Physics of future Electron-Ion Collider (EIC)

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NATIONAL CENTRE FOR NUCLEAR RESEARCH ŚWIERK

Standard Model and Beyond, October 21st, 2022, Katowice

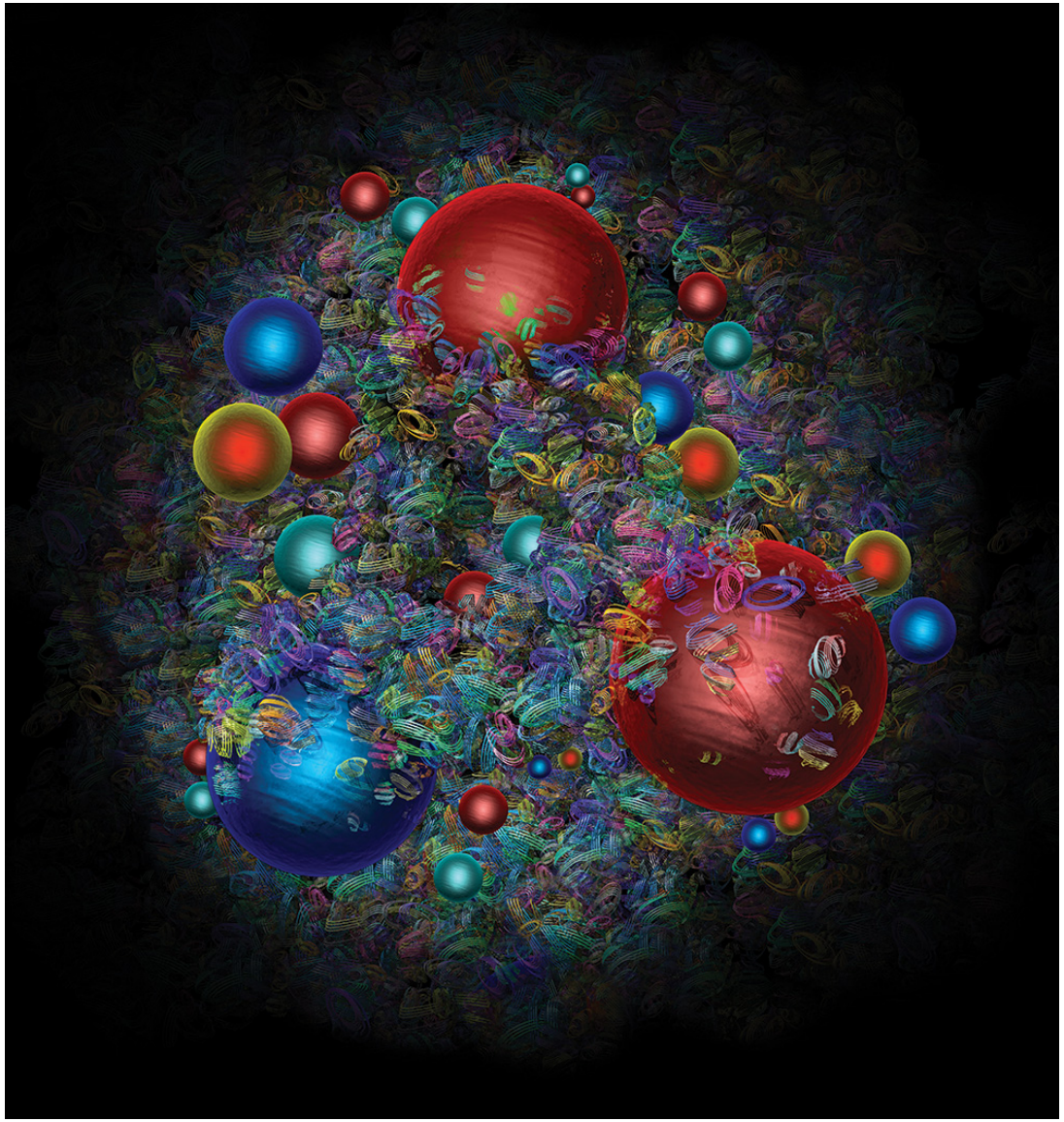
Outline

- General introduction
- EIC project
- Physics case (selected topics)

Introduction

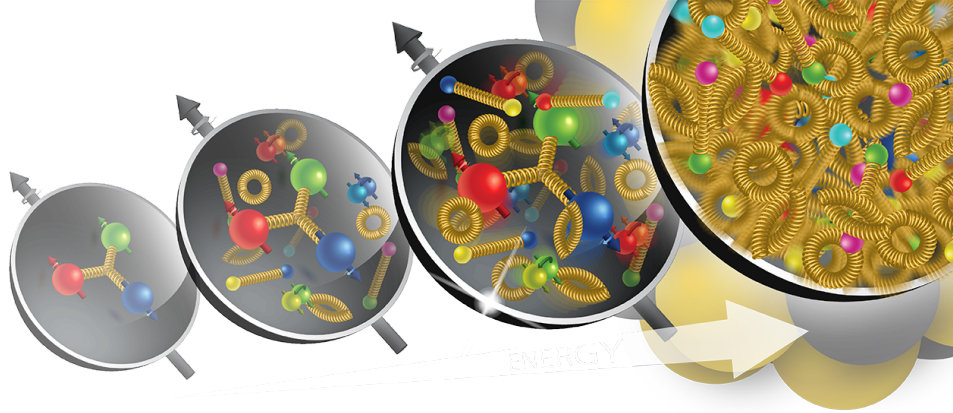
Nucleon is not a point-like particle, it is made out of partons:

- quarks (valance and sea)
- gluons

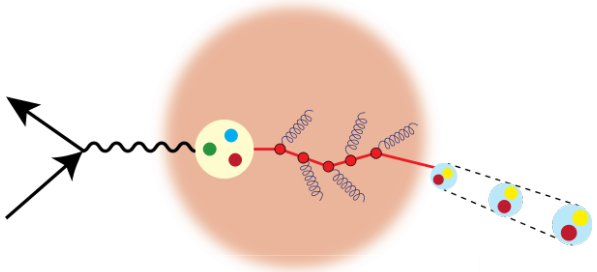


from CERN Courier / D. Dominguez

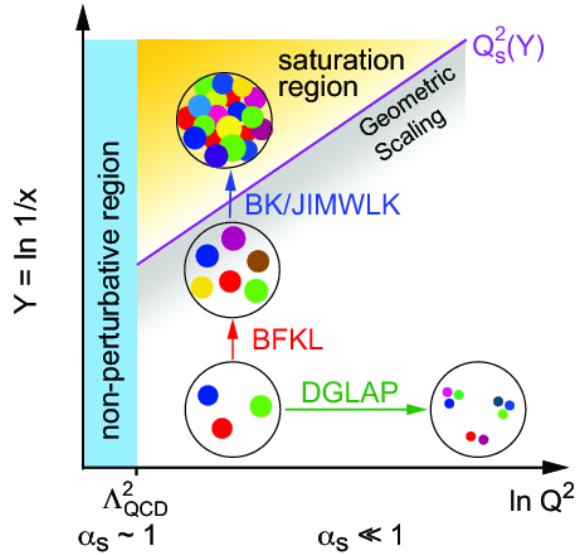
Introduction



- What are momentum distributions of partons?
  For both longitudinal and transverse components.
- How are partons distributed spatially in nucleon?
- How are nucleon properties, such as spin and mass, emerged?



