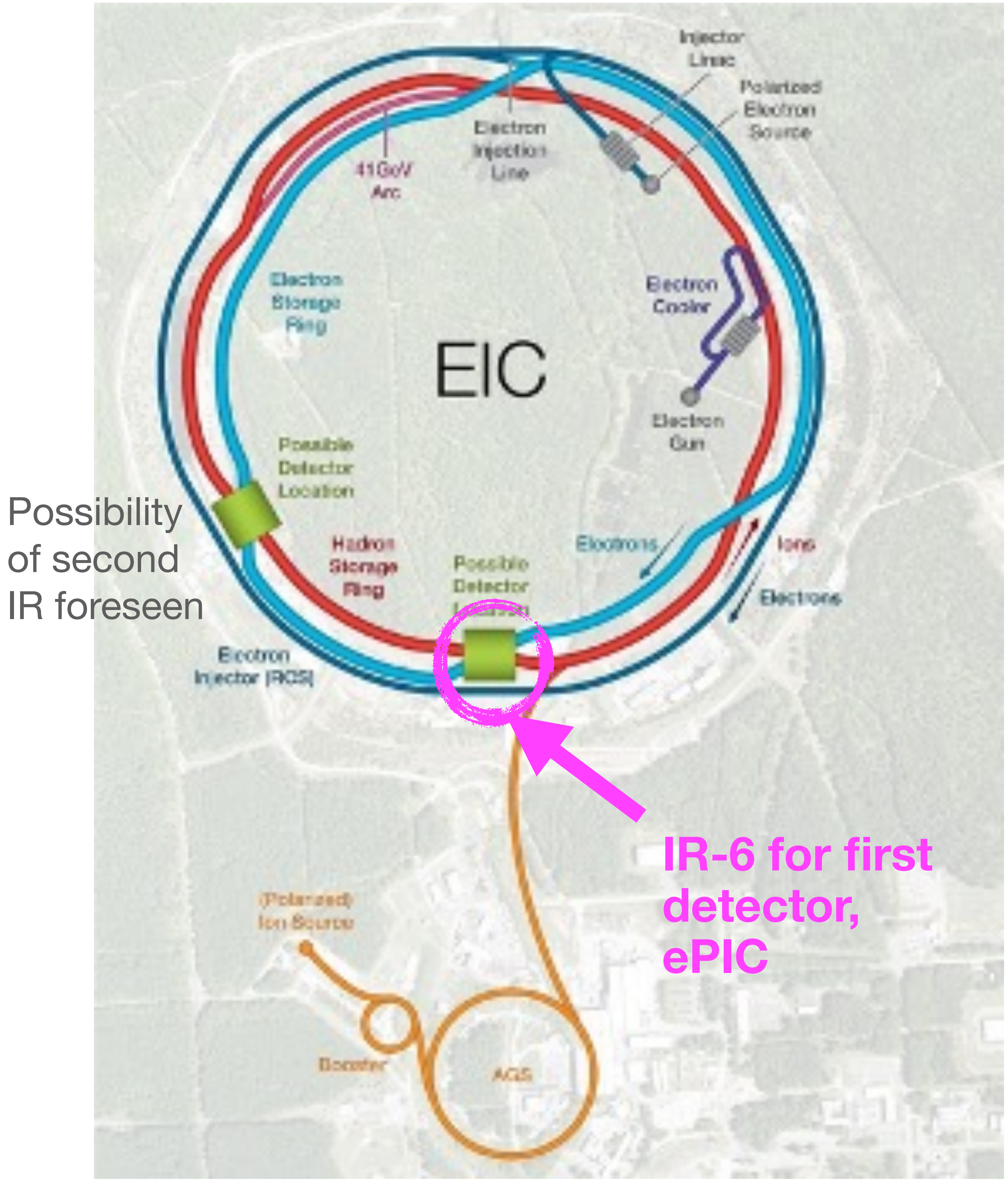
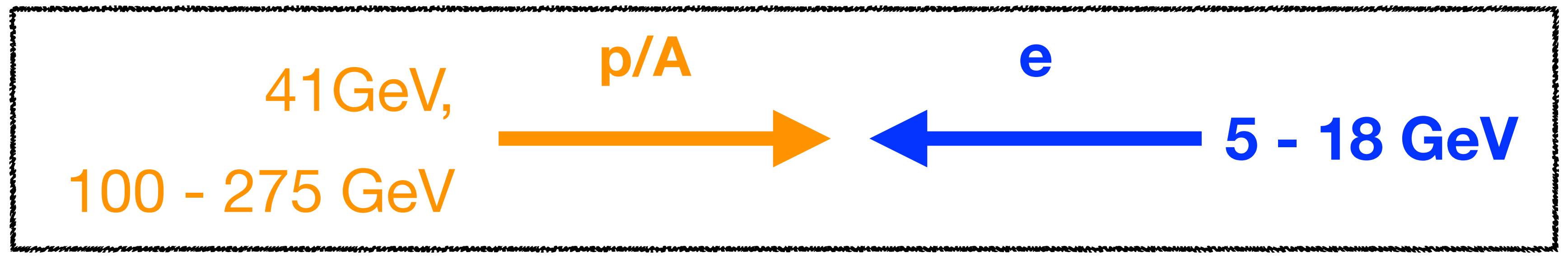
Glimpse into EIC Exclusive Nuclear Structure

Rachel Montgomery (UoG) on behalf of many:

ePIC Collaboration

Exclusive, Diffractive, Tagging Working Group
12/10/23





- World's first polarised electron-proton/light ion and electron-nucleus collider

- To be built at BNL on RHIC complex
- Partnership between BNL and JLab
- Only new collider in the next decade

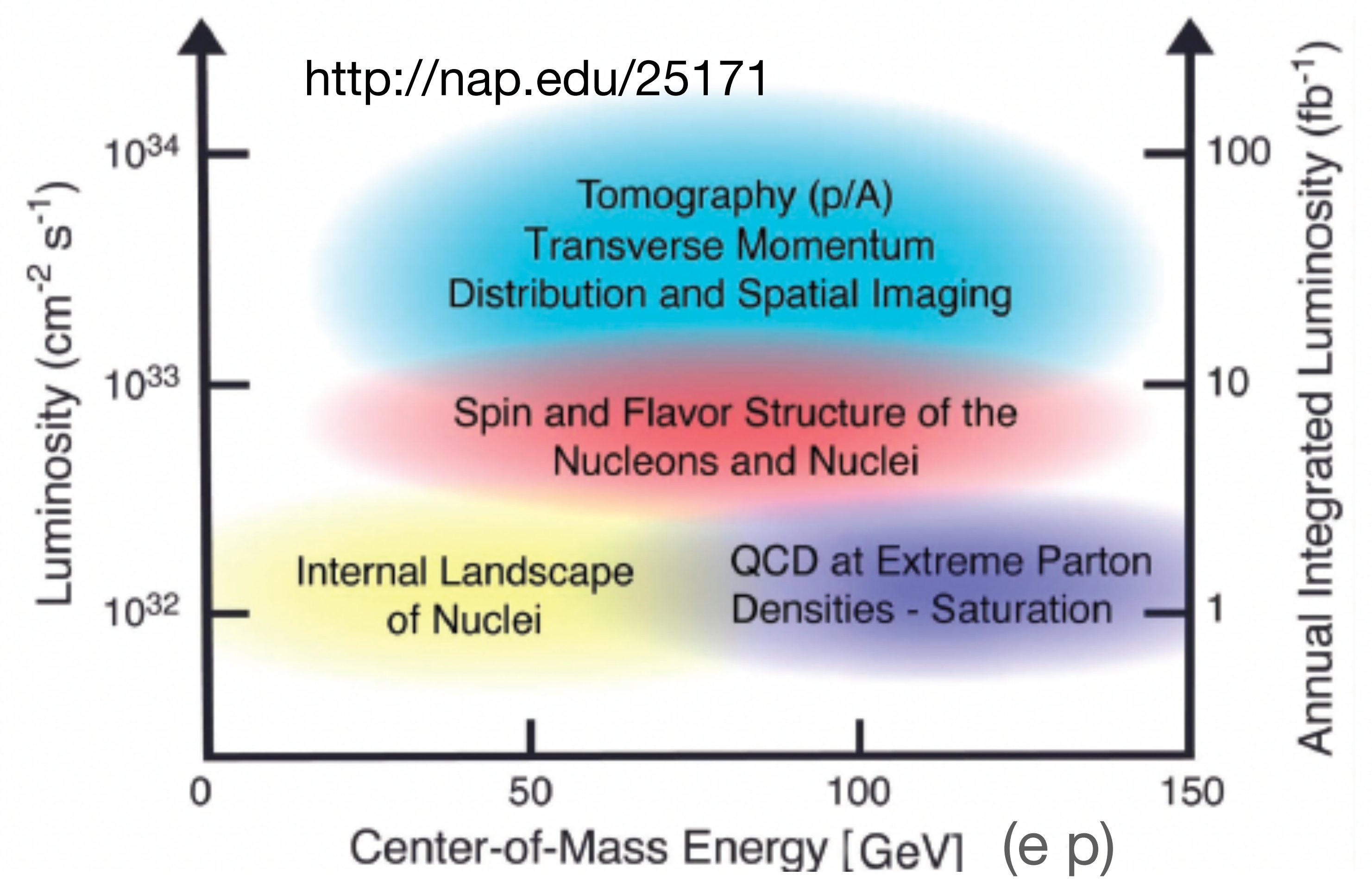
☑ High-luminosity: 10^{33} - 10^{34} cm^{-2}s^{-1}; 10 - 100 fb^{-1}/year; factor 100 - 1000 x HERA

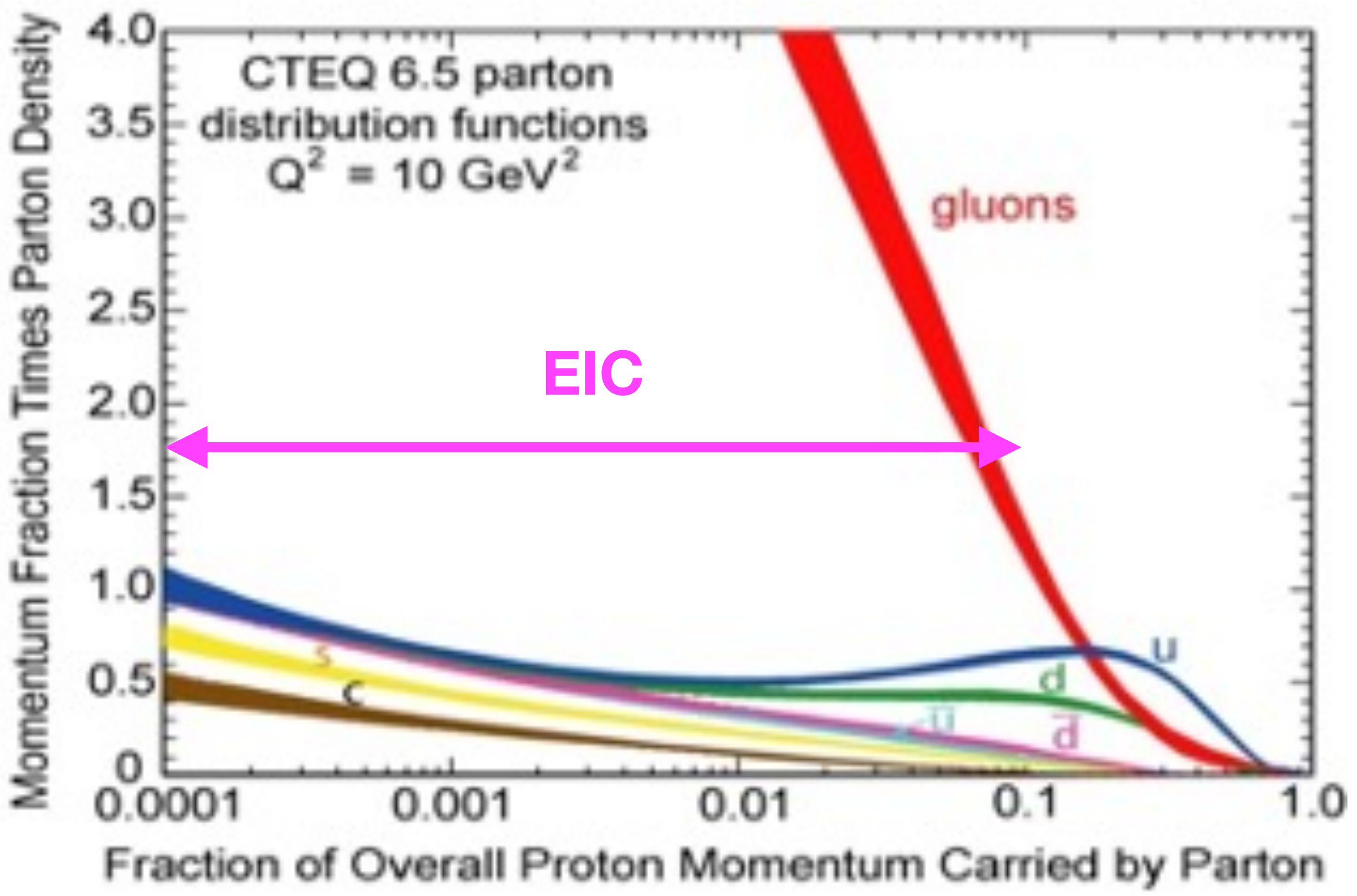
☑ High polarised beams: 70%

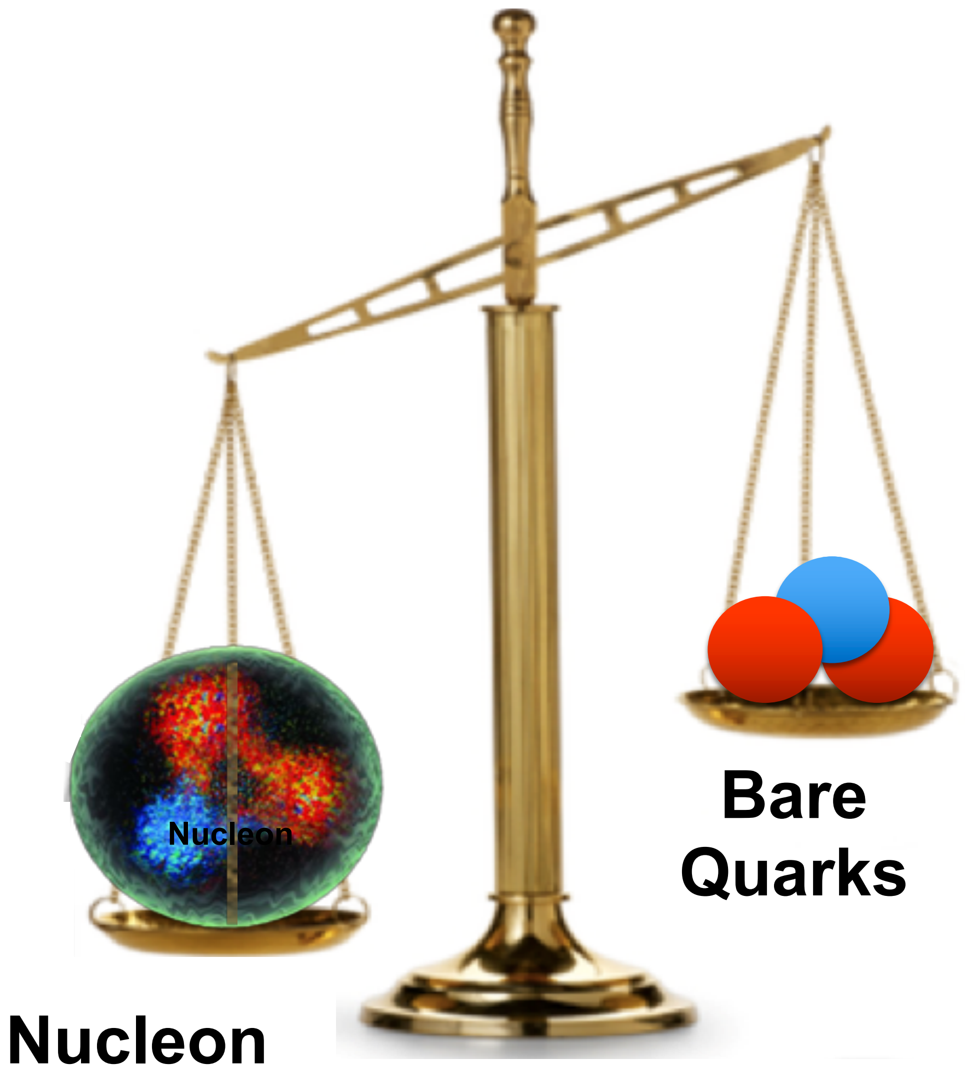
☑ Large and variable centre of mass energy:
  - $29 < E_{CM} < 141$ GeV

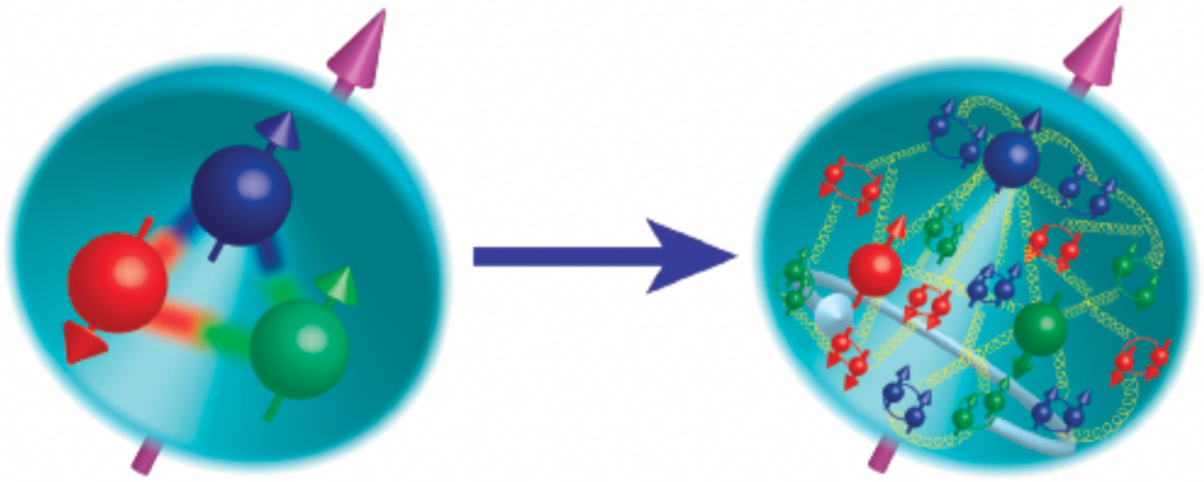
☑ Range of ions: protons, light nuclei, up to uranium

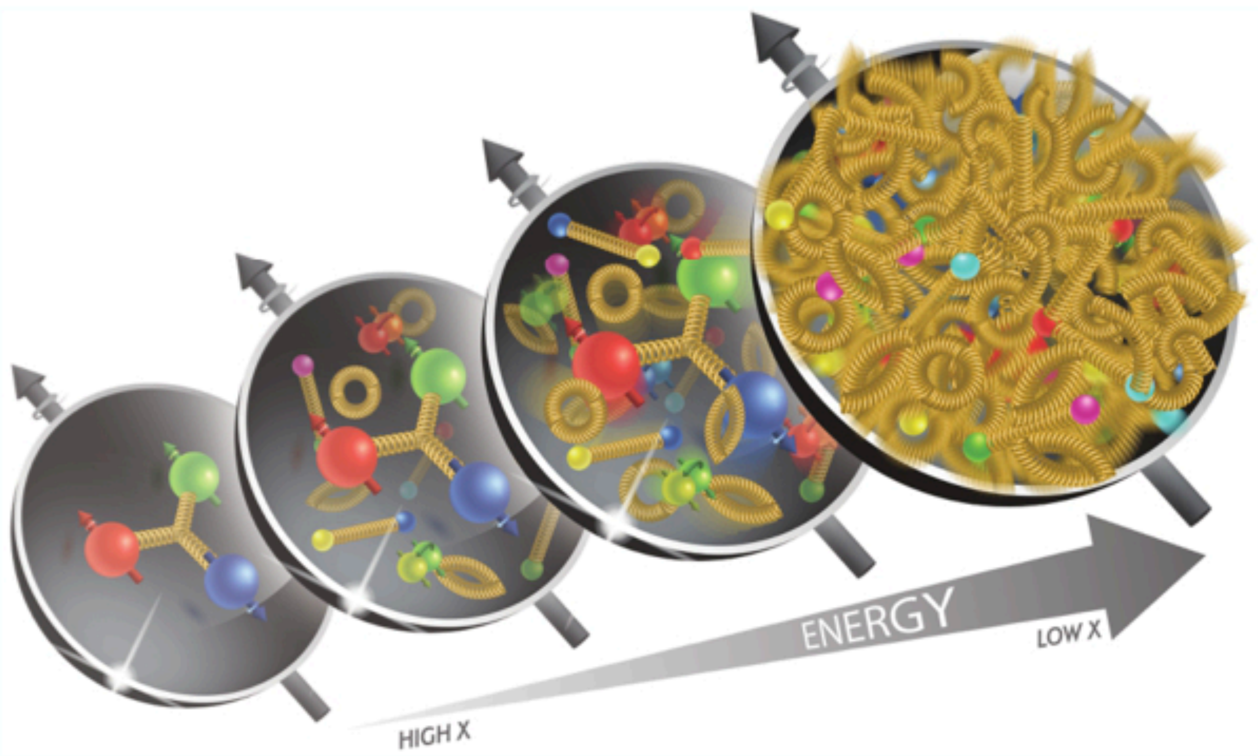
☑ Large detector acceptance









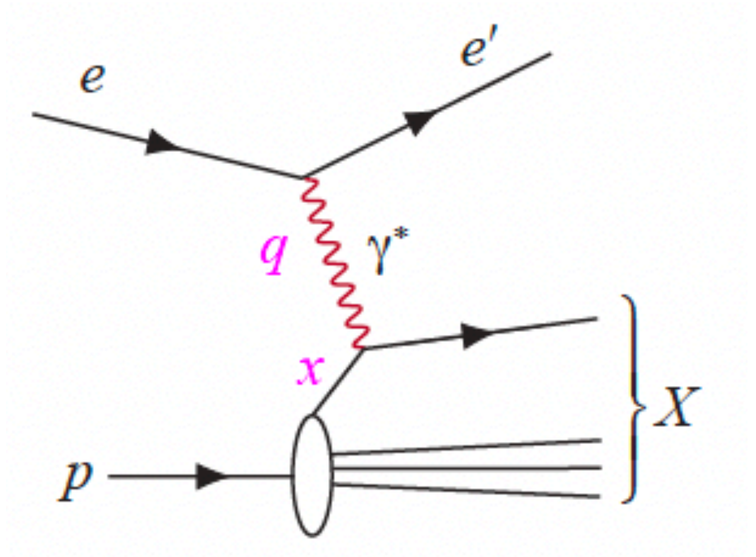


- Science case documented elsewhere
- 2018 NAS report: EIC can uniquely address 3 profound questions about nucleons and how they are assembled:
  - How does the mass of the nucleon arise?
  - How does the spin of the nucleon arise?
  - What are the emergent properties of dense system of gluons?
- EIC ideal to study predicted saturation
- Plus more topics…

See e.g.: arXiv:1212.1701 [nucl-ex]; http://nap.edu/25171; arXiv:1708.01527v3 [nucl-ex]; arXiv:2103.05419v2 [physics.ins-det])

