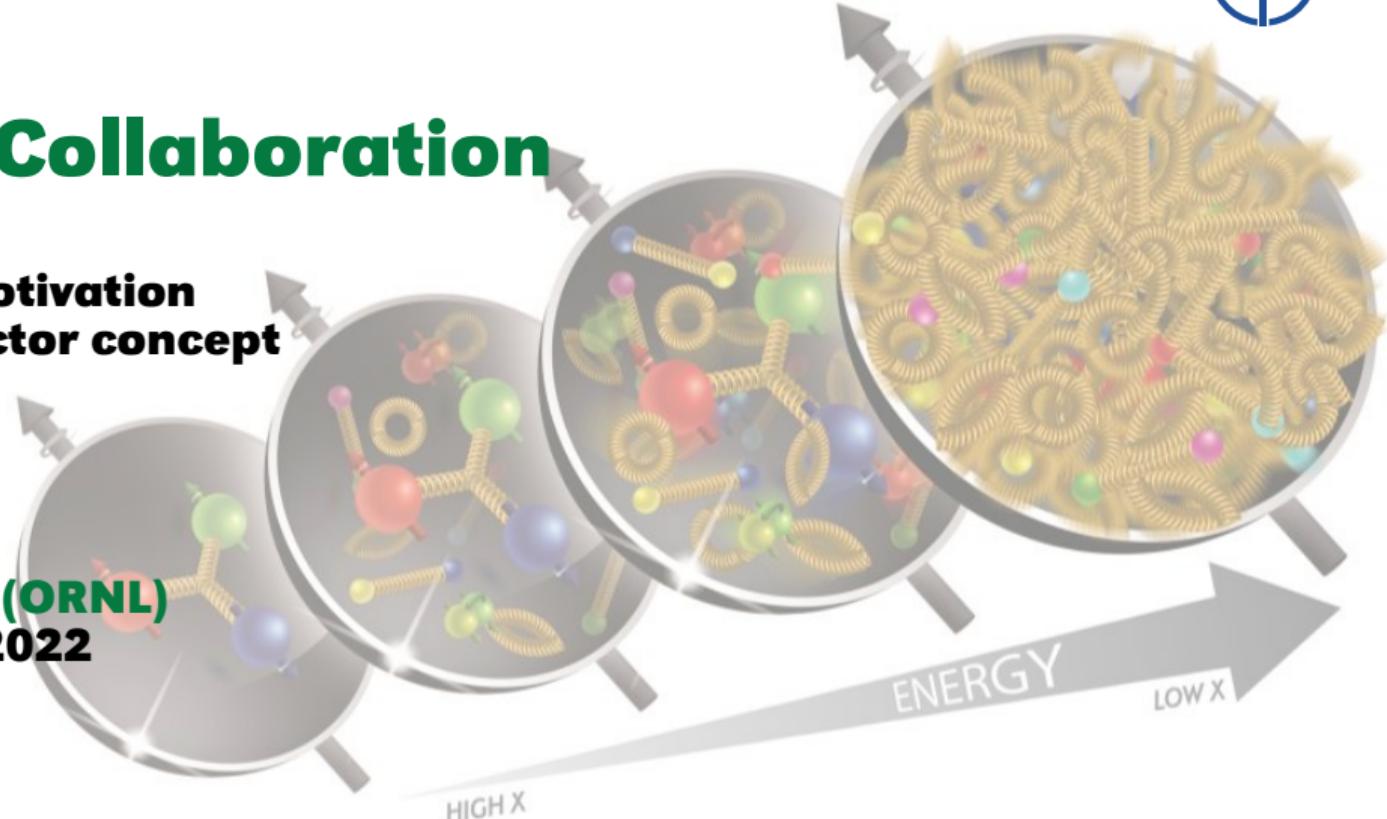


The EPIC Collaboration

**From physics motivation
to a viable detector concept**

**Friederike Bock (ORNL)
September 19, 2022**

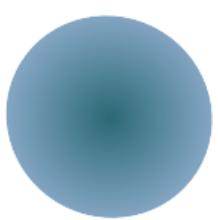
QNP 2022, online



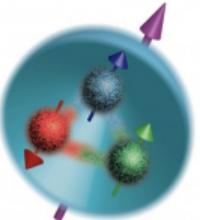
Back to the basics!

Where we are:

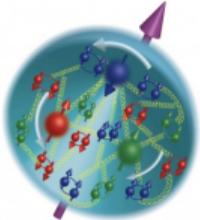
- Elastic lepton scattering determined the nucleon's charge & magnetism distributions in sphere with $\langle r_{ch} \rangle \approx 0.84 \text{ fm}$
- Largest fraction of energy in proton (x) carried by 3 valence quarks (2u,d), but very small fraction of proton spin
- Nucleons additional dynamically generated quark-antiquark pairs & gluons carrying low fraction of energy
- Quark & gluon longitudinal momentum fractions well mapped out
- Nucleon spin & mass have large contributions from quark-gluon dynamics, described by QCD



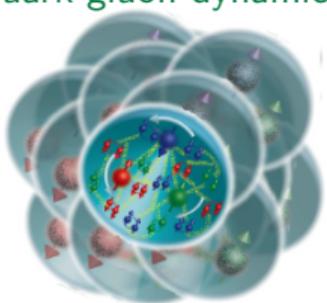
Proton
early 1900s



Proton
1975

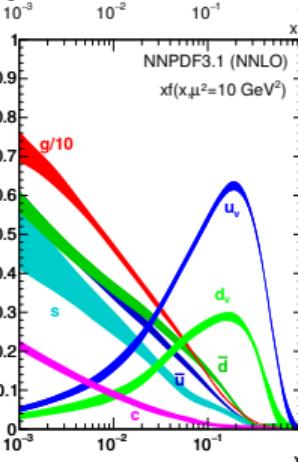
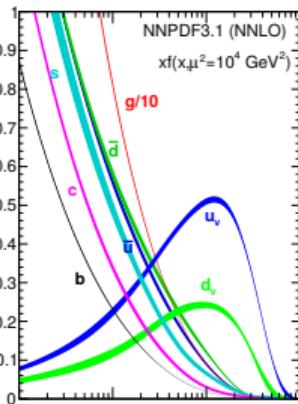


Proton
2015



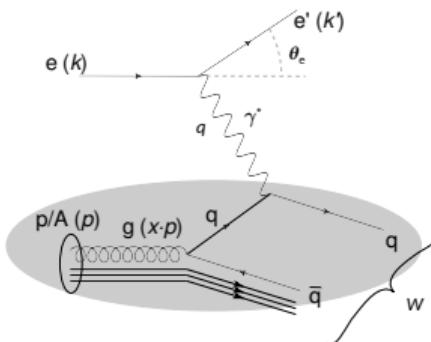
Proton
in a nucleus

EPIC detector



How did we learn this?

Deep Inelastic Scattering (DIS)



$$Q^2 = s \cdot x \cdot y$$

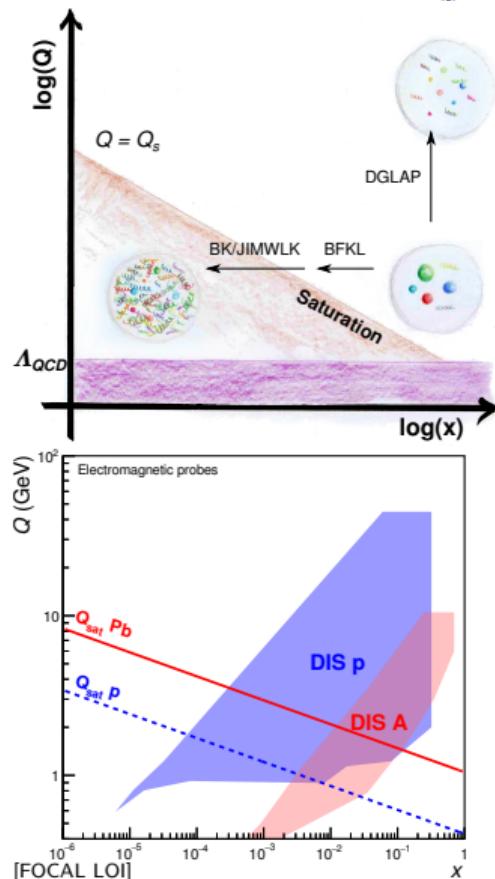
s center-of-mass energy squared

Q^2 resolution power

x the fraction of the nucleon's momentum carried by the struck quark ($0 < x < 1$)

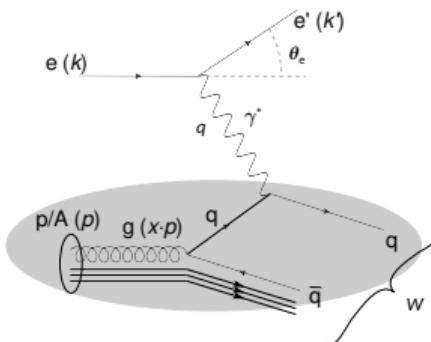
y inelasticity

- As a probe, electron beams provide unmatched precision of the electromagnetic interaction
- Direct, model independent determination of parton kinematics and spin of physics processes at the leading order
- Additional information obtained indirectly from hadron-collider measurements



