Low-X 2023 workshop, Leros, Greece

Diffractive measurements in pp and pA collisions using proton/neutron tagging

05 September 2023

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Grant DE-SC0023908

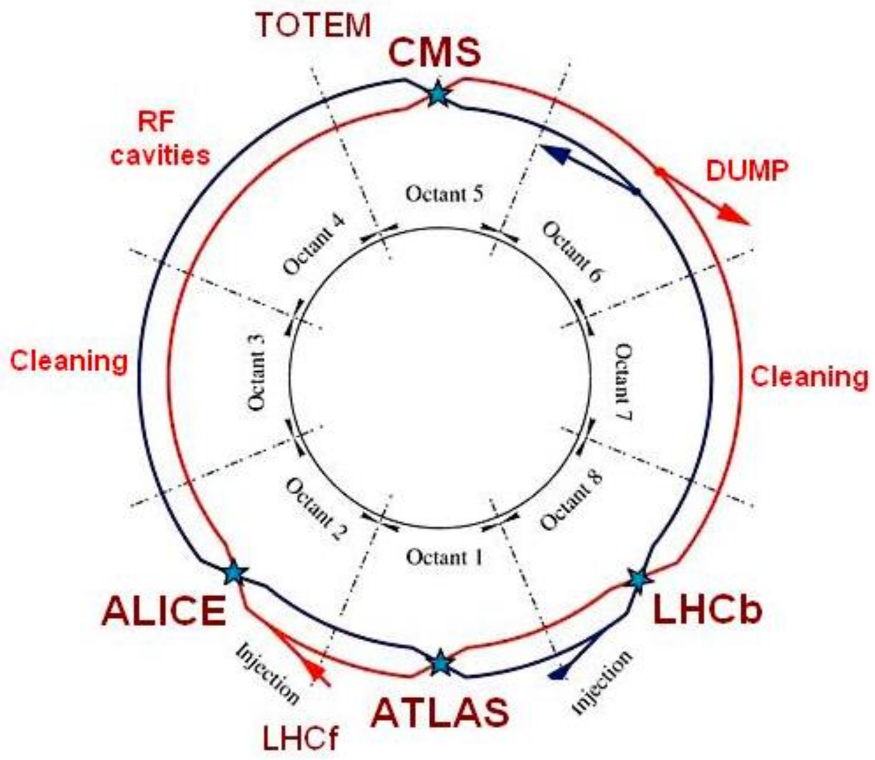
Outline

- Forward proton and neutron tagging at the LHC
- Diffractive pp physics
- Constraining models unceertanties using pO collisions
- Production of light isotopes on pO and OO collisions
- Tagging coherent processes in pA collisions

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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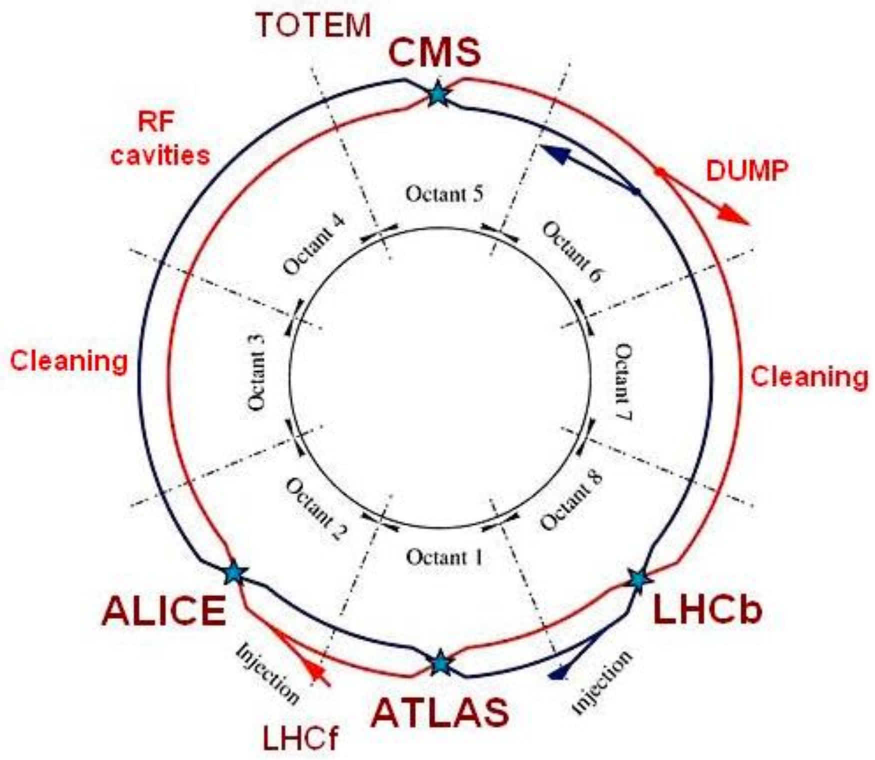
- In practice LHC comprise more than 4 experiments
- Example: forward (neutrino) detectors
  - SND@LHC
  - FASER



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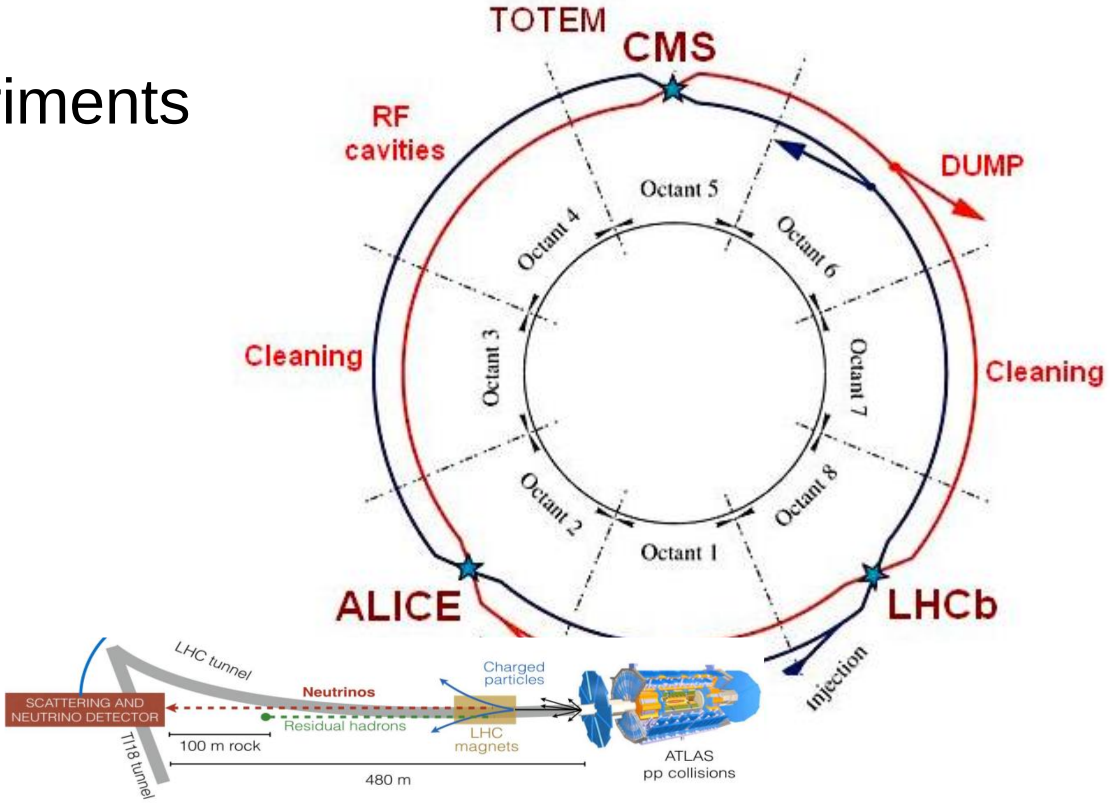

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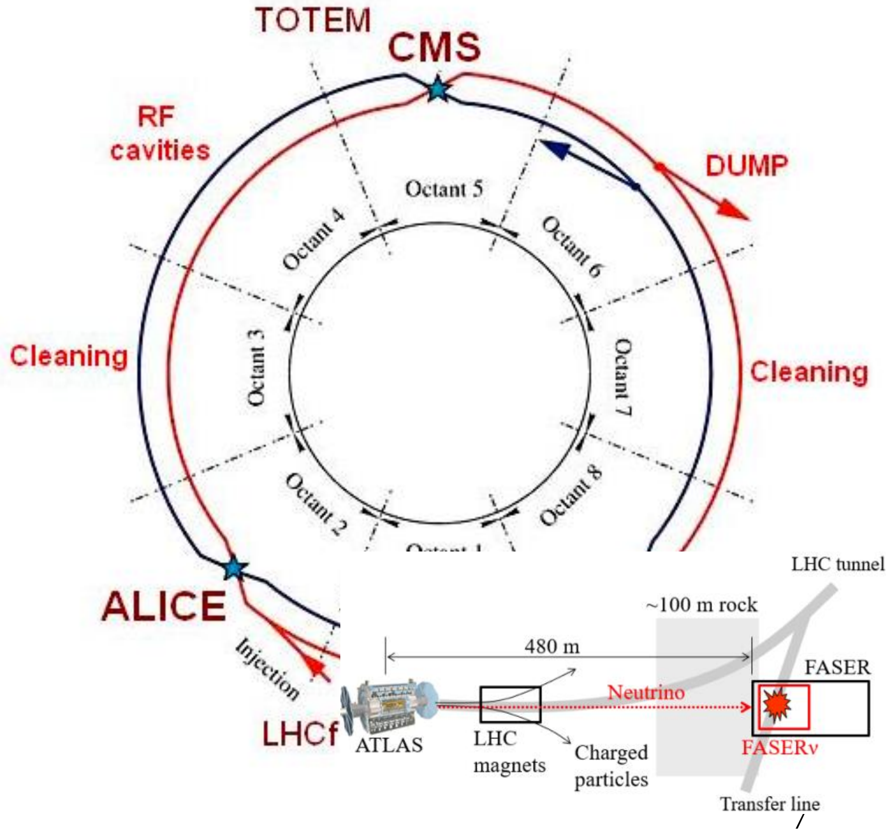
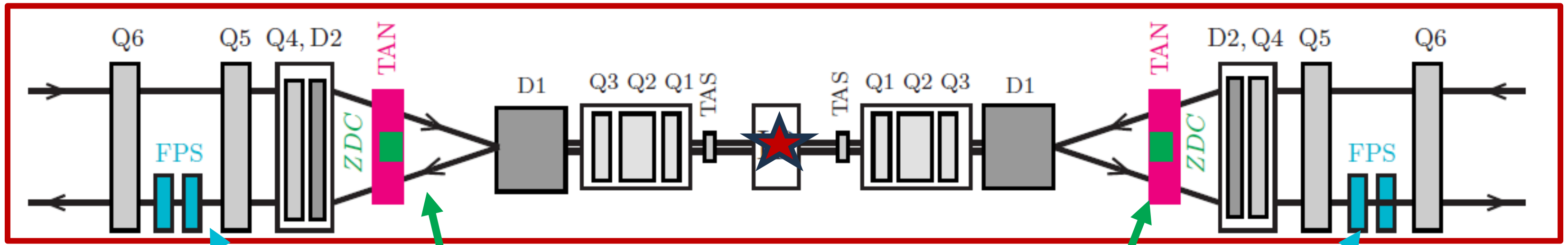


Forward detectors at the LHC

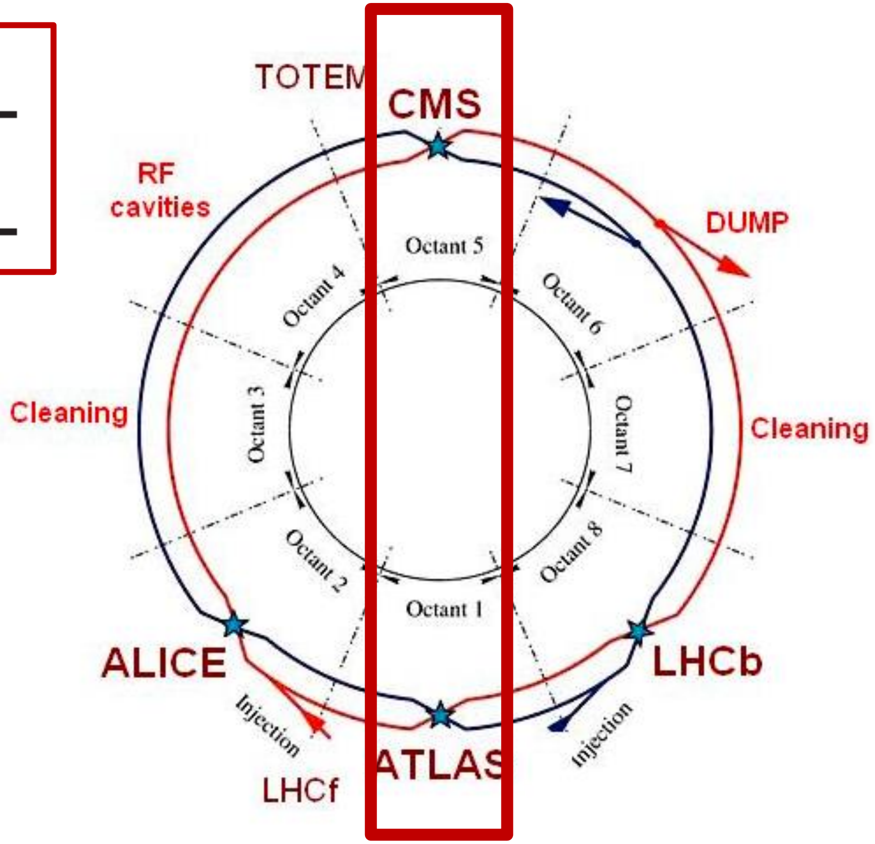
- Two interaction points (CMS / ATLAS) are equipped with forward neutron / proton detectors at about 140 m / 220 m from the IP, respectively on both sides.



Interaction point 1or 5
(ATLAS or CMS)

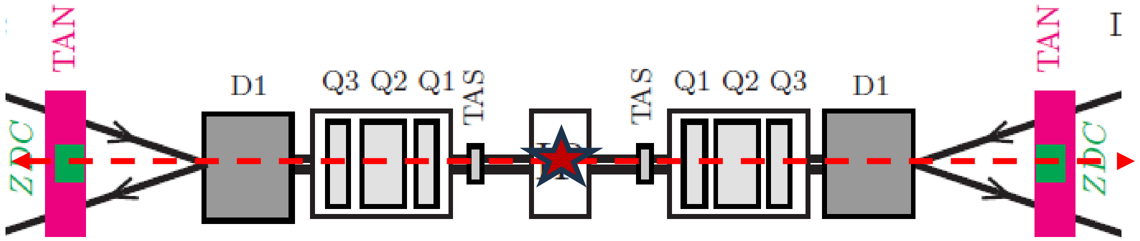
Neutron detectors ~140m
(Zero Degree Calorimeter)

Proton detectors ~220m
(Forward Proton Spectrometer)



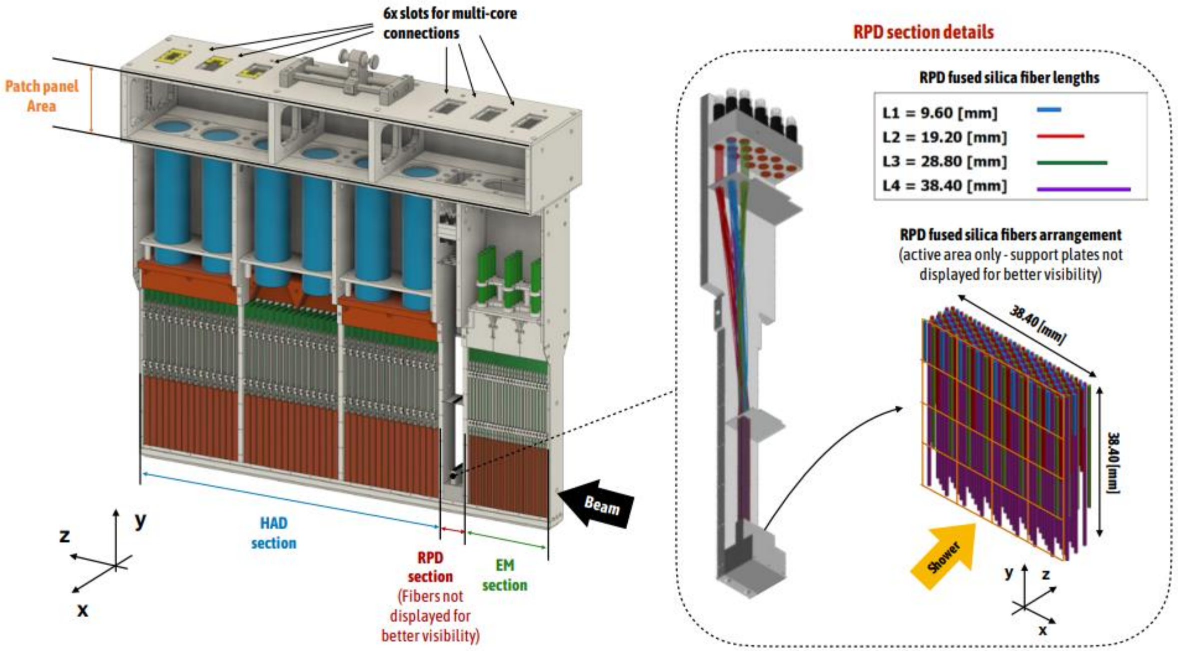
Forward neutron detectors

- 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 ($\xi = \Delta p_Z/p$) and are scattered at small angles (θ_x^*, θ_y^*) → they are deflected away from the beam and measured by the spectrometers

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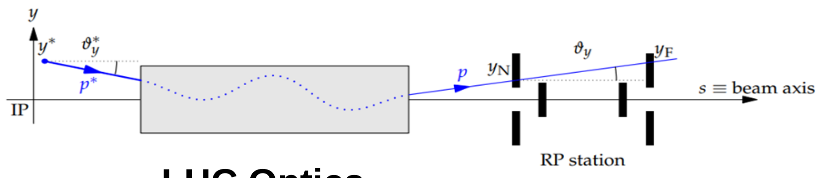
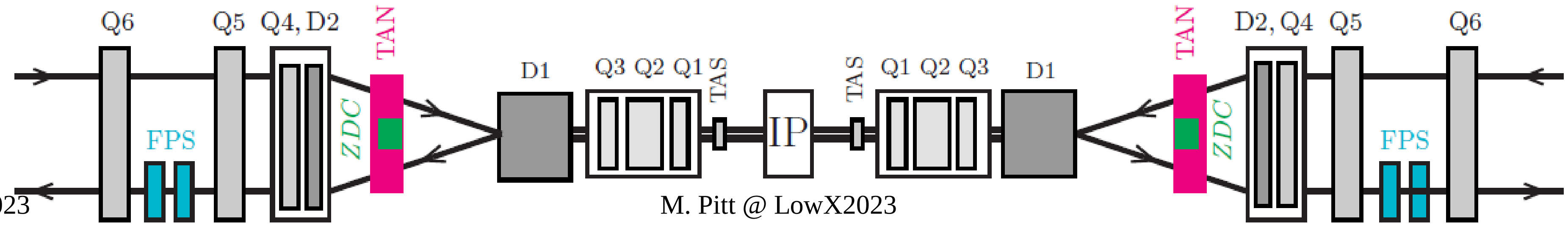


LHC Optics



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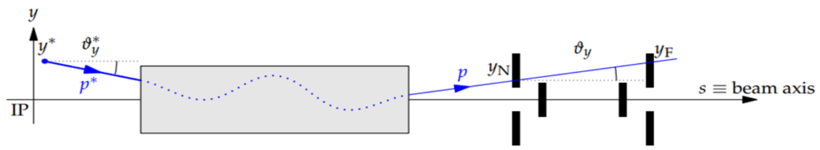

