Measurements of Exclusive and Diffractive Processes at the Electron-Ion Collider

Daria Sokhan

CEA Saclay, France

(*on leave from University of Glasgow, Scotland*)

MC4EIC Workshop

16th November 2022

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Plots and studies presented are from many contributors to the Exclusive, Diffractive & Tagging WG of the Yellow Report, ATHENA, ECCE and ePIC

(not all acknowledged personally)

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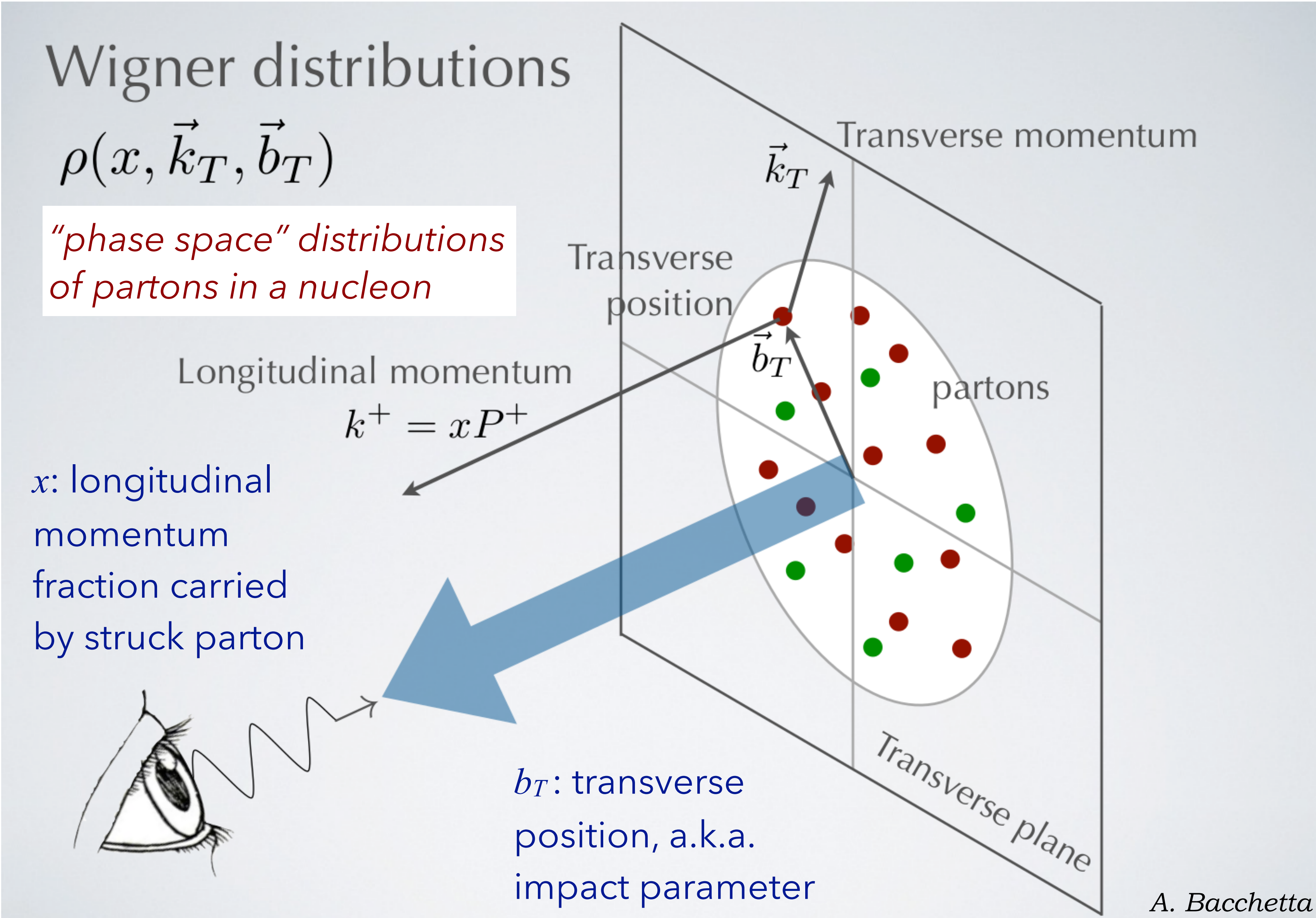
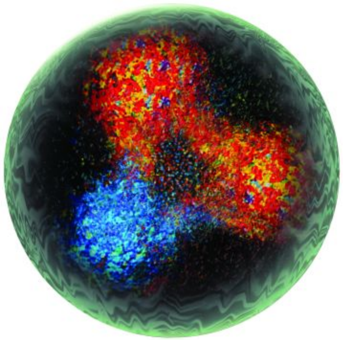
A constructivist view of the nucleon

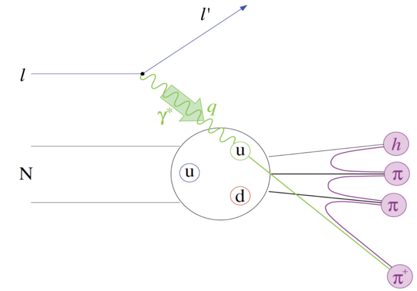




Wigner function:
full phase space parton
distribution of the nucleon

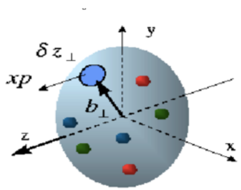
Generalised Transverse Momentum Distributions (GTMDs)

Possible access via exclusive di-jet production or exclusive π⁰-production at high Q².



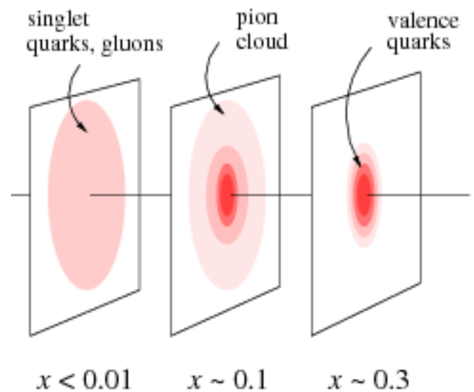
$\int d^2 k_T$

$\int d^2 b_T$



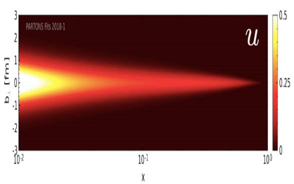
Generalised Parton Distributions (GPDs)

Exclusive processes



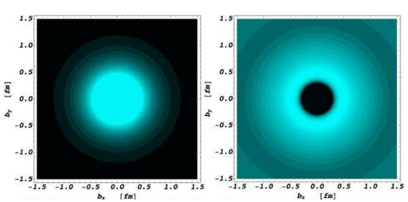
Transverse Momentum-Dependent distributions (TMDs)

Semi-inclusive DIS (SIDIS)



$\int dx$

$\int d^2 k_T$

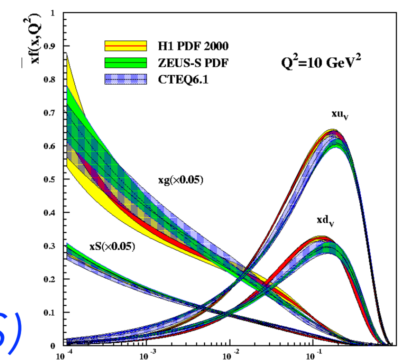


Form Factors

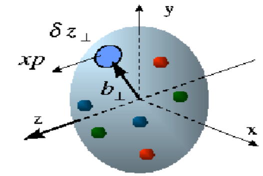
Elastic scattering

Parton Distribution Functions (PDFs)

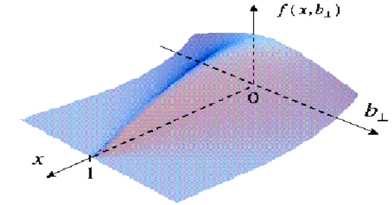
Deep Inelastic Scattering (DIS)



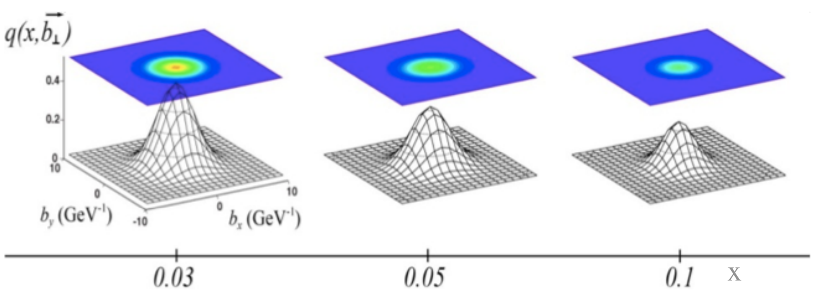
Generalised Parton Distributions



- 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.

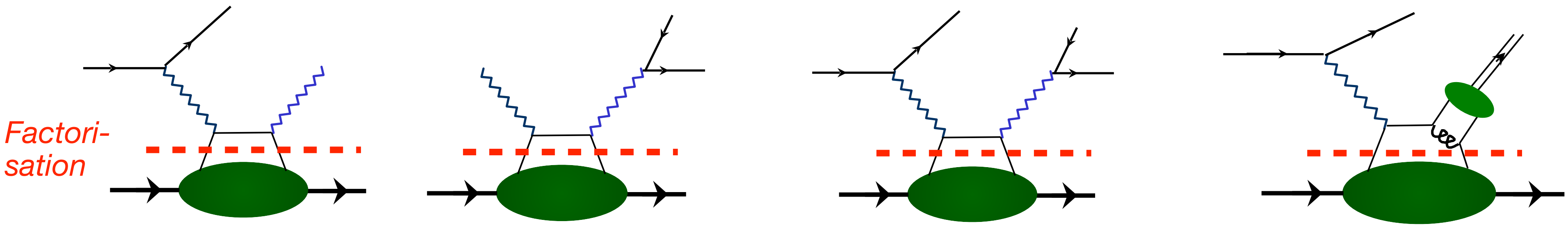
Experimental access to GPDs

Accessible in *exclusive* processes, where 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	**TCS**	**DDVCS**	**DVMP**
Virtual photon space-like	*Virtual photon time-like*	*One time-like, one space-like virtual photon*	*Virtual photon space-like*

Other motivations for exclusive processes

- Exclusive near-threshold production of quarkonia is sensitive to the trace-anomaly of the QCD energy-momentum tensor: insight into the processes of hadron mass generation.

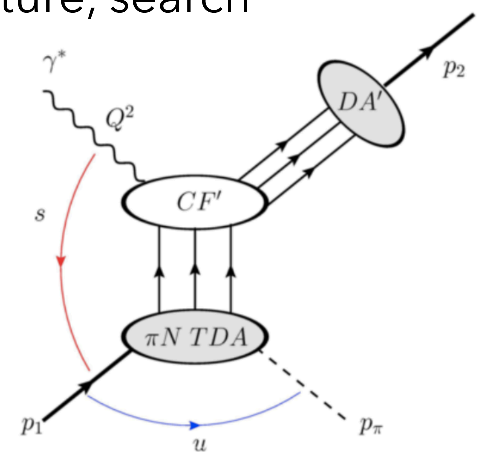
- Scattering from the meson-cloud in the nucleon (Sullivan process): access to form-factors and structure functions of mesons.

- Coherent diffractive meson-production in *eA*: probe of gluon saturation.

- Incoherent diffractive meson-production in *eA* with spectator tagging: medium-modifications, short-range correlations.

- Hadron spectroscopy (t-channel): another route to hadron structure, search for exotics.

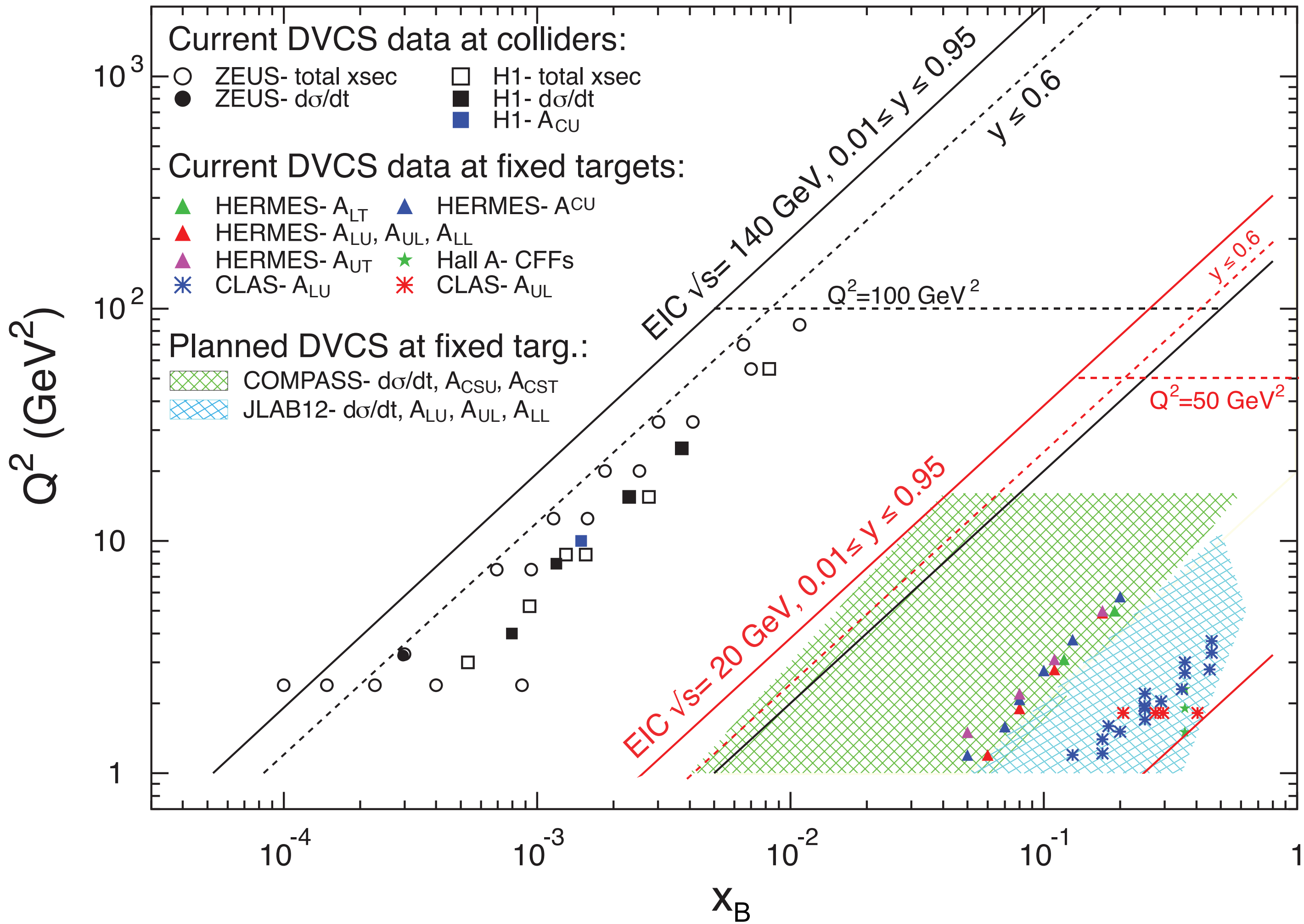
- U-channel meson production: access to Transition Distribution Amplitudes (TDAs), describing the process of a proton transitioning into a meson, sensitivity to diquark clustering in nucleon.

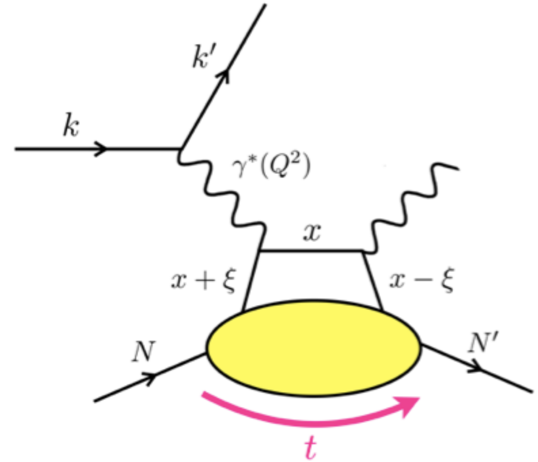


Studies for proposals:

	ATHENA	ECCE
* **DVCS in ep**	EpIC	MILOU3D
* **DVCS (incoherent) in ed**	EpIC	
* **DVCS on He-4**		TOPEG
* **TCS in ep**	EpIC	EpIC
* **J/Psi in ep**		lAger, eSTARlight
* **J/Psi in eA**		lAger, eSTARlight
* **Φ in eAu/Pb**	SARTRE, BeAGLE	SARTRE, BeAGLE
* **Y(1S, 2S, 3S) in ep**	eSTARlight, lAger	
* **u-channel: ω, ρ in ep**	eSTARlight	
* **X,Y Ψ(2S) in ep -> J/Ψ $\pi^+\pi^-$ p**	elSpectro	elSpectro
* **Pion Form Factors**		DEMPgen (?)
* **Pion Structure Functions**		DEMPgen (?)
* **A^n_1 (He-3 double tagging)**		*