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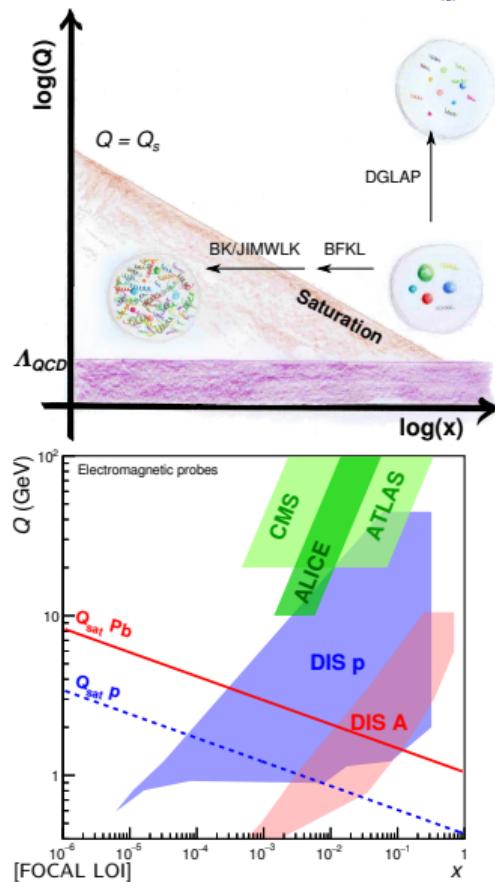
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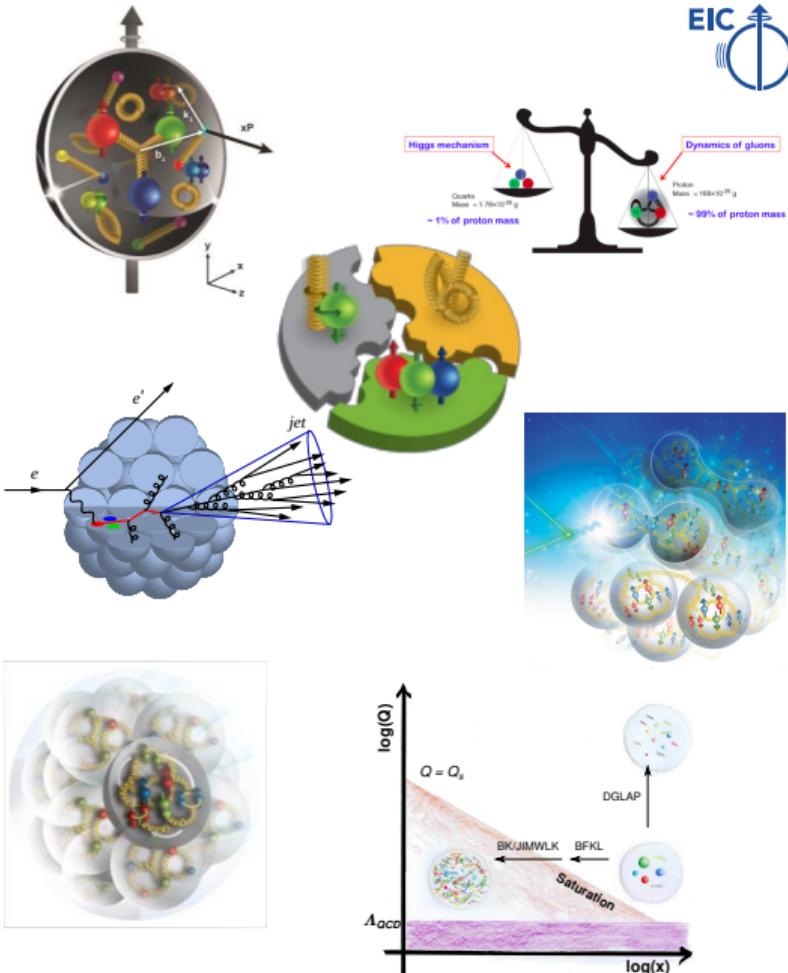
y inelasticity

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What we don't know yet

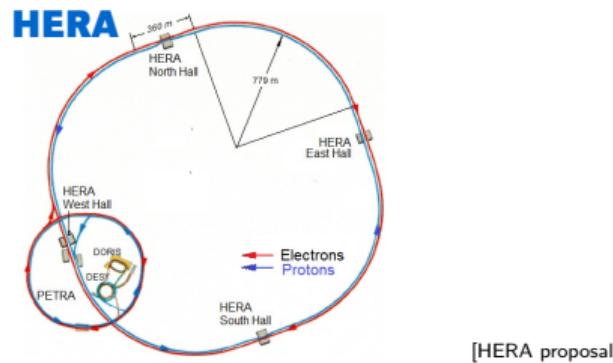
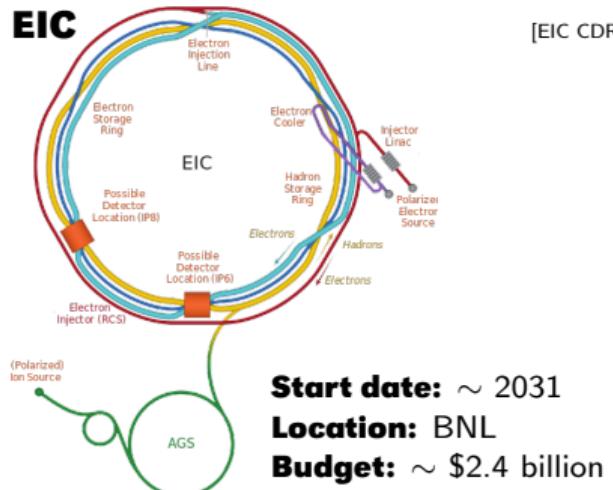
- The 3D distributions of sea quarks & gluons and their spins in nucleon
- How do the **nucleon mass & spin** emerge from them and their interactions?
- The details of **interactions of color-charged quarks and gluons with a nuclear medium**
- How are **nuclear bindings** and **hadronic states** created from quark, gluons and their interactions?
- How does a dense nuclear environment affect the quarks and gluons and their interactions?
- The **gluon density** in nuclei
- Is there a **Color Glass Condensate**?



EIC vs HERA

Machine parameters

- **Center-of-mass energy:** 20 - 140 (218) GeV
 - ▶ electrons: 2.5 - 18 (27.5) GeV
 - ▶ protons: 40- 275 (920) GeV (ions: $Z/A \times E_p$)
- **Luminosity:** 10^{34} (10^{31}) $\text{cm}^{-2} \text{s}^{-1}$
- **Polarization:** up to 70% (electron & ion) (only electron)
- **Ion species:** $p \rightarrow U$ ($A > 1$ only in fixed target)
- **Detectors:**
 - ▶ full coverage: 2 (2)
 - ▶ fixed target: 0 (2 - limited far-forward coverage)



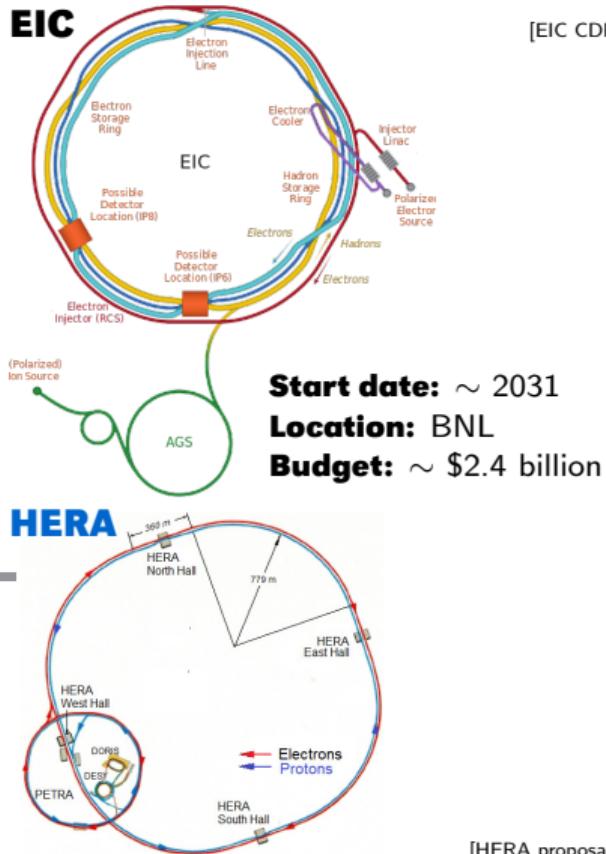
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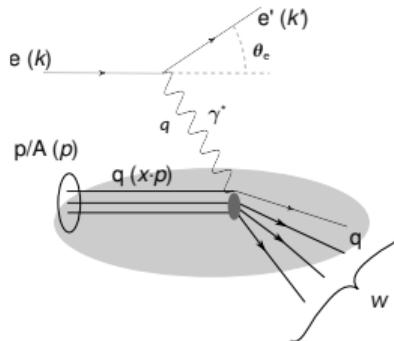
EIC will have:

- | | |
|------------------------|-----------------------|
| ● lower energy | + Hadron polarization |
| ● broader energy range | + Nuclear beams |
| ● higher luminosity | + Modern detector(s) |



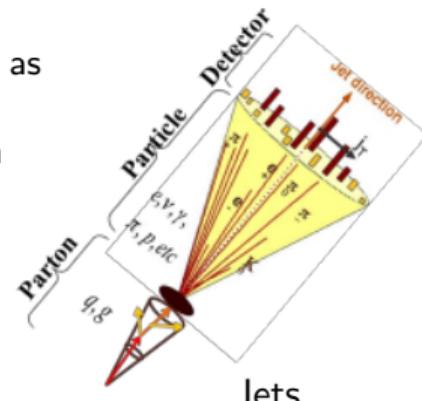
How to access partons at EIC

Neutral current (SI)DIS

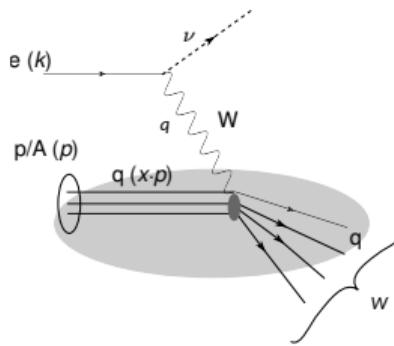


Neutral current (SI)DIS

- Detect scattered lepton (DIS) in coincidence with identified hadrons (SIDIS)
 - ▶ measure correlation between different hadrons as fct. of p_T, z, η
 - ▶ needs FF to correlate hadron type with parton