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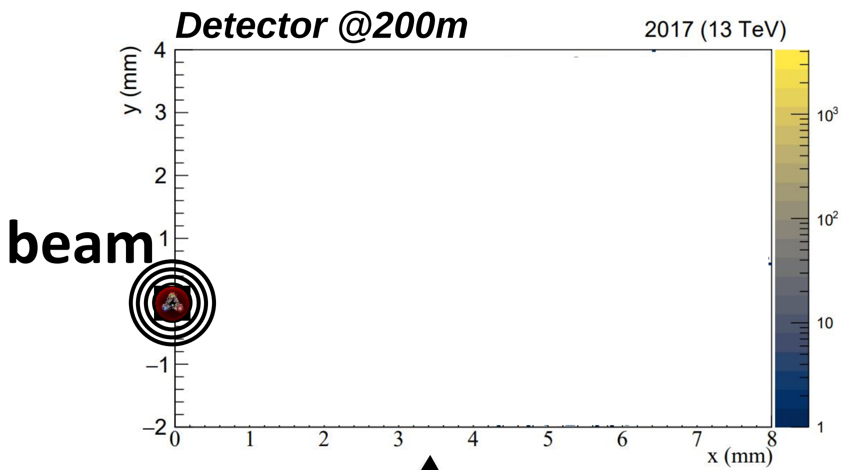

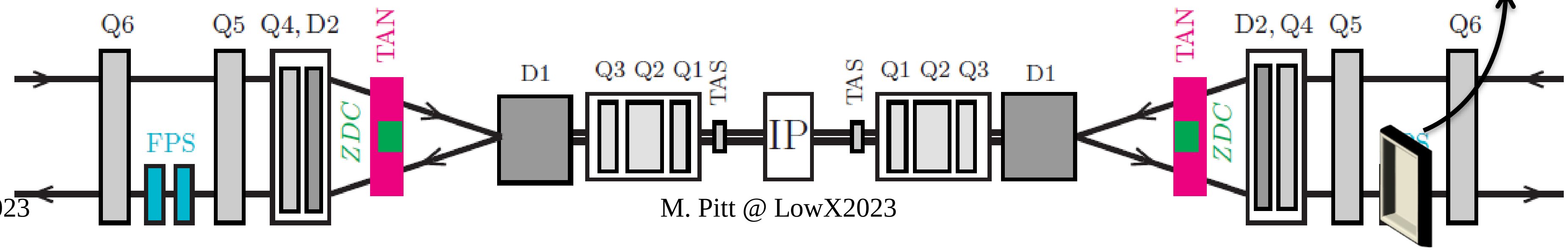

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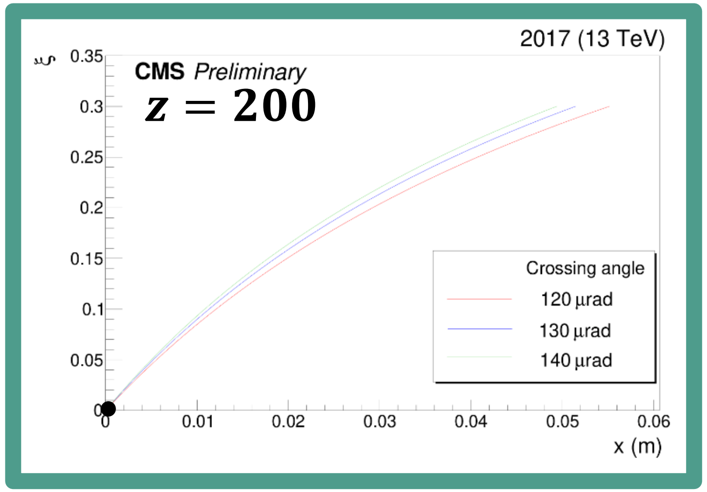

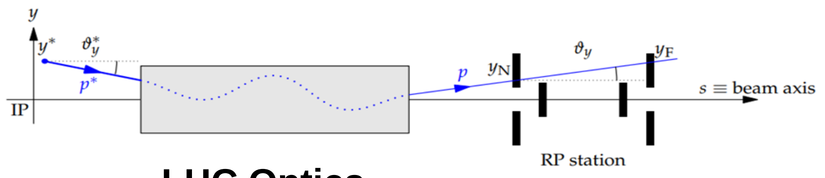

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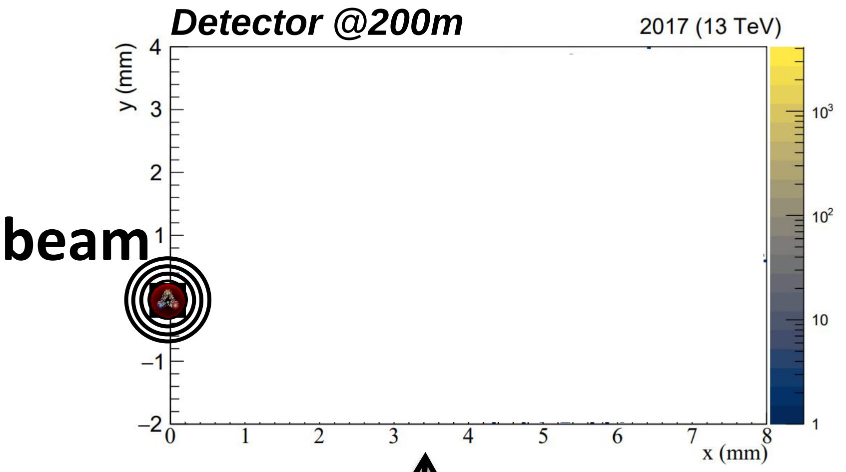

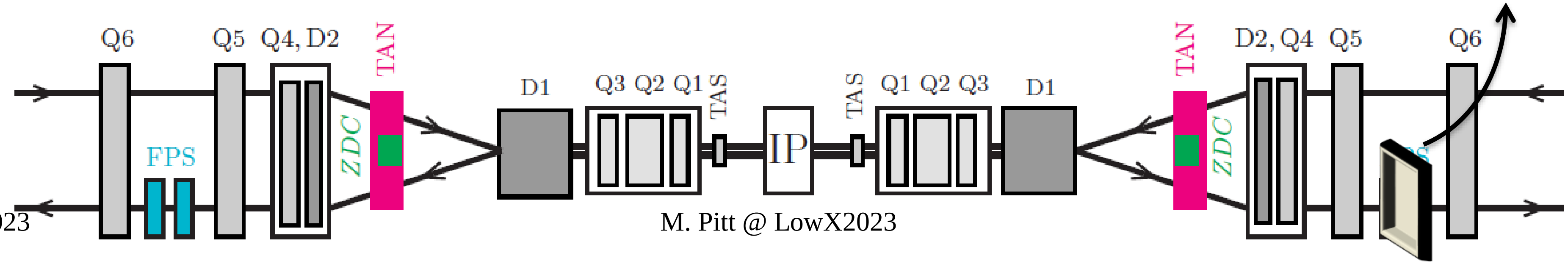

Forward proton detectors

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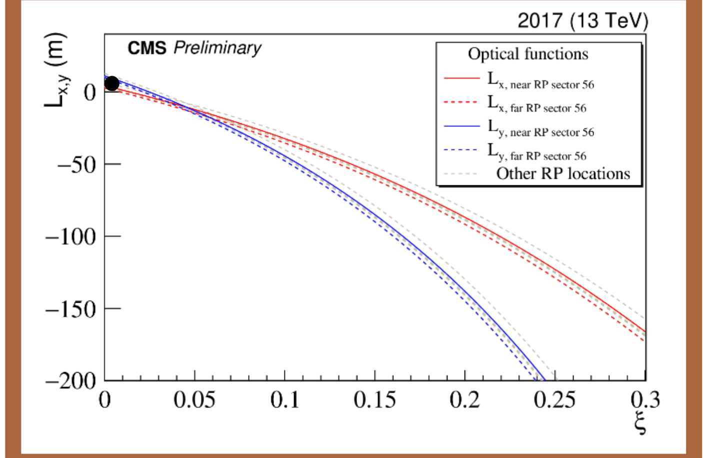

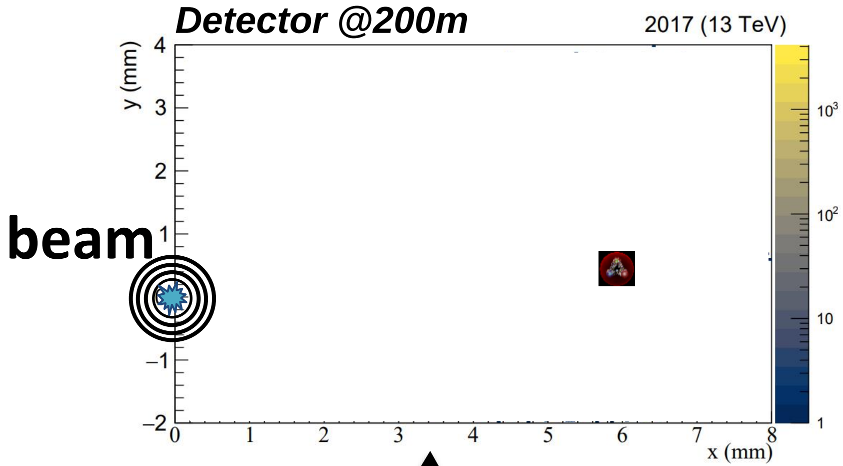

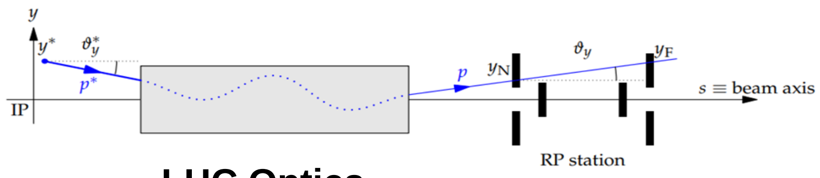

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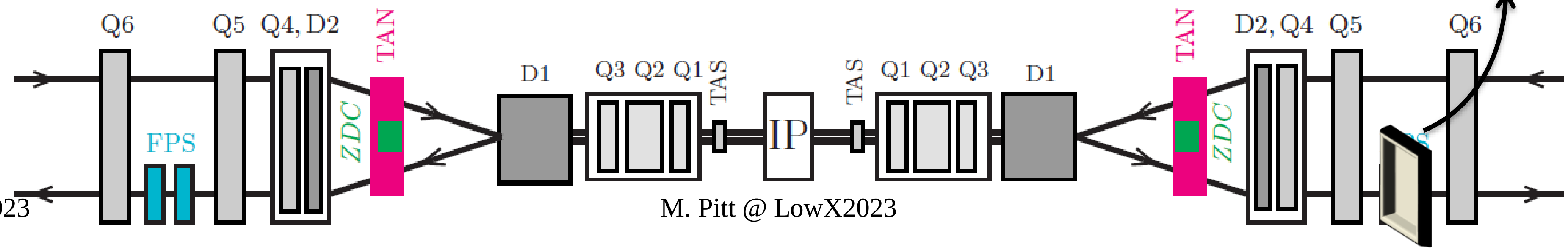

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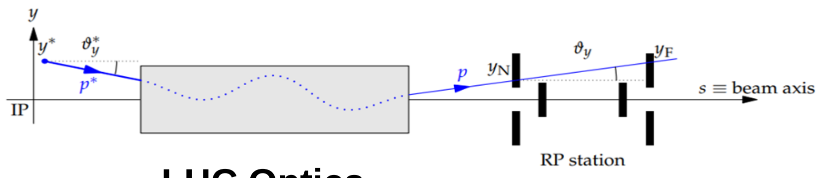
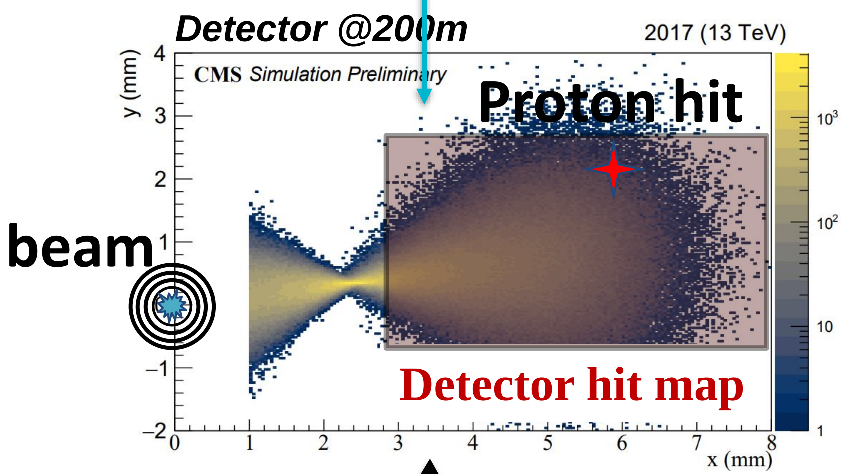


LHC Optics

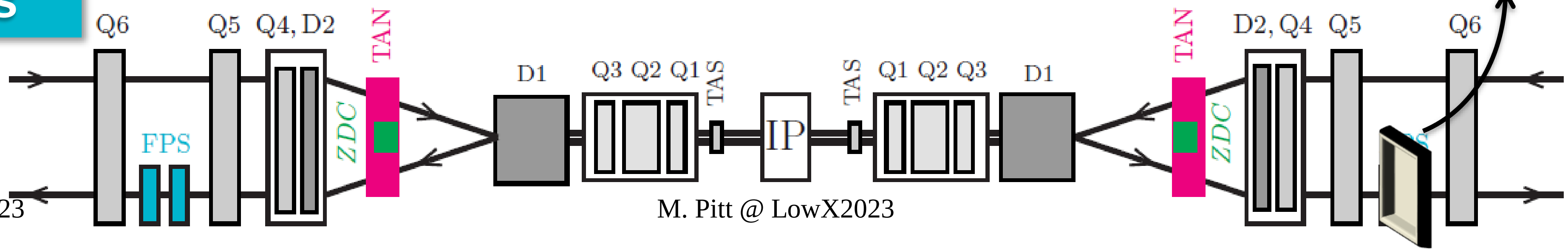
acceptance
2.5% < ξ < 15%

min distance from the beam

Collimators



2 stations



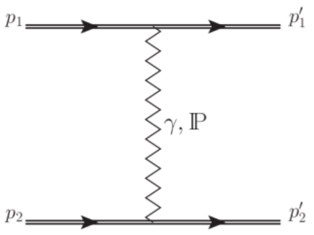
Diffraction in pp collisions with tagged protons

In collaboration with Cristian Baldenegro, Andrea Bellora, Chrostophe Royon

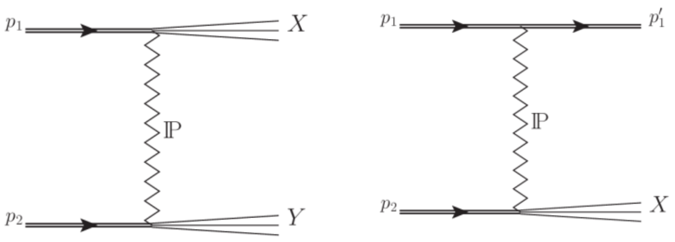
Motivation

Diffractive processes in pp collisions at the LHC

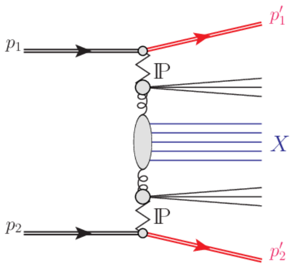
- t-channel exchange of color neutral particles (QED, QCD)



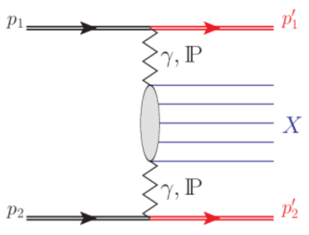
Elastic scattering



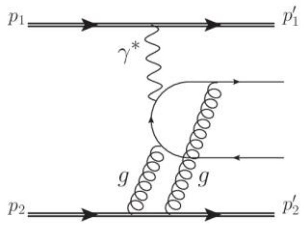
Single/double diffractive dissociation



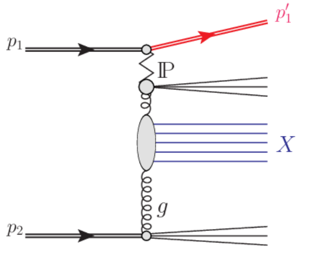
Double pomeron exchange



Central exclusive production



Exclusive photoproduction



Single-diffraction with central system

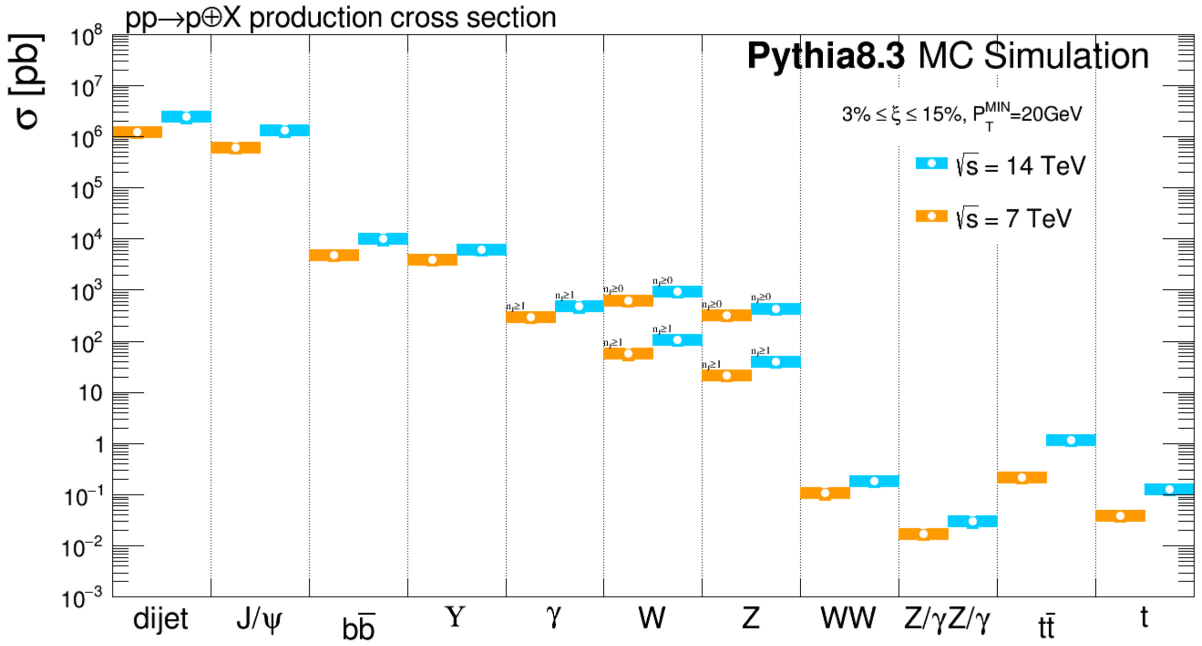
- Spans over large kinematic region (MeV – TeV), and large cross-section range
- Provide a rich scientific program for LHC experiments
- Sometimes protons loose substantial fraction (~ a few%) of their kinetic energy but emerge intact

