Forward physics with special runs in 2025

12 December 2024

Michael Pitt (CERN)

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Grant DE-SC0023908

Outline

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

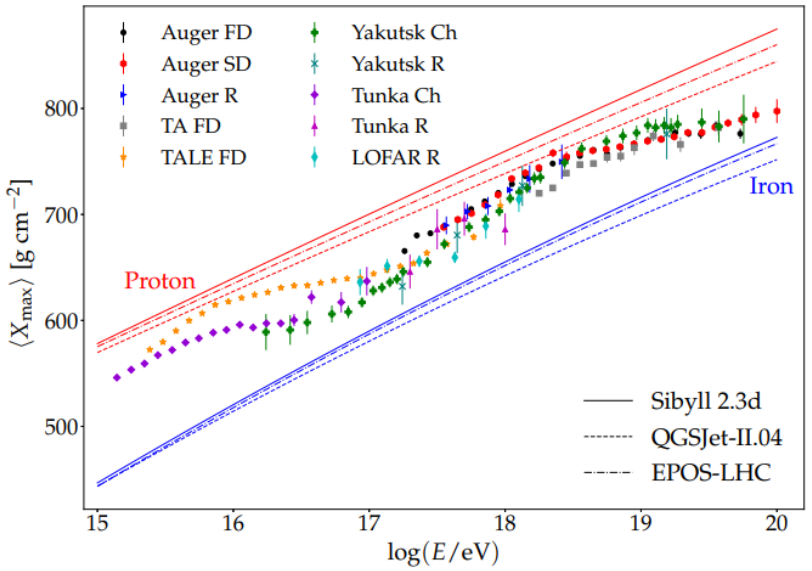
*Most of the material is recycled from the talk at Diffraction and Low-X (10 Sep 2024)
https://indico.cern.ch/event/1354173/contributions/6078710/

Accelerating Oxygen ions at the LHC

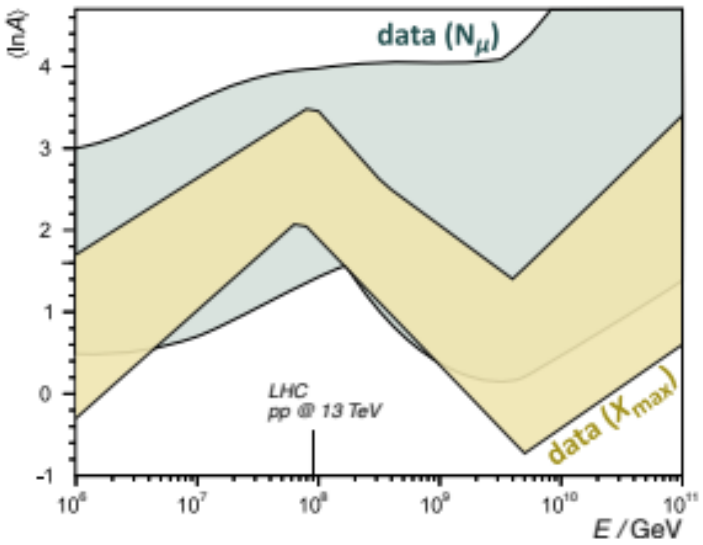
Introduction

Oxygen ions at the LHC

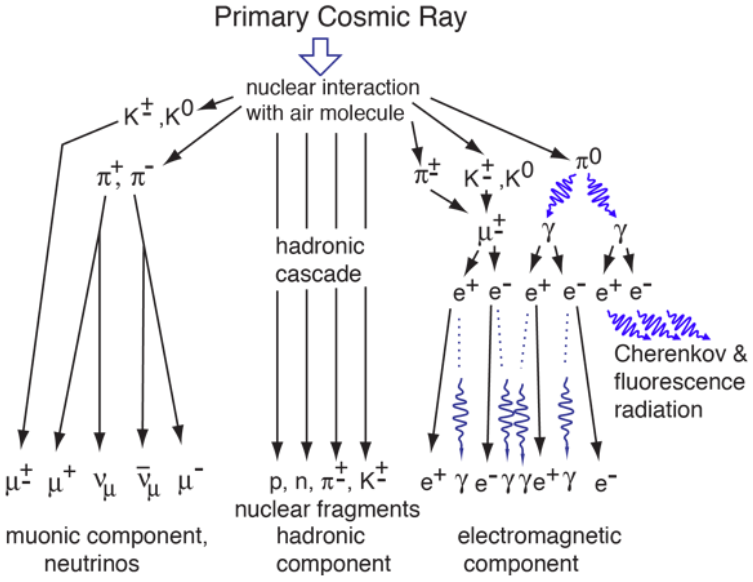
- Oxygen ions (^{16}O) will be injected at the LHC for the first time.
- pO run is scheduled to take place in July 2025, with a run duration of 4 days
- The main goal of the run is to provide input for cosmic ray modeling



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



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

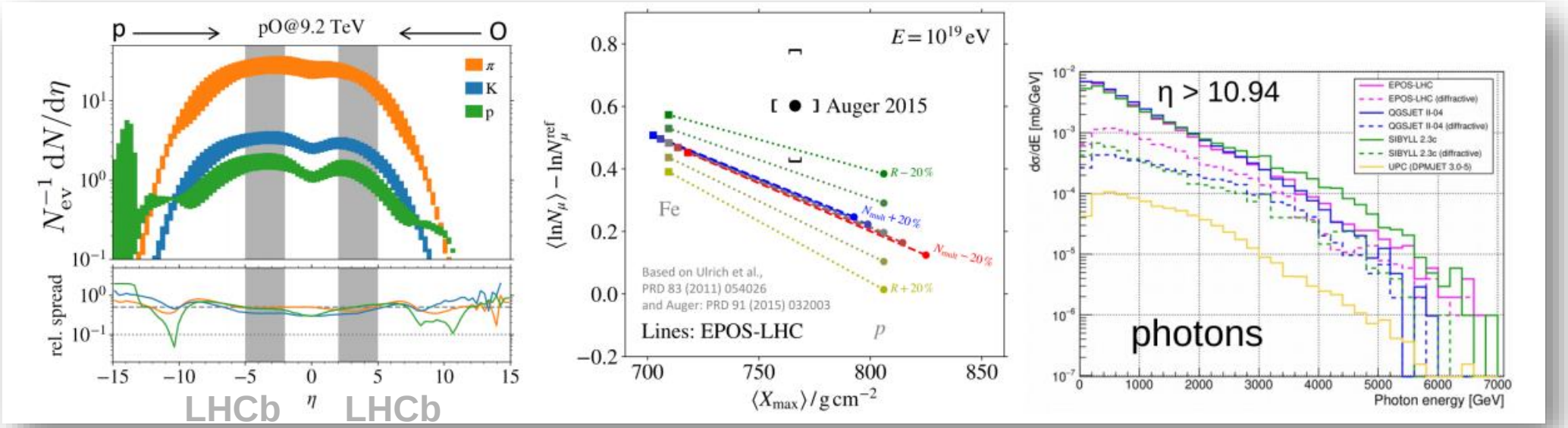


http://hyperphysics.phy-astr.gsu.edu/hbase/Astro/cosmic.html

Introduction

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



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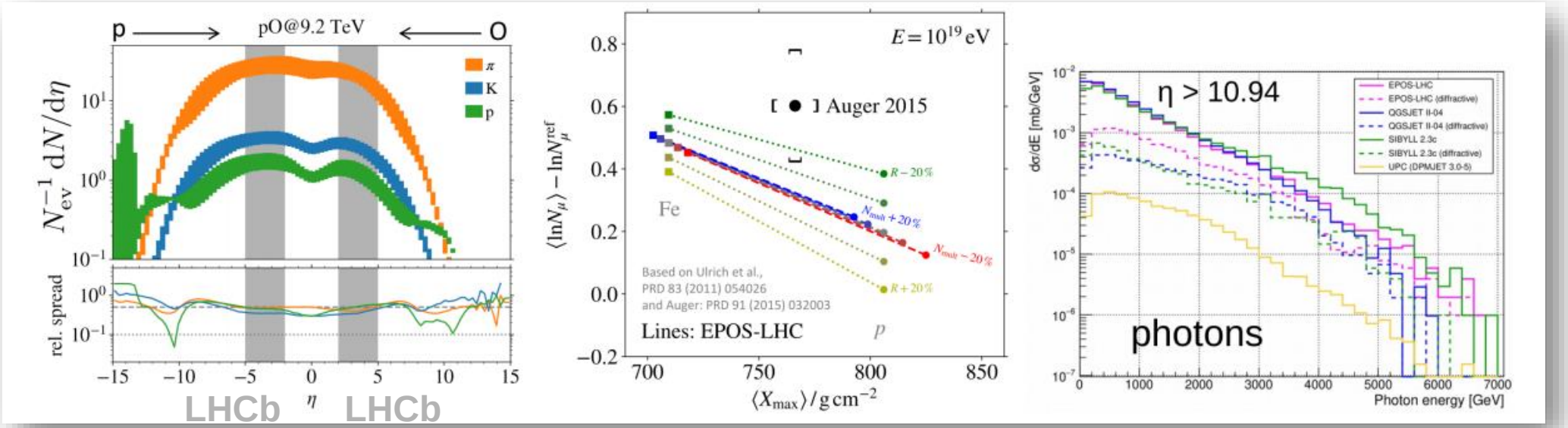


- Does muons puzzle solved with EPOS LHC-R? T. Pierog & K.Werner PoS(ICRC2023)230

Accelerating oxygen ions

Lumi targets / beam parameters

Info from N. Triantafyllou at “light ion collisions at the LHC” (14 Nov 2024)

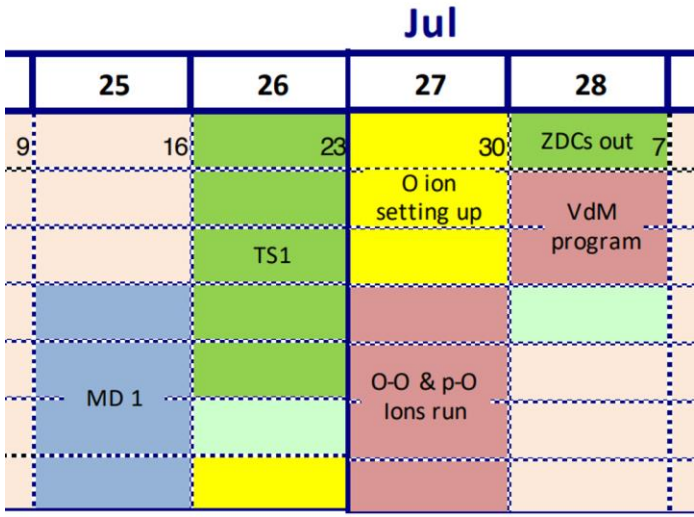
Optics: re-use PbPb machine cycle, ε=2.3μm

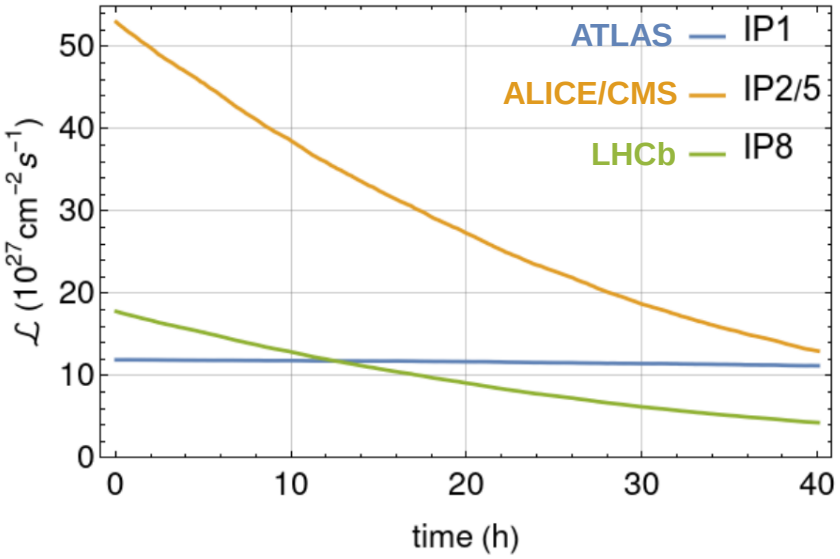
O-O collisions: 0.5/nb for all experiments

- ALICE μ<0.2
- ~20 bunches, ~10 collisions per IP
- ~1d for LHCb/ATLAS/CMS, 1 long 15-21h fill

p-O collisions: 1.5/nb and 2/nb for LHCf and LHCb

- LHCf μ<0.02
- 36 bunches, ~24 collisions per IP
- 2.5d, ~35h for LHCf, several fills for LHCb





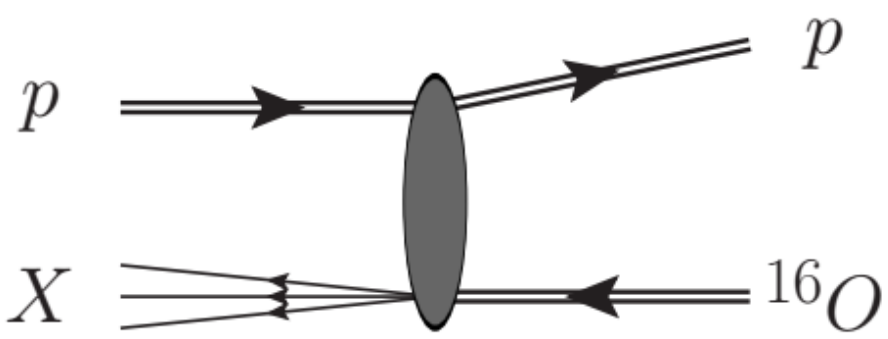
An accurate determination of the absolute beam luminosity is needed for many observables (see Sections 3 and 4). Luminosity precision of 1.5-3% could be achieved by van der Meer (vdM) scans for OO and pO collisions, which take 2-3 hours per experiment (although other experiments can continue collecting data) [4].

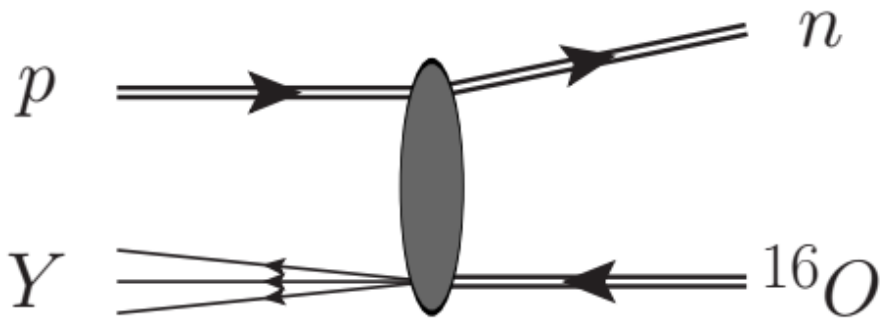
2103.01939

Constrain hadronic models with pO collisions

Extending current research program

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

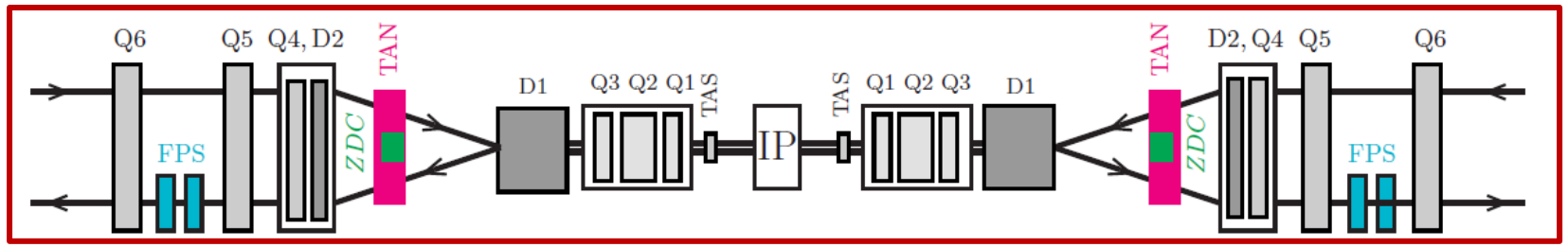




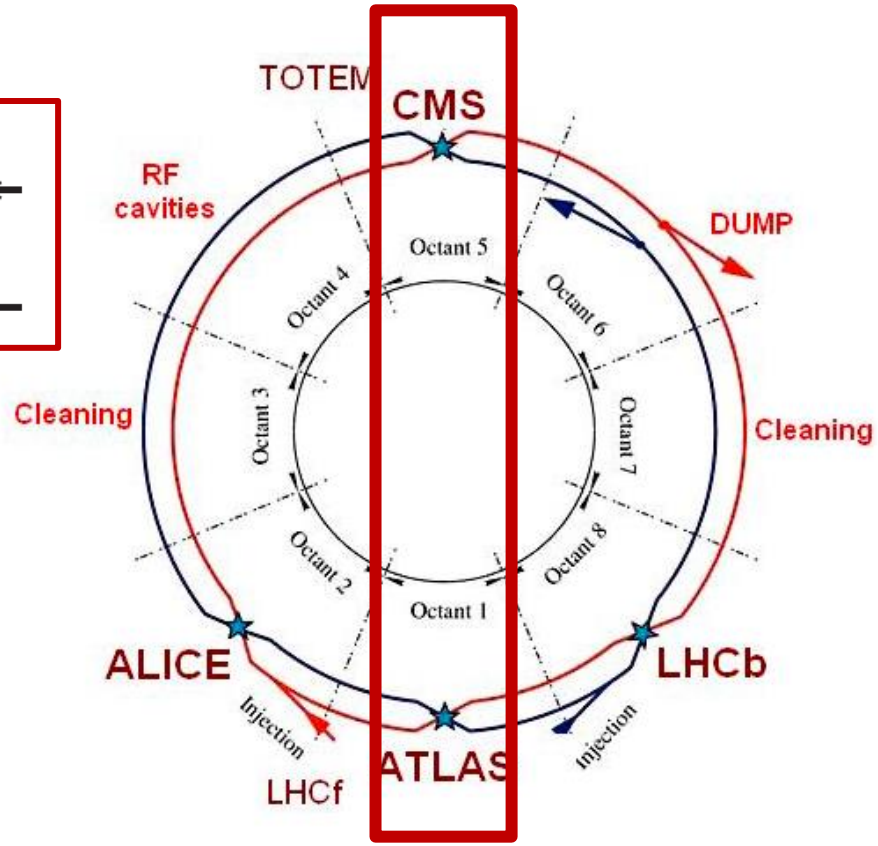
Proton and neutron tagging in ATLAS/CMS

Forward proton detectors

- 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)



