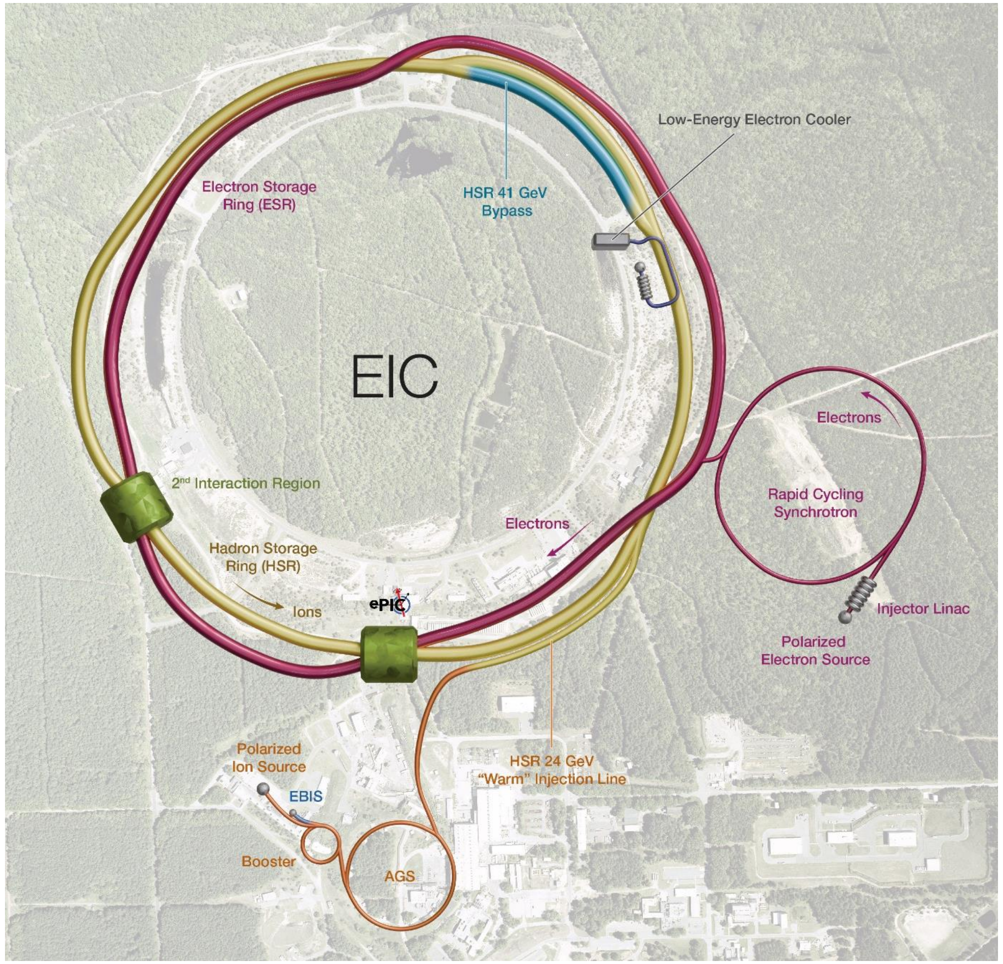


ePIC experiment:

Detector and Physics Opportunities

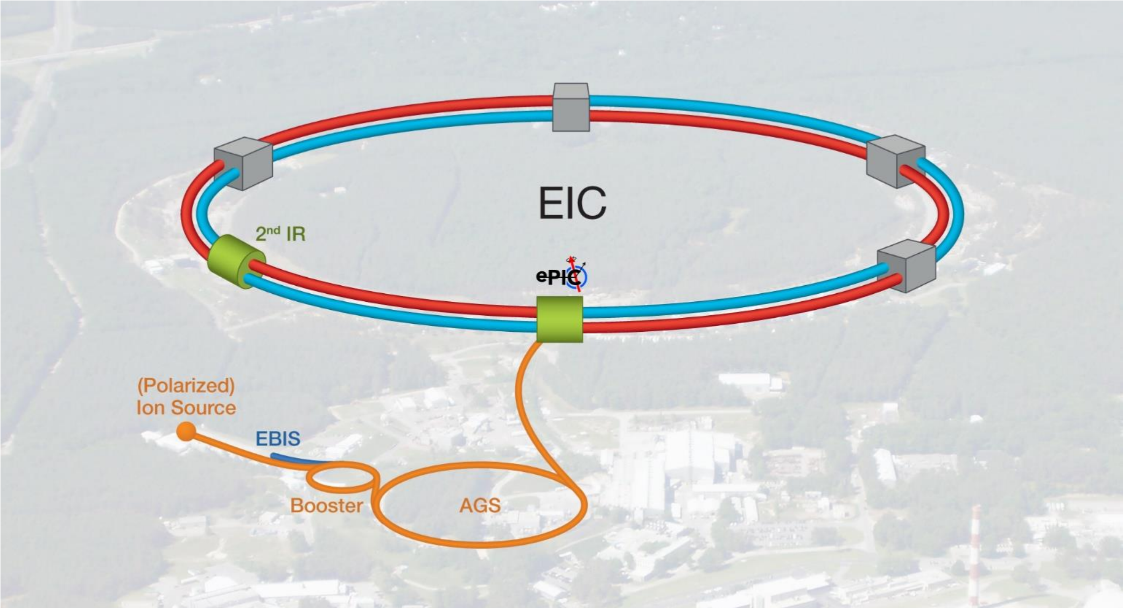
Carlos Muñoz Camacho
IJCLab, CNRS/IN2P3 (France)

Outline

- **The EIC and ePIC in context**
Facility, detector, and NAS science pillars
- **Why an Early Science Report?**
Realistic first-years running assumptions and physics reach
- **Early measurements from inclusive DIS**
Proton/nuclear PDFs, spin structure, and α_s
- **From SIDIS to multidimensional structure**
TMDs, fragmentation, spin–orbit effects, and saturation-sensitive correlations
- **Exclusive, diffractive, and tagged channels**
DVCS/GPDs, gluon imaging, and spectator-tagged F_2^n
- **Jets and heavy flavor as hard probes**
Gluon dynamics, charm hadronization, and cold nuclear matter effects
- **Early science and the path to the full EIC**
What starts immediately, and what requires full energy and luminosity

The EIC facility

- Highly polarized electron / Highly polarized proton and light ions /Unpolarized heavy ions
- CME: ~ 20–140 GeV
- Luminosity: ~ $10^{33\text{-}34}$ $cm^{-2}s^{-1}$

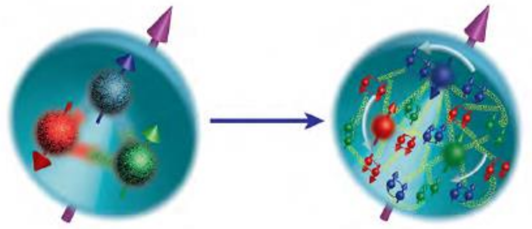


- Polarized electron source and 400 MeV injector linac to feed a rapid cycling synchrotron design to avoid depolarizing resonances up to the maximum e-beam energy of 18 GeV
- Polarized proton beams and ion beams based on existing RHIC facility
- 2 detector interaction points capability in the design

Motivation – the EIC science program

Origin of spin:

How does the spin-1/2 of the nucleon arise from the spin of quarks, gluons and their orbital angular momenta?

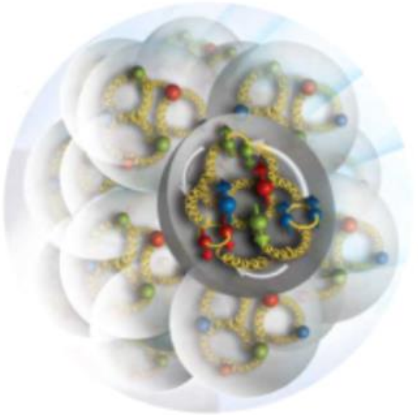


Origin of mass:

How do massless gluons make up for most of the nucleon mass?

