Electron-Ion Collider (EIC) and activities in Japan

Pacific Spin 2024 in Hefei, China

2024.11.8 at RIKEN

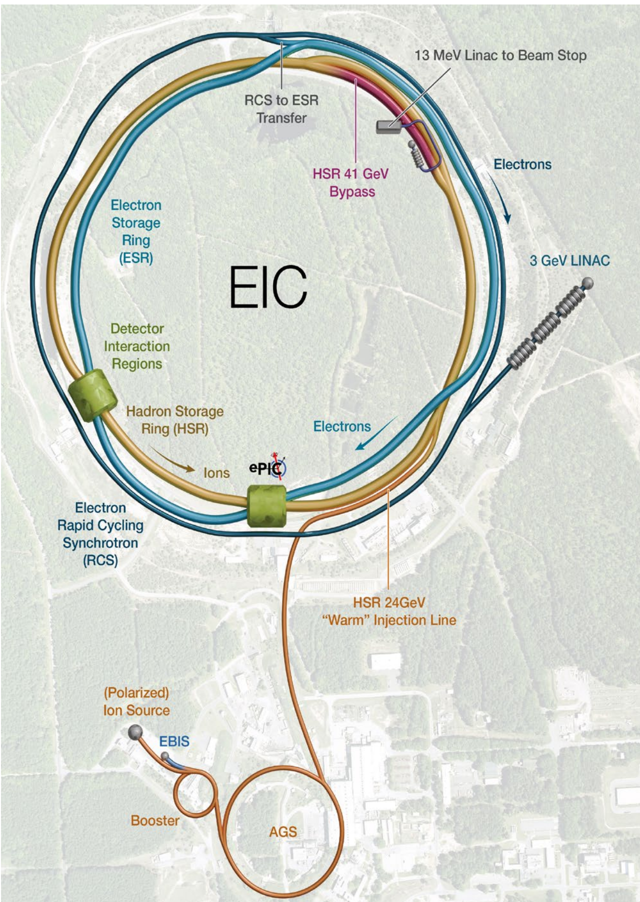
Yuji Goto (RIKEN)

Outline of this talk

- Introduction
- Physics at EIC
  - Origin of nucleon mass and spin
  - 3D structure of the nucleon and nucleus
  - Gluon saturation
  - Hadronization
- EIC status
  - ePIC experiment
  - Activities in Japan

Electron-Ion Collider (EIC)

- 2020.1.9: U.S. Department of Energy selected Brookhaven National Laboratory to host major new nuclear physics facility, the Electron-Ion Collider
- World's first polarized electron + proton / light-ion / heavy-ion collider



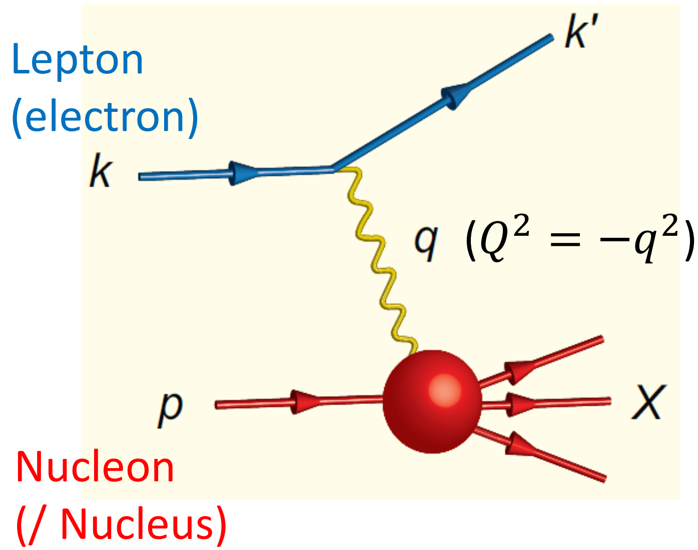
Project Design Goals

- High Luminosity: L= 10^{33} – 10^{34} $cm^{-2}sec^{-1}$, 10 – 100 fb^{-1}/year
- Highly Polarized Beams: 70%
- Large Center of Mass Energy Range: E_{cm} = 29 – 140 GeV
- Large Ion Species Range: protons – Uranium
- Large Detector Acceptance and Good Background Conditions
- Accommodate a Second Interaction Region (IR)

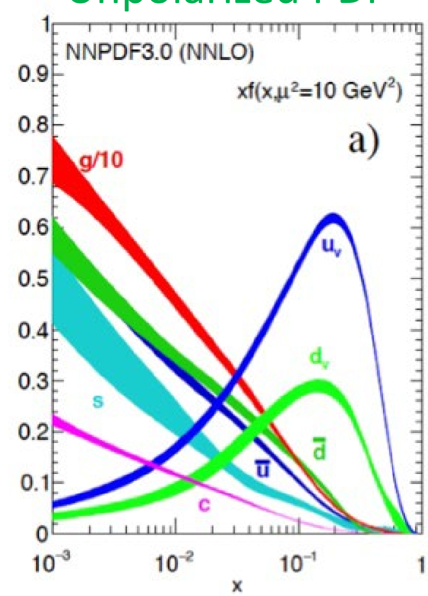
Polarized beam: e, p, d, ^{3}He

Quark-gluon structure

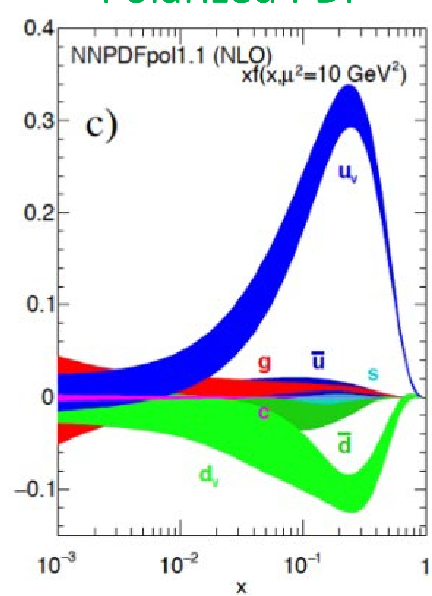
- Deep inelastic scattering (DIS) of lepton (electron)
  - Large Q^2 ($Q^2 = -q^2$) provides a hard scale to resolve quarks and gluons in the proton
- Parton distribution function (PDF) of quarks and gluons
  - 1D longitudinal motion of partons
  - x : momentum fraction of quarks and gluons
  - Significant improvement of precision of the polarized PDF at EIC



