The ePIC Experiment Physics Program Overview

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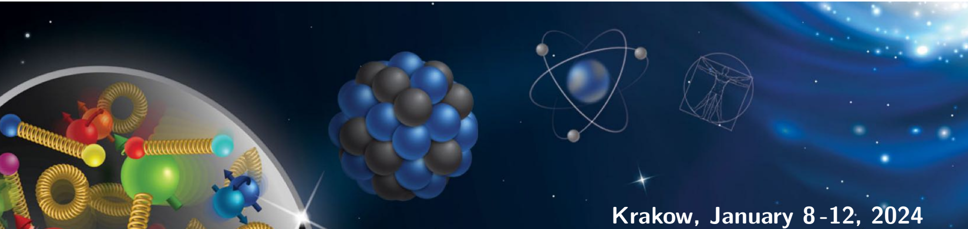
(on behalf of the ePIC Collaboration)

XXX Cracow EPIPHANY Conference
on Precision Physics at High Energy Colliders

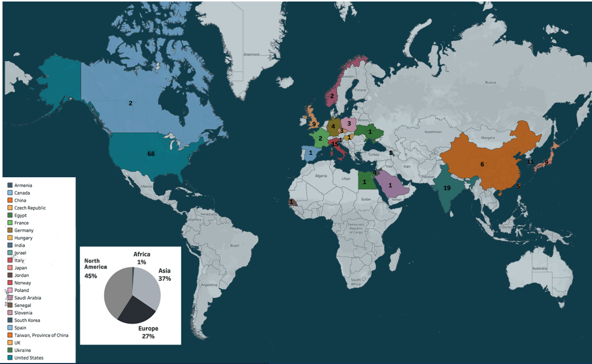


Krakow, January 8 - 12, 2024

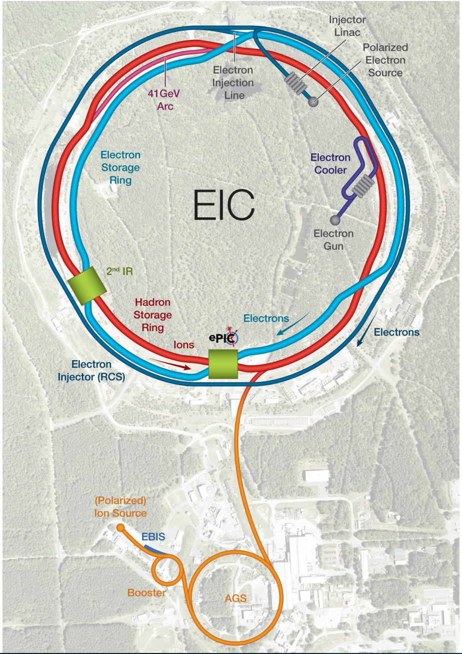
The EIC project and the ePIC Collaboration

- Necessity for a new Electron-Ion Collider, its physics goals and detector requirements have been discussed since the early 2000s.
- January 9, 2020, Washington, D.C. – DOE selected BNL as the site for the EIC.
- December 2021: Detector Proposal Advisory Panel (DPAP) begins review of three detector proposals: ATHENA, CORE, and ECCE.

- March 2022: ECCE adopted as reference design for the first detector; ATHENA and ECCE proto-collaborations merge.
- July 2022: ePIC Collaboration was officially established.
- 2023 NSAC LRP for Nuclear Science: "We recommend the expeditious completion of the EIC as the highest priority for facility construction."



EIC accelerator main parameters



- Making use of RHIC infrastructure: ion source, pre-accelerator chain, ion storage ring (circum. 3.83 km).
- New infrastructure: electron source, electron accelerator (RCS), storage ring.
- Beam energies:

Beam energies:	HERA
$E_e = 2.5 - 18$ GeV	27.5 GeV
$E_p = 40 - 275$ GeV	920 GeV
$E_\mathrm{A} = (Z/A)E_p$	

- $\sqrt{s_{ep}} = 20 - 141$ GeV — 318 GeV
- # of bunches per beam: 1320; collision every ~ 10 ns
- Luminosity: $10^{33\,-\,34}$ cm^{-2}s^{-1}
- Beams polarization (L, T): $> 70\%$
  e, p, light ions (d, ^{3}He) - polarized sources + spin rotators and "siberian snakes"

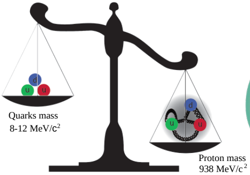
- Ion species: p - Uranium
- # of interaction regions: $1 - 2$

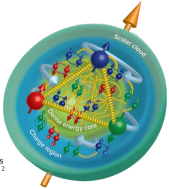
Open questions in QCD - main physics goals of the EIC

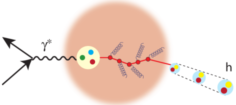
- How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?
- How do the nucleon properties like mass and spin, emerge from them and their interactions?

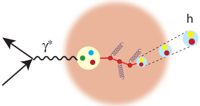
- How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?
- How do the confined hadronic states emerge from these quarks and gluons?
- How do the quark-gluon interactions create nuclear binding?

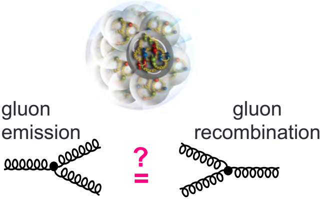
- How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?
- What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?





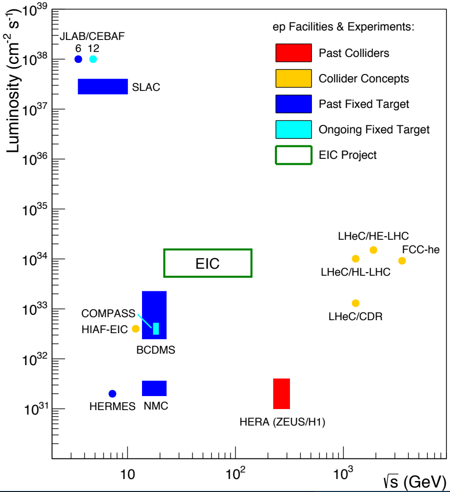


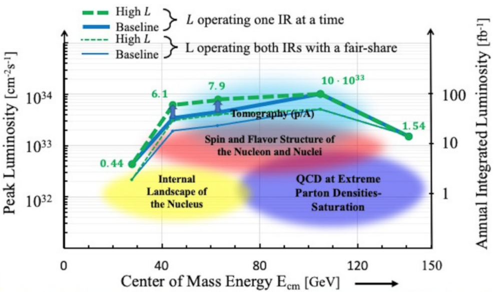




Uniqueness of the EIC among DIS facilities and key physics

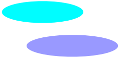
- High luminosity & wide reach in $\sqrt{s}$.
- No other facility has plans for:
  - polarized lepton & hadron beams,
  - (polarized) nuclear beams.





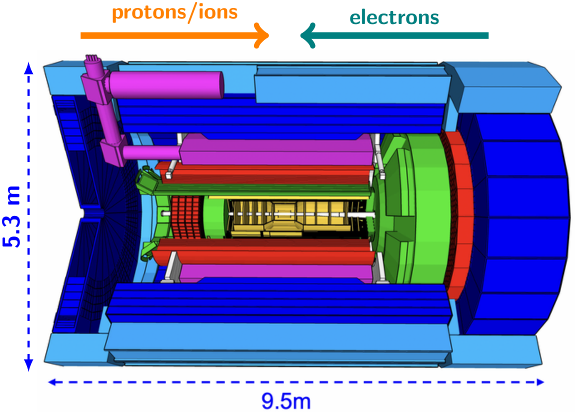
Inclusive DIS - precisely measure scattered electron - (x, Q^2)

Semi-inclusive DIS - detect the scattered lepton in coincidence with identified hadrons, jets, ...