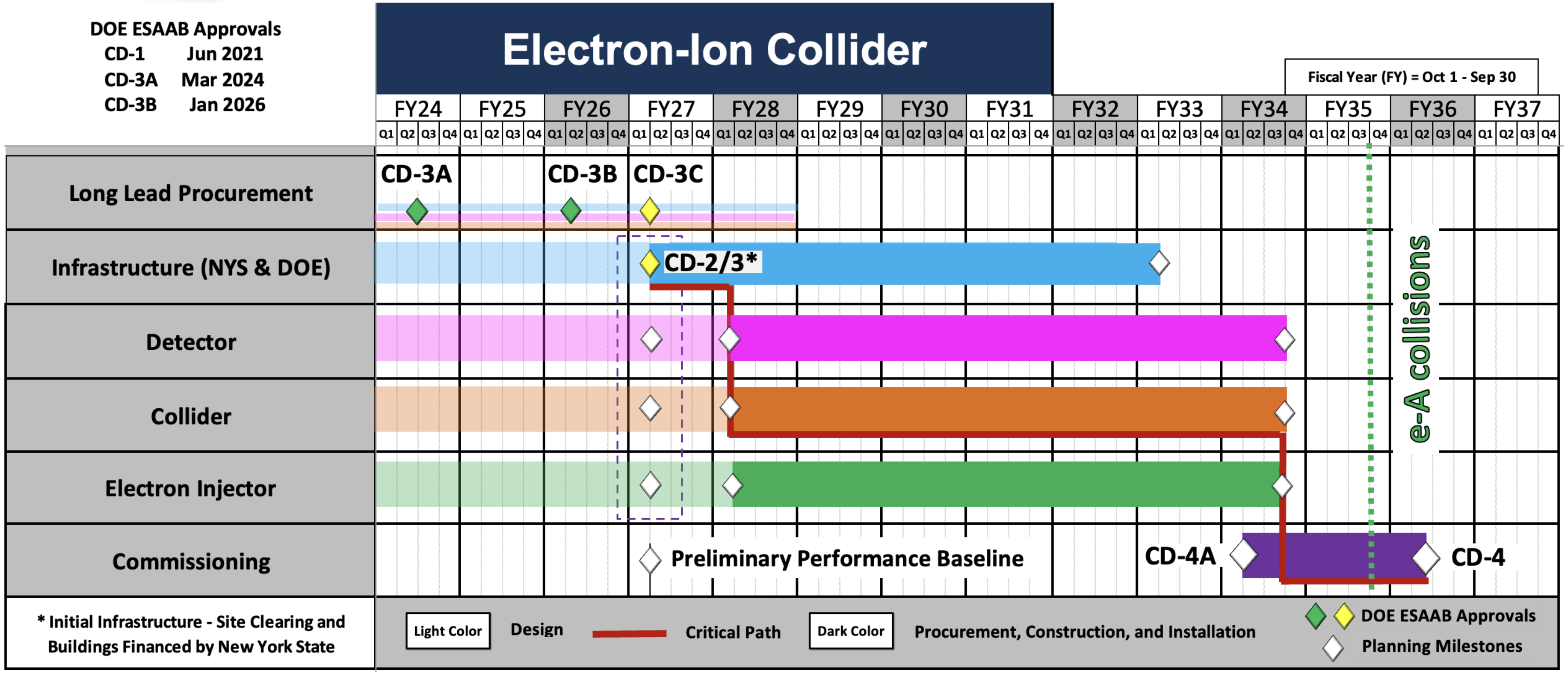
Gluons in nuclei:

Does gluon density saturate at high energy giving rise to a new regime of matter?



EIC reference schedule

DOE ESAAB Approvals
CD-1 Jun 2021
CD-3A Mar 2024
CD-3B Jan 2026



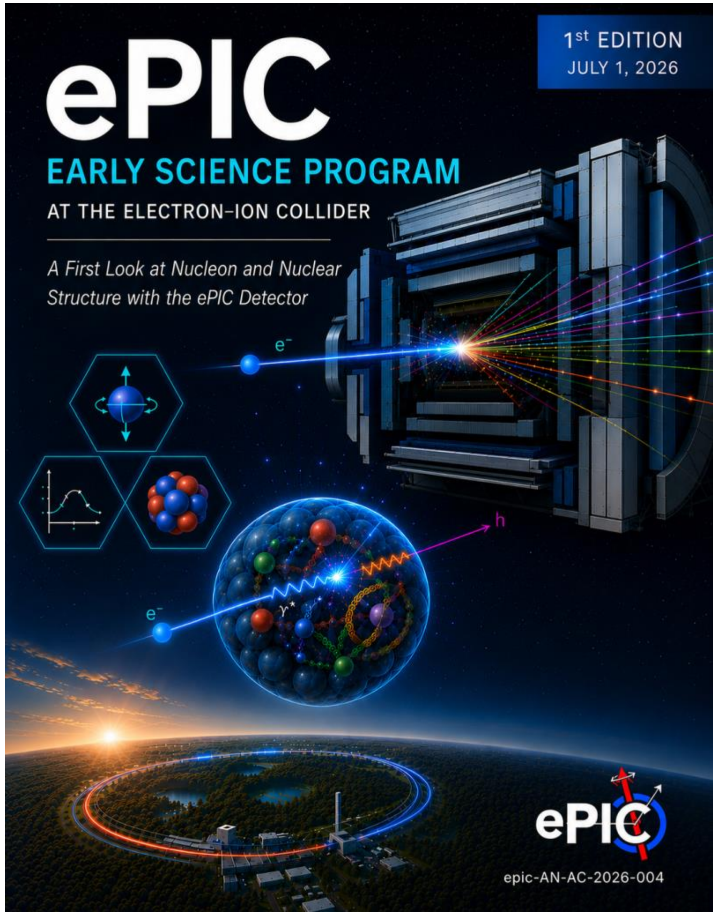
EIC detector milestones

- *Currently: Finalizing detector design*
- 2026: TDR completed (CD-2/3)
- 2027: Detector construction
- 2033/4: Installation/commissioning
- 2035: Start of physics program

DOE project phases:

- CD-0: Approve mission need
- CD-1: Approve Alternative Selection and Cost Range
- CD-2: Approve performance Baseline
- CD-3: Approve Start of Construction
- CD-4: Approve Start of Operations

ePIC Early Science Report



- Prepared in response to a BNL/JLab charge: identify science possible before the ramp-up to full EIC capability.
- Uses realistic early-running beam configurations and full ePIC detector simulations.
- Section 6 is dedicated to Exclusive and Diffractive physics.
- As far as ePIC subdetectors:
  - Inclusive DIS begins with the scattered electron.
  - Exclusive, diffractive and tagged measurements require the whole event: e′, γ or meson, recoil proton, nuclear breakup vetoes and spectator fragments.
  - Roman Pots / OMD provide the essential forward-proton and spectator information. The backward ECal anchors the electron-going electromagnetic reconstruction.

ePIC science and the NAS pillars

NAS Science Pillars and ePIC early science Measurements

Examples inside each cell indicate how ePIC early physics measurements connect to the three NAS pillars

ePIC early science measurement type	Origin of nucleon mass	Origin of nucleon spin	Emergent properties of dense gluon matter
Inclusive DIS	**Supporting** • F_2 and F_L structure functions • Proton PDFs and α_S	**Strong** • $A_1^{p,n}$ and $g_1^{p,n}$ • Gluon helicity PDFs	**Important** • Nuclear F_2 ratios • Nuclear PDF constraints
Semi-inclusive DIS	**Supporting** • Unpolarized TMD PDFs • Nuclear fragmentation functions	**Strong** • Sivers A_{UT} • Collins asymmetries • Quark helicity PDFs	**Strong** • Di-hadron correlations • Nuclear hadronization / fragmentation
Exclusive / Diffractive / Tagged	**Strong** • DVCS / GPD imaging • Quarkonium production • Meson form factors / structure functions	**Important** • Spectator-tagged $A_1(n)$ • GPD constraints on OAM	**Strong** • Coherent/incoherent VM in eA
Jets & Heavy Flavor	**Important** • Open charm production • Λ_c/D^0 ratio	**Supporting** • Δg from charm/jets • Hadron-in-jet Collins FF	**Important** • Charged-jet R_{eA} • D^0-in-jet R_{eA}

Origin of mass
DVCS/GPD imaging, vector mesons, meson form factors and meson structure functions.

Origin of spin
Spectator-tagged neutron observables and GPD constraints relevant to orbital angular momentum.

Dense gluonic matter
Coherent/incoherent vector-meson production in e + A accesses average gluon density and fluctuations.

Detector implication:
The “exclusive/diffractive/tagged” row becomes real only with forward particles and electromagnetic final states reconstructed well.

Early running assumptions

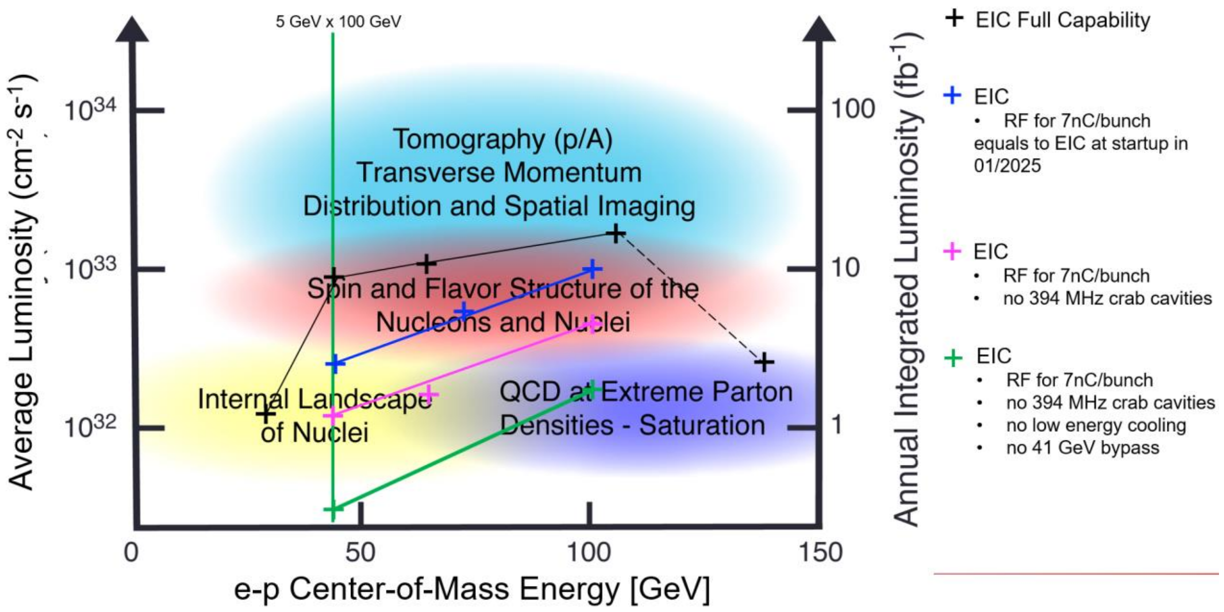
Species	Beam energy (GeV)	Integrated luminosity (fb^{-1})	Electron-beam polarization	Hadron-beam polarization
e+Ag	9×115	1.0	NO	N/A
e+D	9×130	1.5	LONG	NO
$e+p$	9×130	1.0	LONG	TRANS and/or LONG
$e+p$	9×275	2.5	LONG	TRANS and/or LONG
e+Au	9×100	1.0	LONG	N/A
$e+{}^3$He	9×166	1.5	LONG	TRANS and/or LONG

