Activities of the EIC-Japan Group

APCTP Workshop on
the Physics of Electron Ion Collider
November 2nd, 2022

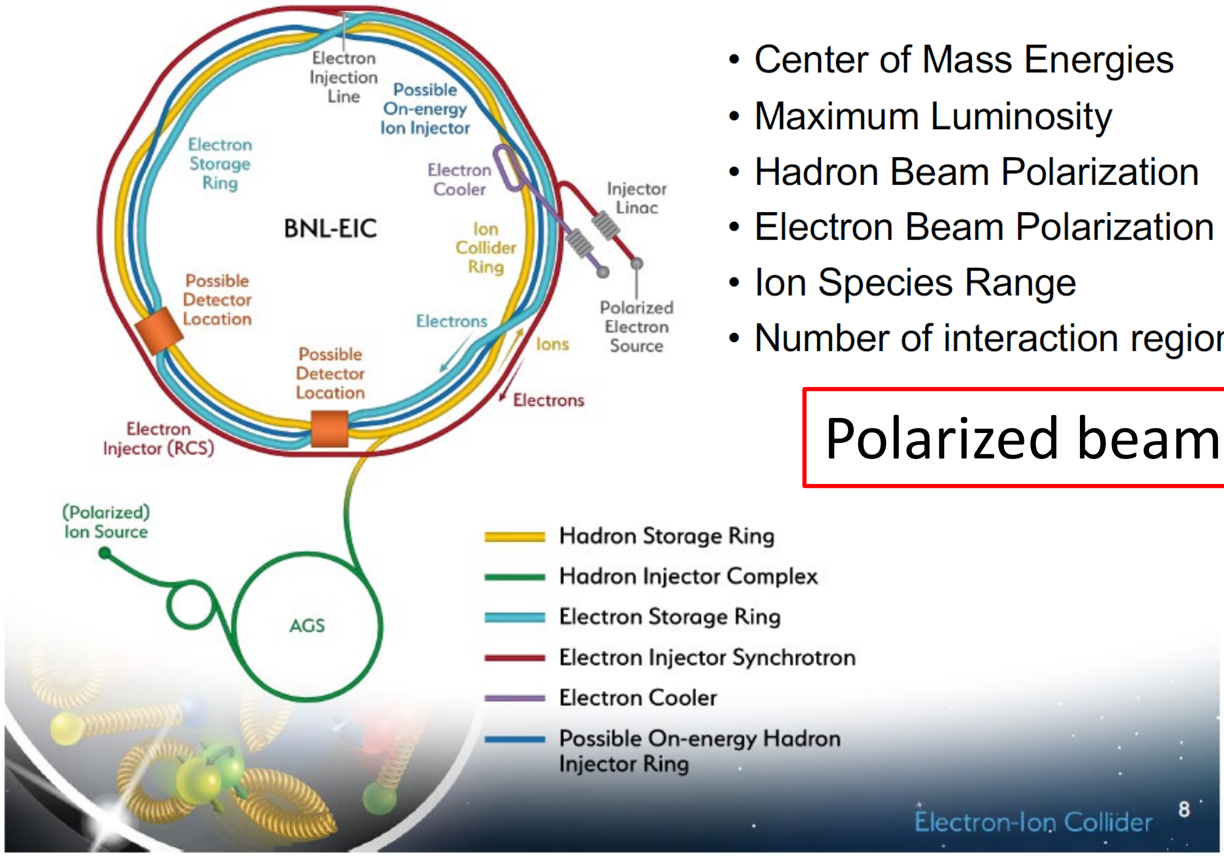
Yuji Goto (RIKEN)

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

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

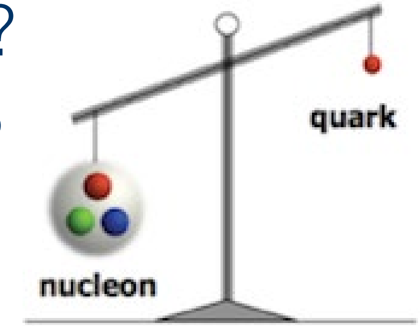


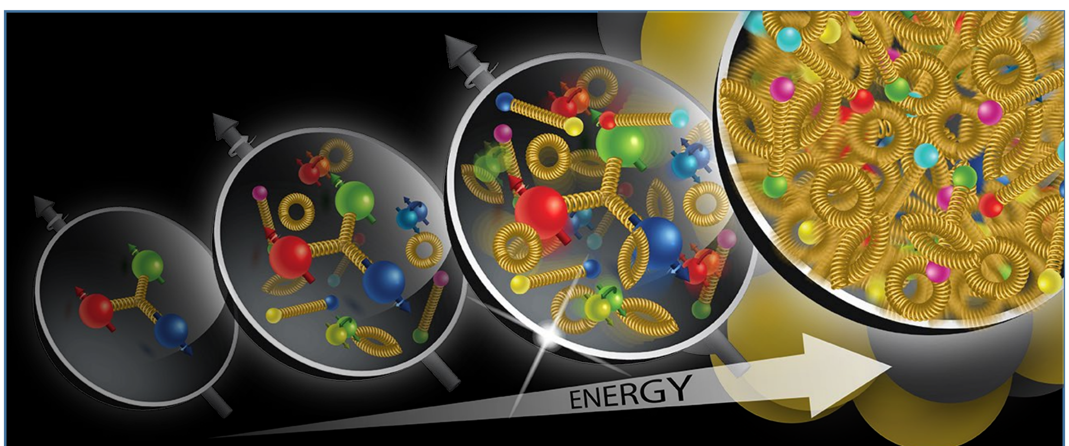
• Center of Mass Energies	20 GeV – 141 GeV
• Maximum Luminosity	10^{34} cm^{-2}s^{-1}
• Hadron Beam Polarization	80%
• Electron Beam Polarization	80%
• Ion Species Range	p to Uranium
• Number of interaction regions	up to two

