Hadron and nuclear physics at the Electron-Ion Collider

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Muon Collider Synergies Workshop

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University of Glasgow

Brookhaven National Lab, NY, USA

Electron-Ion Collider

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

For e-N collisions at the EIC:

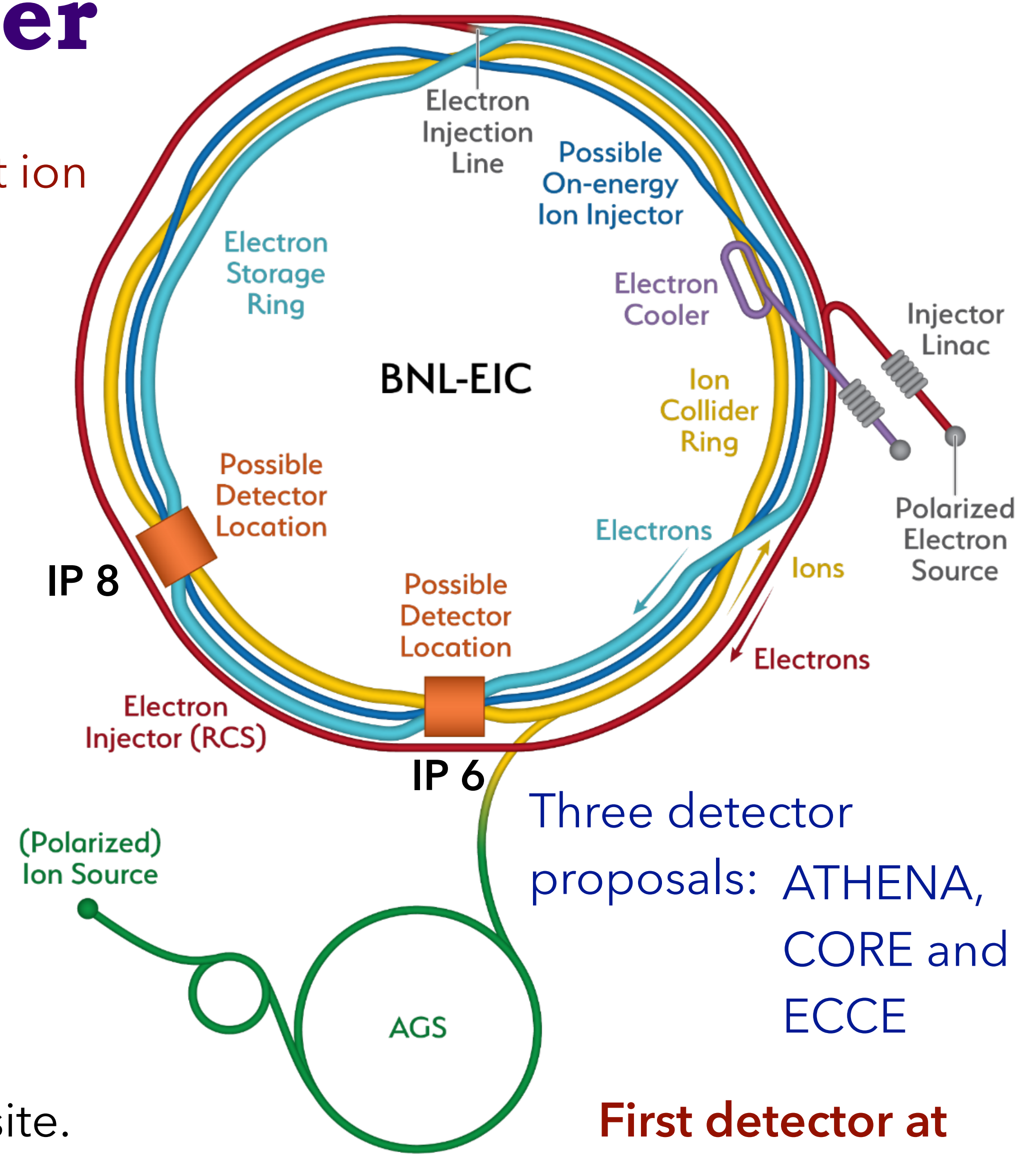
- ✓ Polarized beams (70%): e, p, d/^{3}He
- ✓ e beam 3 - 10 (18) GeV
- ✓ Luminosity L_{ep} ~ 10^{33-34} $cm^{-2}s^{-1}$
- ✓ 20 - 100 (140) GeV Variable CoM

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.

Expected start of operations: early 2030s.

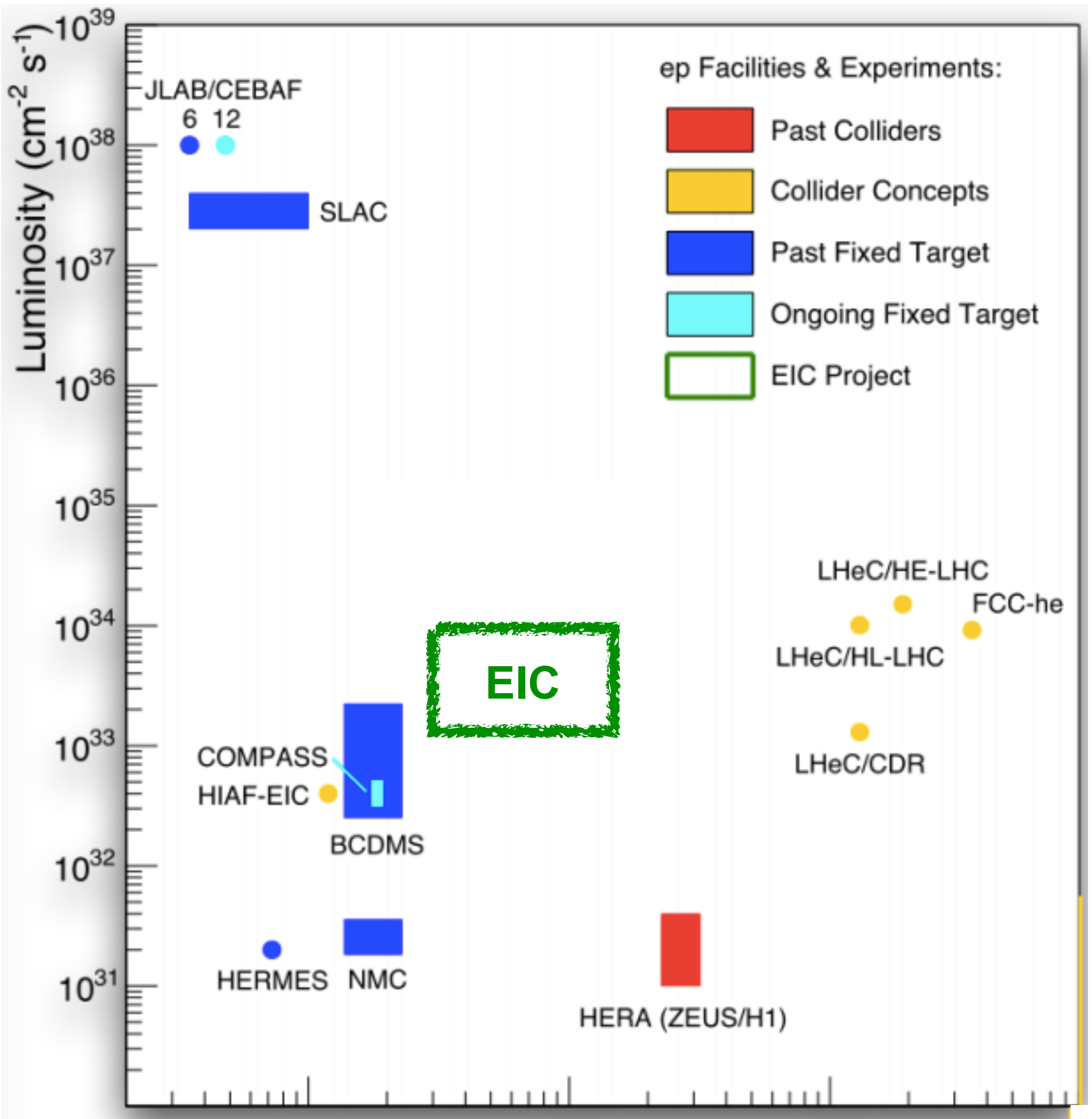


arXiv:1409.1633

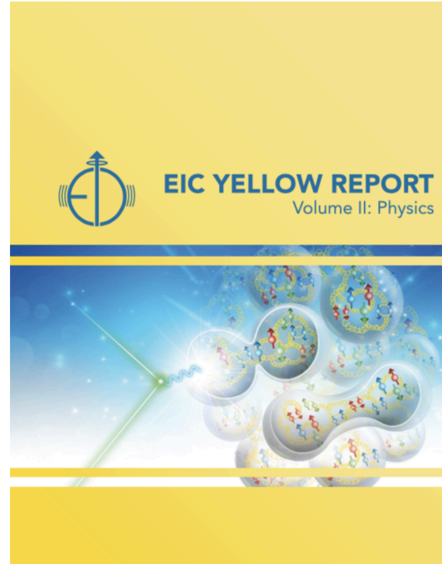
Three detector proposals: ATHENA, CORE and ECCE

First detector at IP 6: ePIC

EIC in context

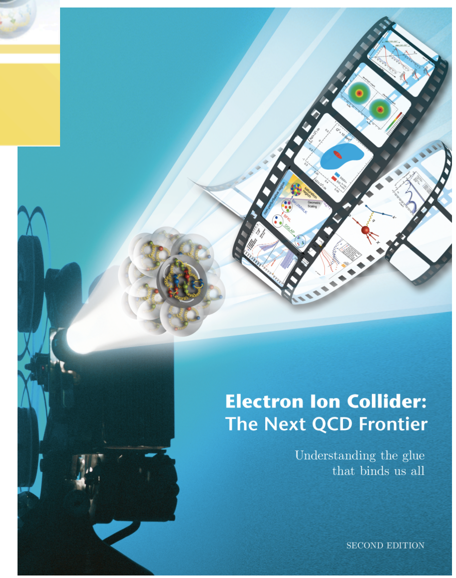


cms Energy



2020 EIC Yellow Report, *Nuc. Phys. A 1026, 122447 (2022)*

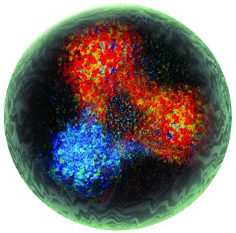
Dedicated studies of EIC physics and design



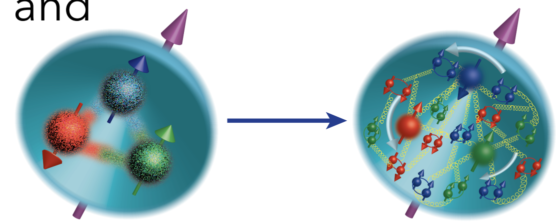
2012 EIC White Paper, *Eur. Phy. J. A 52, 9 (2016)*

What is the EIC for?

- Designed primarily for the study of cold QCD:

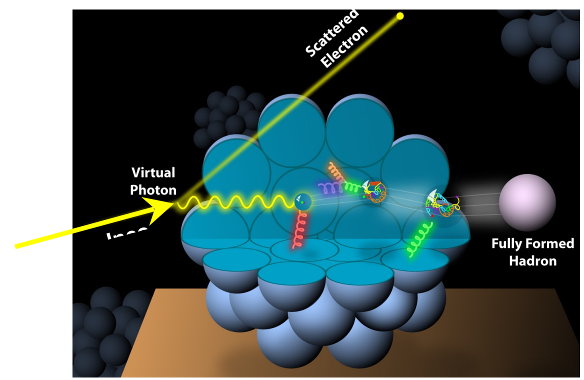


  - What is the origin of nucleon mass and what is the role of glue in it? How is it generated from the almost massless quarks and massless gluons?
  - What is the quark-gluon origin of the nuclear force?
  - How do hadrons and nuclei emerge from quarks and gluons? What is the nature of confinement?



- 3D tomography of the nucleon: distributions of partons from the valence quark region to the quark-gluon sea.
- Nucleon spin puzzle: decomposition of nucleon spin – contribution of sea quarks and gluons.

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

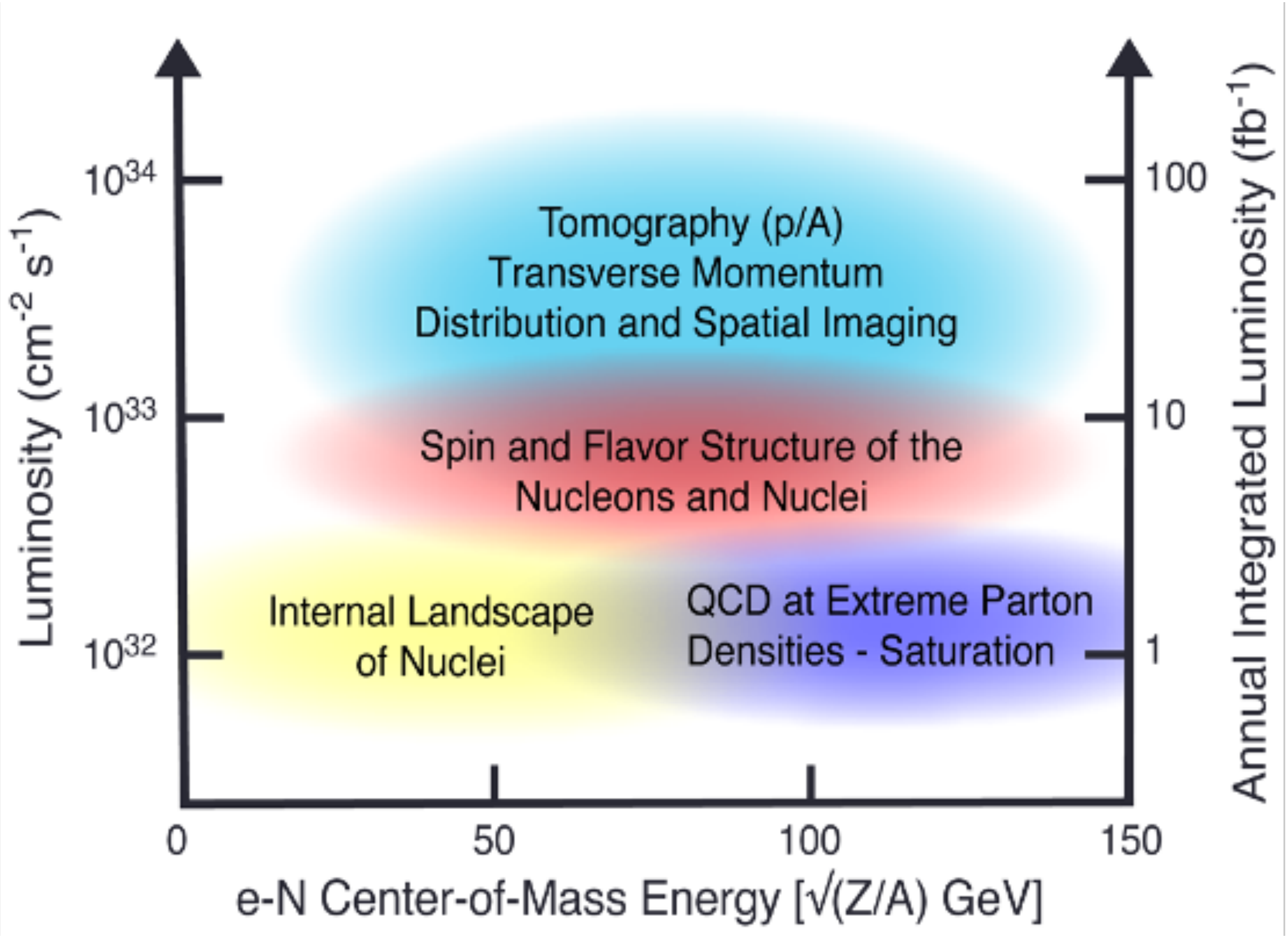


Courtesy of E. Aschenauer

- Effect of nuclear medium on the propagation of a colour charge: insight into hadronisation and the EMC effect.
- Search for gluon saturation: a new form of matter.
- Search for exotic states.

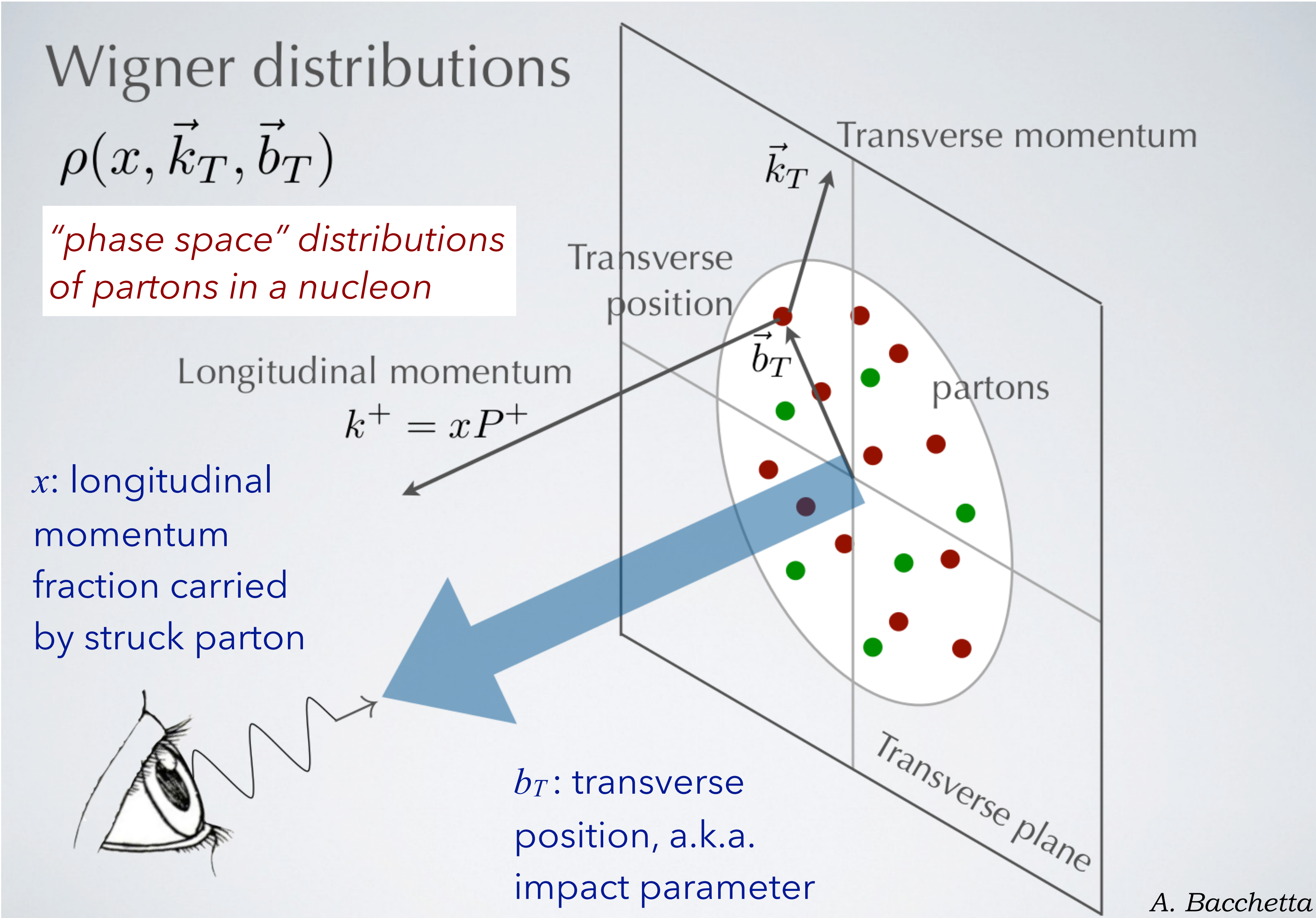
The list is NOT exhaustive…

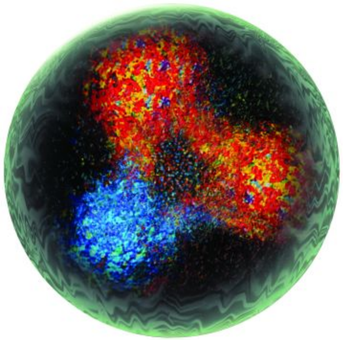
What will the EIC be able to do?



year =10^7 sec

A constructivist view of the nucleon





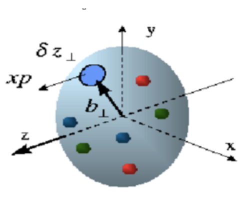
Wigner function:
full phase space parton
distribution of the nucleon

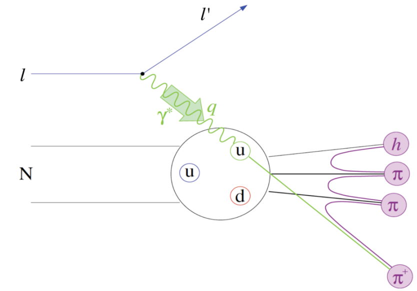
Generalised Transverse Momentum Distributions (GTMDs)

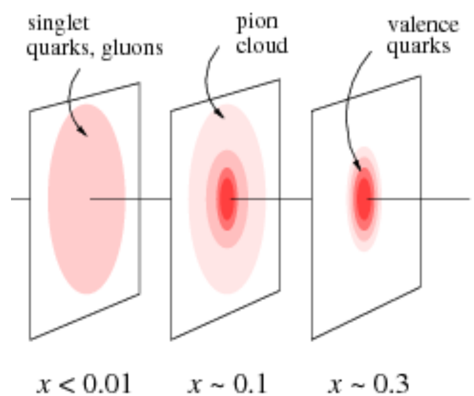
Possible access via exclusive di-jet production or exclusive π^0-production at high Q^2.

$$\int d^2k_T$$

$$\int d^2b_T$$





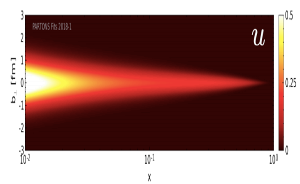


Generalised Parton Distributions (GPDs)

Exclusive processes

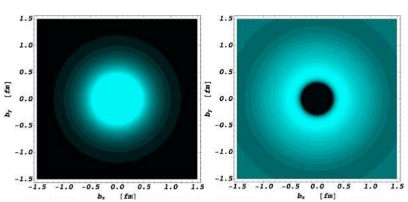
Transverse Momentum-Dependent distributions (TMDs)

Semi-inclusive DIS (SIDIS)



$$\int dx$$

$$\int d^2k_T$$

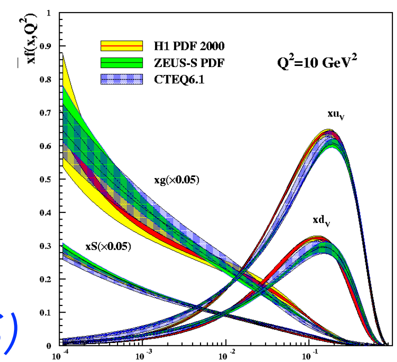


Form Factors

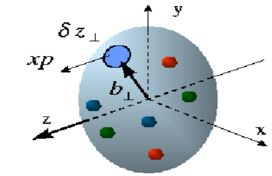
Elastic scattering

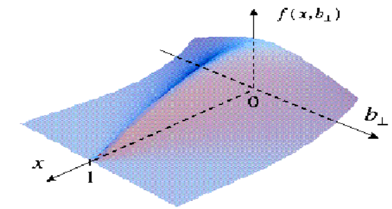
Parton Distribution Functions (PDFs)

Deep Inelastic Scattering (DIS)



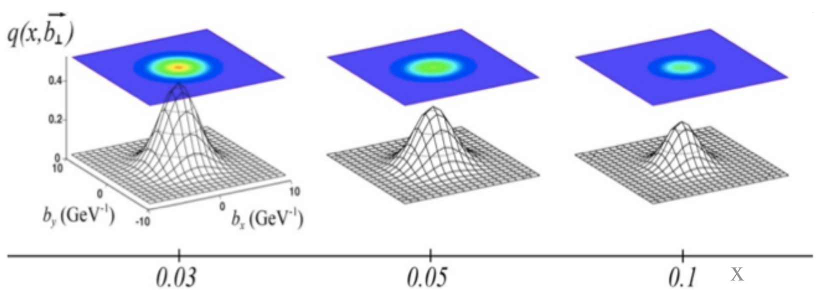
Generalised Parton Distributions





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

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



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

* 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:

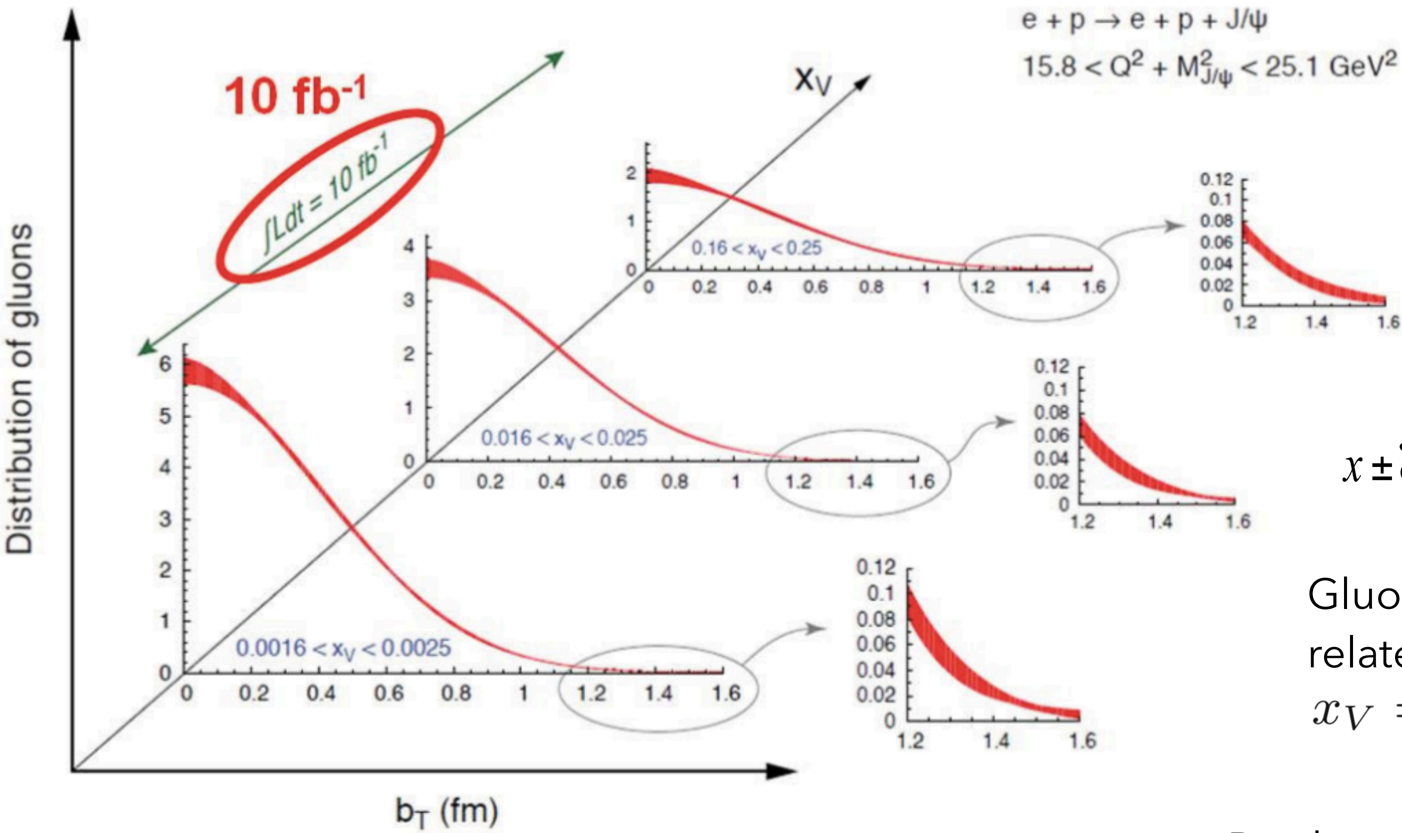
$$J^q = \frac{1}{2} - J^g = \frac{1}{2}\int_{-1}^{1} x\,dx \left\{ H^q(x,\xi,0) + E^q(x,\xi,0) \right\}$$

