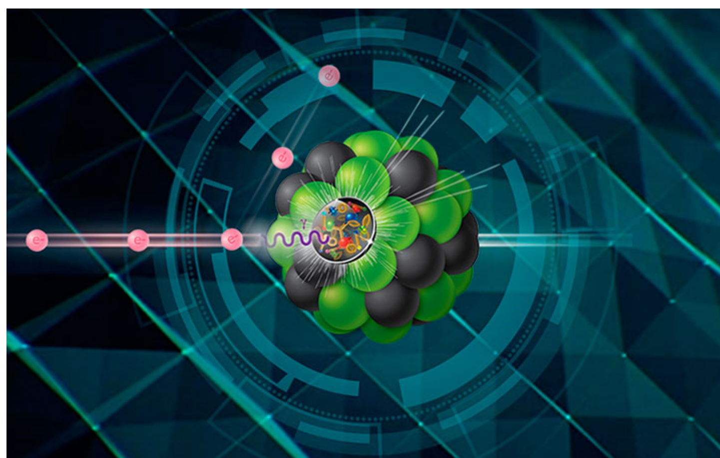
ePIC
(electron-Proton/Ion Collider)
Detector and Collaboration

Bernd Surrow

(surrow@temple.edu)

TEMPLE UNIVERSITY

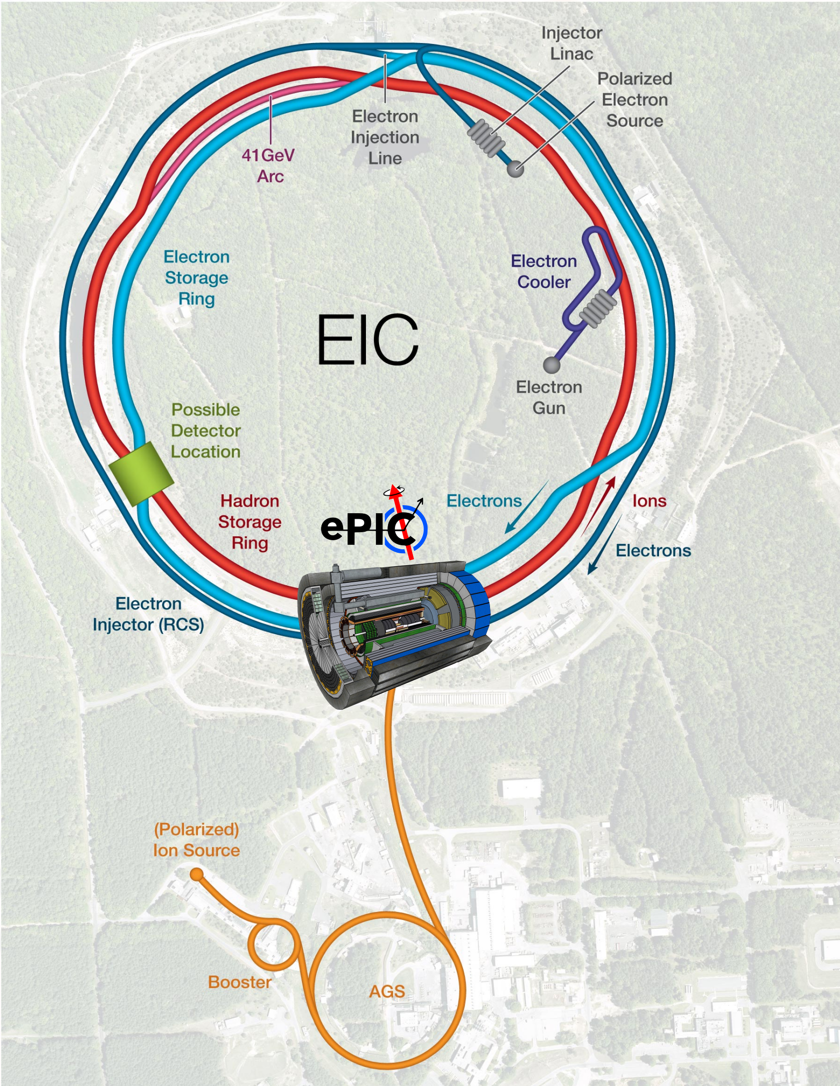


U.S. DEPARTMENT OF ENERGY Office of Science

DOE NP contract: DE-SC0013405

Outline

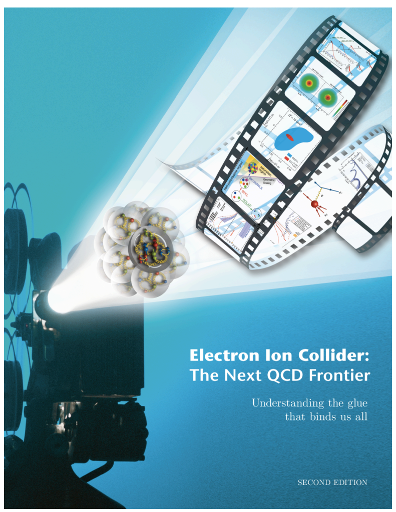
- EIC Project Development
- Selected EIC Physics Pillars ➜ Low-x Physics
- ePIC Detector Layout
- ePIC Collaboration
- Summary And Next Steps



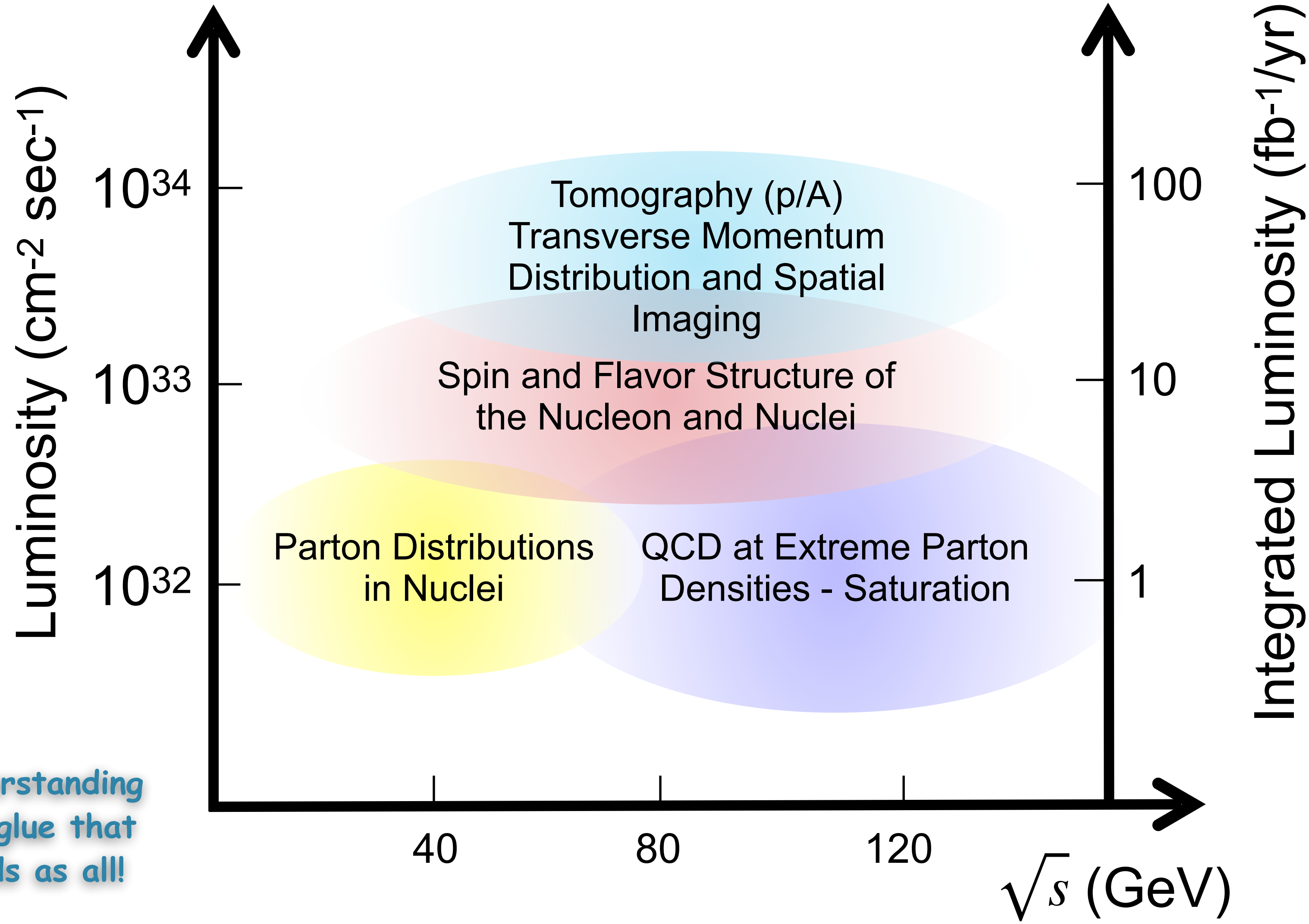
EIC Project Development

- EIC: Study structure and dynamics of matter at high luminosity, high energy with polarized beams and wide range of nuclei
- Whitepaper:

arXiv:1212.1701

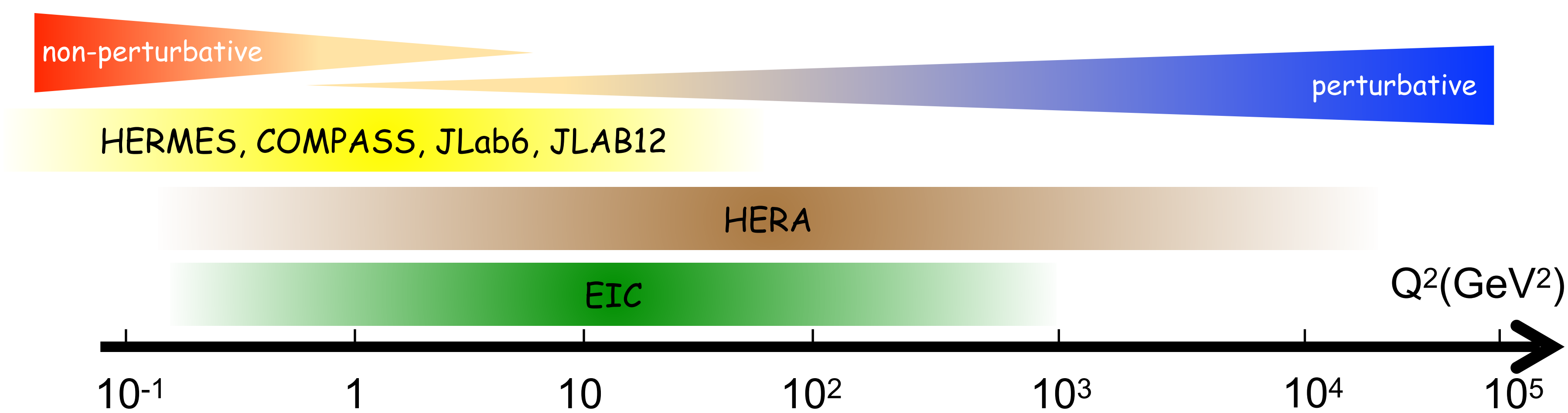


Understanding the glue that binds as all!



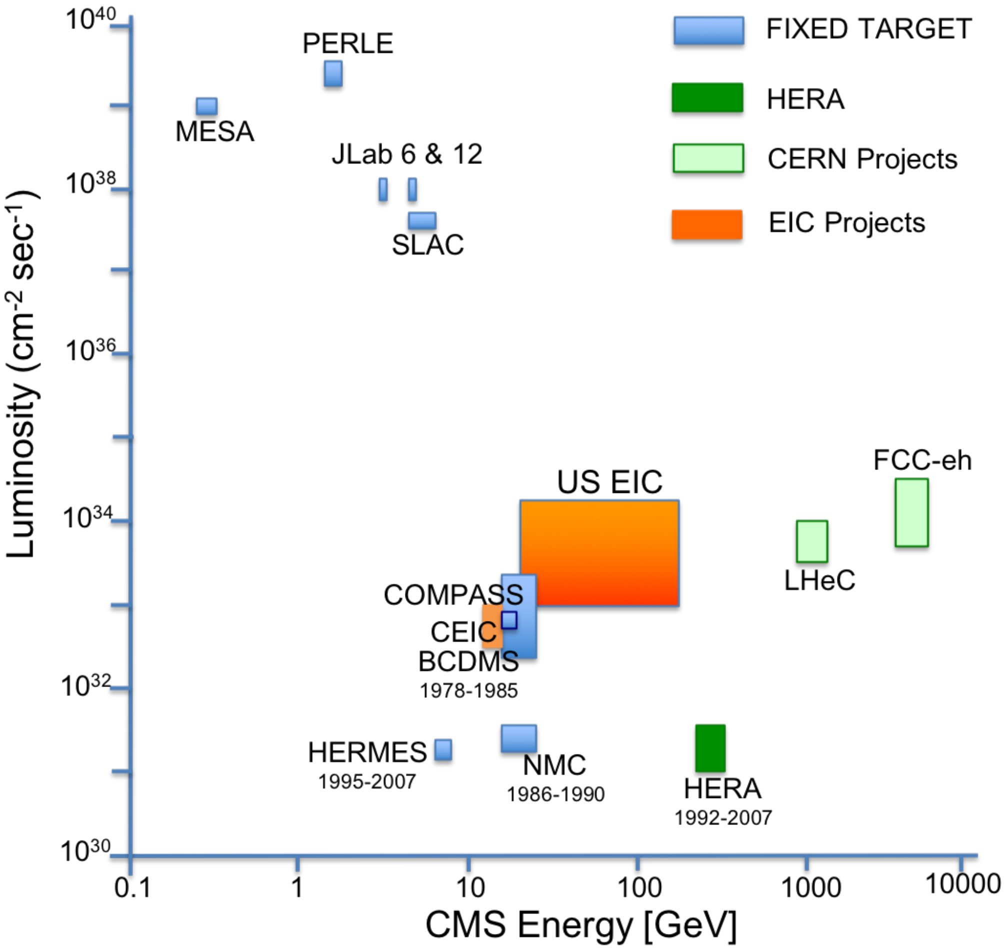
EIC Project Development

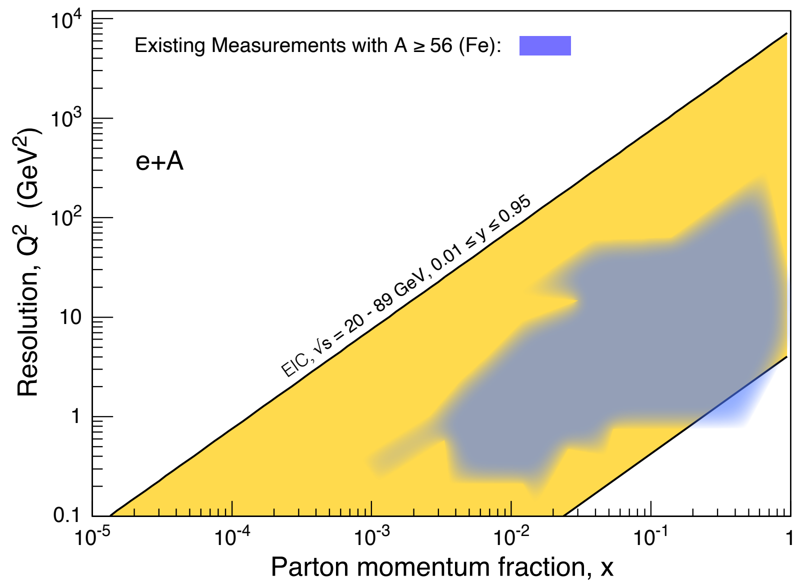
- Requirements
  - Machine:
    - High luminosity: $10^{33}cm^{-2}s^{-1}$ - $10^{34}cm^{-2}s^{-1}$
    - Flexible center-of-mass energy $\sqrt{s} = \sqrt{4 E_e E_p}$: Wide kinematic range $Q^2 = s\,x\,y$
    - Highly polarized electron (0.8) and proton / light ion (0.7) beams: Spin structure studies
    - Wide range of nuclear beams (d to Pb/U): High gluon density
  - Detector:
    - Wide acceptance detector system including particle ID (e/h separation & π, K, p ID - flavor tagging)
    - Instrumentation for tagging of protons from elastic reactions and neutrons from nuclear breakup: Target / nuclear fragments in addition to low Q^2 tagger / polarimetry and luminosity (abs. and rel.) measurement



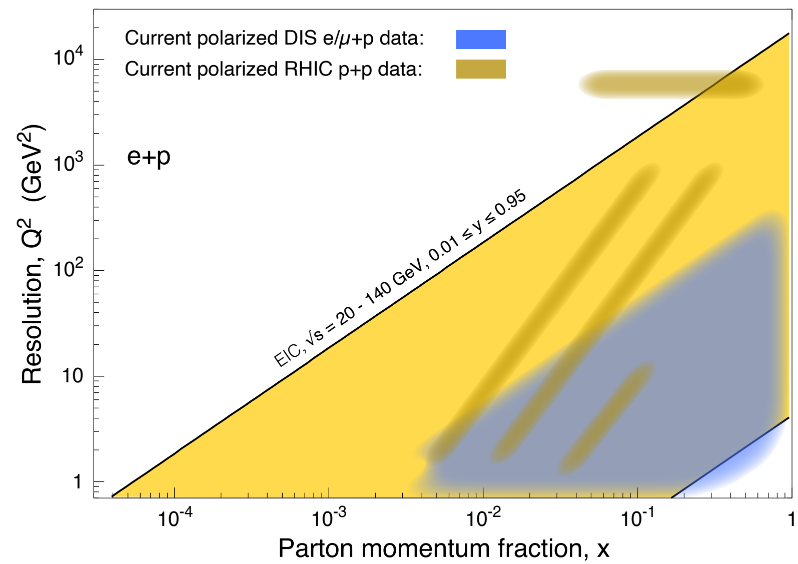
EIC Project Development

- Luminosity / $\sqrt{s}$ / Kinematic coverage





eA



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EIC Project Development

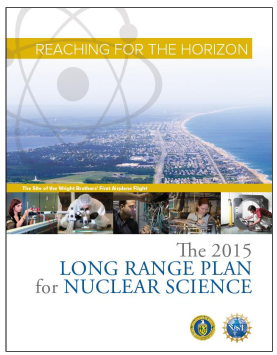
- Critical steps over the last couple of years
  - INT Workshop series / Documentation of Physics Case - Whitepaper: "Understanding the glue that binds us all!"
    - INT Workshop: 2010
    - WP: 2012, updated in 2014 for LRP
  - 2015 Long-range plan (LRP):

T. Hallman

The 2015 Long Range Plan for Nuclear Science

Recommendations:

1. Capitalize on investments made to maintain U.S. leadership in nuclear science.
2. Develop and deploy a U.S.-led ton-scale neutrino-less double beta decay experiment.
3. Construct a high-energy high-luminosity polarized electron-ion collider (EIC) as the highest priority for new construction following the completion of FRIB.
4. Increase investment in small-scale and mid-scale projects and initiatives that enable forefront research at universities and laboratories.

