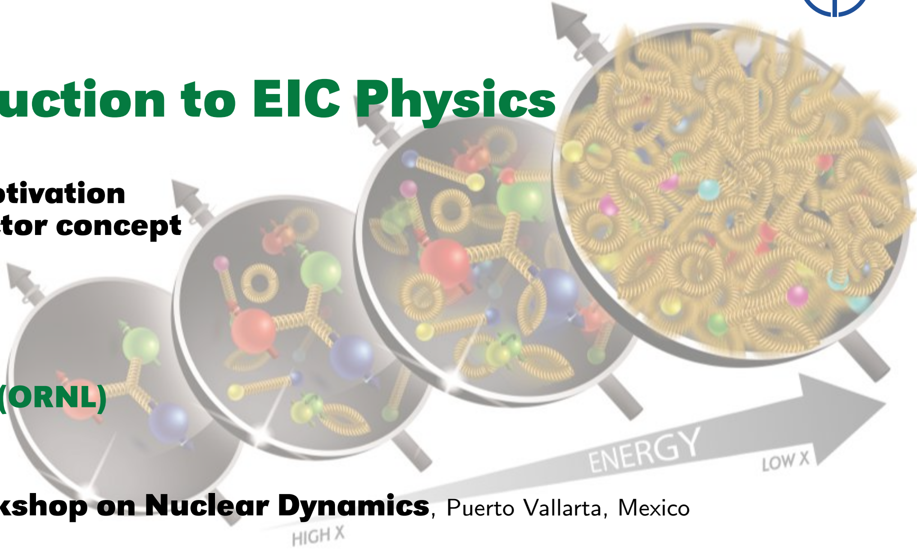
An Introduction to EIC Physics

From physics motivation
to a viable detector concept



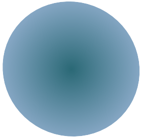
Friederike Bock (ORNL)
March 3, 2022

37th Winter Workshop on Nuclear Dynamics, Puerto Vallarta, Mexico

Back to the basics!

Where we are:

- Elastic lepton scattering determined the nucleon's charge & magnetism distributions in sphere with $\langle r_{ch} \rangle \approx 0.84$ 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

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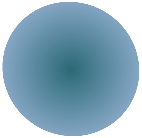

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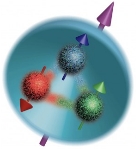
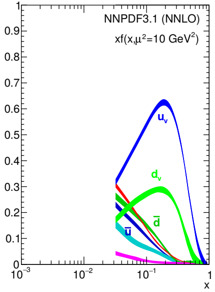


Proton
1975



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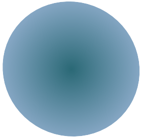

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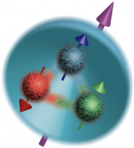

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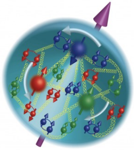
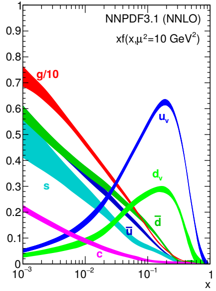


Proton
2015



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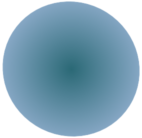

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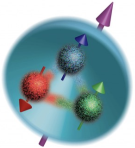

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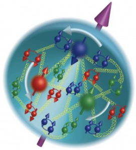

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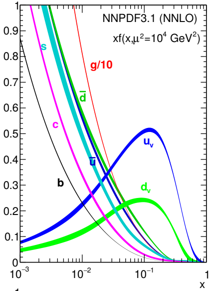
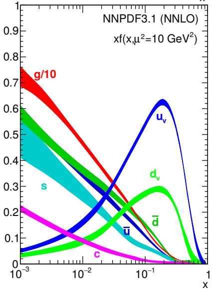
2015





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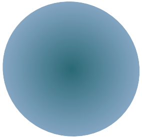

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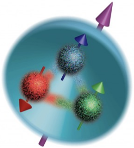

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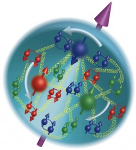

Proton
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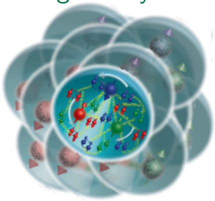
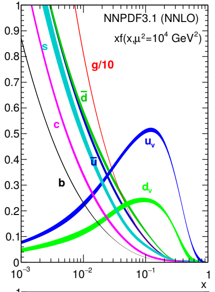
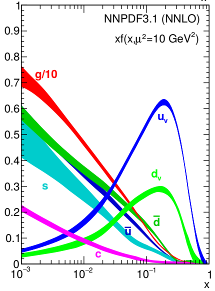


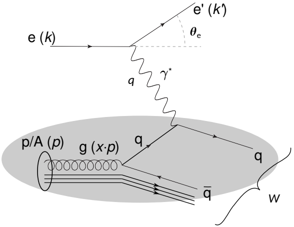
Proton
in a nucleus





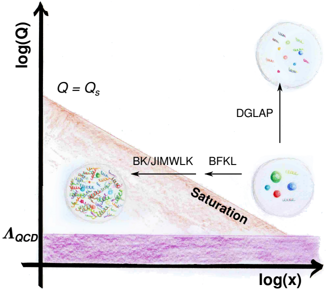
How did we learn this?