EIC kinematic reach: DVCS





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

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

$$Q^2 = -(\mathbf{k} - \mathbf{k}')^2$$

y: inelasticity

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

https://arxiv.org/abs/2103.05419

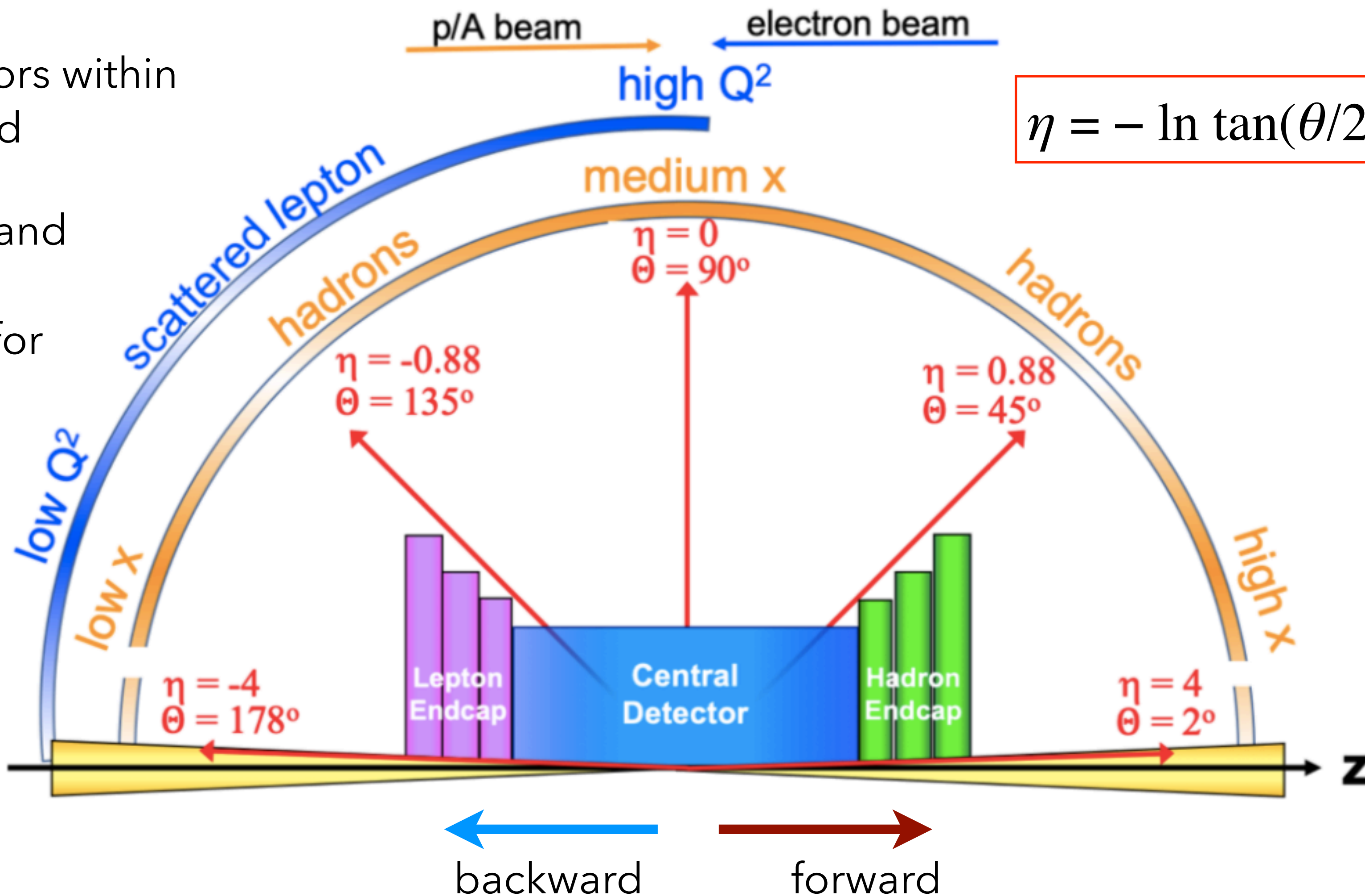
Detector configuration

Very asymmetric beams

Hermetic detectors within a central solenoid

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

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



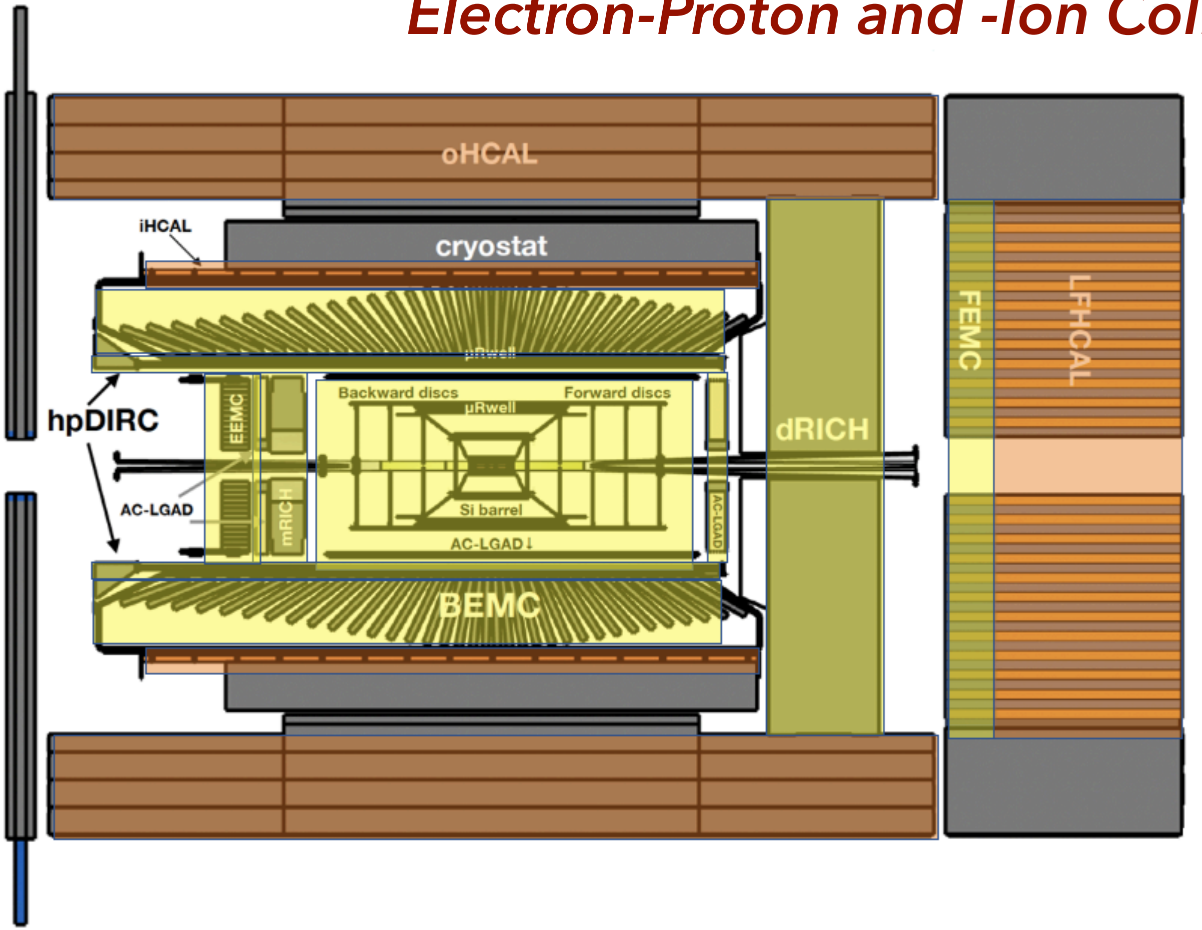
The ePIC detector

Result of the merging of ECCE and ATHENA collaborations.

Electron-Proton and -Ion Collider detector

electron beam

hadron beam



Calorimetry:

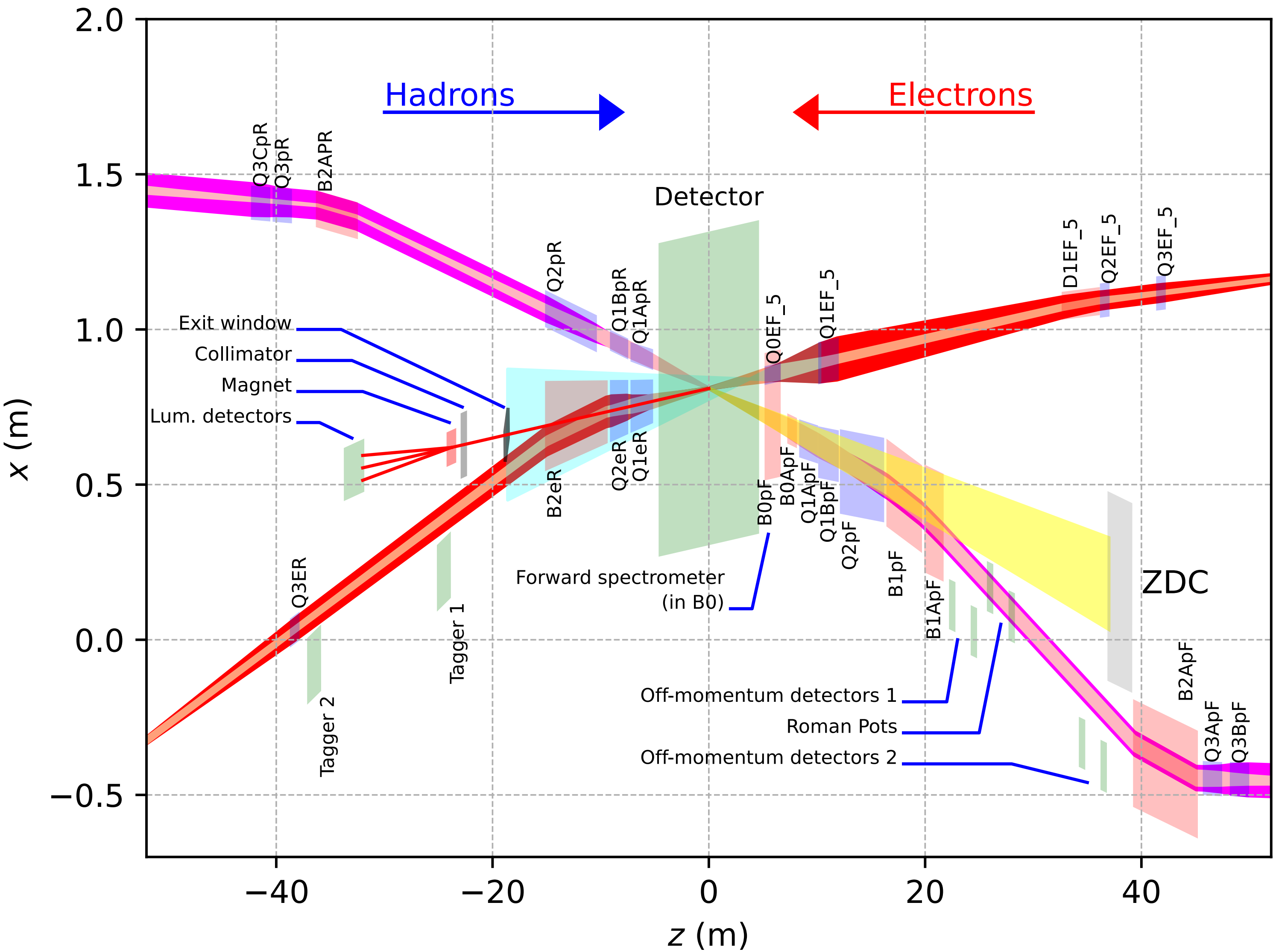
Range of EM and hadron calorimeters.

Particle ID (PID):

High time-resolution Si (AC-LGAD), Cherenkov detectors: RICH, DIRC.

Tracking: New 1.7 T magnet (MARCO), to be built by Saclay.
Light-weight Si tracking (65nm MAPS), micro-pattern gaseous detectors (MPGDs).

The Interaction Region @ IP6

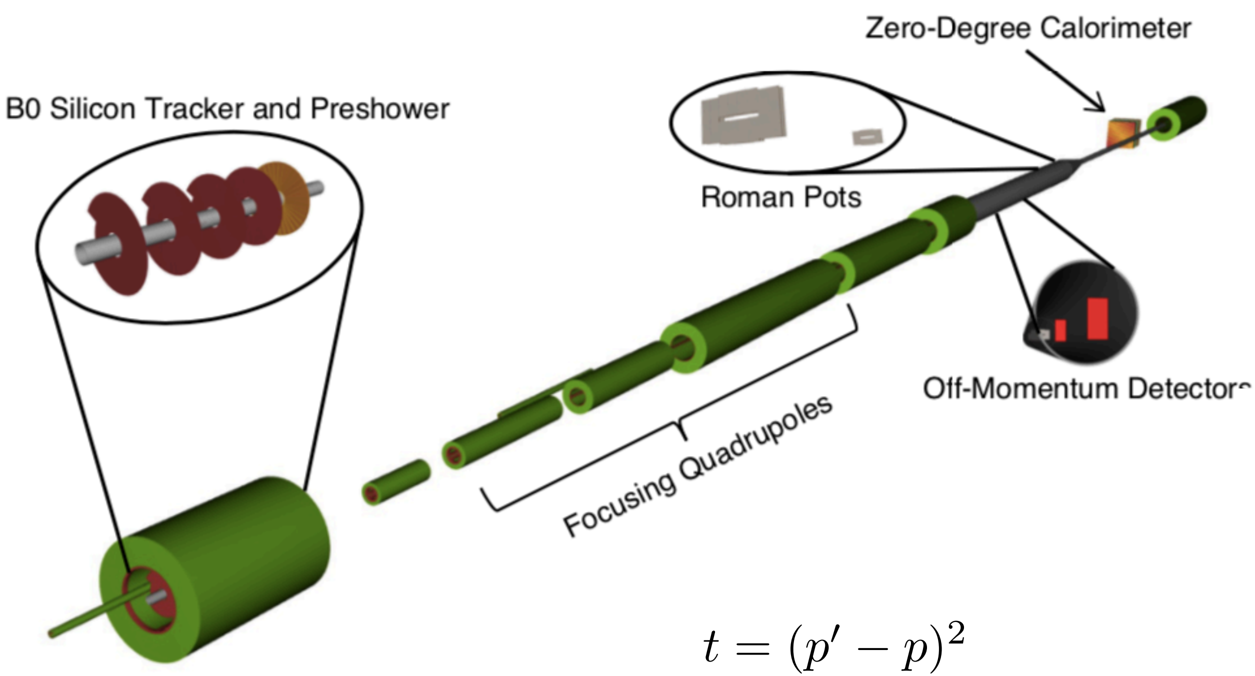


Crossing angle for the beams: 25 mrad.

Recoil protons in *ep*

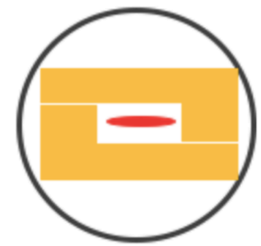
- The impact parameter information in many exclusive processes is encoded in *t*, via a Fourier Transform. Require accurate measurement of *t* from as close to zero as possible and across a wide range in *ep and e(light-A)* collisions.

- Scattered protons / light ions detected in Roman Pots (for the lowest values of *t*) and in the B0 spectrometers (for higher values).

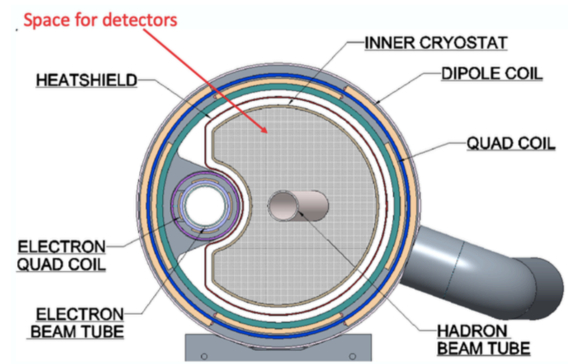


$$t = (p' - p)^2$$

ATHENA proposal



Hadron beam-pipe and Roman Pots in cross-section

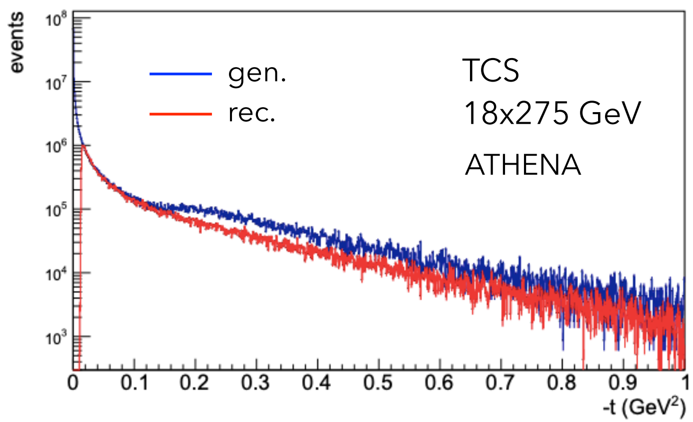


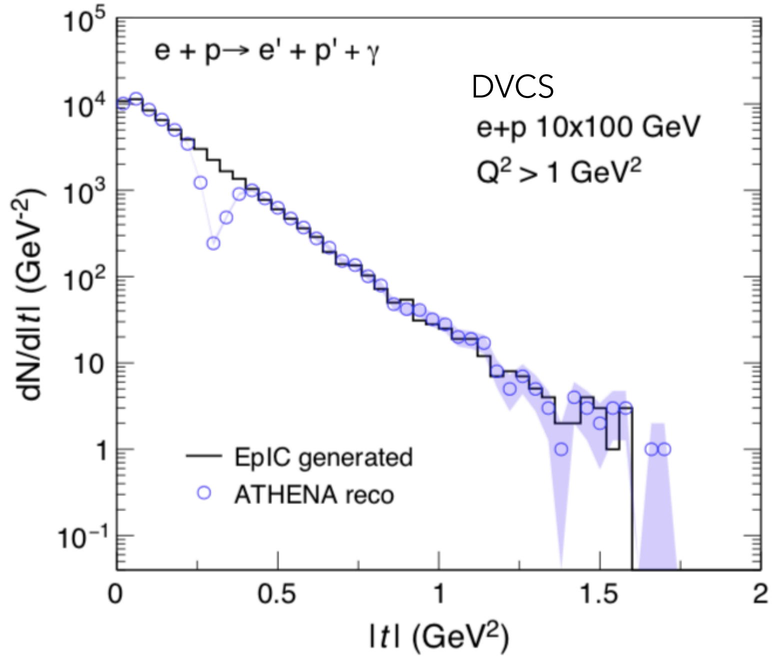
EIC Yellow Report B0 spectrometer configuration

Recoil protons in *ep*

Generator: EpIC

* Scattered protons detected in Roman Pots (for the lowest values of *t*) and in the B0 spectrometers (for higher values).





Light ions bend less and the t-distribution drops faster: detection entirely in the Roman Pots.

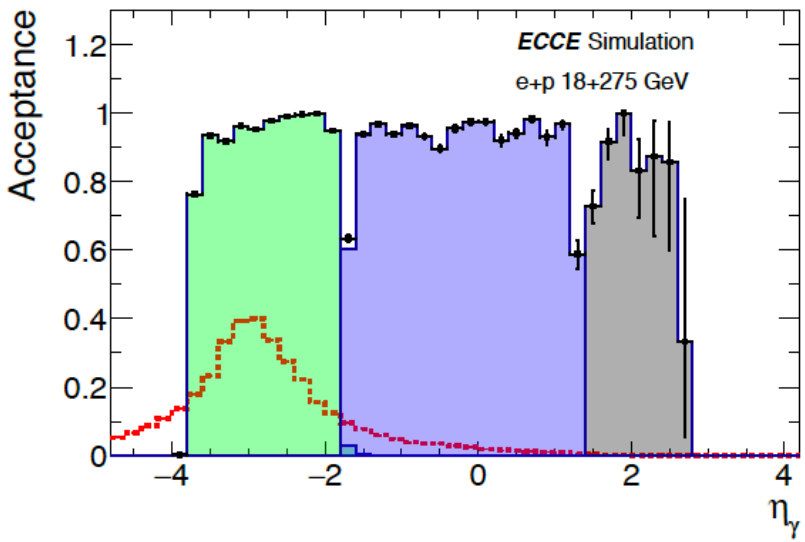
Can study coherent DVCS on He-4: spin-0, so coherent amplitude parametrised by one GPD. Also deuteron (but spin-1, too many GPDs!)

Dip in *t*-distribution is due to a gap between Roman Pots and B0 tracker: intrinsic to interaction region (IR). Gap position depends on proton beam-energy.

Plots: Kong Tu (BNL), D. S.

