ePIC Exclusive Physics overview

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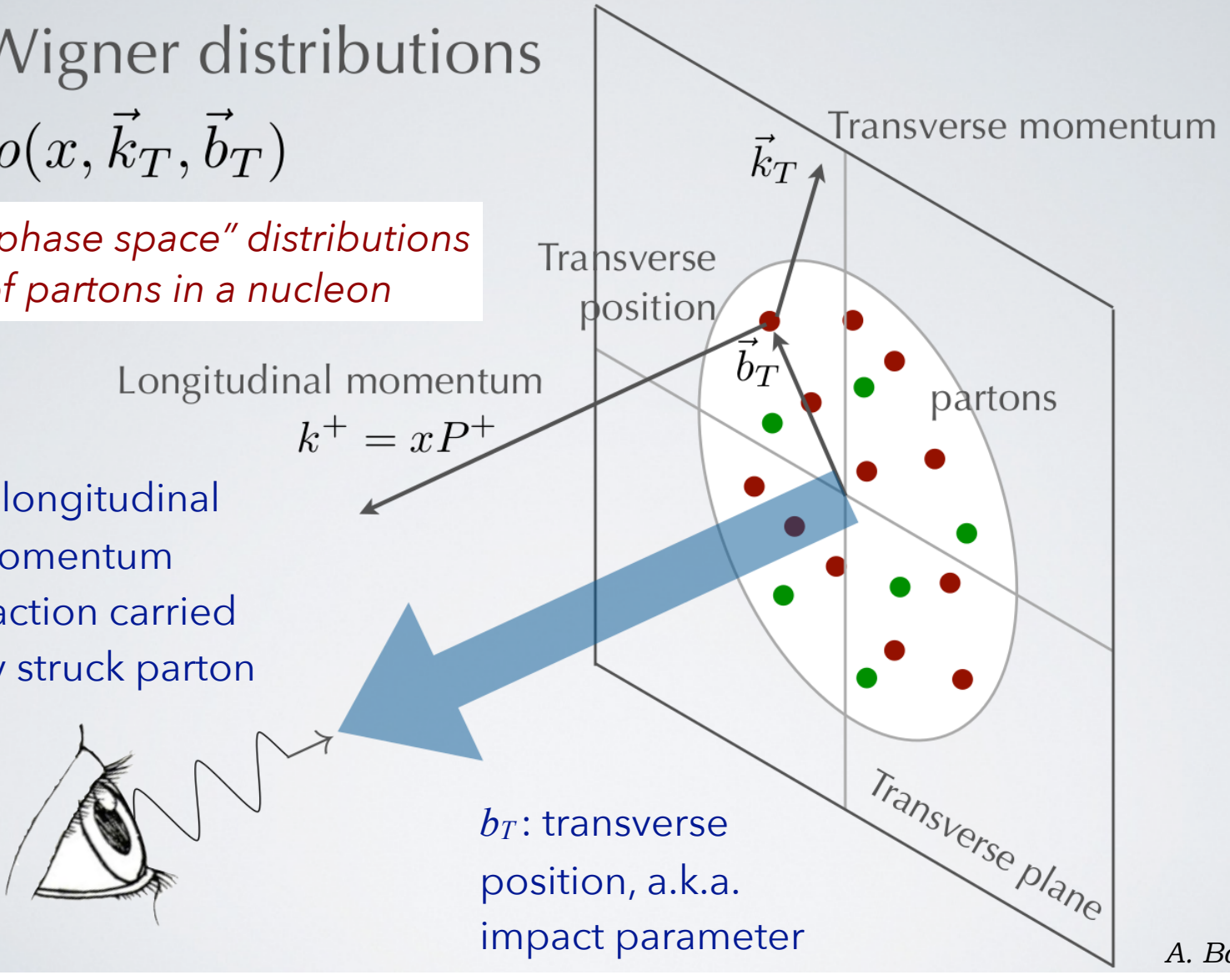
UK EIC Meeting
Birmingham – 18th November 2024

A constructivist view of the nucleon

Wigner distributions

$$\rho(x, \vec{k}_T, \vec{b}_T)$$

"phase space" distributions of partons in a nucleon

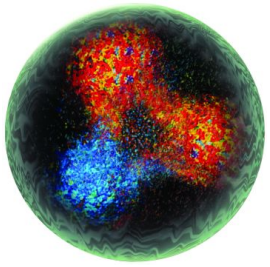


x: longitudinal momentum fraction carried by struck parton

b_T: transverse position, a.k.a. impact parameter

A. Bacchetta

Imaging



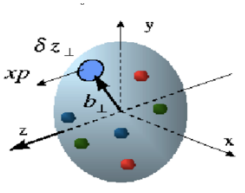
Wigner function: full phase space parton distribution of the nucleon

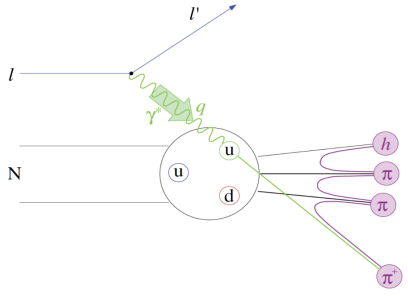
Possible access via exclusive di-jet production or exclusive π^0-production at high Q^2.

Generalised Transverse Momentum Distributions (GTMDs)

$$\int d^2k_T$$

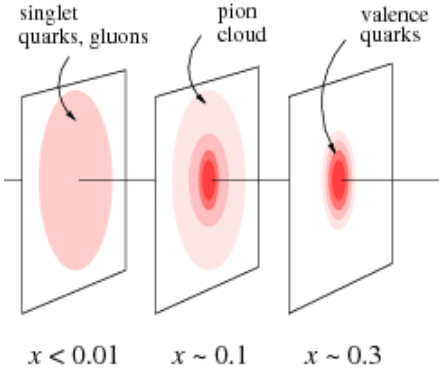
$$\int d^2b_T$$





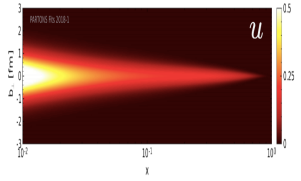
Generalised Parton Distributions (GPDs)

Exclusive processes



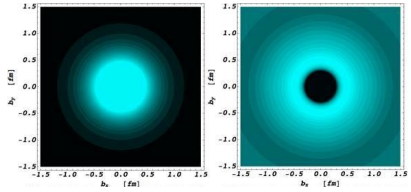
Transverse Momentum-Dependent distributions (TMDs)

Semi-inclusive DIS (SIDIS)



$$\int dx$$

$$\int d^2k_T$$

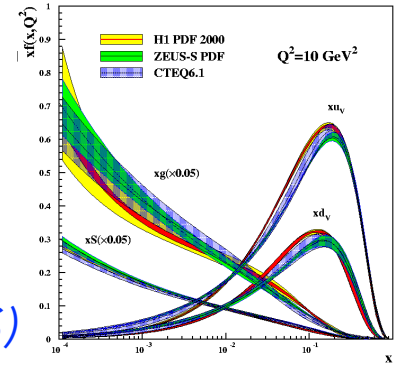


Form Factors

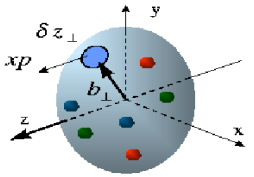
Elastic scattering

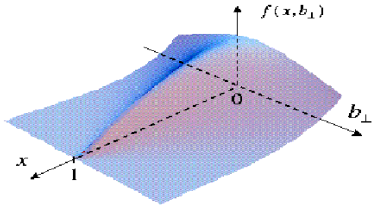
Parton Distribution Functions (PDFs)

Deep Inelastic Scattering (DIS)



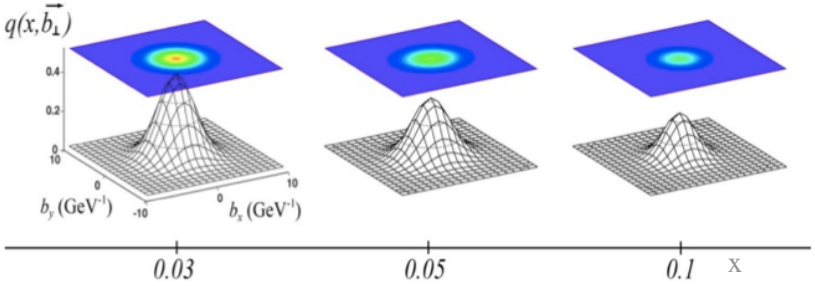
Generalised Parton Distributions





- proposed by Müller (1994), Radyushkin, Ji (1997).
- can be interpreted as relating, in the infinite momentum frame, transverse position of partons (impact parameter $b_\perp$) to longitudinal momentum fraction (x).

* **Tomography** of the nucleon: transverse spatial distributions of quarks and gluons in longitudinal momentum space.



* Information on the orbital angular momentum contribution to nucleon spin: **the spin puzzle**.

$$J_N = \frac{1}{2} = \frac{1}{2}\Sigma_q + L_q + J_g$$

Ji's relation:

$$J^q = \frac{1}{2} - J^g$$

$$= \frac{1}{2}\int_{-1}^{1} x dx \left\{ H^q(x,\xi,0) + E^q(x,\xi,0) \right\}$$

* Indirect access to mechanical properties of the nucleon: possibilities of extracting **pressure distributions** within the nucleon.

* Combine with TMDs to access **spin-orbit correlations** of quarks and gluons, study non-perturbative interactions of partons.

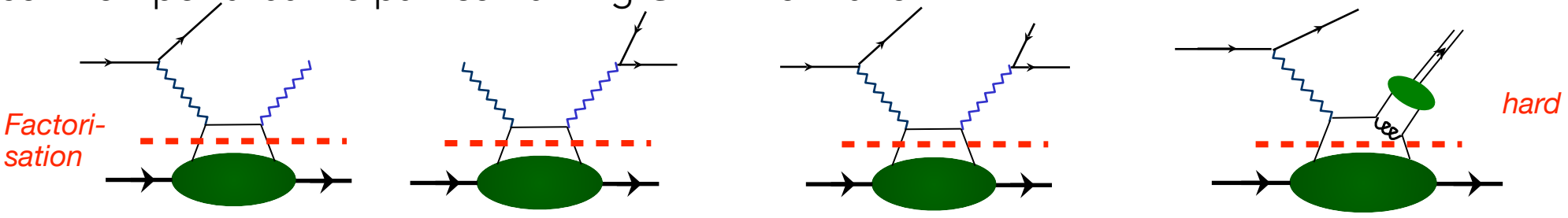
Experimental access to GPDs

Accessible via Compton Form Factors and structure functions in *exclusive* processes (all final state particles are determined), *eg*:

- Deeply Virtual Compton Scattering (DVCS)
- Time-like Compton Scattering (TCS)
- Hard Exclusive Meson Production (HEMP) – a.k.a. Deeply Virtual Meson Production (DVMP)
- Double DVCS
- Certain diffractive processes, eg: diffractive ρ-production with the emission of a meson or virtual photon from the nucleon
- Hard exclusive production of a meson-photon or photon-photon pair
- Charged-current meson production, eg: $ep \to \nu_e \pi^- p$

See EIC Yellow Report for details

Relies on *factorisation* of the process amplitude into a hard, perturbative part and the soft non-perturbative part containing GPD information.



DVCS

Virtual photon space-like

TCS

Virtual photon time-like

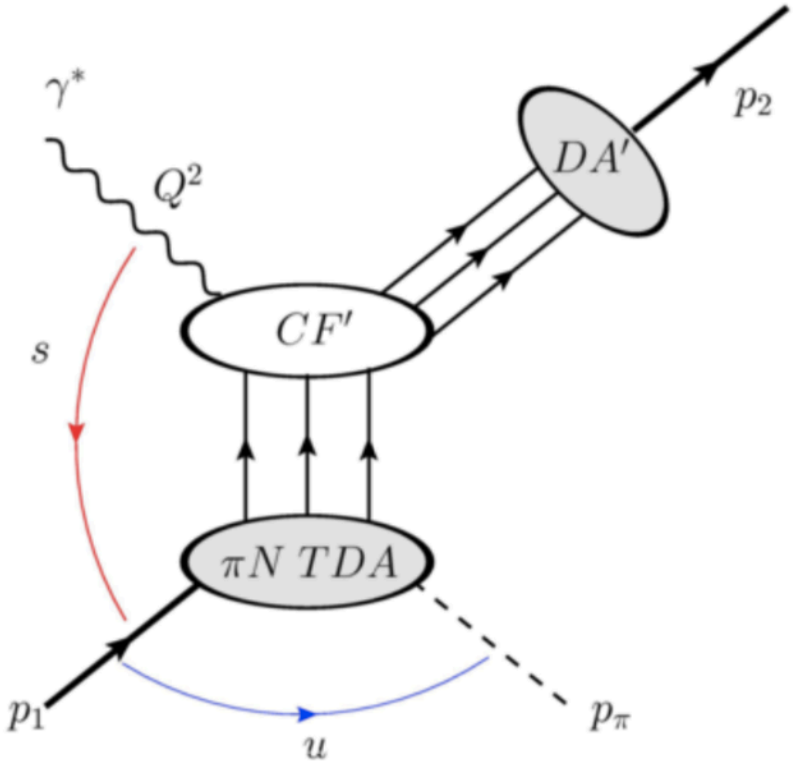
DDVCS

One time-like, one space-like virtual photon

DVMP

Virtual photon space-like

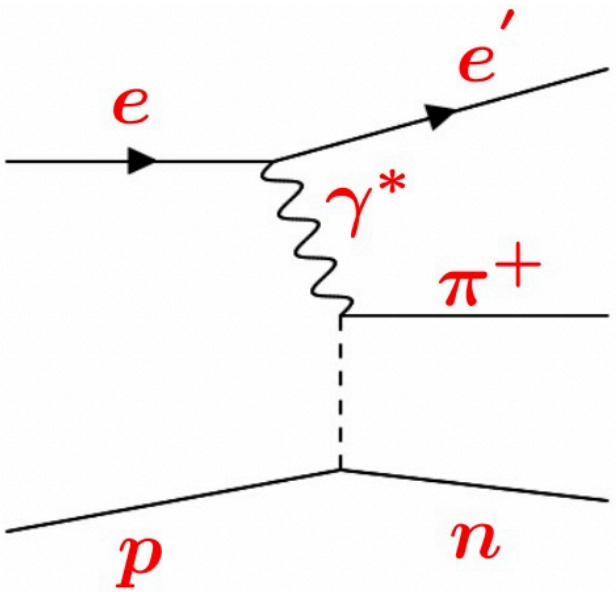
Transition Distribution Amplitudes



- TDAs describe the mechanism by which a baryon transitions into a meson.
- Three parton exchanges between the soft and the hard part of the scattering process: sensitivity to diquark clustering in the nucleon and helicity content of correlated quarks.

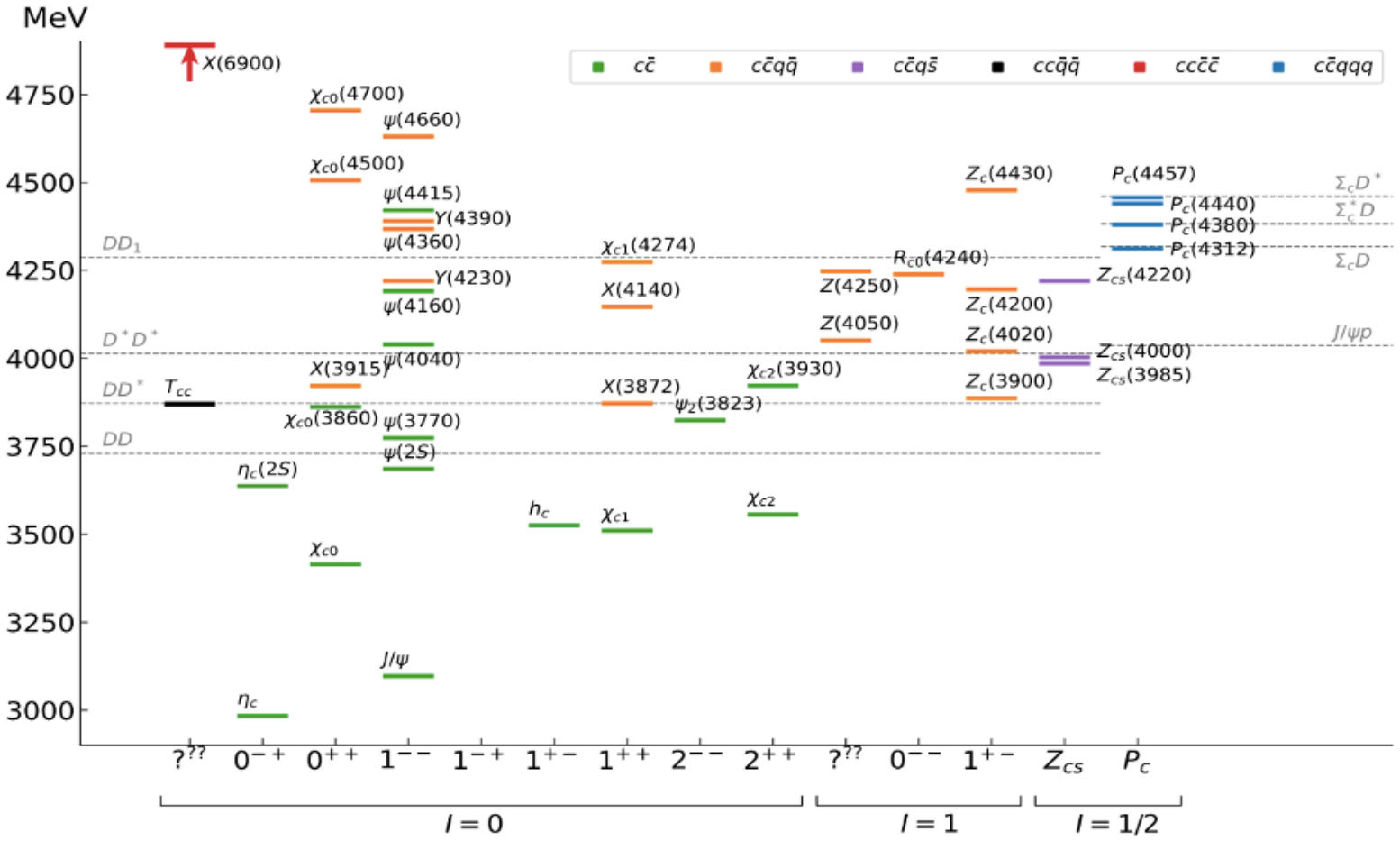
- Fourier transform of a TDA gives info on spatial parton distributions in the impact parameter plane.

Sullivan Process



- At low *t*, observe meson-pole dominance in scattering: it takes place off a meson in the nucleon meson-cloud – pion or kaon.
- Through elastic scattering on the meson can access the pion / kaon form factors.
- Deep Inelastic Scattering has sensitivity to the meson's structure functions.

Spectroscopy of exotics

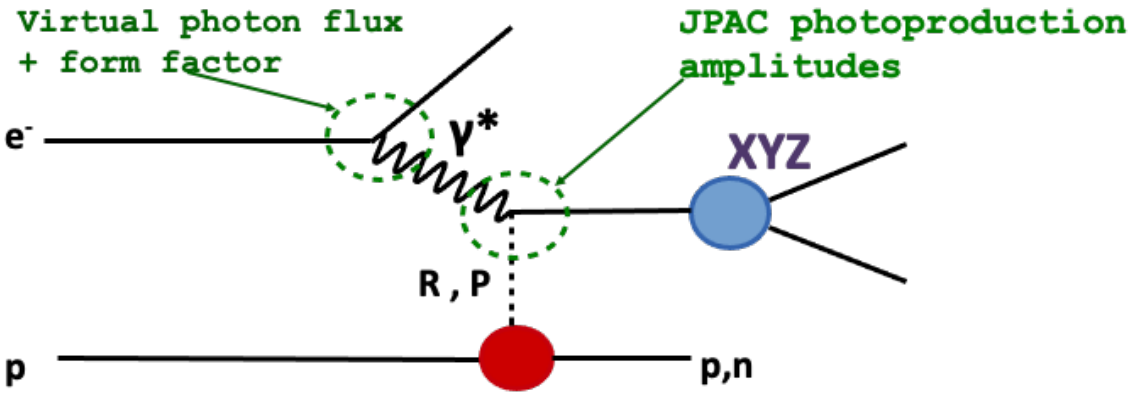


M. Albaladejo *et al.* ***(JPAC),*** *Prog. Part. Nucl. Phys. 127, 103981 (2022)*

EIC offers a means of exploring charmonium exotics through quasi-real photoproduction.

Validation of existing states, most of which seen only in single production mechanisms, search for new ones.

