EIC Japan

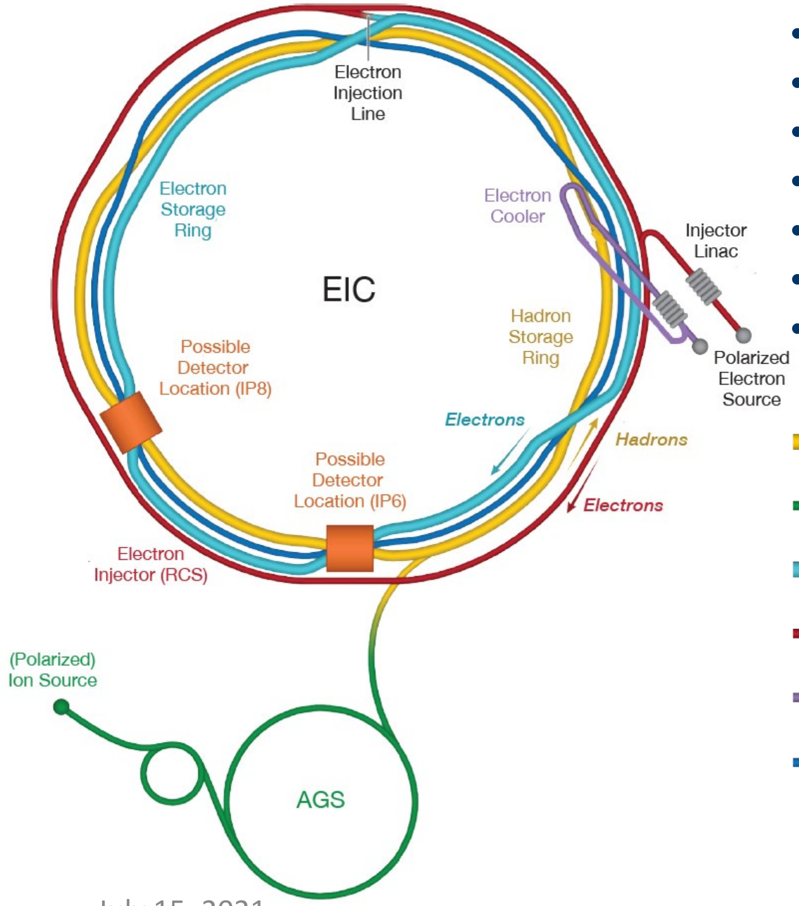
6th Korea-Japan
PHENIX/sPHENIX/RHICf/EIC Collaboration
Online Meeting
July 15th, 2021
Yuji Goto (RIKEN/RBRC)

Outline of this talk

- Overview of EIC
  - U.S. EIC (Electron-Ion Collider)
  - Physics
  - EIC status
- EIC Japan
  - Forward hadron calorimeter
  - Far-forward physics & calorimeter
  - Silicon detector

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}
- Polarized beam: e, p, d, ^{3}He
- Hadron beam polarization: 80%
- Electron beam polarization: 80%
- Ion species range: p to Uranium
- Number of interaction regions: up to two

🟨 **Hadron Storage Ring**

🟩 **Hadron Injector Complex**

🟦 **Electron Storage Ring**

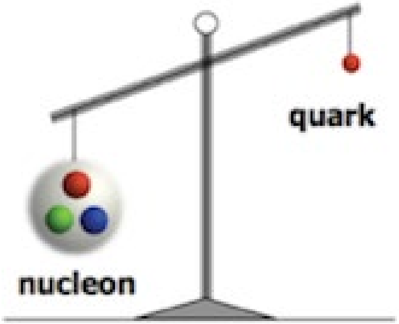
🟥 **Electron Injector Synchrotron**

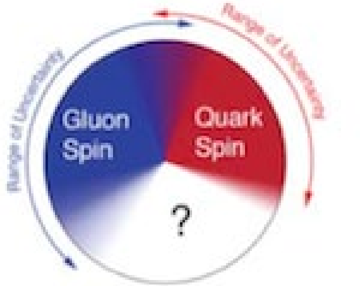
🟪 **Electron Cooler**

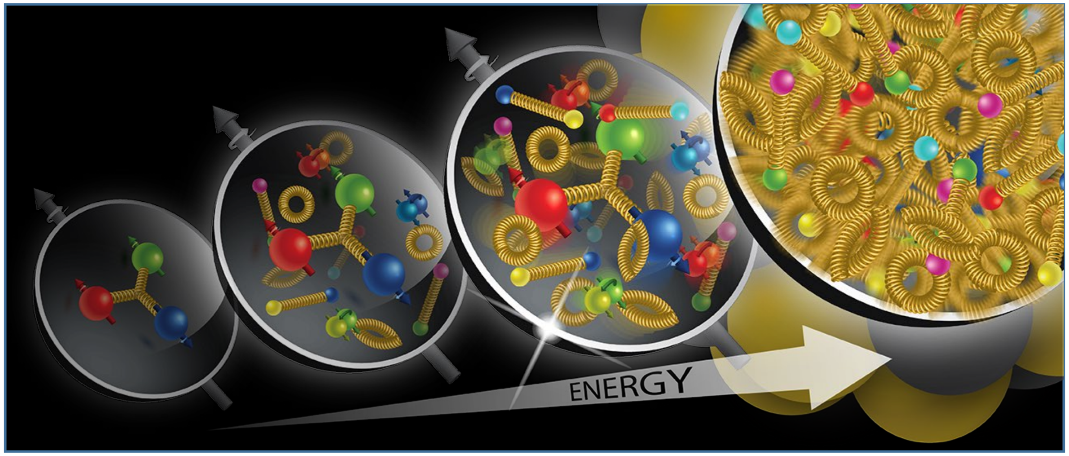
🟦 **Possible On-energy Hadron Injector Ring**

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.

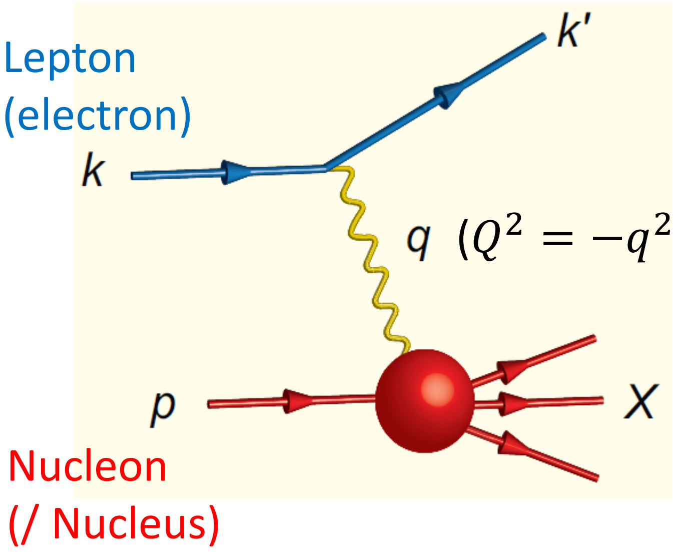




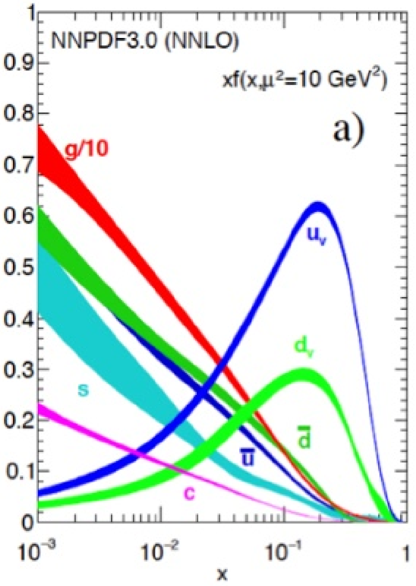


Quark-gluon structure

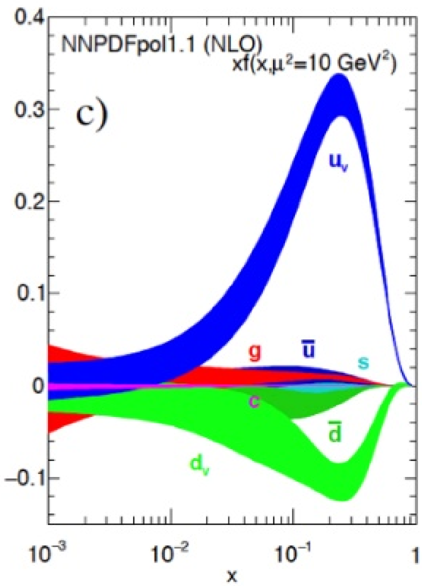
- Deep inelastic scattering (DIS) of lepton (electron)
  - Large Q^2 ($Q^2 = -q^2$) provides a hard scale to resolve quarks and gluons in the proton
- Parton distribution function (PDF) of quarks and gluons
  - 1D longitudinal motion of partons
  - x : momentum fraction of quarks and gluons
  - Significant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



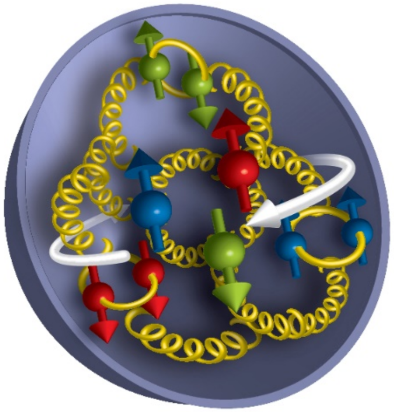
Unpolarized PDF



Polarized PDF



Spin



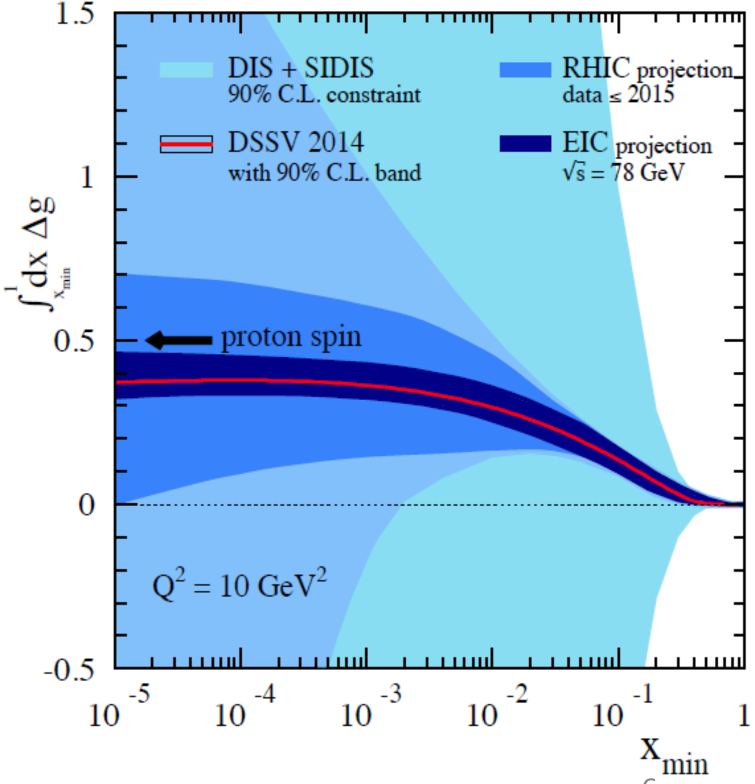
- Spin puzzle
  - Origin of the nucleon spin in the quark-gluon structure

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

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

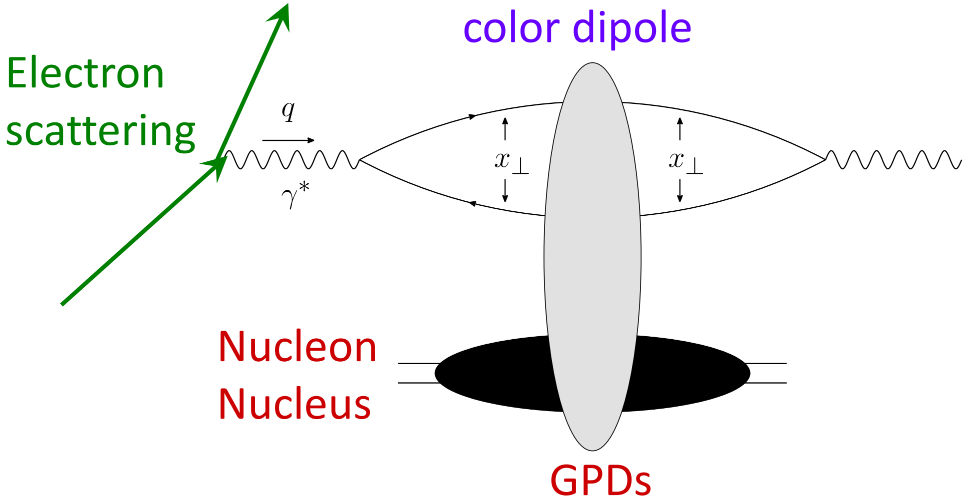
  - Quark-spin contribution is only 20%-30% of the nucleon spin
- Gluon polarization measurement with polarized DIS at EIC
  - Small Bjorken-x region with QCD evolution (DGLAP equation)

Integrated gluon polarization down to x_{min}

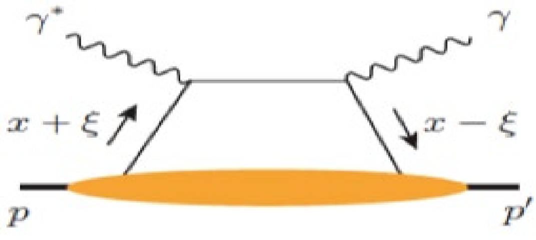


Tomography of the nucleon / nucleus

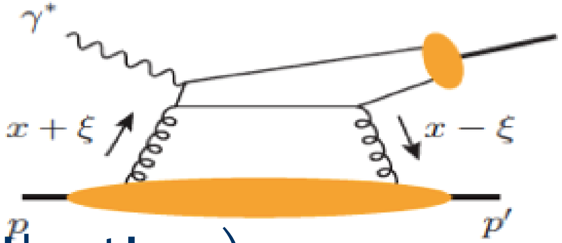
- EIC = color dipole microscope
  - Exclusive process and diffractive process
  - 3D distribution: transverse spatial distribution



DVCS (Deeply Virtual Compton Scattering)



Meson Production

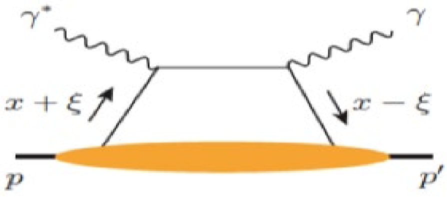


- GPD (Generalized Parton Distribution)
  - Spatial imaging of gluons and quarks = tomography
    - HERA: 1st generation
    - EIC: 2nd generation (high luminosity, heavy ion, polarization)
  - Orbital angular momentum
    - Ji's sum rule
    - Origin of the nucleon spin

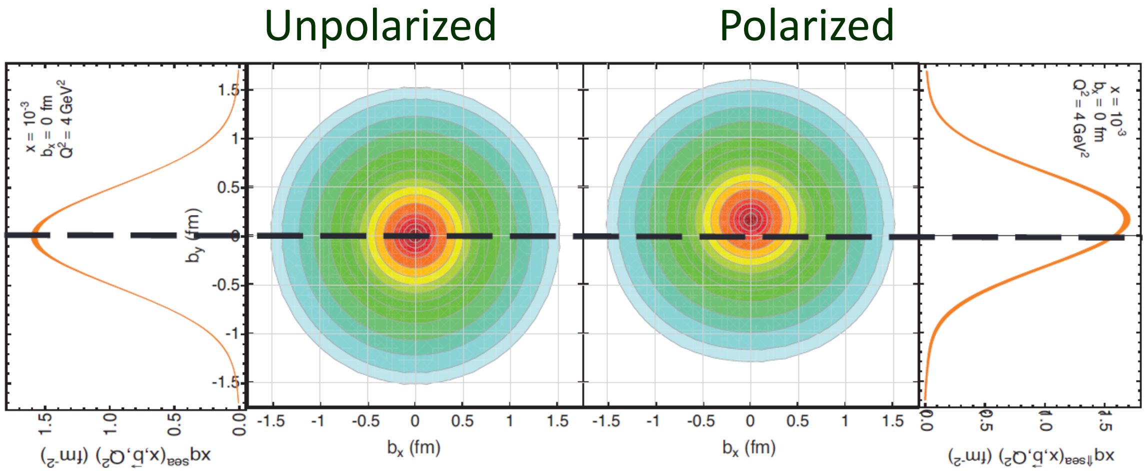
$$J_q^z = \frac{1}{2}\sum_q \Delta q + \sum_q L_q = \frac{1}{2}\left(\int_{-1}^{1} x dx (H^q + E^q)\right)_{t\to 0}$$

Tomography of the nucleon / nucleus

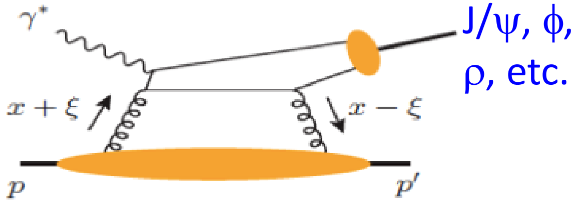
- DVCS
  - Deeply virtual Compton scattering



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

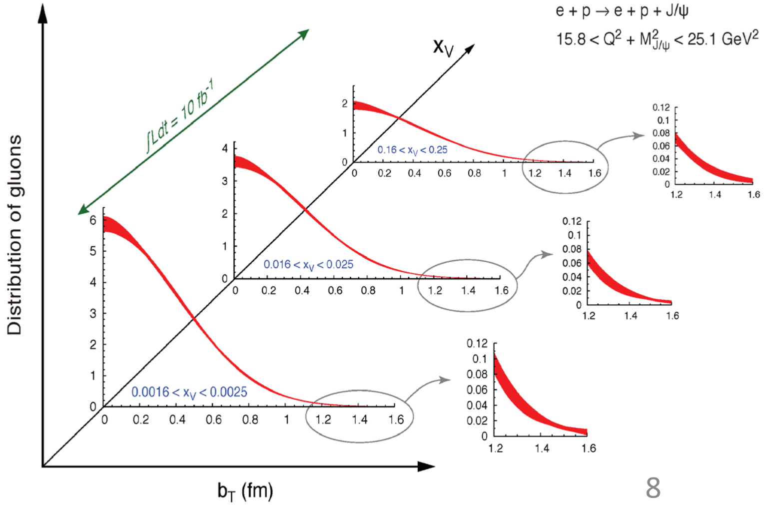


- Meson production
  - Gluon tomography by measuring J/ψ, ϕ, ρ, etc.
  - Precision measurement at large radius with high luminosity



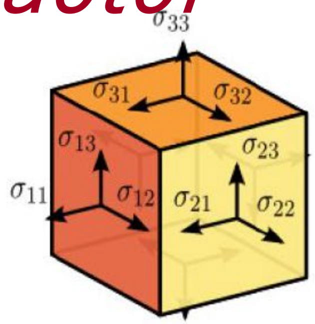
J/ψ, ϕ, ρ, etc.

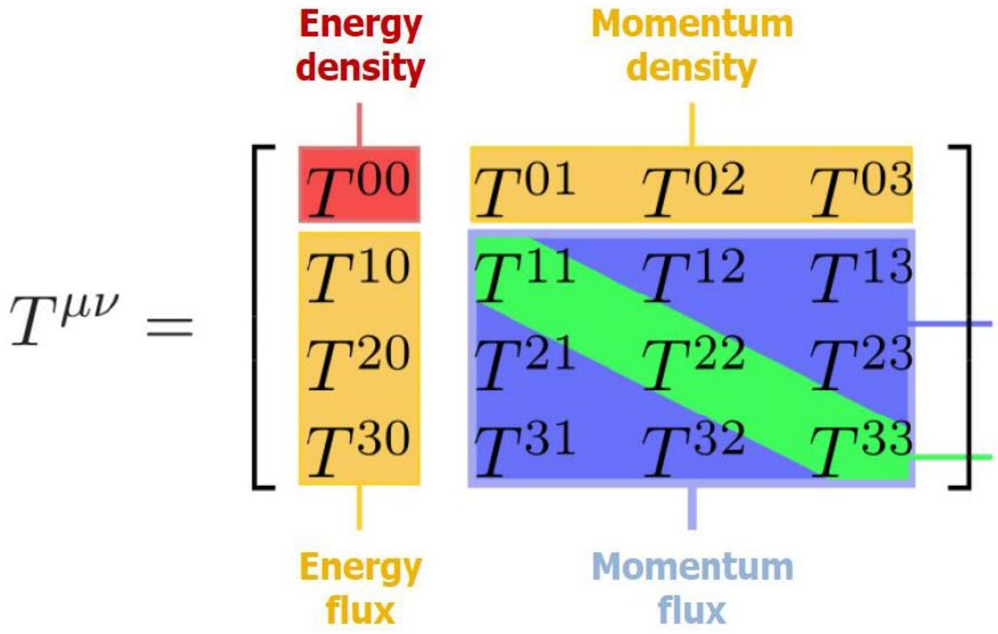
x-dependence of spatial distribution of gluons to be obtained by the exclusive J/ψ production at EIC



Generalization of the form factor

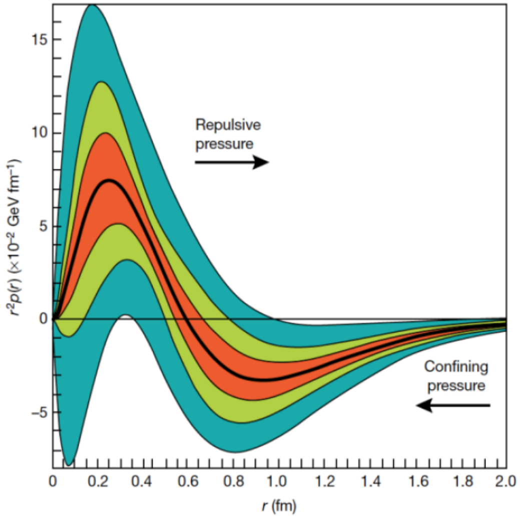
- Energy Momentum Tensor (EMT)





(pressure)

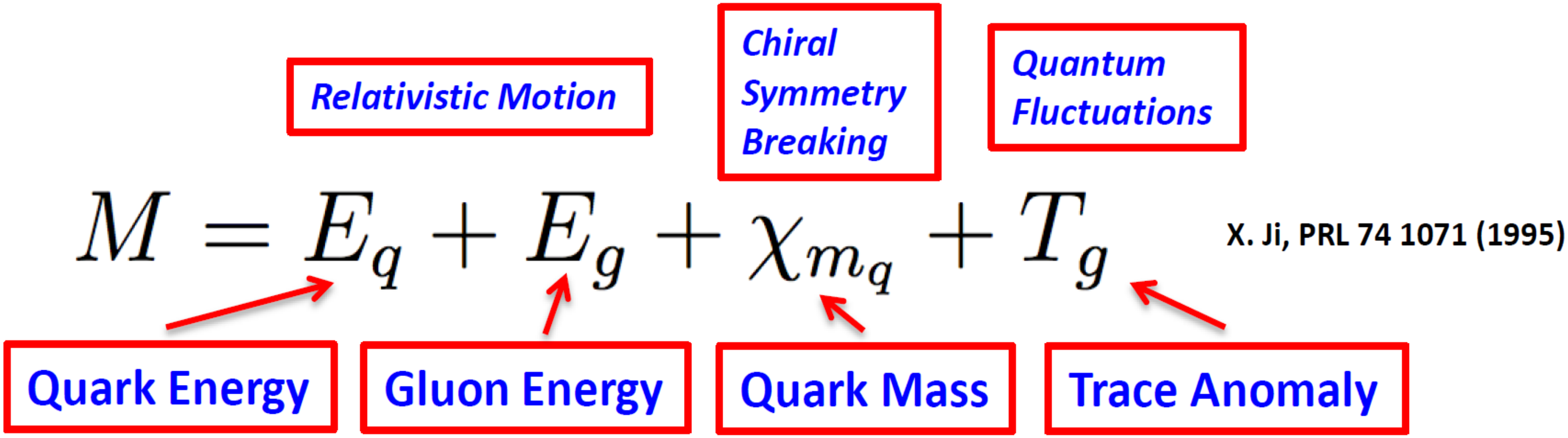
- GPD measurement → 3D distribution of mass, spin, pressure, etc. in the proton
  - 1st measurement of pressure in the proton using DVCS data from JLab



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)

