ALICE-FoCal discussion

RBRC exp group meeting

February 12th, 2020

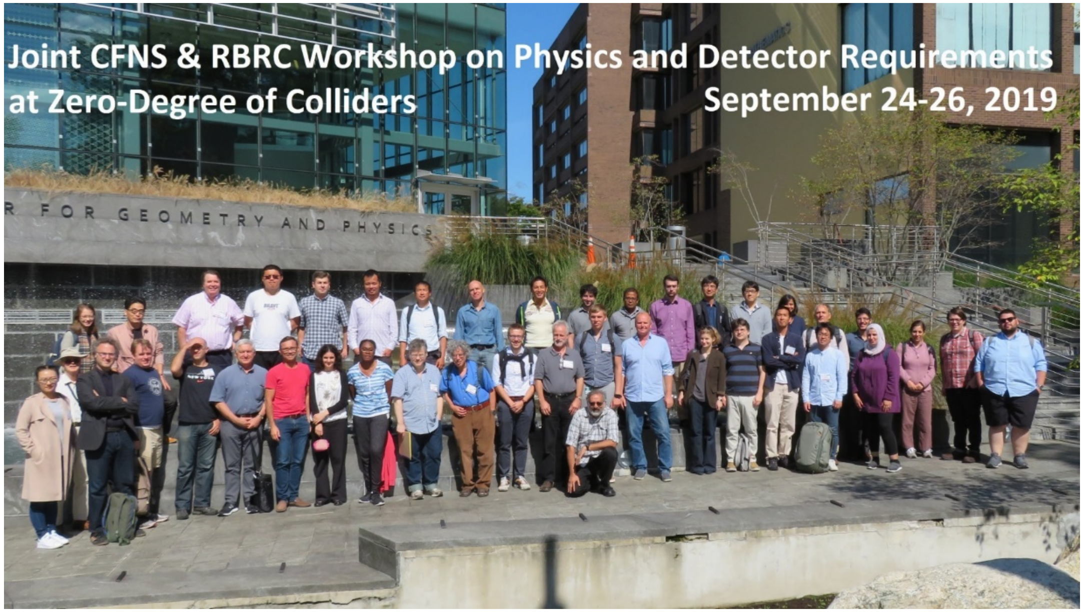
Yuji Goto

Motivations

- We're proposing EIC detector R&D for position sensitive ZDC.
  - It serves critical roles for a number of important physics topics at EIC.
  - ALICE-FoCal is one promising technology.
- We're discussing RHICf upgrade.
  - ALICE-FoCal prototype detector would be one promising choice to be used in the next RHICf experiment in a timely manner.

EIC detector R&D for position sensitive ZDC

- Letter of intent submitted in January
  - Japanese group
    - RIKEN, Nagoya Univ., ICRR, Kobe Univ., Tsukuba Univ., Tokyo Tech., Nihon Univ., Yamagata Univ., JAEA
  - US group
    - BNL, Univ. of Kansas
- Proposal to be submitted in July
- Discussing with
  - Participants in Joint CFNS & RBRC workshop on “Physics and detector requirements at zero-degree of colliders”
    - Stony Brook Univ.
  - Follow-up meeting to be held



EIC detector R&D for position sensitive ZDC

- Full-absorption photon detector
  - Crystal scintillators
- Prototype study of ZDC with position sensitivity
  - EM + Hadron calorimeters
  - ALICE-FoCal / RHICf technology / …
- Radiation hardness study for new technology
  - Plastic scintillators

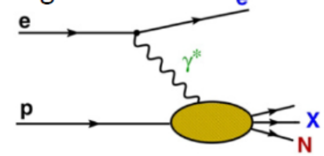
Physics topics at EIC zero degree

- Diffractive process in e + A collisions
  - Breakup of the excited nucleus
    - Exclusive vector meson production
  - Event-by-event characterization of collision geometry
    - Study of nuclear medium effects
- Spectator tagging in e + d / ^{3}He collisions
  - Neutron structure
    - Spin structure, S & D waves
  - Neutron interactions
    - Short-range correlation (SRC) and EMC effect at large x
    - Diffraction and shadowing at small x
- Leading baryons
- Asymmetries at zero degree
- Spectroscopy
- Isotope tagging for nuclear fragments
- Relation to cosmic-ray physics
  - Understanding hadronization
  - Cosmic-ray acceleration in blazars

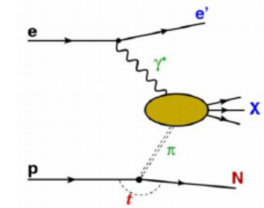
Physics at zero degree of EIC

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

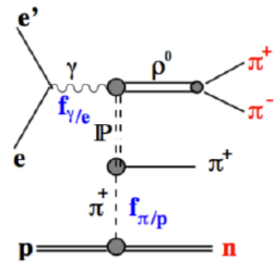
Fragmentation



One Pion Exchange (OPE)



LN in DIS

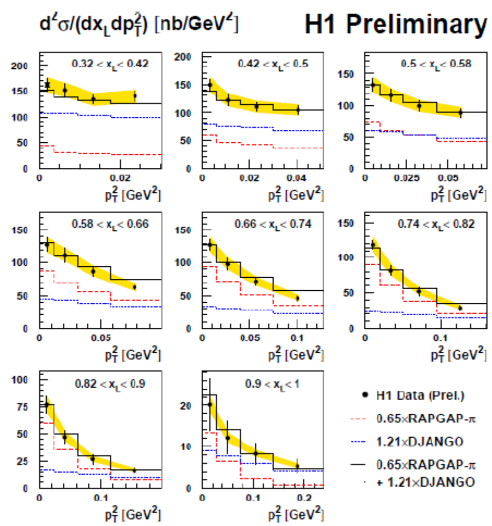


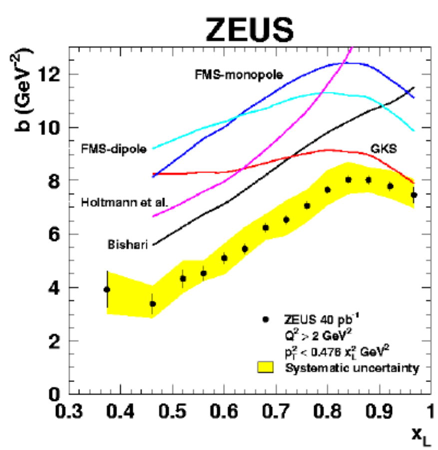
$$d\sigma_{\gamma^* p \to n x} = f_{\pi/p}(x_L, t) \times d\sigma_{\gamma^* \pi \to X}$$

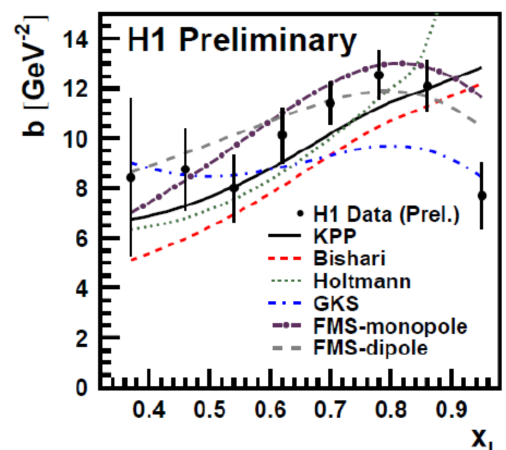
The distribution of p_T^2 (=t) is defined solely by the pion flux

Sensitivity to the pion flux

p_T^2 dependence in bins of x_L







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

18

slide by Ciesielski

Inconsistency @ HERA

→ Need more data to understand production mechanism

ZDC requirements

- Position resolution
  - 1 cm position resolution → 300 μrad angular resolution
  - → 30 MeV p_T resolution for 100 GeV spectator neutron
- Energy resolution
  - Minimum requirement $\Delta E/E = 50\%/\sqrt{E}$ (GeV)
  - → 50 MeV p_T resolution for 100 GeV spectator neutron
- Position layers (or Shower Max Detector)

	Plastic fiber	Crystal bar	Quartz fiber	Silicon
Source	Scintillation		Cherenkov	
Signal	good	good	weak	good
Rad Hardness	poor	OK	excellent	OK
Cost	$	$$	$$	$$$
Position Resolution	good	good	poor	best
Large acceptance	OK	position dependent	OK	OK

RHICf upgrade

- RHICf physics
  - Cosmic ray / neutrino physics
    - Shower evolution
  - Very forward asymmetries of neutron, π^0, …
- RHICf upgrade
  - p + Light-A and/or Light-A + Light-A collisions
  - K^0_S at zero degree
  - As wide acceptance as possible
  - 2022 run at STAR and/or 2024 run at sPHENIX / STAR

ALICE-FoCal

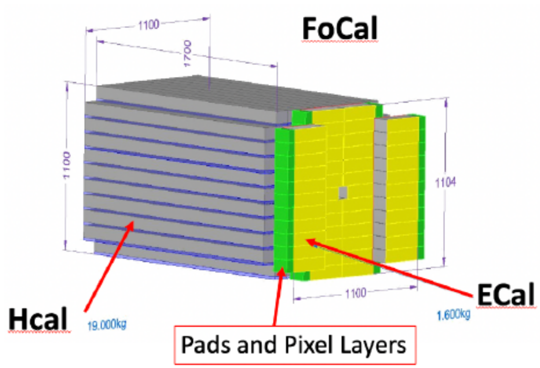
- 2020.1.14 ALICE internal review @ CERN

FoCal

- active R&D since ~2010
- proposed as an ALICE upgrade for LS3
- first version of LoI public
  - some updates during this review
- potential submission to LHCC in February
  - review as input for decision taking in ALICE
- if approved by ALICE and endorsed by LHCC
  - preparation of TDR by end of 2021

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

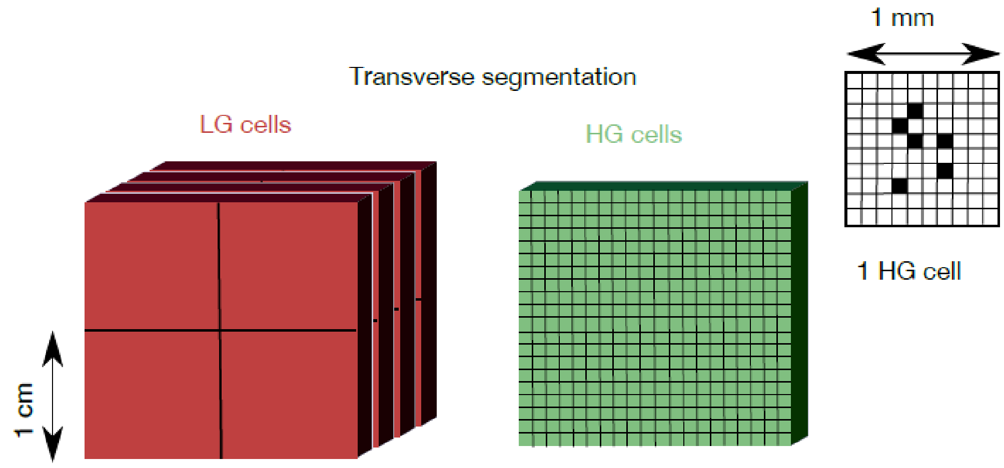
HCal: ~2K channels

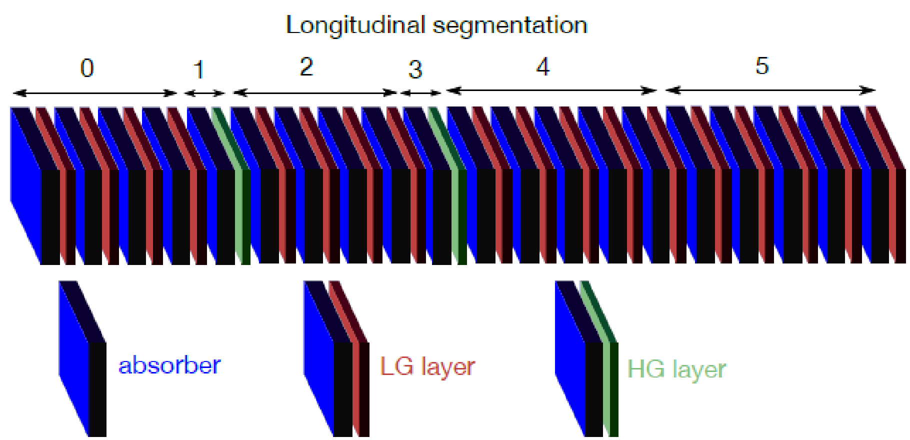
Timescale till Run-4 8

	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

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

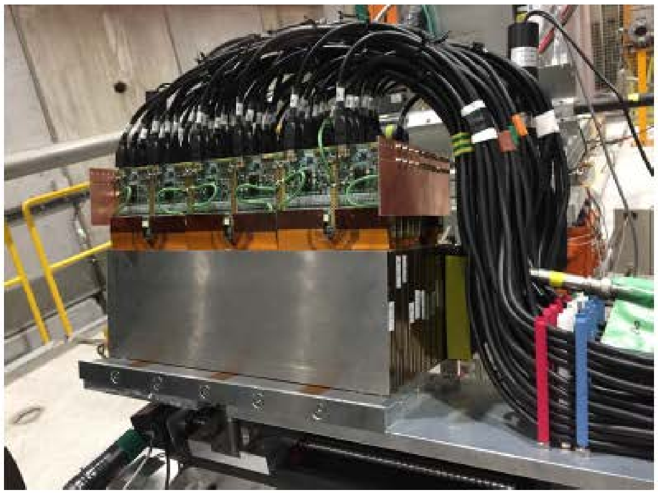
	LG	HG
pixel/pad size	≈ 1 cm^2	≈ 30x30 μm^2
total # of pixels/pads	≈ 2.5 x 10^5	≈ 2.5 x 10^9

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

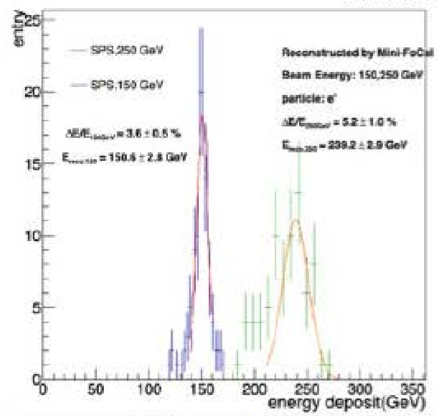
ALICE-FoCal

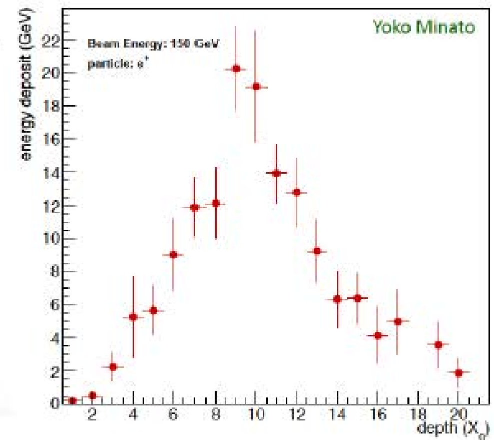
mini-FoCal at PS and SPS (2018)

8



Y. Minato

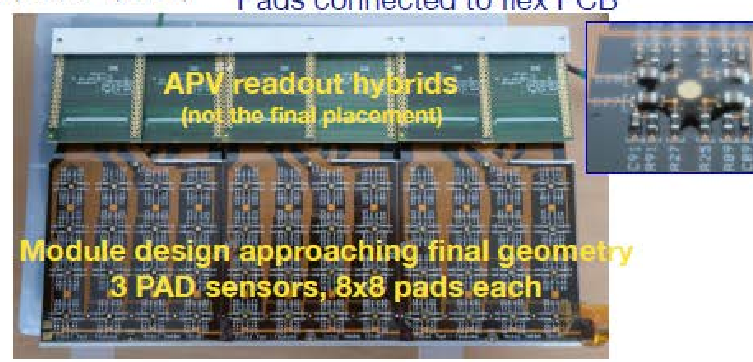




$\Delta E/E = 3.6$ %

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

Pads connected to flex PCB

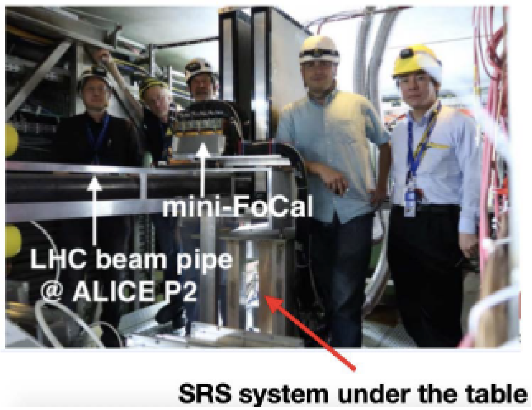


- "mini-FoCal" has been built in Tsukuba, and shipped to CERN for test beam and ALICE test in 2018
- APV25 hybrid + SRS for readout

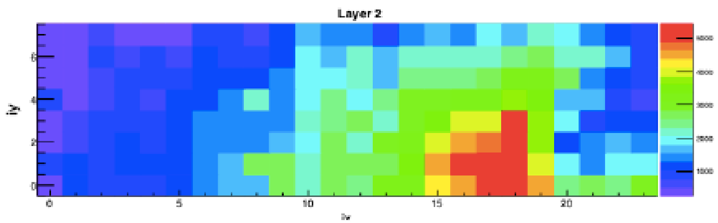
ALICE-FoCal

mini-FoCal in ALICE (2018)

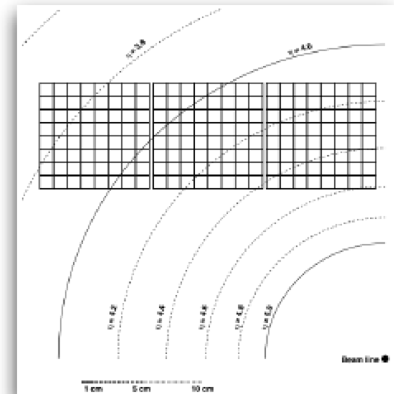
9



Hit Map of mini-FoCal in ALICE



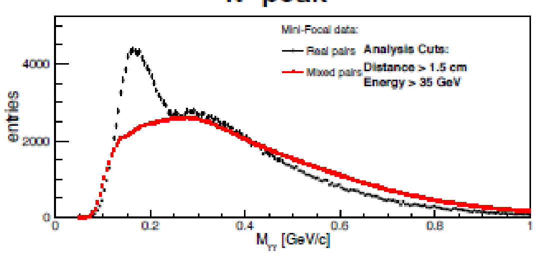
Acceptance



Goal: measure/verify backgrounds in situ with p+p @ $\sqrt{s}$ = 13 TeV collisions in ALICE