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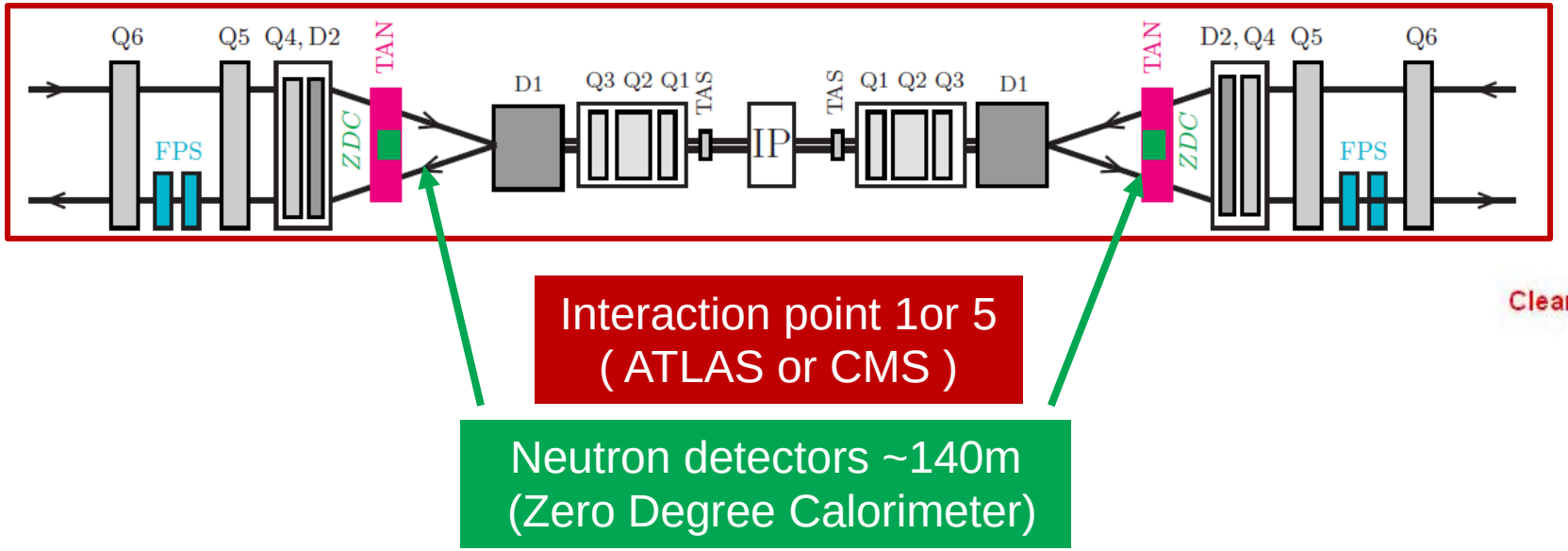

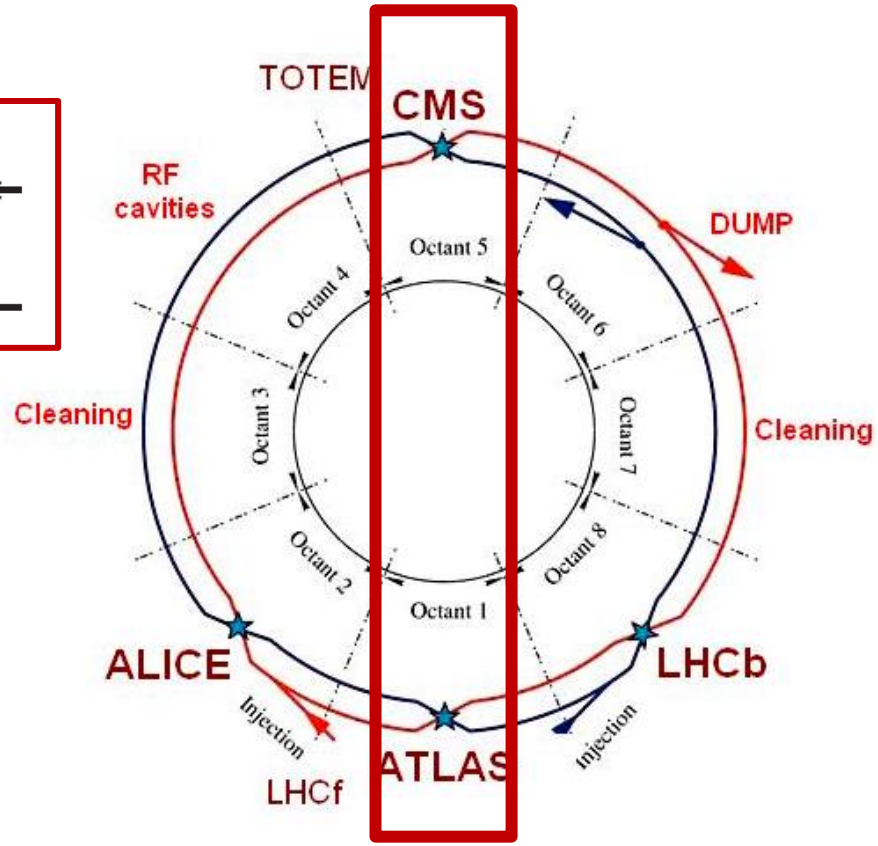

Forward proton detectors

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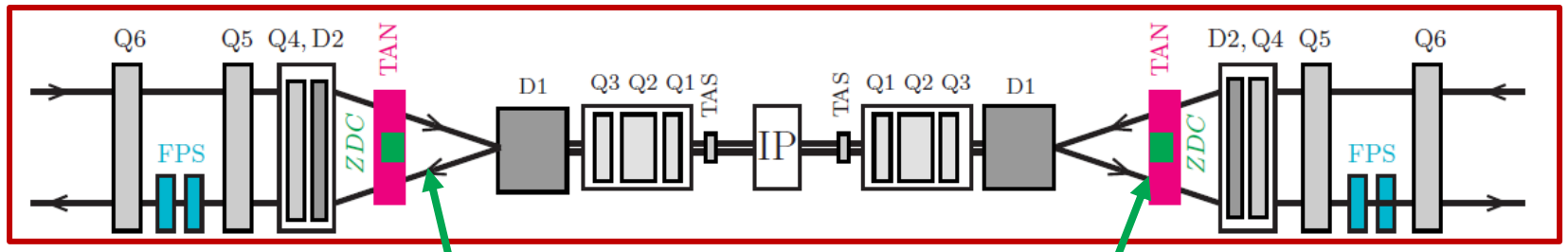
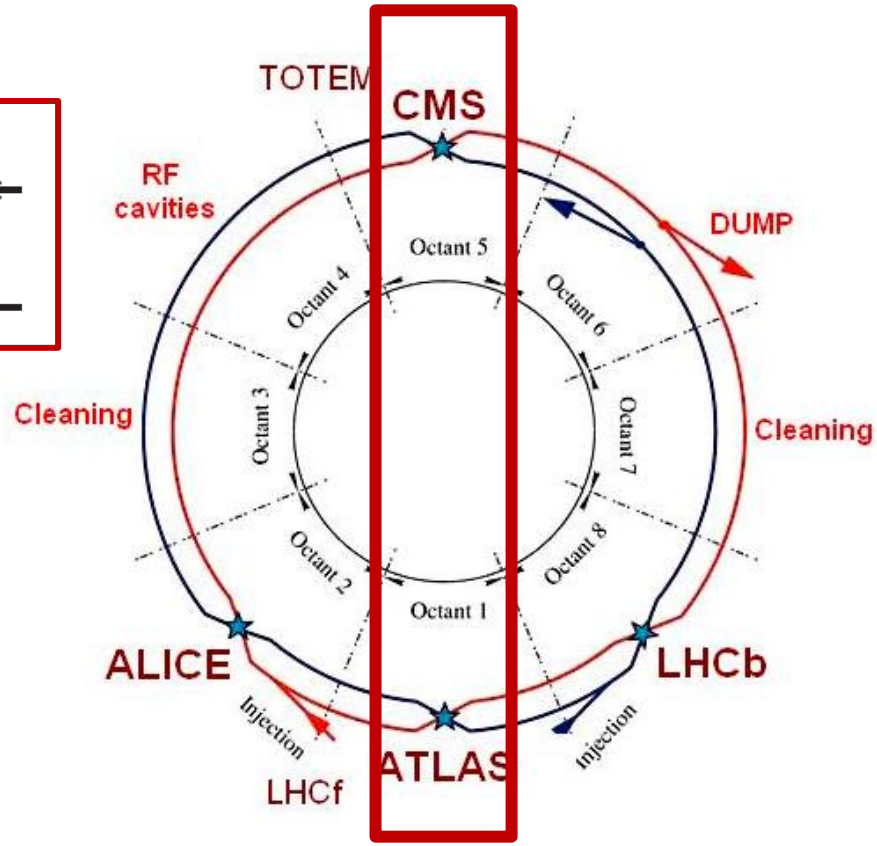
- Proton detectors are operated in standard LHC running conditions (high pileup)



Interaction point 1or 5
(ATLAS or CMS)

Neutron detectors ~140m
(Zero Degree Calorimeter)

Proton detectors ~220m
(Forward Proton Spectrometer)



Forward neutron detectors

Forward neutron detectors

More info in S. Popescu talk

- 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

Forward proton detectors

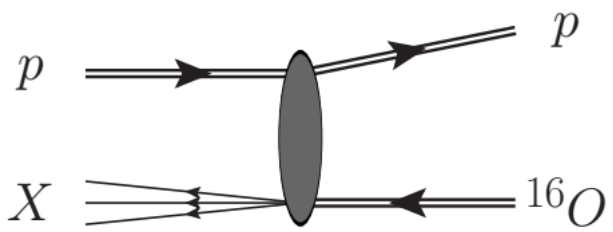
More info in M. Lewicki (ATLAS) and MP (CMS) talks

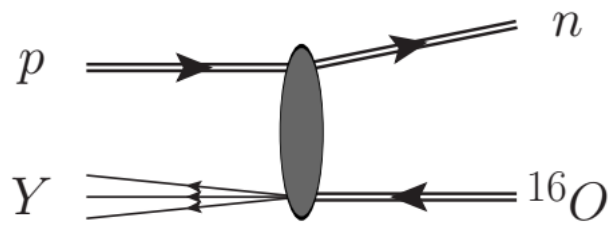
- Located ~ 200m from the interaction point in both arms, equipped with tracking/timing detectors
- Off-momentum protons → smaller magnetic rigidity
- Measure protons with ~85-97% momentum w.r.t. steering magnets (x_L~0.85-0.97).