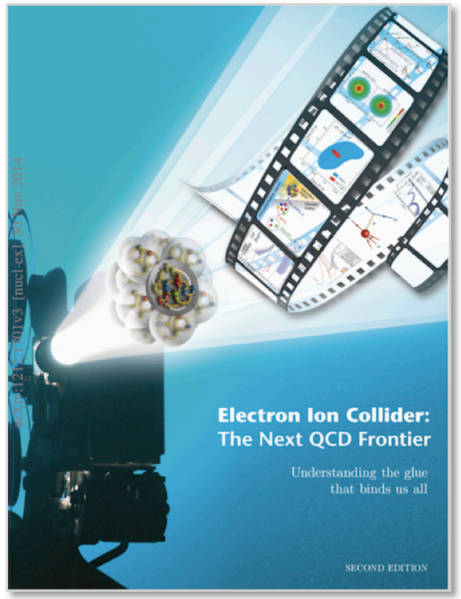
- How does all this information change for nuclei?
- How do interactions between partons form nuclear binding?
- How do probes, such as colour-less jets, interact with nuclear medium?



- What happens with gluon densities in low-x region?
- Are they saturate at high energies, creating a universal gluonic matter?

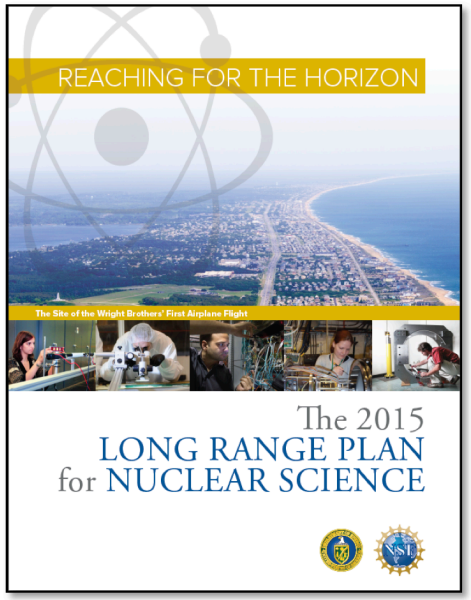
New machine proposed to address these questions: Electron-Ion Collider (EIC)

Milestone publications:



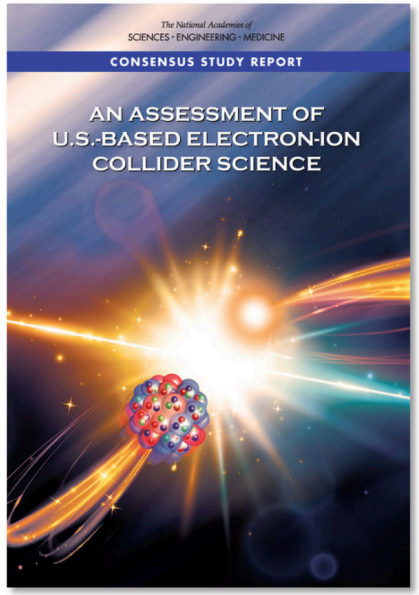
2012

"White paper" - Demonstration of physics case for EIC



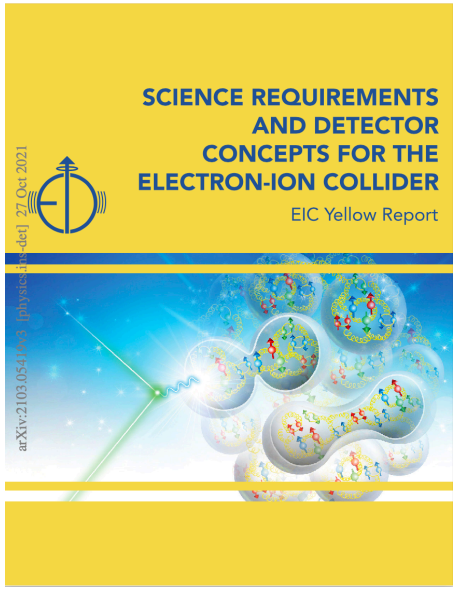
2015

Top recommendation in US Long Range Plan for Nuclear Physics



2017

Assessment of EIC science case



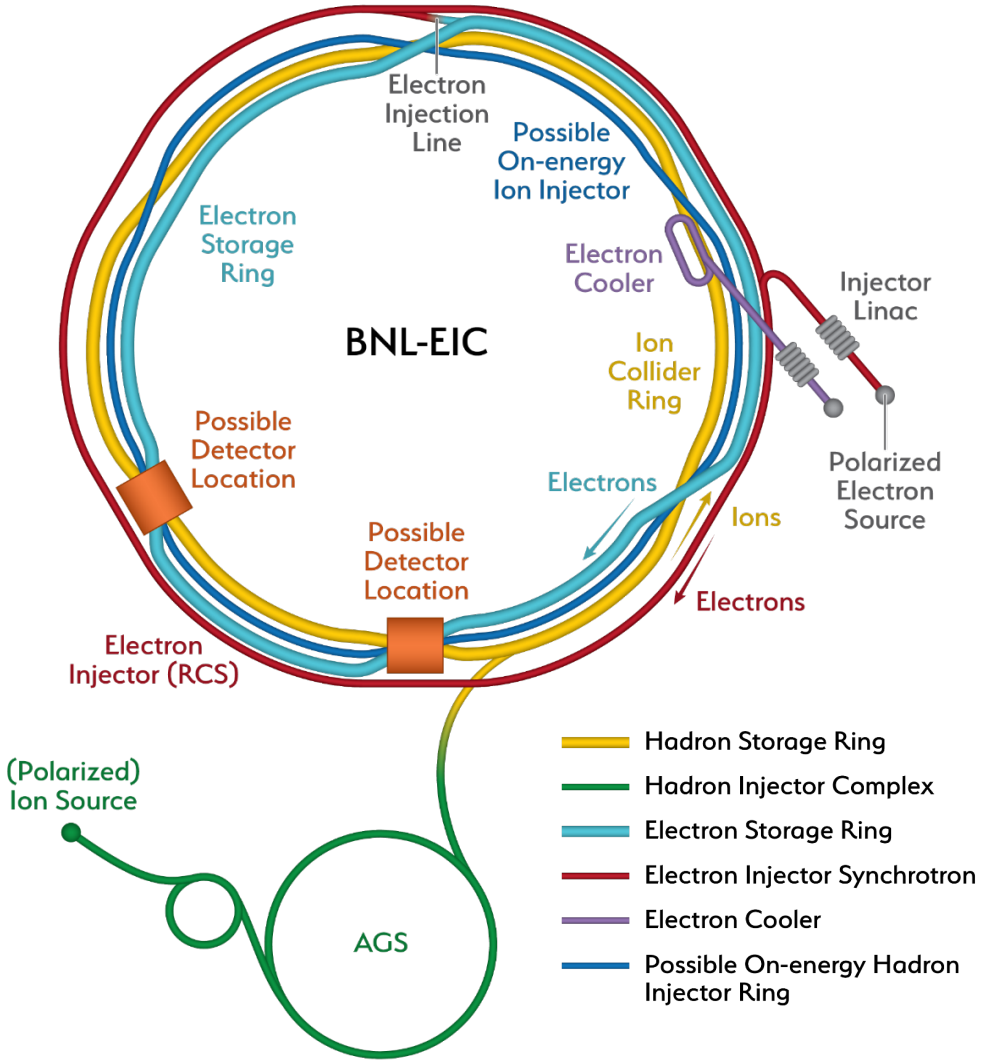
2020

"Yellow paper" - Science requirements and detector concept

2022

Reference detector design

EIC design - accelerator



High energies

Broad range in √s

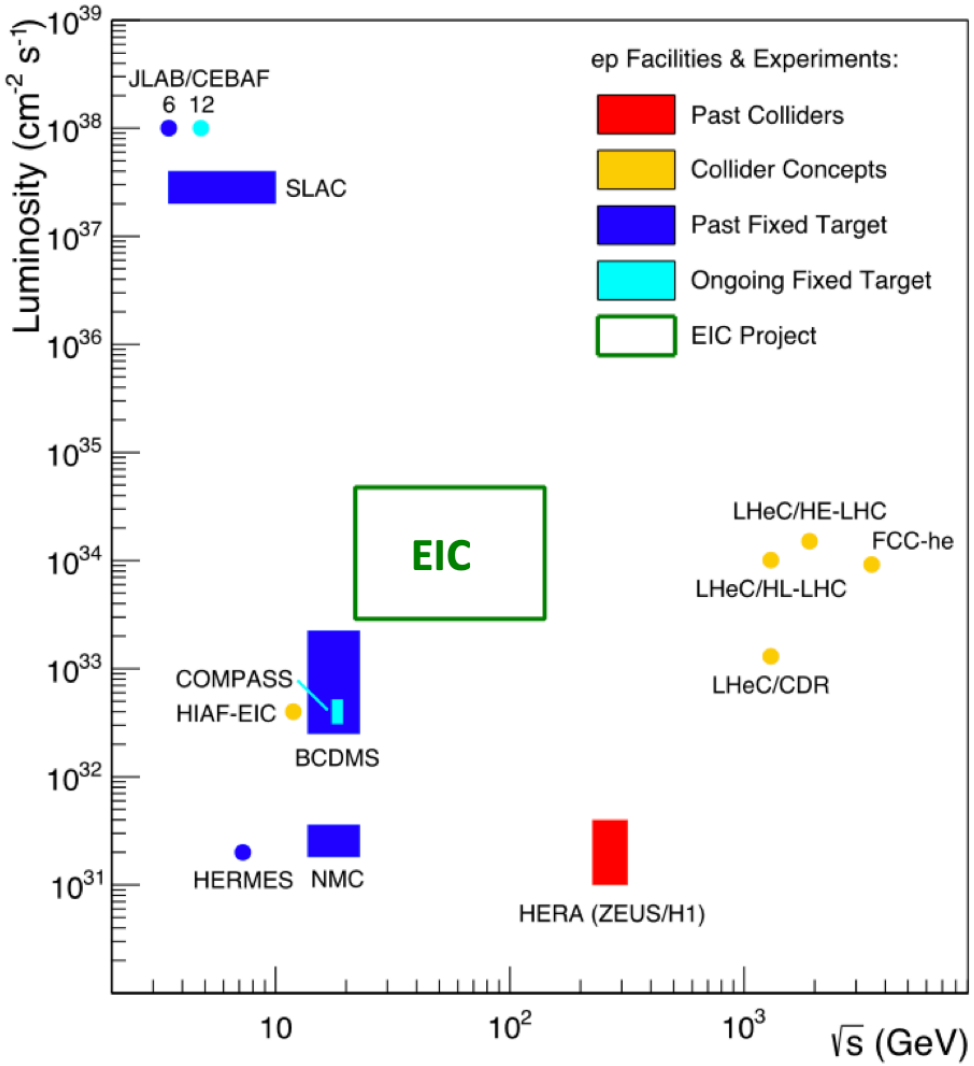
Beam energies	electrons: up to 18 GeV hadrons: up to 275 GeV
Center of mass energy	20 GeV - 140 GeV
Luminosity	10^{33} - 10^{34} $cm^{-2}s^{-1}$ 10 - 100 fb^{-1} / year
Beam polarisations	70%
Hadrons	p to U