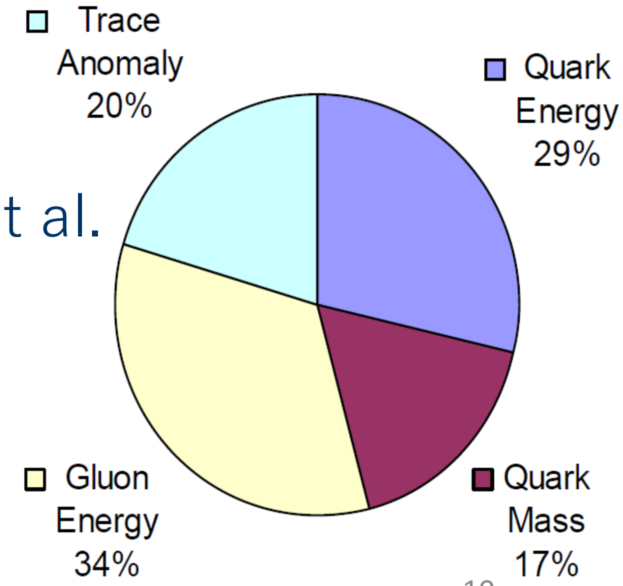
Quark Energy

Gluon Energy

Quark Mass

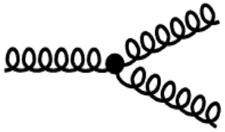
Trace Anomaly

  - 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,⋯

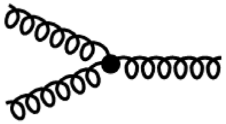


Gluon saturation in e+A collisions

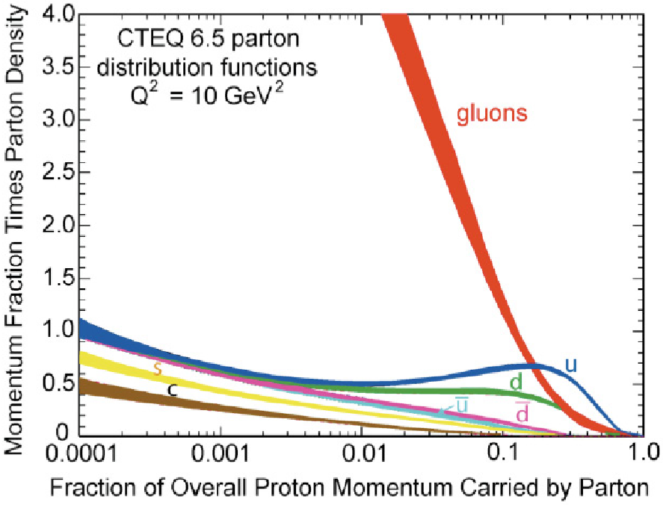
- Gluon emission
  - Divergence at small x

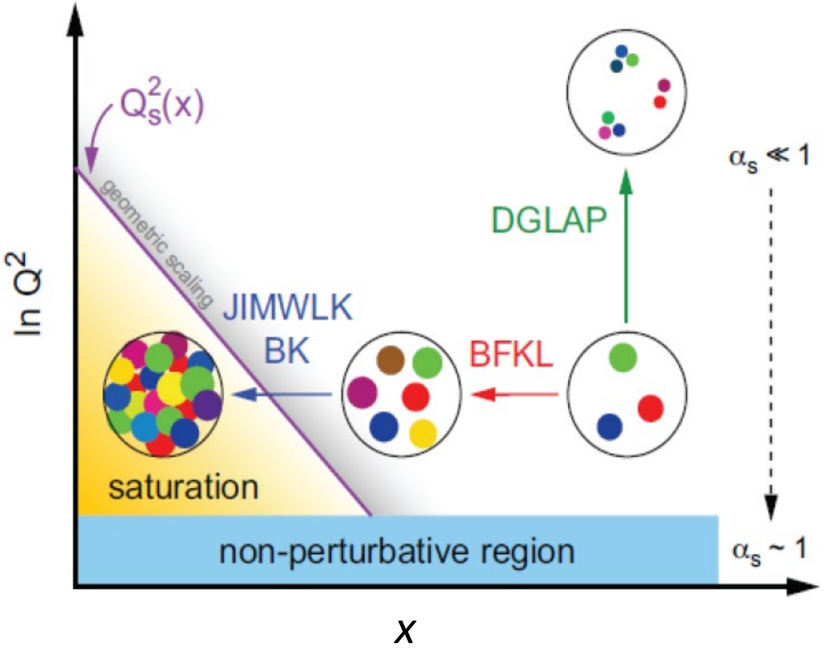


- Gluon recombination
  - Restriction of divergence



- 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

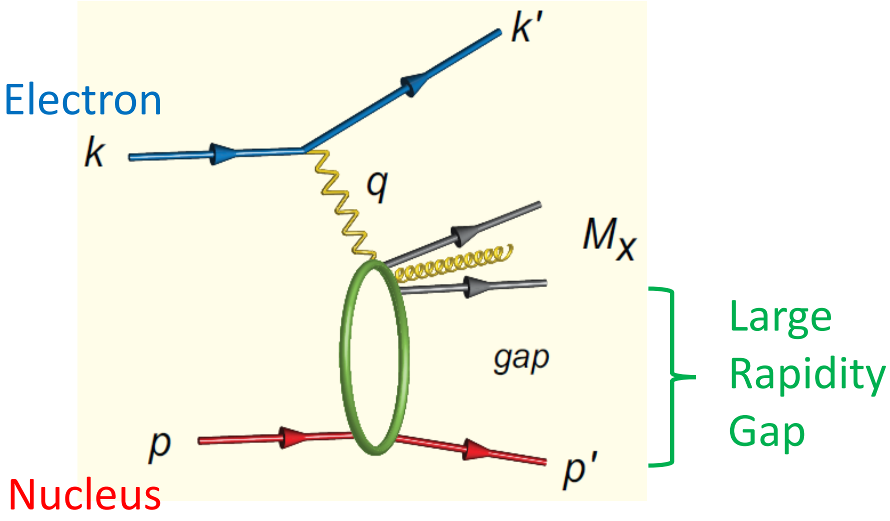


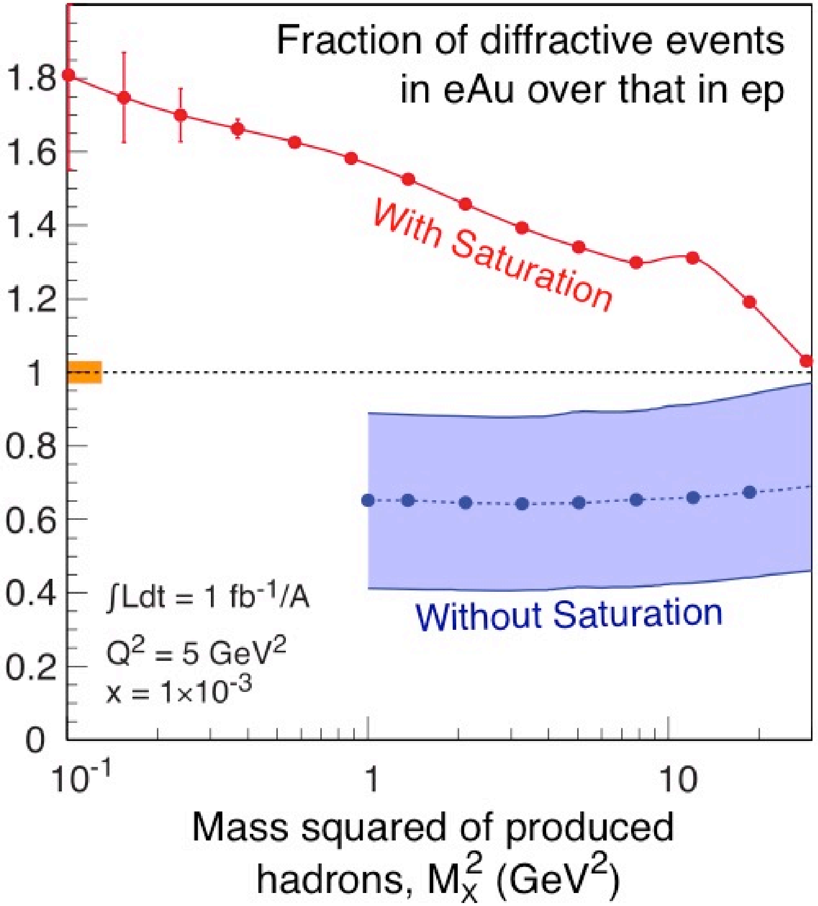


Gluon saturation in e+A collisions

- 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

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

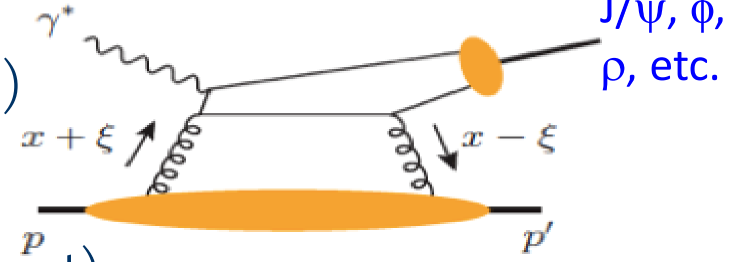


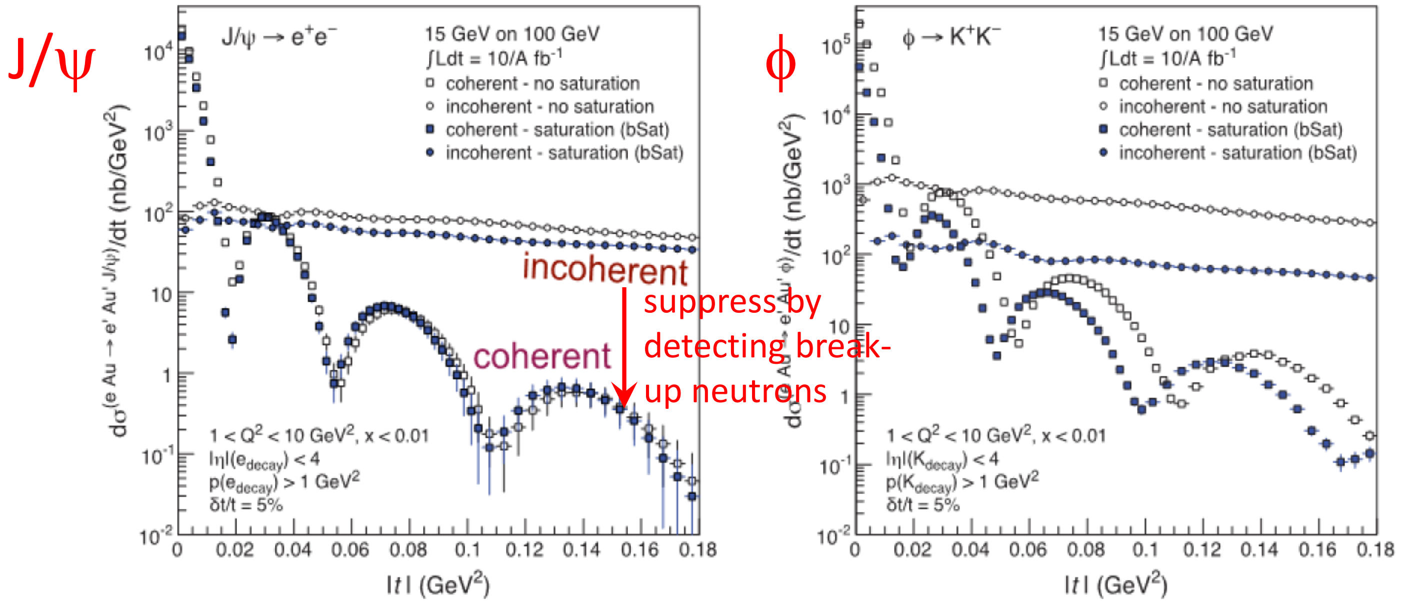


Gluon saturation at extreme density

- 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

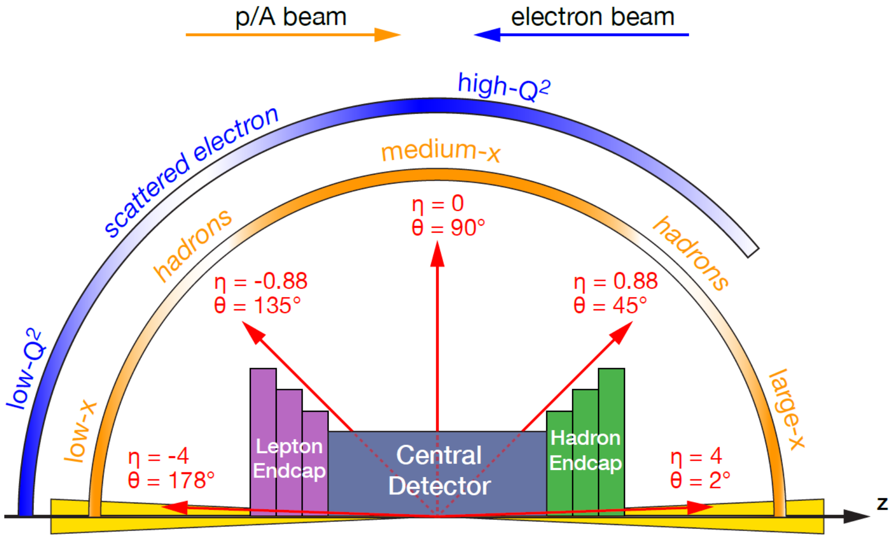
Meson Production

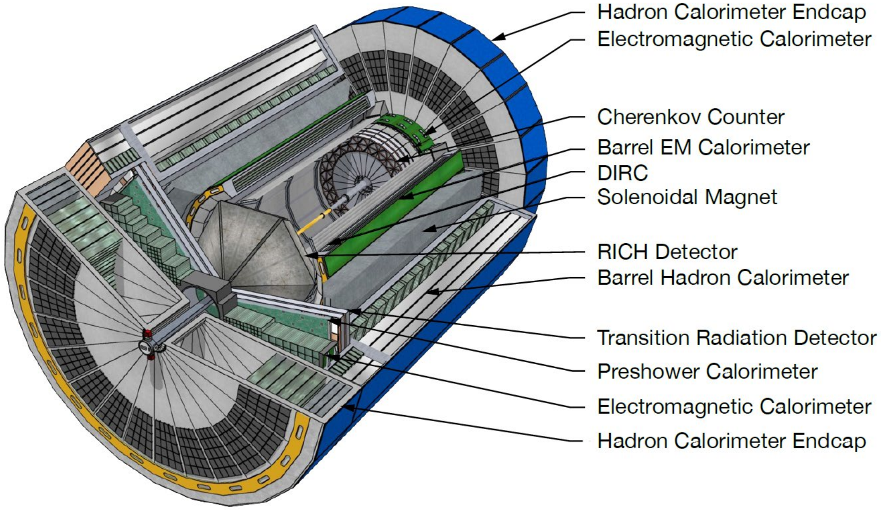




EIC status

- 2019.12: CD-0 (approve mission need)
- 2020.1: Site selection at BNL
- EIC User Group (EICUG) since 2016
  - More than 1200 physicists from over 250 laboratories and universities from around the world
- 2020: EICUG Yellow Report (physics/detector) towards CD-1
  - https://arxiv.org/abs/2103.05419
- 2021.7: CD-1 approval
  - Authorization to begin the project execution phase, starting with preliminary design



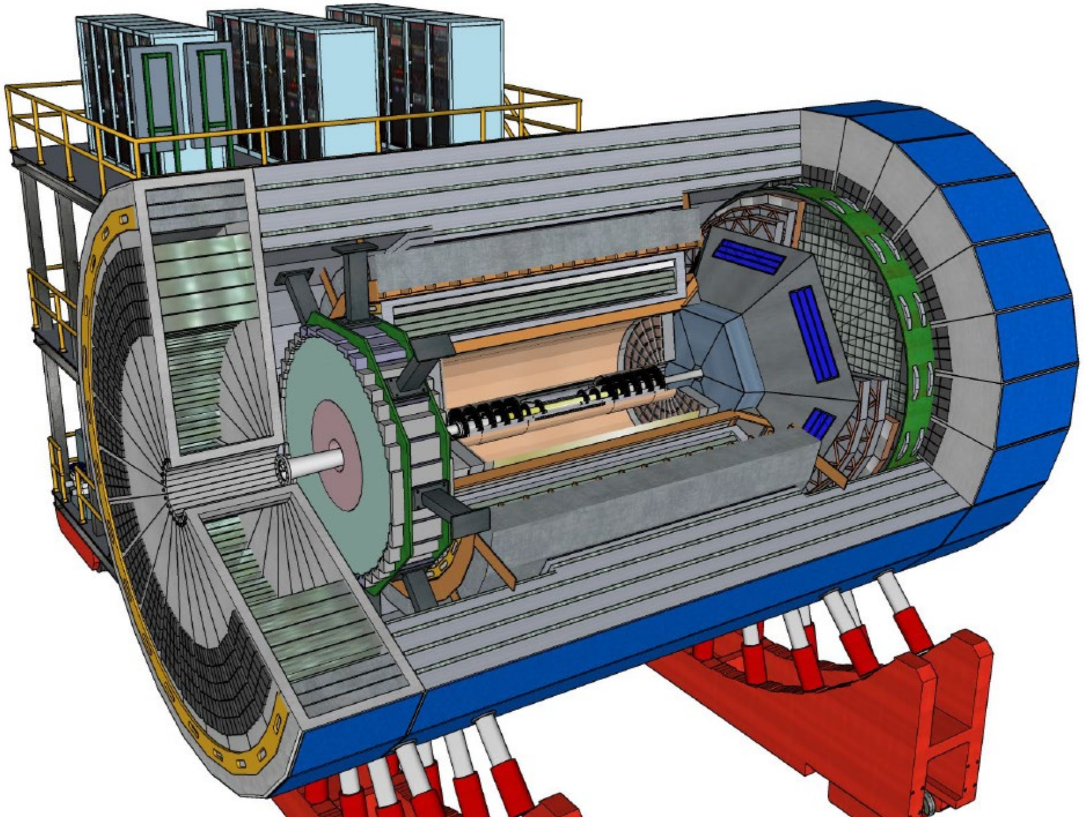


EIC status

- 2020.11: Expression of Interest (EOI) for potential cooperation on the EIC experimental program
  - https://www.bnl.gov/eic/EOI.php
  - https://indico.bnl.gov/event/8552/contributions/
  - 47 EOIs submitted
- 2021: 2nd detector and IR planning
- 2021.3: Call for detector proposals
  - ATHENA
  - ECCE
  - CORE
- 2021.12: Decision on detector(s)
- CD-2 (performance baseline) 2023?
- CD-3 (start of construction) 2024?

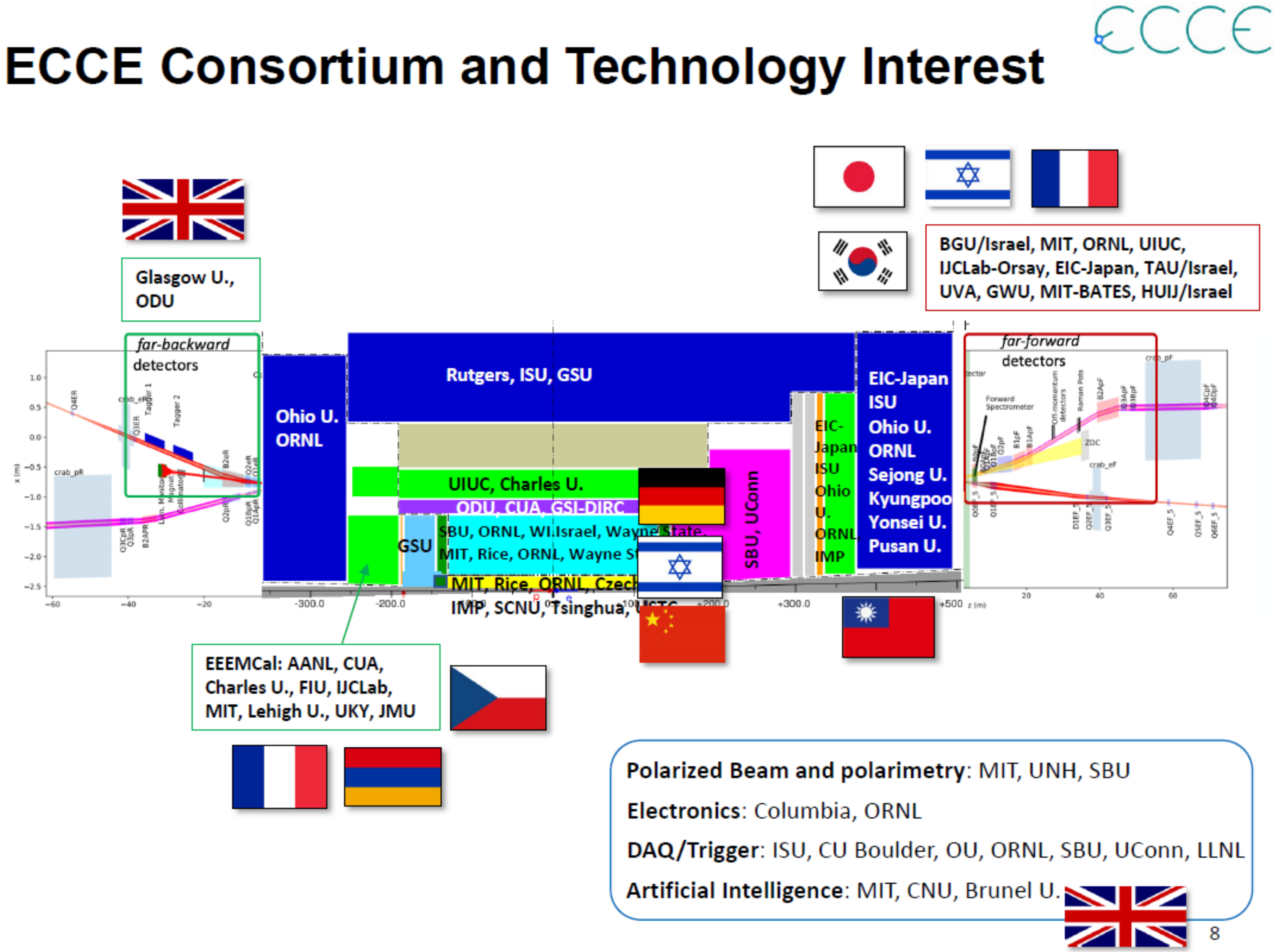
EIC detector

- ECCE consortium
  - 77 institutions
  - Based on an existing 1.5 T solenoid
    - Babar solenoid used at sPHENIX
  - Simulation and analysis for proposal writing and submission on Dec. 1, 2021



EIC detector

- ECCE consortium



ECCE Consortium and Technology Interest

Glasgow U.,
ODU

far-backward
detectors

Ohio U.
ORNL

Rutgers, ISU, GSU

UIUC, Charles U.

ODU, CUA, GSI-DIRC

GSU

SBU, ORNL, WI.Israel, Wayne State,

MIT, Rice, ORNL, Wayne St

MIT, Rice, ORNL, Czech

IMP, SCNU, Tsinghua, USTC

SBU, UConn

EIC-
Japan
ISU
Ohio
U.
ORNL
IMP

EIC-Japan
ISU
Ohio U.
ORNL
Sejong U.
Kyungpoo
Yonsei U.
Pusan U.

far-forward
detectors

BGU/Israel, MIT, ORNL, UIUC,
IJCLab-Orsay, EIC-Japan, TAU/Israel,
UVA, GWU, MIT-BATES, HUIJ/Israel

EEMCal: AANL, CUA,
Charles U., FIU, IJCLab,
MIT, Lehigh U., UKY, JMU

Polarized Beam and polarimetry: MIT, UNH, SBU

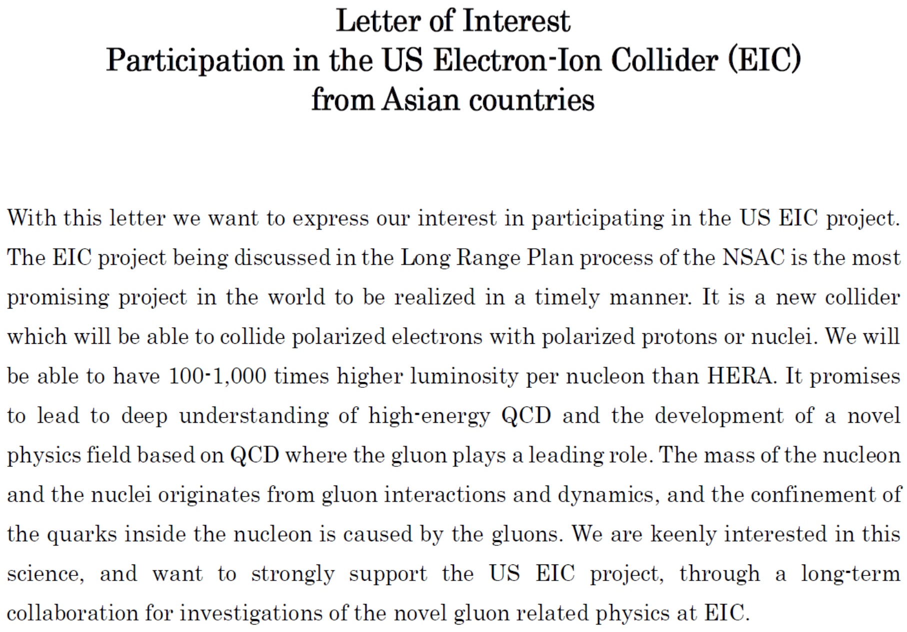
Electronics: Columbia, ORNL

DAQ/Trigger: ISU, CU Boulder, OU, ORNL, SBU, UConn, LLNL

Artificial Intelligence: MIT, CNU, Brunel U.

