Exotic heavy meson spectroscopy and structure with EIC

Diffractive Quarkonium Production of Vector Mesons at the Electron-Ion Collider (EIC)

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2025/04/16

CFNS, Stony Brook University

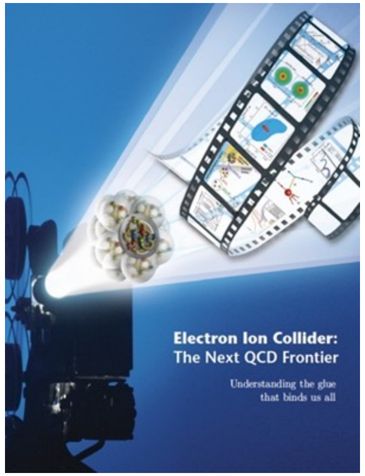
Electron-Ion Collider (EIC) Physics

Investigate **dynamics of gluons** to understand emergence of properties of quarks and gluons in nucleons and nuclei (= **QCD** physics)

Main Questions:

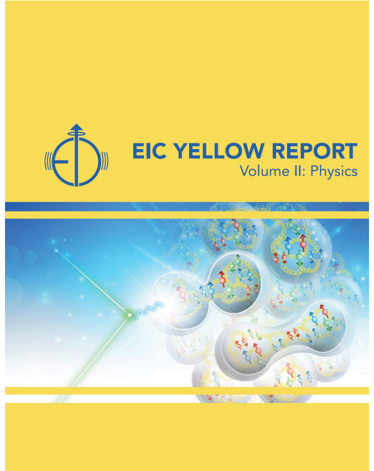
- (**3D Imaging**) How are sea quarks and gluons distributed in space and momentum inside the nucleon?
- (**Origin of Mass and Spin**) How do nucleon properties emerge from sea quarks and gluons and their interaction?
- (**Gluon Saturation**) What happens to gluon density at low-x?

2012



White Paper

2021



Yellow Report

Eur. Phys. J. A (2016) 52: 268, arXiv:1212.1701
Nucl. Phys. A 1026 (2022) 122447, arXiv:2103.05419

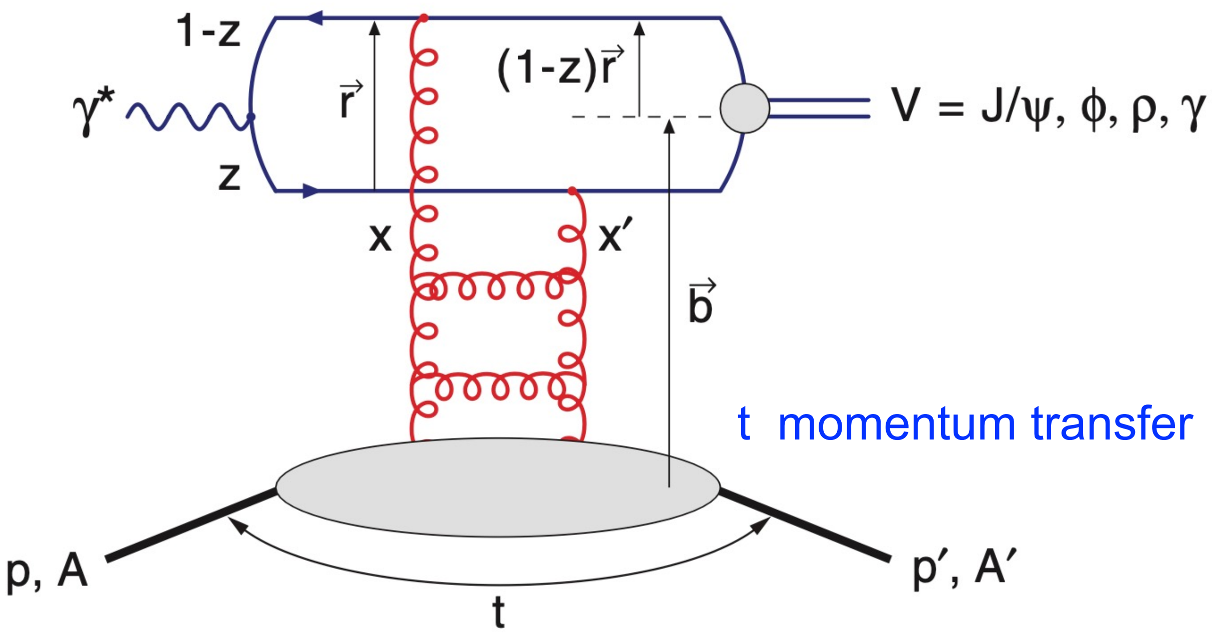
Comprehensively discussed in
White paper (**physics cases**) and Yellow report (**detector requirements + concepts**)

Motivation and How

Diffractive Vector Meson (VM) production

Sensitive probe to **gluon spatial distributions** and **their fluctuations** → **Gluon density**

Phys. Rev. C **87**, 024913 (2013), arXiv:1211.3048



Dipole model of diffractive VM

Measure **Exclusive VM production**

$e + p \rightarrow e' + p' + \mathrm{J}/\psi$

Cross section as a function of momentum transfer (t) reflects spatial distribution of gluons inside nucleus

|t| conjugate to **impact parameter** by *Fourier transform*

$(\vec{p}_{\mathrm{gluon}} \leftrightarrow \vec{b}_{T,\,\mathrm{gluon}})$

Motivation and How

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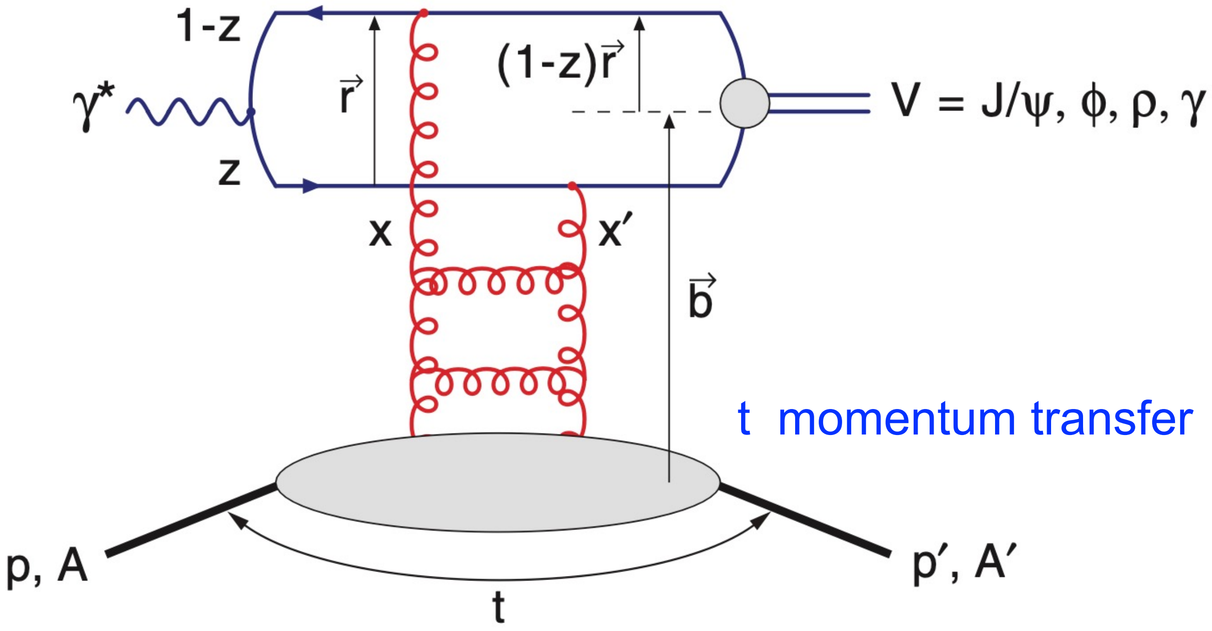

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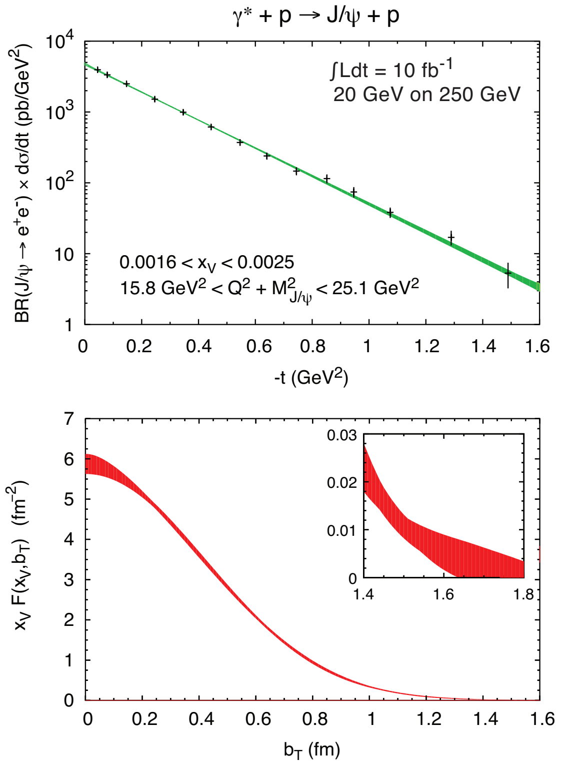
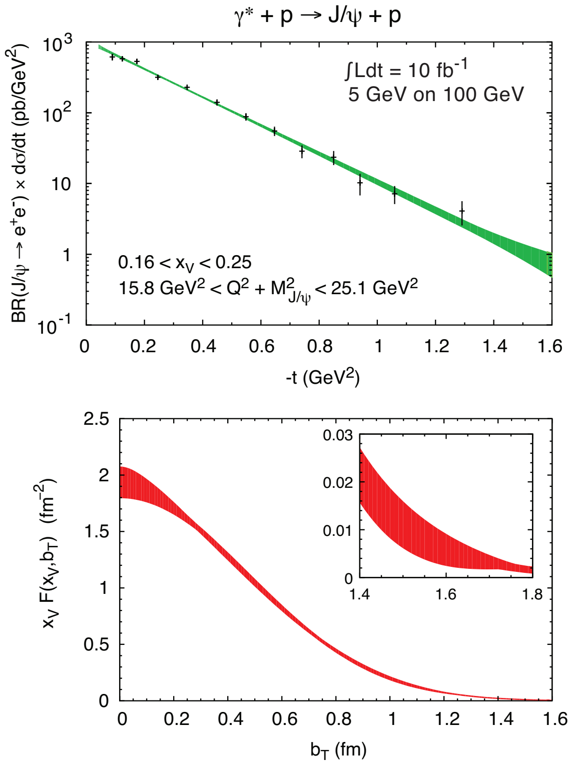
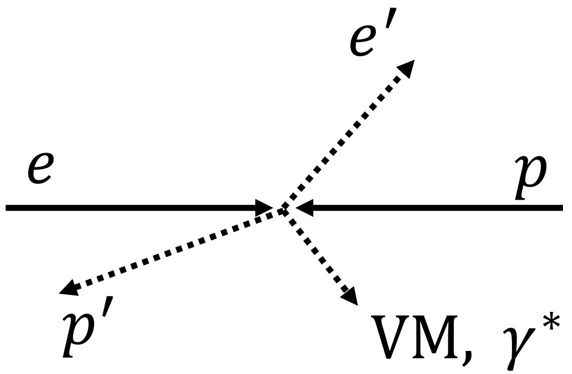




Reconstruction Method of t

$e + p$ Collision

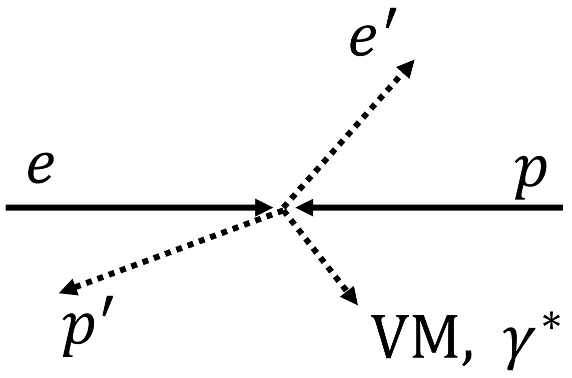


$$t = (p_A - p_{A'})^2$$

p_A is known (beam)
$p_{A'}$ is measured by
far-forward proton spectrometers

Reconstruction Method of t

$e + p$ Collision



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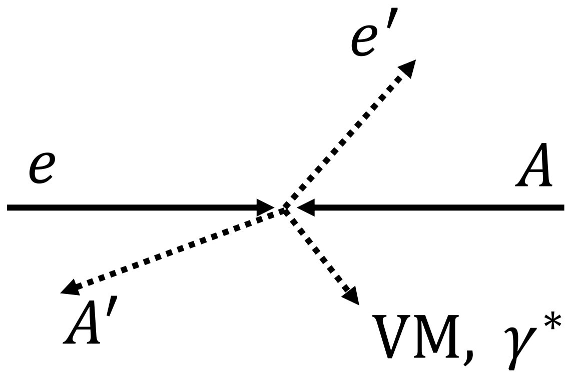

$$t = (p_A - p_{A'})^2$$

p_A is known (beam)
We *cannot* measure $p_{A'}$
In exclusive vector meson production:
$$e + A \rightarrow e' + A' + \mathrm{VM}$$
since 4-momenta from e, A, e', and VM are known

Reconstruction Method of t

- **Method E**xact: $t = (p_{A'} - p_A)^2 = (p_{\text{VM}} + p_{e'} - p_e)^2$
  - **Sensitive to beam effects** (beam divergence and momentum spread)
  - Subtract large incoming and large outgoing momenta to get longitudinal part → small error/smearing/inaccuracy make enormous effect on t

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  - Extensively used at HERA in diffractive vector meson studies

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- **Method L**: t $= |p_A - p_{A',\mathrm{corr}}|^2$
  - Based on Method E and **only valid for coherent events** $p_{A'} = p_A - (p_{\mathrm{VM}} + p_{e'} - p_e)$
  - Corrects $p_{A'}$ and use true invariant mass of nucleus to compensate smearing in electron 4-momentum

Reconstruction Method of t

- **Method E**xact: t $= (p_{A'} - p_A)^2 = (p_{\mathrm{VM}} + p_{e'} - p_e)^2$
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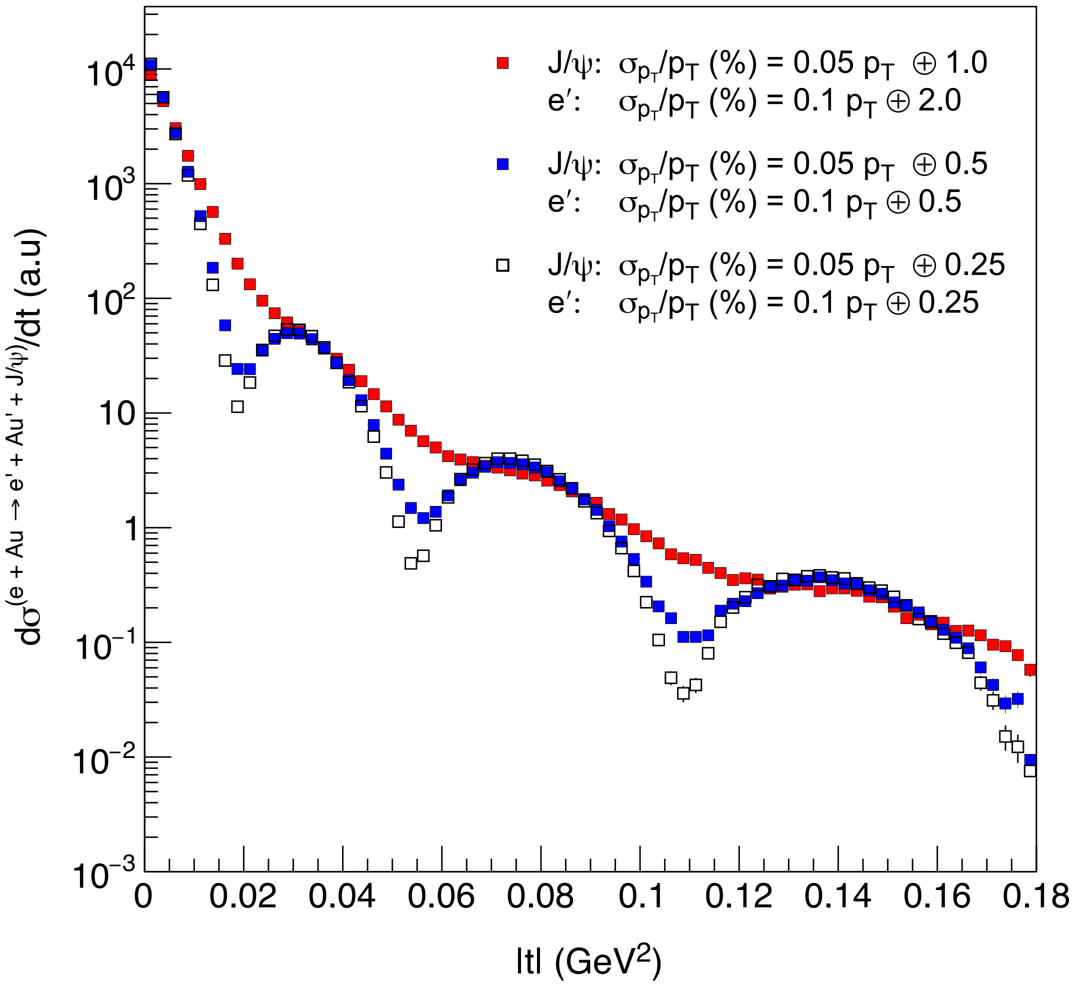
  - Corrects $p_{A'}$ and use true invariant mass of nucleus to compensate smearing in electron 4-momentum
- **A New Approach**: $|t|_{\hat{n}} = (p_{\mathrm{VM}} \cdot \hat{n} + p_{e'} \cdot \hat{n} - p_e \cdot \hat{n})^2 = (p_{\mathrm{VM}} \cdot \hat{n})^2$
  - Measure projection of $|t|_{\perp}$ along $\hat{n}$ of electron scattering plane and **eliminates momentum resolution contribution**

