Electron-Ion Collider (EIC) 2nd Detector Program at BNL

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on behalf of the BNL EIC 2nd Detector Group

Nuclear Particle Astrophysics (NPA) Seminar
@ Wright Lab Yale University 04/18/2024

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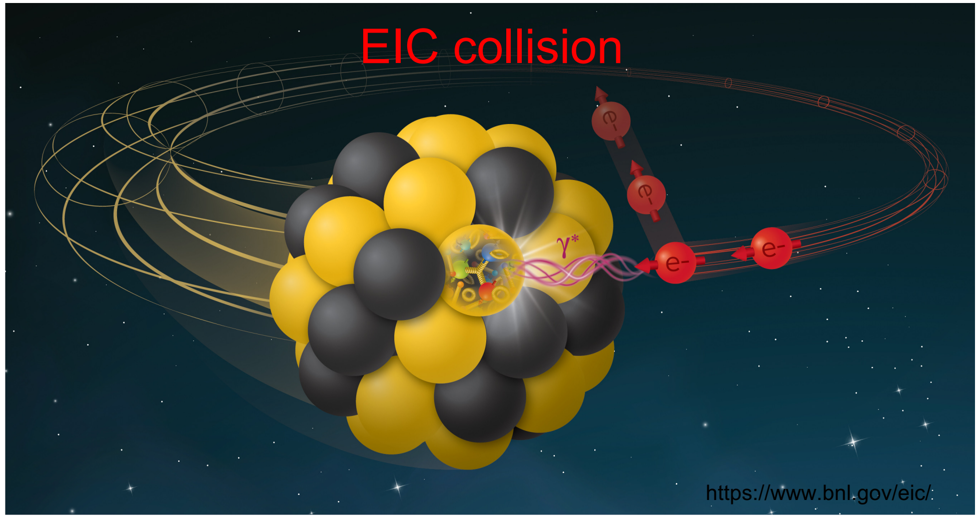
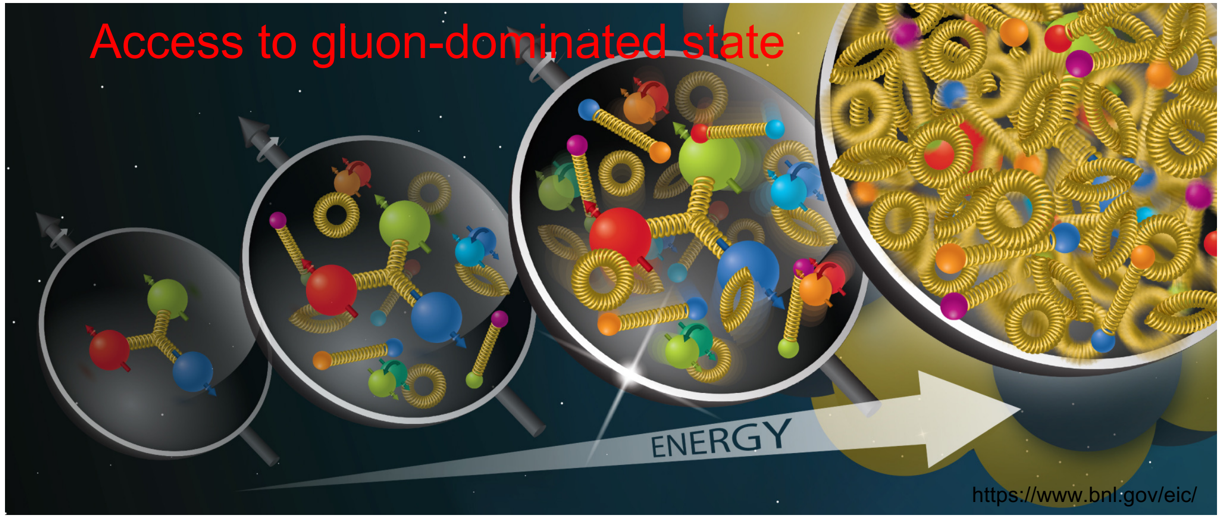
Outline

- Introduction
- EIC 1st detector
- EIC 2nd detector
  - Physics program
  - Detector technologies
- BNL efforts (toward EIC 2nd detector)
- Summary

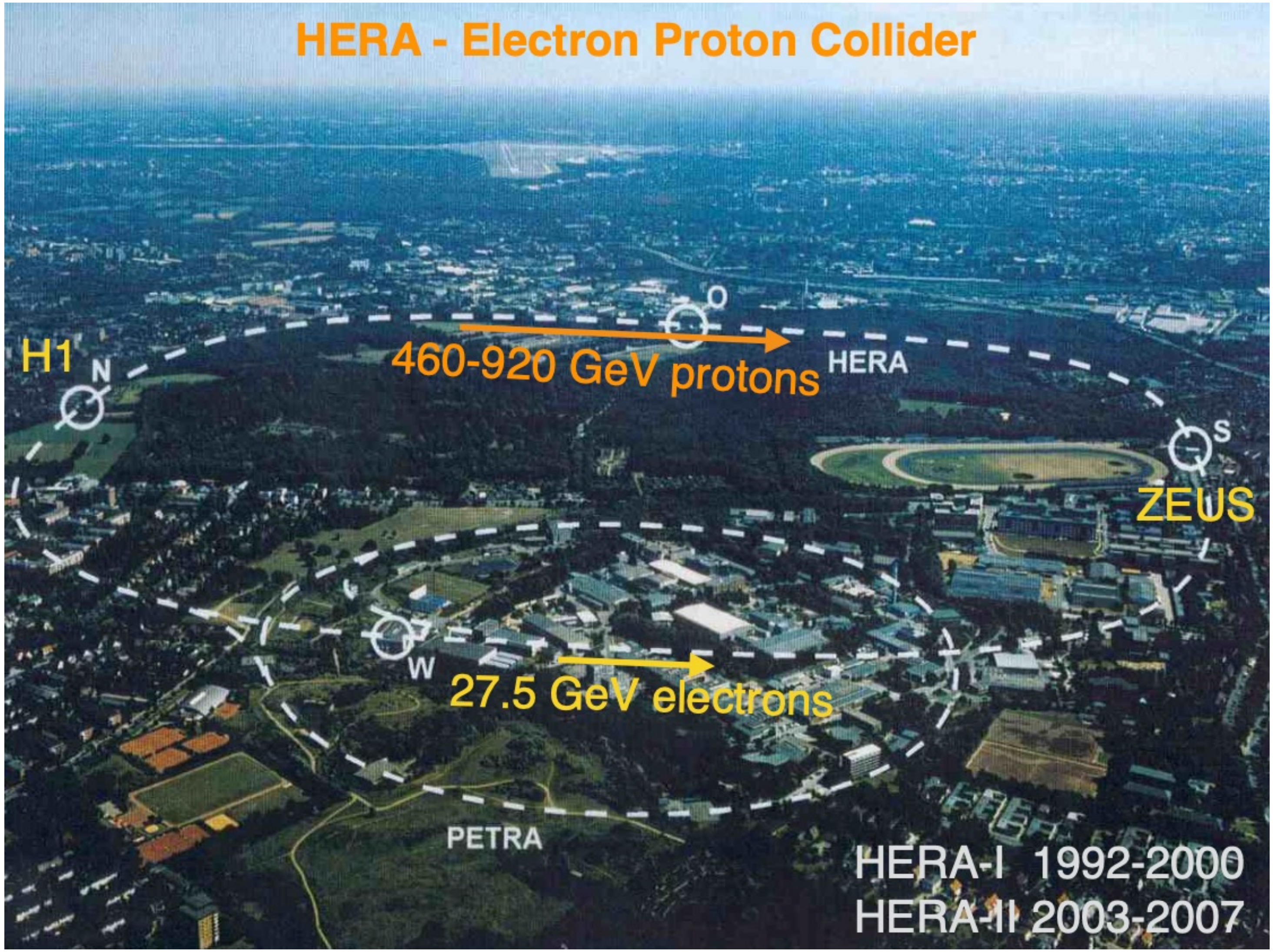




Introduction

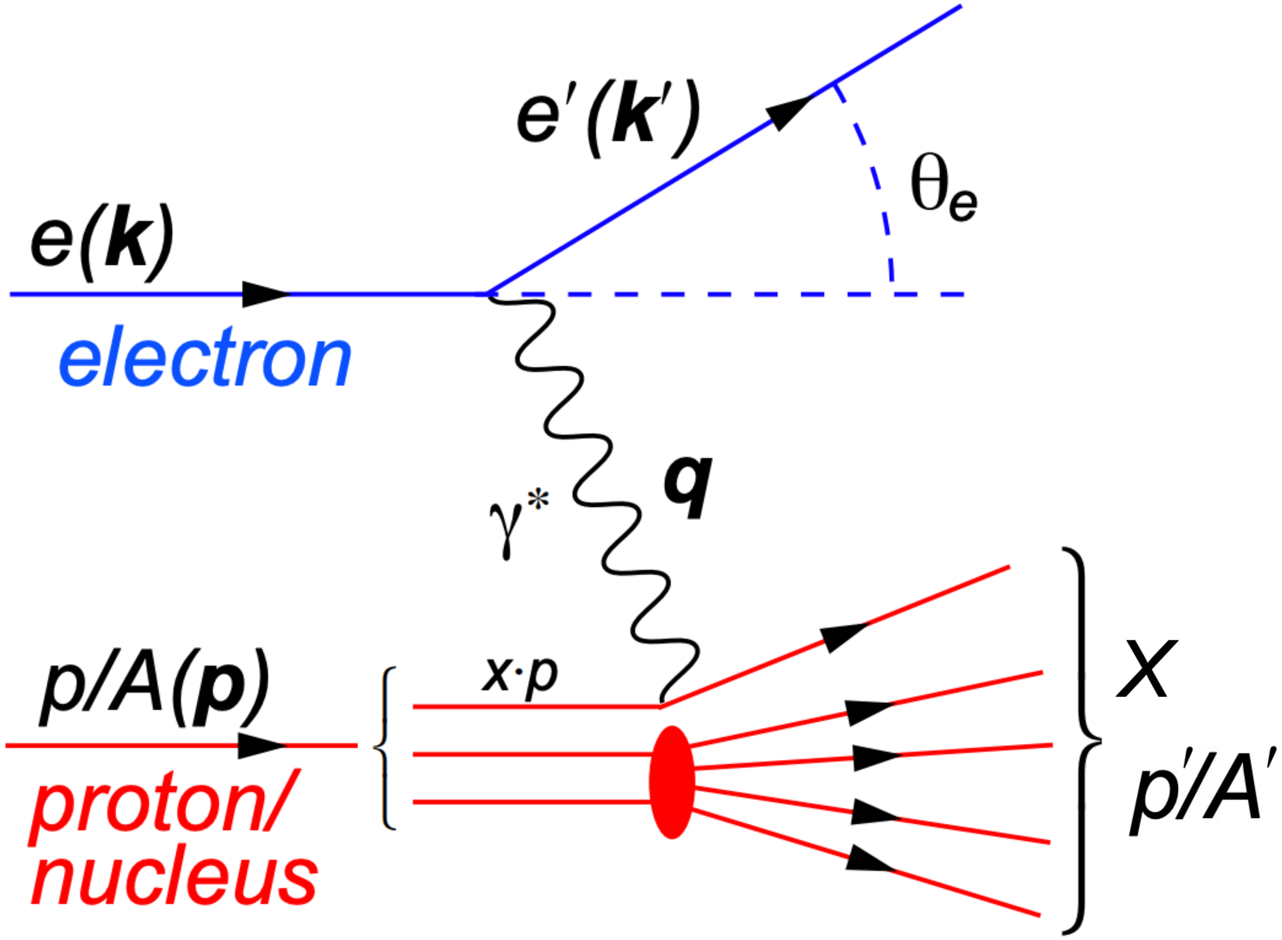
(**H**adron-**E**lectron **R**ing **A**ccelerator: 1992 – 2007)

HERA Facility at DESY



- Electron–proton collider
- Scattering experiments of high energy electrons on protons (**Deep Inelastic Scattering (DIS)**)
- H1, ZEUS, HERMES, and HERA-B experiments
- First polarized **electron** probes interior of proton – "microscope"
  - Study structure of protons and properties of quarks
  - Foundation for next generation of particle physics laboratory

Golden Process: DIS



Deep Inelastic Scattering (DIS)

EM process (well-understood)

To probe gluons (no charge) easily measurable

Resolution power (Q^2)

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

4-momentum transfer from scattered electron

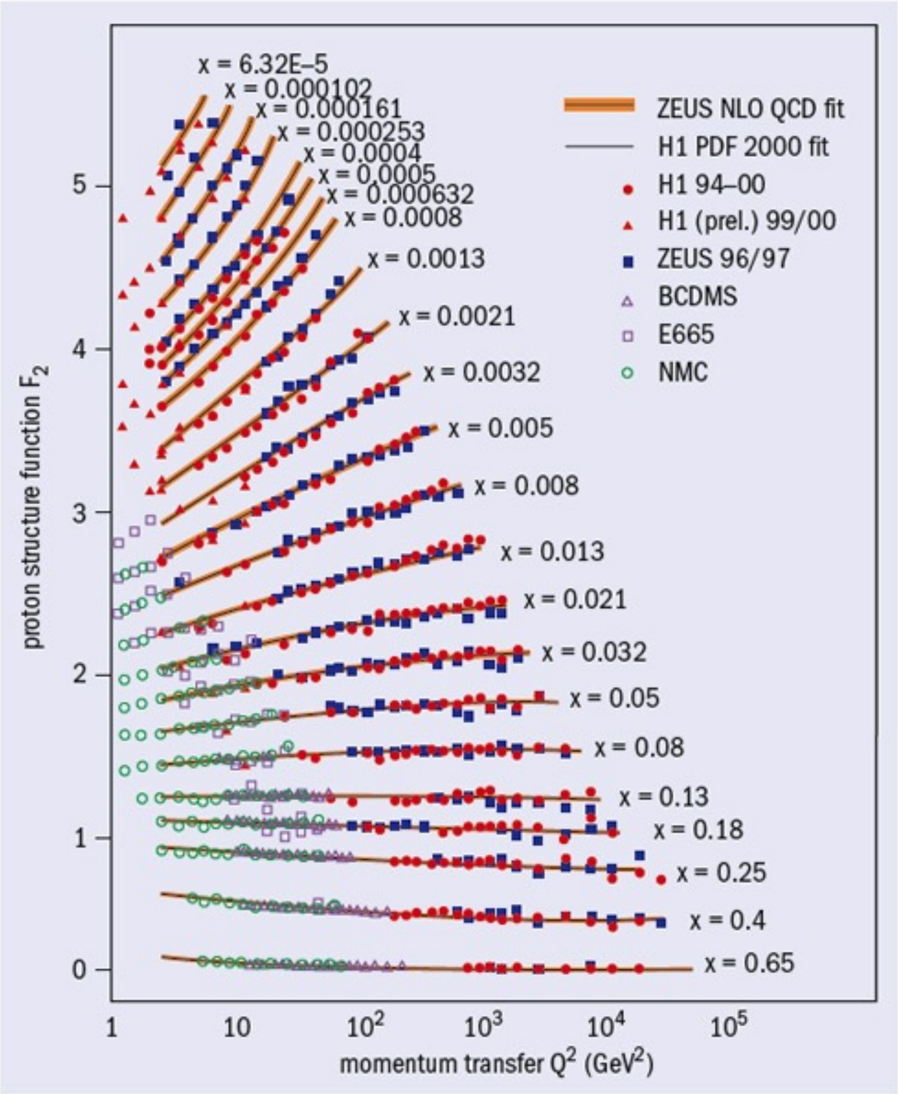
Momentum fraction of parton (**x**)

$$x = \frac{Q^2}{2pq}$$

Bjorken-x

Fraction of nucleon's momentum carried by struck quark

Results from HERA Facility at DESY



- Measured Proton **structure function F_2 (x, Q^2)**
  - Describes quark and anti-quark momentum distribution
- **Bjorken Scaling** F_2 (x, Q^2) → F_2 (x)
  - Virtual photon interacts with a single essentially free quark, hence Q^2 independence
  - High x – Flat (valence quarks)
  - **Low x – Bjorken Scaling broken!**

Interacts with something else

Gluons!