Unpolarized PDF

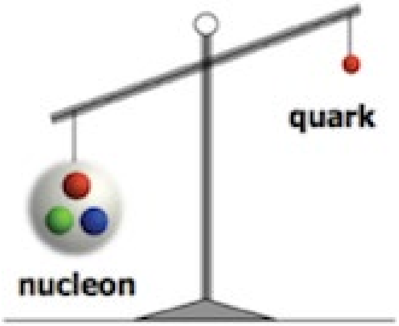


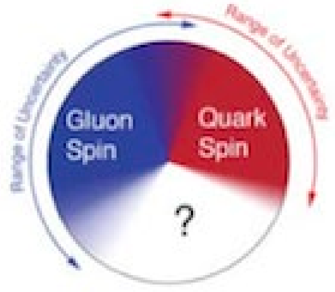
Polarized PDF

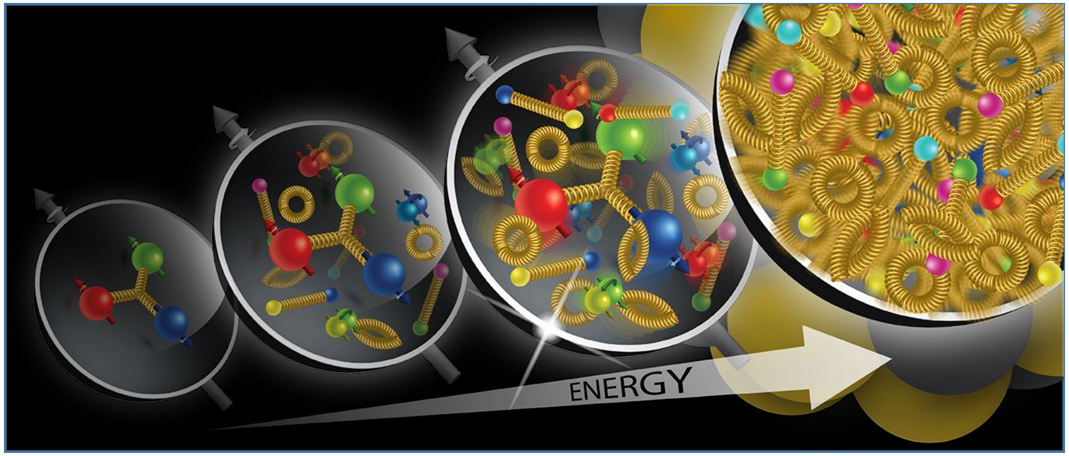


Physics at EIC

- How does the mass of the nucleon arise?
  - The Higgs mechanism accounts for only ~1% of the mass of the proton.
- How does the spin of the nucleon arise?
  - The spin of the quarks accounts for only one-third of the spin of the proton.
- What are the emergent properties of dense system of gluons?
  - The gluon saturation describes a new state of matter at extreme high density.

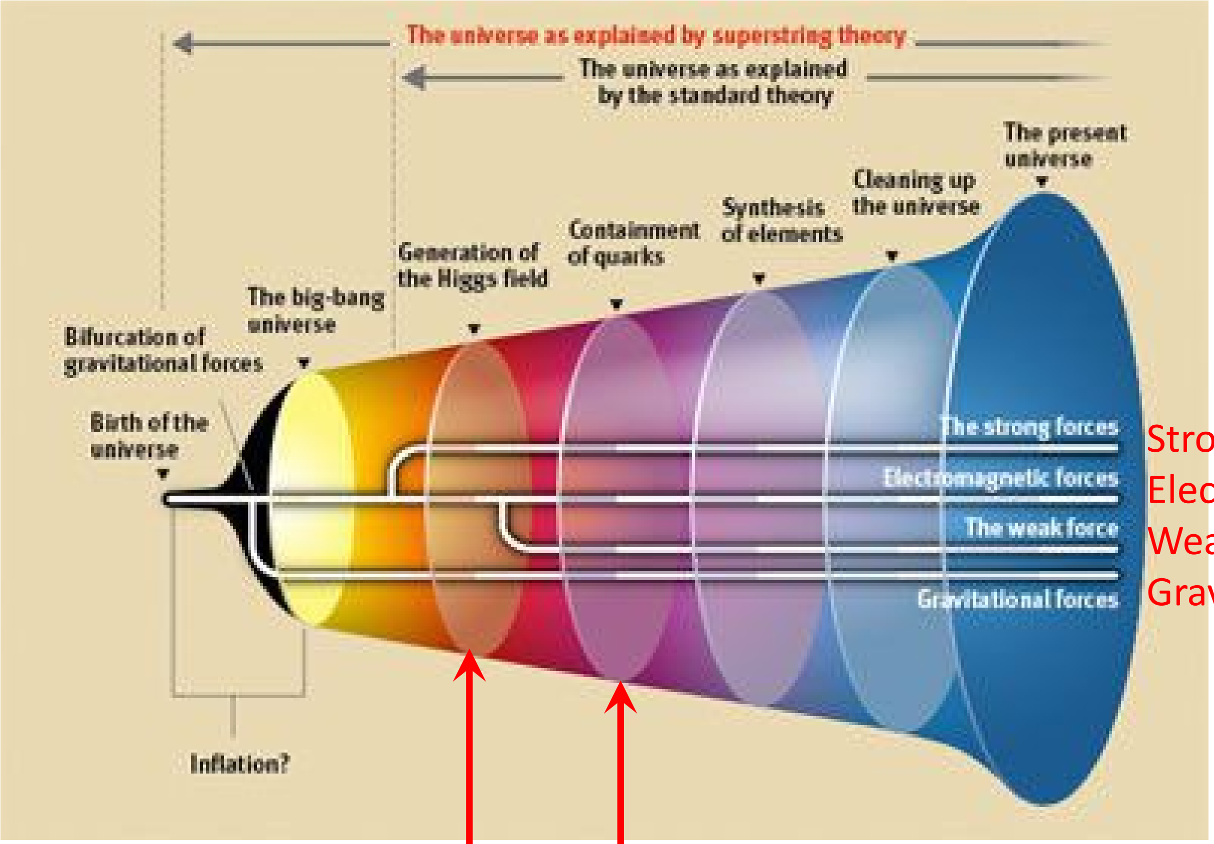






Mass

- The Higgs mechanism accounts for only ~1% of the mass of proton.
- The symmetry breaking emerges the mass.



Strong force
Electromagnetic force
Weak force
Gravitational force

Symmetry breaking of the Higgs field

Confinement of quarks
Chiral symmetry breaking

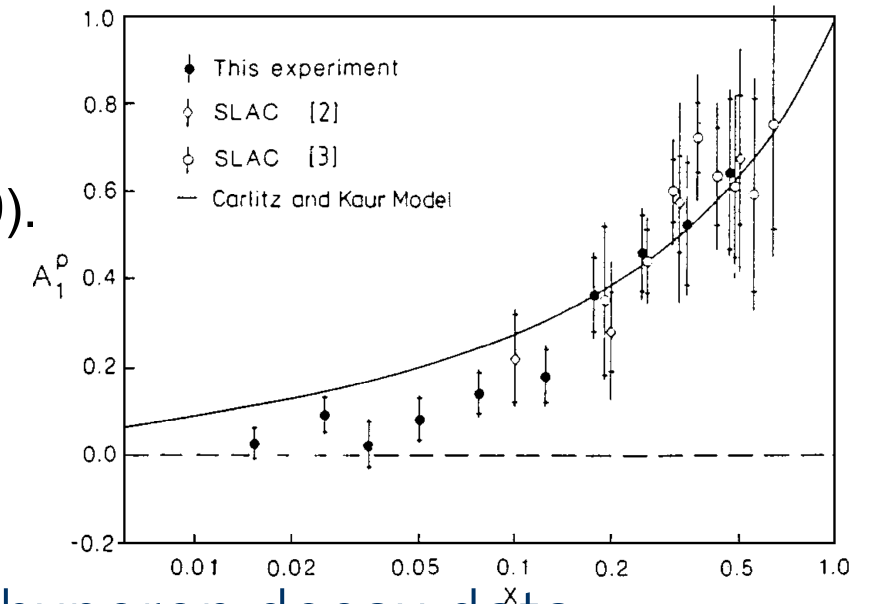
Origin of the nucleon spin 1/2

- EMC experiment at CERN

J. Ashman et al., NPB 328, 1 (1989).

$$\int_0^1 dx g_1^p(x) = \frac{1}{2}\left[\frac{4}{9}\Delta u + \frac{1}{9}\Delta d + \frac{1}{9}\Delta s\right]$$

$$= 0.123 \pm 0.013(\text{stat}) \pm 0.019(\text{syst})$$



- combining with neutron and hyperon decay data

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s = 12 \pm 9(\text{stat}) \pm 14(\text{syst})\%$$

"proton spin puzzle"
"proton spin crisis"

