Zderzacz Elektronowo-Jonowy
Nowe narzędzie dla fizyki wysokich energii

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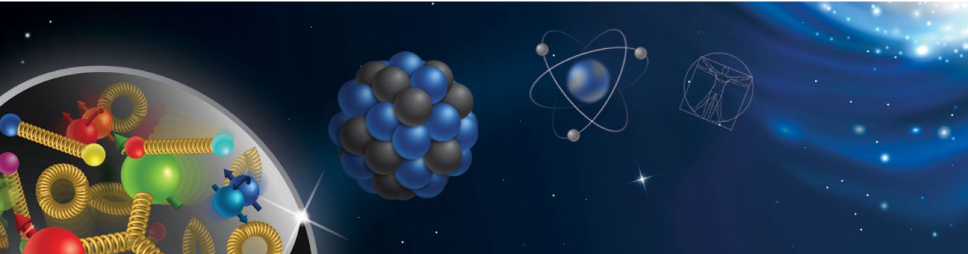
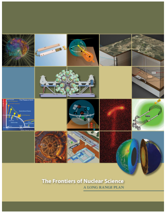
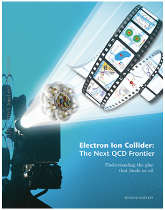
Seminarium WFiIS, 27.11.2020

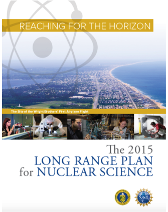


Electron-Ion Collider (EIC) timeline

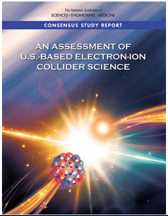


- 2007 NSAC Long Range Plan for Nuclear Science
  "An Electron-Ion Collider (EIC) with polarized beams has been embraced by the U.S. nuclear science community as embodying the vision for reaching the next QCD frontier."
- EIC: The Next QCD Frontier (White Paper), 2012
  "Understanding the glue that binds us all"





- 2015 NSAC Long Range Plan for Nuclear Science
  (Nuclear Science Advisory Committee - advises DoE and NSF on future nuclear pysics projects)
  "Construct a high-energy high-luminosity polarized electron-ion collider (EIC) as the highest priority for new construction following the completion of FRIB."



- An Assessment of U.S.-Based Electron-Ion Collider
  (The National Academies of Science-Engineering-Medicine, 2018)
  "The committee finds that the science that can be addressed by an EIC is compelling, fundamental and timely."

US DoE: Brookhaven National Laboratory to host EIC

- January 9, 2020, WASHINGTON, D.C. – The U.S. Department of Energy (DoE) announced the selection of Brookhaven National Laboratory (BNL), Upton, NY as the site for a planned major new nuclear physics research facility.

  "The Electron Ion Collider (EIC), to be designed and constructed over ten years at an estimated cost between \$1.6 and \$2.6 billion, will smash electrons into protons and heavier atomic nuclei in an effort to penetrate the mysteries of the "strong force" that binds the atomic nucleus together."

- "The EIC promises to keep America in the forefront of nuclear physics research and particle accelerator technology, critical components of overall U.S. leadership in science," said U.S. Secretary of Energy Dan Brouillette. "This facility will deepen our understanding of nature and is expected to be the source of insights ultimately leading to new technology and innovation."

- Funding for the EIC is subject to annual appropriations by Congress.

- This decision was taken after almost ten years of competition between BNL and Jefferson National Laboratory (JLAB) on pure merit foundations.

Brookhaven National Laboratory (BNL)

Brookhaven National Laboratory (BNL)

BNL is one of the leading national laboratories in the USA:

- Relativistic Heavy Ion Collider (RHIC) – nuclear and particle physics, discovery of the Quark-Gluon Plasma (QGP), current experiments: STAR and PHENIX.
  RHIC will provide crucial infrastructure for the new Electron Ion Collider.
- National Synchrotron Light Source-II (NSLS-II) – research with use of one of the brightest light sources (X-ray, ultraviolet and infrared), in the world, e.g. biology, material sciences, semiconductors, etc.
- Center for Functional Nanomaterials (CFN) – open facility for the nanoscience research community and advance the science of nanomaterials,
- NASA Space Radiation Laboratory (NSRL) – use of heavy ions from accelerator to simulate space radiation and study its effects on biological specimens - such as cells, tissues, and DNA - and also industrial materials,
- Accelerator Test Facility – provides users with high-brightness electron- and laser-beams for studying properties of modern accelerators and new techniques of particle acceleration,
- Quantum Research Center - one of five recently awarded by the U.S. DoE centers to conduct basic research in quantum information science.

Key Partners Mark Launch of Electron-Ion Collider Project

- September 18, 2020: Video relation from the meeting available on YouTube
- Key Partners: DoE, Brookhaven Lab, Jefferson Lab, New York State ($100M)
- BNL and JLAB are expected to closely collaborate.
- Special position of the Stony Brook University (closest university, long standing cooperation with BNL)

  New division established for EIC project – Center for Frontiers in Nuclear Science
- Lieutenant Governer of NY Kathleen Hochul:

  "... in scientists we trust, all others we verify ..."
- Senator Kirsten Gillibrand:

  "... this project will keep the United States at the forefront of nuclear physics research ..."
- Senator Chuck Schumer:

  "... science, science, science equals jobs, jobs, jobs ..."
- EIC Project Manager Diane Hatton:

  "... EIC will be a flagship nuclear physics facility, that enables worldwide physics community to solve some of the most challenging scientific questions ..."

A brief history of the proton and its structure

- No Nobel Prize for the discovery of the proton! - discovery assigned to E. Rutherford (1919-1925) - studying reactions like ${}^{14}_{7}\mathrm{N} + \alpha \rightarrow {}^{17}_{8}\mathrm{O} + {}^{1}_{1}\mathrm{H}$ proved that "the hydrogen nucleus is present in other nuclei" (Prout's hypothesis from 1815 regarding atoms).

