Overview of EIC and Calorimeter

KPS Fall Meeting

"Future Collider Projects"

November 5th, 2020

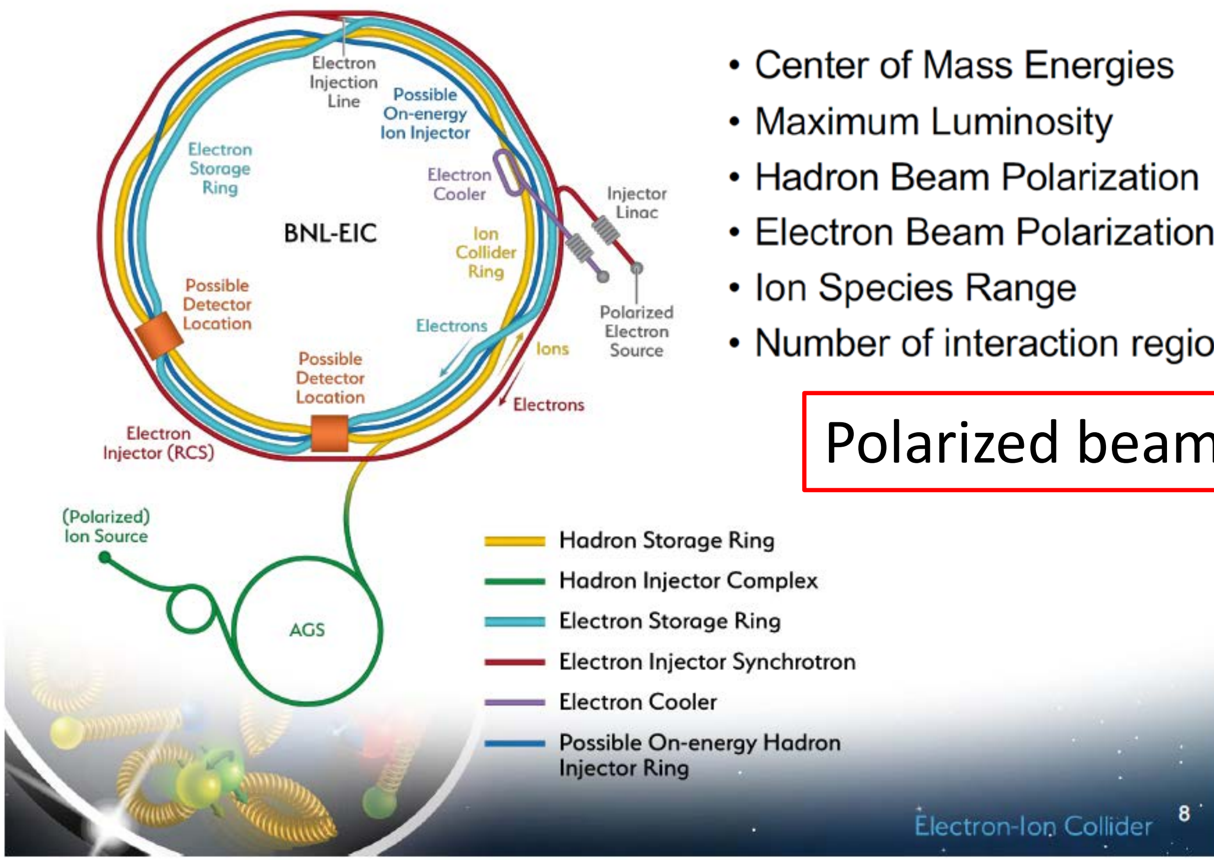
Yuji Goto (RIKEN)

Contents of this talk

- Overview of EIC
    - U.S. EIC (Electron-Ion Collider)
    - Physics
    - EIC status
- Calorimeter
    - (Not overview)
    - Forward and very forward calorimeters at EIC
        - forward and very forward physics at EIC

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

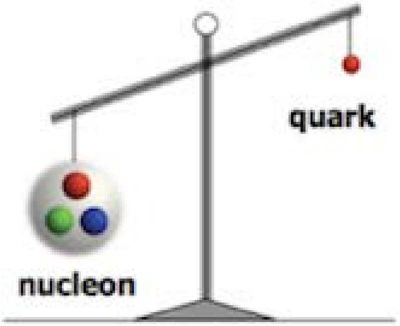


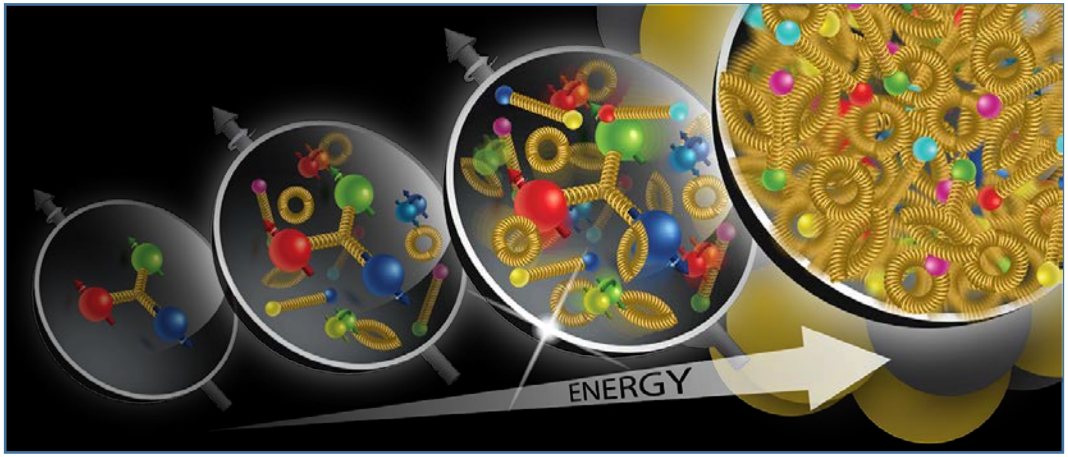
- Center of Mass Energies — 20 GeV – 141 GeV
- Maximum Luminosity — 10^{34} cm^{-2}s^{-1}
- Hadron Beam Polarization — 80%
- Electron Beam Polarization — 80%
- Ion Species Range — p to Uranium
- Number of interaction regions — up to two

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

Physics at EIC

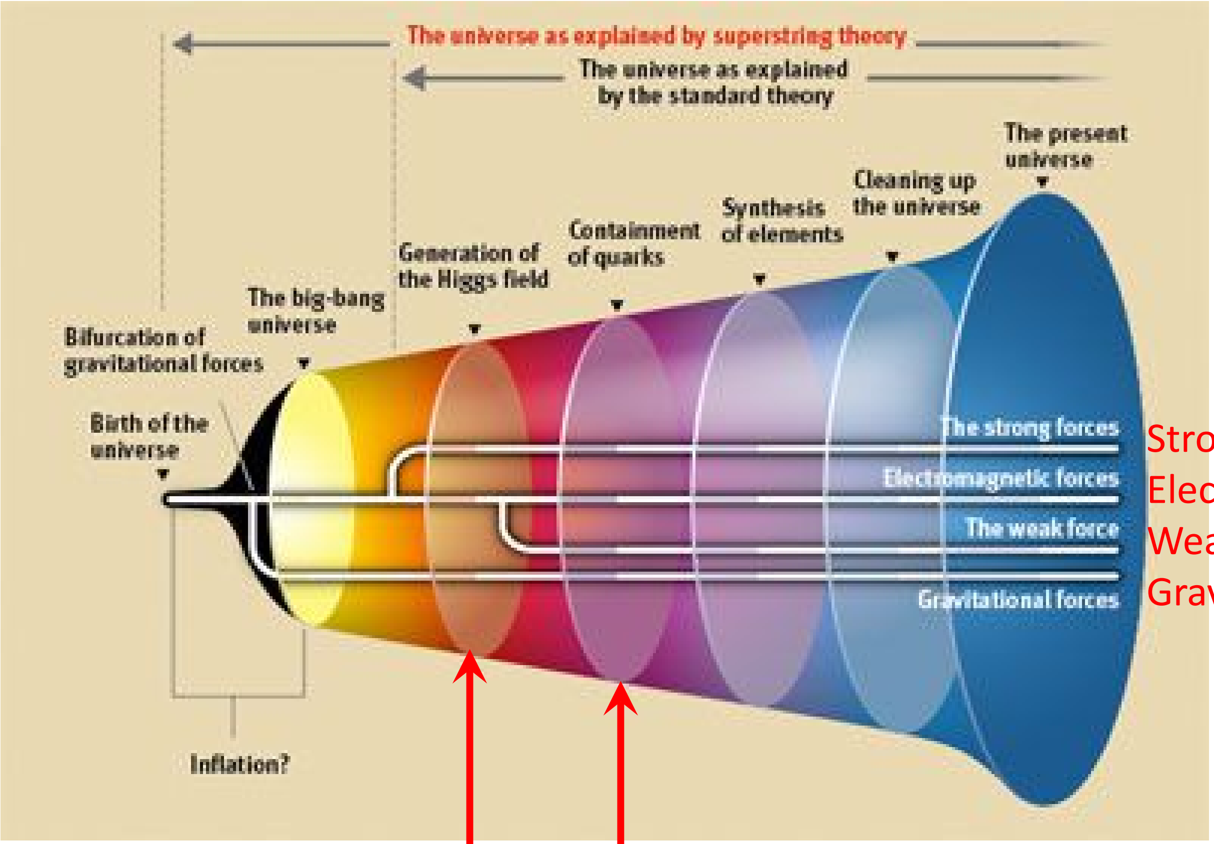
- How does the mass of the nucleon arise?
  - The Higgs mechanism accounts for only ~1% of the mass of the proton.
- How does the spin of the nucleon arise?
  - The spin of the quarks accounts for only one-third of the spin of the proton.
- What are the emergent properties of dense system of gluons?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