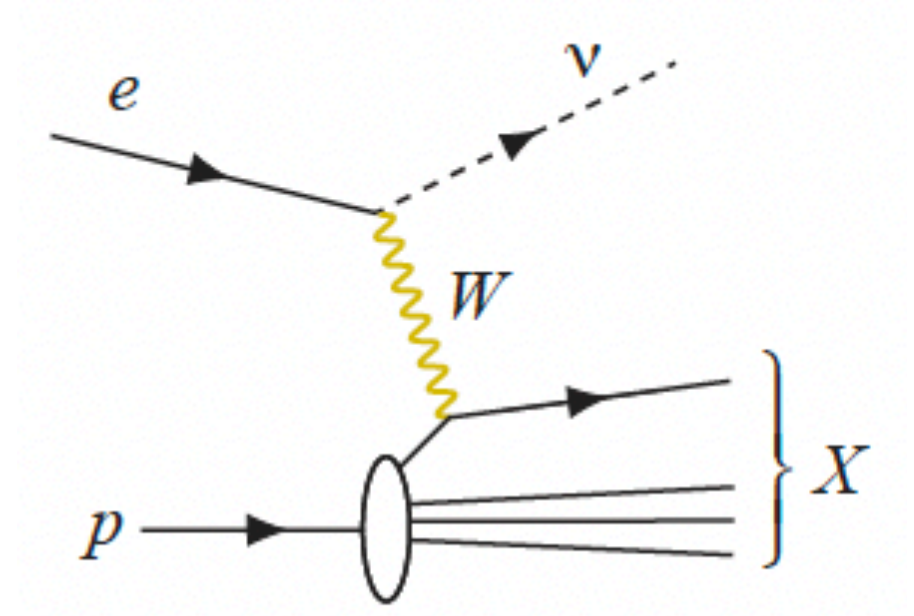
Several Final States

Neutral current inclusive



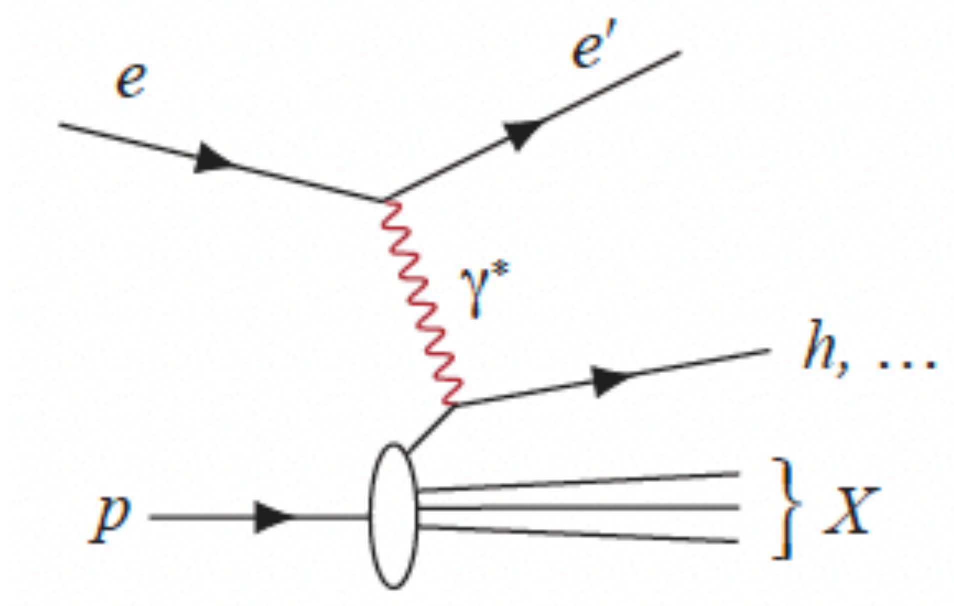
$$e + p/A \to e' + X$$

Charged current inclusive



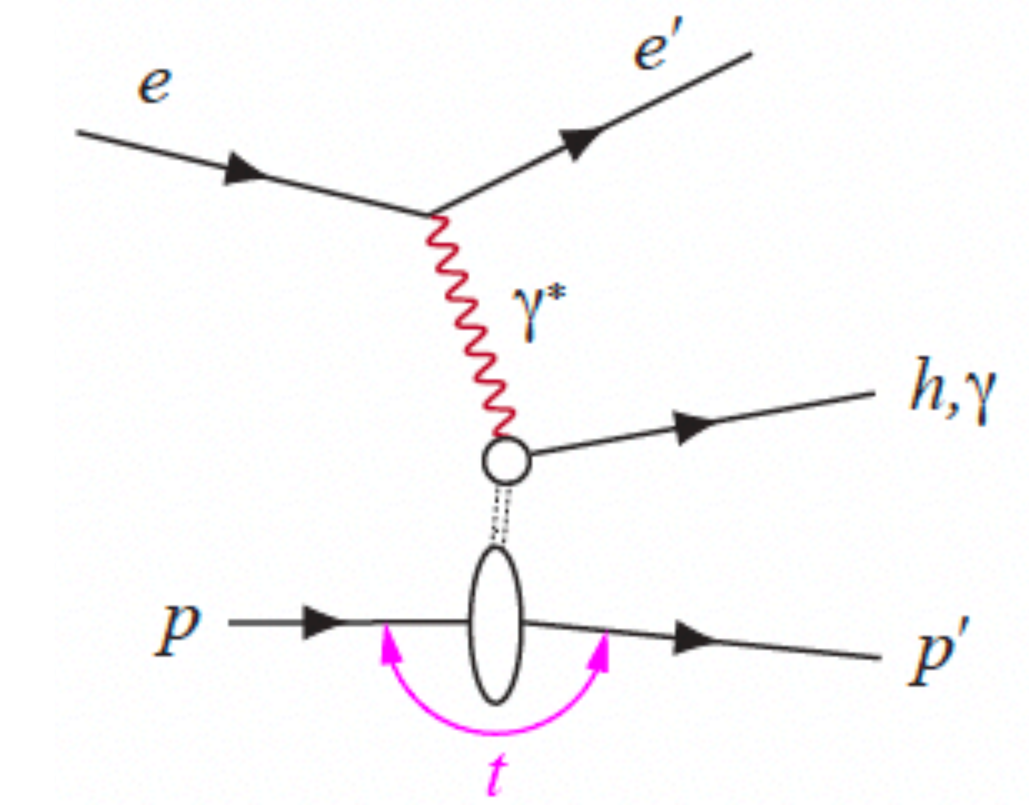
$$e + p/A \to \nu + X$$

Semi-inclusive



$$e + p/A \to e' + h^{\pm,0} + X$$

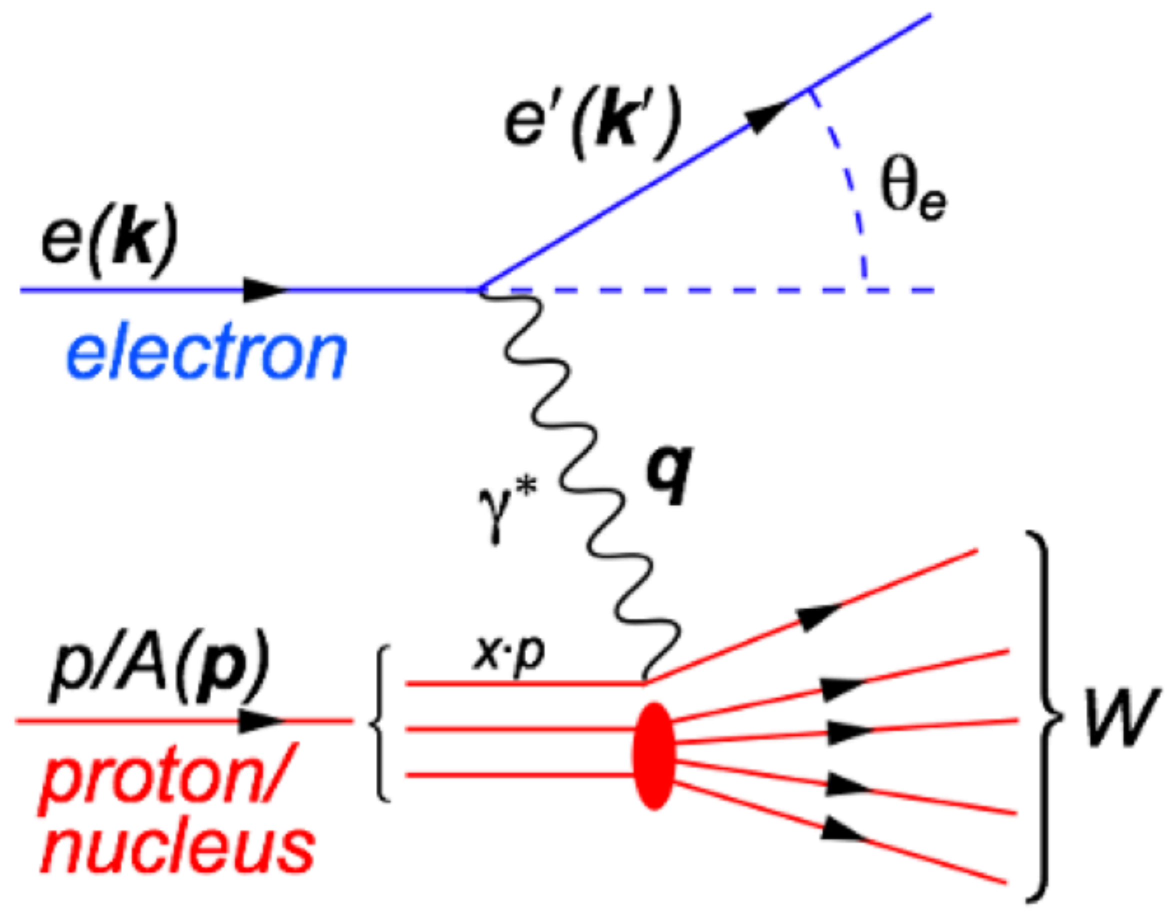
Exclusive



$$e + p/A \to e' + p'/A' + \gamma/h^{\pm,0}/VM$$

$$-t = -(p' - p)^2$$

Deep Inelastic Scattering



e-p E_{CM}^2

$$s = (k+p)^2$$

Photon virtuality - by detecting e

$$Q^2 = -q^2$$

$$y = \frac{p \cdot q}{p \cdot k}$$

Inelasticity

$$x = \frac{-q^2}{2p \cdot q}$$

Bjorken x

- Complete control of kinematics event by event
- Complimentary to e+e-, pp/pA/AA (test eg universality)
- **Exclusive**
  - Multi-particle final states - measure particles with high precision
  - Multi-dimensional binning (e.g. x, Q^2, t, ϕ) - high luminosity
  - Good acceptances (maps to reconstructed kinematic reach), very reliant on forward acceptance …
  - Detectors resolutions and PID for background rejection

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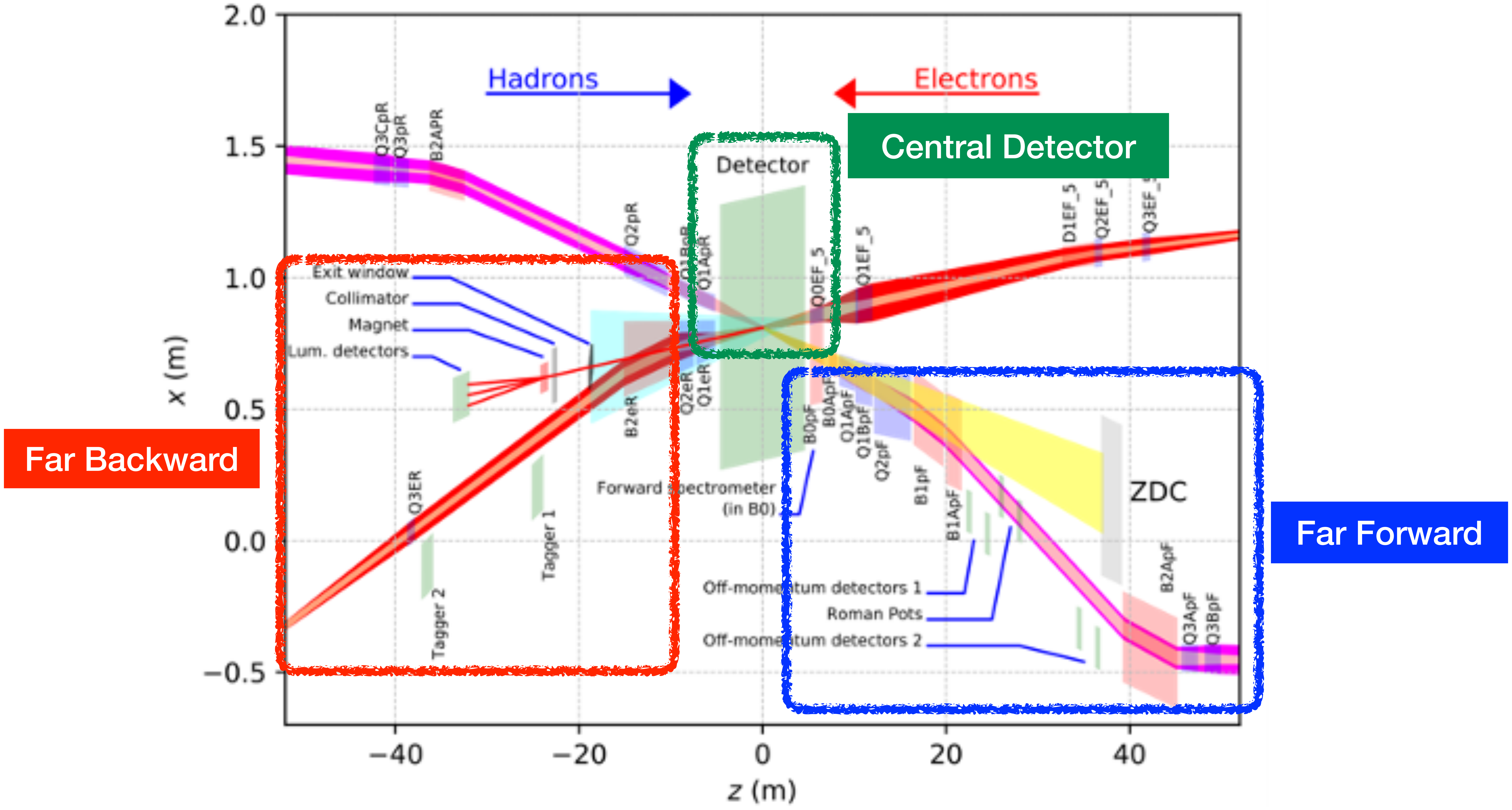
IR Layout

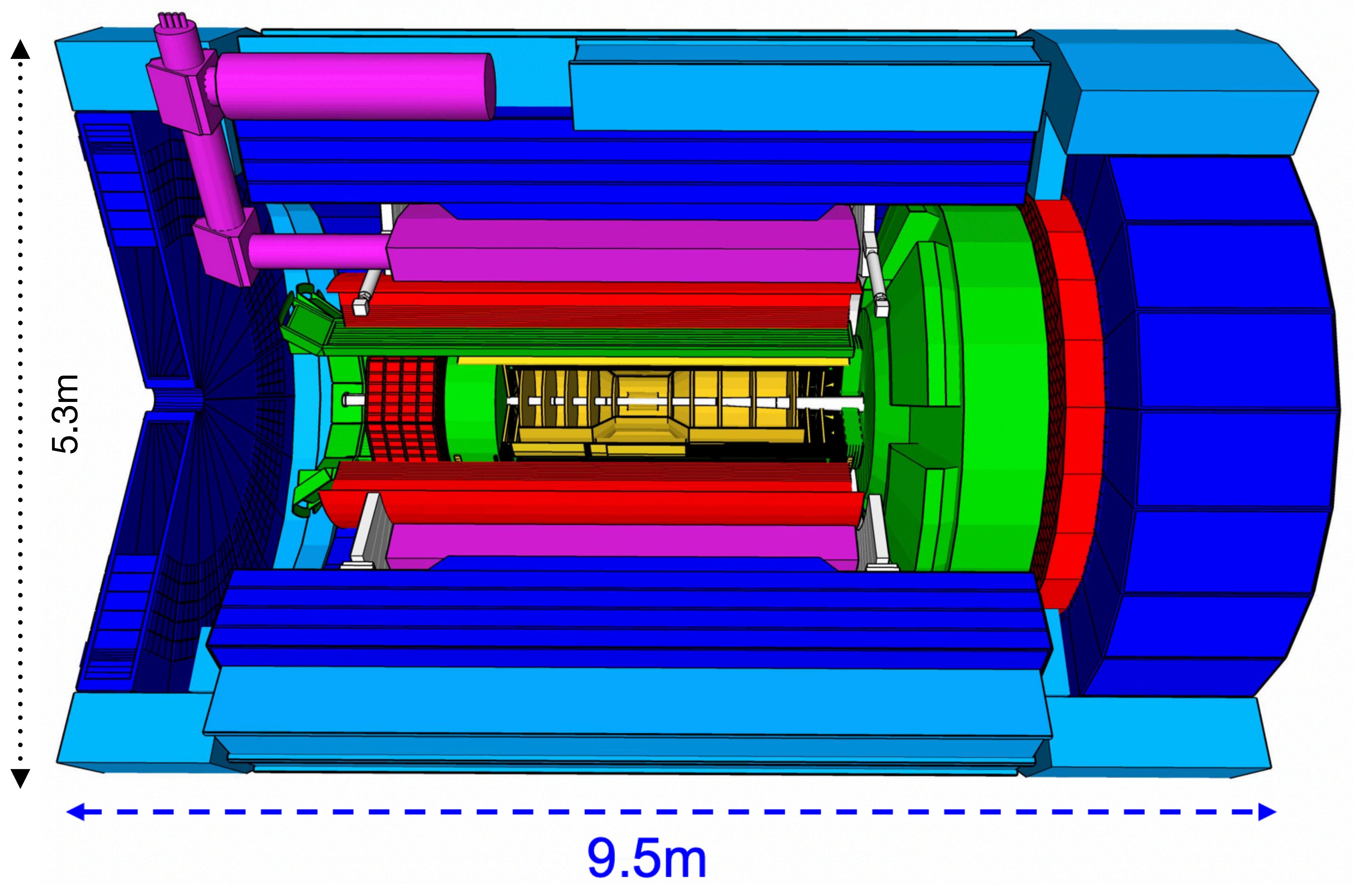
Crossing angle 25mrad



Excellent acceptance for exclusive reactions
Broad range of exclusive final states rely on combinations of all Far Backward, Central Detector and - critically - Far Forward (diffraction, tagging, nuclear breakup)

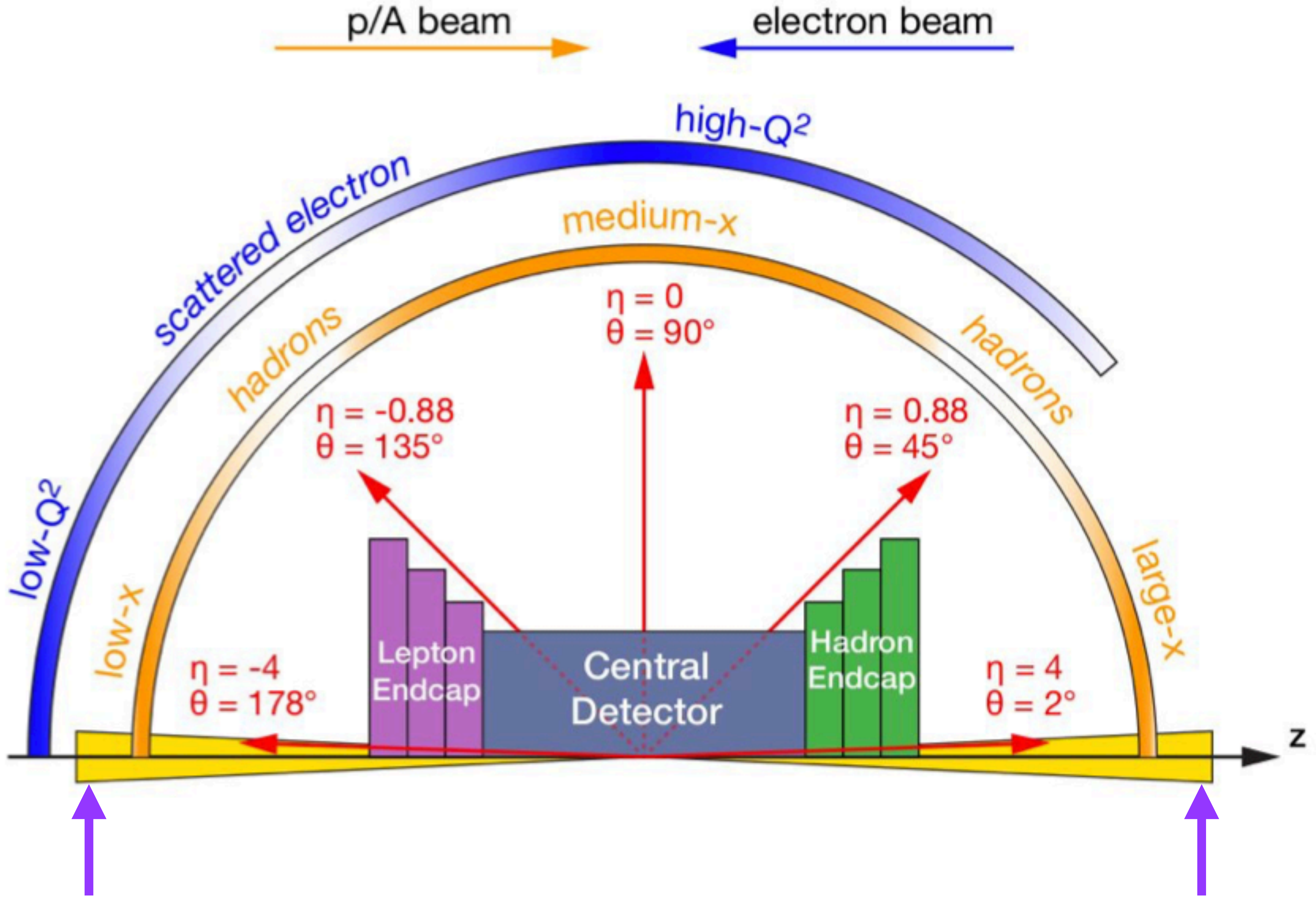
ePIC Detector

electron-proton/ion collider (ePIC) experiment current design



Hermetic central detector: 0° ≤ ϕ ≤ 360°; -4 ≤ η ≤ 4

$$\eta = -\ln \tan(\theta/2)$$

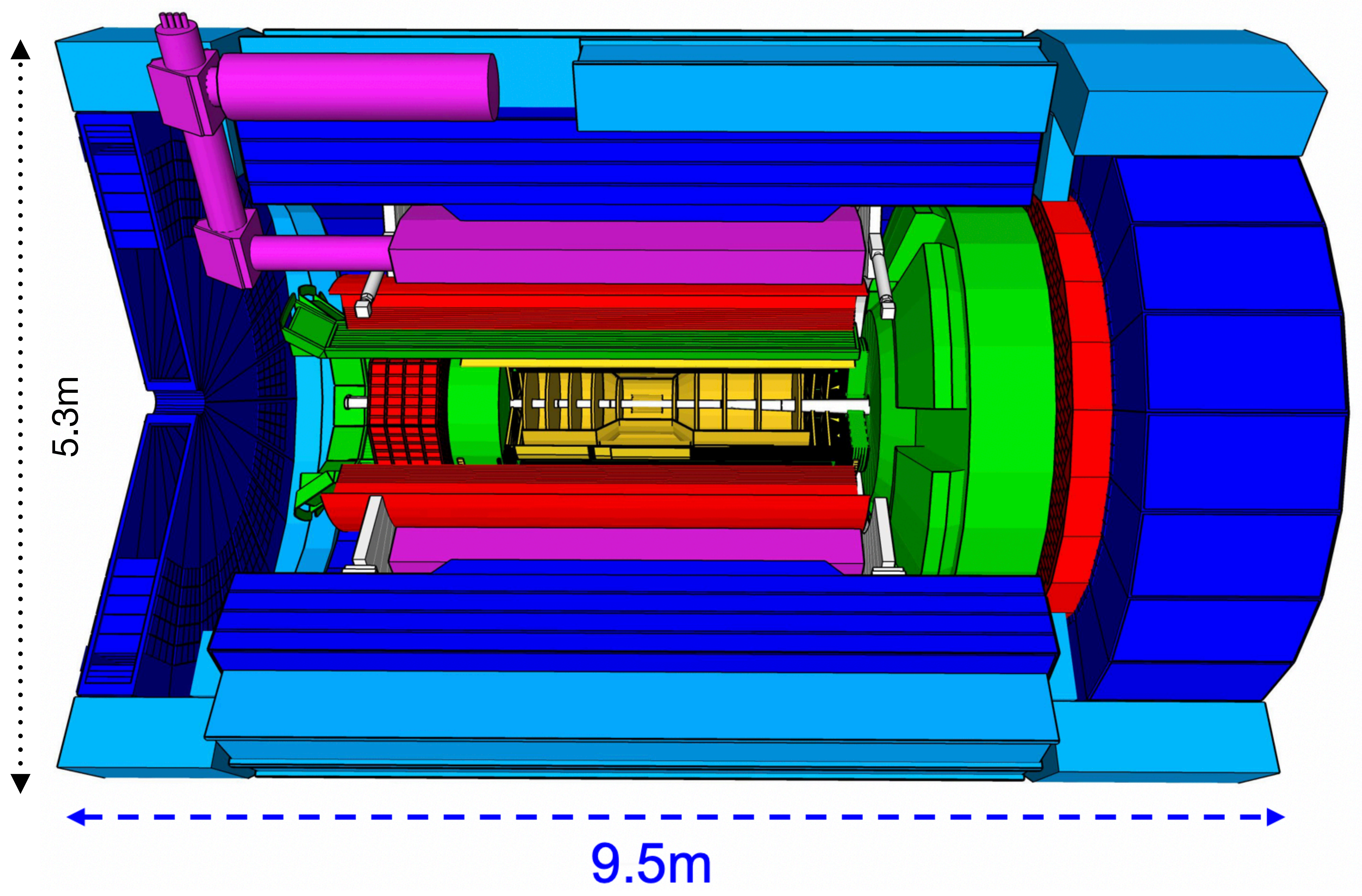


Towards far backward

Towards far forward

ePIC Detector

electron-proton/ion collider (ePIC) experiment current design



Hermetic central detector: $0^\circ \leq \phi \leq 360^\circ$; $-4 \leq \eta \leq 4$

$$\eta = -ln\,tan(\theta/2)$$

E/M Calorimetry

- Imaging EMCal (barrel)
- W-powder / SciFi (forward)
- $PbWO_4$ crystals (backward)

Hadronic Calorimetry

- FeSc from sPHENIX (barrel)
- Steel/Scint - W/Scint (backward/forward)

Particle Identification

- High performance DIRC (barrel)
- Dual radiator (aerogel+gas) RICH (forward)
- Proximity focussing RICH (aerogel) (backward)
- TOF (AC-LGAD) (barrel and forward)

Solenoid

- 1.7T

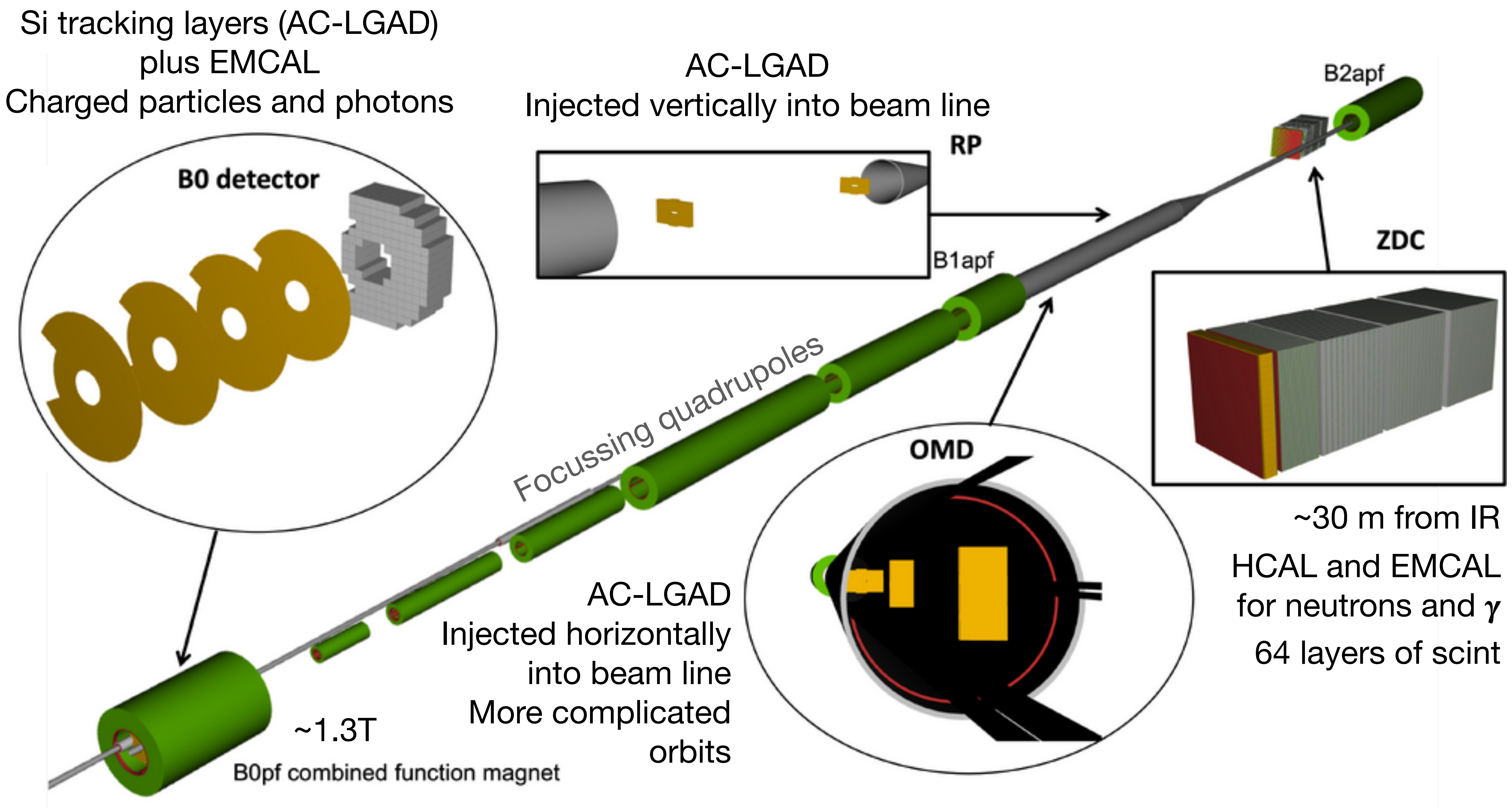
Tracking

- Si MAPS (vertex, barrel, forward and backward disks)
- MPGD (μRWELL; micromegas) (barrel, forward and backward disks)