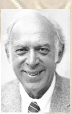
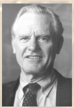
- 1933: Proton's magnetic moment
  $\Rightarrow$ Nobel Prize in Physics 1943:

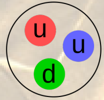
$$\vec{\mu} = g\frac{q}{2m}\vec{S}$$

Dirac's particle: $g = 2$
$\Rightarrow$ proton: $g > 2$

O. Stern "for ... and his discovery of the magnetic moment of the proton."

- 1969: Deep inelastic e-p scattering
  $\Rightarrow$ Nobel Prize in Physics 1990:



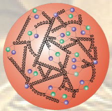
J.I. Friedman, H.W. Kendall, R.E. Taylor
"for their pioneering investigations concerning deep inelastic scattering of electrons on protons ..."

- 1960: Elastic electron-proton scattering
  $\Rightarrow$ Nobel Prize in Physics 1961:

measuring proton form factors, determined charge distribution
$\Rightarrow$ proton is an extended object

R. Hofstadter "for ... and for his thereby achieved discoveries concerning the structure of the nucleons"

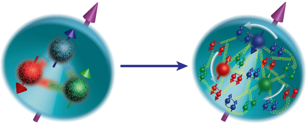
- 1974: QCD Asymptotic Freedom
  $\Rightarrow$ Nobel Prize in Physics 2004:



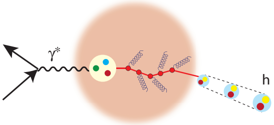

D.J. Gross, H.D. Politzer, F. Wilczek
"for the discovery of asymptotic freedom in the theory of the strong interaction"

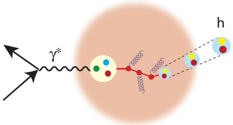
Open questions in QCD - main physics goals of the EIC

- 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?

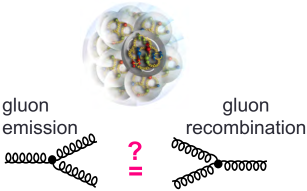


- How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?
- How do the confined hadronic states emerge from these quarks and gluons?
- How do the quark-gluon interactions create nuclear binding?



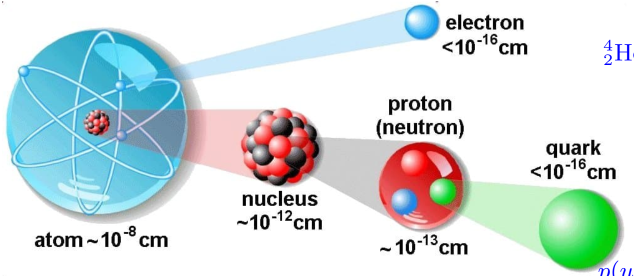


- How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?
- What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?

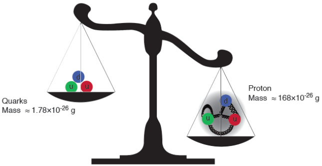


Mass of the nucleon

- Mass of a molecule is lower than the masses of the atoms from which it is constructed. Mass of an atom is lower than the sum of masses of its nucleus and the electrons. These binding energies are responsible for all the phenomena in chemistry, condensed matter physics, material science, nanoscience, etc.
- Mass of a nucleus is lower than the masses of the protons and neutrons - nuclear energy.
- Mass of the nucleon (and other hadrons) is much higher than the masses of the quarks from which it is made of.
  - The Higgs mechanism is far from enough!!! ($\sim 1\%$)
  - The rest of its mass comes from energy related to quantum fluctuations of QCD vacuum - quarks and gluons are moving relativisticaly, and color is fully entangled.



${}^4_2\mathrm{He}$: $3749.7 - 3727.4 = 22.3\,\mathrm{MeV}$

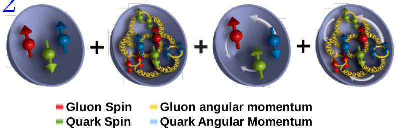


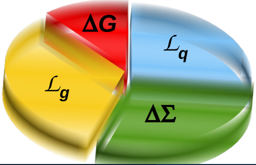
$p(uud)$: $9.4 - 938.3 = -928.9\,\mathrm{MeV}$

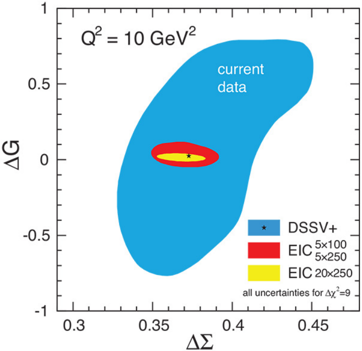
Spin of the nucleon

- 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 (and we use it, e.g. in MRI) that the spin of the nucleon is $1/2$, but we do not understand in full details its origin.
- 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:

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \mathcal{L}_q + \mathcal{L}_g$$





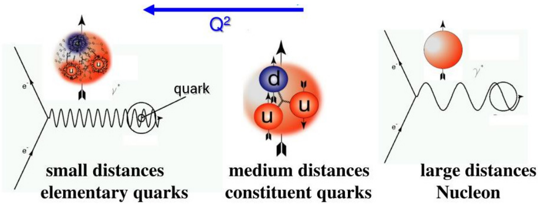


Deep Inelastic electron-proton(nucleon) Scattering (DIS)

- Virtuality of the probe - measure of resolution power:

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

$$\mathbf{Q^2 = 2E_eE'_e(1 - \cos\theta_e)}$$



- Relative lepton energy loss (inelasticity):

