EIC and ZDC

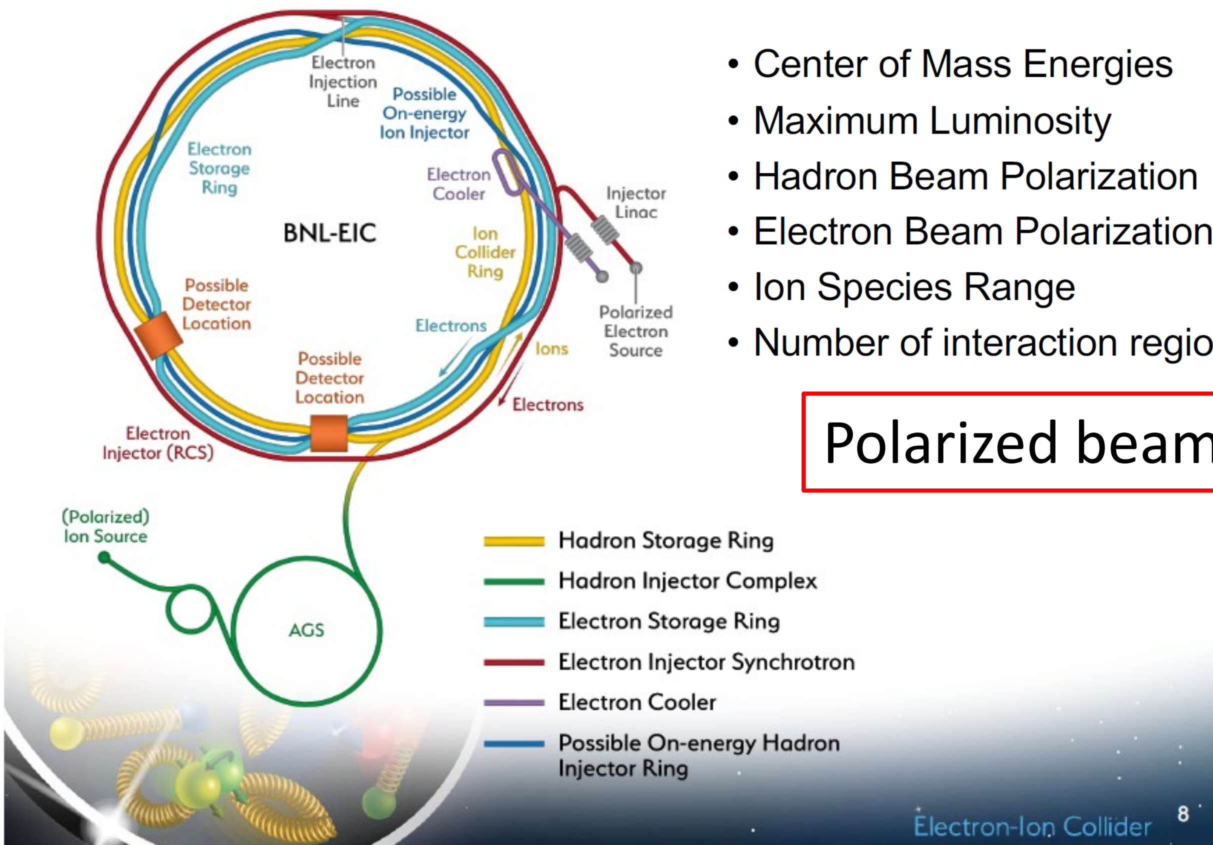
2nd International Workshop on Forward Physics and Forward Calorimeter Upgrade in ALICE

March 15th, 2023 at Tsukuba Univ.

Yuji Goto (RIKEN)

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

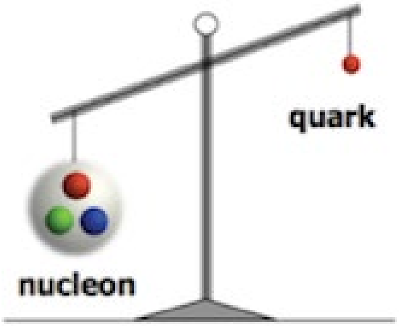


• Center of Mass Energies	20 GeV – 141 GeV
• Maximum Luminosity	10^{34} $cm^{-2}s^{-1}$
• Hadron Beam Polarization	80%
• Electron Beam Polarization	80%
• Ion Species Range	p to Uranium
• Number of interaction regions	up to two

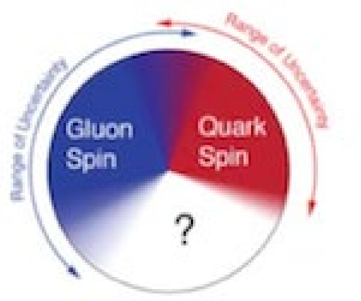
Polarized beam: e, p, d, ^{3}He

Physics at EIC

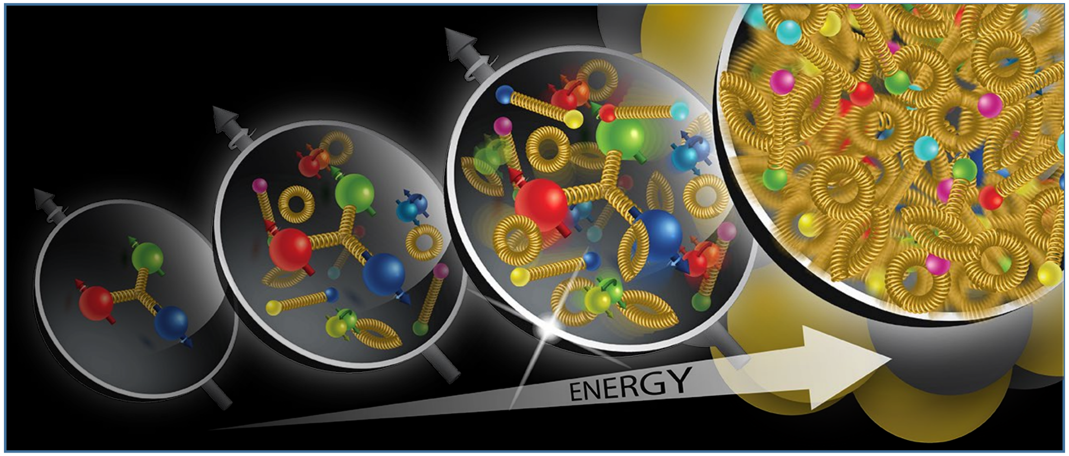
- How does the mass of the nucleon arise?
  - The Higgs mechanism accounts for only ~1% of the mass of the proton.



- How does the spin of the nucleon arise?
  - The spin of the quarks accounts for only one-third of the spin of the proton.

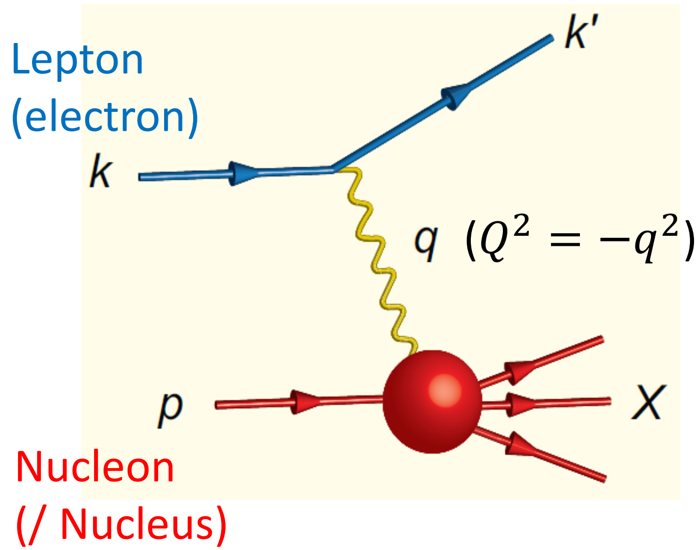


- What are the emergent properties of dense system of gluons?
  - The gluon saturation describes a new state of matter at extreme high density.

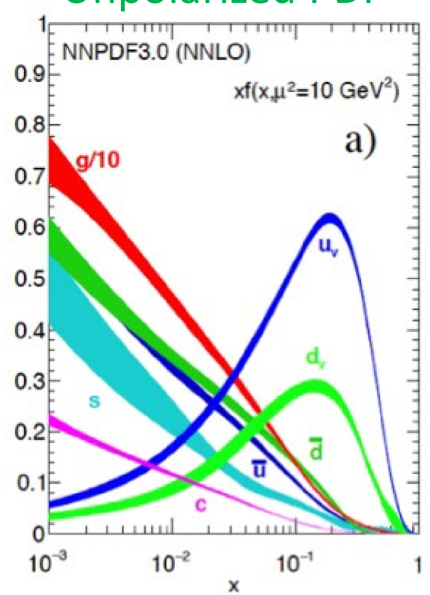


Quark-gluon structure

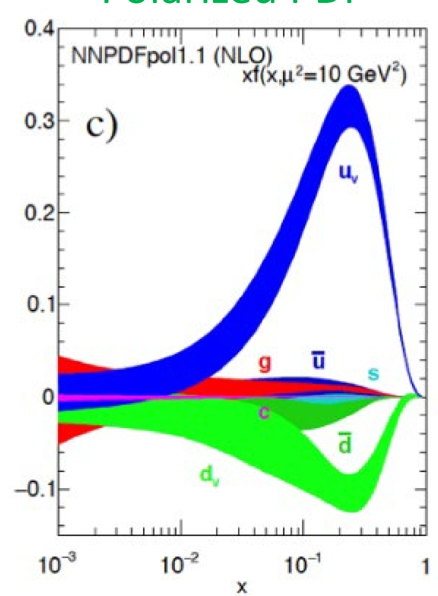
- Deep inelastic scattering (DIS) of lepton (electron)
  - Large Q^2 ($Q^2 = -q^2$) provides a hard scale to resolve quarks and gluons in the proton
- Parton distribution function (PDF) of quarks and gluons
  - 1D longitudinal motion of partons
  - x : momentum fraction of quarks and gluons
  - Significant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



Unpolarized PDF

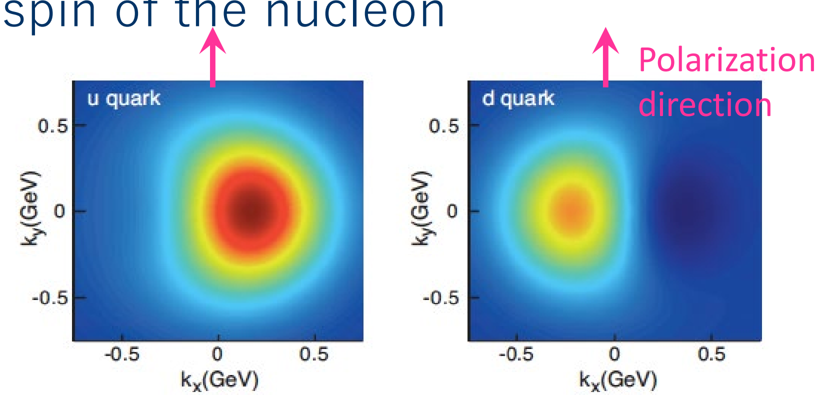


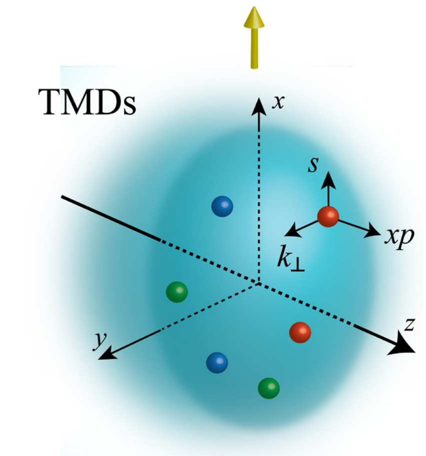
Polarized PDF



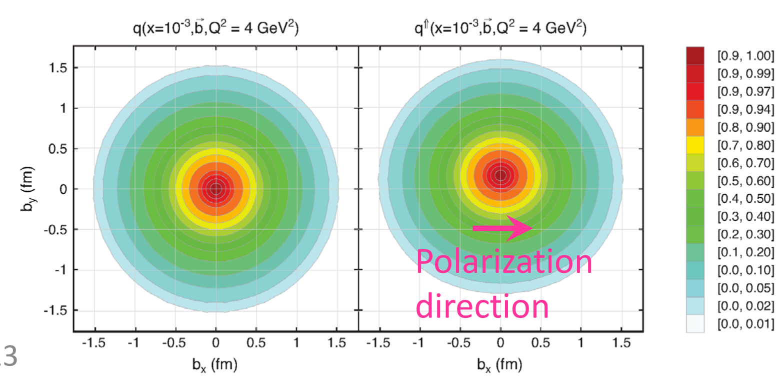
3D structure of the nucleon

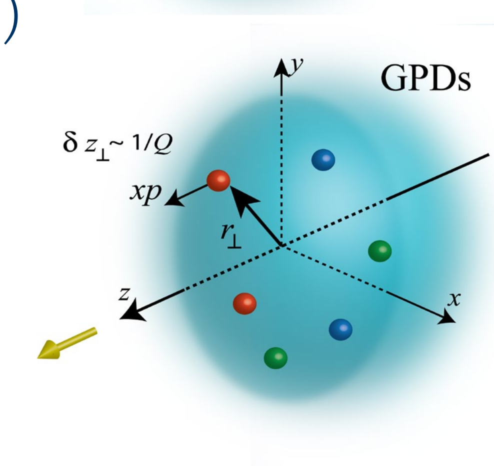
- Conclusive understanding of the nucleon spin
  - Orbital motion inside the nucleon and orbital angular momenta of quarks and gluons
- TMD (Transverse-Momentum Dependent) distribution function
  - Correlation between the (orbital) motion, spin of partons, and spin of the nucleon





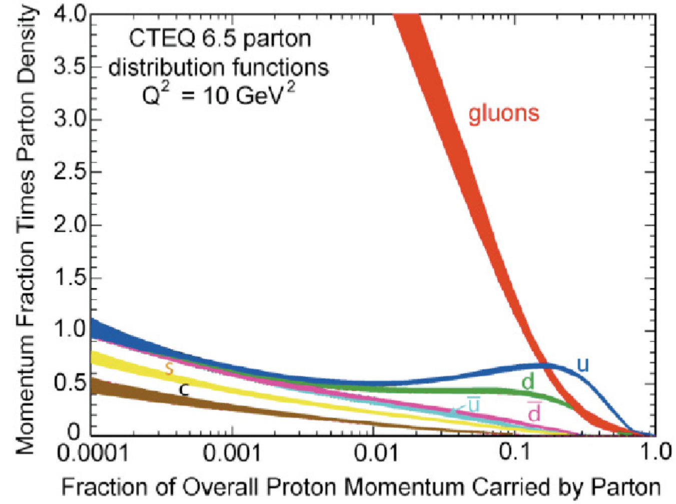
- GPD (Generalized Parton Distribution)
  - Spatial distribution or tomography

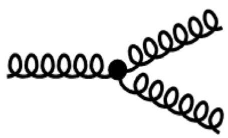


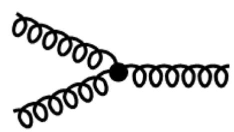


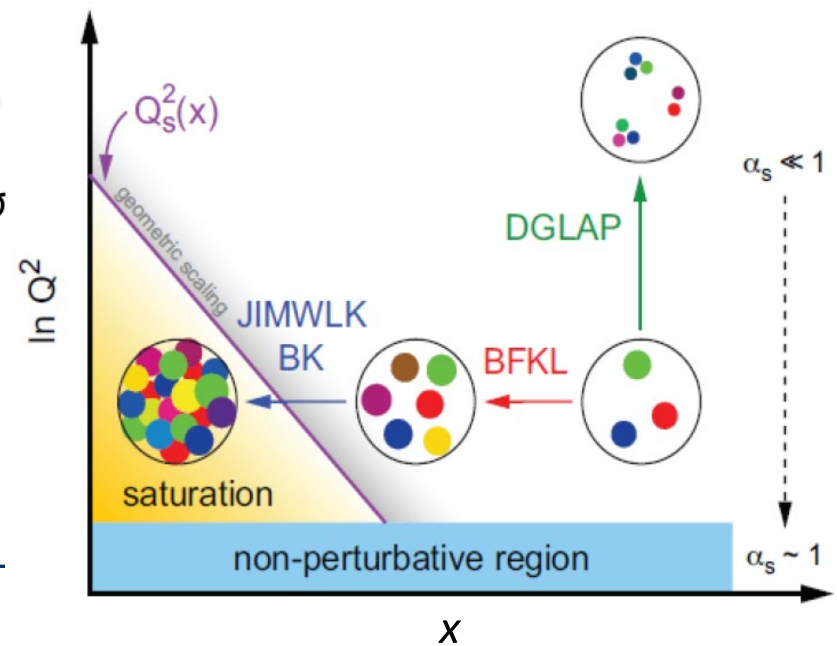
Gluon saturation in e+A collisions

- pQCD and DGLAP & BFKL evolution works with high precision
- Issues with linear DGLAP/BFKL at low-*x*
  - Gluon PDF rapid rise violates unitary bound
- New approach: non-linear evolution
  - Gluon emission
    - Divergence at small *x*
  - Gluon recombination
    - Restriction of divergence
  - At very high energy, recombination compensates gluon emission
- BK/JIMWLK non-linear effects
  - Saturation characterized by $Q_s(x)$
  - Describe physics at low-*x* and low-moderate Q^2



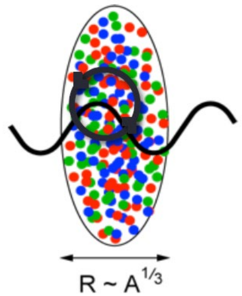






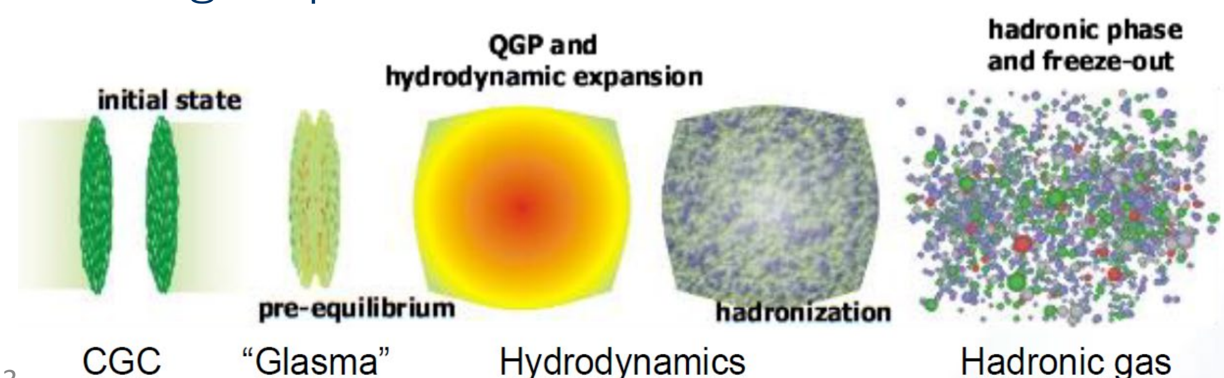
Gluon saturation in e+A collisions

- Color Glass Condensate (CGC)
  - Non-linear evolution
  - Saturation of gluon densities characterized by scale $Q_s(x)$
- Enhancement of Q_s with A
  - Saturation regime reached at significantly lower energy in nuclei



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

- First observation ot a quantum collective gluonic system
  - Precision comparison of experiment and CGC as a theoretical model of the gluon saturation
- Precision understanding of nucleus with the quark-gluon picture necessary as the initial state of the QGP for understanding its production mechanism

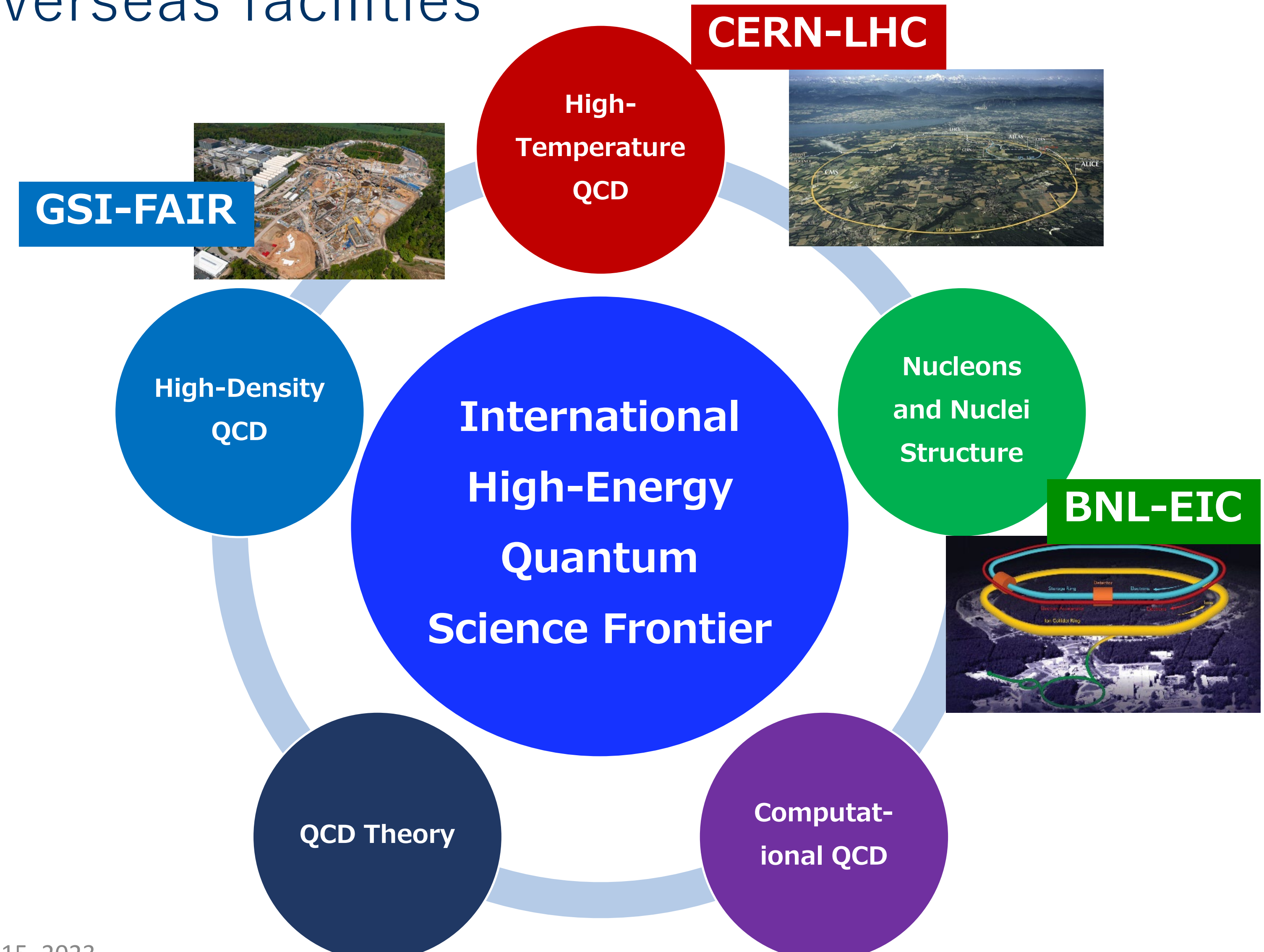


EIC-Japan activities

- 2019: Science Council of Japan Master Plan 2020 proposal of EIC
  - Collaboration including nuclear-physics community and high-energy community
  - Core institutions: Yamagata and RIKEN
  - Participating institutions: Kobe, Nihon, KEK, etc.
- 2020: Yellow Report
- 2020.5: eRD27 “developing a high resolution ZDC for the EIC”
- 2020.11: Expression of Interest (EOI) from EIC-Japan
- 2021.3-12: Call for detector proposal from the EIC project
  - EIC-Japan group participates in the ECCE detector consortium
- 2022: Science Council of Japan “Medium- and Long-term Research Strategy for Science” for "Future Science Promotion Initiative"
  - EIC project proposal submitted as a part of the “International High-Energy Quantum Science Frontier: QCD research at overseas facilities”
  - Prof. Gunji (CNS, Univ. of Tokyo) leading the proposal
  - Including LHC, FAIR, EIC, etc. and Theory

International High-Energy Quantum Science Frontier

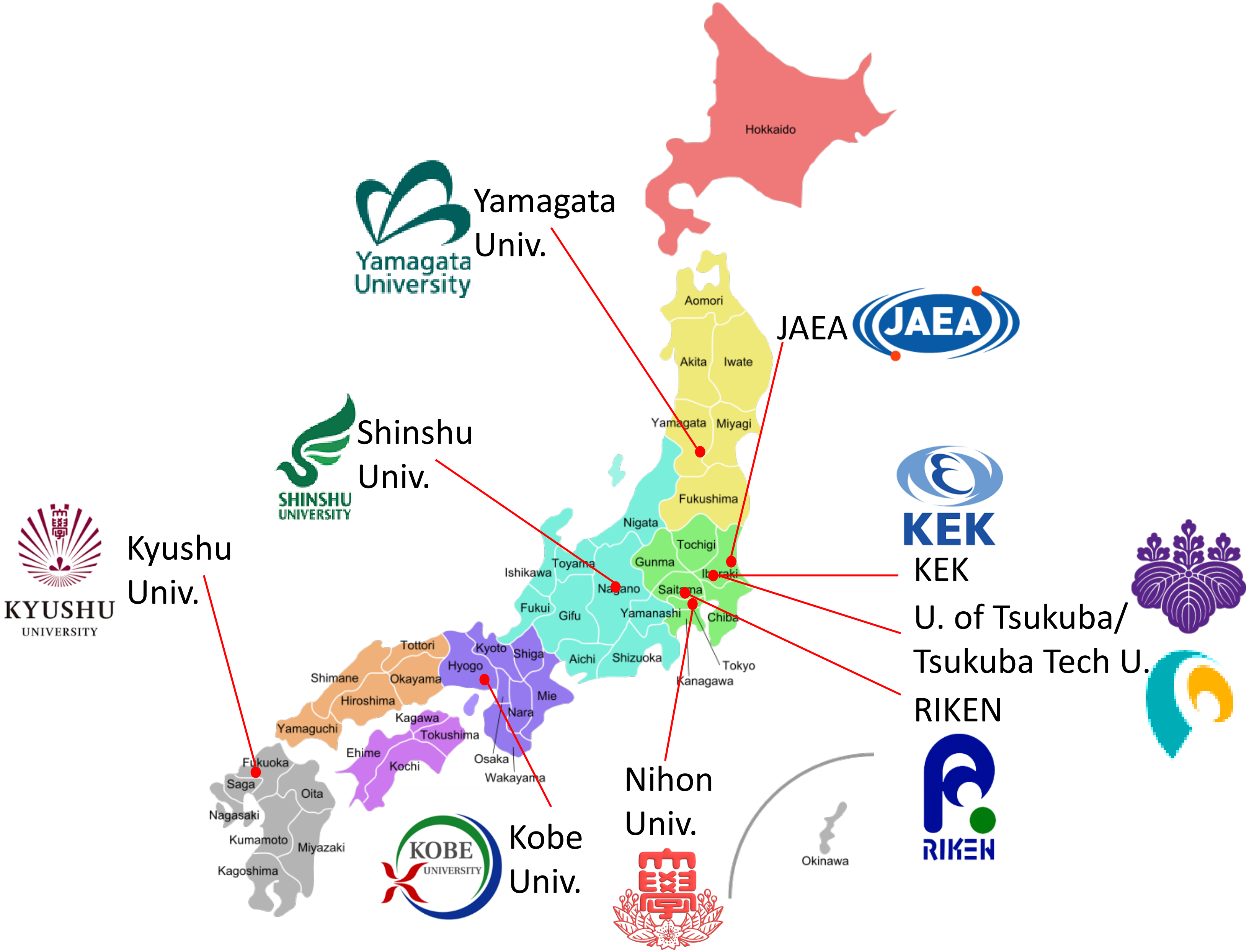
- Promote QCD research to be developed at overseas facilities



EIC-Japan activities

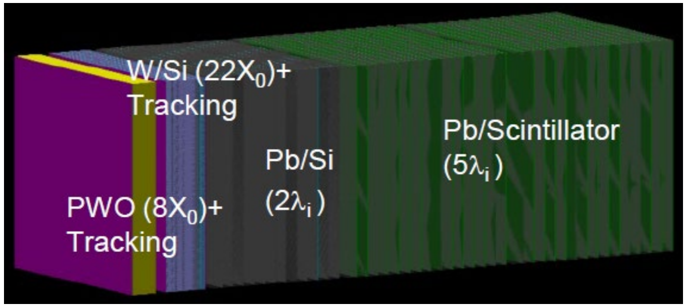
- This proposal to the Science Council of Japan to be a third pillar with J-PARC extension and RIBF upgrade, granted in Japanese Nuclear Physics Committee
- Discussion of cooperation with Korea and Taiwan (Asian) groups
  - 2022.11.2-4 APCTP Workshop on the Physics of EIC (Incheon, Korea)
  - 2022.11.18 EIC Meeting in NCU (Taiwan)
  - 2023.3.16-18 EIC Asia Workshop to be held at RIKEN Wako

Interest in contributing to ZDC

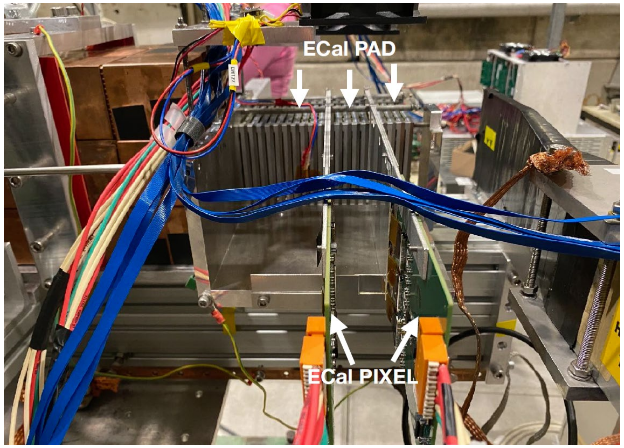


Interest in contributing to ZDC

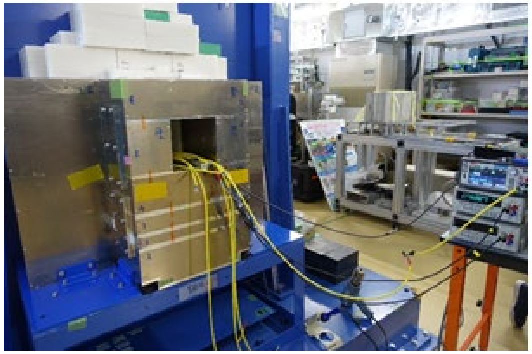
- ECCE/ePIC ZDC (Zero-Degree Calorimeter) design
- ALICE-FoCal-E technology: Tungsten/Silicon
  - Development and evaluation with test beams
- Radiation tolerance test by neutron irradiation
- RIKEN, Tsukuba, Tsukuba Tech, Kobe, Shinshu, Yamagata, JAEA, Nihon, Kyushu, KEK



ECCE/EPIC ZDC

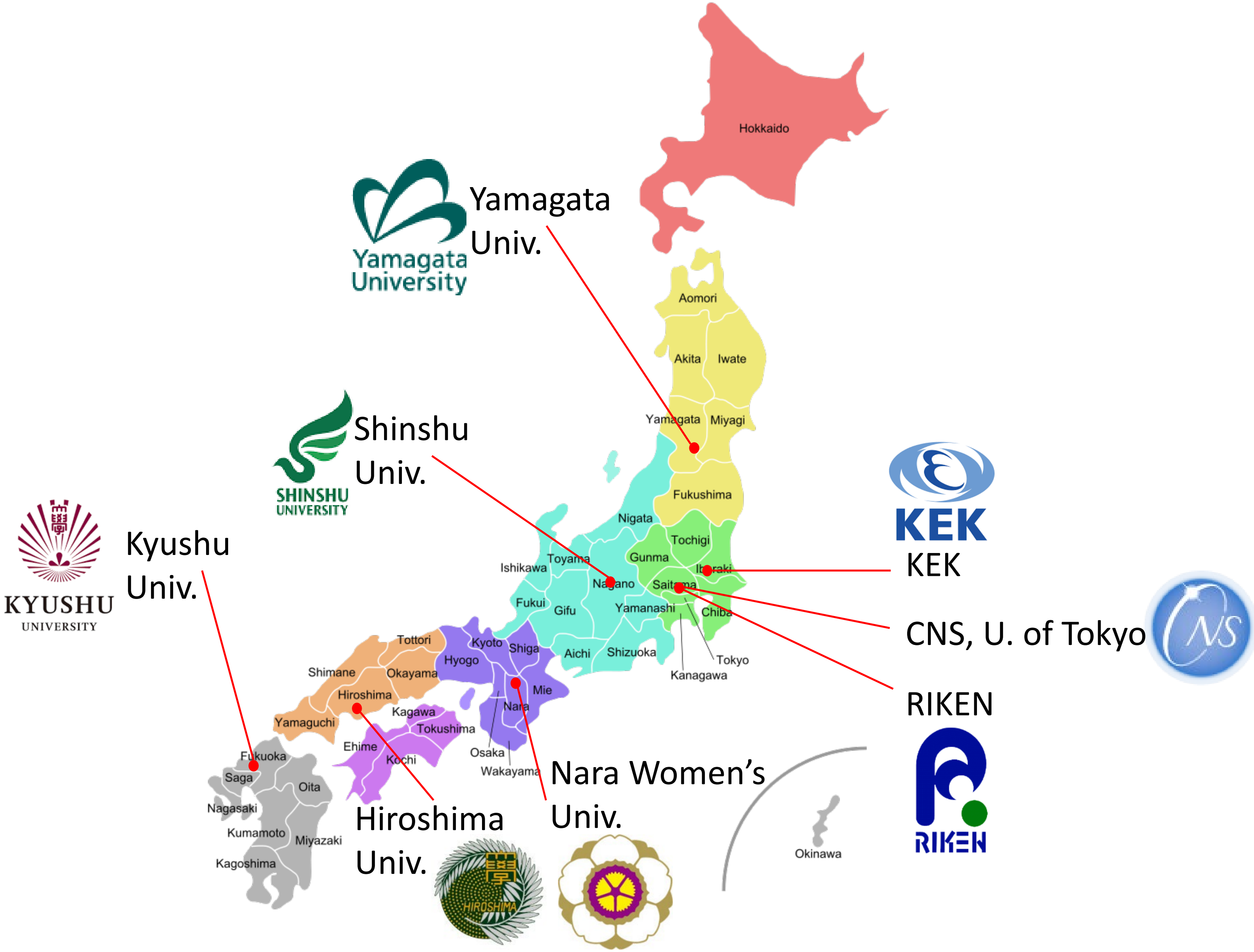


ALICE FoCal-E R&D with test beams



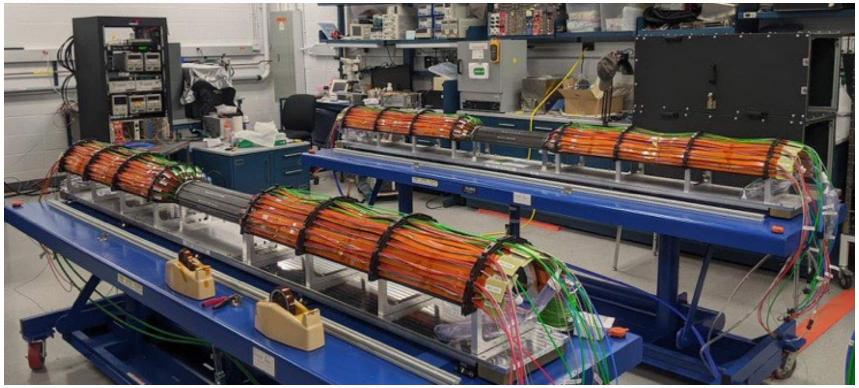
Neutron irradiation at RIKEN RANS

Interest in contributing to AC-LGAD Barrel

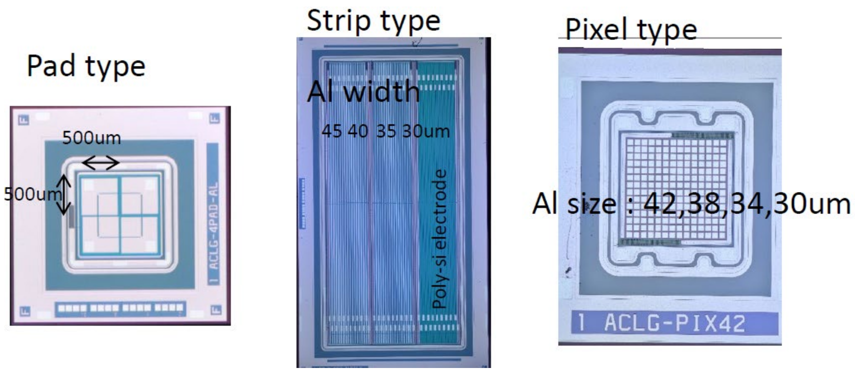


Interest in contributing to AC-LGAD Barrel

- Construction of AC-LGAD (Low-Gain Avalanche Detector) Barrel based on our past experience of PHENIX VTX silicon detector construction and present experience of sPHENIX INTT silicon detector construction
- HPK LGAD development by KEK group
  - To be combined with some readout ASIC
- RIKEN, Hiroshima, Nara Women's, Tokyo CNS, Kyushu, KEK