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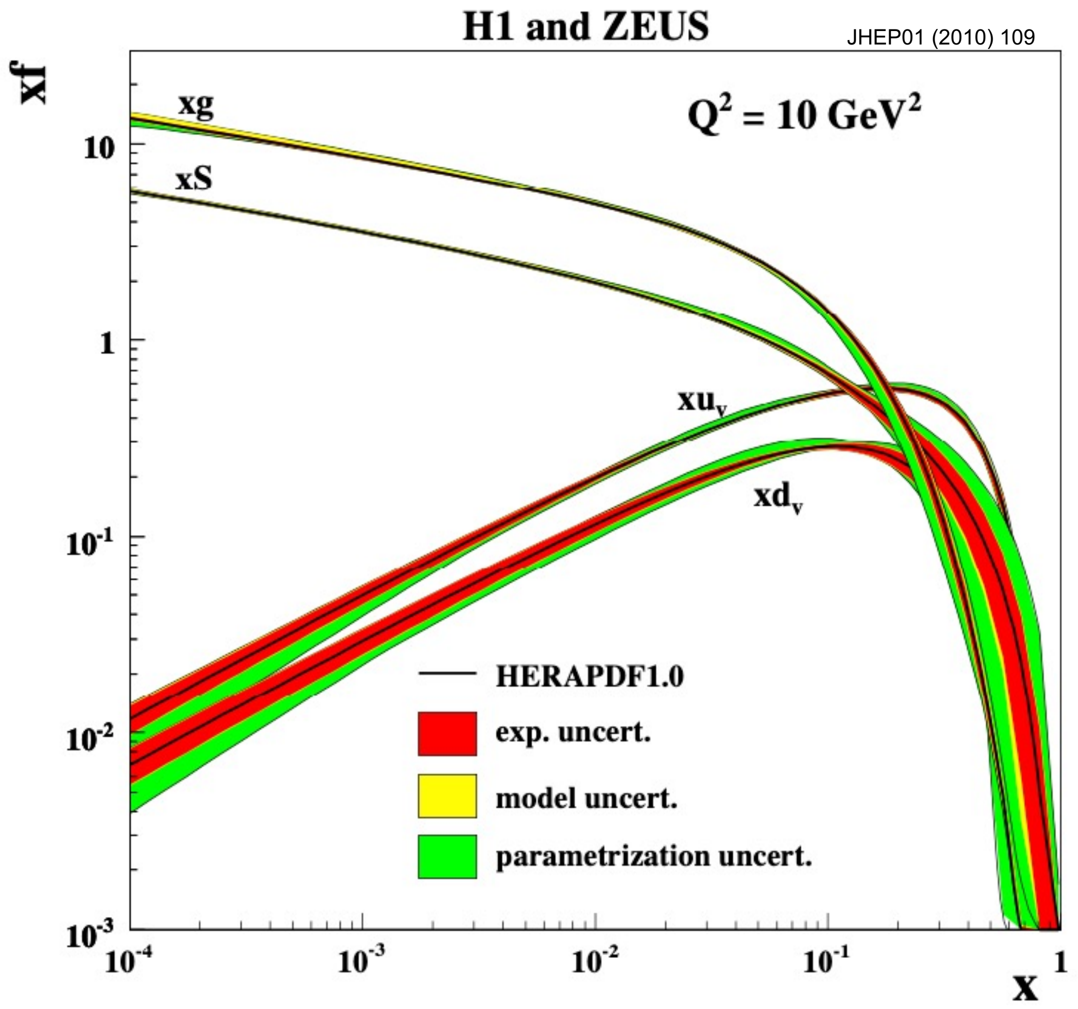
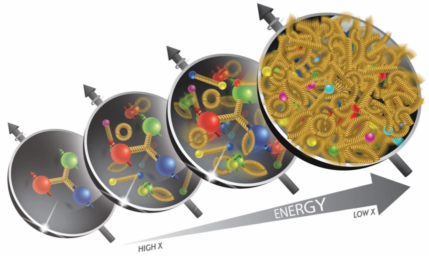
Results from HERA Facility at DESY



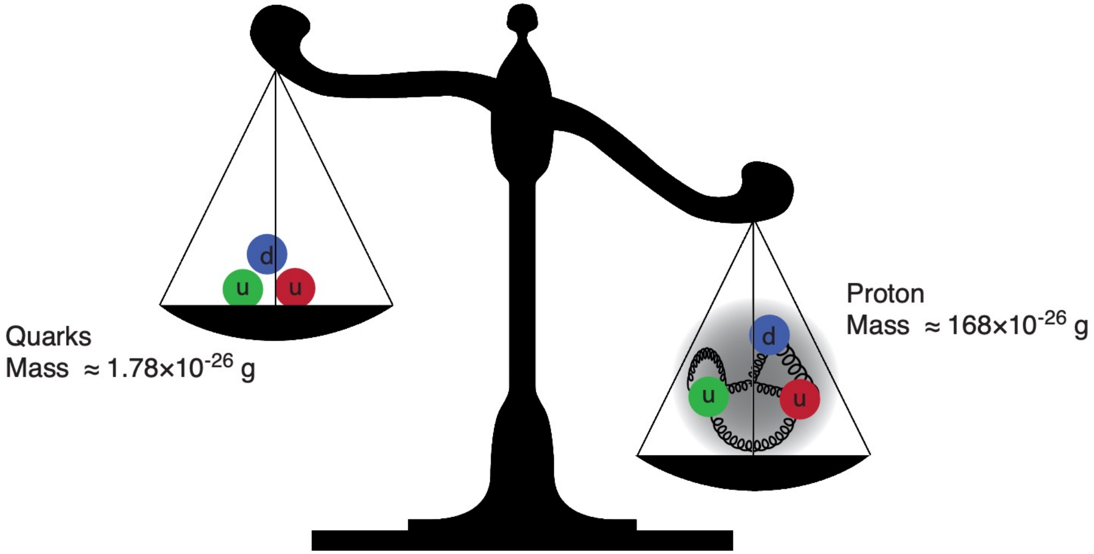
- Structure functions allows us to extract quark and gluon distributions
- **Parton Distribution Function (PDFs)**
- <u>The smaller momentum fraction, the greater the number of quark-antiquark pairs and **gluons** appearing in proton</u>
- **Proton is almost entirely gluons for x < 0.1**

Big Question and Mystery



Nearly all visible matter is made up of quarks and gluons

Building block – proton



Gluon Saturation

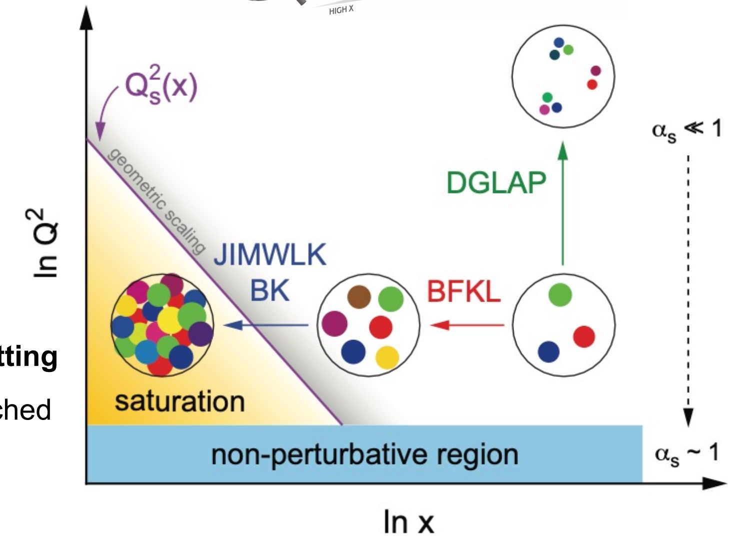
Gluon density is growing and it must saturate

When $Q^2 < Q_S^2$,

Gluon recombination = Gluon splitting

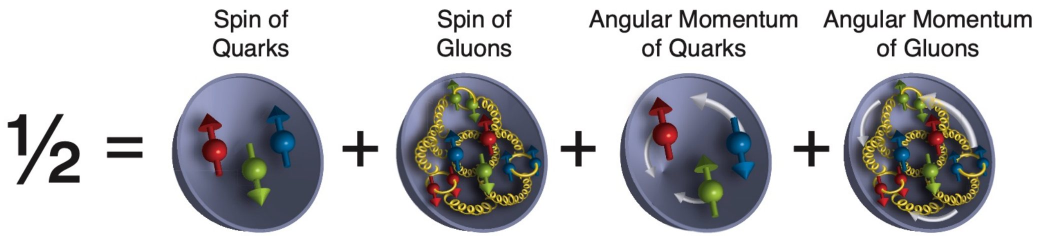
Saturation region is easier to be reached in nuclei:

$$Q_S^2 \propto A^{1/3}$$



Proton Spin Puzzle

More than the number ½



The Mass Puzzle ~ Higgs mechanism 1% of proton mass

Quark-gluon dynamics are responsible for mass of proton

- **How do quark and gluon dynamics generate the proton spin and mass?**
- **What are the emergent properties of dense systems of gluons?**

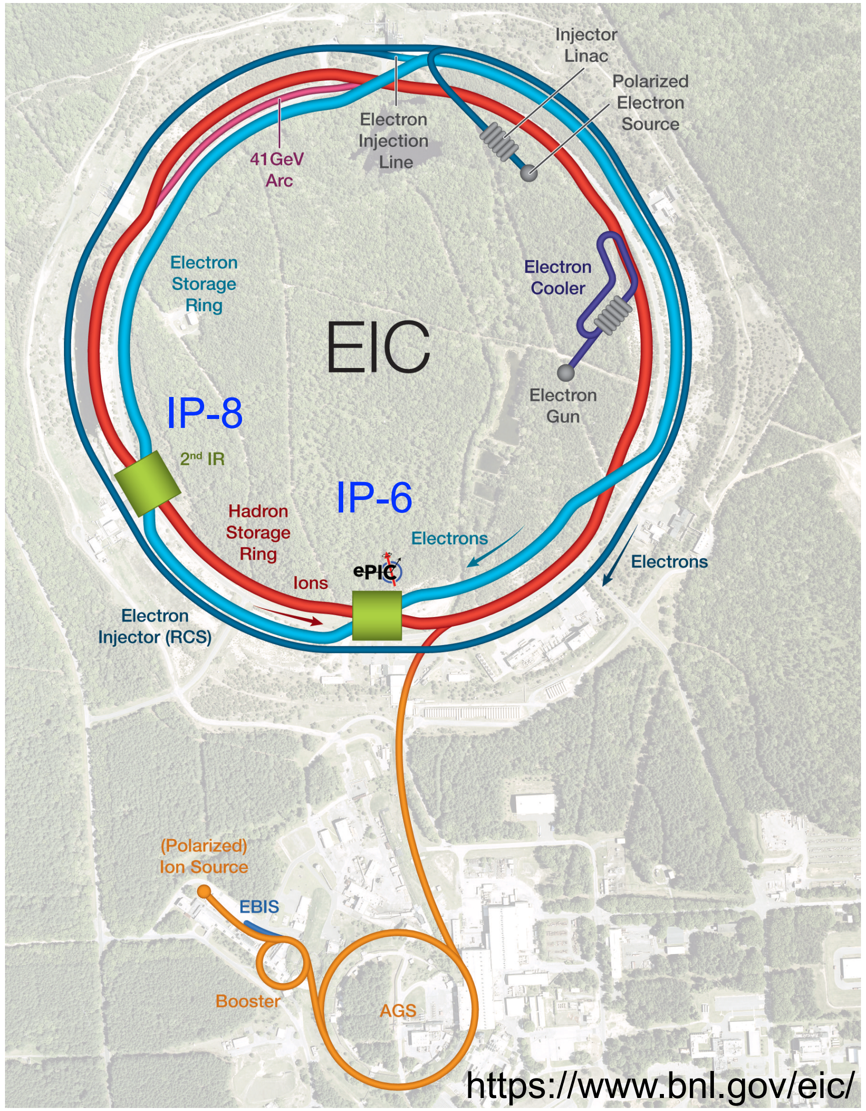
What is Needed to Answer Them

- **Wide center-of-mass energy range**
  - Map out nucleon/nuclei structure from high to low x
- **Polarized electron and hadron beams**
  - Access to spin structure of nucleons and nuclei
  - Access to 3D spatial and momentum structure of nucleon
- **Nuclear beams**
  - Access highest gluon densities
- **High luminosity**
  - Map 3D structure of nucleons and nuclei access to rare probes

What facility can have above requirements? <u>EIC!</u>

Electron-Ion Collider (EIC)

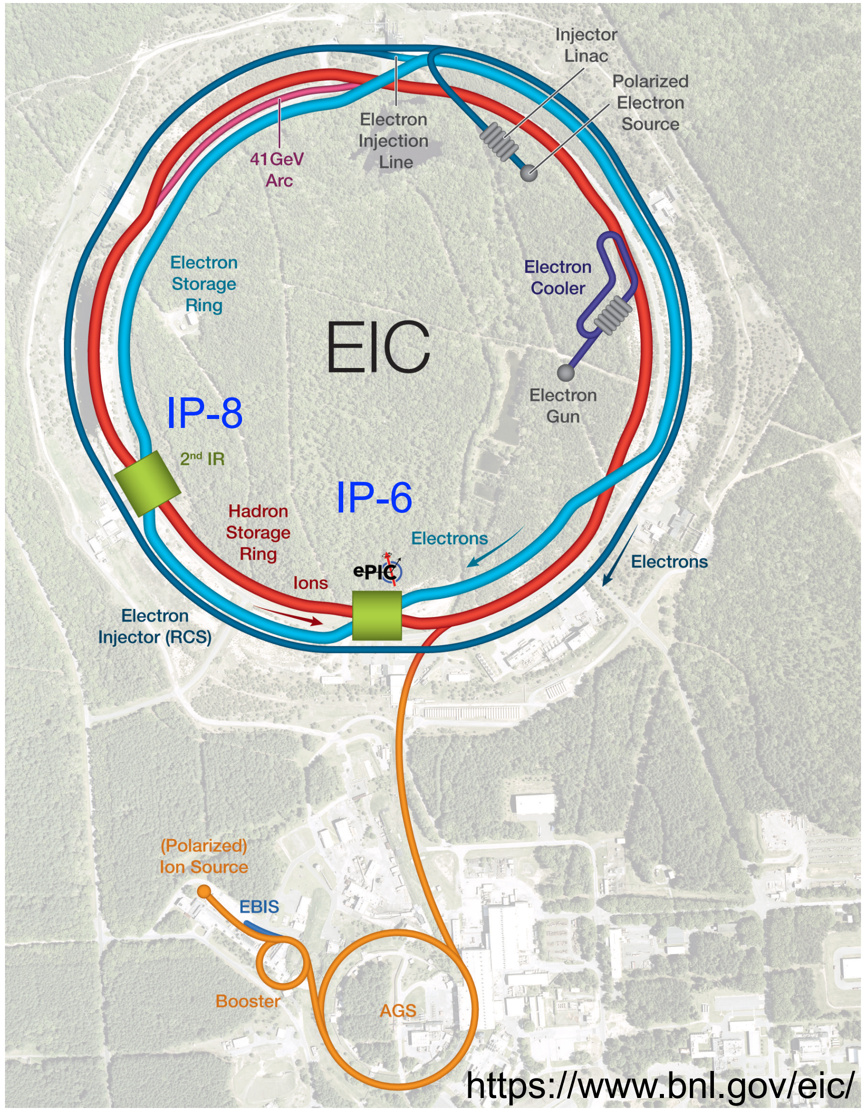
- **First polarized electron- polarized ion collider** based on existing RHIC facility
  - Collides electrons with proton and nuclei
- Based on the Golden process: **DIS**
- To be built at **Brookhaven National Laboratory** on Long Island, in **partnership with Thomas Jefferson National Accelerator Facility**
- **Detector 1,** called **ePIC,** sits on where RHIC STAR currently is located (**IP-6**)
- Expects EIC startup in the early part of 2030s
- RHIC operations concludes in 2025 and then transition into EIC construction stage



https://www.bnl.gov/eic/

Electron-Ion Collider (EIC)

- High Luminosity
  $10^{33} – 10^{34}$ cm^{-2}s^{-1}
- Variety of hadron/ion beams: p to Pb
- Wide center-of-mass energy range
  $\sqrt{s_{ep}} = 20 - 140$ GeV
- Existing hadron storage ring
  41, 100 – 275 GeV
- New electron rapid cycling synchrotron
  1 Hz, 0.4 – 18 GeV
- New electron storage ring
  5 – 18 GeV
- Two Interaction Regions (IR-6 and IR-8)



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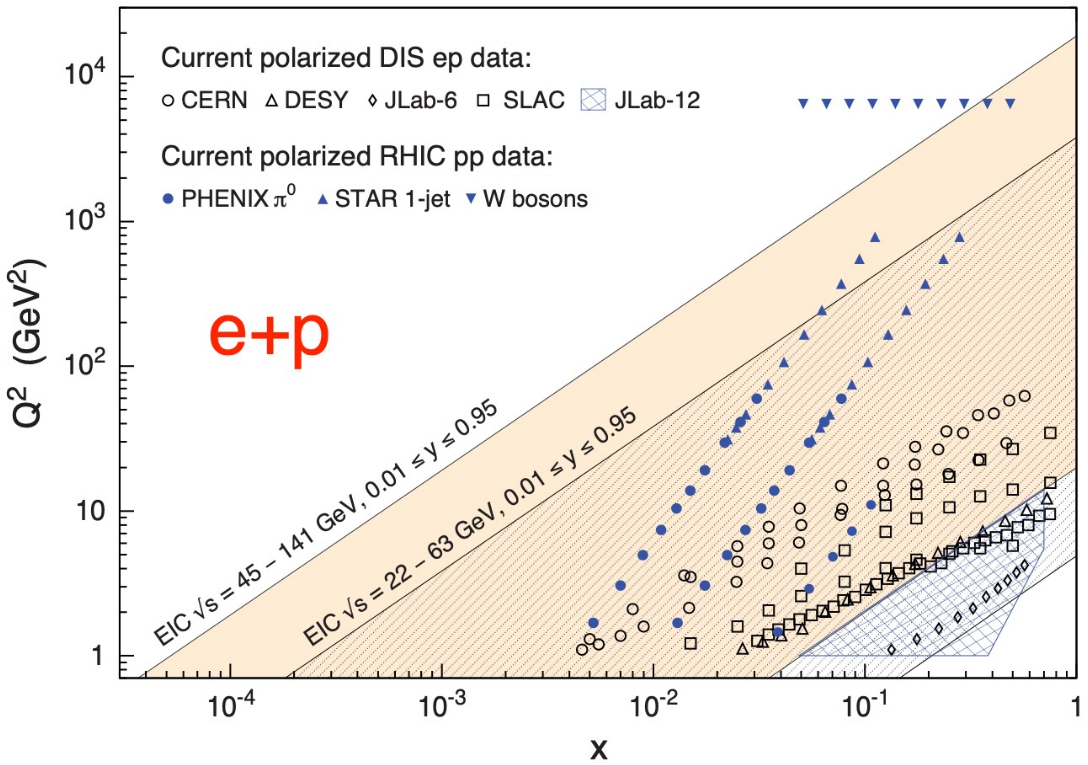
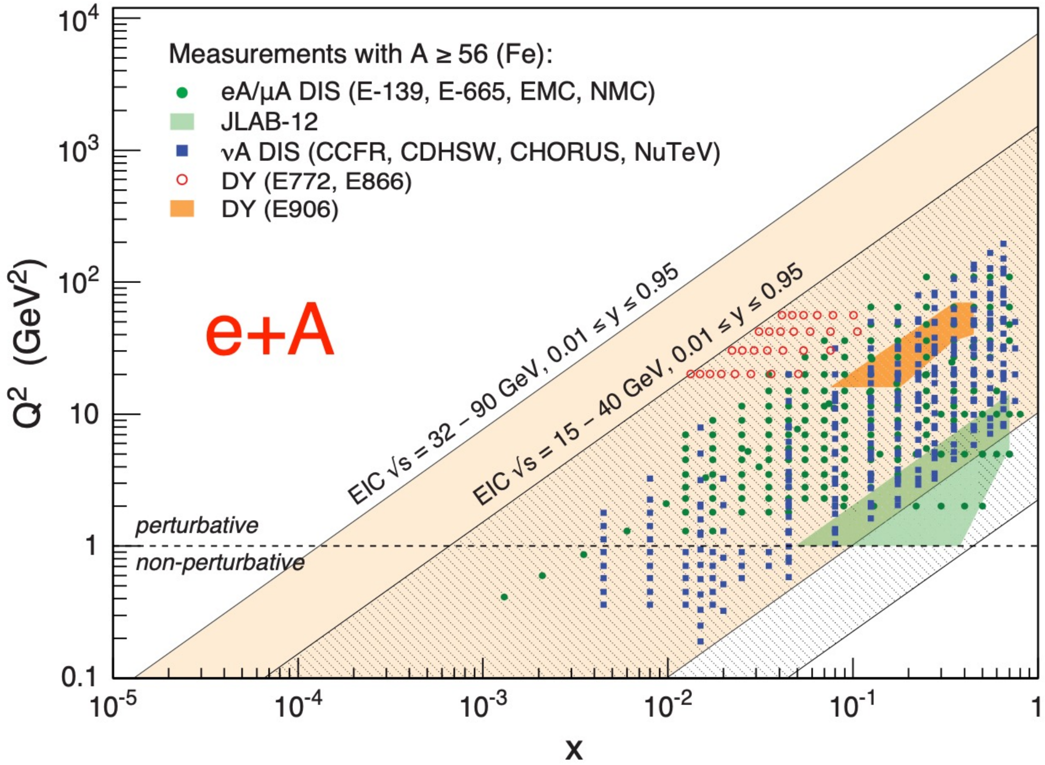
EIC Kinematic Range