Spectroscopy of XYZ

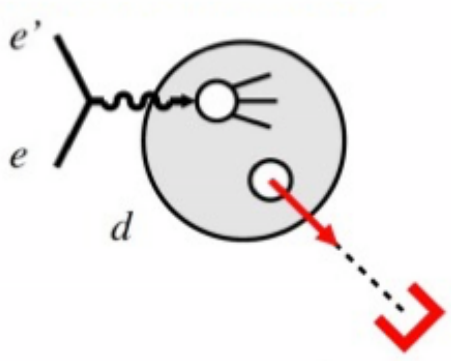


5 x 41 GeV (e x p beam energy), L = 6.1 x 10^{33} cm^{-2} s^{-1}, production rate estimates:

Meson	Cross Section (nb)	Production rate (per day)	Decay Branch	Branch Ratio (%)	Events (per day)
$\chi_{c1}(3872)$	2.3	2.0 M	$J/\Psi\,\pi^+\pi^-$	5	6.1 k
$Y(4260)$	2.3	2.0 M	$J/\Psi\,\pi^+\pi^-$	1	1.2 k
$Z_c(3900)$	0.3	0.26 M	$J/\Psi\,\pi^+$	10	1.6 k
$X(6900)$	0.015	0.013 M	$J/\Psi\,J/\Psi$	100	46
$Z_{cs}(4000)$	0.23	0.20 M	$J/\Psi\,K^+$	10	1.2 k
$Z_b(10610)$	0.04	0.034 M	$\Upsilon(2S)\,\pi^+$	3.6	24

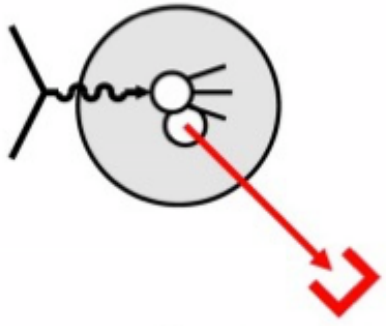
V. Burkert *et al., Prog. Part. Nucl. Phys. 131, 104032 (2023)*

Short-range correlations / EMC effect

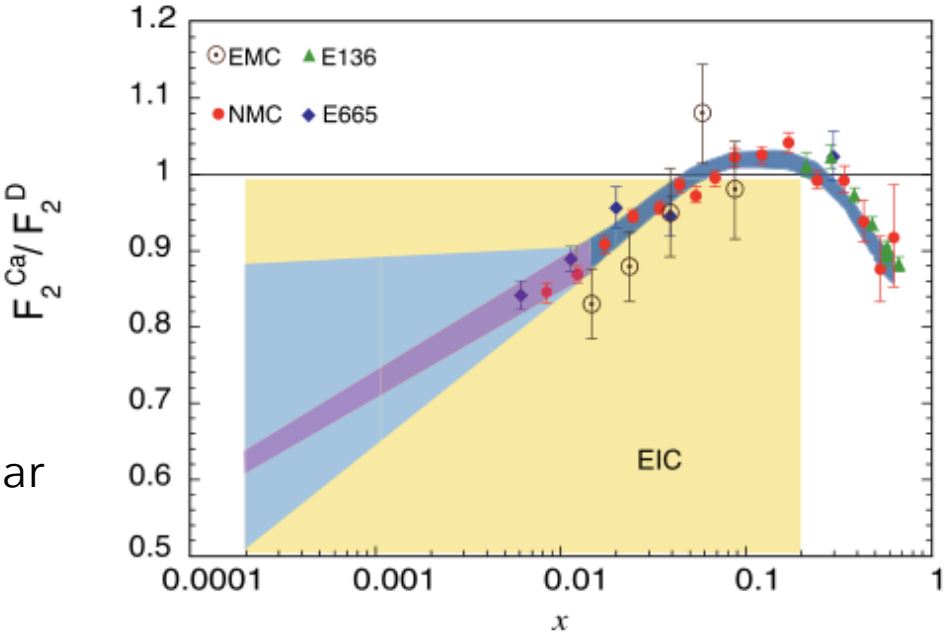


Very low spectator momentum: quasi-free nucleon, on-shell extrapolation.

M. Sargsian, M. Strikman PLB **639** (iss. 3-4) 223231 (2006)



High spectator momentum: nuclear modifications.



EIC White Paper, *Eur. Phy. J. A 52, 9 (2016)*

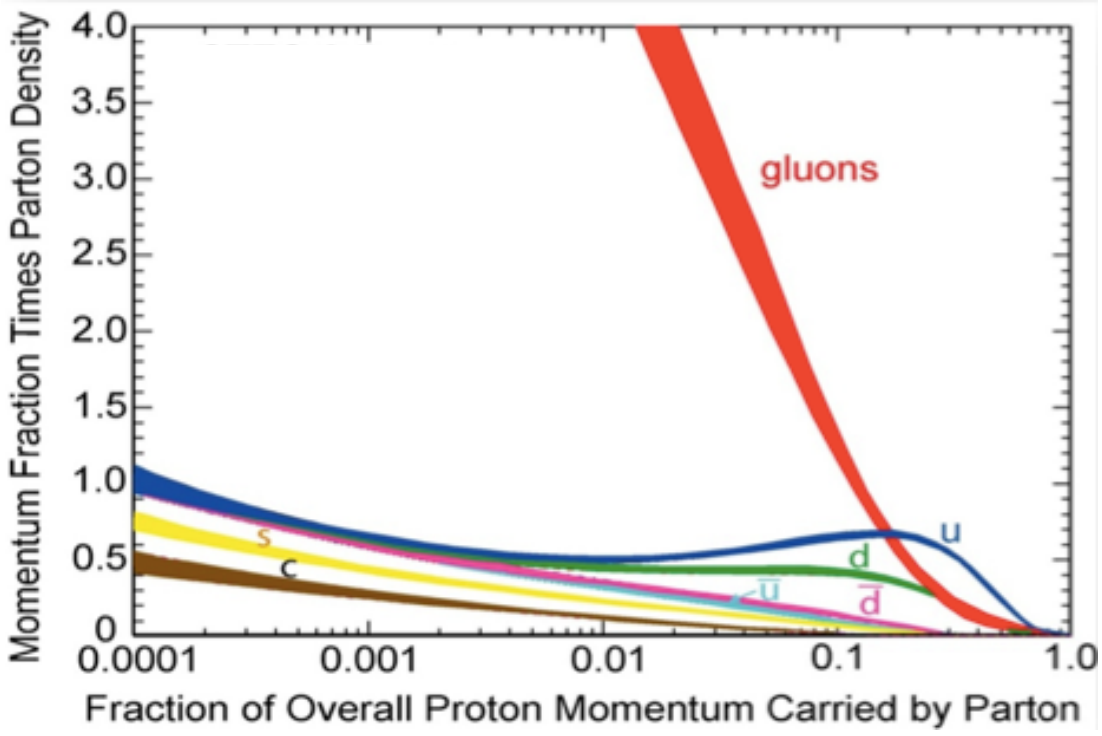
- Measurements of structure functions and other observables on free nucleons and light and heavy nuclei enable the study of nuclear modifications, the EMC effect, anti-shadowing, short-range correlations…

Saturation of gluon density

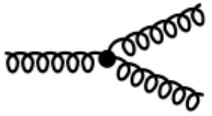
Runaway growth of glue at low-x:

"…A small color charge in isolation builds up a big color thundercloud…."

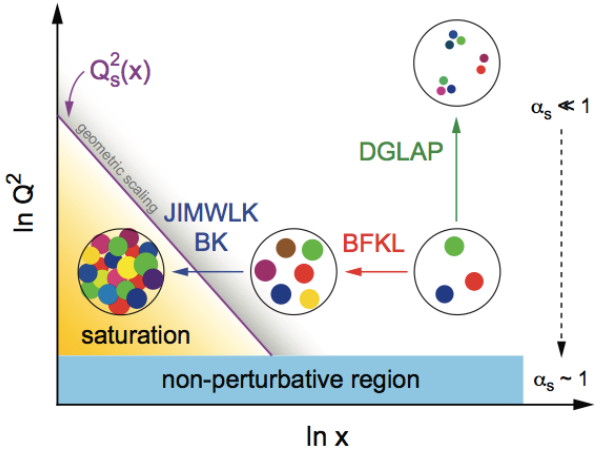
F. Wilczek, in "Origin of Mass"
Nobel Prize, 2004



But somewhere it must saturate…

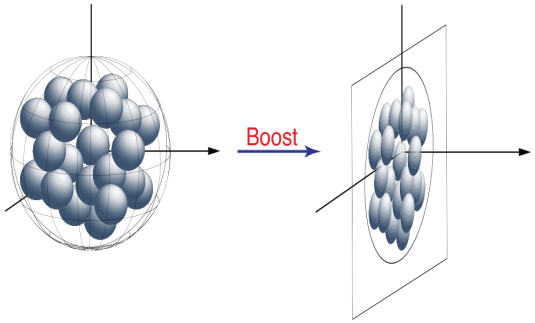
rate of  = rate of 

Recombination of gluons leads to saturation of gluon densities. Possible effective theory: Colour Glass Condensate.

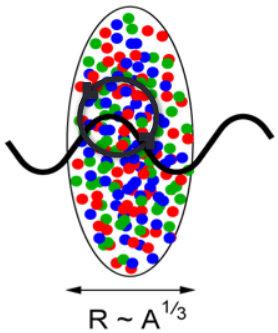


Courtesy of A. Deshpande

Saturation signatures



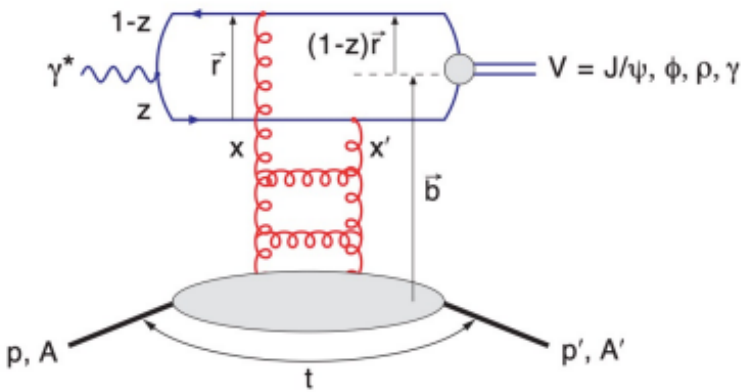
Saturation regime would be accessible at much lower energy in *e-A* collisions than *e-p*.

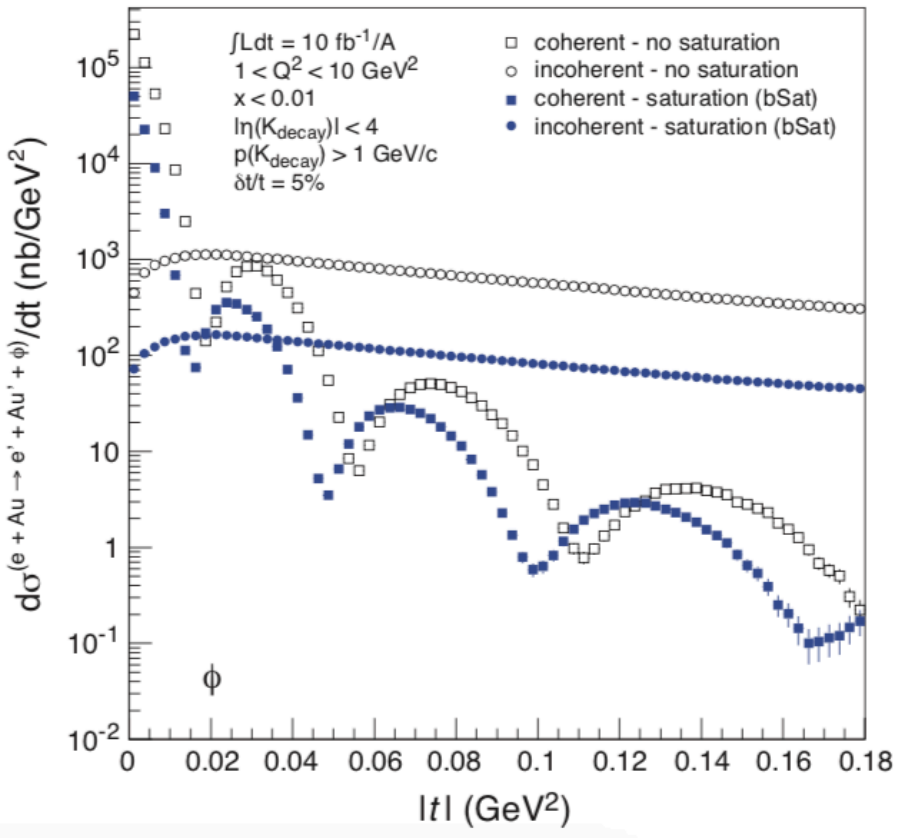


$$(Q_s^A)^2 \approx cQ_0^2 \left[\frac{A}{x}\right]^{1/3}$$

saturation scale

A powerful signature is in diffractive cross-sections:





EIC White Paper, *Eur. Phy. J. A 52, 9 (2016)*

Exclusive Physics topics I

Imaging

Generalised Parton Distributions (GPD)

- production of high-energy mesons and / or photons (virtual or real),
- low t
- typically high Q^2 but some processes are at $Q^2 \sim 0$ (photoproduction)

Transition Distribution Amplitudes (TDA)

- u-channel meson-production, very low u, meson goes far-forward
- very high t
- typically high Q^2 but some processes are at $Q^2 \sim 0$ (photoproduction)

Meson structure (pion form factors and structure functions)

- Sullivan process: scattering off the pion cloud in the nucleon,
- low t (for the nucleon),
- Range of Q^2 from photoproduction to as high as statistics allow

Exclusive Physics topics II

Spectroscopy

- meson quasi-real photo-production, final state often with many particles,
- $Q^2 \sim 0$, detection of scattered electron in the low-Q^2 tagger

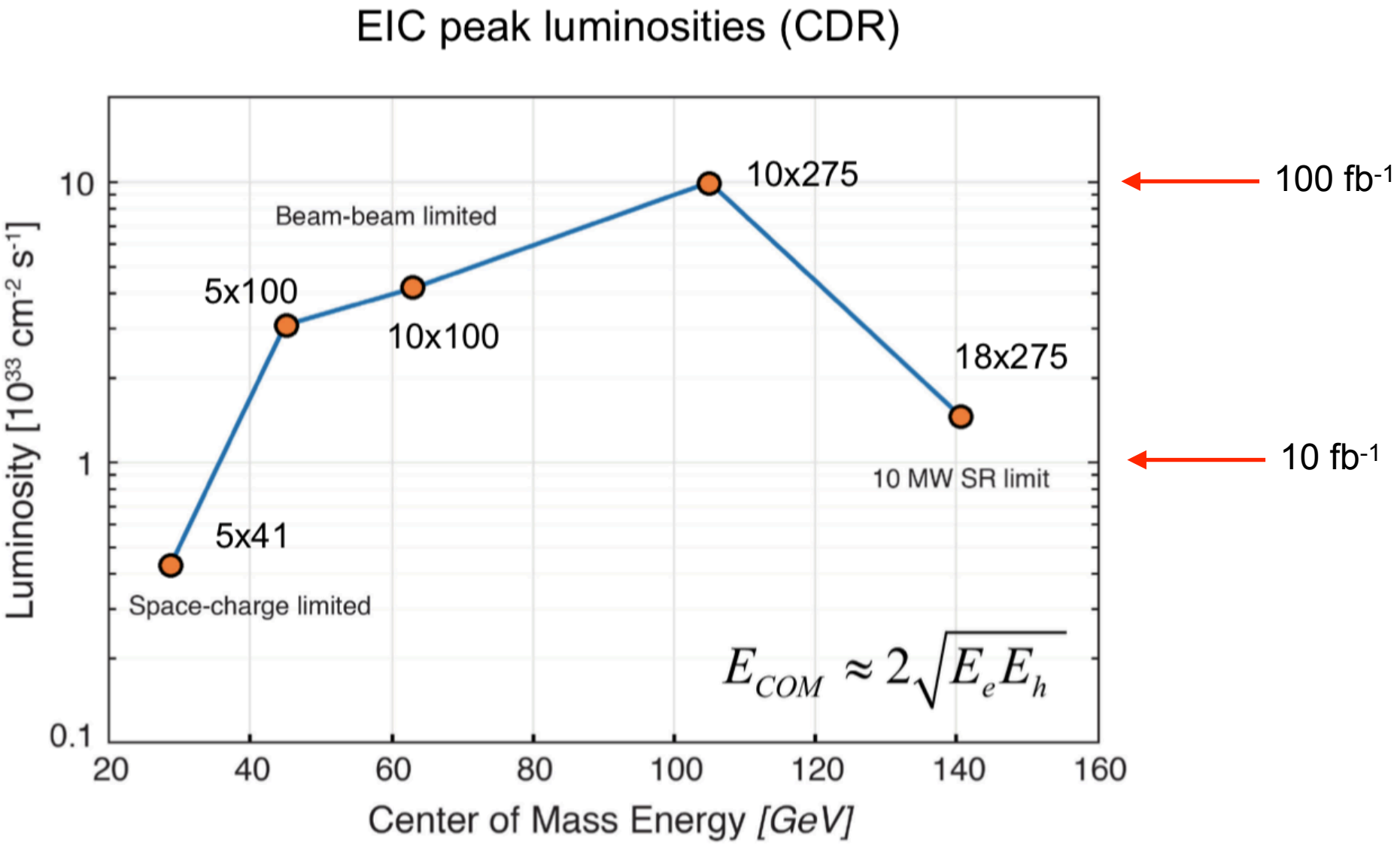
Nuclear modifications

- measurements on a nucleon in a nucleus, involve tagging one or more spectators
- many processes of interest

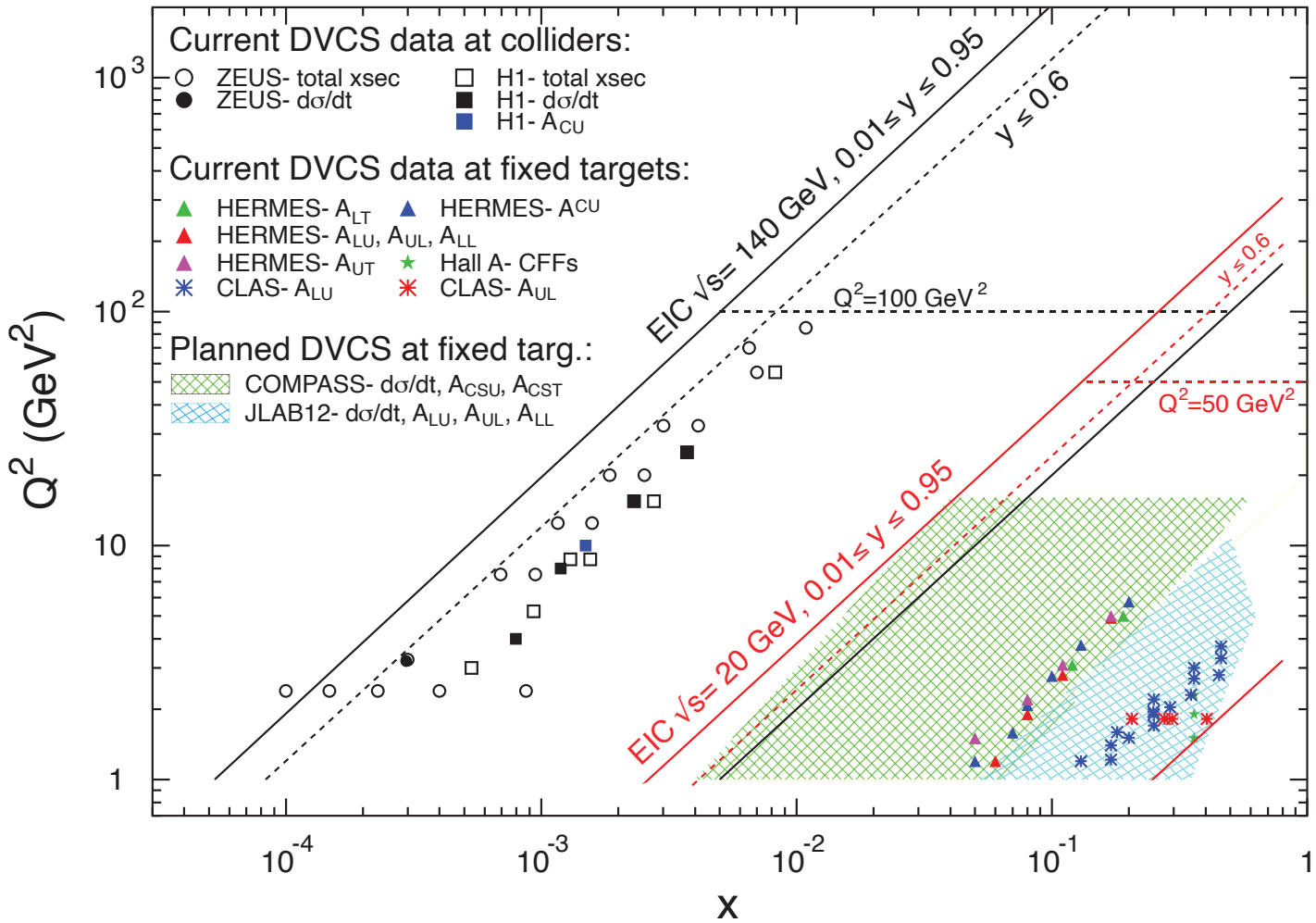
Saturation

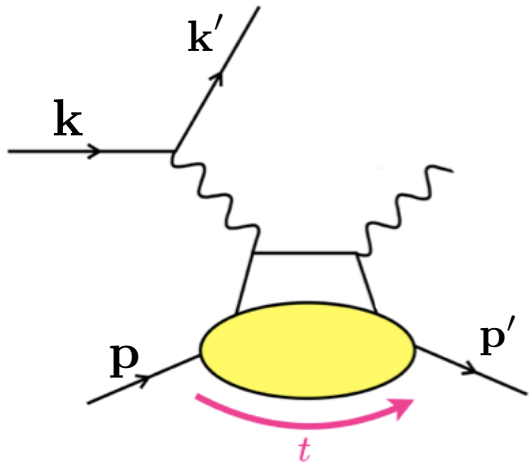
- coherent vector-meson production on heavy ions
- low-*t*, but ion will not be detected – involves a veto of nuclear break-up in the far-forward region

Luminosity


EIC peak luminosities (CDR)
Luminosity [10^33 cm^-2 s^-1]
10
1
0.1
20
40
60
80
100
120
140
160
Center of Mass Energy [GeV]
Beam-beam limited
5x100
10x100
10x275
18x275
5x41
Space-charge limited
10 MW SR limit
$E_{COM} \approx 2\sqrt{E_e E_h}$
100 fb-1
10 fb-1

EIC kinematic reach: DVCS





$$\mathbf{q} = \mathbf{k} - \mathbf{k}'$$

$$Q^2 = -\mathbf{q}^2$$

$$x_B = \frac{Q^2}{2\mathbf{p}\cdot\mathbf{q}}$$

$$t = (\mathbf{p}' - \mathbf{p})^2$$

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

(inelasticity)