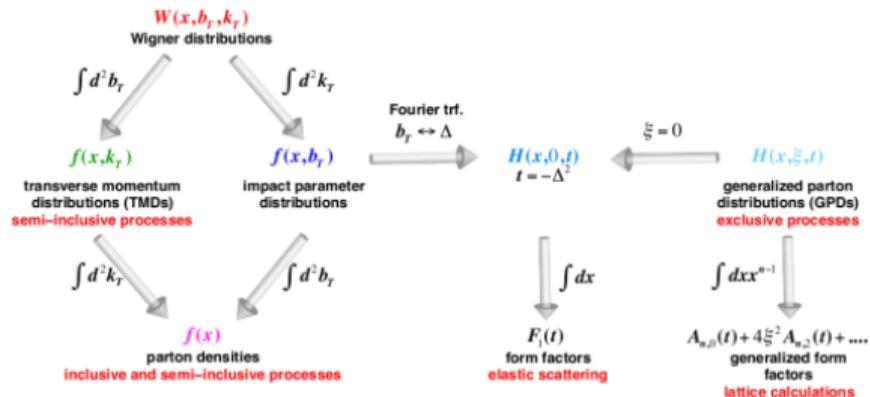
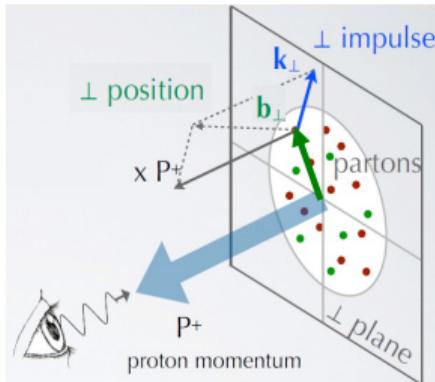
Charged current DIS



Jets

- best observable to access parton kinematics
- tag partons through the sub-processes and jet substructure
 - ▶ di-jets: relative $p_T \rightarrow$ correlated to k_T
 - ▶ tag on PDF

2+1 dimensional Imaging of Quarks & Gluons



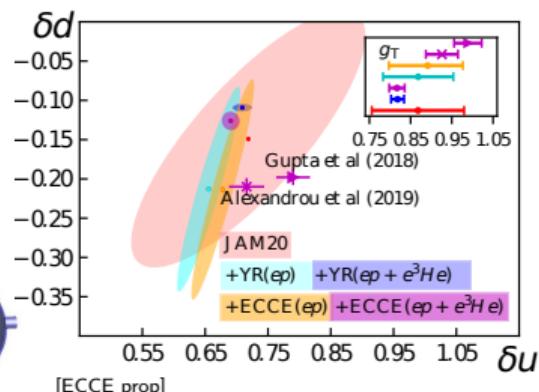
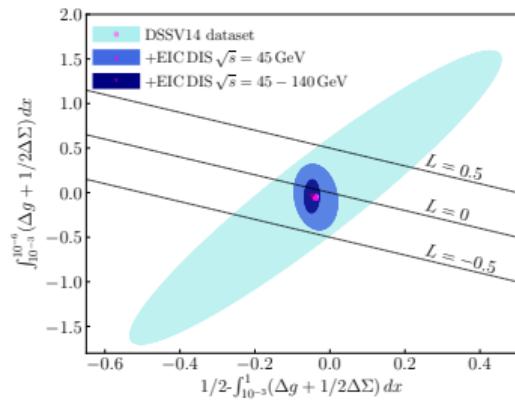
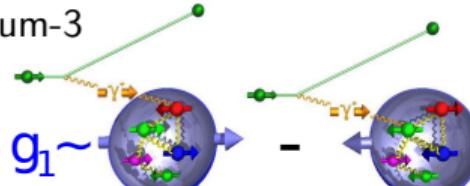
Nuclear Femtography

- Structure mapped in terms of:
 b_T = transverse position
 k_T = transverse momentum
- use different processes to access different aspects of distribution functions
- PDFs**: (SI)DIS cross sections
- GPDs**: Deep Exclusive Scattering (DES) cross sections like:
 deeply virtual Compton scattering (DVCS) $\gamma^* + p \rightarrow \gamma + p$
 or production of a vector meson $\gamma^* + p \rightarrow V + p$
 Spin-dependent 2+1D coordinate space images
- TMDs**: SIDIS cross sections
 Spin-dependent 3D momentum space images

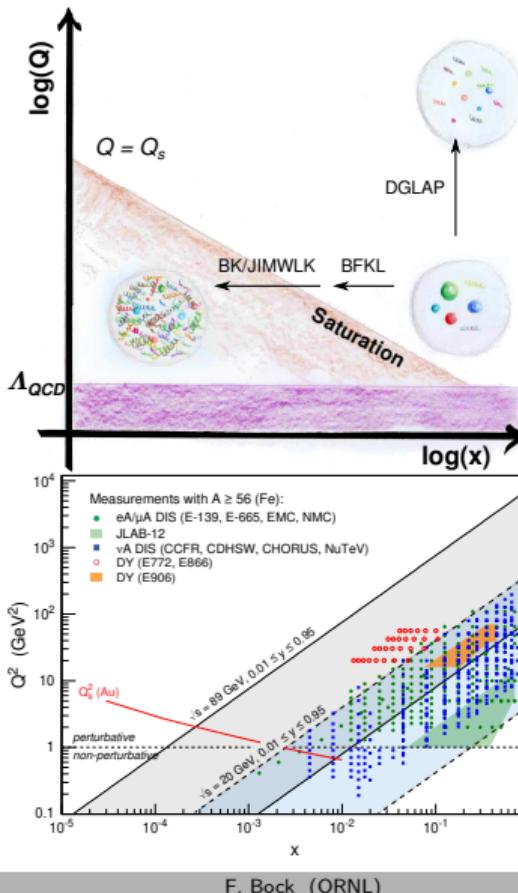
Nucleon Spin

$$\frac{1}{2}\hbar = \left\langle P, \frac{1}{2} | J_{QCD}^z | P, \frac{1}{2} \right\rangle = \overbrace{\frac{1}{2} \int_0^1 dx \Delta \Sigma(x, Q^2)}^{\text{total quark spin}} + \overbrace{\int_0^1 dx \Delta G(x, Q^2)}^{\text{gluon spin}} + \overbrace{\int_0^1 dx \left(\sum_q L_q^z + L_g^z \right)}^{\text{angular momentum}}$$

- quark contribution: integral of g_1 over x from 0 to 1
- gluon contribution: $dg_1(x, Q^2)/d\ln Q^2 \rightarrow \Delta g(x, Q^2)$
- Measured through DIS cross section asymmetry in oppositely polarized collisions
- Improved constraints on the spin of quarks/gluons
 ⇒ Constrain contribution of orbital angular momentum (OAM) of partons to proton spin
- Collisions with polarized deuterons/helium-3
 ⇒ Access to neutron spin



Imaging the Nuclei



DGLAP

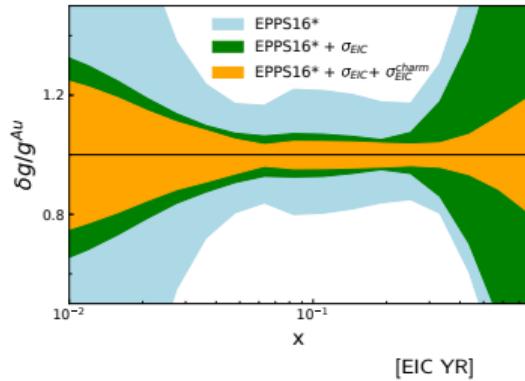
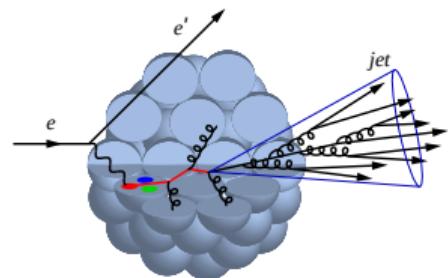
- predicts Q^2 but not A -dependence and x -dependence

Saturation models

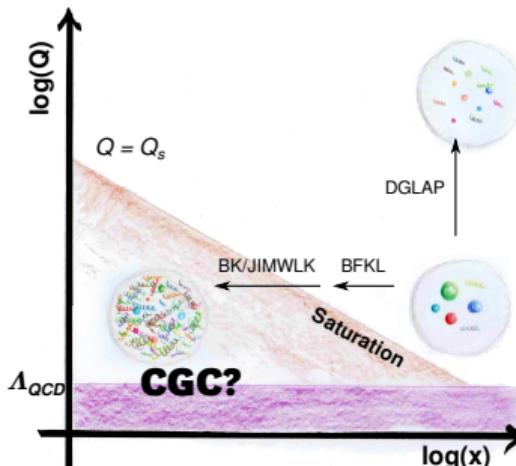
- predict A -dependence and x -dependence but not Q^2

Need: large Q^2 lever-arm for fixed x, A -scan

- Measure different structure function in $eA \rightarrow$ constrain nPDF
- Does the nucleus behave like a proton at low- x ?
- Direct access to gluons at medium to high x by tagging photon-gluon fusion using charm events



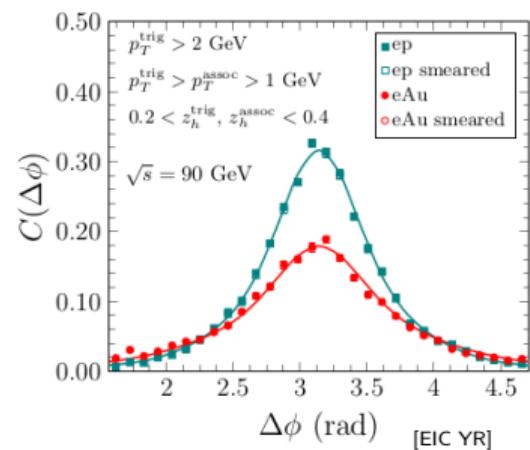
Color Glass Condensate?