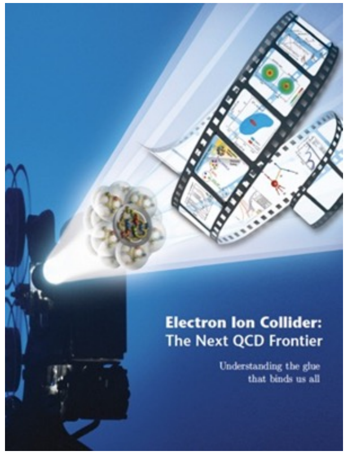


- First <u>polarized **e**</u> and <u>polarized **p**</u> and **eA** collisions
- **Large kinematic coverage** substantially compared to past coverage
- Center-of-mass energy 20-140 GeV → **access to x and Q^2 over a wide range**

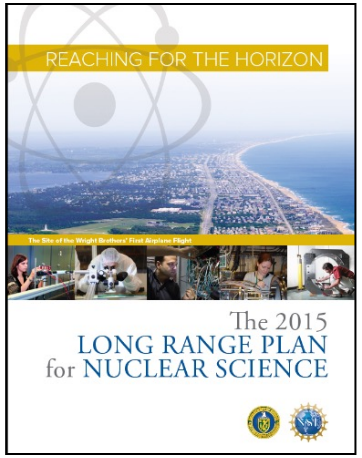
EIC Scientific Foundation

- Scientific foundation for EIC is well-built on series of reports over two decades
  - Unique machine in the next decades - EIC can address three profound questions about nucleons – neutrons and protons – and how they are assembled to form nuclei of atoms
  - **2023 LRP recommendation** “we recommend the expeditious completion of the EIC as the highest priority for facility construction”
- Emphasized and recognized in EIC white paper, NSAC long-range plans, NAS study and report, EIC yellow report, etc

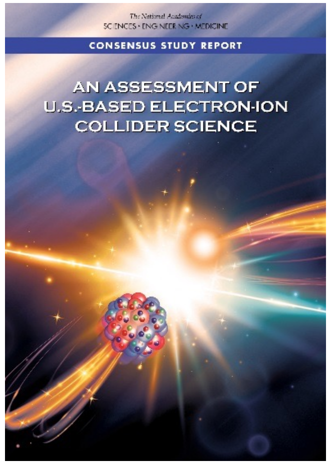
2012



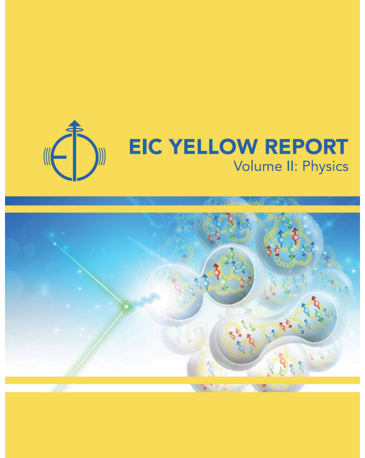
2015



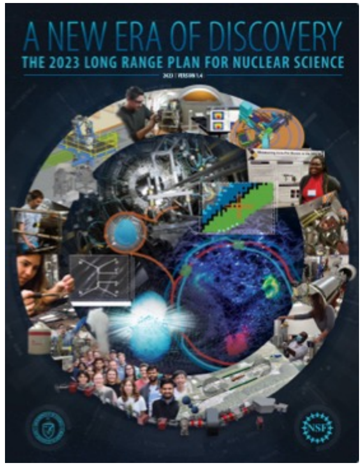
2018



2021

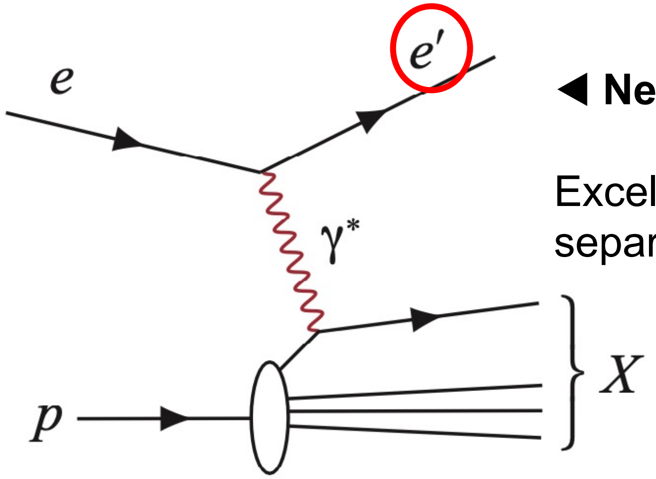


2023



EIC Measurements

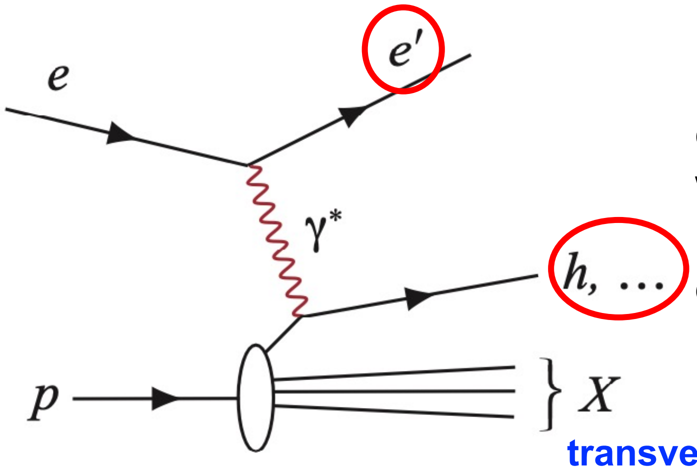
Deep-Inelastic scattering **event kinematics** – scattered electron or final-state particles



◀ **Neutral-current Inclusive DIS**

Excellent electron-hadron separation needed

Parton distributions in nucleons and nuclei

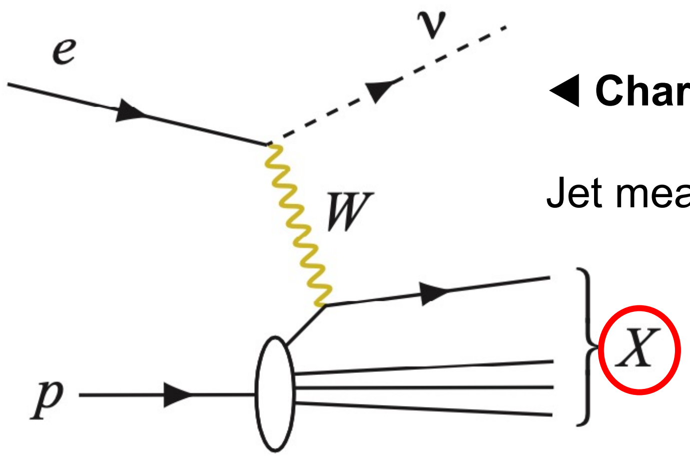


◀ **Semi-inclusive DIS**

Detection of scattered electron in coincidence with at least 1 hadron

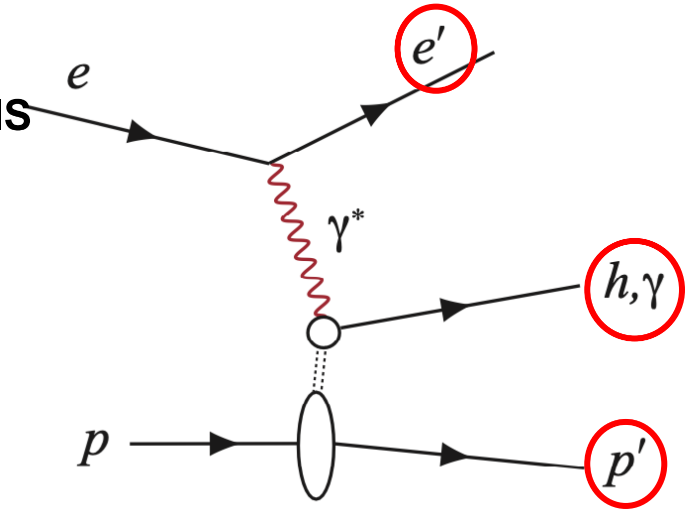
Measurement π^0, decay electrons

Tomography transverse momentum distribution and spatial imaging



◀ **Charged-current Inclusive DIS**

Jet measurement capabilities



◀ **Exclusive DIS**

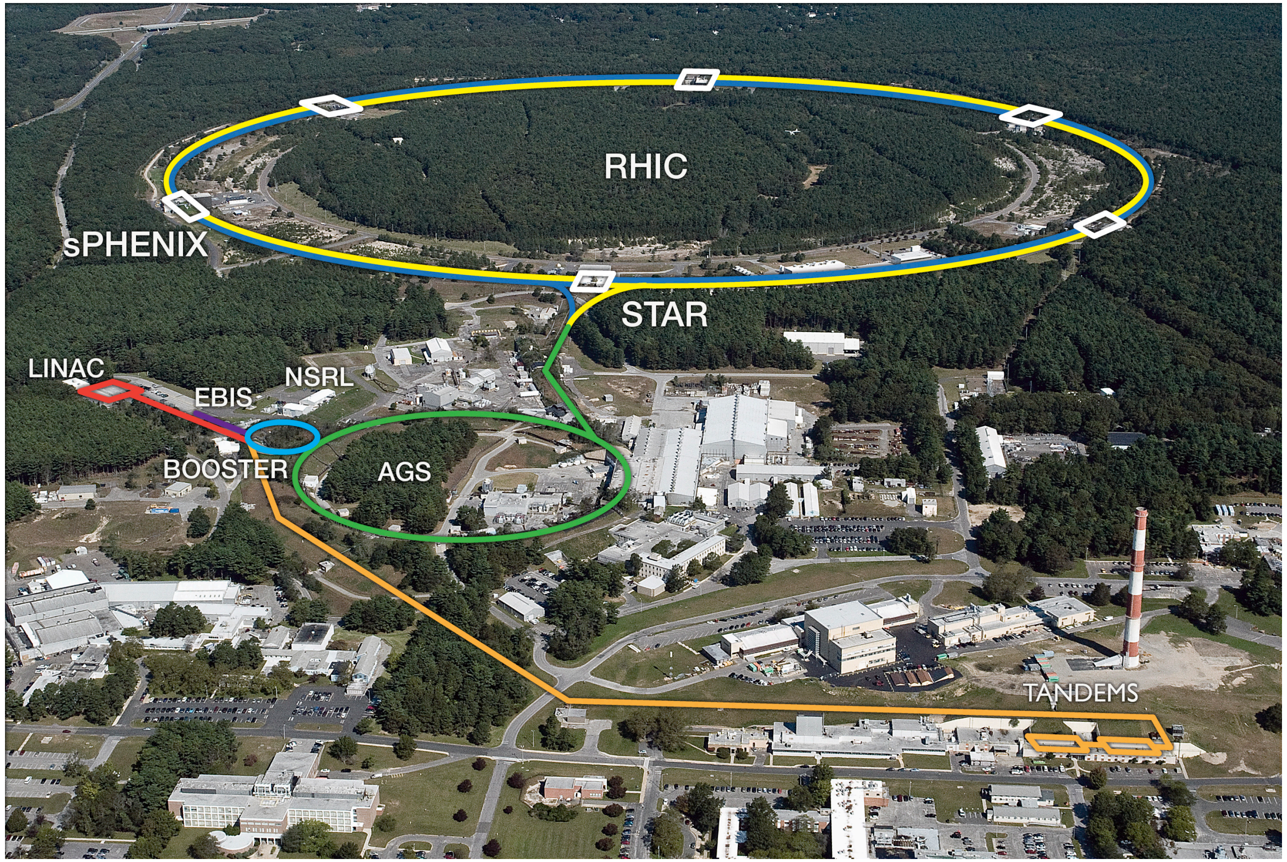
Detection of Deeply-Virtual Photon Scattering γ, exclusive π^0, decay electrons

Separation of γ/π^0

(**R**elativistic **H**eavy **I**on **C**ollider: 2000 – 2025)

EIC Measurements + RHIC Results

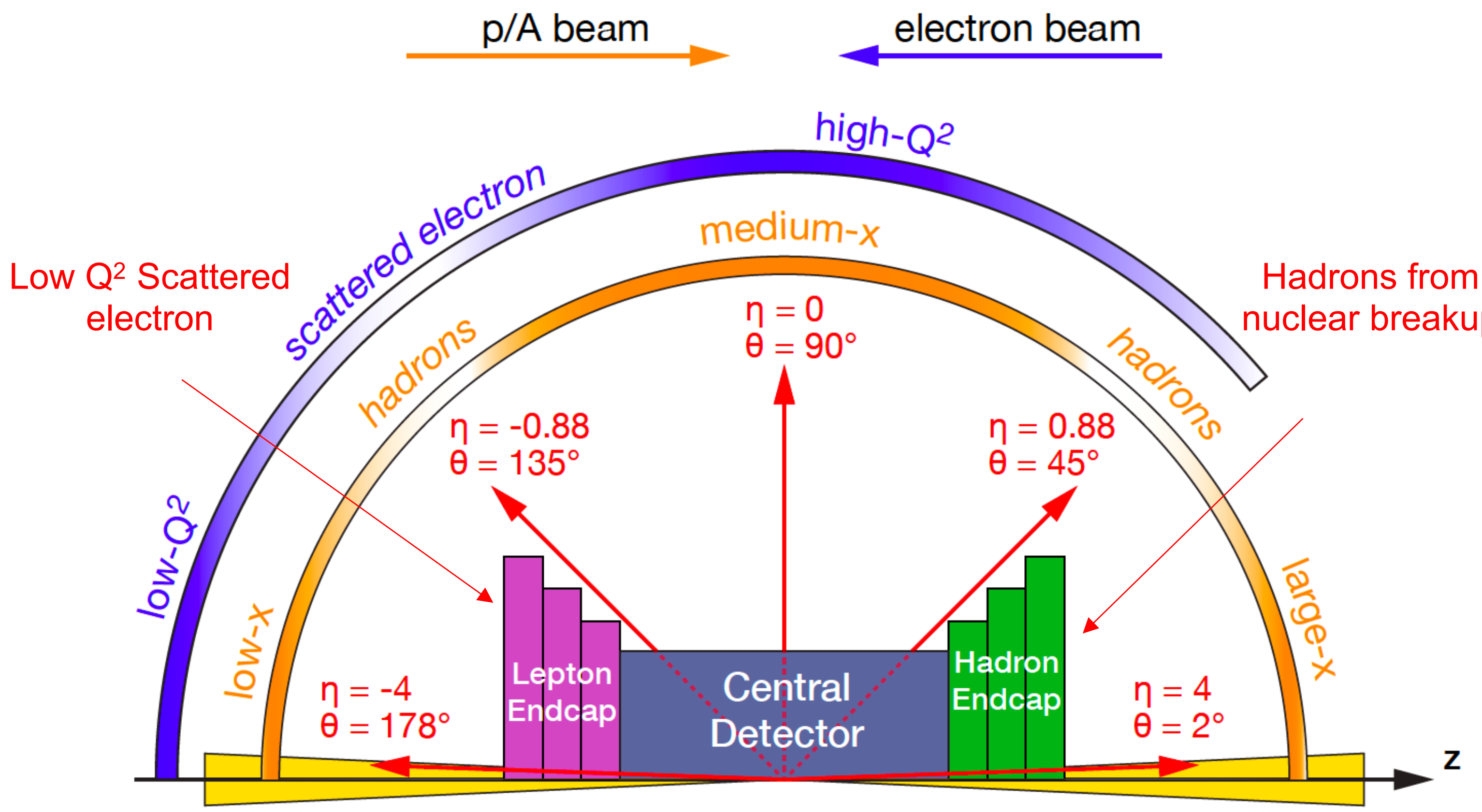
- **First polarized proton** machine
  - STAR, PHENIX, and sPHENIX experiments
  - Collisions of **pp, pA,** and **AA**
- Probe has complex structure comparing to electron probe
  - Gluons can be accessed directly qq & gg → gluon fragmentation
- **Why do we need different probes?**
  - To test and separate interaction dependent dynamics from intrinsic nuclear properties



