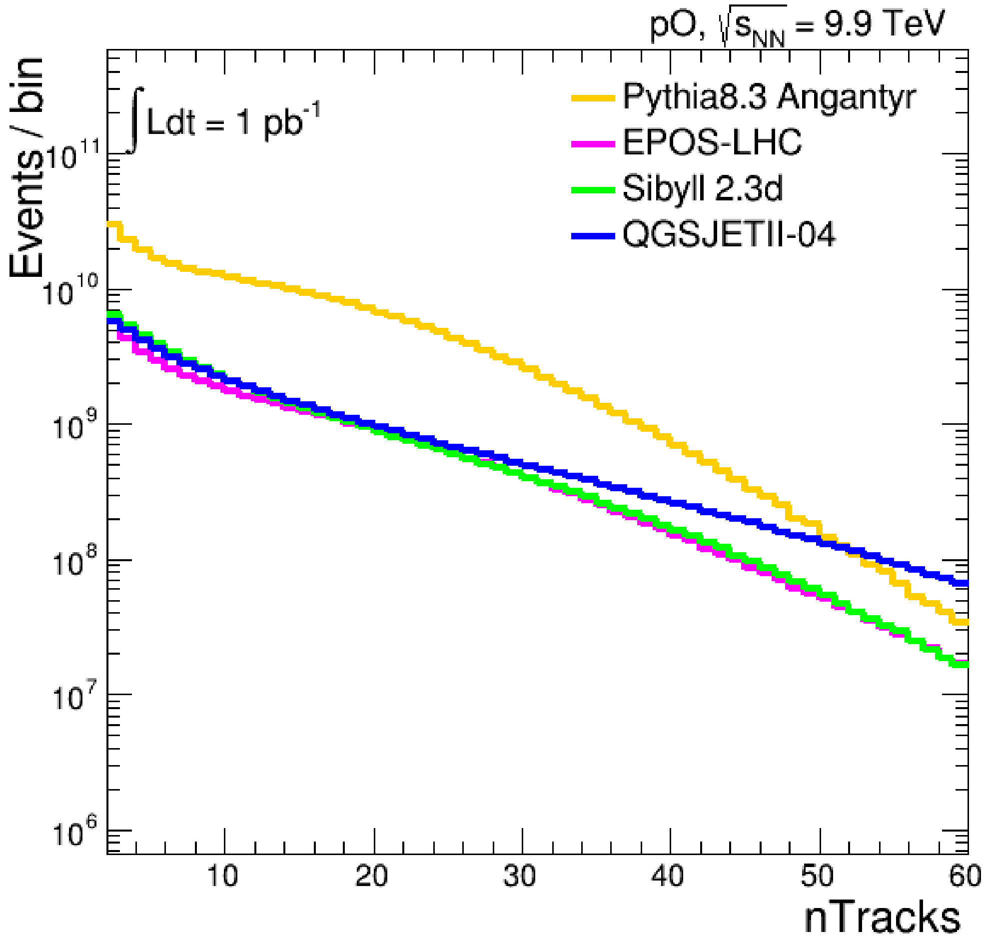
Warning

- Not all kinematic variables are modeled by the event generators
- Once the acceptances are determined, we should reach out to MC authors regarding the measured distributions and update predictions

Forward protons in p-O collisions

- Event kinematics (like track multiplicity) constrain hadronic models





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

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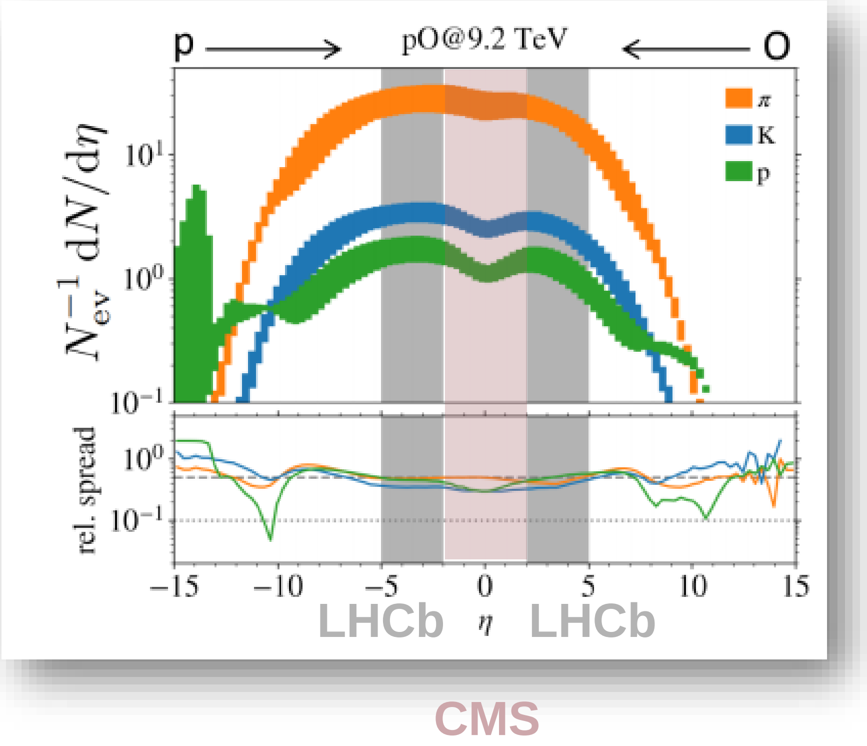
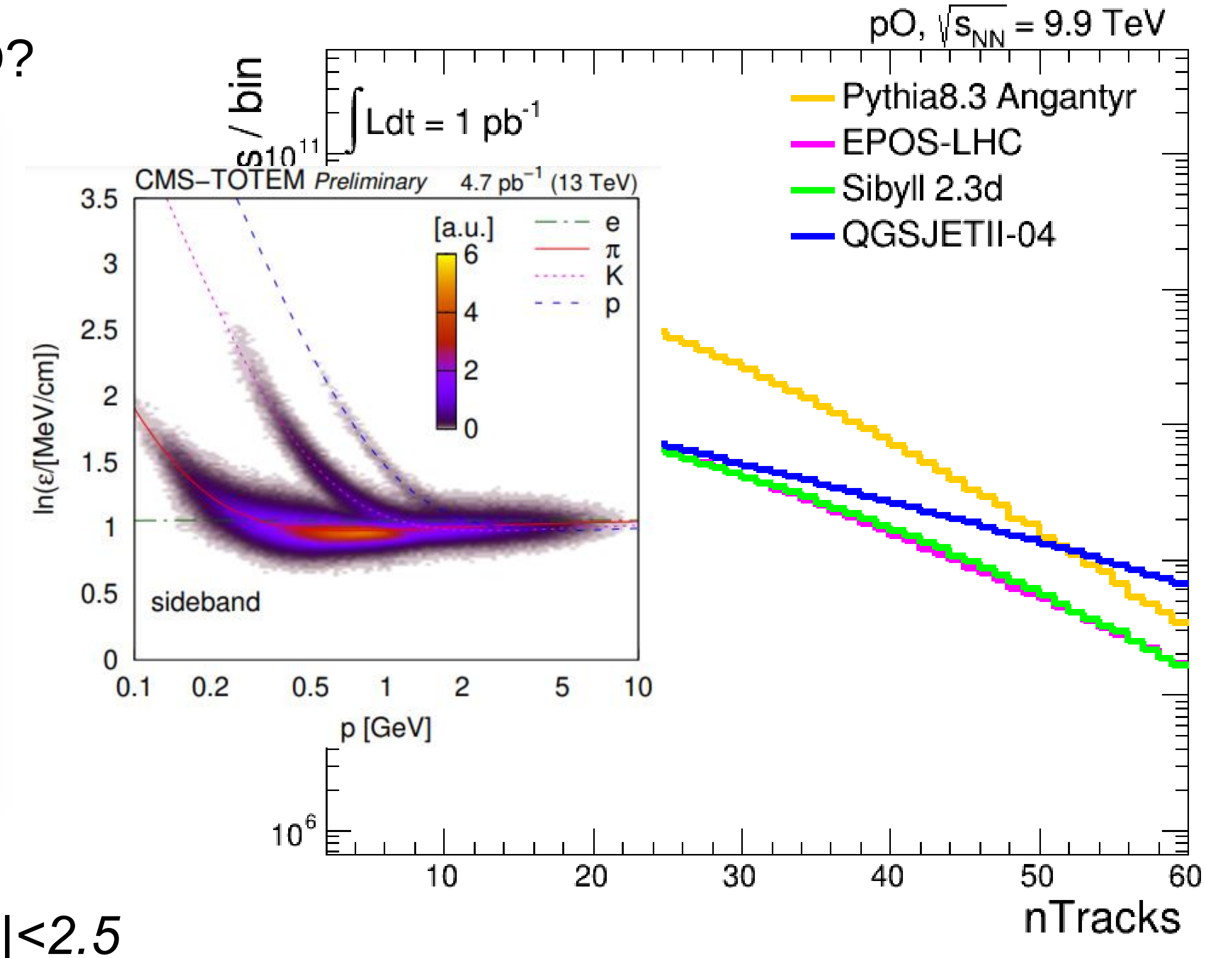
  - ➢ Can we can also test with particle ID?





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Forward protons in p-O collisions

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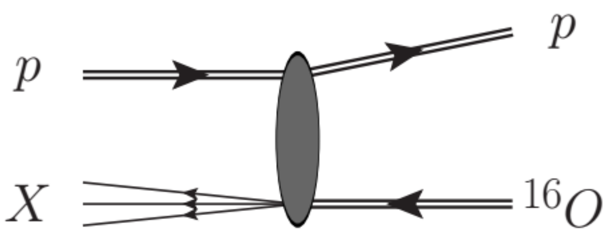
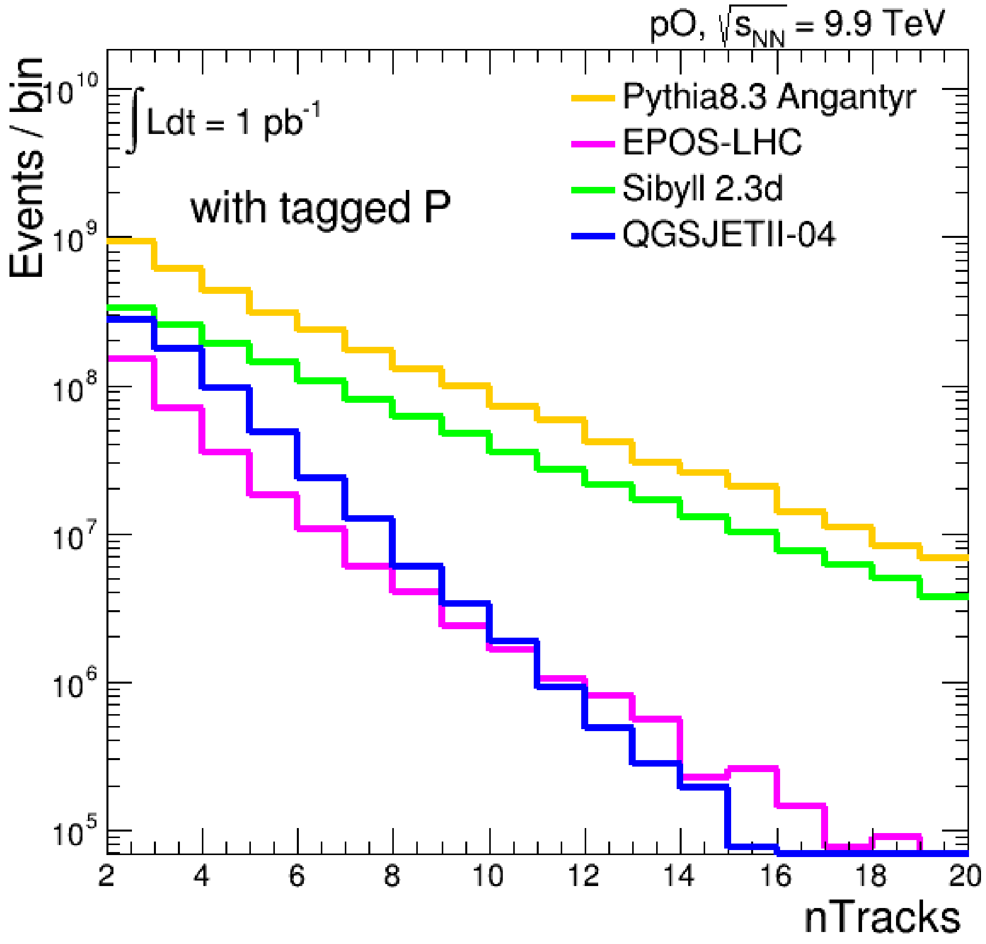
- Diffractive events, ~20%, (with forward protons) often lacks large central activity:





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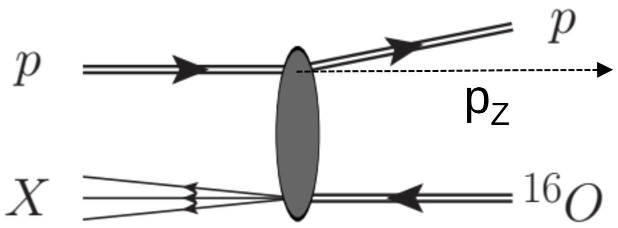
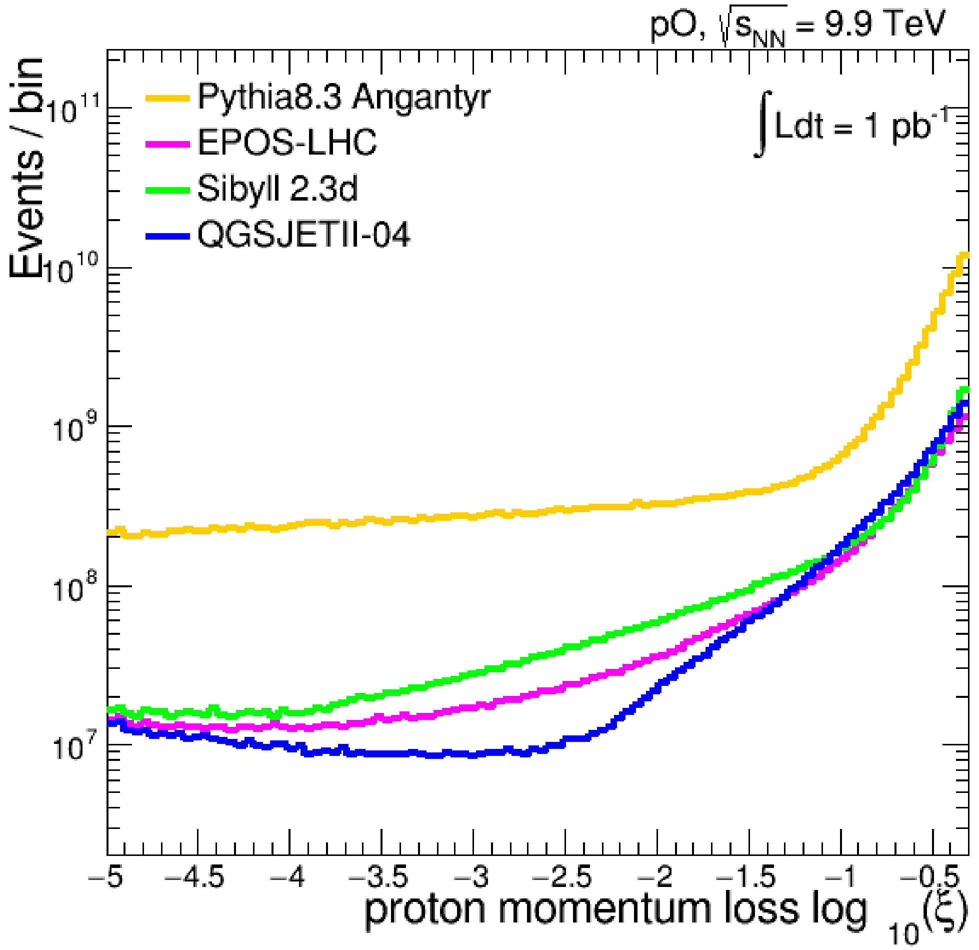
- Proton kinematics are weakly constrained in hadronic models





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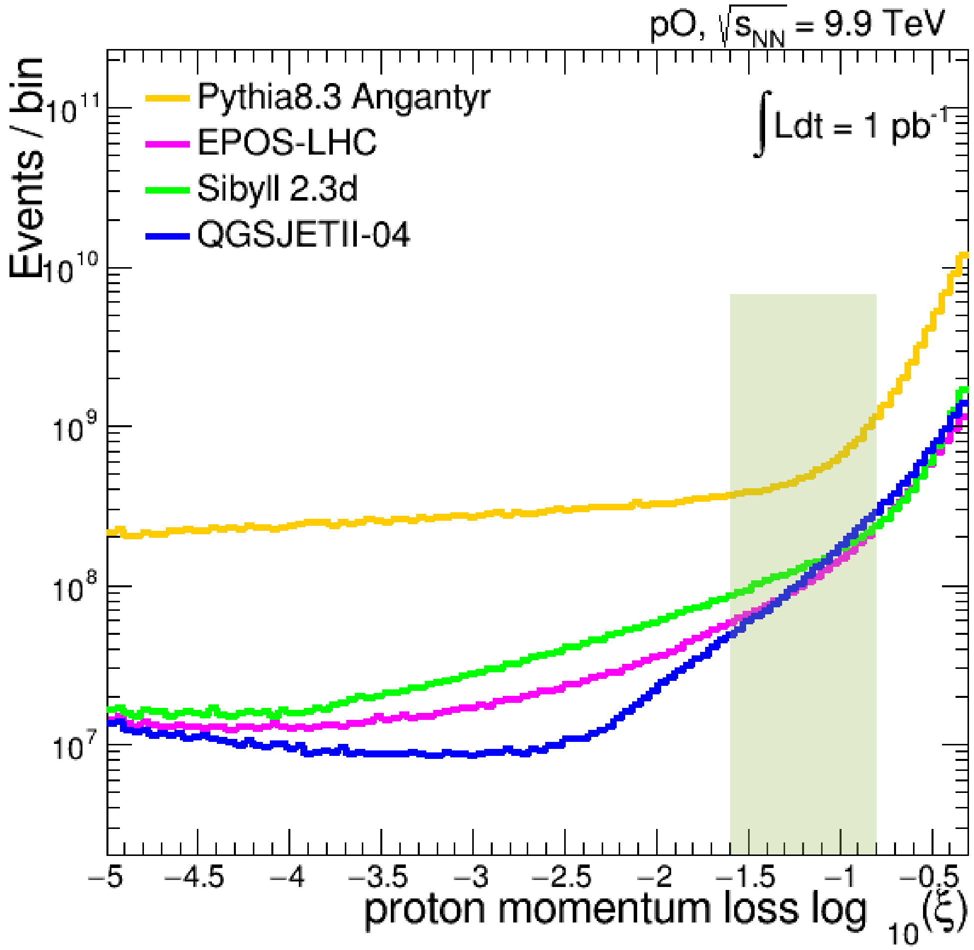
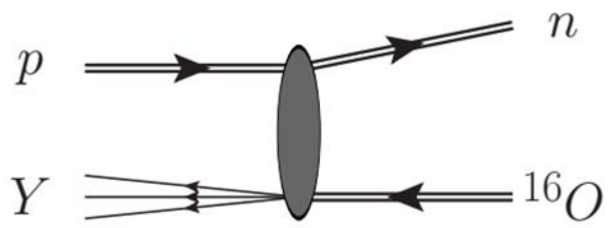
- Proton kinematics are weakly constrained in hadronic models
- Even with small fiducial region (2.5%<ξ<15%), sizable differences in expected rates (±25%):

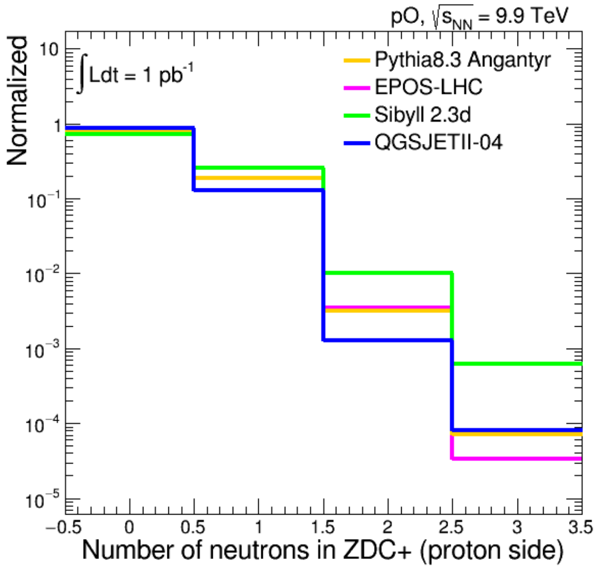
Generator	acc.	σ[mb]
EPOS-LHC	2.24%	75.63
Pythia8	1.40%	498.0
Sibyll	2.90%	76.66
QGSJETII-04	2.60%	77.03

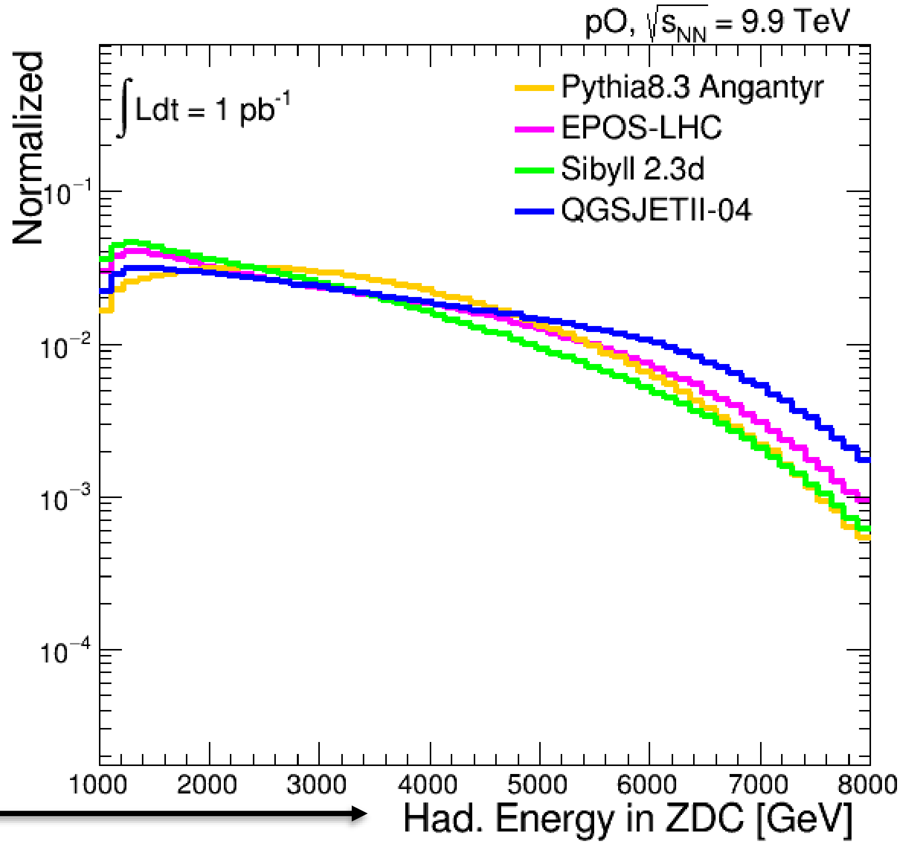


Forward neutrons in p-O collisions

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







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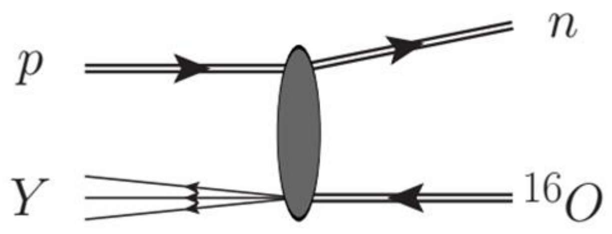
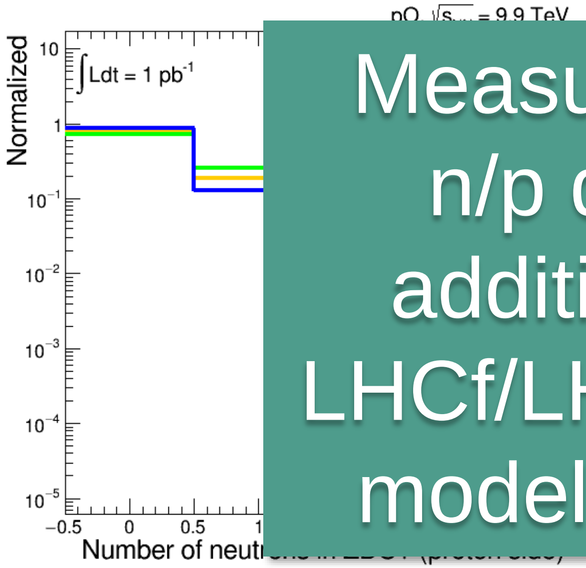
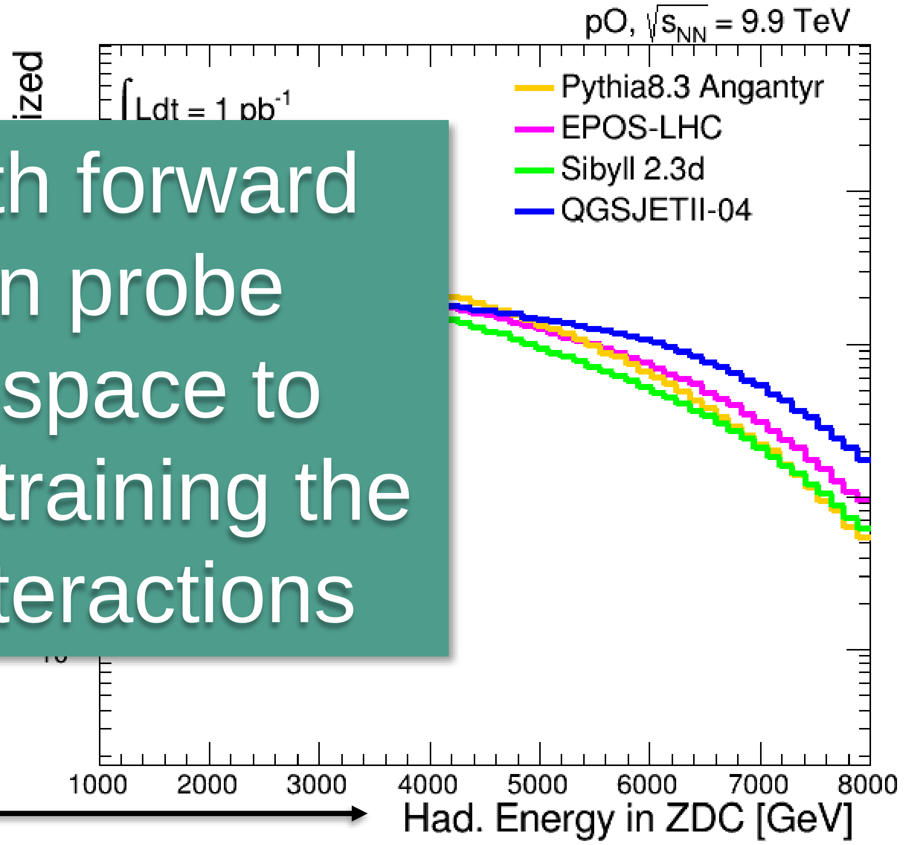