Exclusive processes (diffraction) - all particles are identified (need for hermetic detector including far-forward region).

electron-Proton/Ion Collider (ePIC) Detector



Magnet & Tracking

- New 1.7 T SC solenoid, $\varnothing 2.8$ m
- Si MAPS (vertex, barrel, forward, backward disks)
- Gaseus MPGDs (µRWELL/µMegas) (barrel, forward, backward disks)

EM Calorimetry

- Imaging EMCAL (barrel)
- W-powder/ScFi (forward)
- PbWO$_4$ crystals (backward)

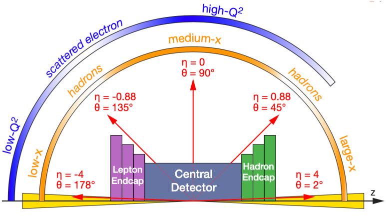
Particle Identification

- hpDIRC (barrel)
- Dual RICH (forward)
- Proximity focusing RICH (aerogel) (backward)
- TOF ($\sim$30ps): AC-LGAD (barrel and forward)

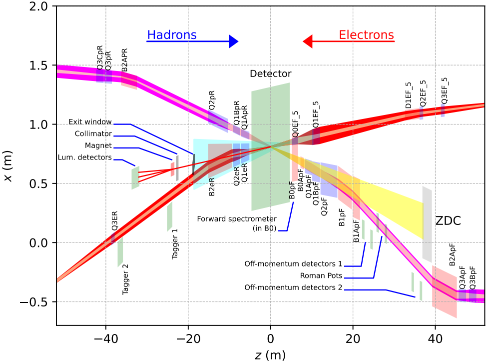
Hadronic Calorimetry

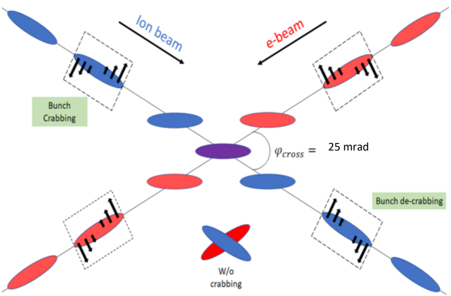
- Fe/Scint reuse from sPHENIX (barrel)
- Steel/Scint - W/Scint (backwards/forward)

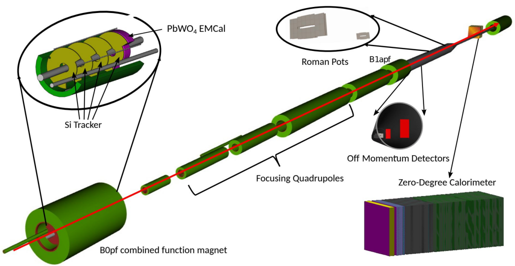
DAQ streaming readout



Interaction Region and Far Forward detection systems

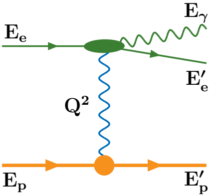


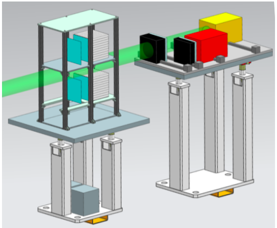




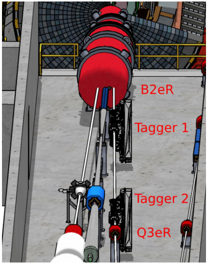
- **Zero Degree Calorimeter (ZDC)**: photons, neutrons; $\theta < 5.5$ mrad.
- **RP stations (two)**: protons, light nuclei; $\theta(10\sigma) < \theta < 5$ mrad.
- **Off-momentum detectors (two)**: charged particles; $0 < \theta < 5$ mrad.
- **B0 detector**: charged particles, tagged photons; $5.5 < \theta < 20$ mrad.

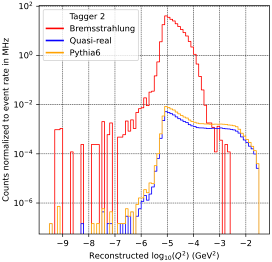
Far Backward detectors and luminosity measurement





- Luminosity measurement using ep Bremsstrahlung process. The photon spectrum will be measured using two methods: convertion to e^+e^- pairs and direct photons.
- Precise luminosity measurement at the EIC, with $\delta L/L < 1\%$, and of 10^{-4} for relative measurements from bunch to bunch, is both crucial to achieve its main physics goals and very challenging (ep: ≈ 10 hard bremsstrahlung photons every 10 ns; e+Au: more than hundred of such photons).
- Forward electron detectors will also suffer from event pileup (ep: ≈ 3 bremsstrahlung electrons every 10 ns, assuming its acceptance range $0.65 < E'/E < 0.85$. For e+A collisions the event pileup will scale approx. with Z^2/A).
- Low-Q^2 taggers will allow to measure clean photoproduction signal over a limited region $10^{-3} < Q^2 < 10^{-1}$ GeV^2



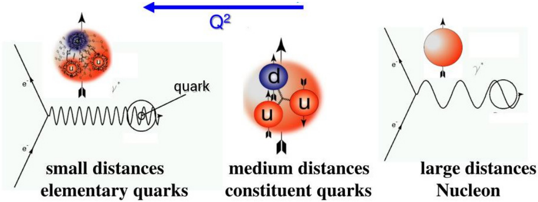


Deep Inelastic electron-proton(nucleon) Scattering (DIS)

- Virtuality of the probe - measure of resolution power:

$$Q^2 \equiv -q^2 = -(k-k')^2 \qquad \lambda \propto \frac{1}{\sqrt{Q^2}}$$

$$Q^2 = 2E_e E'_e(1-\cos\theta_e)$$



- Relative lepton energy loss (inelasticity):

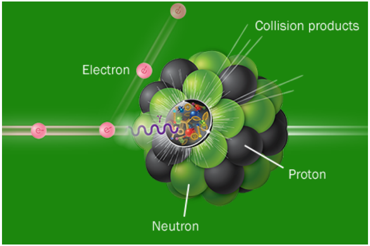
$$y = \frac{p\cdot q}{p\cdot k} = 1 - \frac{E'_e}{E_e}\cos^2\left(\frac{\theta_e}{2}\right)$$

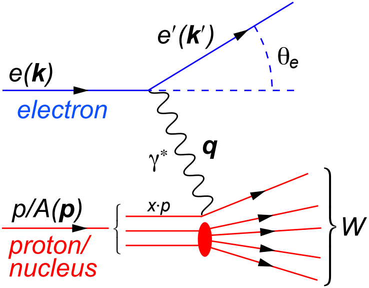
- Momentum fraction of struck quark:

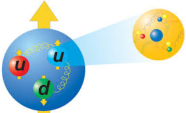
$$x = \frac{Q^2}{2\,p\cdot q} = \frac{Q^2}{sy} \approx \frac{Q^2}{W^2+Q^2}$$

- CMS energies squared in ep and γp frames:

$$s = (k+p)^2 = 4E_eE_p \qquad W^2 = (q+p)^2$$

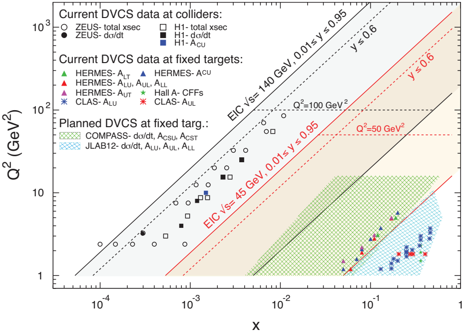


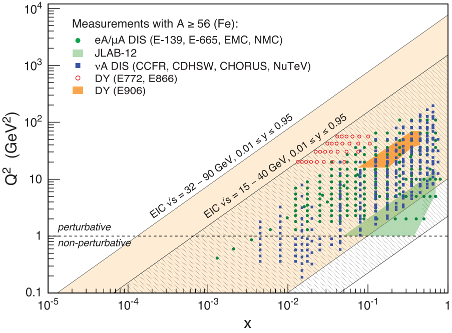




Kinematic coverage for the EIC

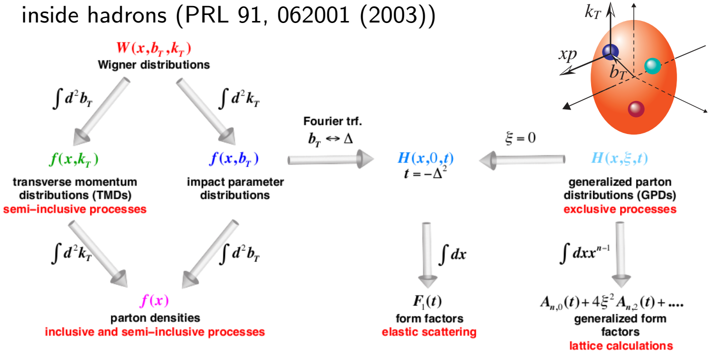
- EIC will allow to explore the QCD landscape over a wide range in x and Q^2 often complementary to other collider and fixed target experiments.
- Access to low-x regime will allow to study high-density gluon matter and modifications of gluons in nuclear environment complementing heavy ion programs at RHIC and LHC.
- Polarized beams will allow to study spin-dependent structure functions and precisely understand the sizes of different contributions to the nucleon spin.
- e+A DIS will allow to directly measure modifications to the nucleon structure when immersed in a nucleus. This study will be performed for different nuclei species.