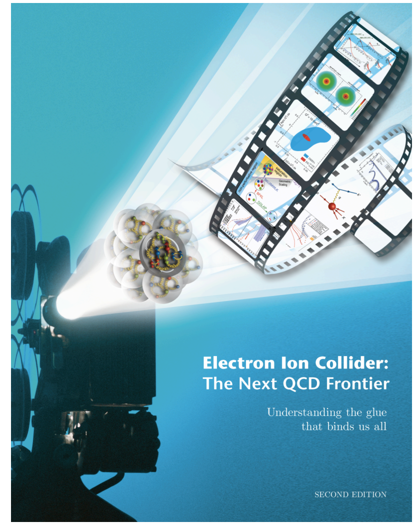


The FY 2018 Request supports progress in important aspects of the 2015 LRP Vision

U.S. DEPARTMENT OF ENERGY | Office of Science   NSAC Meeting   June 2, 2017   16

  - Request to review EIC Science Case by National Academy of Sciences, Engineering, and Medicine (NAS)

arXiv:1212.1701



Understanding the glue that binds as all!

T. Hallman

Next Formal Step on the EIC Science Case is Continuing

THE NATIONAL ACADEMIES OF SCIENCES, ENGINEERING, AND MEDICINE
Division on Engineering and Physical Science
Board on Physics and Astronomy
U.S.-Based Electron Ion Collider Science Assessment

Summary
The National Academies of Sciences, Engineering, and Medicine ("National Academies") will form a committee to carry out a thorough, independent assessment of the scientific justification for a U.S. domestic electron ion collider facility. In preparing its report, the committee will address the role that such a facility would play in the future of nuclear science, considering the field broadly, but placing emphasis on its potential scientific impact on quantum chromodynamics. The need for such an accelerator will be addressed in the context of international efforts in this area. Support for the 18-month project in the amount of $540,000 is requested from the Department of Energy.

"U.S.-Based Electron Ion Collider Science Assessment" is now getting underway. The Chair will be Gordon Baym. The rest of the committee, including a co-chair, will be appointed in the next couple of weeks. The first meeting is being planned for January, 2017

U.S. DEPARTMENT OF ENERGY | Office of Science   NSAC Meeting   June 2, 2017   19

EIC Project Development

- NAS Webinar and NAS report release: 07/24/2018

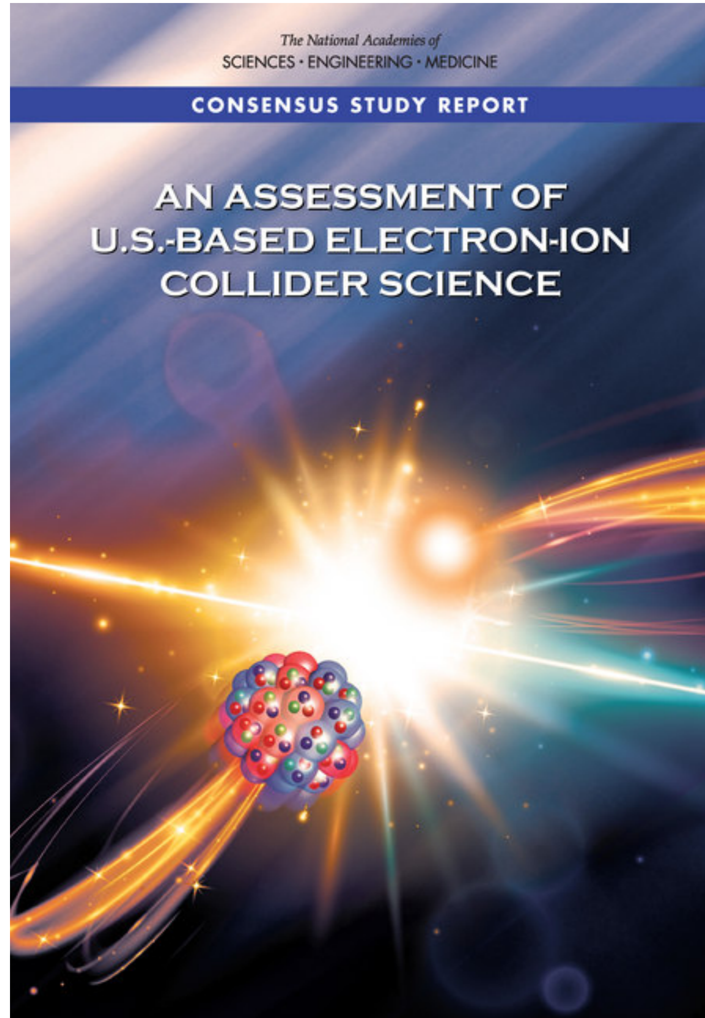
https://www.nap.edu/catalog/25171/an-assessment-of-us-based-electron-ion-collider-science

Download pdf-file of final report!

- Webinar on Tuesday, July 24, 2018 - Public presentation and report release
- Gordon Baym (Co-chair): Webinar presentation

"The committee finds that the science that can be addressed by an EIC is compelling, fundamental and timely."

- Slides from Webinar: https://www.nap.edu/resource/25171/eic-public-briefing-slides.pdf
- Glowing" report on a US-based EIC facility!



EIC Project Development

- Site Selection and award of DOE Critical Decisions 0 (CD-0) and 1 (CD-1)

https://www.energy.gov/articles/us-department-energy-selects-brookhaven-national-laboratory-host-major-new-nuclear-physics

Department of Energy

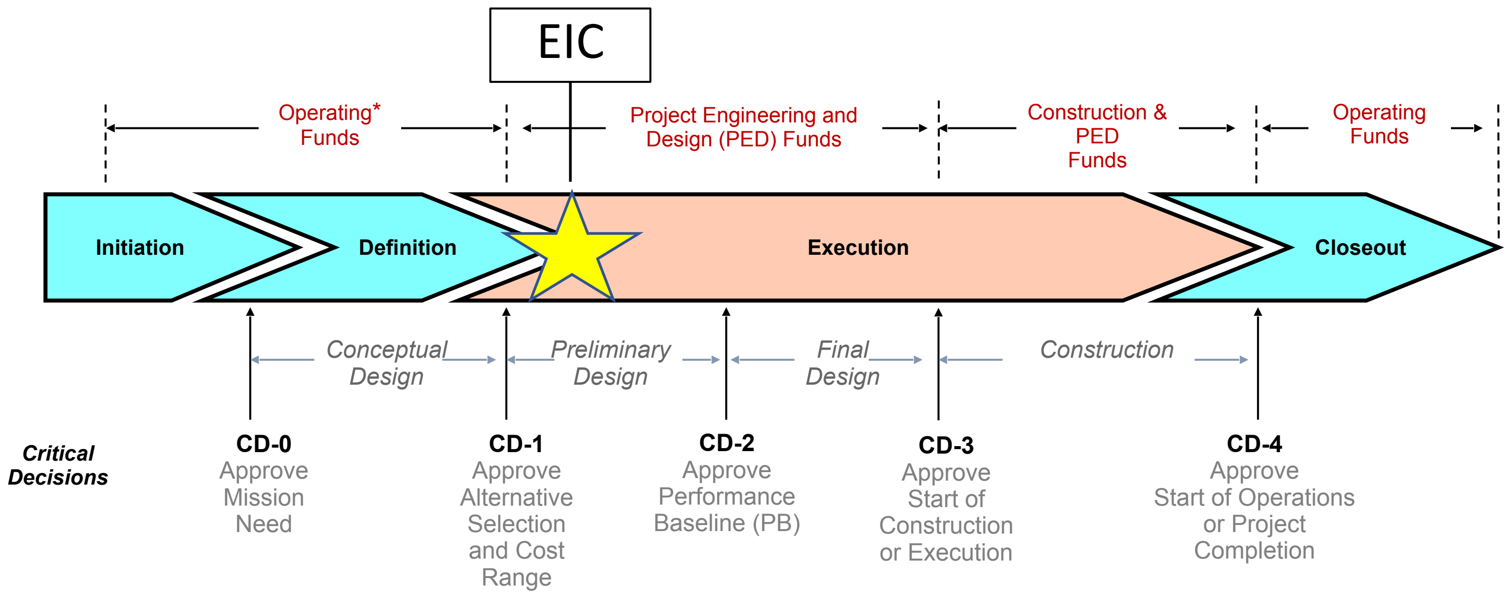
U.S. Department of Energy Selects Brookhaven National Laboratory to Host Major New Nuclear Physics Facility

JANUARY 9, 2020

WASHINGTON, D.C. – Today, the U.S. Department of Energy (DOE) announced the selection of Brookhaven National Laboratory in Upton, NY, as the site for a planned major new nuclear physics research facility. The Electron Ion Collider (EIC), to be designed and constructed over ten years at an estimated cost between $1.6 and $2.6 billion, will smash electrons into protons and heavier atomic nuclei in an effort to penetrate the mysteries of the “strong force” that binds the atomic nucleus together.

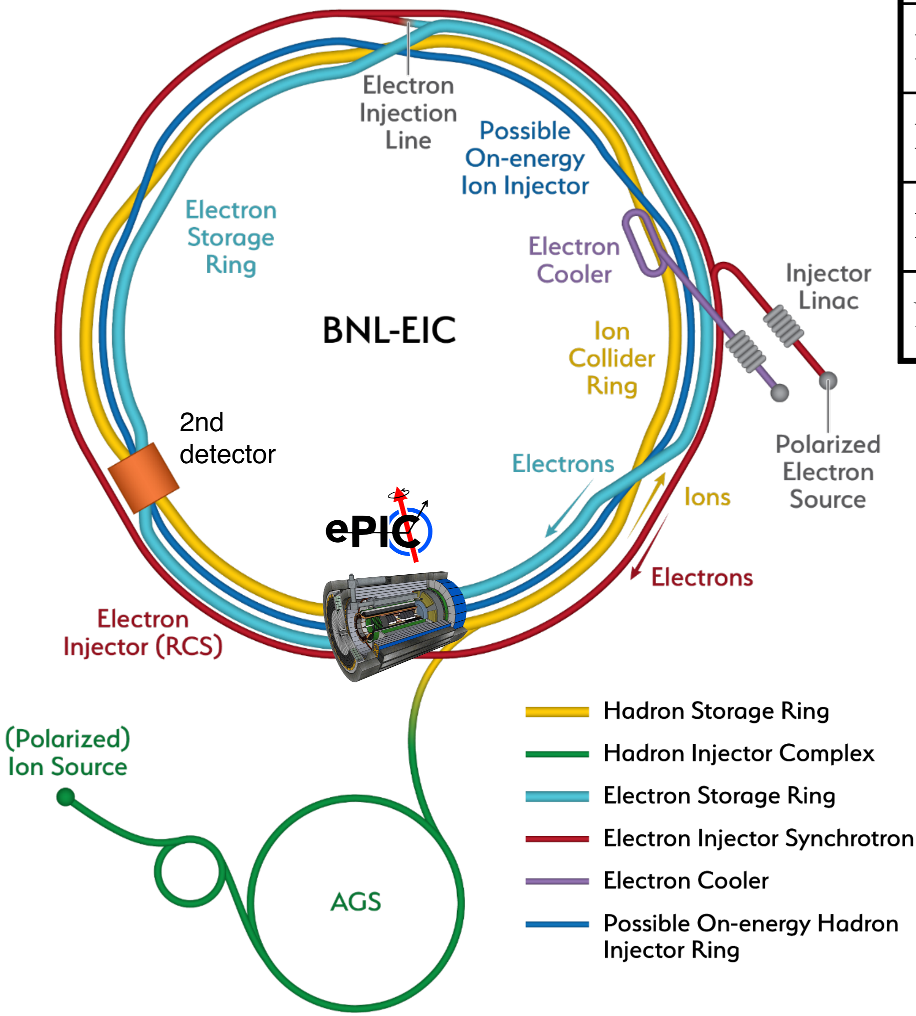
Critical Decision-0 (CD-0), “Approve Mission Need”, approved for the EIC on December 19, 2019.

Critical Decision-1 (CD-1), “Approve Alternative Selection and Cost Range”, was awarded for the EIC on June 29, 2021.

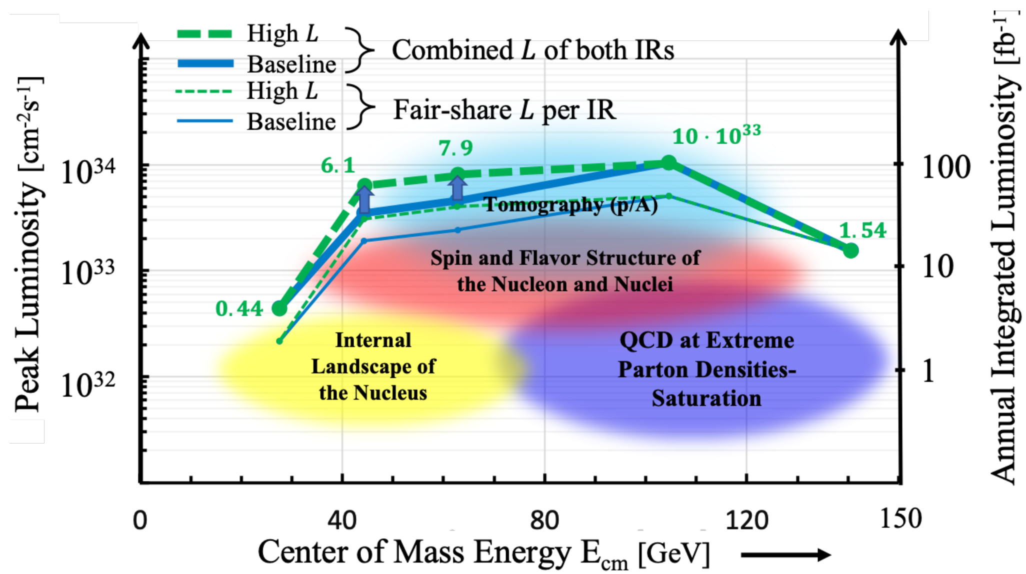


EIC Project Development

- EIC accelerator design



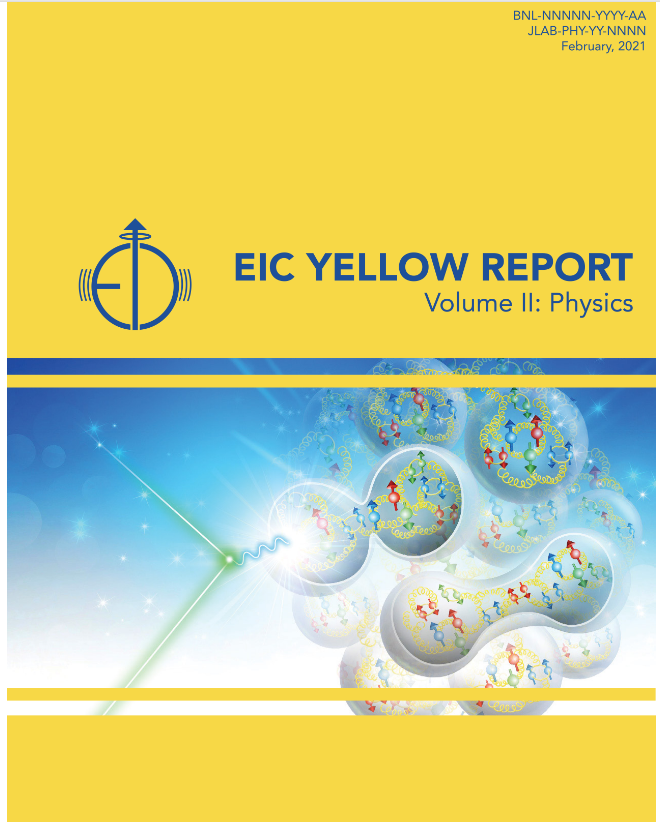
Center of Mass Energies:	20GeV - 140GeV
Luminosity:	10^{33} - 10^{34} $cm^{-2}s^{-1}$ / 10-100fb^{-1} / year
Highly Polarized Beams:	70%
Large Ion Species Range:	p to U
Number of Interaction Regions:	Up to 2!