Measurements with forward n/p detectors can probe additional phase-space to LHCf/LHCb in constraining the modeling of pO interactions

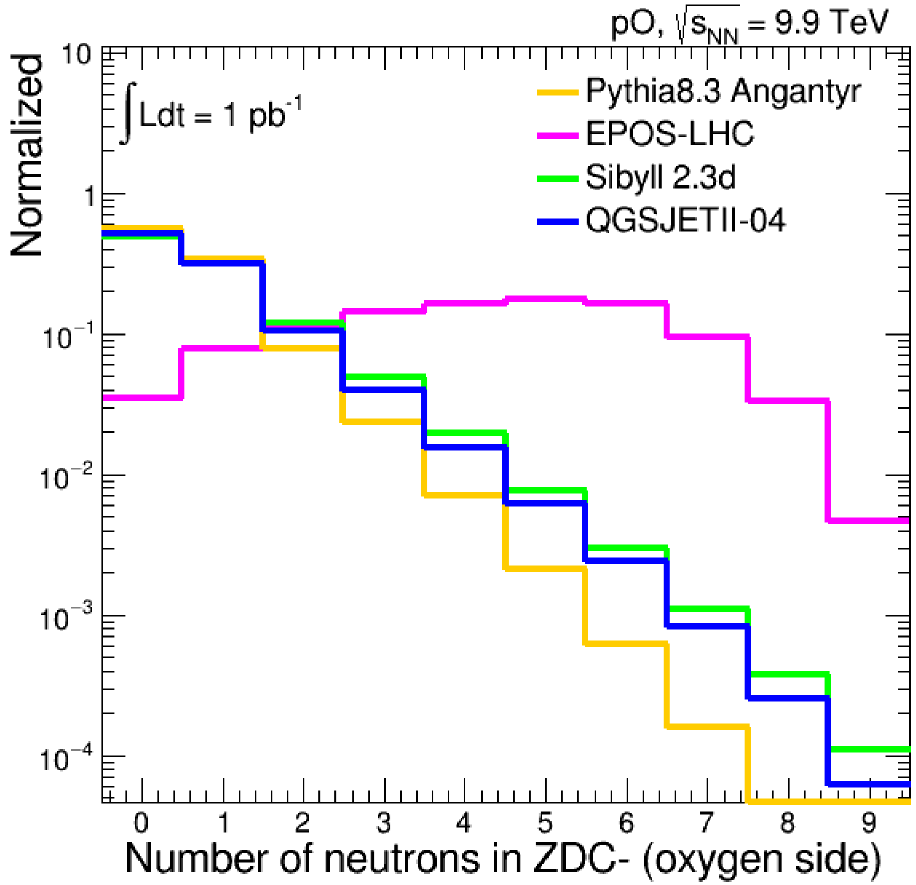


Neutron energy smearing of 15% is applied →

Constraining ion geometry through its fragments

Oxygen side – neutron tagging

- Neutrons can be tagged also in the oxygen side



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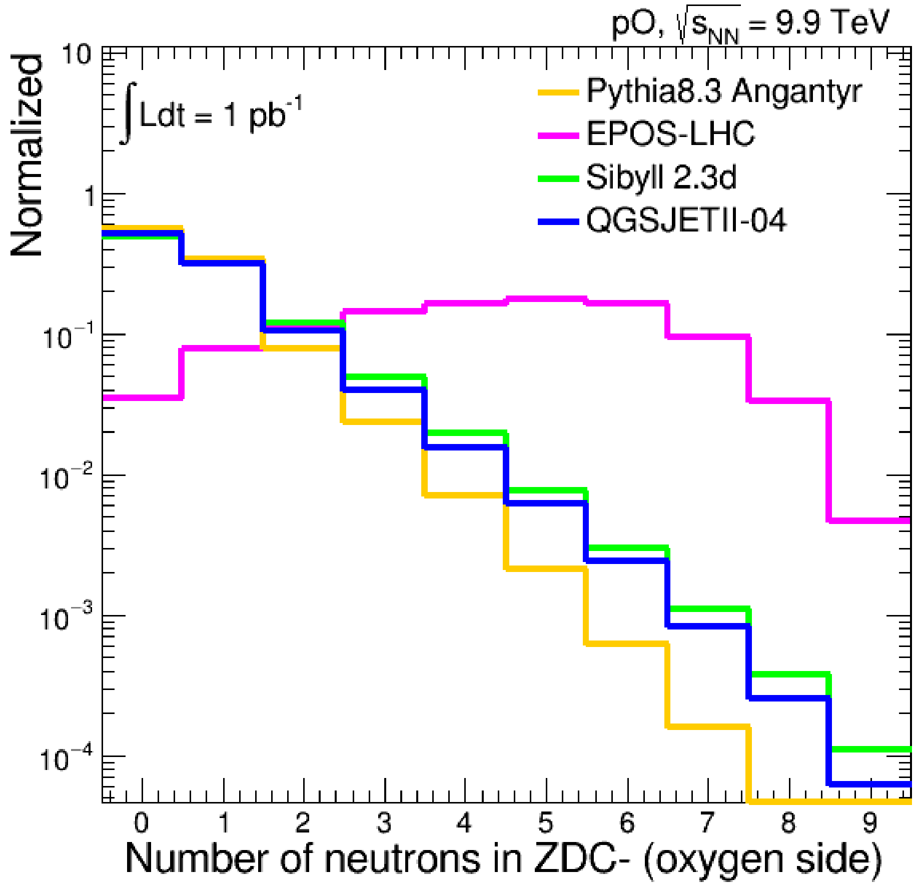
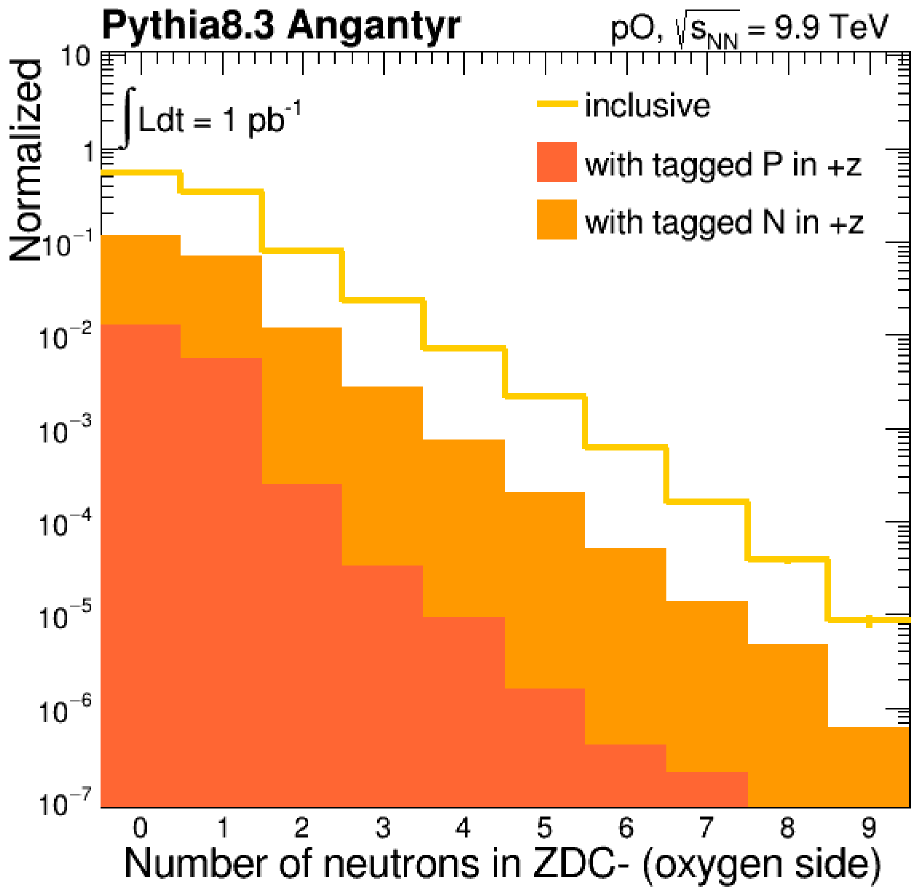
- Neutrons can be tagged also in the oxygen side
- Different ZDC energy spectra for diffractive and non diffractive events



Pythia



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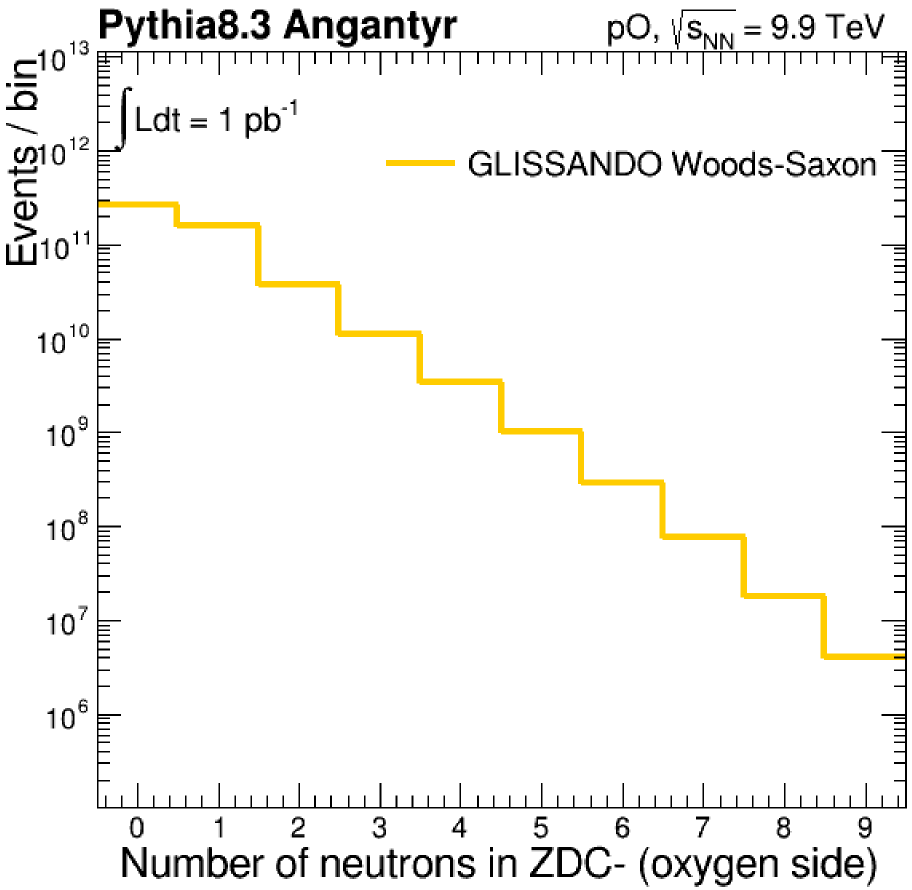