Mass

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



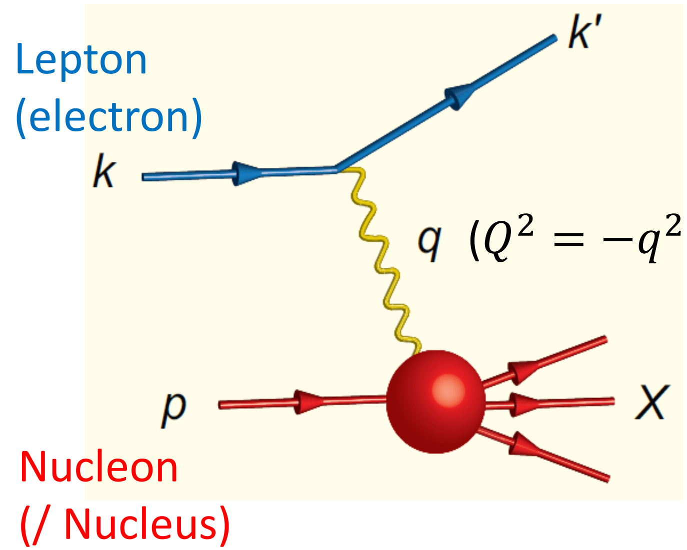
Strong force
Electromagnetic force
Weak force
Gravitational force

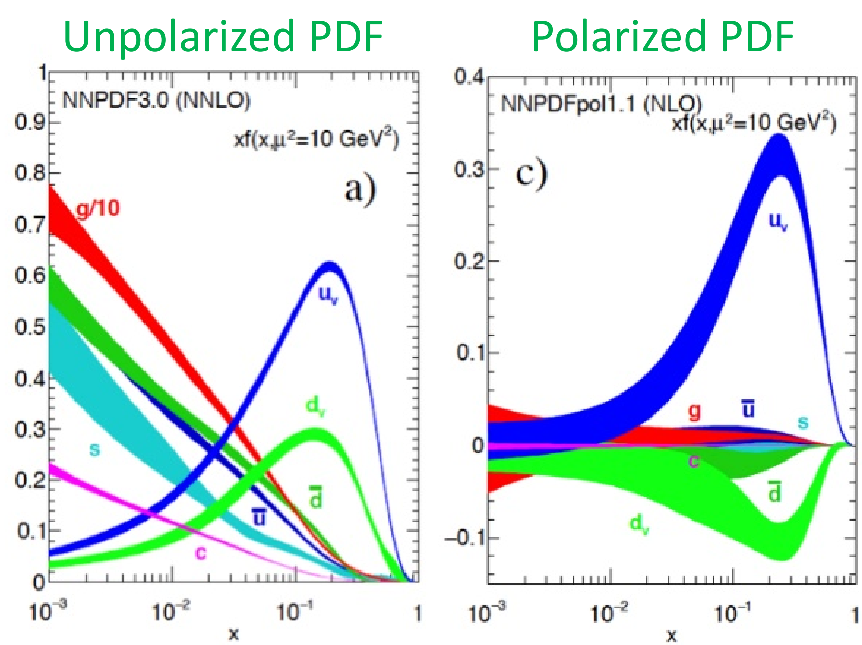
Symmetry breaking of the Higgs field

Confinement of quarks
Chiral symmetry breaking

Quark-gluon structure

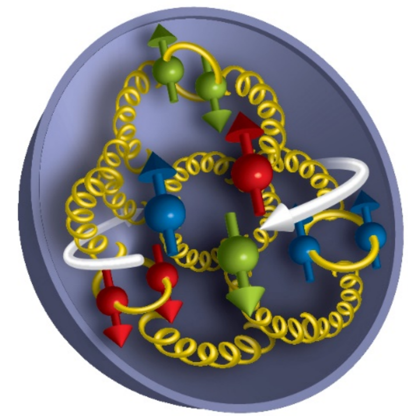
- Deep inelastic scattering (DIS) of lepton (electron)
  - Large Q^2 ($Q^2 = -q^2$) provides a hard scale to resolve quarks and gluons in the proton
- Parton distribution function (PDF) of quarks and gluons
  - 1D longitudinal motion of partons
  - x : momentum fraction of quarks and gluons
  - Significant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





Spin

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

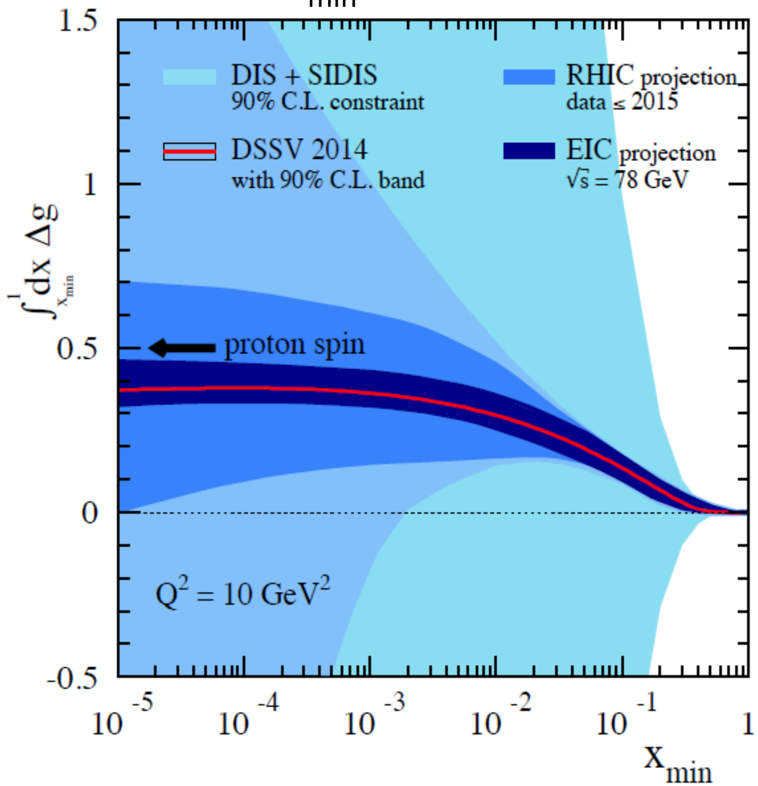


$$\frac{1}{2} = \left[\frac{1}{2}\Delta\Sigma + L_Q\right] + [\Delta g + L_G]$$

$\Delta\Sigma/2$ = 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

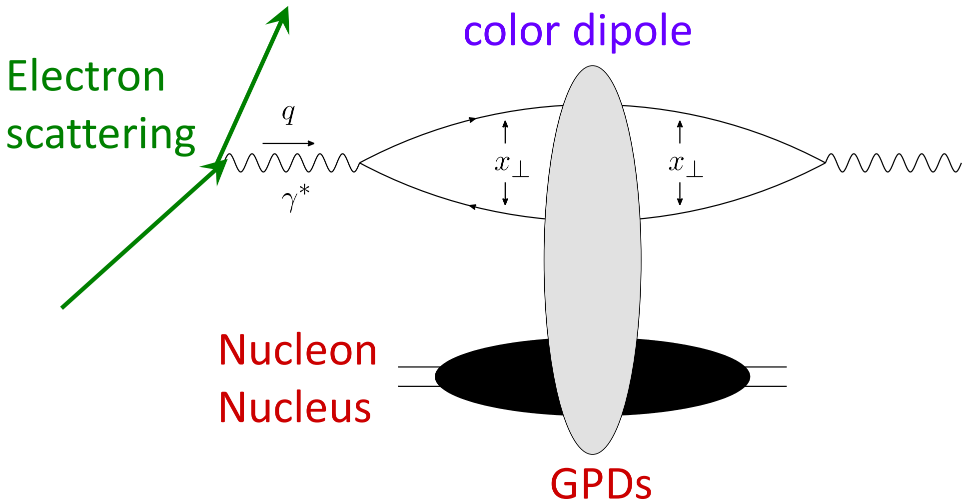
Integrated gluon polarization down to x_{min}



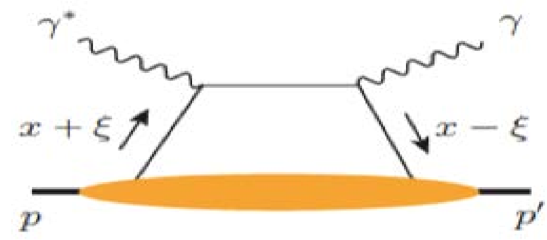
- Gluon polarization measurement with polarized DIS at EIC
  - Small Bjorken-x region with QCD evolution (DGLAP equation)

Tomography of the nucleon / nucleus

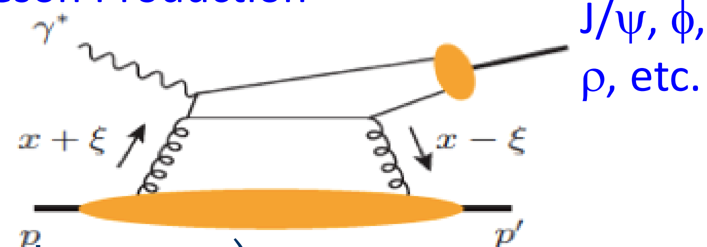
- EIC = color dipole microscope
  - Exclusive process and diffractive process
  - 3D distribution: transverse spatial distribution



DVCS (Deeply Virtual Compton Scattering)



Meson Production

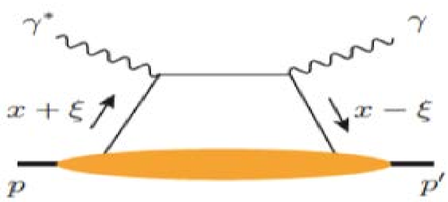


- GPD (Generalized Parton Distribution)
  - Spatial imaging of gluons and quarks = tomography
    - HERA: 1st generation
    - EIC: 2nd generation (high luminosity, heavy ion, polarization)
  - Orbital angular momentum
    - Ji's sum rule
    - Origin of the nucleon spin

