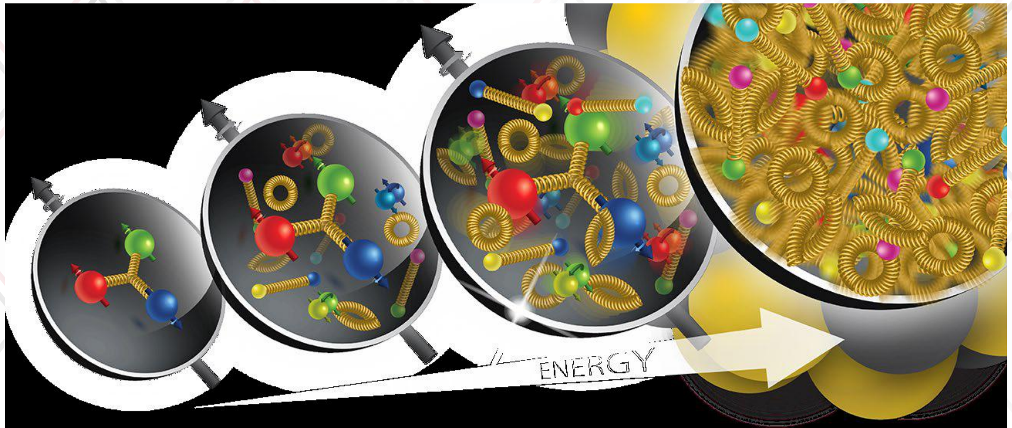
The ElectronIonCollider

15th conference on hypernuclear and strange particle physics,
Tokyo, Oktober 3, 2025,

Ralf Seidl (RIKEN)

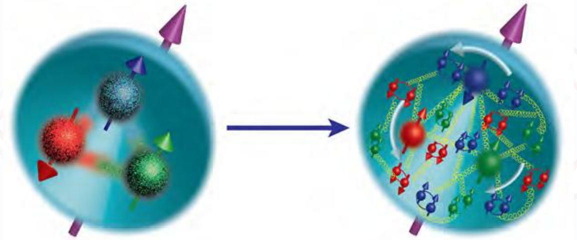


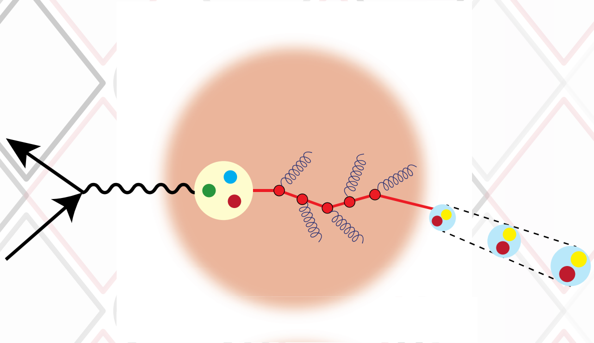
RIKEN

Questions, EIC wants to answer

How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?

How do the nucleon properties emerge from them and their interactions?





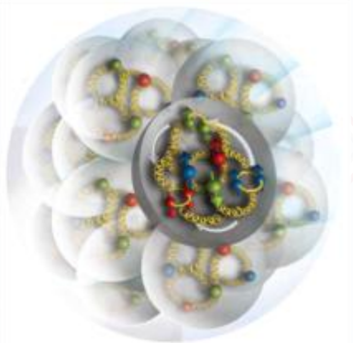
How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

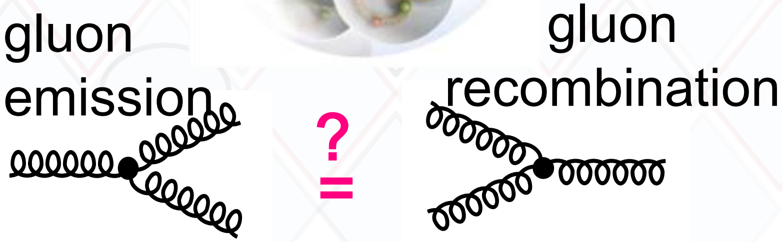
How do the confined hadronic states emerge from these quarks and gluons?

How do the quark-gluon interactions create nuclear binding?

How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?



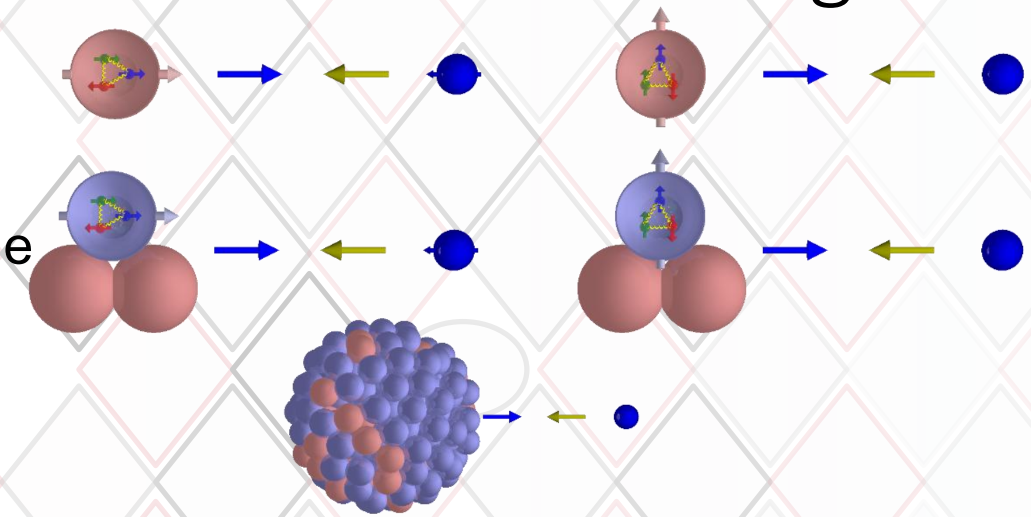


EIC accelerator being build at BNL

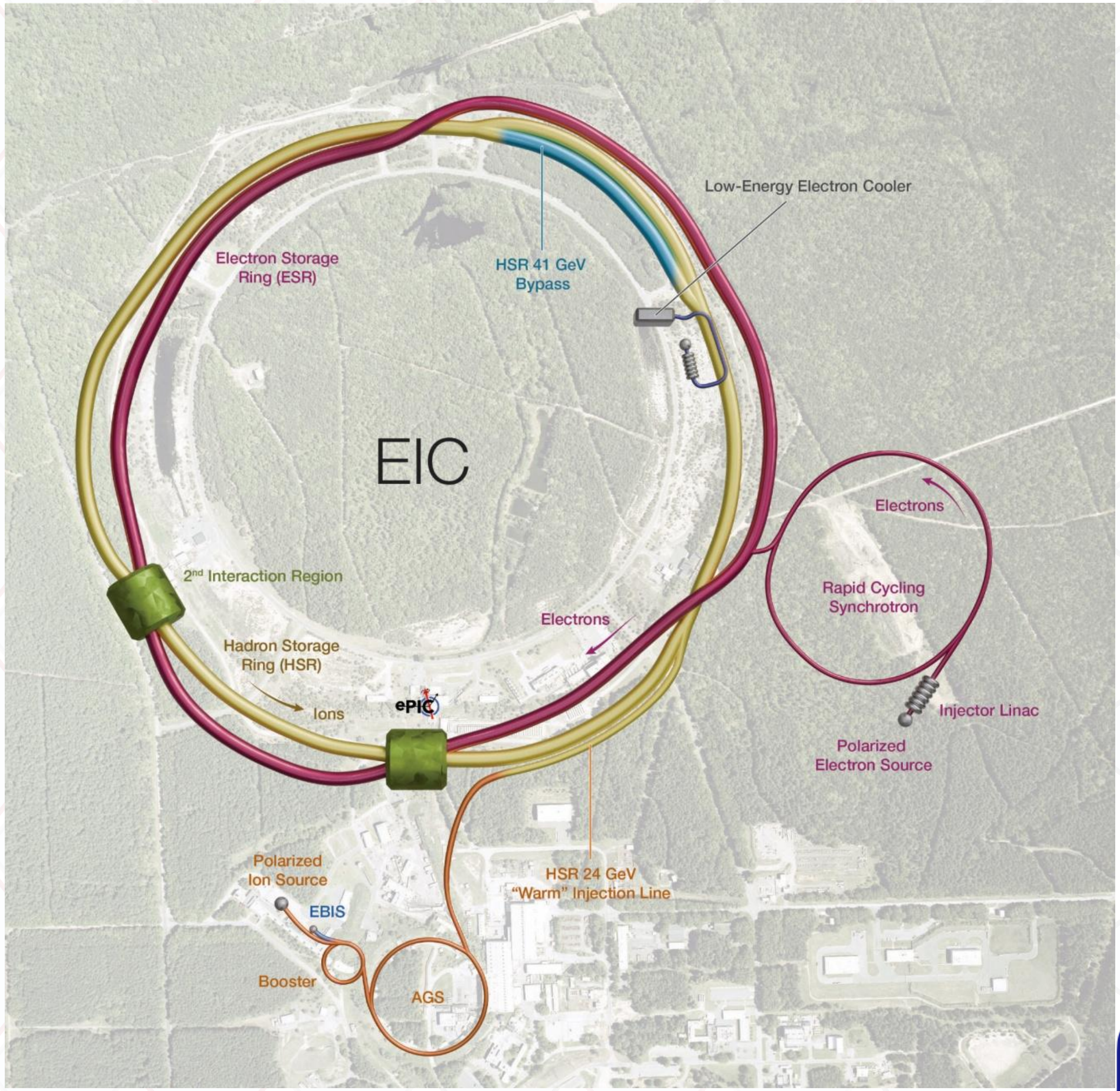
e+p

e+^{3}He

e+A



- 80% polarized electrons from 5-18 GeV
- 70% polarized protons from 40-275 GeV
- Ions from 40-110 GeV/u
- Polarized light ions 40 -184 GeV (^{3}He)
- CMS energies $\sqrt{s}$ = 29 – 140 GeV
- 1000x HERA luminosities: 10^{33}-10^{34} cm^{2}s^{-1}
- CD1 obtained in July 2021



EIC Physics goals

Spin of the nucleon:

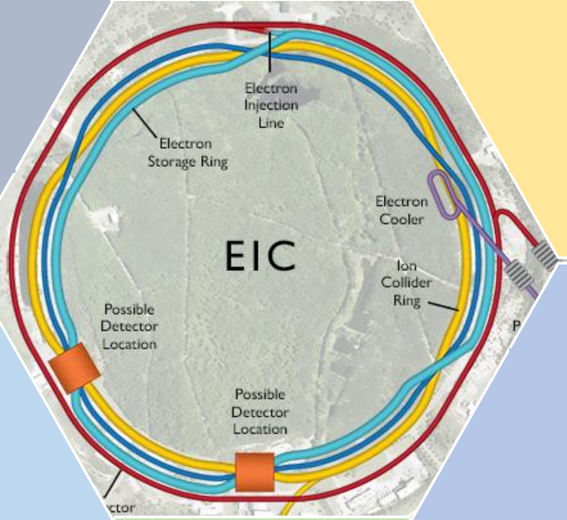
- Gluon spin
- Role of Sea quarks

QCD at high gluon densities

- Saturation effects

Tomography :

- 3D momentum structure (q, g Sivers, Tensor charge, TMD Evolution)
- 3D spatial structure



Nucelar effects

- Nuclear PDFs
- Passage of color through nuclear matter (nFFs, pT broadening)

Origin of the Mass

- Axial anomaly contributions
- meson structure

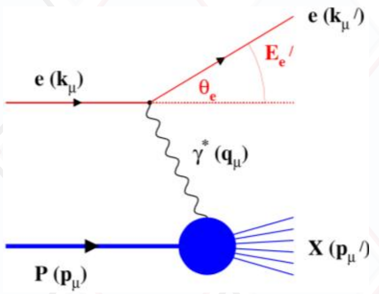
Other

- Spectroscopy (XYZ)
- EW physics
- Fragmentation
- Unpol PDFs

Tools at an EIC and basic requirements

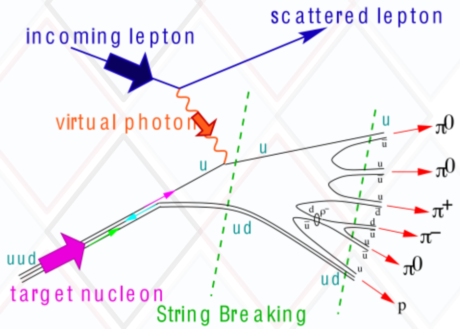
Inclusive Reactions in ep/eA:

- Physics: Structure Fcts.: g_1, F_2, F_L
- Very good electron id → identify scattered lepton
- Momentum/energy and angular resolution of e' critical
- scattered lepton → kinematics of event (x,Q^2)



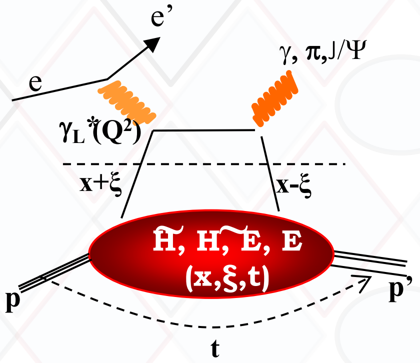
Semi-inclusive Reactions in ep/eA:

- Physics: TMDs, Helicity PDFs, FF → flavor separation, dihadron-corr.,…
  → Pion, Kaon asymmetries, cross sections
- Excellent particle ID: $\pi^\pm$,$K^\pm$,$p^\pm$ separation over a wide range in $-3<\eta<3$
  → excellent p resolution at forward rapidities
- TMDs: full Φ-coverage around γ^*, wide p_t coverage
- Excellent vertex resolution → Charm, Bottom separation