M. Kesler, A.I. Sheikh, R. Ma, Z. Tu, T. Ullrich, Z. Xu, arXiv:2502.15596

Challenges

Nucl. Phys. A 1026 (2022) 122447, arXiv:2103.05419



Structure of coherent diffractive **peaks/dips**

Two major challenges:

- Limited resolution in measuring t

  Outgoing electron momentum resolution

Challenges

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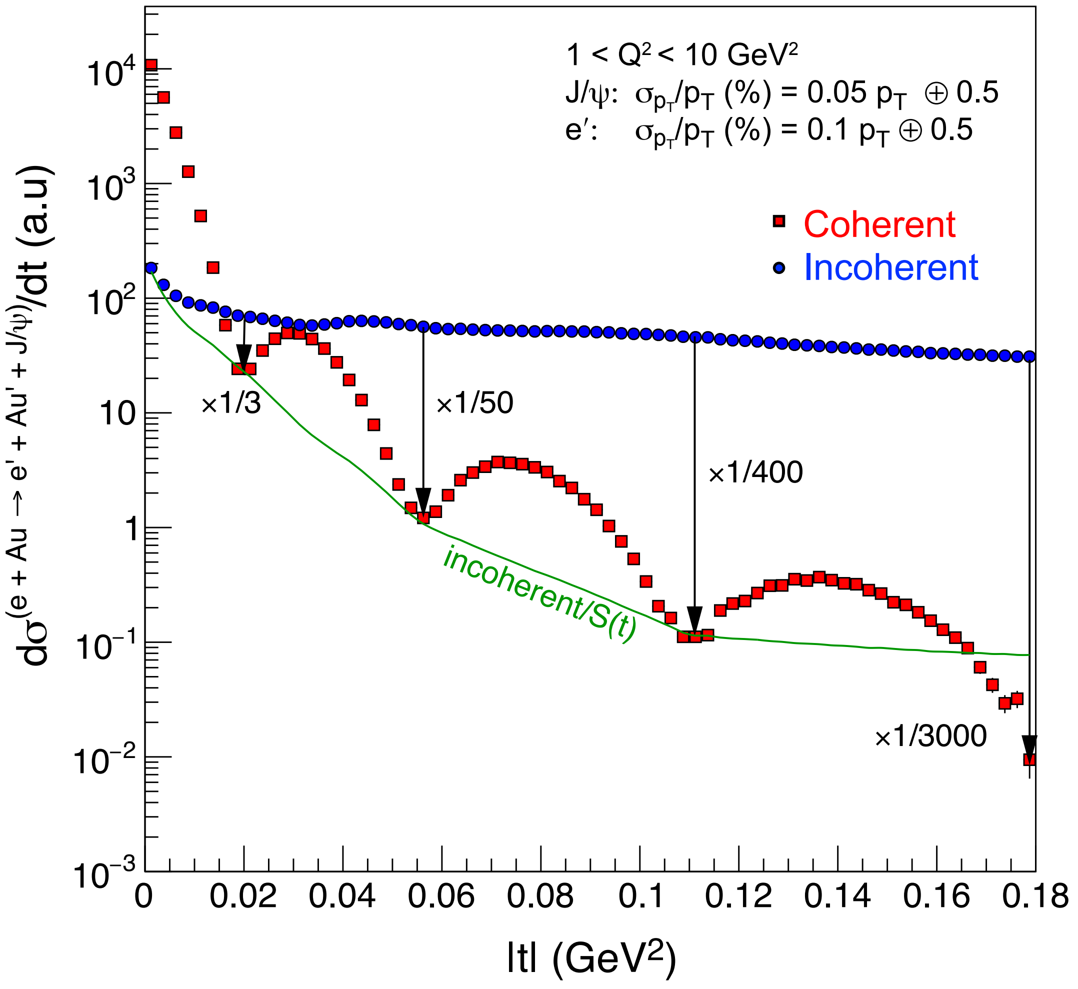


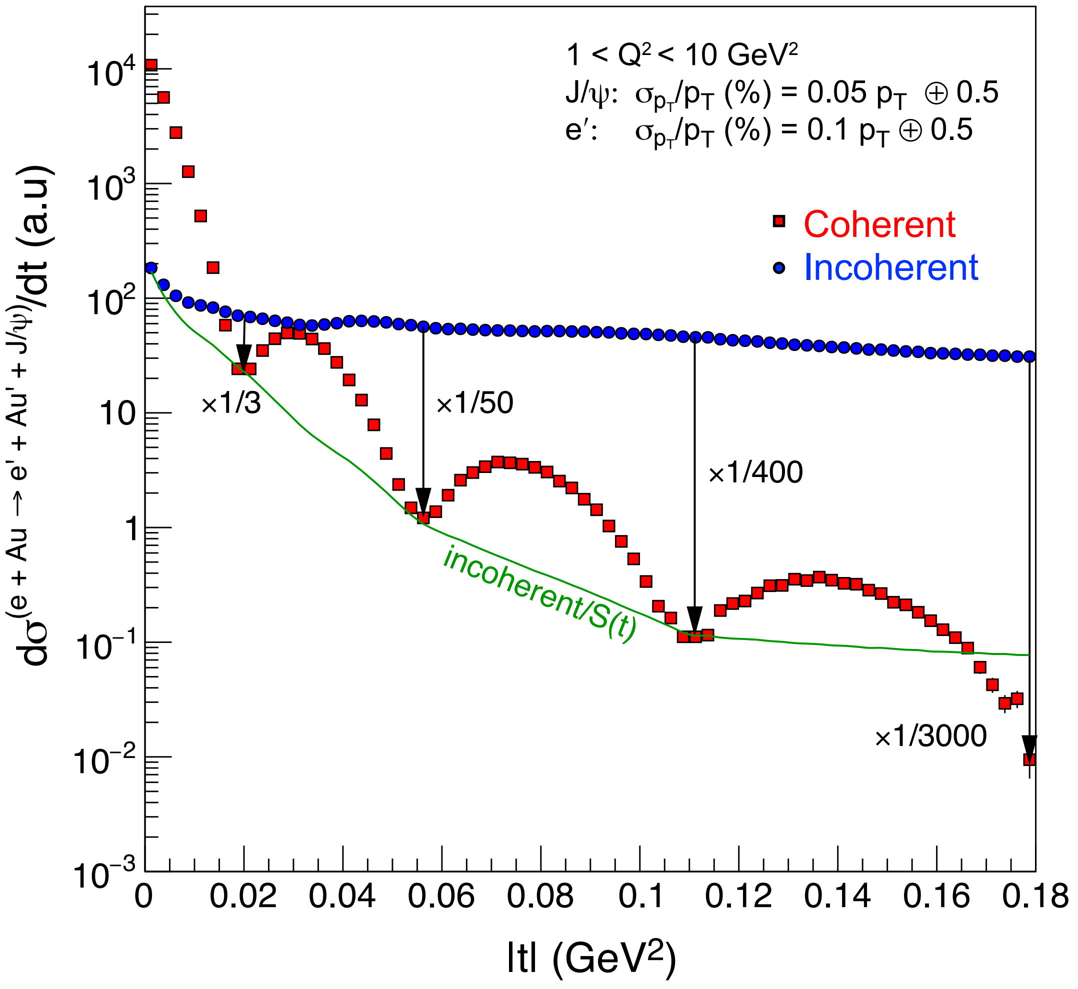
Structure of coherent diffractive **peaks/dips**

Two major challenges:

- Limited resolution in measuring t
  Outgoing electron momentum resolution
- Incoherent background dominates
  Tag incoherent event to veto

Challenges and Opportunities

Nucl. Phys. A 1026 (2022) 122447, arXiv:2103.05419



Structure of coherent diffractive **peaks/dips**

Two major challenges:

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At the Electron-Ion Collider

- High luminosity
- Excellent detector resolution
- Large detector acceptance
- Wide range in (x, Q^2) phase space

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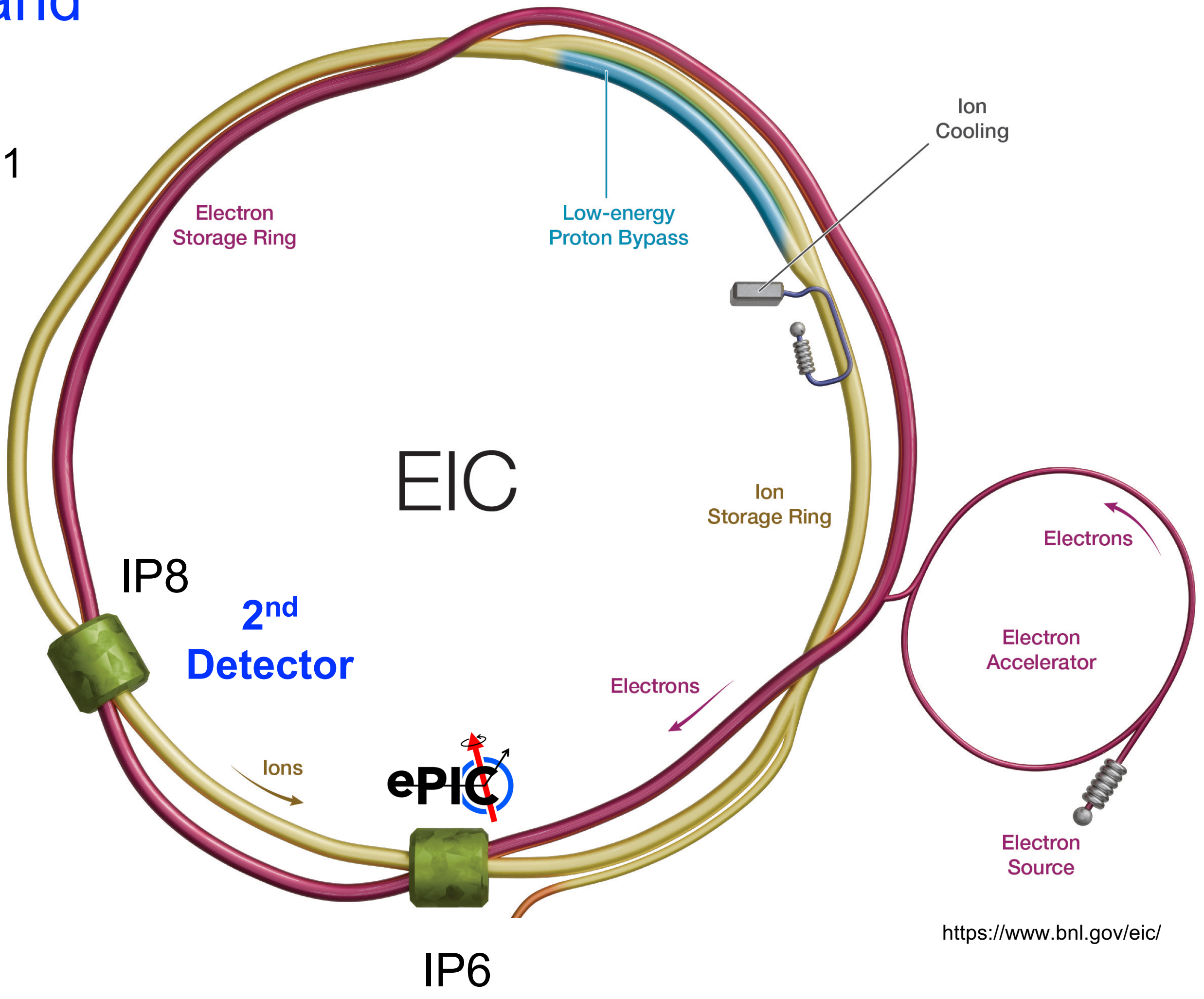
EIC **Machine** and its Realization

Unique, high-energy, high-luminosity, and polarized beam collider in this decade

- **High luminosity** $10^{33} – 10^{34}$ $cm^{-2}s^{-1}$ (100× HERA)
- **Large detector acceptance**
- **Wide center-of-mass energy** range ($\sqrt{s_{ep}} = 30 - 140$ GeV)
- **Polarization** > 70 %
- Electron 5 – 18 GeV
- Ion 41, 100 – 275 GeV
  Variety of hadron/ion beams: p to Pb
  Polarization for light ions



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

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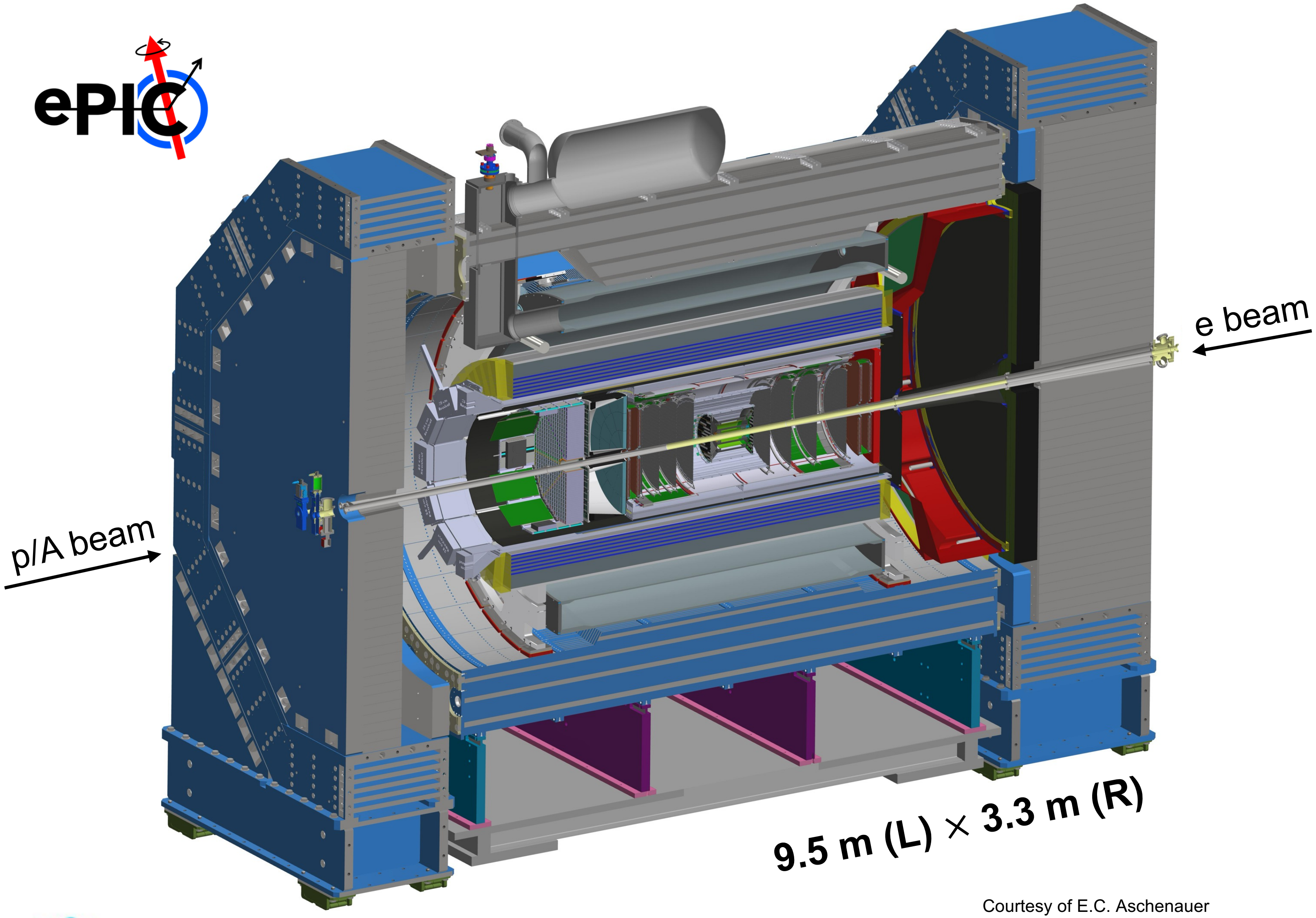
ePIC Central Detector



Courtesy of E.C. Aschenauer

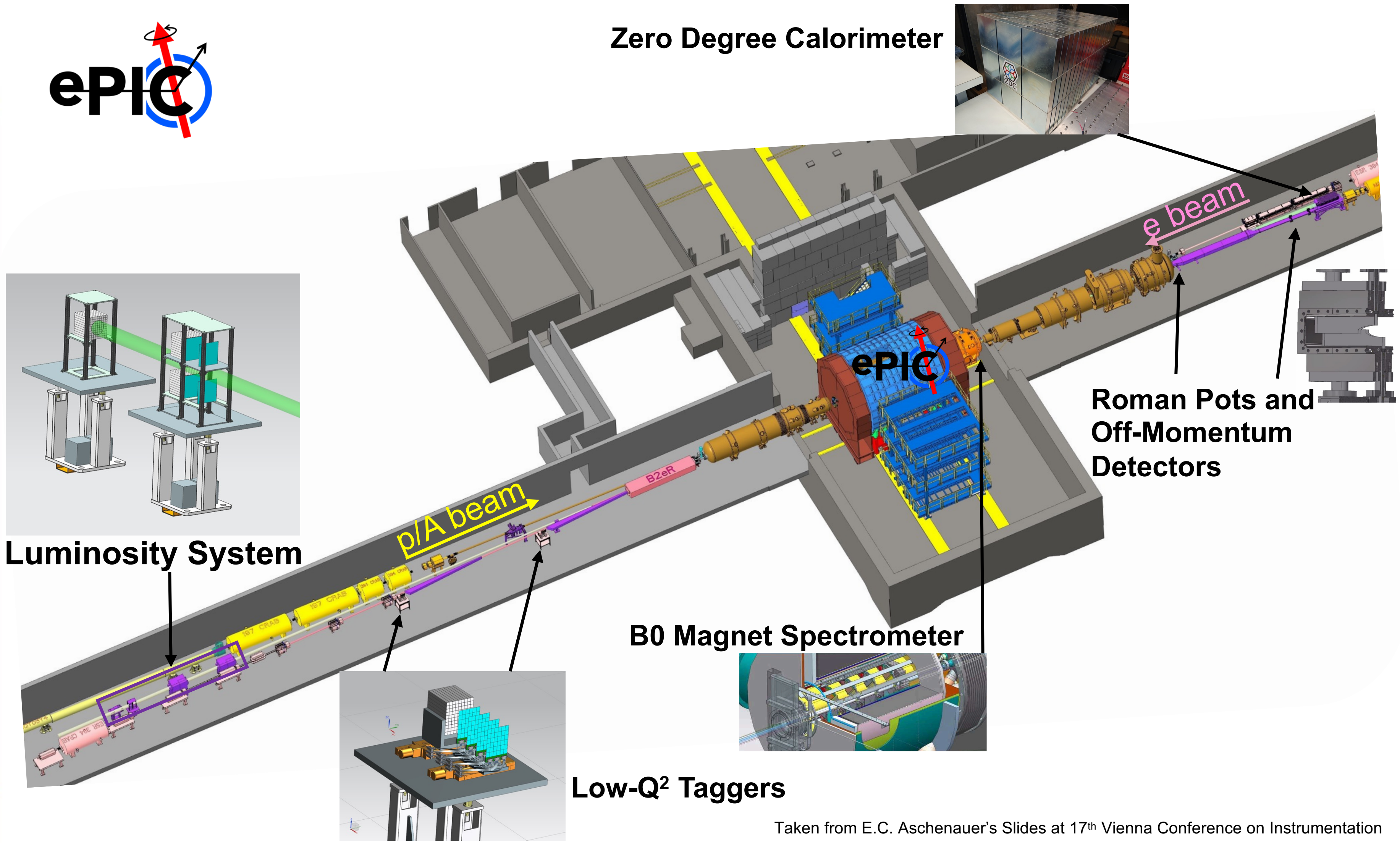
Hermetic detector
Low mass inner tracking
Large rapidity -4 < η < 4