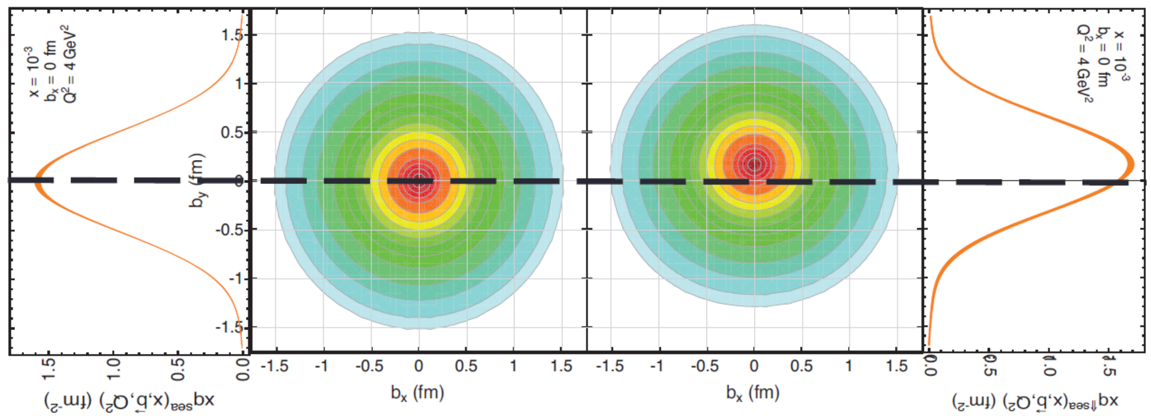
$$J_q^z = \frac{1}{2}\sum_q \Delta q + \sum_q L_q = \frac{1}{2}\left(\int_{-1}^{1} x dx (H^q + E^q)\right)_{t\to 0}$$

Tomography of the nucleon / nucleus

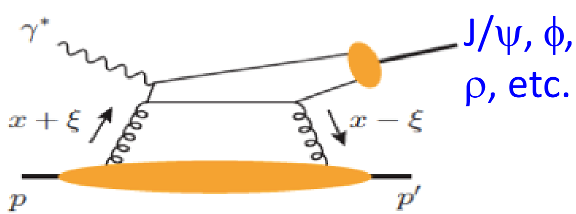
- DVCS
  - Deeply virtual Compton scattering



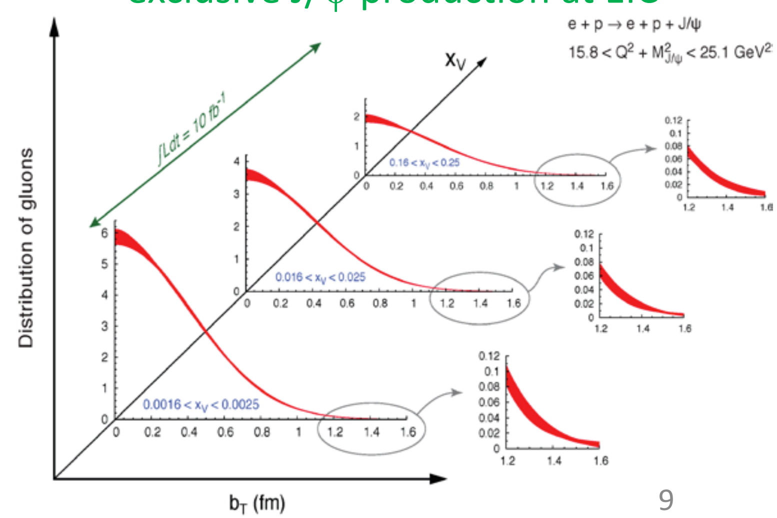
Spatial distribution of sea quarks at EIC 100 fb^{-1} and corresponding density of partons in the transverse plane



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

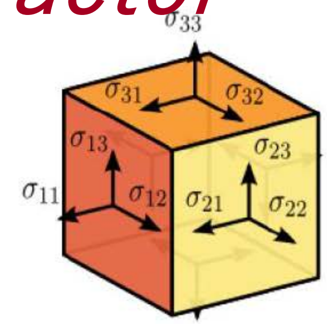


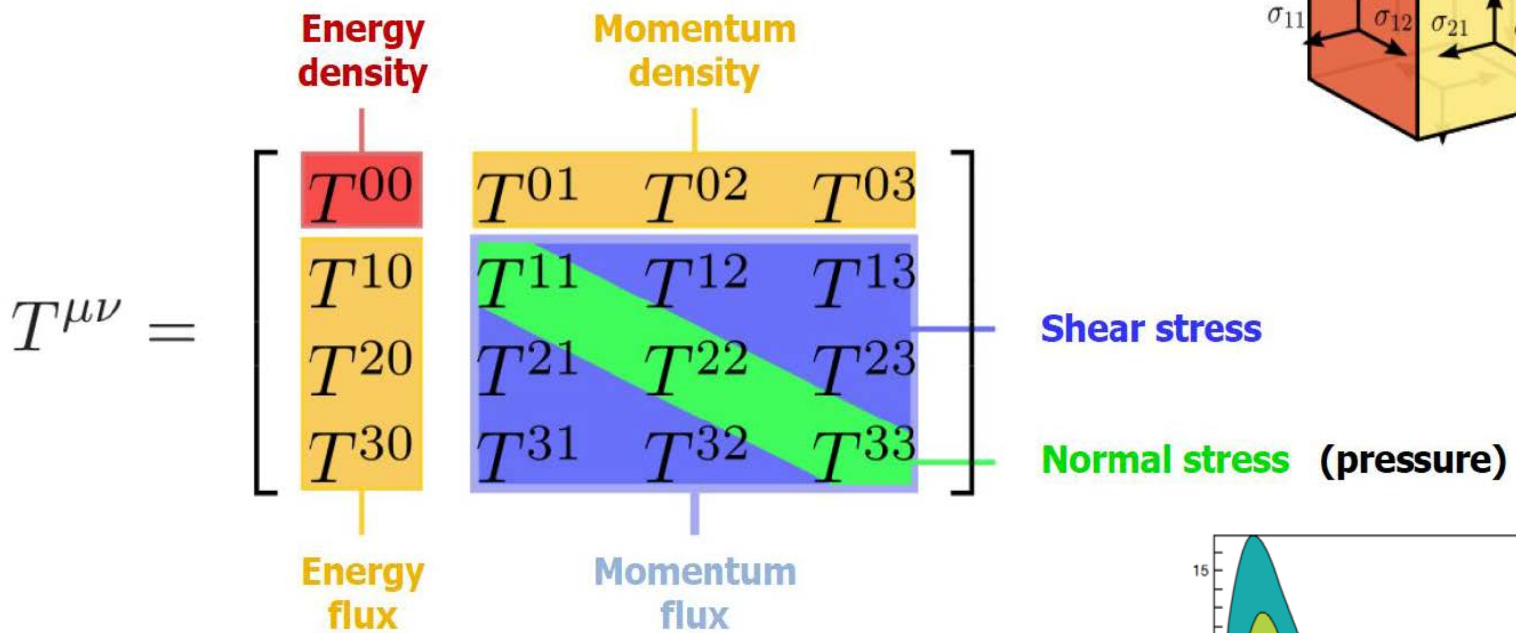
x-dependence of spatial distribution of gluons to be obtained by the exclusive J/ψ production at EIC



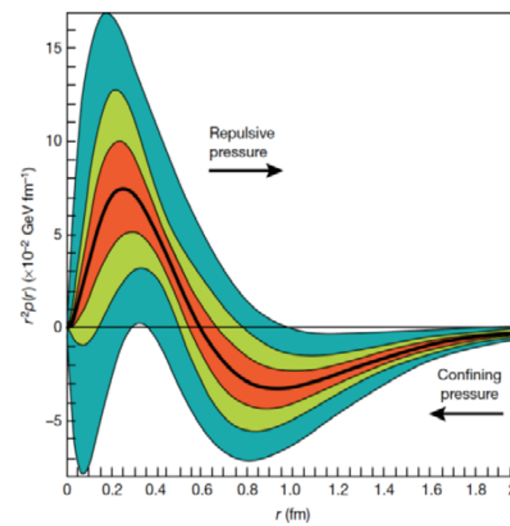
Generalization of the form factor

- Energy Momentum Tensor (EMT)





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



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

Mass of the nucleon

- Sum rule for the nucleon mass

Relativistic Motion

Chiral Symmetry Breaking

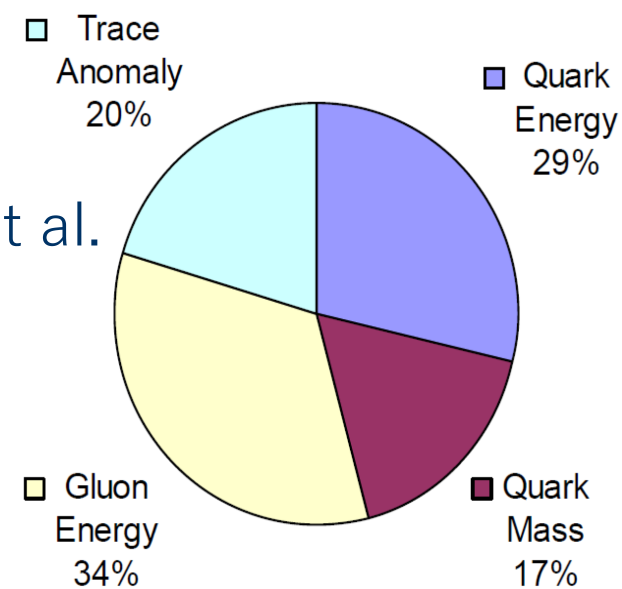
Quantum Fluctuations

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

X. Ji, PRL 74 1071 (1995)

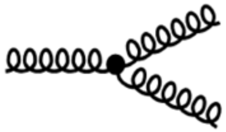
Quark Energy | Gluon Energy | Quark Mass | Trace Anomaly

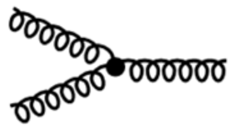
  - How to determine the different contribution not yet reached
- Lattice QCD calculation
  - arXiv:1710.09011, update by K.-F. Liu et al.
- Precision comparison of experiment and theory in the future
  - Mass, spin, pressure, radius,⋯