Table 2: EIC early science matrix. The $e + A$ energy and luminosity are per nucleon.

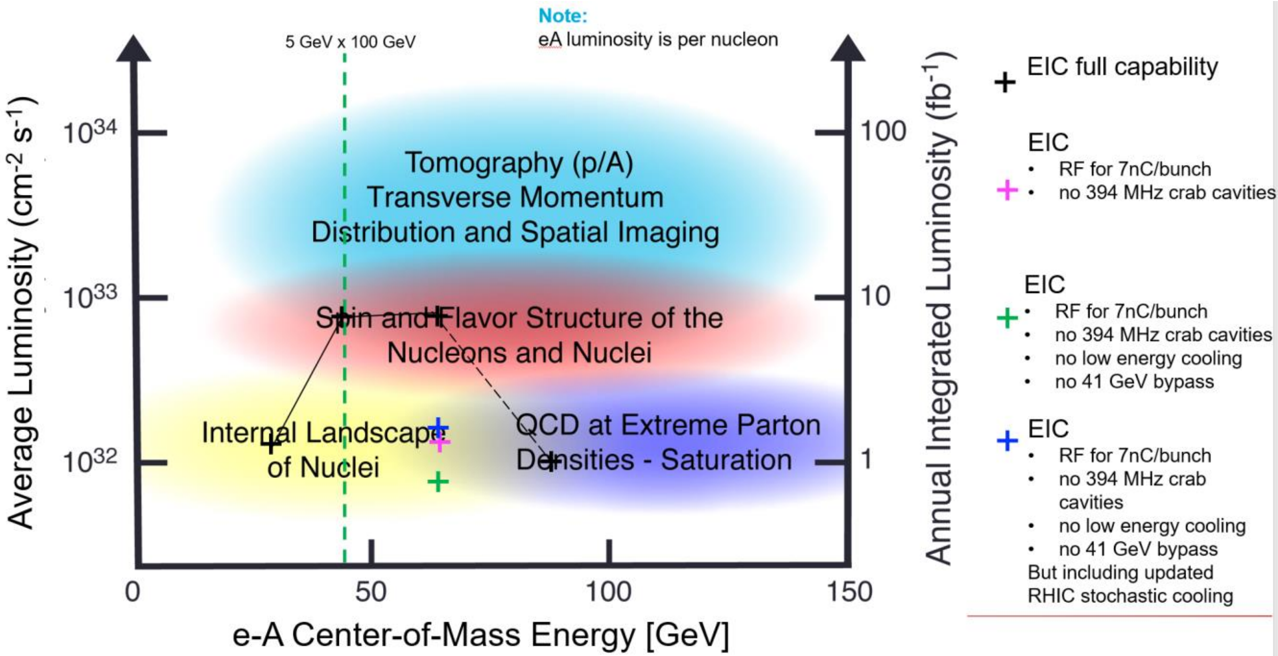
- Baseline electron beam: 9 GeV, with an upgrade path to 18 GeV.
- Initial e + A running supports early diffractive and low-multiplicity nuclear measurements.
- Polarized e + p and e + ^{3}He unlock spin and tagged-neutron observables.
- Far-forward commissioning determines when proton and spectator tagging can be fully exploited.

Luminosity: early science

ep



eA



The EIC detector: ePIC

Calorimetry:
- Backward HCal (Steel+scint)
- $PbWO_4$ EMCal in backward direction
- Sampling & Imaging Barrel EMCal
- Outer HCal (sPHENIX re-use)
- Finely segmented EMCal +HCal in forward direction

hadronic calorimeters

Solenoidal Magnet

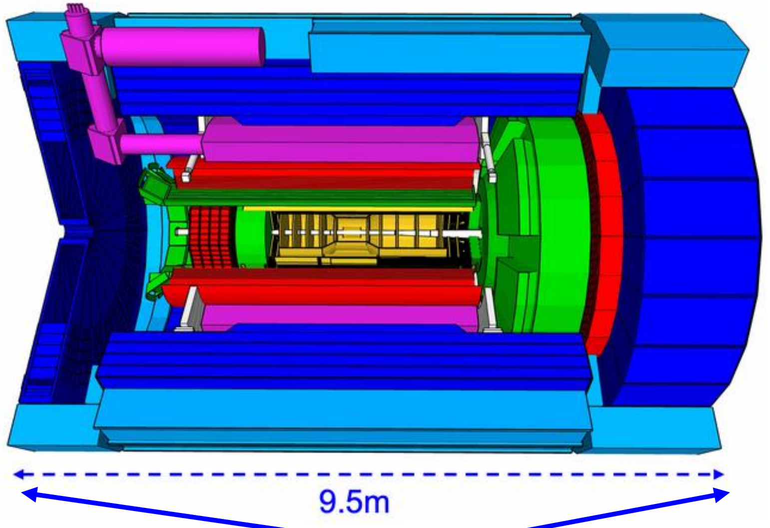
e/m calorimeters

ToF, DIRC, RICH detectors

MPG trackers

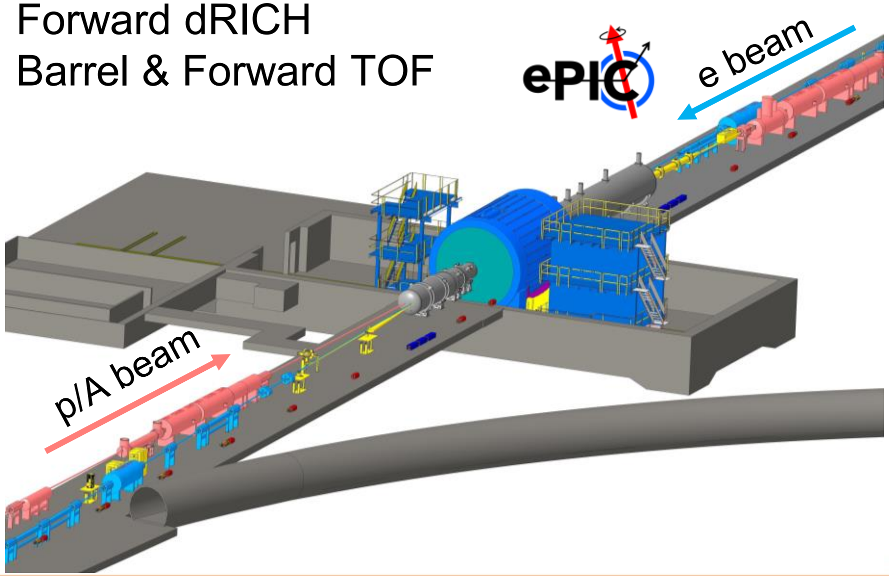
MAPS tracker

25 subdetectors incl. polarimeters



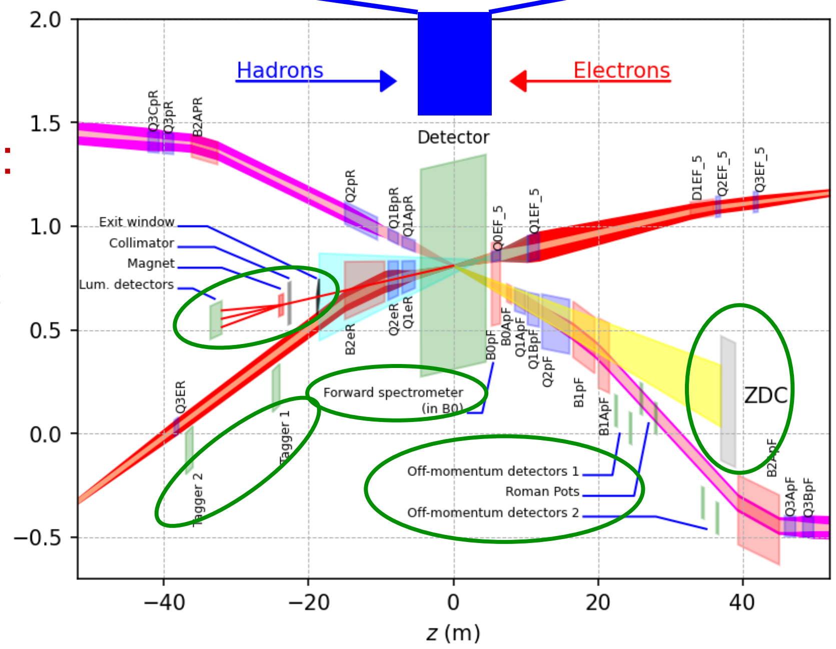
Tracking:
- New 1.7T solenoid
- Si MAPS Tracker
- MPGDs (μRWELL/μMegas)