  - total quark spin constitutes a small fraction of the nucleon spin
- integration in x = 0 ~ 1 makes uncertainty
  - more data to cover wider x region with more precise data necessary

➔ SLAC/CERN/DESY/JLAB experiments

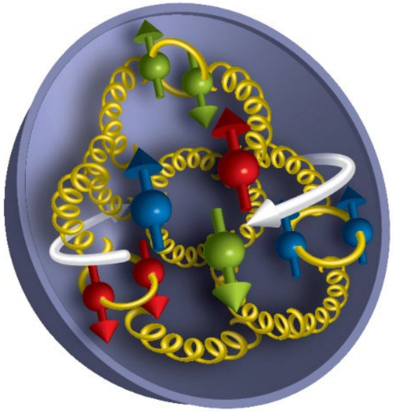
Spin

- Spin puzzle
  - Origin of the nucleon spin in the quark-gluon structure

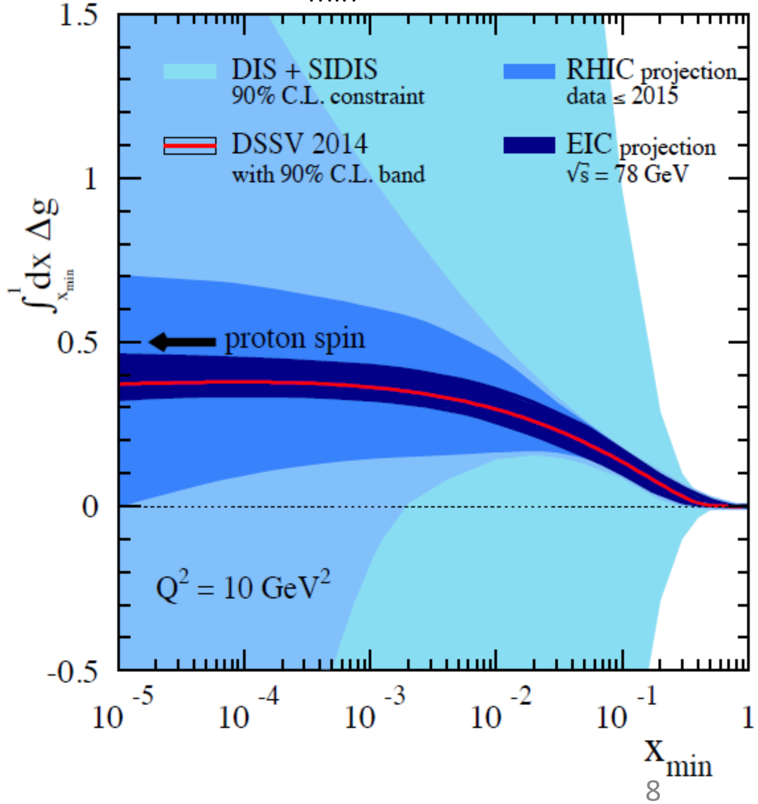
$$\frac{1}{2} = \left[\frac{1}{2}\Delta\Sigma + L_Q\right] + [\Delta g + L_G]$$

$\Delta\Sigma/2$ = Quark contribution to Proton Spin
L_Q = Quark Orbital Ang. Mom
Δg = Gluon contribution to Proton Spin
L_G = Gluon Orbital Ang. Mom

  - Quark-spin contribution is only 20%-30% of the nucleon spin
- Gluon polarization measurement with polarized DIS at EIC
  - Small Bjorken-x region with QCD evolution (DGLAP equation)

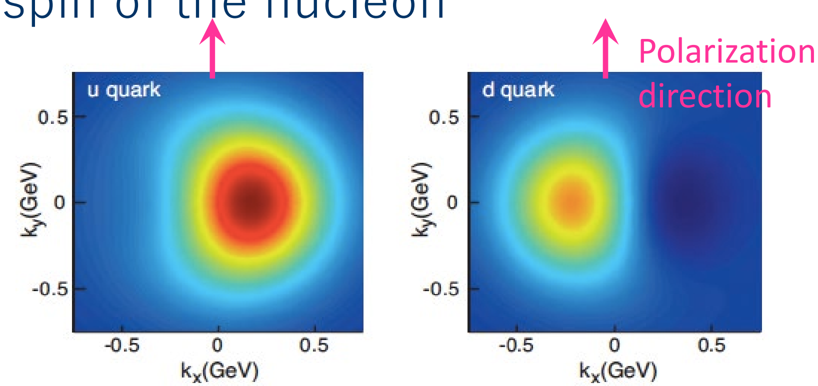


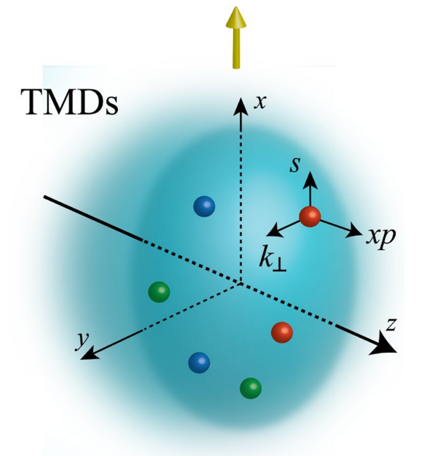
Integrated gluon polarization down to x_{min}



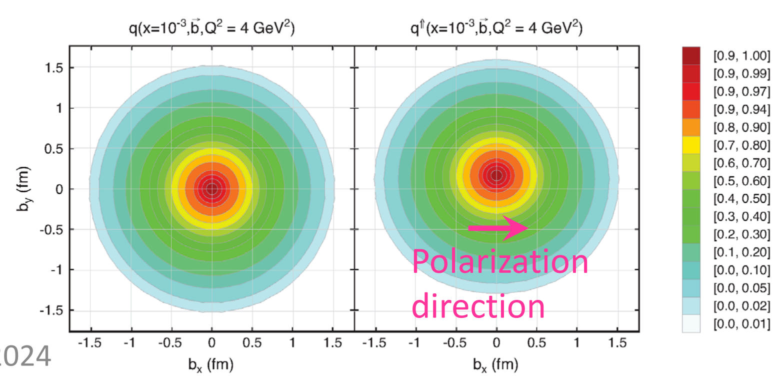
3D structure of the nucleon

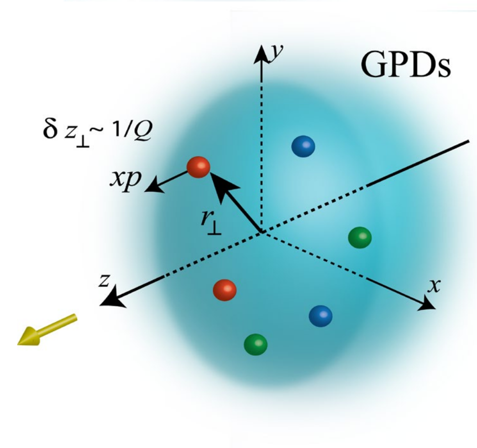
- Conclusive understanding of the nucleon spin
  - Orbital motion inside the nucleon and orbital angular momenta of quarks and gluons
- TMD (Transverse-Momentum Dependent) distribution function
  - Correlation between the (orbital) motion, spin of partons, and spin of the nucleon