- **Physics program at RHIC has unique to hadronic collisions**
- **When combined with data from EIC it will provide a broad foundation to a deeper understanding → Synergy at a future EIC**

EIC Conceptual Detector Design

Requires large rapidity ($-4 < \eta < 4$) coverage: Tracking, particle identification, electromagnetic and hadronic calorimetry



High precision low mass tracking
Good e/h separation
e/p/K separation on track level

Basically 4 pi detector (Large acceptance)

Detector components

- Tracking
- PID
- Calorimeters (ECAL & HCAL)
- Magnet solenoid

Aim to detect all final-state particles

EIC Interaction Region (ex IR-6)

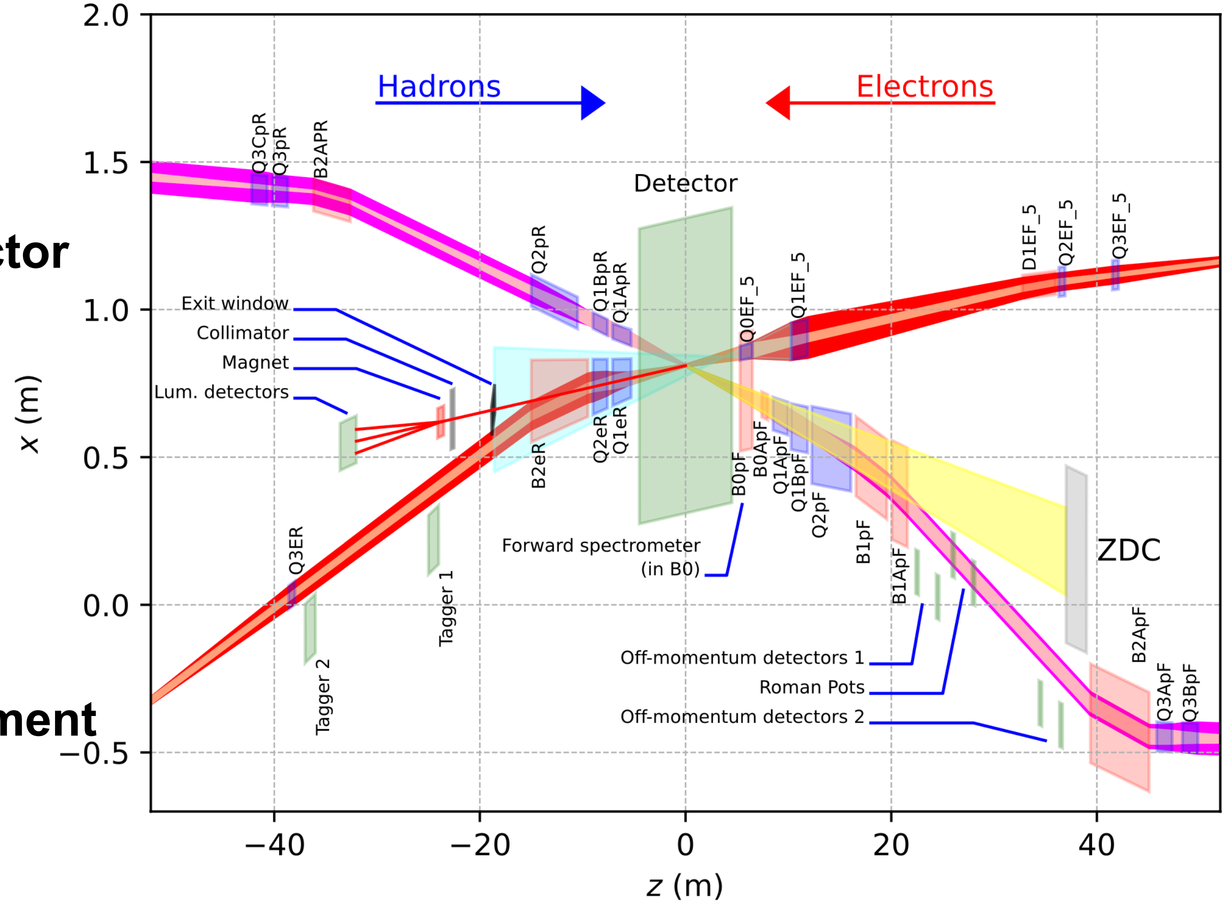
Detector 1, called **ePIC,** sits at IP-6
ePIC: https://wiki.bnl.gov/EPIC/index.php?title=Main_Page

Requires specialized detectors integrated in the interaction region over 80 m

Far-Backward Detector

Very low Q^2 scattered lepton

Low-Q^2 tagger
Luminosity measurement



Far-Forward Detector

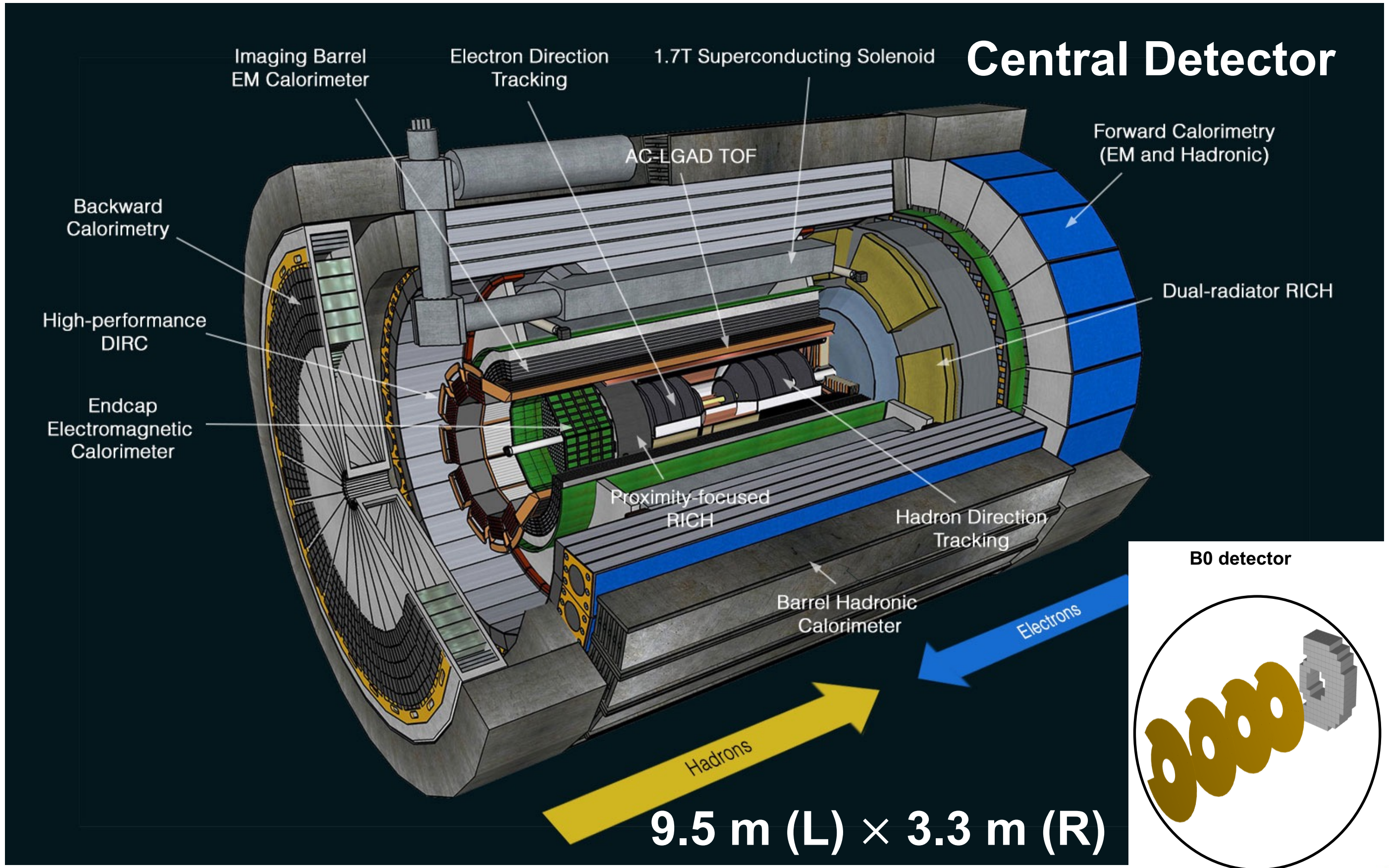
Particles from nuclear breakup

Tagging of charged hadrons (protons/pions)
or
neutral particles (neutrons/photons) at very forward rapidity (η > 4.5)

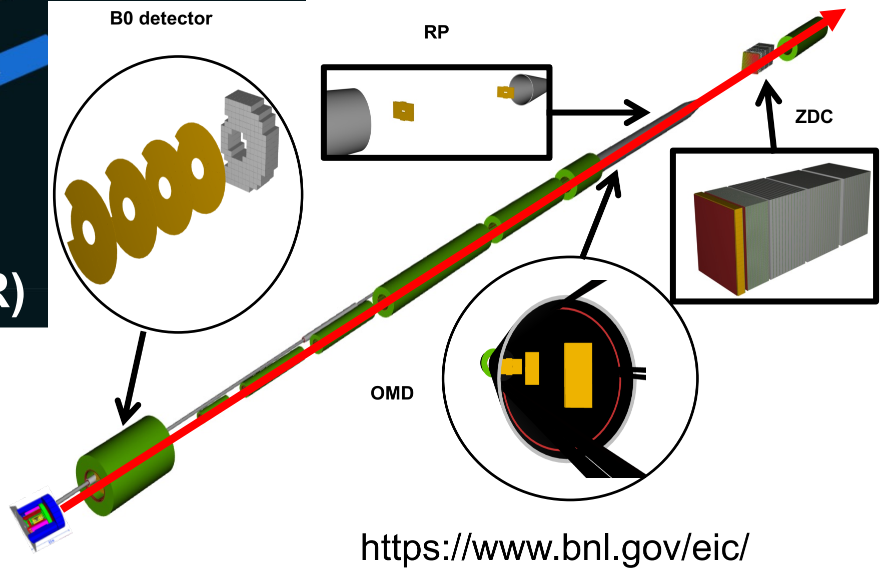
EIC 1st Detector – ePIC

FB detector geometry

Will be added here



Far-Forward Detector



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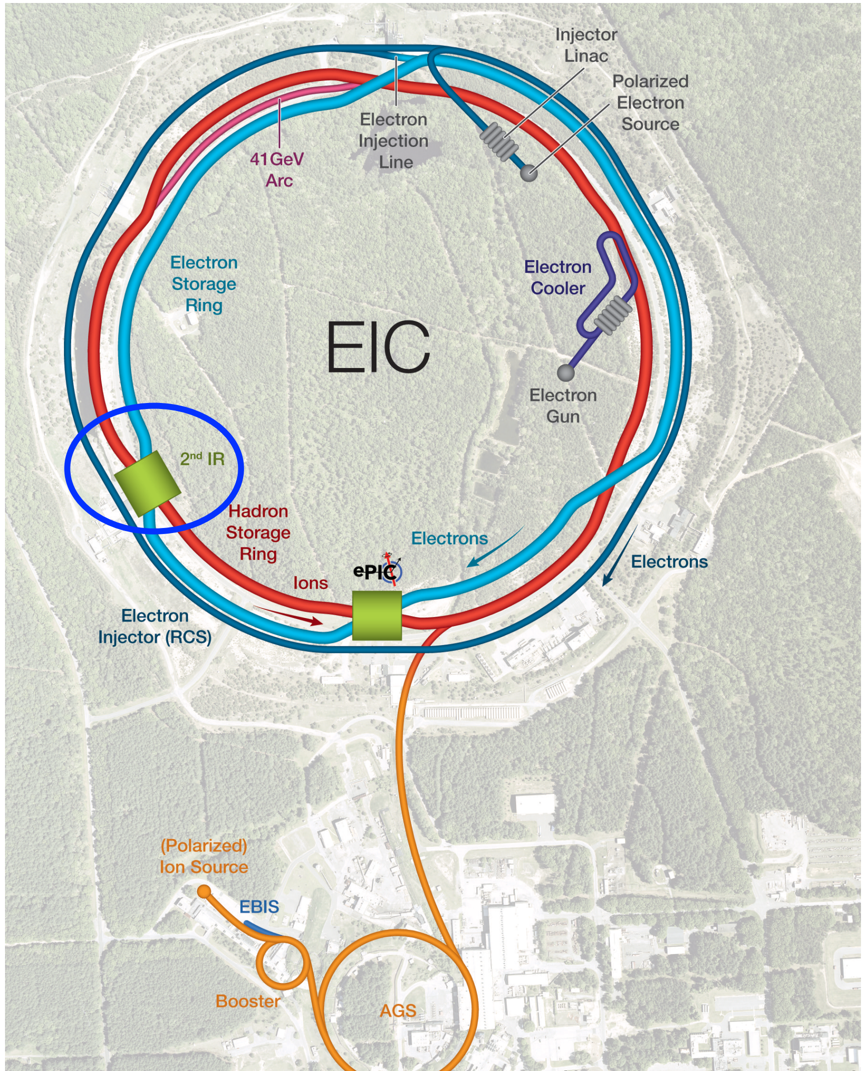
EIC 2nd Detector Motivation

- Favors to accommodate the **second detector** and a **second interaction region** (ex HERA > 2 experiments)
- EIC 2nd detector working group activities
  - Prepare plans and build support for 2nd IR and detector
  - 1st international workshop on a 2nd detector for EIC 2023
  - EICUG 2nd detector meeting 2022
  - Monthly WG meetings



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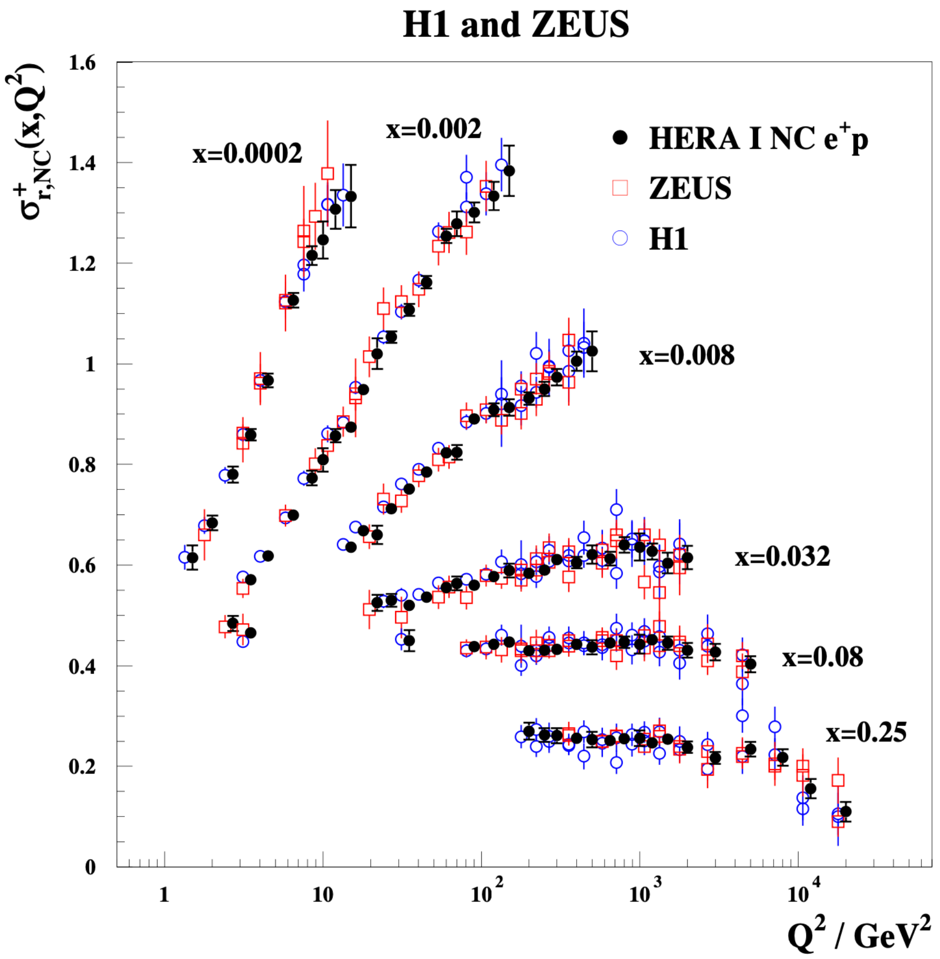
- **A general-purpose collider detector** to support full EIC program (**complementarity**)
  - **Cross-checks & control of systematics**
  - Detector technologies (mitigate risks and potential opportunities R&D)
  - Magnetic field
  - Broaden physics program (different physics focuses)
- Will be installed within few years after EIC Detector 1 is commission