Deep Inelastic Scattering (DIS)

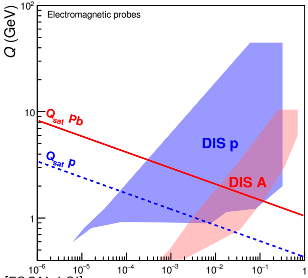


$$Q^2 = s \cdot x \cdot y$$

- 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



[FOCAL LOI]

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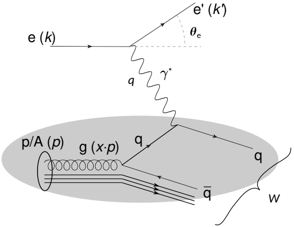

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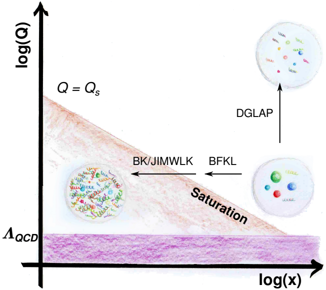

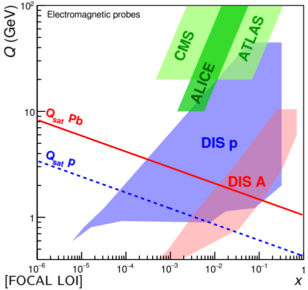

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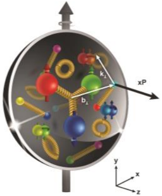
What we don't know yet

- 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?



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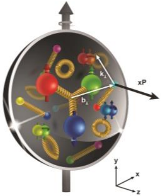

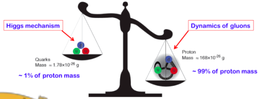

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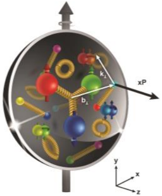

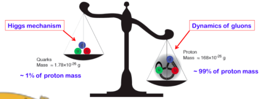

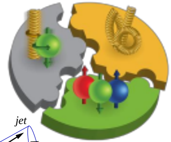

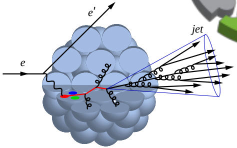

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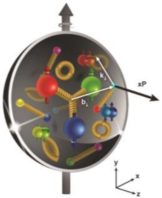

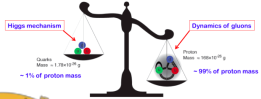

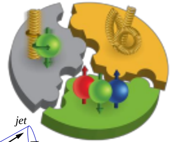

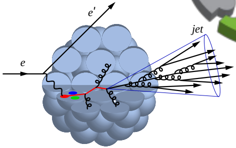

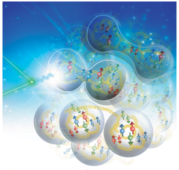

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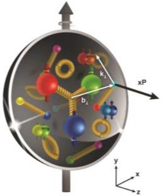

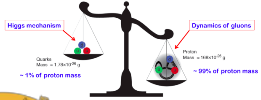

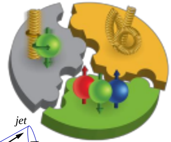

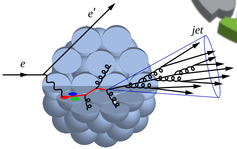

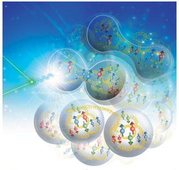

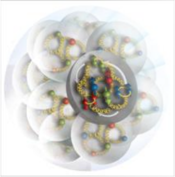

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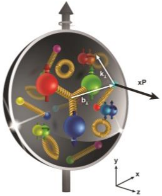

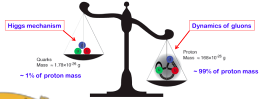

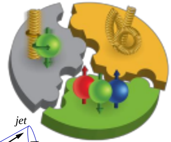

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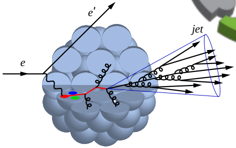
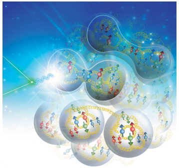
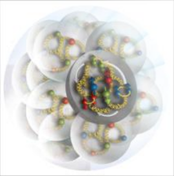
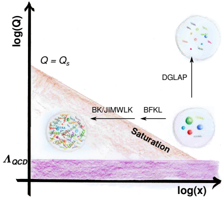








The Electron Ion Collider

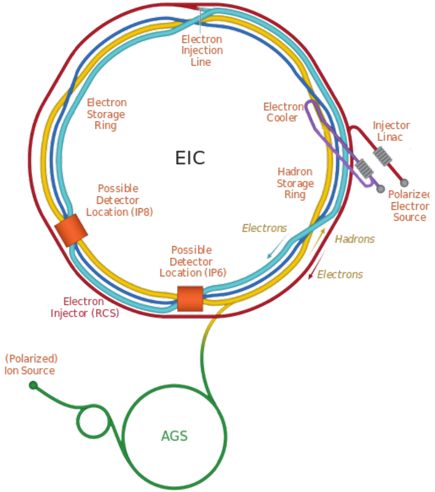
[EIC CDR]