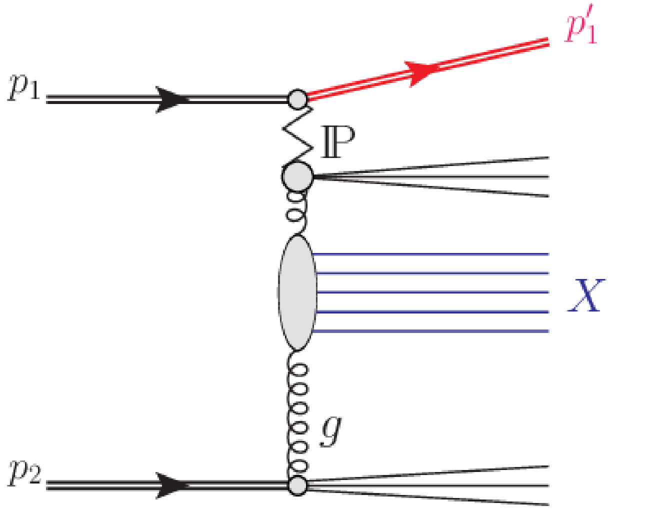
  – **Hard diffraction with forward protons**

Single diffraction with tagged proton

Single diffraction (SD) with high mass central system

- Production of hard process + a diffractive proton
- Hard SD events comprise up to a few % of the inclusive σ
- Could have impact in precision measurement at the HL-LHC



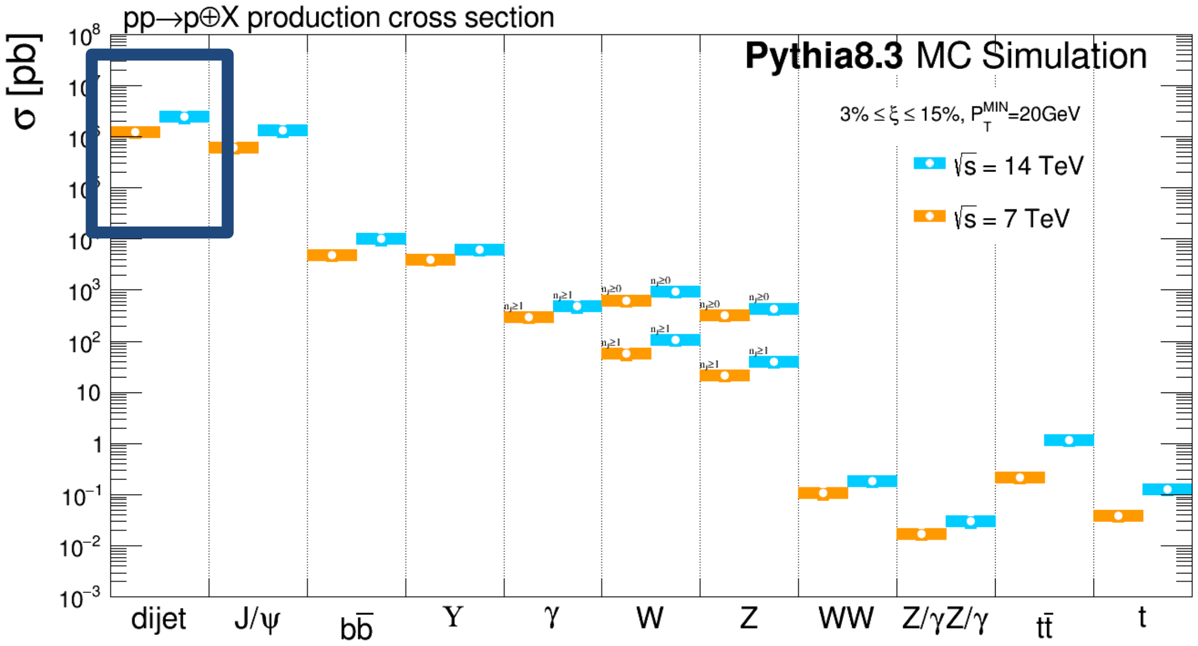


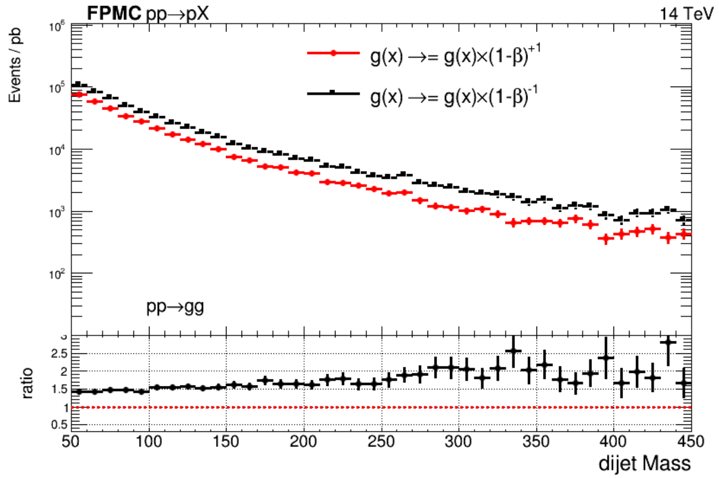
Large fraction of SM processes are accessible by the LHC experiments

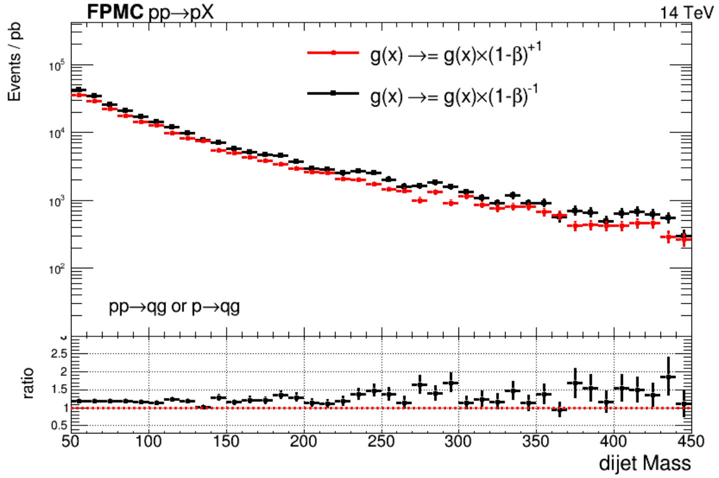
Single diffraction with tagged proton

Single diffraction (SD) – djets

- The highest cross-section (~nb)
- Sufficient statistics to measure survival probabilities
- Using gluon/quark tagging gluon contribution to structure functions can be probed at high x



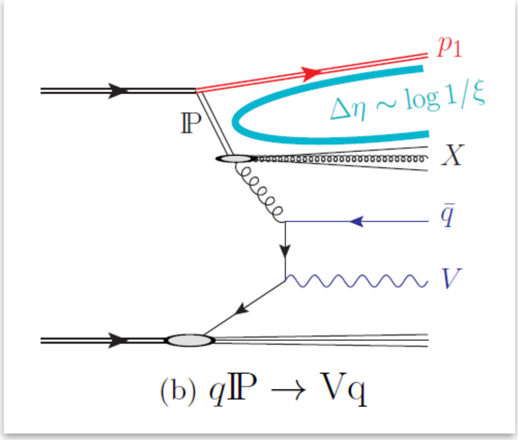




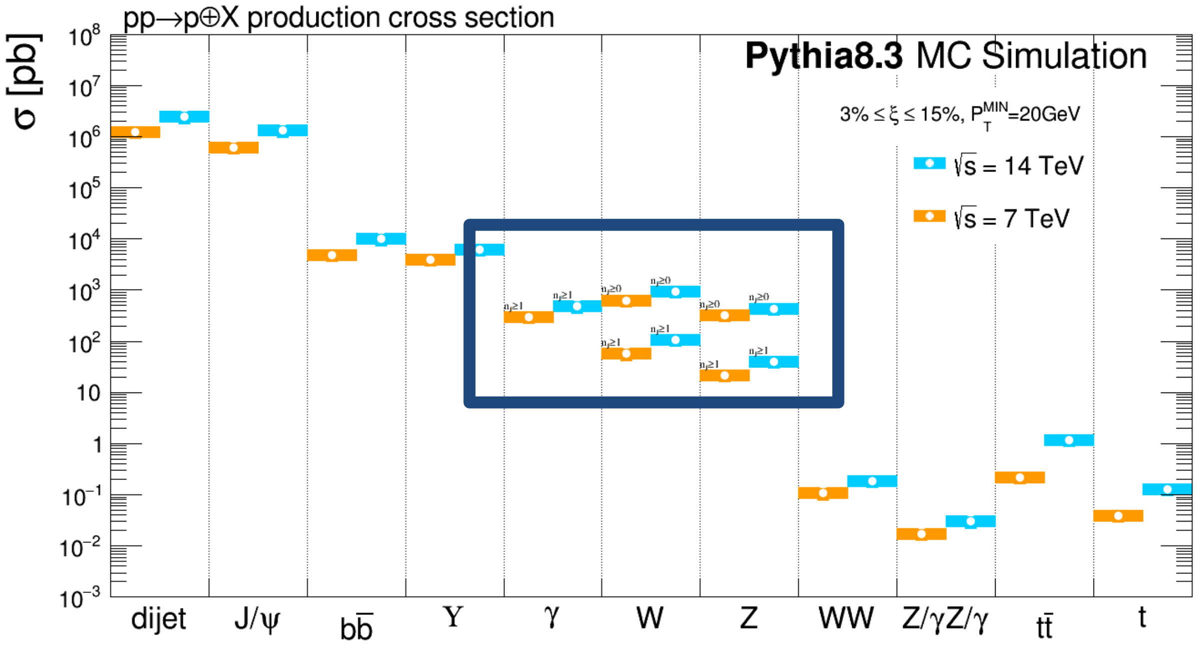
Single diffraction with tagged proton

Single diffraction (SD) – V+jets

- Z/W+jet diffractive production, with q/g/c tagging
- Charge asymmetry in diffractive W production
- photon+jet can be used to probe quark content of dPDF



(b) $q\mathbb{P} \rightarrow$ Vq



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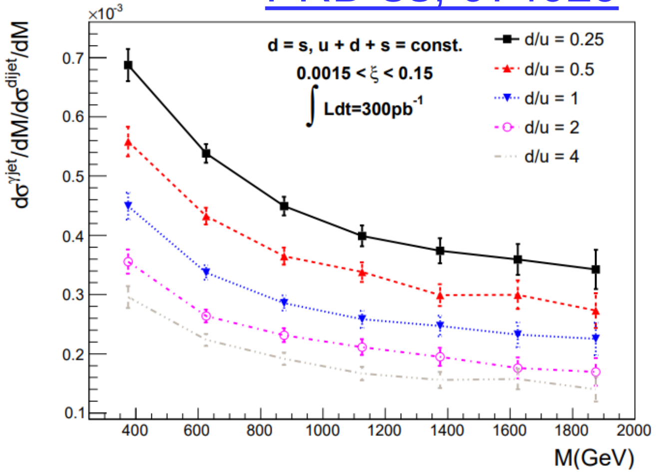
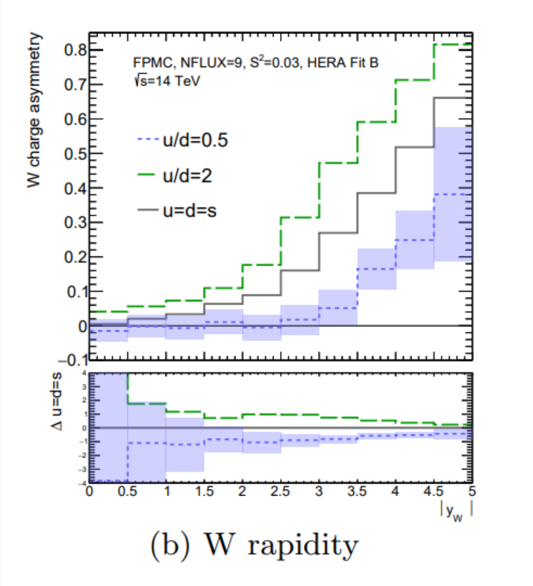




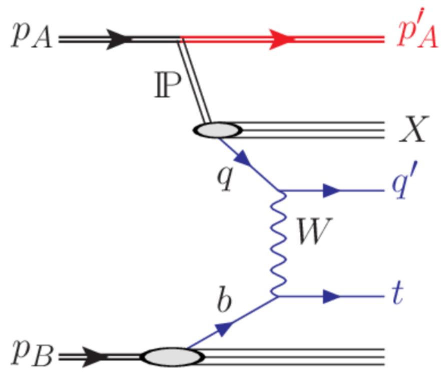
(b) W rapidity

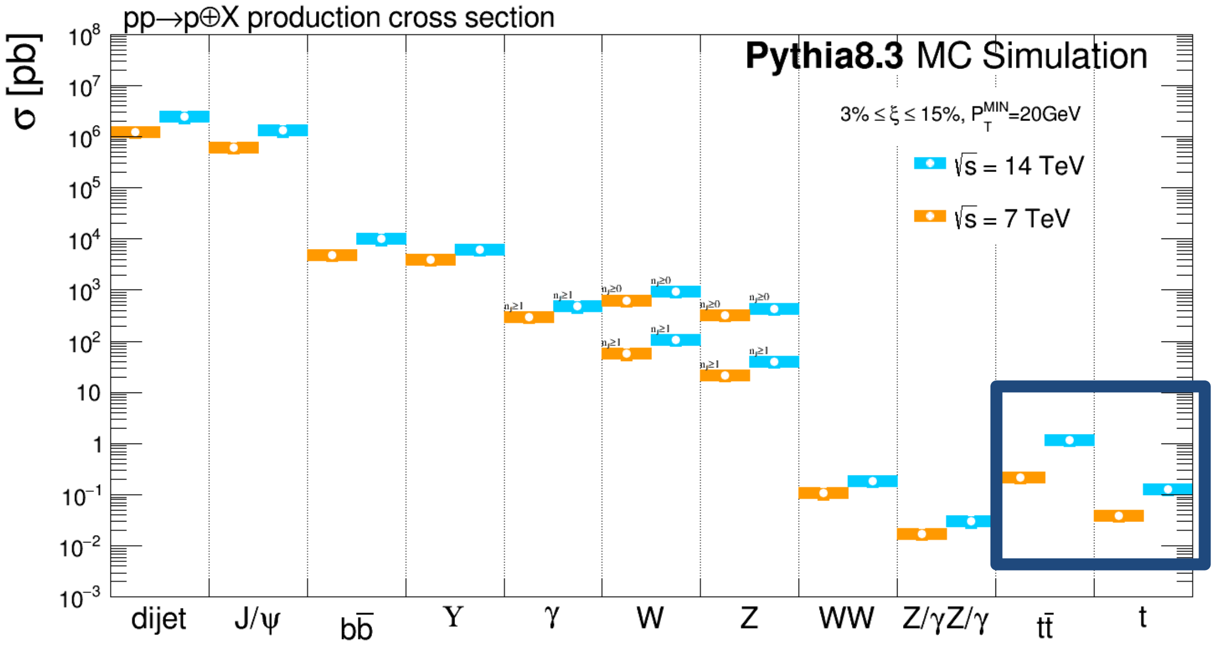
JHEP04(2016)092

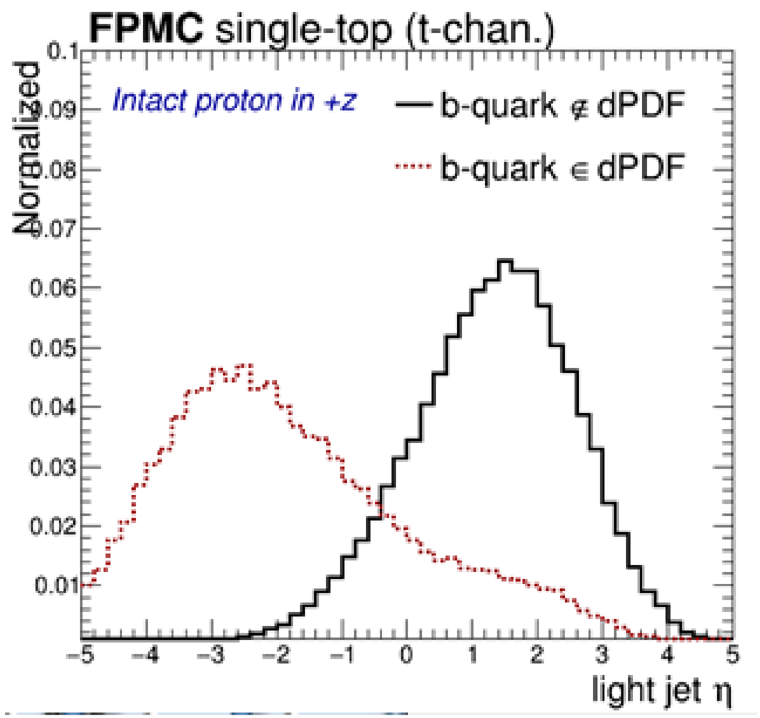
Single diffraction with tagged proton

Single diffraction (SD) – top(s)

- Cross-section is estimated to be of the order of a few pb
- Single-top sensitive to dPDF(b) assume to be zero / not constrained.
- Large asymmetry in the light jet kinematic







Single diffraction with tagged proton

Timing detectors with single diffractive events

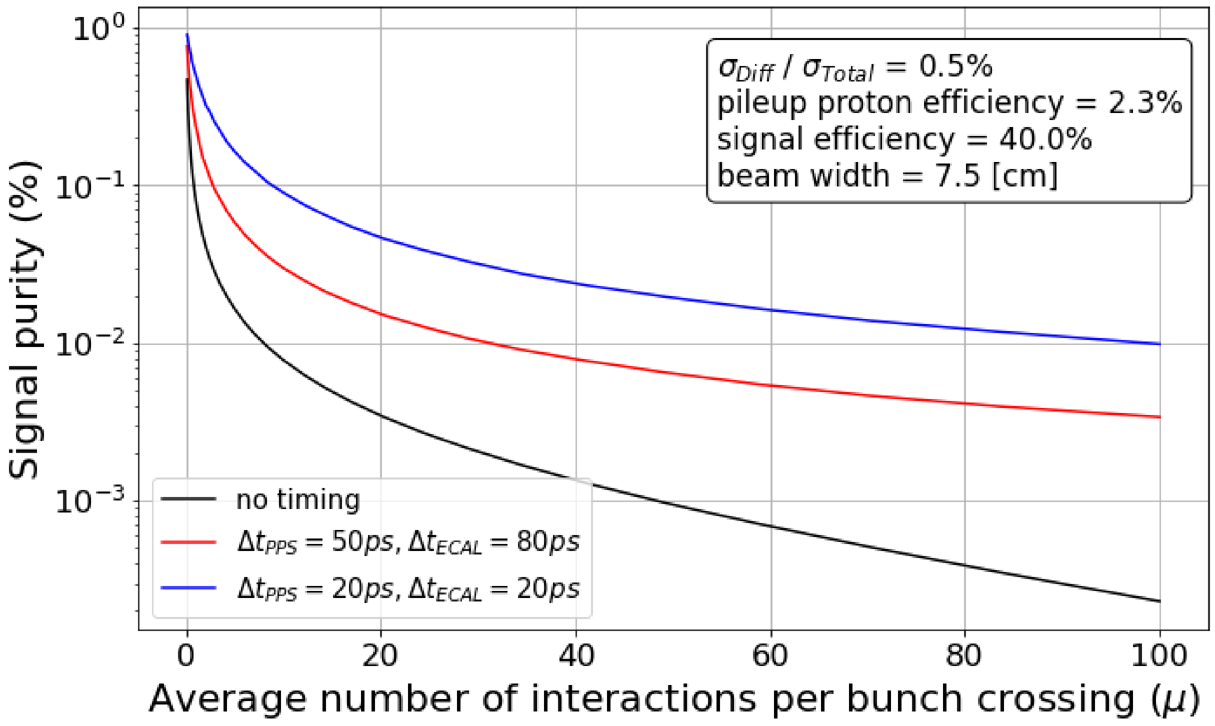
- 0.5% diffractive component is enhanced using time correlation
- Timing detectors can improve background rejection for any single tagged events*