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

Physics at EIC

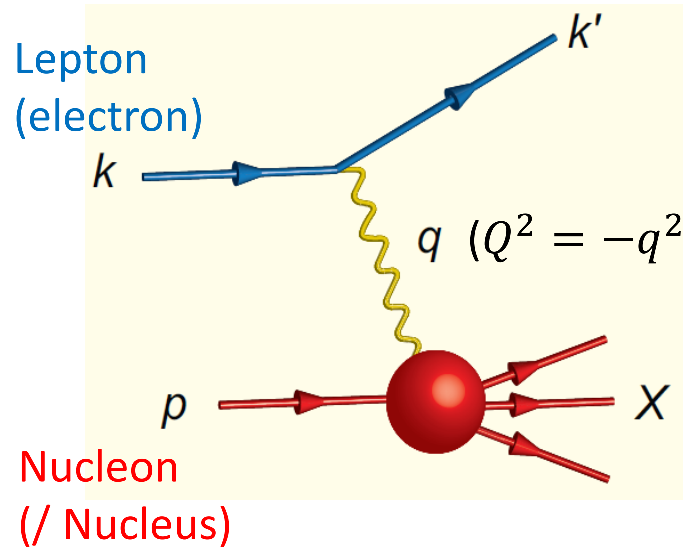
- How does the mass of the nucleon arise?
  - The Higgs mechanism accounts for only ~1% of the mass of the proton.
- How does the spin of the nucleon arise?
  - The spin of the quarks accounts for only one-third of the spin of the proton.
- What are the emergent properties of dense system of gluons?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

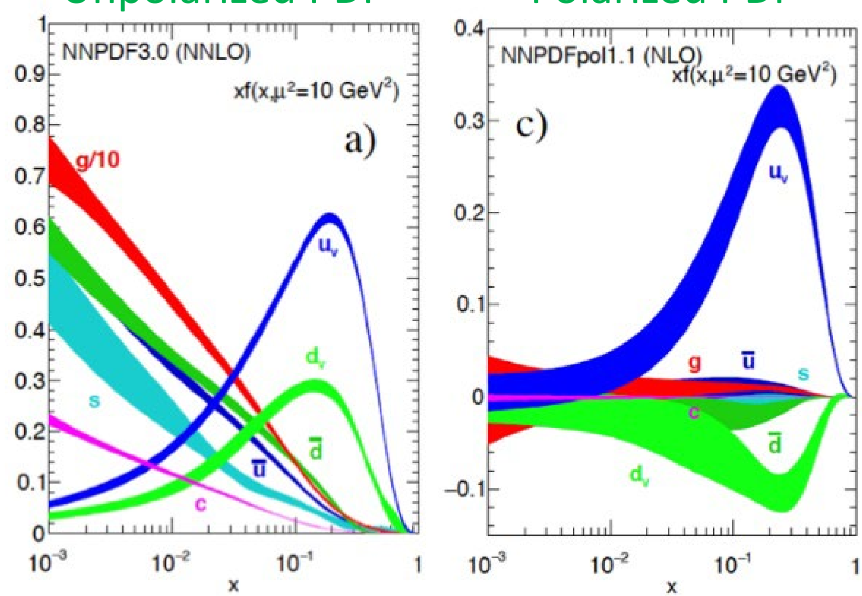




Quark-gluon structure

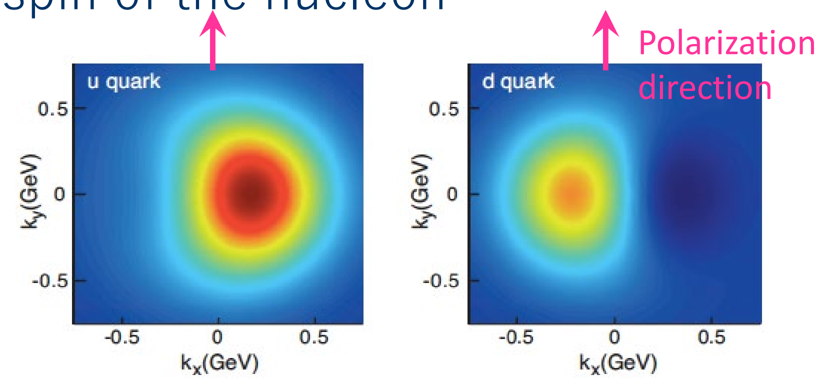
- Deep inelastic scattering (DIS) of lepton (electron)
  - Large Q^2 ($Q^2 = -q^2$) provides a hard scale to resolve quarks and gluons in the proton
- Parton distribution function (PDF) of quarks and gluons
  - 1D longitudinal motion of partons
  - x : momentum fraction of quarks and gluons
  - Significant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

