

Prospects for the study of spin and 3D Parton distributions at the Electron-Ion Collider

Daria Sokhan

CEA Saclay, France

(on leave from University of Glasgow)

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2nd August 2022

A constructivist view of the nucleon

Wigner distributions

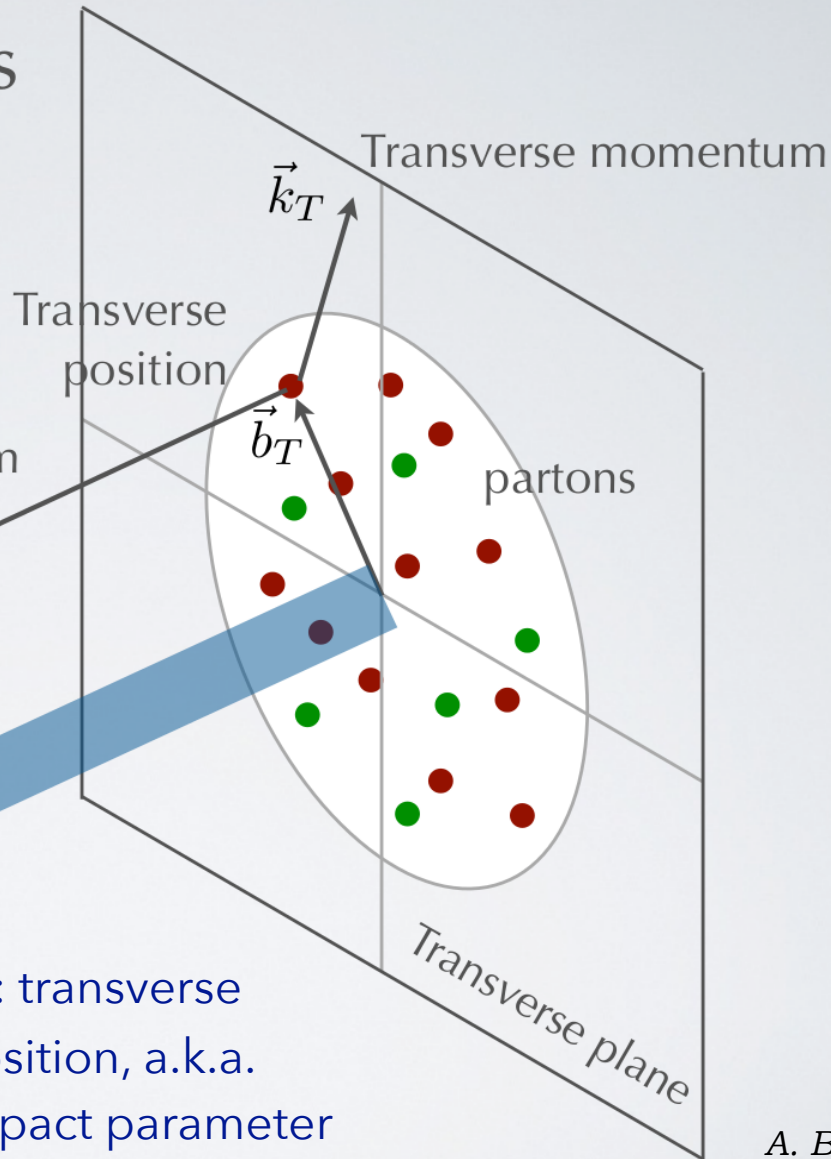
$$\rho(x, \vec{k}_T, \vec{b}_T)$$

*"phase space" distributions
of partons in a nucleon*

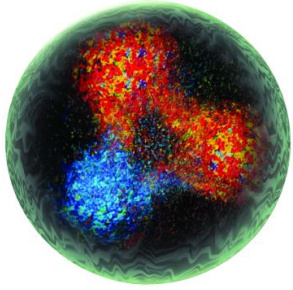
Longitudinal momentum

$$k^+ = xP^+$$

x : longitudinal
momentum
fraction carried
by struck parton



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



*Wigner function:
full phase space parton
distribution of the nucleon*



Generalised Transverse Momentum
Distributions (GTMDs)

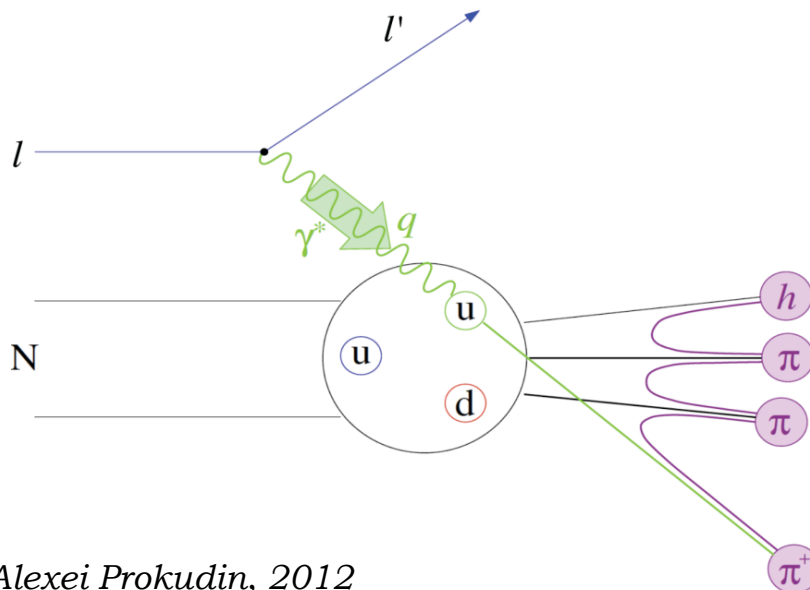


$$\int d^2 b_T$$

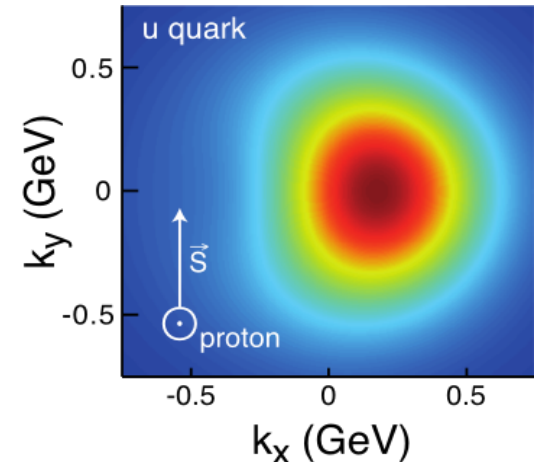


Transverse
Momentum
Distributions
(TMDs)

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

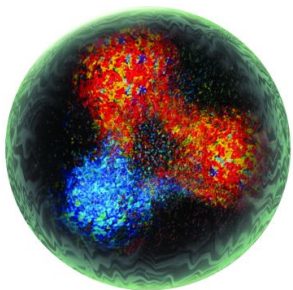


SIDIS:



Sivers function: Alexei Prokudin, 2012

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



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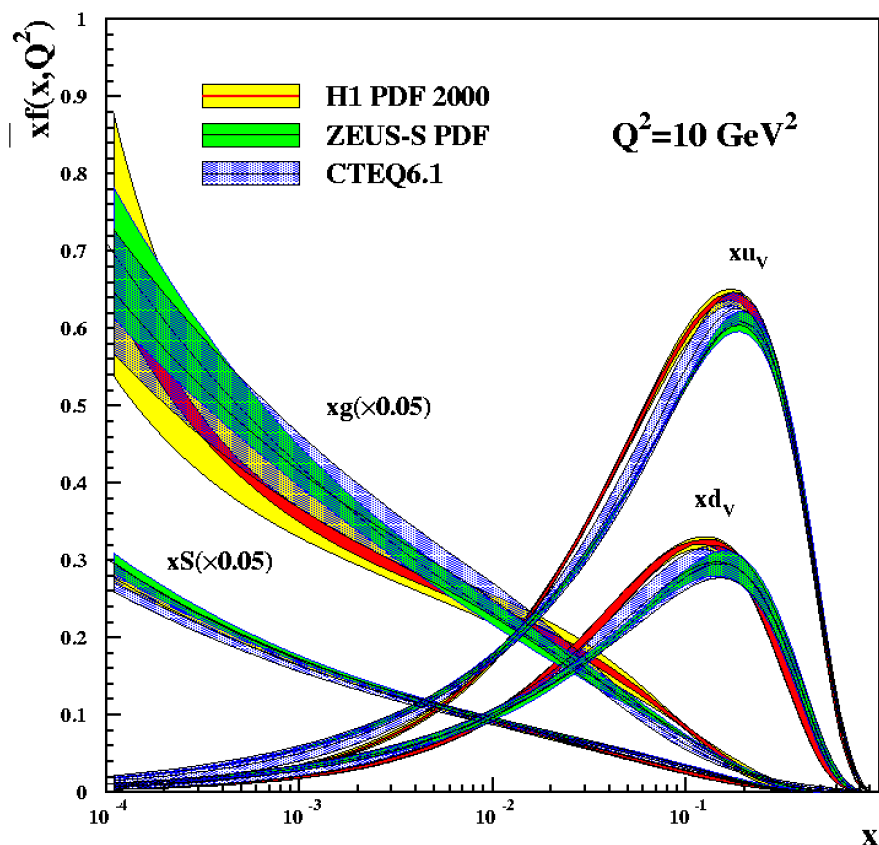
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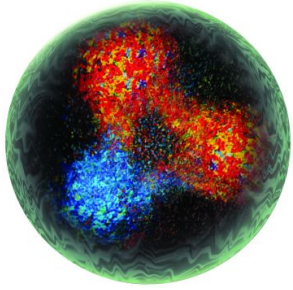
Transverse
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Distributions
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$$\int d^2 k_T$$

Parton Distribution
Functions (PDFs)

* Deep Inelastic
Scattering (DIS)

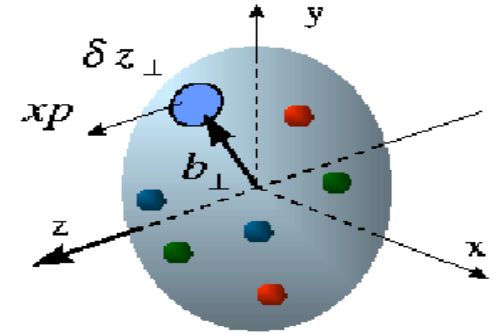




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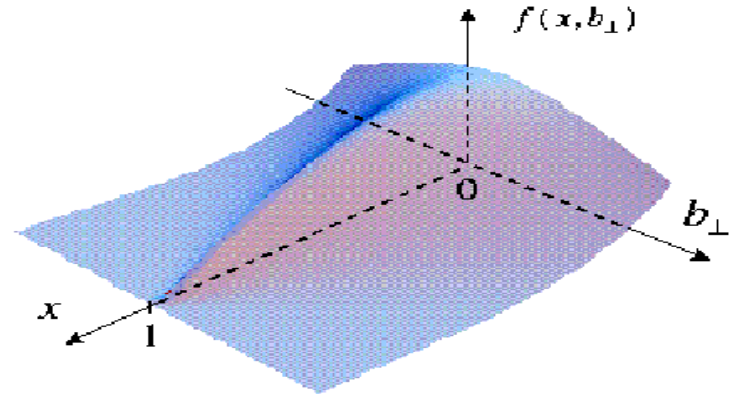
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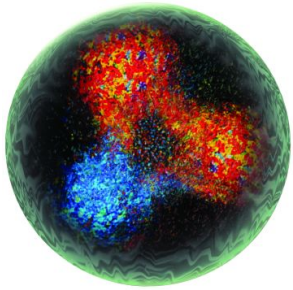


Generalised Parton
Distributions (GPDs)

- 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:
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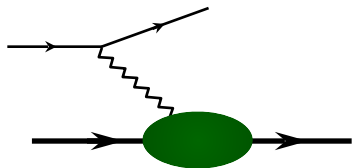
Generalised Transverse Momentum
Distributions (GTMDs)

$$\int d^2 k_T$$

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

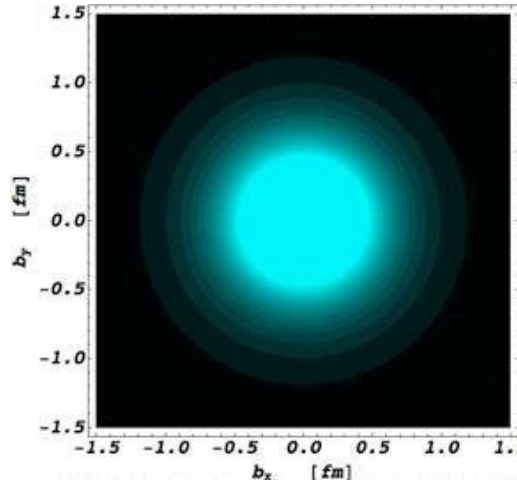
Generalised Parton
Distributions (GPDs)

$$\int dx$$

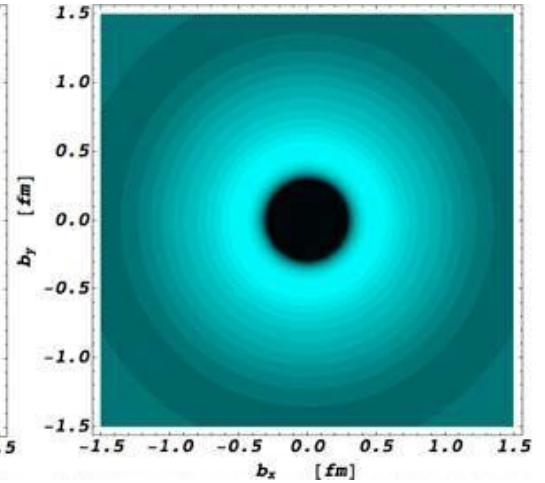


Elastic scattering

Form Factors
eg: G_E, G_M

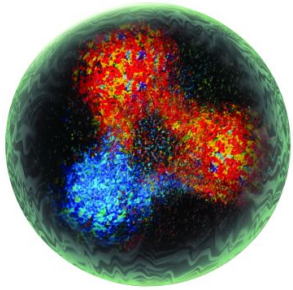


proton



neutron

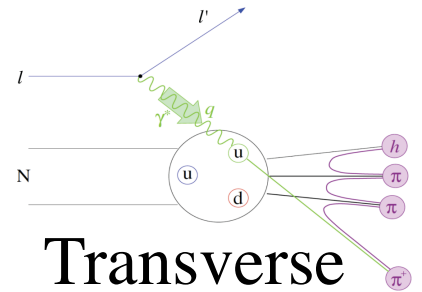
C. Carlson, M. Vanderhaeghen
PRL 100, 032004 (2008)



*Wigner function:
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distribution of the nucleon*

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

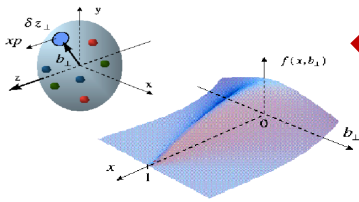
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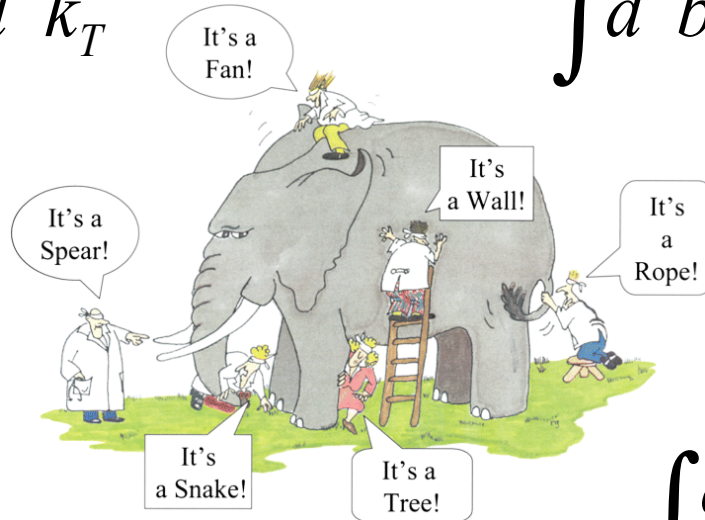
$$\int d^2 k_T$$

$$\int d^2 b_T$$

Generalised Parton
Distributions (GPDs)



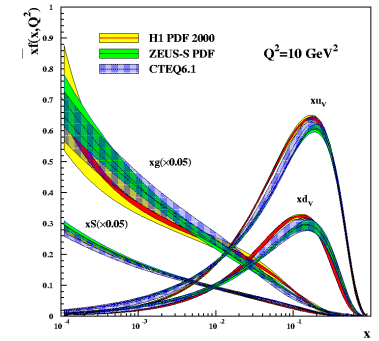
$$\int dx$$



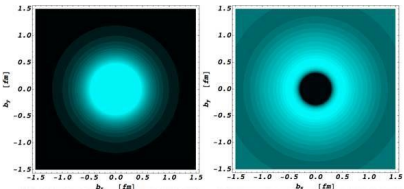
G. Renee Guzlas, artist.

Transverse
Momentum
Distributions
(TMDs)

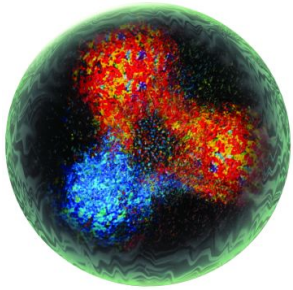
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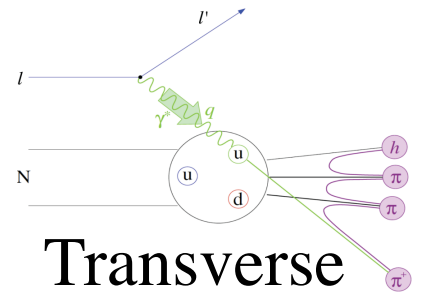
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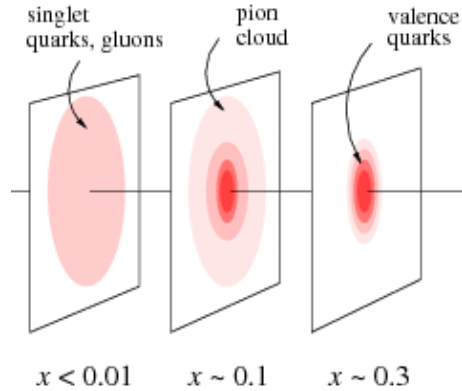
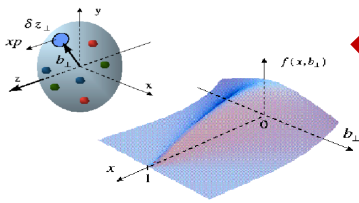
Generalised Transverse Momentum
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$$\int d^2 k_T$$

$$\int d^2 b_T$$

Generalised Parton
Distributions (GPDs)



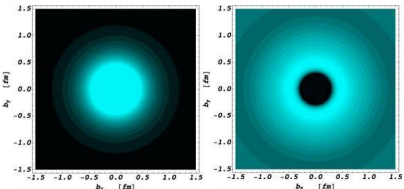
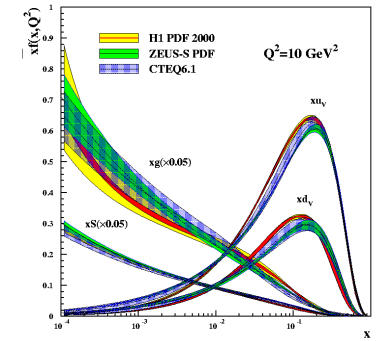
Transverse
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$$\int dx$$

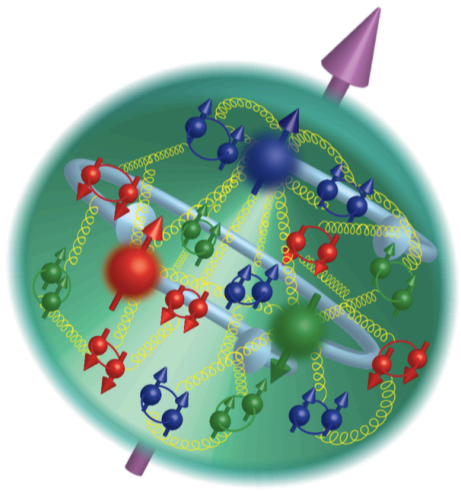
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Parton Distribution
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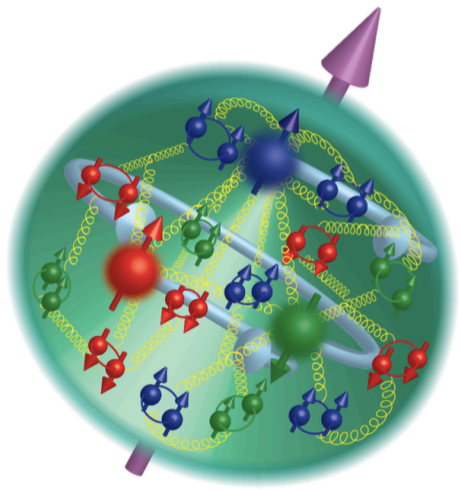


Nucleon spin



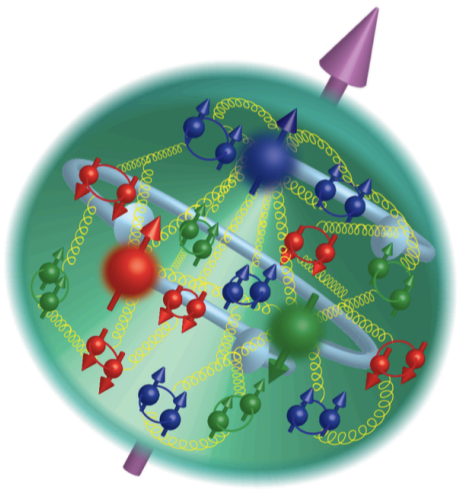
$\frac{1}{2}$

Nucleon spin



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

Nucleon spin

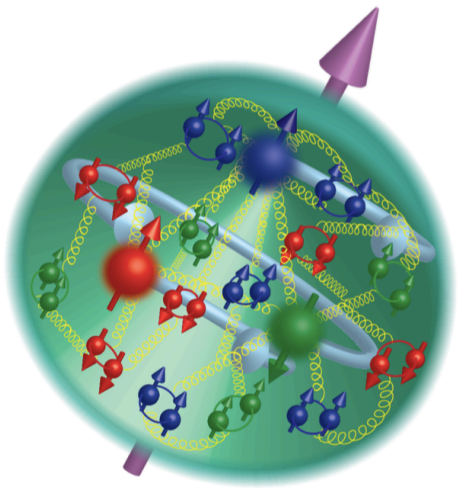


$$\frac{1}{2} = \frac{1}{2} \Delta\Sigma + \Delta G + L_q + L_g$$

Intrinsic quark spin:

$$\Delta\Sigma = \int_x \sum_q (\Delta q - \Delta \bar{q})$$

Nucleon spin



$$\frac{1}{2} = \frac{1}{2} \Delta\Sigma + \Delta G + L_q + L_g$$



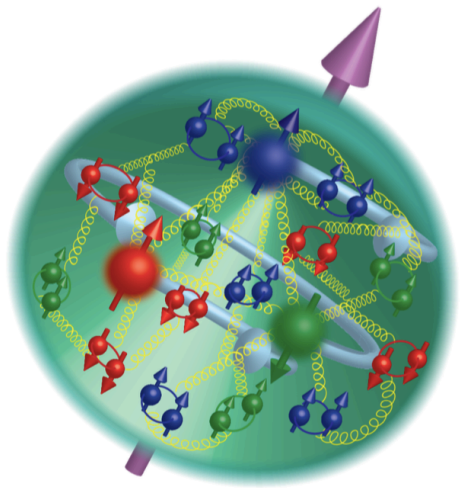
Intrinsic quark spin:

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Intrinsic gluon spin:

$$\Delta G = \int_x \Delta g$$

Nucleon spin



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Intrinsic quark spin:

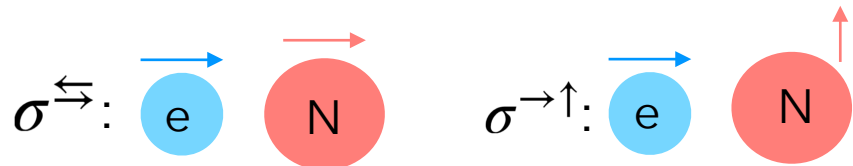
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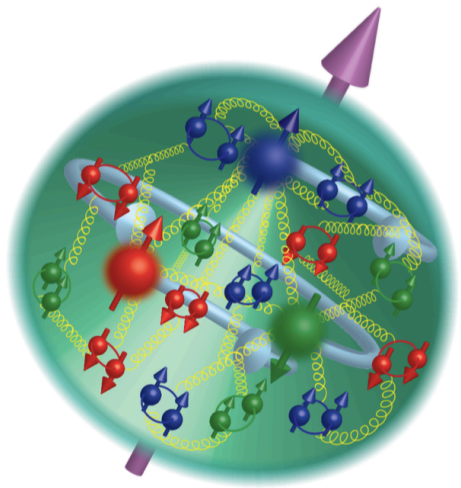
$$\Delta G = \int_x \Delta g$$

Polarised Deep Inelastic Scattering (DIS) to access spin structure function:

$$g_1(x) = \sum_q (\Delta q(x) + \Delta\bar{q}(x))$$



Nucleon spin



Quark and gluon orbital
angular momentum:
accessible
through GPDs

$$\frac{1}{2} = \frac{1}{2} \Delta\Sigma + \Delta G + L_q + L_g$$

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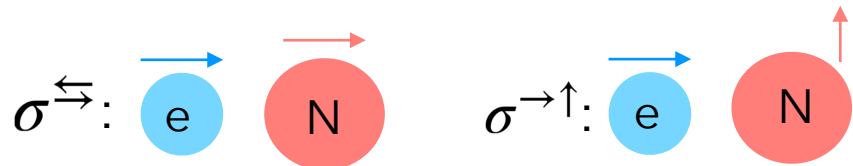
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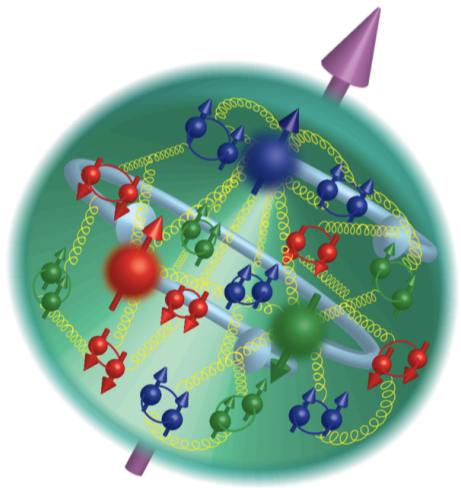
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Nucleon spin



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Quark and gluon orbital angular momentum:
accessible through GPDs
(but watch out for decomposition!)