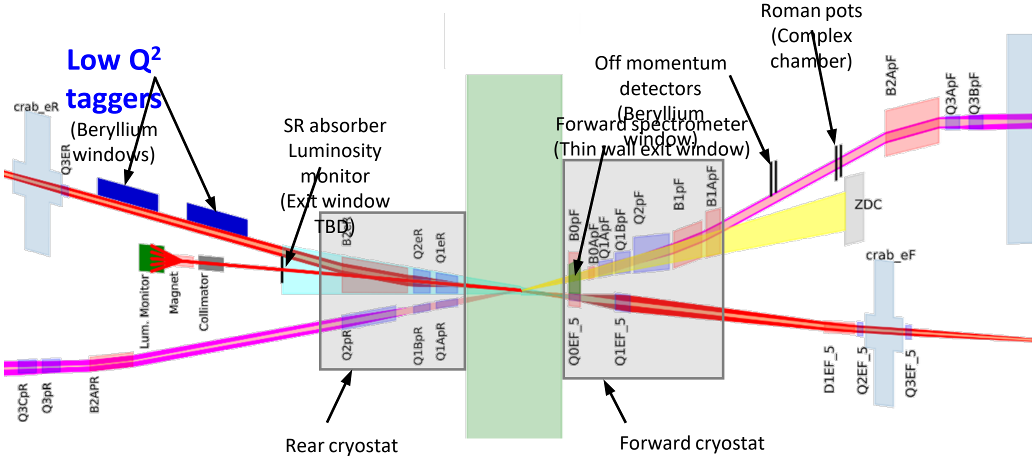
sPHENIX INTT construction



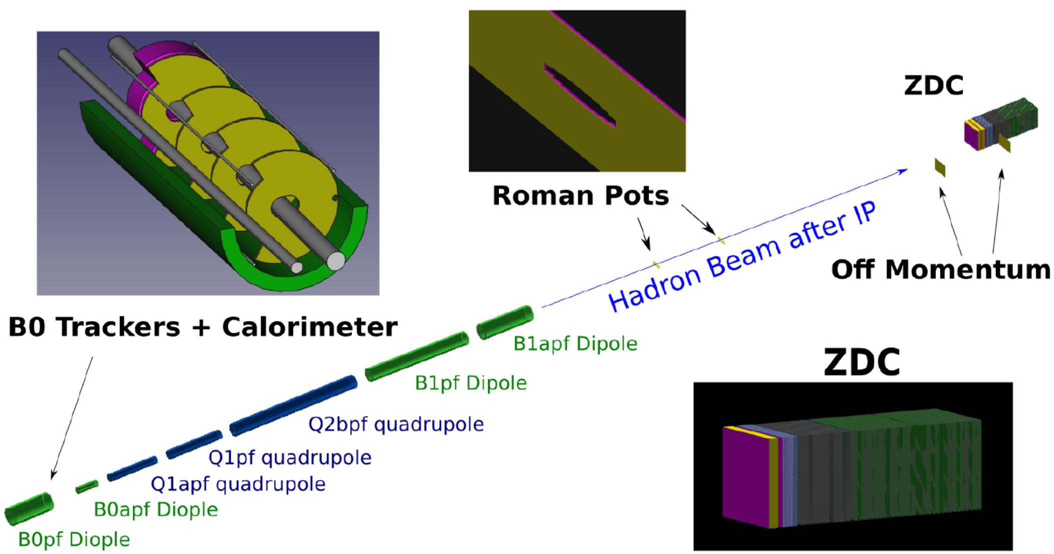
HPK LGAD development

EIC Interaction Region (IP6)

- Extensive integration of forward and backward detector elements into the accelerator lattice

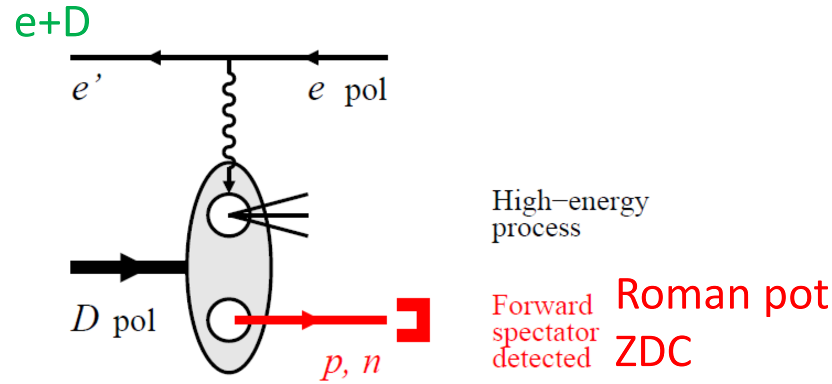


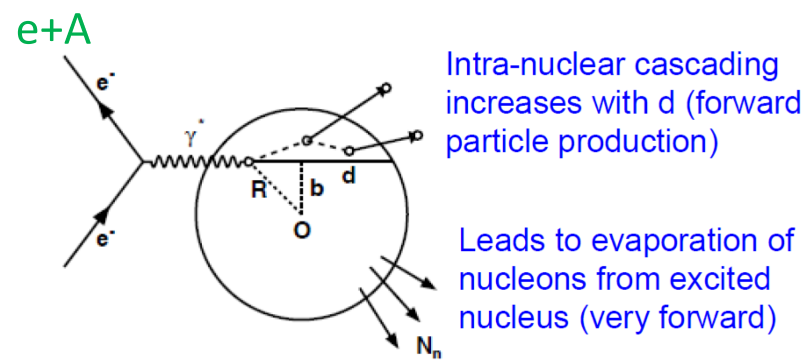
- EIC far-forward region

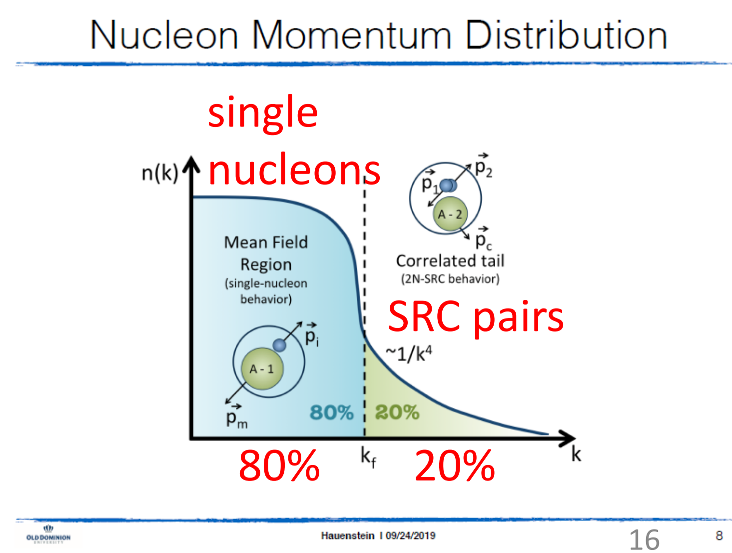


Far-forward physics at EIC

- Spectator tagging in e+d/^{3}He collisions
  - Neutron structure
    - Neutron spin structure, S & D waves
- e+A collisions at zero degree
  - Breakup determination of the excited nucleus
    - Veto with evaporated neutrons and photons from de-excitation
  - Geometry tagging in e+A collisions
    - Event-by-event characterization of collision geometry
    - Study of nuclear medium effects
  - Short-range correlation (SRC) and EMC effect
    - Nuclear PDF significantly modified by SRC pairs







Far-forward physics at EIC

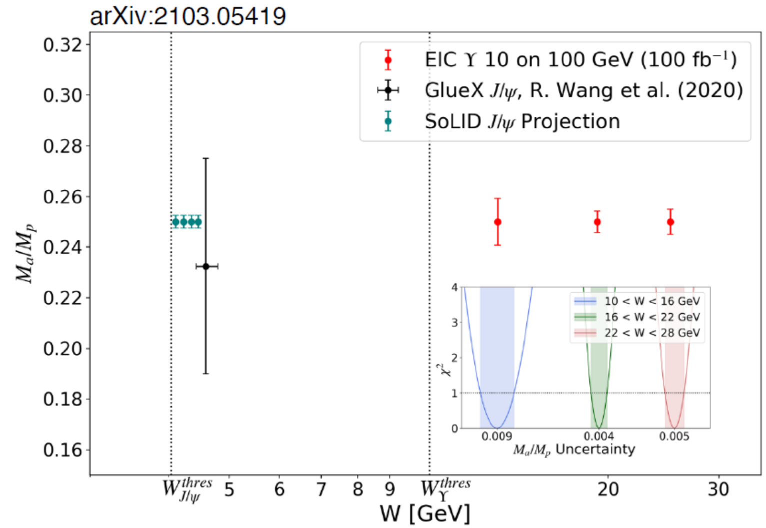
- Mass of the proton, pion, kaon

Relativistic Motion — Chiral Symmetry Breaking — Quantum Fluctuations

$$M = E_q + E_g + \chi_{m_q} + T_g$$

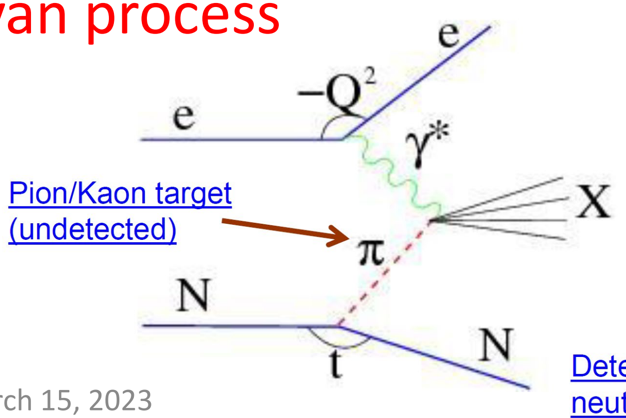
X. Ji, PRL 74 1071 (1995)

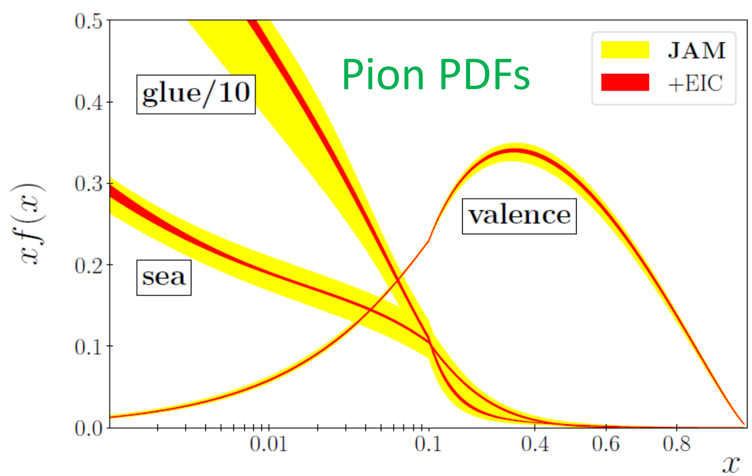
Quark Energy — Gluon Energy — Quark Mass — Trace Anomaly



- Proton
  - Determination of an important term contributing to the proton mass, the so-called “QCD trace anomaly”
  - Through dedicated measurements of exclusive production of J/ψ and Υ close to the production threshold
- Pion and kaon
  - Determination of the quark and gluon contribution to mass with the Sullivan process

Sullivan process





Requirements to ePIC ZDC

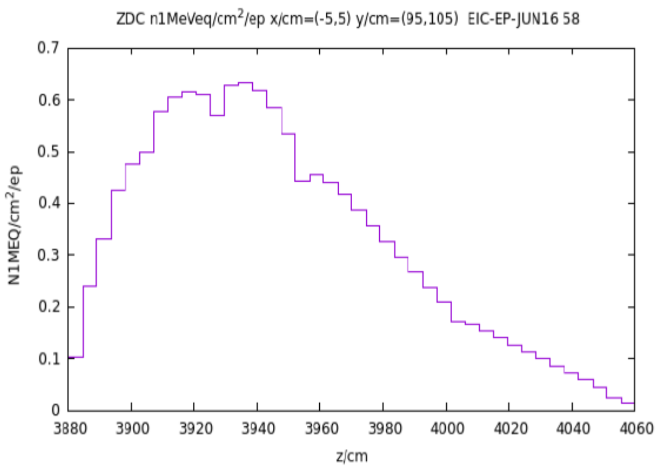
- Large acceptance
  - Large aperture $\rightarrow$ large ZDC
- Soft photon detectrion of O(100) MeV
  - Detection efficiency more than 90%
- Neutron measurement
  - Energy up to 275 GeV (beam energy)
  - Energy resolution $50\%/\sqrt{E(GeV)} + 5\%$
  - Position resolution 3 mrad/$\sqrt{E(GeV)}$
- Photon measurement
  - Soft photon with 20-30% energy resolution
  - 20-40 GeV photon with $35\%/\sqrt{E(GeV)}$ energy resolution and 0.5-1 mm position resolution
- Radiation tolerance
  - 2×10^6 neutron/cm^2/s $\rightarrow$ O(10^{14}) n_{eq}/cm^2 (1MeV neutron eq.) in several years
  - 1.5 – 2.5 kGy / year

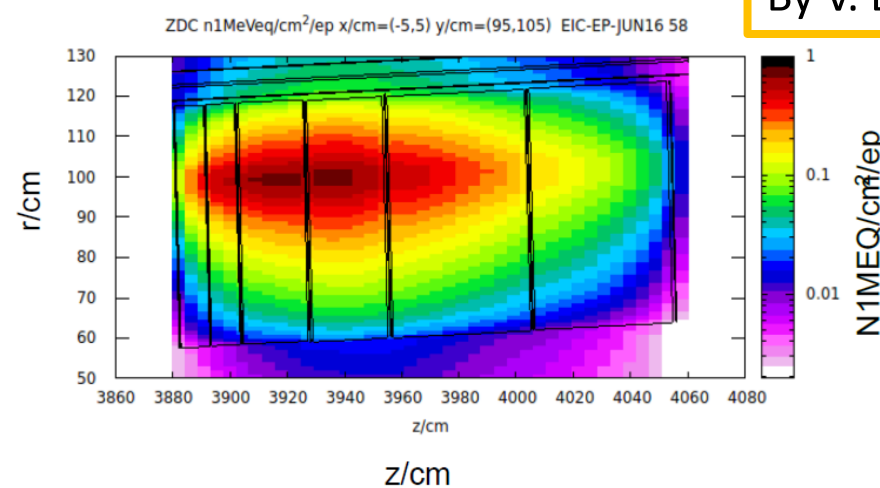
Radiation tolerance

- At ALICE-FoCal, 1-MeV neutron equivalent fluence < 10^{13} n_{eq}/cm^2, or Total ionizasation dose (TID) of 1.5 kGy
- At ePIC ZDC, more than 2 x 10^{13} neutron/cm^2 in one year
- More than 10 times higher radiation than ALICE-FoCal

Electron-Proton collisions. IP6, p(275)+e(10). Si lifetime in ZDC.

By V. Baturin





Assume the ep - collision rate is 1.E+6 [ep/s]

Critical rate dN_{ep+pg}/dt=8.E - 1[N/cm ^{2}/ep]*1.E+6[ep/s]+dN_{pg}/dt=

=8.E+5[Hz/cm ^{2}]+.4 E+5[Hz/cm ^{2}]

ZDC Silicon LifeTime = 1.E+14 [1/cm ^{2}] / 8. 4E+5 [Hz / cm^2] =~0. 12 E+9[s] =

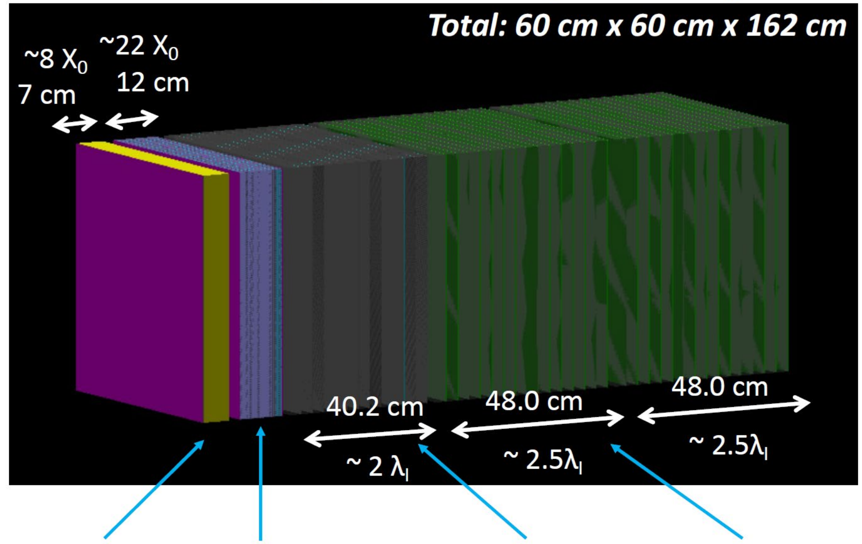
~ **4 years.**

ePIC ZDC first design

- First design
  - ALICE-FoCal-E technology: Tungsten/Silicon
- Single particle simulation
  - Required resolution obtained

Current ZDC design

*note: space for readout may extend the longitudinal length.

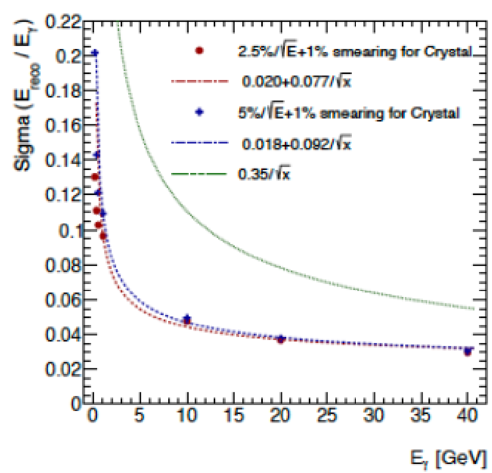


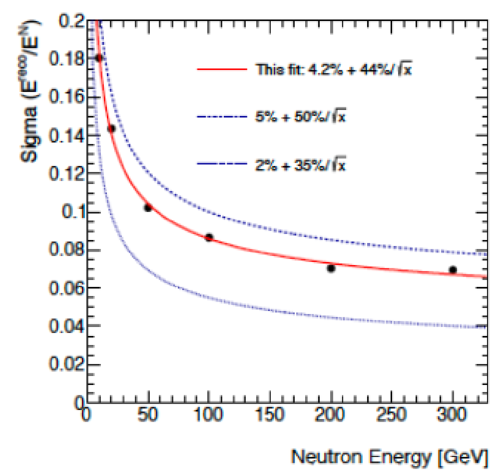
Crystal ($PbWO_4$)
+ Silicon Pixel layer

W/Si calo.
3 Pixel layers are inserted.

Pb/Si calo.

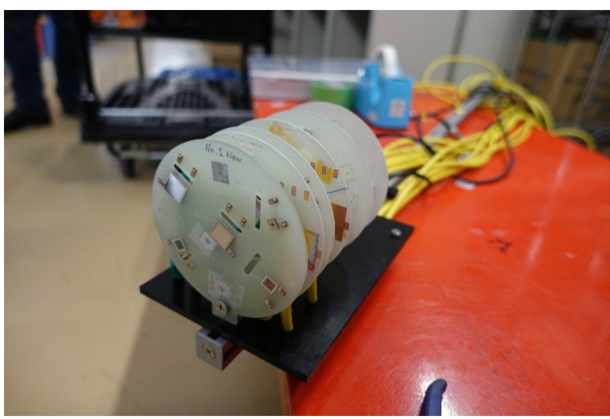
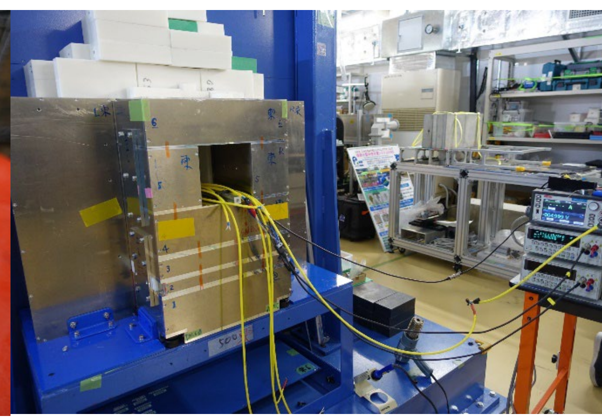
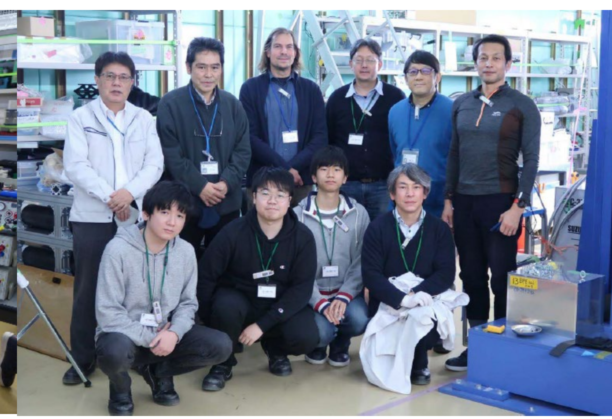
Pb/Sci. calo.





RANS Neutron Irradiation Test

- RIKEN RANS
  - 7MeV proton beam, 100μA, 6 x 10^{13} proton/s
    - Maximum current stable produced about 40μA
  - Neutron 5MeV max, 10^{12} neutron/s from the Be target
  - 2cm from the target: 10^{8} neutron/cm^{2}/s
- 2022.3.3-4 first test
- 2023.3.7-8 second test
  - Tested FoCal-E Pad p-type/n-type baby-chip/MPD, APD/SiPM for readout of crystal calorimeter
  - Monitored by MPD from Kyushu Univ., Indium foil, and thermistor

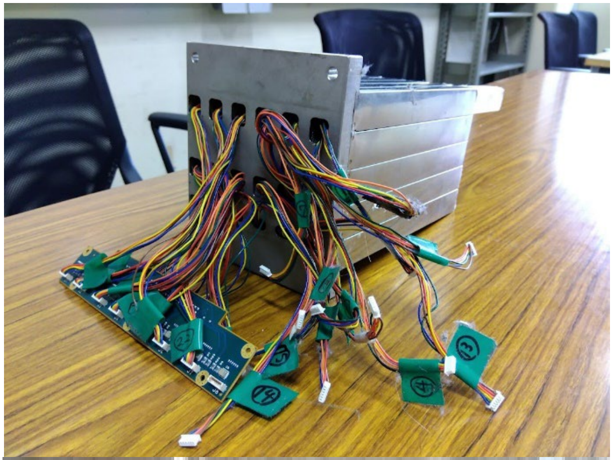




ePIC ZDC

- Design development & optimization
  - Soft photon detection
    - Crystal calorimeter (PWO, LYSO, ⋯) prototype
    - Readout device (APD, PMT, ⋯)
  - EM calorimeter
    - ALICE-FoCal-E technology
    - Sensor, readout (HGCROC), aggregator
  - Hadron calorimeter
    - Light collection, readout
- More development to be done
  - Cooling, support structure
  - Simulation, software development
  - Construction, QA

Crystal Calorimeter

- ALICE-Phos PWO prototype
  - Hiroshima Univ.
  - 2cm x 2cm x 18cm
  - APD readout
  - Shipped to RIKEN



- LYSO crystal by Taiwan group
  - Offer from Taiwan Group for test module production, simulation calculation, etc.

- Considering evaluation using a test beam

Summary of this talk

- Physics at EIC
  - Origin of nucleon mass and spin
  - 3D structure of the nucleon and nucleus
  - Gluon saturation (CGC)
  - Hadronization
- EIC-Japan activities
  - Interest in contributing to ZDC
  - Interest in contributing to AC-LGAD Barrel
  - EIC-Japan Group is developing steadily
- Far-forward physics at EIC & ePIC ZDC
  - Required resolution obtained
  - First design optimization
  - Irradiation test at RIKEN
  - Crystal calorimeter development

Backup Slides

Outline of this talk

- Physics at Electron-Ion Collider (EIC)
  - Origin of nucleon mass and spin
  - 3D structure of the nucleon and nucleus
  - Gluon saturation (Color Glass Condensate)
  - Hadronization
- EIC-Japan activities
  - Interest in contributing to ZDC (Zero-Degree Calorimeter)
  - Interest in contributing to (AC-)LGAD (Low-Gain Avalanche Detector) Barrel
- Collaboration opportunities

EIC-Japan activities

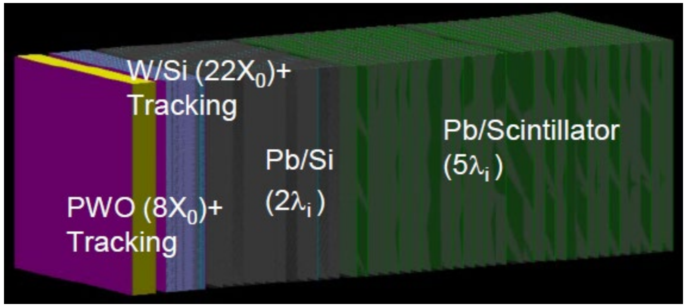
- 2015.4: EIC Letter of Interest from Asian countries
  - 20 participants from Japan: RIKEN, Yamagata, Tokyo Tech, Juntendo, KEK, Kyorin, Kyoto, Niigata, Tohoku, Tokyo Science
  - 7 from China, 3 from India, 4 from Korea
  - To support EIC for NSAC Long Range Plan 2015
- 2019: Science Council of Japan Master Plan 2020 proposal of EIC
  - Collaboration including nuclear-physics community and high-energy community
  - Core institutions: Yamagata and RIKEN
  - Participating institutions: Kobe, Nihon, KEK, etc.
- 2020: Yellow Report
- 2020.5: eRD27 “developing a high resolution ZDC for the EIC”
- 2020.11: Expression of Interest (EOI) from EIC-Japan
- 2021.3-12: Call for detector proposal from the EIC project
  - EIC-Japan group participates in the ECCE detector consortium

EIC-Japan activities

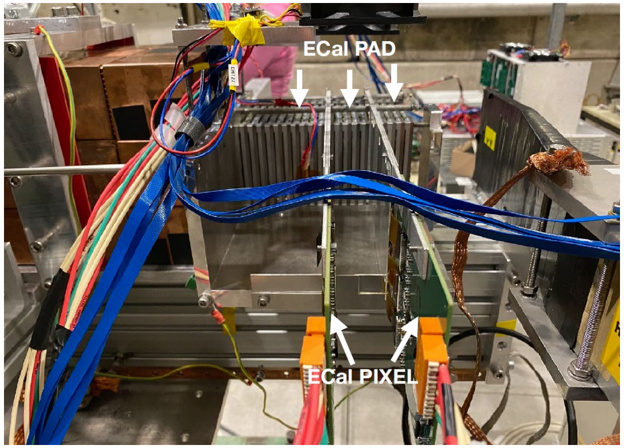
- 2022: Science Council of Japan "Medium- and Long-term Research Strategy for Science" for "Future Science Promotion Initiative"
- EIC project proposal submitted as a part of the "International High-Energy Quantum Science Frontier: QCD research at overseas facilities"
  - Prof. Gunji (CNS, Univ. of Tokyo) leading the proposal
  - Including LHC, FAIR, EIC, etc. and Theory
- This proposal to the Science Council of Japan to be a third pillar with J-PARC extension and RIBF upgrade, granted in Japanese Nuclear Physics Committee
- Dr. Koyasu (head of RIKEN Cluster for Pioneering Research) agreed to host this proposal
  - Leading international-collaboration experiments on a long-term basis at overseas facilities
  - Development of common technologies (detector, data processing, and computation technologies)
  - Cooperation between domestic experiment and theory communities
  - Cooperation among experiments according to project trends
  - A major international-collaboration center connecting Japan, Europe, and the U.S.
  - International circulation of cutting-edge knowledge, technology, and people, and human resource development for the next generation

Interest in contributing to ZDC

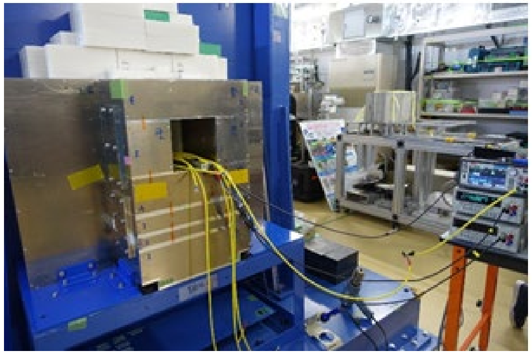
- ECCE/EPIC ZDC (Zero-Degree Calorimeter) design
  - Simulation
  - Performance evaluation
- ALICE-FoCal-E technology: Tungsten/Silicon
  - Test beam studies ongoing
- Radiation tolerance test by neutron irradiation
- RIKEN, Tsukuba, Tsukuba Tech, Kobe, Shinshu, Yamagata, JAEA, Nihon, Kyushu, KEK, Nagoya, Tokyo ICRR



ECCE/EPIC ZDC

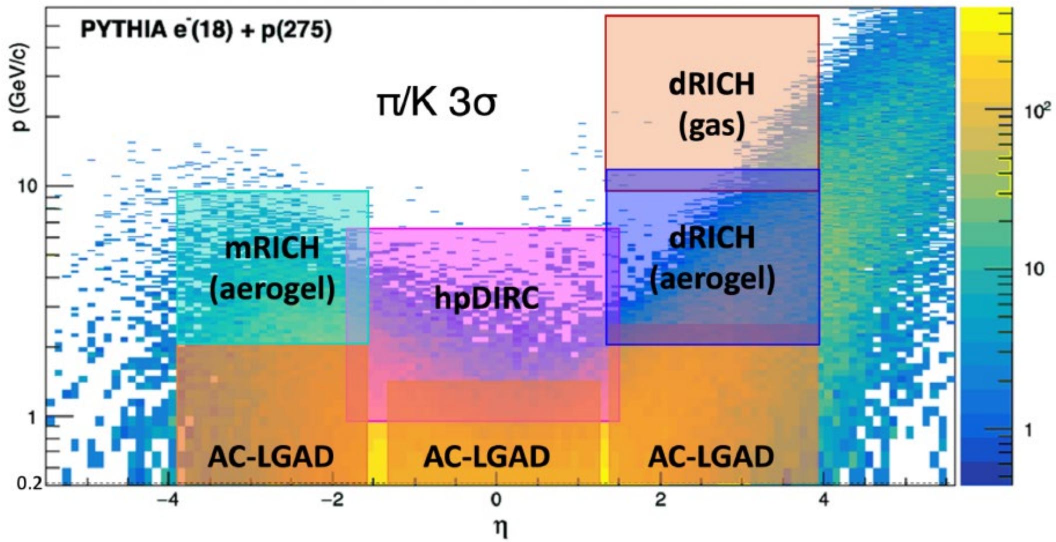


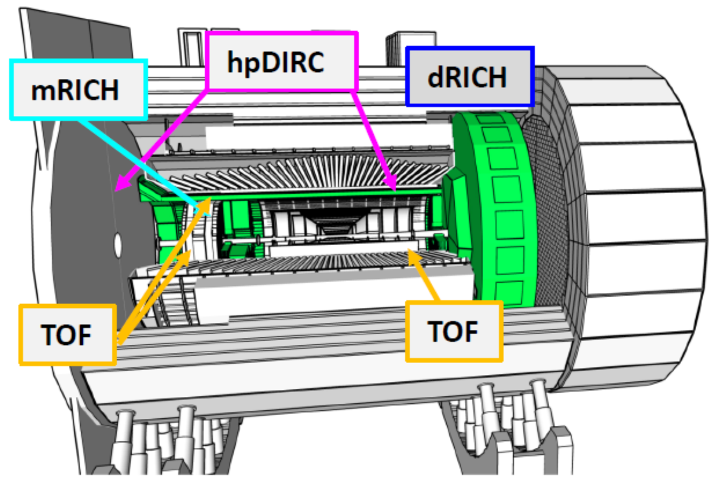
ALICE FoCal-E R&D



Neutron irradiation at RIKEN RANS

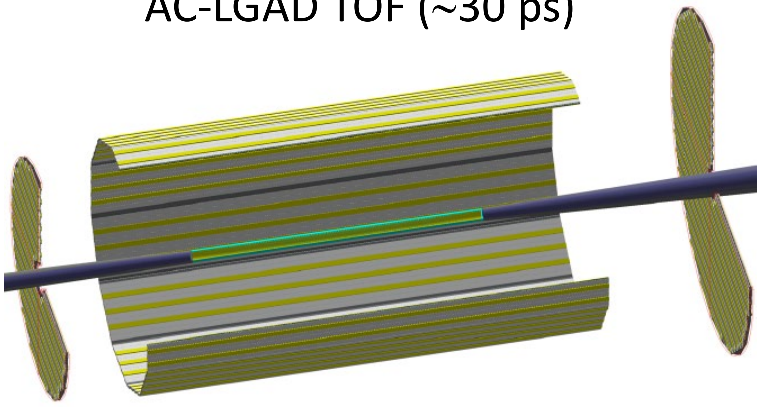
Charged particle ID





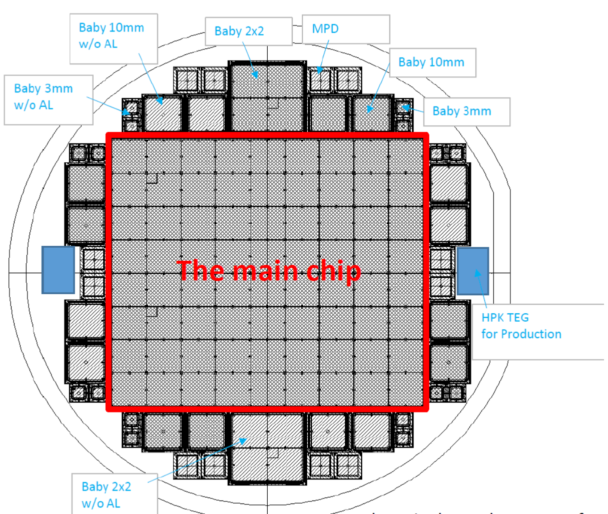
- Need to separate:
  - Electrons from photons
  - Electrons from charged hadrons
    - Calorimeter
  - Charged pions, kaons and protons from each other
    - TOF and Cherenkov
- AC-LGAD based TOF system
  - Hadron PID in momentum range below the thresholds of the Cherenkov detectors

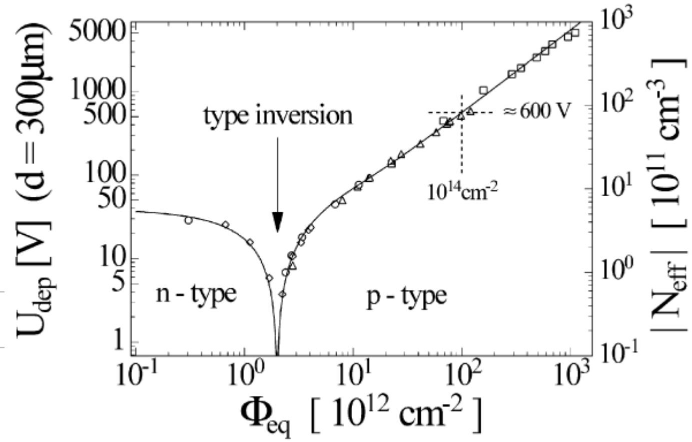
AC-LGAD TOF (~30 ps)

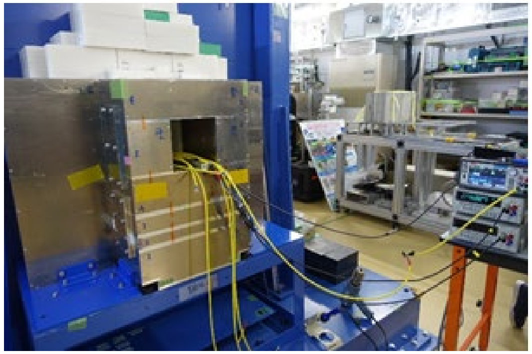


ePIC ZDC

- Measurement of the radiation hardness of the ALICE-FoCal-E Pad sensors
  - To determine if the sensor is sufficiently radiation hard to radiation dose/fluence at zero degree of EIC
- Options: p-type or n-type
  - Type inversion from n-type to p-type at 10^{12} neutron/cm^2