EIC Japan

- 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



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.

- 2016.8.3: Workshop on “Prospects on EIC project” at J-PARC
- 2018.4.15: Pre-DIS EIC workshop at Kobe
- 2018.10.23: JPS/DNP workshop at Hawaii “Hadron structure”
- 2019.9.24-26: CFNS & RBRC workshop at Stony Brook Univ. on “Physics and detector requirements at zero-degree of colliders”

EIC Japan

- 2019: Master Plan 2020 proposal of Electron-Ion Collider (EIC)
  - Selected as a major academic research project
  - Not selected for a hearing for the priority 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

EIC Japan activity

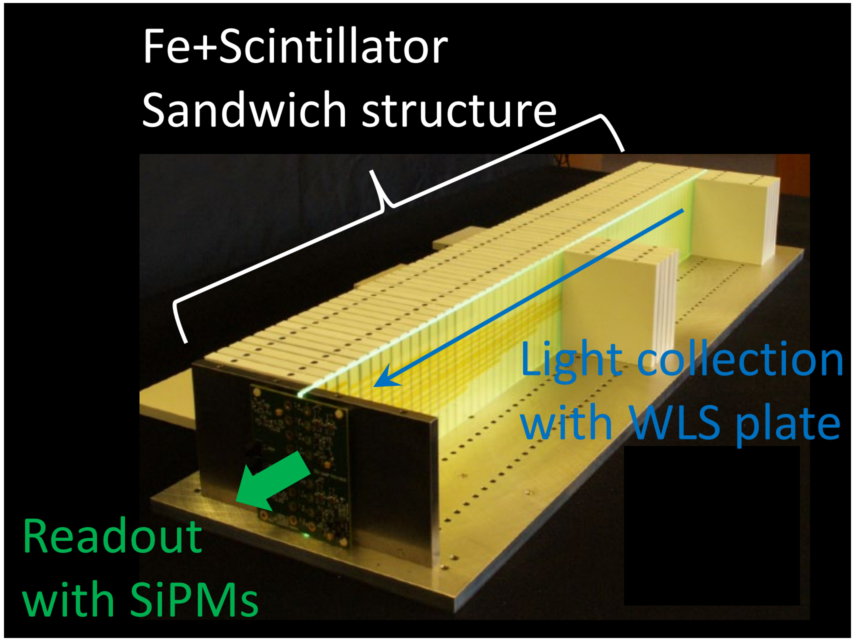
- 2020.5: EIC detector R&D program eRD27
  - “Developing a high resolution ZDC for the EIC”
  - Collaboration with Kansas U., ODU, etc.
- 2020.7: U.S.-Japan science and technology cooperation program in high-energy physics (special category)
- 2020.8: U.S.-Japan hadron physics exchange program for studies of hadron structure and QCD (2020.9-2023.9)
- 2020.8-9: KEK workshop on intersections of particle and nuclear collider physics
- Expression of interest (EOI) from EIC-Japan (2020.11)
  - Forward hadron calorimeter
    - Cooperation with UCLA & Korean group
  - Zero-degree calorimeter (EM & hadron)
    - Cooperation with eRD27
  - Silicon detector
    - Cooperation with ANL, BNL, etc.

Forward hadron calorimeter

- Essential for forward jet reconstruction and hadron energy measurements, as well as triggering
  - Cross-section measurements in the high Bjorken-x region, where a struck quark goes forward
- Position and energy measurements of hadrons take a crucial role especially in the charged current process
  - Struck electron escapes from the detector as a neutrino
  - DIS kinematic variables have to be reconstructed from the angular and energy distribution of the hadronic final state
  - In neutral current events, the hadronic method of reconstructing the DIS kinematics significantly improves the resolution
- Precise measurements of them in the high-x region are expected to improve the understanding of the traditional proton PDFs used in LHC physics

Forward hadron calorimeter

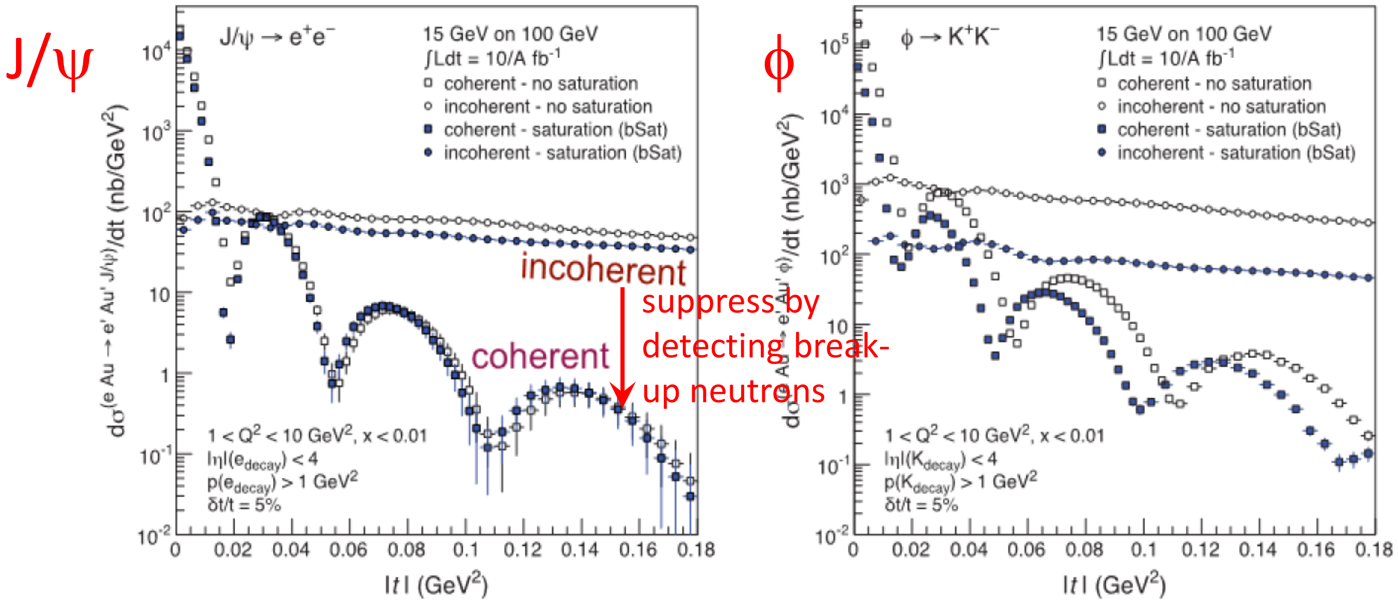
- Collaboration with UCLA group for STAR upgrade and EIC detector R&D eRD1 (calorimeter consortium)
- Scalable and re-configurable with a minimal number of mechanical components
  - Minimal resources required for construction and operation
- Fe + scintillator sandwich, 38 layers for STAR FCS
- 10cm x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



- Higher energy resolution necessary for EIC

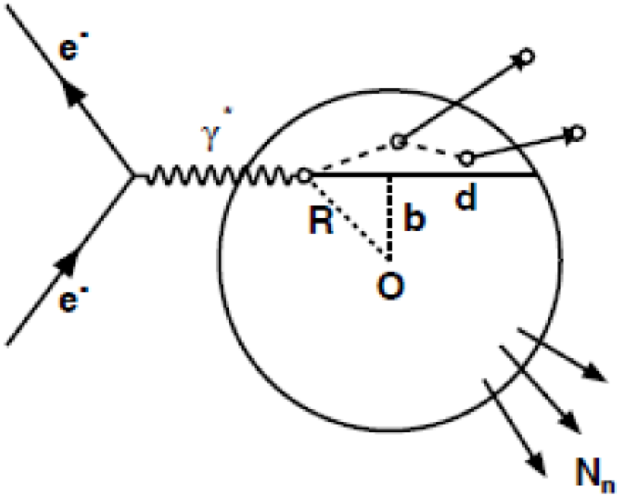
Far-forward physics at EIC

- In e+A collisions, exclusive vector meson production in diffractive process is one of the key measurements sensitive to the gluon saturation
- For the coherent process where the nucleus remains intact, the momentum-transfer dependent cross section can be translated to the transverse spatial distribution of gluons in the nucleus



Far-forward physics at EIC

- Collision geometry is an important measure in e+A collisions for an event-by-event characterization
- Collision geometries can be tagged through forward neutron multiplicities

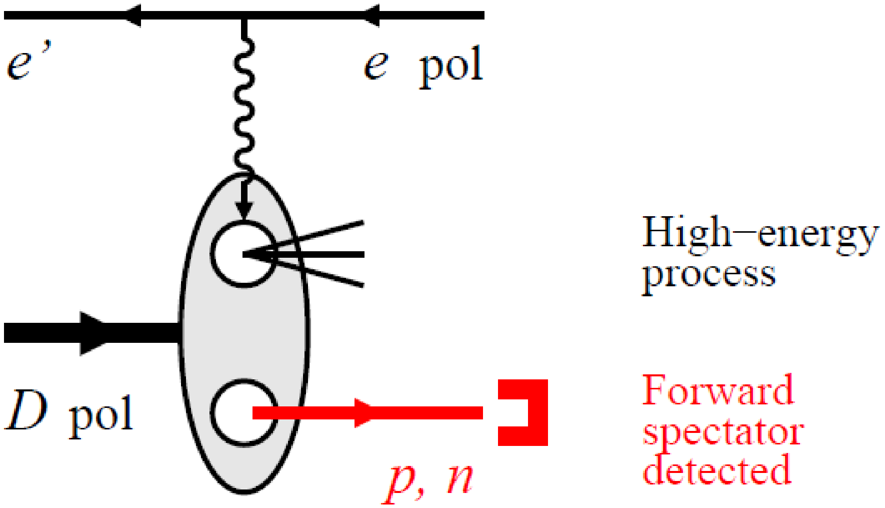


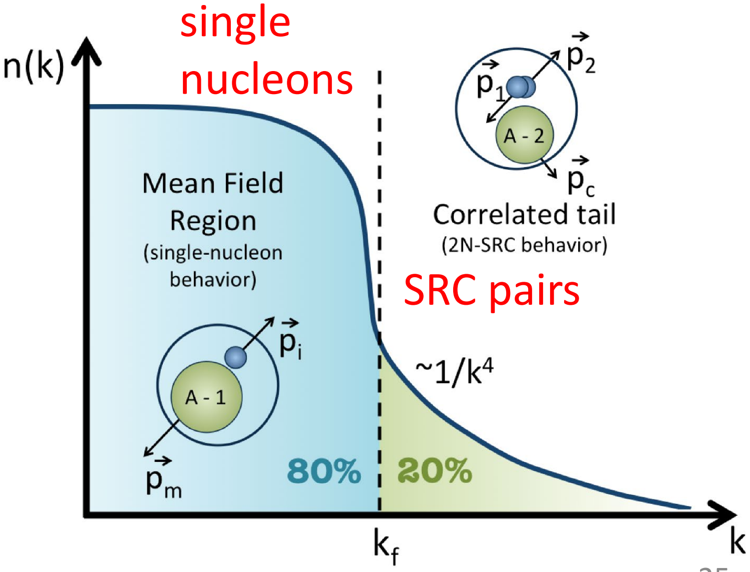
Intra-nuclear cascading increases with d (forward particle production)

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

Far-forward physics at EIC

- In e+d and e+^{3}He collisions at EIC, various physics programs require the tagging of forward neutrons as spectators to identify the target nucleon
- It constrains kinematics for studies of the Short-Range Correlations (SRC)
  - Nucleon-nucleon interaction at very short distance which shows high momentum nucleon in the nucleus rest frame
  - Deep connection to how the quark-gluon structure of a nucleon in a nucleus is modified, known as the EMC effect
  - ~20% of nucleons are in SRC pairs

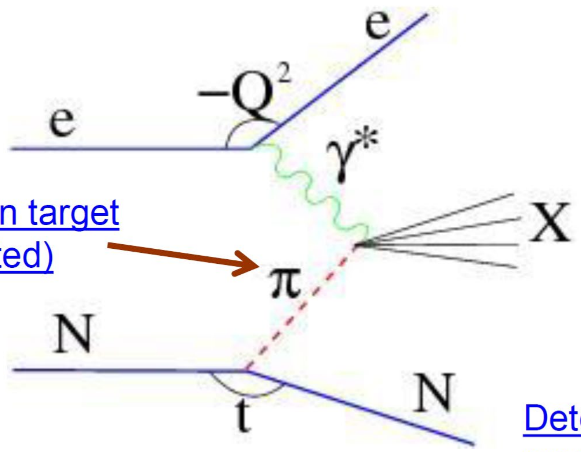




Far-forward physics at EIC

- 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
- For the proton, the EIC will allow determination of an important term contributing to the proton mass, the so-called "QCD trace anomaly"
- For the pion and the kaon, the EIC will allow determination of the quark and gluon contribution to mass with the Sullivan process

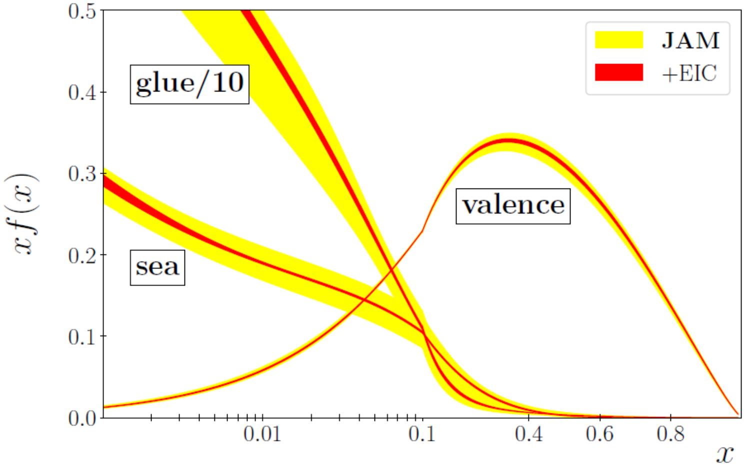
Detect scattered electron



Pion/Kaon target (undetected)

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

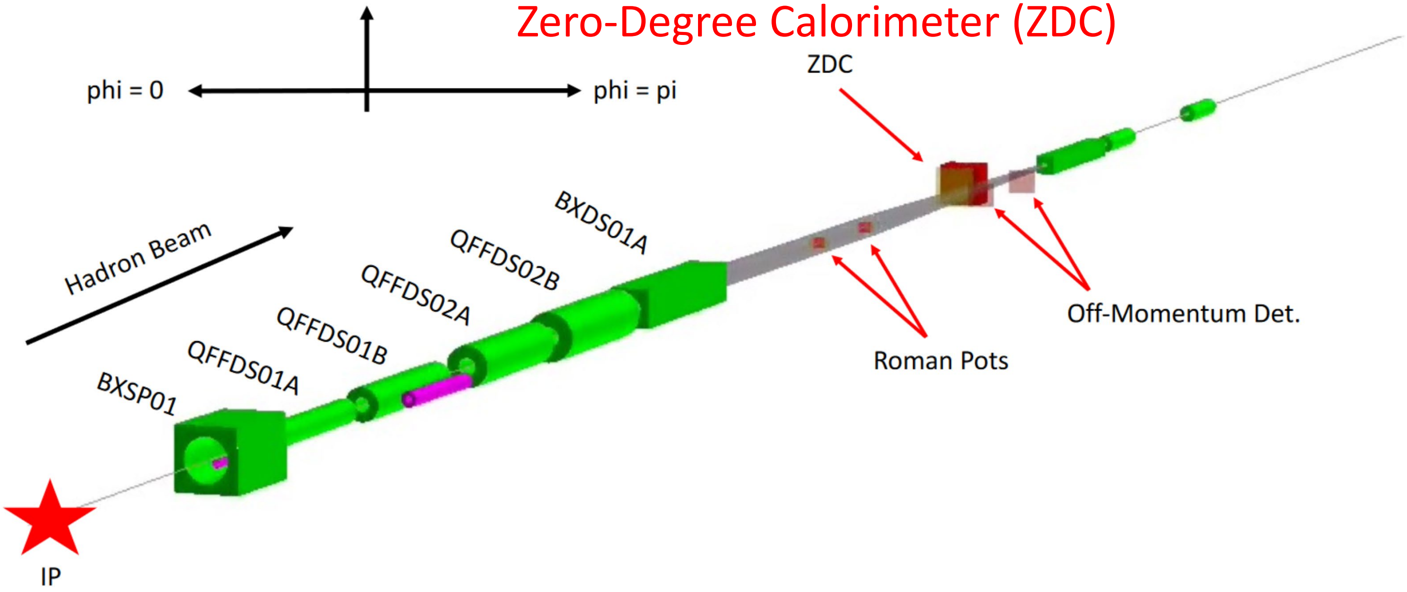
Detect "tagged" neutron/lambda



Far-forward calorimeter

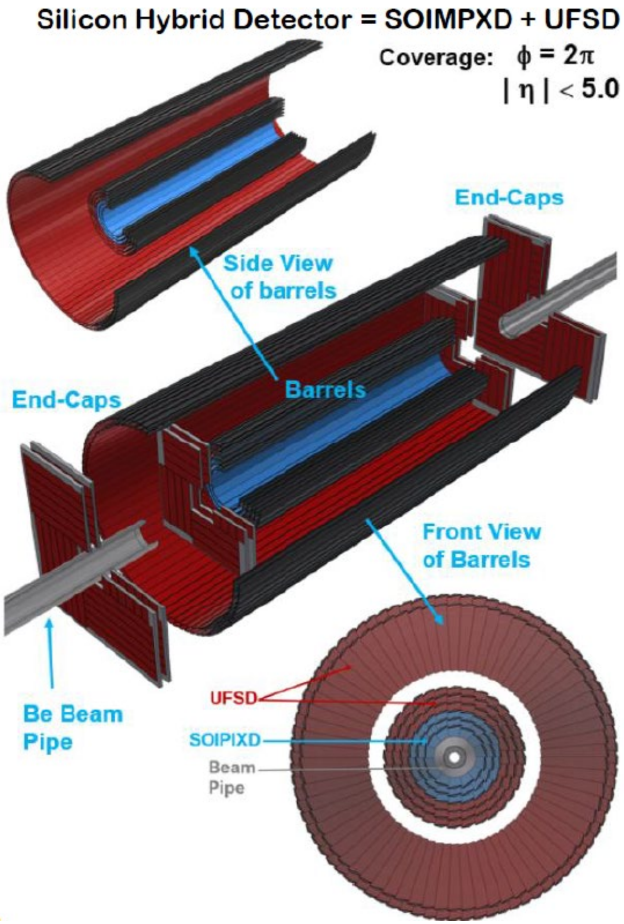
- EIC detector R&D program eRD27
  - “Developing a High Resolution ZDC for the EIC”
- Soft photon
  - Large aperture
  - Full absorption calorimeter
- EM & Hadron calorimeter ‘
  - Acceptance
  - Energy, position and p_T resolution
  - ALICE-FoCal R&D by RIKEN and Tsukuba U.
- Radiation hardness

Zero-Degree Calorimeter (ZDC)



Silicon detector

- Apply silicon sensor based on silicon-on-insulator monolithic pixel (SOIPIX) detector technology developed by KEK group
- SOIPIX is employed as the inner vertex detector of 4π silicon hybrid detector proposed by ANL and BNL collaborators



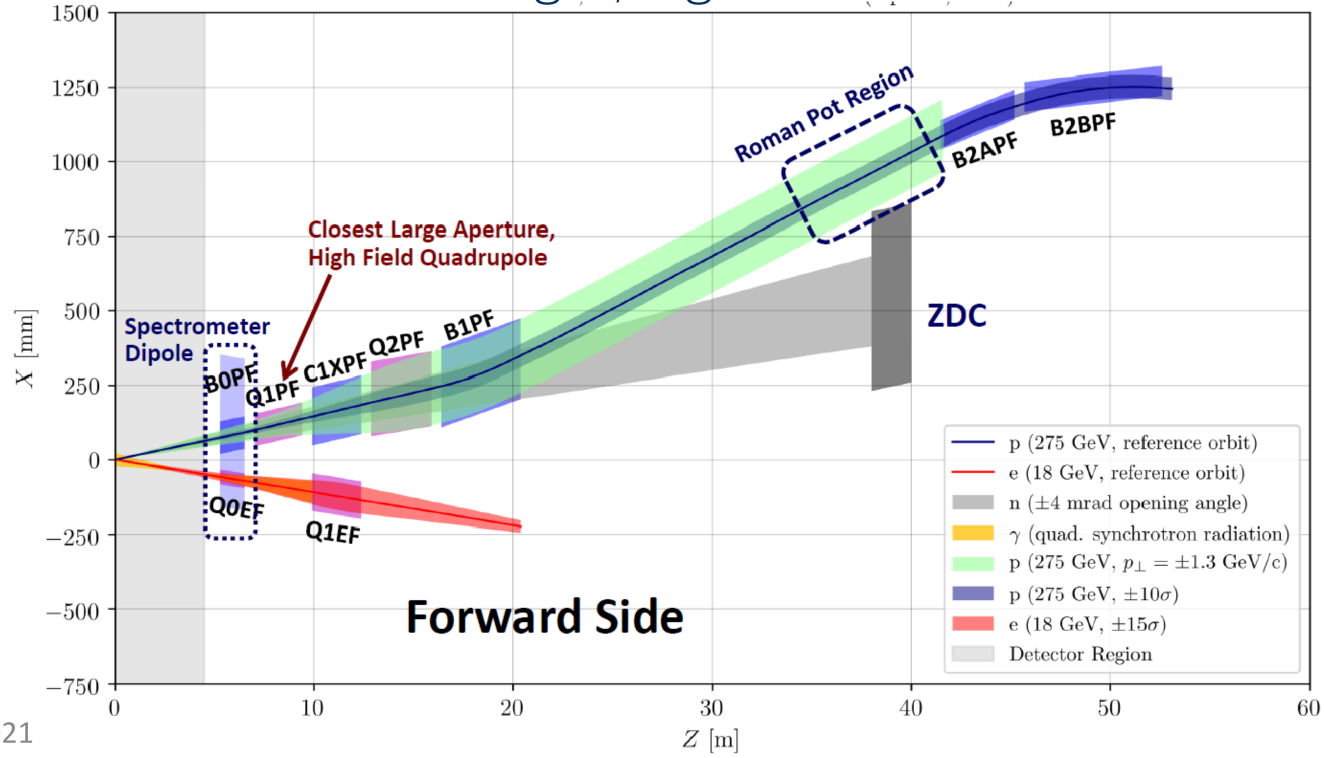
Summary

- EIC will be constructed at BNL
- Physics at EIC
  - Mass of the proton
  - Spin of the proton
  - Gluon saturation: discovery → property
- EIC status
  - Call for detector proposals
    - ECCE consortium
- EIC Japan activity
  - Forward hadron calorimeter
  - Far-forward calorimeter (EM & hadron)
    - Geometry tagging
    - Spectator tagging
    - Meson structure
  - Silicon detector

Backup Slides

Far-forward calorimeter

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

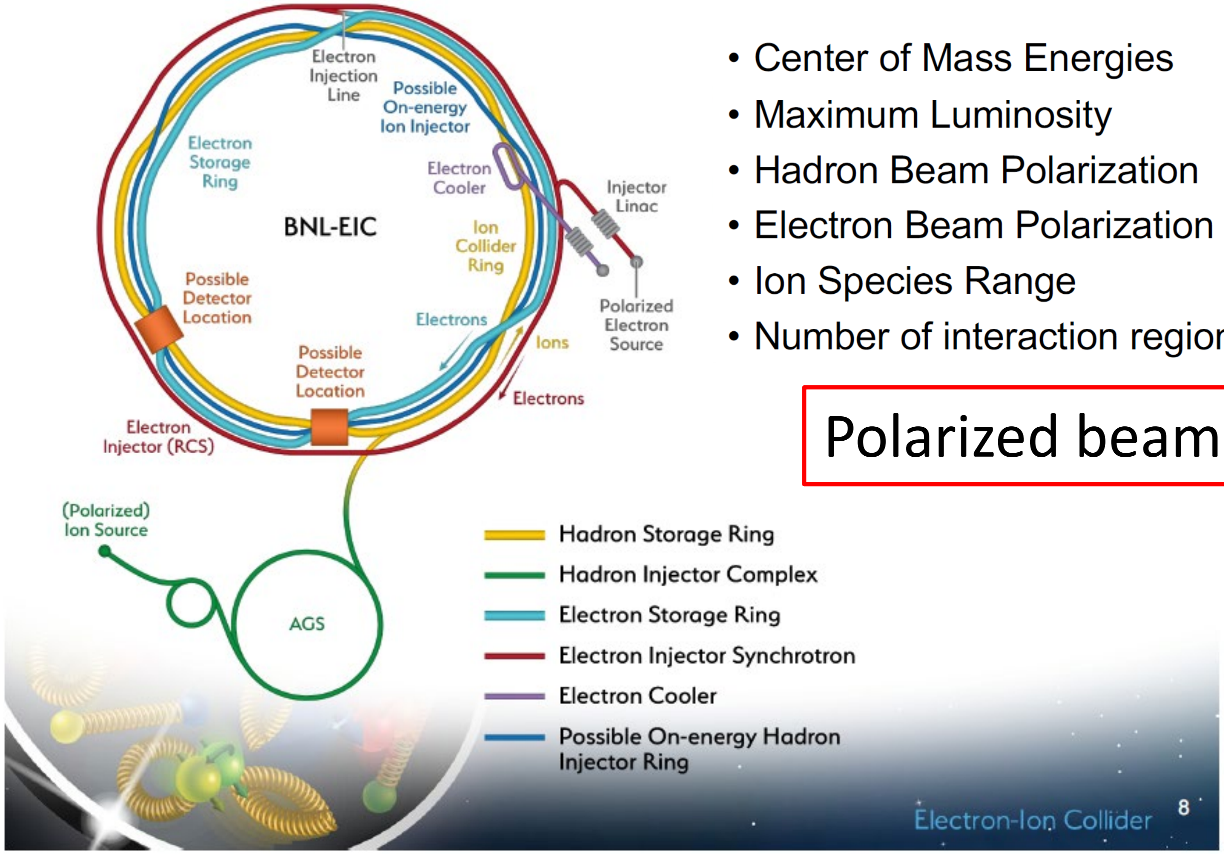


Silicon detector

- Physics
  - Heavy flavor quarks are highlighted at EIC as the ideal probe to study open questions in QCD, such as mass and flavor dependence of the energy loss, fragmentation and hadronization modification in the nuclear medium, nuclear parton distributions and so on
- The performance of the silicon sensors thus plays a crucial role to pursue the research in the heavy flavor physics in satisfactory level
  - key technology commonly employed for the heavy flavor detection by observing their decay vertex precisely

