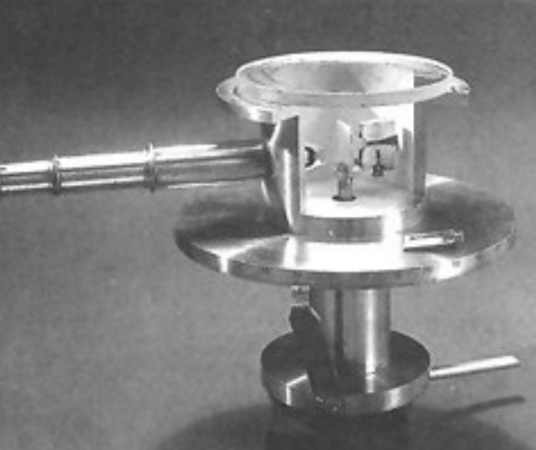
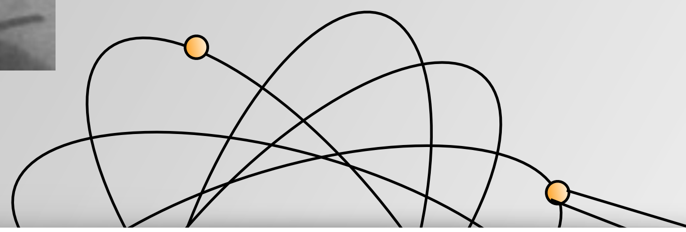
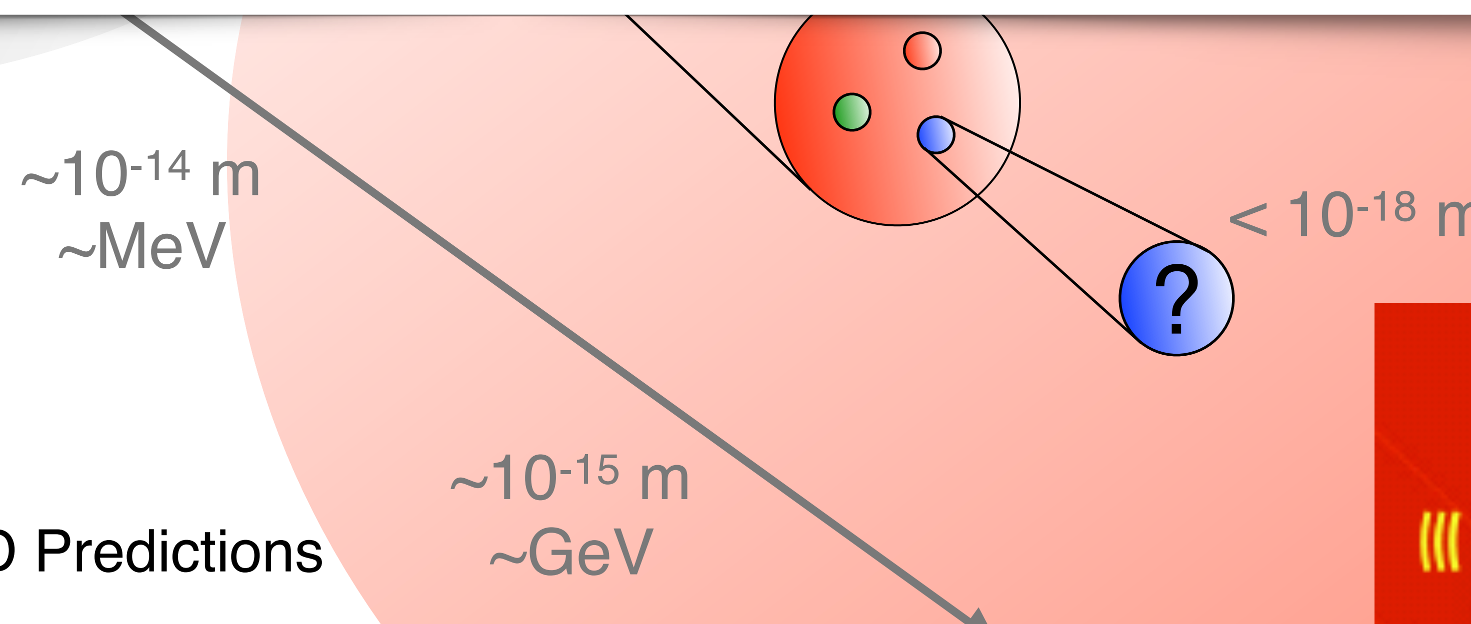
Funding support from:





EIC Experimental Overview

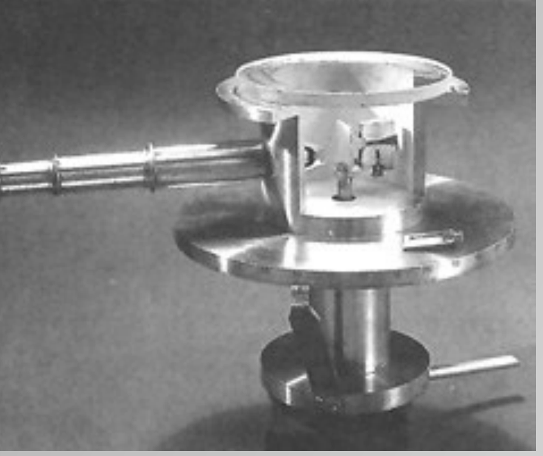
Ernst Sichtermann (Lawrence Berkeley National Laboratory)

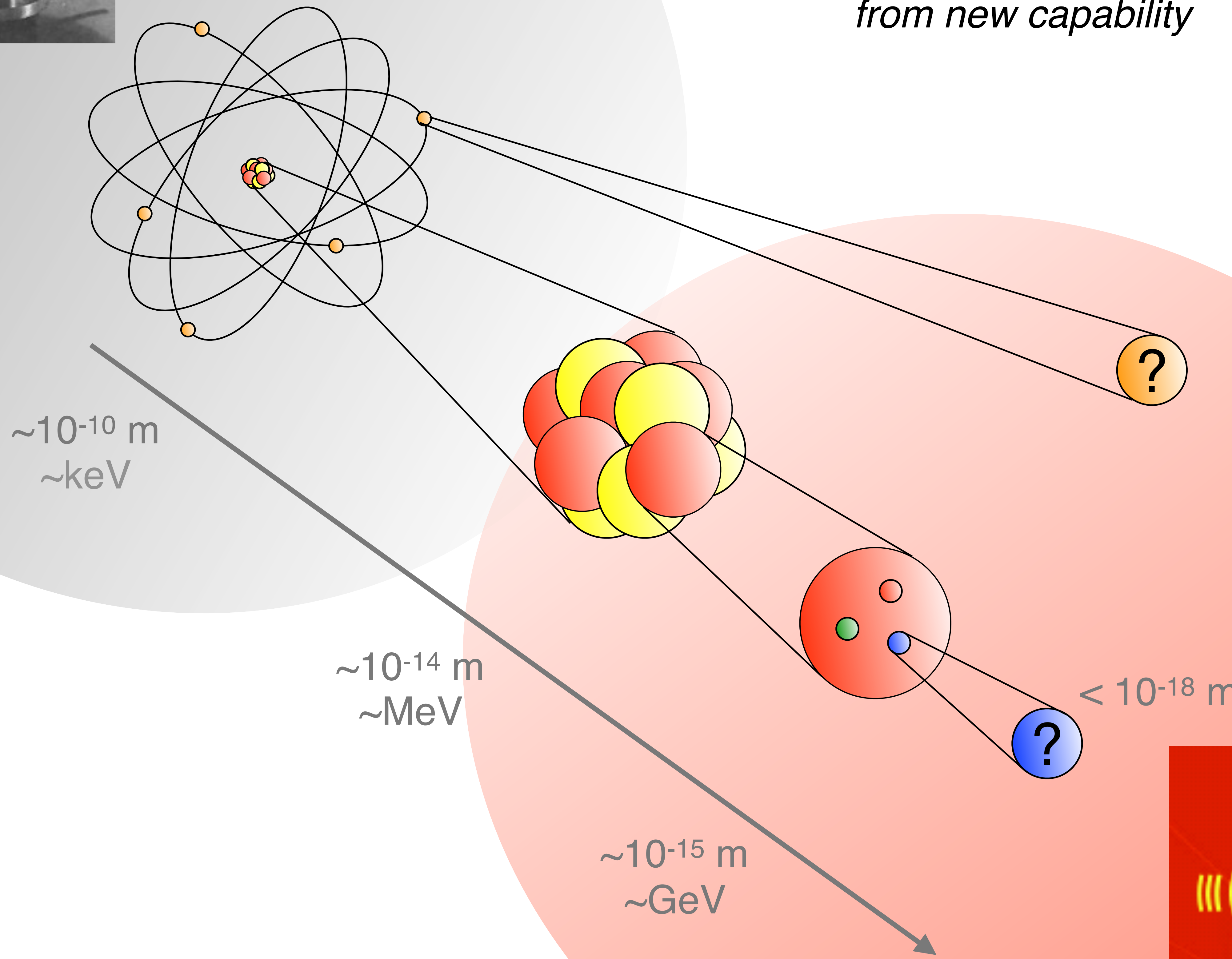


CFNS Workshop: Precision QCD Predictions for ep Physics at the EIC
Stony Brook University — Sept 18-22, 2023

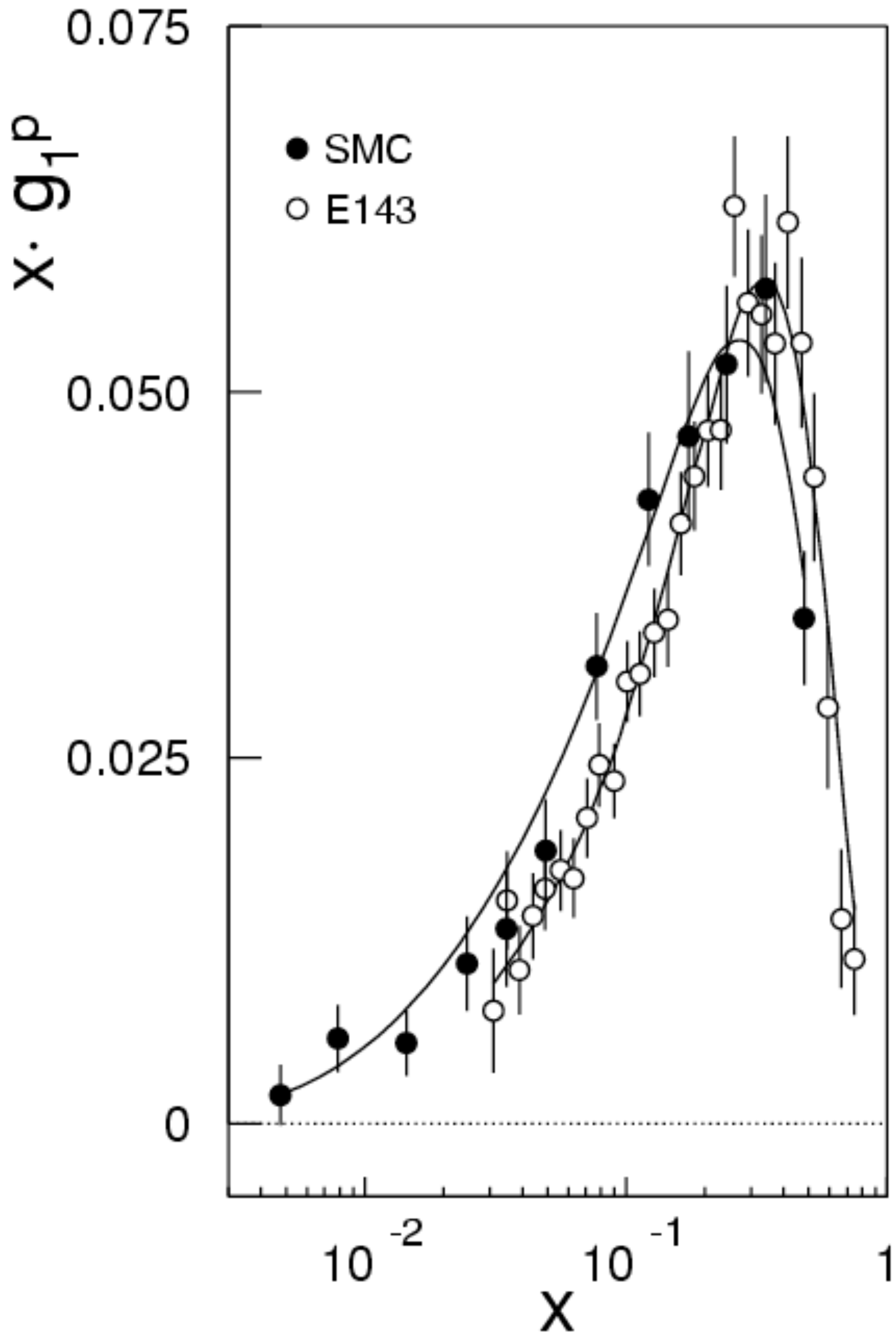
Thank you, Werner and Daniel,
for the invitation!

A history of new insight from new capability





Renewed interest in nucleon spin



Circa ~1995 start of (polarized) pQCD analyses of g_1,

Today:

polarized inclusive hadron measurements e.g. E155,

polarized semi-inclusive data with identified hadrons, including heavy flavor, e.g. HERMES, COMPASS

non-vanishing Collin's and Sivers' asymmetries, HERMES, COMPASS, JLab, and RHIC,

p+p collider data on jet spin-asymmetries and leptonic W-boson decay,

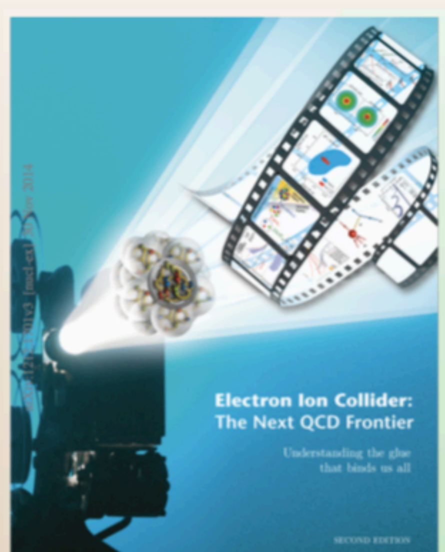
All of these observables are certain to stay.

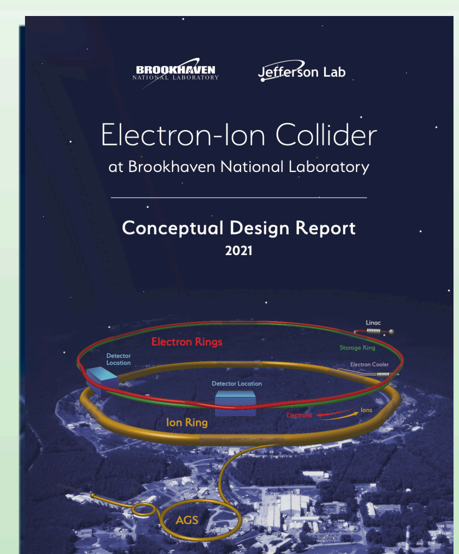
Great prospects for a U.S.-based polarized EIC.

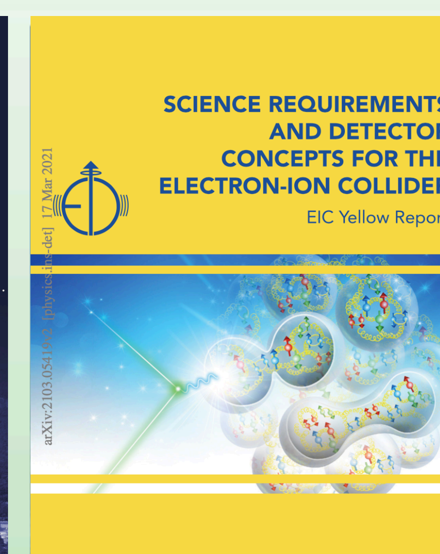
Electron Ion Collider Initiatives

Approach: combine strengths
use existing investments (risk, cost),
pursue luminosity;100x - 1000x HERA
nuclei and *polarization*,
optimized instrumentation.