General Facts

- **Location**: Brookhaven National Laboratory
- **Projected Budget**: ≈ $2.4 billion
- **Start date**: ≈ 2031

Machine parameters for EIC

- **Center-of-mass energy**: 20 - 140 GeV
  - electrons: 2.5 - 18 GeV
  - protons: 40- 275 GeV (ions: $Z/A \times E_p$)
- **Luminosity**: 10^{34} cm^{-2} s^{-1}
- **Polarization**: up to 70% (electron & ion)
- **Ion species**: p → U
- **Detectors**:
  - full coverage: 2
  - fixed target: 0

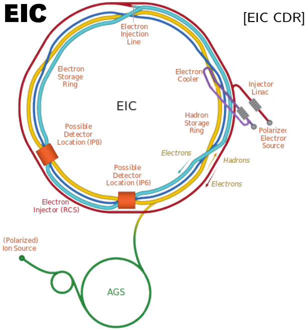


EIC vs HERA

Machine parameters

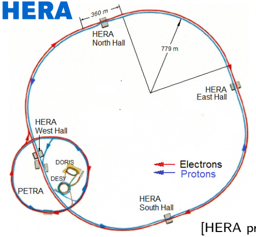
- **Center-of-mass energy**: 20 - 140 (218) GeV
  - electrons: 2.5 - 18 (27.5) GeV
  - protons: 40- 275 (920) GeV (ions: $Z/A \times E_p$)
- **Luminosity**: 10^{34} (10^{31}) cm^{-2} s^{-1}
- **Polarization**: up to 70% (electron & ion) (only electron)
- **Ion species**: p $\rightarrow$ U ($A > 1$ only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

EIC



[EIC CDR]

HERA



[HERA proposal]

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EIC will have:

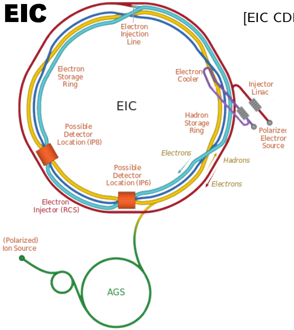
- lower energy
- broader energy range
- higher luminisity

\+ Hadron polarization

\+ Nuclear beams

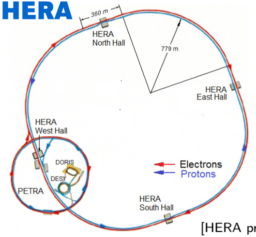
\+ Modern detector(s)

EIC



[EIC CDR]

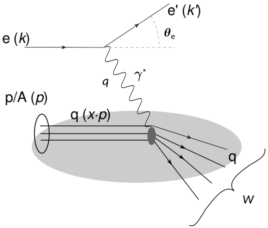
HERA



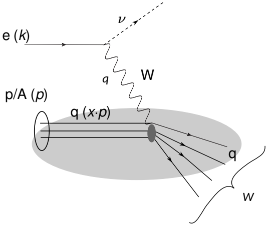
[HERA proposal]

How to access partons @ EIC

Neutral current (SI)DIS



Charged current DIS



Neutral current (SI)DIS

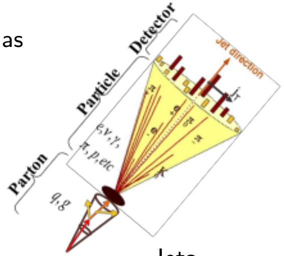
- Detect scattered lepton (DIS) in coincidence with identified hadrons (SIDIS)
  - measure correlation between different hadrons as fct. of p_T, z, η
  - needs FF to correlate hadron type with parton

Charged current DIS - W-exchange

- direct access to the quark flavor no FF – complementary to SIDIS

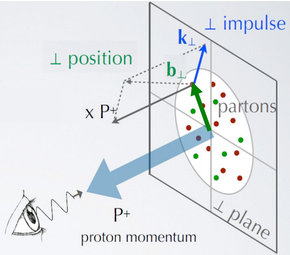
Jets

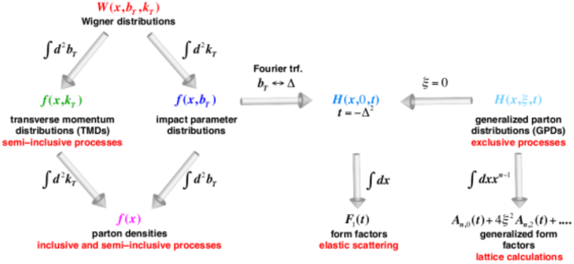
- best observable to access parton kinematics
- tag partons through the sub-processes and jet substructure
  - di-jets: relative $p_T \rightarrow$ correlated to k_T
  - tag on PDF



Jets

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

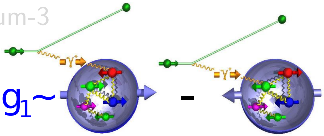
[EIC YR]