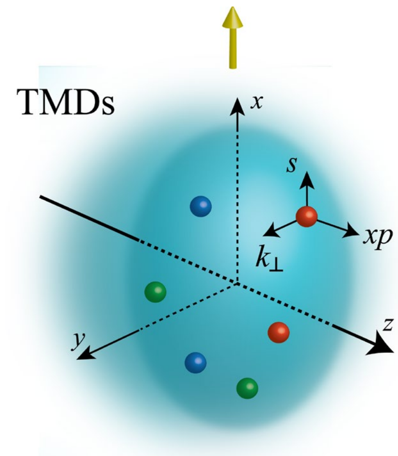




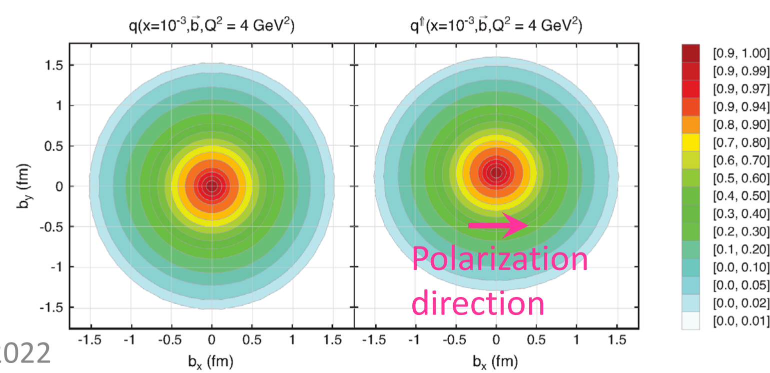
3D structure of the nucleon

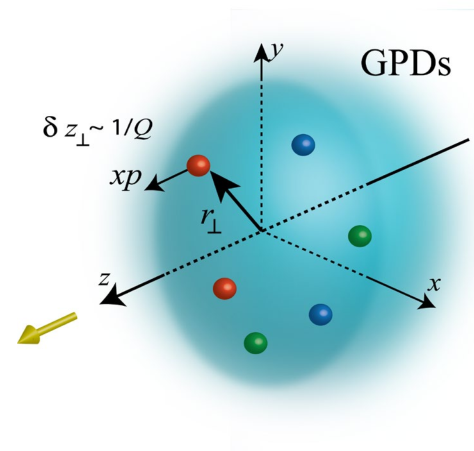
- Conclusive understanding of the nucleon spin
  - Orbital motion inside the nucleon and orbital angular momenta of quarks and gluons
- TMD (Transverse-Momentum Dependent) distribution function
  - Correlation between the (orbital) motion, spin of partons, and spin of the nucleon





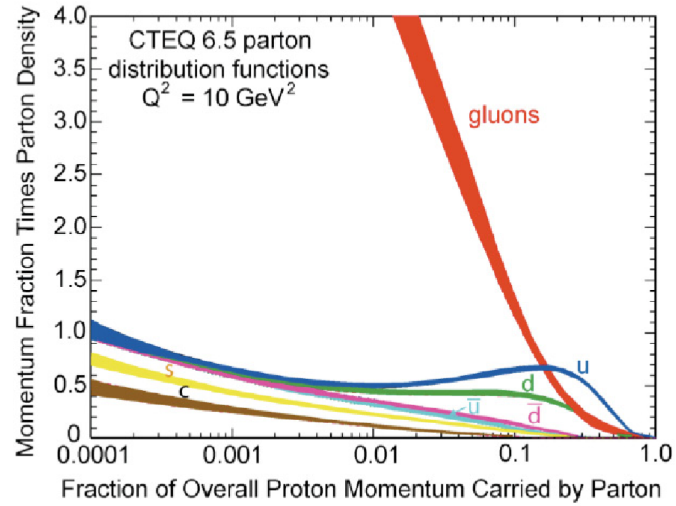
- GPD (Generalized Parton Distribution)
  - Spatial distribution or tomography