EIC Project Development

- Yellow Report Activity - Critical EIC Community activity for CD-1

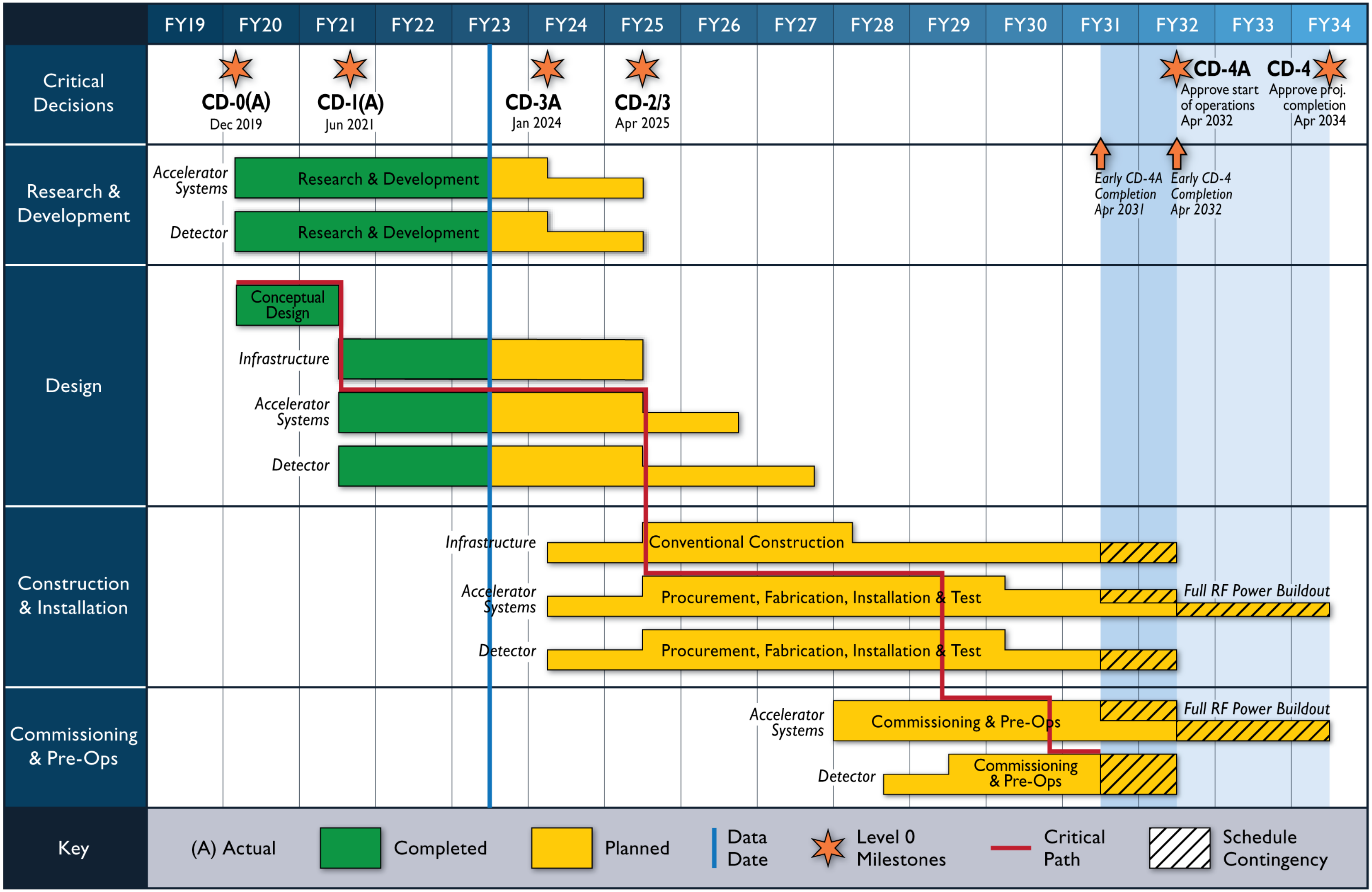
R.~Khalek *et al.* [EIC Users Group], BNL-220990-2021-FORE, arXiv e-Print: 2103.05419, Accepted for publication in Nuclear Physics A



- ~400 authors / ~150 institutions / ~900 pages with strong international contributions!
- Review: Community review within EICUG and external readers (~30) worldwide covering physics and detector expert fields!
- Available on archive: Nucl. Phys. A 1026 (2022) 122447 / https://arxiv.org/abs/2103.05419

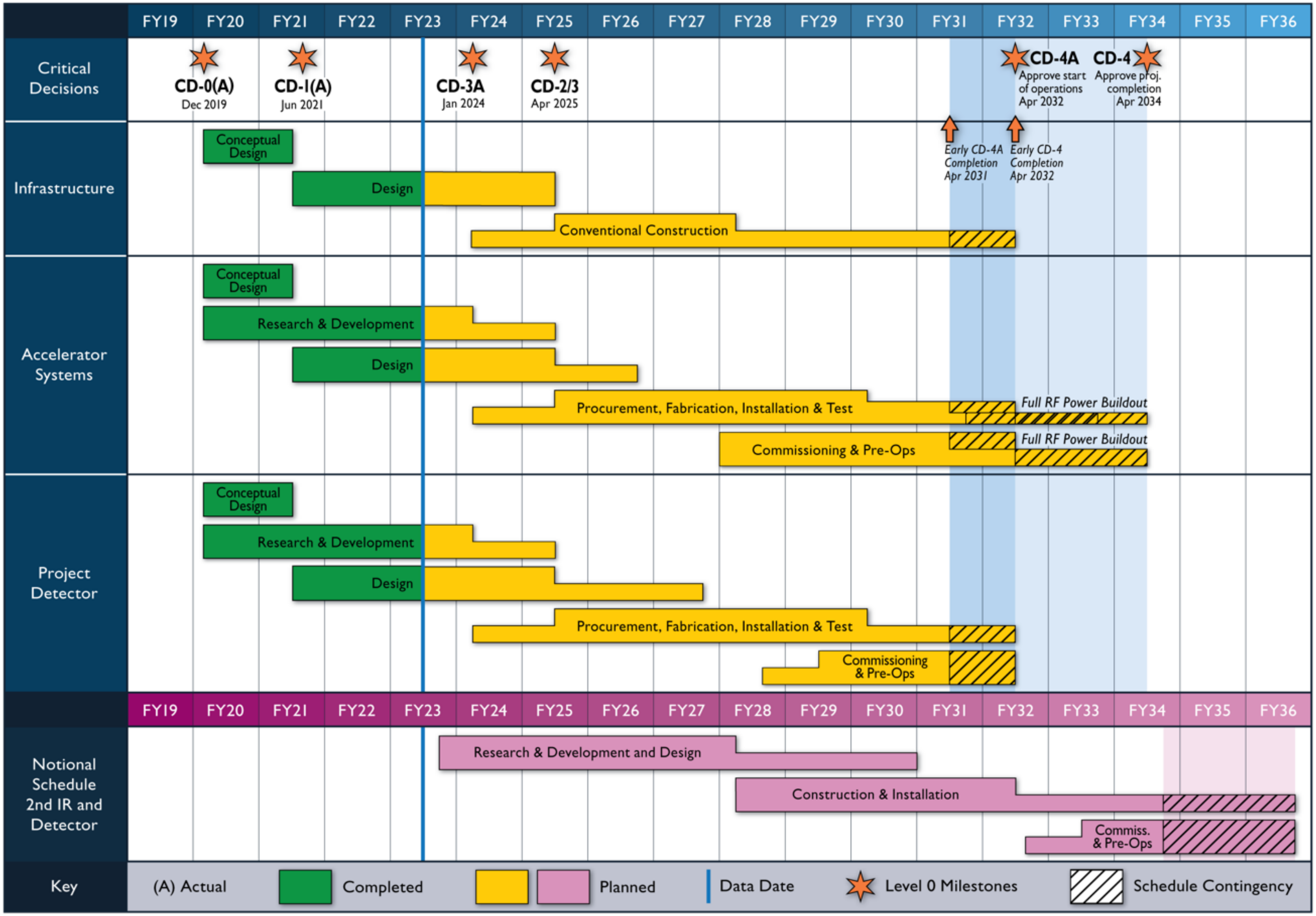
EIC Project Development

- Schedule: EIC Project Detector at IP 6 / ePIC



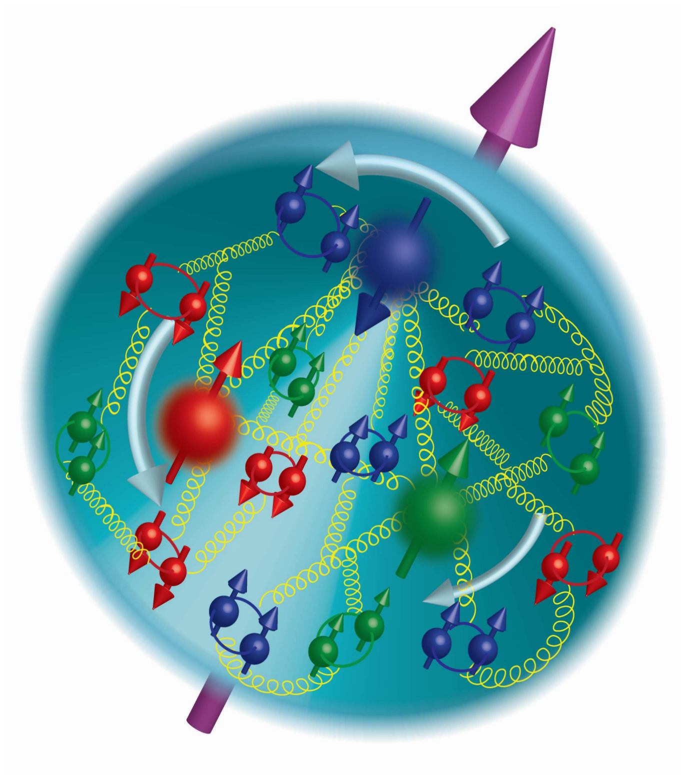
EIC Project Development

- Reference Schedule for 2nd IR and Detector



EIC Physics Pillars

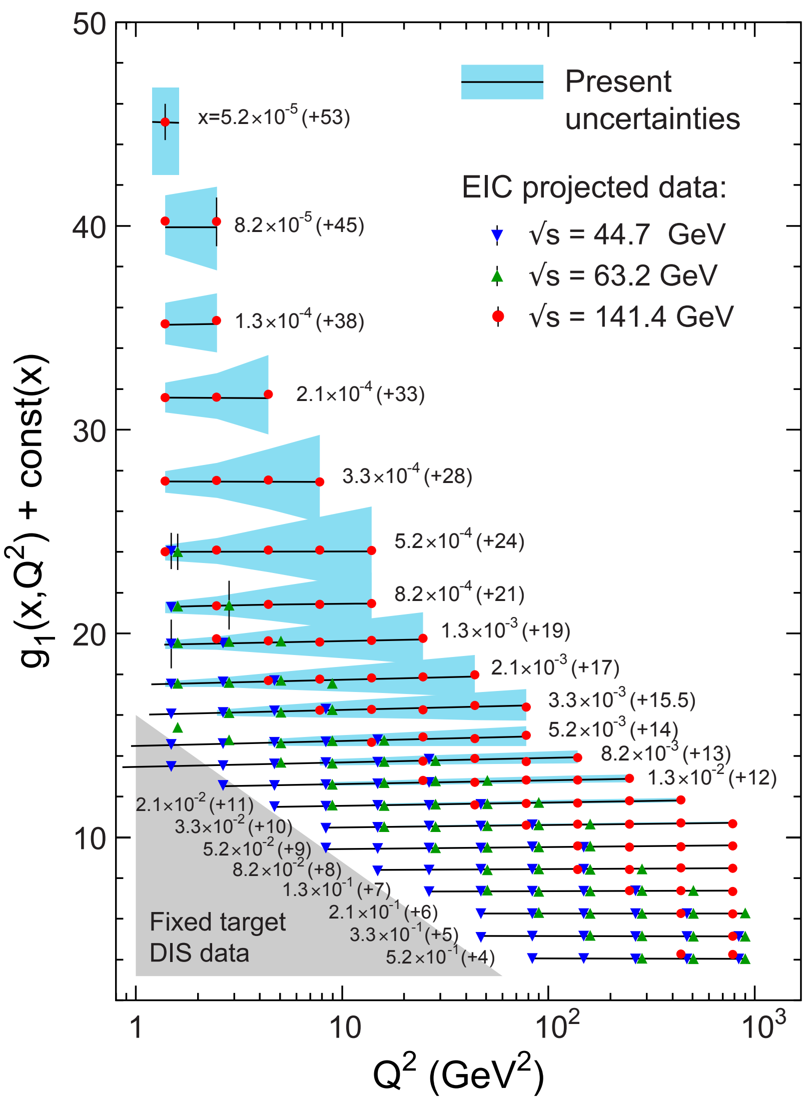
Global properties: Spin

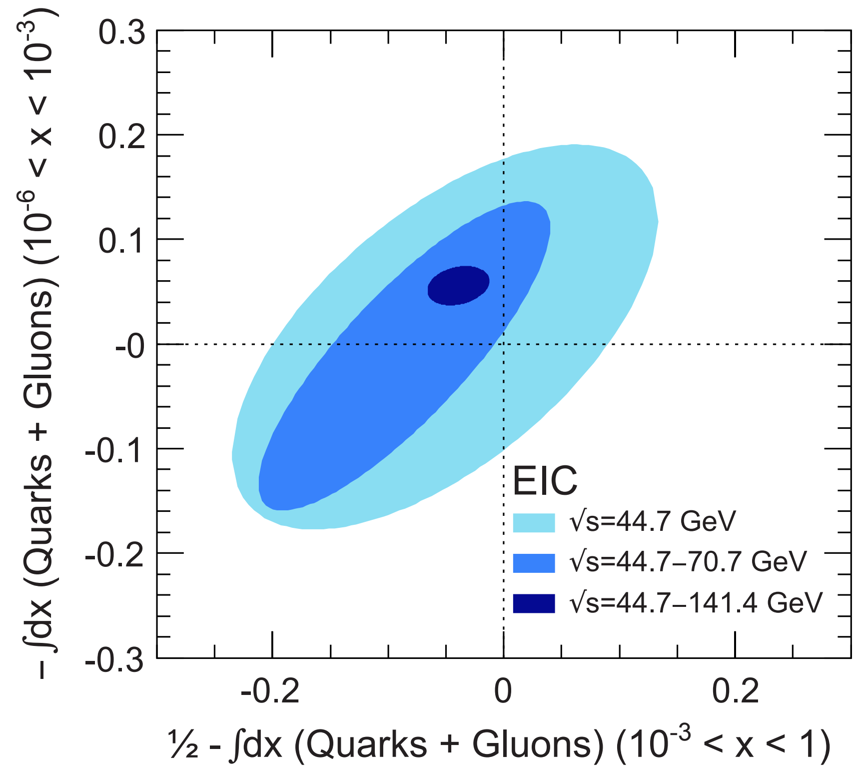


EIC Physics Pillars

- Spin and Flavor Structure of the Nucleon

arXiv:1708.01527



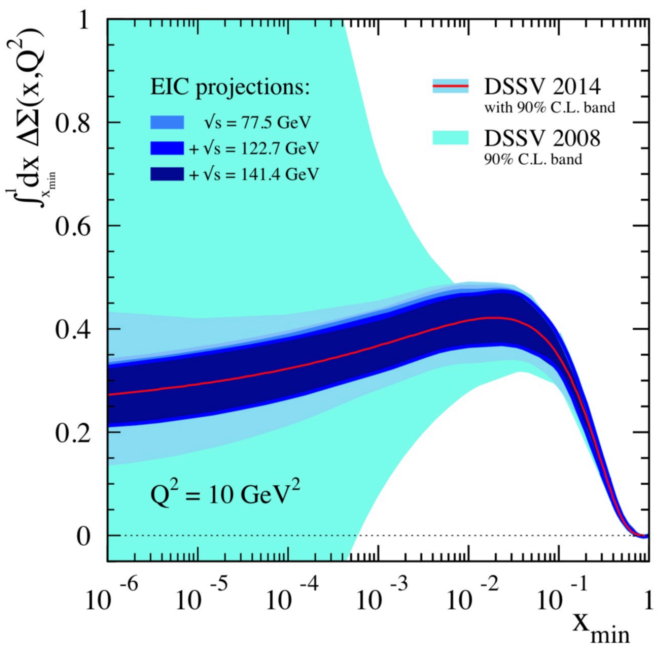


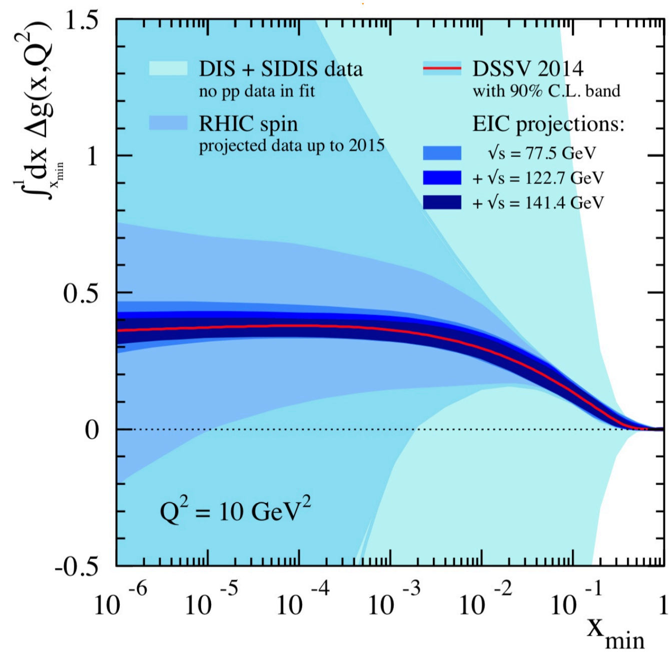
- g_1 stat. uncertainty projections for 10fb^{-1} for range of CME in comparison to DSSV14 predictions incl. uncertainties
- EIC impact on the knowledge of the integral of the quark + gluon spin contribution vs. orbital angular momentum

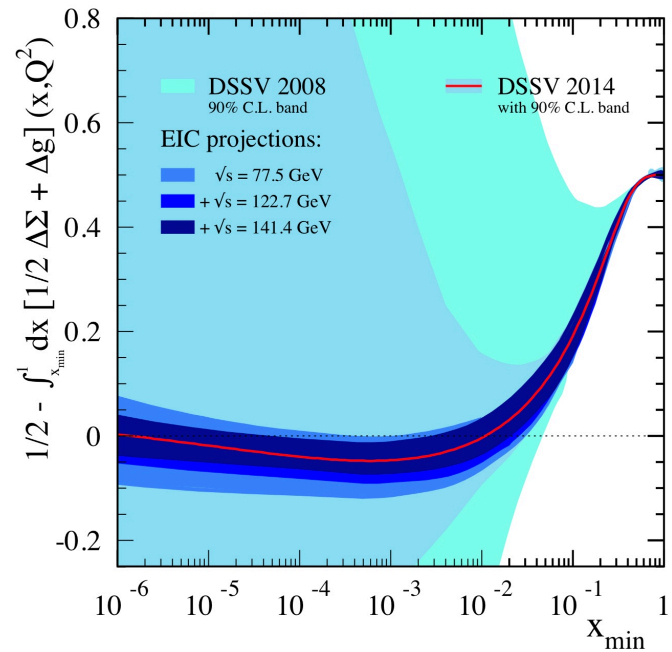
EIC Physics Pillars

Impact on proton spin

E. Aschenauer, R. Sassot and M. Stratmann, Phys. Rev. D92 (2015) 094030.







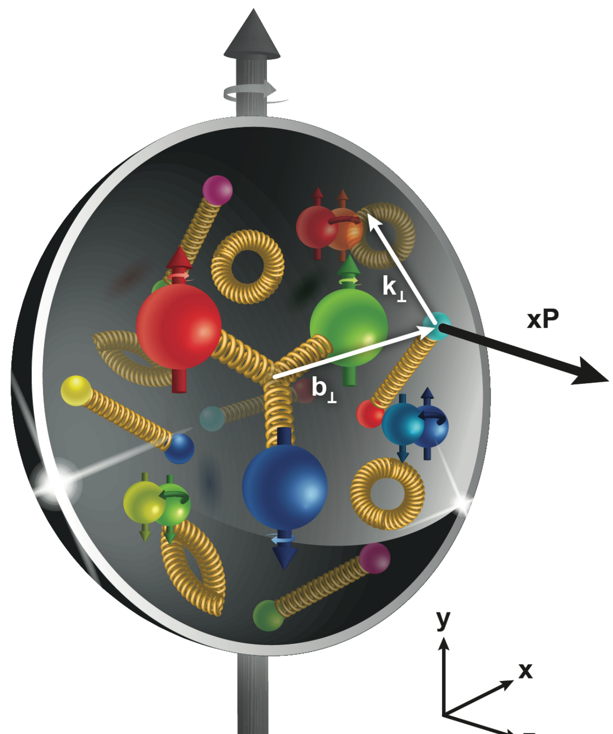
Quark Spin

Gluon Spin

Orbital Angular Momentum

EIC Physics Pillars

Nucleon 3D structure



EIC Physics Pillars

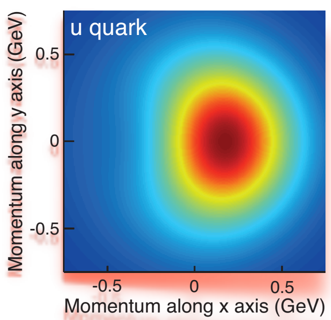
- Transverse Momentum Distribution and Spatial Imaging