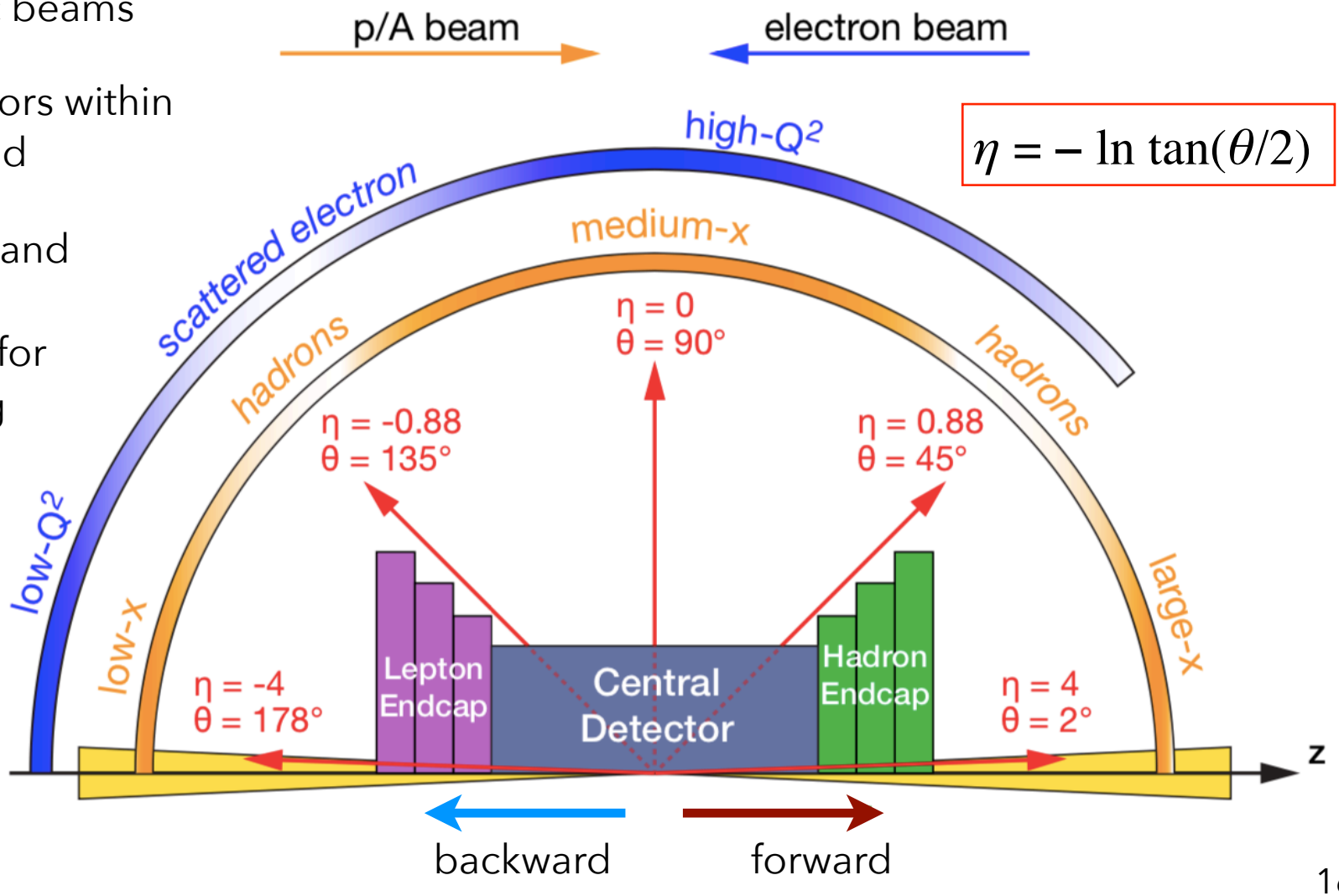
https://arxiv.org/abs/2103.05419

Detector configuration

Very asymmetric beams

Hermetic detectors within a central solenoid

Very far-forward and far-backward instrumentation for lowest scattering angles

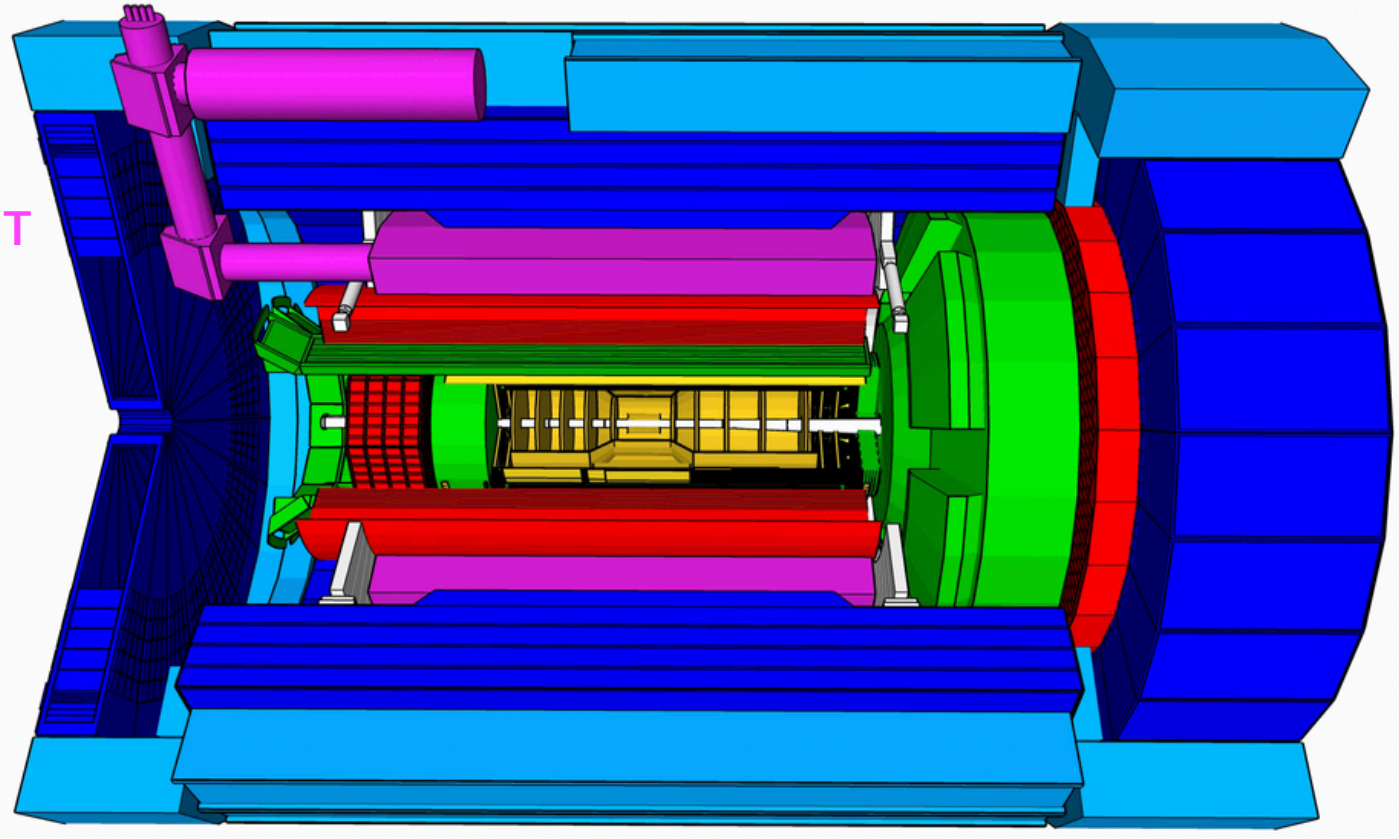


The ePIC detector

The "project detector" to be constructed at IP 6

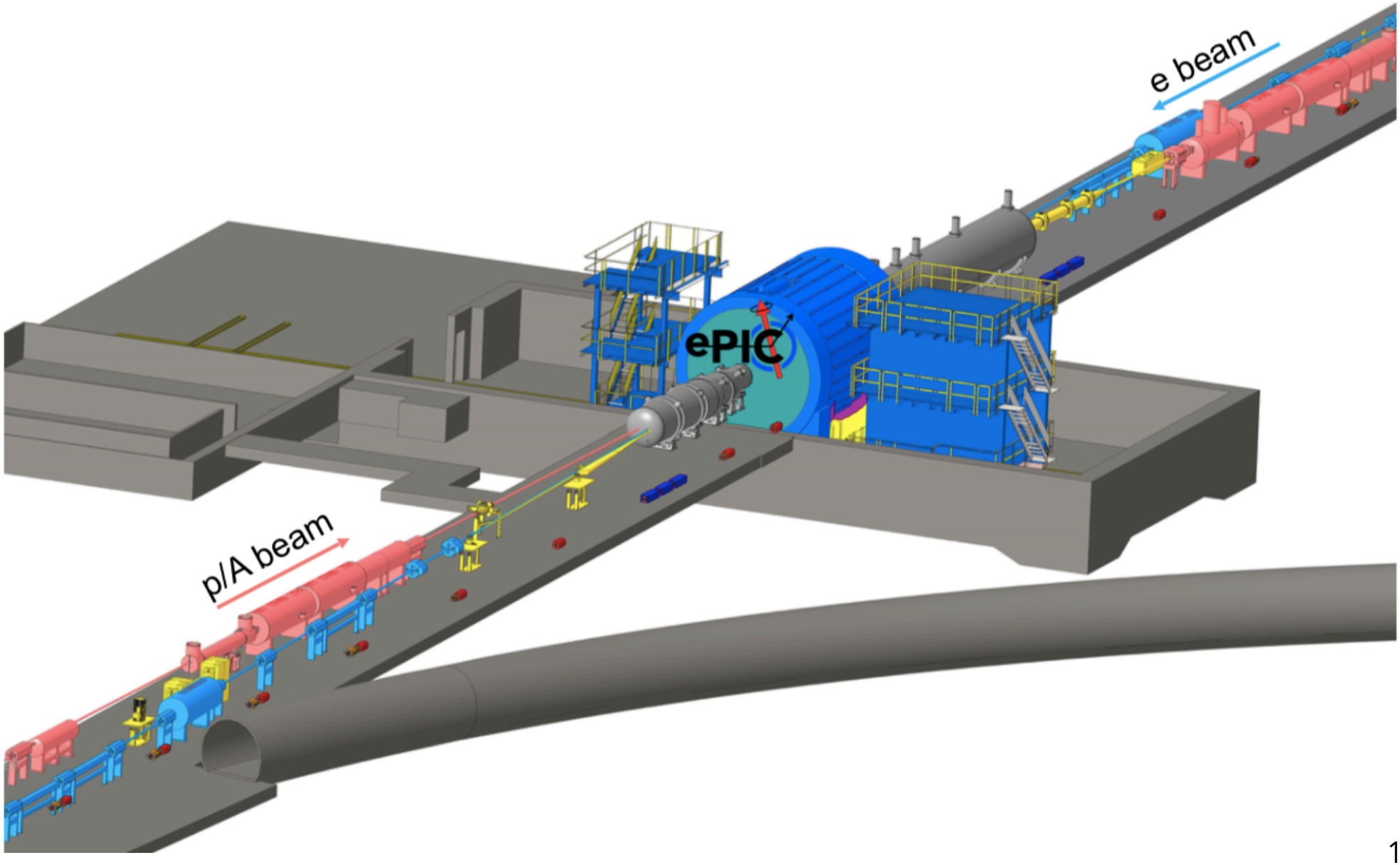
Electron-Proton and -Ion Collider detector

- hadronic calorimeters
- Solenoidal Magnet — 1.7 T
- e/m calorimeters (ECal)
- Time.of.Flight, DIRC, RICH detectors
- MPGD trackers
- MAPS tracker

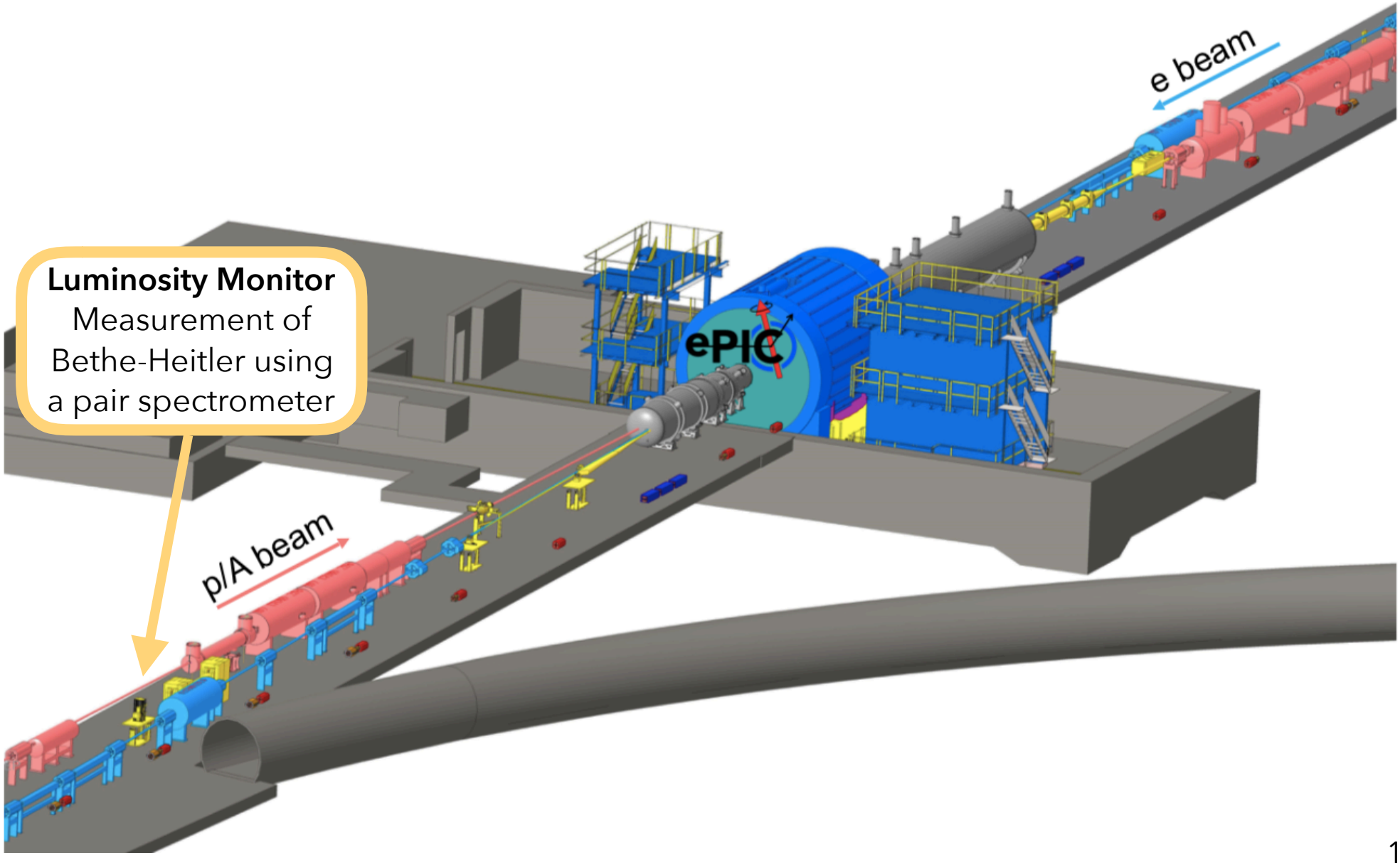


Result of the merging of ECCE and ATHENA collaborations.

Far-forward/-backward detectors

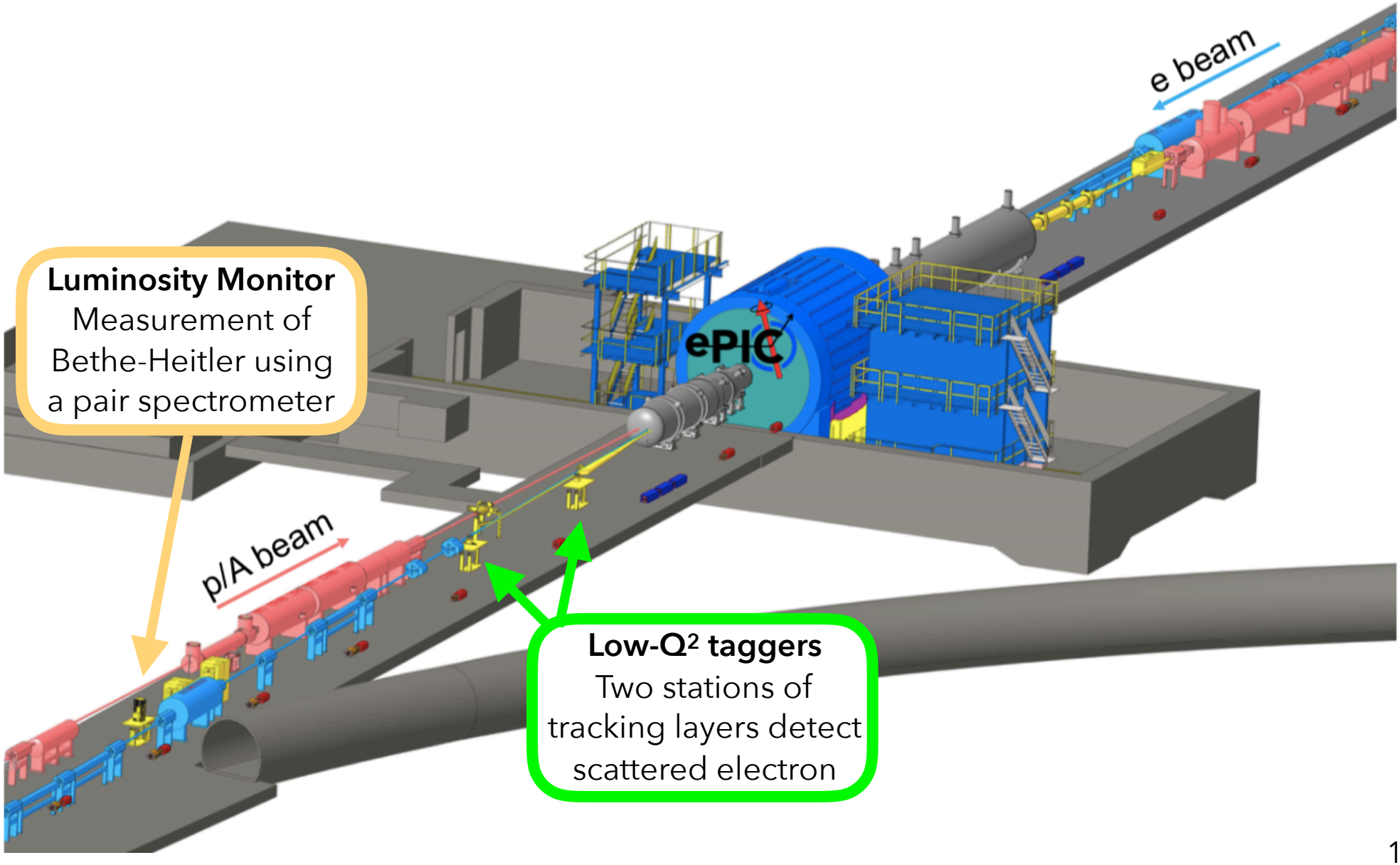


Far-backward detectors



Luminosity Monitor
Measurement of Bethe-Heitler using a pair spectrometer

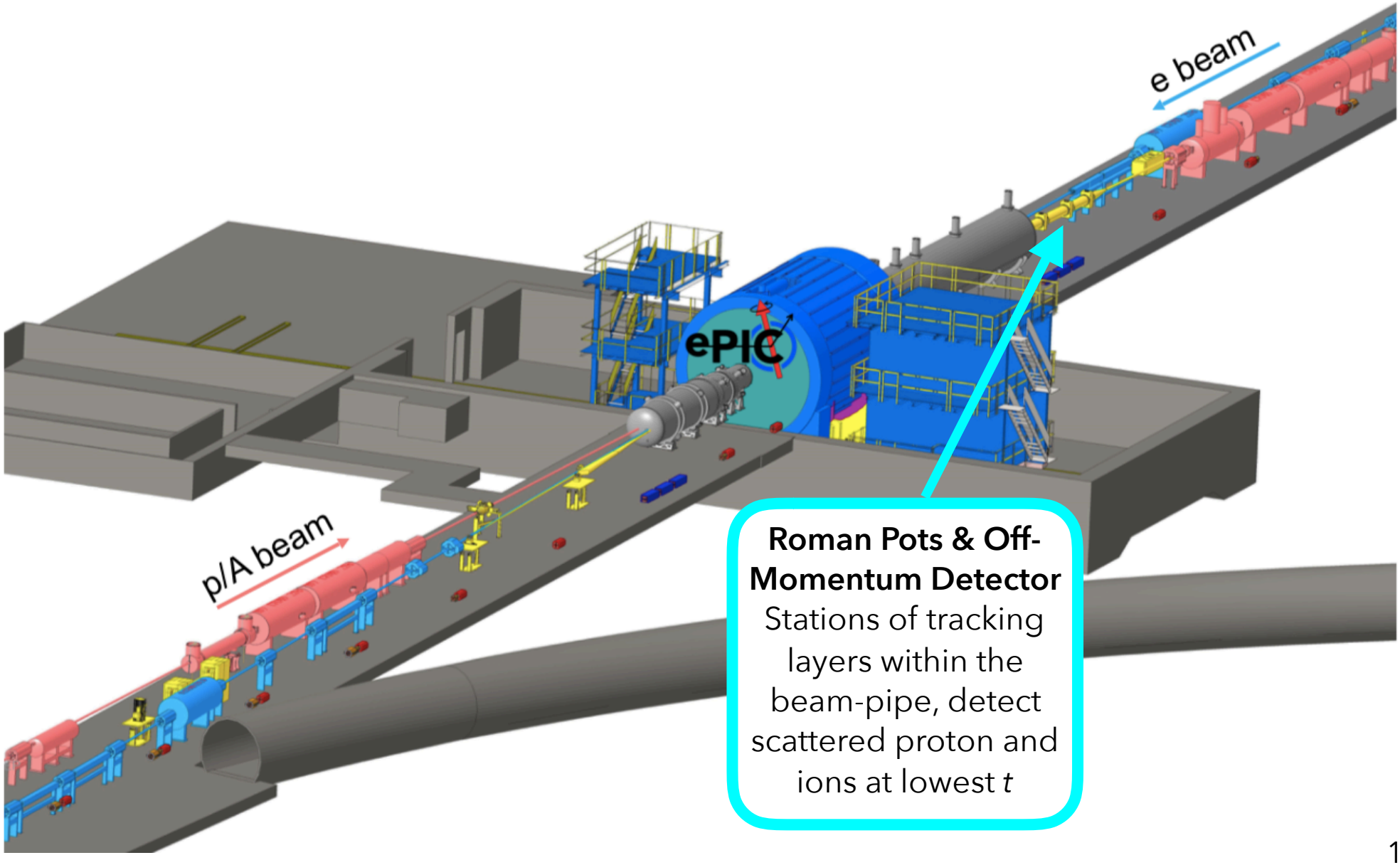
Far-backward detectors



Luminosity Monitor
Measurement of Bethe-Heitler using a pair spectrometer

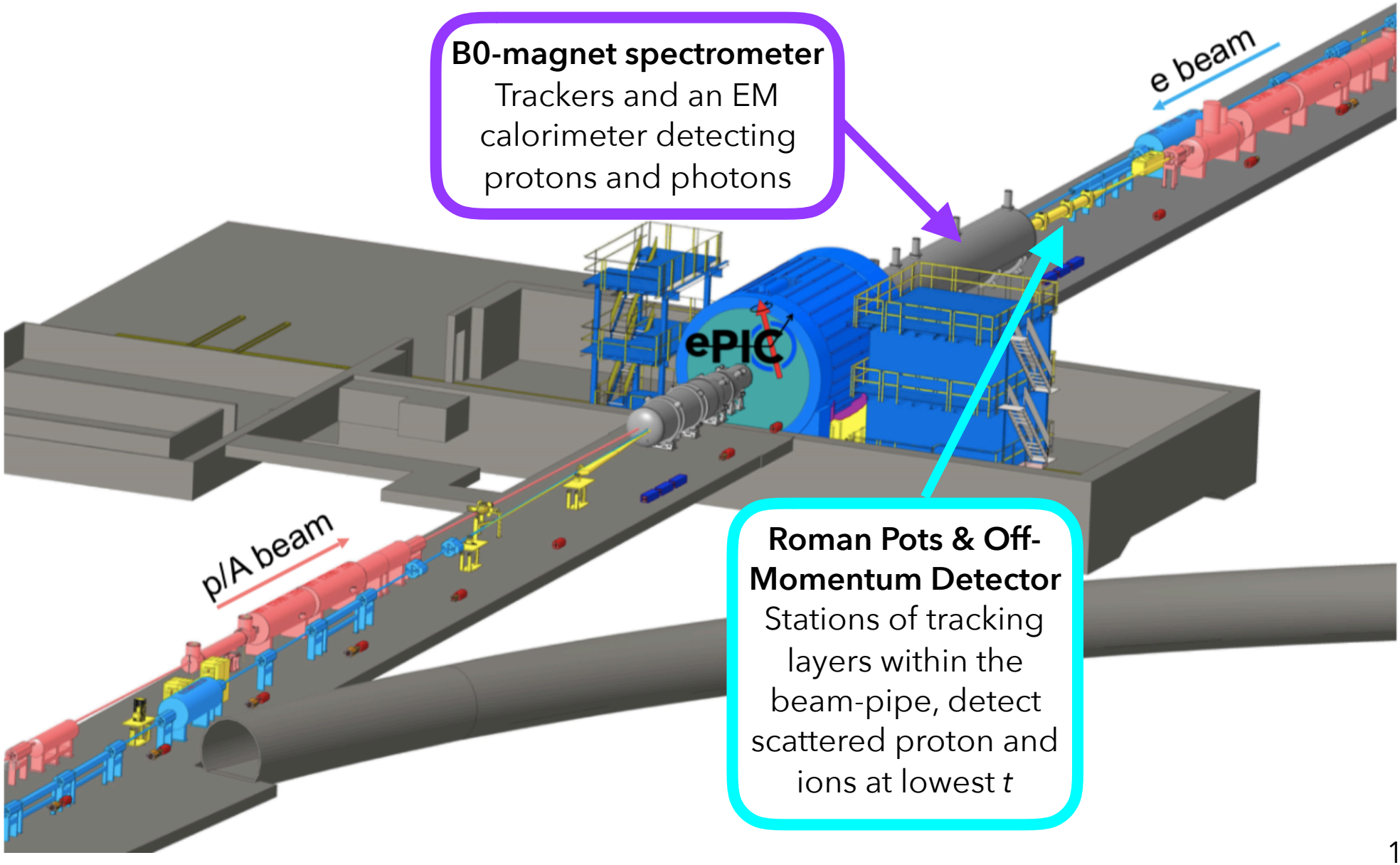
Low-Q^2 taggers
Two stations of tracking layers detect scattered electron