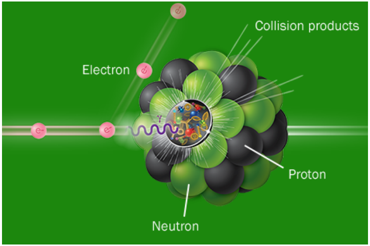
$$\mathbf{y = \frac{p\cdot q}{p\cdot k} = 1 - \frac{E'_e}{E_e}\cos^2\left(\frac{\theta_e}{2}\right)}$$

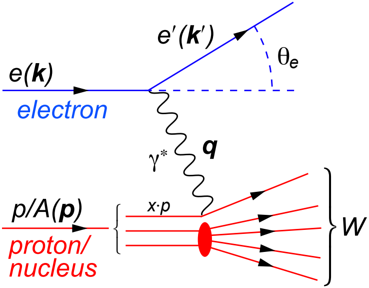
- Momentum fraction of struck quark:

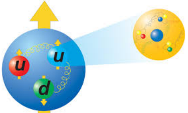
$$\mathbf{x = \frac{Q^2}{2\,p\cdot q} = \frac{Q^2}{sy} \approx \frac{Q^2}{W^2 + Q^2}}$$

- CMS energies squared in ep and γp frames:

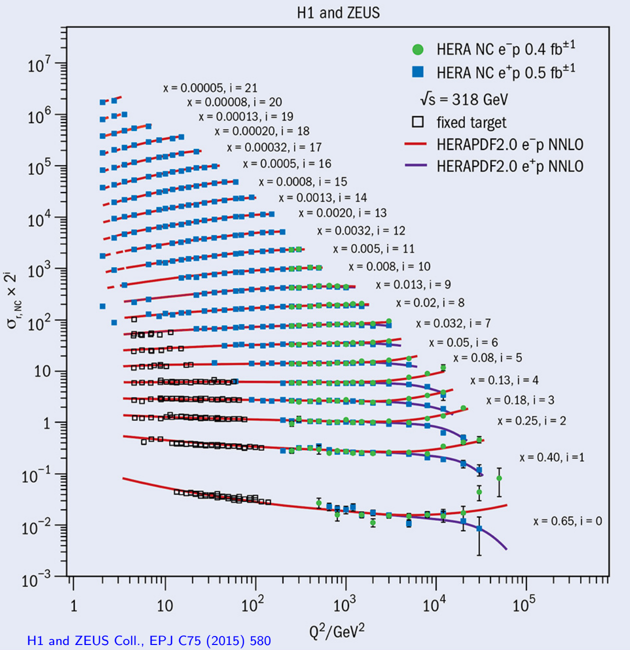
$$\mathbf{s = (k+p)^2 = 4E_eE_p} \qquad \mathbf{W^2 = (q+p)^2}$$







The legacy of HERA



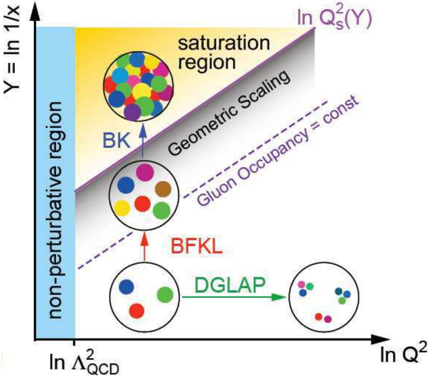
H1 and ZEUS Coll., EPJ C75 (2015) 580

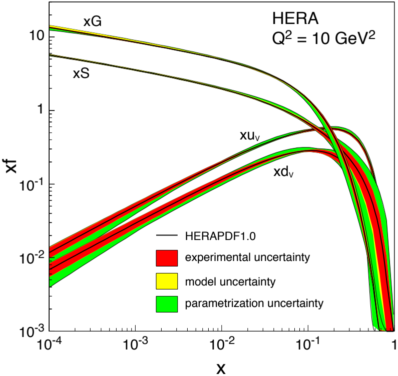
- Covers five orders of magnitude in x and Q^2.
- Consistency with old fixed-target data.
- Scaling with Q^2 at $x \sim 0.1$, and scaling violation elsewhere.
- Splitting at high Q^2 results from $\gamma - Z$ interference term.
- Crucial input to PDF fits: any parton at given x and Q^2, can be source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

Parton distribution functions (PDFs) in the proton

- Gluon density at low-x is strongly rising - what tames this rise?
  - “Black disk limit”: unitarity bound on cross section.
  - Saturation scale $Q_S^2(x)$: where gluon emission and recombination become comparable (BK-JIMWLK evolution, non linear).

  - Gluons start to overlap when $\frac{\alpha_s}{Q^2} xG(x, Q^2) = \pi R_p^2 \;\; \Rightarrow \;\; \ln Q_S^2(Y) = \lambda Y$.
  - Gluon recombination leads to a collective gluonic system, a phenomenon universal for both nucleons and nuclei, which presence has been hinted in heavy-ion experiments.

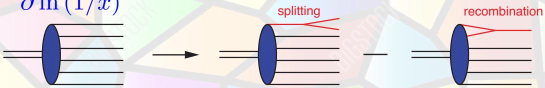


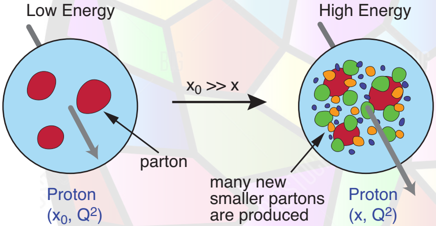


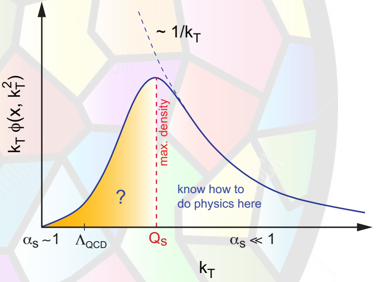
High energy limit of QCD - Color Glass Condensate (CGC)