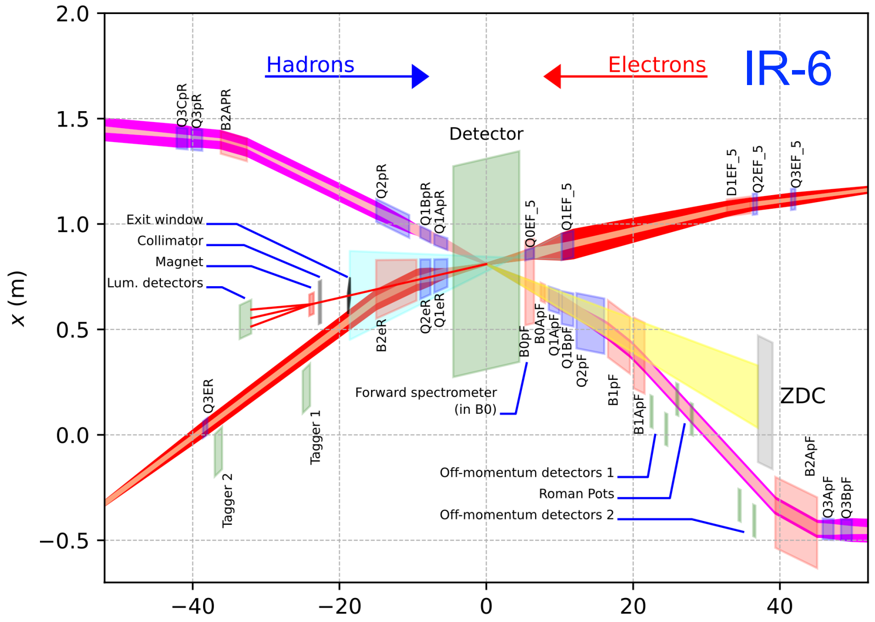


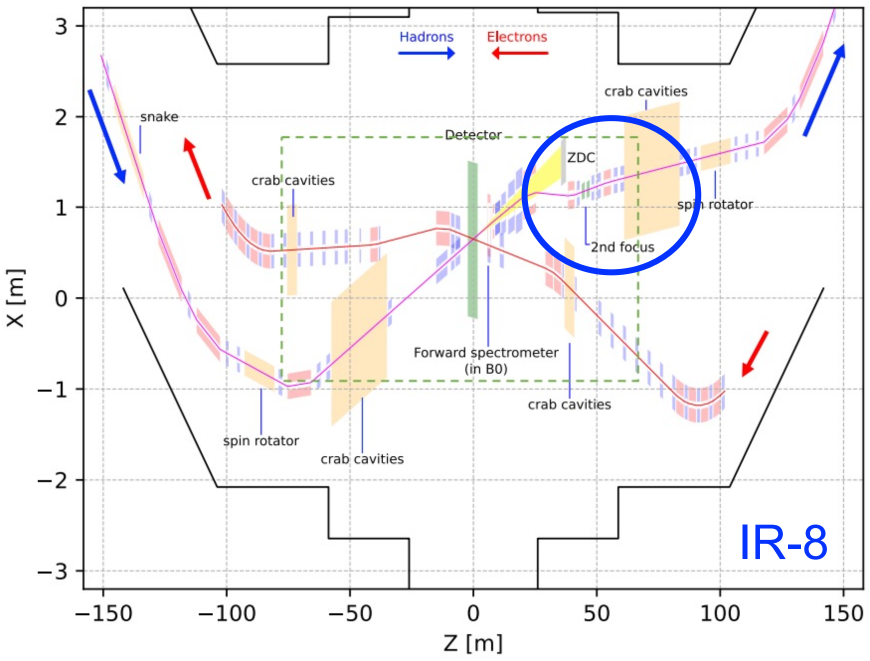
Interaction Region

IR-6 vs IR-8

- Interaction regions: **similar, but different**
- Total crossing angle
  - 25 mrad (IP-6)
  - 35 mrad (IP-8)

- **2nd "beam optics" focus** integrated in **IR-8** layout
  - Better detector acceptance expected in downstream – low p_T
  - Especially in Far-Forward 2nd focus: exclusive, diffractive and tagging physics program using far-forward detectors





Opportunities at EIC 2nd Detector

EIC 2nd detector opportunity

- General-purpose collider detector design along with ePIC
  - To support full and broad physics program
- **Physics** discussion (golden channels)
  - Possible opportunity toward facility upgrades
  - Different physics focuses
- **Detector** discussion
  - Promoting new detector ideas (EIC-related generic detector R&D)
  - Mitigating risks by technology redundancy

Too much details

EIC 2nd detector – Focus Measurements

	Measurement	Physics	Requirements and Challenges
BNL group scope	Double polarized e+D	Transversity in transverse polarized eD collisions →gluons' role in nuclear binding	
	Positron beams	Providing electro-weak data for fundamental studies: quark axial and vector couplings Extends the capabilities of the physics with exclusive measurements	As for electron beams
	Real photon beams through Compton scattering	Enables the generation of a polarized real photon beam →understanding the formation of for example new charmed mesons via spectroscopy measurements →a full complementary approach to LHCb and Belle-II	TBD
	2nd focus integrated in the IR	Soft particles down to p_T ~0 GeV →new understanding of the structure of nuclei	Extended auxiliary detector capabilities
	Fixed targets	Access to very high x physics → complementary to STAR, LHCb and ALICE	Acceptance for fixed target kinematics

- **Target to facility upgrades**
  - Possibilities to have positron and photon beams available
- **IR-8 unique approach**
  - Another beam optics focus in downstream
- **Fixed target** – toward focused physics
  - Complementary to STAR, LHCb and ALICE

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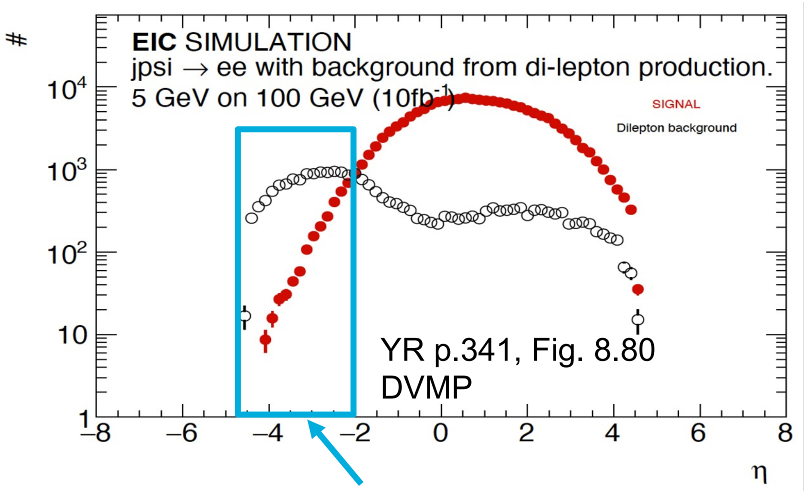
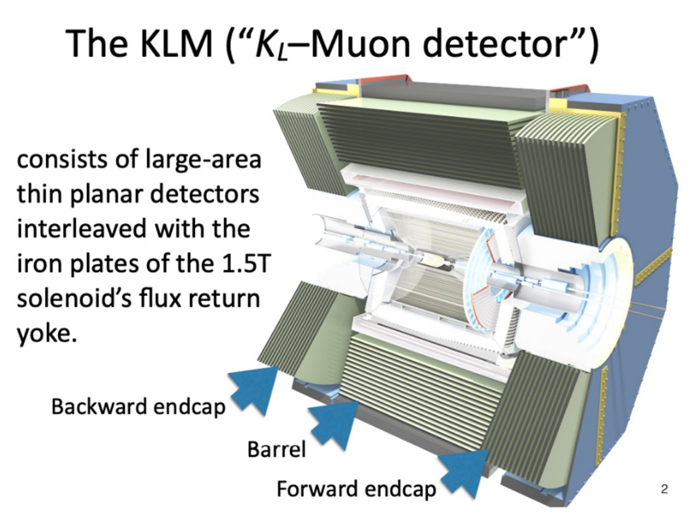
	Fixed targets	Access to very high x physics → complementary to STAR, LHCb and ALICE	Acceptance for fixed target kinematics
Golden channel	Diffractive dijet	Wigner Distribution	forward scattered proton/nucleus low p_T particles
	DVCS on nuclei	Nuclear GPDs	forward scattered proton/nucleus High-resolution photon
	Baryon/Charge Stopping	Origin of Baryon number in QCD	PID low p_T π/K/p
	F_2 at low x and Q^2	Probes transition from partonic to color dipole regime	Maximize Q^2 tagger down to 0.1 GeV^2 integrate into IR
	Coherent VM Production	Nuclear shadowing and saturation	High-resolution tracking for precision t reconstruction

Focus Concept 1 – Muon ID

- In Detector 1 design
  - No dedicated muon ID detector
  - However, identify muon using ECAL and HCAL
- Detection of $\mu^{\pm}$ in exclusive measurements
  - **Cleaner signal** in quarkonium reconstruction compared to $e^{\pm}$
  - **Reduce ambiguity to the scattered electrons**
- **Complementary to ePIC: quarkonium reconstruction with different decay channels**
- Example muon ID technology: KLM at the B factory in KEK
  - **EIC Generic R&D programs**: #18 **KLM-type detector**



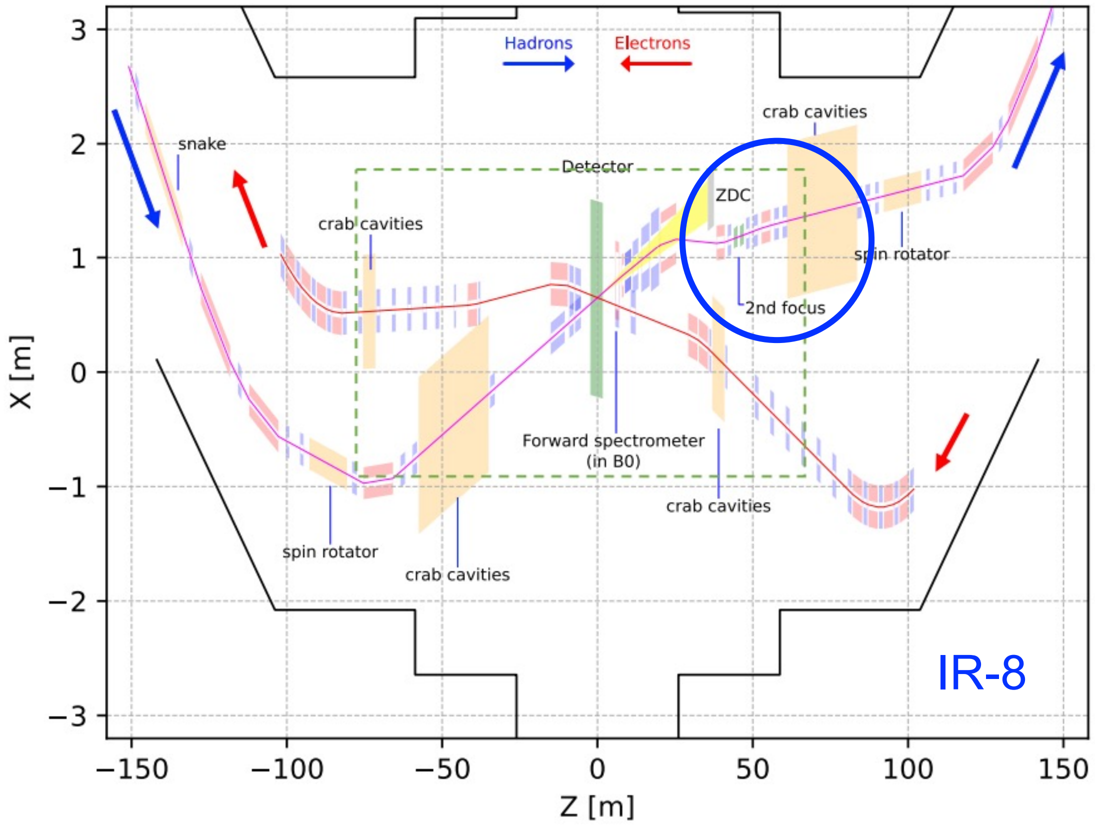
Large background at backward region when use di-electron channel



(Far-Forward)

Focus Concept 2 – 2nd Focus in FF

- This is NOT detector design, but it is **machine design that detector can be benefit from**
- FF 2nd focus by additional magnet to focus beam
  - Higher probability to **detect low p_T (< 250 MeV) particles** around 45 m downstream from interaction point
  - Detects near-beam particles where get out beam envelop
  - Better nuclear breakup tagging
- **Complementary to ePIC: diffractive and tagging physics analysis**

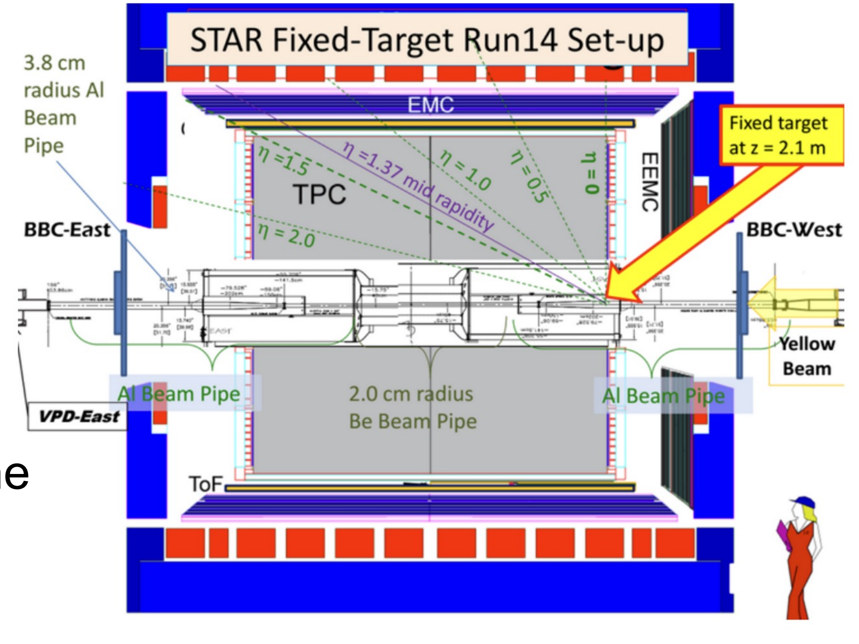


Focus Concept 3 – Fixed Target

- Focuses **high x and low Q^2**
- **Complementary to CLAS12** measurements and other Jefferson Lab experiments
  - DVCS nuclear GPD
  - Spin physics with polarized gas target
- **Complementary to fixed-target measurements at STAR, LHCb, and ALICE**
  - Constrain nuclear PDFs
  - Parton fragmentations
  - Nuclear shadowing
- **Kinematics at fixed target is very different from one at colliding beams**: Everything goes backward (electron-going direction)

Focus Concept 3 – Fixed Target

- Fixed-target setup along with beam-beam collisions configurations
  - **STAR gold target inside beam pipe**
- Detector subsystems needed
  - **Full range (backward + central + forward) tracking system**
  - **Backward ECAL to measure scattered electron**
  - **e/h separation (PID) in backward region for hadron fragments**
- Questions
  - Luminosity and statistical feasibility
  - Kinematics of fixed-target events
  - Material budget due to the beam pipe
  - Machine induced background



Larger pseudo-rapidity coverage depends on the IP location

EIC Detector R&D

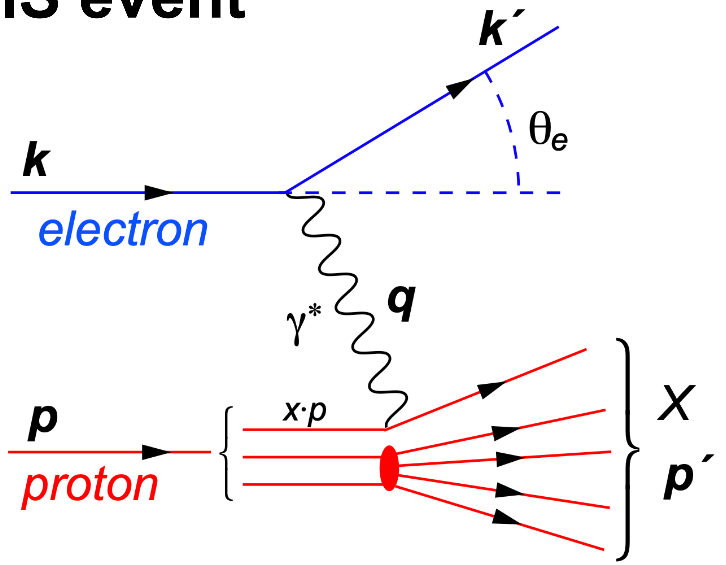
- Generic EIC-related detector R&D program
  - https://www.jlab.org/research/eic_rd_prgm
  - Annual proposal opportunity
- Scope of this program
  - **Aim at Detector 2 or upgrades of Detector 1**
- Invites detector experts to **discuss technology concepts and have open proposal review meeting**
- Many technologies being developed in the program are now used in ePIC and available for Detector 2 – open door for new groups to join

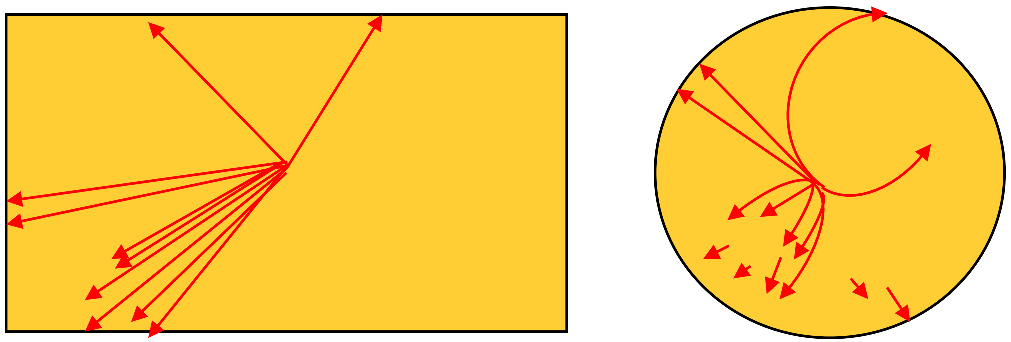
	Calorimetry:		
2	Towards a Few-Degree Calorimeter: bridging the Q^2 gap to support the quest for gluon saturation	M. Arratia	UC Riverside
3	Generic glass scintillators for EIC Calorimeters (ScintCalEIC) R&D	T. Horn	CUA
4	Feasibility of Organic Glass Scintillators for EIC ZDC	G. Carini, E. Aschenauer, A. Bolotnik	BNL Instr. Div., BNL Physics Div.
18	Continuation of EIC KLM R&D Proposal	A. Vossen, W. W. Jacobs	Duke U., Indiana U. CEEM
	PID (non-TOF):		
8	Pressurized RICH	M. Contalbrigo	INFN Ferrara and U. Ferrara
9	Z-Tagging Mini DIRC	C.E. Hyde, Wenliang Li	ODU, SBU and CFNS
13	Performance of GridPIX Detector in Magnetic Field with low mass and high efficiency CO2 cooling	T. K. Hemmick, P. Garg	SBU and CFNS, Yale U.
20	Development of a Novel Readout Concept for an EIC DIRC	G. Kalicy, J. Schwiening	CUA, GSI
	Gaseous Precision Timing and/or Tracking:		
14	Development of High Precision and Eco-friendly MRPC TOF Detector for EIC	Zhenyu Ye, Zhihong Ye	UI at Chicago, Tsinghua U.
16	Development of Double-sided Thin-Gap GEM-µRWELL for Tracking at the EIC	K. Gnanvo	Jlab
	Front End Electronics:		
11	Design, Fabrication and testing of a multi-channel System on a chip for Low-Power High-Density High Timing Precision Readout ASIC for AC-LGADs (HPSoCv3)	L. Macchiarulo, B. Schumm	Nalu Scientific, UC Santa Cruz
	Silicon Detectors		
1	A Fast Timing MAPS Detector for the EIC	X. Li	LANL
5	Slim Edge for LGADs	G. Giacomini	BNL Instr. Div.
6	Photonics-Based Readout and Power Delivery by Light for Large-Area Monolithic Active Pixel Sensors	S. Mandal, S. Rescia	BNL Instr. Div.
	Other New Detectors:		
17	Scintillator Fiber Trackers for the ZDC and off-momentum detectors	C. Ayerbe Gayoso	College of William and Mary
19	Superconducting Nanowire Detectors for the EIC	Sangbaek Lee, W. Armstrong	ANL

