Studying Generalised Parton Distributions with the Electron-Ion Collider

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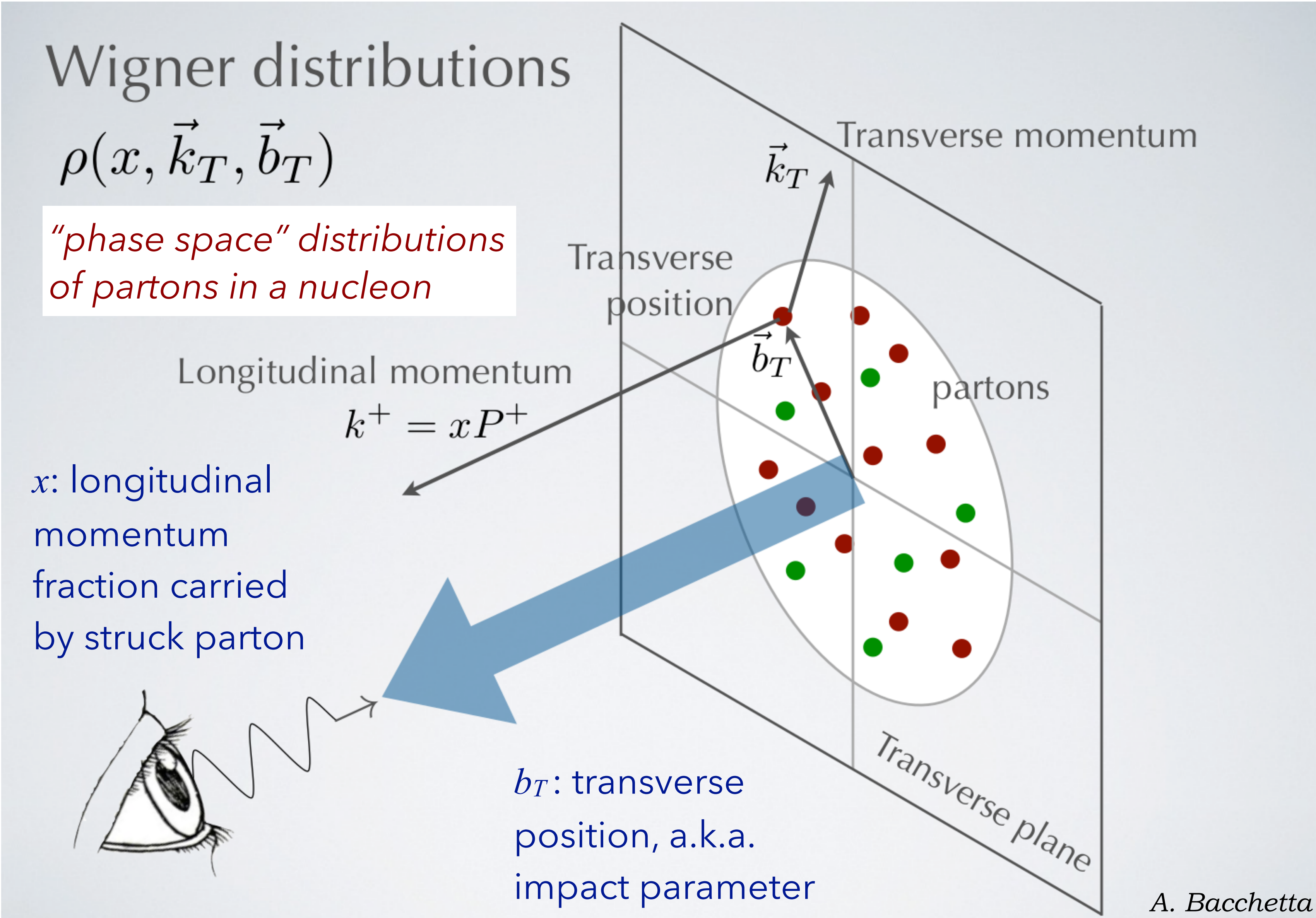
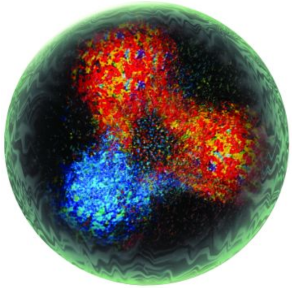
CIPANP - Orlando, Florida, USA

30th August 2022

A constructivist view of the nucleon

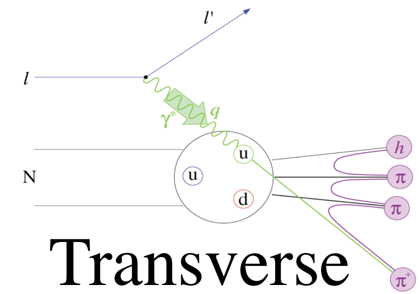




Wigner function:
full phase space parton distribution of the nucleon

Generalised Transverse Momentum Distributions (GTMDs)

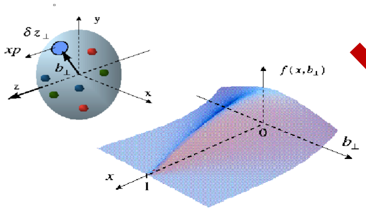
Possible access via exclusive di-jet production or exclusive π⁰-production at high Q².

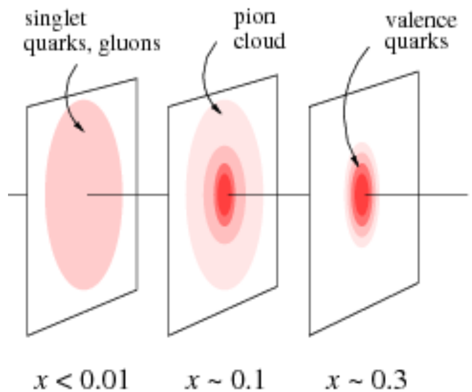


$\int d^2k_T$

$\int d^2b_T$

Generalised Parton Distributions (GPDs)

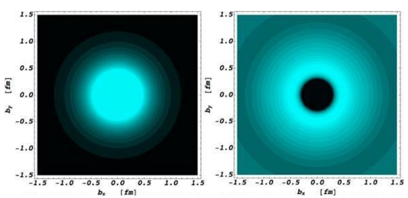




Transverse Momentum Distributions (TMDs)

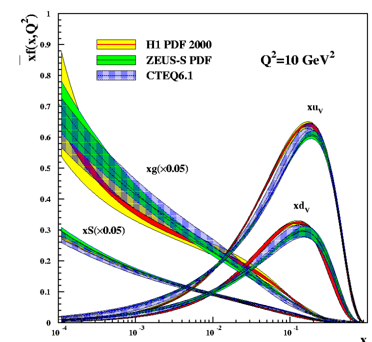
$\int dx$

$\int d^2k_T$

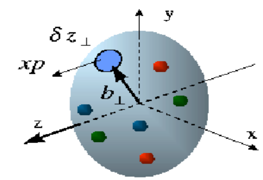


Form Factors
eg: G_{E}, G_{M}

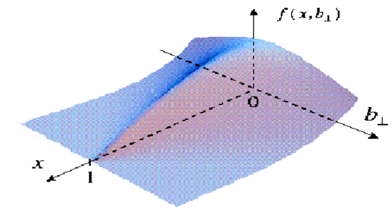
Parton Distribution Functions (PDFs)



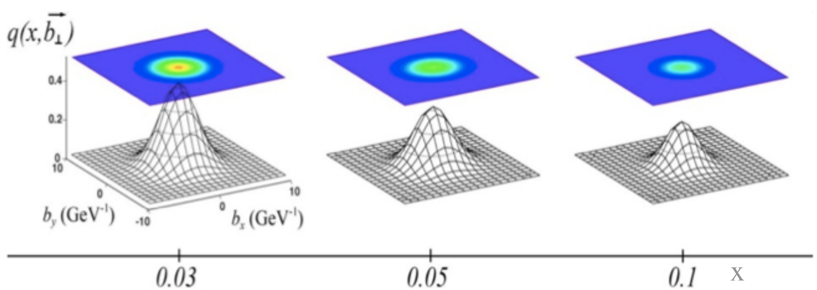
Generalised Parton Distributions



- 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:

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

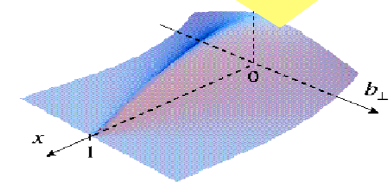
$$= \frac{1}{2}\int_{-1}^{1} xdx \left\{ H^q(x,\xi,0) + E^q(x,\xi,0) \right\}$$

* 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.

Generalised Parton Distributions

A. Metz, Tuesday plenary



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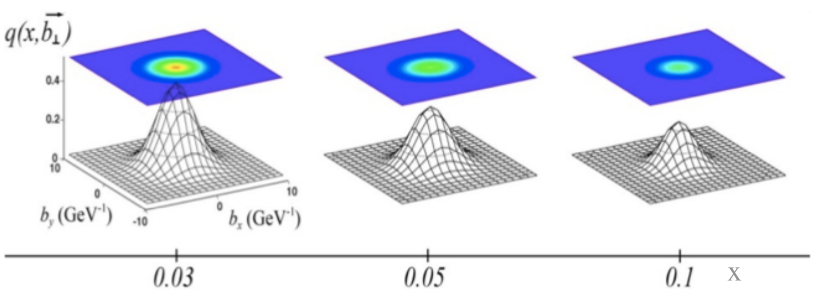

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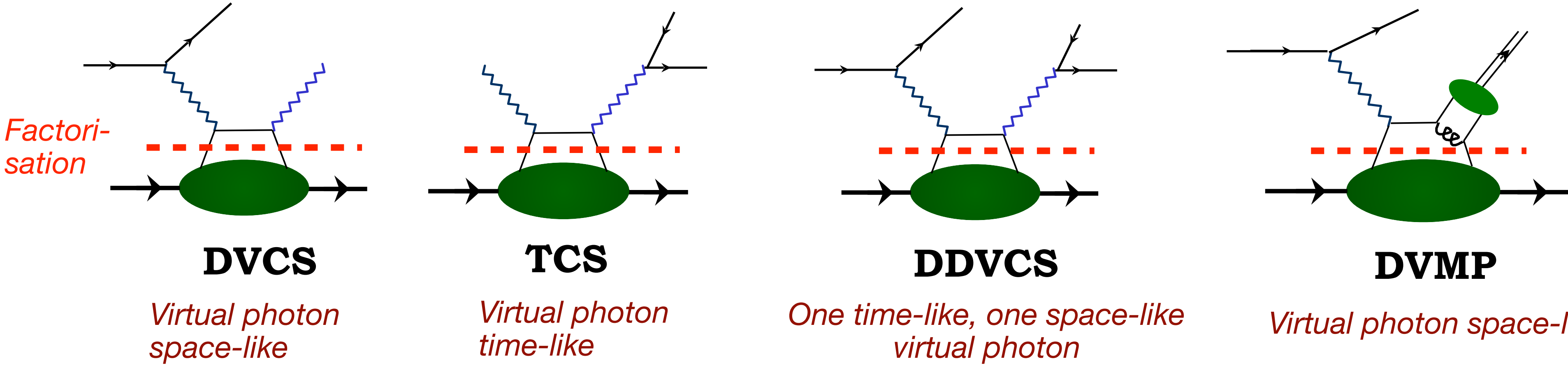
Experimental access to GPDs

Accessible in *exclusive* processes, where all final state particles are determined, *eg*:

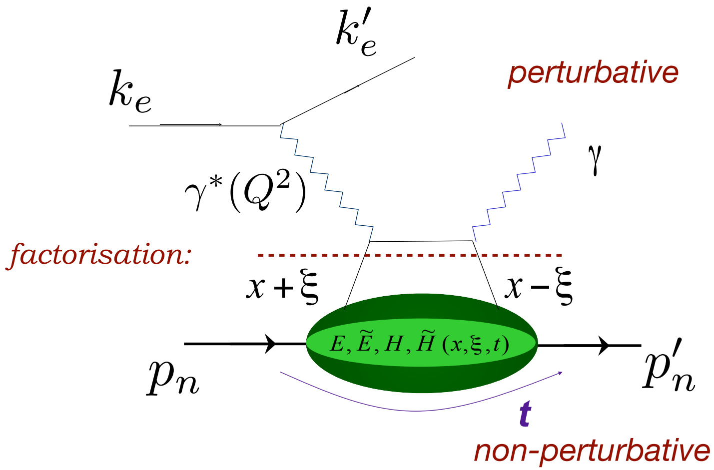
- Deeply Virtual Compton Scattering (DVCS)
- Time-like Compton Scattering (TCS)
- Hard Exclusive Meson Production (HEMP) – a.k.a. Deeply Virtual Meson Production (DVMP)
- Double DVCS
- Certain diffractive processes, eg: diffractive ρ-production with the emission of a meson or virtual photon from the 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.



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

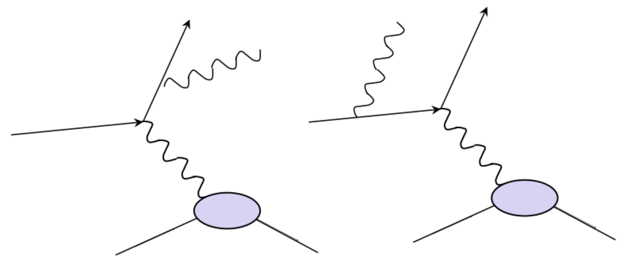
$x \pm \xi$ *longitudinal momentum fractions of the struck parton*

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:

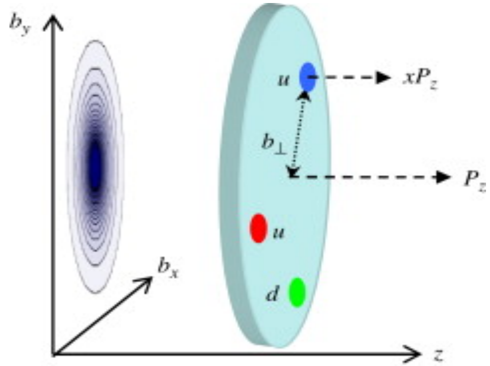


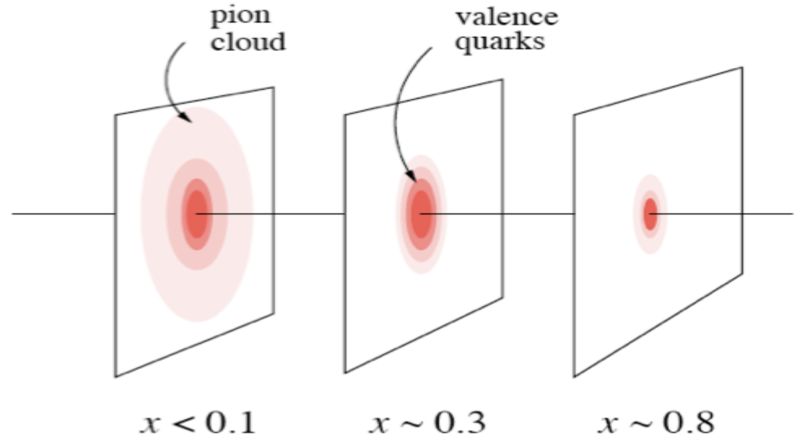
$$d\sigma \propto |T_{DVCS}|^2 + |T_{BH}|^2 + \quad T_{BH}T^*{}_{DVCS} + T_{DVCS}T^*{}_{BH}$$

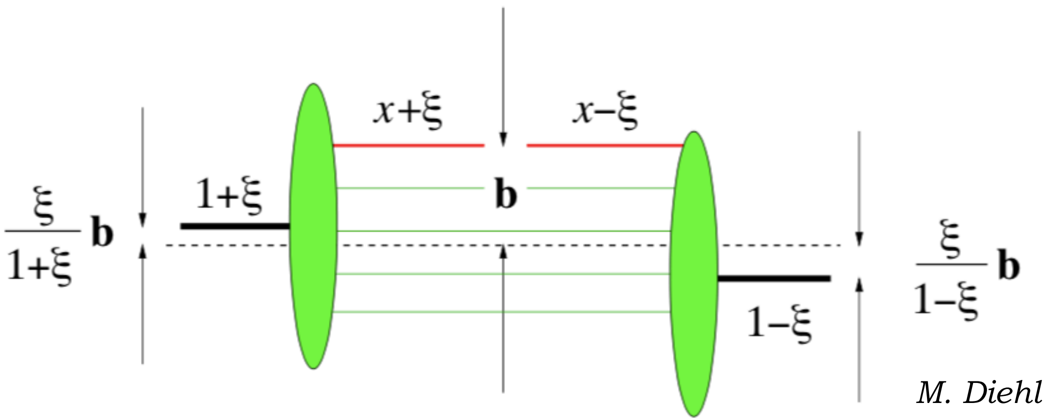
- Observables are parametrised in terms of Compton Form Factors (CFFs): complex functions where $\mathcal{Re}$ parts are integrals of GPDs over x and $\mathcal{Im}$ parts are GPDs at $x = \pm\xi$

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 $\mathcal{Re}$ and $\mathcal{Im}\ \mathcal{H}$:

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

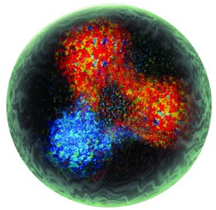
  Assuming double-distribution parametrisation: $\Delta(t) \propto d_1(t)$