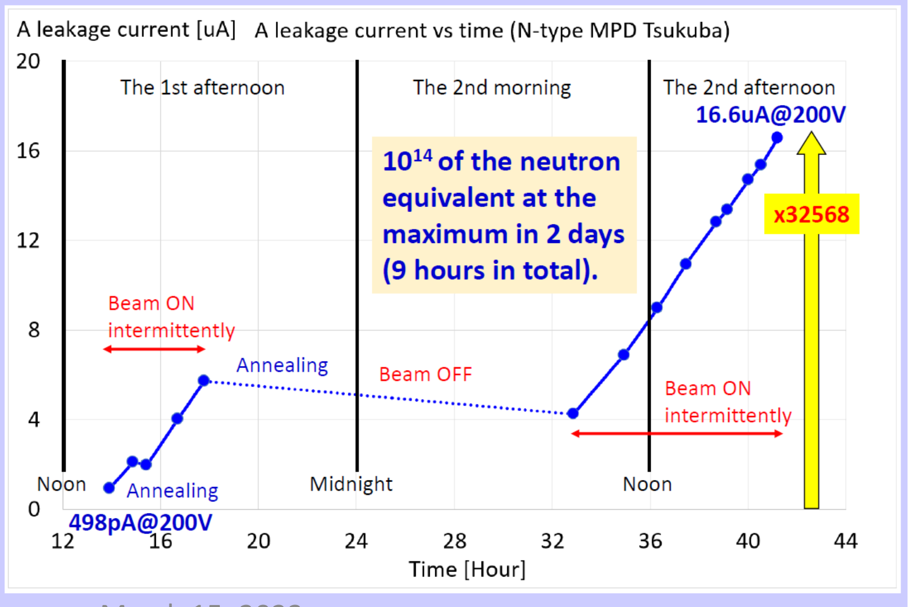
Neutron irradiation at RIKEN RANS

RANS neutron irradiation test

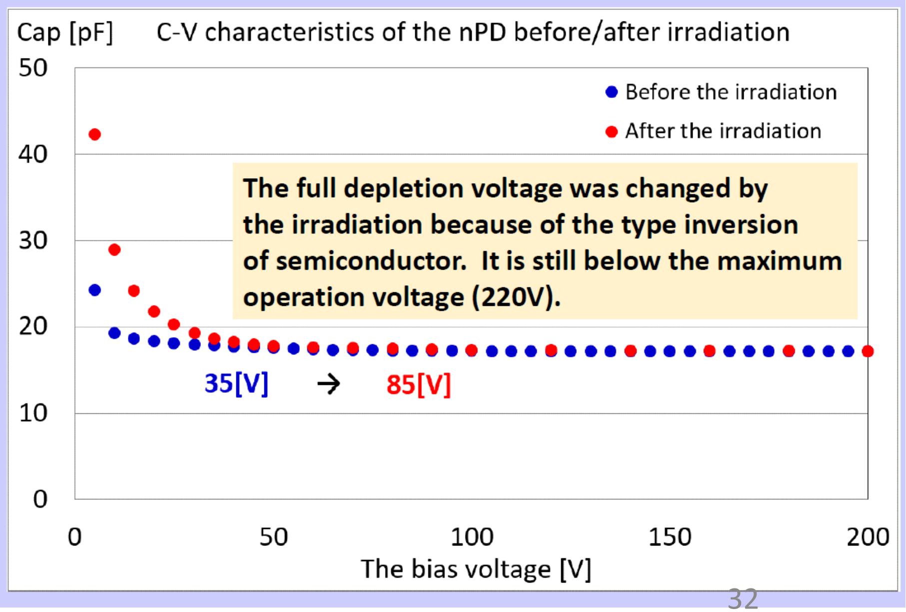
- 10^{14} neutron/cm^2 at the maximum in 2 days, 9 hours in total
- Recorded online a leakage current of the n-type MPD (monitor photo-diode)
- Comparison of the C-V characteristics of the n-type MPD before and after the irradiation
  - Full-depletion voltage: 35V→85V

Inaba-san's slides

The n-substrate monitor PD



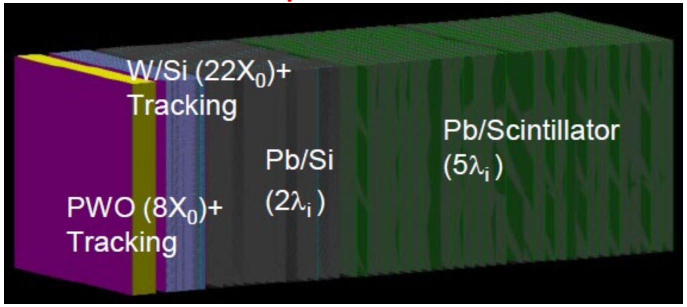
The C-V characteristics of n-substrate MPDs



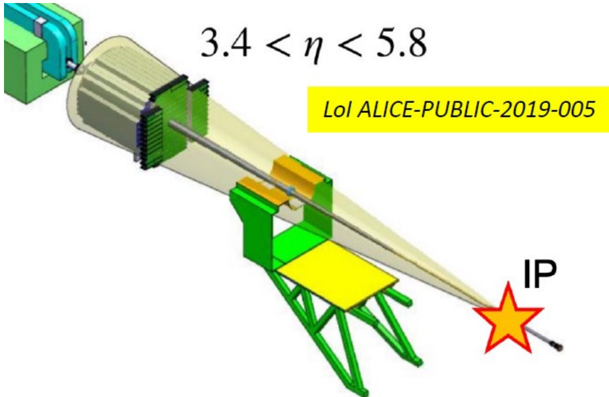
Collaboration opportunities

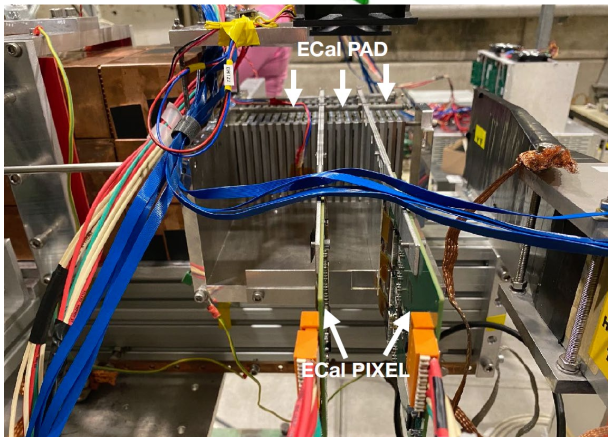
- ePIC ZDC
  - Soft photon detection
    - Crystal calorimeter (PWO, LYSO, ···) prototype
    - Readout device (APD, PMT, ···)
  - EM calorimeter
    - ALICE-FoCal-E technology
      - Pad detector led by Univ. of Tsukuba group and Indian group
      - Pixel detector led by European group
    - Test beam activities ongoing
      - Pad detector at ELPH, Tohoku U.
      - Total system at CERN PS/SPS
    - EM calorimeter optimization
      - Sensor, readout (HGCROC), aggregator
  - Hadron calorimeter
    - Design
      - Light collection, readout

ECCE/EPIC ZDC



ALICE FoCal-E R&D





Collaboration opportunities

- EPIC ZDC
  - Cooling, support structure
  - Simulation, software development
  - Construction, QA
- EPIC (AC-)LGAD Barrel
  - Yano’s talk: Nov. 3 (Thu) afternoon

Summary of this talk

- Physics at EIC
  - Origin of nucleon mass and spin
  - 3D structure of the nucleon and nucleus
  - Gluon saturation (CGC)
  - Hadronization
  - Ultra-precise electron microscope, revealing the origin of mass and spin in three dimensions.
  - Discovery of emergent high-density gluon state (gluon condensation)
- EIC-Japan activities
  - Interest in contributing to ZDC
    - Far-forward physics at EIC
  - Interest in contributing to (AC-)LGAD Barrel
    - Charged particle ID
  - EIC-Japan Group is developing steadily

Outline of this talk

- Physics at EIC
  - Origin of nucleon mass and spin
  - 3D structure of the nucleon and nucleus
  - Gluon saturation
  - Hadronization
- Physics at zero-degree
  - e+A breakup of the excited nucleus & collision geometry
  - e+d/^{3}He spectator tagging & short-range correlation
  - pion and kaon structure (and mass)
- EIC status
  - EIC Users Group
  - EIC-Japan
  - EPIC detector collaboration

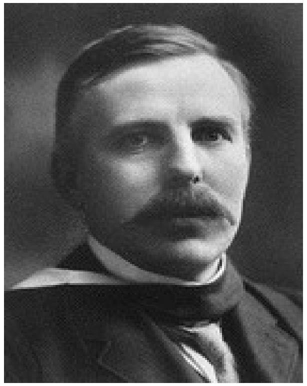
Outline of this talk

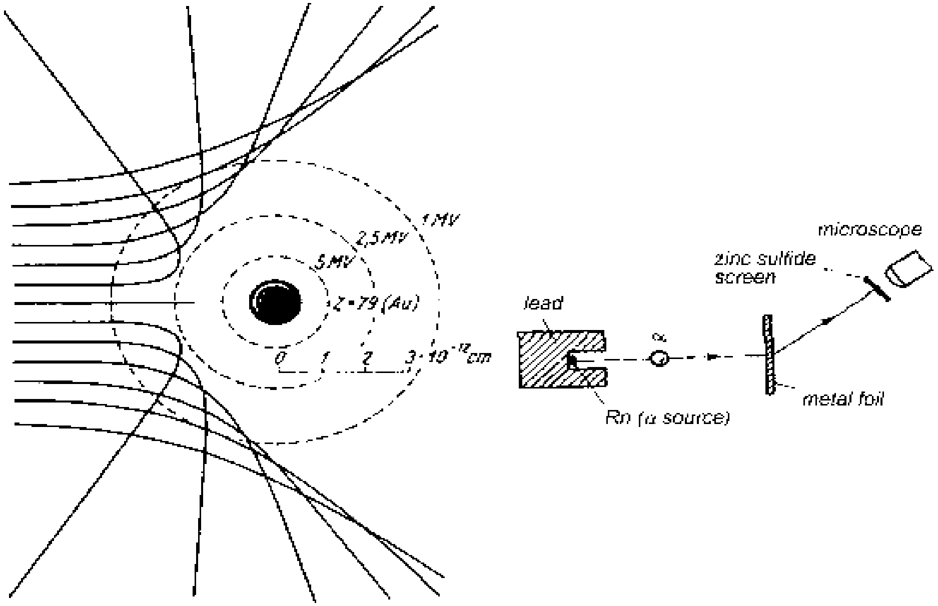
- Physics at Electron-Ion Collider (EIC)
  - Origin of nucleon mass and spin
  - 3D structure of the nucleon and nucleus
  - Gluon saturation (Color Glass Condensate)
  - Hadronization
- EIC status
  - EIC Users Group
  - EIC-Japan
  - EPIC detector collaboration

Atomic structure

- Scattering experiment of α -rays
  - α -ray irradiation to gold foil
  - Only small angle scattering if charge is uniformly distributed in atoms (Thomson model)
  - Observation of large angle scattering, discovery of point nuclei, concentration of charge in a narrow region
- Rutherford scattering (1911)

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Rutherford}} = \frac{Z^2\alpha^2}{4E^2\sin^4\theta/2}$$





Structure of nucleus and nucleon

- Electron Beam Scattering Experiment
  - Mott scattering
  - Electron spin 1/2, target recoil

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Rutherford}} \cdot \cos^2\frac{\theta}{2} \cdot \frac{E'}{E}$$

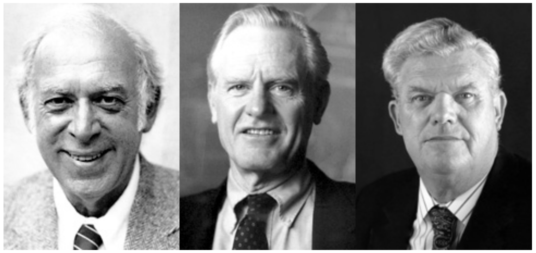
- Electron-proton elastic scattering
  - Electron beam at SLAC (1950s-60s)
  - Form factor measurement
    - Momentum transfer dependence of angular distribution
  - Rosenbluth formula

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \left[\frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1+\tau} + 2\tau G_M^2(Q^2)\tan^2\frac{\theta}{2}\right]$$

    - G_E : Electric form factor
    - G_M : Magnetic form factor
  - Measurement of proton size: 0.8 fm
    - Internal structure of nucleons shown as a mean distribution

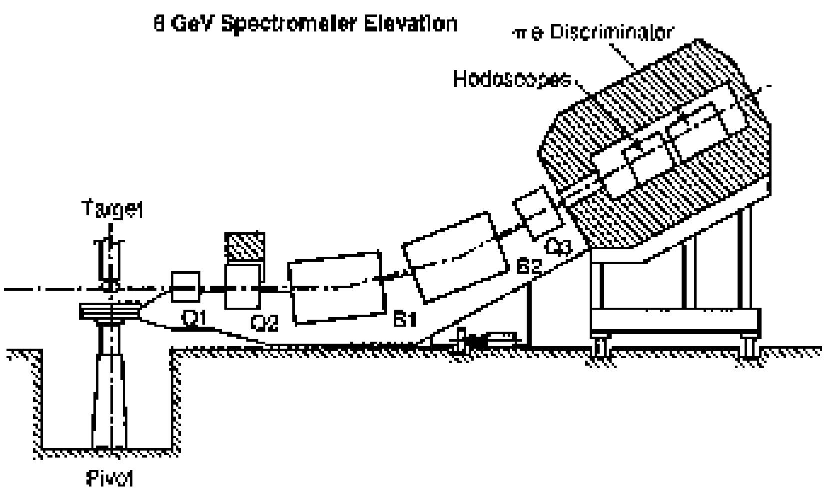
Nucleon structure

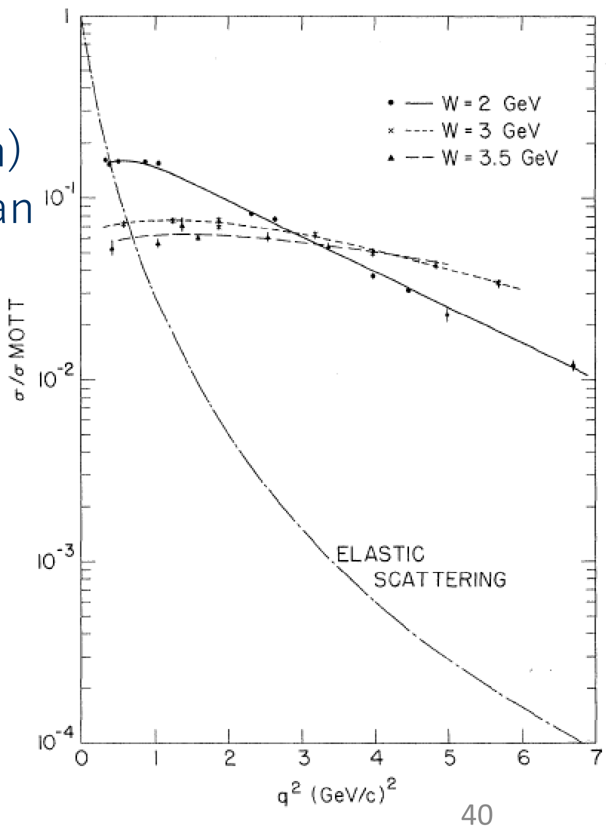
- Deep Inelastic Scatterin (DIS) Experiment



$$\frac{d^2\sigma}{dQ^2 d\nu} = \sigma_{\mathrm{Mott}} \left[W_2(Q^2, \nu) + 2W_1(Q^2, \nu) \tan^2 \frac{\theta}{2} \right]$$

- MIT-SLAC experiment (1969, Friedman, Kendall, Taylor)
  - Scattering cross section does not decrease as Q^2 increases
    - Large angle scattering
    - Point-like components in the proton (parton)
  - Scattering with point-like components rather than scattering by the nucleon as a whole





Quark-Parton Model (QPM)

- Bjorken scaling rule

$$\frac{d^2\sigma}{dQ^2dx} = \frac{4\pi\alpha^2}{Q^4}\frac{E'}{E}\frac{1}{x}\left[F_2(Q^2,x)\cos^2\frac{\theta}{2} + \frac{Q^2}{2x^2M^2}2xF_1(Q^2,x)\sin^2\frac{\theta}{2}\right]$$

  - F_2 and F_1 are functions of x only, independent of Q^2
  - Dirac scattering: spin 1/2 target like muon

$$\left(\frac{d\sigma}{dQ^2}\right)_{\mathrm{Dirac}} = \frac{4\pi Z^2\alpha^2}{Q^4}\left(\frac{E'}{E}\right)^2\left[\cos^2\frac{\theta}{2} + \frac{Q^2}{2M^2}\sin^2\frac{\theta}{2}\right]$$

- Callan-Gross relation

$$F_2 = 2xF_1$$

  - Parton spin 1/2 as muon

$$\frac{d^2\sigma}{dQ^2dx} = \frac{4\pi\alpha^2}{xQ^4}\{1 + (1-y)^2\}F_2(Q^2,x)$$

  - DIS is the superposition of elastic scattering with a point-like component (parton) in the proton

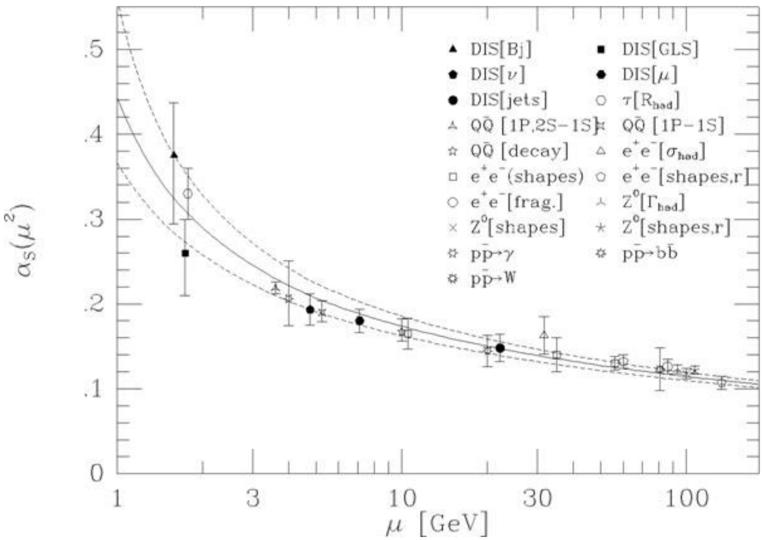
- Parton Distribution Function (PDF)

$$F_2 = x\sum_q e_q^2 q(x)$$

  - Internal structure of nucleon shown as parton distribution
  - $q(x)$: parton distribution function of quark q

From QPM to QCD

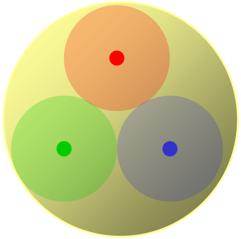
- Breaking of the scaling rule
  - When measured precisely, the Callan-Gross relation is broken
    - F_2 depends on Q^2
  - Gluon presence
- QCD
  - Asymptotic freedom and confinement



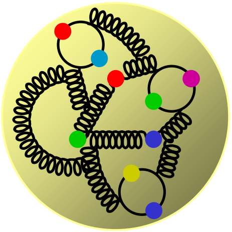
Gross Politzer Wilczek

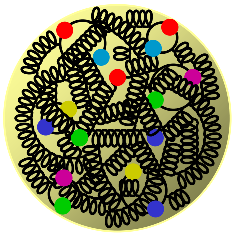
Nucleon structure

- Constituent-quark model
  - Quarks with the effective mass (caused by the gluon)
  - Explains the magnetic moment of the nucleons
  - But, the quark spin cannot explain the nucleon spin ("spin puzzle")



- Quark-gluon model
  - Current quarks and gluon interaction
  - Initial state of high-energy hadron colliders

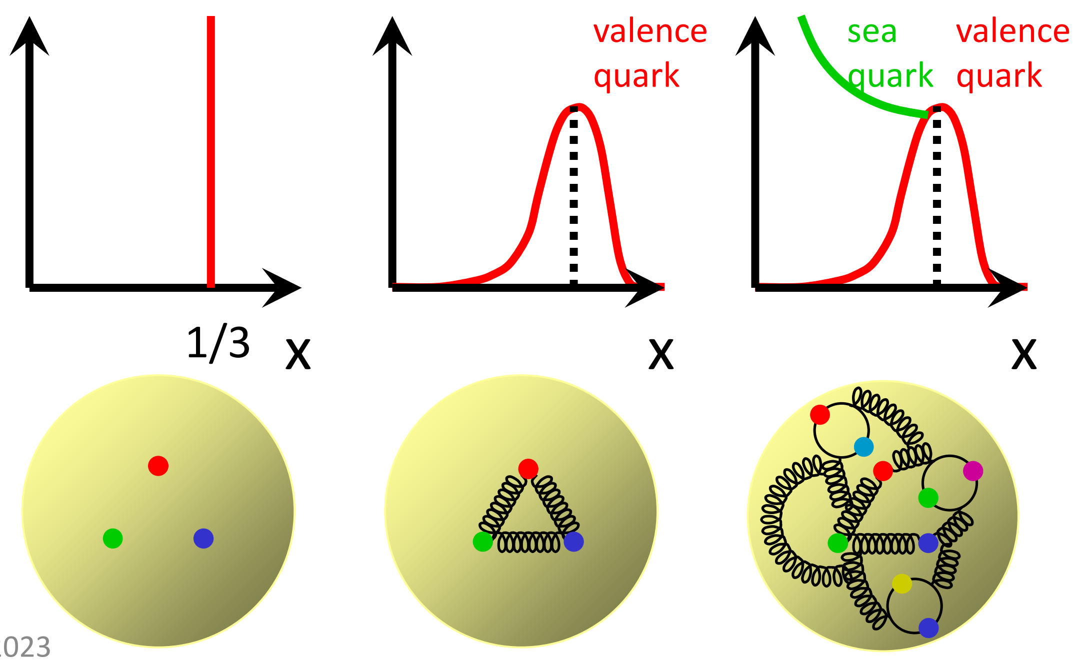




- Understanding the differences (or gap) of these models
  - Chiral symmetry (breaking)
  - Confinement

Nucleon structure

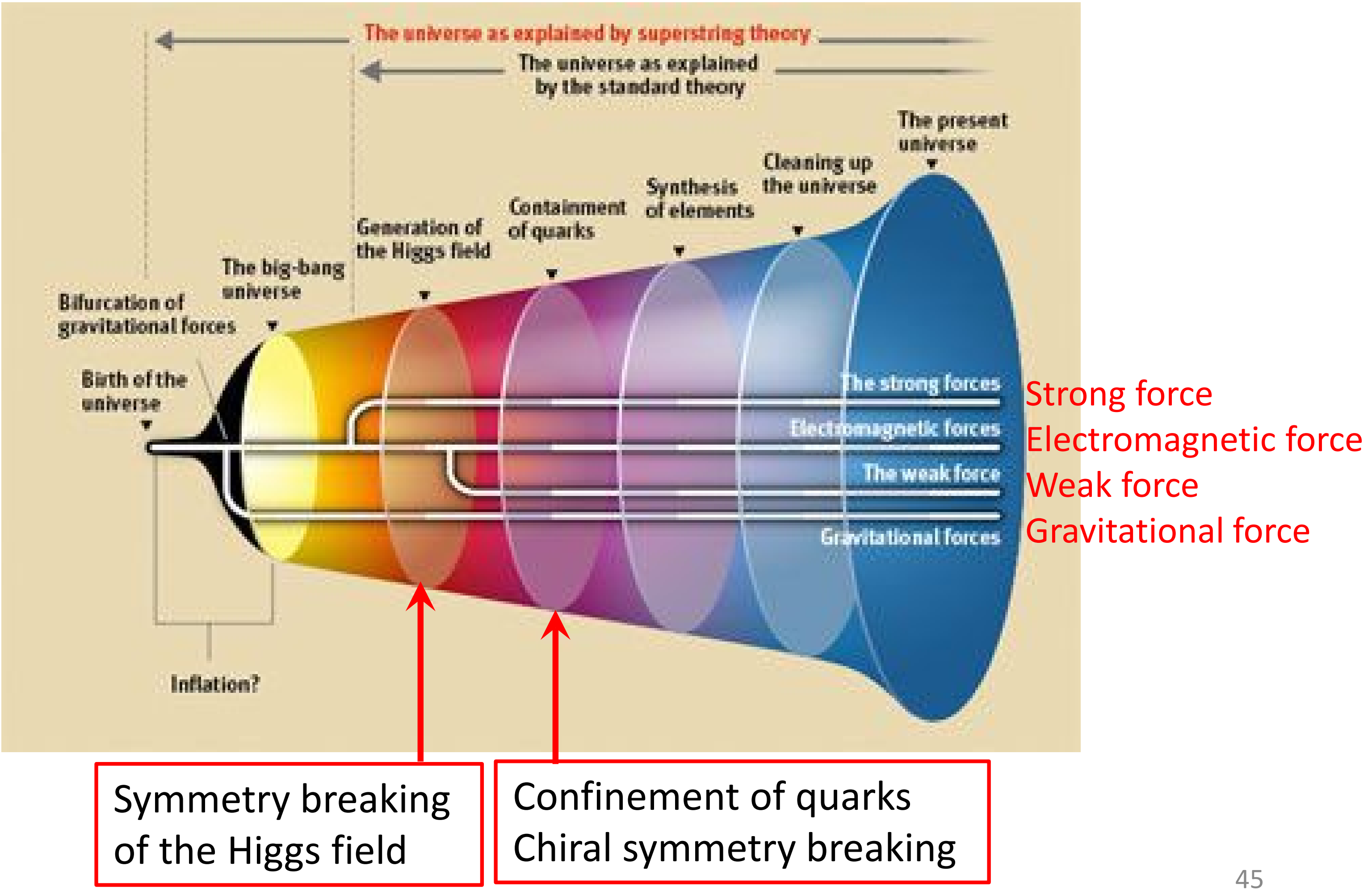
- Nucleon: the simplest multi-body system for studying dynamics of confined quarks and gluons
- Simple parton picture
  - 1-dimensional picture: in "longitudinal" direction
  - The nucleon consists of incoherent quarks and gluons
  - Described by the parton distribution functions (PDF)



x: Bjorken's x
"longitudinal"
momentum fraction
(1-dimensional picture)

Mass

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



DIS kinematics

- Deep inelastic scattering (DIS) of lepton

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

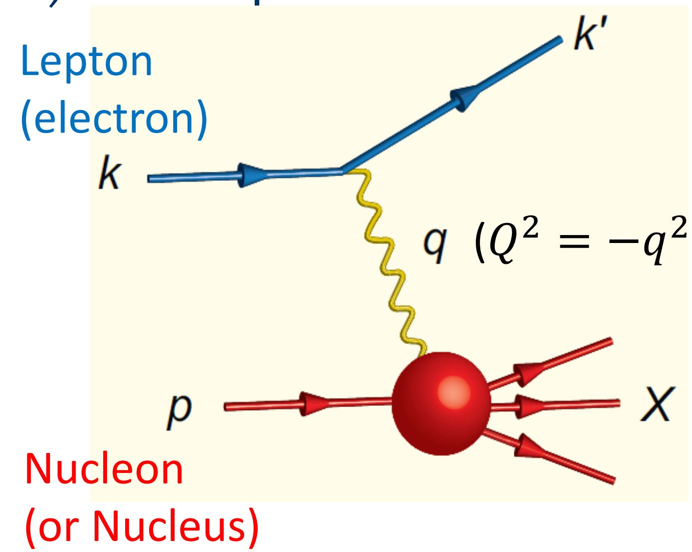
Measure of resolution power

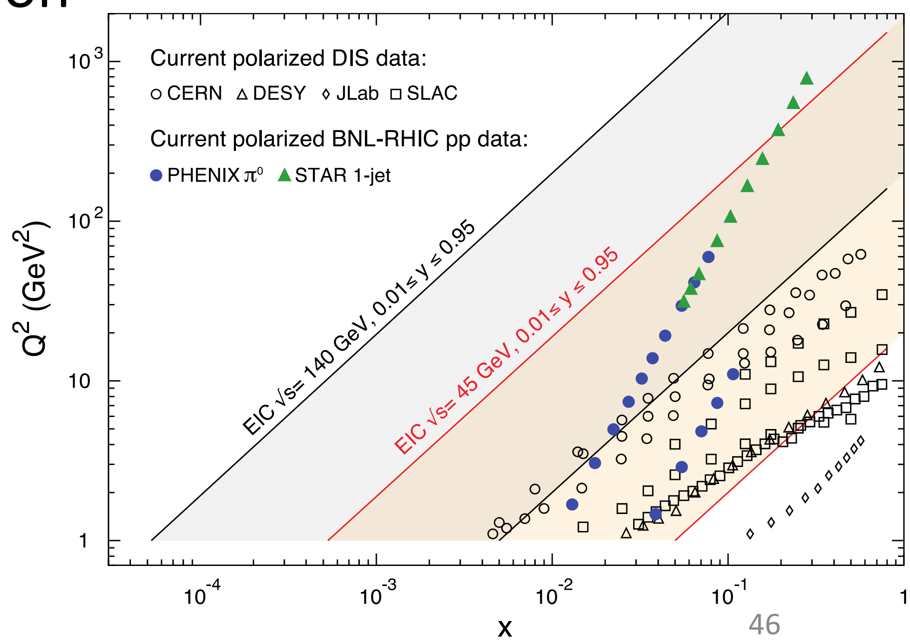
$$x = \frac{Q^2}{2(p \cdot q)}$$

Measure of momentum fraction by struck quark

$$y = \frac{p \cdot q}{p \cdot k}$$

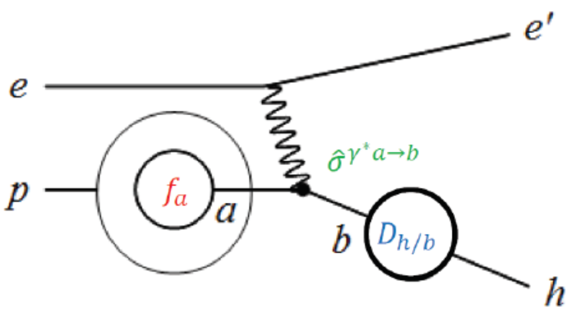
Measure of inelasticity



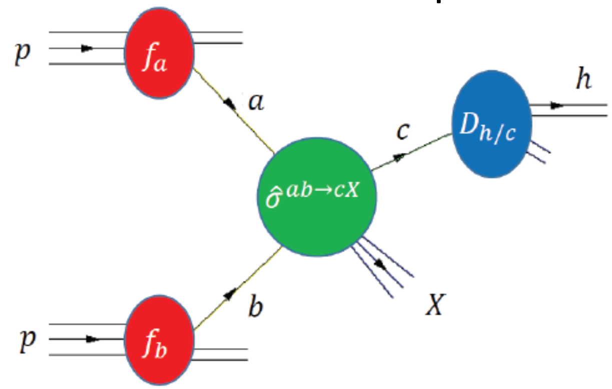


QCD factorization

Semi-inclusive DIS process



Proton collision process



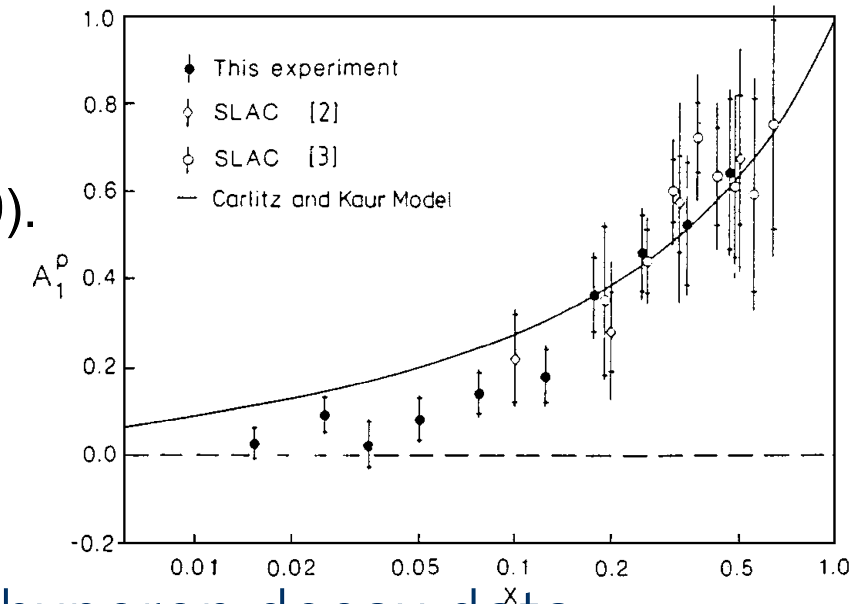
- Long distance term
  - unpol. & pol. PDFs – partonic structure of the nucleon
  - fragmentation functions
  - determined from experimental data
  - "universal" property of the nucleon – same in each reaction
  - Q^2 dependence calculated by the evolution equation of the perturbative QCD
- Short distance term
  - unpol. & pol. partonic cross section – hard interaction of partons
  - calculated by the perturbative QCD – process dependent
  - the first order (next-to-leading order, NLO) corrections are generally indispensible for a firmer theoretical prediction

$$d\hat{\sigma}_{ab}^{c} = d\hat{\sigma}_{ab}^{c,(0)} + \frac{\alpha_s}{\pi} d\hat{\sigma}_{ab}^{c,(1)} + \ldots$$

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

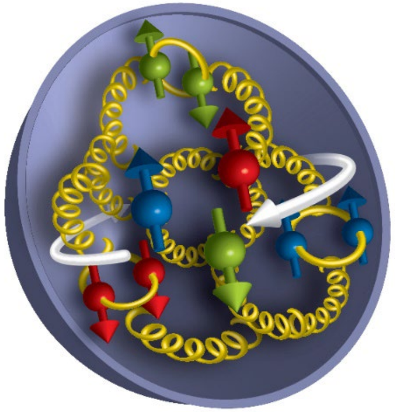
$$\Delta\Sigma = \Delta u + \Delta d + \Delta s = 12 \pm 9(\text{stat}) \pm 14(\text{syst})\%$$

"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



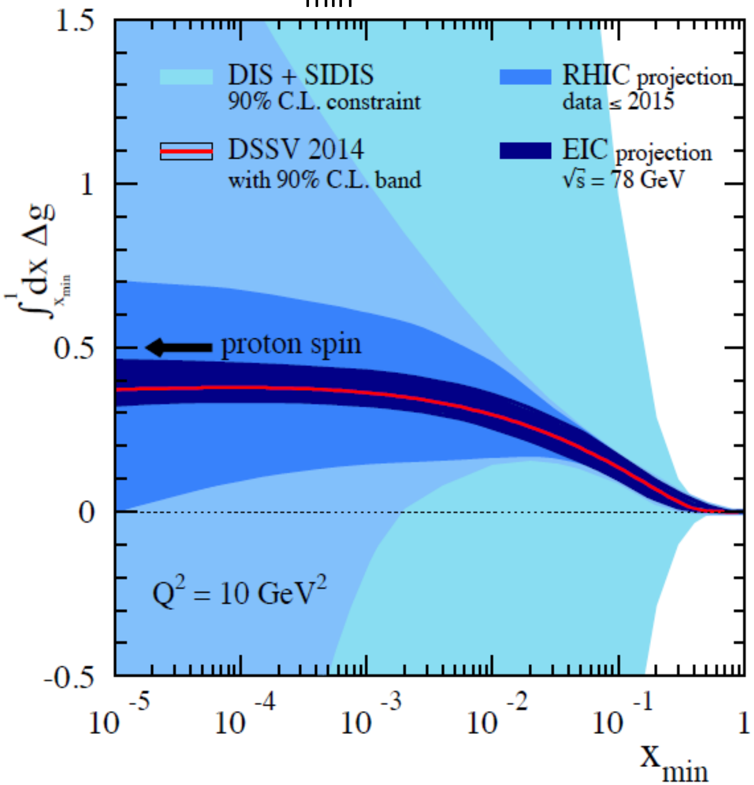
- Spin puzzle
  - Origin of the nucleon spin in the quark-gluon structure