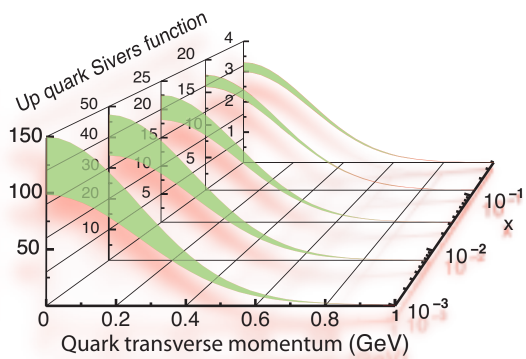
arXiv:1212.1701

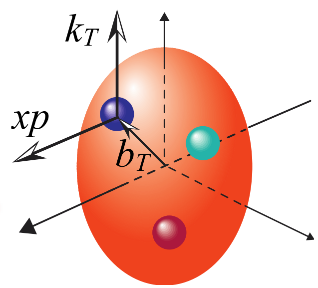
$f(x, k_T)$ 1+2D $\int d^2 b_T$ $W(x, b_T, k_T)$ $\int d^2 k_T$ $f(x, b_T)$ 1+2D

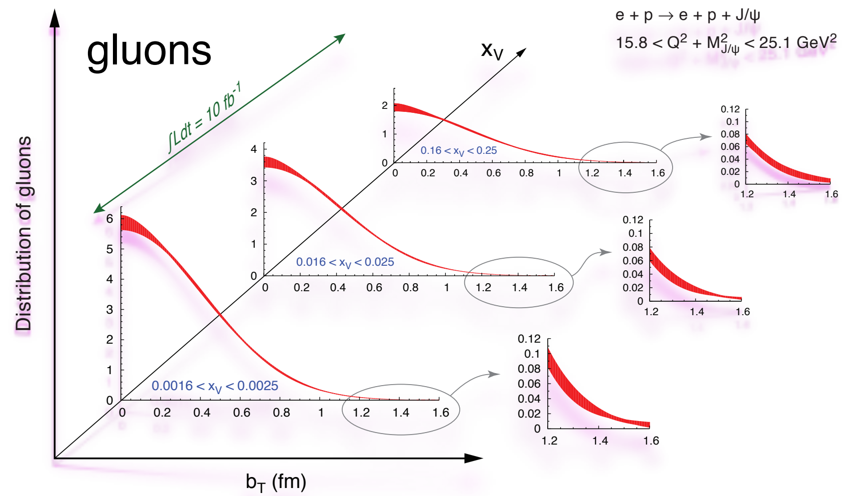
Transverse Momentum Distribution (TMD) — Wigner Distribution — Impact Parameter Distribution

quarks









- Spin-dependent 1+2D momentum space (transverse) images from semi-inclusive scattering
- Spin-dependent 1+2D impact parameter (transverse) images from exclusive scattering

Fourier transf.
$b_T \longleftrightarrow \Delta$: $t = -\Delta^2$

$H(x, 0, t)$

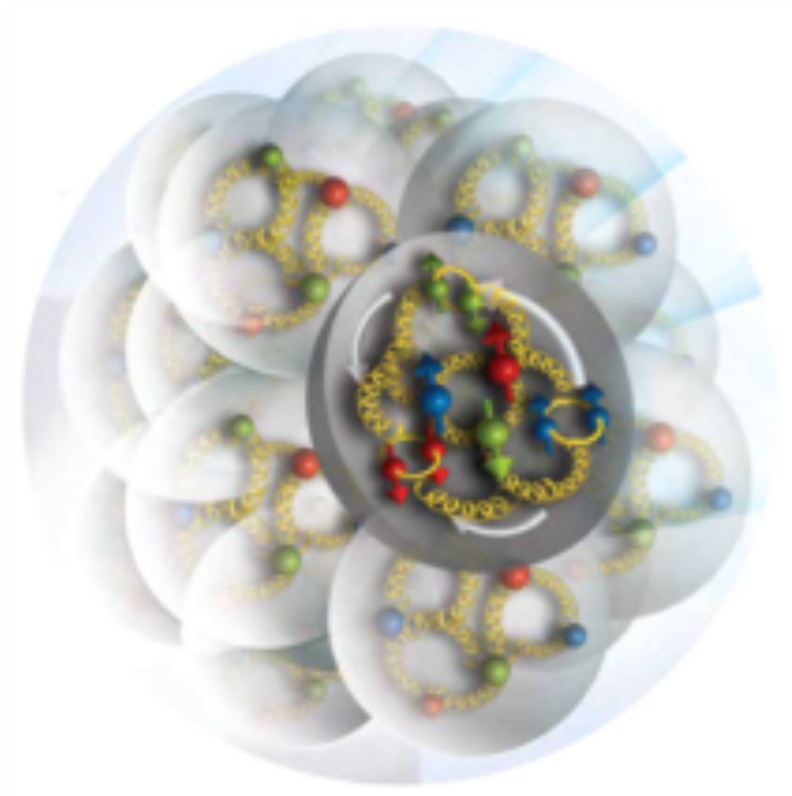
$\xi = 0$

$H(x, \xi, t)$

Generalized Parton Distribution (GPD)

EIC Physics Pillars

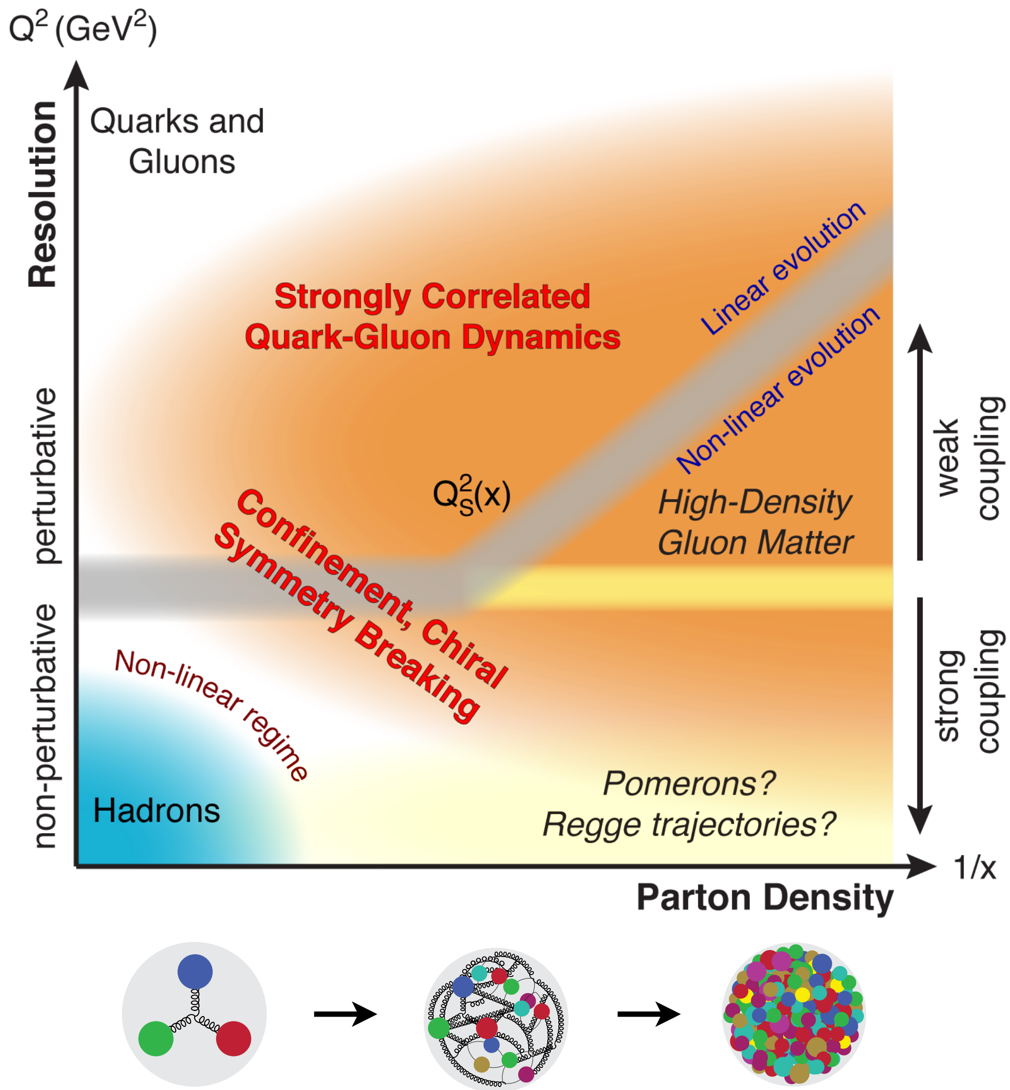
Low-x physics



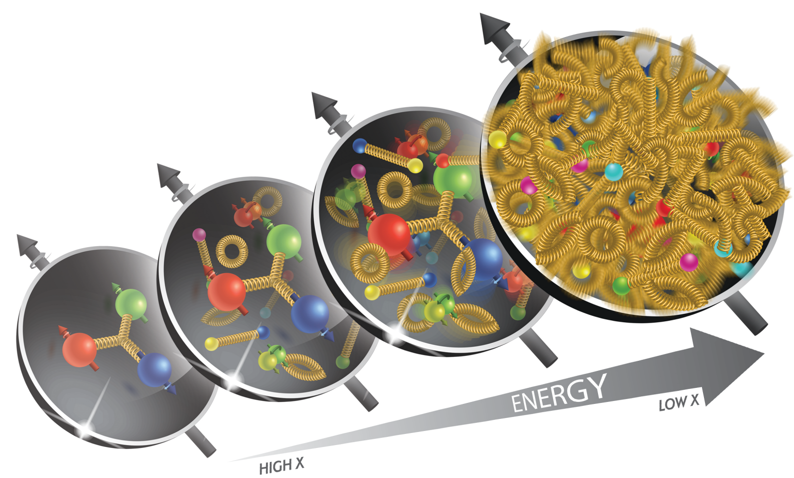
EIC Physics Pillars

- QCD dynamics

arXiv:1708.01527



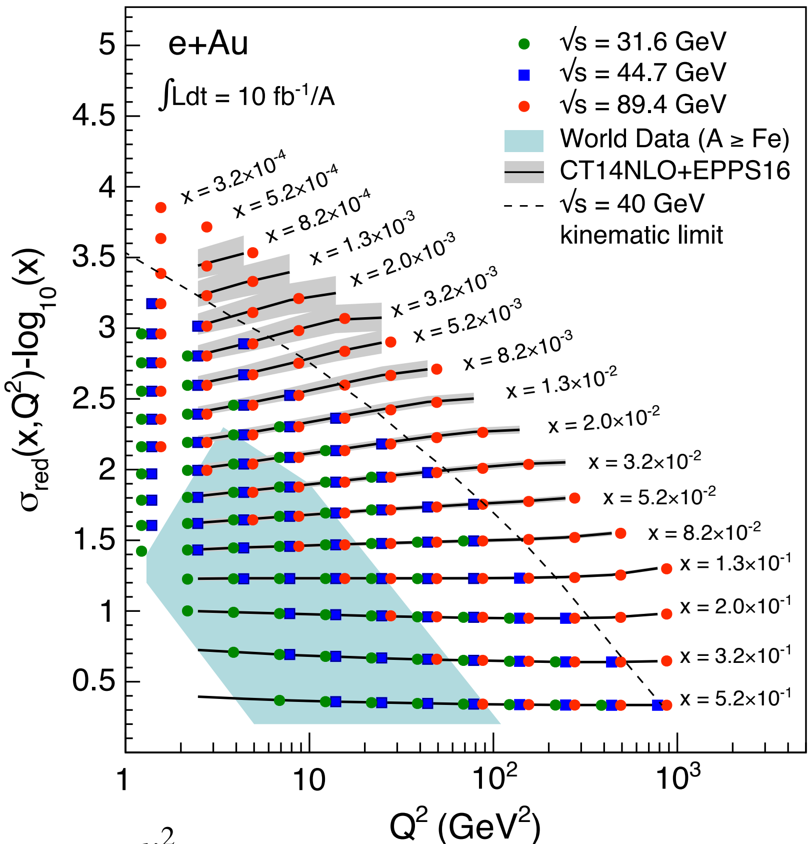
- Explore QCD landscape in various aspects over a wide range in x and Q^2
- Heavy nuclei at high energy critical to explore high-density gluon matter!

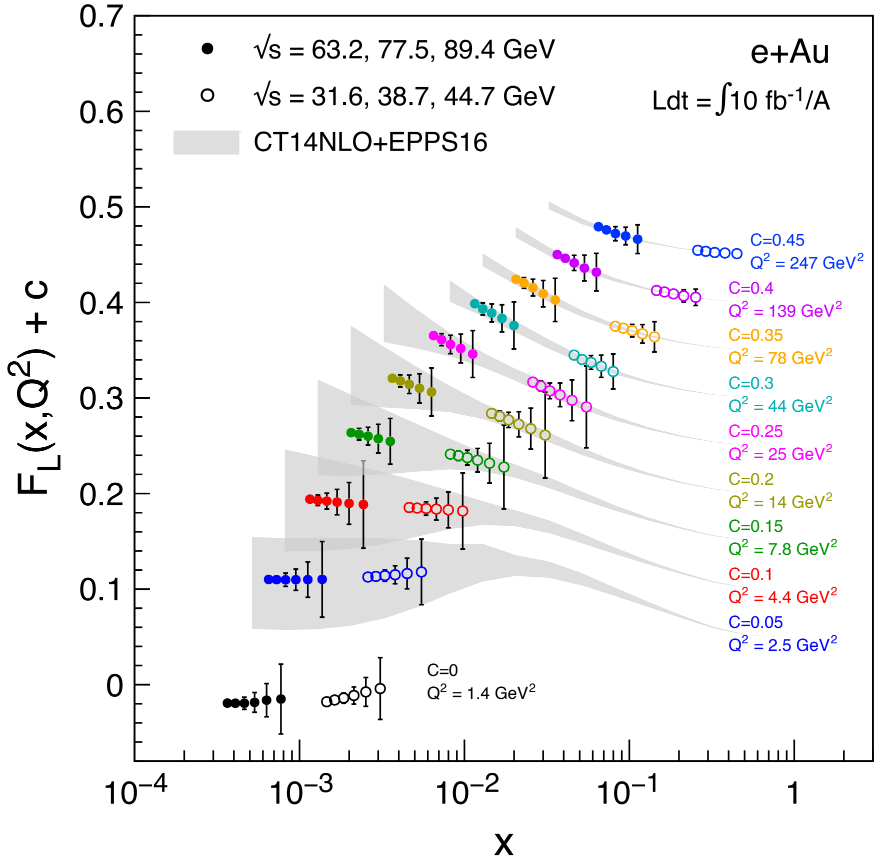


EIC Physics Pillars

- Inclusive eA scattering measurements

arXiv:1708.01527





$$\sigma_{\mathrm{red}} = F_2 - \frac{y^2}{Y_+} F_L$$

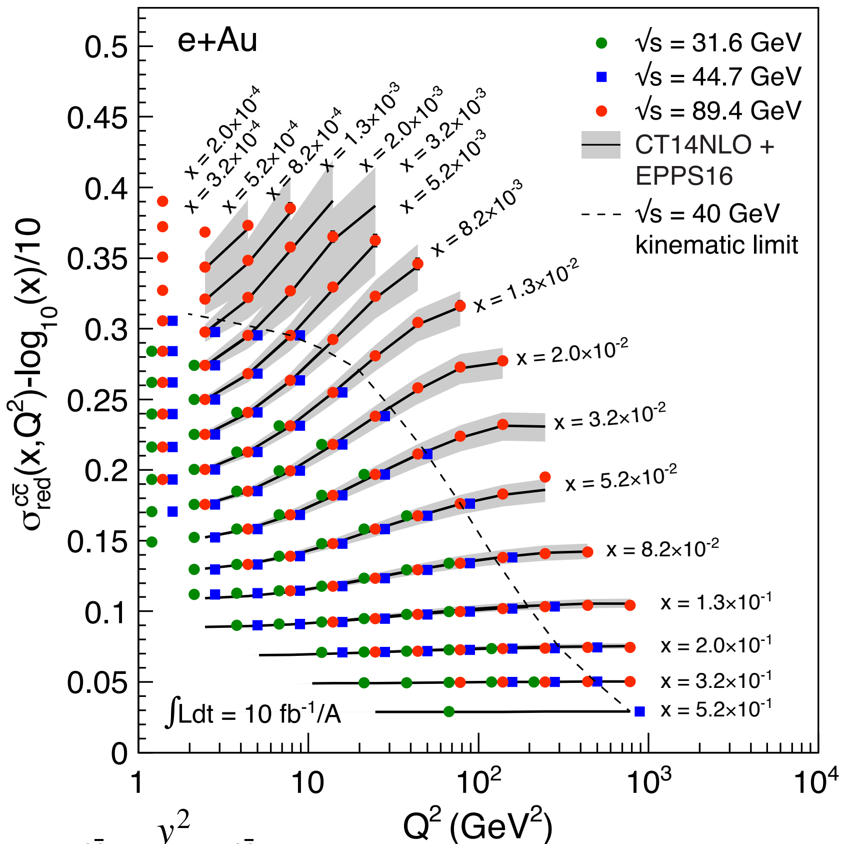
$$\left(\frac{d^2\sigma}{dx\,dQ^2}\right) = \frac{2\pi\alpha^2 Y_+}{xQ^4}\left(F_2 - \frac{y^2}{Y_+} F_L\right)$$