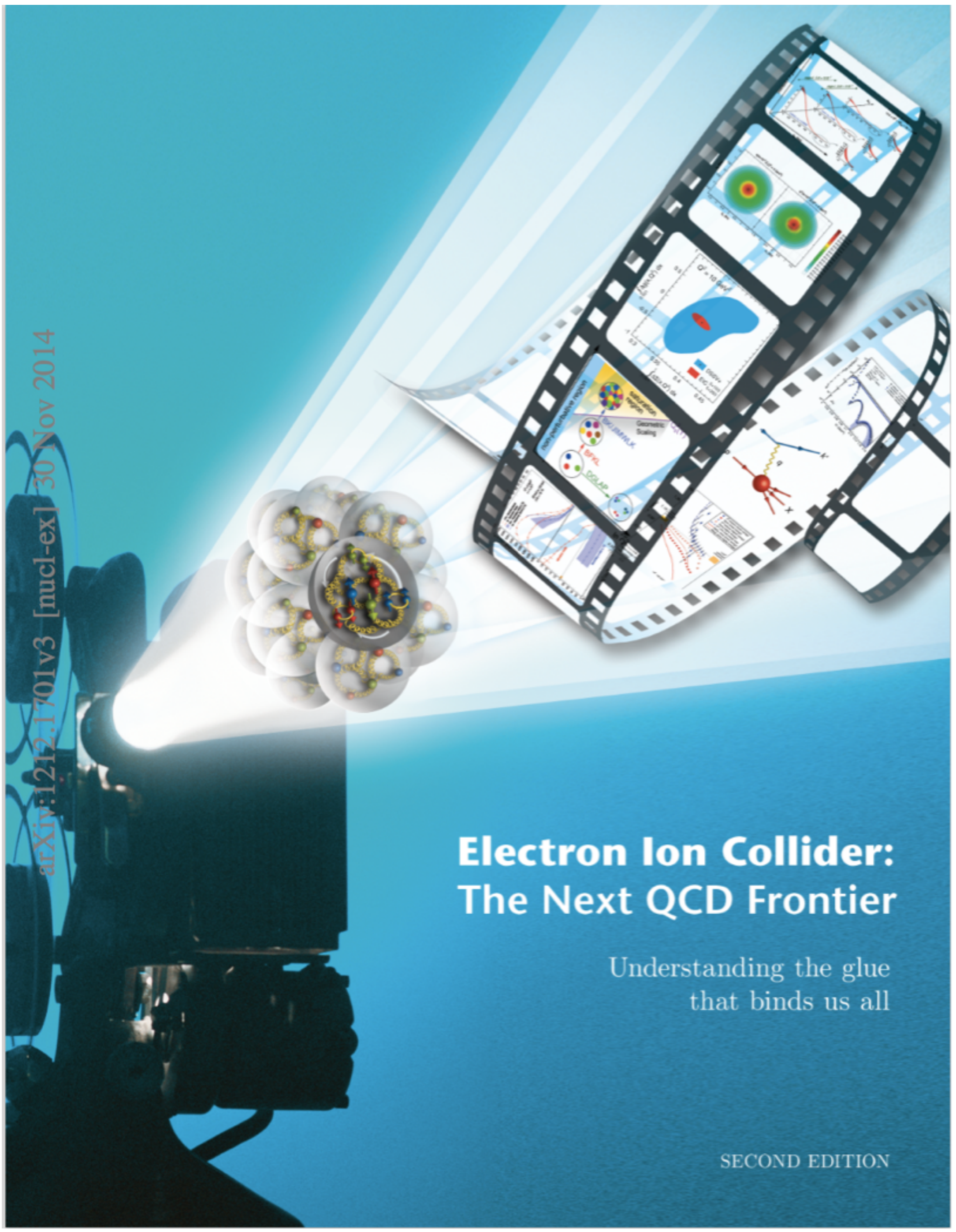
	HERA @ DESY	LHeC @ CERN	EIC in China	EIC in U.S.
$\sqrt{s_{ep}}$ [GeV]	320	200 - 1300	17	20 - 100 (140)
proton x_{min}	1 x 10^{-5}	5 x 10^{-7}	3 x 10^{-3}	
ion	p	p, Pb, ...	p - Pb	p - U
polarization	-	-	p, light nuclei	p, d, ^{3}He, Li
L [$cm^{-2}s^{-1}$]	2 x 10^{31}	1 x 10^{34}	5 x 10^{33}	10^{33} - 10^{34}
Interaction Points	2	1	1	2
Timeline	1992 - 2007	post ALICE	> 2028	> 2028







U.S. EIC Science Case

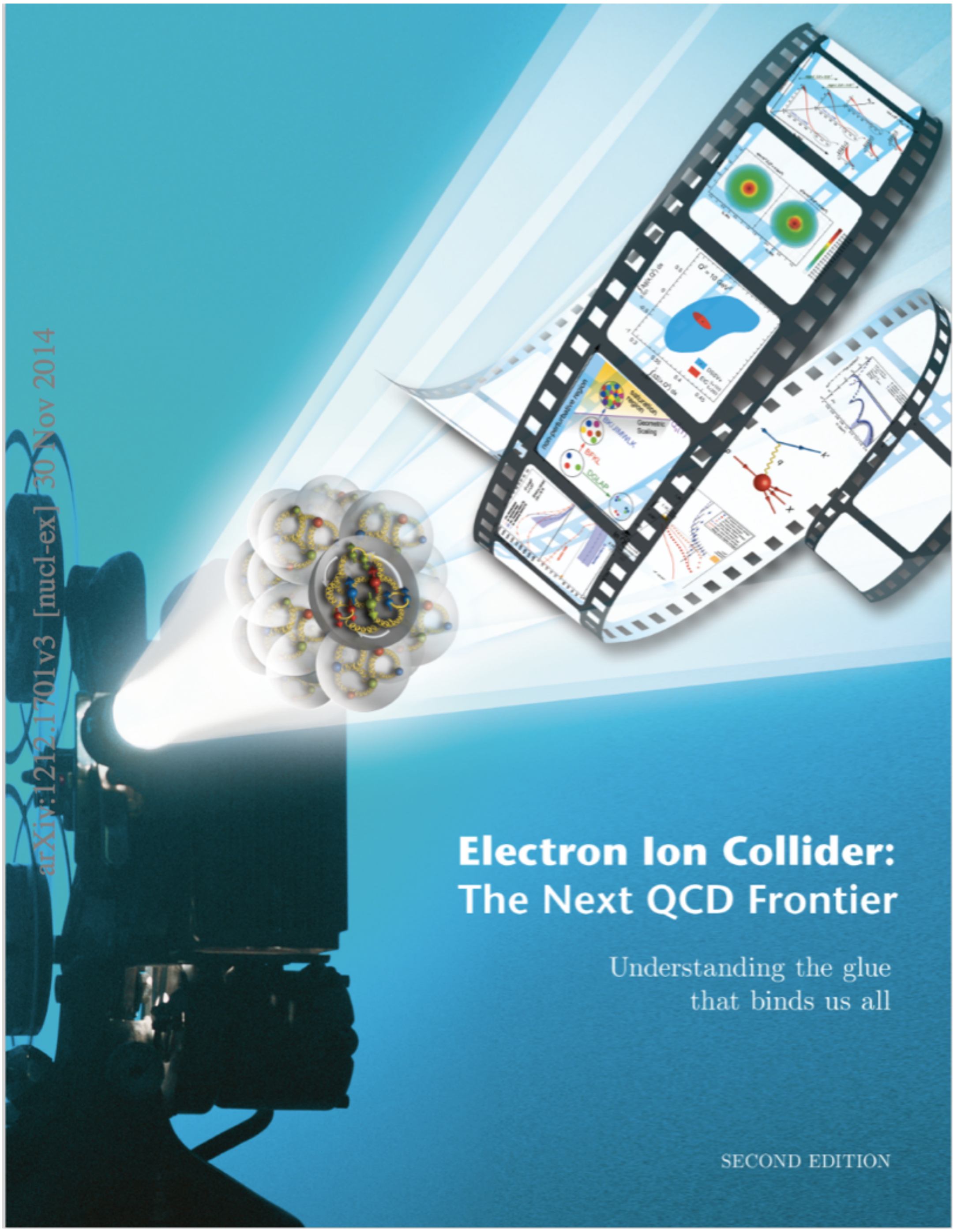


Eur. Phys. J. A52 (2016) no.9, 268

See also Rept.Prog.Phys. 82 (2019) 024301

- *How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleus?*
- *Where does the saturation of gluon densities set in?*
- *How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?*

U.S. EIC Science Case



Organized around four themes:

- *Proton spin,*
  quark and gluon helicity distributions,
  orbital motion
- ***Imaging** of nucleons and nuclei*
  TMDs, GPDs, Wigner functions
- ***Saturation***
  Non-linear evolution,
  Color-glass condensate,
- *Hadronization and fragmentation,*
  in-medium propagation,attenuation

Identified measurements and impact.

Eur. Phys. J. A52 (2016) no.9, 268

See also Rept.Prog.Phys. 82 (2019) 024301

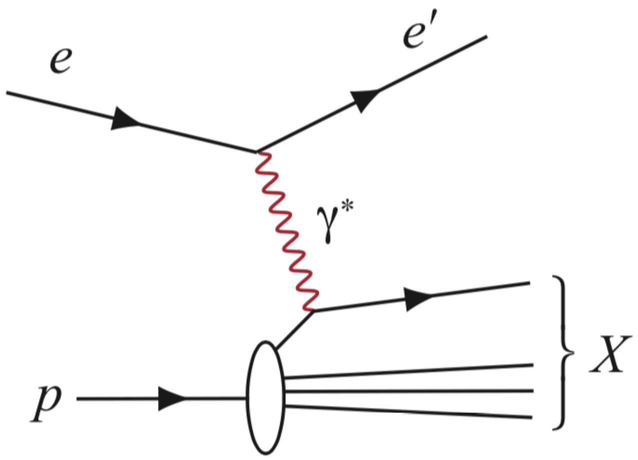
U.S.-based EIC - key processes (at LO)

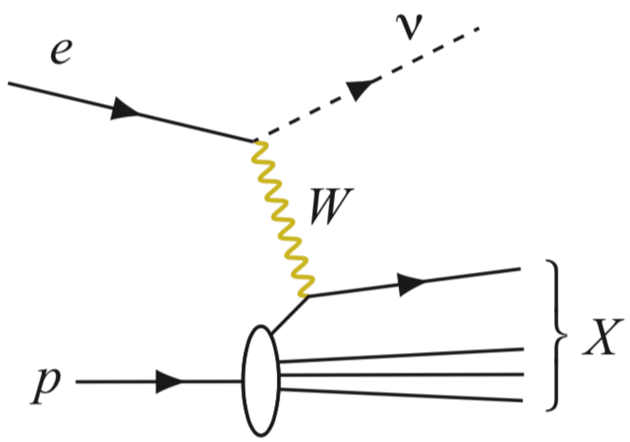
Inclusive deep-inelastic scattering

primarily about scattered electrons,

acceptance in x, Q^2 — low x,Q^2 affects IR

~ 1 fb^{-1}





Semi-inclusive deep-inelastic scattering

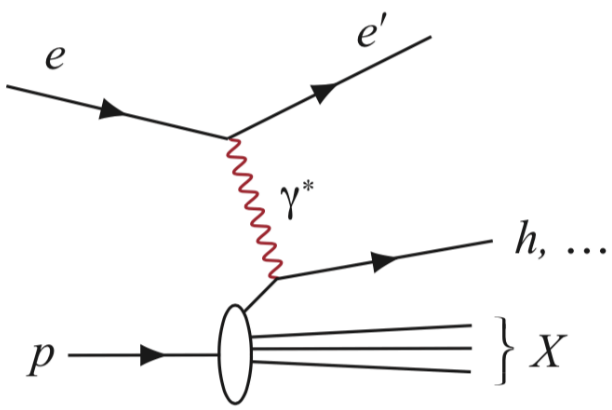
scattered electron and one or more (identified) hadrons,

multidimensional binning: x, Q^2, z, p_T, ø

particle identification 0.3 — 60 GeV/c,

energy scale in the case of jets

~ 10 fb^{-1}



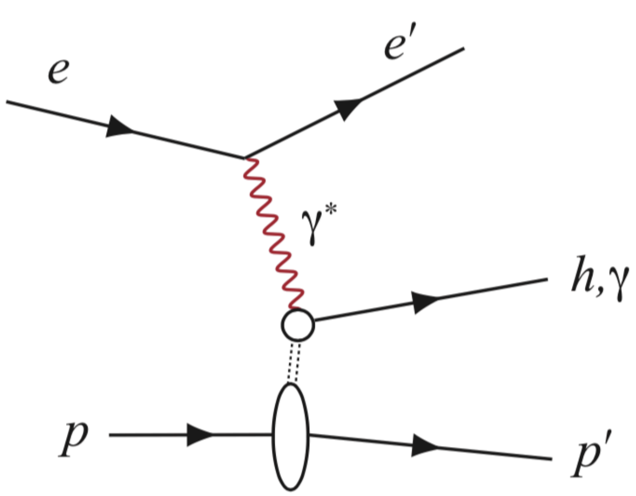
Exclusive deep-inelastic scattering

~all particles in the event,

multidimensional binning: x, Q^2, t, ξ

p' over ~$0.2 < p_T <$ ~1.4 GeV needs instruments tightly integrated in IR

~ 100 fb^{-1}



U.S.-based EIC - Observables

Key questions:

- *How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleus?*
- *Where does the saturation of gluon densities set in?*
- *How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?*

Key measurements:

- *Inclusive Deep-Inelastic Scattering,*
- *Semi-inclusive deep-inelastic scattering with one or two of the particles in the final state,*
- *Exclusive deep-inelastic scattering,*
- *Diffraction.*

U.S.-based EIC - Observables

Key requirements:

- *Electron identification - scattered lepton*
- *Momentum and angular resolution - x, Q^2*
- *π^+, π^-, K^+, K^-, p^+, p^-, ... identification, acceptance*
- *Rapidity coverage, t-resolution*

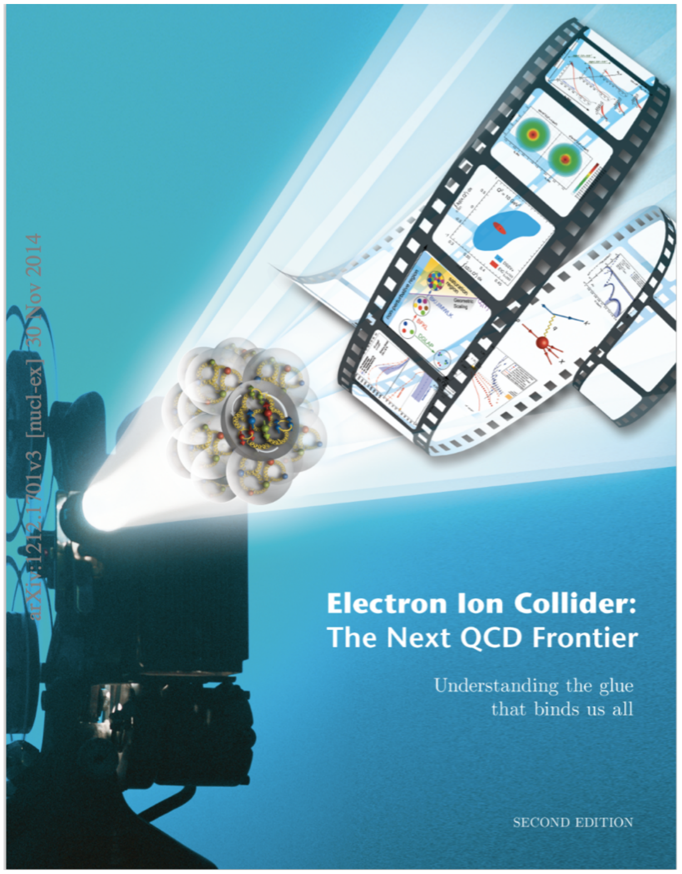
Key measurements:

- *Inclusive Deep-Inelastic Scattering,*
- *Semi-inclusive deep-inelastic scattering with one or two of the particles in the final state,*
- *Exclusive deep-inelastic scattering,*
- *Diffraction.*

multi-dimensional and **multi-channel**

U.S.-based EIC - Towards realization

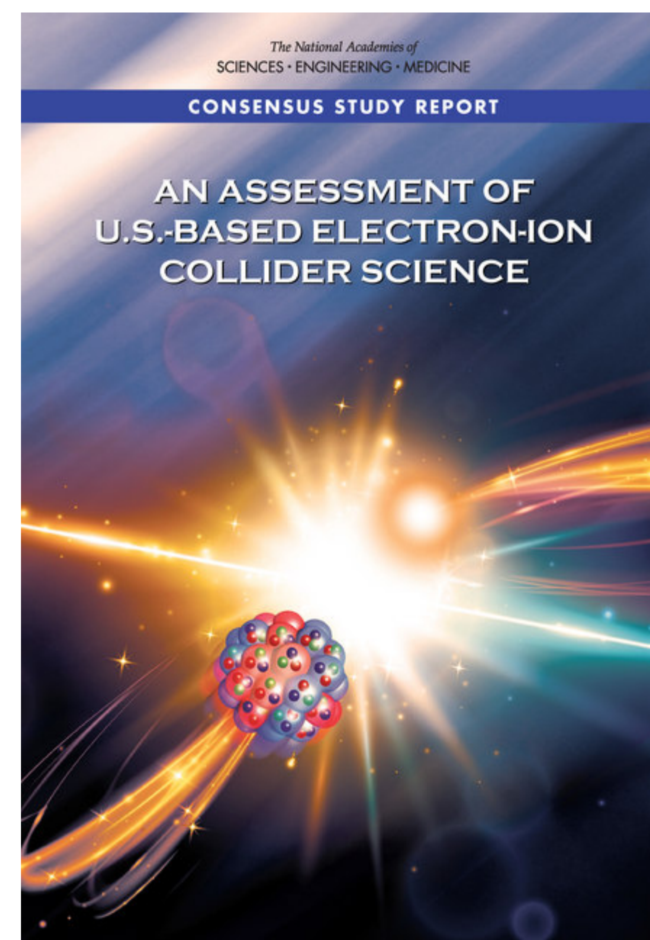
arXiv:1212.1701, EPJ A52 (2016) 268



Four central nuclear physics themes:

- nucleon spin,
- **imaging** in nucleon and nuclei,
- gluon-dense matter / **saturation**,
- hadronization and fragmentation

U.S.-based Electron-Ion Collider is strongly endorsed in the 2015 Long Range Plan for Nuclear Physics,



2018 NAS Science Assessment:

"EIC is compelling, fundamental, and timely"

Science case: theory, experiment, *and* accelerator,

Note — "Finding 7: To realize fully the scientific opportunities an EIC would enable, a theory program will be required to predict and interpret the experimental results within the context of QCD, and further, to glean the fundamental insights into QCD that an EIC can reveal."

2020 site selection and project start (CD-0) announced,

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.

...

The EIC's high luminosity and highly polarized beams will push the frontiers of particle accelerator science and technology and provide unprecedented insights into the building blocks and forces that hold atomic nuclei together.

...

Secretary Brouillette approved Critical Decision-0, "Approve Mission Need," for the EIC on December 19, 2019.

That is, EIC is a DOE 413.3B project,

CD-0 — December, 2019

CD-1 — June, 2021

Looking ahead,

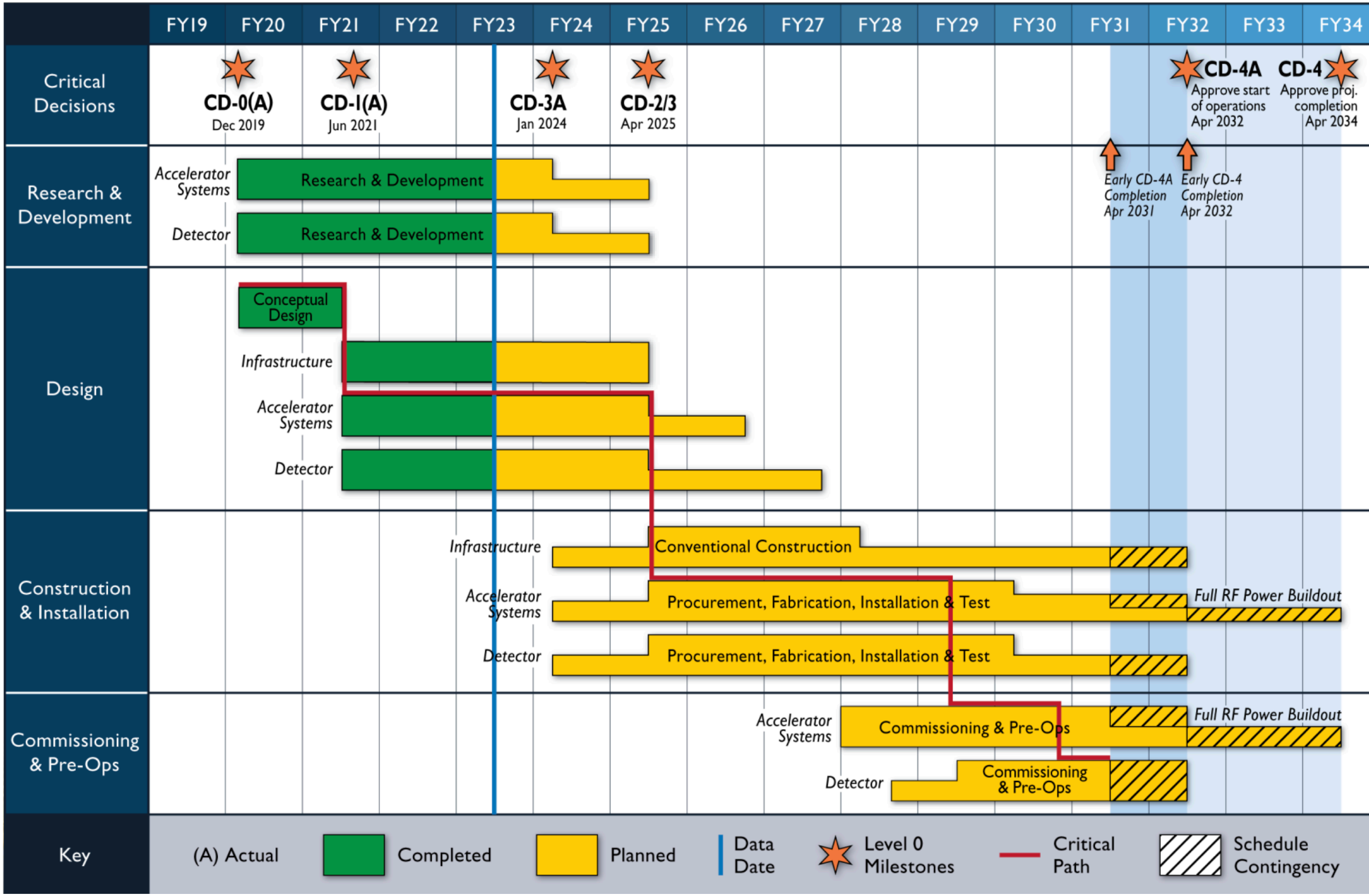
CD-3A — January, 2024

CD-2/3 — Spring 2025

Transition to operations — 2032–2034

Project includes Facility and (one) Detector. Facility has the possibility of two IRs.