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

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







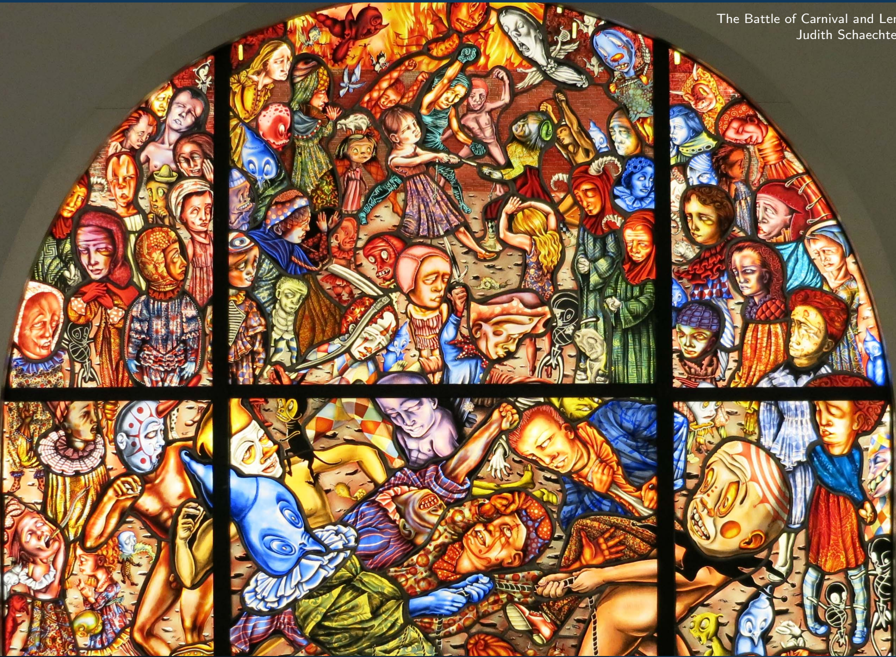
"Color Glass Condensate"

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.

Color Glass Condensate in the QCD engineering era?



The Battle of Carnival and Lent
Judith Schaechter

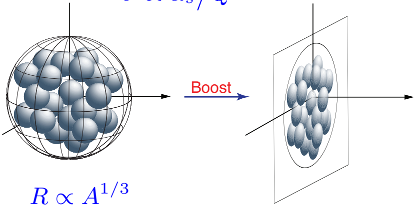
Access to gluon saturation via electron-ion collisions

- Gluon density per unit of transverse area:

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

- Cross section for gluon recombination:

$$\sigma \propto \alpha_s/Q^2$$



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

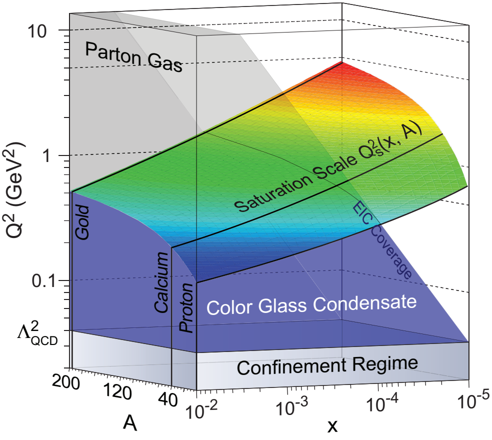
- Saturation for:

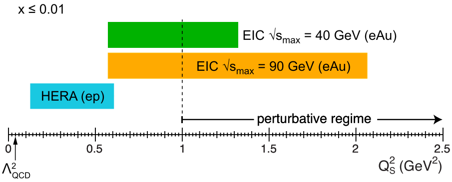
$$1 < n\sigma \quad \Rightarrow \quad Q^2 < Q_S^2(x) \propto A^{1/3}\left(\frac{1}{x}\right)^{\lambda}$$

where $\lambda = 0.2 - 0.3$.

- Saturation regime would be accessible at much lower energy in e+A collisions than ep - we do not need a TeV collider.

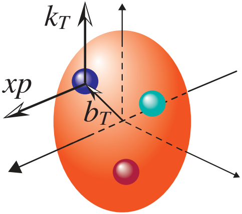
$\Rightarrow$ High potential for a discovery and study at the EIC!





Multi-dimensional nucleon tomography

- The nucleon is much more complicated!
  - partons also have transverse momentum $\vec{k}_T$
  - and are spread in impact parameter space $\vec{b}_T$
- Wigner function: full phase space parton distribution of the nucleon - Generalised Transverse Momentum Distributions (GTMDs):



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

$\int d\vec{b}_\perp$ ↓ $f(x, \vec{k}_\perp)$ **TMD**

$\int d\vec{k}_\perp$ ↓ **GPD** $f(x, \vec{b}_\perp)$

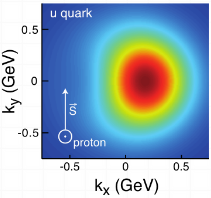
$f(x, \vec{k}_\perp)$ → $\int d\vec{k}_\perp$ → $f(x)$ **PDF**

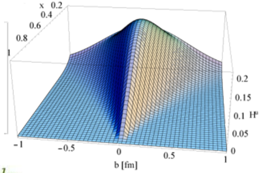
$f(x, \vec{b}_\perp)$ → $\int d\vec{b}_\perp$ → $f(x)$ **PDF**

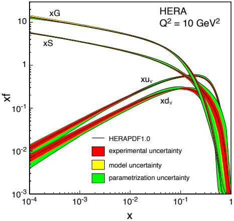
$f(x, \vec{b}_\perp)$ → $\int dx$ → **Form Factor** $F(\vec{b}_\perp)$

