Forward physics at the EIC

14 June 2024

Michael Pitt* (michael.pitt@cern.ch)
The University of Kansas
** also with the Ben Gurion University of the Negev*

Thanks to Spencer Klein, Zach Sweger, and Rachel Montgomery for the fruitful feedback

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

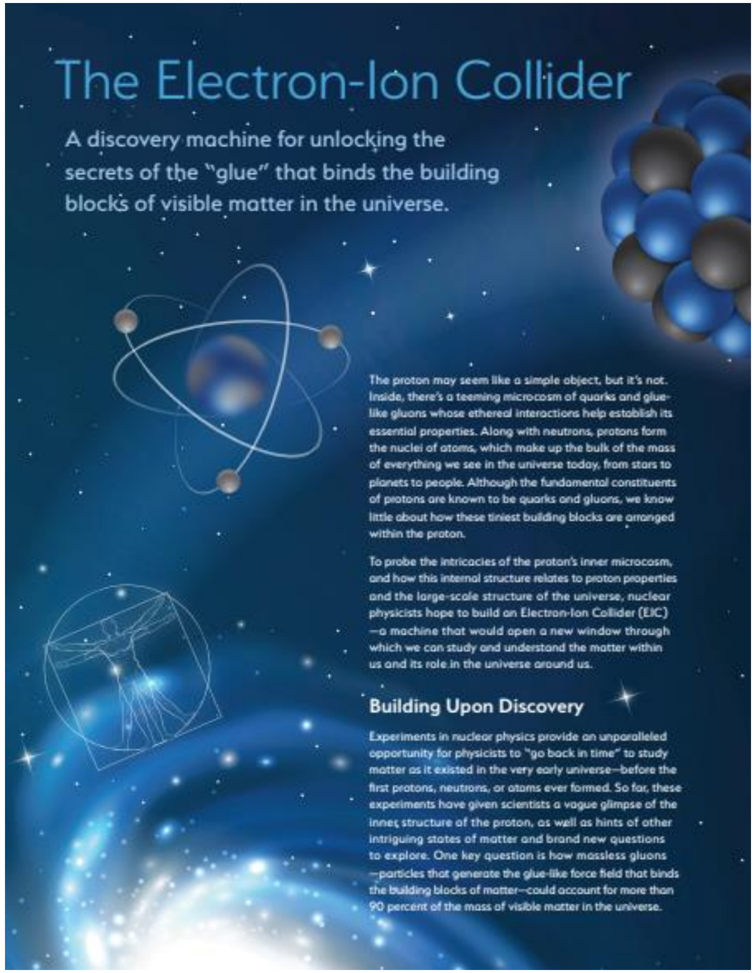
U.S. DEPARTMENT OF ENERGY | Office of Science
Grant DE-SC0023908

The EIC project

EIC – is a discovery machine!

- The scientific goals of the EIC:
  1. Precision 3D imaging of nucleons and nuclei
     - ➢ Quark/gluon structure of nuclei
     - ➢ Origin of hadron mass
  2. Search for saturation
  3. Solving the proton spin puzzle

More about EIC physics in Anna Staśto talk:
https://indico.ectstar.eu/event/208/contributions/4773/


The Electron-Ion Collider

A discovery machine for unlocking the secrets of the "glue" that binds the building blocks of visible matter in the universe.

The proton may seem like a simple object, but it's not. Inside, there's a teeming microcosm of quarks and glue-like gluons whose ethereal interactions help establish its essential properties. Along with neutrons, protons form the nuclei of atoms, which make up the bulk of the mass of everything we see in the universe today, from stars to planets to people. Although the fundamental constituents of protons are known to be quarks and gluons, we know little about how these tiniest building blocks are arranged within the proton.

To probe the intricacies of the proton's inner microcosm, and how this internal structure relates to proton properties and the large-scale structure of the universe, nuclear physicists hope to build an Electron-Ion Collider (EIC) —a machine that would open a new window through which we can study and understand the matter within us and its role in the universe around us.

Building Upon Discovery

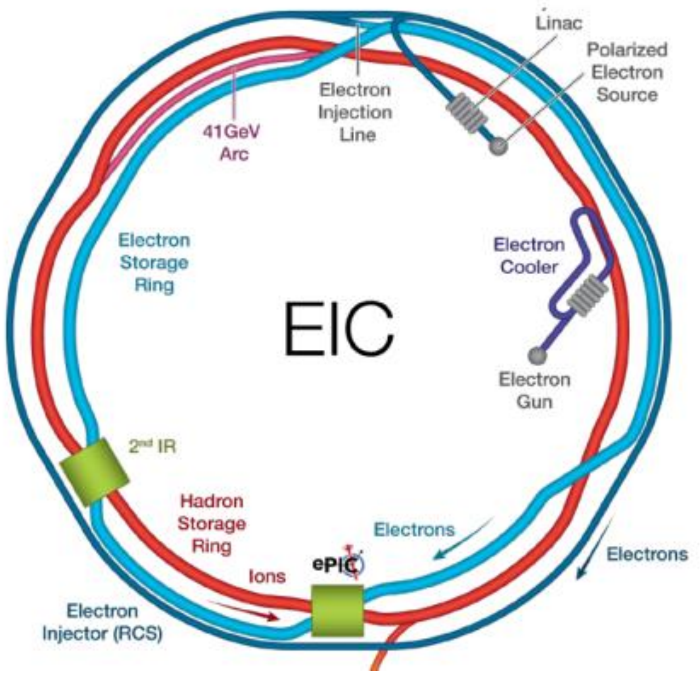
Experiments in nuclear physics provide an unparalleled opportunity for physicists to "go back in time" to study matter as it existed in the very early universe—before the first protons, neutrons, or atoms ever formed. So far, these experiments have given scientists a vague glimpse of the inner structure of the proton, as well as hints of other intriguing states of matter and brand new questions to explore. One key question is how massless gluons —particles that generate the glue-like force field that binds the building blocks of matter—could account for more than 90 percent of the mass of visible matter in the universe.

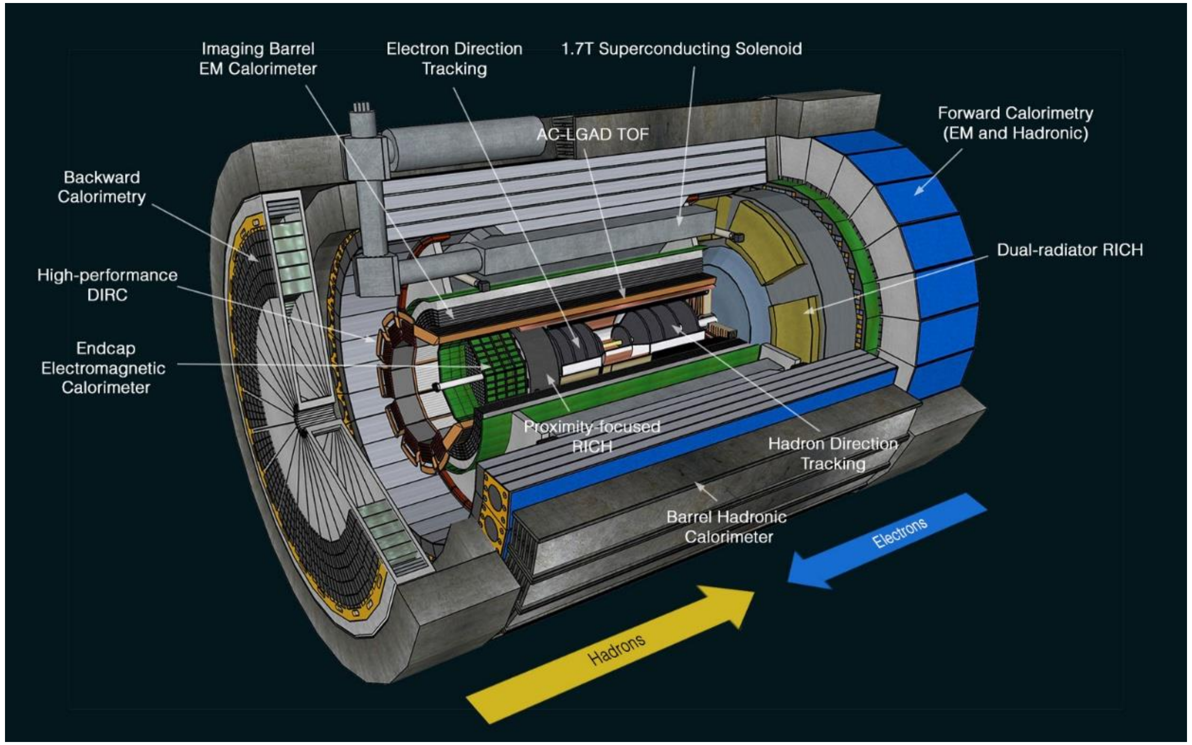
https://www.bnl.gov/newsroom/factsheets/files/pdf/eic_brochure.pdf

Introduction

The EIC project

- Currently only one detector experiment is planned (ePIC)
- State-of-the-art detector technologies



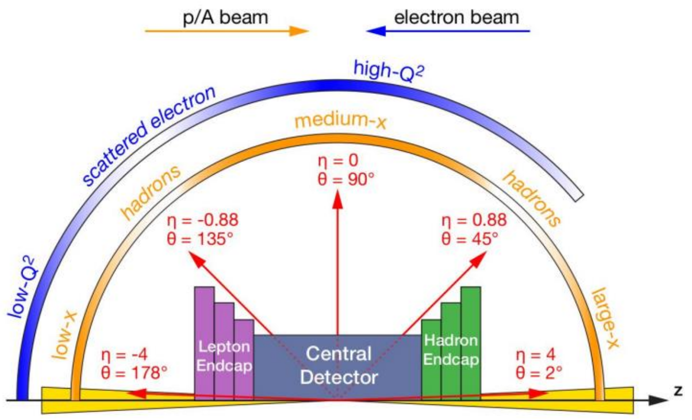


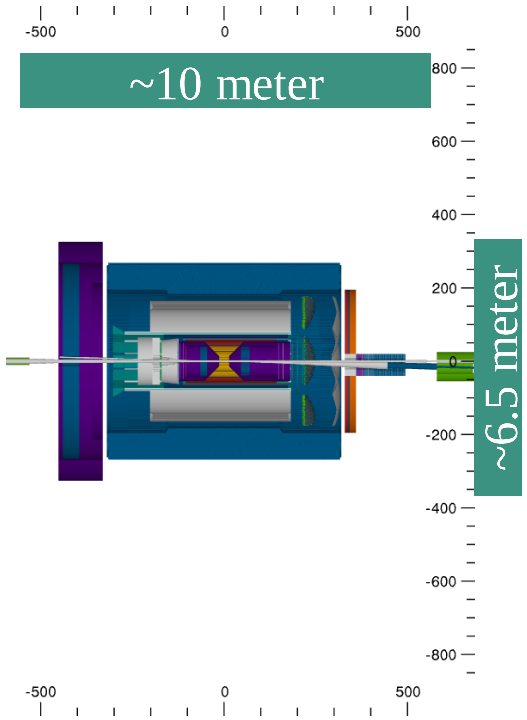
https://www.bnl.gov/eic/epic.php

- ➢ High-precision tracking
- ➢ High-resolution calorimeters
- ➢ Particle Identification
- ➢ Efficient DAQ involving AI/ML

The ePIC detector at the EIC

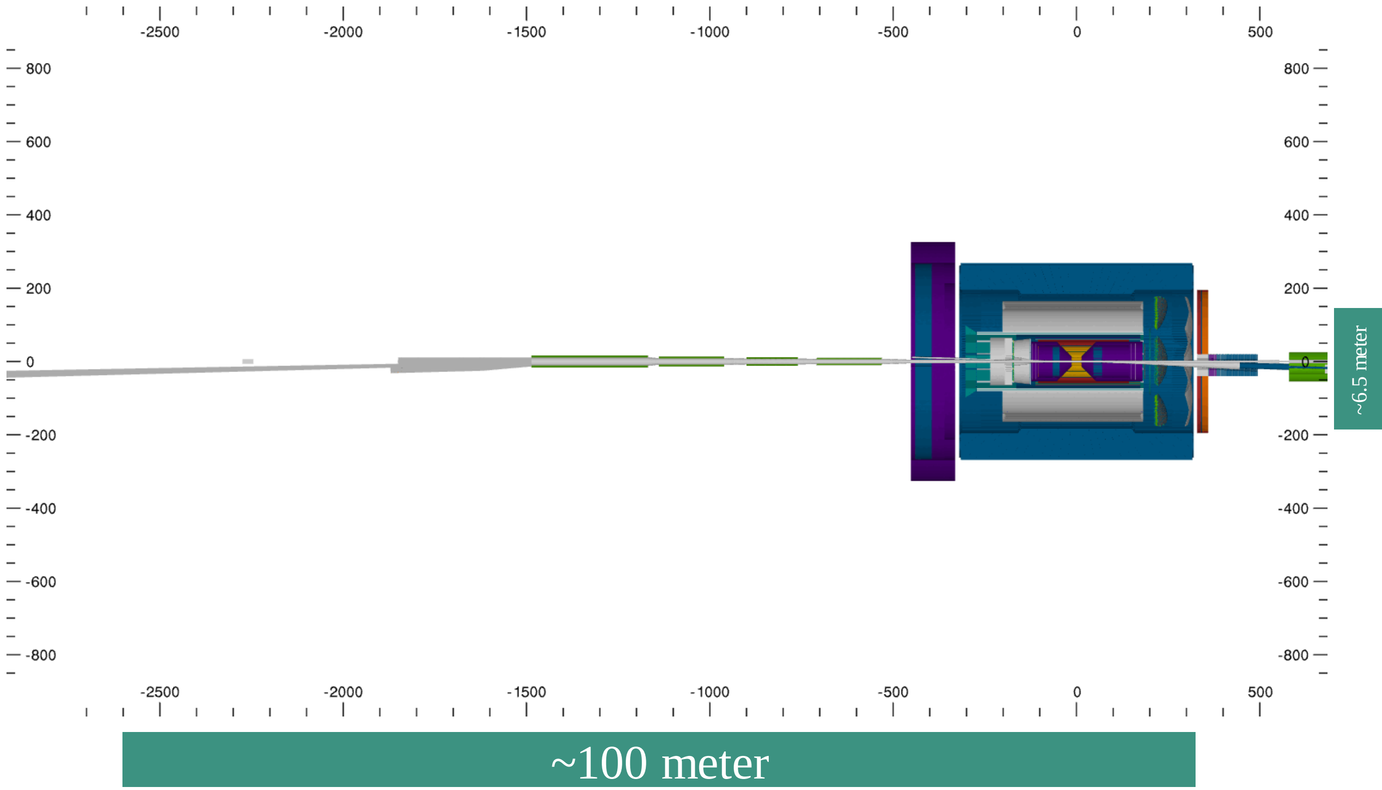
- The ePIC experiment, scheduled to start in the early 2030s
- It comprises:
  - A 10-meter-long cylindrical barrel detector, covering rapidity range from η=-4 to 4





The ePIC detector at the EIC

- The ePIC experiment, scheduled to start in the early 2030s
- It comprises:
  - A 10-meter-long cylindrical barrel detector, covering rapidity range from η=-4 to 4
  - An additional detector array that extends ~50m in each direction aiming for a full coverage



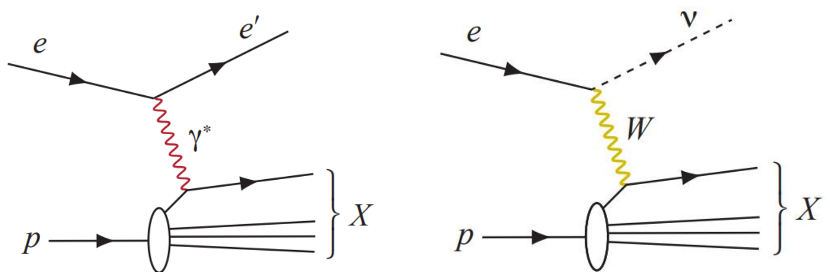
The ePIC detector at the EIC

- The extended detector's array required to enable primary physics objectives:

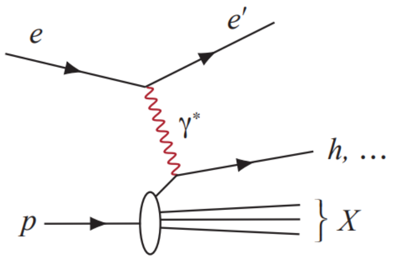
- The ePIC experiment, scheduled to start in the early 2030s
- It comprises:
  - A 10-meter-long cylindrical barrel detector, covering rapidity range from η=-4 to 4
  - An additional detector array that extends ~50m in each direction aiming for a full coverage

The ePIC detector at the EIC

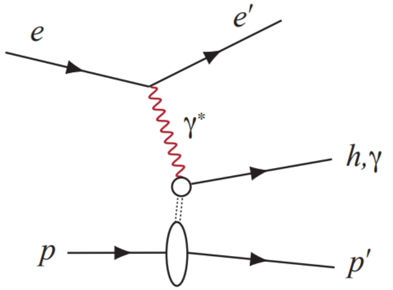
- The extended detector’s array required to enable primary physics objectives:



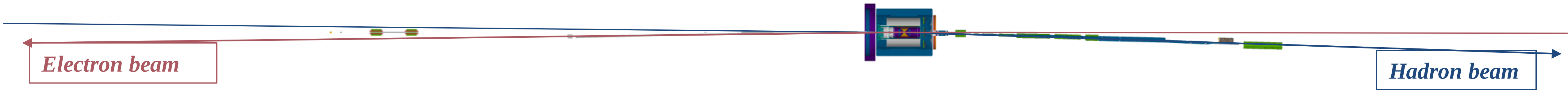
NC+CC Inclusive DIS (~1 fb^{-1})