- e interacts over distances $L \sim (2mNx)^{-1}$
 - For $L > 2R_A \sim A^{1/3}$ probe cannot distinguish between nucleons in front or back
 - Probe interacts coherently with all nucleons
- ⇒ **Enhancement of Q_s with $A \rightarrow$ non-linear QCD regime reached at significantly lower energy in A than in proton**

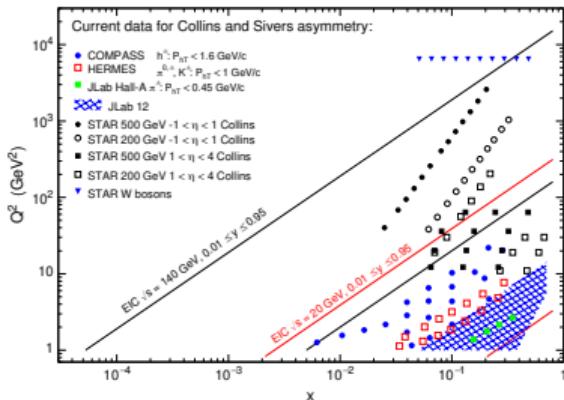
Di-Hadron or Di-Jet Correlations

- Low p/A gluon n density (ep): pQCD 2 → 2 process predicts ⇒ back-to-back di-jet
- High gluon density (eA): 2 → many process ⇒ expect broadening of away-side
- **EIC allows to study the evolution of Q_s with x**

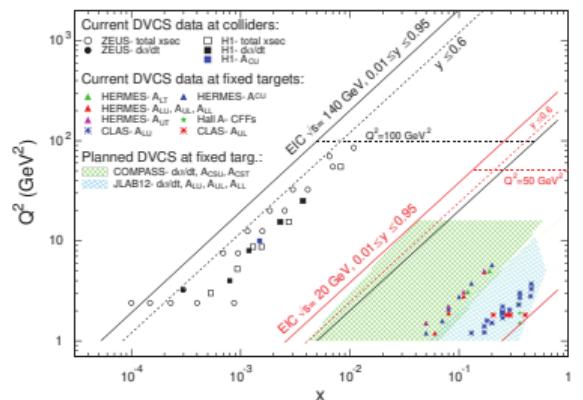


Kinematic Coverage

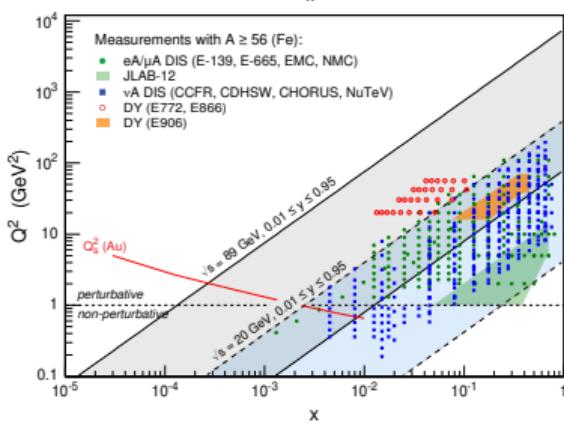
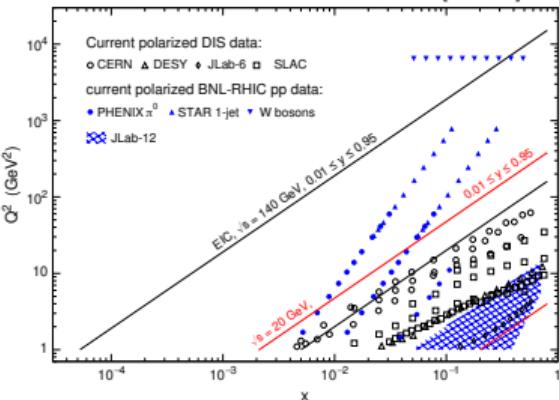
DIS



SIDIS



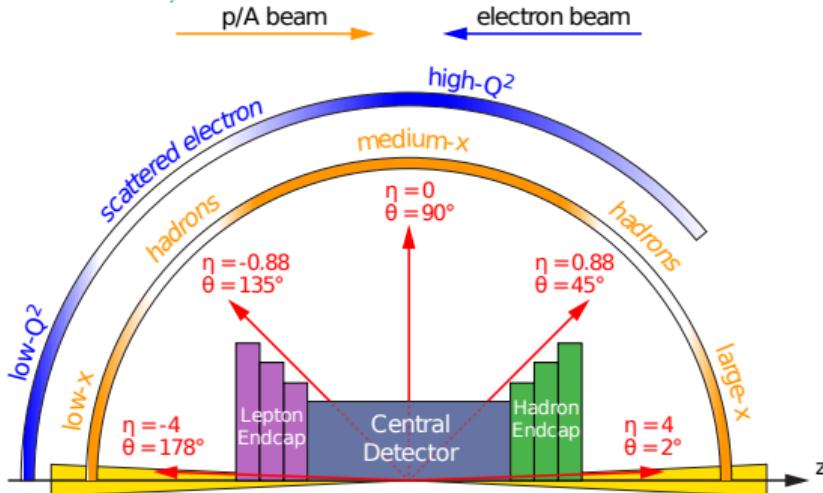
DVCS



Accelerator gives access to extensive kinematic range

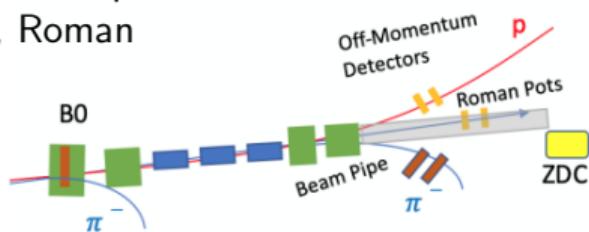
⇒ Now we need a detector to match

Generalized detector design considerations



- Large rapidity coverage for central detector
- Specialized far-forward detectors for p kinematics measurements
- High precision low mass tracking
- Hermetic coverage of tracking, electromagnetic & hadronic calorimetry
- High performance single track PID for π , K, p separation

- Large acceptance for diffraction, tagging, neutrons from nuclear breakup
- many auxillary detectors integrated in beam line: low- Q^2 tagger, Roman pots, ZDCs ...
- High control of systematics
- luminosity monitors, electron & hadron polarimetry

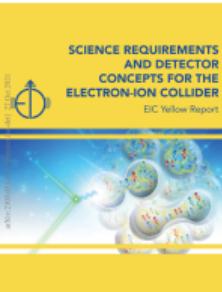
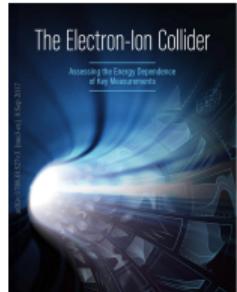
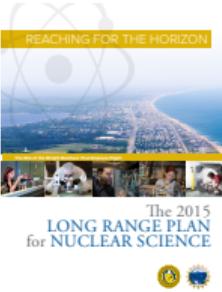
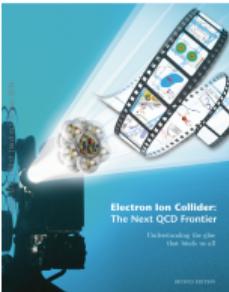


Highly integrated design between detector and machine for IR

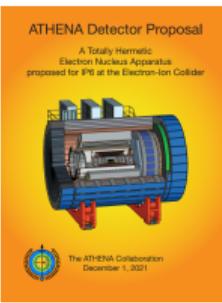
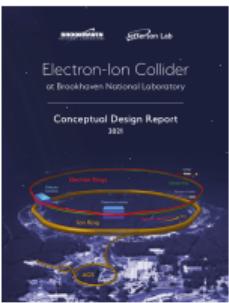
[EIC YR]

The detector design process

Define physics objectives & generic machine/detector parameters

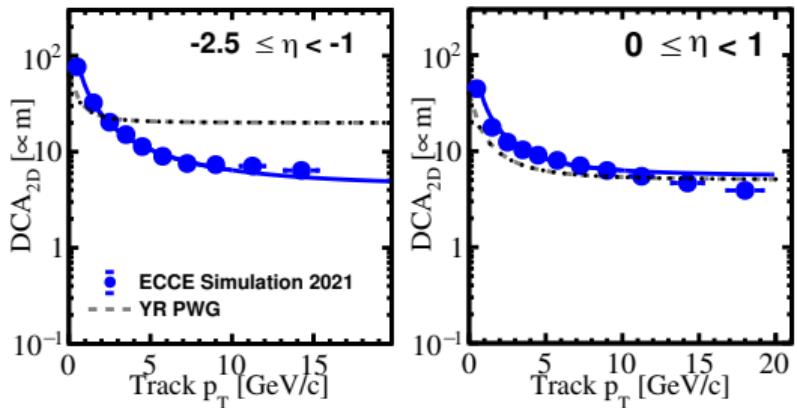


Realistic machine & detector concepts

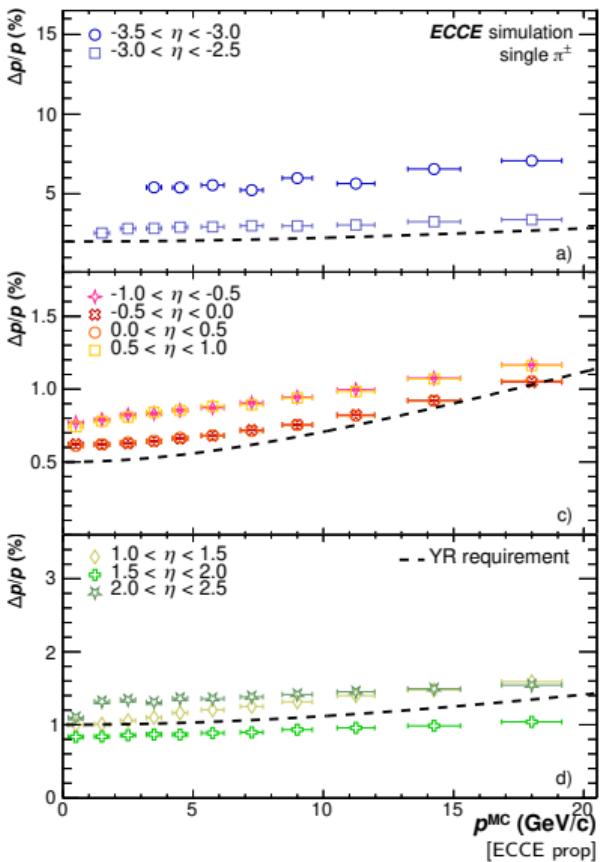


- Detector & machine design driven by physics objectives
- NSAC recommendation: "... a high-energy high-luminosity polarized EIC ... highest priority for new facility construction ..."
- **Jan. 2020:** BNL site selection
- Extensive generic detector R&D for EIC for PID, tracking & calorimetry
- YR outlines general detector requirements for benchmark physics observables
- **Mar. 2021:** Call for Detector Proposals
- Detector proposal based on more realistic full detector simulations
- Mar. 2022: ECCE chosen as reference design for detector 1
- **Mar. 2022 - now:** EPIC collaboration formation & consolidation process