PID:
- Backward pfRICH
- Barrel hpDIRC
- Forward dRICH
- Barrel & Forward TOF

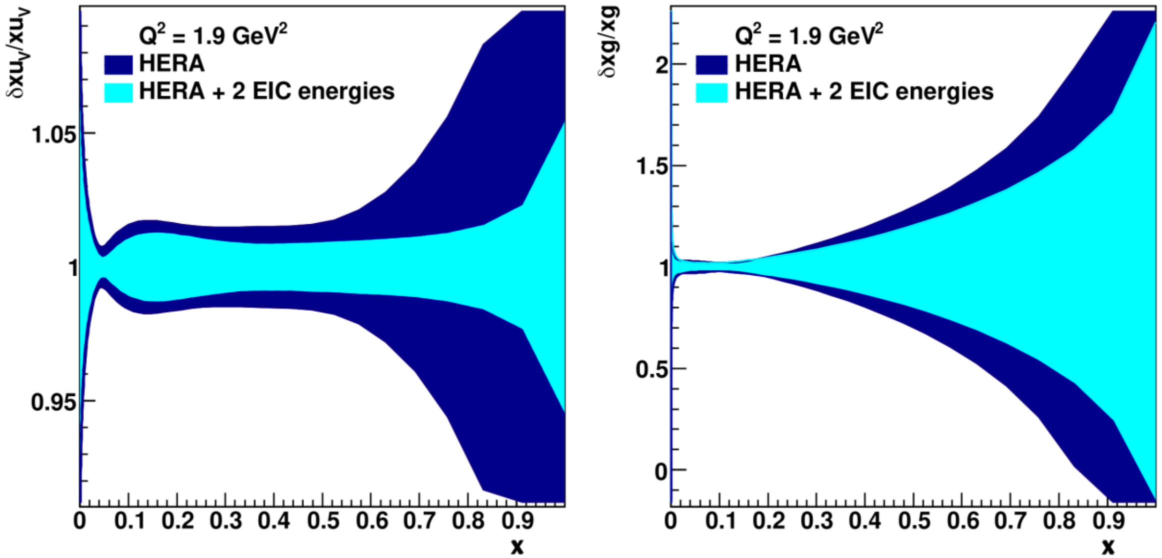


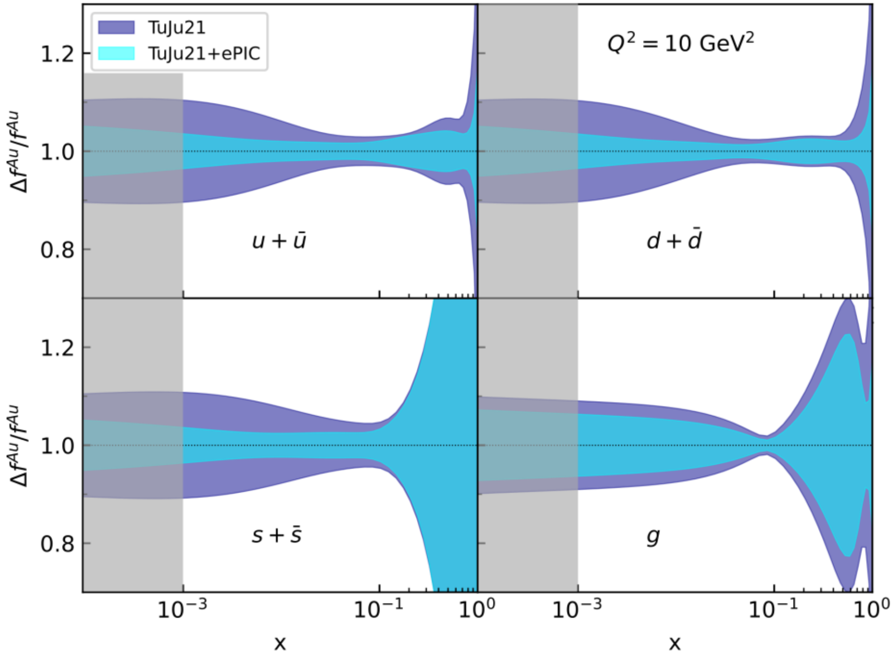
Far-Backward Detectors:
- Luminosity monitor.
- Low-Q^2 Tagger

Far-Forward Detectors:
- B0 Tracking and Photon Detection
- Roman Pots and Off-Momentum Detectors.
- Zero-Degree Calorimeter



Inclusive DIS measurements





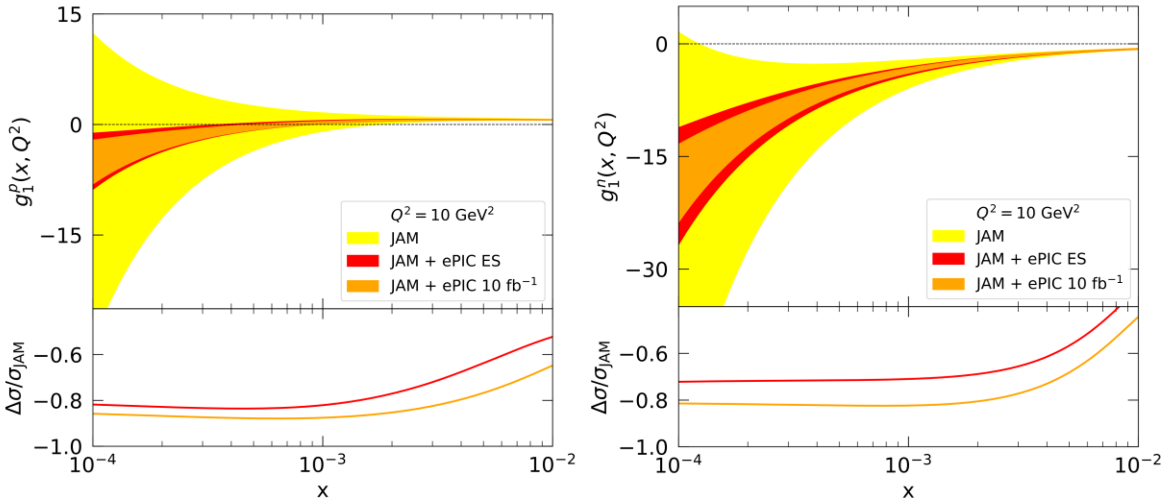
Proton PDFs

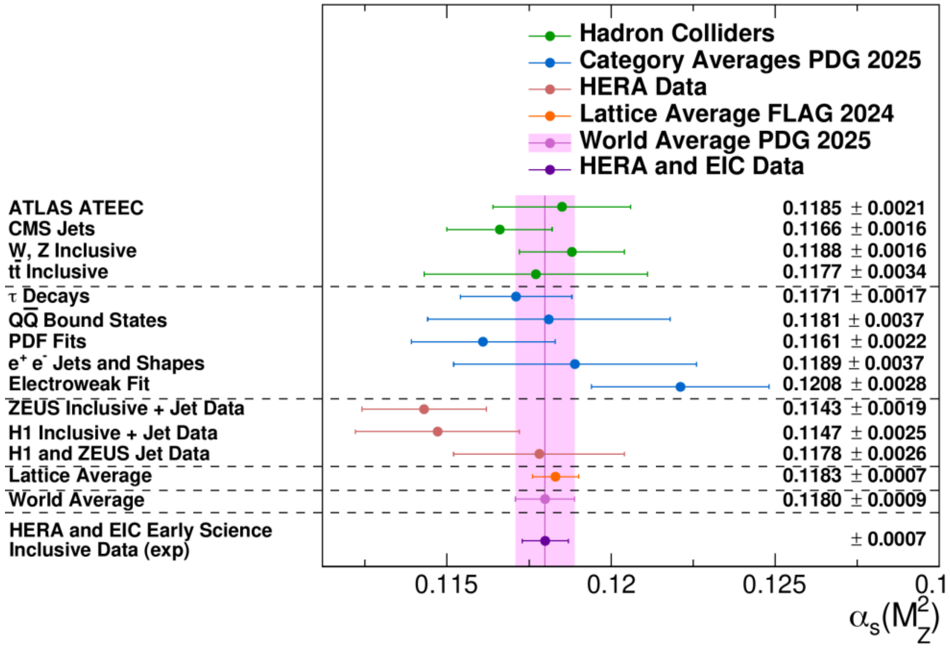
Early e+p DIS reduces uncertainty for up-valence and gluon PDFs, especially at intermediate and high x.