Intrinsic quark spin:

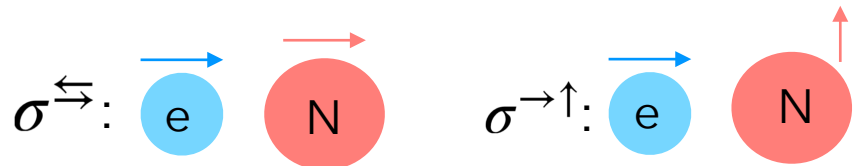
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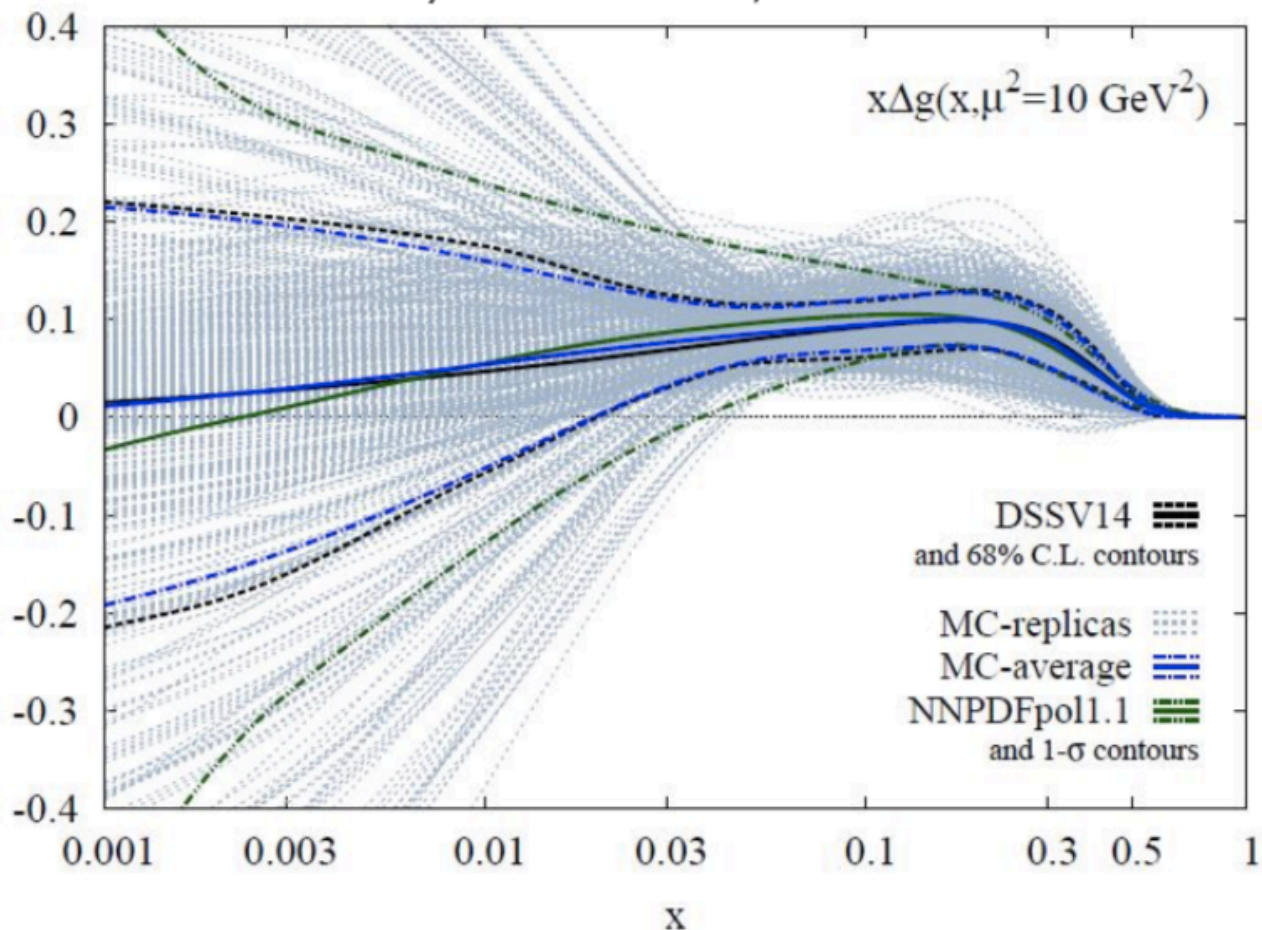
Spin structure function

$$\frac{1}{2} = \frac{1}{2} \Delta\Sigma + \Delta G + L_q + L_g$$

~ 30% huge uncertainties
uncertainties
??

Huge uncertainties on polarised gluon PDFs, L contribution unknown...

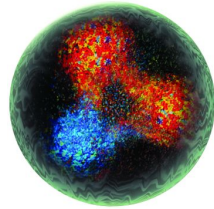
Phys. Rev. D **100**, 114027



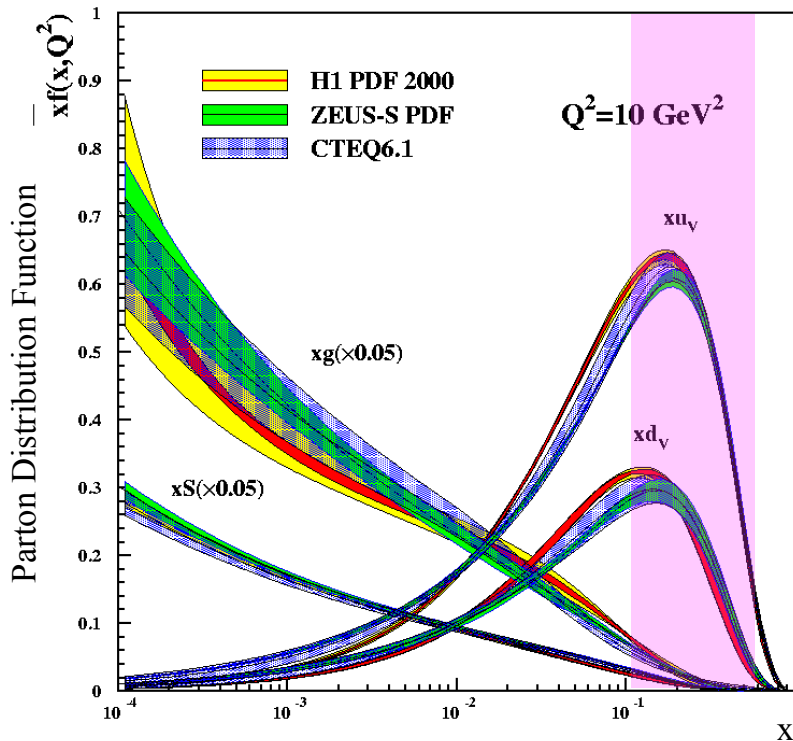
Nucleon at different scales

Valence quarks

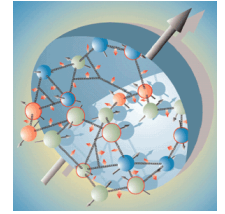
Jefferson Lab: fixed-target
electron scattering



$$0.1 < x_B < 0.7$$

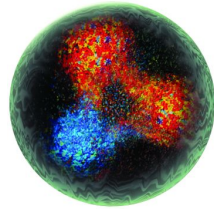


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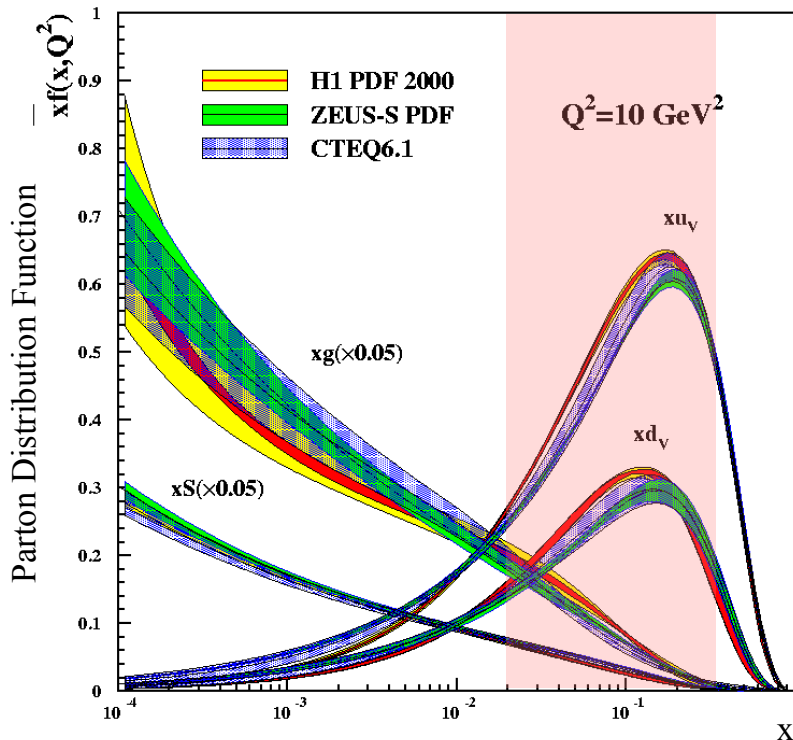
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Sea quarks

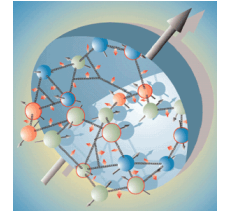


HERMES: fixed gas-target electron/positron scattering

$$0.02 < x_B < 0.3$$

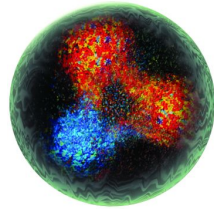


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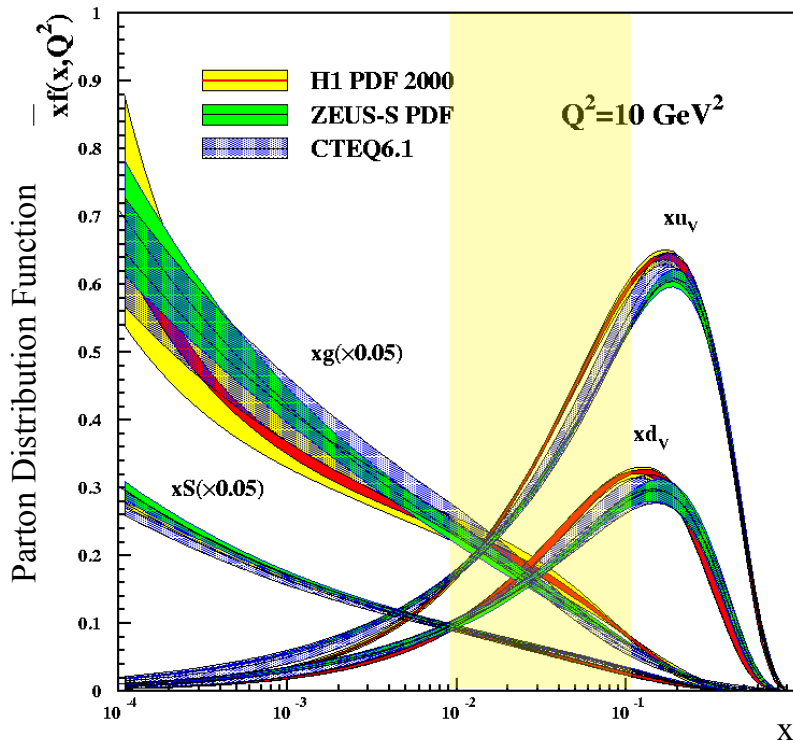
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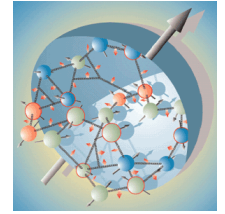


COMPASS: fixed-target muon scattering

$$0.01 < x_B < 0.1$$

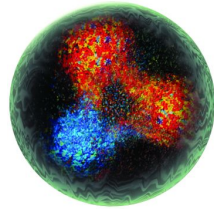


Nucleon at different scales



Valence quarks

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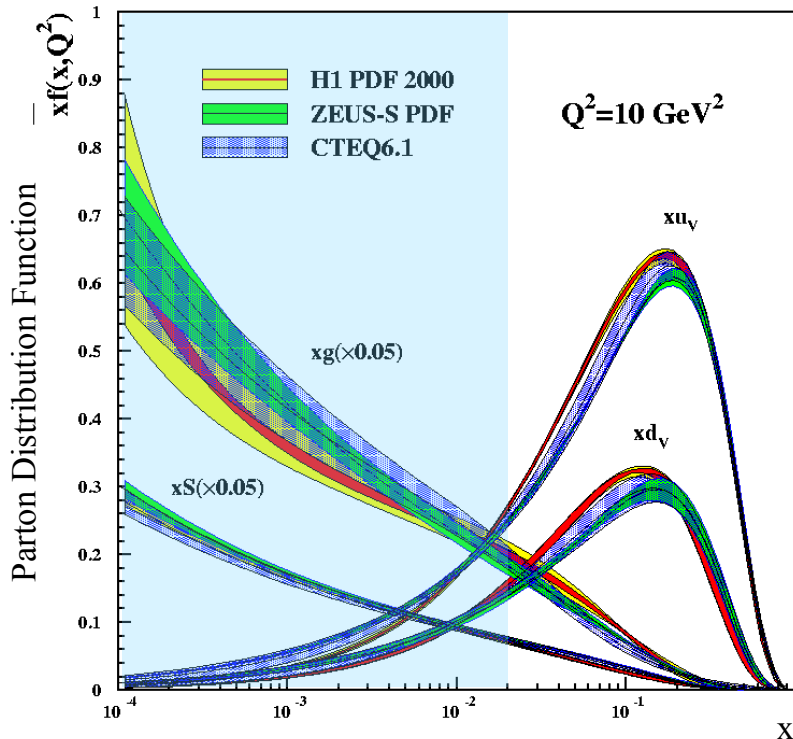
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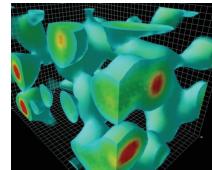
COMPASS: fixed-target muon scattering

$$0.01 < x_B < 0.1$$

The glue

ZEUS/H1: electron/positron-proton collider

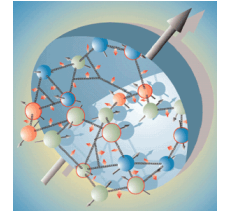
$$10^{-4} < x_B < 0.02$$



Derek Leinweber

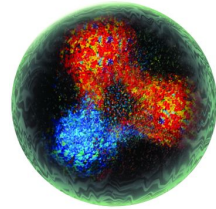


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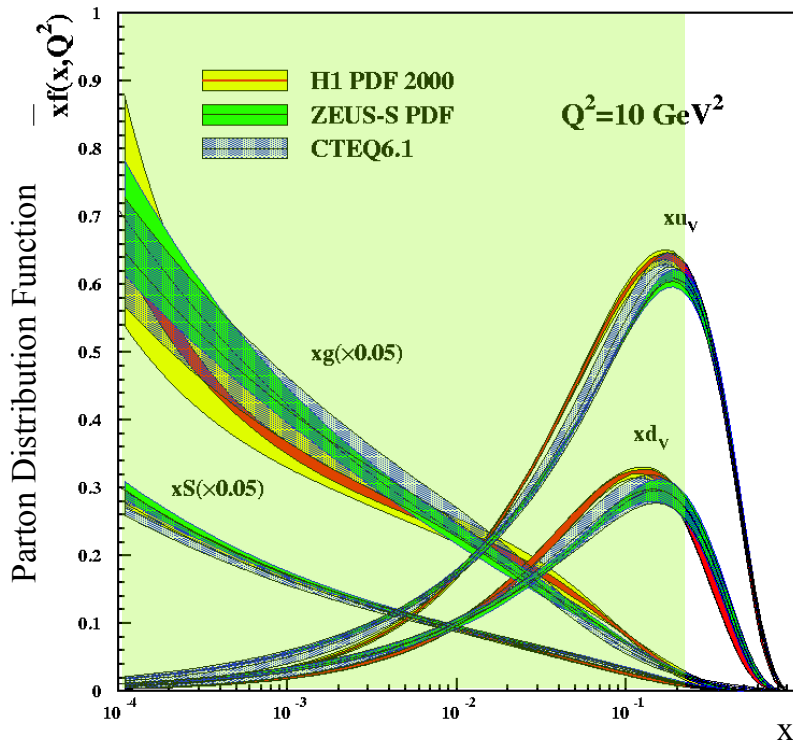


Valence quarks

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Sea quarks



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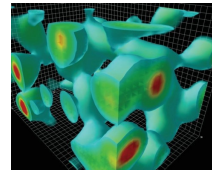
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COMPASS: fixed-target muon scattering

$$0.01 < x_B < 0.1$$

The glue



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/³He
- ✓ e beam 3 - 10 (18) GeV
- ✓ Luminosity $L_{ep} \sim 10^{33-34} \text{ cm}^{-2}\text{s}^{-1}$
- ✓ 20 - 100 (140) GeV Variable CoM

For e-A collisions at the EIC:

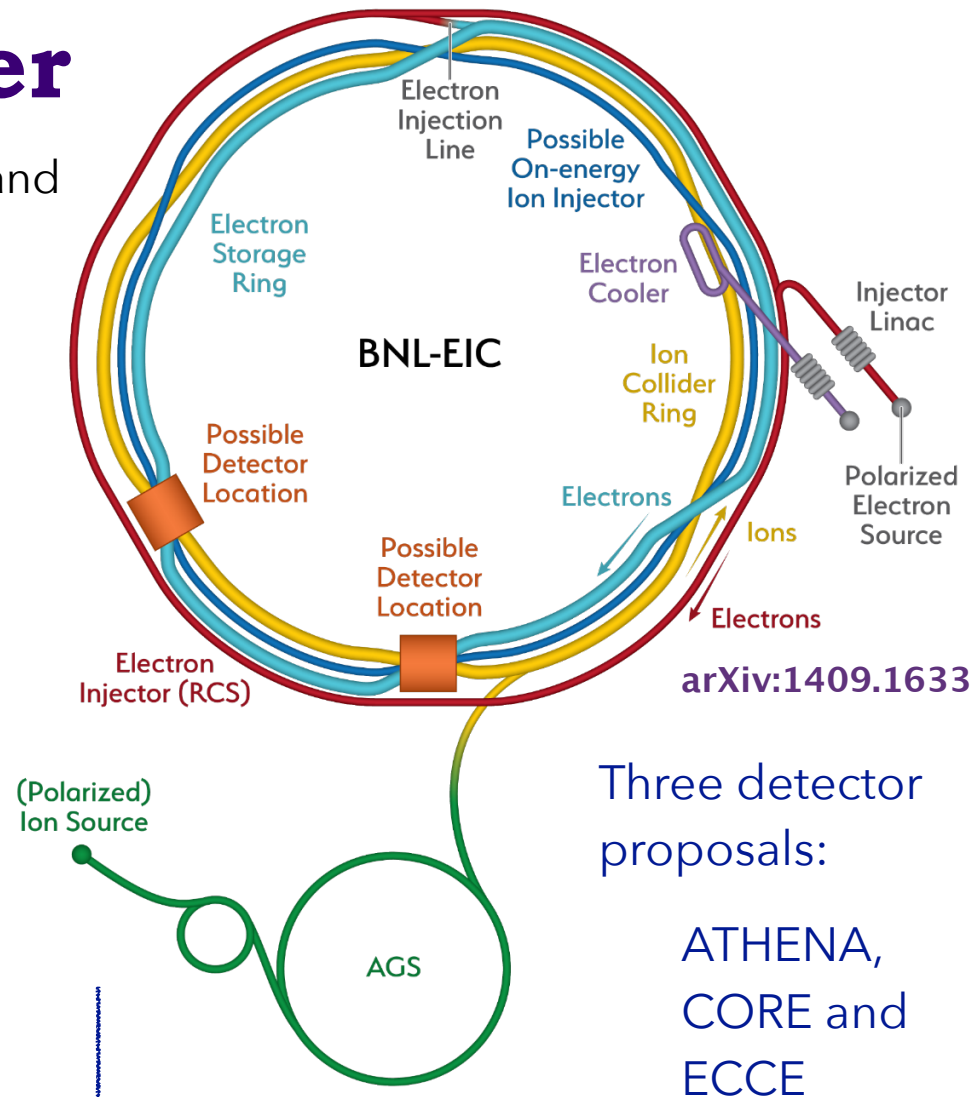
- ✓ Wide range of nuclei
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable centre of mass energy

Brookhaven National Lab selected as the site

Dedicated studies of EIC physics and design:

EIC White Paper, [Eur. Phys. J. A 52, 9 \(2016\)](#)

EIC Yellow Report, <https://arxiv.org/abs/2103.05419>



Three detector proposals:

ATHENA,
CORE and
ECCE

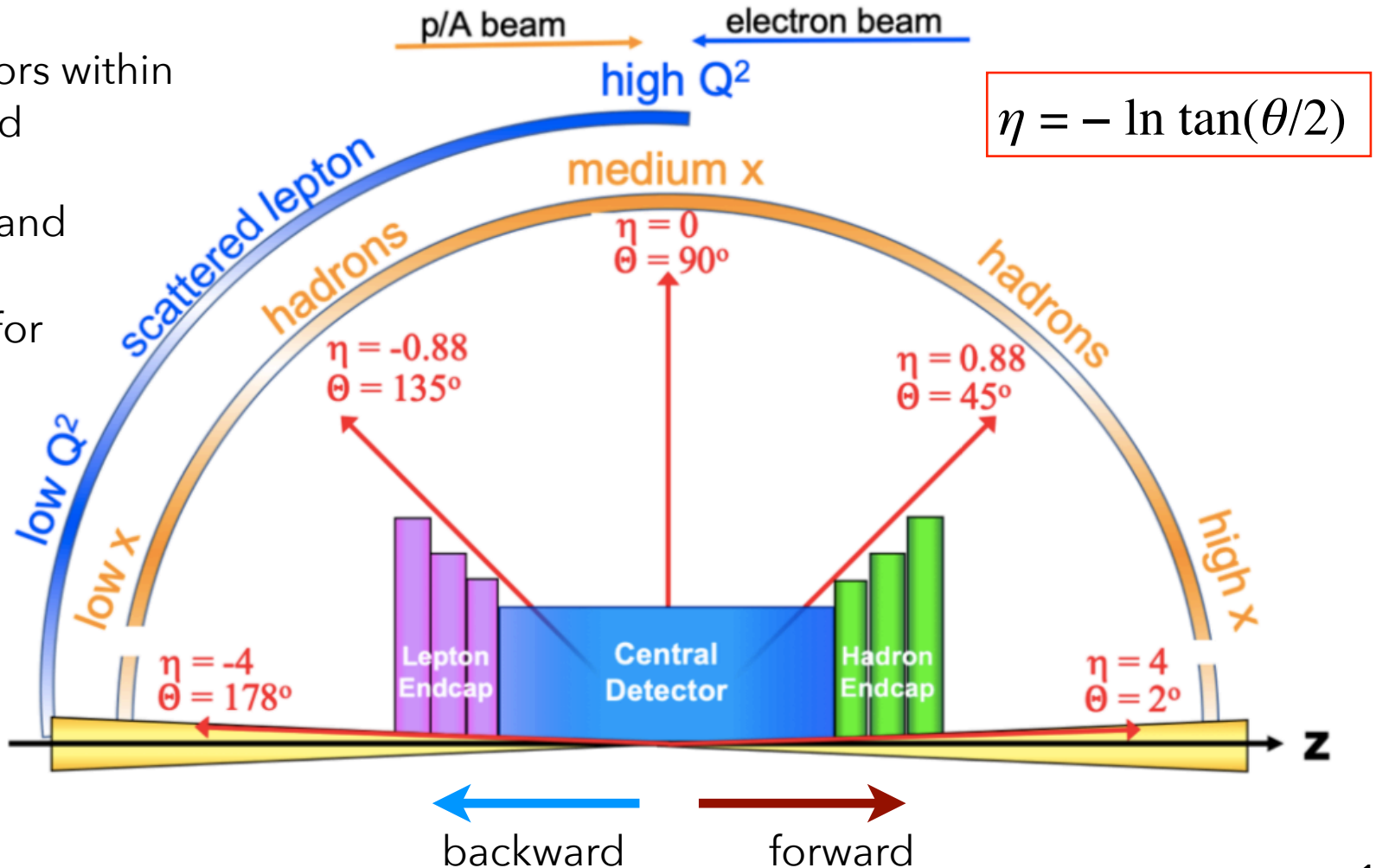
Merged to form the new "Detector 1" collaboration: EPIC

Detector configuration

Very asymmetric beams

Hermetic detectors within a central solenoid

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



Detector requirements

4 π hermetic detector with low mass inner tracking.

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

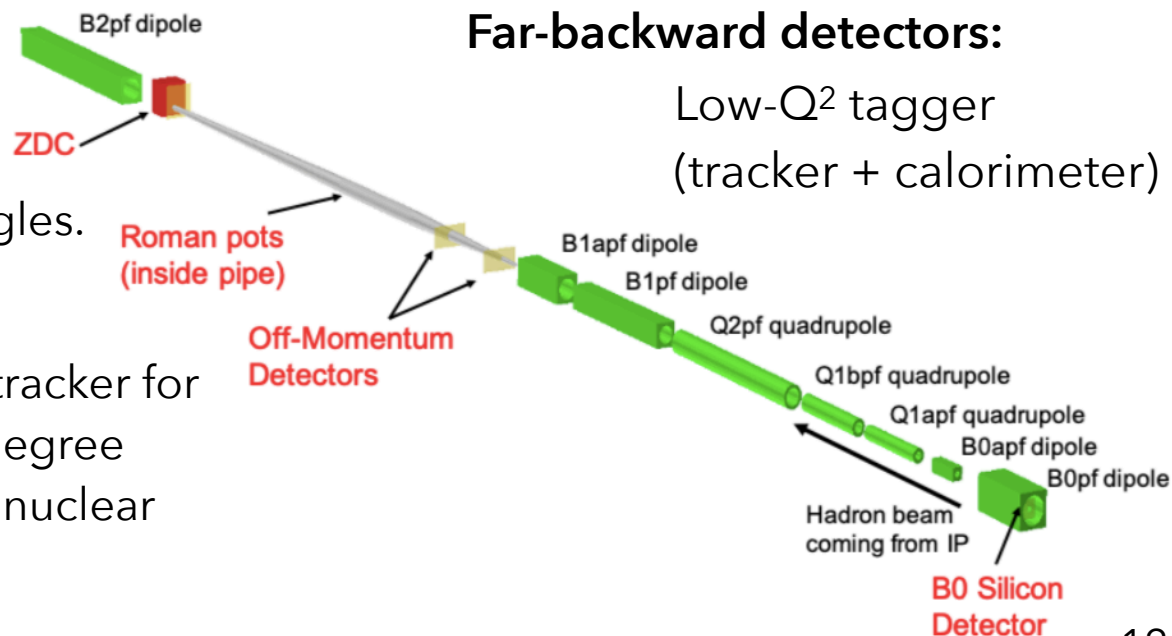
- Tracking and momentum measurement
- Electron ID
- Hadron ID
- Jet energy measurement

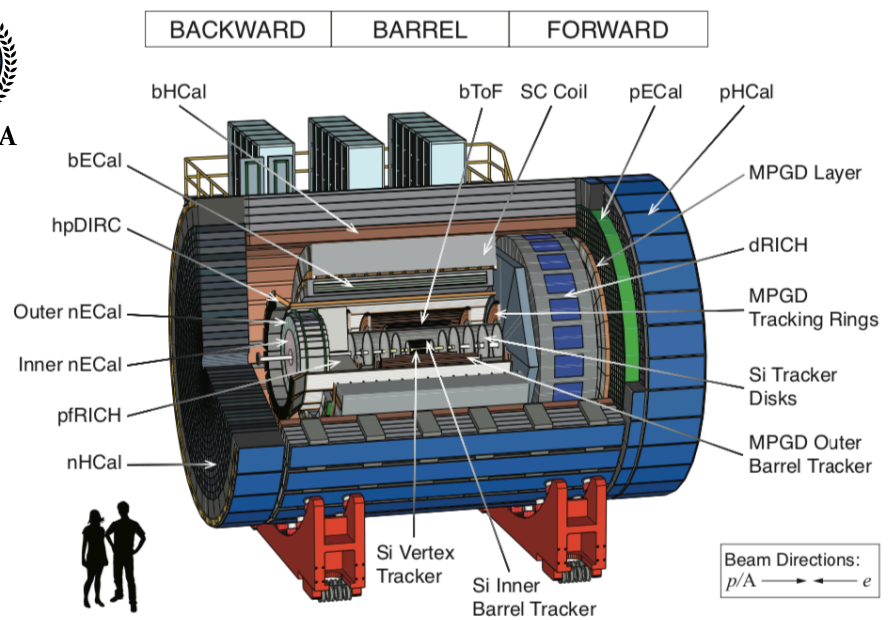
Barrel detector ($|\eta| < 1$) + two disc **end-caps** (forward/hadron end-cap and backward/electron endcap).