Nucleus Models - the nuclear geometry

- 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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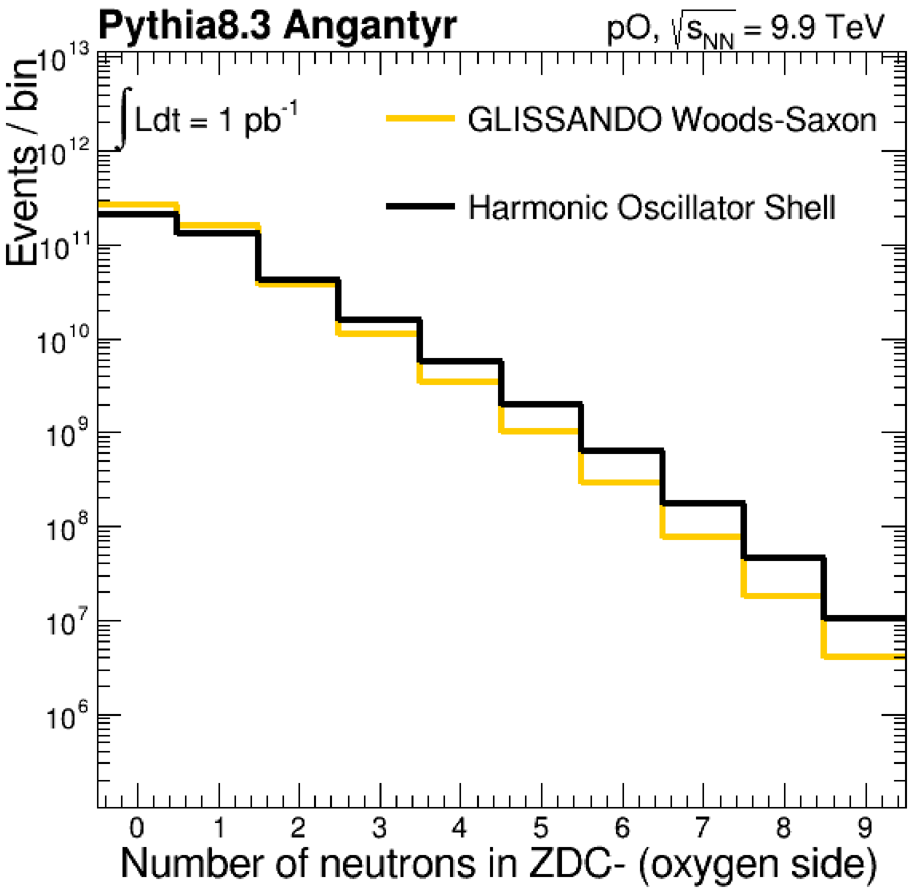

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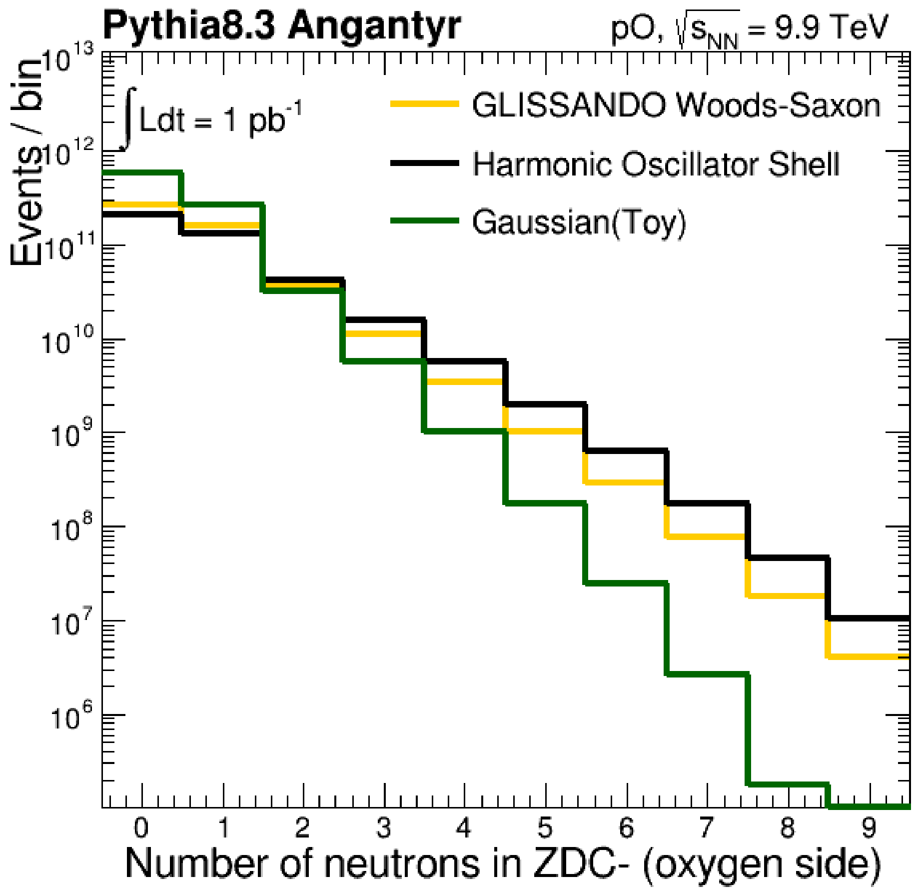

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- Gaussian model

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

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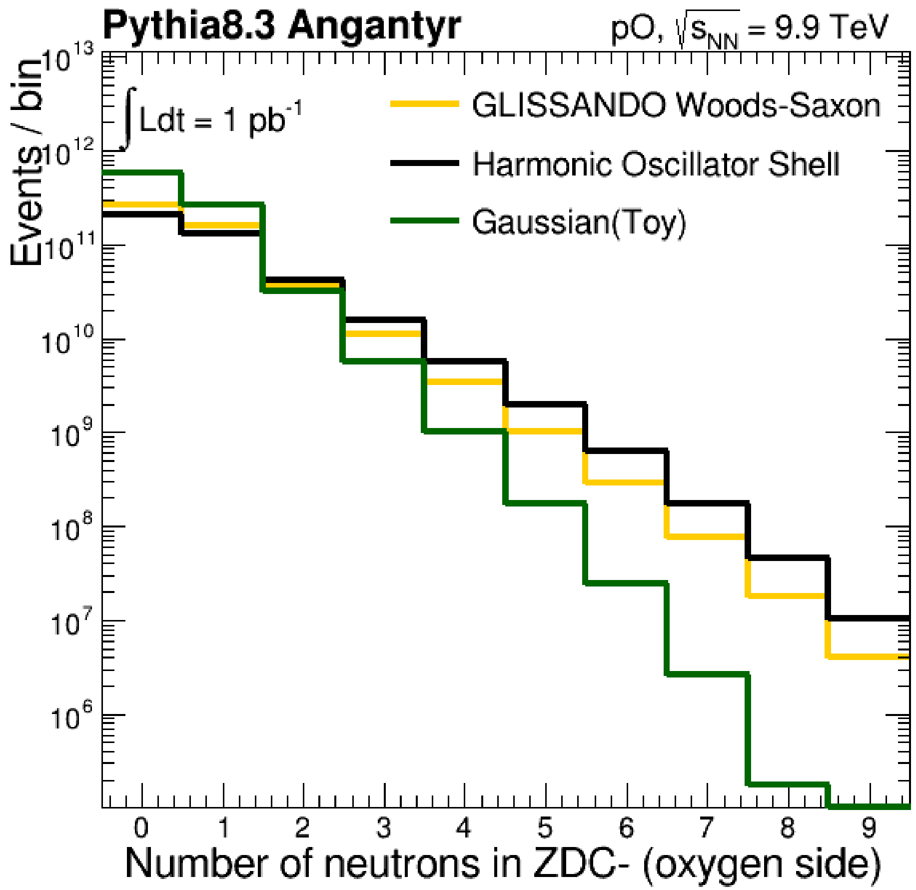

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Ab initio calculations CERN-TH-2024-021 can be implemented in Pythia (Work in progress)

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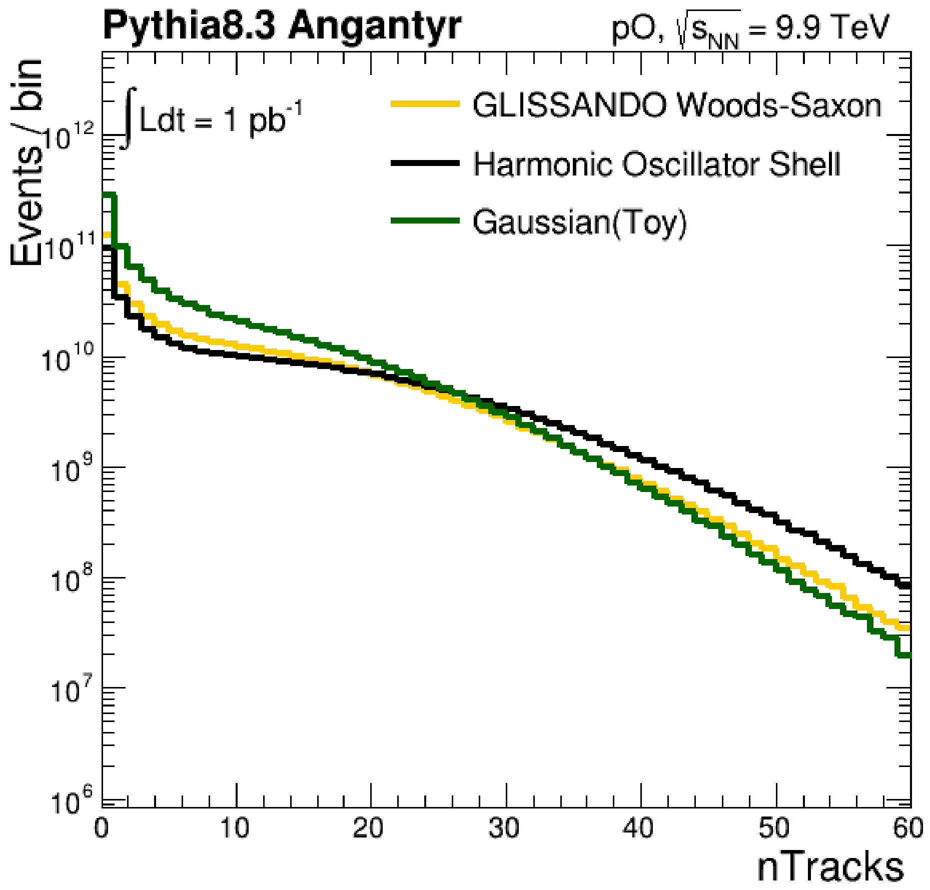
Many observables are sensitive to nuclear geometry



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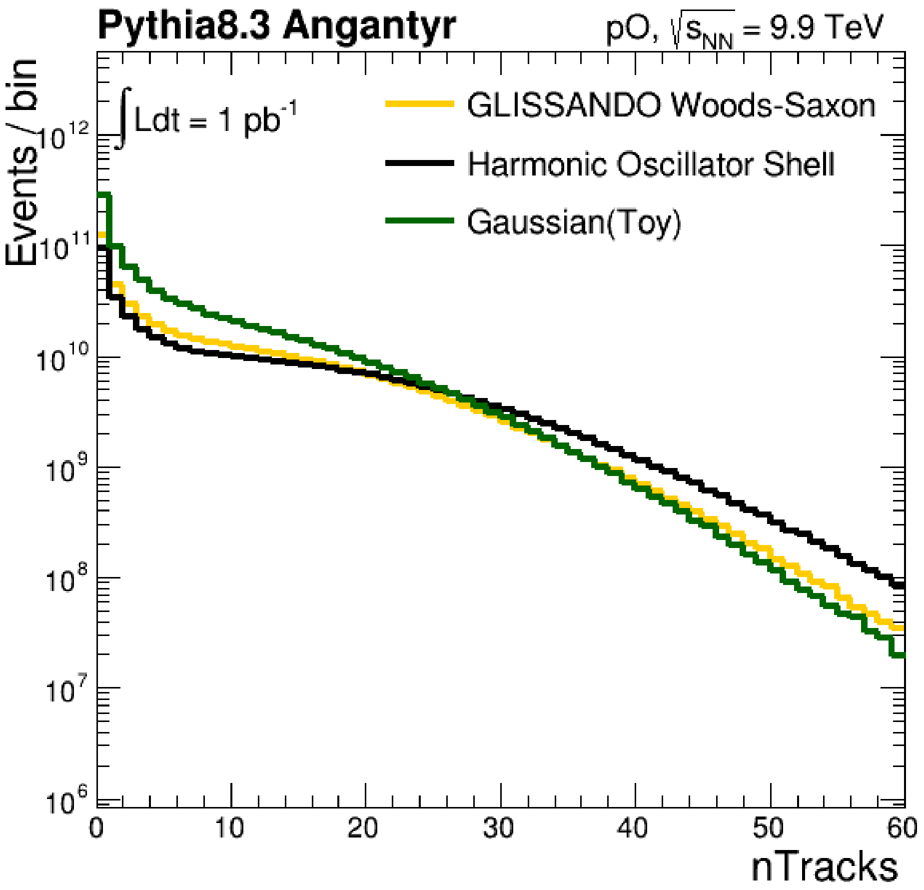