Multi-dimensional nucleon tomography

- Wigner distributions encode all quantum information of how partons are distributed inside hadrons (PRL 91, 062001 (2003))



$W(x,b_T,k_T)$
Wigner distributions

$\int d^2b_T$ $\quad$ $\int d^2k_T$

$f(x,k_T)$
transverse momentum distributions (TMDs)
semi–inclusive processes

$f(x,b_T)$
impact parameter distributions

Fourier trf.
$b_T \leftrightarrow \Delta$

$H(x,0,t)$
$t=-\Delta^2$

$\xi = 0$

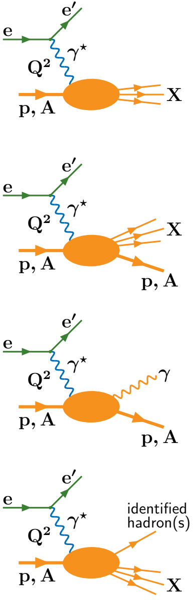
$H(x,\xi,t)$
generalized parton distributions (GPDs)
exclusive processes

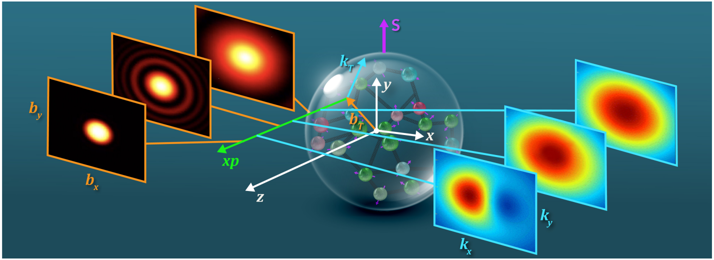
$\int d^2k_T$ $\quad$ $\int d^2b_T$ $\quad$ $\int dx$ $\quad$ $\int dx\,x^{n-1}$

$f(x)$
parton densities
inclusive and semi–inclusive processes

$F_1(t)$
form factors
elastic scattering

$A_{n,0}(t)+4\xi^2A_{n,2}(t)+\ldots$
generalized form factors
lattice calculations



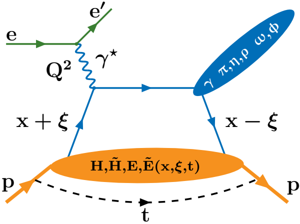


https://www.anl.gov/phy/quantom

Generalised Parton Distributions and OAM

- GPDs can be understood as a Bjorken-x decomposition of form factors. GPDs provide information about the longitudinal momentum and the transverse position of partons (see e.g. M. Diehl, Phys. Rep. 388 (2003) 41-277).
- 4 chiral-even and 4 chiral-odd (or transversity) GPDs at leading twist for a spin-$\frac{1}{2}$ hadron.
- Can be accessed via hard exclusive processes: cross section and asymmetries in DVCS and DVMP.

		Quark polarization		
		U	L	T
Nucleon polarization	U	H		E_T
	L		$\tilde{H}$	$\tilde{E}_T$
	T	E	$\tilde{E}$	$H_T, \tilde{H}_T$

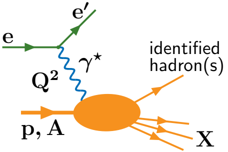


- The 2D FT of the GPD $H^q(x,0,t)$ yields the distribution $q(x,\vec{b}_\perp)$ in impact parameter space for unpolarized quarks and target:

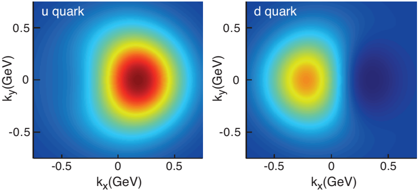
$$q(x,\vec{b}_\perp) = \int \frac{d^2\vec{\Delta}_\perp}{(2\pi)^2} H^q(x,0,-\Delta_\perp^2) e^{-i\vec{b}_\perp\cdot\vec{\Delta}_\perp}, \qquad \vec{\Delta}_\perp = \vec{p}\,'_\perp - \vec{p}_\perp$$

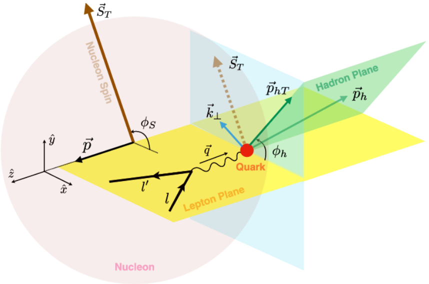
- $E(x,0,t)$ describes the transverse deformation of quark distributions in a transversely polarized target and allows e.g. to relate the average transverse deformation to the contribution from the corresponding quark flavor to the anomalous magnetic moment.
- Access to quark OAM via $J_q \equiv \frac{1}{2}\Delta q + L_q = \frac{1}{2}\int_0^1 dx\, x\,[H^q(x,0,0) + E^q(x,0,0)]$

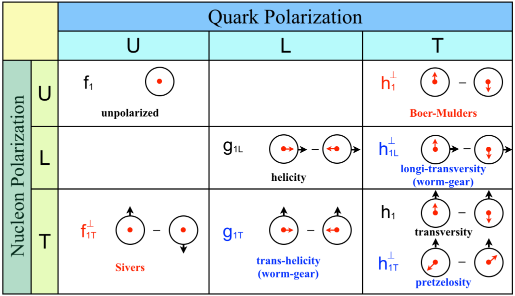
Transverse Momentum Dependent distributions



- TMDs represent the intrinsic (confined) motion of partons inside the nucleon (in momentum space: x, k_T).
- TMDs can be accesed in SIDIS processes with single hadron or in other semi-inclusive processes (di-hadrons, jets) in the final state.
- TMDs provide information on partons' orbital motion, spin-orbit correlations and color gauge invarinace (differences between processes).
- Sivers function (right): deformation of up and down quarks TMDs - unpolarized quarks with $x = 0.1$ in polarized (along y-axis) nucleon.



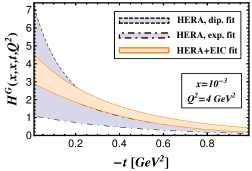


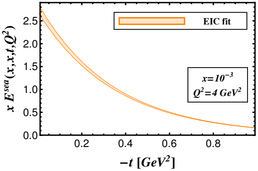


		Quark Polarization		
		U	L	T
Nucleon Polarization	U	f_1 unpolarized		$h_1^\perp$ Boer-Mulders
	L		g_{1L} helicity	$h_{1L}^\perp$ longi-transversity (worm-gear)
	T	$f_{1T}^\perp$ Sivers	g_{1T} trans-helicity (worm-gear)	h_1 transversity $h_{1T}^\perp$ pretzelosity

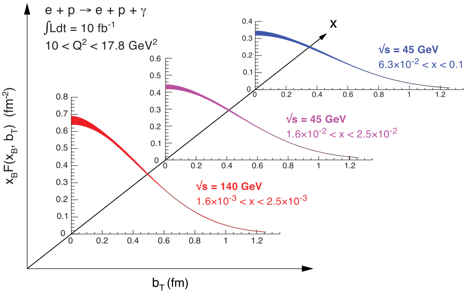
Spacial imaging of quarks and gluons at the EIC

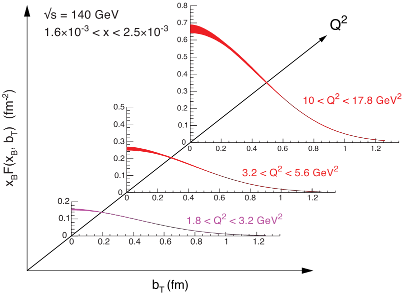
- EIC will enable parton “femtoscopy” - correlating information on parton contributions to the proton’s spin with their transverse momentum (TMDs) and spacial (GPDs) distributions.
- The 3D parton structure (GPDs) is uncovered in DIS by measurements of exclusive final states, wherein the proton remains intact, e.g. DVCS and DVMP (J/ψ, ϕ, π, K).
- Measurements at EIC will provide significant constraints at low-x and enable extraction of as-yet unknown GPDs.





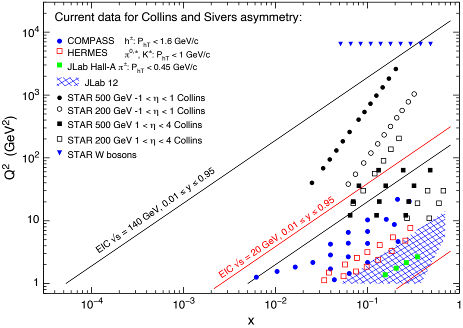
JHEP 09, 093 (2013)



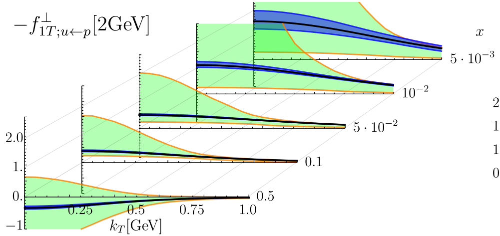


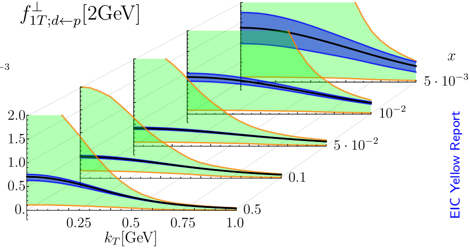
Rep. Prog. Phys. 82, 024301 (2019)

Transverse Momentum Dependent distributions at the EIC



- Significant extension of kinematic reach at EIC for Collins and Sivers asymmetries.
- Access to TMDs primarily through SIDIS for single hadrons, as well as other semi-inclusive processes with di-hadrons and jets.
- EIC has large potentail in significantly reduce uncertainties in TMDs for valence quarks and provide new measurements for sea quarks and gluons.