Far-forward detectors:

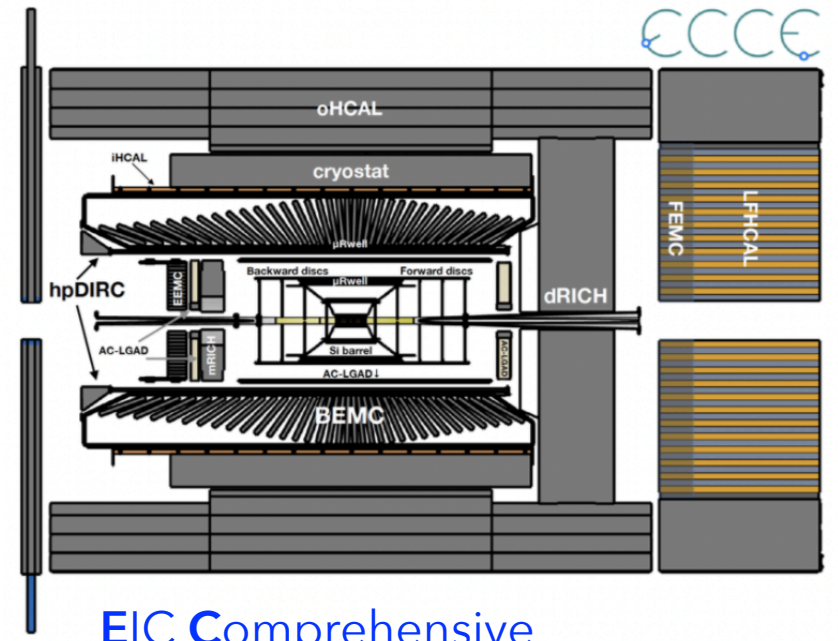
Far from interaction point, very low angles.

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)





A Totally Hermetic Electron-Nucleus Apparatus
<https://sites.temple.edu/eicatip6/>



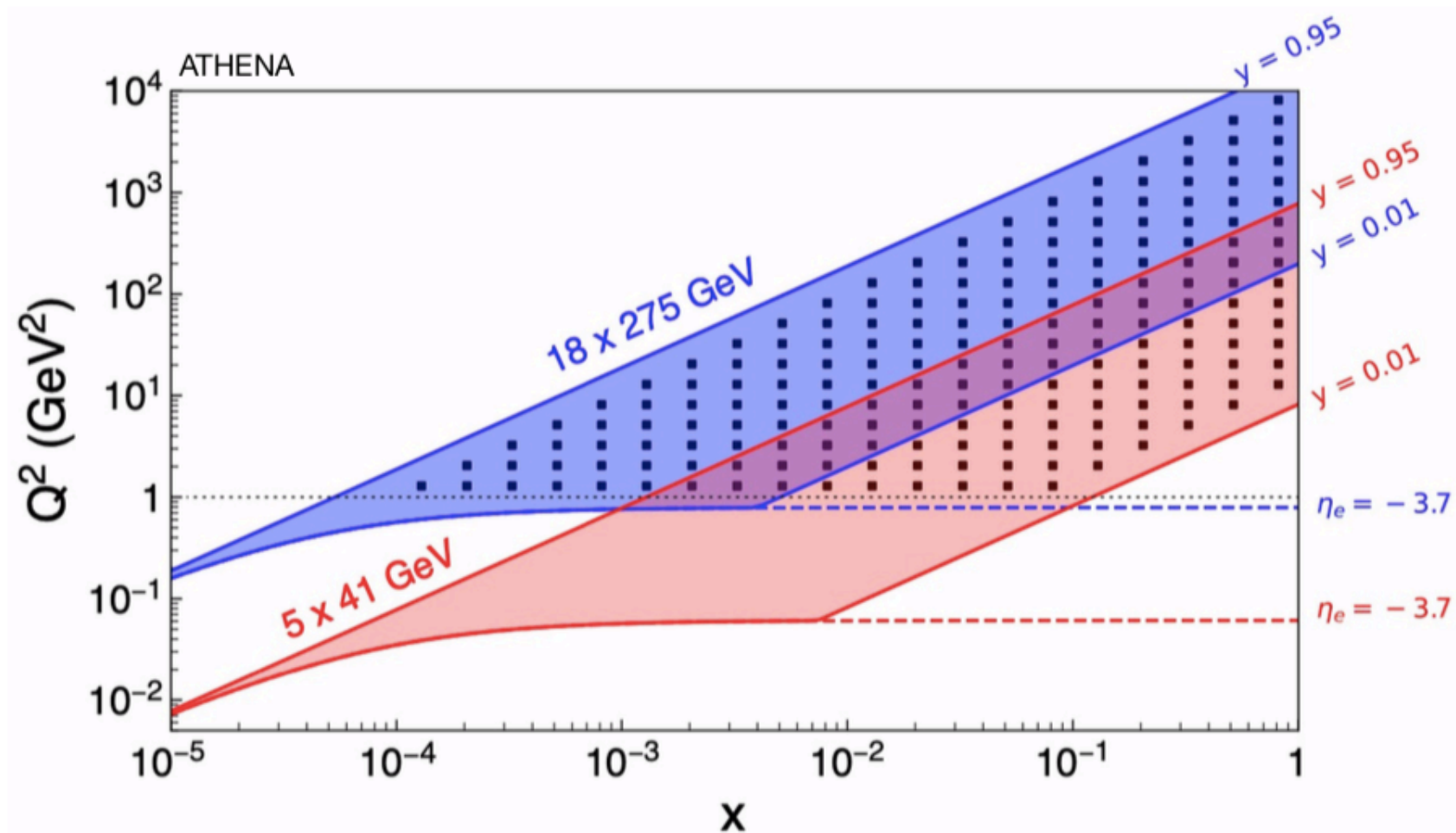
EIC Comprehensive Chromodynamics Experiment
<https://www.ecce-eic.org>

EPIC (Electron-Proton and -Ion Collider):

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

Design still in flux, to be finalised this year.

EIC Kinematic reach: DIS

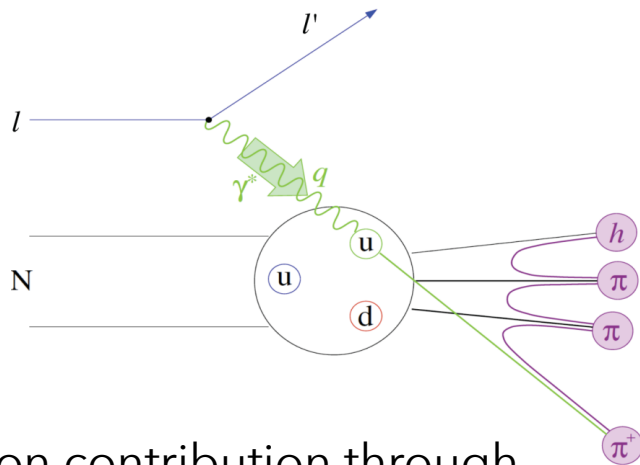


Spin structure function

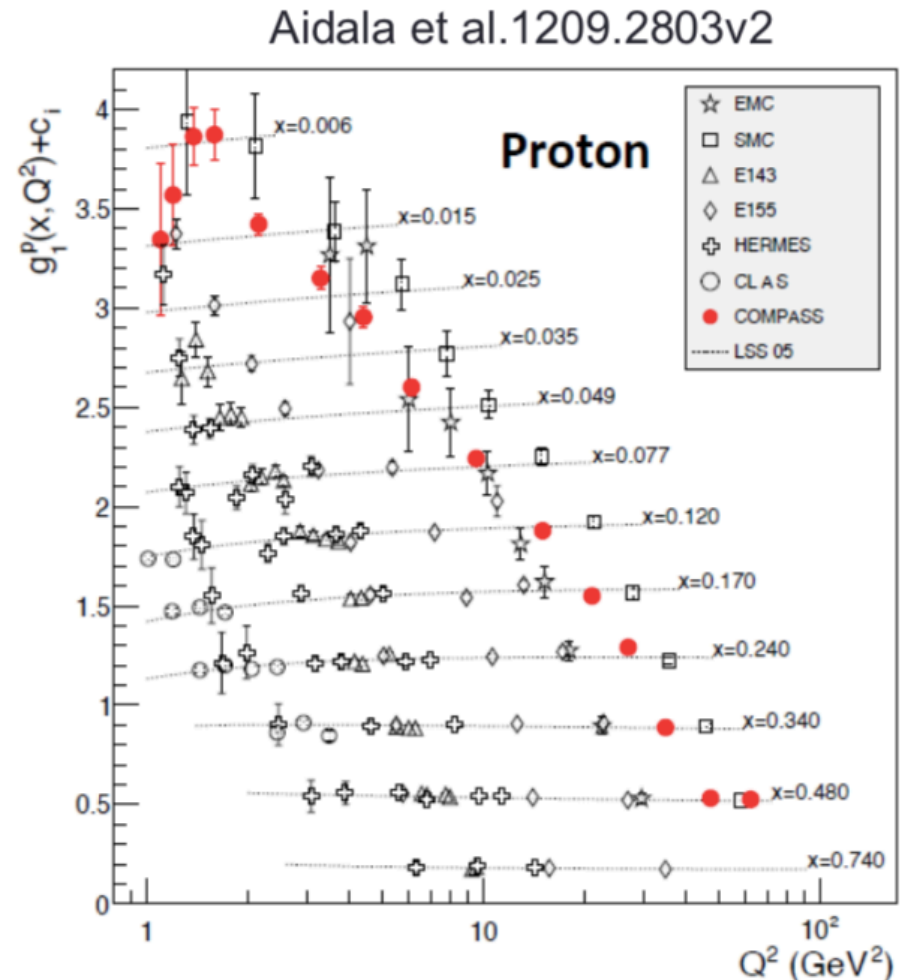
Access by measuring spin asymmetries in DIS, eg: $A_1(x) \approx g_1(x)/F_1(x)$

$$A_{\parallel} = \frac{\sigma^{\leftrightarrow} - \sigma^{\rightarrow}}{\sigma^{\leftrightarrow} + \sigma^{\rightarrow}} \quad A_{\perp} = \frac{\sigma^{\rightarrow\uparrow} - \sigma^{\rightarrow\downarrow}}{\sigma^{\rightarrow\uparrow} + \sigma^{\rightarrow\downarrow}}$$

Semi-inclusive (detect a meson): access flavour information through convolution with Fragmentation Function:

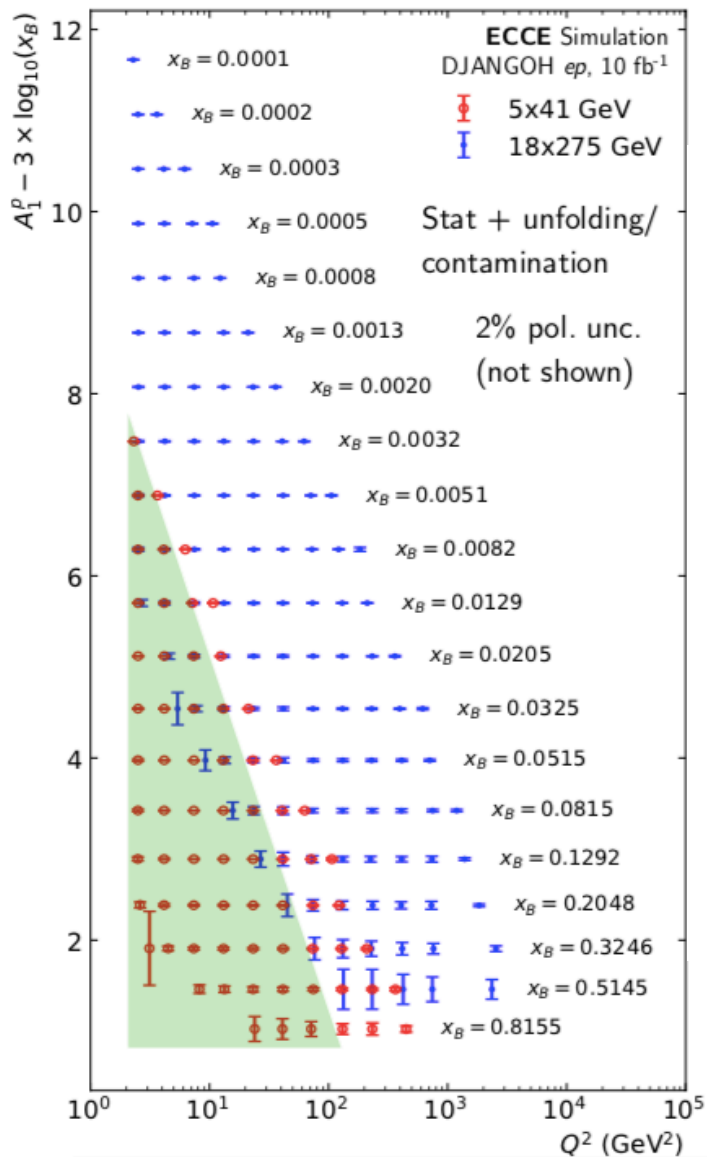


Access gluon contribution through Q^2 -dependence

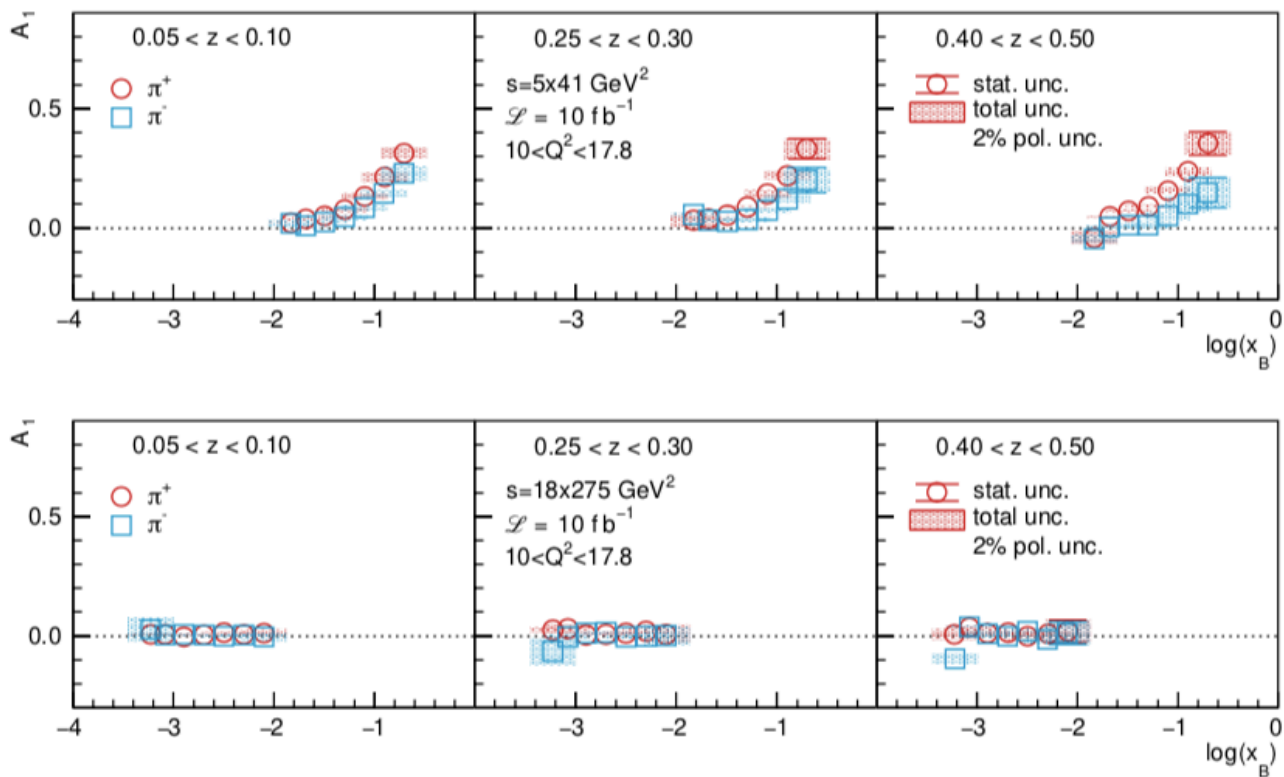


A_1^P projected results

Inclusive:

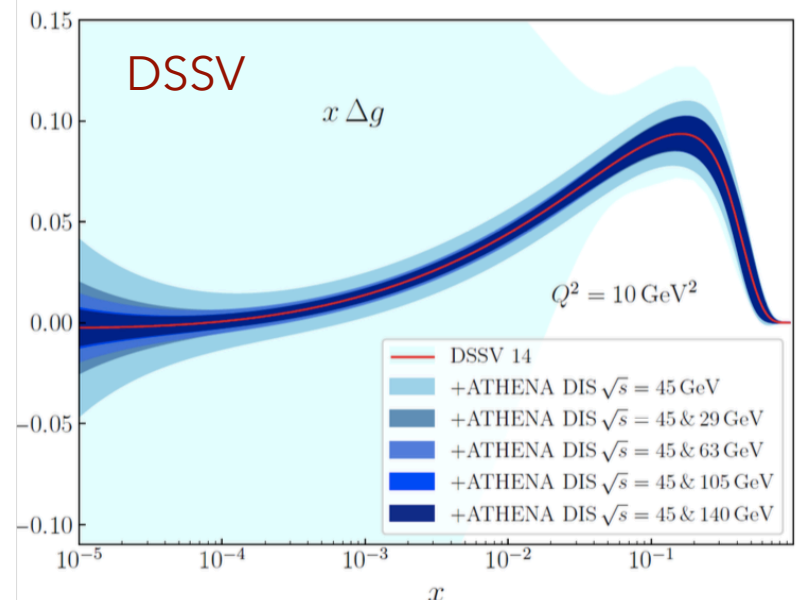
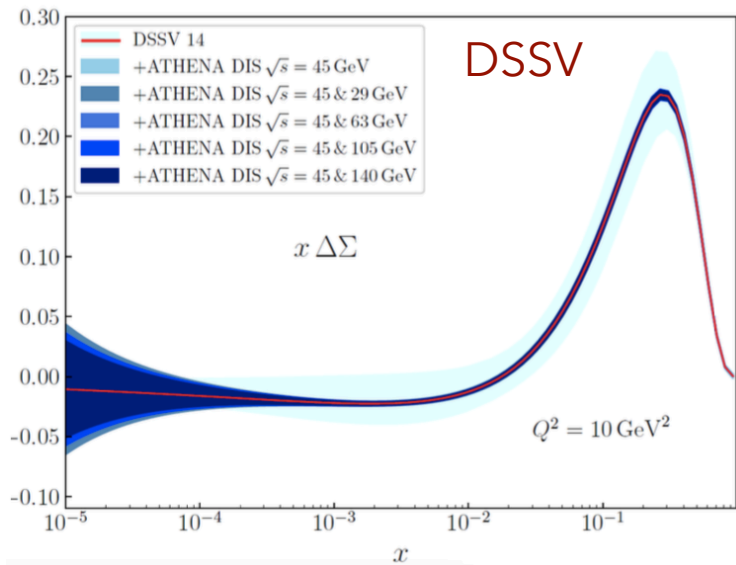


Semi-inclusive (z – parton longitudinal momentum fraction):



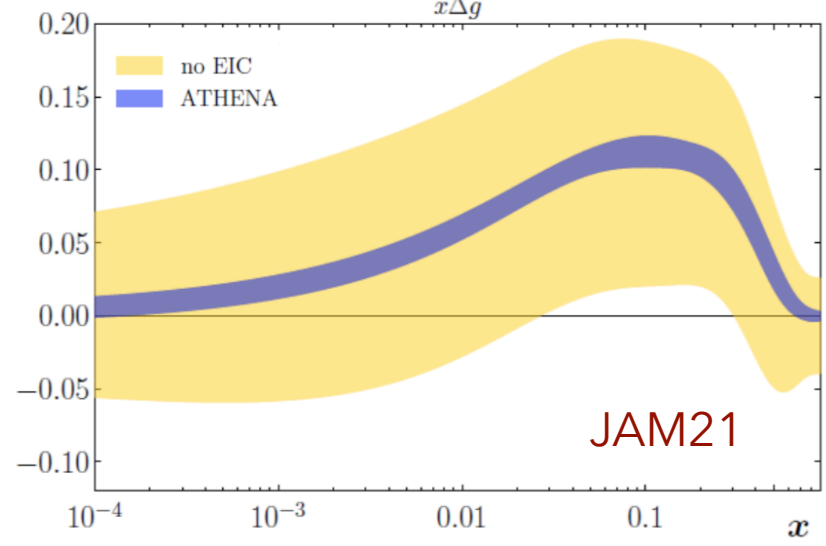
Simulations with ECCE detector design

EIC impact on polarised PDFs



Very significant constraints on gluon PDFs from inclusive e-p measurements.

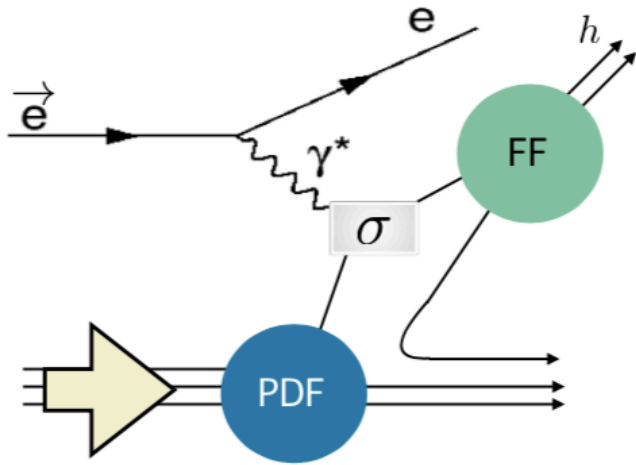
Study with ATHENA detector design



Transverse Momentum-Dependent Distributions

Can define TMDs for the nucleon in terms of x and k_T : [3D momentum distributions](#).

In SIDIS, structure functions are convolutions of TMDs with Fragmentation Functions (FF), defined in terms of z (parton's longitudinal momentum fraction in the hadron) and k_T : describe hadronisation of outgoing parton.

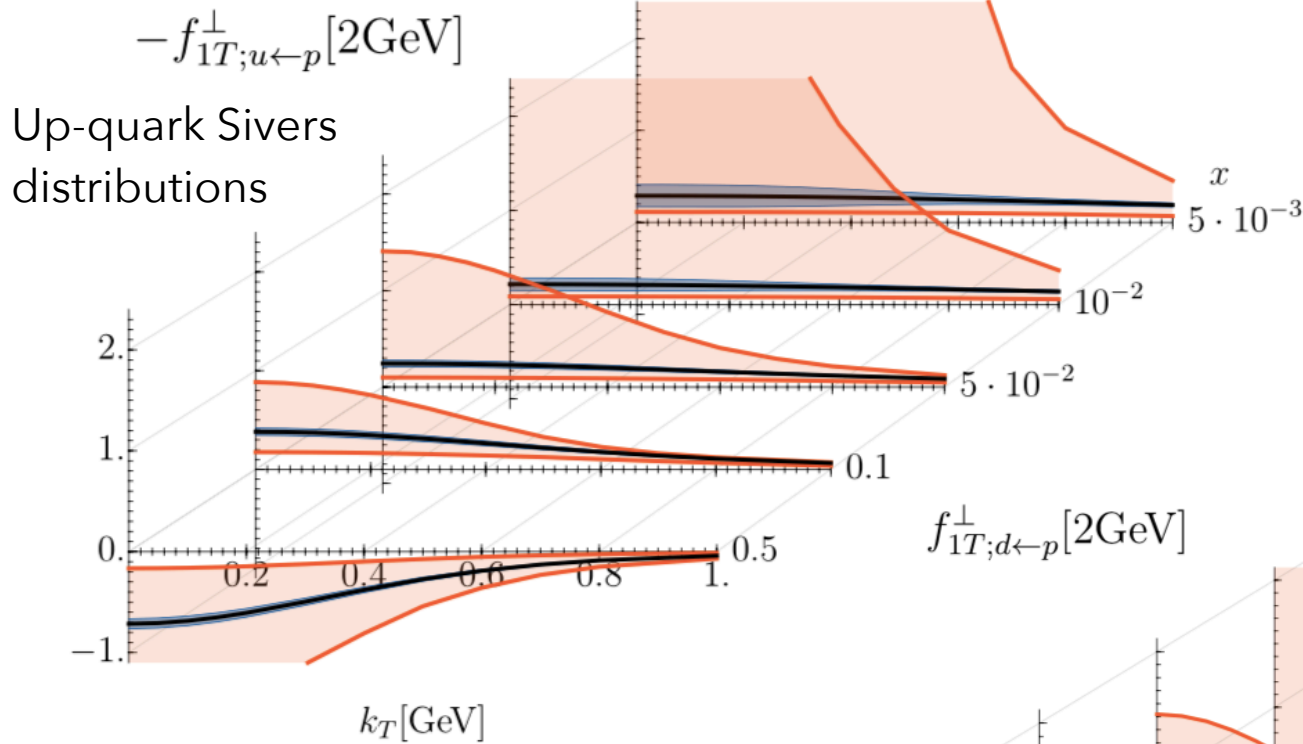


Formalism relies on TMD factorisation: applicable in certain regimes.