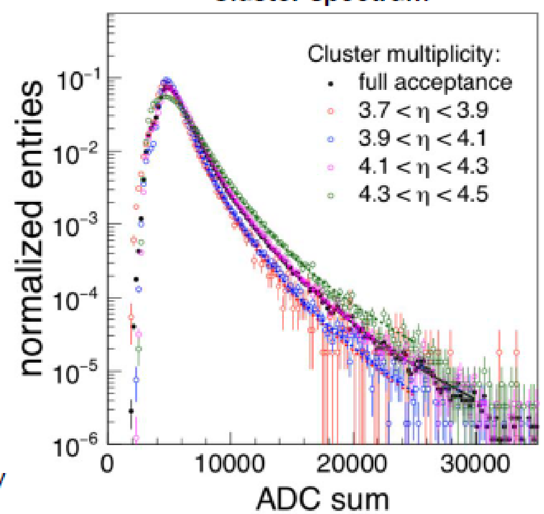
- Calibration based on test beam
- Comparison to MC (cluster spectrum, slid lines)

π^0 peak



N. Novitzky

Cluster spectrum



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

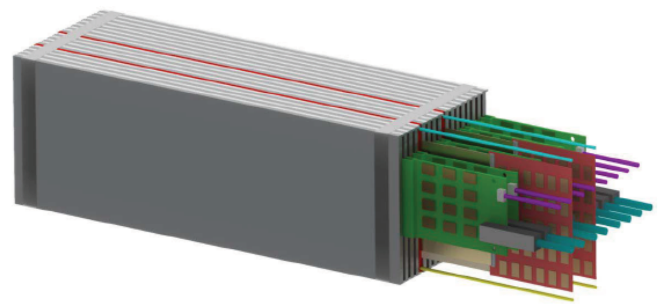
Pad 01	sensor specification
Pad 02	readout board design (and connection)
Pad 03	module mechanical design and cooling
Pad 04	LV power infrastructure
Pad 05	HV for sensors
Pad 06	QA performance, componets and system test
Pad 07	FLP/EPN connections and software
Pad08	DCS/controls

ALICE-FoCal

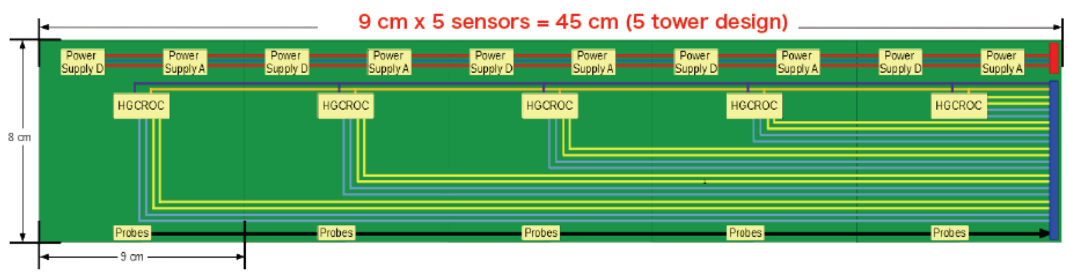
- For RHICf upgrade (2022 or 2024)
  - Space restriction at RHICf
    - FoCal prototype with new readout scheme for RHICf?
  - Readout electronics integration to sPHENIX electronics & DAQ system

4

Module: 18 layers of Pad + 2 layers of MAPS



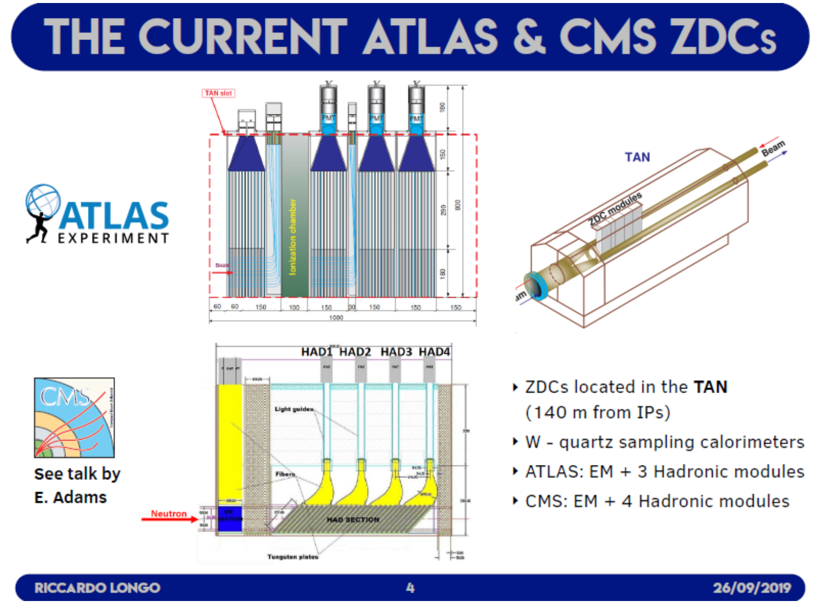
Layer: 5 silicon sensors side by side with PCB

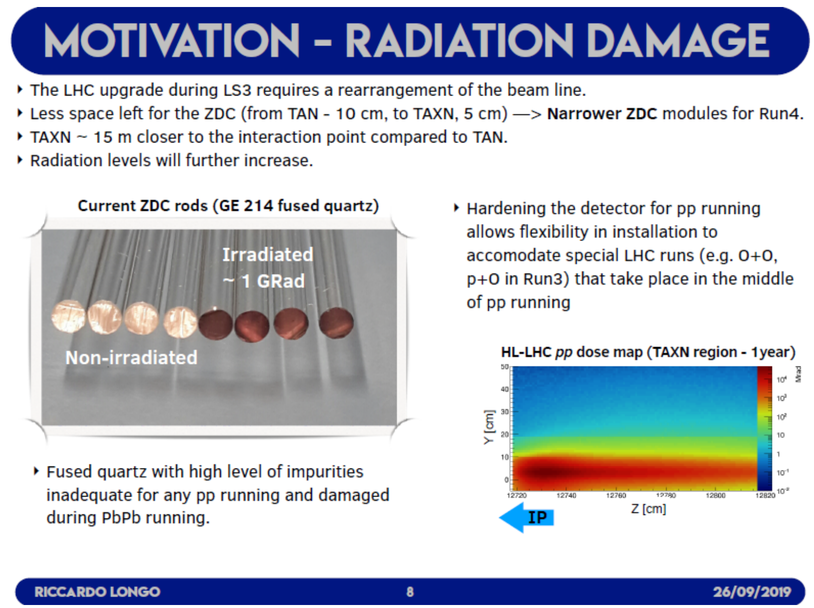


ZDC at LHC

- ATLAS & CMS ZDC
  - W-quartz sampling calorimeter

- JZCaP collaboration
  - ATLAS + CMS joint R&D effort
  - Radiation-hard fused silica rods
  - Increasing H_2 concentration



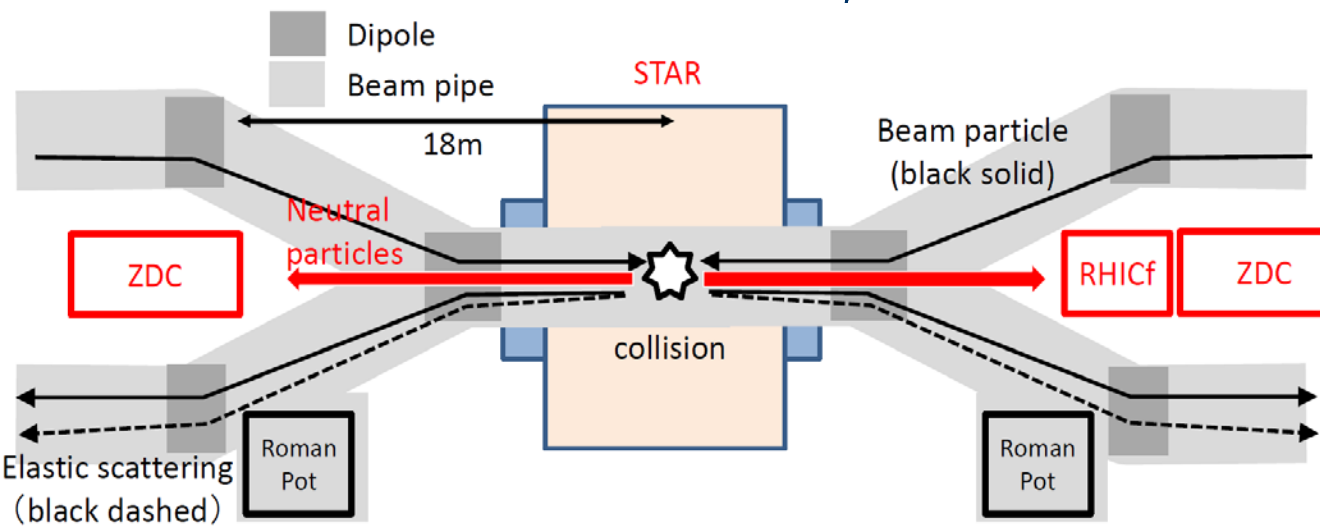


slides by Longo

Backup Slides

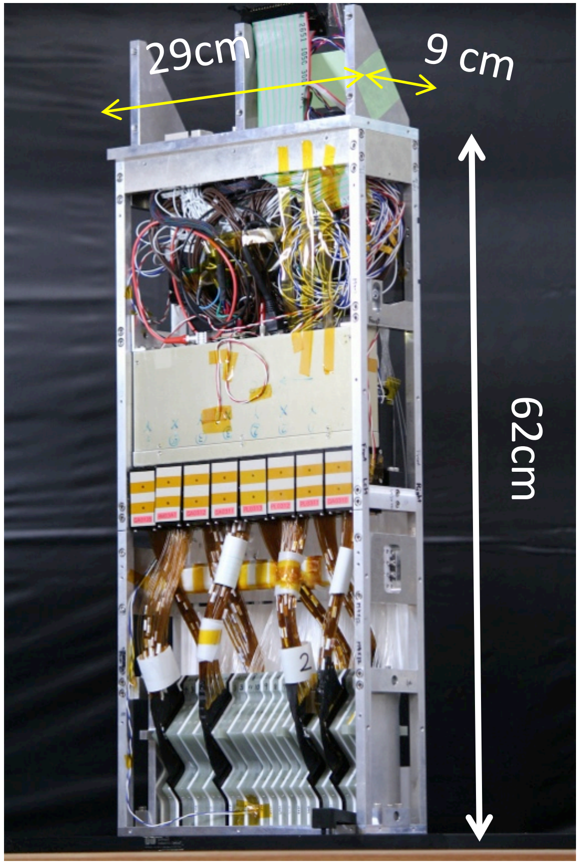
RHICf experiment

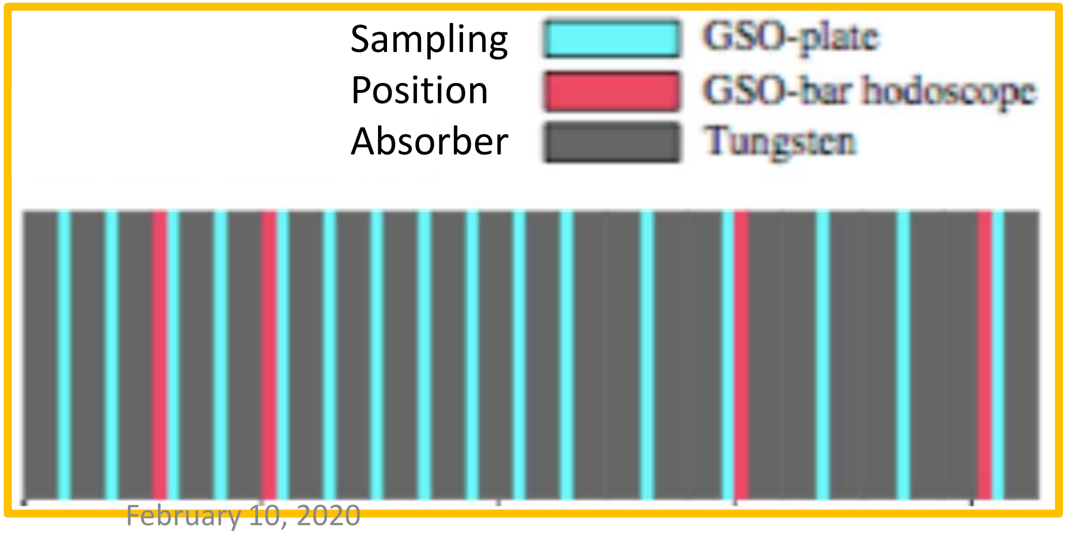
- EM calorimeter (RHICf detector) installed in front of the ZDC+SMD of the STAR experiment
  - Cross section and asymmetry measurement of neutral particle production (neutron, photon, π^0) with $\sqrt{s}$ = 510 GeV polarized proton collisions
  - Wide p_T region covered by changing the position of the RHICf detector vertically (up to 1.2 GeV/c)
  - Much higher position resolution than ZDC+SMD so that enable us higher resolution of p_T measurement

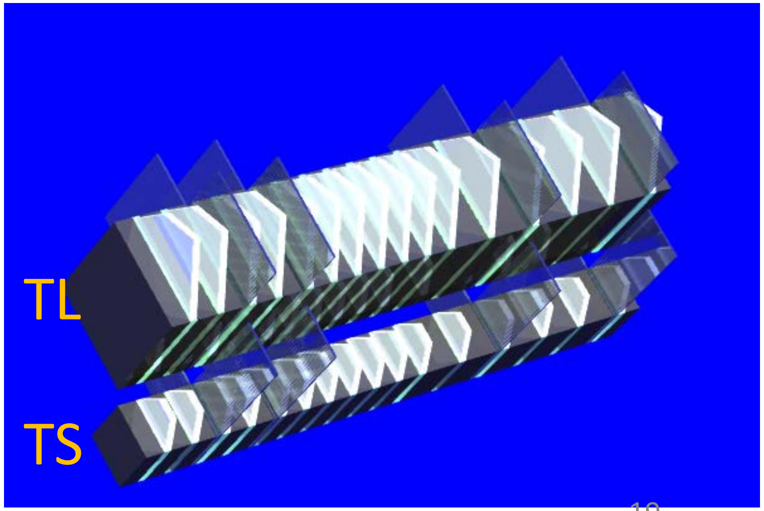


RHICf detector

- Two position-sensitive sampling calorimeters
  - TS (small tower): 20mm x 20mm
  - TL (large tower): 40mm x 40mm
  - Tungsten absorber (44 X_0, 1.6 λ_{int})
  - 16 GSO sampling layers
  - 4 XY pairs of GSO-bar position layers (MAPMT readout)

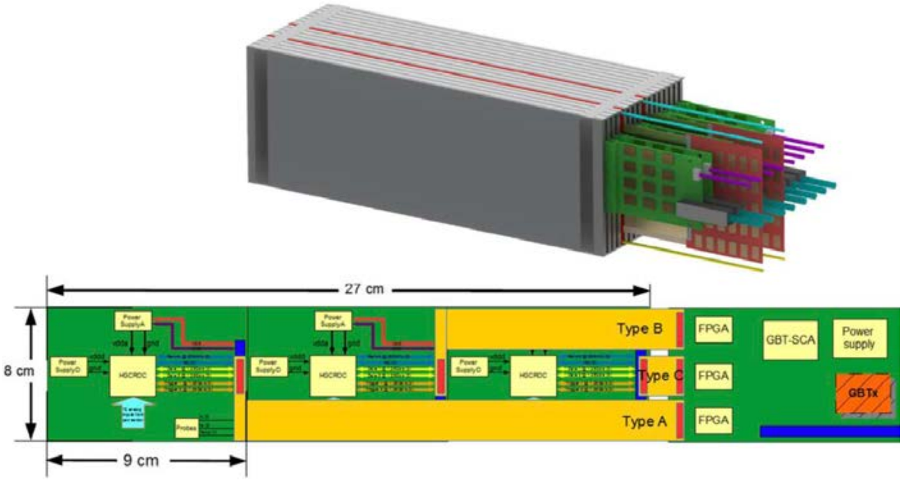






Discussions for ALICE-FoCal

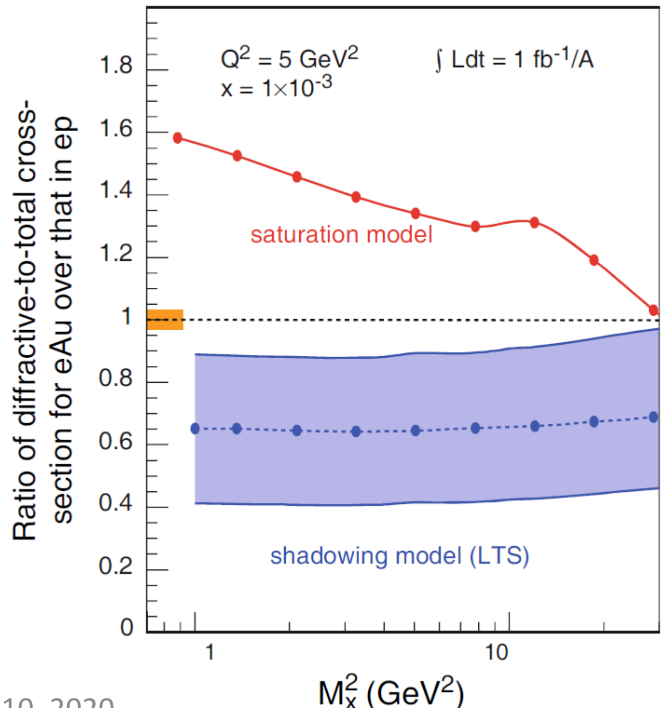
- For RHICf upgrade (2024)
    - Space restriction at RHICf
        - Possible new mini-FoCal with new readout scheme for RHICf?
    - Readout electronics integration to sPHENIX electronics & DAQ system