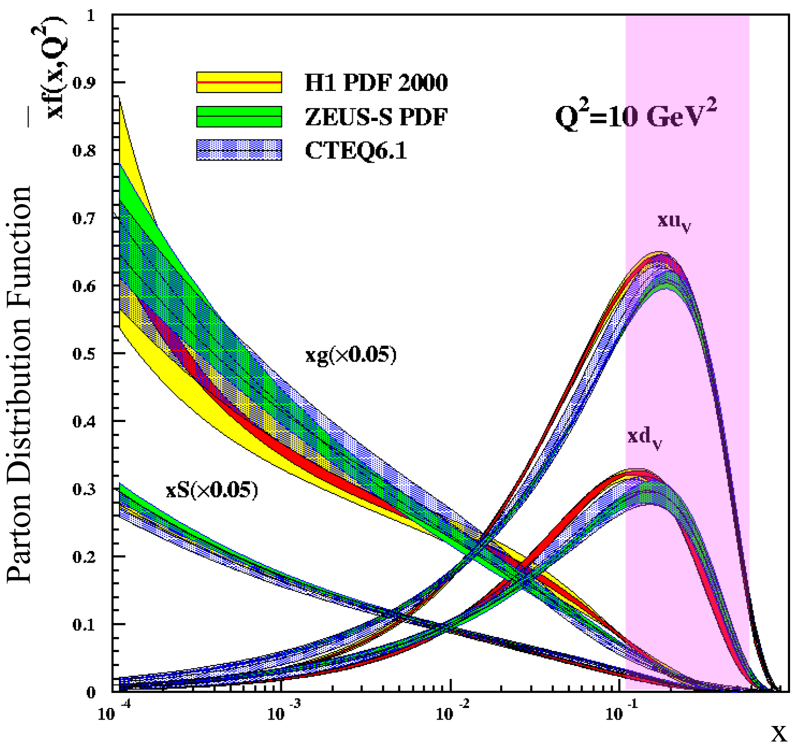
Nucleon at different scales

Valence quarks

Jefferson Lab: fixed-target electron scattering

$0.1 < x_B < 0.7$





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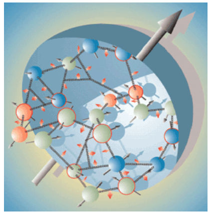

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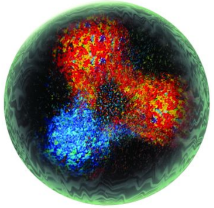
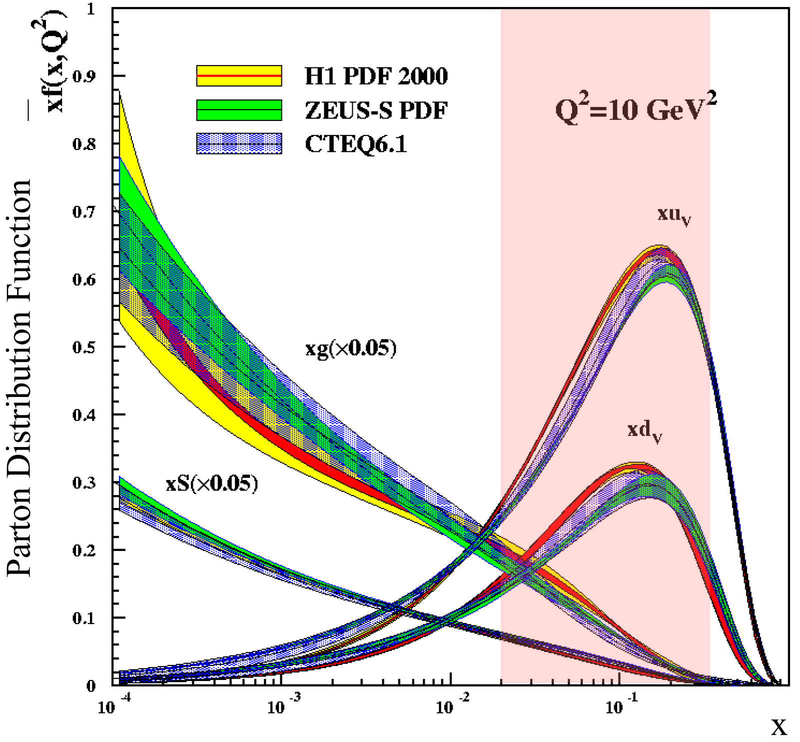


Sea quarks

hermes

HERMES: fixed gas-target electron/positron scattering

$0.02 < x_B < 0.3$



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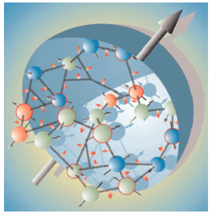

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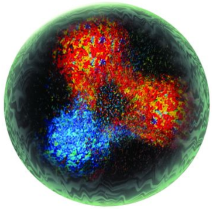
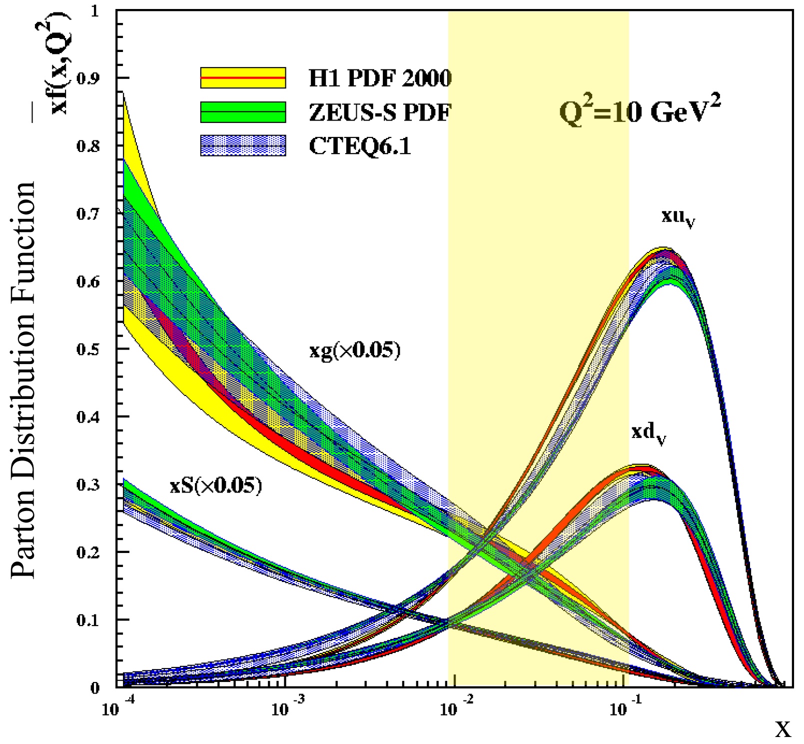




Sea quarks

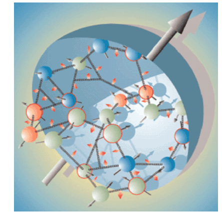
HERMES: fixed gas-target electron/positron scattering

$0.02 < x_B < 0.3$

COMPASS: fixed-target muon scattering

$0.01 < x_B < 0.1$

Nucleon at different scales



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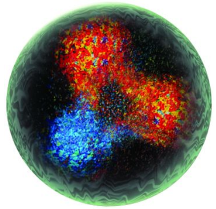

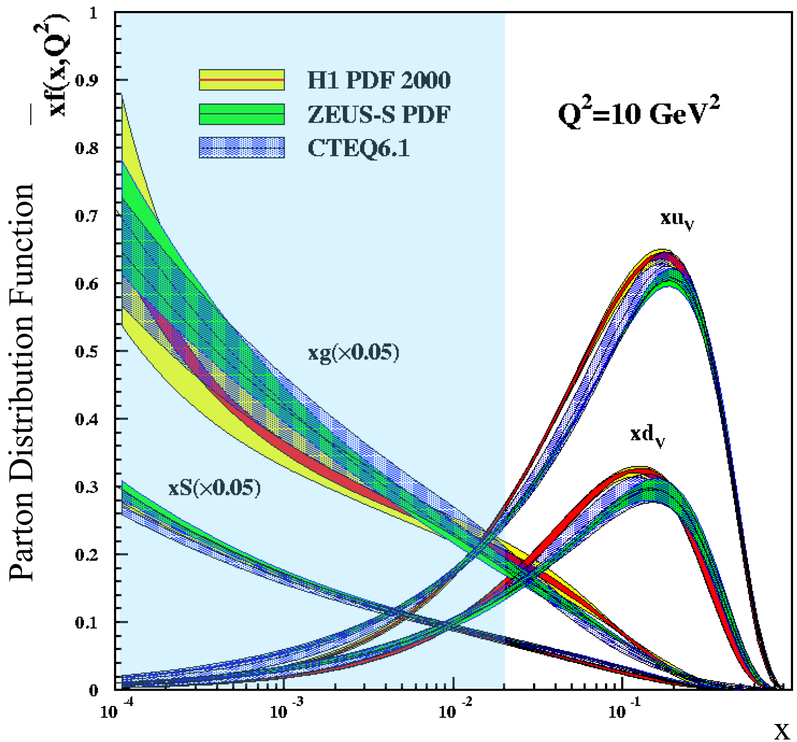

Sea quarks

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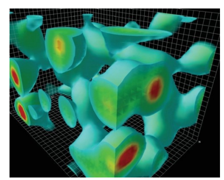
The glue

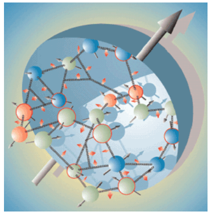


Derek Leinweber

ZEUS/H1: electron/positron-proton collider

$10^{-4} < x_B < 0.02$

Nucleon at different scales



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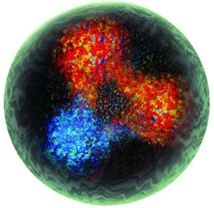

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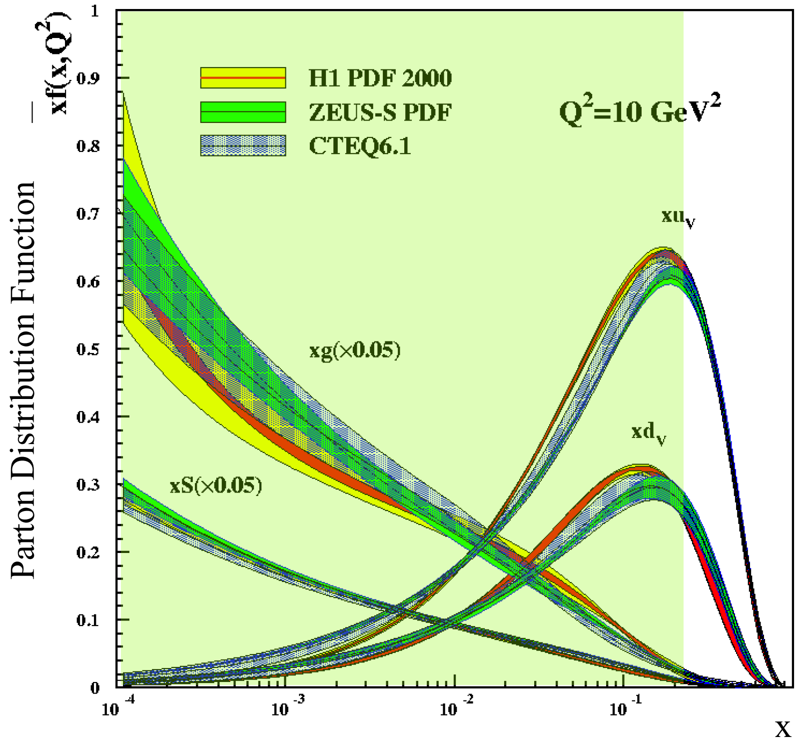

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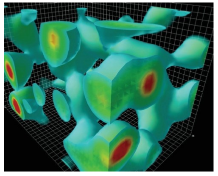

Derek Leinweber

ZEUS/H1: electron/positron-proton collider

$10^{-4} < x_B < 0.02$

EIC: $10^{-4} < x_B < 0.2$

Luminosity 100 - 1000 times that of HERA

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

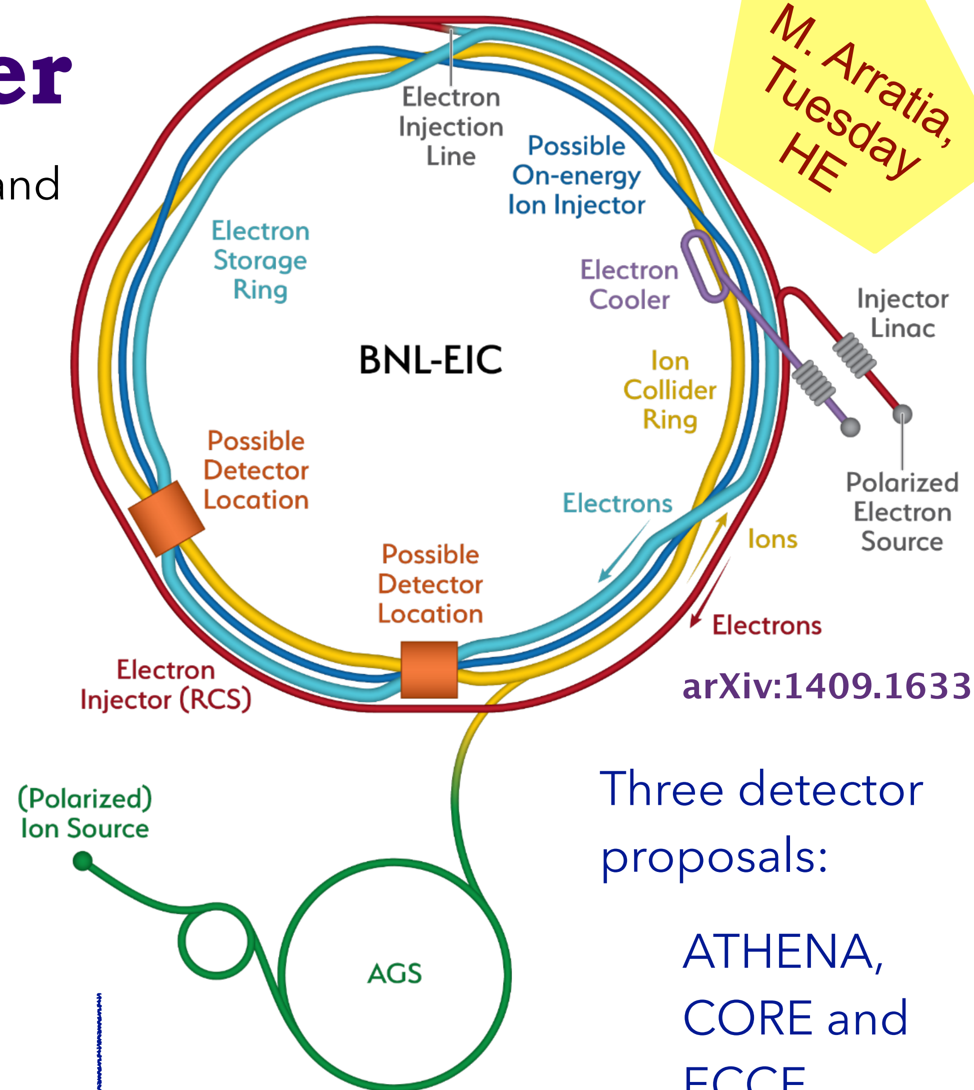
Brookhaven National Lab selected as the site

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)

M. Arratia, Tuesday HE



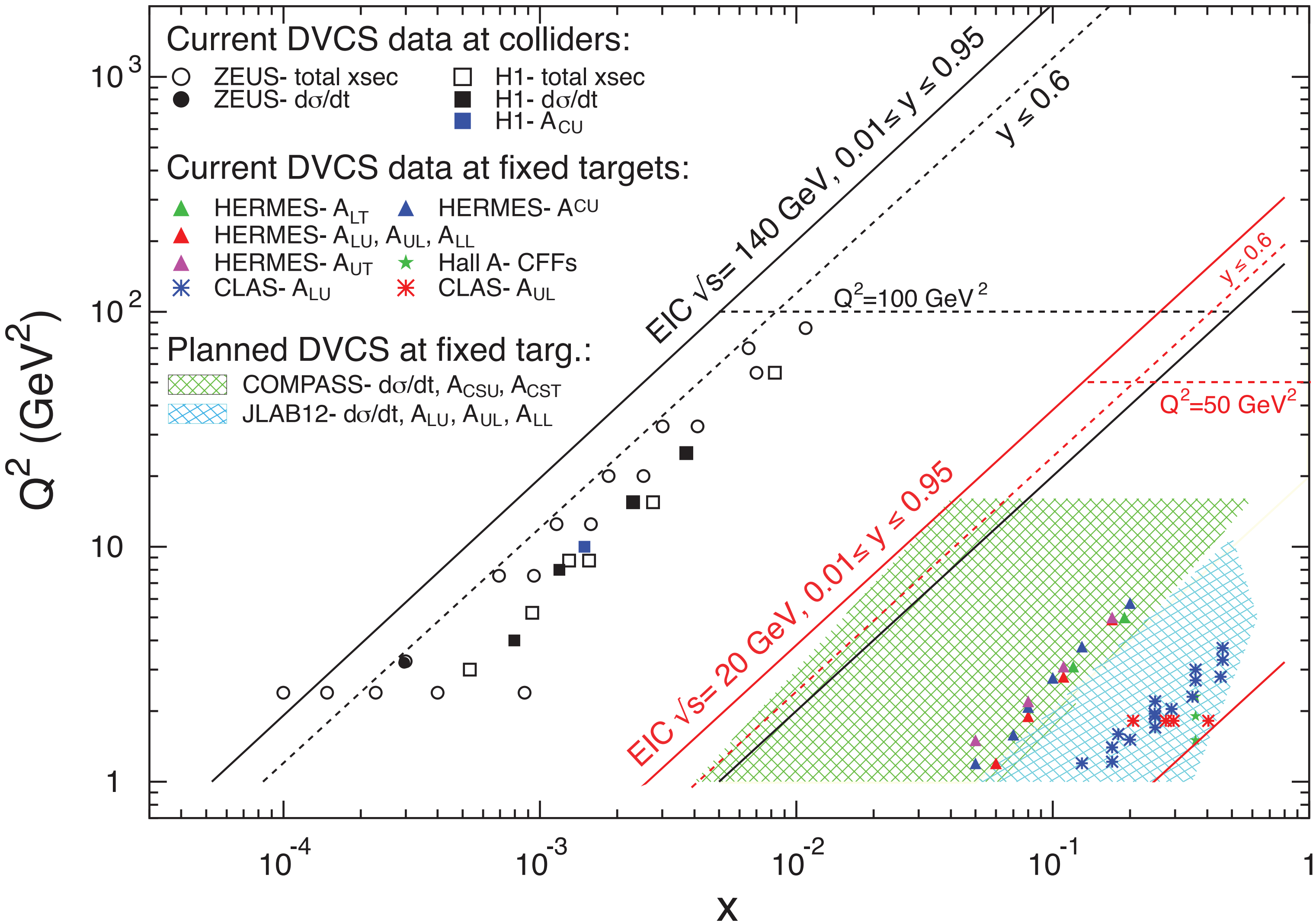
arXiv:1409.1633

Three detector proposals:

ATHENA, CORE and ECCE

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

EIC kinematic reach: DVCS



https://arxiv.org/abs/2103.05419

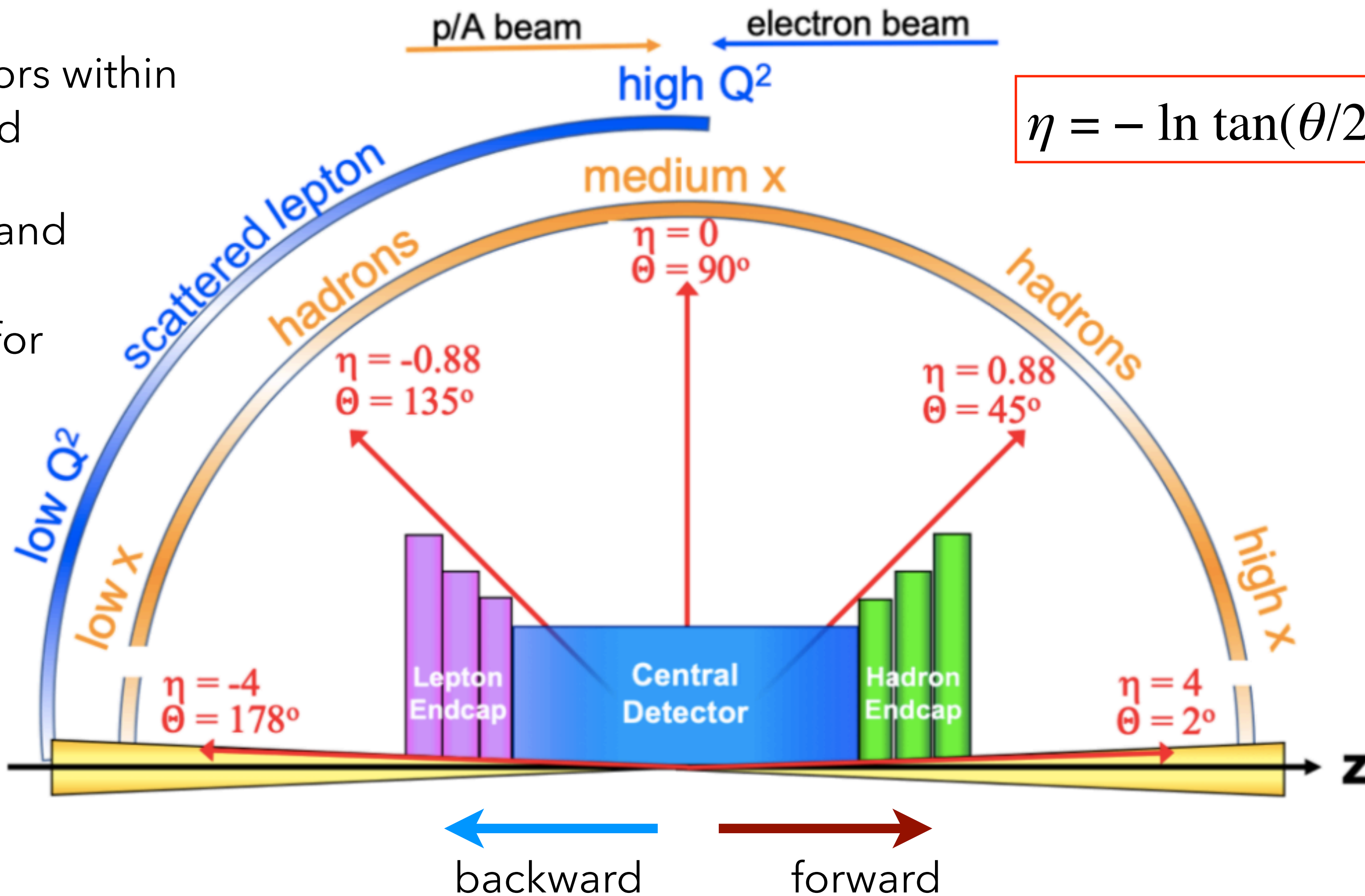
Detector configuration

Very asymmetric beams

Hermetic detectors within a central solenoid

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

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



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

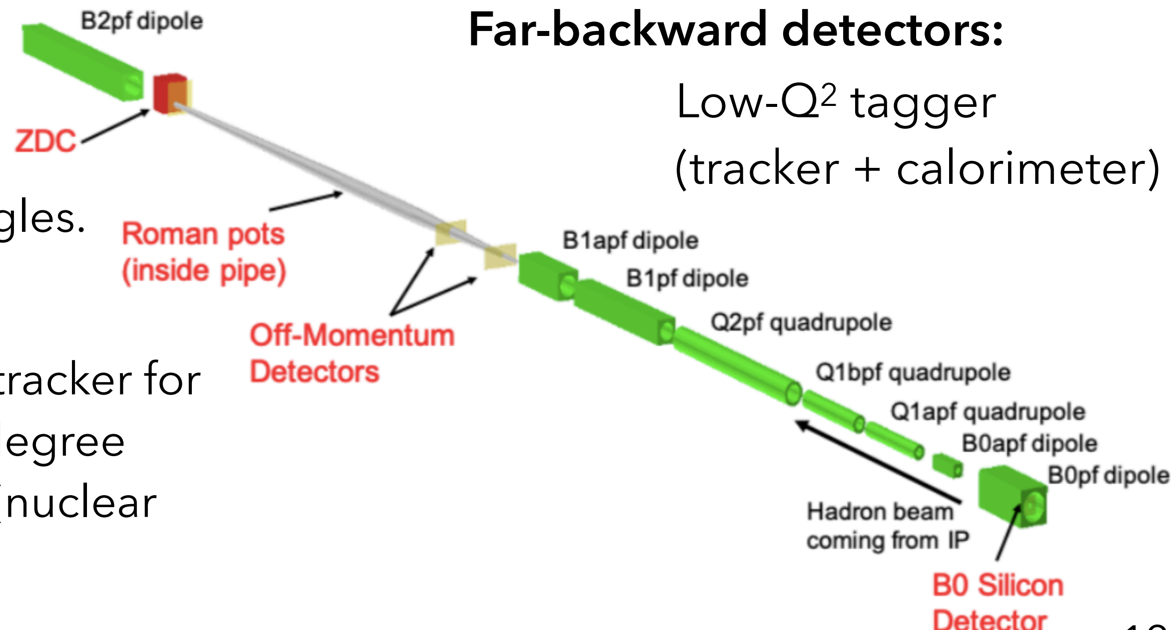
Barrel detector ($|\eta| < 1$) + two disc end-caps (forward/hadron end-cap and backward/electron endcap).

Far-backward detectors:

Low-Q^2 tagger
(tracker + calorimeter)

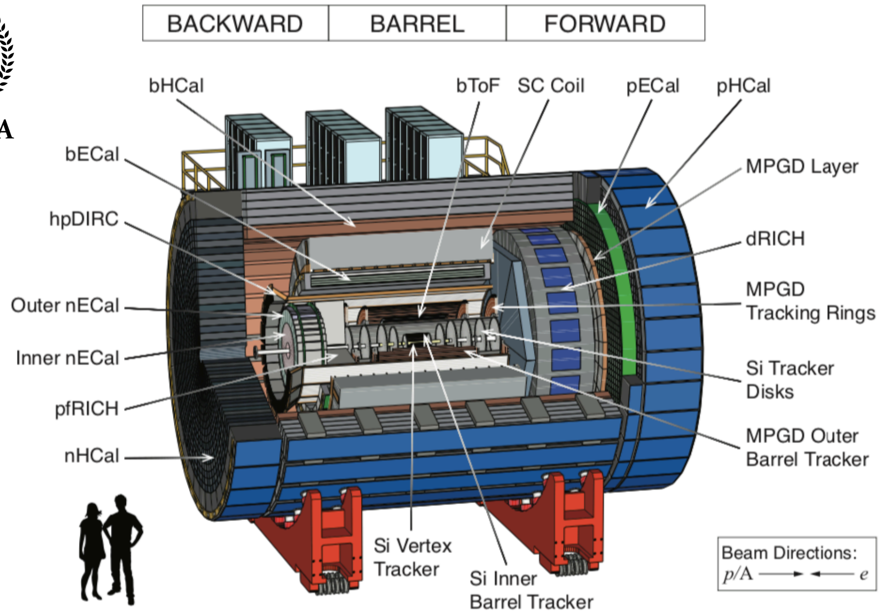
Far-forward detectors:

Far from interaction point, very low angles.



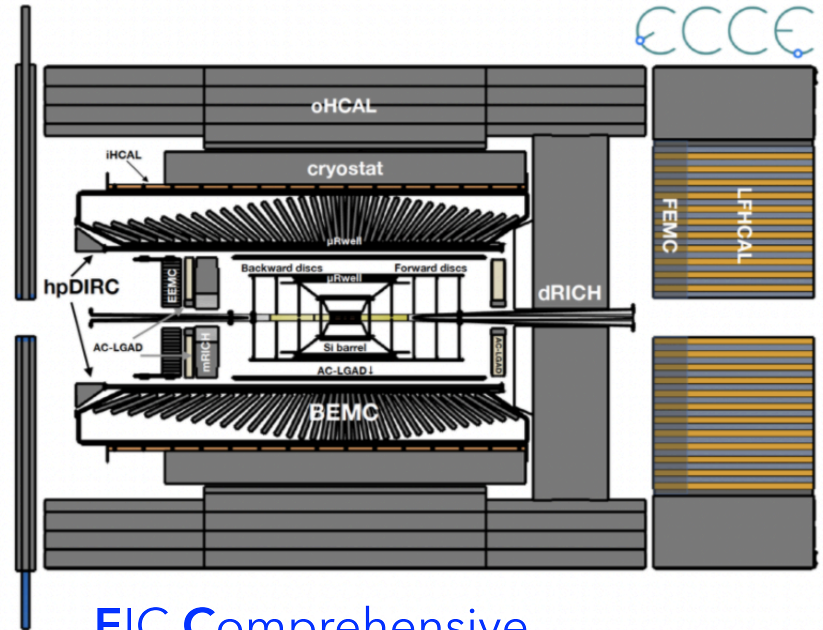
Roman Pots inside the beam pipe, B0 tracker for larger angles, large acceptance Zero degree Calorimeter (ZDC) to detect neutrons (nuclear breakup / neutral decay products)

ATHENA



A Totally Hermetic Electron-Nucleus Apparatus

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



EIC Comprehensive Chromodynamics Experiment

https://www.ecce-eic.org

EPIC (Electron-Proton and -Ion Collider):

The new detector 1 collaboration detector, based around the geometry of the 1.4T BaBaR solenoid, incorporating sub-detector designs from both the ECCE and ATHENA proposals.

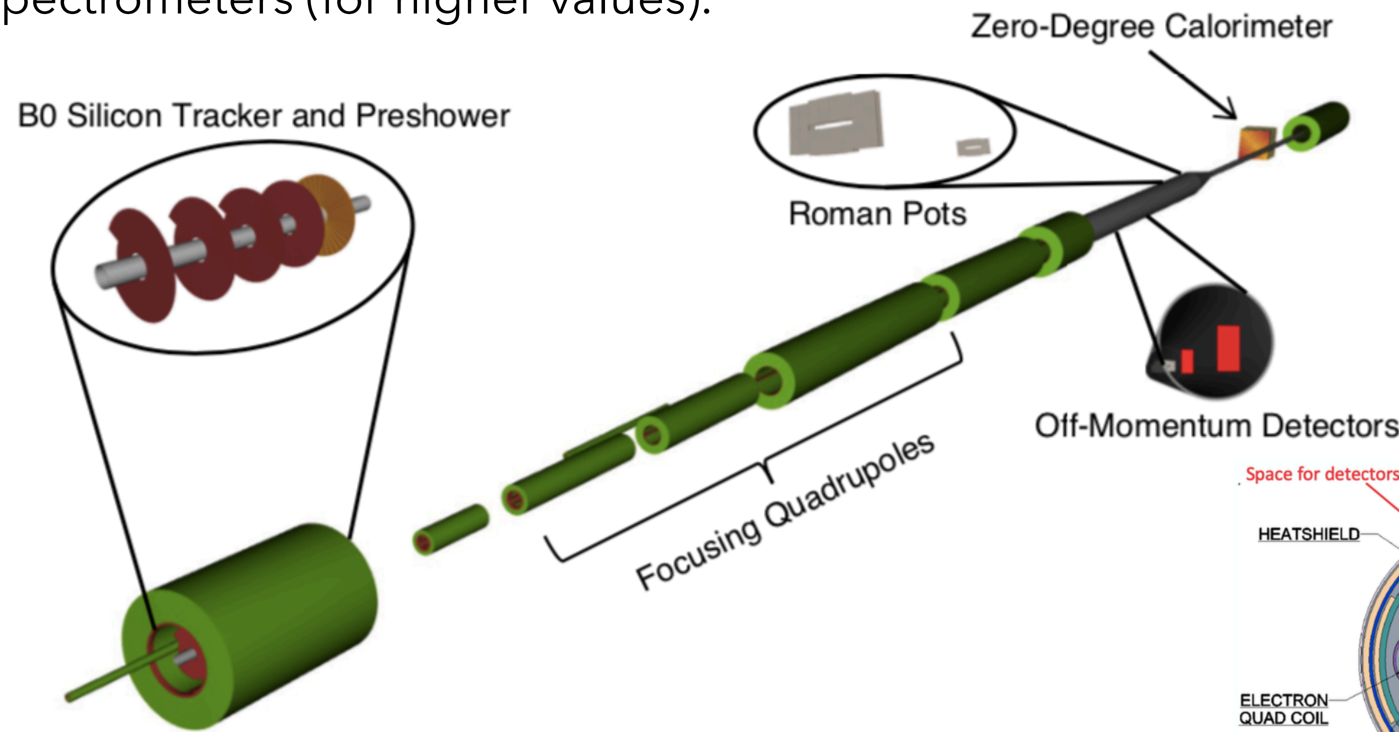
Design still in flux, to be finalised this year.

Recoil protons in *ep*

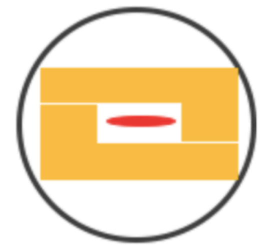
- The impact parameter information in DVCS/TCS or meson-production processes is encoded in *t*. Require accurate measurement of *t* across a wide range in *ep* collisions:

$$0.03 < |t| < 1.6 \text{ GeV}^2 \qquad t = (p' - p)^2$$

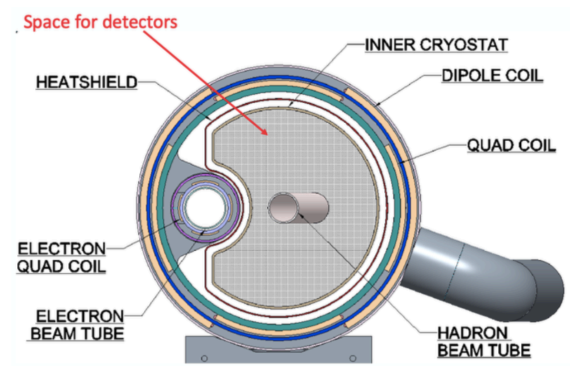
- Scattered protons detected in Roman Pots (for the lowest values of *t*) and in the B0 spectrometers (for higher values).