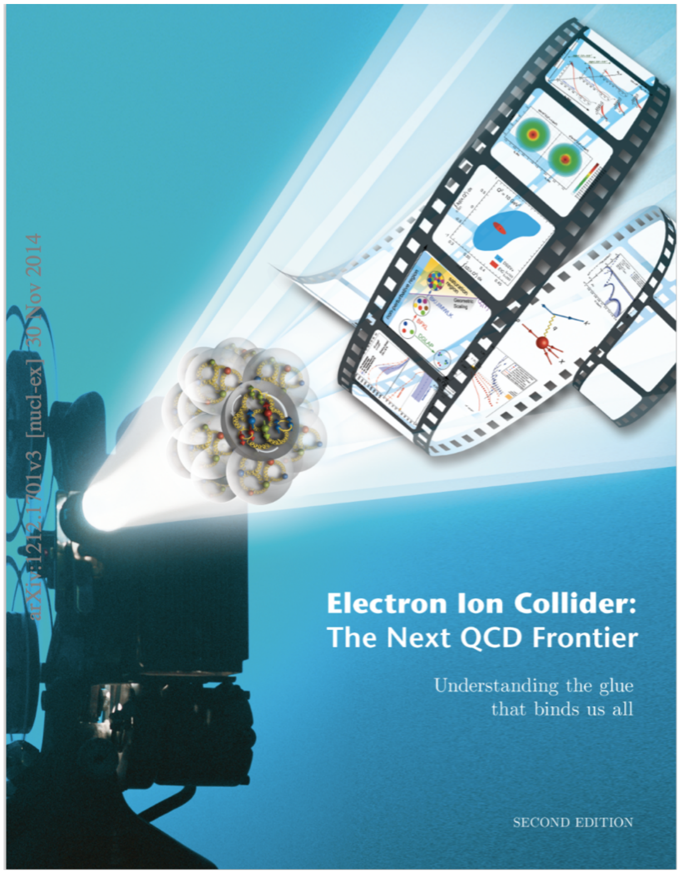
See e.g. J. Yeck, 2023 EIC User Group Meeting — https://indico.cern.ch/event/1238718/



Source: J. Yeck, 2023 EIC User Group Meeting — https://indico.cern.ch/event/1238718/

U.S.-based EIC - Towards realization

arXiv:1212.1701, EPJ A52 (2016) 268



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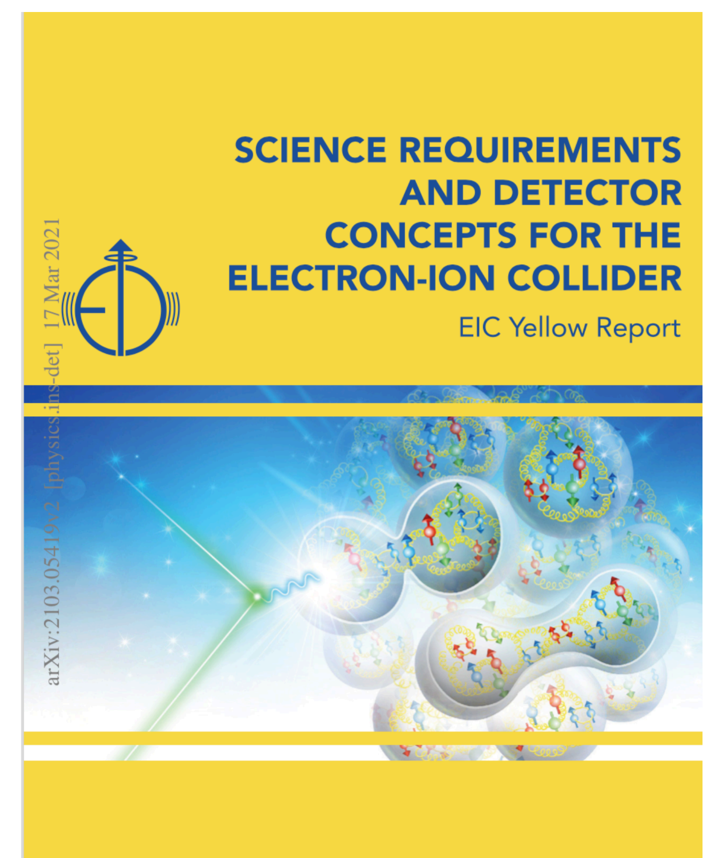
arXiv:2103.05419, NPA 1026 (2022) 12447



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"EIC is compelling, fundamental, and timely"

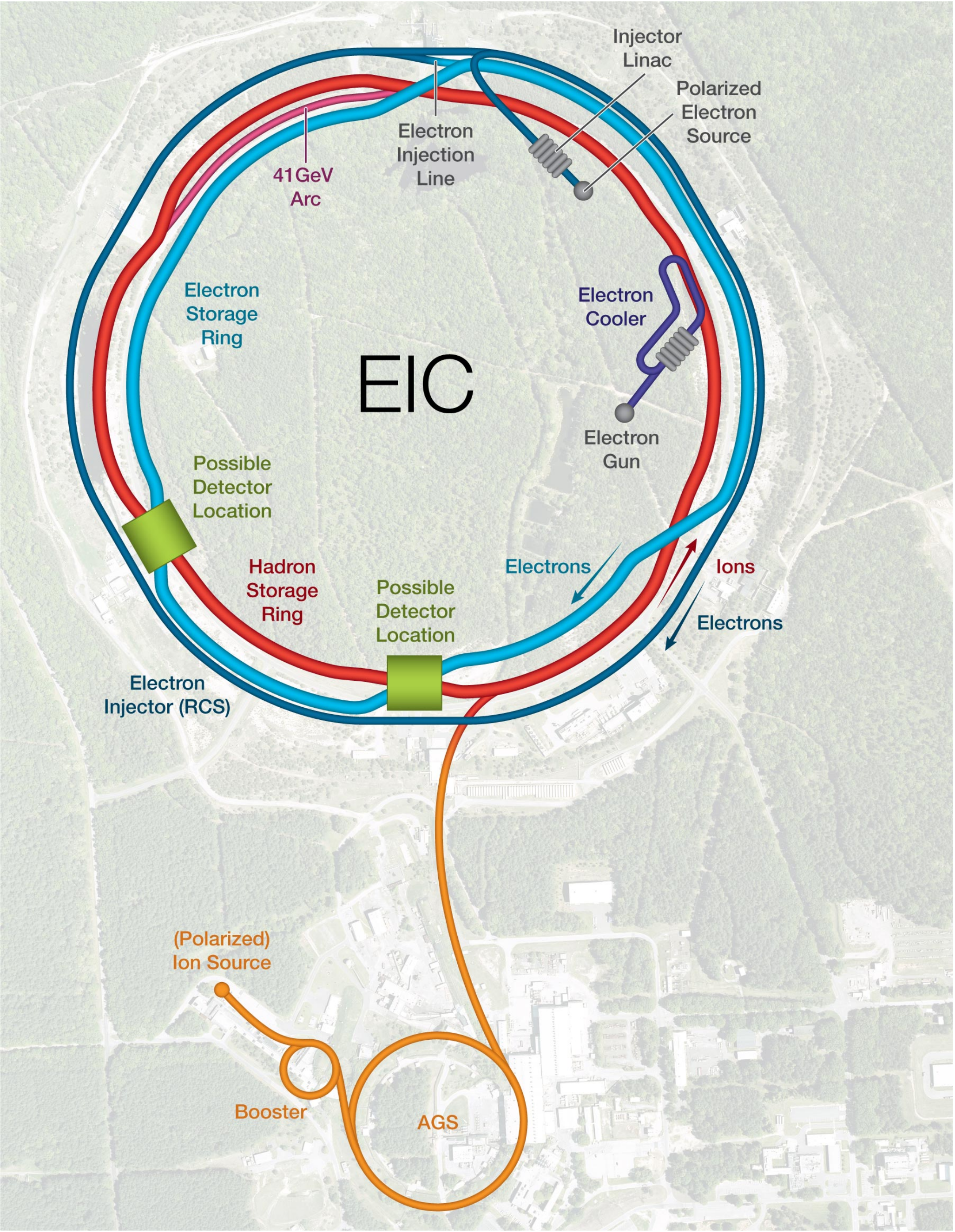
Science case: theory, experiment, *and* accelerator,

2020 site selection and project start (CD-0) announced,

2021 Yellow Report — works out initial requirements,
two detector reference designs
identifies further physics opportunities

led (in-)to call for detector proposals.

U.S.-based EIC

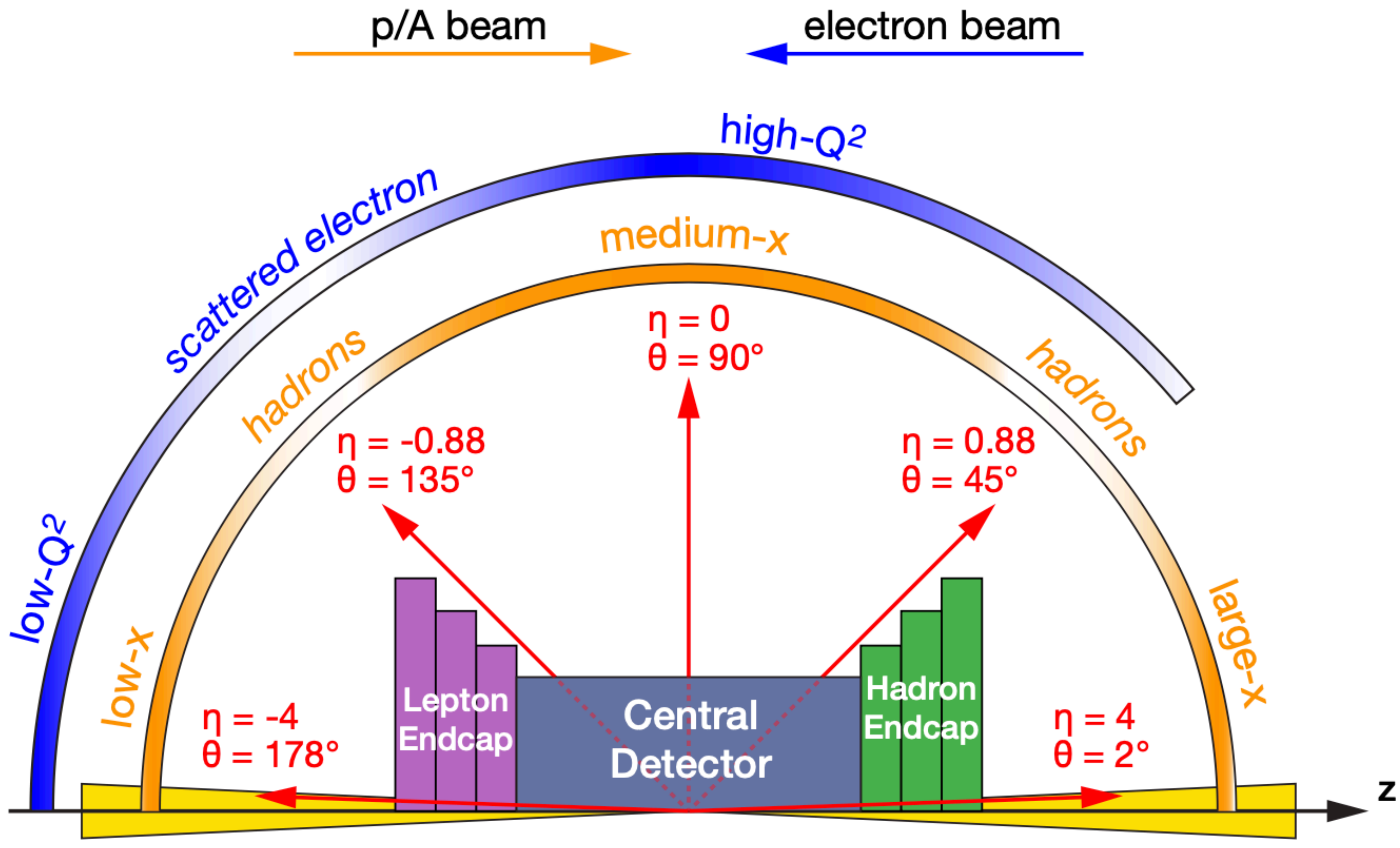


Design Goals:

- High Luminosity: L= 10^{33} – 10^{34}cm^{-2}s^{-1}, 10 – 100 fb^{-1}/year
- Highly Polarized Beams: 70%
- Large Center of Mass Energy Range: E_{cm} = 29 – 140 GeV
- Large Ion Species Range: protons – Uranium
- Large Detector Acceptance and Good Background Conditions
- Possibility of a Second Interaction Region (IR)

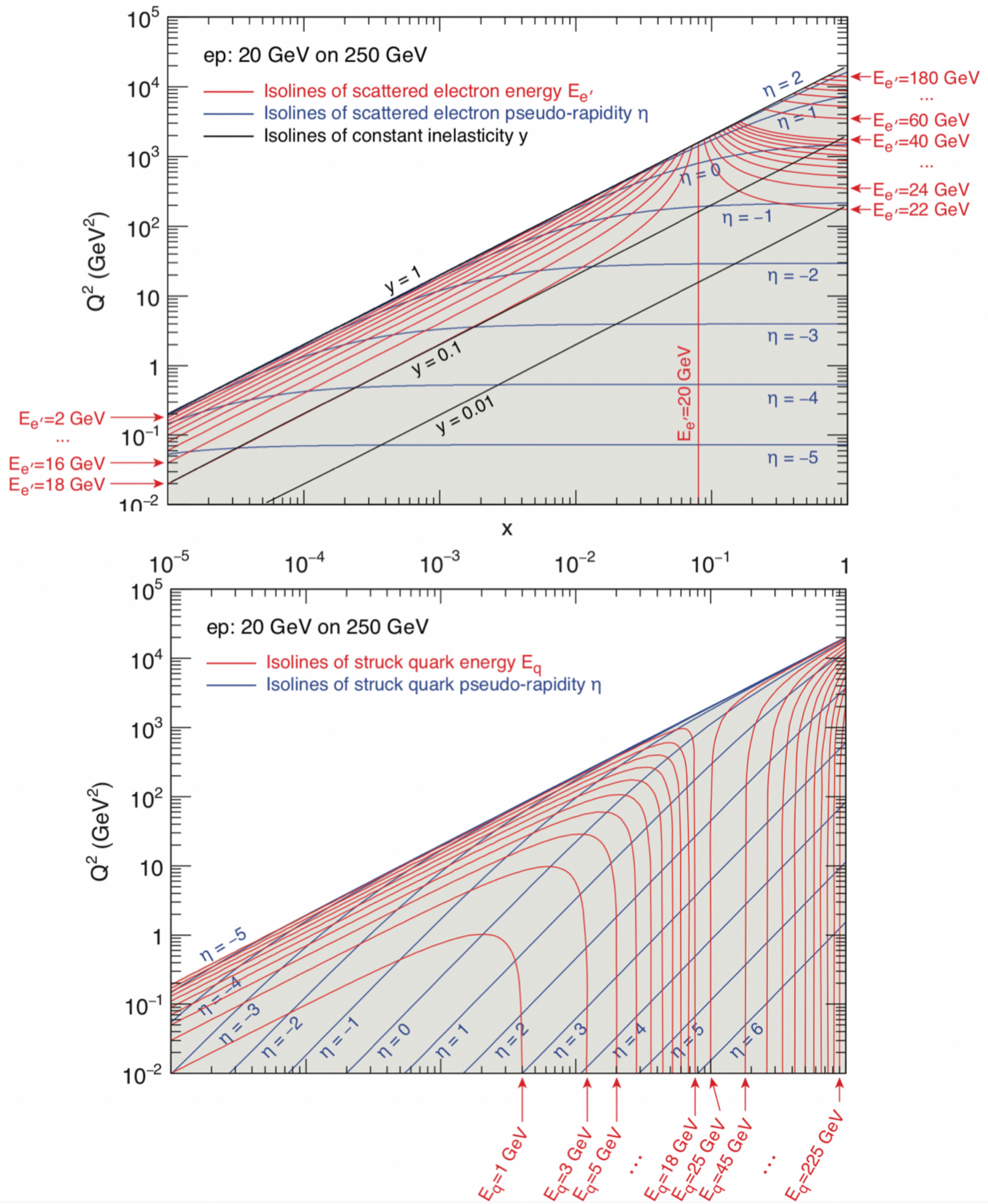
"Best of both U.S.-based spin-physics facilities — Jefferson Lab and RHIC"