Constraining models of 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



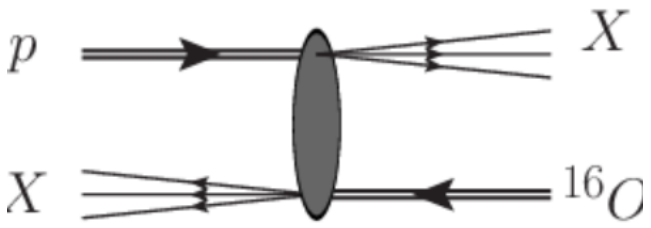


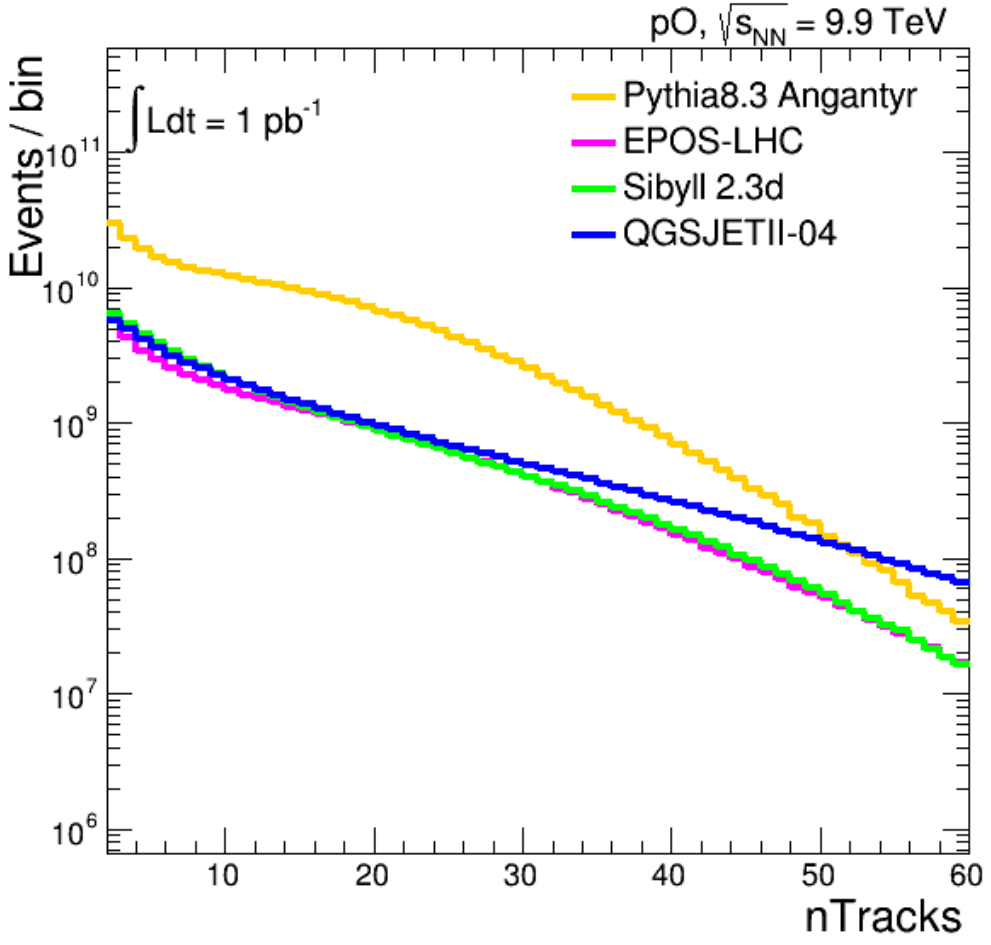
Warning

- 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

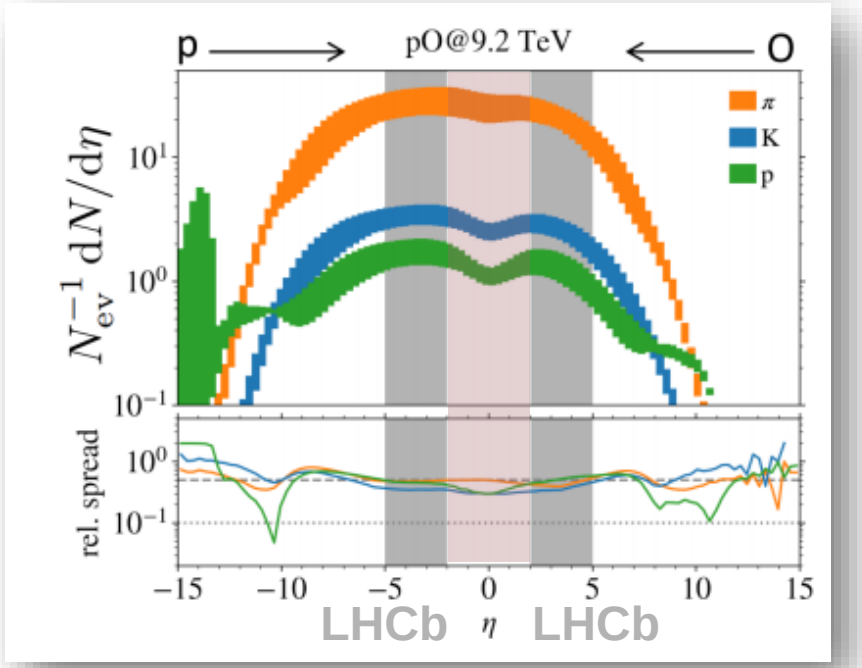




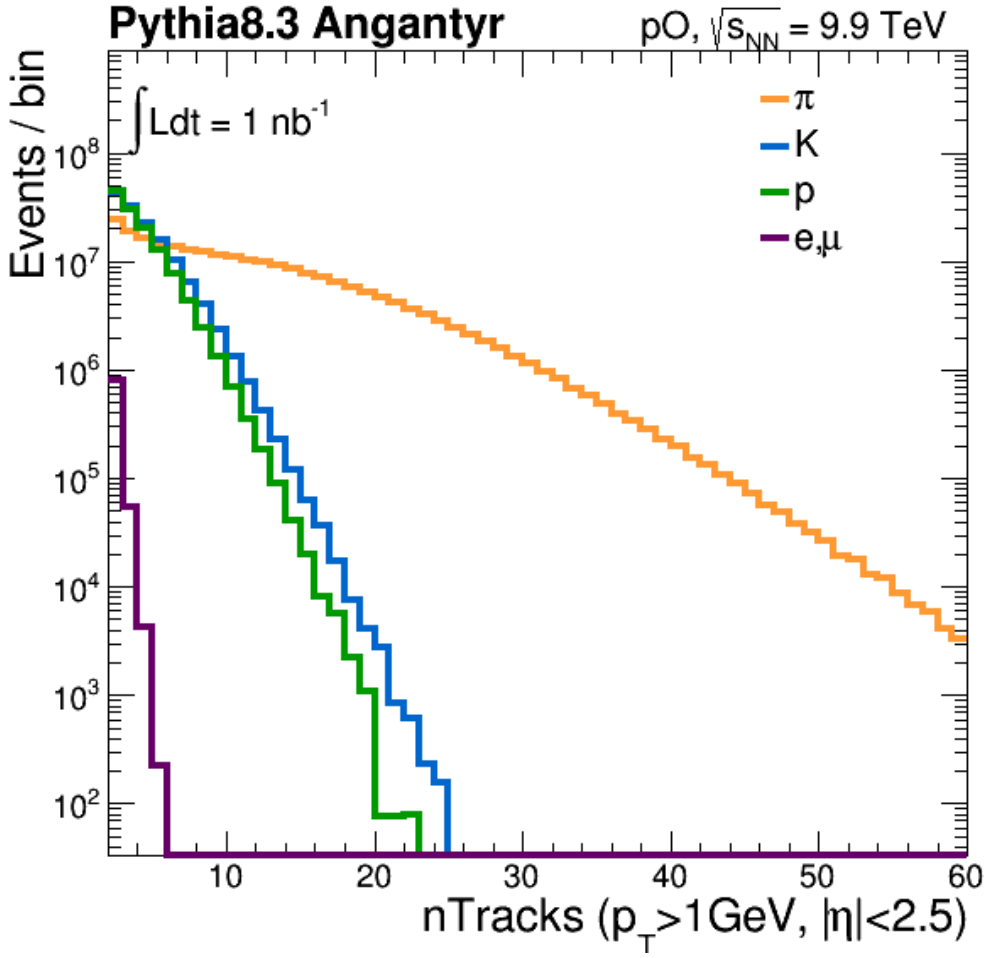
nTracks = charged particles with pT>1GeV and |η|<2.5

Forward protons in p-O collisions

- Event kinematics (like track multiplicity) constrain hadronic models
  - Can we do particle ID?



ATLAS/CMS



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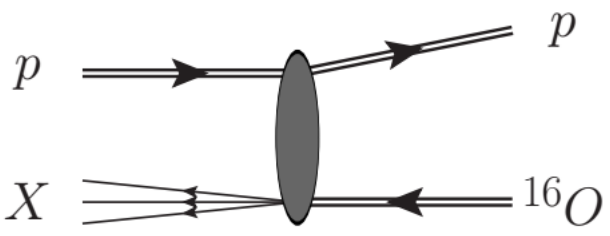
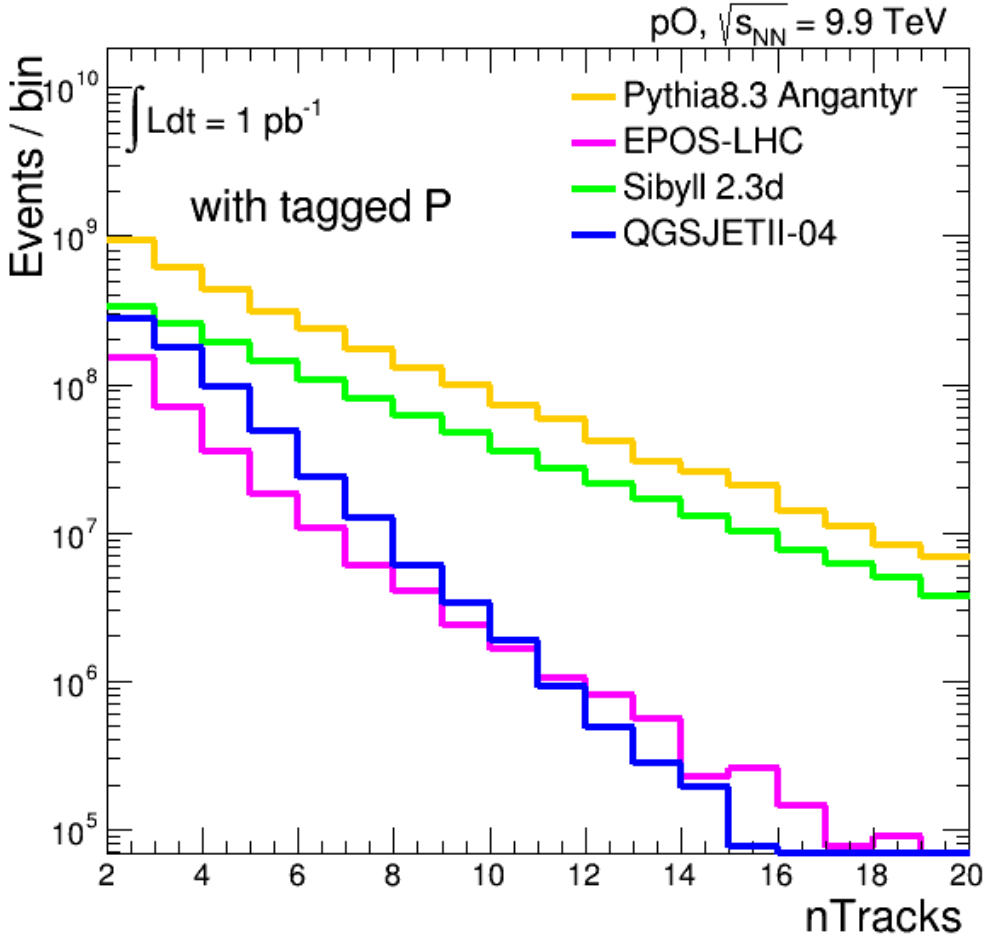
Forward protons in p-O collisions

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





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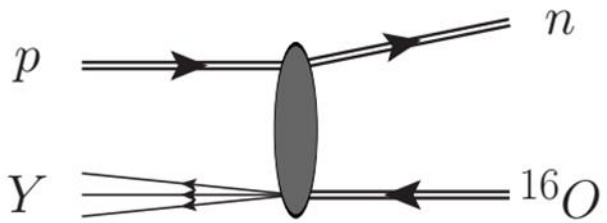
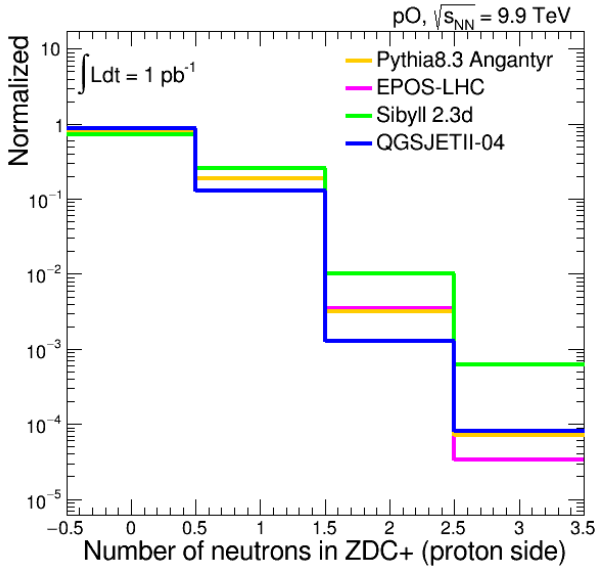
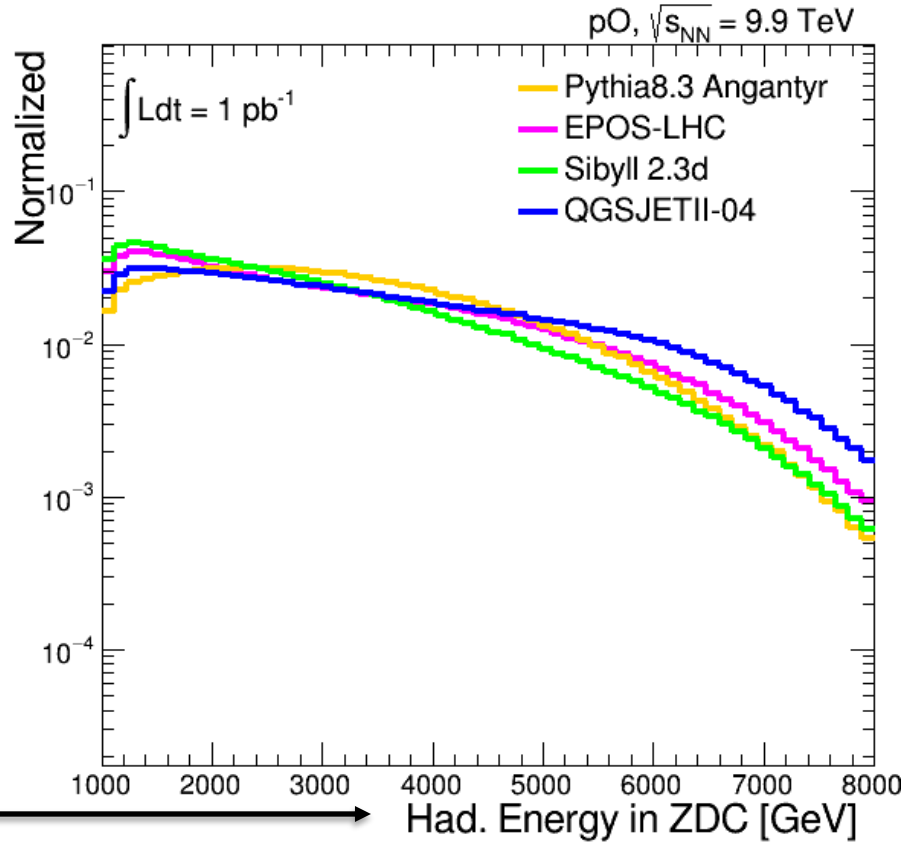
Forward neutrons in p-O collisions

- 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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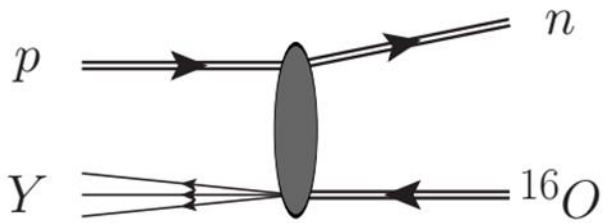
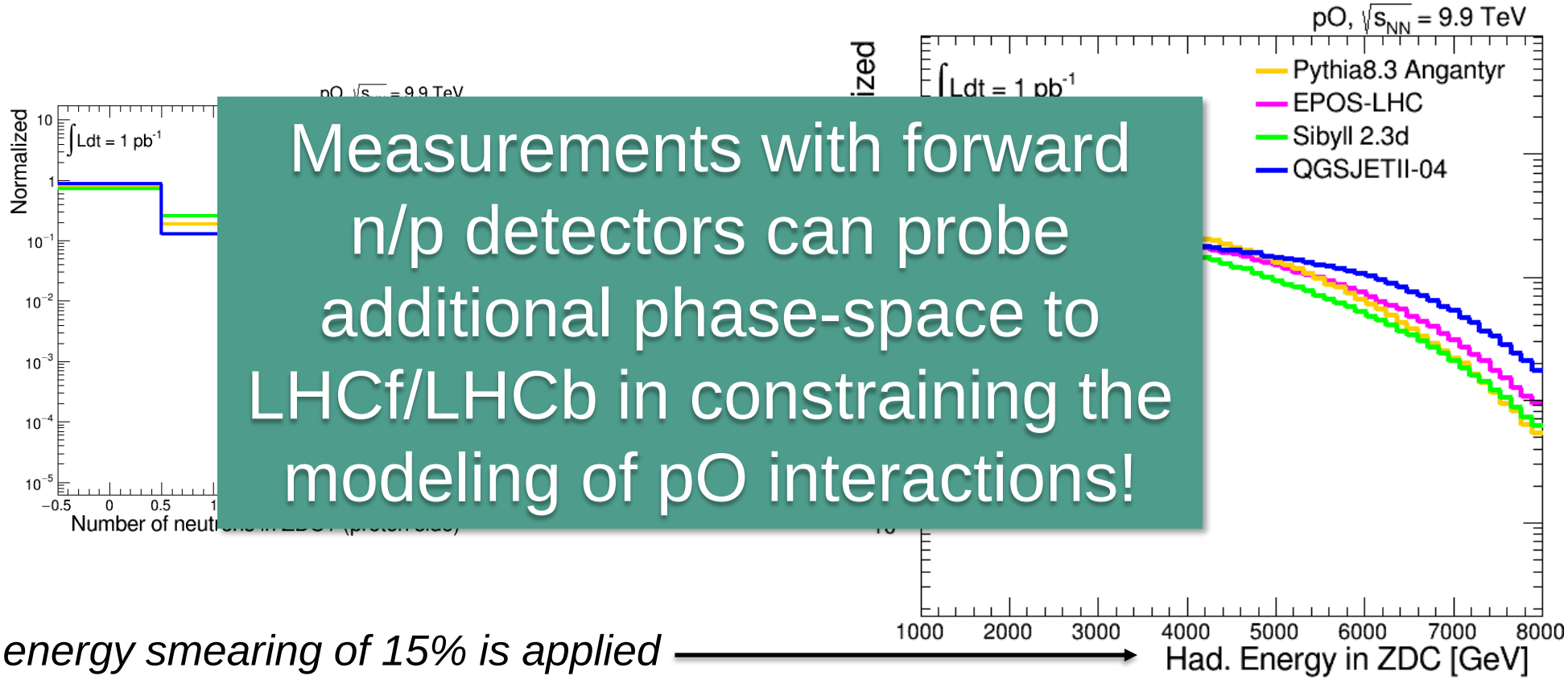




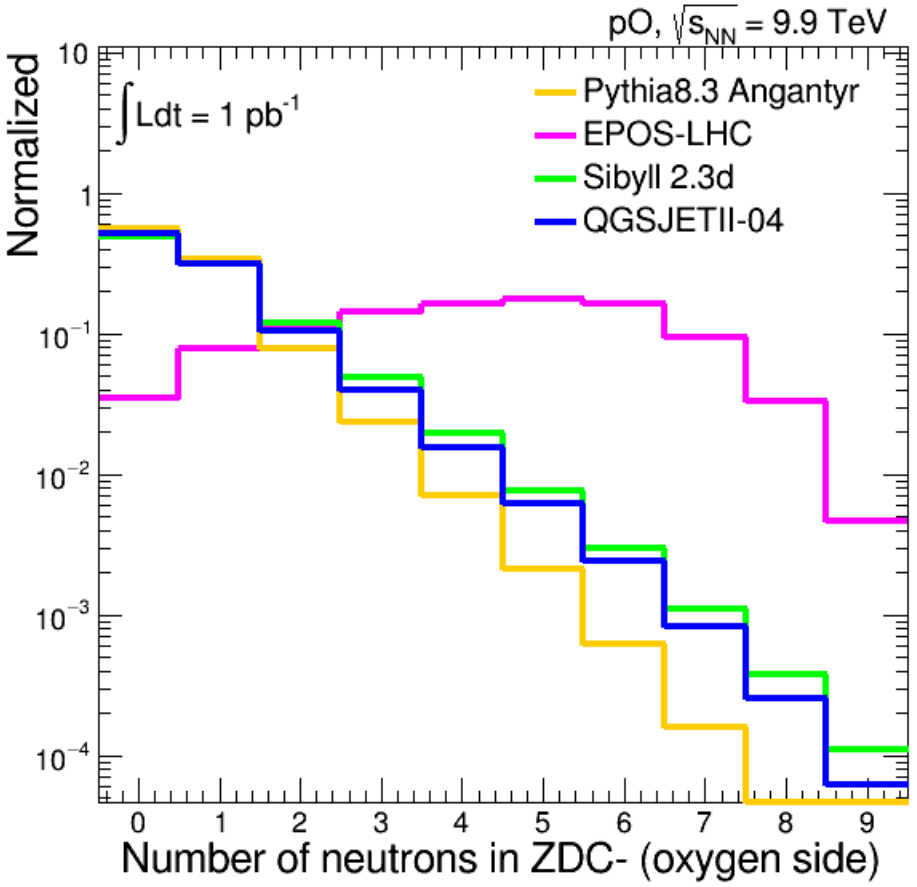
Measurements with forward n/p detectors can probe additional phase-space to LHCf/LHCb in constraining the modeling of pO interactions!