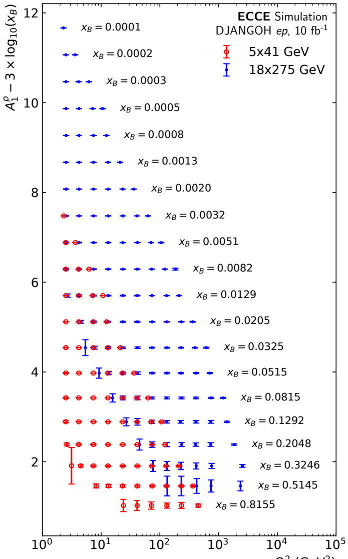
Nucleon Spin

total quark spin — gluon spin — angular momentum

$$\frac{1}{2}\hbar = \left\langle P, \frac{1}{2} | J^z_{QCD} | P, \frac{1}{2} \right\rangle = \underbrace{\frac{1}{2}\int_0^1 dx \Delta\Sigma(x,Q^2)}_{\text{total quark spin}} + \underbrace{\int_0^1 dx \Delta G(x,Q^2)}_{\text{gluon spin}} + \underbrace{\int_0^1 dx (\sum_q L^z_q + L^z_g)}_{\text{angular momentum}}$$

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





[ECCE prop]

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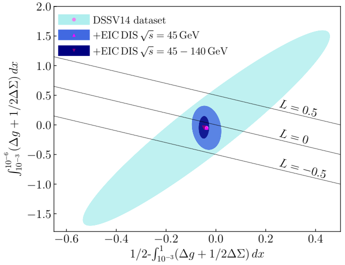
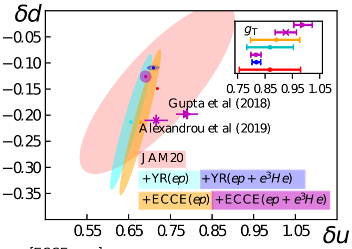
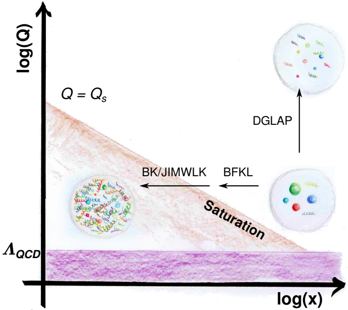
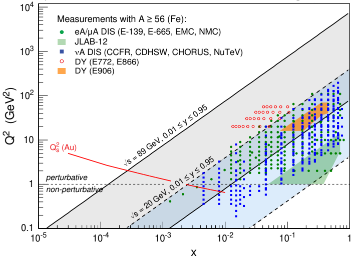




[ECCE prop]

Imaging the Nuclei





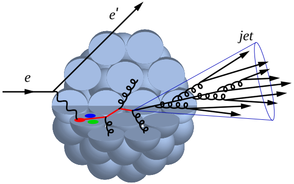
DGLAP

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

Saturation models

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

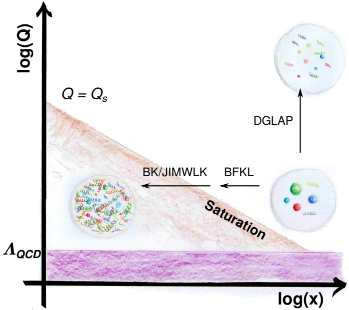
Need: large Q^2 lever-arm for fixed x, A-scan

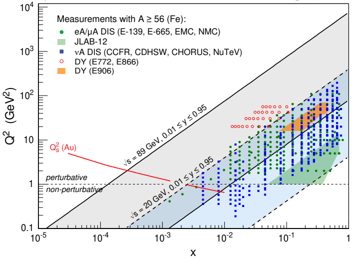


- Measure different structure function in eA → constrain nPDF
- Does the nucleus behave like a proton at low-x?
- Direct Access to gluons at medium to high x by tagging photon-gluon fusion using charm events

[EIC YR]

Imaging the Nuclei





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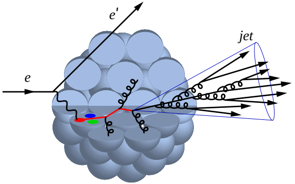

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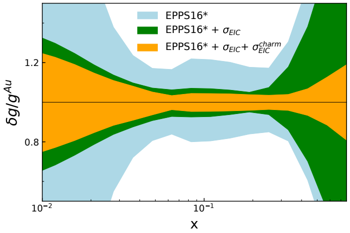
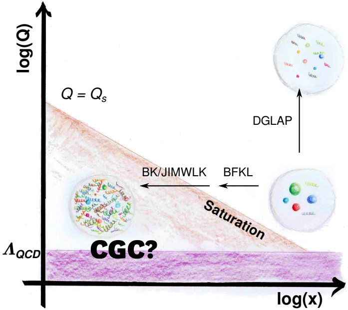


[EIC YR]

Color Glass Condensate?