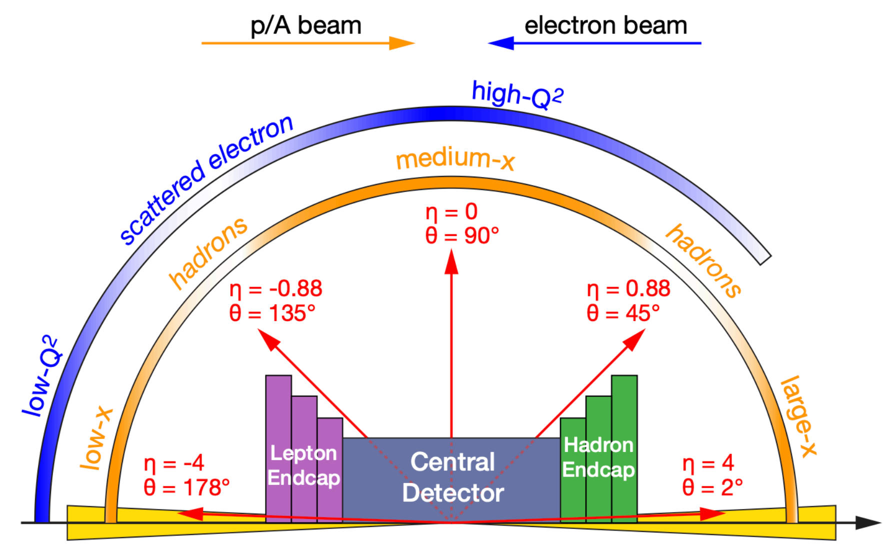
EIC - Central Detector View



High luminosity drives the need for a compact device, ~ 9m along the beam axes,
Large acceptance required by the science drives the need for (very) careful integration,
Combination with calorimetry and PID drives the need for a compact tracking subsystem,

EIC - Central Detector View and Acceptance





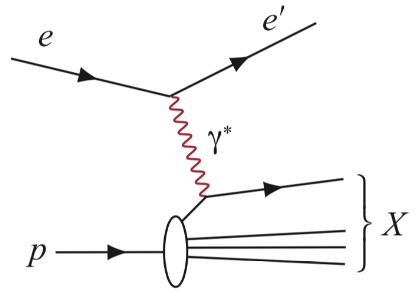
The DIS cross-section typically goes as $1/Q^4$

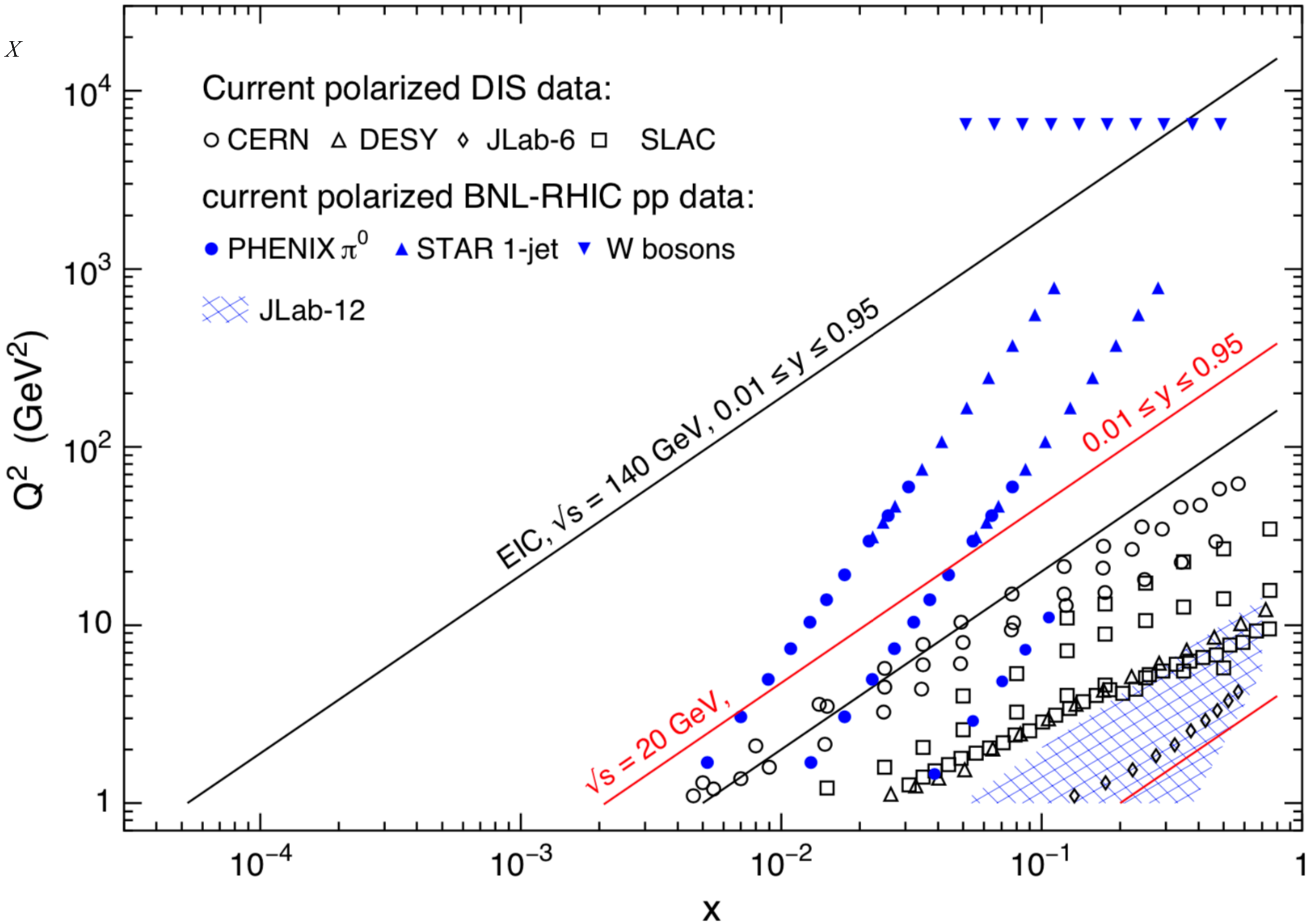
High momenta, be they electron or hadron, are typically associated with large *x* processes,

Physics in all areas of this (these) kinematic plane(s),

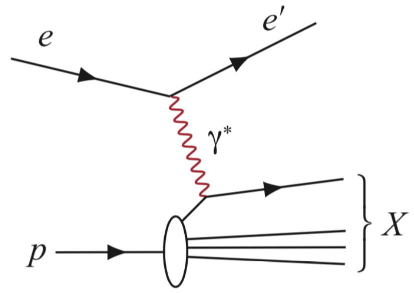
Unique EIC physics afforded by kinematics, luminosity, diverse ion species, detector capabilitiies,

Polarized inclusive DIS Landscape - U.S.-based EIC



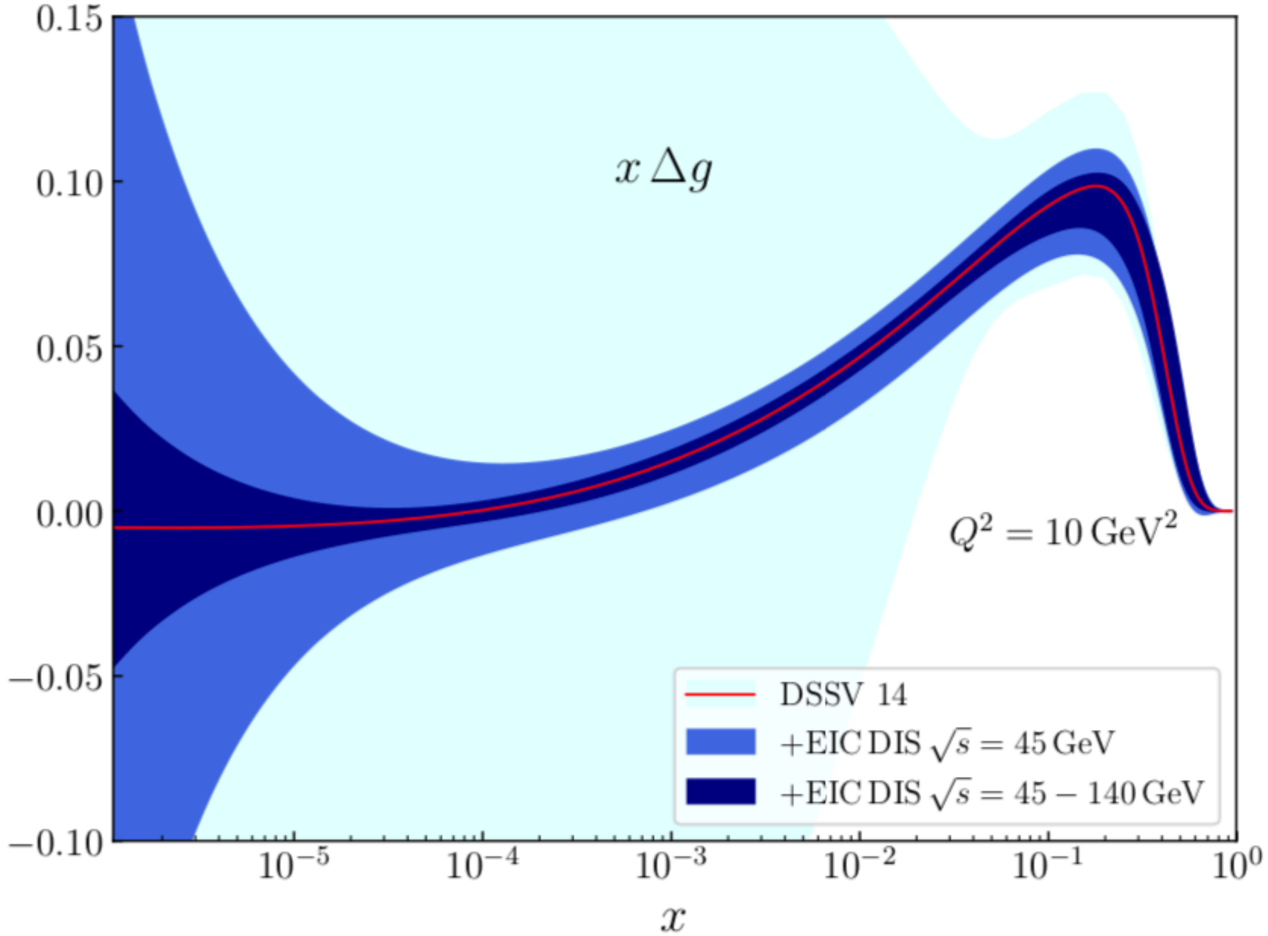


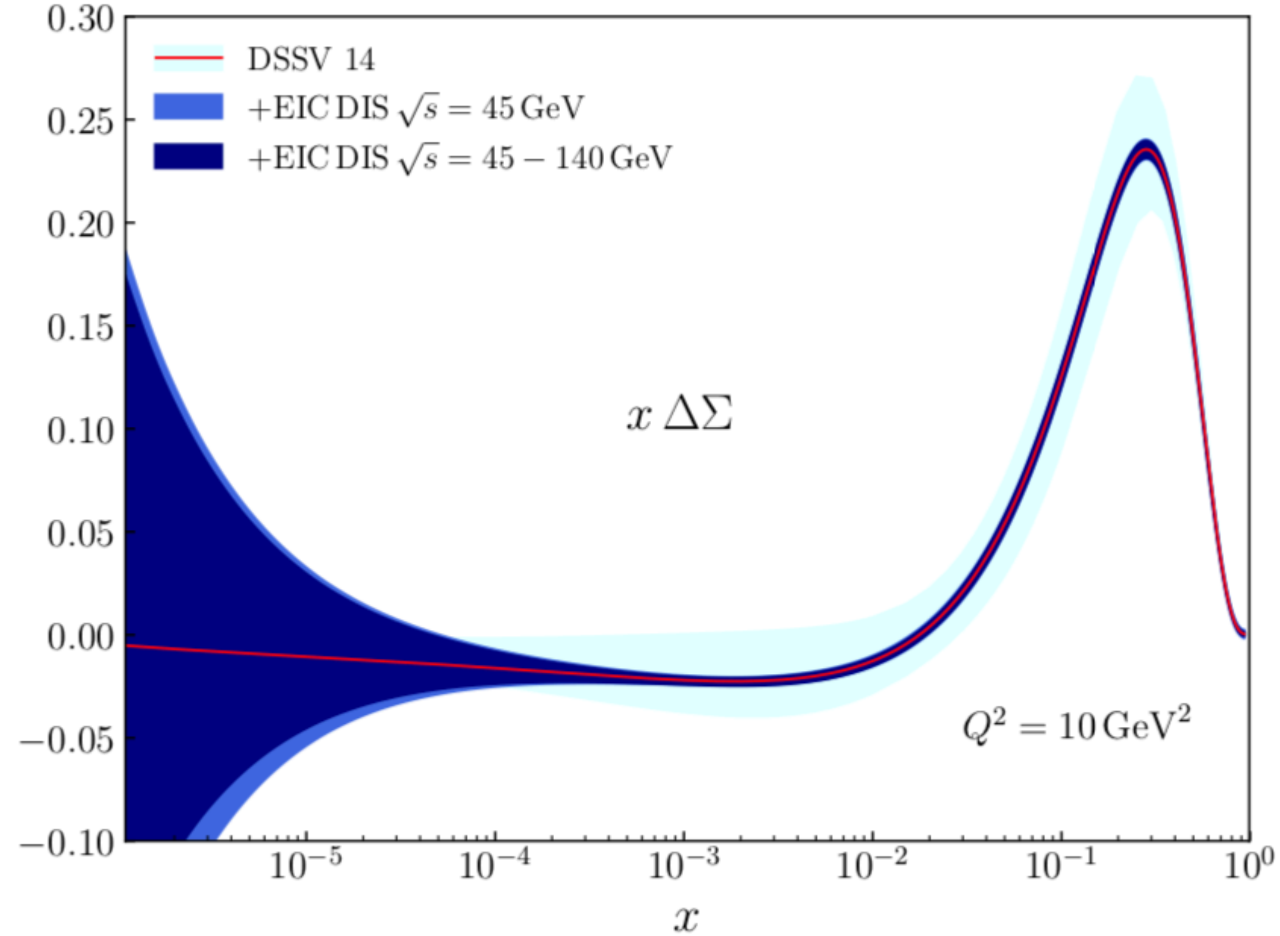
U.S.-based EIC - polarized inclusive DIS



+ NLO

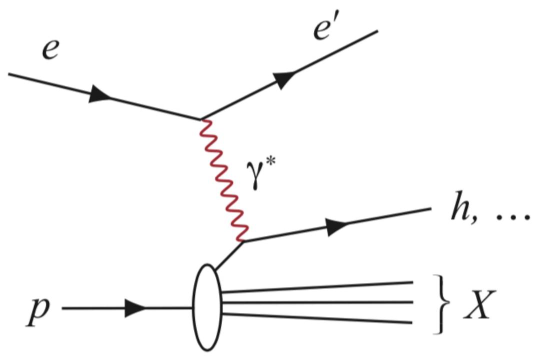
Phys.Rev.D 99 (2019) 094004

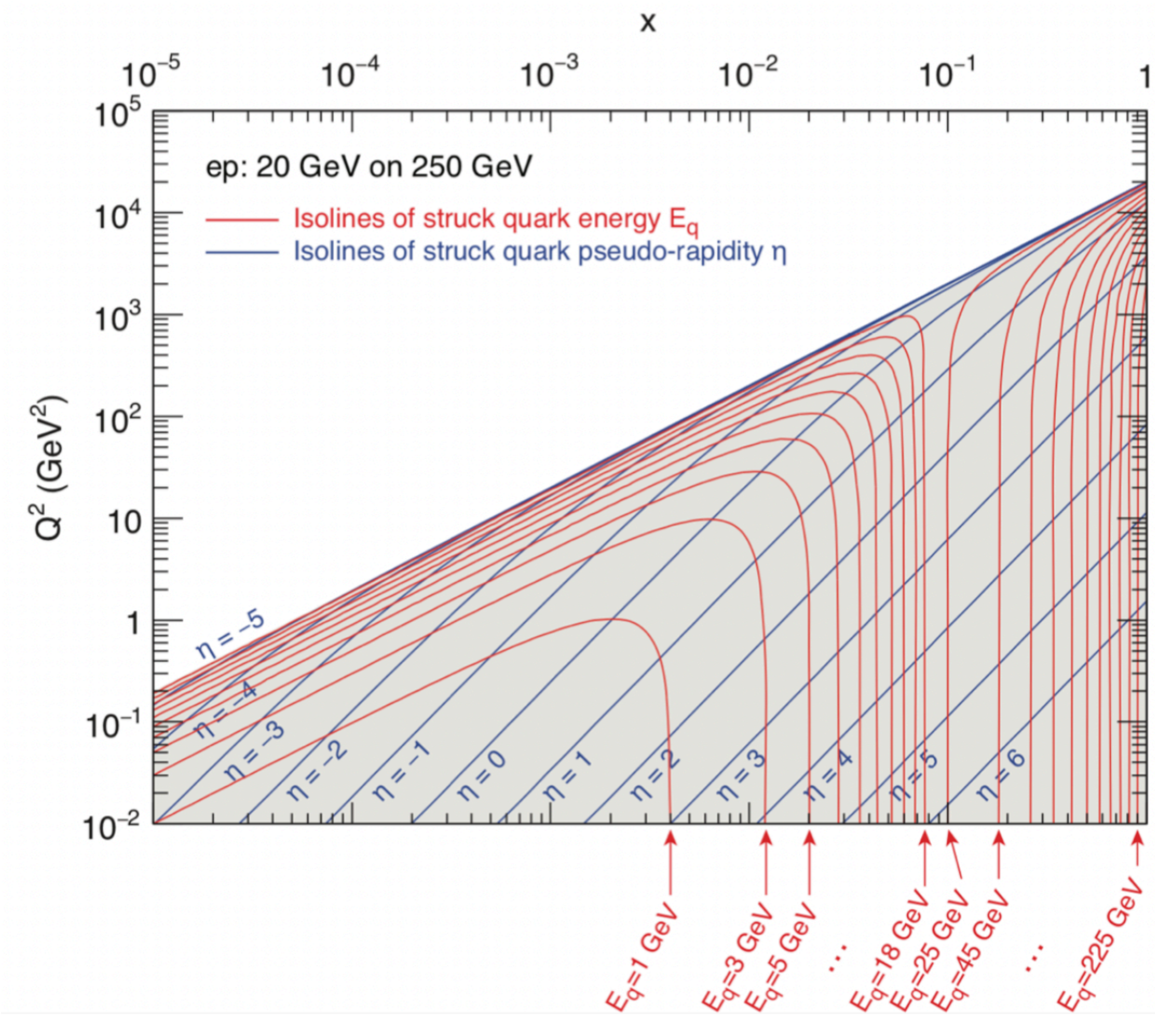


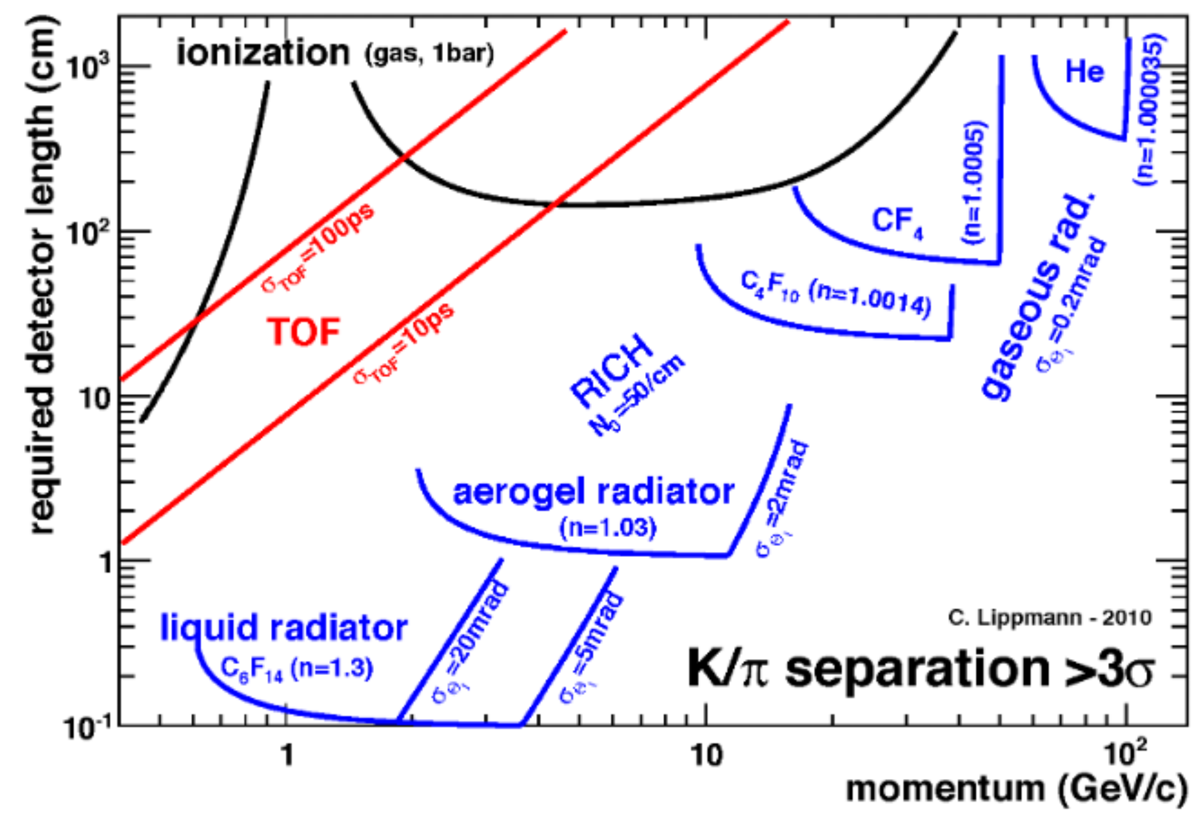


Core answers will include what is the gluon spin contribution to the proton spin?
what is the quark and anti-quark spin contribution (at low-*x*)?