Neutron energy smearing of 15% is applied

Determination of nuclear geometry

Oxygen side - neutron tagging

- Neutrons can be tagged also in the oxygen side



Oxygen side - neutron tagging

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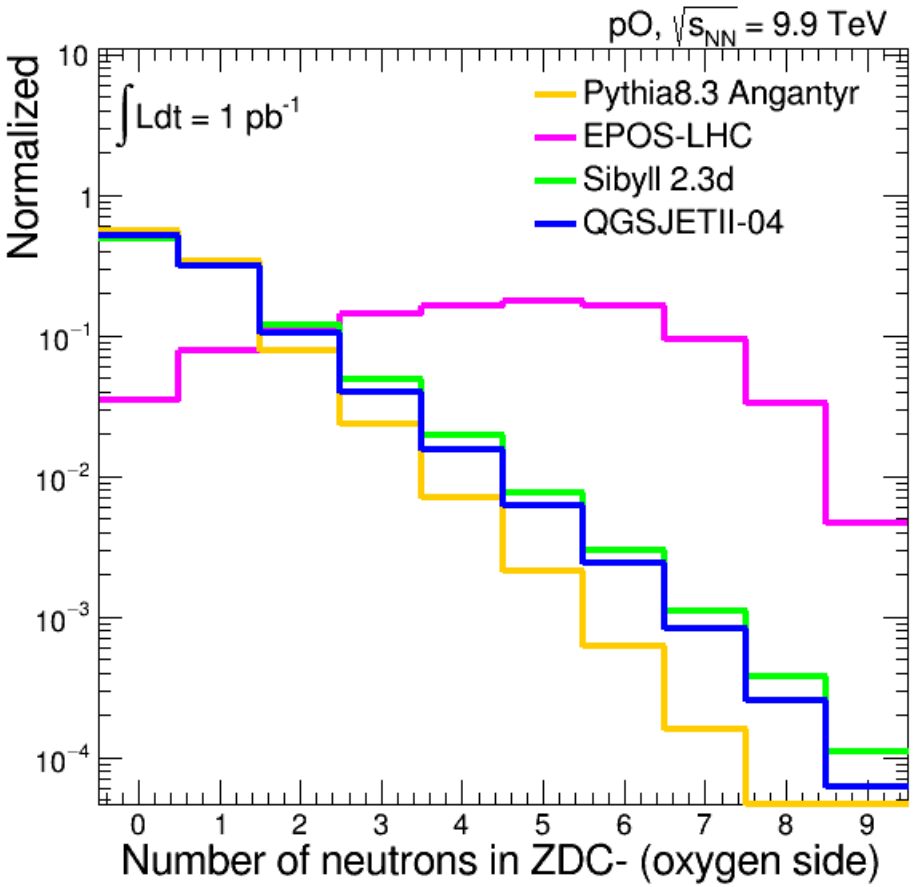
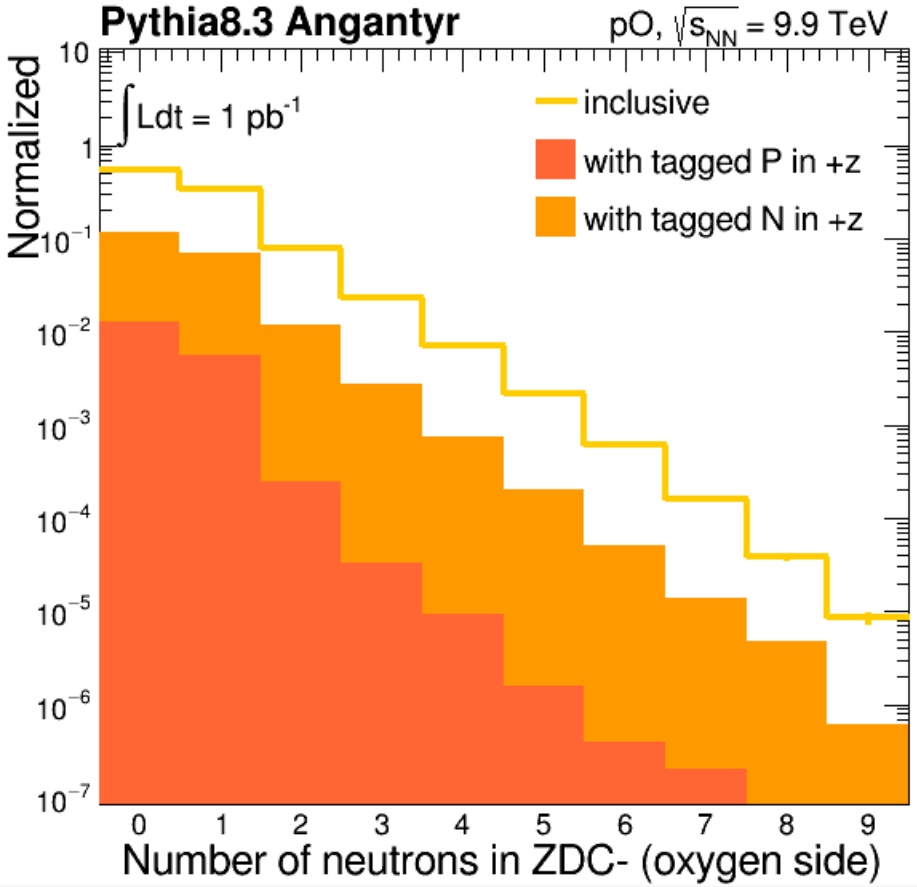
- Different ZDC energy spectra for diffractive and non diffractive events



Pythia



Neutron multiplicity is not validated in Pythia

Oxygen side - neutron tagging

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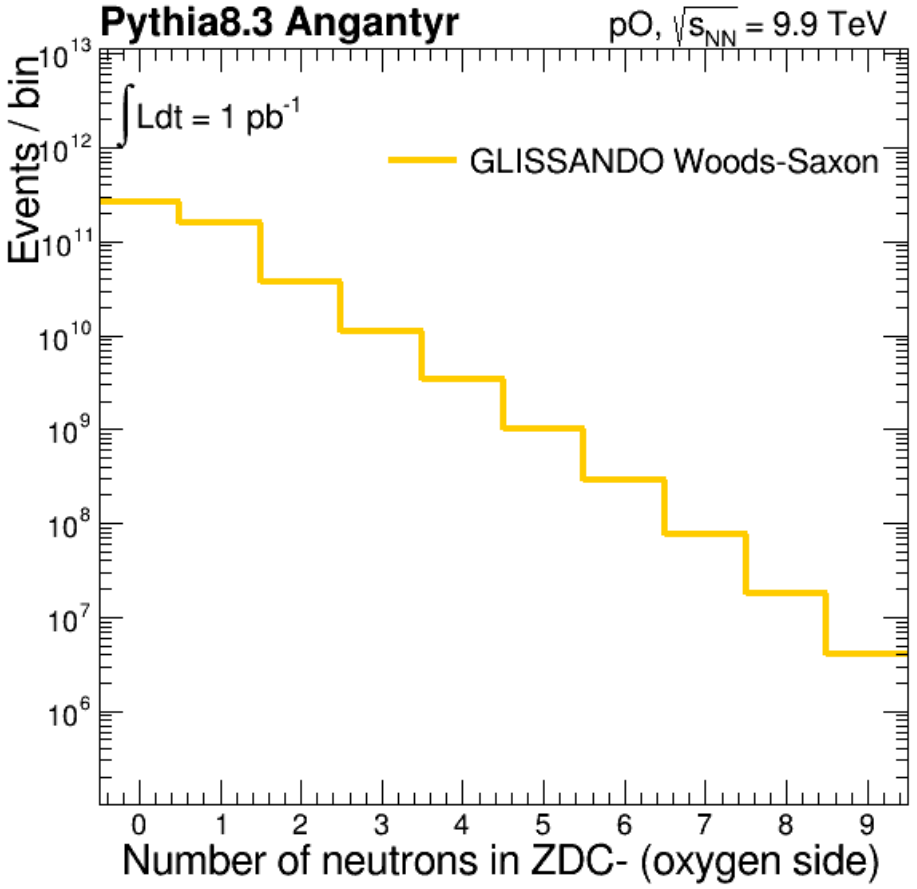
- https://pythia.org/latest-manual/HeavyIons.html



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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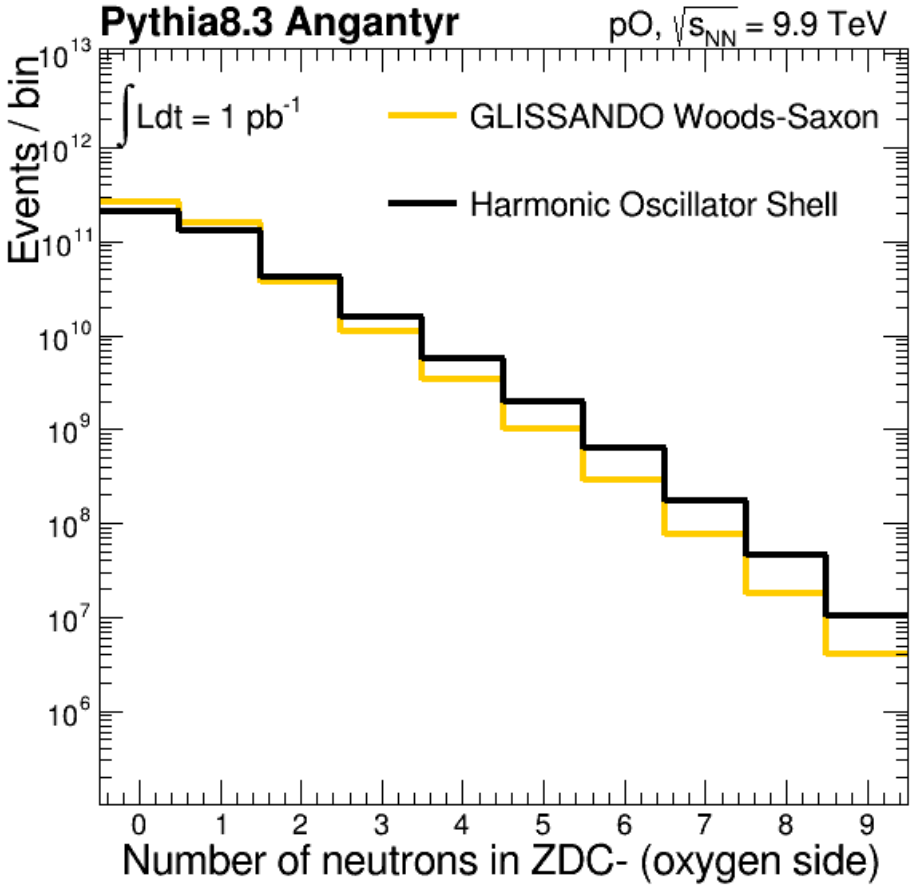

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$\rho(r) = \frac{4}{\pi^{\frac{3}{2}}C^3}\left(1+\frac{(A-4)r^2}{6C^2}\right)e^{-\frac{r^2}{C^2}}$ with $C = \left(\frac{5}{2}-\frac{4}{A}\right)^{-1}\left(\langle r^2\rangle_A - \langle r^2\rangle_p\right)$, $\langle r^2\rangle_A = 0.77\text{fm}^2$

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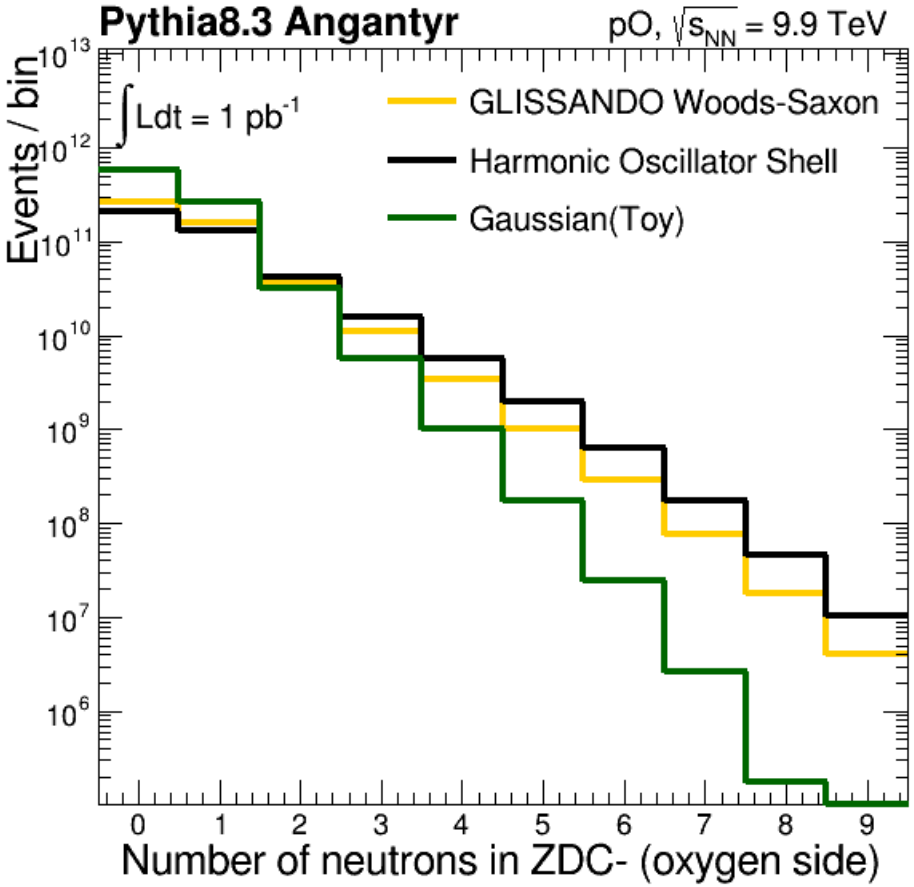