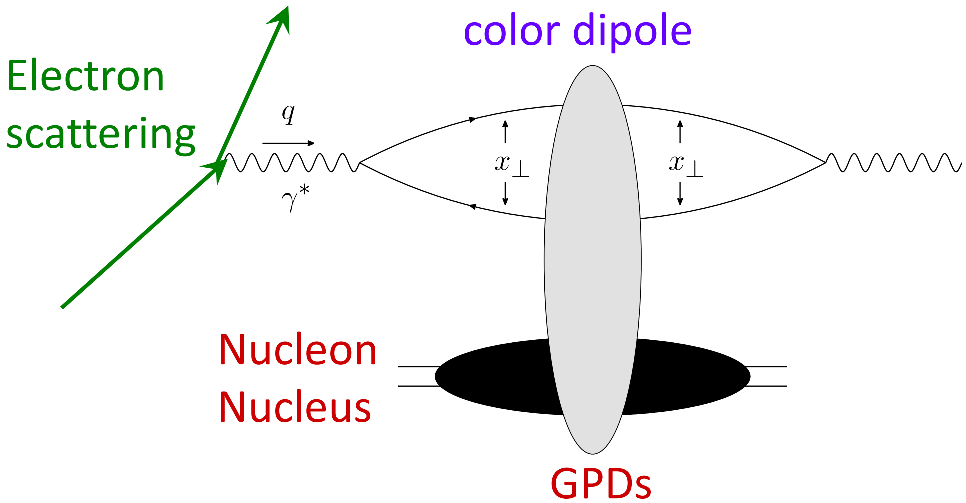
- GPD (Generalized Parton Distribution)
  - Spatial distribution or tomography



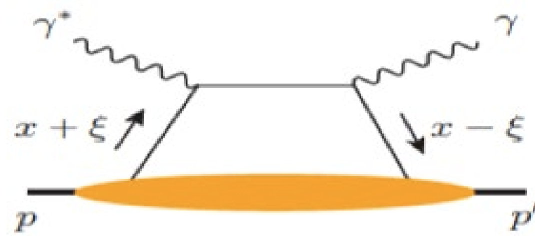


Tomography of the nucleon / nucleus

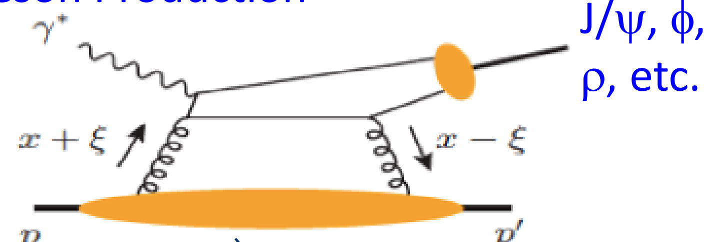
- EIC = color dipole microscope
  - Exclusive process and diffractive process
  - 3D distribution: transverse spatial distribution



DVCS (Deeply Virtual Compton Scattering)



Meson Production

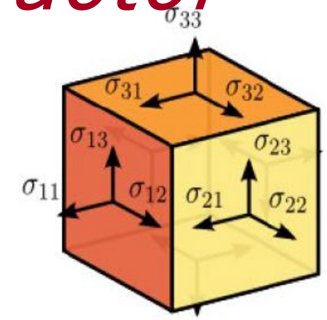


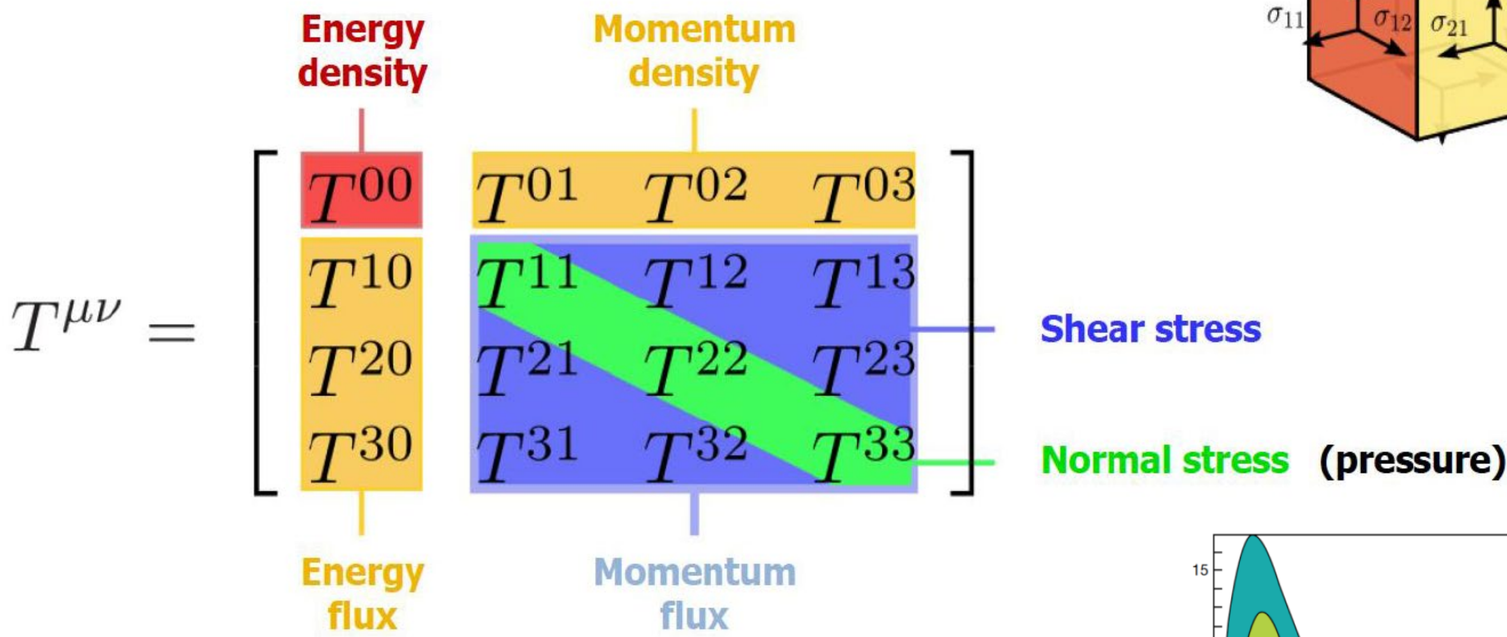
- GPD (Generalized Parton Distribution)
  - Spatial imaging of gluons and quarks = tomography
    - HERA: 1st generation
    - EIC: 2nd generation (high luminosity, heavy ion, polarization)
  - Orbital angular momentum
    - Ji's sum rule
    - Origin of the nucleon spin

$$J_q^z = \frac{1}{2}\sum_q \Delta q + \sum_q L_q = \frac{1}{2}\left(\int_{-1}^{1} x dx (H^q + E^q)\right)_{t\to 0}$$

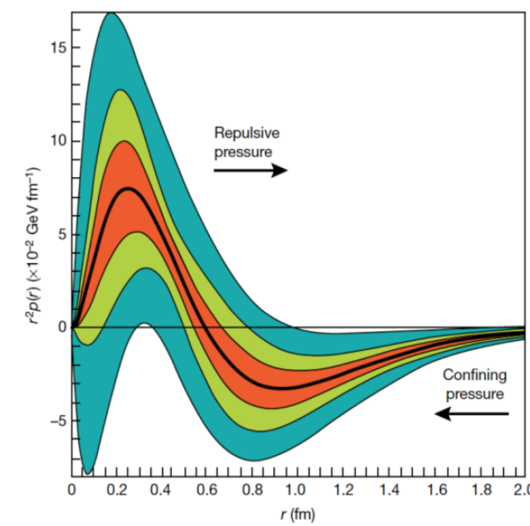
Generalization of the form factor

- Energy Momentum Tensor (EMT)





- GPD measurement → 3D distribution of mass, spin, pressure, etc. in the proton
  - 1st measurement of pressure in the proton using DVCS data from JLab