ATHENA proposal



Hadron beam-pipe and Roman Pots in cross-section



EIC Yellow Report

B0 spectrometer configuration

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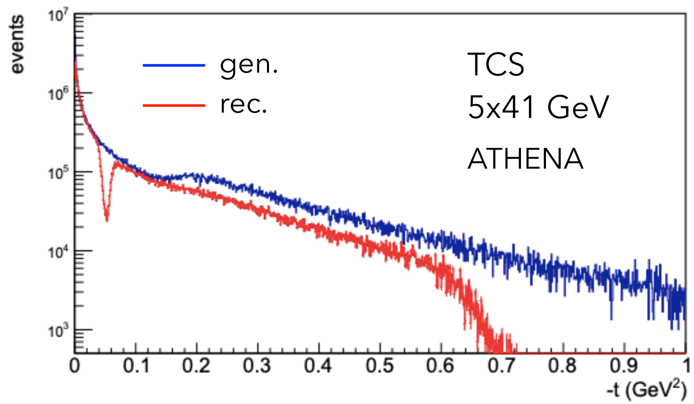
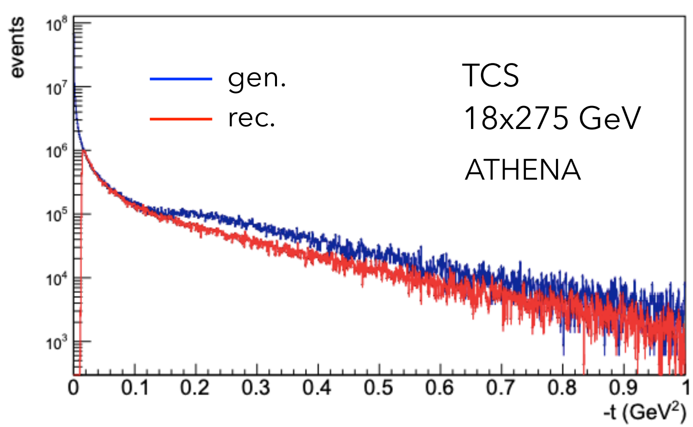
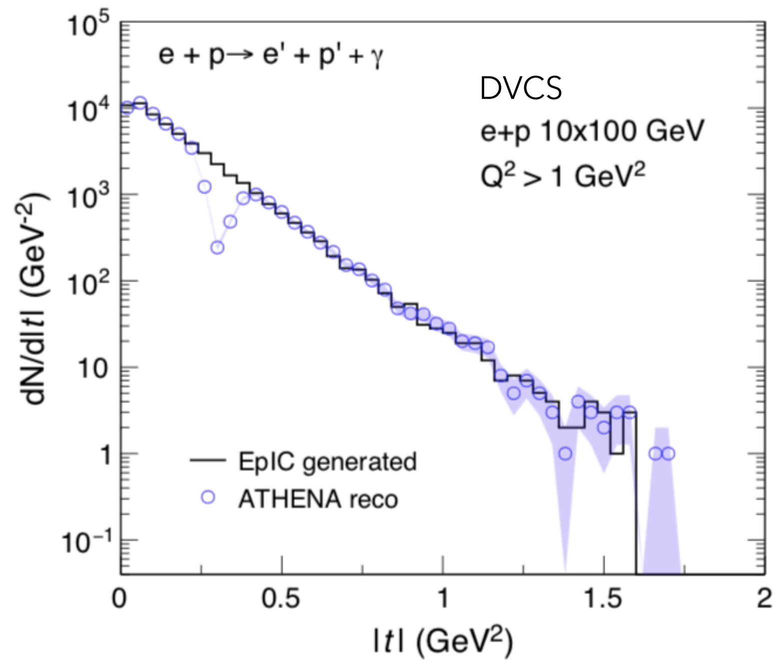






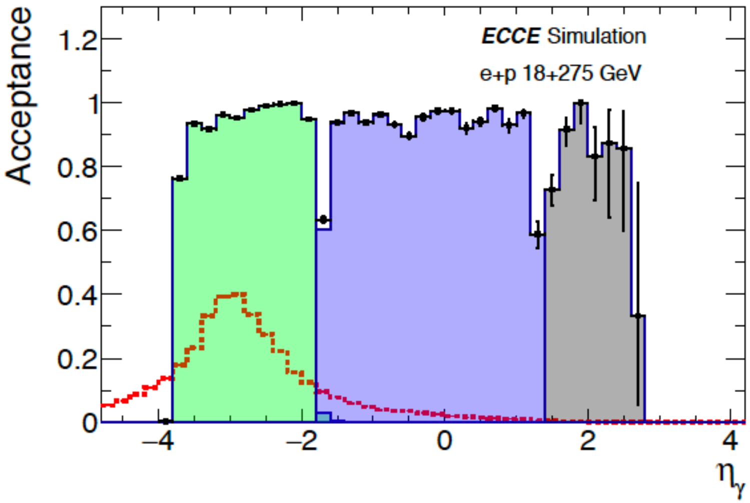
Dip in *t*-distribution is due to a gap between Roman Pots and B0 tracker: intrinsic to IR. Gap position depends on proton beam-energy.

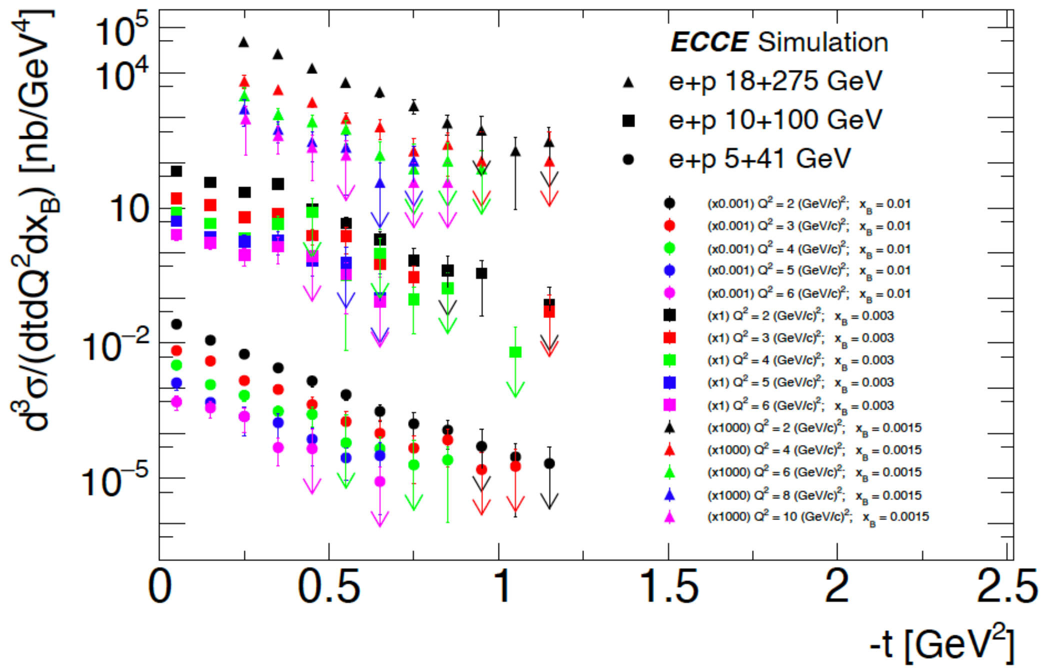
Plots: Kong Tu (BNL), D. S.

Coherent DVCS at the EIC

Plots: I. Korover (MIT)

- DVCS on the proton:





- Practically hermetic coverage for photons, wide range of *t*.

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

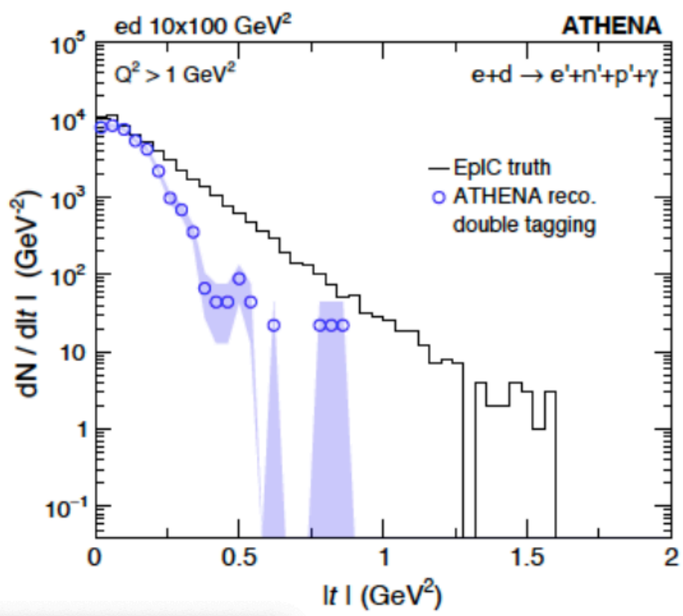
* Study also done for coherent DVCS on He-4: spin-0 nucleus, parametrisation of coherent amplitude in terms of only one GPD.

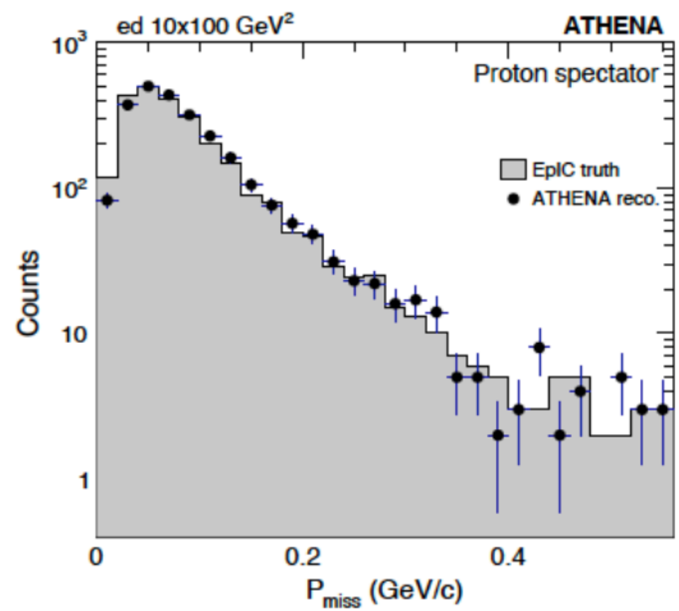
* Acceptance of He′ ions in forward direction crucial.

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*:

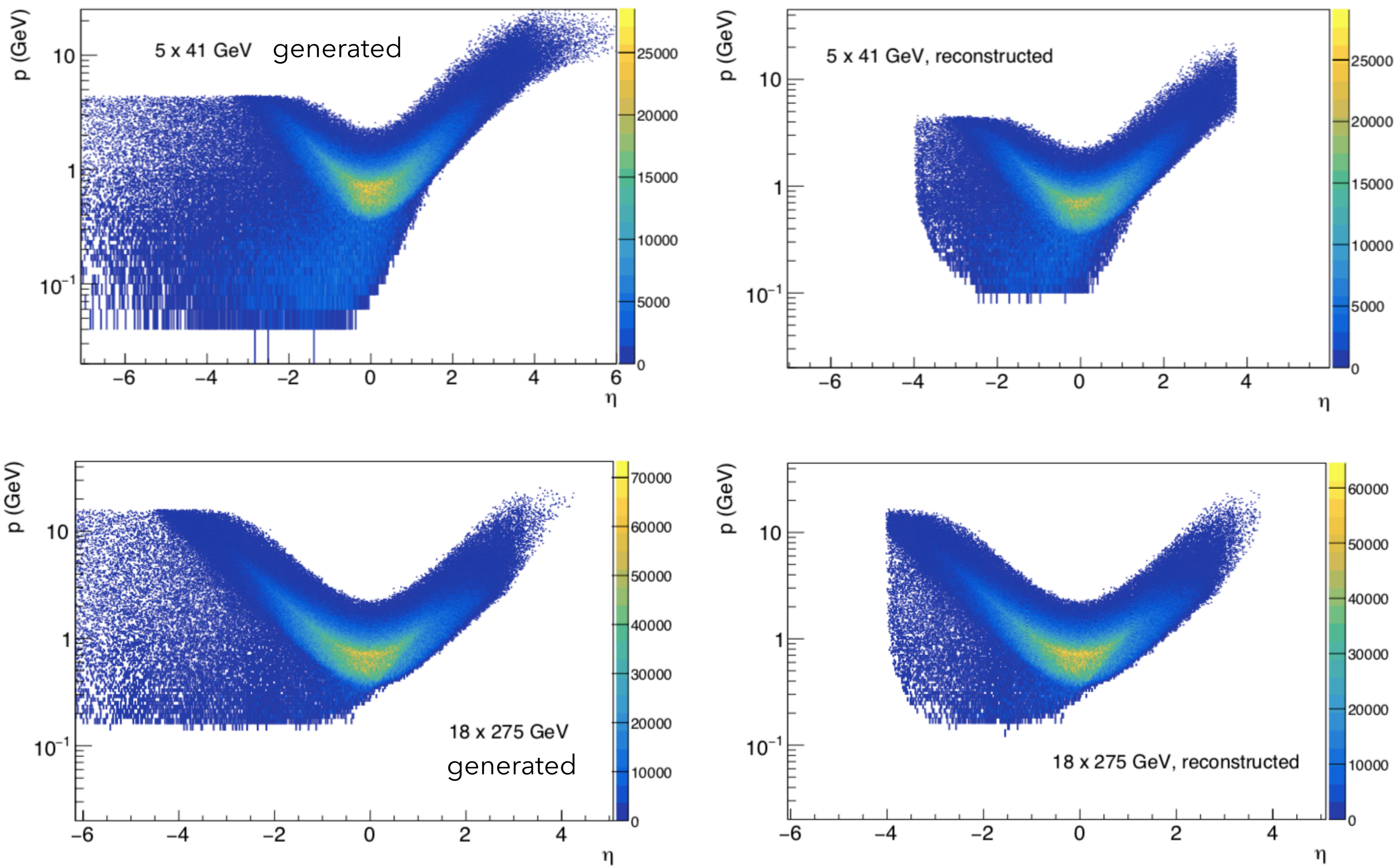




- Scattered neutron tagged in ZDC: loss of *t*-acceptance at high *t* is due to limitations of ZDC acceptance. Can obtain better *t* acceptance from electron - photon.

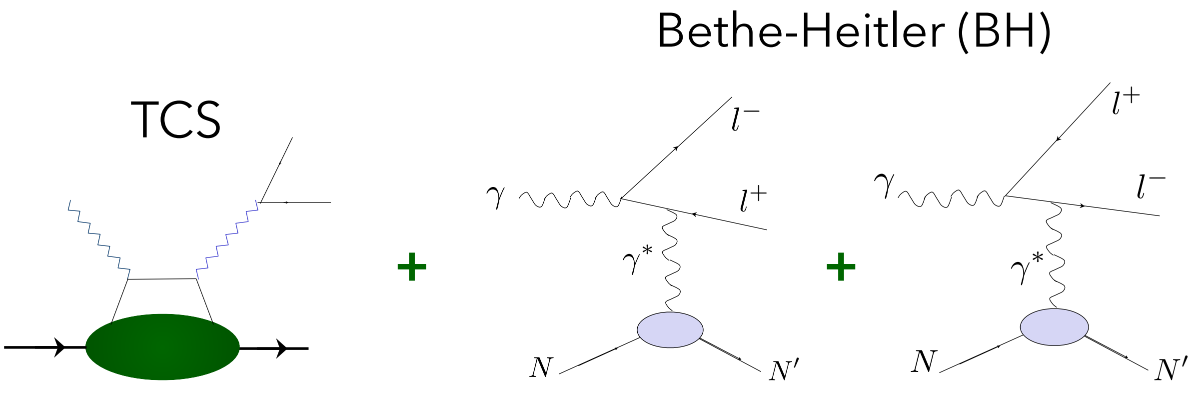
TCS e^+e^-

- TCS-produced virtual photon decays into e^+e^- pairs at mid-rapidity – need excellent acceptance in central region (barrel+ end-caps), as scattered electron will in general be reconstructed though missing mass and momentum (low-Q^2 tagger can provide direct detection only in a part of the phase space).



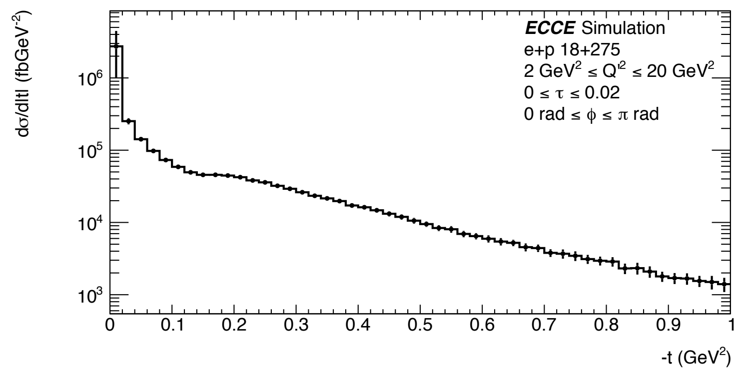
TCS (+ BH + Int) e⁺e⁻: observables

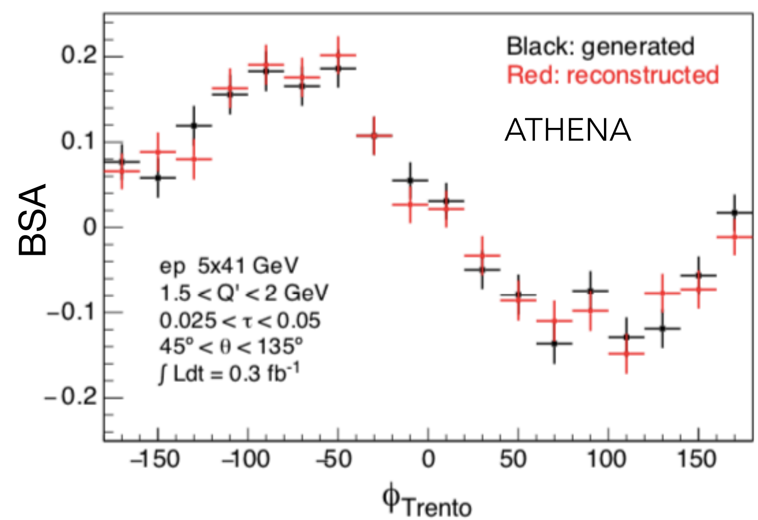
- Pure TCS cross-section is dominated by a factor of ~100 by Bethe-Heitler (BH): extract TCS signal from the BH-TCS interference.



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

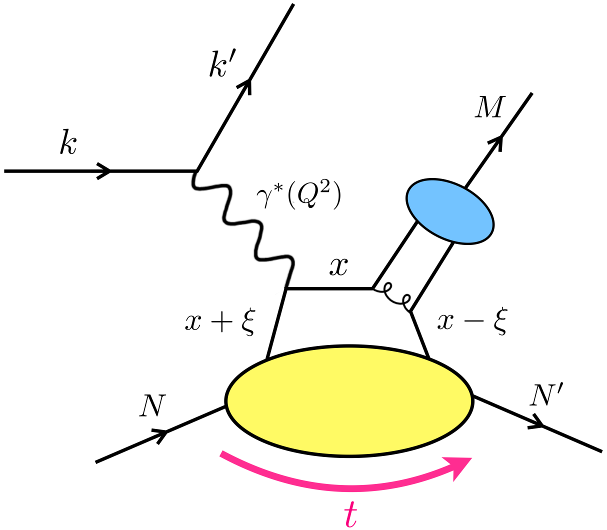
- Sensitivity to Interference term in single-sin asymmetries: beam-spin (BSA), target-spin.