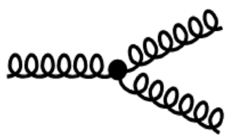


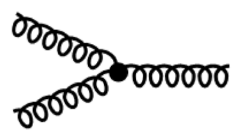


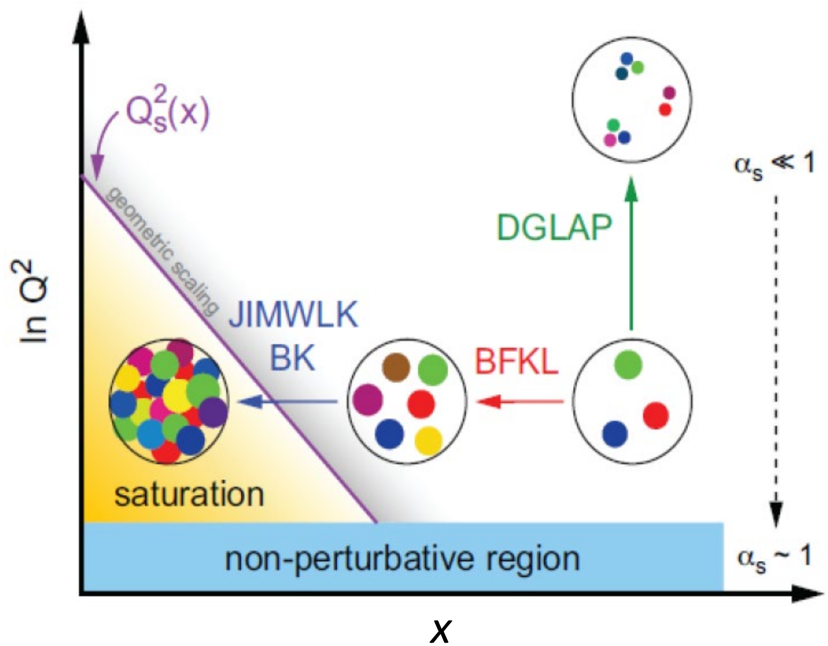
Gluon saturation in e+A collisions

- 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



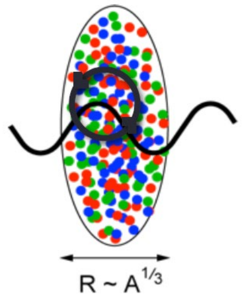






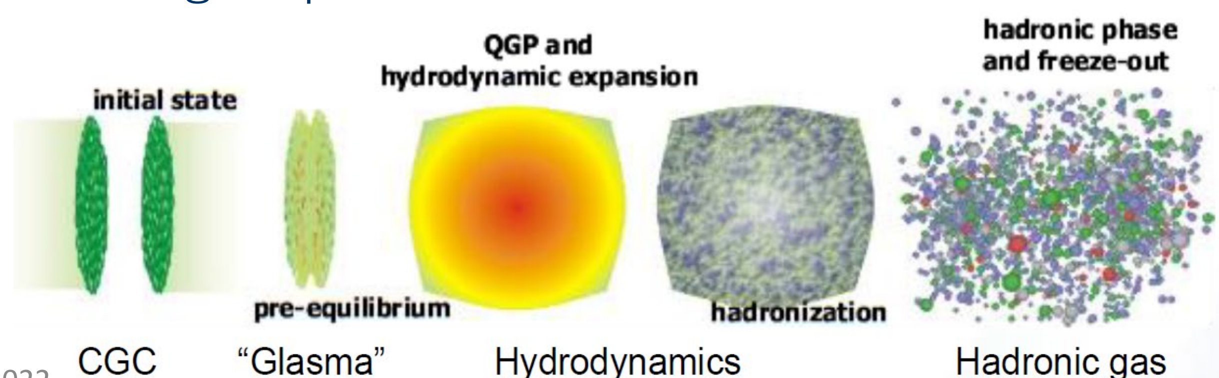
Gluon saturation in e+A collisions

- 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



$$(Q_s^A)^2 \approx c Q_0^2 \left[\frac{A}{x}\right]^{1/3}$$

- First observation of 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

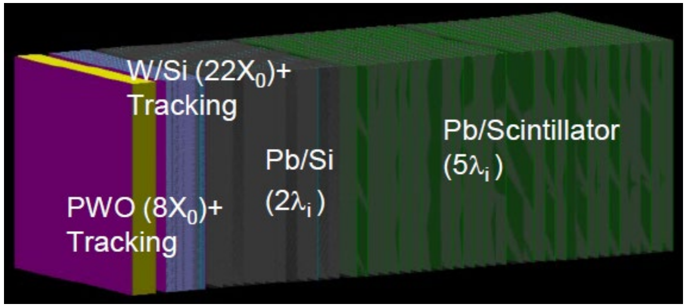


EIC-Japan activities

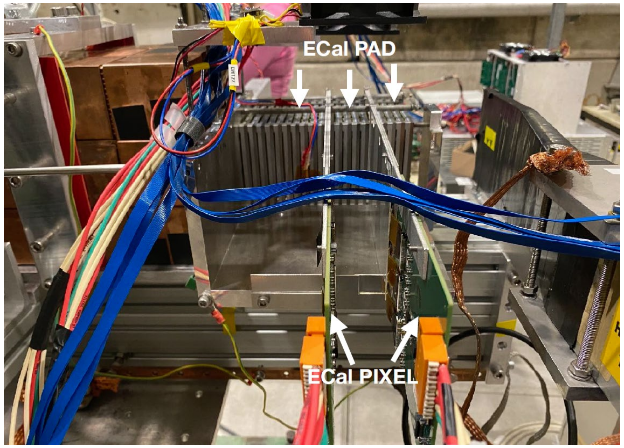
- 2015.4: EIC Letter of Interest from Asian countries
  - 20 participants from Japan: RIKEN, Yamagata, Tokyo Tech, Juntendo, KEK, Kyorin, Kyoto, Niigata, Tohoku, Tokyo Science
  - 7 from China, 3 from India, 4 from Korea
  - To support EIC for NSAC Long Range Plan 2015
- 2019: Science Council of Japan 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

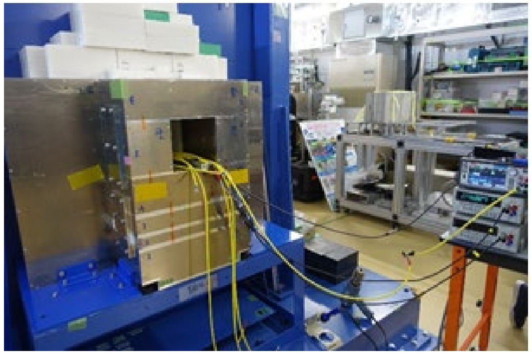
- ECCE/EPIC ZDC (Zero-Degree Calorimeter) design
  - Simulation
  - Performance evaluation
- ALICE-FoCal-E technology: Tungsten/Silicon
  - Test beam studies ongoing
- Radiation tolerance test by neutron irradiation
- RIKEN, Tsukuba, Tsukuba Tech, Kobe, Shinshu, Yamagata, JAEA, Nihon, Kyushu, KEK, Nagoya,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