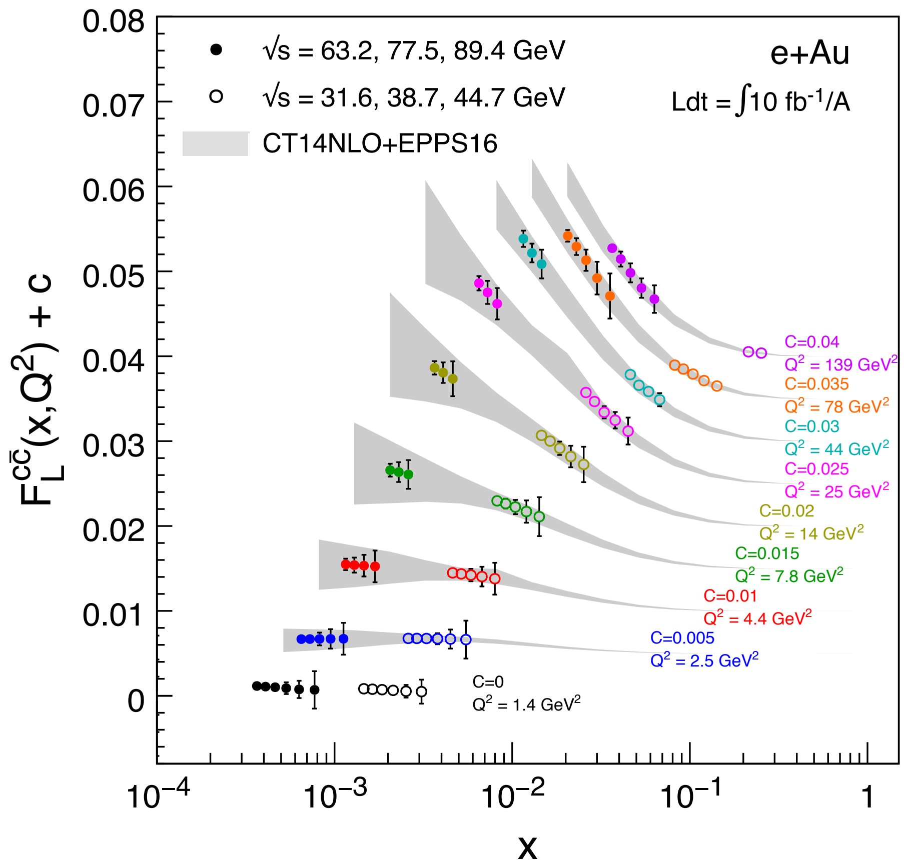
$$Y_+ = 1 + \left(1 - y\right)^2$$

EIC Physics Pillars

- Charm-associated eA scattering measurements

arXiv:1708.01527





$$\sigma_{\text{red}}^{c\bar{c}} = F_2^{c\bar{c}} - \frac{y^2}{Y_+} F_L^{c\bar{c}}$$

$$\left(\frac{d^2\sigma}{dx dQ^2}\right)^{c\bar{c}} = \frac{2\pi\alpha^2 Y_+}{xQ^4}\left(F_2^{c\bar{c}} - \frac{y^2}{Y_+} F_L^{c\bar{c}}\right)$$

$$Y_+ = 1 + (1-y)^2$$

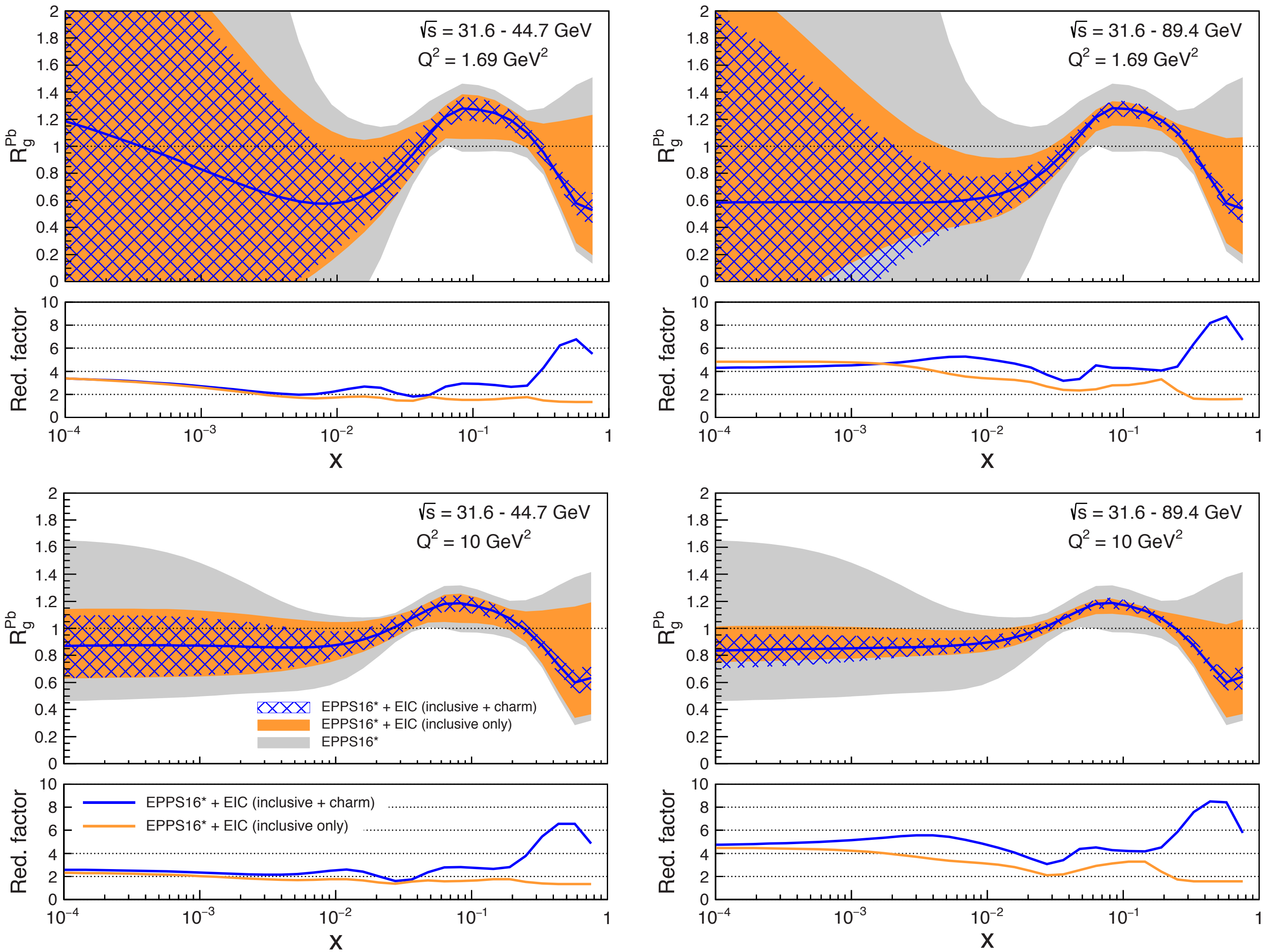
EIC Physics Pillars

- Impact on nuclear gluon behavior in eA scattering

arXiv:1708.01527

Modifications of nuclear environment: R_g^{Pb}

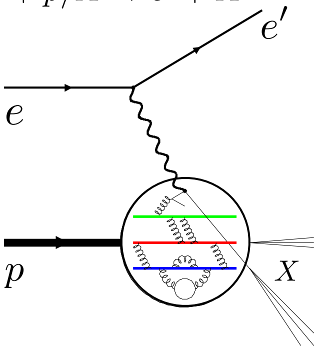
Ratio of gluon distribution in Pb compared to proton



ePIC Detector Layout

Overview of processes and final states

$e + p/A \rightarrow e' + X$

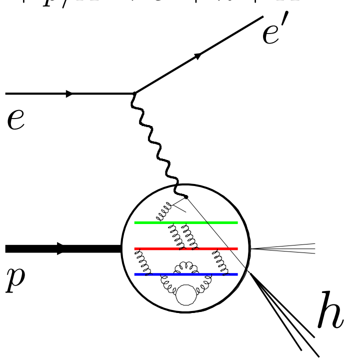


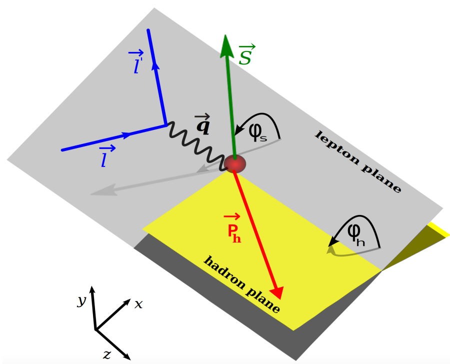
Inclusive DIS

- Inclusive: Unpolarized $f_i(x,Q^2)$ and helicity distribution $\Delta f_i(x,Q^2)$ functions through unpolarized and polarized structure function measurements (F_2, F_L, g_1)
- Define kinematics (x, y, Q^2) through electron (e-ID and energy+angular measurement critical) / hadron final state or combination of both depending on kinematic x-Q^2 region

Semi-Inclusive DIS (SDIS)

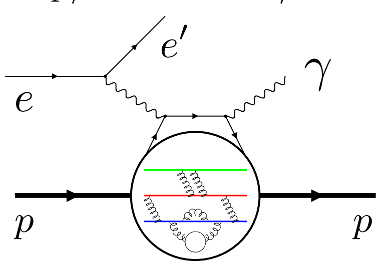
$e + p/A \rightarrow e' + h + X$





- SDIS: Flavor tagging through hadron identification studying FF / TMD's (Transverse momentum, k_T, dependence) requiring azimuthal asymmetry measurement - Full azimuthal acceptance
- Heavy flavor (charm / bottom): Excellent secondary vertex reconstruction

$e + p/A \rightarrow e' + N'/A' + \gamma/m$



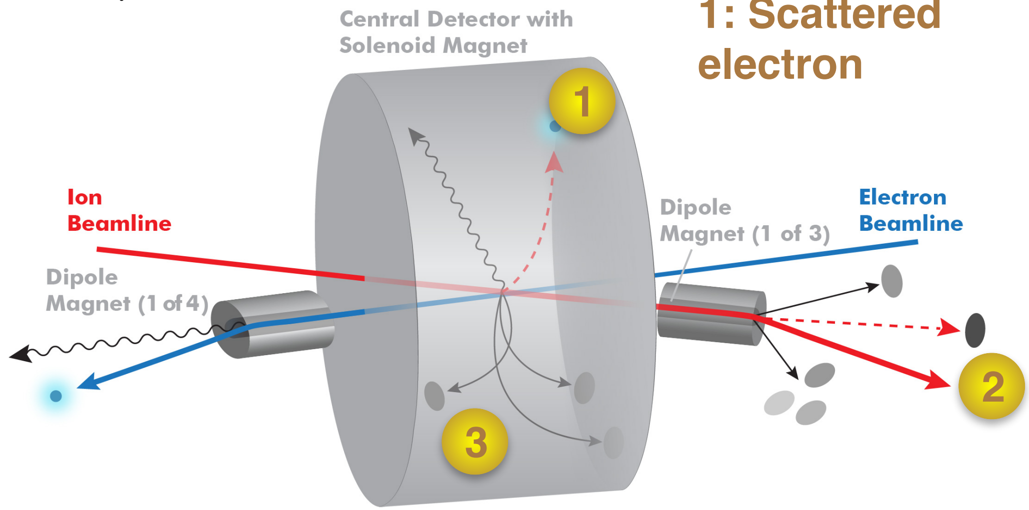
Deeply-Virtual Compton Scattering (DVCS)

- Exclusive: Tagging of final state proton using Roman pot system studying GPD's (Impact parameter, b_T, dependence) using DVCS and VM production
- eA: Impact parameter determination / Neutron tagging using Zero-Degree Calorimeter (ZDC)

ePIC Detector Layout

- Overview of general requirements

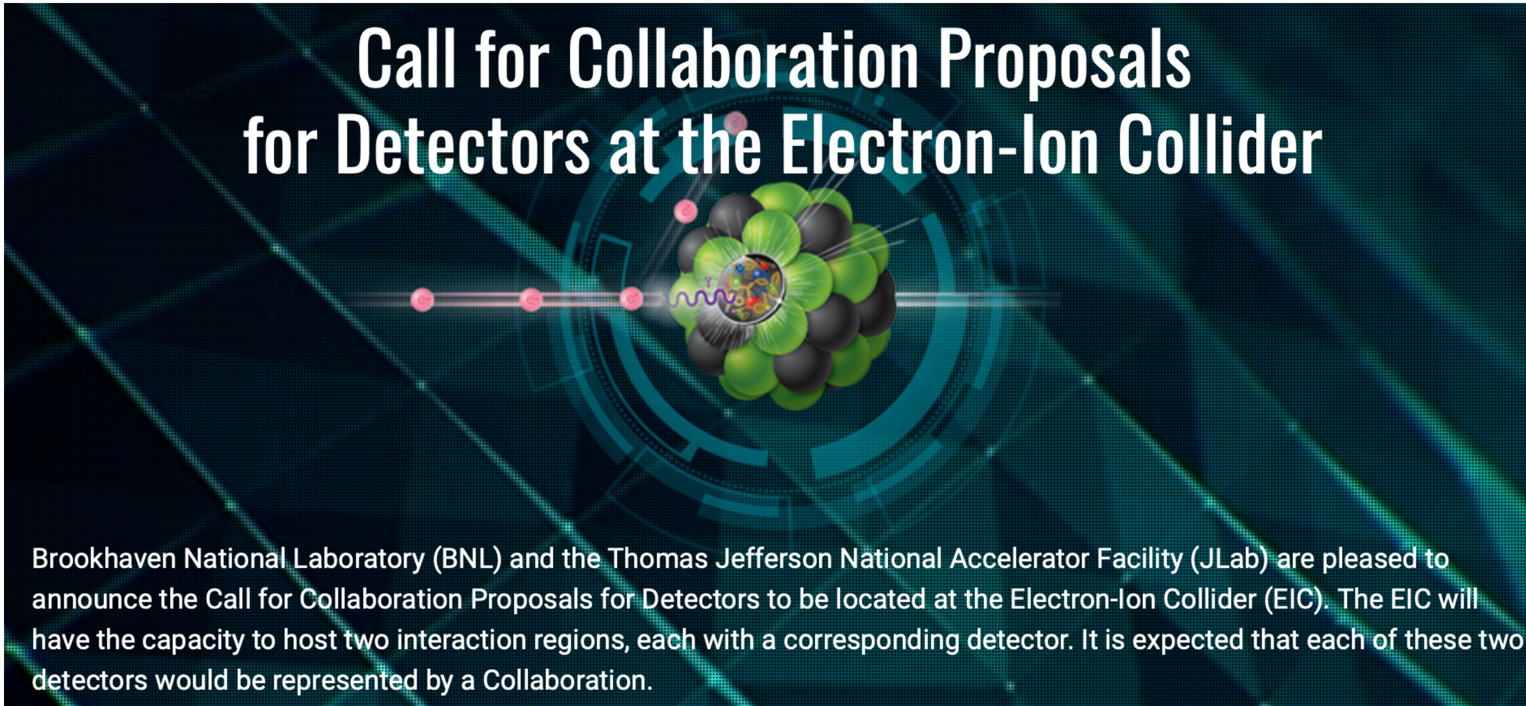
arXiv:1212.1701



- Acceptance: Close to 4π coverage with a η-coverage ($\eta = -\ln(\tan(\theta/2))$) of approximately $\eta < |3.5|$ combined calorimetry (EM CAL and hadron CAL at least in forward direction) and tracking coverage
- Low dead material budget in particular in rear direction (~10% X/X_0)
- Good momentum resolution $\Delta p/p$ ~ few %
- Electron ID for e/h separation varies with θ / η at the level of 1:10^4 / ~2-3%/√E for η<-2 and ~7%/√E for -2<η<1
- Particle ID for π/K/p separation over wide momentum range (Forward η up to ~50GeV/c / Barrel η up to ~4GeV/c / Rear η up to ~6 GeV/c)
- High spatial vertex resolution ~ 10-20μm for vertex reconstruction
- Low-angel taggers:
  - Forward proton / A fragment spectrometer (Roman pots)
  - Low Q^2 tagger
  - Neutrons on hadron direction
- Luminosity (Absolute and relative) and local polarization direction measurement

ePIC Detector Layout

- Open Call for Detector Proposals



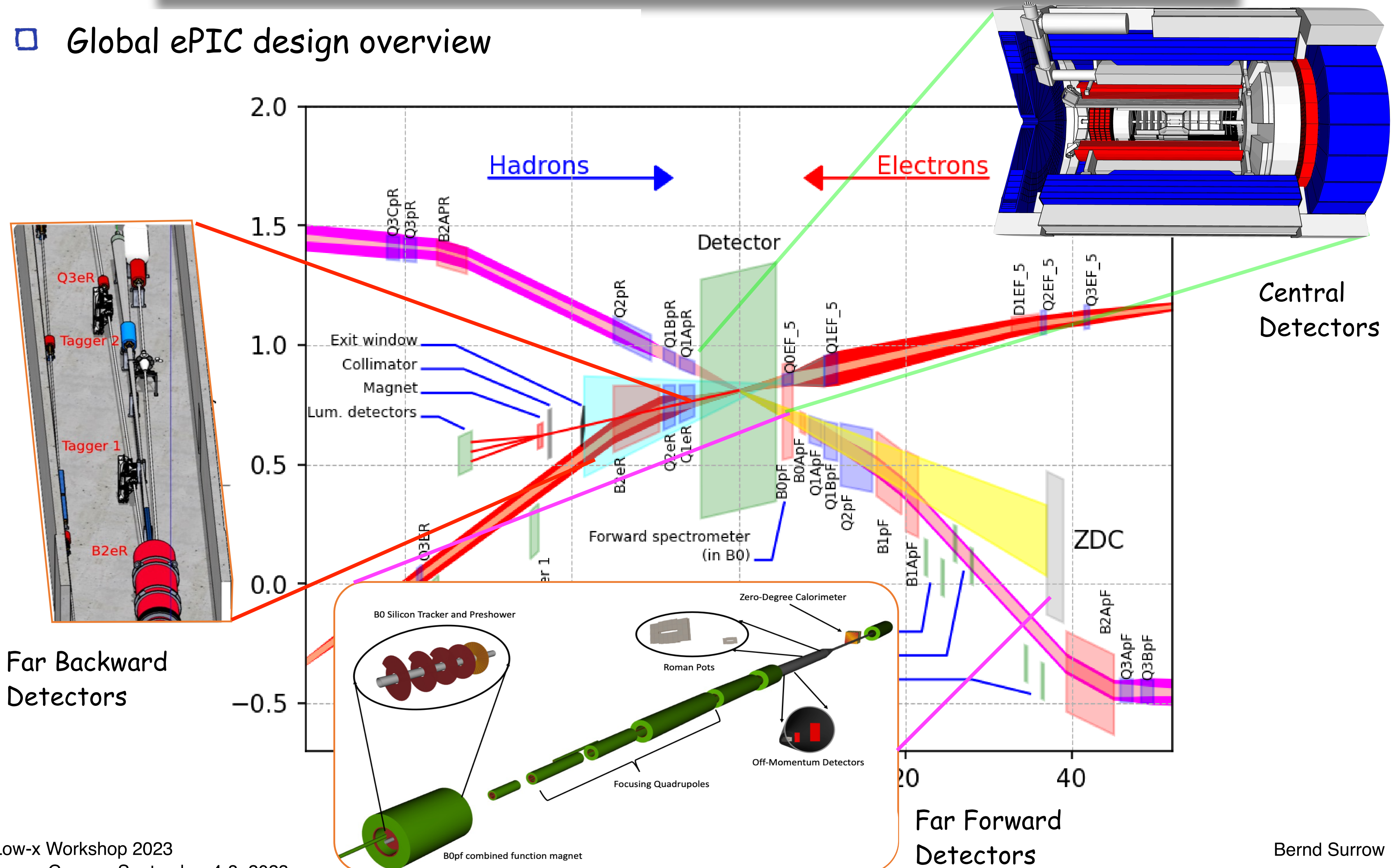
ATHENA: A Totally Hermetic Electron-Nucleus Apparatus
Concept: General purpose detector inspired by the YR studies based on a new central magnet of up to 3T
WWW-page: https://www.athena-eic.org