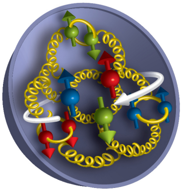


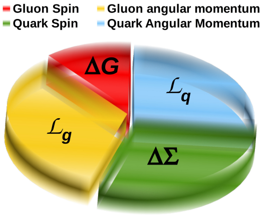
EIC Yellow Report

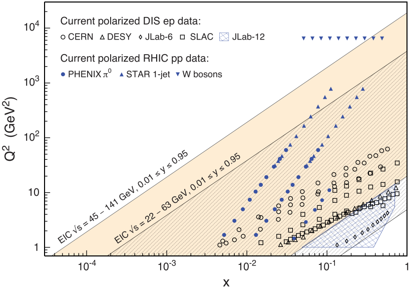
Spin of the nucleon

- Spin (or an intrinsic angular momentum) is a fundamental property of all elementary particles: matter particles (quarks and leptons) have a spin of $1/2$ (in $\hbar$ units), and force carriers (like photons and gluons) have spin 1.
- Spins of atoms or nuclei are well understood within the QM as the sums of the spins and the orbital motions of their constituent objects.
- We know that the spin of the nucleon is 1/2, but we do not understand how are quarks and gluons, and their intrinsic spins distributed in space & momentum inside the nucleon.
- From the current fixed target experiments, it is known that the total spin carried by quarks and gluons does not amount to 1/2, one needs orbital angular momentum:

$$\frac{1}{2} = \frac{1}{2}\int_0^1 dx\,\Delta\Sigma(x,Q^2) \;+\; \int_0^1 dx\,\Delta G(x,Q^2) \;+\; \int_0^1 dx(\mathcal{L}_q + \mathcal{L}_g)$$







Current status:

$\Delta\Sigma \sim 25-30\%,\quad \Delta G \sim 25-30\%,\quad \mathcal{L}_q\,?,\quad \mathcal{L}_g\,?$

Polarized DIS - spin structure functions

- Unpolarized structure functions $F_1(x,Q^2)$ and $F_2(x,Q^2)$:

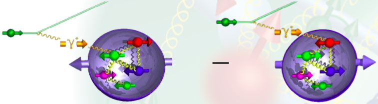
$$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\uparrow + \uparrow\uparrow) = \frac{8\alpha^2\cos^2(\theta/2)}{Q^4}\left[\frac{1}{\nu}F_2(x,Q^2) + \frac{2}{M}\,\mathrm{tg}^2(\theta/2)F_1(x,Q^2)\right]$$

- Polarized structure functions $g_1(x,Q^2)$ and $g_2(x,Q^2)$:

L : $$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\uparrow - \uparrow\uparrow) = \frac{4\alpha^2}{MQ^2}\frac{E'}{\nu E}\left[(E + E'\cos\theta)g_1(x,Q^2) - \frac{Q^2}{\nu}g_2(x,Q^2)\right]$$

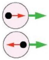
T : $$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\rightarrow - \uparrow\rightarrow) = \frac{4\alpha^2\sin\theta}{MQ^2}\frac{E'^2}{\nu^2 E}\left[\nu g_1(x,Q^2) + 2Eg_2(x,Q^2)\right]$$

$g_1 \propto$

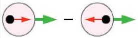


q^+ quark spin ⇈ proton mom.

q^- quark spin ⇅ proton mom.



$$g_1(x) \equiv \frac{1}{2}\sum_q e_q^2\underbrace{\left(q^+(x) - q^-(x)\right)} = \frac{1}{2}\sum_q e_q^2\Delta q(x)$$



$\Delta q(x)$ - quark helicity distribution

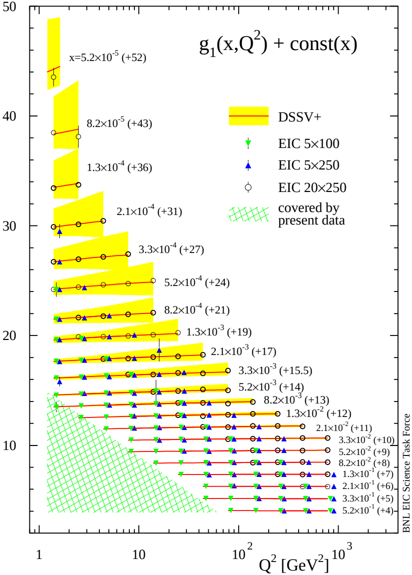
- Inclusive asymmetry: $A_1(x,Q^2) = \dfrac{\sigma_{\uparrow\downarrow} - \sigma_{\uparrow\uparrow}}{\sigma_{\uparrow\downarrow} + \sigma_{\uparrow\uparrow}} \approx \dfrac{\sum_q e_q^2\Delta q(x,Q^2)}{\sum_q e_q^2 q(x,Q^2)} = \dfrac{g_1(x,Q^2)}{F_1(x,Q^2)}$

- Semi-inclusive asymmetry: $A_1^h(x,z,Q^2) = \dfrac{\sigma^h_{\uparrow\downarrow} - \sigma^h_{\uparrow\uparrow}}{\sigma^h_{\uparrow\downarrow} + \sigma^h_{\uparrow\uparrow}} \approx \dfrac{\sum_q e_q^2\Delta q(x,Q^2)D_q^h(z,Q^2)}{\sum_q e_q^2 q(x,Q^2)D_q^h(z,Q^2)}$

Spin of the nucleon from $g_1(x, Q^2)$ structure function

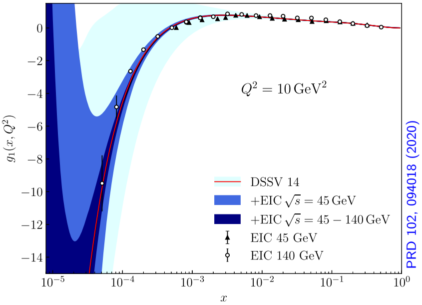
Current polarized DIS data:

down to $x \approx 0.005$, $Q^2 \approx 1 - 100$ GeV^2



BNL EIC Science Task Force

- EIC will allow for measurement of g_1 with greatly improved precision, and in significantly extended phase space: $x \approx 10^{-4}$ and $Q^2 \approx 1 - 10^3$ GeV^2
- To estimate its impact on g_1, EIC pseudodata at $\sqrt{s} = 45$ GeV have been included in new global DSSV fit.

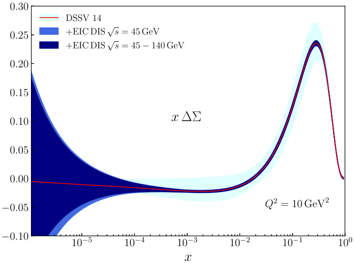


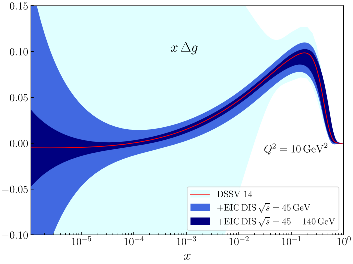
PRD 102, 094018 (2020)

- Polarized d / ^{3}He will allow for measurement of g_1 in neutron.

Spin of the nucleon at EIC

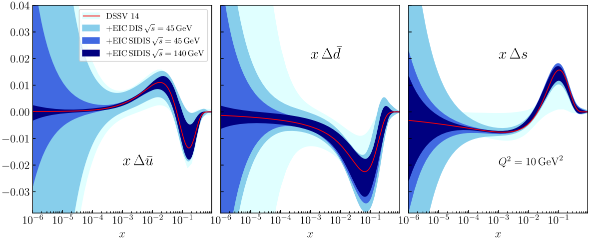
- Estimation of quark contribution to proton spin requires integration of $g_1(x)$ from 0 to 1
- g_1 is also sensitive to gluon contribution Δg at higher orders via scaling violations:





$$\Delta g \propto \frac{\partial g_1(x, Q^2)}{\partial \log Q^2}$$

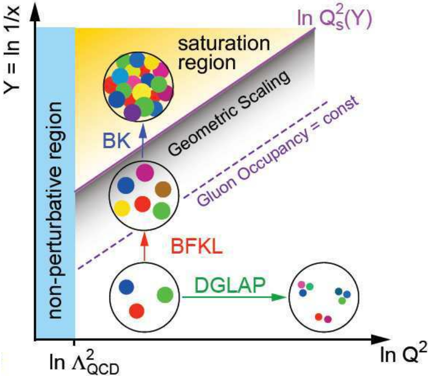
- Sensitivity to sea quarks helicities via SIDIS measurements with pions and kaons through measurements of semi-inclusive asymmetries $A_1^{\pi^-}(\Delta\bar{u})$, $A_1^{\pi^+}(\Delta\bar{d})$, $A_1^{K}(\Delta s)$
- Improved constraints on the spin of quarks/gluons will further constrain contribution of orbital angular momentum (OAM) of partons to the proton spin.