Subsystems:
Tracker w/ Vertexing
PID
EMCAL and HCAL
Magnet

Overall,
Good momentum resolution
Excellent PID $\pi/K/p$
Forward: up to 50 GeV/c
Central: up to 8 GeV/c
Backward: up to 7 GeV/c

In electron-going direction,
Excellent energy resolution
In hadron-going direction,
Good energy resolution

And Far Detectors in Interaction Region



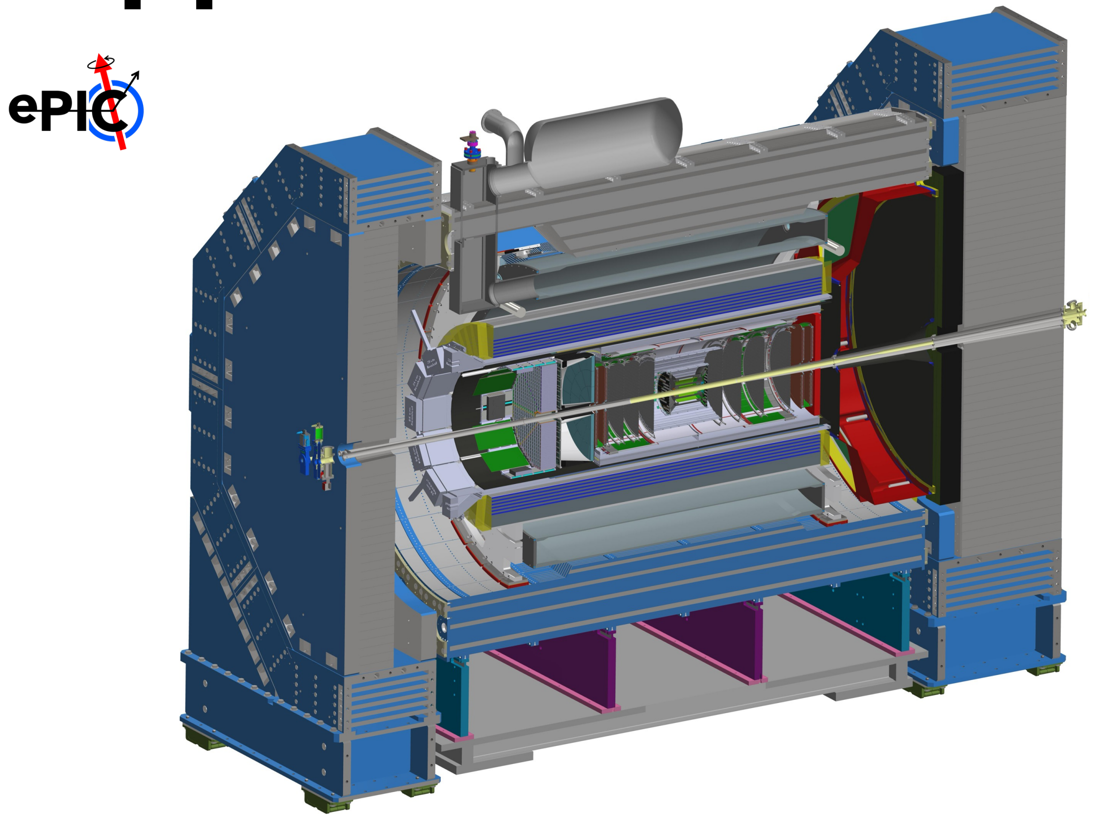
In electron-going direction,
Low-Q^2 scattered lepton

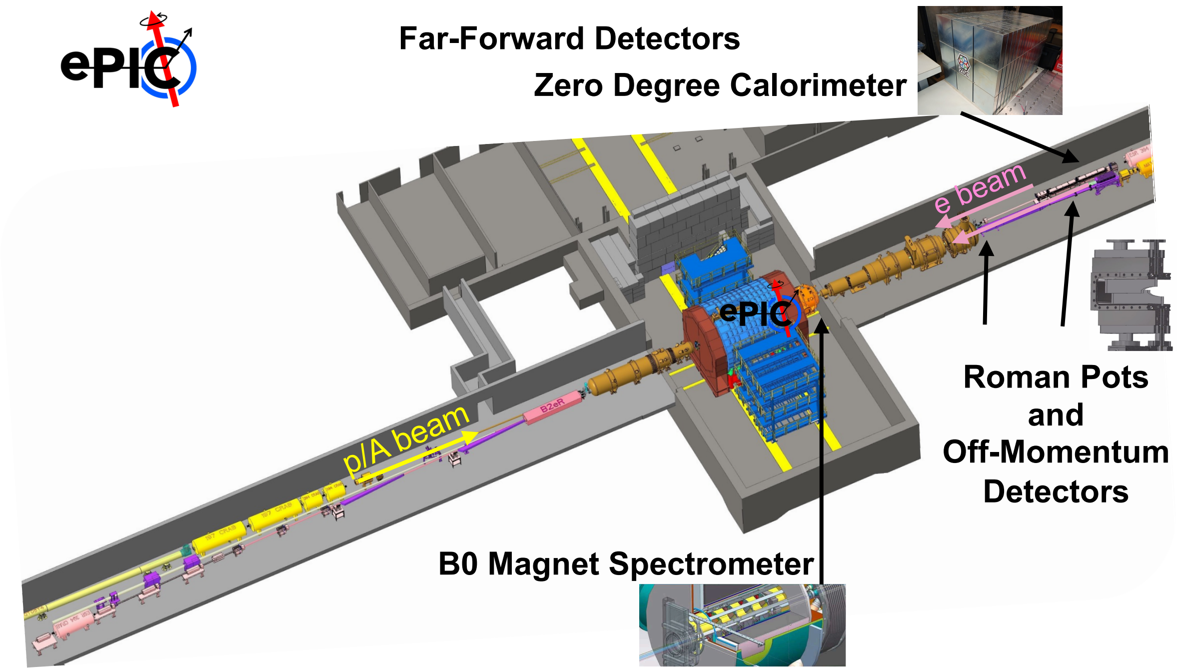
In hadron-going direction,
Nuclear breakup
Diffractive reactions

Subsystems:
Tracker
EMCAL and HCAL
Luminosity Monitor
Low-Q^2 Tagger

Taken from E.C. Aschenauer's Slides at 17th Vienna Conference on Instrumentation

Opportunities and Highlights at EIC

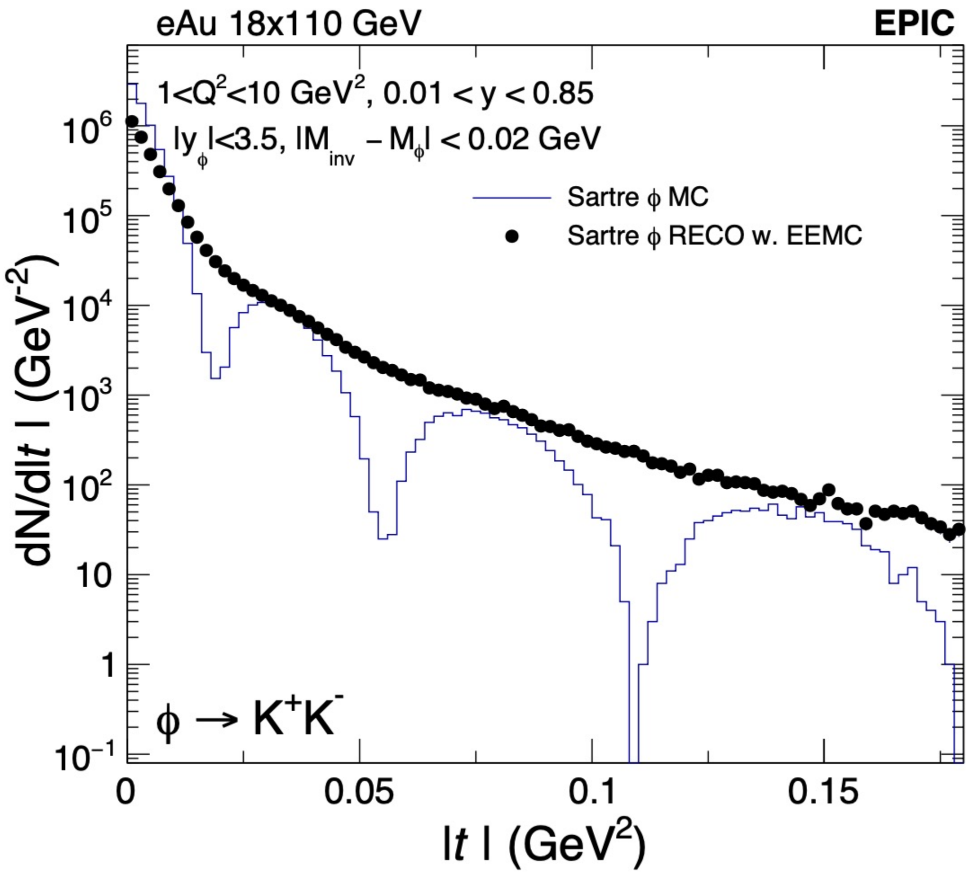




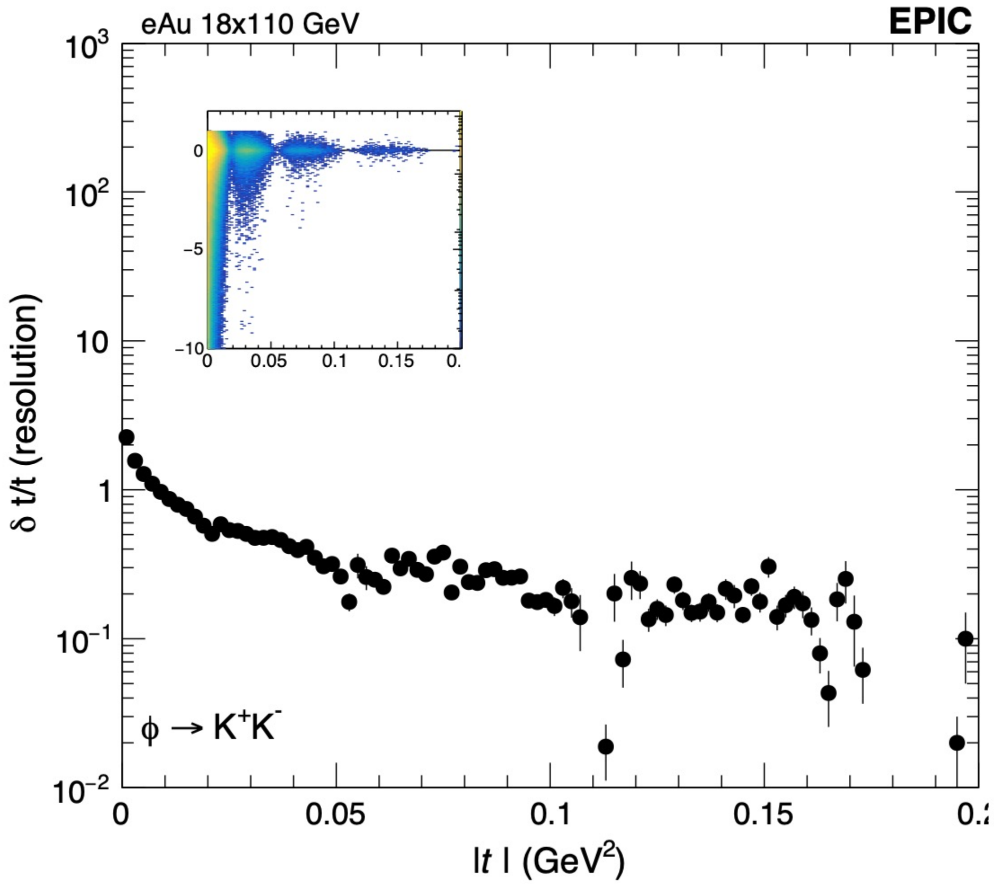
- Good momentum resolution for VM – 2 T magnetic field for tracking
- Excellent energy resolution for scattered electron – Backward EM calorimeter $PbWO_4$ crystals
- Incoherent background suppression – Larger far-forward detector acceptance

t Reconstruction Results – ePIC

ePIC Simulation Campaign Dec 2023



From Zhoudunming (Kong) Tu's Slides at EIC Theory WG Meeting
ePIC Work In Progress



No background, neither machine nor physics

Resolution is 200% at low t and 20% at high t

t Reconstruction Results – ePIC

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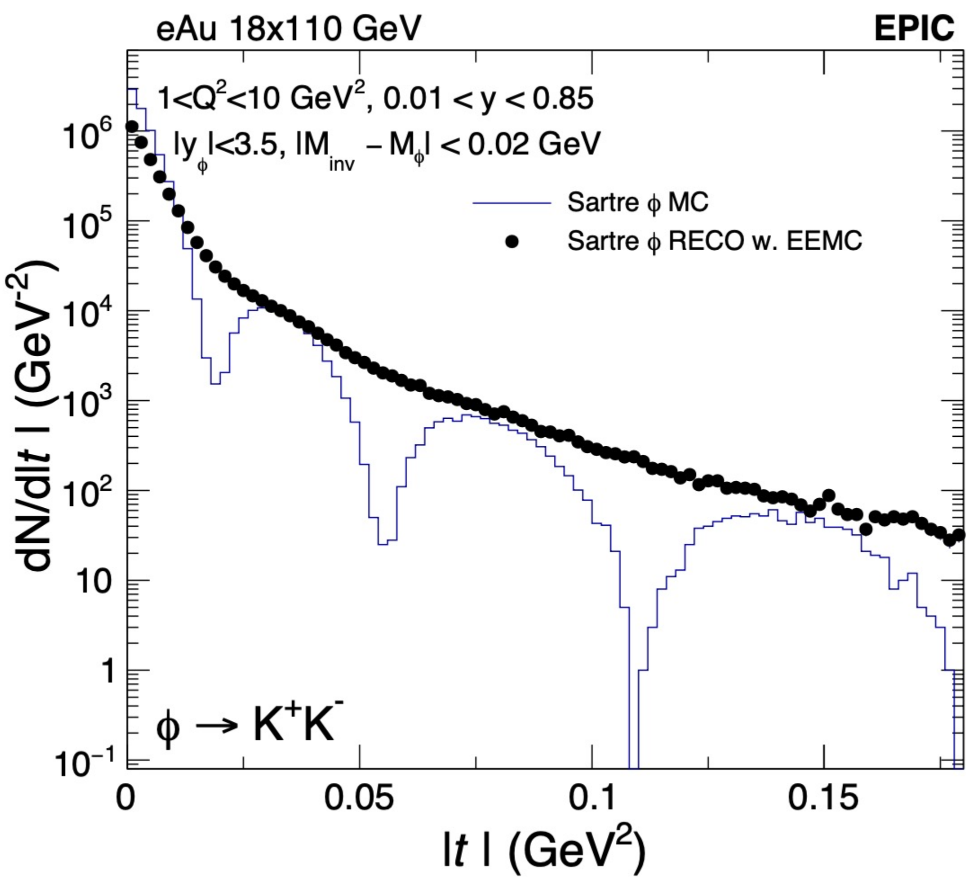