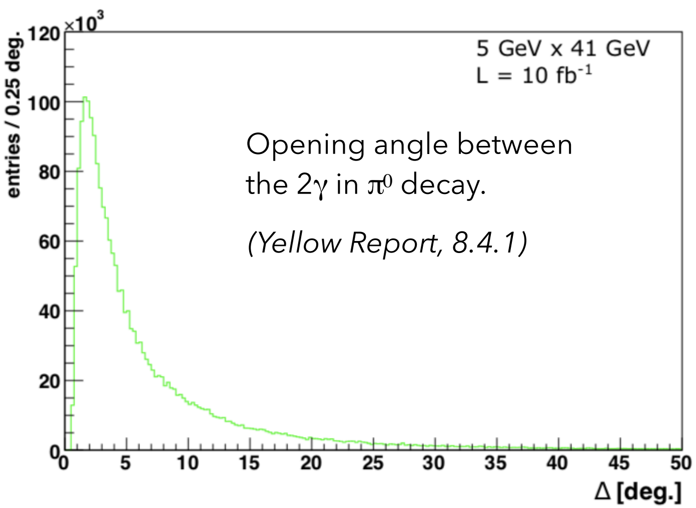
Coherent DVCS at the EIC

Generators: MILOU3D, toy MC



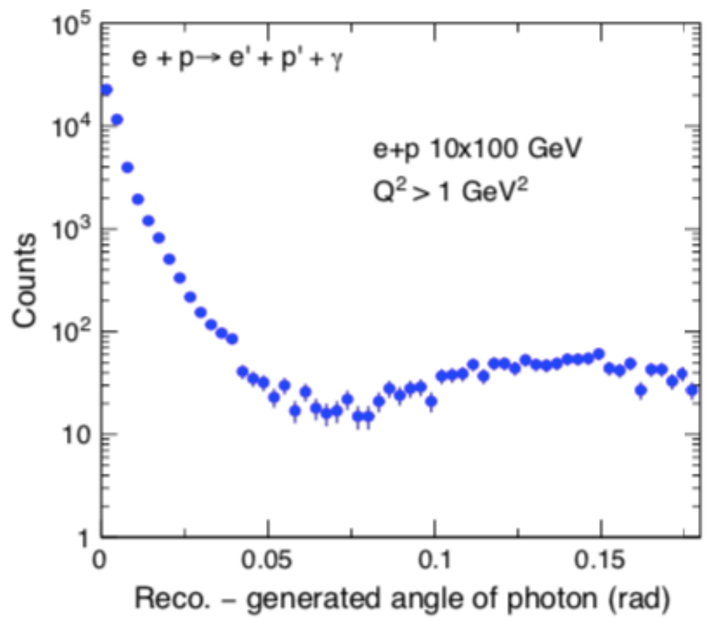
Main background from meson-production of π^0 which decays into 2γ pairs:

- Minimise risk of missing one photon: practically hermetic calorimeter coverage.
- Good calorimeter resolution to ensure photon clusters don't merge.



Opening angle between the 2γ in π^0 decay.

(Yellow Report, 8.4.1)



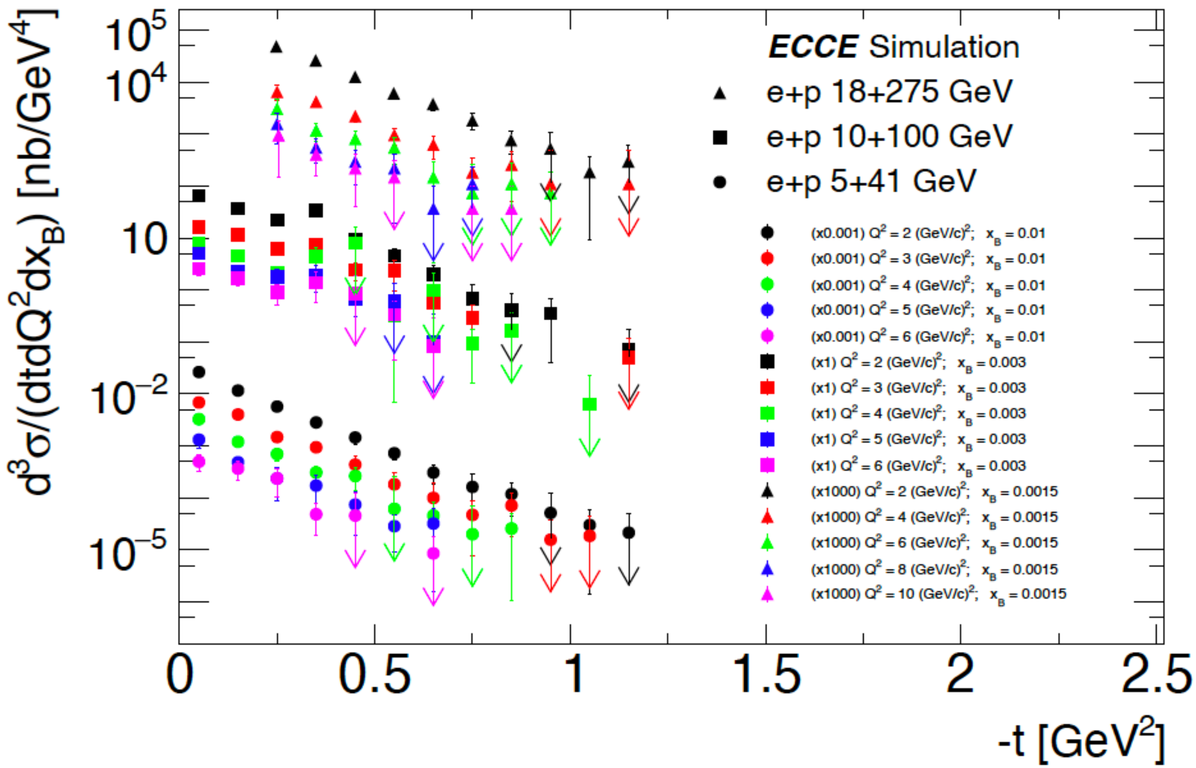
Difference between generated and reconstructed DVCS photon mainly < 0.17mrad (1deg): smallest opening angle for π^0 decay.

Coherent DVCS at the EIC

Plots: I. Korover (MIT)

Generator: MILOU3D

- DVCS on the proton:

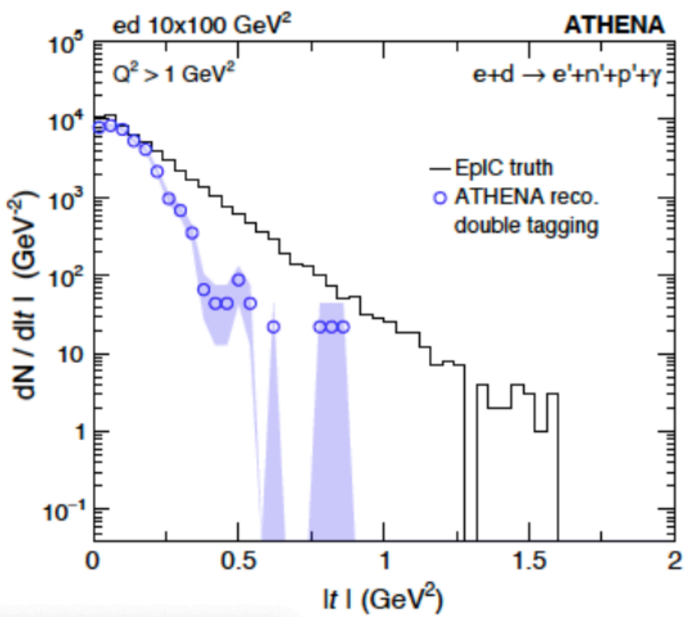


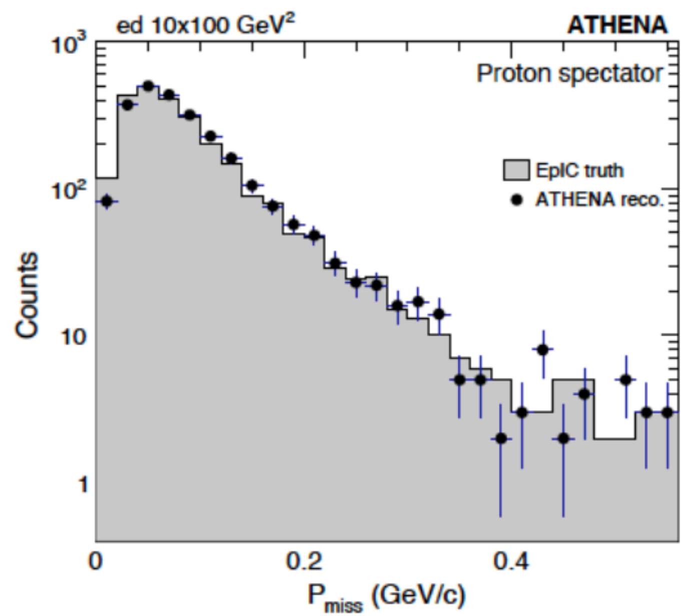
Multi-dimensional binning: strong constraints on extraction of Compton Form Factors.

DVCS in ed

Plots: Kong Tu (BNL)

- Enables measurement on neutron in deuterium: quark-flavour separation of GPDs, sensitivity to other Compton Form Factors (eg: Im E in DVCS beam-spin asymmetry on neutron vs Im H in BSA on proton).
- Both the spectator proton and the scattered neutron tagged in the measurement.
- Spectator proton is used to determine initial neutron momentum, to enable reconstruction of *t*:





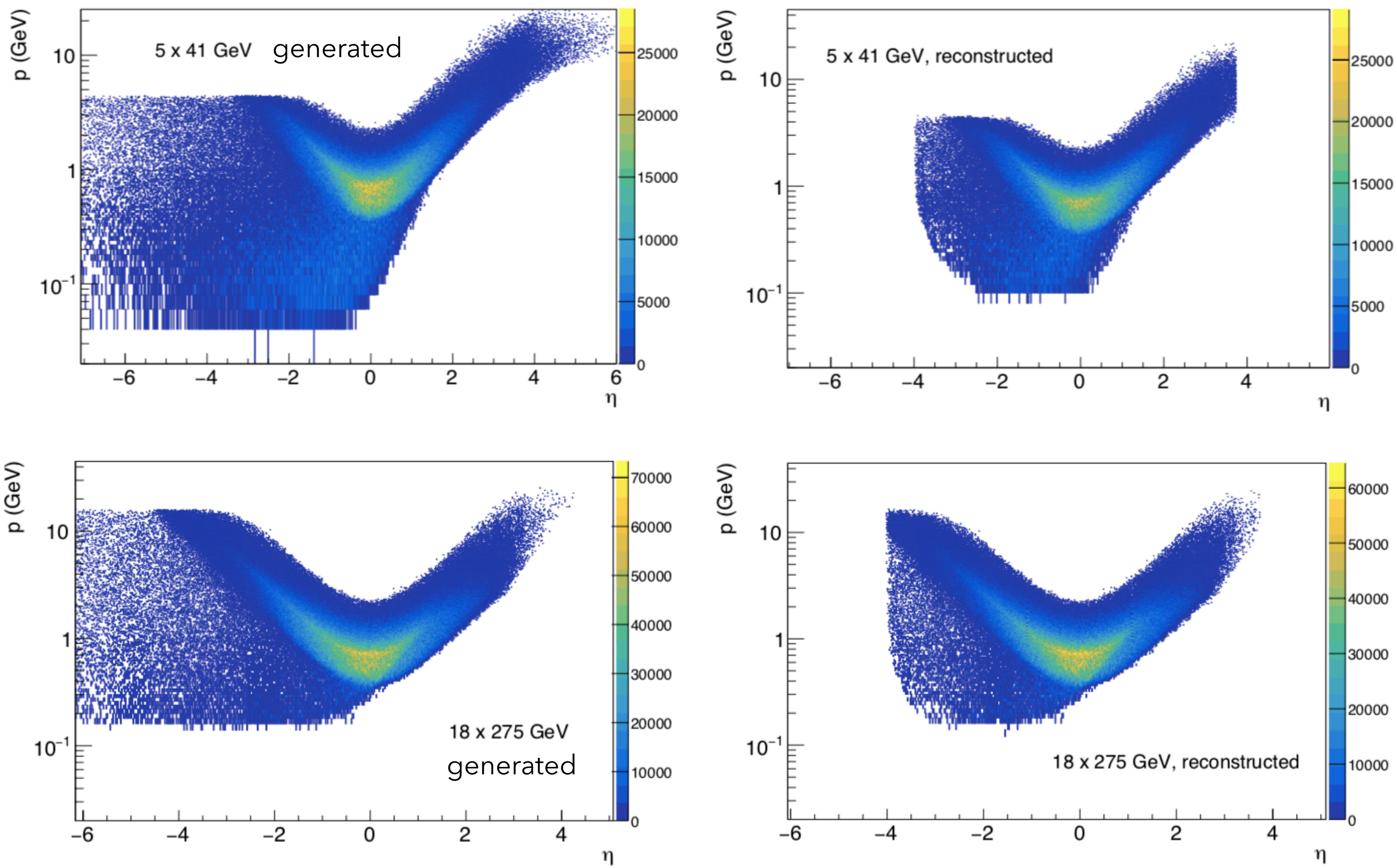
Generator: EpIC

- Scattered neutron tagged in ZDC: loss of *t*-acceptance at high *t* is due to limitations of ZDC acceptance. Can obtain better *t* acceptance from electron - photon.

TCS e^+e^-

* TCS-produced virtual photon decays into e^+e^- pairs at mid-rapidity – need excellent acceptance in central region (barrel+ end-caps), scattered electron will be detected in the low-Q^2 tagger for part of the phase space – for the rest, rely on missing mass and momentum

Generator: EpIC



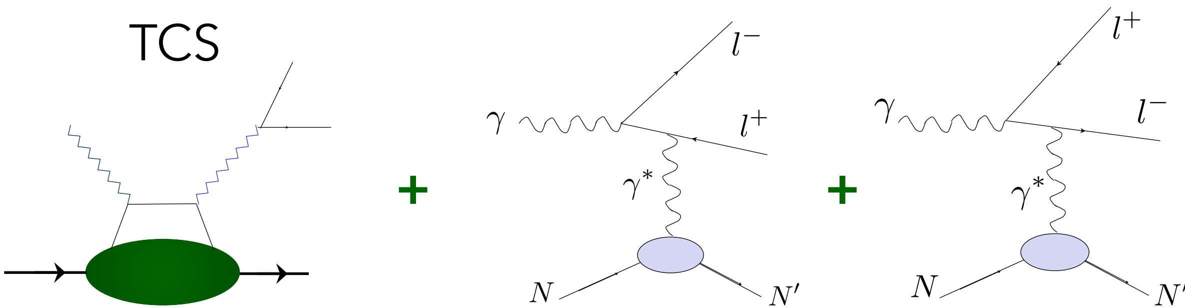
TCS (+ BH + Int) e^+e^-: observables

Generator: EpIC

- Pure TCS cross-section is dominated by a factor of ~100 by Bethe-Heitler (BH): extract TCS signal from the BH-TCS interference.

Bethe-Heitler (BH)

TCS

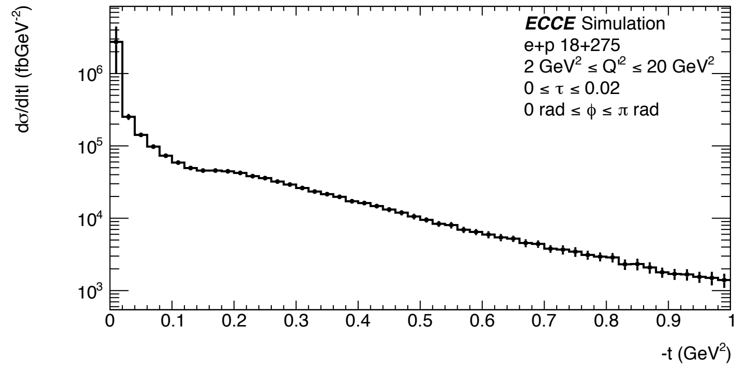


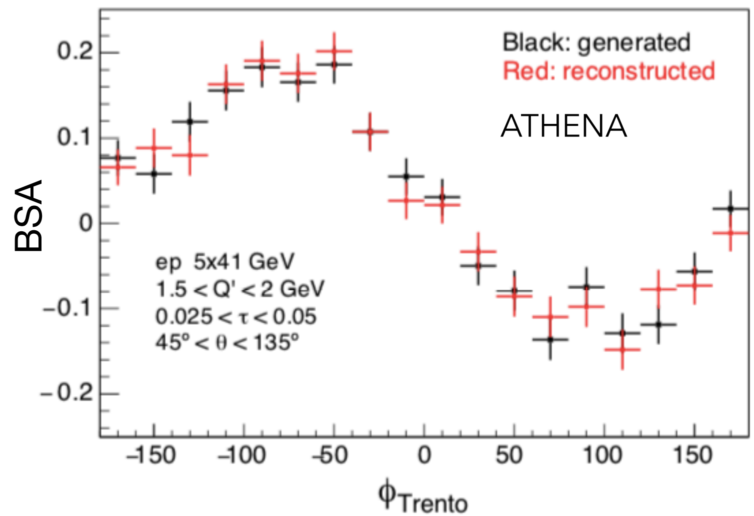
$$\sigma(\gamma p \to p' e^+ e^-) = \sigma_{BH} + \sigma_{TCS} + \sigma_{INT}$$

- Sensitivity to Interference term in single-spin asymmetries: beam-spin (BSA), target-spin.

- Studied with the EpIC generator using the PARTONS framework.

E. C. Aschenauer *et al. Eur. Phys. J. C* **82**, 819 (2022).





Plots: Kayleigh Gates (Glasgow), D.S.