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

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

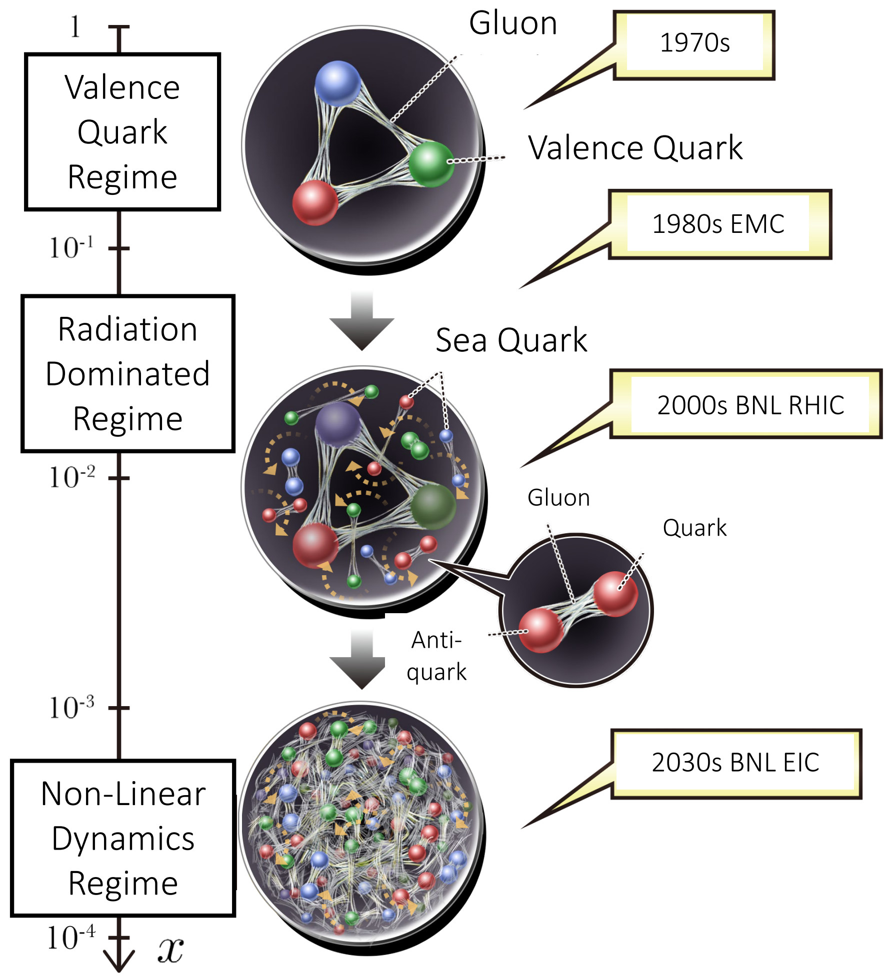
  - Quark-spin contribution is only 20%-30% of the nucleon spin
- Gluon polarization measurement with polarized DIS at EIC
  - Small Bjorken-x region with QCD evolution (DGLAP equation)

Integrated gluon polarization down to x_{min}



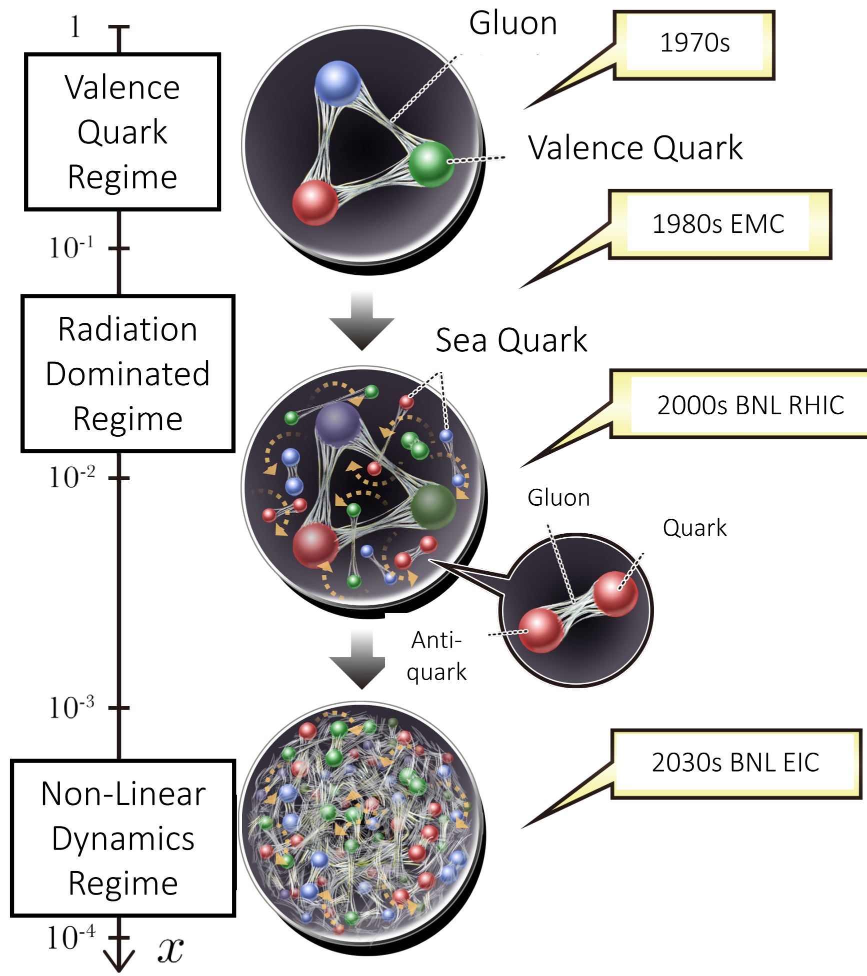
Quark-gluon structure

- Establishing new 3-D picture of the nucleon
  - Nucleon puzzles: spin, radius, mass, pressure…
- Gluon saturation at small-*x*
  - Color Glass Condensate (CGC) → Quark Gluon Plasma (QGP)
- and more for standard model & beyond, stability of universe…
  - Neutron EDM, Neutron lifetime, Proton lifetime…
- Importance of precise comparison with Lattice QCD



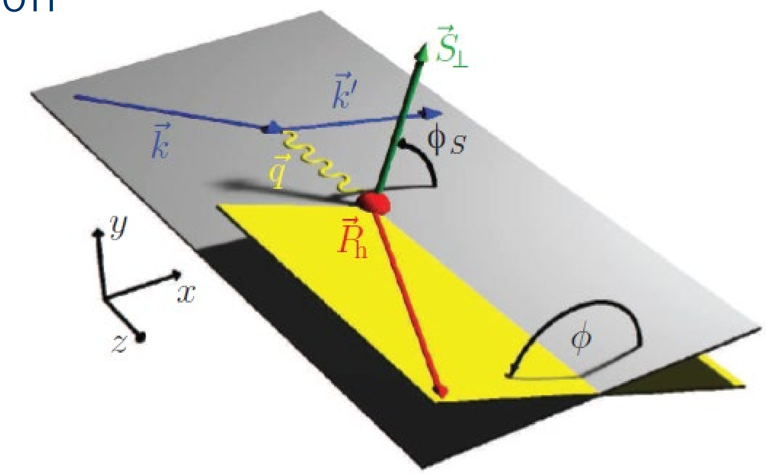
Quark-gluon structure

- Establishing new 3-D picture of the nucleon
  - Nucleon puzzles: spin, radius, mass, pressure…
- Ultra-precise electron microscope, revealing the origin of mass and spin in three dimensions
- Gluon saturation at small-x
  - Color Glass Condensate (CGC) → Quark Gluon Plasma (QGP)
- Discovery of emergent high-density gluon state (gluon condensation)
- Importance of precise comparison with theory, including Lattice QCD

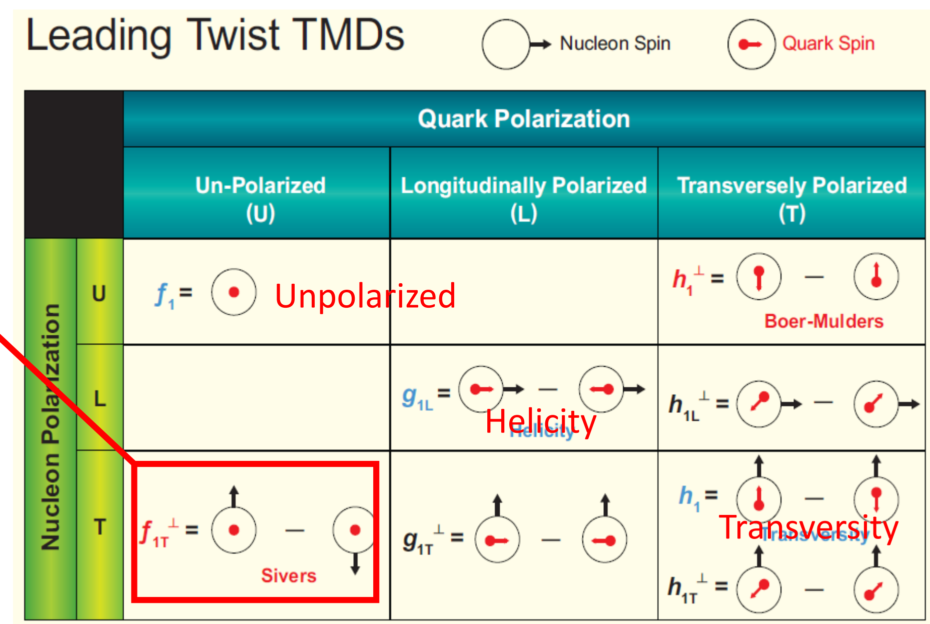


Precision measurement of PDFs

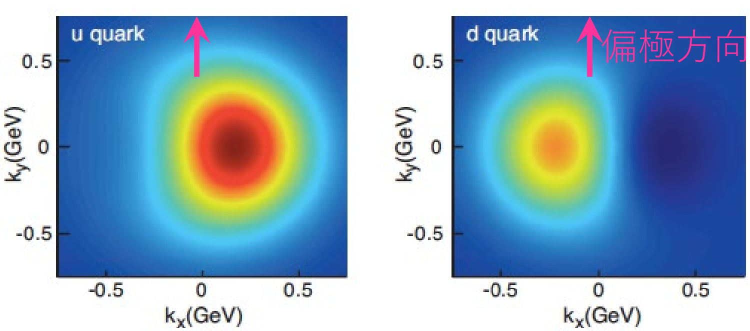
- Semi-Inclusive DIS (SIDIS)
  - Flavor dependence of quark polarization
  - Transverse-momentum dependence (orbital motion)
- TMD distribution function
  - TMD = Transverse Momentum Dependent
  - Quark, antiquark, gluon
  - 3D distribution including transverse momentum
  - Correlation between spin and orbital motion



Sivers function:
Correlation between nucleon spin and parton transverse momentum



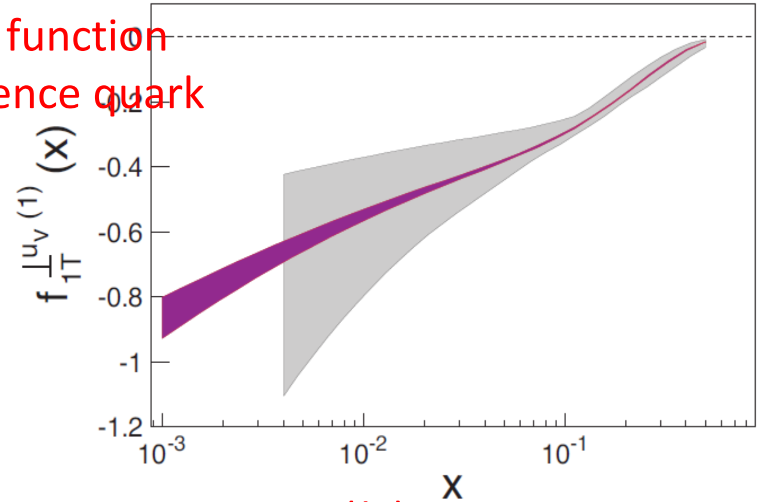
Sivers function at x = 0.1



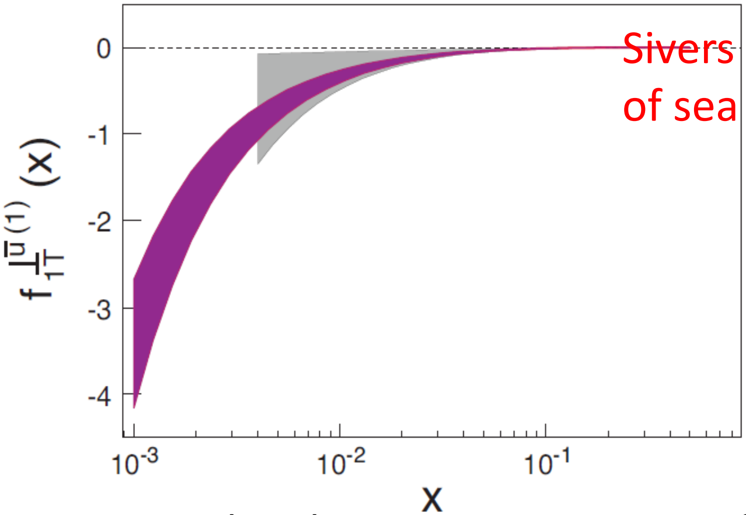
TMDs at EIC

Sivers function extracted for valence (left) and sea (right) up quarks from (grey) currently available data and (purple) projection at EIC $\sqrt{s}$ = 45 GeV, 10 fb^{-1}

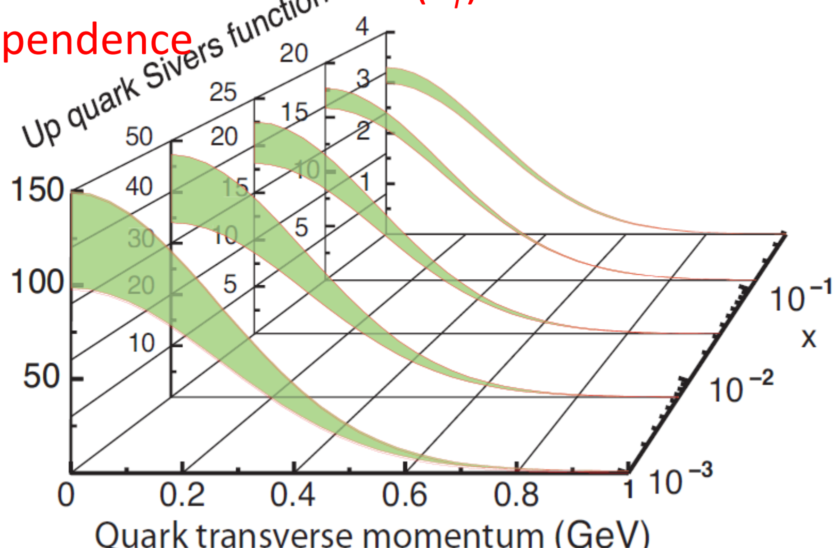
Sivers function of valence quark



Sivers function of sea qurk

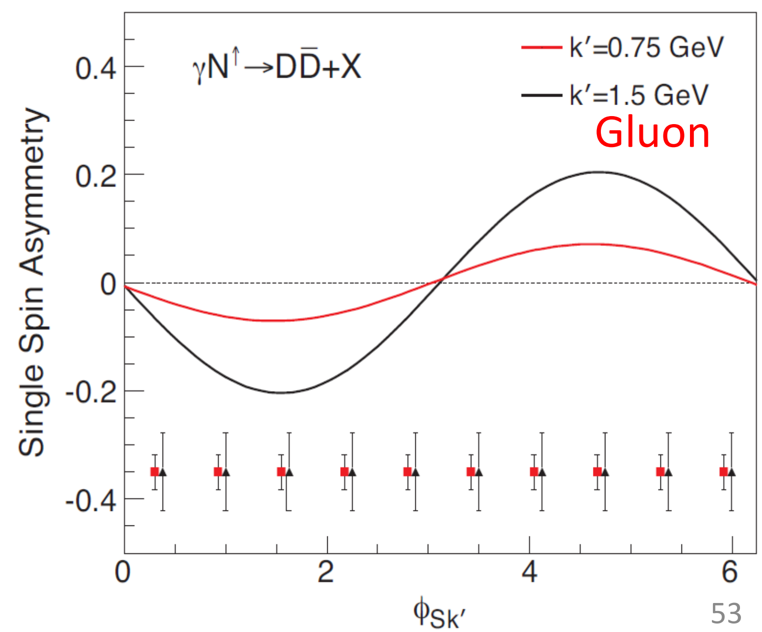


Transverse-momentum (k_T) dependence



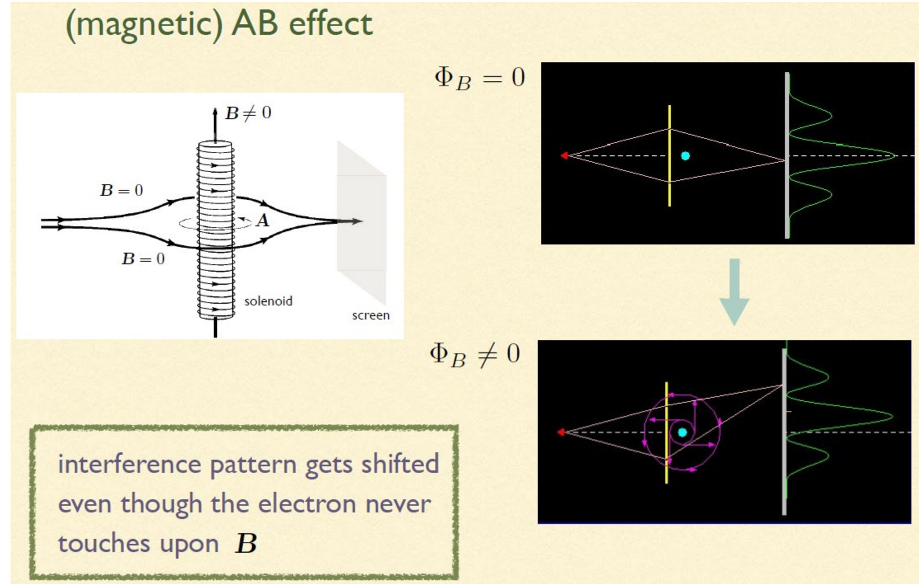
k_T

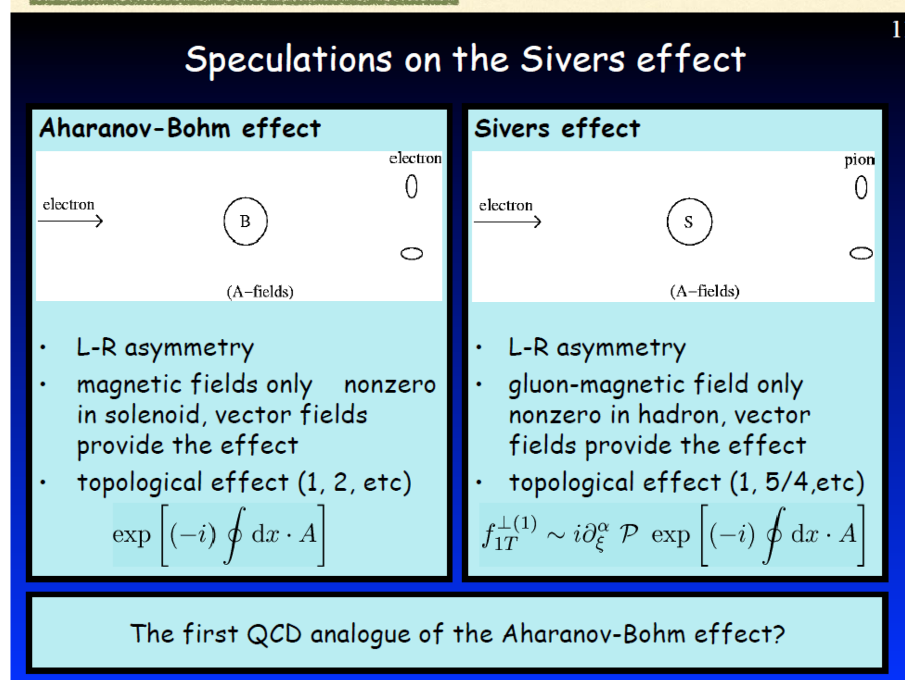
Access to the gluon TMDs at EIC 100 fb^{-1}



TMD and Aharonov-Bohm effect

- Color Aharonov-Bohm effect
  - Pion production in electron-proton or proton-proton scattering with the polarized proton
  - As the Aharonov-Bohm effect is the left-right asymmetry of the final electron, there is also a left-right asymmetry in the produced pion
  - Sivers effect = Aharonov-Bohm effect in QCD

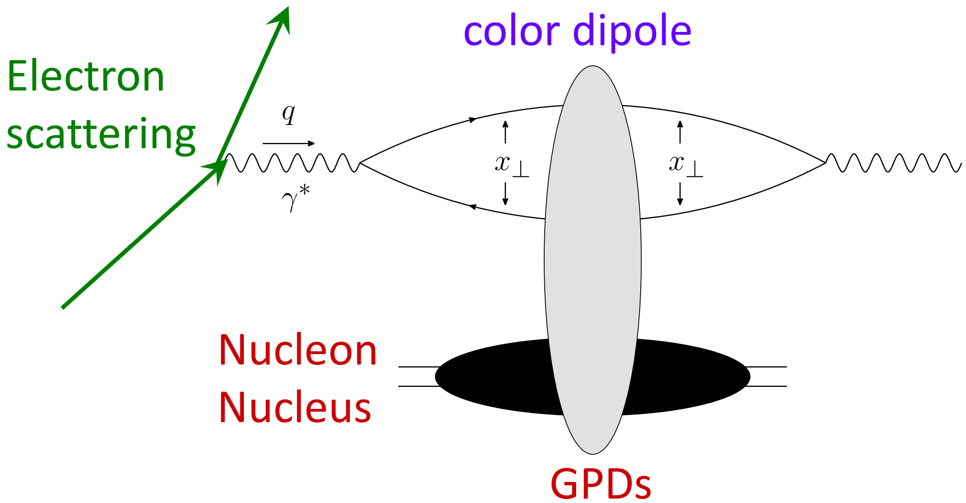




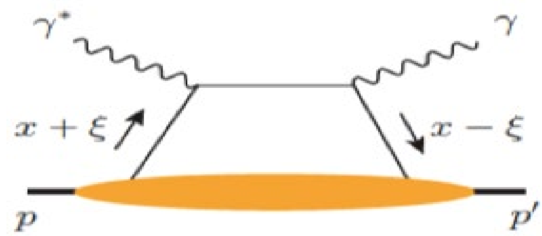
F. Pijlman, SIR 2005 workshop, JLab

Tomography of the nucleon / nucleus

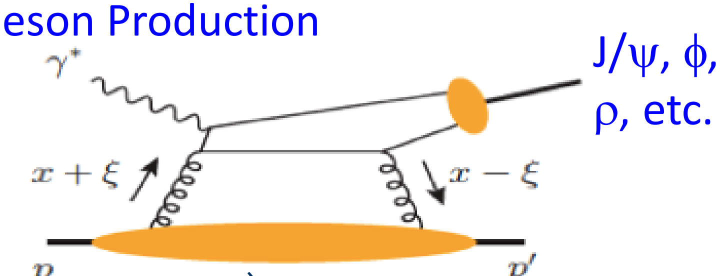
- EIC = color dipole microscope
  - Exclusive process and diffractive process
  - 3D distribution: transverse spatial distribution



DVCS (Deeply Virtual Compton Scattering)



Meson Production

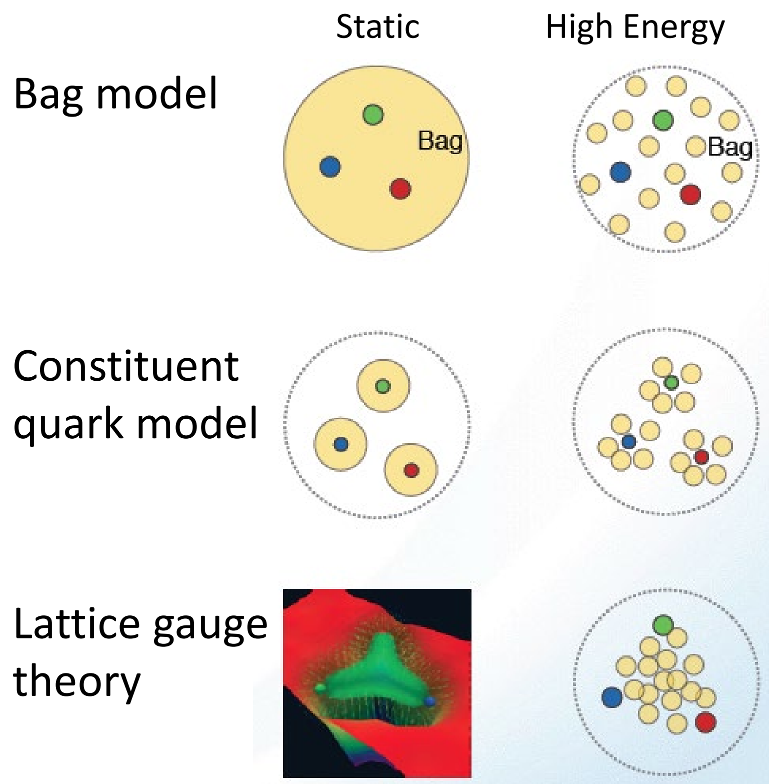


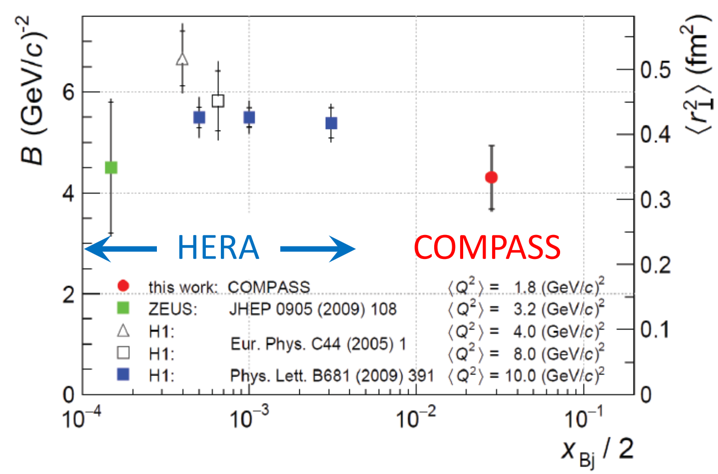
- GPD (Generalized Parton Distribution)
  - Spatial imaging of gluons and quarks = tomography
    - HERA: 1st generation
    - EIC: 2nd generation (high luminosity, heavy ion, polarization)
  - Orbital angular momentum
    - Ji's sum rule
    - Origin of the nucleon spin

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

3D structure of the nucleon

- How are quarks and gluons confined inside the nucleon?
  - Bag model
    - gluon radius > charged radius
  - Constituent quark model
    - gluon radius ~ charged radius
  - Lattice gauge theory (with slow moving quarks)
    - gluon radius < charged radius
- Need measurement of transverse images of the quarks and gluons in the nucleon
- Proton tomography with GPD measurement
  - R = 0.6 – 0.7 fm for gluon (HERA) and sea quark (COMPASS)
  - Smaller than 0.85 fm with EM interaction



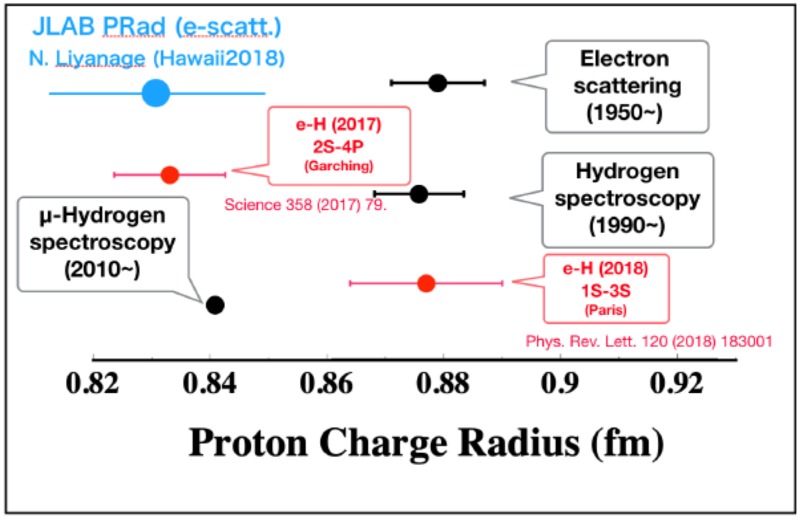


Proton radius puzzle

Conclusions

SpinPhysics@Matsue
Feb. 23-24, 2021

Proton Charge Radius Puzzle ??



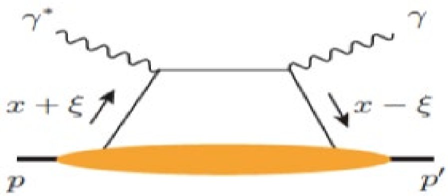
- disagreements : not yet understood.
- the "correct" proton radius is important.
- further experimental and theoretical efforts.

e-scattering : PRad (JLAB), ULQ2 (Tohoku), MESA (Mainz)
μ-scattering : MUSE (PSI), COMPASS (CERN)

Slide by Suda

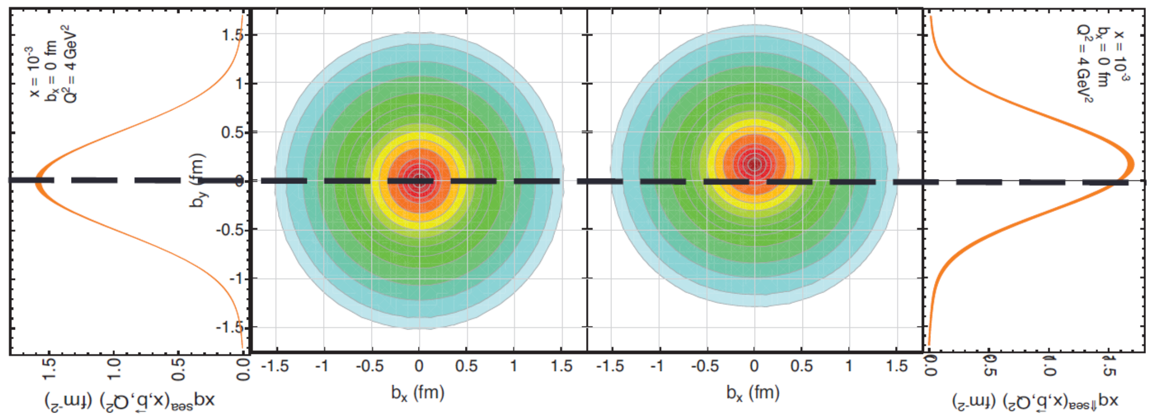
Tomography of the nucleon / nucleus

- DVCS
  - Deeply virtual Compton scattering



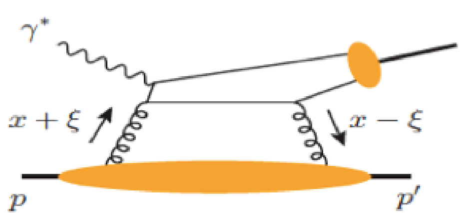
Spatial distribution of sea quarks at EIC 100 fb^{-1} and corresponding density of partons in the transverse plane

Unpolarized Polarized

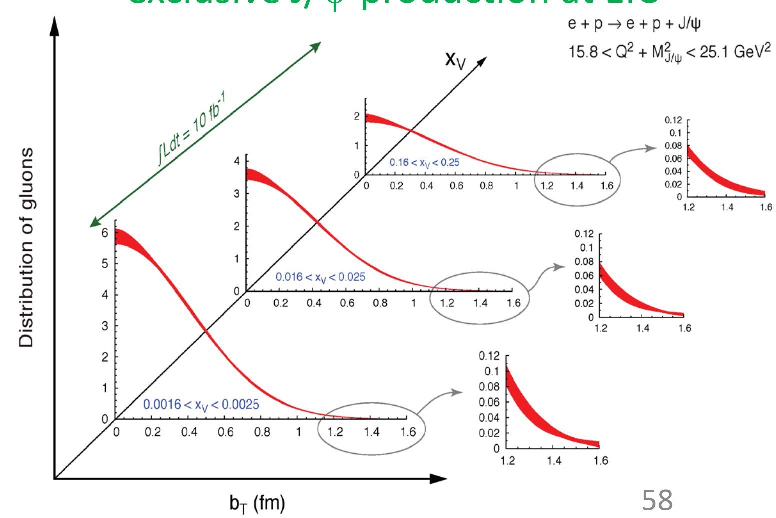


- Meson production
  - Gluon tomography by measuring J/ψ, ϕ, ρ, etc.
  - Precision measurement at large radius with high luminosity

x-dependence of spatial distribution of gluons to be obtained by the exclusive J/ψ production at EIC

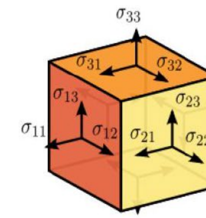


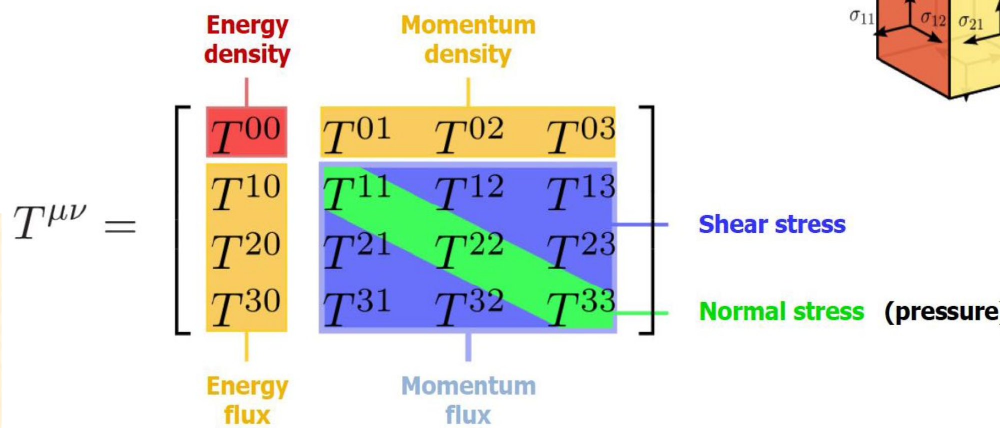
J/ψ, ϕ, ρ, etc.



Mass of the nucleon

- Energy Momentum Tensor Form Factor





Origin of nucleon mass

Nucleon mass: $M = \langle p|H|p\rangle, \quad H = \int d^3x\, T^{00}(x)$

Energy-momentum tensor:

$$T^{\mu\nu}(x) = \frac{1}{2}\bar{q}(x) i\overleftrightarrow{D}^{(\mu}\gamma^{\nu)} q(x) + \frac{1}{4} g^{\mu\nu} F^2(x) - F^{\mu\alpha}(x) F^{\nu}{}_{\alpha}(x)$$

We need theoretical and experimental efforts to decompose nucleon mass for finding its origin.

X. Ji, PRL 74 (1995) 1071.

$$T^{\mu\nu} = \hat{T}^{\mu\nu} + \bar{T}^{\mu\nu} = \left(T^{\mu\nu} - \frac{1}{4} g^{\mu\nu} T^{\alpha}{}_{\alpha}\right)_{\text{traceless}} + \left(-\frac{1}{4} g^{\mu\nu} T^{\alpha}{}_{\alpha}\right)_{\text{trace}}, \quad T^{\alpha}{}_{\alpha} = \bar{q}\, m\, q + \frac{\beta(g)}{2g} F^2$$

$$H = H_q(\text{quark energy}) + H_g(\text{gluon energy}) + H_m(\text{quark mass}) + H_a(\text{trace anomaly})$$

$$H_q = \int d^3x\, \bar{q}(x)\left(-i\vec{D}\cdot\vec{\alpha}\right) q(x), \quad H_g = \int d^3x \frac{1}{2}\left(\vec{E}^2 + \vec{B}^2\right)$$

$$H_m = \int d^3x\, \bar{q}(x)\, m\, q(x), \quad H_s = \int d^3x \frac{9\alpha_s}{16\pi}\left(\vec{E}^2 + \vec{B}^2\right)$$

Recent progress on trace-anomaly, gravitational form factor, scale depdence in perturbative QCD:

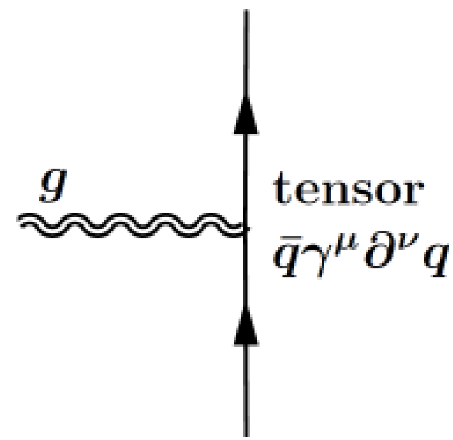
Y. Hatta, A. Rajan, and K. Tanaka, JHEP 12 (2018) 008;

K.Tanaka, JHEP 01 (2019) 120.