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

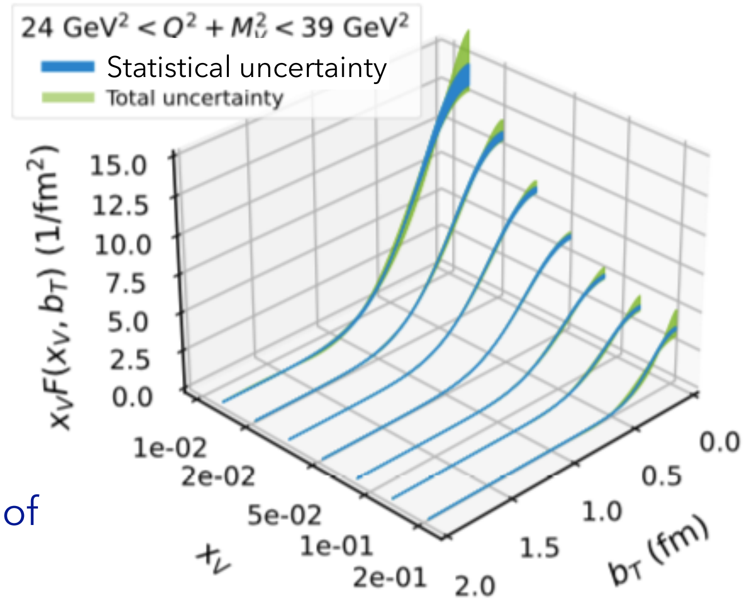
GPDs through meson-production



✱ 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 scatterin given by: $Q^2 + M_v^2$

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

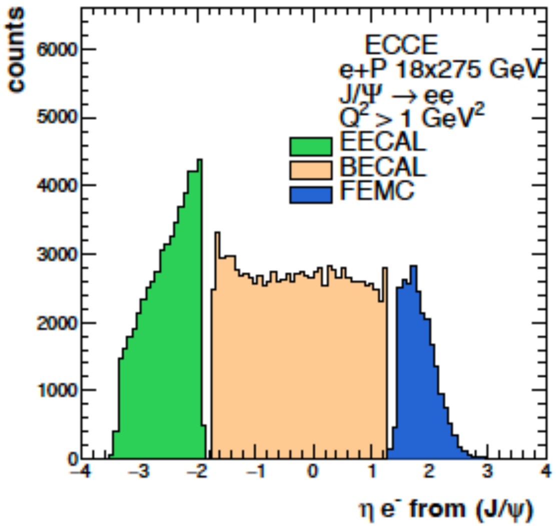


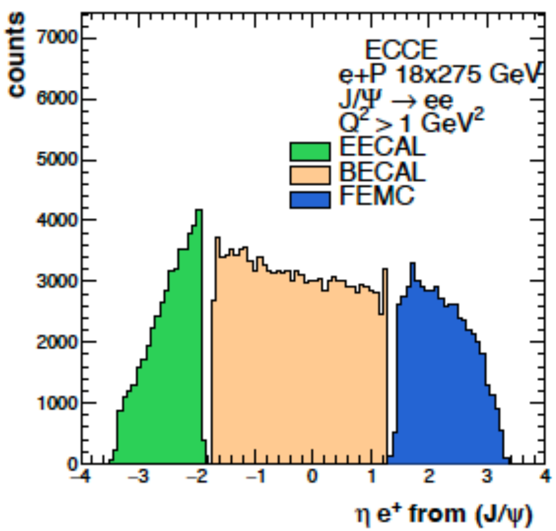
Fourier transform of J/Psi-production cross-section

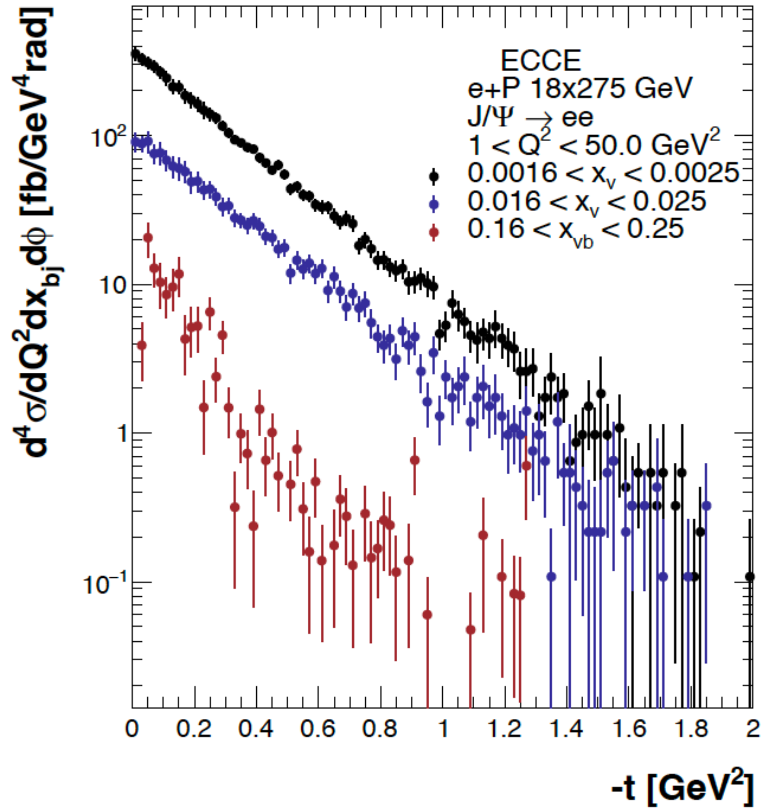
✱ Light vector-meson production additionally enables flavour-decomposition of GPDs.

✱ 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.

J/Psi production







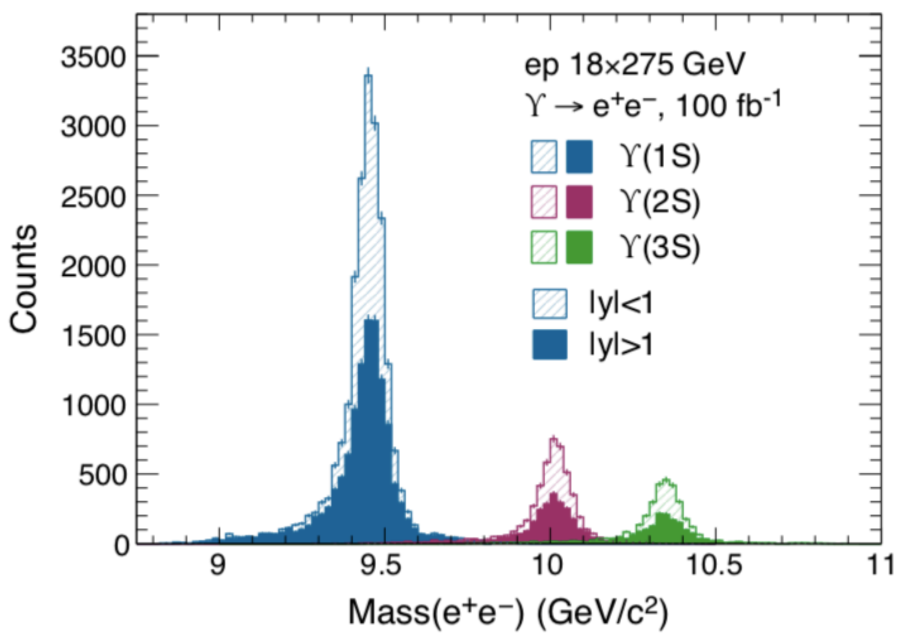
- Excellent acceptance coverage for J/Psi decay leptons
- Multi-dimensional binning

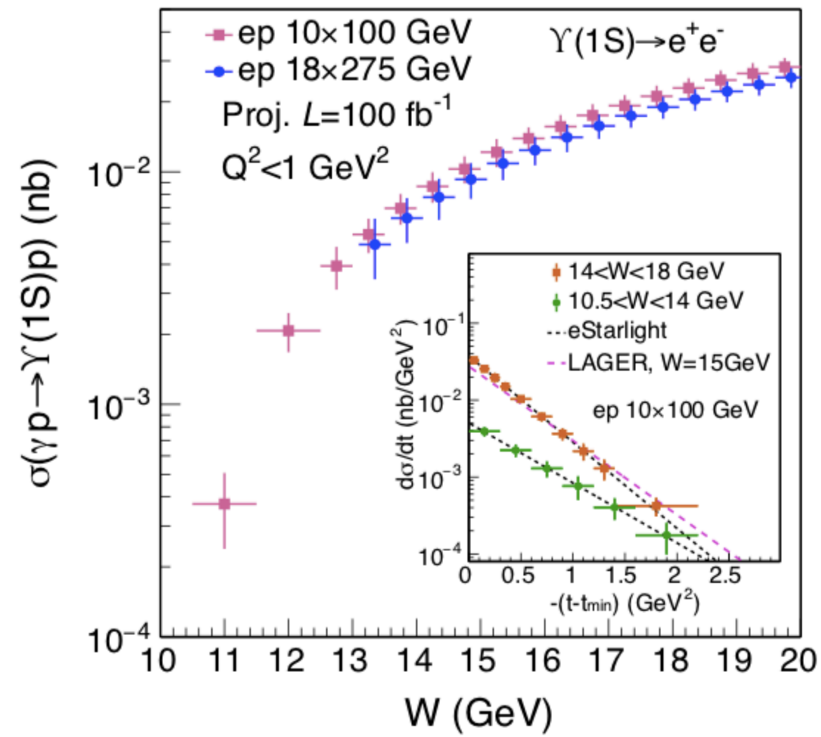
Plots: N. Santiesteban

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).





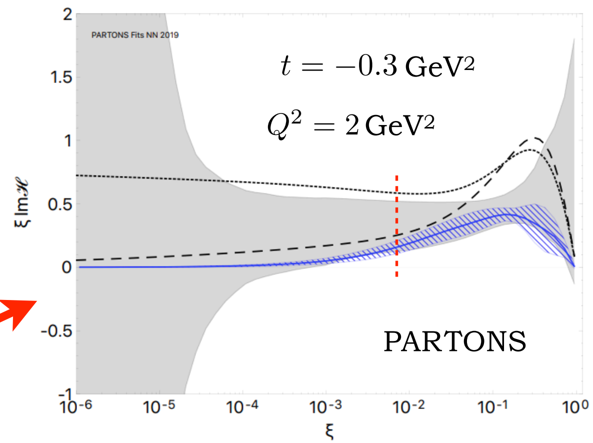
Plots: Yuangjing Ji (LBNL)

Extracting GPDs

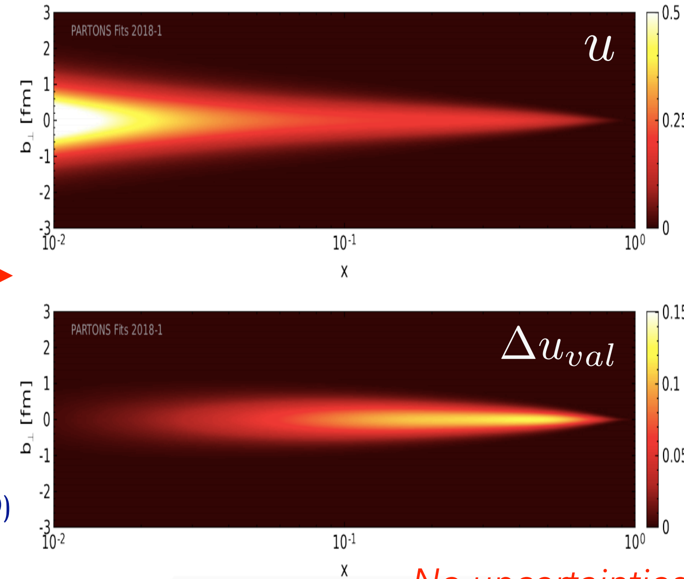
Ongoing imaging efforts on available world-data, strongest constraints in the valence region:

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.



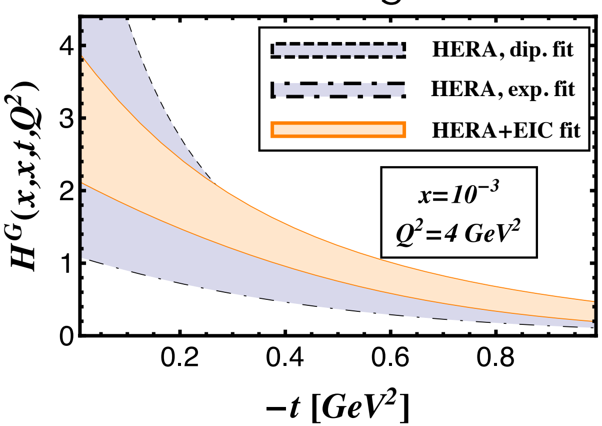
H. Moutarde *et al.*, Eur. Phys. J C79, 614 (2019)



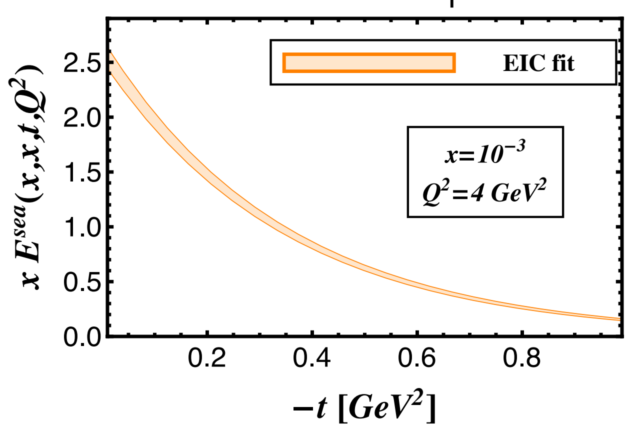
No uncertainties shown

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

Extracting GPDs

Ongoing imaging efforts on available world-data, strongest constraints in the valenc

H. Dutrieux, Wednesday PDF 1pm

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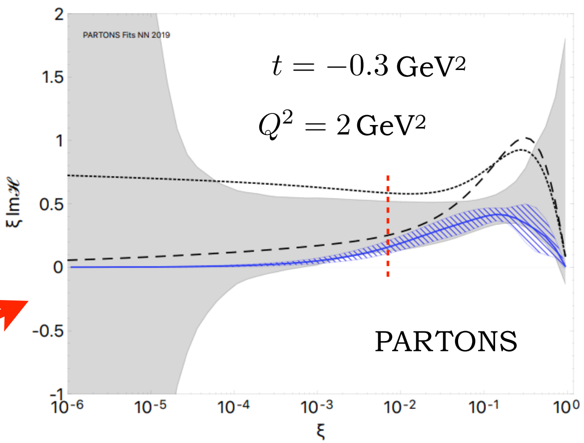
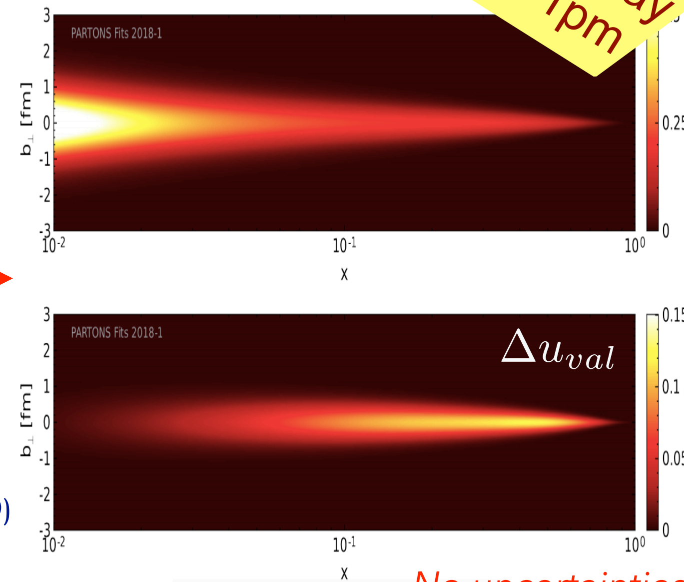


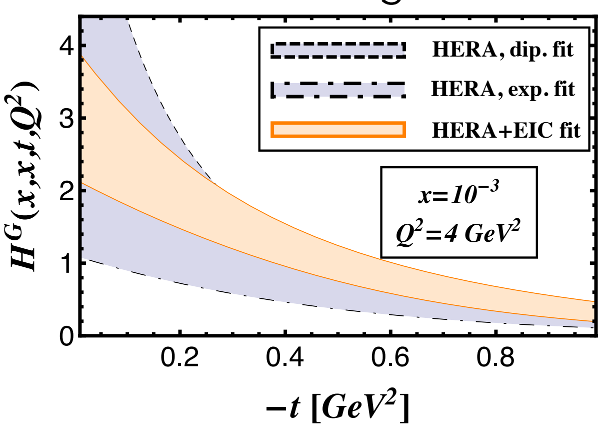
H. Moutarde *et al.*, Eur. Phys. J C79, 614 (2019)



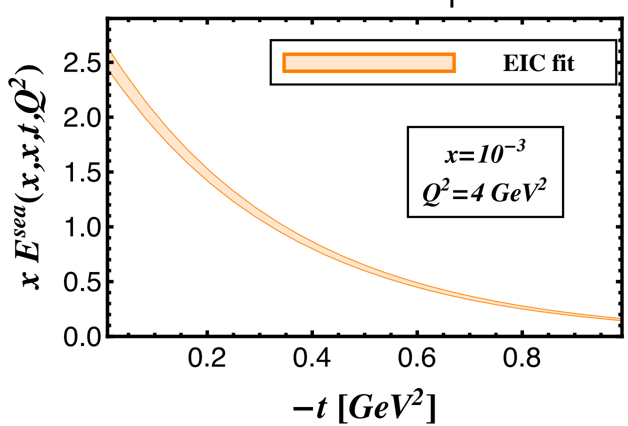
No uncertainties shown

Anticipated constraints from EIC on GPDs H and E:

GPD H for gluons



GPD E for sea quarks

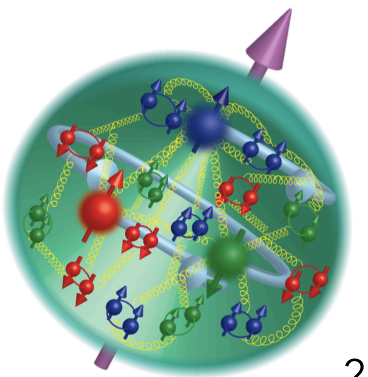


Measurements at EIC will provide significant constraints at low-x and enable extraction of as-yet unknown GPDs.

https://arxiv.org/abs/2103.05419

Summary

- Electron-Ion Collider to be built at Brookhaven National Laboratory, start operation ~2031.
- Large range of CoM energies (20 - 140 GeV), high luminosity ($10^{32\text{-}33}$ $cm^{-2}s^{-1}$): high precision measurements across wide swathes of phase space from the gluon sea to the valence quark region.
- Design of the first detector being finalised this year: the EPIC collaboration.
- 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.
- Exclusive processes such as DVCS, TCS and meson-production provide access to GPDs.
- Dramatic constraints on GPDs expected from EIC in the low-x region, shedding new light the structure of the nucleon.
- Join the effort! http://www.eicug.org/




Thank you!
Any questions?