DAQ

- Streaming/triggerless, inclusion of AI

Far Forward

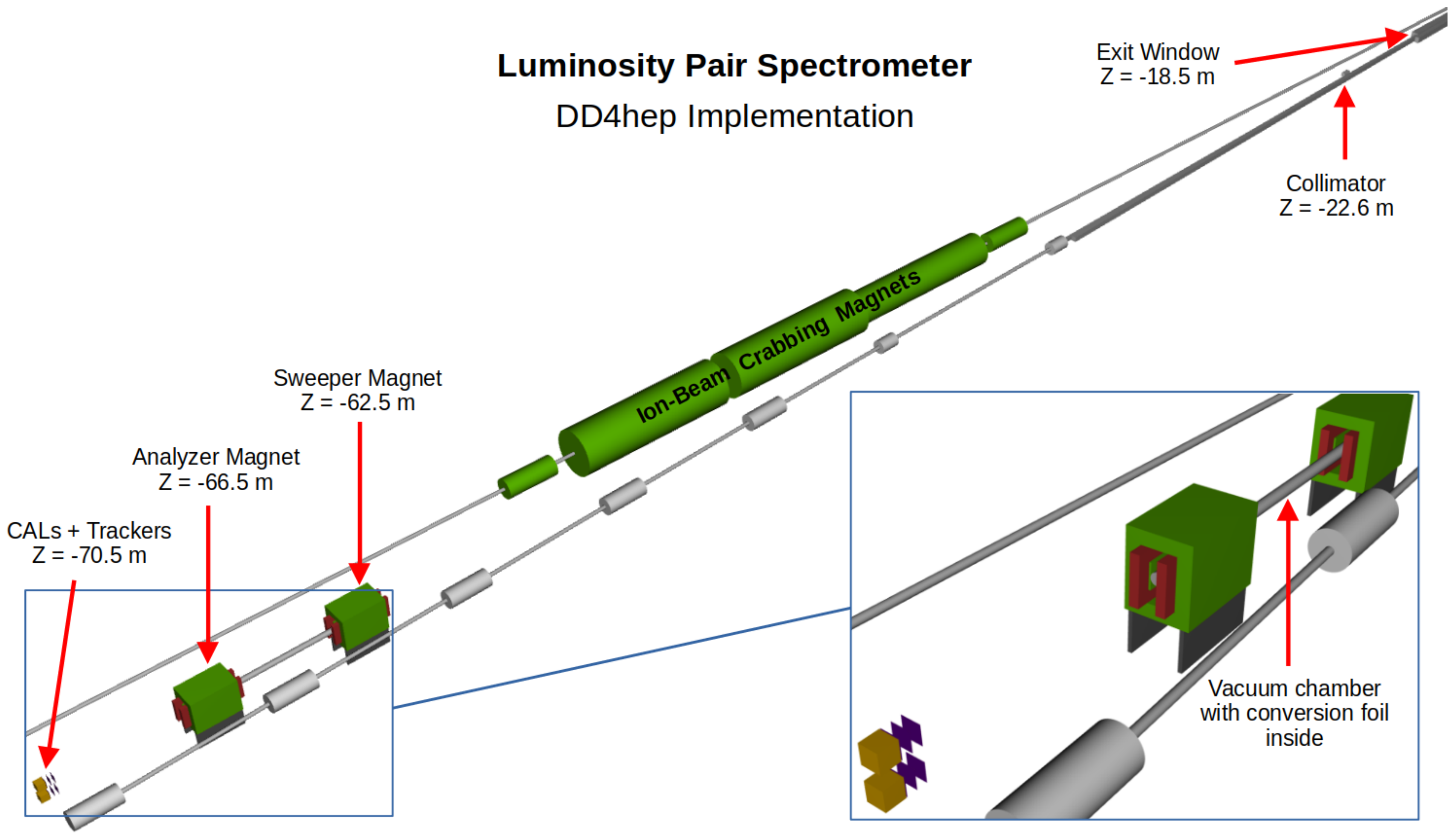


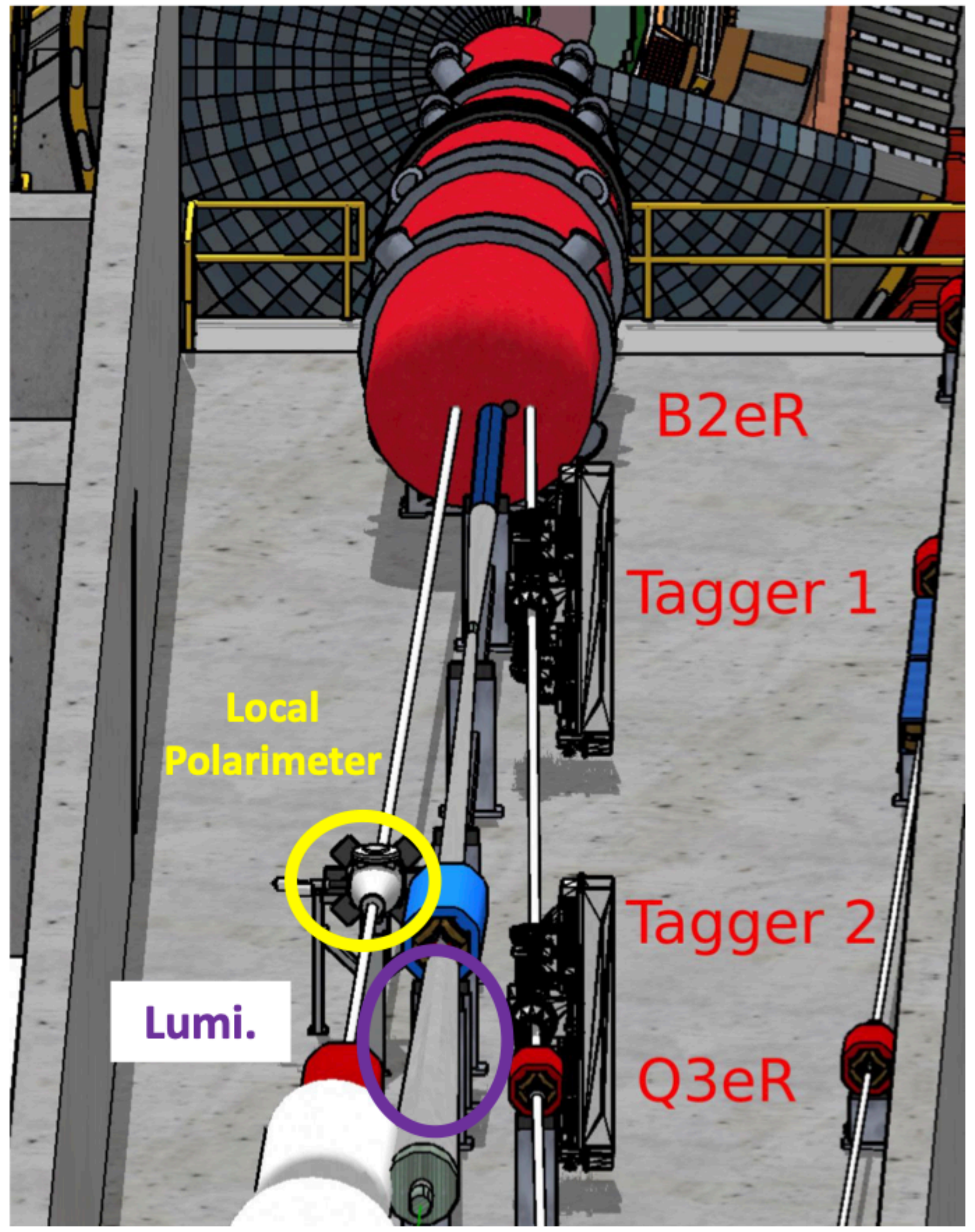
Detector	Acceptance
Zero-degree calorimeter (ZDC)	θ < 5.5 mrad (η > 6)
Roman pots (RP) (2 stations)	0.0 < θ < 5.0 mrad (η > 6)
Off-Momentum Detectors (OMD) (2 stations)	0.0 < θ < 5.0 mrad (η > 6)
B0	5.5 < θ < 20.0 mrad (4.6 < η < 5.9)

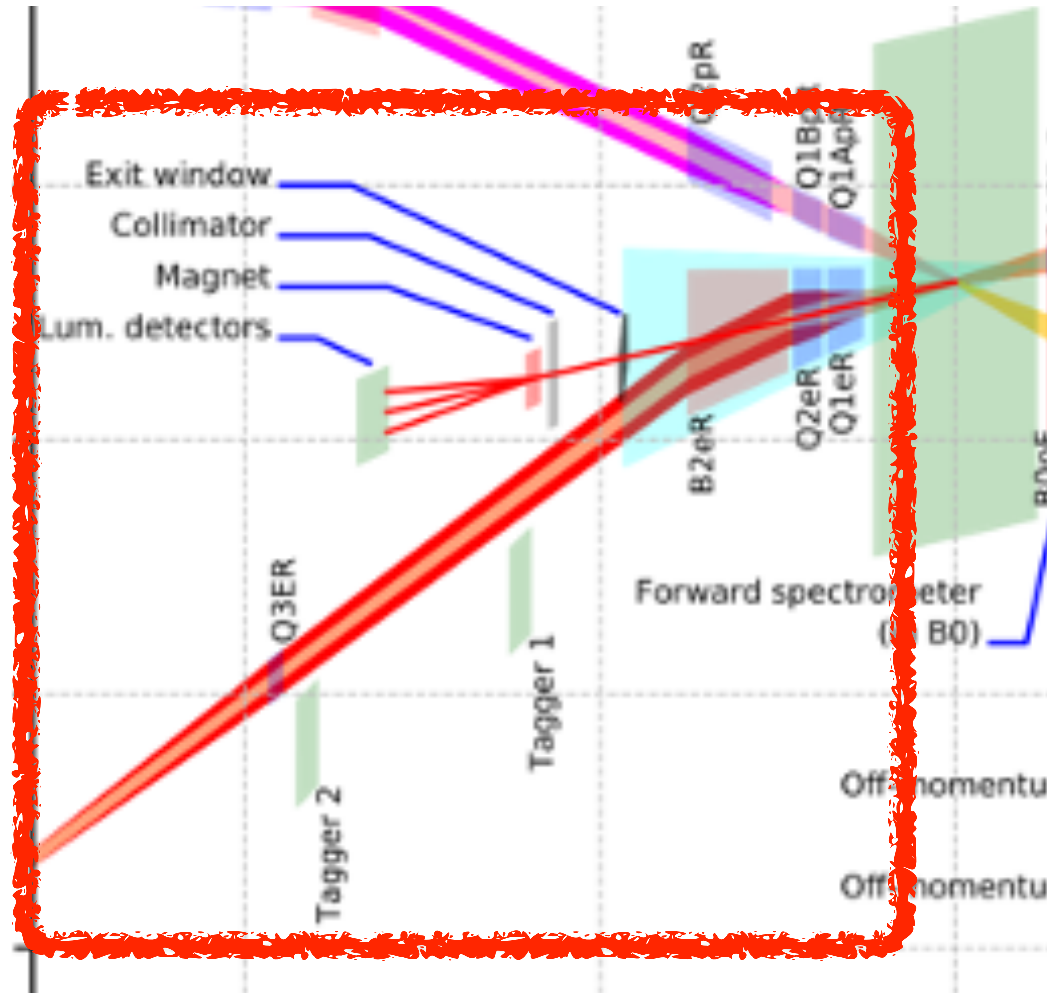
- Integration with accelerator
- Tagging at very small scattering angles η>4.5 !
- charged hadrons (protons, π) or neutrals (neutrons, γ), nuclei with different magnetic rigidity from beam
- Variety of final states
- Several ion species
- Wide range of beam/particle energies

- Essential for exclusive physics program
  - e.g. tagging; nuclear breakup/incoherent vetoing; t reconstruction…
  - e.g. deeply virtual Compton scattering (ep→e'p'γ), p' in B0 for low energy setting, RP for high setting

Far Backward







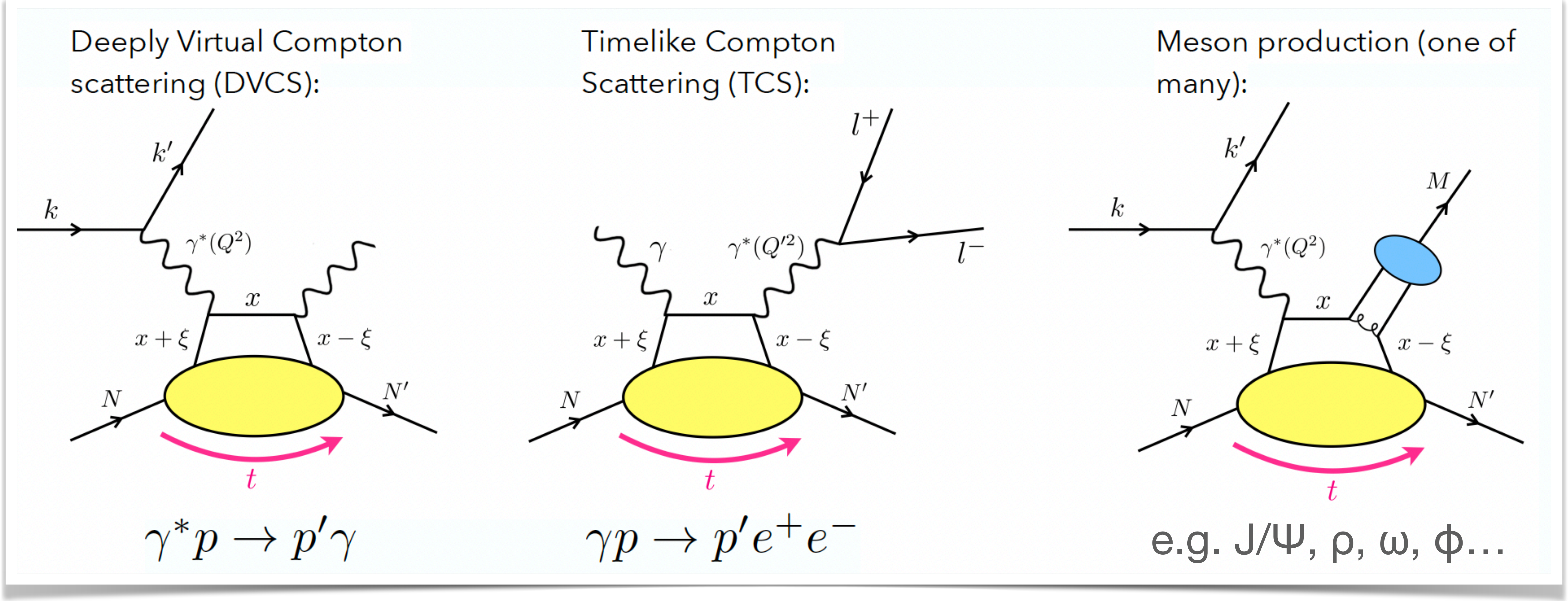
- Complementary luminosity monitors
- Direct photon detector
  - Calorimetry - Bremsstrahlung γ
  - Synchrotron radiation
- Pair spectrometer
  - Convert Bremsstrahlung γ to e^+e^-
  - No synchrotron radiation
- Absolute and relative luminosity - physics normalisations
  - Absolute $\delta L/L<\sim 1\%$
  - Relative up to 10^{-4} - 10^{-5}
- Low Q2 electron tagging
  - Verify luminosity measurements
  - Physics: extends kinematic range for electrons, or quasi real photons
  - e.g. studied in exclusive program for XYZ spectroscopy

Exclusive Activities - Just Some Examples

Encompasses many topics

Numerous studies on-going, planned, still expanding/ evolving

Only some examples here



Example hard exclusive processes

- QCD at extreme parton densities - saturation
- Nucleon/Nuclear femtography: imaging of partons

- Hard exclusive reactions: Generalised Parton Distributions (GPD) - nucleon/nuclear tomography, nucleon spin (orbital angular momentum contribution), mechanical properties of nucleon (pressure, shear forces)
- Diffractive meson production: saturation probe in eA, gluon distributions, at threshold production sensitive to mass generation
- Sullivan process: scattering from meson cloud, meson form factors and structure functions - meson structure and nucleon mass enigma
- Spectroscopy: structure of nucleons, search for exotics

Not exhaustive!

Exclusive Activities - Just Some Examples

Encompasses many topics

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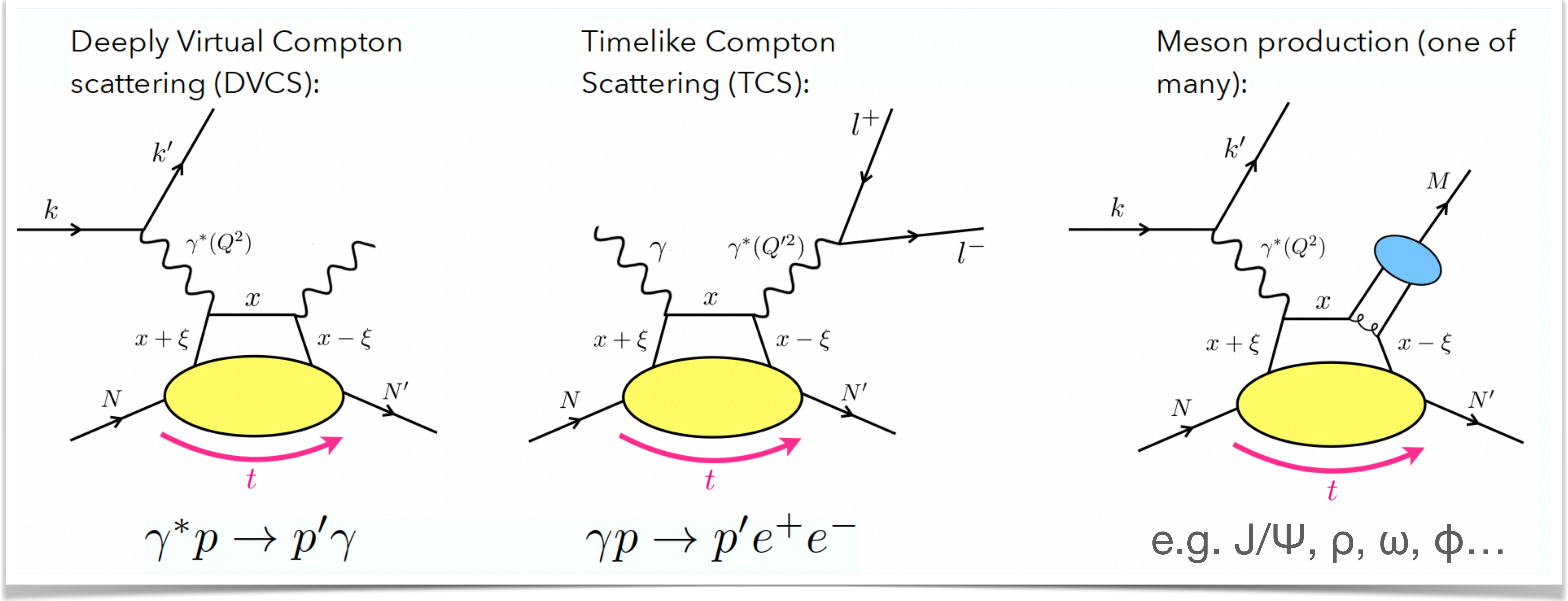
Only some examples here



Example hard exclusive processes

- Example recent activities for EIC detector 1 proposals and ePIC (still more to be studied):

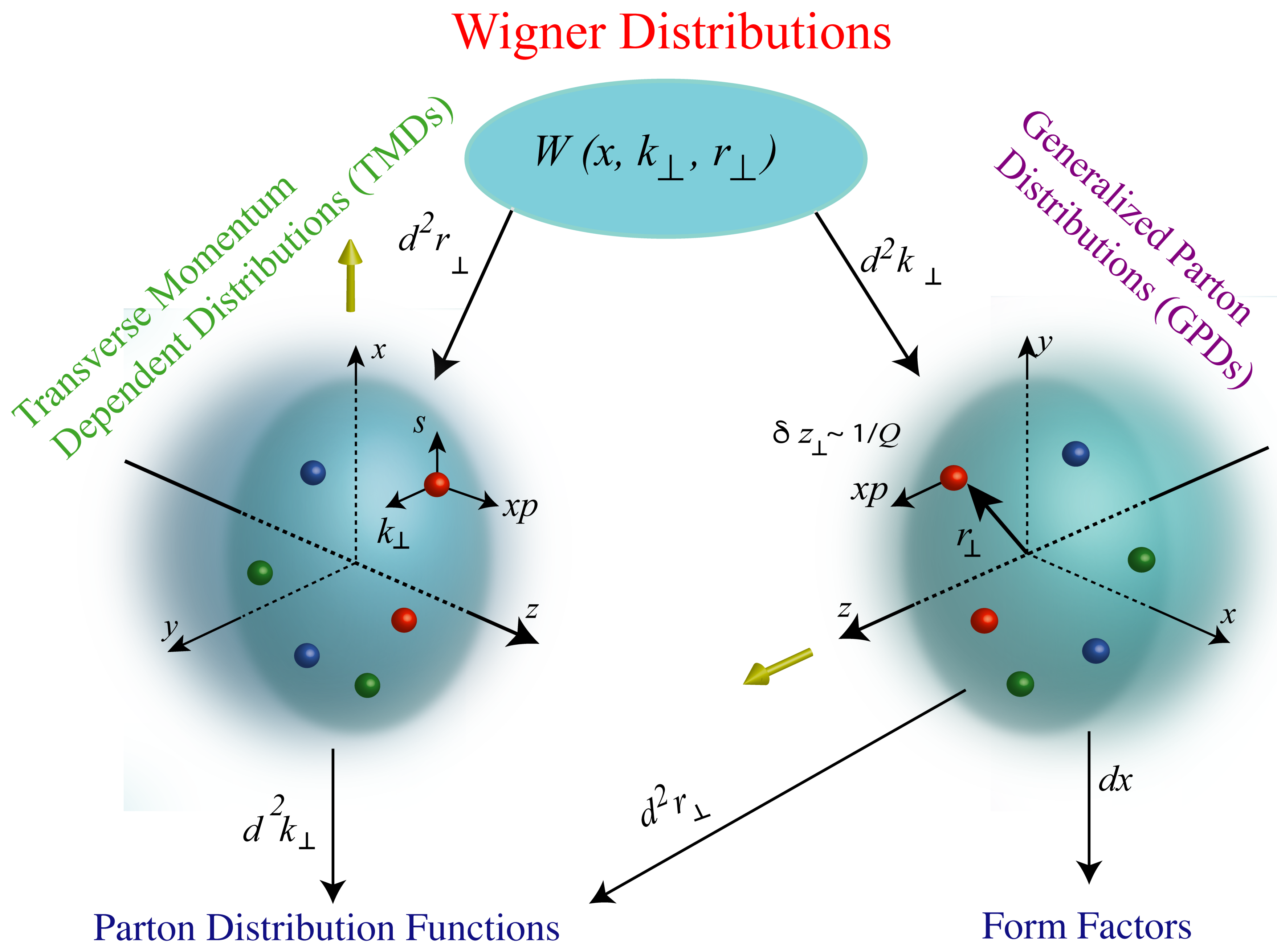
DVCS in ep	u-channel VCS	J/Psi in eA	Pion structure functions
TCS in ep	u-channel: ω, ρ in ep	Phi in eA	Pion form factors
DVCS in eHe-4	J/Psi in ep	X,Y Ψ(2S) in ep → J/Ψ$\pi^+\pi^-$p	Pion DVCS via Sullivan

Now a few examples…

Tomography

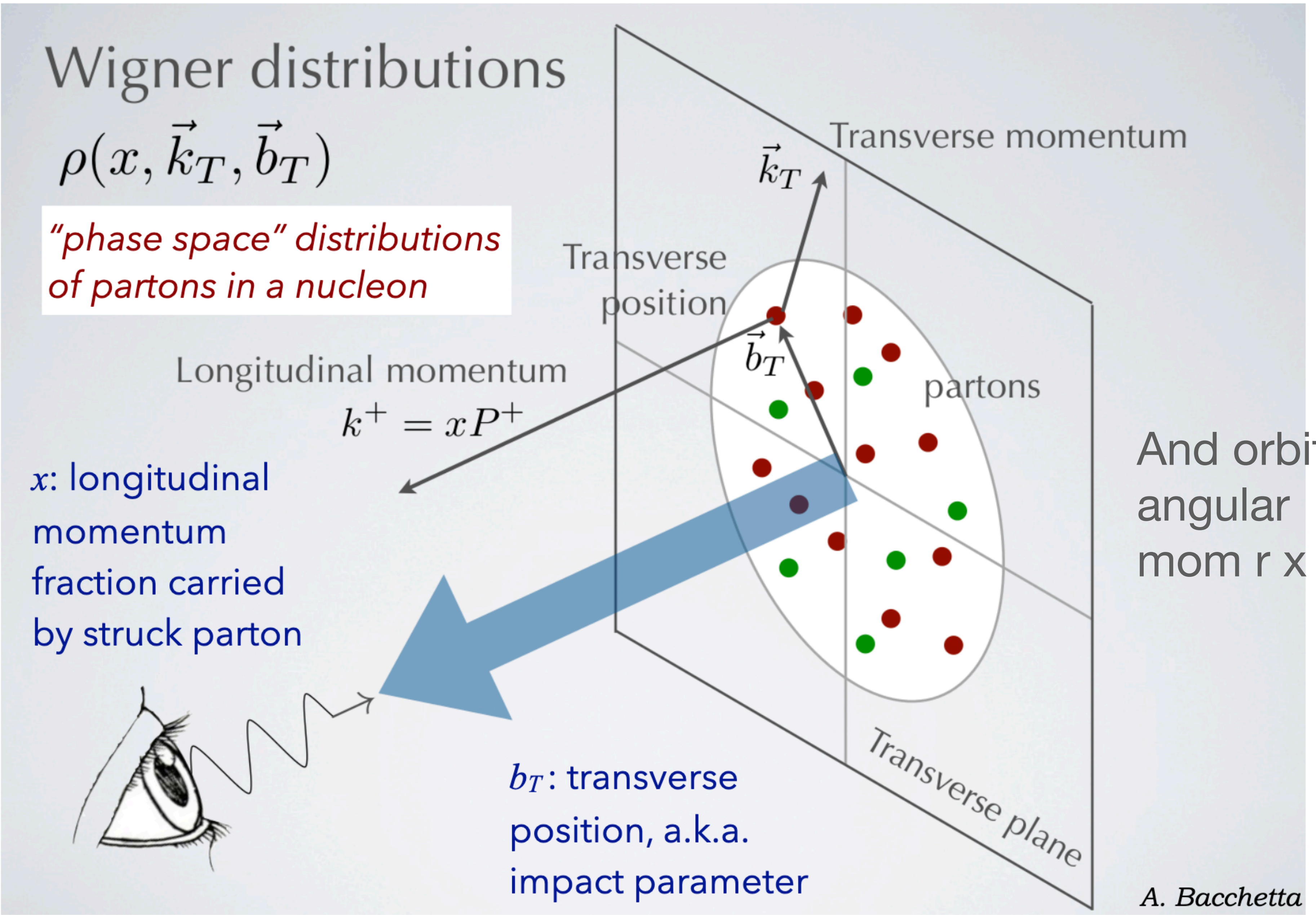
longitudinal momentum and transverse momentum f(x, k$_T$)