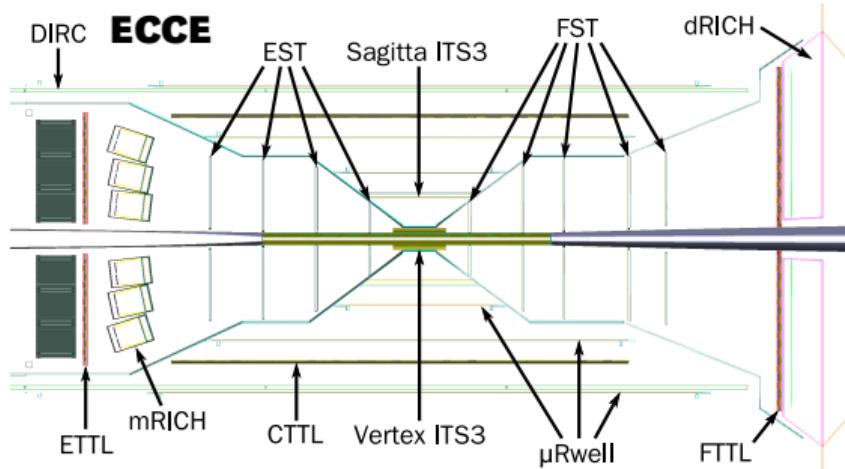
Tracking (1)



- Embedded in BABAR 1.5T magnet
 - Yellow Report requirements tough to meet
 - Meeting primary vertex resolution YR-requirement
 - Momentum resolution harder to fullfil, all designs (ECCE/ATHENA) currently slightly above requirements
- No significant negative impact on physics performance observed



Tracking (2)



Technology mix

- **MAPS based Si-detectors:**
 $\sigma = 10\mu\text{m}$, $X/X_0 \sim 0.05 - 0.15(0.55)\%/\text{layer}$
- **μ Rwells:**
 $\sigma = 55\mu\text{m}$, $X/X_0 \sim 0.2\%/\text{layer}$
- **AC-LGADs:**
 $\sigma = 30\mu\text{m}$, $X/X_0 \sim 6 - 7(1.5 - 2)\%/\text{layer}$

mid-rapidity:

Ultra thin MAPS based Si-detectors, μ Rwells & AC-LGADs

Adapting Si-radii & support structure design

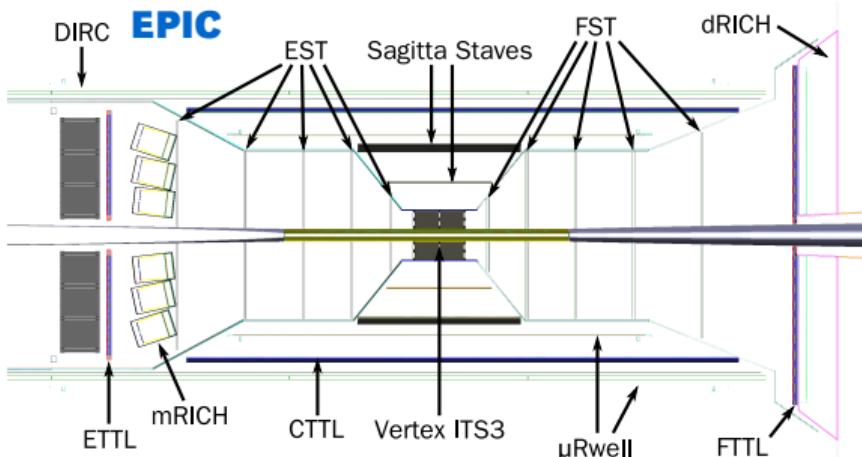
Forward and Backward:

MAPS based Silicon discs & AC-LGADs

- Outer layers placed to provide ideal track points before/after PID detectors

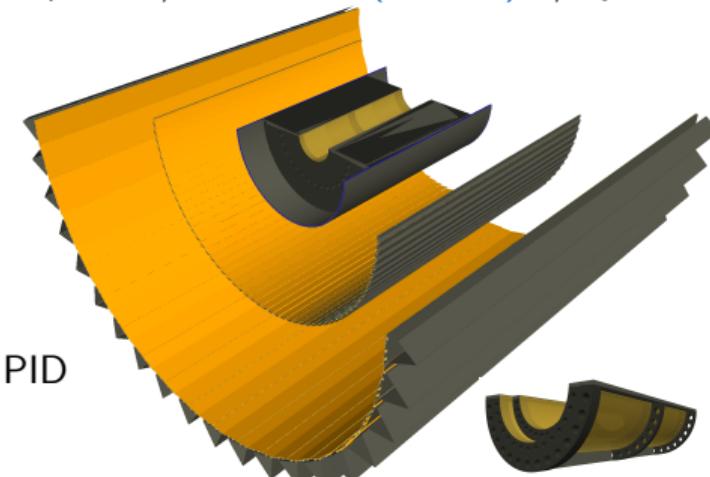
- New Magnet with BABAR dimensions $B = 1.7 - 2\text{T}$

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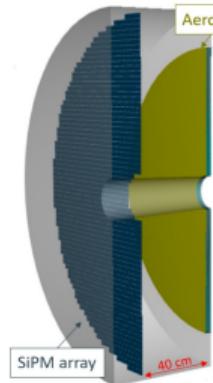
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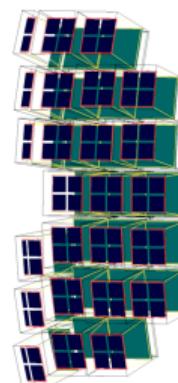
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Cherenkov-PID

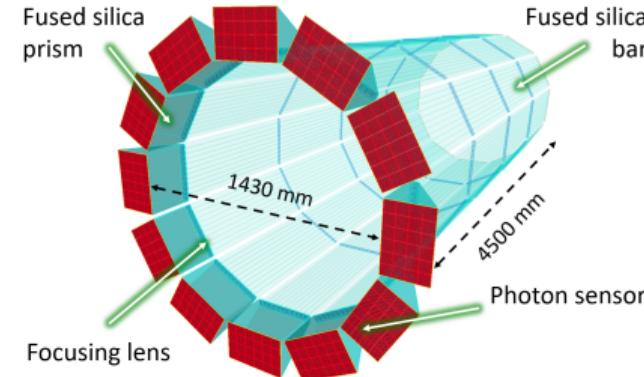
pfRICH



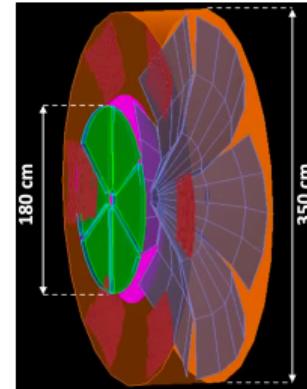
mRICH



hpDIRC



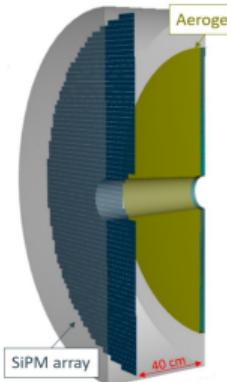
dRICH



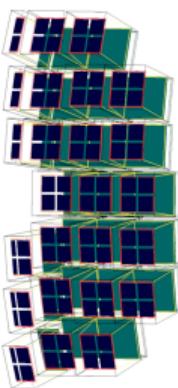
- Optimized for charged pion, kaon & proton separation
 - Particular focus on large η coverage
 - Complemented by calorimetry & TOF
 - Geometries optimized to fit ECCE baseline design while maintaining required performance
 - Two alternatives for backward region, pfRICH & mRICH
- ⇒ Global optimization process ongoing