Example from CMS in Run 2:

- Forward detectors $\sigma \sim 90ps$
- Central ECAL, neighboring crystals $\sigma > 100\ ps$

Run 4:

- Central detector resolution expected to improve well bellow 50ps
- Similar expectation from the forward detectors



Diffraction in pp collisions with tagged neutrons

Motivation

- Measurement of very forward neutron energy spectra for $\sqrt{s} = 7$ TeV proton–proton collisions at the Large Hadron Collider (*PLB 750 (2015) 360-366*)
- Measurement of inclusive forward neutron production cross section in proton-proton collisions at $\sqrt{s} = 13$ TeV with the LHCf Arm2 detector (*JHEP 11 (2018) 073*)

A B S T R A C T

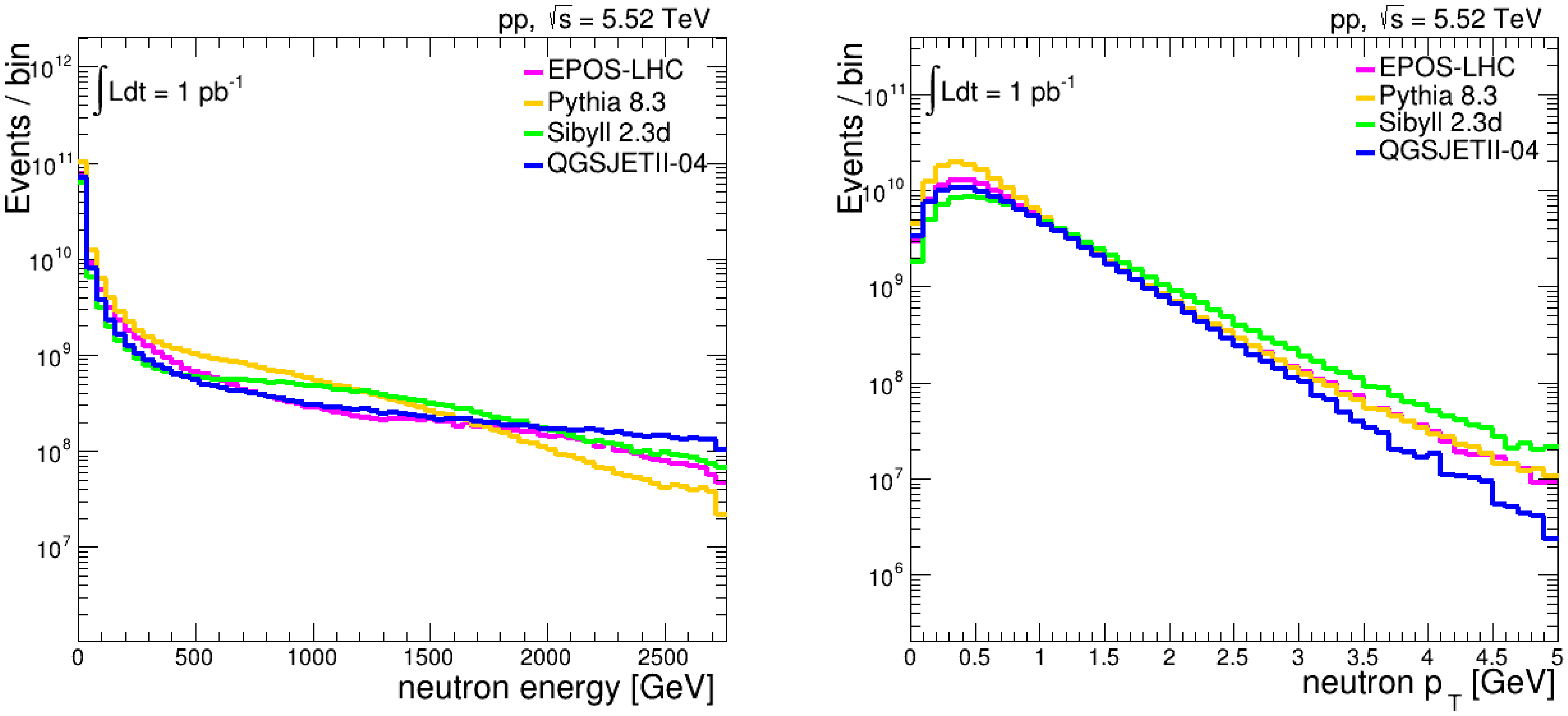
The Large Hadron Collider forward (LHCf) experiment is designed to use the LHC to verify the hadronic-interaction models used in cosmic-ray physics. Forward baryon production is one of the crucial points to understand the development of cosmic-ray showers. We report the neutron-energy spectra for LHC $\sqrt{s} = 7$ TeV proton–proton collisions with the pseudo-rapidity η ranging from 8.81 to 8.99, from 8.99 to 9.22, and from 10.76 to infinity. The measured energy spectra obtained from the two independent calorimeters of Arm1 and Arm2 show the same characteristic feature before unfolding the detector responses. We unfolded the measured spectra by using the multidimensional unfolding method based on Bayesian theory, and the unfolded spectra were compared with current hadronic-interaction models. The QGSJET II-03 model predicts a high neutron production rate at the highest pseudo-rapidity range similar to our results, and the DPMJET 3.04 model describes our results well at the lower pseudo-rapidity ranges. However, no model perfectly explains the experimental results over the entire pseudo-rapidity range. The experimental data indicate a more abundant neutron production rate relative to the photon production than any model predictions studied here.

ABSTRACT: In this paper, we report the measurement relative to the production of forward neutrons in proton-proton collisions at $\sqrt{s} = 13$ TeV obtained using the LHCf Arm2 detector at the Large Hadron Collider. The results for the inclusive differential production cross section are presented as a function of energy in three different pseudorapidity regions: $\eta > 10.76$, $8.99 < \eta < 9.22$ and $8.81 < \eta < 8.99$. The analysis was performed using a data set acquired in June 2015 that corresponds to an integrated luminosity of $0.194\ \text{nb}^{-1}$. The measurements were compared with the predictions of several hadronic interaction models used to simulate air showers generated by Ultra High Energy Cosmic Rays. None of these generators showed good agreement with the data for all pseudorapidity intervals. For $\eta > 10.76$, no model is able to reproduce the observed peak structure at around 5 TeV and all models underestimate the total production cross section: among them, QGSJET II-04 shows the smallest deficit with respect to data for the whole energy range. For $8.99 < \eta < 9.22$ and $8.81 < \eta < 8.99$, the models having the best overall agreement with data are SIBYLL 2.3 and EPOS-LHC, respectively: in particular, in both regions SIBYLL 2.3 is able to reproduce the observed peak structure at around 1.5–2.5 TeV.

Neutron tagging in pp collisions

MC simulation for 5.52 TeV data

- MC simulation for pp at 5.52TeV, with inclusive selection (no cuts)



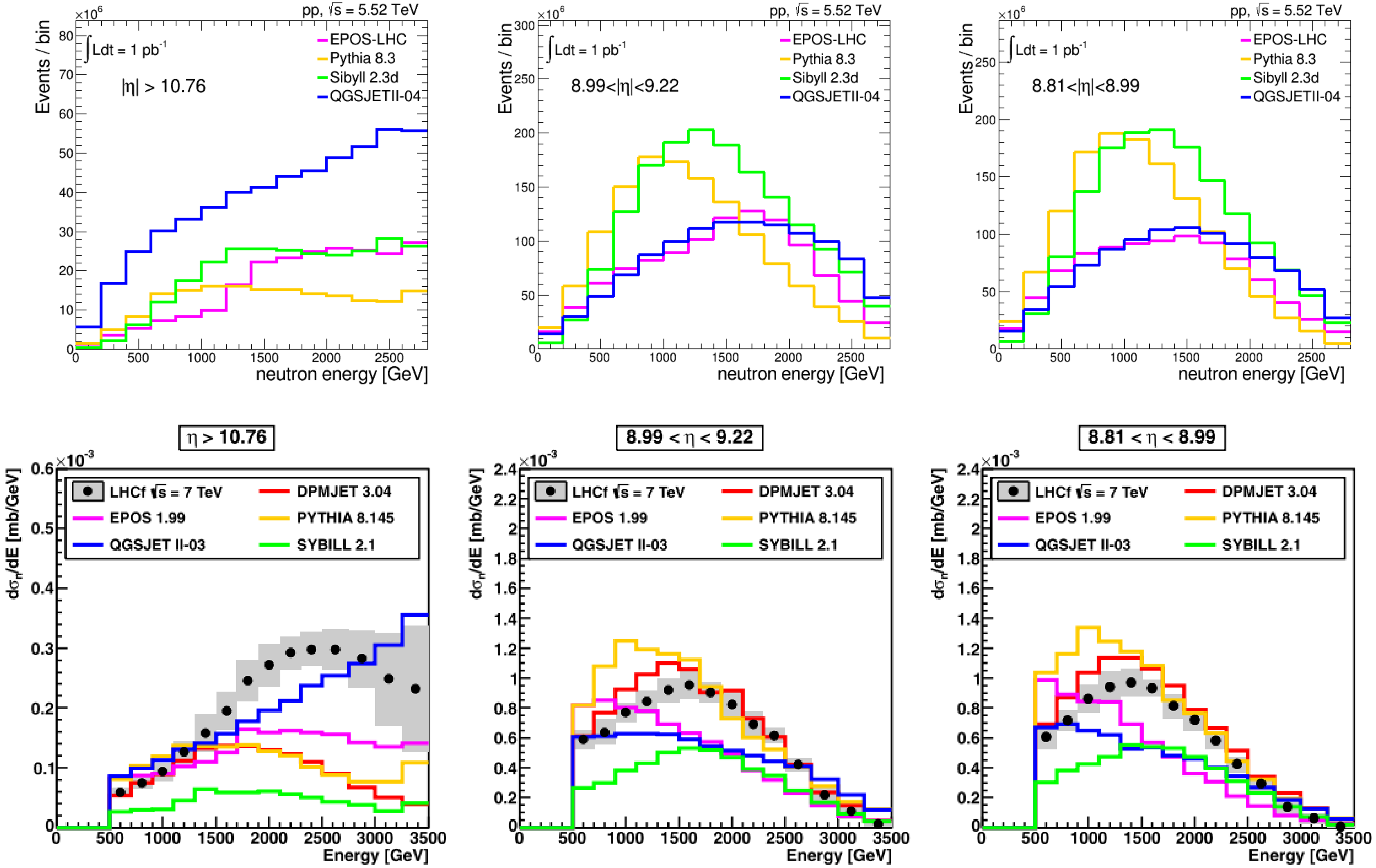
Neutron tagging in pp collisions

Don't match LHCf preselection

Don't expect large difference between 7 and 5.5 TeV

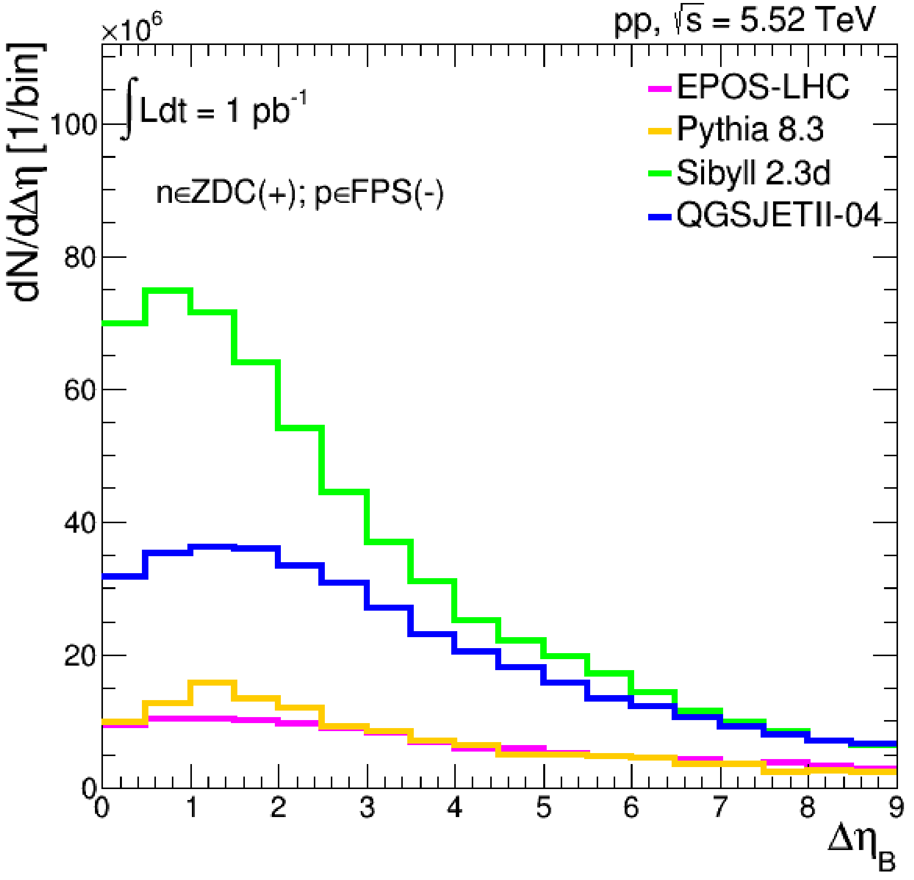
Different predictions among the models with 5.52TeV data

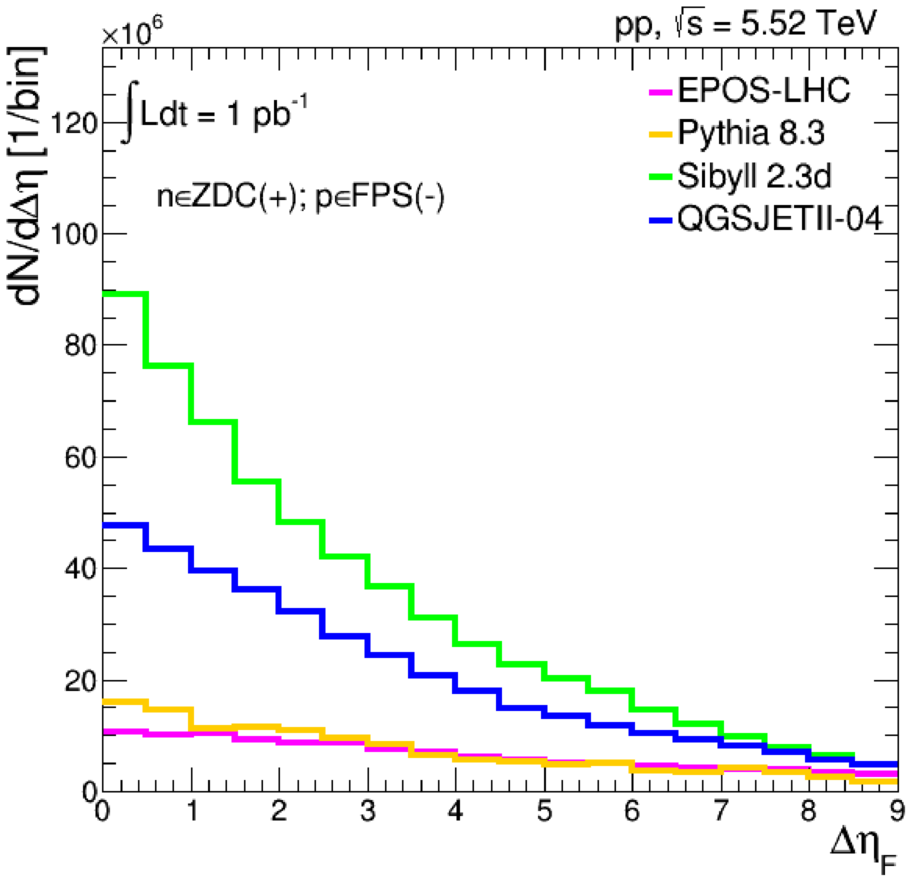
Need to project for RPD acceptance



adding proton tagging

- Compare rapidity gaps in forward / background regions
- Proton and neutron in FPS and ADC acceptance respectively





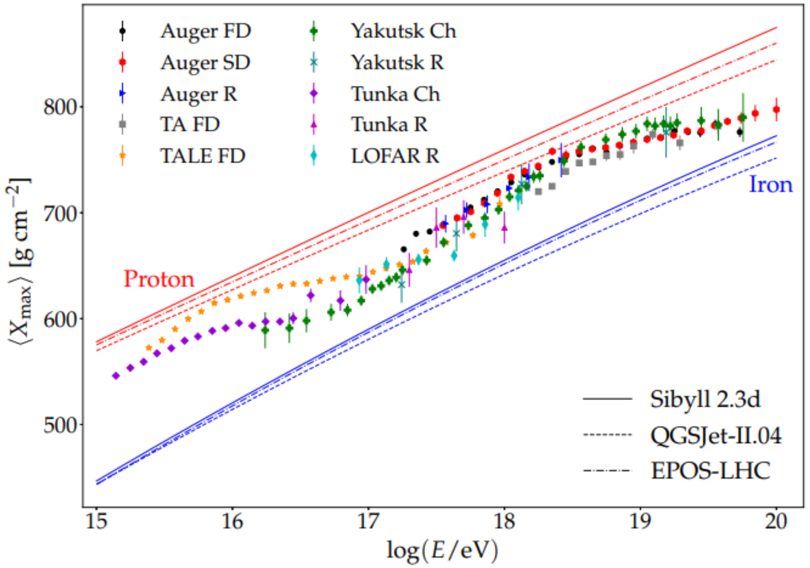
Constraining models of hadronic showers using pO collisions

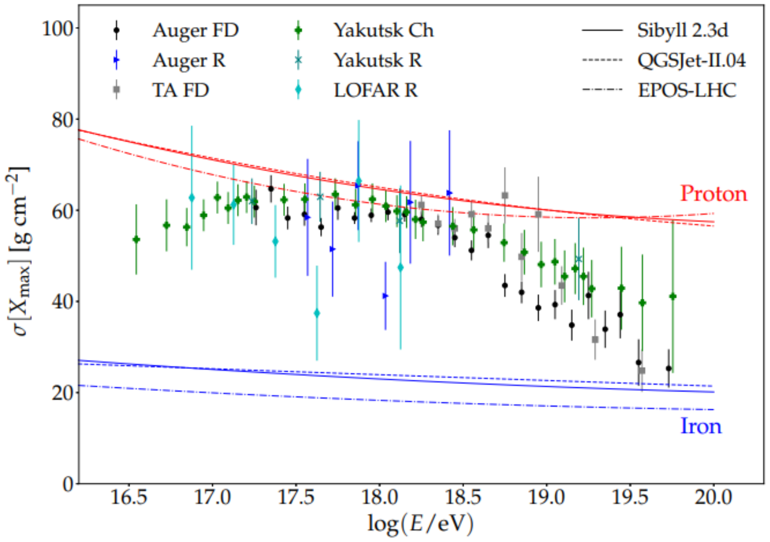
PoS ICRC2023 (426)