Nature, **557**, May 17, 2018

Mass of the nucleon

- Sum rule for the nucleon mass

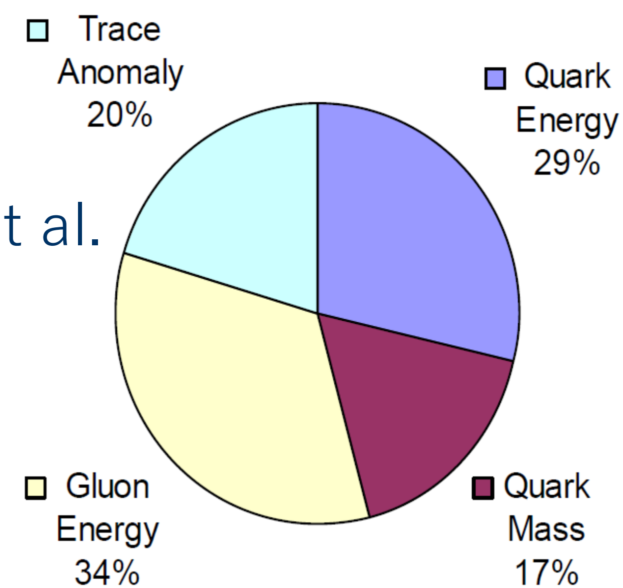
Relativistic Motion | *Chiral Symmetry Breaking* | *Quantum Fluctuations*

$$M = E_q + E_g + \chi m_q + T_g$$

X. Ji, PRL 74 1071 (1995)

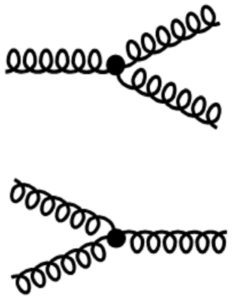
Quark Energy | **Gluon Energy** | **Quark Mass** | **Trace Anomaly**

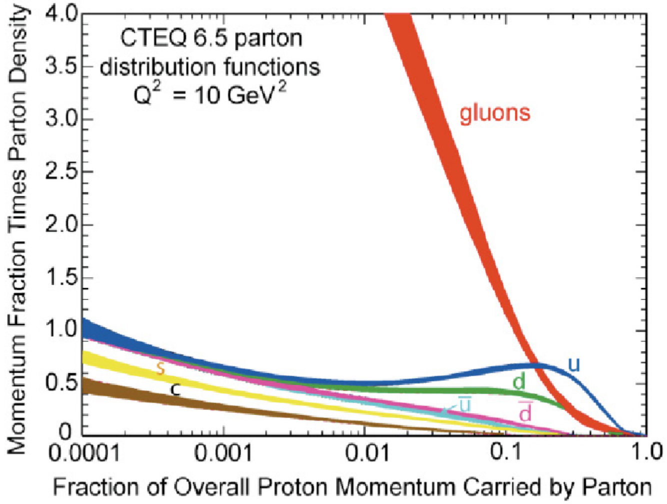
  - How to determine the different contribution not yet reached
- Lattice QCD calculation
  - arXiv:1710.09011, update by K.-F. Liu et al.
- Precision comparison of experiment and theory in the future
  - Mass, spin, pressure, radius,⋯

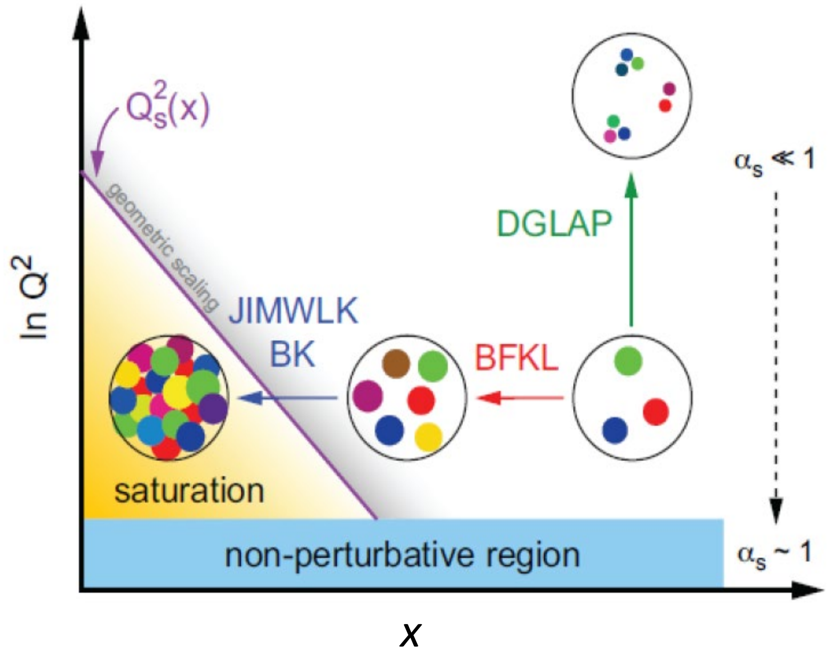


Gluon saturation

- Gluon emission
  - Divergence at small *x*
- Gluon recombination
  - Restriction of divergence
- Gluon saturation in balanced
  - Based on classical idea of the saturation
- Discovery of quantum collective gluon
  - Saturated gluon model, the color glass condensate (CGC) model, allows precision comparison with experiments
- Precision understanding of nucleus with the quark-gluon picture necessary as the initial state of the QGP for understanding its production mechanism