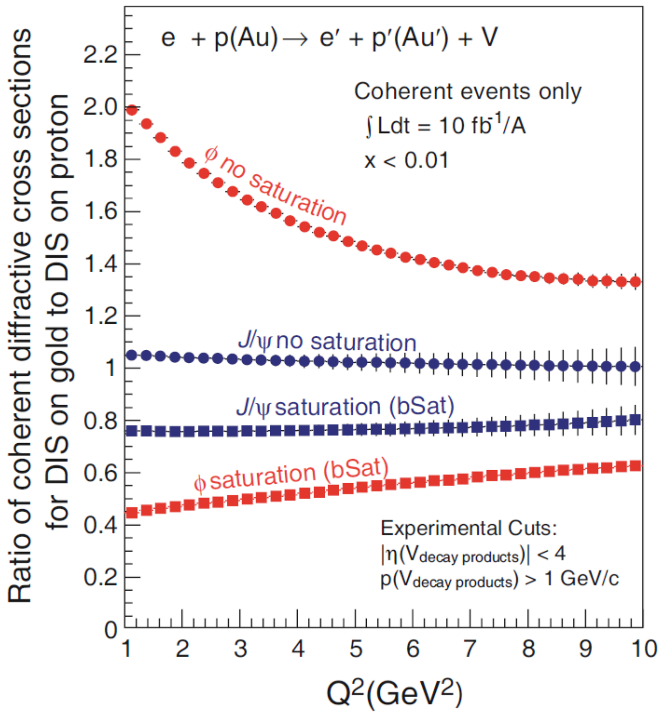


- For ZDC at EIC
    - EM + Hadron calorimeters
    - e.g. 60cm x 60cm

Gluon saturation at extreme density

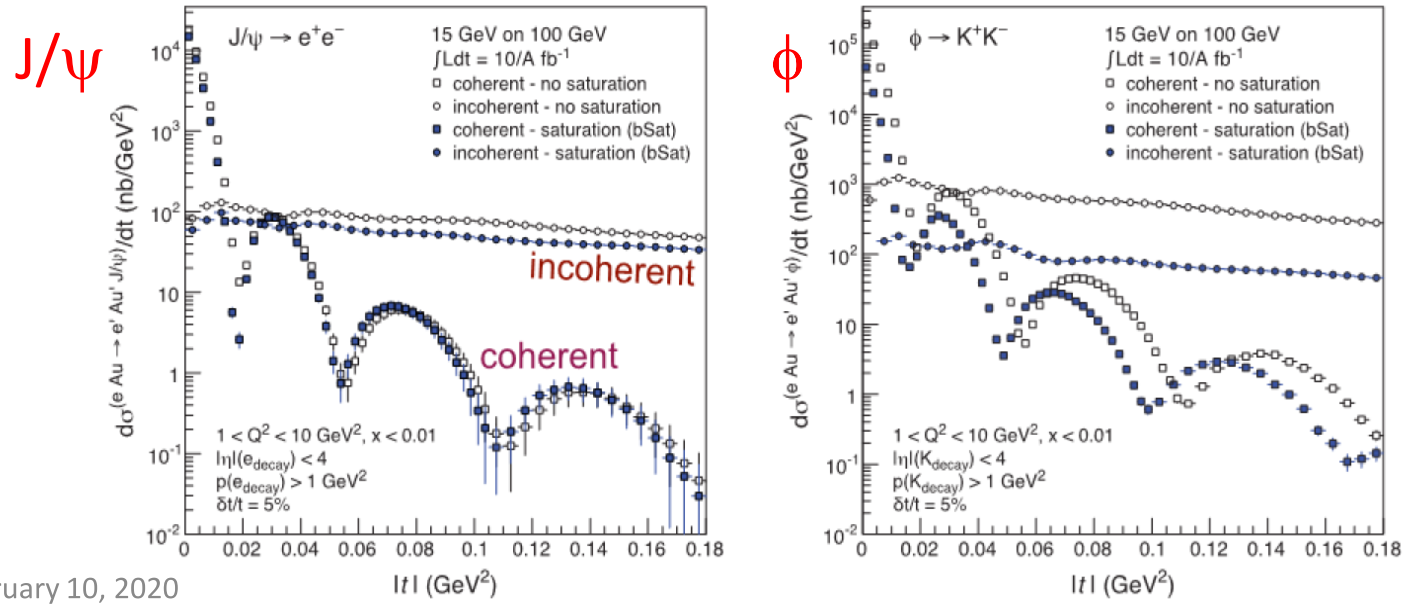
- Diffractive process in e + A collision
  - Rapidity gap & coherent (nucleus remains intact)
- Diffractive cross section
  - First evidence for gluon saturation
- Exclusive vector meson production
  - e + Au $\rightarrow$ e' + Au' + J/ψ, ϕ, ρ





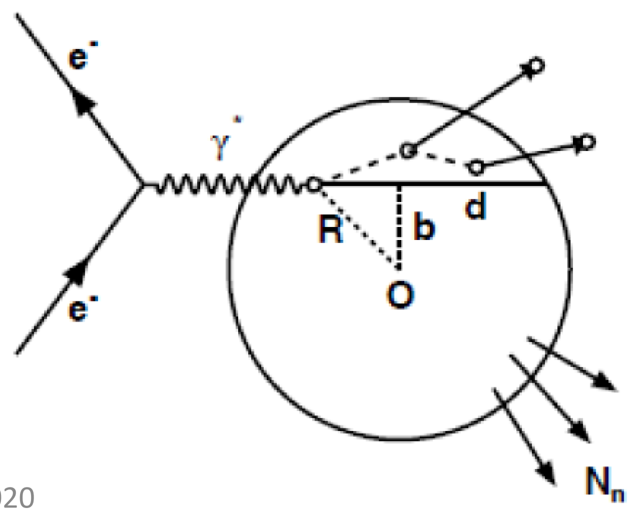
Gluon saturation at extreme density

- 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



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

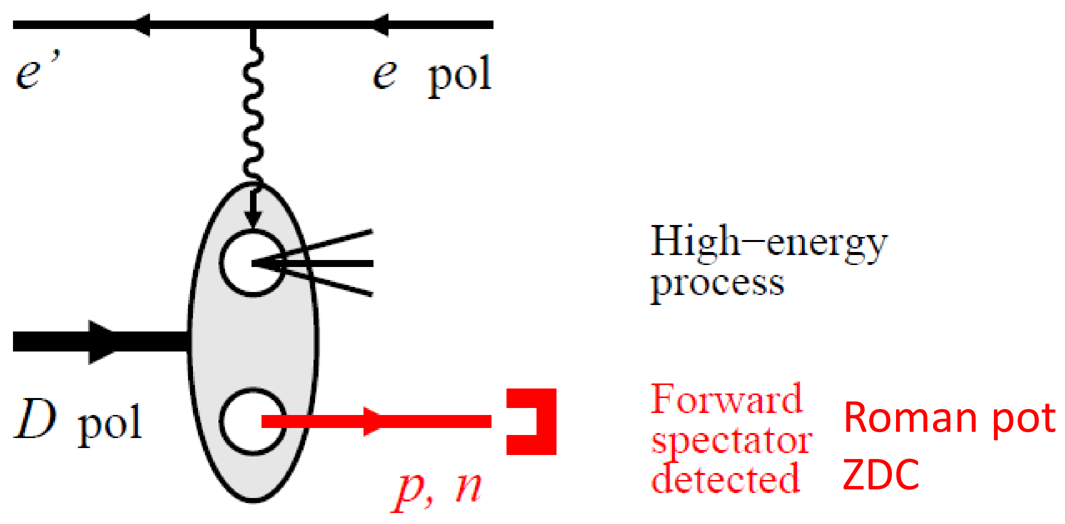


Intra-nuclear cascading increases with d (forward particle production)

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

e + 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*

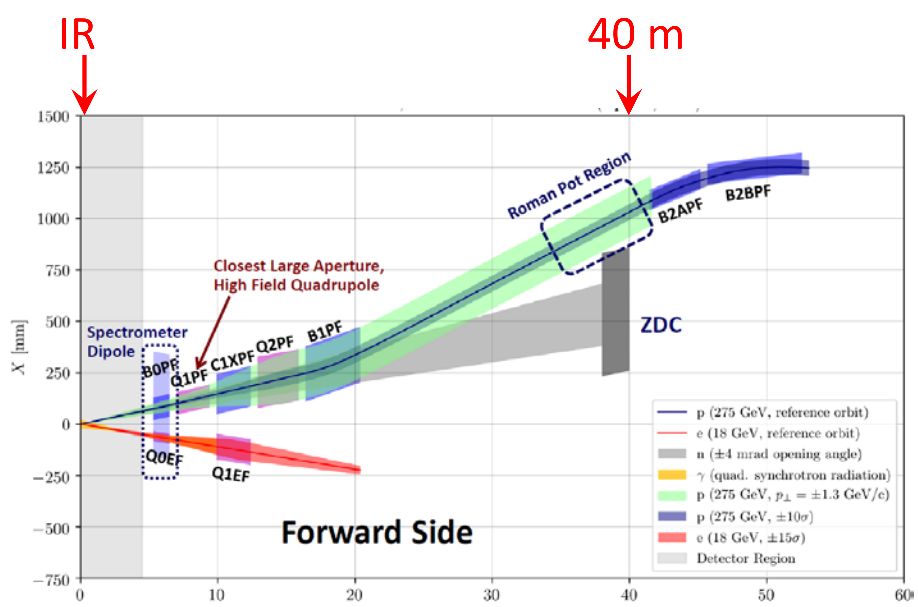


Detector performance requirements

- Photon detection
  - To identify the nuclear excitation states in addition to the neutron detection
  - Photon energy < 300 MeV
- Full absorption calorimeter, e.g. crystal calorimeter
  - $PbWO_4$
    - X_0 = 8.9 mm, r_M = 2.2 cm, τ = 25 nsec
    - 5% resolution at 300 MeV
  - LYSO
    - X_0 = 11.4 mm, r_M = 2.1 cm, τ = 40 nsec
    - 2.6% resolution at 300 MeV (SuperB prototype)

ZDC requirements

- 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

Other physics

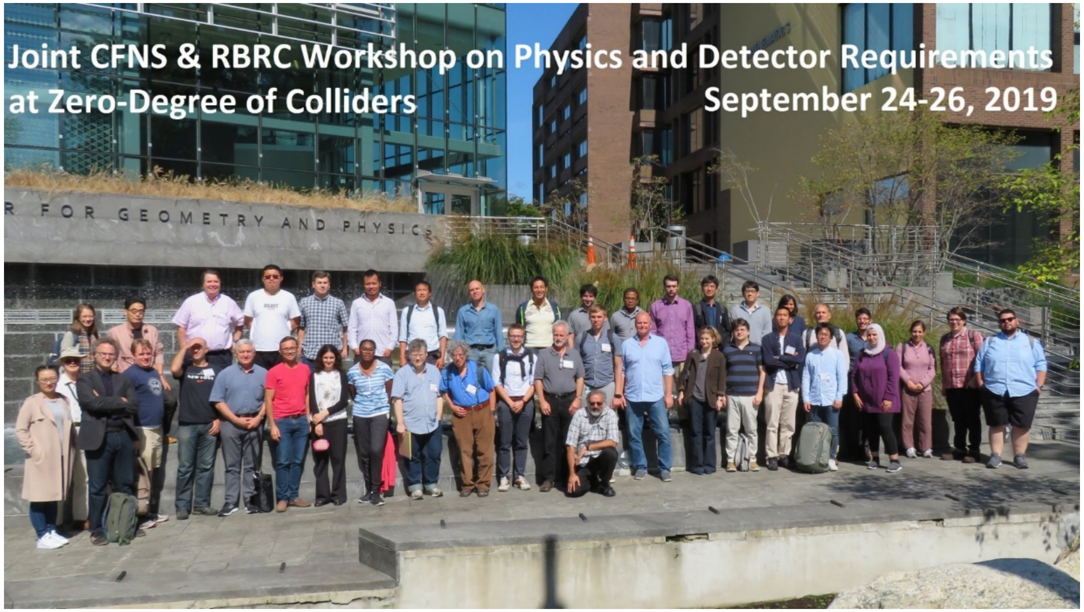
- Asymmetries at zero degree
  - Leading baryons
- Spectroscopy
- Isotope tagging for nuclear fragments
- Relation to cosmic-ray physics
  - Understanding hadronization
  - Cosmic-ray acceleration in blazars

Detector performance requirements

- Radiation hardness
  - $\sim O(100\text{k} - 1\text{MGy})$ or $n_{eq} = 3\times10^{12} - 10^{13}$ for 1-year operation
  - $n_{eq} > 10^{14}$ for lifetime
- Silicon and LYSO should be OK for the dose
- Plastic scintillators?
  - Very good resolution for hadrons
    - Good e/h
  - Some plastic like PEN stands for > 0.1 MGy radiation

Collaborators

- Japanese group
  - RIKEN, Nagoya Univ., ICRR, Kobe Univ., Tsukuba Univ., Tokyo Tech., Nihon Univ., Yamagata Univ., JAEA
- US group
  - BNL, Univ. of Kansas
- Discussing with
  - Participants in Joint CFNS & RBRC workshop on “Physics and detector requirements at zero-degree of colliders”
  - Follow-up meeting to be held



Summary

- We'd like to propose EIC R&D of ZDC
  - Full-absorption photon detector
    - Crystal scintillators
  - Prototype study of ZDC with position sensitivity
    - EM + Hadron calorimeters
    - ALICE-FoCal / RHICf technology / …
  - Radiation hardness study for new technology
    - Plastic scintillators
- Physics at zero degree
  - Diffractive process in e + A collision
    - Breakup of the excited nucleus
    - Event-by-event characterization of collision geometry
  - Spectator taggin in e + d/^{3}He collision
  - Leading baryons and forward asymmetries at zero degree
  - …

ZDC at RHIC and EIC

- We’re proposing EIC R&D of ZDC
  - Full-absorption photon detector
    - Crystal scintillators
  - Prototype study of ZDC with position sensitivity
    - EM + Hadron calorimeters
    - ALICE-FoCal / RHICf technology
  - Radiation hardness study for new technology
    - Plastic scintillators
- We also want RHICf calorimeter upgrade
  - RHICf = LHCf at RHIC
    - 2017 at STAR
    - 2022 at STAR and/or 2024 at sPHENIX
- We want to discuss ALICE-FoCal technology
  - To be applied for EIC R&D and RHICf upgrade

EIC status

- Critical Decision-0 “Approved Mission Need” for the EIC on December 19, 2019
- Selection of Brookhaven National Laboratory as the site for the EIC on January 9, 2020

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U.S. Department of Energy Selects Brookhaven National Laboratory to Host Major New Nuclear Physics Facility

JANUARY 9, 2020

Home » U.S. Department of Energy Selects Brookhaven National Laboratory to Host Major New Nuclear Physics Facility

WASHINGTON, D.C. – Today, the **U.S. Department of Energy (DOE)** announced the selection of Brookhaven National Laboratory in Upton, NY, as the site for a planned major new nuclear physics research facility.

The Electron Ion Collider (EIC), to be designed and constructed over ten years at an estimated cost between $1.6 and $2.6 billion, will smash electrons into protons and heavier atomic nuclei in an effort to penetrate the mysteries of the “strong force” that binds the atomic nucleus together.

“The EIC promises to keep America in the forefront of nuclear physics research and particle accelerator technology, critical components of overall U.S. leadership in science,” said **U.S. Secretary of Energy Dan Brouillette**. “This facility will deepen our understanding of nature and is expected to be the source of insights ultimately leading to new technology and innovation.”

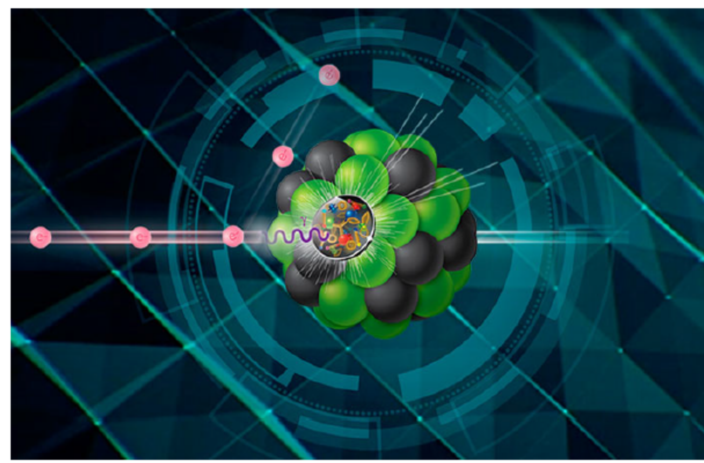
2020/1/13 Department of Energy Selects Site for Electron-Ion Collider | BNL Newsroom

Contact: Karen McNulty Walsh, (631) 344-8350, or Peter Genzer, (631) 344-3174

Department of Energy Selects Site for Electron-Ion Collider

New facility to be located at Brookhaven Lab will allow scientists from across the nation and around the globe to peer inside protons and atomic nuclei to reveal secrets of the strongest force in nature

January 10, 2020



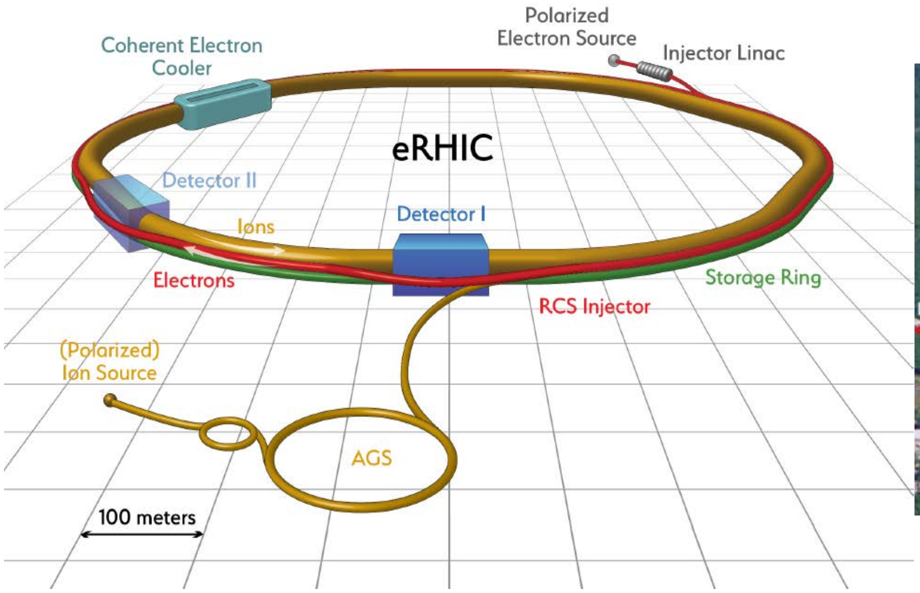
Electrons will collide with protons or larger atomic nuclei at the Electron-Ion Collider to produce dynamic 3-D snapshots of the building blocks of all visible matter.