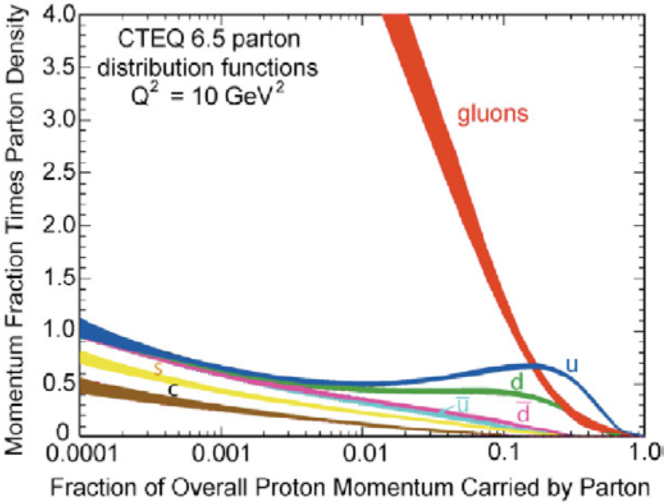


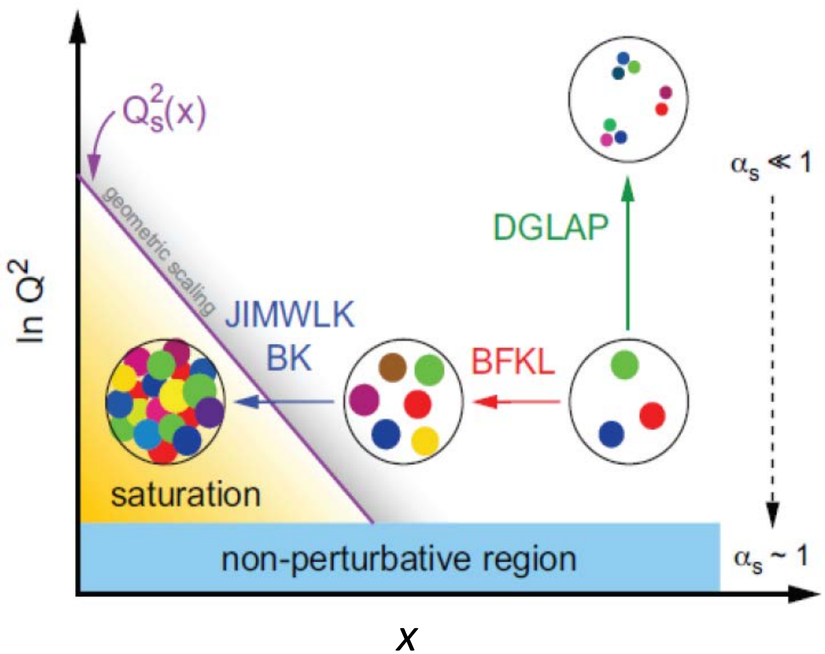
Gluon saturation in e+A collisions

- Gluon emission
  - Divergence at small x
- Gluon recombination
  - Restriction of divergence
- Gluon saturation in balanced
  - Based on classical idea of the saturation
- First observation of a quantum collective gluonic system
  - Precision comparison of experiment and Chiral Glass Condensate (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





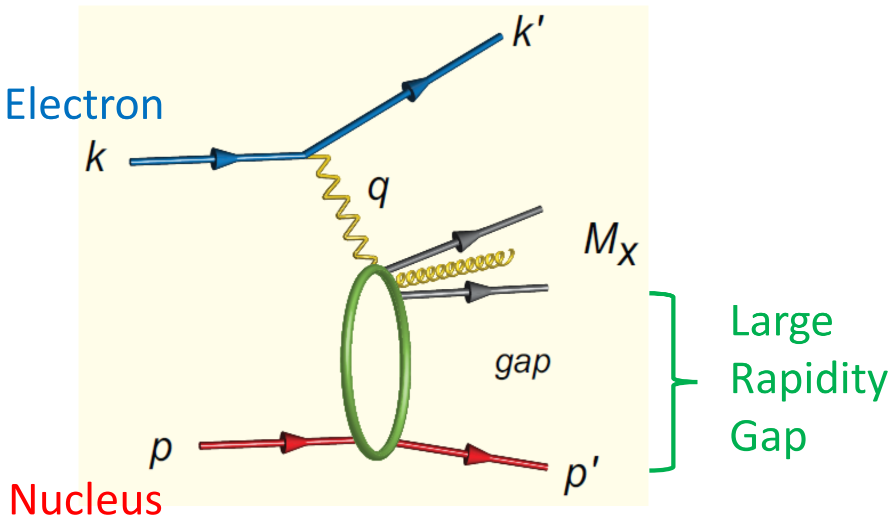


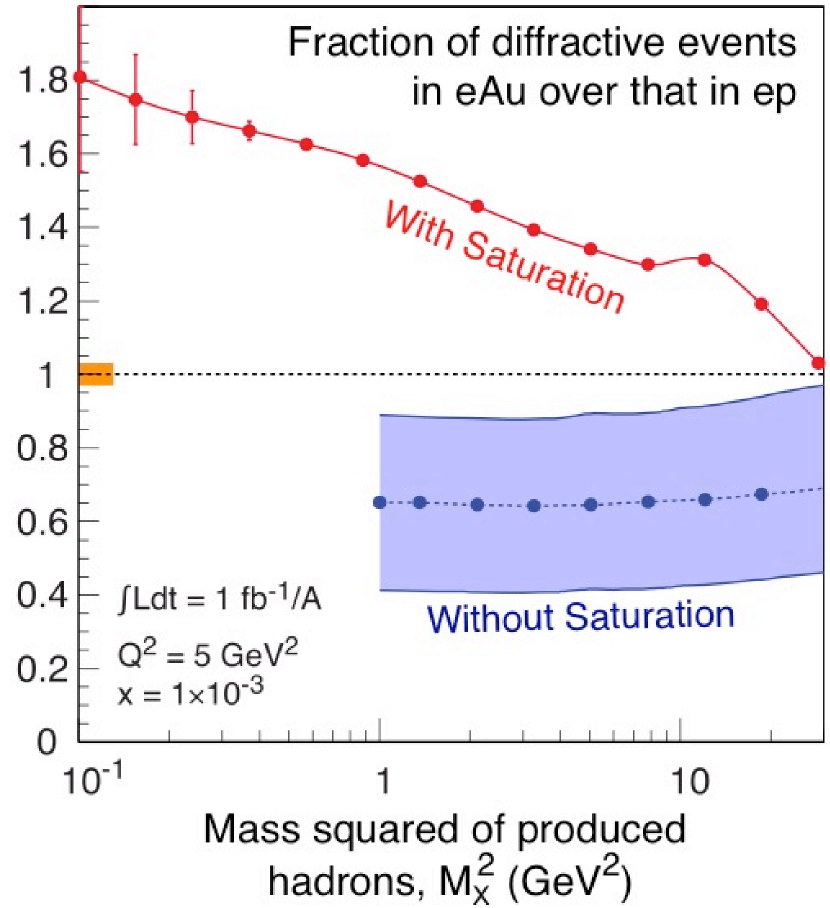


Gluon saturation in e+A collisions

- 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

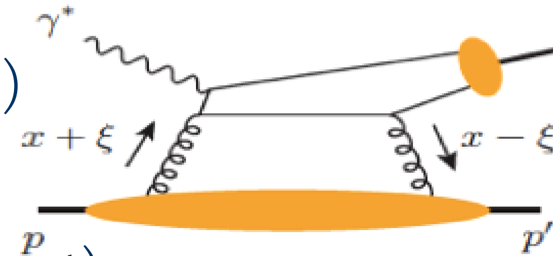
$$\sigma_{\text{diff}} \propto [g(x, Q^2)]^2$$