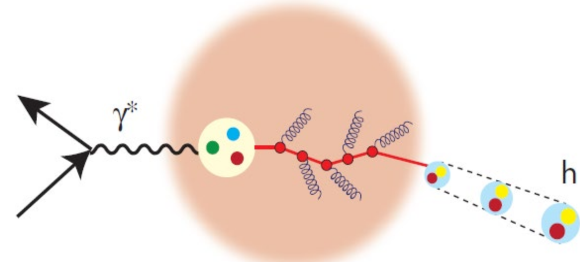


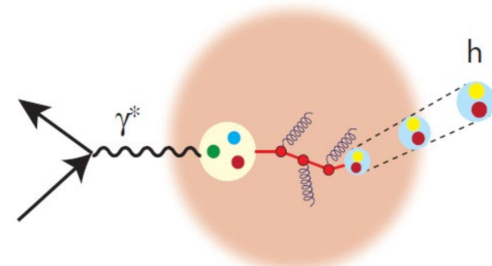


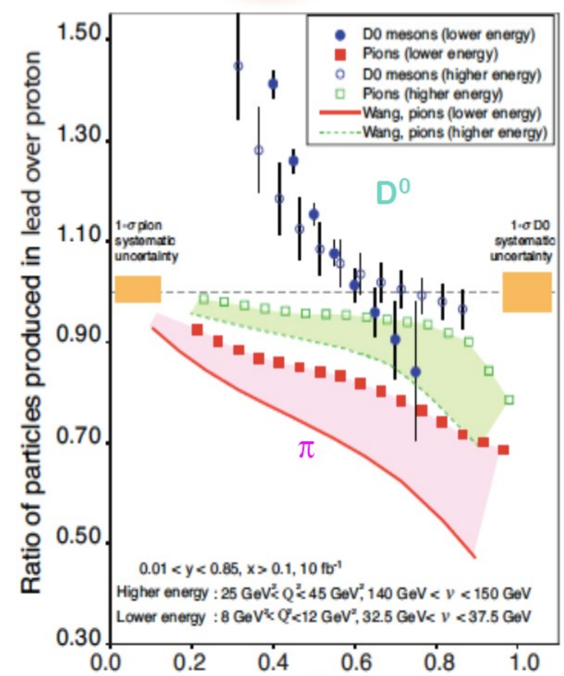


Hadronization in the nucleus

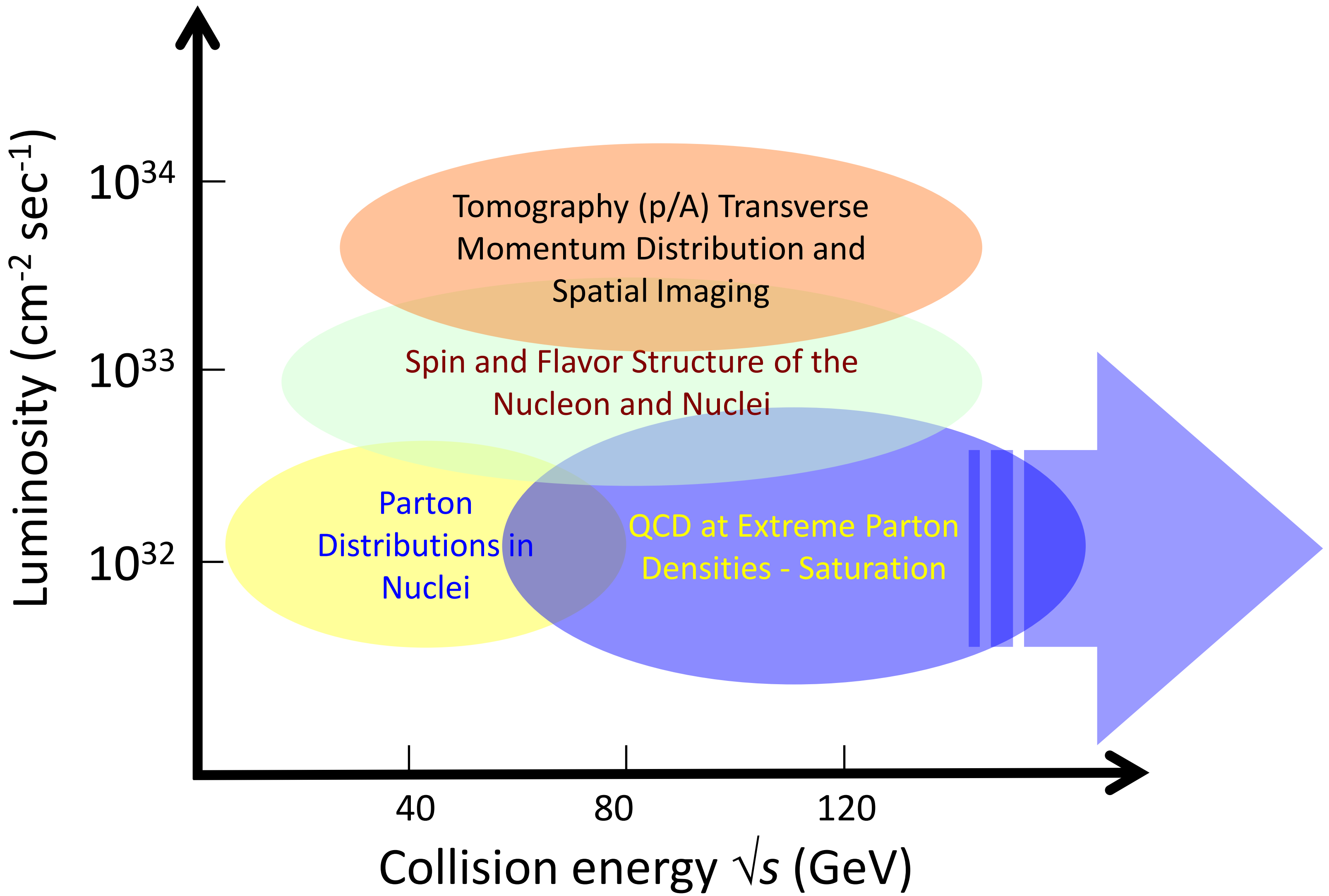
- Hadron and jet production from quarks and gluons in the nucleus (cold nuclear matter)
  - Response of nuclear matter to fast moving color charge passing through it?
  - Structure of jet?
- Mass dependence of hadronization
  - Energy loss by light vs. heavy quarks
- Comparison with hot nuclear matter (QGP)







EIC physics vs luminosity & energy



EIC Users Group

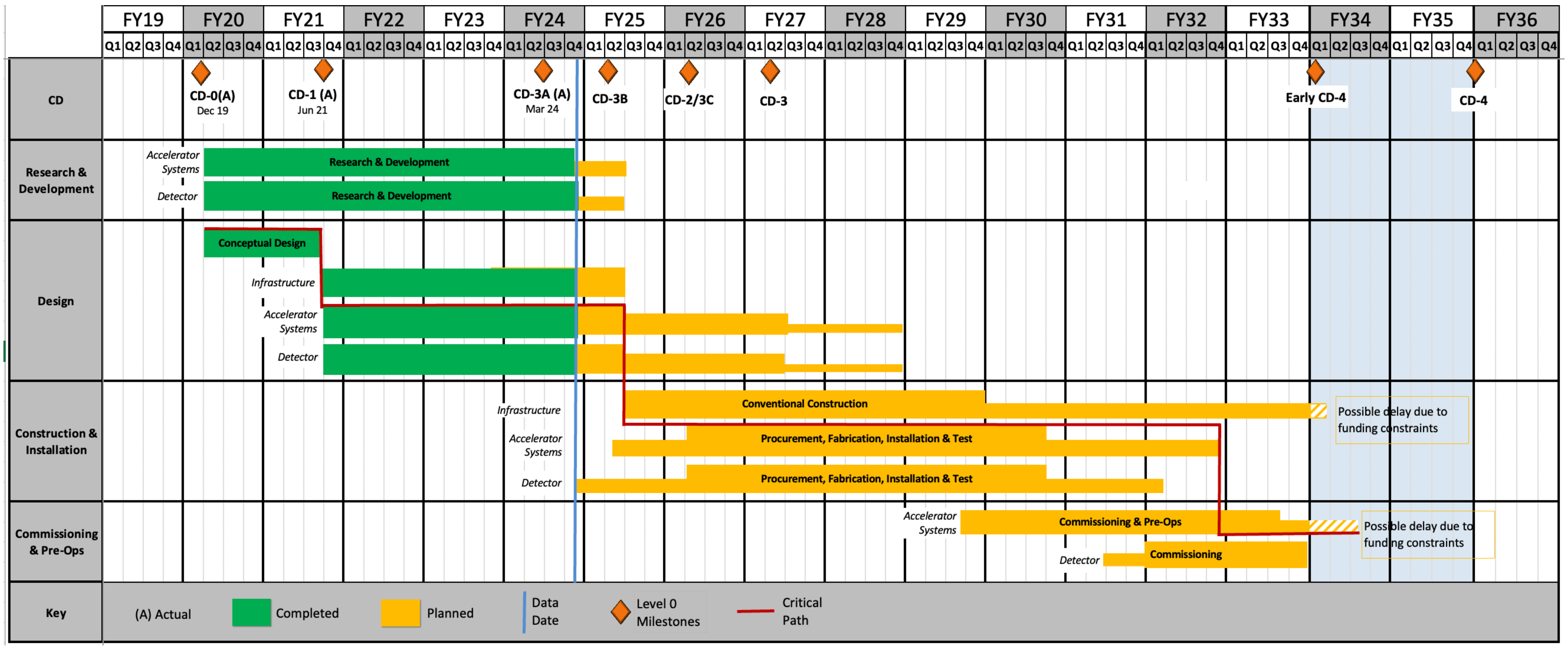
- Formally established in 2016
- More than 1,300 members
  - 36 countries, 266 institutions
  - Experiment (detector, data collection and analysis), theory, computer, accelerator
  - North America 59%, Europe 25%, Asia 12%
- 2020: Yellow report (physics and detector design report) by EIC User Group
- 2020.11: Call for Expressions of Interest (EOI) from the EIC project regarding cooperation in the EIC experimental program
  - EIC-Japan group submitted one EOI from Japan
  - 47 EOIs submitted in total