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- Gaussian model

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

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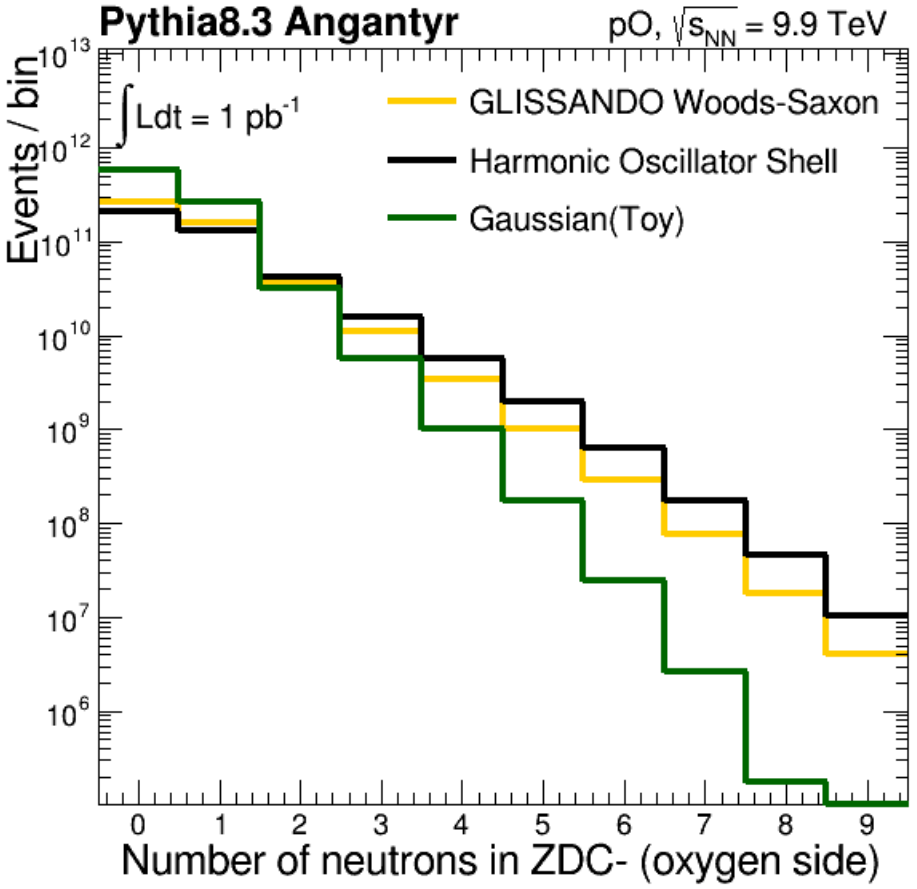

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Ab initio calculations CERN-TH-2024-021 can be implemented in Pythia

Oxygen side - neutron tagging

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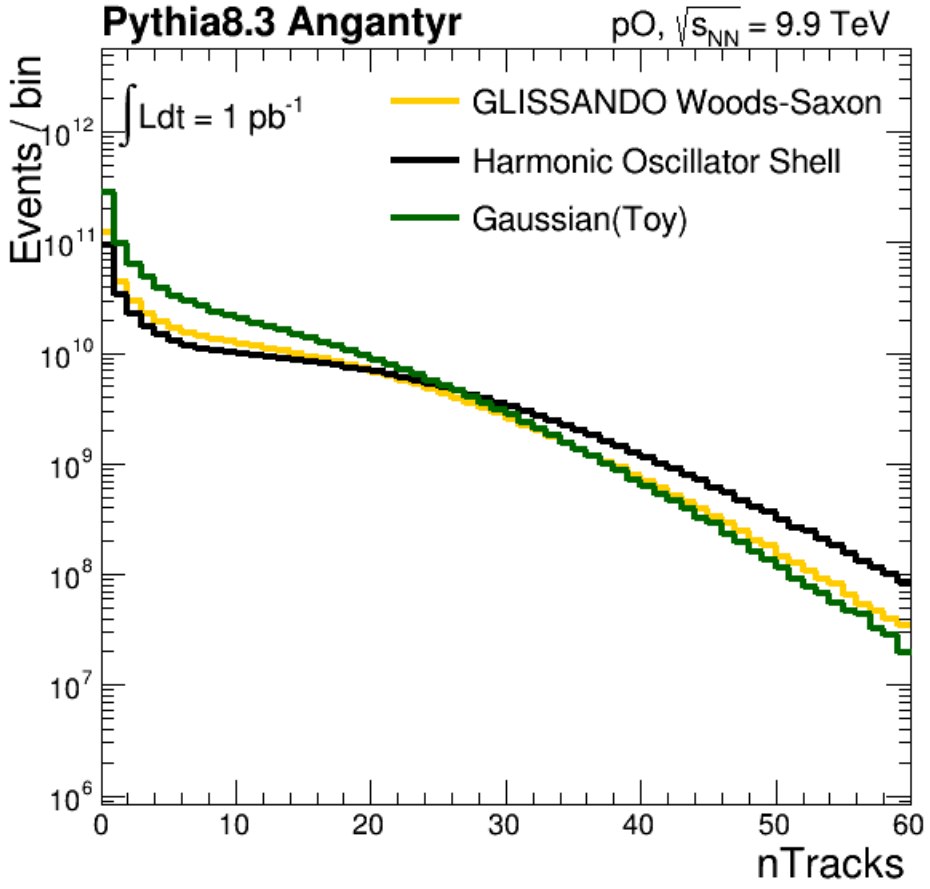
Many observables are sensitive to nuclear geometry



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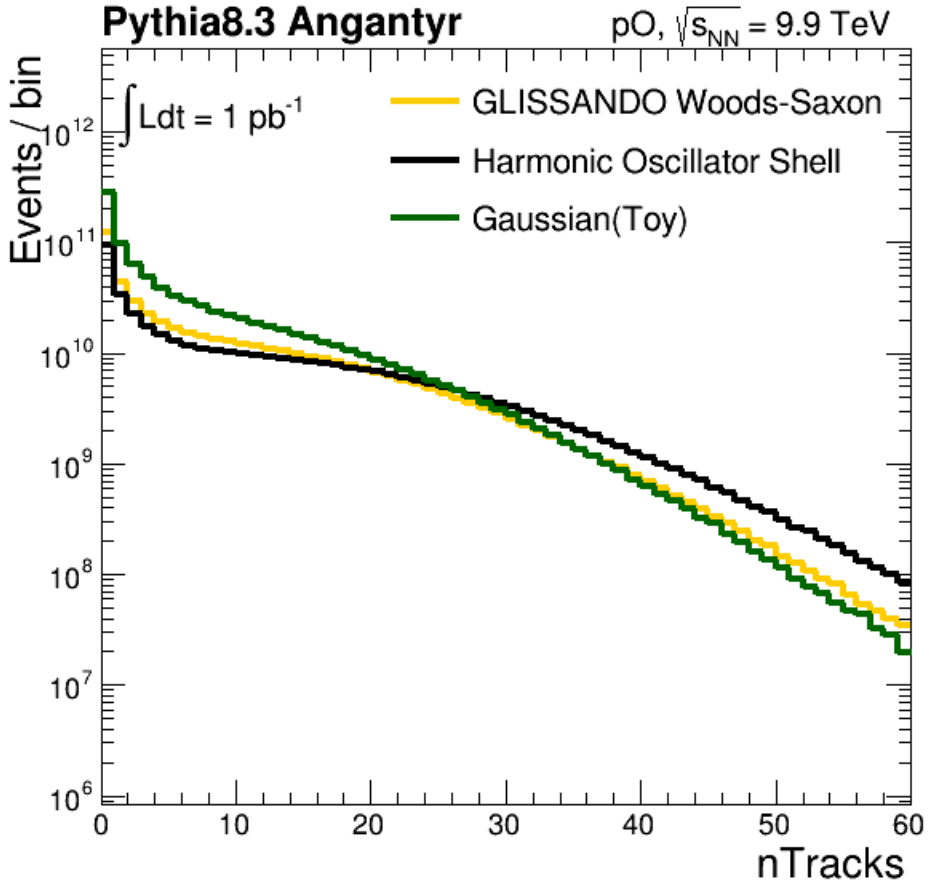
- Neutrons can be tagged also in the oxygen side
- https://pythia.org/latest-manual/HeavyIons.html

Many observables are sensitive to nuclear geometry



Nucl

- Gl

$\rho(r) =$

- Ha

$\rho(r) =$

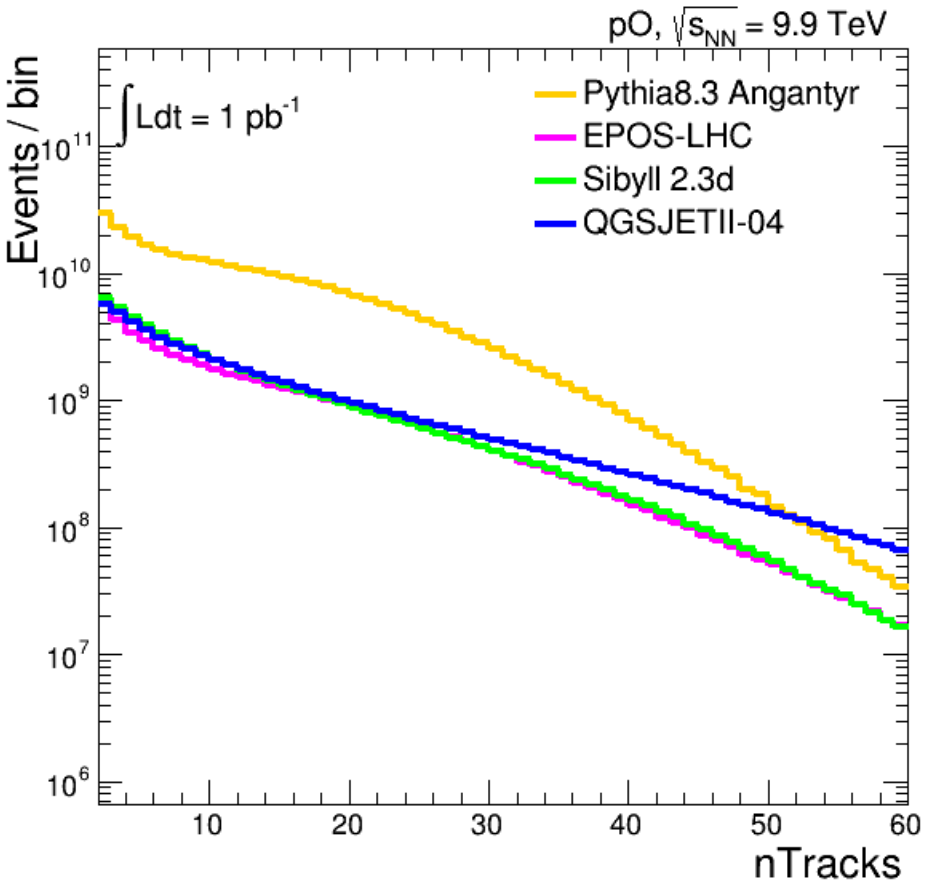
- Ga

The Ga

with Ch

- Al

Ab init



310.5475):

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

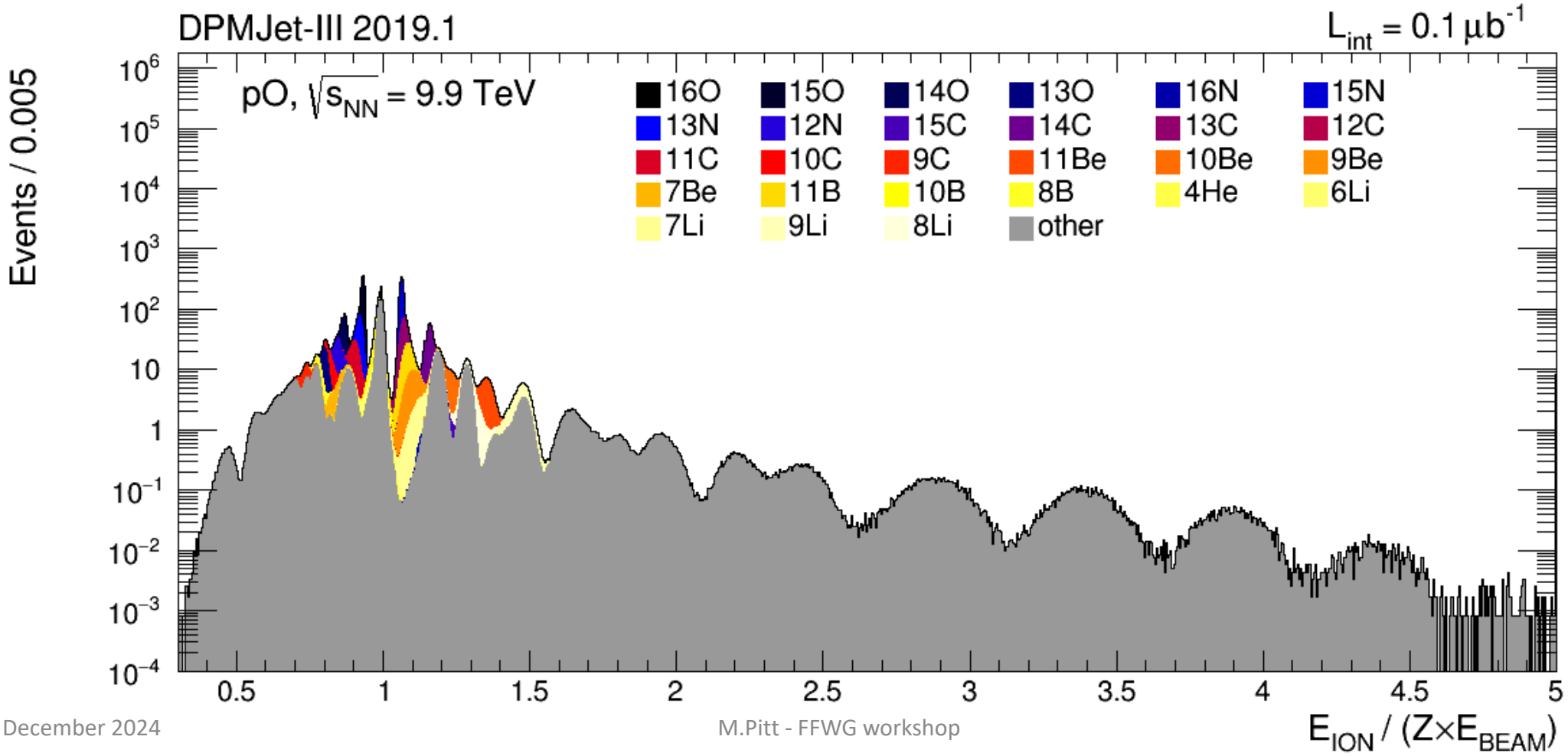
Gaussian distribution

in Pythia (Work in

How distinguish differences between hadronic interactions and nuclear geometry?

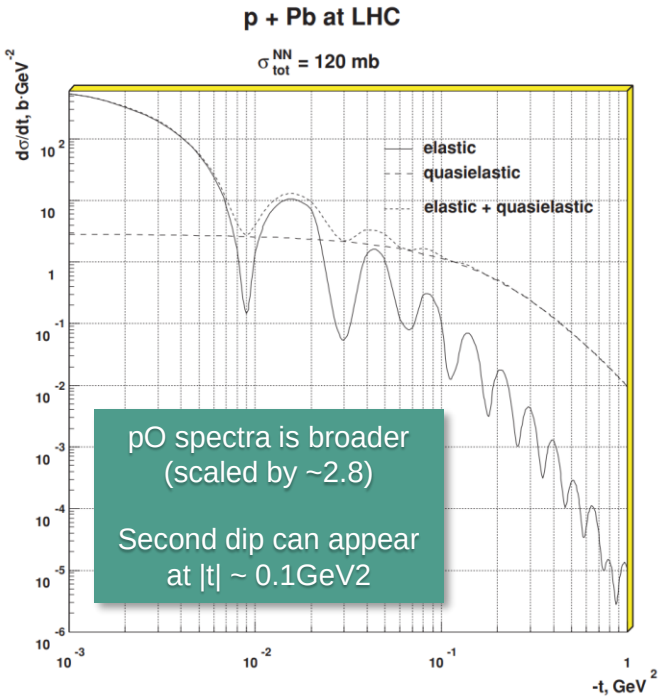
Ion tagging at the LHC

- Fragments with different rigidity will be bent differently by the magnets
- Ion energy for stable orbit is $E = Z \cdot E_{BEAM}$



Elastic pO collisions

- Elastic proton spectra could be sensitive to Oxygen geometry (gluon density)
- 20 years ago, such measurement was a part of a FELIX (full-acceptance detector at the LHC) proposal.