TMDs at play in combinations of quark and nucleon polarisations (at leading twist):

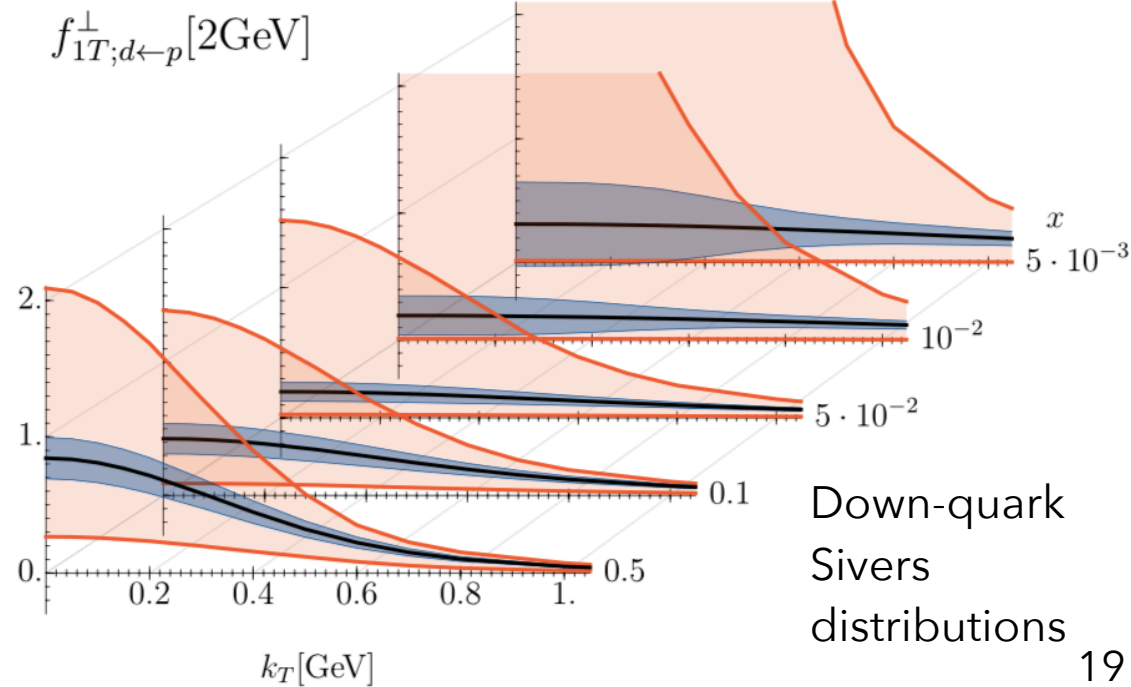
		Nucleon		
		Unpol.	Long.	Trans.
Quark	Unpol.	$f_1 = \text{circle with dot}$		$f_{1T}^\perp = \text{circle with dot up} - \text{circle with dot down}$ Sivers
	Long.		$g_{1L} = \text{circle with dot right} - \text{circle with dot left}$ Helicity	$g_{1T} = \text{circle with dot up right} - \text{circle with dot up left}$ Worm-gear Transversity
	Trans.	$h_1^\perp = \text{circle with dot up} - \text{circle with dot down}$ Boer-Mulders	$h_{1L}^\perp = \text{circle with dot right up} - \text{circle with dot left up}$ Worm-gear	$h_{1T}^\perp = \text{circle with dot up right} - \text{circle with dot up left}$ $h_{1T}^{\perp\perp} = \text{circle with dot up right} - \text{circle with dot down right}$ Pretzelosity

EIC constraints on Sivers



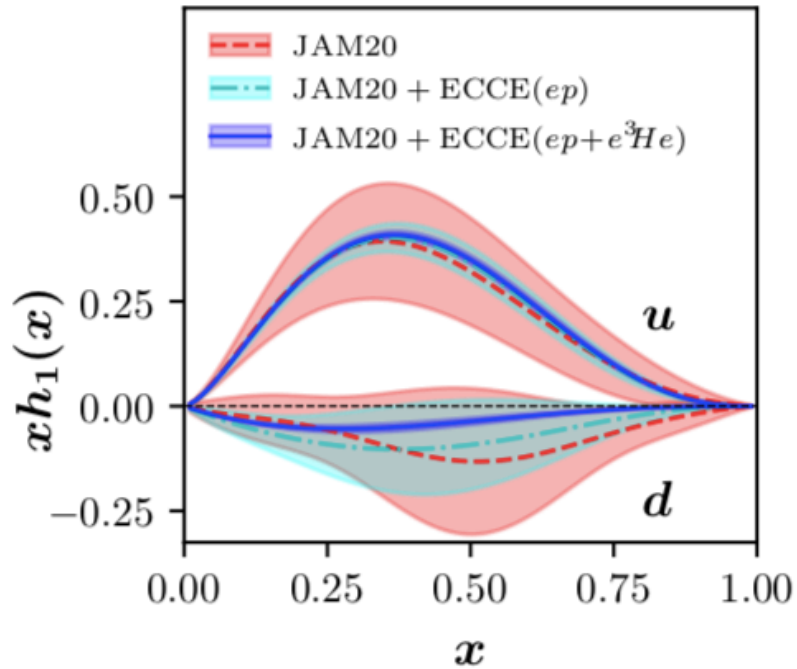
Orange: current uncertainties.
 Blue: EIC constraints from
 SIDIS pion and kaon pseudo-
 data, with ECCE pseud-data.

Transverse-momentum dependence
 of Sivers function obtained by
 measuring p_T -dependence of SIDIS
 cross-sections.

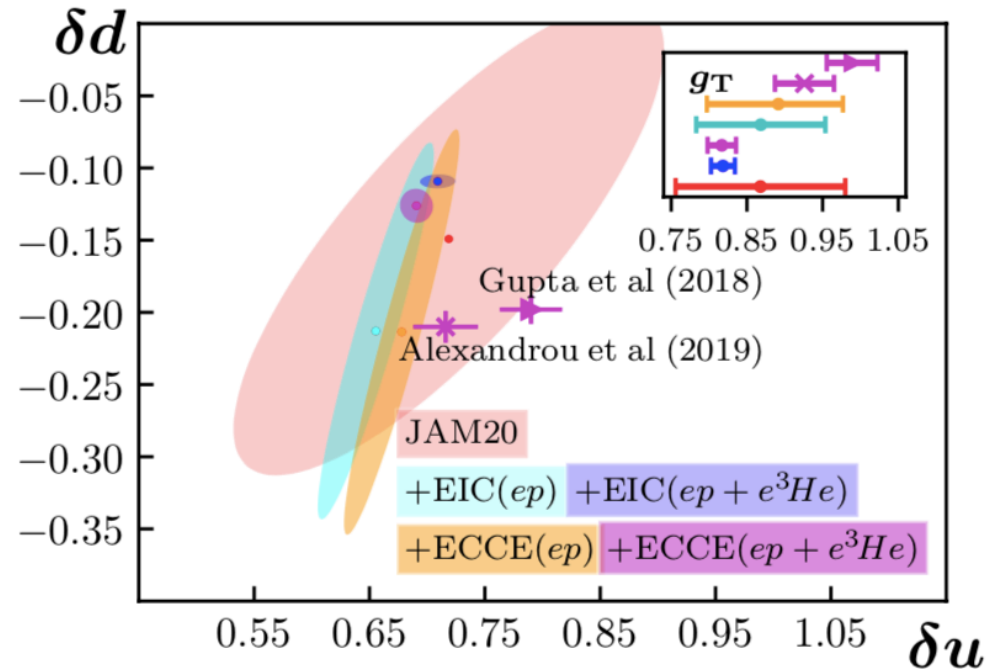


Down-quark
 Sivers
 distributions

Transversity and tensor charges



Transversity distributions for up and down quarks

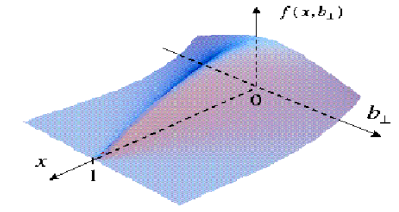
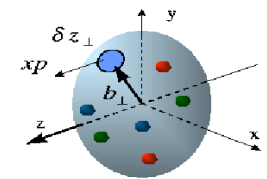


Up, down, and iso-vector combination tensor charges

[arXiv:2207.10890v1 \[hep-ex\]](https://arxiv.org/abs/2207.10890v1)

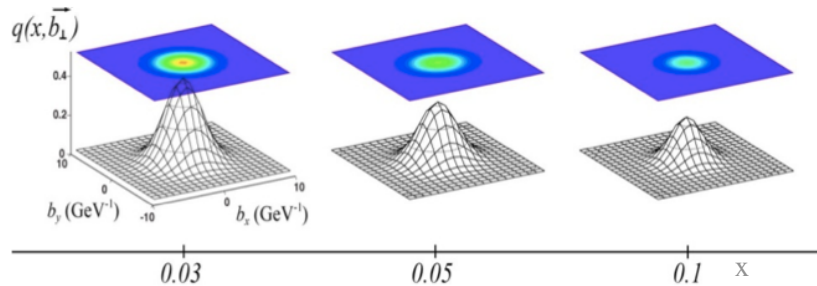
Study with ECCE detector design

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.

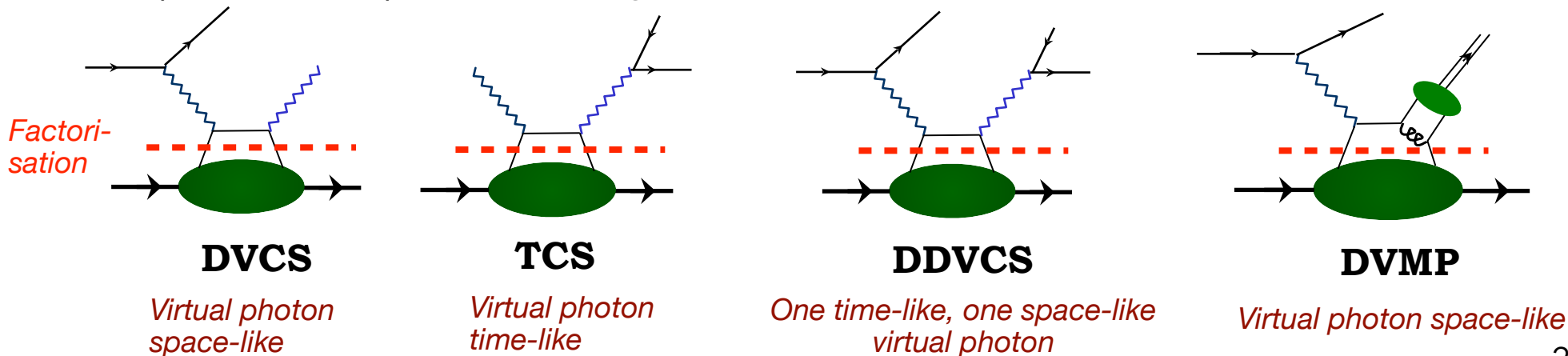
Experimental access to GPDs

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

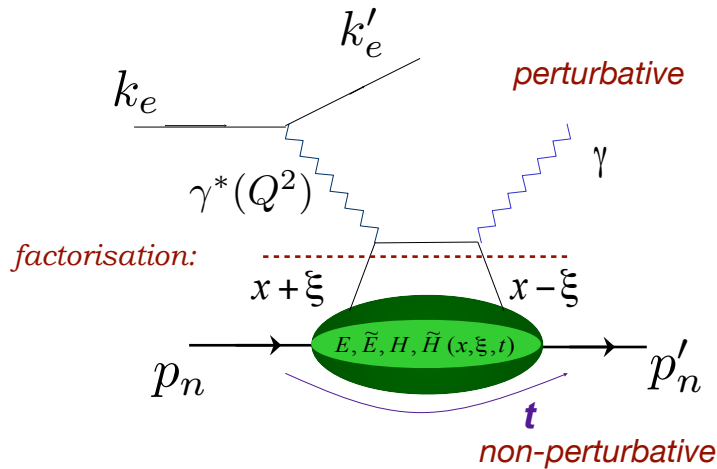
- * Deeply Virtual Compton Scattering (DVCS)
- * Time-like Compton Scattering (TCS)
- * Hard Exclusive Meson Production (HEMP) – a.k.a. Deeply Virtual Meson Production (DVMP)
- * Double DVCS
- * Certain diffractive processes, eg: diffractive ρ -production with the emission of a meson or virtual photon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

See 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

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

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

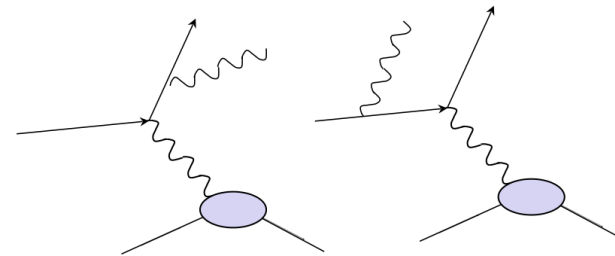
$x \pm \xi$ longitudinal momentum fractions of the struck parton

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

- * 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:

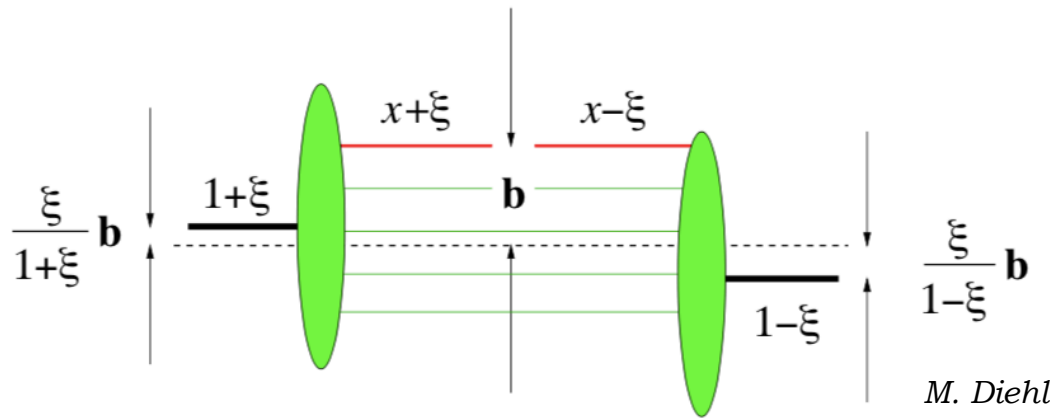
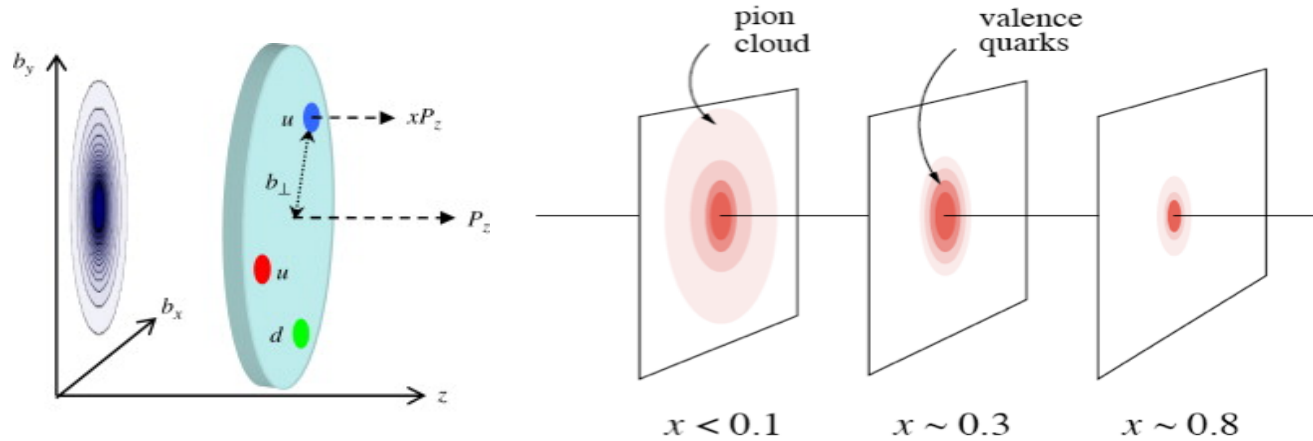


$$d\sigma \propto |T_{DVCS}|^2 + |T_{BH}|^2 + T_{BH} T_{DVCS}^* + T_{DVCS} T_{BH}^*$$

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

Nucleon Tomography from GPDs

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



Formally, the radial separation, \mathbf{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:

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

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, *PRD* **55**, 7114-7125 (1997)

M. Polyakov, *PLB* **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: $\int x [H(x, \xi, t) + E(x, \xi, t)] dx = 2J(t)$

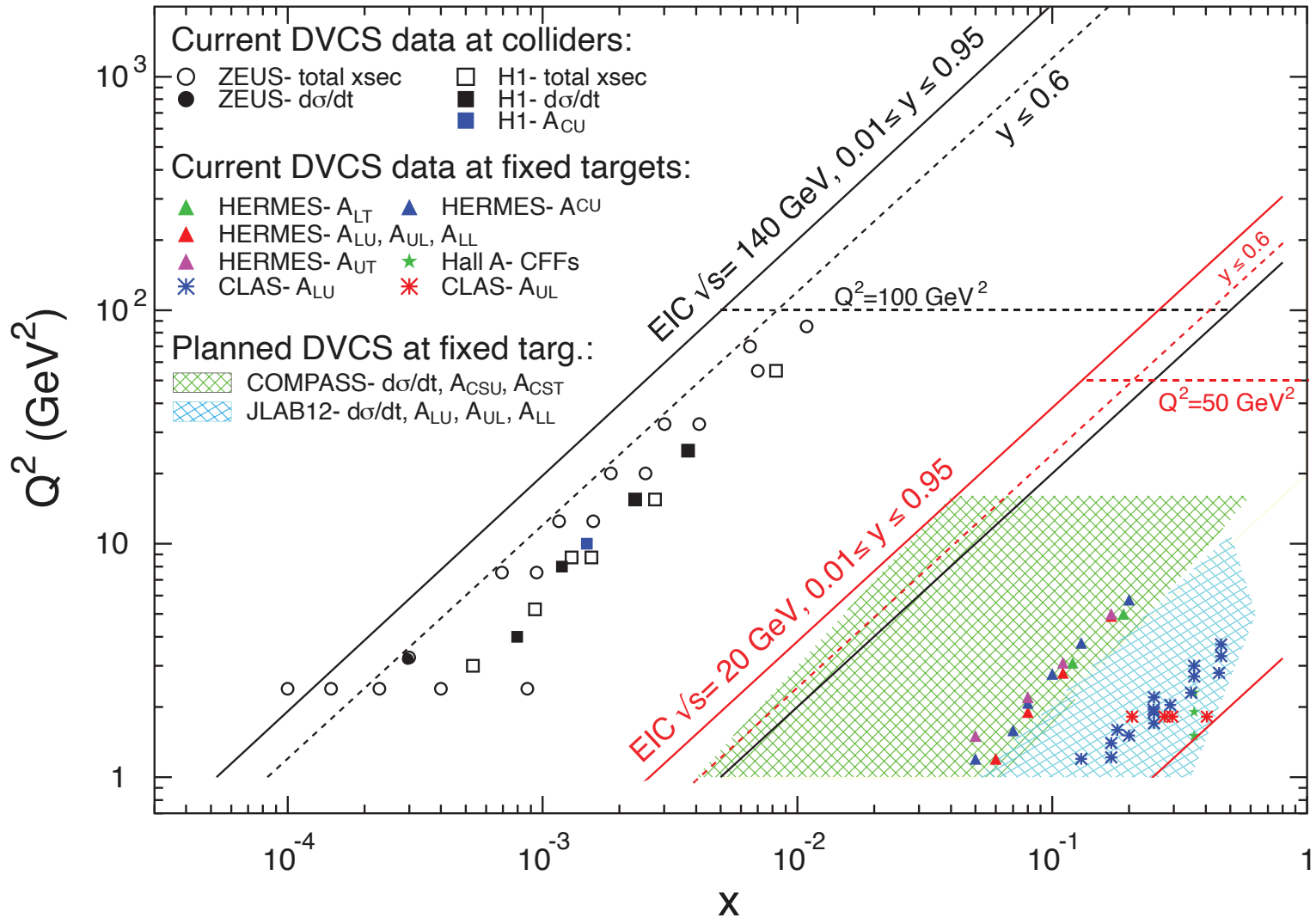
$$\int x H(x, \xi, t) dx = M_2(t) + \frac{4}{5} \xi^2 d_1(t) \quad (\text{Ji's relation}) \quad J_N = \frac{1}{2} = \frac{1}{2} (\Sigma_q + L_q) + J_g$$

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

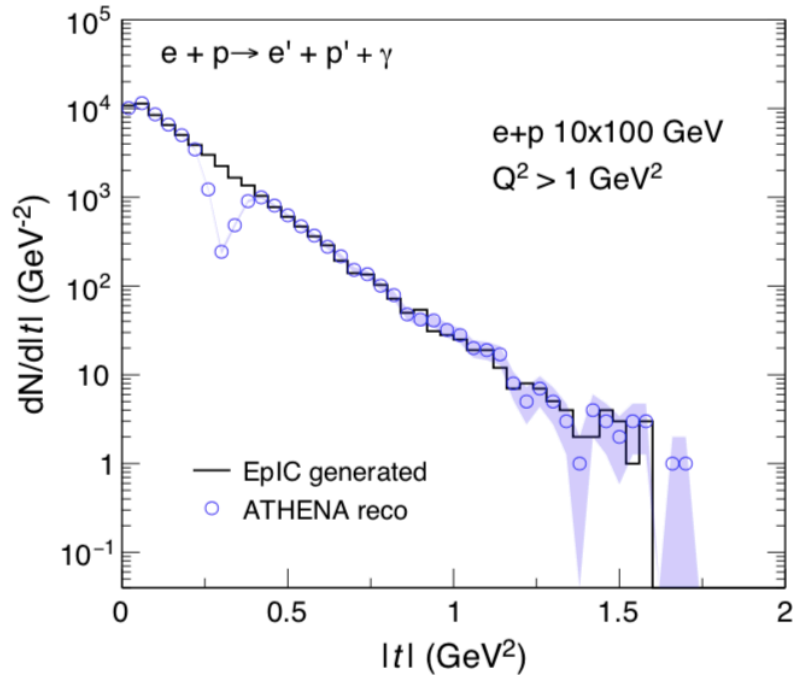
$$\text{Dispersion relation: } \text{Re}\mathcal{H}(\xi, t) = \int_{-1}^1 \left(\frac{1}{\xi - x} - \frac{1}{\xi + x} \right) \text{Im}\mathcal{H}(\xi, t) dx + \Delta(t).$$

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

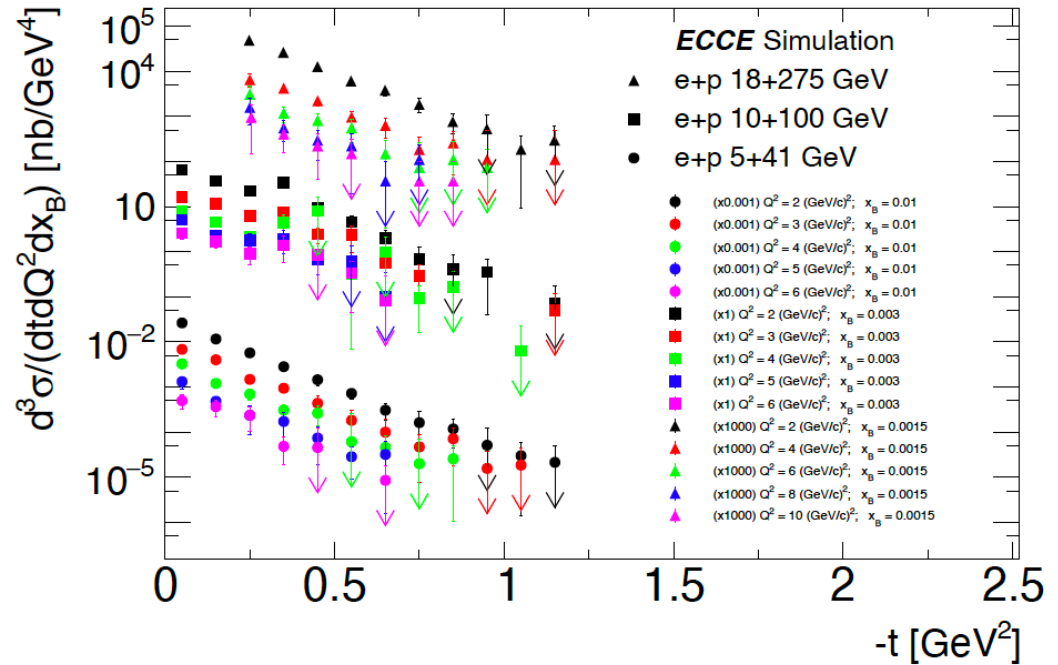
EIC kinematic reach: DVCS



DVCS with the EIC detector

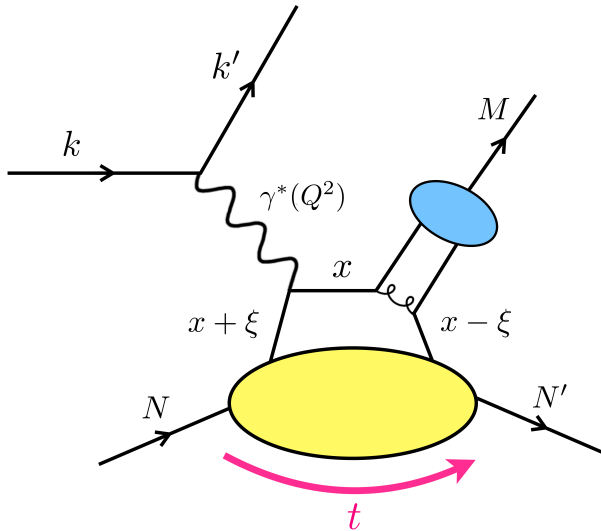


Reconstruction of t -distribution across very wide range – dip due to unavoidable gap between detectors: collision energy tunes the gap to different position in t



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

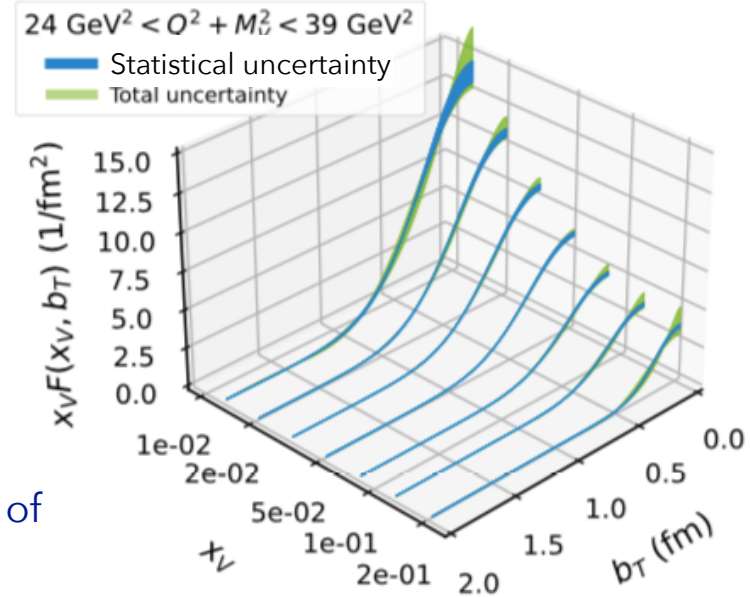
GPDs through meson-production



- * 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: $Q^2 + M_v^2$

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



Fourier transform of J/Ψ -production cross-section

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

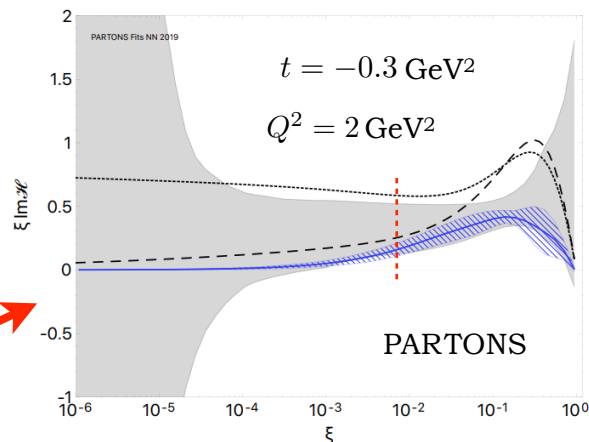
- * Light pseudo-scalar meson production gives, at high Q^2 , access to parity-odd GPDs: \tilde{H} , \tilde{E} and at low Q^2 to chiral-odd, transversity GPDs which are not accessible at leading-twist in DVCS processes.