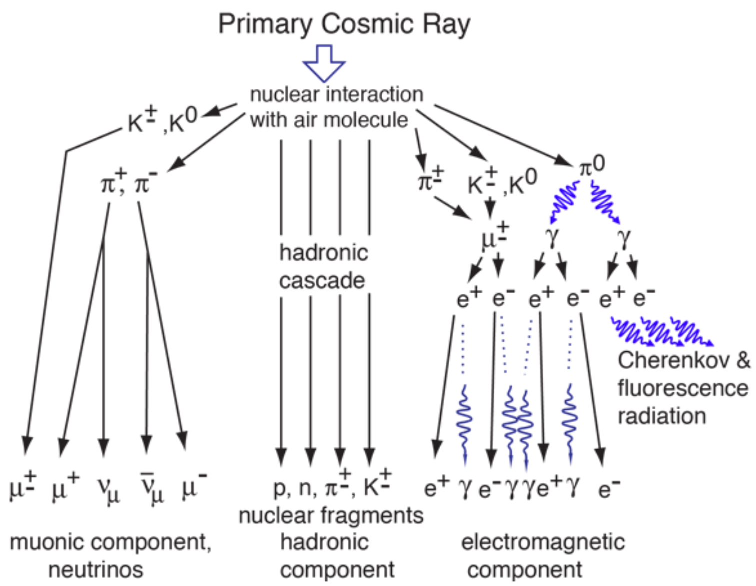
Motivation

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







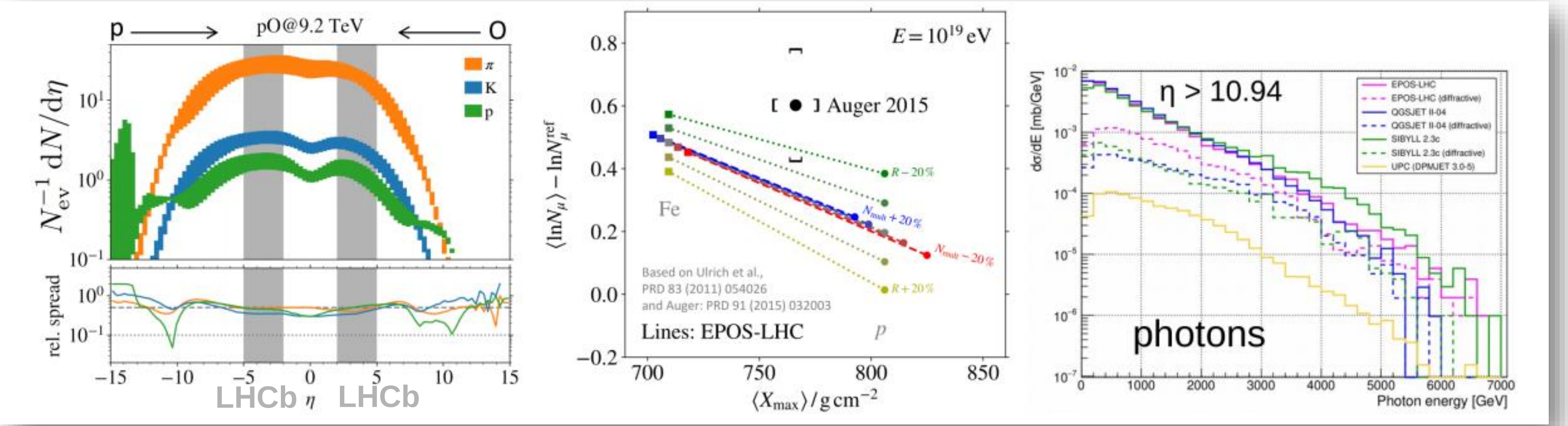
A. D. Supanitsky Galaxies 10 (2022) 3, 75

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

Constrain hadronic models with pO collisions

Opportunities of OO and pO collisions at the LHC

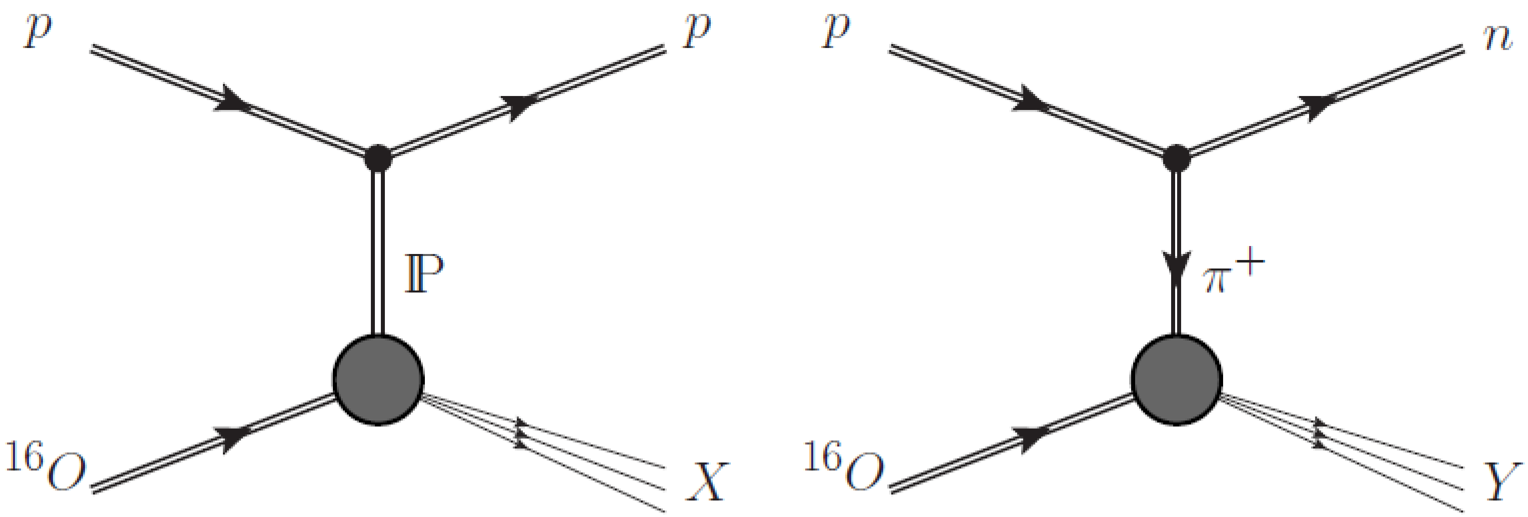
- Discussed in 2021 at a dedicated workshop at CERN (http://cern.ch/OppOatLHC)
- Summary available here 2103.01939



Constrain hadronic models with pO collisions

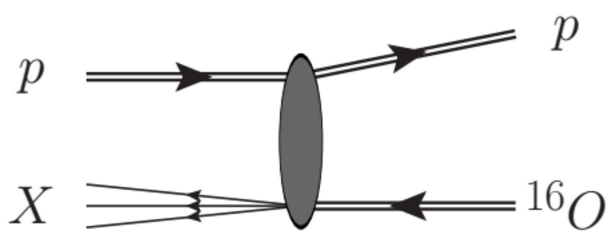
Extending current research program

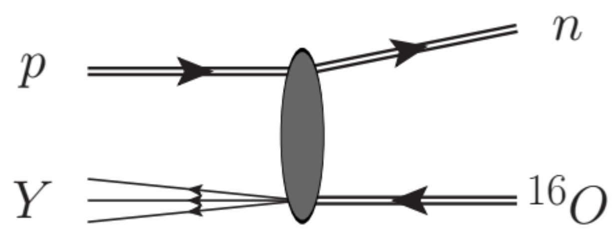
- Besides the standard research program involving pO / OO interactions, we suggest utilizing the forward proton and forward neutron detectors to expand the probed phase-space (this talk)



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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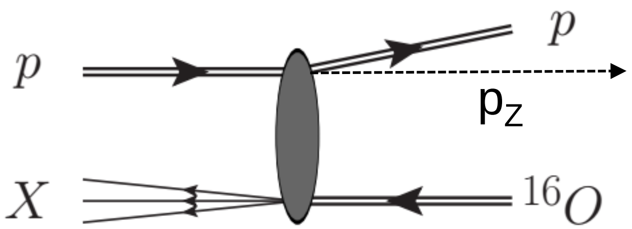

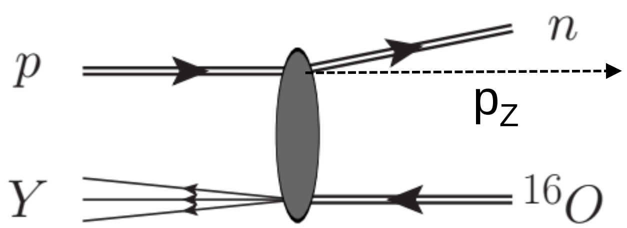

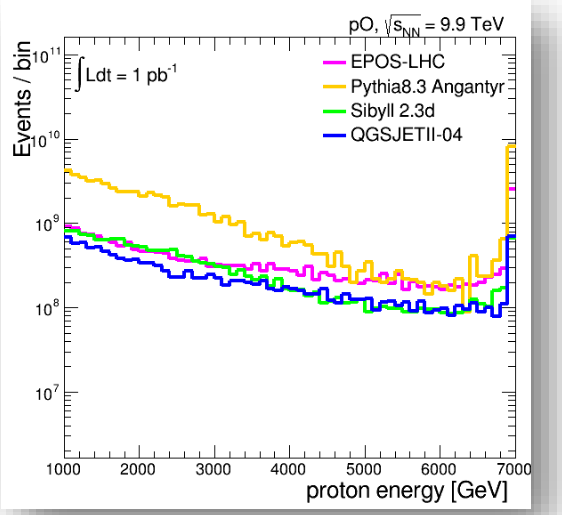

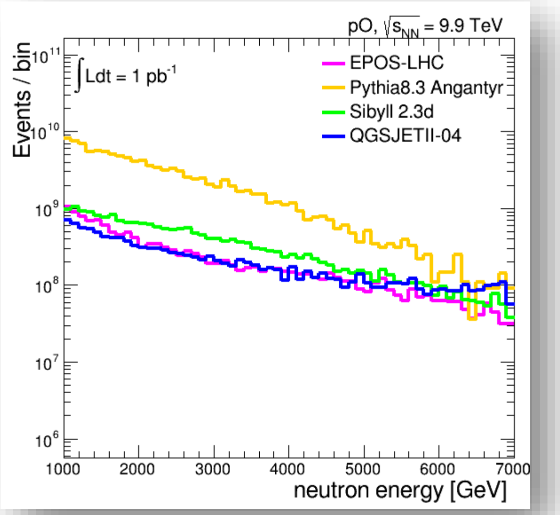

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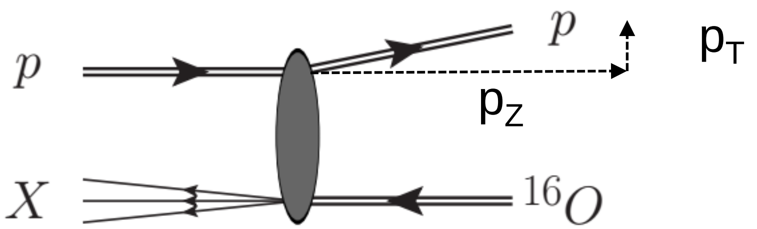
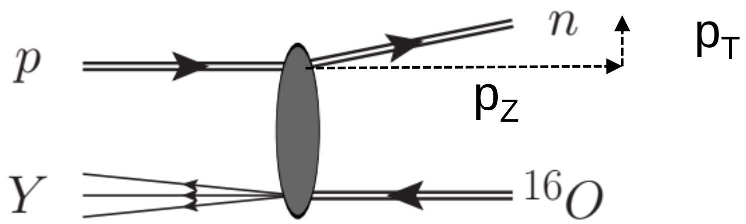
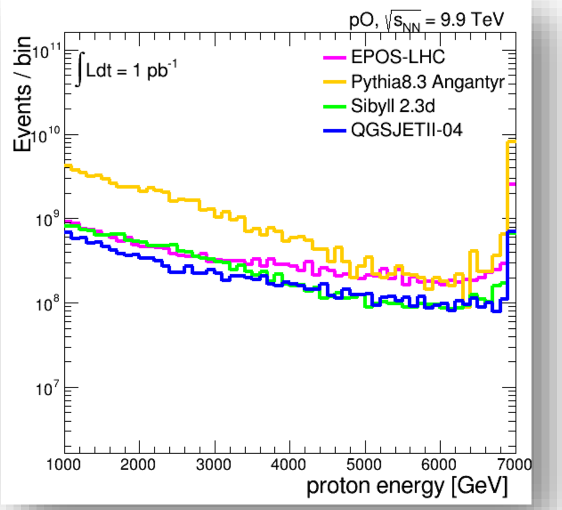
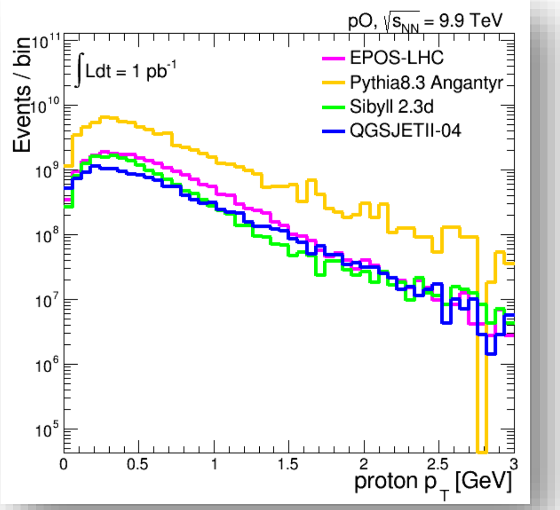
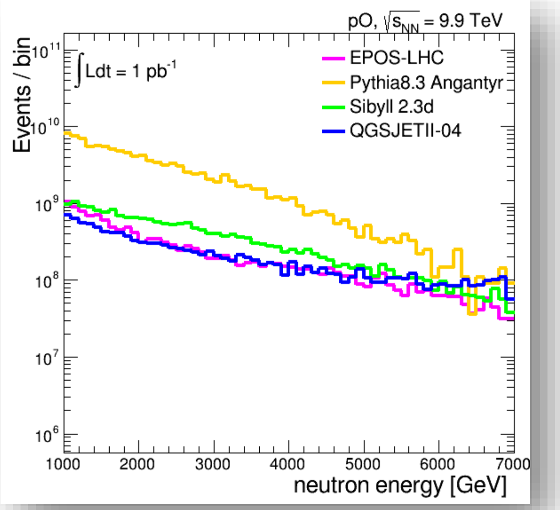
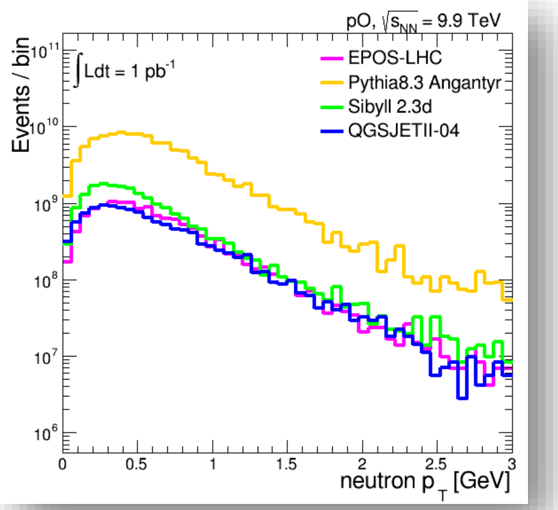




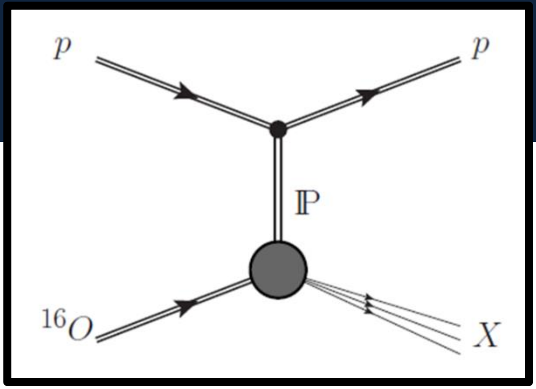




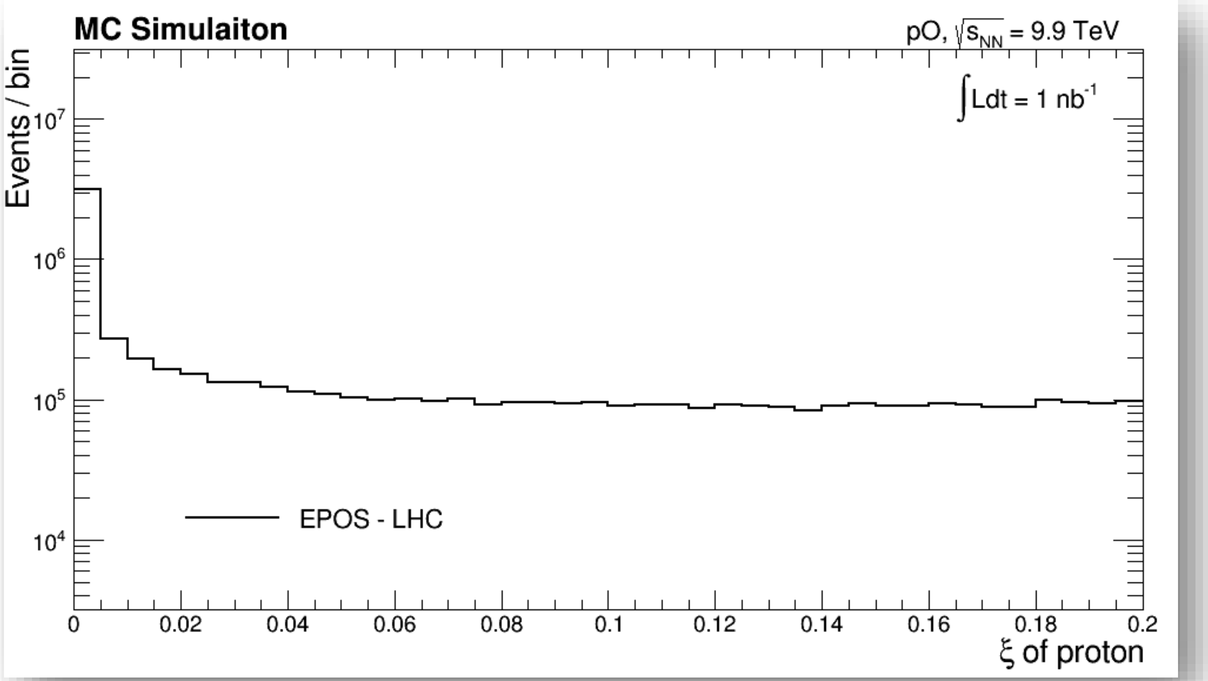


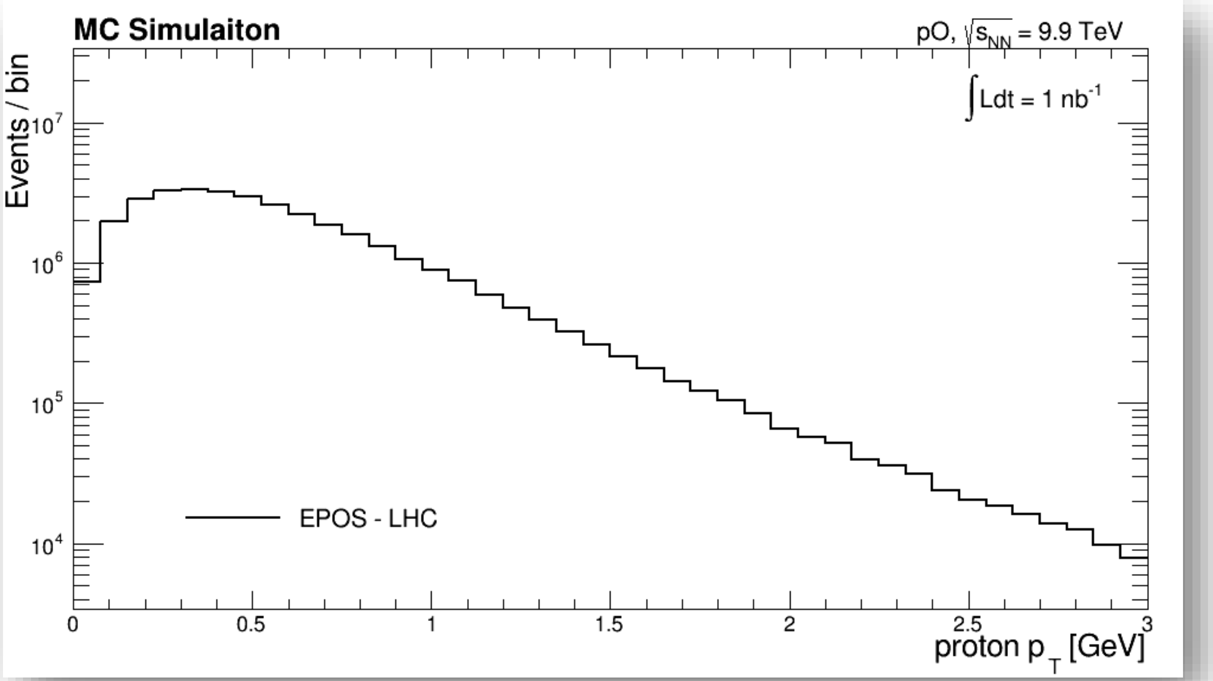


Proton kinematics



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





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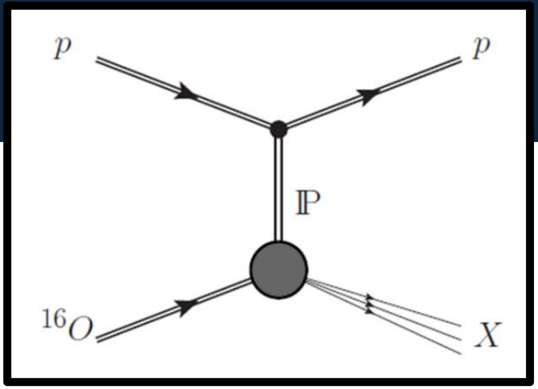