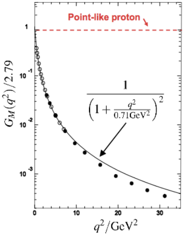
$f(x)$ → $\int dx$ → Q **charge**

$F(\vec{b}_\perp)$ → $\int d\vec{b}_\perp$ → Q **charge**

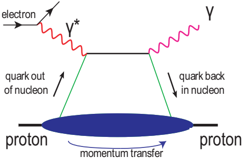


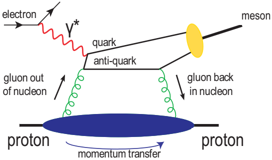


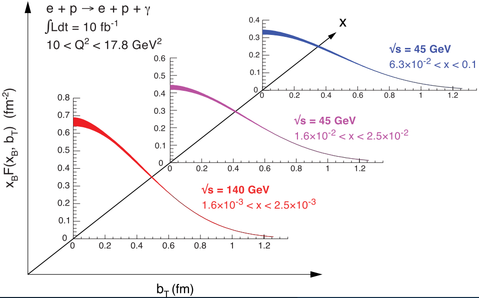


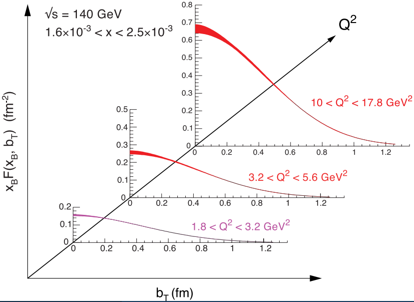


- EIC will enable parton "femtoscopy" - correlating information on parton contributions to the proton's spin with their transverse momentum and spaciall distribution.
- The 3D parton structure (GPDs) is uncovered in DIS by measurements of exclusive final states, wherein the proton remains intact, e.g. DVCS and DVMP (J/ψ, ϕ, π, K).
- Transverse position of the scattered parton is obtained from a Fourier transform of the $d\sigma/dt$.
- GPDs provide information on e.g. the total quark angular momentum and total gluon angular momentum of the proton.



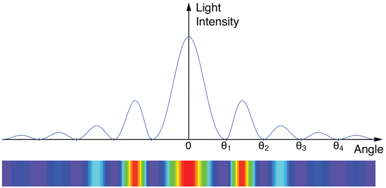




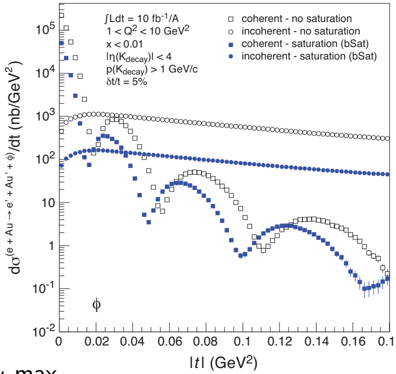


Diffraction in high energy physics

- Diffraction in optics - plane wave with wave number k incident on an obstacle of radius R - positions of minima at $\theta_i \sim 1/(kR)$.
- Analogous diffractive pattern exhibits cross section for elastic staterring of a hadron on nucleus $d\sigma_{el}/dt$.



- Identifying the projectile hadron with the plane wave and obstacle with nucleus, and writing $|t| \approx k^2\theta^2$, the patterns become similar ⇒ describe very similar physics, e.g. the minima are also related to the inverse size of the target, $|t_i| \sim 1/R^2$.
- Essential differences between QCD and wave optics:
  - proton/nuclear target is not always "black disk": in DIS, the photon with lower Q^2 (probing larger distances) is more sensitive to saturation physics - the diffractive cross section arises from exchanges of several partons with zero net color between the target and the projectile.
  - projectile or target may break up - the event is diffractive if there is a rapidity gap, although the cross section does not exhibit the diffractive min & max.



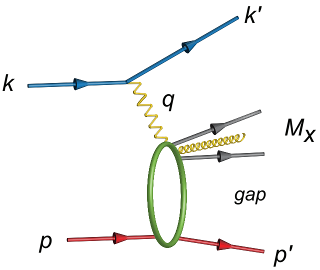
EIC - best place to study diffraction in 21th century

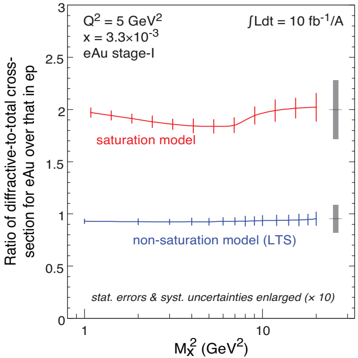
- Diffraction in the ep or $e{+}A$ collisions proceeds via exchange of a color neutral object called Pomeron (two gluons in the lowest pQCD order).
- Define additional (to DIS) kinematic variables:

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

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

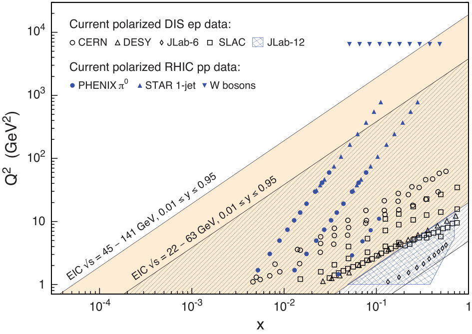
- Diffractive processes are most sensitive to the underlying gluon distribution and give access to the spacial distribution of gluons in nuclei.
- Production of (heavy) VM sensitive to saturation effects in nuclei.
- Special detection techniques required (Roman Pot detectors for scattered protons and 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!