Semi-Inclusive DIS (~10 fb^{-1})

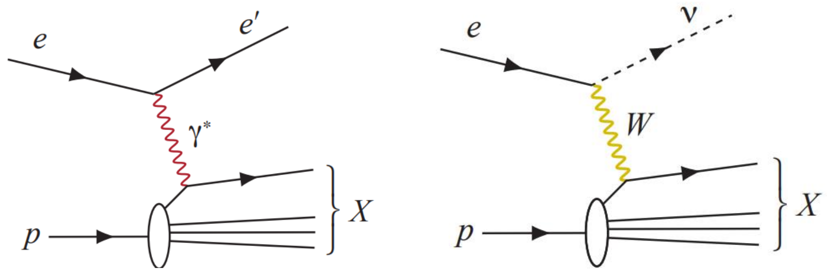


Exclusive DIS (>10 fb^{-1})

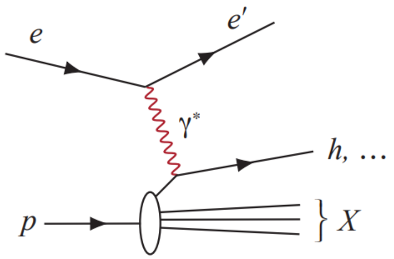


The ePIC detector at the EIC

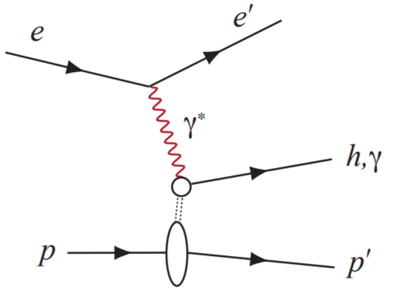
- The extended detector’s array required to enable primary physics objectives:



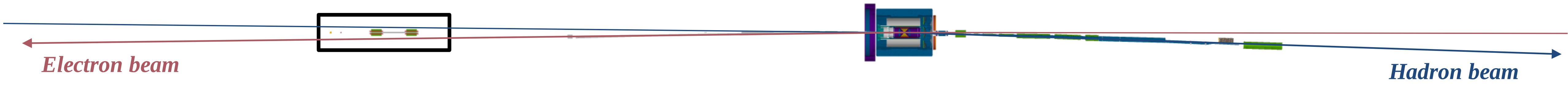
NC+CC Inclusive DIS (~1 fb^{-1})

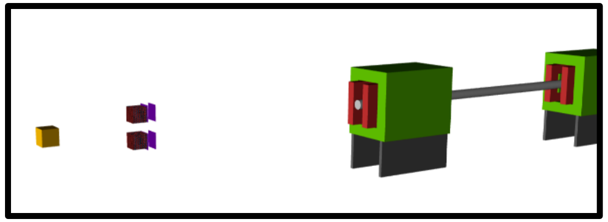


Semi-Inclusive DIS (~10 fb^{-1})



Exclusive DIS (>10 fb^{-1})



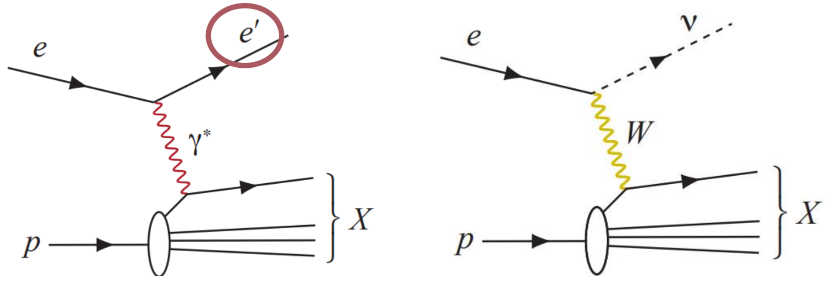


Luminosity monitor

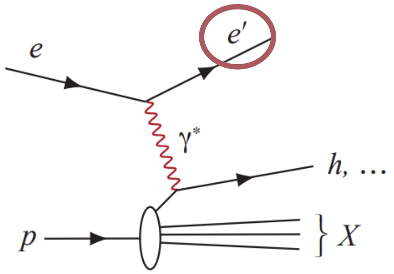
Far-Backward detectors

The ePIC detector at the EIC

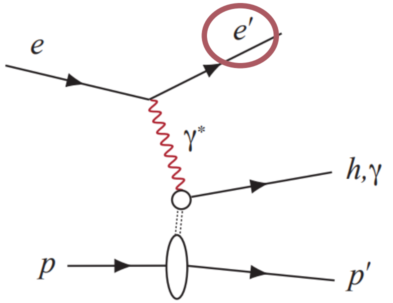
- The extended detector's array required to enable primary physics objectives:



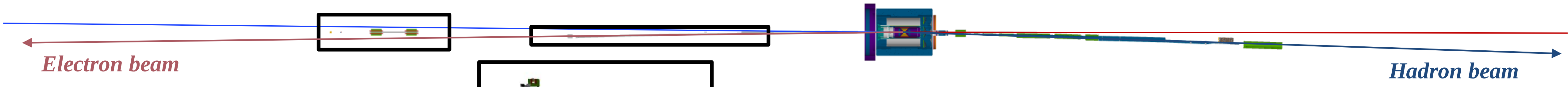
NC+CC Inclusive DIS (~1 fb^{-1})

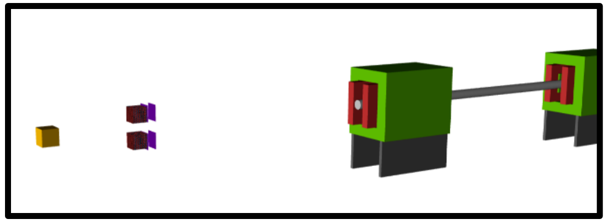


Semi-Inclusive DIS (~10 fb^{-1})

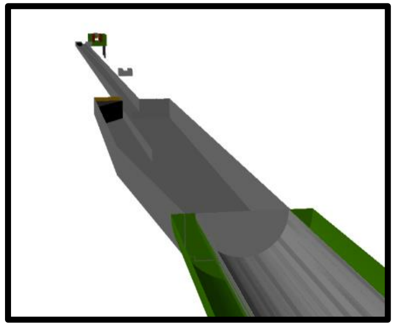


Exclusive DIS (>10 fb^{-1})





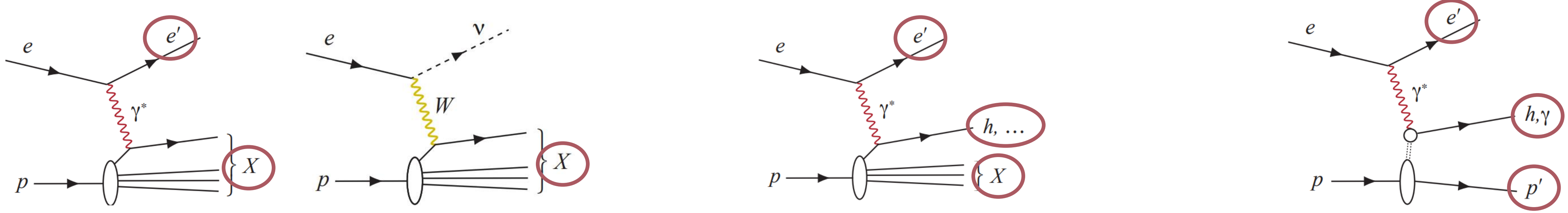
Luminosity monitor



Low Q^2 taggers

The ePIC detector at the EIC

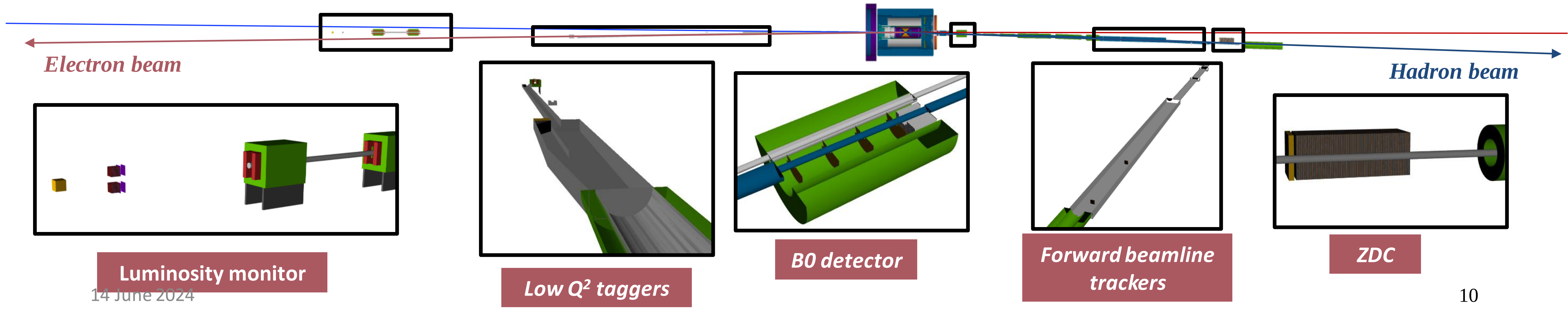
- The extended detector's array required to enable primary physics objectives:



NC+CC Inclusive DIS (~1 fb^{-1})

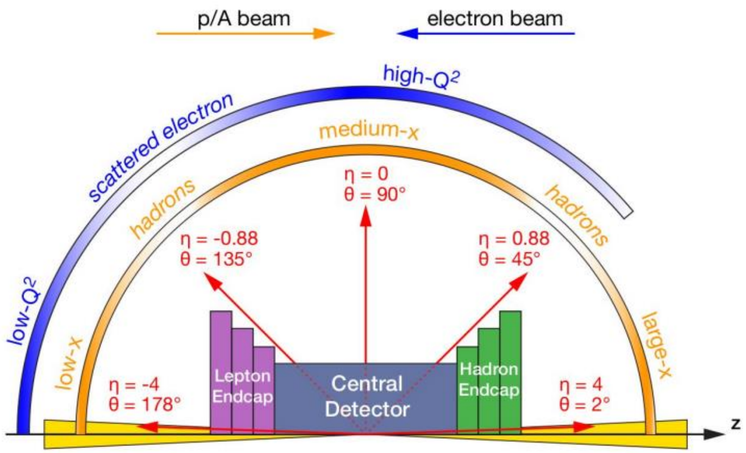
Semi-Inclusive DIS (~10 fb^{-1})

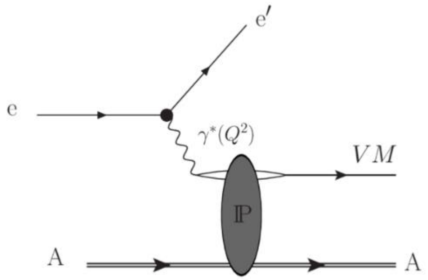
Exclusive DIS (>10 fb^{-1})

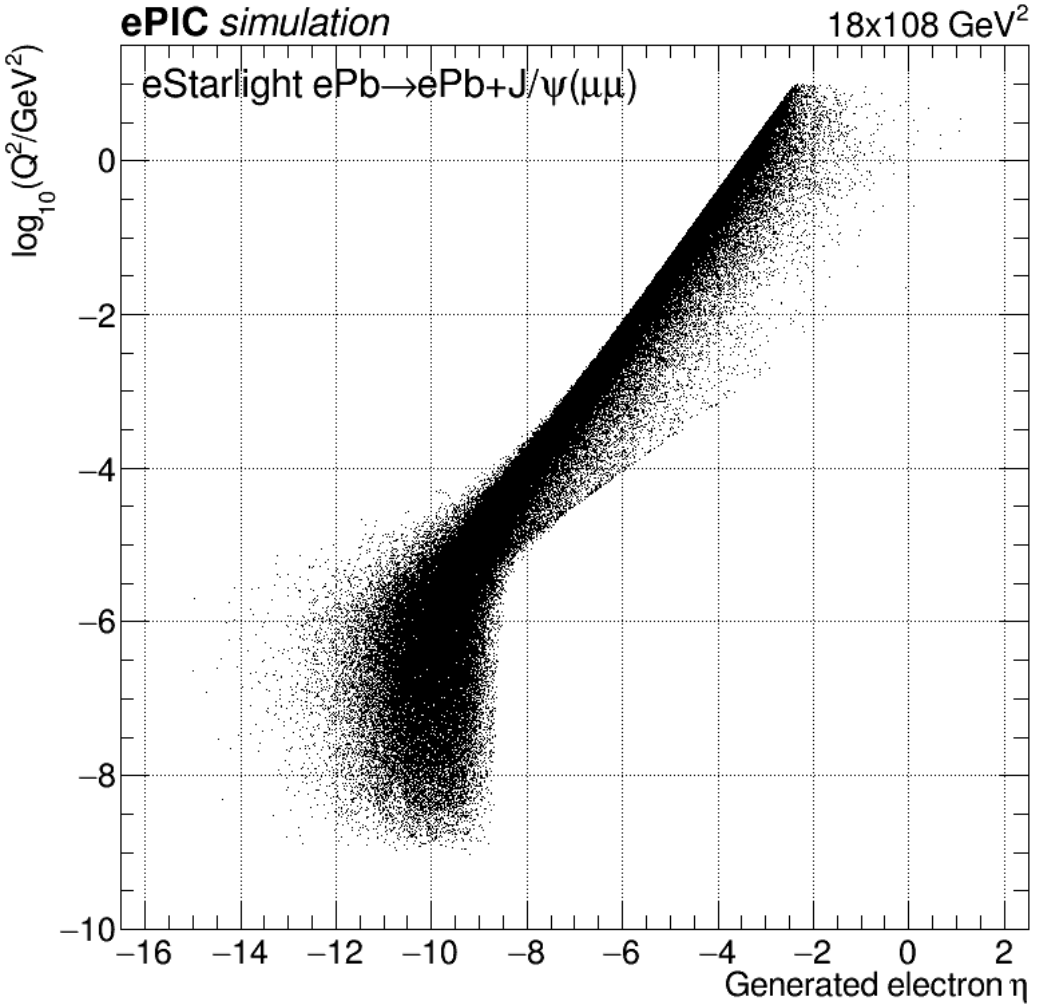


Low Q^2 electron tagger

- Photon virtuality (Q^2) is reflected in the scattering angle of the outgoing electron