EIC status

- 2019.12: CD-0 approval (approve mission need)
- 2020.1: Site selection at BNL
- 2020: EICUG Yellow Report (physics/detector)
- 2021: Detector collaboration formation and proposal
- 2021.6: CD-1 approval (approve alternative selection and cost range)
  - Authorization to begin the project execution phase, starting with preliminary design
  - Cost range $1.7B - $2.8B
- 2022.3: Selection of project detector
- 2024.3: CD-3A approval (long lead procurements)
- 2025: CD-3B
- 2026: CD-2/3C (performance baseline)
- 2027: CD-3 (start of construction)

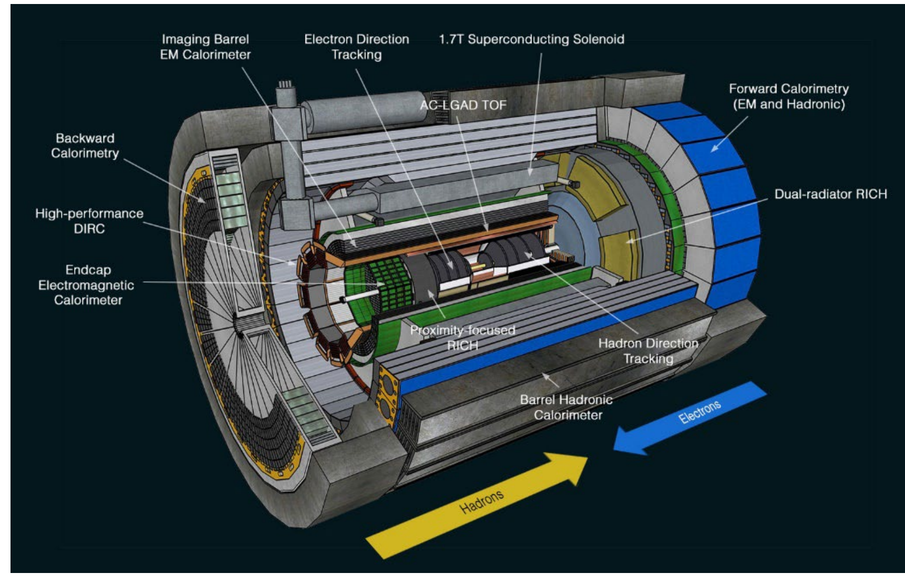
EIC status

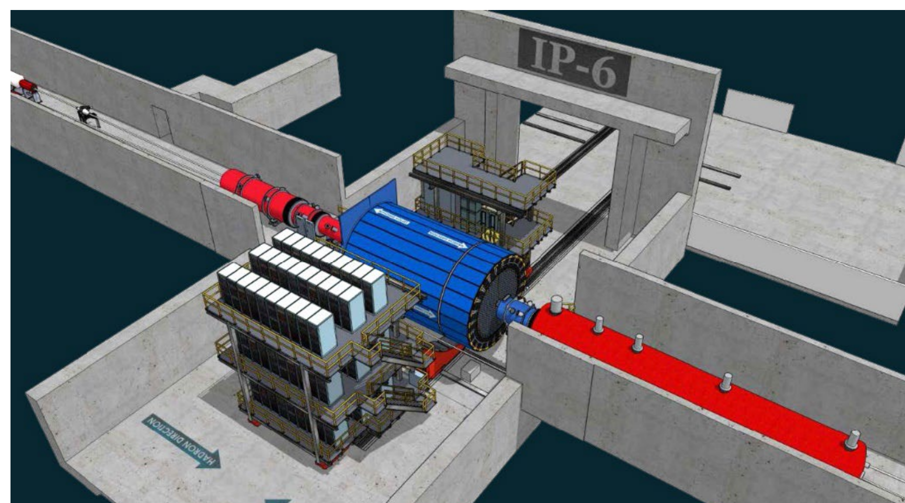
- 2027: CD-3 (start of construction)
- 2029-30: Accelerator system commissioning & pre-operations
- 2031: Detector commissioning
- 2034: early CD-4 (start of operations)



ePIC detector collaboration

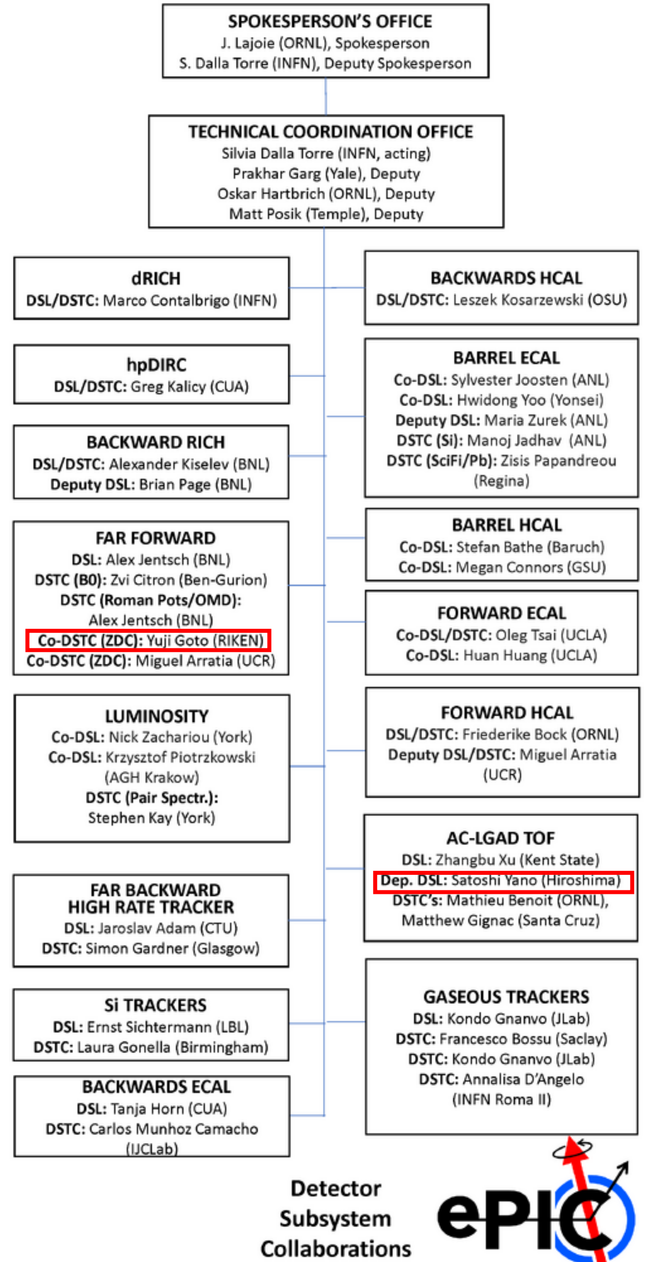
- 2021.3: Call for detector proposal from the EIC project
- 2021.12: Submission of 3 detector proposals
  - EIC-Japan group participates in the ECCE detector consortium
- 2022.3: DPAP (Detector Proposal Advisory Panel) adopts the ECCE detector as the baseline design for the project detector
  - Project detector integrating ECCE and other detector collaborations
- 2022.7: EPIC detector collaboration