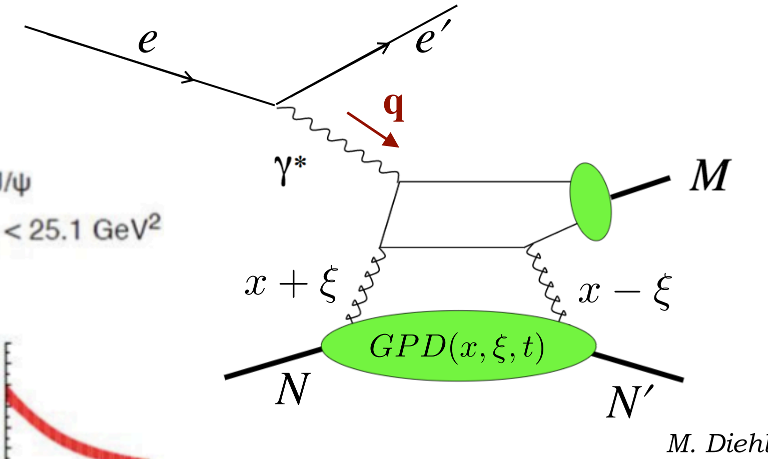
GPDs

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

Nucleon tomography: imaging glue at EIC

- 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:





$$Q^2 = -q^2 = (e - e')^2$$

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

Gluon momentum fraction related to:

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

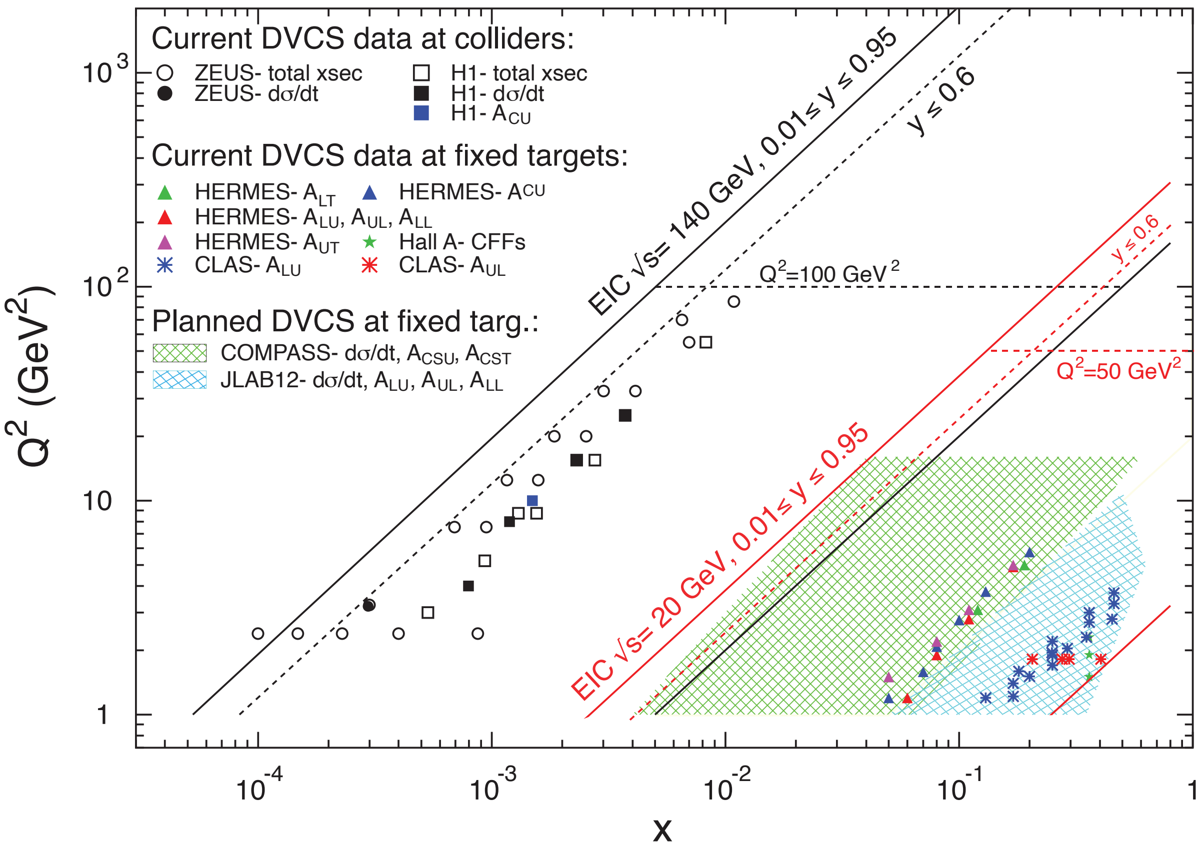
Bjorken variable $x_B = \frac{Q^2}{2\mathbf{p_n} \cdot \mathbf{q}}$

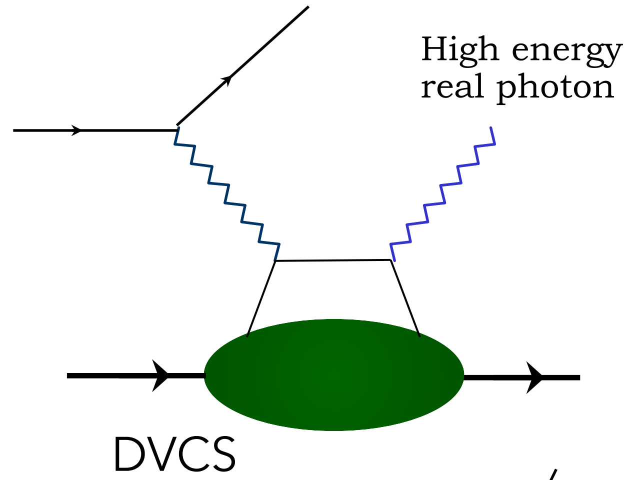
EIC White Paper, *Eur. Phy. J. A 52, 9 (2016)*

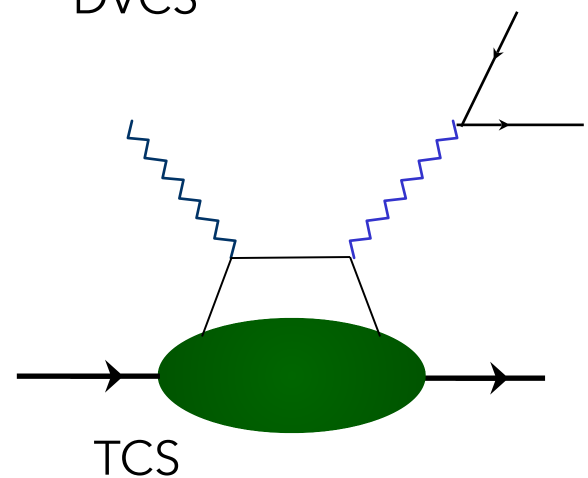
Nucleon tomography: imaging quarks at EIC

* Quark GPDs are accessible in a related processes: Deeply Virtual Compton Scattering (DVCS), Timelike Compton scattering (TCS).

DVCS kinematic reach at the EIC:



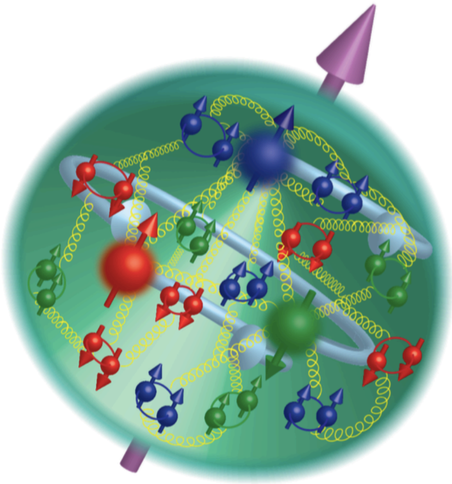




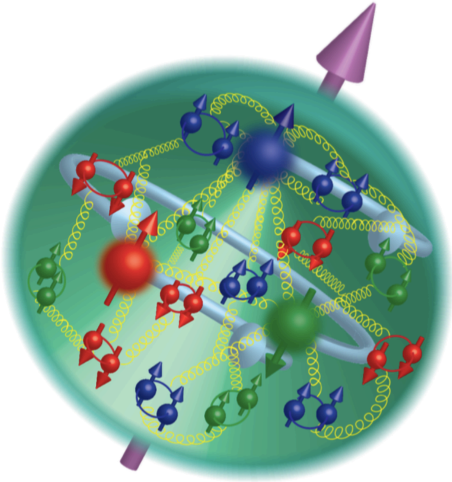
* 3D images of sea quark and gluon distributions from exclusive reactions: DVCS and DVMP.

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

Nucleon spin

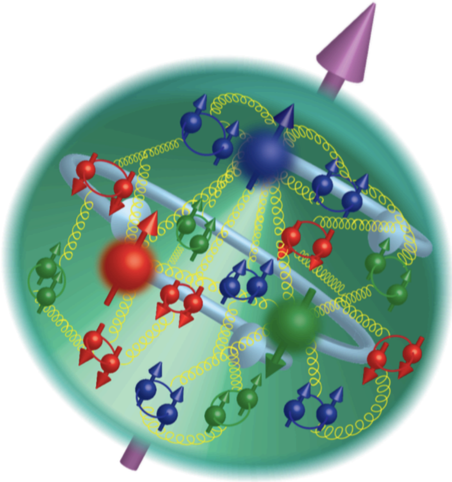


$\frac{1}{2}$



Nucleon spin

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



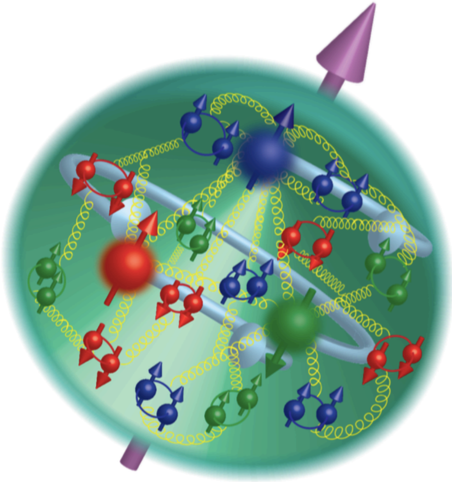
Nucleon spin

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

Intrinsic quark spin:

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

Nucleon spin



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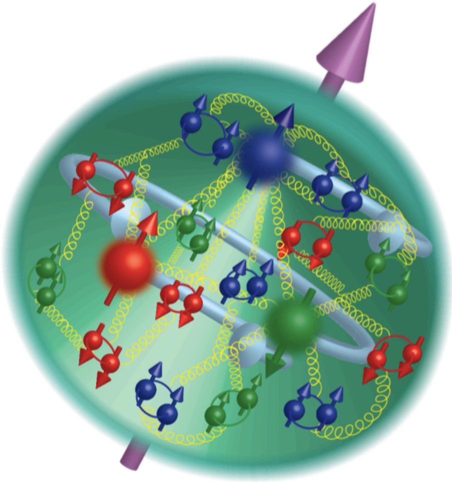

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Intrinsic gluon spin:

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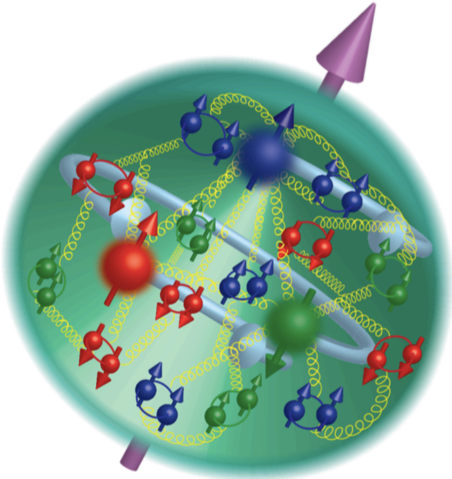
Polarised Deep Inelastic Scattering (DIS) to access spin structure function:

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

$\sigma^{\leftrightarrows}$: e N

$\sigma^{\rightarrow\uparrow}$: e N

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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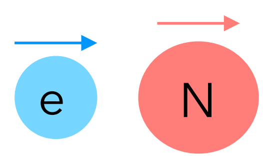
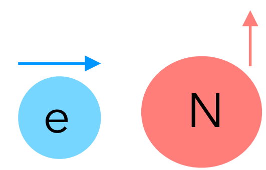
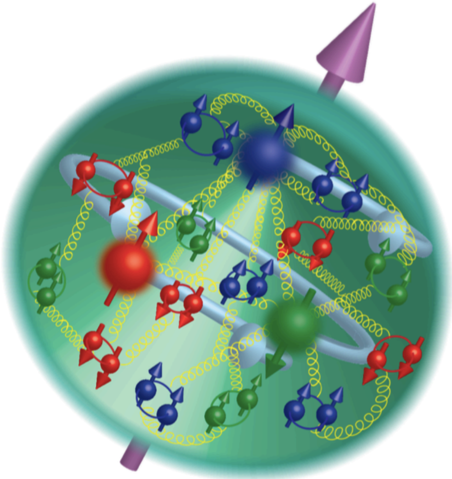


$\sigma^{\rightarrow\uparrow}$:





Nucleon spin

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

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

Intrinsic quark spin:

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

Intrinsic gluon spin:

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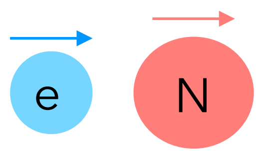
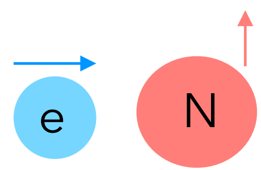
$\sigma^{\leftrightarrows}$: 

$\sigma^{\rightarrow\uparrow}$: 

Spin structure function

~ 30%

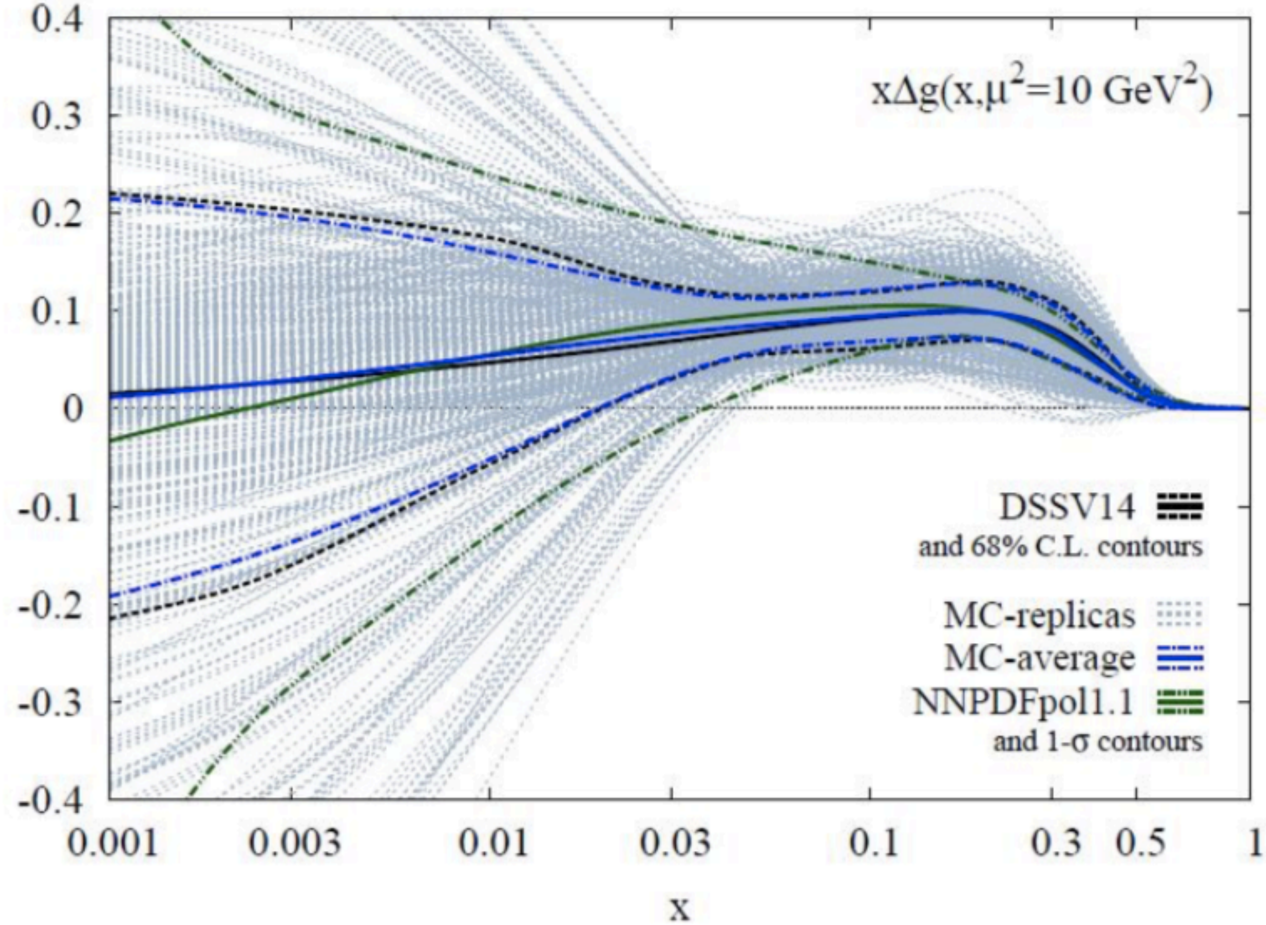
huge uncertainties

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

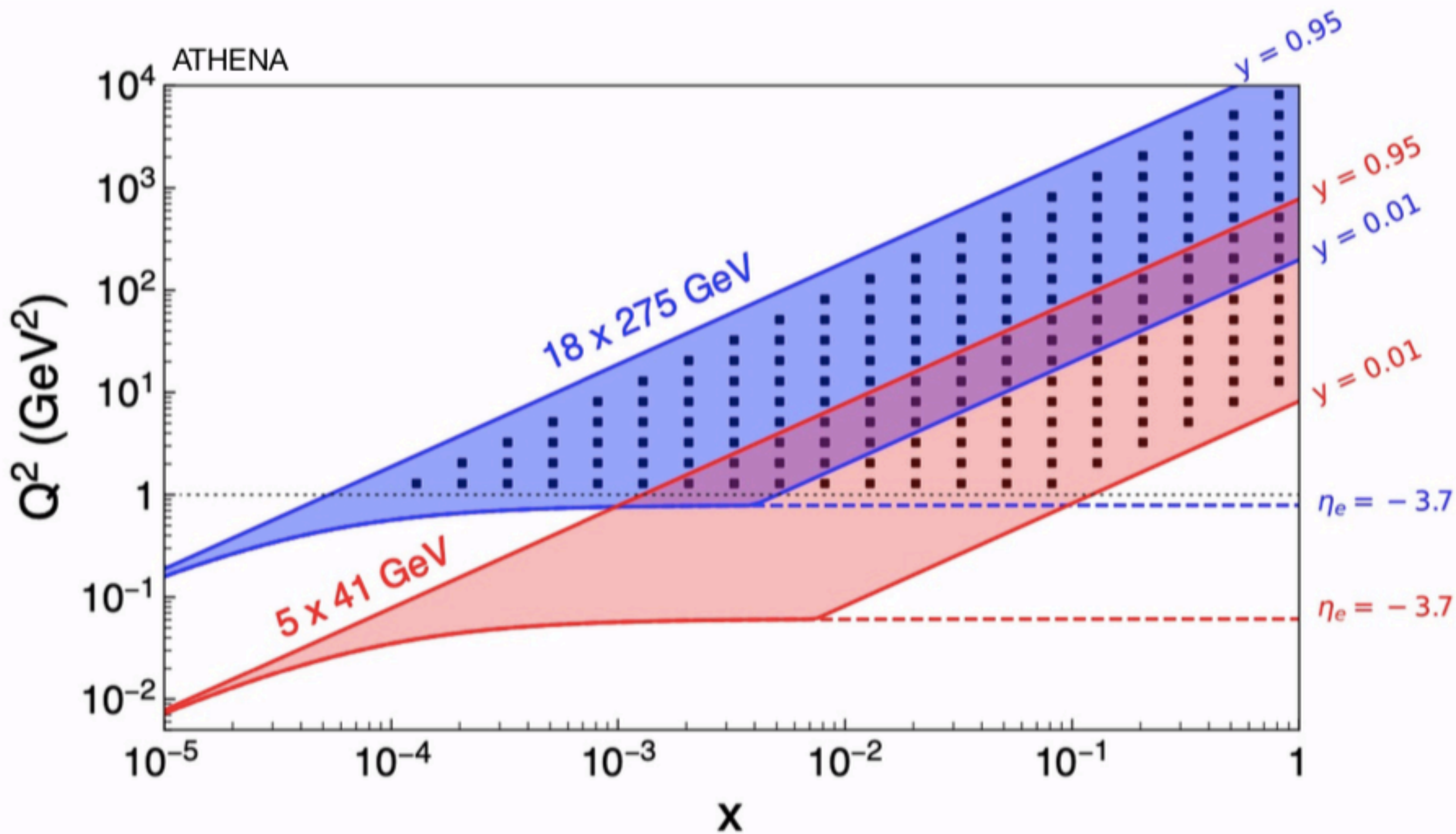
??

Huge uncertainties on polarised gluon PDFs, *L* contribution unknown…

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



EIC Kinematic reach: DIS

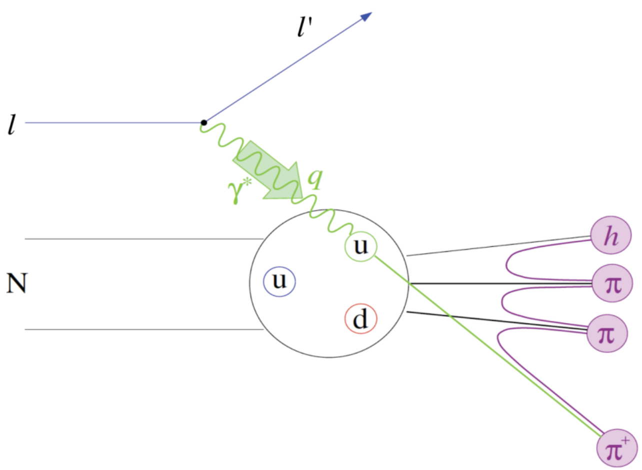


Spin structure function

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

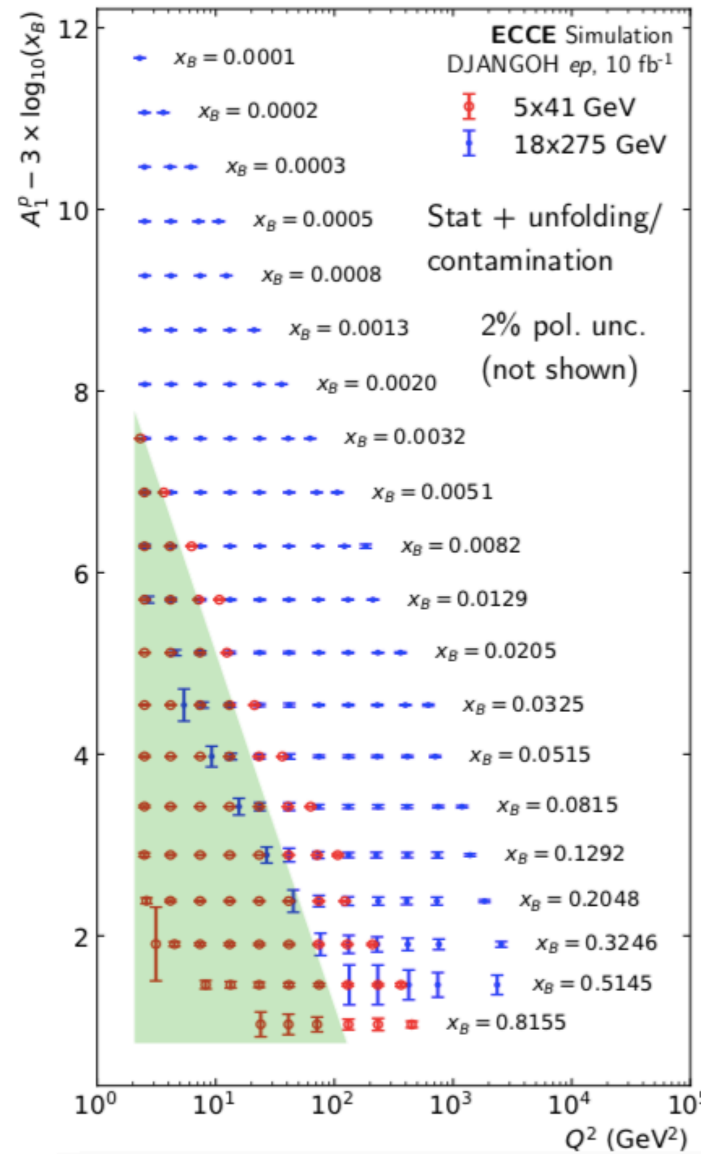
$$A_{\parallel} = \frac{\sigma^{\leftrightarrows} - \sigma^{\rightrightarrows}}{\sigma^{\leftrightarrows} + \sigma^{\rightrightarrows}} \qquad A_{\perp} = \frac{\sigma^{\rightarrow\uparrow} - \sigma^{\rightarrow\downarrow}}{\sigma^{\rightarrow\uparrow} + \sigma^{\rightarrow\downarrow}}$$

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

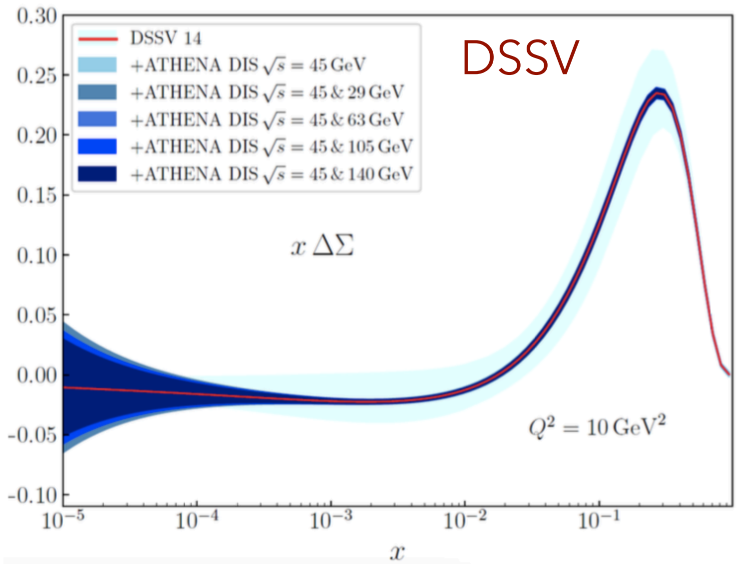


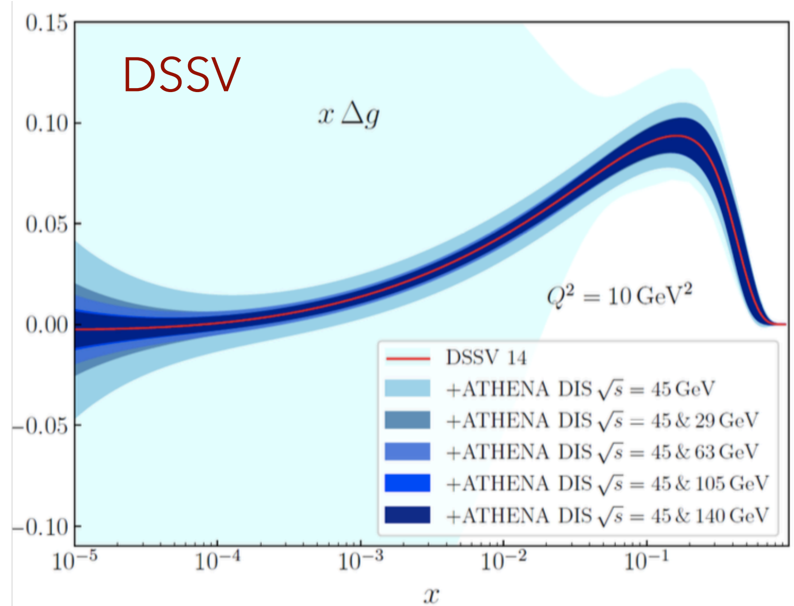
Access gluon contribution through Q^2-dependence