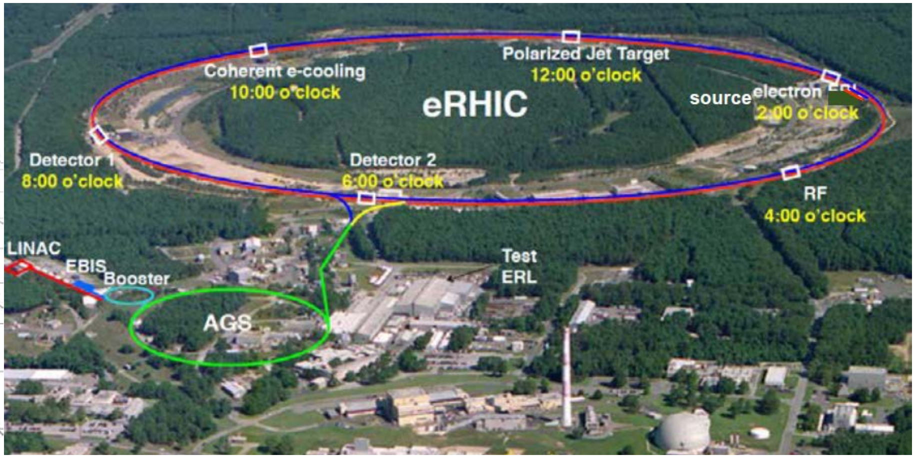
UPTON, NY— Yesterday, the U.S. Department of Energy (DOE) named Brookhaven National Laboratory on Long Island in New York as the site for building an Electron-Ion Collider (EIC), a one-of-a-kind nuclear physics research facility. This announcement, following DOE's approval of “mission need” (known as Critical Decision 0) on December 19, 2019, enables work to begin on R&D and the conceptual design for this next-generation collider at Brookhaven Lab.

"The EIC promises to keep America in the forefront of nuclear physics research and particle accelerator technology, critical components of overall U.S. leadership in science," said U.S. Secretary of Energy Dan Brouillette. "This facility

EIC - Electron Ion Collider

- Electron + proton / light-ion collision
  - Polarized beam: e, p, d/^{3}He
  - High luminosity: $L_{ep} \sim 10^{33\text{-}34}\,cm^{-2}s^{-1}$, 100-1000 times HERA
  - Collision energy: $\sqrt{s}$ = 20 – 100 (140) GeV
- Electron + heavy-ion collision
  - Wide range in nuclei

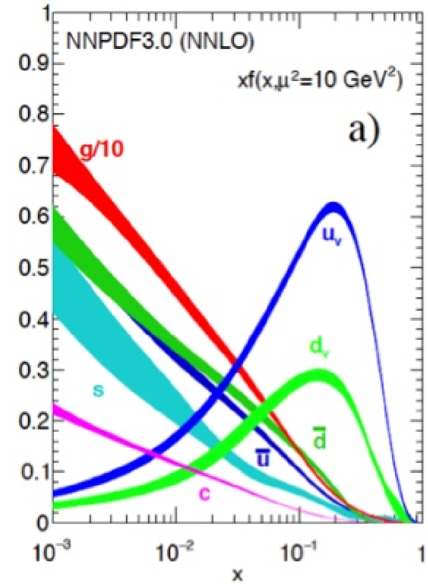




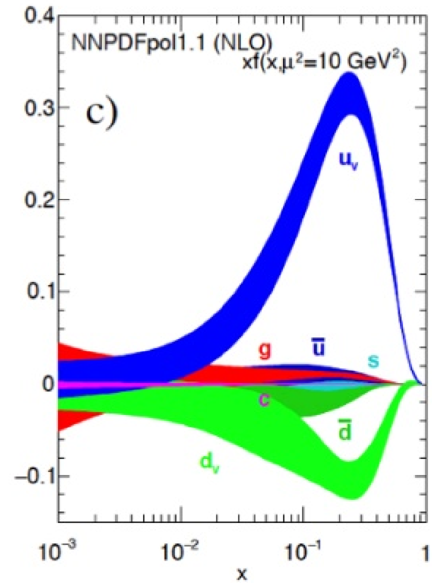
EIC physics

- Spin and flavor structure of the nucleons and nuclei
  - How does the spin of the nucleon arise?
  - Parton distribution function (PDF) of quarks and gluons
  - Significant improvement of precision of the polarized PDF at EIC, especially gluon polarization
- 3D picture of the nucleons and nuclei
  - How does the mass of the nucleon arise?
  - Generalized parton distribution (GPD) function
  - New picture to be established at EIC

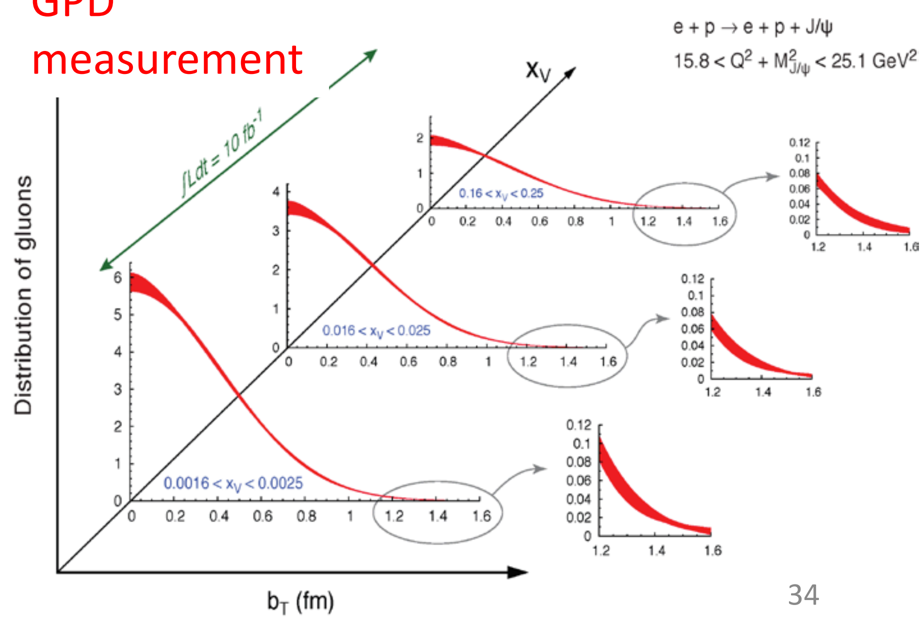
Unpolarized PDF



Polarized PDF

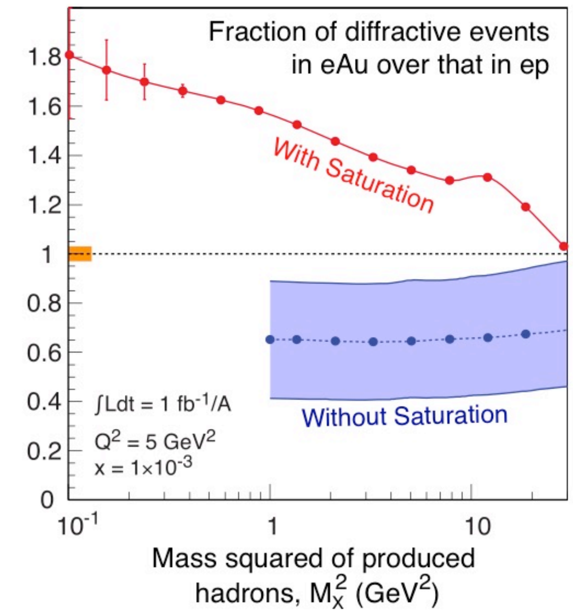


GPD measurement

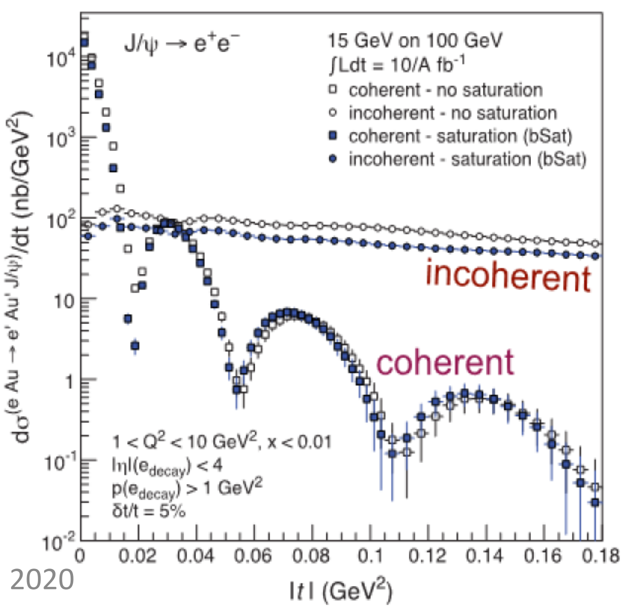


EIC physics

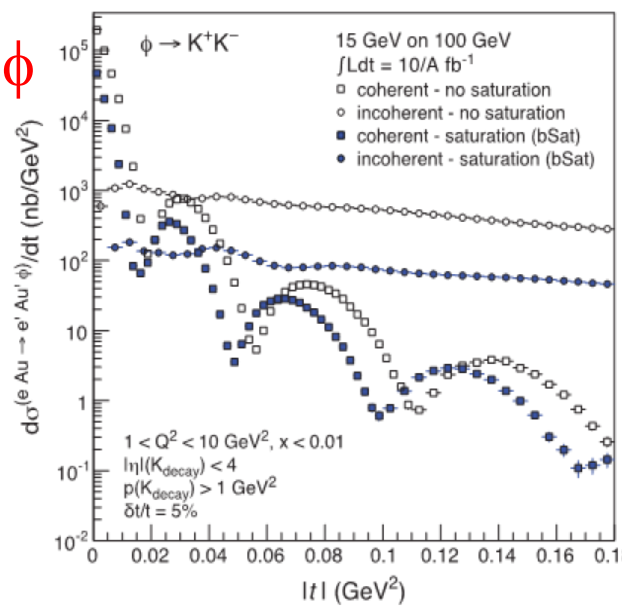
- Gluon saturation at extreme density
  - What are the emergent properties of dense system of gluons?
- Diffractive cross section
  - 10-15% diffractive at HERA e+p
  - 25-30% diffractive predicted by Color Glass Condensate (CGC) at EIC e+A
- Diffractive vector meson production
  - ϕ meson sensitive to the gluon saturation



J/ψ

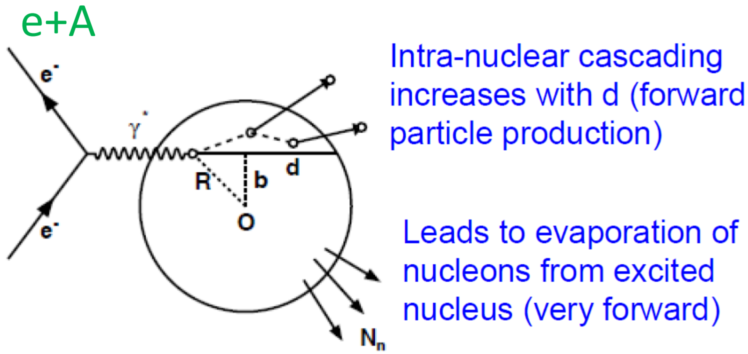


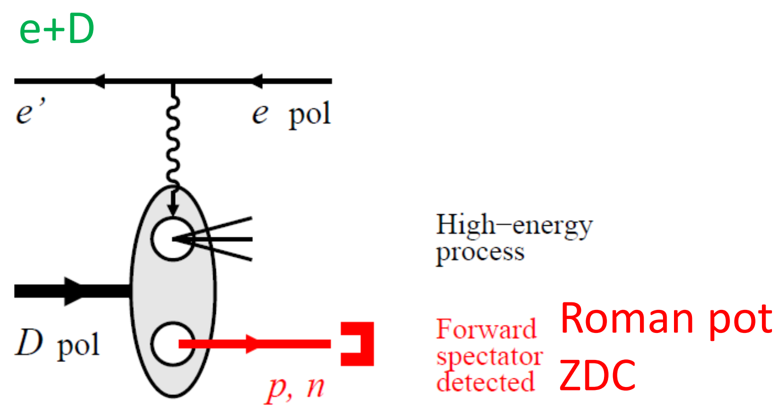
ϕ



EIC physics at zero degree

- e+A collision geometry
  - Exclusive vector meson production in diffractive process
    - Coherence requires forward scattered nucleus to stay intact
    - Veto breakup through neutron detection
  - Event-by-event characterization of collision geometry
    - *b*: impact parameter & *d*: path length
    - "Centrality" (high *d*) & "Skin" (low *d*)
- Spectator tagging in e+d/^{3}He
  - 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*
- Leading baryons and very forward asymmetries



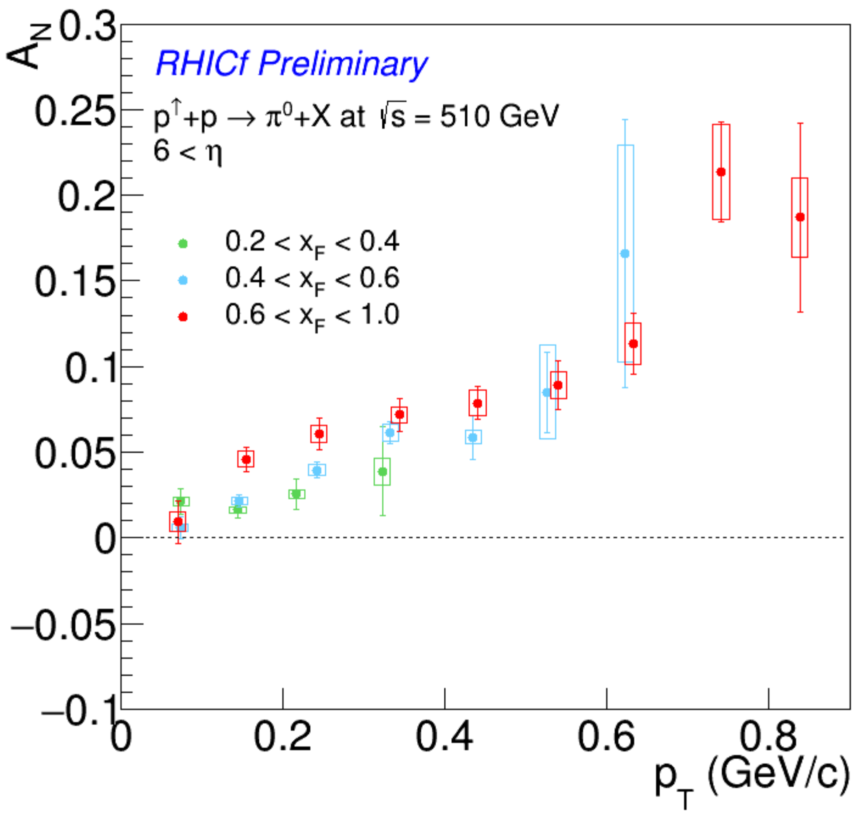


Detector performance requirements for EIC

- Photon detection
  - To identify the nuclear excitation states in addition to the neutron detection
  - Photon energy < 300 MeV
  - Full absorption calorimeter, e.g. crystal calorimeter (LYSO, PWO, …)
- ZDC
  - Acceptance
    - 25 mrad crossing angle for EIC at BNL (aka eRHIC)
    - Forward magnet aperture $\pm$4 mrad opening angle for ZDC
  - Position resolution
    - 1 cm position resolution $\rightarrow$ 300 μrad angular resolution
    - $\rightarrow$ 30 MeV p_T resolution for 100 GeV spectator neutron
  - Energy resolution
    - Minimum requirement $\Delta E/E = 50\%/\sqrt{E}$ (GeV)
    - $\rightarrow$ 50 MeV p_T resolution for 100 GeV spectator neutron
- Radiation hardness
  - 100k – 1MGy or $n_{eq} = 3\text{x}10^{12} - 10^{13}$ for 1-year operation
  - $n_{eq} > 10^{14}$ for lifetime

A_N of very forward π^0

- p_T dependence
  - Large asymmetry (up to 0.1) even at low p_T ($p_T < 0.6$ GeV/c)
  - Becoming larger (more than 0.1) at high p_T (0.6 GeV/$c < p_T$)



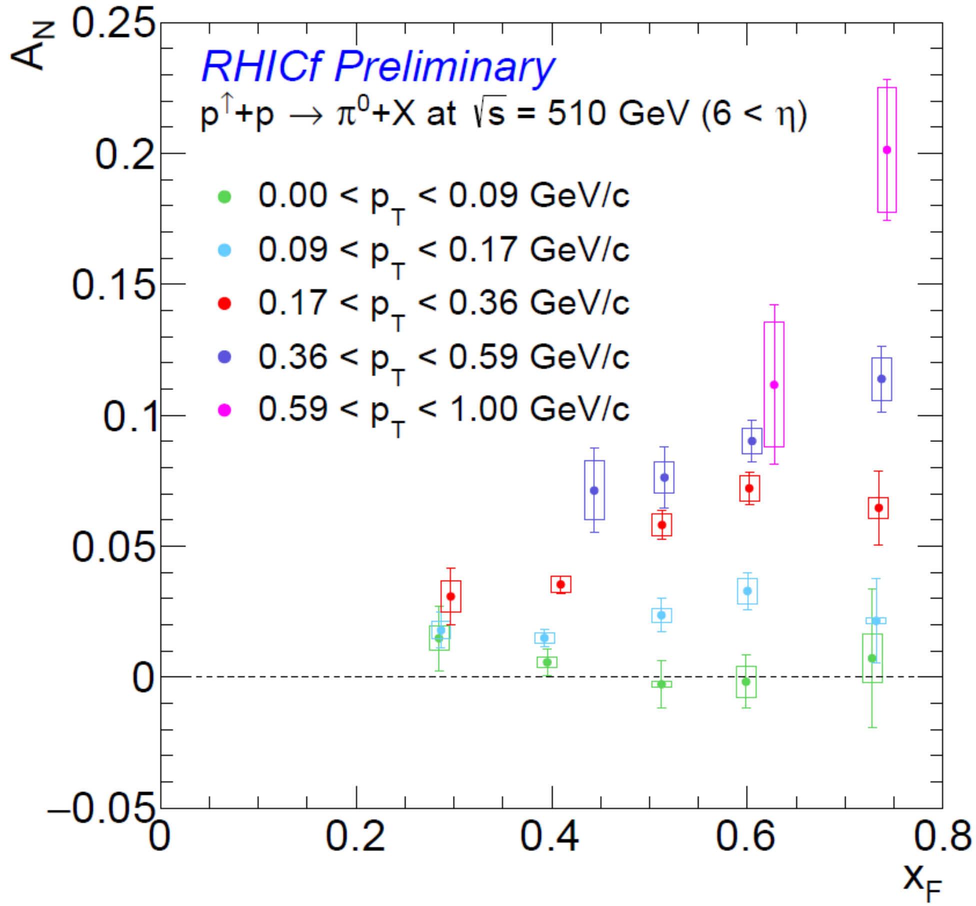
Data analysis has been performed by Minho Kim (Korea Univ.)