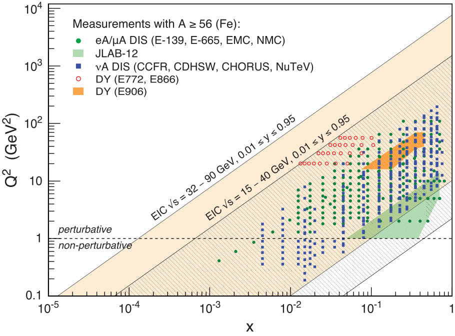




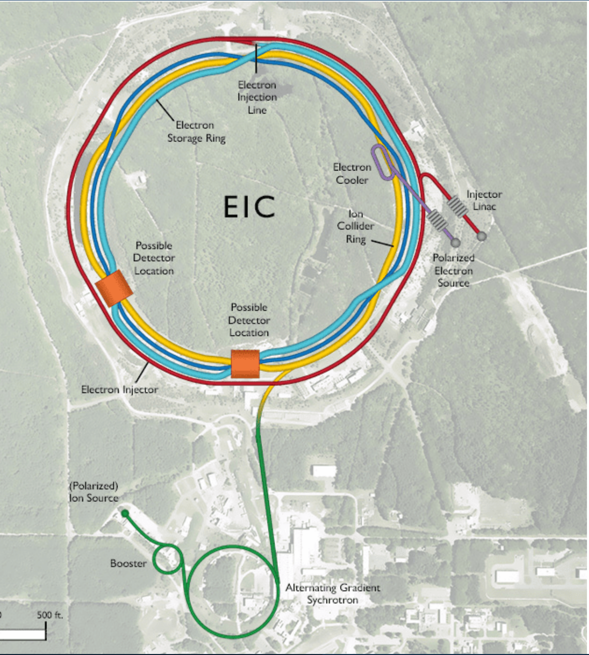
Kinematic coverage for the EIC

- 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.





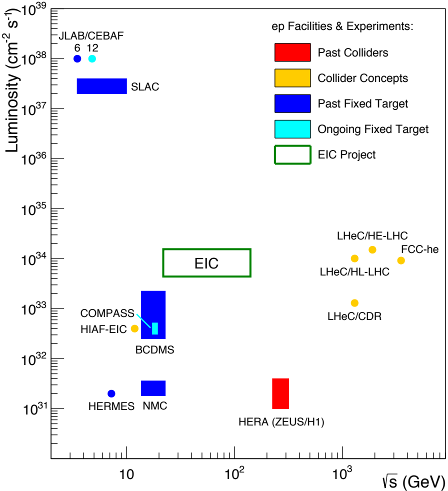
EIC accelerator parameters

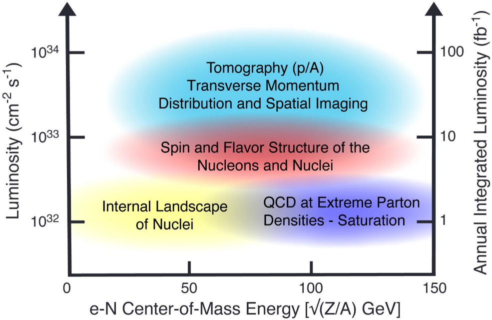


- Make use of existing RHIC infrastructure: ion sources, pre-accelerator chain, ion storage ring (circum. 3.83 km).
- New: electron source, electron accelerator, storage ring.
- Beam energies:
  $E_e = 2.5 - 18$ GeV
  $E_p = 40 - 275$ GeV
  $E_A = (Z/A)E_p$
- $\sqrt{s_{ep}} = 20 - 141$ GeV
- # of bunches per beam: 1320; collision every 8.9 ns
- Luminosity: $\sim 10^{34}$ cm^{-2}s^{-1}
- Beams polarization: $> 70\%$
  e, p, and light ions: d, ^{3}He (longitudinal and transverse)
- Ion species: p - Uranium
- # of interaction regions: $1 - 2$

Uniqueness of the EIC among DIS Facilities and key physics

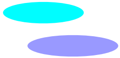
- High luminosity & wide reach in $\sqrt{s}$.
- No other facility has plans for:
  - polarized lepton & hadron beams,
  - (polarized) nuclear beams.





Inclusive DIS - measure scattered electron with high precision,

Semi-inclusive DIS - detect the scattered lepton and final state (jets, hadrons, correlations),



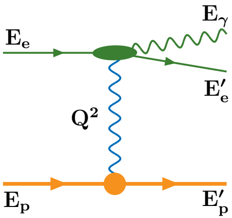
Exclusive processes (diffraction) - all particles are identified.

Luminosity measurement at the EIC

- Luminosity, L, is a coefficient which relates the number of observed events of a given process with its cross section:

$$N = L \cdot \sigma$$

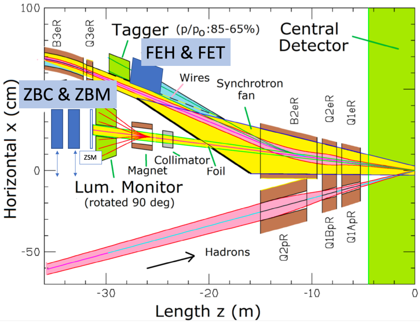
- Luminosity is determind using a process for which the cross section is well known theoretically and which has a clean experimental signature - e.g. Bremsstrahlung at ep colliders.