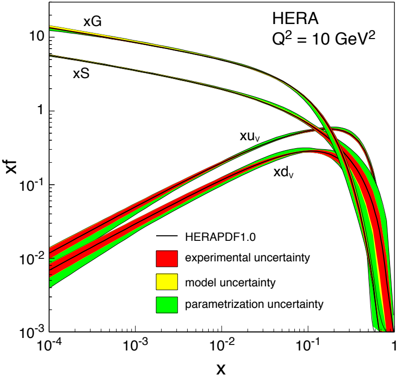


Parton distribution functions (PDFs) in the proton

- Gluon density at low-x is strongly rising - what tames this rise?
  - **Black disk limit** for scattering on a sphere: $\sigma_{\text{tot}} \leqslant \pi R^2$
  - In QCD - **Froissart-Martin unitarity bound**: $\sigma_{\text{tot}} \propto \ln^2 s$
  - From BFKL growth of gluon density: $\sigma_{\text{tot}} \propto s^{\lambda}$ clearly violates F-M bound at high energy.

- **Saturation scale $Q_S^2(x)$**: scale at which gluon emission and recombination become comparable (BK-JIMWLK evolution, non linear).
- Gluons start to overlap (MV model): $\dfrac{\alpha_s}{Q^2} xG(x, Q^2) = \pi R_p^2 \;\;\Rightarrow\;\; \ln Q_S^2(Y) = \lambda Y$

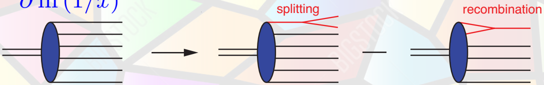


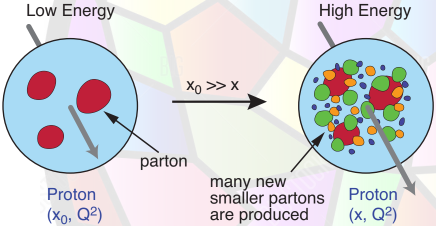


High energy limit of QCD - Color Glass Condensate (CGC)

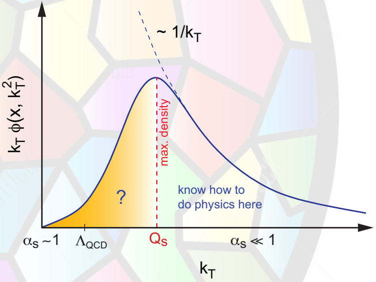
- What happens to the gluon density at high energy? Does gluon recombination leads to saturation in to a gluonic form of matter of universal properties?
- Non-linear evolution equation (BK):

$$\frac{\partial N(x, r_T)}{\partial \ln(1/x)} = \alpha_s K_{BFKL} \otimes N(x, r_T) - \alpha_s \left[N(x, r_T)\right]^2$$





"Color Glass Condensate"



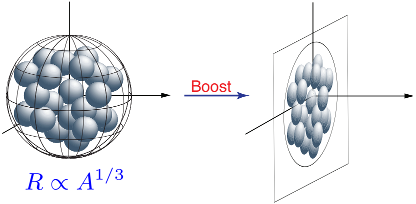
Color	gluons have color,
Glass	created from "frozen" random color source, that evolves slowly compared to natural time scale,
Condensate	High density! occupation number $\sim 1/\alpha_s$ at saturation.

Access to gluon saturation via electron-ion collisions

- Gluon density per unit of transverse area:

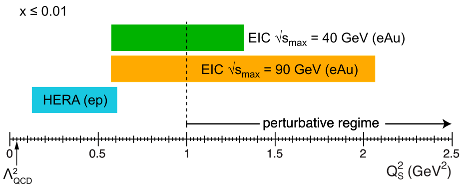
$$n \propto xg(x,Q^2)/\pi R^2$$

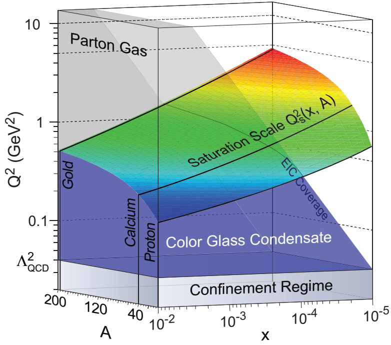
- Cross section for gluon recombination: $\sigma \propto \alpha_s/Q^2$

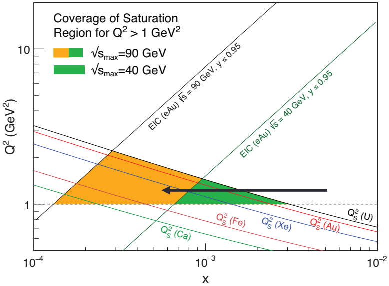


$R \propto A^{1/3}$

- Saturation: $1 < n\sigma \quad \Rightarrow \quad Q^2 < Q^2_{\mathrm{S}}(x) \propto A^{1/3}\left(\frac{1}{x}\right)^{\lambda}$ where $\lambda = 0.2 - 0.3$.
- Saturation regime is accessible at much lower energy in e+A collisions than ep collisions.







Measurement of saturation at the EIC

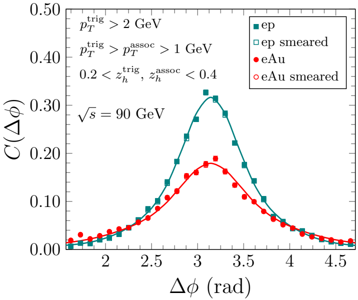
- Observables: di-hadrons, di-jets in ep and e+A, photon+jet/di-jet, also in diffraction, ...
- To directly probe the Weizsäcker-Williams (WW) gluon distribution and gluon saturation effects at low x, one can measure the azimuthal angle difference between two back-to-back charged hadrons (or jets):

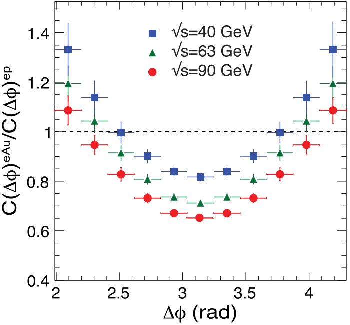
$$C(\Delta\phi) = \frac{d\sigma(\gamma^\star + A \rightarrow h_1 + h_2 + X)}{dz_1\, dz_2\, d\Delta\phi} \Big/ \frac{d\sigma(\gamma^\star + A \rightarrow h_1 + X)}{dz_1\, d\Delta\phi}$$

$$\frac{d\sigma(\gamma^\star + A \rightarrow h_1 + h_2 + X)}{dz_1\, dz_2\, d^2 p_{\mathrm{T},1}\, d^2 p_{\mathrm{T},2}} \propto \mathcal{F}(x_g, q_{\mathrm{T}}) \otimes$$

$$\mathcal{H}(z_q, k_{\mathrm{T},1}, k_{\mathrm{T},2}) \otimes D_q(z_1/z_q, p_{\mathrm{T},1}) \otimes D_q(z_2/z_q, p_{\mathrm{T},2})$$

- Due to saturation, the WW gluon TMD can provide additional transverse momentum broadening to the back-to-back correlation and cause disappearance of the away-side peak when saturation is overwhelming.
- Clear differences between the ep and eA: suppression of the correlation peak in eA due to saturation effects.
- EIC will allow to unambiguously map the transition from a non-saturated to saturated regime.

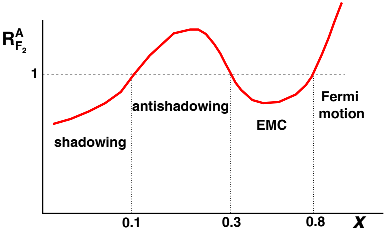




Nuclear shadowing

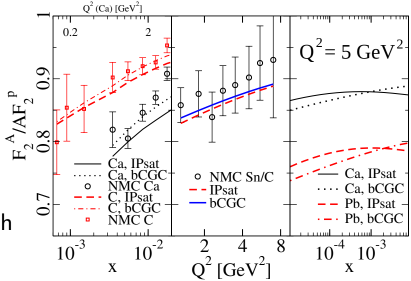
- How quarks and gluon distributions in the proton get modified in nuclei?
- Measure the ratio of cross section on a nucleus to the proton (scaled by mass number A):

$$R^{\mathsf{A}}_{F_2}(x,Q^2) = \frac{F_2^{\mathsf{A}}(x,Q^2)}{\mathsf{A}\cdot F_2^{\mathsf{nucleon}}(x,Q^2)}$$



- General features of $R^{\mathsf{A}}_{F_2}(x,Q^2)$ behaviour:
  - Fermi motion: for $x \gtrsim 0.8$ - due to motion of bound nucleons inside the nucleus.
  - EMC region (EMC effect): for $0.3 \lesssim x \lesssim 0.8$ - discovered by the EMC Collaboration.

    Possible explanation: Short range correlations between nucleons, most nucleons are not modified but some experiencing SRC are modified (about 20%).
  - Antishadowing: $R^{\mathsf{A}}_{F_2} > 1$ for $0.1 \lesssim x \lesssim 0.3$ - momentum sum rule (?)
  - Shadowing: $R^{\mathsf{A}}_{F_2} < 1$ for $x \lesssim 0.1$
    Shadowing inreases with increasing A and with decreasing x.
    Shadowing decreases with increasing Q^2.