~ 100 - 1000 more than in HERA

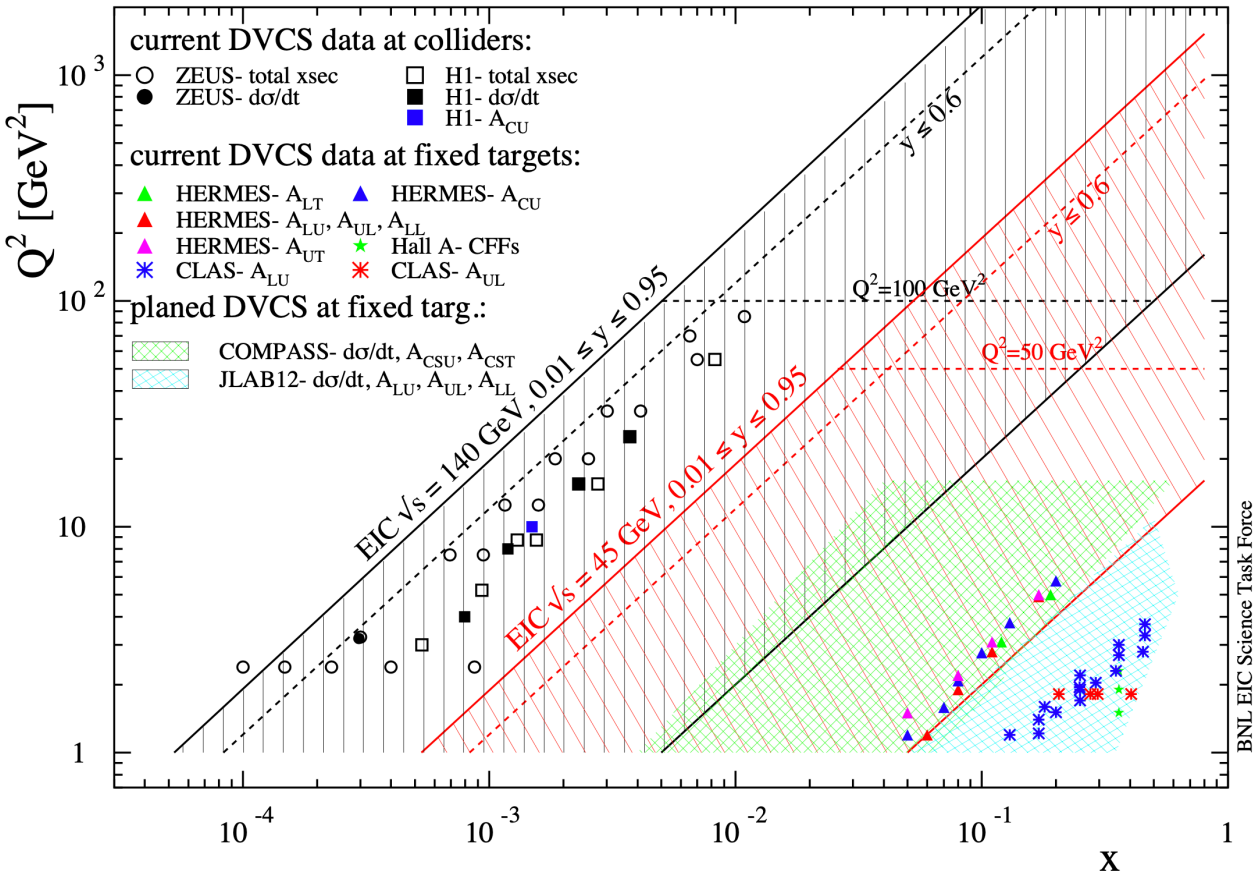
High polarisation

Wide selection of nuclei

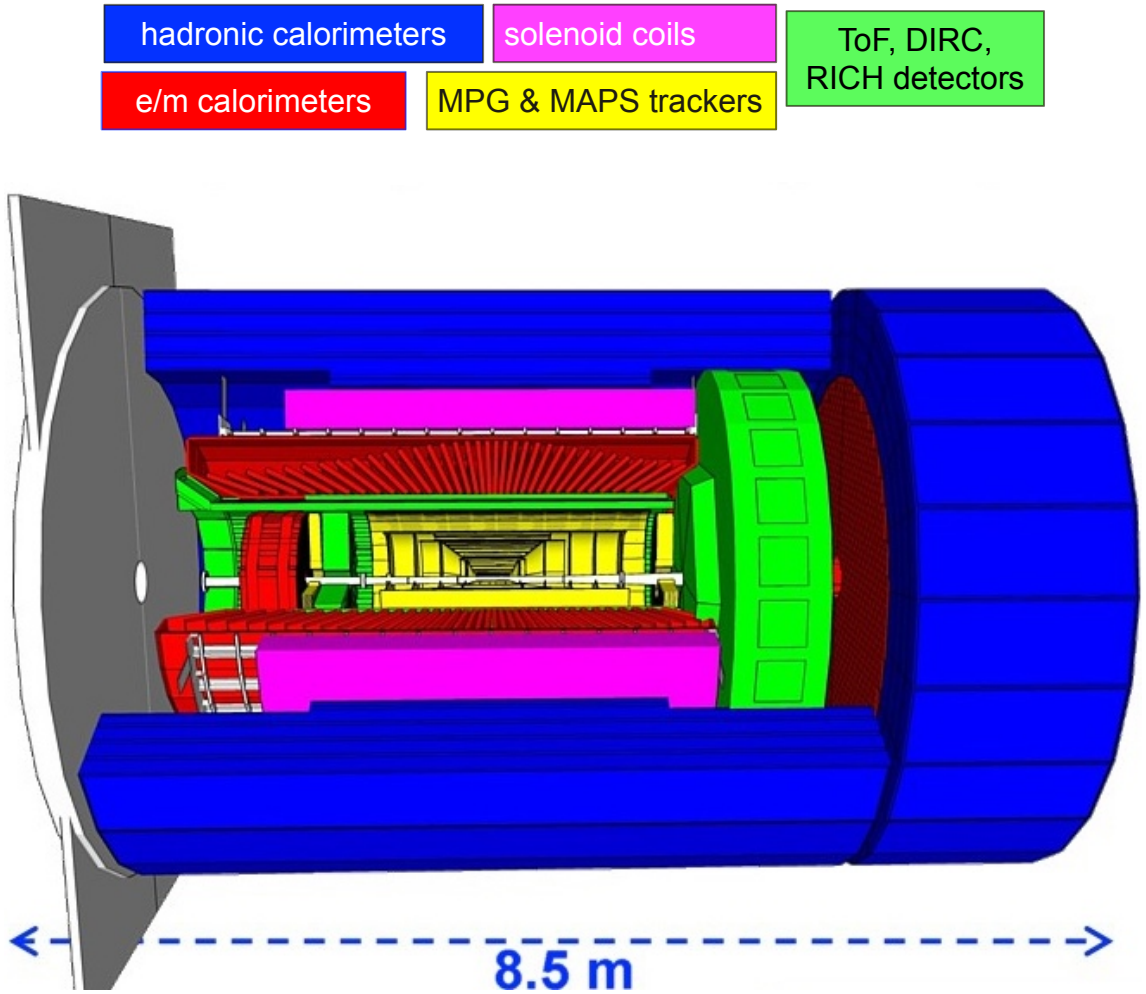
Complementarity with other facilities



- **Wide range of Q^2 → important to study evolution effects**
- **Wide range of x → from valance region to low-x physics**



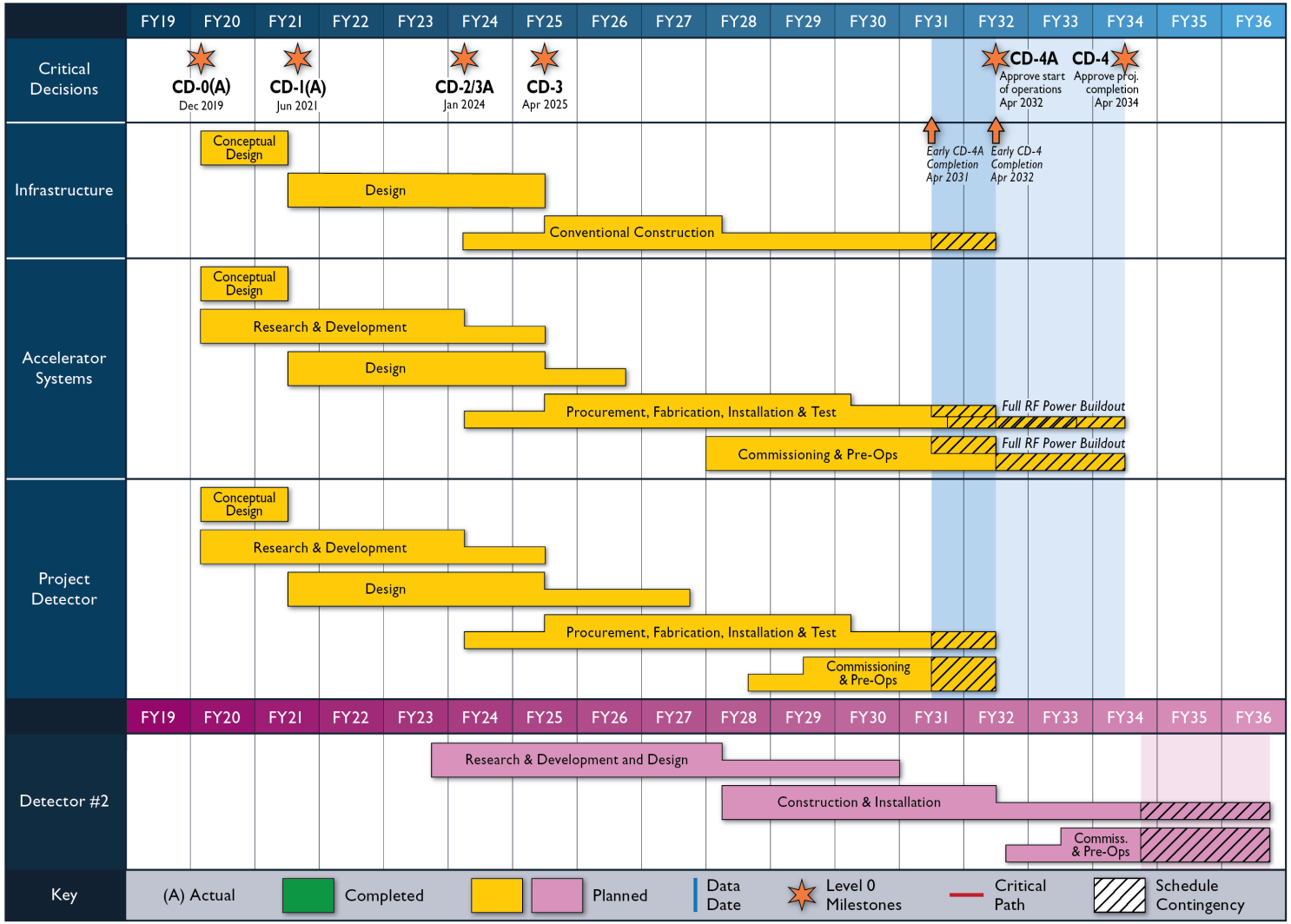
EIC design - EPIC detector



- Large rapidity (-4 < η < 4) coverage
  large acceptance for diffraction, tagging, neutrons from nuclear breakup
- Many ancillary detector along the beam lines
  low-Q2 tagger, roman pots, zero-degree calorimeter
- High precision low mass tracking
  small (μ-vertex Silicon) and large radius (gas-based) tracking
- Electromagnetic and Hadronic Calorimetry
  equal coverage of tracking and EM-calorimetry
- High performance PID to separate e, π, K, p
  good e/h separation critical for scattered electron ID
- Maximum scientific flexibility
  streaming DAQ with AI/ML
- Excellent control of systematics
  luminosity monitor, electron & hadron polarimetry