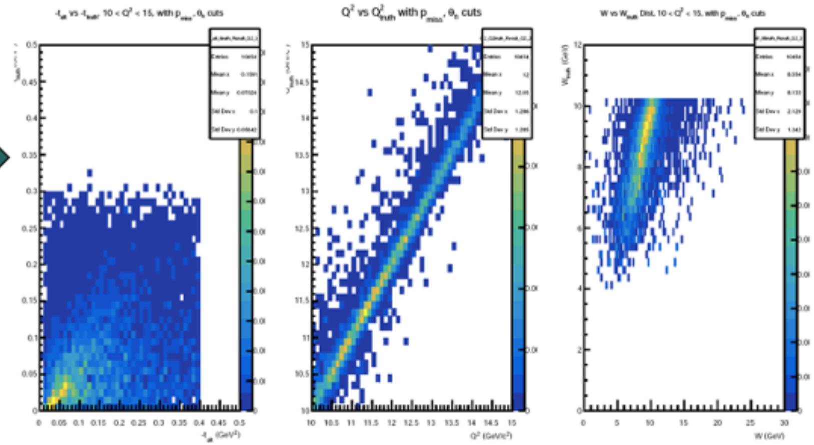
Deep Exclusive Meson Production $p(e,e'\pi^+n)$

- **Continuing pion form factor studies with 5x100 beam profiled in Yellow Report and ECCE proposal**
- Investigating 5x41 and 10x100 and comparing IR6:IR8, to better understand detector requirements, and improve overlap w/JLab-12

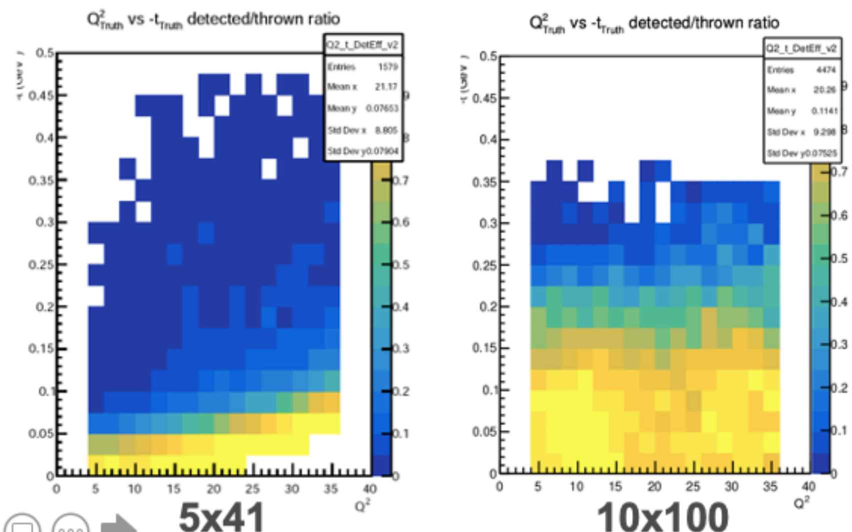
Generator: DEMPgen

Plots by Stephen Kay (Regina) & Maggie Kerr (Mt Allison)

-t,Q²,W: reconstr (x) vs true (y) → excellent reconstruction resolution for $10<Q^2<15$ @ 5x100



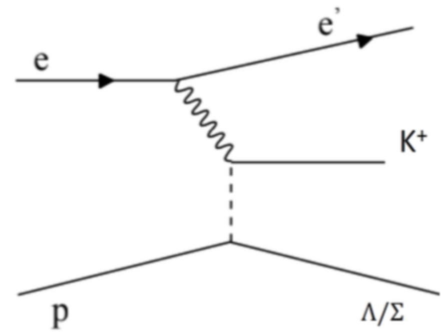
IR6 detect effic vs Q^2, -t:
Triple coin after cuts
Effic higher @ 10x100
Study still in progress

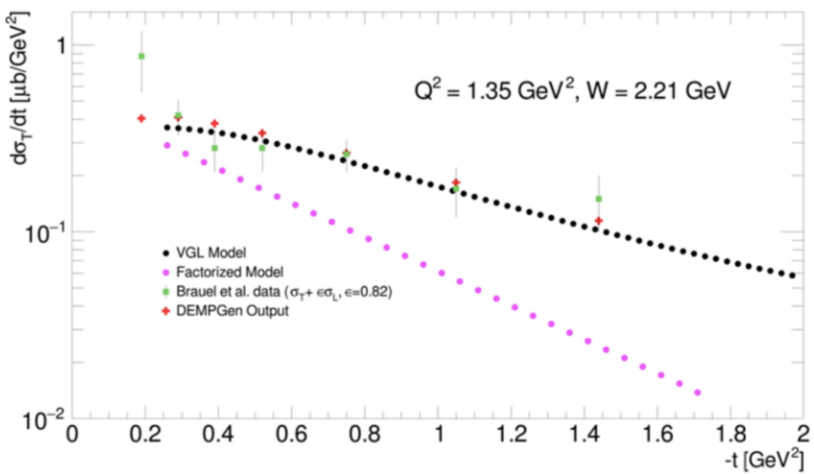


University of Regina

Deep Exclusive Meson Production $p(e,e'K^+\Lambda)$

- Preliminary testing of $p(e, e'K^+\Lambda)$ showed kinematics were similar to $p(e, e'\pi^+ n)$
- Very forward going Λ
  - Carries the majority of the momentum
- Decay and subsequent detection of the Λ in the far forward region is the biggest challenge for this measurement
- URegina MSc student Love Preet working on adding Kaon DEMP event generator module to DEMPGen
  - Starting with $p(e, e'K^+\Lambda)$
- Parametrise a Regge-based model in a similar way to the pion
- For $p(e, e'K^+\Lambda)$ module, use the Vanderhagen, Guidal, Laget (VGL) model



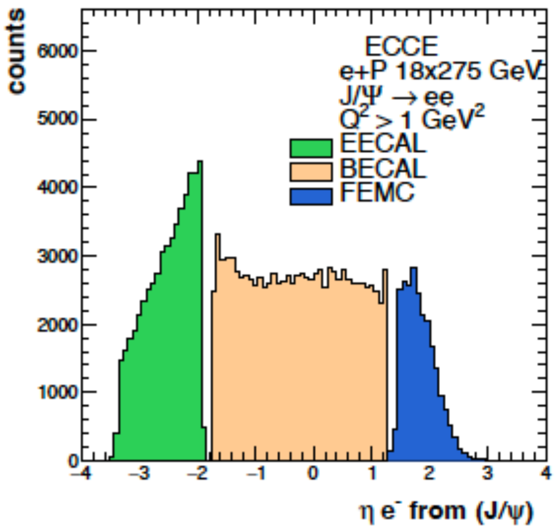


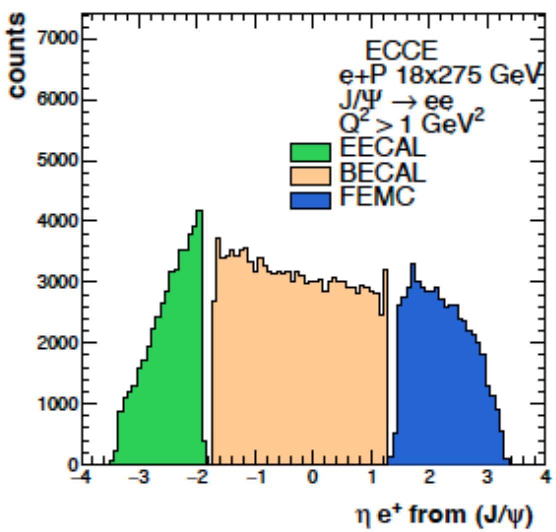
Generator: DEMPgen

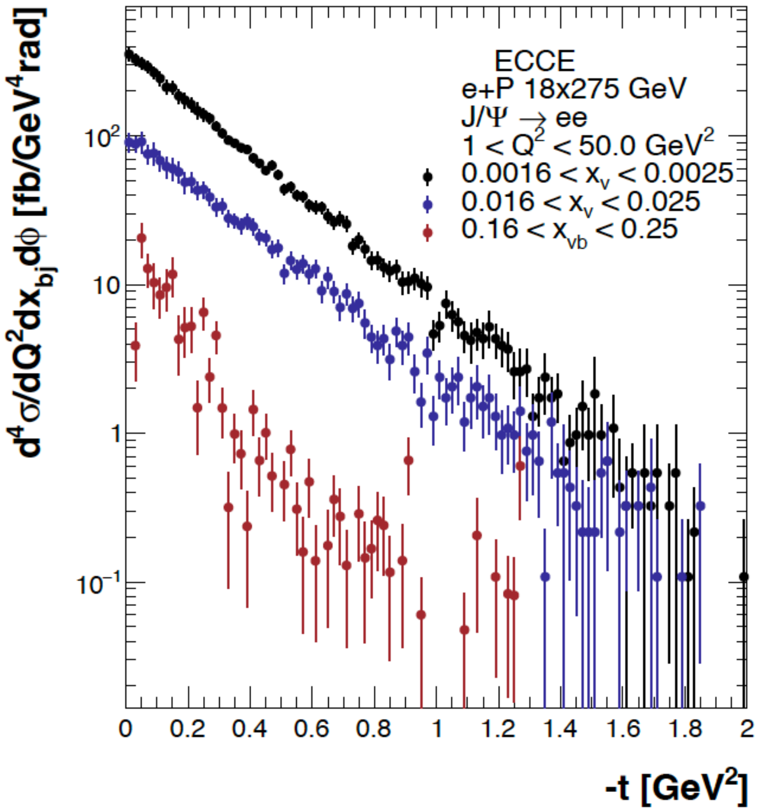
Slide material from Stephen Kay (U. Regina)

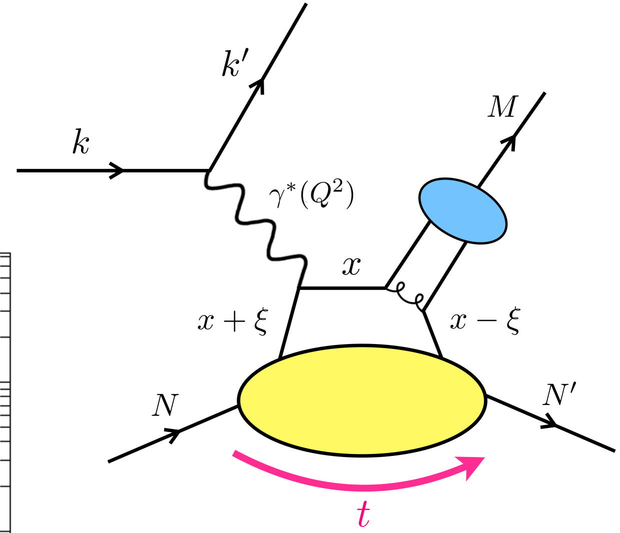
Generators: lAger, eSTARlight

J/Psi production









- Excellent acceptance coverage for J/Psi decay leptons
- Multi-dimensional binning

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

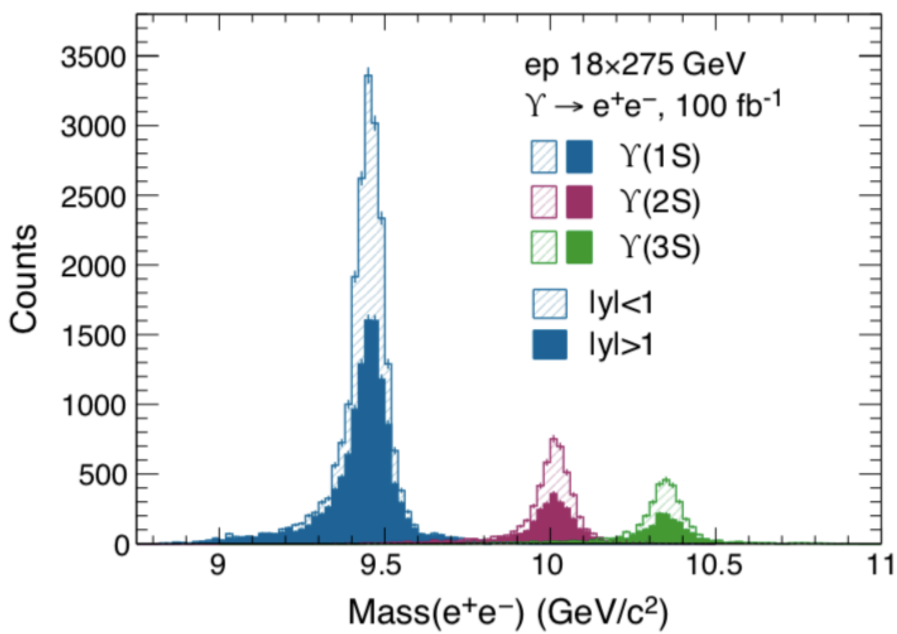
* Light vector-meson production additionally enables flavour-decomposition of GPDs.

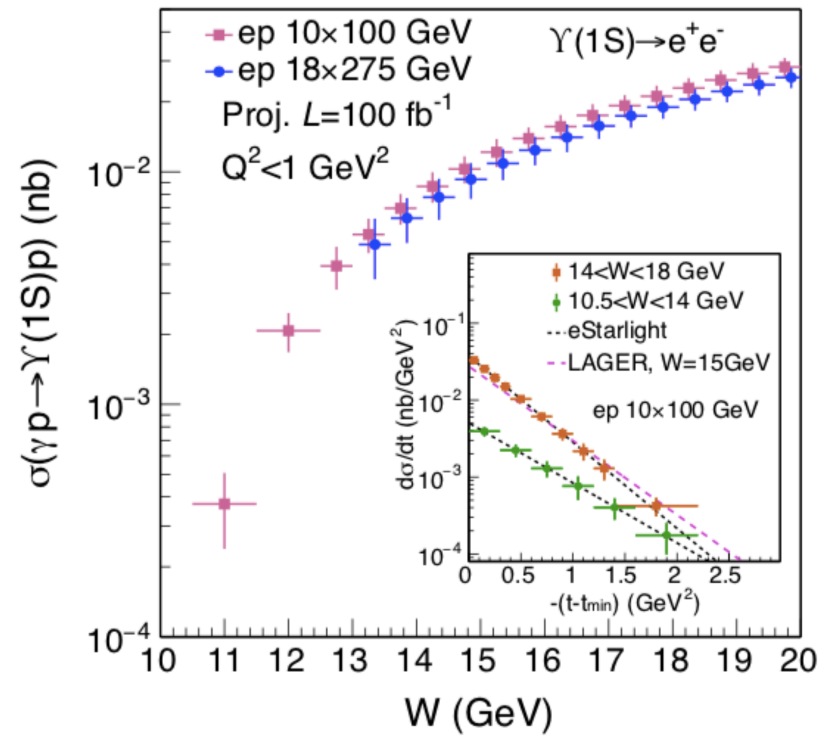
Plots: N. Santiesteban

Upsilon-production

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

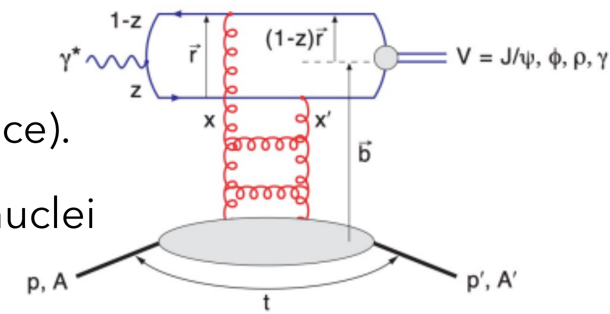
Photoproduction ($Q^2 < 1$ GeV^2) and electroproduction ($Q^2 > 1$ GeV^2).



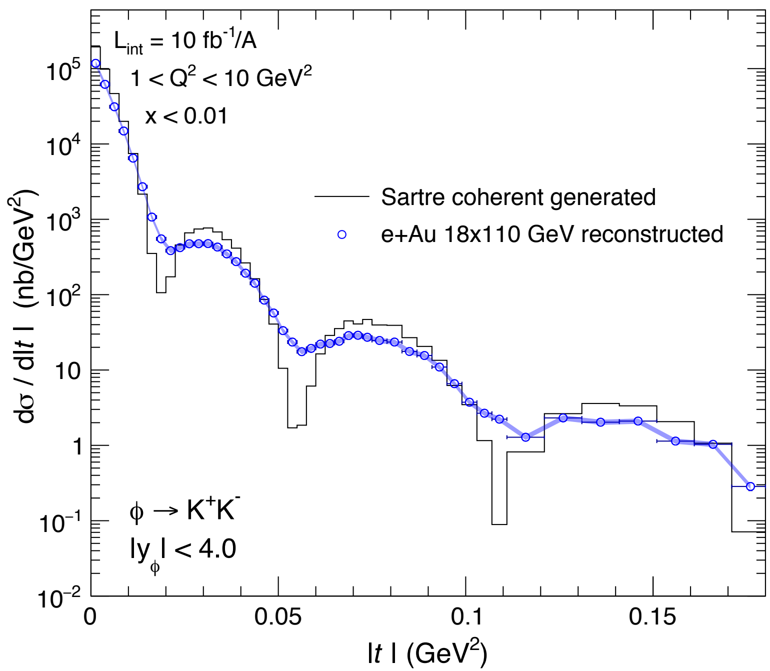


Plots: Yuangjing Ji (LBNL)

Coherent VM production in eA

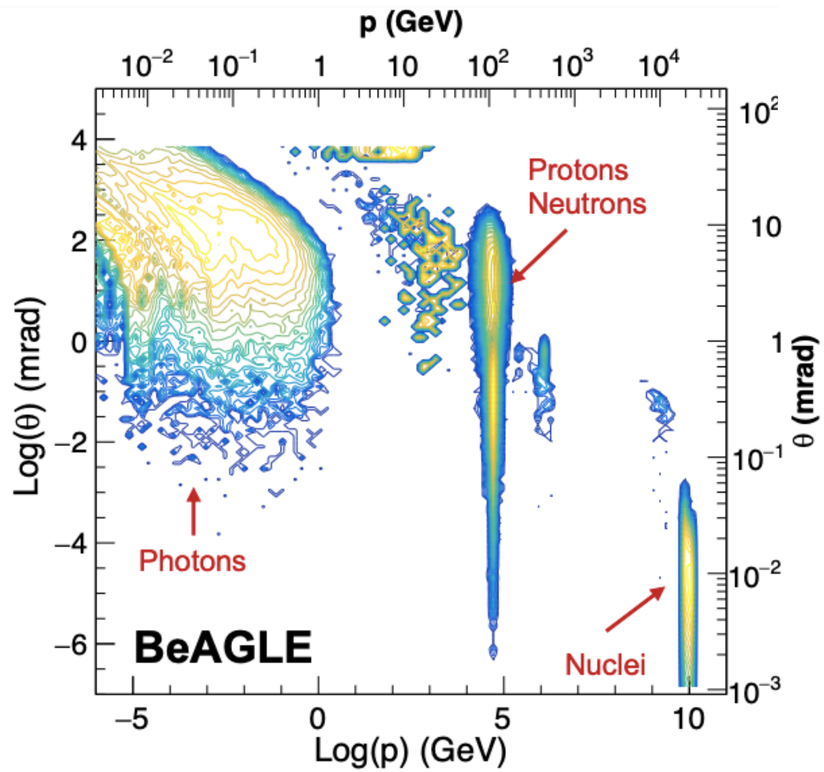


- Gluon distributions in nuclei and a probe of saturation (in Q^2-depedence).
- Detector challenge: reconstruct *t* from leptons and mesons, not from nuclei (these escape undetected): resolution is crucial to identify *t* minima.
- Suppression of incoherent background by vetoing nuclear break-up in Far-Forward detectors.