Towards nucleon tomography

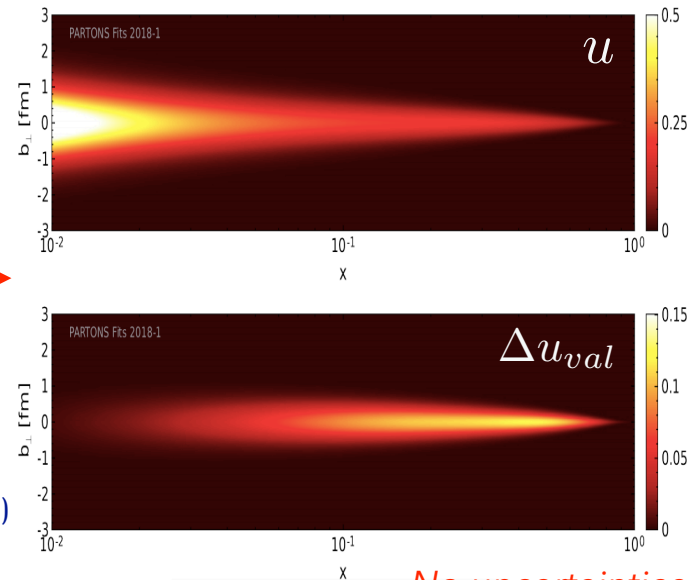
Ongoing imaging efforts on available world-data, strongest constraints in the valence region:

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.



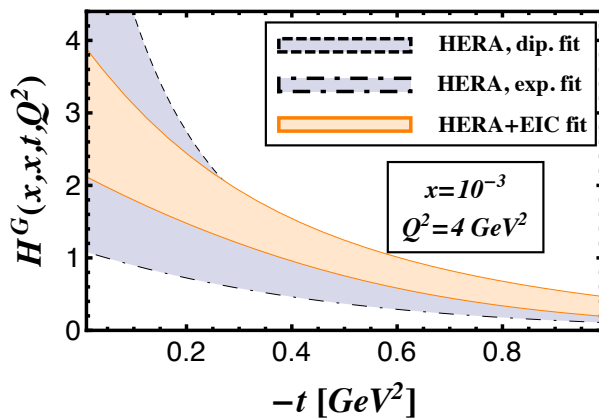
H. Moutarde *et al.*, Eur. Phys. J C79, 614 (2019)



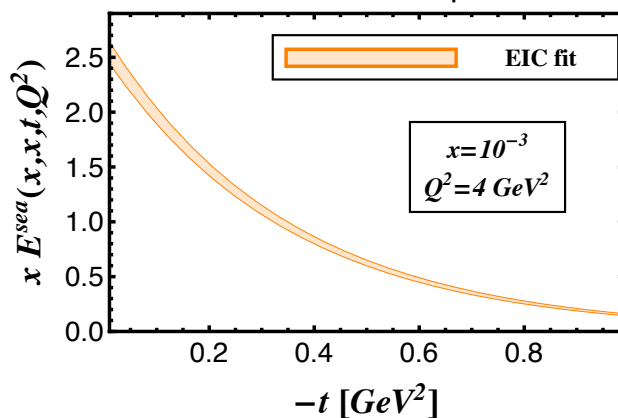
No uncertainties shown

Anticipated constraints from EIC on GPDs H and E:

GPD H for gluons



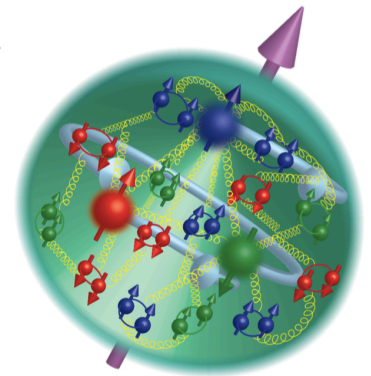
GPD E for sea quarks



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

Summary

- * Electron-Ion Collider to be built at Brookhaven National Laboratory, start operation ~2031.
- * Large range of CoM energies (20 - 140 GeV), high luminosity ($10^{32-33} \text{ cm}^{-2}\text{s}^{-1}$): 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.
- * Dramatic constraints on polarised PDFs, TMD structure functions and GPDs expected, shedding new light on spin and the elusive 3D structure of the nucleon.
- * Join the effort! <http://www.eicug.org/>

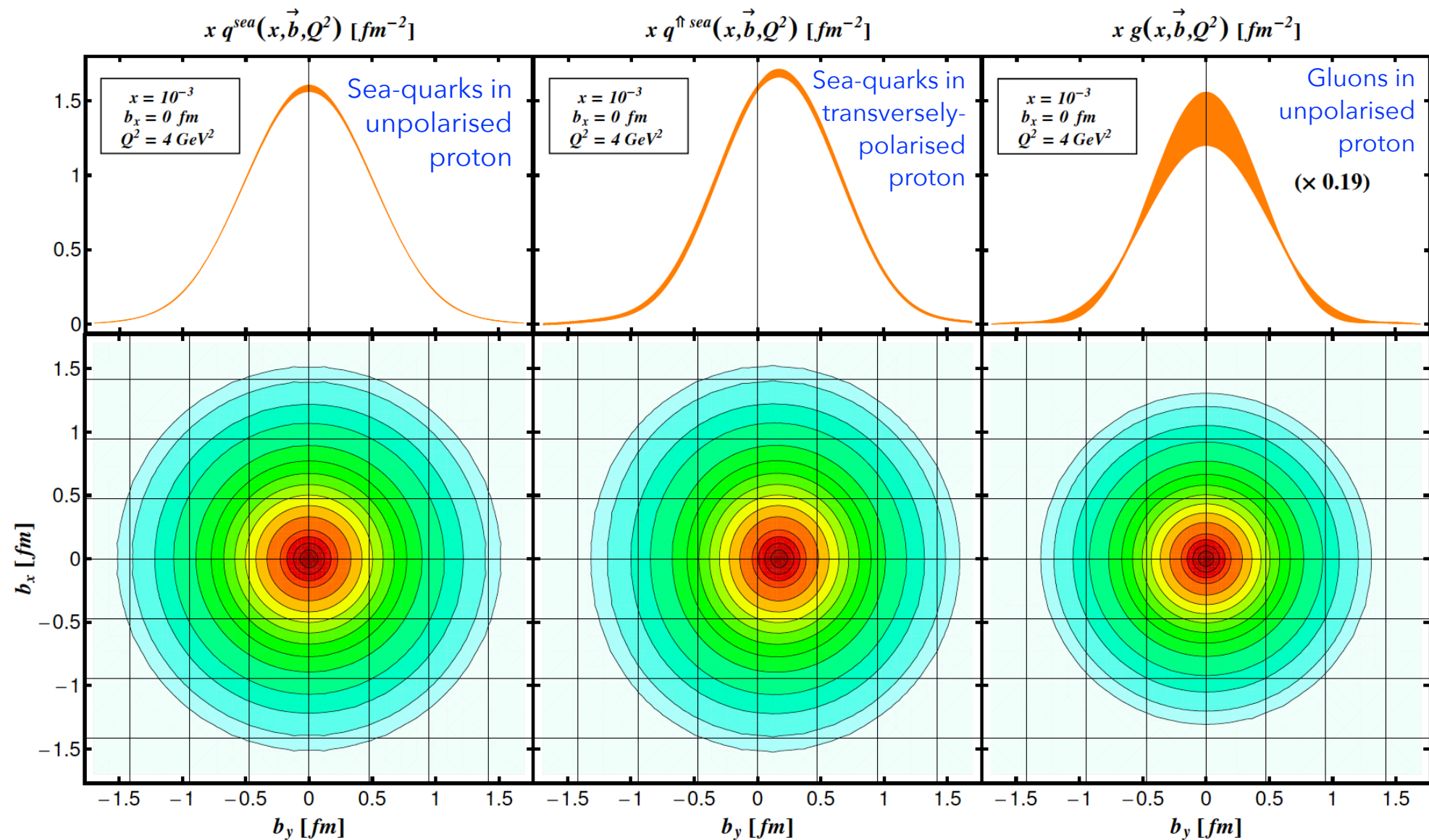


A vibrant field of sunflowers with bright yellow petals and dark brown centers, set against a clear blue sky with scattered white clouds. The sunflowers are in full bloom and are surrounded by lush green leaves. The scene is bright and cheerful, suggesting a sunny day in a garden or field.

Thank you!

Any questions?

Tomography @ EIC



Imaging light nuclei

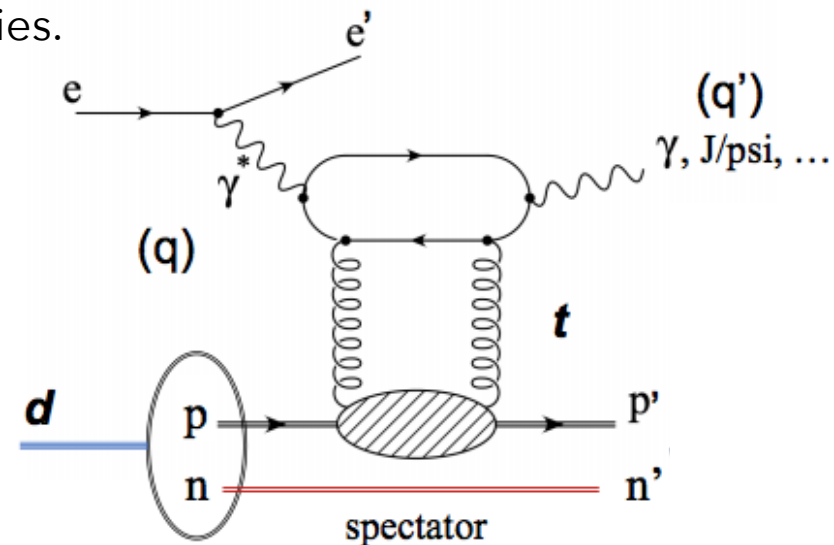
Coherent DVCS on light nuclei requires their intact detection and provides access to nuclear GPDs: imaging of partons in a nuclear medium.

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

^3He : 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.

^4He : 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, *PRD* **55**, 7114-7125 (1997)

M. Polyakov, *PLB* **555**, 57-62 (2003)

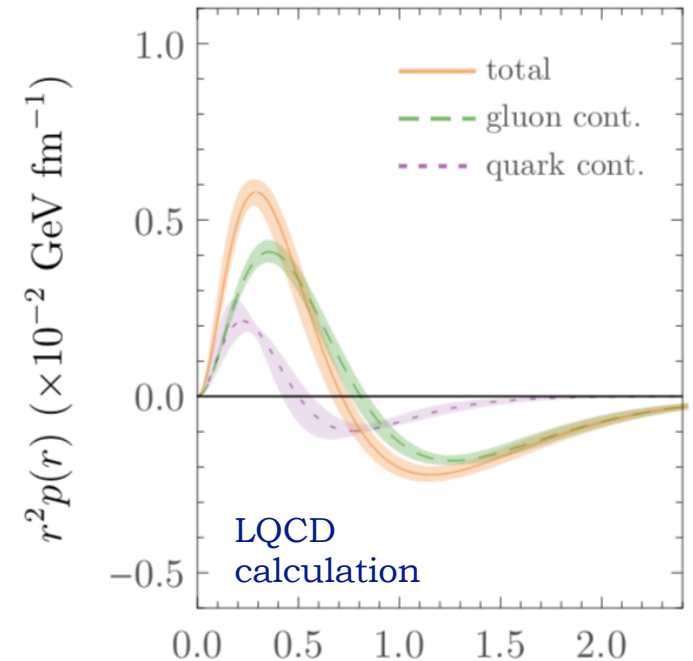
- * Four GFFs, functions of t , of which three are related to moments of GPDs: they encode pressure and shear forces ($d_1(t)$), mass ($M_2(t)$) and angular momentum distributions ($J(t)$):

$$\int x [H(x, \xi, t) + E(x, \xi, t)] dx = 2J(t)$$

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

- * 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, *PLB* **776**, 38-47 (2018)



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

Studies for proposals:

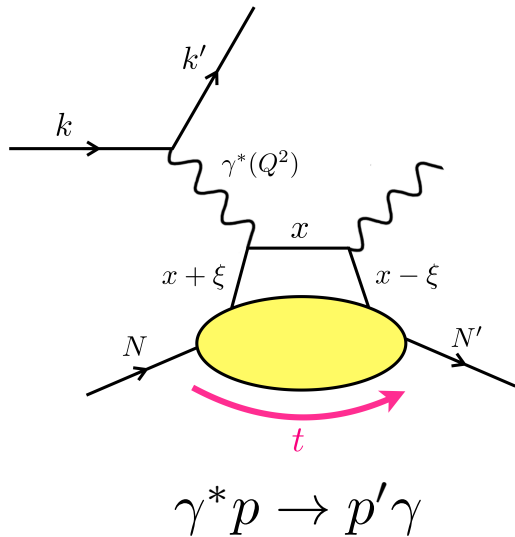
ATHENA

ECCE

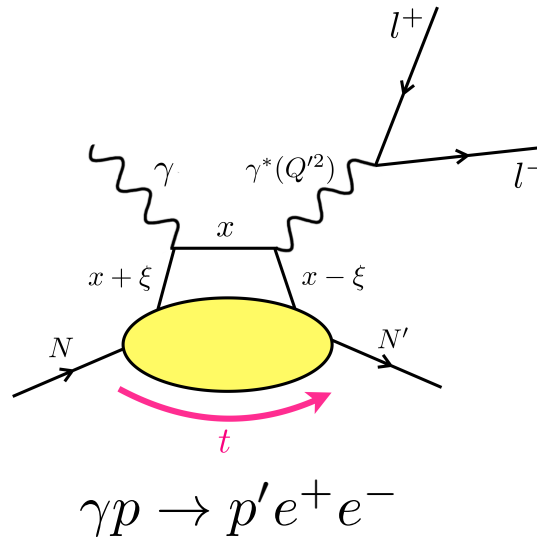
* DVCS in ep	EpIC	MILOU3D
* DVCS (incoherent) in ed	EpIC	
* DVCS on He-4		TOPEG
* TCS in ep	EpIC	EpIC
* J/Psi in ep		IAger, eSTARlight
* J/Psi in eA		IAger, eSTARlight
* Φ in eAu/Pb	SARTRE, BeAGLE	SARTRE, BeAGLE
* Y(1S, 2S, 3S) in ep	eSTARlight, IAger	
* u-channel: ω , ρ in ep	eSTARlight	
* X,Y $\Psi(2S)$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

Exclusive processes

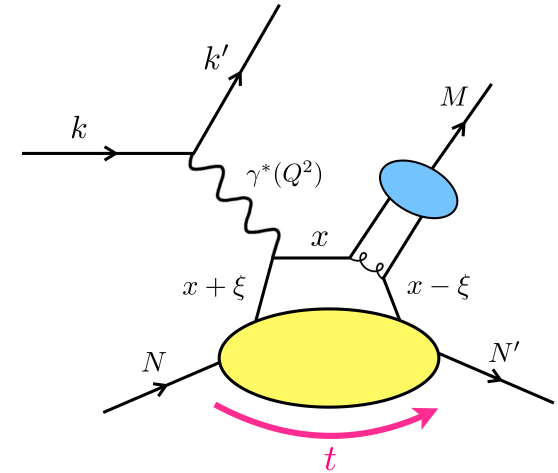
Deeply Virtual Compton scattering (DVCS):



Timelike Compton Scattering (TCS):



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.

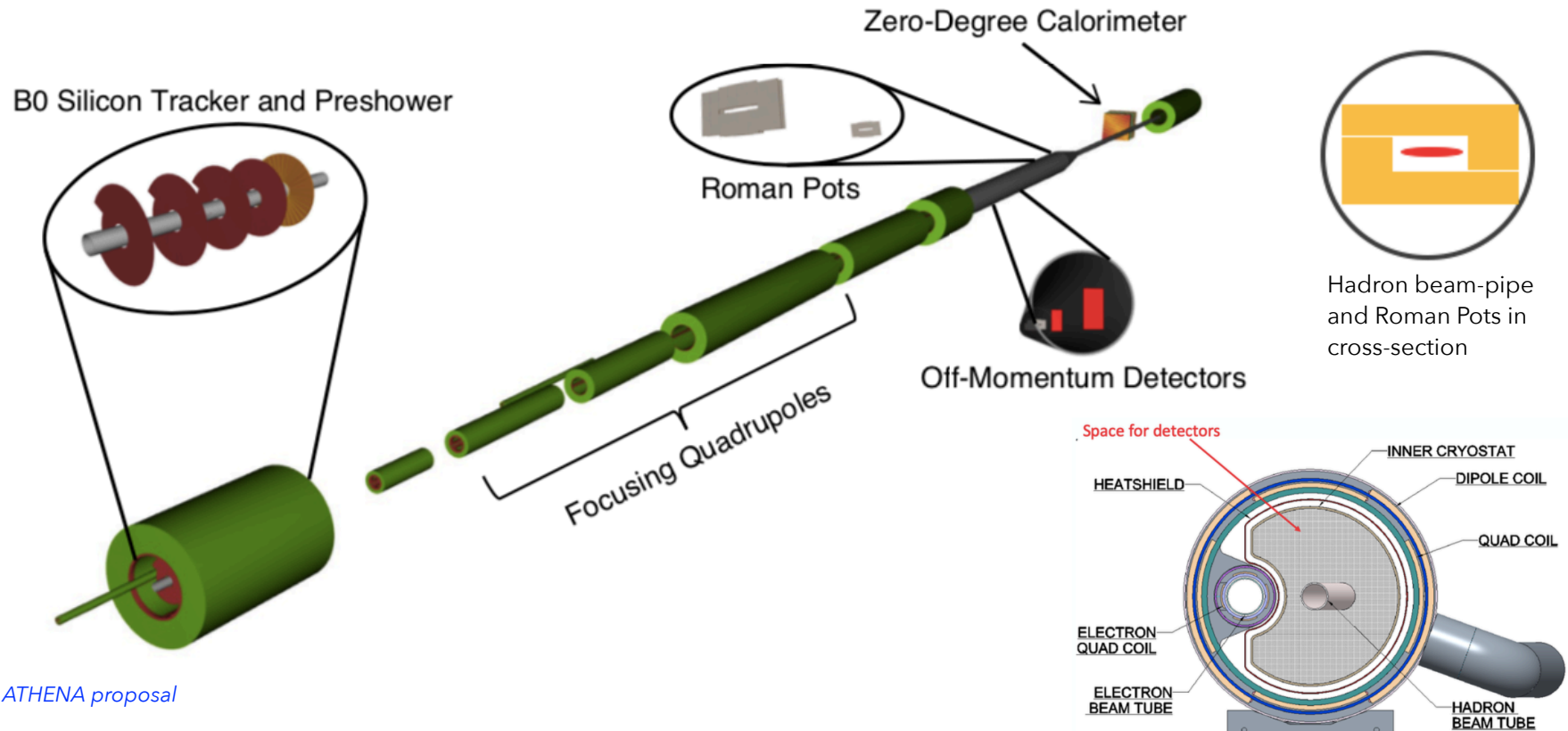
Recoil protons in ep

- * 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).



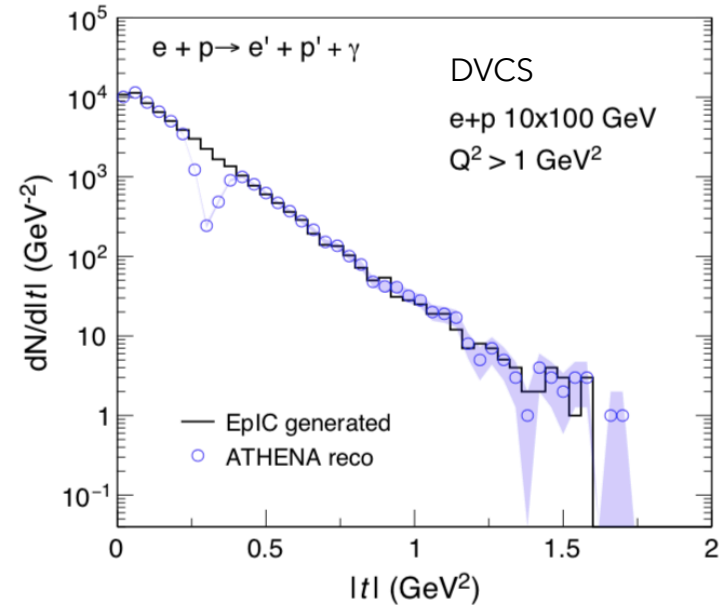
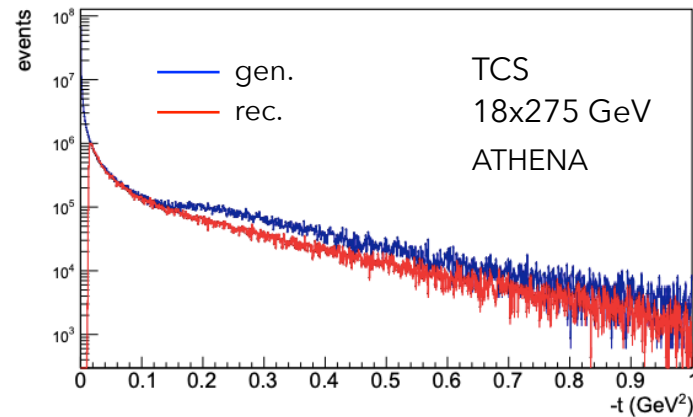
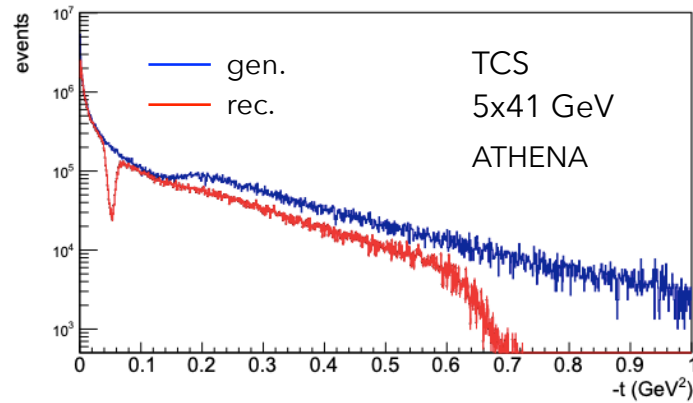
ATHENA proposal

EIC Yellow Report

B0 spectrometer configuration

Recoil protons in ep

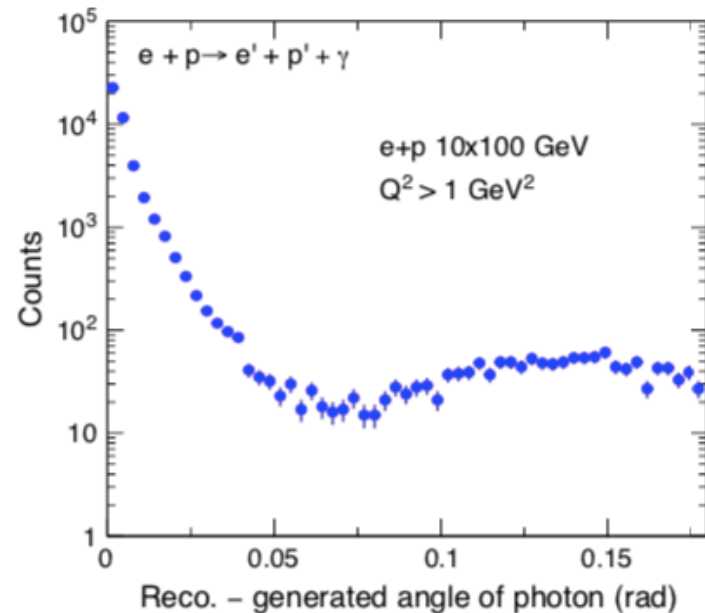
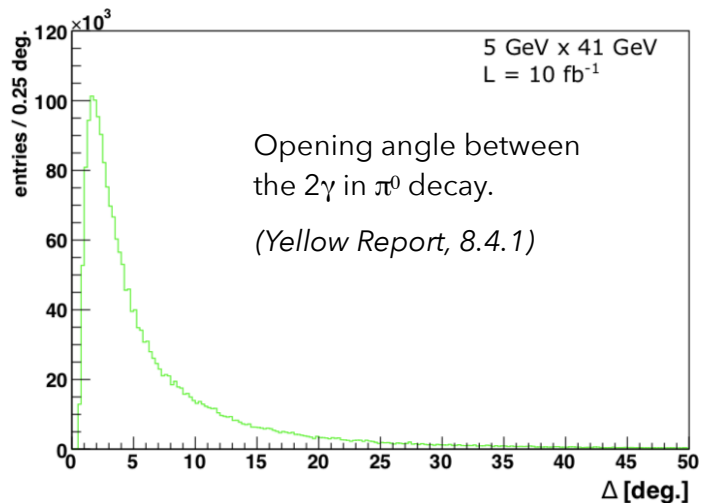
- * Scattered protons detected in Roman Pots (for the lowest values of t) and in the B0 spectrometers (for higher values).



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.

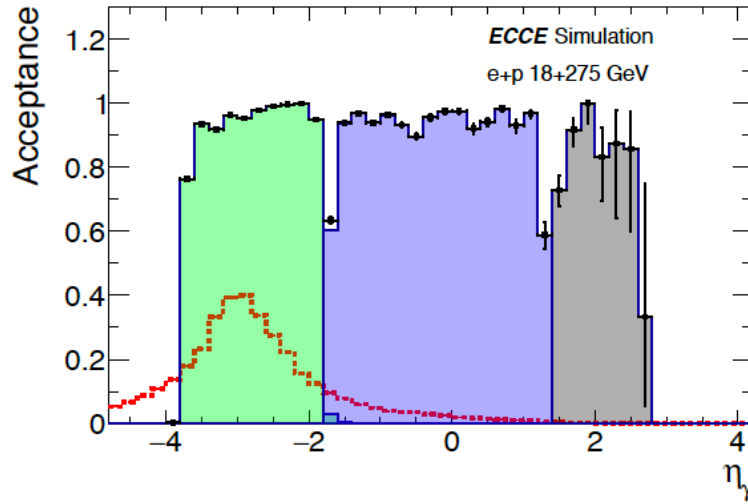
Detecting photons (DVCS/ π^0)

- * 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.