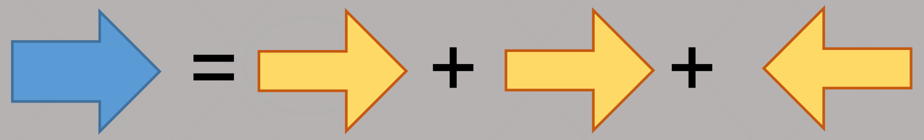
Exclusive Reactions in ep/eA:

- Physics: DVCS, excl. VM/PS prod. → GPDs, parton imaging in b_T; $g(x,Q^2,b_T)$
- Exclusivity → large rapidity coverage → rapidity gap events
  ↘ reconstruction of all particles in event
- high resolution, wide coverage in t → b_t → Roman pots
- eA: veto nucleus breakup, determine impact parameter of collision
  → acceptance for neutrons in ZDCs



The Spin sum rule

Naïve Quark Model picture: 3 valence quarks make up the spin of the nucleon:



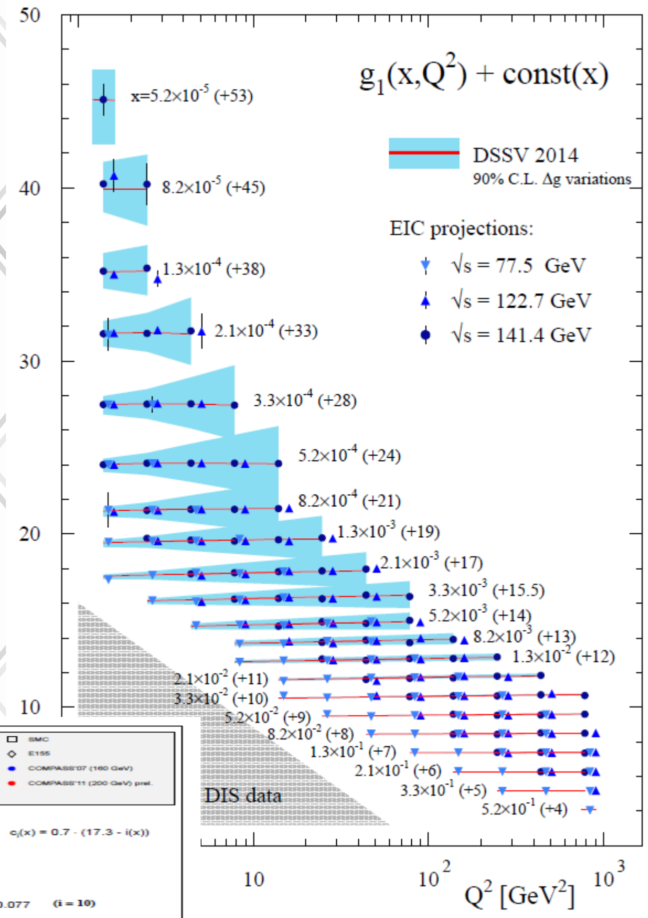
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$$ Jaffe, Manohar

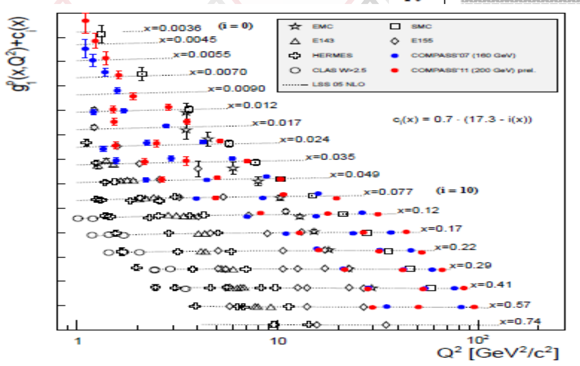
Quark spin — Gluon spin — Orbital angular momentum

$$\Delta\Sigma = \int dx \left[(\Delta u(x) + \Delta\bar{u}(x)) + (\Delta d(x) + \Delta\bar{d}(x)) + (\Delta s(x) + \Delta\bar{s}(x)) \right]$$

- Spin Crisis (1980s): Quark spin contributes only little
- $\Delta\Sigma$ and ΔG can be accessed in longitudinally polarized (SI)DIS and pp collisions (currently for x>0.01)
- Where is the rest of the spin? Gluons? Lower momentum fractions? Orbital angular momentum?

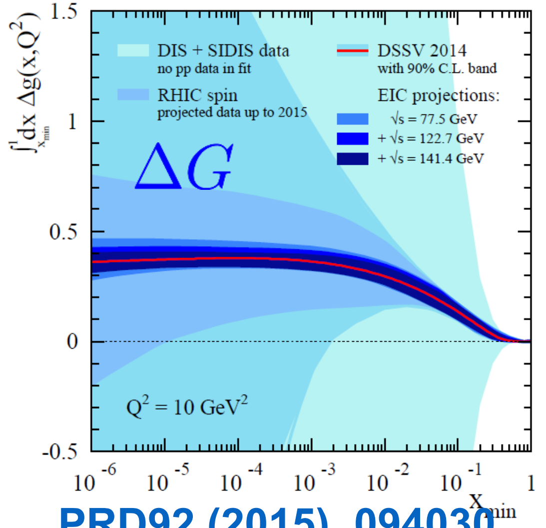
Inclusive DIS and $\Delta g(x)$





PRD92 (2015), 094030

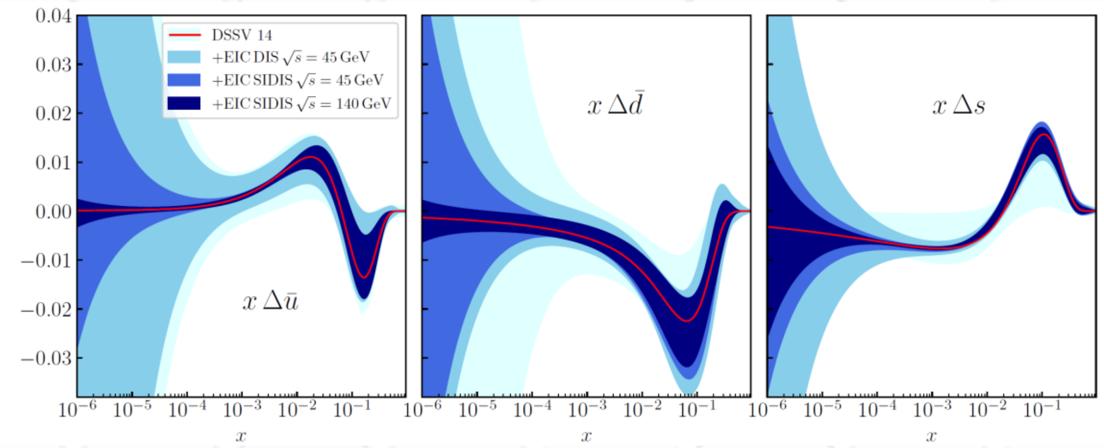
- Currently no lever arm to access gluon helicities via DIS (lepton-proton scattering)
- Nonzero gluon polarization found from 200/510 GeV RHIC data
- EIC: Several orders of magnitude of Q^2 at same x allows to determine gluon helicity via DGLAP (scale) evolution

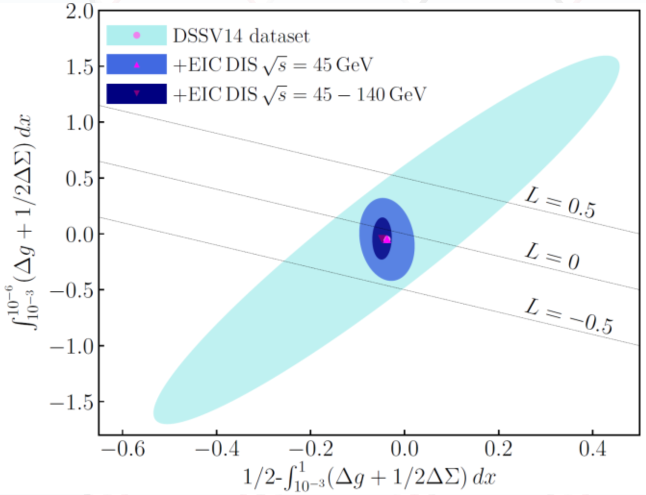


PRD92 (2015), 094030

Gluon and sea polarization

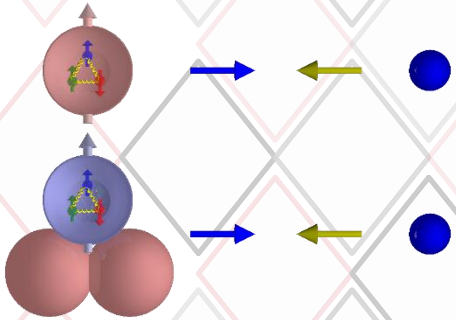
- 1 year of EIC running will pin down gluon polarization
- Using SIDIS: precise determination of sea quark helicities, especially strange contribution of interest
- Indirect determination of orbital angular momentum via sum rule
- Also, interesting access to flavor via charged current reactions





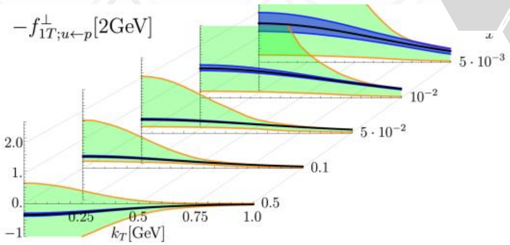
[PRD 102 (2020), 094018]

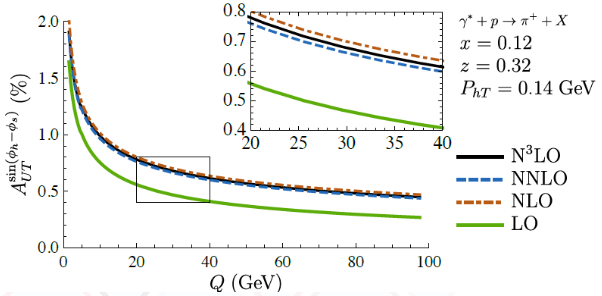
Motivation: 3D Transverse spin and momentum structure

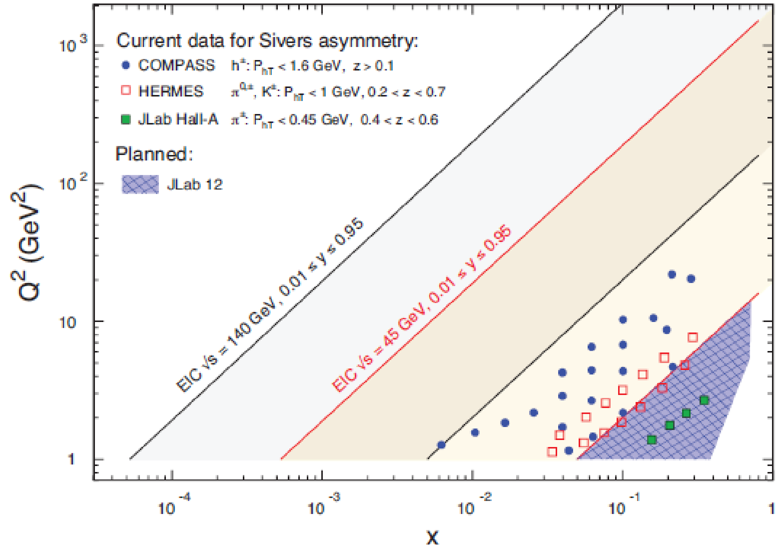


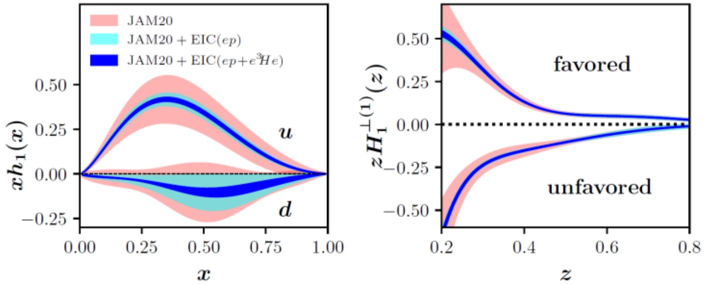
Deliverables	Observables	What we learn	Stage I	Stage II
Sivers & unpolarized TMD quarks and gluon	SIDIS with Transverse polarization; di-hadron (di-jet)	Quantum Interference & Spin-Orbital correlations	3D Imaging of quarks valence+sea	3D Imaging of quarks & gluon; Q^2 (P_{hT}) range QCD dynamics
Chiral-odd functions: Transversity; Boer-Mulders	SIDIS with Transverse polarization	3[rd] basic quark PDF; novel hadronization effects	valence+sea quarks	Q^2 (P_{hT}) range for detailed QCD dynamics