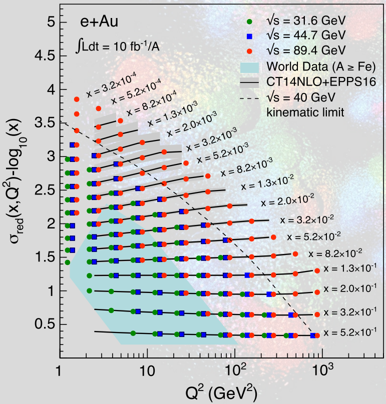


PRL 100, 022303 (2008)

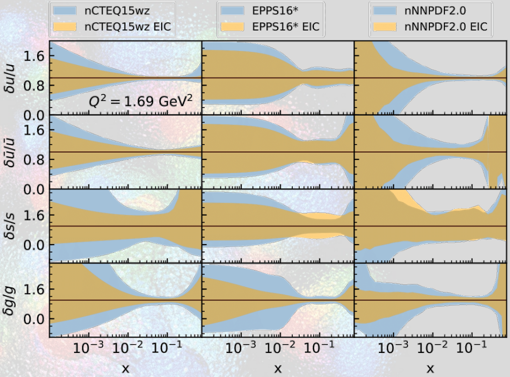
Nuclear structure - impact of the EIC

- Precise measurement of nPDFs for wide range of nuclei and wide kinematic range with negligible stat. uncertainties and syst. uncertainties of few percent.

$$\sigma_{\mathrm{r}}(x,Q^2) = \\ = F_2(x,Q^2) - \frac{y^2}{1+(1-y)^2} F_L(x,Q^2)$$

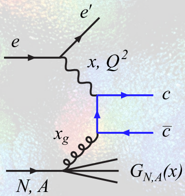


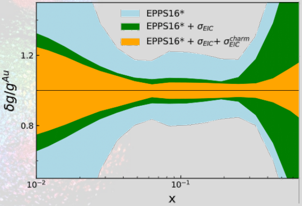
Rep. Prog. Phys. 82, 024301 (2019)



EIC Yellow Report

- Significant impact of the charm cross section on the gluon nPDF at high-x.





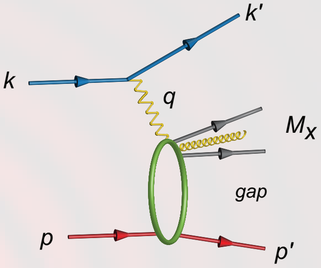
EIC - best place to study diffraction in 21th century

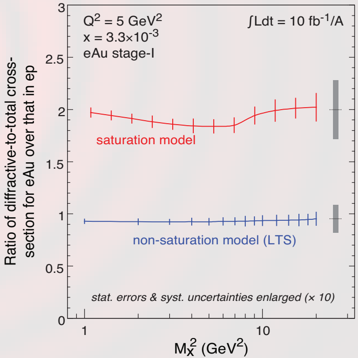
- Diffraction in the ep or e+A collisions proceeds via exchange of a color neutral object called Pomeron (two gluons in the lowest pQCD order).
- Define additional (to DIS) kinematic variables:

$$x_{\mathbb{P}} = \frac{q \cdot (p - p')}{q \cdot p} \approx \frac{Q^2 + M_X^2}{Q^2 + W^2}$$

$$\boldsymbol{\beta} = \frac{Q^2}{2q \cdot (p - p')} = \frac{x}{x_{\mathbb{P}}} \approx \frac{Q^2}{W^2 + M_X^2}$$

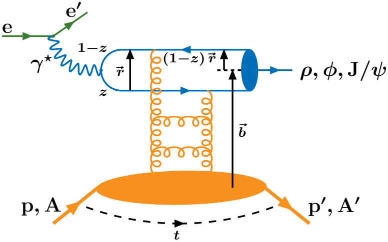
- Diffractive processes are most sensitive to the underlying gluon distribution and give access to the spacial distribution of gluons in nuclei.
- Production of (heavy) VM sensitive to saturation effects in nuclei.
- Special detection techniques required (Roman Pot detectors for scattered protons and ZDC for excited nuclei).
- Prediction for EIC: TeV electron hits a nucleus with binding energy of ~ 8 MeV/nucleon - nucleus remains intact in at least 1 in 5 events!





Diffraction at the EIC

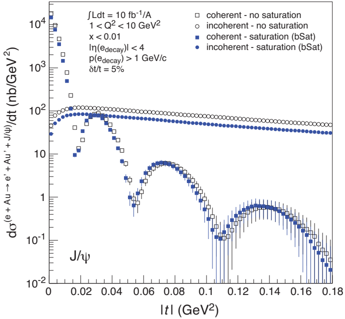
- Exclusive VM production as a probe of saturation:

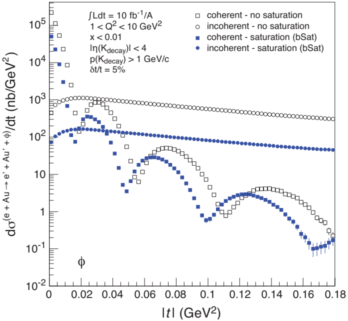


$l_{\text{coh}} \approx \dfrac{1}{2m_N x}$

for $x \approx 10^{-3}$ get

$l_{\text{coh}} \approx 100$ fm





- Coherent collisions (nucleus stays intact) depend on the shape of the source (provide average distribution).
- Incoherent collisions (nucleus breaks up) provide information on the fluctuations of the source.
- Coherent distributions can be used to obtain information about the gluon distribution in the impact parameter space:

$$F(b) = \int_0^\infty \frac{dq\, q}{2\pi} J_0(qb) \sqrt{\frac{d\sigma_{\text{coherent}}}{dt}}$$

- J/ψ is smaller, less sensitive to saturation effects.
- ϕ meson is larger, more sensitive to saturation effects.

Summary

- The EIC will be the first high-luminosity $e + p/\mathrm{A}$ collider with polarized both projectile and target and with a large kinematic coverage.
- The EIC project is on schedule - the ePIC Collaboration was formed to build the first EIC detector and implement the science potential of the EIC.
- The ePIC detector design is mature and uses innovative technologies.
  A Technical Design Report (TDR) is planned to be ready in this year.
- EIC will be a superb "stereoscopic camera", which allows us to depict the 3D internal structure of protons and heavy nuclei with unprecedented precision and significantly advance our knowledge of hadron structure.
- Main physics topics to be explored at the EIC are nucleon structure - full 3D momentum and spatial structure, as well as its spin structure, the origin of hadron mass, and study of dense partonic systems in nuclei, diffraction, saturation, hadronization, and many more.
- EIC science program will profoundly impact our understanding of the most fundamental inner structure of the matter.
- More details on EIC science and detector requirements in **EIC Yellow Report**

Thank you for your attention!