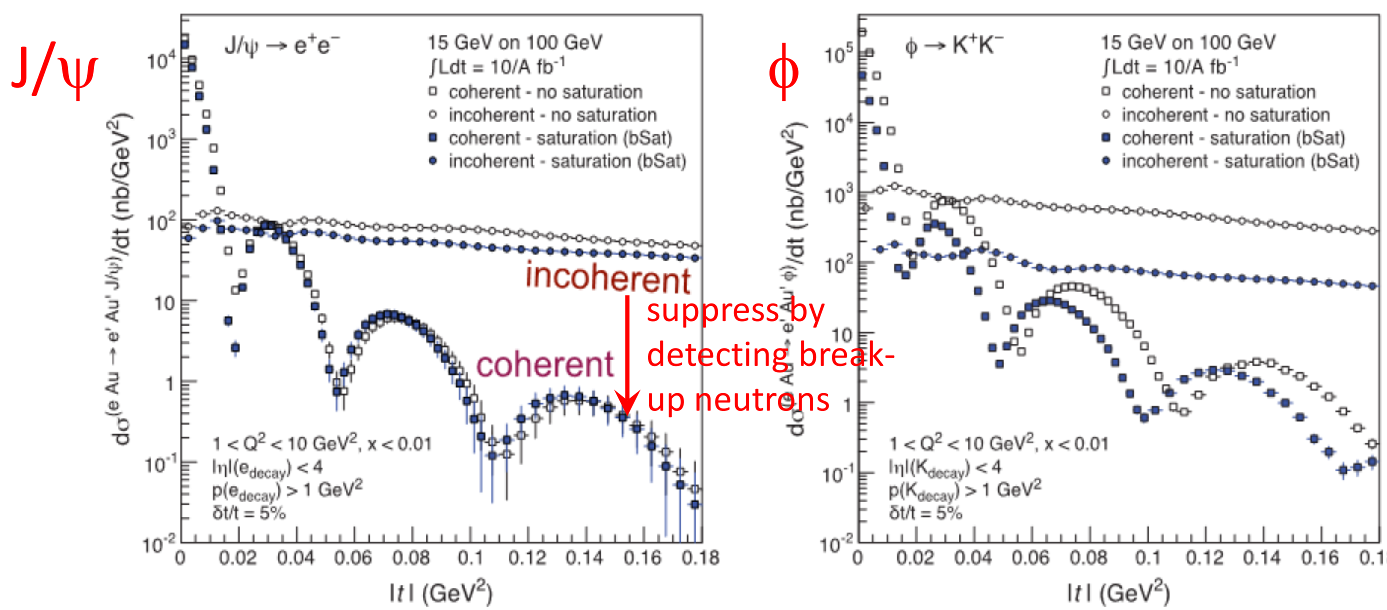




Gluon saturation at extreme density

- 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





EIC status

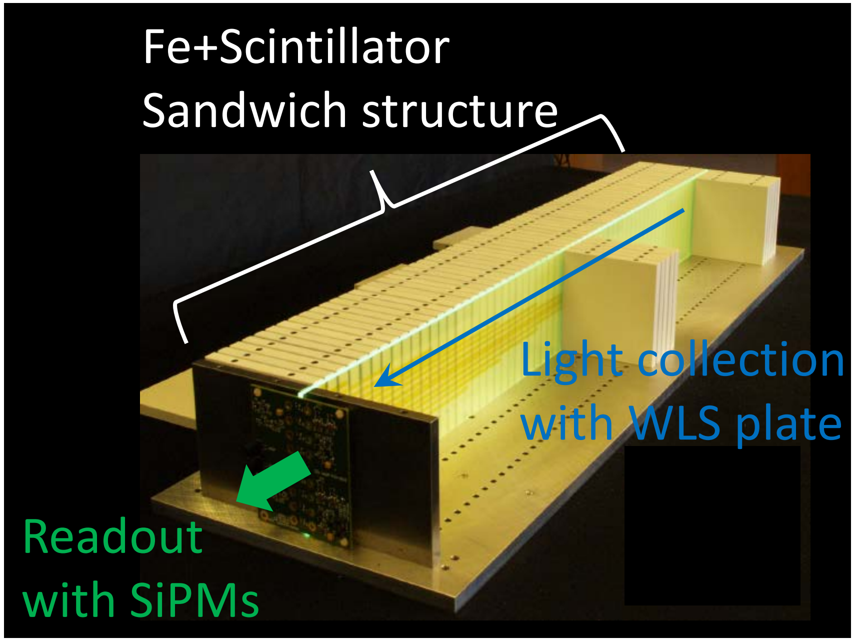
- 2019.12: CD-0 (approve mission need)
- 2020.1: Site selection at BNL
- 2020: EICUG (EIC User Group) Yellow Report (physics/detector) towards CD-1
- 2020.11: Expression of Interest (EOI) for potential cooperation on the EIC experimental program
- 2nd detector and IR planning
- 2021: Detector proposal
- CD-3 (start of construction) 2023?

Forward physics

- A key item in high-x region
- DIS kinematics reconstructed from the hadronic final state
  - Takes a crucial role especially in the charged current process ($e+q \rightarrow \nu+q'$)
  - Significantly improves the resolution in the neutral current process
- Forward hadron calorimeter provide the hermeticity to identify a large rapidity gap of diffractive events
  - Or positively tag the gluon radiation for measuring the energy flow

Forward hadron calorimeter R&D

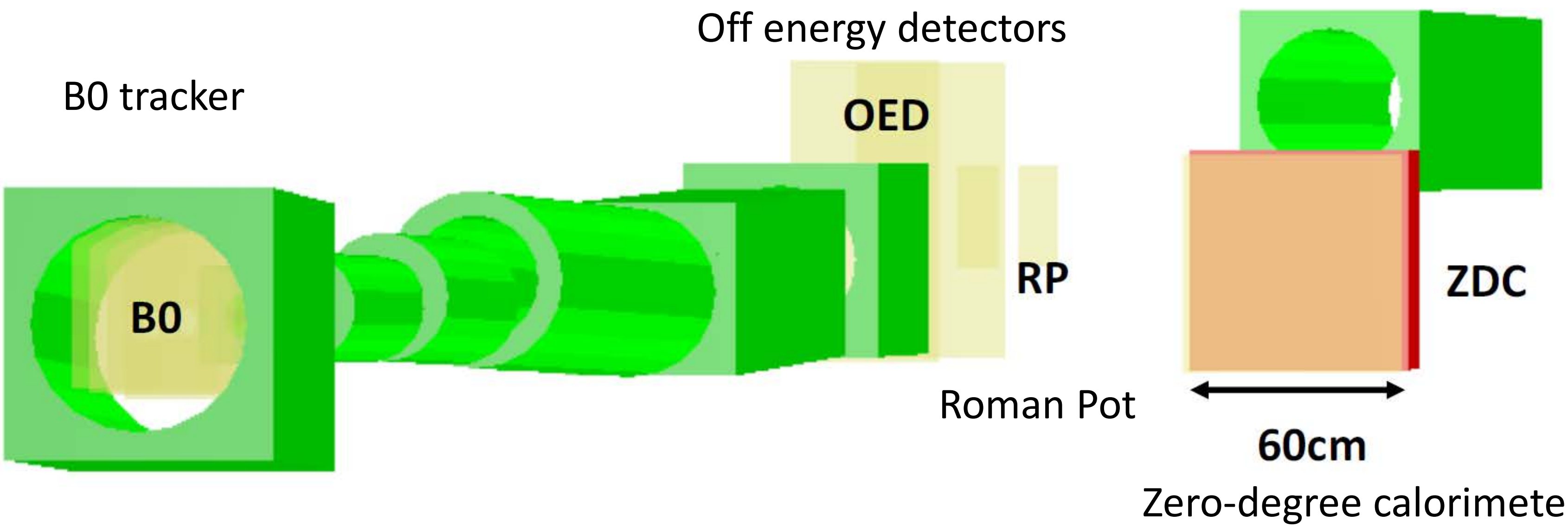
- Essential for forward jet reconstruction, hadron energy measurement, and triggering
- Collaboration with UCLA group for STAR upgrade and EIC detector R&D eRD1 (calorimeter consortium)
- Scalable and re-configurable with a minimal number of mechanical components
  - Minimal resources required for construction and operation
- Fe + scintillator sandwich, 38 layers for STAR FCS
- 10cm x 10cm x 90cm tower
- 4.5 interaction length
- WLS light collection
- SiPM readout
- Expected energy resolution
  - $\sigma_E/E = 70\%/\sqrt{E}$ (GeV)
  - Constant/noise terms?



eRD27

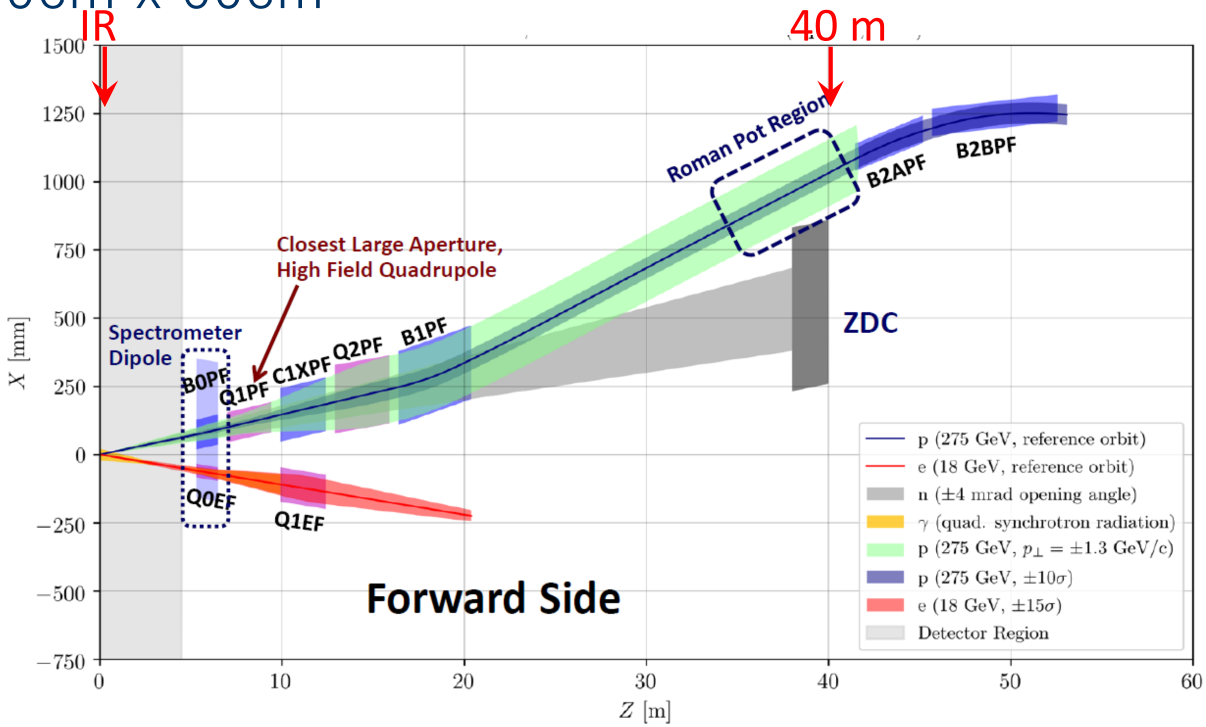
- General detector R&D program for an EIC
- eRD27 approved in 2020.8
- "Developing a High Resolution ZDC for the EIC"

Integrated forward system



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



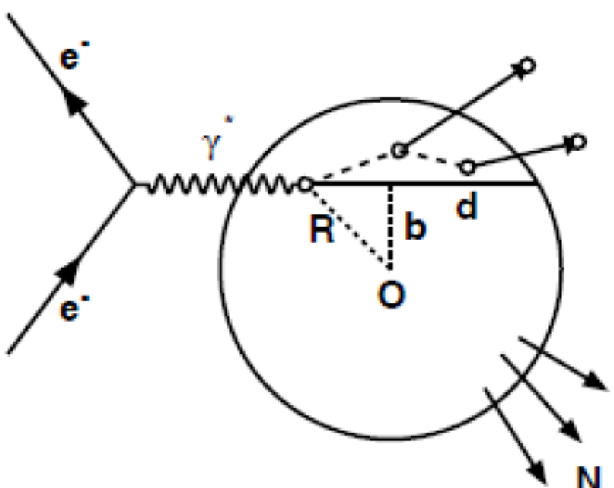
IR design of EIC at BNL

eRD27

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

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)