Nuclear PDFs

Early e+Au data extend nuclear DIS reach toward x ~ 10^{-3} and constrain sea, valence and gluon nPDFs.

Inclusive DIS measurements





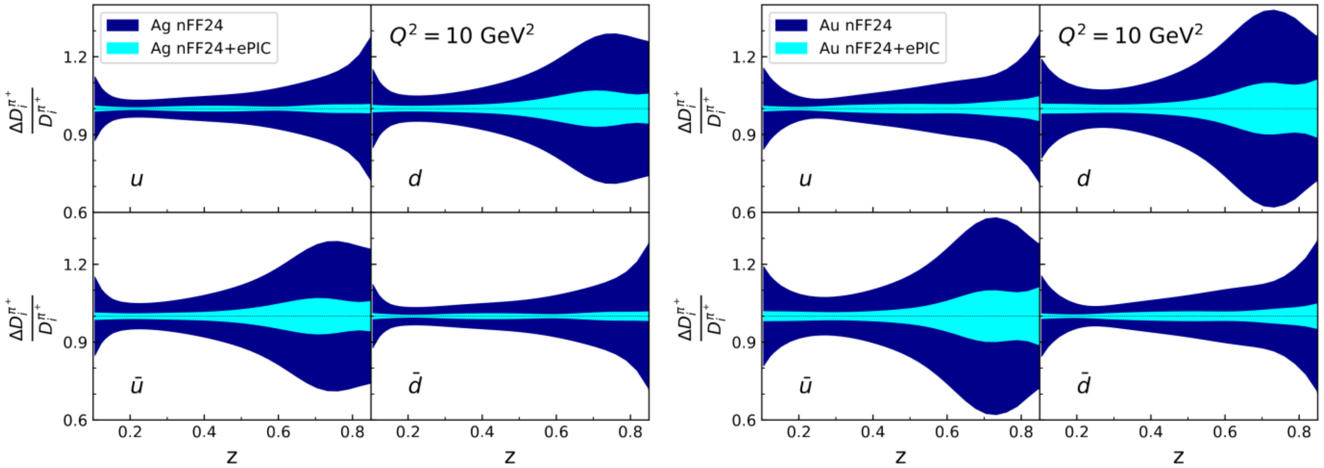
Spin structure

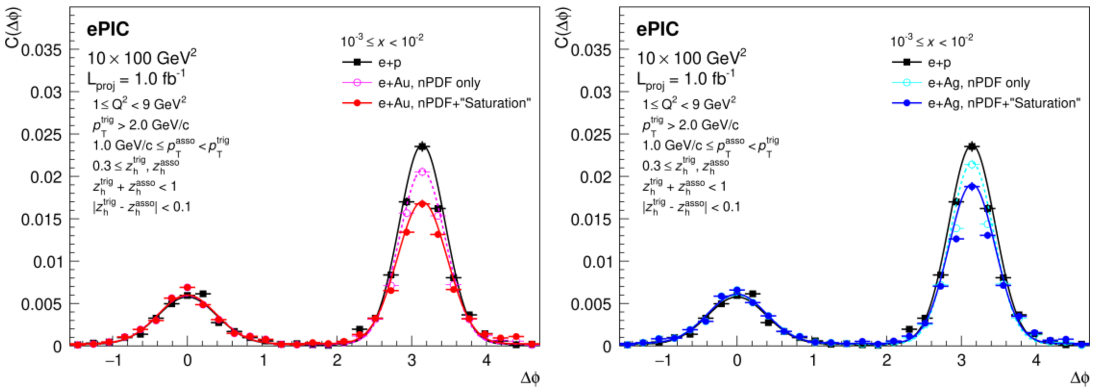
Polarized DIS expands g1 constraints into the low-x region for proton and neutron spin studies.

Strong coupling constant α_s

- Fit early e+p reduced cross sections together with HERA data in an NNLO DGLAP framework.
- PDFs and the strong coupling are determined simultaneously, giving a precision test of QCD from clean DIS data.

Semi-inclusive DIS





Nuclear fragmentation functions

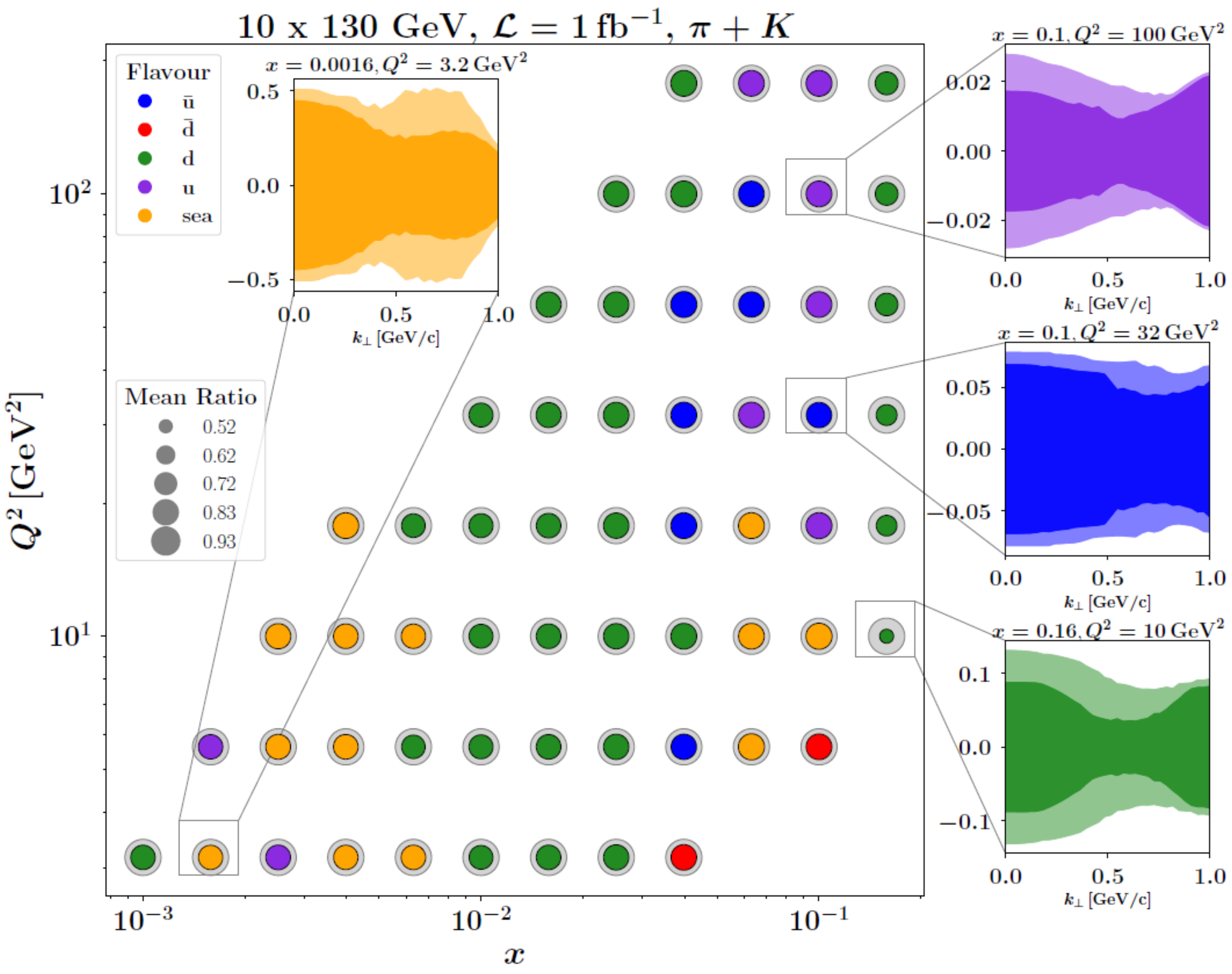
e+Ag and e+Au SIDIS multiplicities sharply reduce nFF uncertainties, improving cold-nuclear-matter baselines.