A Ageev et al 2002 J. Phys. G: Nucl. Part. Phys. 28 R117

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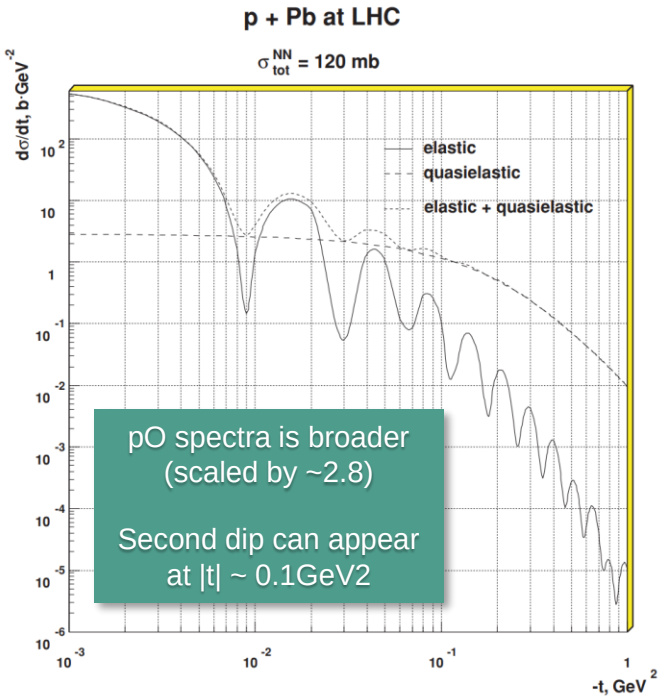


Quasi-elastic protons: protons that elastically scatter from a nucleon, have harder t spectra

t-acceptance (example of CMS):

Ly(β*=60cm) = ~10 m → $|t| > 1.4$ GeV^2

Ly(β*=90m) = ~250 m → $|t| > 3e\text{-}3$ GeV^2
(https://arxiv.org/abs/2411.19749)

A Ageev et al 2002 J. Phys. G: Nucl. Part. Phys. 28 R117

Elastic pO collisions

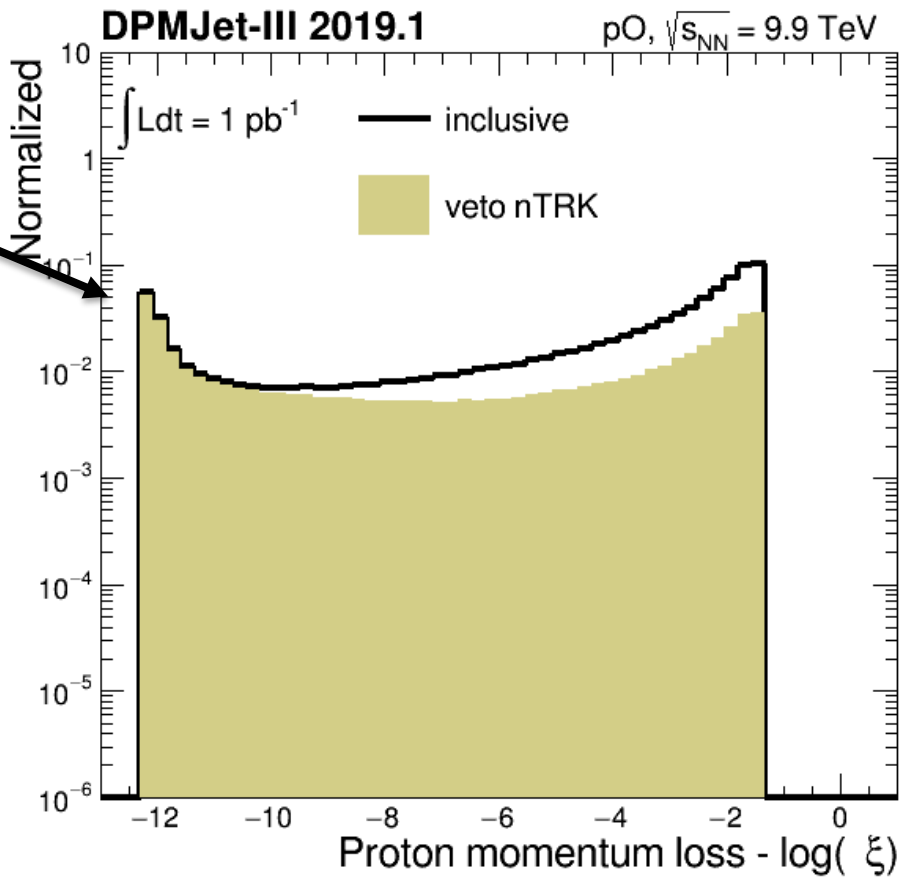
- Tagging (quasi)-elastic protons:
  - Assume 4π coverage:

Veto Barrel (trk/CAL) with |η|<2.5

Veto HF with 2.5<|η|<5.0

Veto ZDC with |η|> 8.0

Veto FSC with 5.0<|η|<8.0



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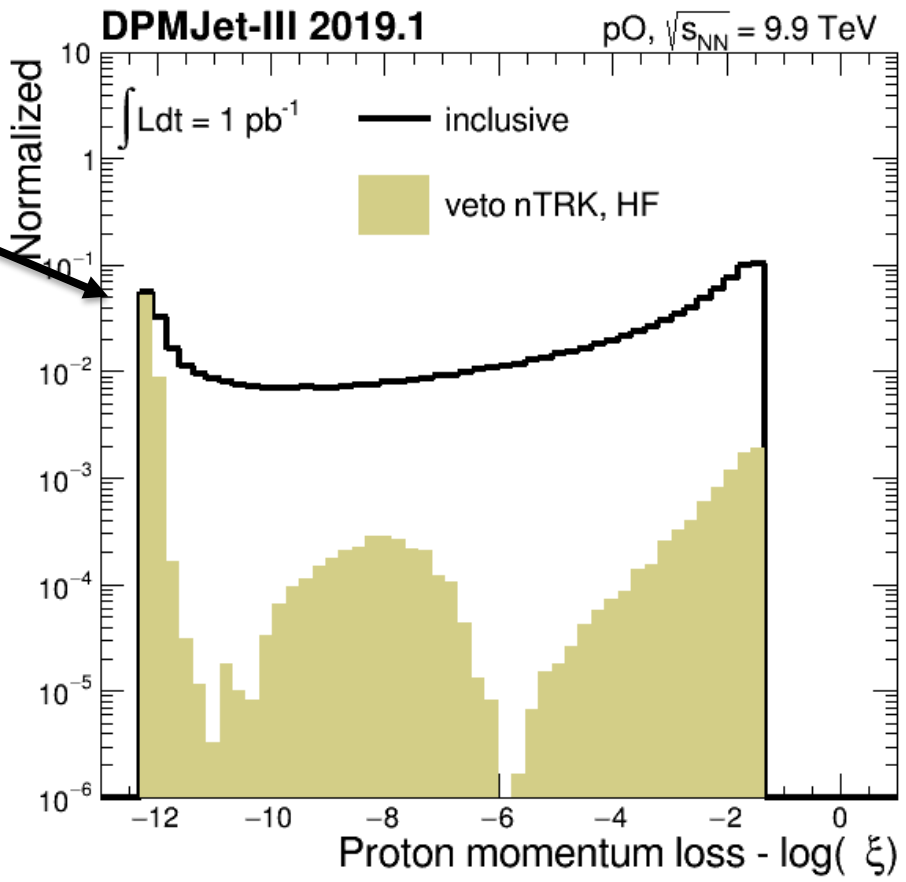

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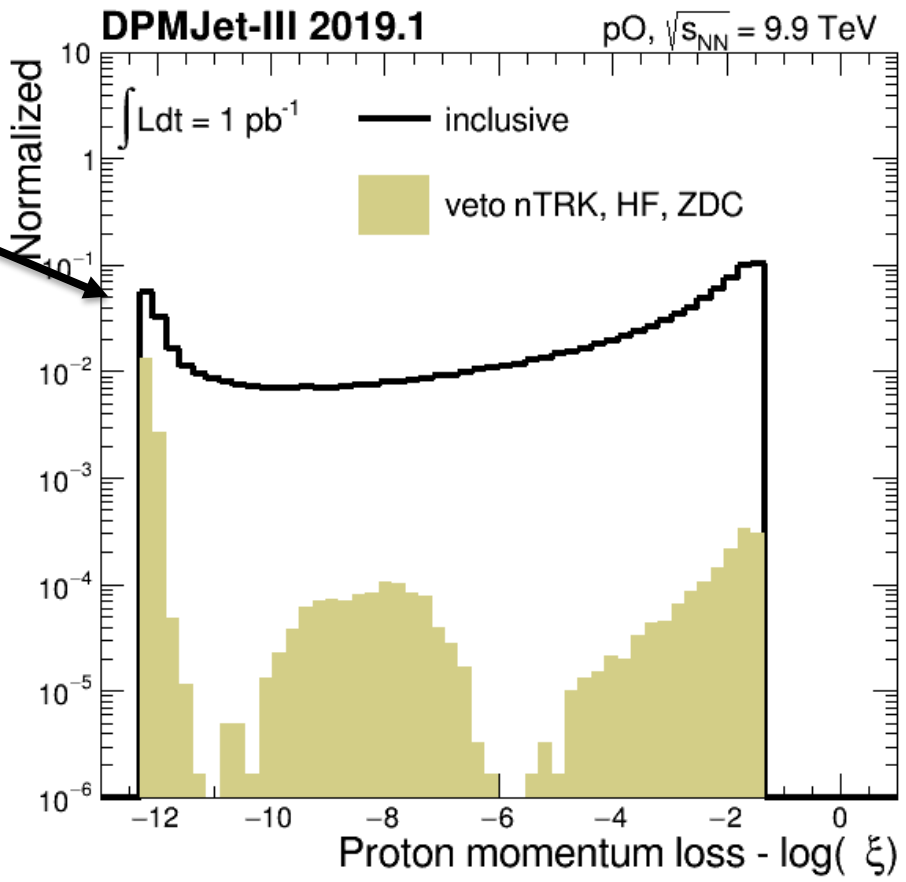

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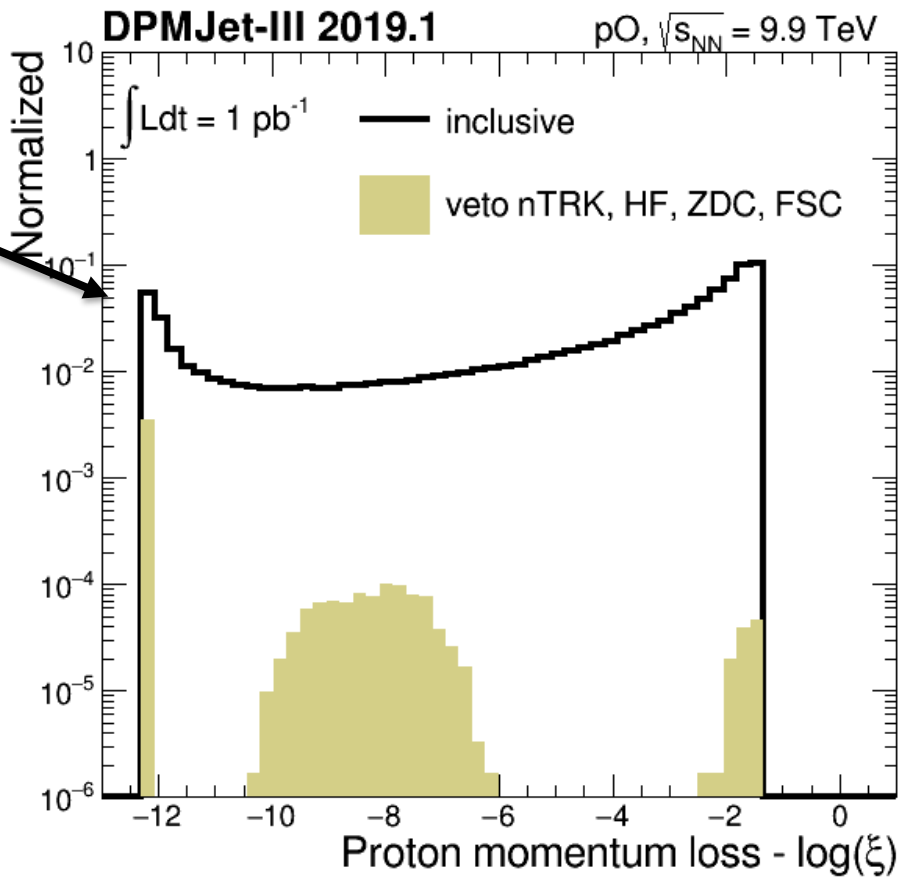

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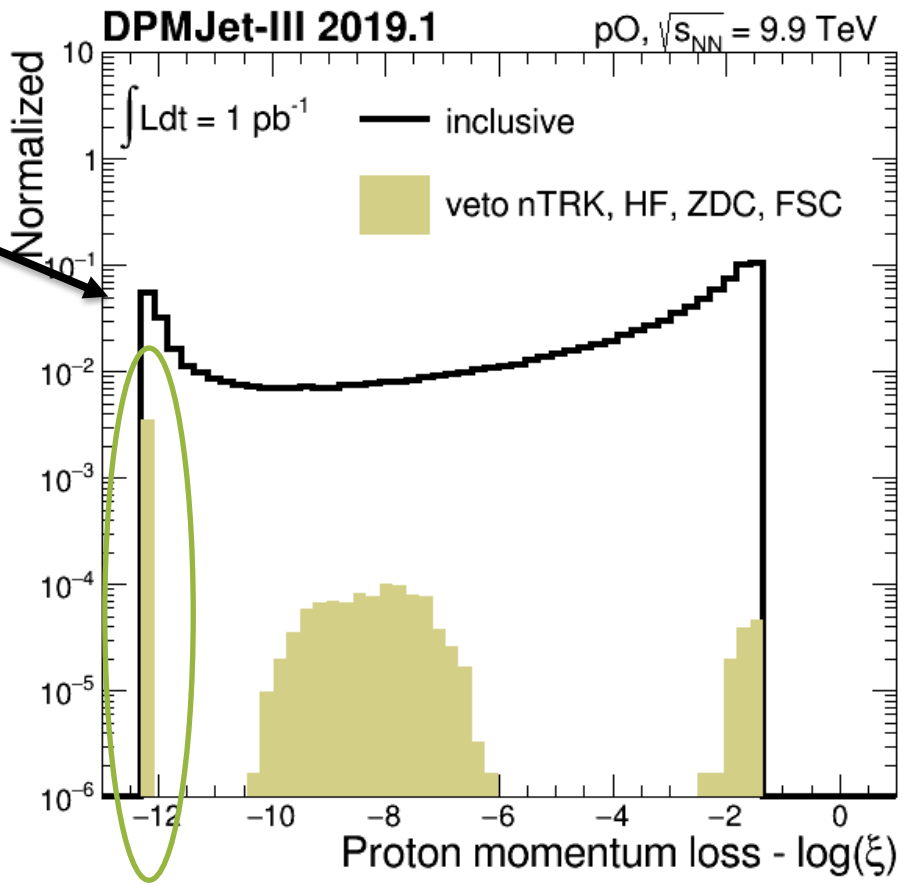
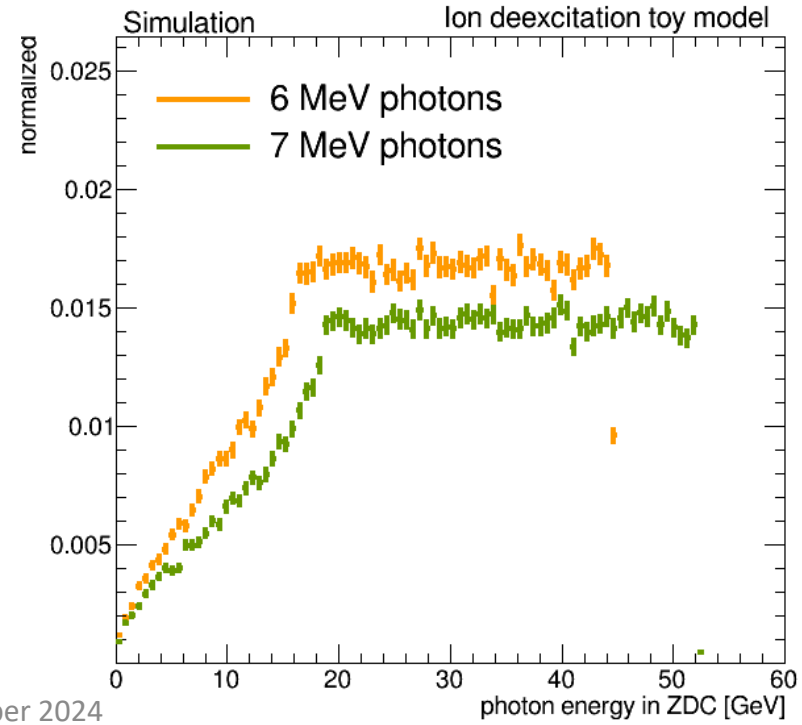
- High purity with forward coverage!