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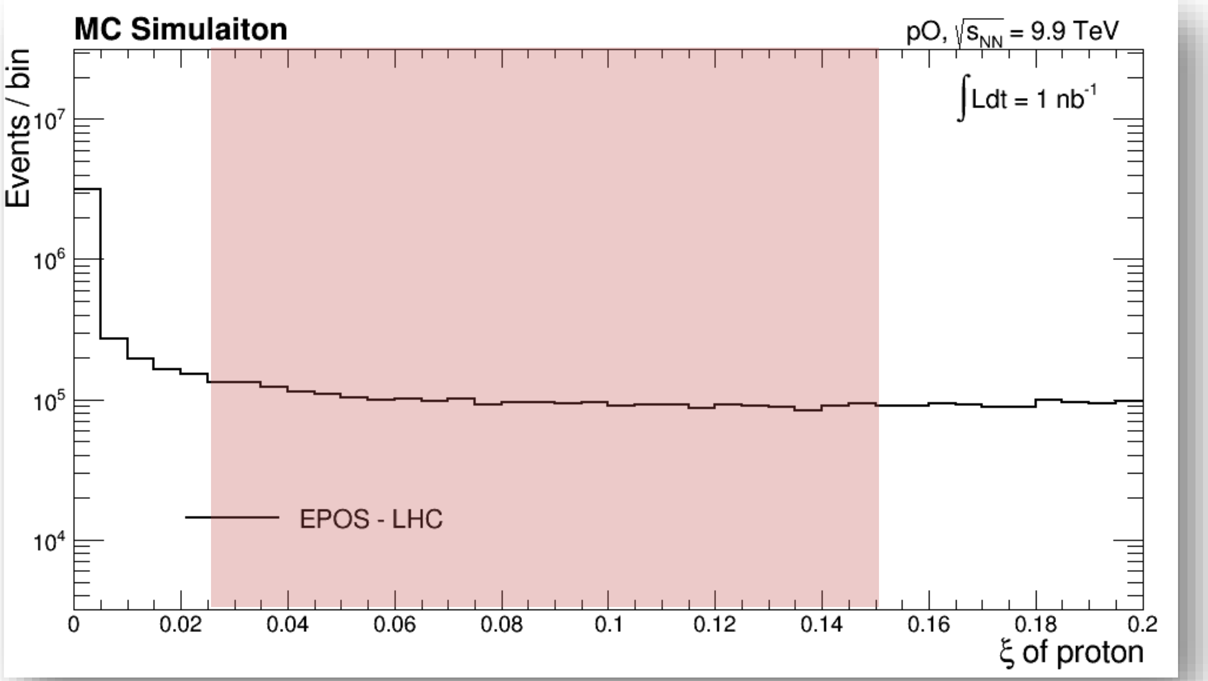
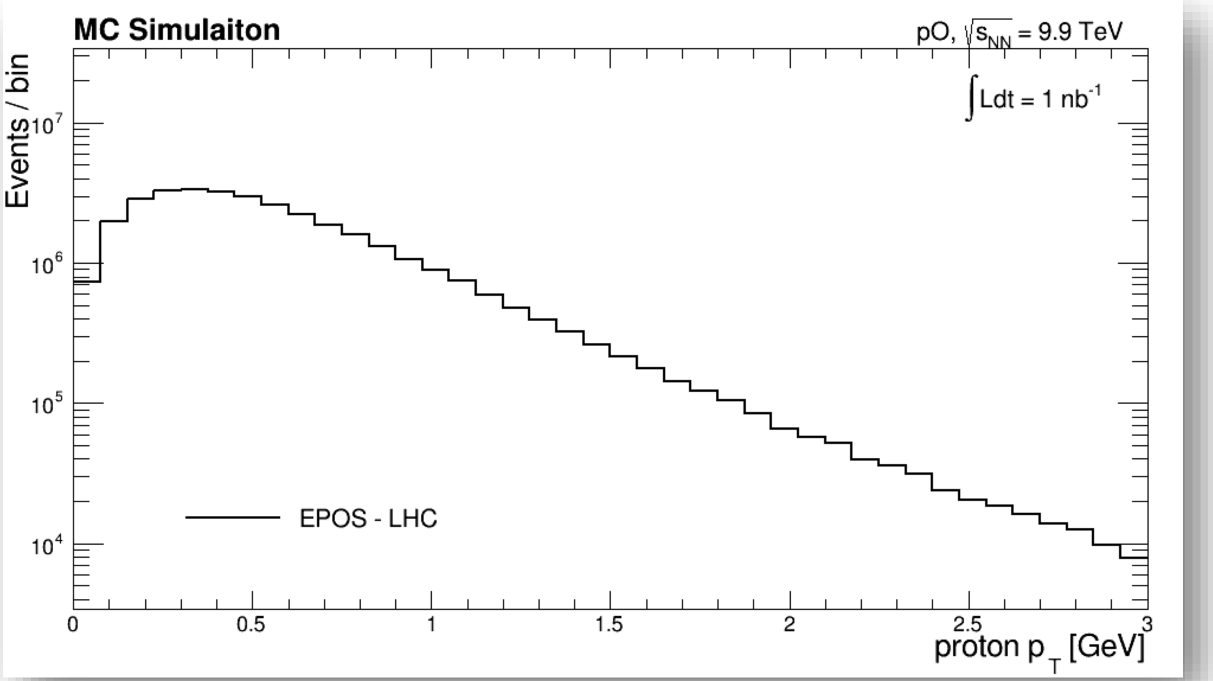
- In 2-4% of all events proton momentum loss is within 2.5% < ξ < 15%





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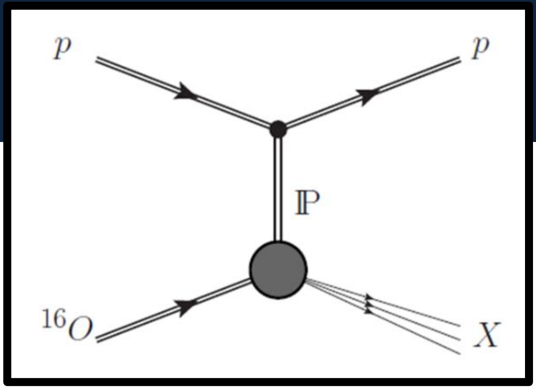
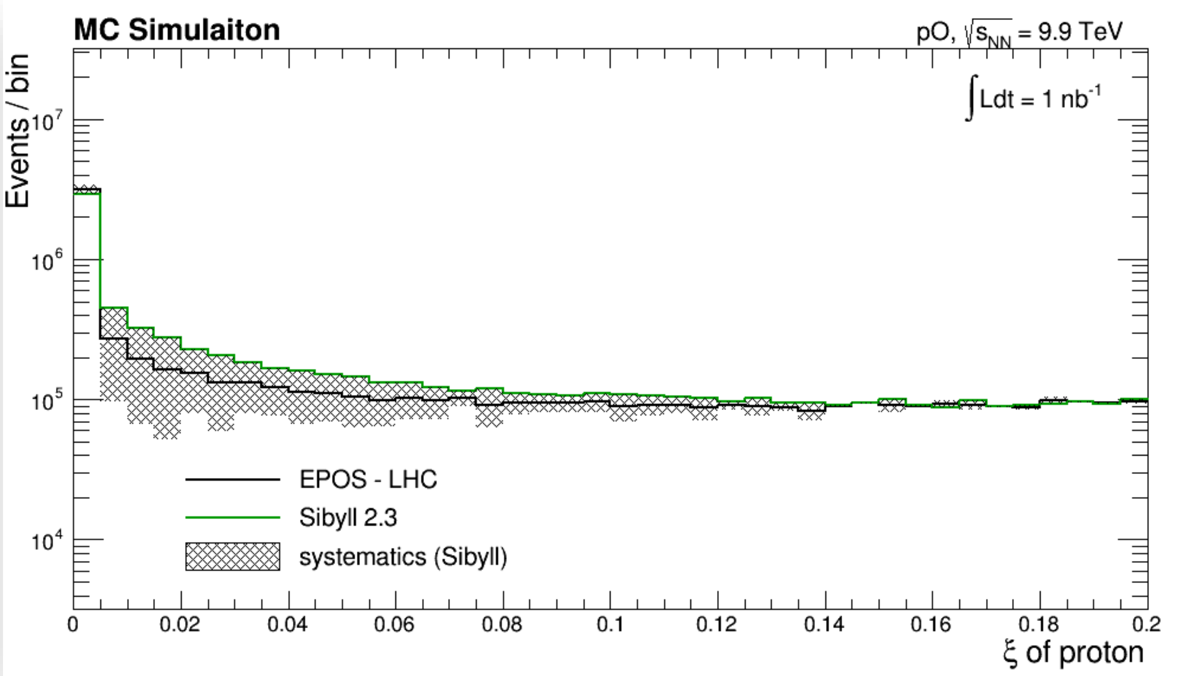
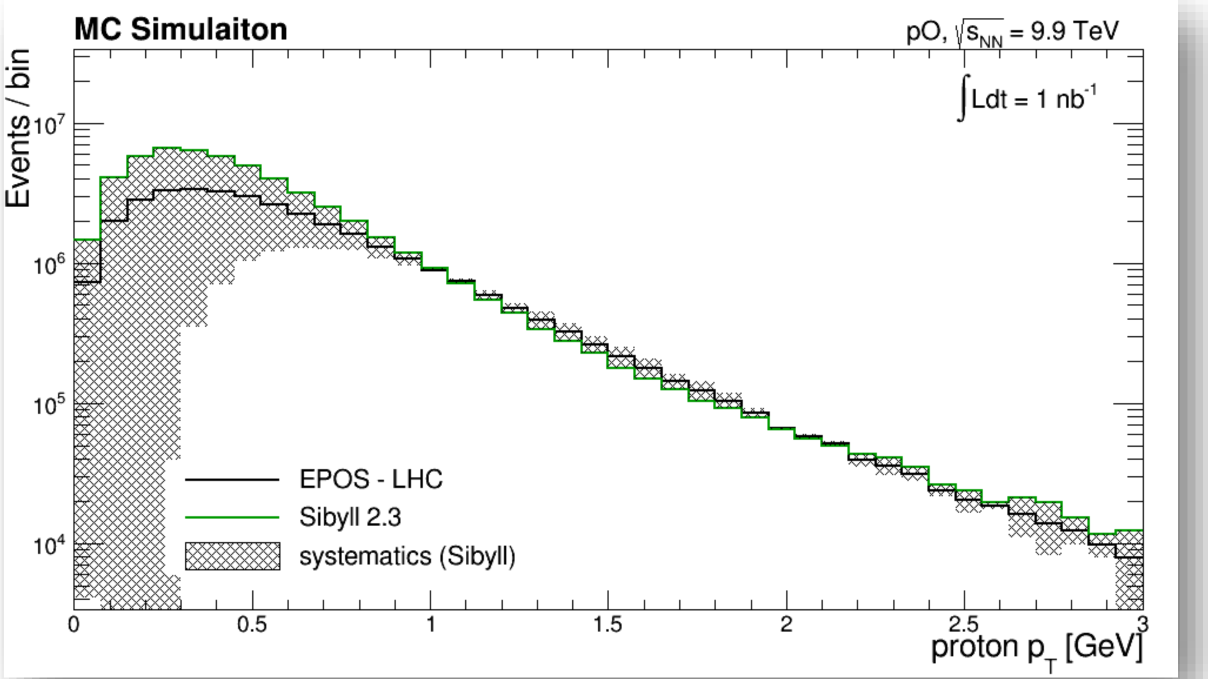


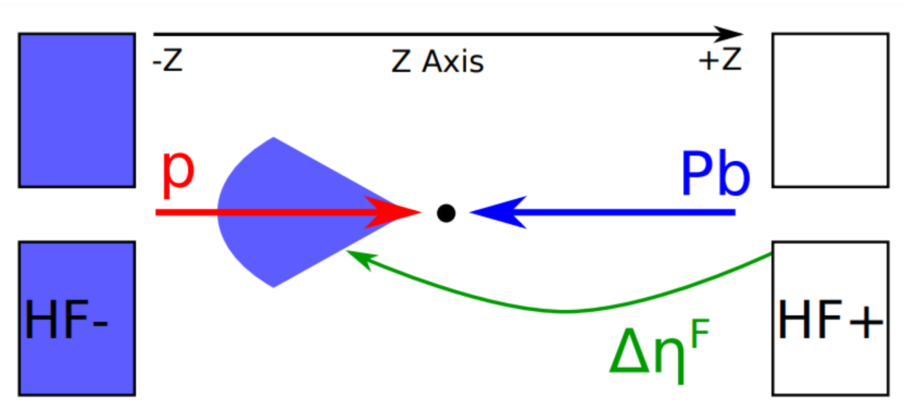
- About ~20% of p-O interactions will have an intact proton (ξ ~ inelasticity K)
- In 2-4% of <u>all events</u> proton momentum loss is within $2.5\% < \xi < 15\%$
- Comparison between EPOS-LHC and Sibyll2.3 – some difference between the generators

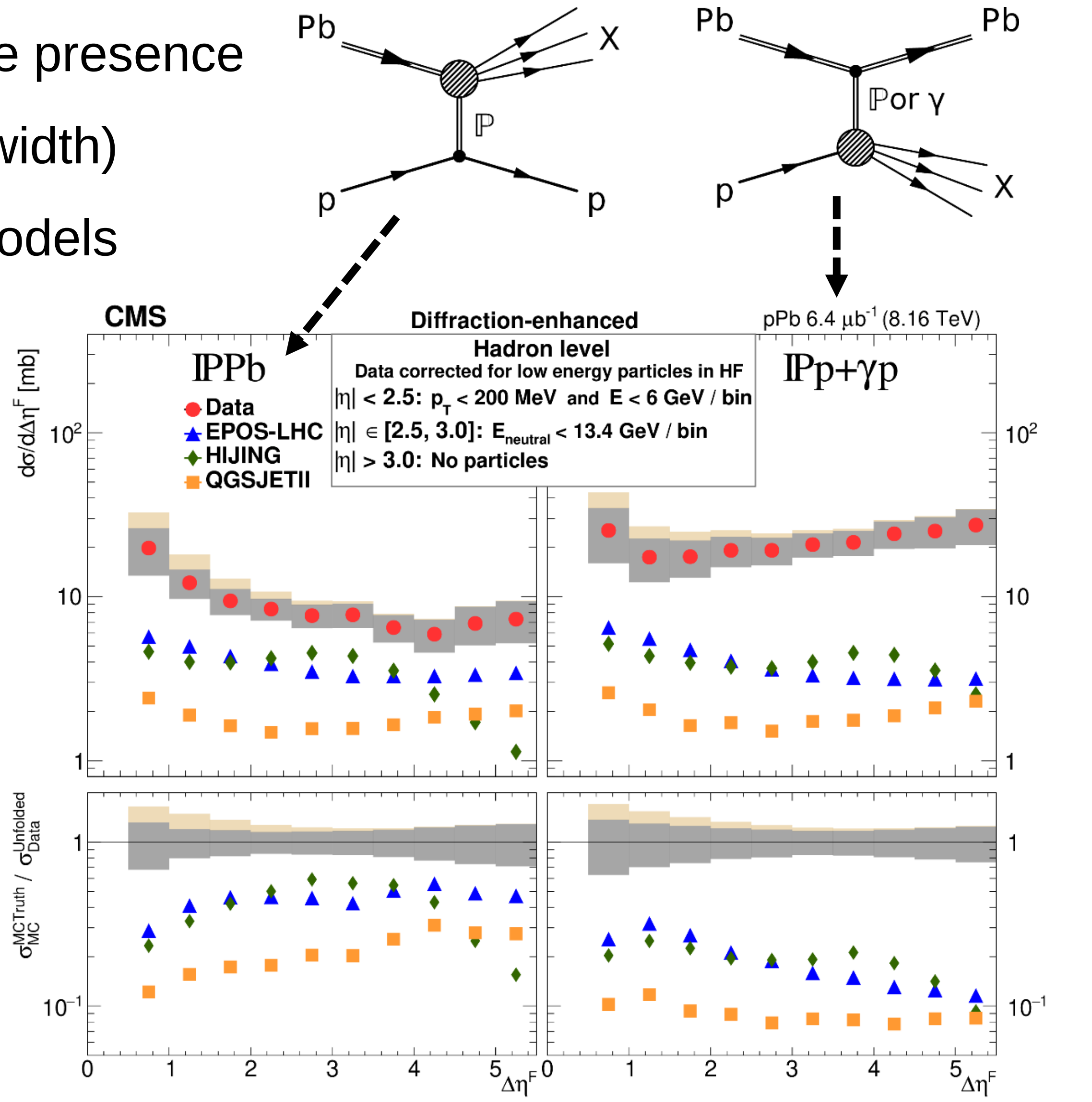




Rapidity gaps in color neutral exchange

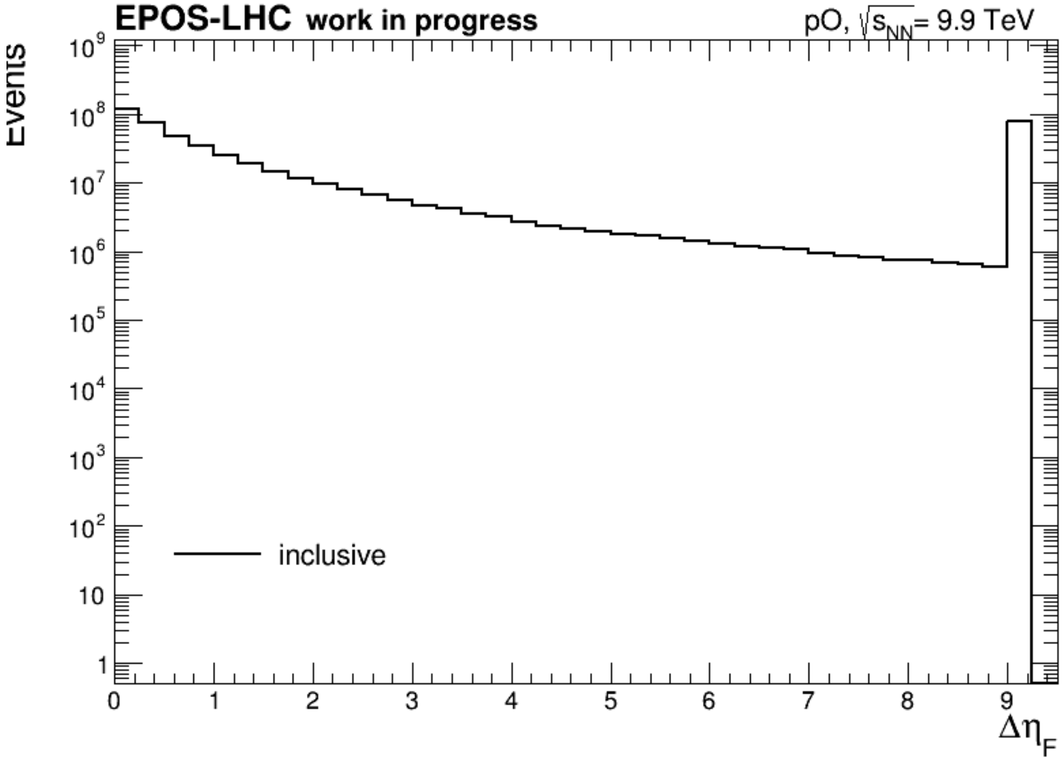
- Events with a diffractive proton are characterized by the presence of large Rapidity Gaps (RG) (~ relative to the shower width)
- This component is weakly constrained in the current models (example from CMS pPb data arXiv:2301.07630)