Di-hadron correlations

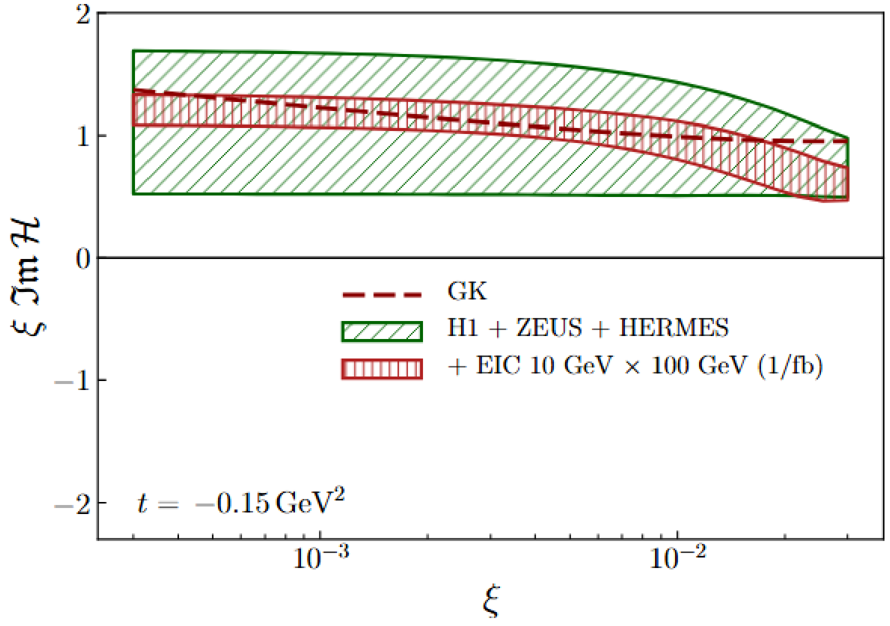
Away-side peak suppression in e+A relative to e+p provides an early saturation-sensitive observable.

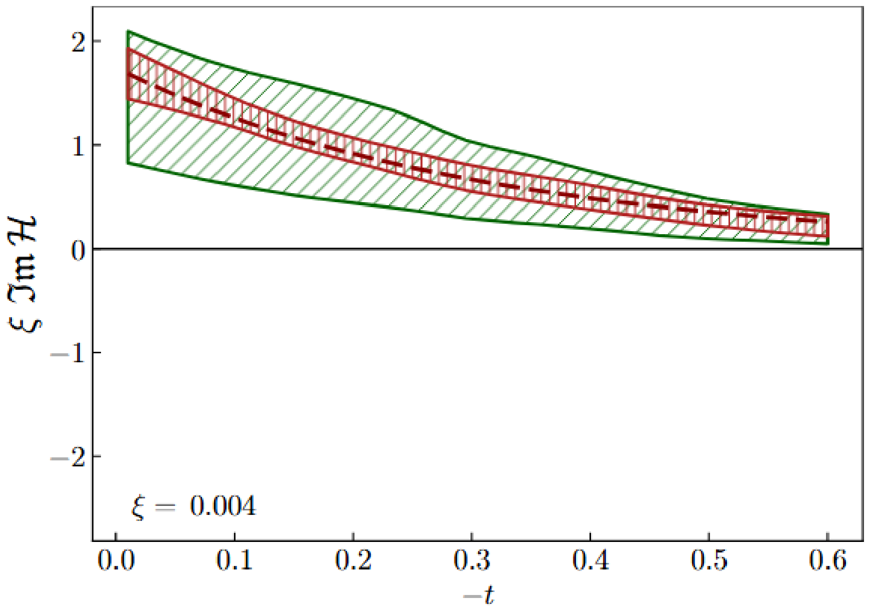
Semi-inclusive DIS: TMDs

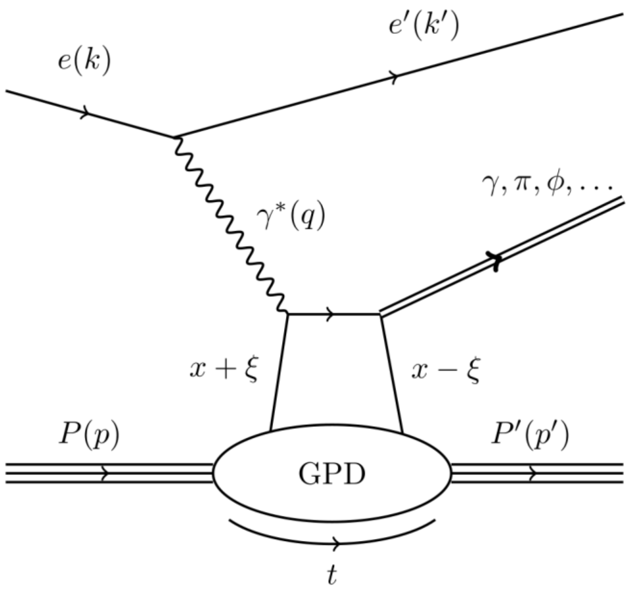
- Identified hadrons add flavor sensitivity and access to fragmentation.
- Unpolarized TMD PDFs establish the baseline for all polarized TMD extractions.
- Sivers and Collins observables probe spin-orbit correlations, transversity, and tensor charges.



Exclusive measurements: DVCS





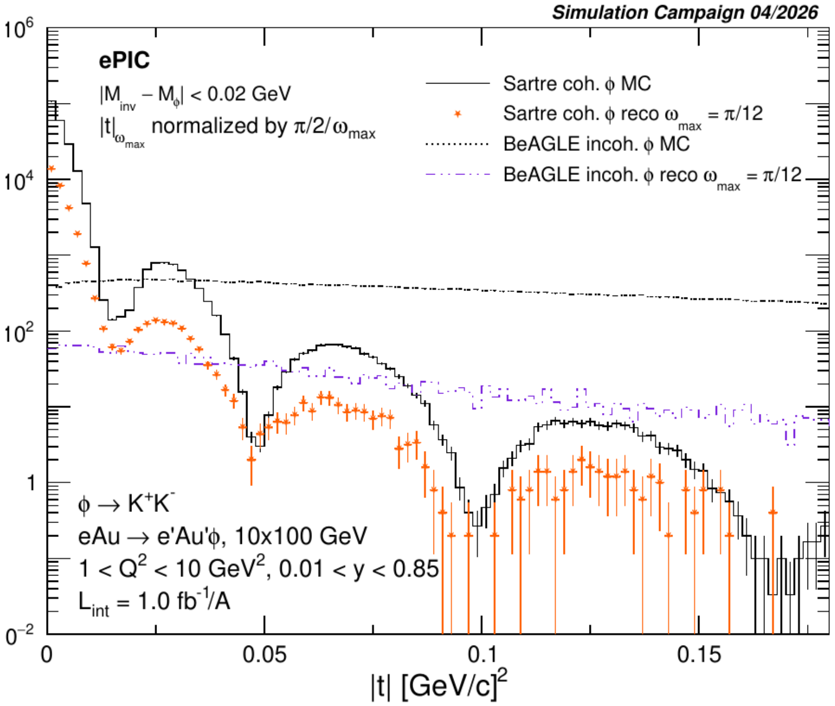


Early Physics Impact:

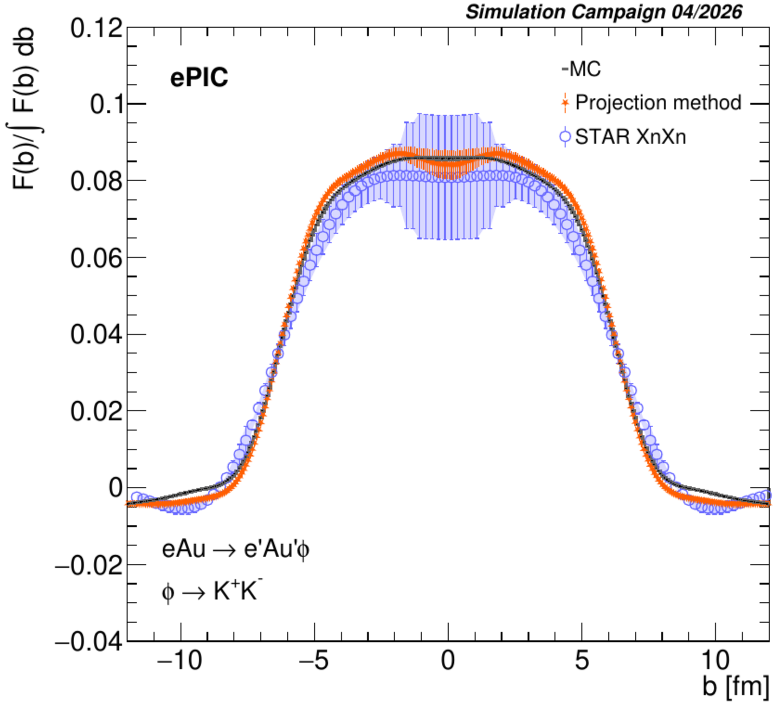
Projected DVCS data narrow uncertainty bands on Im H, one of the Compton form factors entering the DVCS amplitude.

- DVCS is the clean benchmark for Compton Form Factors and GPD-based proton imaging.

Coherent φ in e+Au: diffraction & *g* imaging



Projection-method |t| reconstruction resolves the diffractive structure and follows the MC truth more closely than the standard method.