Semi-inclusive deep inelastic processes



longitudinal momentum and transverse position f(x,b$_T$)

Exclusive Processes



And orbital angular mom r x p

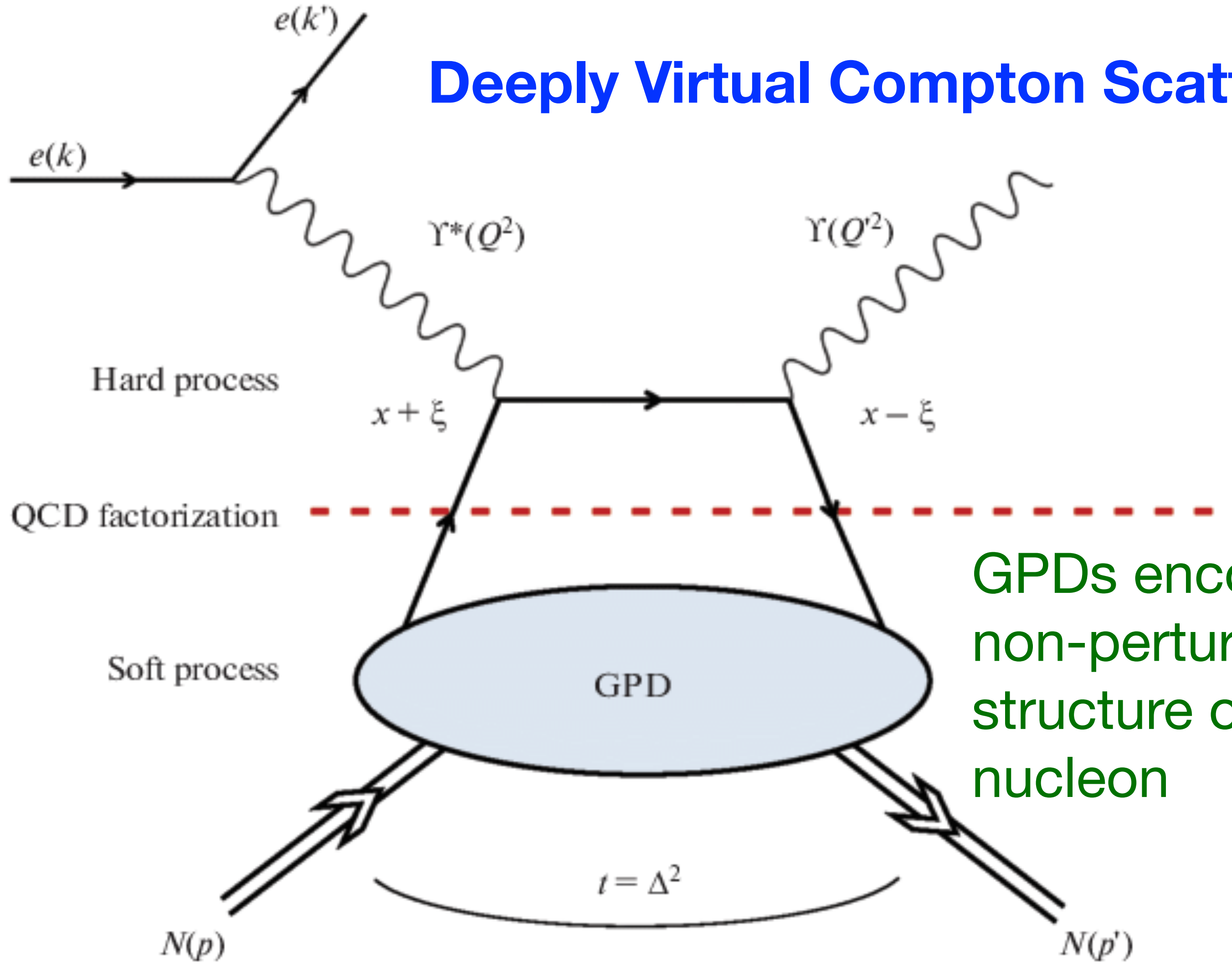
Our goal: understand distributions of partons inside hadrons - how they move, how they are located

Variables as before, plus:

Longitudinal momentum fractions of struck parton $x \pm \xi$

Skewness $\xi = \dfrac{x_B}{2 - x_B}$

Deeply Virtual Compton Scattering



GPDs encode non-perturbative structure of nucleon

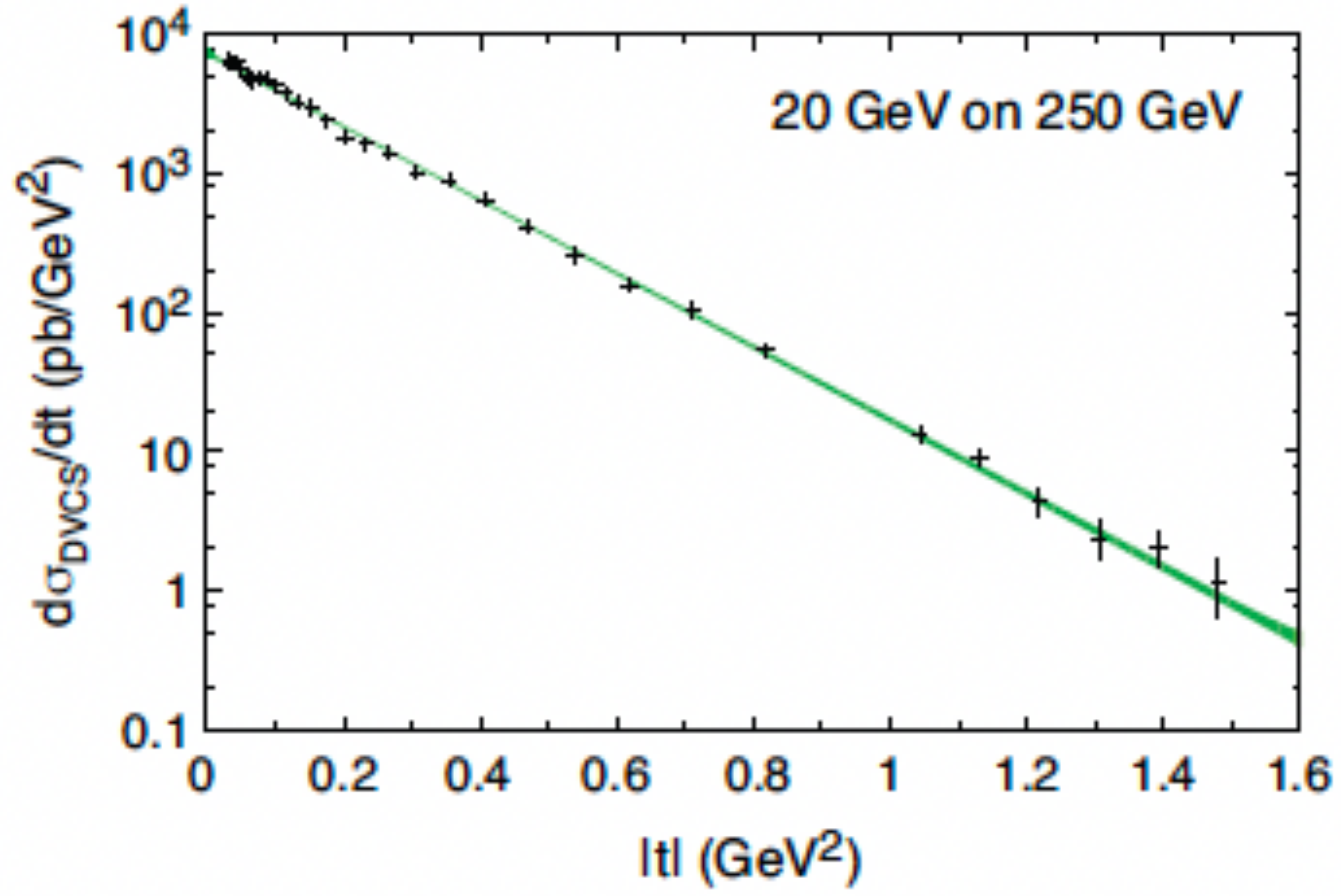
- High Q^2, low t → clean access to four parton helicity-conserving chiral-even GPDs:

$$E^q, \tilde{E}^q, H^q, \tilde{H}^q(x, \xi, t)$$

- Access to: transverse spatial positions in longitudinal momentum space; pressure distributions (indirectly); orbital angular momentum

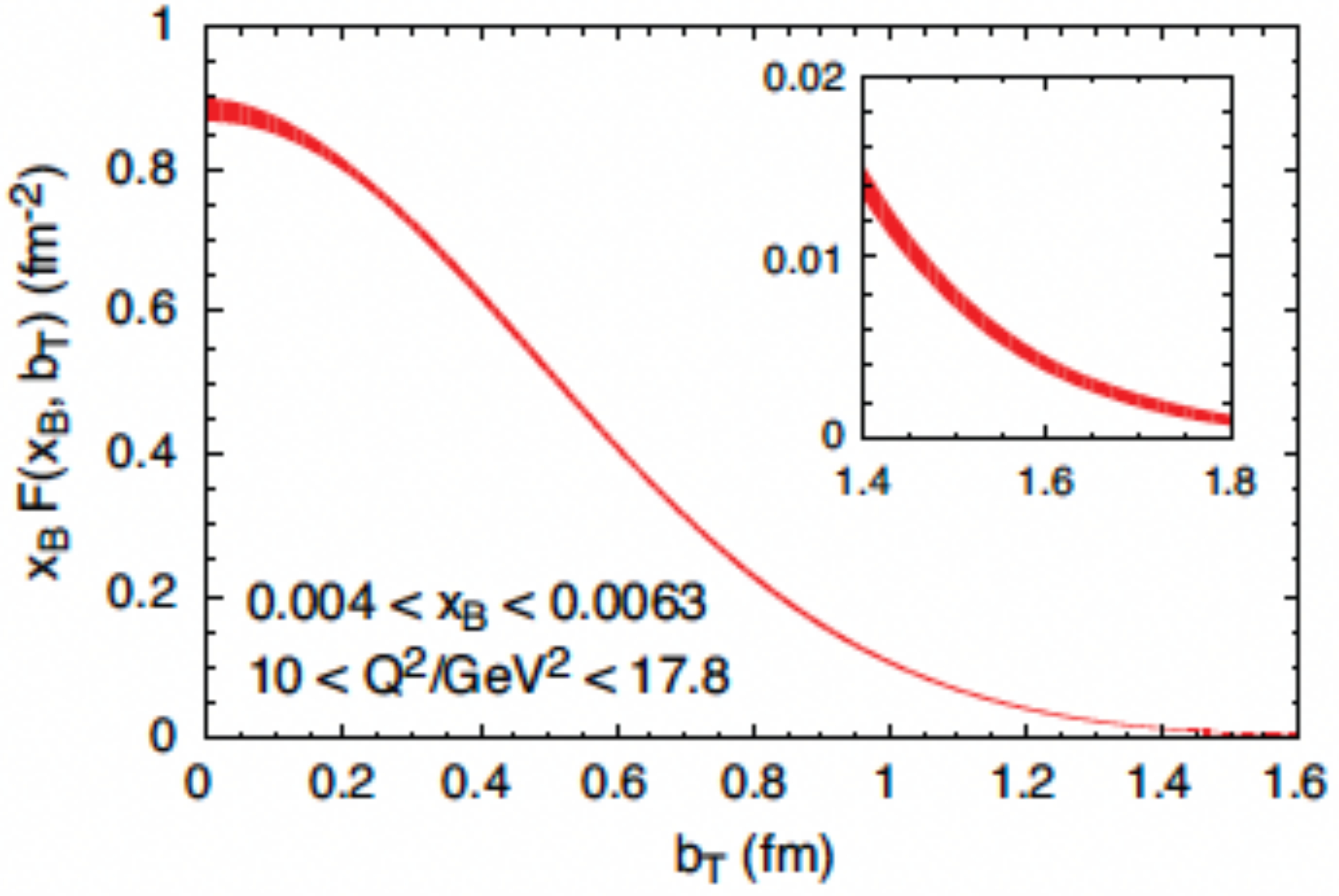
Tomography at EIC

arXiv:1212.1701 [nucl-ex] $\gamma^* + p \rightarrow \gamma + p$

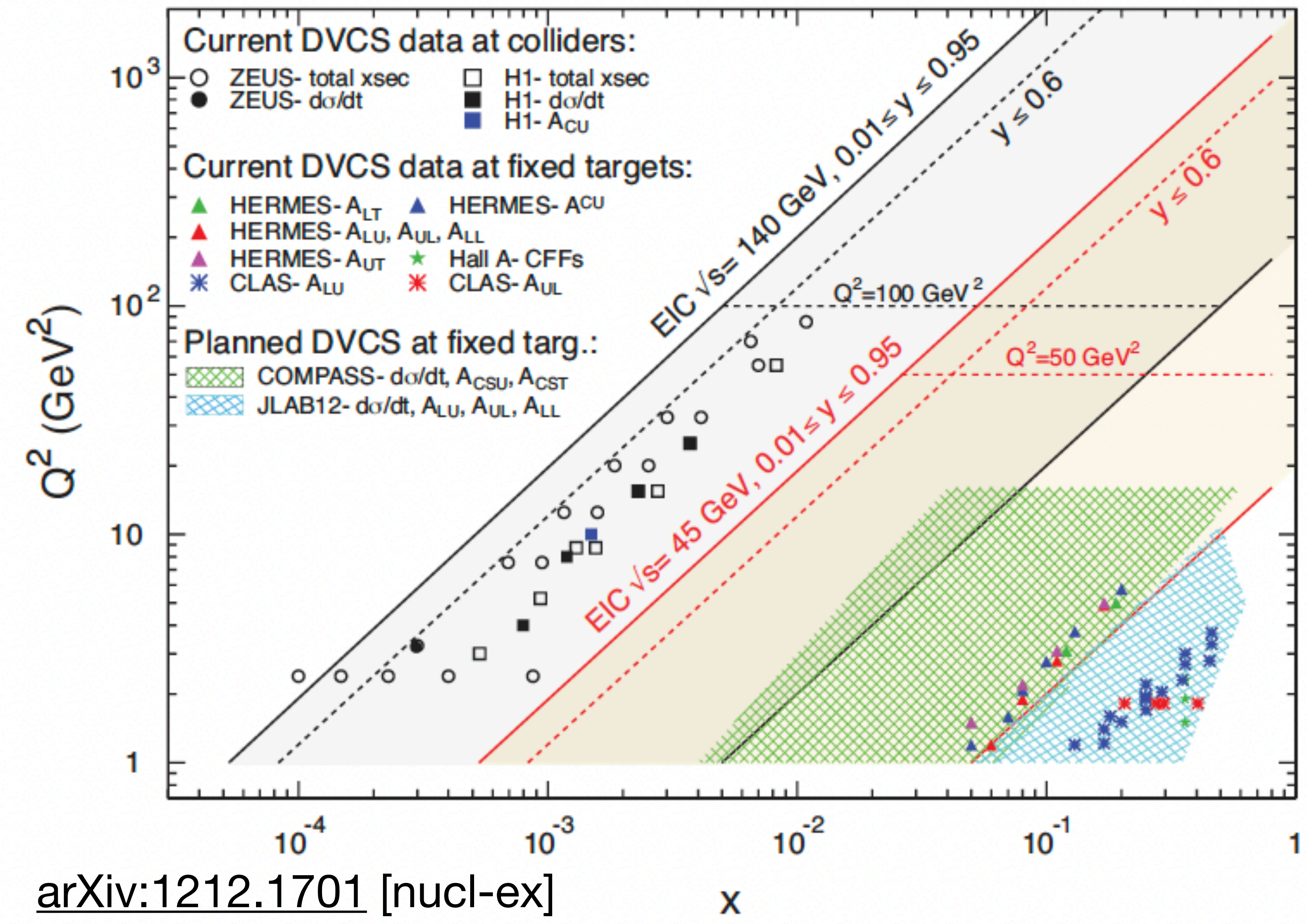


DVCS ep

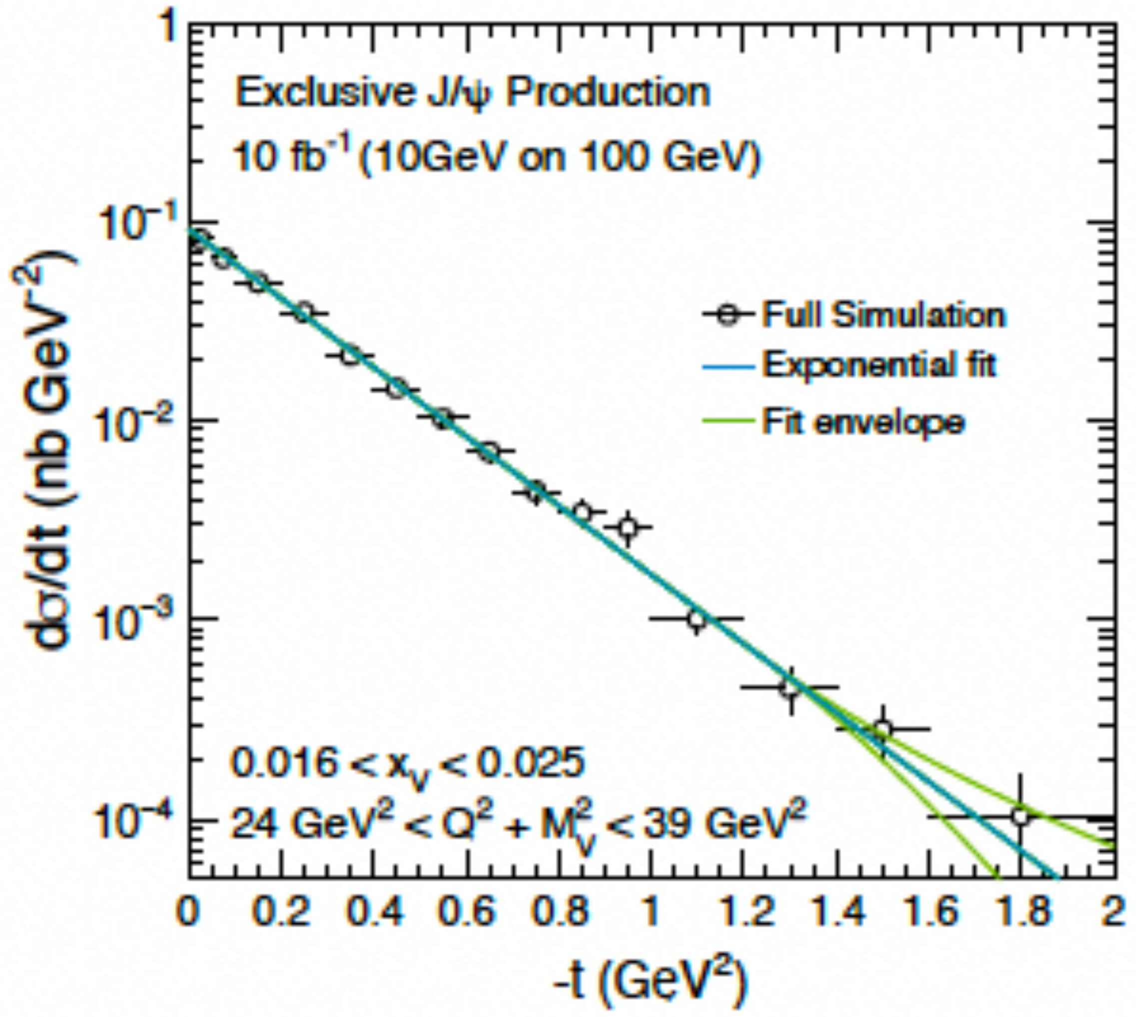
Fourier Transform in t

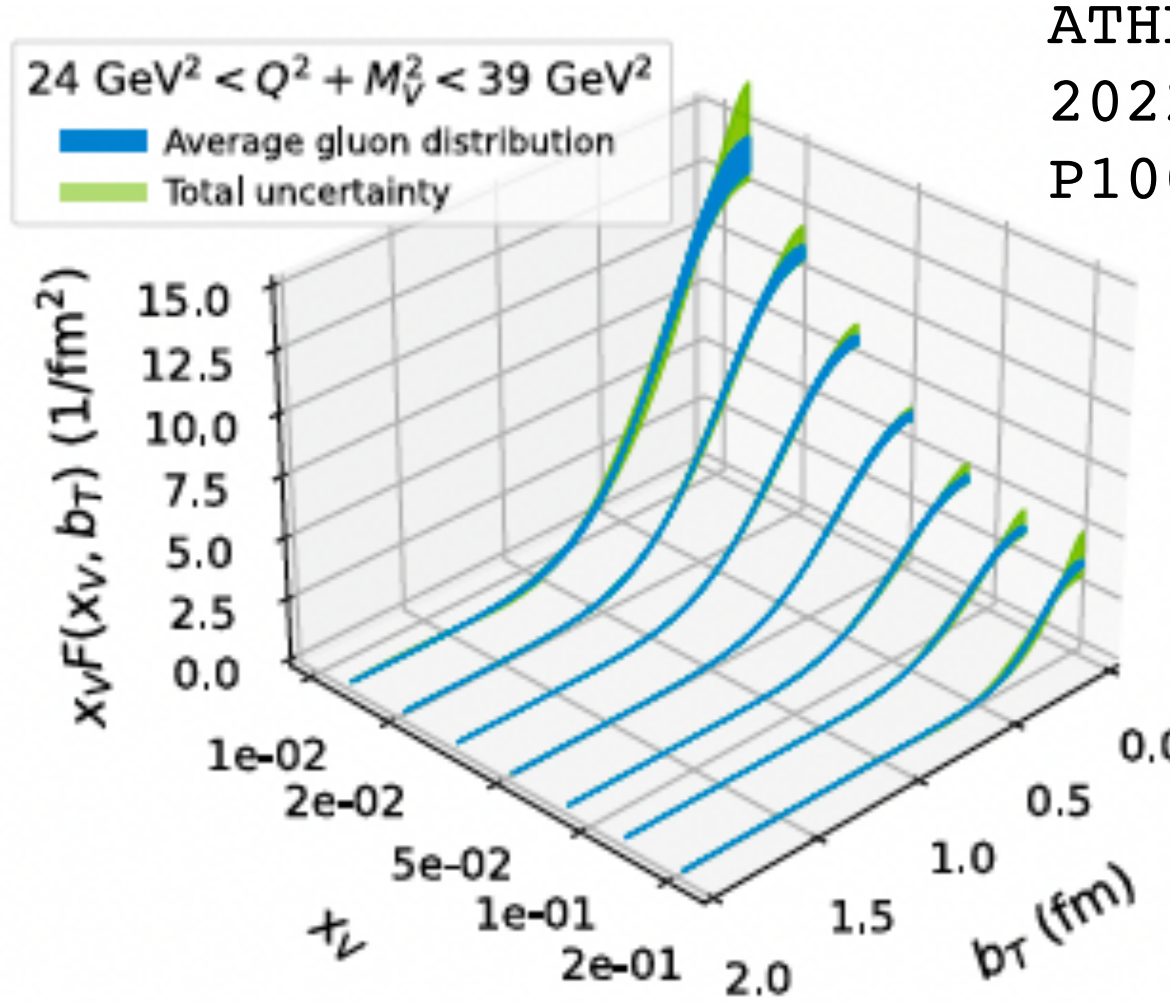


At fixed Q2, x and Ɛ=0, slope of cross section related to transverse spatial distributions of quarks inside nucleon



arXiv:1212.1701 [nucl-ex]