Cherenkov-PID

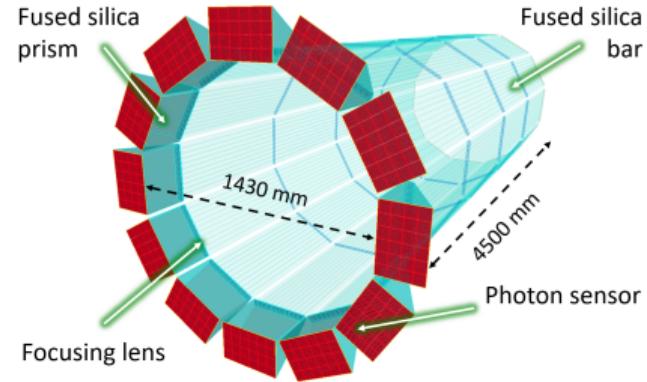
pfRICH



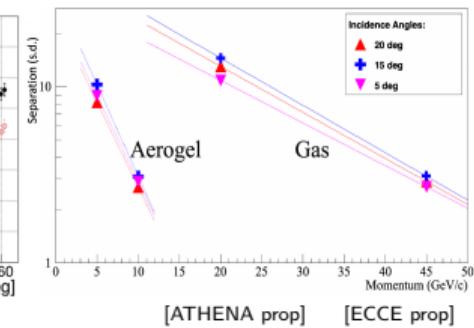
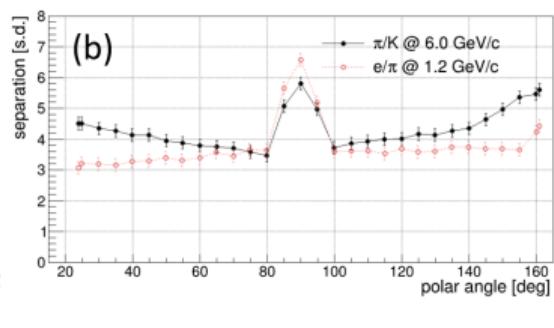
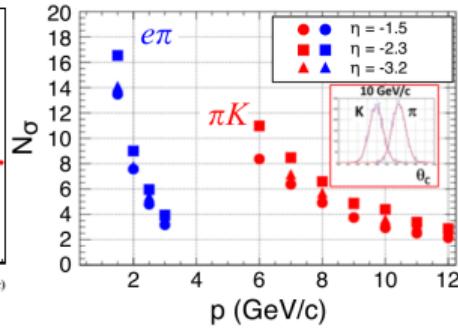
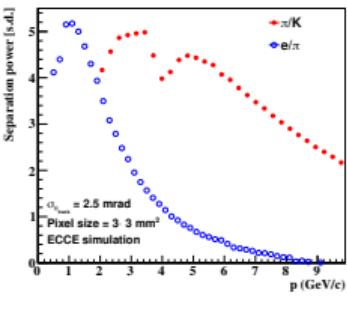
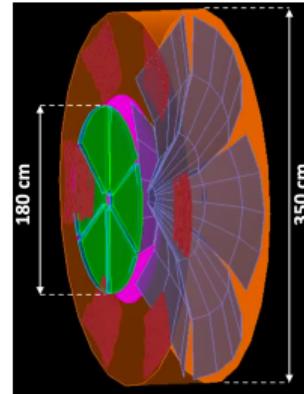
mRICH



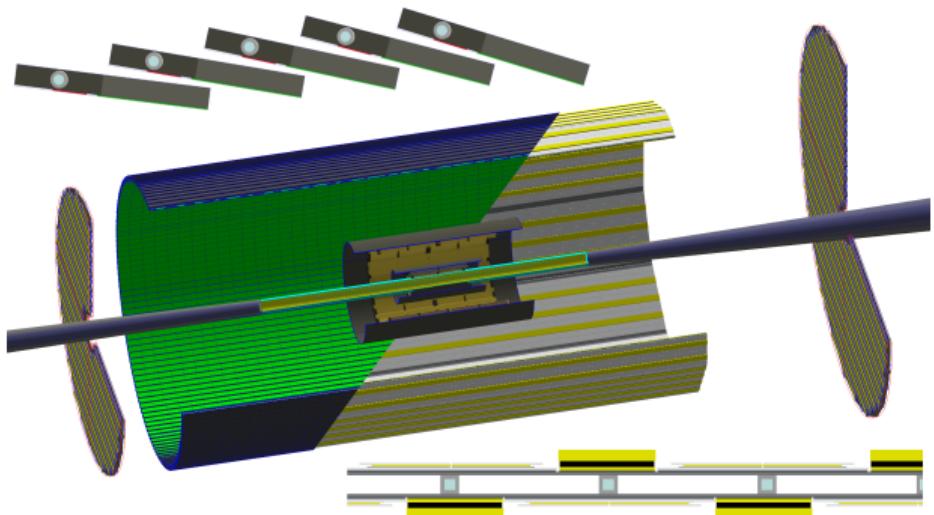
hpDIRC



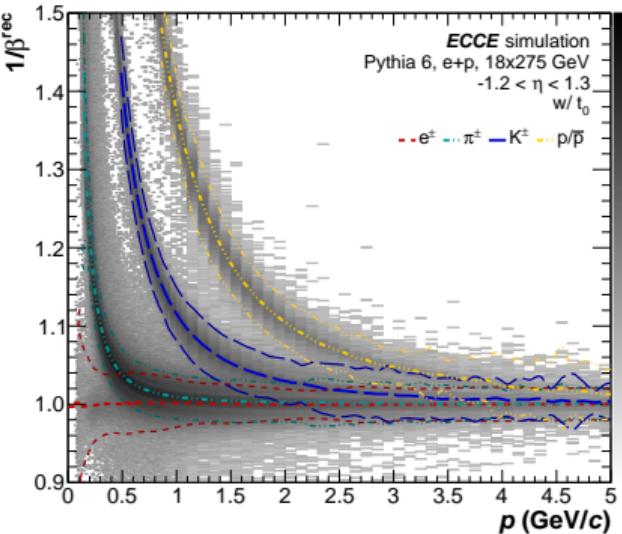
dRICH



Time of flight (TOF)

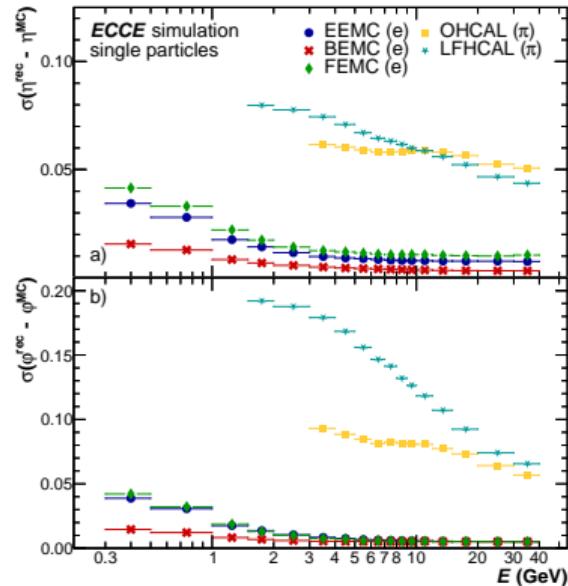
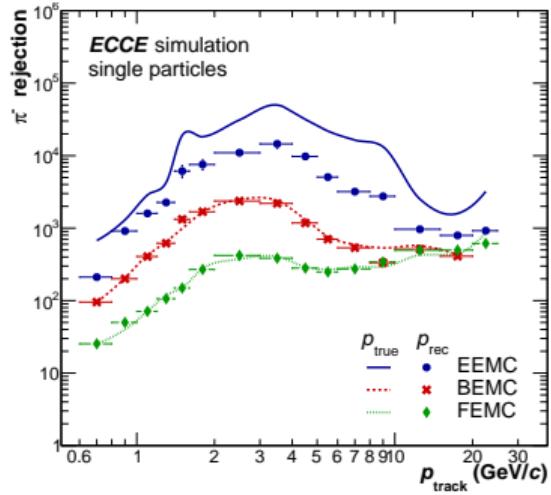
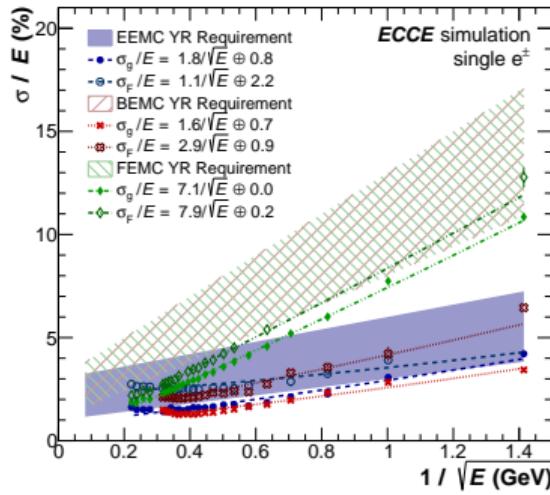


- Analog Coupled - Low Gain Avalanche Detectors (AC-LGADs) with **25 ps time resolution**
- Combined PID & tracking detector
- Positions optimized for low momentum e/π , π/K , K/p separation
- Full η -coverage for simultaneous start time determination
- Alternative barrel design with less X/X_0



PID	ETTL	CTTL	FTTL
e/π	< 0.5	< 0.45	< 0.6
π/K	< 2.1	< 1.3	< 2.2
K/p	< 3.3	< 2.2	< 3.7

Electromagnetic Calorimetry (1)



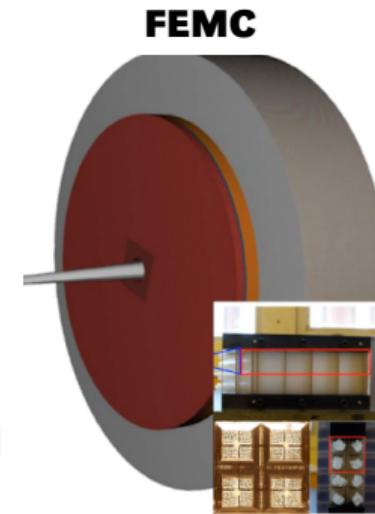
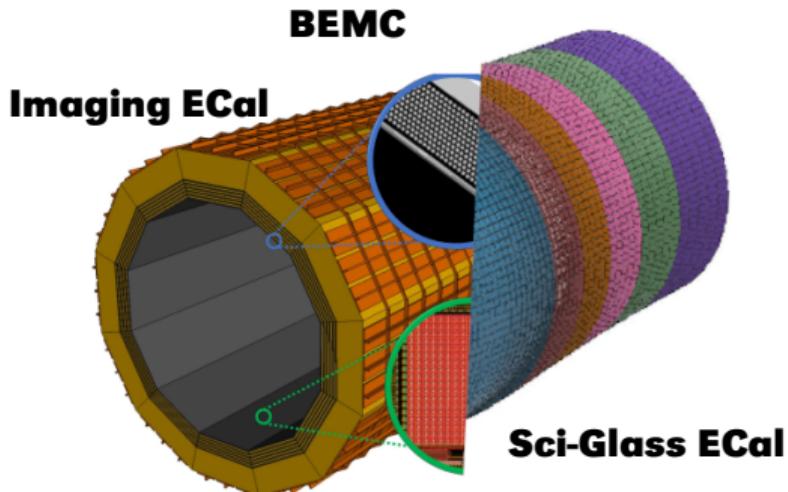
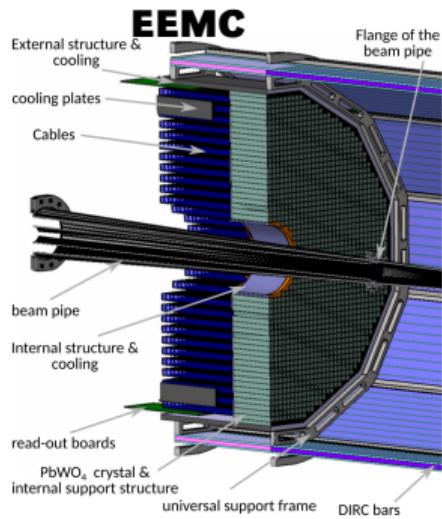
Optimization criteria