Far-forward detectors



Roman Pots & Off-Momentum Detector
Stations of tracking layers within the beam-pipe, detect scattered proton and ions at lowest *t*

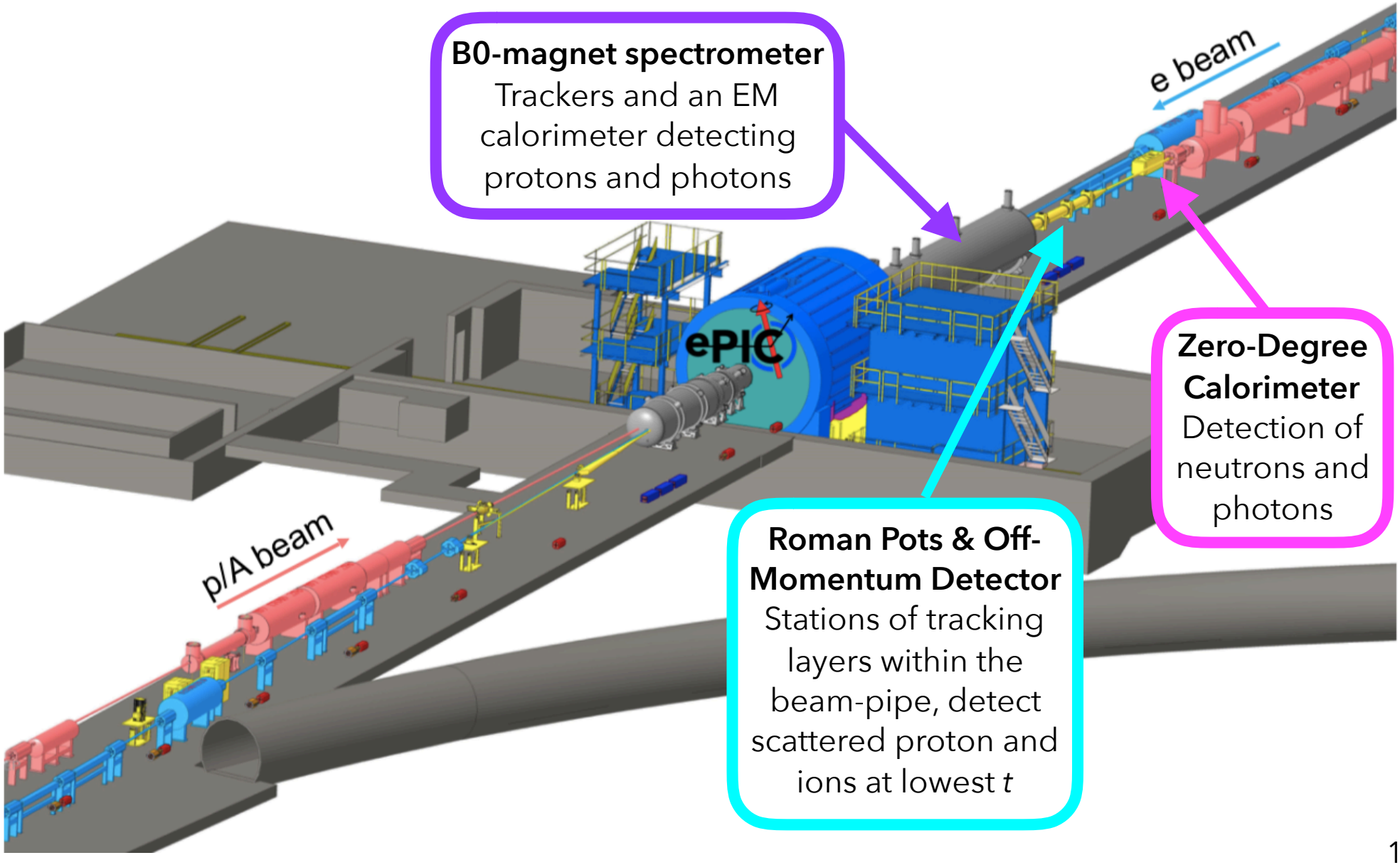
Far-forward detectors



B0-magnet spectrometer
Trackers and an EM calorimeter detecting protons and photons

Roman Pots & Off-Momentum Detector
Stations of tracking layers within the beam-pipe, detect scattered proton and ions at lowest *t*

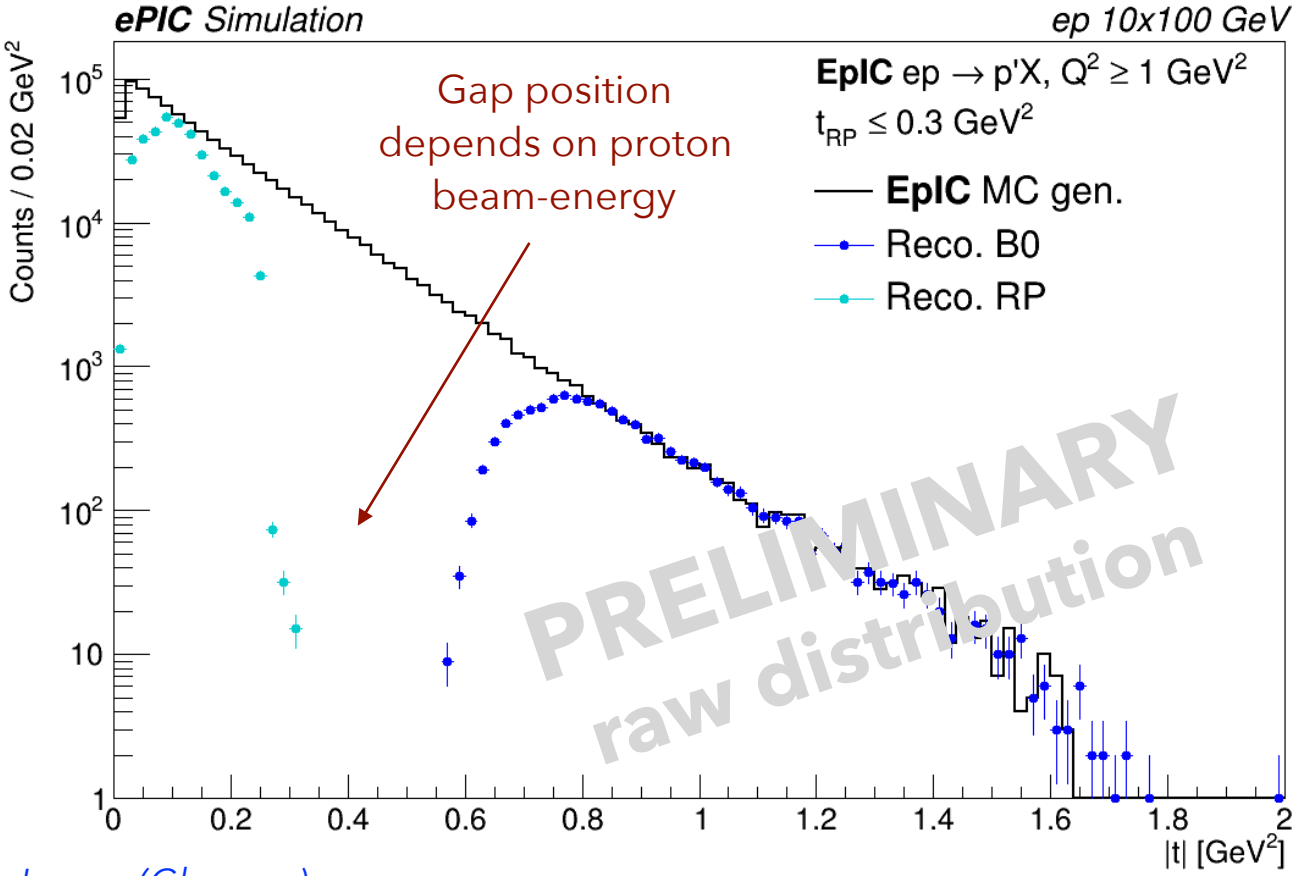
Far-forward detectors



Recoil protons in *ep*

- The impact parameter information in many exclusive processes is encoded in *t*, via a Fourier Transform. Require accurate measurement of *t* from as close to zero as possible and across a wide range in *ep and e(light-A)* collisions.

$$t = (\mathbf{p}' - \mathbf{p})^2$$

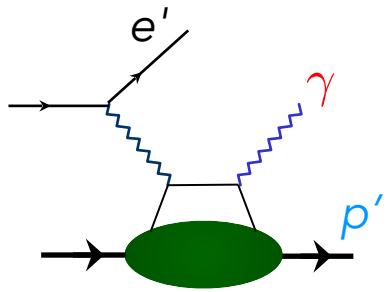


- Scattered protons detected in Roman Pots (for the lowest values of *t*) and in the B0 spectrometer (for higher values).
- Light ions bend less and the *t*-distribution drops faster: detection entirely in the Roman Pots.

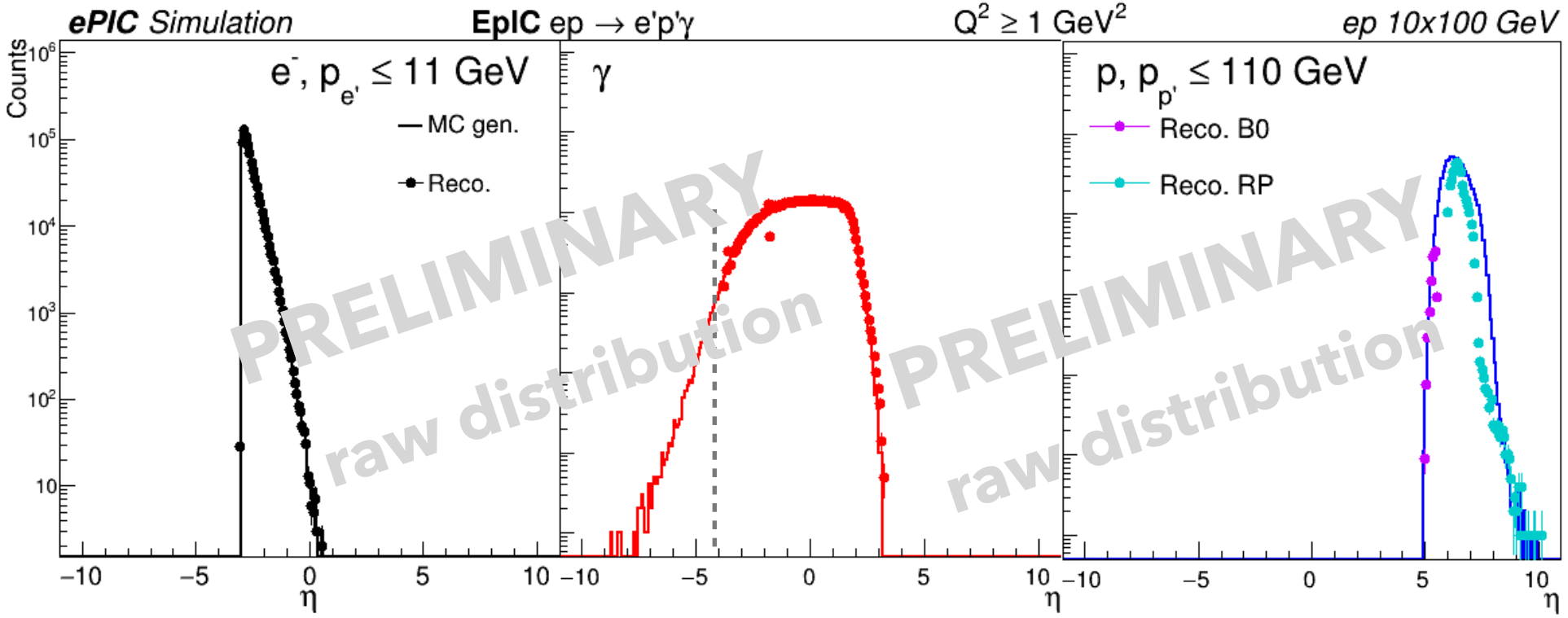
Generator: EpIC
EPJ C **82**, 819 (2022)

O. Jevons (Glasgow)

Reconstructing DVCS



ePIC has excellent acceptance for the scattered electron and proton, good acceptance for the produced photon

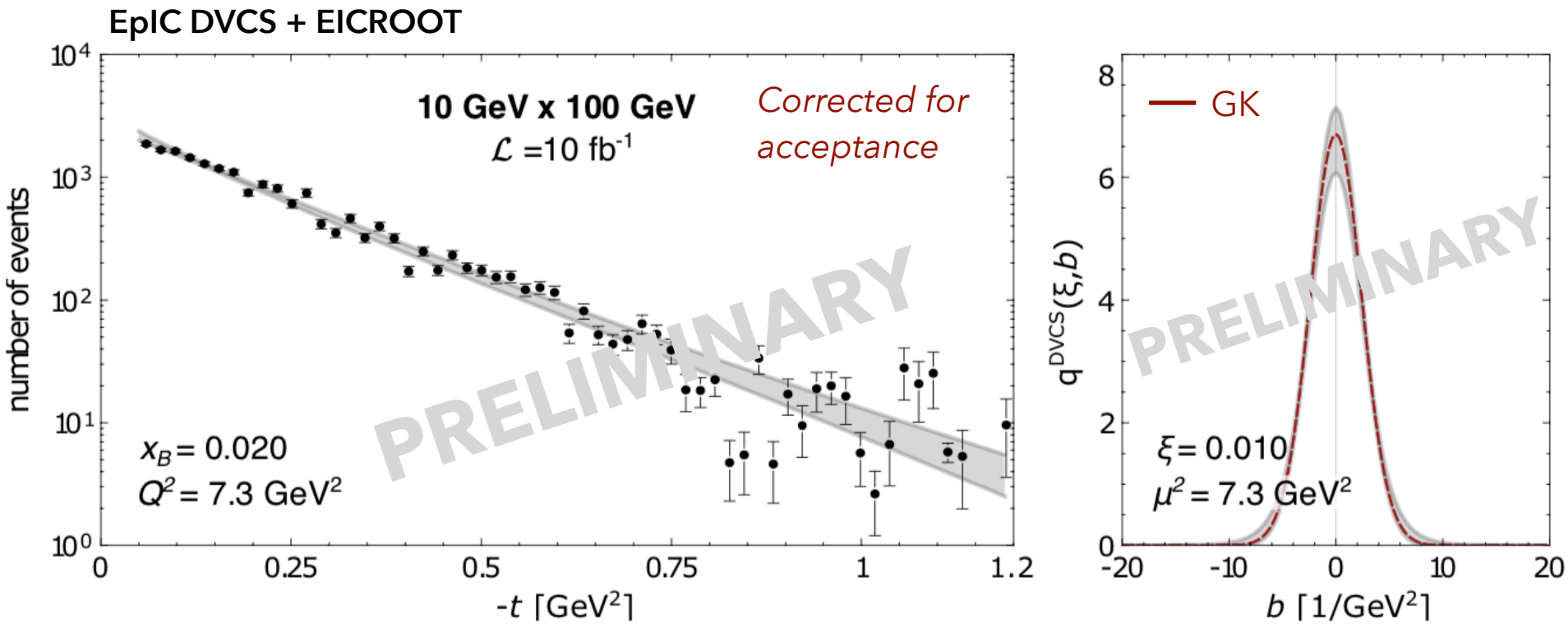


η: pseudorapidity

Generator: EpIC

EPJ C **82**, 819 (2022)

Towards nucleon tomography



Simulation using EpIC MC generator and EICROOT incorporating the ePIC geometry and resolutions

Impact parameter (b) distribution extracted from a Fourier transform of the t-distribution returns the curve of the Goloskokov-Kroll (GK) model used in the EpIC generator

E. Aschenauer, V. Batozskaya, S. Fazio, A. Jentsch, K. Kumerički, H. Moutarde, K. Passek-K., D. S., H. Spiesberger, P. Sznajder, K. Tezgin: on arXiv soon

Imaging light nuclei

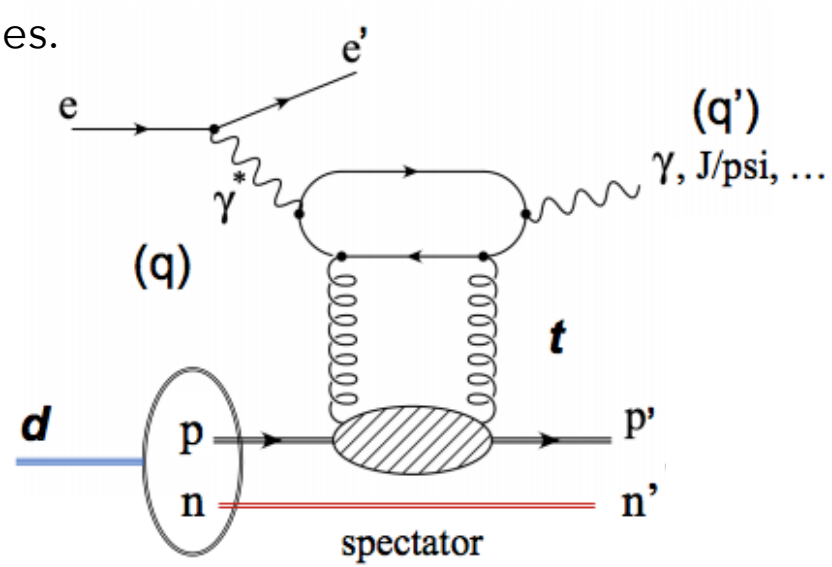
Coherent DVCS on light nuclei requires their intact detection and provides access to nuclear GPDs: imaging of partons in a nuclear medium.

Deuteron: spin-1. Many more GPDs at leading twist – theoretically well-described, experimentally almost untested. Challenge to detect *d* at low-*t*: use veto of deuteron breakup.

^{3}He: spin-1/2. DVCS amplitude has same GPD decomposition as for nucleon, binding energy larger than for deuteron – ideal to look for onset of nuclear effects.
Polarised neutron – possibility for completely new studies.

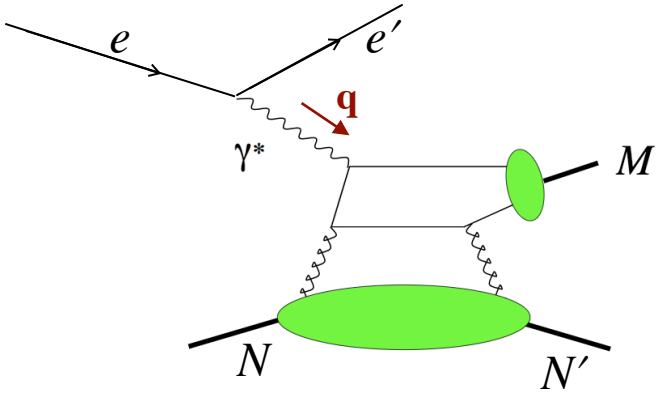
^{4}He: spin-0. Only one leading-twist GPD! Fully bound nucleus – access to medium-modification effects.

Incoherent DVCS (or meson-production): scatter from the nucleon, tag the process by detecting the spectator recoil → access to measurements on a quasi-free neutron.