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

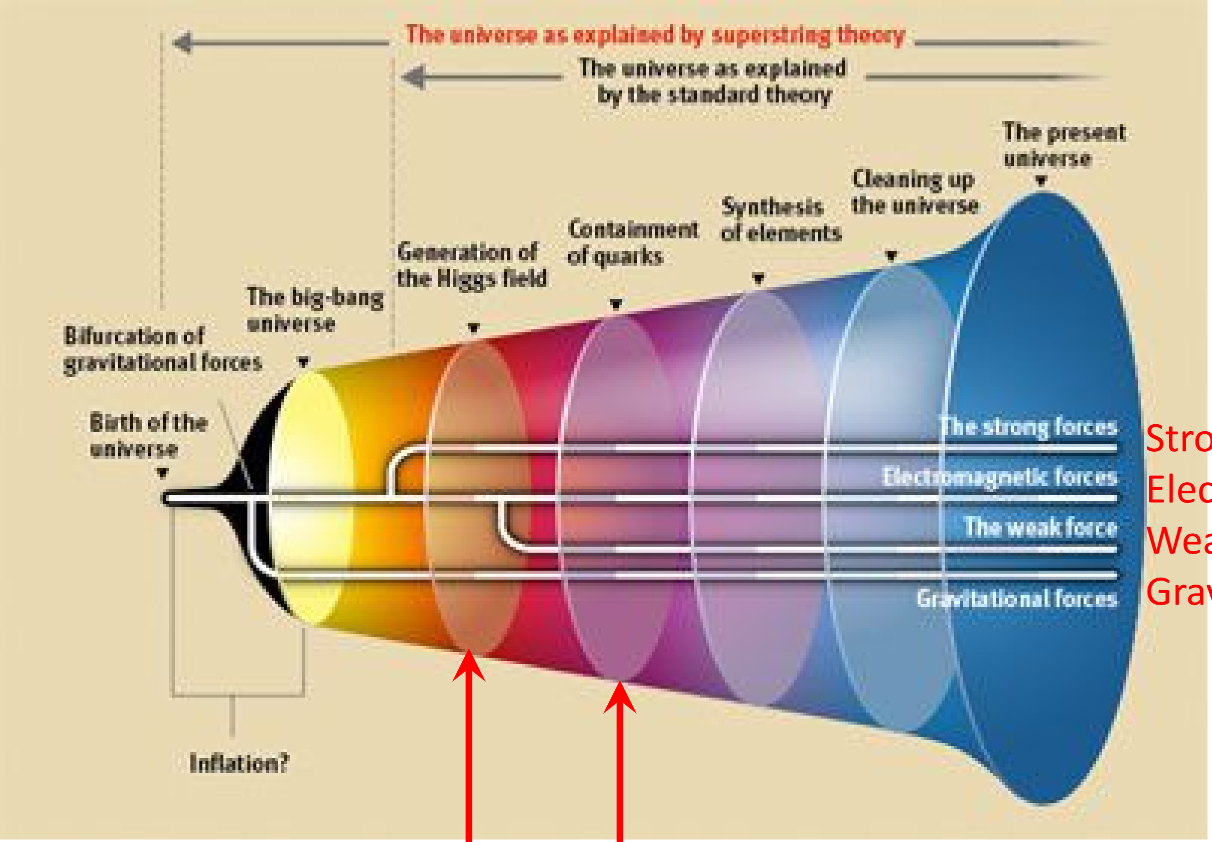


• Center of Mass Energies	20 GeV – 141 GeV
• Maximum Luminosity	10^{34} cm^{-2}s^{-1}
• Hadron Beam Polarization	80%
• Electron Beam Polarization	80%
• Ion Species Range	p to Uranium
• Number of interaction regions	up to two

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

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

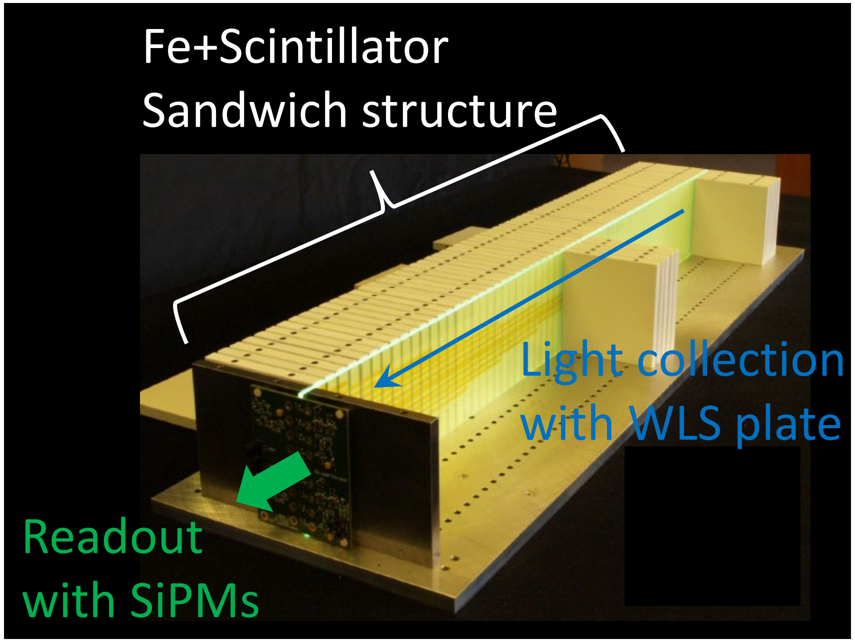
Confinement of quarks
Chiral symmetry breaking

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 → ν+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
  - $\sigma_E/E = 70\%/\sqrt{E}\,(\mathrm{GeV})$
  - Constant/noise terms?



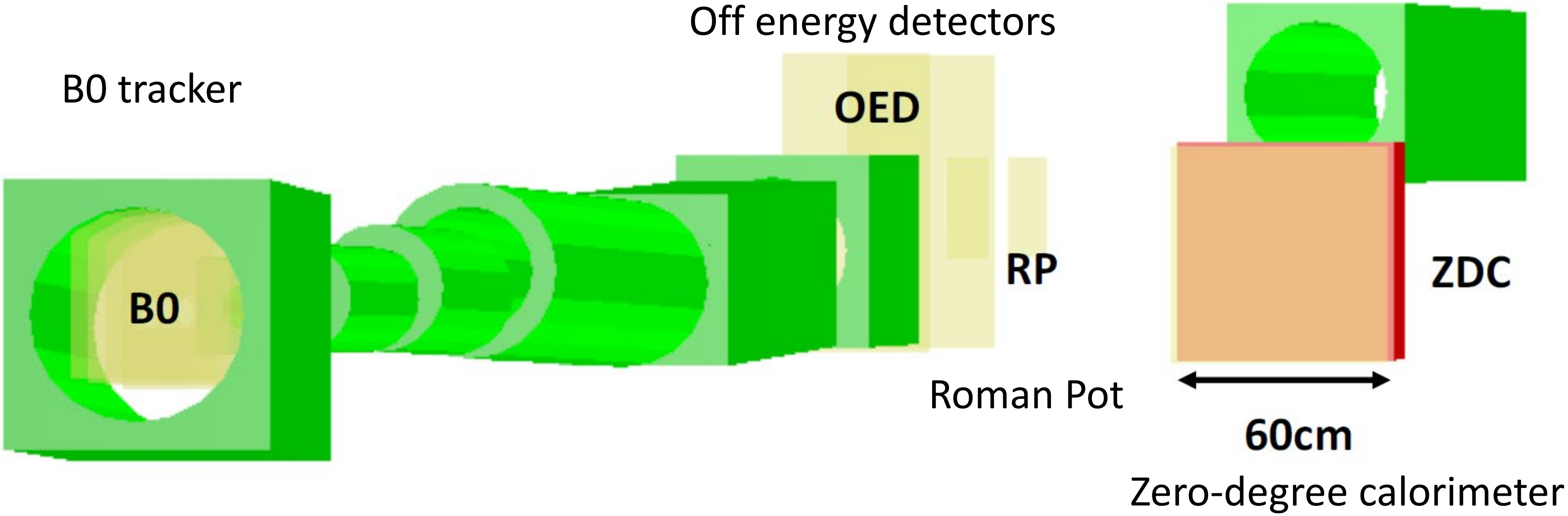
Far-forward physics at EIC

- Meson structures
  - Properties of the nearly massless pion are the cleanest expressions of the mechanism that is responsible for the emergence of the mass
  - Measurable implications for the pion form factor and meson structure functions
  - Effects of the Higgs mechanism play a more substantial role for the kaon mass due to its strange quark content
  - Comparison of the charged pion and charged kaon form factors over a wide range in Q^2 would provide unique information relevant to understanding the generation of hadronic mass

eRD27

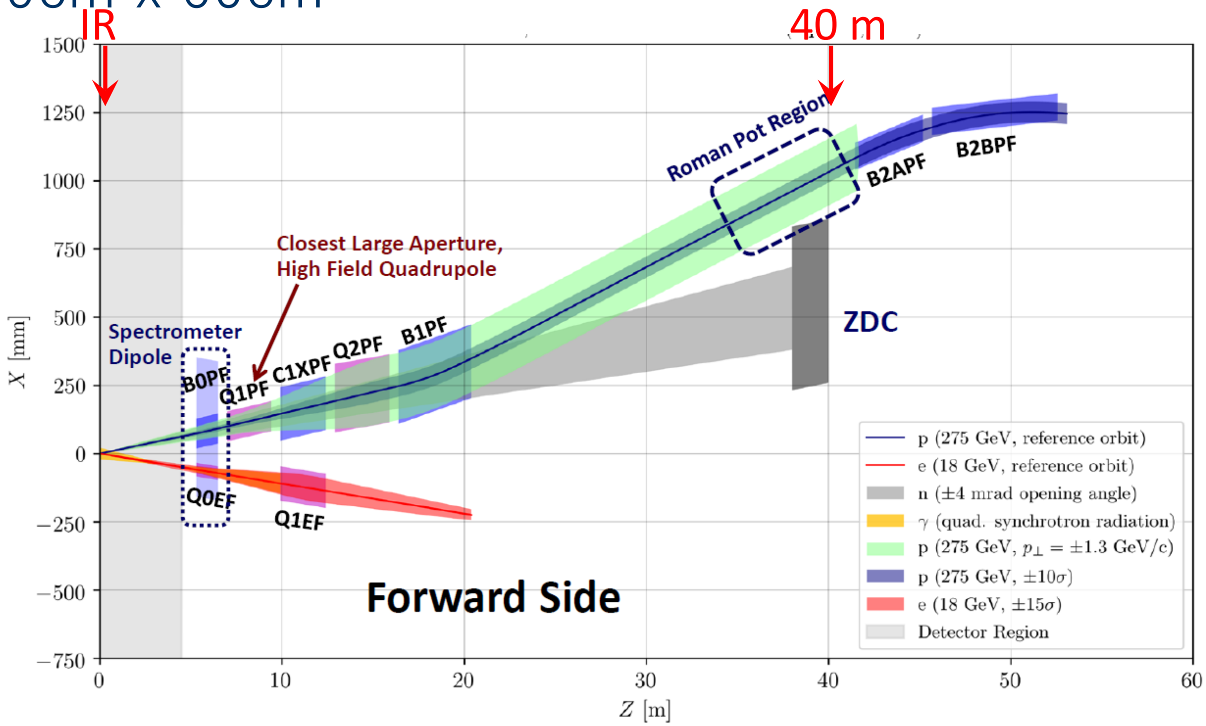
- General detector R&D program for an EIC
- eRD27 approved in 2020.8
- “Developing a High Resolution ZDC for the EIC”

Integrated forward system



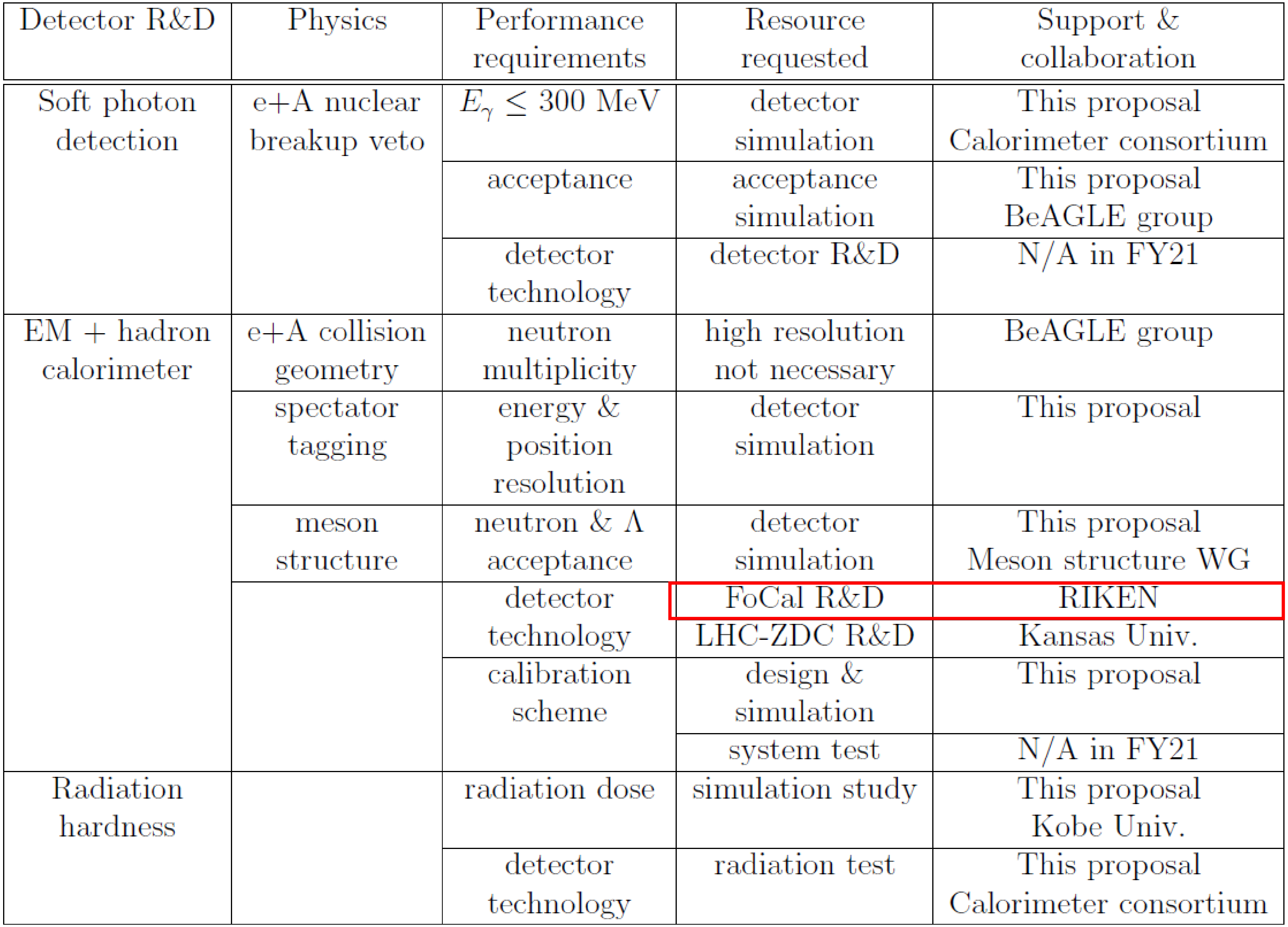
EIC IR design

- 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

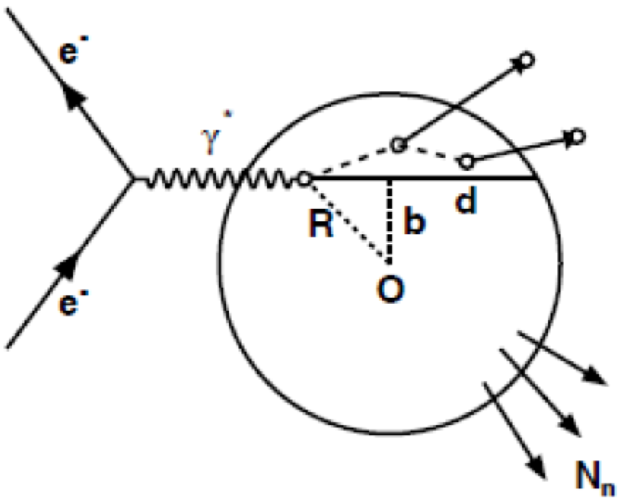
eRD27



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

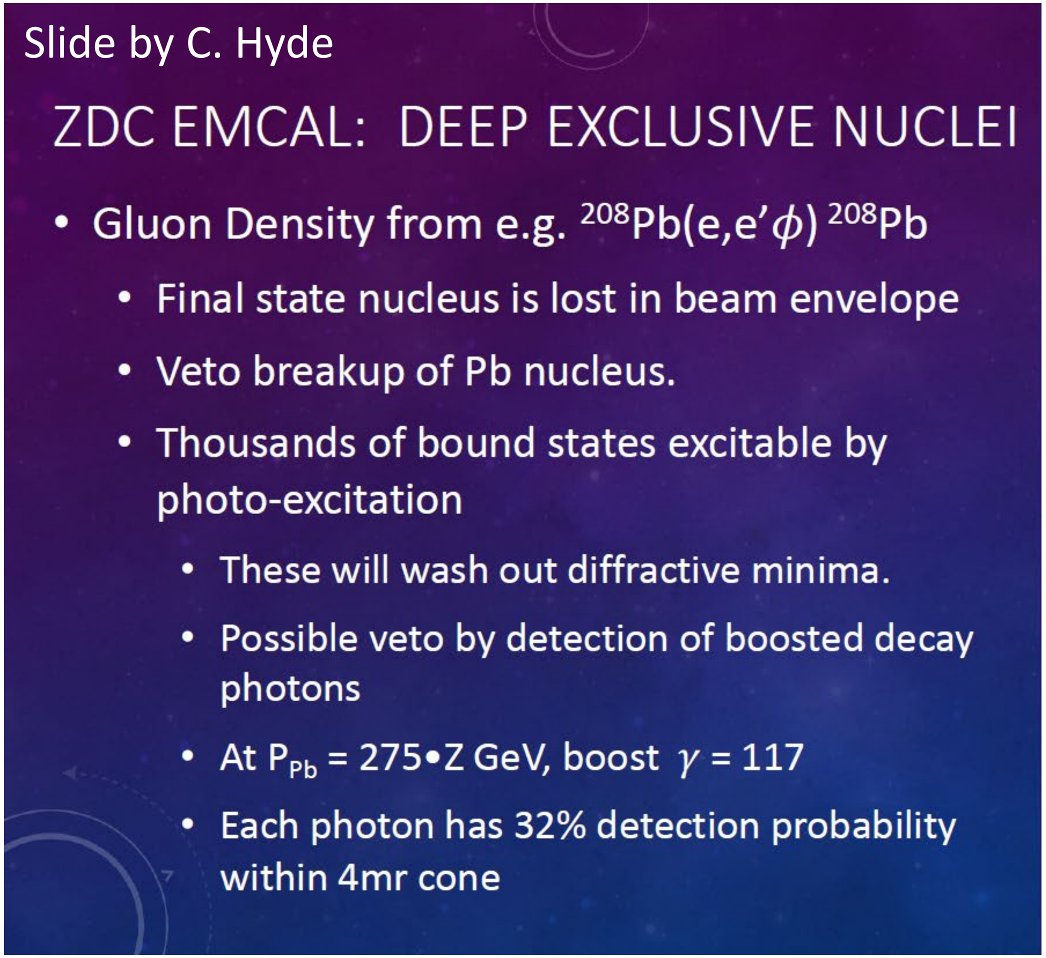
- Breakup of the excited nucleus
  - Evaporated neutrons (& protons)
    - Separate the coherent process ~90%
  - Photons from de-excitation of the excited nucleus
  - Requirement to measure neutrons and photons at zero degree in a wide *t* range
- Event-by-event characterization of collision geometry
  - 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)

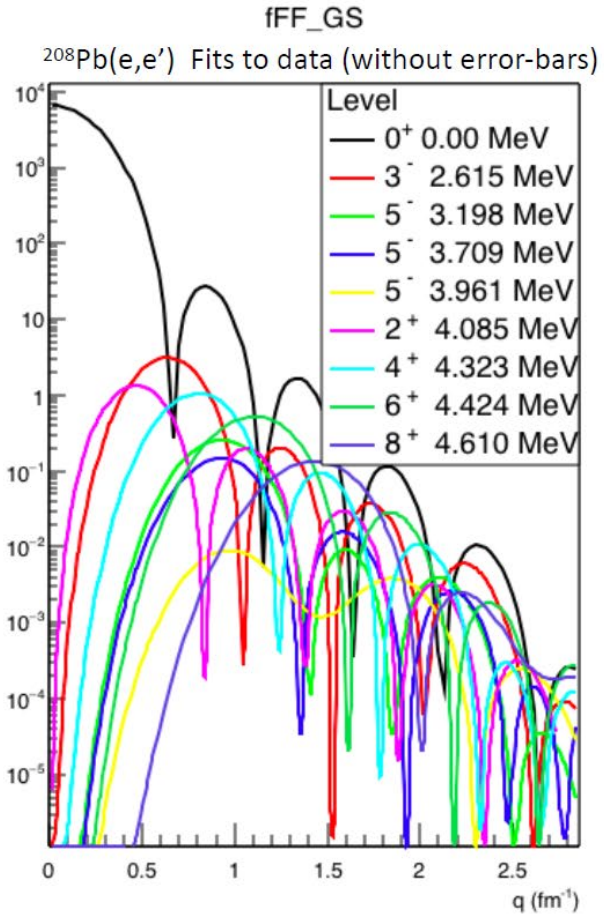
e + A collision at zero degree



Slide by C. Hyde

ZDC EMCAL: DEEP EXCLUSIVE NUCLEI

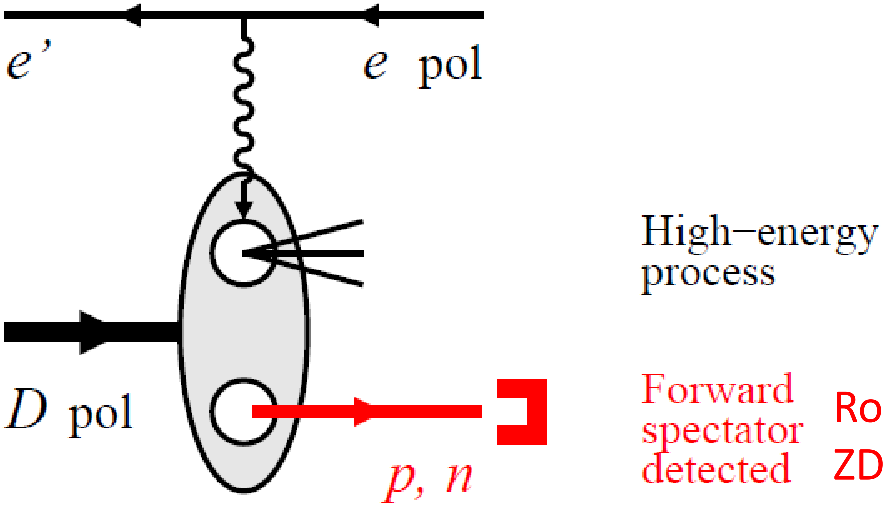
- Gluon Density from e.g. ^{208}Pb(e,e′ϕ) ^{208}Pb
  - Final state nucleus is lost in beam envelope
  - Veto breakup of Pb nucleus.
  - Thousands of bound states excitable by photo-excitation
    - These will wash out diffractive minima.
    - Possible veto by detection of boosted decay photons
    - 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