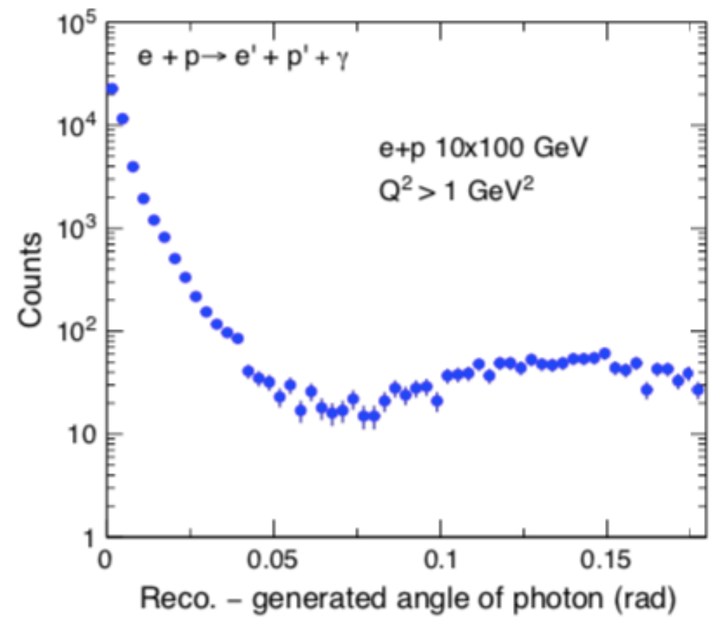

Back-up

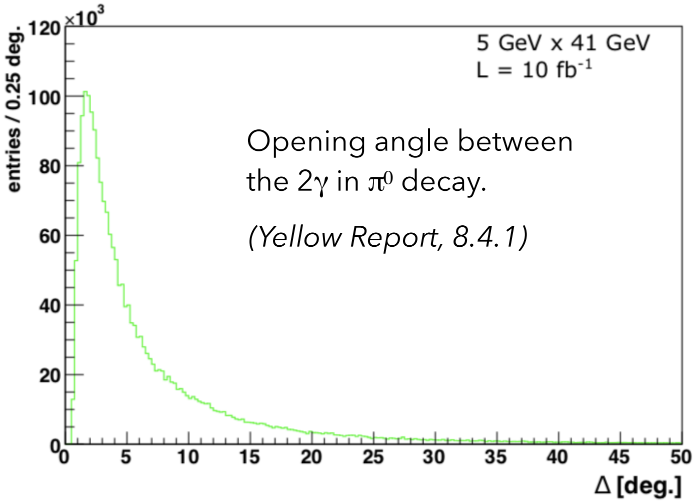
Detecting photons (DVCS/π^0)

- The DVCS channel requires detection of the produced photon in the ECAL. Biggest background comes from mesons that decay into 2γ pairs, mainly π^0. Two challenges to suppress it:

  - One photon may be missed and the π^0 event may mimic a DVCS one: address by providing maximum calorimeter acceptance in the kinematic range of interest (central rapidities, central detector: barrel + end-caps).

  - The two photons from the decay may merge into one cluster in the ECAL (if their opening angle is small) and be reconstructed as a single photon: address by having a high ECAL resolution.

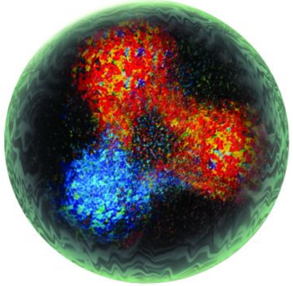




Opening angle between the 2γ in π^0 decay.

(Yellow Report, 8.4.1)

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



Wigner function:
full phase space parton distribution of the nucleon

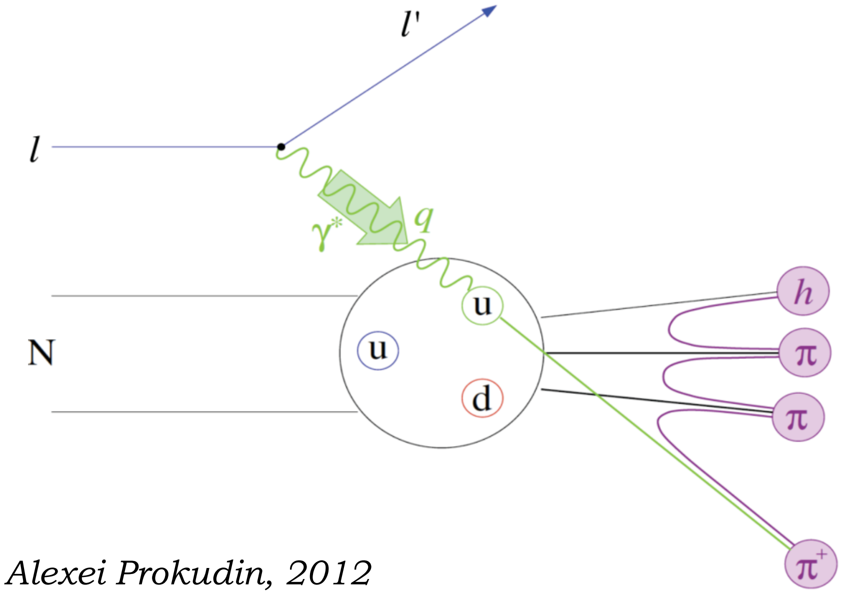
Generalised Transverse Momentum Distributions (GTMDs)

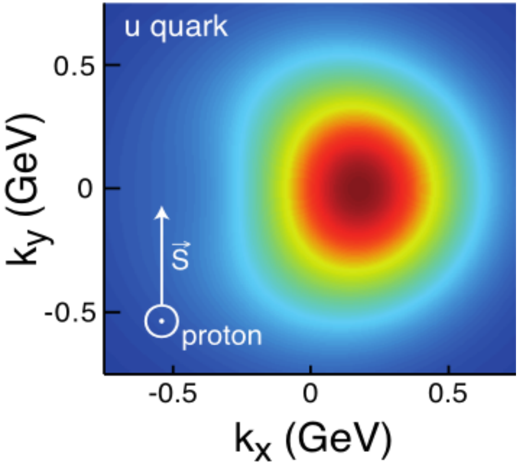
$$\int d^2 b_T$$

Transverse Momentum Distributions (TMDs)

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

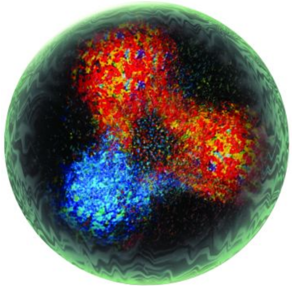
SIDIS:





Sivers function: Alexei Prokudin, 2012

(using M. Anselmino et al., J. Phys. Conf. Ser. 295, 012062 (2011))



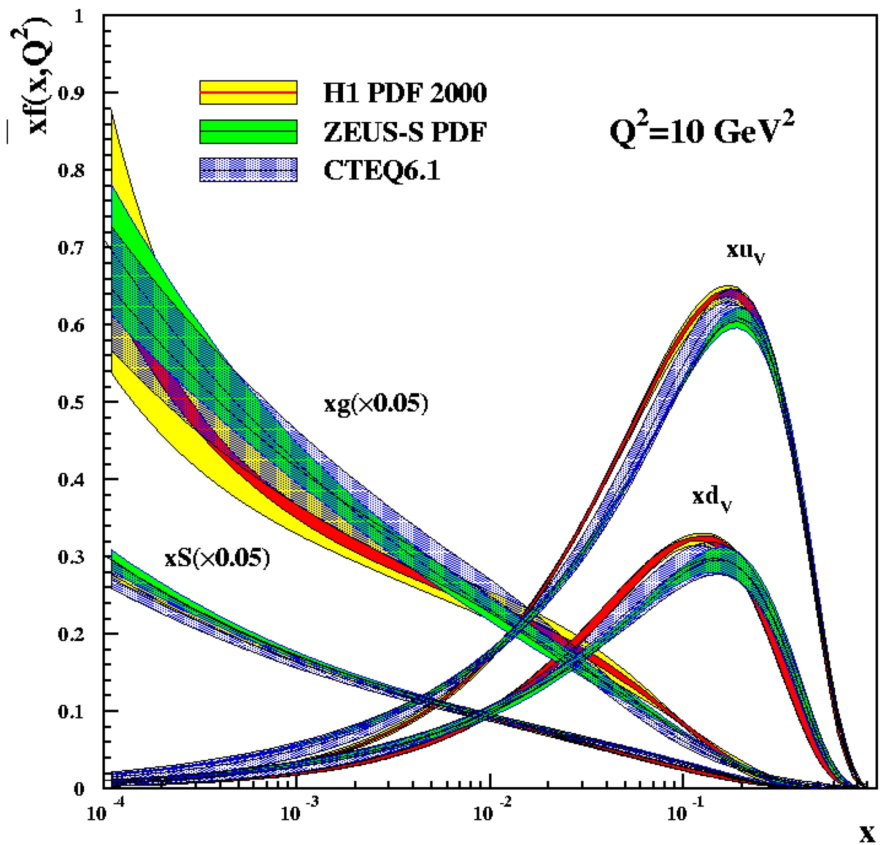
Wigner function:
full phase space parton
distribution of the nucleon

Generalised Transverse Momentum
Distributions (GTMDs)

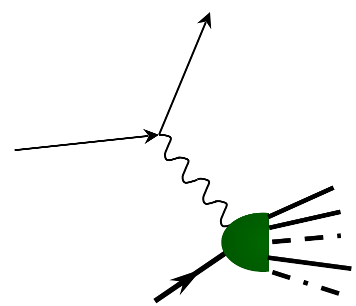
$$\int d^2 b_T$$

Transverse
Momentum
Distributions
(TMDs)

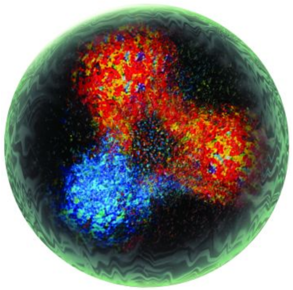
$$\int d^2 k_T$$



Parton Distribution
Functions (PDFs)



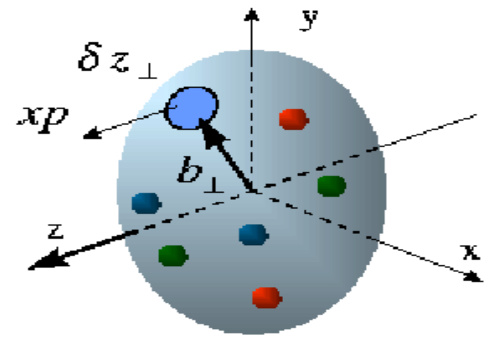
* Deep Inelastic
Scattering (DIS)



Wigner function: full phase space parton distribution of the nucleon

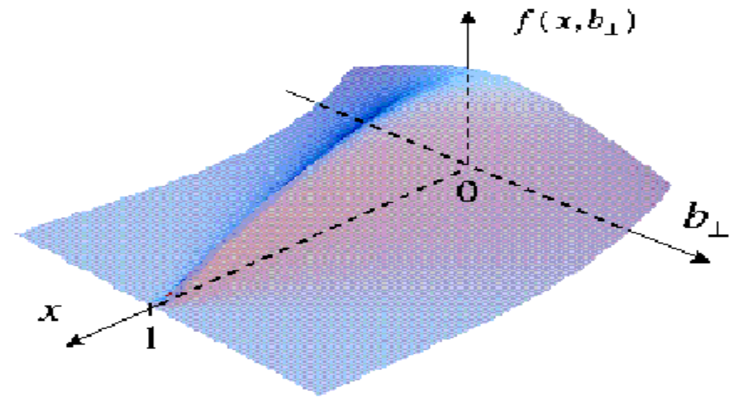
Generalised Transverse Momentum Distributions (GTMDs)

$$\int d^2 k_T$$

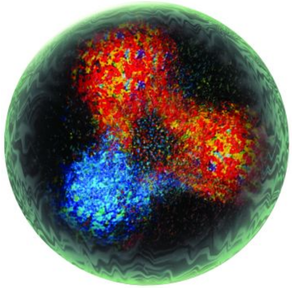


Generalised Parton Distributions (GPDs)

- 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.



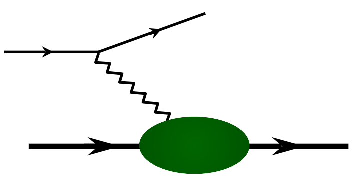
Wigner function: full phase space parton distribution of the nucleon

Generalised Transverse Momentum Distributions (GTMDs)

$\int d^2 k_T$

Generalised Parton Distributions (GPDs)

$\int dx$

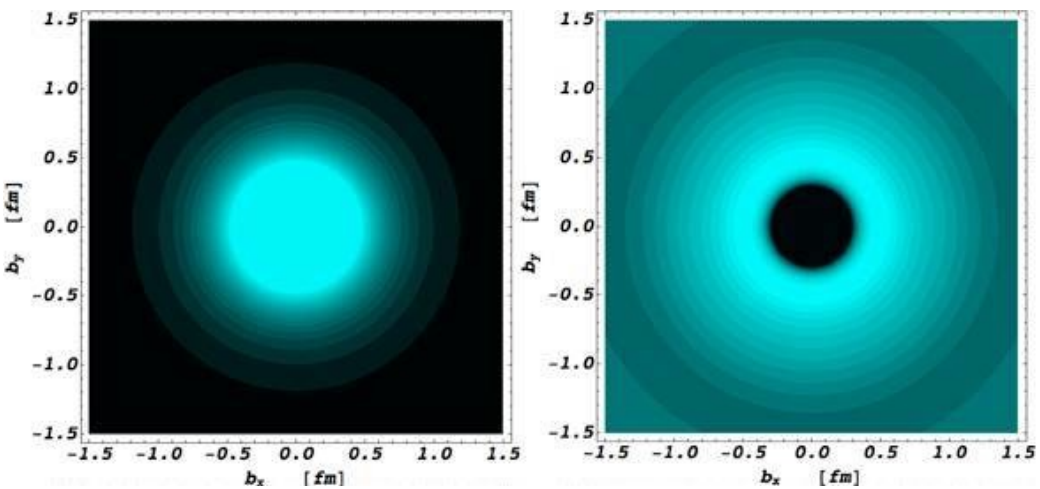


Elastic scattering

Form Factors

eg: G_{E}, G_M

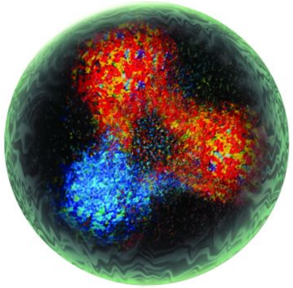
Fourier Transform of electric Form Factor: transverse charge density of a nucleon



proton

neutron

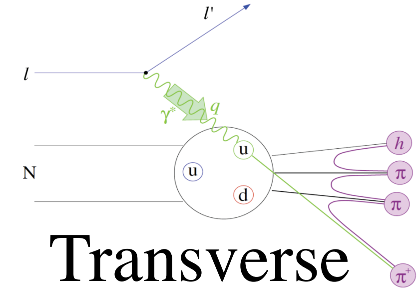
C. Carlson, M. Vanderhaeghen PRL 100, 032004 (2008)



Wigner function:
full phase space parton distribution of the nucleon

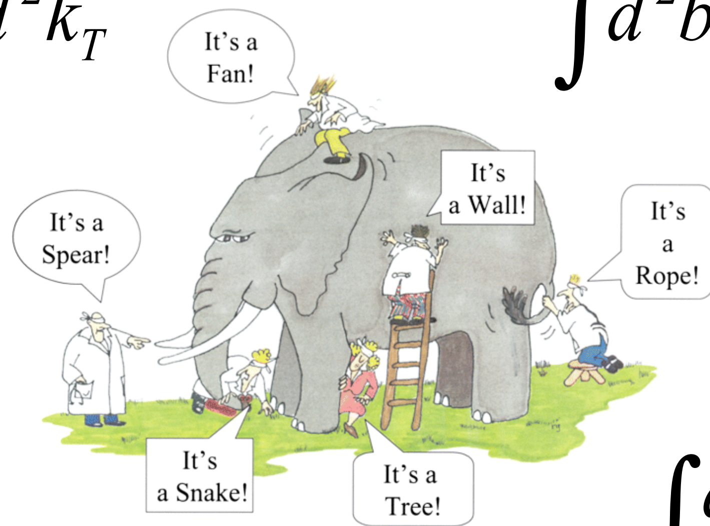
Generalised Transverse Momentum Distributions (GTMDs)