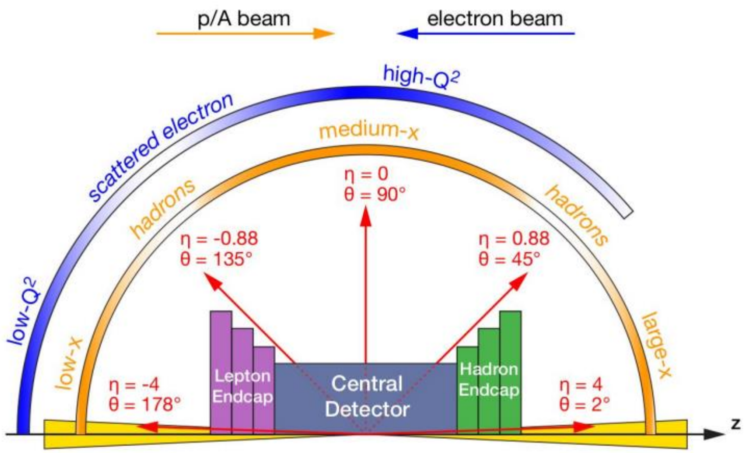


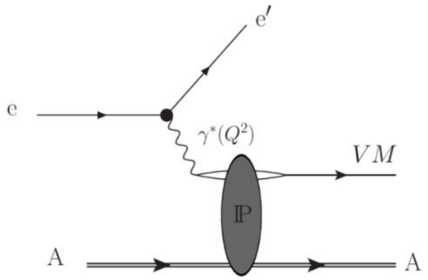


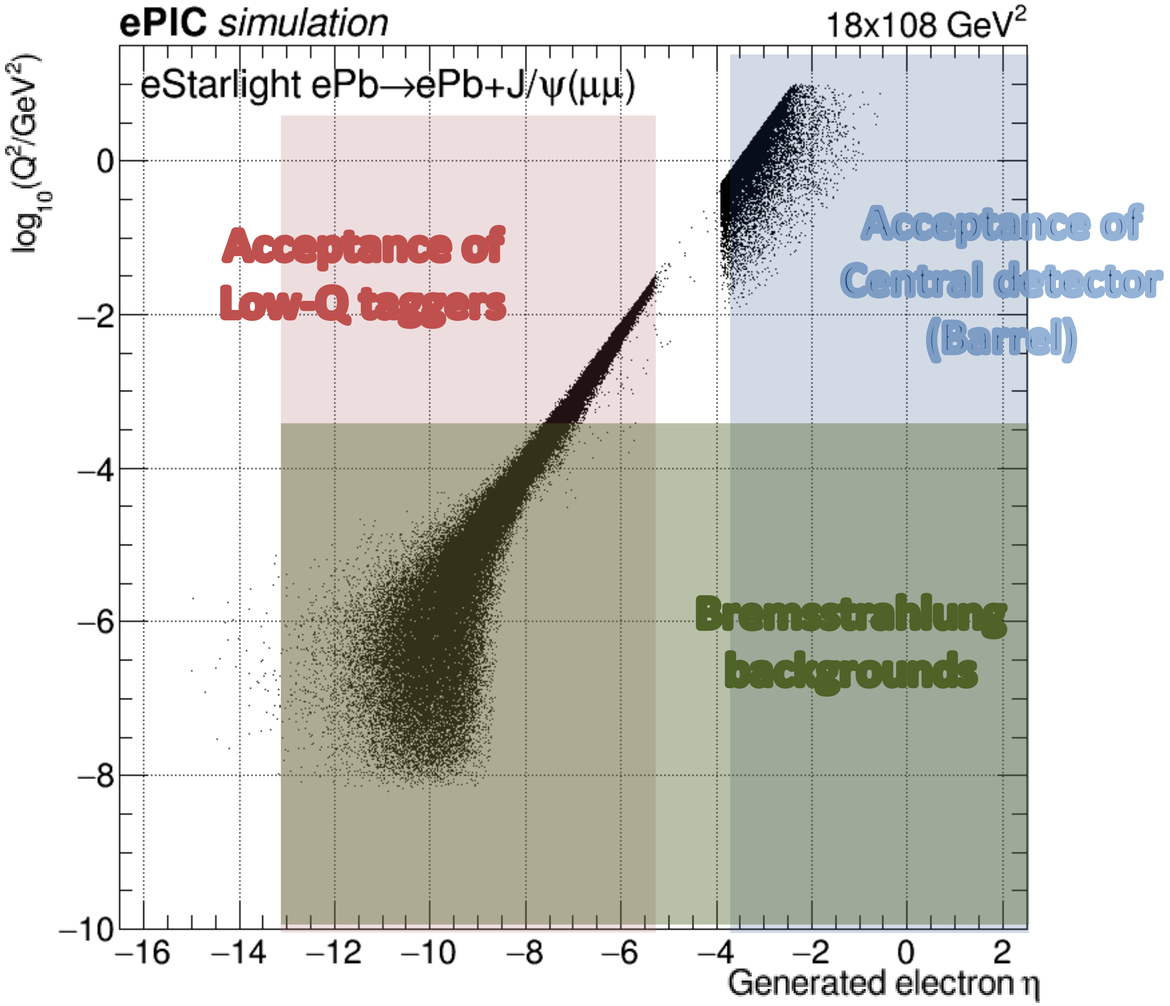


Low Q^2 electron tagger

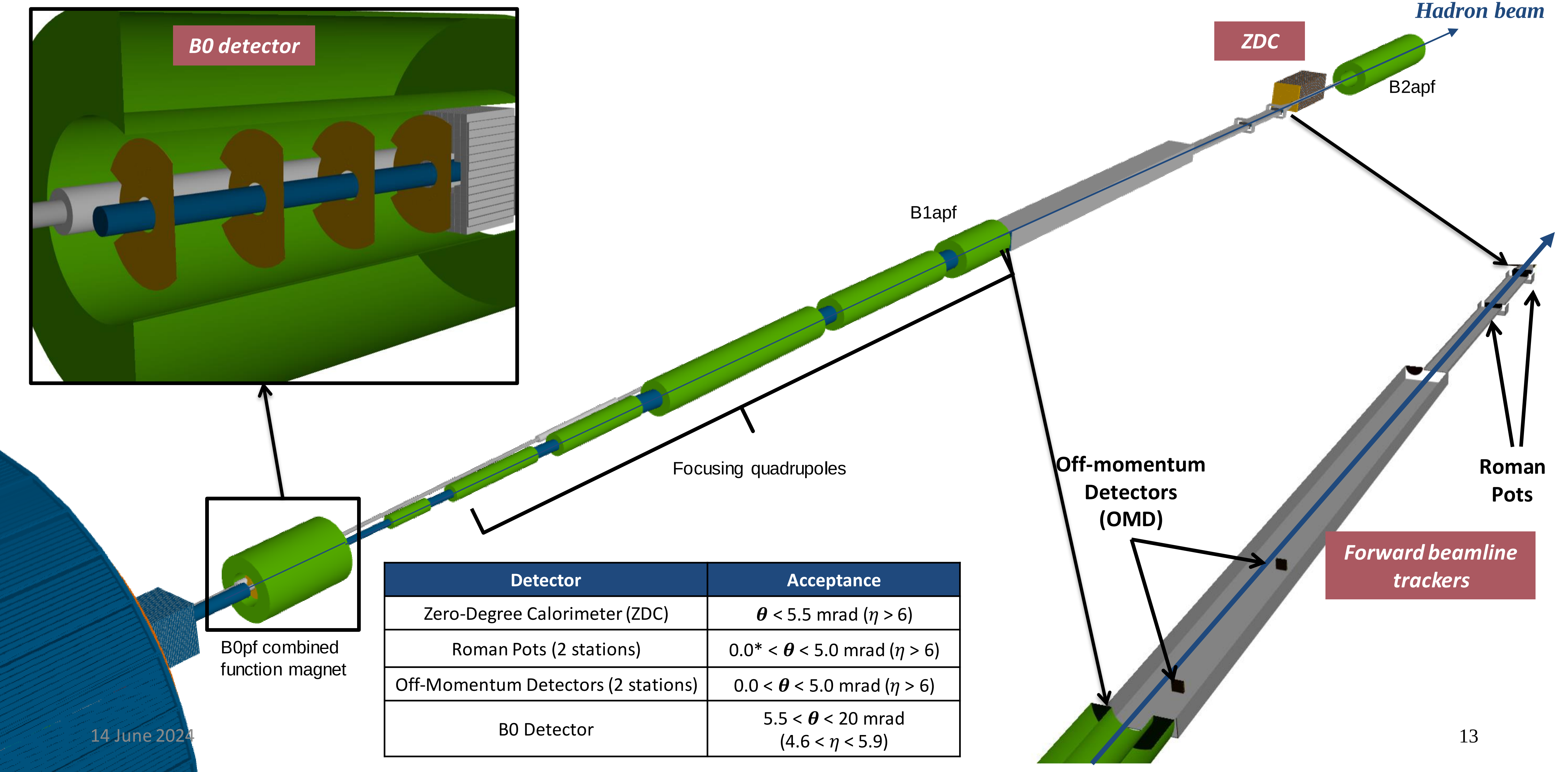
- Central detector acceptance: Q > 1 GeV outgoing electrons
- Low-Q2 taggers allows $Q^2 > 10^{-3.5}$ GeV^2





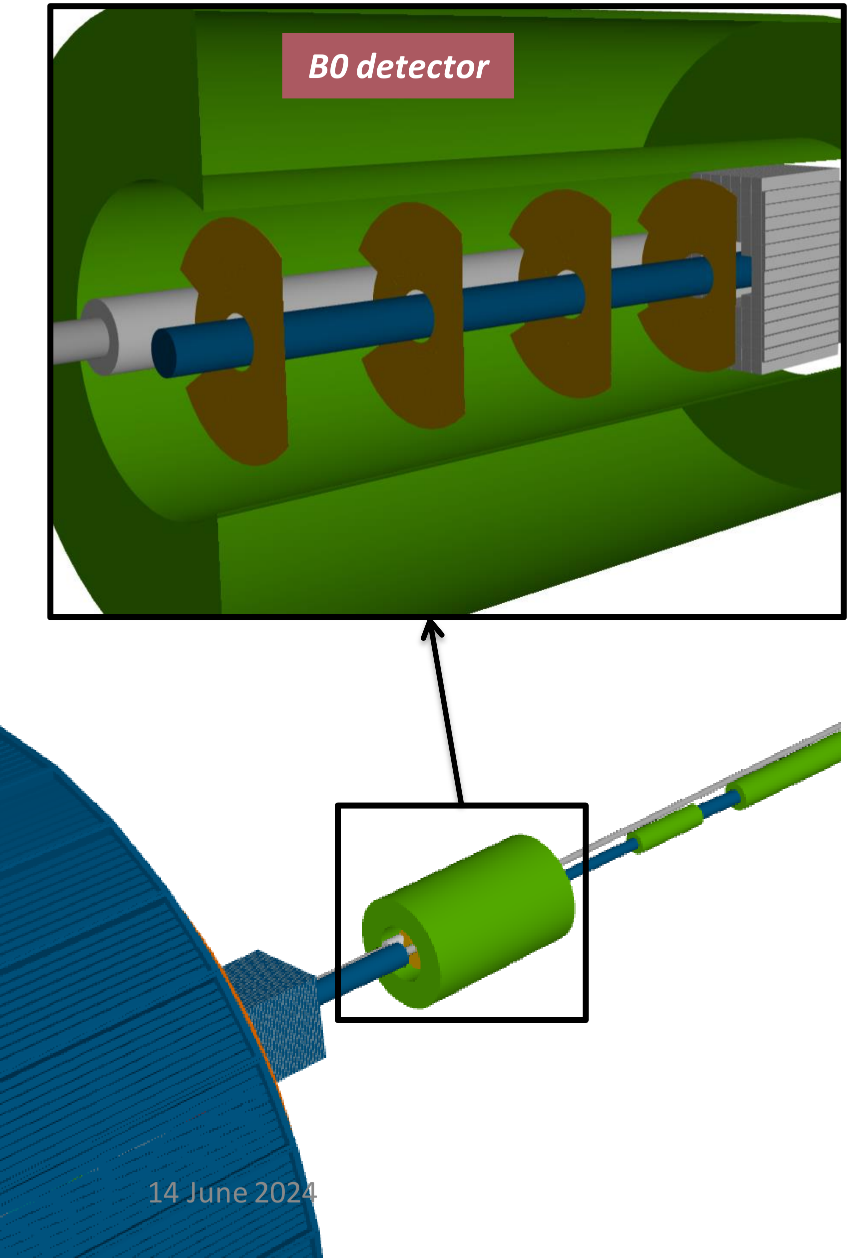


The Far-Forward detectors

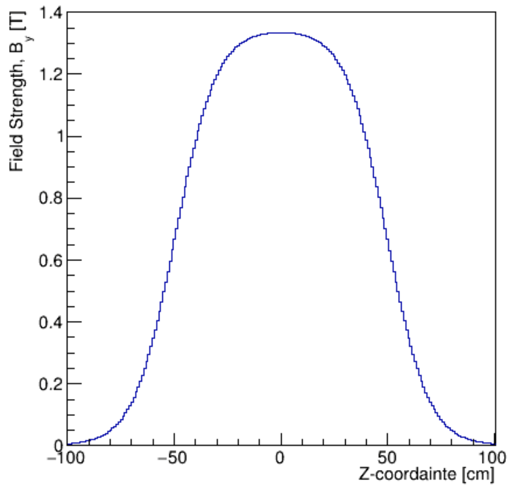


Detector	Acceptance
Zero-Degree Calorimeter (ZDC)	θ < 5.5 mrad (η > 6)
Roman Pots (2 stations)	0.0* < θ < 5.0 mrad (η > 6)
Off-Momentum Detectors (2 stations)	0.0 < θ < 5.0 mrad (η > 6)
B0 Detector	5.5 < θ < 20 mrad (4.6 < η < 5.9)

The Far-Forward detectors



- Acceptance 5.5 < θ < 20 mrad
- Very low material budget in 5 < η < 5.5
  - ➢ Si Tracker: 4 Layer of AC-LGAD
  - ➢ EM Calorimeter: 20 cm $PbWO_4$ crystals



- **Photons:**

➢ High acceptance in a broad energy range (> 50 MeV), including ~MeV de-excitation photons

➢ Energy resolution of 6-7%

➢ Position resolution of ~3 mm

- **Protons:**

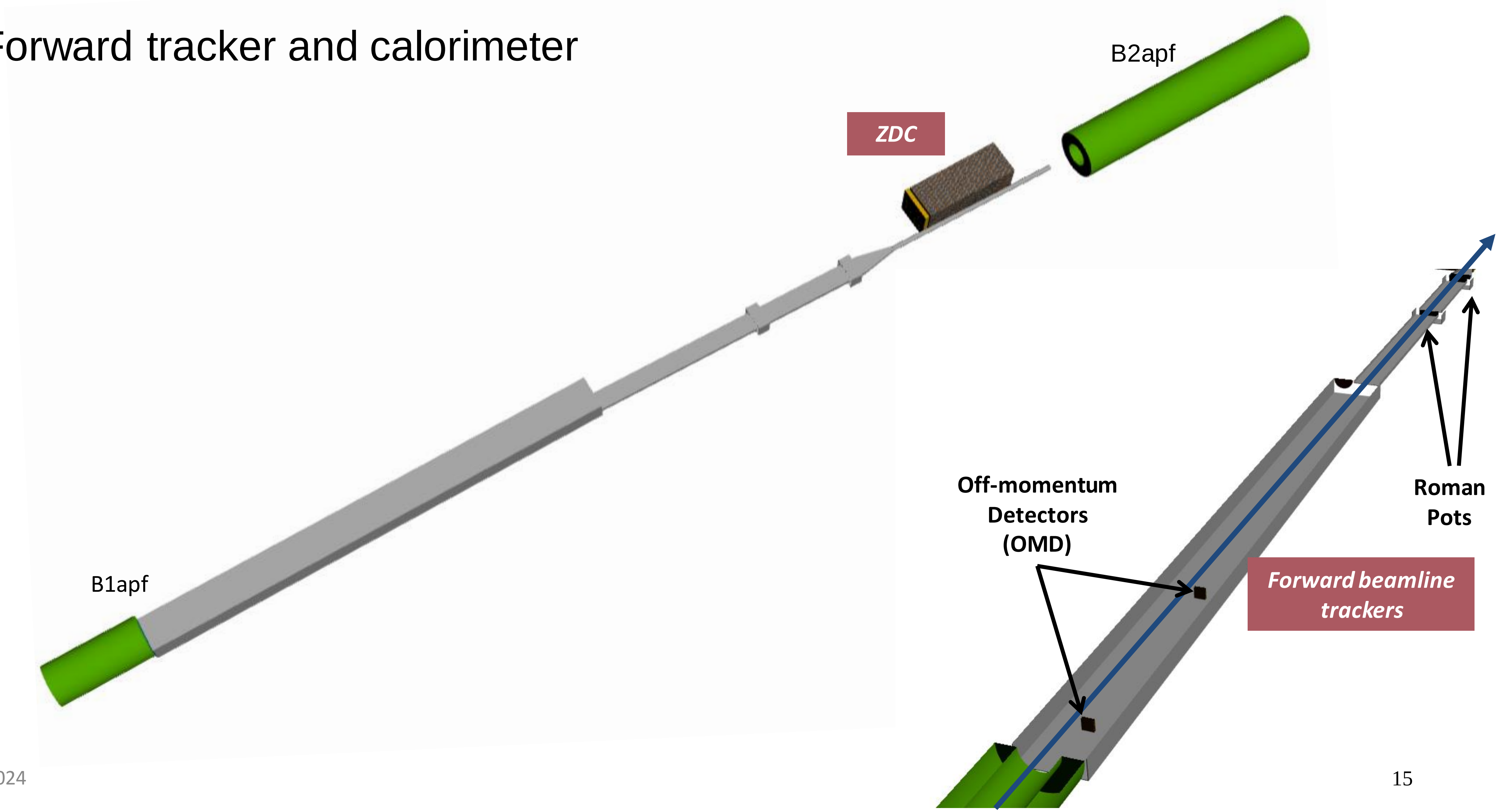
➢ Momentum resolution (dp/p) of ~ 2-4%

- **Neutrons:**

➢ 50% detection efficiency (λ is almost 1)