U.S.-based EIC - polarized semi-inclusive DIS



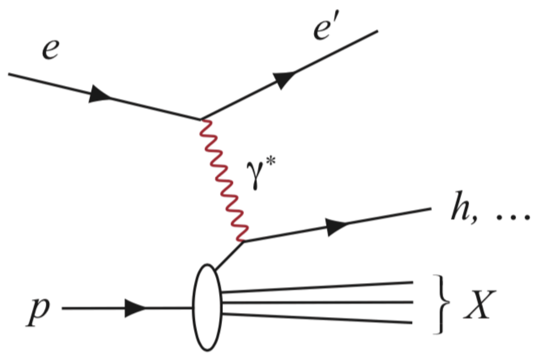




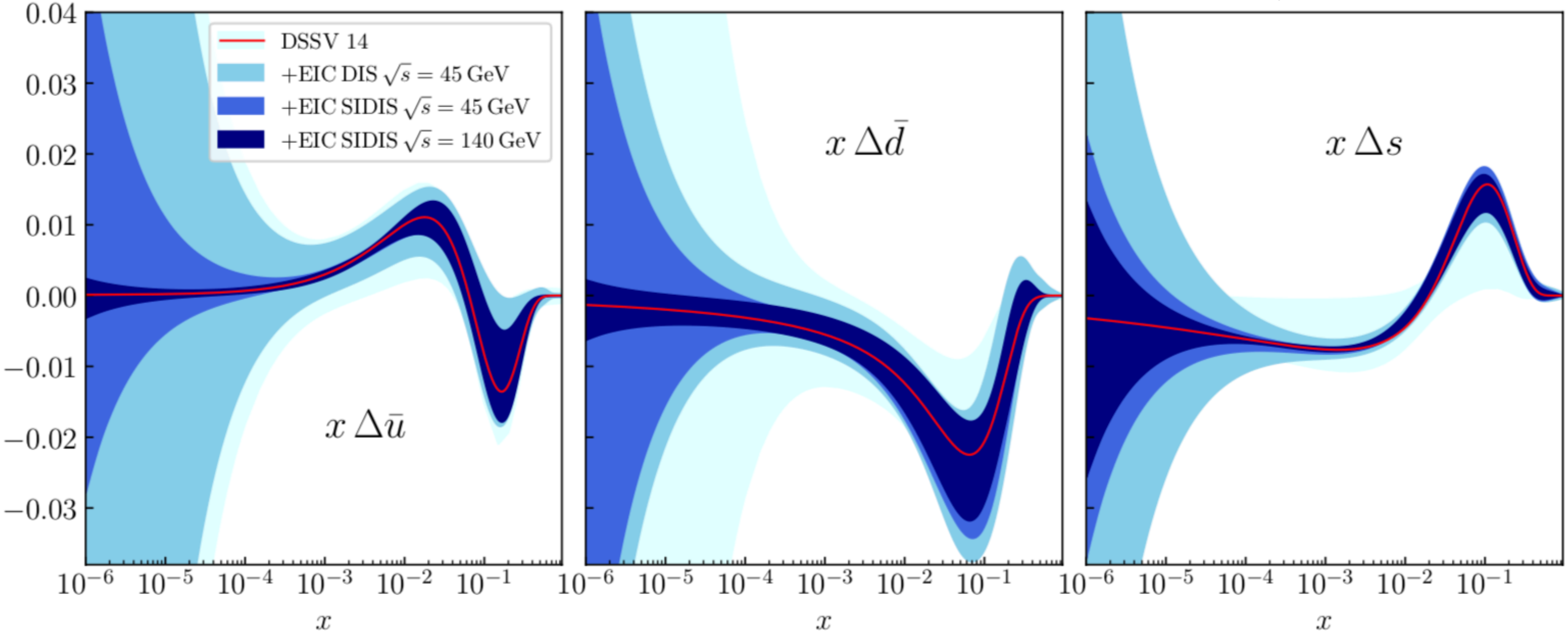
Exp: Wide range of momenta imposes multiple identification technologies/techniques,

Th.: Simultaneous determination of PDFs and FFs will prove key, in my opinion.

U.S.-based EIC - polarized semi-inclusive DIS



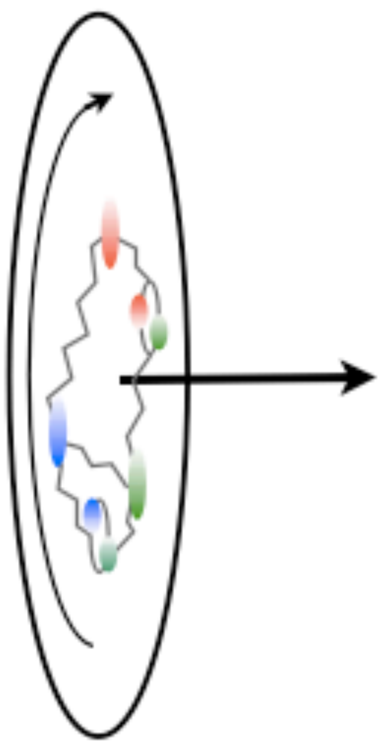
Phys.Rev.D 99 (2019) 094004

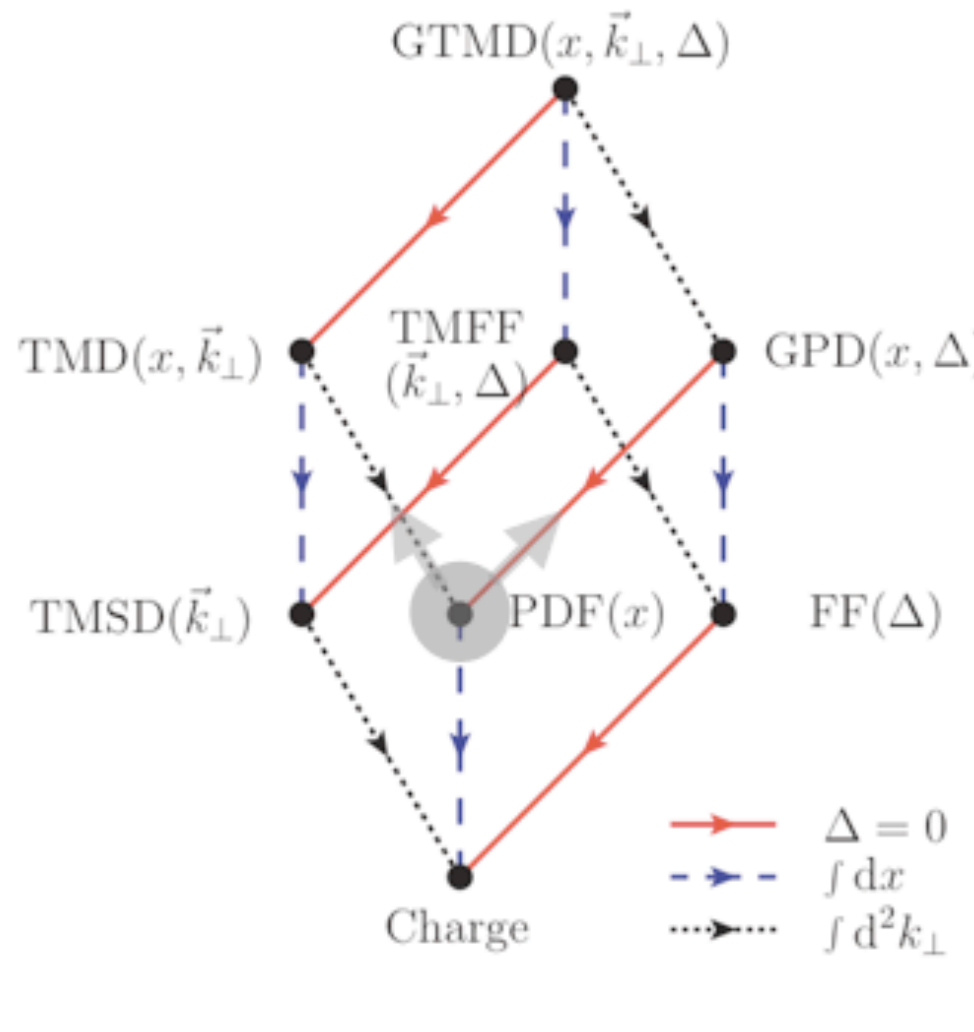


Semi-inclusive measurements will vastly advance insights in the polarized quark sea,
come with particle-identification challenges,

Charged-current measurements provide unique opportunities, e.g. g_5

U.S.-based EIC - beyond collinear parton distributions





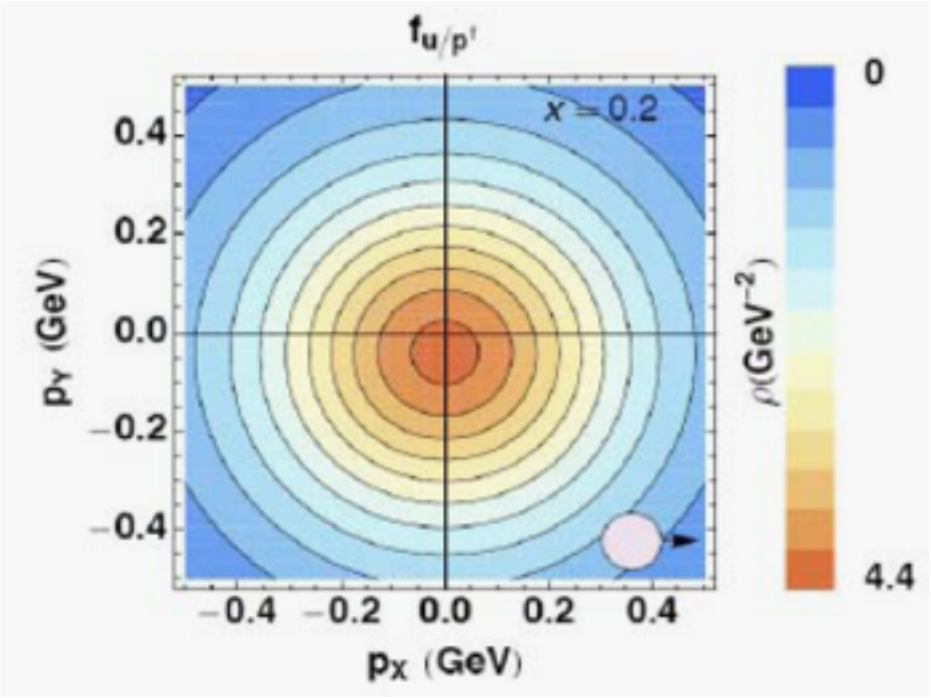
Lorce, Pasquini, Vanderhaeghen

Semi-inclusive measurements, together with exclusive measurements, are key to
probe beyond collinear parton distributions,
image the nucleon — orbital angular momenta.

U.S.-based EIC - Two Approaches to Imaging

TMDs

2+1 D picture in **momentum space**

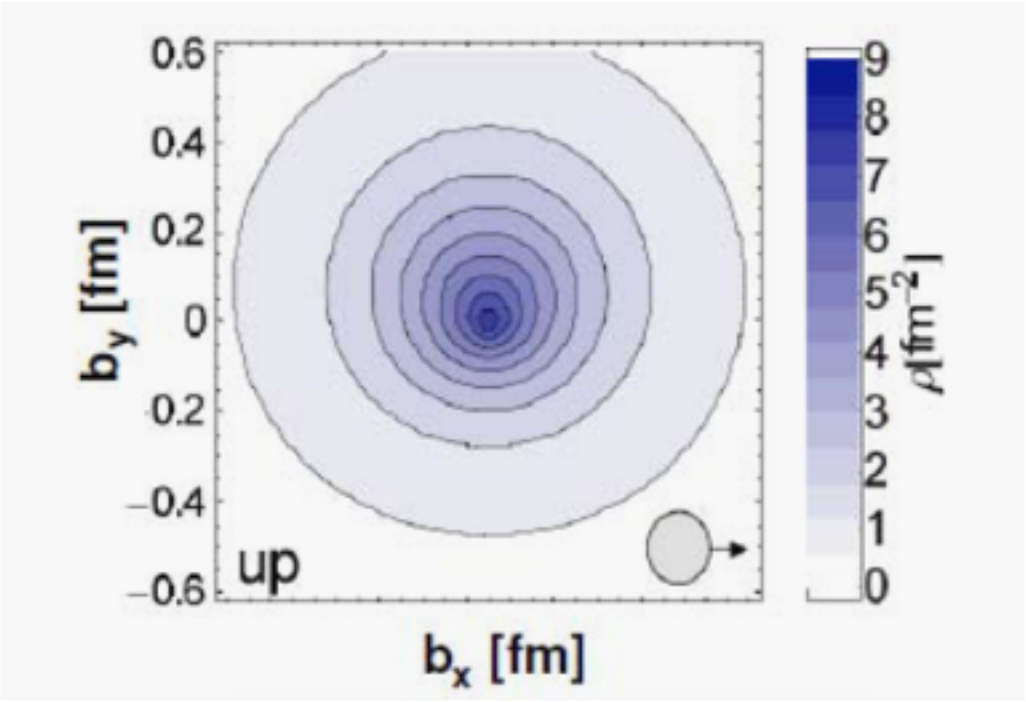


Bacchetta, Conti, Radici

- intrinsic transverse motion
- spin-orbit correlations = indicator of OAM
- non-trivial factorization
- accessible in SIDIS, DY (and at RHIC)

GPDs

2+1 D picture in **impact-parameter space**

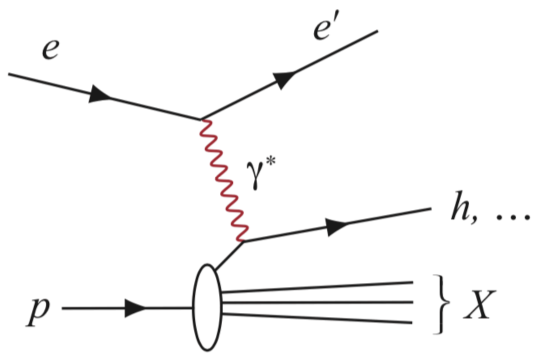


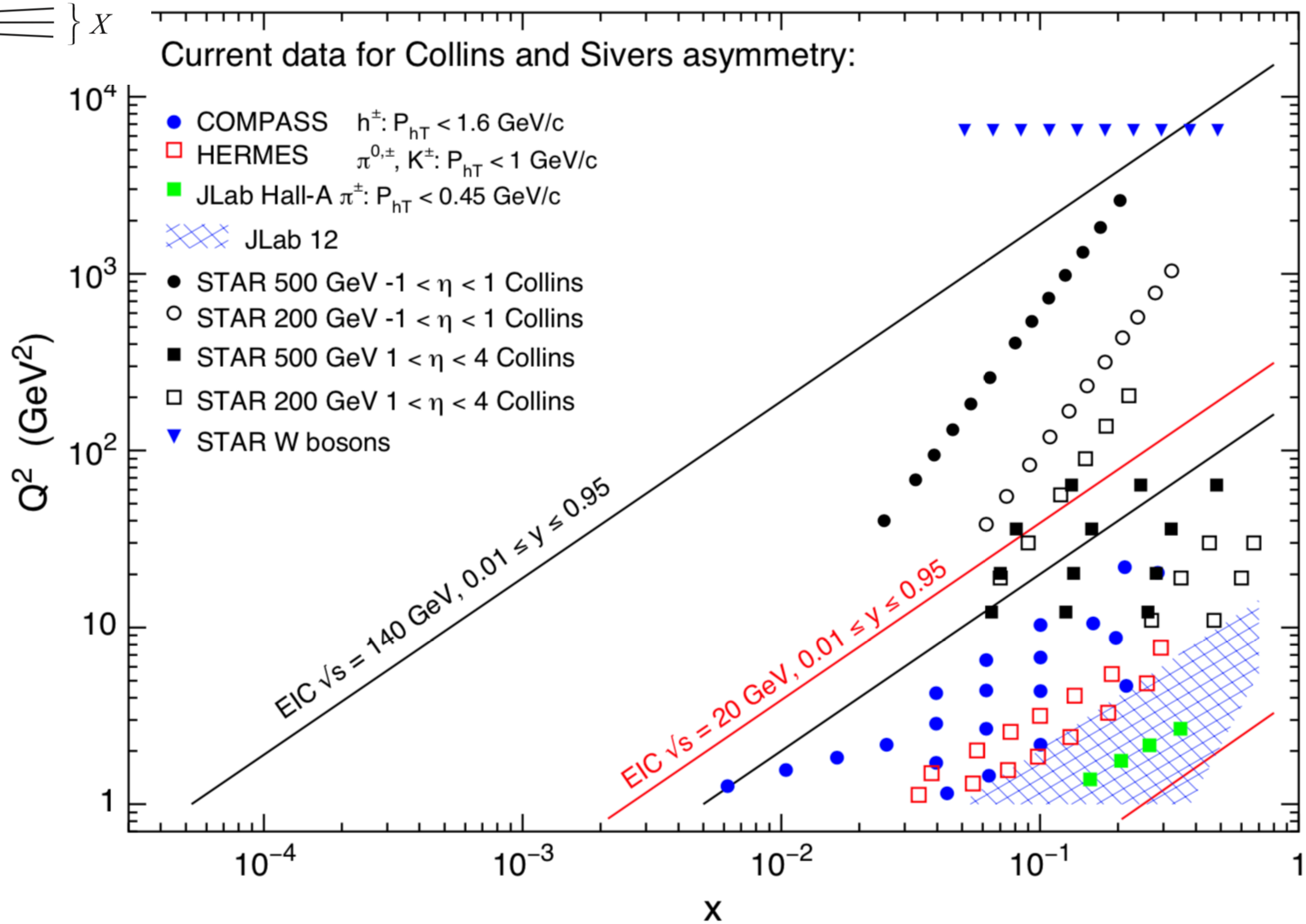
QCDSF collaboration

- collinear but long. momentum transfer
- indicator of OAM; access to Ji's total $J_{q,g}$
- existing factorization proofs
- DVCS, exclusive vector-meson production