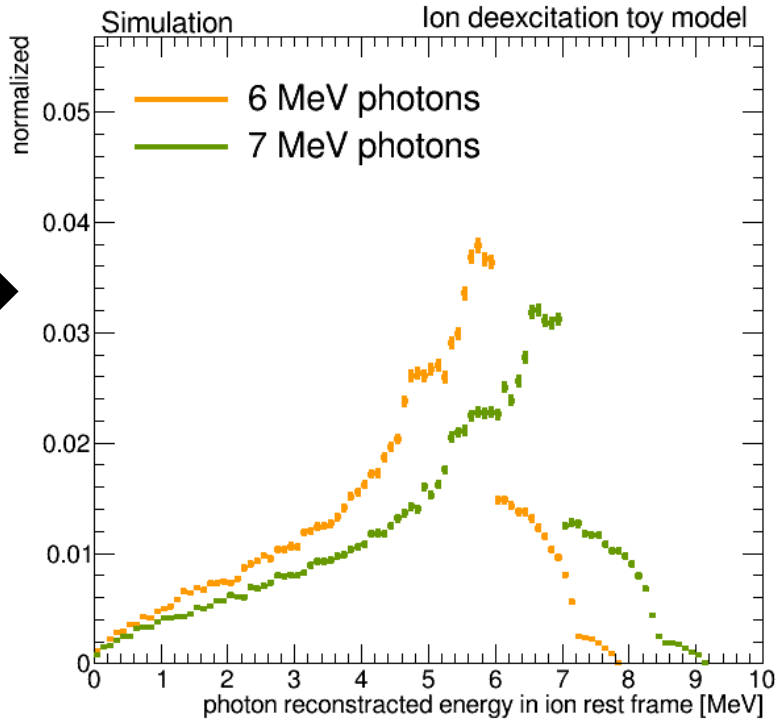
Elastic pO collisions

- Tagging quasi-elastic protons – two types of quasi-elastic processes are expected:
  - Proton elastically scattered from a nucleon
  - Proton excites from nuclei which emits a photon
- The lowest energy level of oxygen ~6 MeV

No segmentation in Y
ΔX=2cm segmentation in X



Boost to ion rest frame (γ ~ 3700)



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, …)
- Forward proton detectors can be included if ATLAS/CMS **both** ask for Beam-Based Alignment time

Probing nuclear geometry through ion tagging

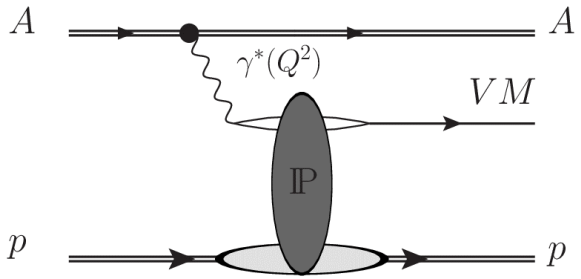
- Forward proton detectors can be sensitive to ion remnants.
- Challenges – tracking with high Q, multiple scattering, …

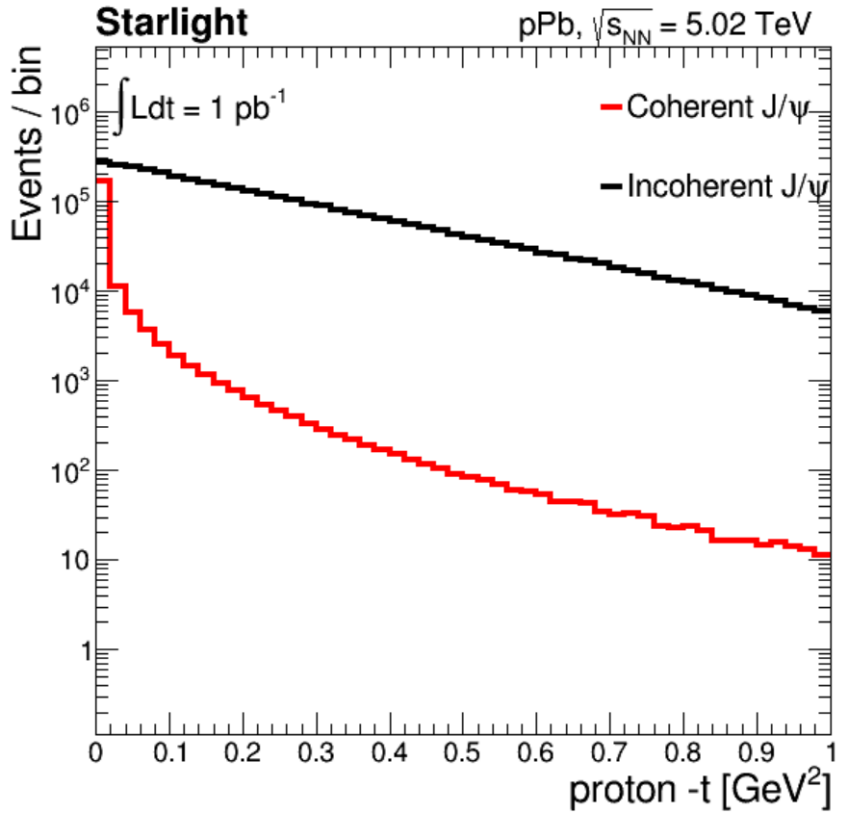
Feedback is welcomed: feel free to contact michael.pitt@cern.ch

Proton tagging in pA runs

Exclusive VM production

- Vector mesons (Spin 1) are produced in $\gamma - IP$ interactions
- Ions emit a photon at $Q^2 \sim 0$ ($t \sim p_T$)
- In coherent production proton remain intact

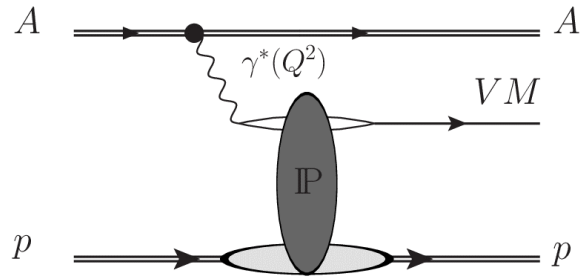


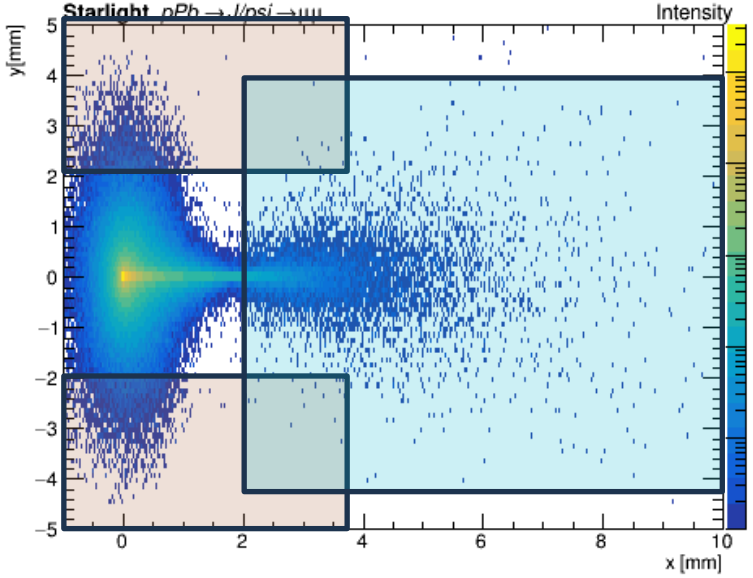


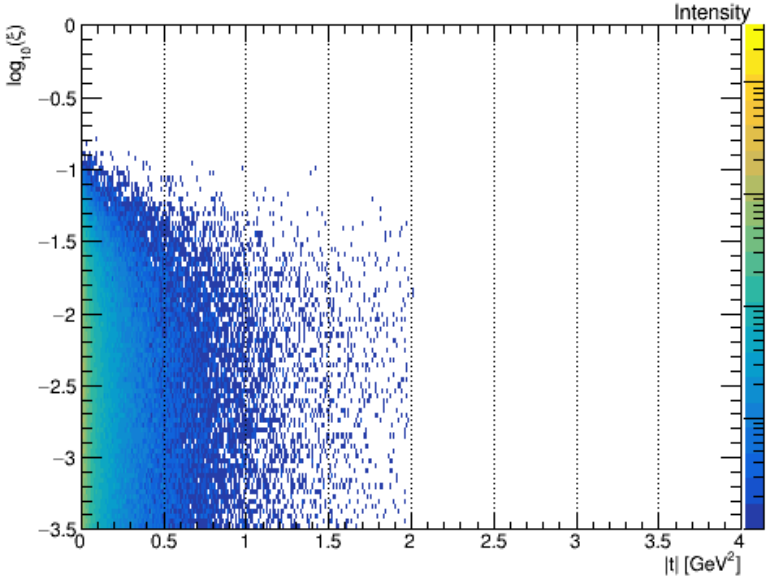
proton tagging in pA collisions

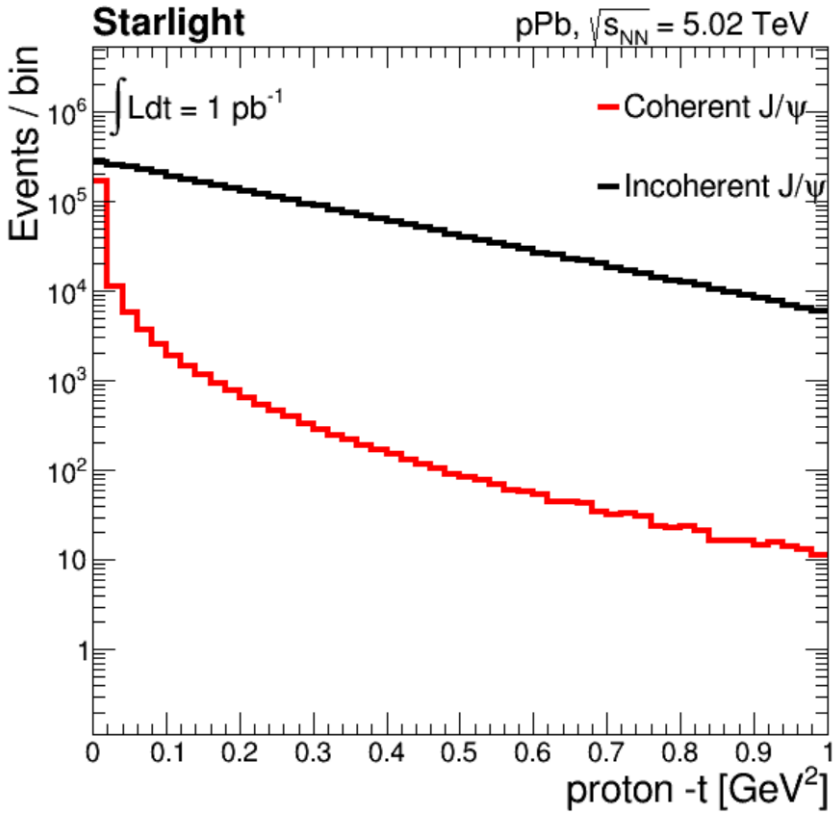
Exclusive VM production

- Vector mesons (Spin 1) are produced in $\gamma - IP$ interactions
- Ions emit a photon at $Q^2 \sim 0$ ($t \sim p_T$)
- In coherent production proton remain intact
- Fraction of scattered protons reach the PPS detectors









proton tagging in pA collisions

Exclusive VM production

- Vector mesons (Spin 1) are produced in $\gamma - IP$ interactions
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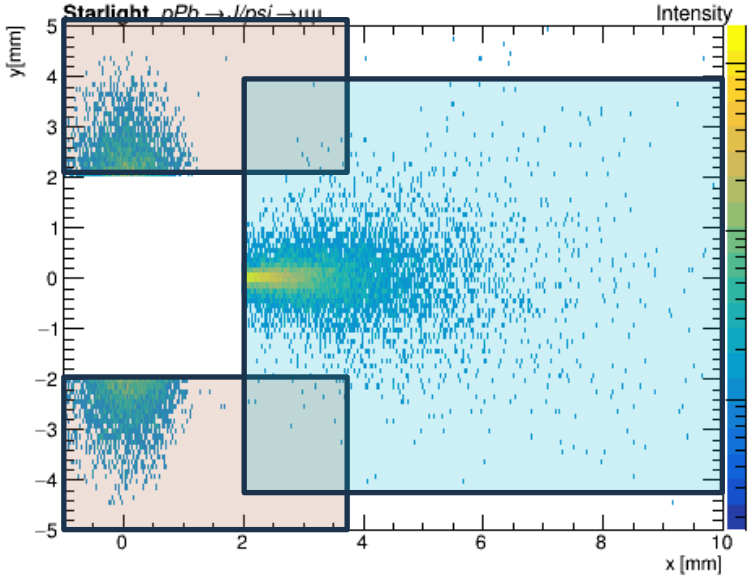
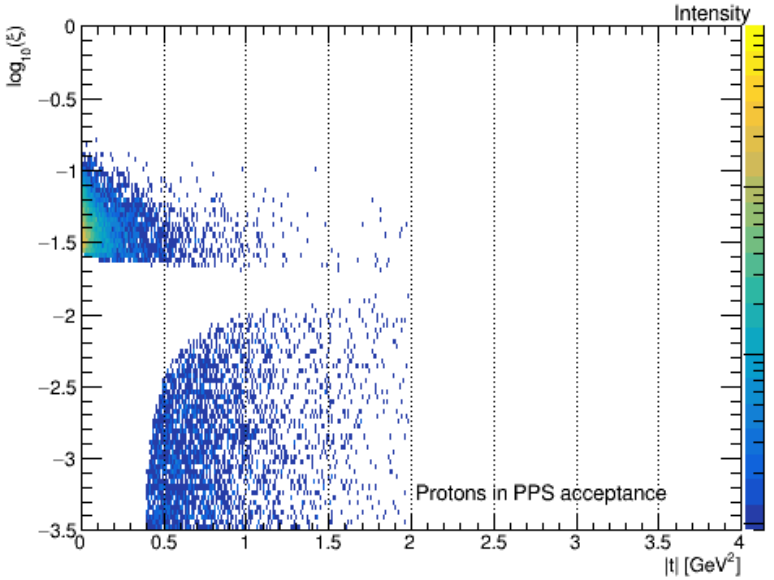
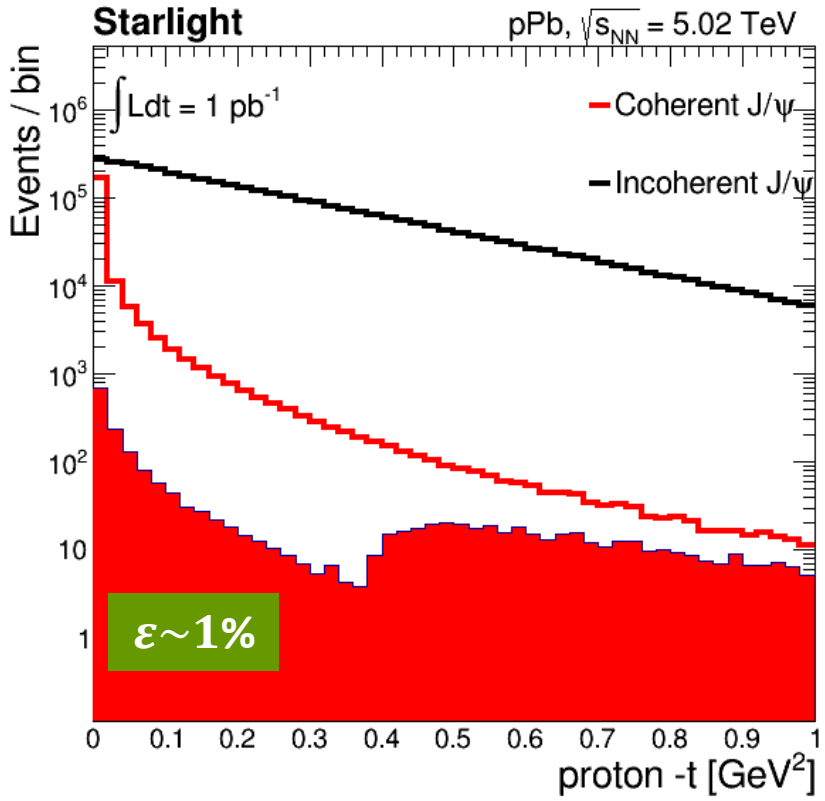
- In coherent production proton remain intact
- Majority of tagged events in horizontal stations (low pT)