- Minimal acceptance gaps
- Scattered electron detection & identification (energy resolution & E/p)
- Shower separation within jets & good energy resolution (h-endcap)
- Most stringent constraints in e-endcap & barrel**
- h-endcap with high granularity & good energy resolution**

	EEMC	BEMC	FEMC
η	[−4 ... −1.8]	[−1.7 ... 1.3]	[1.3 ... 4]
σ_E/E	$2\%/\sqrt{E} + 1\%^*$	$2.5\%/\sqrt{E} + 1.6\%^*$	$7.1\%/\sqrt{E} + 0.3\%$

*Based on prototype beam tests and earlier experiments

Electromagnetic Calorimetry (2)



Endcap regions:

- **EEMC** - homogenous high resolution PbWO₄ crystal ECal
- **FEMC** - highly granular W-Scintilating Fiber calorimeter
 - modified ECCE design to improve resolution & reduce construction complexity

Barrel region - alternatives:

- **Sci-Glass**: homogenous, projective Sci-Glass ECal
- **Imaging**: 5 layers of 0.5x0.5mm Astro-Pix Silicon layers, interleaved with Pb-SciFi calorimeter

Hadronic Calorimetry

- Designed to complement tracking in Particle-Flow algorithm

- OHCAL/IHCAL**

- Fe/Scint sampling calorimeter
- partial sPHENIX re-use & magnet flux return

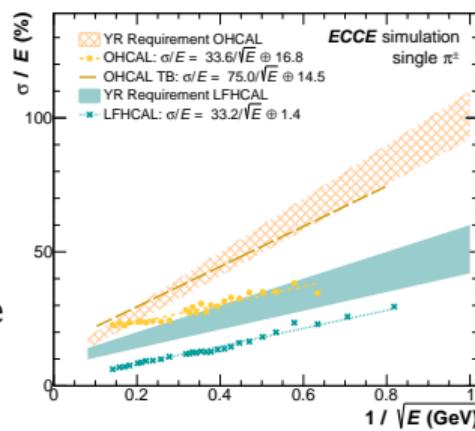
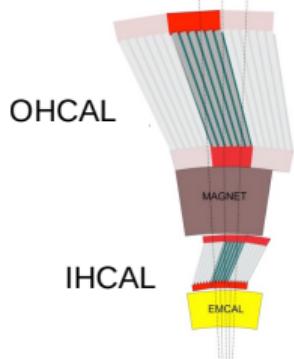
- LFHCAL**

- Fe/Scint & W/Scint sampling calorimeter
- Highly segmented (7 long. segments)
- W-segment as tail catcher

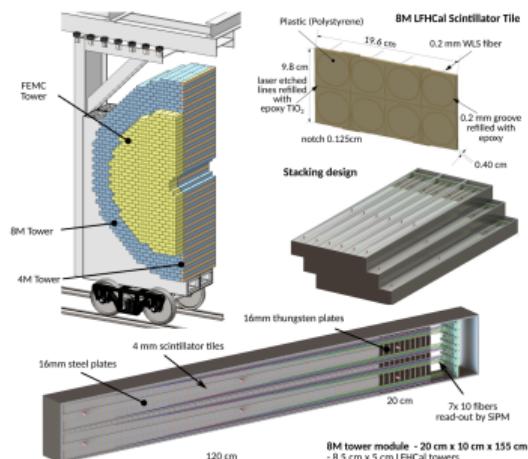
- High granularity inserts under discussion for forward E&HCal

- Electron end-cap HCal as upgrade option, no first day physics need

OHCAL+IHCAL



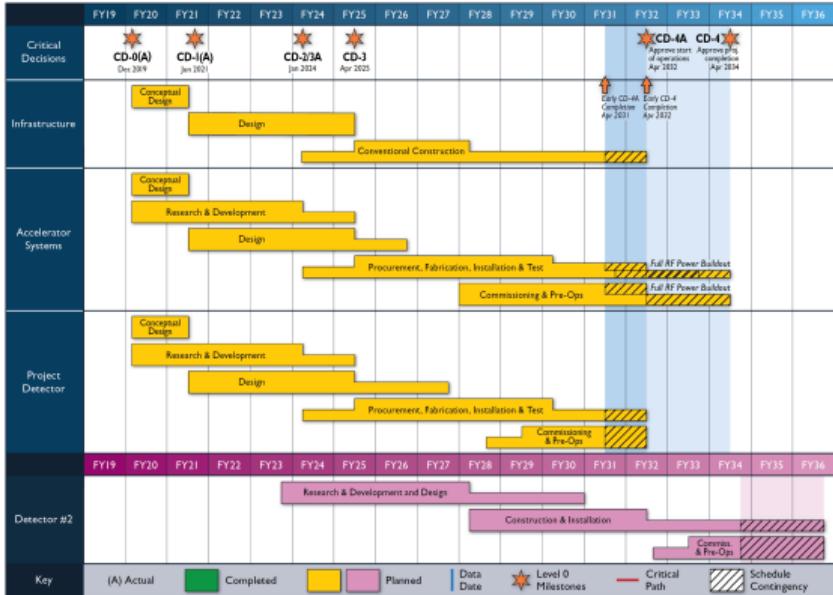
LFHCAL



Barrel HCal LFHCAL

η	[-1 .. 1]	[1 .. 4]
σ_E/E	$\sim 75\%/\sqrt{E} + 15\%^*$	$\sim 33\%/\sqrt{E} + 1.4\%$
depth	$\sim 4-5 \lambda_I$	$\sim 7-8 \lambda_I$

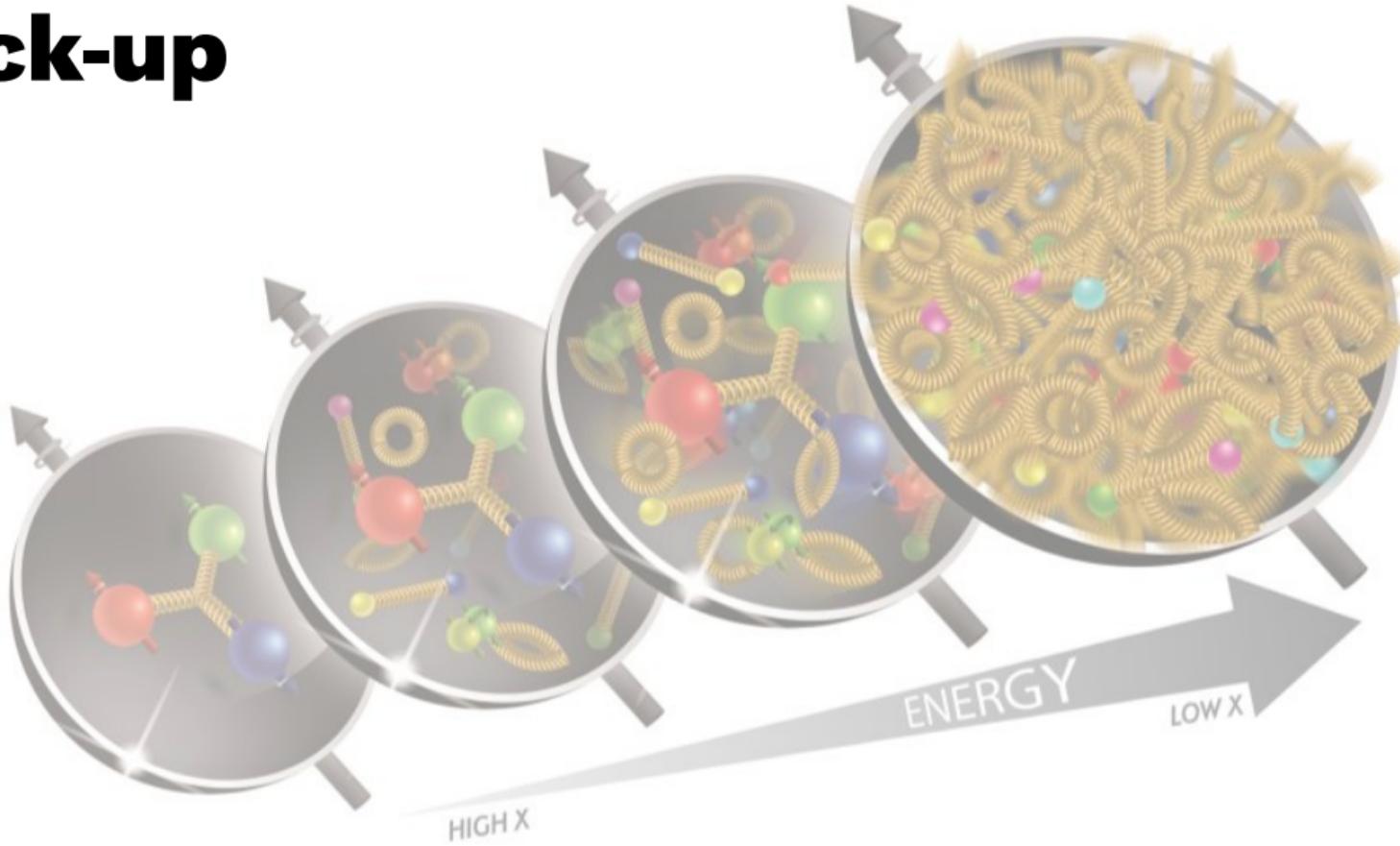
*Based on prototype beam tests and earlier experiments



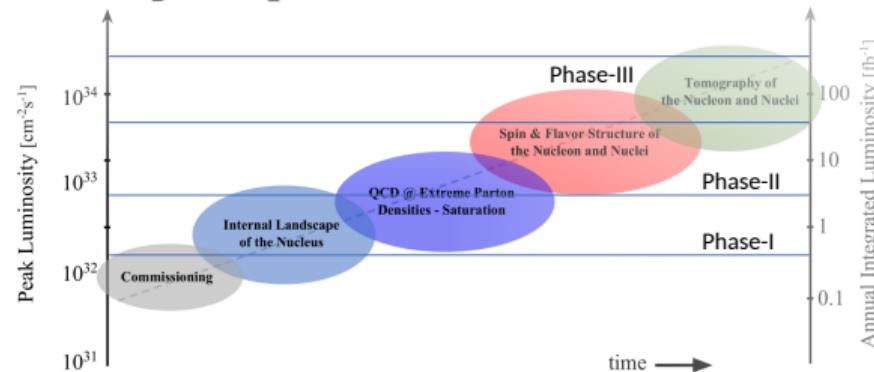
The EIC is coming! fast!