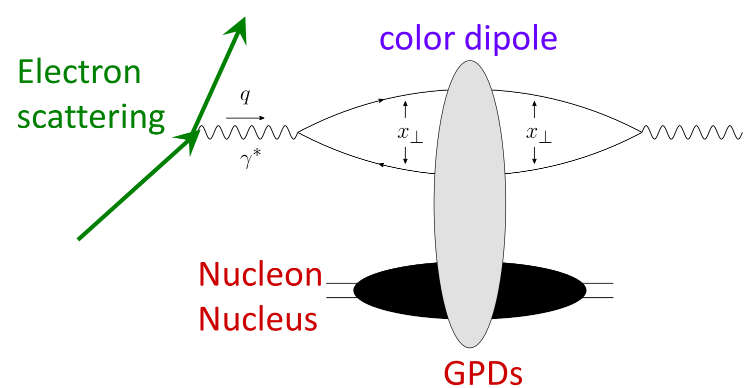
Slide by Kumano

Mass of the nucleon

- Gravity
  - Calculated from energy and momentum measurements
    - $M^2=E^2-p^2$
  - Mass of the nucleon = ~1 GeV
- Electroweak
  - Given by the Higgs mechanism
    - ~10 MeV as the sum of the masses of the 3 valence quarks
  - Cannot be measured in EW
- QCD
  - Measuring the form factor of the Energy-Momentum Tensor (EMT) of QCD
    - Quark and gluon kinetic energy and chiral symmetry breaking (quark and gluon condensations)
  - Can be measured cleanly using spin-2 graviton, but not possible
  - Can be taken out of GPD to be measured by EIC



(c) gravitational



Mass of the nucleon

- Sum rule for the nucleon mass

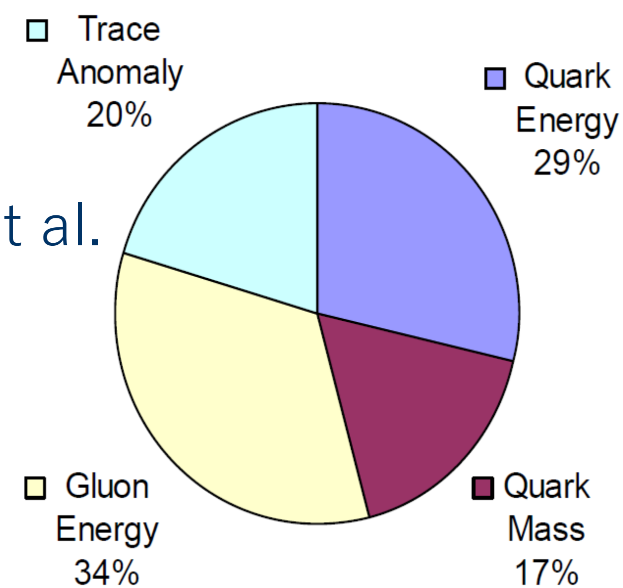
Relativistic Motion | *Chiral Symmetry Breaking* | *Quantum Fluctuations*

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

X. Ji, PRL 74 1071 (1995)

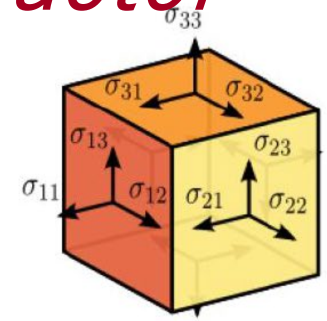
Quark Energy | **Gluon Energy** | **Quark Mass** | **Trace Anomaly**

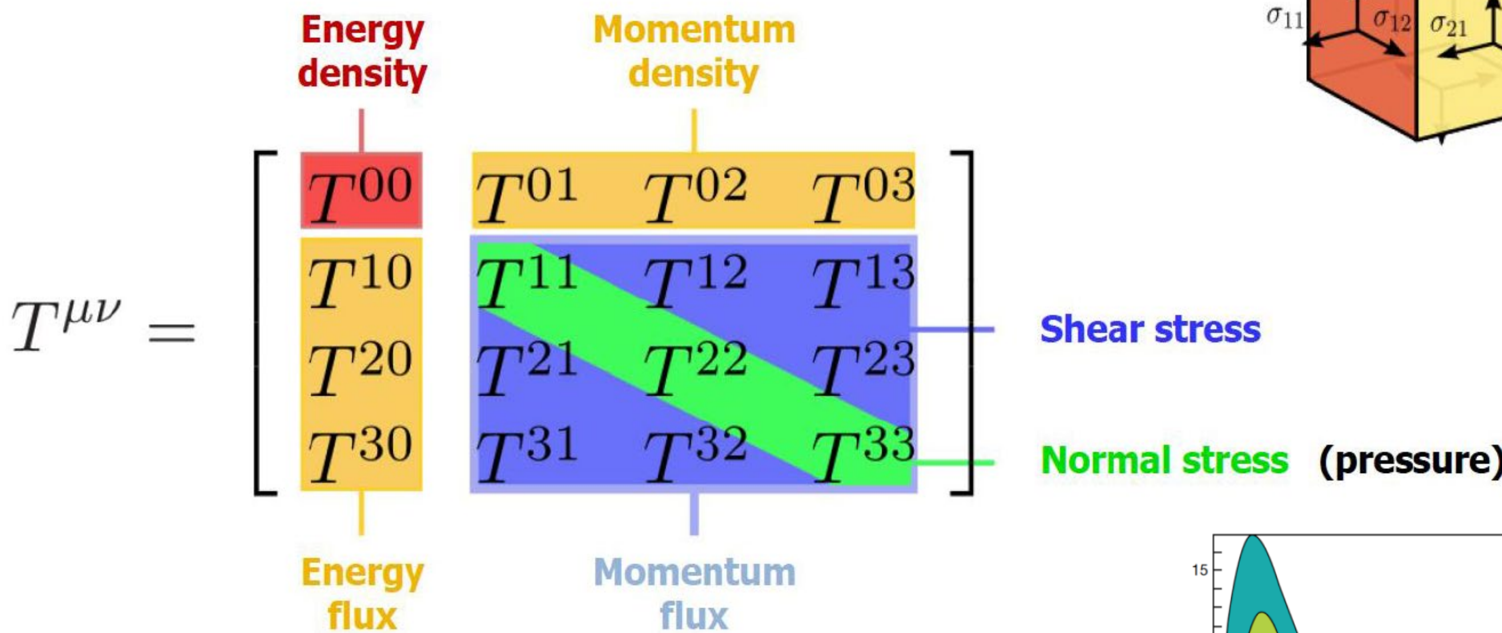
  - How to determine the different contribution not yet reached
- Lattice QCD calculation
  - arXiv:1710.09011, update by K.-F. Liu et al.
- Precision comparison of experiment and theory in the future
  - Mass, spin, pressure, radius,⋯



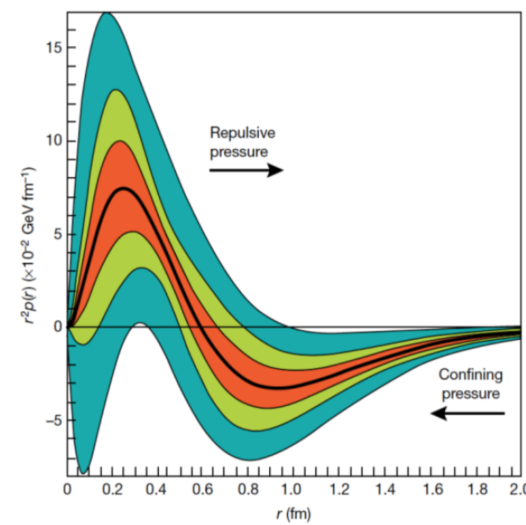
Generalization of the form factor

- 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



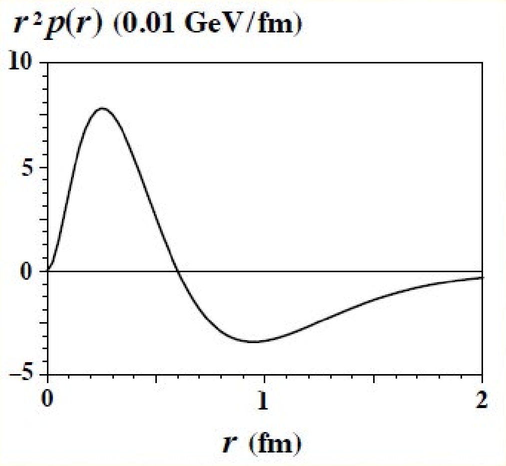
Nature, **557**, May 17, 2018

Nucleon pressure

Nucleon pressure

$$\langle N(p')|T_q^{\mu\nu}(0)|N(p)\rangle = \bar{u}(p')\left[A\gamma^{(\mu}\bar{P}^{\nu)} + B\frac{\bar{P}^{(\mu}i\sigma^{\nu)\alpha}\Delta_\alpha}{2M} + D\frac{\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2}{M} + \bar{C}Mg^{\mu\nu}\right]u(p)$$

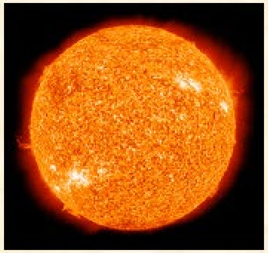
Recent progress
- V. D. Burkert, L. Elouadrhiri, and F. X. Girod, Nature 557 (2018) 396;
- M. V. Polyakov and P. Schweitzer, Int. J. Mod. Phys. A 33 (2018) 1830025;
- C. Lorce, H. Moutarde, and A. P. Tranwinski, Eur. Phys. J. C 79 (2019) 89.



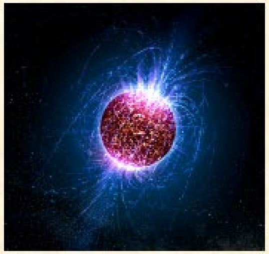
Highest pressure in nature 1 Pa (Pascal) = 1 N/m^2

Earth atmosphere
10^5 Pa =1000 hPa

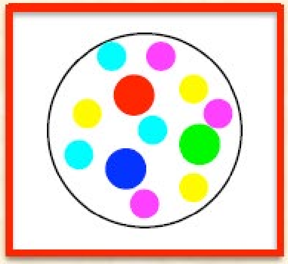
Center of earth
10^{11} Pa = 100GPa



Center of Sun
10^{16} Pa = 10 PPa



Neutron star
10^{34} Pa

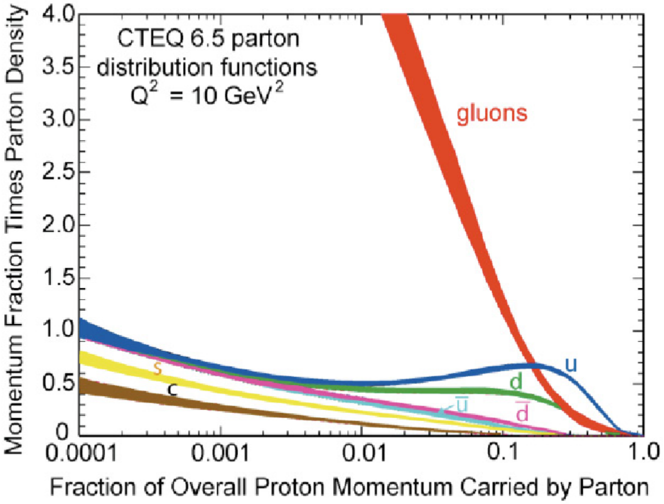


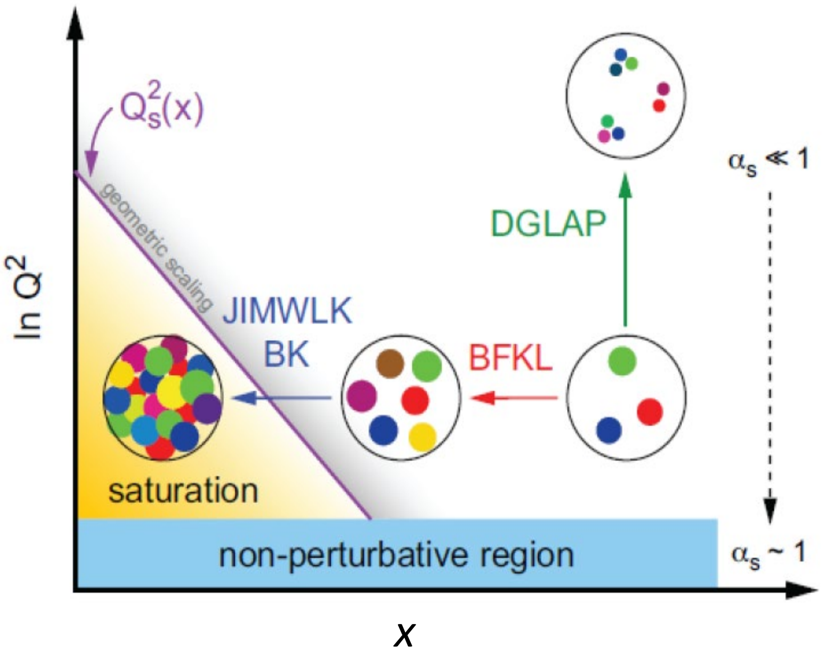
Hadron
10^{35} Pa

Slide by Kumano

Gluon saturation in e+A collisions

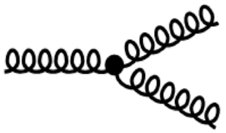
- pQCD and DGLAP & BFKL evolution works with high precision
- Issues with linear DGLAP/BFKL at low-x
  - Gluon PDF rapid rise violates unitary bound
- New approach: non-linear evolution
  - At very high energy, recombination compensates gluon splitting
  - BK/JIMWLK non-linear effects
  - Saturation characterized by $Q_s(x)$
  - Describe physics at low-x and low-moderate Q^2



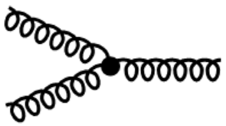


Gluon saturation in e+A collisions

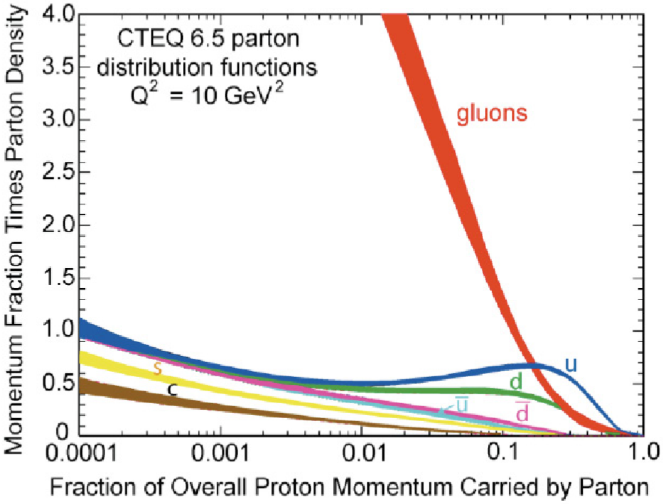
- Gluon emission
  - Divergence at small *x*

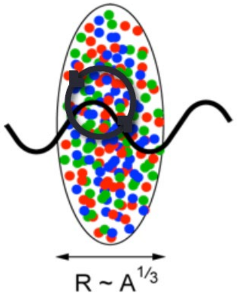


- Gluon recombination
  - Restriction of divergence

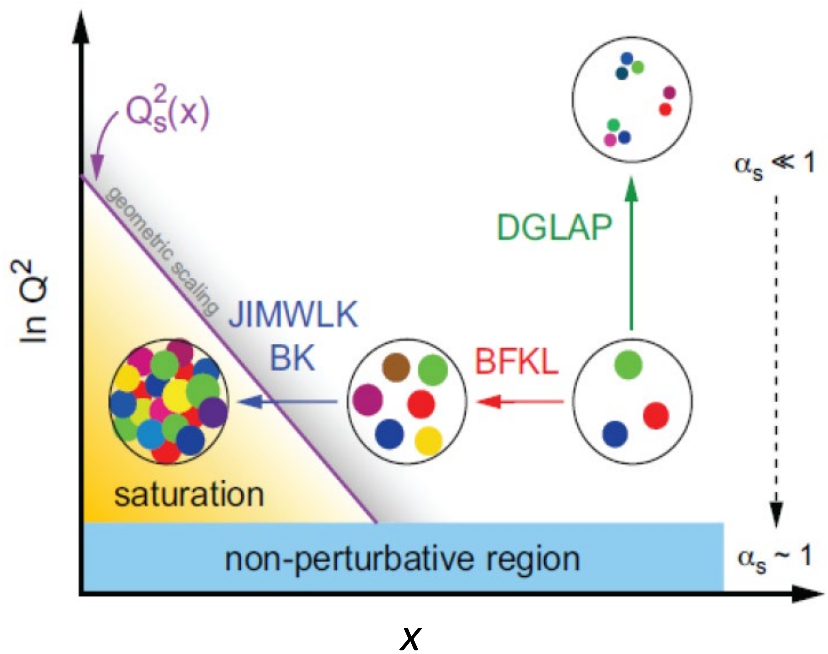


- Gluon saturation in balanced
  - Based on classical idea of the saturation
- Non-linear evolution
  - Saturation of gluon densities characterized by scale $Q_s(x)$
- Enhancement of Q_s with A: saturation regime reached at significantly lower energy in nuclei



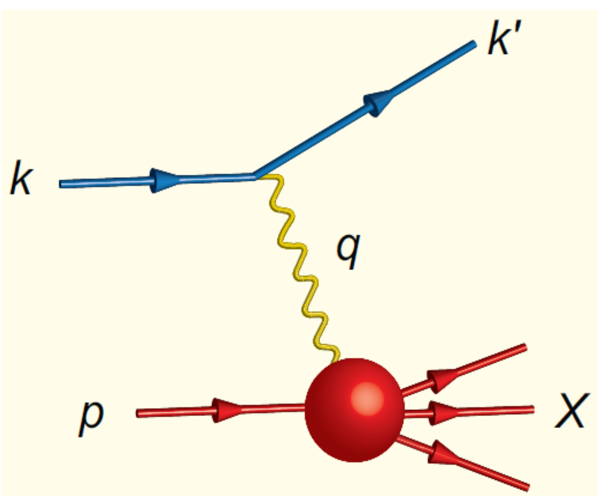


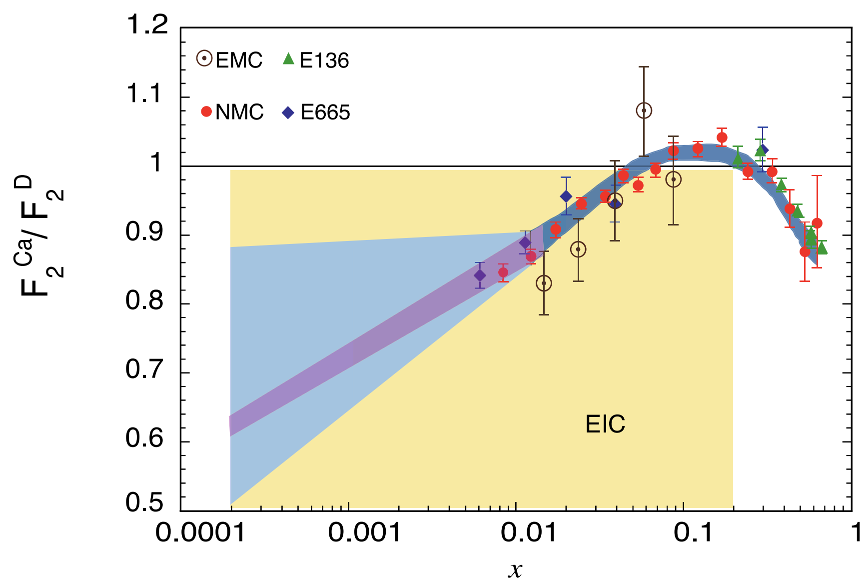
$$(Q_s^A)^2 \approx cQ_0^2 \left[\frac{A}{x}\right]^{1/3}$$



Gluon saturation in e+A collisions

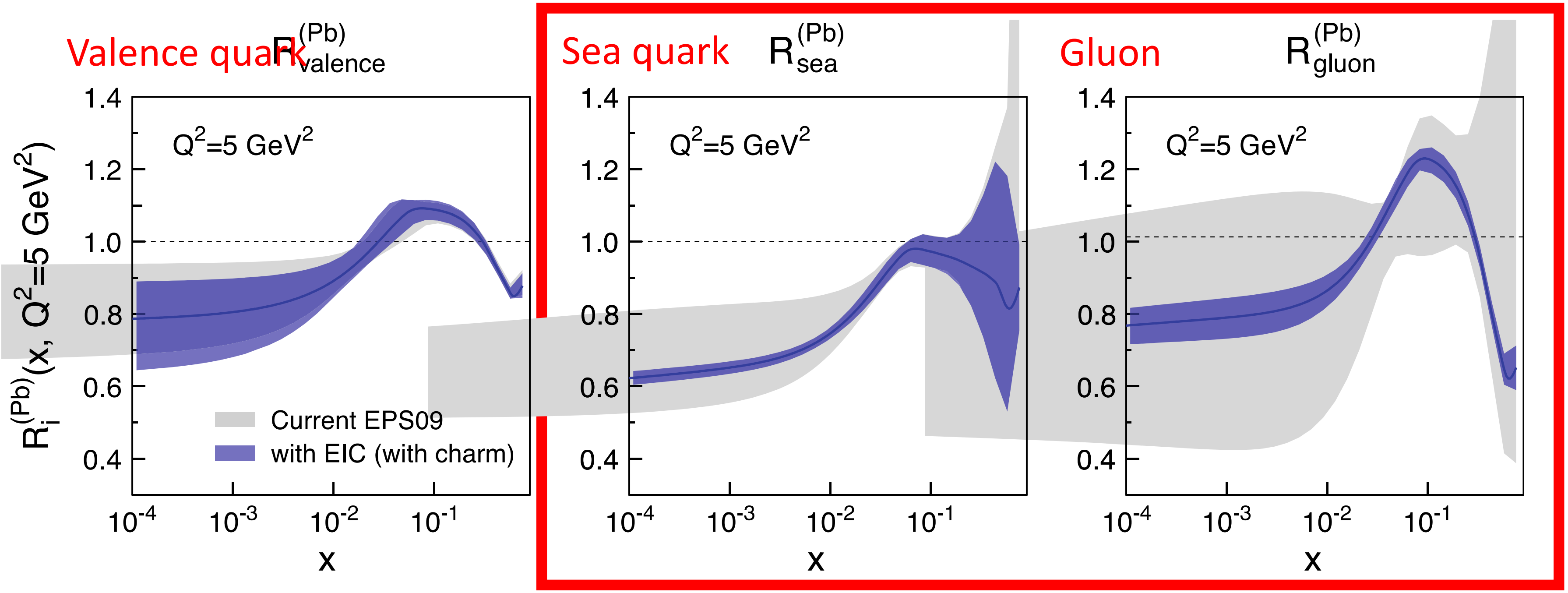
- Inclusive DIS
- Probed by the change of the nuclear structure functions
- Ratio of the structure function F_2
  - How quark / gluon distribution and interaction affected in the nucleus?
  - Fermi motion, EMC effect, shadowing, saturation





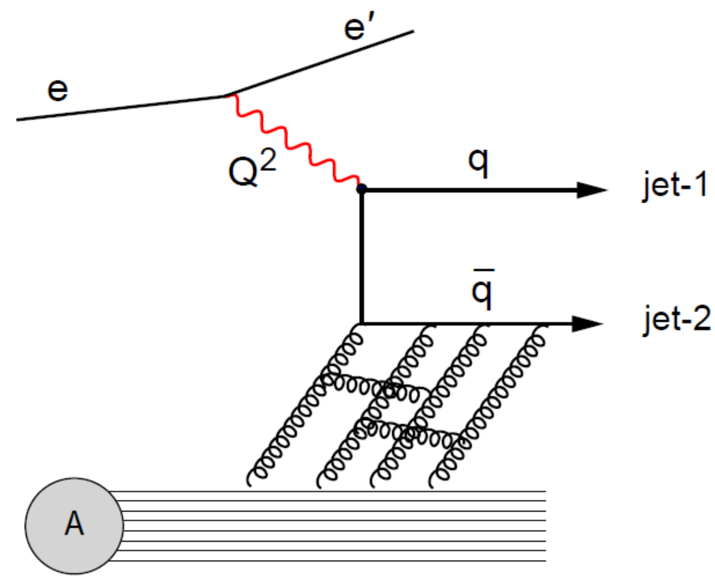
Gluon saturation in e+A collisions

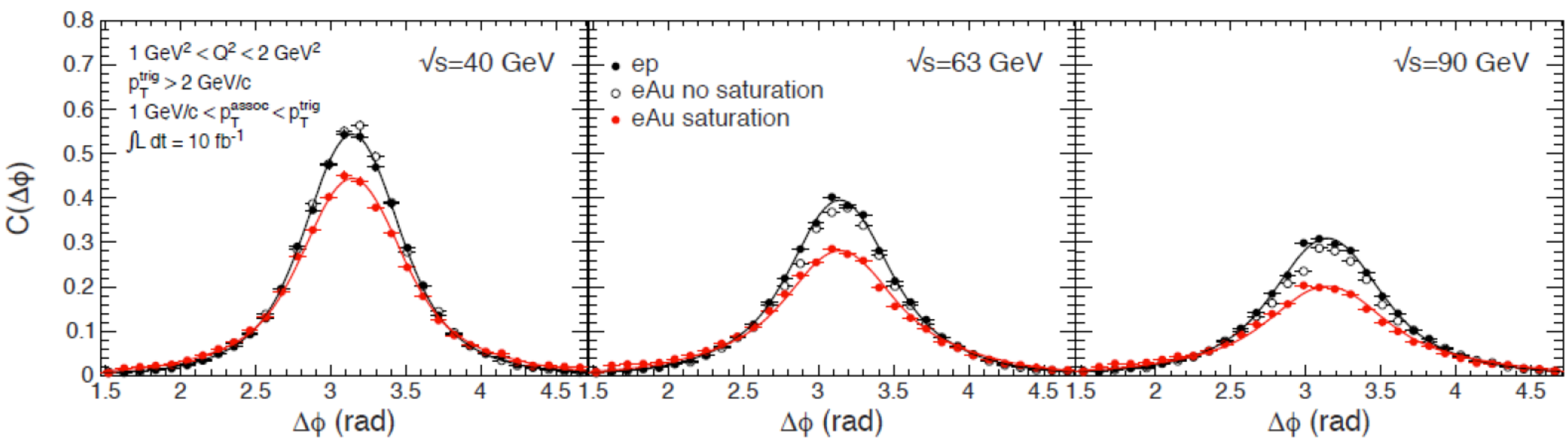
- Nuclear PDF (nPDF)
  - nPDF measurements for sea quarks and gluons that cannot be reached by LHC and RHIC
  - Discovery of gluon saturation in a small Bjorken-x region



Gluon saturation in e+A collisions

- Semi-inclusive DIS
- Di-hadron correlation
  - Sensitive to the transverse momentum dependence of the gluon distribution and gluon correlations

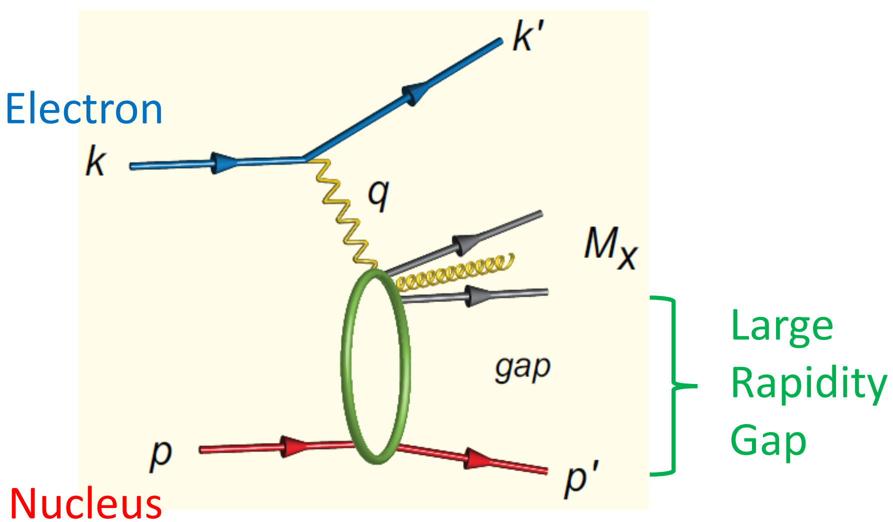


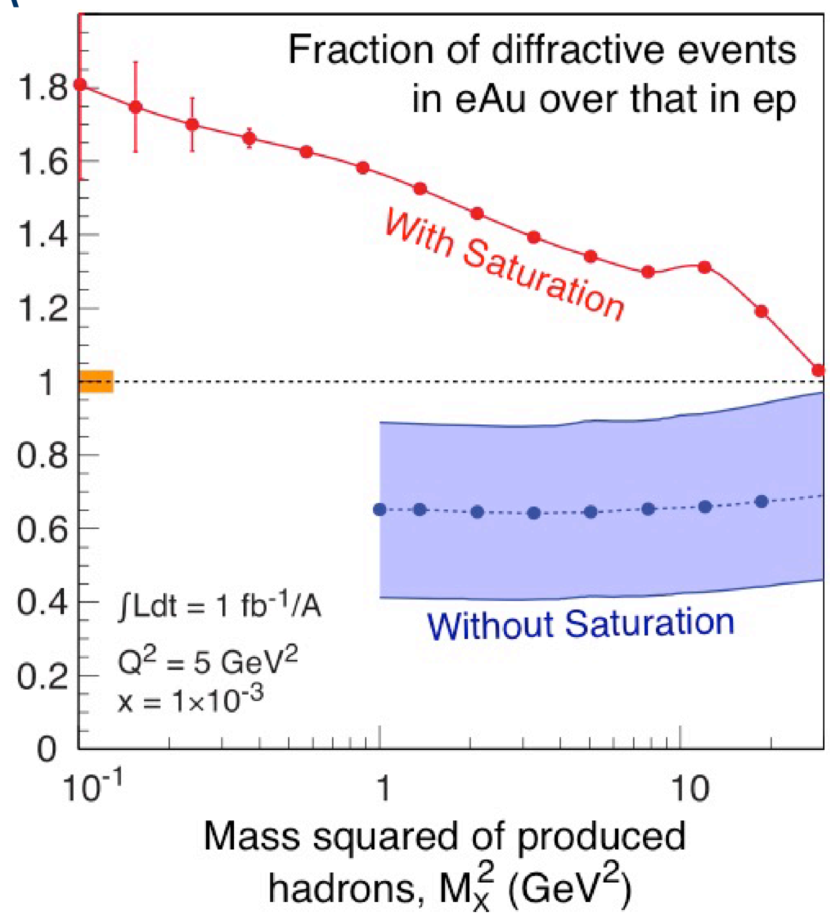


Gluon saturation in e+A collisions

- Diffractive cross section
  - Most sensitive way to study the gluon saturation
- 10-15% diffractive at HERA e+p
- 25-30% diffractive predicted by CGC at EIC e+A

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

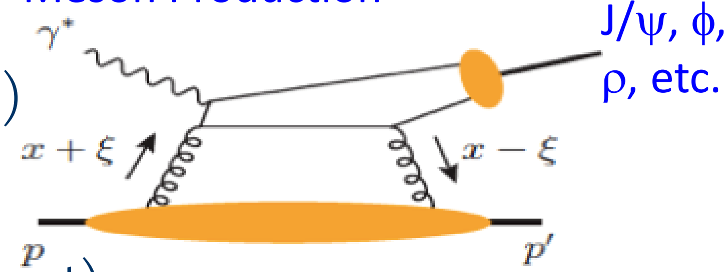


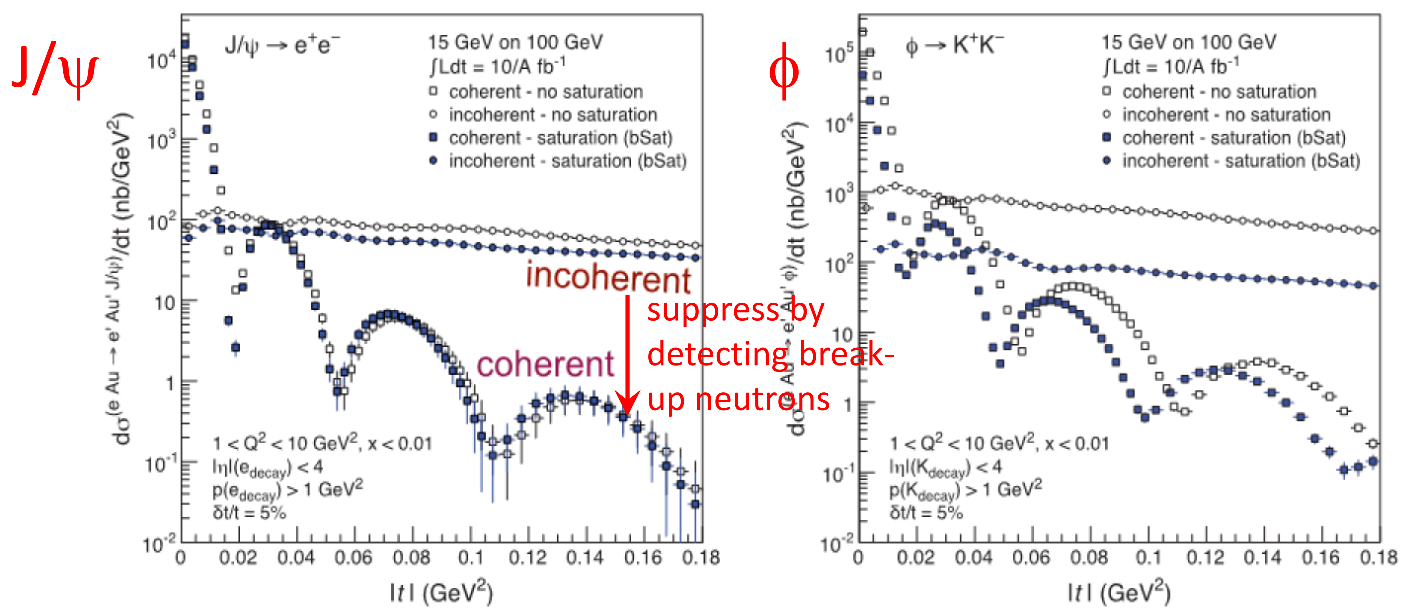


Gluon saturation in e+A collisions

- Exclusive vector meson production
  - Momentum transfer *t* dependence translated to the transverse spatial distribution of gluons in the nucleus
- Incoherent process (nucleus breaks up)
  - Spatial density fluctuation in nucleus
  - Much larger than the coherent process
- Coherent process (nucleus remains intact)
  - Sensitive to the gluon saturation
  - Identify & veto breakup of the excited nucleus

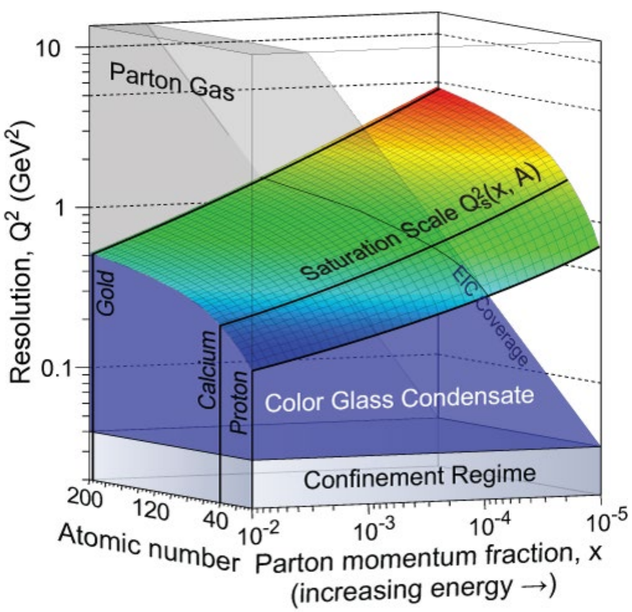
Meson Production

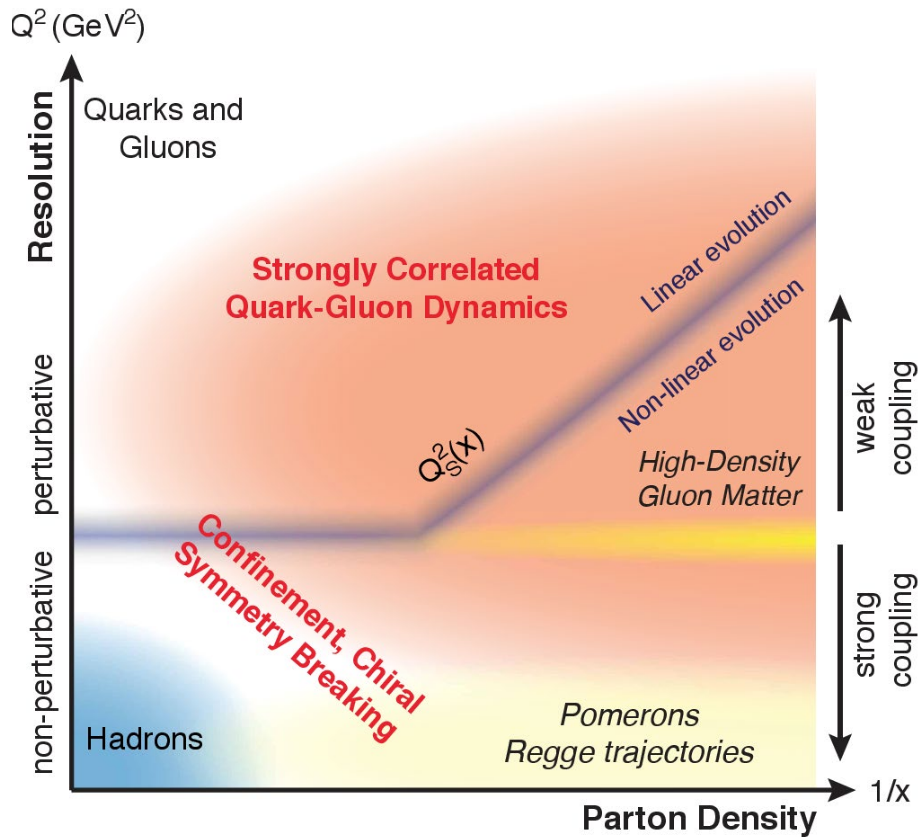




Gluon saturation in e+A collisions

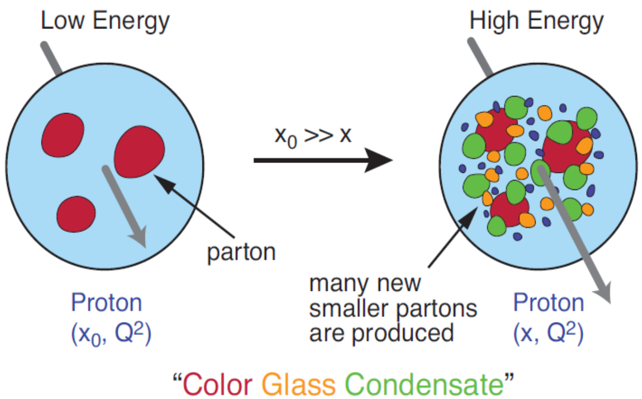
- What are the emergent properties of dense system of gluons?
  - The gluon saturation describes a new state of matter at extreme high density
- Gluon density saturated where gluon emission and recombination comparable
- First observation of a quantum collective gluonic system



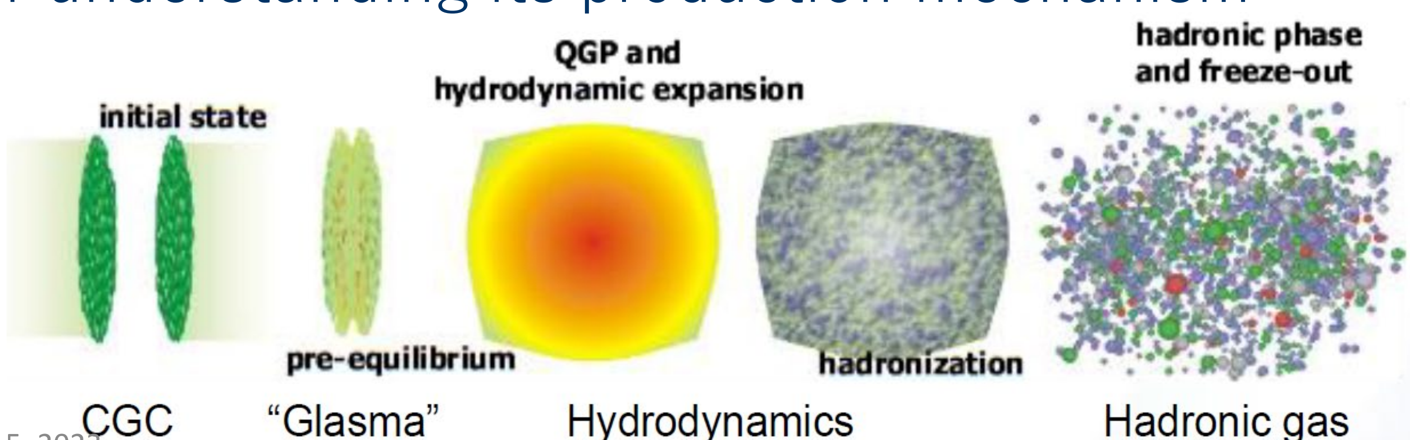


Gluon saturation

- Precision comparison of experiment and Color Glass Condensate (CGC) as a theoretical model of the gluon saturation
  - Not understandable classically if not discovered?