- Acceptance to t~0
- High t tail needs high L



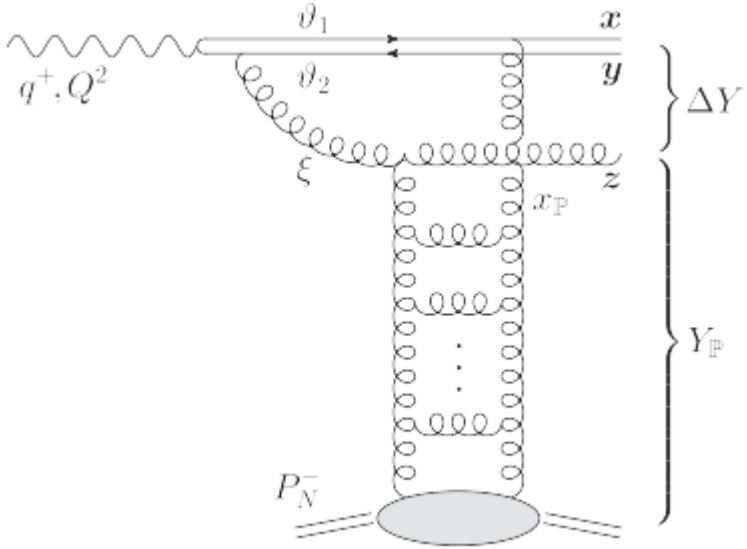




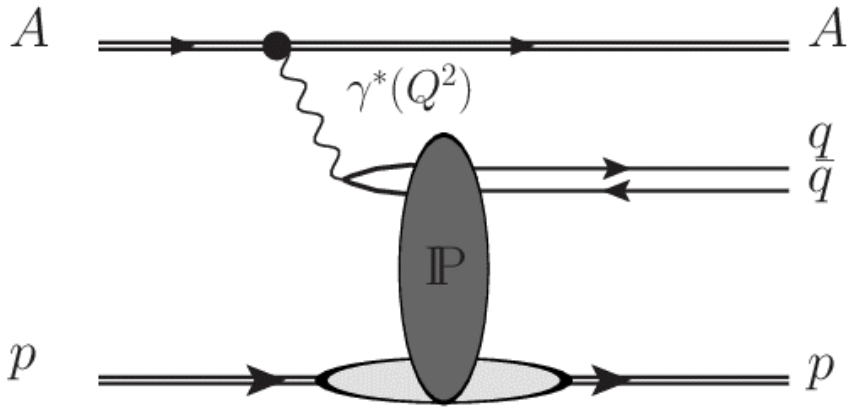
Exclusive dijet production

- Higher mass di-quark can be produced in $\gamma - IP$ interactions
- Ions emit a photon at Q2~0, high energy transfer (jet pT>10GeV)
- Phenomenological interest for such topology
  - Example1: soft gluon emissions for saturation studies

https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.128.202001



- Example2: Exclusive production



proton tagging in pA collisions

Exclusive dijet production

- Higher mass di-quark can be produced in $\gamma - IP$ interactions
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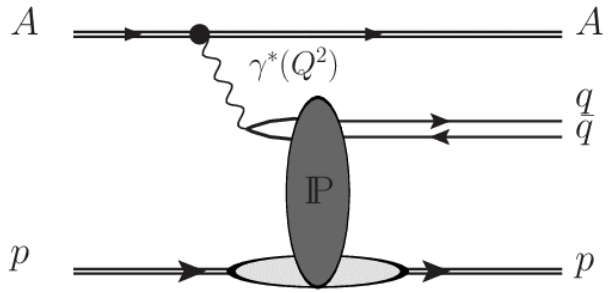
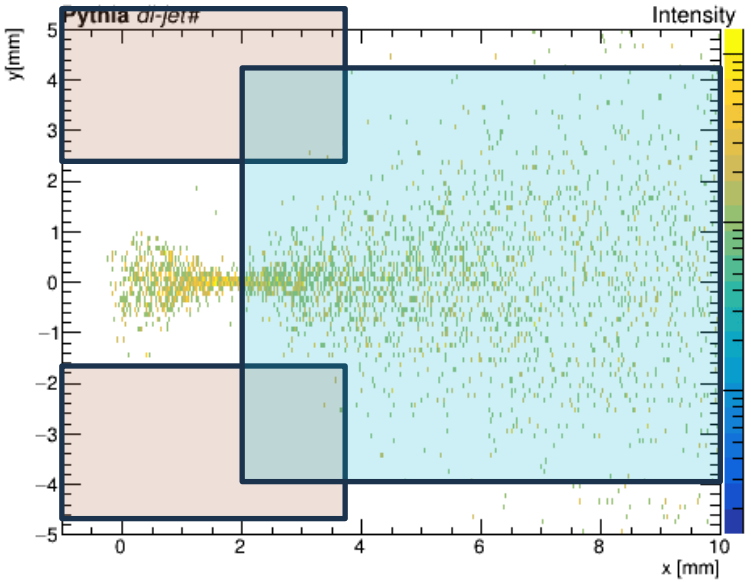
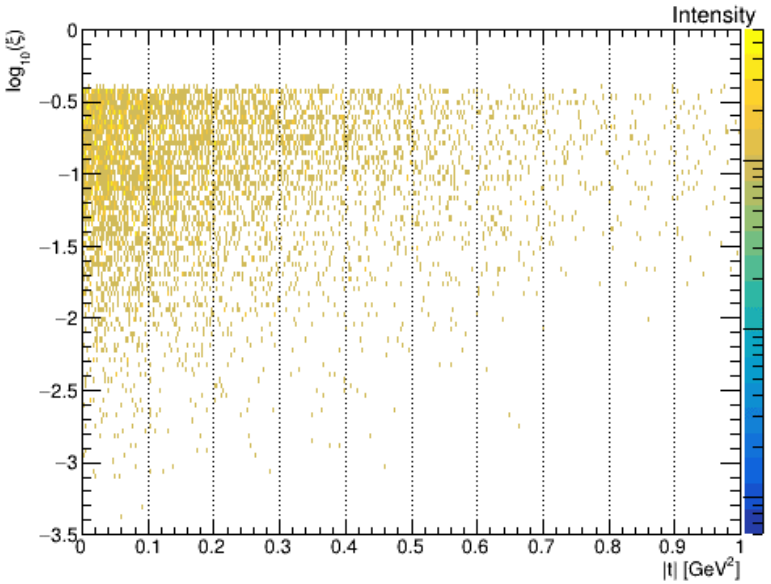
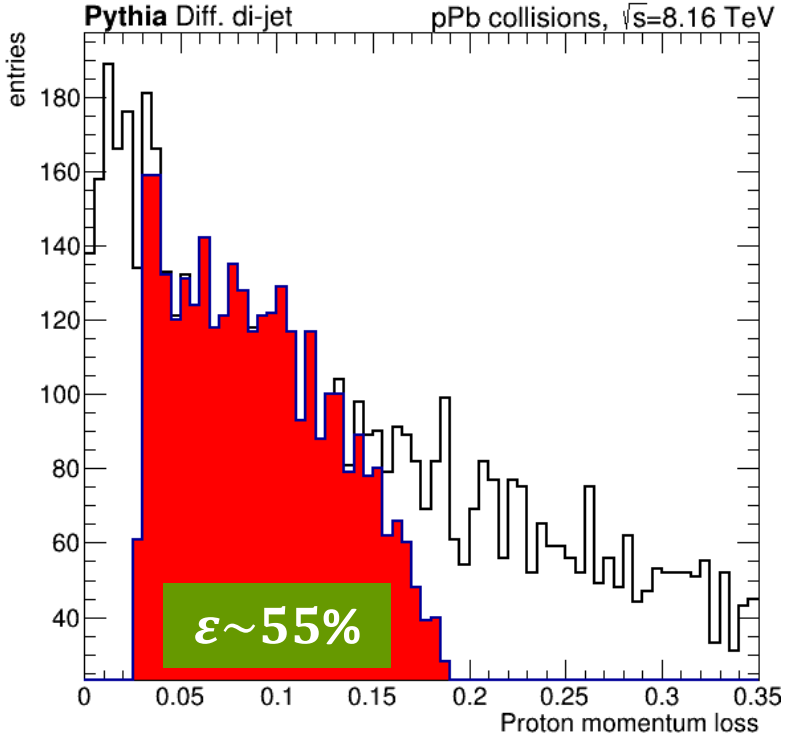
- Good acceptance with horizontal stations









Summary – proton tagging in pA

Tagging (in pO)

- Minimum bias events can be studied in 2025, which serve as a proof of concept for future pA
- In addition, ion tagging can be studied for the first time (challenging measurement).

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- Proton detectors are a part of CMS standard pp program at the HL-LHC.
- Insertion of proton detectors requires a dedicated alignment run (12h ~2b / fill).
- Proton tagging can be used to:
  - Tag coherent VM production – can target only very low pT (large proton momentum transfer), sensitivity to high pT region seems to be low, but it depends on the integrated luminosity and can be re-evaluated.
  - Tag Higher mass states (like di-jet events) which have very high tagging efficiency (access proton kinematics).

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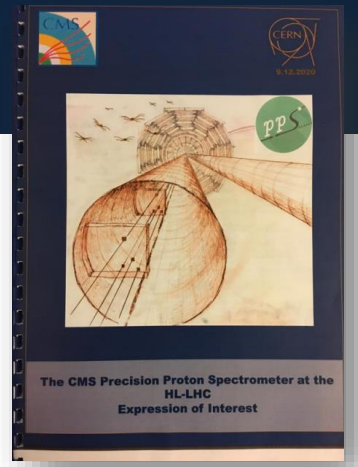
Thank you for the attention

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

Backup

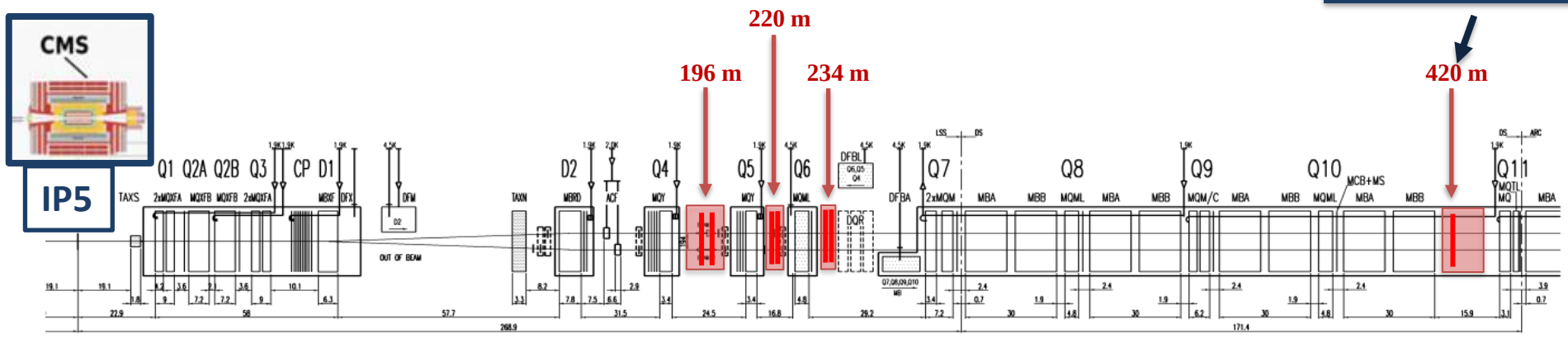
CMS Precision Proton Spectrometer (PPS)



- Since during the LS3 the whole beamline will be rearranged, a new spectrometer design was proposed (2020), and approved in Sep 2023
- PPS Upgrade with extended acceptances in pp collisions:
  1.42% < ξ < 20% for the first 3 stations (from Run 4)
  0.33% < ξ < 20% for 4 stations (from Run 5+)
- Higher ξ is defined by the TCL position

CMS-NOTE-2020-008, arxiv:2103.02752

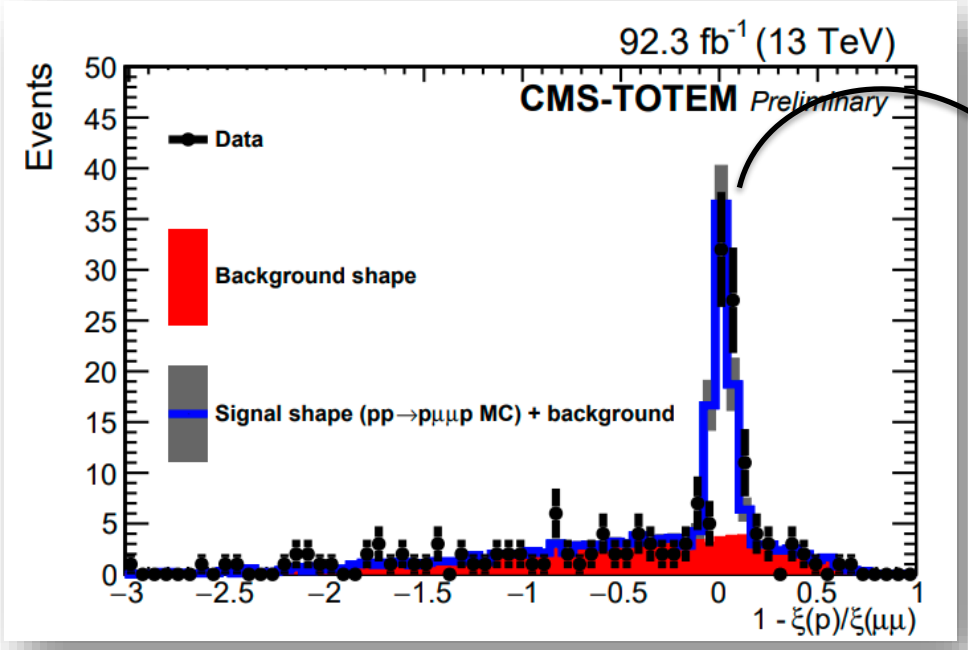
Staged installation



Main goal to extends current LHC physics program (WW, di-τ, top, ALPs, SUSY, etc…)

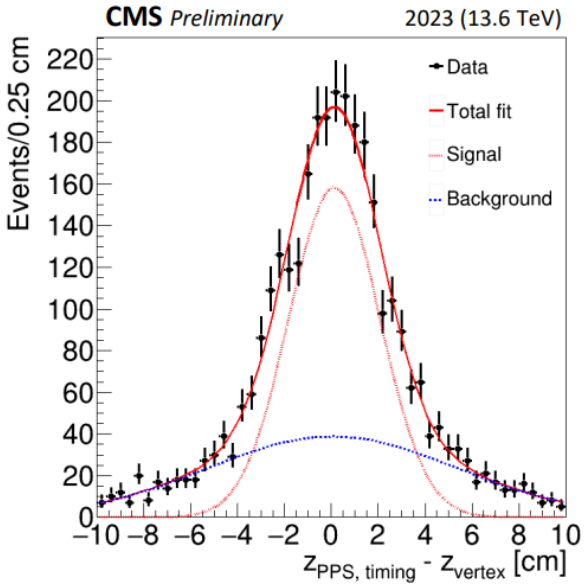
PPS | Performance

- Tracking:
  - Using (semi)-exclusive di-muon sample
  - Compare ξ(CMS) vs ξ(PPS)
  - **A few% resolution(!!!)**



Validation of the calibration sequence

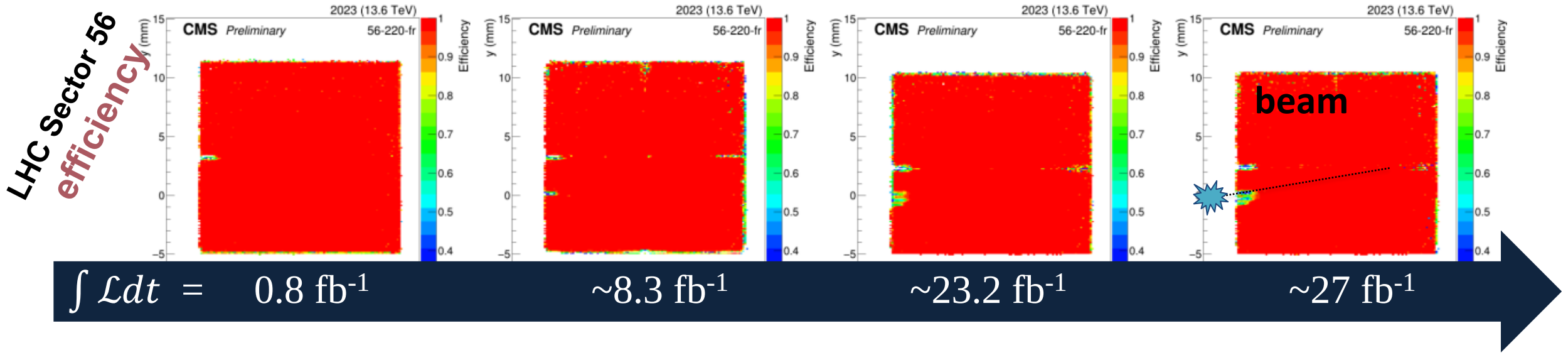
- Timing:
  - Using central diffractive events in μ~1 sample
  - Compare Z(PV) vs Z(PPS)
  - **All track resolution: $\sigma_z = 1.9\ cm$**



[JINST 18 (2023) P09009]

[CMS DP-2024/009]

PPS | Tracking efficiency in 2023

CMS DP-2024/008

- Challenges in the standard LHC runs:
  - Efficiency drop due to irradiation
  - Higher x -> Higher ξ -> Higher minimal accepted mass
  - Detectors were shifted by 0.5mm using internal movement system