CORE: COmpact detectoR for the Eic
Concept: Nearly hermetic, general-purpose compact detector, 2T baseline
WWW-page: https://userweb.jlab.org/~hyde/EIC-CORE/

ECCE: EIC Comprehensive Chromodynamics Experiment
Concept: General purpose detector based on 1.5T BaBar magnet
WWW-page: https://www.ecce-eic.org

ePIC Detector Layout

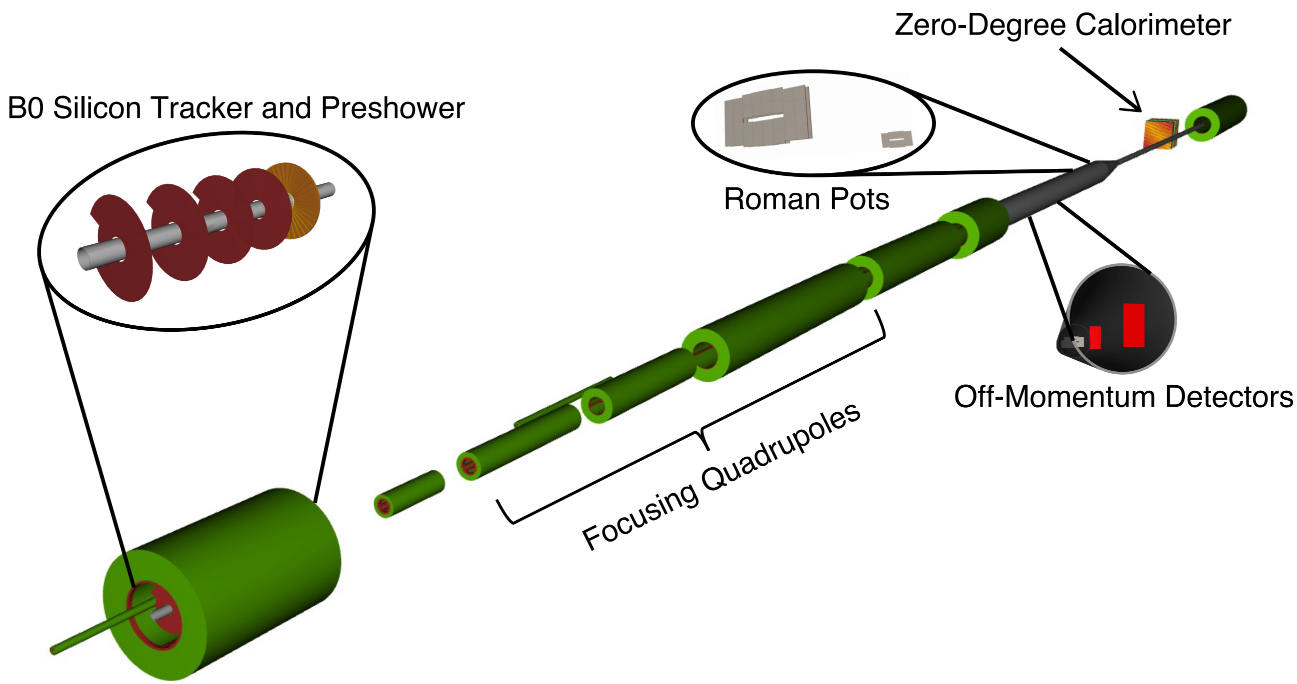
- Global ePIC design overview



ePIC Detector Layout

FarForward detector system

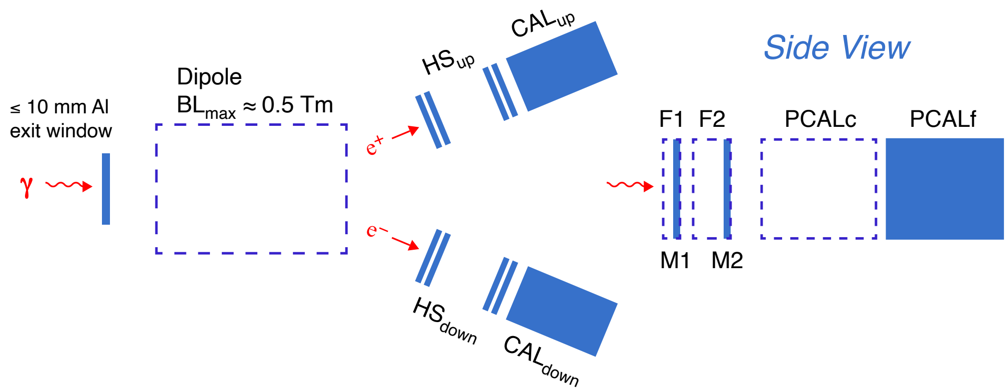
- FarForward detector system to measure very forward neutral and charged particle production: 4 detector systems
- B0 system: Measures charged particles in the forward direction and tags neutral particles
- Off-momentum detectors: Measure charged particles resulting from decays
- Roman pot detectors: Measure charged particles near the beam
- Zero-degree calorimeter: Measures neutral particles at small angles

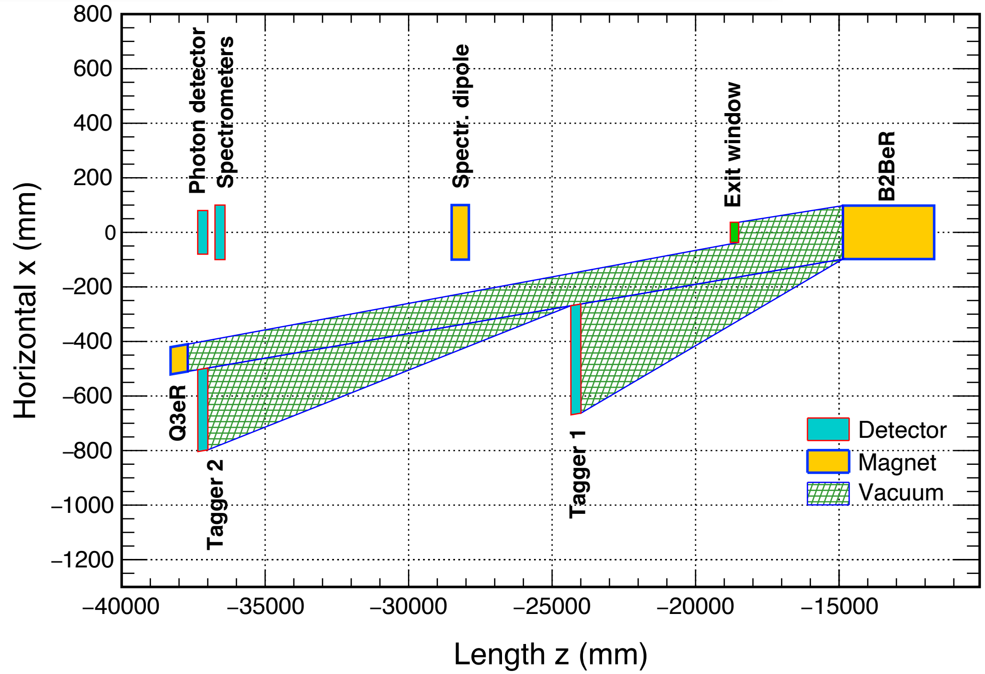


Detector	θ accep. [mrad]	Rigidity accep.	Particles	Technology
B0 tracker	5.5–20.0	N/A	Charged particles Tagged photons	MAPS AC-LGAD
Off-Momentum Detector	0.0–5.0	45%–65%	Charged particles	AC-LGAD
Roman Pots	0.0–5.0	60%–95%*	Protons Light nuclei	AC-LGAD
Zero-Degree Calorimeter	0.0–4.0	N/A	Neutrons Photons	W/SciFi (ECal) Pb/Sci (HCal)

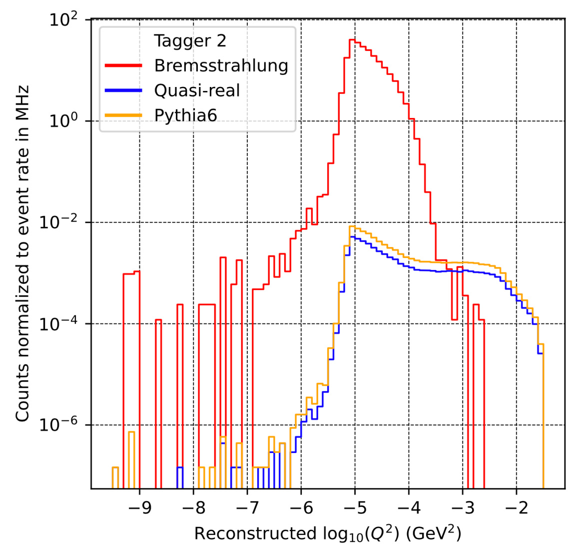
ePIC Detector Layout

- FarBackward system





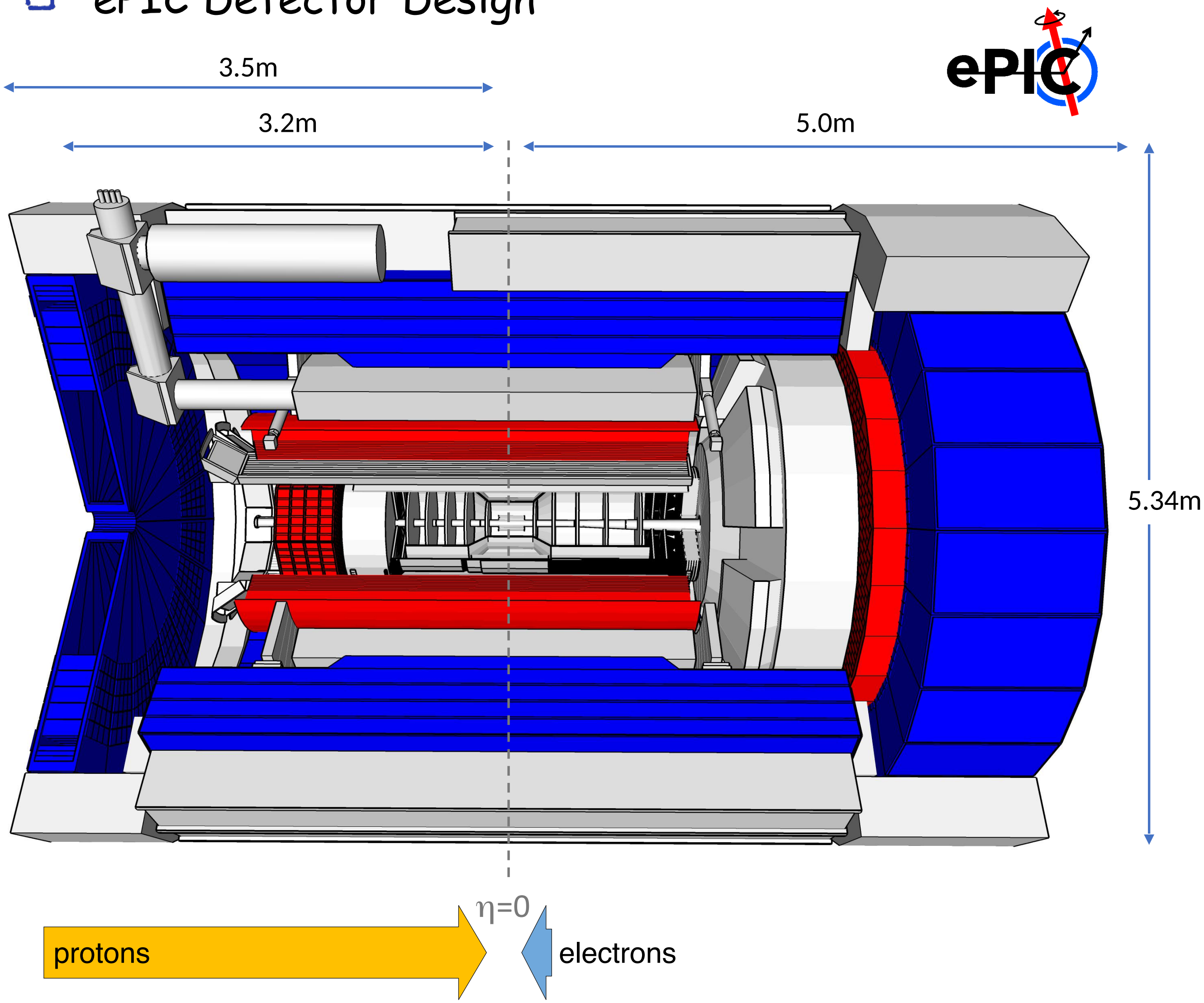
- High precision luminosity measurement at 1% level for absolute luminosity and 0.01% for relative luminosity measurement using several methods based on the Bremsstrahlung process:
  1. Counting photons converted in thin exit window using dipole field and measuring e^+e^- pairs
  2. Energy measurement of unconverted photons
  3. Counting of unconverted photons



- Low Q2 taggers - PHP tagger

ePIC Detector Layout

- ePIC Detector Design



Tracking:

- New 1.7T solenoid
- Si MAPS Tracker
- MPGDs (μRWELL/μMegas)

PID:

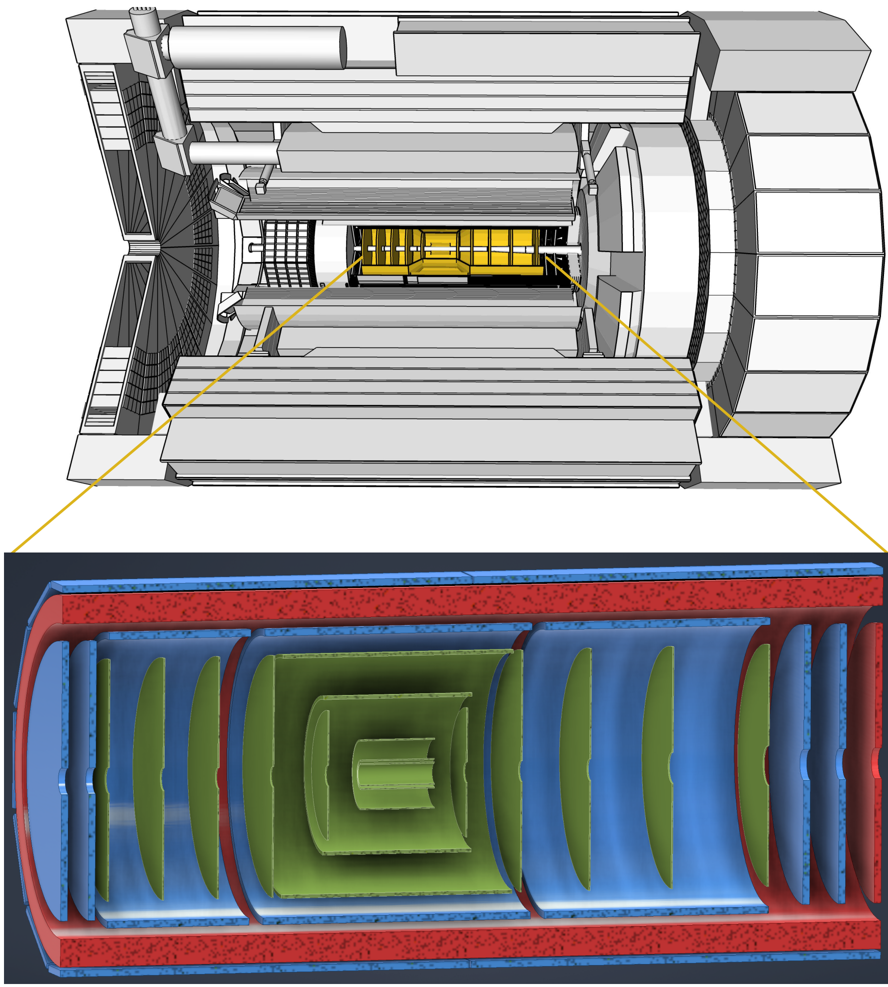
- hpDIRC
- pfRICH
- dRICH
- AC-LGAD (~30ps TOF)