from A. Deshpande presentation at IWHSS'22

Timeline



2019
Accepted!

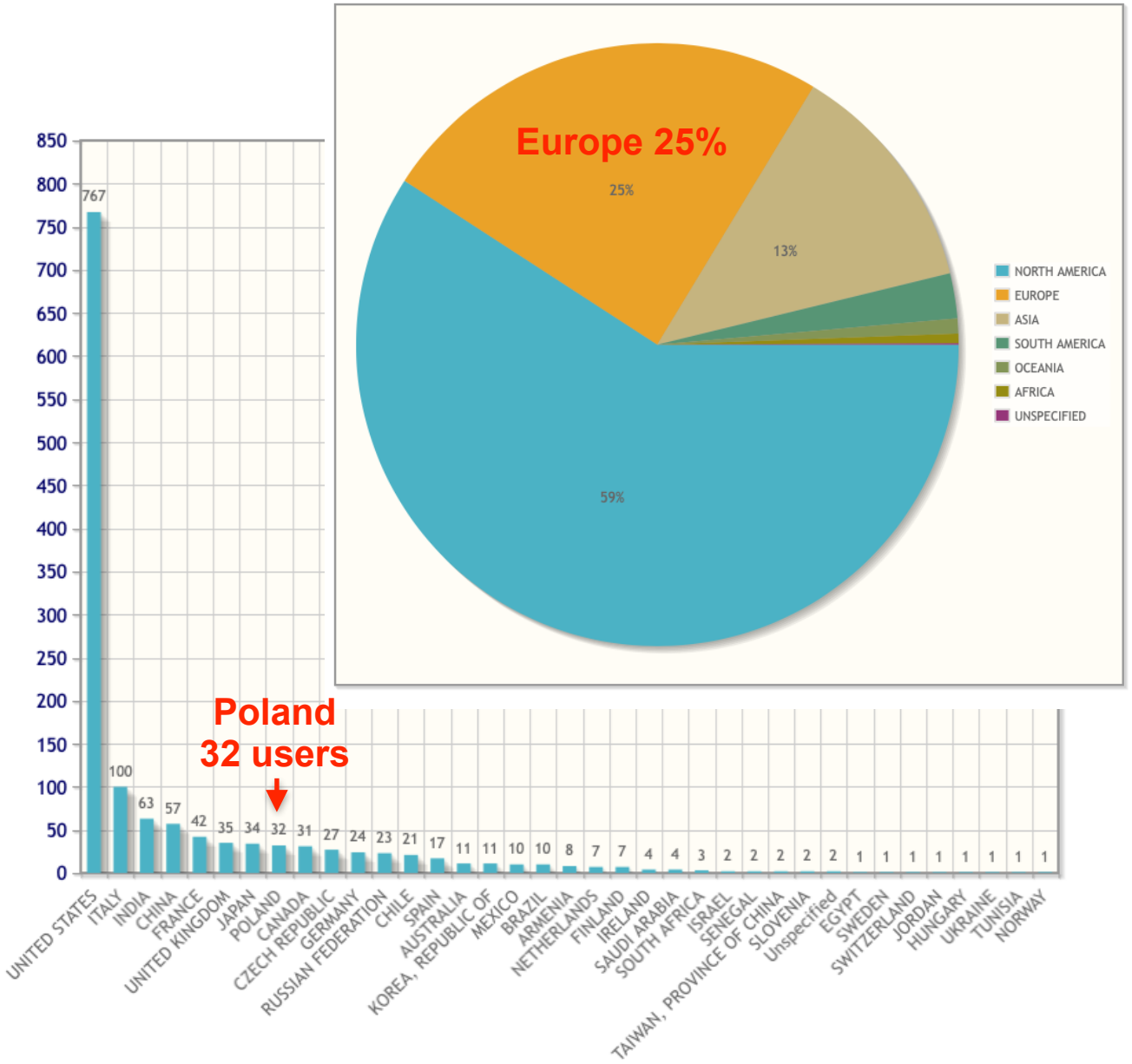
2024
Begin of construction

2032
First beam

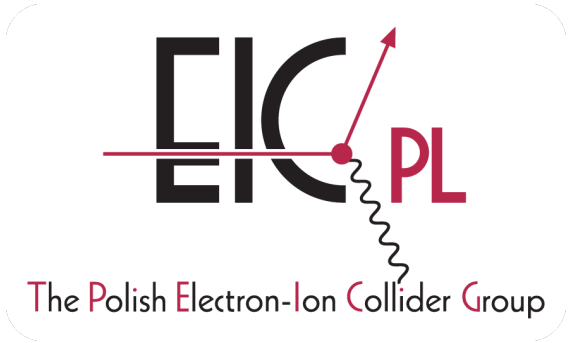
from A. Deshpande presentation at IWHSS'22

EIC Users Group

- 1364 members, 267 institutions, 36 countries (experimentalists: 845, theoreticians: 345, accelerator scientists: 159, other: 15)
- Annual meetings: Stony Brook (2014), Berkeley (2015), ANL (2016), Trieste (2017), CAU (2018), Paris (2019), FIU (2020), Remote (2021), Stony Brook (2022, Hybrid), **Warsaw 2023**
- EICUG Structures: Steering Committee, Institutional Board, Speaker's Committee, Election & Nominations Committee
- for more information see: http://eicug.org



Polish community of EIC users



- Polish groups engaged both in the theoretical research related to a variety of topics to be studied at EIC and in the development of hardware

- Groups formed a community to:
  - promote the engagement of Polish scientific institutions in EIC
  - promote related physics topics (in particular among Early Career Researchers)

- Next major events:
  - Epiphany'23 in Kraków
  - EICUG'23 in Warsaw

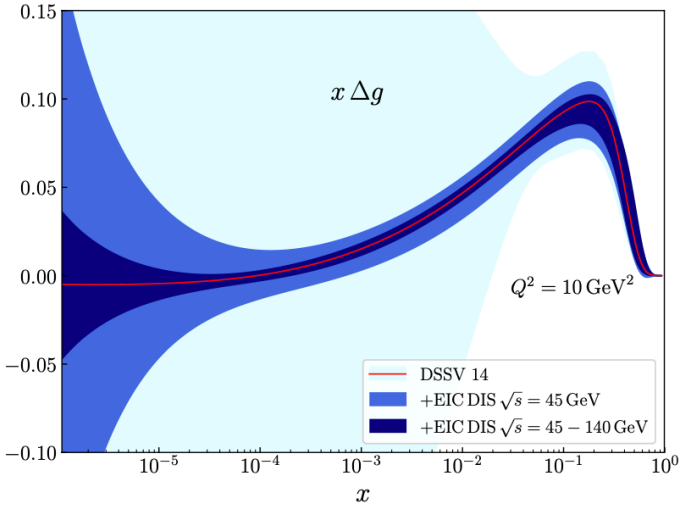
- for more information see: https://eicpl.ifj.edu.pl