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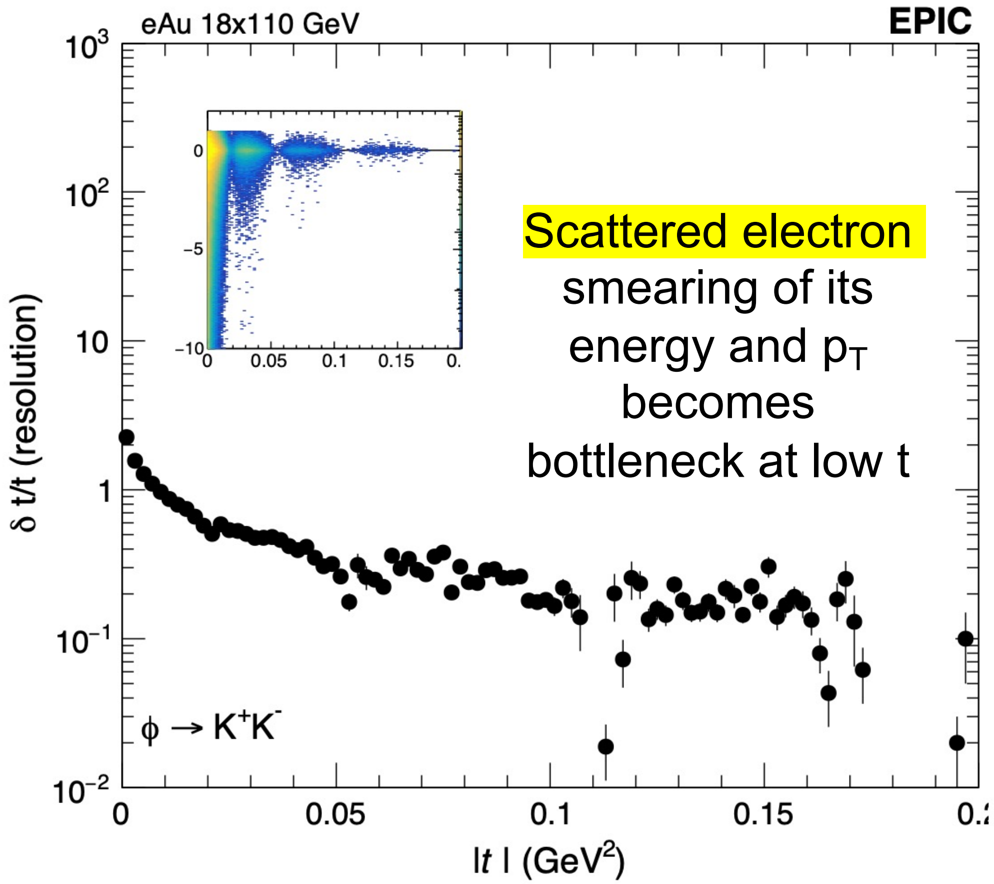

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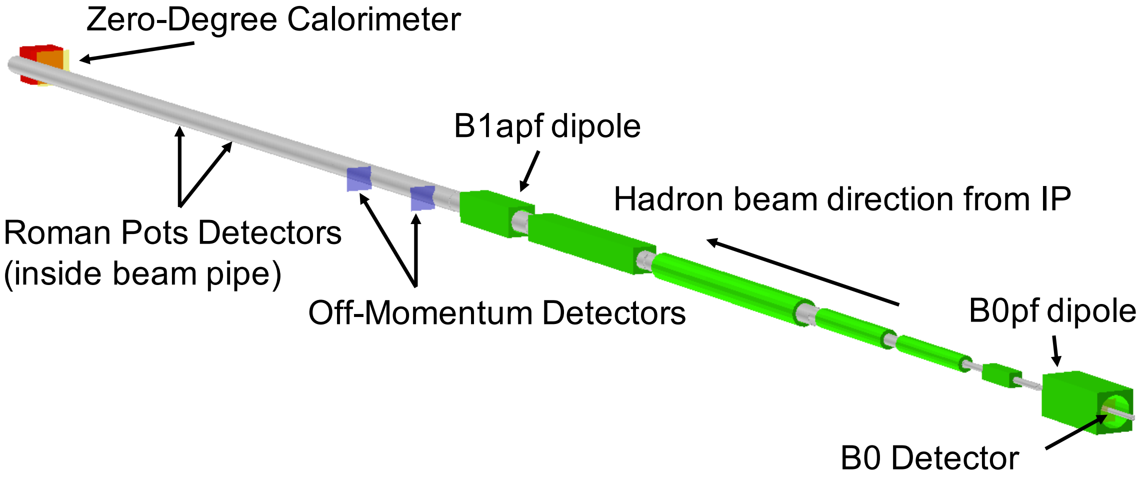
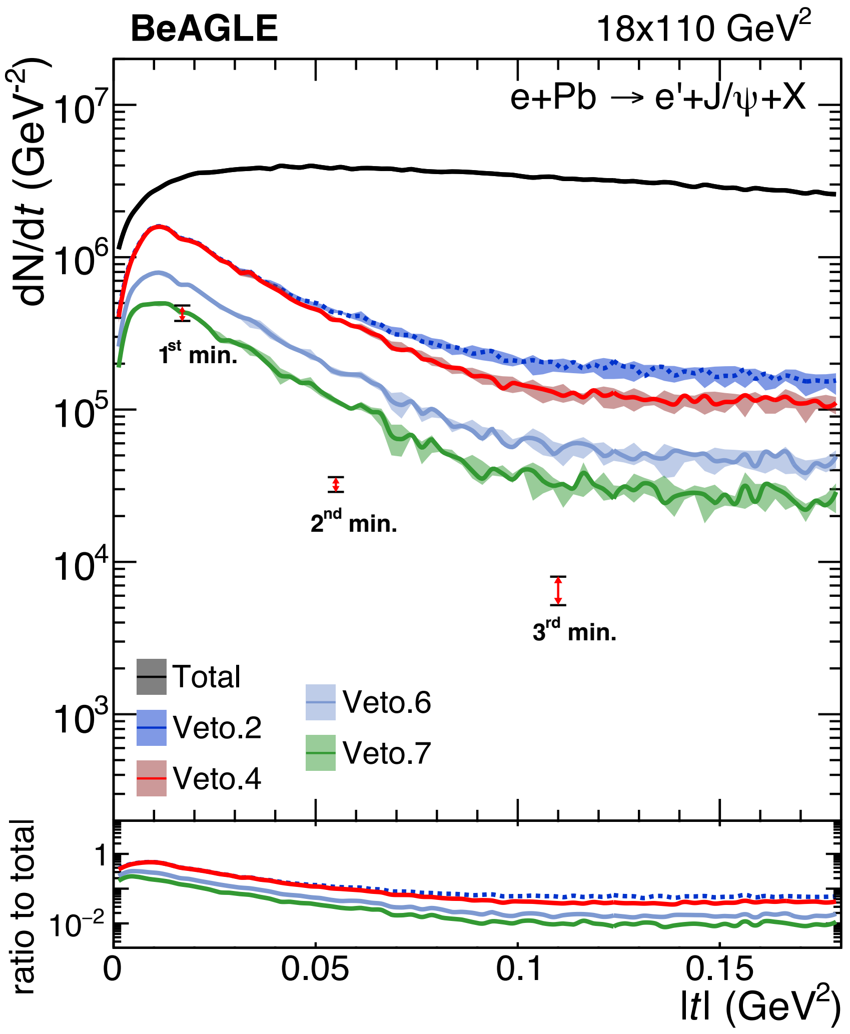
Incoherent Background Results – IP-6



- Veto 2: No neutrons in ZDC
- Veto 3-5: No proton in any forward detectors
- Veto 6-7: No photon > 50 MeV in B0 or ZDC

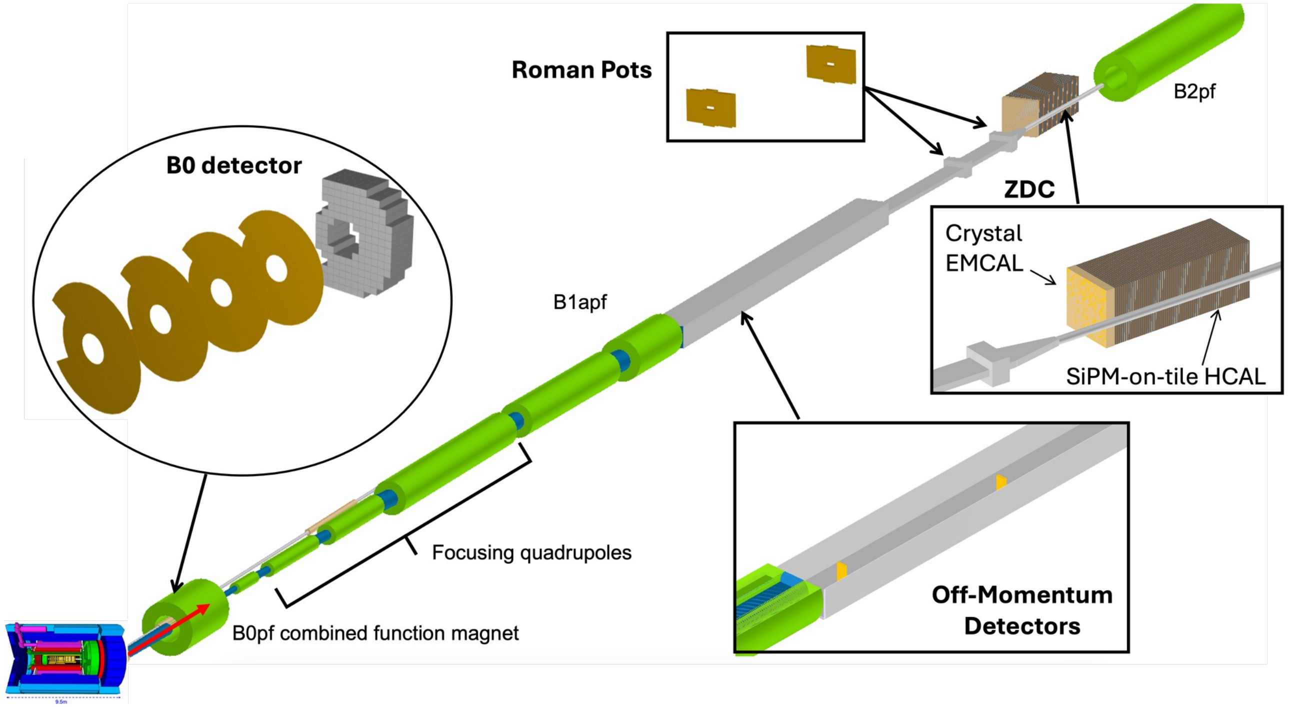
Based on 5 % t resolution assumed,
1^{st} minimum can be resolved,
but not 2^{nd} or 3^{rd} minima

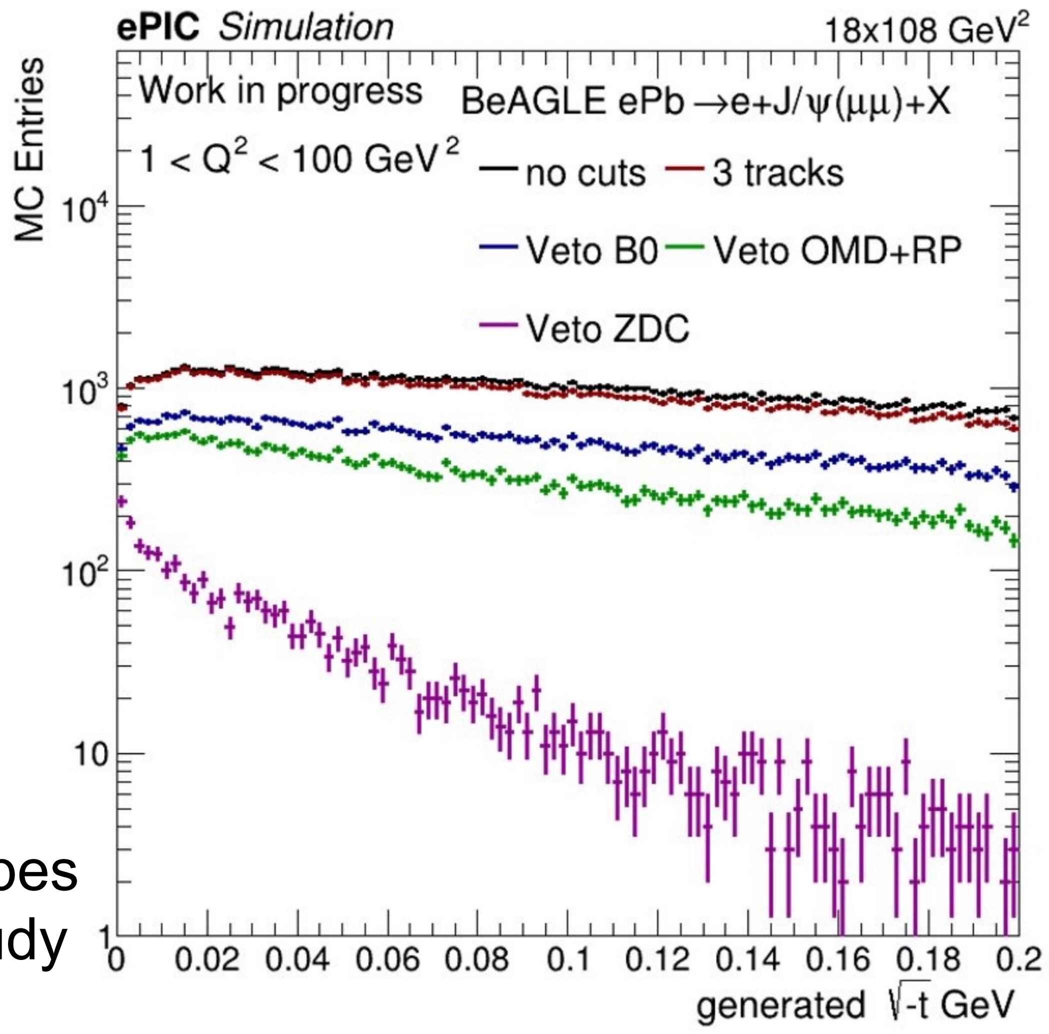


Phys. Rev. D **104**, 114030 (2021)

Incoherent Background Results – ePIC

E.C. Aschenauer, V. Batozskaya, S. Fazio, A. Jentsch, J. Kim, K. Kumerički, H. Moutarde, K. Passek-K, D. Sokhan, H. Spiesberger, P. Sznajder, K. Tezgin, arXiv:2503.05908





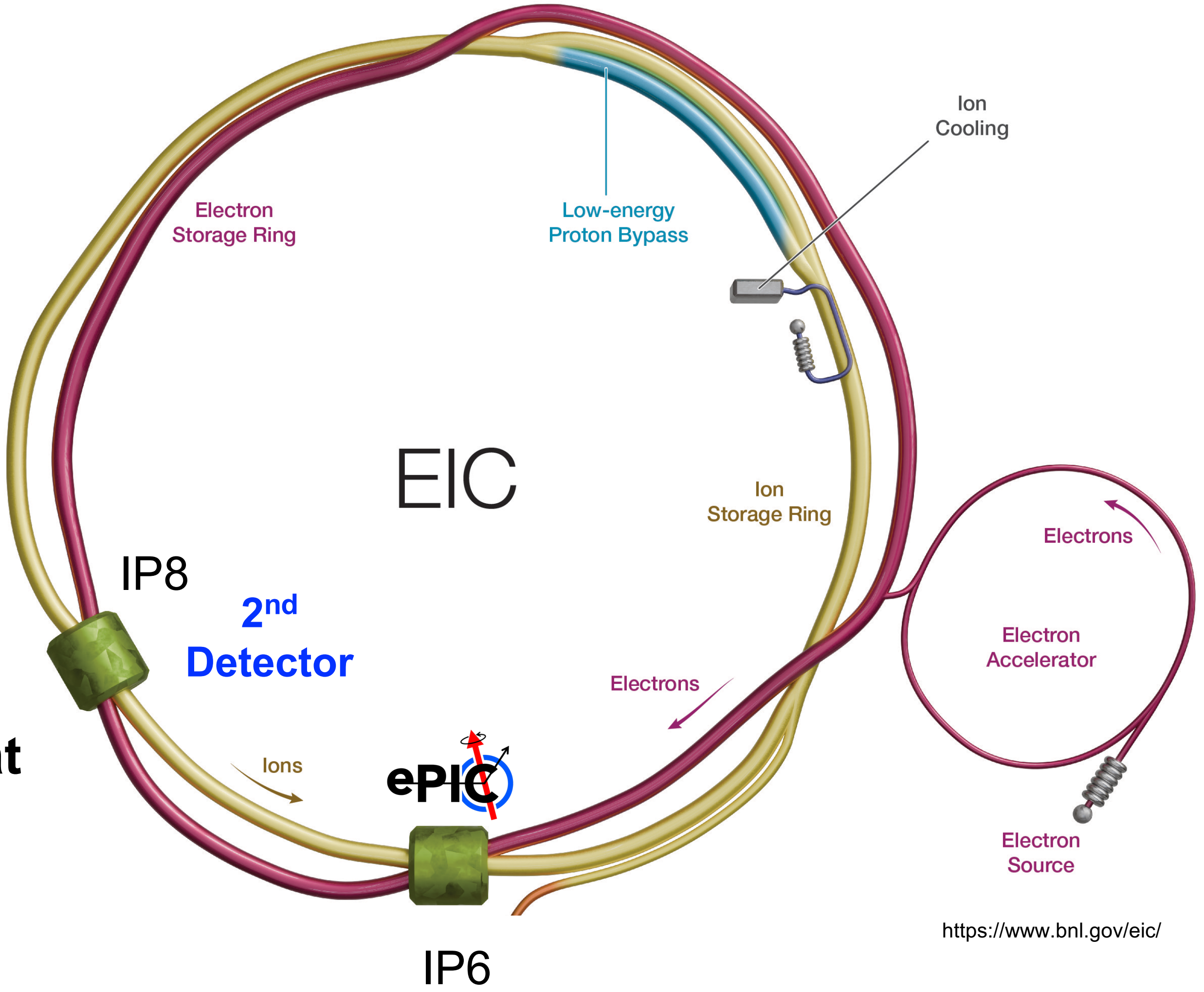
More detailed and realistic
IR-6 and far-forward detector geometry + beampipes
Similar to previous IP-6 standalone simulation study

Study from Michael Pitt, Eden Mautner (BGU)
ePIC Work In Progress

EIC Detector(s)

- Capable of accommodate **two** detectors and **two** interaction regions (IP6 and **IP8**)

- **Complementarity of interaction region**
  - Potential new feature for far detectors
    - **2nd Beam Focus**
  - Squeeze beam: as small as IP
  - Scattered particles can get out of beam envelop → **larger acceptance at low-p_T**
  - EIC 2nd detector can **benefit from machine design**