Plot: Kong Tu (BNL)

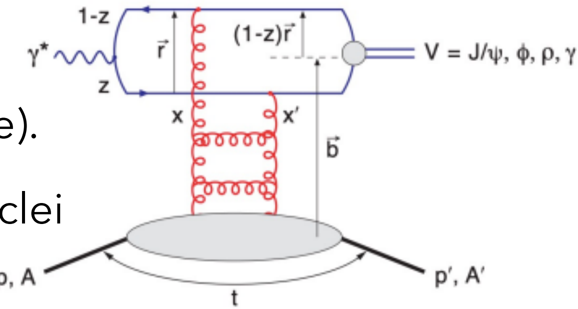
Generator: Sartre



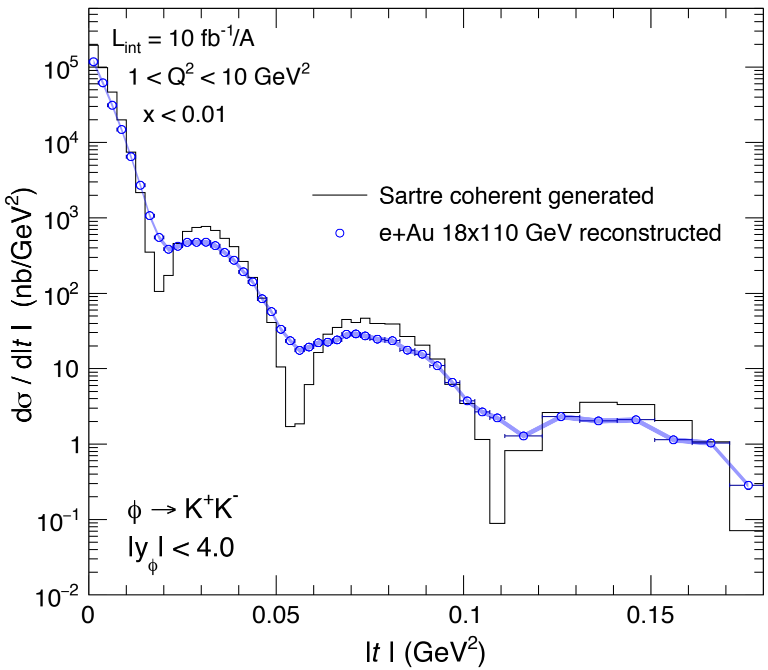
Incoherent backgrounds

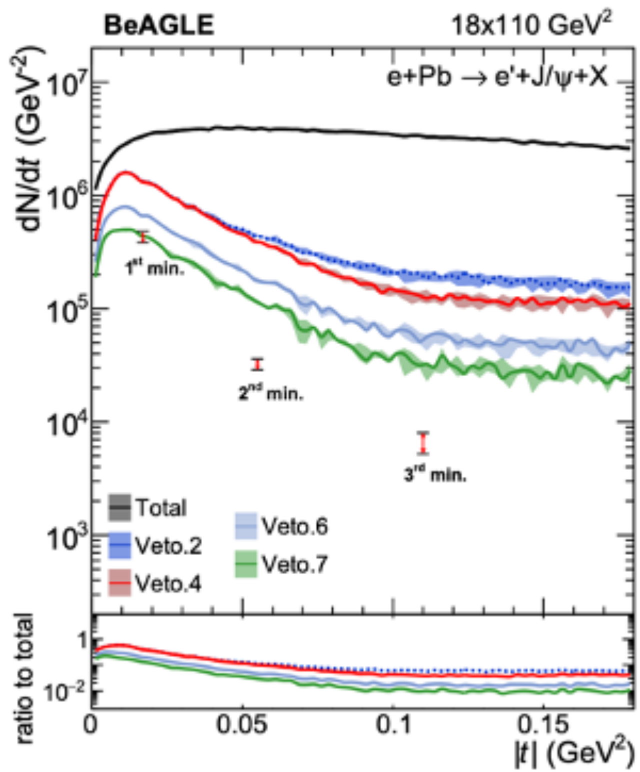
Phys. Rev. D **104**, 114030

Coherent VM production in eA



- Gluon distributions in nuclei and a probe of saturation (in Q^2-depedence).
- Detector challenge: reconstruct *t* from leptons and mesons, not from nuclei (these escape undetected): resolution is crucial to identify *t* minima.
- Suppression of incoherent background by vetoing nuclear break-up in Far-Forward detectors.





Plot: Kong Tu (BNL)

Generators: Sartre, BeAGLE

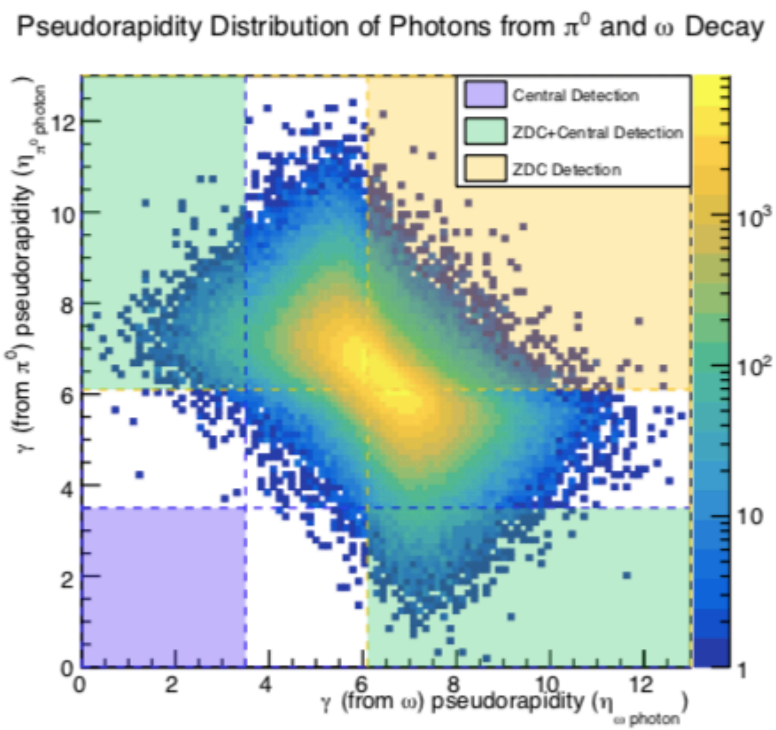
*Phys. Rev. D **104**, 114030*

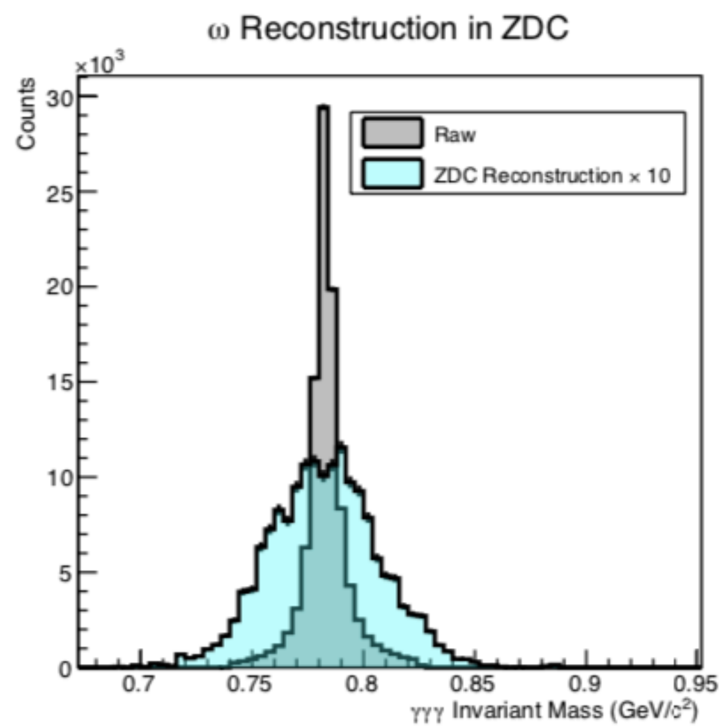
Backward production of omega

Generator: eSTARlight

- Similar to normal meson photo-production, but proton at mid-rapidity and meson goes forward with high momentum: u-channel.
- Sensitivity to Transition Distribution Amplitudes (TDA).
- Proton (a few hundred MeV) detected in central detector. Photons from meson decay detected in a combination of central and ZDC.

$$\omega \to \pi^0 \gamma$$

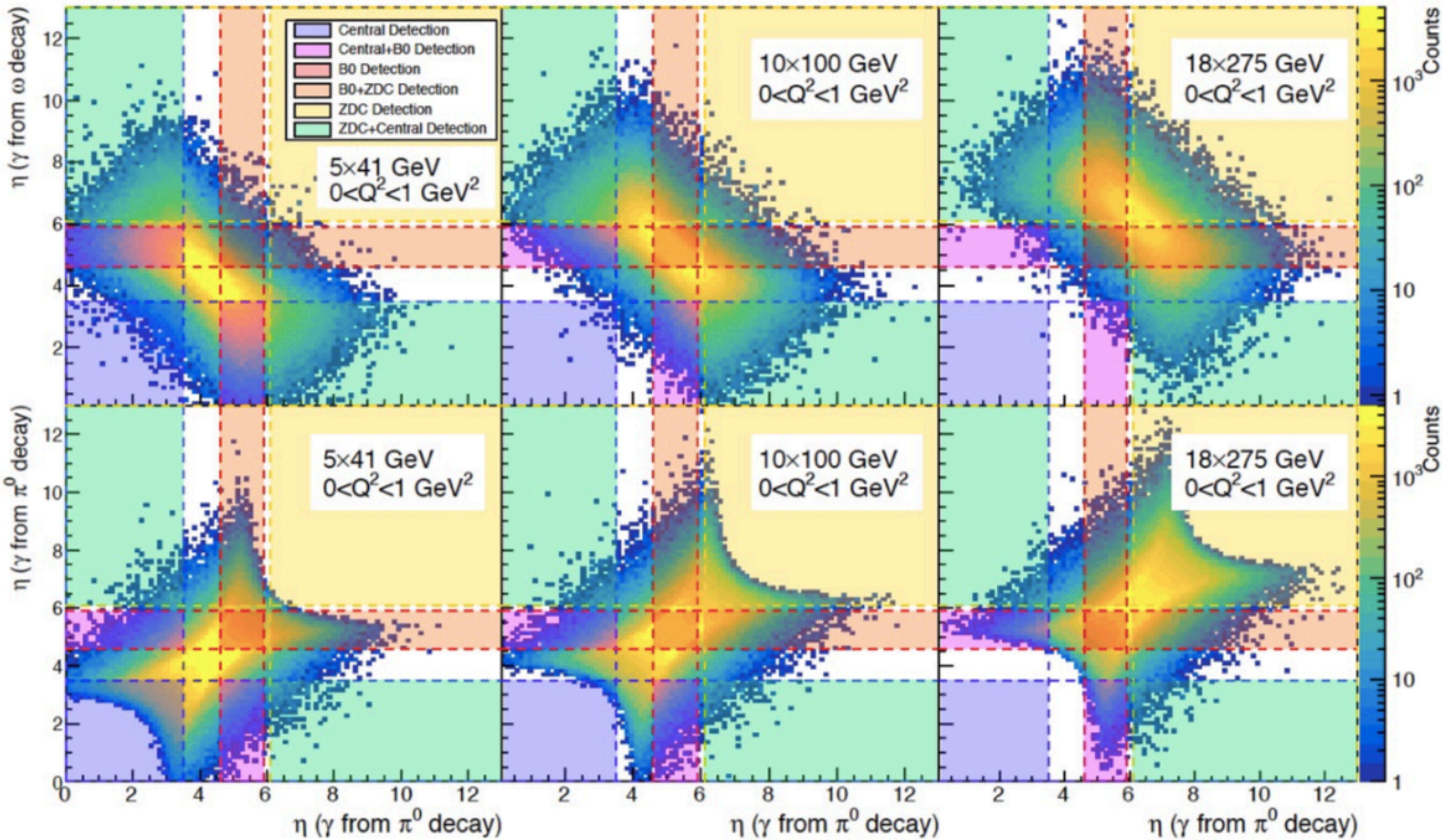




Plots: Zachary Sweger (UC Davis)

18 x 275 GeV, $Q^2 < 1$ GeV^2

Backward production of omega



Proton beam energy	ω eff. cent.+ZDC	ω eff. cent.+B0+ZDC
41 GeV	1.4%	18%
100 GeV	1.3%	41%
275 GeV	6%	63%

Generator: eSTARlight

Plots: Zachary Sweger (UC Davis)

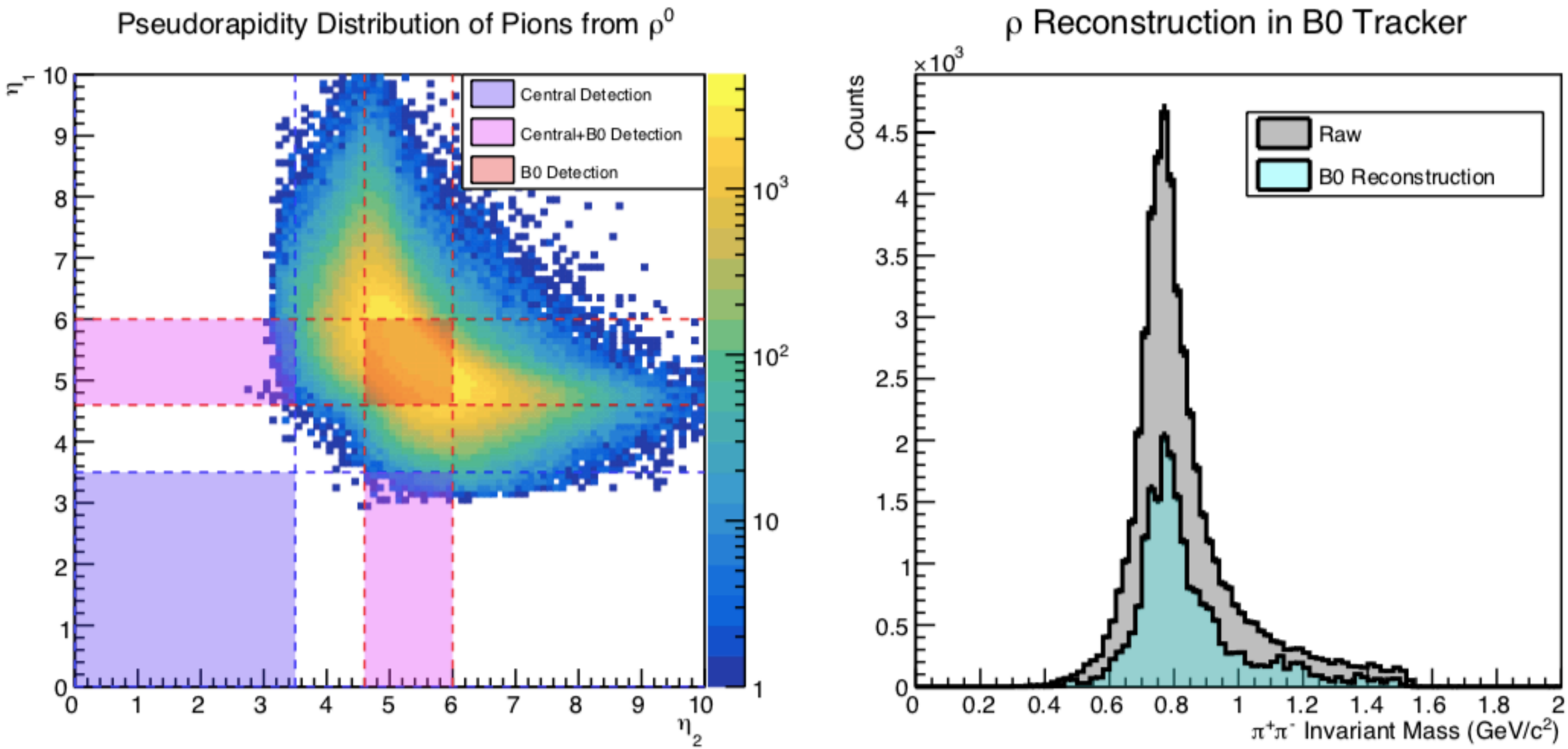
Backward production of rho

Generator: eSTARlight

- Charged mesons in the u-channel production can also be reconstructed using Central detector, ZDC and B0 tracker.

$$\rho \to \pi^+\pi^-$$

10 x 100 GeV, $Q^2 < 1$ GeV^2



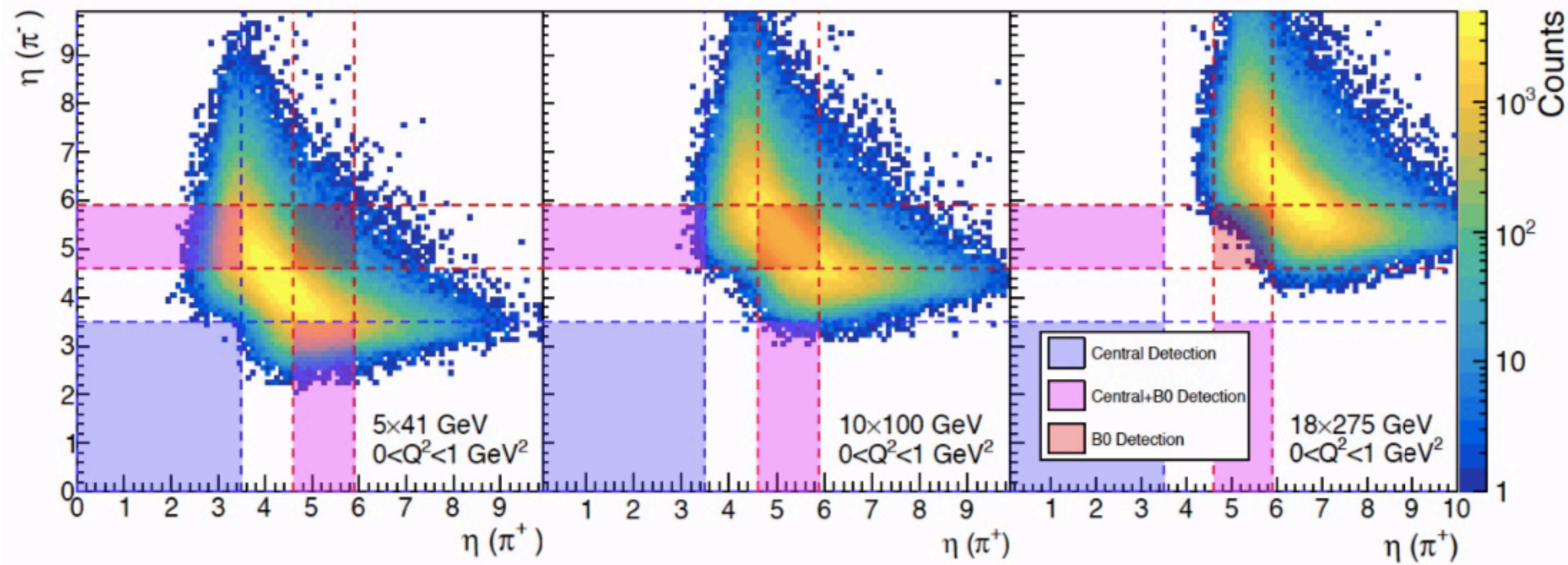
Plots: Zachary Sweger (UC Davis)

https://link.aps.org/doi/10.1103/PhysRevC.106.015204

Backward production of rho

Generator: eSTARlight

$\rho^0 \to \pi^+ \pi^-$ (100%)



Proton beam energy	ρ eff. cent.+B0
41 GeV	13%
100 GeV	49%
275 GeV	0.7%

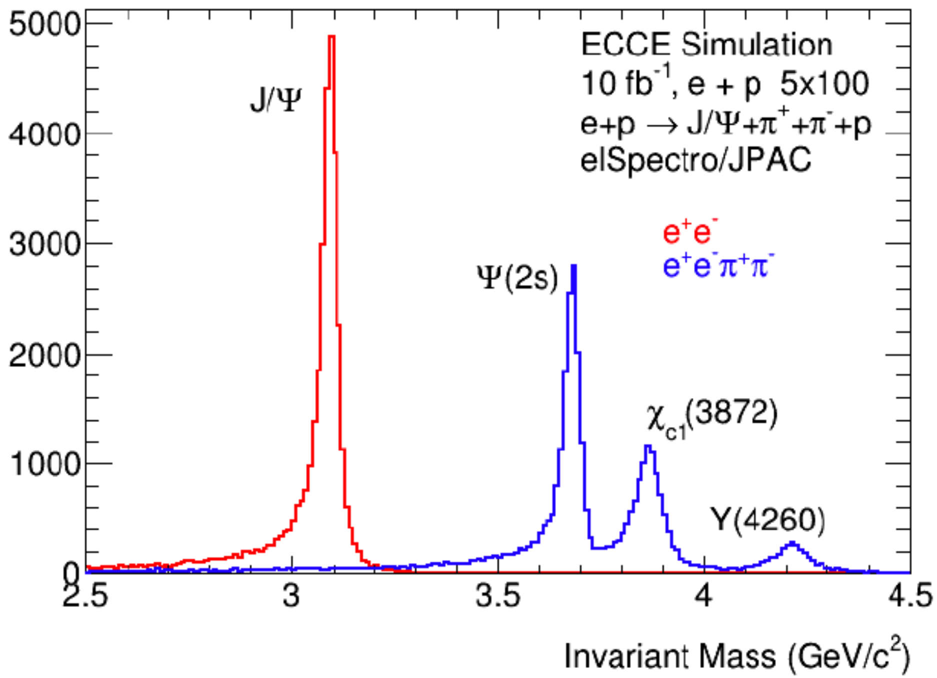
- Paper published:

https://link.aps.org/doi/10.1103/PhysRevC.106.015204

Plots: Zachary Sweger (UC Davis)

XYZ Spectroscopy

Generator: elSpectro



- XYZ Spectroscopy, spectroscopy of mesons with charm quarks
- New XYZ states have unexpectedly narrow widths inconsistent with quark model predictions
- Resolution sufficient to separate states
- Some kinematics and decays may benefit from low Q^2 tagger

Plots: Derek Glazier (Glasgow)

Planned measurements

- DVCS
- DVCS with He-4
- Incoherent DVCS on deuteron
- TCS
- Exclusive / diffractive vector mesons – a wide variety of measurements
- Upsilon production
- J/Psi in ep
- Backwards (u-channal) production: vector mesons, photon.
- Pion / kaon form factors
- Pion / kaon structure functions
- XYZ Spectroscopy
- Lambda in the target fragmentation

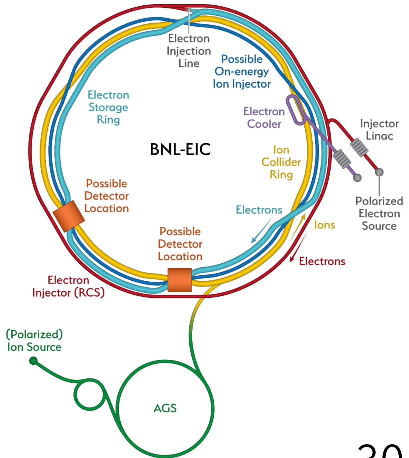
Concluding remarks

* A range of exclusive processes have been studied during the Yellow Report, proposal preparation and now EPIC design stages – studies ongoing.