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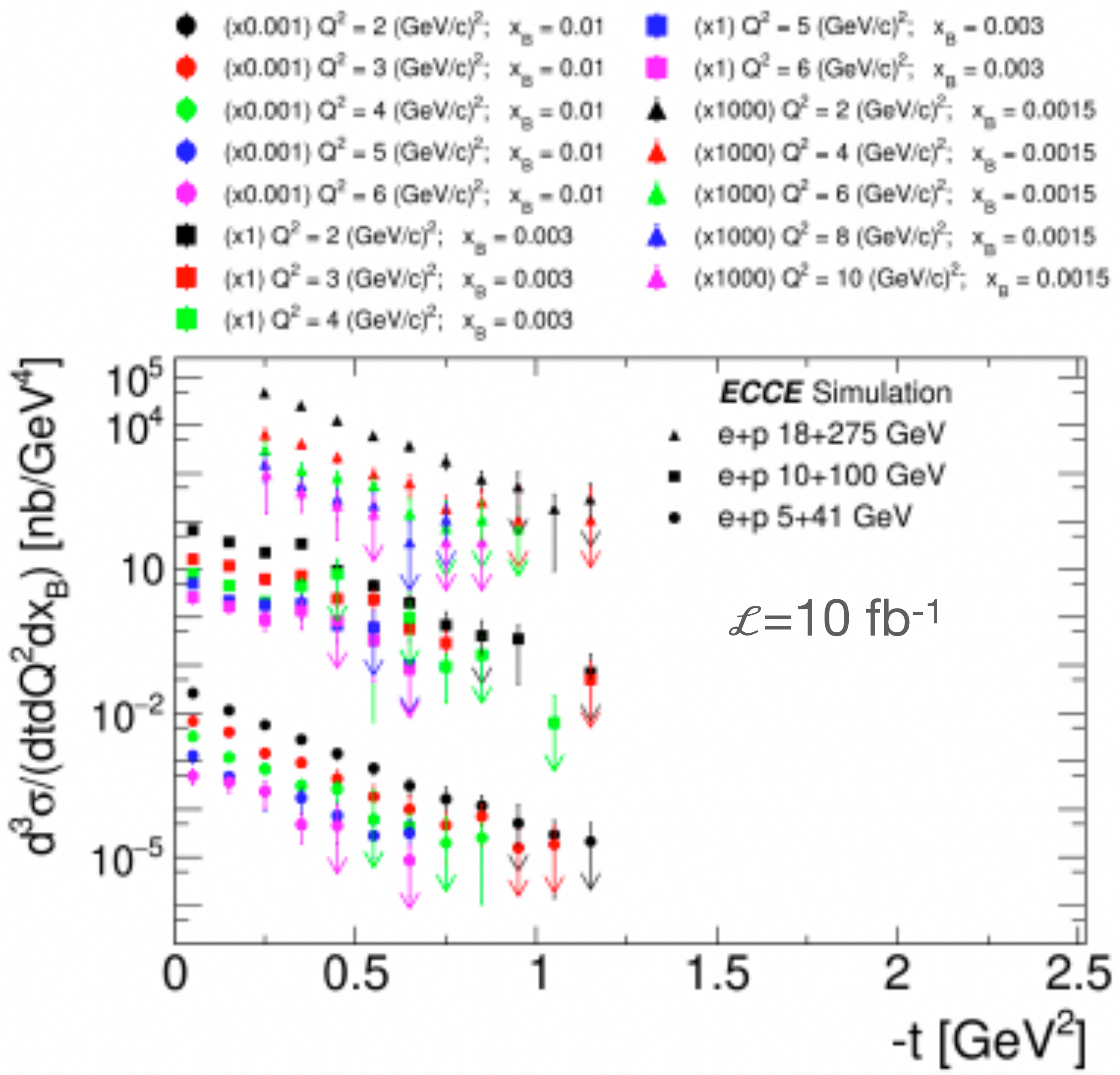
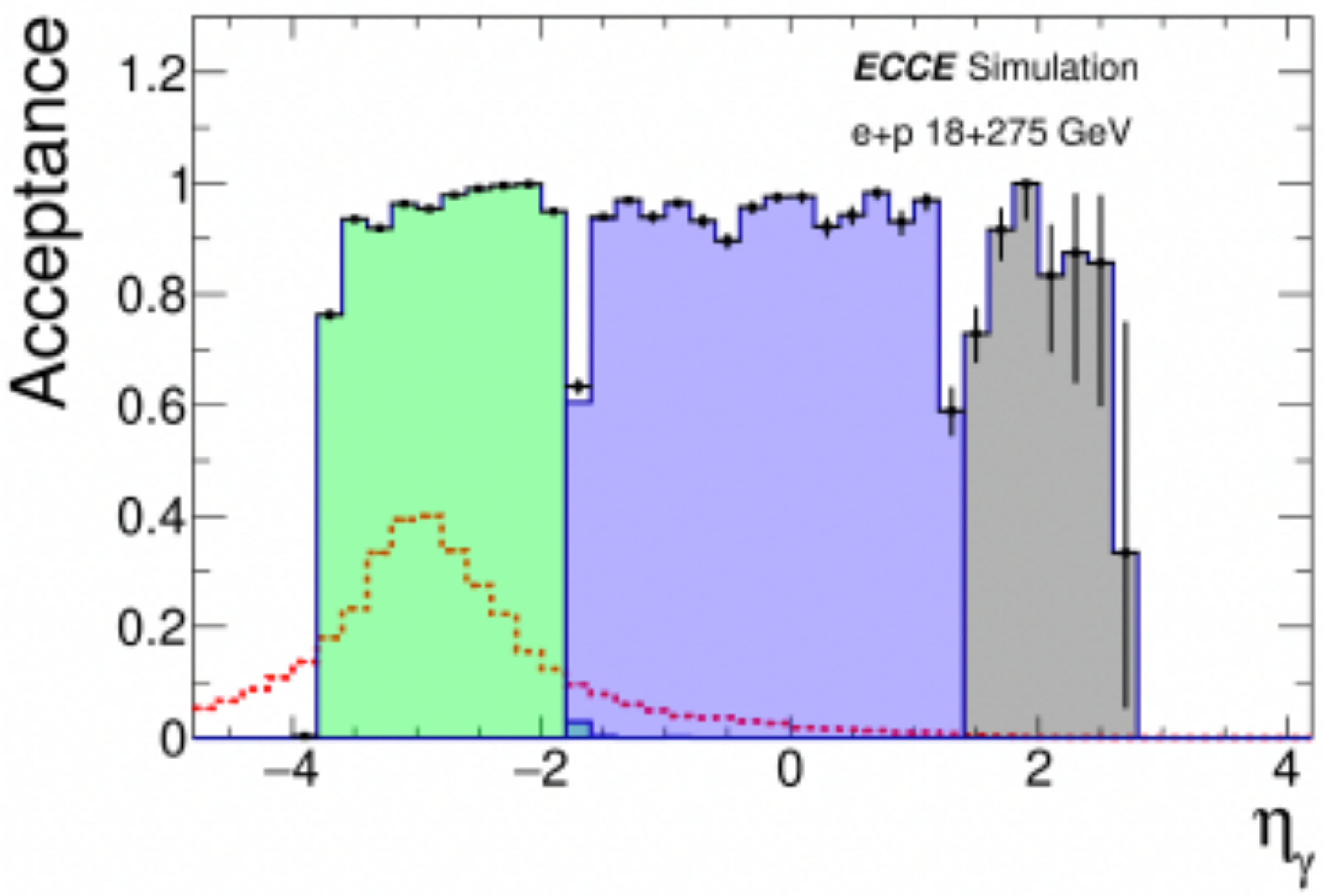
Similar for deeply virtual meson production in ep at EIC (e.g. J/Ψ, ϕ…)
Offers access to gluon spatial distributions at different x-bins

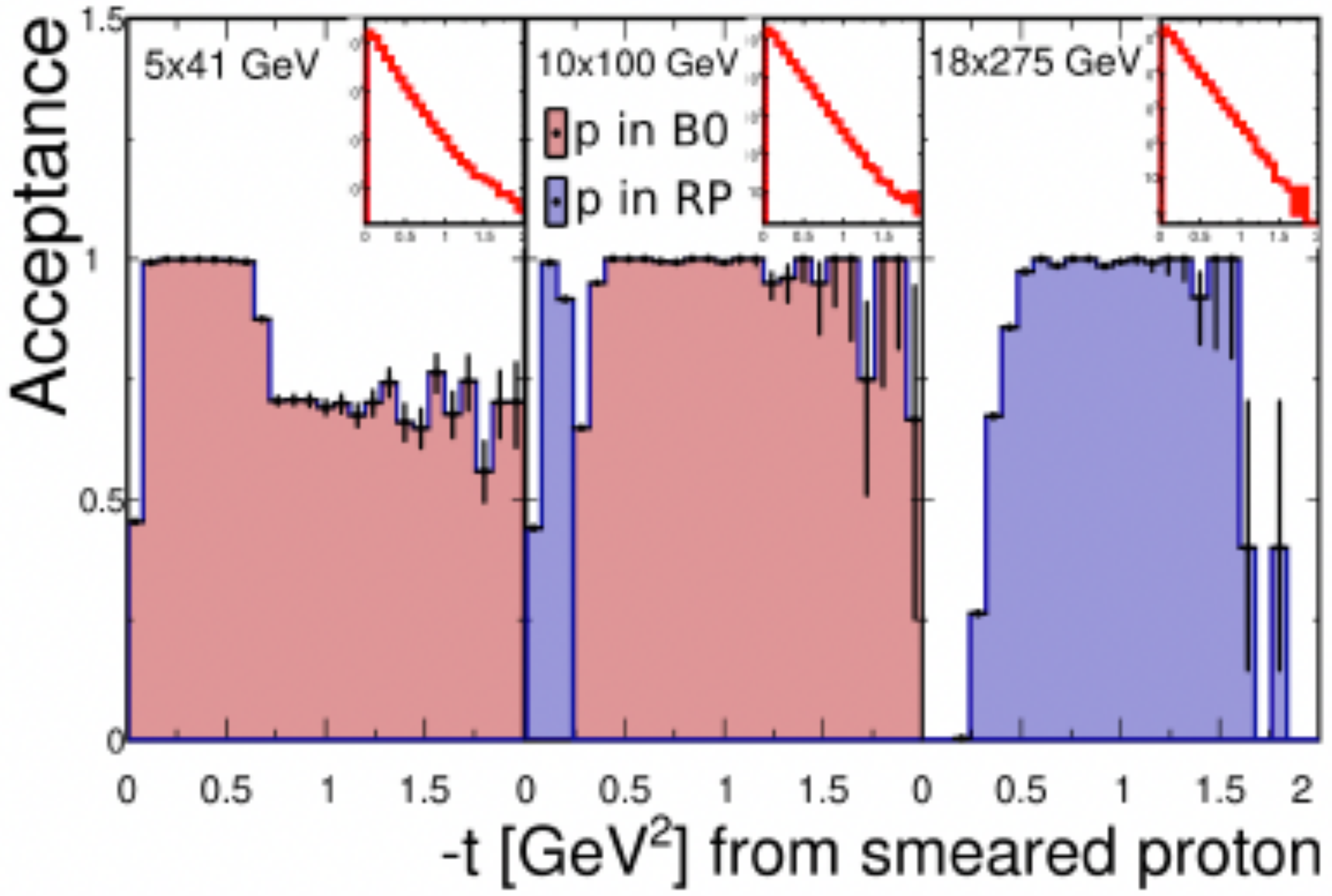
DVCS at EIC

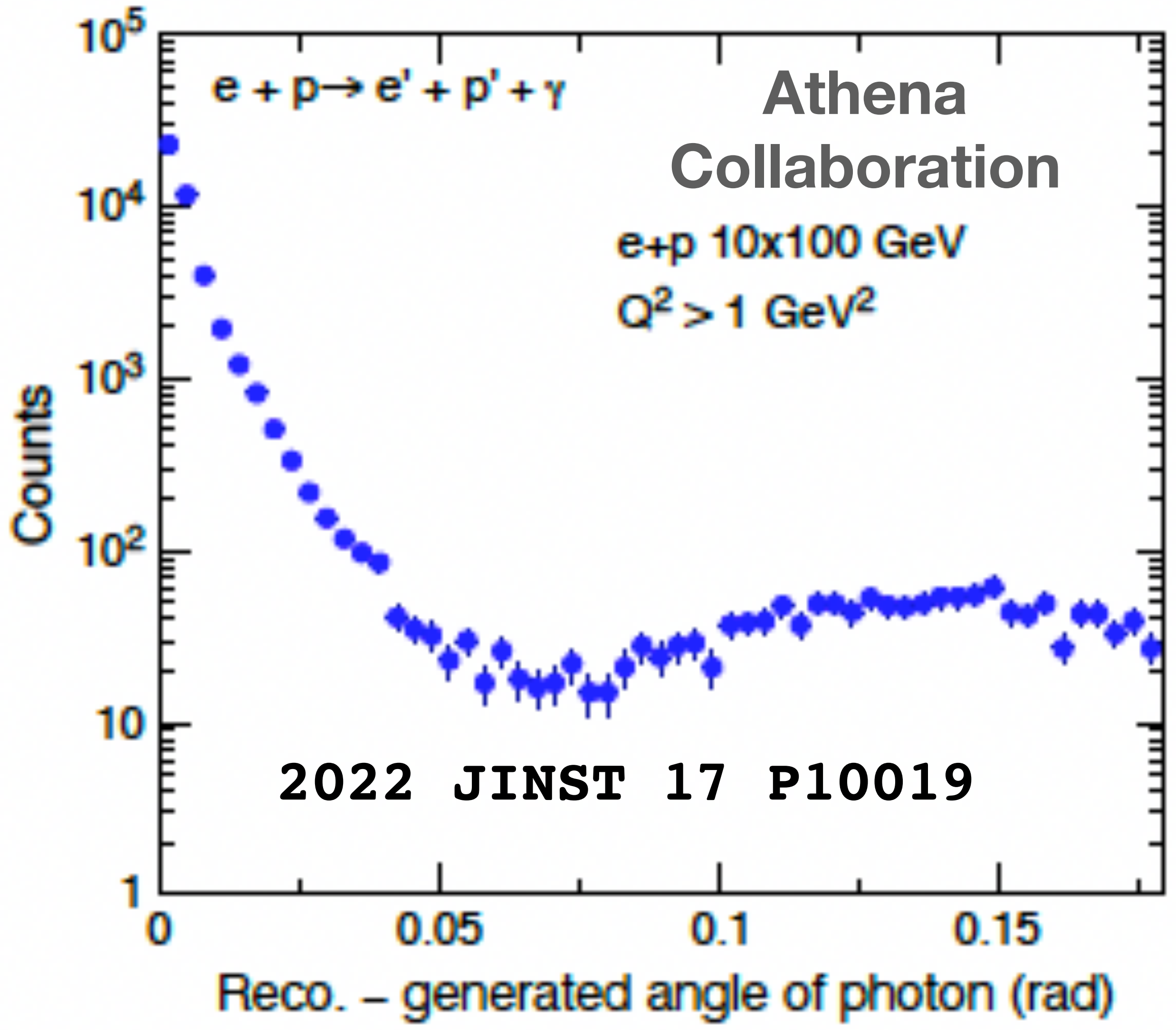
arXiv:2208.14575v2 [physics.ins-det] and I. Korover (MIT)



arXiv:2208.14575v2 [physics.ins-det] and I. Korover







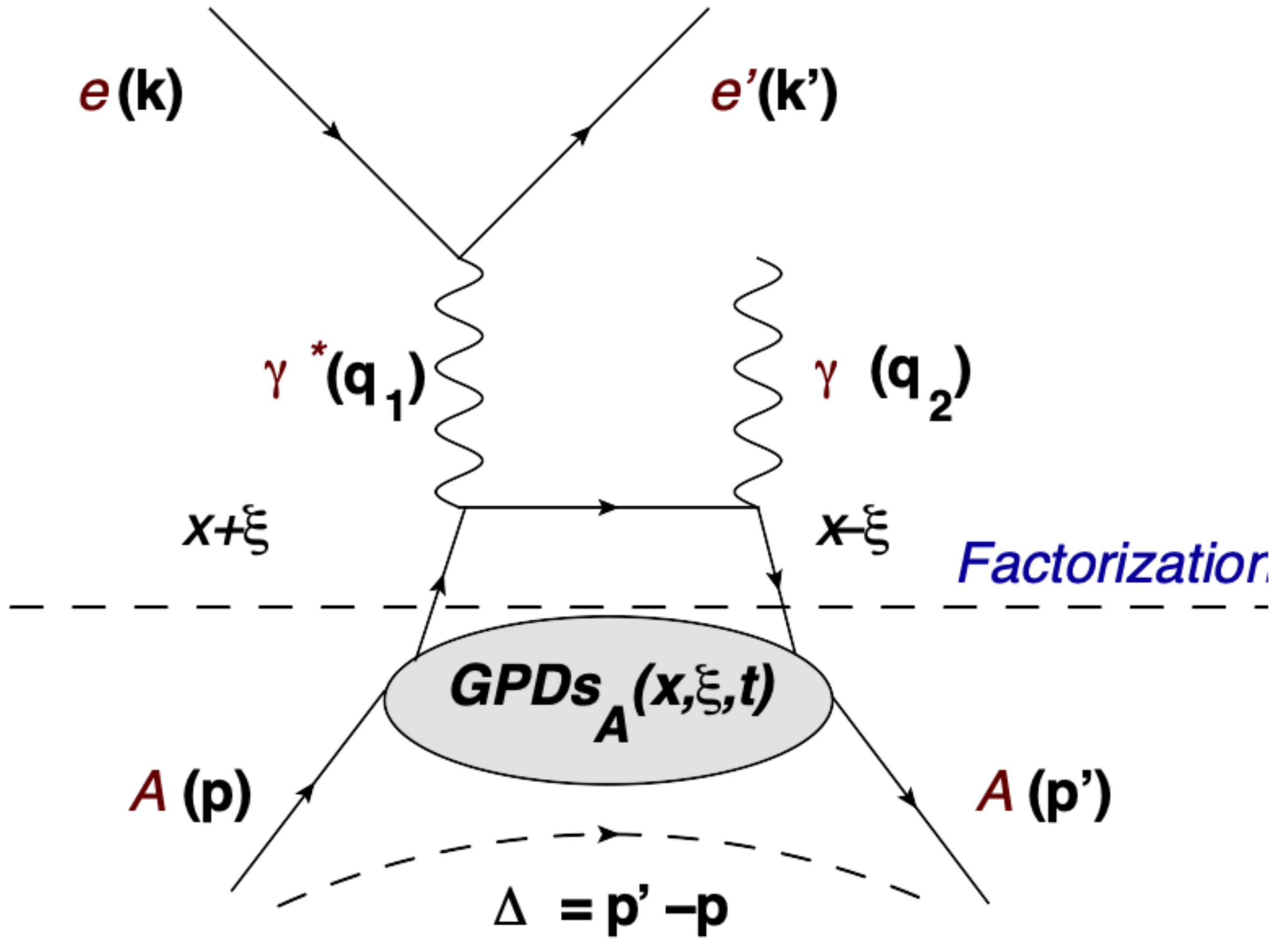
DVCS ep→e'p'γ:

- e' in central detector, γ in central detector EMCals
- p' tagged in far forward

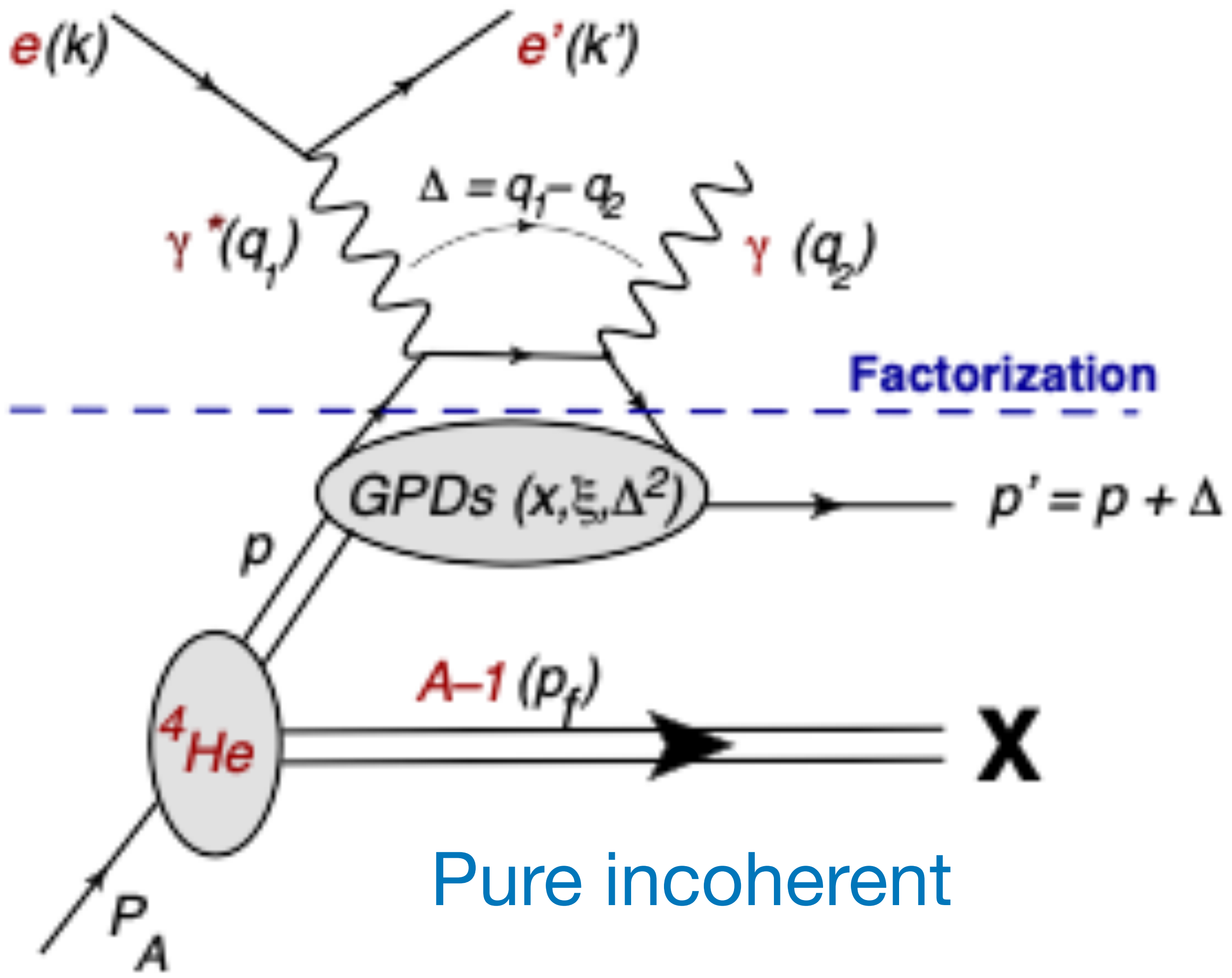
- Multidimensional binning over large t range
- Excellent proton tagging in far forward region
- Real photon reconstruction allows to separate main background ($\pi^0\to\gamma\gamma$)

Program extends to eA…

Handbag approximation to pure coherent DVCS off 4He



S. Fucini et al., arXiv:1910.07458 [nucl-th]

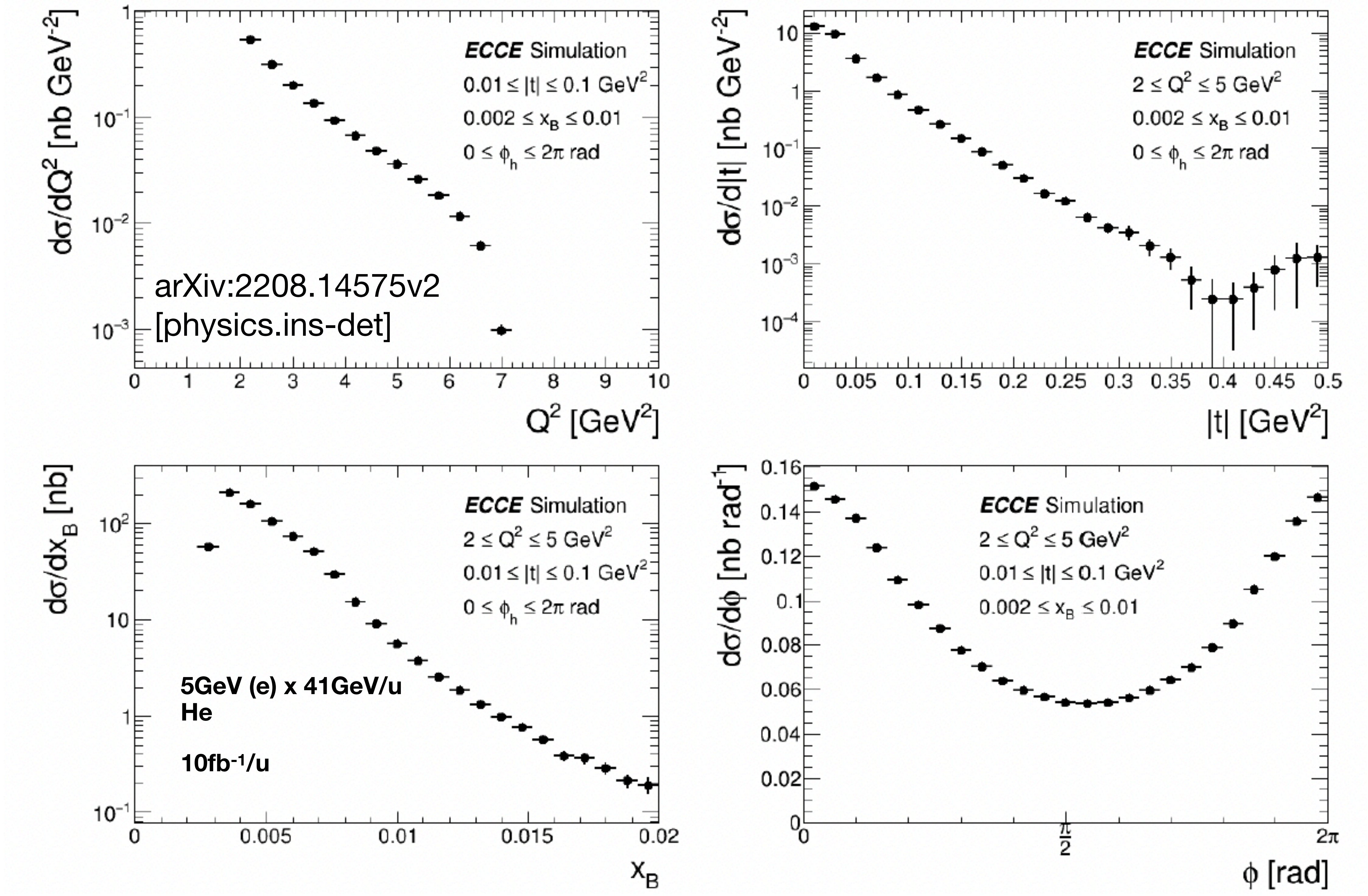


Pure incoherent

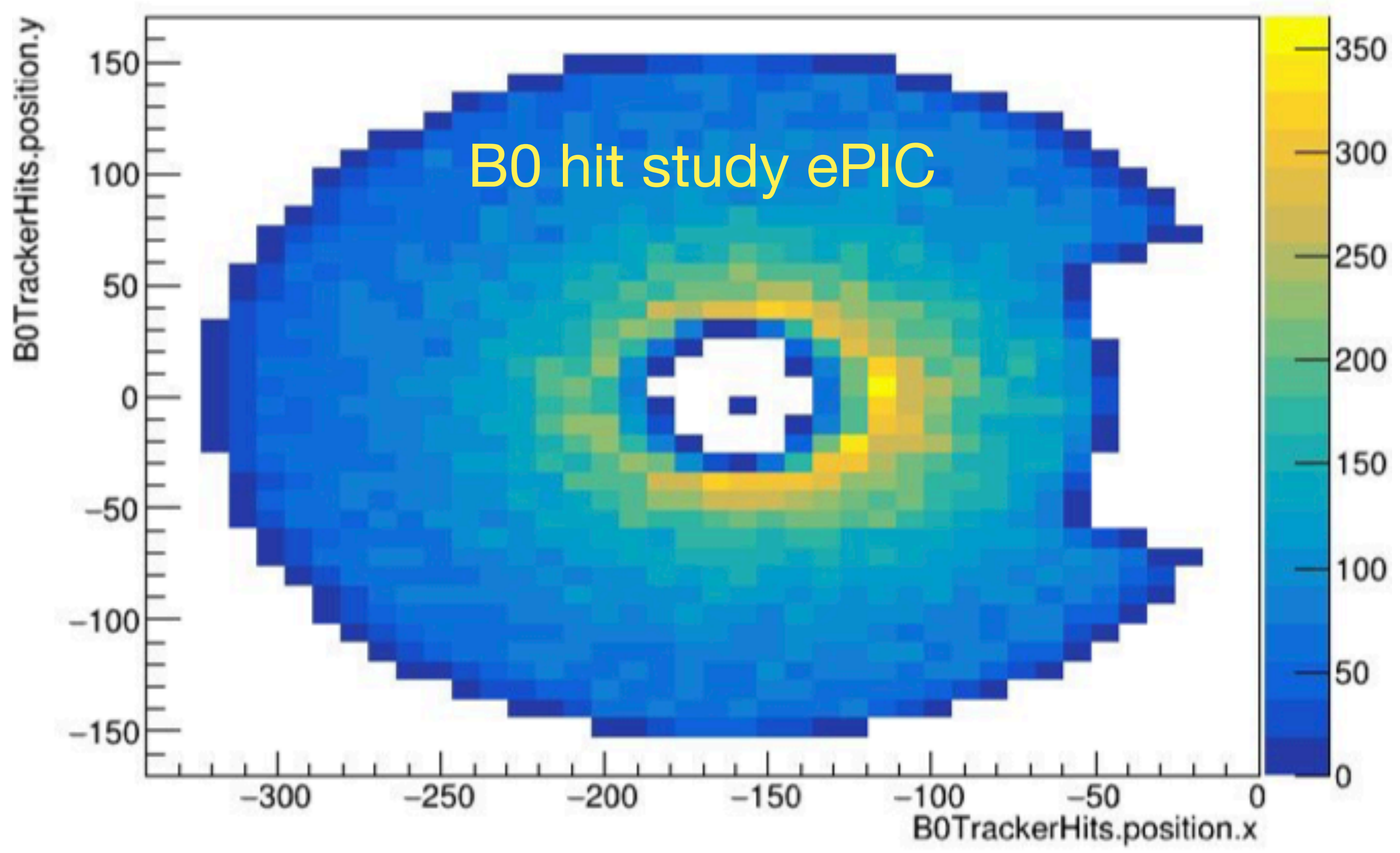
DVCS eA:

- Map GPDs and partonic structure of
  - whole nucleus (coherent)
  - bound nucleons (incoherent)
- EMC effect
- GPD flavour decomposition
  - e.g. D_2 for neutron GPD by tagging spectator p in far forward (almost 100% acceptance expected from YR studies)
- e.g. ^{4}He @ JLab CLAS → BSA for coherent vs incoherent
  - PRL 119 202004 (2017); PRL 123 (2019) no.3 032502
- spin0 nucleus: parameterisation of coherent amplitude in terms of only one chiral even GPD

Coherent DVCS on ^{4}He at EIC



Thanks to G. Penman (UoG) for Plots and Study



- Coherent DVCS e^{4}He → e'γ^4He'
- Using Topeg generator (R. Dupré et al)
  - https://gitlab.in2p3.fr/dupre/nopeg

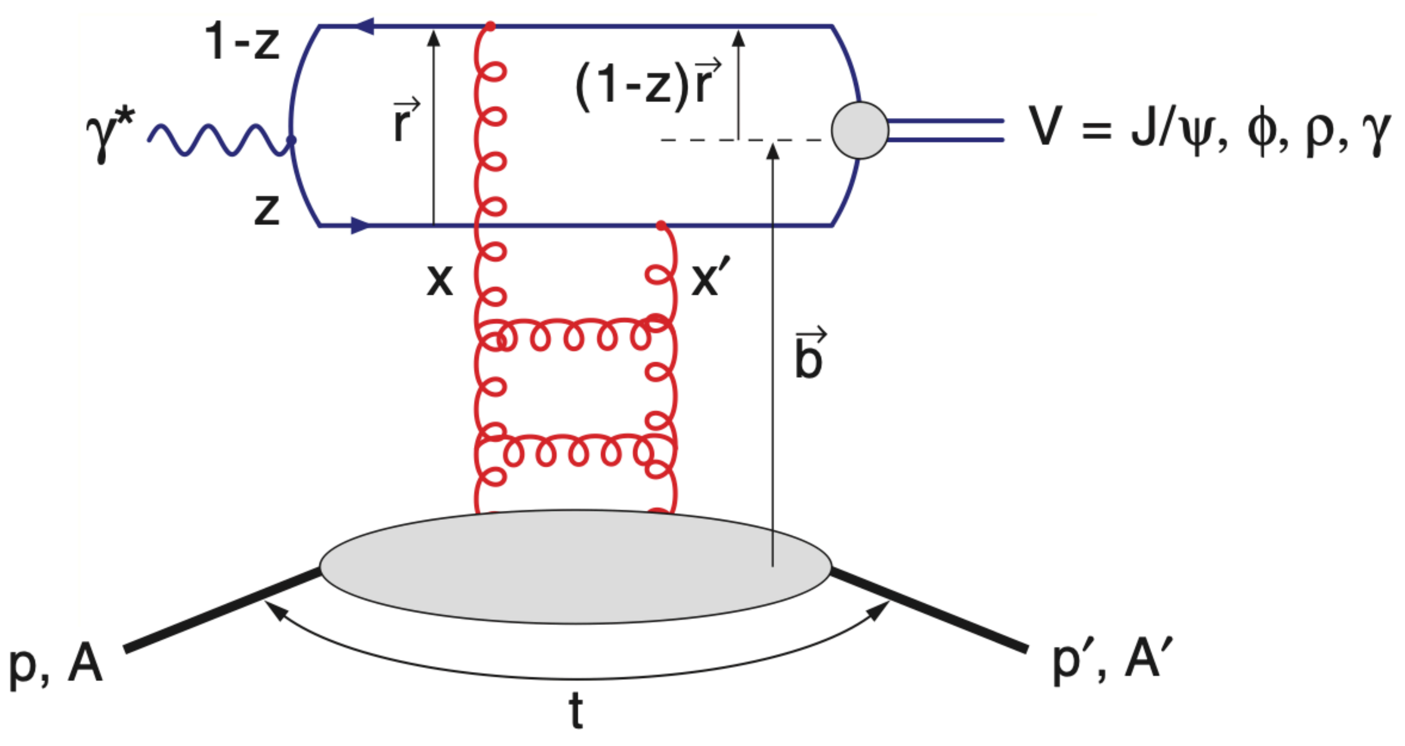
- e' and γ in central detector
- He' far forward (B0 and RP)
  - drives acceptance/statistics

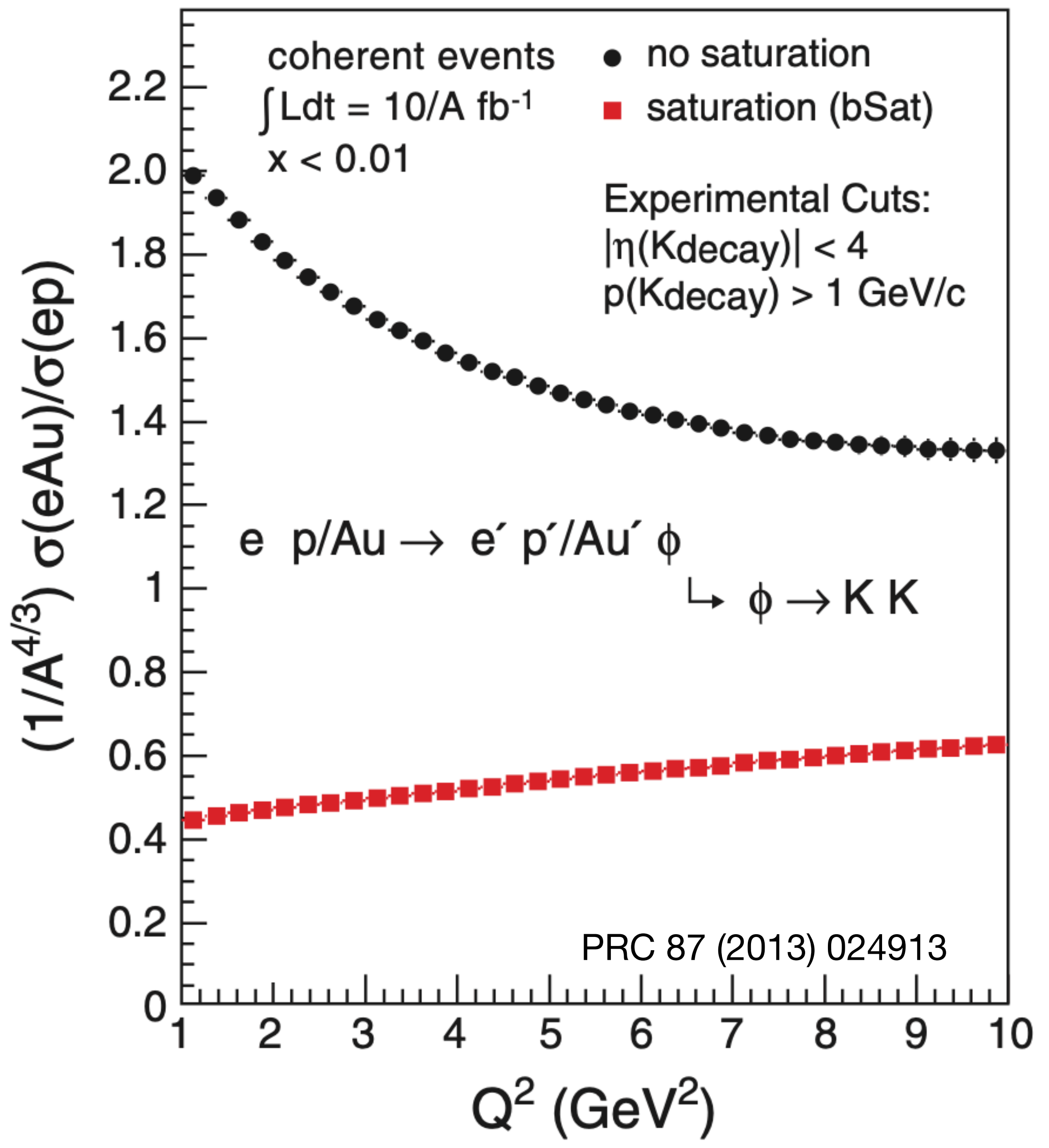
- |t| reconstructed using He' optimal
- Allows reaches to low |t|

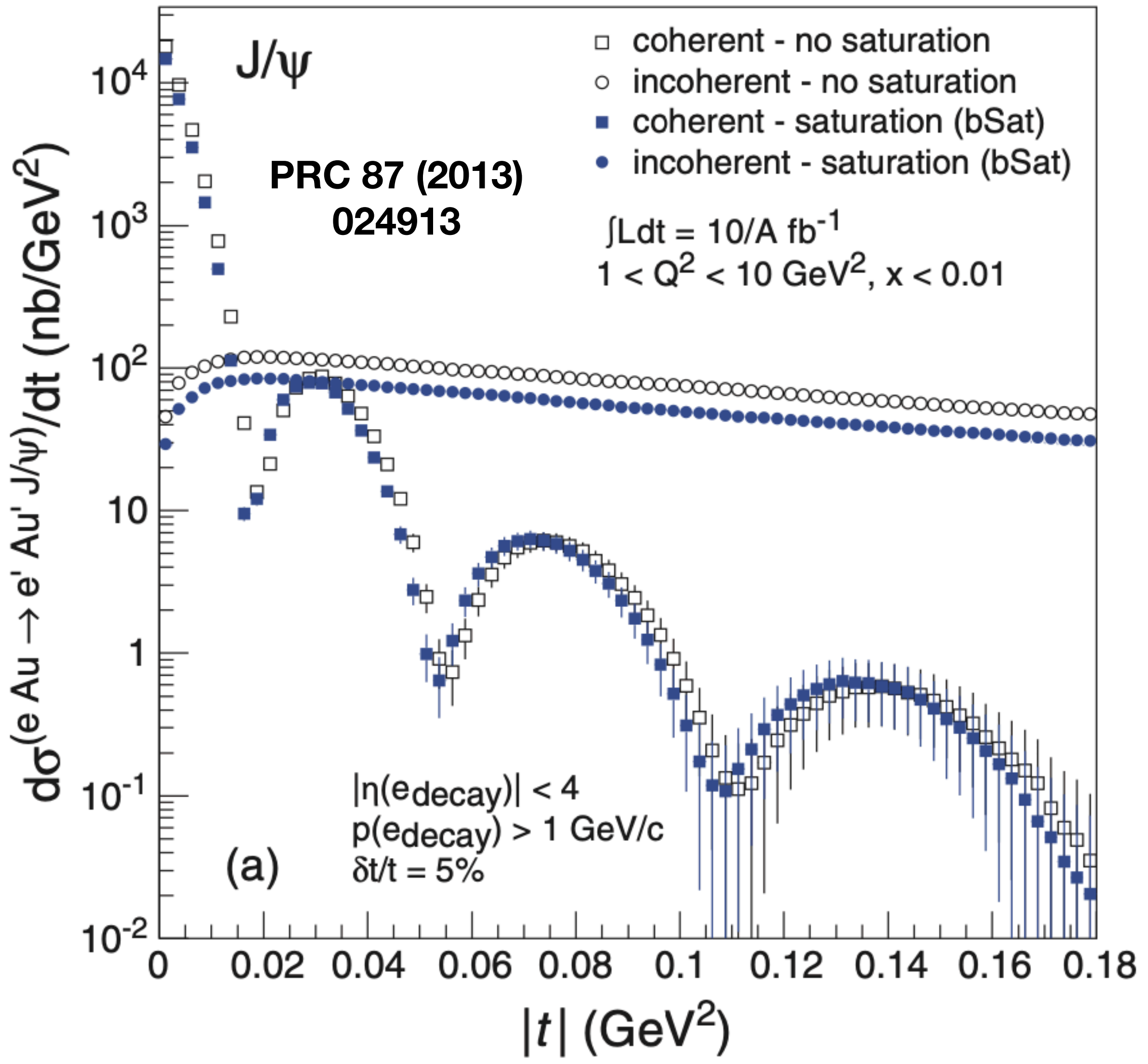
- Studies with ePIC continue
  - e.g. optimisation of FF region

Diffractive VM Production in eA

Toll, Ulrich, PRC 87 (2013) 024913

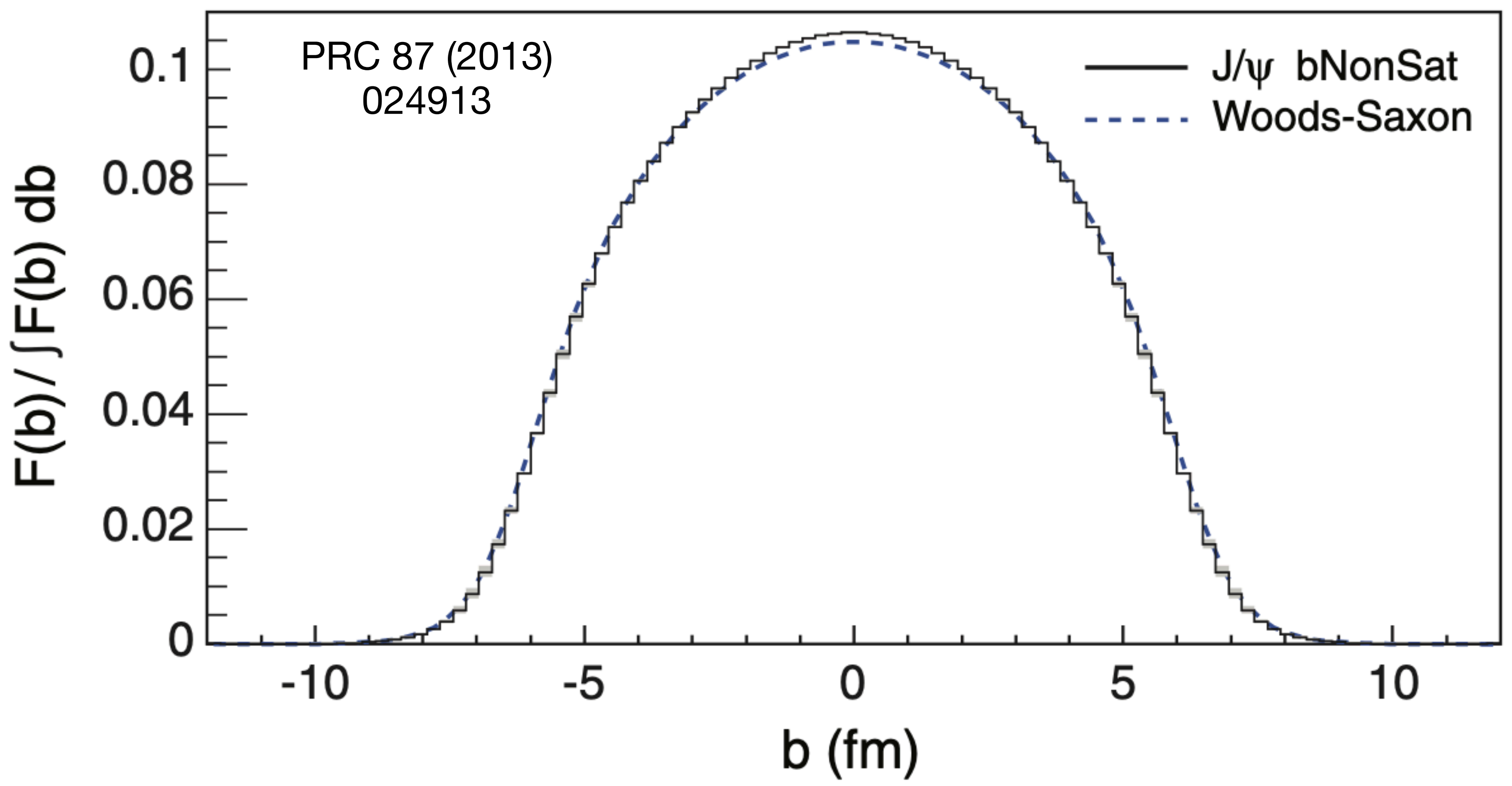






Fourier Transform Coherent

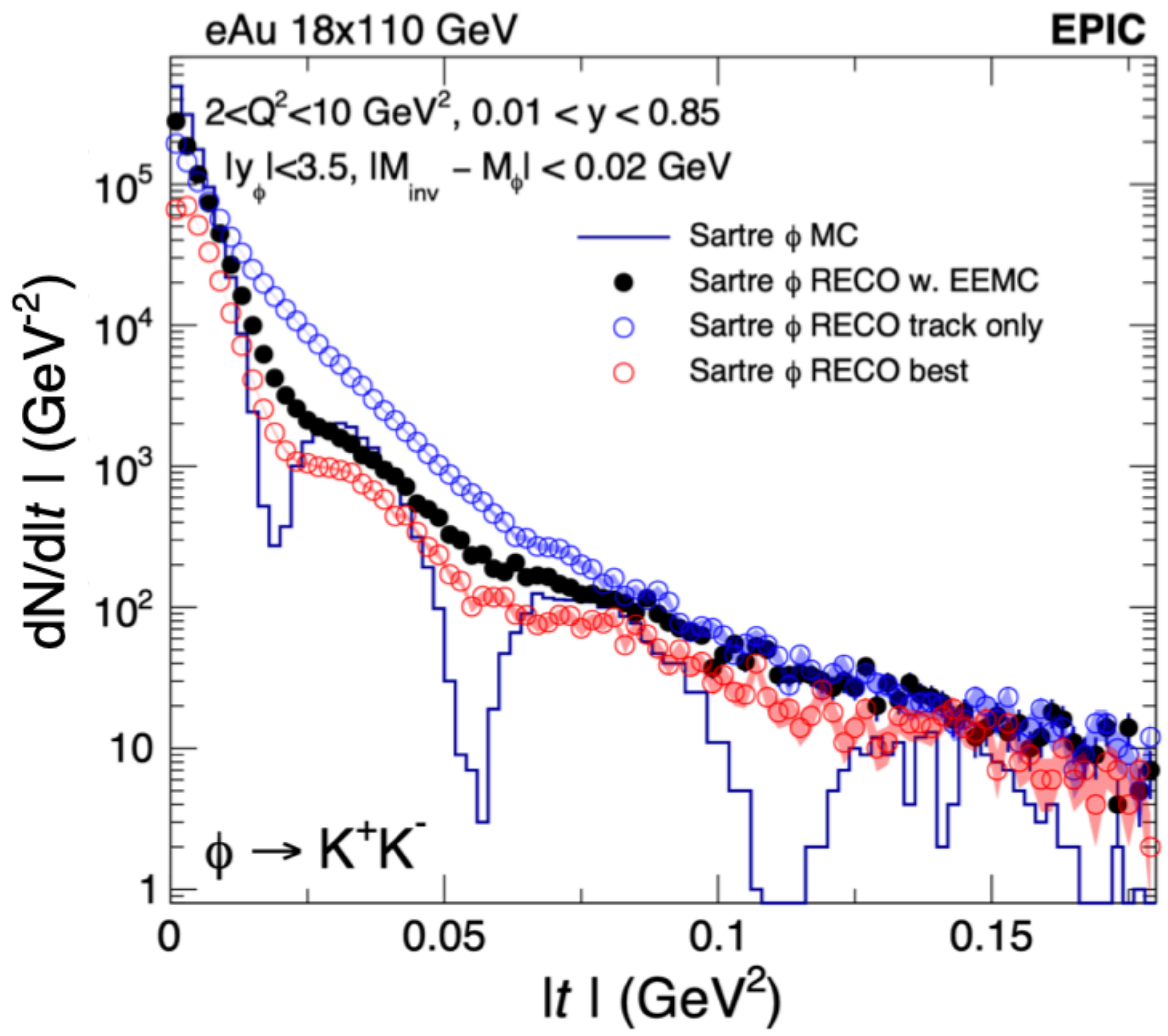
|t| conjugate p_T



- Key EIC measurements: e + A → e' + A' + VM
- Cross section sensitive to gluon density
  - Gluon spatial distributions within nuclei
  - Low-x structure of nucleus, probe of gluon saturation (with Q^2)
- Coherent - sensitive to average nuclear geometry
- 1st minima → info on nuclear parton density
- EIC: range of mesons, several ions, wide range Q^2
  - e.g. J/Ψ, ϕ, ρ, ω, ϒ under study
- |t| resolution crucial for pattern - very challenging
  - How pronounced will pattern be?
  - How to remove incoherent?
- VM escapes down beam pipe
  - A' reconstructed from decay products and exclusive kinematics
  - Need high resolution for e' and VM decay
  - *Several studies ongoing into what extent pattern can be resolved*

Coherent Diffractive ϕ Production in eAu

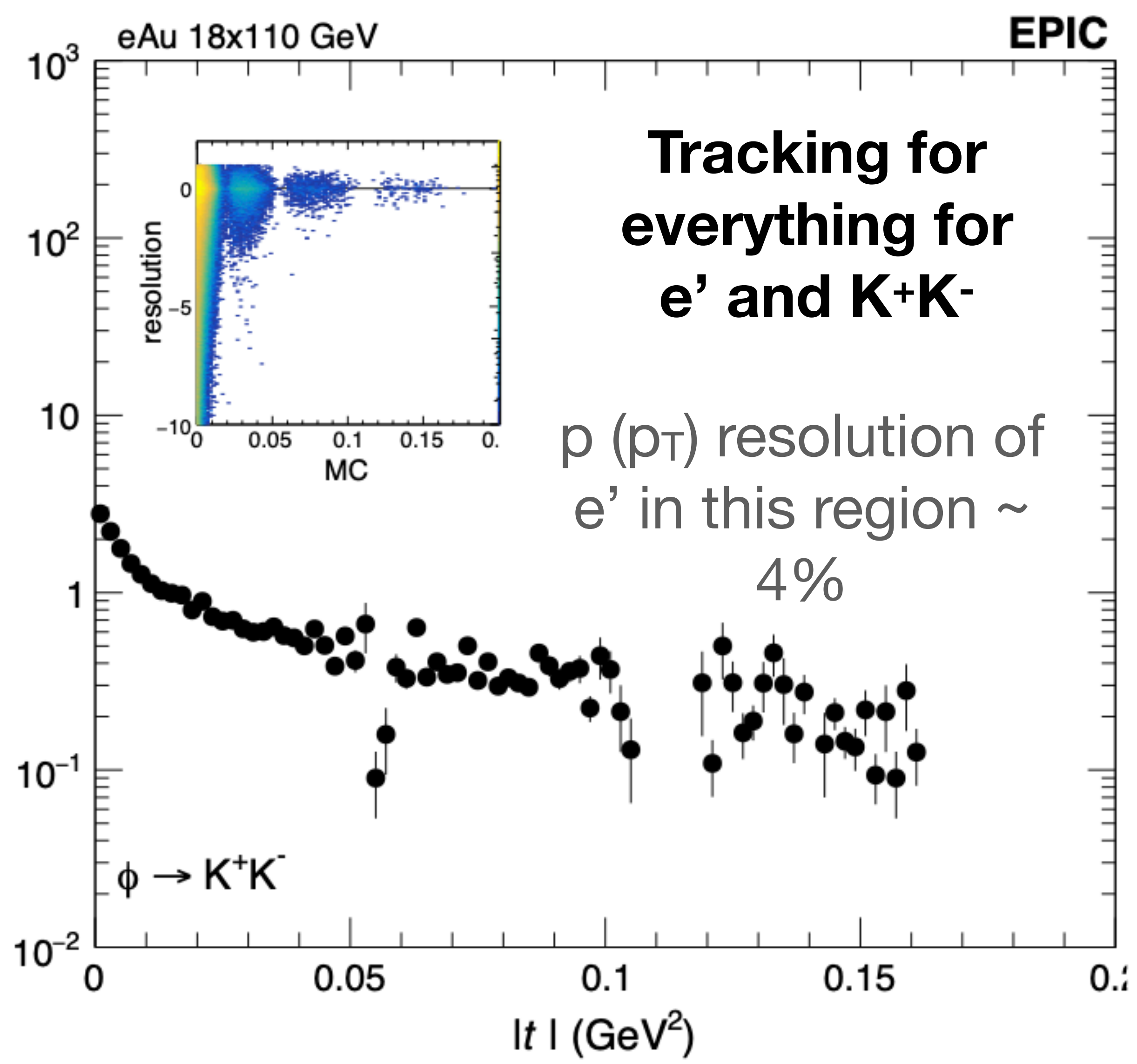
Thanks to plots and study from Z. Tu (BNL) (DIS2023)