Tables from original EIC white paper



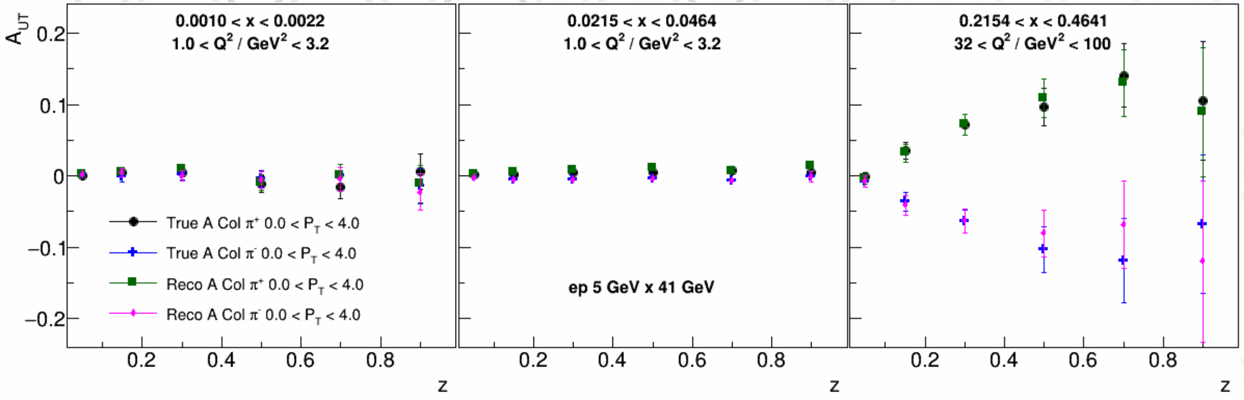


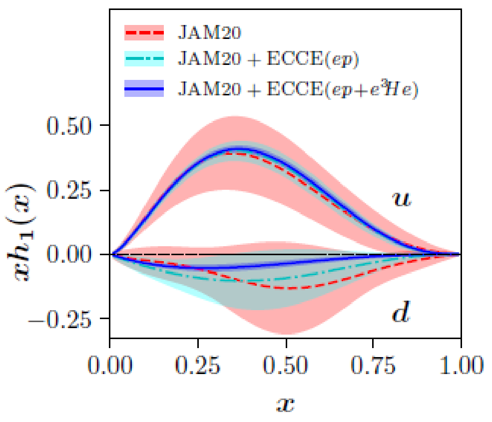


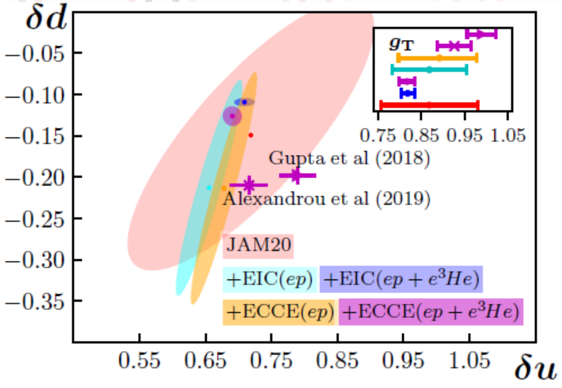


Current coverage for transverse spin related measurements

EIC Impact studies (e.g. Tensor charges – moment of transversity)





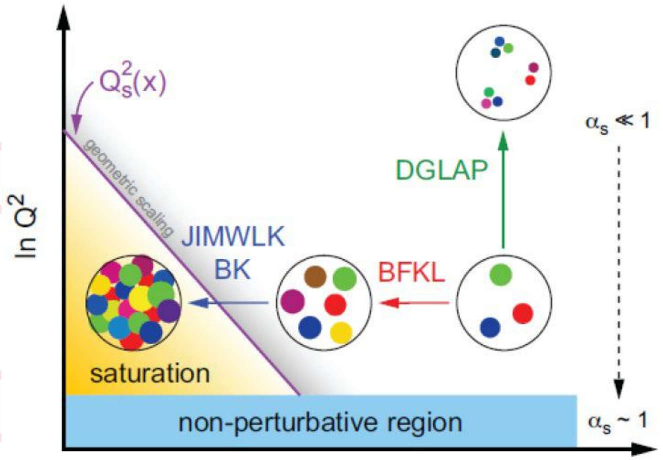


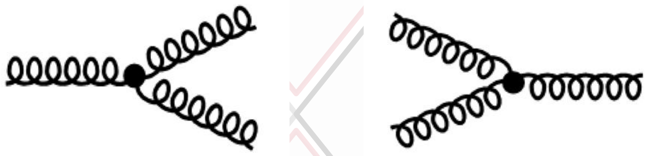
NIMA 1049 (2023) 168017

- Precise determination of tensor charges via Collins and di-hadron channels
- Better precision than lattice → potential access to BSM physics in case of discrepancies
- Preform full integrals, study role of sea quark transversity

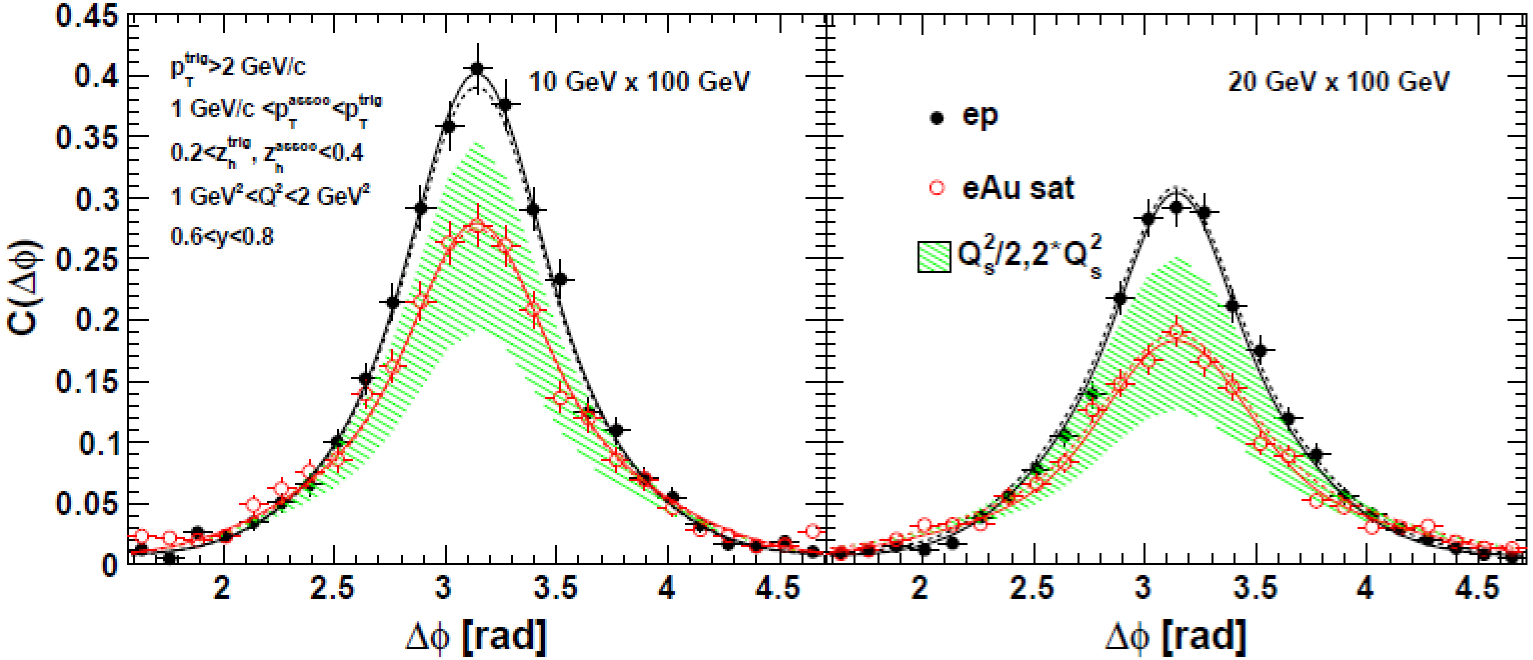
Similarly:
Single hadron channel (YR : Fig 7.54 Gamberg et al *Phys.Lett.B* 816 (2021) 136255)
Di-hadron channel (YR : Fig 7.56, Radici)

Di-hadron de-correlations to cleanly probe saturation





[PRD89 (2014) 074037](#)



Saturation: at low-x equilibrium of gluon splitting and recombination, Indication seen at HERA (geometric scaling)

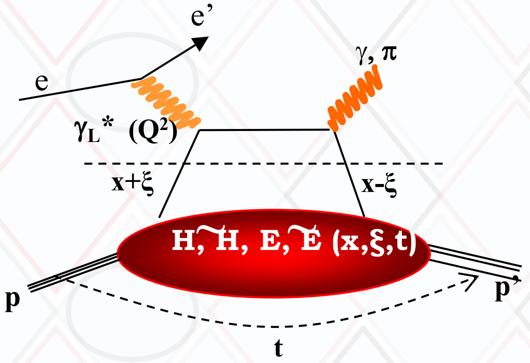
- Measure back-to-back hadron(jet) - hadron or hadron(jet) - photon correlations
- Suppression of away peak as direct probe for saturation
- Need to understand parton showers and transverse momentum dep. fragmentation
- Different probes to access various low-x gluon TMDs, also diffraction

Spatial imaging of quarks →DVCS

Deeply virtual Compton scattering:

- Access to generalized parton distributions and orbital angular momentum (OAM)
- Ji sum rule allows access to J_q (total angular momentum) via exclusive reactions:

$$J^q = \frac{1}{2}\int dx\, x\left[H^q(x,\xi,t=0) + E^q(x,\xi,t=0)\right]$$



- GPDs related to regular PDFs and form factors:

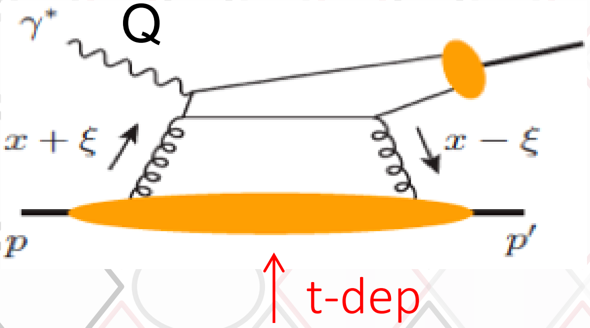
  H→ q, $\widetilde{H}$ →Δq for ξ →0

$$\sum_q e_q \int dx\, H^q(x,\xi,t) = F_1^p(t)\,, \qquad \sum_q e_q \int dx\, E^q(x,\xi,t) = F_2^p(t)$$

- Any access to gluon OAM only via Twist 3
- t-dependence as FT of impact parameter →spatial imaging

Spatial imaging of gluon density

- **Exclusive vector meson production:**

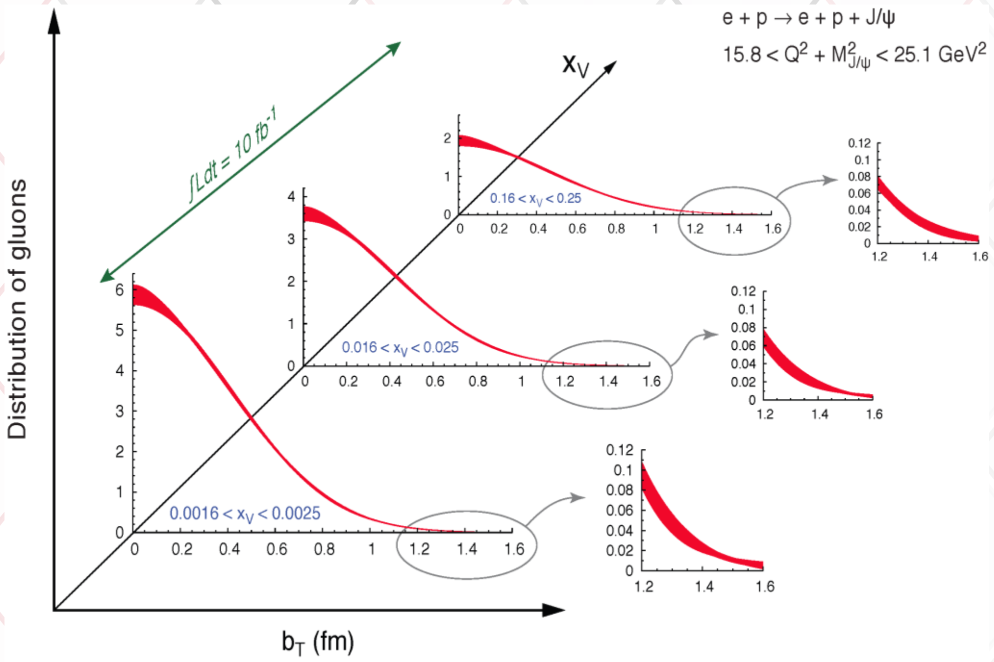


$$\frac{d\sigma}{dx_B dQ^2 dt}$$

Fourier transform of the t-dependence

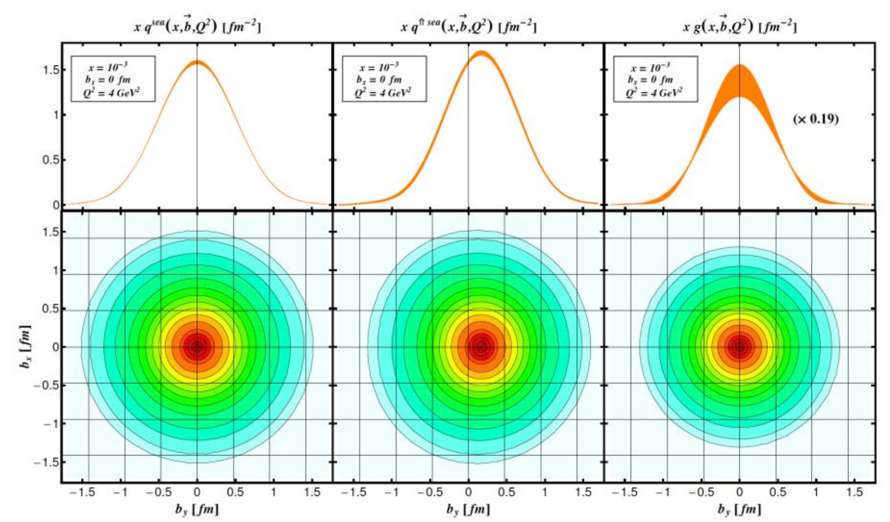
→ Spatial imaging of glue density

- **Gluon imaging from simulation:**

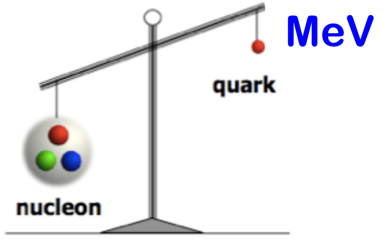


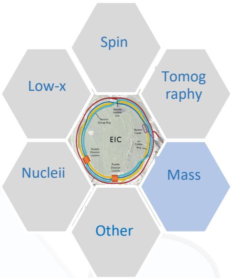
Images of gluons from exclusive J/ψ production

Only possible at the EIC: From the valence quark region deep into the sea quark region