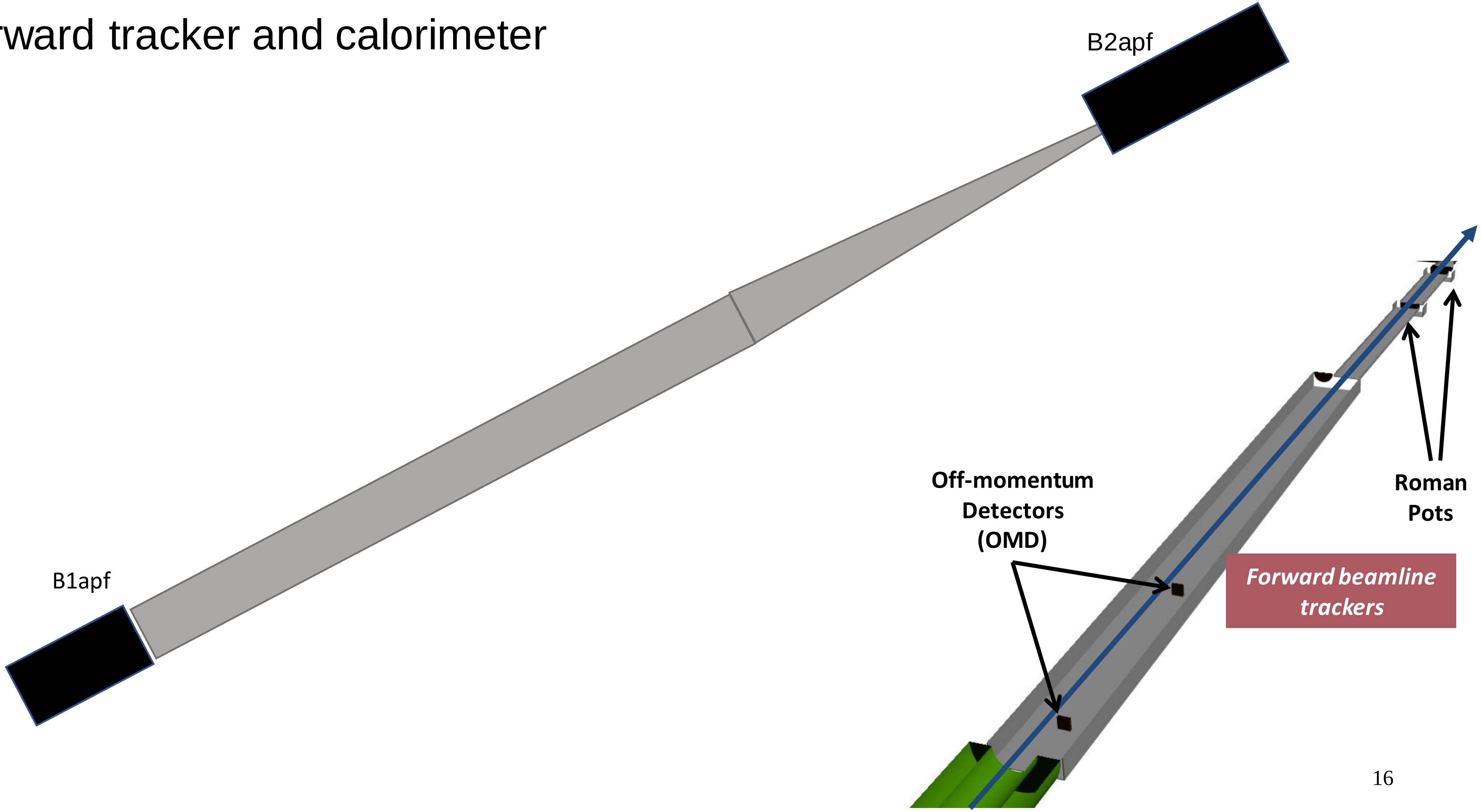
The Far-Forward detectors

- Very Forward tracker and calorimeter



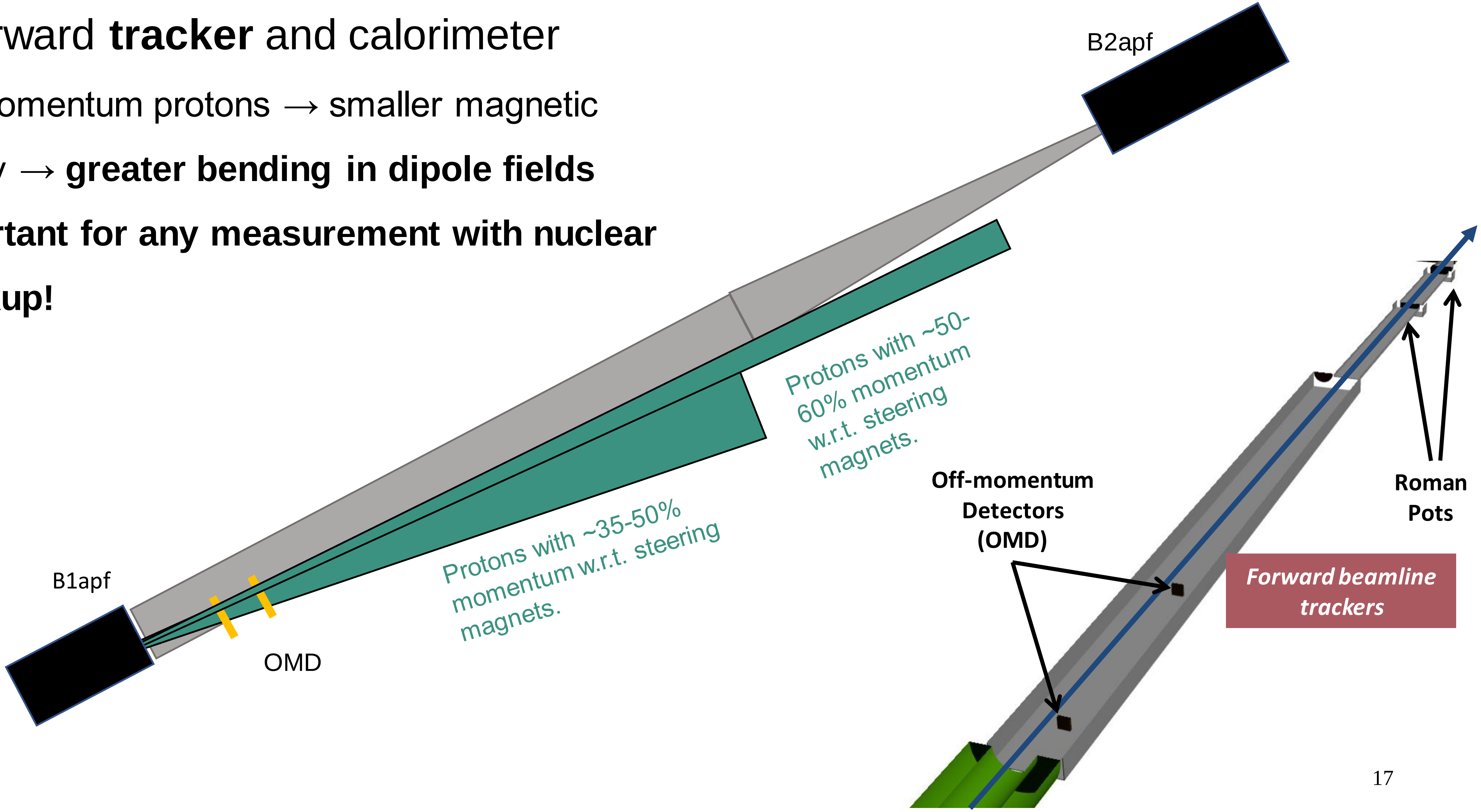
The Far-Forward detectors

- Very Forward tracker and calorimeter



The Far-Forward detectors

- Very Forward **tracker** and calorimeter
  - Off-momentum protons → smaller magnetic rigidity → **greater bending in dipole fields**
  - **Important for any measurement with nuclear breakup!**

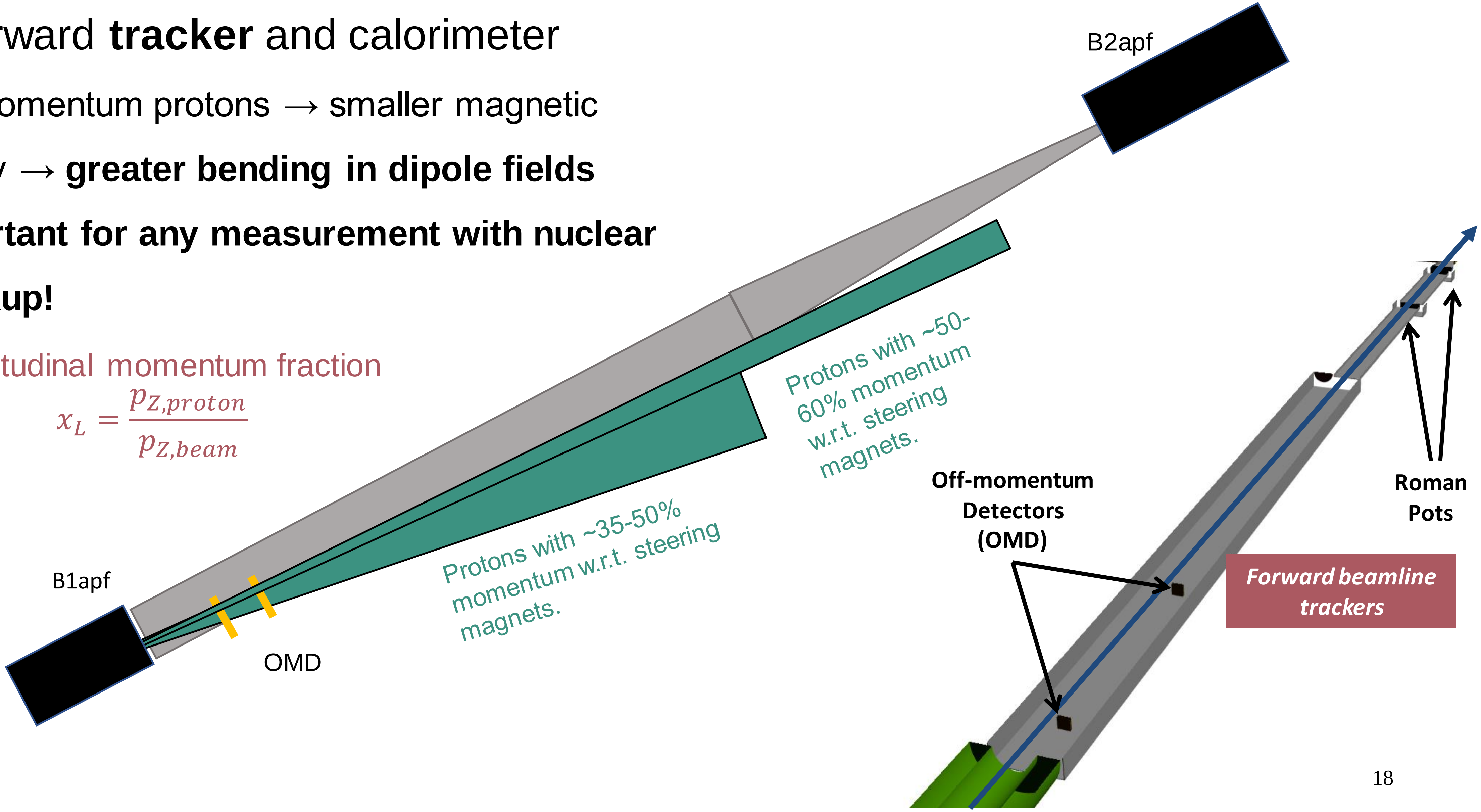


The Far-Forward detectors

- Very Forward **tracker** and calorimeter
  - Off-momentum protons → smaller magnetic rigidity → **greater bending in dipole fields**
  - **Important for any measurement with nuclear breakup!**

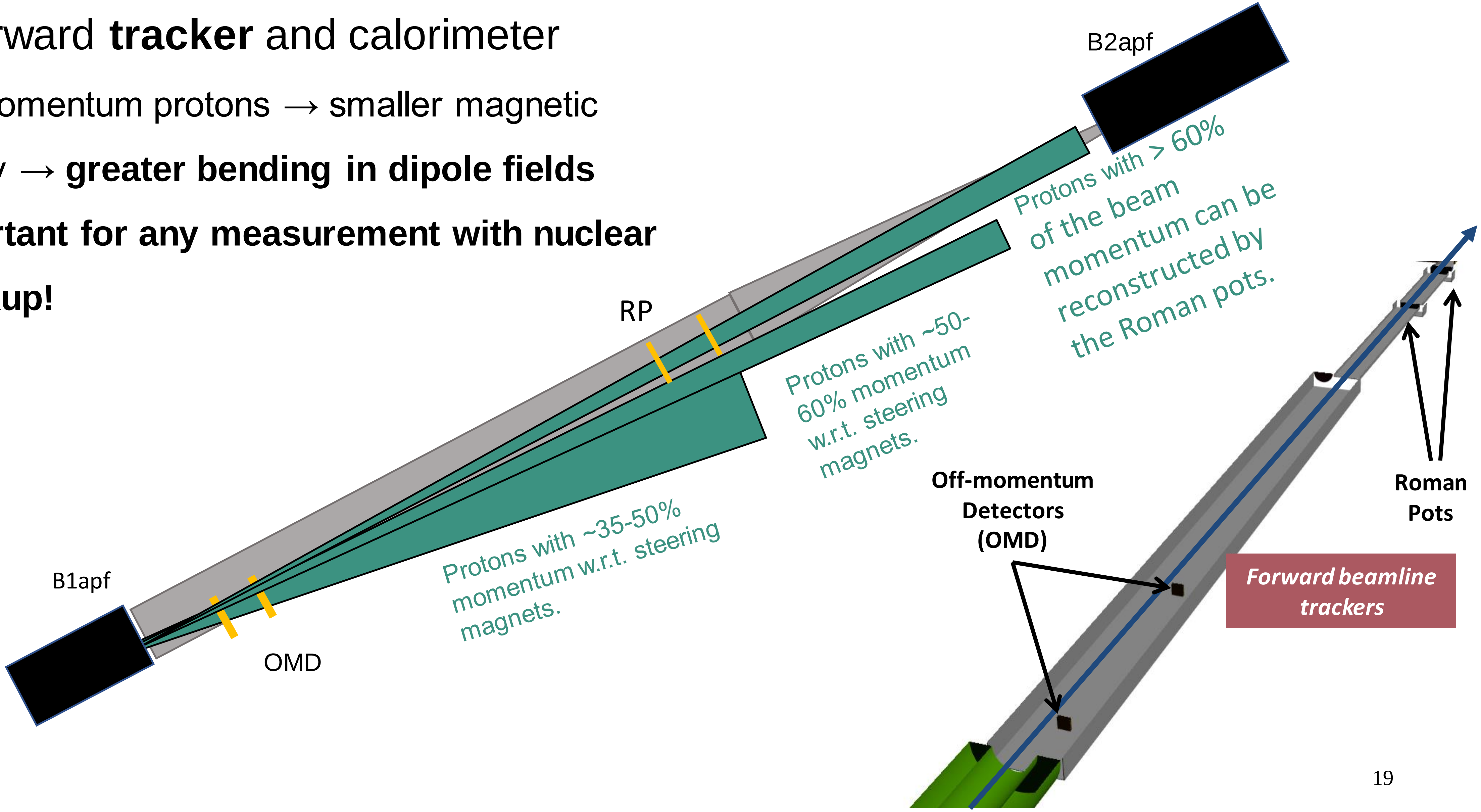
Longitudinal momentum fraction

$$x_L = \frac{p_{Z,proton}}{p_{Z,beam}}$$



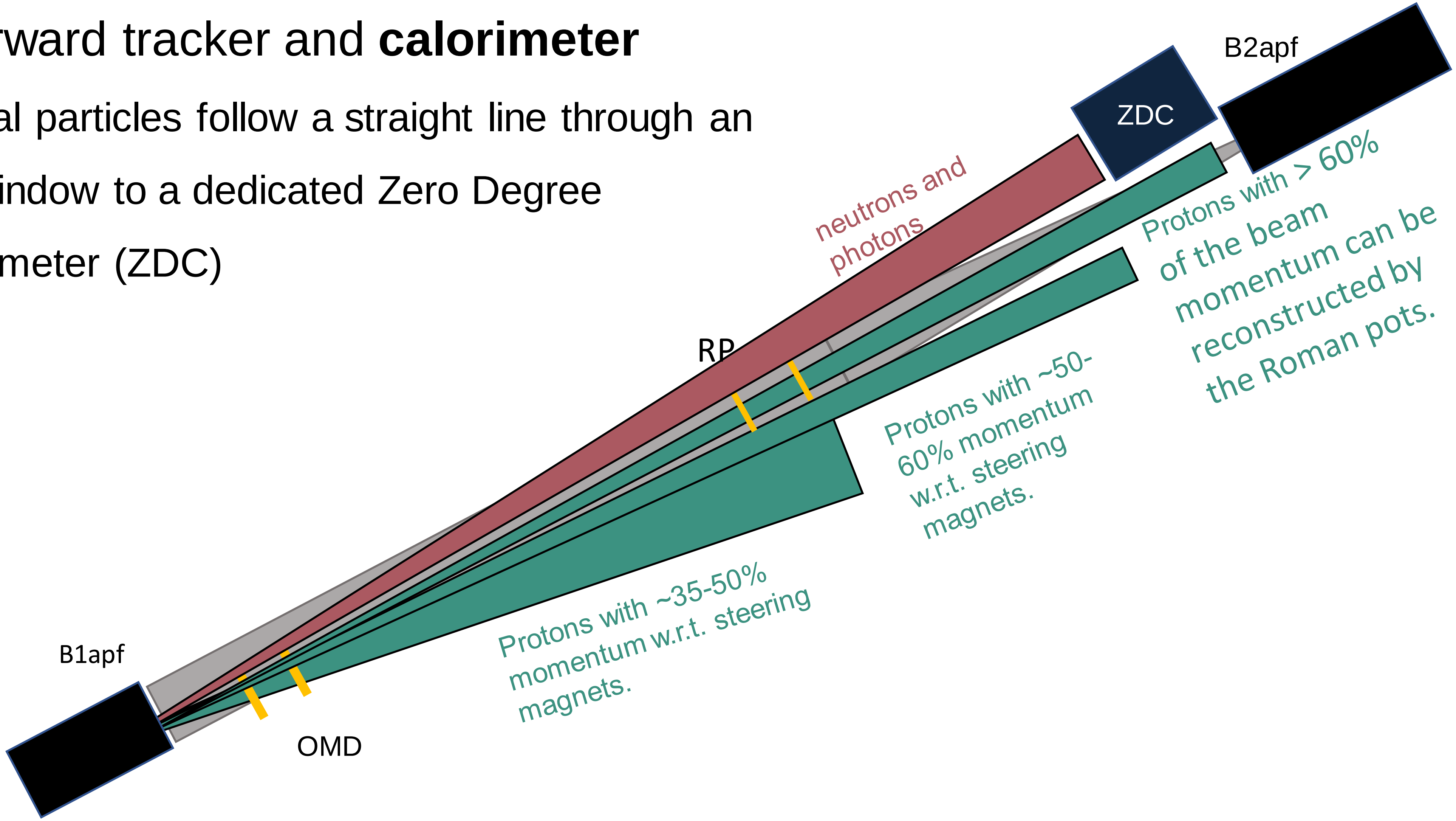
The Far-Forward detectors

- Very Forward **tracker** and calorimeter
  - Off-momentum protons → smaller magnetic rigidity → **greater bending in dipole fields**
  - **Important for any measurement with nuclear breakup!**