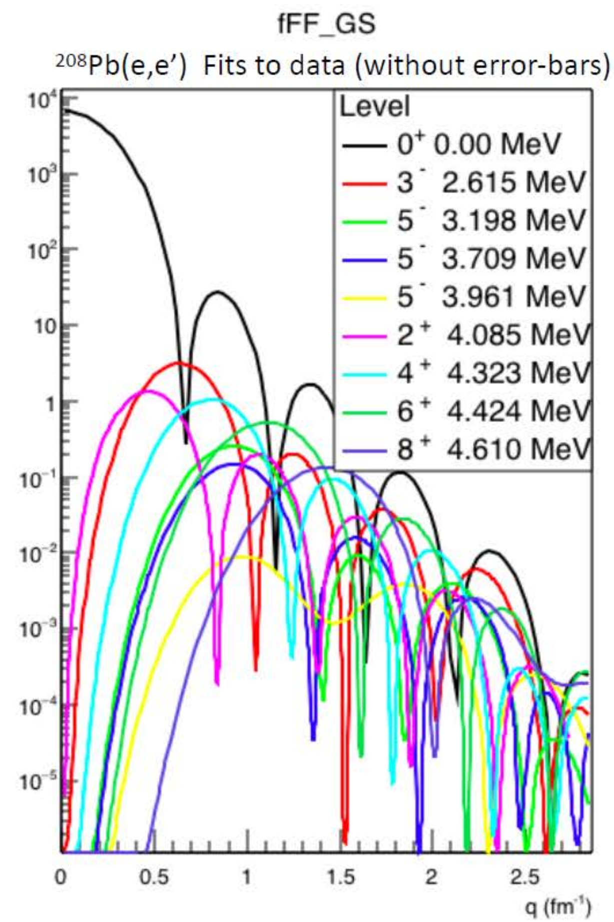
Leads to evaporation of nucleons from excited nucleus (very forward)

e + A collision at zero degree

Slide by C. Hyde

ZDC EMCAL: DEEP EXCLUSIVE NUCLEI

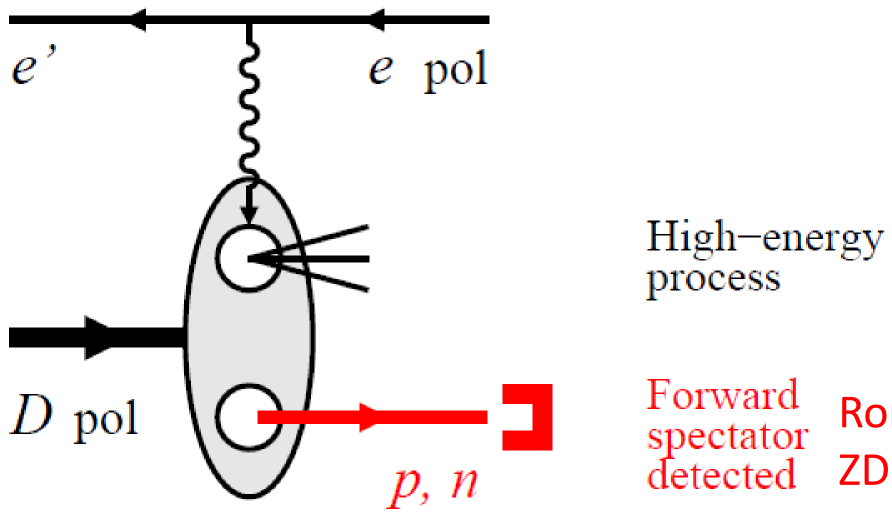
- Gluon Density from e.g. $^{208}Pb(e,e'\phi)\,^{208}Pb$
  - Final state nucleus is lost in beam envelope
  - Veto breakup of Pb nucleus.
  - Thousands of bound states excitable by photo-excitation
    - These will wash out diffractive minima.
    - Possible veto by detection of boosted decay photons
    - At P_{Pb} = 275•Z GeV, boost γ = 117
    - Each photon has 32% detection probability within 4mr cone



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

e + d/^{3}He collision at zero degree

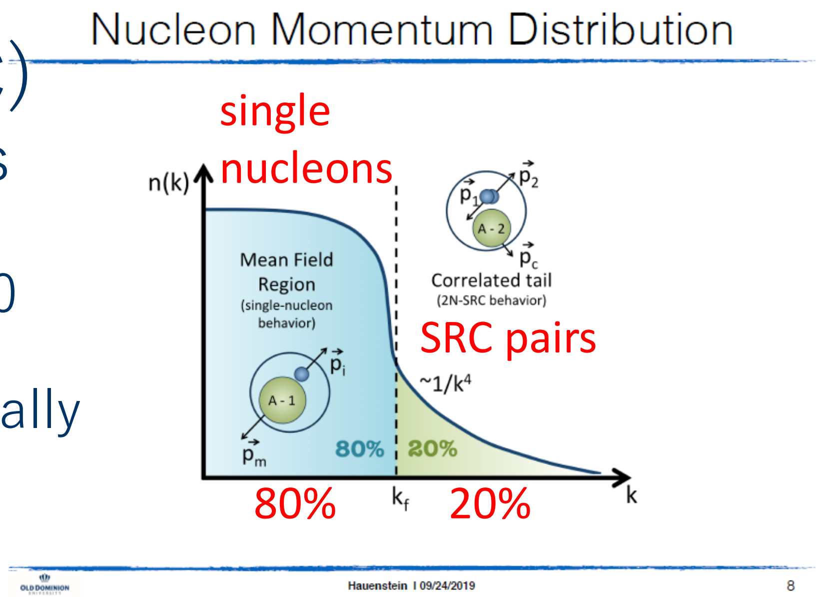
- Spectator tagging
  - Neutron structure
    - Neutron spin structure, S & D waves
  - Nucleon interactions
    - Short-range correlation (SRC) and EMC effect at large *x*
    - Diffraction and shadowing at small *x*

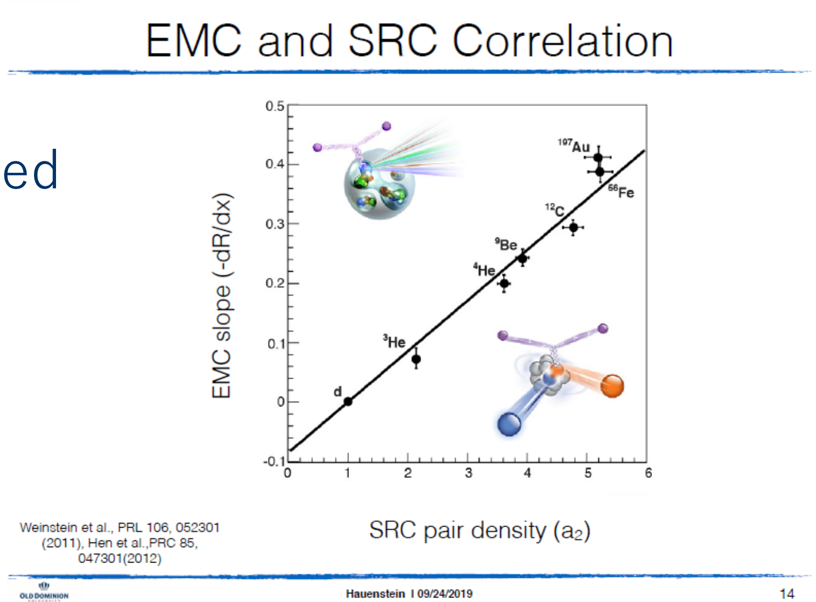


Roman pot
ZDC

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 spatially 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



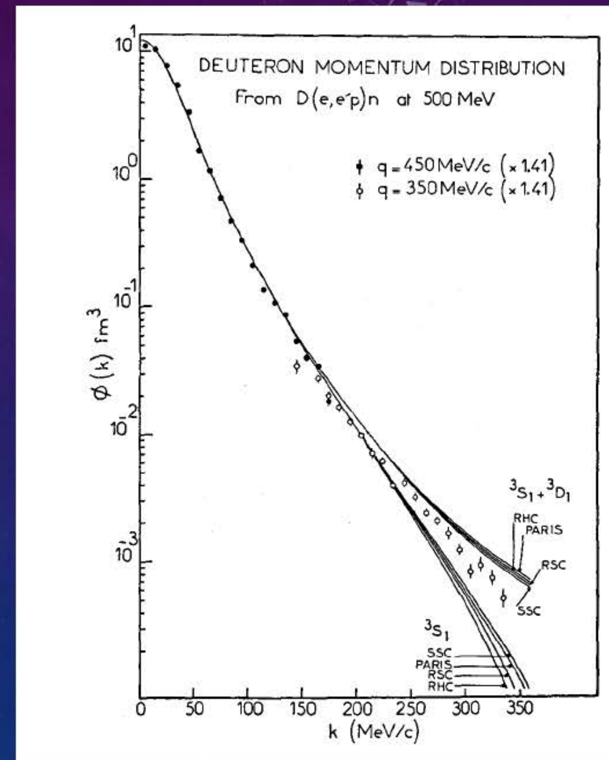


slides by Heuenstein

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



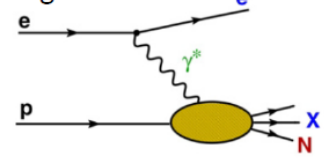
Slide by C. Hyde

- 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

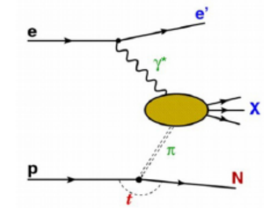
Physics at zero degree of EIC

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

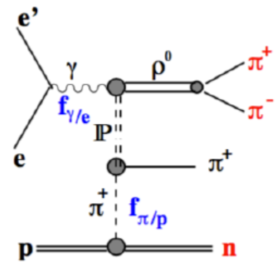
Fragmentation



One Pion Exchange (OPE)