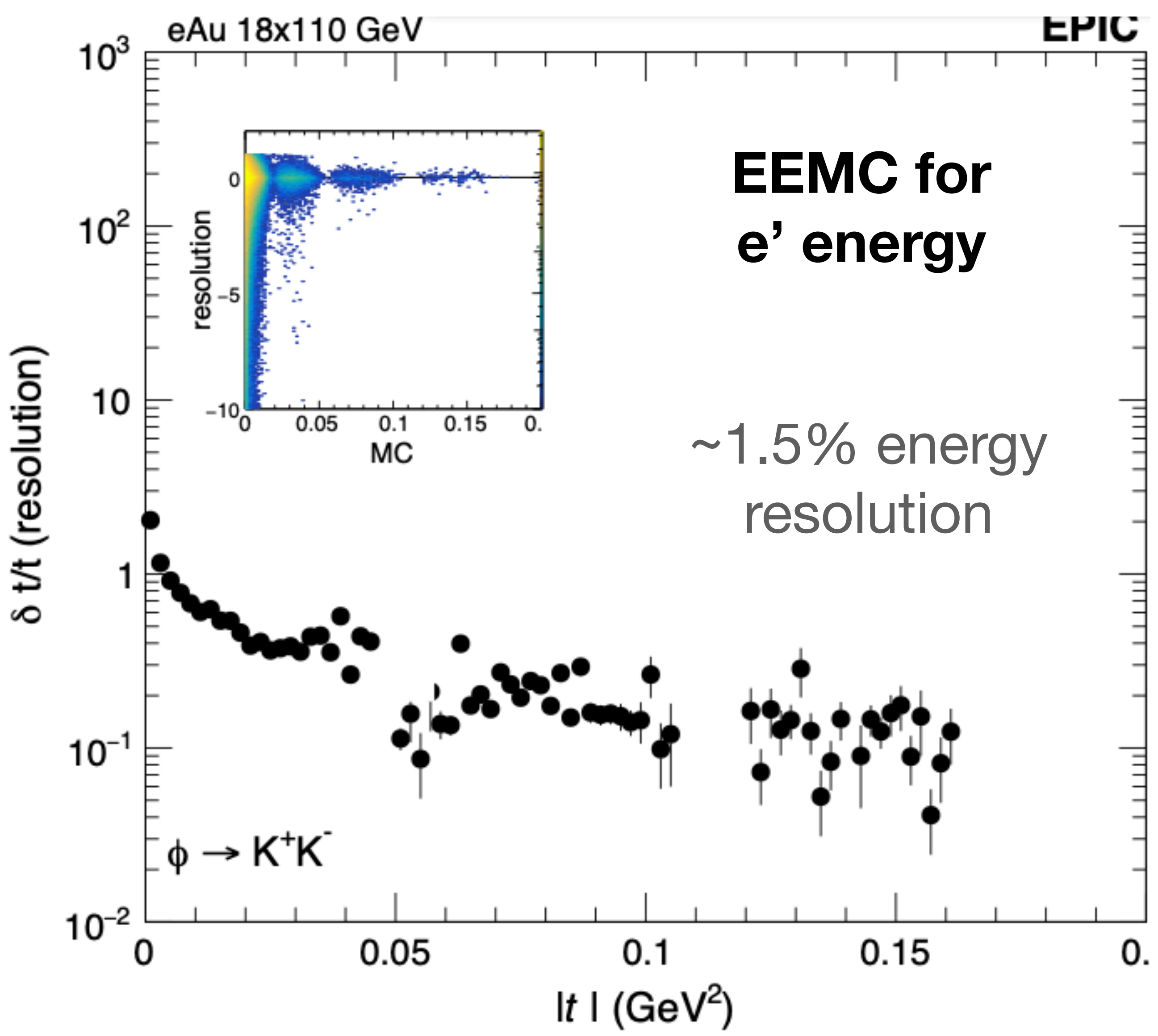


Legend details:

- w. EEMC: electron energy from EEMC, electron mass (PDG), angle (eta,phi) from tracking; φ→KK from tracking.
- Track only: e', φ→KK, all from tracking
- Best: average of the above 2 E-by-E.

$$\boxed{-t = -(\mathbf{p}_{\mathbf{A}',\mathbf{corr}} - \mathbf{p}_{\mathbf{A}})^2}$$

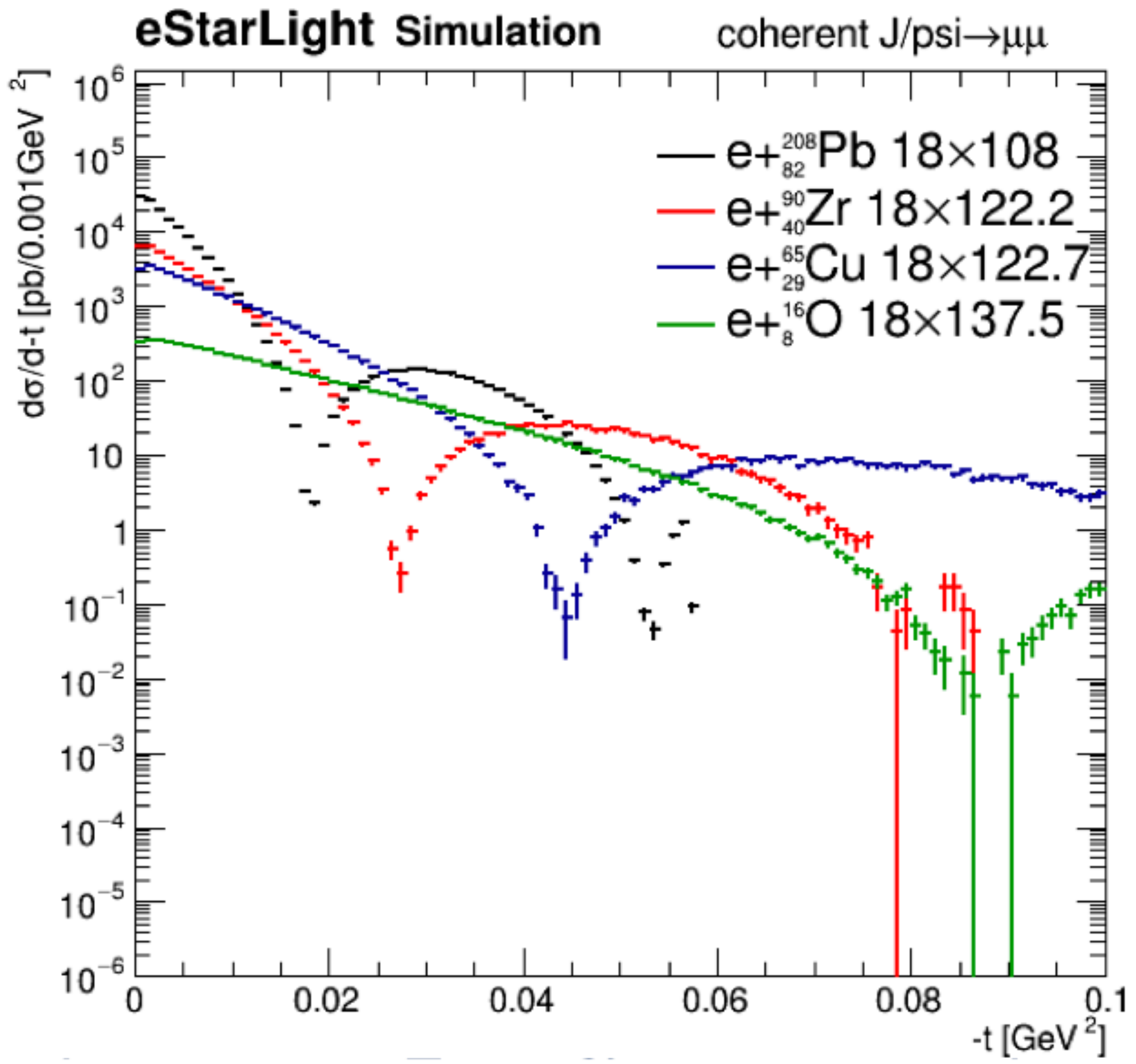


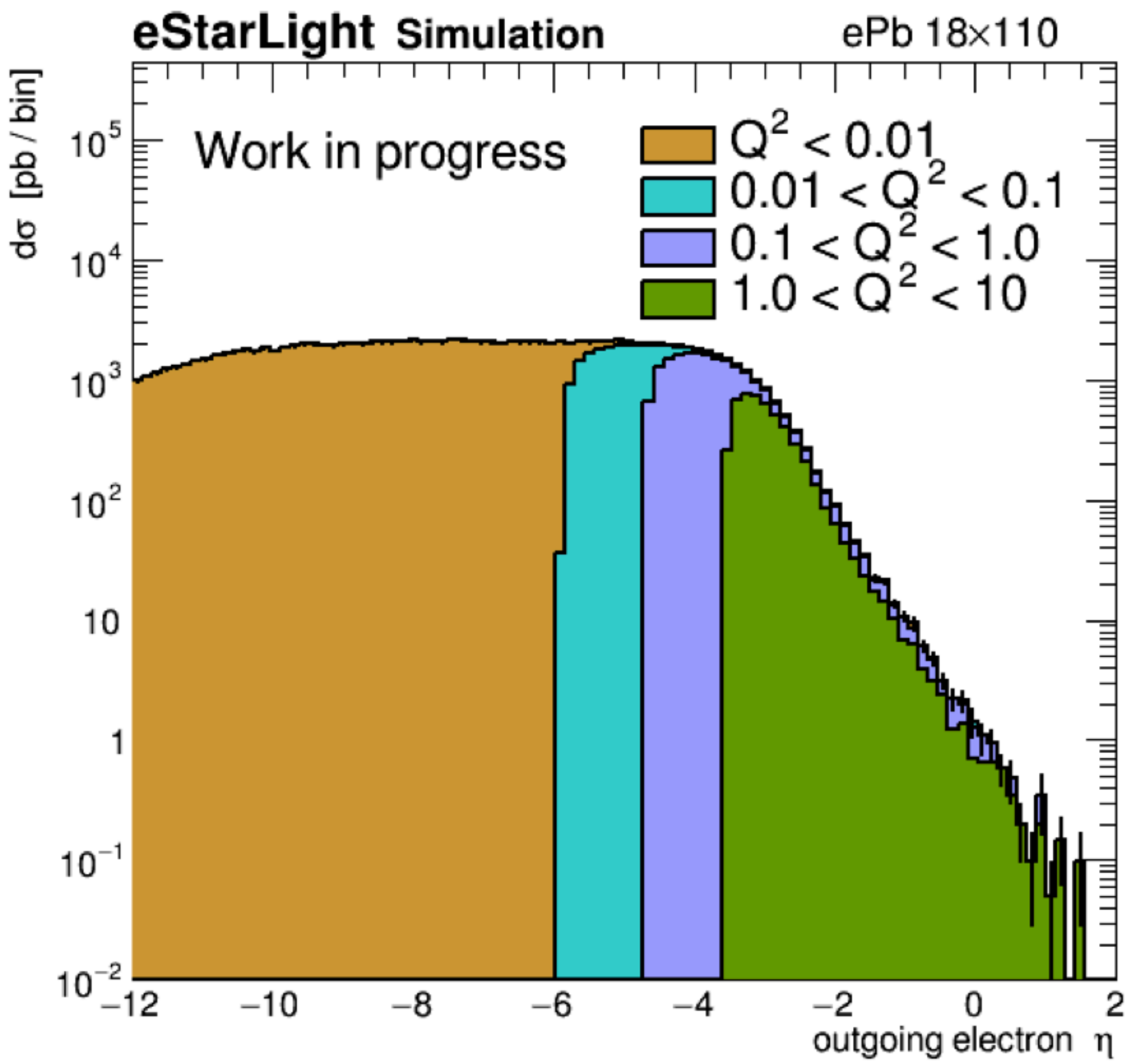


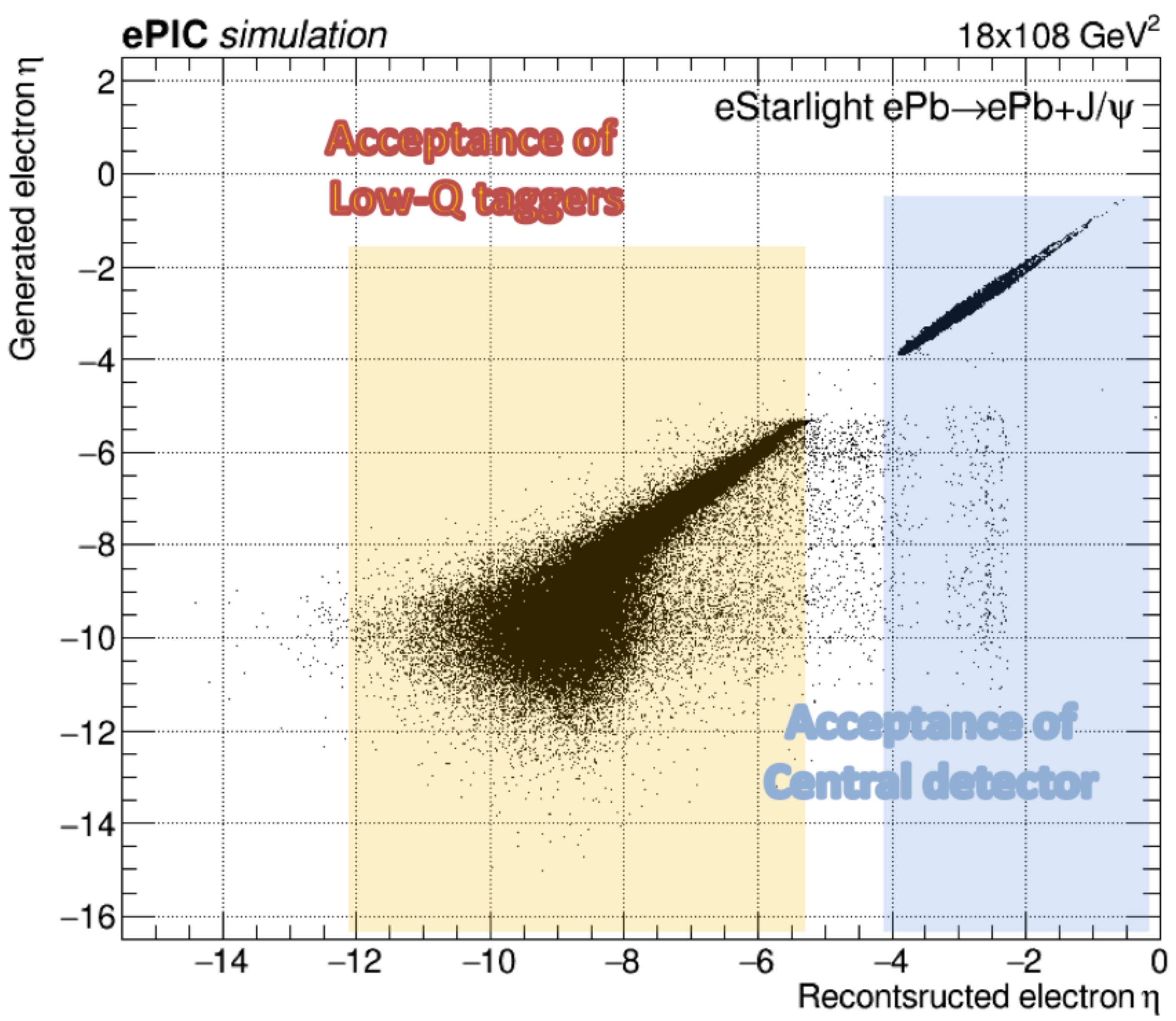
- Coherent e + Au → e' + Au + ϕ → e' + K^+K^-
- e' central detector, K^+K^- (very soft) central detector, Au' escapes
- Detector challenge: reconstruct |t|
- Exclusivity corrected -t method ($p_{A',corr}$ constrained by exclusive reaction)
  - (see EIC YR arXiv:2103.05419v2 [physics.ins-det])
  - insensitive to beam effects (momentum/angular spread)
- Optimised reconstruction event-by-event → pattern starts to resolve
- Improvements expected as ePIC detector and software advances
- Other potential improvements - Bayesian unfolding (see P. Steinberg BNL ECCE proposal work), low Q^2 tagging…

Coherent Studies with Q^2

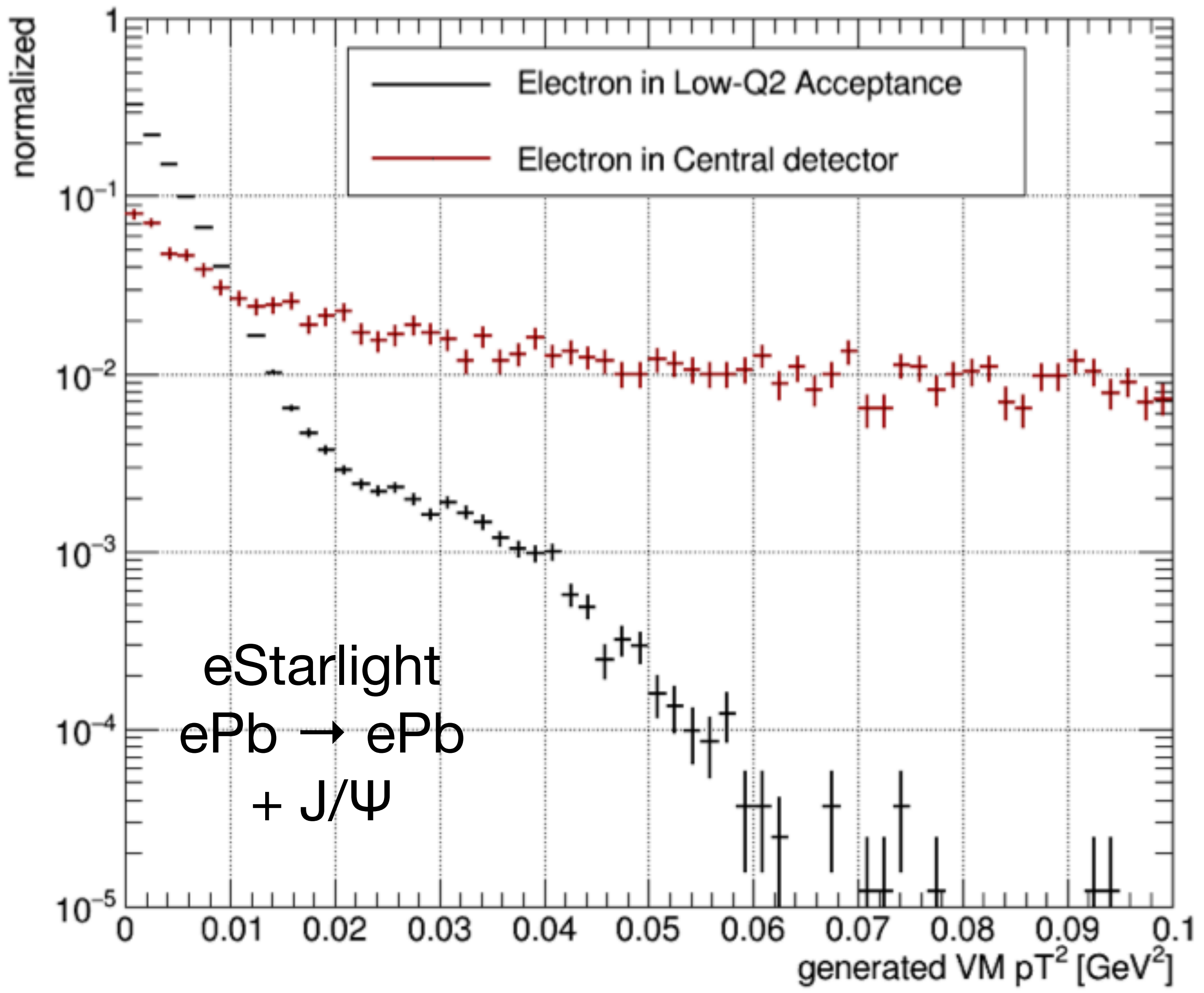
Plots and on-going study Ben-Gurion University (Thanks M. Pitt, Z. Citron, E. Mautner)





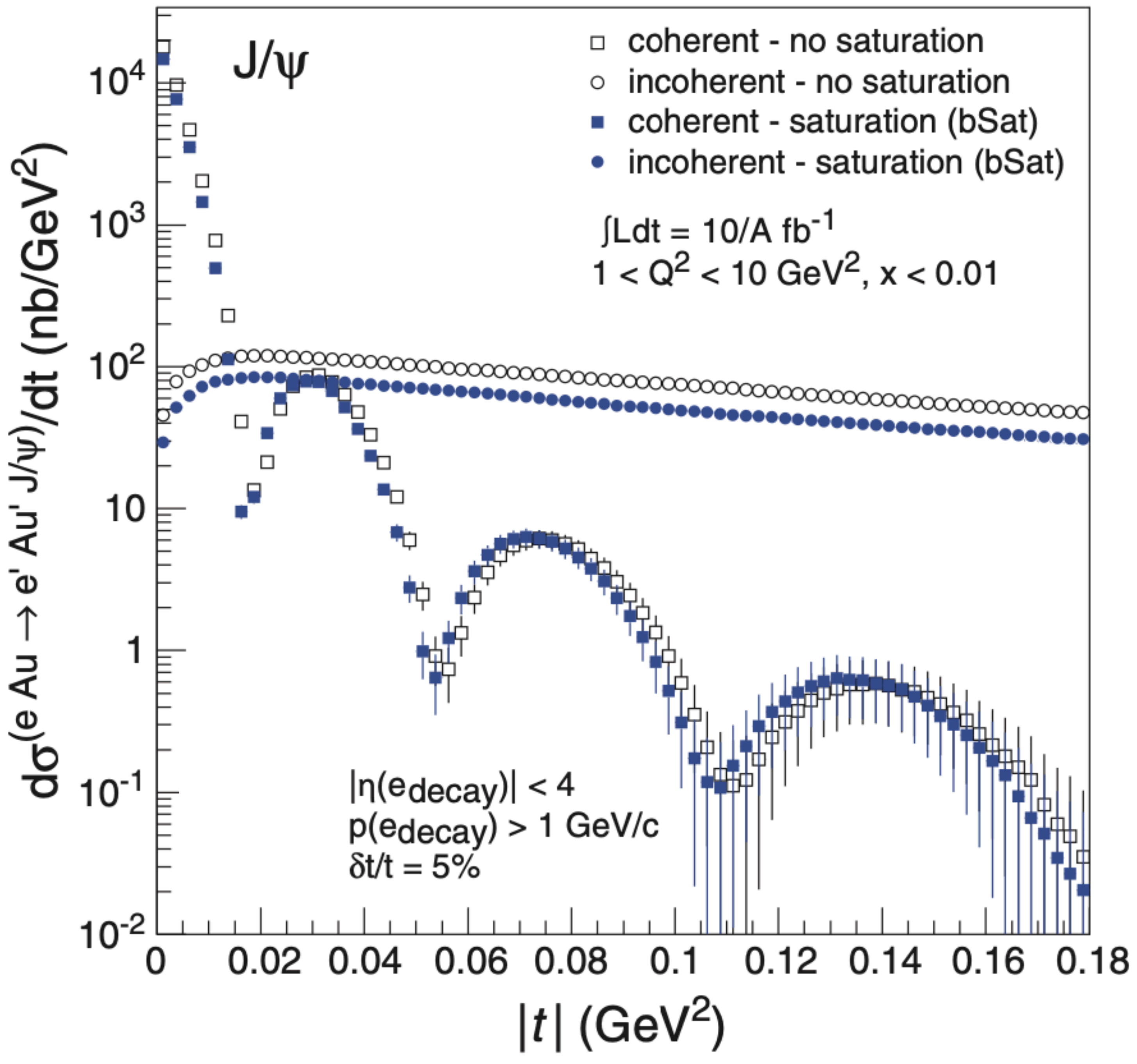


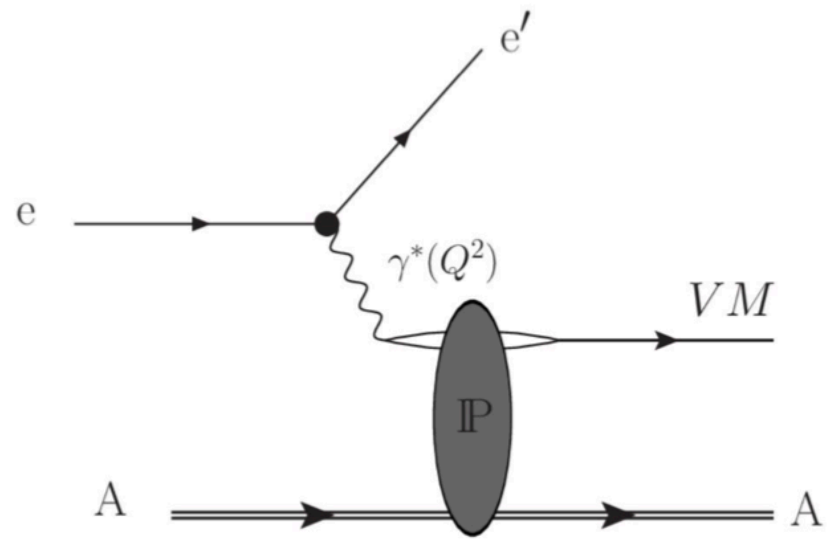
p_T proxy for t

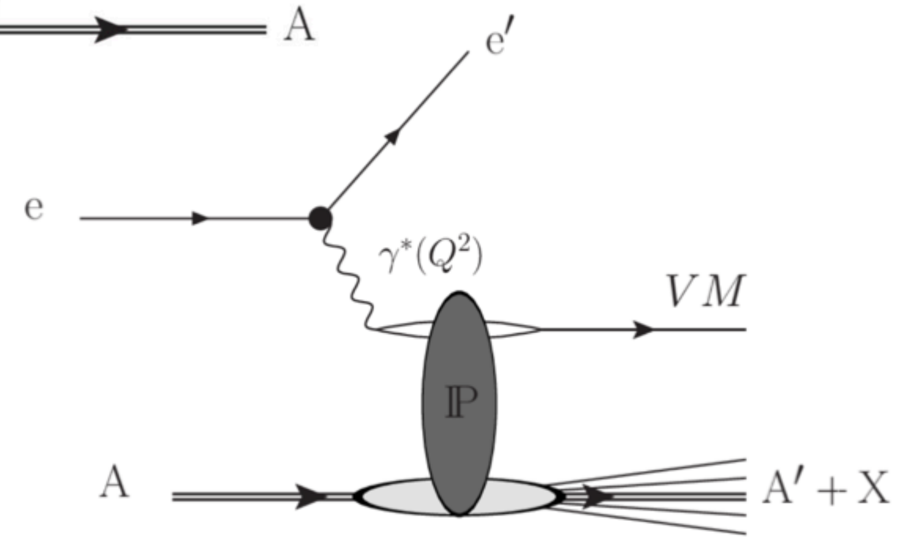


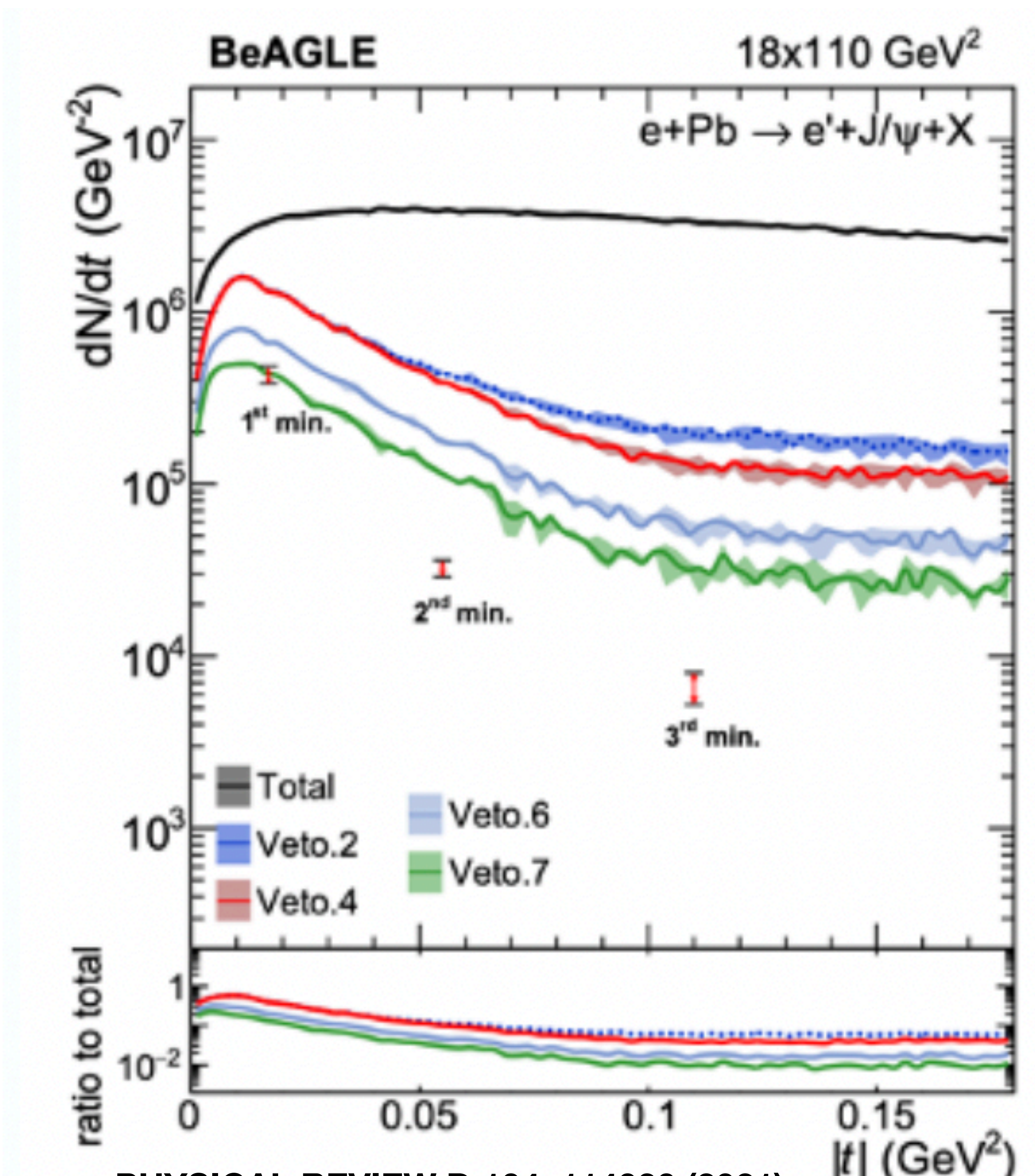
- Different ranges of Q^2 for VM production correlated to electron rapidity $\eta_{e'}$
- ^{16}O, ^{63}Cu, ^{90}Zr, ^{208}Pb, several energies, and several mesons ρ, ω, Υ, J/Ψ, ϕ
- J/Ψ Pb shown as example
- Adding low Q2 tagger increases acceptance by factor 5
- Electron resolutions better with low Q^2 reconstruction than central detector
  - start to see 1st dip
- Work in progress (e.g. t-reconstruction next)
- Other things to consider: background eg incoherent, synchrotron radiation