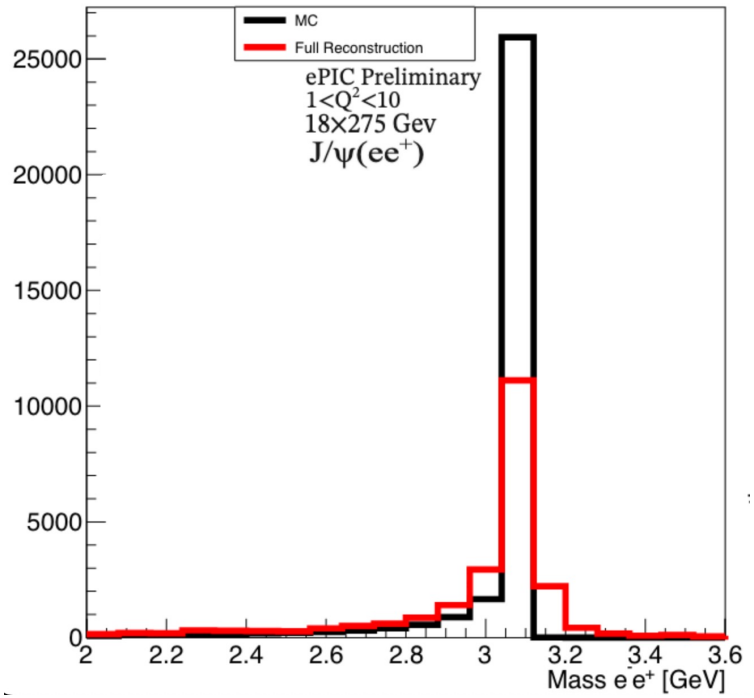


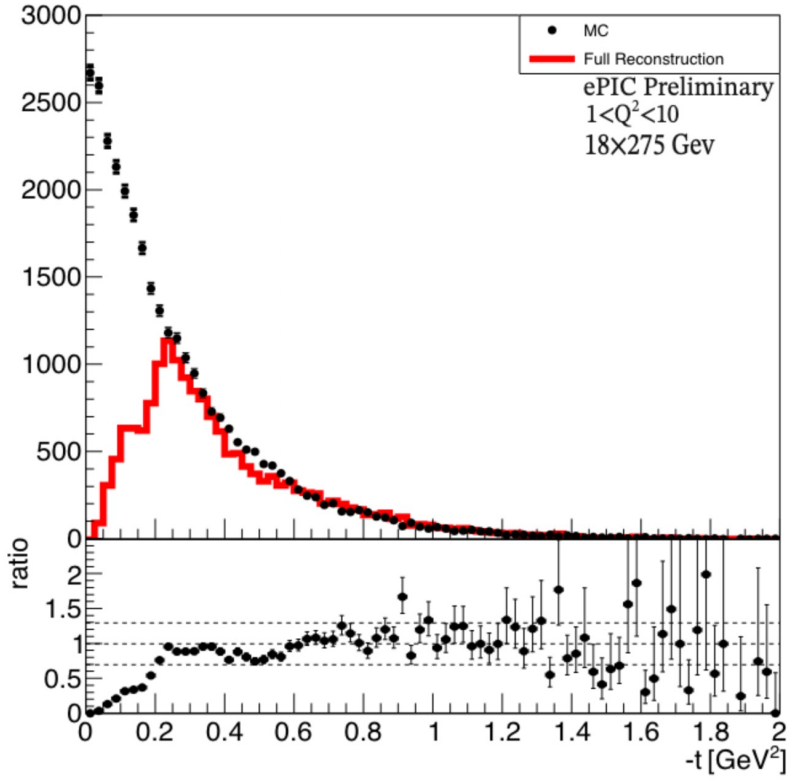
Flavour-decomposition, sensitivity to different GPDs…

Vector-meson production: J/Ψ



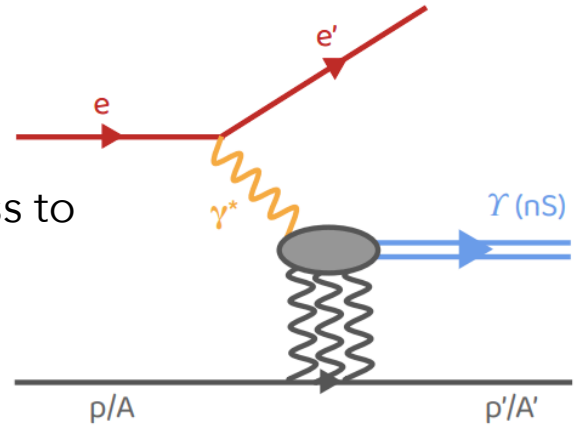
Hard exclusive electro-production of vector mesons gives access to gluon GPDs, particularly clean in heavy mesons: J/Ψ and Υ



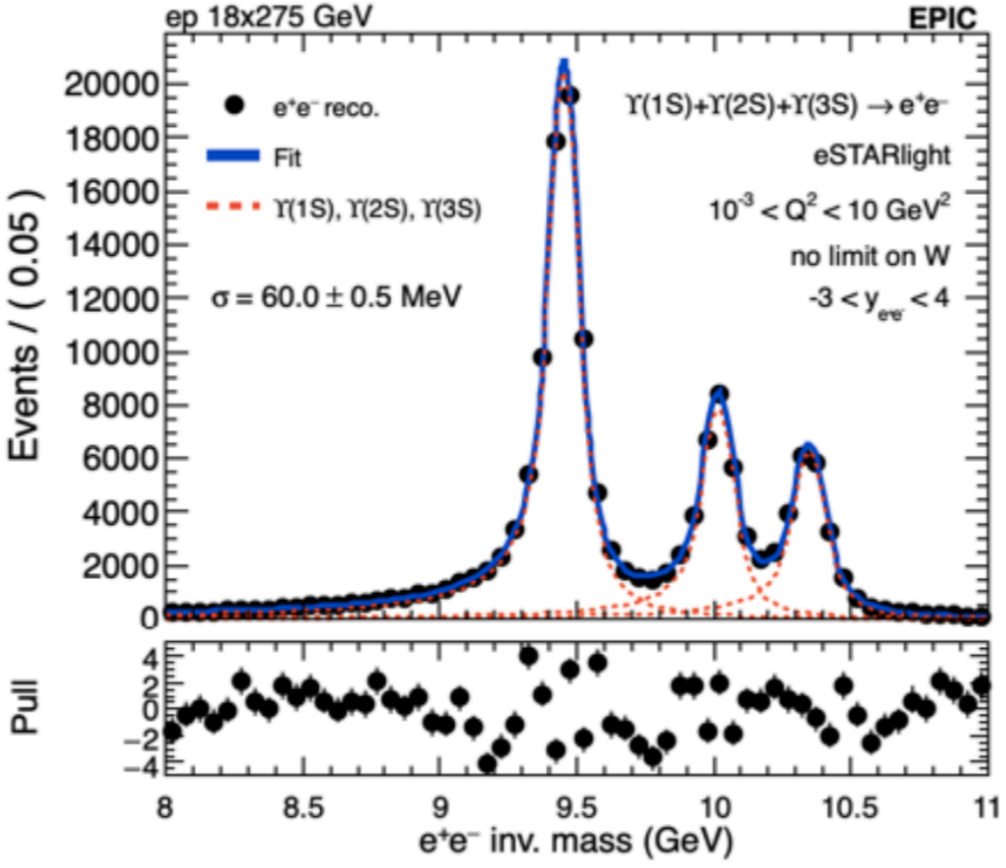


O. Olokunboyo (New Hampshire)

Upsilon-production



Hard exclusive electro-production of vector mesons gives access to gluon GPDs, particularly clean in heavy mesons: J/Ψ and Υ



Additionally:

- Sensitivity to gluon distributions,
- information on colour correlations,
- upsilon-proton scattering lengths,
- possibly saturation.
- Near-threshold production: little-known, twist-4 effects contribute significantly.

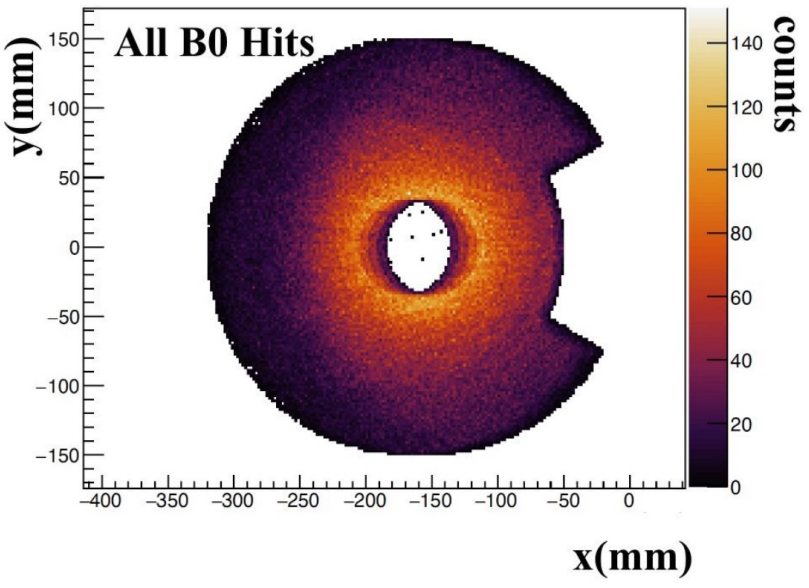
Good separation of the three Υ states through most of the rapidity region.

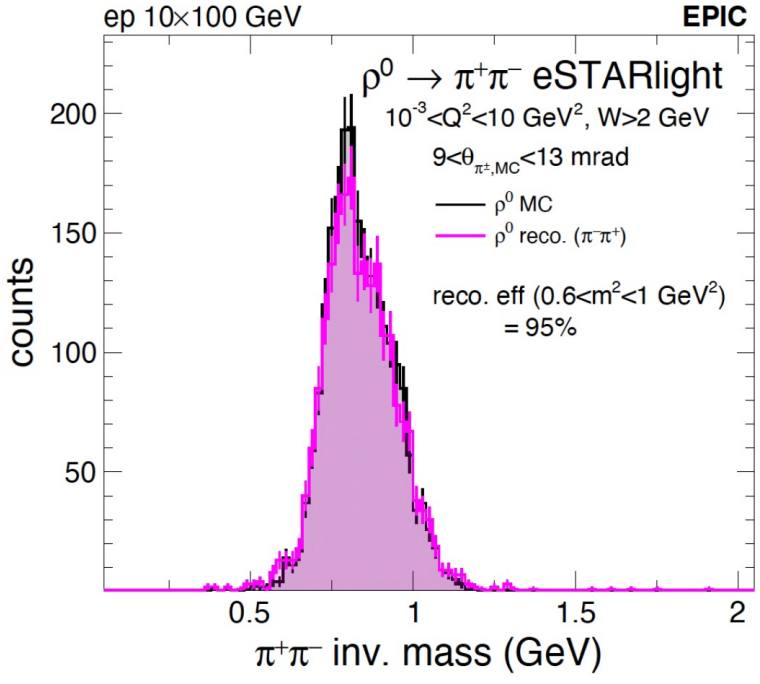
S. Yoo (Davis), M. Kim (Berkeley), S. Klein (Berkeley), D. Cebra (Davis)

Backward production of rho

- Meson photo-production, but proton at mid-rapidity and meson goes forward with high momentum: u-channel.
- Sensitivity to Transition Distribution Amplitudes (TDA), baryon stopping.
- Proton (a few hundred MeV) detected in central detector.
- Charged mesons in the u-channel production reconstructed using Central detector, ZDC and B0 tracker.

$$\rho \rightarrow \pi^+\pi^-$$

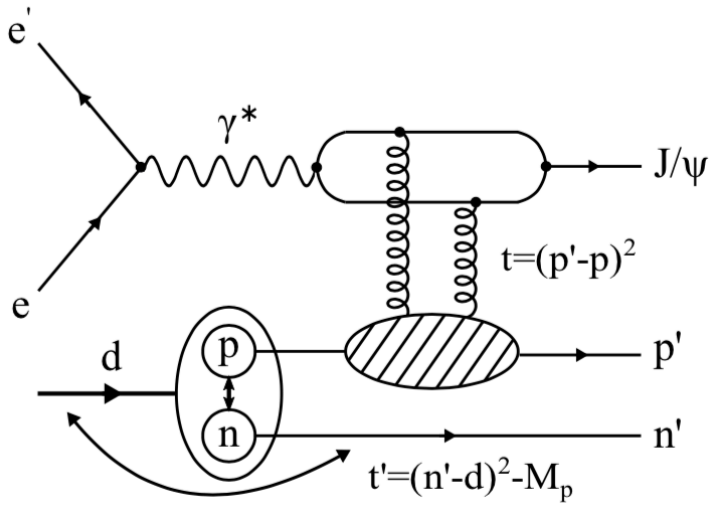




Z. Sweger (UC Davis), S. Klein (Berkeley)

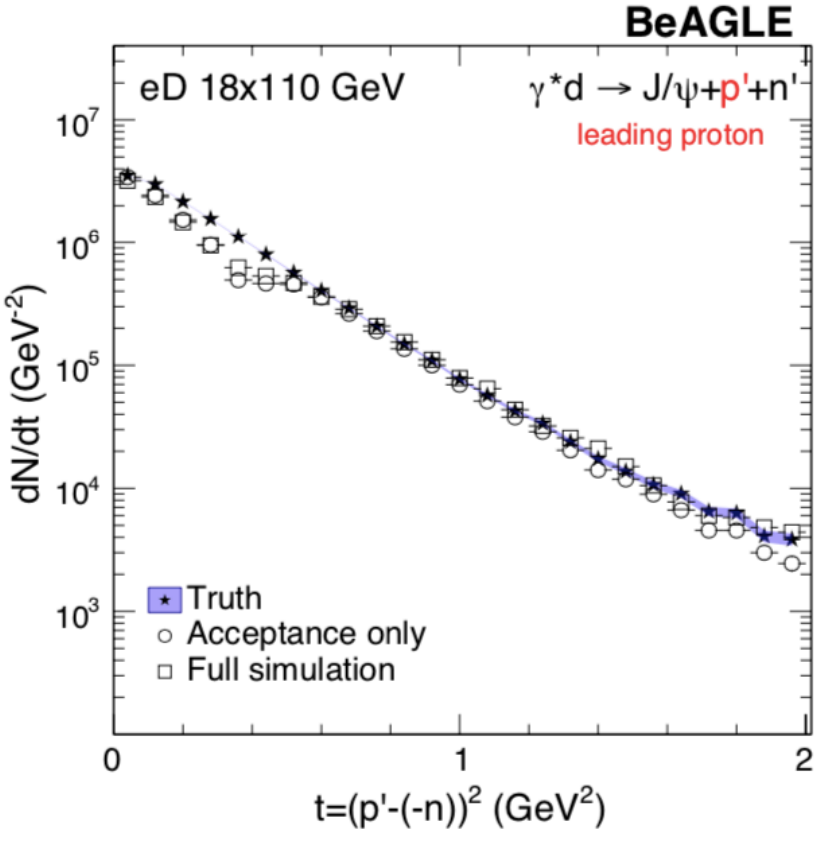
Scattering on bound nucleon

- J/Ψ production off a bound proton in deuterium:



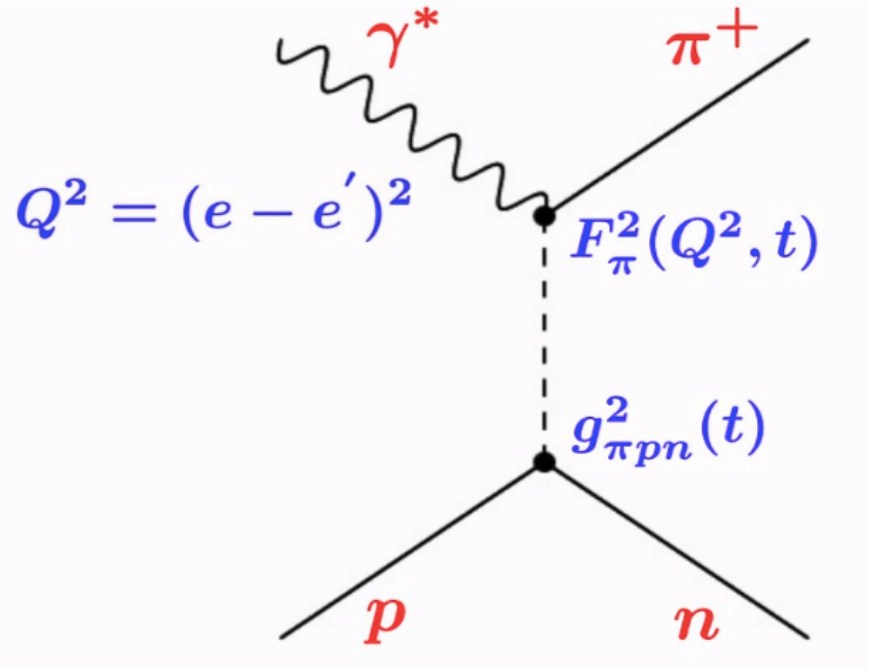
- Tagging of spectator neutron in the ZDC and of the recoil proton in far-forward detectors: control over nuclear configuration.

- Gluon imaging of the nucleon and sensitivity to short-range correlations arising from glue at low *x*.



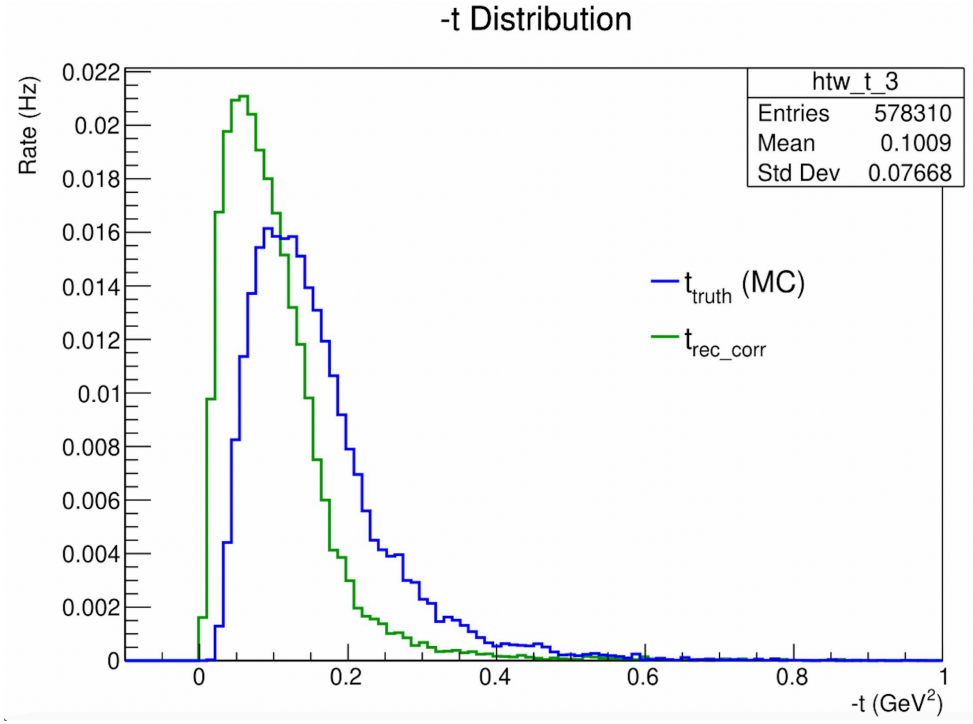
Z. Tu et al., Phys. Lett. B, 811 (2020)

Pion form factors



- Dominance of the pion pole at low *t*:

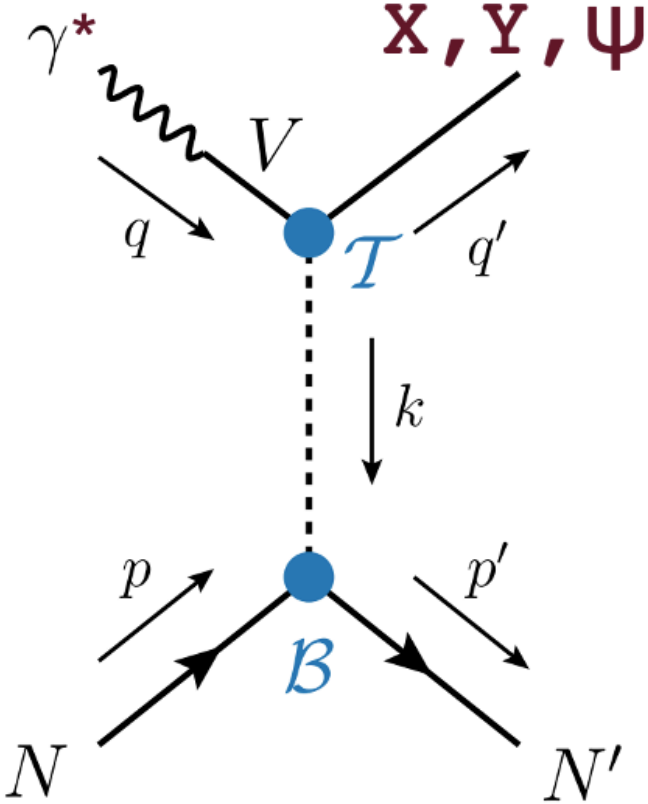
$$\frac{d\sigma_L}{dt} \propto \frac{-tQ^2}{(t-m_\pi^2)^2} g^2_{\pi pn}(t) F_\pi^2(Q^2, t)$$

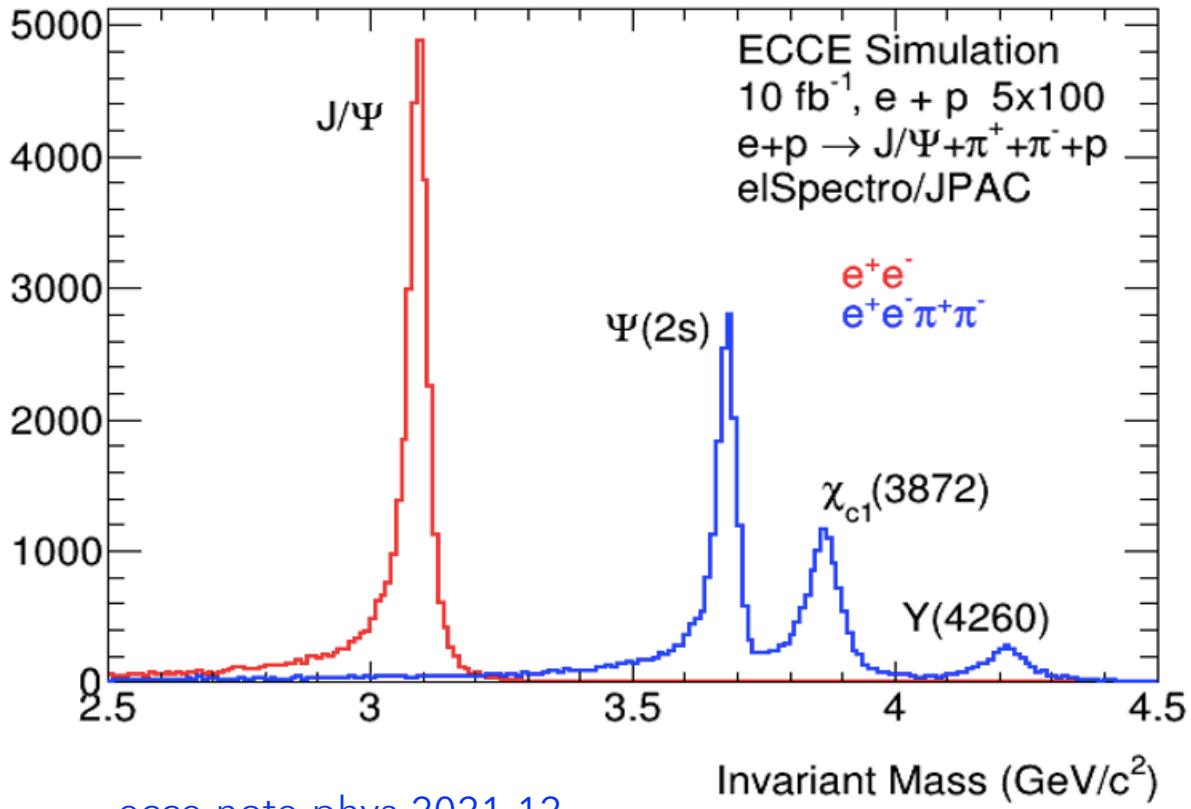


- For exclusive reconstruction, detect neutron in the ZDC and electron and pion in the central detector.