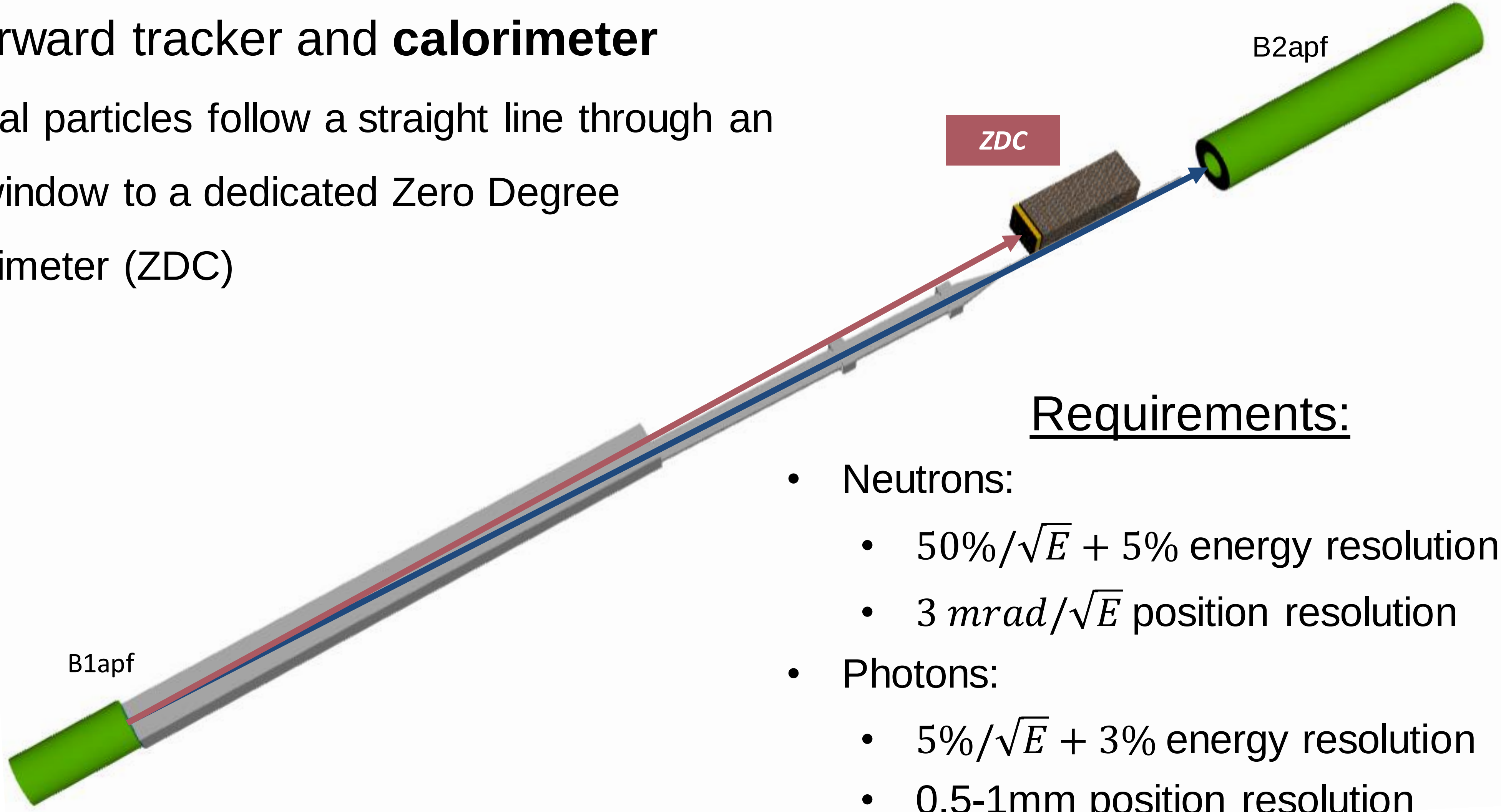
The Far-Forward detectors

- Very Forward tracker and **calorimeter**
  - Neutral particles follow a straight line through an exit window to a dedicated Zero Degree Calorimeter (ZDC)



The Far-Forward detectors

- Very Forward tracker and **calorimeter**
  - Neutral particles follow a straight line through an exit window to a dedicated Zero Degree Calorimeter (ZDC)

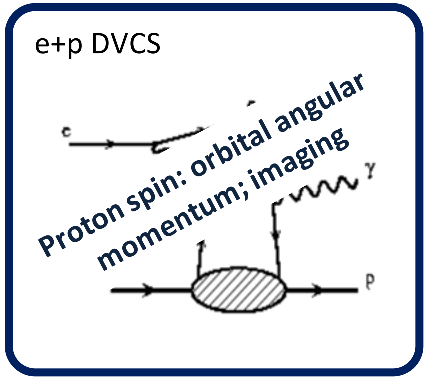


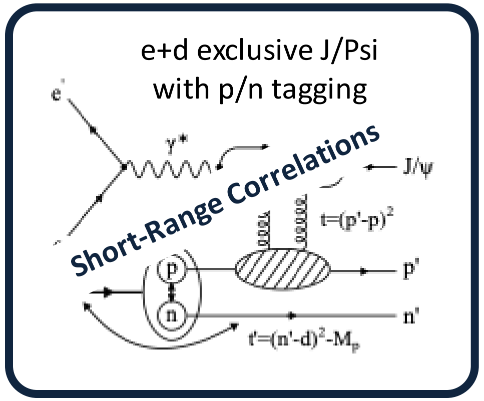
Requirements:

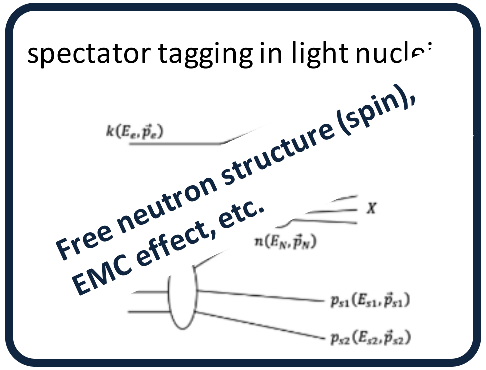
- Neutrons:
  - $50\%/\sqrt{E} + 5\%$ energy resolution
  - $3\ mrad/\sqrt{E}$ position resolution
- Photons:
  - $5\%/\sqrt{E} + 3\%$ energy resolution
  - 0.5-1mm position resolution

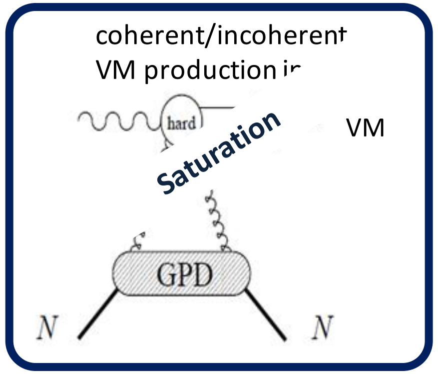
Forward physics at the EIC

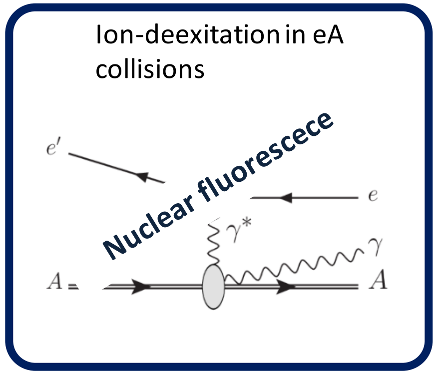
- Far-Forward detectors extend the physics program which was initially envisioned, enhancing the EIC's research potential:

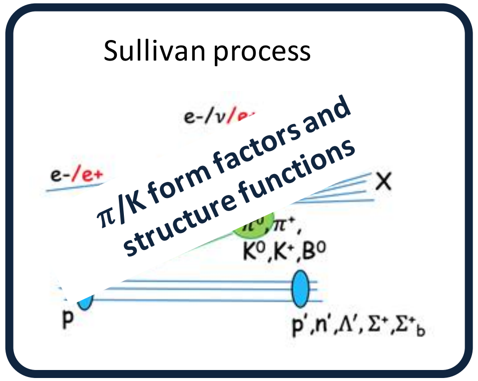


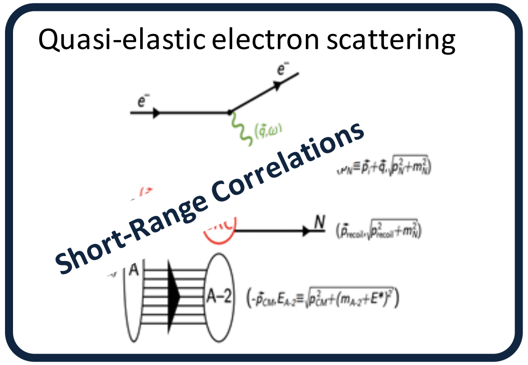


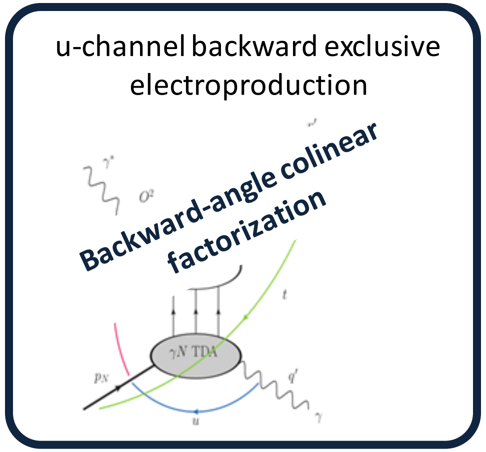


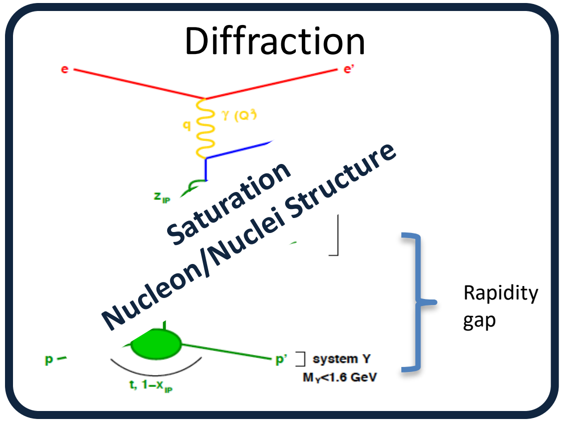






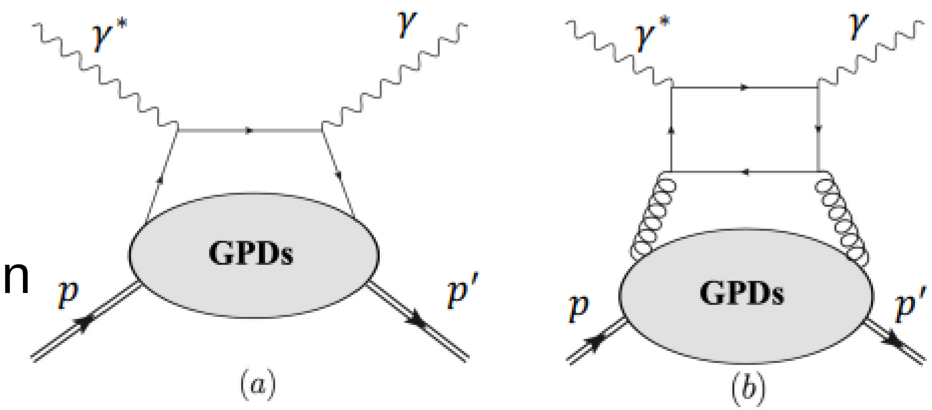


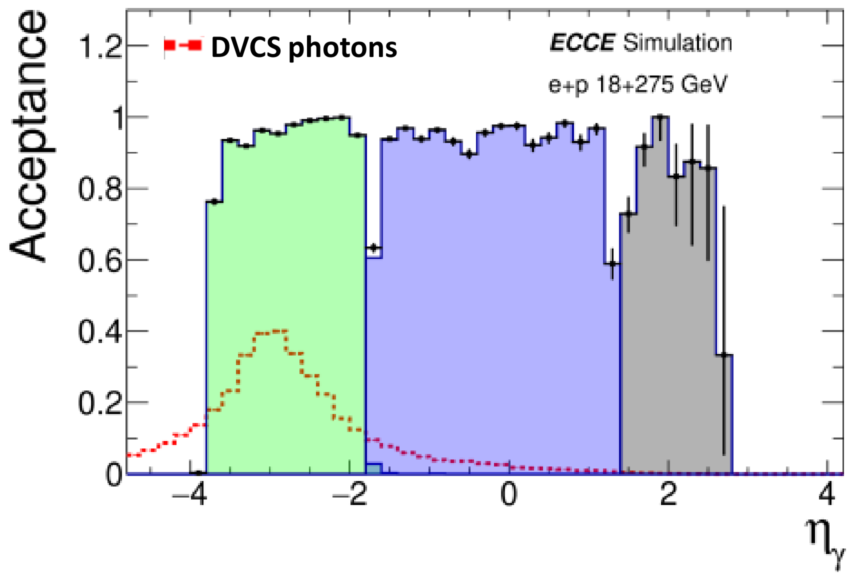


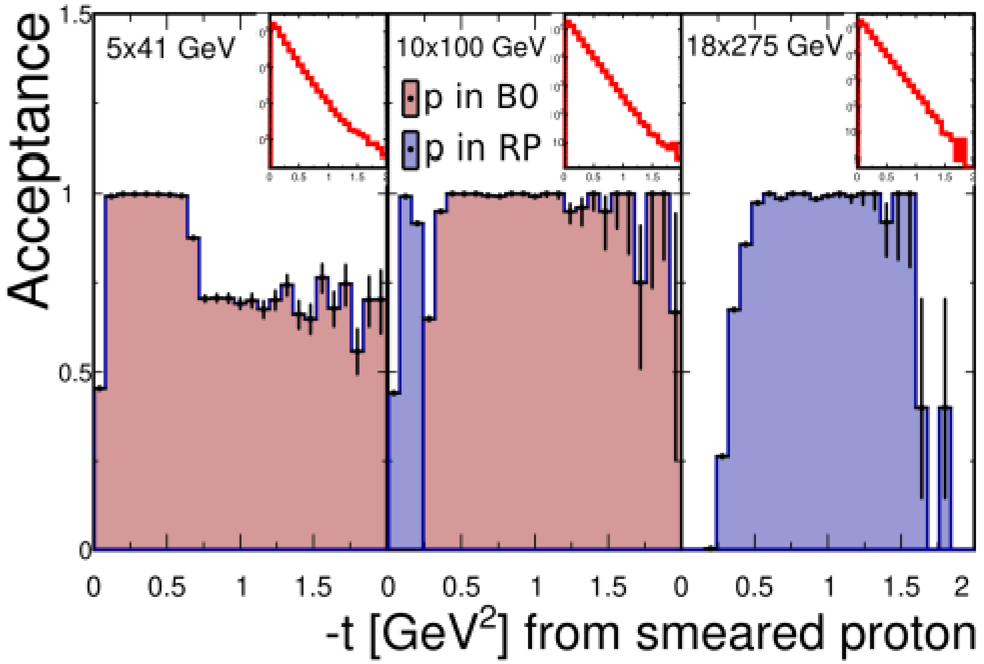


Physics perspectives (examples)

- ep Deep Virtual Compton Scattering
  - Core of the physics program
  - Study of the Generalized Parton Distributions of the proton
  - Main background: Bethe-Heitler process



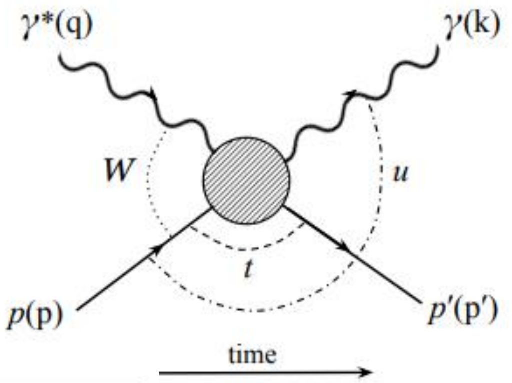


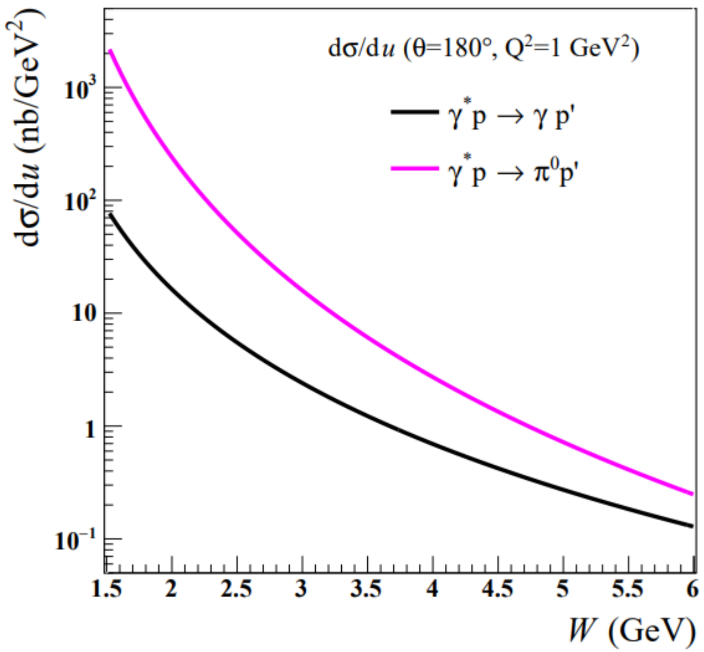


NIMA 1052(2023) 168238

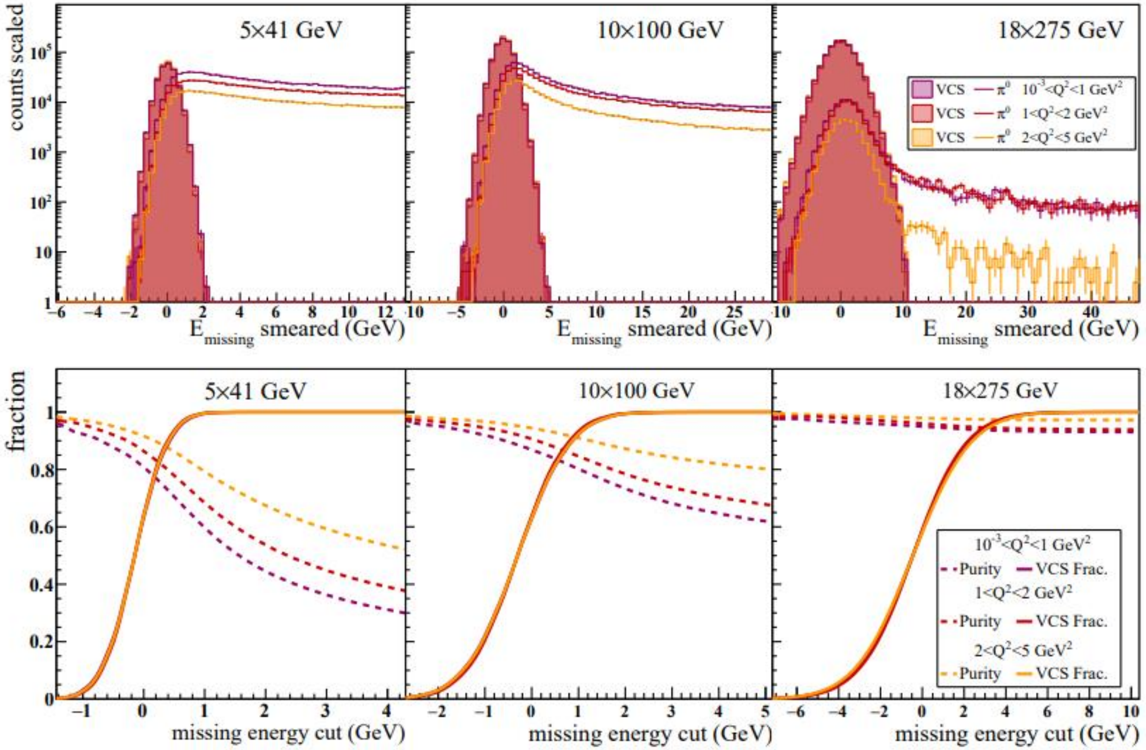
Physics perspectives (examples)