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



$\int d^2 k_T$

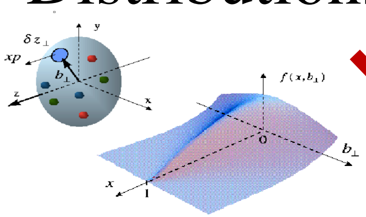
$\int d^2 b_T$



G. Renee Guzlas, artist.

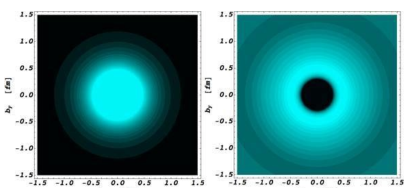
Generalised Parton Distributions (GPDs)

Transverse Momentum Distributions (TMDs)



$\int dx$

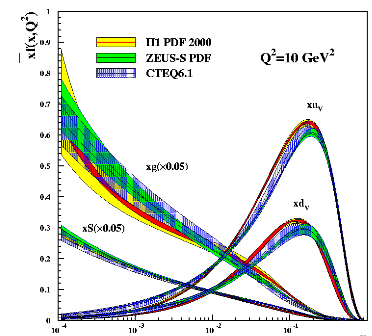
$\int d^2 k_T$



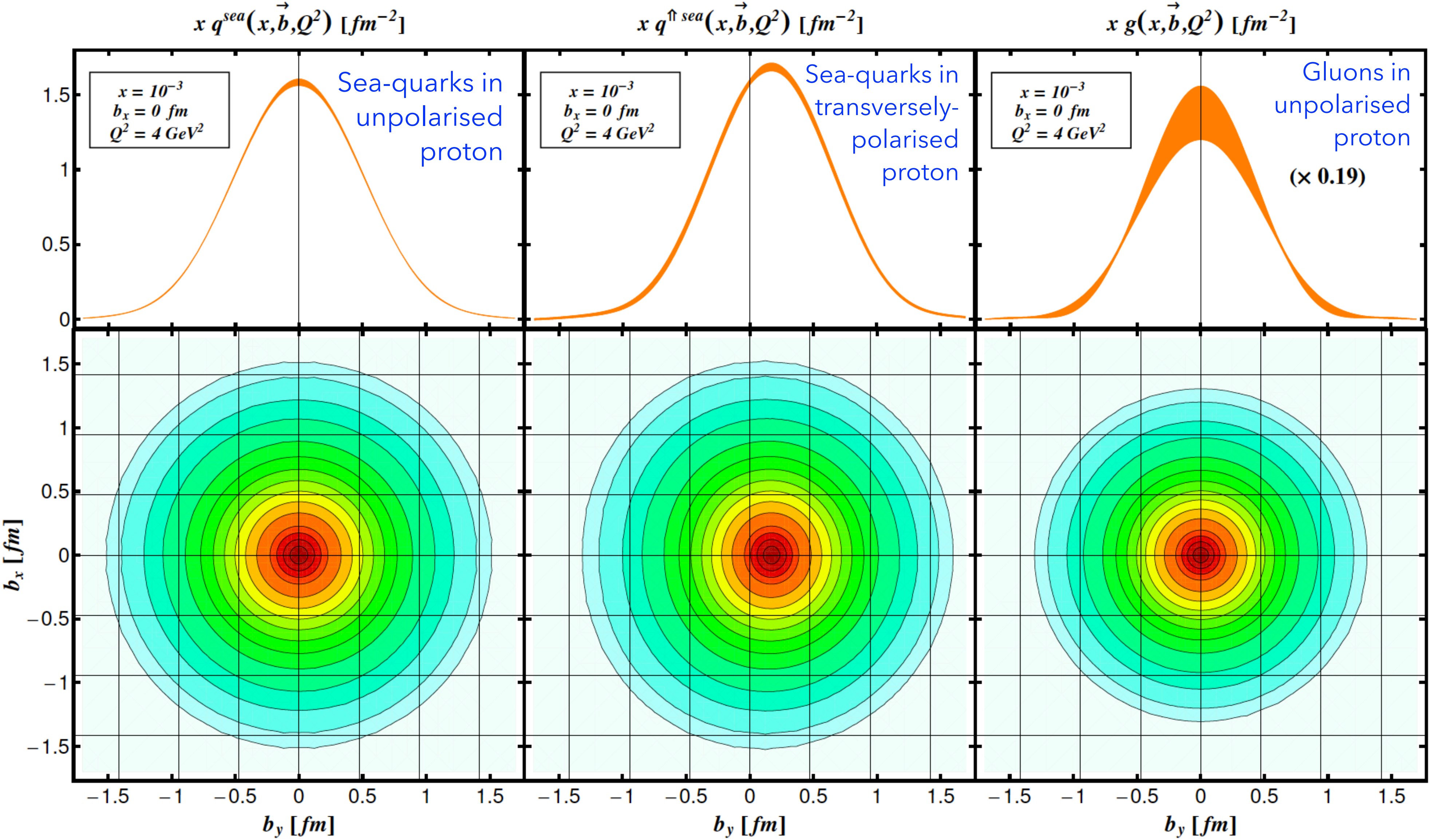
Form Factors

eg: G_E, G_M

Parton Distribution Functions (PDFs)



Tomography @ EIC



Combined fit to HERA data and EIC pseudo-data

https://arxiv.org/abs/2103.05419

Imaging light nuclei

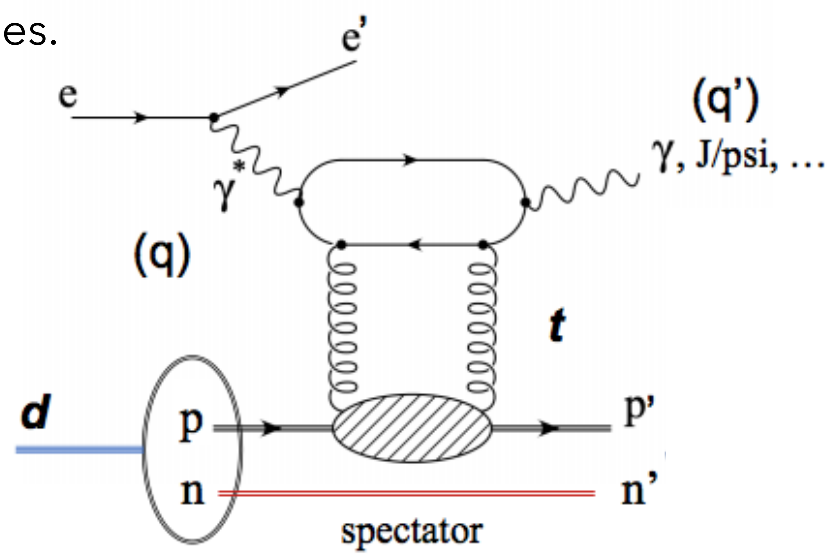
Coherent DVCS on light nuclei requires their intact detection and provides access to nuclear GPDs: imaging of partons in a nuclear medium.

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).

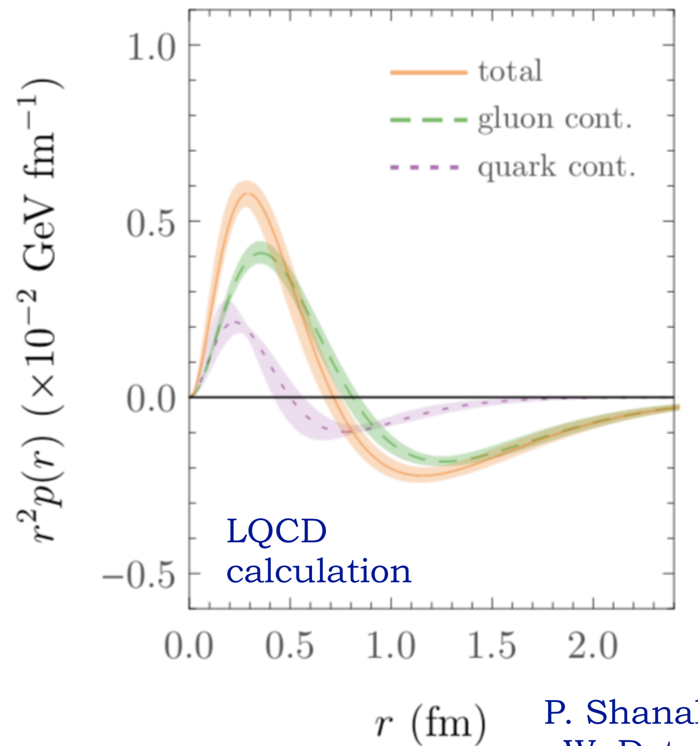
  X. D. Ji, PR**D 55**, 7114-7125 (1997)   M. Polyakov, PL**B 555**, 57-62 (2003)

- 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.



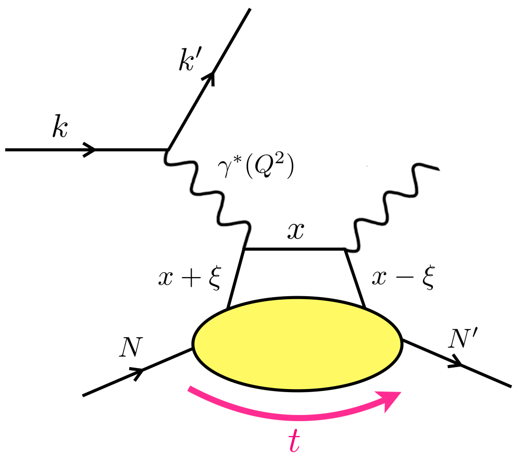
P. Shanahan, W. Detmold, PRL 122,072003 (2019)

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

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
* Υ(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		*
* Pion Structure Functions		*
* A^n_1 (He-3 double tagging)		*

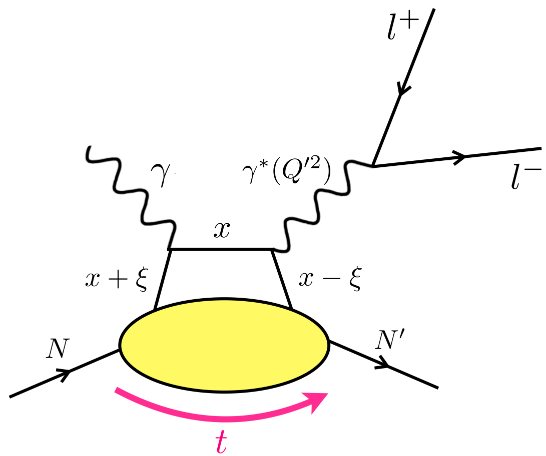
Exclusive processes

Deeply Virtual Compton scattering (DVCS):



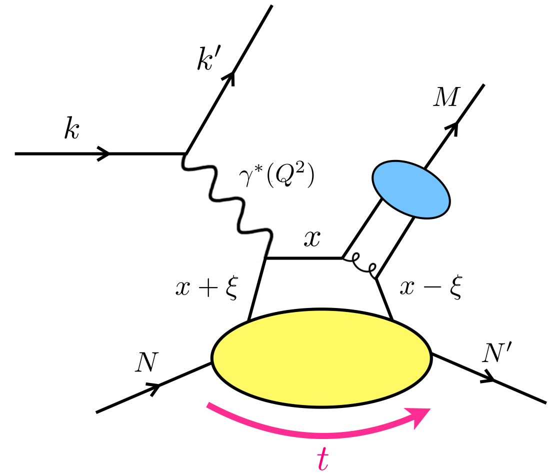
$$\gamma^* p \to p' \gamma$$

Timelike Compton Scattering (TCS):



$$\gamma p \to p' e^+ e^-$$

Meson production (one of many):



- Access to Generalised Parton Distributions (GPDs), tomography of the nucleon, composition of nucleon spin (contribution to orbital angular momentum), mechanical properties of the nucleon (pressure, shear forces)
- Diffractive meson production: saturation probe (in eA), gluon distributions, at-threshold production sensitive to mass generation.
- Scattering from the meson cloud: meson form factors, structure functions – structure of mesons.
- Spectroscopy: structure of nucleons, search for exotics.

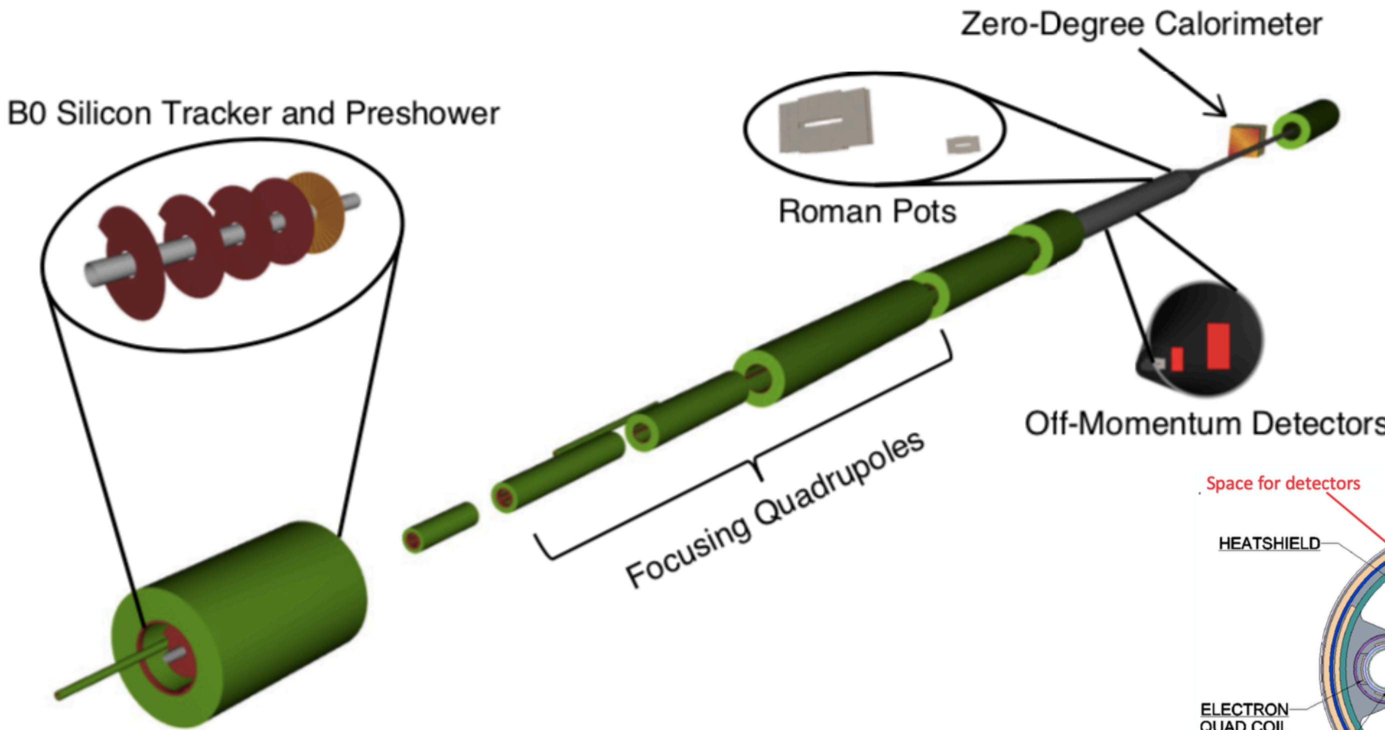
Recoil protons in *ep*

- The impact parameter information in DVCS/TCS or meson-production processes is encoded in *t*. Require accurate measurement of *t* across a wide range in *ep* collisions:

$$0.03 < |t| < 1.6 \text{ GeV}^2$$

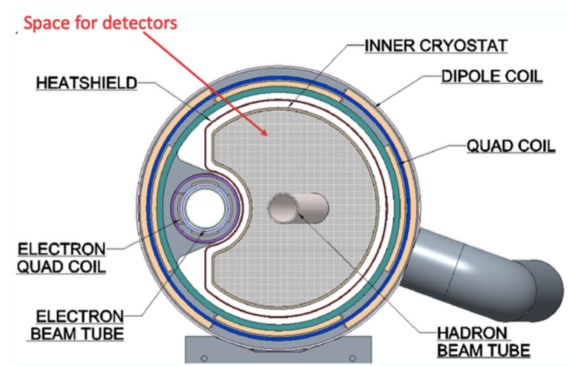
$$t = (p' - p)^2$$

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



ATHENA proposal

Hadron beam-pipe and Roman Pots in cross-section

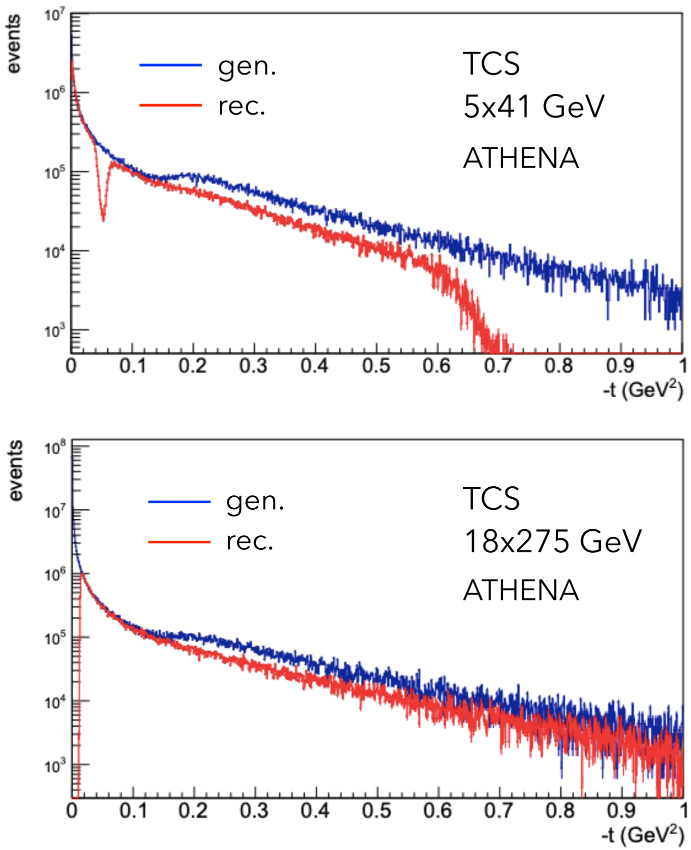


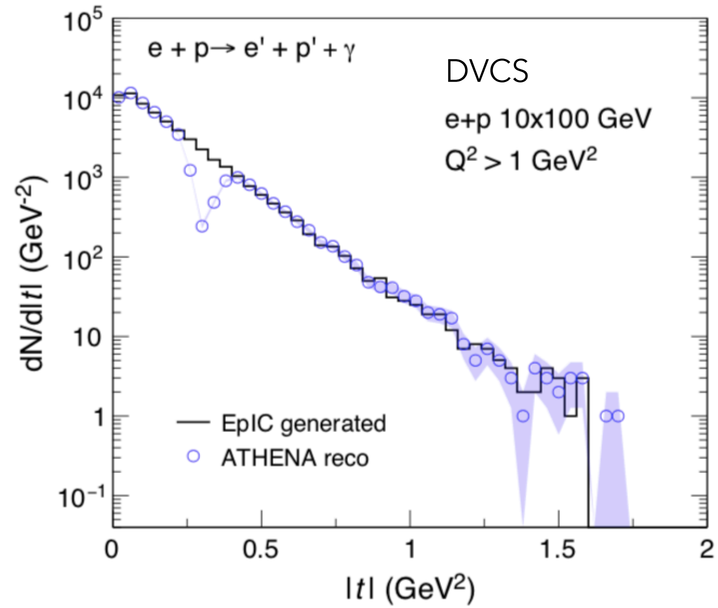
EIC Yellow Report

B0 spectrometer configuration

Recoil protons in *ep*

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





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

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

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 $\mathcal{I}m\ \mathcal{H}$