L. Preet, G. Huber, S. Kay (U. of Regina, Canada)

Spectroscopy of XYZ



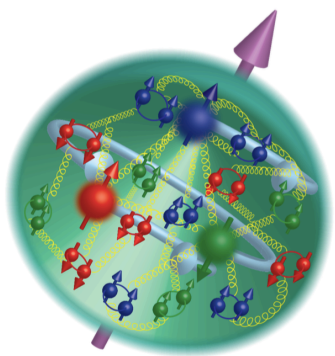


ecce-note-phys-2021-12

Studies of many more processes in progress…

Summary

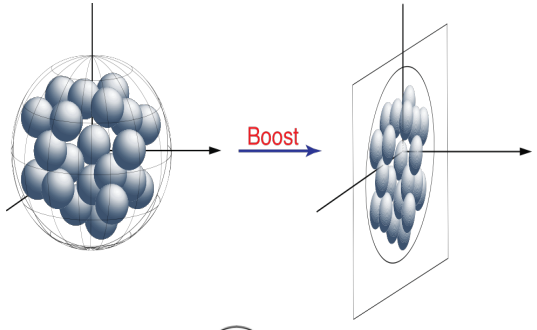
- Large range of CoM energies (30 - 140 GeV), high luminosity ($10^{33\text{-}34}$ $cm^{-2}s^{-1}$): high precision measurements across wide swathes of phase space from the gluon sea to the valence quark region.
- First detector to be placed at interaction point 6: ePIC
- Hermeticity, tracking, PID, neutral particle detection. Focus on the far-forward region – excellent reconstruction of scattered protons and light ions at the smallest angles. Detection of neutral particles at low angles. Detection of scattered electron at lowest angles with low-Q^2 tagger in quasi-real photoproduction.
- A range of exclusive processes accessible with ePIC: sensitivity to a wide variety of physics: nucleon imaging, meson structure, spectroscopy of exotic states, saturation, nuclear modification effects and more…



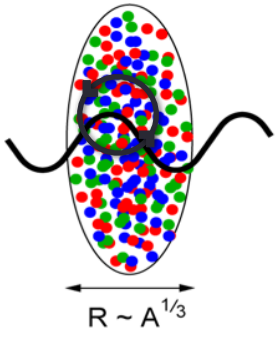

Thank you!
Any questions?


Back-up

Can we reach saturation at EIC?



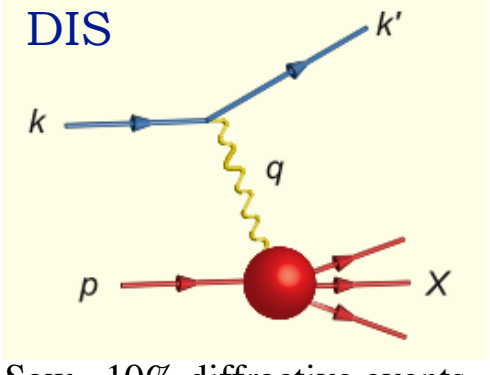
Saturation regime would be accessible at much lower energy in *e-A* collisions than *e-p*. You do not need a TeV collider!



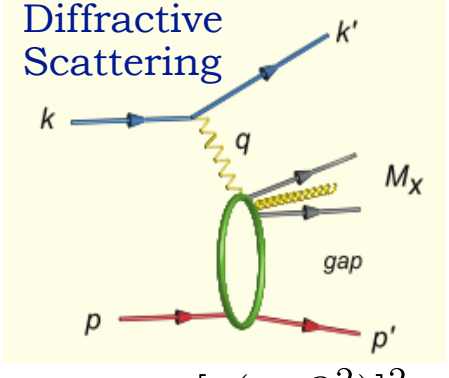
$$(Q_s^A)^2 \approx cQ_0^2 \left[\frac{A}{x}\right]^{1/3}$$

saturation scale

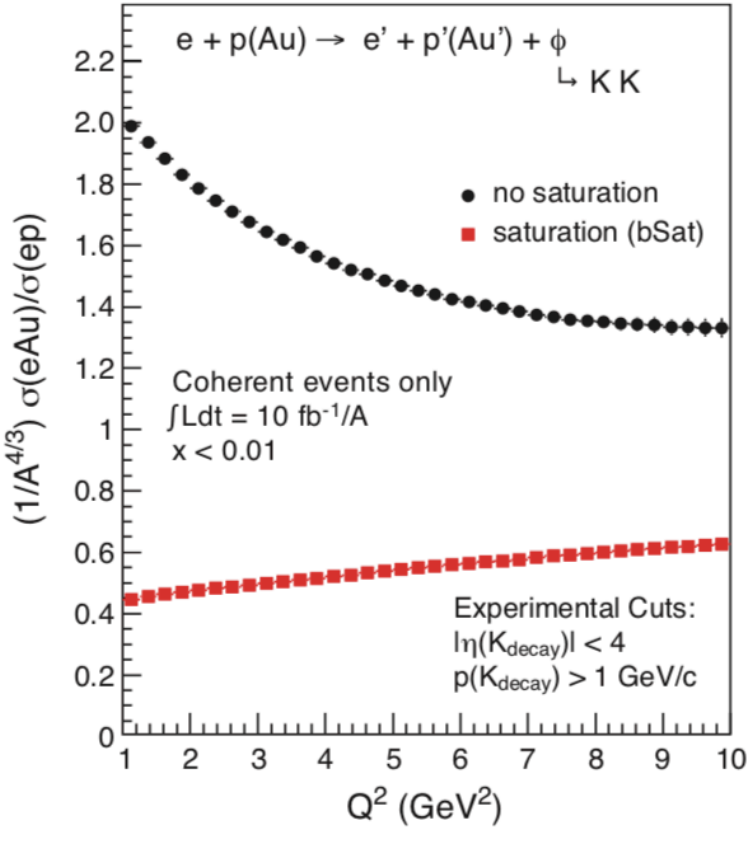
A powerful signature is diffractive cross-sections:



Saw ~10% diffractive events at HERA.



$\sigma_{\text{diff}} \propto [g(x, Q^2)]^2$



EIC White Paper, *Eur. Phy. J. A 52, 9 (2016)*

Electron-Ion Collider

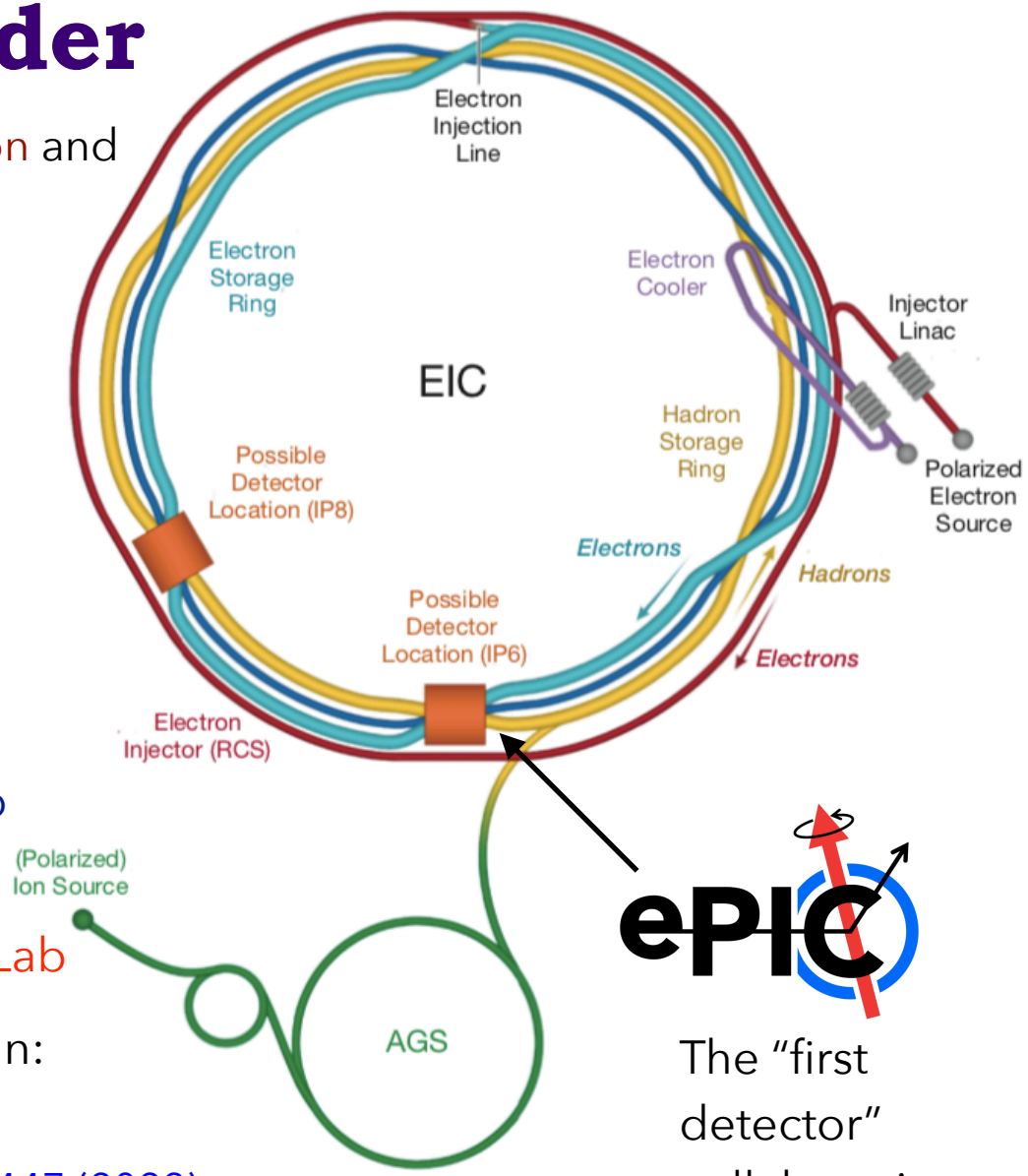
World's first polarized electron-proton/light ion and electron-Nucleus collider.

For e-N collisions at the EIC:

- ✓ Polarized beams: e, p, d/^{3}He
- ✓ e beam 5 - 18 GeV
- ✓ Luminosity $L_{ep} \sim 10^{33\text{-}34}$ cm^{-2}s^{-1}
- ✓ 30 - 140 GeV variable CoM

For e-A collisions at the EIC:

- ✓ Wide range of nuclei
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable centre of mass energy



To be constructed at Brookhaven National Lab

Dedicated studies of EIC physics and design:

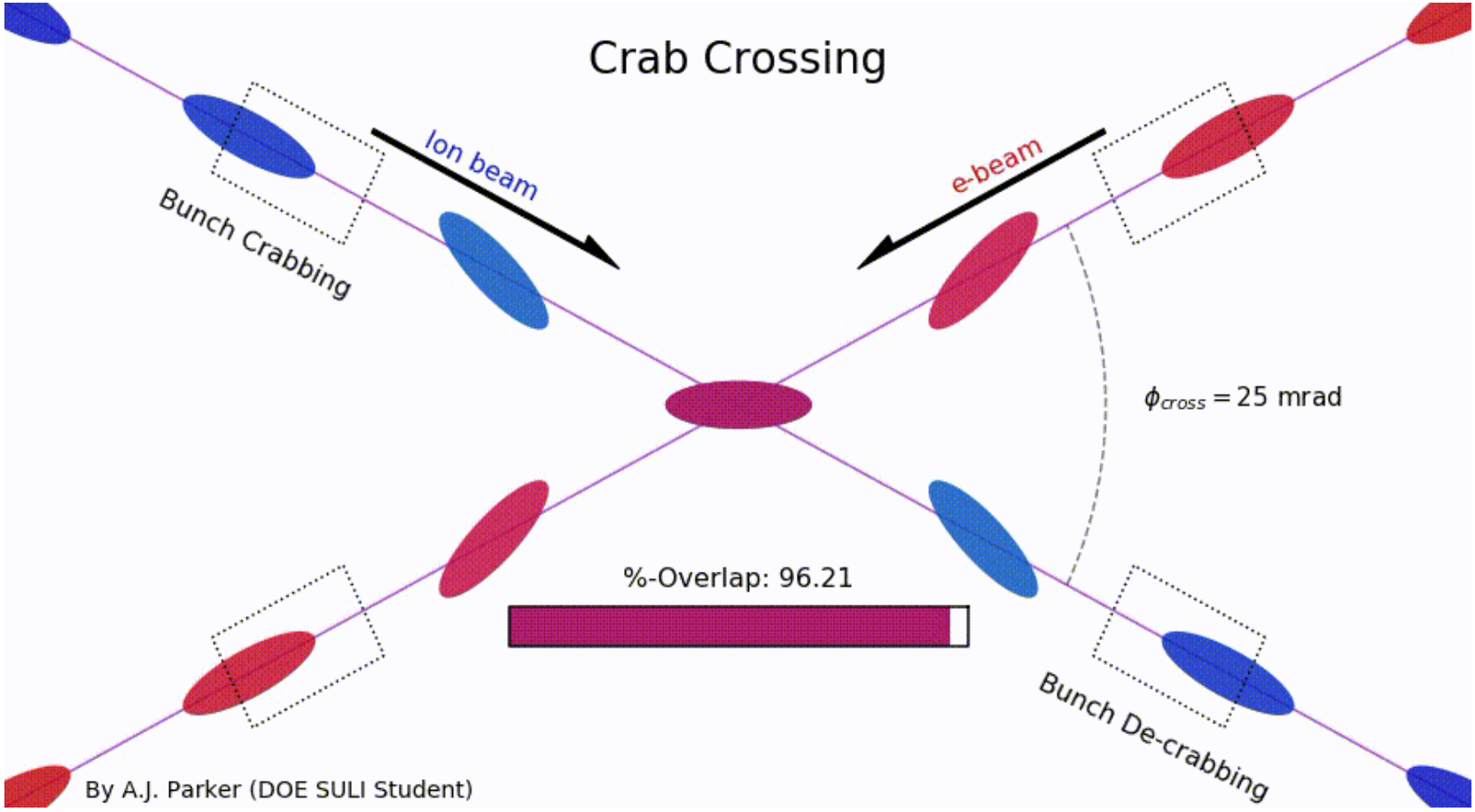
- EIC White Paper, Eur. Phy. J. A 52, 9 (2016)
- EIC Yellow Report, Nuc. Phys. A 1026, 122447 (2022)
- Three proposals for first detector: ATHENA, CORE, ECCE

ePIC

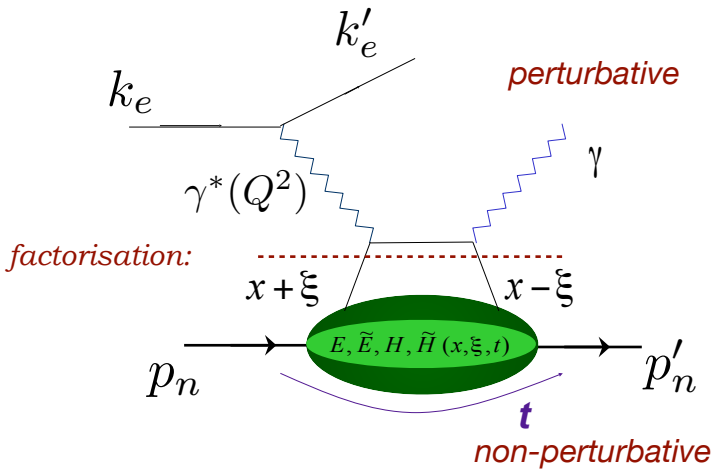
The "first detector" collaboration

Interaction Point

Crab cavities rotate the beam bunches for near-full overlap at the interaction point



Deeply Virtual Compton scattering



"Handbag" diagram

$$Q^2 = -(\mathbf{k} - \mathbf{k}')^2 \qquad t = (\mathbf{p'_n} - \mathbf{p_n})^2$$

$$\textit{Bjorken variable:}\quad x_B = \frac{Q^2}{2\mathbf{p_n}\cdot\mathbf{q}}$$

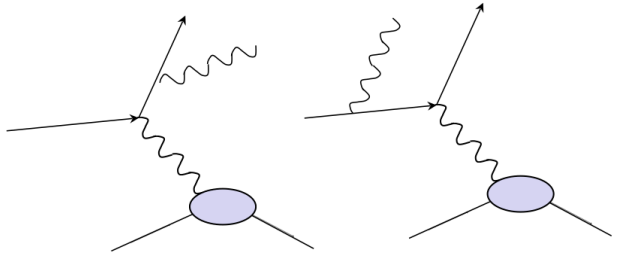
$x \pm \xi$ *longitudinal momentum fractions of the struck parton*

$$\textit{Skewness:}\quad \xi \cong \frac{x_B}{2 - x_B}$$

- At high exchanged Q^2 and low t sensitivity to four parton helicity-conserving, chiral-even GPDs:

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

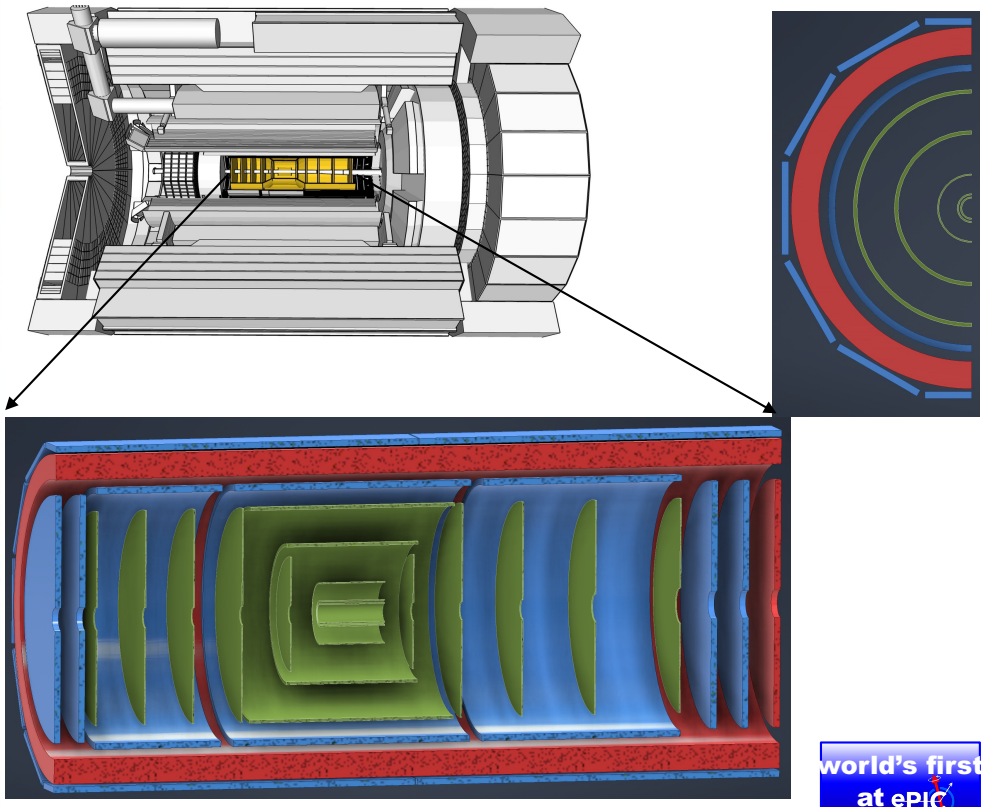
- Experimentally, measure DVCS, Bethe-Heitler and their interference:



$$d\sigma \propto \left|T_{DVCS}\right|^2 + \left|T_{BH}\right|^2 + \quad T_{BH}T^*_{DVCS} + T_{DVCS}T^*_{BH}$$

- Observables are parametrised in terms of Compton Form Factors (CFFs): complex functions where $\mathcal{R}e$ parts are integrals of GPDs over x and $\mathcal{I}m$ parts are GPDs at $x = \pm\xi$

The ePIC Detector: Tracking



- MAPS Barrel + Disks
- MPGD Barrels + Disks
- AC-LGAD based ToF

world's first at ePIC

- **MAPS Tracker:**
  - Small pixels (20 μm), low power consumption (<20 mW/cm^2) and material budget (0.05% to 0.55% X/X_0) per layer
  - Based on ALICE ITS3 development
  - Vertex layers optimized for beam pipe bakeout and ITS-3 sensor size
  - Inner silicon layers will be curved, wafer-scale stitched sensors with a carbon foam support to minimize the material
  - Barrel layers based on EIC LAS development
  - Forward and backwards disks

world's first at ePIC

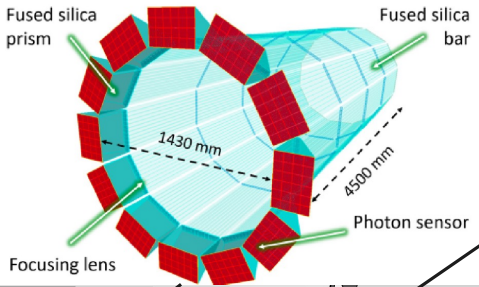
- **MPGD Layers:**
  - Provide timing and pattern recognition redundancy
  - Cylindrical μMEGAs
  - Planar μRWell's before hpDIRC
    - Impact point and direction for ring seeding
- **AC-LGAD TOF and AstroPix (BECAL)**
  - Additional space point for pattern recognition / redundancy