Inclusive

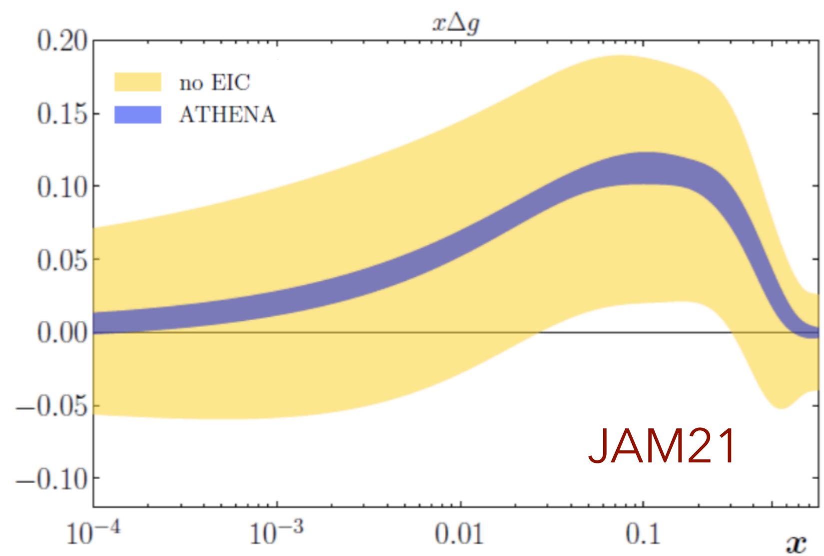


EIC impact on polarised PDFs





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

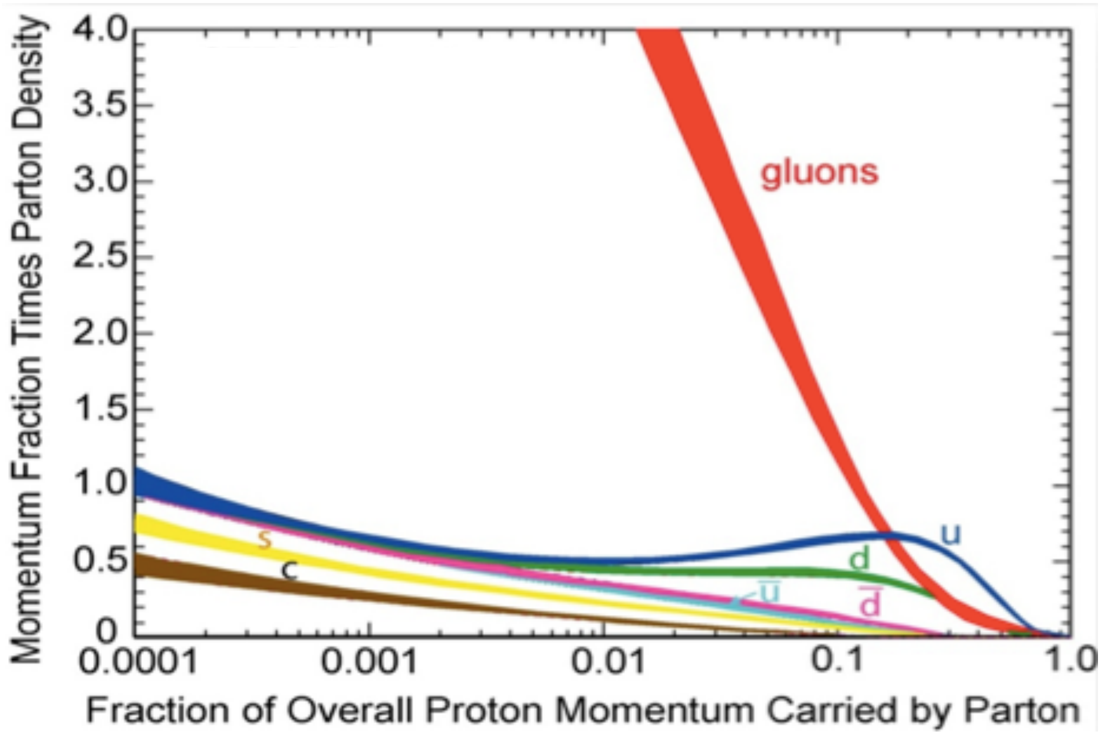


Study with ATHENA detector design

Saturation of gluon density

- Runaway growth of glue at low-x:

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

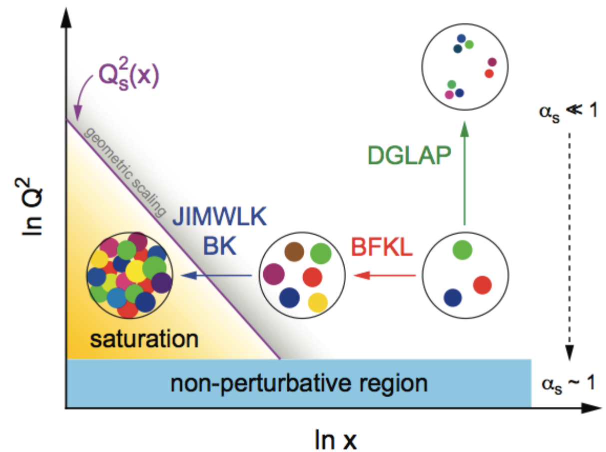


F. Wilczek, in "Origin of Mass"
Nobel Prize, 2004

But somewhere it must saturate…

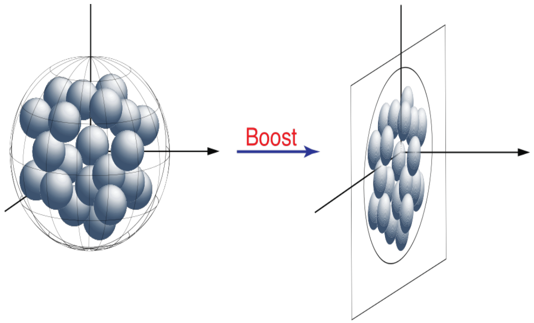
rate of  = rate of 

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

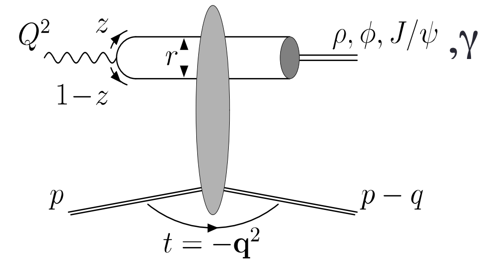


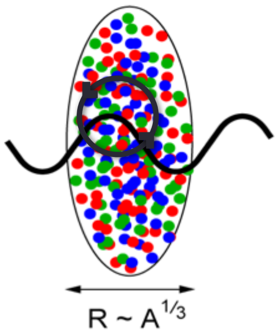
Courtesy of A. Deshpande

Can we reach saturation at EIC?



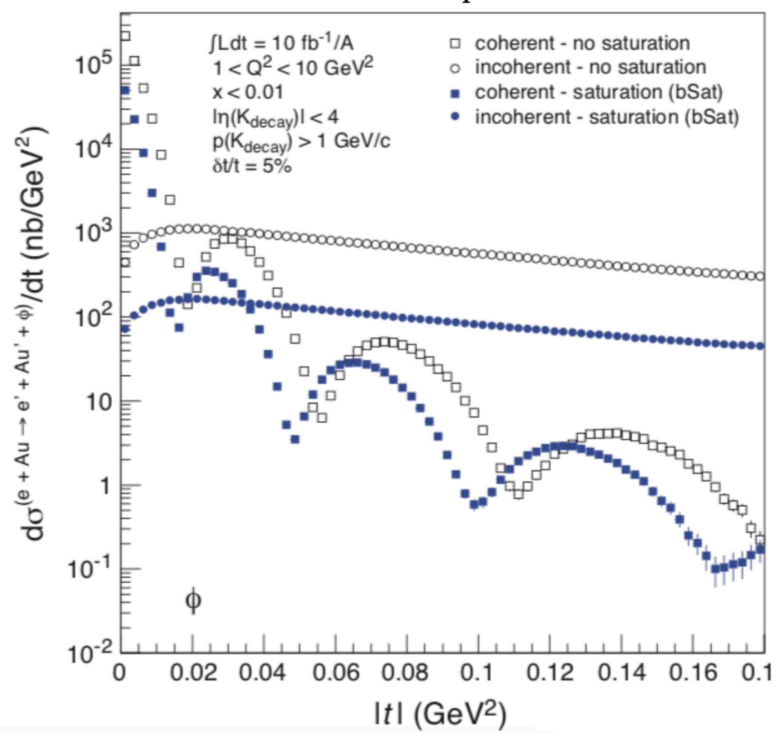
Saturation regime would be accessible at much lower energy in *e-A* collisions than *e-p*. You do not need a TeV collider!



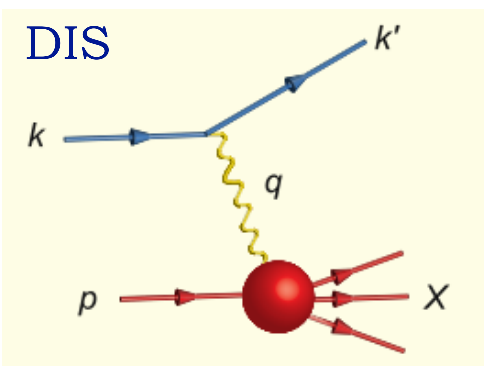


$$(Q_s^A)^2 \approx c Q_0^2 \left[\frac{A}{x}\right]^{1/3}$$

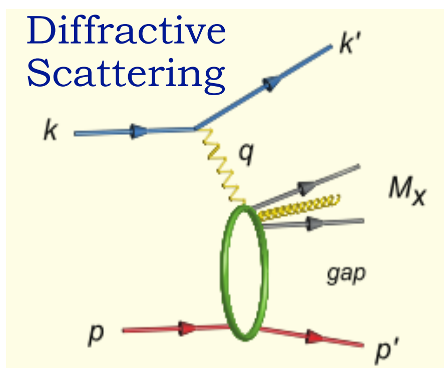
saturation scale



A powerful signature is diffractive cross-sections:



Saw ~10% diffractive events at HERA.



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

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

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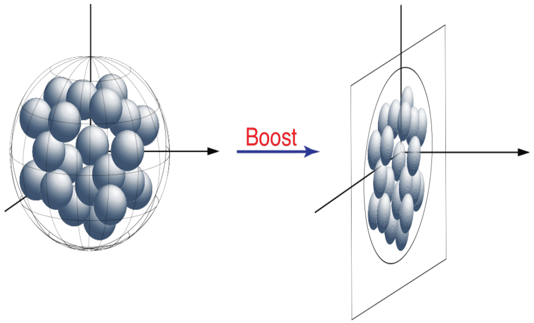

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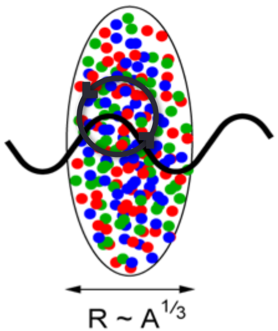
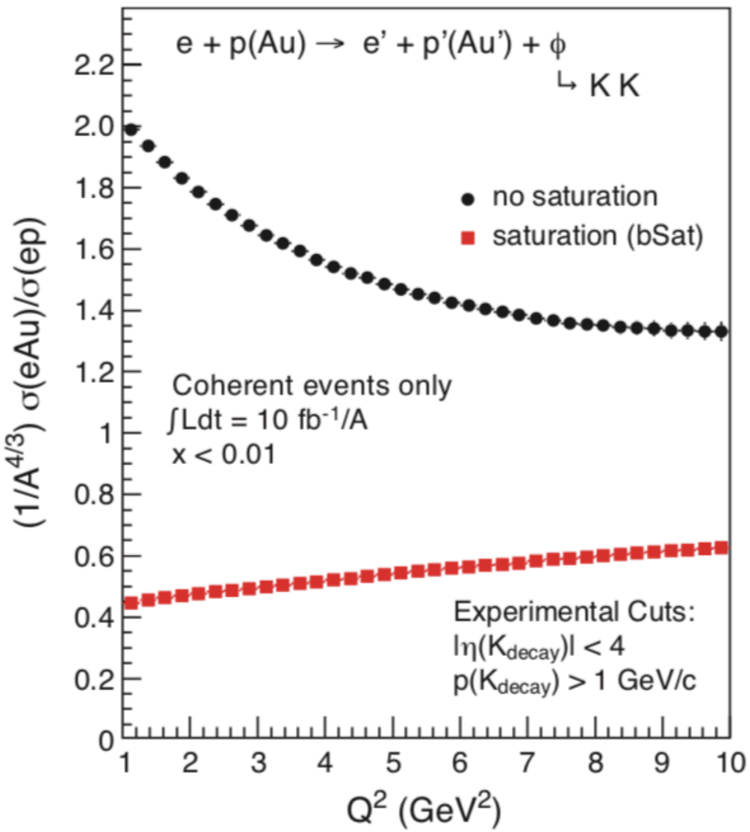
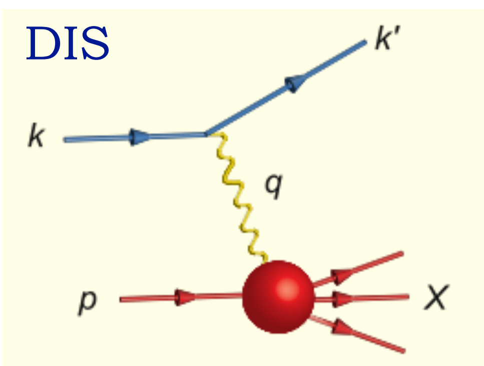


$$(Q_s^A)^2 \approx cQ_0^2 \left[\frac{A}{x}\right]^{1/3}$$

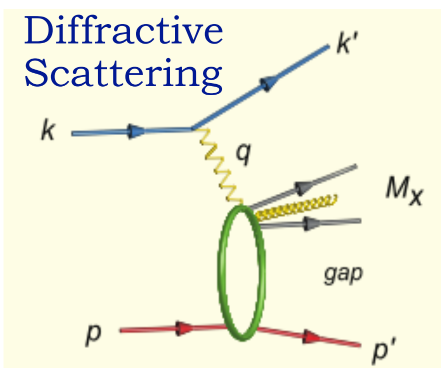
saturation scale



A powerful signature is diffractive cross-sections:



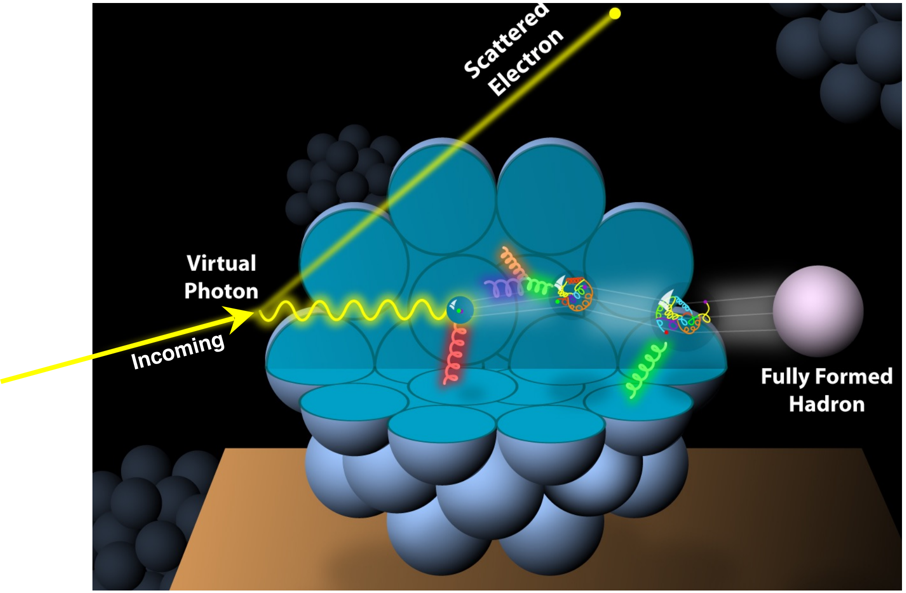
Saw ~10% diffractive events at HERA.



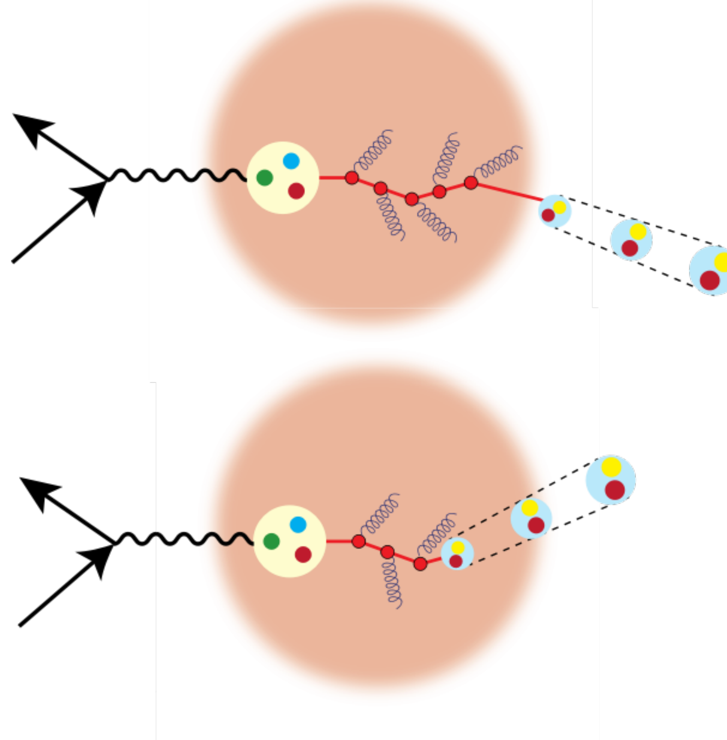
$\sigma_{\mathrm{diff}} \propto [g(x, Q^2)]^2$

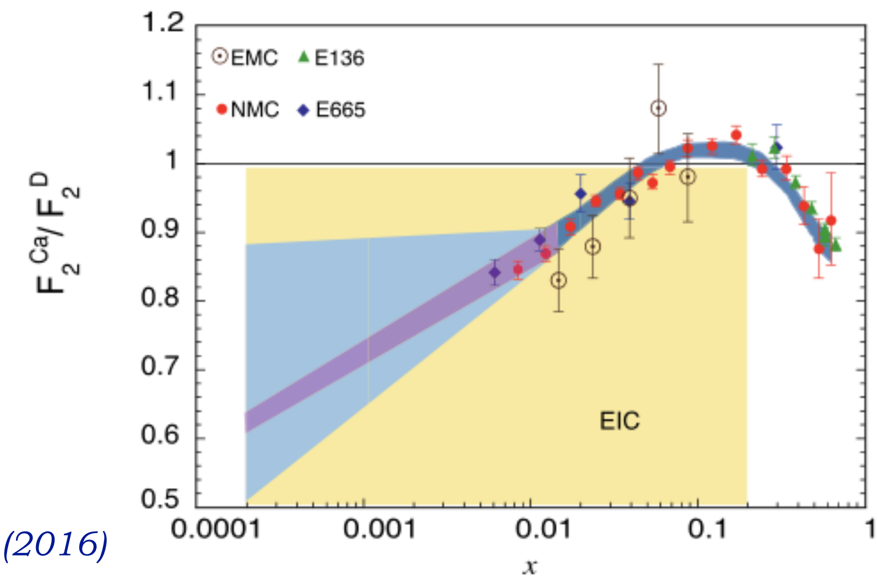
EIC White Paper, *Eur. Phy. J. A 52, 9 (2016)*

Hadronisation



Courtesy of E. Aschenauer



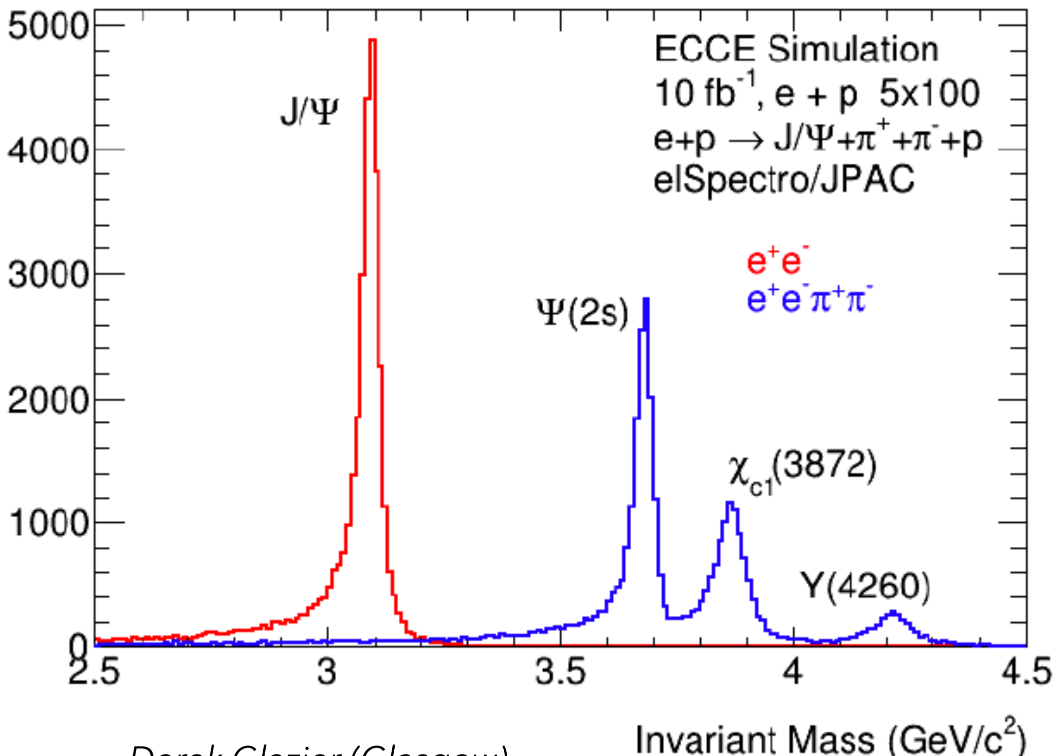


- How does the nuclear environment affect the distributions of quarks and gluons and their interactions inside nuclei?
- How does nuclear matter respond to fast moving color charge passing through it?
- Are there differences for light and heavy quarks?

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

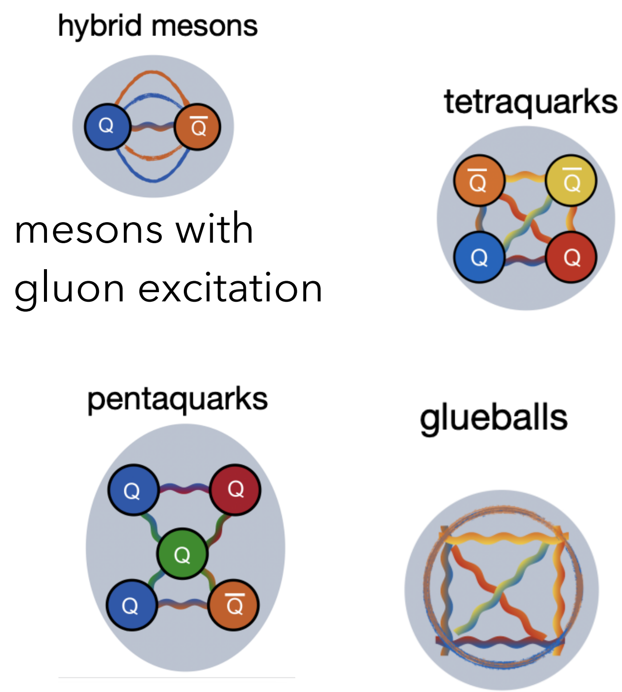
XYZ Spectroscopy

- XYZ Spectroscopy, spectroscopy of mesons with charm quarks.
- New XYZ states have unexpectedly narrow widths inconsistent with quark model predictions.
- Low-Q2 tagger will enable fully exclusive reconstruction of photoproduction in part of the kinematics.
- Resolution sufficient to separate states:



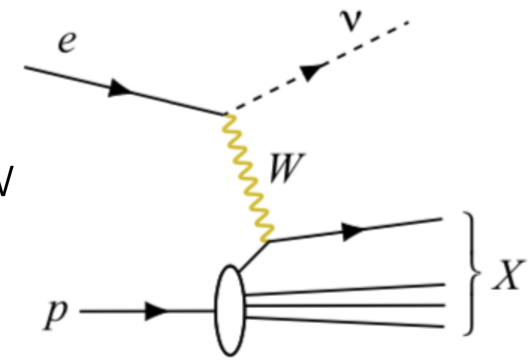
Derek Glazier (Glasgow)

- Search for exotics:



hexaquarks, etc…

Charged currents in DIS

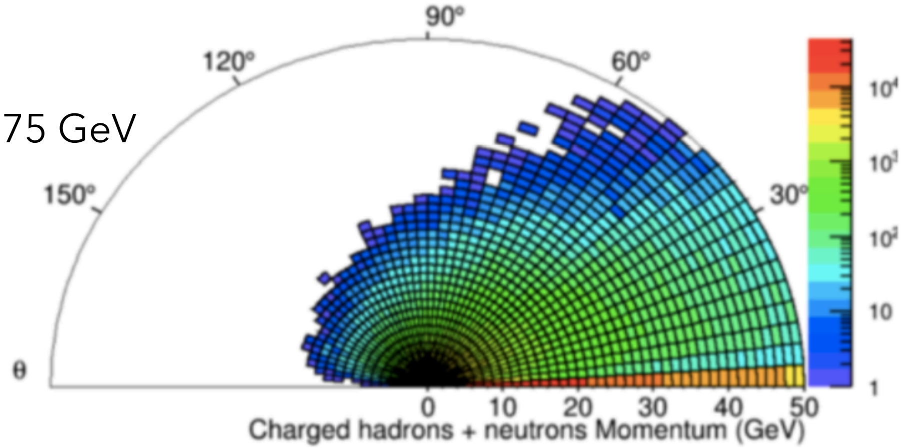


- Charged current DIS: test chiral structure of charged-current interactions: in SM, only left-handed electrons and right-handed positrons couple to W – SM predicts linear dependence on lepton beam polarisation.

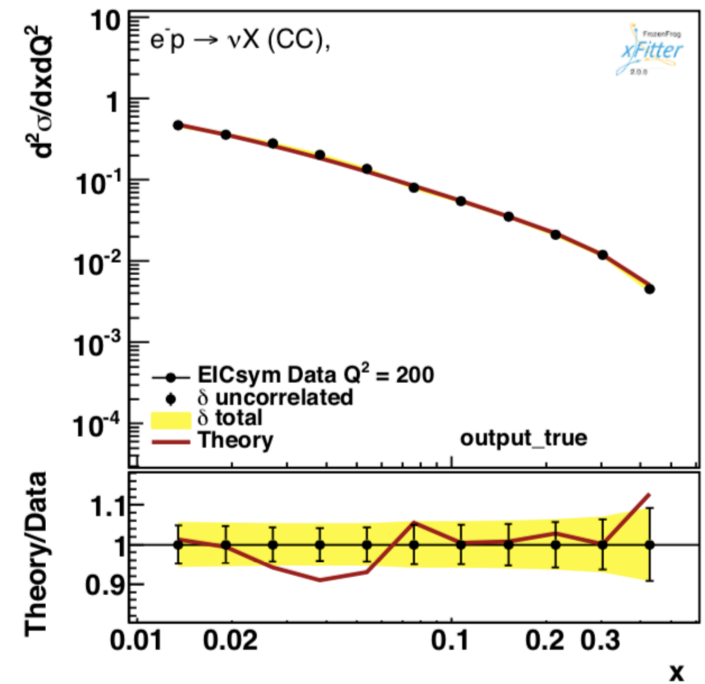
- Can only reconstruct event kinematics using the Jacquet-Blondel method, using final state hadrons:

$$Q^2_{JB} = \frac{p_T^2}{1 - y_{JB}} \qquad y_{JB} = \frac{(E - p^z)}{2E} \qquad x_{JB} = \frac{Q^2_{JB}}{s y_{JB}}$$

e+p:
18 x 275 GeV



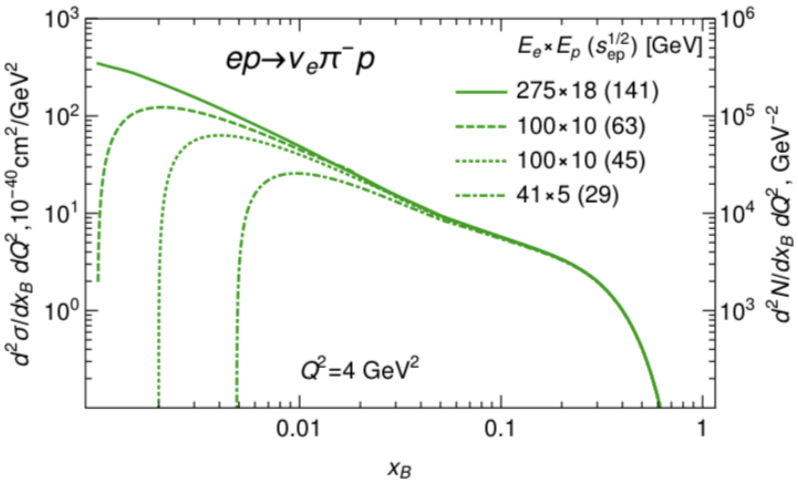
Hadrons – photons follow very similar distribution.