Nucl

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- Ha

$\rho(r) =$

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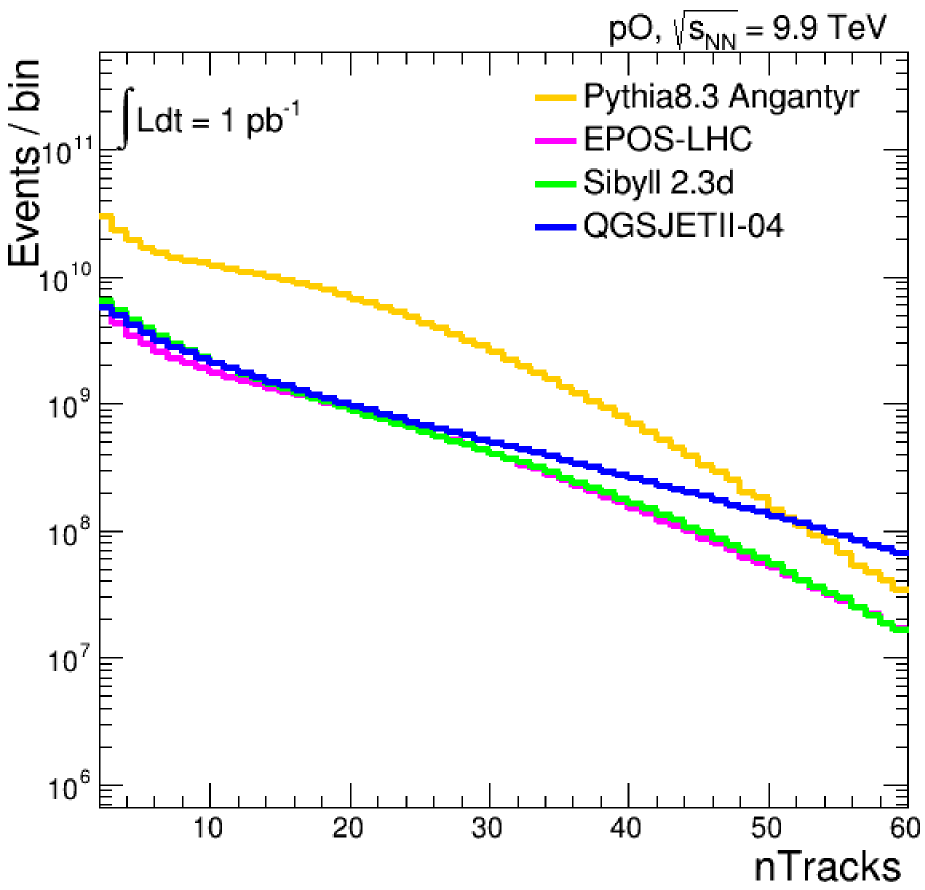


310.5475):

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

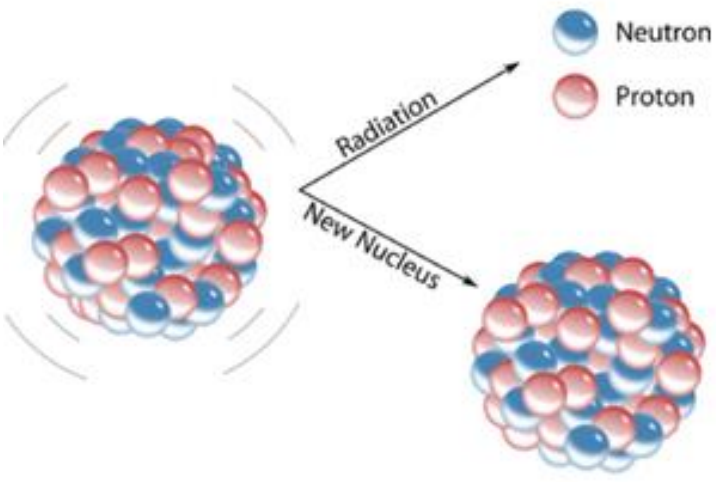
Gaussian distribution

in Pythia (Work in

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%)

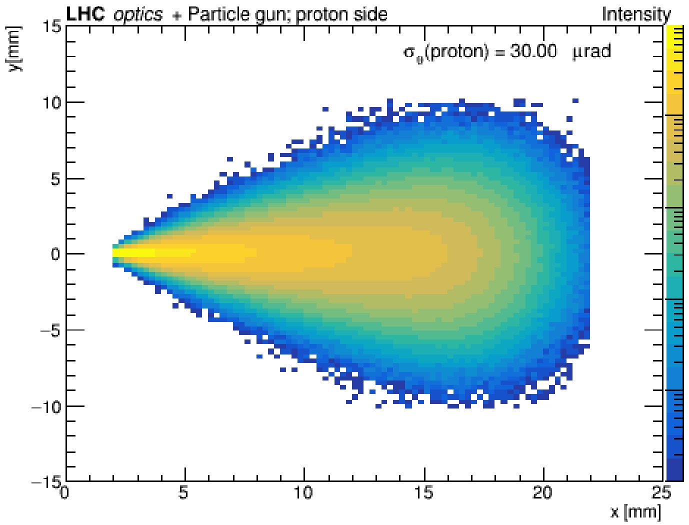
Ions with (A,Z) will be deflected from the beam center as beam particles with ~50(A/Z)% momentum w.r.t. steering magnets.

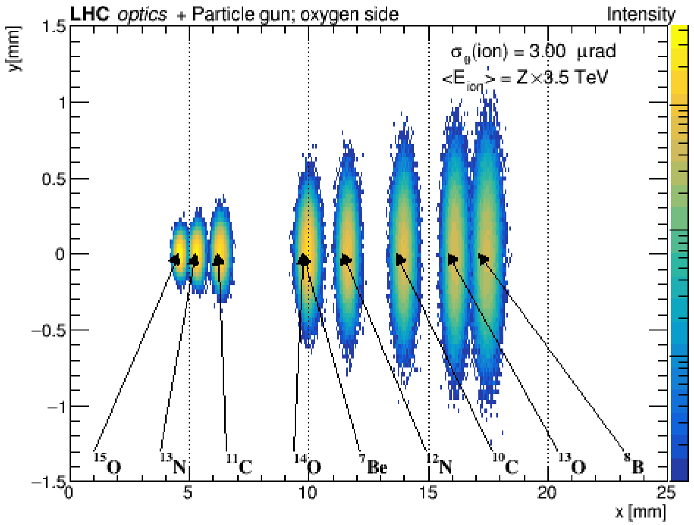
QCD interactions with proton tagging

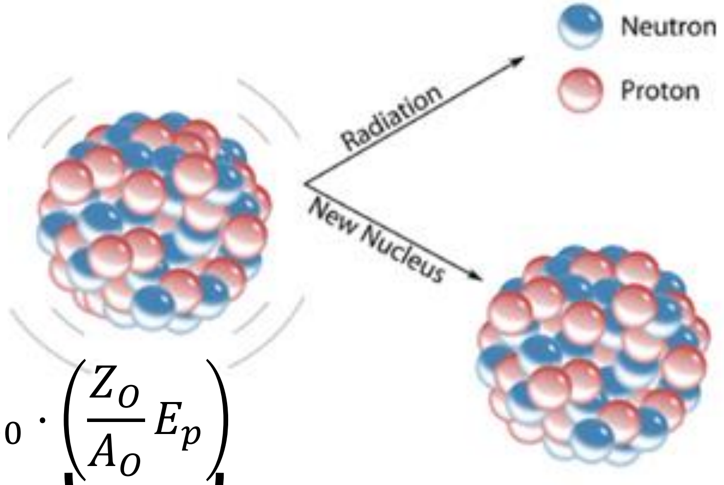
Ion tagging in pO events

- 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.

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







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

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

Proton detectors

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- Adding fermi motion (**exaggerated**)

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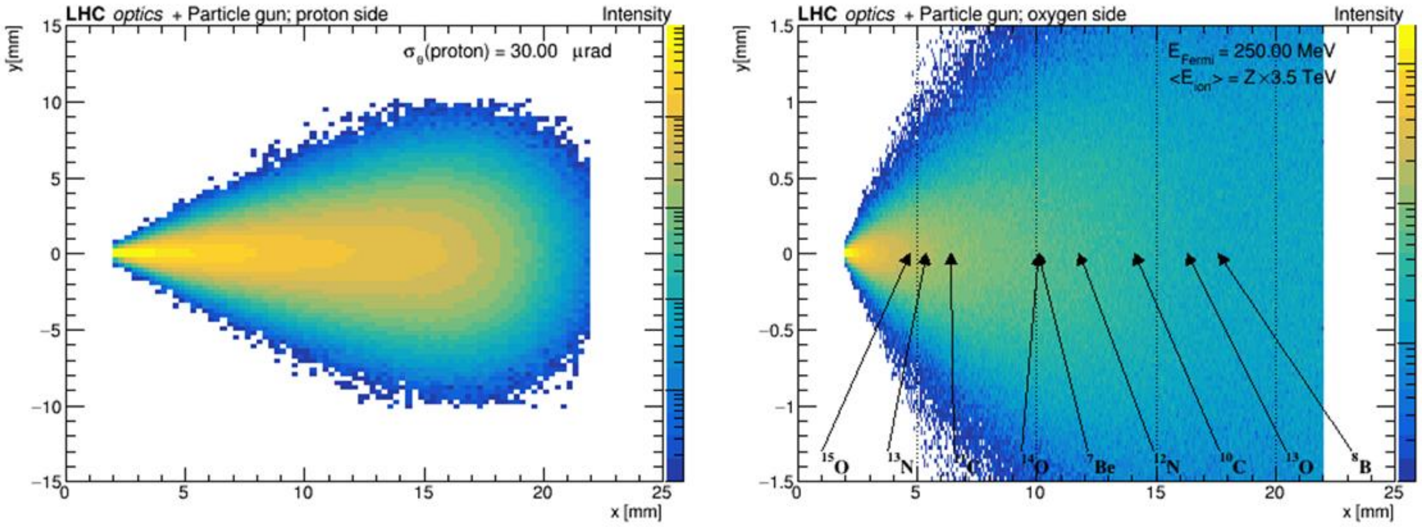

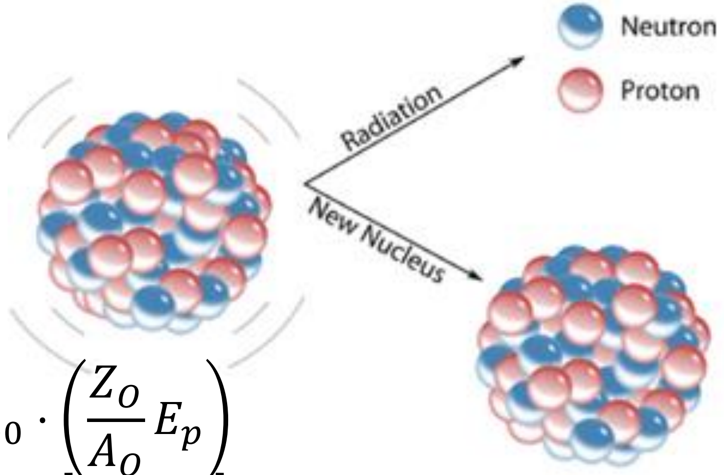

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Proton detectors

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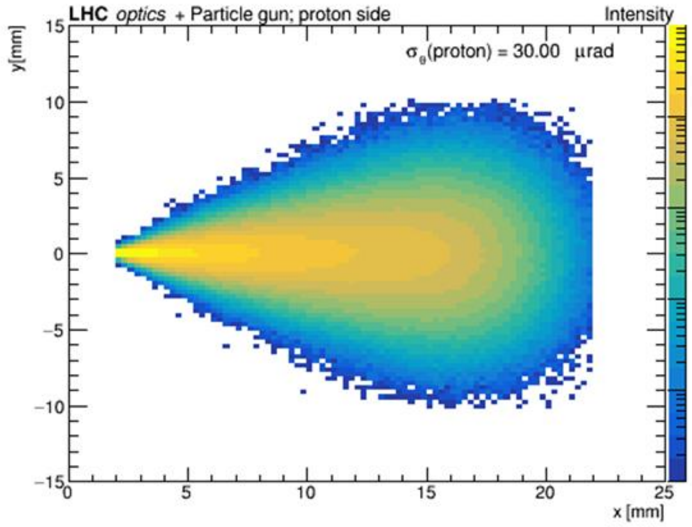