- Precision understanding of nucleus with the quark-gluon picture necessary as the initial state of the QGP for understanding its production mechanism



Gluon saturation in e+A collisions

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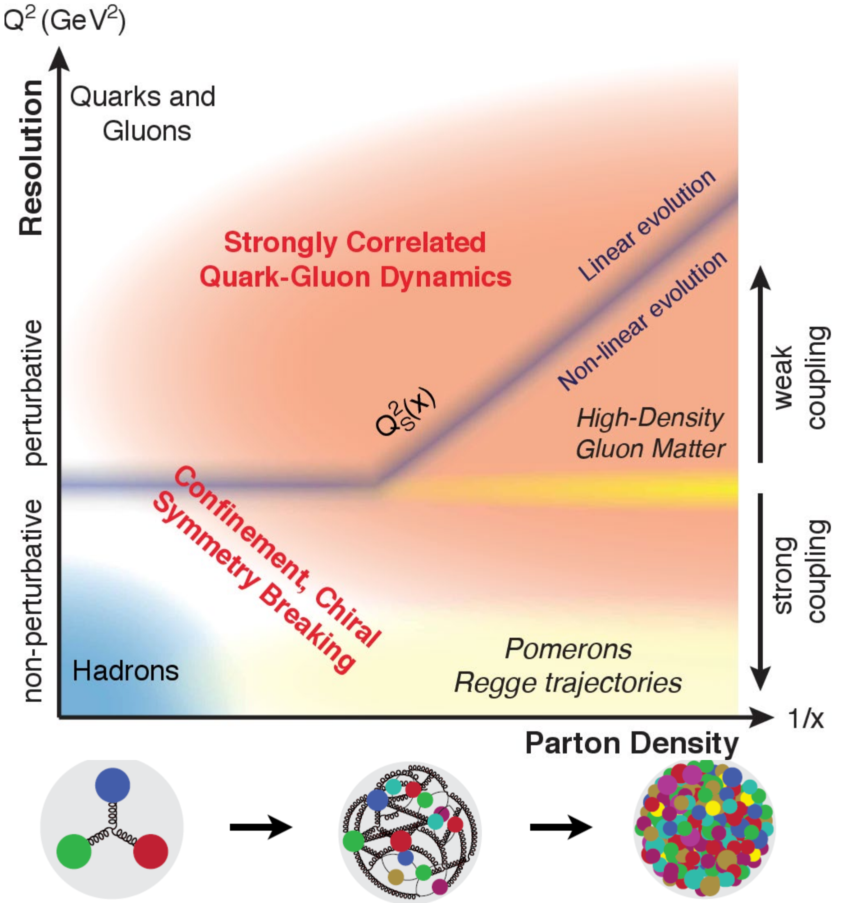
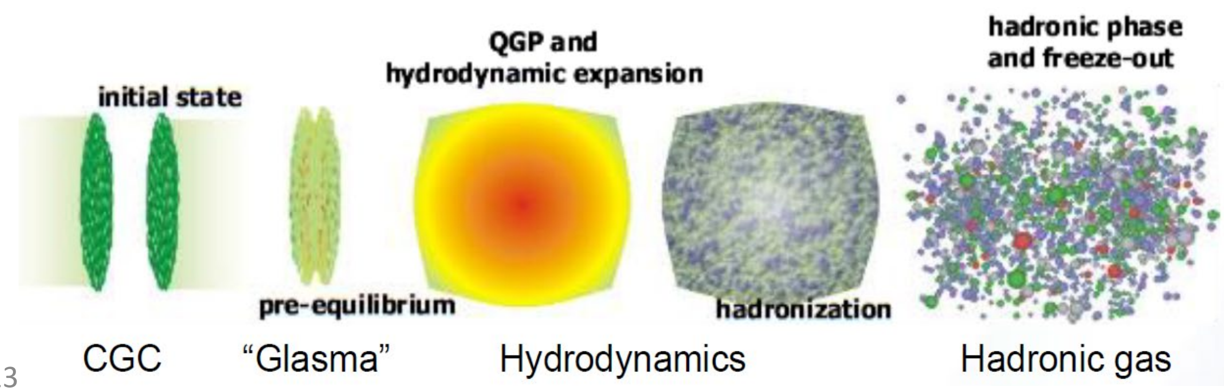
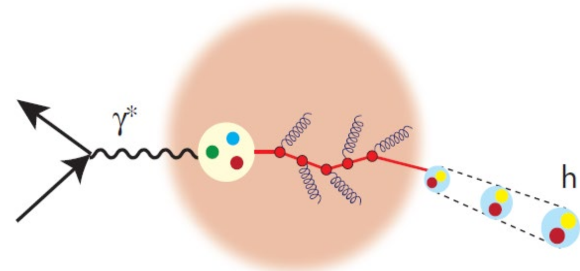
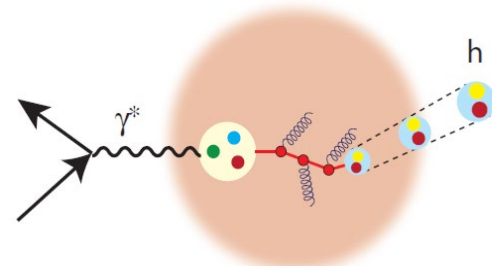


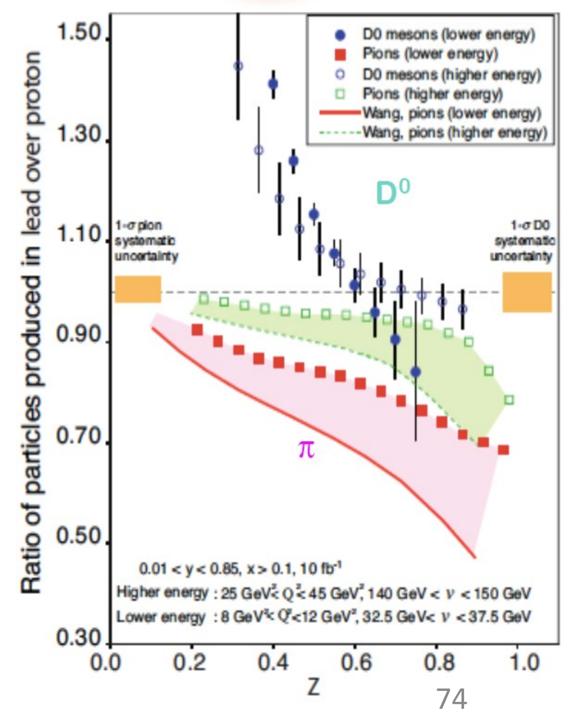


Hadronization in the nucleus

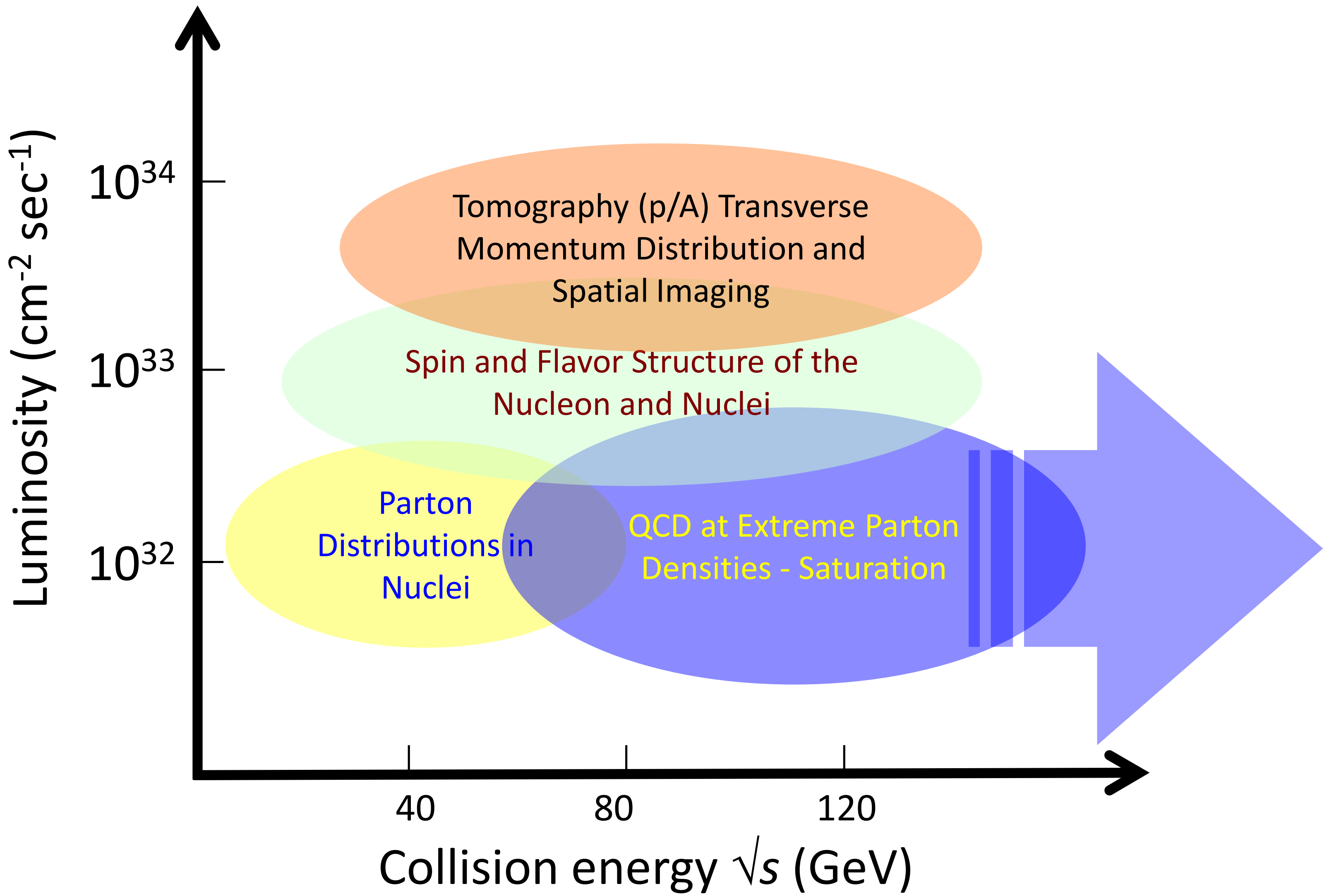
- Hadron and jet production from quarks and gluons in the nucleus (cold nuclear matter)
  - Response of nuclear matter to fast moving color charge passing through it?
  - Structure of jet?
- Mass dependence of hadronization
  - Energy loss by light vs. heavy quarks
- Comparison with hot nuclear matter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







EIC physics vs luminosity & energy



Development of lattice QCD

- Lattice QCD over the next decade will match or exceed experimental accuracy
  - Advances in computational technology
  - Need for computational projects
- Quark and gluon physics advances toward EIC as lattice QCD advances
- Study QCD by comparing precise theoretical calculations with precise experimental measurements to establish an understanding of nucleons, nuclei, and QGP

Supercomputer Fugaku

Other physics at EIC

- Hadron spectroscopy
  - Exotics
- Tensor charge of the nucleon
  - Transversity measurement
- Polarized e + d/^{3}He collisions
  - Polarized structure of the neutron
  - “n+p” wave function of the deuteron
- Short range correlations
  - EMC effect by high-momentum “n+p” pairs in nuclei
- High-energy cosmic-ray/neutrino reaction
  - Energy flow in the very forward region
  - Event generator for shower evolution

EIC Users Group

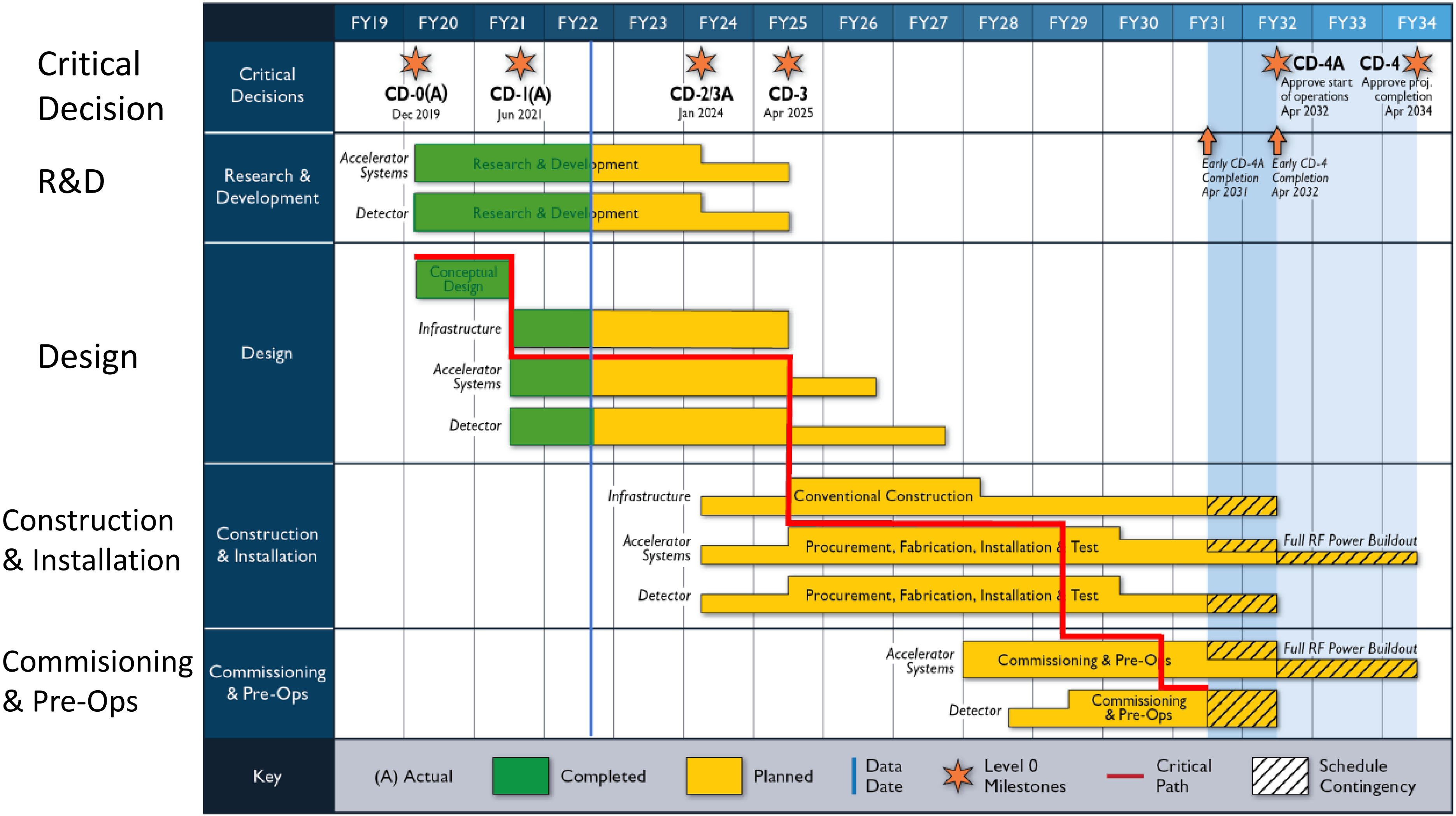
- Formally established in 2016
- More than 1,300 members
  - 36 countries, 266 institutions
  - Experiment (detector, data collection and analysis), theory, computer, accelerator
  - North America 59%, Europe 25%, Asia 12%
- 2020: Yellow report (physics and detector design report) by EIC User Group
- 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

- 2021: Detector collaboration formation and proposal
  - 2021.3: Call for detector proposals
  - 2021.12: Detector proposals due
- 2021.6: CD-1 approval
  - Authorization to begin the project execution phase, starting with preliminary design
  - Cost range $1.7B - $2.8B
- 2022.3: Selection of project detector
- 2024: CD-2/3A (performance baseline)
- 2025: CD-3 (start of construction)
- 2032: CD-4A (start of operations)

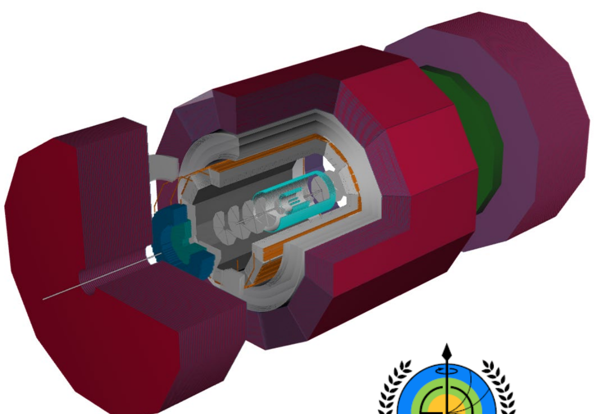
EIC status: Schedule

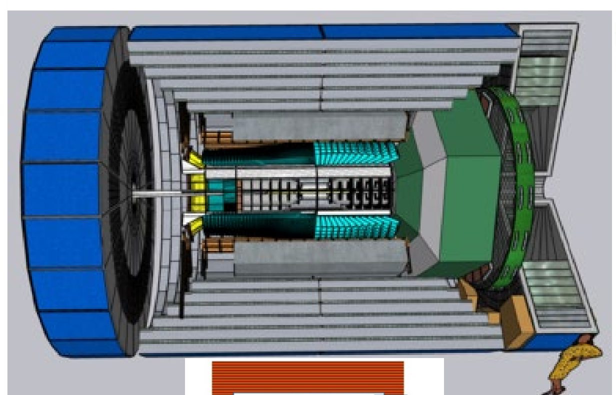
- 2032 CD-4A: Start of operation

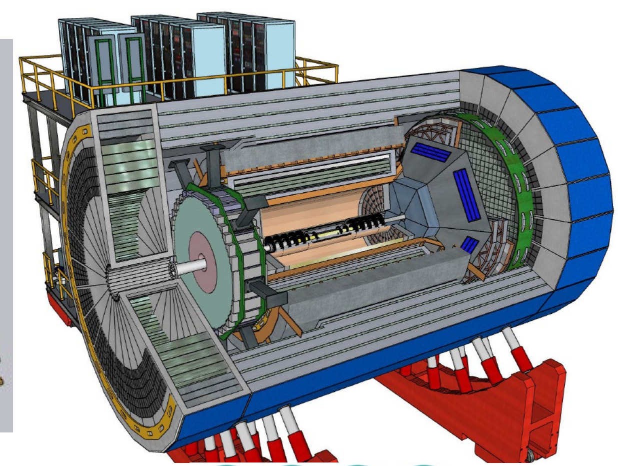


Call for detector proposals

- 3 detector proto-proposals
  - ATHENA
    - A Totally Hermetic Electron-Nucleus Apparatus
    - https://sites.temple.edu/eicatip6
  - CORE
    - a Compact detector for the EIC
    - https://eic.jlab.org/core
  - ECCE
    - EIC Comprehensive Chromodynamics Experiment
    - https://www.ecce-eic.org
- A White Paper for a dedicated IR/detector for lower CM energy being prepared
    - https://indico.bnl.gov/event/11669
    - Second PSQ@EIC meeting co-hosted by APCTP



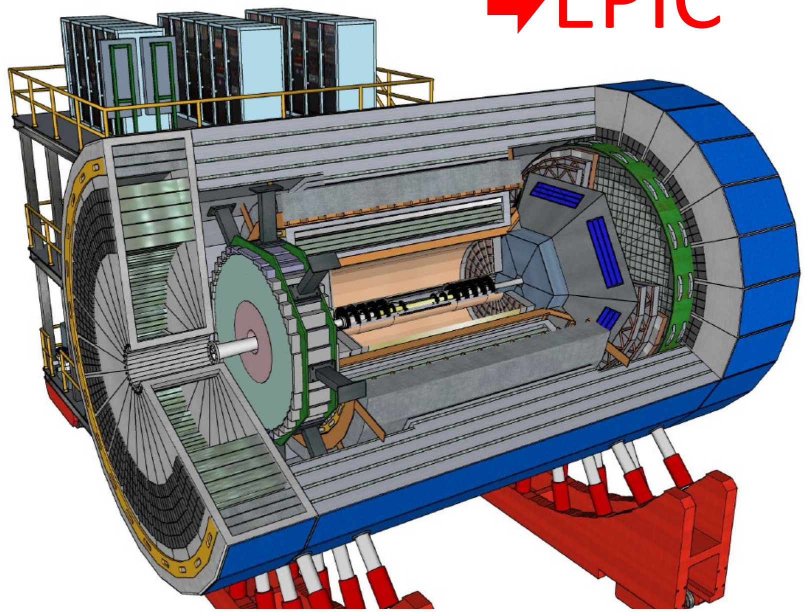


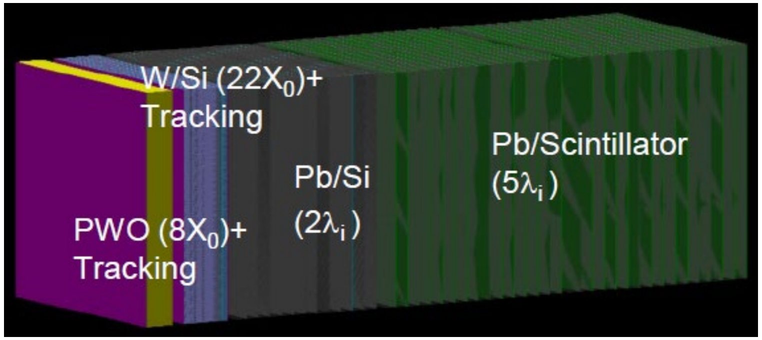


EPIC detector collaboration

- 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
- EPIC detector collaboration
  - ECCE takes the lead in integrating other detector collaborations
- EIC-Japan group
  - 2020.5: EIC R&D program proposal "Developing a high resolution ZDC for the EIC" (eRD27)
  - ECCE/EPIC ZDC designed by Shimizu

ECCE ➡EPIC

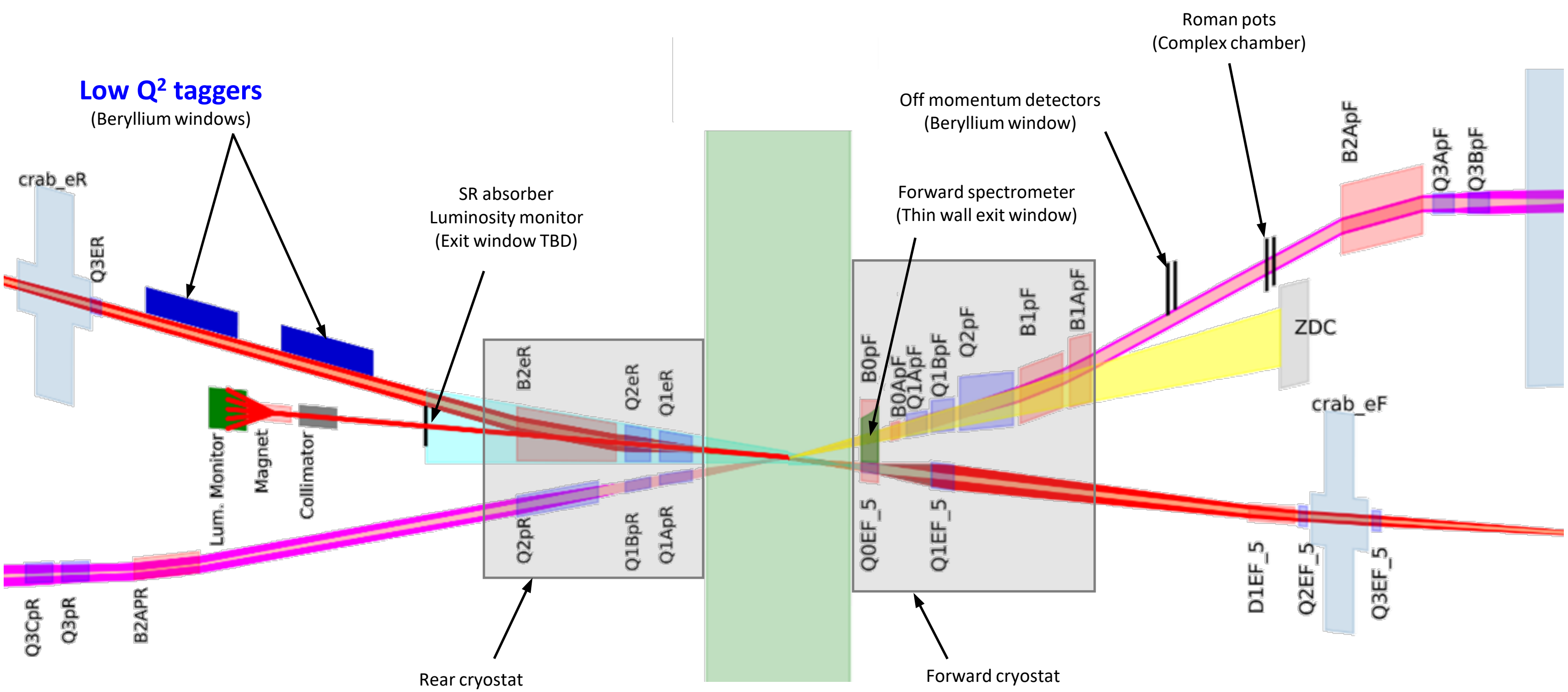




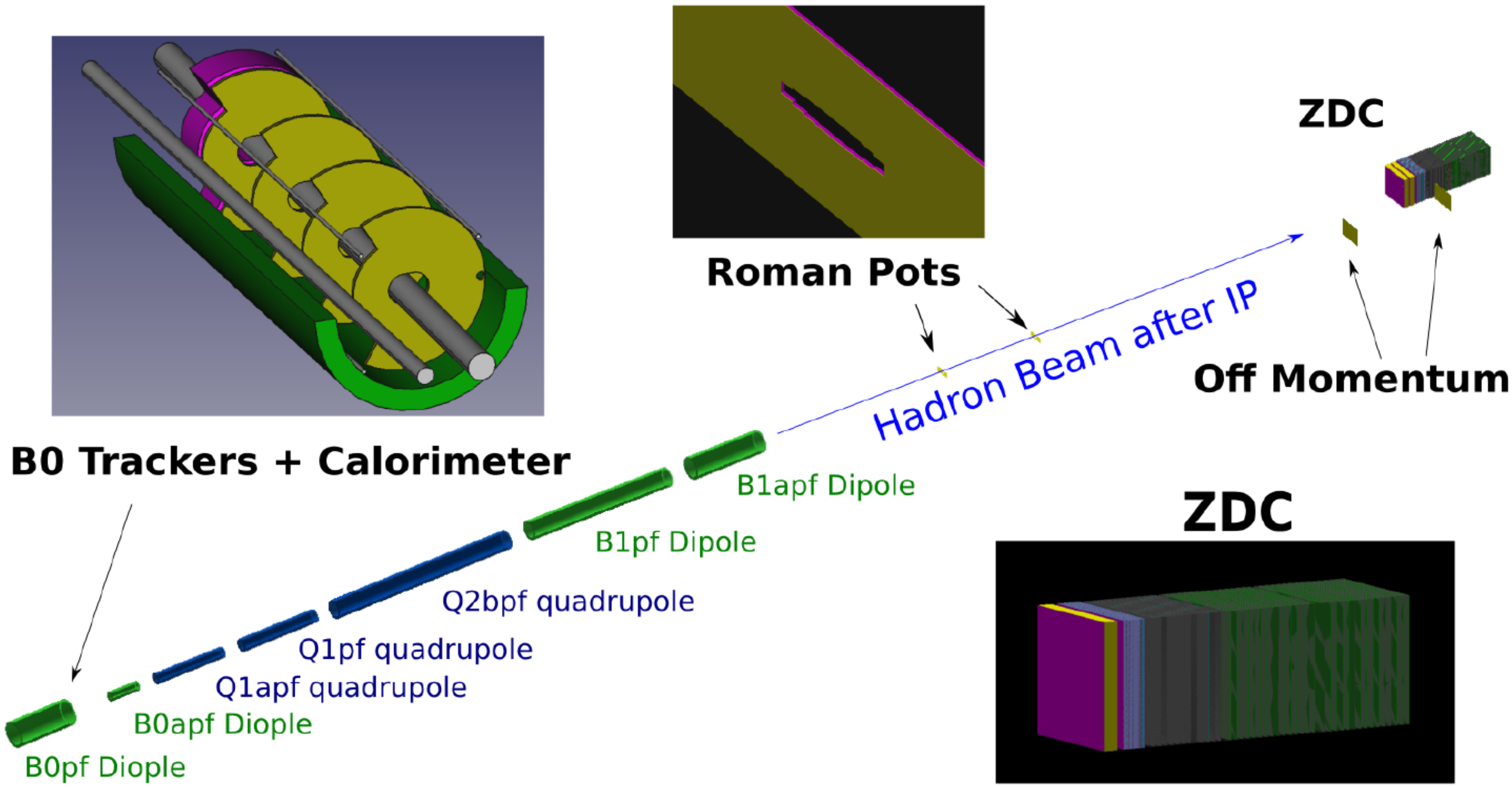
ECCE/EPIC ZDC

EIC Interaction Region (IP6)

- Extensive integration of forward and backward detector elements into the accelerator lattice



EIC Far-forward region



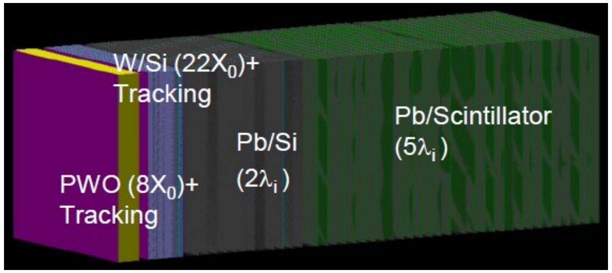
Detector	(x,z) Position [m]	Dimensions	θ [mrad]	Notes
ZDC	(-0.96, 37.5)	(60cm, 60cm, 1.62m)	$\theta < 5.5$	$\sim$4.0 mrad at $\phi = \pi$
Roman Pots (2 stations)	(-0.83, 26.0) (-0.92, 28.0)	(30cm, 10cm)	$0.0 < \theta < 5.5$	$10\,\sigma$ cut.
Off-Momentum Detector	(-1.62, 34.5), (-1.71, 36.5)	(50cm, 35cm)	$0.0 < \theta < 5.0$	$0.4 < x_L < 0.6$
B0 Trackers and Calorimeter	(x = -0.15, 5.8 < z < 7.0)	(32cm, 38m)	$6.0 < \theta < 22.5$	$\sim$20 mrad at ϕ=0

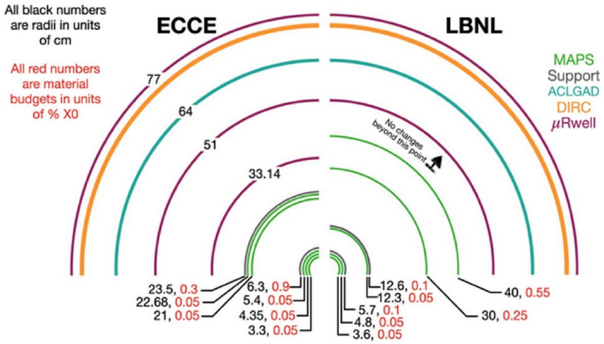
EIC Japan

- 2019: Master Plan 2020 proposal of Electron-Ion Collider (EIC)
  - Selected as a major academic research project
  - Core institutions: Yamagata Univ. & RIKEN
  - Participating institutions: Kobe Univ., Nihon Univ., KEK, etc.
- Collaboration including nuclear-physics community and high-energy community
  - Nuclear physics: Yamagata U., RIKEN, Nihon U., U. of Tsukuba, JAEA
  - High-energy physics: Kobe U., Shinshu U., Kyushu U., KEK
  - Cosmic ray: Nagoya U., ICRR
- 2020.5: EIC detector R&D program eRD27
  - "Developing a high resolution ZDC for the EIC"
  - Collaboration with Kansas U., ODU, etc.
- 2020.11: Expression of interest (EOI) from EIC-Japan
  - Forward hadron calorimeter
    - Cooperation with UCLA & Korean group
  - Zero-degree calorimeter (EM & hadron)
    - Cooperation with eRD27
  - Silicon detector
    - Cooperation with ANL, BNL, etc.