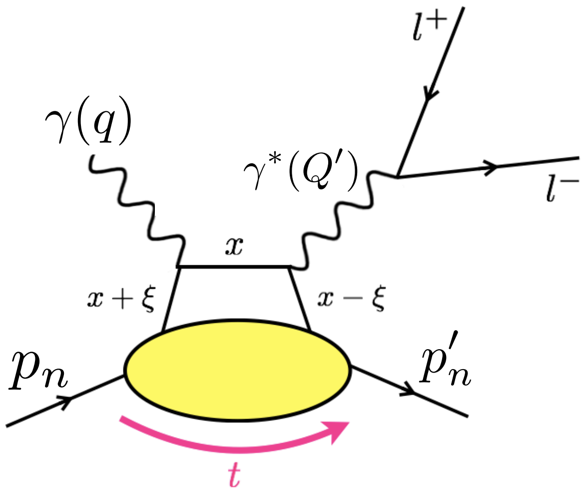
- Forward - backward asymmetry:

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

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:

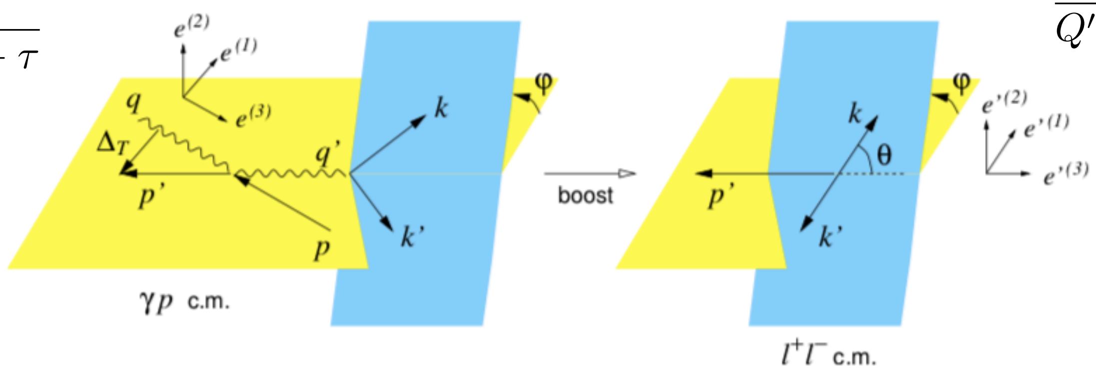
$$\frac{t}{Q'^2} << 1$$

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

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

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

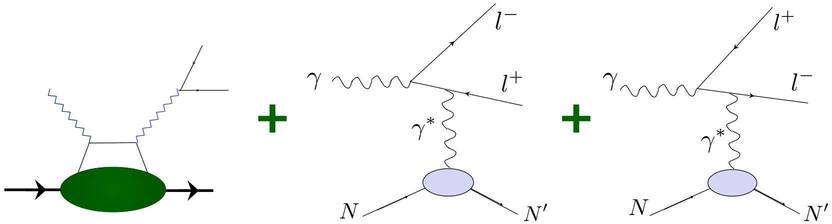
θ: angle between l^+ and scattered proton in lepton CMS



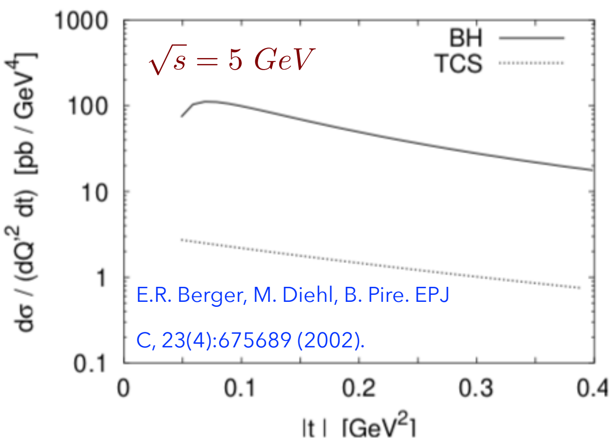
- Measurements establish dependence on Q^2, x, t and φ (angle between leptonic and hadronic planes).

TCS observables

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



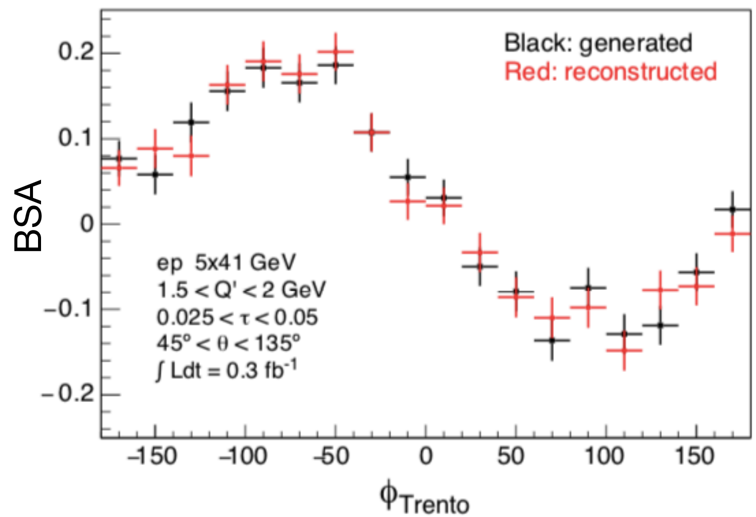
$$\sigma(\gamma p \to p' e^+ e^-) = \sigma_{BH} + \sigma_{TCS} + \sigma_{INT}$$



- 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 $\mathcal{Im}\ \mathcal{H}$



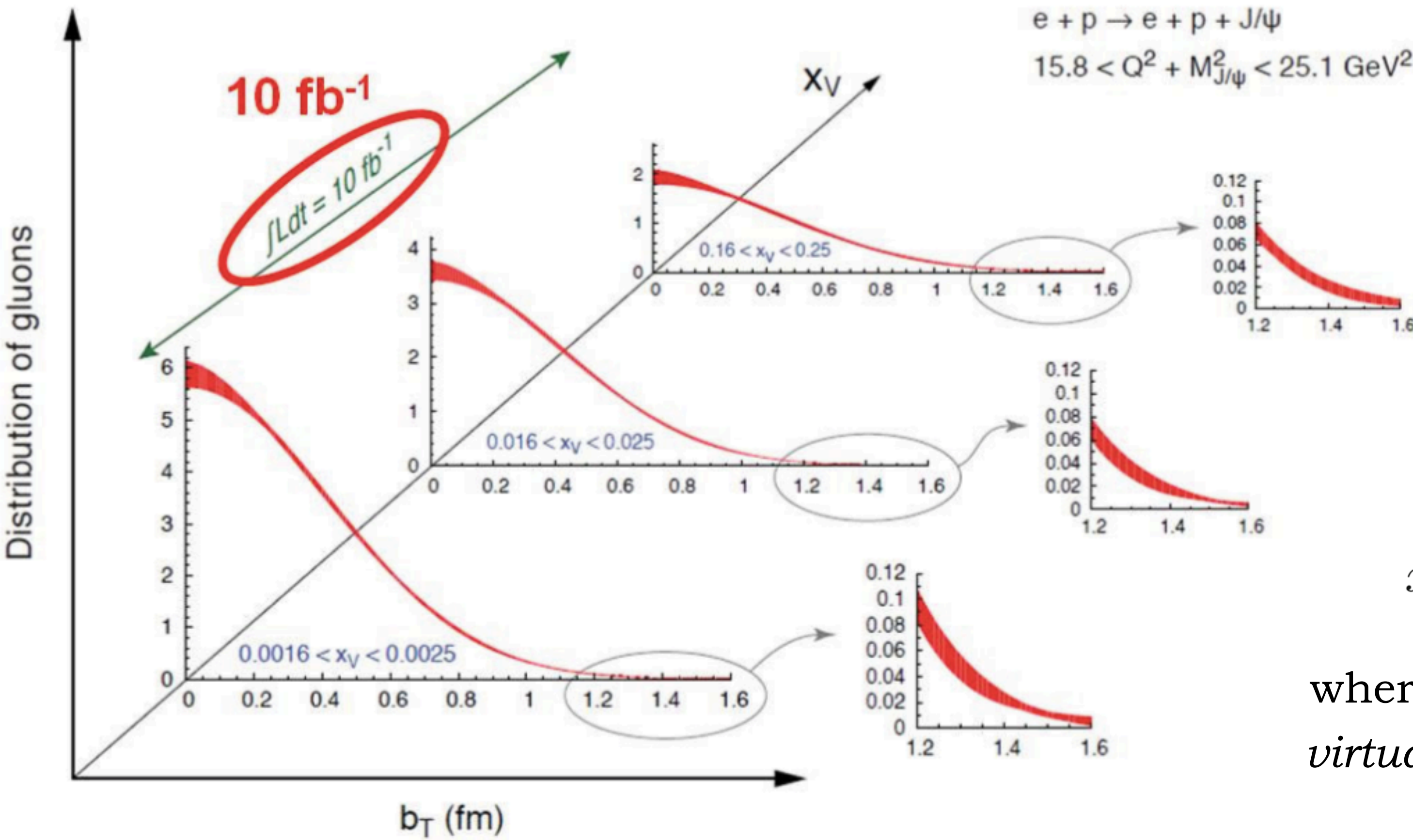
- Forward - backward asymmetry:

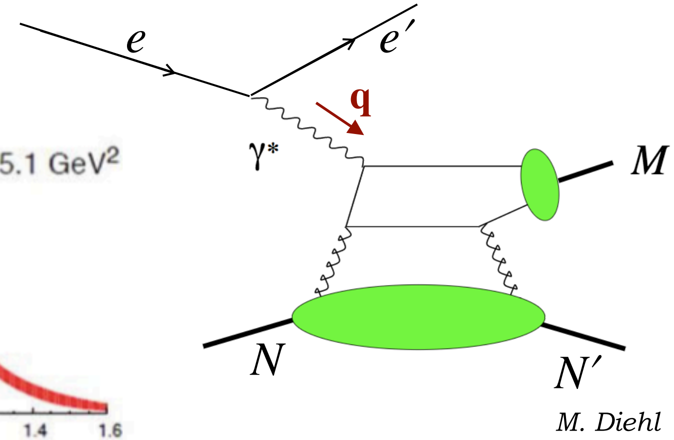
$$A_{FB}(\theta, \phi) = \frac{d\sigma(\theta, \phi) - d\sigma(180° - \theta, 180° + \phi)}{d\sigma(\theta, \phi) + d\sigma(180° - \theta, 180° + \phi)}$$

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

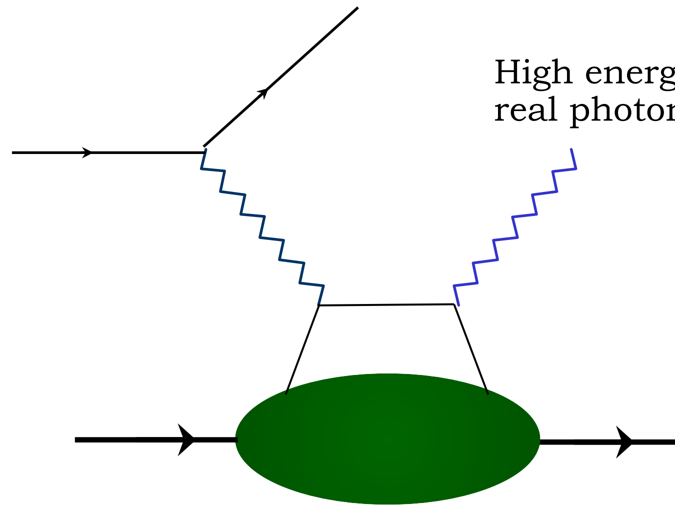
virtuality of exchanged photon

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

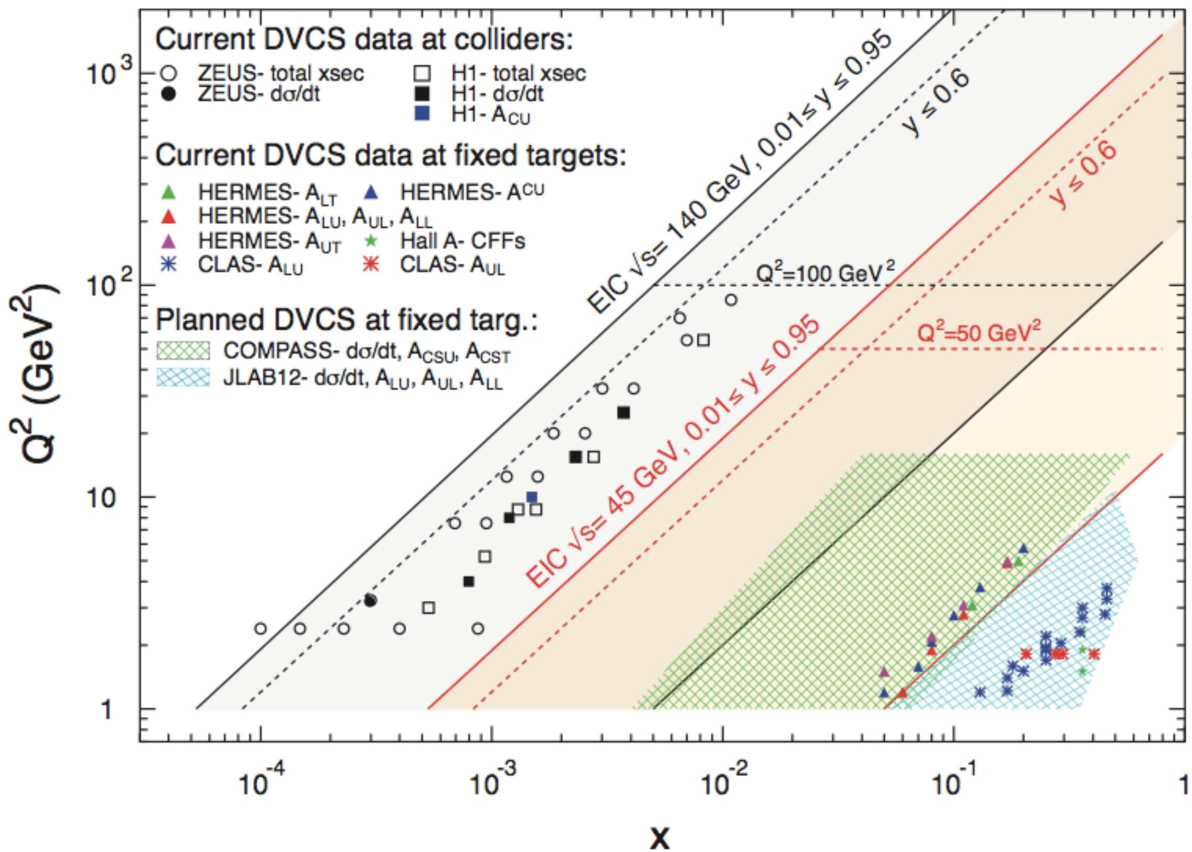
EIC White Paper, *Eur. Phy. J. A 52, 9 (2016)*

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)

The Nucleon Spin Puzzle

✳ What contributes to nucleon spin?

✳ 1980's: European Muon Collaboration (EMC) measures contribution of valence quarks to proton spin to be ~ 30 %. Subsequent deep inelastic scattering (DIS) experiments confirm.

Where is the rest? → **Proton spin crisis!**

Quark spin: extracted from helicity distributions measured in polarised DIS.

Gluon spin and OAM: measurements of DIS and polarised proton collisions indicate gluon spin ΔG contribution is very small, although in a different decomposition.

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

Quark orbital angular momentum (OAM): can be accessed, in Ji's decomposition, via **GPDs**, which contain information on total angular momentum, J_q.

Caveat:

In Ji's decomposition of nucleon spin, the gluon spin and OAM terms cannot be separated.