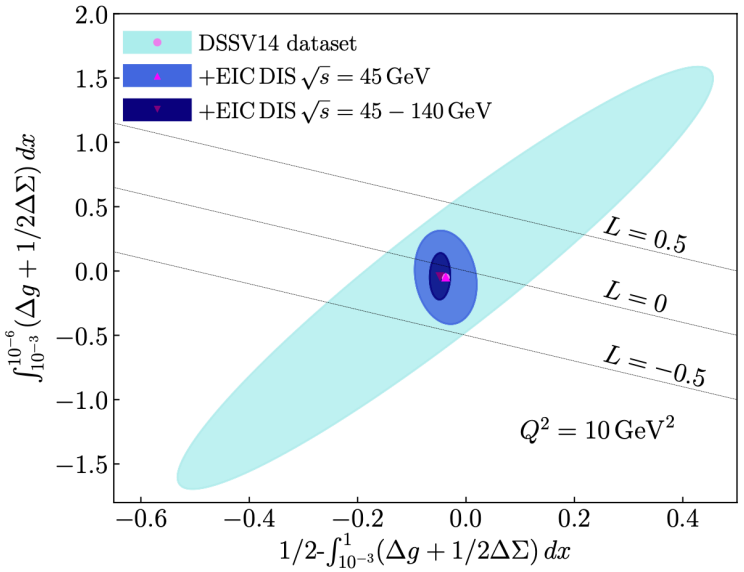
List of institutions and members

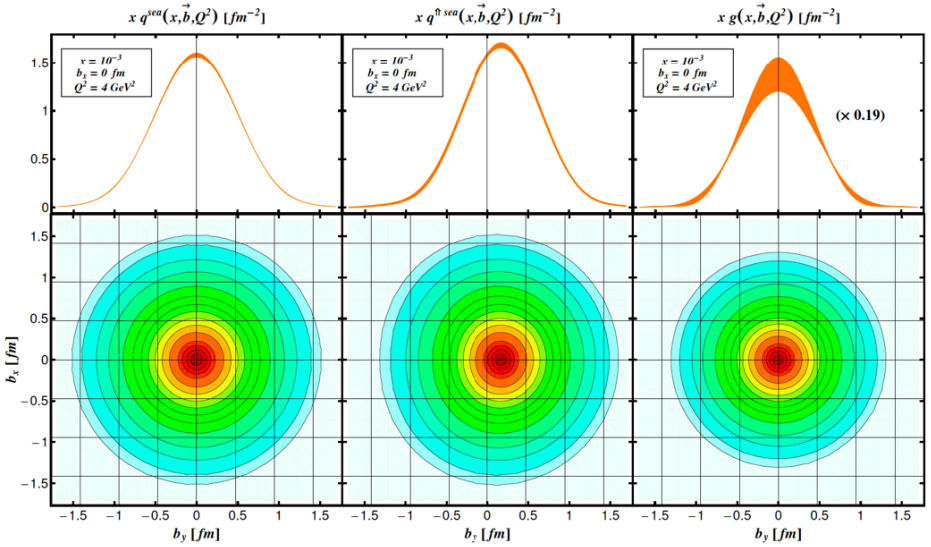
- **Akademia Górniczo-Hutnicza (AGH)** link
  - Leszek Adamczyk
  - Marek Idzik
  - Piotr Kotko
  - Mariusz Przybycień contact
- **Instytut Fizyki Jądrowej Polskiej Akademii Nauk (IFJ PAN)** link
  - Janusz Chwastowski contact
  - Aleksander Kusina
  - Krzysztof Kutak contact
  - Krzysztof Golec-Biernat
  - Rafał Staszewski
  - Maciej Trzebiński
  - Martin Rohrmoser
  - Wolfgang Schafer
- **Narodowe Centrum Badań Jądrowych (NCBJ)** link
  - Tolga Altinoluk
  - Guillaume Beuf
  - Andrzej Sandacz
  - Paweł Sznajder
  - Lech Szymanowski
  - Jakub Wagner contact
- **Politechnika Krakowska (PK)** link
  - Agnieszka Łuszczak contact
  - Robert Gębarowski
- **Politechnika Warszawska (PW)** link
  - Daniel Kikoła contact
- **Uniwersytet Jagielloński (UJ)** link
  - Piotr Korcyl contact
  - Wojciech Słomiński
- **Uniwersytet Rzeszowski (UR)** link
  - Marta Łuszczak contact
- **Uniwersytet Warszawski (FUW)** link
  - Barbara Badełek contact