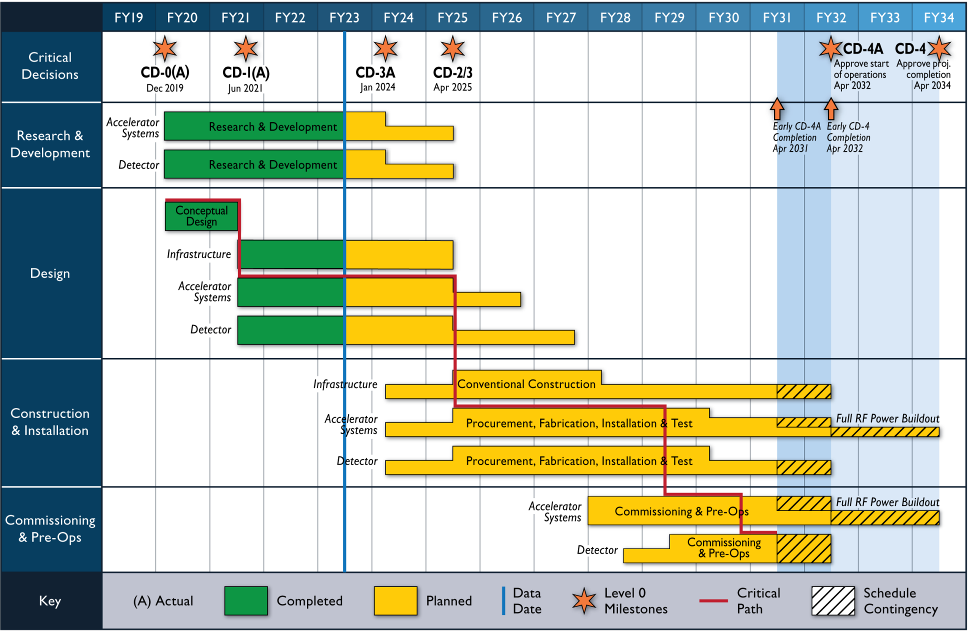
Backup slides

Physics opportunities beyond the EIC's core science

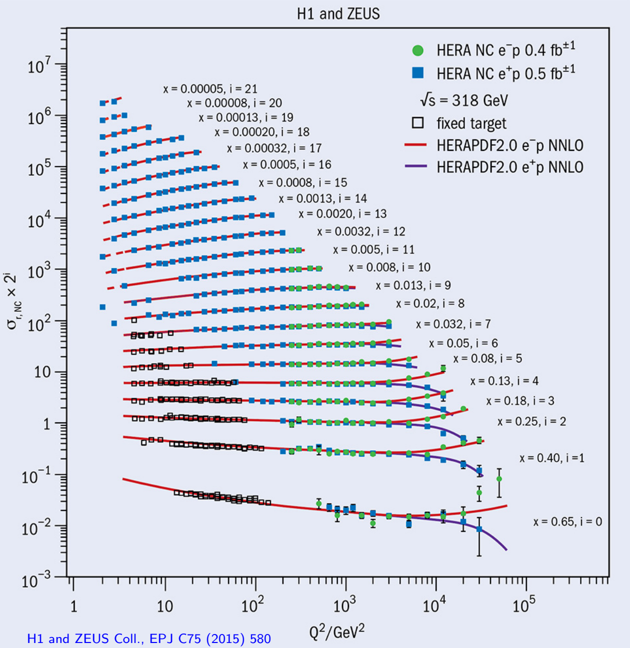
Snowmass 2021 White Paper: Electron Ion Collider for High Energy Physics

- New Studies with proton or neutron target:
  - Impact of precision measurements of unpolarized PDFs at high x/Q^2, on LHC-upgrade results(?)
  - Precision calculation of α_s: higher order pQCD calculations, twist-3.
  - Heavy quark and quarkonia (c, b quarks) studies with 100-1000 times lumi of HERA and with polarization.
  - Polarized light nuclei in the EIC.
- Physics with nucleons and nuclear targets:
  - Quark Exotica: 4,5,6 quark systems...? Much interest after recent LHCb results.
  - Physics of and with jets with EIC as a precision QCD machine:
    - Jets as probe of nuclear matter & internal structure of jets: novel new observables, energy variability.
    - Entanglement, entropy, connections to fragmentation, hadronization and confinement.
- Precision electroweak and BSM physics:
  - Electroweak physics & searches beyond the SM: parity, charge symmetry, lepton flavor violation.
  - LHC-EIC synergies & complementarity.
- Study of universality: $e+p$/A vs. p+A, d+A, A+A at RHIC and LHC.

Schedule of the EIC project



The legacy of HERA

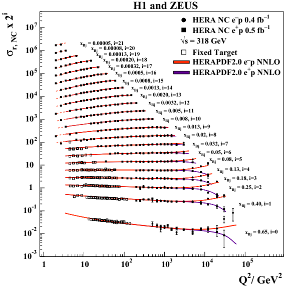


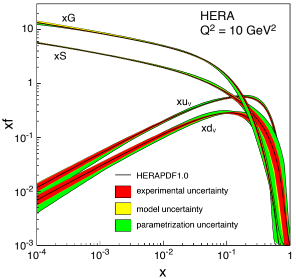
H1 and ZEUS Coll., EPJ C75 (2015) 580

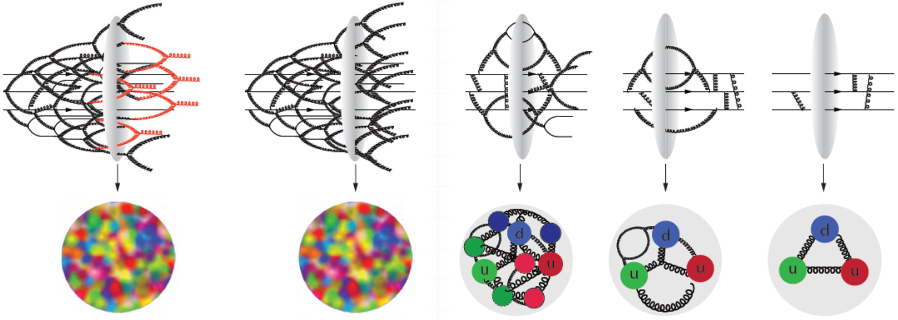
- Reduced cross section:
$$\sigma_r(x,Q^2) = F_2(x,Q^2) - \frac{y^2}{1+(1-y)^2}F_L(x,Q^2)$$
- Covers five orders of magnitude in x and Q^2.
- Consistency with old fixed-target data.
- Scaling with Q^2 at $x \sim 0.1$ & scaling violation elsewhere.
- Splitting at high Q^2 results from $\gamma - Z$ interference term.
- Crucial input to PDF fits: any parton at given $(x,\,Q^2)$ can be source of partons at $x' < x$ and $(Q')^2 > Q^2$.
- PDFs are universal - factorization of long and short distance physics.

Picture of the proton in pQCD

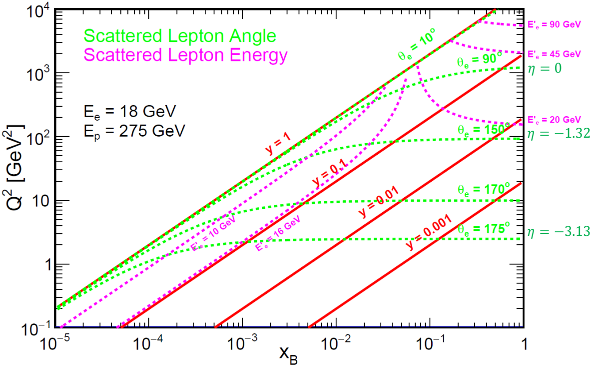
- Proton structure is embedded in the quark and gluon PDFs.
- Gluons dominate for $x \lesssim 0.1$
- So far we have only the longitudinal information.
- Need transverse information to understand the full structure of the proton at high energies.







Scattered electron reconstruction



Low y

- Reconstruction of x_B using the scattered electron becomes impossible (due to $1/y$ dependence).
- The detector needs to use information from the hadronic final state to reconstruct x_B. This requires good energy and p_{T} resolution in the hadronic endcap.

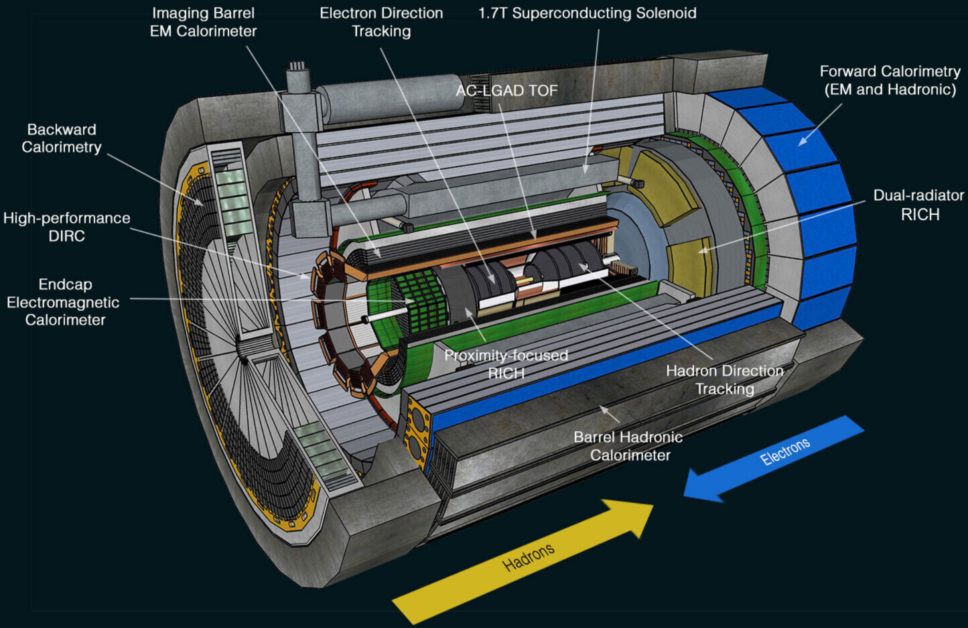
High y

- Large photoproduction bkgr. to DIS electron and large QED radiative corrections.
- Detector needs very good electron identification at low/moderate momenta, and the ability to reconstruct the total $E - p_z$ for the event.