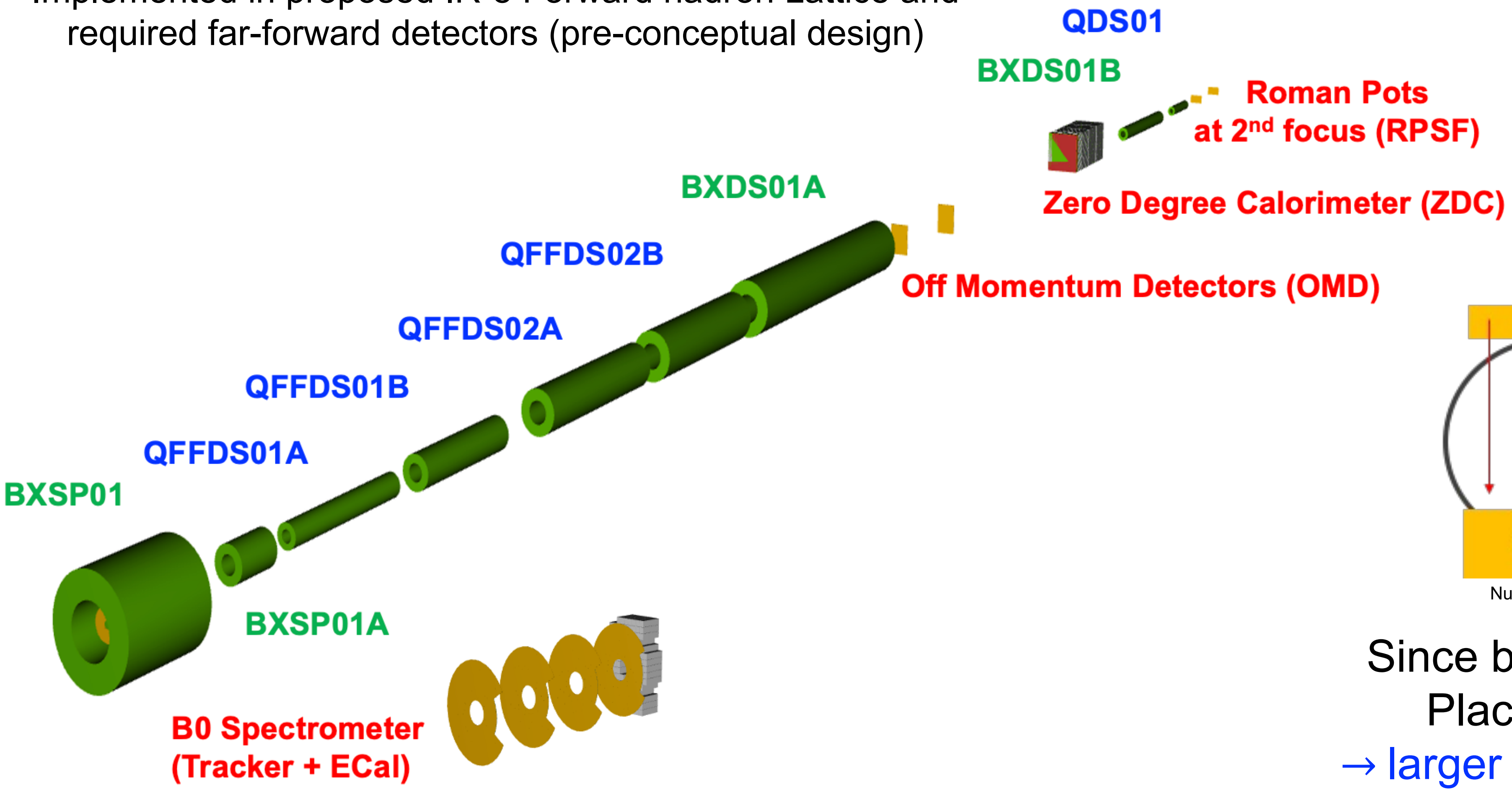


https://www.bnl.gov/eic/

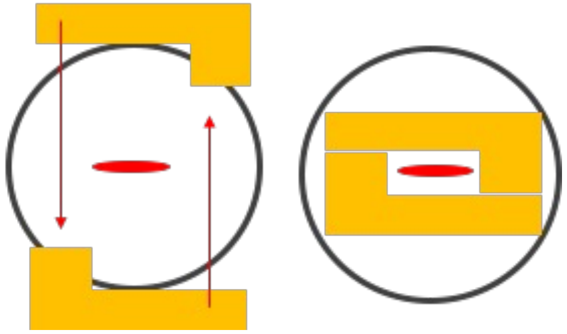
Potential New Feature for Far Detectors

Implemented in proposed IR-8 Forward hadron Lattice and required far-forward detectors (pre-conceptual design)

E.C. Aschenauer, A. Bazilevsky, A. Jentsch, J. Kim, A. Kiselev, B.S. Page, Z. Tu, T. Ullrich, C.P. Wong, arXiv:2501.12410



Roman Pot concept

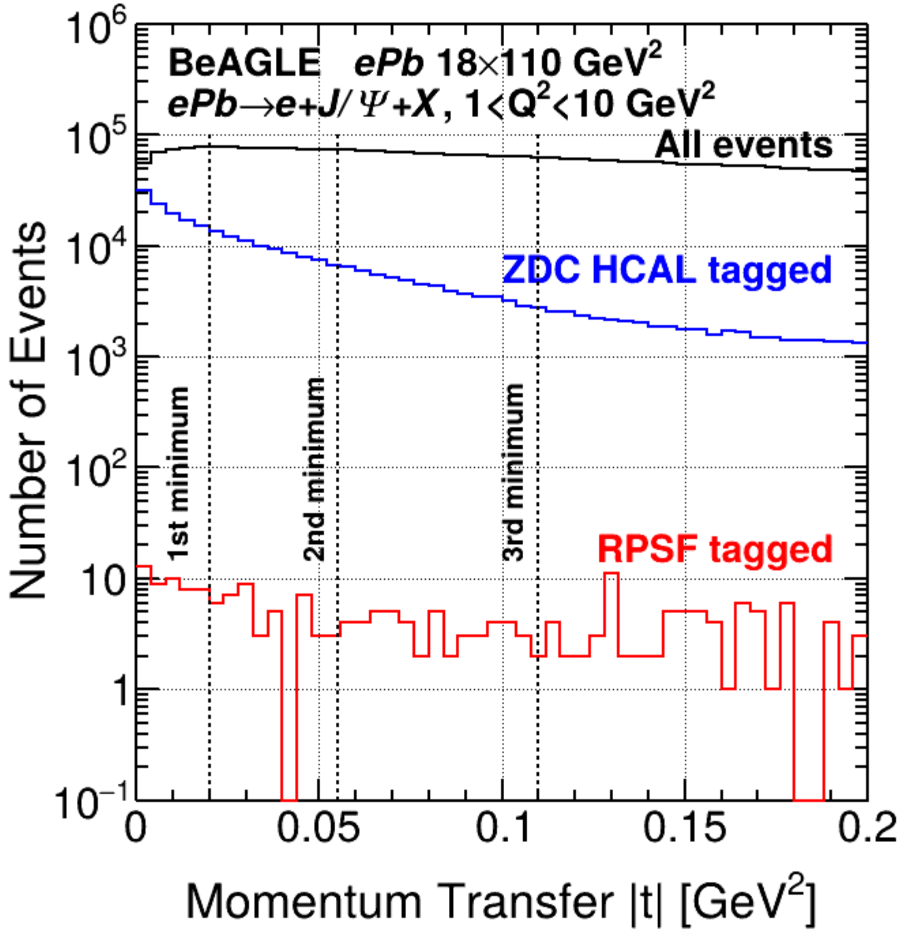


Nucl. Phys. A 1026 (2022) 122447, arXiv:2103.05419

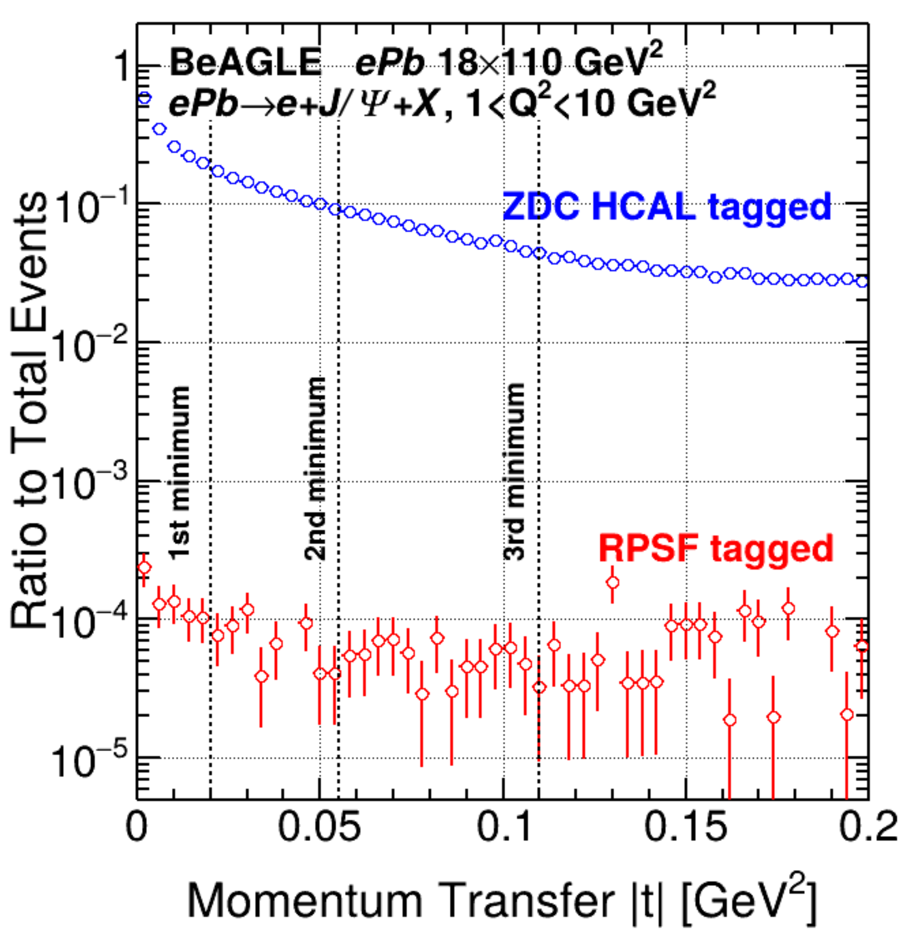
Since beam become small,
Place detector closer
→ larger acceptance at low-p_T

Incoherent Background Results – IP-8

Number of non-vetoed incoherent events



Vetoing power distribution



ZDC hcal tagged (neutrons)
RPSF tagged (protons, nuclear fragments)

E.C. Aschenauer, A. Bazilevsky, A. Jentsch, J. Kim, A. Kiselev, B.S. Page, Z. Tu, T. Ullrich, C.P. Wong, arXiv:2501.12410, accepted to PRD

Found to be enough to suppress incoherent contribution at three minima (**vetoing eff. ≫ 99.99 %**)

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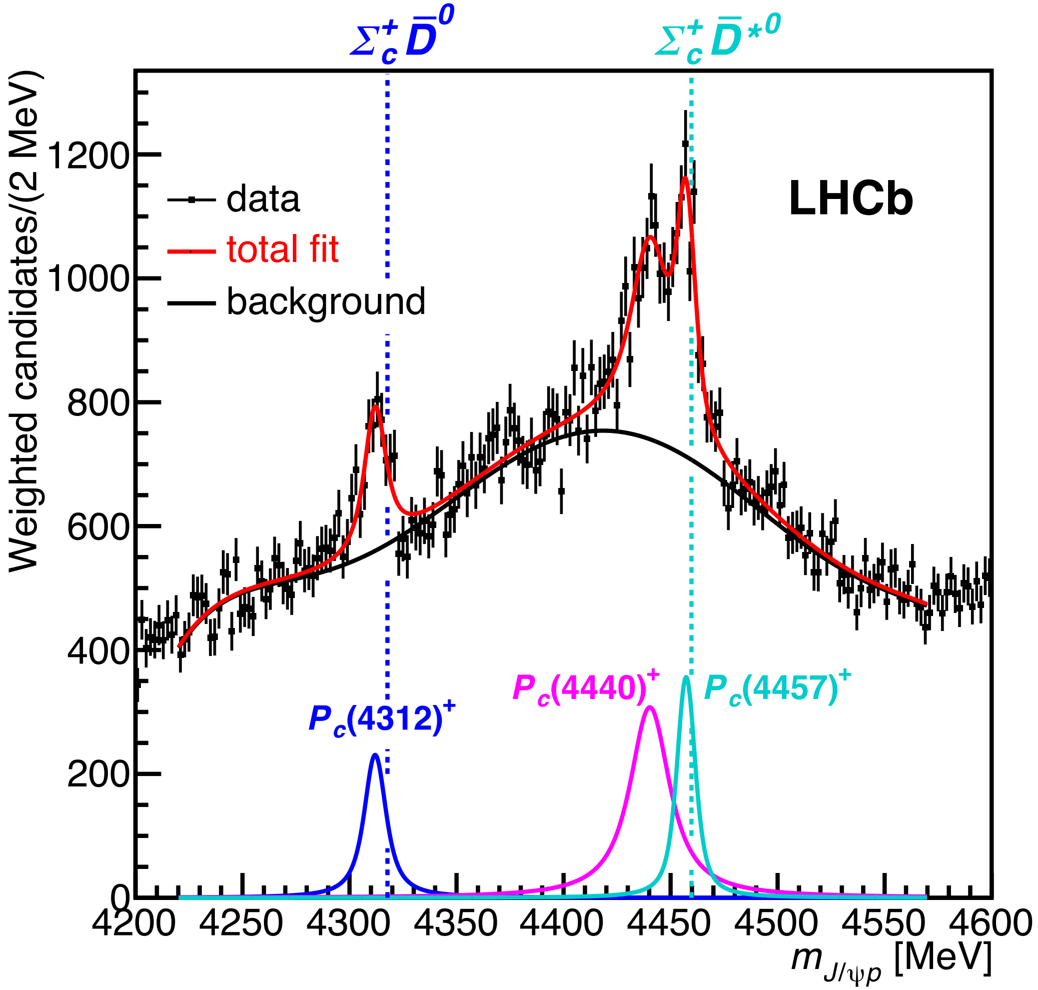
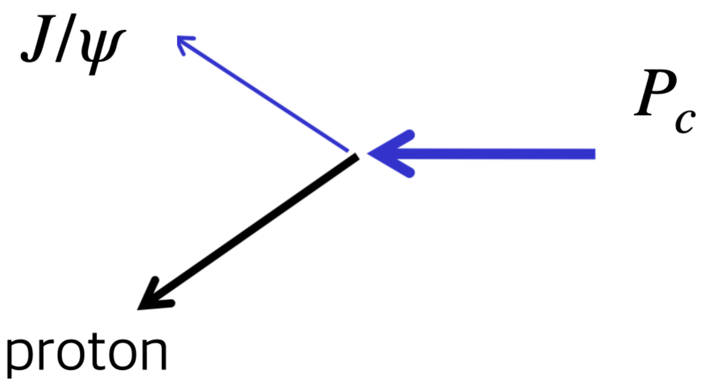
Opportunity of Pentaquark at EIC

Phys. Rev. Lett. **122**, 222001 (2019), arXiv:1904.03947



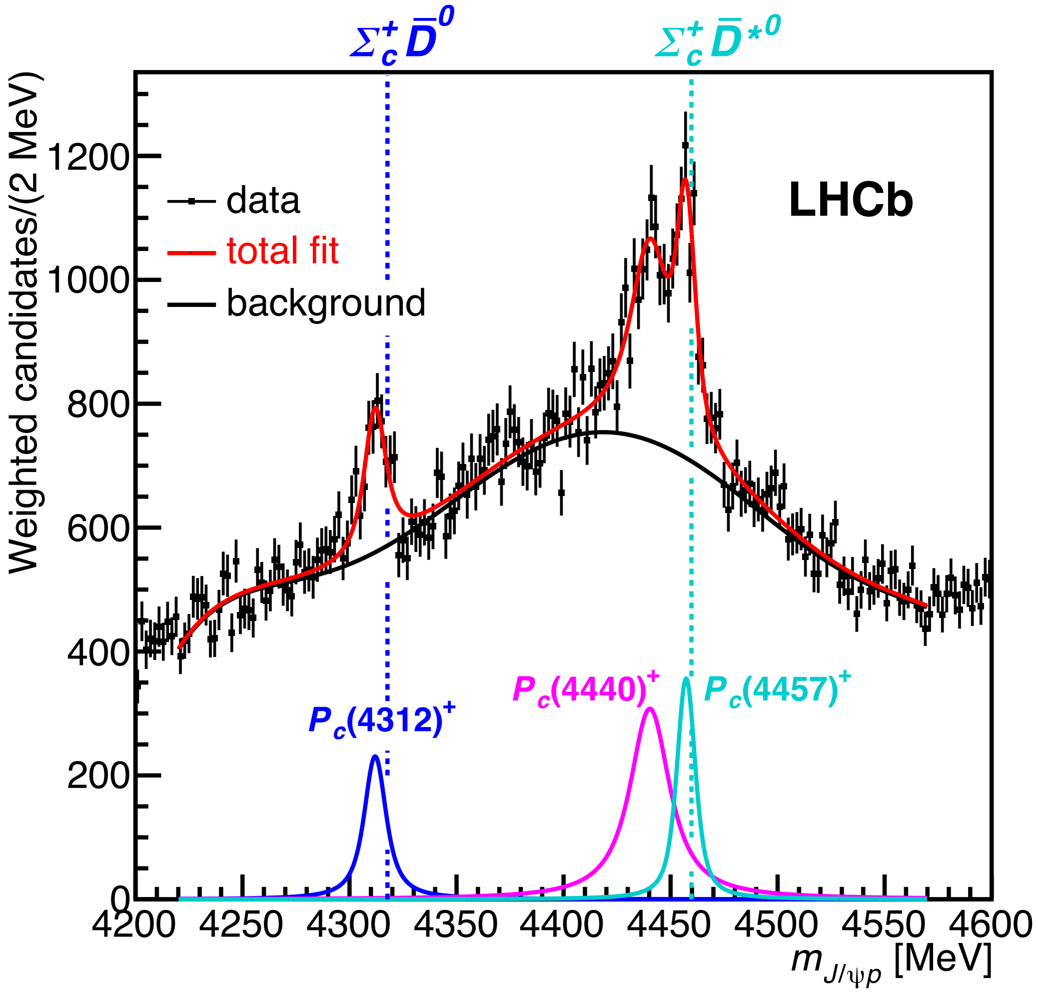
P_c particles discovered by LHCb



Yet internal structure and quantum numbers remains in questions like spin 1/2? 3/2? 5/2?