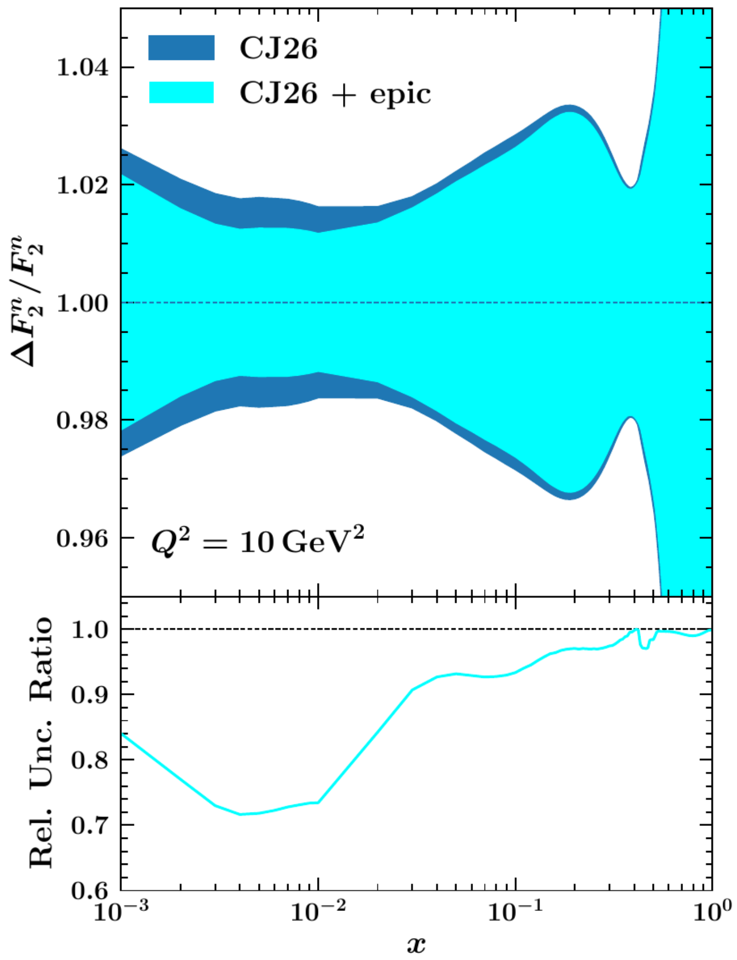
The Fourier–Bessel transform converts the measured |t| distribution into the transverse gluon spatial profile.

Key detectors:

OMD/RP/ZDC vetoes and tags control coherent vs incoherent breakup; electron and kaon reconstruction controls exclusivity

Spectator-tagged deuteron data: F_2^n

CJ26 baseline uncertainty on F_2^n at $Q^2 = 10$ GeV^2, compared with CJ26 + ePIC spectator-tagged pseudo-data.



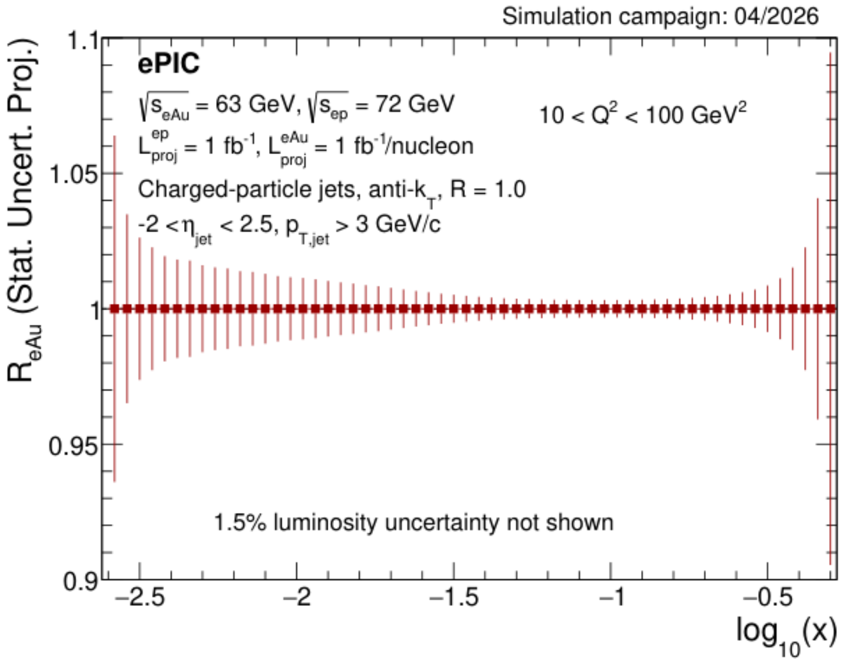
- ➢ Use deuterium as an effective neutron target: $e+d \to e' + X + p_{spec}$
- ➢ A low-momentum spectator proton tags DIS on the neutron and fixes the initial p/n configuration.
- ➢ Extrapolation to the deuteron pole selects the large-separation p+n limit, where the struck neutron is effectively free.
- ➢ This minimizes nuclear binding and final-state-interaction corrections, enabling a clean extraction of the free-neutron structure function F_2^n).

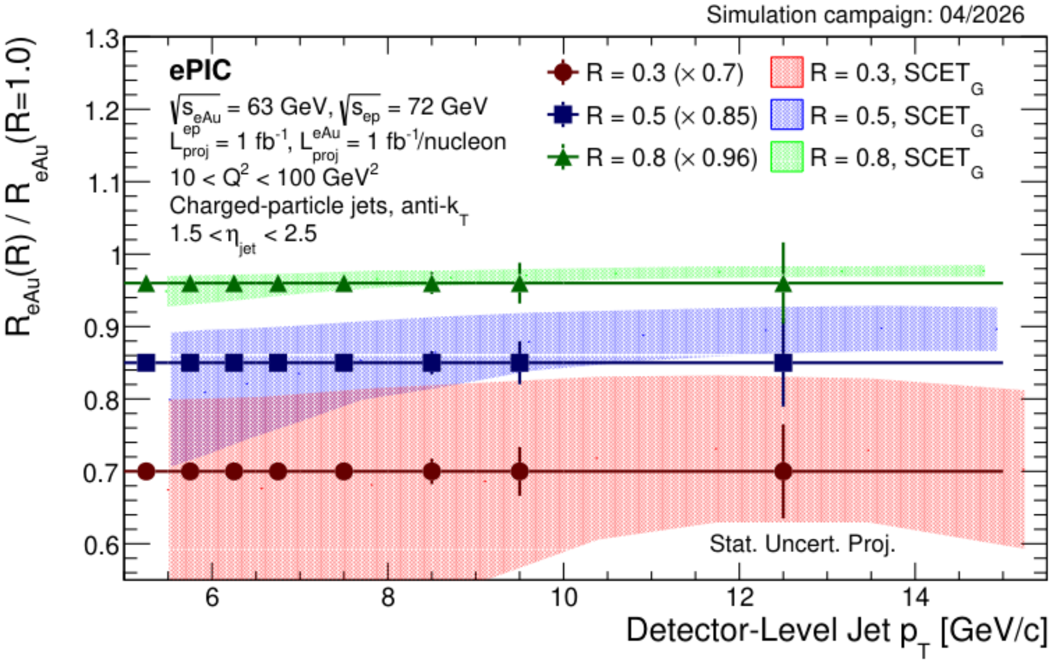
- The relative uncertainty is reduced over a broad x range; around $x \simeq 5\times10^{-3}$, about 2% → 1.5% (≈25–30% reduction)
- This brings neutron-structure uncertainties closer to the scale required for deuteron shadowing tests and robust flavor-separated PDF constraints

F_2^n is a concrete early deliverable unlocked by far-forward tagging

Jets and heavy flavor

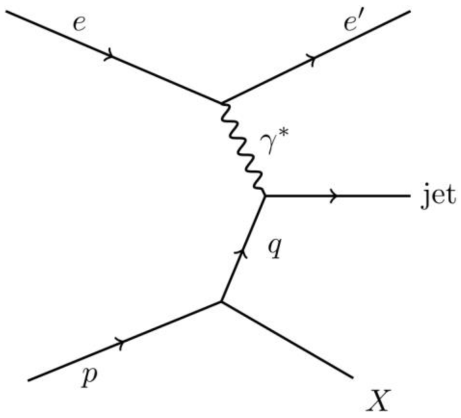
Inclusive charged-jet nuclear modification in e+Au