* Several generator efforts are in progress to enable the studies.

* Areas in need of particular effort:

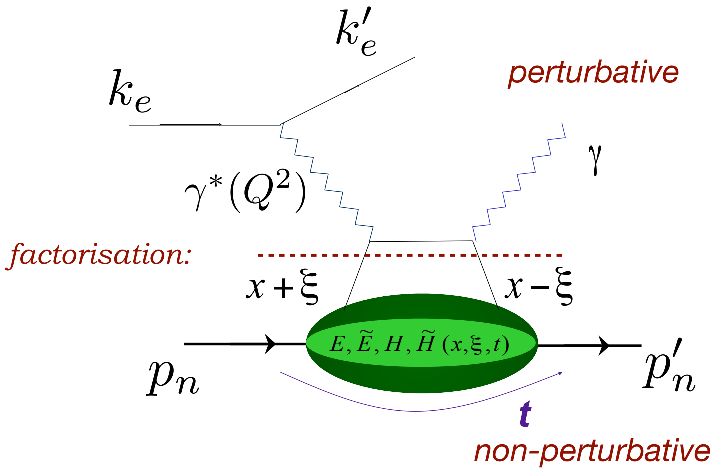
    - radiative effects (so far incorporated only into some generators),
    - generation of a very wide range of vector mesons in a range of eA
    - incorporation of backgrounds (incoherent backgrounds in eA, pi0-production backgrounds for DVCS)
    - comparison of different MC generators (eg: SARTRE and BeAGLE): benchmarking




Thank you!
Any questions?


Back-up

Deeply Virtual Compton scattering



"Handbag" diagram

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

Bjorken variable: $x_B = \dfrac{Q^2}{2\mathbf{p}_\mathbf{n} \cdot \mathbf{q}}$

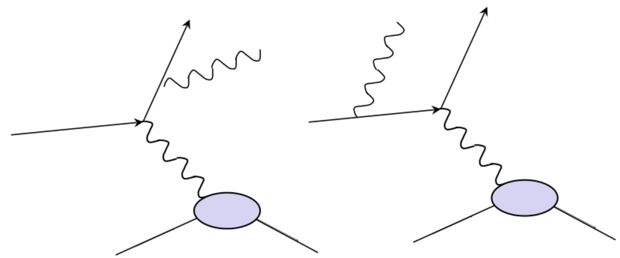
$x \pm \xi$ *longitudinal momentum fractions of the struck parton*

Skewness: $\xi \cong \dfrac{x_B}{2 - x_B}$

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

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

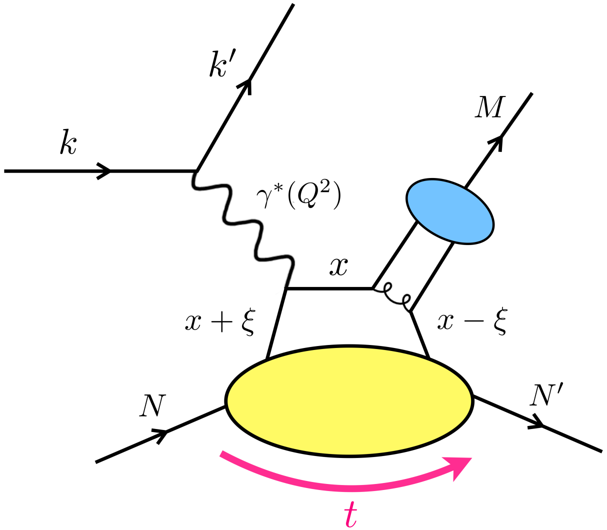
- Experimentally, measure DVCS, Bethe-Heitler and their interference:



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

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

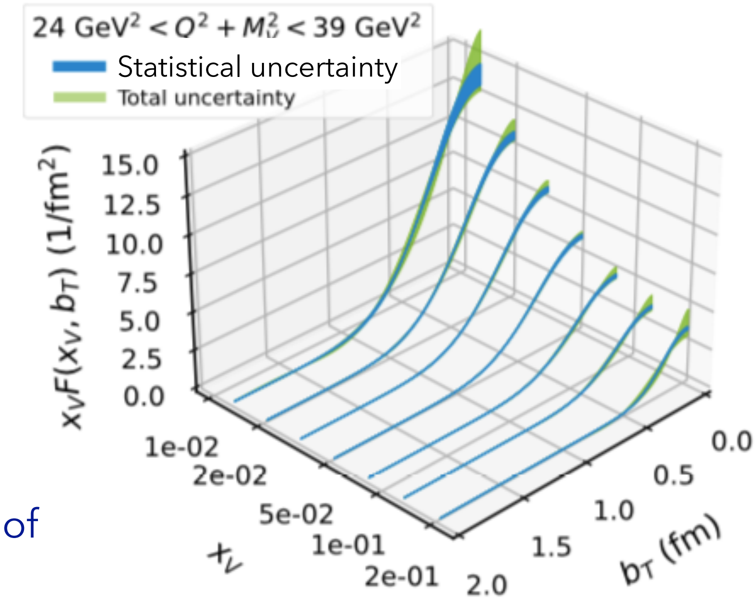
GPDs through meson-production



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

Hard scale in the scattering given by: $Q^2 + M_v^2$

Hence: $x_v = \frac{Q^2+M_v^2}{2\mathbf{p}\cdot\mathbf{q}}$



Fourier transform of J/Psi-production cross-section

- Light vector-meson production additionally enables flavour-decomposition of GPDs.

- Light pseudo-scalar meson production gives, at high Q², access to parity-odd GPDs: $\tilde{H}$, $\tilde{E}$ and at low Q² to chiral-odd, transversity GPDs which are not accessible at leading-twist in DVCS processes.

Detector requirements

4π hermetic detector with low mass inner tracking.

Central detector, including a solenoid magnet: acceptance in $-4 < \eta < 4$, with full coverage in $|\eta| < 3.5$.

- Tracking and momentum measurement
- Electron ID
- Hadron ID
- Jet energy measurement

Barrel detector ($|\eta| < 1$) + two disc end-caps (forward/hadron end-cap and backward/electron endcap).

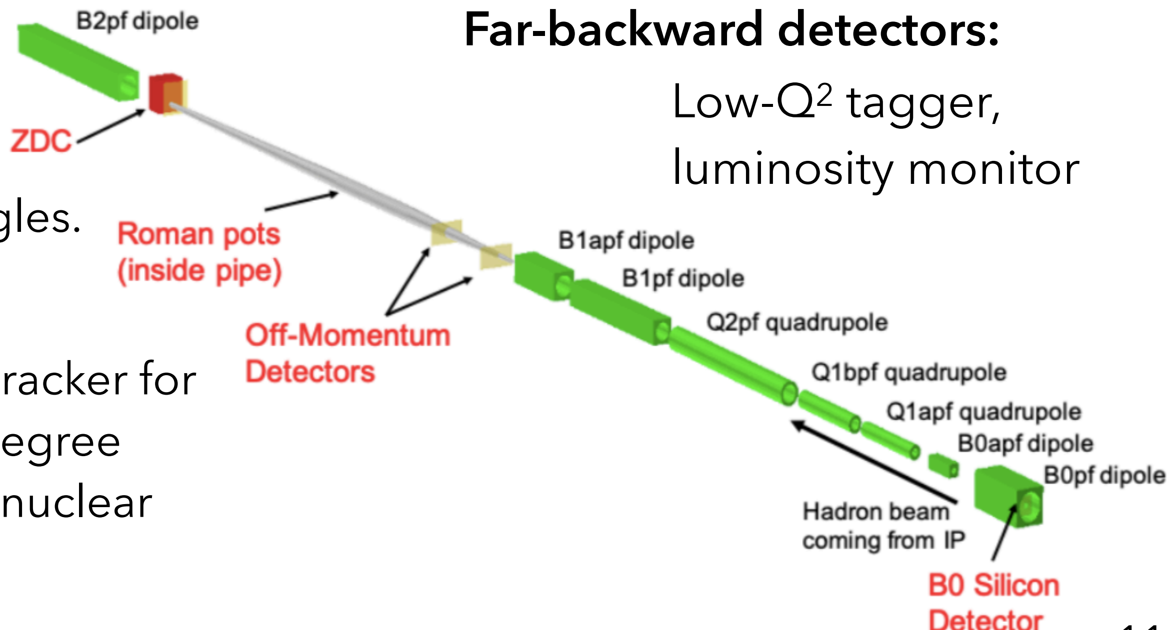
Far-backward detectors:

Low-Q^2 tagger, luminosity monitor

Far-forward detectors:

Far from interaction point, very low angles.

Roman Pots inside the beam pipe, B0 tracker for larger angles, large acceptance Zero degree Calorimeter (ZDC) to detect neutrons (nuclear breakup / neutral decay products)



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 3 - 10 (18) GeV
- ✓ Luminosity L_{ep} ~ 10^{33-34} $cm^{-2}s^{-1}$
- ✓ 20 - 100 (140) GeV Variable CoM

For e-A collisions at the EIC:

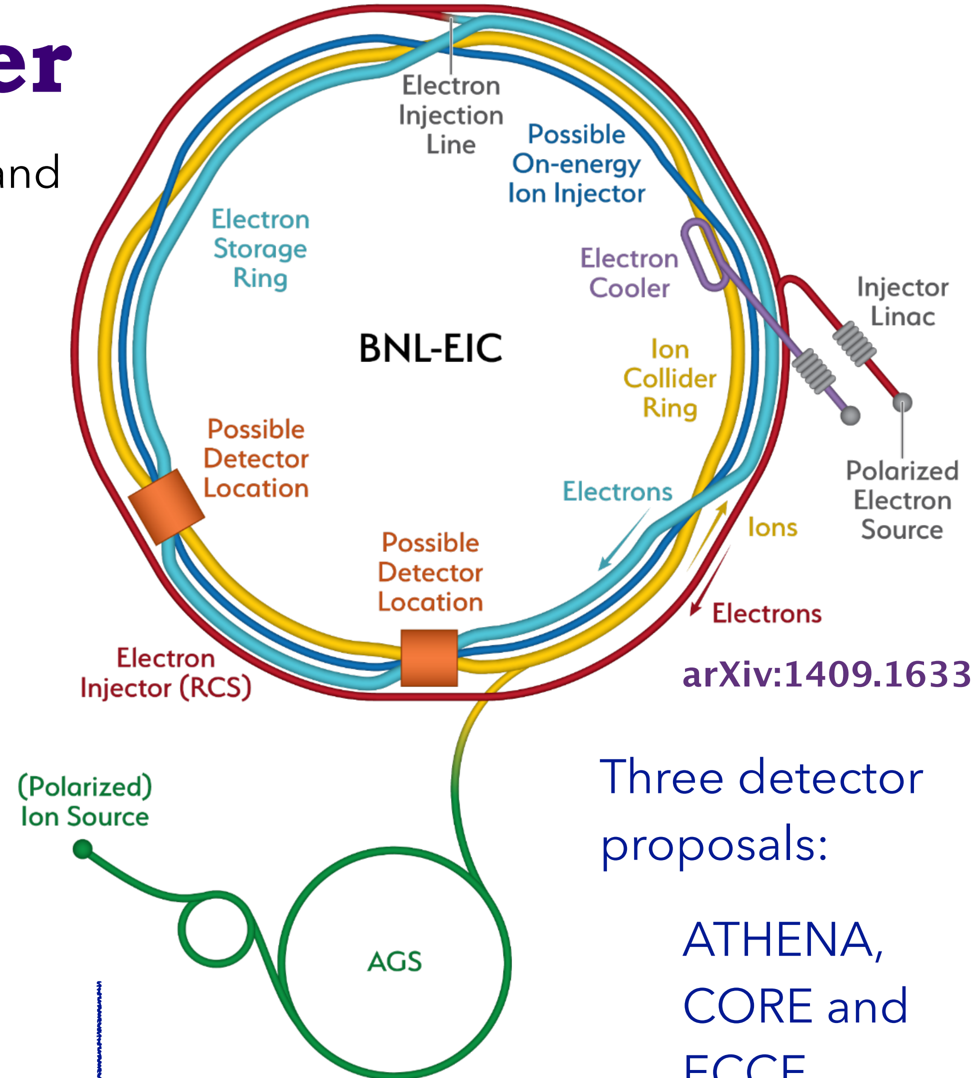
- ✓ Wide range of nuclei
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable centre of mass energy

Brookhaven National Lab selected as the site

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)



arXiv:1409.1633

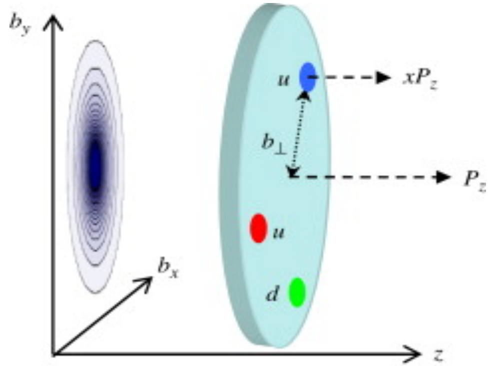
Three detector proposals:

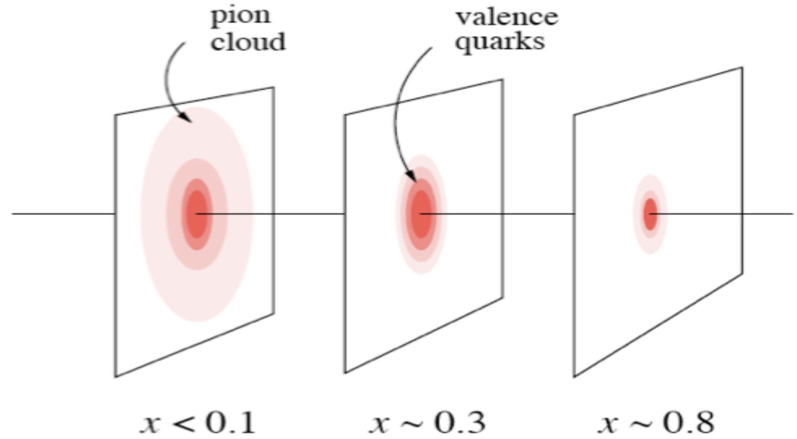
ATHENA, CORE and ECCE

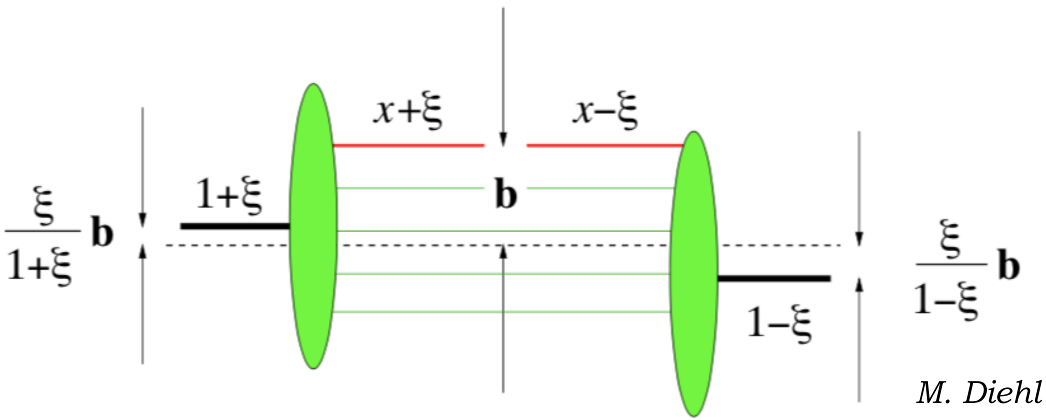
Merged to form the new "Detector 1" collaboration: ePIC

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.