Back-up



Luminosity dependence - Main measurements



$\int L dt = 1 \text{ fb}^{-1}$

inclusive DIS

- measure scattered electron
- precision EM-Calorimetry
- multi-dimensional binning:
 x, Q^2
- maximize x, Q^2 coverage & determines interaction region design

10 fb^{-1}

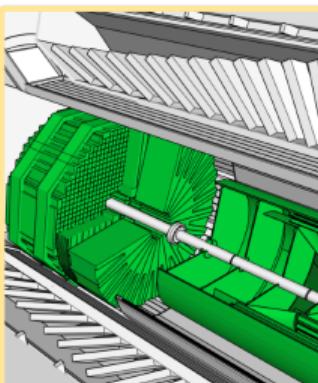
semi-inclusive DIS

- measure scattered electron in coincidence with identified hadrons
- multi-dimensional binning:
 x, Q^2, z, θ, p_T
- maximize PID detector coverage in whole phase space

$10\text{-}100 \text{ fb}^{-1}$

Exclusive processes

- measure all particles in event
- hermetic tracking + hadronic calorimetry
- multi-dimensional binning:
 x, Q^2, z, θ, p_T
- measure proton kinematics
- strong constraints on far-forward detector & interaction region



Backward Endcap

Tracking:

- ITS3 MAPS Si discs (x4)
- AC-LGAD

PID:

- mRICH
- AC-LGAD TOF
- PbWO₄ EM Calorimeter (EMEC)



Barrel

Tracking:

- ITS3 MAPS Si (vertex x3; sagitta x2)
- μ RWell outer layer (x2)
- AC-LGAD (before hpDIRC)
- μ RWell (after hpDIRC)

h-PID:

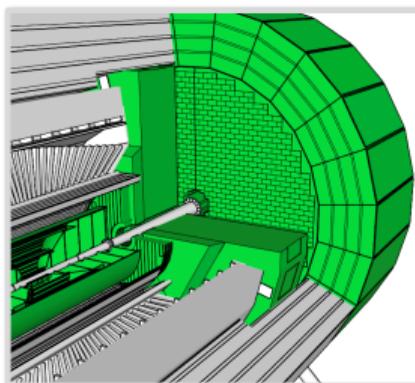
- AC-LGAD TOF
- hpDIRC

Electron ID:

- SciGlass EM Cal (BEMC)

Hadron calorimetry:

- Outer Fe/Sc Calorimeter (oHCAL)
- Instrumented frame (iHCAL)



Forward Endcap

Tracking:

- ITS3 MAPS Si discs (x5)
- AC-LGAD

PID:

- dRICH
- AC-LGAD TOF

Calorimetry:

- Pb/ScFi shashlik (FEMC)
- Longitudinally separated hadronic calorimeter (LHFCA)

EIC Comprehensive Chromodynamics Experiment

- Scientists from 98 international & US based institutions
- Objective:

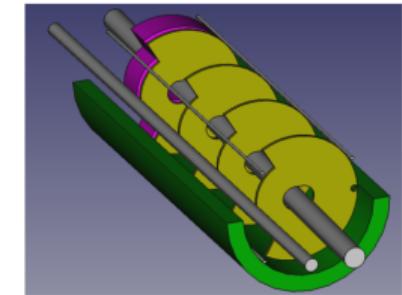
"Produce a purpose-built detector, designed to optimally deliver the full EIC science program by carefully balancing technology choices, costs and risk"

- Physics driven detector design choices with strong connection to YR
- Effective use of funds with minimized risks

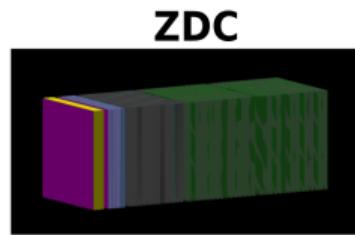
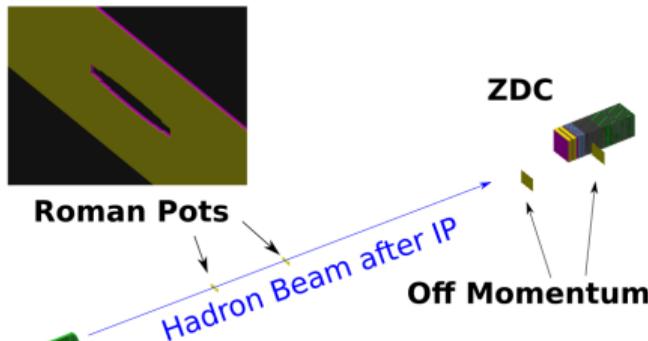
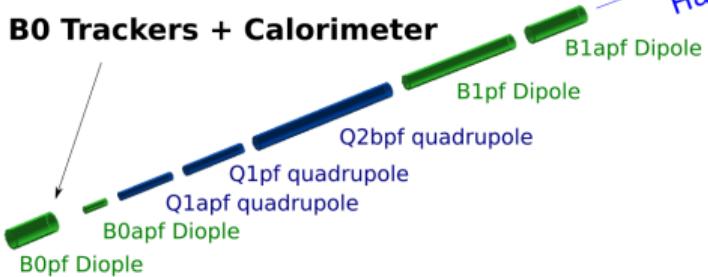
Chosen as reference detector 1 design Mar. 2022

CCCE

Far-forward Region



B0 Trackers + Calorimeter

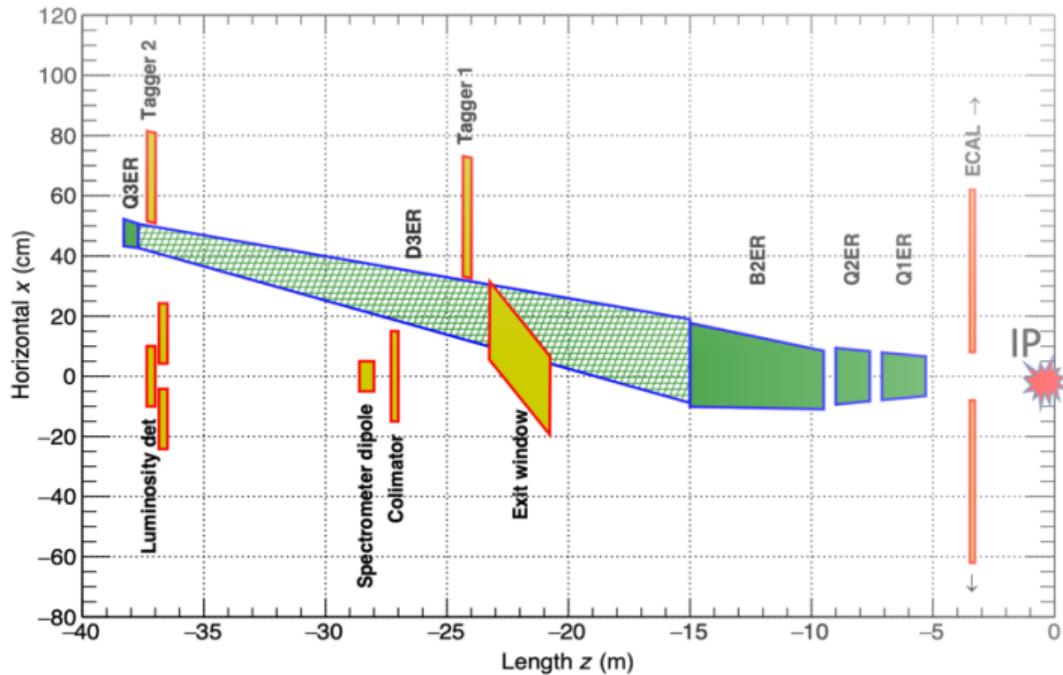


ZDC

- **B0 system** for charged-particle measurement in forward direction & neutral-particle tagging
- **off-momentum detectors** measure charged particles with different rigidity than the beam, e.g., those following decay and fission.
- **roman pot detectors** charged particles measurement close to beam envelope
- **zero-degree calorimeter** measures neutral particles at small angles.

Detector	(x,z) Position [m]	Dimensions	θ [mrad]	Notes
ZDC	(-0.96, 37.5)	(60cm, 60cm, 1.62m)	$\theta < 5.5$	~ 4.0 mrad at $\phi = \pi$
Roman Pots (2 stations)	(-0.83, 26.0) (-0.92, 28.0)	(30cm, 10cm)	$0.0 < \theta < 5.5$	10σ cut.
Off-Momentum Detector	(-1.62, 34.5), (-1.71, 36.5)	(50cm, 35cm)	$0.0 < \theta < 5.0$	$0.4 < x_L < 0.6$
B0 Trackers and Calorimeter	(x = -0.15, 5.8 < z < 7.0)	(32cm, 38m)	$6.0 < \theta < 22.5$	~ 20 mrad at $\phi=0$

Far-backward Region



- This area is designed to measure scattered electrons at small, far-backward angles
- Strong technology synergies with central detector systems
- **Low Q₂-tagger**
 - ▶ Double-layer AC-LGAD tracker at 24 & 37m from IP
 - ▶ PbWO₄ EMCAL (20cm x 2cm² crystals)
- **Luminosity Monitor**
 - ▶ AC-LGAD and PbWO₄ to provide accuracy of the order of 1% or relative luminosity determination exceeding 10^{-4} precision