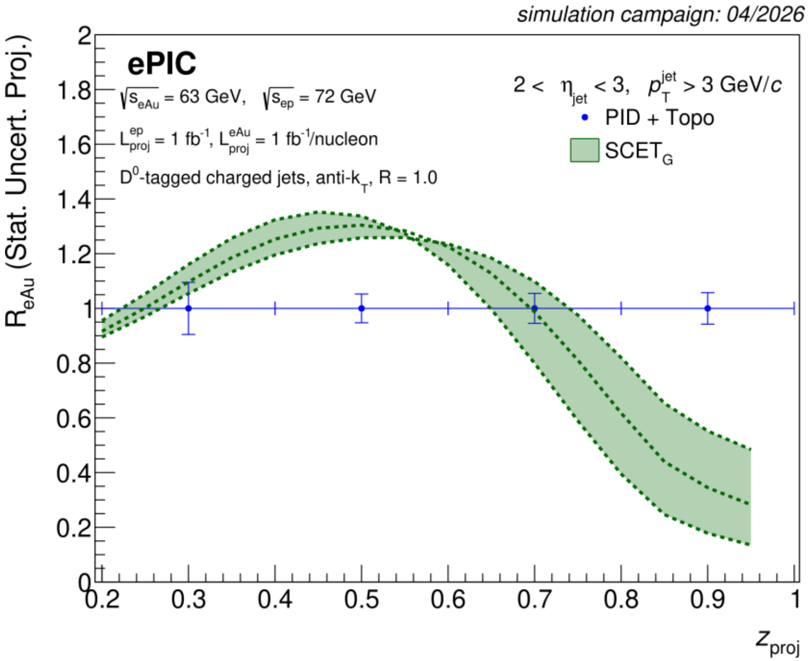


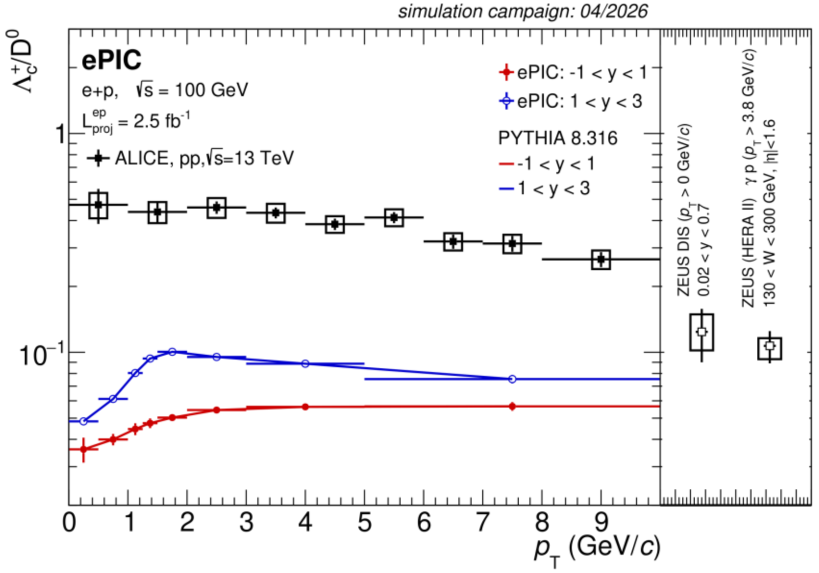


- Large-radius jets (R = 1.0): ReA mainly probes initial-state nuclear effects / nPDFs while minimizing final-state shower effects; projected statistical precision is generally below 2%.
- Jet-radius ratio ReA(R)/ReA(R = 1.0): initial-state effects largely cancel, enhancing sensitivity to final-state cold-nuclear-matter energy loss and shower broadening.
- Early e+Au and e+p running at 1 fb^-1 already provides quantitative constraints on parton propagation in cold nuclear matter.

Jets and heavy flavor







- Inclusive charged-jet ReA separates nPDF effects from final-state energy loss using jet-radius dependence.
- Charm production is a clean photon-gluon-fusion probe of gluon dynamics.
- Λ_c/D^0 and D^0-in-jet measurements test charm hadronization and cold nuclear matter modification.

EIC early running: limitations

Kinematic reach	9 GeV electrons limit the low-x frontier; fully entering saturation requires the 18 GeV upgrade path.
Luminosity	Early luminosities are powerful for benchmarks but limit fine multidimensional binning in x, Q^2 and t.
GPD tomography	DVCS can initiate the CFF/GPD program; quantitative model-independent tomography needs full luminosity.
Saturation	Coherent VM imaging in e + A provides early constraints; discovery-level saturation studies need full energy and luminosity.
Rare channels	Near-threshold quarkonium and some hard-probe channels are deferred beyond the early configuration.

Detector framing: early ePIC validates and begins the program; full EIC capability completes the NAS science case

Conclusion

Early ePIC is a physics program from day one.

Immediate impact

High-statistics inclusive and semi-inclusive measurements begin constraining proton, neutron and nuclear structure early.

Distinctive EIC capabilities

Collider e+A, polarization, tagged light nuclei, diffraction and hard probes open measurements unavailable elsewhere.

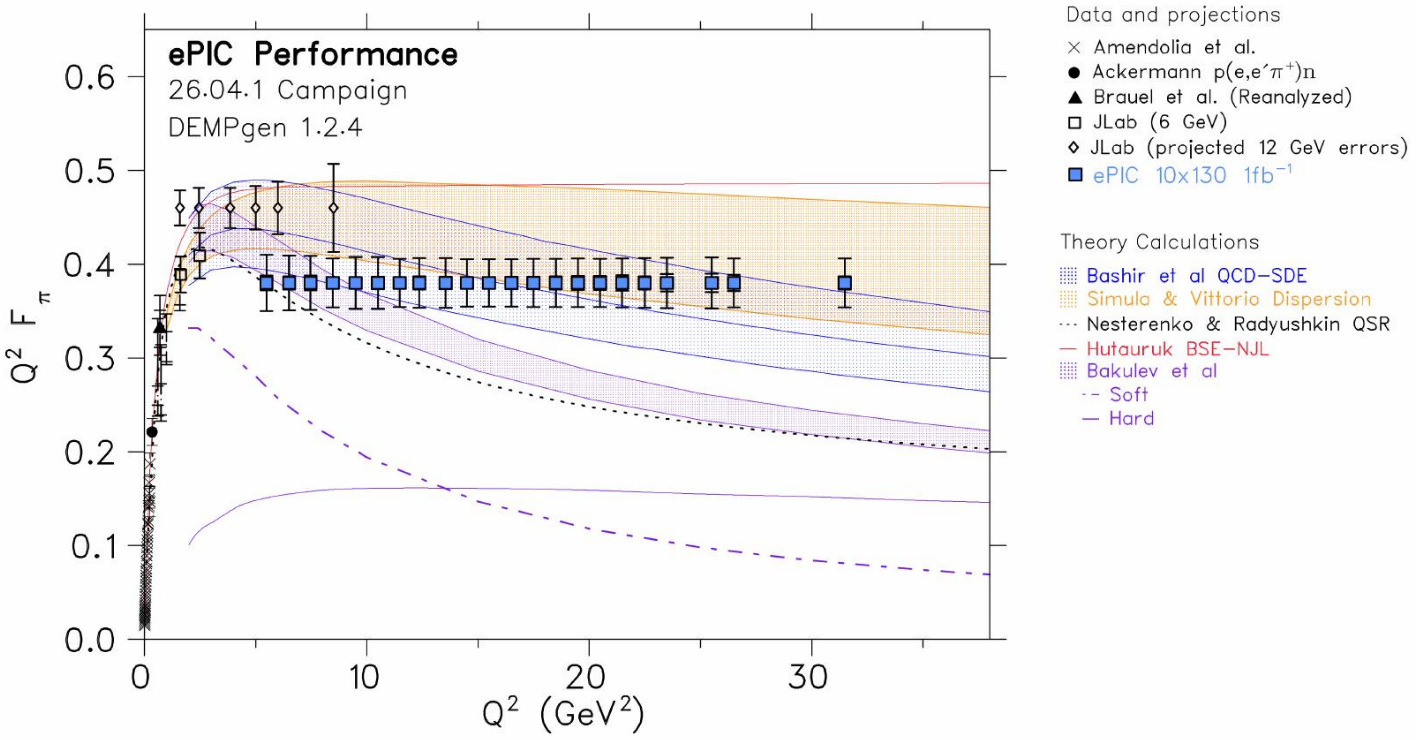
Path to full EIC

The early program establishes methods, benchmarks and first discoveries; the full machine completes the NAS science case.

The early science report shows a coherent first-stage program: world-leading QCD results now, and the foundation for the full EIC mission.

Backup

Meson structure measurements



Pion form factor:

Forward neutron tagging in ep → e′ π+ n enables access to Q^2F_π in collider kinematics.

Pion / kaon structure:

Tagged semi-inclusive measurements provide a route to pion and kaon structure functions; Λ tagging is a key handle for kaon structure.

Detector subsystems:

ZDC and far-forward instrumentation provide the tag; the backward ECal anchors scattered-electron kinematics entering the extraction.

Current pion form-factor projections include statistical and assumed systematic contributions; dedicated detector-level systematics remain to be finalized.

Changes in collider configuration

- 18 GeV electron beam energy will be an upgrade, but all preconditions to do so are included in the project
- ESR Main SRF systems are relocated from the currently planned IR-10 location to IR-08.
  - Potential 2nd detector location would move to IR-12
  - Would require a new Hall at IR-12 for a later EIC Detector 2 project
  - IR-12 has the same machine layout as IR-8, so design feasibility studies for 2nd IR/detector remain valid
- Production and installation of half of the RCS main arc girders (half-cells) deferred to upgrade.
- revise infrastructure to adapt to the changes
- several other smaller changes to safe money

→ no impact on Mission need and NAS science program

- Reduce ESR Main SRF Systems from 6x to 2x. Defer remaining ESR Main SRF Systems to incremental operational upgrades. Relative to SRF capability to support maximum ESR design beam current:
  - 9 GeV: 2x SRF systems supports 10nC per bunch x 1160 bunches, 35% of maximum ESR beam current capability.
  - 10 GeV: 2x SRF systems supports 7nC per bunch x 1160 bunches, 25% of maximum ESR beam current capability.

→ the 10 GeV solution is equal to the start up solution for EIC already provided

Title