- Backward DVCS (u-channel)
- Challenge: Large backgrounds from backward π^0 production
- Background rejection – well-segmented ZDC ($\Delta x^{\gamma\gamma} \approx 70 \cdot m_\pi / E_{beam}$ [meter])



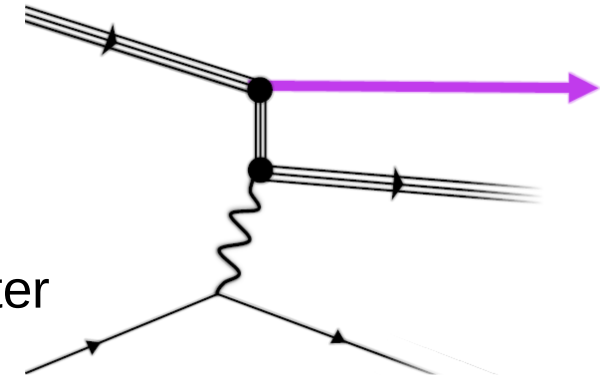


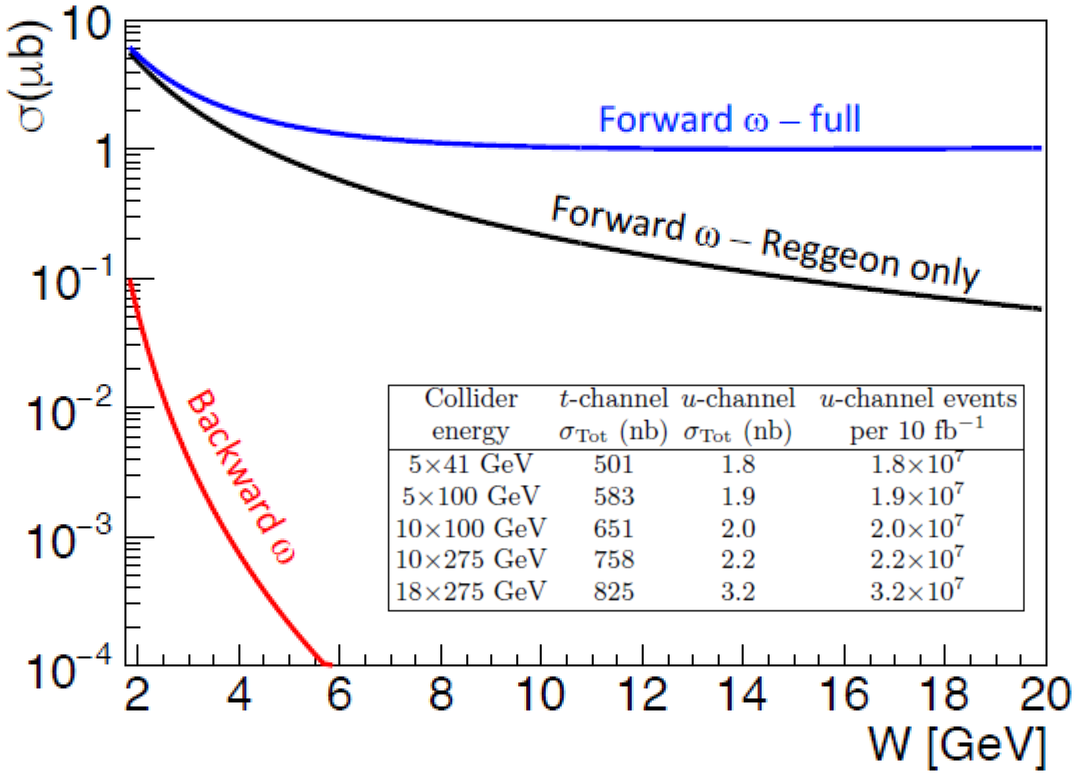
[PRC **108** (2023) 5, 055205]



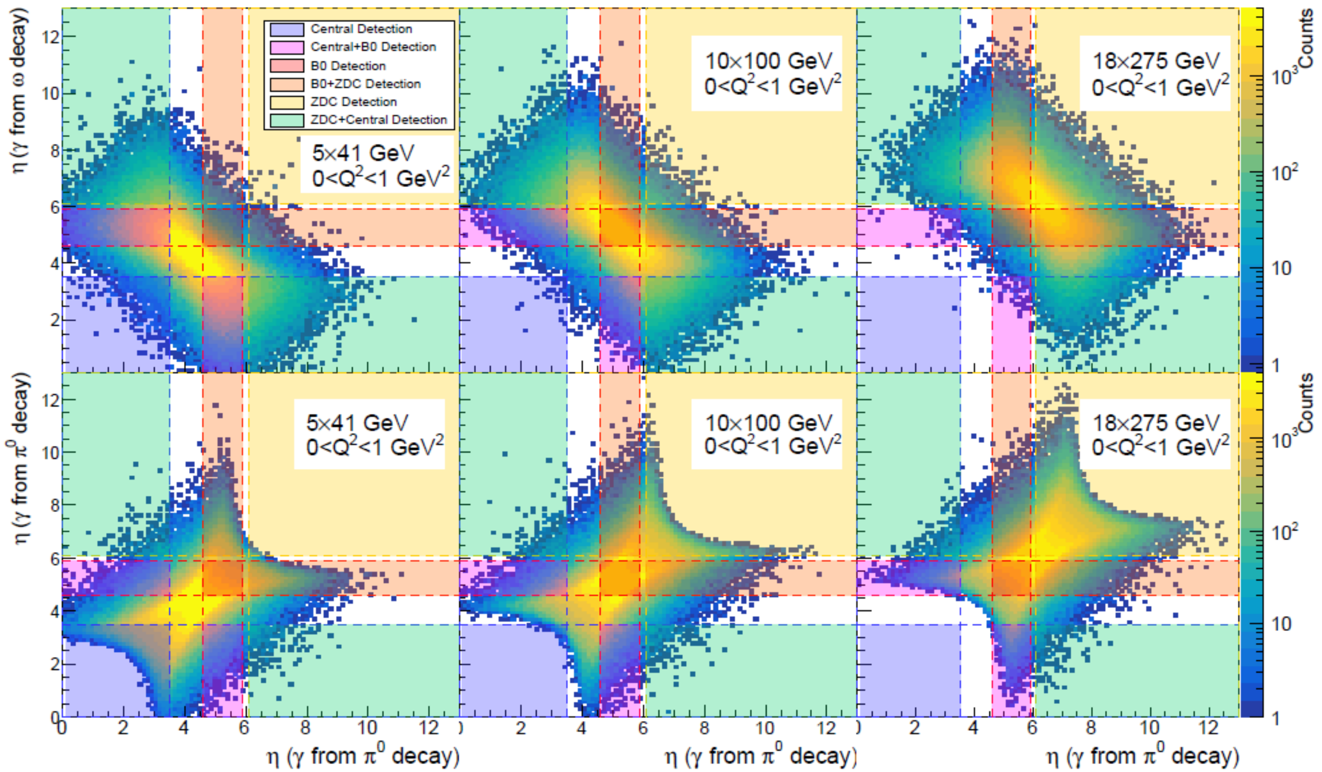
Physics perspectives (examples)

- Backward ω production (u-channel)
- Via $\omega \to \pi^0 \gamma \to \gamma\gamma\gamma$ decay mode (8.3%)
- ω could be faithfully reconstructed, but at a low efficiency without B0 calorimeter





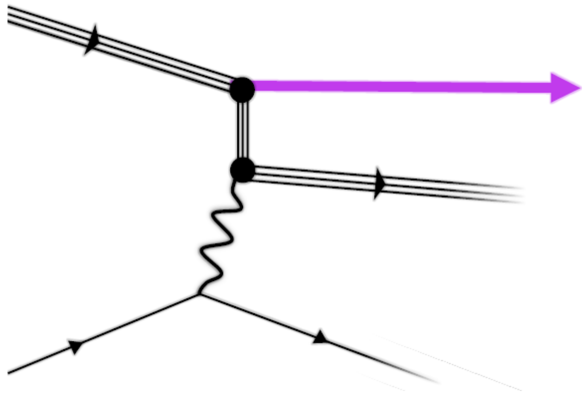
Collider energy	t-channel σ_{Tot} (nb)	u-channel σ_{Tot} (nb)	u-channel events per 10 fb^{-1}
5×41 GeV	501	1.8	1.8×10^7
5×100 GeV	583	1.9	1.9×10^7
10×100 GeV	651	2.0	2.0×10^7
10×275 GeV	758	2.2	2.2×10^7
18×275 GeV	825	3.2	3.2×10^7

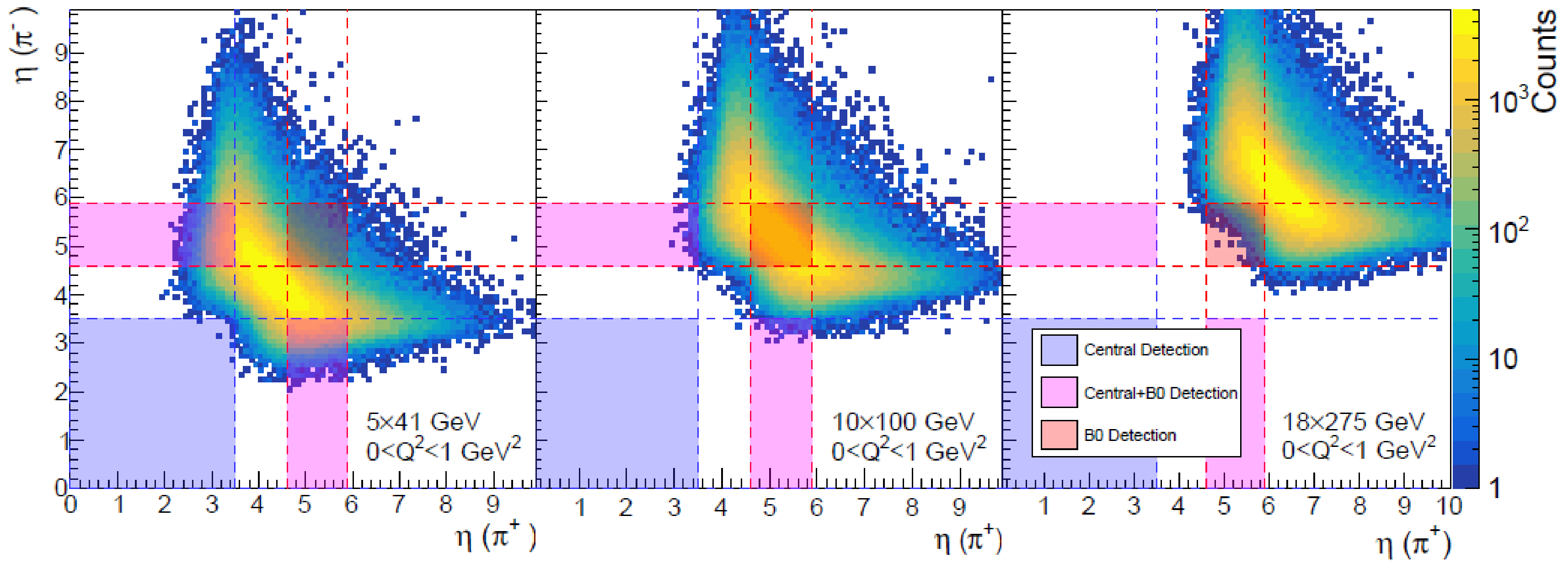


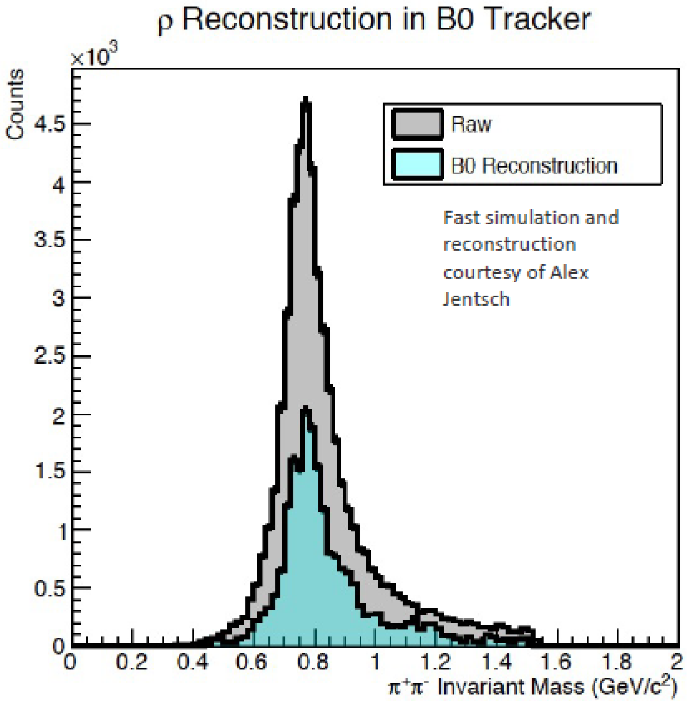
PRC **106** (2022) 015204

Physics perspectives (examples)

- Backward ρ^0 production (u-channel)
- Via $\rho^0 \rightarrow \pi^+\pi^-$ decay mode
- B0 tracking should be the priority for this channel (10x100 GeV^2)