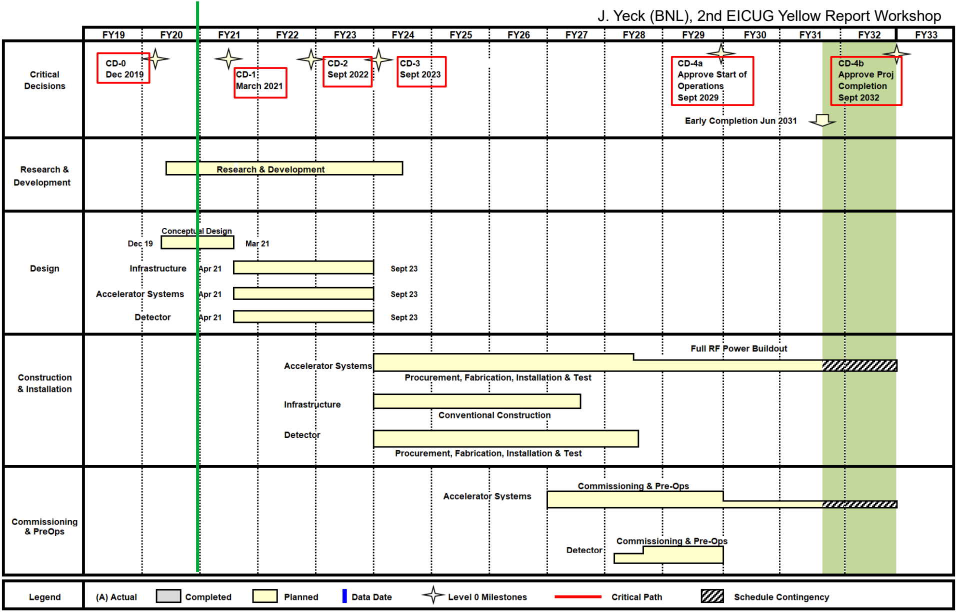
- Luminosity depends on beams parameters at the interaction point, and its uncertainty directly limits the precision of cross-section measurements.

- Precise luminosity measurement at the EIC, with $\delta L/L < 1\%$, 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).



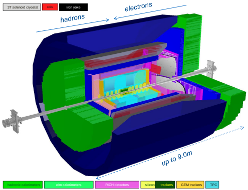
EIC construction schedule



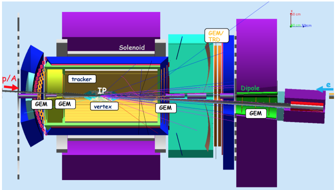
The EIC detector concepts

- EIC community desires two general-purpose detectors (standard at other colliders).
- Estimated cost $\sim \$300$M/detector requires strong international participation.
- Rough concepts exist but work is ongoing on refined designs (CDR 2021; R&D ~ 2024).
- EIC detectors are unique and challenging to realize:
  - Hermetic ($\sim 4\pi$ coverage, $|\eta| < 4 +$ forward detectors).
  - High resolution in momentum/energy of reconstructed particles.
  - Particle identification needed in unprecedented wide range from 0.25 GeV to 50 GeV.

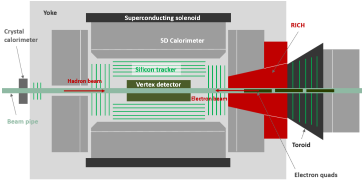
BNL concept: BEAST



JLAB concept: JLEiC



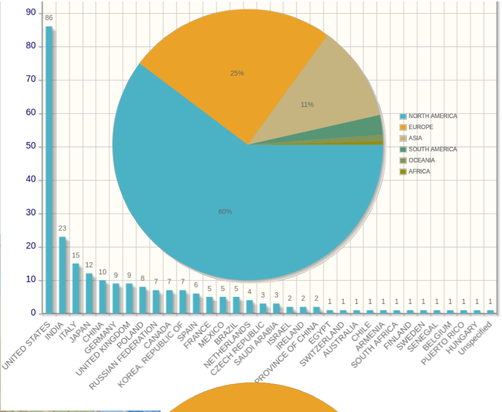
ANL concept: TOPSiDE

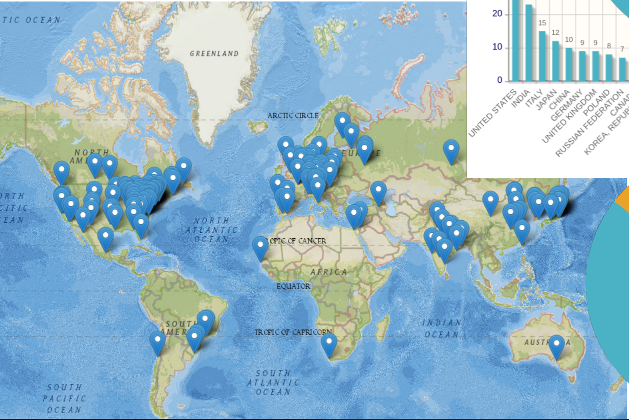


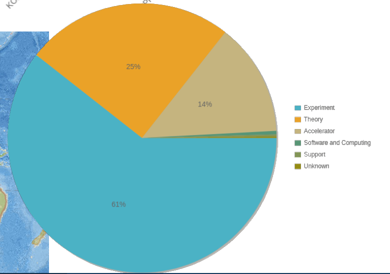
- The experimental collaboration(s) which will build and later operate the detector(s) will be established in the next year, and it is expected that each will consist of ~ 500 people.

Electron-Ion Collider User Group

- Current statistics:
  - ~ 1200 members (Poland - 27),
  - 243 institutions (Poland - 8),
  - 33 countries
- Institutional Board,
- Annual meetings - 2021, Warsaw, Poland







EIC and the Polish HEP Community

- Currently eight Polish institutions expressed interest in the EIC project:
- Presentation of Polish HEP Community Expressing Interest in the EIC project at BNL (slides) at the last EIC User Group Meeting in "Miami", July 15-17, 2020.
- We plan to apply for including the EIC on the Polish Roadmap for Research Infrastructures.
- Any serious involvement in the apparatus building for EIC requires special and significant support from the MNiSW $\rightarrow$ MEiN.
- Nationwide seminars on the EIC physics and machine/detectors for students started on October 19th, and takes place every second Monday at 13:00 - https://indico.bnl.gov/category/318/
- The next EIC User Group Meeting, Warsaw Univ. (or online), August 1-7, 2021.
- Also the 61 Cracow School of Theoretical Physics (Zakopane or online) will be devoted to the EIC physics.