EIC Japan

- 2022: Science Council of Japan, "Medium- and Long-term Research Strategy for Science"
  - 7/18 Status report at future planning committee meeting of Nuclear Physics Committee
  - Participation in the EIC project as part of the High Energy QCD Frontier Initiative
- Mailing list
  - eic-japan-l@ml.riken.jp
- Meeting held on Thursdays at 10:30AM
  - Participating groups: RIKEN, Yamagata Univ., JAEA, Nihon Univ., Virginia Univ., Kobe Univ., Shinshu Univ., Kyushu Univ., KEK, Nagoya Univ., Univ. of Tokyo ICRR, Univ. of Tsukuba, Tsukuba Univ. of Technology, Univ. of Tokyo CNS, Hiroshima Univ., Nara Women's Univ.
- EIC detector prototype R&D
  - ZDC
  - AC-LGAD



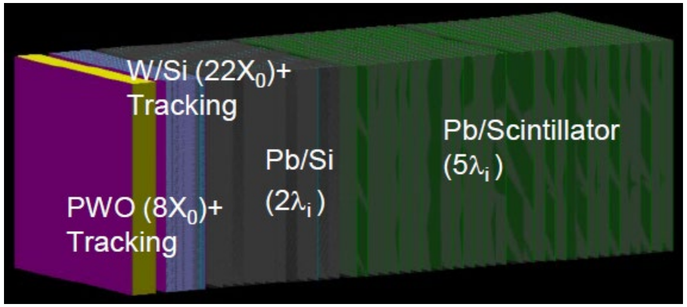


EIC-Japan group involvement

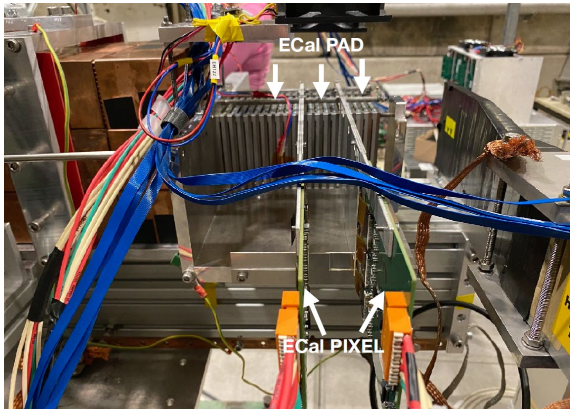
- 2015.4: EIC Letter of Interest from Asian countries
  - 20 participants from Japan: RIKEN, Yamagata, Tokyo Tech, Juntendo, KEK, Kyorin, Kyoto, Niigata, Tohoku, Tokyo Science
  - 7 from China, 3 from India, 4 from Korea
  - To support EIC for NSAC Long Range Plan 2015
- 2019: Science Council of Japan Master Plan 2020 proposal of EIC
  - Collaboration including nuclear-physics community and high-energy community
  - Core institutions: Yamagata and RIKEN
  - Participating institutions: Kobe, Nihon, KEK, etc.
- 2020: Yellow Report
- 2020.5: eRD27 “developing a high resolution ZDC for the EIC”
- 2020.11: Expression of Interest (EOI) from EIC-Japan
- 2021.3-12: Call for detector proposal from the EIC project
  - EIC-Japan group participates in the ECCE detector consortium
- 2022: Science Council of Japan “Medium- and Long-term Research Strategy for Science”
  - EIC project proposal to be submitted as a part of the High-Energy QCD Frontier Initiative

Interest in contributing to ZDC

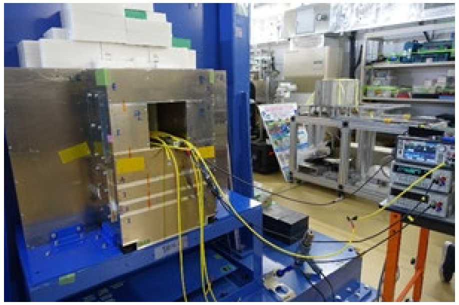
- ECCE/EPIC ZDC design
  - Simulation
  - Performance evaluation
- ALICE-FoCal-E technology: Tungsten/Silicon
  - Test beam studies ongoing
- Radiation tolerance test by neutron irradiation
- RIKEN, Tsukuba, Tsukuba Tech, Kobe, Shinshu, Yamagata, JAEA, Nihon, Kyushu, KEK, Nagoya, Tokyo ICRR



ECCE/EPIC ZDC



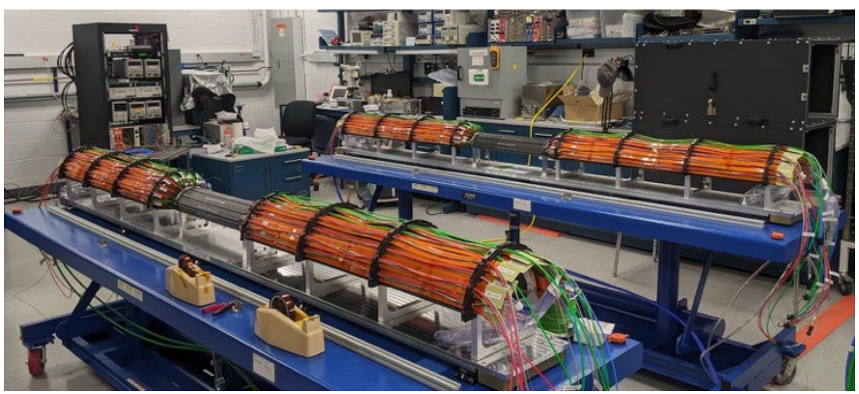
ALICE FoCal-E R&D



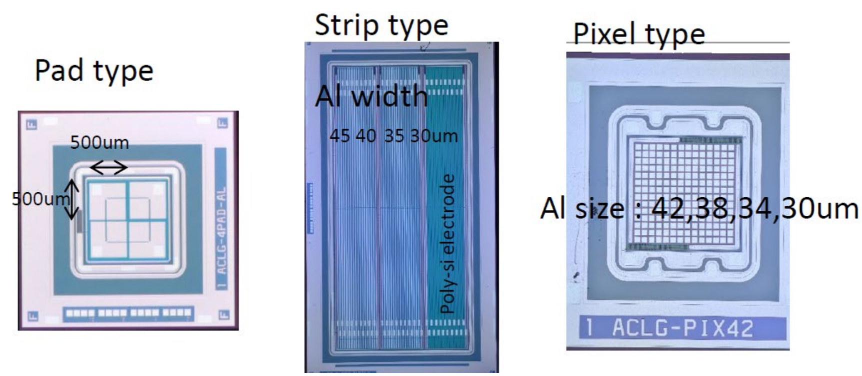
Neutron irradiation at RIKEN RANS

Interest in contributing to (AC-)LGAD Barrel

- Construction of (AC-)LGAD Barrel based on our past experience of PHENIX VTX silicon detector construction and present experience of sPHENIX INTT silicon detector construction
- HPK LGAD development by KEK group
  - To be combined with some readout ASIC
- RIKEN, Hiroshima, Nara Women's, Tokyo CNS, Kyushu, KEK



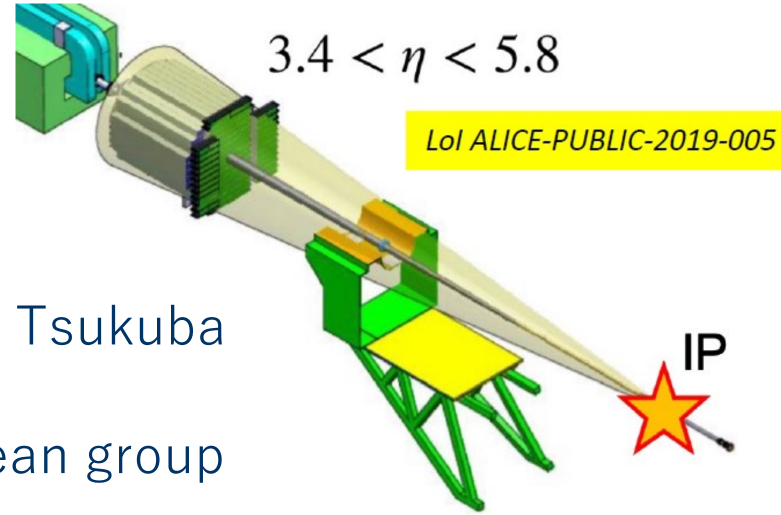
sPHENIX INTT construction

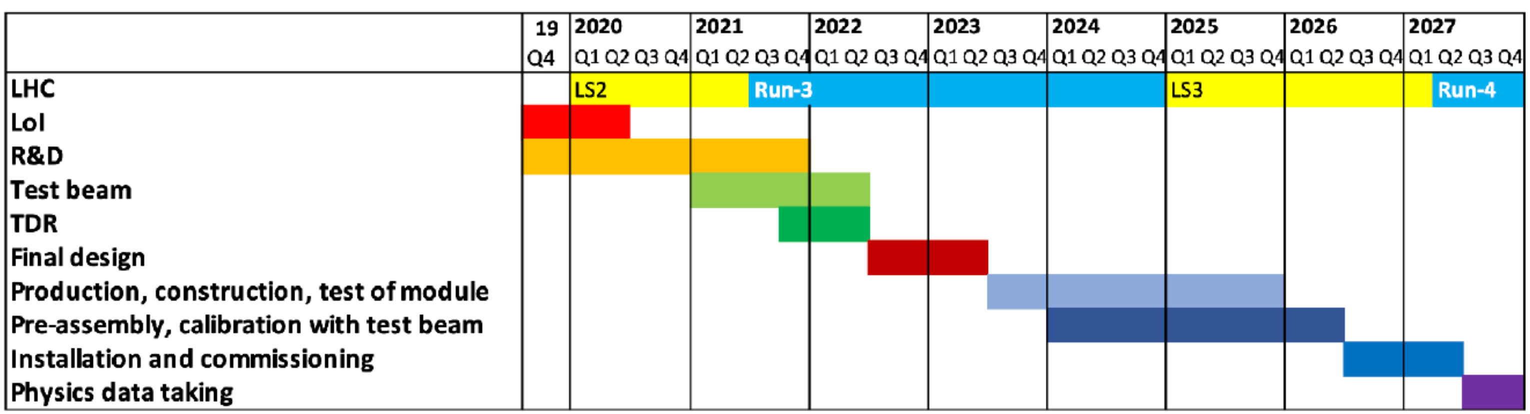


HPK LGAD development

Calorimeter development

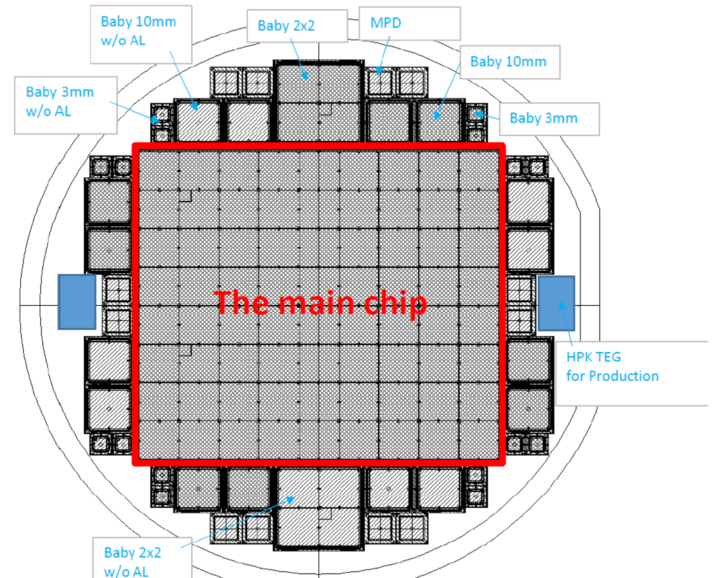
- ALICE-FoCal
  - 2027-29 LHC Run-4
  - FoCal-E Pad & Pixel
    - Pad detector led by Univ. of Tsukuba group (and Indian group)
    - Pixel detector led by European group
  - Test beam activities ongoing
    - Pad detector at ELPH, Tohoku Univ.
    - Total system at CERN SPS
  - TRD to be made in 2022



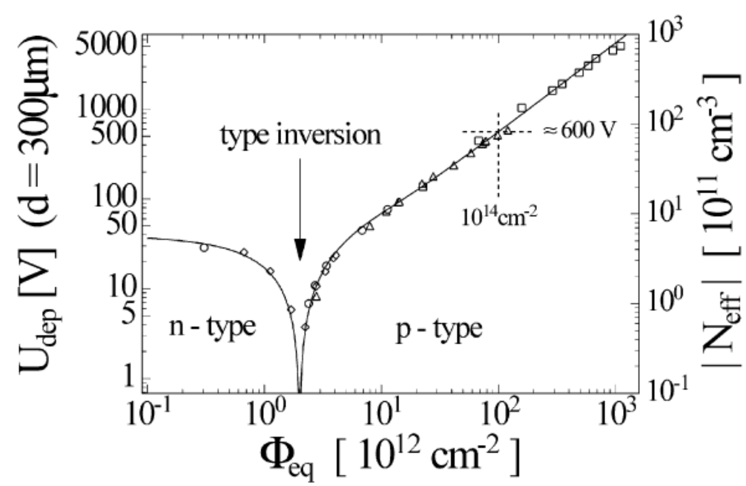


Irradiation test

- Measurement of the radiation hardness of the ALICE-FoCal-E Pad sensors
  - To determine if the sensor is sufficiently radiation hard to radiation dose/fluence at zero degree of EIC
  - At ALICE-FoCal, 1-MeV neutron equivalent fluenceで $< 10^{13}$ n_{eq}/cm^2, or Total ionizasation dose (TID) of 1.5 kGy
- HPK Pad sensor
  - Test its baby chip and MPD
- Options: p-type or n-type
  - Type inversion from n-type to p-type at 10^{12} neutron/cm^2



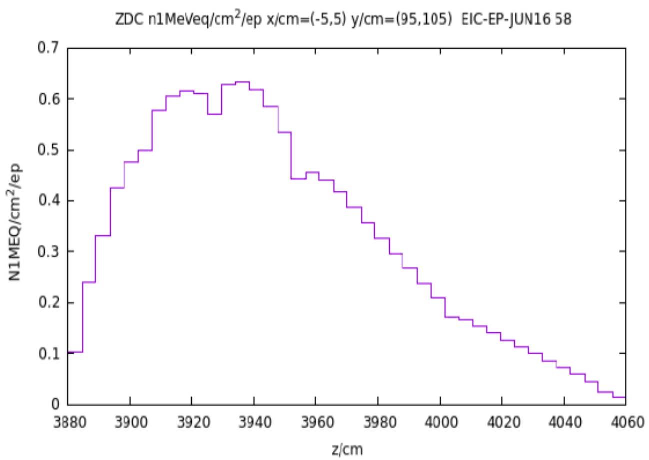
The 6-inch p-substrate wafer

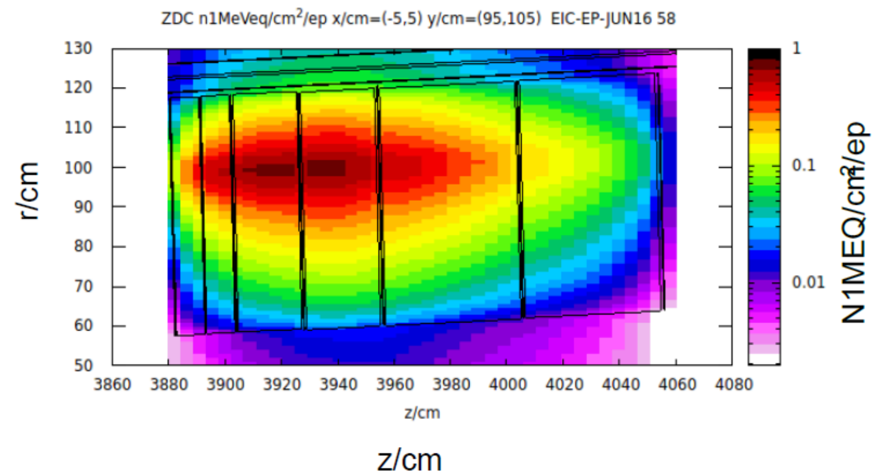


EIC-ZDC

- More than 2 x 10^{13} neutron/cm^2 in one year at EIC-ZDC
  - More than 10 times higher radiation than ALICE-FoCal

Electron-Proton collisions. IP6, p(275)+e(10). Si lifetime in ZDC.





Assume the ep - collision rate is 1.E+6 [ep/s]

Critical rate dN_{ep+pg}/dt=8.E - 1[N/cm ^{2}/ep]*1.E+6[ep/s]+dN_{pg}/dt=

=8.E+5[Hz/cm ^{2}]+.4 E+5[Hz/cm ^{2}]

ZDC Silicon LifeTime = 1.E+14 [1/cm ^{2}] / 8. 4E+5 [Hz / cm^2] =~0. 12 E+9 [s] =

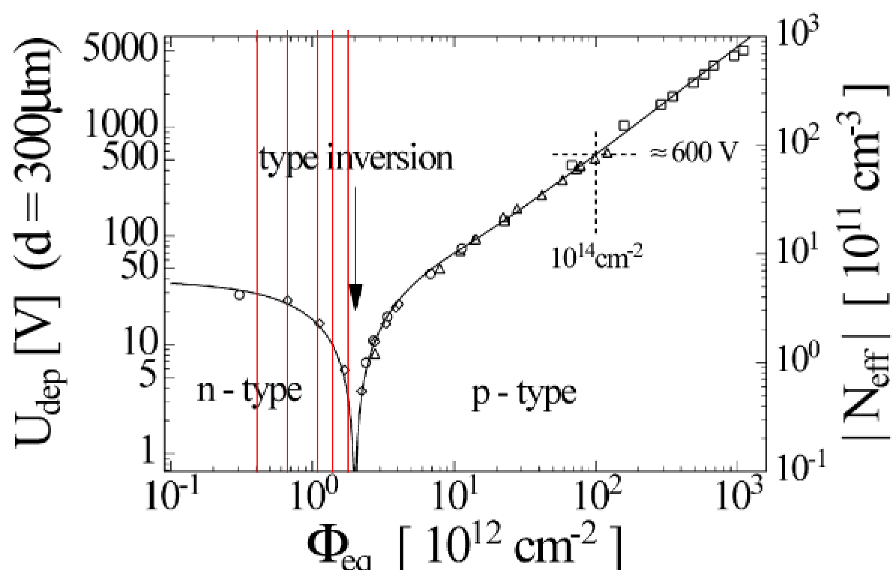
~ 4 years.

Test plan & menu

- Proton 7MeV, 100μA, 6 x 10^{13} proton/s
  - Maximum current stable produced about 40μA
- Neutron 5MeV max, 10^{12} neutron/s from the target
- 2 cm from the target: 10^8 neutron/cm^2/s
  - After the Be target, several x 10μm silver wax, 5mm vanadium, 5mm water, and 5mm titanium
- Maximum operation time per day about 5 hours
  - Up to 1 hour of continuous operation with a 10-minute stop for the next irradiation
- Measurement of I-V and C-V characteristics every hour to evaluate U_{dep}

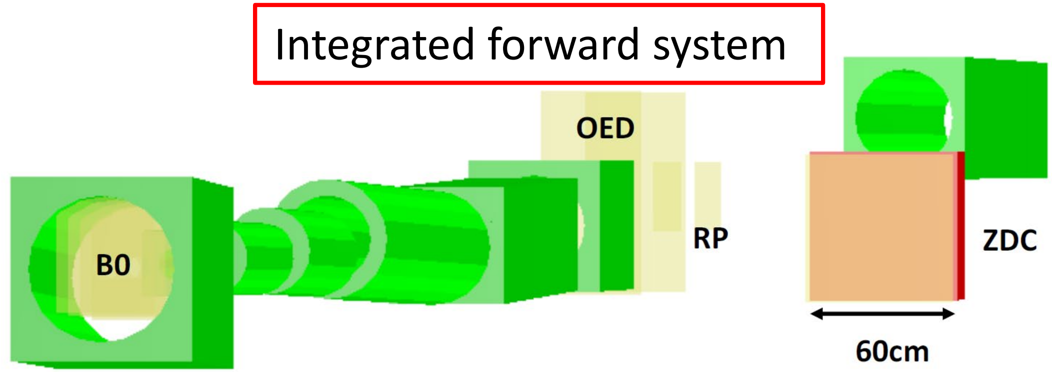
位置	1 時間	2 時間	3 時間	4 時間	5 時間
2cm	0.36	0.72	1.08	1.44	1.80
5cm	0.06	0.12	0.17	0.23	0.29
10cm	0.01	0.03	0.04	0.06	0.07

Table 1: 1 日の運転で得られる照射量の見積もり（$\times 10^{12} n_{eq}/cm^2$）。



EIC Detector R&D

- "Developing a High Resolution ZDC for EIC"
  - Submitted in 2020.5
  - eRD27 approved in 2020.8
- Soft photon detection
  - Large aperture
  - Full absorption calorimeter
- EM and hadron calorimeter
  - Acceptance
  - Energy, position and p_T resolution
  - ALICE-FoCal R&D by RIKEN & Tsukuba
- Radiation hardness



Performance requirements and resources requested

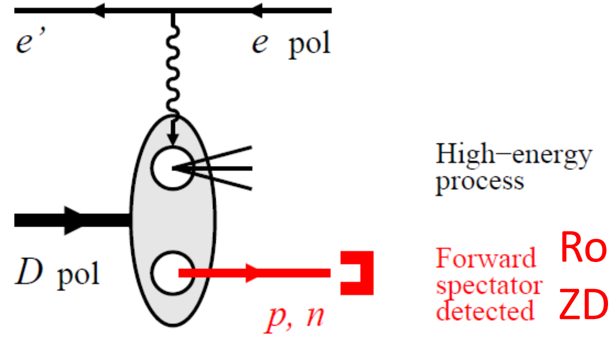
Detector R&D	Physics	Performance requirements	Resource requested	Support & collaboration
Soft photon detection	e+A nuclear breakup veto	$E_\gamma \leq 300$ MeV	detector simulation	This proposal Calorimeter consortium
		acceptance	acceptance simulation	This proposal BeAGLE group
		detector technology	detector R&D	N/A in FY21
EM + hadron calorimeter	e+A collision geometry	neutron multiplicity	high resolution not necessary	BeAGLE group
	spectator tagging	energy & position resolution	detector simulation	This proposal
	meson structure	neutron & Λ acceptance	detector simulation	This proposal Meson structure WG
		detector technology	FoCal R&D	RIKEN
			LHC-ZDC R&D	Kansas Univ.
		calibration scheme	design & simulation	This proposal
			system test	N/A in FY21
Radiation hardness		radiation dose	simulation study	This proposal Kobe Univ.
		detector technology	radiation test	This proposal Calorimeter consortium

Table 1: Table of performance requirements.

Physics at zero degree of EIC

- Spectator tagging
  - Neutron structure
    - Neutron spin structure, S & D waves
  - Nucleon interactions
    - SRC/EMC at large *x*
    - Diffraction and shadowing at small *x*

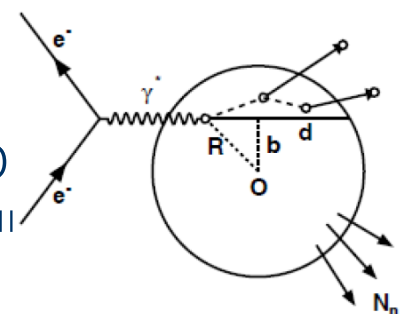
e+D



Roman pot
ZDC

- Geometry tagging in e+A collisions
  - *b*: impact parameter & *d*: path length
  - "Centrality" (high *d*) & "Skin" (low *d*)
  - Breakup determination & veto with ZD
    - + forward photons requiring wide apertu

e+A

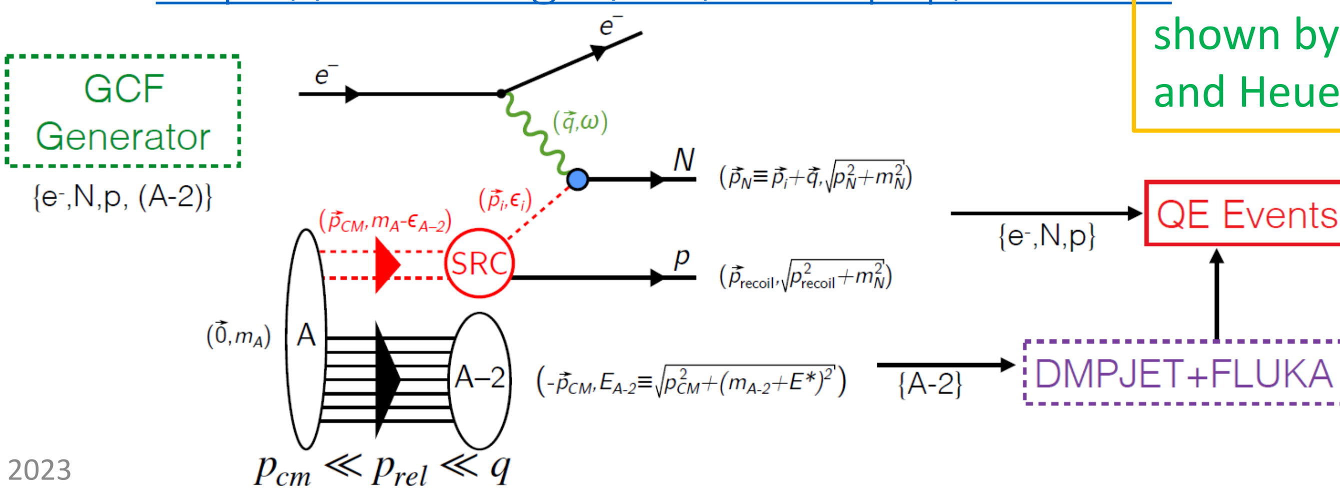


Intra-nuclear cascading increases with d (forward particle production)

Leads to evaporation of nucleons from excited nucleus (very forward)

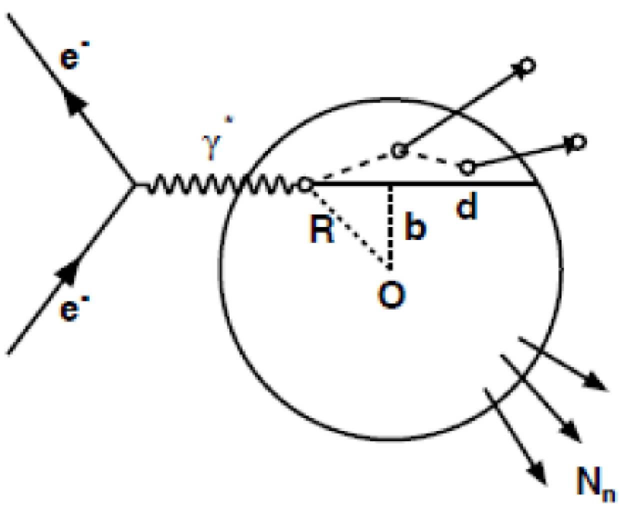
- Event generator
  - GCF: https://www.mit.edu/~src_emc/fri/schmidt_20190322.pdf
  - BeAGLE: https://wiki.bnl.gov/eic/index.php/BeAGLE

shown by Weiss, Baker and Heuenstein



e + A collision at zero degree

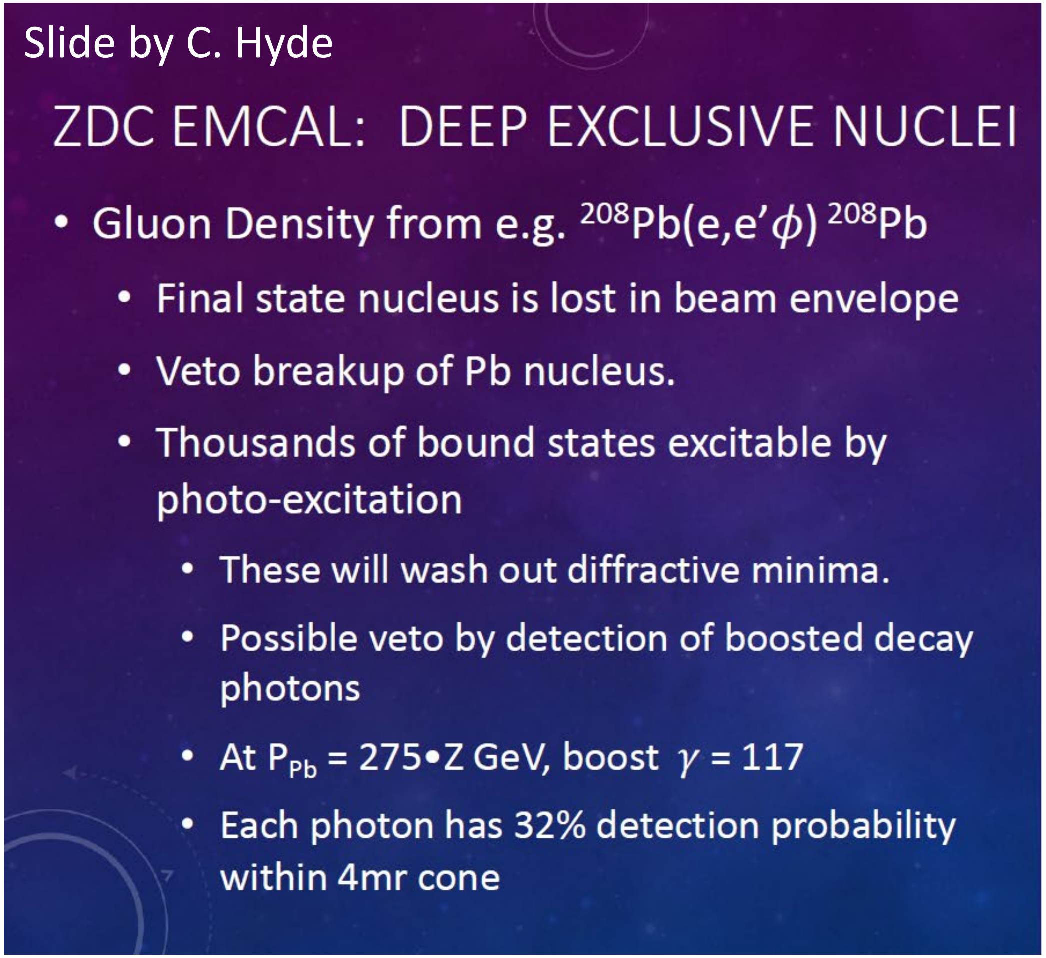
- Breakup of the excited nucleus
  - Evaporated neutrons (& protons)
    - Separate the coherent process ~90%
  - Photons from de-excitation of the excited nucleus
  - Requirement to measure neutrons and photons at zero degree in a wide *t* range
- Event-by-event characterization of collision geometry
  - Tagged through forward neutron multiplicities at zero degree
  - *b*: impact parameter
  - *d*: path length of struck parton in nucleus
  - “centrality” (high *d*) & “skin” (low *d*)
  - Study of nuclear medium effects

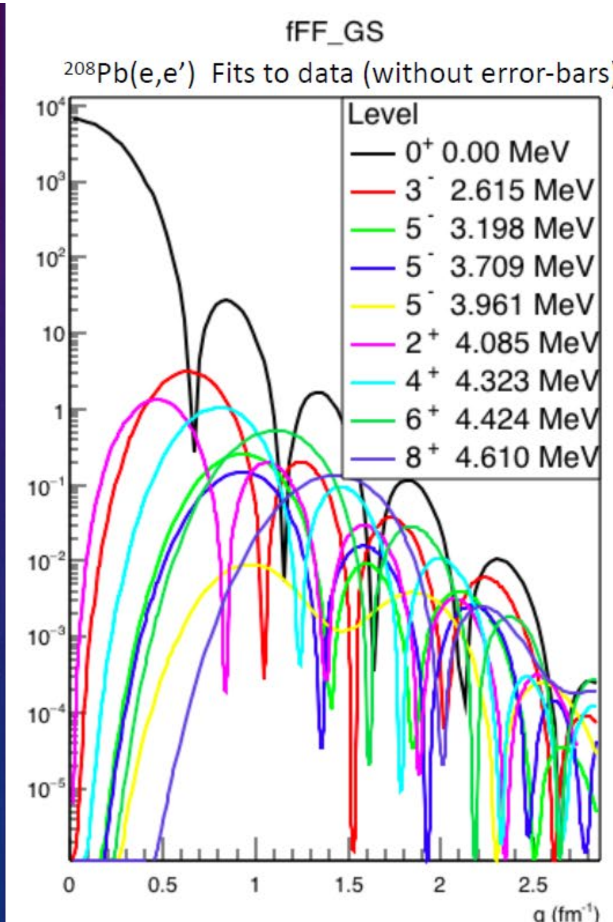


Intra-nuclear cascading increases with d (forward particle production)

Leads to evaporation of nucleons from excited nucleus (very forward)

e + A collision at zero degree

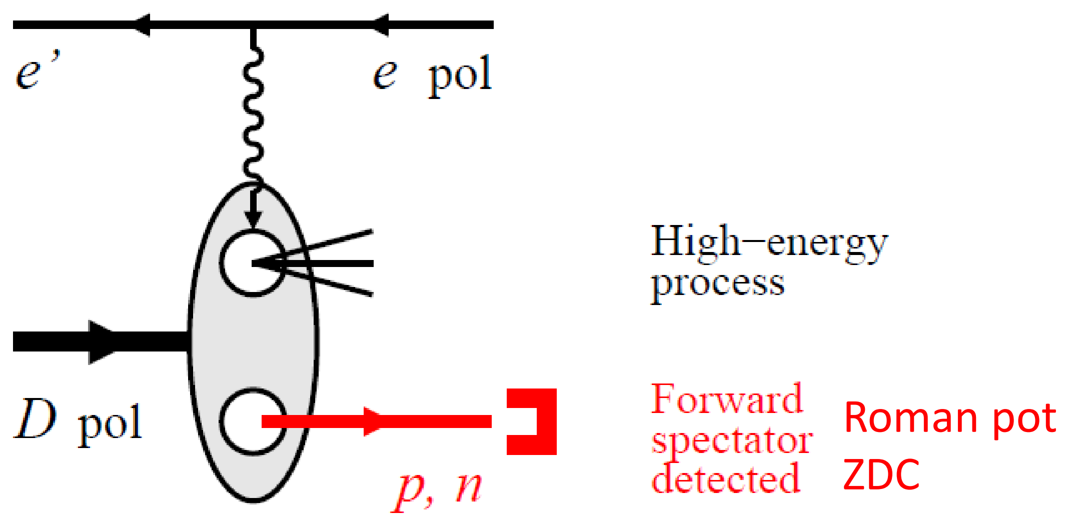




- Removing excited nucleus event by detecting excitation photon
- Soft photon ~300 MeV
- Low detection probability within 4 mrad cone

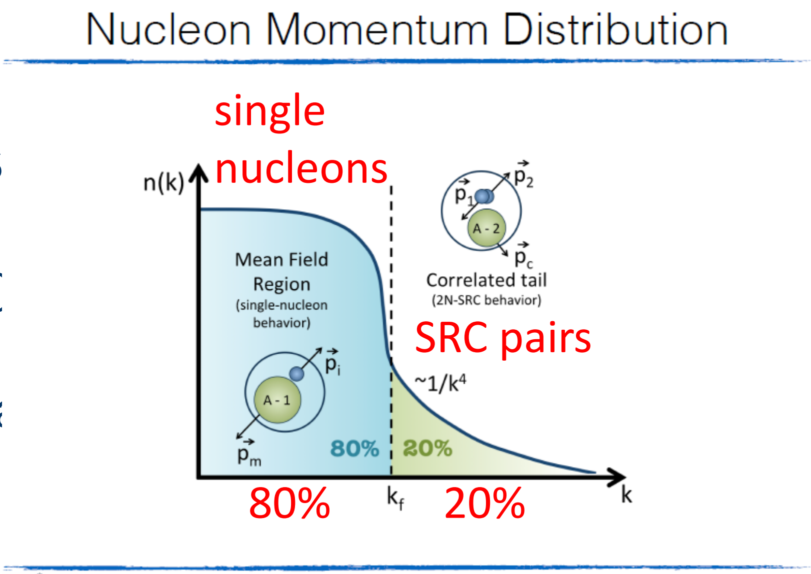
e + d/³He collision at zero degree

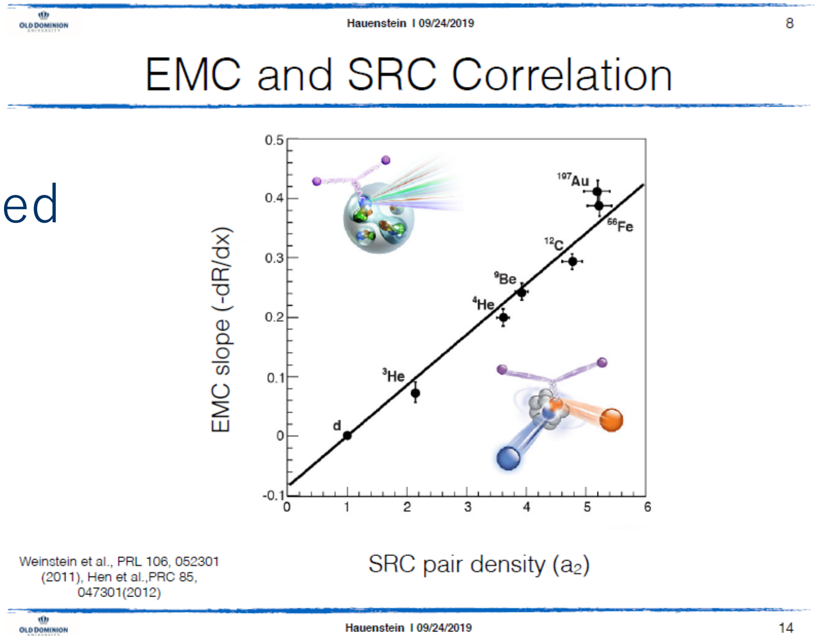
- Spectator tagging
  - Neutron structure
    - Neutron spin structure, S & D waves
  - Nucleon interactions
    - Short-range correlation (SRC) and EMC effect at large *x*
    - Diffraction and shadowing at small *x*



Physics at zero degree of EIC

- Short range correlation (SRC
  - ~20% of nucleons in SRC pairs
    - 18% p-n pairs
    - Large relative momentum (> 300 MeV/c)
    - Small c.m. momentum and spati very close each other
  - EMC effect
    - Nuclear structure modification found in nuclear DIS in the EMC experiment
    - Nuclear PDF significantly modified by SRC pairs
- Tagged DIS at JLab → EIC
  - e+D at JLab: Hall B & C
  - e+D & e+A at EIC
- Tagged SRC at EIC