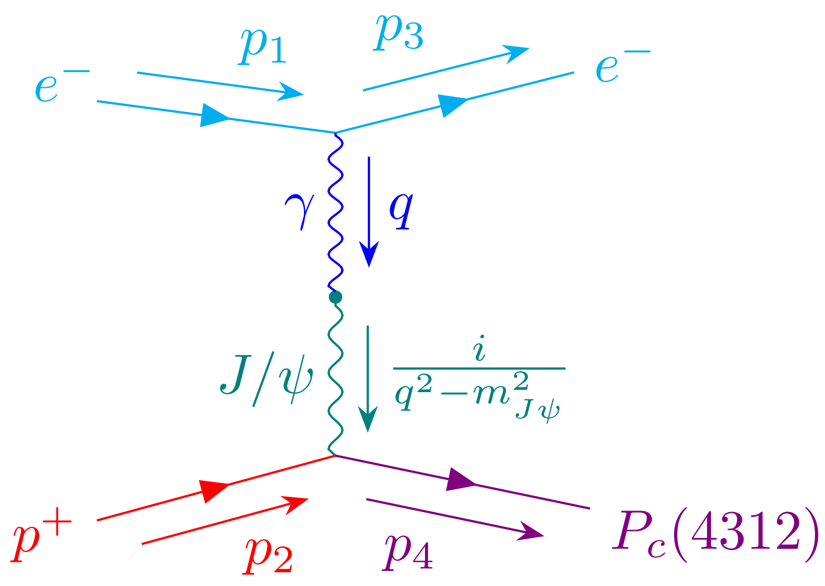
Opportunity of Pentaquark at EIC

Phys. Rev. Lett. **122**, 222001 (2019), arXiv:1904.03947



In Woo Park, Sungtae Cho, Yongsun Kim, Su Houng Lee, arXiv:2503.02676

EIC may shed light on



Perhaps we can create P_c by

$J/\psi + p \rightarrow P_c$

Opportunity of Pentaquark at EIC

Expected P_c yields to be measured by ePIC
at $\sqrt{s}$ = 141 GeV (N_{141}) and $\sqrt{s}$ = 40 GeV (N_{40})
Assuming integrated luminosity of 100 fb^{-1}

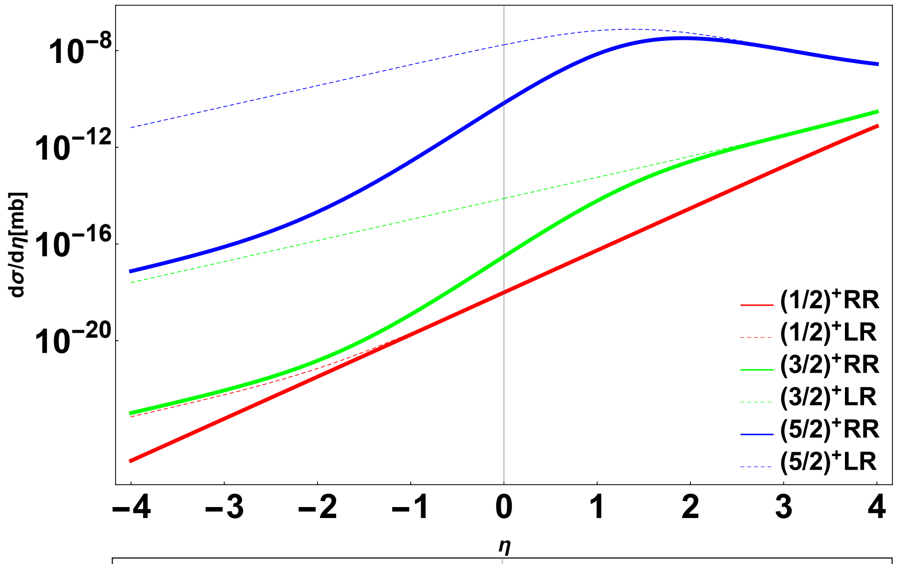
J^P	$(1/2)^+$	$(1/2)^-$	$(3/2)^+$	$(3/2)^-$	$(5/2)^+$	$(5/2)^-$
N_{141}	790	350	5.1×10^3	2.0×10^3	4.1×10^7	1.0×10^8
N_{40}	1.7×10^5	7.7×10^4	2.8×10^5	1.1×10^5	4.8×10^6	1.2×10^7

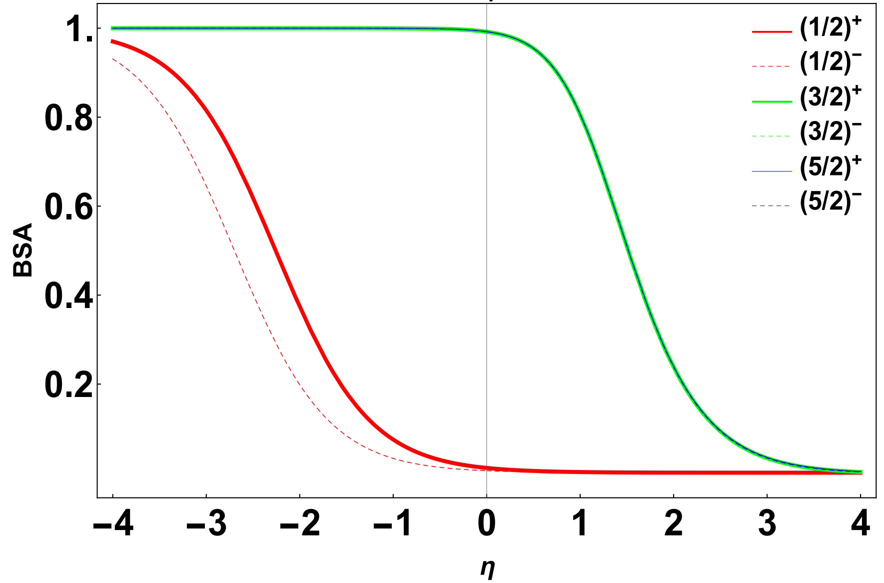
In Woo Park, Sungtae Cho, Yongsun Kim, Su Houng Lee, arXiv:2503.02676

In ePIC, it can be measured in **forward detector** and/or **far-forward detectors**

Beam spin asymmetry (BSA)
for (1/2)$^\pm$, (3/2)$^\pm$, and (5/2)$^\pm$ states

$$\text{BSA}(\eta) = \frac{d\sigma/d\eta[RL] - d\sigma/d\eta[RR]}{d\sigma/d\eta[RL] + d\sigma/d\eta[RR]}$$





Summary and Outlook

- Diffractive Vector Meson is a powerful experimental tool to study nucleon and nuclear structure, e.g. gluon spatial distributions
- Both challenges and opportunities at the EIC
- To achieve this measurement,
  - Better t resolution using the scattered electron
  - Vetoing capability of incoherent background (IR-8 looks promising)

- For EIC 2nd Detector, large interests and inputs will drive project forward
  - Your input is extremely valuable
  - If you would like to share your idea, please reach out to EICUG Detector-II WG conveners (https://eicug.github.io/content/wg.html#detector-iiip8-group)

Thank you!

The work of J. Kim is supported by Laboratory Directed Research and Development (LDRD) funding, “A Second EIC Detector: Physics Case and Conceptual Design” from Brookhaven National Laboratory under LDRD-23-050 project.

Backup Slides

EIC 2nd Detector Motivation

Another general-purpose collider detector to support full EIC program (**complementarity**); 1 + 1 > 2

- **Cross-Checking**

  ex) **HERA** (H1 & ZEUS), **RHIC** (PHENIX & STAR), **LHC** (ATLAS, CMS, LHCb, & ALICE), **B factory** (BaBar at PEP II & BELLE at KEK-B), **Tevatron** (CDF & D0), etc

- **Cross-Calibration**

  Beyond $\sqrt{N}$ statistical improvement

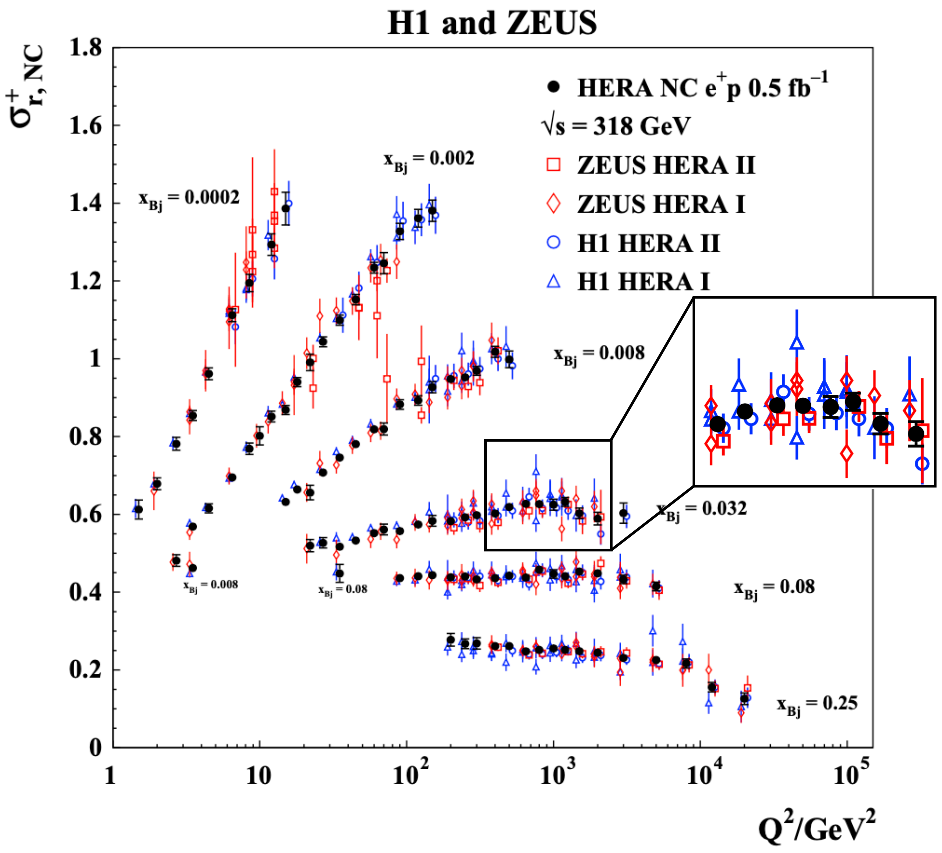
  Reducing uncertainties associated with a single detector configuration

- **Technology Redundance**

  Different technologies to similar physics aims

- **Primary Physics Focus**

  Optimizing overall sensitivity to full physics scope



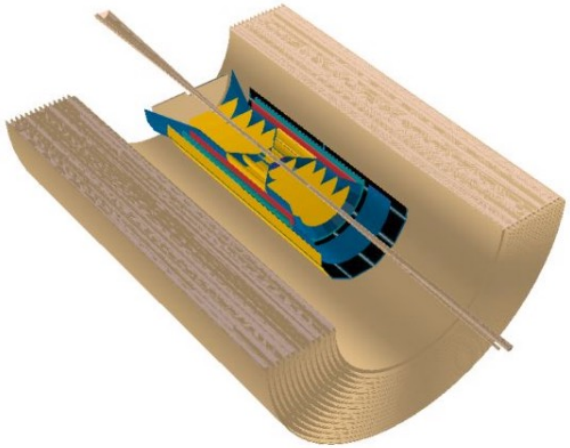
Eur. Phys. J. C 75, 580 (2015), arXiv:1506.06042

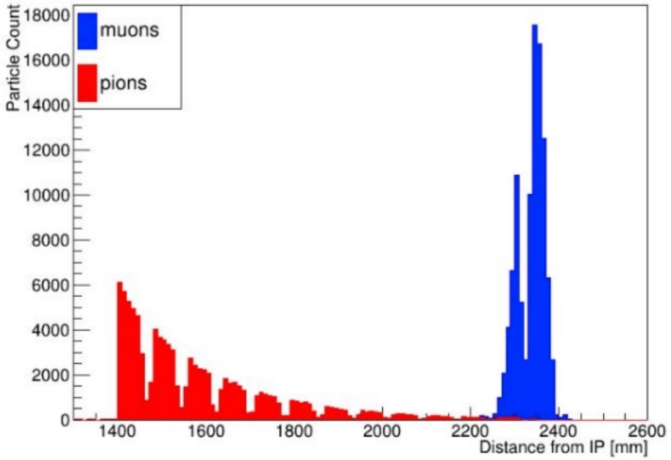
Complementarity of Technologies

System	ePIC	2nd Detector Ideas	Comments
Magnet	2 T Solenoid	2-3 T Solenoid with large radius	Space for services, deeper detector depth, and improve resolution
Tracker	MAPS + MPGDs	Gaseous detectors + Outer MAPS layers	Improve pattern recognition and tracking efficiency
PID	dRICH (gas + aerogel) + TOF	Gaseous-RICH + TOF	Simple RICH and TOF R&D 10 ps resolution
Barrel EMCAL	Imaging calorimeter (AstroPix + Pb/SciFi)	Improved version of SciGlass	Cost effective R&D SciGlass
Barrel HCAL	Steel/Scintillator plates	Belle-II style KLM	R&D Improved KLM + muon detection

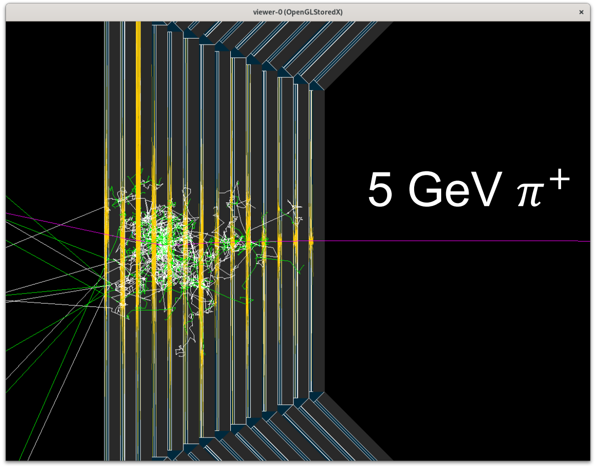
Noted that some were selected and illustrated here

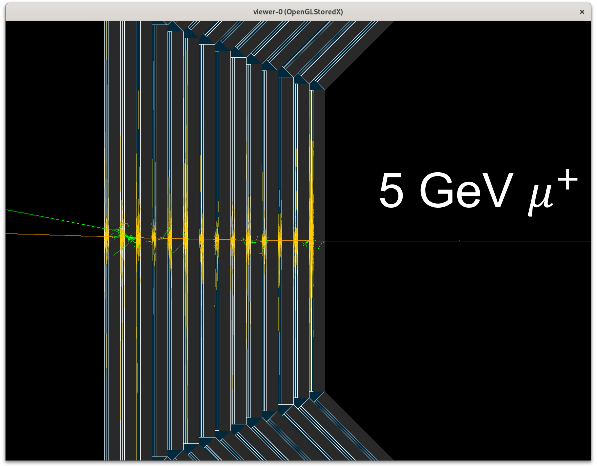
EIC 2nd Detector Muon Detector





Taken from Generic EIC-related detector R&D proposal - #18 KLM-type detector
https://www.jlab.org/sites/default/files/eic_rd_prgm/files/2023_Proposals/EIC_KLM_R_D_Proposal_2023_EICGENRandD2023_18.pdf





Taken from A. Vossen's Slides at Precision QCD predictions for ep physics at the EIC (III): opportunities with a second IR

Dedicated muon ID detector

Muon channel (quarkonium)

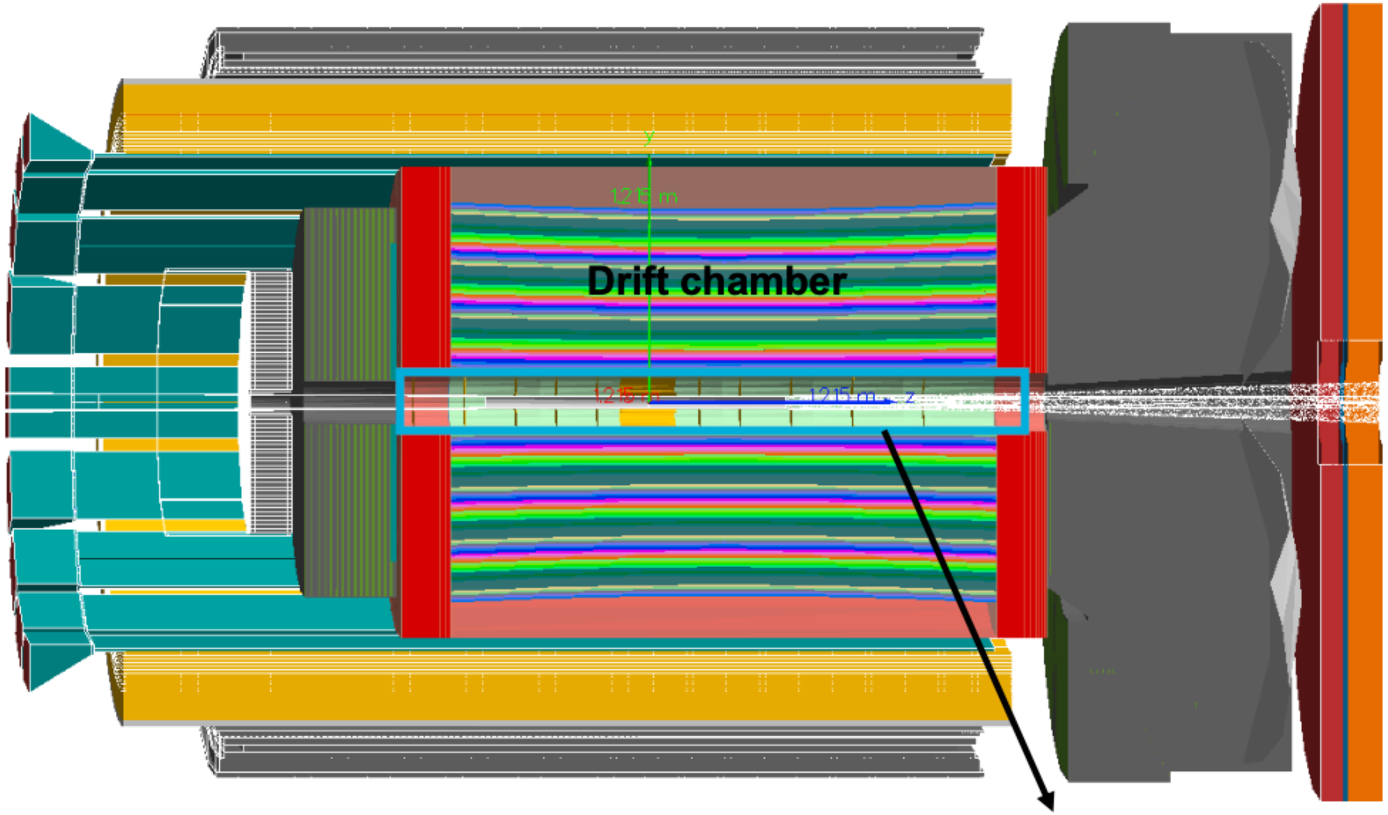
Served as cost effective HCAL

- **Iron/Scintillator** sandwich (like Belle-II)
- Longitudinal segmentation for better h/μ ID and energy reconstruction
- μ ID at low ($\approx$1 GeV) momenta
- Possible solution for **endcap HCAL**