Nuc. Phys. A 1026, 122447 (2022)

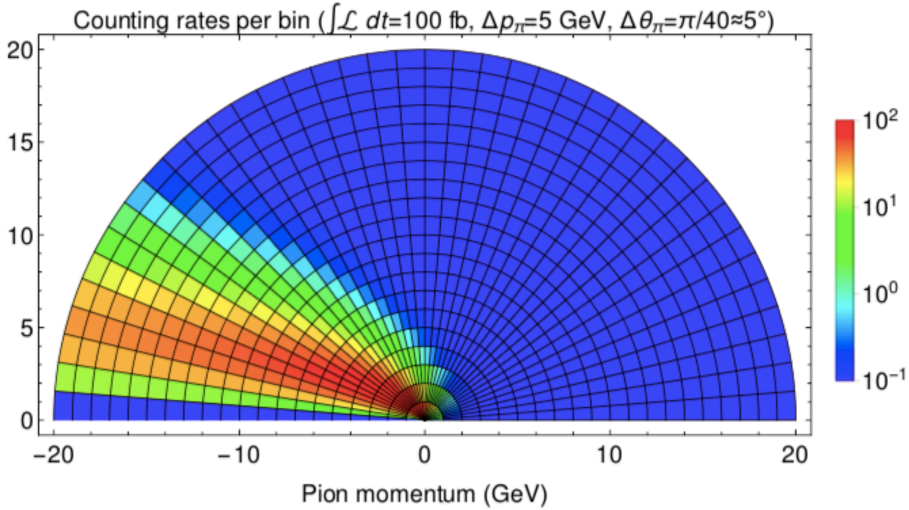
Charged currents in semi-inclusive & exclusive

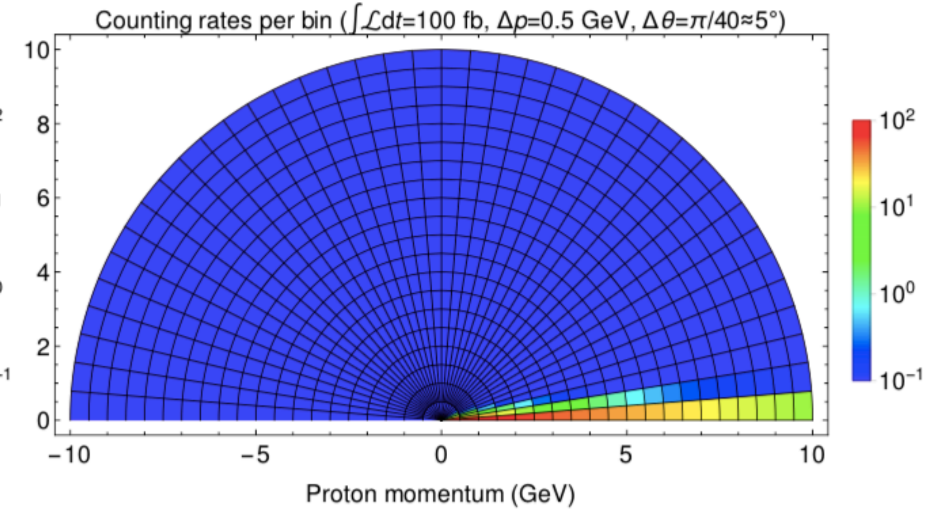
- Semi-inclusive charged current processes: jet-production for TMD extraction.
- Hard exclusive meson production via charged currents: access to GPDs.



$$ep \to \nu_e\, \pi^-\, p$$

Suppression of photoproduction background and that from misidentified quasi-elastic scattering hinges on kinematic cuts: excellent tracking resolution crucial.





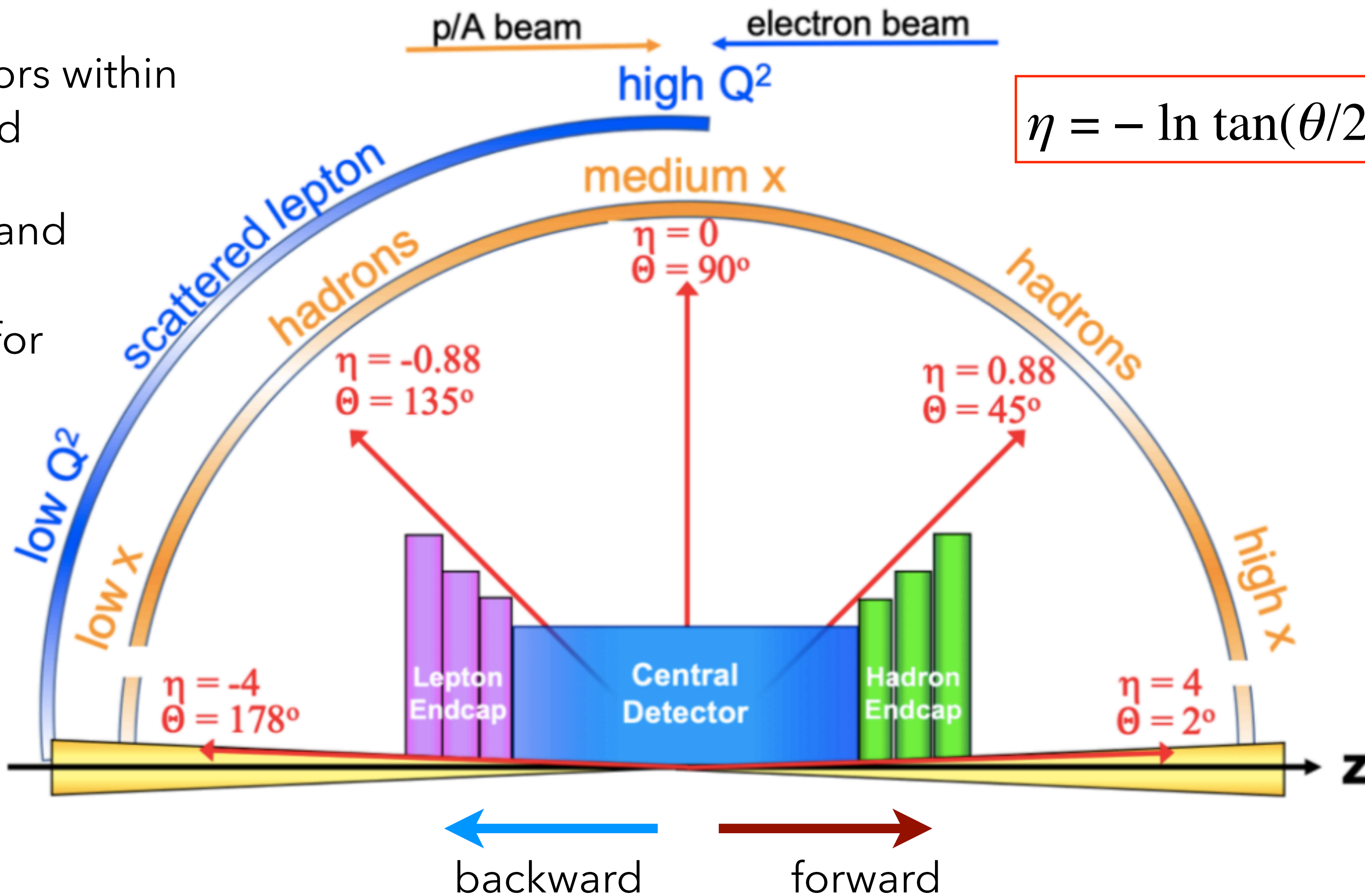
Detector configuration

Very asymmetric beams

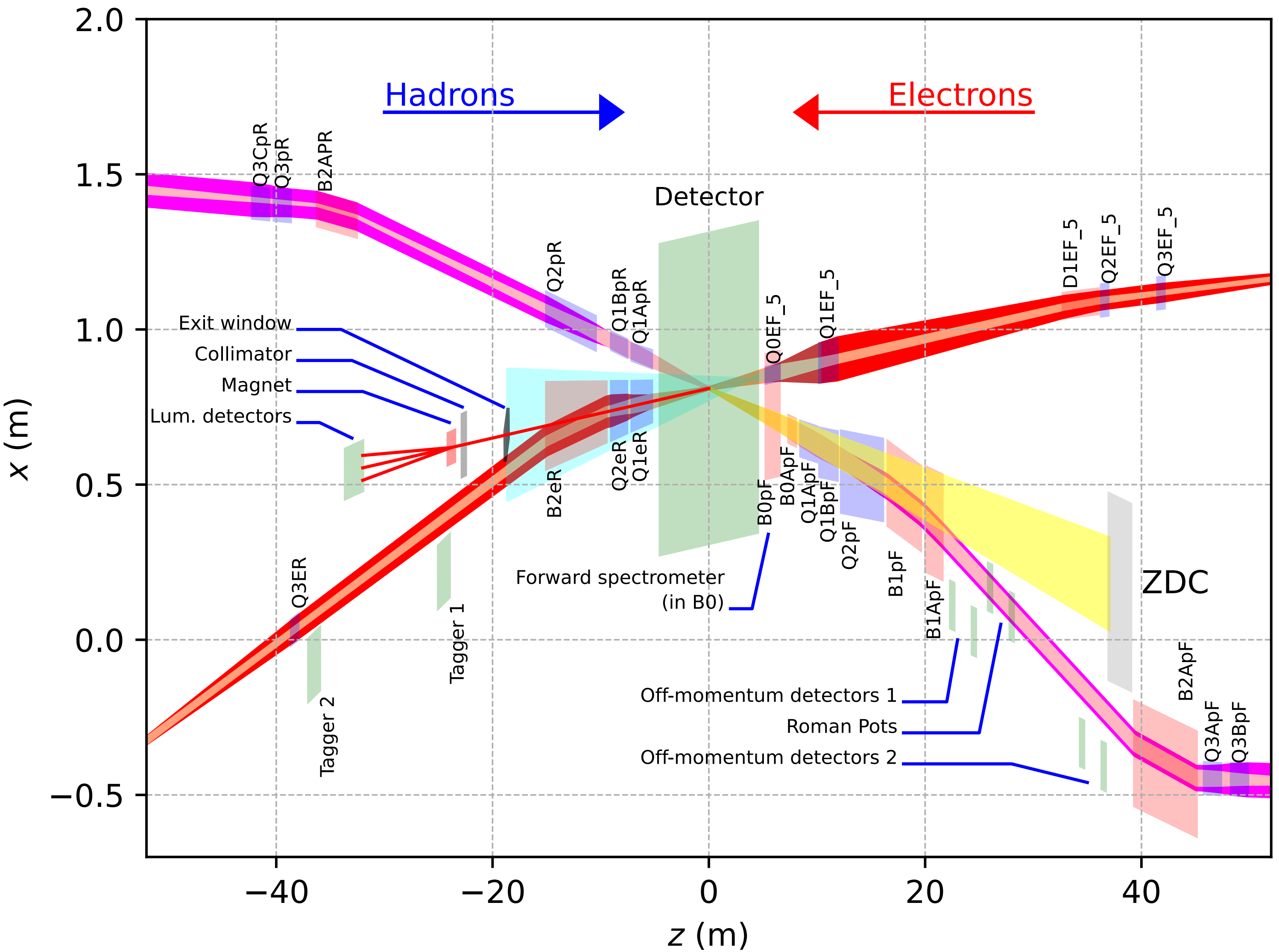
Hermetic detectors within a central solenoid

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

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



The Interaction Region @ IP6



Crossing angle for the beams: 25 mrad.

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

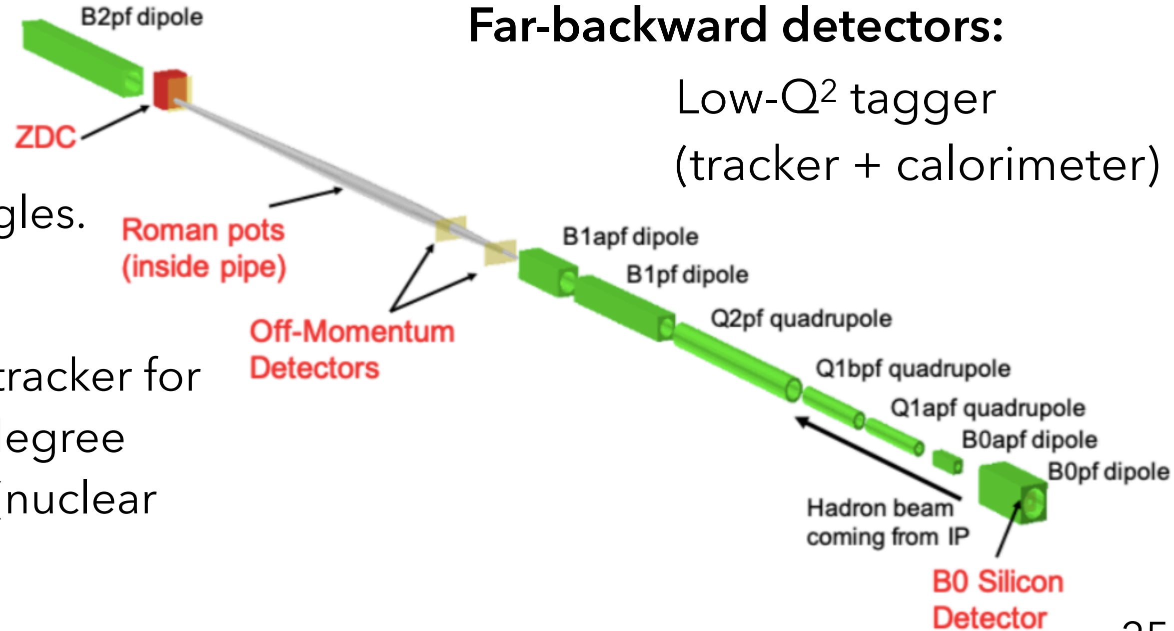
Barrel detector ($|\eta| < 1$) + two disc end-caps (forward/hadron end-cap and backward/electron endcap).

Far-backward detectors:

Low-Q^2 tagger (tracker + calorimeter)

Far-forward detectors:

Far from interaction point, very low angles.



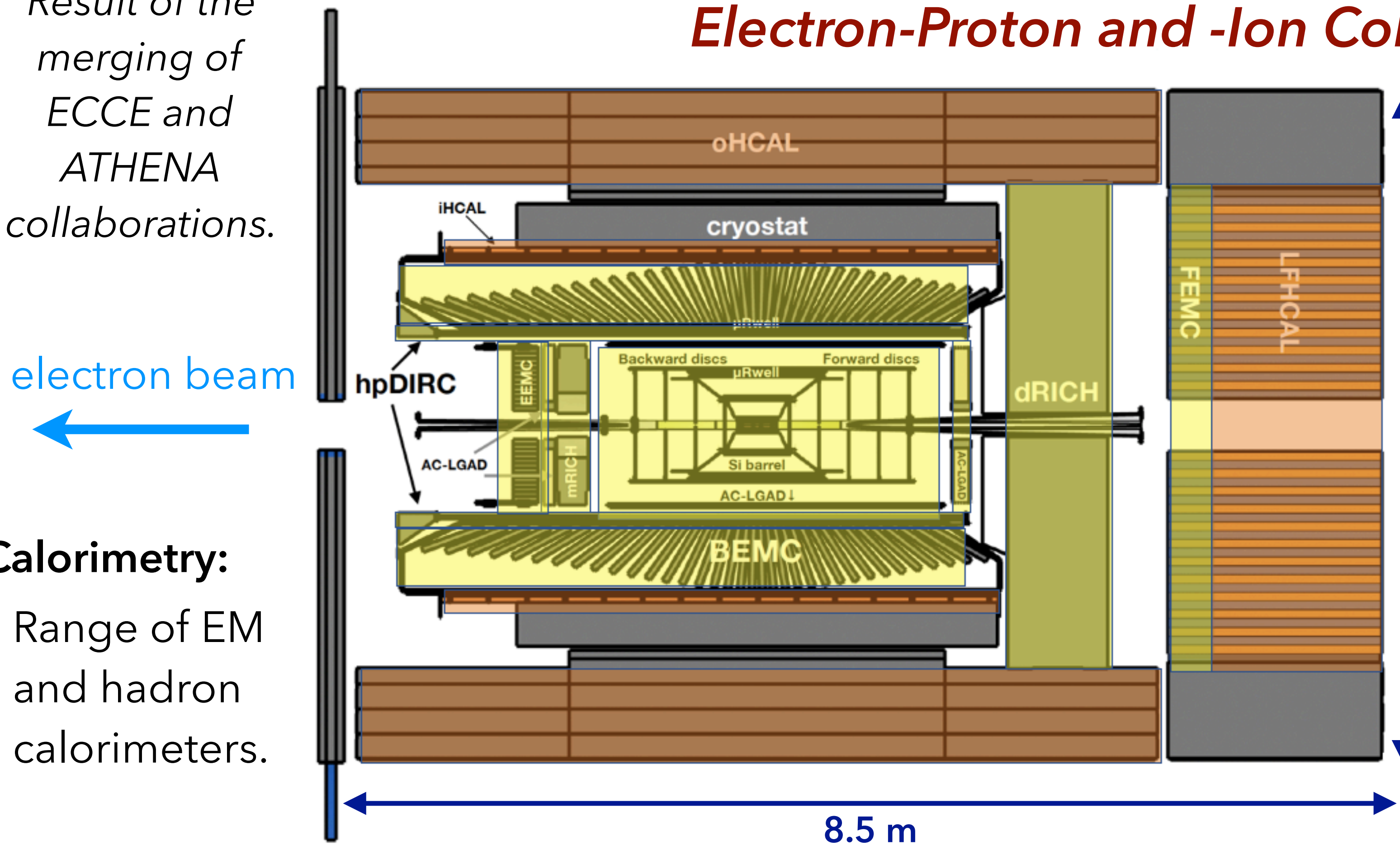
Roman Pots inside the beam pipe, B0 tracker for larger angles, large acceptance Zero degree Calorimeter (ZDC) to detect neutrons (nuclear breakup / neutral decay products)

The ePIC detector

Electron-Proton and -Ion Collider detector

Result of the merging of ECCE and ATHENA collaborations.

The "project detector" to be constructed at IP 6



Calorimetry:

Range of EM and hadron calorimeters.

Particle ID (PID):

~30ps Si (AC-LGAD) time-of-flight; Cherenkov detectors: RICH, DIRC.

Tracking: New 1.7 T magnet (MARCO)

Light-weight Si tracking (65nm MAPS), micro-pattern gaseous detectors (MPGDs).

The EIC Users Group

1386 members, 275 Institutes, 36 Countries

856 experimentalists, 355 theorists, 160 accelerator-scientists, 15 other

www.eicug.org

and growing…

Summary

- EIC for the moment is the only (imminent) facility to provide collisions of polarised ions and polarised electrons – expect first data in ~2032.

- EIC is the only facility to be built primarily for the study of QCD!

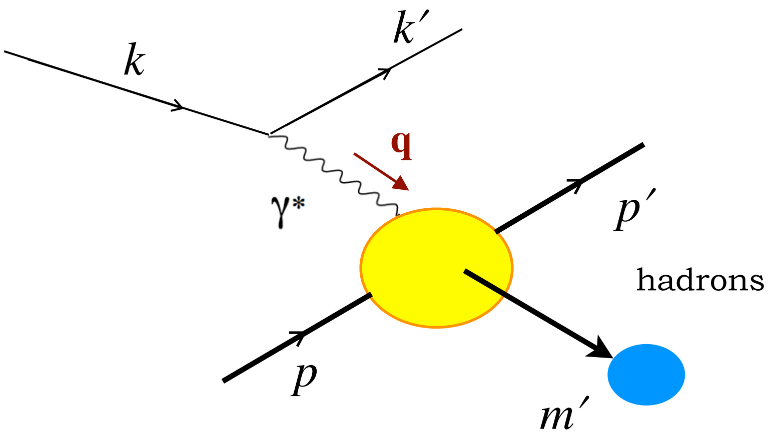
- Wide CoM energy range, high luminosity, hermetic multi-purpose detectors, triggerless data acquisition, possibility of measurement of a range of processes in electro- and photoproduction.

- First detector is ePIC – but a second detector is also intended!

- Possibilities of extracting gluon GPDs (gluon tomography, spin and pressure composition), accessing the trace anomaly for the composition of nucleon mass, probing gluon saturation, searching for exotics and much much more!

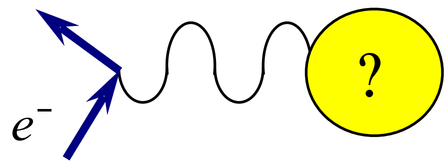

Thank you!
Any questions?

Kinematics in the Deep Inelastic regime

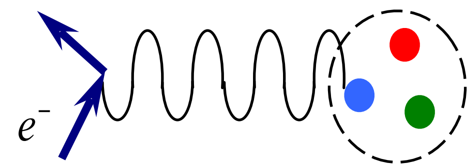


$$Q^2 = -q^2 = -(k - k')^2$$

virtuality of exchanged photon / resolution:



$Q^2 \sim MeV^2$



$Q^2 >> GeV^2$

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

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

Inelasticity: $y = \dfrac{q \cdot p}{k \cdot p}$ *defines also the polarisation of the virtual photon*

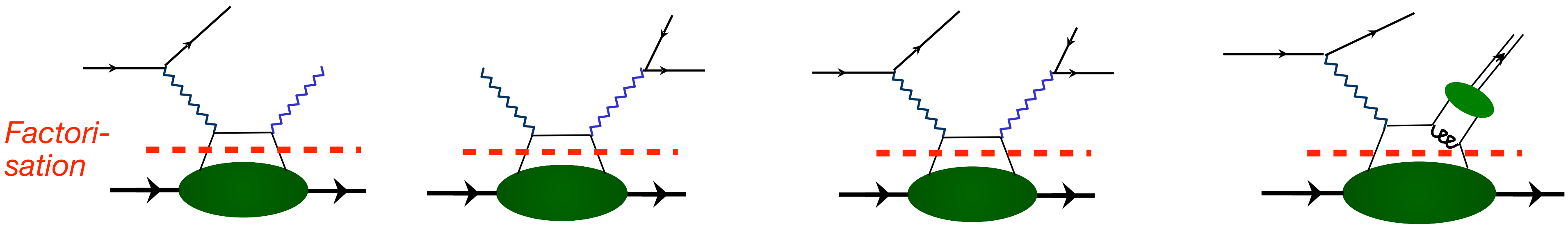
Experimental access to GPDs

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

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

See EIC Yellow Report for details

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



DVCS — *Virtual photon space-like*

TCS — *Virtual photon time-like*

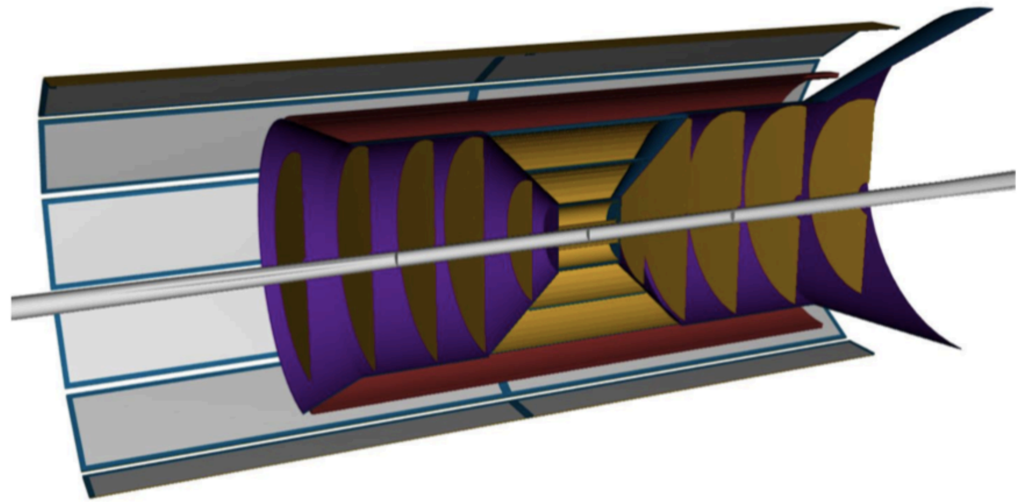
DDVCS — *One time-like, one space-like virtual photon*

DVMP — *Virtual photon space-like*

ePIC Tracking

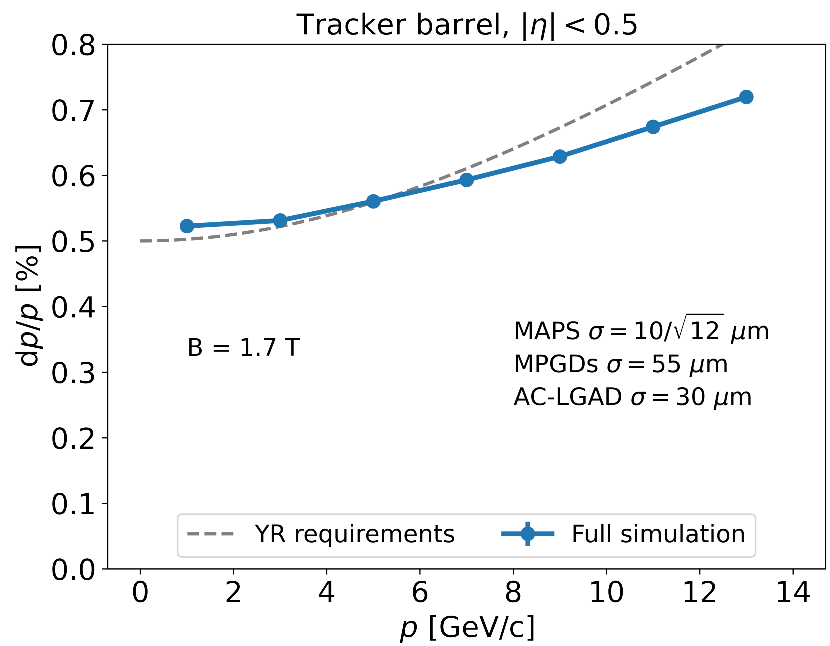
Current design:

- 5 barrel layers of Si: 2 vertex layers, 2 sagitta layers, one multi-purpose.
- 5 Si endcap disks at each end.
- MPGD barrel and forward layer outside the Si: to improve pattern recognition.
- 1 AC-LGAD ToF barrel layer and a hadron endcap disk.



Technologies:

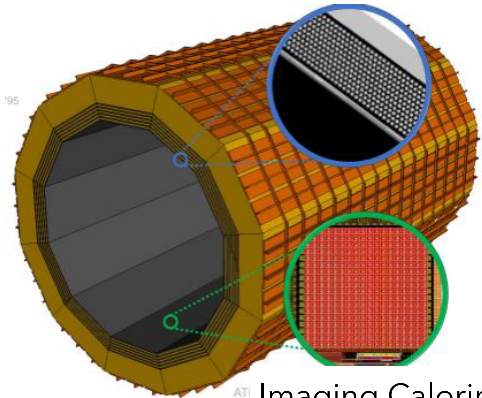
- Si tracking: 65nm MAPS technology, based on ALICE ITS3 upgrade development.
- MPGD: Cylindrical Micromegas, backup technology: µRWELL.



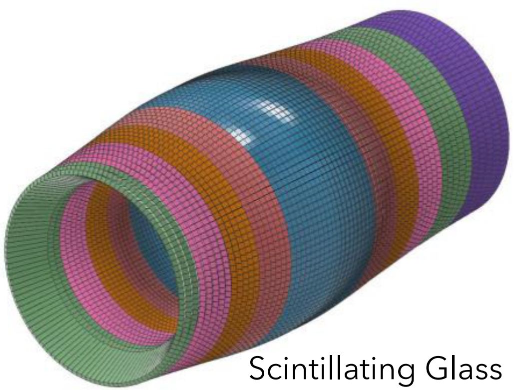
ePIC Calorimetry

EM Calorimeter

- Detection of photons, electron ID
- Barrel: either imaging calorimeter (6 layers of Si sensors (AstroPix) + 5 SciFi/Pb layers, large section of SciFi/Pb) or Scintillating Glass (based on PANDA design, readout with SiPMs).