ECCE/EPIC ZDC



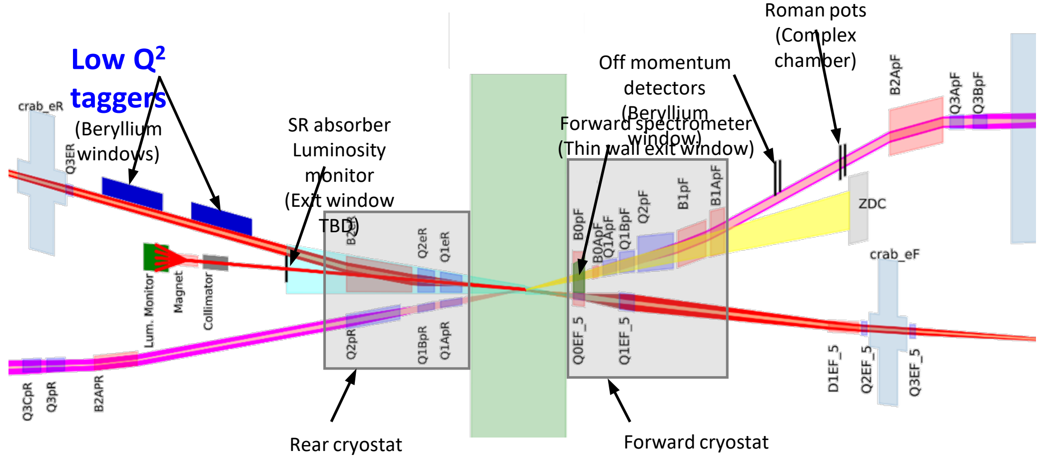
ALICE FoCal-E R&D



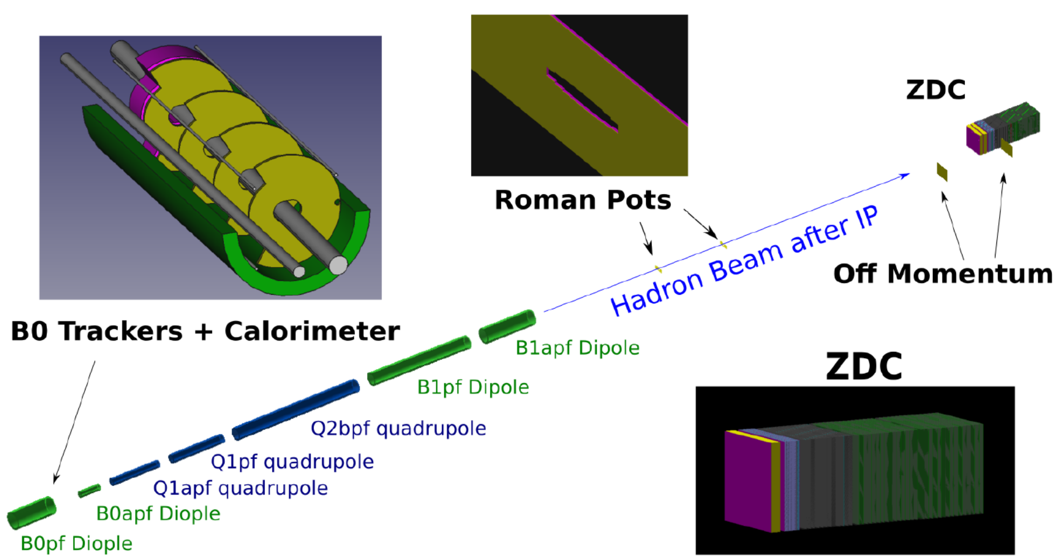
Neutron irradiation at RIKEN RANS

EIC Interaction Region (IP6)

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



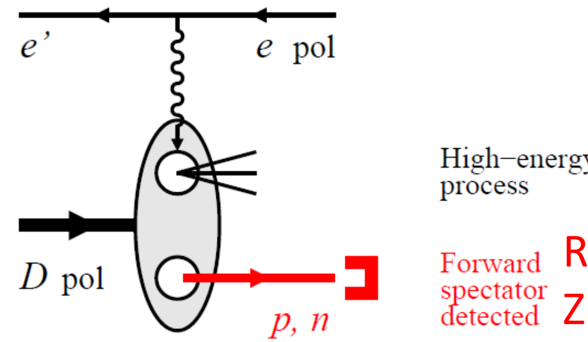
- EIC far-forward region



Far-forward physics at EIC

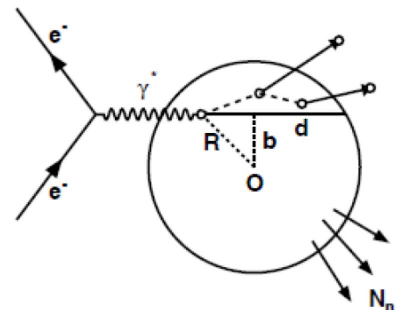
- Spectator tagging in e+d/^{3}He collisions
  - Neutron structure
    - Neutron spin structure, S & D waves
- e+A collisions at zero degree
  - Breakup determination of the excited nucleus
    - Veto with evaporated neutrons and photons from de-excitation
  - Geometry tagging in e+A collisions
    - 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

e+D



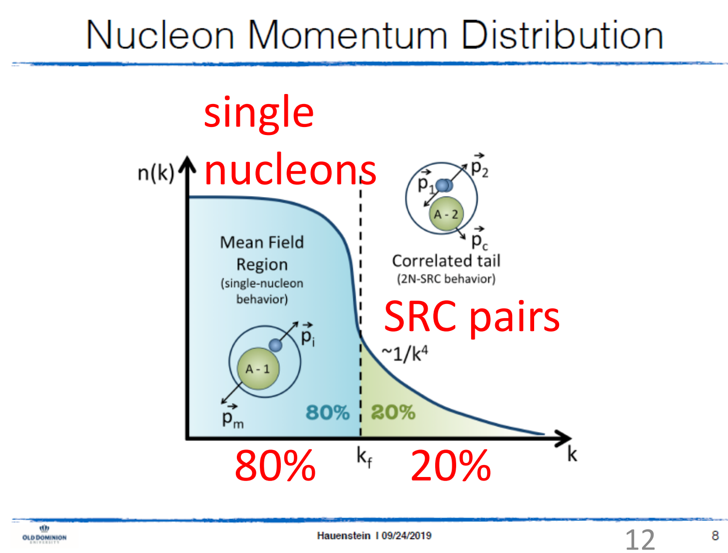
Roman pot
ZDC

e+A



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

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



Far-forward physics at EIC

- Mass of the proton, pion, kaon
  - 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
  - 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

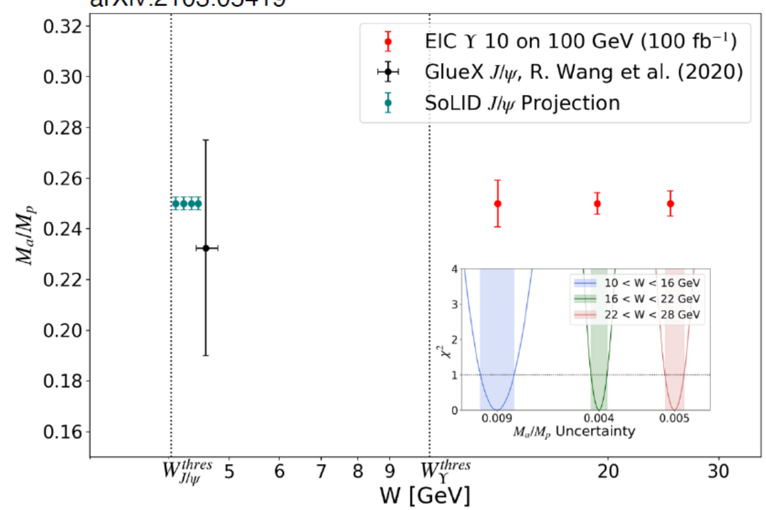
Relativistic Motion | *Chiral Symmetry Breaking* | *Quantum Fluctuations*