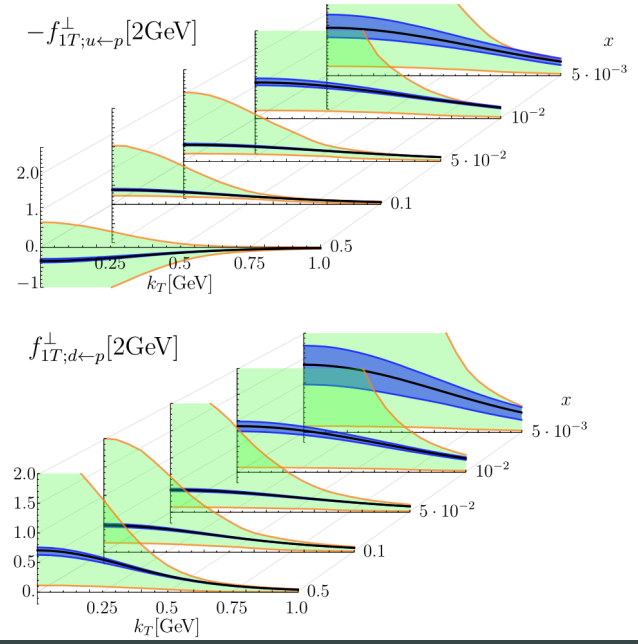
3D description of hadrons

Gluon polarisation

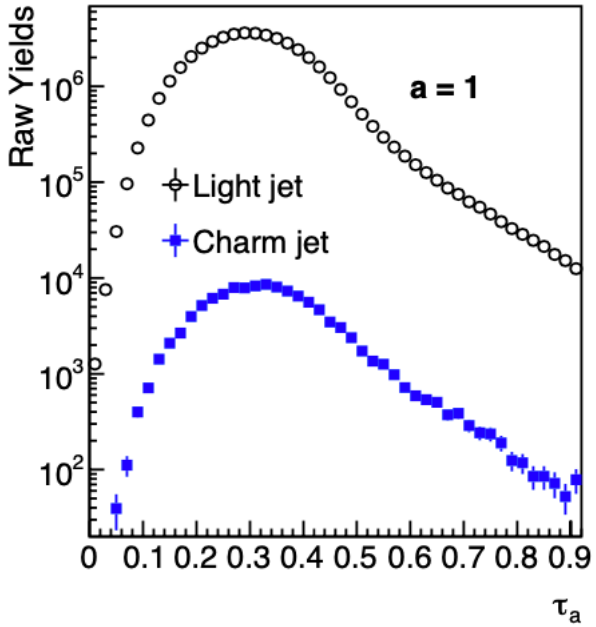






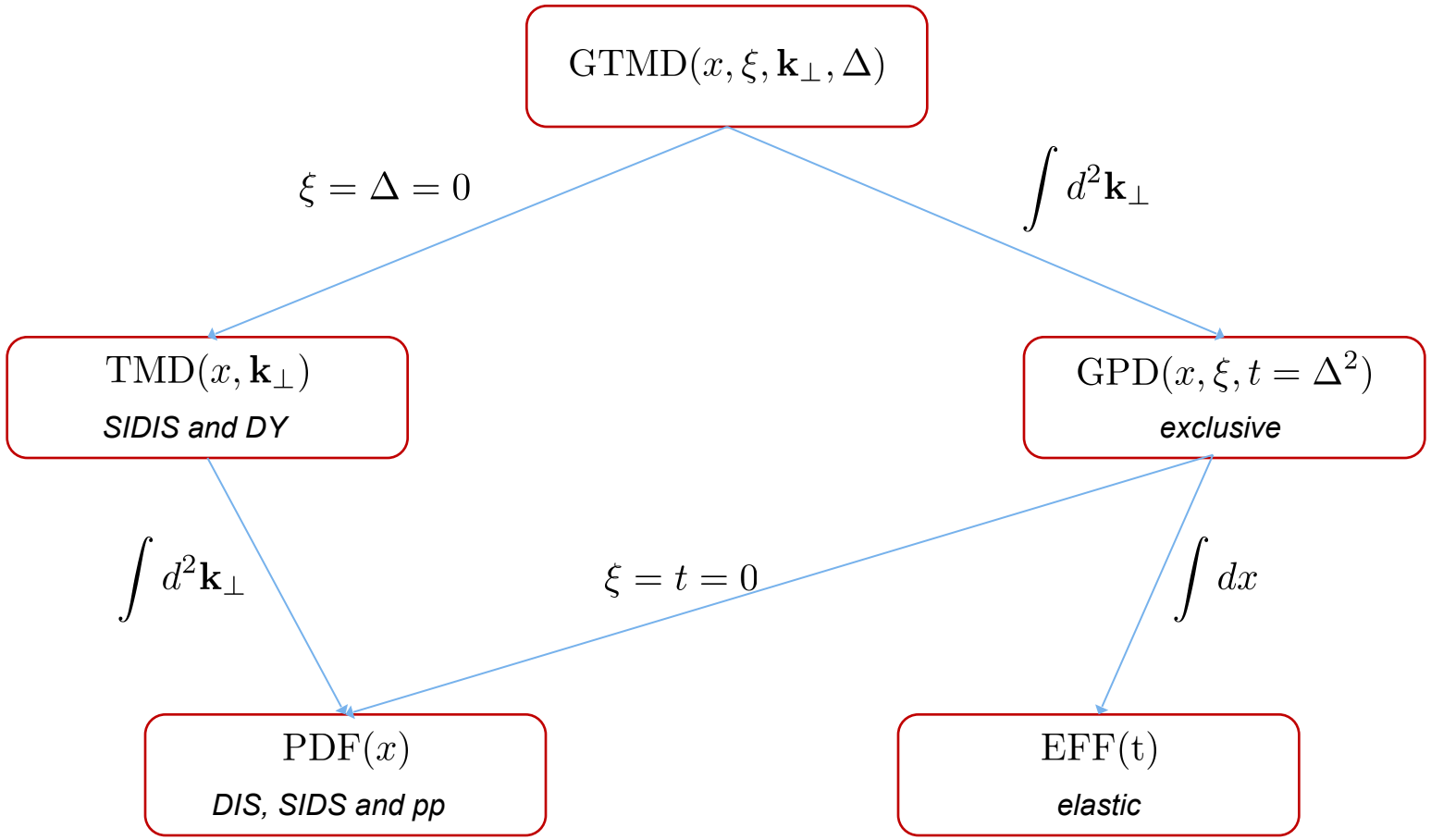


Jets to study nuclear media



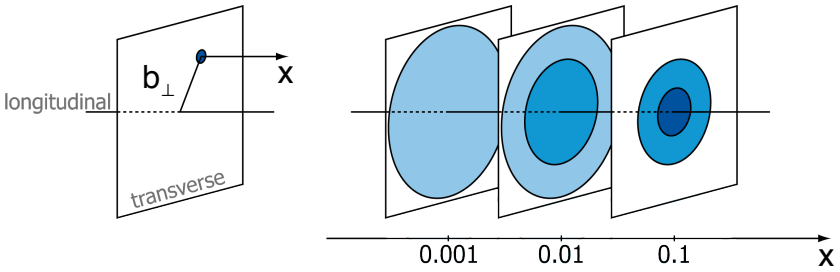
You can find more projections in EIC Yellow Paper Nucl. Phys. A 1026 (2022) 122447

Generalised partons distributions



Generalised partons distributions

Nucleon tomography:



$$q(x,\mathbf{b}_\perp)=\int\frac{\mathrm{d}^2\boldsymbol{\Delta}}{4\pi^2}e^{-i\mathbf{b}_\perp\cdot\boldsymbol{\Delta}}H^q(x,0,t=-\boldsymbol{\Delta}^2)$$

Energy momentum tensor in terms of form factors (OAM and mechanical forces):

$$T^{\mu\nu}=\begin{bmatrix}\textcolor{red}{T^{00}} & \textcolor{orange}{T^{01}} & \textcolor{orange}{T^{02}} & \textcolor{orange}{T^{03}}\\ \textcolor{orange}{T^{10}} & T^{11} & T^{12} & T^{13}\\ \textcolor{orange}{T^{20}} & T^{21} & T^{22} & T^{23}\\ \textcolor{orange}{T^{30}} & T^{31} & T^{32} & T^{33}\end{bmatrix}$$

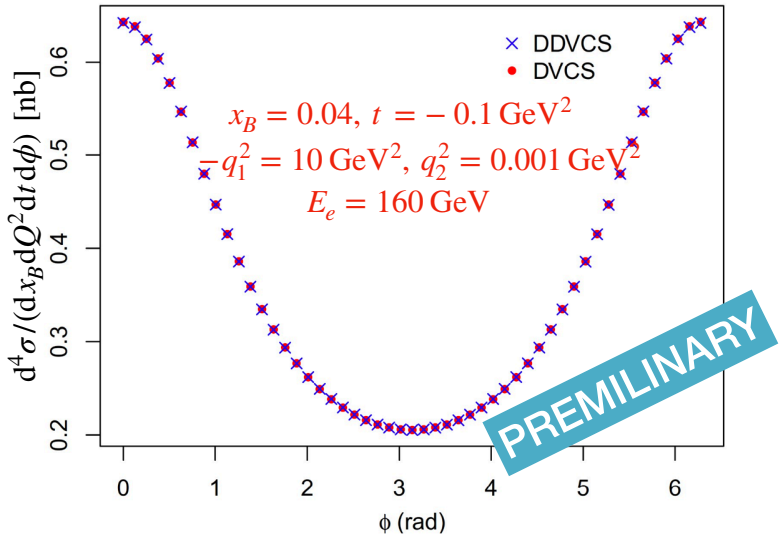
Energy density — Momentum density — Shear stress — Normal stress — Energy flux — Momentum flux

$$\langle p',s'|\widehat{T}^{\mu\nu}|p,s\rangle=\bar{u}(p',s')\left[\frac{P^\mu P^\nu}{M}A(t)+\frac{\Delta^\mu\Delta^\nu-\eta^{\mu\nu}\Delta^2}{M}C(t)+M\eta^{\mu\nu}\bar{C}(t)+\right.$$
$$\left.\frac{P^\mu i\sigma^{\nu\lambda}\Delta_\lambda}{4M}[A(t)+B(t)+D(t)]+\frac{P^\nu i\sigma^{\mu\lambda}\Delta_\lambda}{4M}[A(t)+B(t)-D(t)]\right]u(p,s)$$

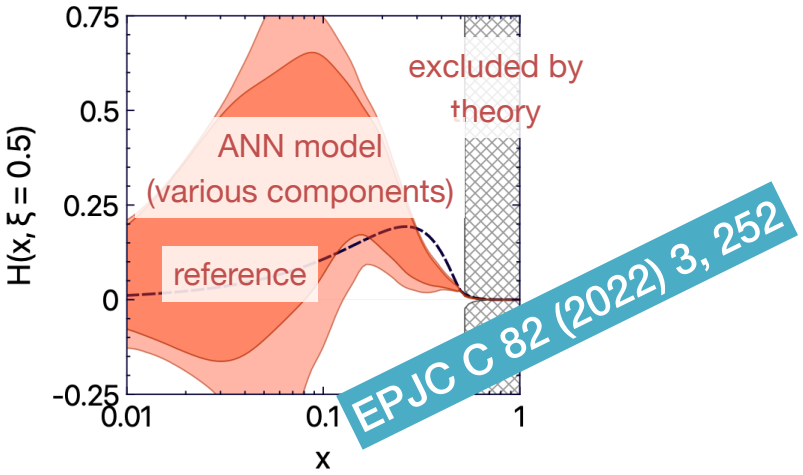
GPD group at NCBJ

- Members: K. Deja, V. Martínez-Fernández, PS, J. Wagner, L. Szymanowski, V. Batozskaya (experimentalist)
- The group works e.g. on:
  - description of exclusive processes to check their measurability at EIC and, latter, for interpretation of data
    Example: study of double deeply virtual Compton scattering
  - phenomenology methods
    Example: first neural network parameterisation of GPDs
  - delivering tools used by the community to study GPDs
    Example: EpIC MC generator and PARTONS framework