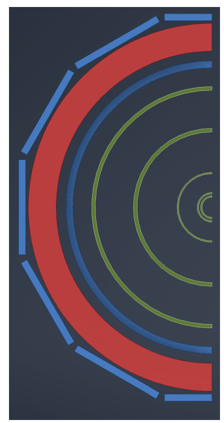
Calorimetry:

- Imaging Barrel EMCal
- PbWO4 EMCal in backward direction
- Finely segmented EMCal +HCal in forward direction
- Outer HCal (sPHENIX re-use)
- Backwards HCal (tail-catcher)

ePIC Detector Layout

- ePIC Tracking Detectors: Layout





- MAPS Barrel + Disks
- MPGD Barrels + Disks
- AC-LGAD based ToF

- MAPS Tracker:
  - Small pixels (20 μm), low power consumption (<20 mW/cm²) and material budget (0.05% to 0.55% X/X_0) per layer
  - Based on ALICE ITS3 development
  - Vertex layers optimized for beam pipe bake-out and ITS-3 sensor size
  - Forward and backward disks
- MPGD Layers:
  - Provide timing and pattern recognition
  - Cylindrical μMEGAs
  - Planar μRWell's before hpDIRC - Impact point and direction for ring seeding
- AC-LGAD TOF and AstroPix (BECAL):
  - Additional space point for pattern recognition / redundancy
  - Fast hit point / Low p PID

ePIC Detector Layout

ePIC Tracking Detectors: Performance

Technology:

ITS3 MAPS based Si-detectors:

- $O(20\mu m)$ pitch, $X/X_0 \sim 0.05$ – 0.55%/ layer

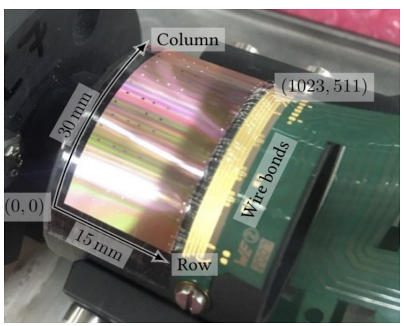
Gaseous tracker:

- $\sigma = 150\ \mu m$, $X/X_0 \sim 0.5$-1.0%/layer

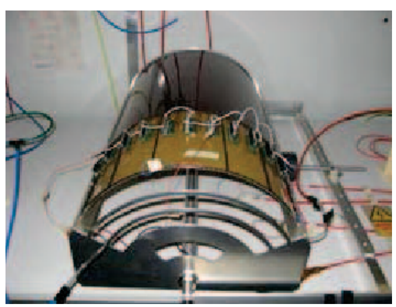
AstroPix outer tracker layer:

- $500\mu m$ pixel pitch ($\sigma = 144\ \mu m$)

First "μITS3" assembly at CERN

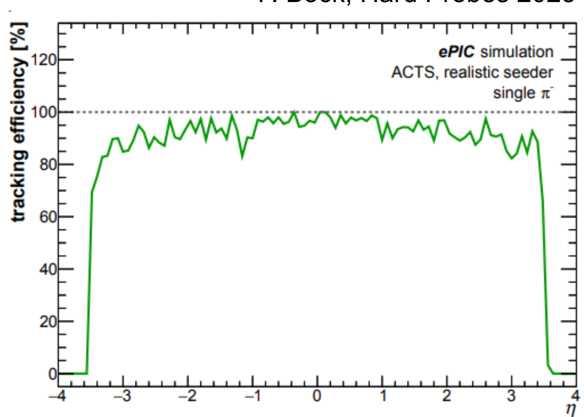


Cylindrical MicroMegas detector

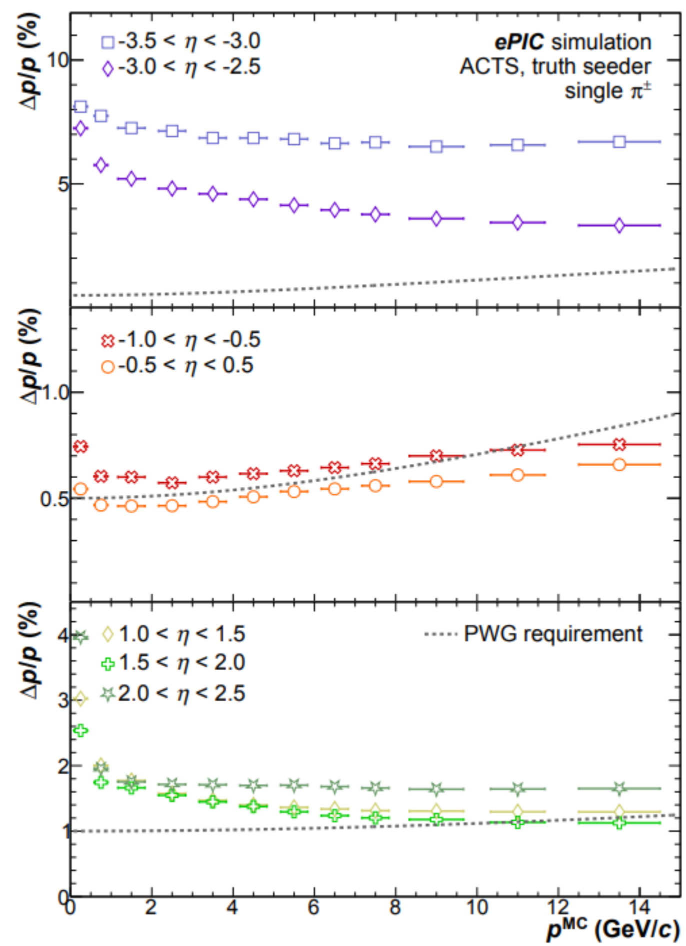


Simulated performance:

F. Bock, Hard Probes 2023



F. Bock, Hard Probes 2023

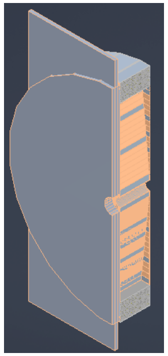


E. Yeats, R. Cruz-Torres, N. Schmidt, S. Maple

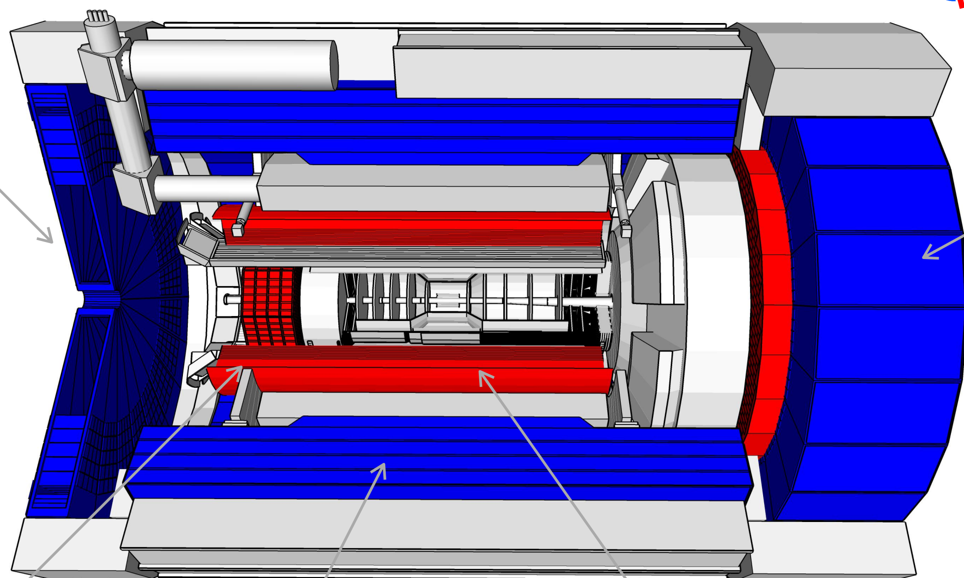
- Meets EICUG Yellow Report design requirements
- Backward momentum resolution complemented by calorimetric resolution

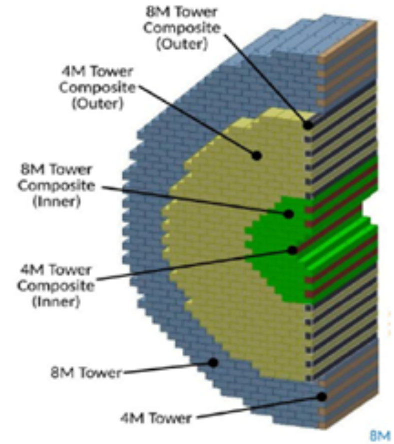
ePIC Detector Layout

ePIC Calorimeter Detectors: Layout

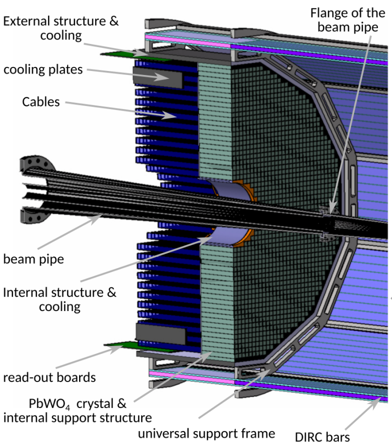


Backwards HCal
Steel/Sc Sandwich tail catcher



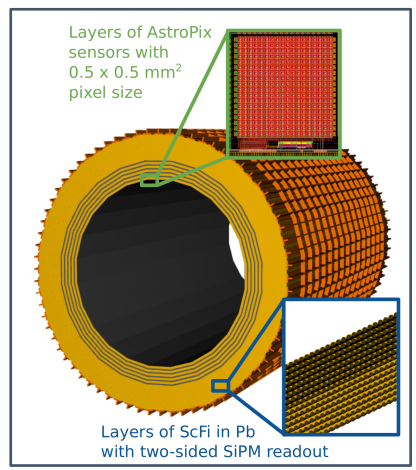


High granularity W/SciFi EMCal
Longitudinally separated HCAL with high-η insert

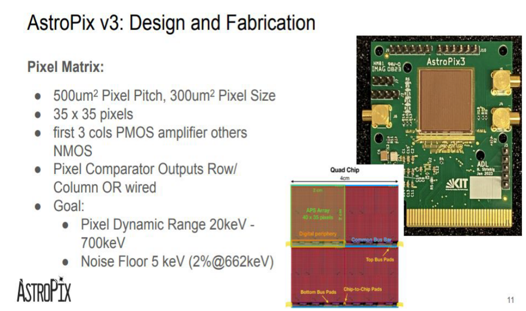


Backwards EMCal
PbW04 crystals, SiPM photosensor

Barrel HCAL
(sPHENIX re-use)



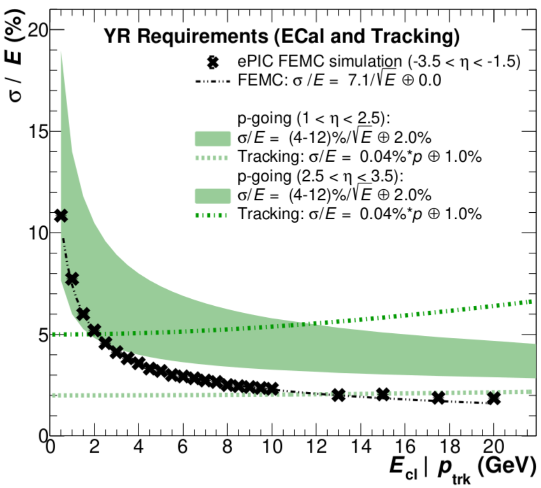
Barrel BECAL

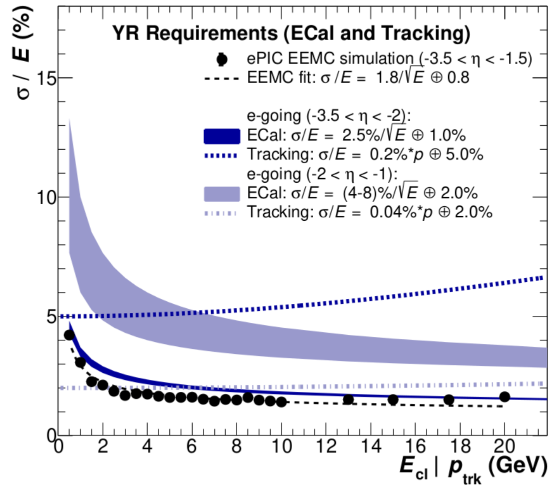


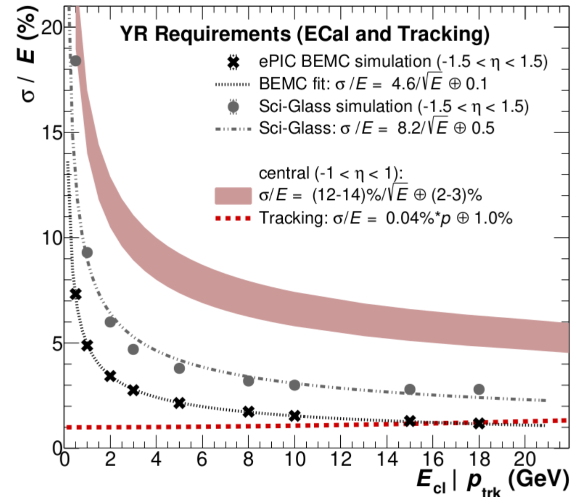
ePIC Detector Layout

ePIC Calorimeter Detectors: Performance

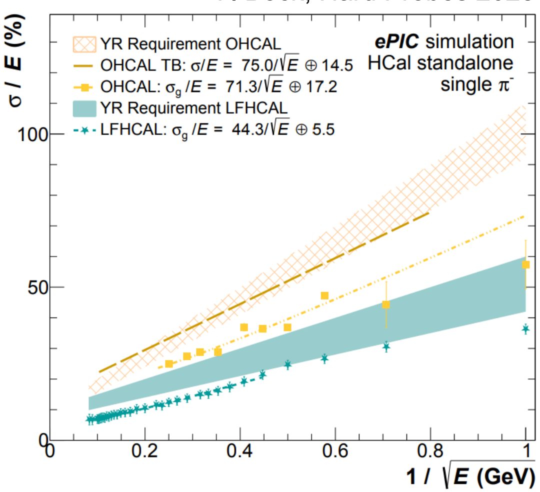
N. Schmidt







F. Bock, Hard Probes 2023



Performance on energy resolution and matching:

- Technologies fulfill YR requirements for energy resolution
- Ongoing simulation studies related to overlaps between different η regions for calorimetry and reconstruction algorithms

Ongoing work on Monte-Carlo validation:

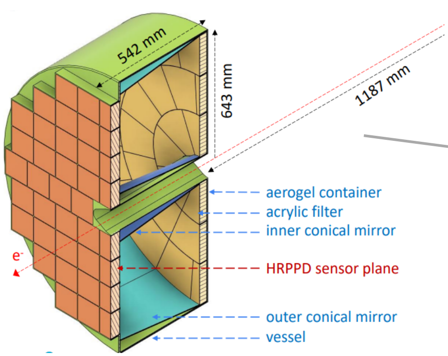
- Validation for high Z absorbers

ePIC Detector Layout

ePIC PID Detectors: Layout

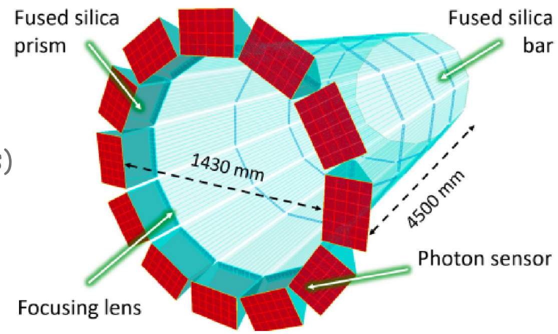
Proximity Focused (pfRICH)

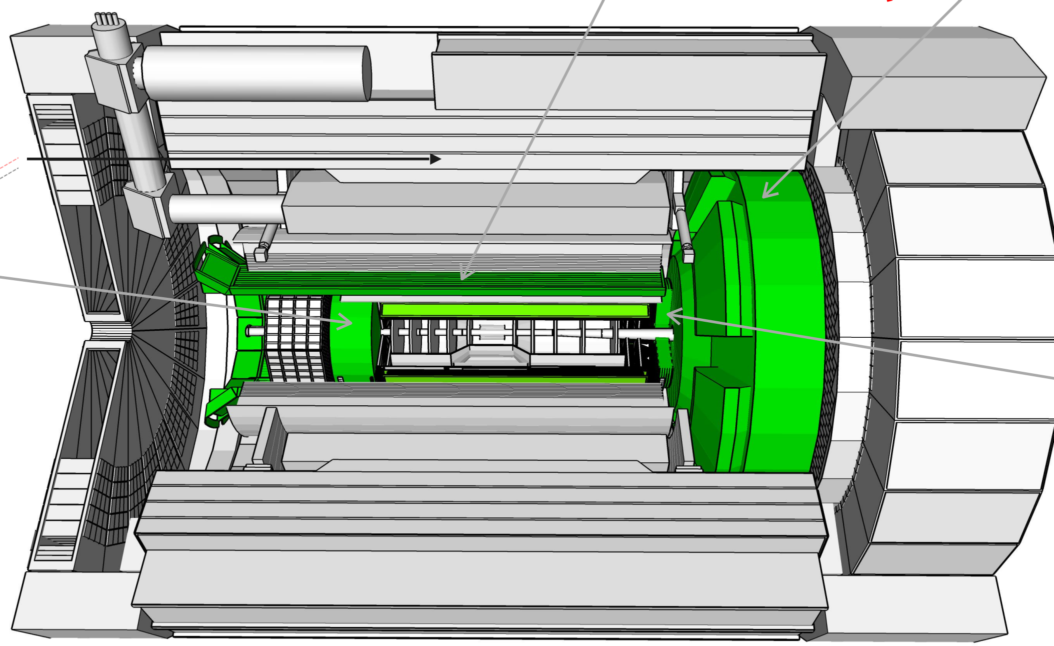
- Long proximity gap (~40 cm)
- Sensor: LAPPDs
- up to 9 GeV/c 36 π/K sep.