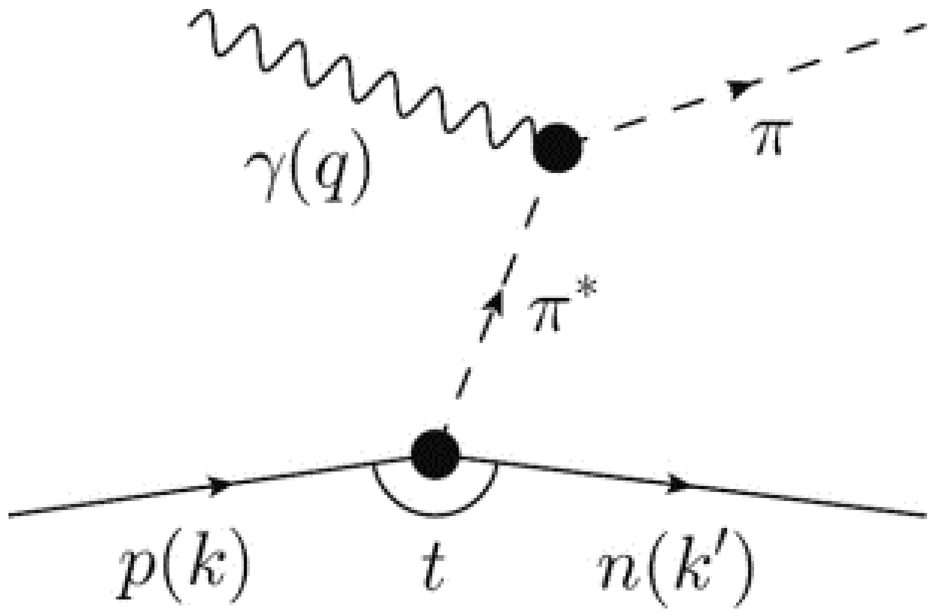


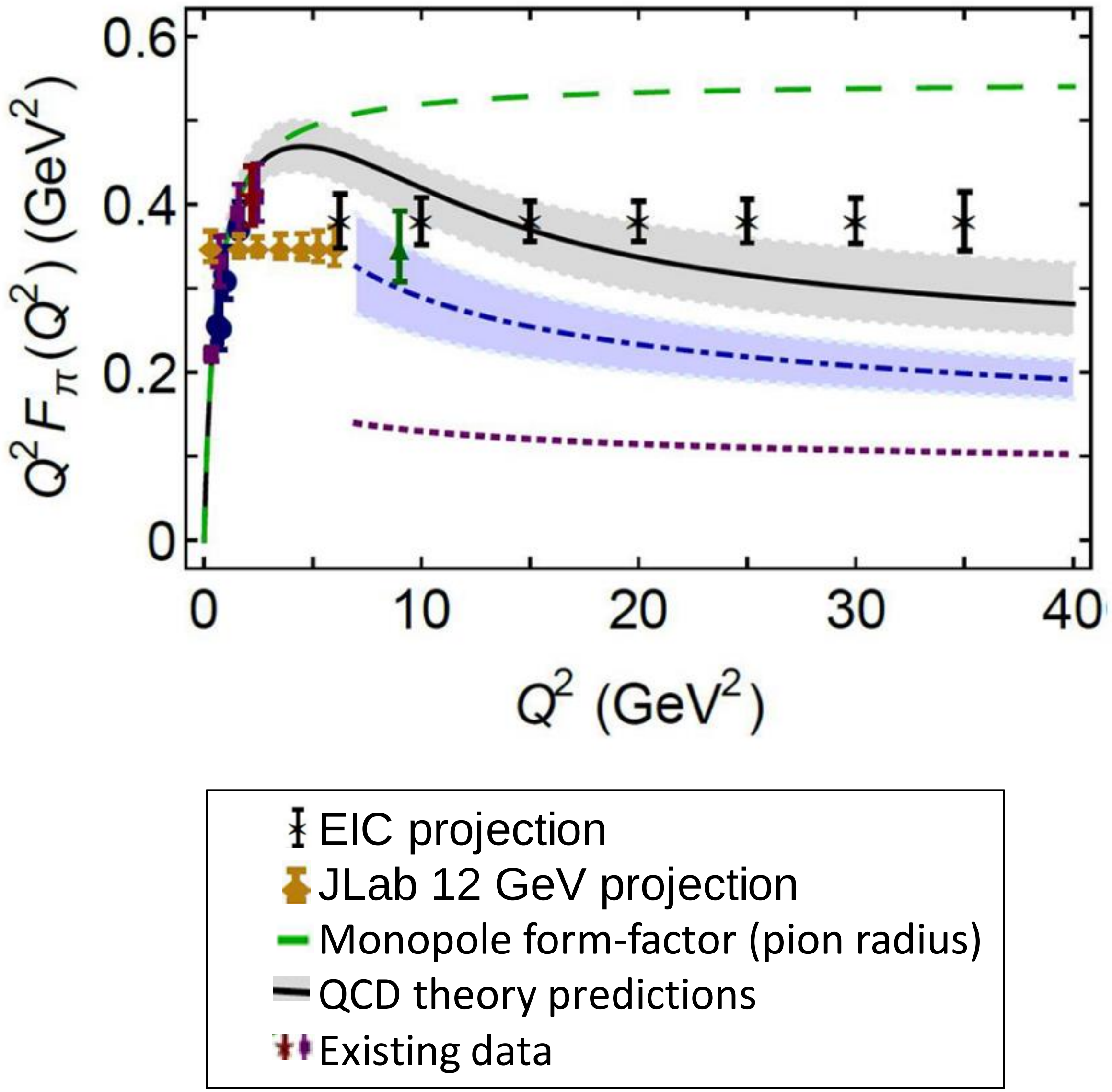


PRC **106** (2022) 015204

Physics perspectives (examples)

- Pion/Kaon form factors
  - Exclusive electroproduction
  - Challenges: Tagging the forward particles

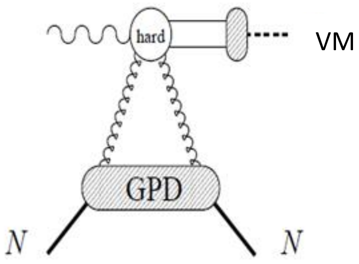


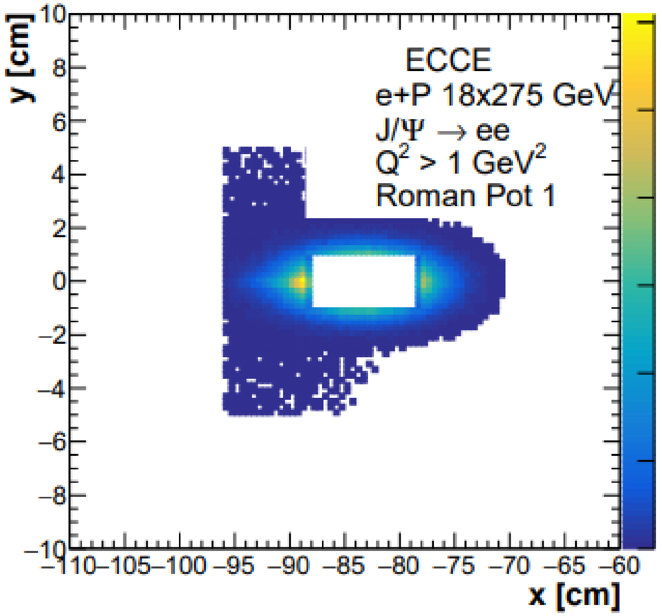


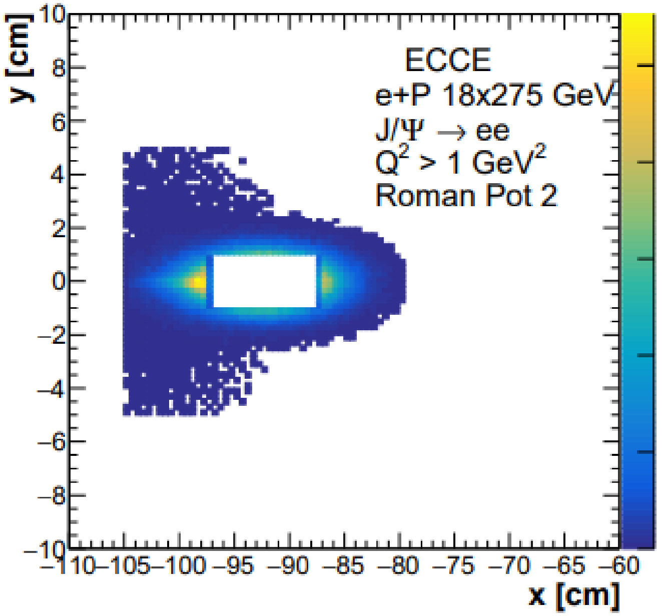
EPJA **55** (2019) 10, 190

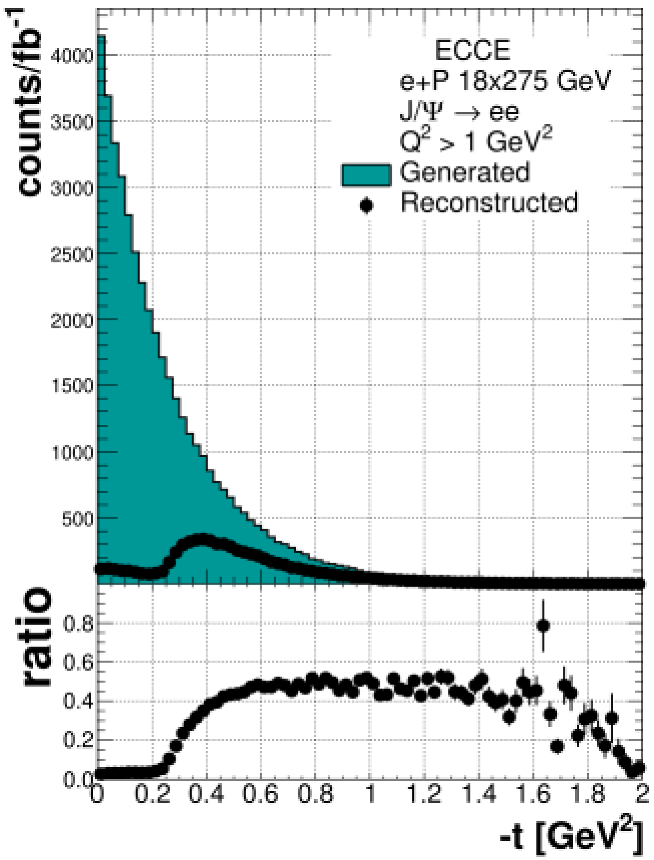
Physics perspectives (examples)

- Coherent VM production in ep collisions
  - Challenge: Forward proton acceptance
  - Pending updates with the recent ePIC geometry





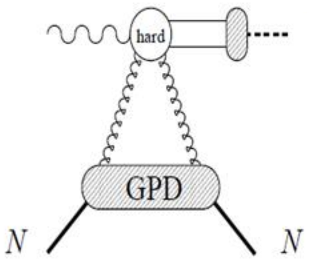


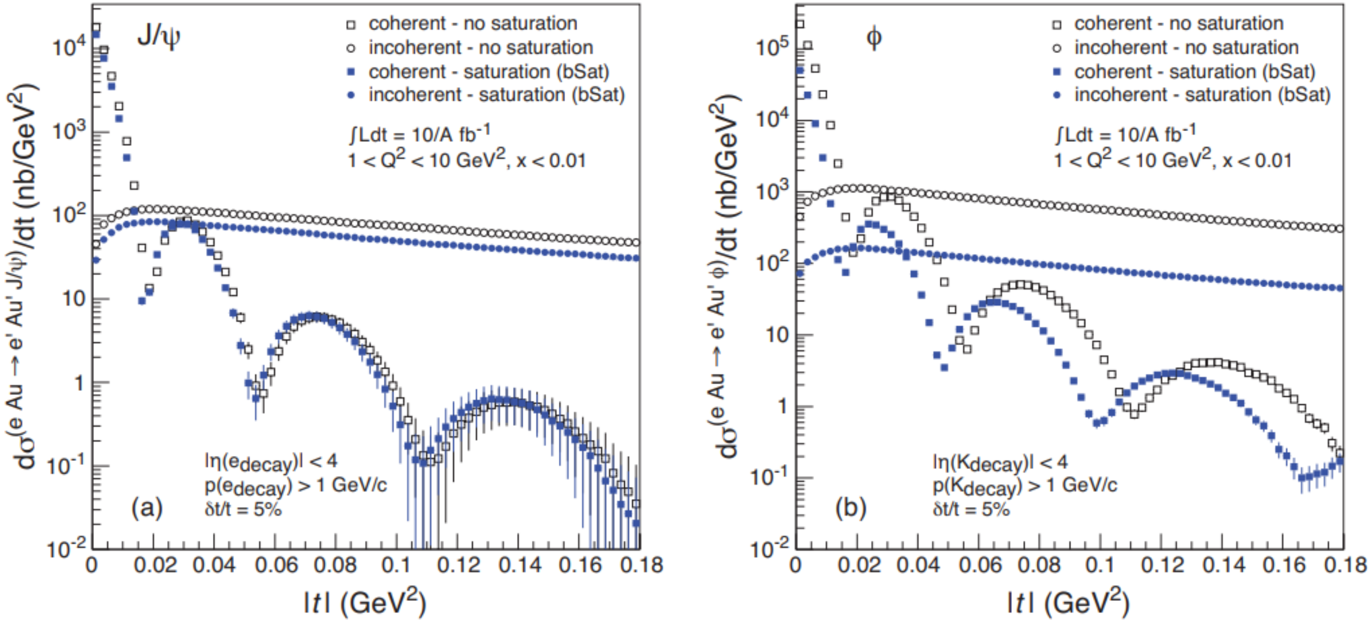


[NIMA **1052** (2023) 168238]

Physics perspectives (examples)

- Coherent/incoherent VM production in eA collisions
  - Spectra is sensitive to saturation models





PRC **87** (2013) 2, 024913

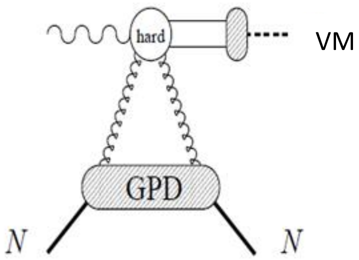
Some challenge to the Good-Walker paradigm

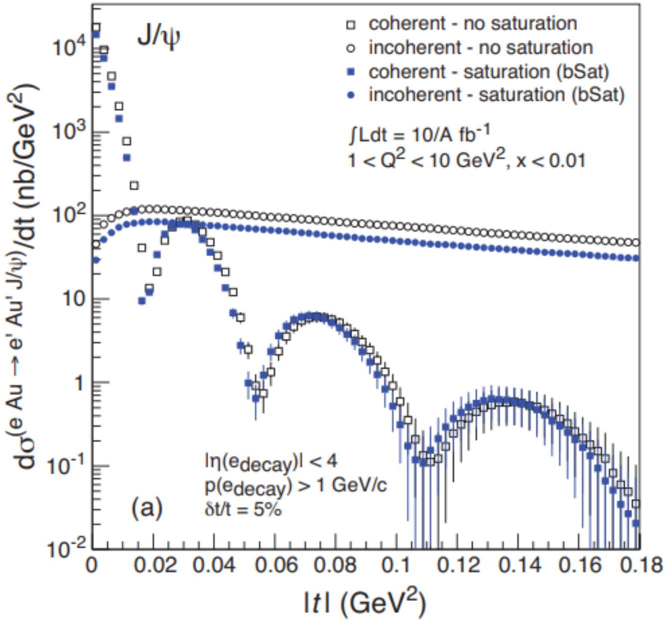
Significant differences suggested between ^{197}Au and ^{208}Pb, due to different lowest excited state energy 77 keV vs 2.6MeV respectively.

PRC 107 (2023) 5, 055203

Physics perspectives (examples)

- Coherent VM production in eA collisions
  - Challenge: Large backgrounds (incoherent production processes)

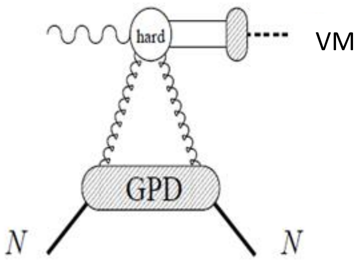


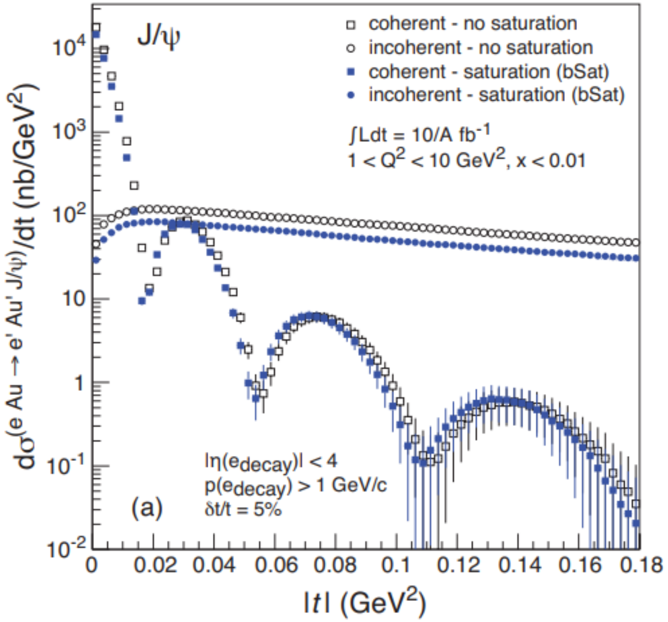


PRC **87** (2013) 2, 024913

Physics perspectives (examples)

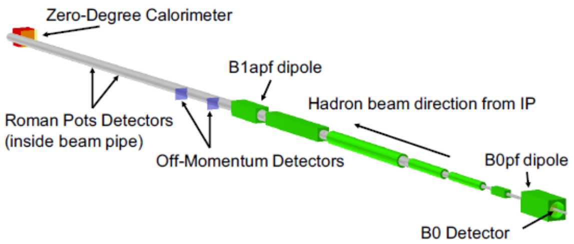
- Coherent VM production in eA collisions
  - Challenge: Large backgrounds (incoherent production processes)
  - The forward detectors array allows strong background rejection





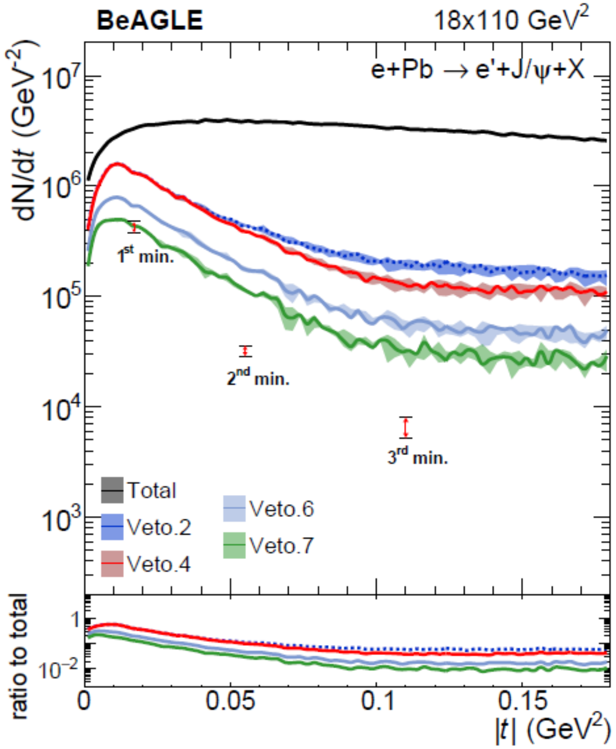
PRC **87** (2013) 2, 024913

+



- Veto.1: no activity other than e^- and J/ψ in the main detector ($|\eta| < 4.0$ and $p_T > 100$ MeV/c) ;
- Veto.2: Veto.1 and no neutron in ZDC;
- Veto.3: Veto.2 and no proton in RP;
- Veto.4: Veto.3 and no proton in OMDs;
- Veto.5: Veto.4 and no proton in B0;
- Veto.6: Veto.5 and no photon in B0;
- Veto.7: Veto.6 and no photon with $E > 50$ MeV in ZDC.