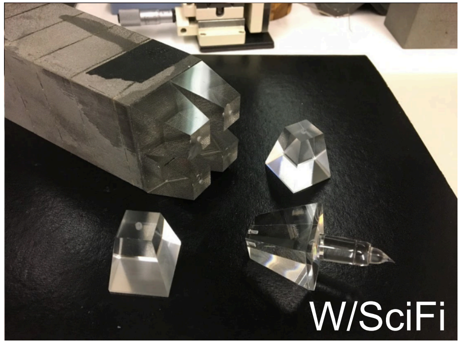


Imaging Calorimeter



Scintillating Glass

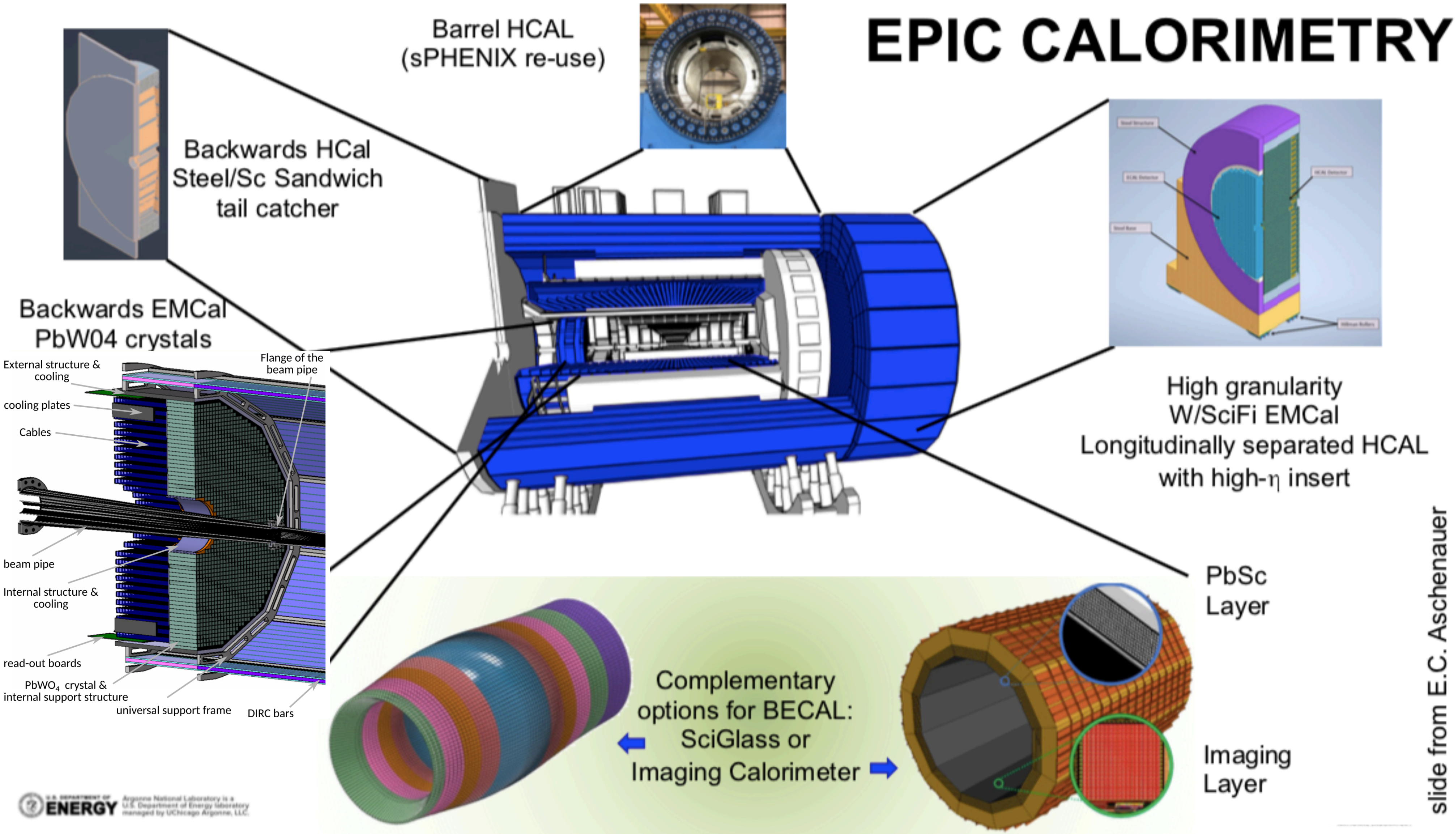
- Forward endcap: W/SciFi spacial
- Backward endcap: $PbWO_4$ crystals



Hadron Calorimeter

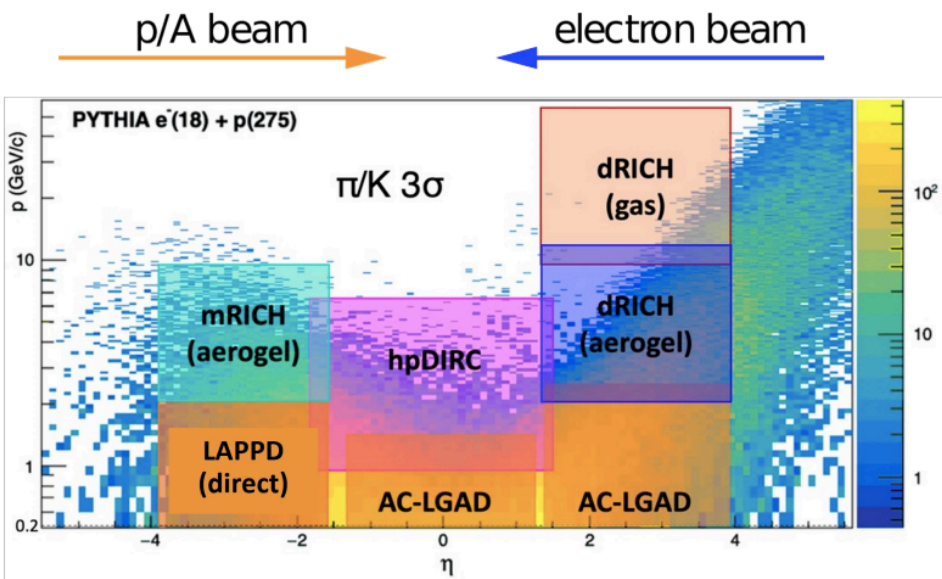
- Charged hadrons, neutrons, K_L^0
- Fe/Sc sandwich: backward and barrel (outside solenoid).
- Fe/Sc and W/Sc: forward endcap.
- Forward endcap inset: Sci/ Fe+W sampling calorimeter.

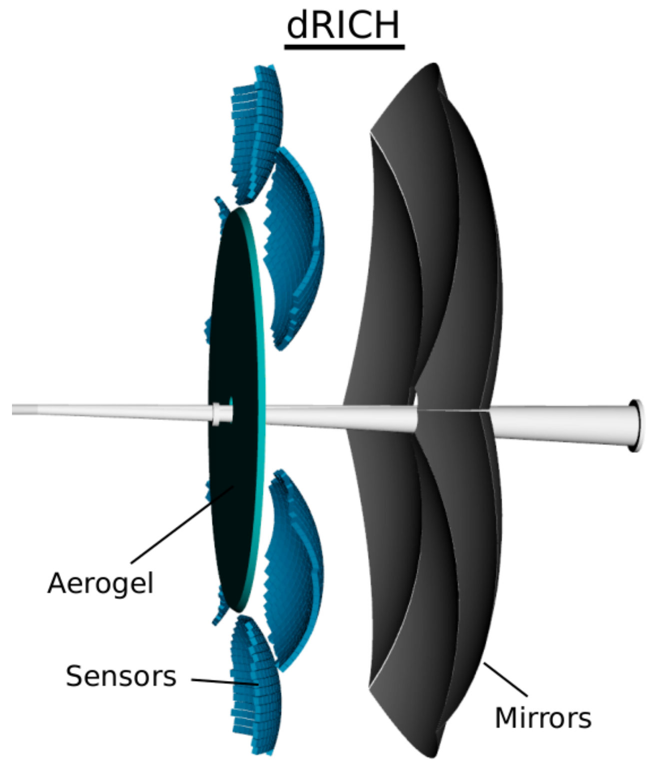
EPIC CALORIMETRY



Cerenkov and AC-LGAD ToF PID

- Barrel: hpDIRC (high-performance DIRC), fused-silica radiator, 3σ π/K separation up to ~6 GeV
- Forward endcap: dRICH (dual-RICH): aerogel + C_2F_6 gas
- Backward endcap (both using aerogel):
    - mRICH (modular RICH): compact, Fresnel lens focussing
    - pfRICH (proximity-focussing RICH): gas threshold-based electron ID, requires expansion volume





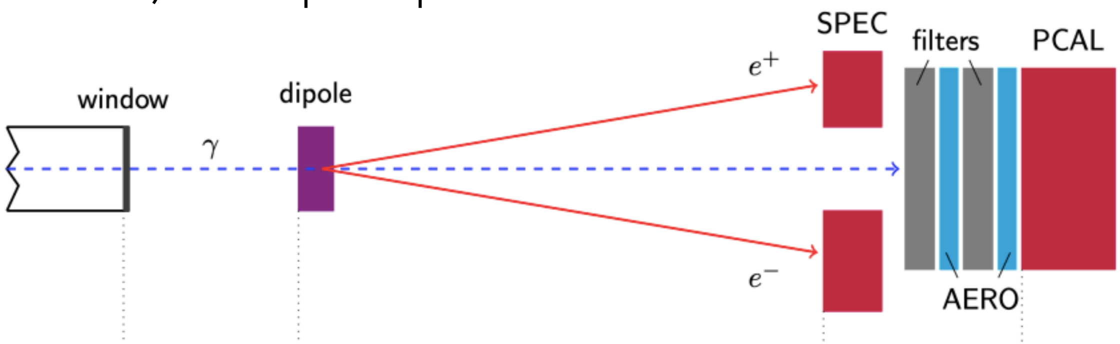
- Barrel and Forward AC-LGAD ToF: improves tracking resolution when a hit in a Si layer is missing

Far-backward detectors

Luminosity Monitors:

- Use Bremsstrahlung
- Accuracy of 1% or better than 10^{-4} precision on relative luminosity of different bunch crossings.
- Direct photon detector (calorimeter) and a pair-spectrometer

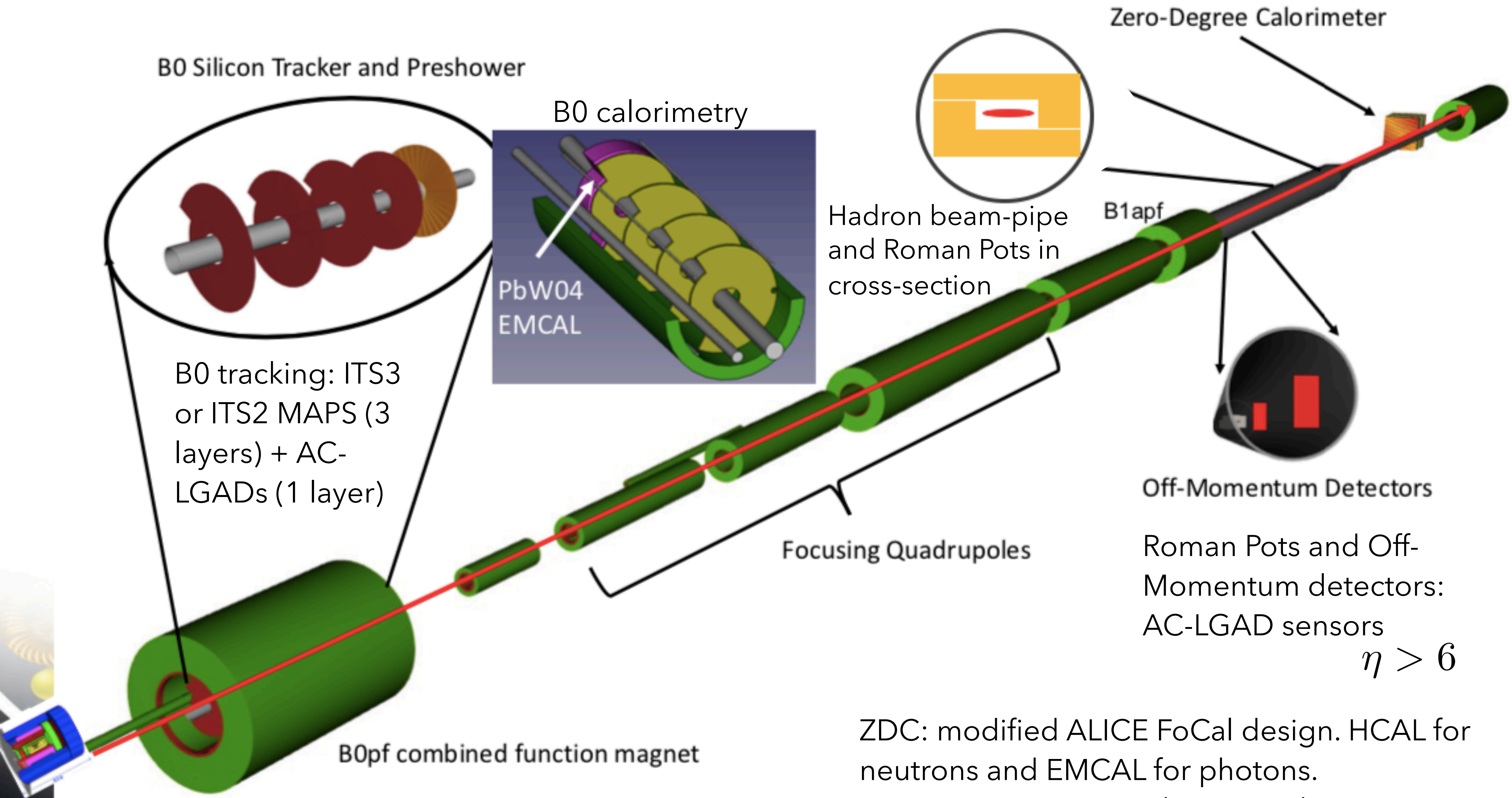
Modification of the HERA II design:



Low-Q2 Taggers:

- Two Tagger stations, in the primary vacuum (θ_e < 10 mrad)
- Each tagger: tracking layers (MAPS or AC-LGAD sensors, Timepix4 + i-LGAD)
- Calorimeter: under consideration, possible technologies PbWO4, sampling W/SciFi, quartz fibres or W-Si.
- Photoproduction signal, above region of Bremsstrahlung: $10^{-3} < Q^2 < 10^{-1}$

Far-forward detectors



Roman Pots and Off-Momentum detectors: AC-LGAD sensors

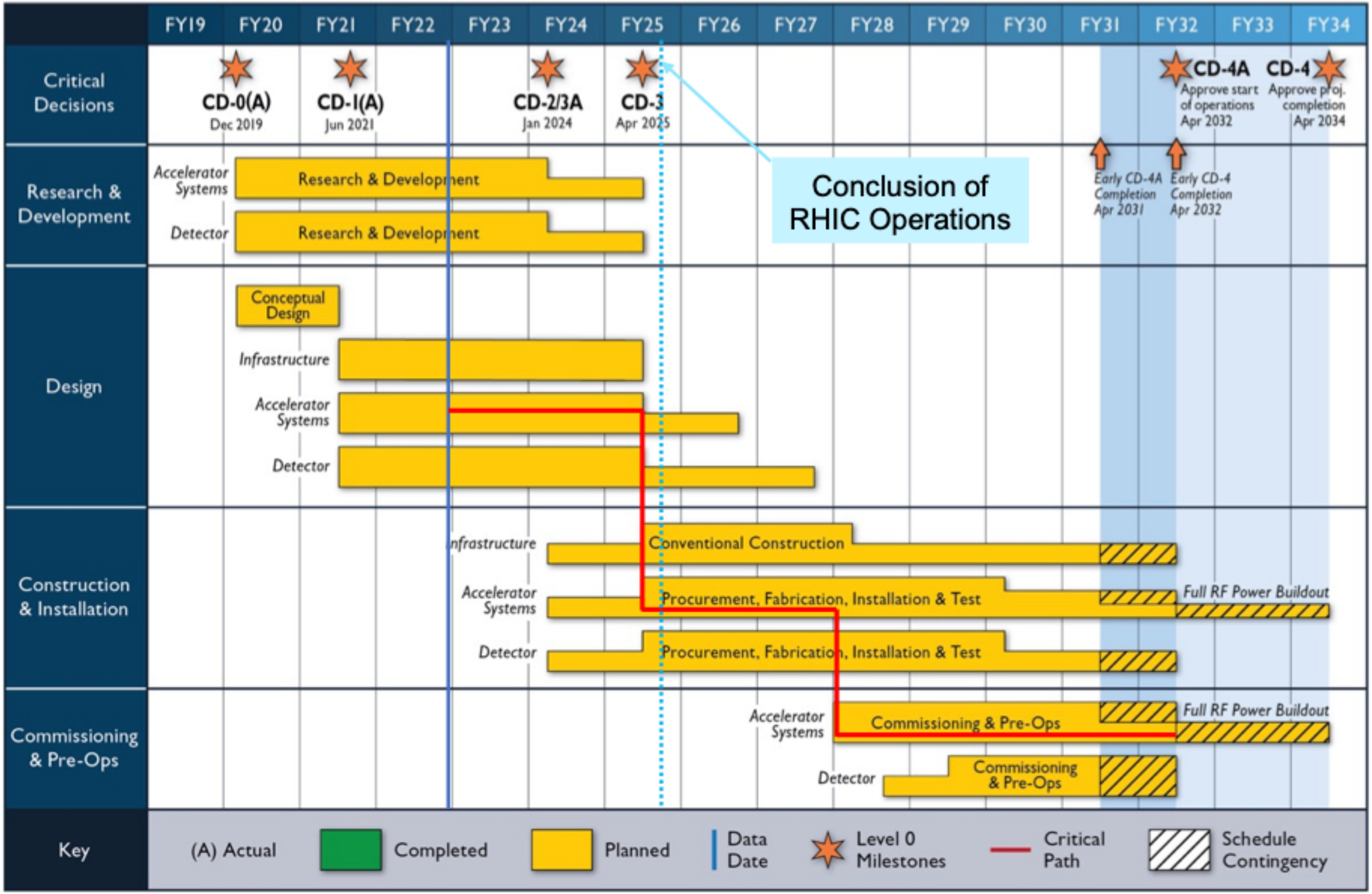
$\eta > 6$

ZDC: modified ALICE FoCal design. HCAL for neutrons and EMCAL for photons. Acceptance: +4.5mrad, -5.5mrad.

$\eta > 6$

B0 acceptance: $4.6 < \eta < 5.9$

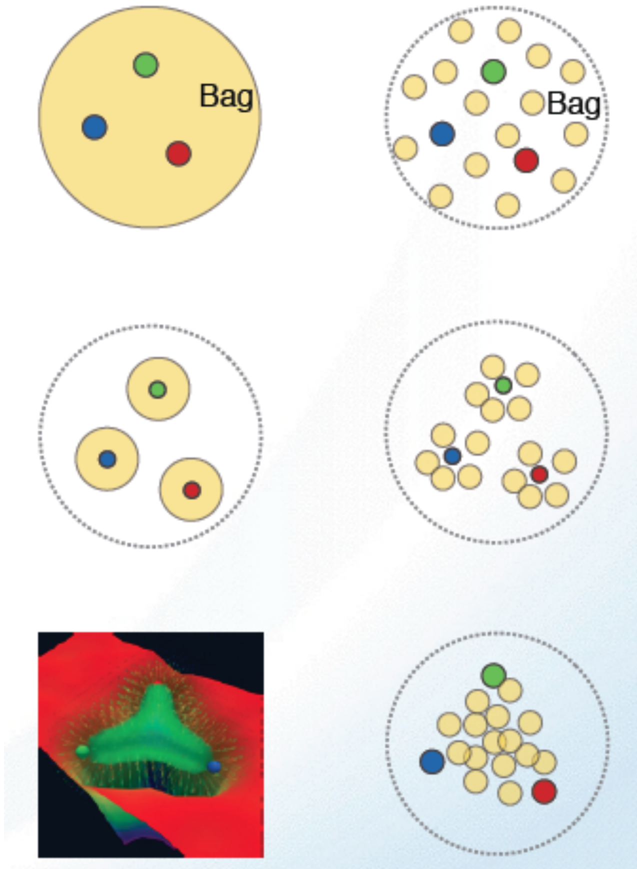
EIC Reference Schedule - V3



Slide: Rolf Ent

Interpretations of the nucleon

What do spatial distributions tell us?



Courtesy of A. Deshpande

Bag Model: Gluon field distribution is wider than the fast moving quarks.

Gluon radius > Charge Radius

Constituent Quark Model: Gluons and sea quarks hide inside massive quarks.

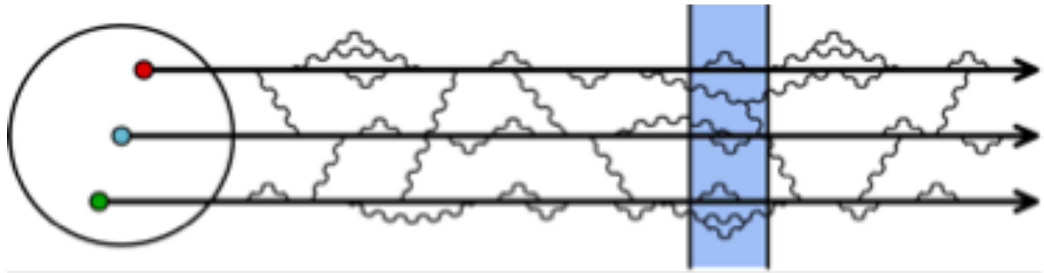
Gluon radius ~ Charge Radius

Lattice Gauge theory (with slow moving quarks), gluons more concentrated inside the quarks:

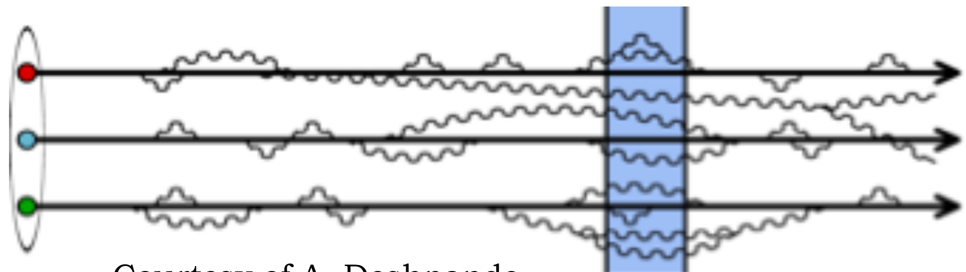
Gluon radius < Charge Radius

Need transverse images of the quarks and gluons in confinement: form factors

Runaway glue



- Nucleon probed at low Q^2, high x.



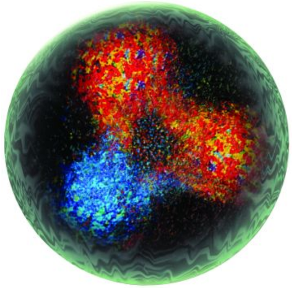
- Nucleon probed at large Q^2, low x.

Courtesy of A. Deshpande

- Gluons are charged under colour: can generate (and absorb) other gluons.

- Nucleon probed at high energies, time dilation of strong interaction processes: gluons appear to live longer, emitting more and more gluons. Runaway growth! Runaway growth?

Images of the nucleon

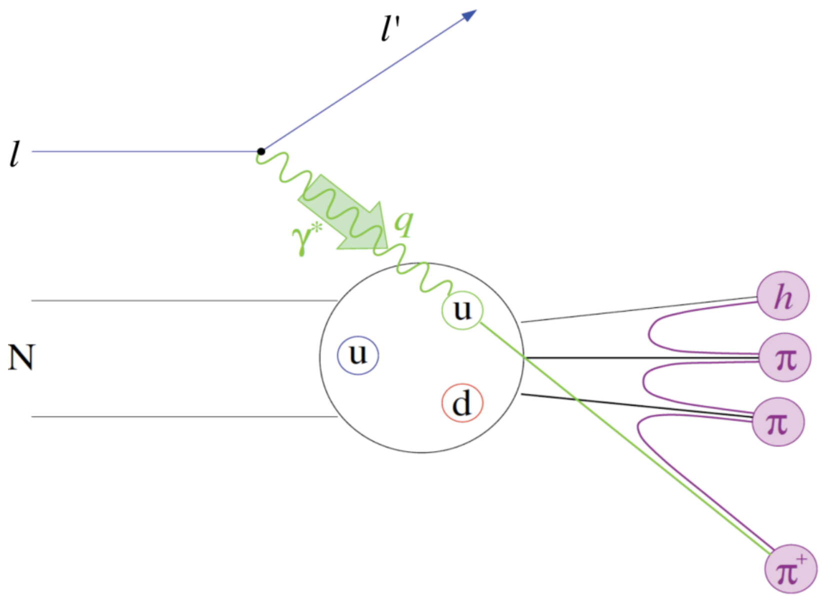


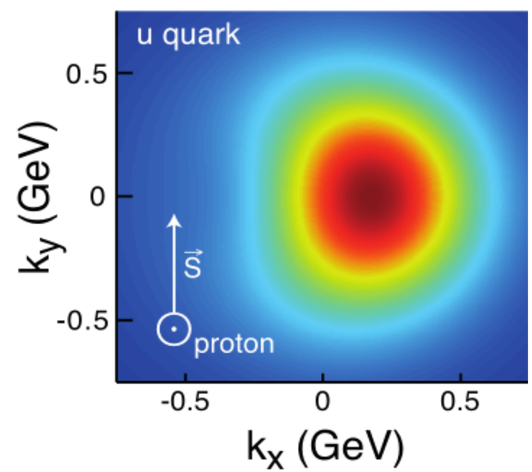
Wigner function:
full phase space parton distribution of the nucleon

$$\int d^2 b_T$$

Transverse Momentum Distributions (TMDs)

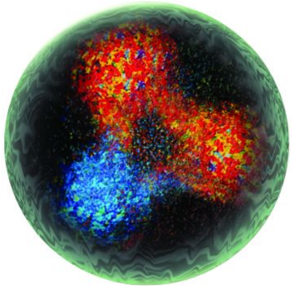
* Semi-inclusive Deep Inelastic Scattering (SIDIS)





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

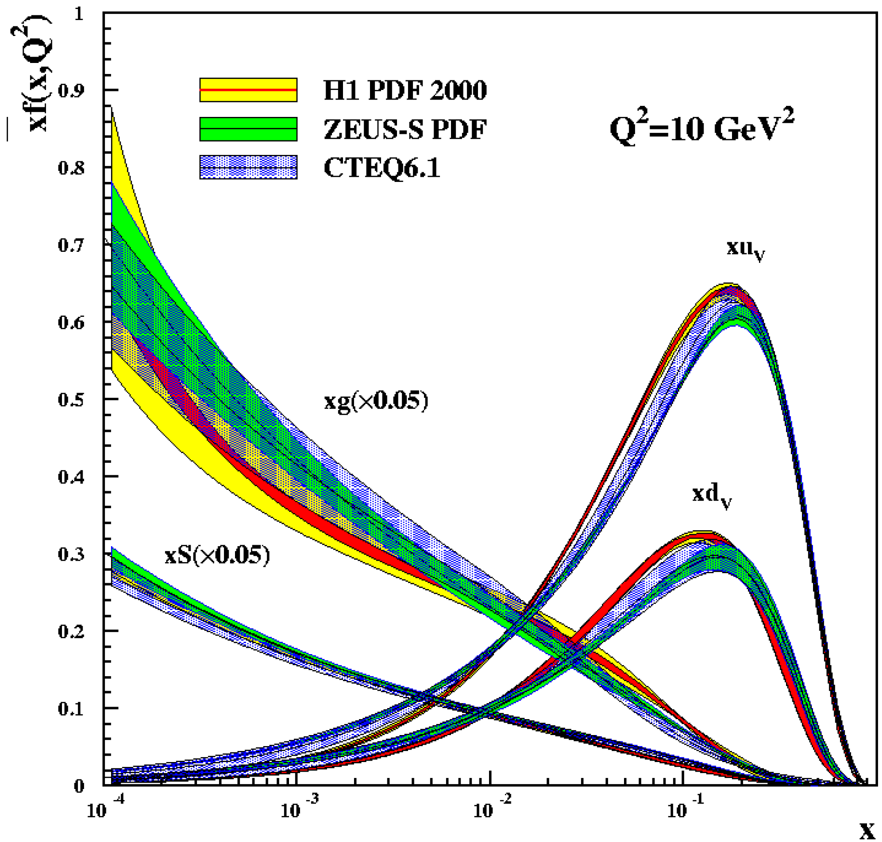
Images of the nucleon



Wigner function:
full phase space parton
distribution of the nucleon

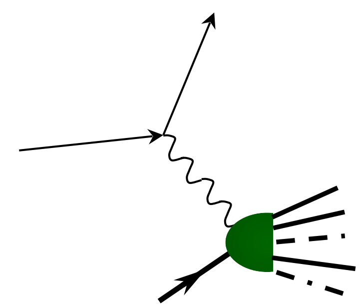
$$\int d^2 b_T$$

Transverse
Momentum
Distributions
(TMDs)



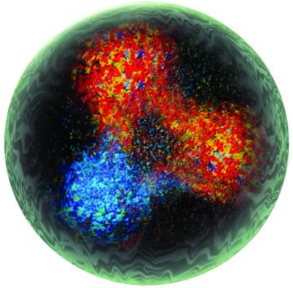
$$\int d^2 k_T$$

Parton Distribution
Functions (PDFs)

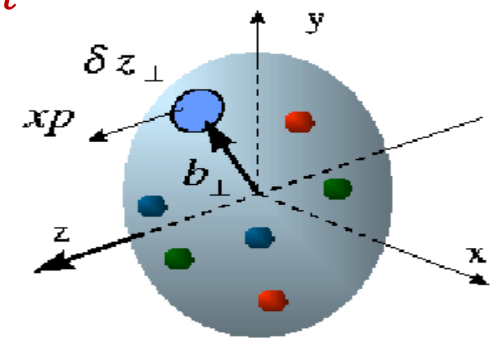


* Deep Inelastic
Scattering (DIS)

Images of the nucleon



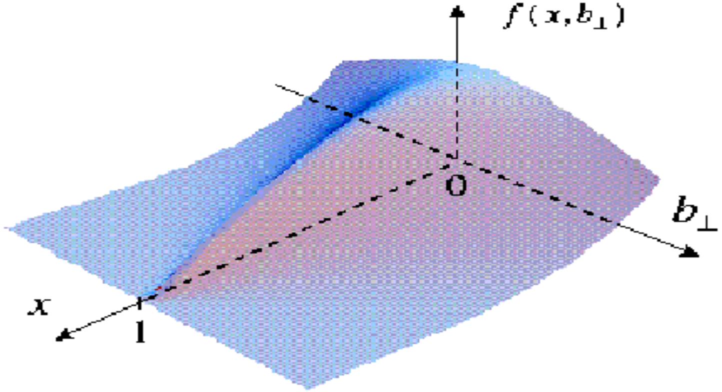
Wigner function:
full phase space parton distribution of the nucleon



$\int d^2 k_T$

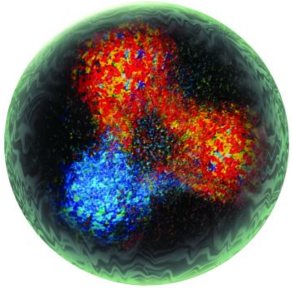
Generalised Parton Distributions (GPDs)

- 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.