Slide from Alex Jentsch (BNL)

The ePIC Detector: Particle ID

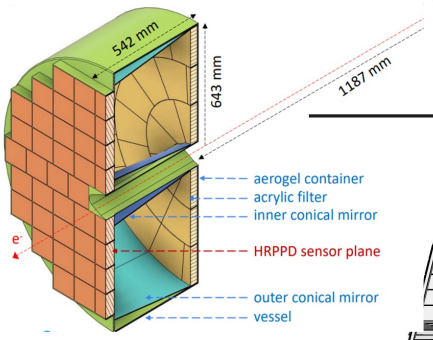
High-Performance DIRC

- Quartz bar radiator (BaBAR bars)
- light detection with MCP-PMTs
- Fully focused
- **π/K 3σ separation at 6 GeV/c**



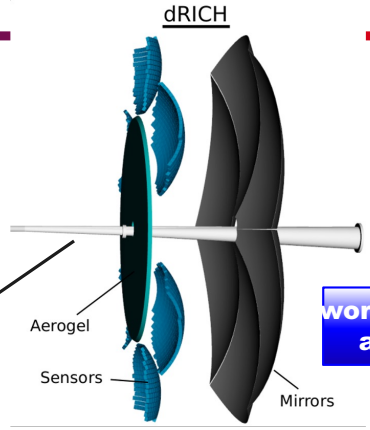
Proximity Focused (pfRICH)

- Long proximity gap (~40 cm)
- Sensor: HRPPDs
- **up to 9 GeV/c 3σ π/K sep.**



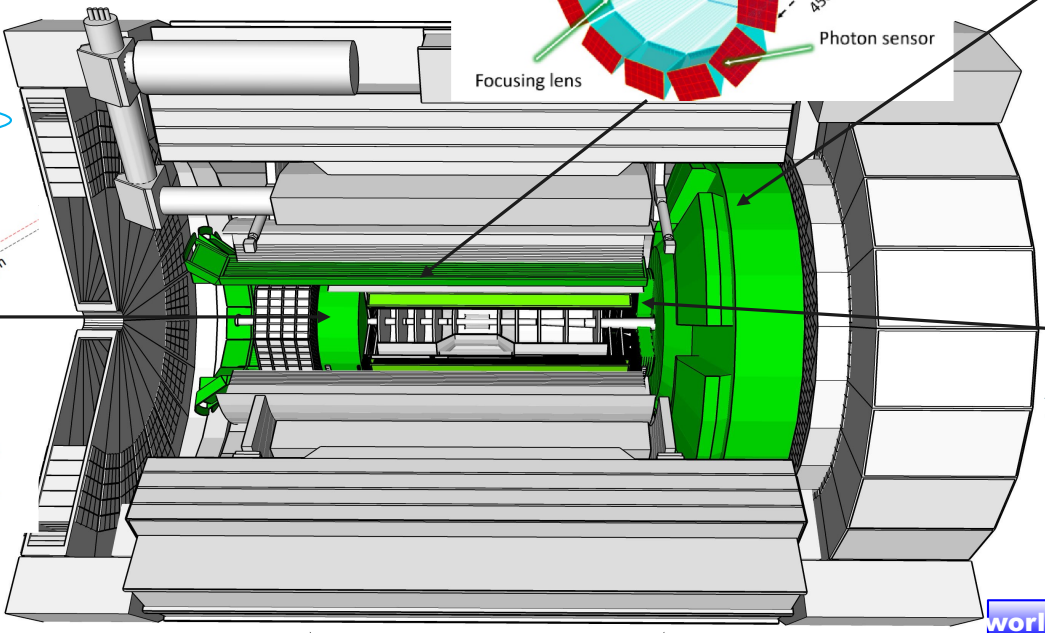
world's first at ePIC

Dual-Radiator RICH(dRICH)

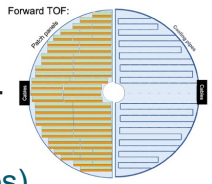


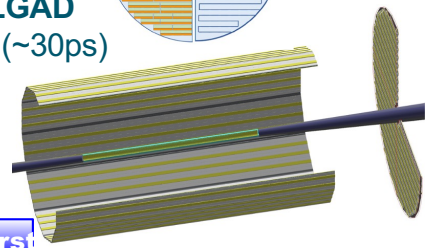
world's first at ePIC

- C_2F_6 Gas Volume and Aerogel
- Sensors tiled on spheres (SiPMs)
- **π/K 3σ sep. at 50 GeV/c**



AC-LGAD TOF (~30ps)



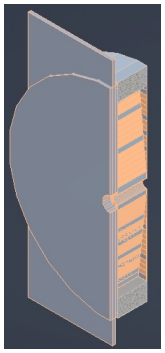


world's first at ePIC

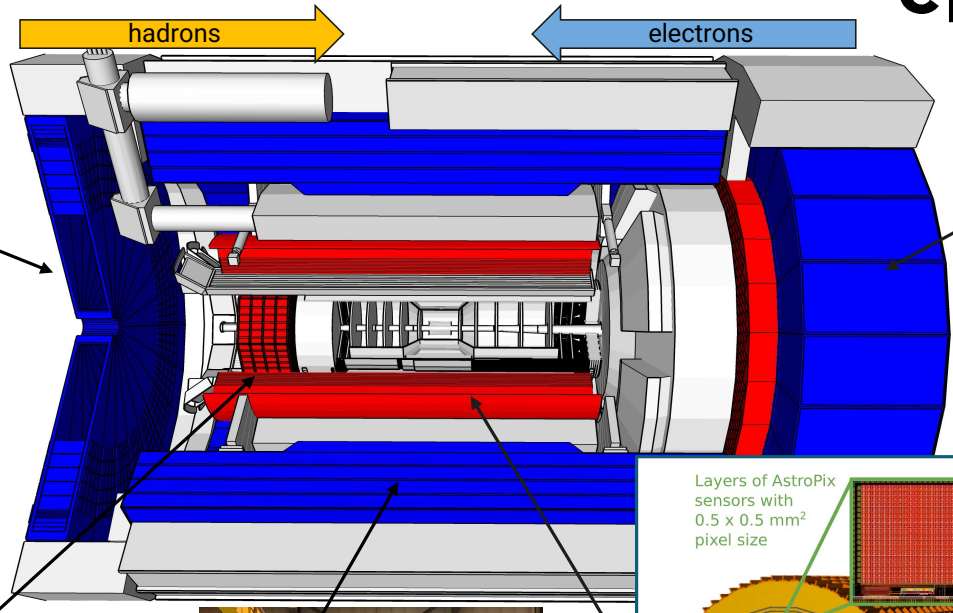
- Accurate space point for tracking
- forward disk and central barrel

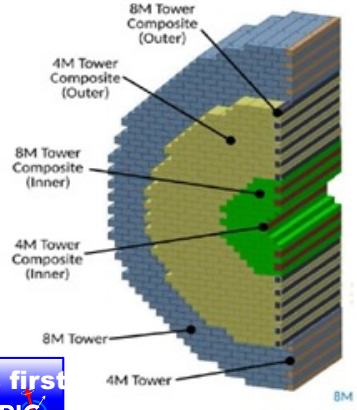
Slide from Alex Jentsch (BNL)

The ePIC Detector: Calorimetry



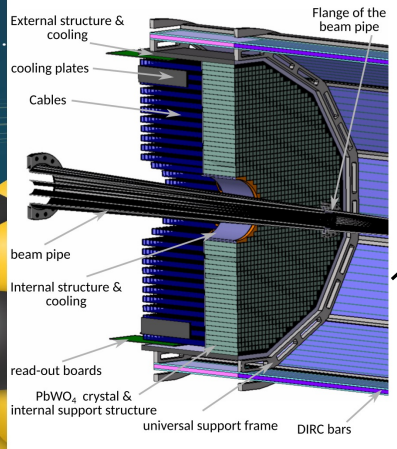
Backwards HCal Steel/Sc Sandwich tail catcher





world's first at ePIC

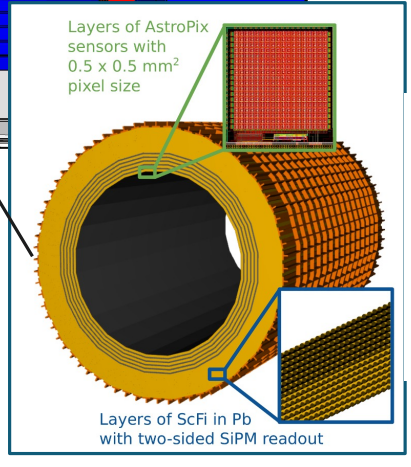
High granularity W/SciFi EMCal Longitudinally separated HCAL with high-η insert

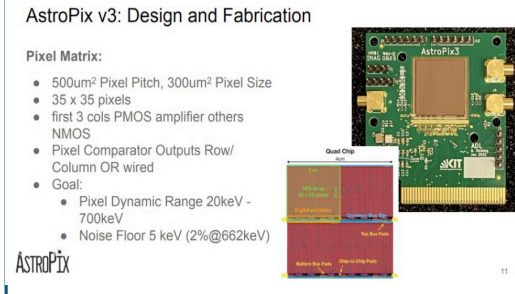


Backwards EMCal PbW04 crystals, SiPM photosensor



Barrel HCAL (sPHENIX re-use)





world's first at ePIC

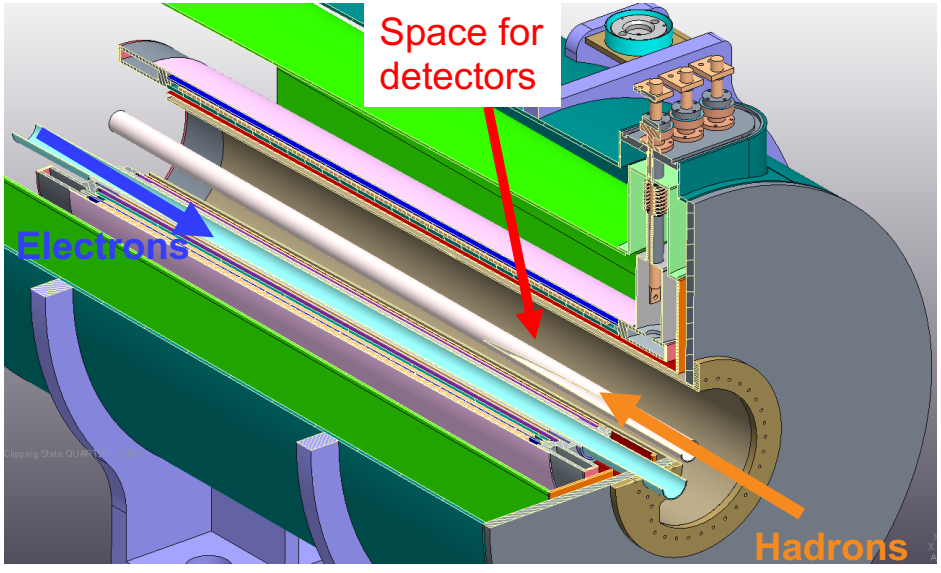
Higher EMCAL resolution

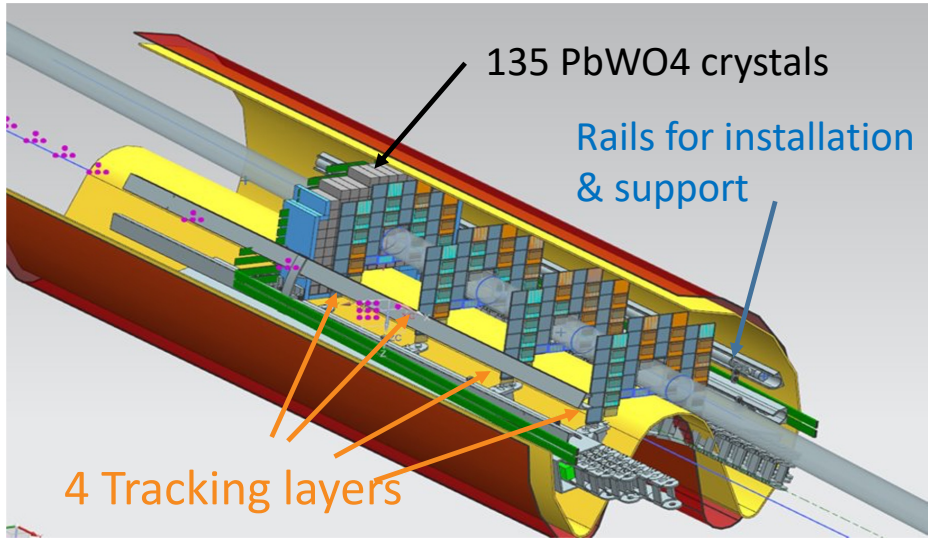
Higher HCAL resolution

Slide from Alex Jentsch (BNL)

B0 Detector(s)

- Detector subsystem(s) embedded in an accelerator magnet.

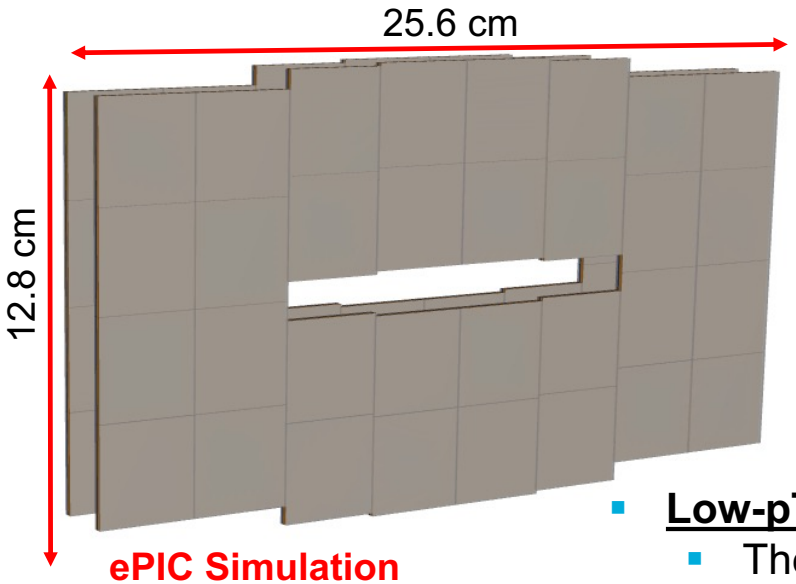




- **Two detectors**:
  - AC-LGAD based silicon tracking detector.
  - PbWO4 EM calorimeter
- Primary challenges are related to integration with the machine (detector fully embedded in machine dipole magnet) and achieving required performance of tracking detector.

Slide from Alex Jentsch (BNL)

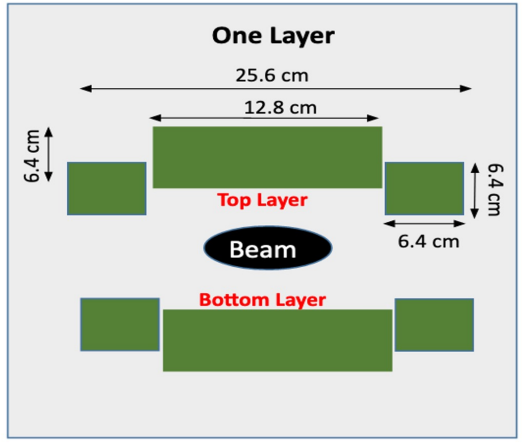
Roman Pots @ the EIC



ePIC Simulation

$\sigma(z)$ is the Gaussian width of the beam, $\beta(z)$ is the RMS transverse beam size. ε is the beam emittance.

$$\sigma(z) \sim \sqrt{\varepsilon \cdot \beta(z)}$$



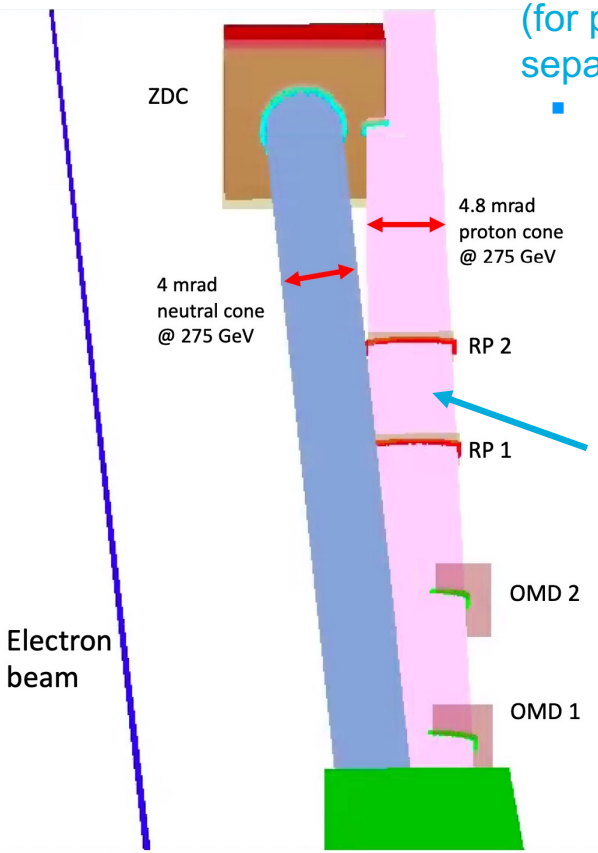
- **Low-pT cutoff determined by beam optics.**
  - The safe distance is ~10σ from the beam center (1σ ~ 1mm).
- **Optics change with energy**
  - Can also be changed within a single energy to maximize *either acceptance at the RP, or the luminosity*.
- AC-LGADs are the chosen technology to deliver needed spatial and timing resolution.

- **Detectors need to be able to move to different positions for different optics configurations.**

Slide from Alex Jentsch (BNL)

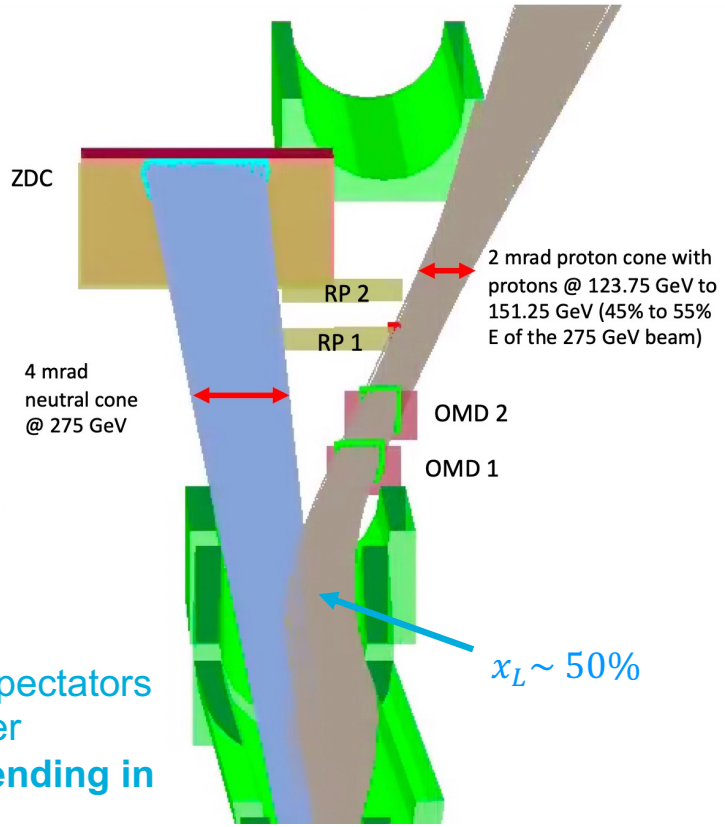
Off-Momentum Detectors (OMD)

- Neutral particle cone and proton cone (for protons with p ~ beam momentum) separate around 30m from the IP.
  - Roman pots placed in this region.



$$\textit{longitudinal momentum fraction}\quad x_L = \frac{p_{z,proton}}{p_{z,beam}}$$

$x_L \gtrsim 65\%$



$x_L \sim 50\%$

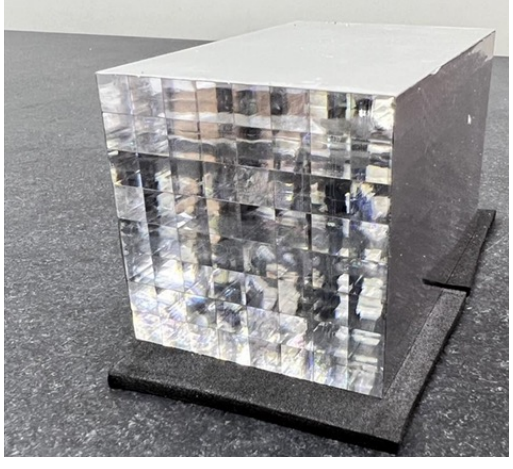
- Off-momentum protons (e.g. spectators in deuteron breakup) → smaller magnetic rigidity → **greater bending in dipole fields.**

Crucial for the entire light-nuclei program (e.g. deuterons, He-3)!

Slide from Alex Jentsch (BNL)

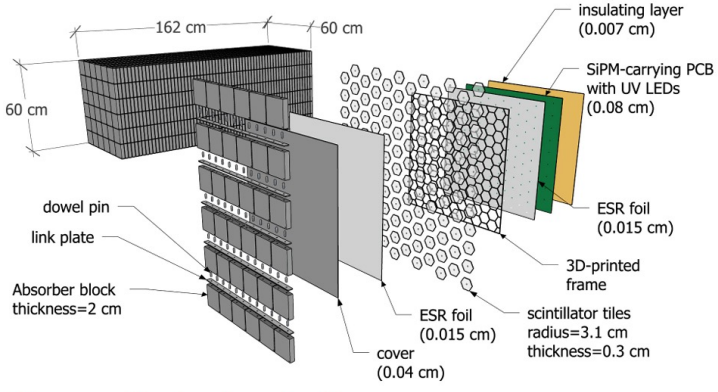
Zero-Degree Calorimeter

EM Calorimeter – LYSO or PbWO4



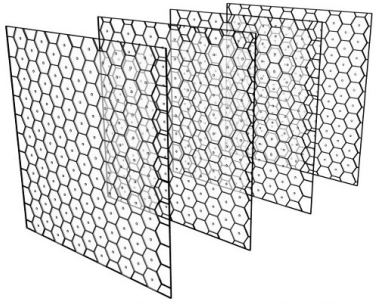
LYSO crystal array with
2x2x7cm crystals.