$e + d/^3He$ 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*

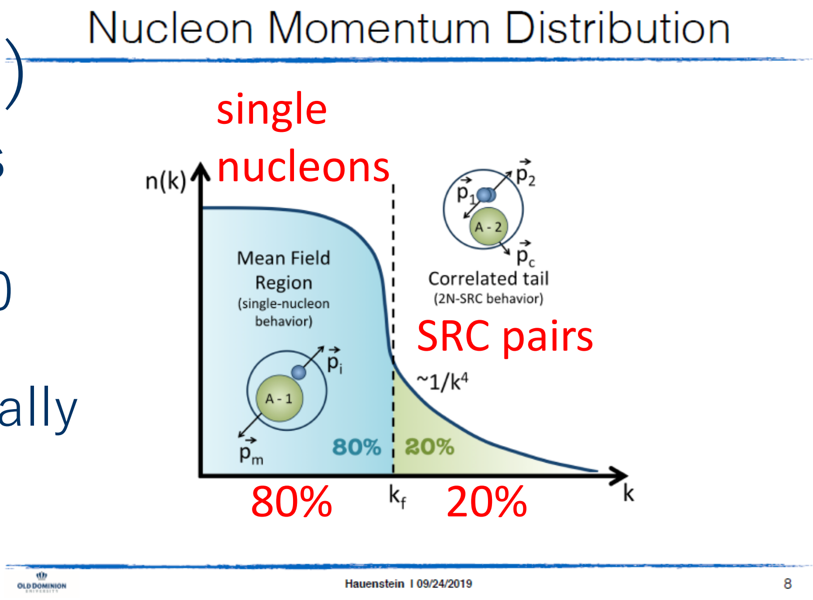


Roman pot

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



Nucleon Momentum Distribution

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Hauenstein I 09/24/2019

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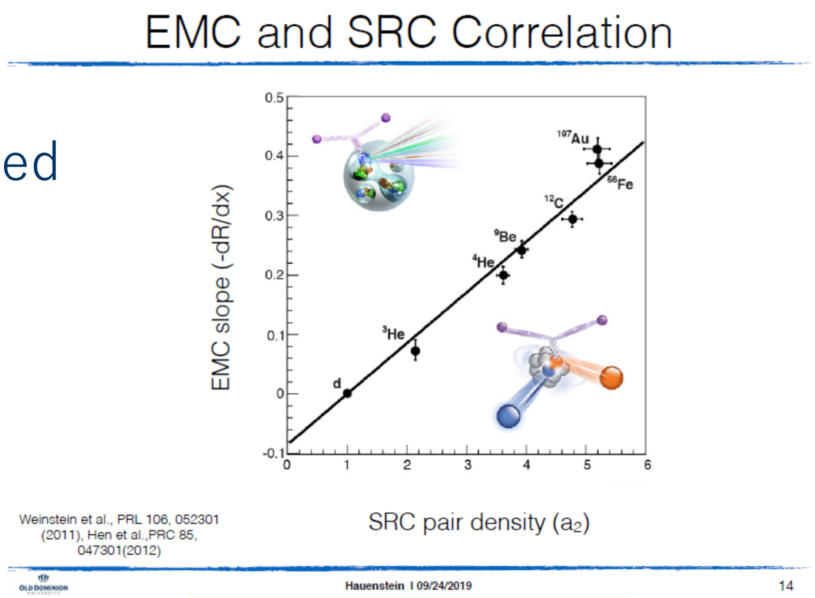

EMC and SRC Correlation

Weinstein et al., PRL 106, 052301 (2011), Hen et al.,PRC 85, 047301(2012)

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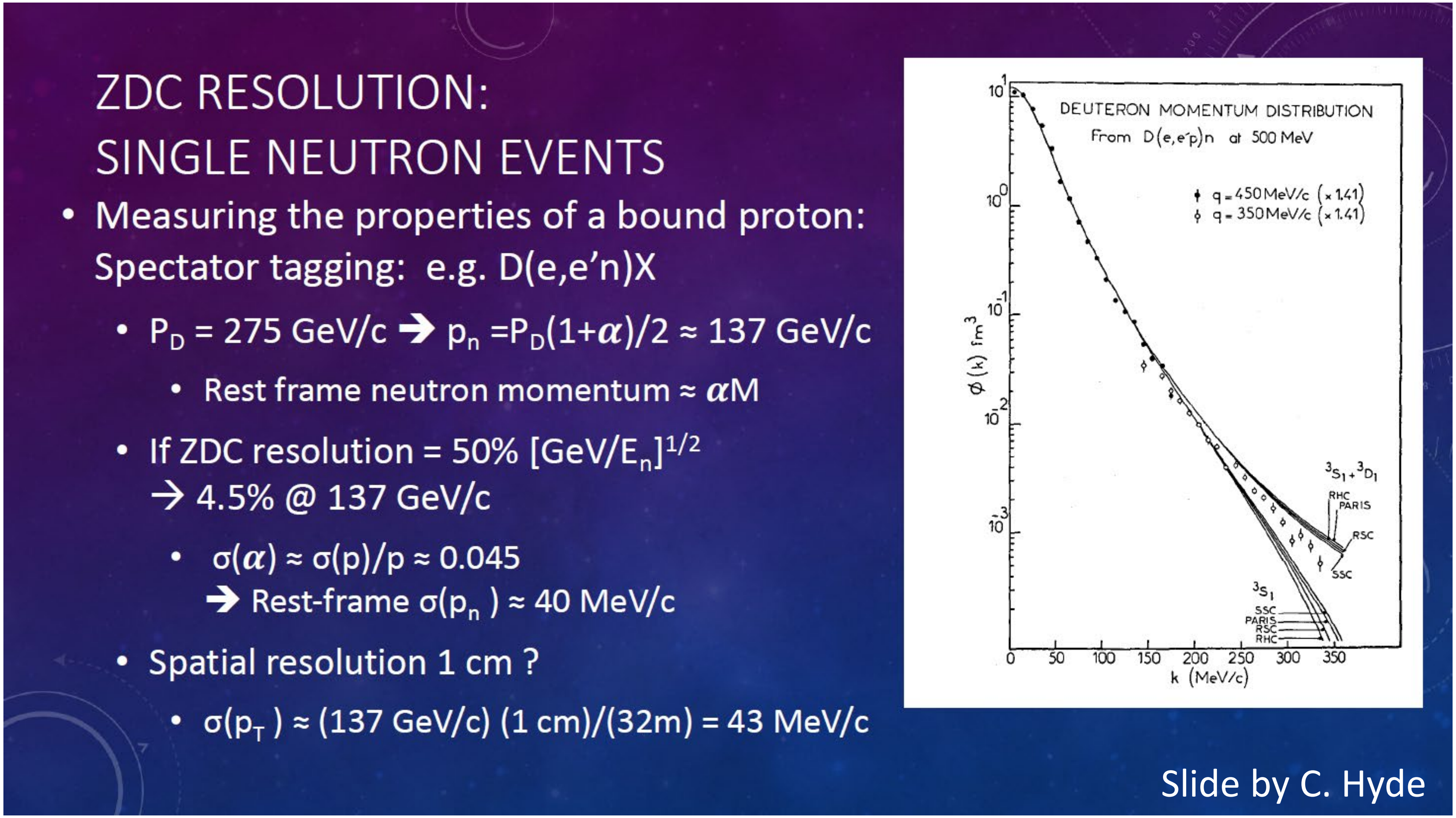
slides by Heuenstein

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 $\approx \alpha M$
  - 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

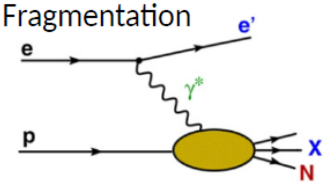
Slide by C. Hyde

- 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

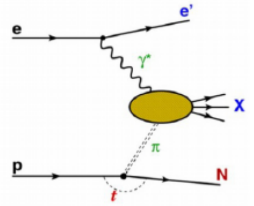
Physics at zero degree of EIC

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

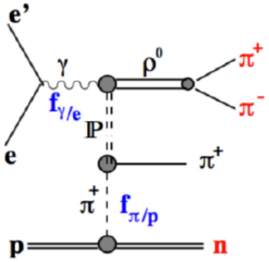
Fragmentation



One Pion Exchange (OPE)



LN in DIS

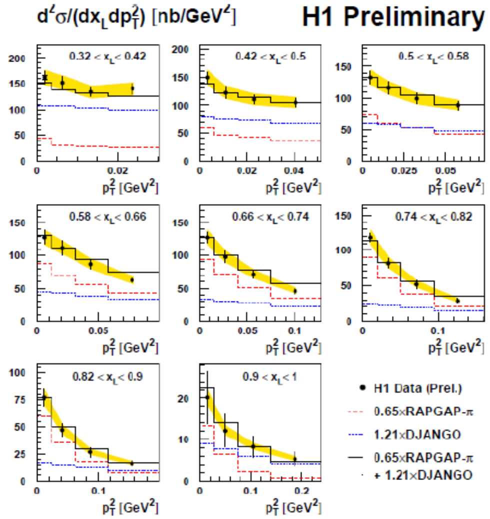


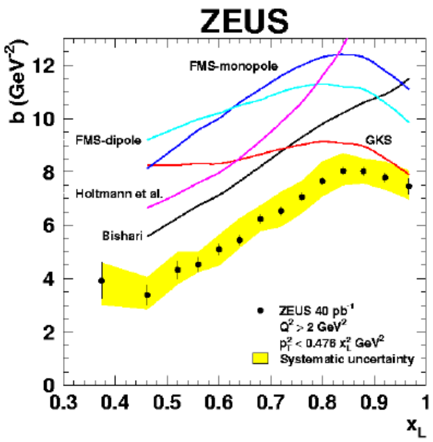
$$d\sigma_{\gamma^* p\to nx} = f_{\pi/p}(x_L,t)\times d\sigma_{\gamma^*\pi\to X}$$

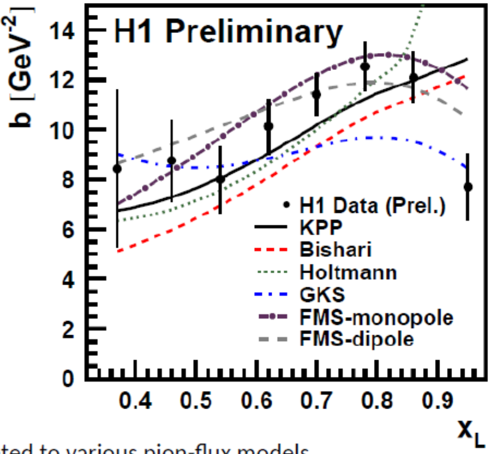
The distribution of p_T^2 (=t) is defined solely by the pion flux

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

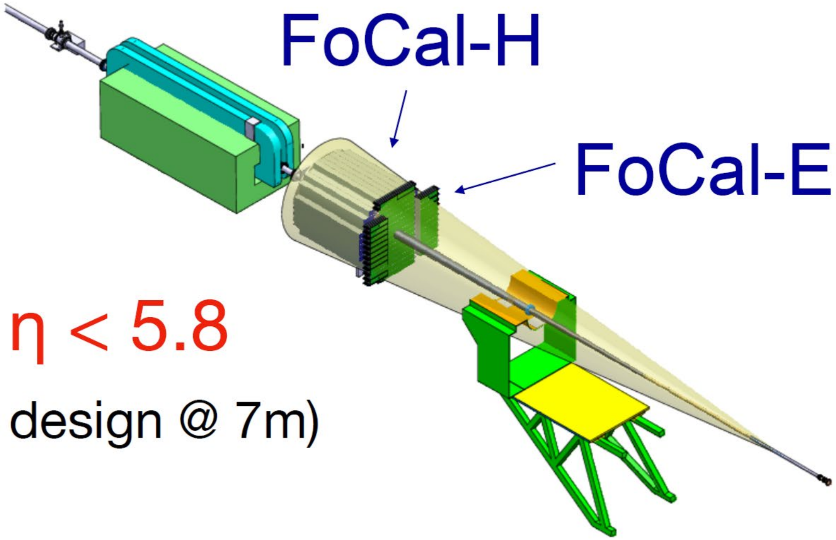
slide by Ciesielski

Inconsistency @ HERA

→ Need more data to understand production mechanism

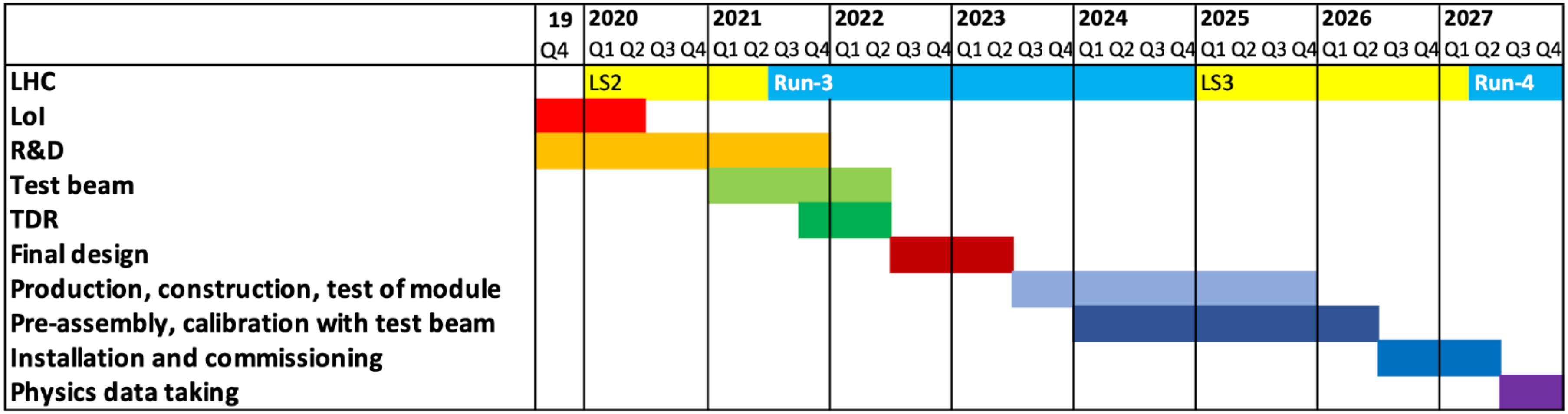
ALICE FoCal

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



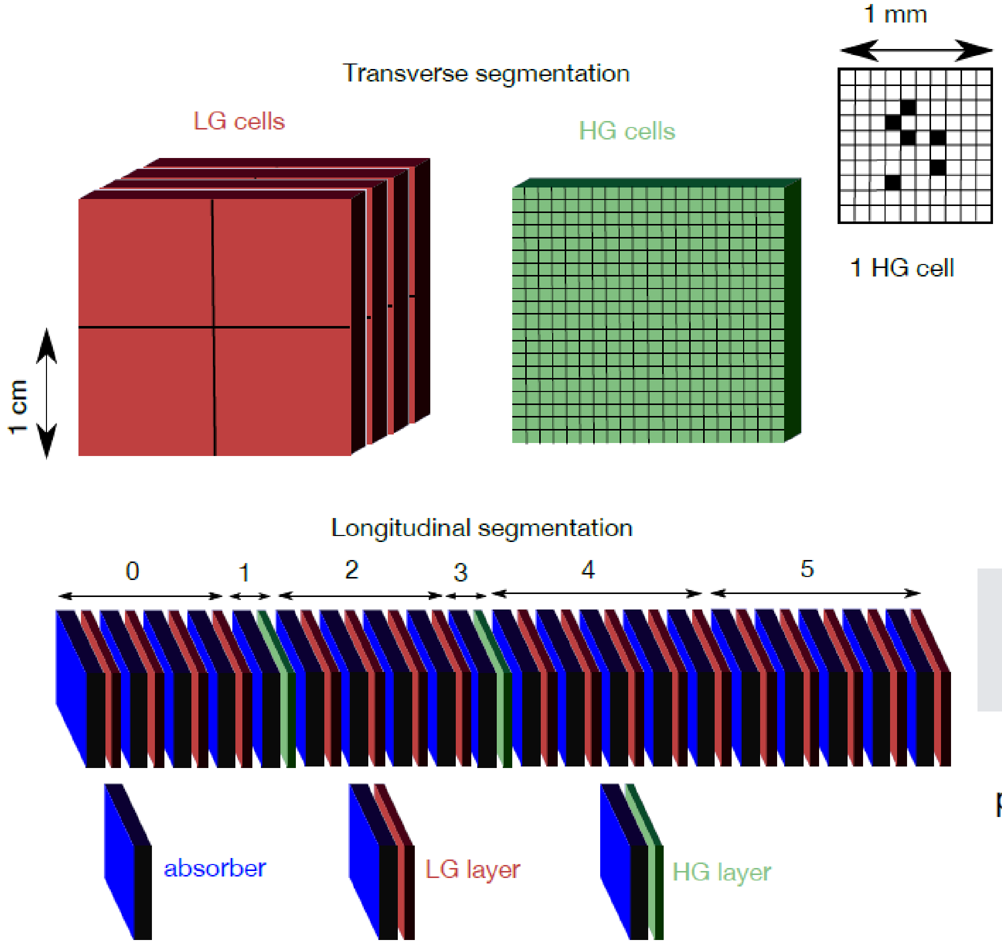
$3.4 < \eta < 5.8$

(baseline design @ 7m)



	19	2020				2021				2022				2023				2024				2025				2026				2027			
	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
LHC		LS2	■	■	■	■	■	Run-3	■	■	■	■	■	■	■	■	■	■	■	■	■	LS3	■	■	■	■	■	■	■	■	Run-4	■	■
LoI	■	■	■																														
R&D	■	■	■	■	■	■	■	■	■																								
Test beam						■	■	■	■	■	■																						
TDR									■	■	■																						
Final design												■	■	■	■																		
Production, construction, test of module																■	■	■	■	■	■	■	■	■	■								
Pre-assembly, calibration with test beam																		■	■	■	■	■	■	■	■	■	■						
Installation and commissioning																												■	■	■	■		
Physics data taking																																■	■

FoCal-E basic design



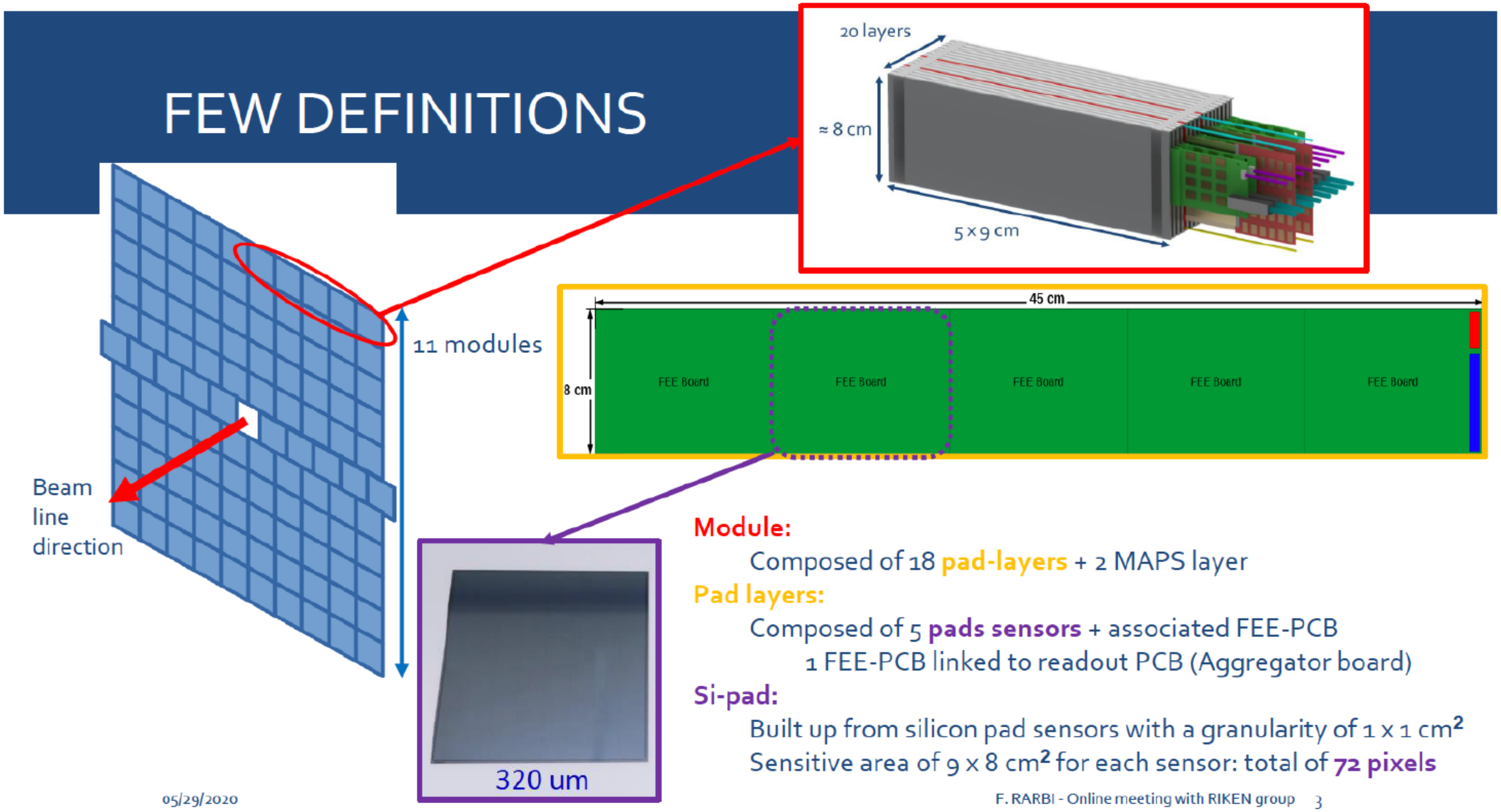
The design of the detector:

- 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 cm²	≈ 30x30 μm²
total # of pixels/pads	≈ 2.5 x 10^5	≈ 2.5 x 10^9

The surface area of the detector will be about 1 m²

ALICE FoCal-E



FEW DEFINITIONS

Module:

Composed of 18 **pad-layers** + 2 MAPS layer

Pad layers:

Composed of 5 **pads sensors** + associated FEE-PCB

1 FEE-PCB linked to readout PCB (Aggregator board)

Si-pad:

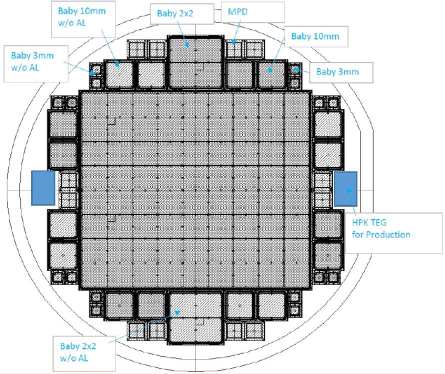
Built up from silicon pad sensors with a granularity of 1 x 1 cm^2