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



GAP := P_T > 1 GeV, with |η|<4.5

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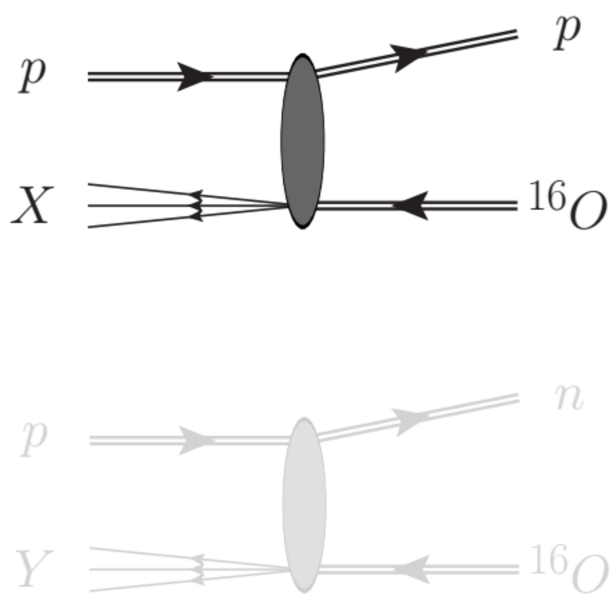

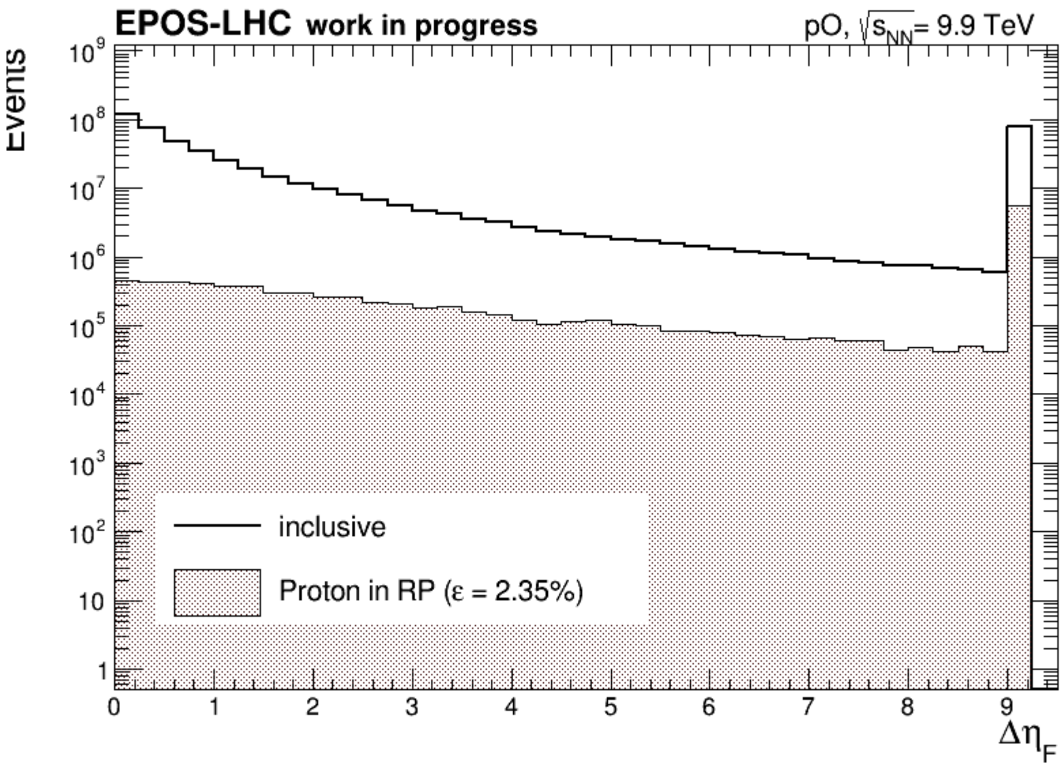

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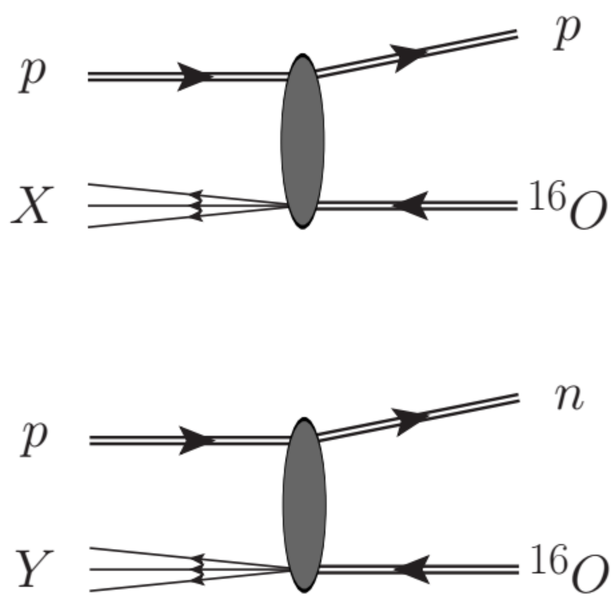

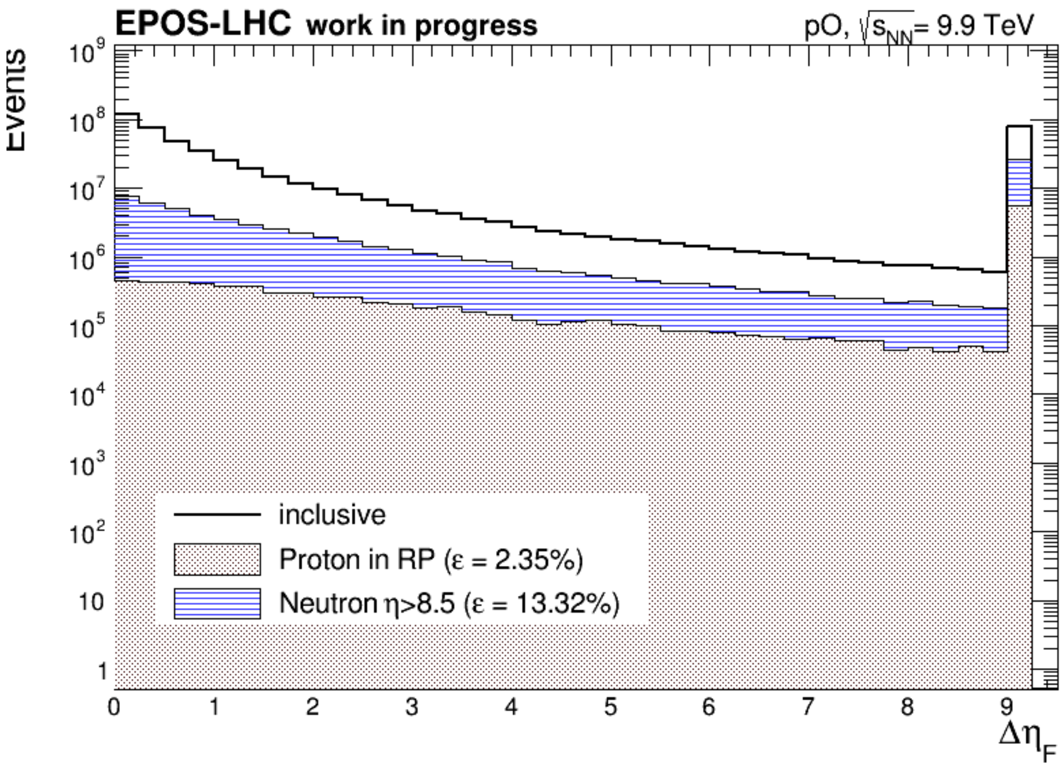

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Rapidity gaps in color neutral exchange

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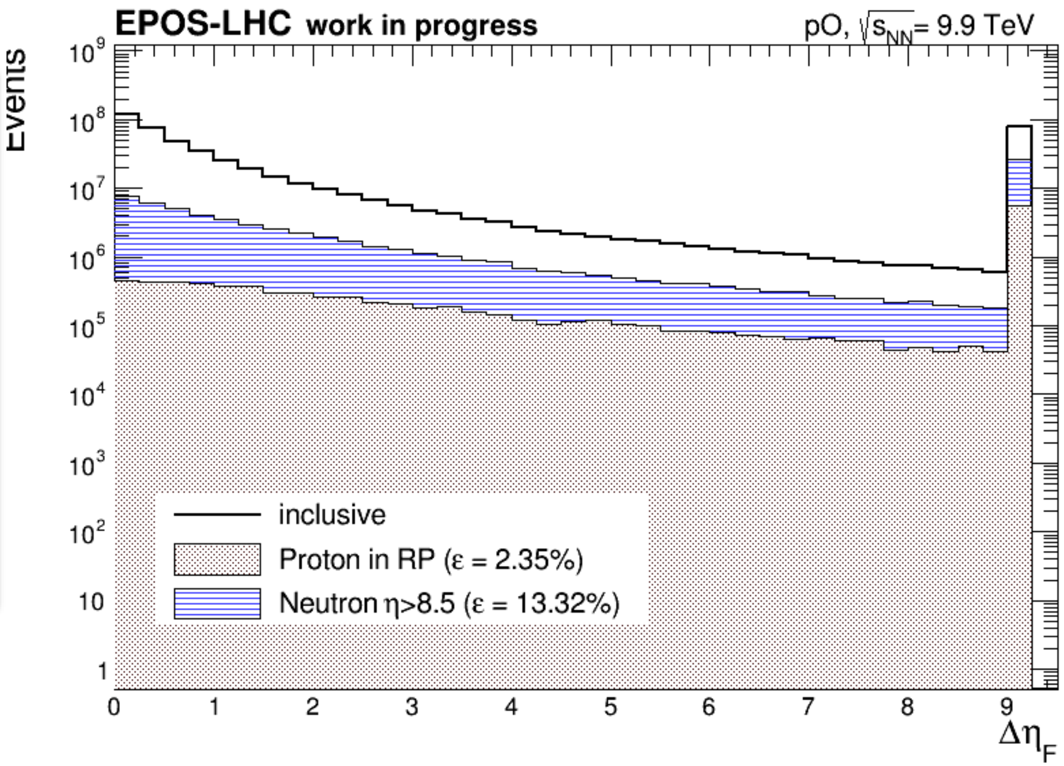
Measurements with forward n/p detectors can probe additional phase-space to LHCf/LHCb in constraining the modeling of pO interactions!



GAP := P_T > 1 GeV, with |η|<4.5

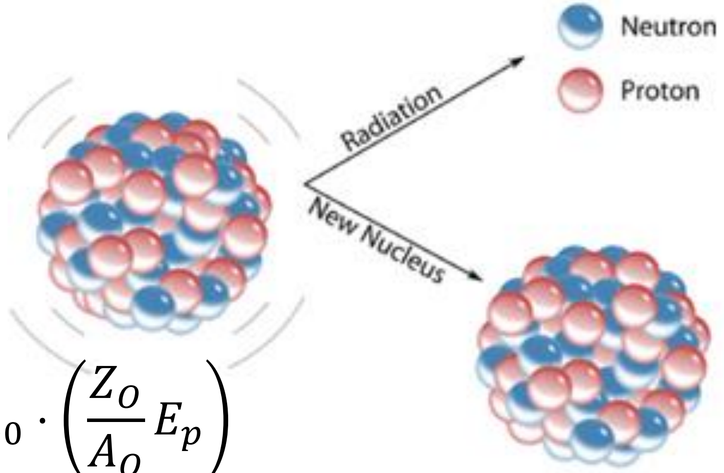
Production of light isotopes on pO and OO collisions

PoS ICRC2023 (426)

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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- Yet, some lighter ions with different kinematics can reach the FPS
- **Proton detector as ion "mass" (A/Z) spectrometer!**

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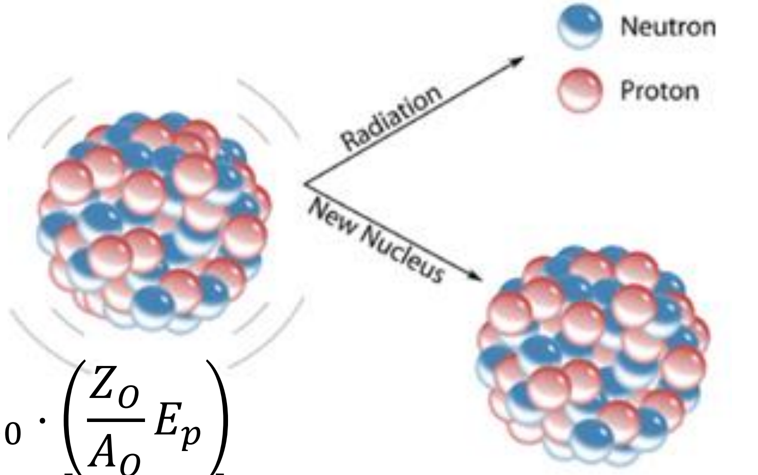

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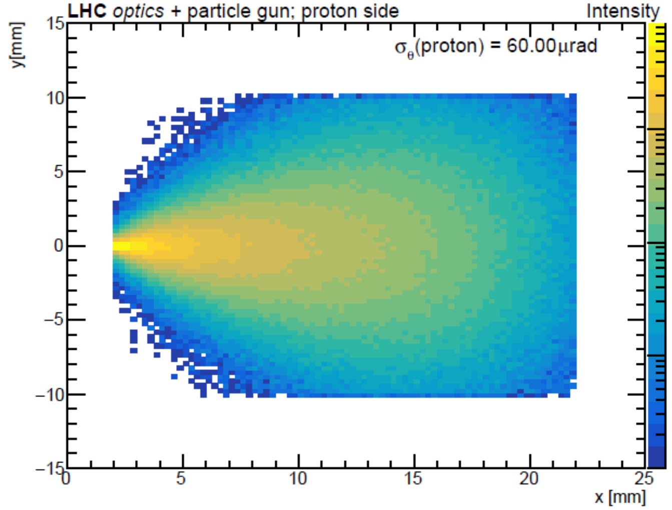
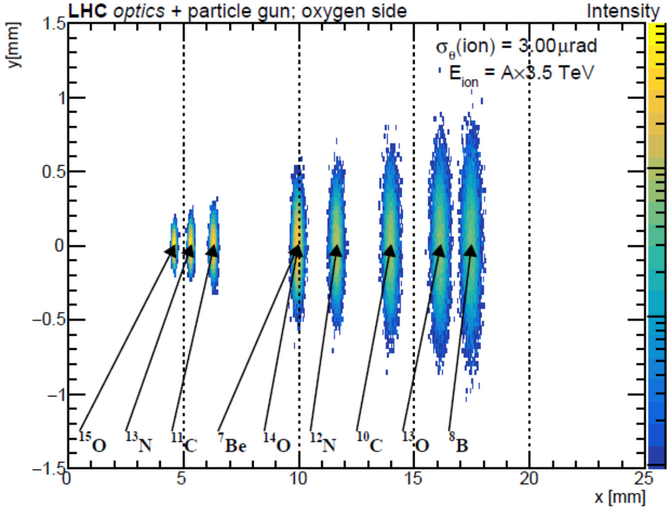
PoS ICRC2023 (426)





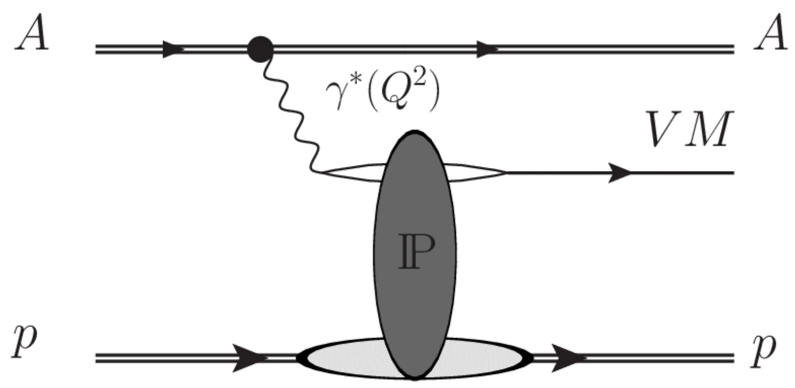
Low energy nuclear physics

Tagging coherent processes in pA collisions

Introduction

Goals

- Probing the low-X structure of the nucleus
- Probing spatial parton structure of nuclei

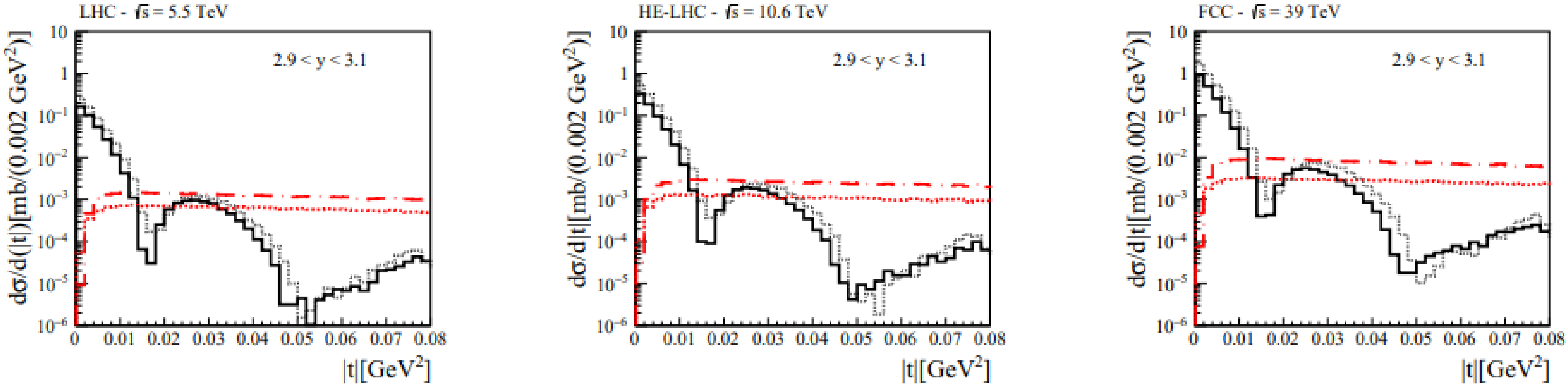


Methodology

- Measuring coherent vector meson (VM) production
- In AA interactions, Q2~0 (collinear photon), easy to reconstruct ion momentum transfer via IP
- Differential cross-section $(d\sigma/dt)$ as a function of momentum transfer → spatial distributions of gluons