Background asymmetry (measured, zero consistent) subtracted

Bar: statistical error
Box: systematic uncertainties including beam center correction, acceptance correction, polarization, and background asymmetry subtraction

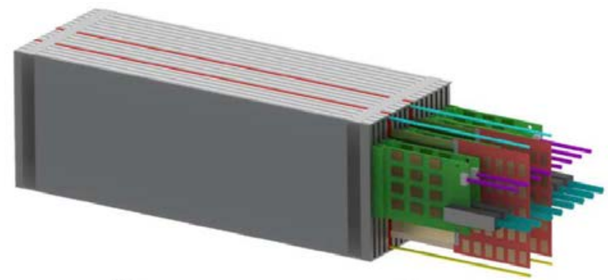
A_N of very forward π^0

- x_F dependence
  - $A_N \sim 0$ at $p_T < 0.09$ GeV/c
  - $A_N > 0$ at 0.09 GeV/$c < p_T$ and rising with x_F

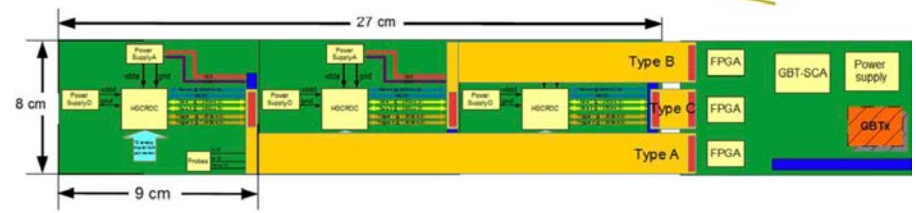


Discussions for ALICE-FoCal

- For RHICf upgrade (2022 and/or 2024)
  - Space restriction at RHICf
    - Possible new mini-FoCal with new readout scheme for RHICf?
  - Readout electronics integration to STAR and/or sPHENIX electronics & DAQ system
  - Pad and/or pixel
    - π^0 identification
    - Schedule?



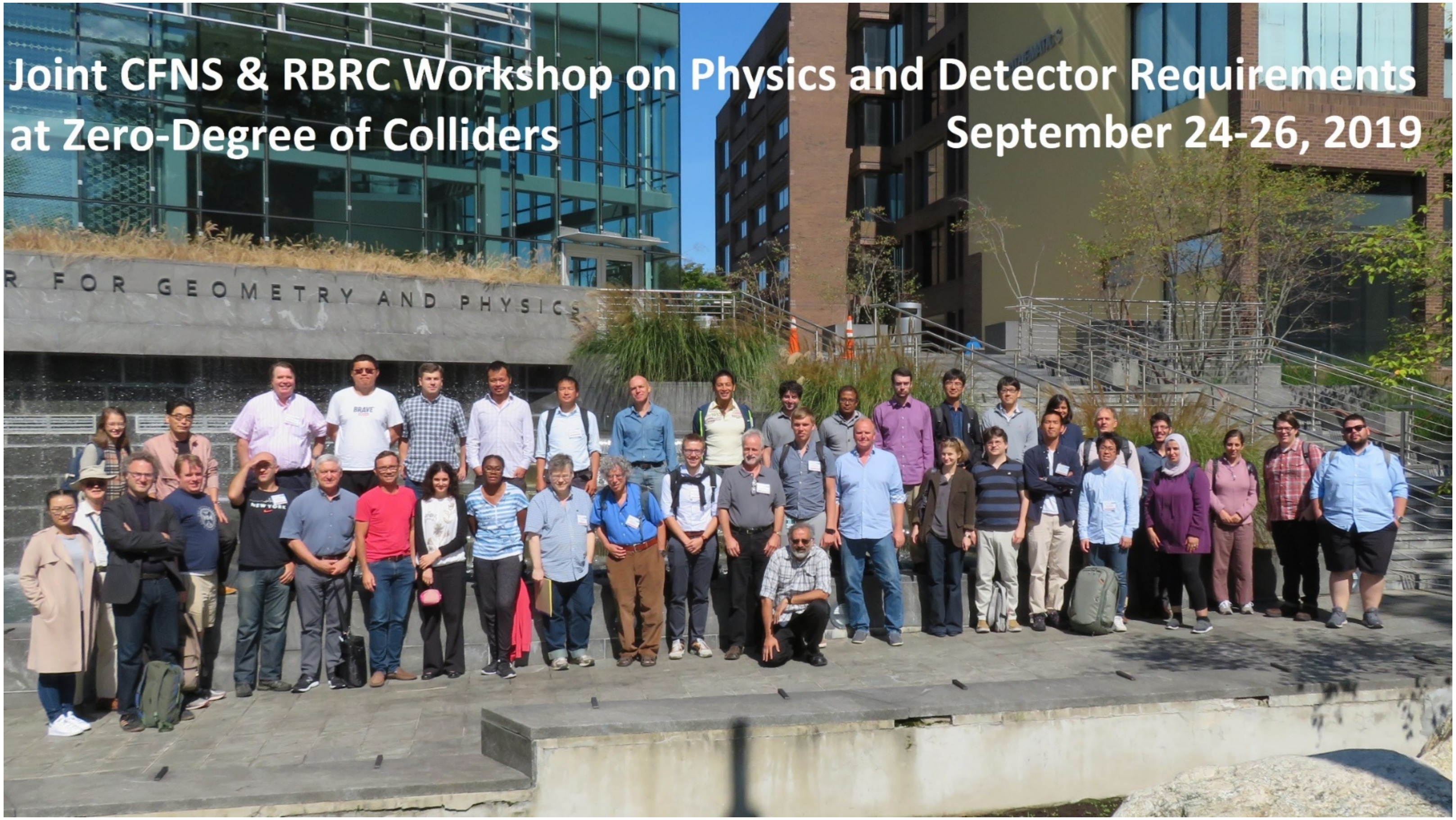
- For ZDC at EIC
  - EM + Hadron calorimeters
  - e.g. 60cm x 60cm



- For ALICE-FoCal
  - What would be contribution or deliverable from RIKEN if RIKEN participates?

Joint CFNS & RBRC workshop

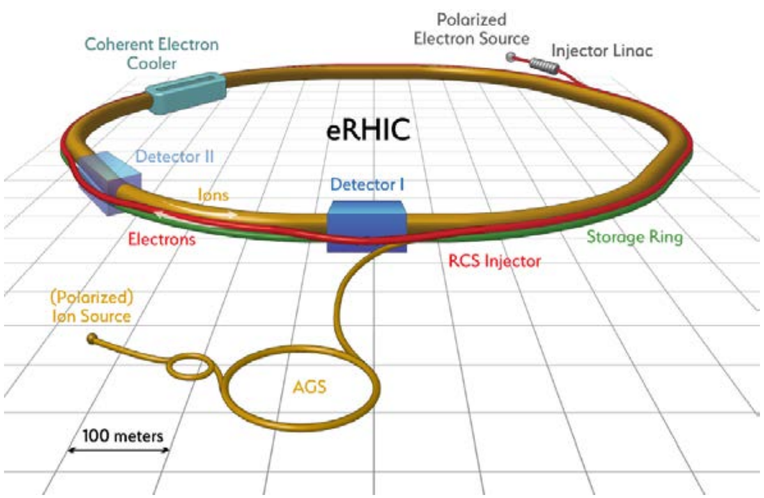
- Physics and detector requirements at zero-degree of colliders
  - 24-26 September 2019
  - Stony Brook University



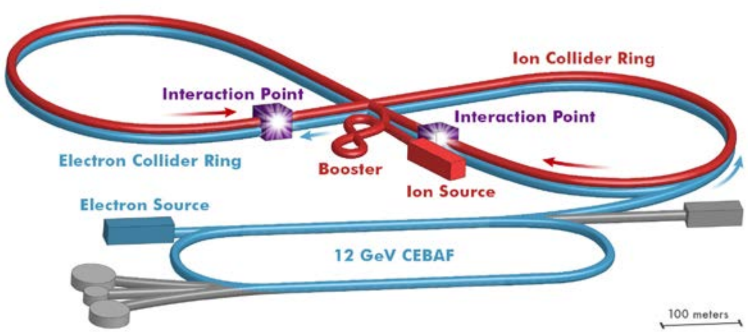
EIC - Electron Ion Collider

- 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
    - $L_{ep} \sim 10^{33\text{-}34}$ 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

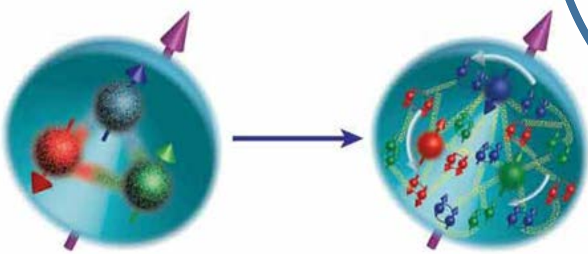


JLEIC at Jefferson Lab



Physics at EIC

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

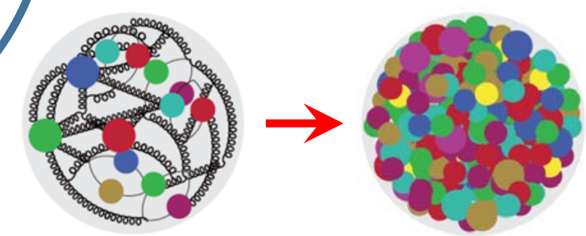


How does the mass of the nucleon arise?

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

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*

Luminosity

Collision Energy

Discovery

What are the emergent properties of dense systems of gluons?

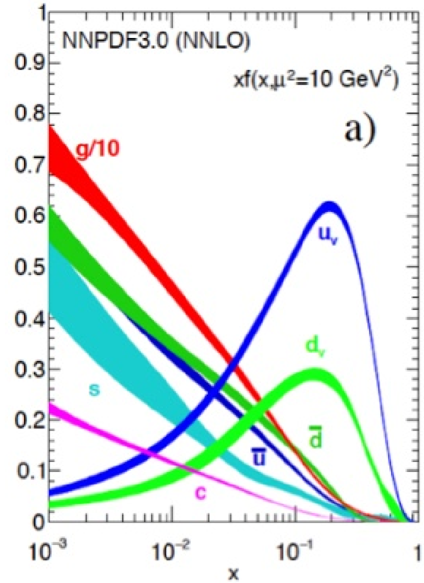
Gluon Saturation at Extreme Density

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

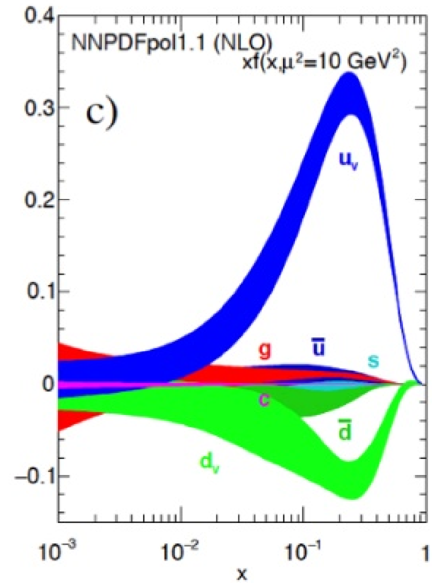
Quark-gluon structure

- 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

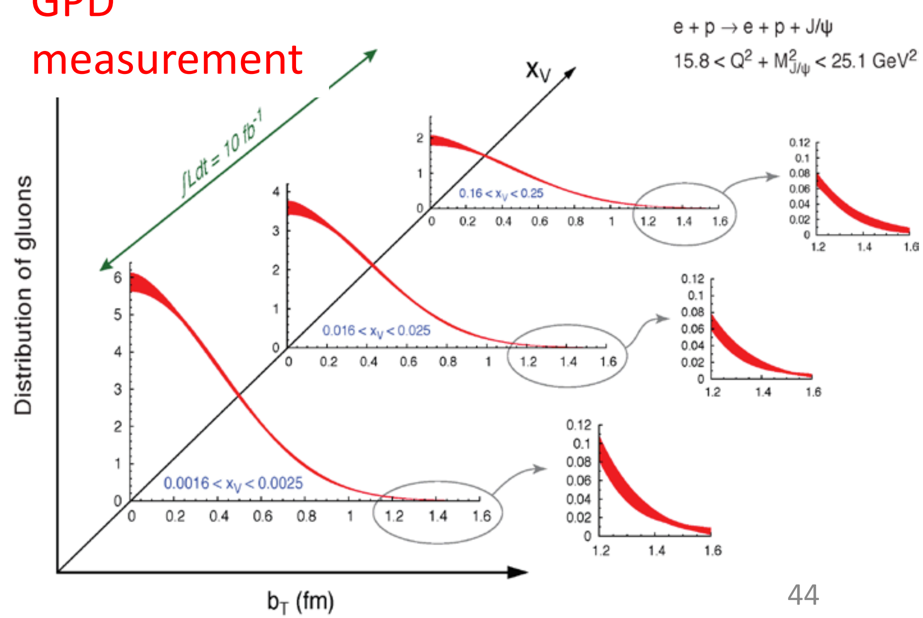
Unpolarized PDF



Polarized PDF

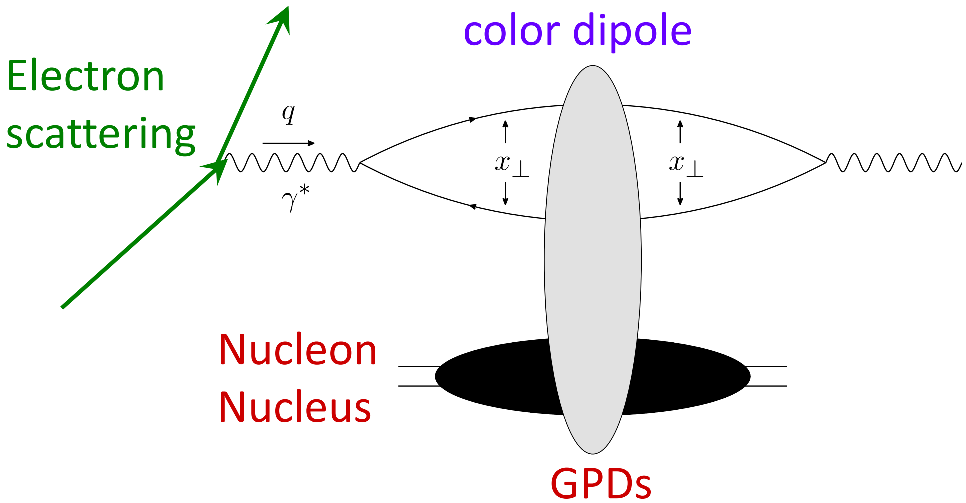


GPD measurement

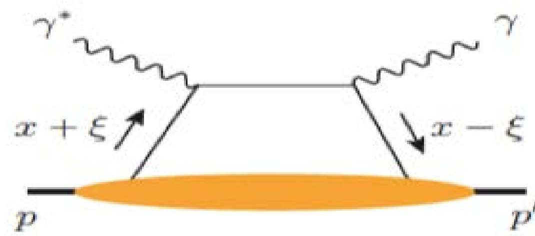


Tomography of the nucleon / nucleus

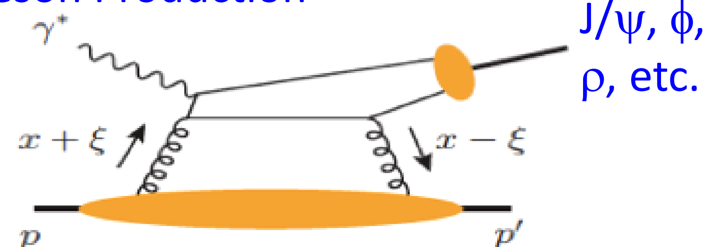
- EIC = color dipole microscope
  - Exclusive process and diffractive process
  - 3D distribution: transverse spatial distribution



DVCS (Deeply Virtual Compton Scattering)



Meson Production



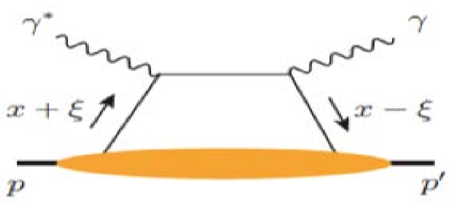
- GPD (Generalized Parton Distribution)
  - Spatial imaging of gluons and quarks = tomography
    - HERA: 1st generation
    - EIC: 2nd generation (high luminosity, heavy ion, polarization)
  - Orbital angular momentum
    - Ji's sum rule
    - Origin of the nucleon spin