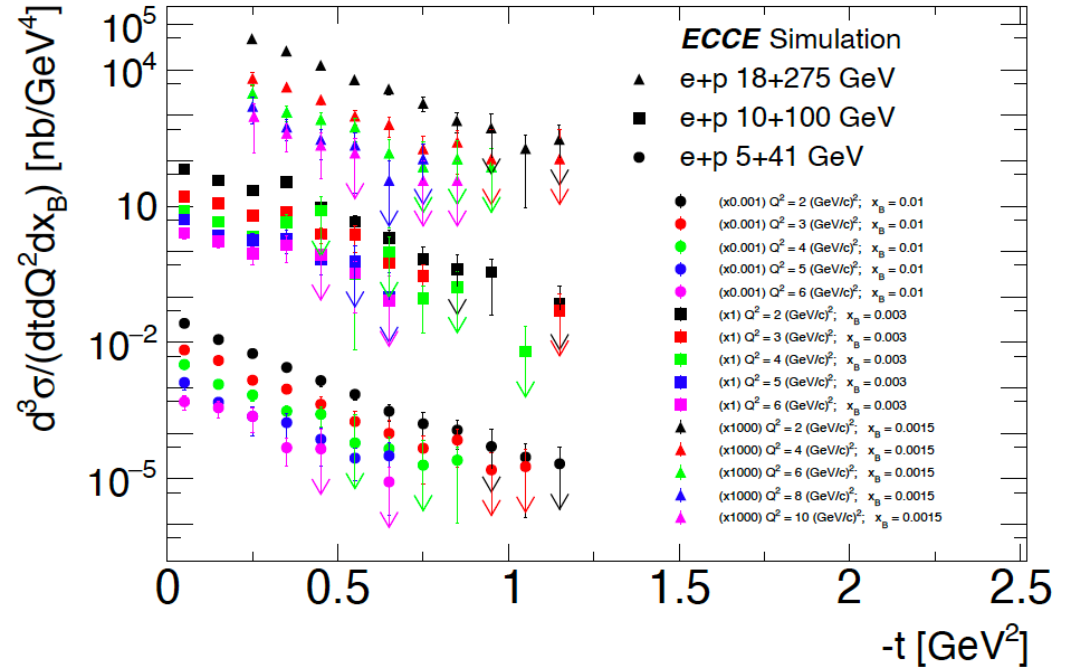
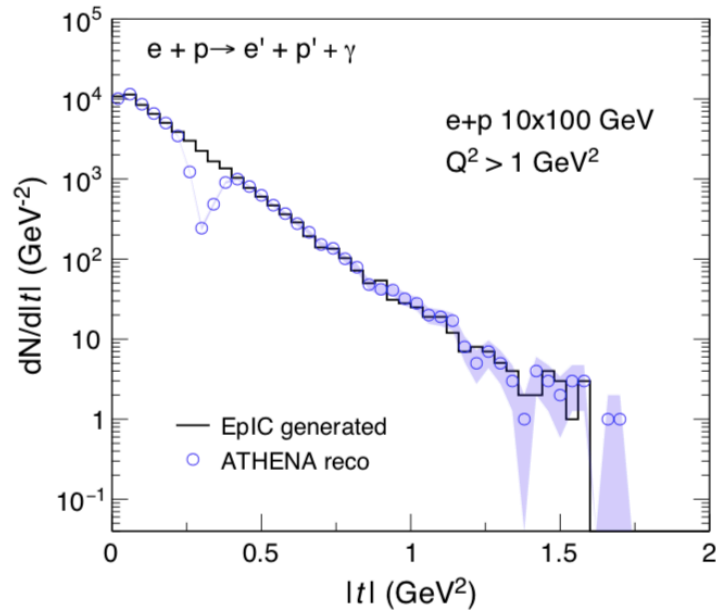


- Difference between generated and reconstructed DVCS photon mainly $< 0.17 \text{ mrad}$ (1 deg): smallest opening angle for π^0 decay.

DVCS



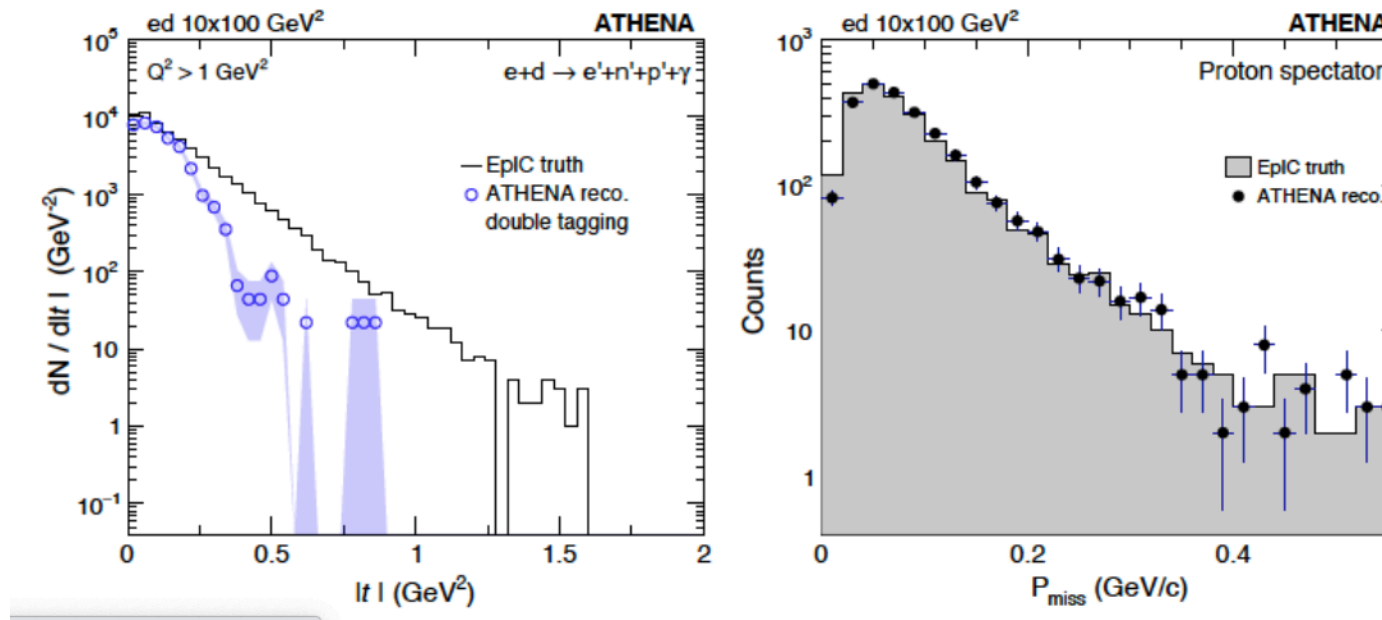
- Practically hermetic coverage for photons, wide range of t .
- Multi-dimensional binning possible



DVCS in ed

Plots: Kong Tu (BNL)

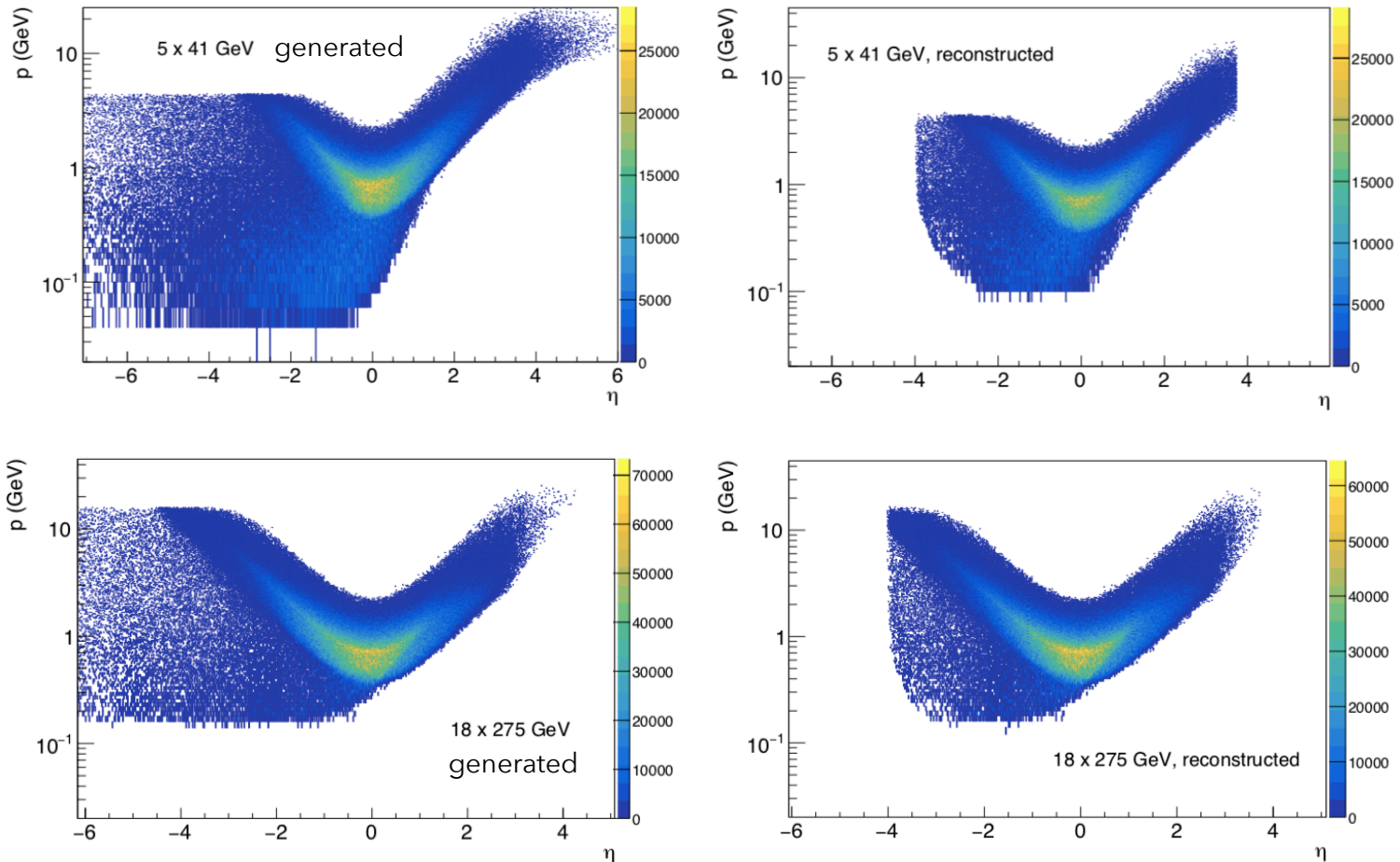
- Enables measurement on neutron in deuterium: quark-flavour separation of GPDs, sensitivity to other Compton Form Factors (eg: $\text{Im } E$ in DVCS beam-spin asymmetry on neutron vs $\text{Im } H$ in BSA on proton).
- Both the spectator proton and the scattered neutron tagged in the measurement.
-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



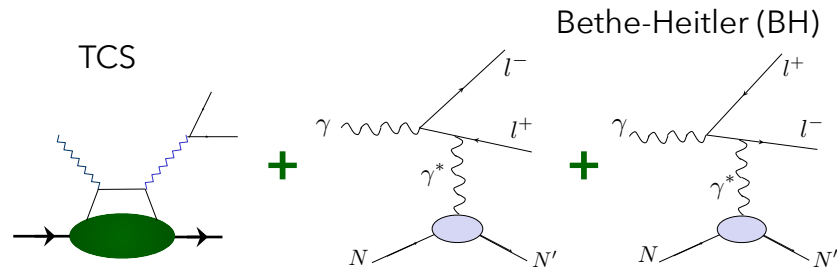
- Scattered neutron tagged in ZDC: loss of t -acceptance at high t is due to limitations of ZDC acceptance. Can obtain better t acceptance from electron - photon.

TCS e^+e^-

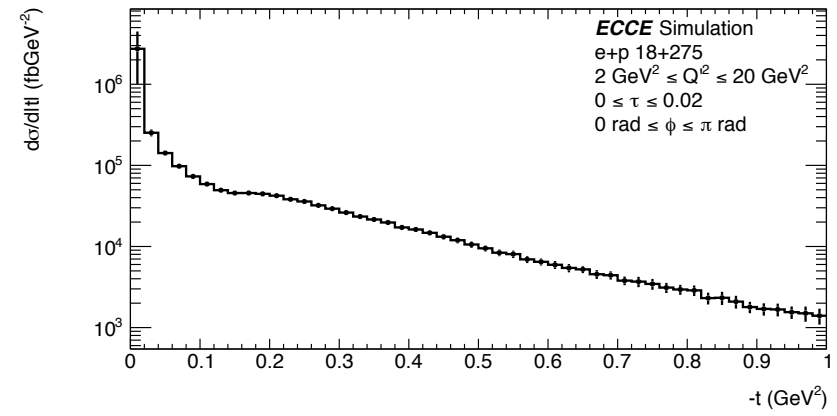
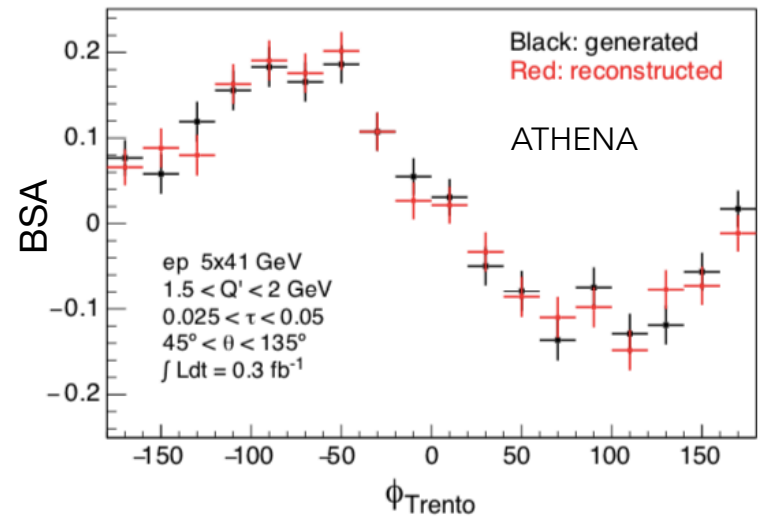
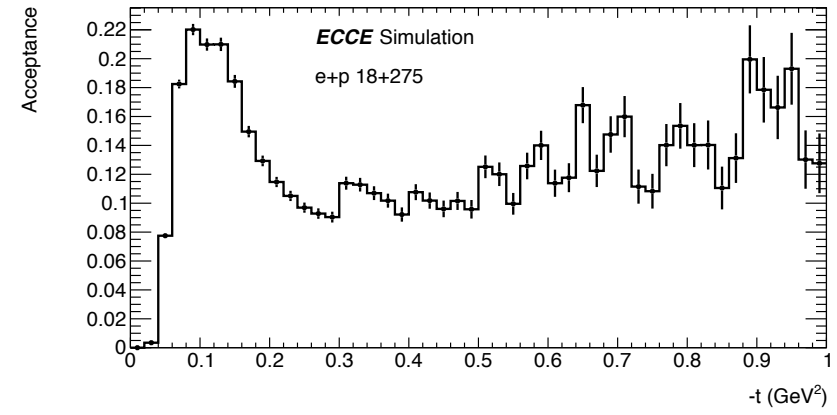
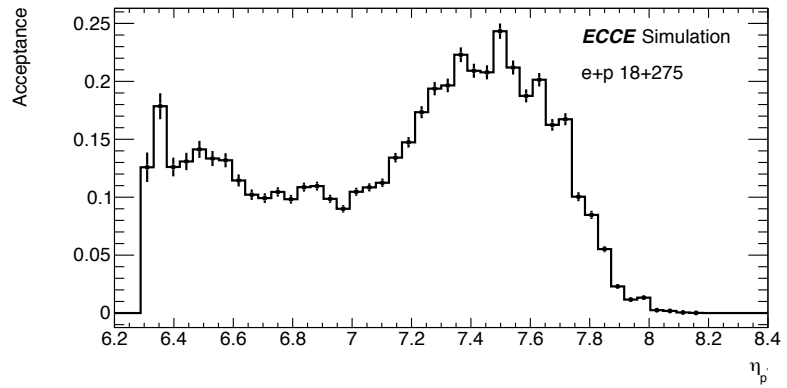
- * TCS-produced virtual photon decays into e^+e^- pairs at mid-rapidity – need excellent acceptance in central region (barrel+ end-caps), as scattered electron will in general be reconstructed though missing mass and momentum (low- Q^2 tagger can provide direct detection only in a part of the phase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



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

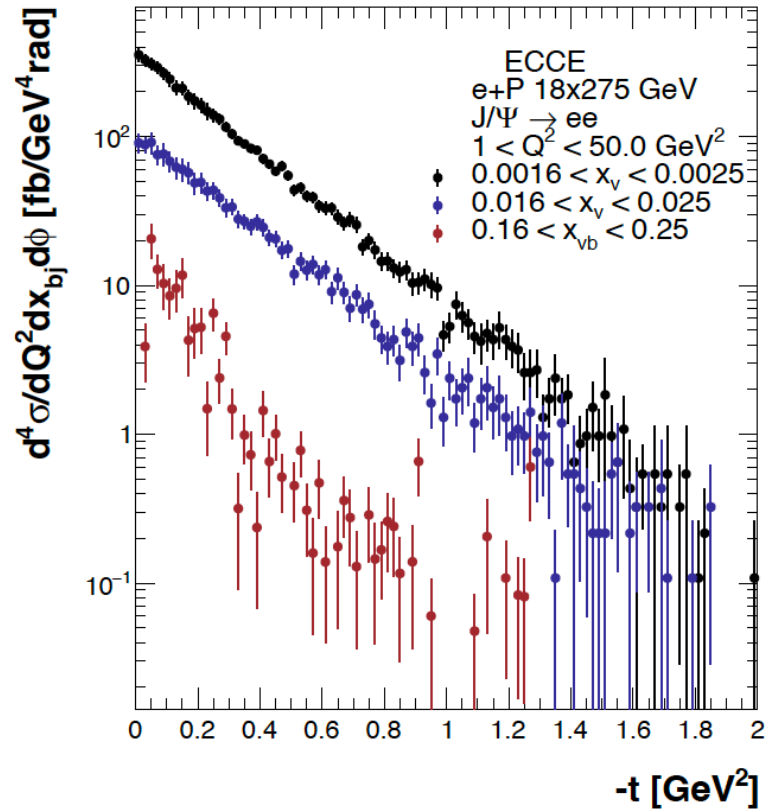
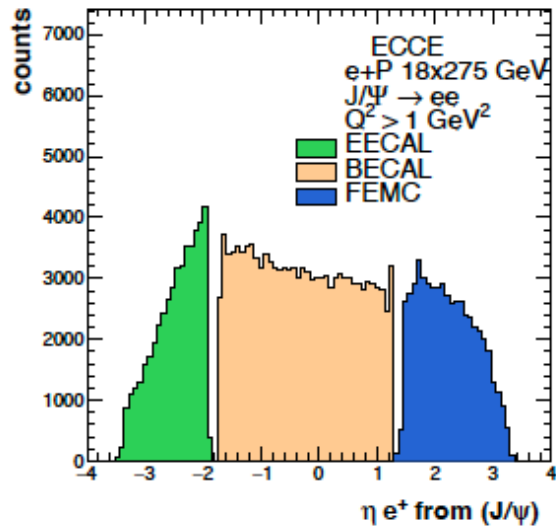
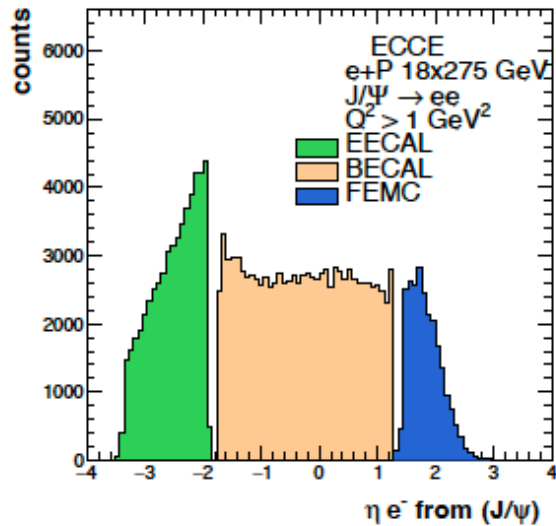


$$\sigma(\gamma p \rightarrow p' e^+ e^-) = \sigma_{BH} + \sigma_{TCS} + \sigma_{INT}$$



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

J/Psi production

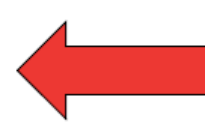
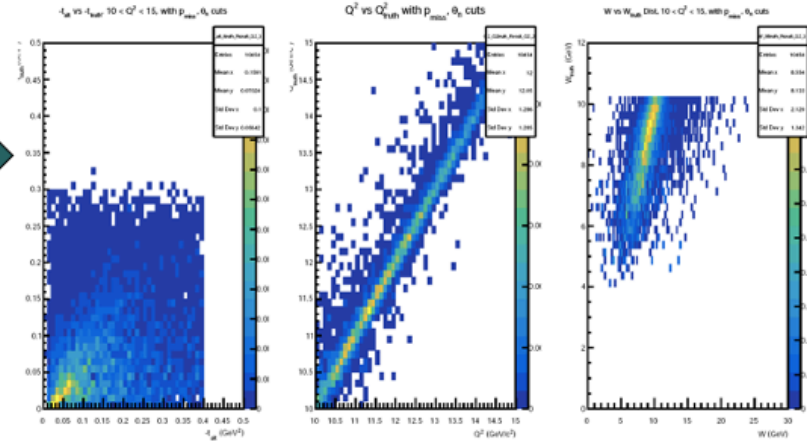


- Excellent acceptance coverage for J/Psi decay leptons
- Multi-dimensional binning

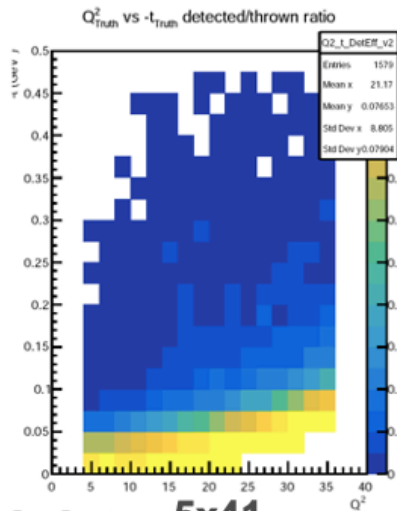
Deep Exclusive Meson Production $p(e, e' \pi^+ n)$

- 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

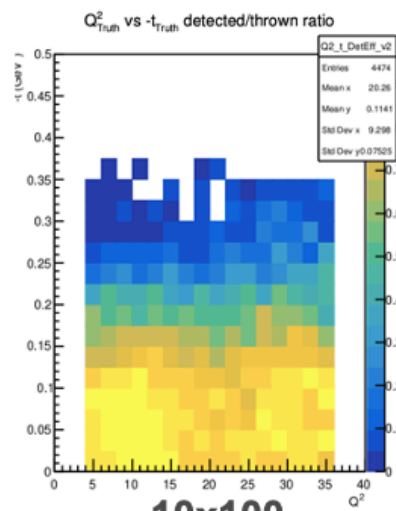
-t, Q², W: reconstr (x) vs true (y)
 → excellent reconstruction
 resolution for 10 < Q² < 15 @ 5x100



IR6 detect effic vs Q², -t:
 Triple coin after cuts
 Effic higher @ 10x100
 Study still in progress



5x41



10x100

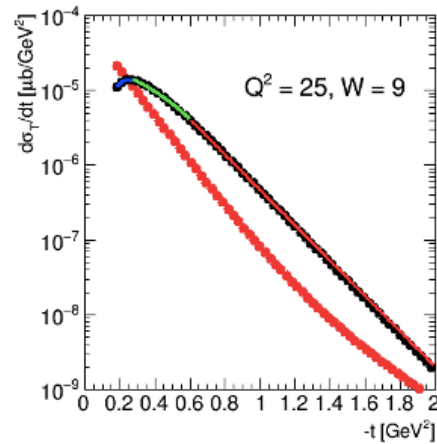
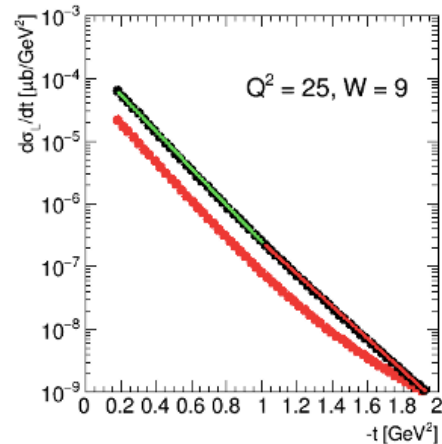
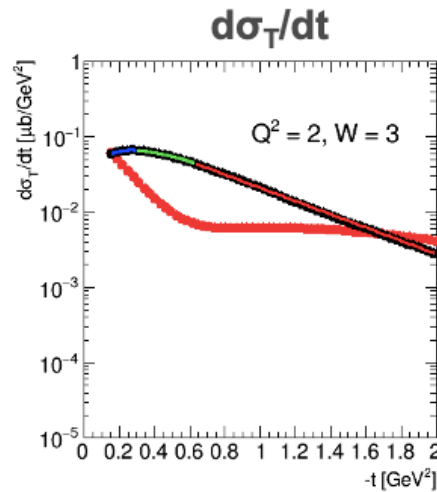
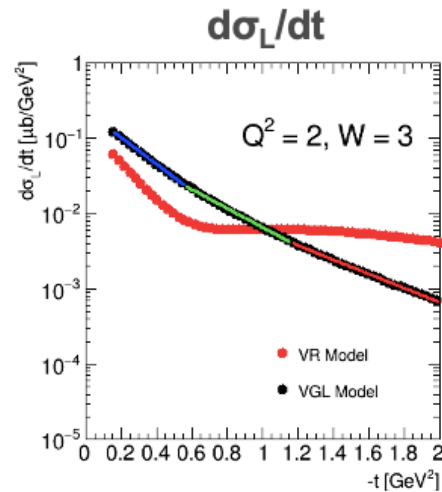
Plots by Stephen Kay (Regina) & Maggie Kerr (Mt Allison)



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

- Writing an improved exclusive K^+ physics generator, to enable feasibility studies of K^+ form factor measurements at EIC

Plots by Love Preet (Regina)