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

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

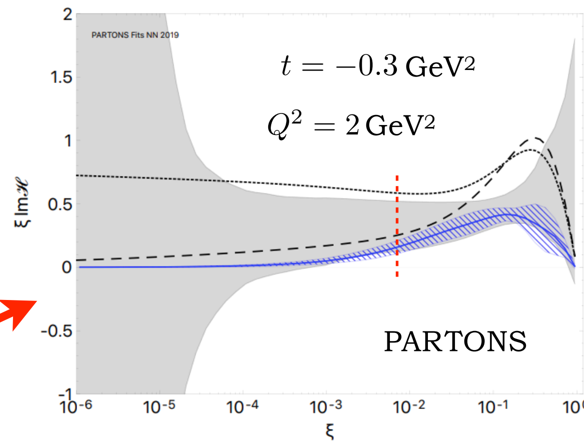
  Assuming double-distribution parametrisation: $\Delta(t) \propto d_1(t)$

Extracting GPDs

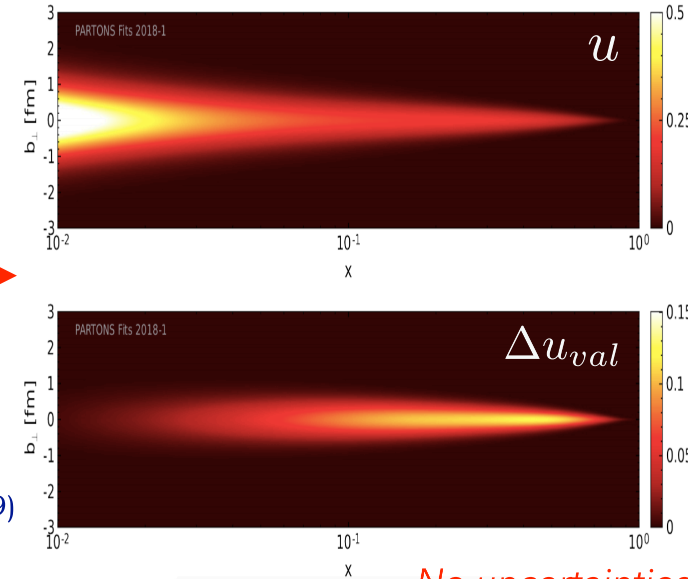
Ongoing imaging efforts on available world-data, strongest constraints in the valence region:

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.



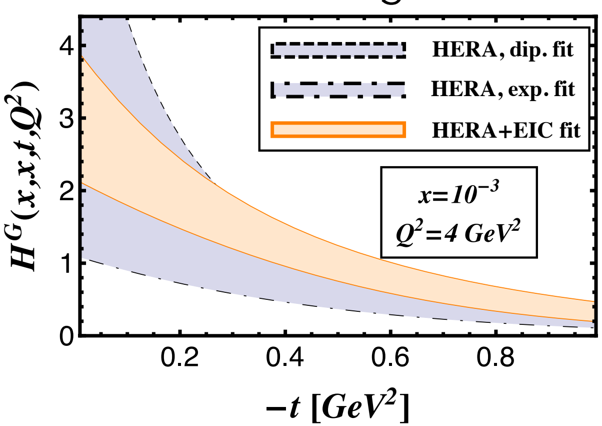
H. Moutarde *et al.*, Eur. Phys. J C79, 614 (2019)



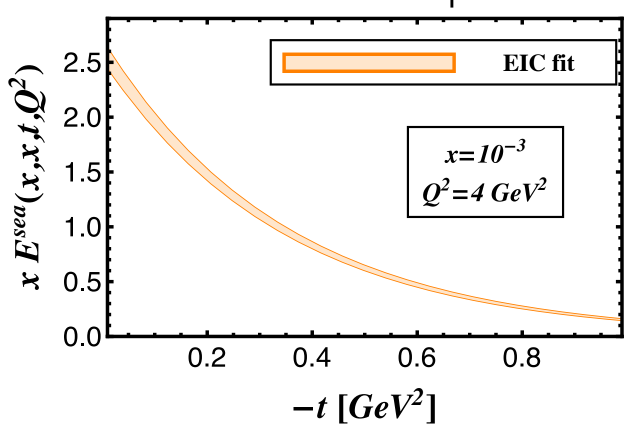
No uncertainties shown

Anticipated constraints from EIC on GPDs H and E:

GPD H for gluons

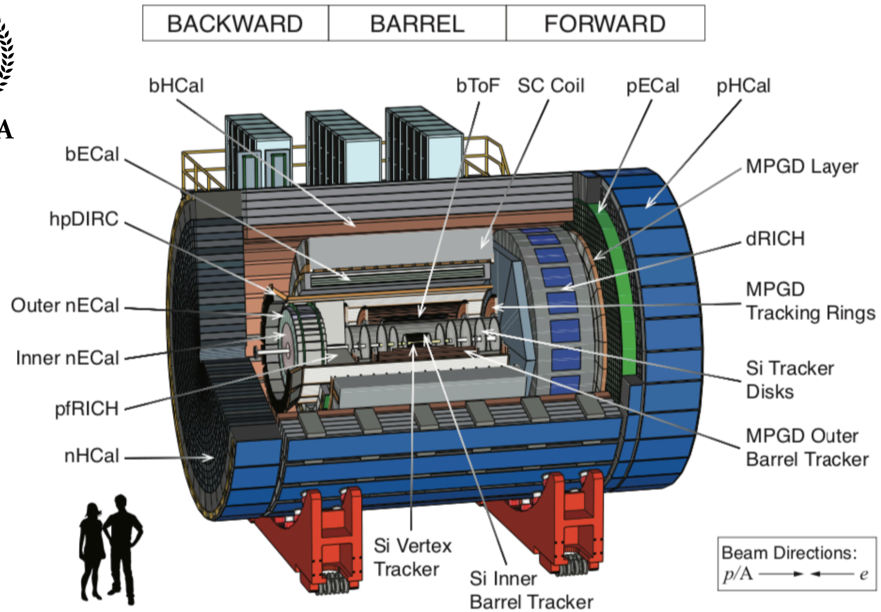


GPD E for sea quarks



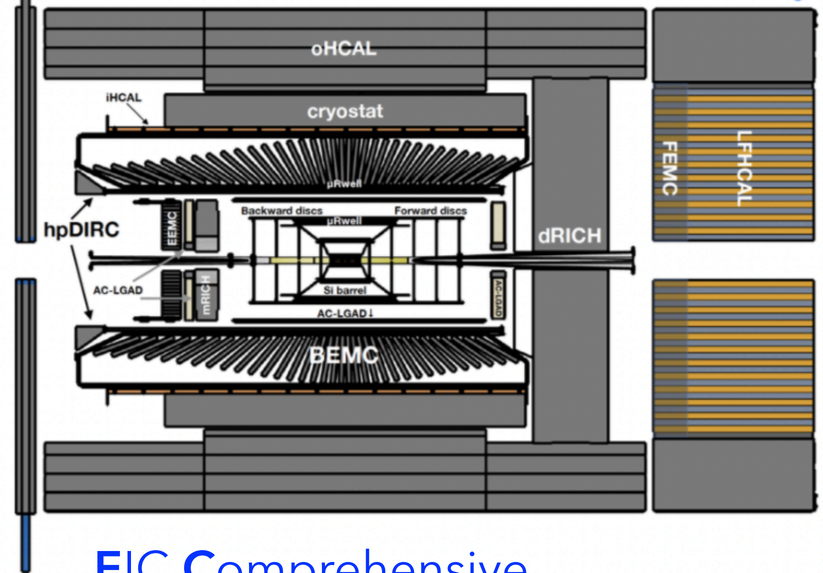
Measurements at EIC will provide significant constraints at low-x and enable extraction of as-yet unknown GPDs.

https://arxiv.org/abs/2103.05419



A **T**otally **H**ermetic **E**lectron-**N**ucleus **A**pparatus

https://sites.temple.edu/eicatip6/



EIC **C**omprehensive **C**hromodynamics **E**xperiment

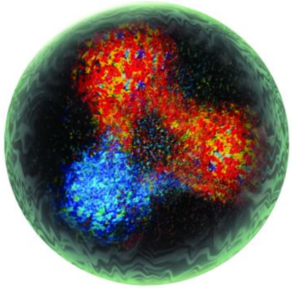
https://www.ecce-eic.org

ePIC (Electron-Proton and -Ion Collider detector):

The new detector 1 collaboration detector, based around the geometry of the BaBaR solenoid, incorporating sub-detector designs from both the ECCE and ATHENA proposals.

Design still in flux, to be finalised this year.

New solenoid (MARCO) to be built by Saclay: 1.7 T (max field possible: 2T)



Wigner function:
full phase space parton
distribution of the nucleon

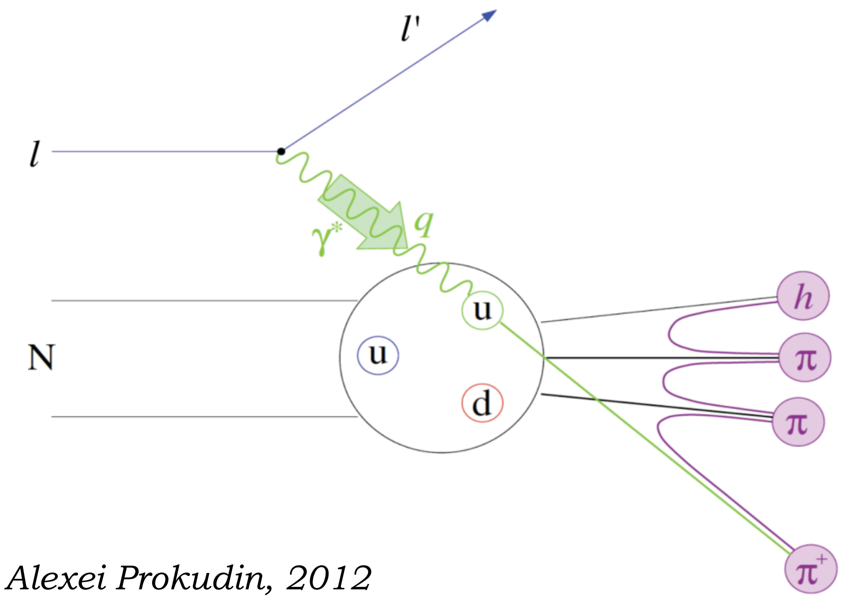
Generalised Transverse Momentum Distributions (GTMDs)

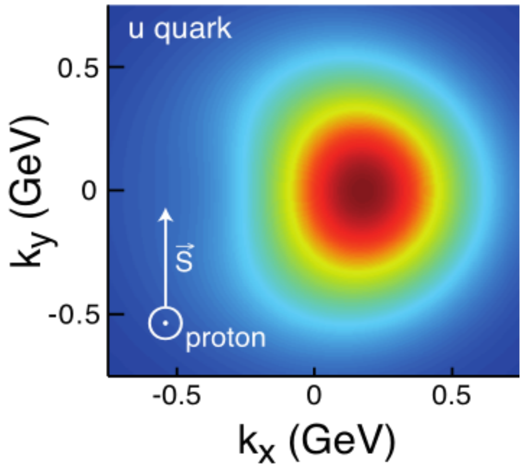
$$\int d^2 b_T$$

Transverse Momentum Distributions (TMDs)

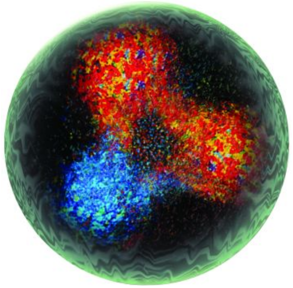
* Semi-inclusive Deep Inelastic Scattering (SIDIS), di-hadron production, jets, Drell-Yann.

SIDIS:





Sivers function: Alexei Prokudin, 2012
(using M. Anselmino et al., J. Phys. Conf. Ser. 295, 012062 (2011))



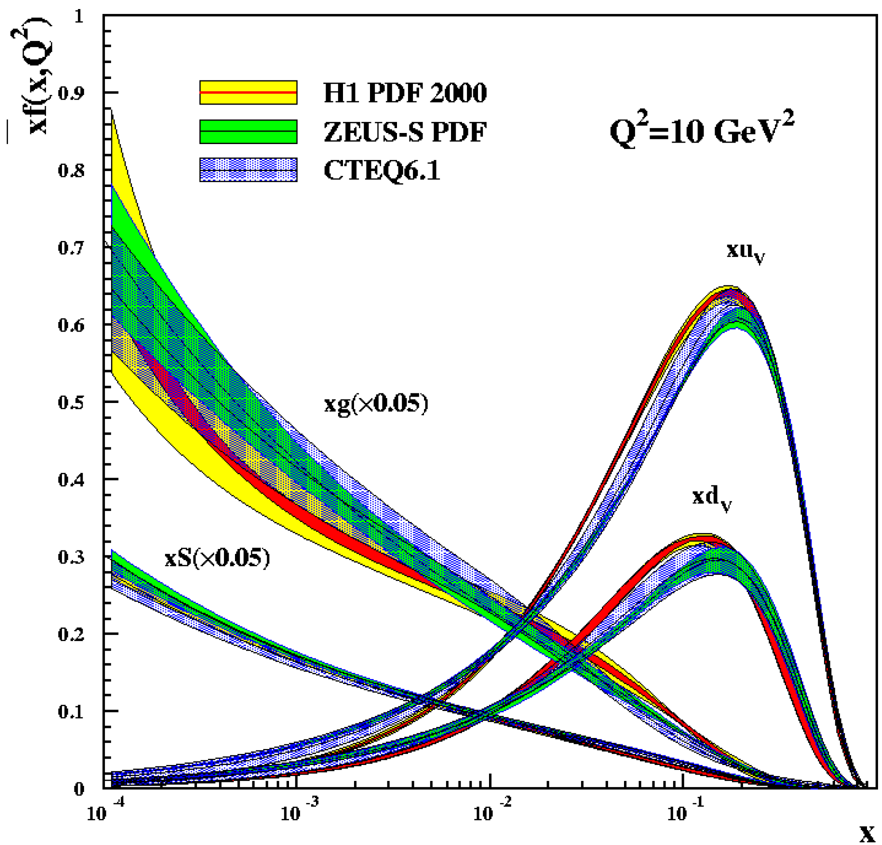
Wigner function:
full phase space parton distribution of the nucleon

Generalised Transverse Momentum Distributions (GTMDs)

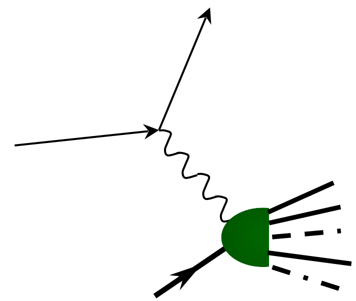
$$\int d^2 b_T$$

Transverse Momentum Distributions (TMDs)

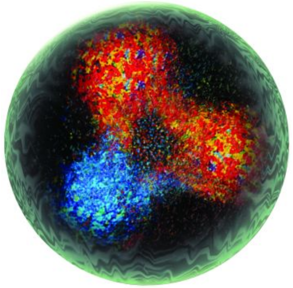
$$\int d^2 k_T$$



Parton Distribution Functions (PDFs)

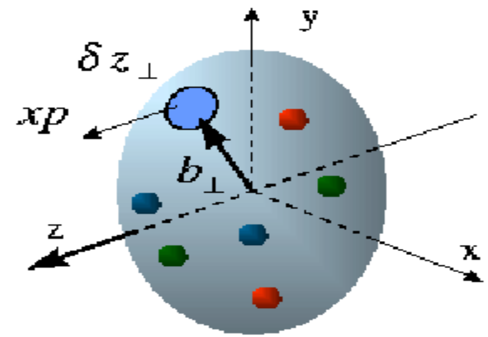


* Deep Inelastic Scattering (DIS)



Wigner function: full phase space parton distribution of the nucleon

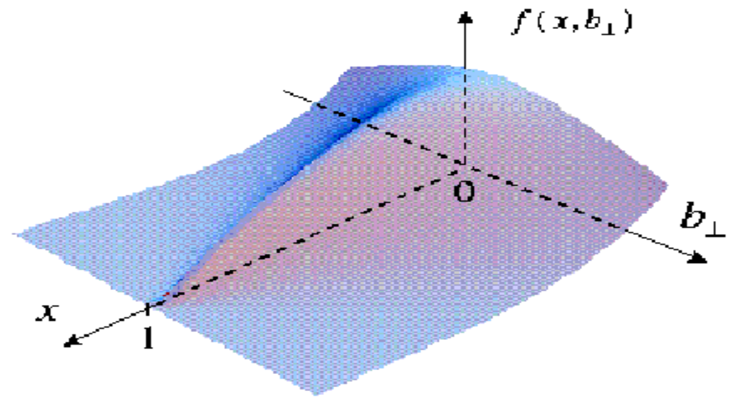
Generalised Transverse Momentum Distributions (GTMDs)



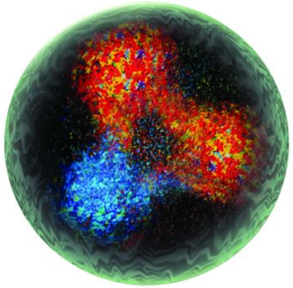
$$\int d^2 k_T$$

Generalised Parton Distributions (GPDs)

- relate, in the infinite momentum frame, transverse position of partons ($b_{\perp}$) to longitudinal momentum (x).



✱ Deep exclusive reactions, e.g.: Deeply Virtual Compton Scattering, Deeply Virtual Meson production.



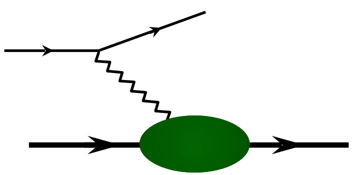
Wigner function:
full phase space parton
distribution of the nucleon

Generalised Transverse Momentum Distributions (GTMDs)

$$\int d^2 k_T$$

Generalised Parton Distributions (GPDs)

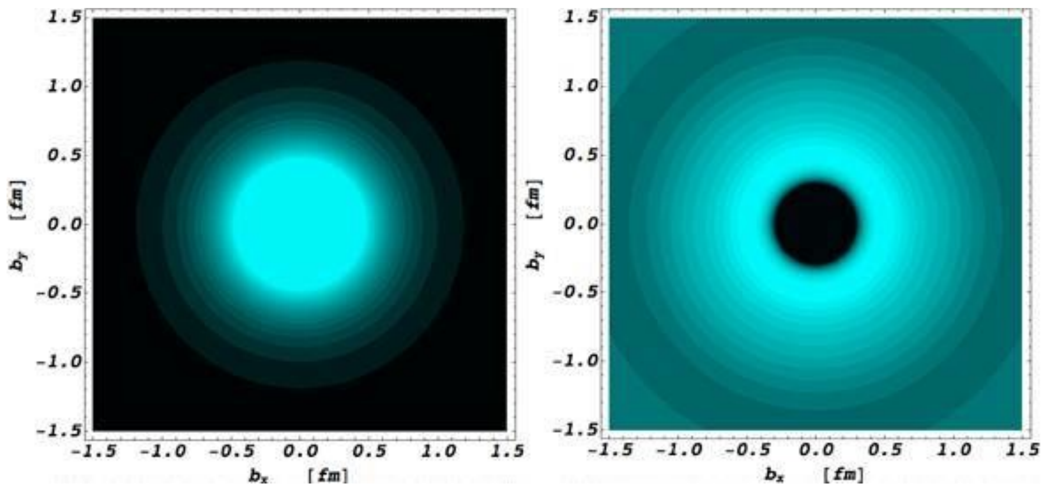
$$\int dx$$



Elastic scattering

Form Factors
eg: $G_{E,}\ G_M$

Fourier Transform of electric Form Factor: transverse charge density of a nucleon



proton neutron

C. Carlson, M. Vanderhaeghen
PRL 100, 032004 (2008)

Imaging light nuclei

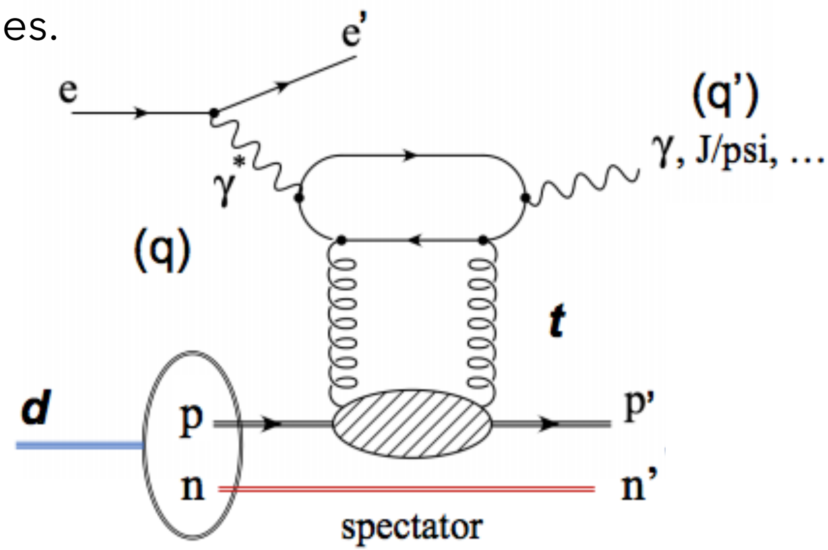
Coherent DVCS on light nuclei requires their intact detection and provides access to nuclear GPDs: imaging of partons in a nuclear medium.