LN in DIS

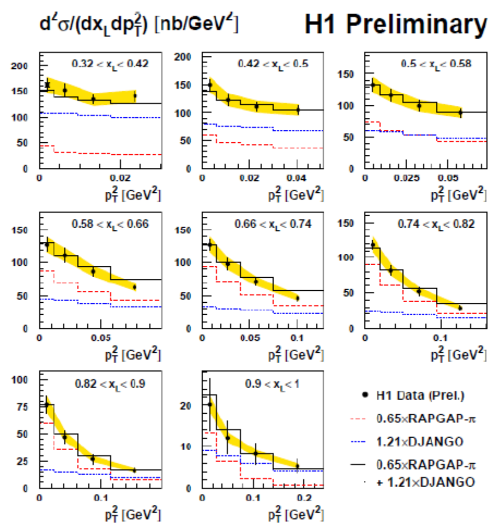


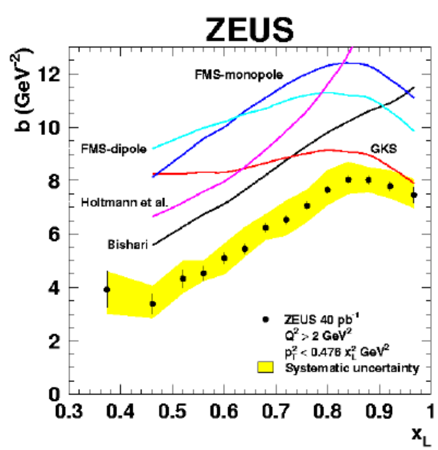
$$d\sigma_{\gamma^* p \to nx} = f_{\pi/p}(x_L, t) \times d\sigma_{\gamma^* \pi \to X}.$$

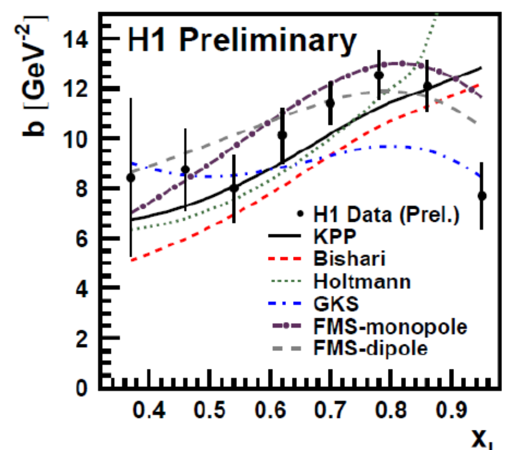
The distribution of p_T^2 (=t) is defined solely by the pion flux

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

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slide by Ciesielski

Inconsistency @ HERA

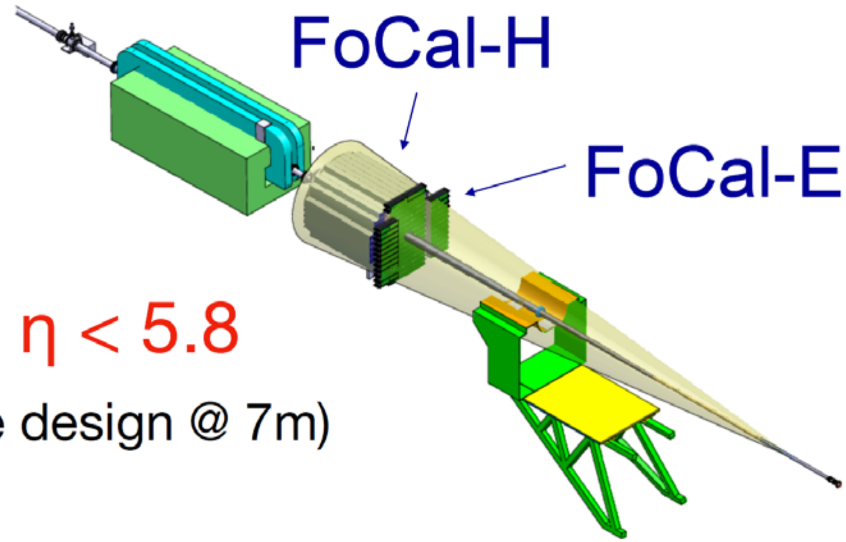
→ Need more data to understand production mechanism

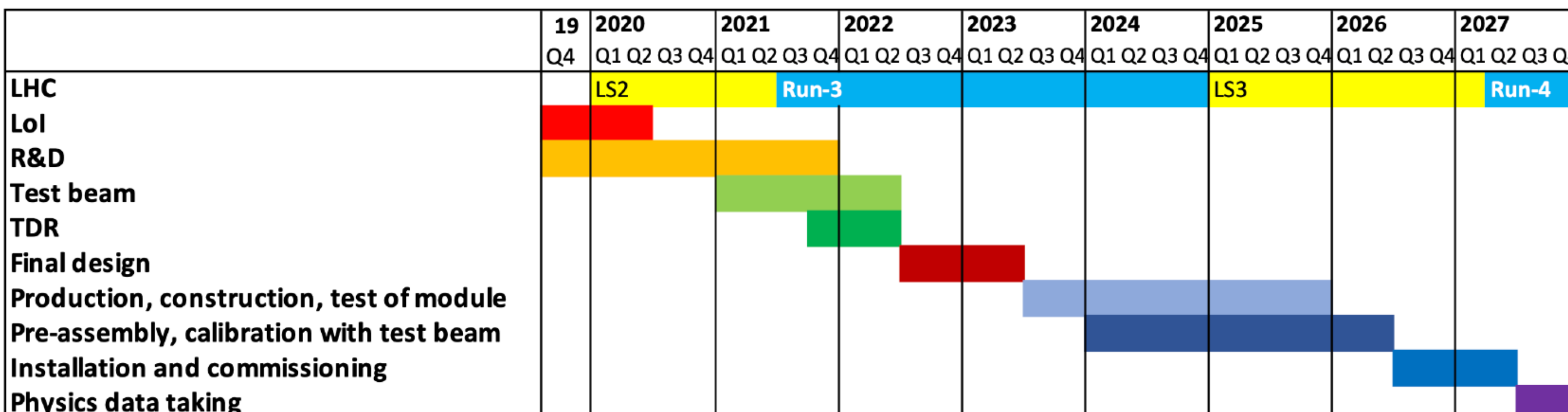
ALICE FoCal

- FoCal-E
  - High-granularity Si-W calorimeter for photon and π^0
- FoCal-H
  - Conventional metal-scintillator sampling calorimeter for photon isolation and jets

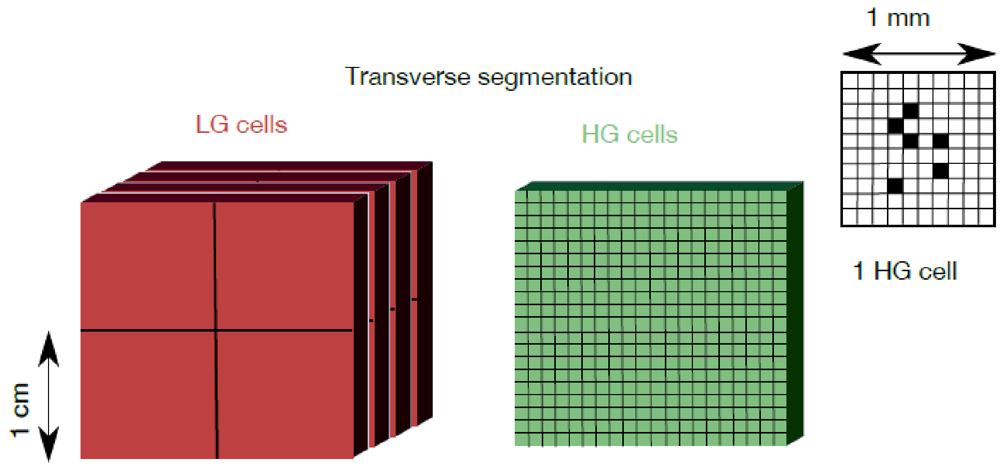
$3.4 < \eta < 5.8$

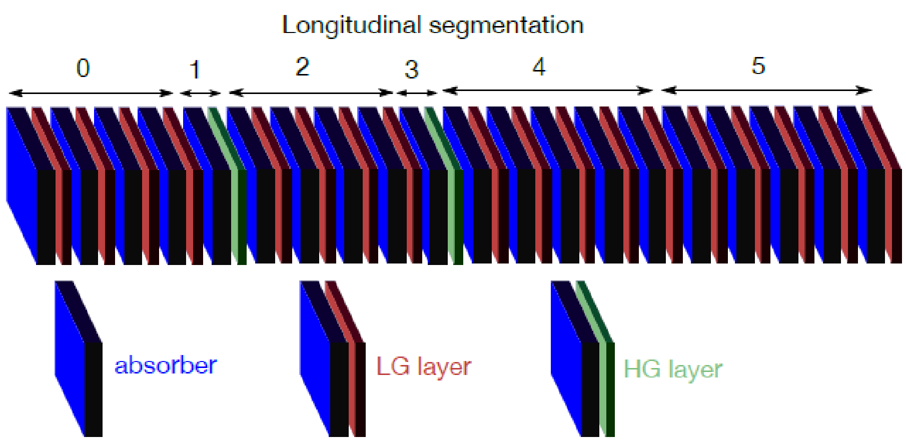
(baseline design @ 7m)