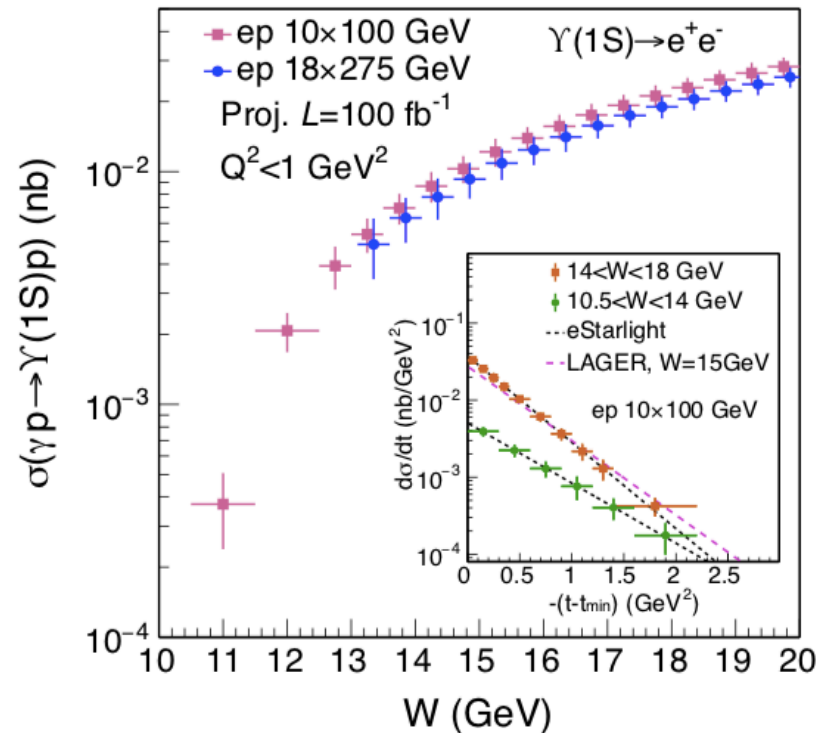
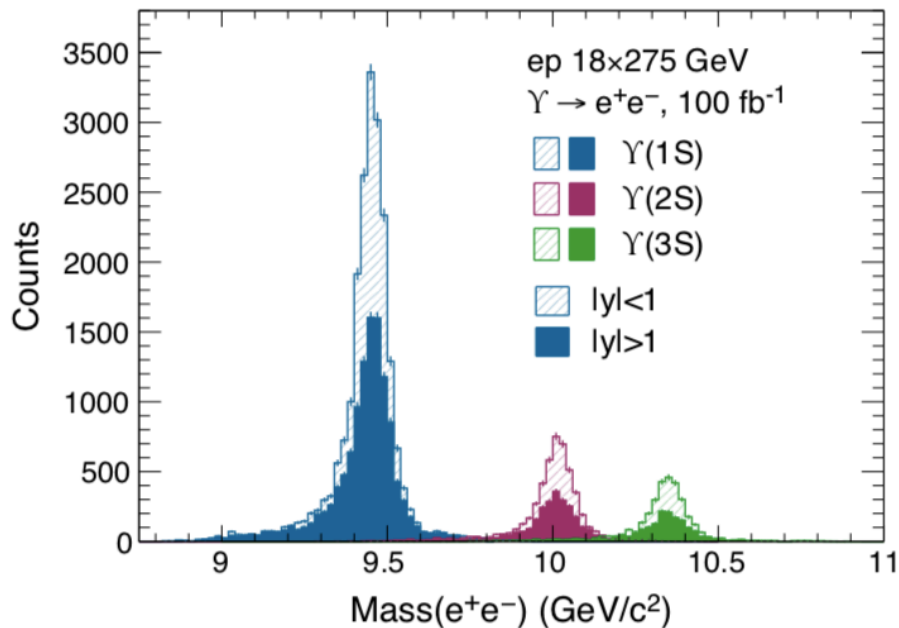
- We compared Vrancx-Ryckebusch (VR) and Vanderhaeghen-Guidal-Laget (VGL) Regge models of exclusive K^+ electroproduction
- DEMP** event generator will use a parameterization of $d\sigma_L$, $d\sigma_T$ from VGL model for $2 < W < 10$, $1 < Q^2 < 35$, $0 < -t < 2.0$, as it behaves better at high $-t$
- Implementation and testing of the generator is in progress



Upsilon-production

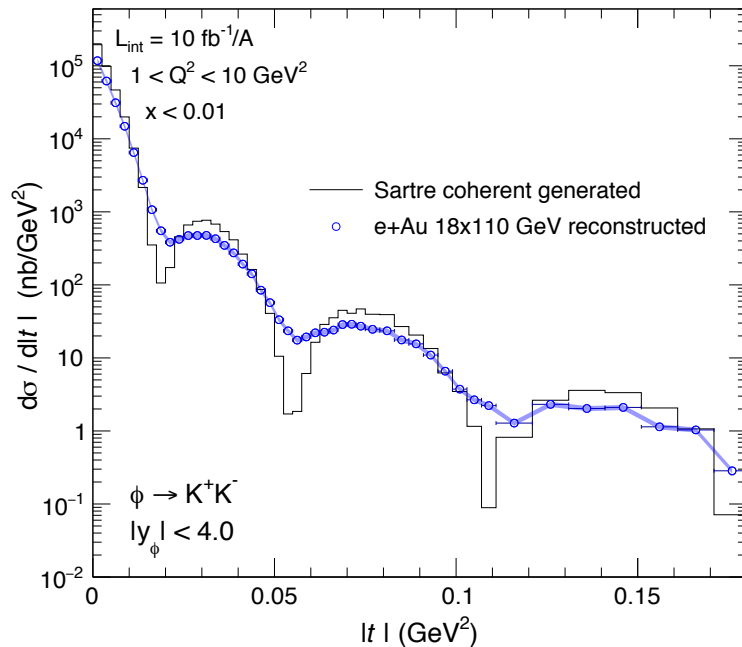
- Sensitivity to gluon distributions, information on colour correlations, upsilon-proton scattering lengths, possibly saturation. Near-threshold production: little-known, twist-4 effects contribute significantly.

Photoproduction ($Q^2 < 1 \text{ GeV}^2$) and electroproduction ($Q^2 > 1 \text{ GeV}^2$).

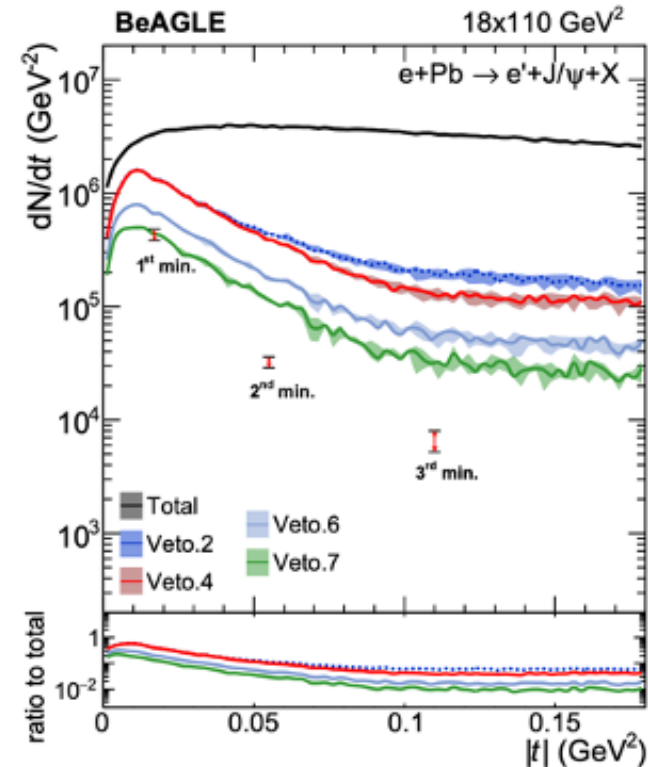


Coherent VM production in eA

- Gluon distributions in nuclei and a probe of saturation (in Q^2 -dependence).
- 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.



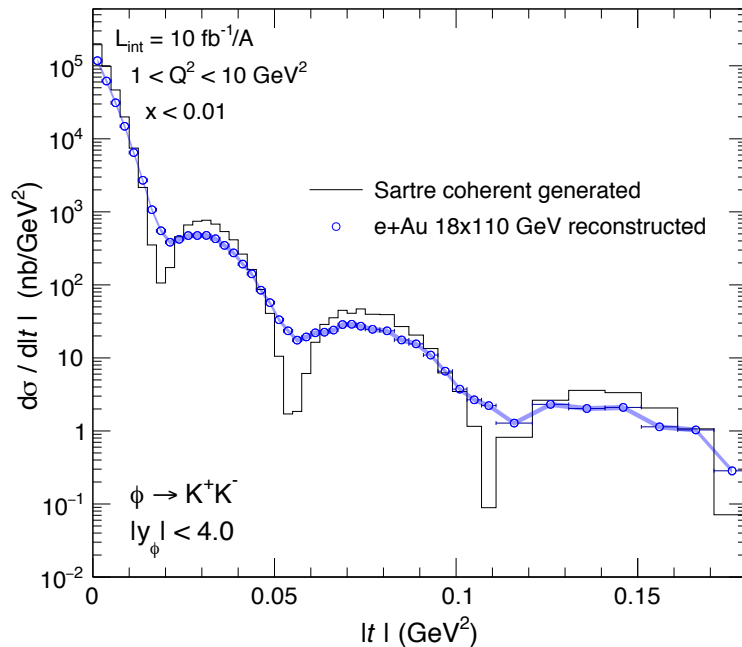
Plot: Kong Tu (BNL)



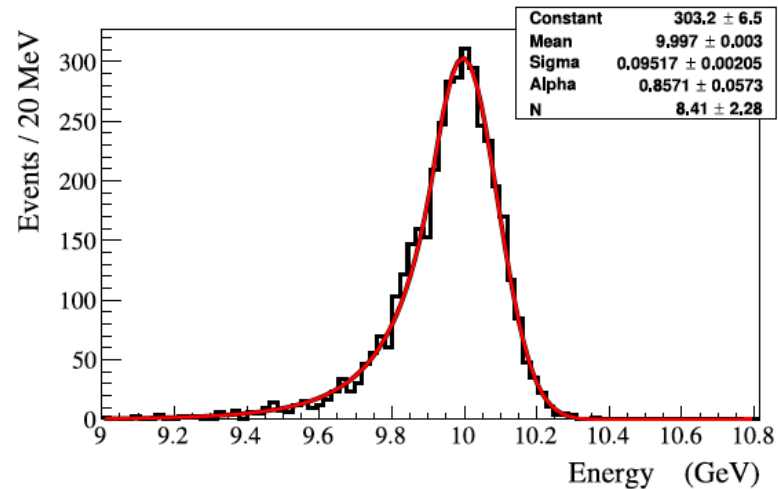
Phys. Rev. D **104**, 114030

Coherent VM production in eA

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Plot: Kong Tu (BNL)

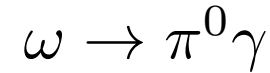


Nucl.Instrum.Meth.A 1013 (2021) 165683

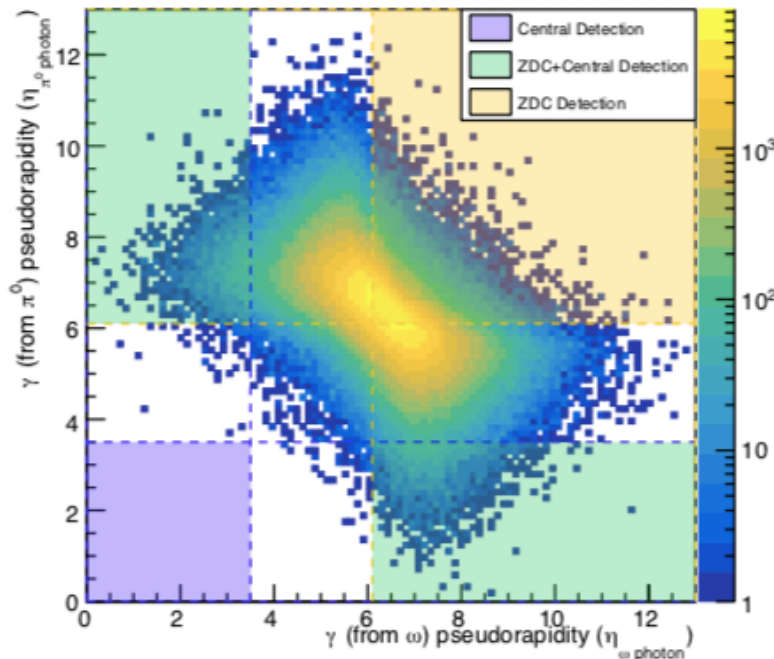
*Beam tests of $PbWO_4$ crystals at JLab:
non-Gaussian tail in the electron
energy reconstruction*

Backward production of omega

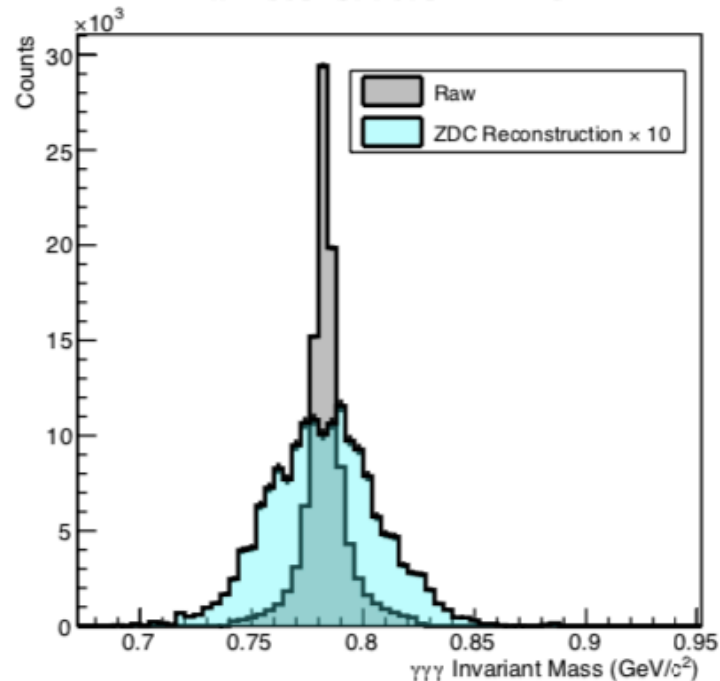
- Similar to normal meson photo-production, but proton at mid-rapidity and meson goes forward with high momentum: u-channel.
- Sensitivity to Transition Distribution Amplitudes (TDA).
- Proton (a few hundred MeV) detected in central detector. Photons from meson decay detected in a combination of central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



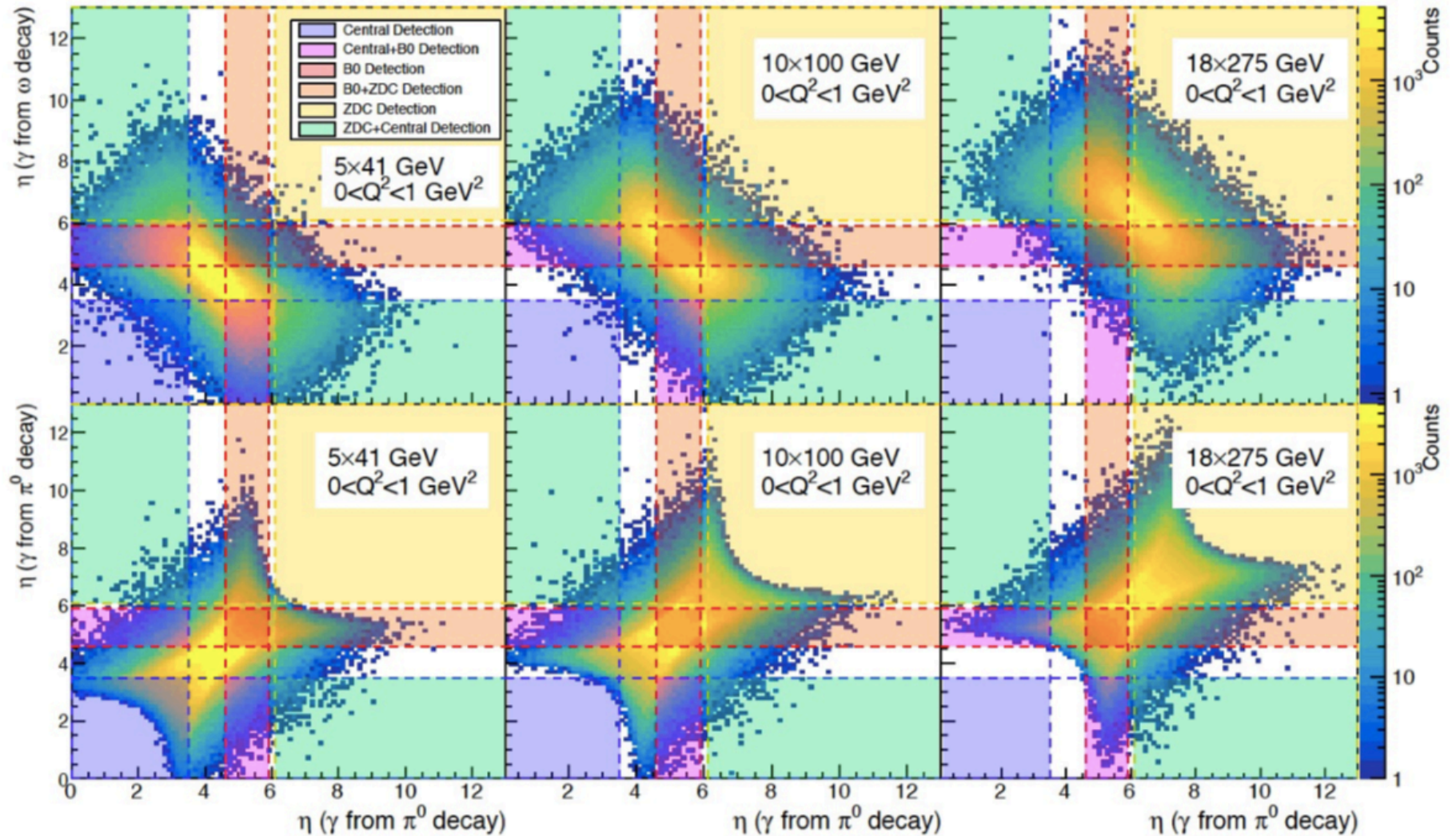
Pseudorapidity Distribution of Photons from π^0 and ω Decay



ω Reconstruction in ZDC



Backward production of omega

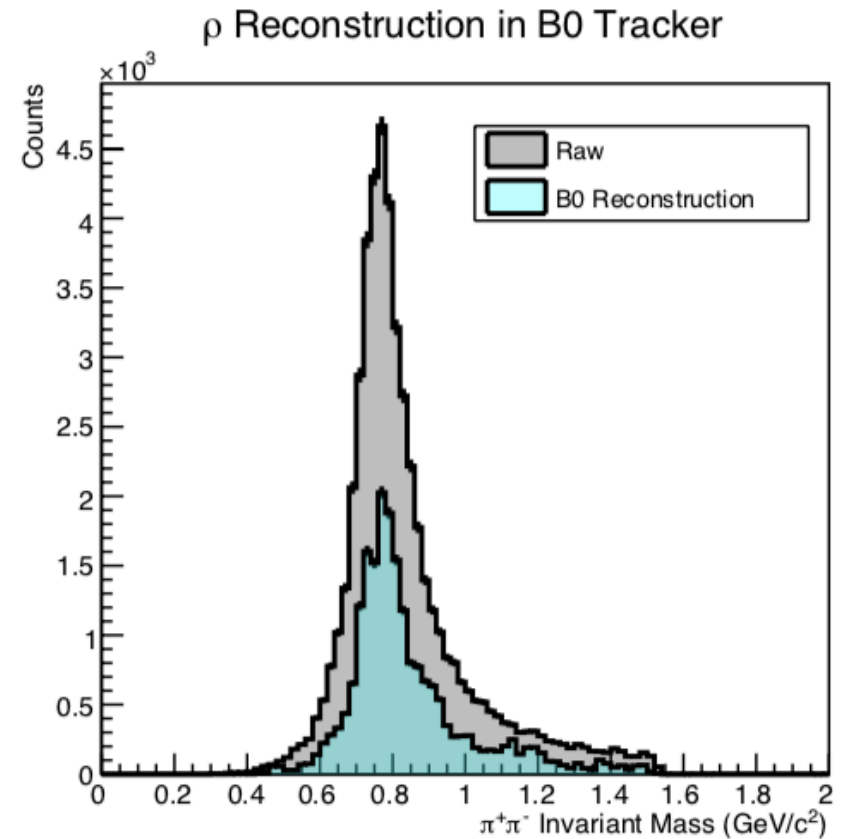
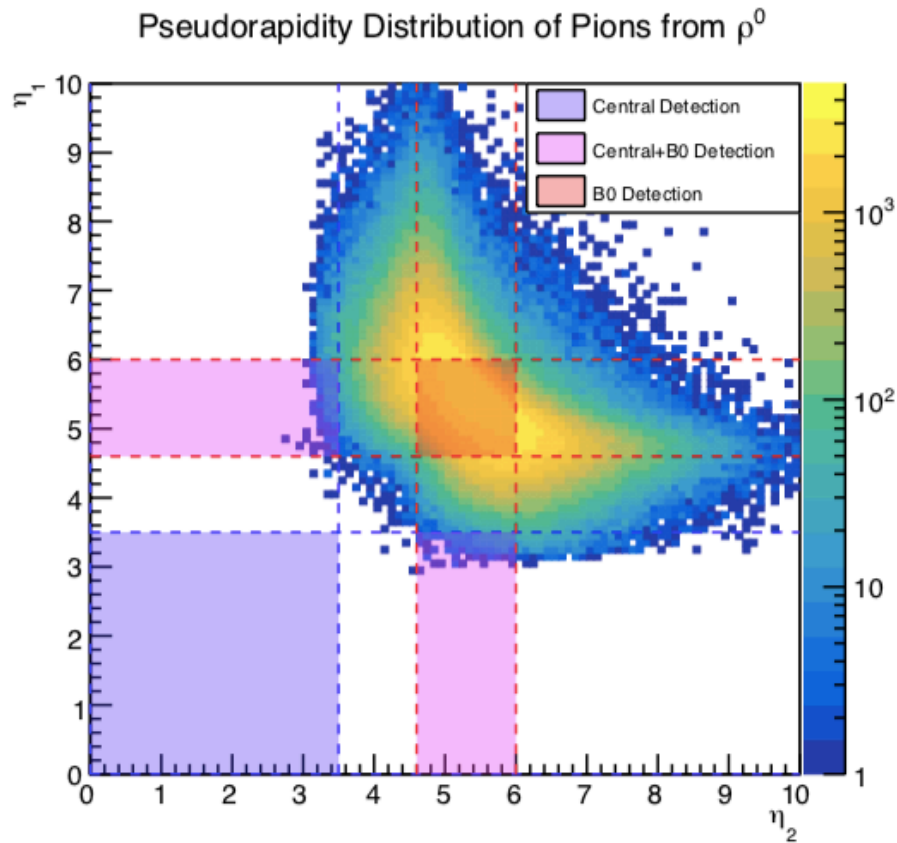
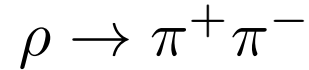


Proton beam energy	ω eff. cent.+ZDC	ω eff. cent.+B0+ZDC
41 GeV	1.4%	18%
100 GeV	1.3%	41%
275 GeV	6%	63%

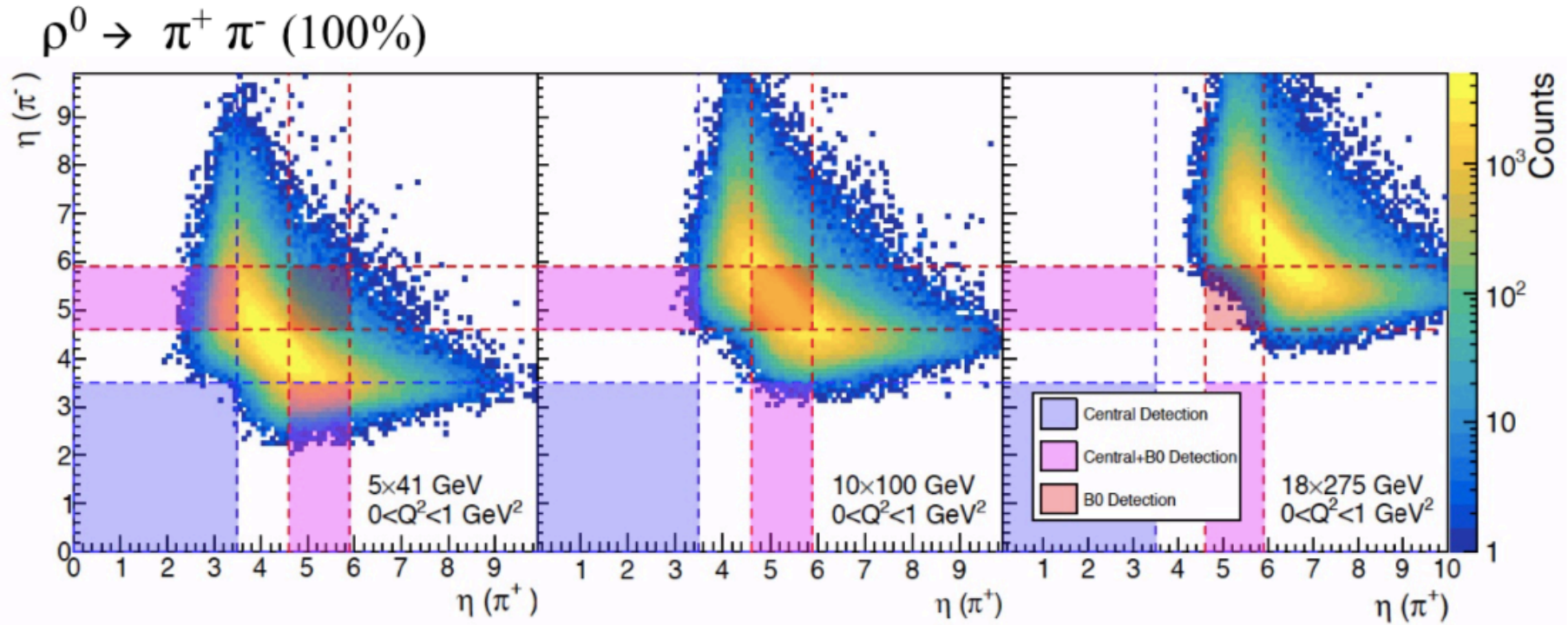
Plots: Zachary Sweger (UC Davis)

Backward production of rho

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



Backward production of rho

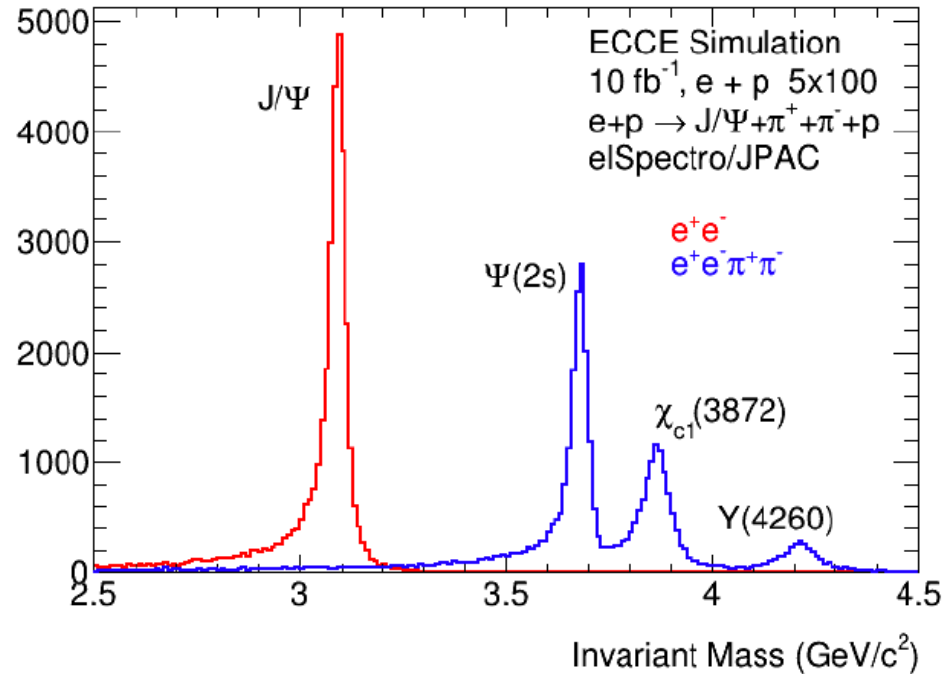


Proton beam energy	ρ eff. cent.+B0
41 GeV	13%
100 GeV	49%
275 GeV	0.7%

- Paper published:

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

XYZ Spectroscopy



- 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 Q² tagger

TCS observables

- Unpolarised cross-sections:

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

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

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

suppressed

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

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

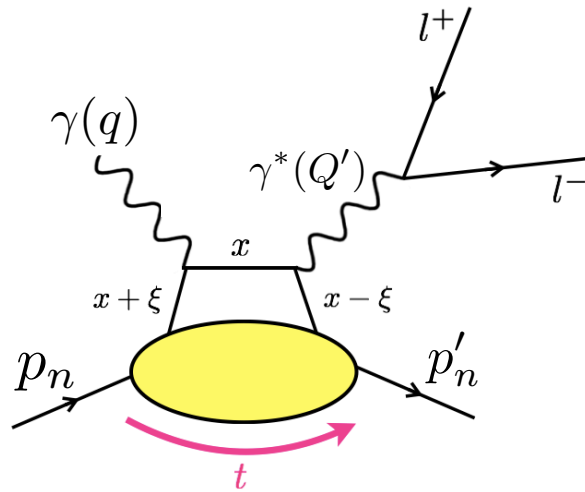
access to $\text{Im } \mathcal{H}$

- 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 $\text{Re } \mathcal{H}$

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.