Sensitive area of 9 x 8 cm^2 for each sensor: total of **72 pixels**

05/29/2020

F. RARBI - Online meeting with RIKEN group 3

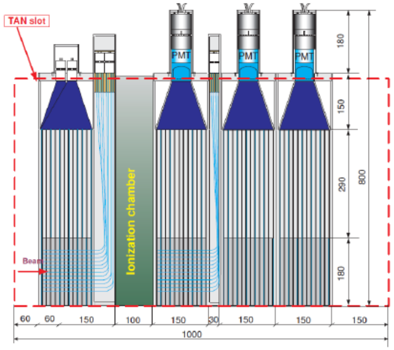
New silicon pad sensor for final FoCal

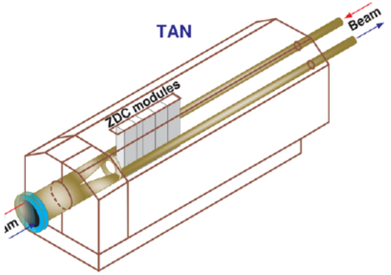


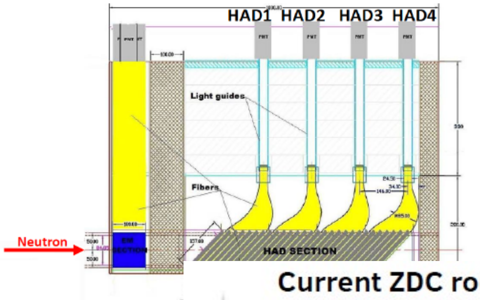
ZDC at LHC

slides by Longo

- ATLAS & CMS ZDC
  - W-quartz sampling calorimeter





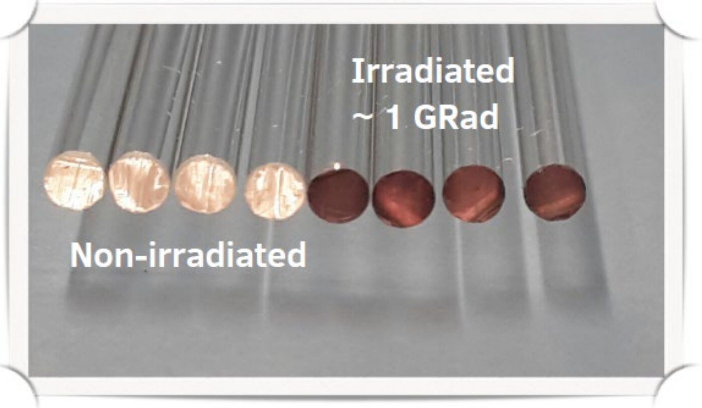


See talk by
E. Adams

- 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

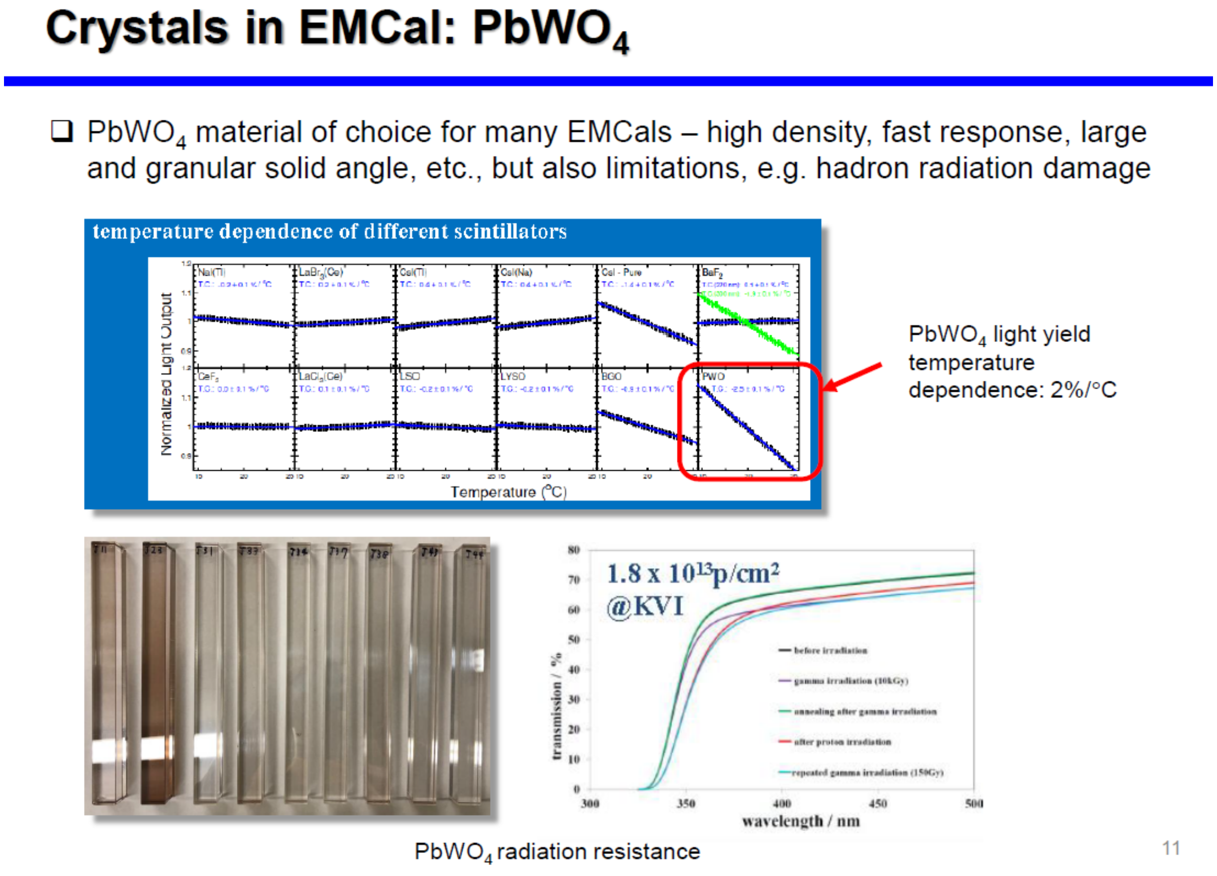
Current ZDC rods (GE 214 fused quartz)



- 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: $PbWO_4$

☐ $PbWO_4$ 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

Slide by T. Horn

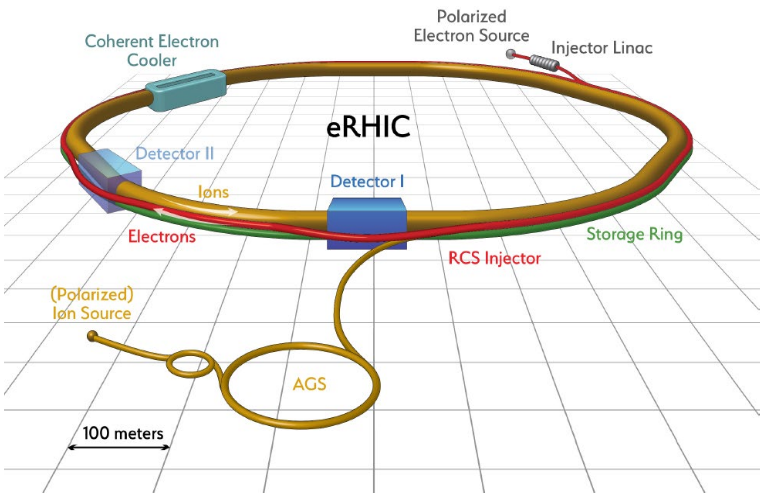
Summary

- EIC will be constructed at BNL
- Physics at EIC
  - Mass of the proton
  - Spin of the proton
  - Gluon saturation (discovery → 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

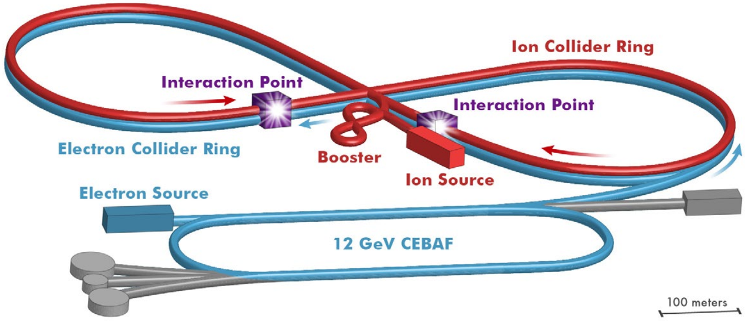
EIC - Electron Ion Collider

- High-energy QCD frontier to study nucleon (hadron) and nucleus (cold nuclear matter) from quarks and gluons
- World's first polarized electron + proton / light-ion / heavy-ion collider
  - Wide (Q^2, x) region
- Electron + proton / light-ion collision
  - Polarized beam
    - e, p, d/^{3}He
  - High luminosity
    - $L_{ep} \sim 10^{33\text{-}34}\ \mathrm{cm^{-2}s^{-1}}$
    - 100-1000 times HERA
  - Collision energy
    - $\sqrt{s} = 20 – 100\ (140)$ GeV
- Electron + heavy-ion collision
  - Wide range in nuclei

eRHIC at BNL

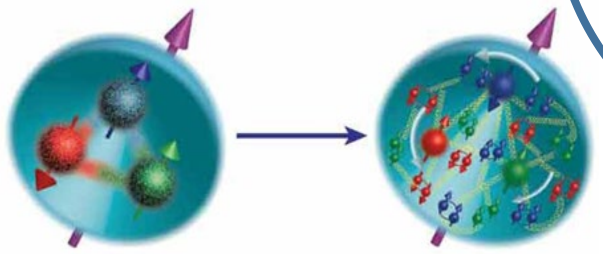


JLEIC at Jefferson Lab



Physics at EIC

Understanding how the nucleon structure and properties emerge from quarks and gluons and their interactions from QCD

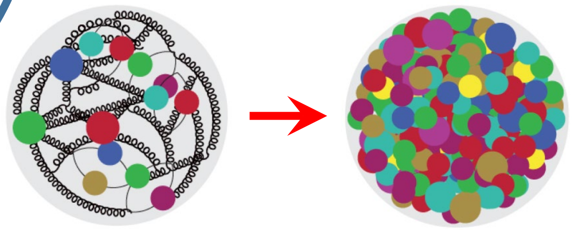


How does the mass of the nucleon arise?

3D Picture of the Nucleons and Nuclei

- *Transverse -Momentum Distribution and Spatial Imaging*
- *Orbital Motion of Quarks and Gluons Inside*

Systematic understanding of the structure of nucleons and nuclei covering the wide kinematic range



New Picture

Precision Measurement

Luminosity

Collision Energy

Discovery

How does the spin of the nucleon arise?

Spin and Flavor Structure of the Nucleons and Nuclei

- *Gluon Polarization*
- *Quarks and Gluons Inside the Nuclei*
- *Hadronization*

What are the emergent properties of dense systems of gluons?

Gluon Saturation at Extreme Density

- *Initial State of the QGP (Quark-Gluon Plasma)*

Spin

- Quark-gluon structure
  - Parton distribution function (PDF) of quarks and gluons
  - *x* : momentum fraction of quarks and gluons
- Spin puzzle
  - Gluon polarization measurement with polarized DIS
    - Small Bjorken-x region with QCD evolution (DGLAP equation)

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

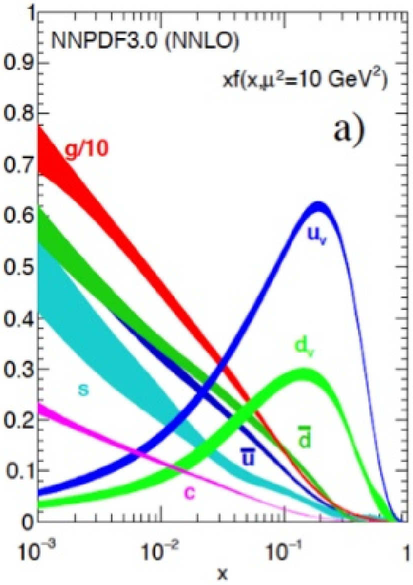
$\Delta\Sigma/2$ = Quark contribution to Proton Spin

L_Q = Quark Orbital Ang. Mom

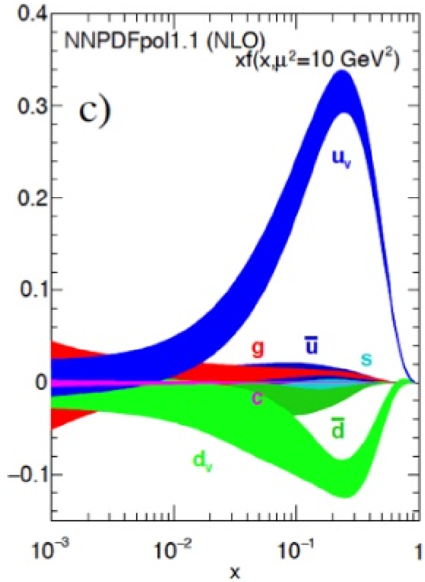
Δg = Gluon contribution to Proton Spin

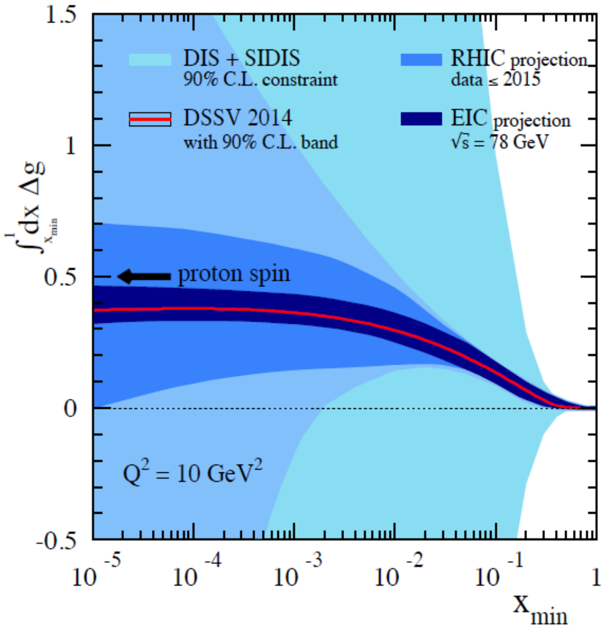
L_G = Gluon Orbital Ang. Mom

Unpolarized PDF



Polarized PDF

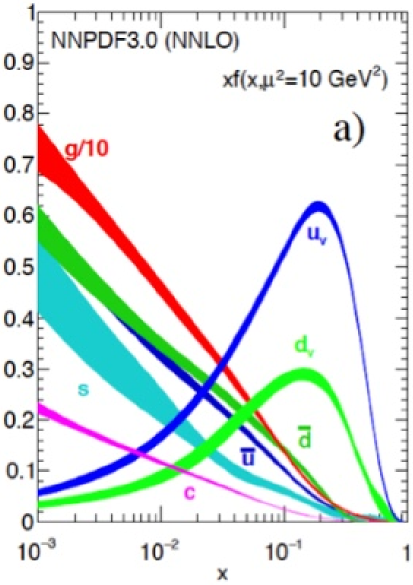




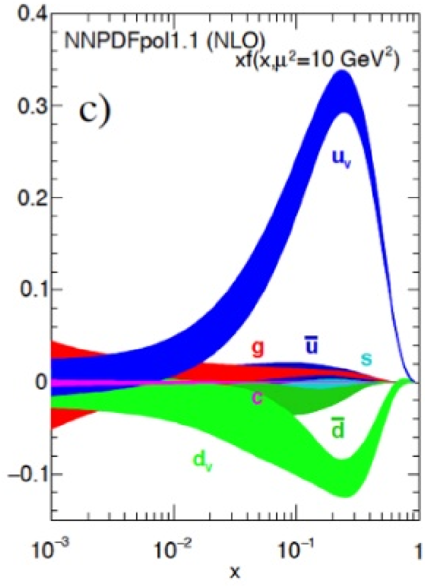
Quark-gluon structure

- 1-D picture
  - Parton distribution function (PDF) of quarks and gluons
  - *x*: momentum fraction of quarks and gluons
  - Significant improvement of precision of the polarized PDF at EIC
    - especially gluon polarization
- 3-D picture
  - Generalized parton distribution (GPD) function
    - charge distribution
    - magnetic-moment distribution
    - mass distribution
  - Comparison of radii (R)
  - New picture to be established at EIC

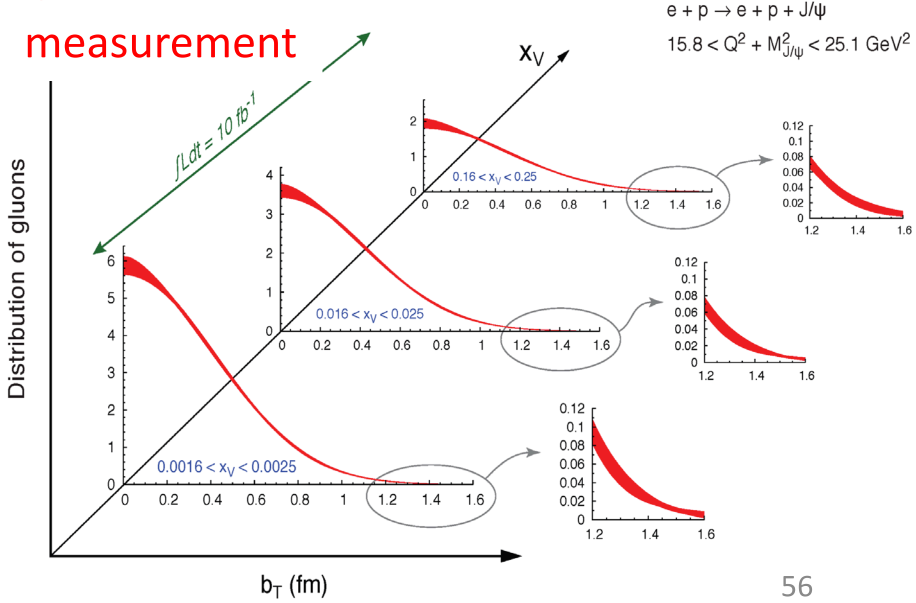
Unpolarized PDF



Polarized PDF

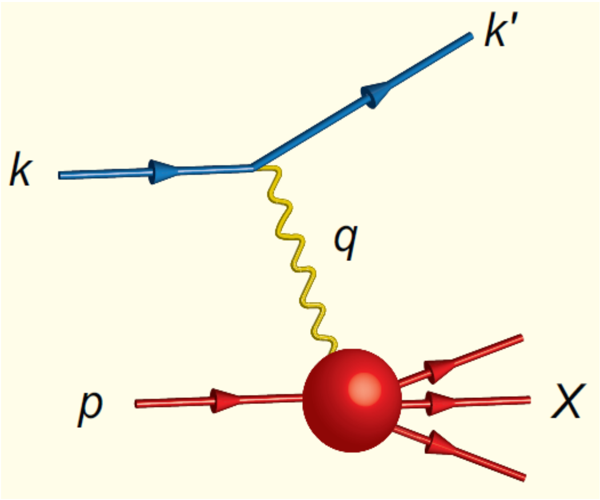


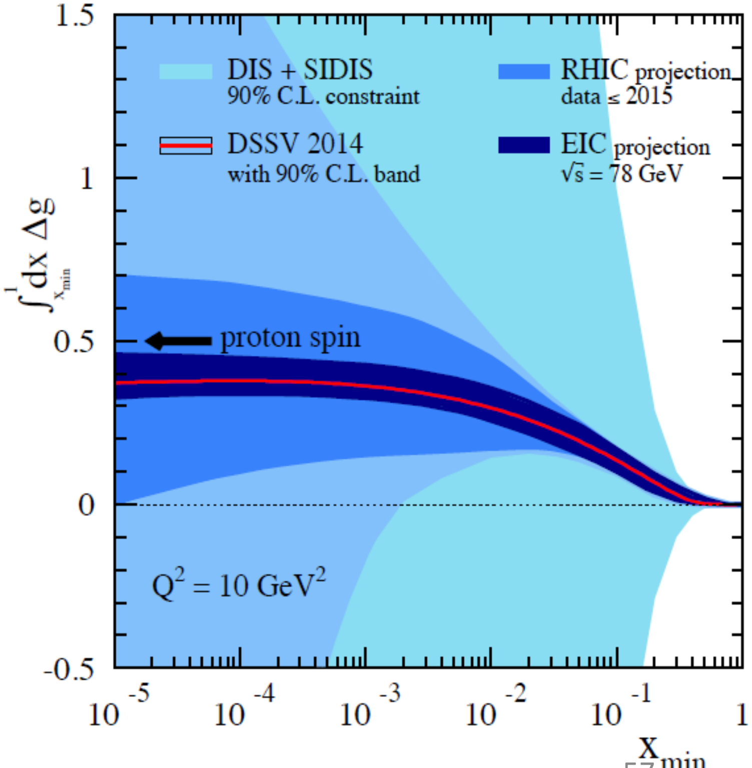
GPD measurement



Precision measurement of PDFs

- Inclusive DIS
  - Large Q^2 ($Q^2 = -q^2$) provides a hard scale to resolve quarks and gluons in the proton
  - 1D longitudinal motion of partons
- Spin puzzle
  - Gluon polarization measurement with polarized DIS
    - Small Bjorken-x region with QCD evolution (DGLAP equation)





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

$\Delta\Sigma/2$ = Quark contribution to Proton Spin

L_Q = Quark Orbital Ang. Mom

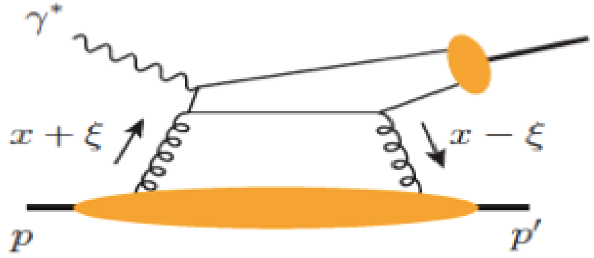
Δg = Gluon contribution to Proton Spin

L_G = Gluon Orbital Ang. Mom

3D structure of the nucleus

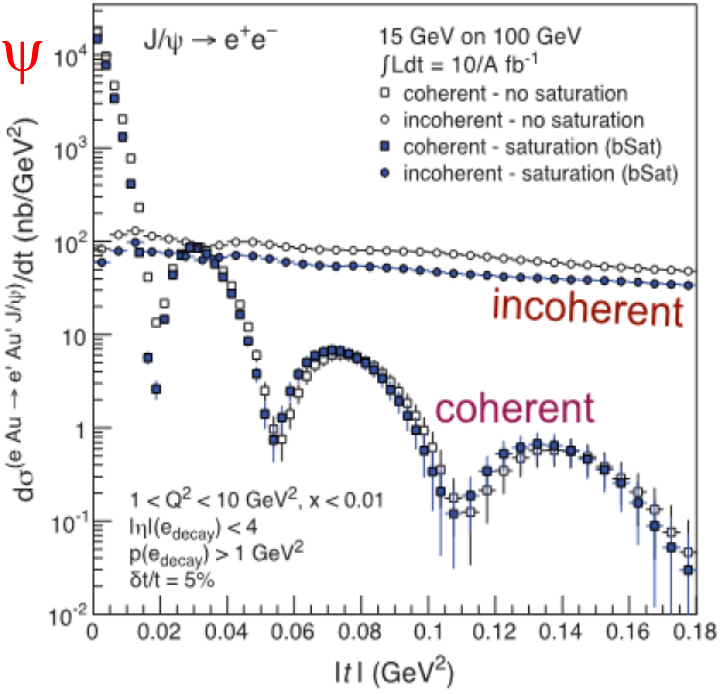
- Diffractive vector meson production
  - ϕ meson sensitive to the gluon saturation

Meson Production

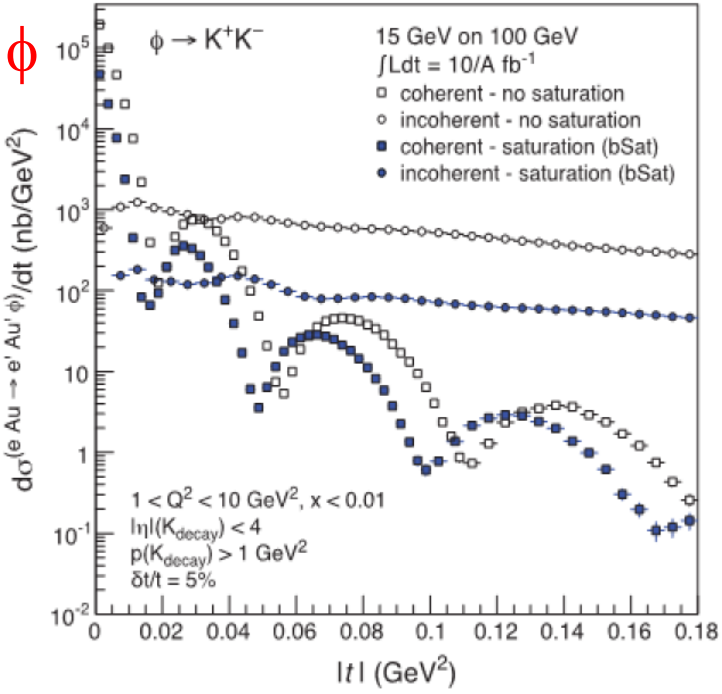


J/ψ, ϕ, ρ, etc.