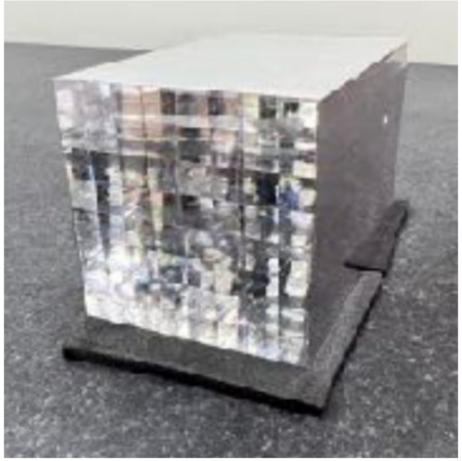
Status of the ePIC experiment

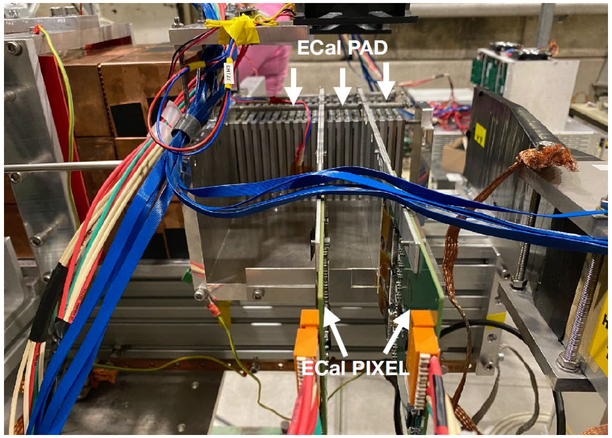
- ePIC Executive Board (EB)
  - ePIC EB formed at the 2023.10 Collaboration Council (CC)
  - CC elected member: Barbara Jacak (Berkeley), Paul Newman (Birmingham), Taku Gunji (Tokyo)
- 2024-25: TDR (Technical Design Report) strategy & publication
- ePIC Collaboration Meeting
  - 2023.7: Warsaw Univ, Poland (joint with EICUG meeting)
  - 2024.1: Argonne National Laboratory
  - 2024.7: Lehigh Univ (joint with EIC UG Meeting)
  - 2025.1: Frascati, Italy
- EIC Asia Workshop
  - 2022.11: Inchon, Korea
  - 2023.3: RIKEN, Japan
  - 2024.1: NCKU, Tainan, Taiwan
  - 2024.7: Fudan Univ, Shanghai, China

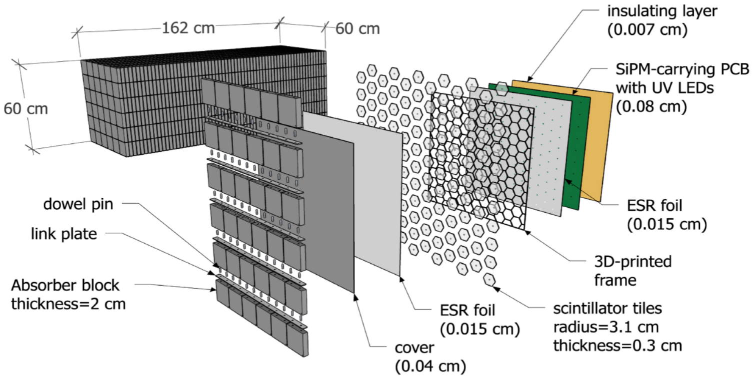


ePIC ZDC

- Crystal calorimeter
  - Prototype LYSO crystal calorimeter made by Taiwan group
  - Test beam @ ELPH, Tohoku Univ.
- Tangusten+Silicon calorimeter
  - ALICE-FoCal-E technology
  - FoCal test beam @ CERN-PS, SPS
  - FoCal-E test beam @ ELPH
  - Neutron irradiation test @ RIKEN RANS
- Hadron calorimeter
  - SiPM-on-tile technology from ePIC forward hadron calorimeter
  - Fe+Scintillator

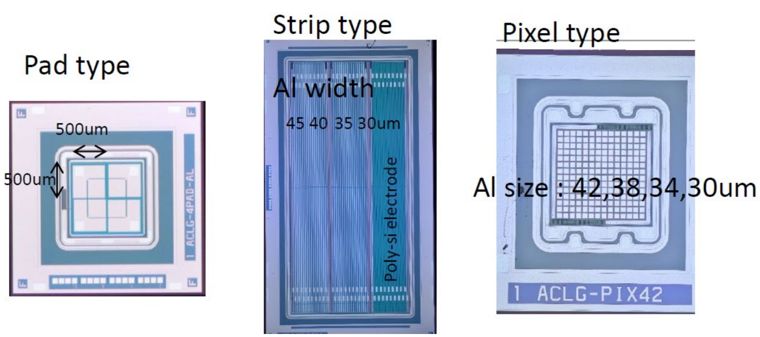




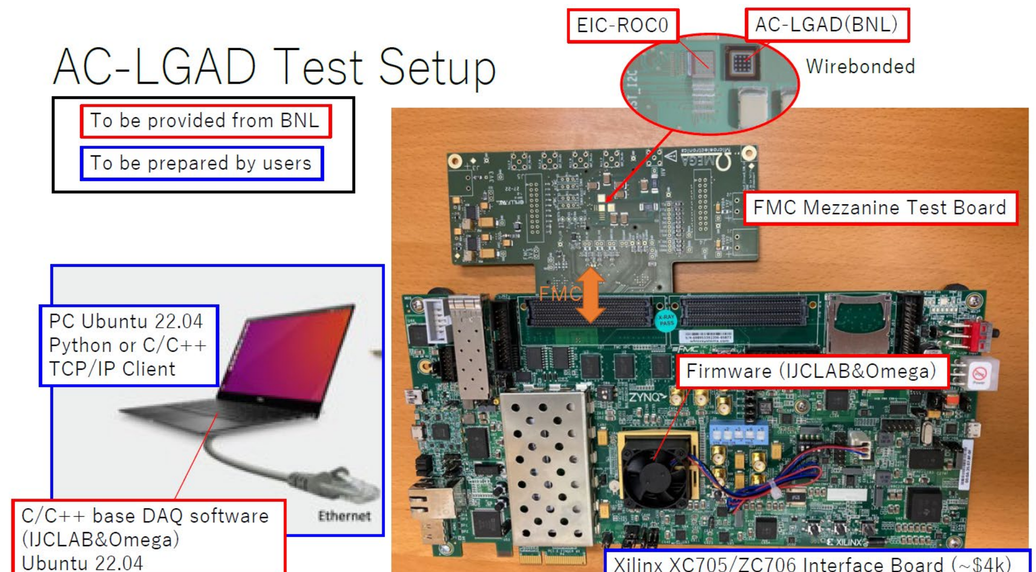


AC-LGAD

- Development of time-of-flight PID barrel section using AC-LGAD with excellent time and position resolution
- Test board obtained that combines a sensor made at BNL and a readout ASIC made in France
- High-performance measurement equipment prepared and a test bench set up at Hiroshima University
- Sensor development with HPK and performance evaluation of many types of sensors and ASICs in the future
- Beginning evaluation of overall design, including effects on momentum measurements
- Aiming to lead the construction of test and actual detectors



HPK LGAD development



Streaming DAQ system

- Triggerless DAQ of all events with EIC collision rate of 500 kHz
- 100 Tbps total data volume from frontend
- Online reconstruction of raw data using FPGAs and GPUs
- Univ of Tokyo CNS cooperating with SPADI-Alliance in Japan
  - Development of online data processing systems using hardware acceleration
  - Application of AI/ML technologies
  - Benchmarking for resource development
  - Detailed design of stream data processing systems

Summary of this talk

- Physics at EIC
  - Origin of nucleon mass and spin
  - 3D structure of the nucleon and nucleus
  - Gluon saturation
  - Hadronization
  - Ultra-precise electron microscope, revealing the origin of mass and spin in three dimensions
  - Discovery of emergent high-density gluon state (gluon condensation)
- Activities in Japan
  - Zero-Degree Calorimeter (ZDC)
  - Barrel TOF PID with AC-LGAD
  - Streaming DAQ