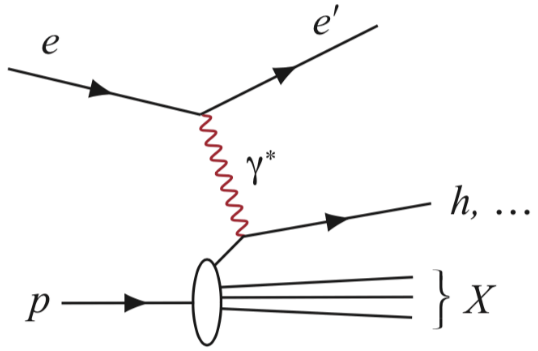
currently no direct, model-independent relation known between TMDs and GPDs

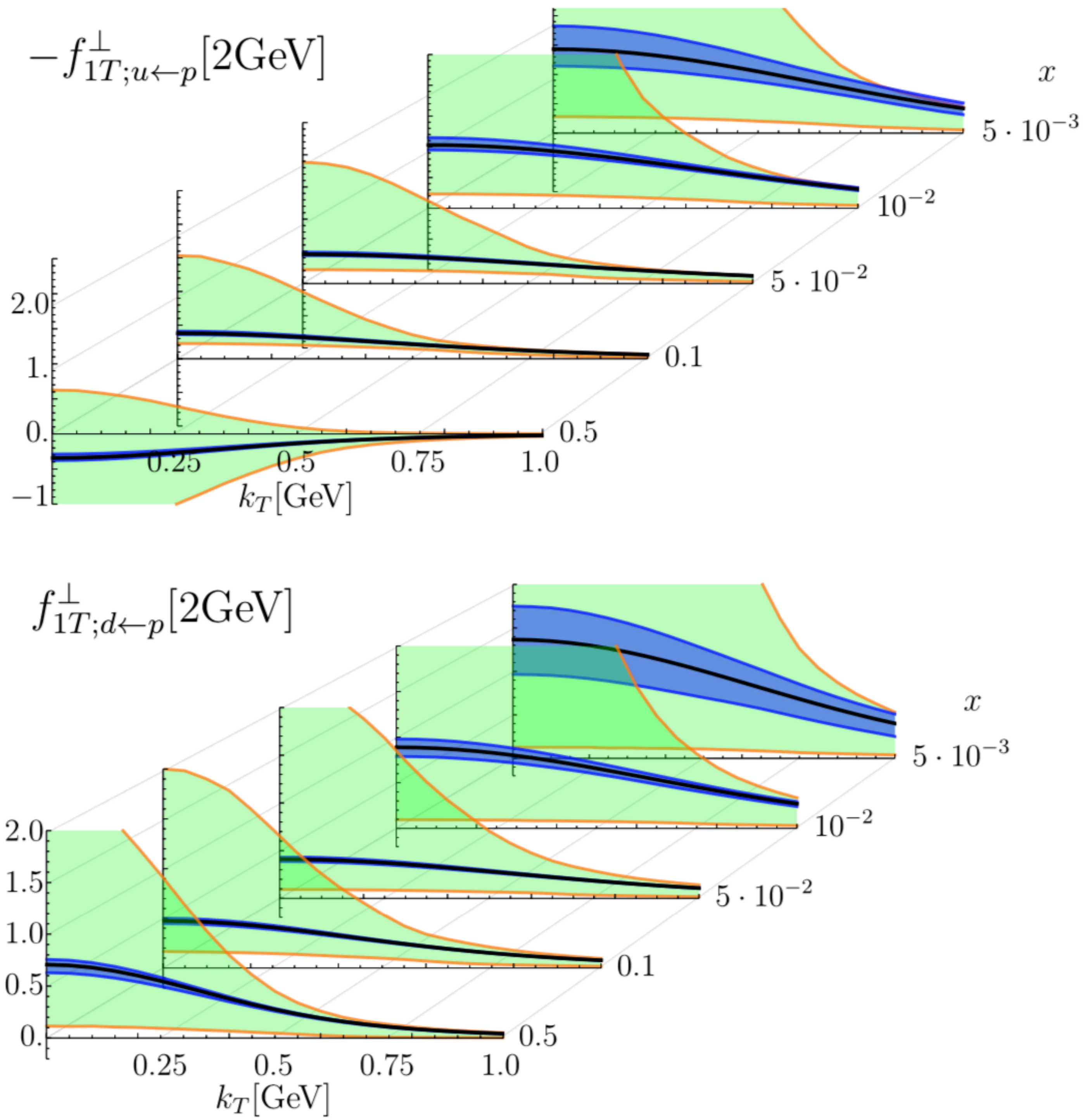
U.S.-based EIC - polarized semi-inclusive DIS





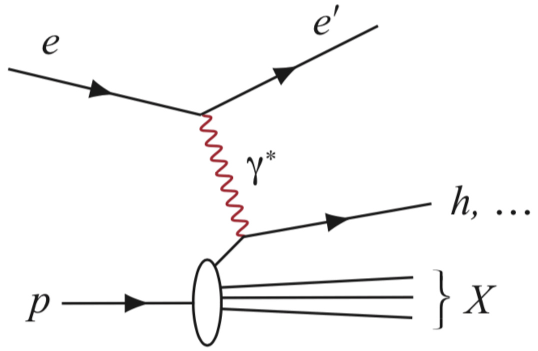
U.S.-based EIC - polarized semi-inclusive DIS

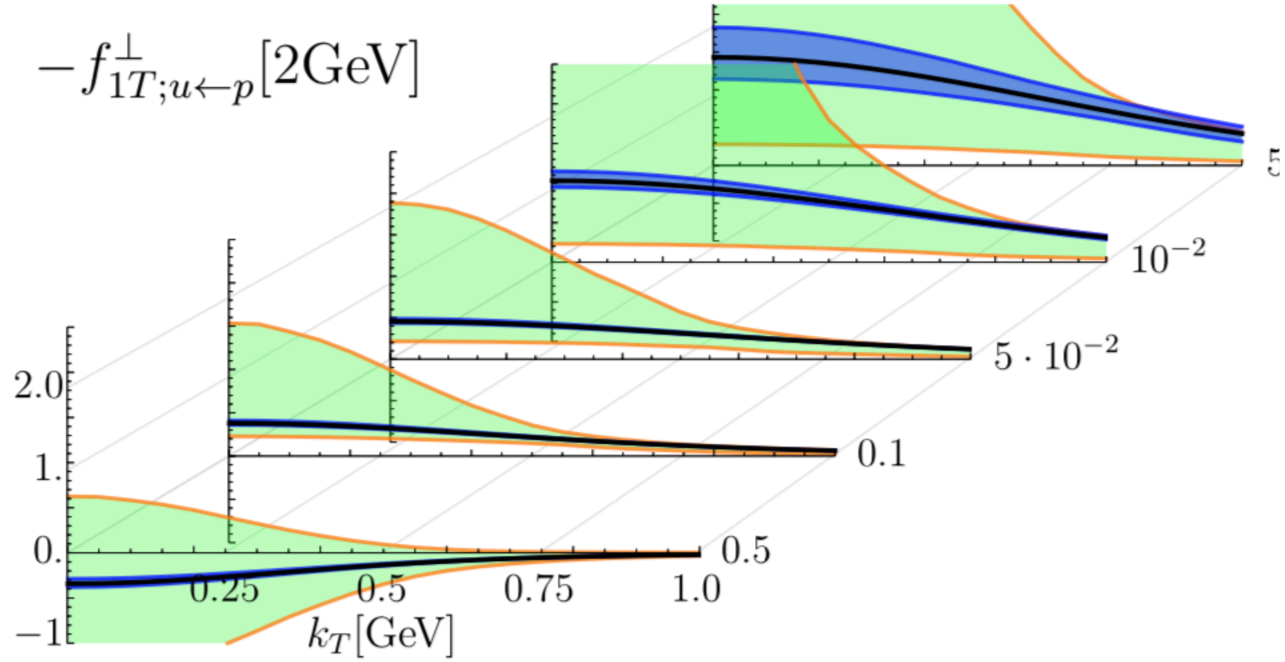


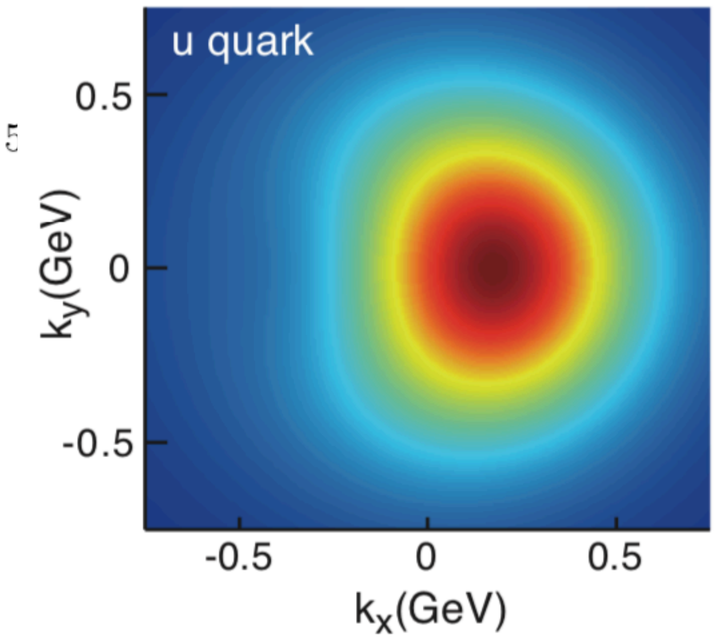


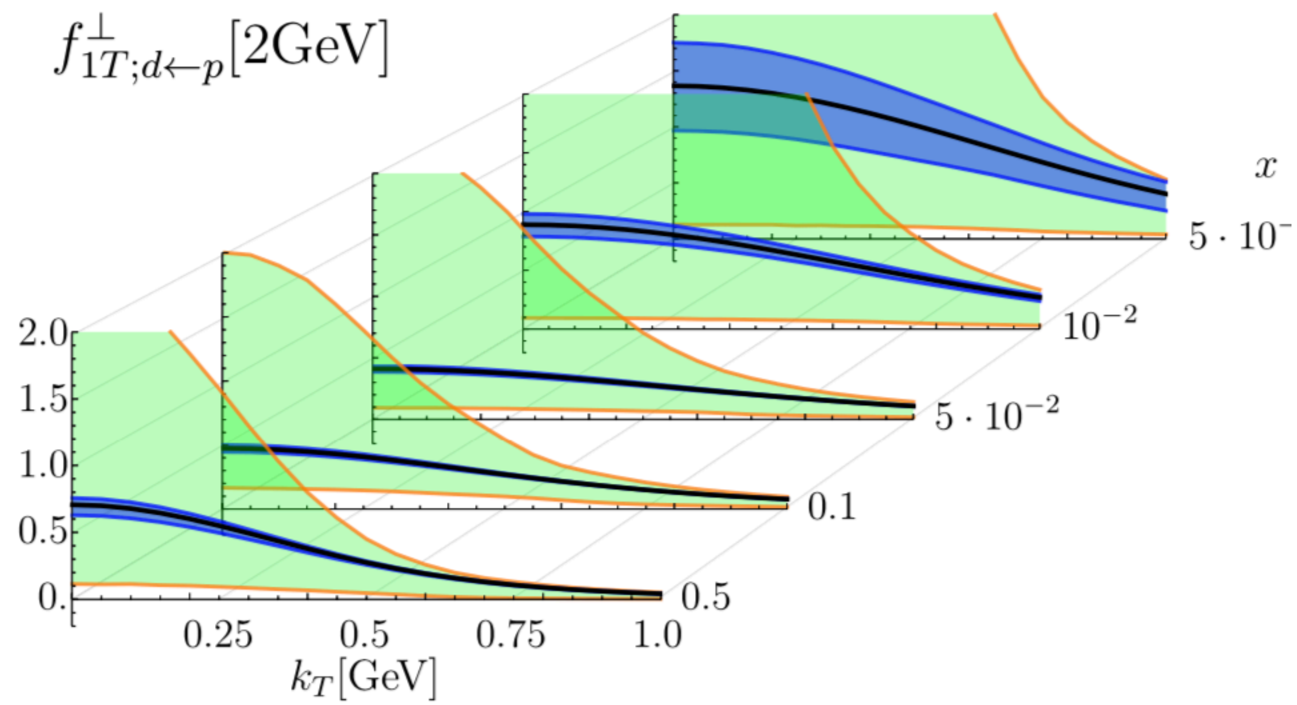
Imaging nucleon (spin) is a major EIC objective - illustrated here is the impact on the up and down Sivers' functions

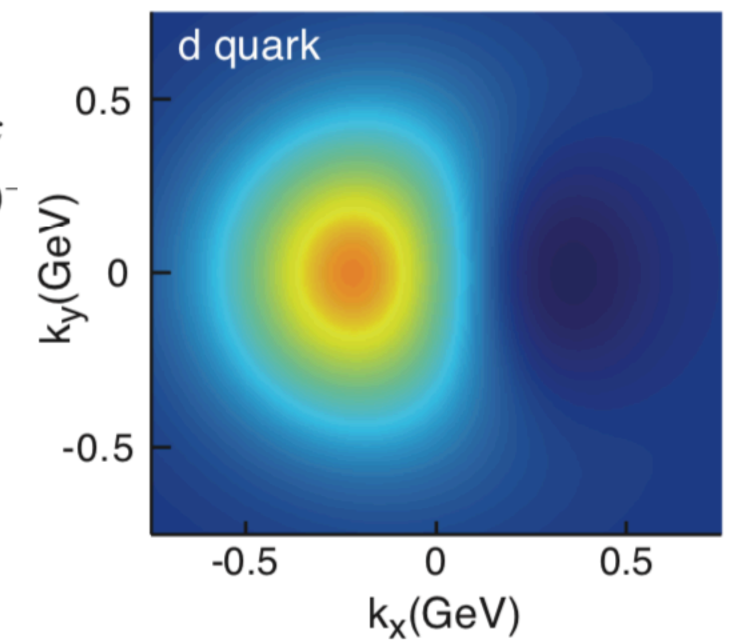
U.S.-based EIC - polarized semi-inclusive DIS





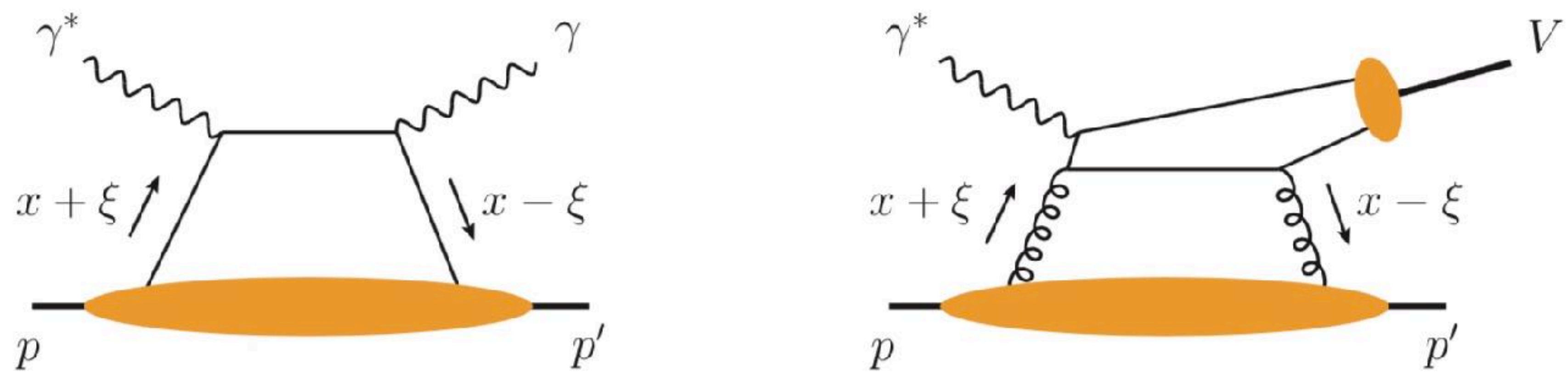


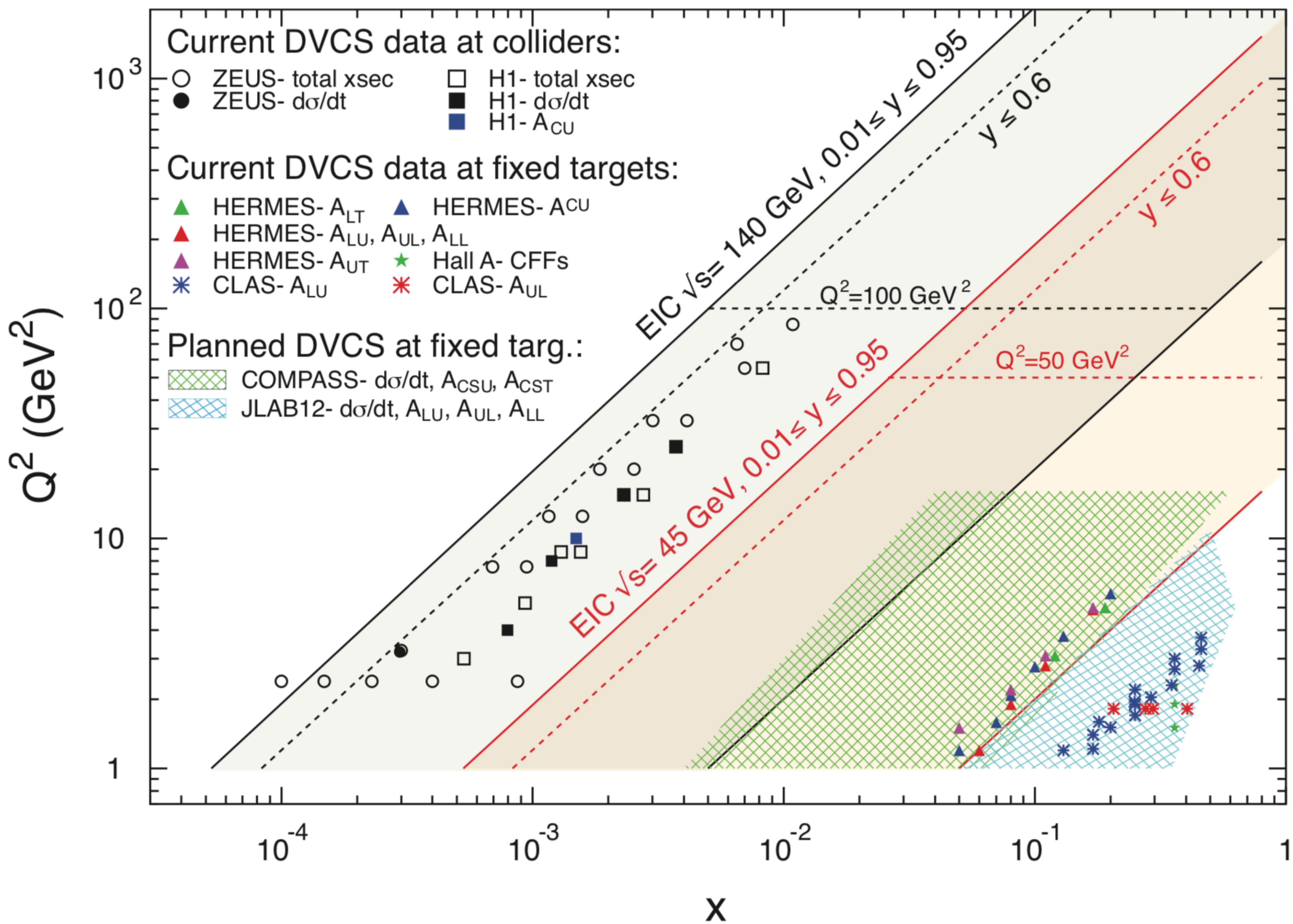




Imaging nucleon (spin) is a major EIC objective — well into the gluon dominated regime.