Understanding Mass of Hadrons





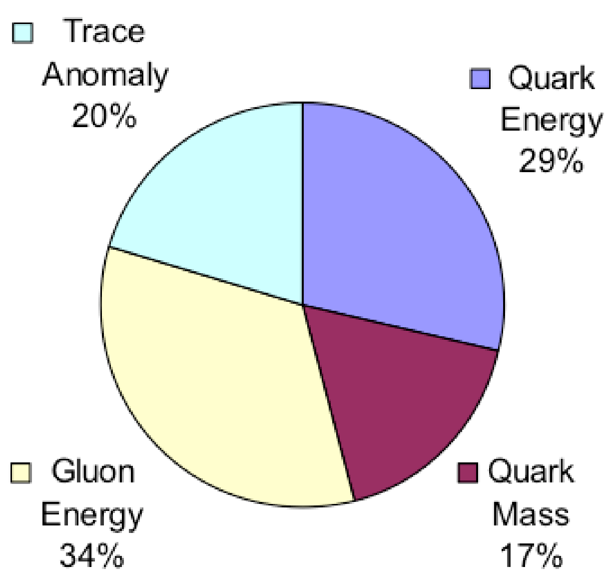
Relativistic motion | χ Symmetry Breaking | Quantum fluctuation

$$M = \overbrace{E_q + E_g}^{\text{Relativistic motion}} + \chi_{m_q} + T_g$$

Quark Energy | Gluon Energy | Quark Mass | Trace Anomaly

"… The vast majority of the nucleon's mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. …" *The 2015 Long Range Plan for Nuclear Science*

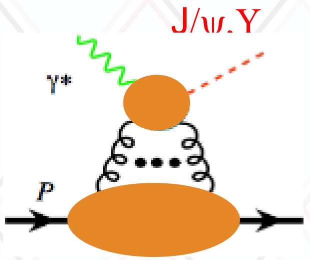
❑ Preliminary Lattice QCD results:



❑ EIC projected measurements:

- ✧ Trace anomaly:

  Upsilon production near the threshold

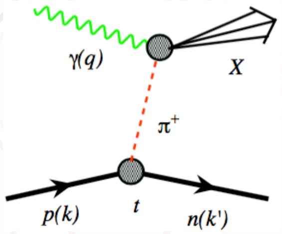


- ✧ Quark-gluon energy:

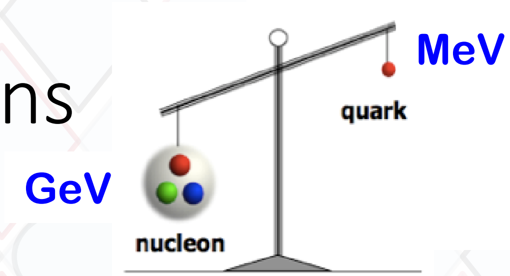
  ∝ *quark-gluon momentum fractions*

  In nucleon with DIS and SIDIS

  In pions and kaons with Sullivan process



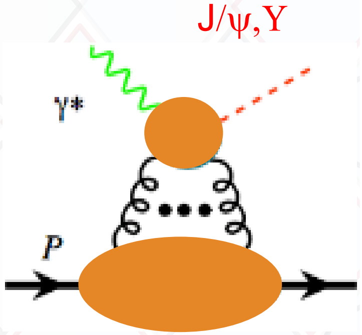
Understanding Mass of Hadrons

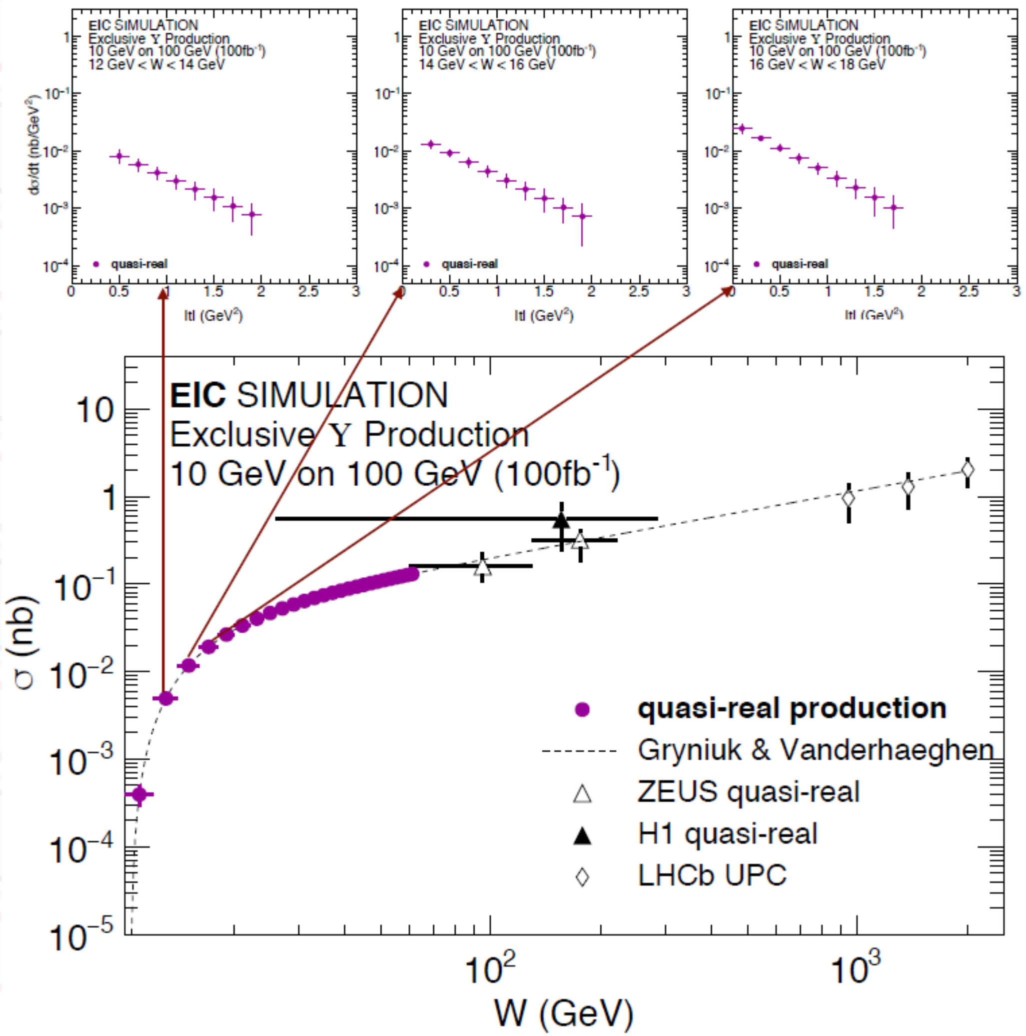


"… The vast majority of the nucleon's mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. …"

The 2015 Long Range Plan for Nuclear Science

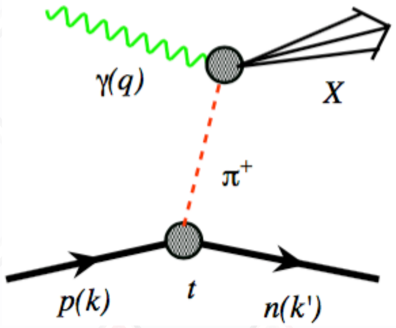
- Access at the EIC:
  - Study trace anomaly contribution via J/Psi/Υ production at threshold

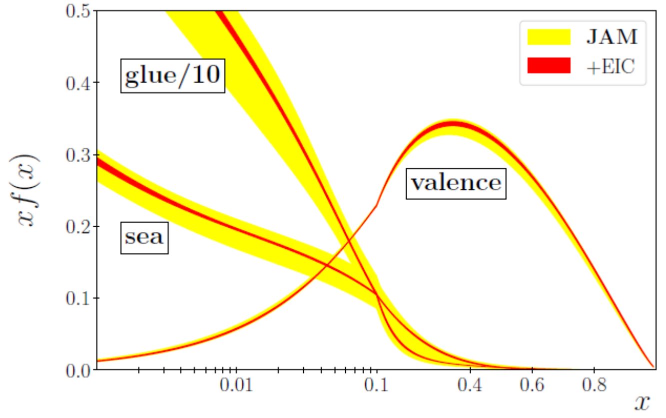


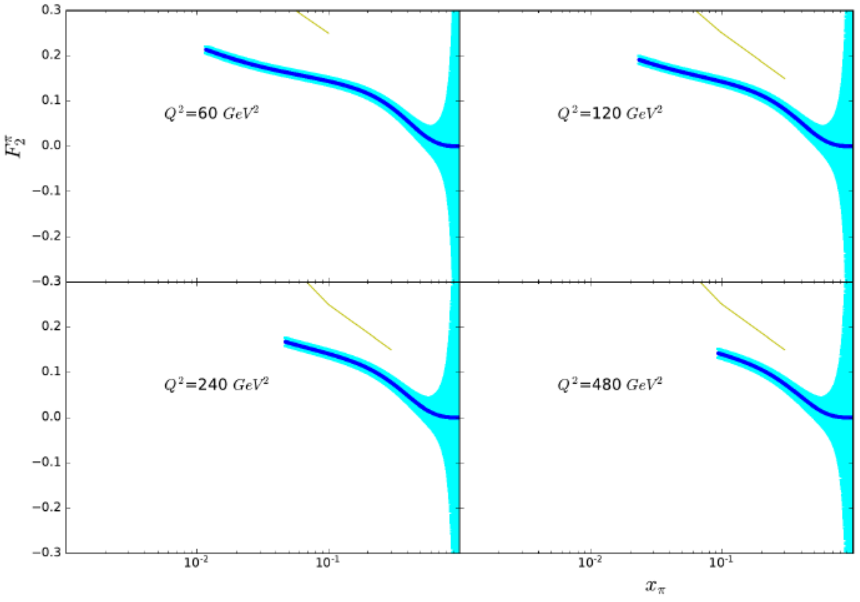


Pion/Kaon structure

- Quark-gluon energy contribution to mass: Use Sullivan process (scattering on virtual meson emitted from nucleon) to extract pion/Kaon Form Factors and PDFs
- Especially for kaon, need to reconstruct the far forward Λ decay $p+\pi^-$ or $n+\pi^0$ in B0 magnet, roman pots, or ZDC

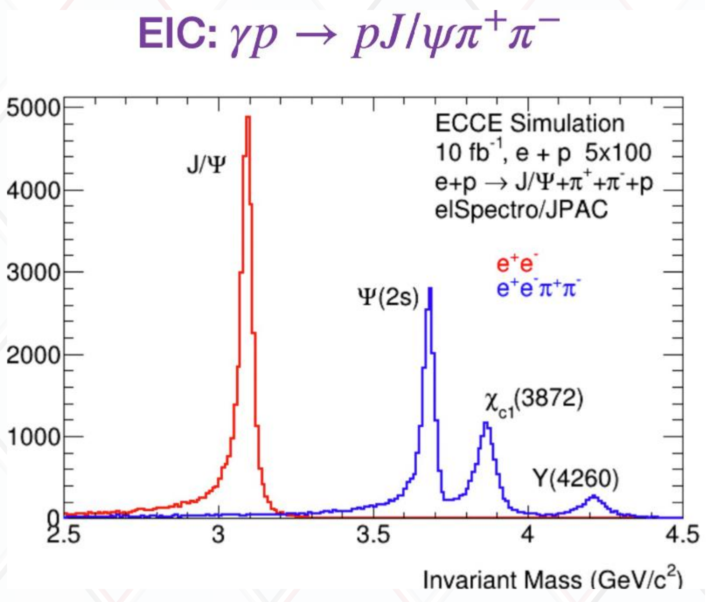


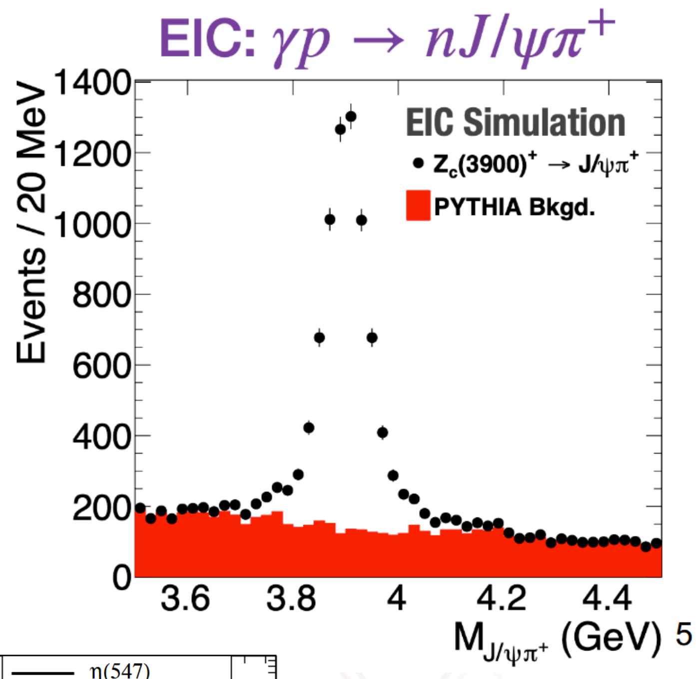


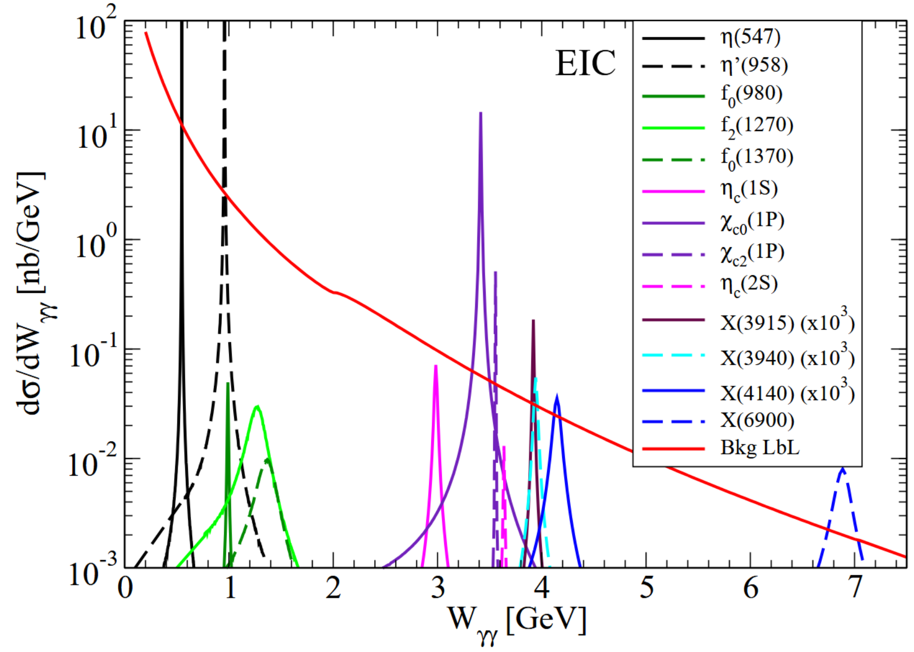


Exotics

- Many possibilities to produce exotics via photo-production and Pomeron exchange
- Also, possibilities in e-A via di-photon production
- Plenty of hyperon production also in regular (SI)DIS events
- Possibility to study P_c states at EIC?