Selected (past) studies

- Coherent and incoherent J/ψ photoproduction in PbPb collisions at the LHC, HE-LHC and FCC (2007.13625):

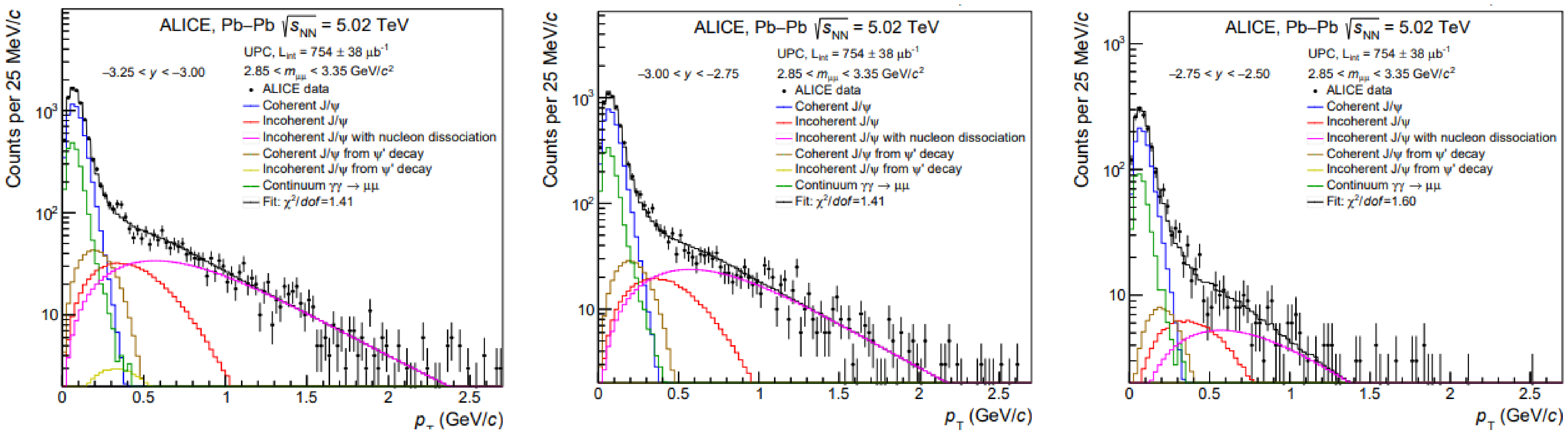


- Expected large rates
- Tagging of coherent events is a subject of ongoing studies

Introduction

Selected (past) studies

- Coherent J/ψ photoproduction at forward rapidity in PbPb UPC (1904.06272)

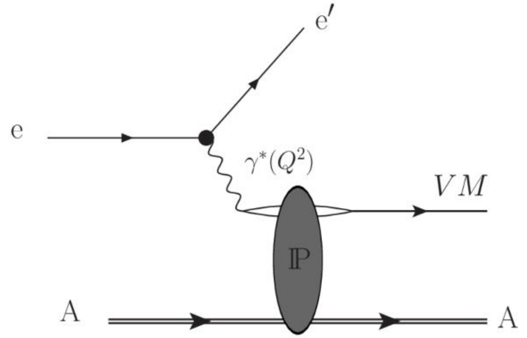


- **Expected large rates**
- **Observing the dips in coherent events is a subject of ongoing studies**

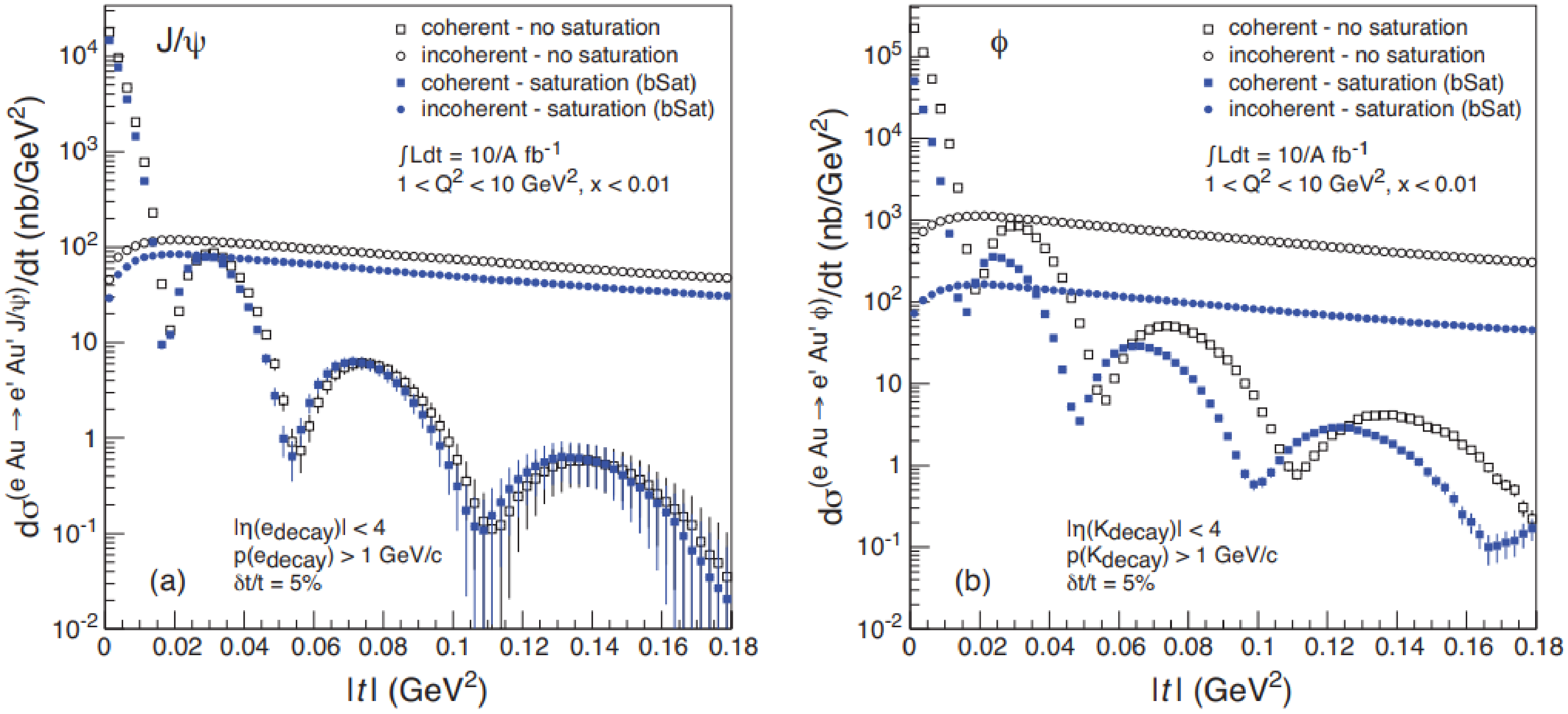
Introduction

Also targeted by future colliders

- Exclusive diffractive processes in electron-ion collisions (1211.3048):



Target Q^2>1 GeV^2 – backward electron reconstruction

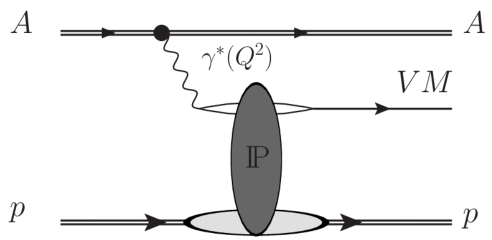


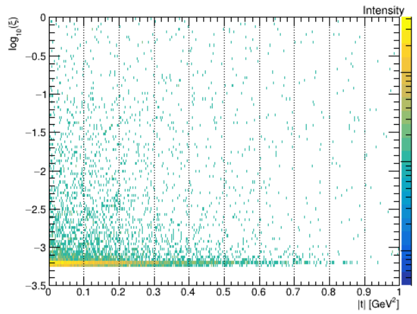
J/ψ less sensitive to saturation

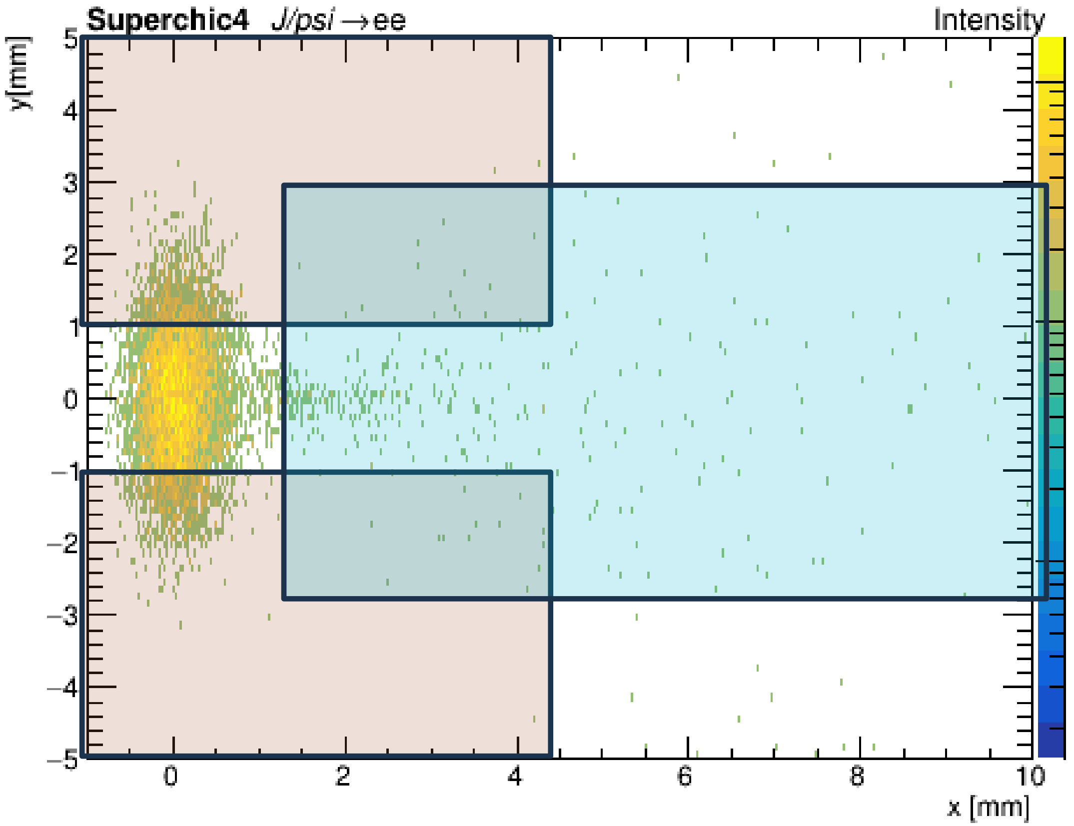
Coherent J/psi with tagged protons

Exclusive VM production

- Vector mesons (Spin 1) are produced in $\gamma - IP$ interactions
- Ions emit a photon at Q2~0
- pPb events simulated at $\sqrt{s} = 5.52$ TeV
- Proton momentum transfer can be measured by forward proton detectors







Work in progress

- Determination of desired luminosity
- Looking into alternative models (Starlight)

Summary

Diffraction in pp collisions

- Hard SD can constrain diffractive models, while a low-PU data is required to measure SD events, improvement in the timing detectors will allow measuring diffraction in standard LHC runs.
- Neutron detectors with moderate granularity sensitive to hadronic model parameters

pO and OO collisions with p/n tagging

- Participation of ZDC/FPS detectors in p-O / O-O collisions are currently investigated
- Improved modeling of (in)elasticity in proton – Air collisions
- Forward spectrometers sensitive to a few ions -> systematic measurements of ion disintegration.

Proton tagging in pA

- Clean selection of coherent processes
- Can be considered at the HL-LHC following the success of pO runs.

Backup

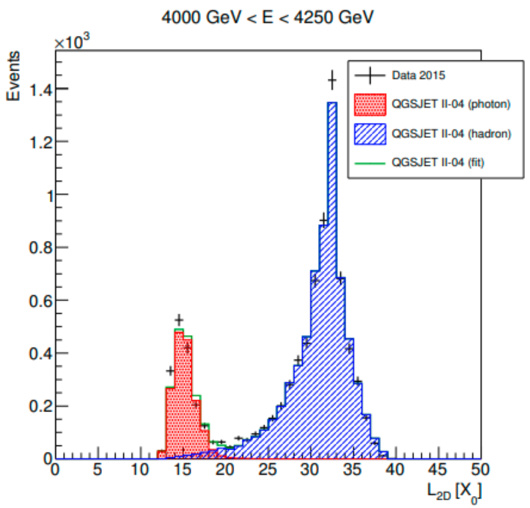
Motivation

Data samples

- 7 TeV: 0.68 nb^{-1} and 0.53 nb^{-1} for Arm1 and Arm2 respectively.
- 13 TeV: 0.194nb^{-1} Arm2 only. μ = 0.007 – 0.012

Events selection

- PID (neutrons, photons) based on radiation depth of the shower



development. Two simple parameters called $L_{20\%}$ and $L_{90\%}$ were introduced to characterize the shower shape. These parameters were defined as the depths in radiation length containing 20% and 90%, respectively, of the total energy deposited within the layers. Considering the correlation between $L_{20\%}$ and $L_{90\%}$ an optimized parameter L_{2D} was defined as $L_{2D} = L_{90\%} - 1/4 \times L_{20\%}$ to improve the selection efficiency and purity compared to previous analyses.

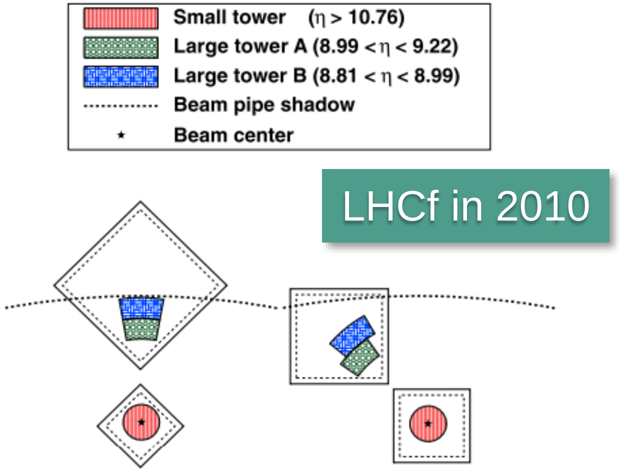


Fig. 1. Cross sections of the LHCf calorimeters (black squares) viewed from IP1. Left and right figures correspond to Arm1 and Arm2, respectively. The three pseudo-rapidity ranges used in the analysis are also indicated. Particles emitted in the direction above the dotted 'Beam pipe shadow' line hit the beam pipe before arriving at the LHCf detectors.

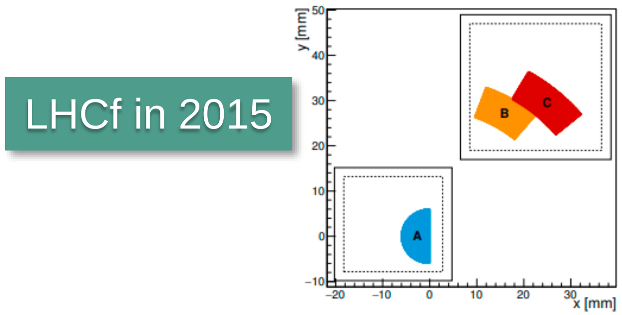
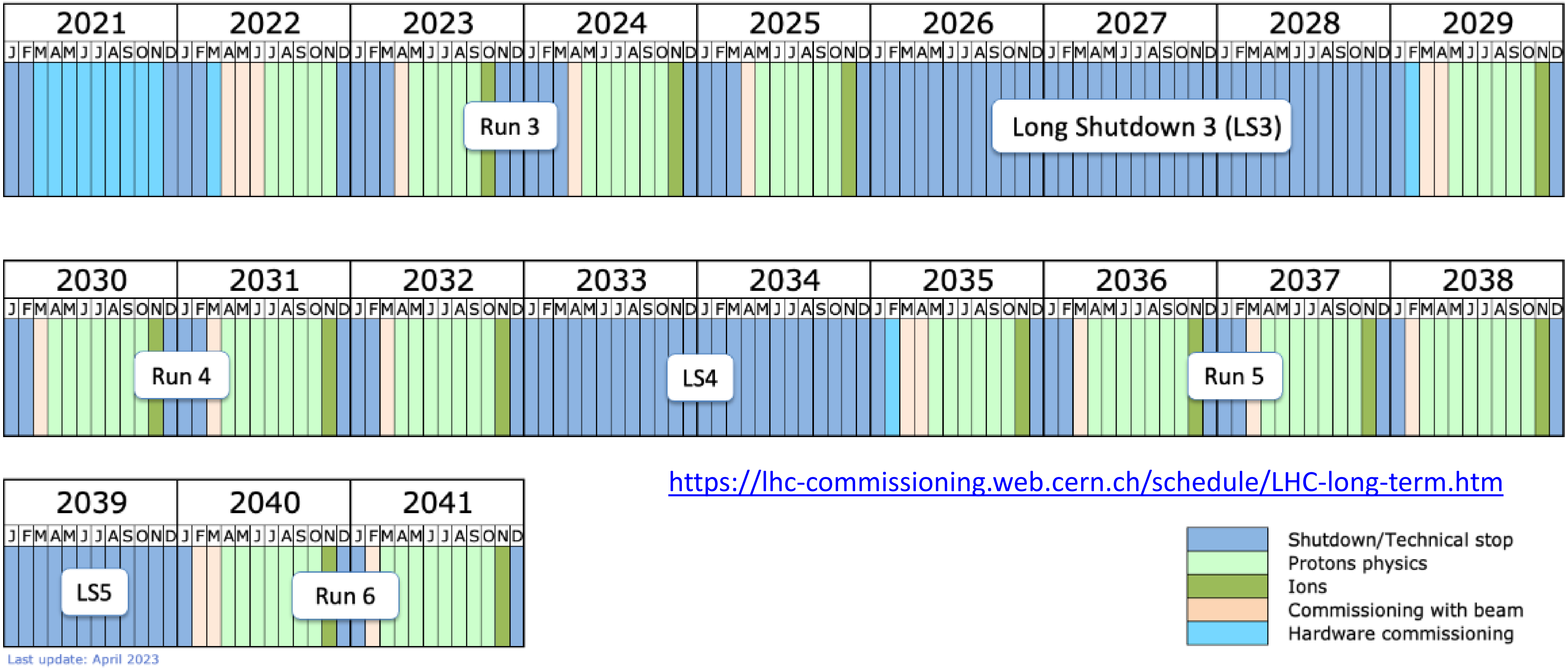


Figure 1. Definition of the three pseudorapidity regions A (blue), B (yellow) and C (red) on the Arm2 detector seen from IP1. The origin of the reference frame is centered on the projection of beam center on the detector during Fill 3855. The left and the right squares correspond to the small tower and the large tower, respectively. All analysis regions are chosen within a fiducial area (dashed line), which is 2 mm inside the edges of the towers (solid line).

LHC Run schedule



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