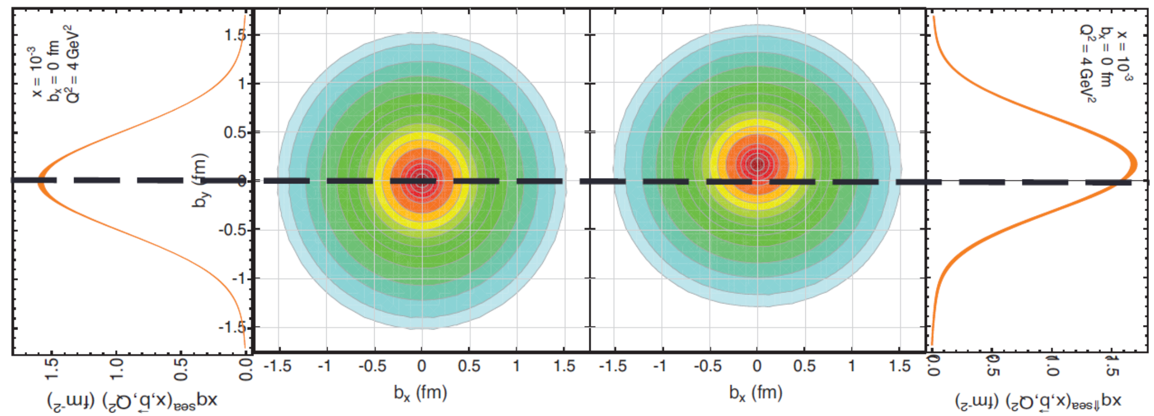
$$J_q^z = \frac{1}{2}\sum_q \Delta q + \sum_q L_q = \frac{1}{2}\left(\int_{-1}^{1} x dx (H^q + E^q)\right)_{t\to 0}$$

Tomography of the nucleon / nucleus

- DVCS
  - Deeply virtual Compton scattering

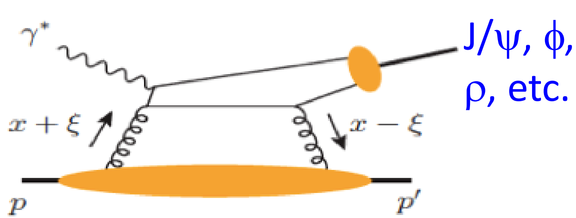
Spatial distribution of sea quarks at EIC 100 fb^{-1} and corresponding density of partons in the transverse plane

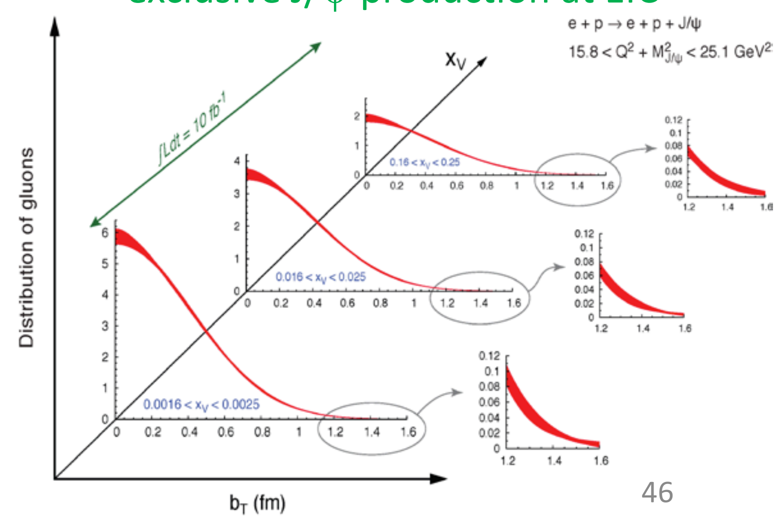




- Meson production
  - Gluon tomography by measuring J/ψ, φ, ρ, etc.
  - Precision measurement at large radius with high luminosity

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



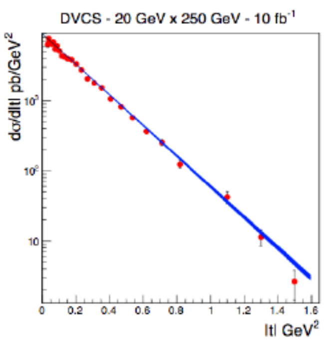


Physics at zero degree of EIC

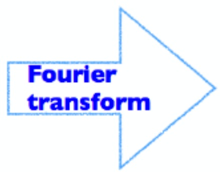
- Very forward proton acceptance for DVCS exclusive measurement

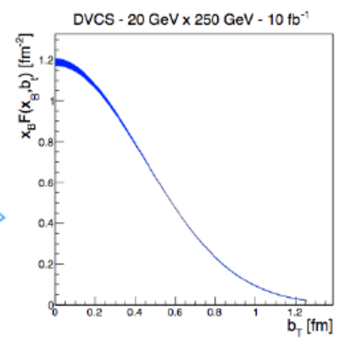
Measurement

Physics observable (cross-section vs impact parameter)

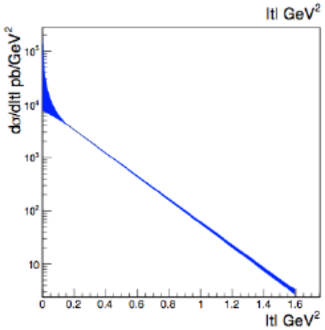


Plots from EIC White Paper:

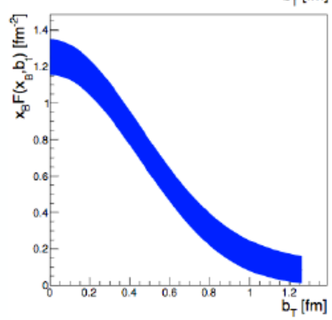




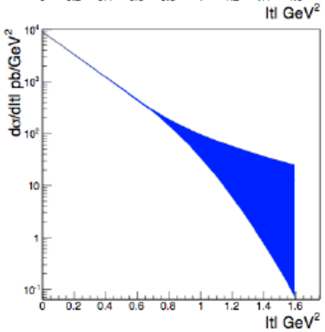
Requirement:
$\int L_{int}=10fb^{-1}$
$0.18 < p_t$ (GeV) < 1.3
$0.03 < |t|$ (GeV²) < 1.6



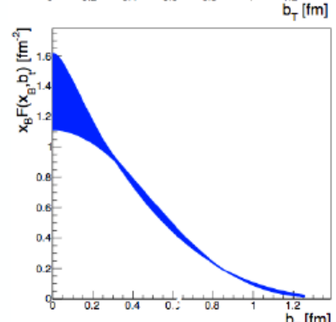
limited lower p_T-acceptance



Uncertainty in normalization
$\int L_{int}=10fb^{-1}$
$0.44 < p_T$(GeV) < 1.3



limited higher p_T-acceptance



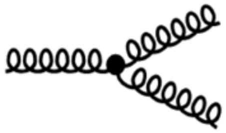
Uncertainty in slope and shape
$\int L_{int}=10fb^{-1}$
$0.18 < p_T$ (GeV) < 0.8

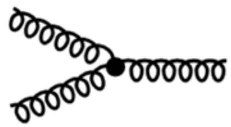
We need a proton spectrometer with large acceptance!

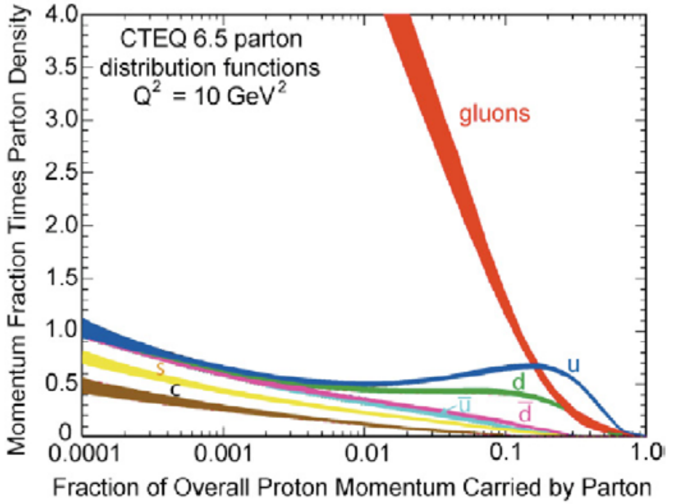
shown by Fazio & Jentsch

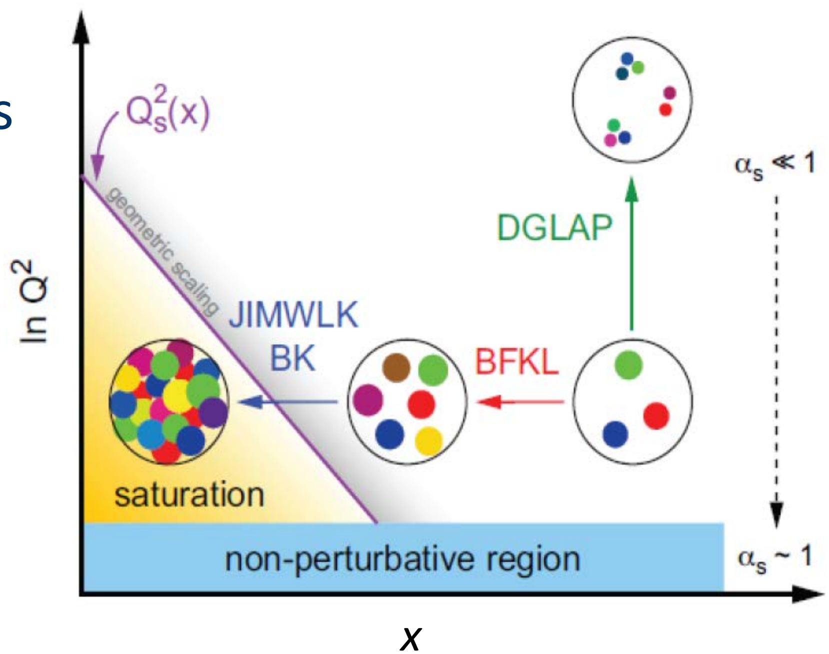
Gluon saturation in e+A collisions

- 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 Color 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







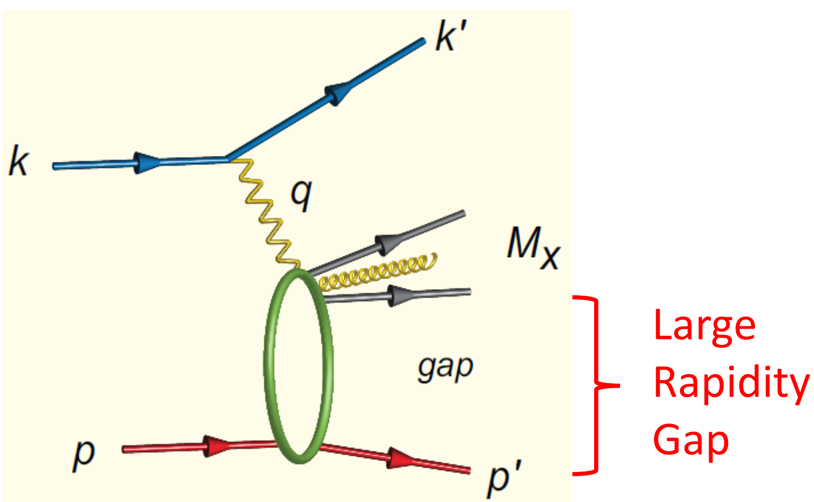


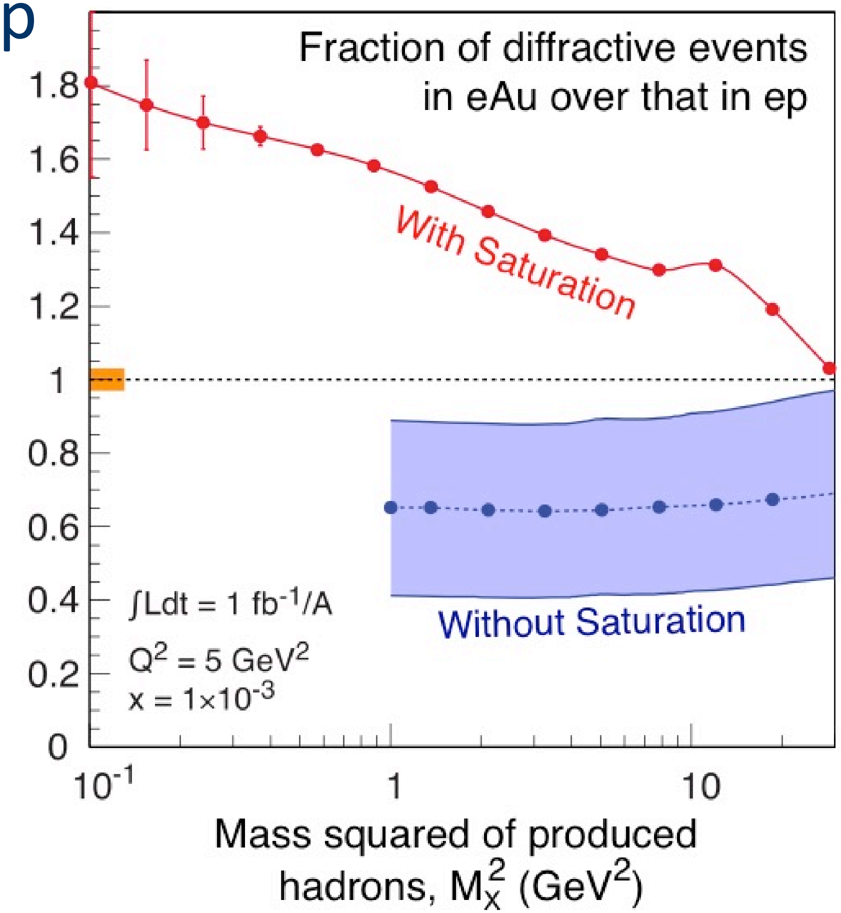
Gluon saturation in e+A collisions

- Diffractive cross section
  - Most sensitive way to study the gluon saturation

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

- 10-15% diffractive at HERA e+p
- 25-30% diffractive predicted by CGC at EIC e+A

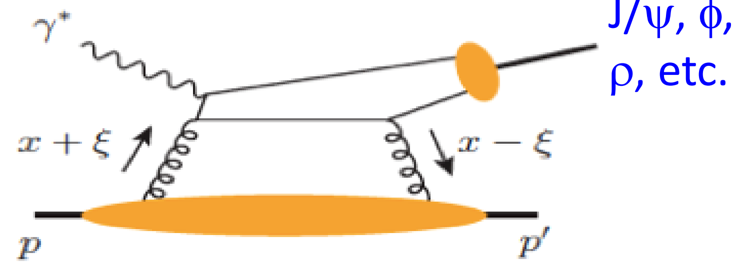


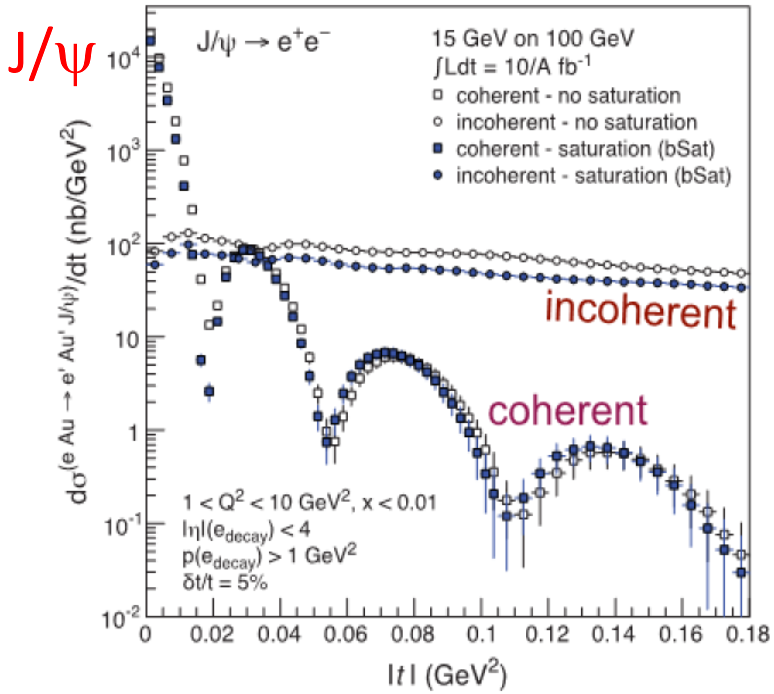


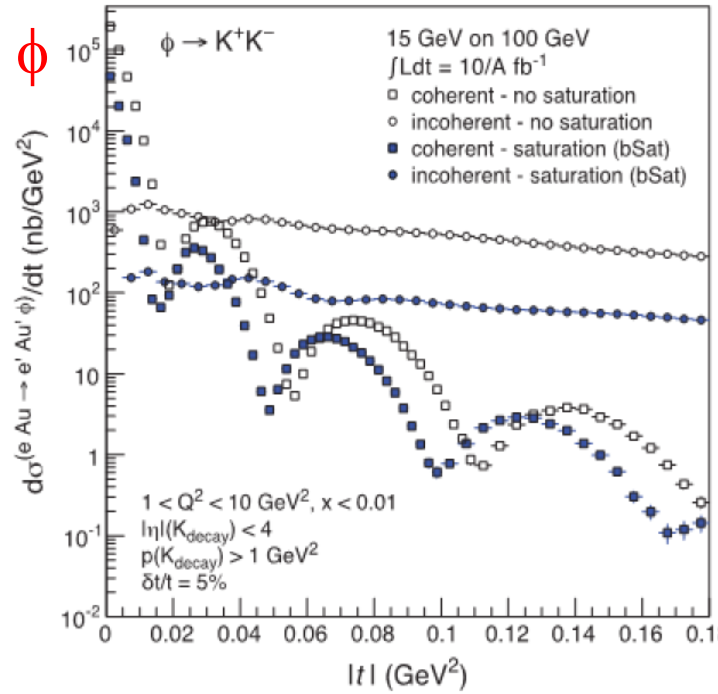
3D structure of the nucleus

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

Meson Production

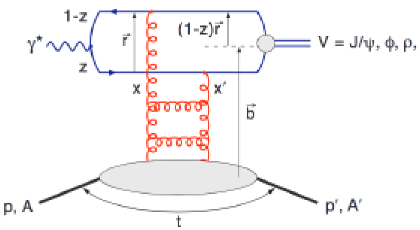






GPD studies with exclusive processes

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

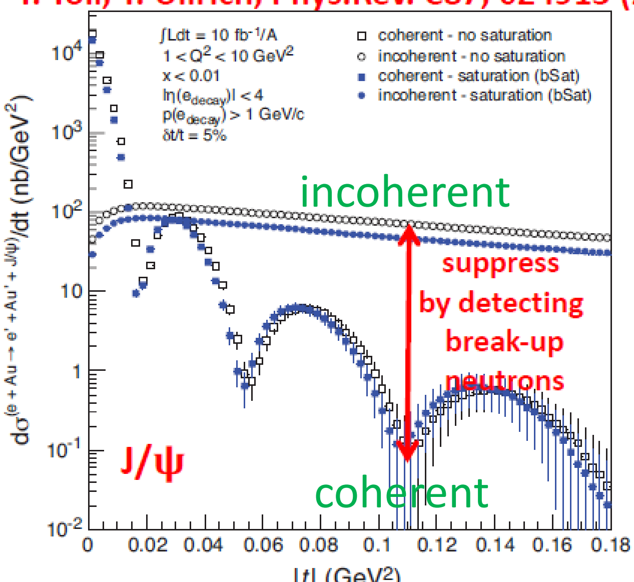
Hot topic:

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

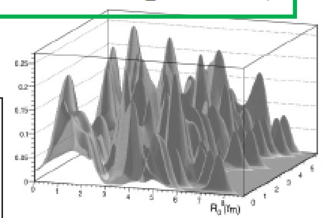
❑ coherent part probes "shape of black disc"

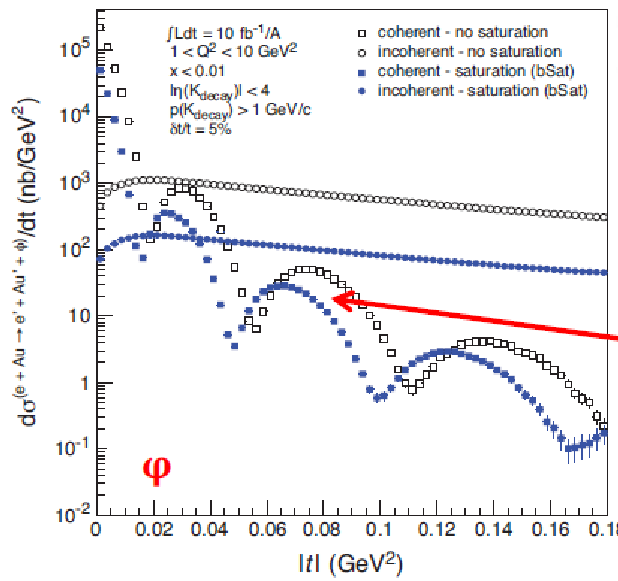
❑ incoherent part (large t) sensitive to "lumpiness" of the source [= proton] (fluctuations, hot spots, ...)

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



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





Sensitive to saturation effects!

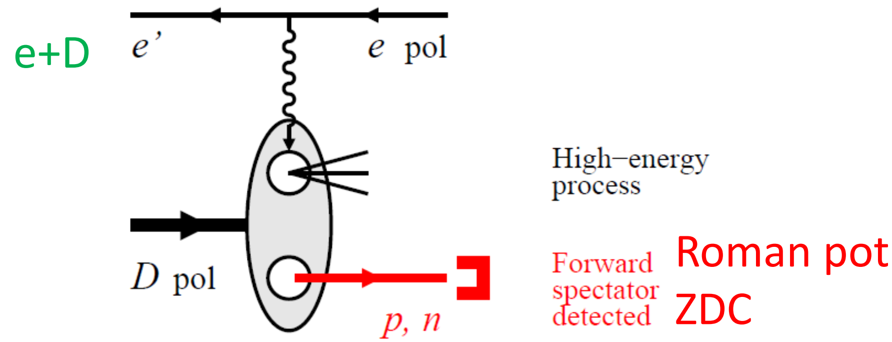
Coherent requires forward scattered nucleus needs to stay intact

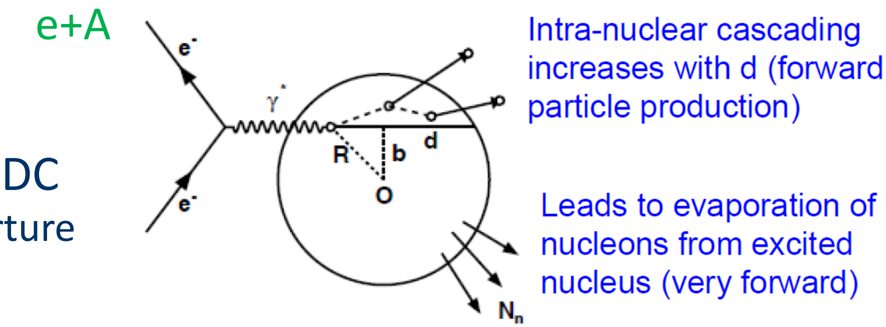
→ Veto breakup through neutron detection

slide by Fazio

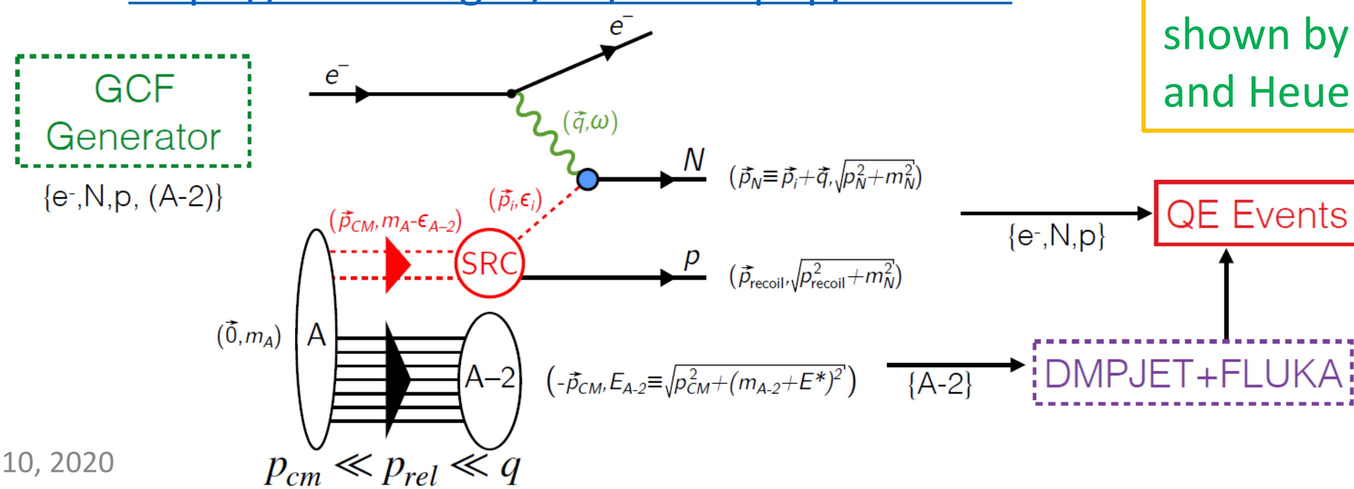
Physics at zero degree of EIC

- Spectator tagging
  - Neutron structure
    - Neutron spin structure, S & D waves
  - Nucleon interactions
    - SRC/EMC at large *x*
    - Diffraction and shadowing at small *x*
- Geometry tagging in e+A collisions
  - *b*: impact parameter & *d*: path length
  - "Centrality" (high *d*) & "Skin" (low *d*)
  - Breakup determination & veto with ZDC
    - + forward photons requiring wide aperture
- Event generator
  - GCF: https://www.mit.edu/~src_emc/fri/schmidt_20190322.pdf
  - BeAGLE: https://wiki.bnl.gov/eic/index.php/BeAGLE



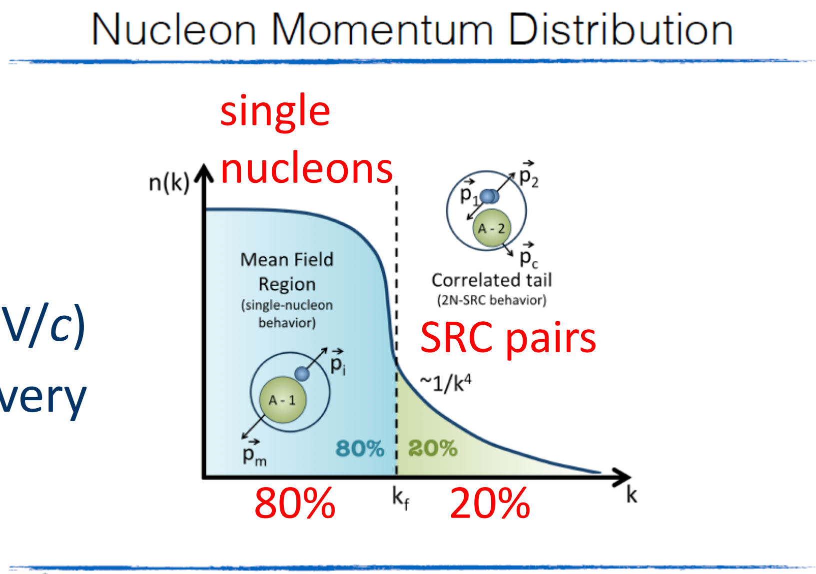


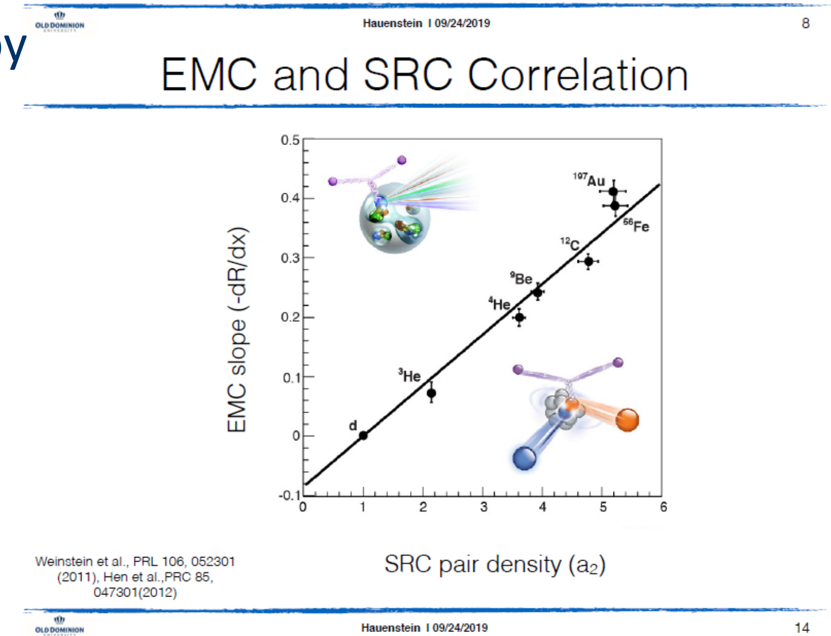
shown by Weiss, Baker and Heuenstein



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 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



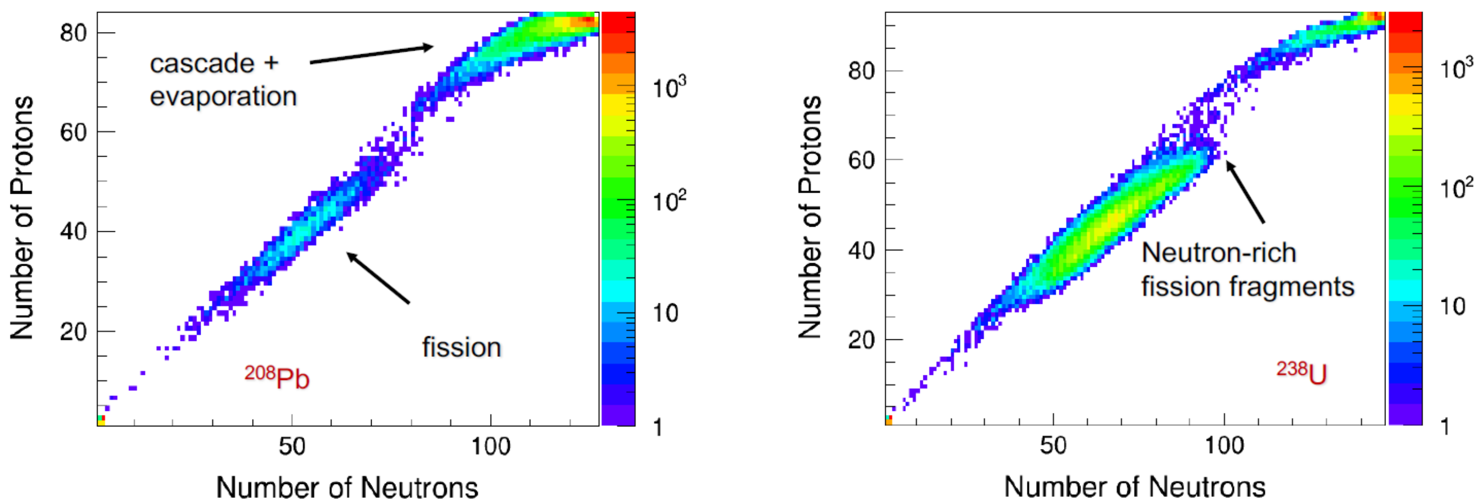


slides by Heuenstein

Physics at zero degree of EIC

- Isotope tagging
  - Nuclear fragments need to be tagged to reconstruct the Fermi momentum of the struck nucleon
- Rates at the EIC?
  - Needs further studies

Nuclei from ^{208}Pb and ^{238}U (1s of simulated beam time at the EIC)

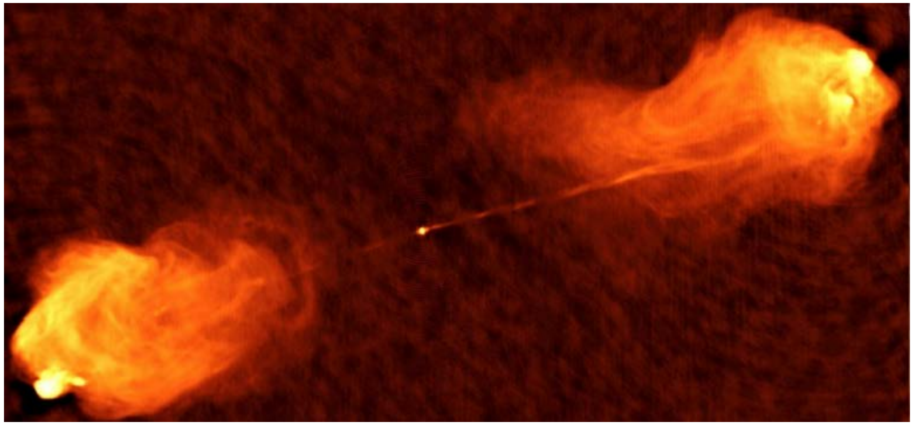


- ^{208}Pb (left) produces mainly heavy isotopes from evaporation
- ^{238}U (right) produces fewer, but heavier isotopes from evaporation. It also produces very neutron-rich fission fragments (medium-mass nuclei have fewer neutrons).

slide by Nadal-Turonski

Relation to cosmic-ray physics

- e+p, e+A at EIC
  - Limited relation to cosmic-ray physics
    - Understanding hadronization
  - Cosmic ray acceleration in blazars?
    - Source of high-energy cosmic ray & neutrino?