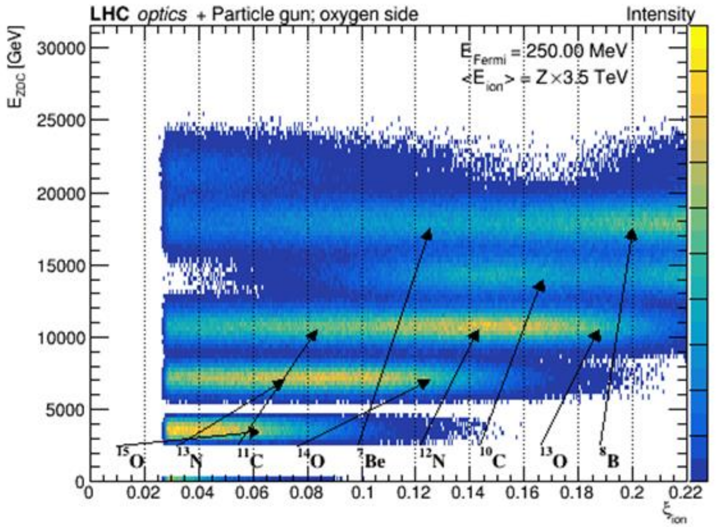

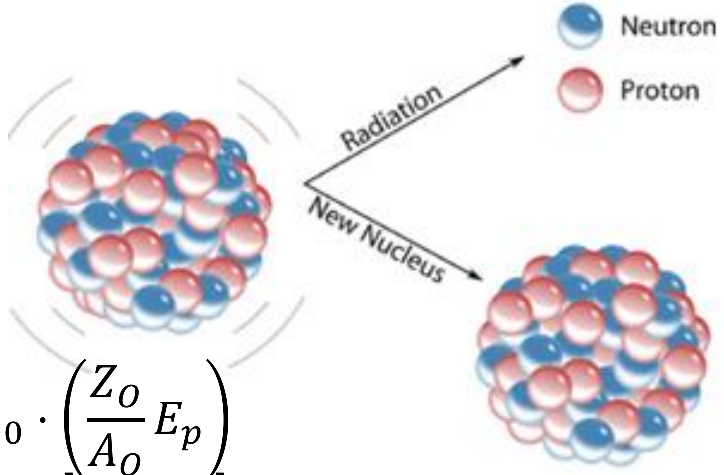

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Proton detectors

QCD interactions with proton tagging

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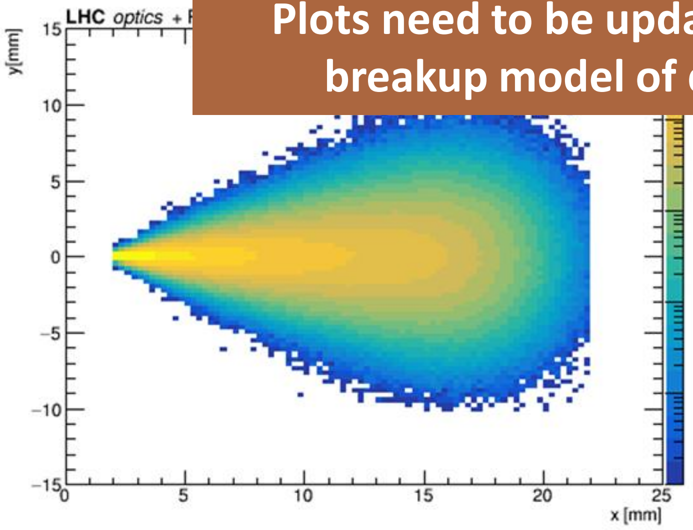
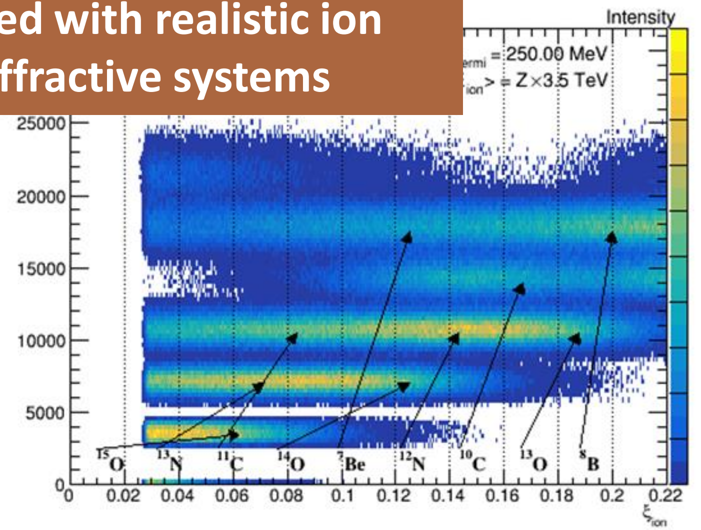
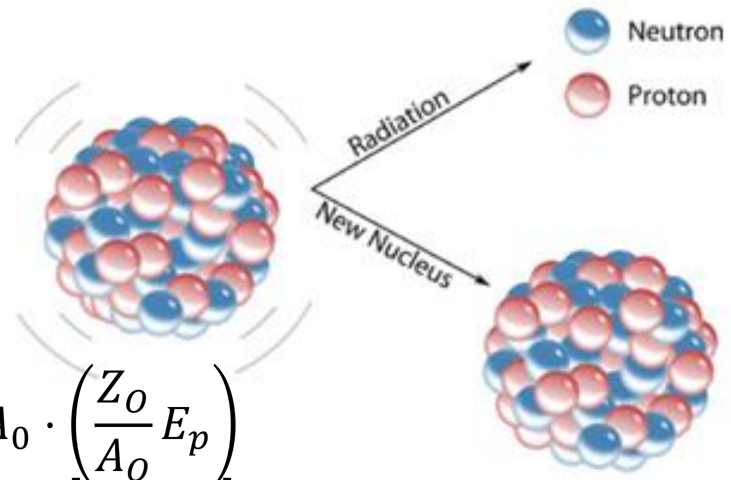
Plots need to be updated with realistic ion breakup model of diffractive systems







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

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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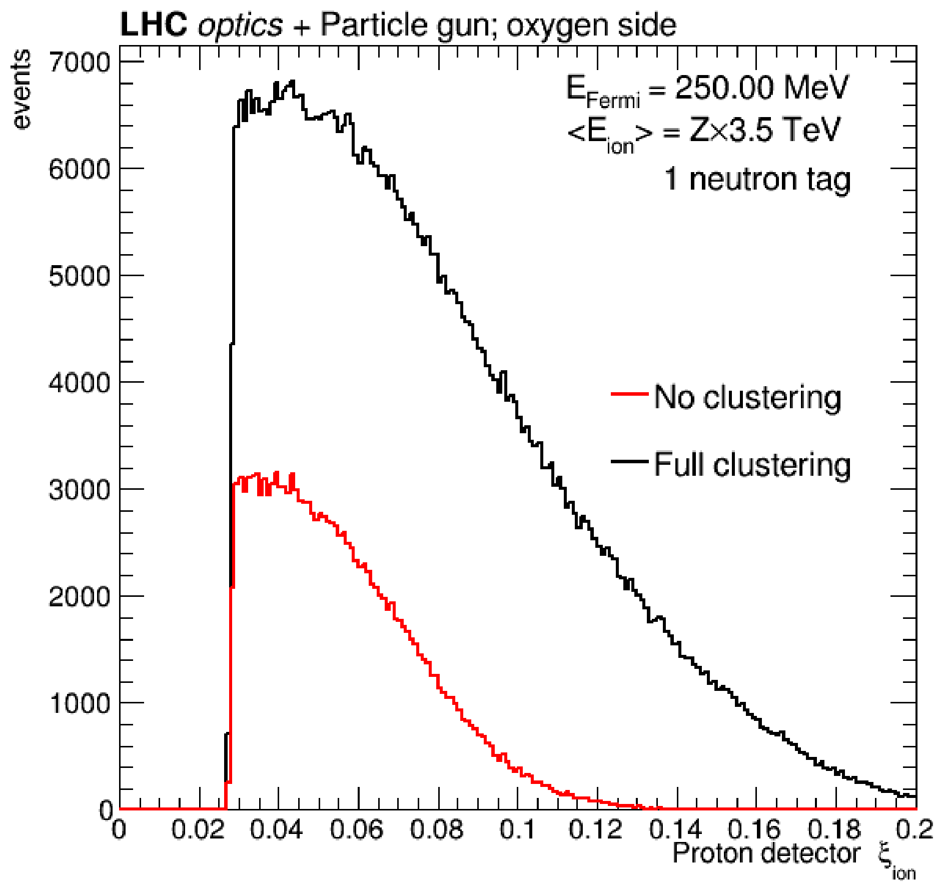
  - 16O → 15O + 1n with ξ=6%
  - 16O → 7Be + 1n + 2α ξ=12.5%



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

QCD interactions with proton tagging

Physics with Ion tagging – α clusters

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

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(11C h

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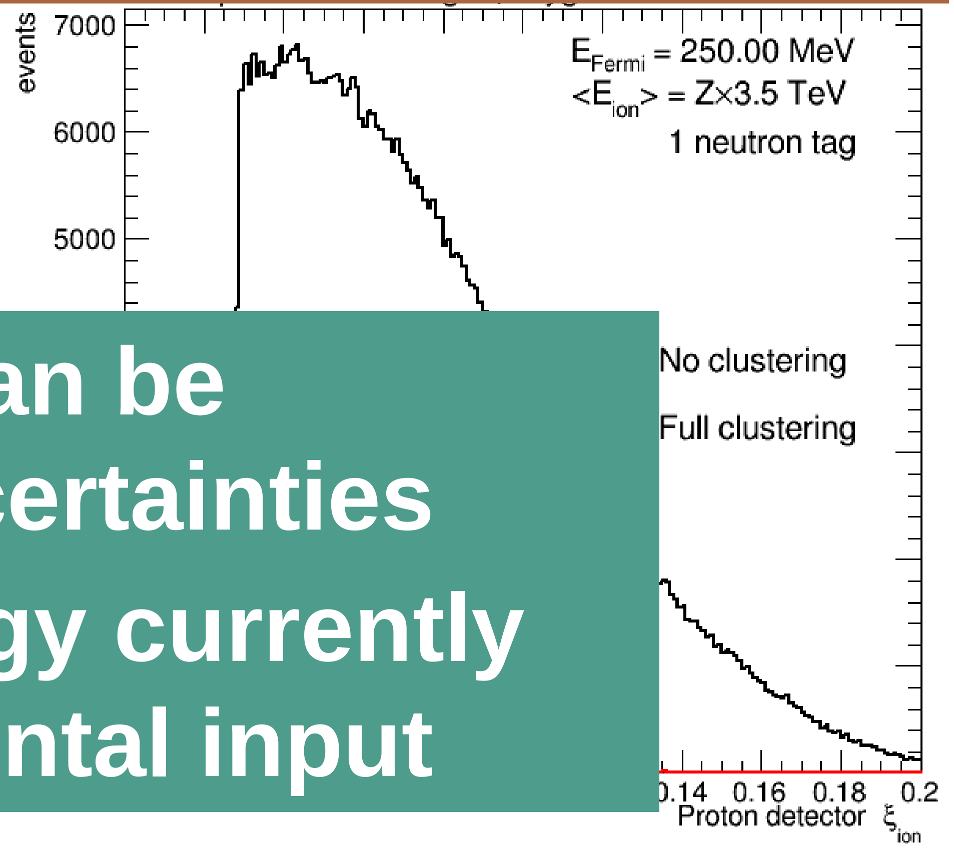


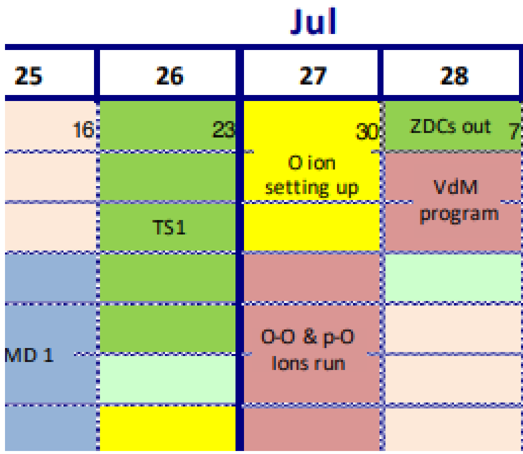
- **Fragment composition can be measured with some uncertainties**
- **Ion breakup at high energy currently lacks sufficient experimental input**

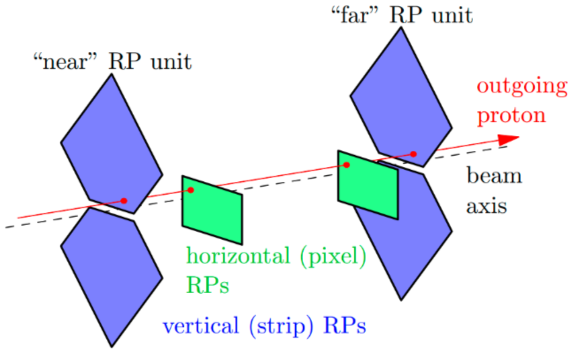
In 1n channel, when alphas are emitted more isotopes with 1n detected

QCD interactions with proton tagging

Physics with Ion tagging – α clusters

- Can we access ion geometry through elastic proton scattering?

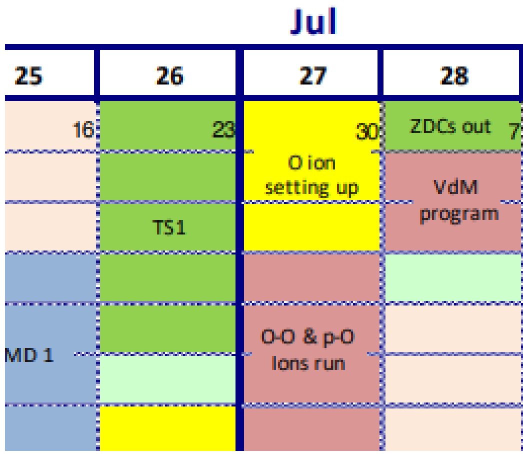


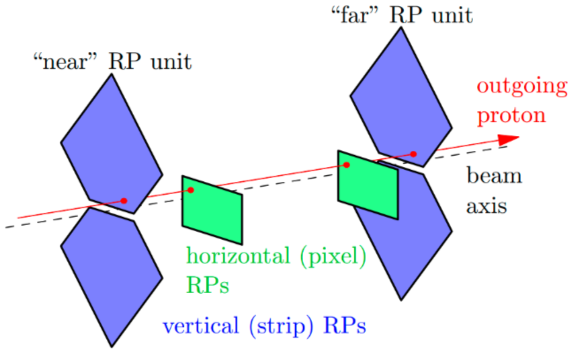


Physics with Ion tagging – α clusters

- Can we access ion geometry through elastic proton scattering?
  - ➢ Participation of PPS in pO/OO runs

    (alignment during the O setup days?)