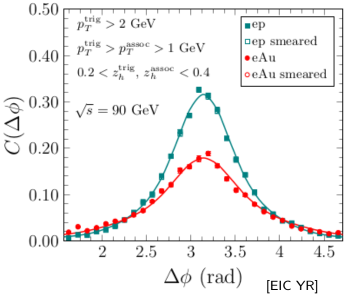


- e interacts over distances $L \sim (2mNx)^{-1}$
- For $L > 2R_A \sim A^{1/3}$ probe cannot distinguish between nucleons in front or back
- Probe interacts coherently with all nucleons

$\Rightarrow$ **Enhancement of Q_s with $A \to$ non-linear QCD regime reached at significantly lower energy in A than in proton**

Di-Hadron or Di-Jet Correlations

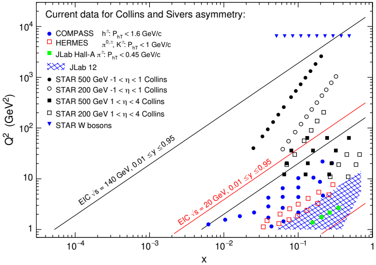
- Low p/A gluon n density (ep): pQCD $2 \to 2$ process predicts $\Rightarrow$ back-to-back di-jet
- High gluon density (eA): $2 \to$ many process $\Rightarrow$ expect broadening of away-side
- **EIC allows to study the evolution of Q_s with x**



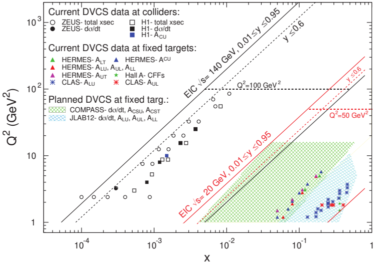
[EIC YR]

Kinematic Coverage

DIS

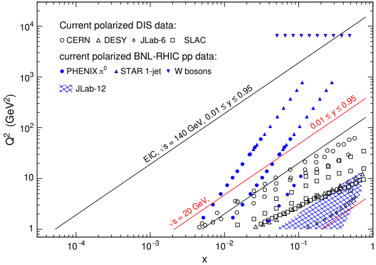


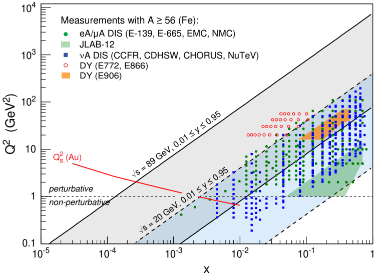
SIDIS



DVCS

[EIC YR]

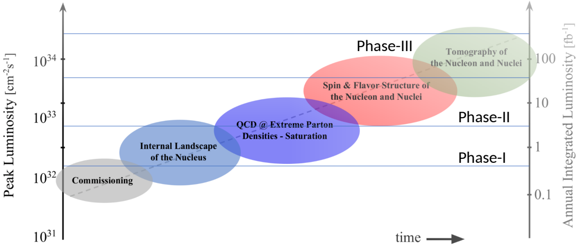




Accelerator gives access to extensive kinematic range

⇒ Now we need a detector to match

Luminosity dependence - Main measurements



design luminosity:

$L = 10^{34}$ cm^{-2} s^{-1}

$\int$ Ldt $= 100$ fb^{-1} per year

$\int$ Ldt **1 fb^{-1}**

inclusive DIS

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

10 fb^{-1}

semi-inclusive DIS

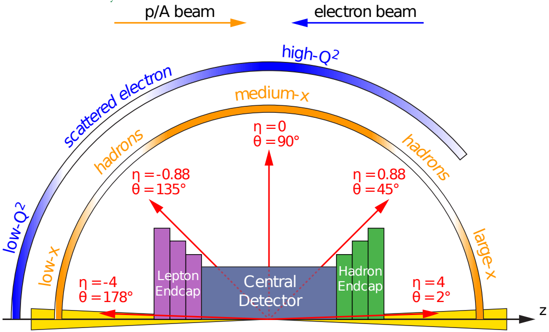
- measure scattered electron in coincidence with identified hadrons
- multi-dimensional binning: x, Q^2, z, θ, p_T
- → maximize PID detector coverage in whole phase space

10-100 fb^{-1}

Exclusive processes

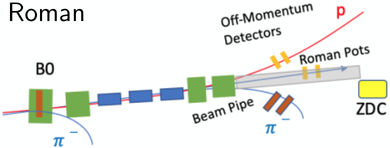
- measure all particles in event
- → hermetic tracking + hadronic calorimetry
- multi-dimensional binning: x, Q^2, z, θ, p_T
- measure proton kinematics
- → strong constraints on far-forward detector & interaction region

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 seperation

- 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 if systematics
  luminisity monitors, electron & hadron polarimetry

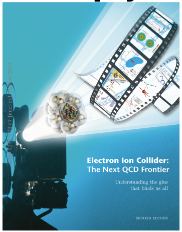


Highly integrated design between detector and machine for IR

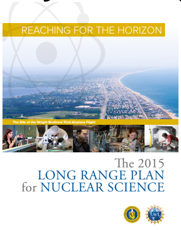
[EIC YR]

The detector design process

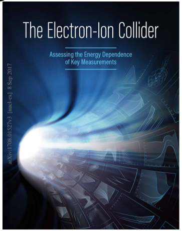
Define physics objectives & generic machine/detector parameters