Rowan Kelleher, Simon Schneider, Anselm Vossen, Nilanga Wickramaarachchi (Duke), Will Jacobs (Indiana) Yordanka Ilieva (USC)

EIC 2nd Detector **Central Tracker**

HCAL/Muon Detector not shown



Cheuk-Ping Wong (BNL)

Mixed-tracking technologies

- Inner silicon vertex tracker
- **Gaseous detector** (TPC or drift chamber)

Cons

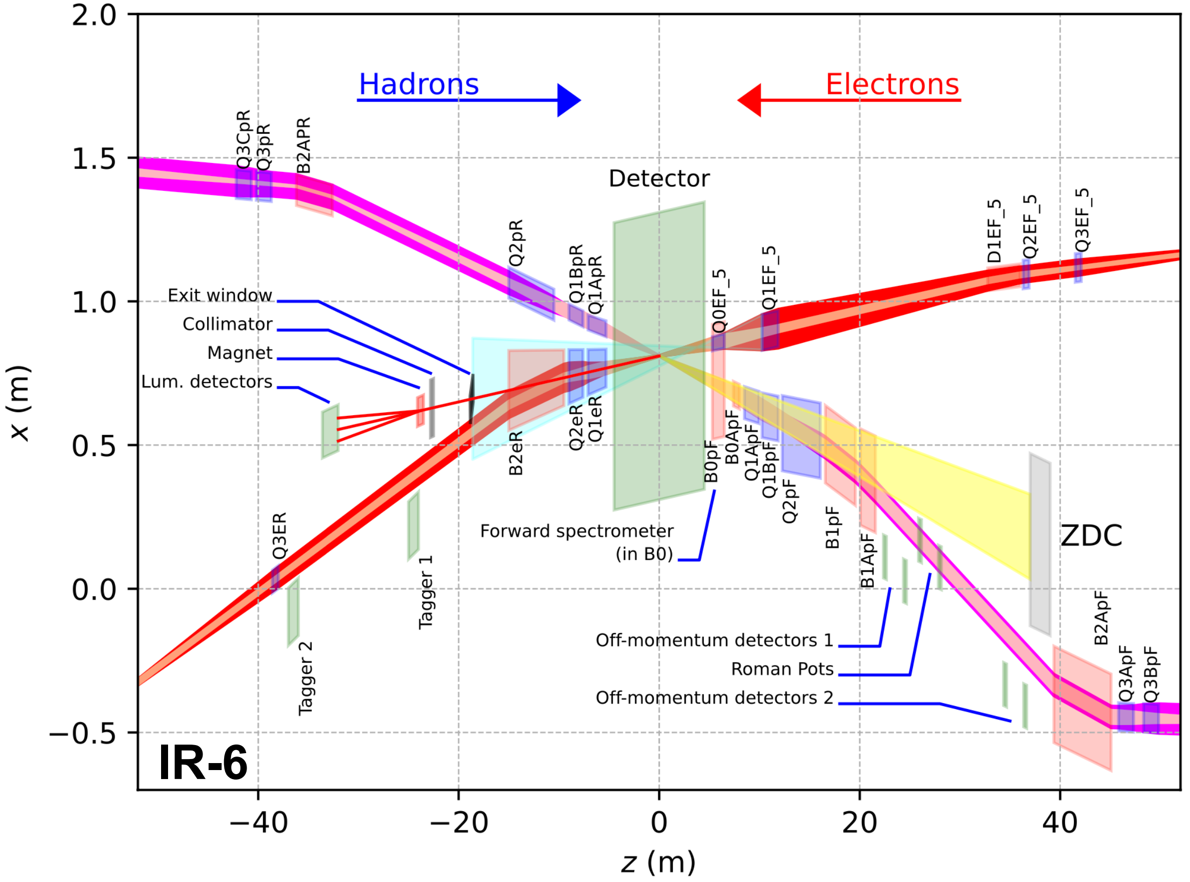
- More materials at endcap
- Worse spatial resolution compared to pixelated silicon sensor

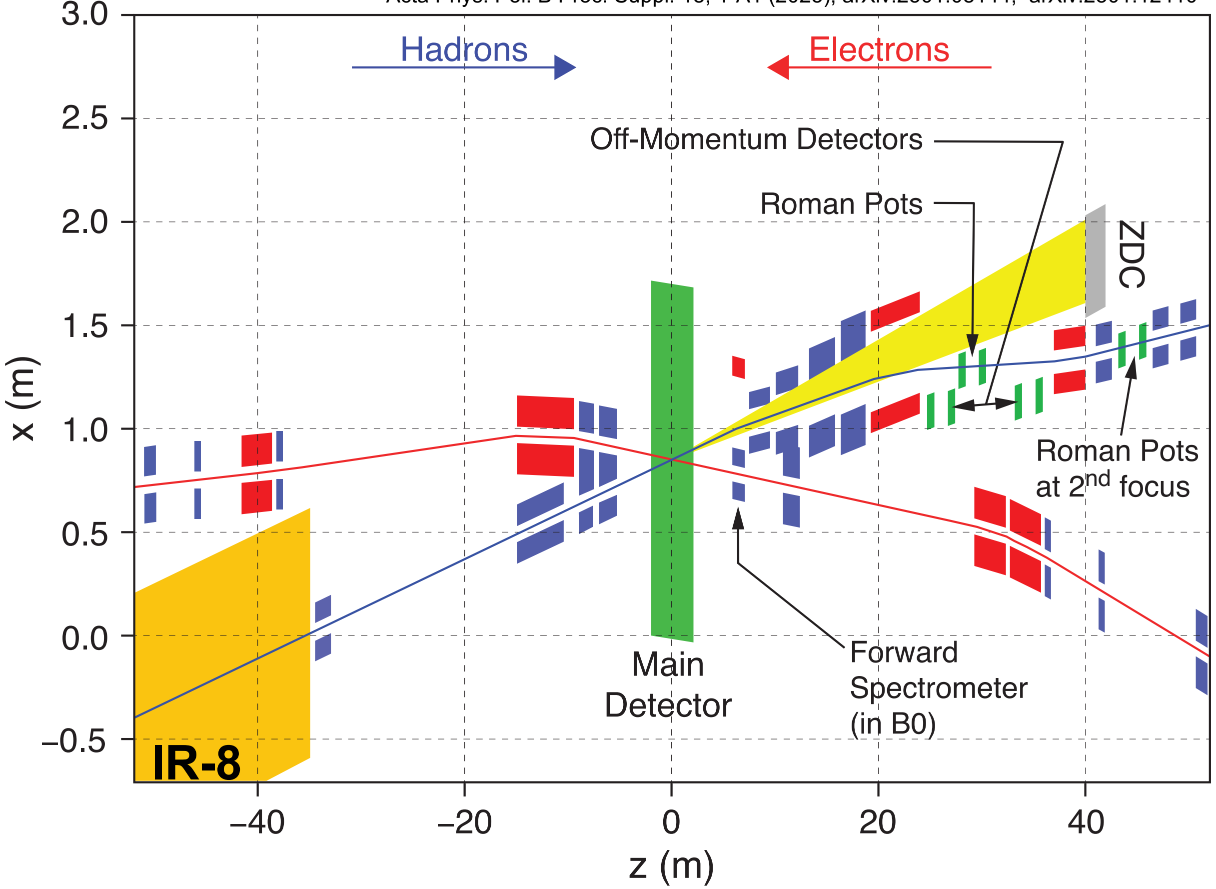
Pros

- More hits → **better pattern recognition**
- PID info at low-momentum using dE/dx

Complementarity of Interaction Region

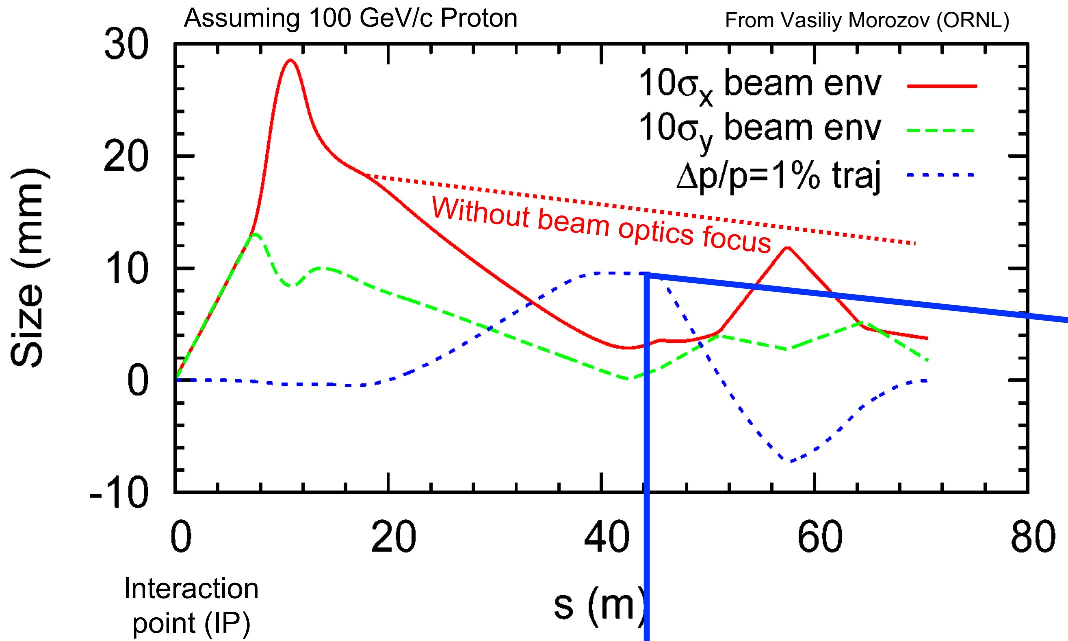
Acta Phys. Pol. B Proc. Suppl. 18, 1-A1 (2025), arXiv:2501.08144, arXiv:2501.12410





25 mrad	crossing angle	**35 mrad**
	potential new feature	**2nd beam focus**

Potential New Feature for Far Detectors

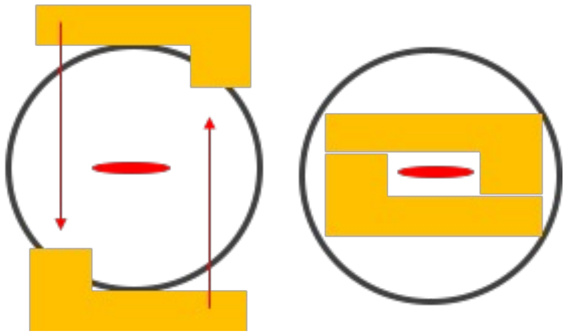


Squeeze beam
so that
beam as small as at IP

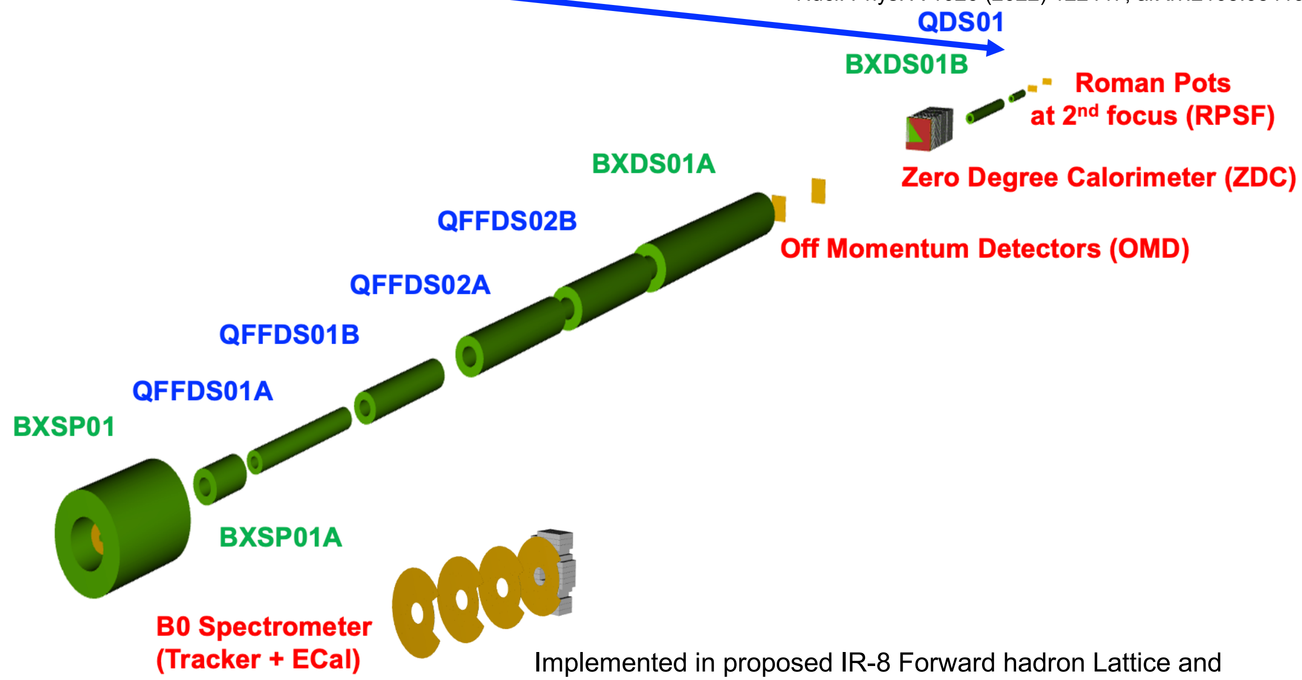
→ **Scattered particles can**
get out of beam envelope

Since beam become small,
Place detector closer
→ larger acceptance at low-p_T

Roman Pot concept



Nucl. Phys. A 1026 (2022) 122447, arXiv:2103.05419



arXiv:2501.12410

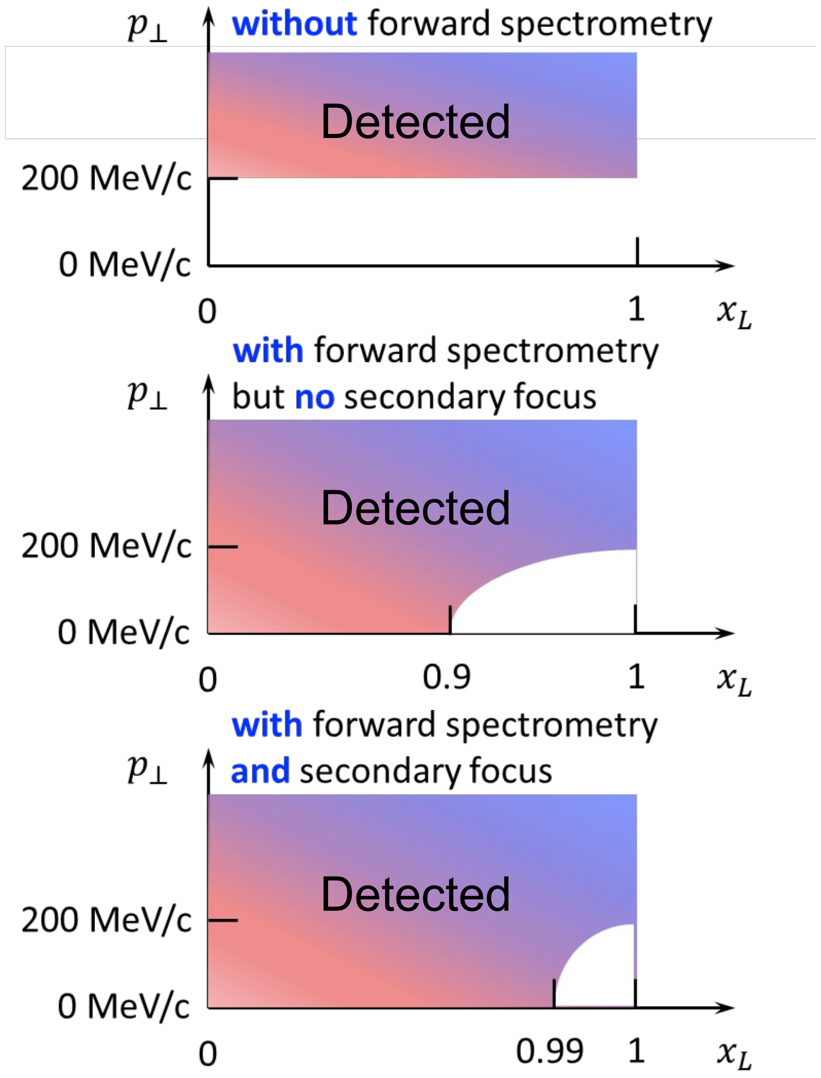
Implemented in proposed IR-8 Forward hadron Lattice and required far-forward detectors (pre-conceptual design)