FoCal-E basic design





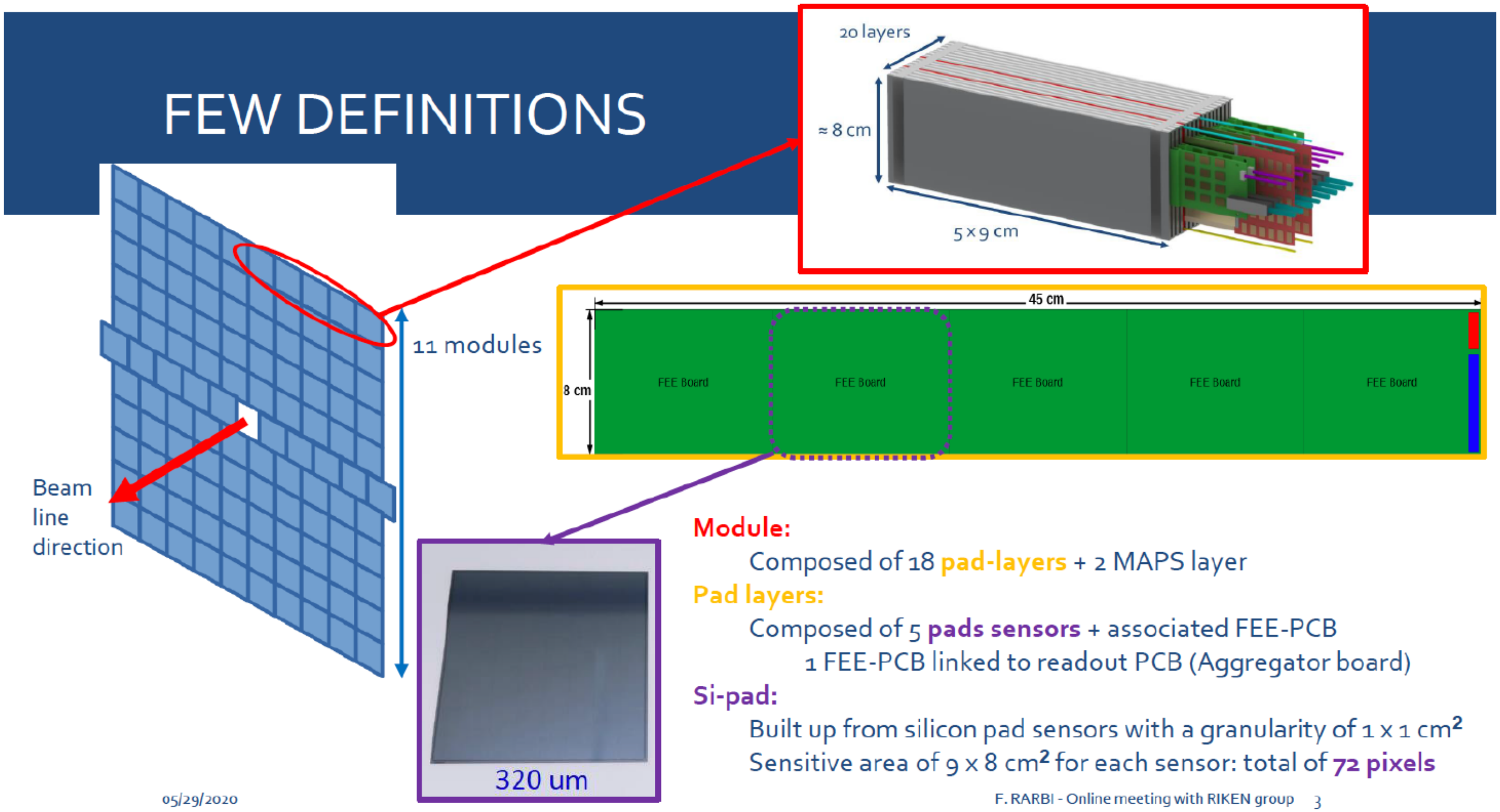
The design of the detector:

- 20 layers: W (**3.5mm ≈ 1 X_0**) + Si-sensors (2 types):
  - **low granularity (LG), Si-pads**
  - **high granularity (HG), pixels (e.g. CMOS-MAPS)**
- Moliere radius ~ 1-2 cm

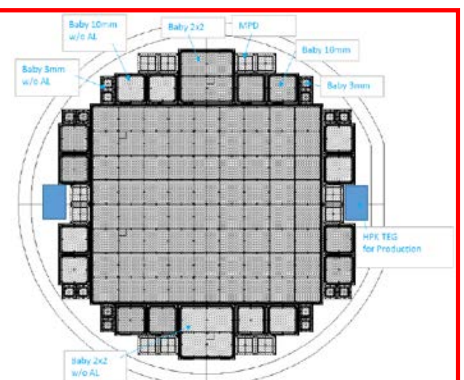
	LG	HG
pixel/pad size	≈ 1 cm^2	≈ 30x30 μm^2
total # of pixels/pads	≈ 2.5 x 10^5	≈ 2.5 x 10^9

The surface area of the detector will be about 1 m^2

ALICE FoCal-E



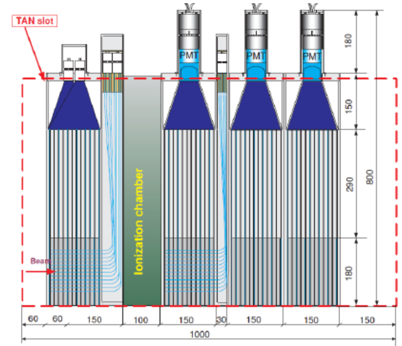
New silicon pad sensor for final FoCal

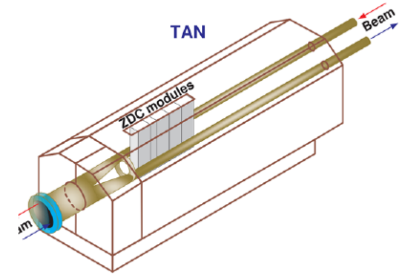


ZDC at LHC

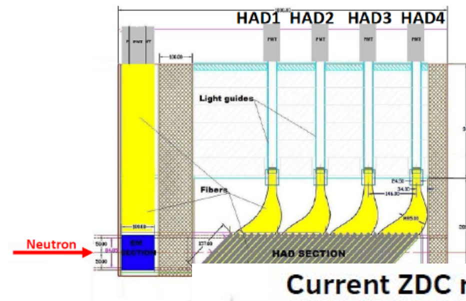
slides by Longo

- ATLAS & CMS ZDC
  - W-quartz sampling calorimeter





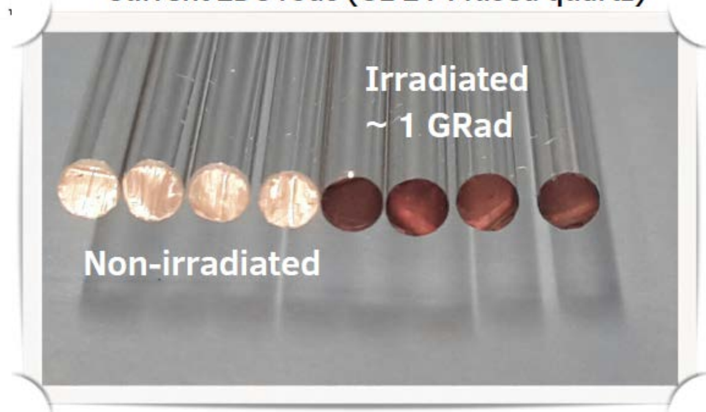
See talk by E. Adams



- ZDCs located in the **TAN** (140 m from IPs)
- W - quartz sampling calorimeters
- ATLAS: EM + 3 Hadronic modules
- CMS: EM + 4 Hadronic modules

- JZCaP collaboration
  - ATLAS + CMS joint R&D effort
  - Radiation-hard fused silica rods
  - Increasing H_2 concentration
  - Tested at higher doses than we expect at EIC
  - LHC group done significant work on calibrating Fluka dose simulation

Current ZDC rods (GE 214 fused quartz)



- Fused quartz with high level of impurities inadequate for any pp running and damaged during PbPb running.

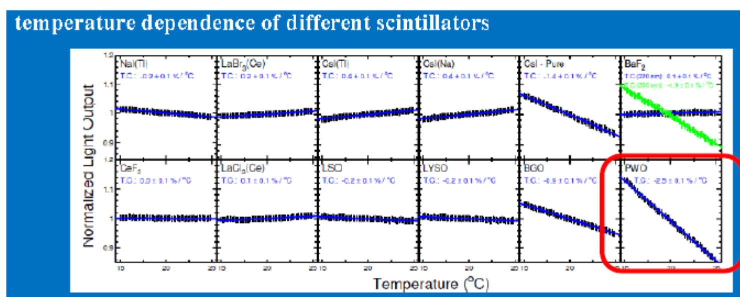
Calorimeter Consortium (eRD1)

- Crystal calorimeter
  - $PbWO_4$
  - For soft photon detection < 300 MeV (full absorption?)
- Glass scintillator
  - Optical and radiation hardness

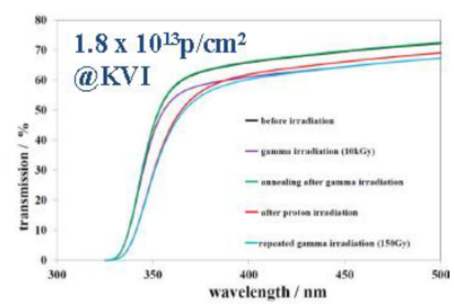
Crystals in EMCal: $PbWO_4$

Slide by T. Horn

- ❑ $PbWO_4$ material of choice for many EMCals – high density, fast response, large and granular solid angle, etc., but also limitations, e.g. hadron radiation damage



$PbWO_4$ light yield temperature dependence: 2%/°C



$PbWO_4$ radiation resistance

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Summary

- EIC will be constructed at BNL
- Physics at EIC
  - Mass of the proton
  - Spin of the proton
  - Gluon saturation (discovery $\rightarrow$ property)
- Forward & very forward physics at EIC
  - Geometry tagging
  - Spectator tagging
  - Leading baryons
  - π/K structure
- Forward & very forward calorimeters R&D
  - ALICE FoCal technology
  - LHC ZDC technology
  - Soft photon detection
  - Radiation hardness
- We'd like to activate collaboration between Korea and Japan