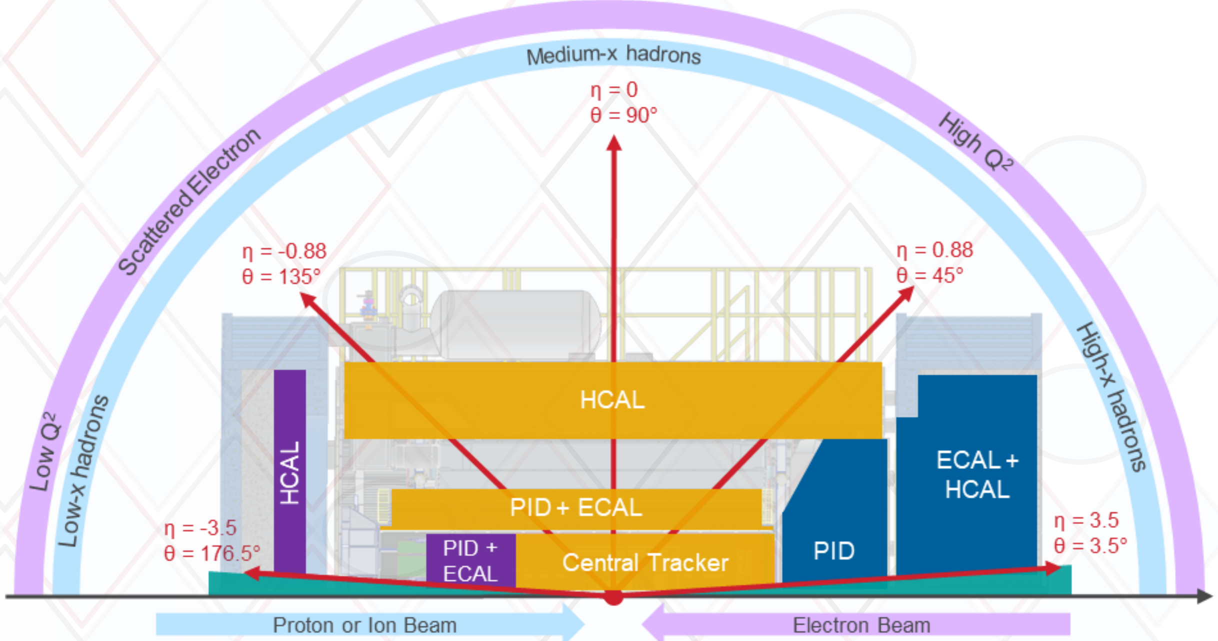


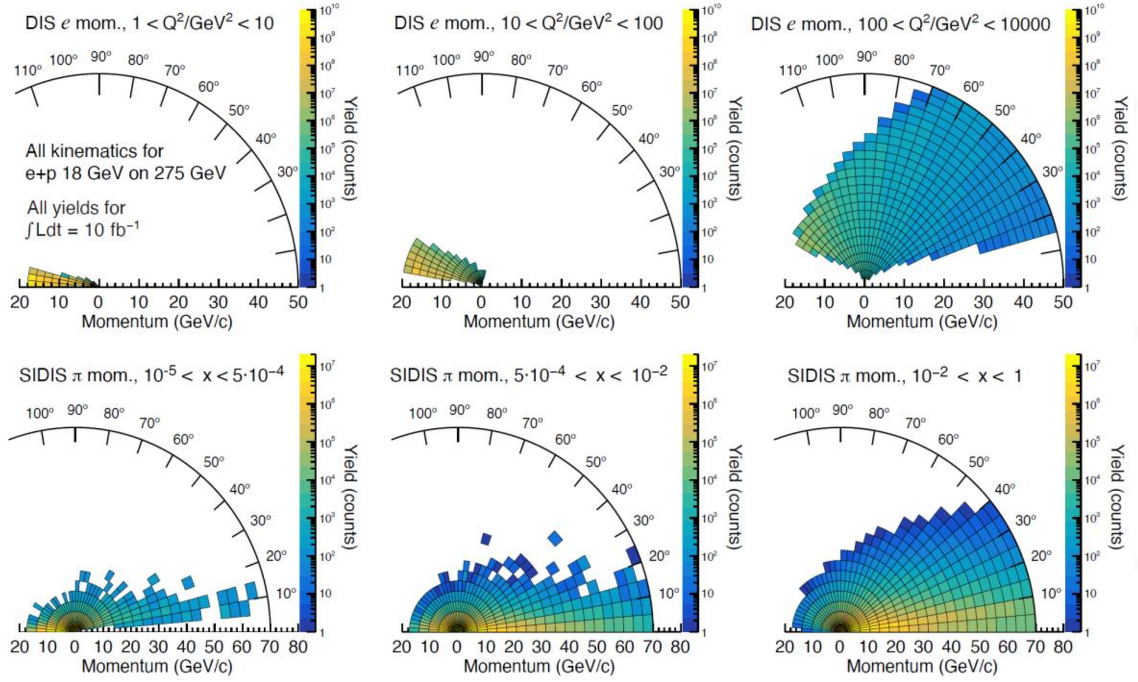
J. Stevens, at NStar24

Bertulani, et. al, PRC 111 (2025) 025201

Detector requirements

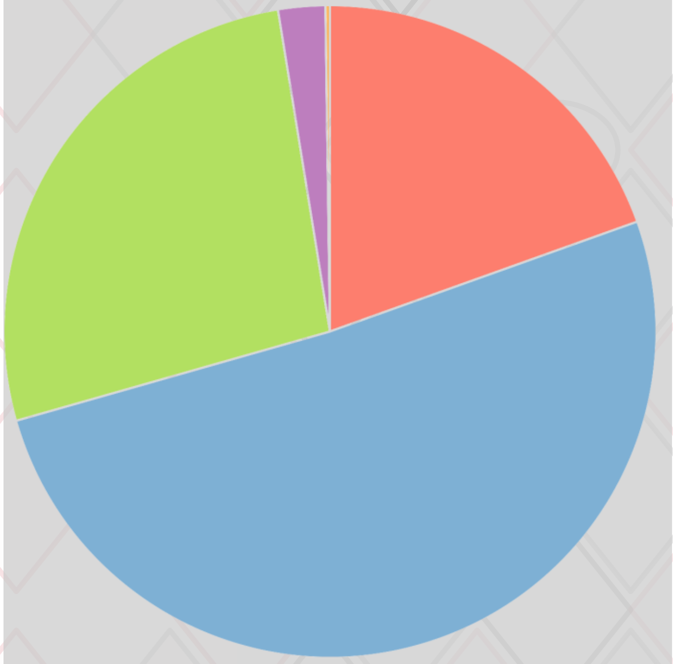
- Need full coverage over a large range of rapidities
- Precise lepton kinematic measurements in backward/central/forward rapidities
- Precise hadron kinematics and PID in the forward/central region
- Auxiliary detectors far forward (ZDCs, roman pots)
- Auxiliary detectors far backward (low Q^2 tagger)
- Dedicated polarimetry/luminosity detectors





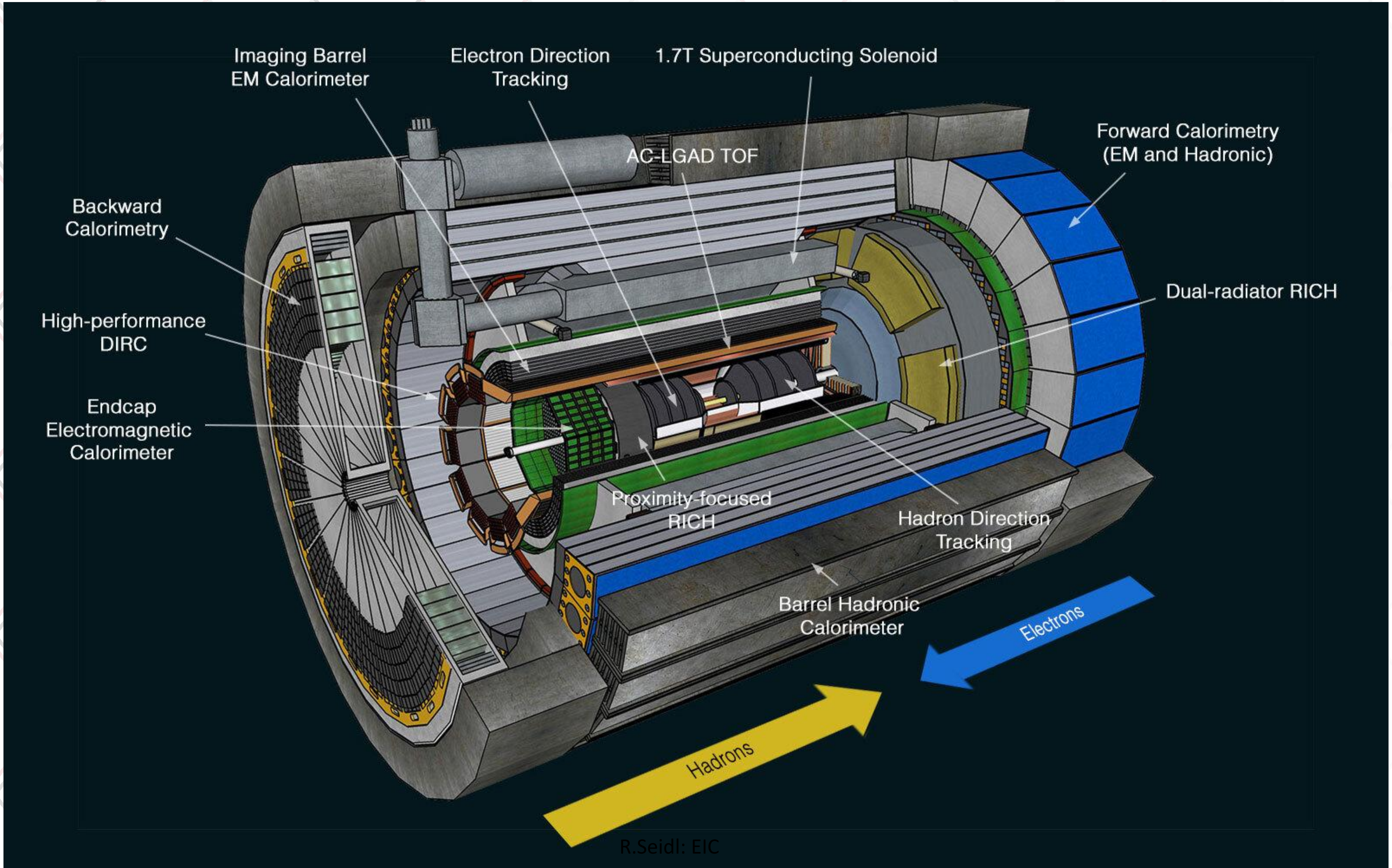
The ePIC collaboration

- >1000 members
- 182 Institutions
- 26 countries



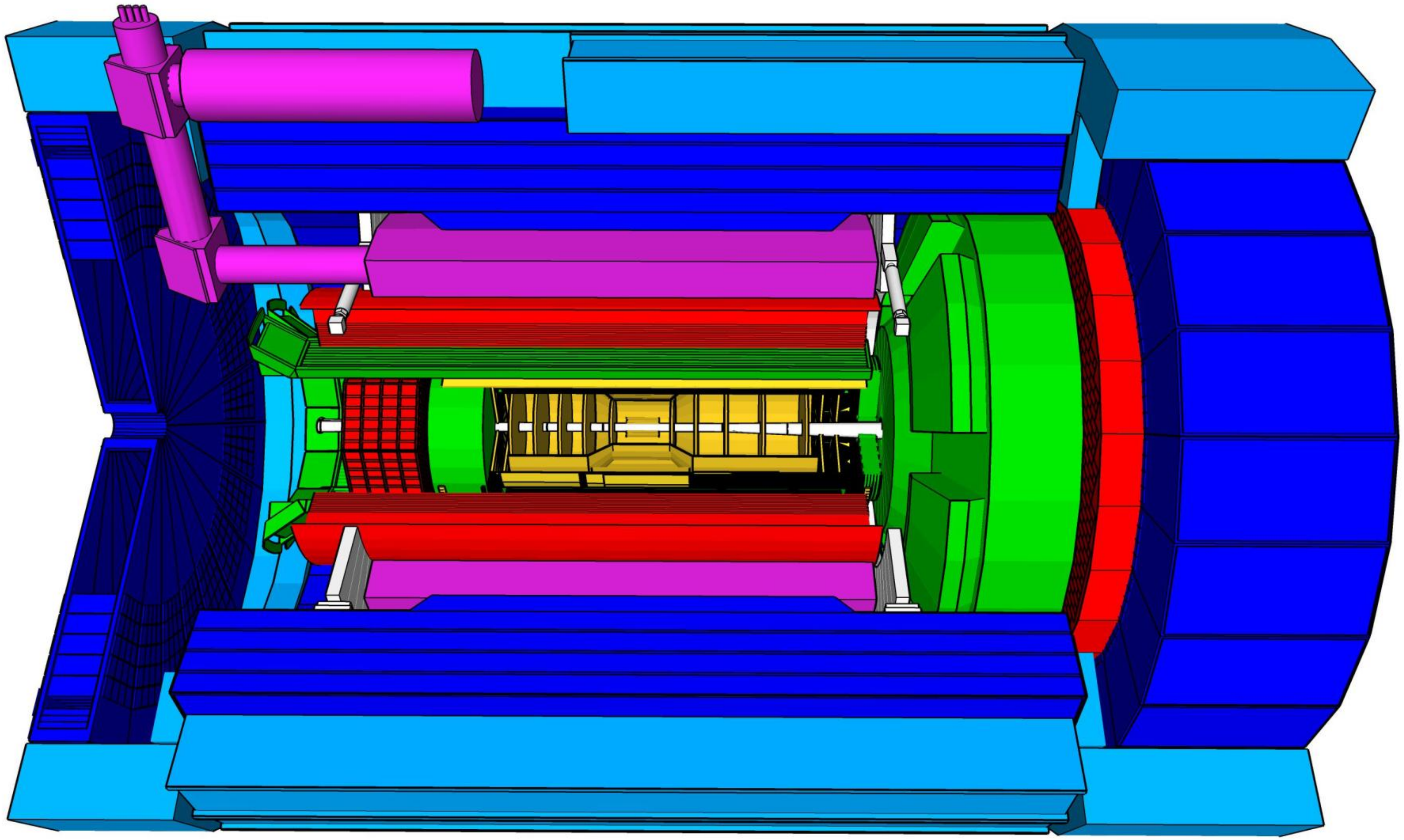
ASIA, 19.53% NORTH AMERICA, 51.05% EUROPE, 26.86% AFRICA, 2.33%
UNSPECIFIED, 0.22%