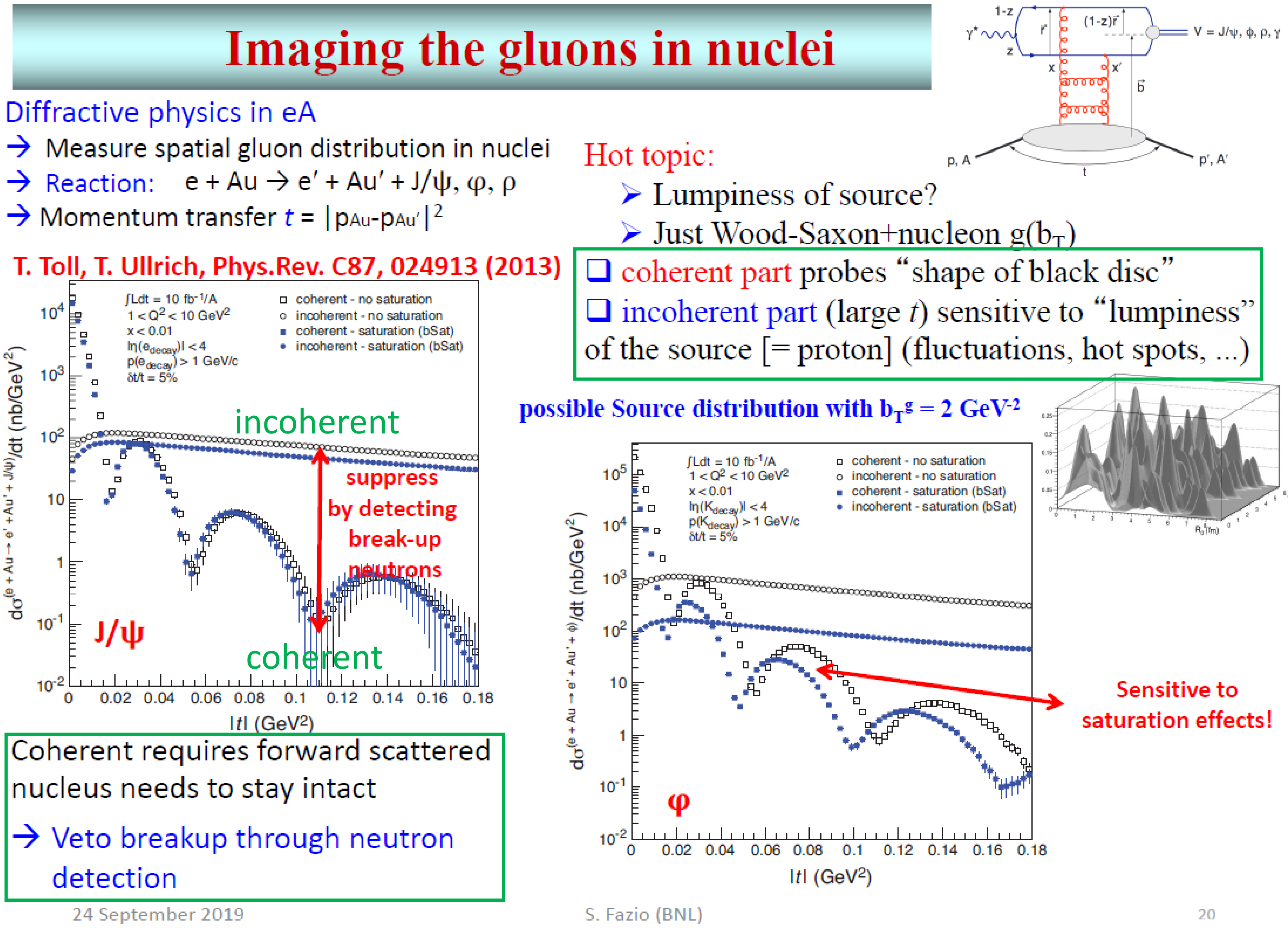
J/ψ



ϕ



GPD studies with exclusive processes



Imaging the gluons in nuclei

Diffractive physics in eA

→ Measure spatial gluon distribution in nuclei

→ Reaction: e + Au → e′ + Au′ + J/ψ, φ, ρ

→ Momentum transfer $t = |p_{Au} - p_{Au'}|^2$

Hot topic:

- ➢ Lumpiness of source?
- ➢ Just Wood-Saxon+nucleon $g(b_T)$

❑ coherent part probes “shape of black disc”

❑ incoherent part (large *t*) sensitive to “lumpiness” of the source [= proton] (fluctuations, hot spots, ...)

T. Toll, T. Ullrich, Phys.Rev. C87, 024913 (2013)

Coherent requires forward scattered nucleus needs to stay intact

→ Veto breakup through neutron detection

possible Source distribution with $b_T^g = 2$ GeV^{-2}

Sensitive to saturation effects!

24 September 2019

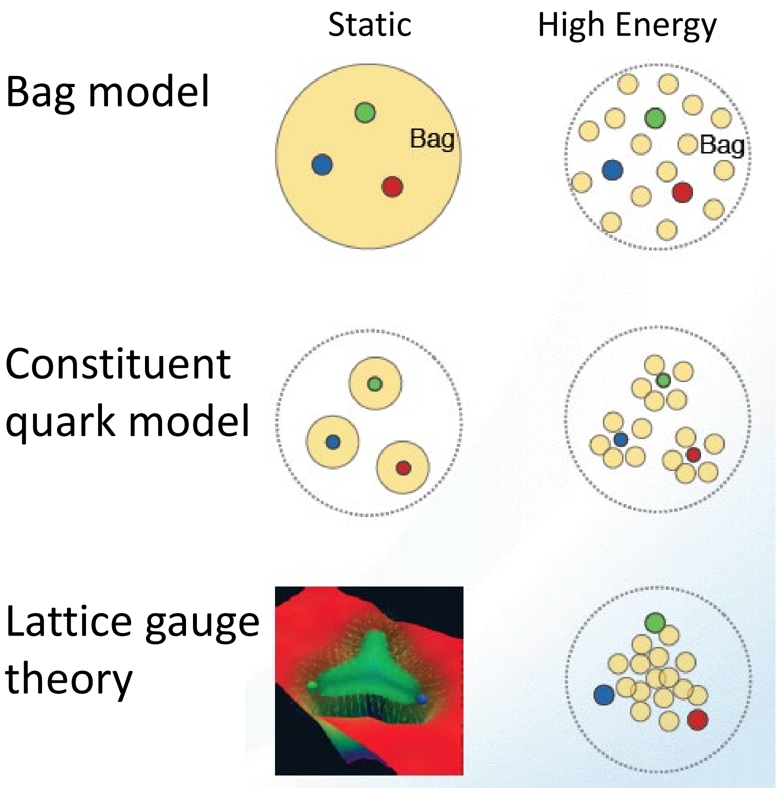
S. Fazio (BNL)

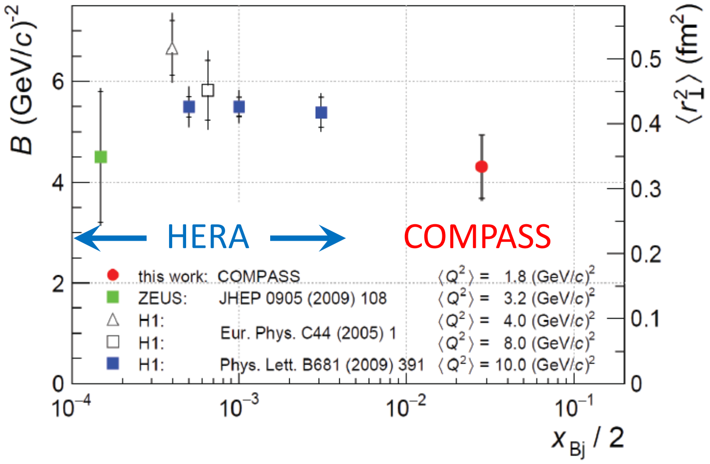
20

slide by Fazio

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



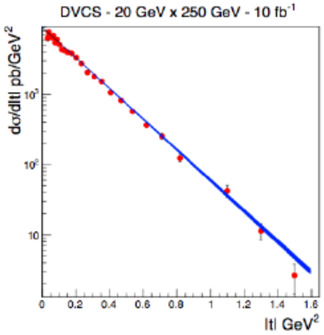


Physics at zero degree of EIC

- Very forward proton acceptance for DVCS exclusive measurement

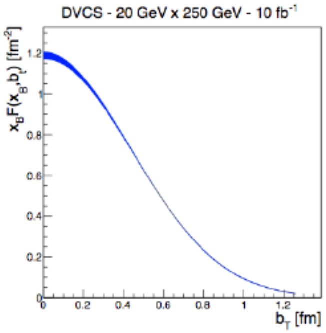
Measurement

Physics observable (cross-section vs impact parameter)



Plots from EIC White Paper:

Fourier transform

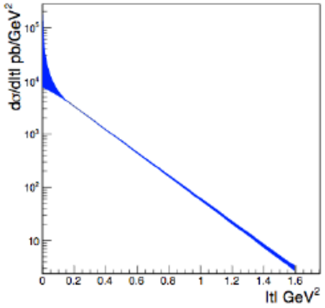


Requirement:

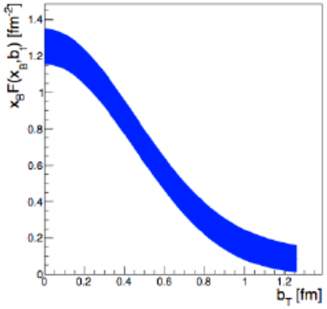
$\int L_{int} = 10 fb^{-1}$

$0.18 < p_t$ (GeV) < 1.3

$0.03 < |t|$ (GeV^2) < 1.6



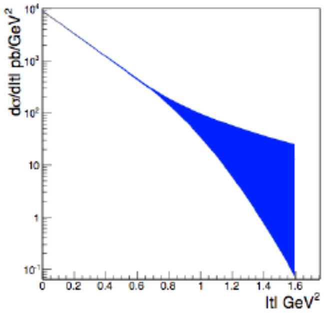
limited lower p_T-acceptance



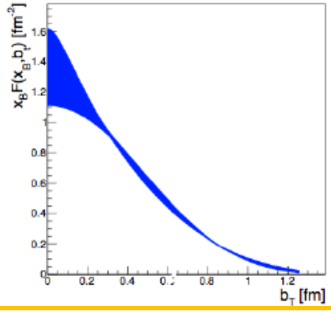
Uncertainty in normalization

$\int L_{int} = 10 fb^{-1}$

$0.44 < p_T$(GeV) < 1.3



limited higher p_T-acceptance



Uncertainty in slope and shape

$\int L_{int} = 10 fb^{-1}$

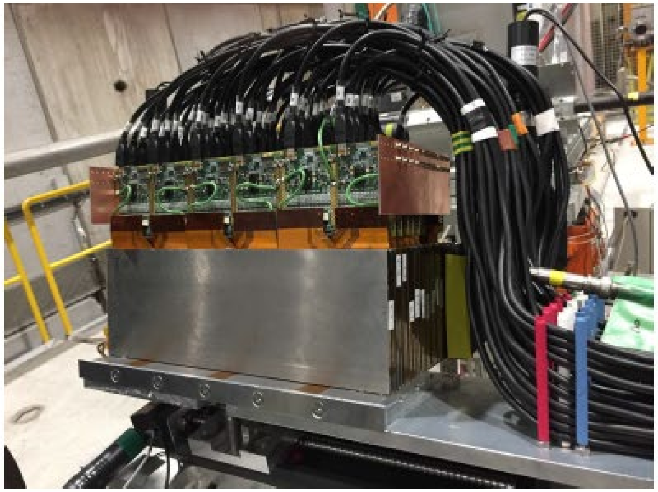
$0.18 < p_T$ (GeV) < 0.8

We need a proton spectrometer with large acceptance!

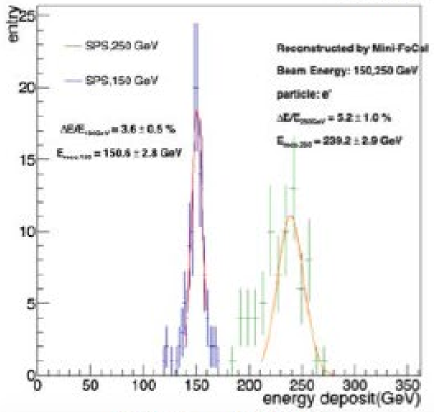
shown by Fazio & Jentsch

ALICE FoCal-E

mini-FoCal at PS and SPS (2018)

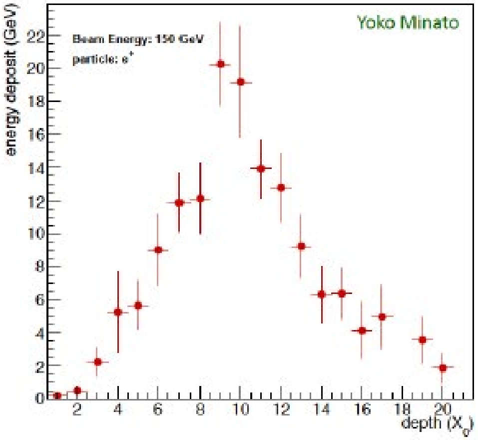


Y. Minato



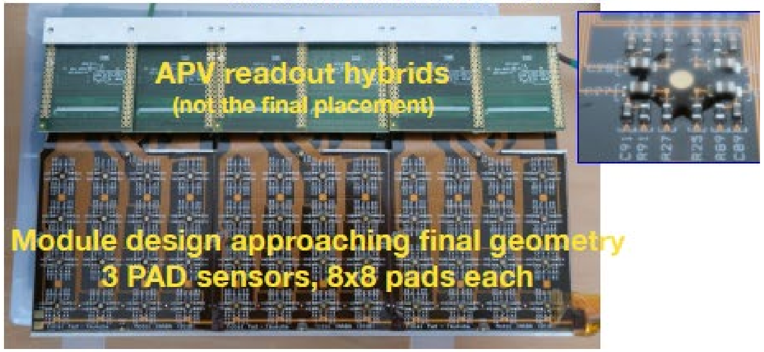
ΔE/E = 3.6 %

@ 150 GeV/c , e^- (SPS)



- “mini-FoCal” has been built in Tsukuba, and shipped to CERN for test beam and ALICE test in 2018
- APV25 hybrid + SRS for readout

Pads connected to flex PCB

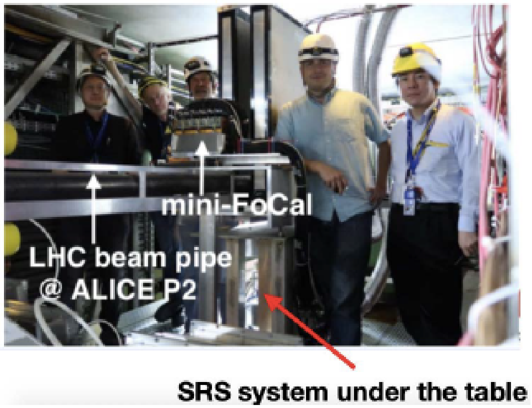


APV readout hybrids
(not the final placement)

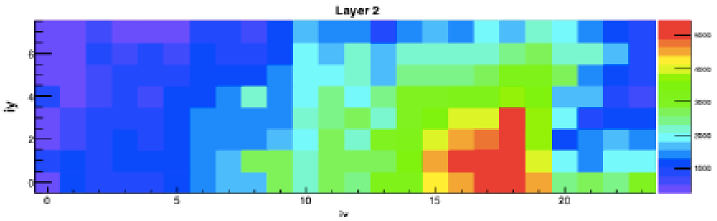
Module design approaching final geometry
3 PAD sensors, 8x8 pads each

ALICE FoCal-E

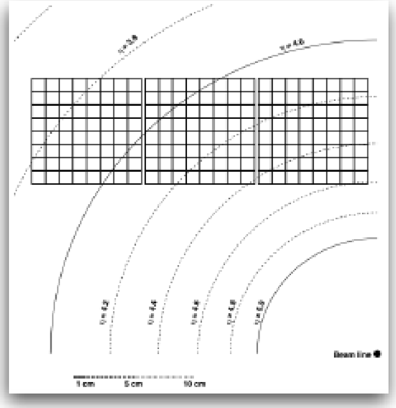
mini-FoCal in ALICE (2018)



Hit Map of mini-FoCal in ALICE



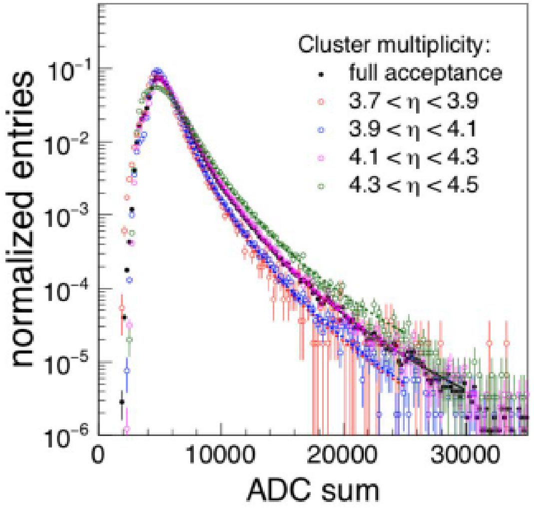
Acceptance



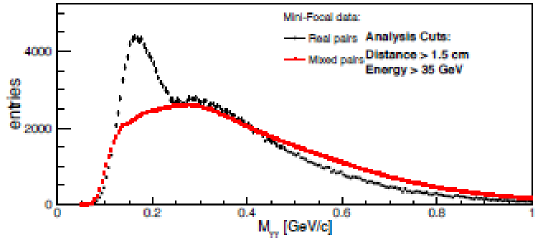
Goal: measure/verify backgrounds in situ with p+p @ √s = 13 TeV collisions in ALICE

- Calibration based on test beam
- Comparison to MC (cluster spectrum, slid lines)

Cluster spectrum

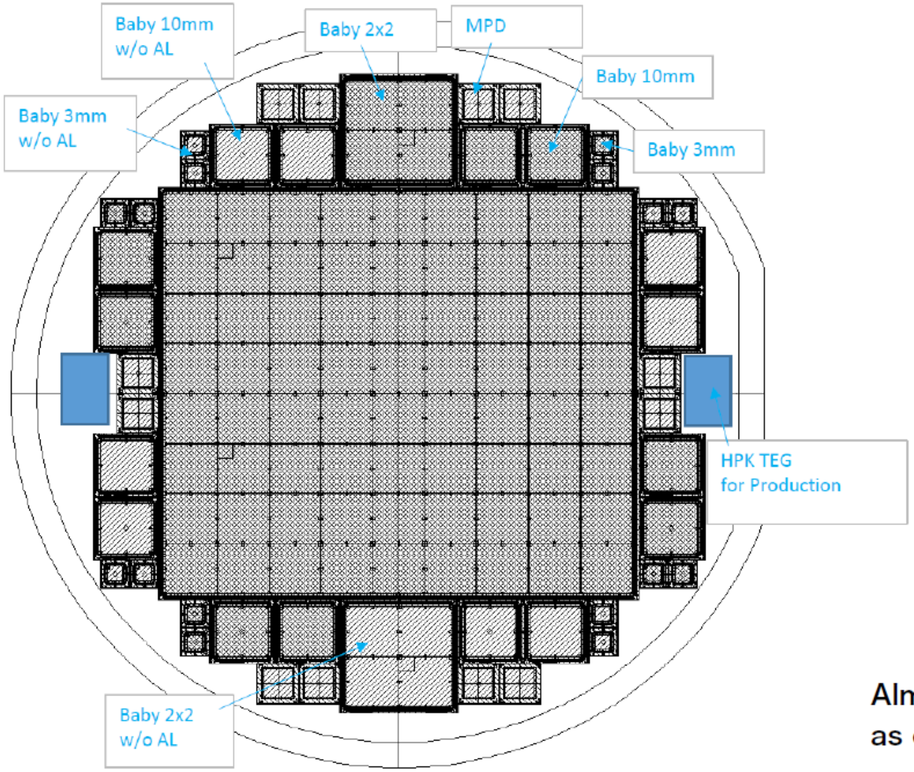


π⁰ peak



N. Novitzky

1. New silicon pad sensor for final FoCal



Almost final version
as of Aug. 19, 2020

ALICE FoCal

- RIKEN participation in FoCal
  - FoCal-E pad readout and trigger development
  - Test beam
- Participants
  - Yuji Goto (scientist): 0.25 FTE
  - Itaru Nakagawa (scientist): 0.25 FTE
  - Minho Kim (new postdoc from Oct. 2020): 1 FTE
- Budgetary contribution
  - Additional FoCal-E pad sensors in 2020-2021
  - Student support for Japanese & non-Japanese universities
    - Tsukuba U.
  - Travel support for visiting staffs

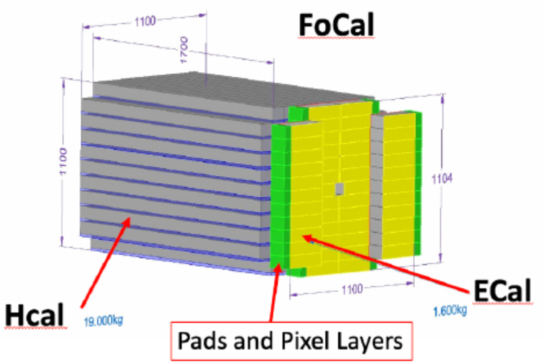
ALICE FoCal

- We'd like to build approx. 10cm x 20cm prototype FoCal-E detector to be used at RHIC/sPHENIX in 2024
  - Approx. size of 10cm x 20cm
  - Located at zero degree, in front of ZDC
  - Measurement of photon, pi0, and neutron cross section and left-right asymmetry in polarized p+p and p+A collisions
  - Construction in 2022-2023 by RIKEN budget
  - We'll need appropriate contract with FoCal group for technology transfer and purchase
- In 2023, we may consider prototype test at RHIC/sPHENIX in A+A collisions

ALICE-FoCal

FoCal - main components

3



Pads

1 layer = 5 towers design, and silicon sensor (8 x 9 cells)

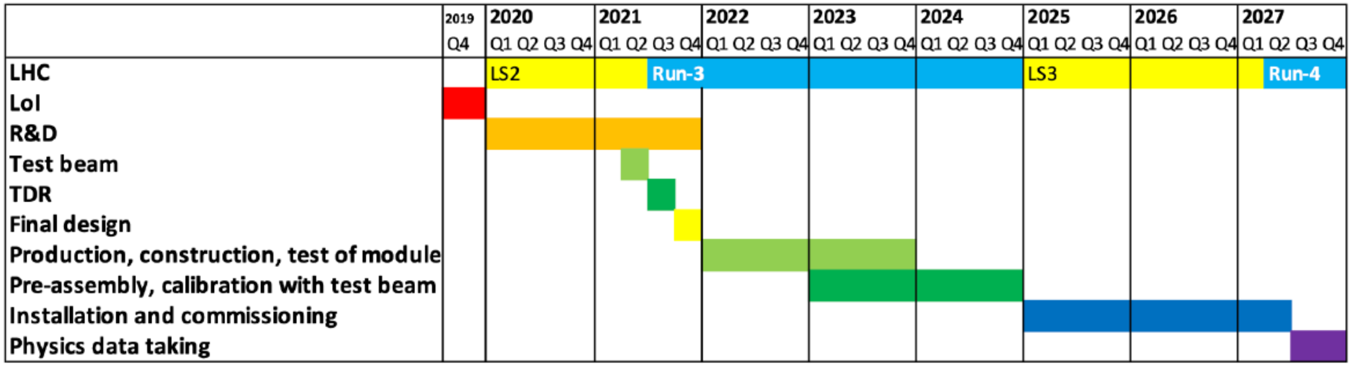
1) Total number of modules: 11 x 2 = 22 modules
2) Total number of Pad layers: 22 x 18 = 396 layers
3) Total number of towers : 22 x 5 = 110 towers
4) Total number of silicon sensors: 396 x 5 = 1,980 sensors
5) Total number of readout ch.: (8 x 9) x 1,980 = 142,560 ch

+396 FEE PCB, 180 aggregator boards, 8 CRU

HCal: ~2K channels

Timescale till Run-4

8



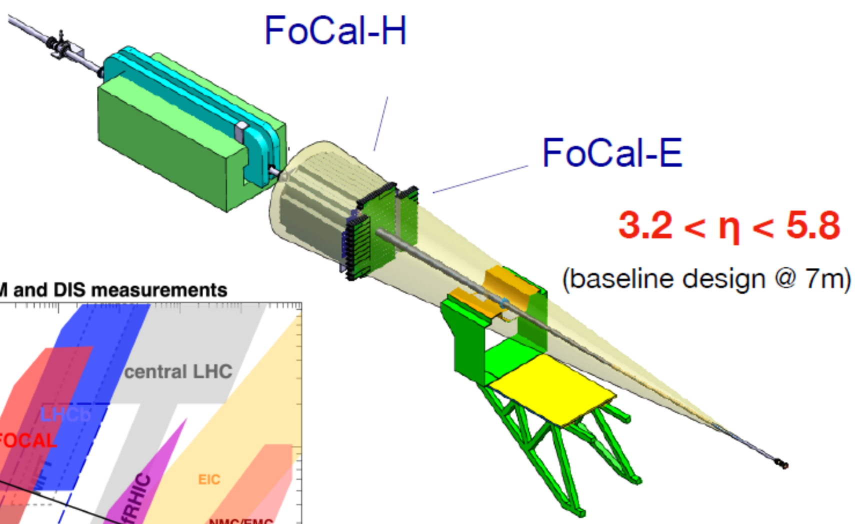
	2019	2020				2021				2022				2023				2024				2025				2026				2027			
	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
LHC		🟨 LS2	🟨	🟨	🟨	🟨	🟨	🟦 Run-3	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟨 LS3	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟦 Run-4	🟦	🟦
LoI	🟥																																
R&D		🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧																								
Test beam							🟩																										
TDR								🟩																									
Final design									🟨																								
Production, construction, test of module										🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩																
Pre-assembly, calibration with test beam														🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩												
Installation and commissioning																						🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦		
Physics data taking																																🟪	🟪

ALICE FoCal

ALICE FoCal upgrade for LHC-Run4 (2027-)

FoCal-E (PAD & PIXEL): high-granularity Si-W sampling calorimeter for photons and π^0

FoCal-H: conventional Cu-Sc sampling calorimeter for photon isolation and jets

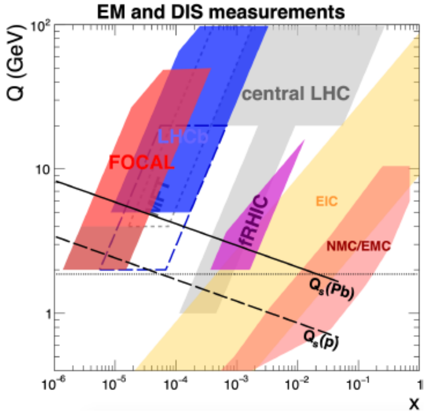


3.2 < η < 5.8

(baseline design @ 7m)