Images of the nucleon

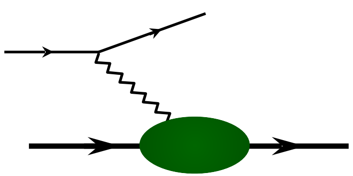


Wigner function: full phase space parton distribution of the nucleon

$$\int d^2 k_T$$

Generalised Parton Distributions (GPDs)

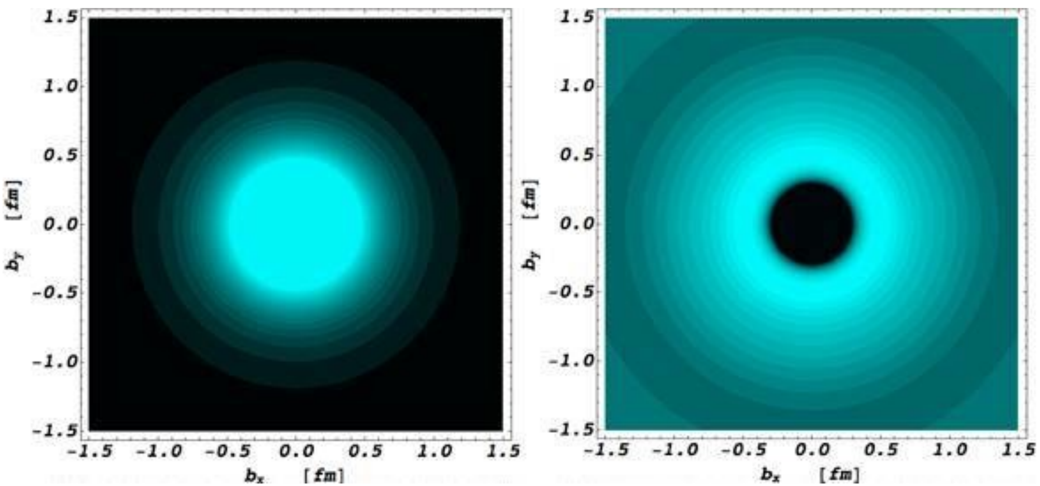
$$\int dx$$



Elastic scattering

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

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



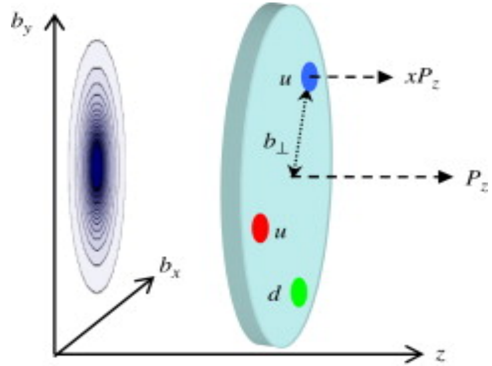
proton

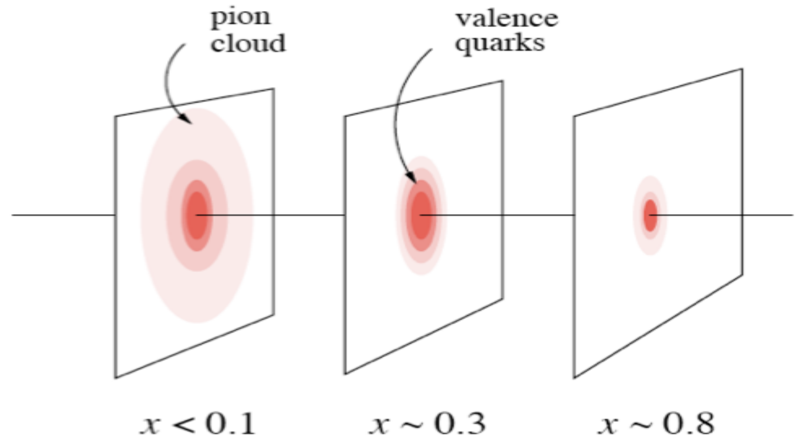
neutron

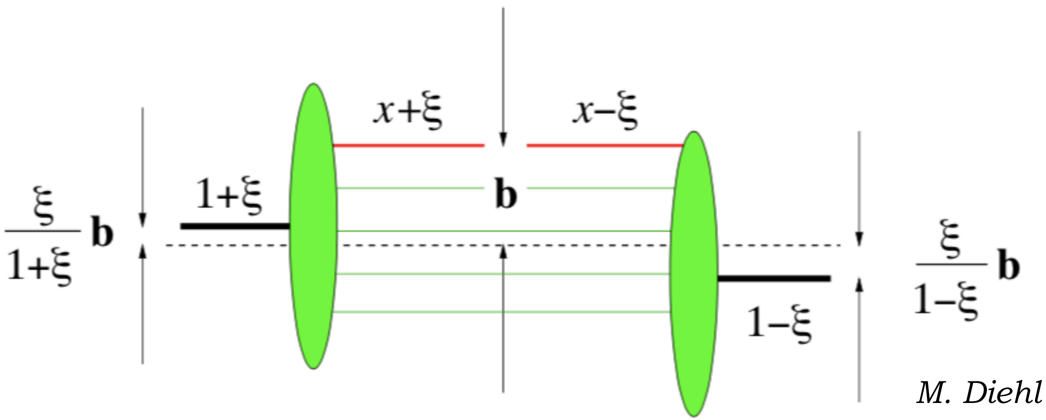
C. Carlson, M. Vanderhaeghen
PRL 100, 032004 (2008)

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.







M. Diehl

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

Experimentally, look for the t-dependence of structure functions (from meson-production) or Compton Form Factors (from DVCS/TCS).

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: $\Delta(t) \propto d_1(t)$

Trace anomaly

Composition of proton mass: quark energy, gluon energy, quark mass and **trace anomaly:** $M_a = \frac{1}{4}(1 - b) M_N$

EPJC 80 (6) (2020) 507

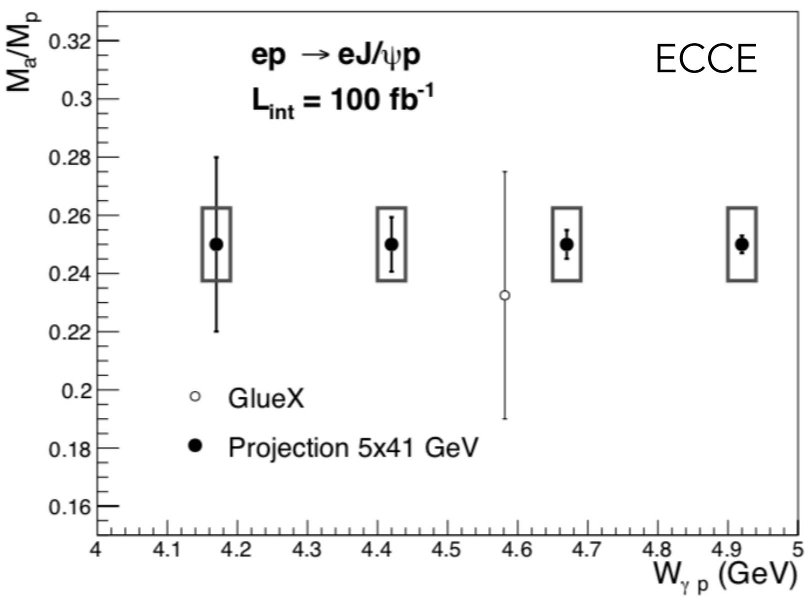
Assuming Vector Dominance Model:

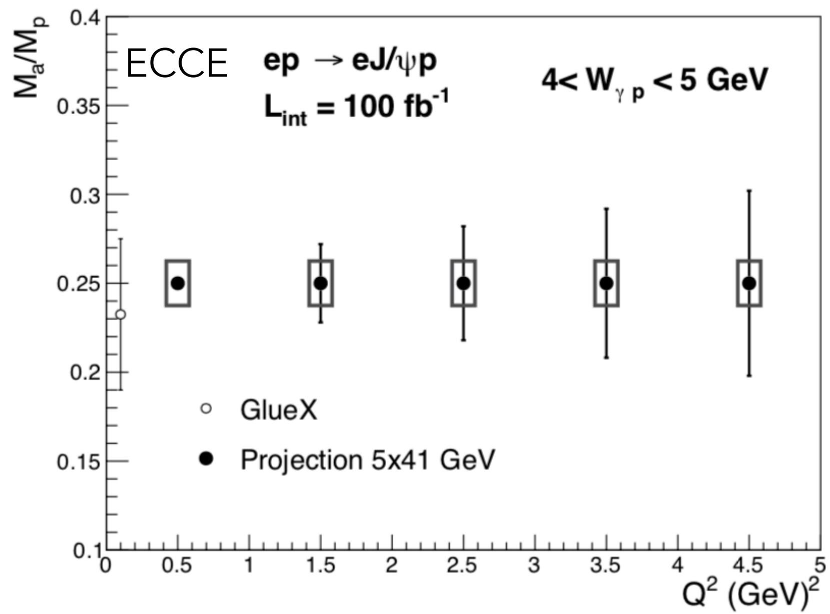
$$\left.\frac{d\sigma_{J/\Psi N \to J/\Psi N}}{dt}\right|_{t=0} = \frac{1}{64\pi} \frac{1}{m^2_{J/\psi}(\lambda^2 - m_N^2)} |F_{J/\Psi N}|^2$$

nucleon energy in charmonium rest-frame

At low energy:

$$F_{J/\Psi N} \simeq r_0^3 d_2 \frac{2\pi^2}{27} 2M_N^2 (1-b)$$





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?

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.

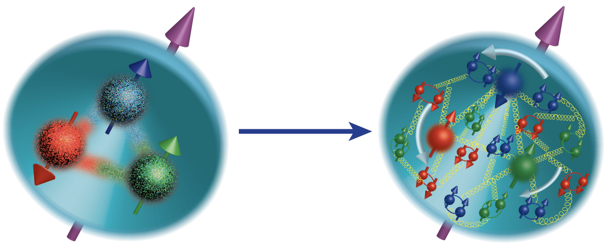
Caveat:

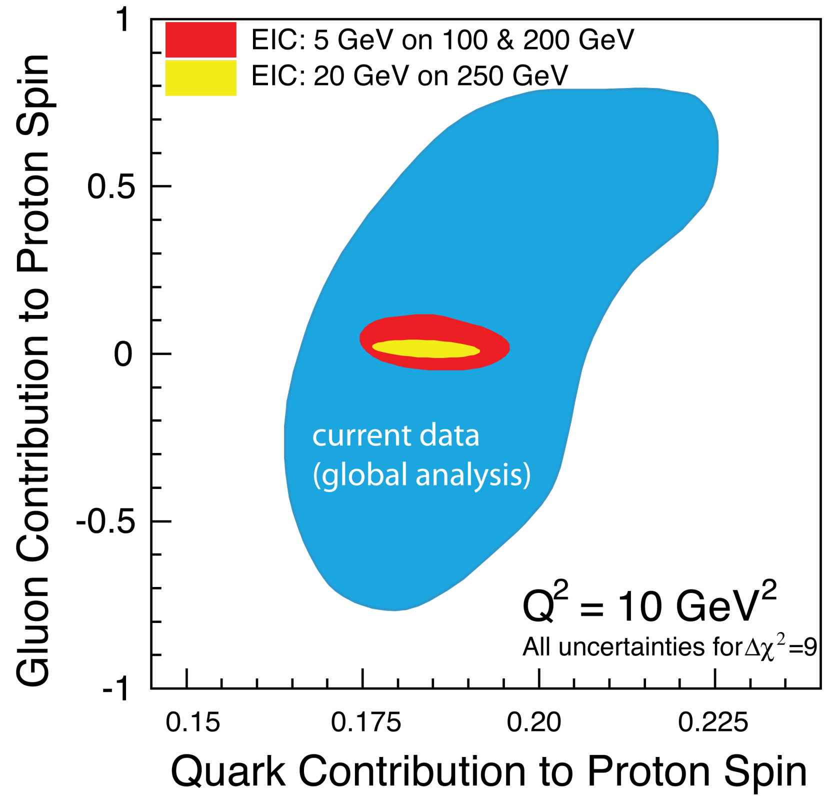
In Ji's decomposition of nucleon spin, the gluon spin and OAM terms cannot be separated.

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?

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

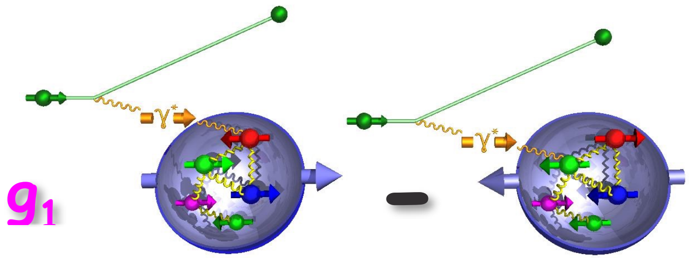




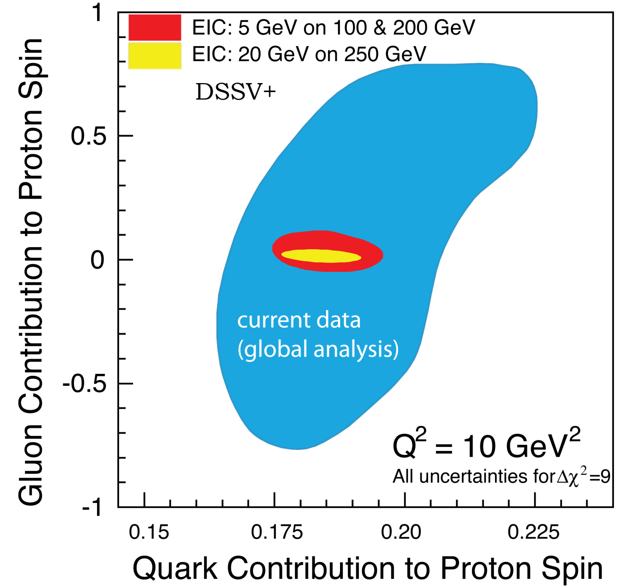
- 3D imaging of hadrons across the widest range of scales.

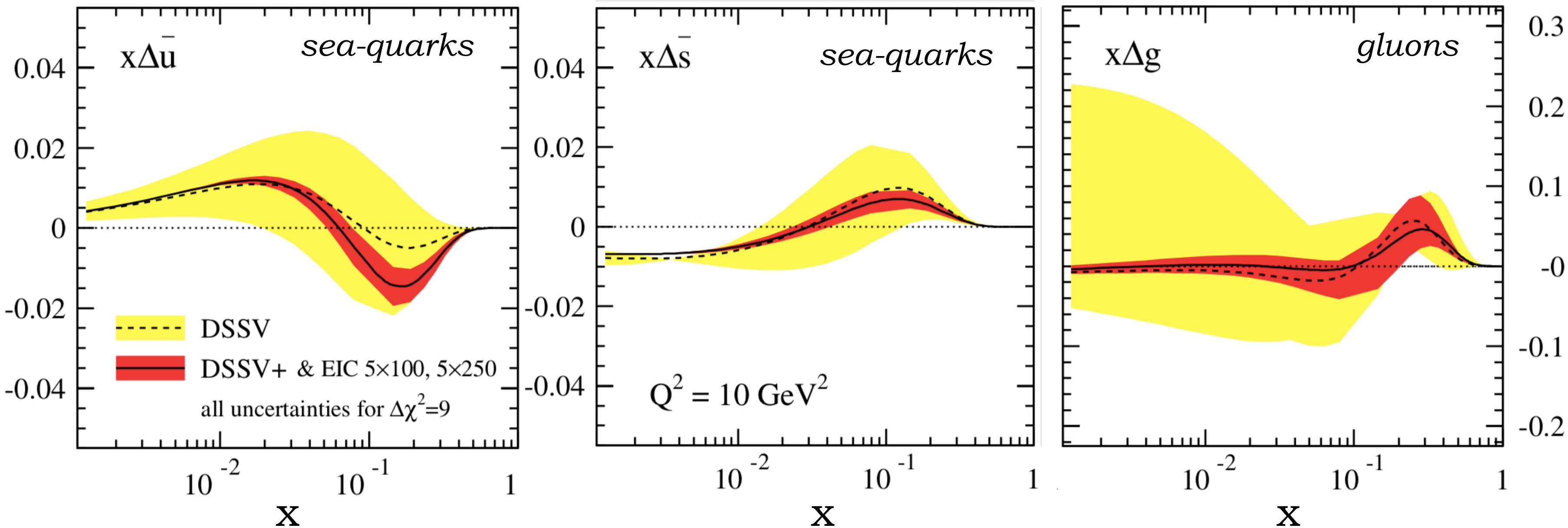
Gluon spin

* DIS and SIDIS will contribute extremely precise measurements of the helicity distributions of sea-quarks and gluons.



$$\Delta\Sigma(Q^2) = \int_0^1 g_1(x,Q^2)\,dx = \int_0^1 \Delta q_f(x,Q^2)\,dx$$





E. Aschenauer *et al.*,
Phys. Rev. D 86, 054020 (2012)

DSSV: D. de Florian, R. Sassot, M. Stratmann, W. Vogelsang, Phys. Rev. **D 80**, 034030 (2009).

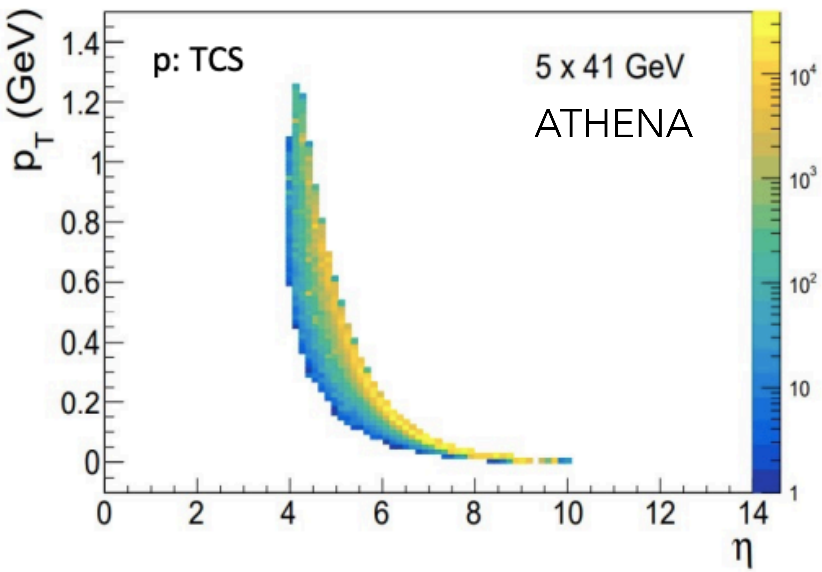
DSSV+: arXiv:1112.0904 [hep-ph]

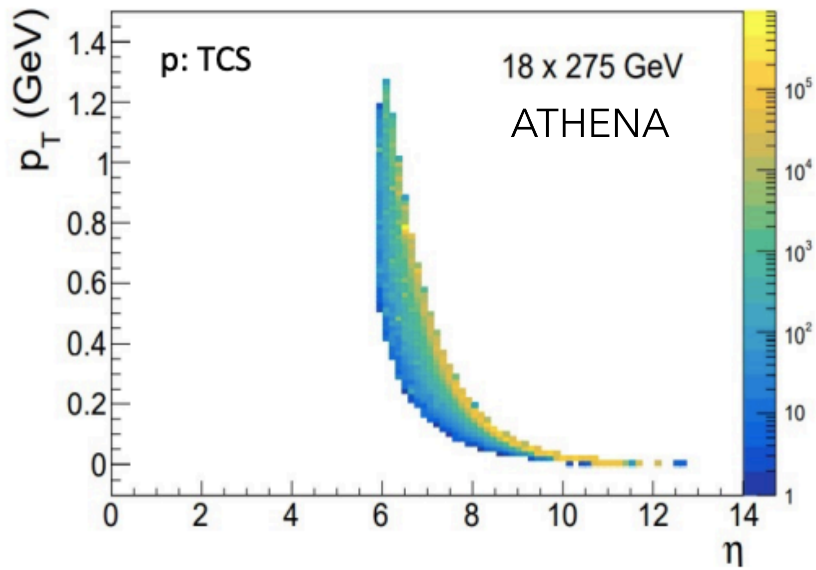
Recoil protons in *ep*

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

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

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





Note: produced particle collinear, carries off most longitudinal momentum. So almost all t corresponds to a transverse kick of the proton / ion.

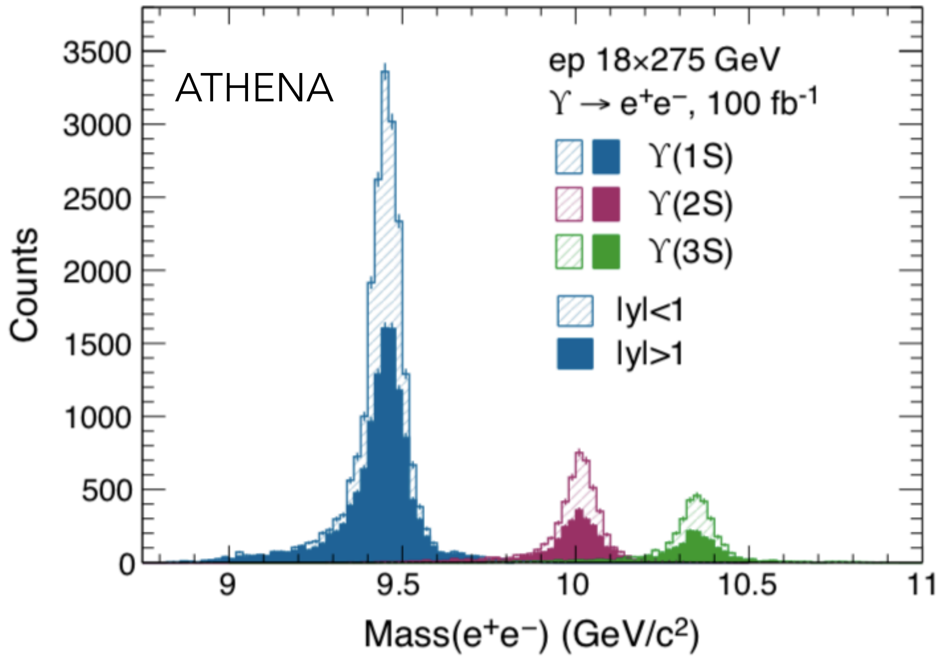
Quarkonium production

- Sensitivity to 3D gluon distributions (via Generalised Parton Distributions)

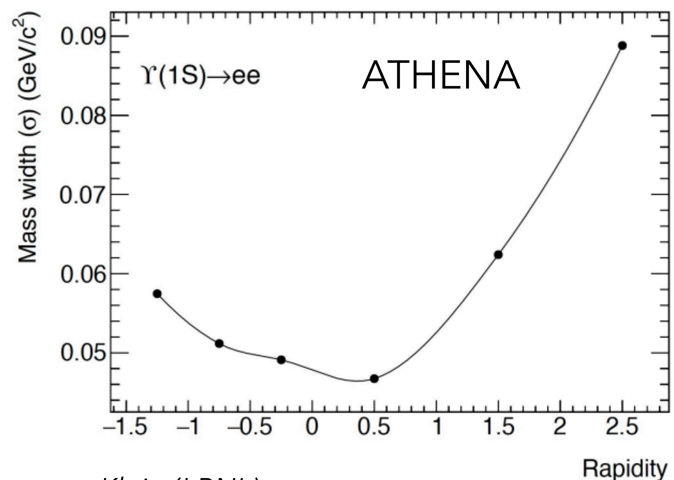
Near-threshold production in particular:

- Information on colour correlations
- Quarkonium-proton scattering lengths
- May act as a saturation probe (in eA)
- Sensitivity to the composition of proton mass via the trace anomaly.
- Photoproduction: sensitivity to gravitational form-factor? Perhaps not directly:

PRD 101 (11) (2020)114004, PRD 103 096010 (2021), PLB 822:10(2021), 136655



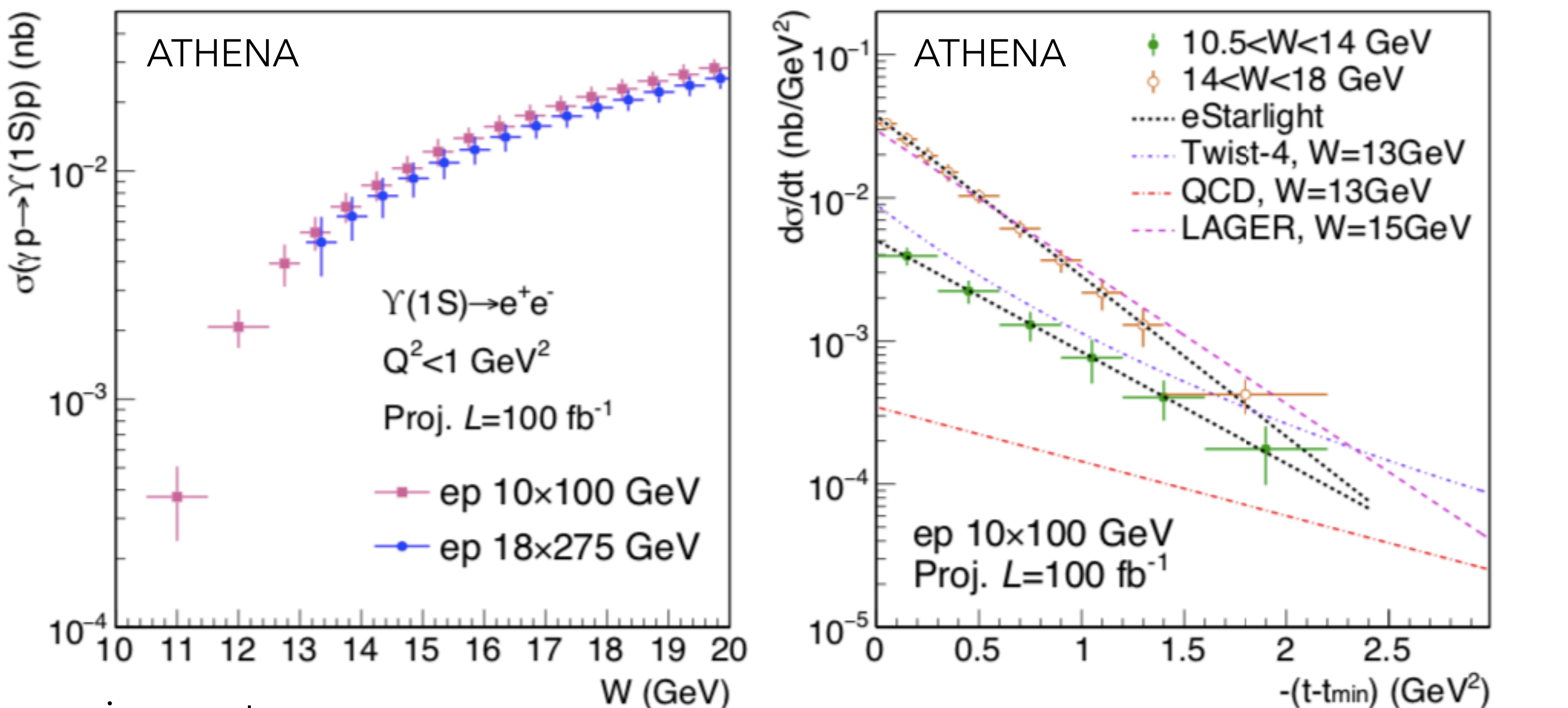
- Measurement requires good mass resolution (< 100 MeV) to separate Upsilon states.