U.S.-based EIC - DVCS, DVMP, and Imaging



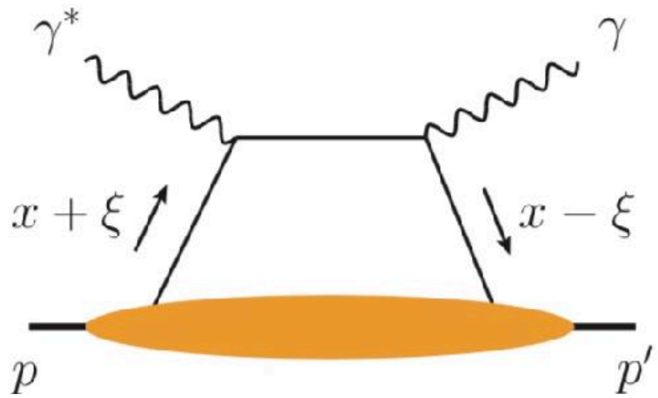


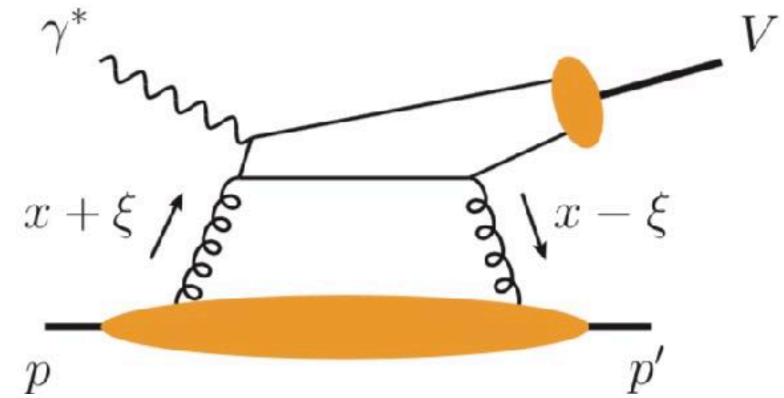
<u>Luminosity</u>, Polarization, Nuclei, Detectors,

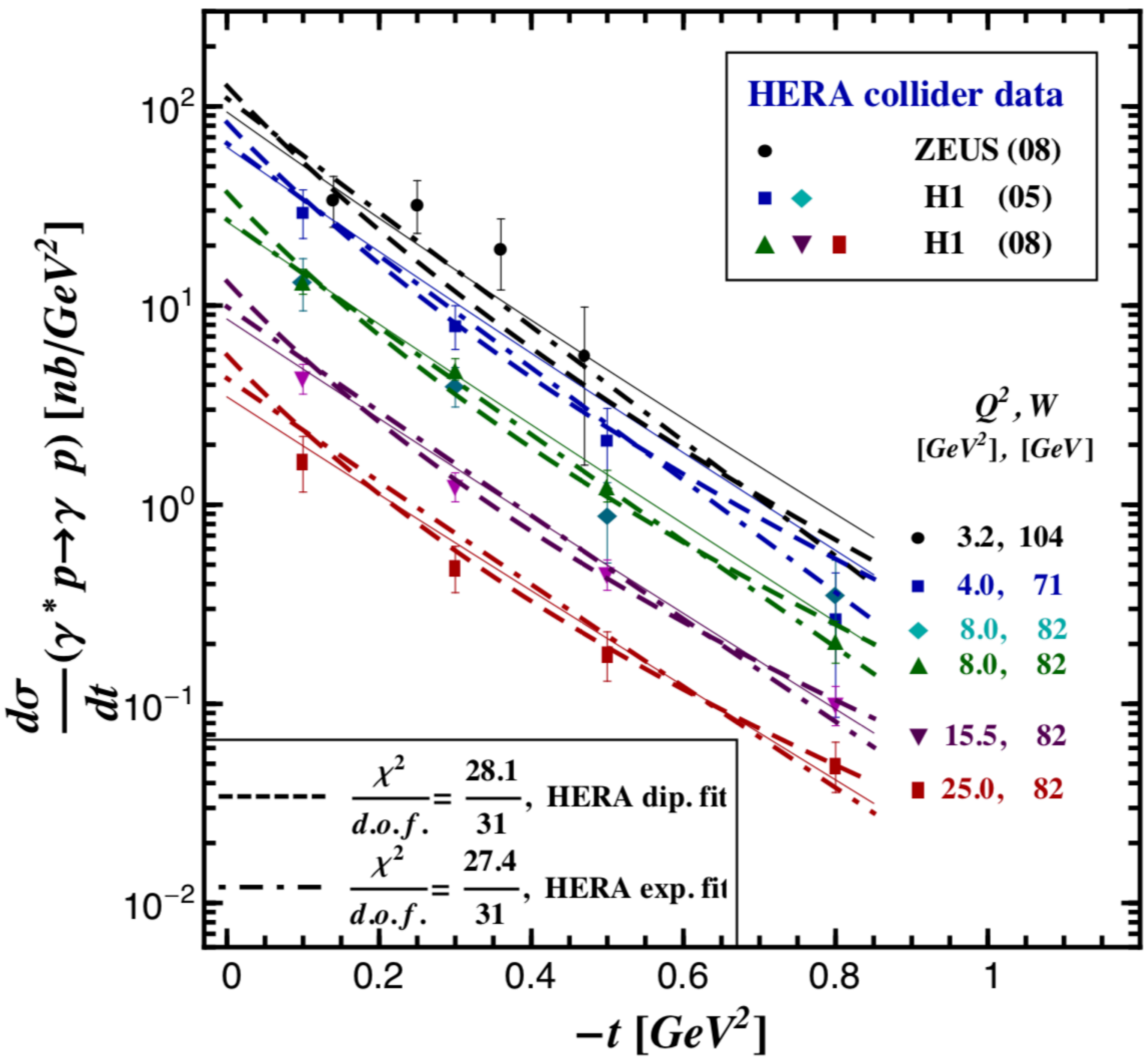
Less so about x, Q^2 range

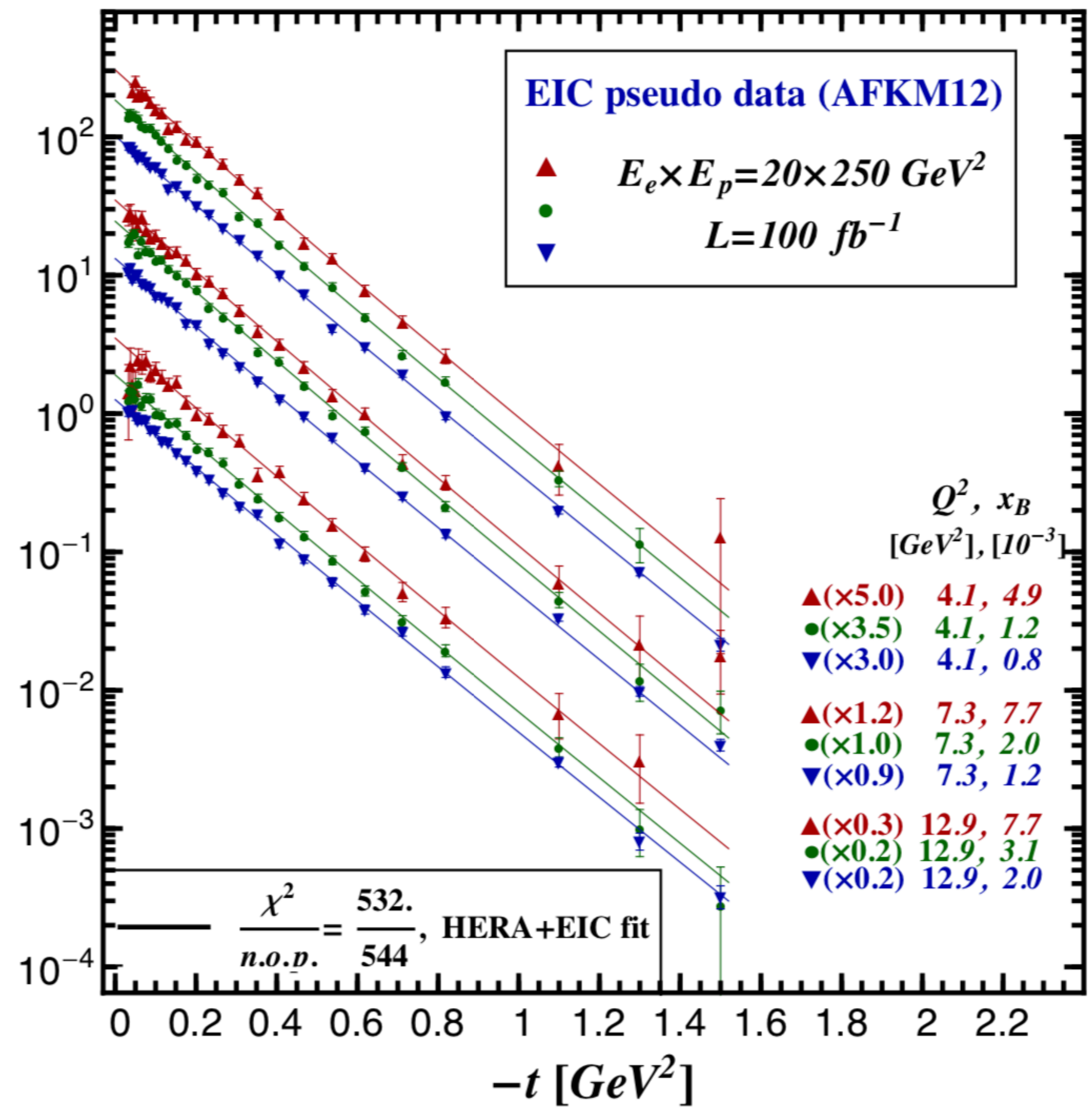
t, however, …

U.S.-based EIC - DVCS, DVMP, and Imaging



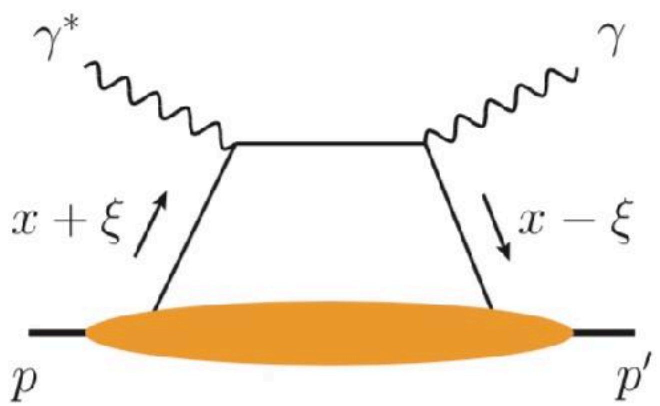


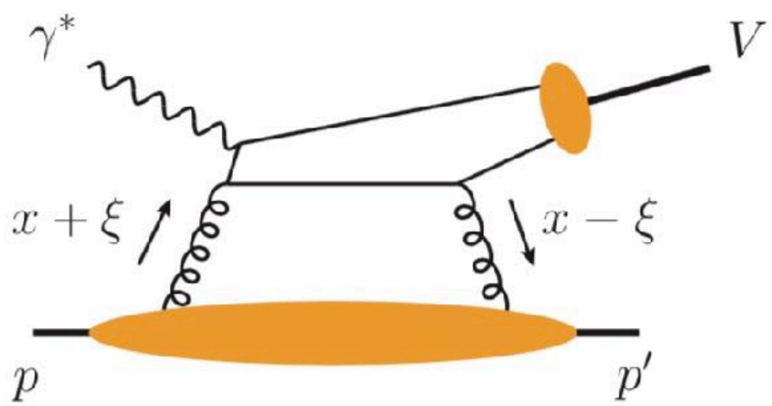


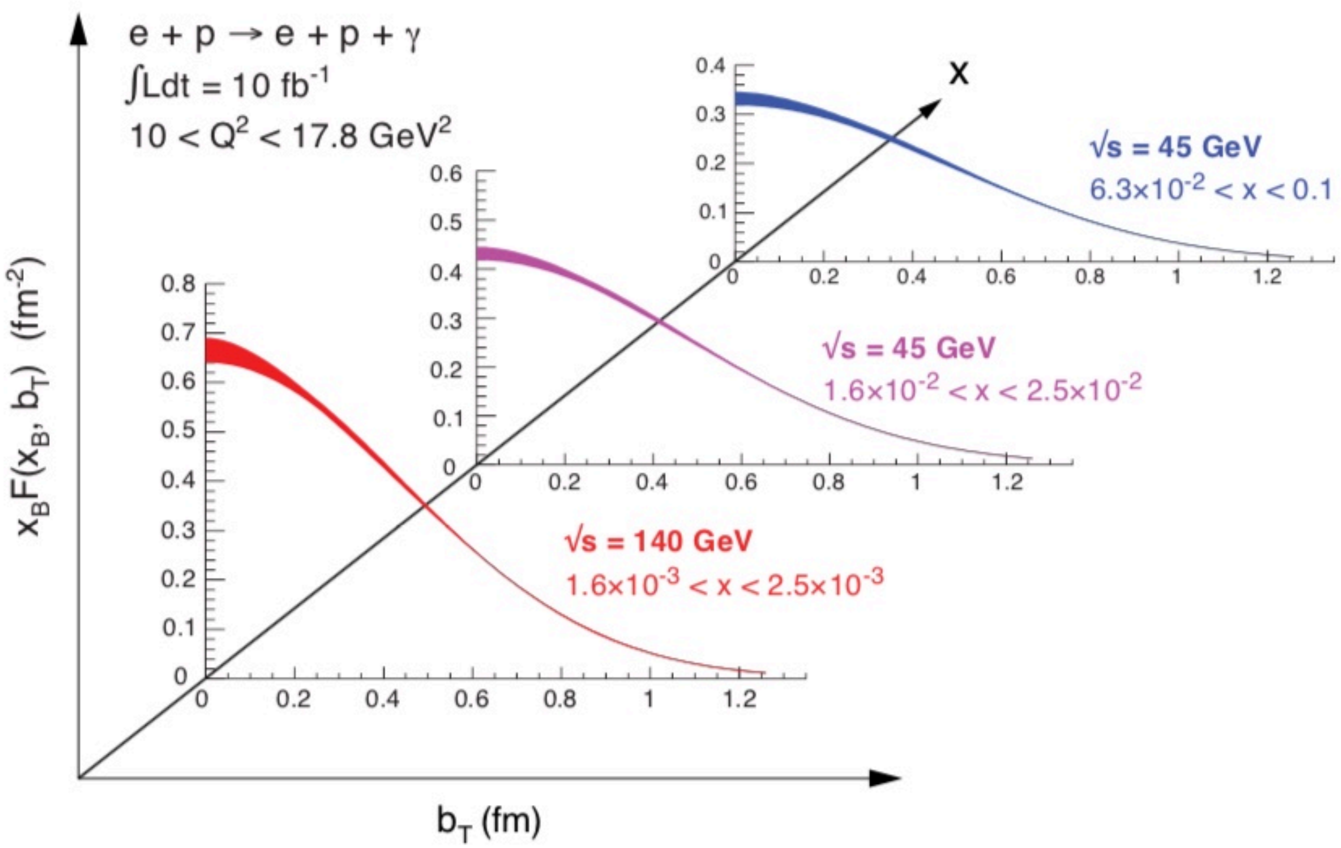


Drives (part of) the instrumentation integrated with the IR in the far-forward region.