Deuteron: spin-1. Many more GPDs at leading twist – theoretically well-described, experimentally almost untested.

^{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.



K. Tu, A. Jentsch

Flavour-decomposition, sensitivity to different GPDs…

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).

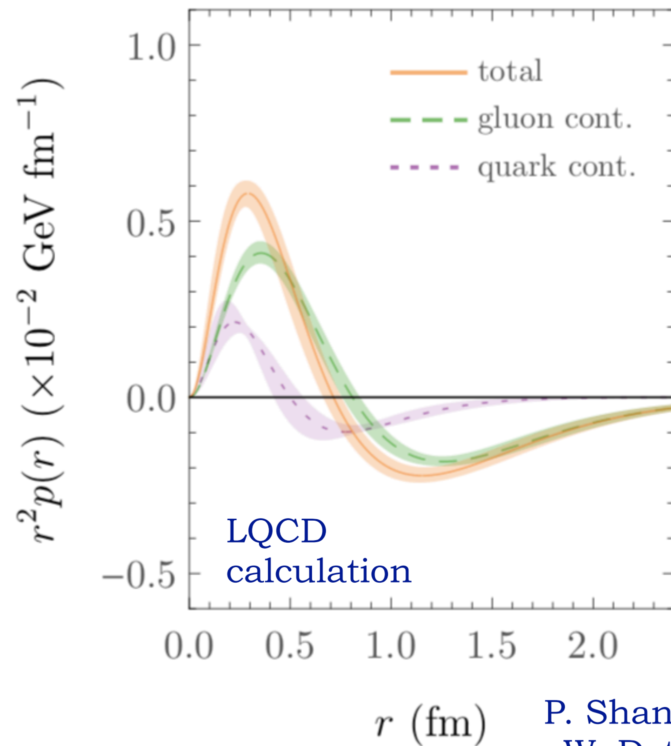
X. D. Ji, PR**D 55**, 7114-7125 (1997) M. Polyakov, PL**B 555**, 57-62 (2003)

- 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.



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

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

TCS observables

- Unpolarised cross-sections:

  sensitive to $\mathcal{R}e\ \mathcal{H}$.

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

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

suppressed

- Circularly-polarised photon cross-section: access to $\mathcal{I}m\ \mathcal{H}$.
- 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 $\mathcal{I}m\ \mathcal{H}$

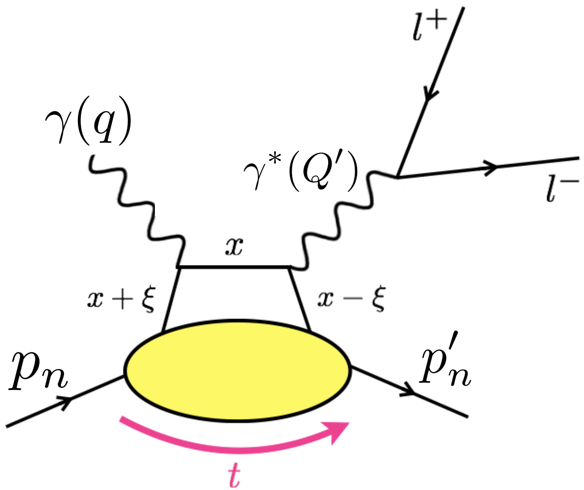
- Forward - backward asymmetry:

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

access to $\mathcal{R}e\ \mathcal{H}$

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

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.

- Factorisation ensured by hard scale of γ^* virtuality:

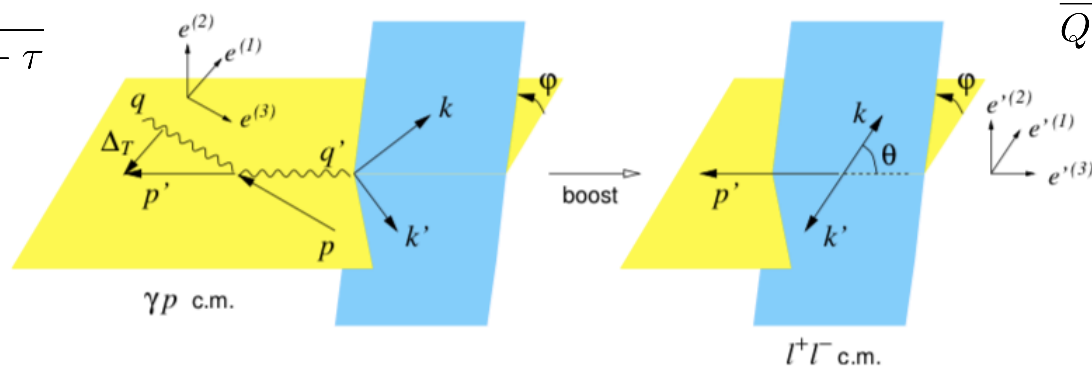
$$\frac{t}{Q'^2} << 1$$

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

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

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

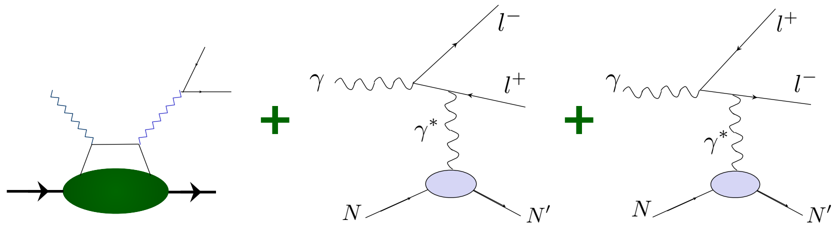
θ: angle between l^+ and scattered proton in lepton CMS



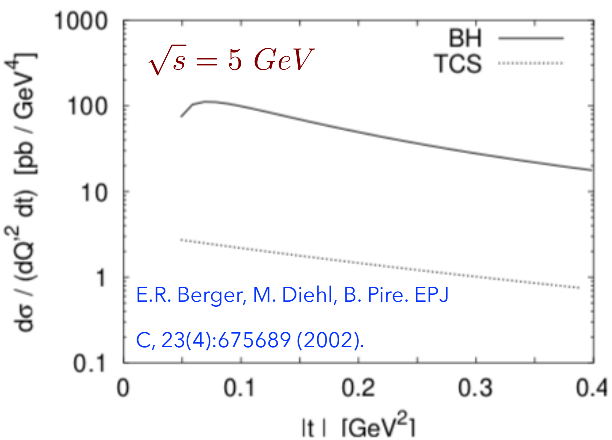
- Measurements establish dependence on Q^2, x, t and φ (angle between leptonic and hadronic planes).

TCS observables

- Similarly to DVCS, TCS process interferes with Bethe-Heitler at the amplitude level.



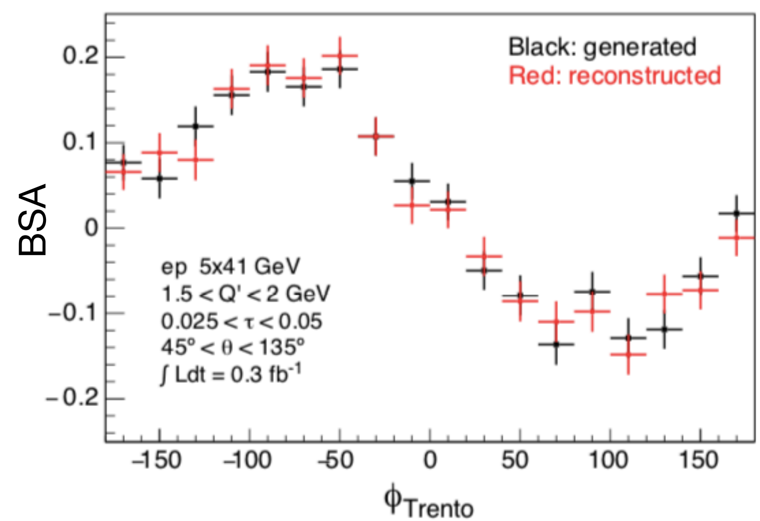
$$\sigma(\gamma p \to p' e^+ e^-) = \sigma_{BH} + \sigma_{TCS} + \sigma_{INT}$$



- TCS suppressed by factor of 100 wrt BH: hard to measure cross-sections. Asymmetries dominated by interference term.

- 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:

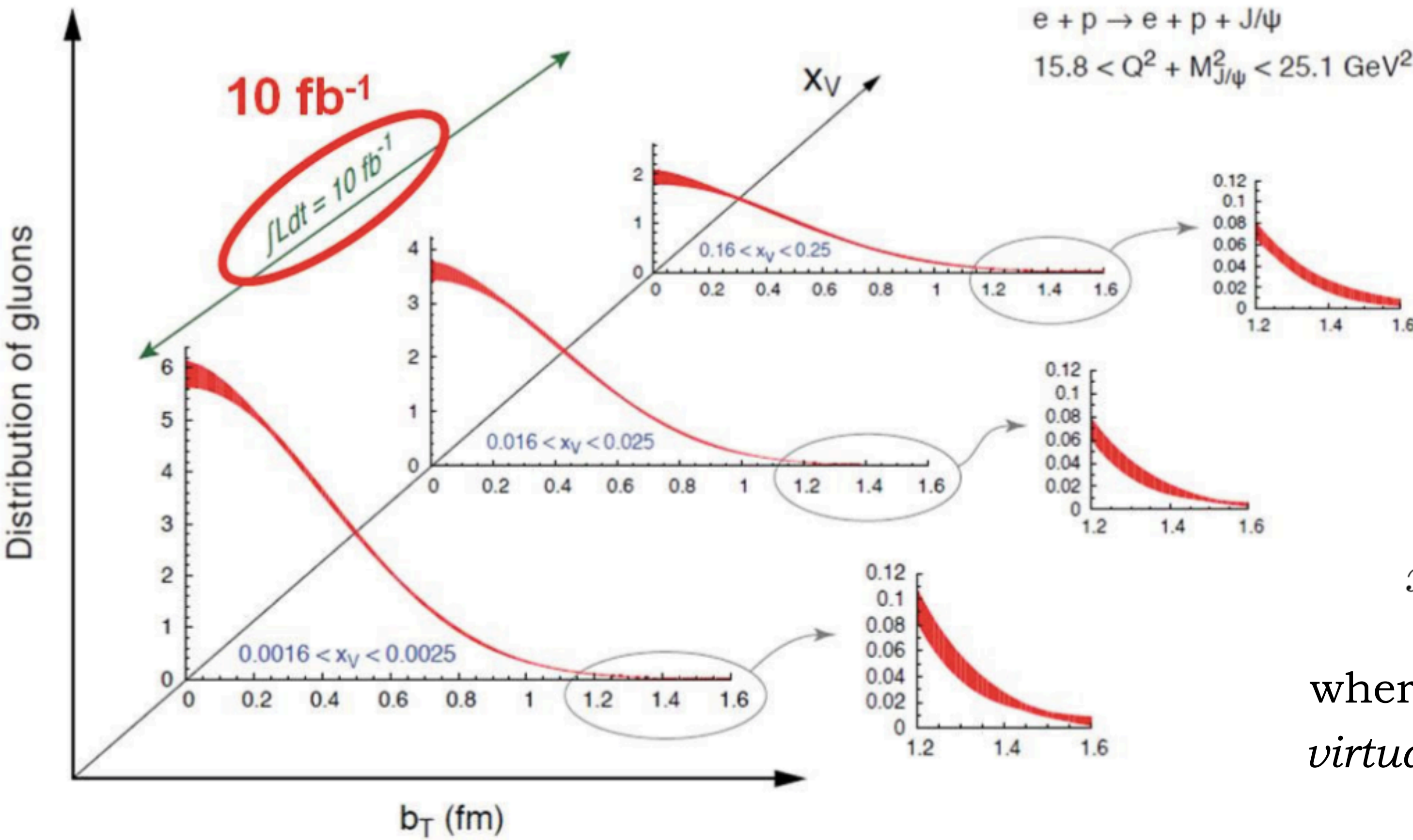
$$A_{FB}(\theta, \phi) = \frac{d\sigma(\theta, \phi) - d\sigma(180^\circ - \theta, 180^\circ + \phi)}{d\sigma(\theta, \phi) + d\sigma(180^\circ - \theta, 180^\circ + \phi)}$$

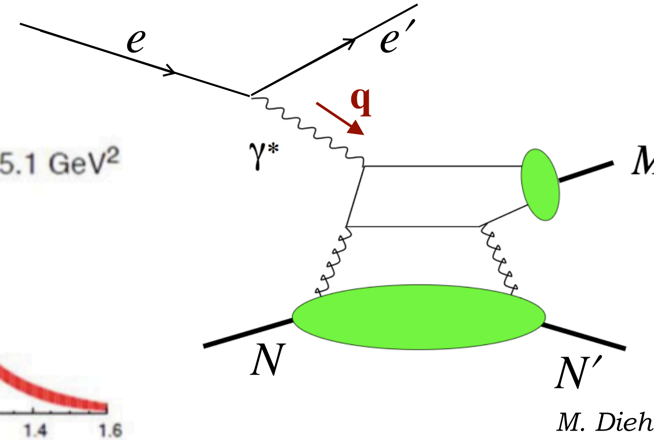
access to $\mathcal{Re}\ \mathcal{H}$

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 $Q^2 = -\mathbf{q}^2 = -(\mathbf{p}_e - \mathbf{p}_e')^2$

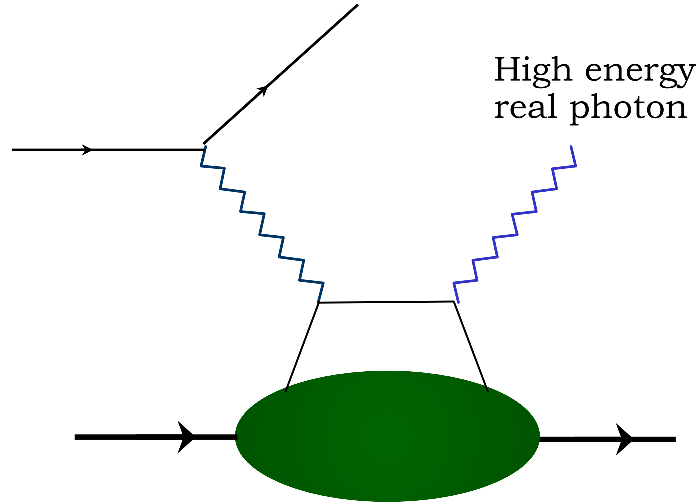
virtuality of exchanged photon

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

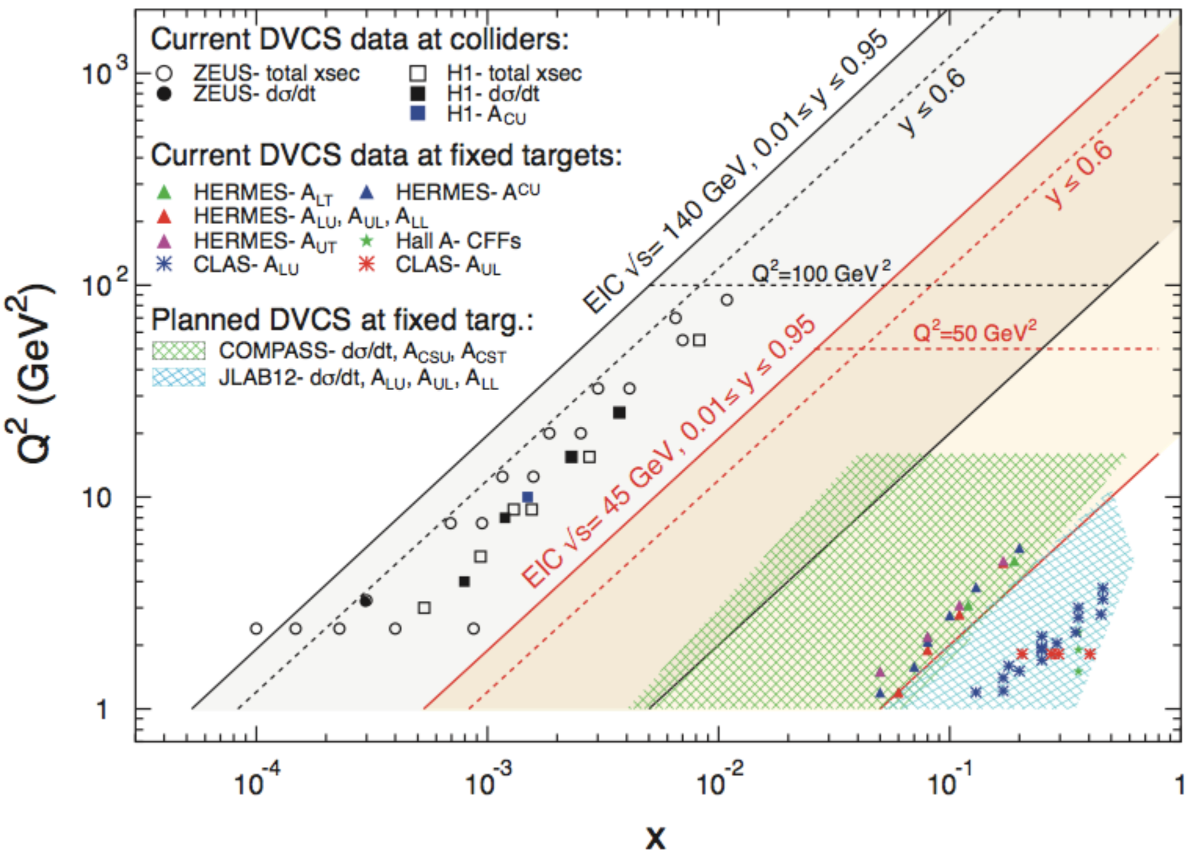
EIC White Paper, *Eur. Phy. J. A 52, 9 (2016)*

Nucleon tomography: imaging quarks

* Quark GPDs are accessible in a related process: Deeply Virtual Compton Scattering (DVCS)



DVCS kinematic reach at the EIC:



* 3D images of sea quark and gluon distributions from exclusive reactions: DVCS and DVMP.

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