Yuangjing Ji, Spencer Klein (LBNL)

At-threshold Upsilon photo-production

- Upsilon near-threshold production is little-known, twist-4 effects contribute significantly.

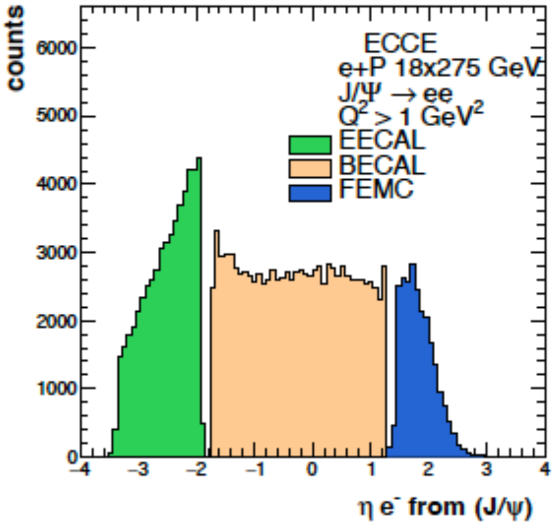


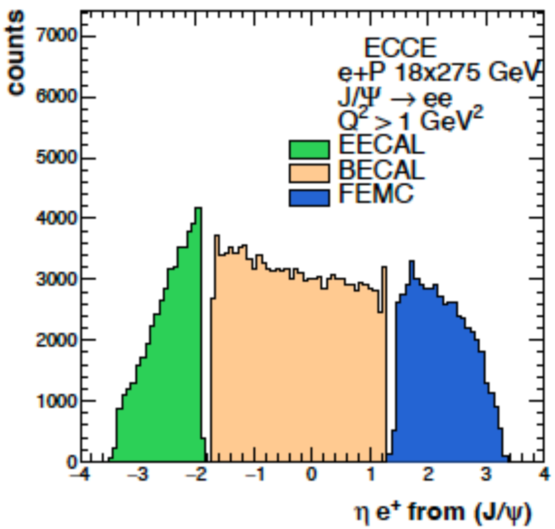
Detector requirements:

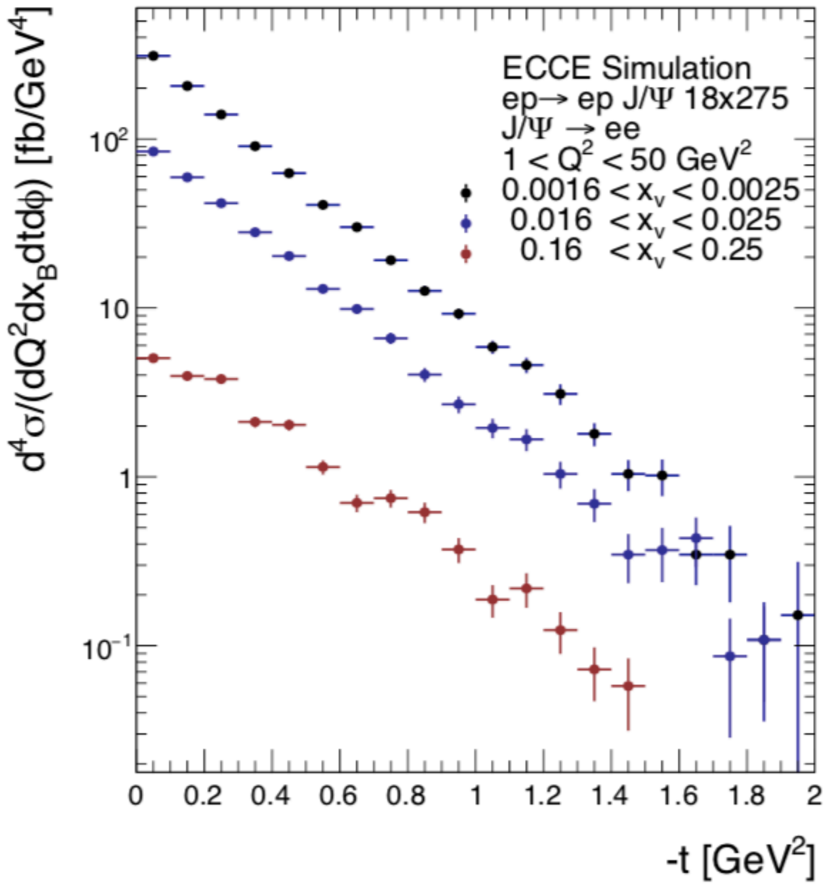
- Good t resolution.
- Good PID and momentum resolution to reject continuum (background suppression).
- Good rapidity coverage to reject events with other particles in final state.

Twist-4 : PLB 822:10(2021), 136655
QCD (GPD factorization) : PRD 103, 096010 (2021)
LARGER: PRD 102, 014016 (2020)

J/Psi production



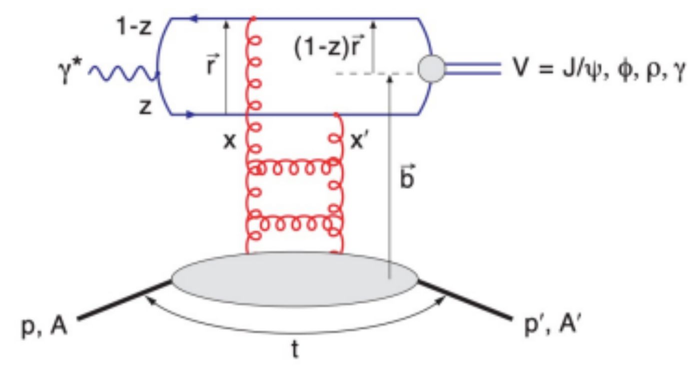




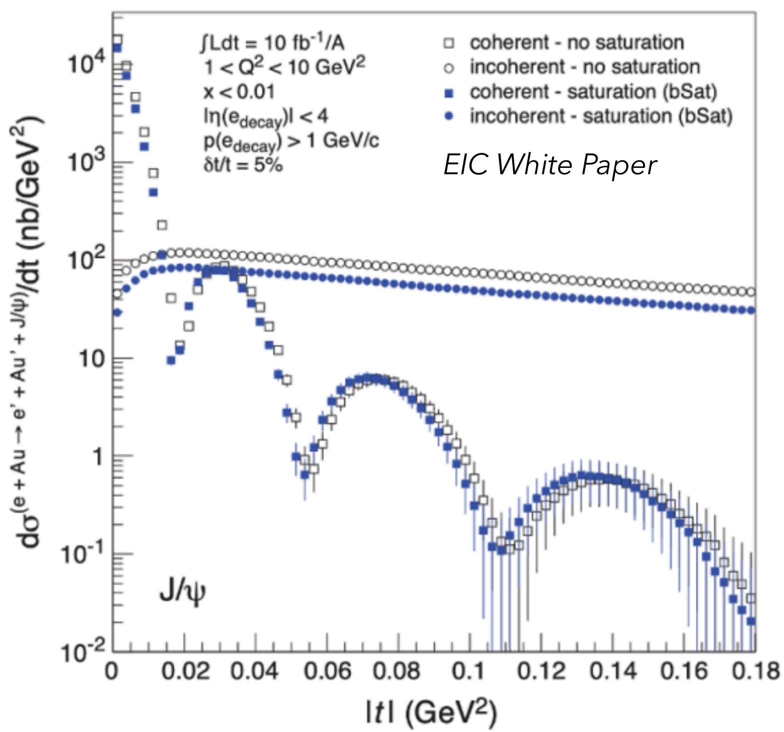
- Excellent acceptance coverage for J/Psi decay leptons
- Multi-dimensional binning possible

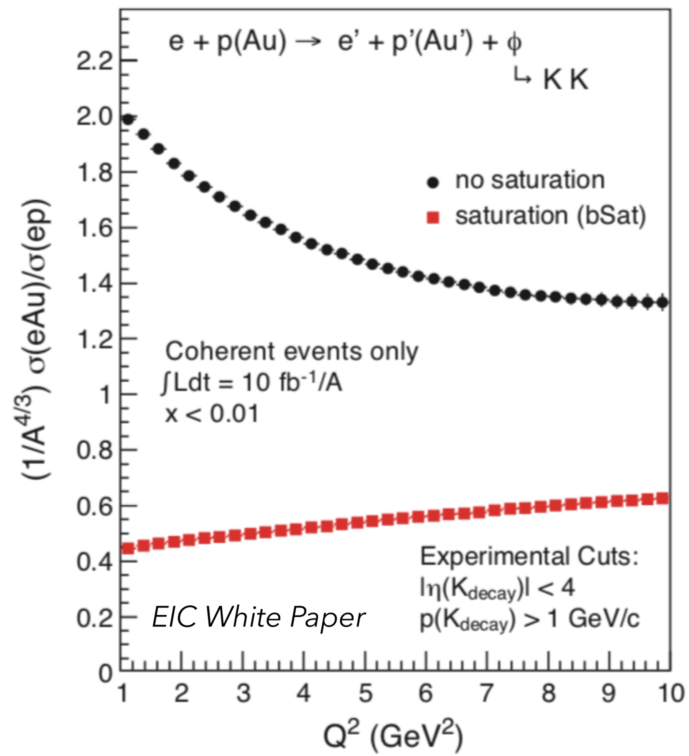
Coherent VM production in eA

- Gluon distributions in nuclei and a probe of gluon saturation.
- Detector challenge: reconstruct *t* from leptons and mesons, not from nuclei (these escape undetected): resolution is crucial to identify *t* minima.
- Incoherent backgrounds dominate greatly at anything other than the lowest *t*:



t ~ momentum transfer (kicks)

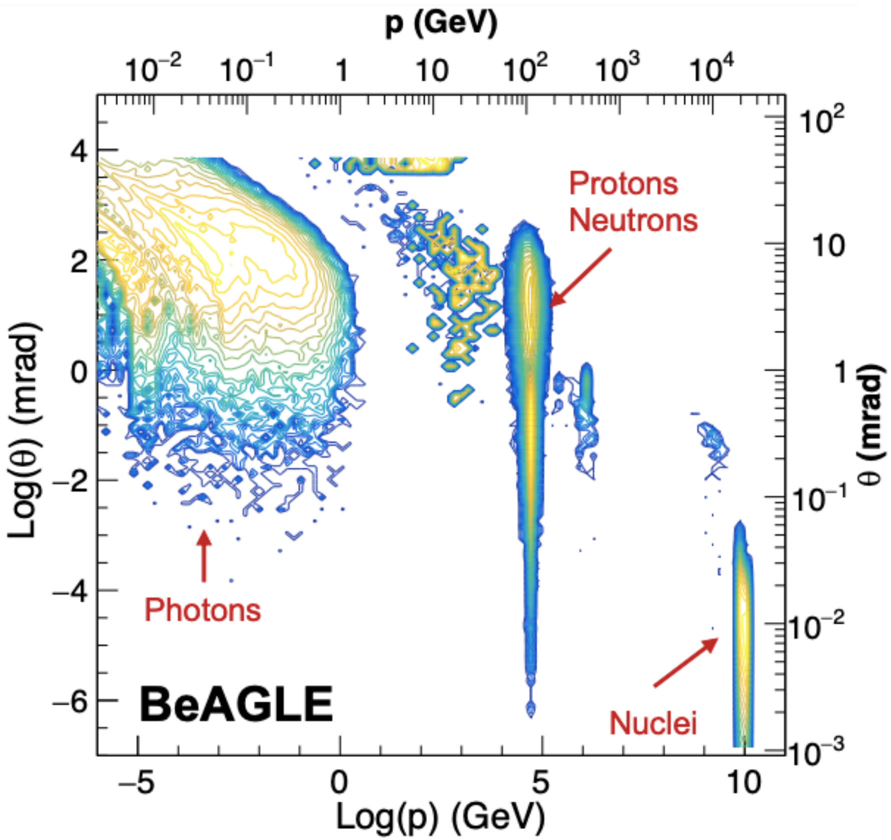


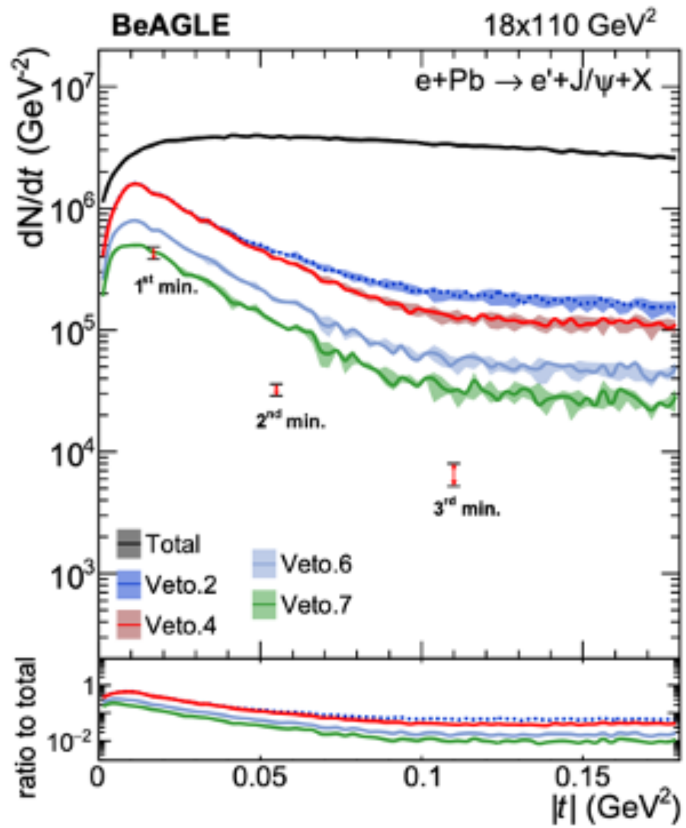


Incoherent backgrounds in eA

- Suppression of incoherent background by vetoing nuclear break-up in Far-Forward detectors:

Incoherent backgrounds:

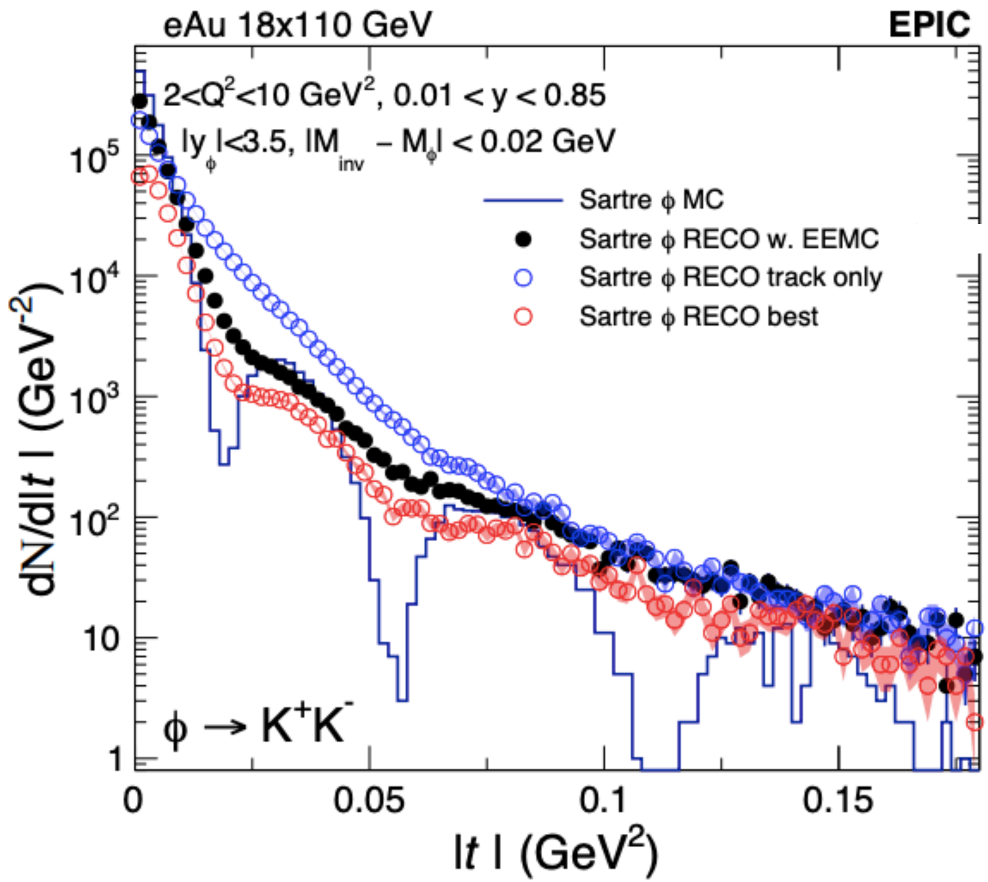




Phys. Rev. D ***104***, *114030*

Coherent production of φ in eAu

- First simulations out of ePIC, on φ in eAu. Gradual improvements in the reconstruction: these are only the first steps!

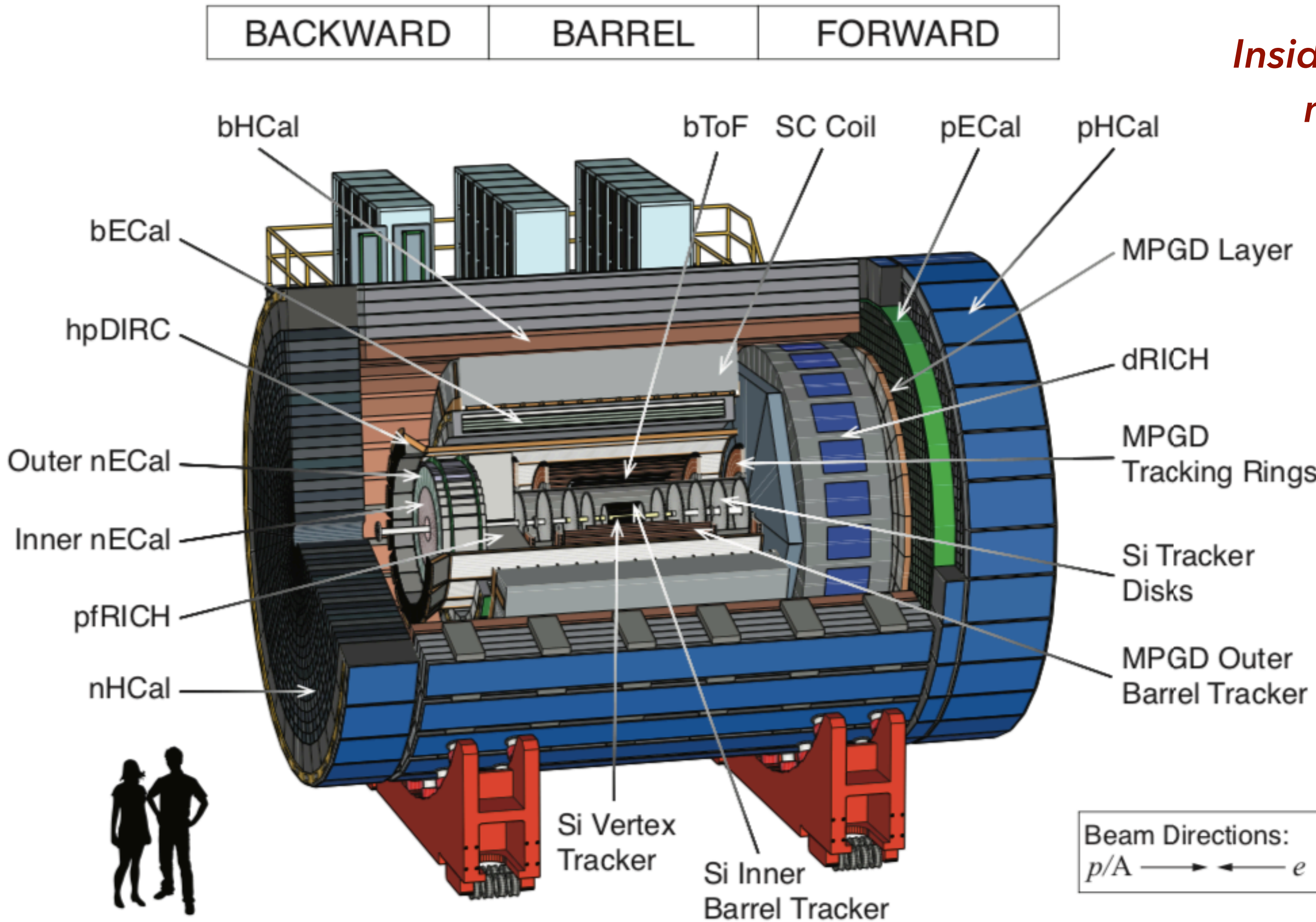


Similar challenges for J/Ψ and Upsilon…

Kong Tu (BNL)

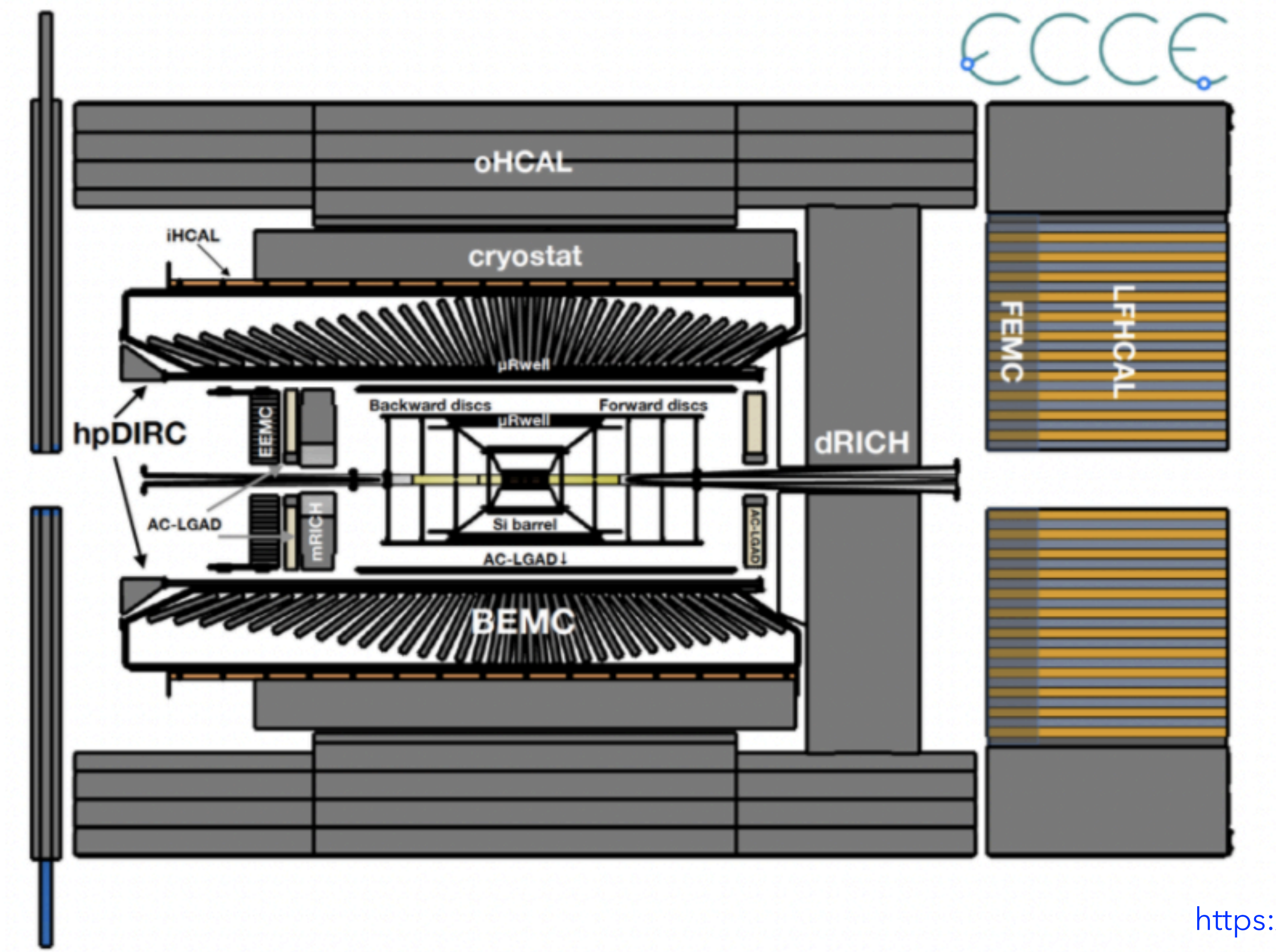
ATHENA:
A Totally Hermetic Electron Nucleus Apparatus

Inside a new 3T magnet



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

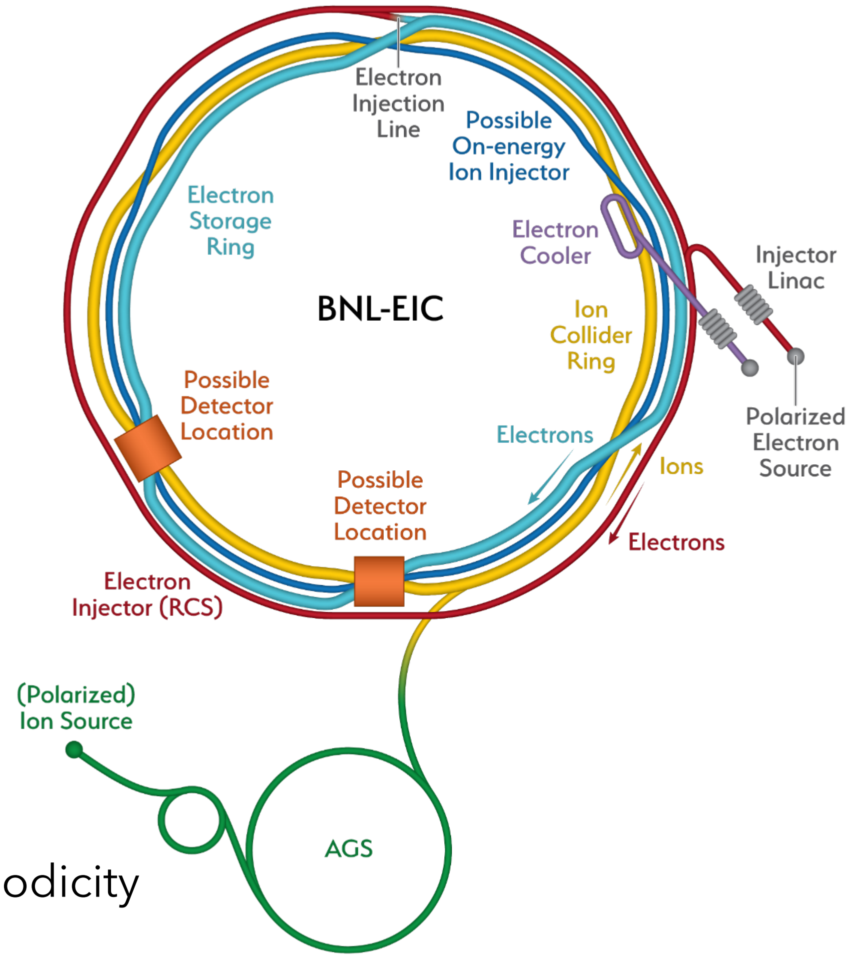
ECCE: EIC Comprehensive Chromodynamics Experiment



Reusing the 1.4T BaBaR solenoid magnet

https://www.ecce-eic.org

EIC accelerator



Hadron storage ring (HSR): 41-275 GeV (based on RHIC)

- up to 1160 bunches, 1A beam current (3x RHIC)
- bright vertical beam emittance (1.5 nm)
- strong cooling (coherent electron cooling, ERL)

Electron storage ring (ESR): 2.5–18 GeV (new)

- up to 1160 bunches
- high polarization by continual reinjection from RCS
- large beam current (2.5 A) ➔ 9 MW SR power
- superconducting RF cavities

Rapid cycling synchrotron (RCS): 0.4-18 GeV (new)

- 2 bunches at 1 Hz; spin transparent due to high periodicity

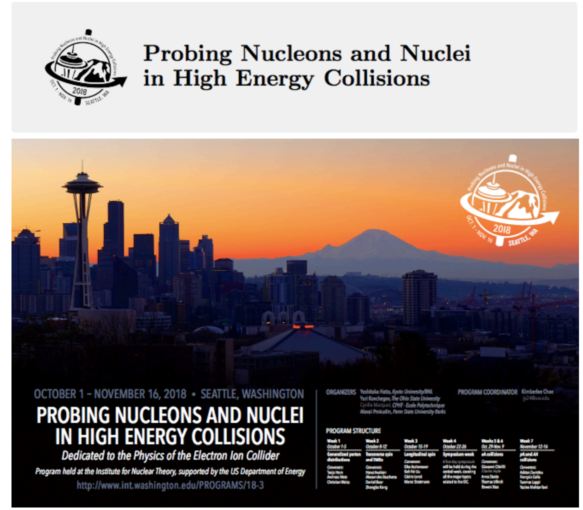
High luminosity interaction region(s) (new)

- $L = 10^{34}\ cm^{-2}s^{-1}$
- superconducting magnets
- 25 mrad crossing angle with crab cavities
- spin rotators (produce longitudinal spin at IP)

EIC in the making

- **2007 Nuclear Physics Long Range Plan** "*The EIC is embodying the vision of reaching the next QCD frontier*"
- **2011:** US DOE starts to fund generic R&D (**eRD programme**)
- **2012:** **EIC White Paper**
- **2015 Nuclear Physics Long Range Plan** "*high-energy, high-luminosity polarised EIC as the highest priority for new facility construction following completion of FRIB*"
- **2016: Users Group** acquires formal charter / elected board of representatives (eicug.org)
- **2017-18 National Academies of Science (NAS) Review:** "*the science questions that an [EIC] would answer are central to completing our understanding of atomic nuclei… An EIC can **uniquely** address three profound questions about nucleons … and how they are assembled to form the nuclei of atoms*"

EIC in the making



- **2018: "Probing Nucleons and Nuclei in High Energy Collisions"**: 7-week workshop programme at INT, Seattle. https://arxiv.org/abs/2002.12333

- **2019:** DOE **Independent Cost review Exercise**, DOE-led meetings with international funding agencies / government representatives.