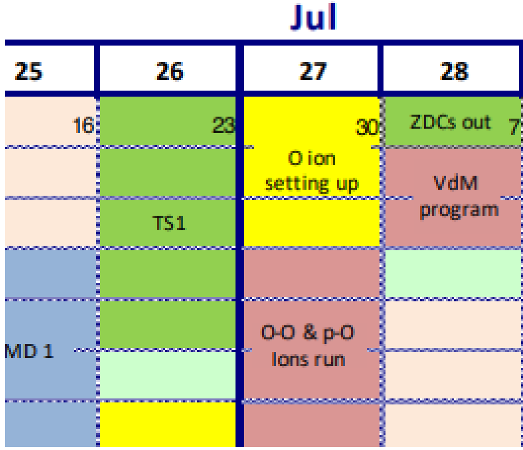


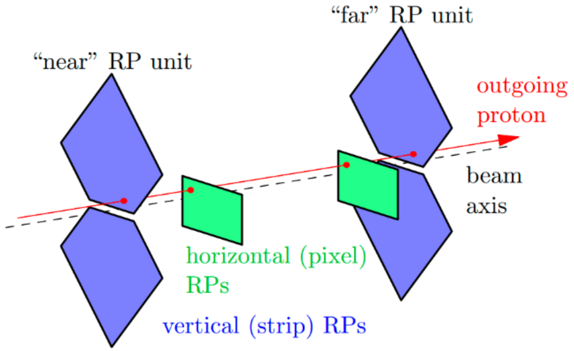


QCD interactions with proton tagging

Physics with Ion tagging – α clusters

- Can we access ion geometry through elastic proton scattering?
  - ➢ Participation of PPS in pO/OO runs (alignment during the O setup days?)
  - ➢ Which LHC optics will allow acceptance of elastic protons?





QCD interactions with proton tagging

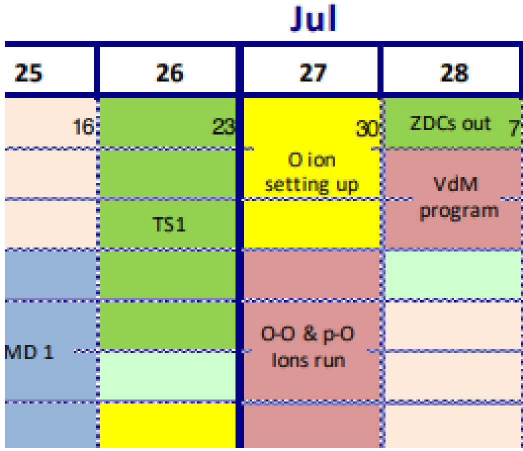
Physics with Ion tagging – α clusters

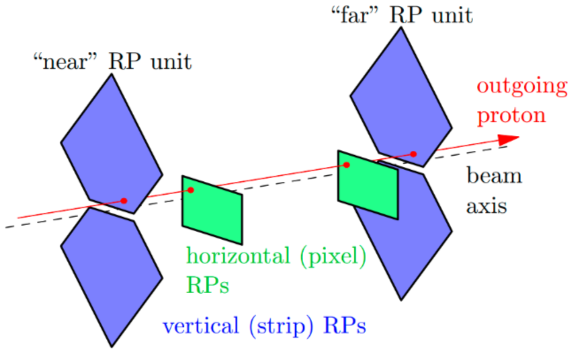
- Can we access ion geometry through elastic proton scattering?

  - ➢ Participation of PPS in pO/OO runs (alignment during the O setup days?)

  - ➢ Which LHC optics will allow acceptance of elastic protons?

  - ➢ Calibration of verticals (it can be done in elastic pp collisions, but how to do it in pO)





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?
- Can elastic interaction be measured? Photons from the lowest Oxygen exited state (8.8 MeV NNDC)?
- Challenges – tracking with high Q, multiple scattering, have the LHC with the right settings

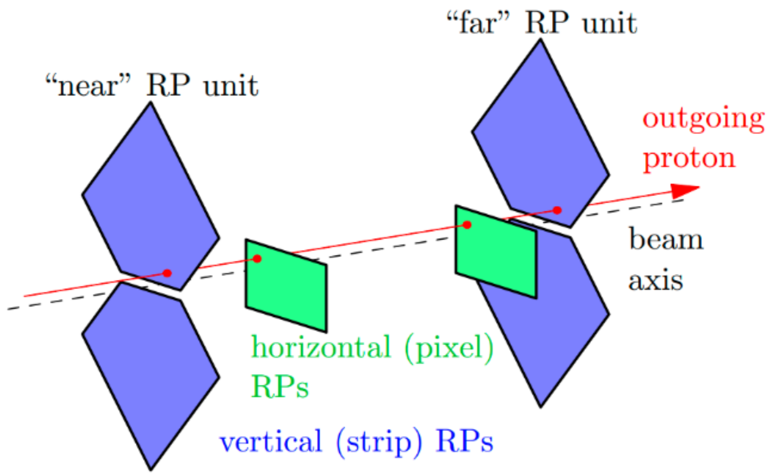
Feedback is welcomed: feel free to contact

Backup

Forward detectors – commissioning

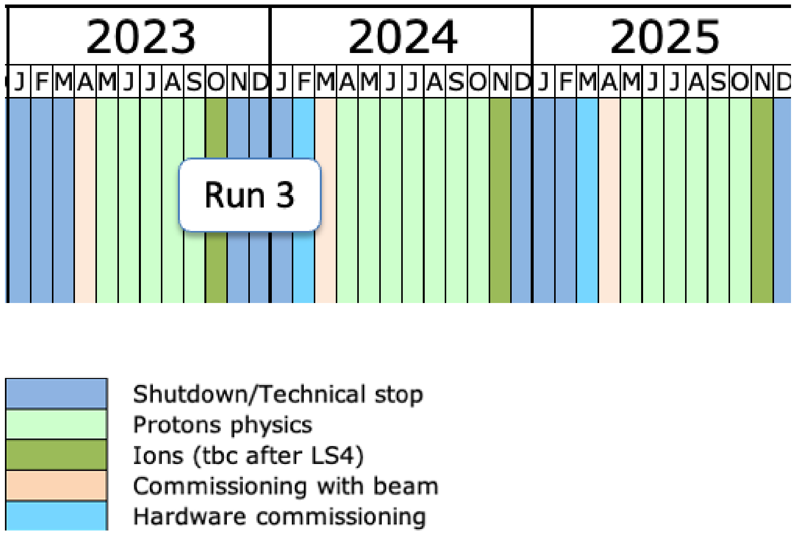
Precision Proton Spectrometer

- **<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



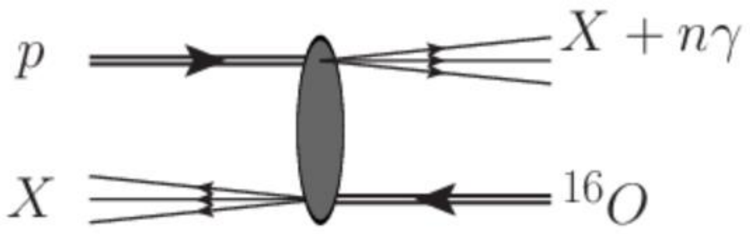
Zero Degree Calorimeter

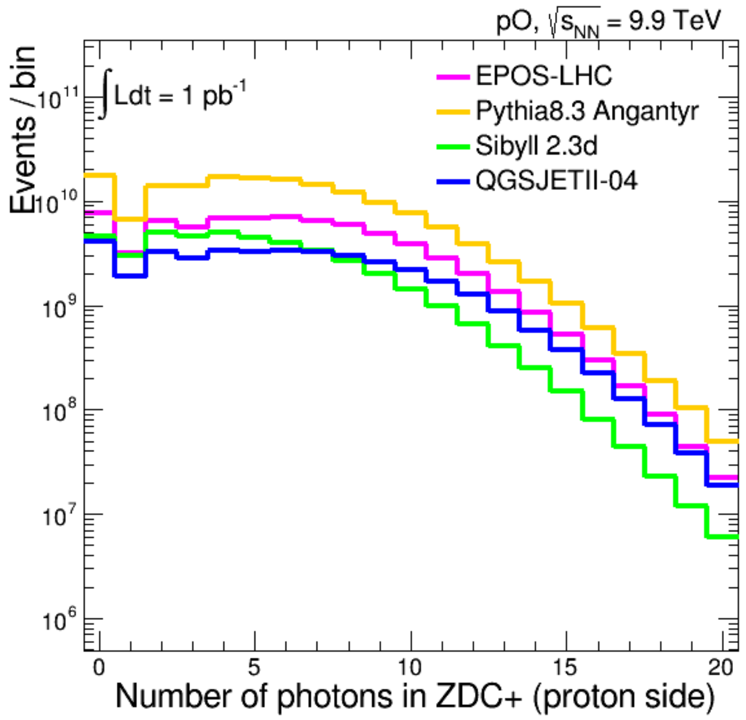
- ZDC is not installed during standard pp runs
- Before data taking: Need access, installation often takes ~ 1 day (usually after MD/TS)
- After data taking – access is needed to deinstall the detectors (offer done during the YETS)

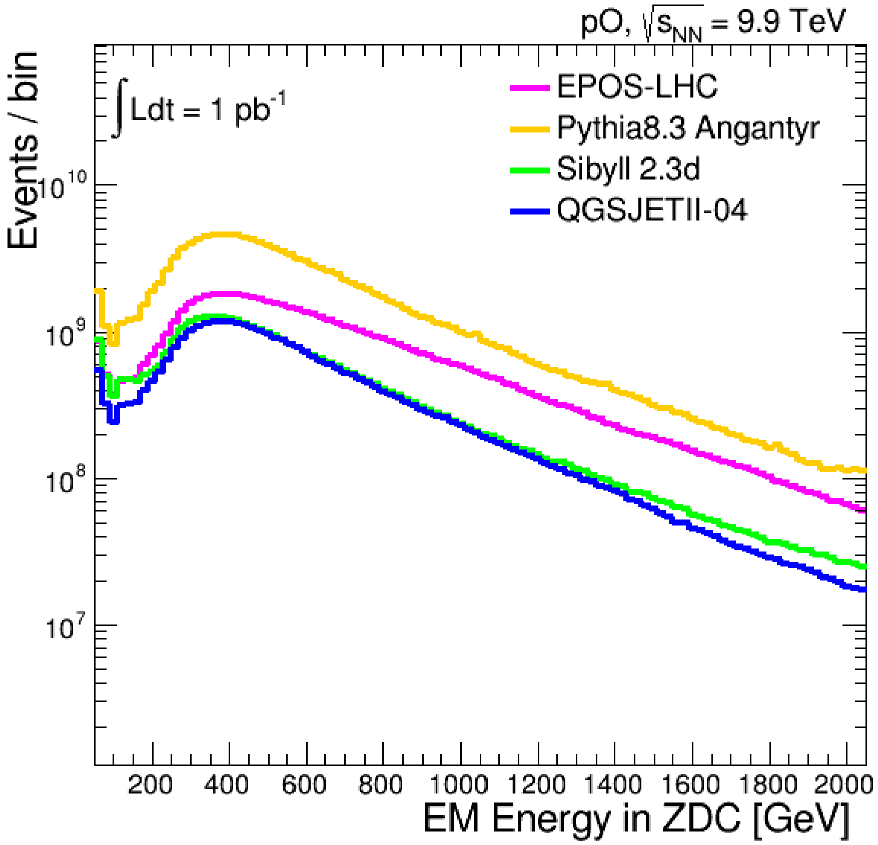


Forward neutrons in p-O collisions

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

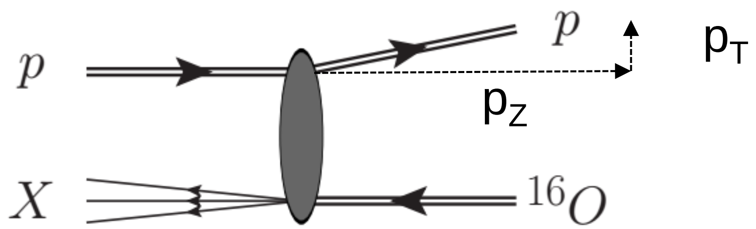


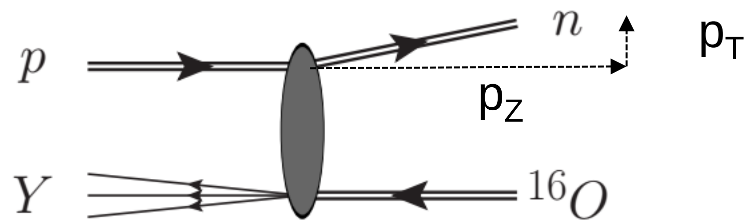


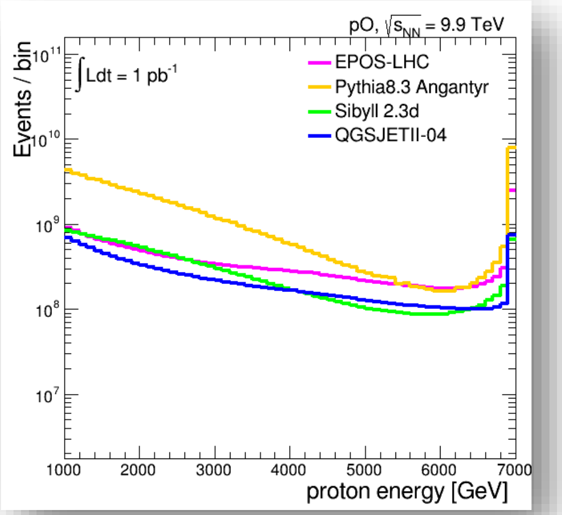


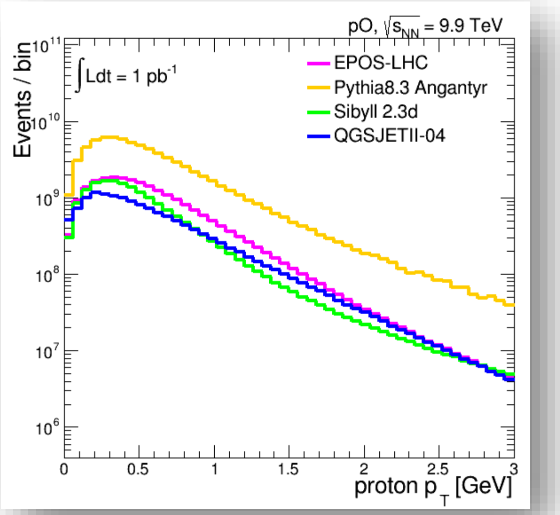
Forward protons / neutrons in p-O collisions