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

X. Ji, PRL 74 1071 (1995)

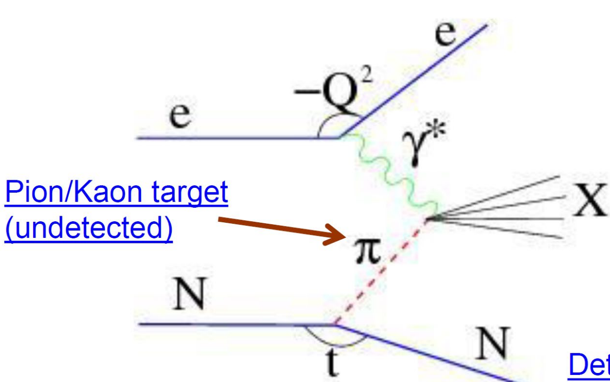
Quark Energy | **Gluon Energy** | **Quark Mass** | **Trace Anomaly**

arXiv:2103.05419



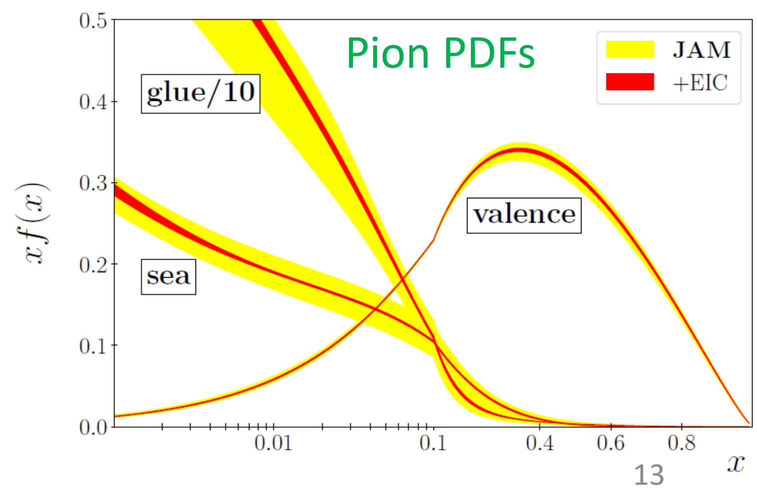
Sullivan process

Detect scattered electron



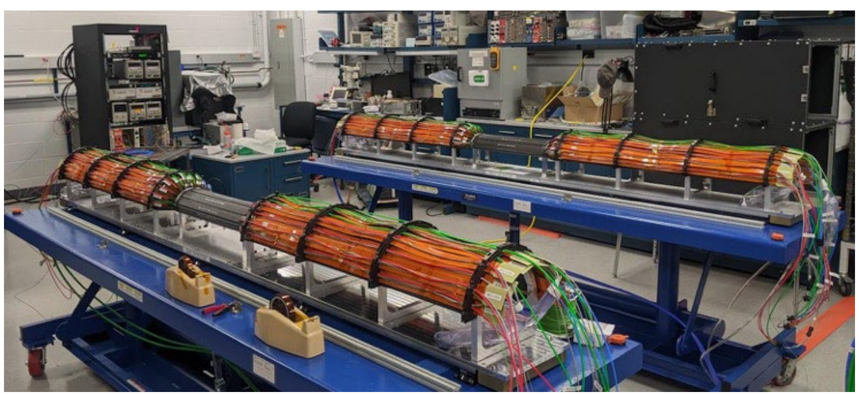
DIS event – reconstruct x, Q^2, W^2, also M_X (W_π) of undetected recoiling hadronic system