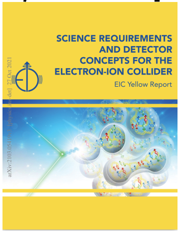
2012



2015

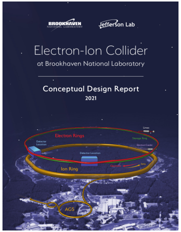


2017

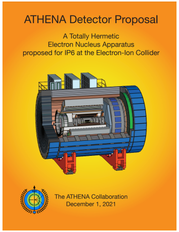


2020

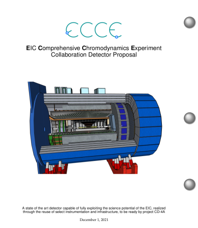
Realistic machine & detector concepts



Feb. 2021

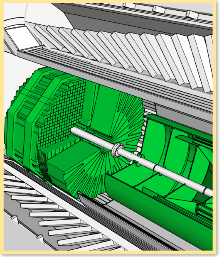


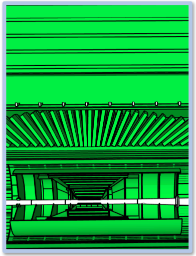
Dec. 2012

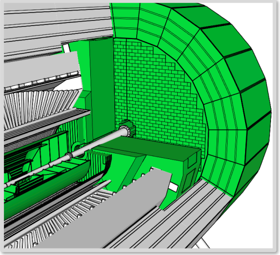


- Detector & machine design driven by physics objectives
- NSAC recommendation: "... a high-energy high-luminosity polarized EIC ... highest priority for new facility construction ..."
- Jan. 2020: BNL site selection
- Extensive generic detector R&D for EIC for PID, tracking & calorimetry
- YR outlines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

ECCE







Backward Endcap

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

PID:
- mRICH
- AC-LGAD TOF
- $PbWO_4$ EM Calorimeter (EEMC)

Barrel

Tracking:
- ITS3 MAPS Si (vertex x3; sagitta x2)
- μRWell outer layer (x2)
- AC-LGAD (before hpDIRC)
- μRWell (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

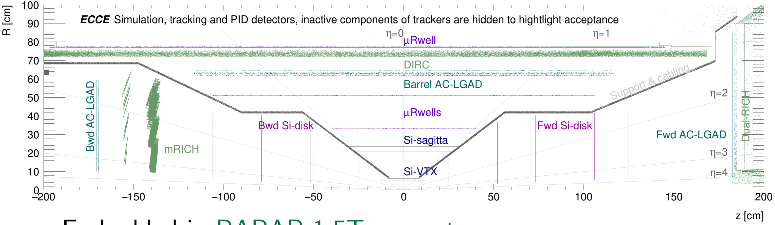
Calorimetry:
- Pb/ScFi shashlik (FEMC)
- Longitudinally separated hadronic calorimeter (LHFCAL)

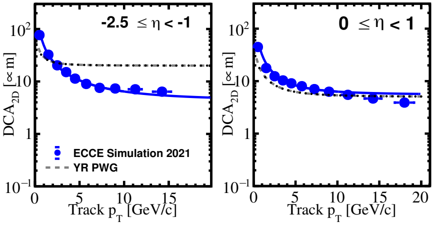
EIC Comprehensive Chromodynamics Experiment

- Scientiest 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

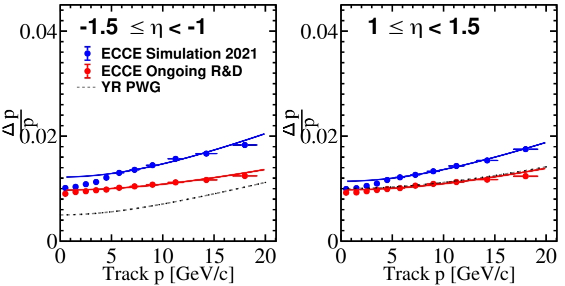
[ECCE prop]

Tracking





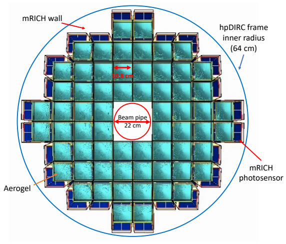
- Embedded in BABAR 1.5T magnet
- Mid-rapidity: Ultra thin MAPS based Si-detectors, μRwells & AC-LGAD detectors
- Forward and Backward: MAPS based Silicon discs & AC-LGAD detectors
- AI-Assisted optimization of placement of tracking layers & support reduction
- Outer layers placed to provide ideal track points before/after PID detectors



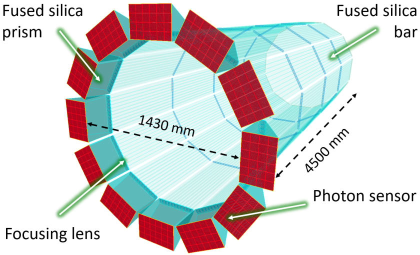
[ECCE prop]

Cherenkov-PID

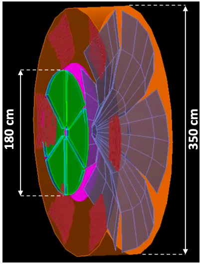
mRICH



hpDIRC



dRICH

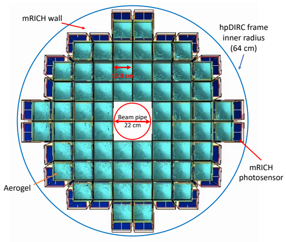


- Optimized for charged pion, kaon & proton separation
- Complemented by calorimetery & TOF
- Geometries optimized to fit ECCE baseline design while maintaining required performance
- Particular focus on large η coverage