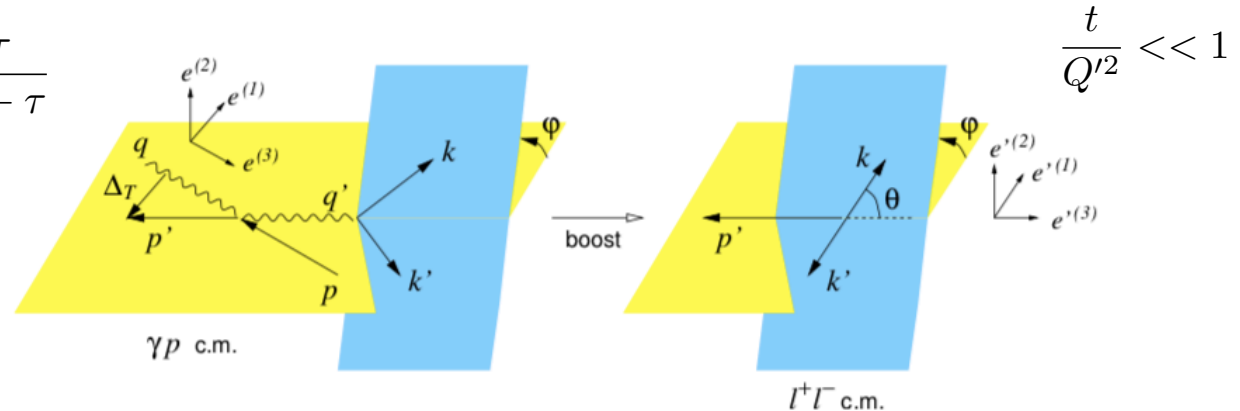
- Factorisation ensured by hard scale of γ^* virtuality:

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

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

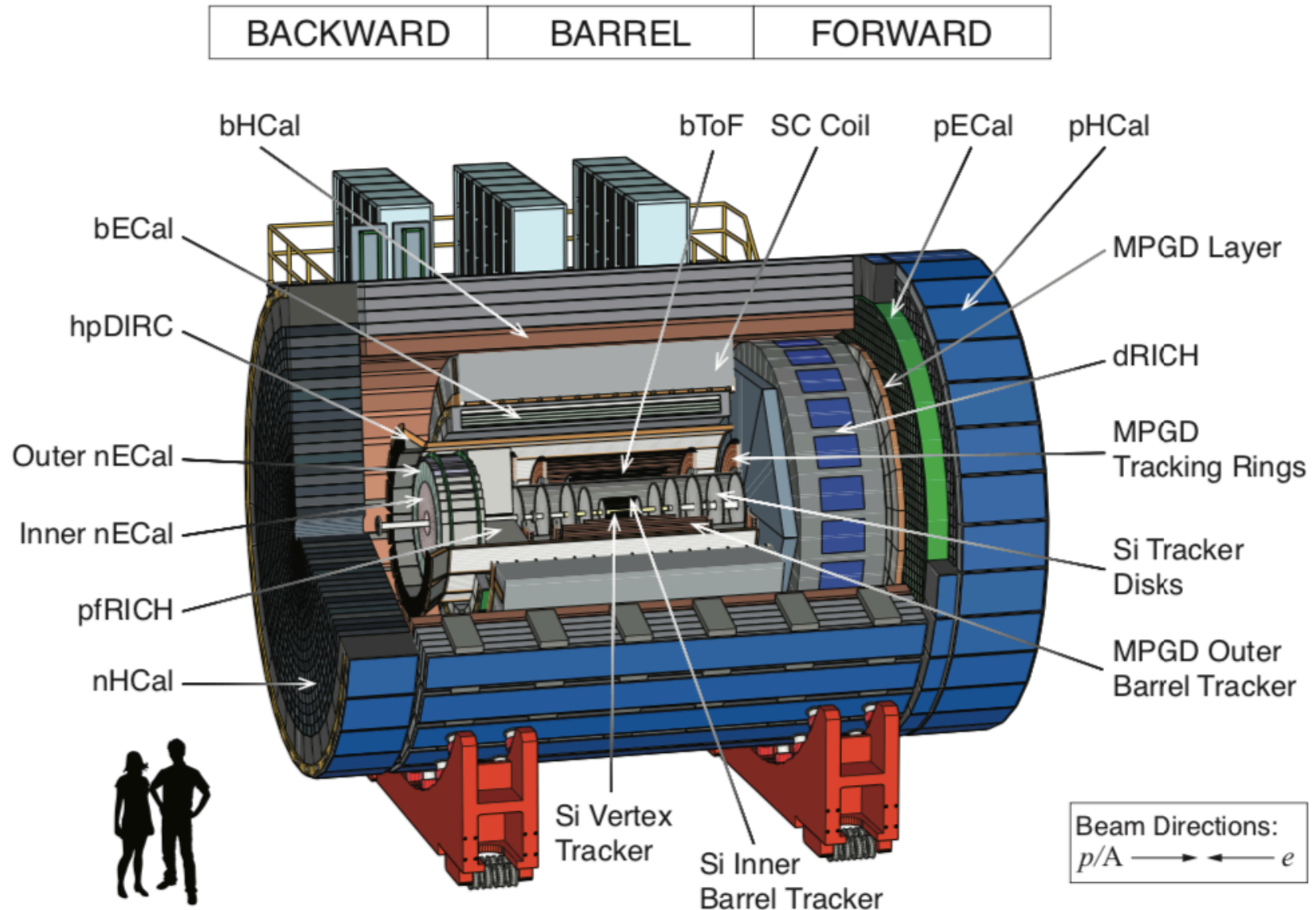
$$\tau = \frac{Q'^2}{s - m_p^2}$$

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



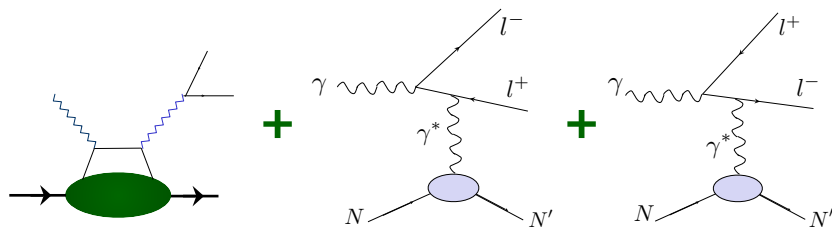
- Measurements establish dependence on Q^2, x, t and φ (angle between leptonic and hadronic planes).

Central ATHENA Detector

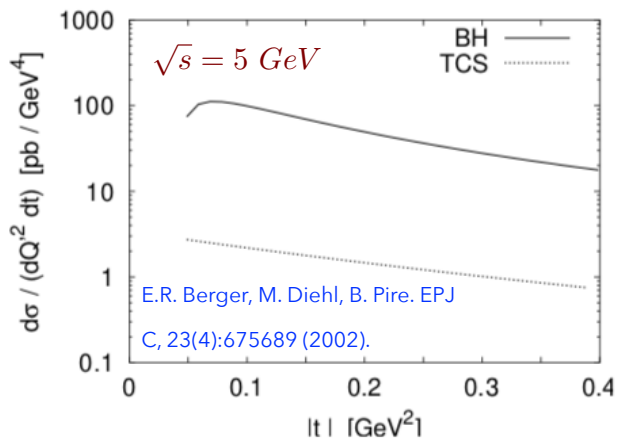


TCS observables

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



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



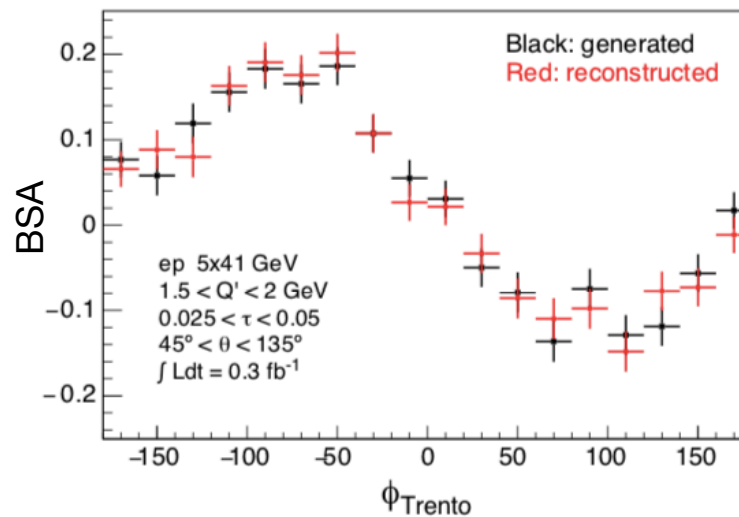
- TCS suppressed by factor of 100 wrt BH: hard to measure cross-sections. Asymmetries dominated by interference term.
- Photon-polarisation (beam-spin) asymmetry:

$$A_{\odot U} = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} \quad \text{access to } \text{Im } \mathcal{H}$$

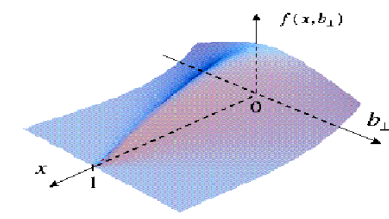
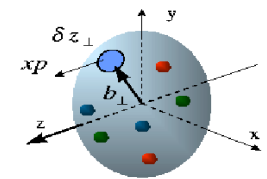
- Forward - backward asymmetry:

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

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

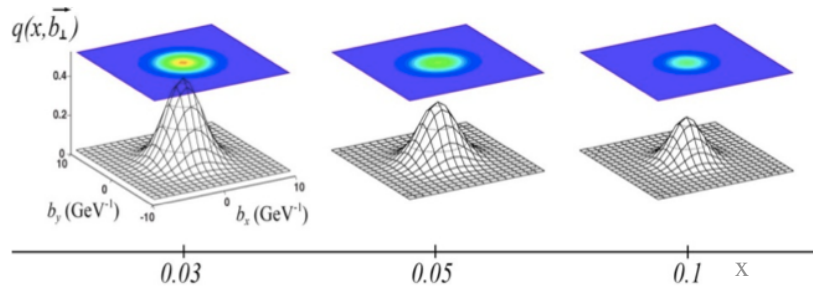


Generalised Parton Distributions



- 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:

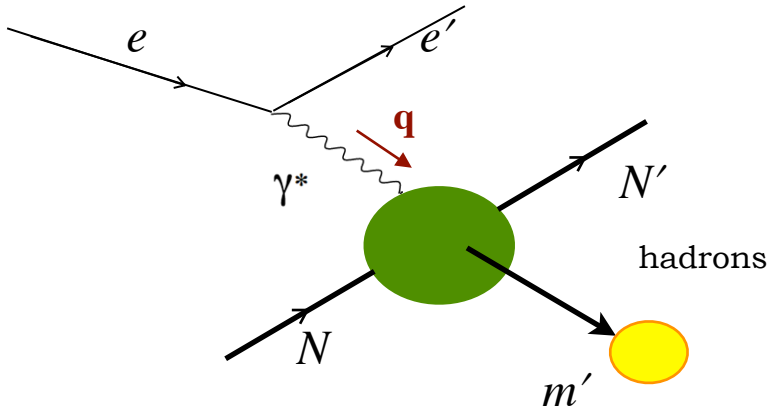
$$J^q = \frac{1}{2} - J^g$$

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

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

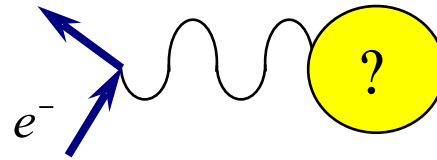
* Combine with TMDs to access **spin-orbit correlations** of quarks and gluons, study non-perturbative interactions of partons.

Kinematics in the Deep Inelastic regime

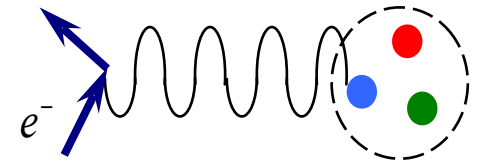


$$Q^2 = -\mathbf{q}^2 = -(\mathbf{p}_e - \mathbf{p}_{e'})^2$$

virtuality of exchanged photon / resolution:



$$Q^2 \sim \text{MeV}^2$$



$$Q^2 \gg \text{GeV}^2$$

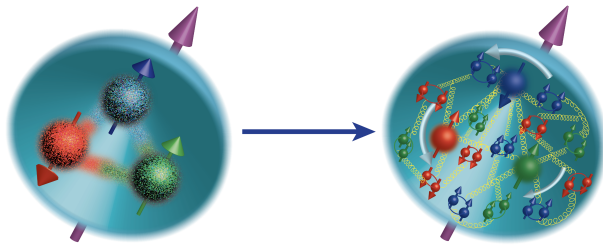
Bjorken variable:
$$x_B = \frac{Q^2}{2\mathbf{p}_n \cdot \mathbf{q}}$$

In Deep Inelastic Scattering, can be equated to x (fraction of longitudinal momentum of nucleon carried by struck quark)

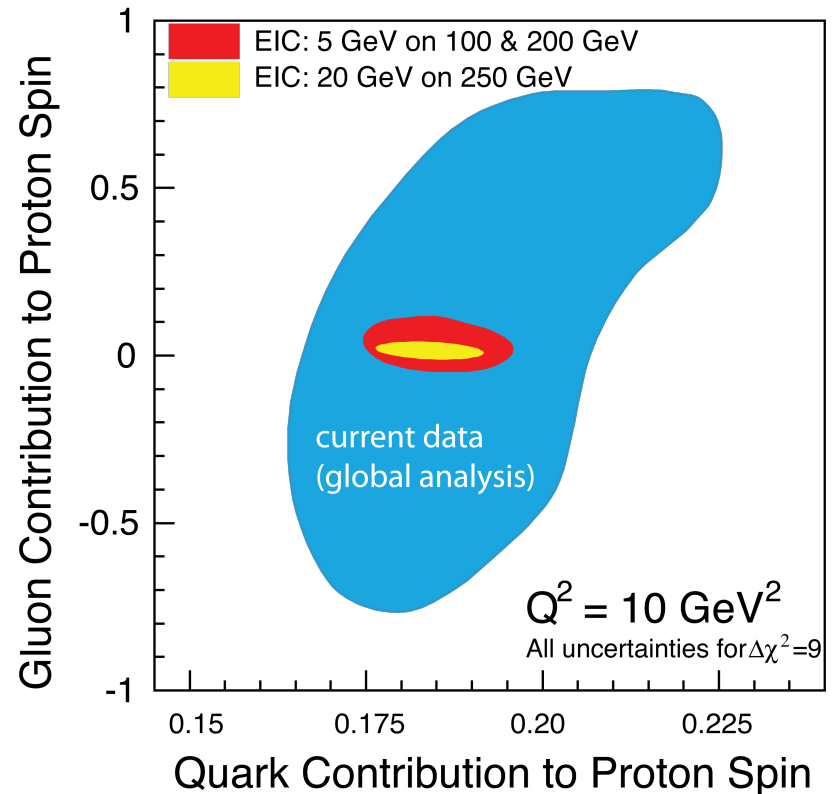
The puzzle of nucleon spin

- * Gluons carry a sizeable fraction of nucleon momentum and give rise to transverse momentum of quarks. What is their contribution to nucleon spin? How do sea quarks contribute?

$$J_q = \frac{1}{2} \Delta\Sigma + L_q + J_g$$

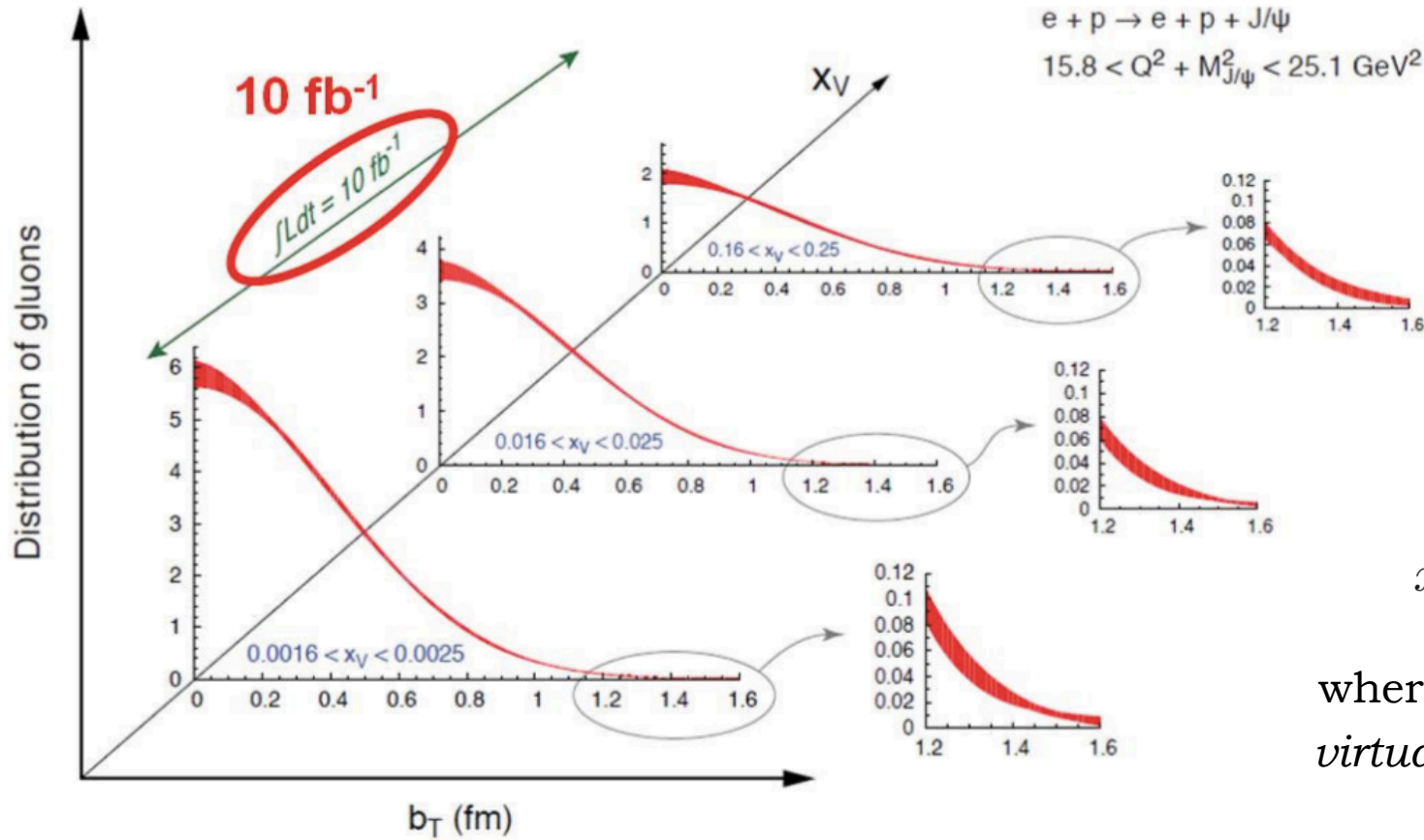


- * 3D imaging of hadrons across the widest range of scales.



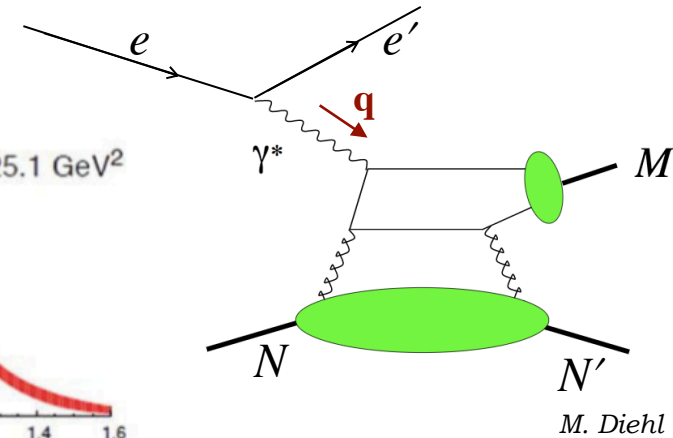
Nucleon tomography: imaging glue

- * 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:



$$e + p \rightarrow e + p + J/\psi$$

$$15.8 < Q^2 + M_{J/\psi}^2 < 25.1 \text{ GeV}^2$$



Gluon momentum fraction related to:

$$x_V = x_B \left(1 + \frac{M_{J/\psi}^2}{Q^2} \right)$$

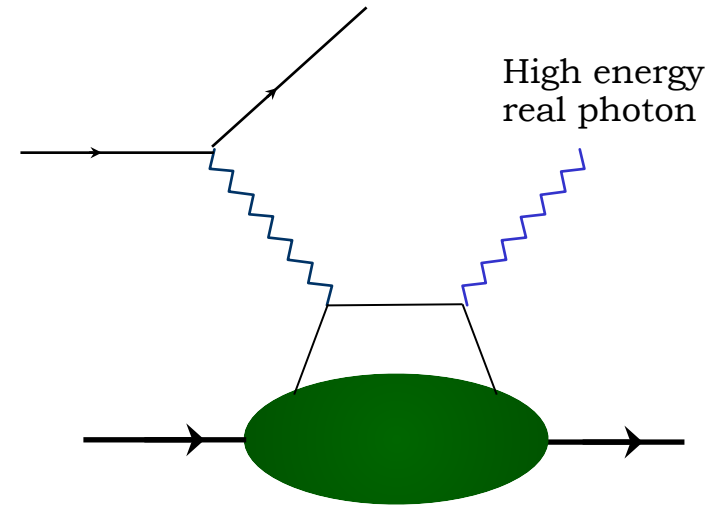
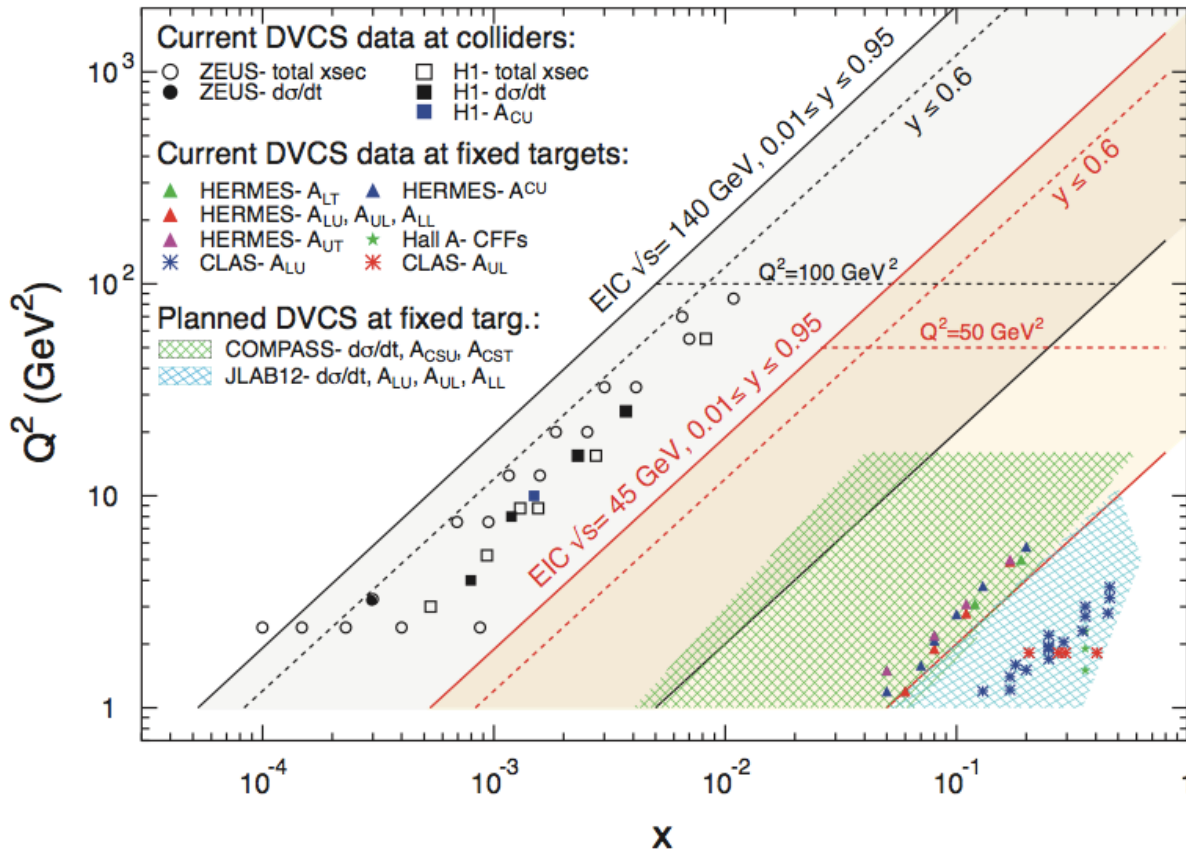
where $Q^2 = -\mathbf{q}^2 = -(\mathbf{p}_e - \mathbf{p}_{e'})^2$
virtuality of exchanged photon

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

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.

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 $\sim 30\%$. Subsequent deep inelastic scattering (DIS) experiments confirm.

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

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

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

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

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.