BNL Efforts

Diffractive Physics Program

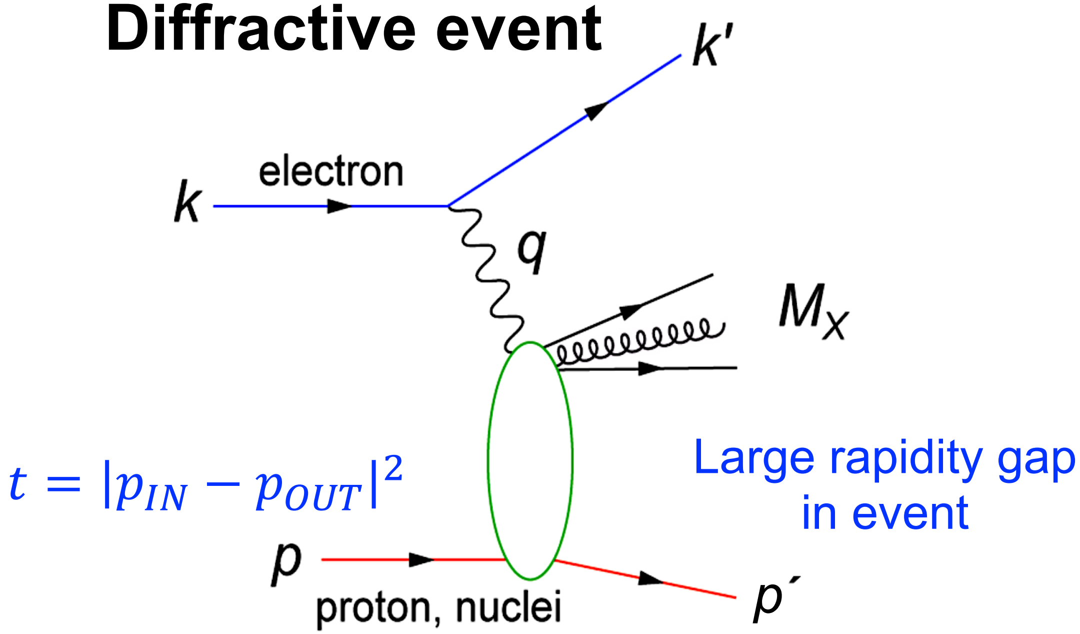
DIS event

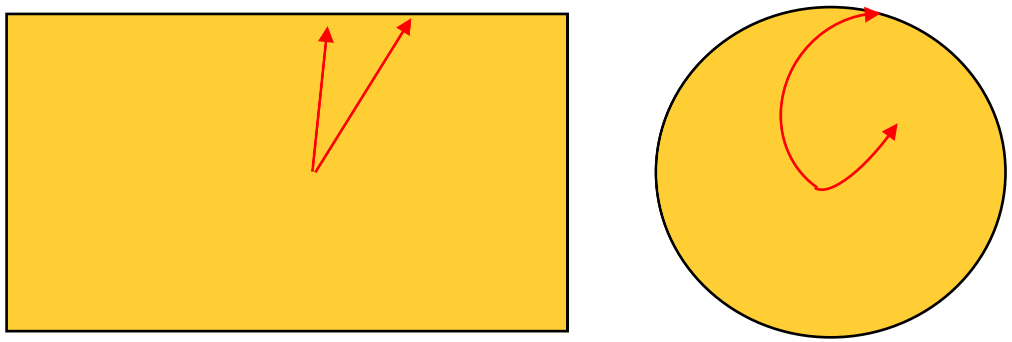




Central Detector

Diffractive event

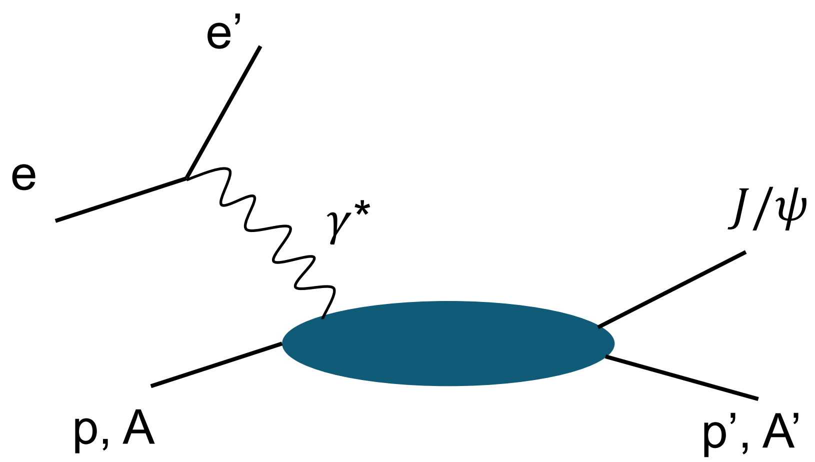




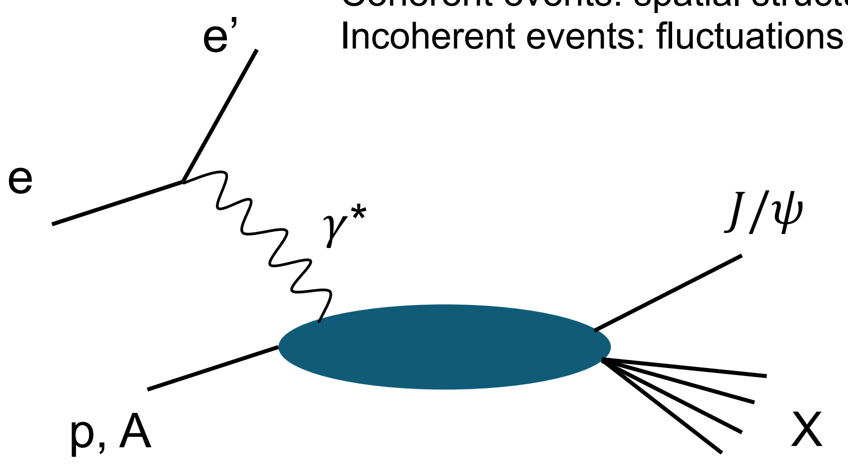
Central Detector

Diffractive Physics Program

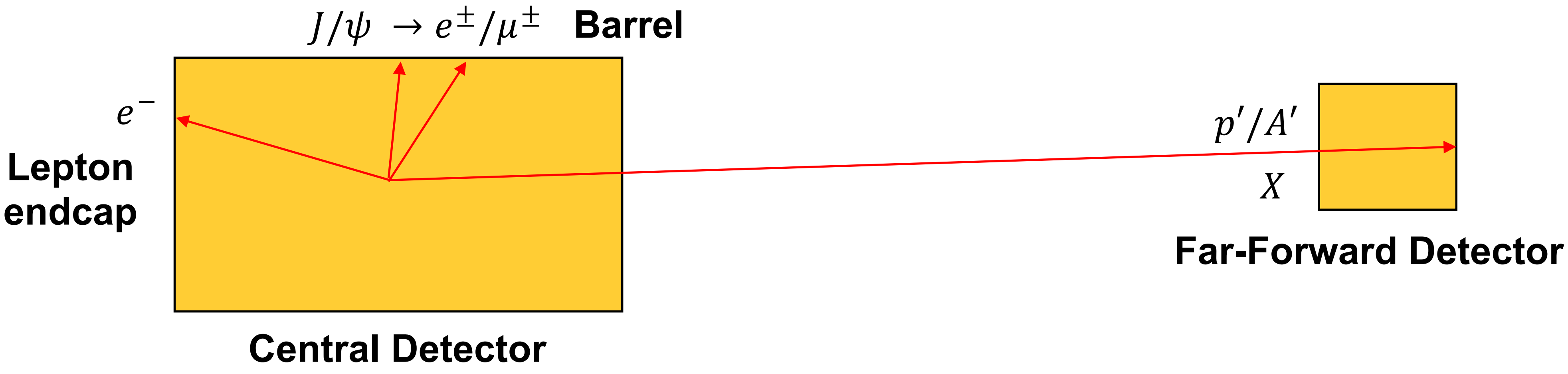
Coherent events: spatial structure of gluons (mean)
Incoherent events: fluctuations



Coherent – Target stays intact



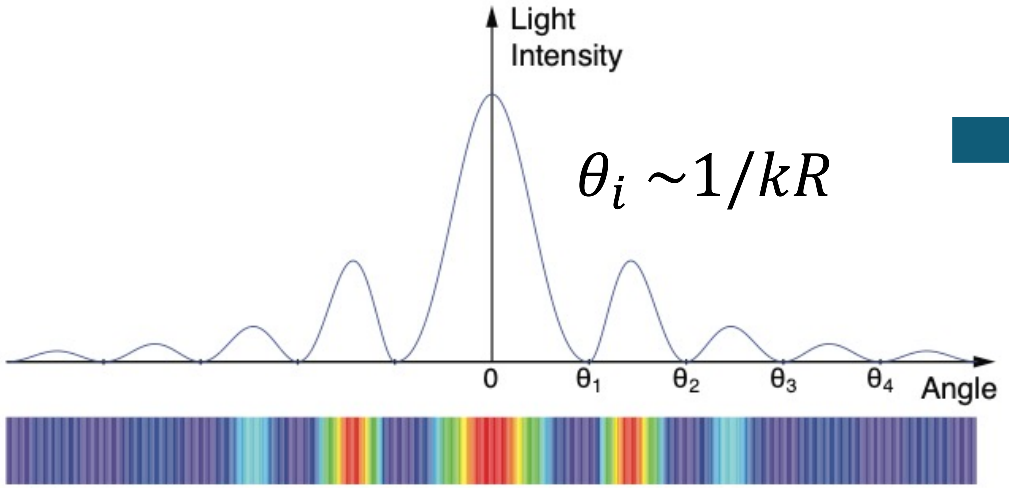
Incoherent – Target breaks up



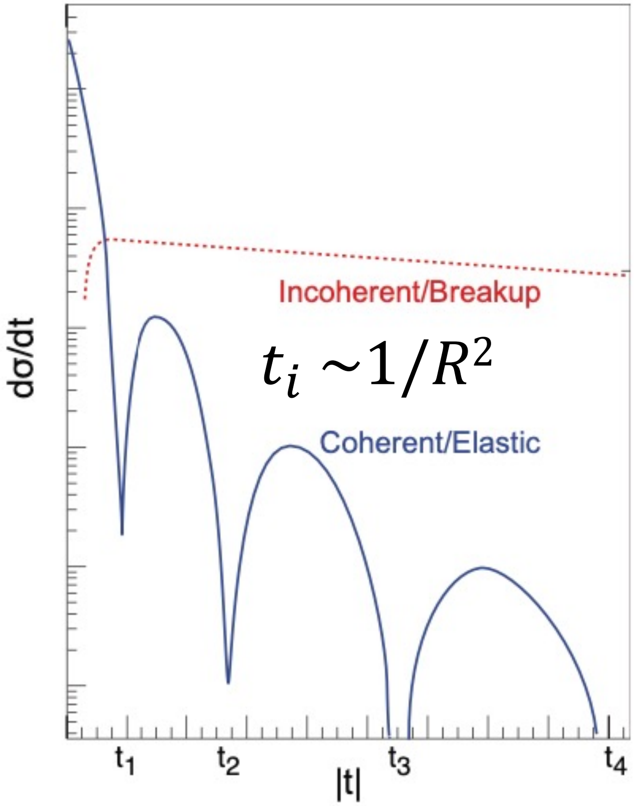
Diffractive Physics Program

- Diffractive pattern in optics (ex small angle scattering)
  Position of minima θ_i related to size *R* of screen

- **Similarly,** in coherent scattering cross section resembles **diffractive pattern where** $|t| \approx k^2\theta^2$



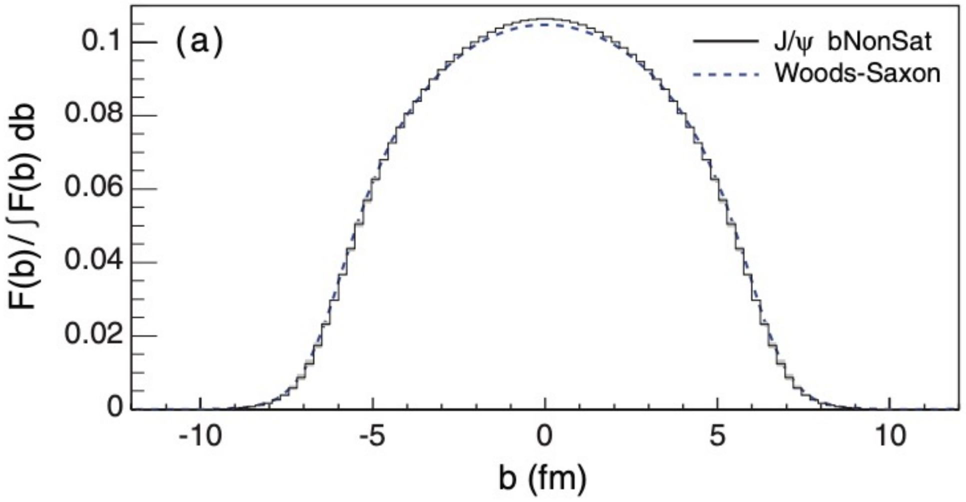
EIC white paper



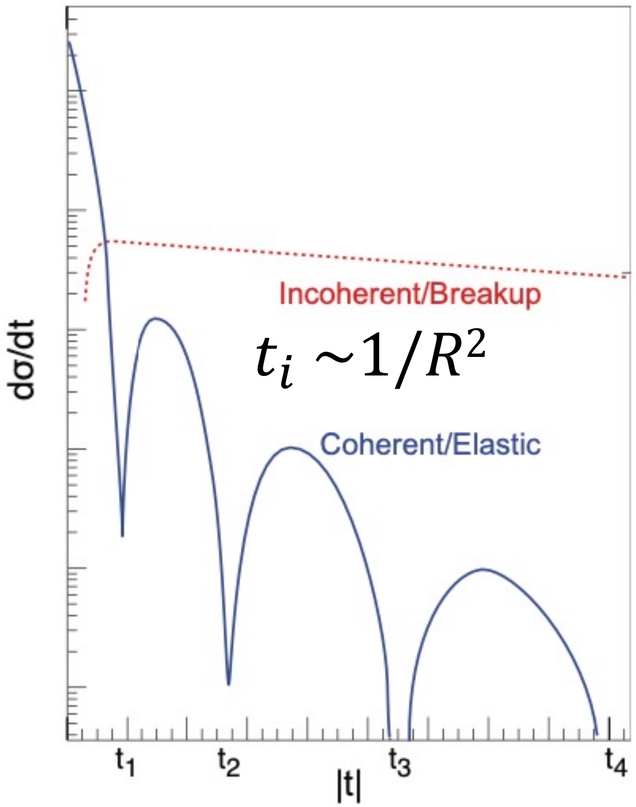
Diffractive Physics Program

$$F(b) = \frac{1}{2\pi}\int_0^{\infty} d\Delta\,\Delta J_0(\Delta b)\sqrt{\frac{d\sigma_{\text{coherent}}}{dt}(\Delta)}\Bigg|_{\text{mod}}$$