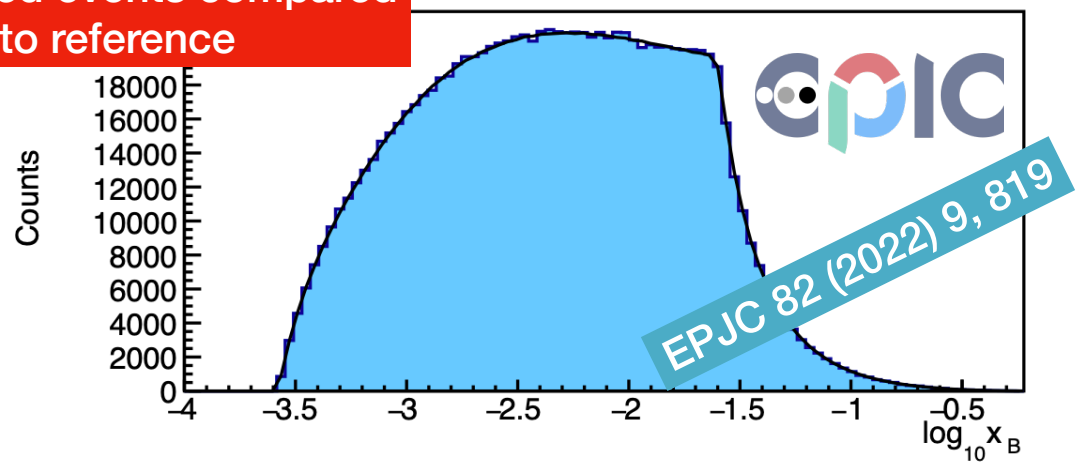
DVCS limit of DDVCS



ANN model fitted to reference in restricted kin. range



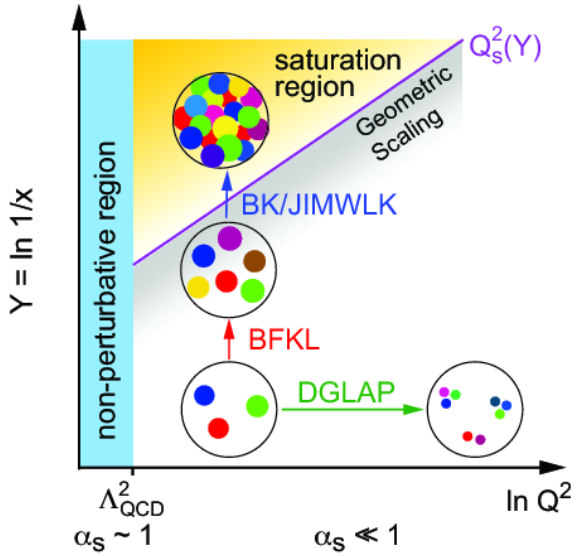
Generated events compared to reference



Small-x group at NCBJ

- Members: T. Altinoluk, G. Beuf, A. Czajka, L. Szymanowski, A. Tymowska, S. Mulani

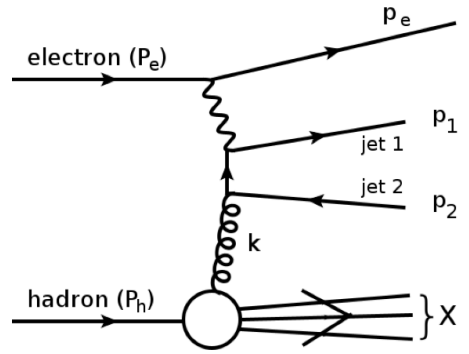
- Physics case:
  - study of saturation effects is one of the pillars of EIC physics programme
  - discovery of new regime of QCD will have a profound impact of our understanding of strong interactions
  - accomplishment of such ambitious goal requires high precision of theory predictions



- The group works e.g. on:
  - calculation of NLO corrections for observables at EIC
    Motivation: theory of gluon saturation at Leading Order (LO) in coupling constant is in qualitative agreement with the data from all types of collisions, but there is lack of precision at LO in order to unambiguously confirm the gluon saturation effects
  - calculation of the finite energy contributions for observables at EIC
    Motivation: formalism for gluon saturation theory is based on Eikonal Approximation.
    This amounts to assuming infinite energy for collisions and considering only the leading terms at high energy.
    Quantitative understanding of the Next-to-Eikonal corrections (aka finite energy corrections) is needed for saturation studies at EIC

Electron-dijet correlations analysis by AGH and IFJ group

- Authors: P. Kotko, K. Kutak, S. Sapeta, A. van Hameren, E. Żarów

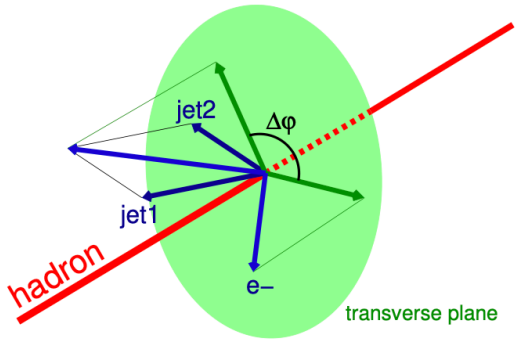


- Motivation is to study:
  - gluon number density (the so-called Weizsacker-Williams gluon distribution) at EIC

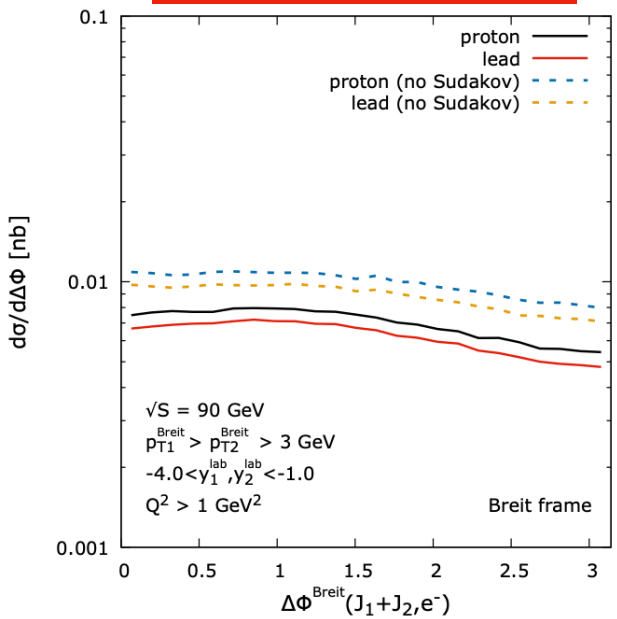
$$d\sigma_{eh\to e'+2j+X} = \int \frac{dx}{x}\frac{d^2k_T}{\pi}\,\mathcal{F}_{gg}^{(3)}(x,k_T,\mu)\,\frac{1}{4xP_e\cdot P_h}\,d\Phi(P_e,k;p_e,p_1,p_2)\,|\overline{M}_{eg^*\to e'+2j}|^2$$

  - interplay between the effect of the soft gluon emissions (the Sudakov form factor) and the gluon saturation effects.

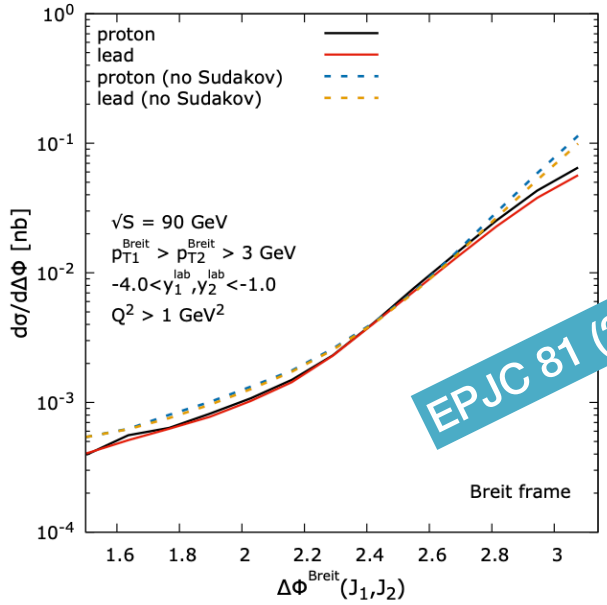
- Results:



Angle between dijets



Angle between di-jet and electron



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Summary

- EIC will be build, first data expected in 2032
  Accelerator and detector projects are currently being finalised
- Strong and important participation of Polish groups in the project
- EIC will push our understanding of hadronic structures and QCD dynamics