The ePIC detector

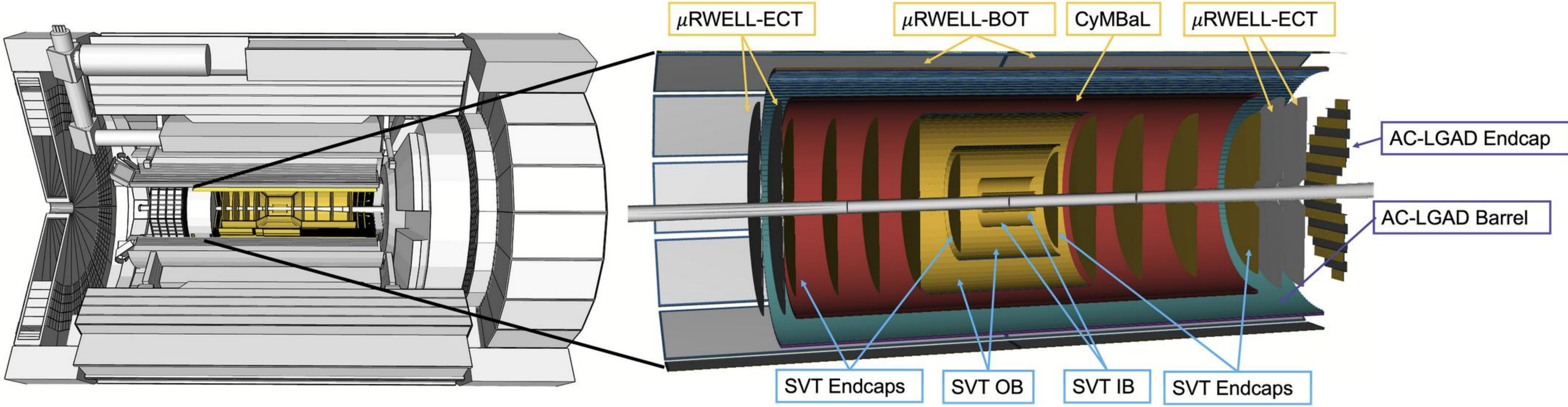


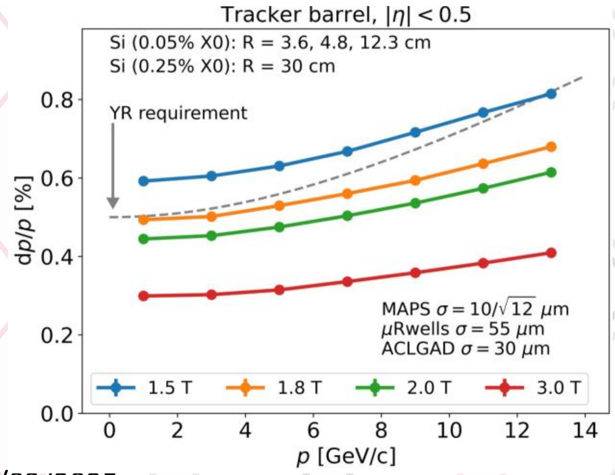
Central ePIC detector

- Magnet
  - New 1.7 T magnet
- Tracking
  - MAPS based tracking (ITS3)
  - MAPS barrel and discs
  - MGD (central)
- PID
  - high performance DIRC (central)
  - Dual radiator RICH (forward)
  - Proximity focused RICH (backward)
  - ACLGAD TOF (central and forward)
- EM Calorimetry
  - $PbW0_4$ crystals (backward)
  - Imaging EMCAL (central)
  - W powder/SciFi (forward)
- Hadronic Calorimetry
  - FeScintillator (reuse sPHENIX)
  - Steel/Fe – Scintillator (forward/backward)



Tracking





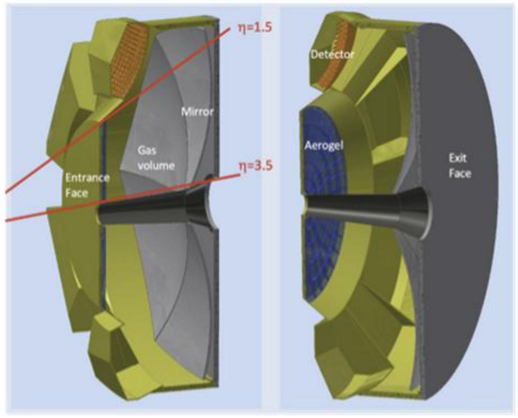
Detector Solutions

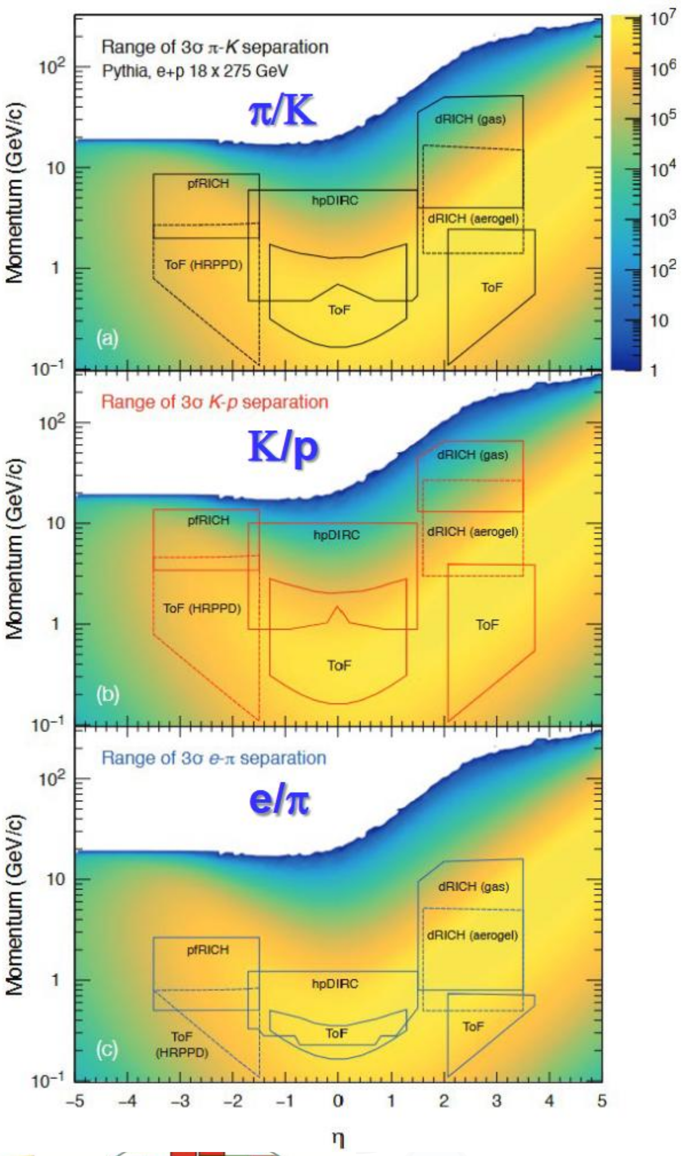
- Ultra-low-mass **barrel vertex tracker** using ALICE ITS3 curved MAPS technology, with 20µm pixel pitch and 0.05% X/X_0
- **Outer barrel and endcap silicon tracker** using new ITS3-based EIC Large Area Sensors (LAS), with 20µm pixel pitch and 0.55% X/X_0
- **MicroMegas barrel tracker** (CyMBaL) with X/X_0
- **GEM-µRWell barrel and endcap tracker** with 10ns time resolution, 150µm spatial resolution and 1-2% X/X_0

Particle ID

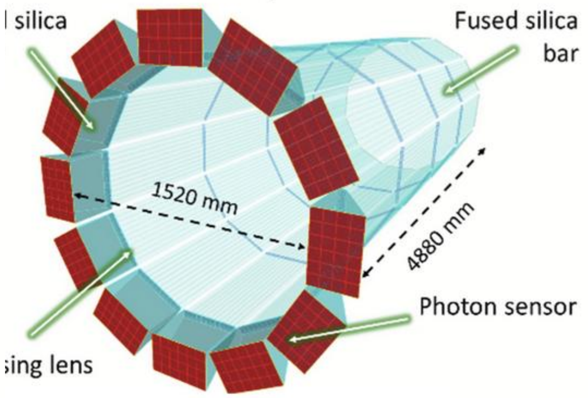
- Various solutions for different momentum ranges cover all regions for hadrons
- Additionally, electron/h separation using EMCals+Tracking