Incoherent e + A → e' + A' + VM + X VM Production in eA









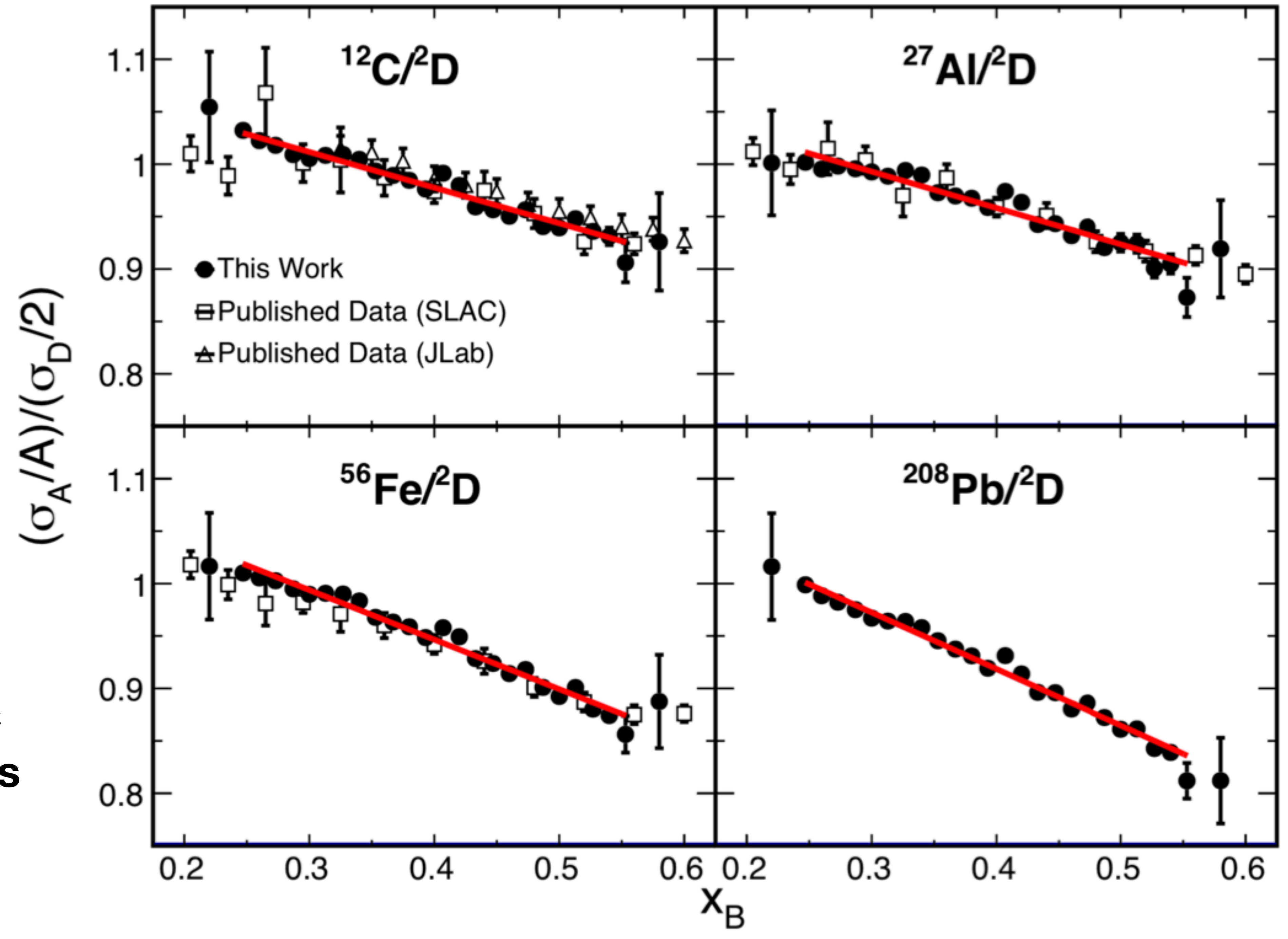
PHYSICAL REVIEW D 104, 114030 (2021)

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

- Interesting in its own right (partonic fluctuations)
- Biggest background for coherent
  - except small |t|
- Event by event tagging in far forward EIC region to veto incoherent
  - B0, RP, ZDC, OMD
  - How much is needed?
  - Challenges will likely exist due to eg pileup and sometimes missing products of nuclear excitation
  - ePIC studies with most up-to-date FF geometries/detectors on-going, e.g.:
    - veto incoherent deuteron breakup for light ion coherent VM with Beagle
    - Incoherent in heavier nuclei
    - Photons/nuclear de-excitation in B0 (e + A → e' + A' + VM + γ)

SRC Opportunities Via Tagging

B. Schmookler et al. (CLAS collaboration), Nature 566, 354 (2019)



EMC slopes

B. Schmookler et al. (CLAS collaboration), Nature 566, 354 (2019)

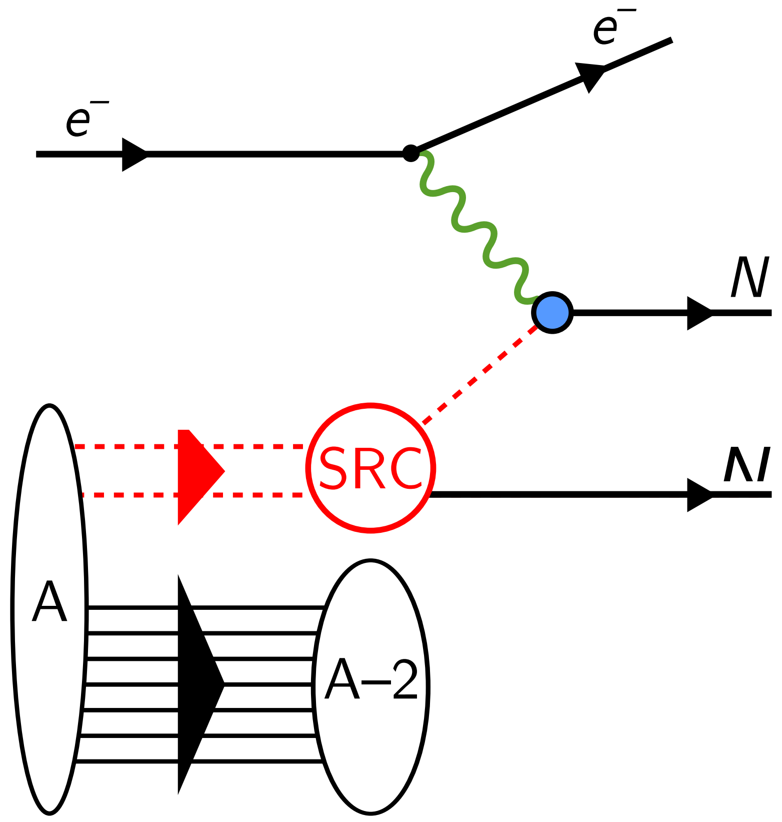
- EMC effect
- Quasielastic knock-out experiments with tagging at JLab imply SRC can shed light on EMC effect
- SRC:
  - Can be measured in (e,e’pN)
  - Nucleons pair close together in nucleus (NN)
  - Higher relative and lower centre of mass momentum compared to Fermi momentum
  - np-dominance
- EIC:
  - Range of A targets
  - New channels
  - Larger recoil momentum acceptance
  - Higher and wide range in Q^2
  - Excellent tagging in far forward for spectators and nuclei

Thanks F. Hauenstein (JLab) and A. Jentsch (BNL) for SRC input

SRC Opportunities Via Tagging

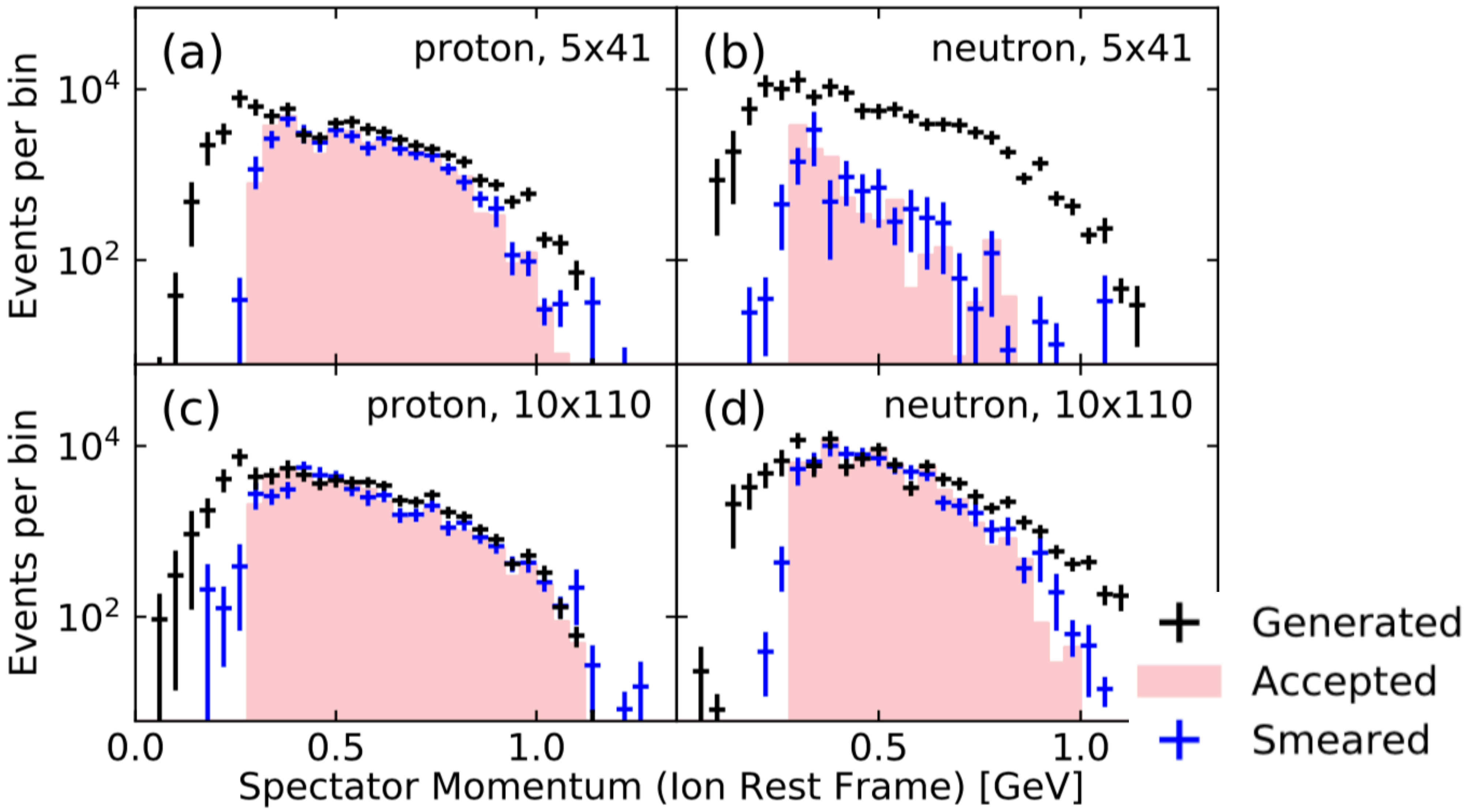
n.b. Studies on this page for EIC yellow report (not ePIC/ATHENA/ECCE)

Quasielastic



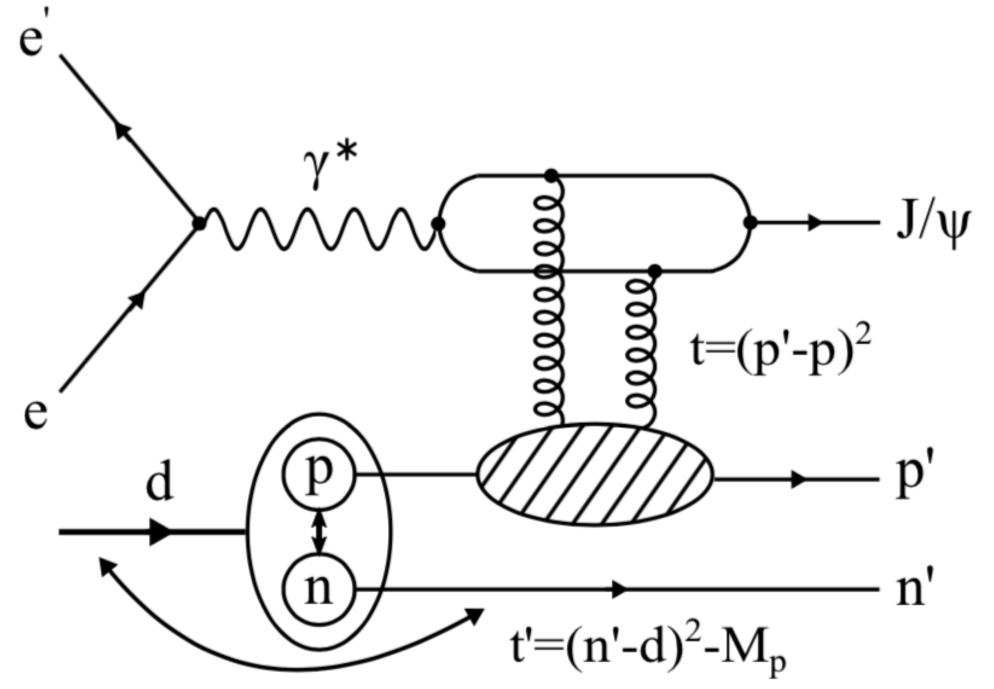
F. Hauenstein. et al., PRC 105, 034001 (2022)

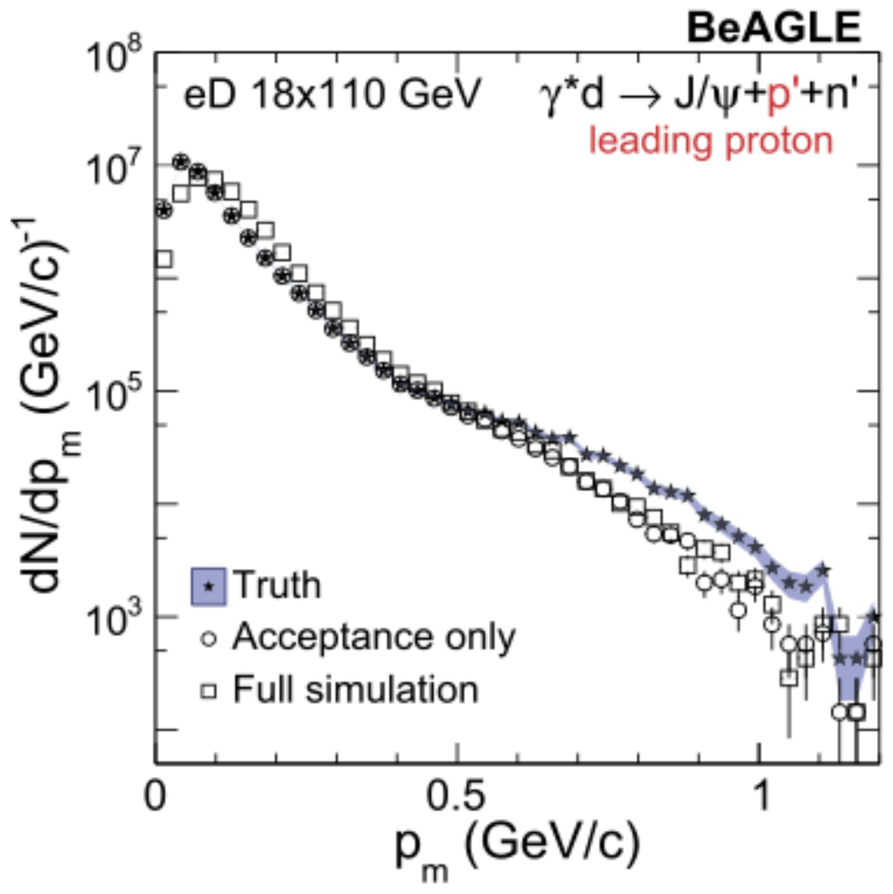
Recoil Momentum Distribution P_{IRF}

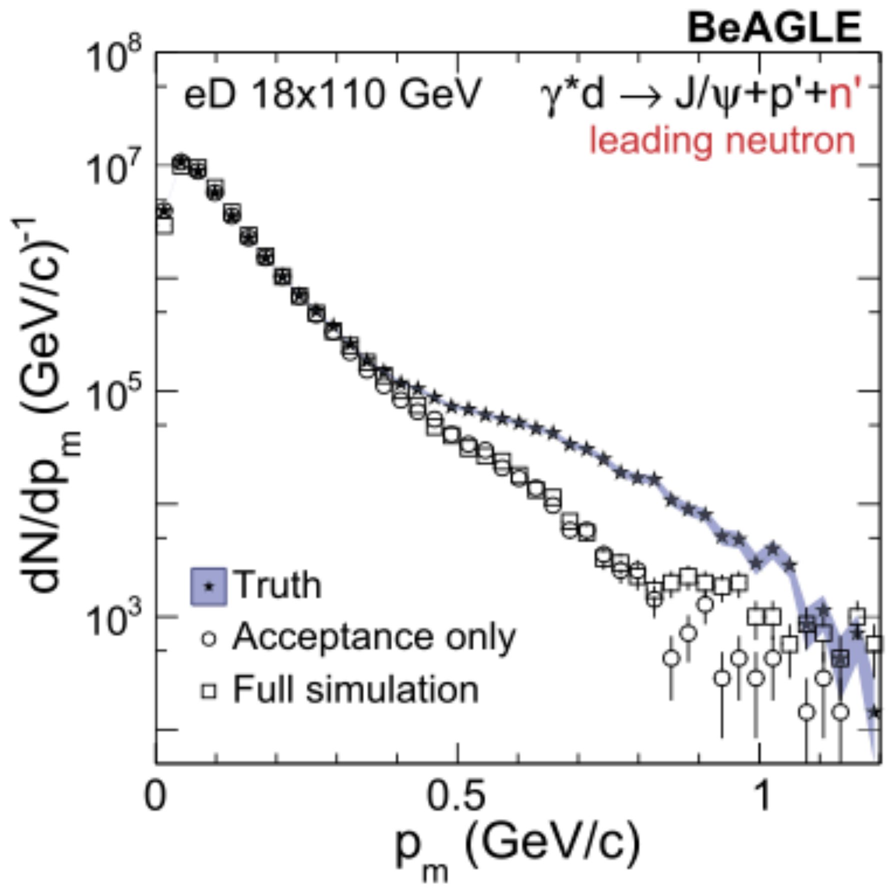


- Quasi-elastic scattering on nuclear targets
- Central detector e'; far forward for nuclear remnants, protons and neutrons
- Shown: acceptances for tagged recoil nucleons in QE SRC breakup in eC
  - C(e,e'pp)X, C(e,e'nn)X, C(e,e'np)X, and C(e,e'pn)X
- Acceptance over full momentum range
- Preference for 10 GeV x 110 GeV
- Deuterium was also studied d (e, e' N N)

Incoherent Diffractive J/psi







Z. Tu, A. Jentsch et al., PLB 811, 135877 (2020)

- J/Ψ can shed light of role of gluons in SRC
- e+d→e'+J/Ψ+p'+n'
- Tag active and spectator nucleons in far forward to control nuclear configuration
- Spectator 3-momenta shown - wide range, SRC region (>300MeV/c) accessible
- Work continues in ePIC on this

Summary

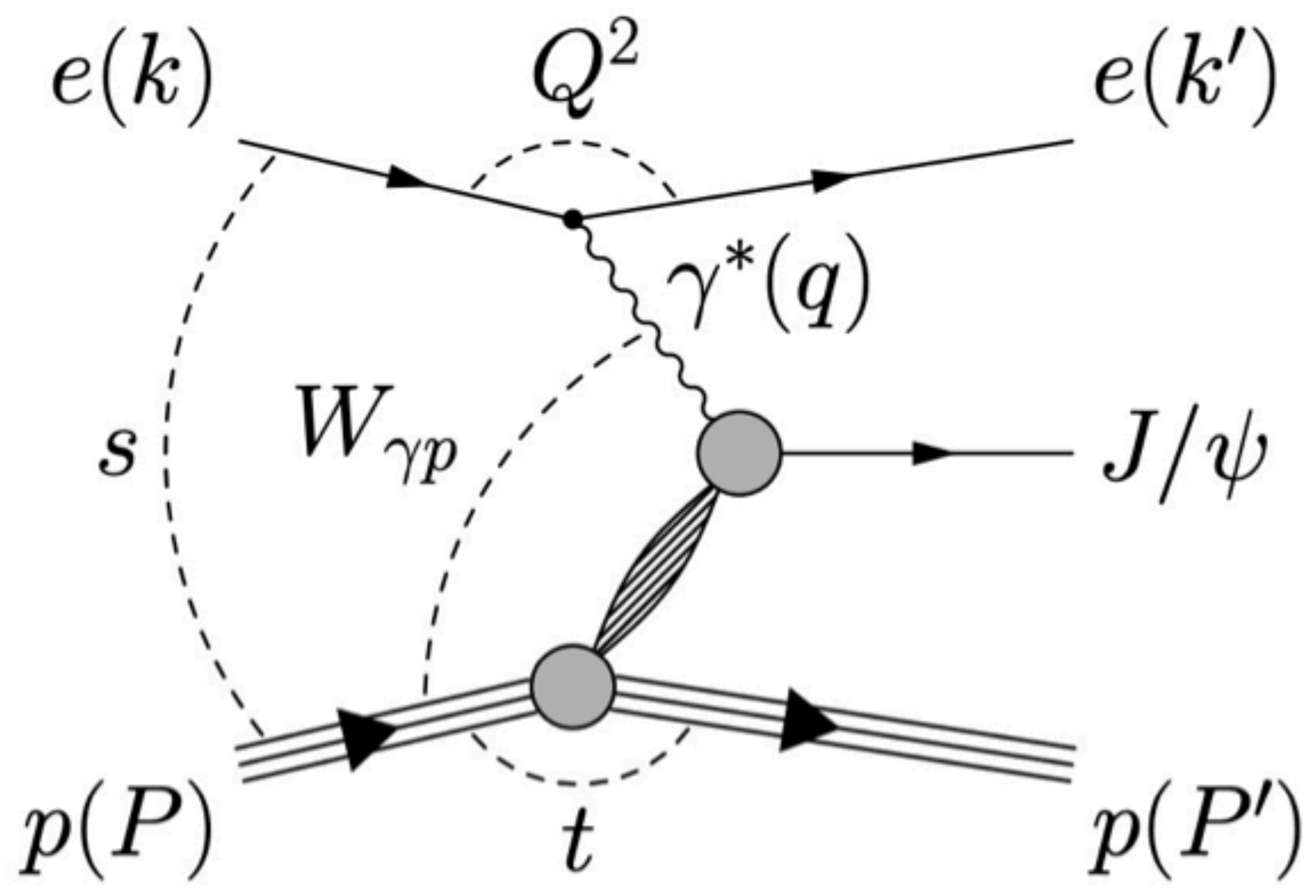
- EIC will be a unique opportunity to probe nucleon/nuclear structure in unexplored regimes using ep/eA
- Complimentary to e+e-, pp/pA/AA - needed for fuller QCD understanding

- Numerous exciting exclusive measurements will shed light on several topics
  - in particular nucleon and nuclear tomography and gluon saturation
- Several studies on-going, and more to be developed (everyone welcome to join us in these efforts)

- Some examples were highlighted
  - DVCS in nuclei
  - Diffractive exclusive VM production
  - Tagging for SRC opportunities

- These were just some glimpses, not an exhaustive summary
- (Many more potential topics, e.g. nuclear deformations/nuclear structure…)

Thank You



- Method Exact (E): $-t = -(\boldsymbol{p}_{\mathrm{e}} - \boldsymbol{p}_{\mathrm{e'}} - \boldsymbol{p}_{\mathrm{VM}})^2 = -(\boldsymbol{p}_{\mathrm{A'}} - \boldsymbol{p}_{\mathrm{A}})^2$
- Method Approximate (A) (UPCs) $-t = (p_{\mathrm{T,e'}} + p_{\mathrm{T,VM}})^2$
- Method with **exclusivity corrected** (L): $-t = -(\boldsymbol{p}_{\mathrm{A',corr}} - \boldsymbol{p}_{\mathrm{A}})^2$,

where $\boldsymbol{p}_{\mathrm{A',corr}}$ is constrained by exclusive reaction.