Detect "tagged" neutron/lambda

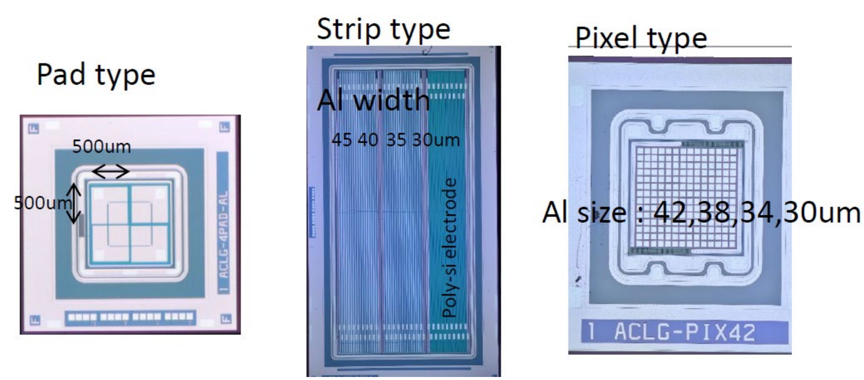


Interest in contributing to (AC-)LGAD Barrel

- 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

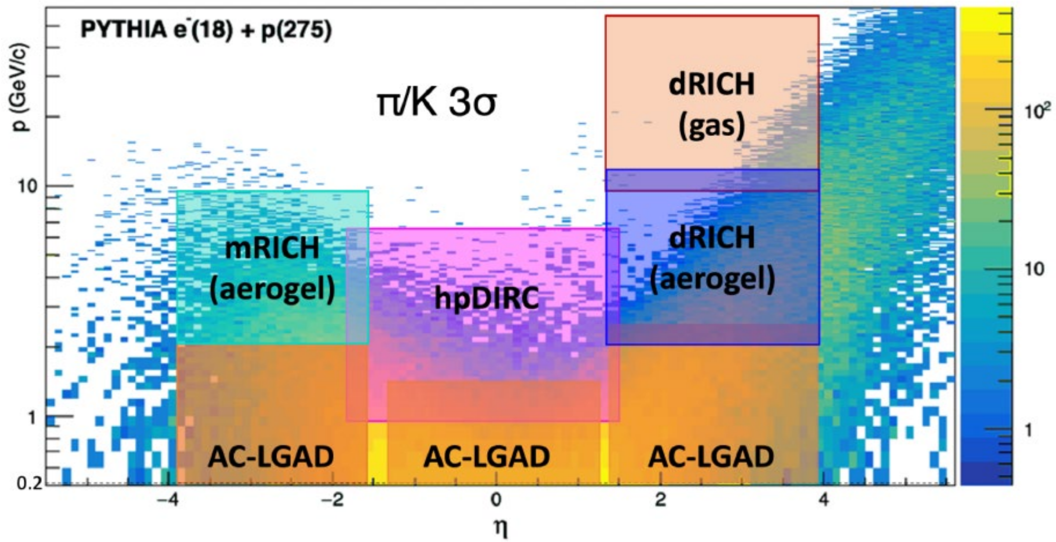


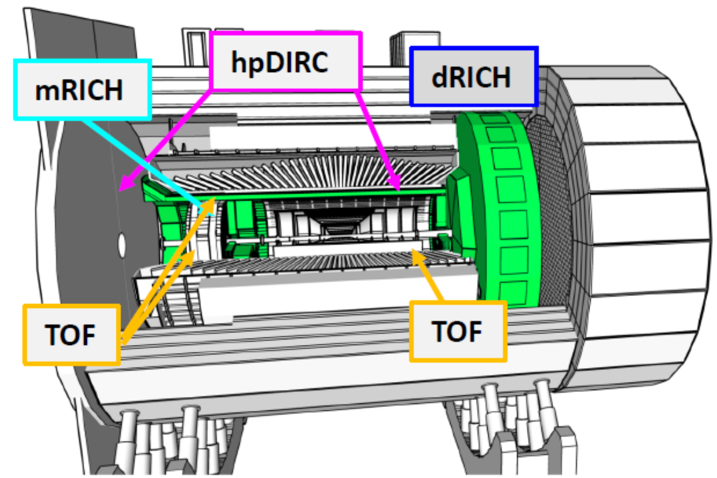
sPHENIX INTT construction



HPK LGAD development

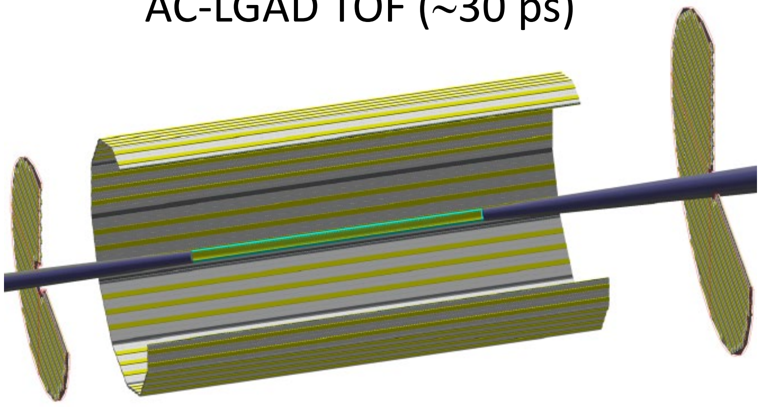
Charged particle ID





- 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

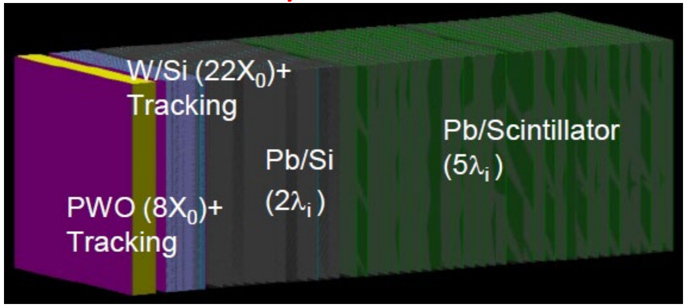
AC-LGAD TOF (~30 ps)



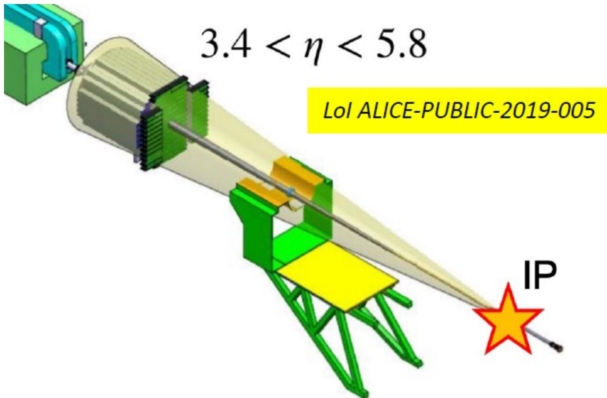
Collaboration opportunities

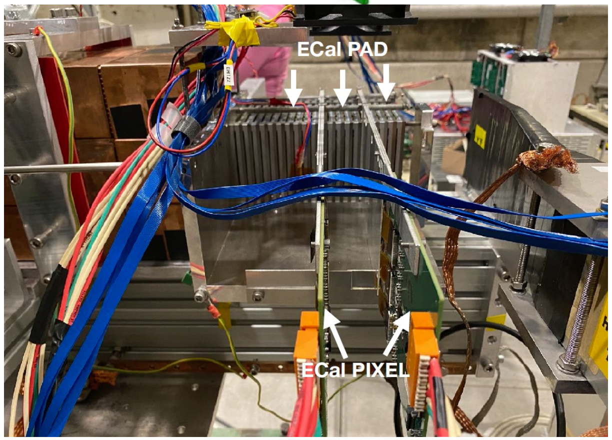
- EPIC ZDC
  - Soft photon detection
    - Crystal calorimeter (PWO, LYSO, ⋯) prototype
    - Readout device (APD, PMT, ⋯)
  - EM+hadron calorimeter
    - ALICE-FoCal-E technology
      - Pad detector led by Univ. of Tsukuba group and Indian group
      - Pixel detector led by European group
    - Test 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