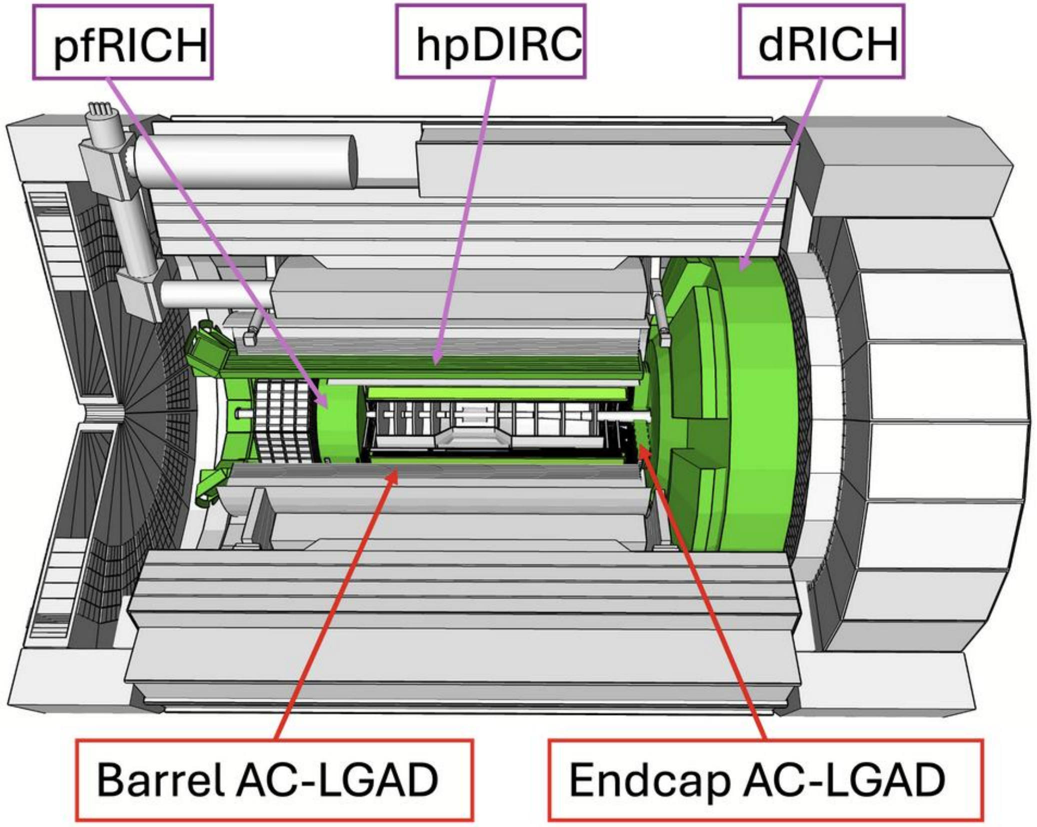
dRICH



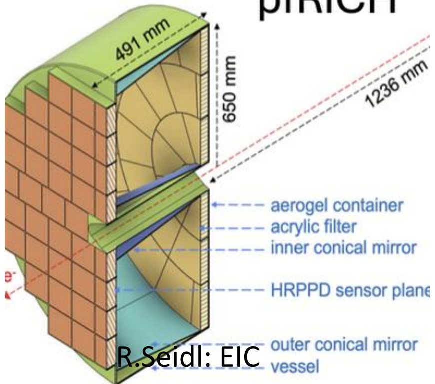


hpDIRC

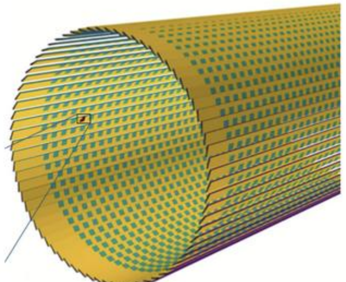


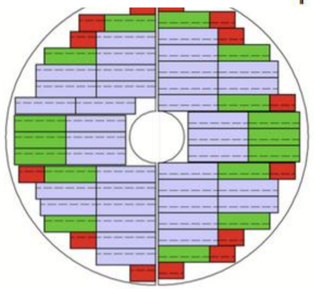


pfRICH



Barrel AC-LGAD





EM Calorimetry

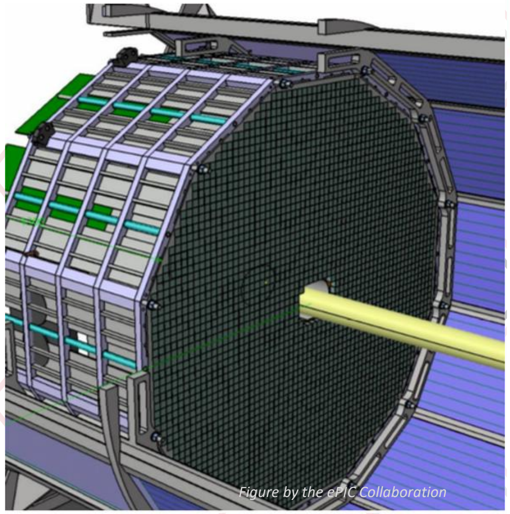
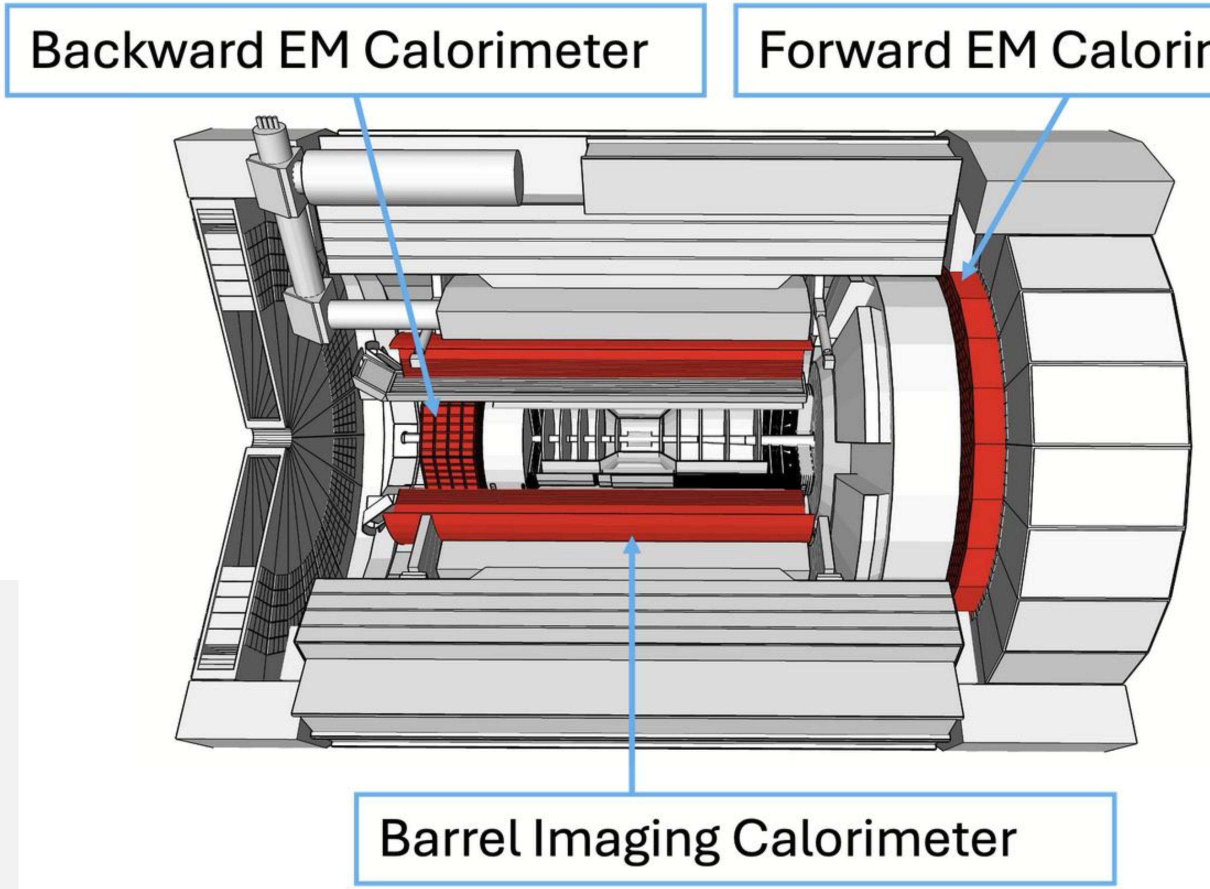


Figure by the ePIC Collaboration

Backward ECAL (EEEMCAL)

- High-precision $PbWO_4$ crystal calorimeter for precision scattered lepton measurements
- First use of SiPMs in a crystal calorimeter



- Hybrid imaging calorimeter: 6 layers of AstroPix sensors interleaved with 5 Pb/ScFi layers, followed by a large section of Pb/ScFi
- Pb/ScFi technology based on the GlueX design, using SiPMs for readout at either end of the barrel
- AstroPix: HV-MAPS sensor with 500µm pixel pitch and ~3.2ns time resolution developed for the NASA AMEGO-X mission.

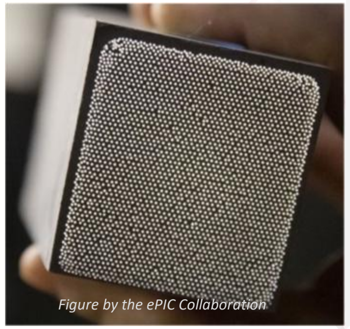
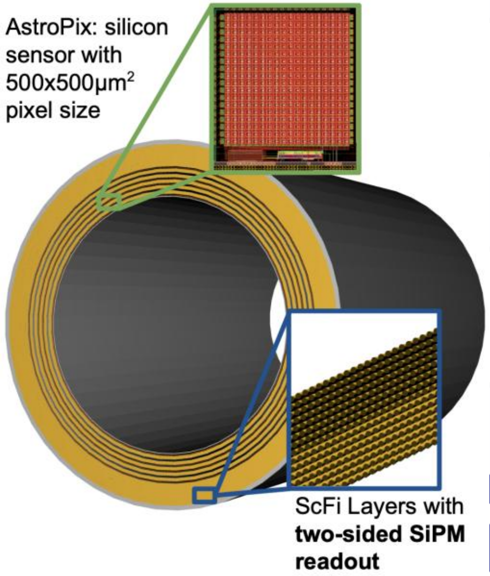