Gluon Imaging



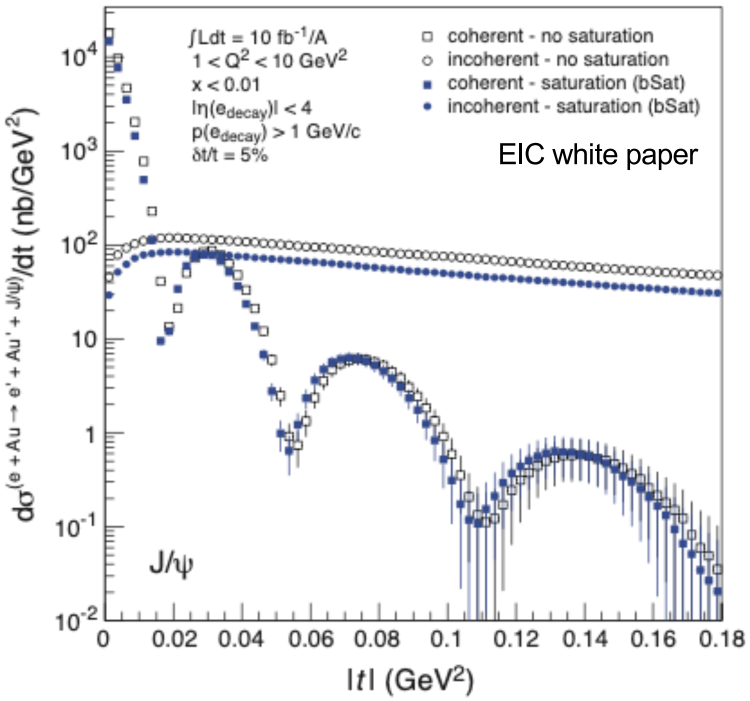
EIC white paper

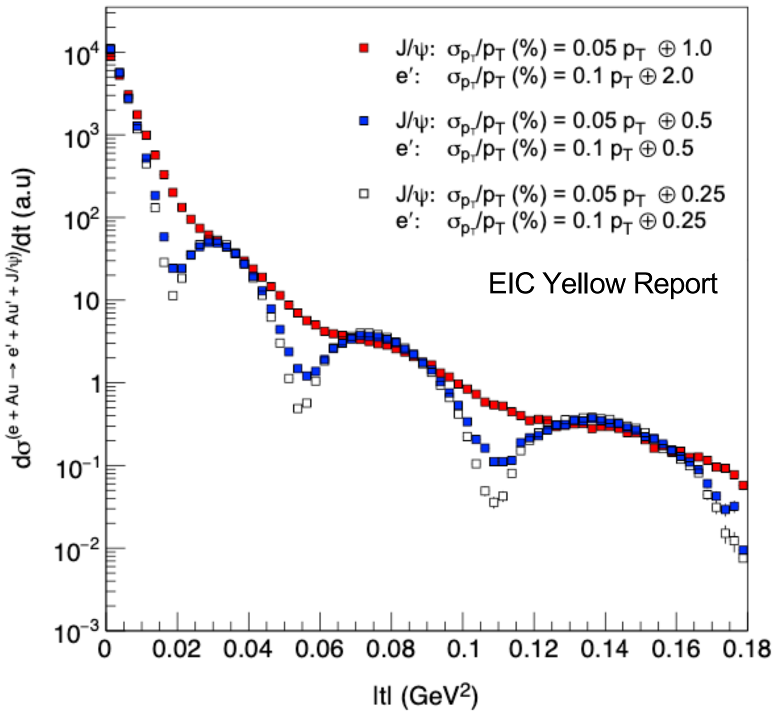


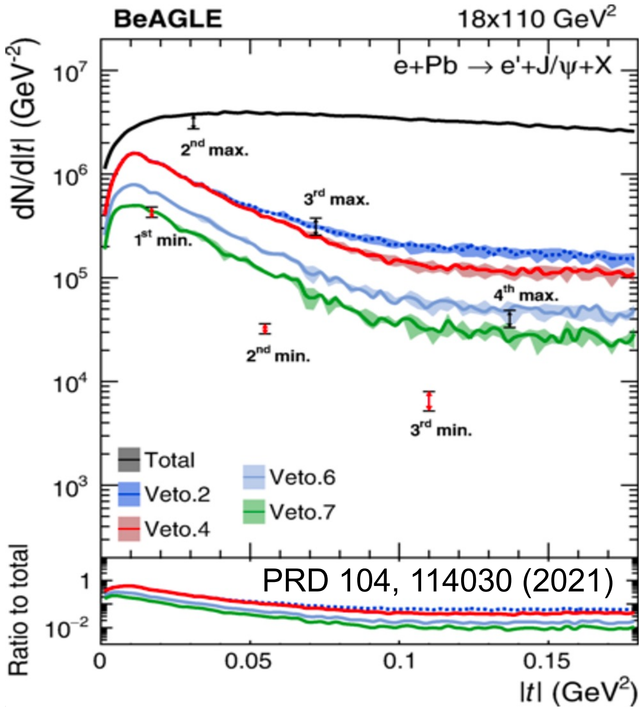
- The Fourier transform of t spectrum → **gluon distribution in impact-parameter space**
- Diffractive cross-section leads to **spatial imaging of nucleons**

Diffractive Physics Program

- Experimentally, **measured spectra** in vector meson production contain **sum of coherent and incoherent processes**
  - Low t – coherent events dominate, but **higher t – incoherent events dominate**
  - Measuring coherent events is **very challenging → tagging nuclear breakups and vetoing incoherent events instead**
  - **Tracking resolution (p_T in particular)** allows to measure position of dip patterns

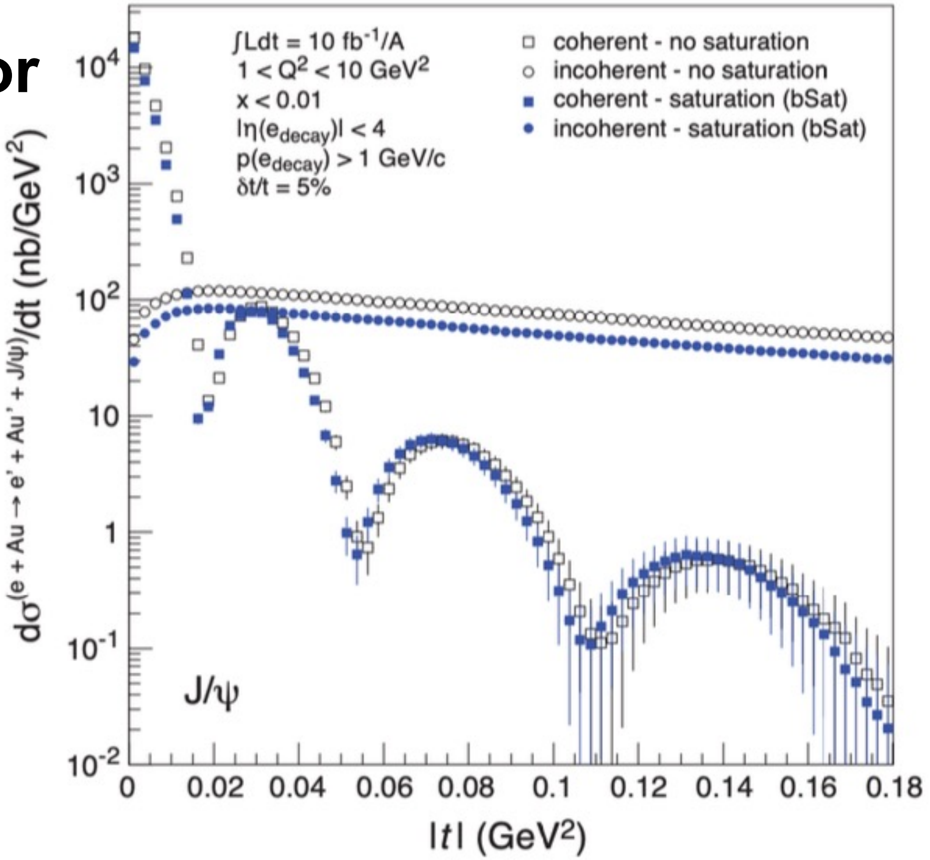






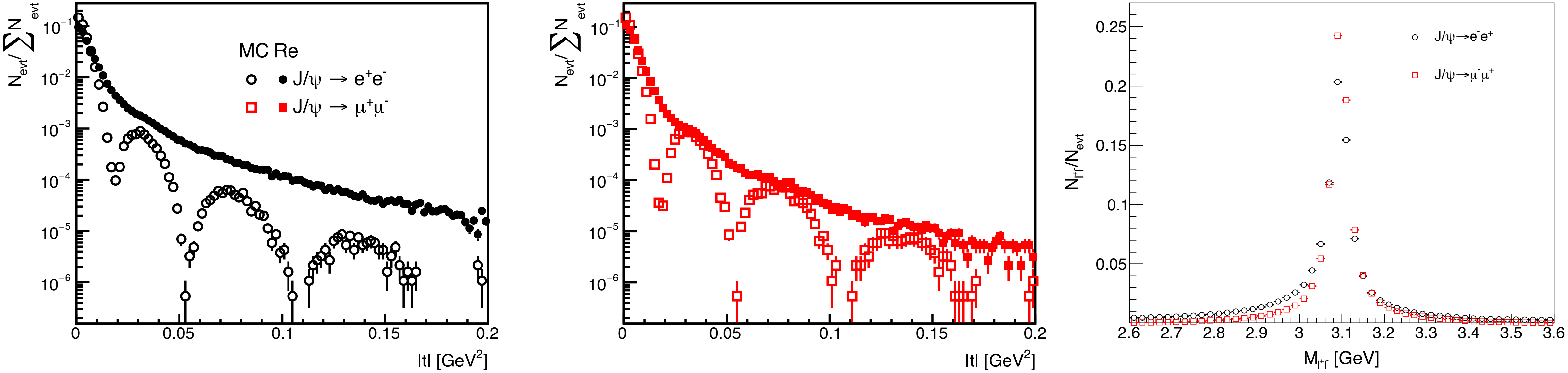
BNL Physics Program – Golden Channel

- Focus **exclusive, diffractive and tagging physics program**
  - Coherent vector meson production
- Use **central tracking** and **far-forward detector**
  - Muon ID
  - Tracking detector
  - Backward EM calorimeter
  - Inclusion of 2nd focus
  - Far-Forward acceptance
- **Improvement in |t| resolution**
- **Vetoing efficiency for incoherent events**



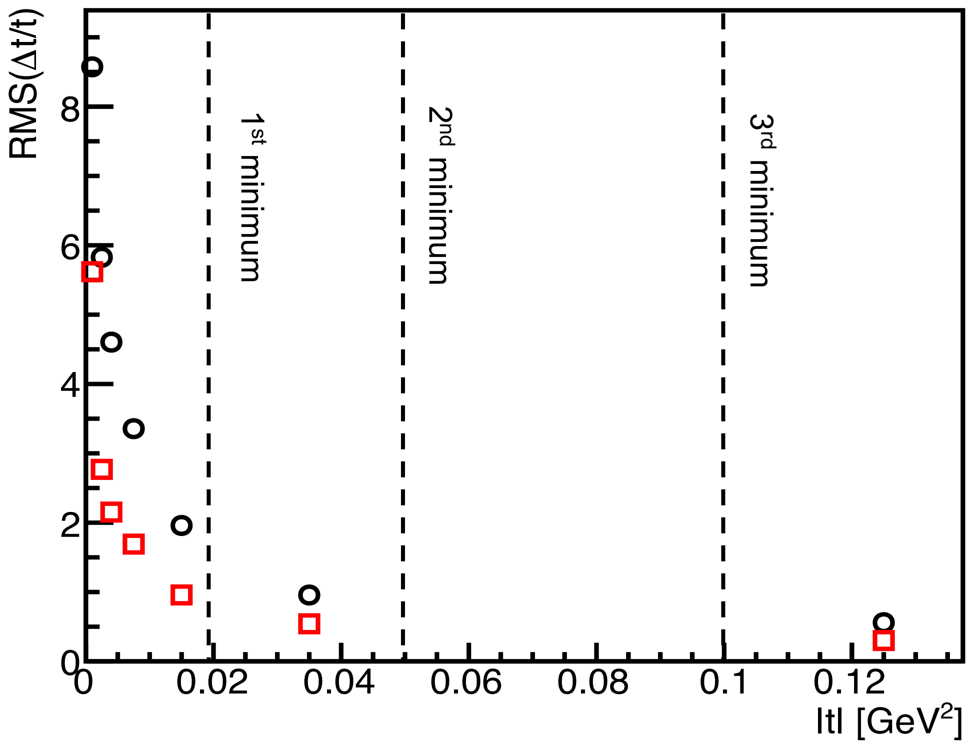
Central Detector – Track and Calorimeter

Study by Cheuk-Ping Wong (BNL)



- Larger combinatorial background at lower spectrum due to bremsstrahlung radiation when using di-electron channel
- **In calculation of t, needs scattered electron (backward) to be a precise**

Central Detector – Track and Calorimeter



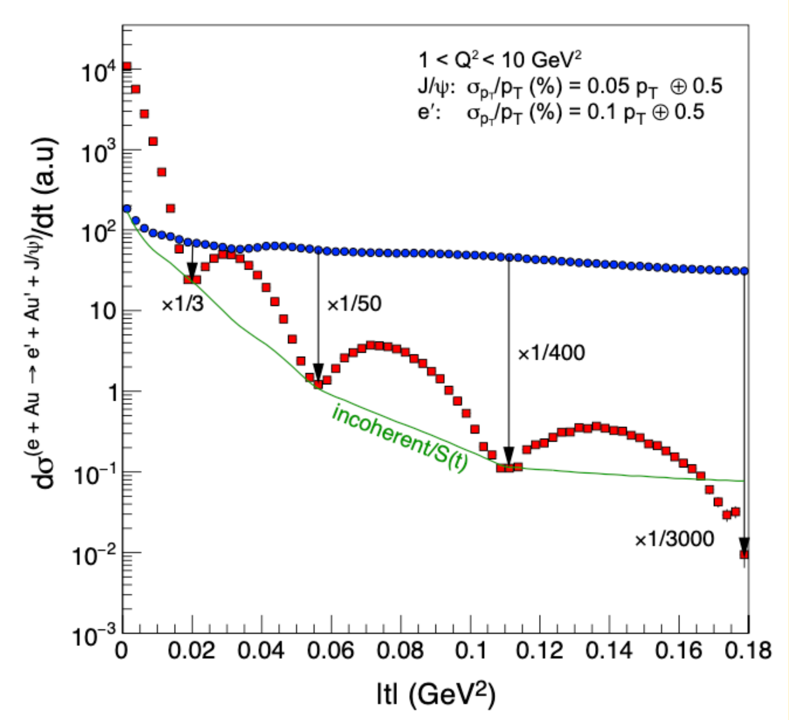
- Different tracker designs ex) Drift chamber/TPC to **have more hit points to improve backward tracking performance**
- **Fast simulation to establish different tracker performance**

- **Require significant improvement in scattered electron measurements**
- Beyond excellent backward tracking/ECAL with a momentum/energy resolution smaller than 2%

Far-Forward Detector – Incoherent Veto

- Separate coherent from incoherent process
  - **By tagging nuclear fragments using far-forward detectors**, understand background of coherent vector meson productions (ex. J/ψ)
- Use Far-Forward detectors to measure
  - Charged hadrons (protons/pions)
  - Neutral particles (neutrons/photons)
- **Evaluate veto efficiency using incoherent events**

Reference from EIC YR p.352

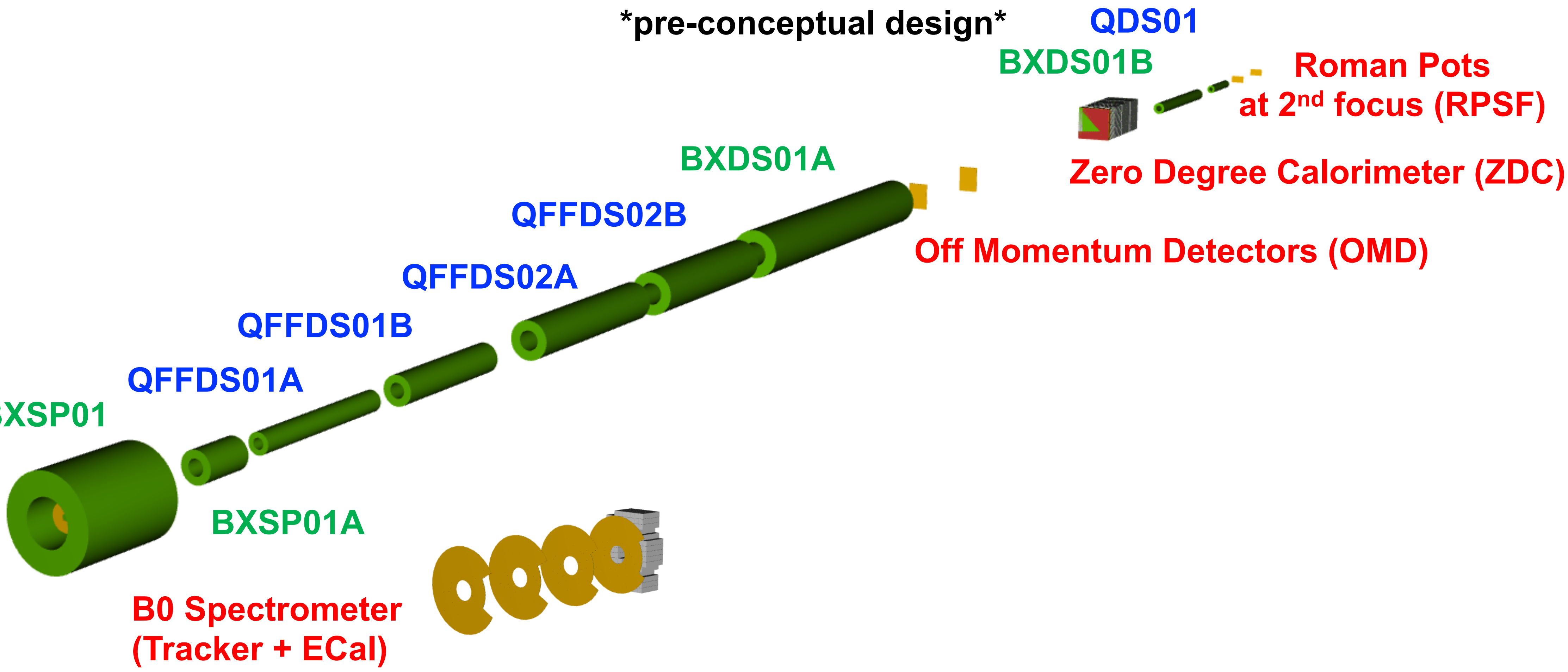


At position of third diffractive minimum, rejection factor for incoherent event better than 400:1 must be achievable

Far-Forward Detector – Layout

Study by Jihee Kim (BNL)

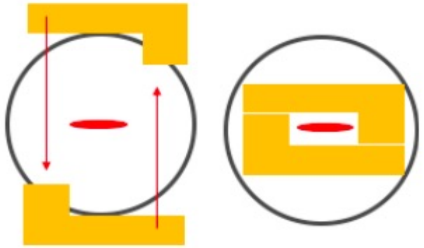
Implemented in **IP-8 Forward Hadron Lattice** and IP-6 detector configuration