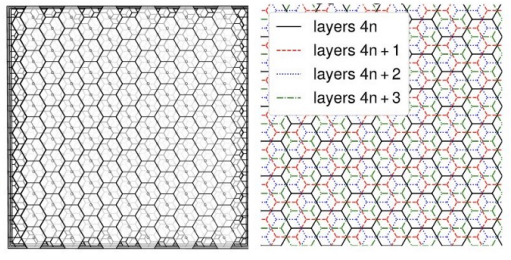
Hadronic Calorimeter – SiPM-on-Tile



Staggered design described in
"Leveraging staggered tessellation for enhanced spatial resolution in high-granularity calorimeters" NIMA 1060 (2024) 169044

ZDC

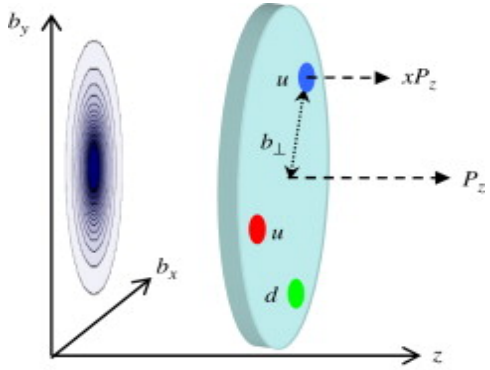


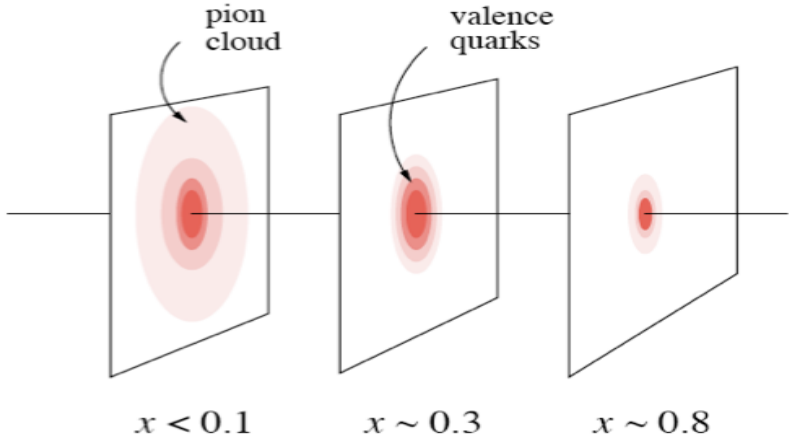


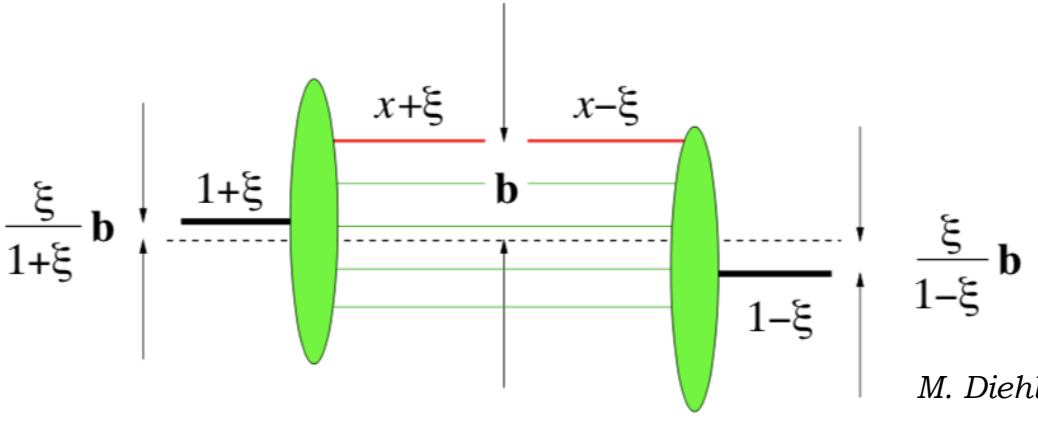
Slide from Alex Jentsch (BNL)

Nucleon Tomography from GPDs

At a fixed Q^2, x_B and ξ=0 slope of GPD with t is related, via a Fourier Transform, to the transverse spatial distribution.







M. Diehl

Formally, the radial separation, **b**, *between the struck parton and the centre of momentum of the remaining spectators.*

Experimentally, can fit the t-dependence of structure functions (from meson-production) or Compton Form Factors (from DVCS/TCS) with an exponential:

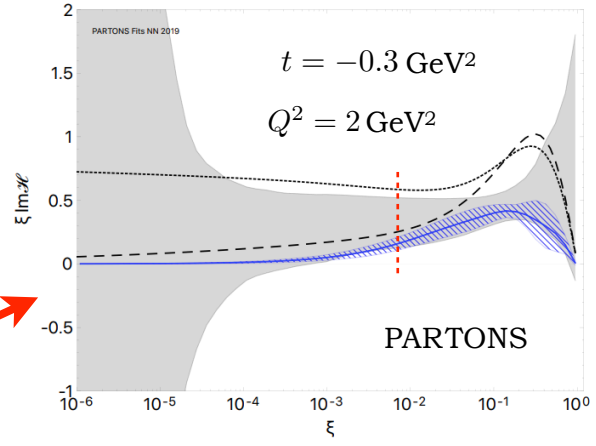
$$eg: \quad \frac{d\sigma_U}{dt} = Ae^{Bt}$$

Towards nucleon tomography

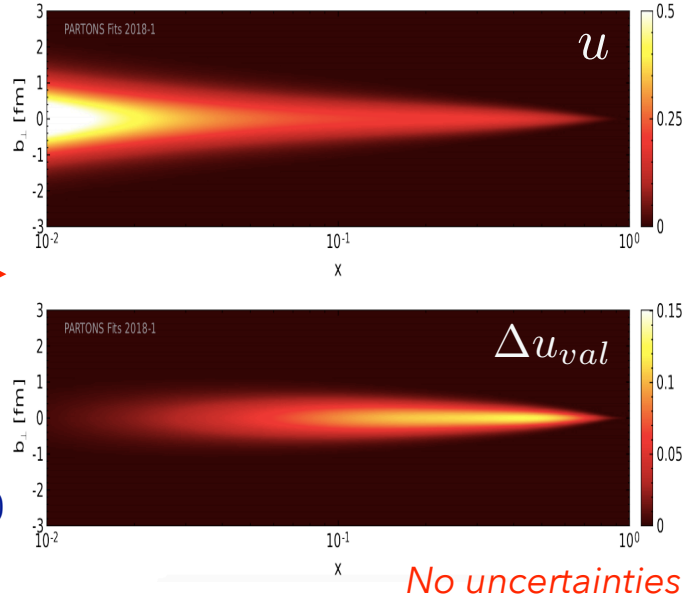
Ongoing imaging efforts on available world-data, strongest constraints in the valence region:

Uncertainties in the extraction of CFFs translate into uncertainties in spatial distributions.

PARTONS global fit with neural networks to minimise model-dependence in the extraction of CFFs.



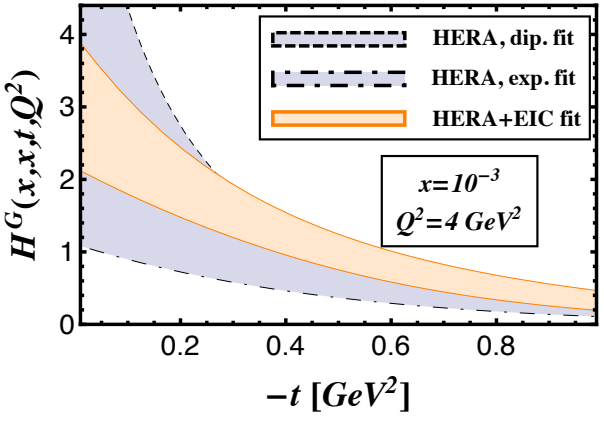
H. Moutarde *et al.*, Eur. Phys. J C79, 614 (2019)



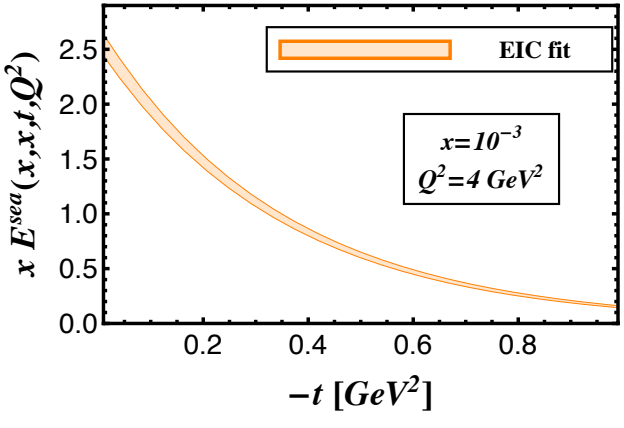
No uncertainties shown

Anticipated constraints from EIC on GPDs H and E:

GPD H for gluons



GPD E for sea quarks



Measurements at EIC will provide significant constraints at low-*x* and enable extraction of as-yet unknown GPDs.

https://arxiv.org/abs/2103.05419

Spin and pressure in the nucleon

- GPDs also provide indirect access to mechanical properties of the nucleon (encoded in the gravitational form factors, GFFs, of the energy-momentum tensor).

  X. D. Ji, PR**D 55**, 7114-7125 (1997)
  M. Polyakov, PL**B 555**, 57-62 (2016)

- Three scalar GFFs, functions of *t*: encode pressure and shear forces ($d_1(t)$), mass ($M_2(t)$) and angular momentum distributions ($J(t)$).

- Can be related to GPDs via sum rules: $\int x\,[H(x,\xi,t)+E(x,\xi,t)]\,\mathrm{d}x = 2J(t)$

$$\int xH(x,\xi,t)\mathrm{d}x = M_2(t) + \frac{4}{5}\xi^2 d_1(t)$$

(Ji's relation)

$$J_N = \frac{1}{2} = \frac{1}{2}\Sigma_q + L_q + J_g$$

- $d_1(t)$ (D-term) "last unknown global property of the nucleon" – can be accessed via the $\mathcal{R}e$ and $\mathcal{I}m\ \mathcal{H}$:

Dispersion relation: $\mathrm{Re}\mathcal{H}(\xi,t) = \int_{-1}^{1}\left(\frac{1}{\xi-x}-\frac{1}{\xi+x}\right)\mathrm{Im}\mathcal{H}(\xi,t)\ dx + \Delta(t).$

Assuming double-distribution parametrisation: $\Delta(t) \propto d_1(t)$

Spin and pressure

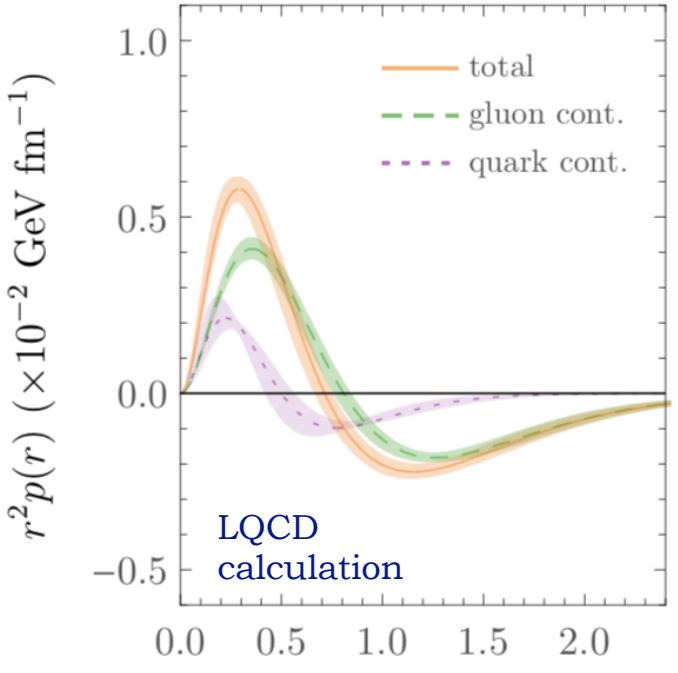
- GPDs provide indirect access to mechanical properties of the nucleon (encoded in the gravitational form factors, GFFs, of the energy-momentum tensor).

X. D. Ji, PR**D 55**, 7114-7125 (1997) M. Polyakov, PL**B 555**, 57-62 (2003)

- Four GFFs, functions of *t*, of which three are related to moments of GPDs: they encode pressure and shear forces ($d_1(t)$), mass ($M_2(t)$) and angular momentum distributions ($J(t)$):

$$\int x\,[H(x,\xi,t)+E(x,\xi,t)]\,\mathrm{d}x = 2J(t)$$

$$\int xH(x,\xi,t)\mathrm{d}x = M_2(t)+\frac{4}{5}\xi^2 d_1(t)$$

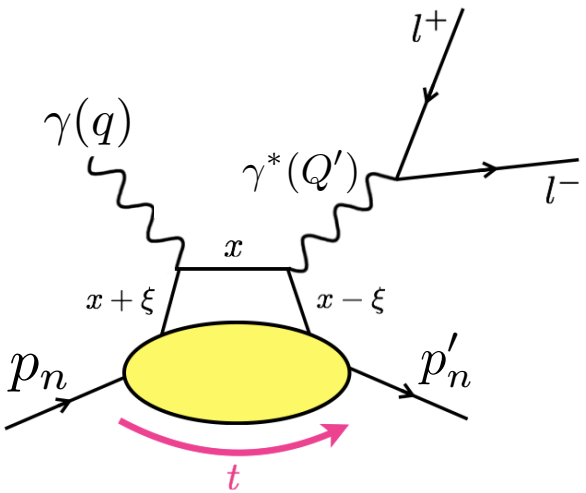


- The D-term: "last unknown global property of the nucleon" -- can be related to spatial distribution of shear forces and pressure within the nucleon.

- Possibilities of "imaging" spatial distributions of angular momentum: C. Lorcé, M. Montovani, B. Pasquini, PL**B 776**, 38-47 (2018)

P. Shanahan, W. Detmold, PRL 122,072003 (2019)

Timelike Compton Scattering



- Time-reversal process of DVCS: parametrised in terms of same Compton Form Factors (their complex conjugates).
  - Verification of GPD universality.
  - Another route to access the D-term.

$$Q' = l^+ + l^- \qquad \xi = \frac{\tau}{2-\tau}$$

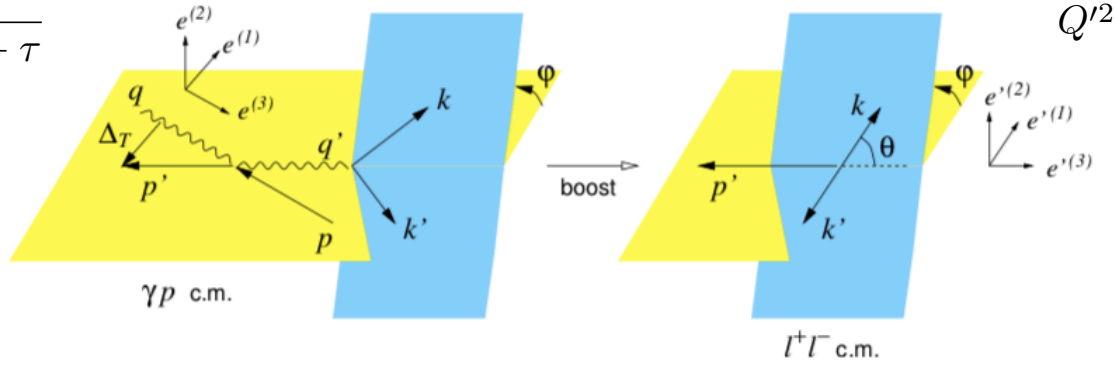
$$s = (q + p_n)^2$$

$$\tau = \frac{Q'^2}{s - m_p^2}$$

θ: angle between l^+ and scattered proton in lepton CMS

- Factorisation ensured by hard scale of γ* virtuality:

$$\frac{t}{Q'^2} << 1$$



- Measurements establish dependence on Q^2, x, t and φ (angle between leptonic and hadronic planes).

TCS observables

- Unpolarised cross-sections:

  sensitive to $\mathcal{Re}\,\mathcal{H}$.

$$\frac{d^4\sigma_{INT}}{dQ'^2 dt d\Omega} = A\frac{1+\cos^2\theta}{\sin\theta}[\cos\phi\ \mathrm{Re}\tilde{M}^{--} - \nu\cdot\sin\phi\ \mathrm{Im}\tilde{M}^{--}]$$

$$\tilde{M}^{--} = \left[F_1\mathcal{H} - \xi(F_1+F_2)\tilde{\mathcal{H}} - \frac{t}{4m_p^2}F_2\mathcal{E}\right]$$

suppressed

- Circularly-polarised photon cross-section: access to $\mathcal{Im}\,\mathcal{H}$.
- More promising observables: asymmetries and cross-section ratios.
- Photon-polarisation (beam-spin) asymmetry:

$$A_{\odot U} = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-}$$

access to $\mathcal{Im}\,\mathcal{H}$

- Forward - backward asymmetry:

$$A_{FB}(\theta,\phi) = \frac{d\sigma(\theta,\phi) - d\sigma(180^\circ-\theta, 180^\circ+\phi)}{d\sigma(\theta,\phi) + d\sigma(180^\circ-\theta, 180^\circ+\phi)}$$

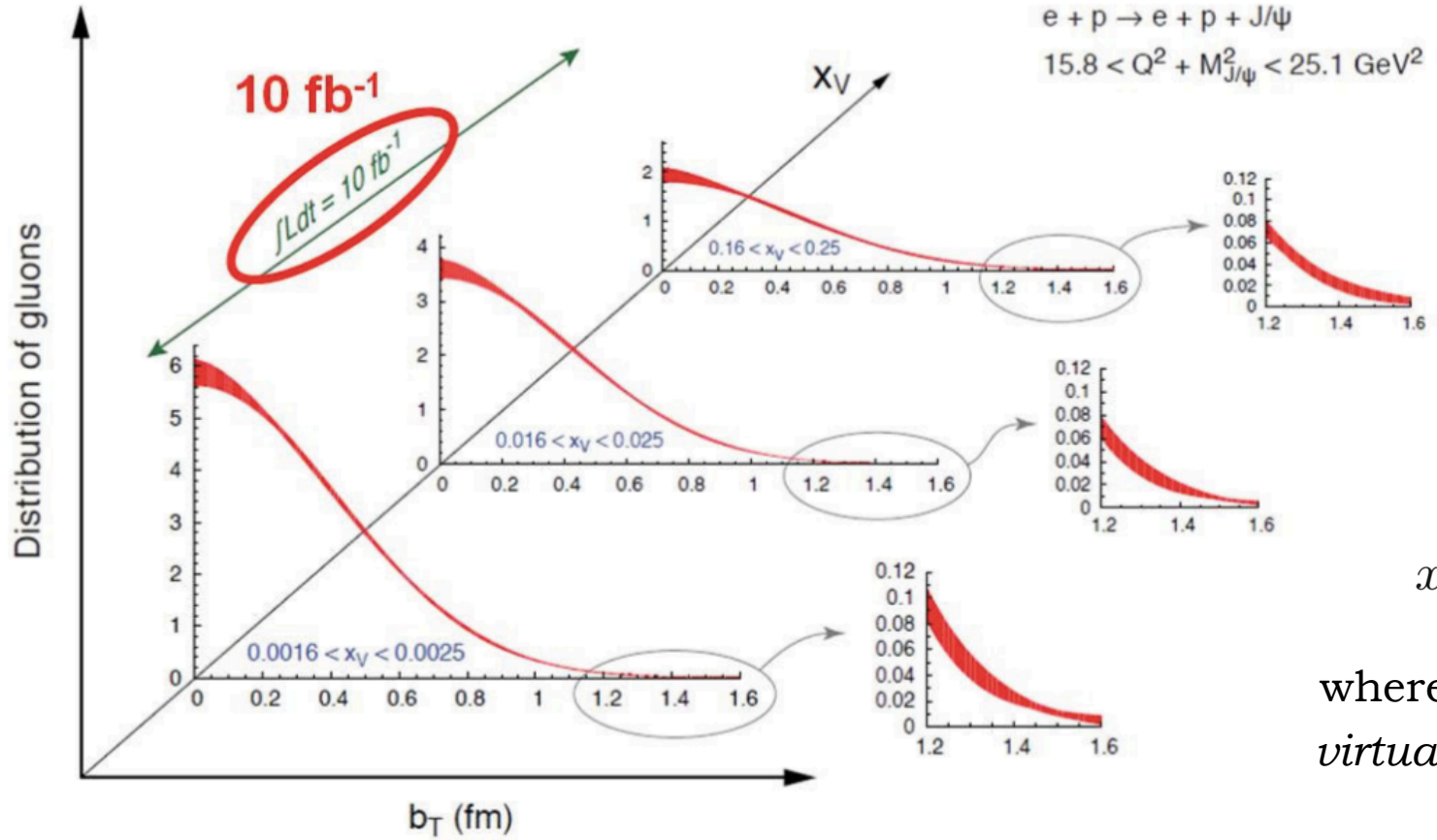
access to $\mathcal{Re}\,\mathcal{H}$

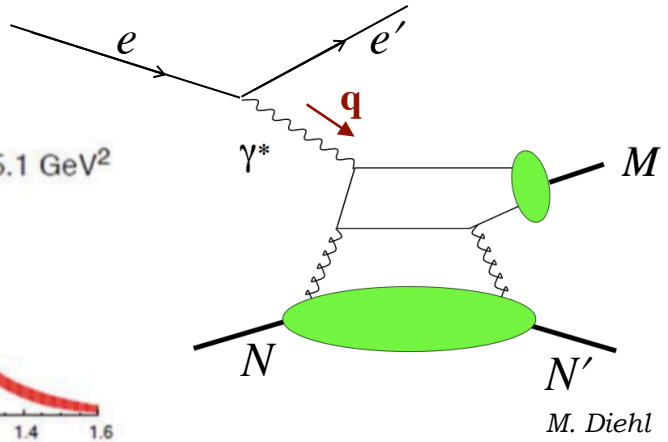
P. Chatagnon et al. (CLAS): arXiv:2108.11746 [hep-ex], *accepted (PRL)*

Nucleon tomography: imaging glue

* Gluon GPDs can be accessed through deeply virtual meson production (DVMP), eg: J/Ψ

* Access to spatial distributions of gluons at different longitudinal momentum fractions:





Gluon momentum fraction related to:

$$x_V = x_B(1 + M^2_{J/\Psi}/Q^2)$$

where $Q^2 = -\mathbf{q}^2 = -(\mathbf{p_e} - \mathbf{p_e}')^2$

virtuality of exchanged photon

Bjorken variable $x_B = \dfrac{Q^2}{2\mathbf{p_n}\cdot\mathbf{q}}$

EIC White Paper, *Eur. Phy. J. A 52, 9 (2016)*