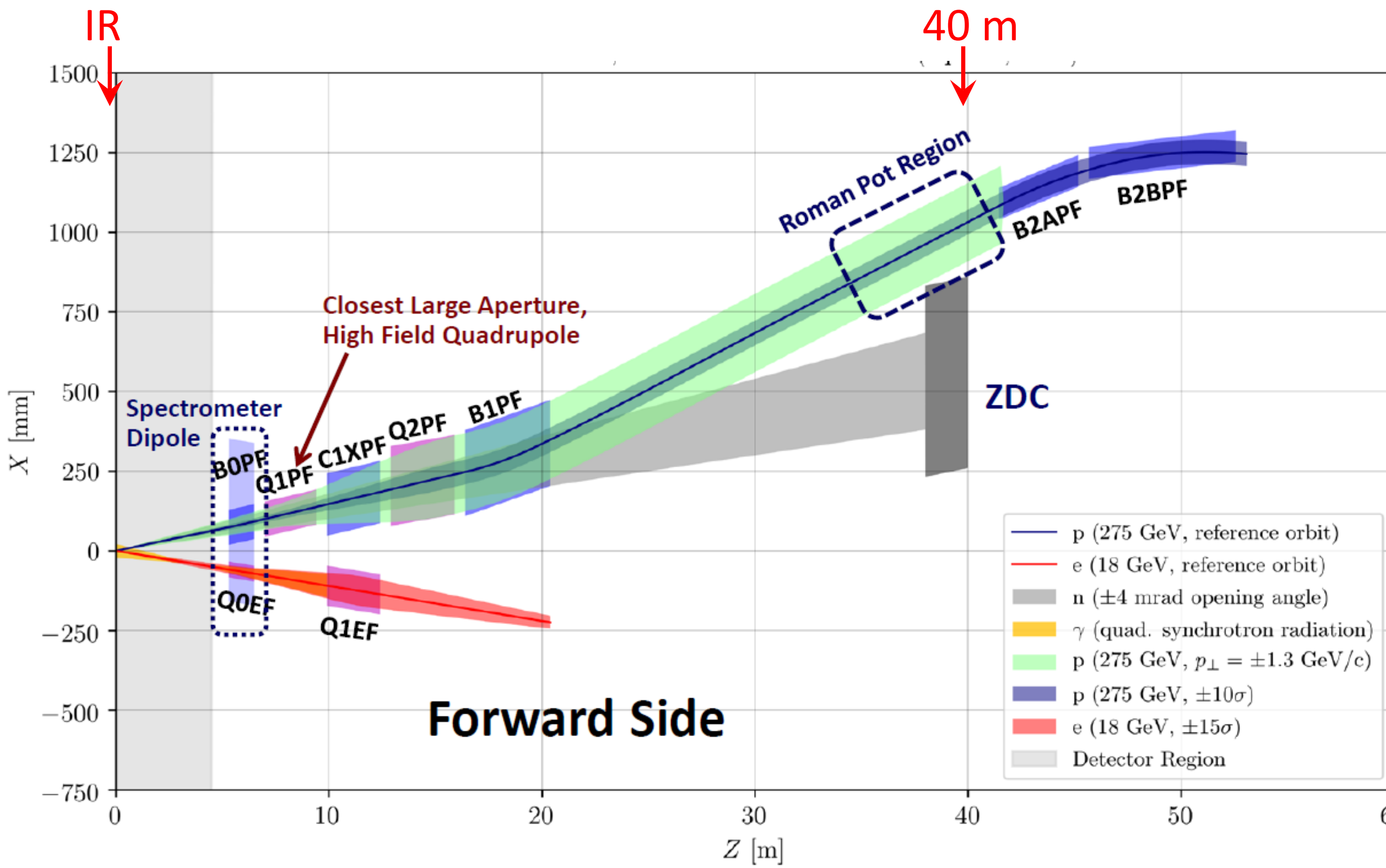


shown
by Liodakis

- p+p, p+A, A+A (at RHIC & LHC)
  - More relevance to the cosmic-ray physics
    - Understanding air-shower evolution
    - Event generator development

IR design of EIC at BNL (aka eRHIC)

- 25 mrad crossing angle
- Forward magnet aperture
  - ±4 mrad opening angle for neutron (ZDC)

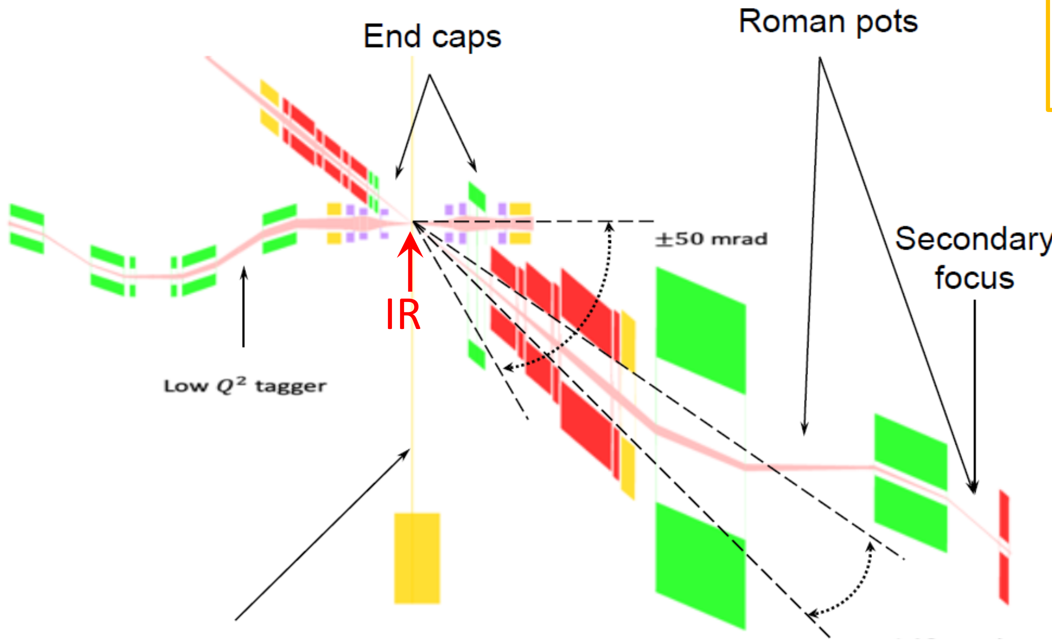


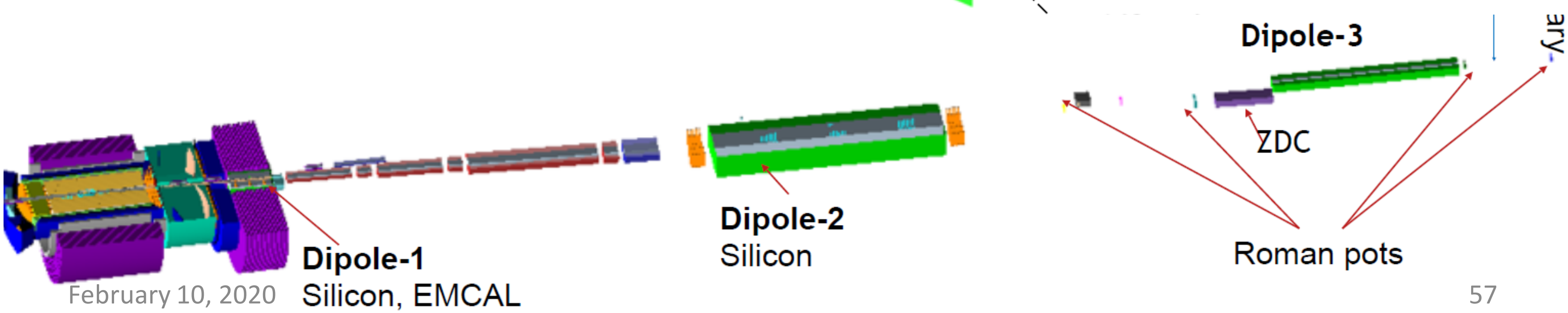
shown by Montag

JLEIC IR design

- 50 mrad crossing angle
- Forward magnet aperture
  - ±10 mrad opening angle for neutron

shown by
Furletova & Weiss

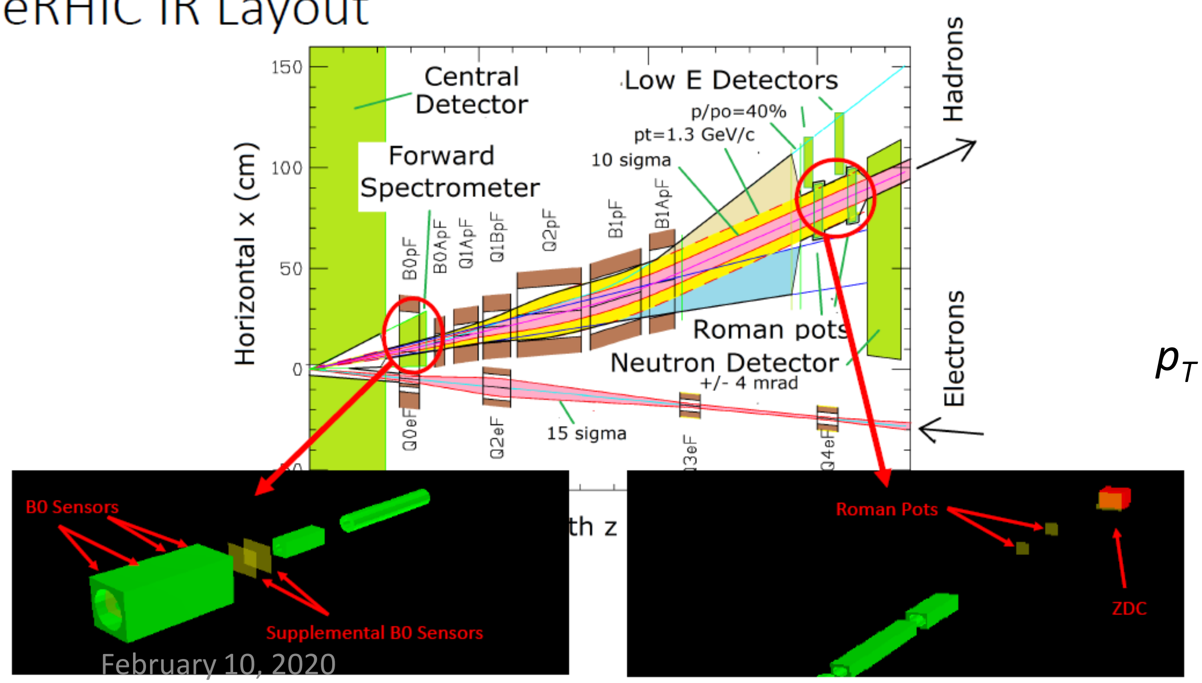




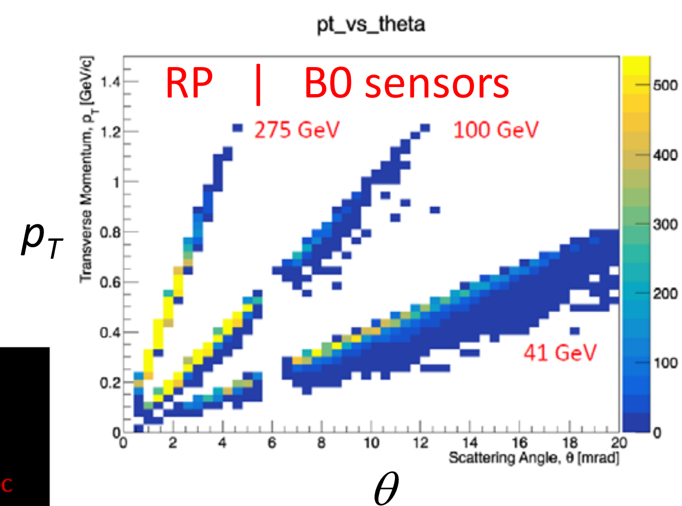
Proton spectrometer

- GPD measurement
  - Normalization (low p_T or $|t|$ coverage)
  - Slope and shape (high p_T or $|t|$ coverage)
- Veto of nuclear breakup events in e+A
  - for proton detection, with ZDC for neutron detection
- Isotope tagging
  - with particle ID
- B0 sensors and Roman pots at eRHIC
  - ± 1.3 GeV/c p_T for 275 GeV proton (Roman pot)

eRHIC IR Layout

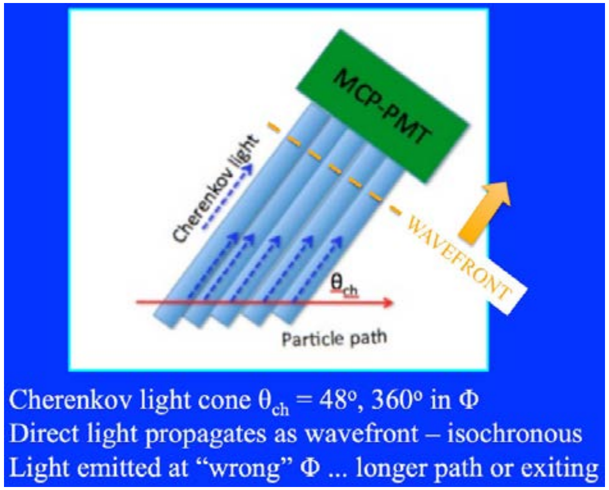


shown by Jentsch

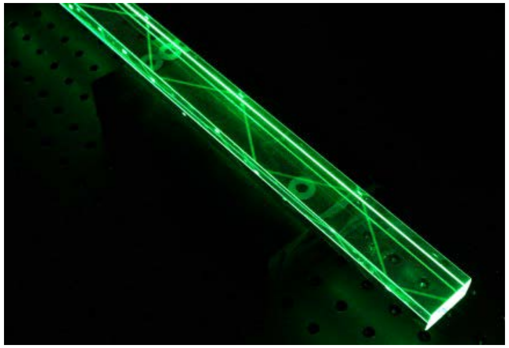


Particle ID

- psTOF in very forward region
  - MCP-PMT shows 5 ps capability
  - Mass (M) and charge (Z)
  - 0.1 ps required for 1% mass resolution
- Mini-DIRC inside a Roman pot
  - Identify ions to ~1% in Z^2
- Isotope tagging
  - Mass, charge and rigidity
- Spectroscopy
  - Strangeness and heavy flavors



shown by Chiu



shown by Nadal-Turonski

Zero Degree Calorimeter (ZDC)

- Position sensitive ZDC
  - Energy (E) resolution
    - Geometry tagging
  - Position (or θ) resolution
  - p_T (or $|t|$) resolution
    - Need both E and θ resolution
    - Intrinsic momentum spread from beam emittance
    - Spectator tagging
    - Isotope tagging
  - Uniformity (position dependence)
  - Aperture (IR & detector design)
    - $\pm$4 mrad @ BNL (eRHIC)
    - $\pm$10 mrad @ JLab (JLEIC)
  - Radiation dose & hardness

ZDC at EIC

- Position resolution
  - 1 cm position resolution -> 300 urad angular resolution -> 30 MeV pT resolution for 100 GeV spectator neutron
- Energy resolution
  - Minimum requirement $\Delta E/E = 50\%/\sqrt{E}$ (GeV) for 50 MeV pT resolution for 100 GeV neutron

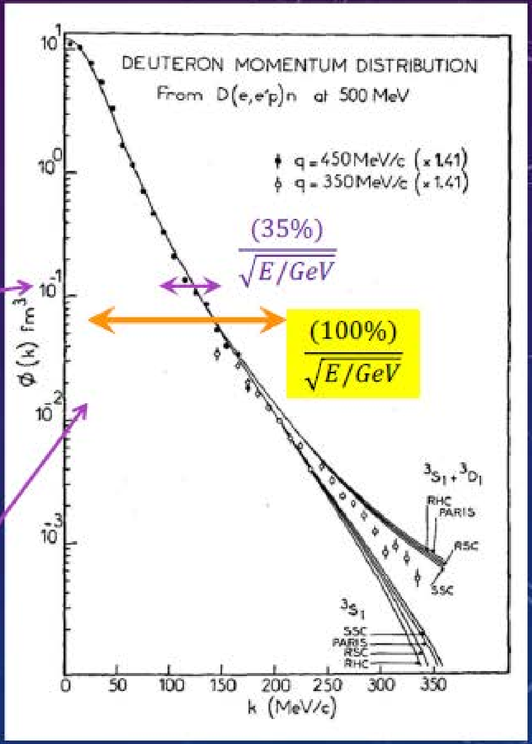
ZDC at EIC

- Detector requirements for spectator neutron tagging
  - p_T resolution

D(e,e'n_S)X ≈ p_{bound}(e,e')X

200 GeV/c D ➔ 100 GeV/c spectator neutron

- Hadronic Calorimeter at 45 m (JLEIC)
- Impact point resolution 1.5 cm *rms*:
  - $\frac{\delta p_T}{p} = 0.33$ mrad ➔ $\delta p_T = 33$ MeV
  - Equivalent to *rms* beam spread
- If energy Resolution $\frac{\delta E}{E} = \frac{(35\%)}{\sqrt{E/GeV}}$
  - $\alpha = A\frac{p_n^+}{P_A^+} \approx \left[1 + \frac{p_n}{M_N}\right]_{Deuteron\ Rest-Frame}$
  - $\delta\alpha = \frac{\delta E}{E} = 3.5\%$ ➔ $\delta p_n^{D\text{-}rest} \approx 35$ MeV/c
  - If $\frac{(100\%)}{\sqrt{E/GeV}}$ ➔ $\delta p_n^{D\text{-}rest} \approx 100$ MeV/c

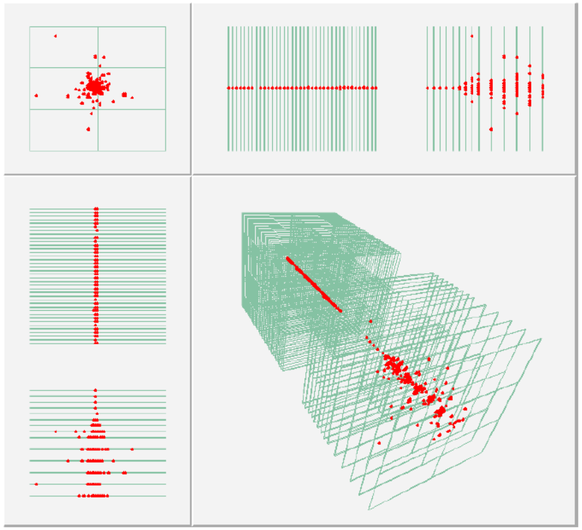


C.Hyde 9/25/19 4

slide by Hyde

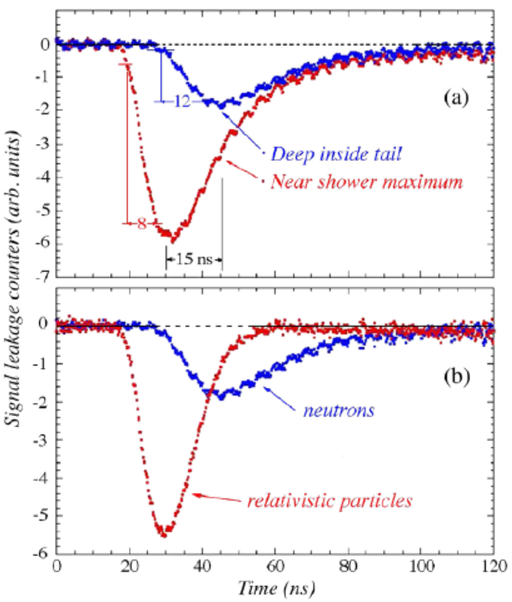
Detector requirements

- 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

Detector requirements

- Position layers (or Shower Max Detector)
  - Scintillation fiber/bar
    - Plastic fiber
    - Crystal bar (~1mm)
  - Cherenkov
    - Quartz fiber
  - Silicon sensor

	Plastic fiber	Crystal bar	Quartz fiber	Silicon
Source	Scintillation		Cherenkov	
Signal	good	good	weak	good
Rad Hardness	poor	OK	excellent	OK
Cost	$	$$	$$	$$$
Position Resolution	good	good	poor	best
Large acceptance	OK	position dependent	OK	OK

Summary

- Physics at zero degree of EIC
  - GPD, gluon saturation in e+A, leading baryons, spectator tagging, geometry tagging, SRC/EMC, isospin tagging, spectroscopy, …
- IR & detector requirements
  - Proton spectrometer, partic ID, ZDC, …
- Next goals
  - Physics, detector and IR requirements at zero degree to be compiled in an EIC detector R&D letter of interest of the zero-degree apparatus (January, 2020)
  - Next meeting to be planned before making an EIC detector R&D proposal (July, 2020)
  - Please consider to join us