[ECCE prop]

Cherenkov-PID

mRICH



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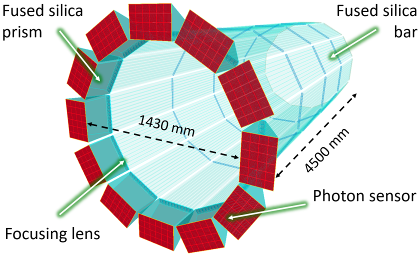

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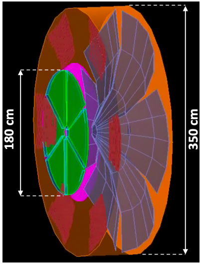
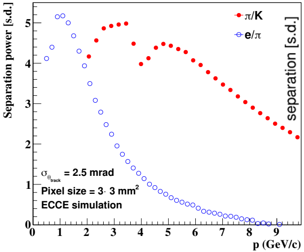
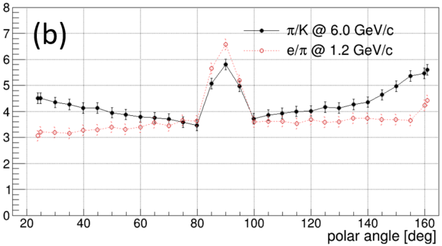
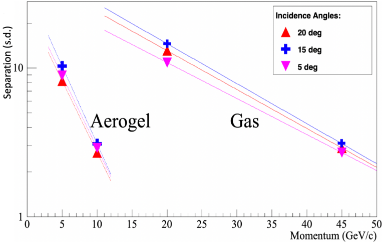


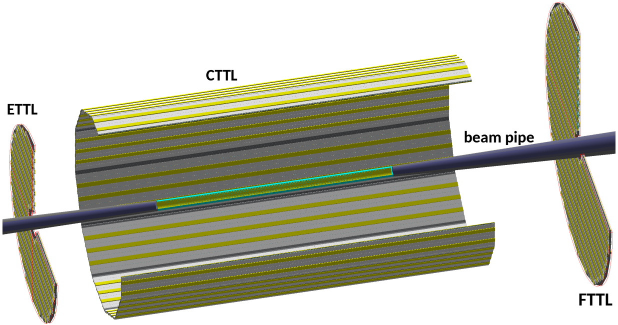


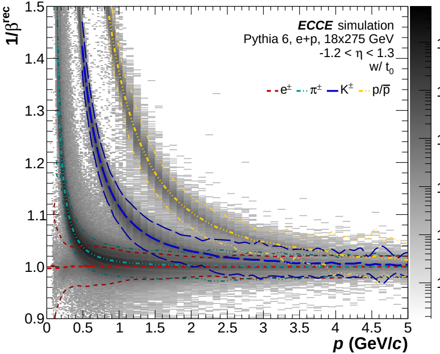




[ECCE prop]

Time of flight (TOF)





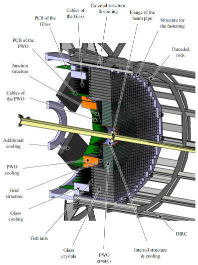
- Analog Coupled - Low Gain Avalanche Detectors (AC-LGADs) with 25 ps time resolution resolution
- Combined PID & tracking detector
- Positions optimized for low momentum e/π, π/K, K/p separation
- Full η-coverage for simultaneous start time determination

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

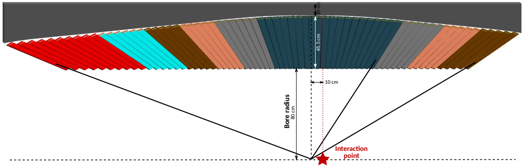
[ECCE prop]

Electromagnetic Calorimetery

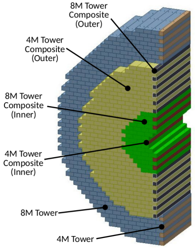
EEMC



BEMC



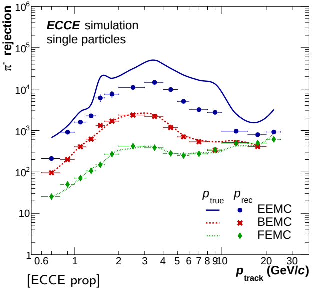
FEMC



	EEMC	BEMC	FEMC
η	[-4 .. -1.8]	[-1.7 .. 1.3]	[1.3 .. 4]
σ_E/E	2%/√E+1%*	2.5%/√E+1.6%*	7.1%/√E+0.3%

*Based on prototype beam tests and earlier experiments

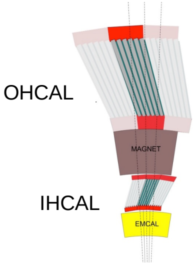
- **EEMC** - homogenous high resolution $PbWO_4$ crystal ECal
- **BEMC** - homogenous, projective Sci-Glass ECal
- **FEMC** - high granular shashlik Pb/Scint sampling ECal, integrated within module LFHCAL
- Minimized acceptance gaps
- EEMC/BEMC optimized for scattered electron detection
- FEMC optimized for shower separation within jets