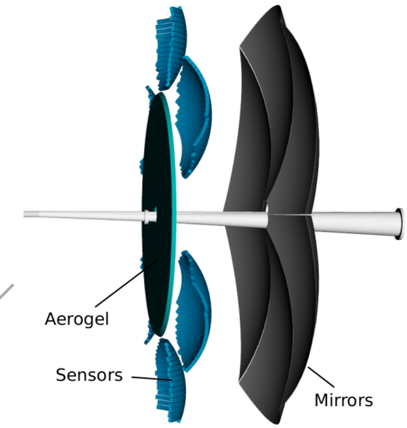
High-Performance DIRC

- Quartz bar radiator (BaBAR bars)
- light detection with MCP-PMTs
- Fully focused
- π/K 36 separation at 6 GeV/c



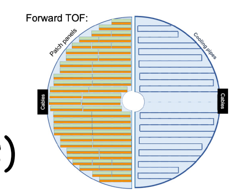


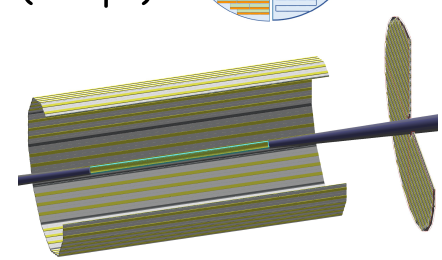
Dual-Radiator RICH (dRICH)



- C_2F_6 Gas Volume and Aerogel
- Sensors tiled on spheres (SiPMs)
- π/K 3σ sep. at 50 GeV/c

AC-LGAD TOF (~30ps)





- Accurate space point for tracking / Low p PID
- Forward disk and central barrel

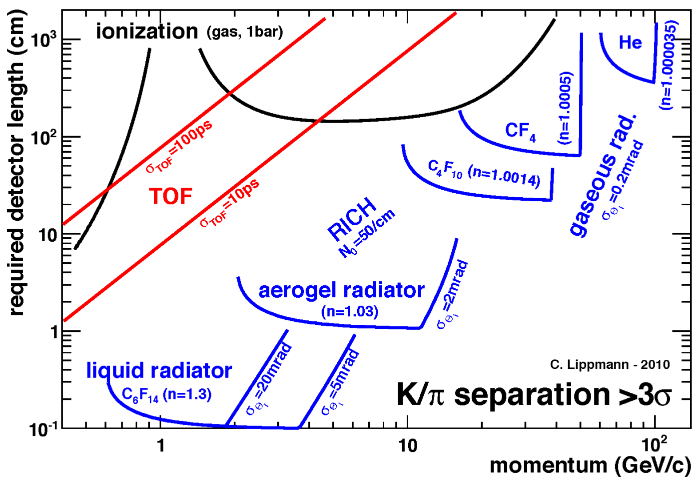
ePIC Detector Layout

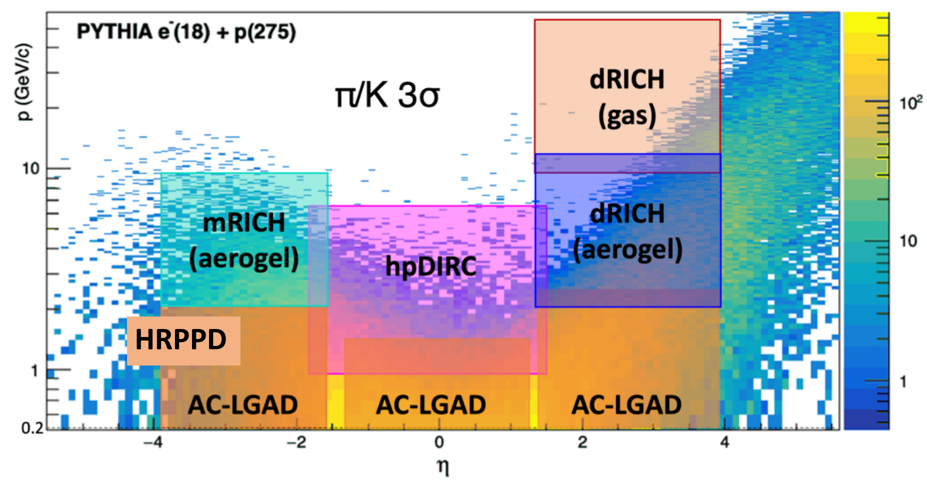
ePIC PID Detectors: Performance

Particle IDentification needs:

- Electrons from photons ➜ 4π coverage in tracking
- Electrons from charged hadrons ➜ mostly provided by calorimetry and tracking
- Charged pions, kaons, and protons from each other on track level ➜ Cherenkov detectors, complemented by ToF

Rapidity	π/K/p and π^0/γ	e/h	Min p_T (E)
-3.5 – -1.0	7 GeV/c	18 GeV/c	100 MeV/c
-1.0 – 1.0	8-10 GeV/c	8 GeV/c	100 MeV/c
1.0 – 3.5	50 GeV/c	20 GeV/c	100 MeV/c

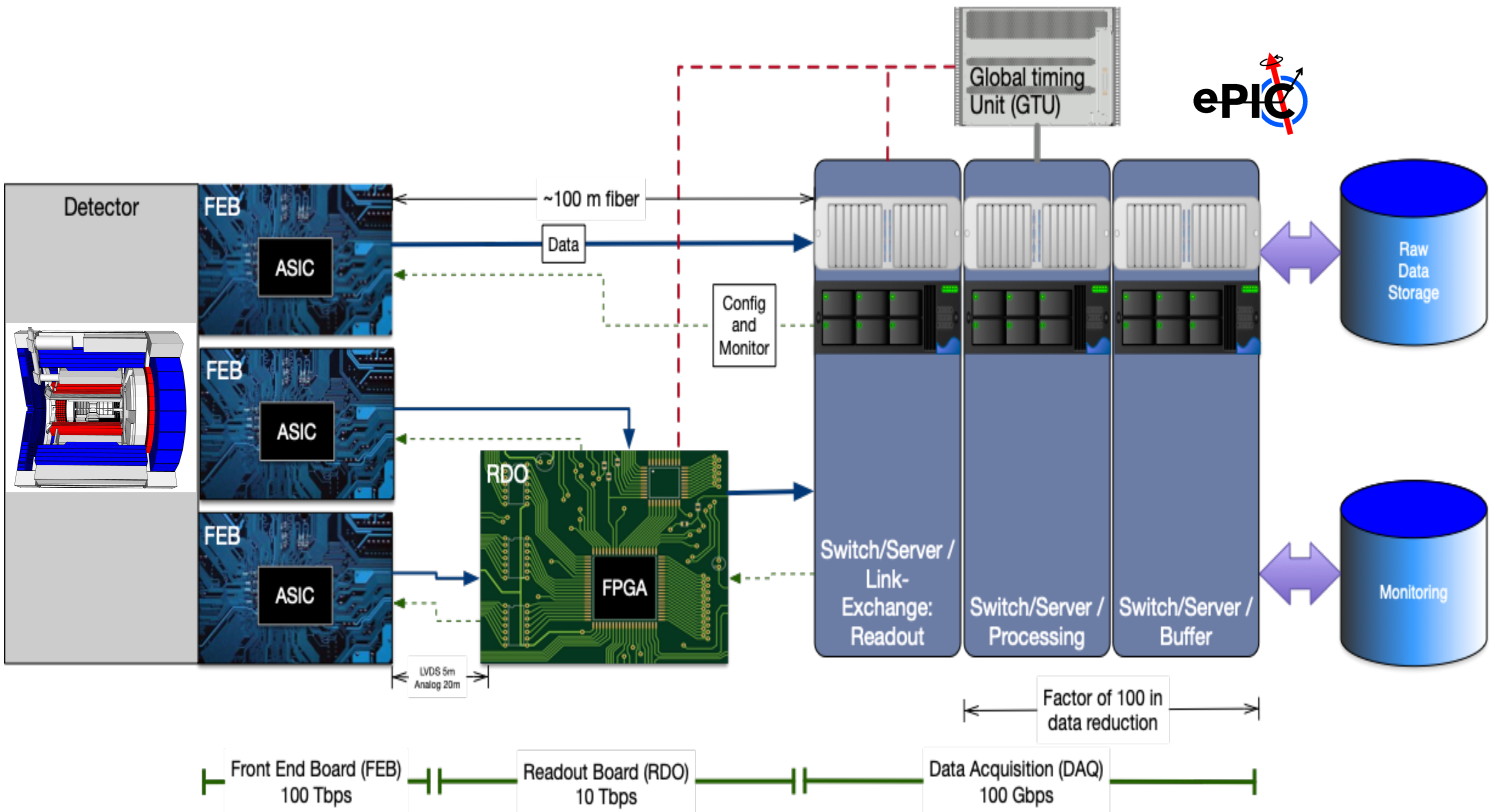




Critical: Need more than one technology to cover the entire momentum ranges at different rapidities!

ePIC Detector Layout

- ePIC Streaming DAQ system



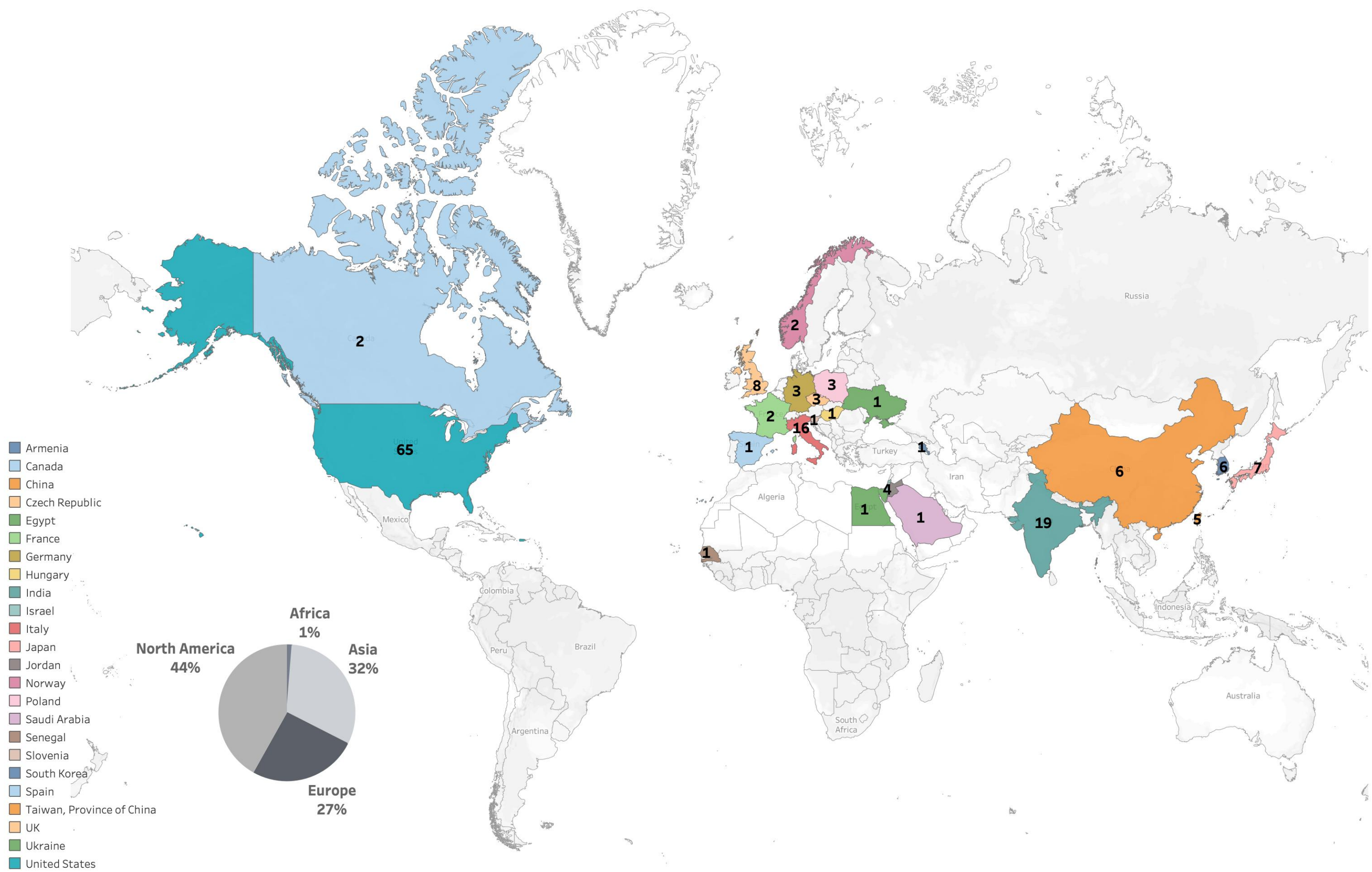
- No External trigger
- All collision data digitized, but zero suppressed at FEB
- Low / zero dead-time
- Event selection can be based on full data from all detectors (in real-time, or later)
- Collision data flow is independent and unidirectional ➜ no global latency requirements
- Avoiding hardware triggers avoids complex custom hardware and firmware
- Data volume is reduced as much as possible at each stage

ePIC Collaboration

- World Map - Institutions

ePIC - A global pursuit for a new EIC experiment at IP6 at BNL

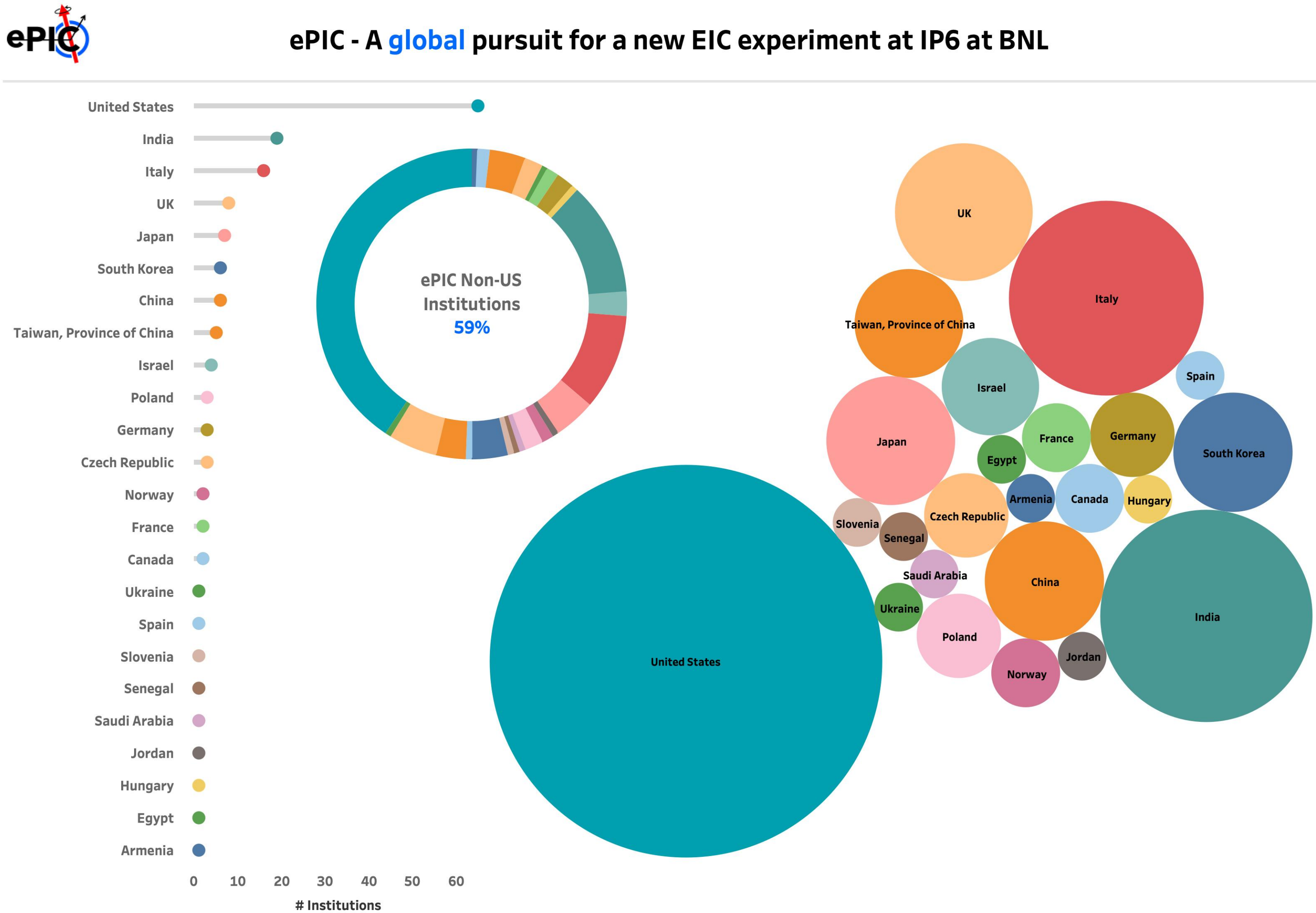
ePIC Institutions	ePIC Countries	ePIC World Region
160	24	4



Interactive Tableau link

ePIC Collaboration

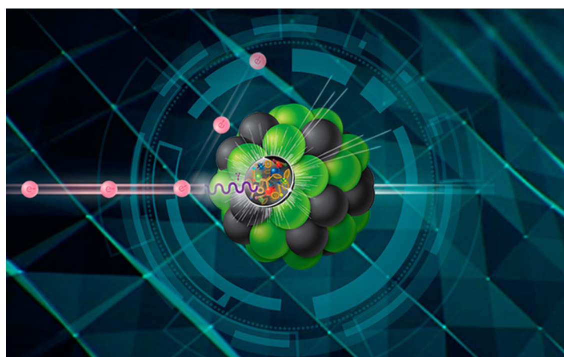
Number of Institutions



Interactive Tableau link

Summary and Next Steps

- Over two decades, the nuclear physics community has developed the scientific and technical case for the Electron-Ion Collider, to push the frontiers of human understanding of the fundamental structure and dynamics of matter ➜ Emergent phenomena in QCD!
- Enormously profit from a diverse set of experiences among experimentalists and theorists at numerous institutions worldwide ➜ Critical for a broad EIC scientific program
- Successful merging of several proposal efforts, forming a new collaboration in 2022/2023: ePIC collaboration
- A very exciting time is ahead of us to explore the structure and dynamics of matter at a new ep/eA collider facility following years of preparation - Join us!



Summary and Next Steps

- Schedule: EIC Project Detector at IP 6 / ePIC