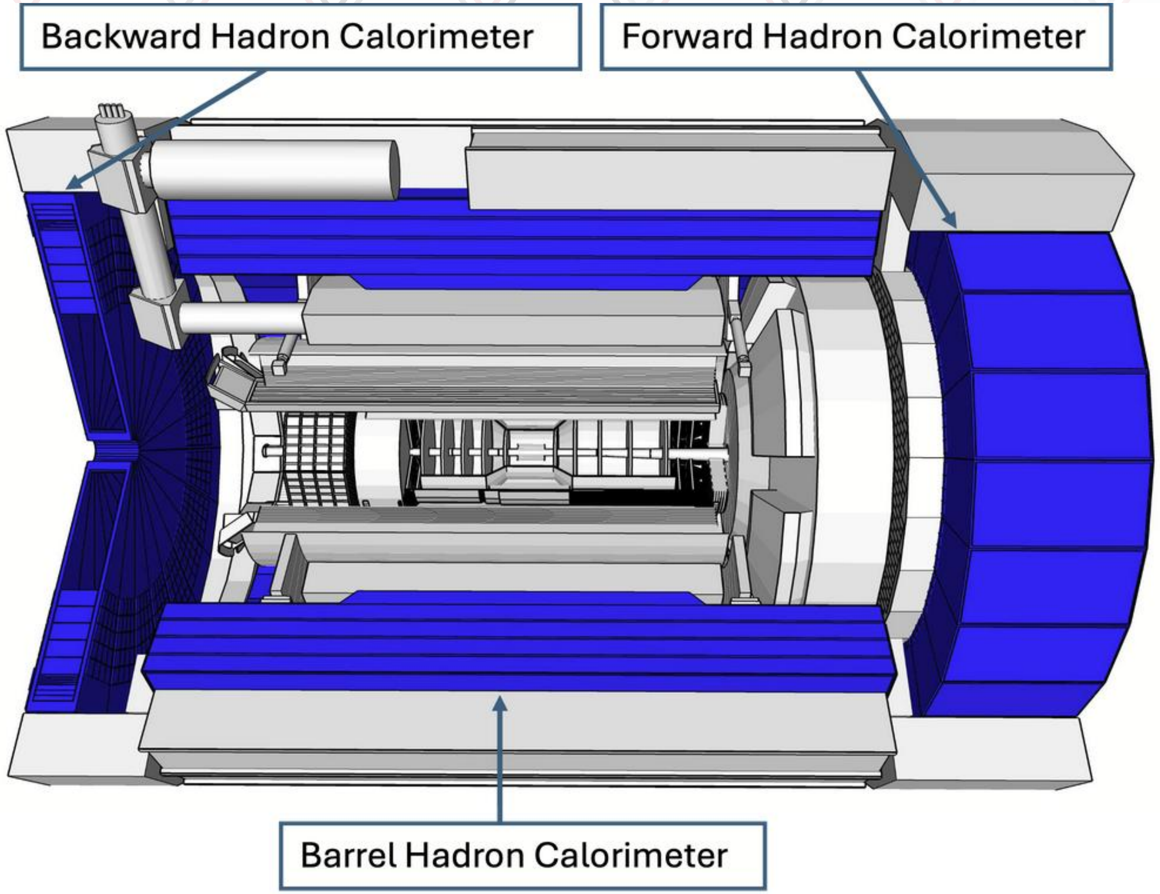
Figure by the ePIC Collaboration

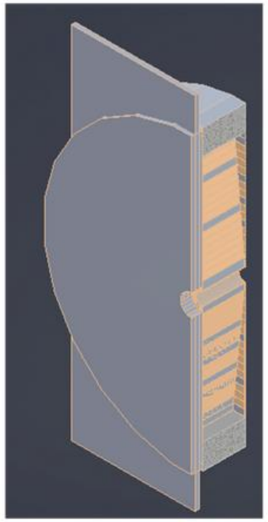
Forward Ecal

- W-powder/ScIFi SPACAL design developed through EIC R&D and used in sPHENIX



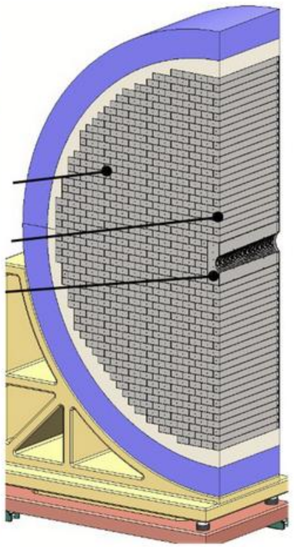
Hadronic calorimetry





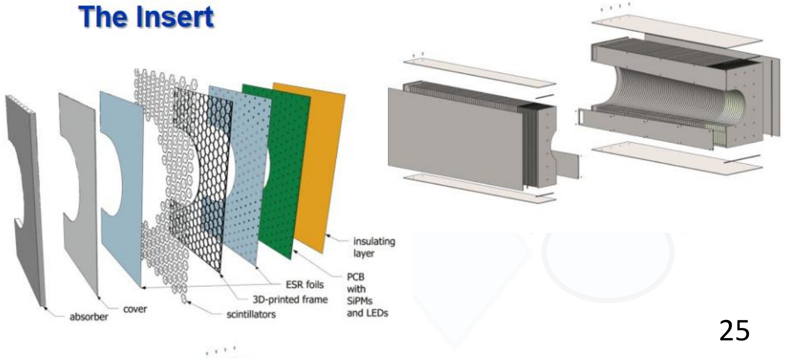
Backward Hadron Calorimeter

Barrel Hadron Calorimeter



Forward Hadron Calorimeter

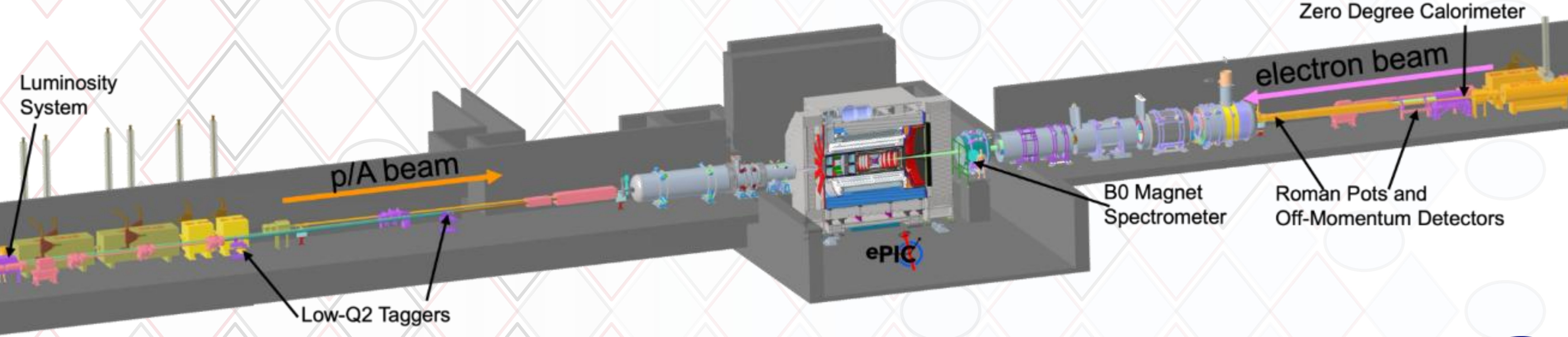
The Insert



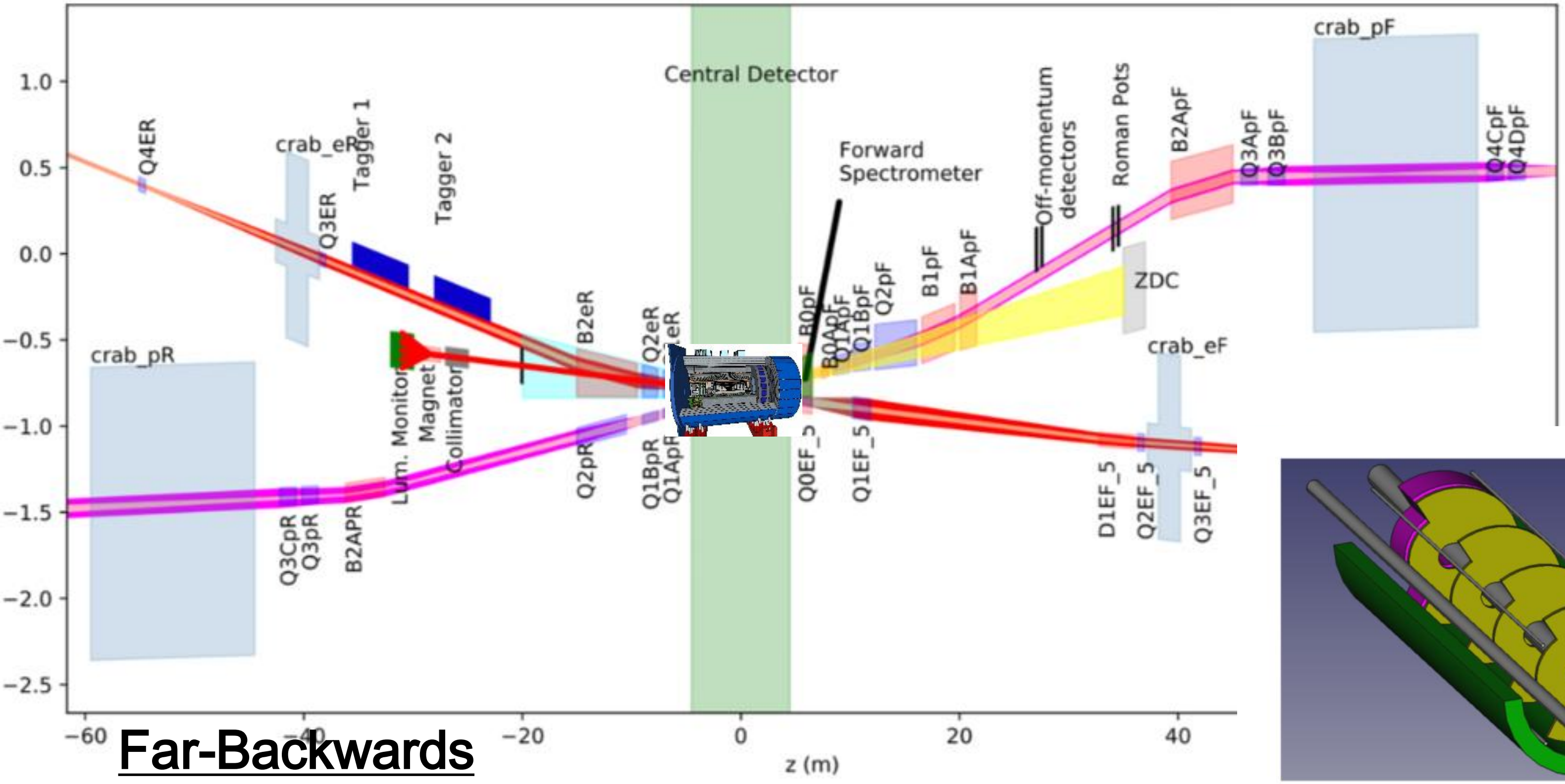
- Fe-Scintillator detectors for most rapidities
- SiPM on a tile insert at most forward region

The full ePIC detector

- Closely integrated in the Accelerator lattice
- About 60 m long



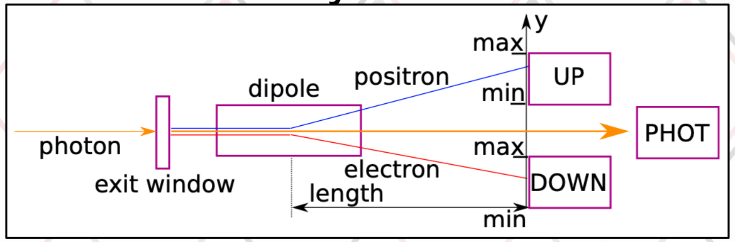
Far-Forward / Backward Instrumentation



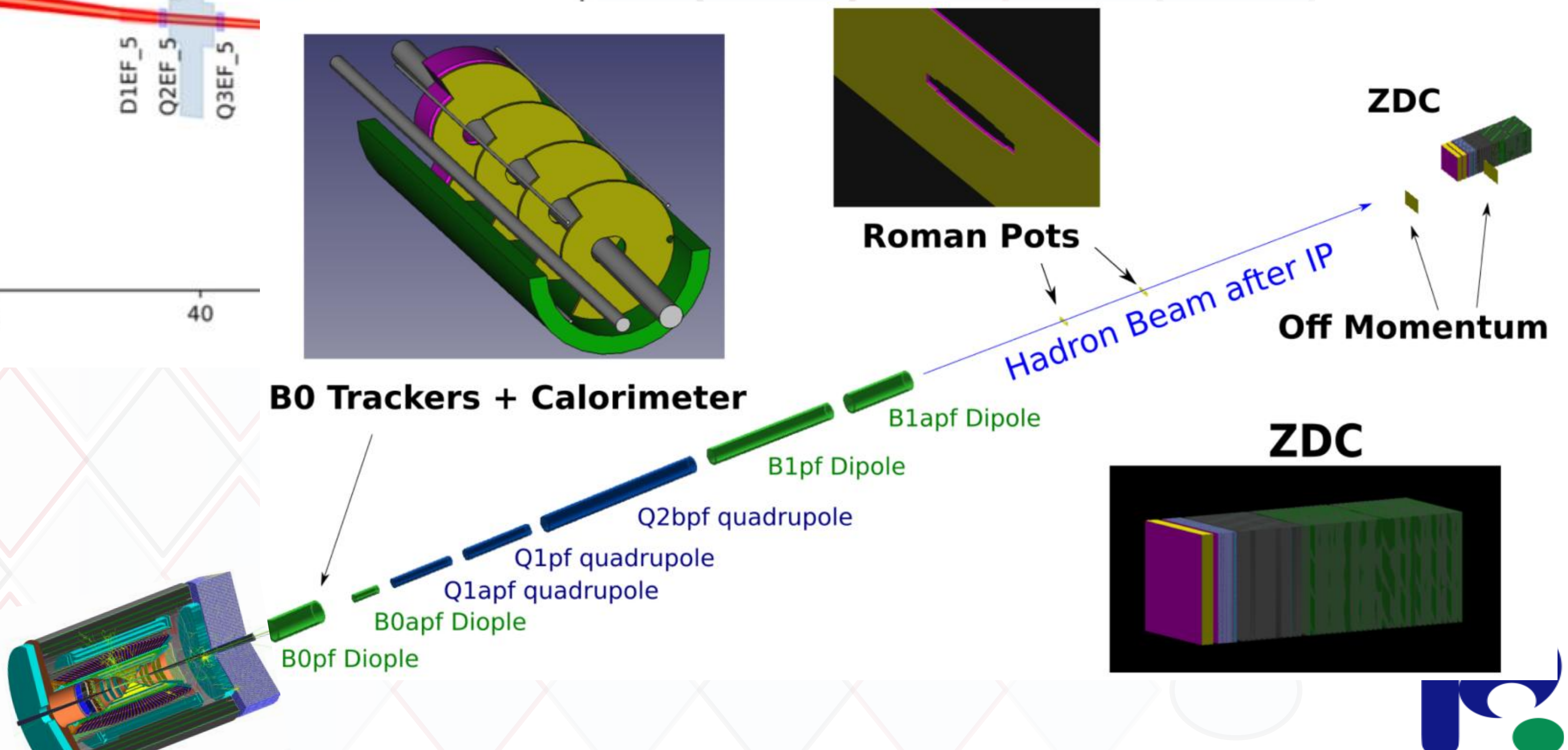
EIC detectors are highly integrated with the accelerator – extensive cooperation required to achieve science goals!

Far-Backwards

- Low-Q^2 tagger
- Luminosity monitor

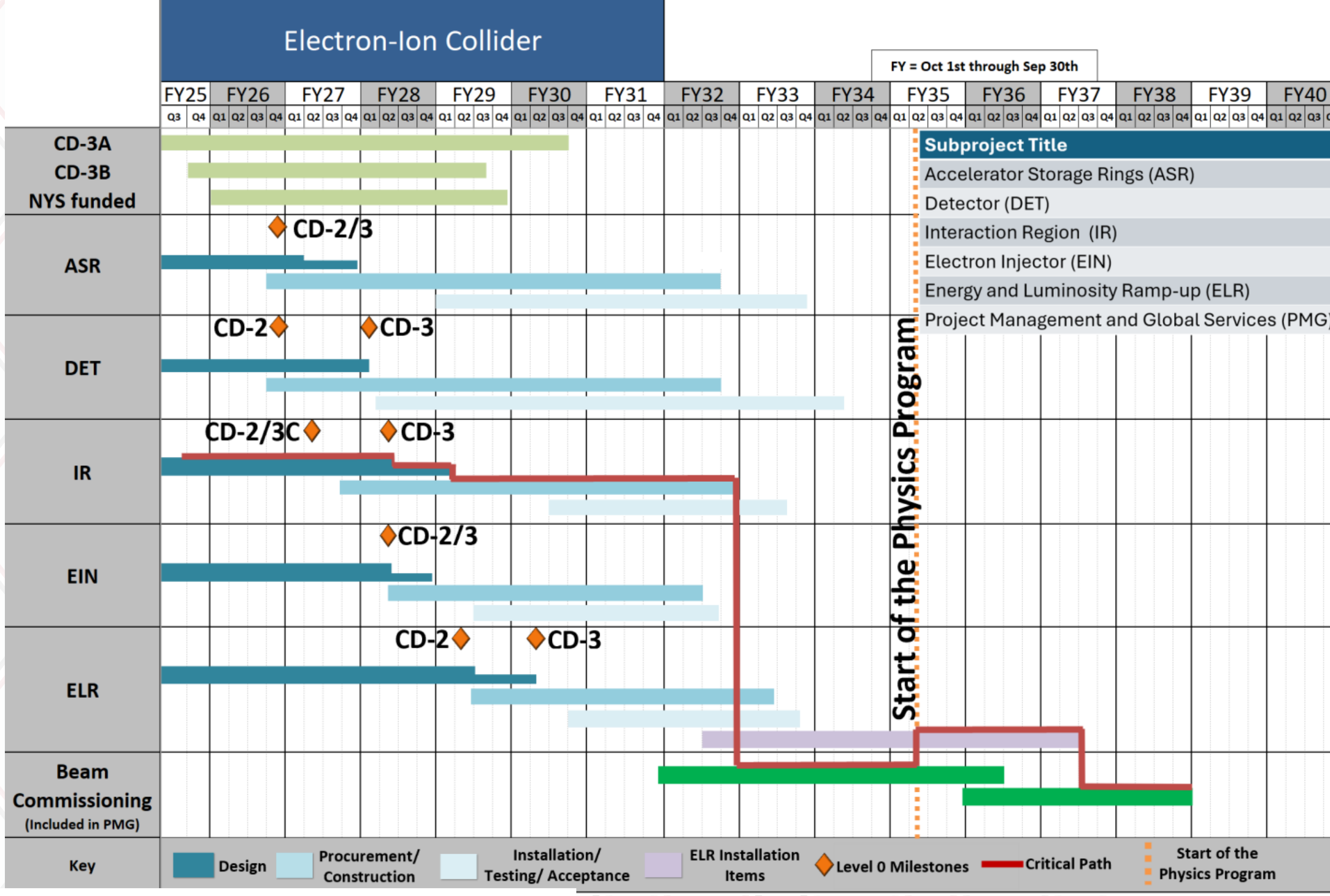


Far-Forward Instrumentation



EIC Project Schedule

- Long procurement items have been already started (magnet, accelerator components)
- Main CD2 for detector expected end of 2026
- Start of the physics program in about 10 years from now, significant physics questions to be addressed in first few years of operation



	Species	Energy (GeV)	Luminosity/year (fb-1)	Electron polarization	p/A polarization
YEAR 1	e+Ru or e+Cu	10 x 115	0.9	NO (Commissioning)	N/A
YEAR 2	e+D e+p	10 x 130	11.4 4.95 - 5.33	LONG	NO TRANS
YEAR 3	e+p	10 x 130	4.95 - 5.33	LONG	TRANS and/or LONG
YEAR 4	e+Au e+p	10 x 100 10 x 250	0.84 6.19 - 9.18	LONG	N/A TRANS and/or LONG
YEAR 5	e+Au e+3He	10 x 100 10 x 166	0.84 8.65	LONG	N/A TRANS and/or LONG

Summary

- The EIC will be a very versatile collider of polarized protons, deuterons and ^{3}He, as well as heavier nuclei
- The high luminosity will allow to address many key questions of QCD, such as the spin of the nucleon, the three-dimensional position and momentum structure, saturation effects at low-x, and the origin of mass
- The ePIC detector will be the main detector at EIC, covering the central interaction region including particle identification, and dedicated detectors in the far forward and backward regions
- A very exciting physics program is just around the corner