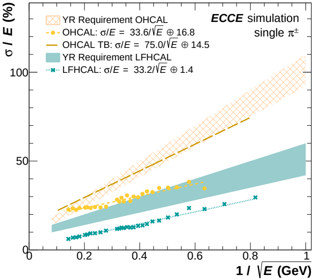


Hadronic Calorimetery

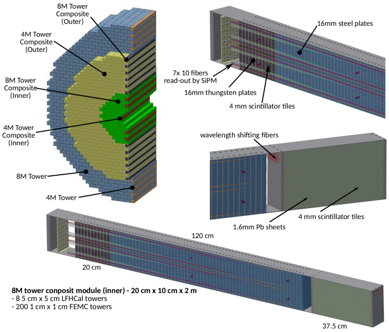
- Designed to complement tracking in Particle-Flow algorithm
- **OHCAL/IHCAL**
  - Fe/Scint sampling calorimeter
  - partial sPHENIX re-use & magnet flux return
- **LFHCAL**
  - Fe/Scint & W/Scint sampling calorimeter
  - highly segmented (7 long. segments) & integrated with FEMC for support material reduction
  - W-segment as tail catcher
- No electron end-cap HCAL, no strong enough physics motivation

OHCAL+IHCAL





LFHCAL

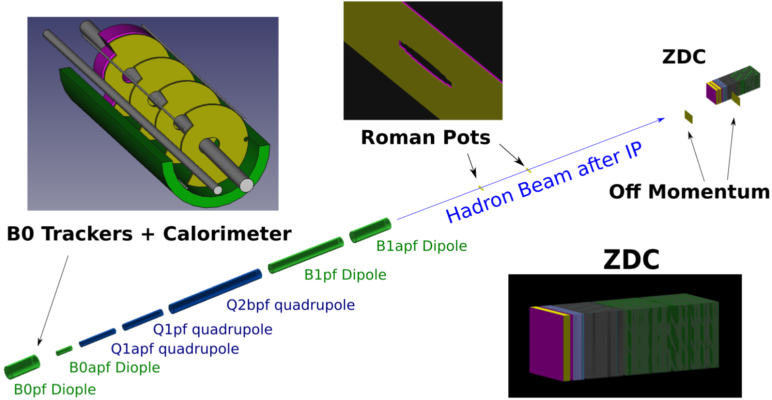


	Barrel HCal	LFHCAL
η	[-1 .. 1]	[1 .. 4]
σ_E/E	~75%/√E + 15%*	~33%/√E + 1.4%
depth	~4-5 λ_I	~7-8 λ_I

*Based on prototype beam tests and earlier experiments

[ECCE prop]

Far-forward Region

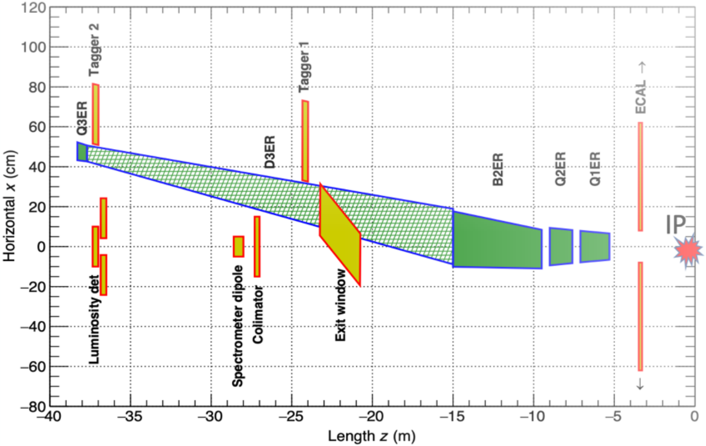


- **B0 system** for charged-particle measurement in forward direction & neutral-particle tagging
- **off-momentum detectors** measure charged particles with different rigidity than the beam, e.g., those following decay and fission.
- **roman pot detectors** charged particles measurement close to beam 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)	$\theta < 5.5$	$\sim$4.0 mrad at $\phi = \pi$
Roman Pots (2 stations)	(-0.83, 26.0) (-0.92, 28.0)	(30cm, 10cm)	$0.0 < \theta < 5.5$	$10\,\sigma$ 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)	$6.0 < \theta < 22.5$	$\sim$20 mrad at ϕ=0

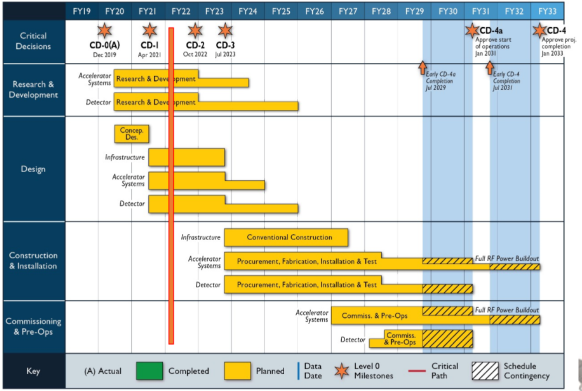
[ECCE prop]

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

[EIC YR] [ECCE prop]



The EIC is coming! fast!

Exiting times ahead!

Thank you!