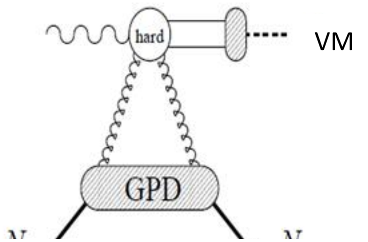
=



PRD **104** (2021) 11, 114030

Physics perspectives (examples)

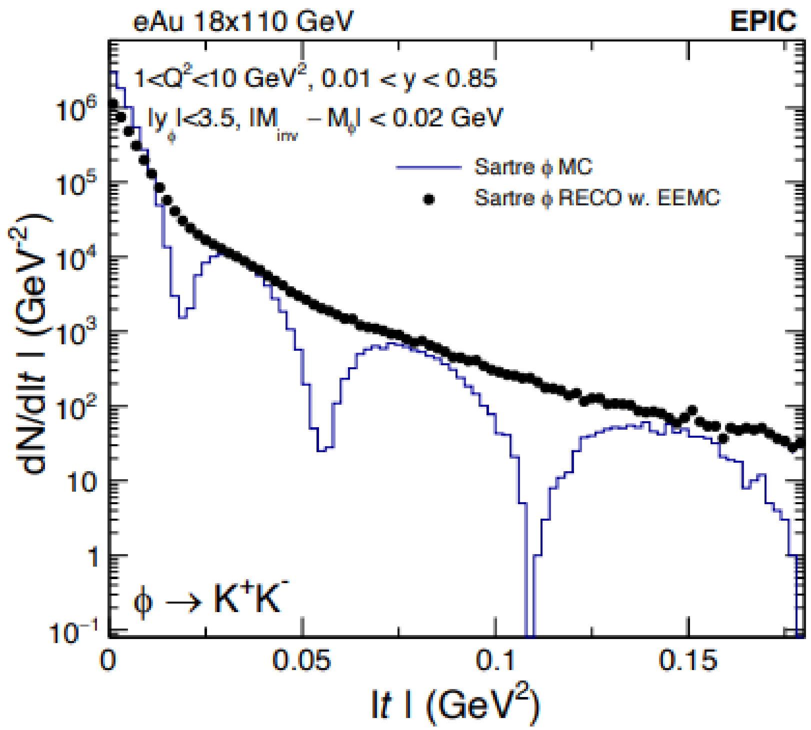
- Coherent VM production in eA collisions
  - Challenge 2: t reconstruction



Main challenge is reconstructing the dips

Legend details:

- w. EEMC: electron energy from EEMC, electron mass (PDG), angle (η, φ) K, from tracking

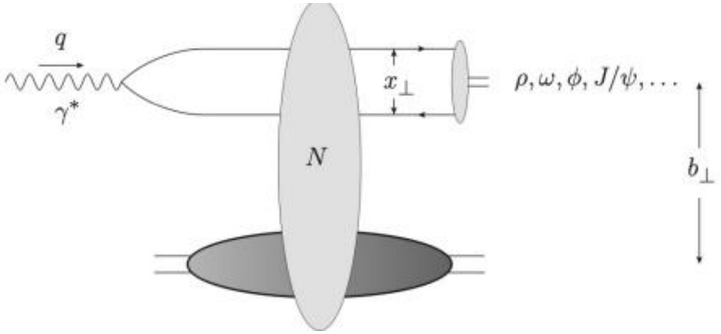


Kong Tu@EPIC Seminar (Mar 13, 2024)

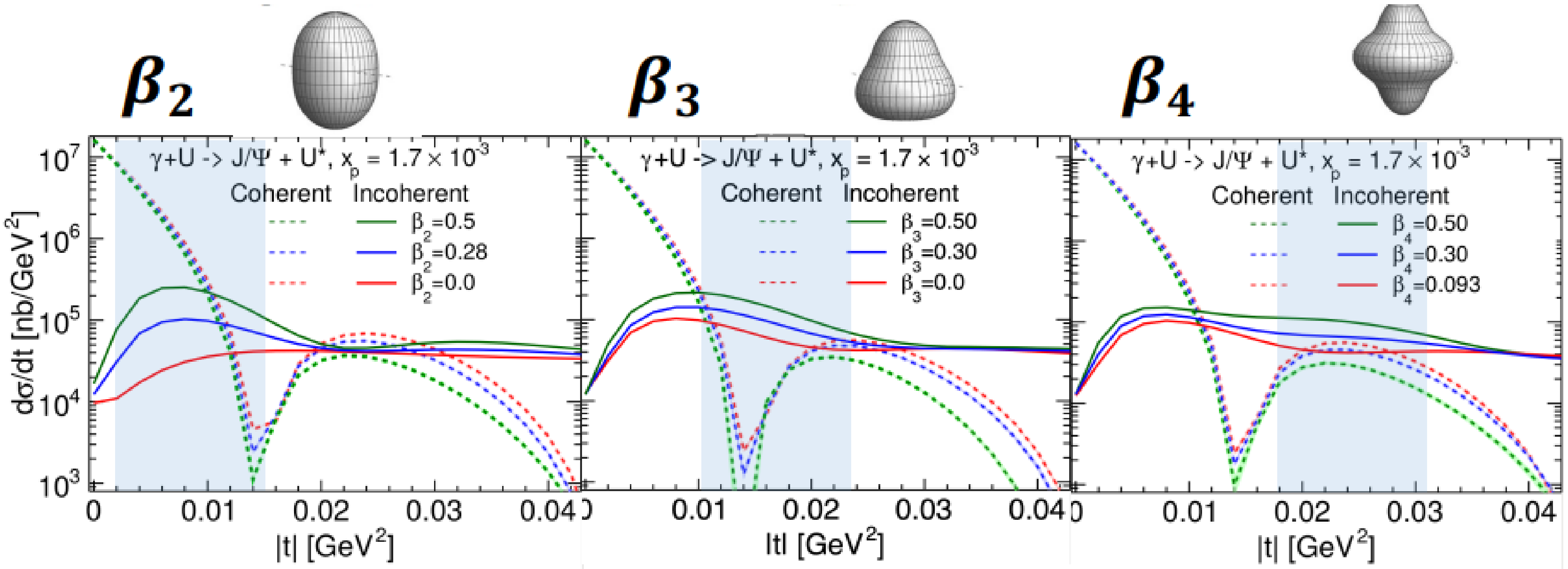
Physics perspectives (examples)

- Incoherent VM production in eA collisions
  - Probing the nuclear structure:

$$\rho(r,\Theta,\Phi) \propto \frac{1}{1+\exp\left([r-R(\Theta,\Phi)]/a\right)}, \quad R(\Theta,\Phi) = R_0\left[1+\underline{\beta_2}\left(\cos\underline{\gamma}Y_{20}(\Theta)+\sin\underline{\gamma}Y_{22}(\Theta,\Phi)\right)+\underline{\beta_3}Y_{30}(\Theta)+\underline{\beta_4}Y_{40}(\Theta)\right]$$



W. Zhao@LHCP2024



PRL 131 (2023) 062301

Summary

- There is an impressive extension of the nominal physics program[1] foreseen with the current detectors of the ePIC experiment
- All Forward detector acceptances and detector performance are well-understood with currently available information
- A large focus has been placed now on simulation studies of various processes in preparation for the ePIC Technical Design Report (TDR)

Coming soon[2]: the full list of the physics projections for the ePIC detector including the extended Forward Physics programm

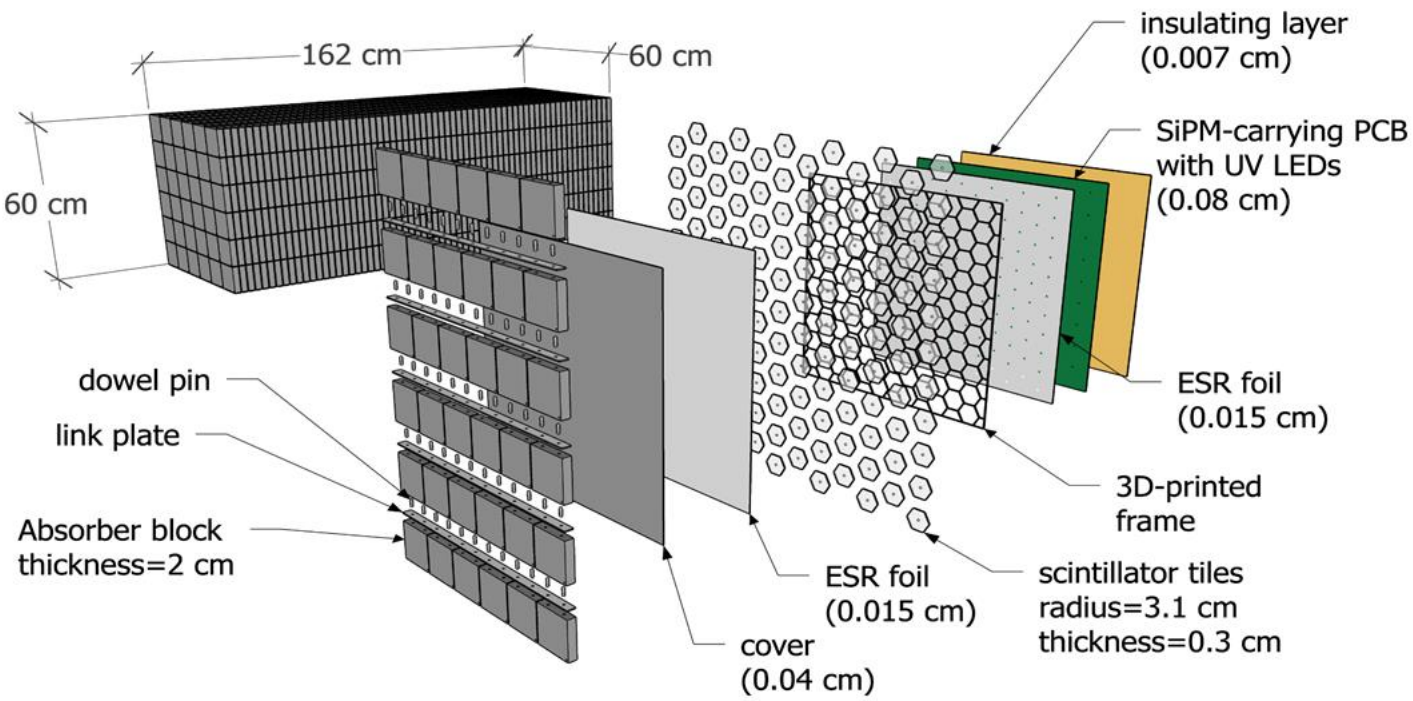
[1] EIC Yellow report (Nucl. Phys. A 1026 (2022) 122447)

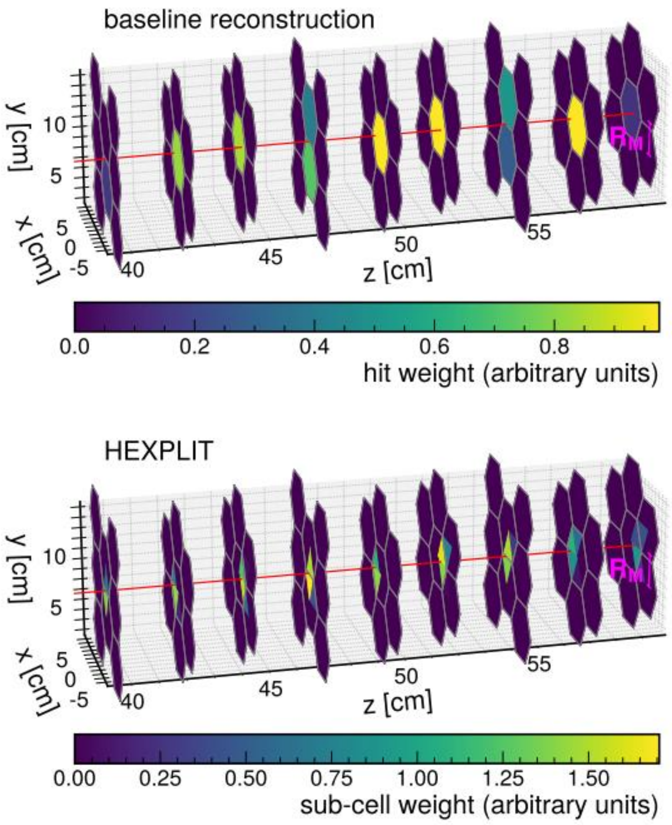
[2] Early 2025

Backup

The Far-Forward detectors

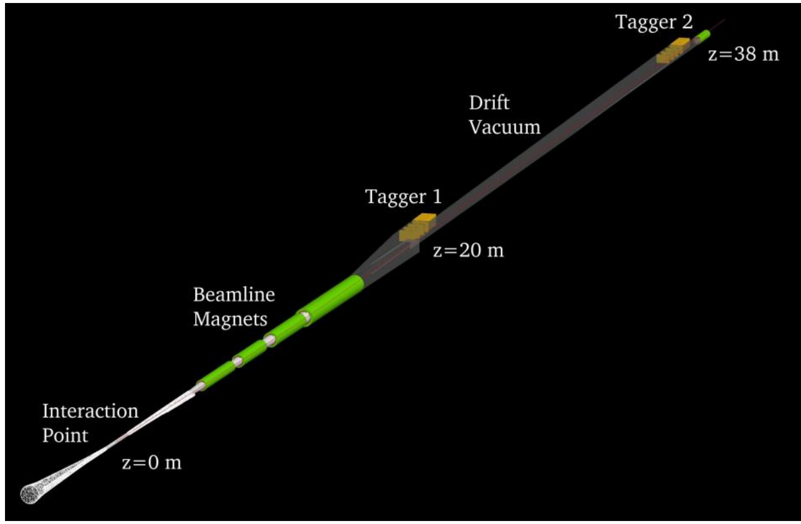
- Zero Degree Calorimeter (ZDC)
  - Hadronic section – similar to forward hadron calorimeter (see more in Henry Klest talk)
  - ML based reconstruction using the HEXPLIT algorithm (2308.06939)

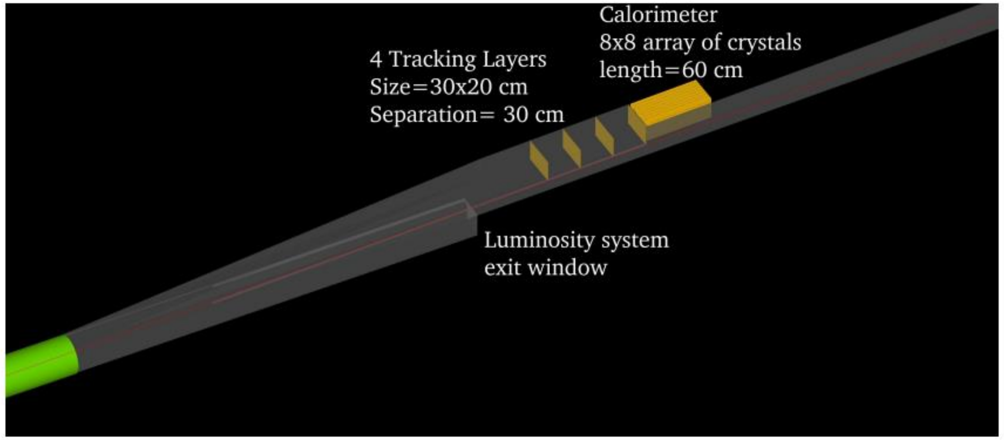


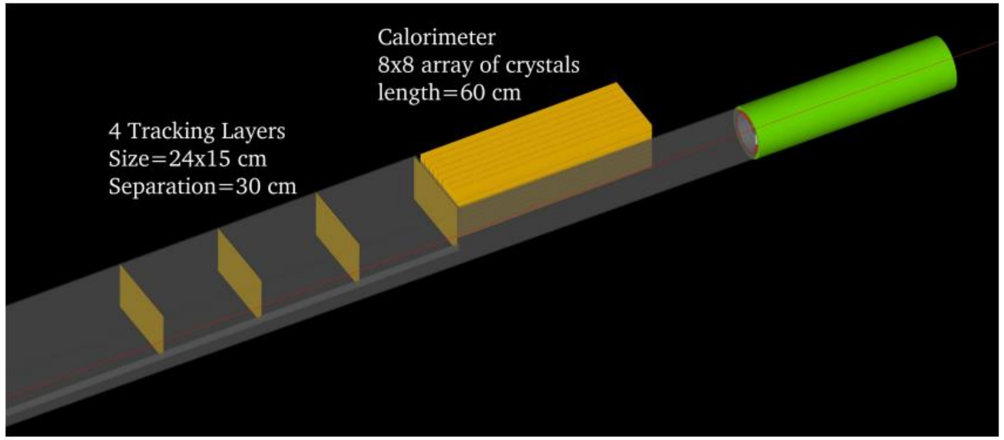


Low Q^2 electron tagger

- Central detector acceptance: $Q^2 > 0.1\ GeV^2$ outgoing electrons
- Allow quasi real (Q<<1) physics
  - 2 taggers:
    - ✓ Pixel-based 4 trackers (Timepix4), with rate capability of > 10 tracks per bunch
    - ✓ Calorimeters (for calibration)
  - Challenges: high, non-uniform Brem. background







https://arxiv.org/abs/2305.02079