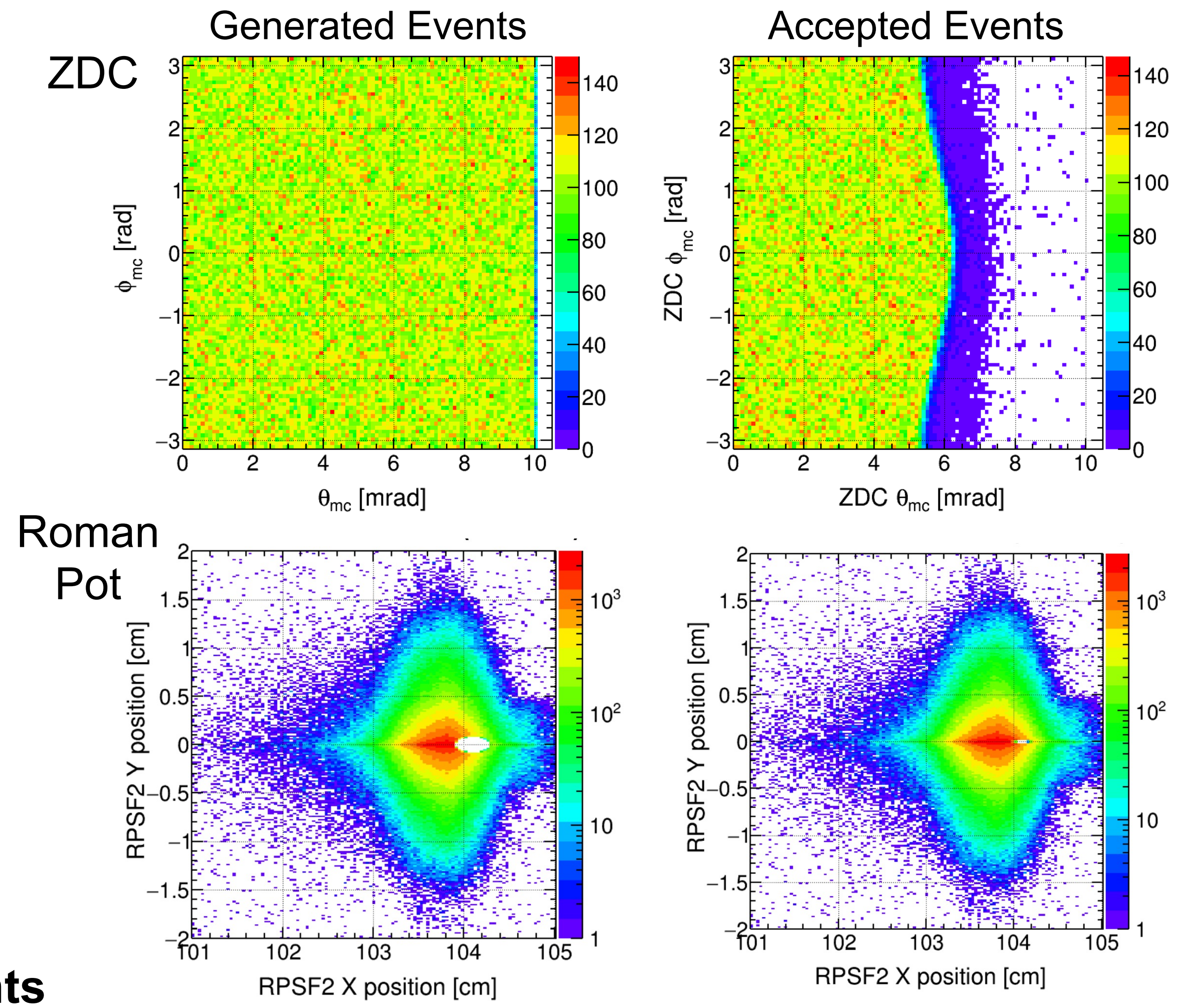
Far-Forward Detector – Acceptance

- Detector acceptance
  - ZDC < 5.5 mrad uniformly ~100 %
  - **Needs to evaluate beam pipe impact on neutrons**

Roman Pot concept



- Roman Pot (@ 2nd focus)
  - Windows on pots depending on the **beam optics (transverse beam size)**
  - With 2nd focus makes difference in how close detector safely placed
- Benefits
  - **Larger acceptance in low p_T** in particular
  - **Reduce risk to miss nuclear fragments**

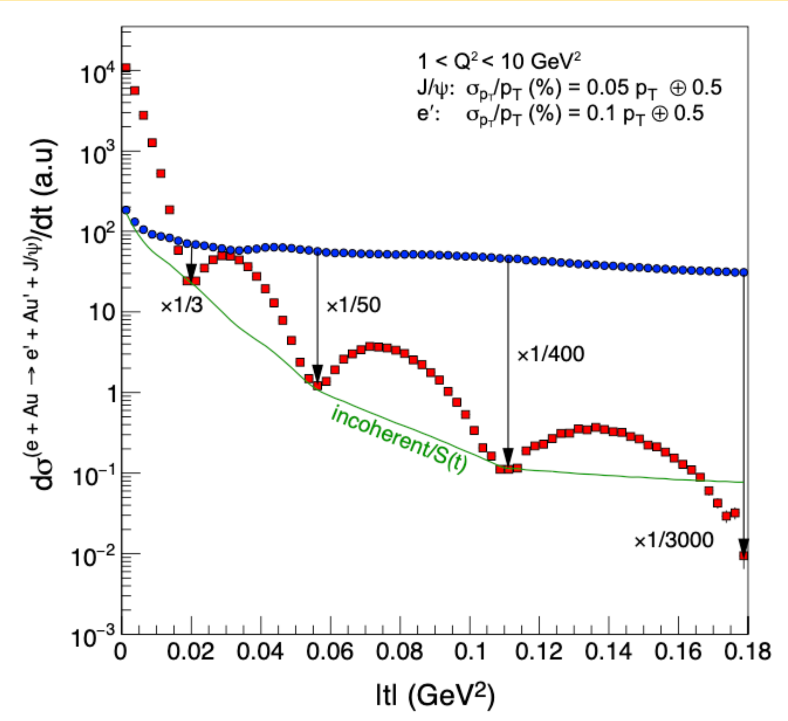


Brookhaven National Laboratory

JIHEE KIM

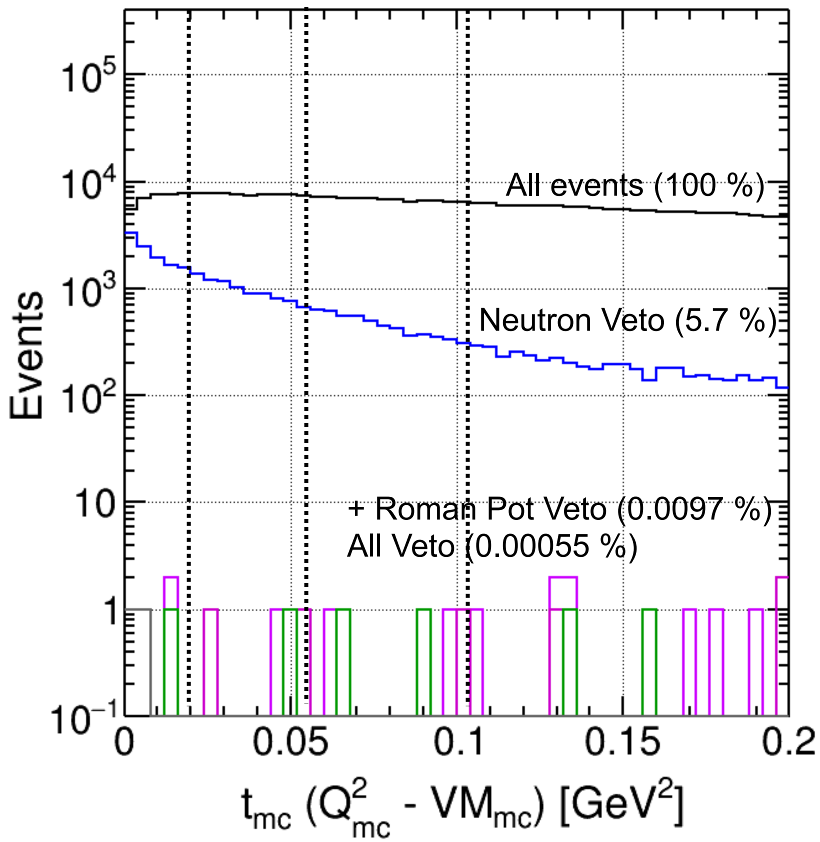
Far-Forward Detector – Incoherent Veto

Reference from EIC YR p.352



At position of third diffractive minimum, **rejection factor for incoherent event better than 400:1 must be achievable (0.0025 % inefficiency)**

Veto inefficiency for incoherent events



ZDC hcal tagged
(neutrons)
RPSF tagged
(protons, nuclear fragments)
OMD tagged
(charged particles)
B0 tracker tagged
(charged particles)
B0 ecal tagged
(photons)
ZDC ecal tagged
(photons)

Vetoing power > 10^3

Found to be enough to suppress incoherent contribution at three minima
Vetoing efficiency is > 99.99%

Going Forward

- EIC 2^{nd} detector comes few years after EIC Detector 1 starts
- Continue exploring detector technologies for 2^{nd} detector
- Formulate preliminary detector requirements and concept
- Establish advantages in IP-8 and facility upgrade toward physics program benefits

- Toward EIC 2^{nd} detector Yellow report in 2025 including physics scope, detector requirements, and detector concept/technology

Summary

- Community favors to have EIC 2^{nd} detector as complimentary
  - Cross-check, complimentary to ePIC, and new opportunities
- Small group, but working towards establishment on physics program
- Work with community toward building support for EIC 2^{nd} detector
- Attract international collaborations
- At BNL, focus exclusive, diffractive and tagging physics program using central tracking and far-forward detectors

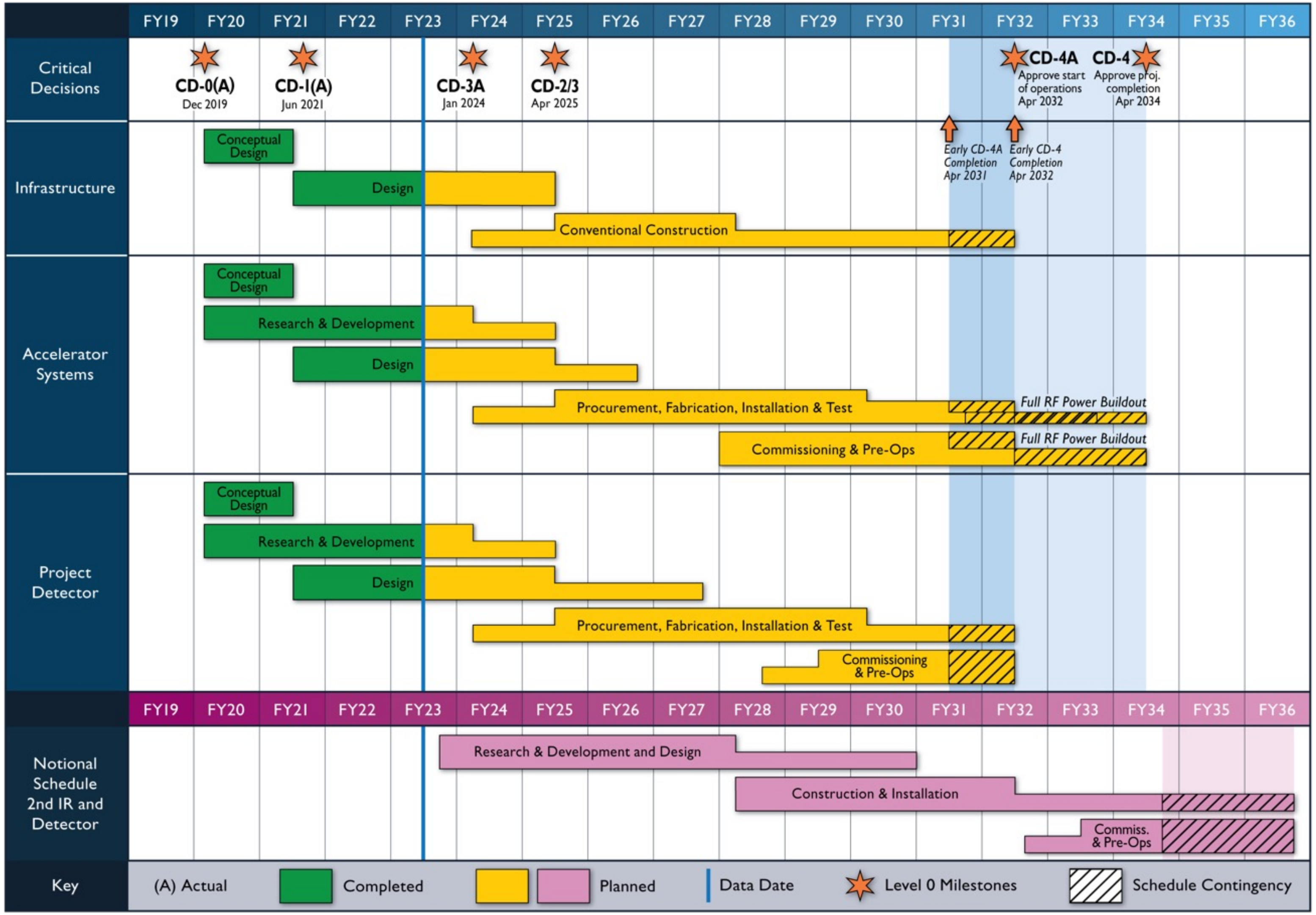
Going Far-Forward – 2nd Det Community

- **Yale group is already engaged** in simulations, R&D, design and prototyping of ePIC detector
  - pfRICH and Fwd Hcal in ePIC and R&D for future gaseous tracking detectors utilizing GEM and GridPix technologies
- Welcome to bring new input, approach, perspective, participation…

- EIC 2nd detector working group
  - Group page: https://eicug.github.io/content/wg.html#detector-iiip8-group
  - Conveners are: Charles Hyde (ODU), Sanbaek Lee (ANL), Simonetta Liuti (UVA), Pawel Nadel-Turonski (CFNS/SBU), Bjoern Schenke (BNL), Ernst Sichtermann (LBNL), **Thomas Ullrich (BNL/Yale)**, Anselm Vossen (Duke/JLab)
  - Software coordinators: Wenliang Li (CFNS/SBU) and Zhoudunming Tu (BNL)
  - Convener mailing list: eic-det2-conveners-l@lists.bnl.gov

Backup Slides

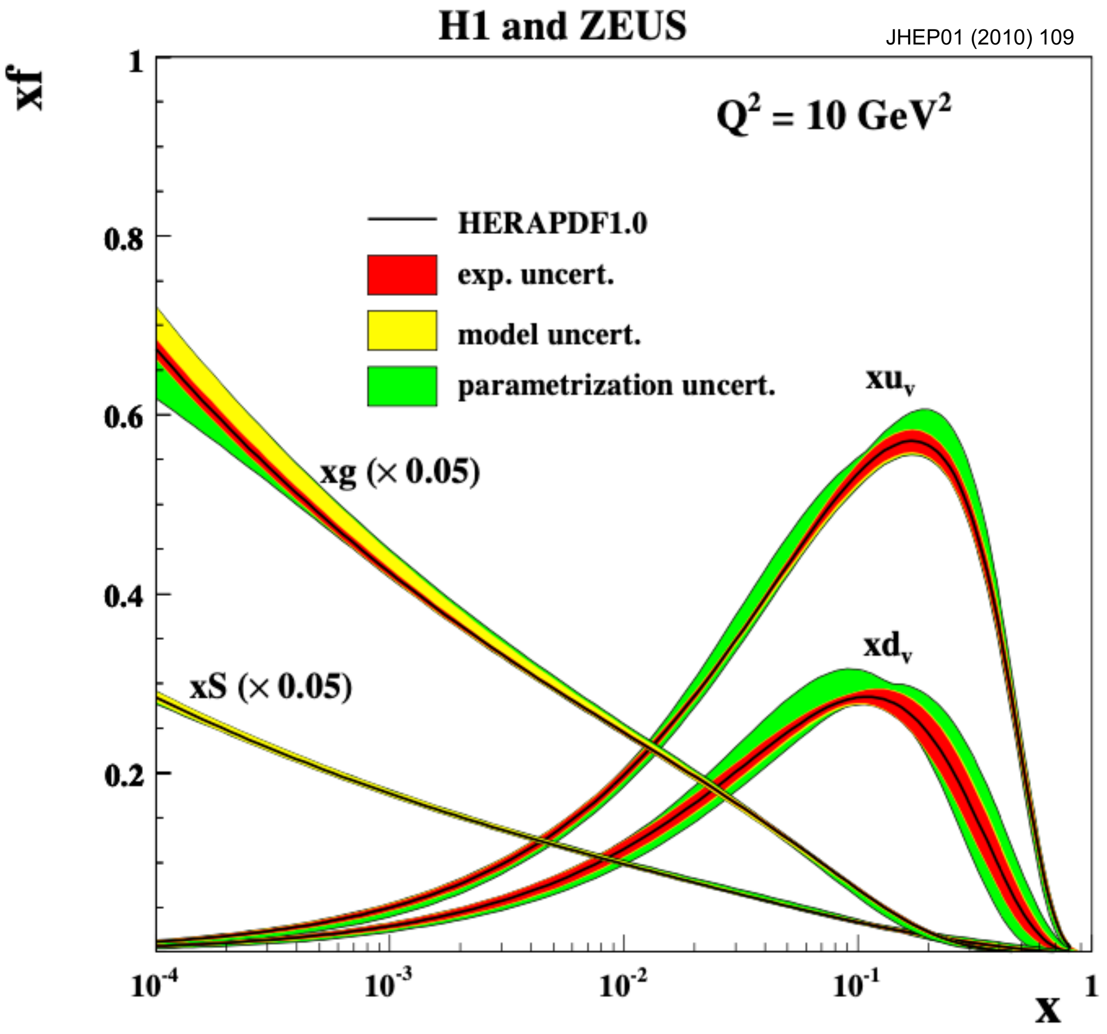
EIC 2nd Detector Timeline



Reference schedule for 2nd IR and detector from EICUG meeting July 2023

← EIC 2nd detector

Results from HERA Facility at DESY



JHEP01 (2010) 109

- Structure functions allows us to extract quark and gluon distributions
- **Parton Distribution Function (PDFs)**
- The smaller momentum fraction, the greater the number of quark-antiquark pairs and **gluons** appearing in proton
- **Proton is almost entirely gluons for x < 0.1**