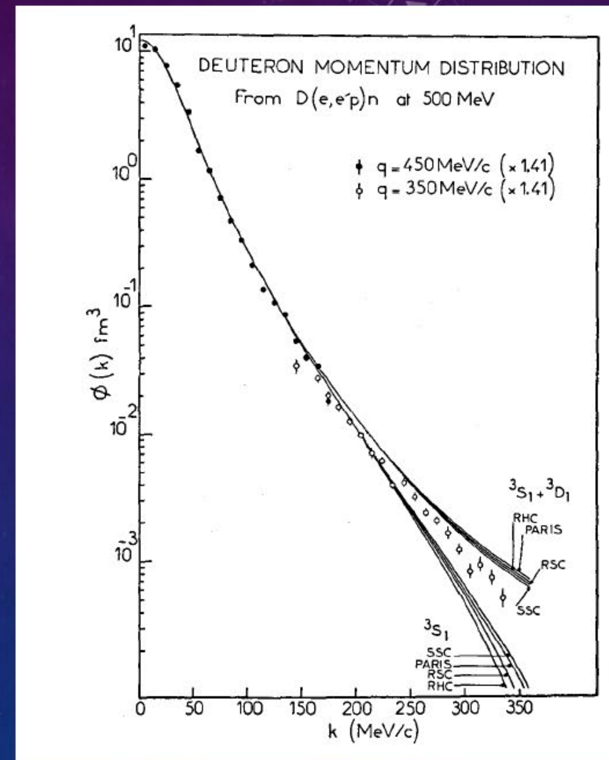


slides by Heuenstein

Spectator tagging

ZDC RESOLUTION:
SINGLE NEUTRON EVENTS

- Measuring the properties of a bound proton: Spectator tagging: e.g. D(e,e'n)X
  - P_D = 275 GeV/c ➔ $p_n = P_D(1+\alpha)/2 \approx$ 137 GeV/c
    - Rest frame neutron momentum ≈ αM
  - If ZDC resolution = 50% $[\mathrm{GeV}/E_n]^{1/2}$ → 4.5% @ 137 GeV/c
    - $\sigma(\alpha) \approx \sigma(p)/p \approx 0.045$ ➔ Rest-frame $\sigma(p_n) \approx$ 40 MeV/c
  - Spatial resolution 1 cm ?
    - $\sigma(p_T) \approx$ (137 GeV/c) (1 cm)/(32m) = 43 MeV/c



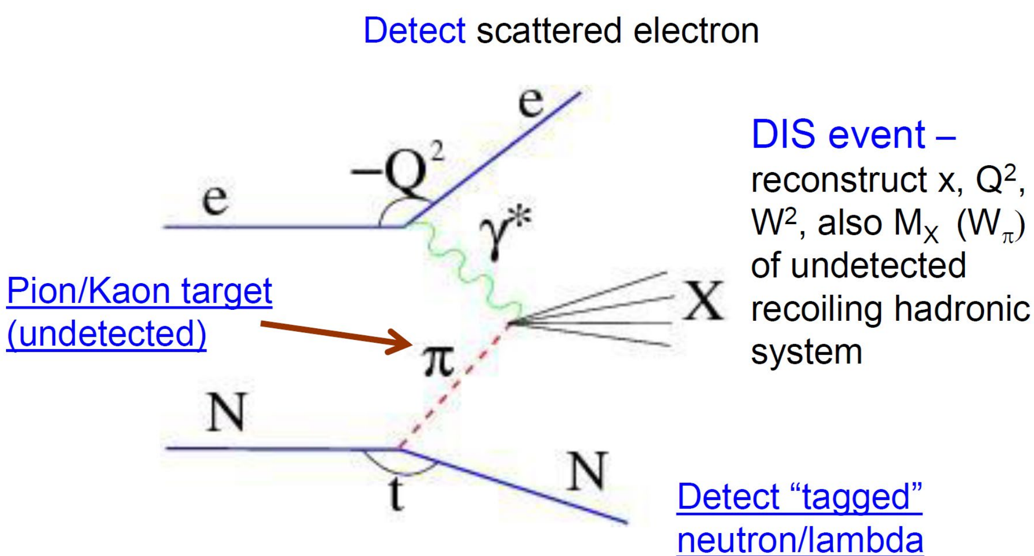
Slide by C. Hyde

- p_T resolution equivalent to beam spread ~40-50 MeV/c
- Spacial resolution 1cm → p_T resolution ~40 MeV/c
- ZDC energy resolution 50%/√E (GeV) or 4.5% @ 137 GeV/c → p_T resolution ~40 MeV/c

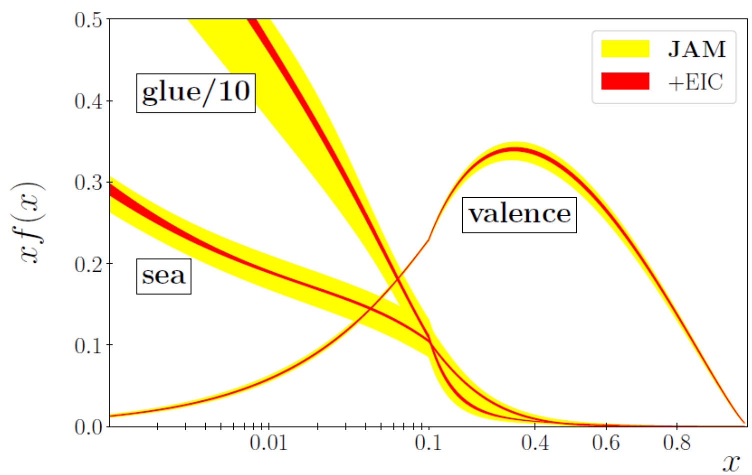
Far-forward physics at EIC

- Mass of the proton, pion, kaon
  - Visible world mainly made of light quarks: its mass emerges from quark-gluon interactions, Higgs mechanism hardly plays a role
  - Strange quark is at the boundary: both emergent-mass and Higgs-mass generation mechanism are important
- Proton
  - EIC will allow determination of an important term contributing to the proton mass, the so-called "QCD trace anomaly"
- Pion and kaon
  - EIC will allow determination of the quark and gluon contribution to mass with the Sullivan process

Sullivan process



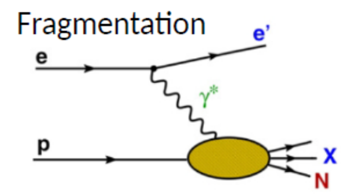
Pion PDFs

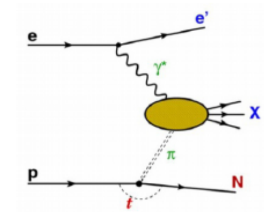


Physics at zero degree of EIC

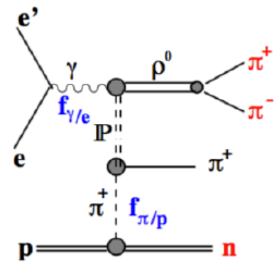
- Leading baryons
  - Fragmentation
  - One pion exchange (OPE)

One Pion Exchange (OPE)





LN in DIS

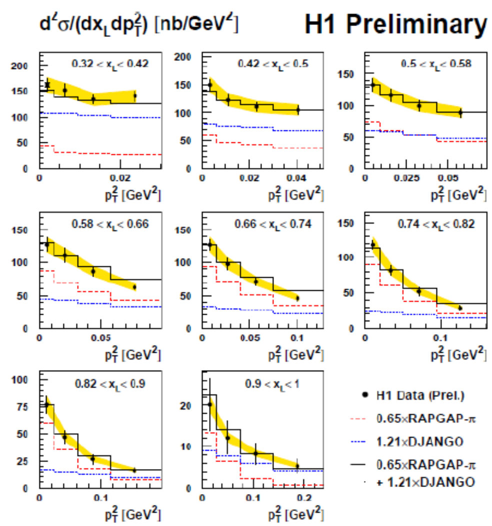


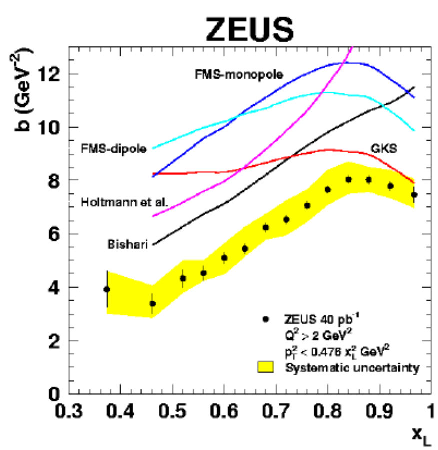
$$d\sigma_{\gamma^* p\to nx} = f_{\pi/p}(x_L,t)\times d\sigma_{\gamma^*\pi\to X}$$

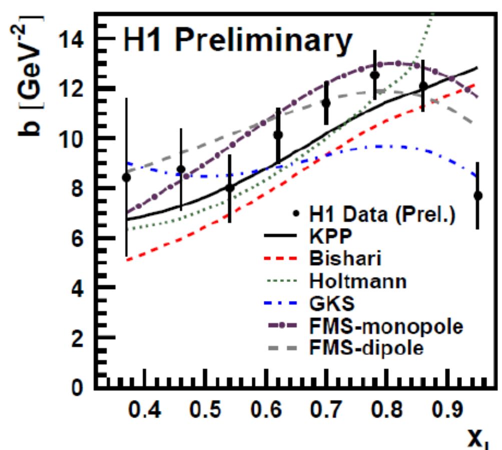
The distribution of p_T^2 (=t) is defined solely by the pion flux

Sensitivity to the pion flux

p_T^2 dependence in bins of x_L







Slope of exponential p_T^2 dependence compated to various pion-flux models

18

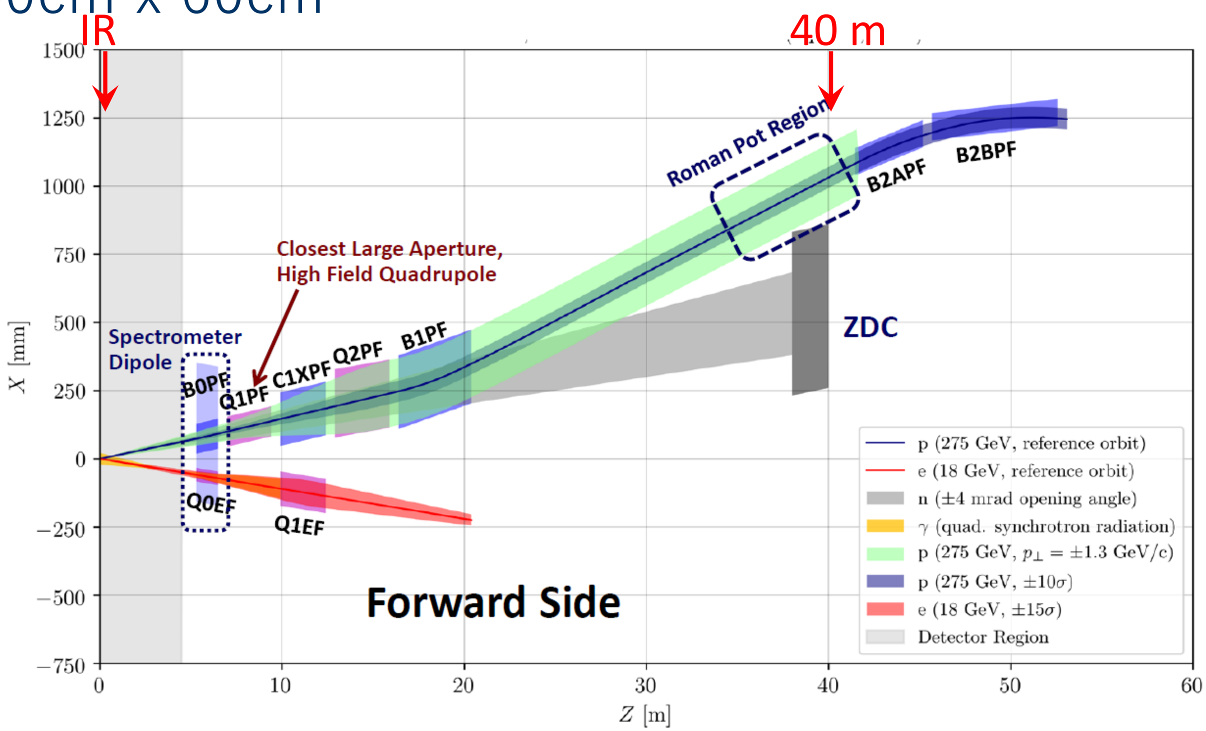
slide by Ciesielski

Inconsistency @ HERA

→ Need more data to understand production mechanism

EIC IR design

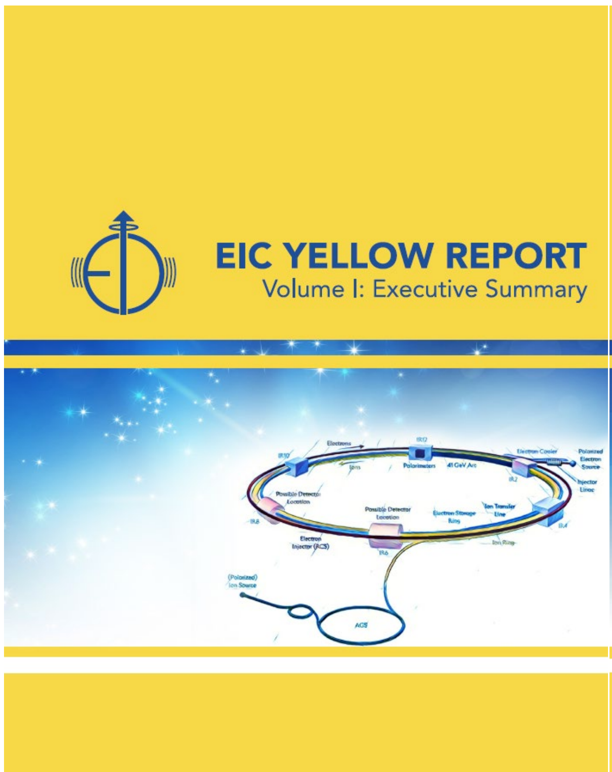
- Acceptance
  - 25 mrad crossing angle for EIC at BNL
  - Forward magnet aperture ±4 mrad opening angle for ZDC
- Sufficient transverse size to avoid transverse leakage
  - ~2 interaction length
  - e.g. 60cm x 60cm

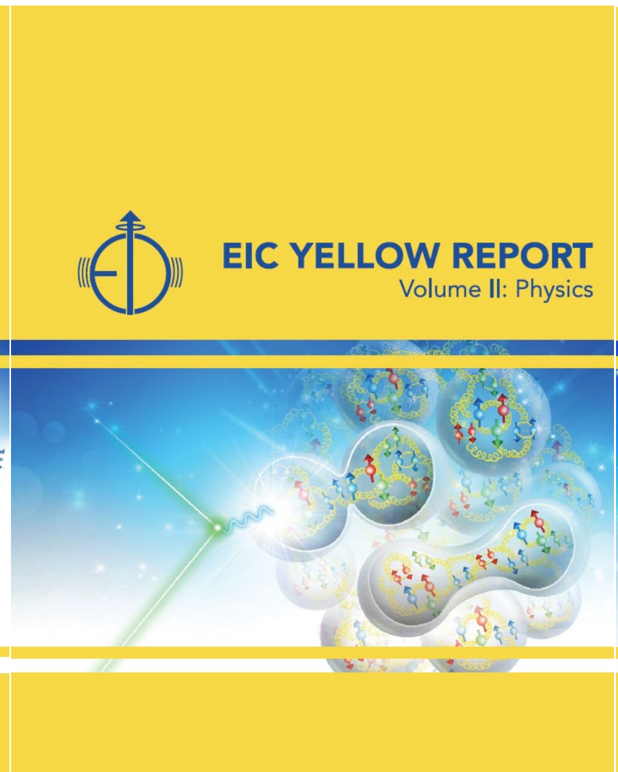


IR design of EIC at BNL

EICUG Yellow Report

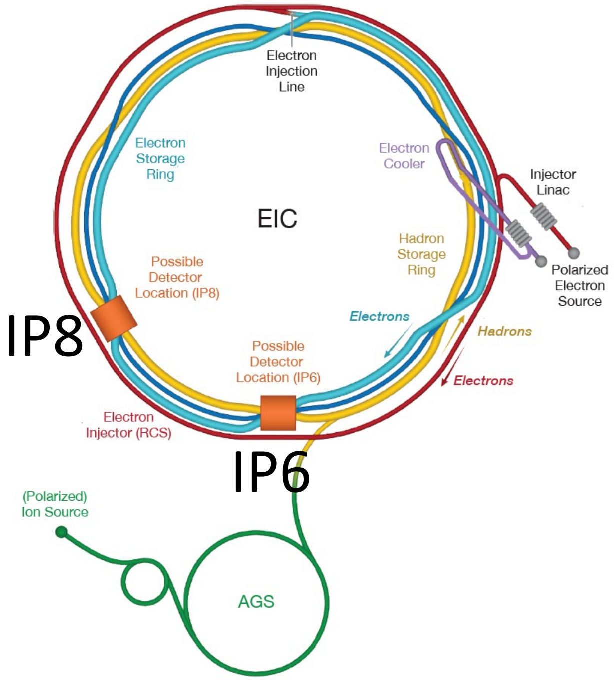
- ~400 authors / ~150 institutions / ~900 pages with strong international contributions
  - Volume I: Executive Summary
  - Volume II: Physics
  - Volume III: Detector
- https://arxiv.org/abs/2103.05419





Call for detector proposals

- Detector 1 (D1)
  - Within the scope of the EIC project
- Detector 2 (D2)
  - Not within the scope of the EIC project
  - How to realize it being explored
- Location of D1 and D2 between IP6 and IP8 is left open, so far assumed D1 will go to IP6



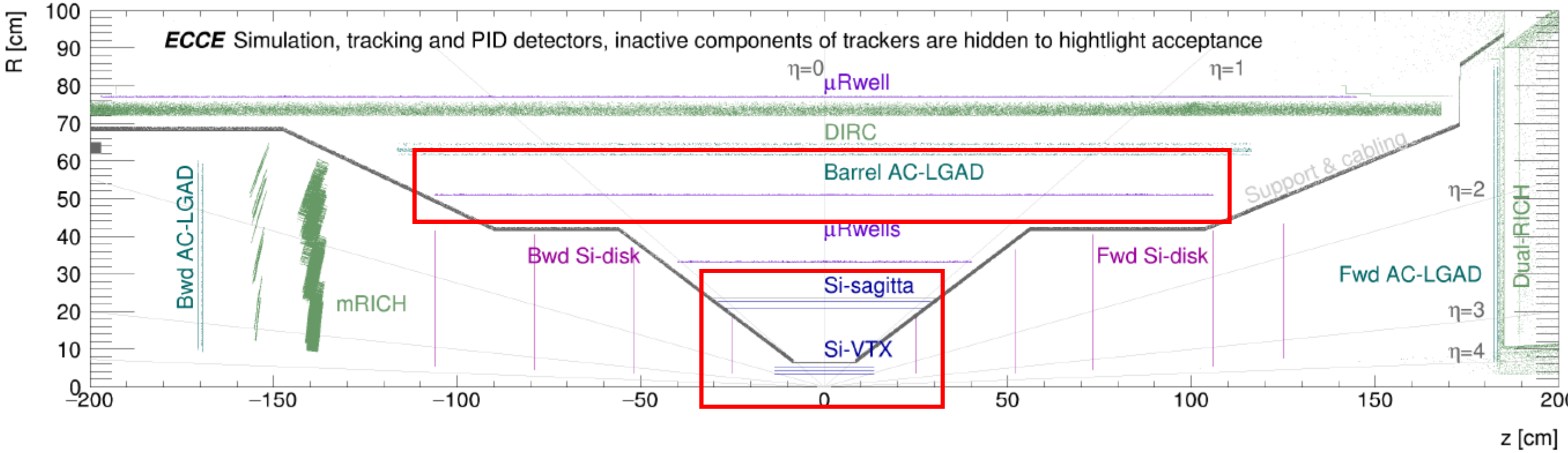
Asian collaboration for EIC

- 2015.4 EIC Letter of Interest from Asian countries
  - 20 from Japan
    - RIKEN, Yamagata U, Tokyo Tech, Juntendo U, KEK, Kyorin U, Kyoto U, Niigata U, Tohoku U, Tokyo U of Science
  - 7 from China
    - CIAE, IMP, Nanjing U
  - 3 from India
    - TIFR, NISER
  - 4 from Korea
    - Seoul National U, Korea U, Daegu U, Chonbuk National U
  - To support EIC for NSAC Long Range Plan 2015
- 2020.11 EoIs from Asian countries
  - EIC-Japan Expression of Interest
  - EoI for China
  - EoI for Indian Consortium
  - EoI for Korean Institutions

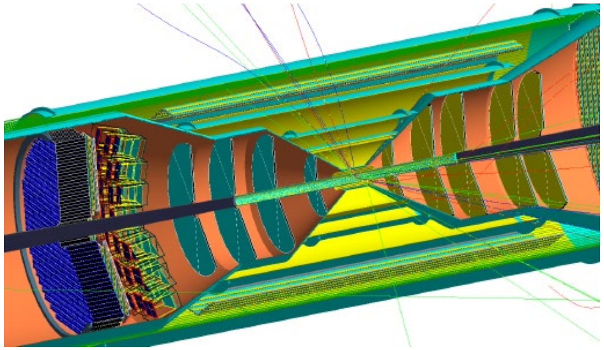
Letter of Interest
Participation in the US Electron-Ion Collider (EIC)
from Asian countries

With this letter we want to express our interest in participating in the US EIC project. The EIC project being discussed in the Long Range Plan process of the NSAC is the most promising project in the world to be realized in a timely manner. It is a new collider which will be able to collide polarized electrons with polarized protons or nuclei. We will be able to have 100-1,000 times higher luminosity per nucleon than HERA. It promises to lead to deep understanding of high-energy QCD and the development of a novel physics field based on QCD where the gluon plays a leading role. The mass of the nucleon and the nuclei originates from gluon interactions and dynamics, and the confinement of the quarks inside the nucleon is caused by the gluons. We are keenly interested in this science, and want to strongly support the US EIC project, through a long-term collaboration for investigations of the novel gluon related physics at EIC.

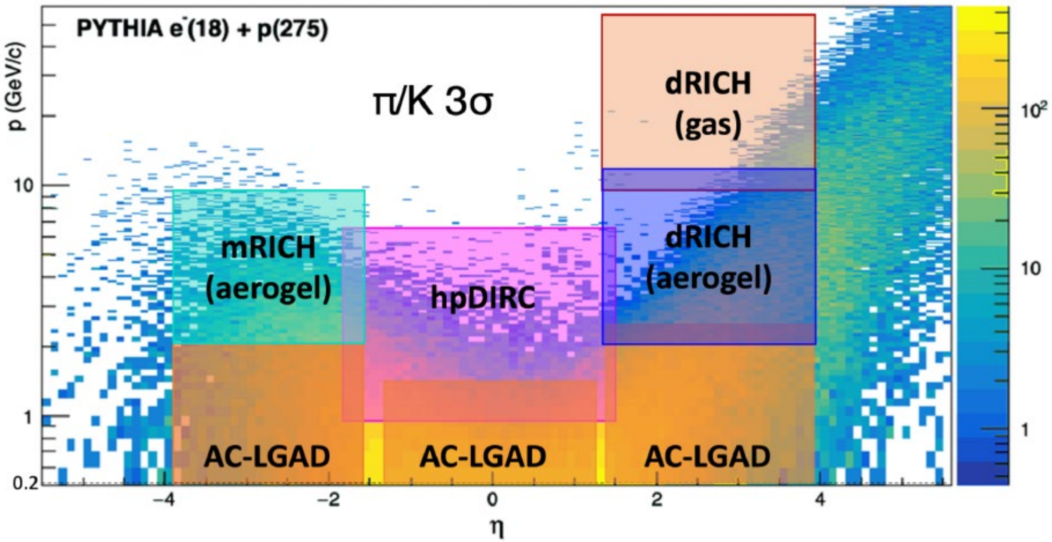
ECCE tracking system



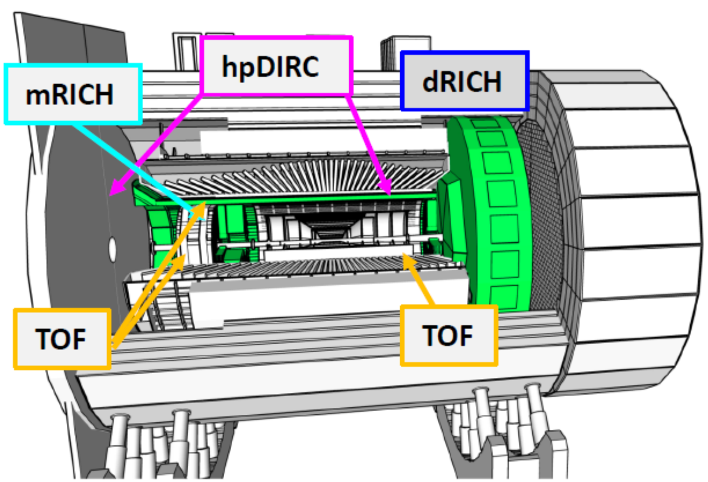
- MAPS
  - 3-layer silicon vertex, 2-layer silicon sagitta, 5 disks in the hadron endcap, 4 disks in the electron endcap
  - For primary and secondary vertex reconstruction
  - Low material budget: 0.05% X/X_0 per layer
  - High spatial resolution: 10 μm pitch MAPS (ALICE ITS3)
  - TowerJazz 65 nm technology (ongoing R&D Si Consortium)
- AC-LGAD
  - TOF layer integrated with PID



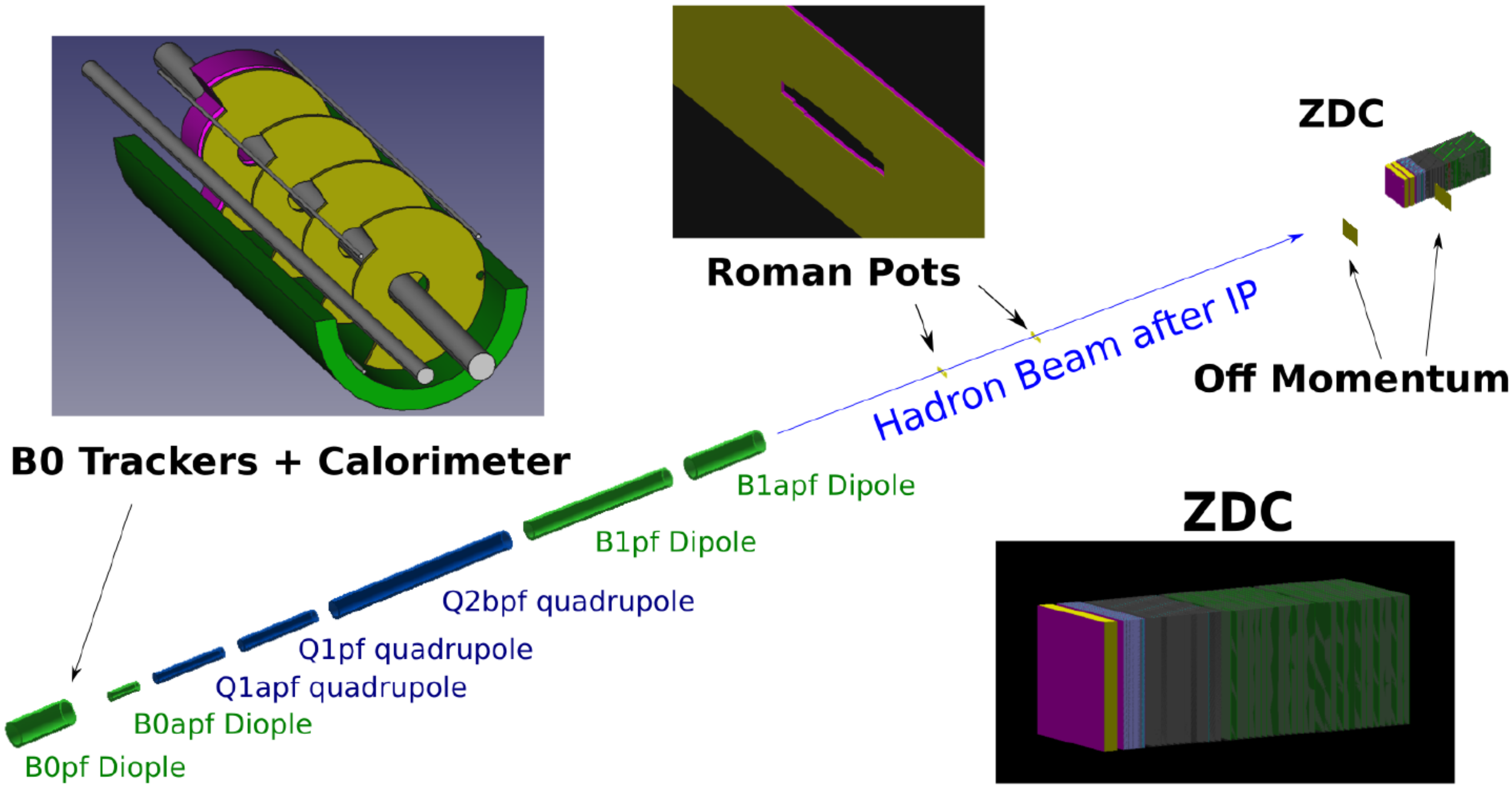
ECCE charged particle ID



- Need to separate:
  - Electrons from photons
  - Electrons from charged hadrons
    - Calorimeter
  - Charged pions, kaons and protons from each other
    - TOF and Cherenkov
- AC-LGAD based TOF system
  - Hadron PID in momentum range below the thresholds of the Cherenkov detectors



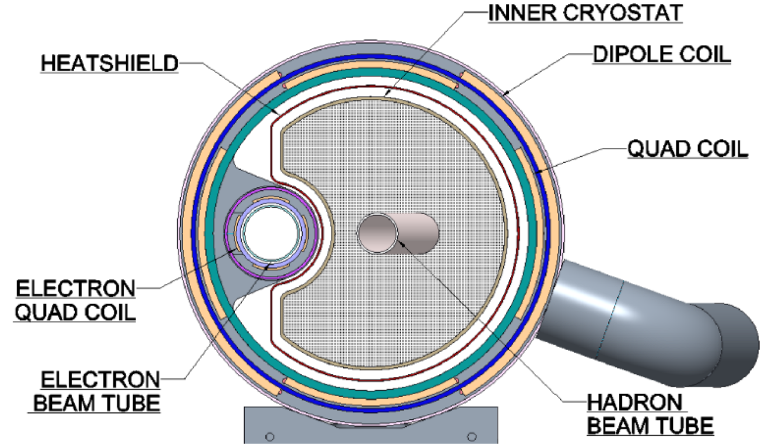
ECCE far-forward region

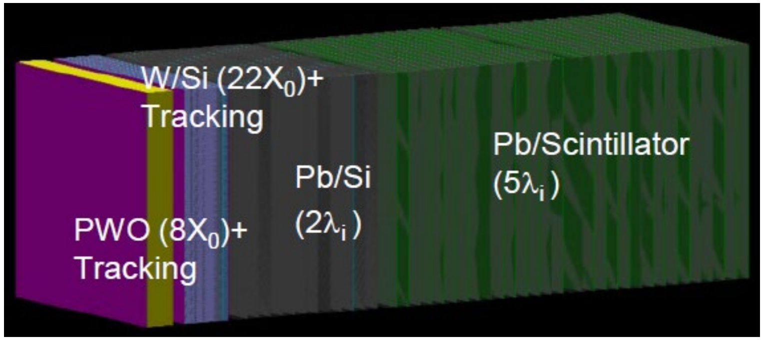


Detector	(x,z) Position [m]	Dimensions	θ [mrad]	Notes
ZDC	(-0.96, 37.5)	(60cm, 60cm, 1.62m)	$\theta < 5.5$	~4.0 mrad at $\phi = \pi$
Roman Pots (2 stations)	(-0.83, 26.0) (-0.92, 28.0)	(30cm, 10cm)	$0.0 < \theta < 5.5$	$10\,\sigma$ cut.
Off-Momentum Detector	(-1.62, 34.5), (-1.71, 36.5)	(50cm, 35cm)	$0.0 < \theta < 5.0$	$0.4 < x_L < 0.6$
B0 Trackers and Calorimeter	(x = -0.15, 5.8 < z < 7.0)	(32cm, 38m)	$6.0 < \theta < 22.5$	~20 mrad at ϕ=0

ECCE far-forward region

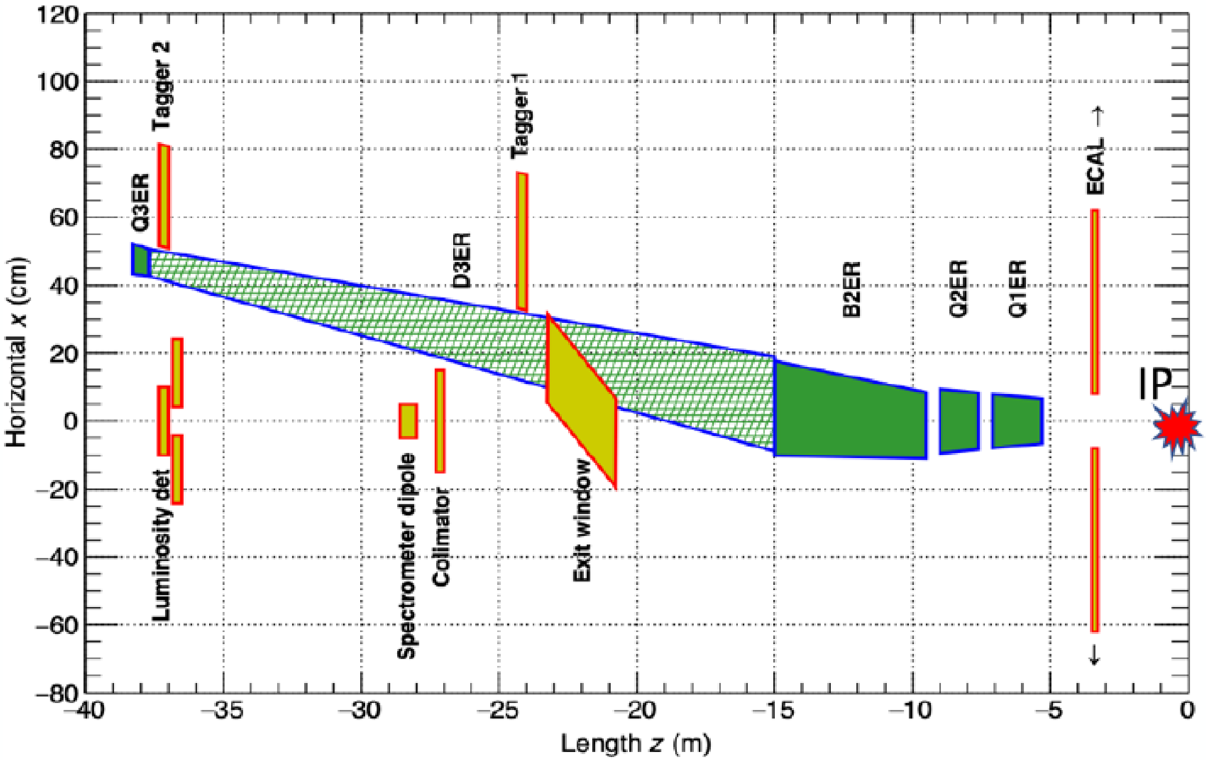
- B0 spectrometer
  - 4 AC-LGAD tracers with 30 cm spacing between each layer providing charged particle detection for $6 < \theta < 22.5$ mrad
- Roman pots
  - Two double-layer 25 x 12 cm^2 AC-LGAD stations
  - Located inside the beam line
  - 10 σ from the main beam
- Off-momentum detectors
  - AC-LGAD for fast timing
- Zero-Degree Calorimeter (ZDC)
  - W/Si EMCal
    - Position & p_T resolution
    - Radiation hardness
  - Pb/Si HCal





ECCE far-backward region

- Electron-going region
- Low Q^2 tagger
  - Double-layer AC-LGAD tracker
  - 40.5 cm x 40.5 cm at 24 m and 30 cm x 30 cm at 37 m from IP
- Luminosity monitor
  - AC-LGAD and PWO
  - Accuracy of the order of 1% or relative luminosity determination exceeding 10^{-4} precision



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)
- Physics at zero-degree
  - e+A breakup of the excited nucleus & collision geometry
  - e+d/^{3}He spectator tagging & short-range correlation
  - pion and kaon structure (and mass)
- EIC status
  - EIC Users Group
  - EIC-Japan
  - EPIC detector collaboration
  - The EIC project and EPIC experiment are progressing very well
  - EIC-Japan Group is developing steadily
  - Japan takes the lead in completing QCD research at EIC

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