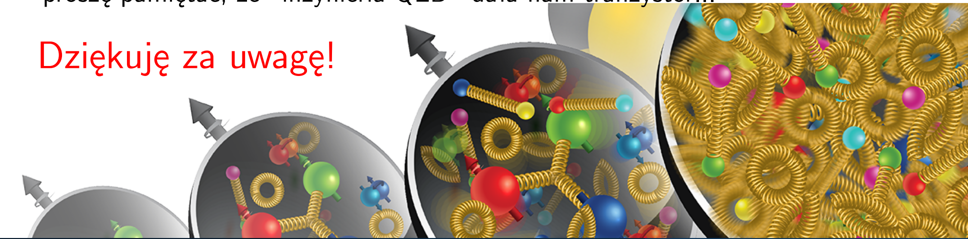
Plans of the AGH UST team

- Current team at FPACS: L. Adamczyk, M. Idzik++, P. Kotko, K. Piotrzkowski (from July 2021), and M. Przybycien.
- For some of us the research on the proton structure at the EIC will be extension of the research performed at the beginnings of our scientfic carriers at the ZEUS experiment at HERA.
- From the perspective of detector related activities at HERA, we were involved in the luminosity detector bulding and the luminosity measurement.
- Luminosity at the EIC will be measured using the same process - bremsstrahlung - as was used at HERA.
- Our plan is that AGH UST makes significant contributions to the construction of the detection apparatus for the measurements of the bremsstrahlung process and for tagging electrons scattered in the very forward direction (photoproduction).
- We have just answered for the call for Expressions of Interest regarding participation in the detector building for an experiment at the EIC.
- The EoI "Instrumentation in the lepton hemisphere" was send by an informal consortium of AGH UST, IFJ PAN, BNL and Temple Univ. with an agreement that the project will be led by AGH UST. Decisions to be made in the mid 2021.

Podsumowanie

- EIC to nowy gigantyczny mikroskop elektronowy (< 0.01 fm) który pozwoli na lepsze zrozumienie własności materii hadronowej i jądrowej.
- Dzięki szerokiemu zakresowi kinematycznemu, swobody w wyborze rodzaju wiązki, możliwości polaryzacji wiązek oraz wysokiej świetlności, EIC pozwoli zmierzyć rozkłady kwarków morza i gluonów w nukleonie oraz w jądrze atomowym, a także zbadać własności QCD w obszarze wysycenia pola kolorowego.
- EIC będzie także narzędziem, które pozwoli na badanie i odkrywanie zjawisk wyłaniających się (emergent) z QCD, takich jak masa i spin nukleonu, a także na określenie roli koloru i gluonów w tym procesie.
- Duże możliwości współpracy i rozwoju dla studentów i doktorantów.
- Jeszcze daleko nam do wykorzystania QCD w zastosowaniach inżynierskich, ale proszę pamiętać, że “inżynieria QED” dała nam tranzystor...

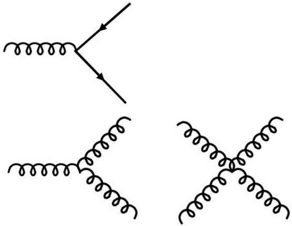
Dziękuję za uwagę!



Backup slides

Gluon in the Standard Model

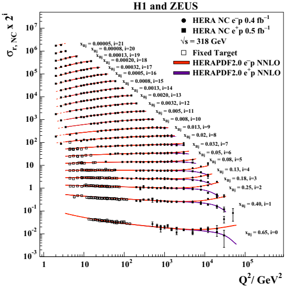
- Discovery of the gluon: TASSO Collaboration, Evidence for a Spin One Gluon in Three Jet Events, Phys. Lett. B 97 (1980) 453-458.
- Gluon: carrier of the strong force (QCD).
- Chargeless, massless, but carries color-charge (color+anti-color).
- Gluons can interact between themselves: three-gluon and four-gluon vertices.
- Gluons carry $\sim 50\%$ the proton's momentum, ?% of the nucleon's spin, and are responsible for the transverse momentum of quarks.

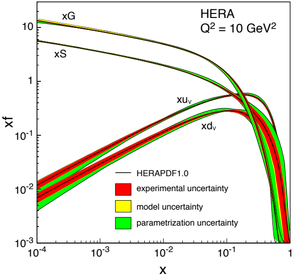


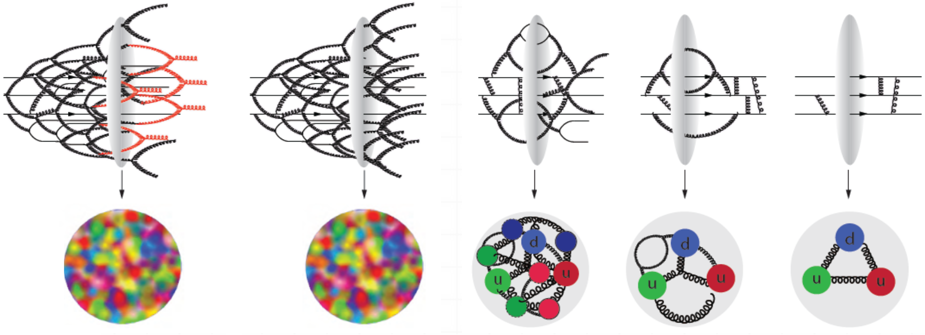
- Massless gluons & almost massless quarks, through their interactions, generate more than 99% of the mass of the nucleons.

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 transvers information to understand the full structure of the proton at high energies.







Interaction region