- **Dec 2019: CD0 (Critical Decision 0) status granted by US DoE**: establishes "mission need" & formal launch of project. Funding envelope: $1.6 - $2.6 billion.

- **2020: EIC Yellow Report**

- **2020: Expressions of Interest** from the international community

- **2021:** Development of detector proposals: **ATHENA, ECCE, CORE**

- **2021: Conceptual Design Report**

- **June 2021: CD1 status granted by DOE:** "approve alternative selection and cost range"

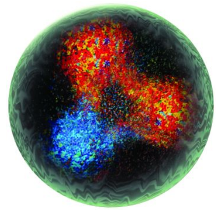
- **2022:** Formation of the **ePIC Collaboration**, design of the "project detector" (detector 1).

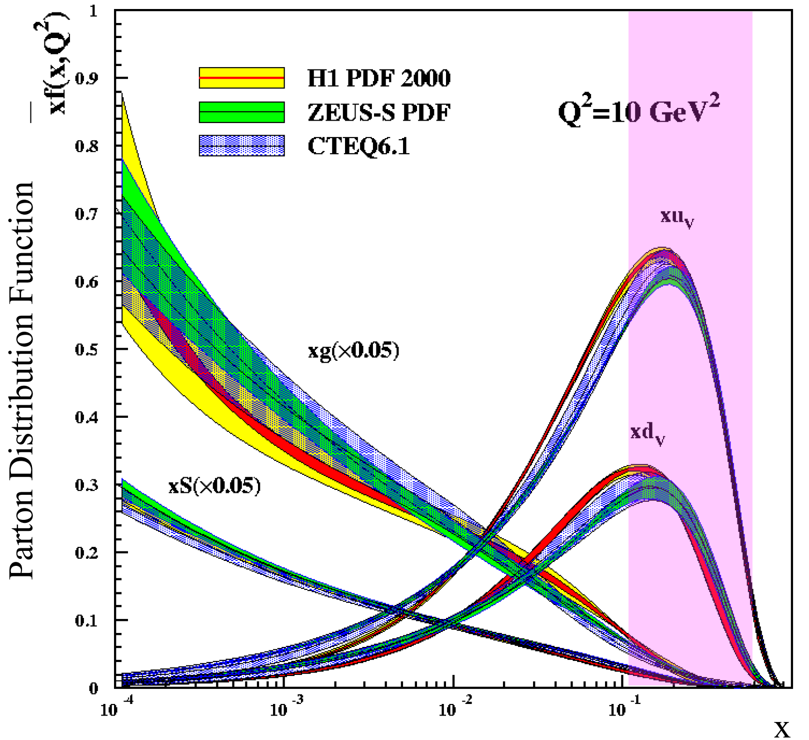
Nucleon at different scales

Valence quarks

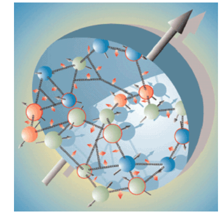
Jefferson Lab: fixed-target electron scattering

$0.1 < x_B < 0.7$





Nucleon at different scales



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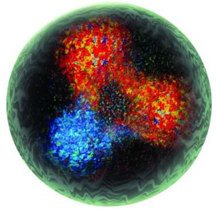
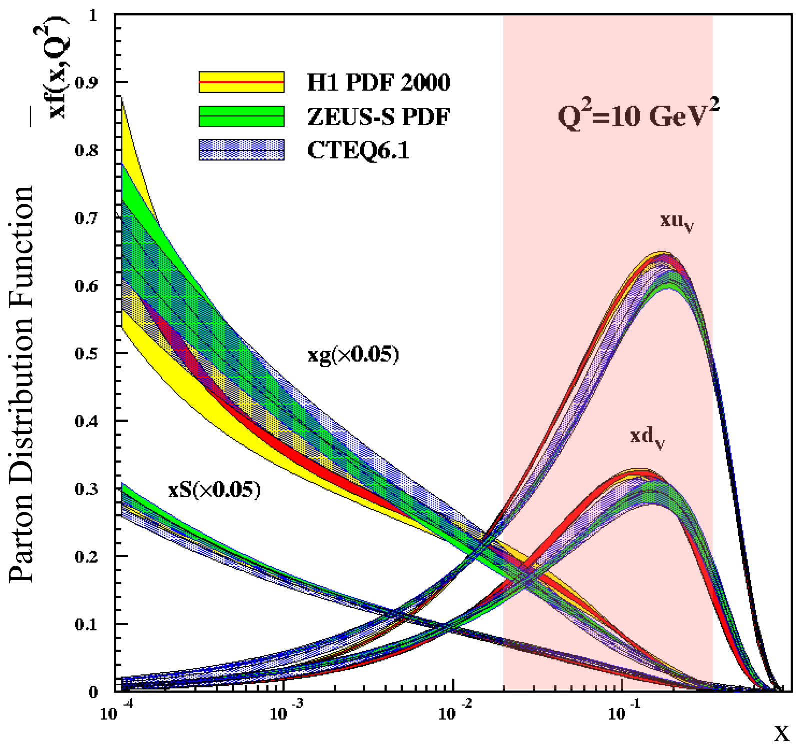


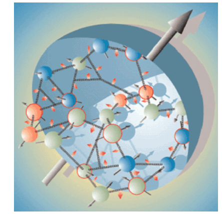
Sea quarks

HERMES: fixed gas-target electron/positron scattering

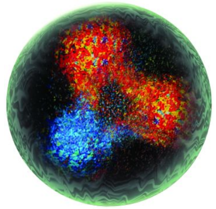
$0.02 < x_B < 0.3$



Nucleon at different scales



Valence quarks



Jefferson Lab: fixed-target electron scattering

$$0.1 < x_B < 0.7$$

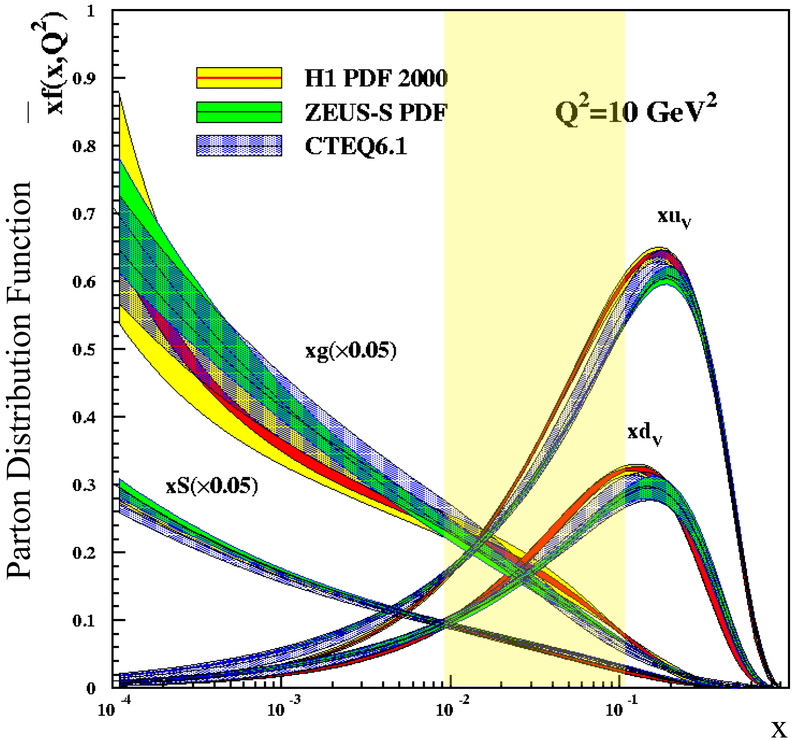
Sea quarks

HERMES: fixed gas-target electron/positron scattering

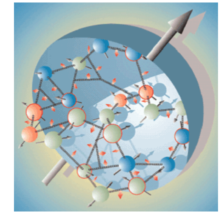
$$0.02 < x_B < 0.3$$

COMPASS: fixed-target muon scattering

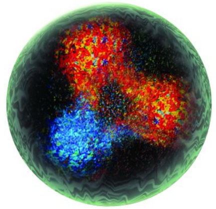
$$0.01 < x_B < 0.1$$



Nucleon at different scales

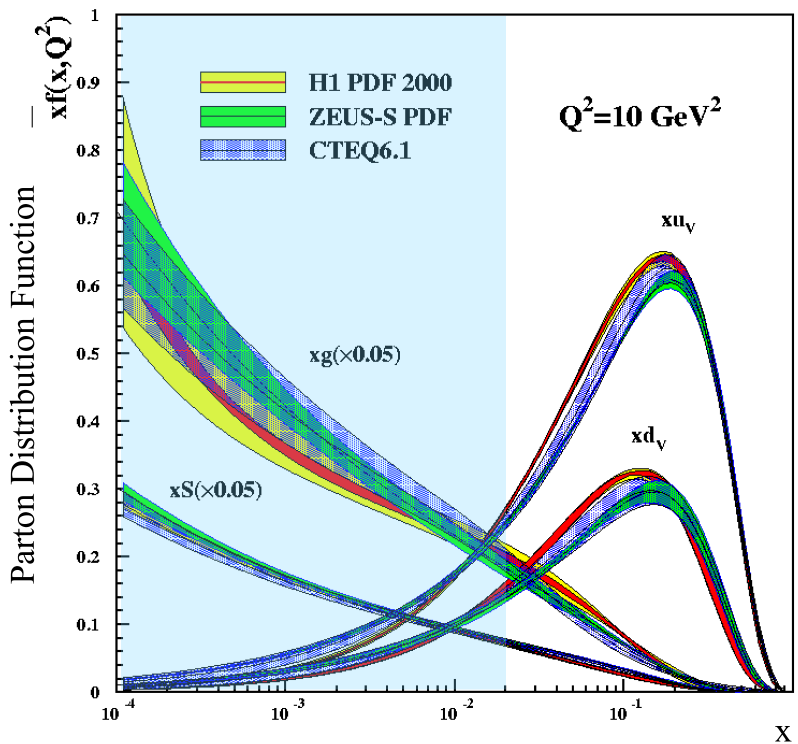


Valence quarks



Jefferson Lab: fixed-target electron scattering

$0.1 < x_B < 0.7$



Sea quarks

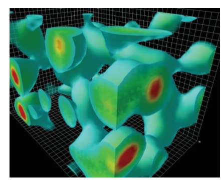
HERMES: fixed gas-target electron/positron scattering

$0.02 < x_B < 0.3$

COMPASS: fixed-target muon scattering

$0.01 < x_B < 0.1$

The glue

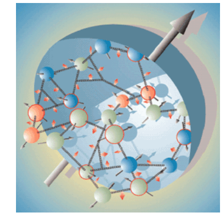


Derek Leinweber

ZEUS/H1: electron/ positron-proton collider

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

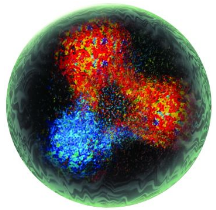
Nucleon at different scales

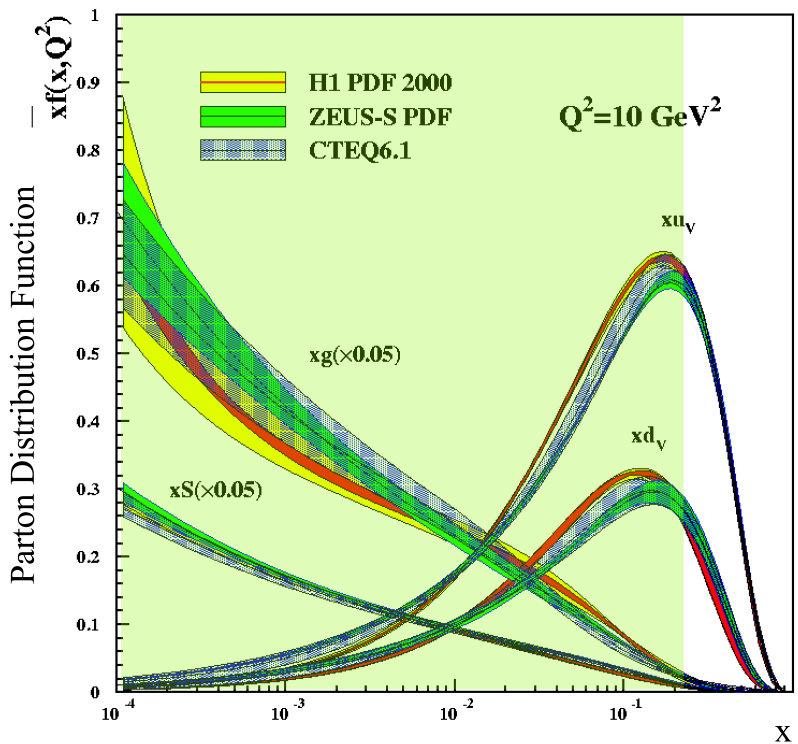


Valence quarks

Jefferson Lab: fixed-target electron scattering

$0.1 < x_B < 0.7$





Sea quarks

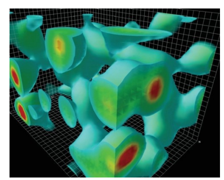
HERMES: fixed gas-target electron/positron scattering

$0.02 < x_B < 0.3$

COMPASS: fixed-target muon scattering

$0.01 < x_B < 0.1$

The glue



Derek Leinweber

ZEUS/H1: electron/positron-proton collider

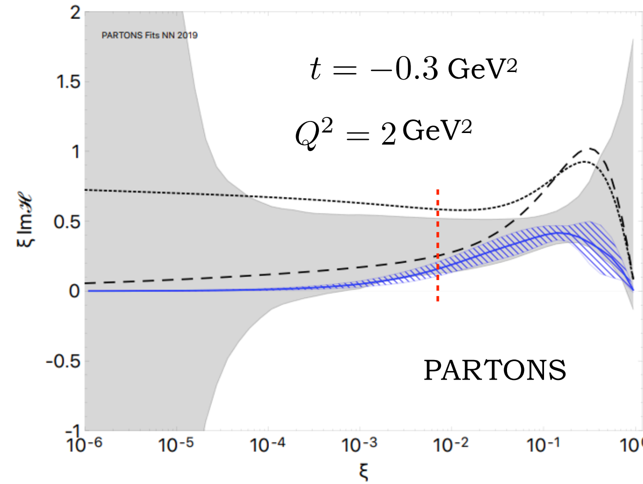
$10^{-4} < x_B < 0.02$

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

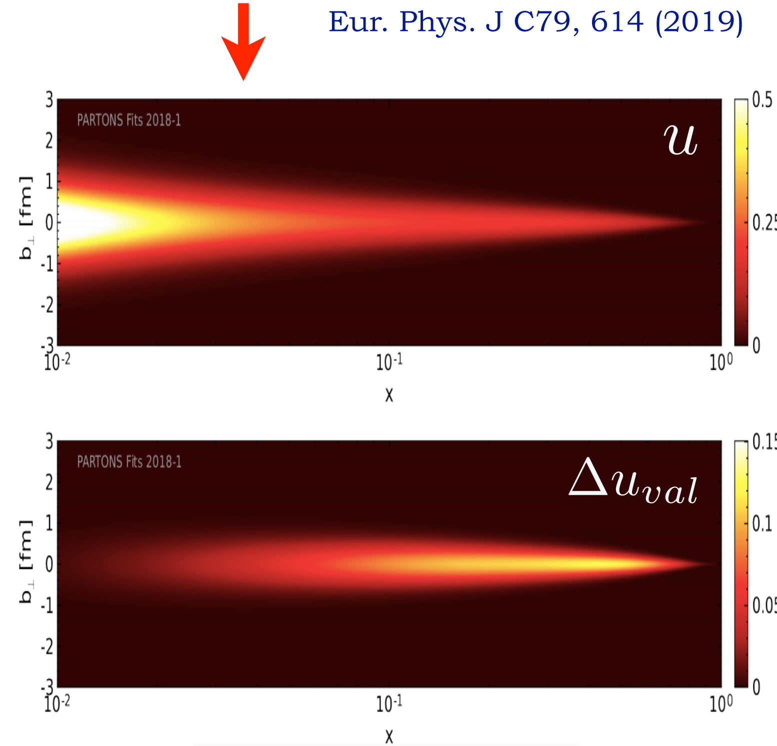
Luminosity 100 - 1000 times that of HERA

Nucleon tomography

Ongoing imaging efforts on available world-data in exclusive channels with sensitivity to Generalised Parton Distributions, strongest constraints in the valence region.



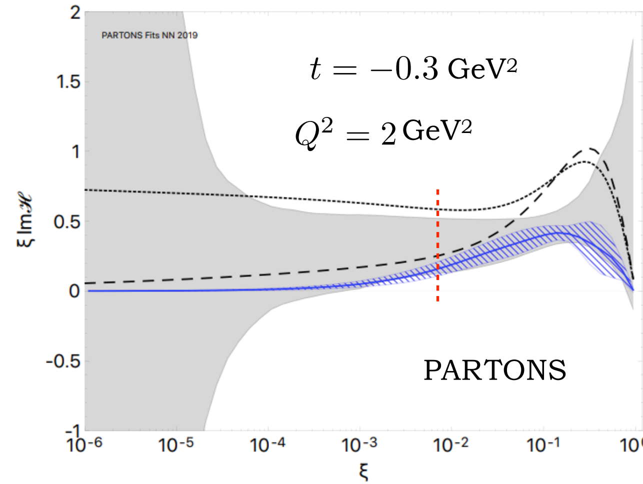
Eur. Phys. J C79, 614 (2019)



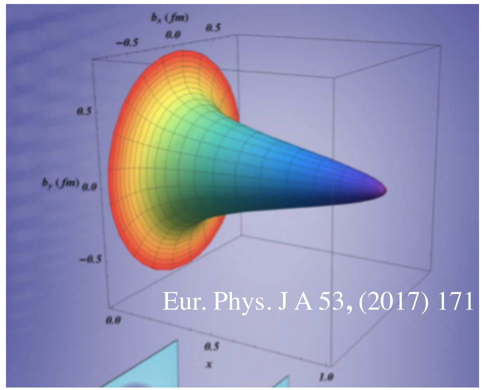
Transverse distributions of up-quarks carrying different momentum fractions x

Nucleon tomography

Ongoing imaging efforts on available world-data in exclusive channels with sensitivity to Generalised Parton Distributions, strongest constraints in the valence region.

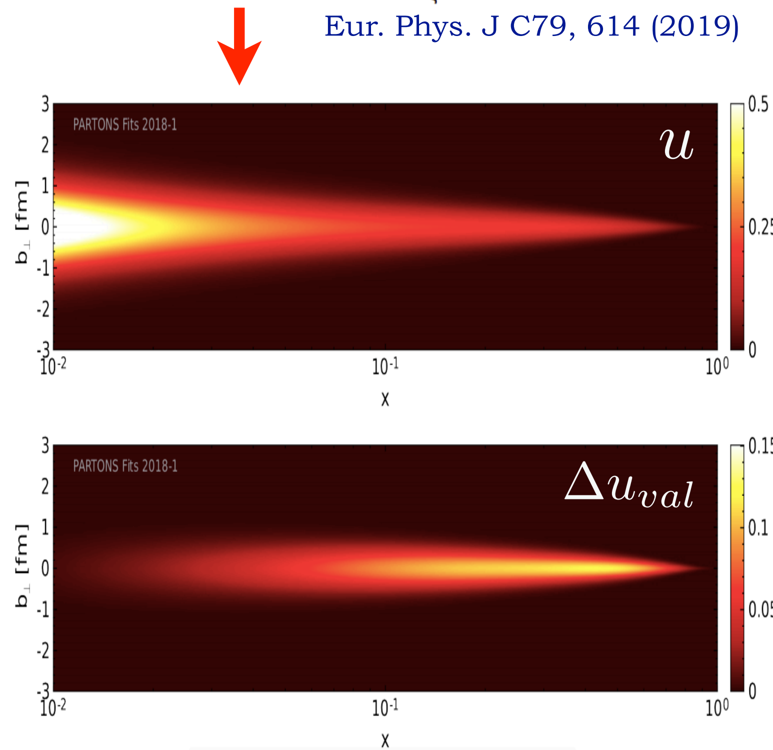


Eur. Phys. J C79, 614 (2019)



Artists impression of transverse quark distributions at different x

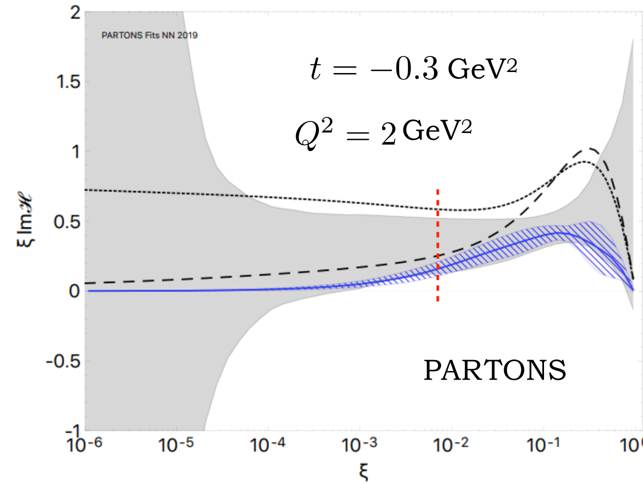
No uncertainties shown!



Transverse distributions of up-quarks carrying different momentum fractions x

Nucleon tomography

Ongoing imaging efforts on available world-data in exclusive channels with sensitivity to Generalised Parton Distributions, strongest constraints in the valence region.



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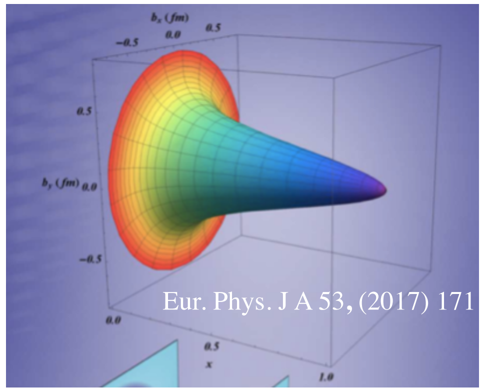
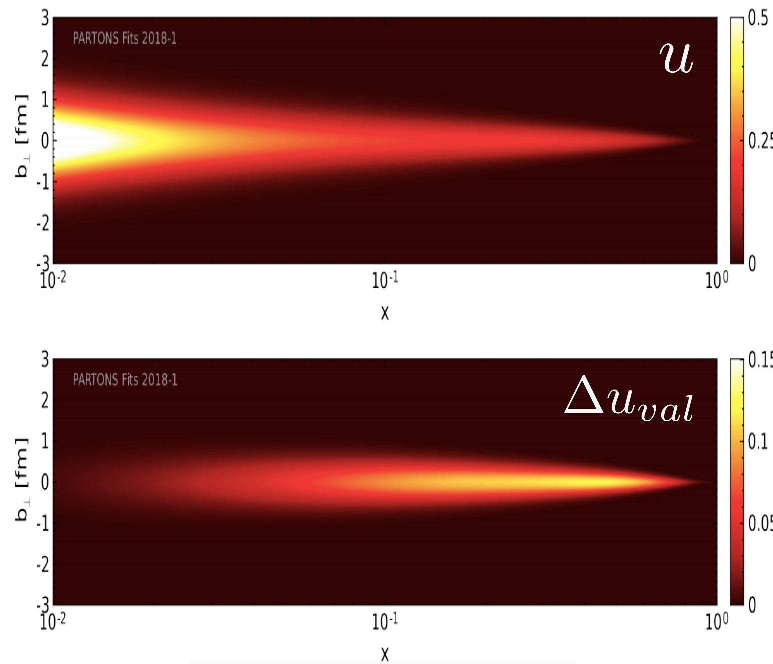
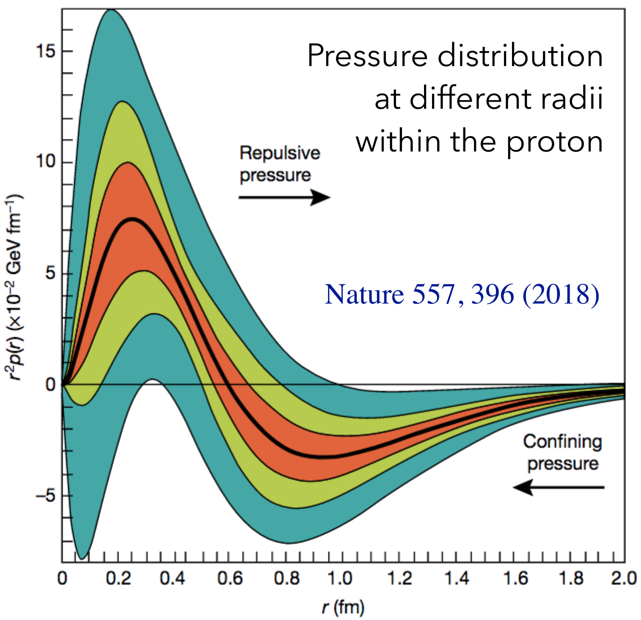
Possibility of accessing distributions of pressure and shear forces in the nucleon.



Artists impression of transverse quark distributions at different x



Transverse distributions of up-quarks carrying different momentum fractions x



No uncertainties shown!

Images are strongly model-dependent: need measurements across a full range of x to fully map the 3D nucleon structure.