Observables:

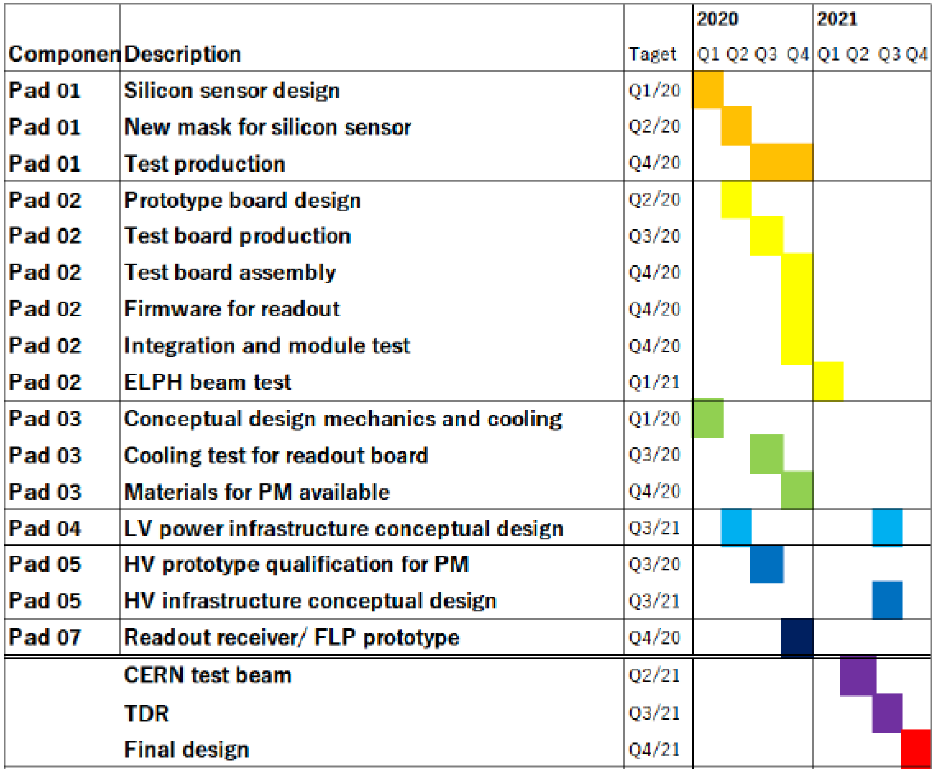
- π^0 (and other neutral mesons)
- Isolated photons
- Jets (and di-jets)
- J/ψ (Υ) in UPC
- W, Z maybe possible
- Event plane and centrality



ALICE-FoCal

4. Timescale and cost

Pad (short term, 2020-2021)



Componen	Description	Taget	2020 Q1	2020 Q2	2020 Q3	2020 Q4	2021 Q1	2021 Q2	2021 Q3	2021 Q4
Pad 01	Silicon sensor design	Q1/20	🟧							
Pad 01	New mask for silicon sensor	Q2/20		🟧						
Pad 01	Test production	Q4/20			🟧	🟧				
Pad 02	Prototype board design	Q2/20		🟨						
Pad 02	Test board production	Q3/20			🟨					
Pad 02	Test board assembly	Q4/20				🟨				
Pad 02	Firmware for readout	Q4/20				🟨				
Pad 02	Integration and module test	Q4/20				🟨				
Pad 02	ELPH beam test	Q1/21					🟨			
Pad 03	Conceptual design mechanics and cooling	Q1/20	🟩							
Pad 03	Cooling test for readout board	Q3/20			🟩					
Pad 03	Materials for PM available	Q4/20				🟩				
Pad 04	LV power infrastructure conceptual design	Q3/21		🟦					🟦	
Pad 05	HV prototype qualification for PM	Q3/20			🟦					
Pad 05	HV infrastructure conceptual design	Q3/21							🟦	
Pad 07	Readout receiver/ FLP prototype	Q4/20				🟦				
	CERN test beam	Q2/21						🟪		
	TDR	Q3/21							🟪	
	Final design	Q4/21								🟥

[PM] : Prototype Module

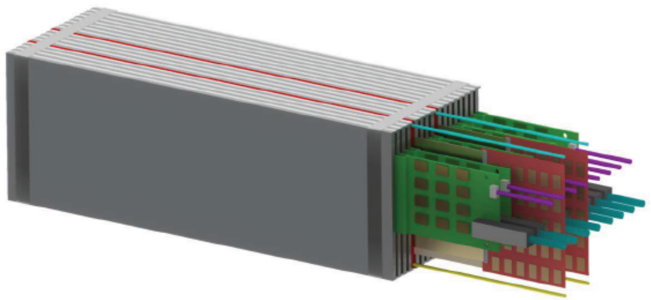
Pad 01	sensor specification
Pad 02	readout board design (and connection)
Pad 03	module mechanical design and cooling
Pad 04	LV power infrastructure
Pad 05	HV for sensors
Pad 06	QA performance, componets and system test
Pad 07	FLP/EPN connections and software
Pad08	DCS/controls

ALICE-FoCal

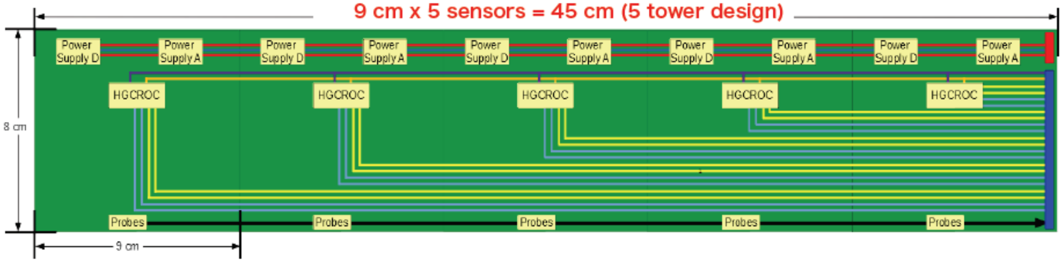
- For RHICf upgrade (2022 or 2024)
  - Space restriction at RHICf
    - FoCal prototype with new readout scheme for RHICf?
  - Readout electronics integration to sPHENIX electronics & DAQ system

4

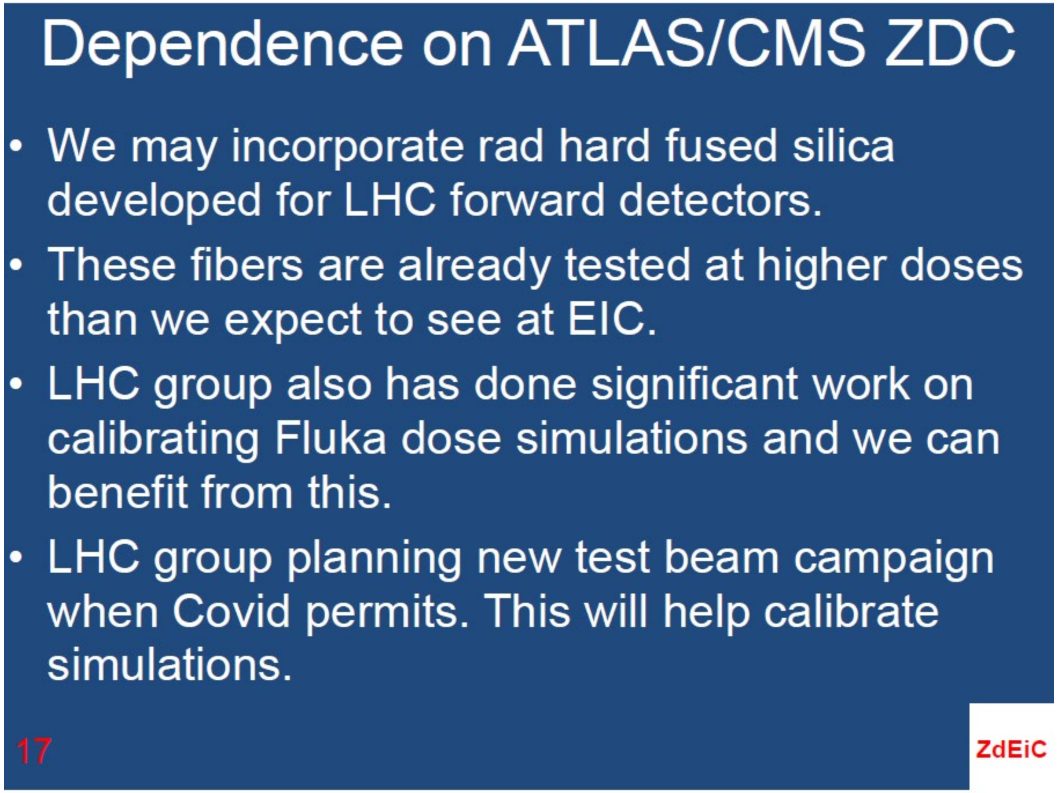
Module: 18 layers of Pad + 2 layers of MAPS



Layer: 5 silicon sensors side by side with PCB



ZDC at LHC



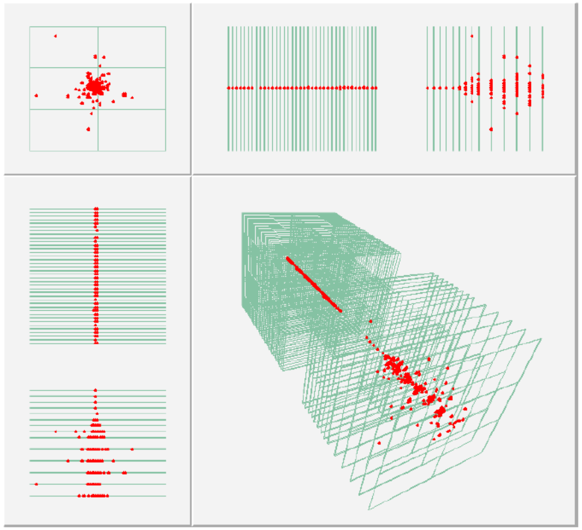
Dependence on ATLAS/CMS ZDC

- We may incorporate rad hard fused silica developed for LHC forward detectors.
- These fibers are already tested at higher doses than we expect to see at EIC.
- LHC group also has done significant work on calibrating Fluka dose simulations and we can benefit from this.
- LHC group planning new test beam campaign when Covid permits. This will help calibrate simulations.

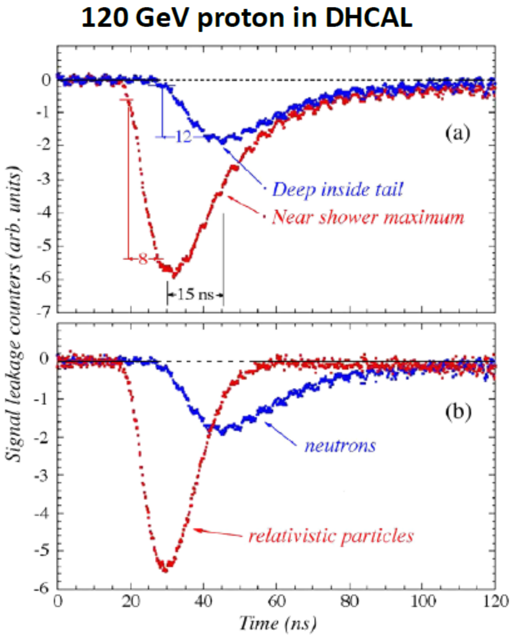
ZdEiC

Detector requirements

- TOPSiDE / CALICE
  - Imaging calorimeter
  - Improving e/h with software compensation
- EIC HCal R&D
  - Improving e/h with timing (dual-gate offline compensation)
  - Energy resolution better than ~40%/√E (GeV) + few% is challenging
- ALICE FoCal



shown by Repond



120 GeV proton in DHCAL

shown by Tsai

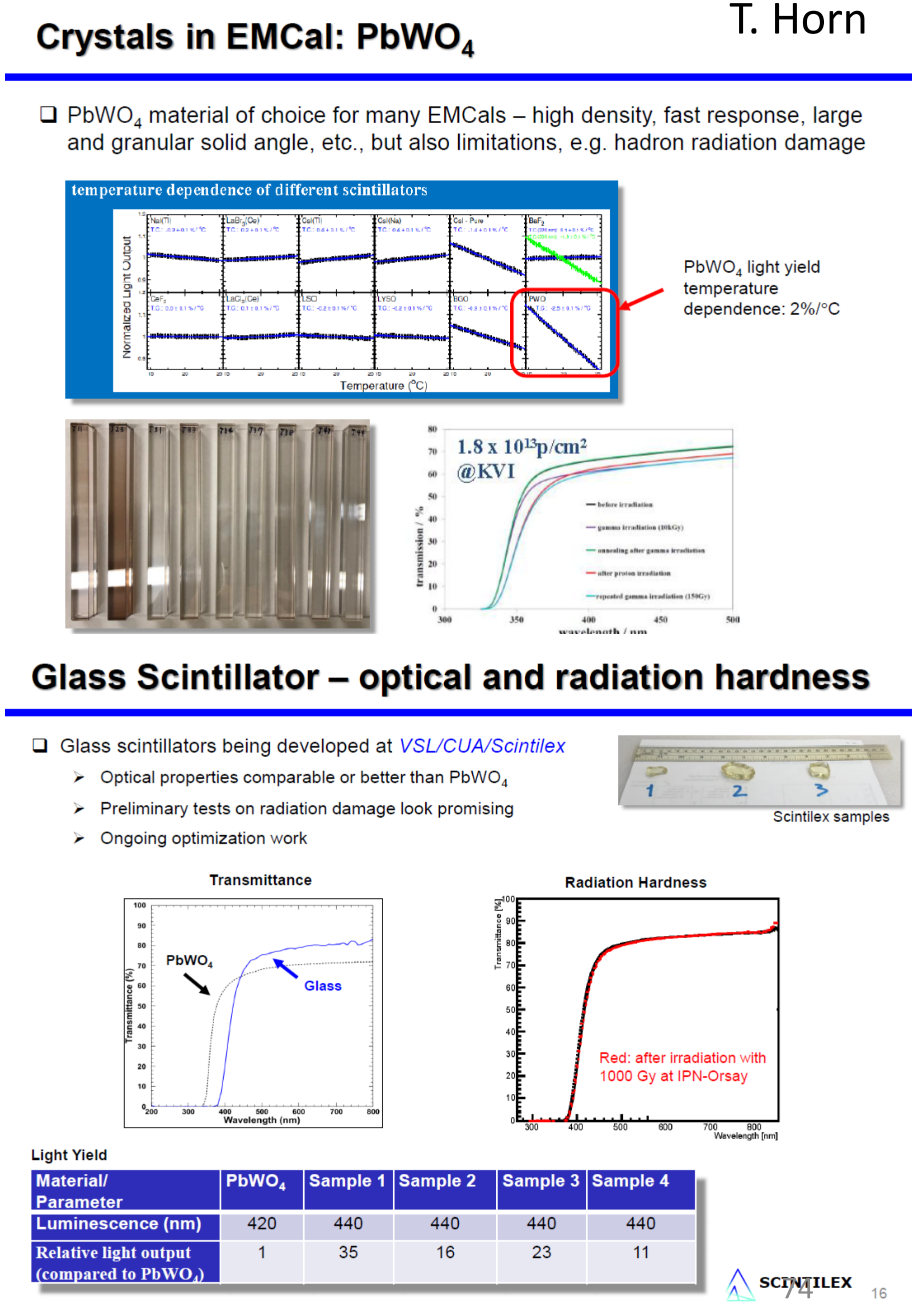
Simulation studies

- Collaboration with BeAGLE group (eRD17) and calorimeter consortium (eRD1)
  - ALICE FoCal geometry included in Geant4 (g4e framework)
- Soft photon detection
  - Acceptance & efficiency
  - Detector simulation & evaluation
  - Effect for downstream calorimeter (resolution, pID)
- EM + hadron calorimeter
  - Detector simulation
    - EM + hadron configuration & evaluation
    - Energy & position resolution
      - Leakage (size), e/h (technology)
    - Calibration system evaluation
  - Physics simulation
    - Evaluation for spectrum measurement
- Radiation dose

Calorimeter Consortium

Slide by
T. Horn

- Crystal calorimeter
  - PWO
  - For soft photon detection < 300 MeV
    - Full absorption
- Glass scintillator
  - Radiation hard



Crystals in EMCal: $PbWO_4$

☐ $PbWO_4$ 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

Glass Scintillator – optical and radiation hardness

☐ Glass scintillators being developed at *VSL/CUA/Scintilex*
  - Optical properties comparable or better than $PbWO_4$
  - Preliminary tests on radiation damage look promising
  - Ongoing optimization work

Scintilex samples

Transmittance

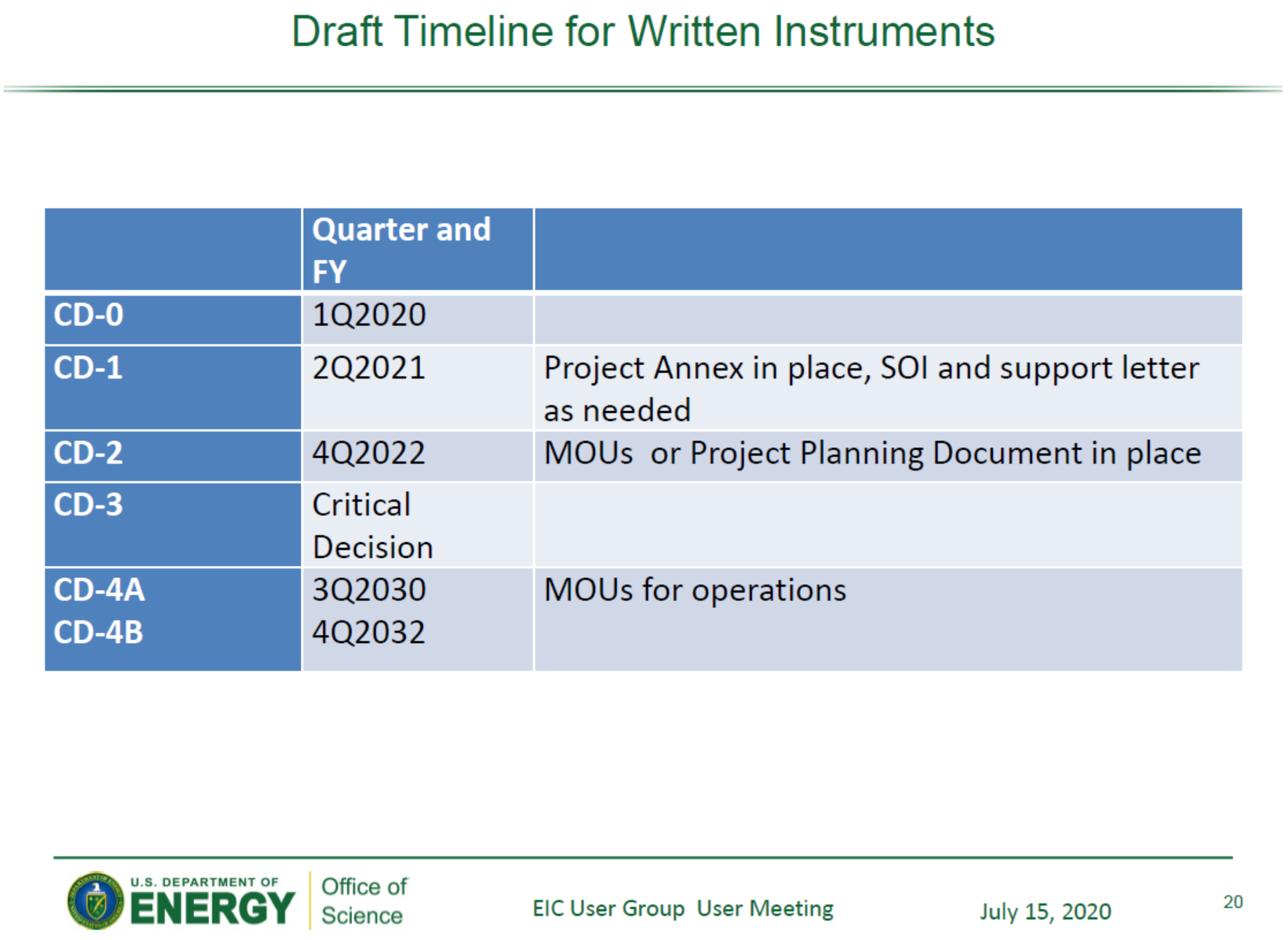
Radiation Hardness

Red: after irradiation with 1000 Gy at IPN-Orsay

Light Yield

Material/ Parameter	$PbWO_4$	Sample 1	Sample 2	Sample 3	Sample 4
Luminescence (nm)	420	440	440	440	440
Relative light output (compared to $PbWO_4$)	1	35	16	23	11

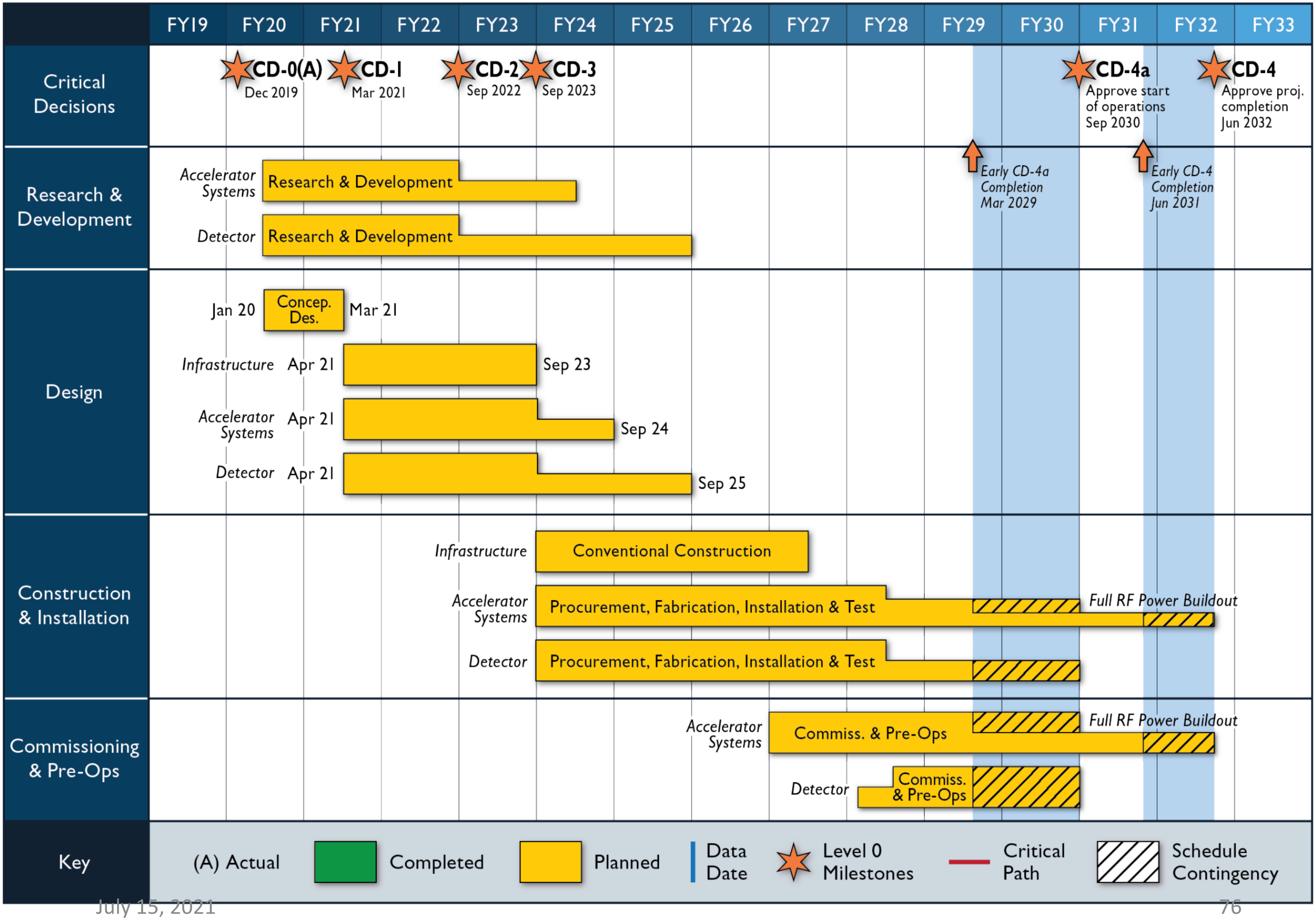
SCINTILEX



Draft Timeline for Written Instruments

	Quarter and FY	
CD-0	1Q2020	
CD-1	2Q2021	Project Annex in place, SOI and support letter as needed
CD-2	4Q2022	MOUs or Project Planning Document in place
CD-3	Critical Decision	
CD-4A **CD-4B**	3Q2030 4Q2032	MOUs for operations

EIC Schedule



EIC Schedule