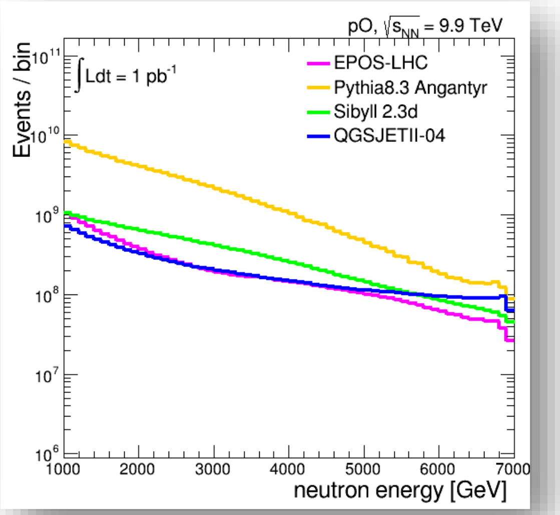
- High energy protons and neutrons emerge from p-O interactions
- By measuring the production rates, and event kinematics one can constrain their modeling

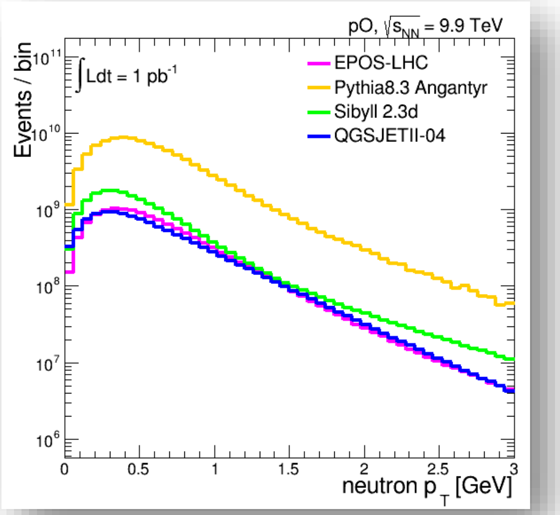








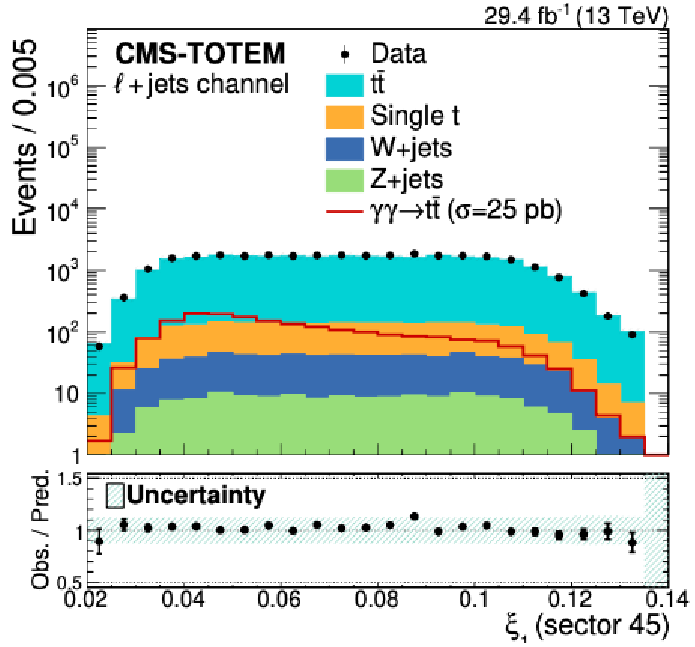




Example of forward detectors performance

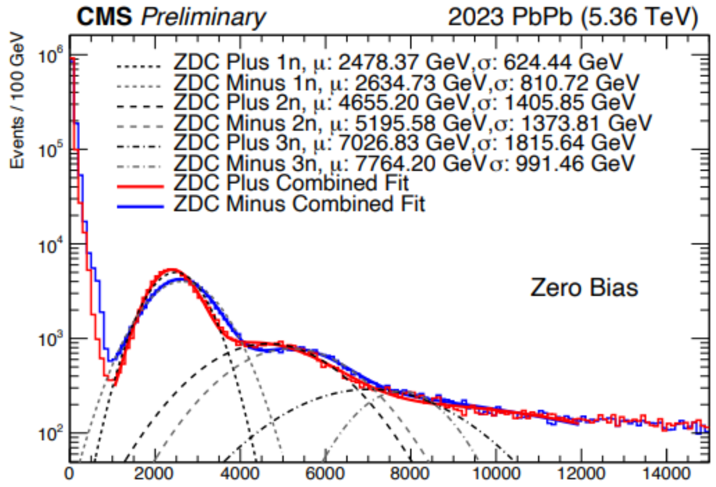
Proton Detectors (PPS)

- 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

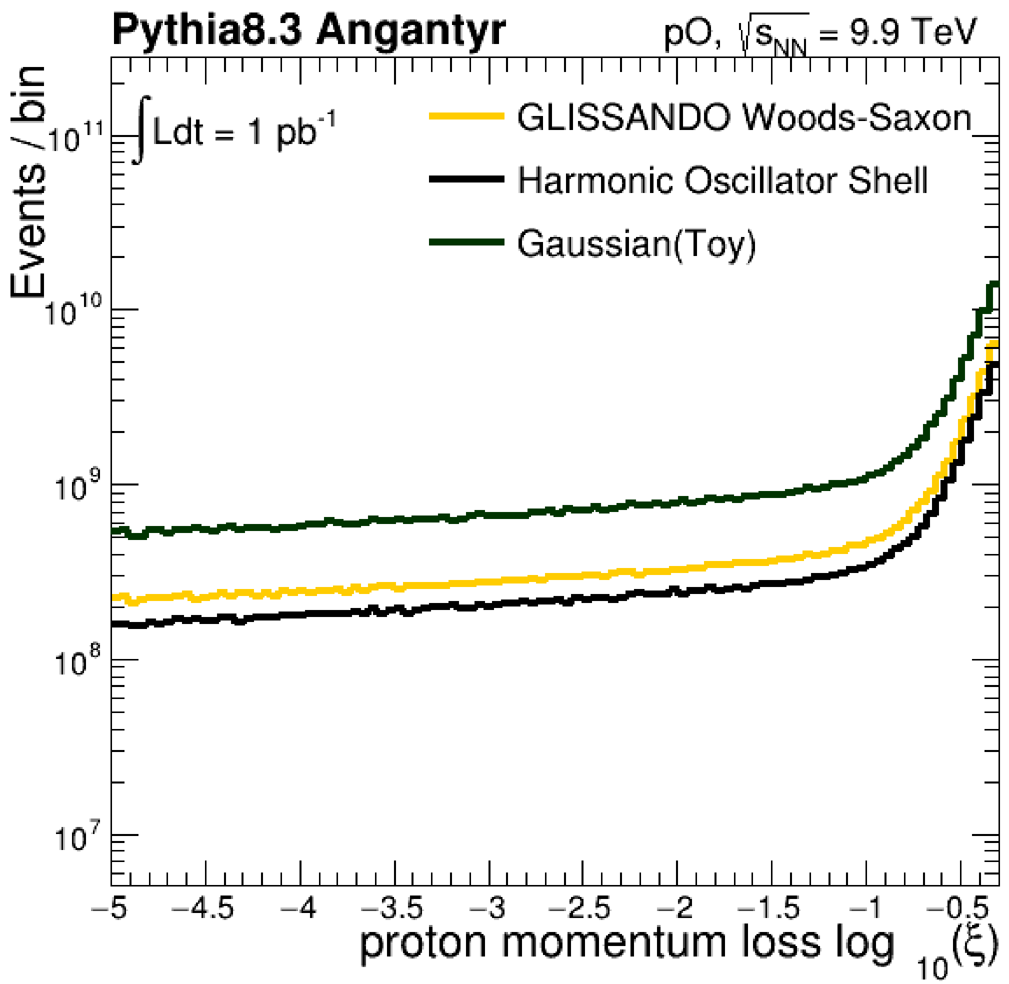
- Operated at very low pileup – can sustain integrated luminosity up to ~ 1fb^{-1} and *at pileup rate up to μ ~ several*
    - *Measures* neutral particles with |η|>8.3 (can resolve single neutrons)
    - Neutron peaks are fitted with 28% width (res. + smearing)
    - EM has 5 horizontal divisions (can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



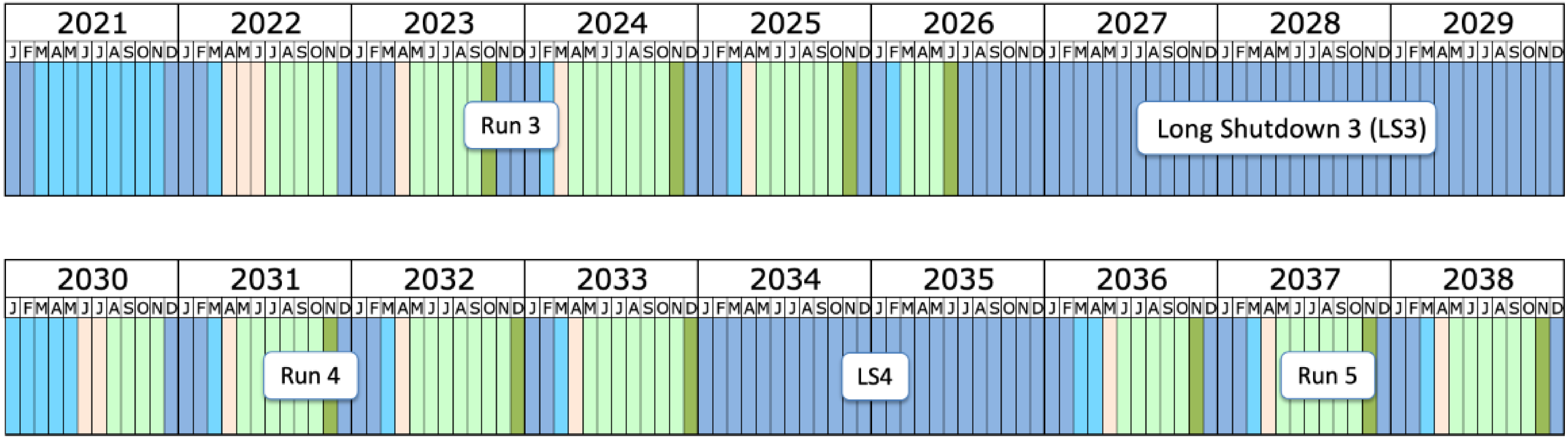
CMS DP–2024/002

Protons vs geometry

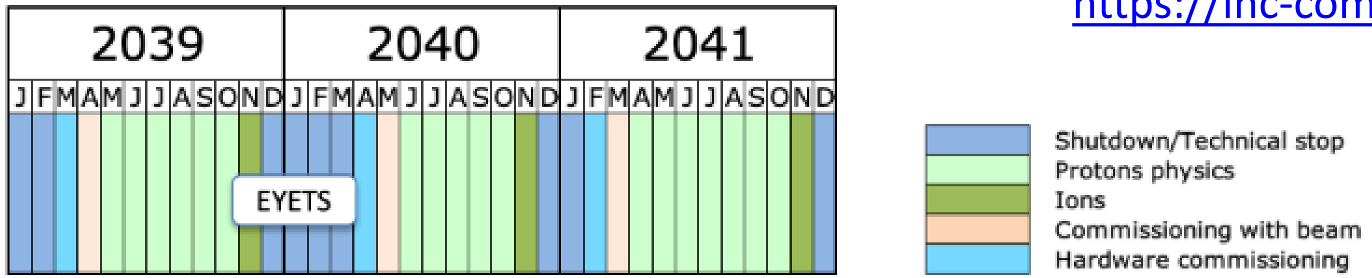
- Diffraction and ion geometry – we can tag diffractive protons in pO collisions and to look at event kinematics or oxygen remnants
- From the simulation it seems that diffraction is similarly modeled with respect to different geometries



LHC Run schedule



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



Last update: November 24