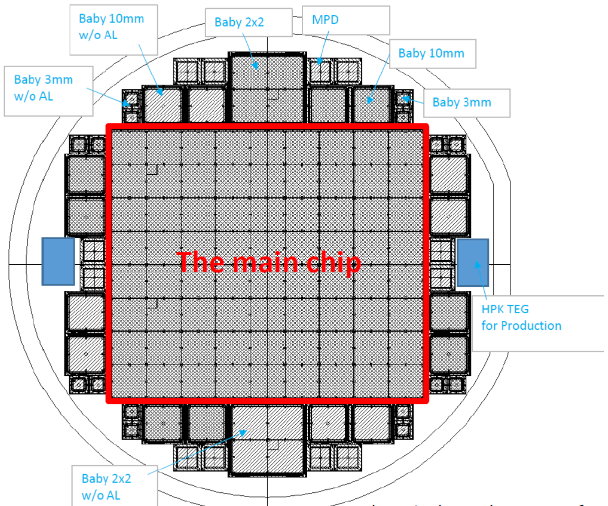
ALICE FoCal-E R&D



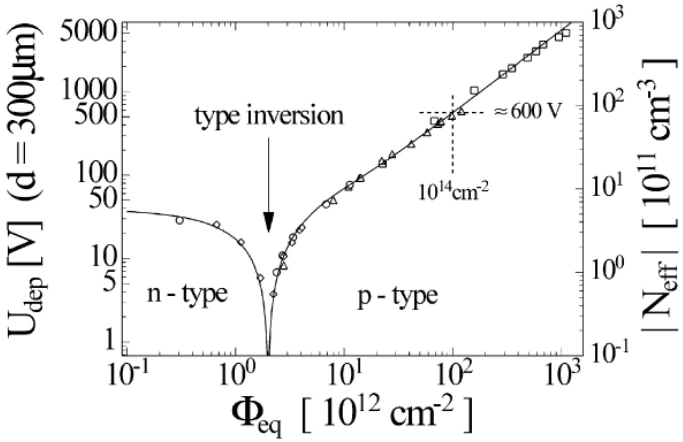


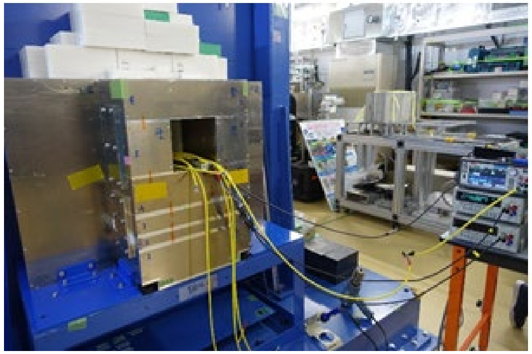
EPIC ZDC

- 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



The 6-inch p-substrate wafer



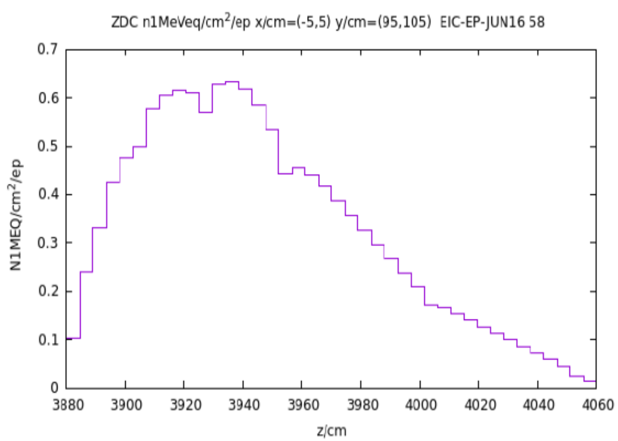


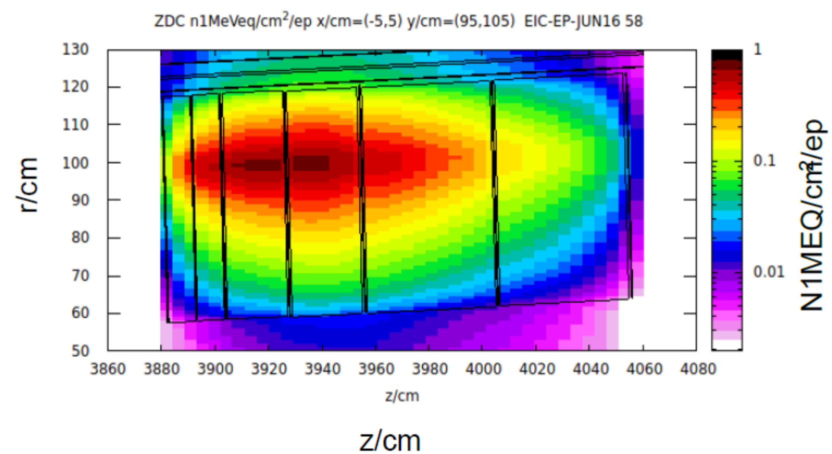
Neutron irradiation at RIKEN RANS

EPIC ZDC

- 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 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.

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