Compelling Opportunity with New Feature

EIC 2nd detector can **benefit from machine design**

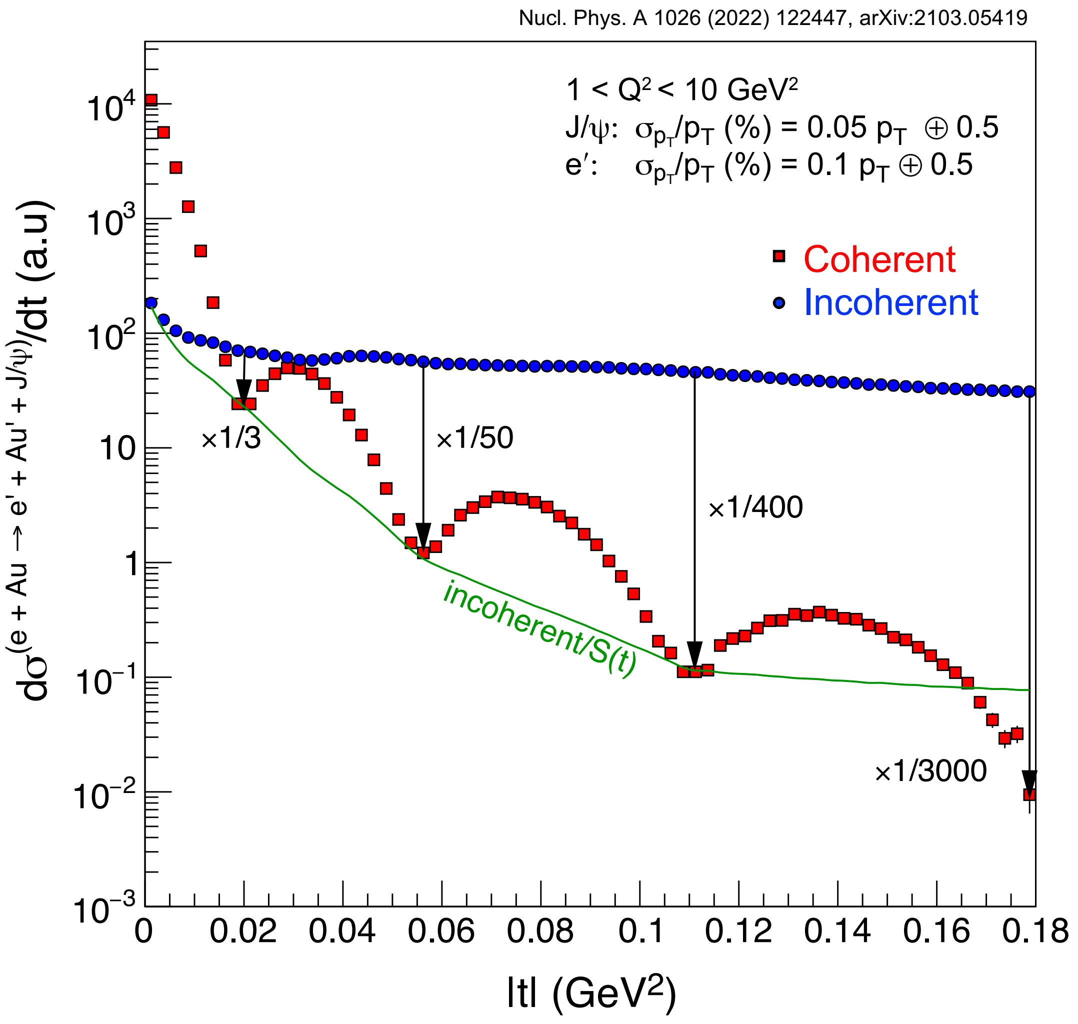
- Allows access to **low-p_T particles/fragments**
  - Higher probability to detect low-p_T (< 250 MeV)
- **New physics opportunities**:
  - Exclusive/diffractive measurements at low t
  - Recoiling nuclei and fragments from nuclear breakup
  - Coherent diffraction on heavy nuclei
- **Challenges**:
  - Chromaticity budget
- **Unique capabilities to enhance overall EIC exclusive, tagging and diffractive physics program**

($x_L = p'/p_{\text{beam}} \sim 1 - x$)



JACoW IPAC2021 (2021), arXiv:2105.13564

Coherent Diffraction on Heavy Nuclei



For $e + A$ program:

Suppression of incoherent background

Diffractive cross section
(ex $e + \mathrm{Au} \rightarrow e' + \mathrm{Au}' + \mathrm{J}/\psi$):

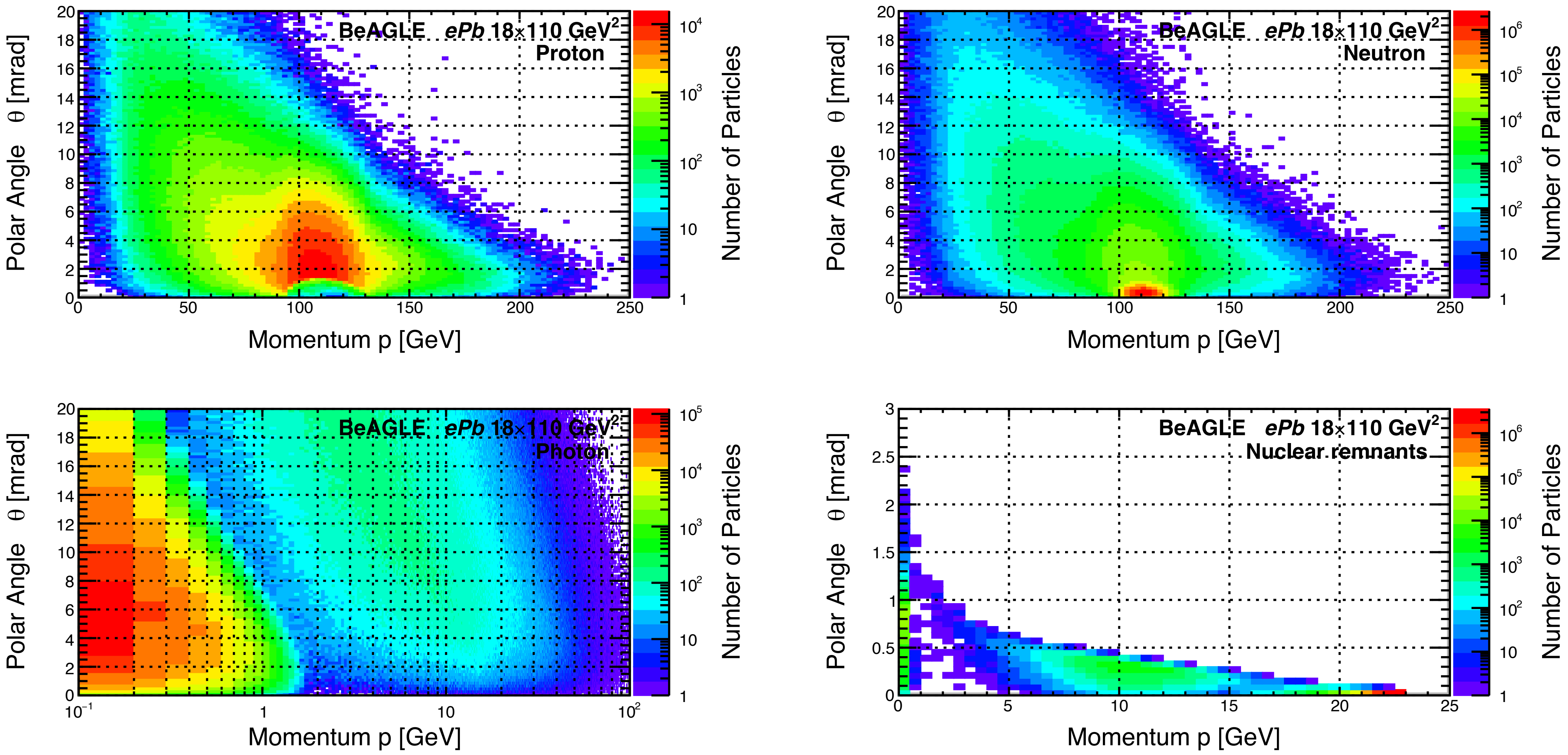
Sum of coherent (nucleus stays intact) and incoherent (nucleus breaks up) processes
→ **Very challenging!**

How to veto incoherent process:

By tagging nucleus breakups using far-forward detectors

Nuclear Breakups Distribution

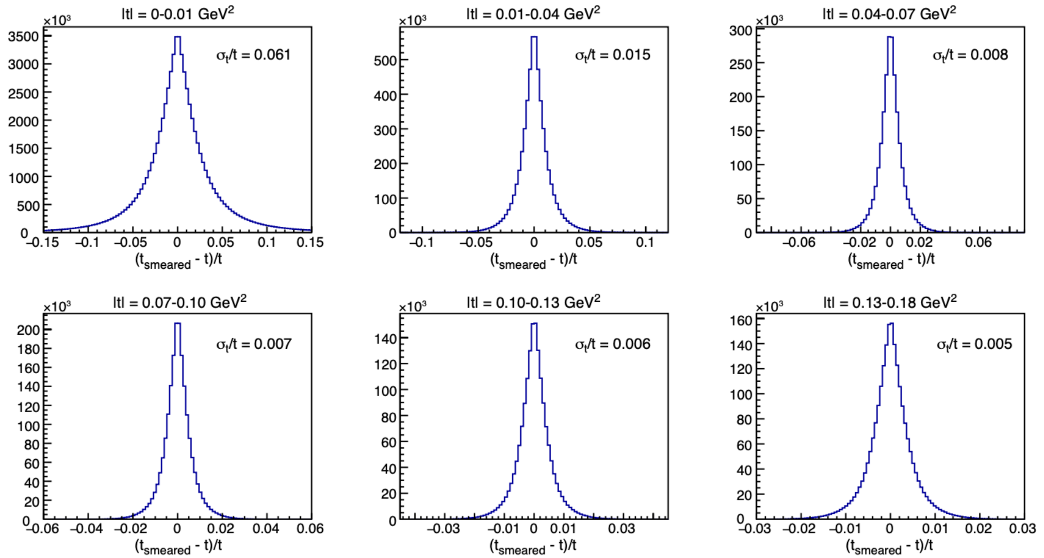
E.C. Aschenauer, A. Bazilevsky, A. Jentsch, J. Kim, A. Kiselev, B.S. Page, Z. Tu, T. Ullrich, C.P. Wong, arXiv:2501.12410



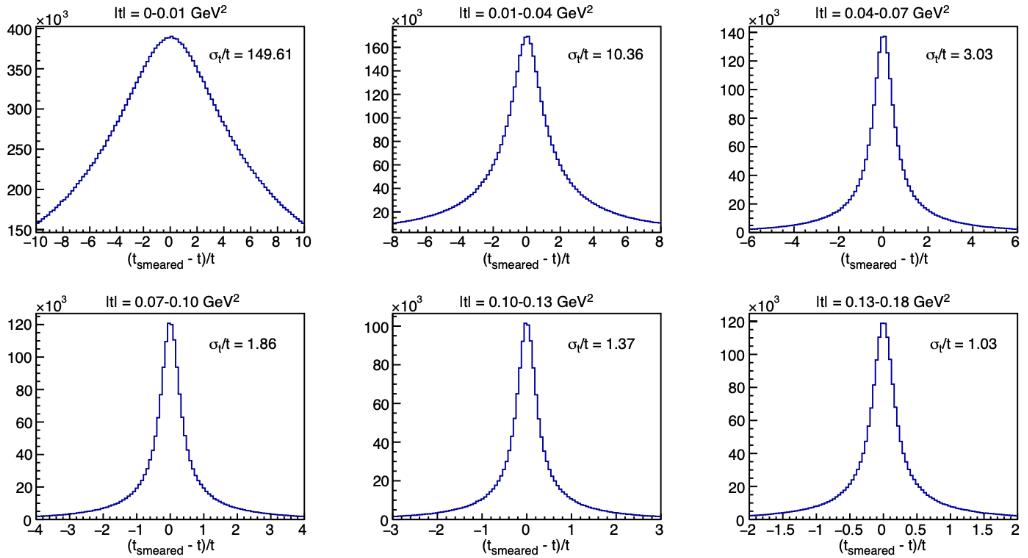
Method E

From Thomas Ullrich

Sensitivity to beam effects: $\sigma_t/t = (t_{\text{measured}} - t_{\text{true}})/t_{\text{true}}$



EIC beam divergence



EIC beam momentum spread

- Beam divergence affects little: σ_t/t ~ 6% to 0.5%
- Beam momentum spread is devastating: σ_t/t ~ 15000% to 103%

From Thomas Ullrich

Method L

- How the method works
  - Calculate p of outgoing A': $p_{A'} = p_A - (p_V + p_{e'} - p_e)$
  - Express and correct the outgoing nucleus in light cone variables:
    - $p^+_{A'} = E_{A'} + p_{z,A'}$
    - $p^2_{T,A'} = p^2_{x,A'} + p^2_{y,A'}$
    - $p^-_{A'} = (M^2_A + p^2_{T,A'})/p^+_{A'}$ where $p^-_{A'}$ is now modified by using the true mass M^2_A.
  - The corrected 4-momentum of the outgoing nuclei is now

$$p^{\mathrm{corr}}_{A'} = \left[p_{x,A'},\ p_{y,A'},\ (p^+_{A'} - p^-_{A'})/2,\ (p^+_{A'} + p^-_{A'})/2\right]$$

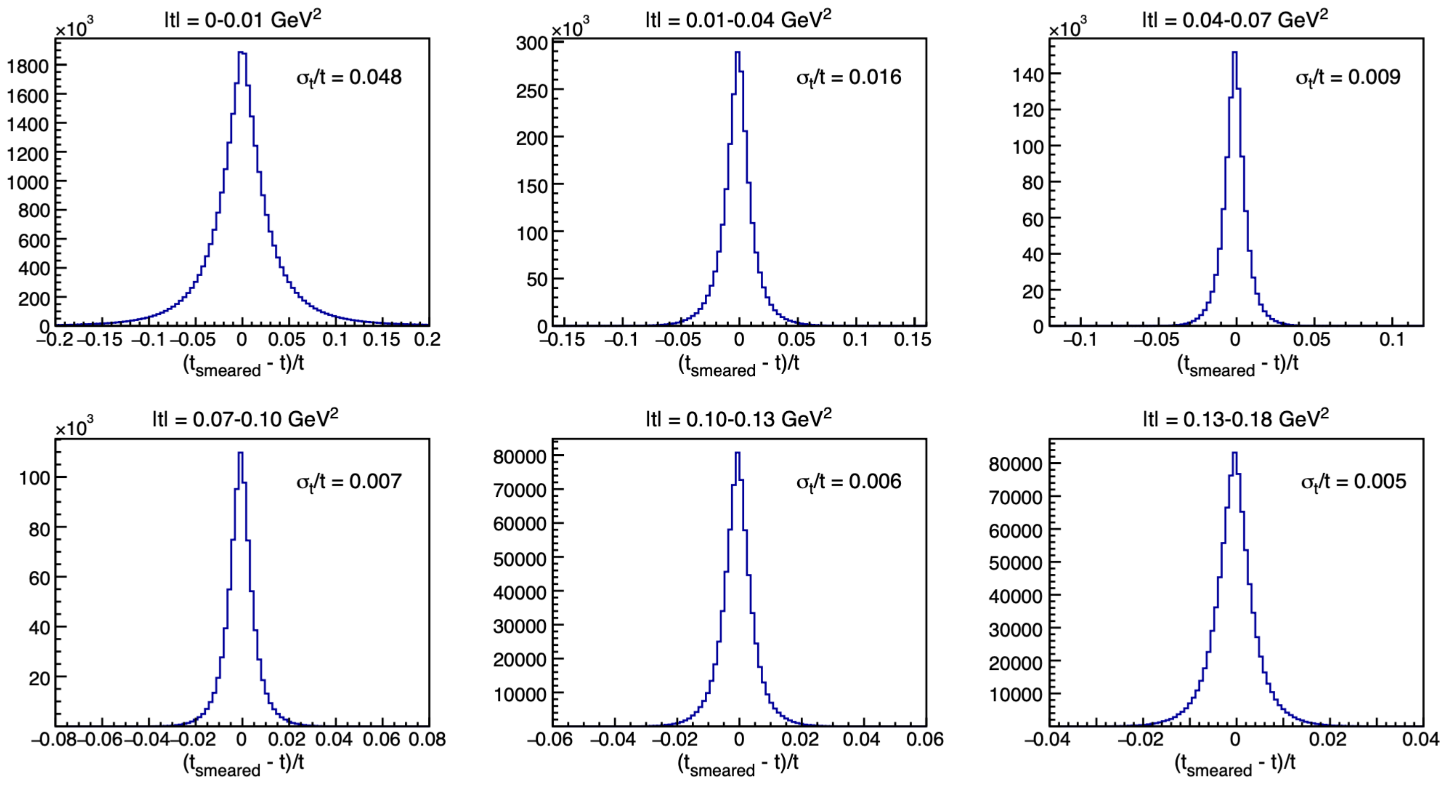
  - In short, you are using the true invariant mass of the nucleus to compensate the smearing in the larger component of the electron 4-momentum by modifying $E_{A'}$ and $p_{z,A'}$ simultaneously.
  - Now simply: $t_{\mathrm{corr}} = \left|p_A - p^{\mathrm{corr}}_{A'}\right|^2$

12

Brookhaven National Laboratory

Method L

From Thomas Ullrich



All beam effects on

method	effect	t-range (GeV^2)					
		0-0.1	0.1-0.4	0.04 - 0.07	0.07 - 0.10	0.10 - 0.13	0.13 - 0.18
E	beam divergence	0.061	0.015	0.008	0.007	0.006	0.005
E	beam mom. spread	149.61	10.36	3.03	1.86	1.37	1.03
L	divergence & mom. spread	0.048	0.016	0.009	0.007	0.006	0.005