Intermediate y / lower Q^2

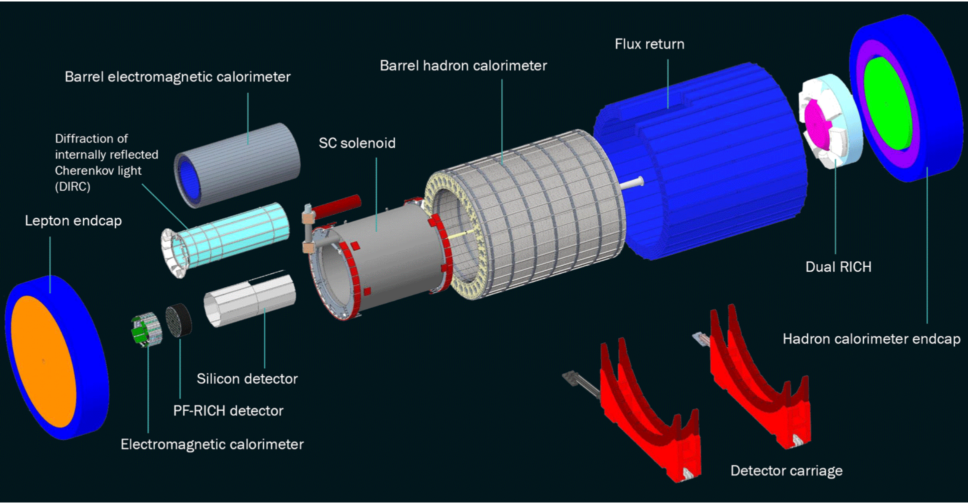
- Scattered electron goes into endcap - i.e. it has small scattering angle w.r.t. electron beam, and large momentum.
- Detector needs very good tracking and EMCal resolution in the endcap, allowing tracker momentum and calorimeter energy to complement each other.

Cutaway view of the ePIC detector



General requirements for the ePIC detector

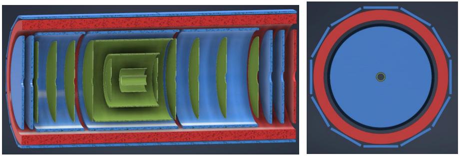
- Large rapidity coverage of central detector + specialized FF & FB detection systems.
- Hermetic coverage of tracking, electromagnetic & hadronic calorimetry.
- High precision low mass tracking and high performance PID for π, K, and p, separation.
- High control of systematics (luminosity monitors, electron & hadron polarimetry).

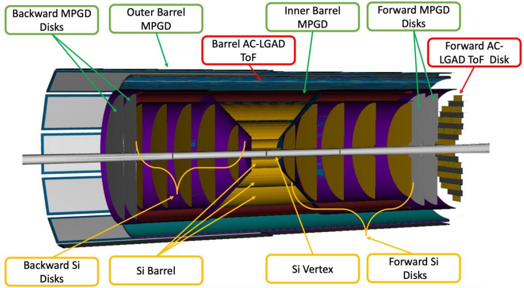


ePIC tracking system and particle identification

MPGD and AC-LGAD TOF detectors provide

- additional hit points for track reconstruction,
- fast timing (~ 20 ps) hits for background rejection.





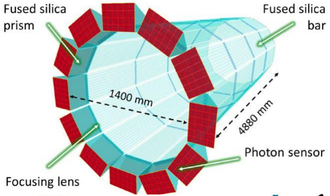
Silicon Vertex Tracker (**SVT**)

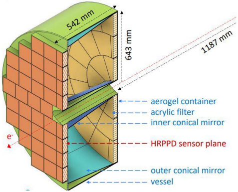
Inner Barrel (IB)	Outer Barrel (OB)
2 curved silicon vertex layers	1 stave-based sagitta layer
1 curved dual-purpose layer	1 stave-based outer layer

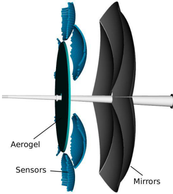
Electron/Hadron Endcaps (EE, HE) - 5 disks on each side of IP

High-Performance DIRC (**hpDIRC**)

- Quartz bar radiator; MCP-PMTs sensors.
- π/K separation up to 6 GeV/c.







Proximity Focused (**pfRICH**)

- Long Proximity gap (~ 40 cm)
- Sensors: HRPPDs (also provides timing)
- e/π (< 2.5 GeV/c), π/K (< 10 GeV/c)

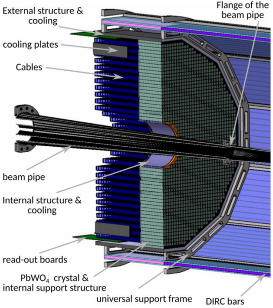
Dual-Radiator RICH (**dRICH**)

- C_2F_6 Gas Volume and Aerogel.
- Sensors: SiPMs tiled on spheres.
- π/K separation up to 50 GeV/c

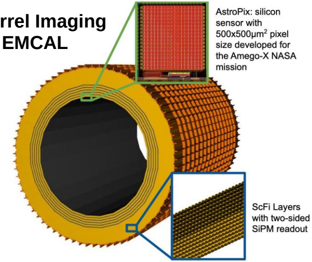
ePIC electromagnetic calorimetry

Electron Endcap EMCal

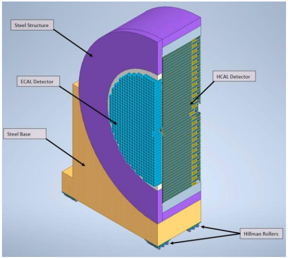
$PbWO_4$ crystals



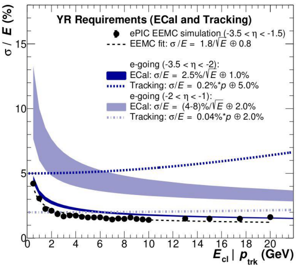
Barrel Imaging EMCAL

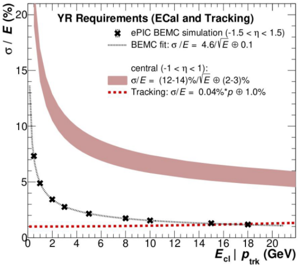


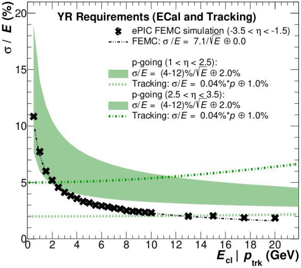
Hadron Endcal EMCal



High granularity W-powder/SciFi EMCal

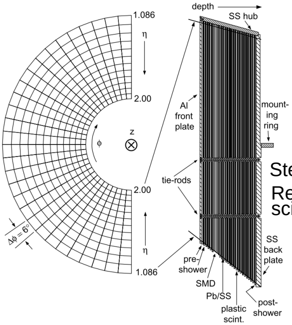


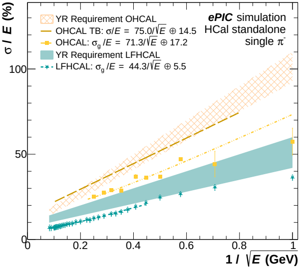


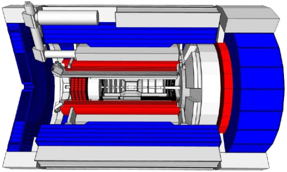


ePIC hadronic calorimetry

Electron Endcap HCal







Steel/Sci (10 l.)

Reuse of STAR scint. tiles

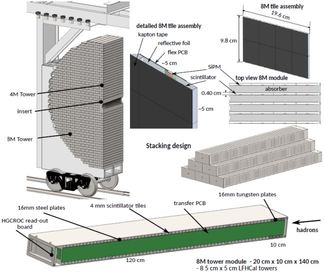
Barrel HCal

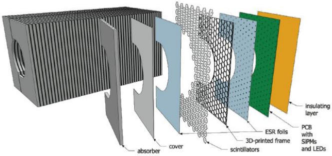
sPHENIX BHCal with new SiPMTs

Hadron Endcap HCal

Longitudinally separated HCAL Steel/Scint. & W/Scint. sandwich

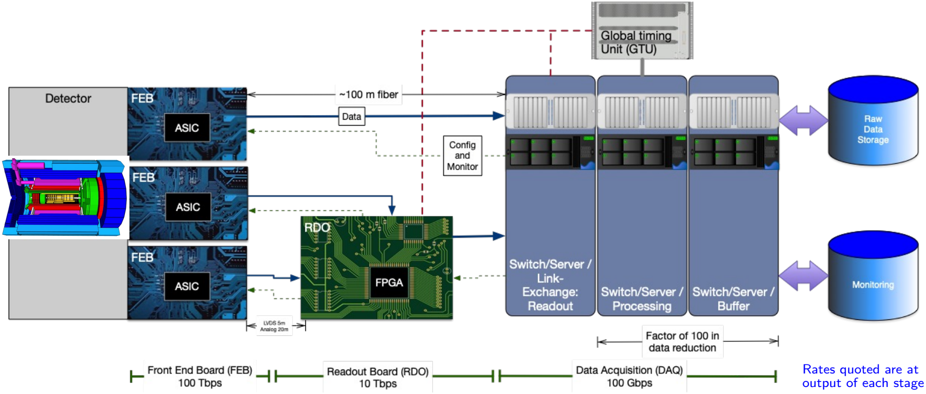
SiPM-on-tile readout





High-granularity insert at most forward pseudorapidity to aid in reconstructio of HFS

DAQ - streaming readout architecture



Rates quoted are at output of each stage

- Triggerless streaming architecture gives much more flexibility to do physics.
- No external trigger - event selection can be based on full data from all detectors.
- All collision data digitized, but zero suppressed at FEB.
- Low/zero deadtime.
- Collision data flow is independent and unidirectional - no global latency required.
- Data volume is reduced as much as possible at each stage ensuring that biases are controlled.