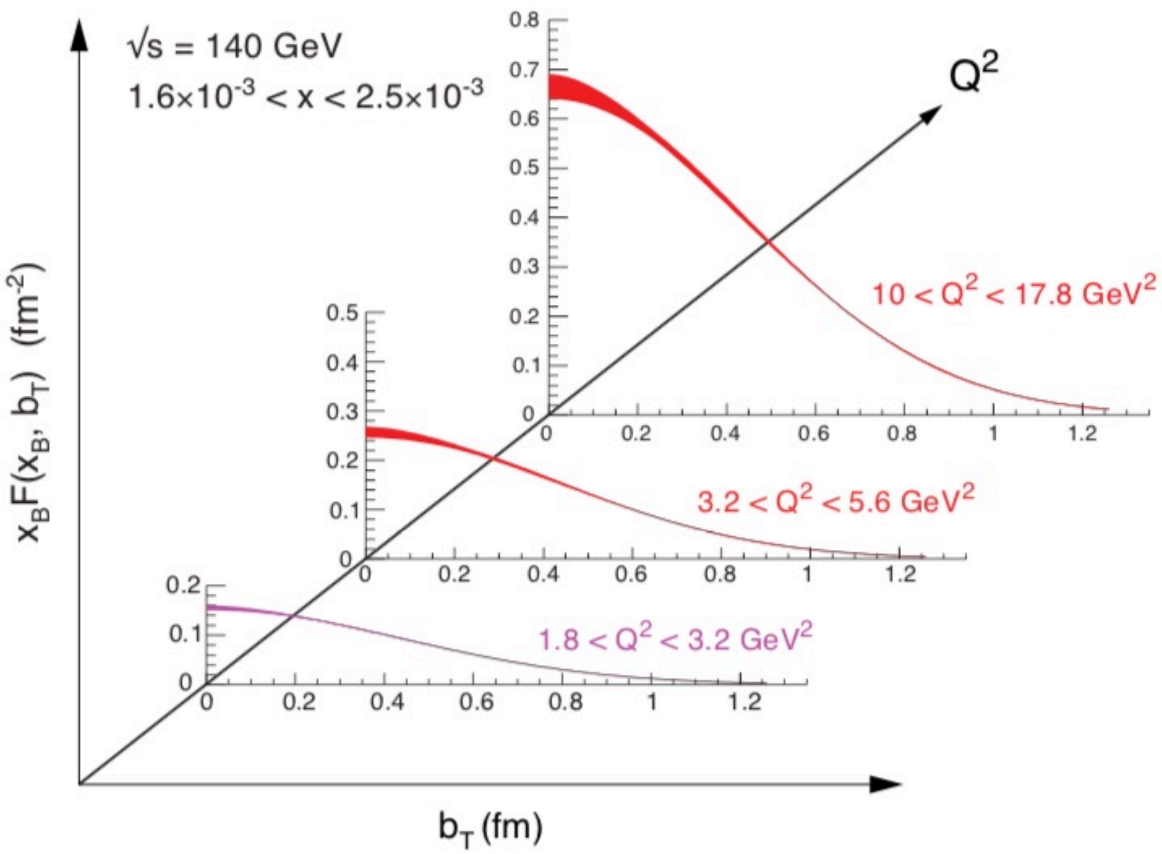
EIC - DVCS, DVMP, and Imaging



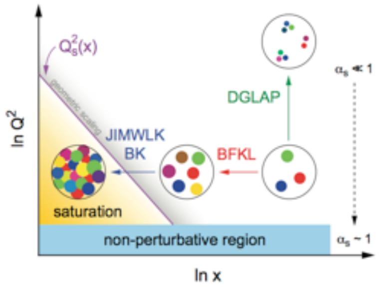




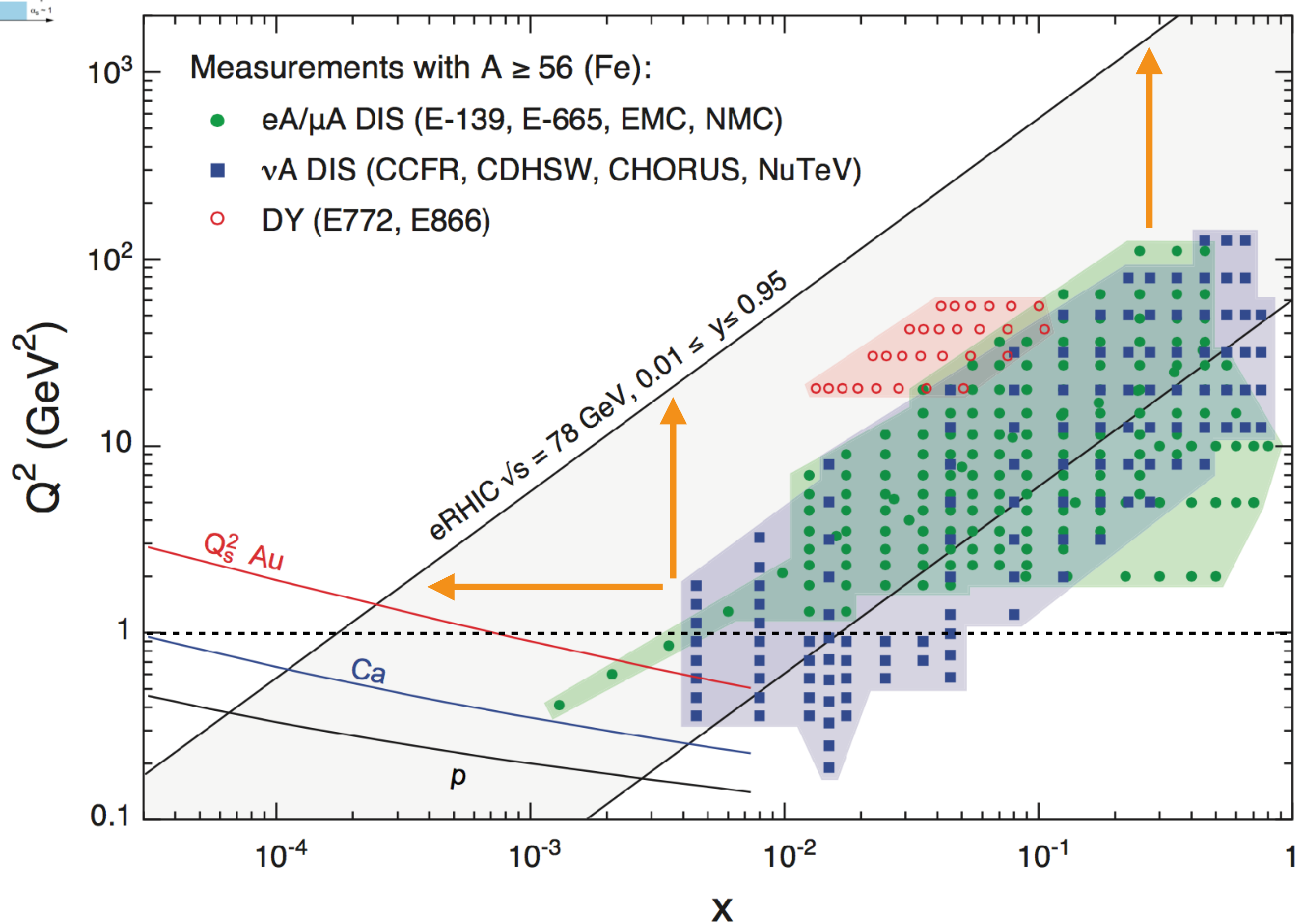
x-dependence at fixed Q^2



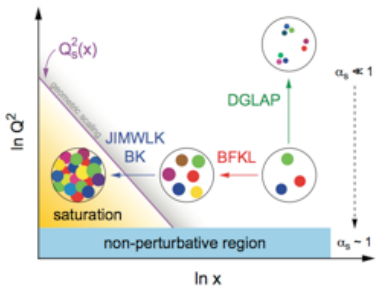
Q^2-dependence at fixed x



U.S.-based EIC - The Nuclear Landscape

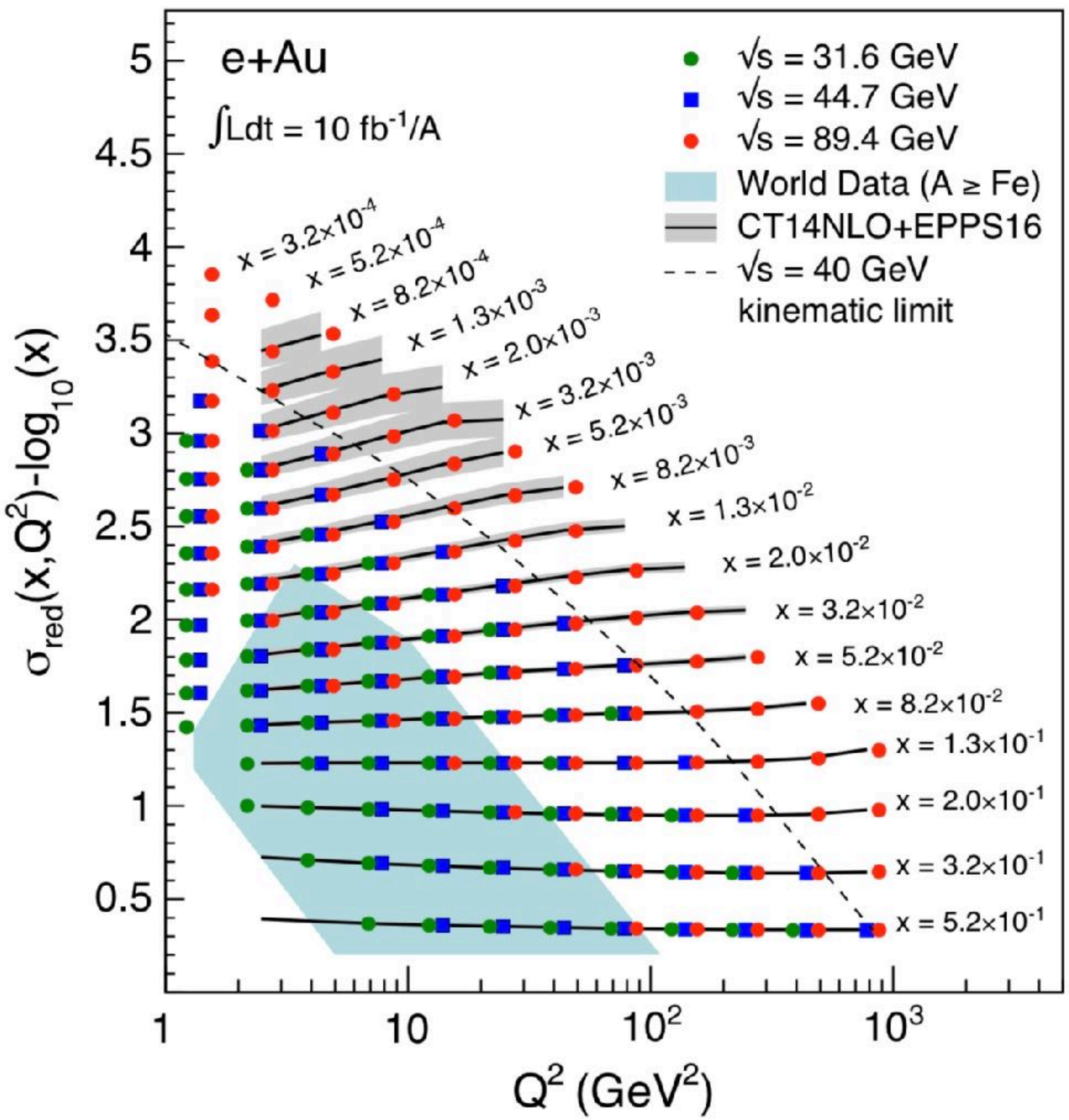


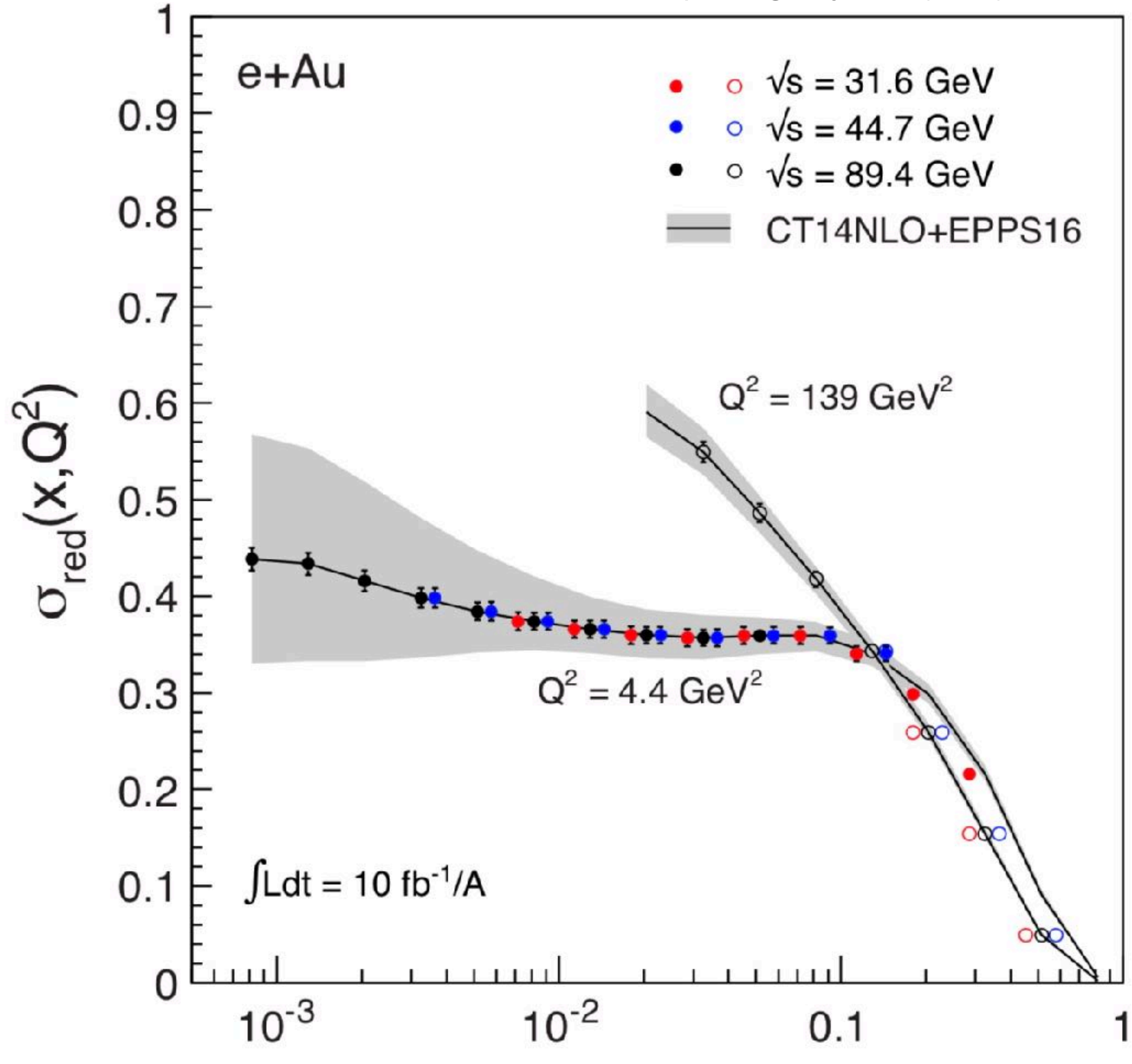
Complementarity with ongoing and future RHIC and LHC measurements,



U.S.-based EIC - The Nuclear Landscape

Rept.Prog.Phys. 82 (2019) 024301

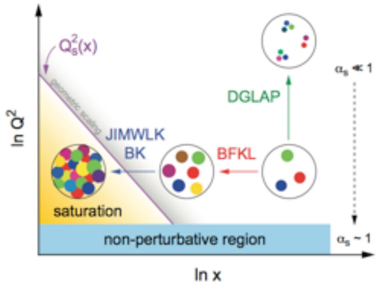




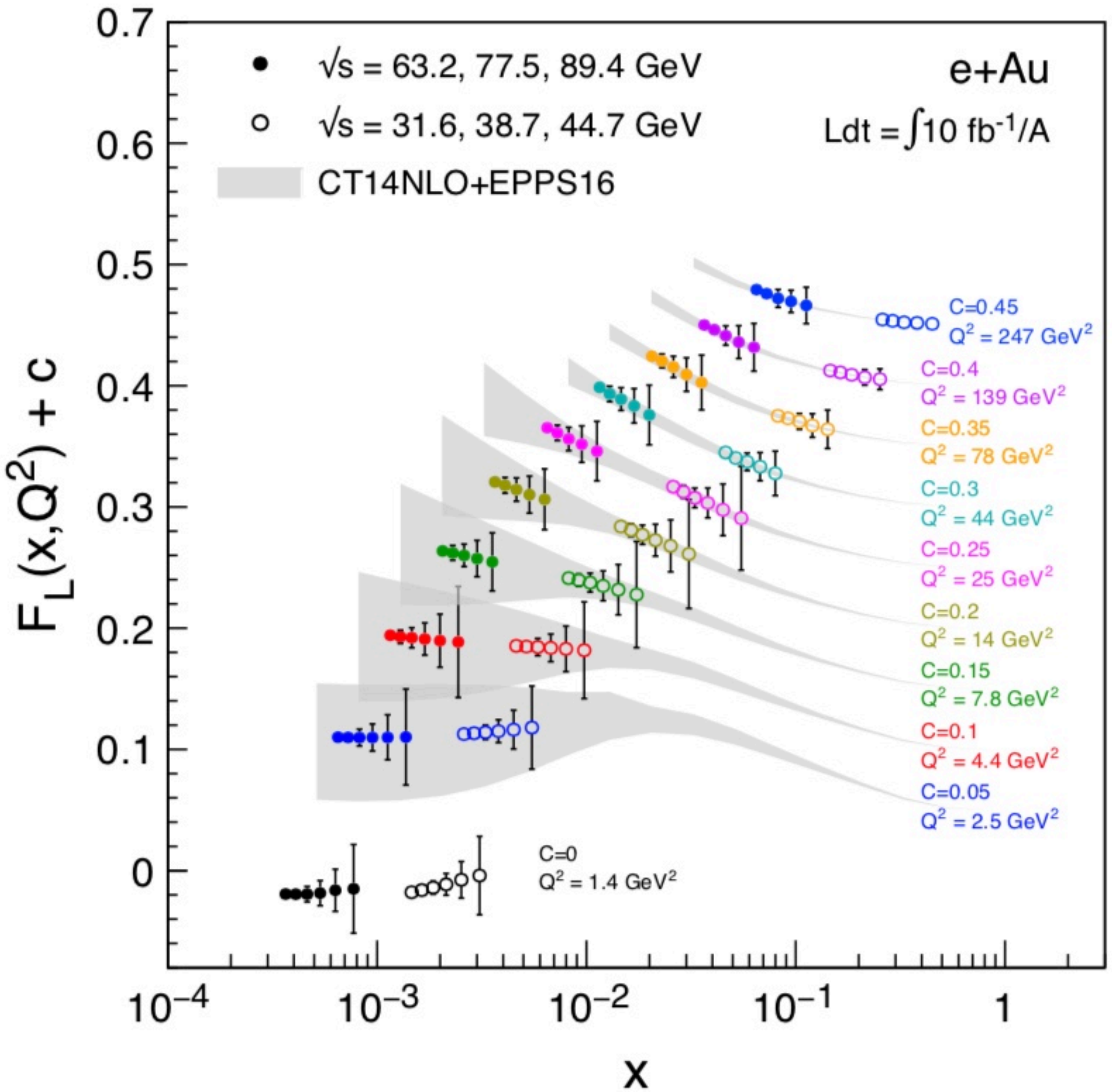
$$\sigma_{\text{reduced}} = F_2(x, Q^2) - \frac{y}{1+(1-y)^2} F_L(x, Q^2)$$

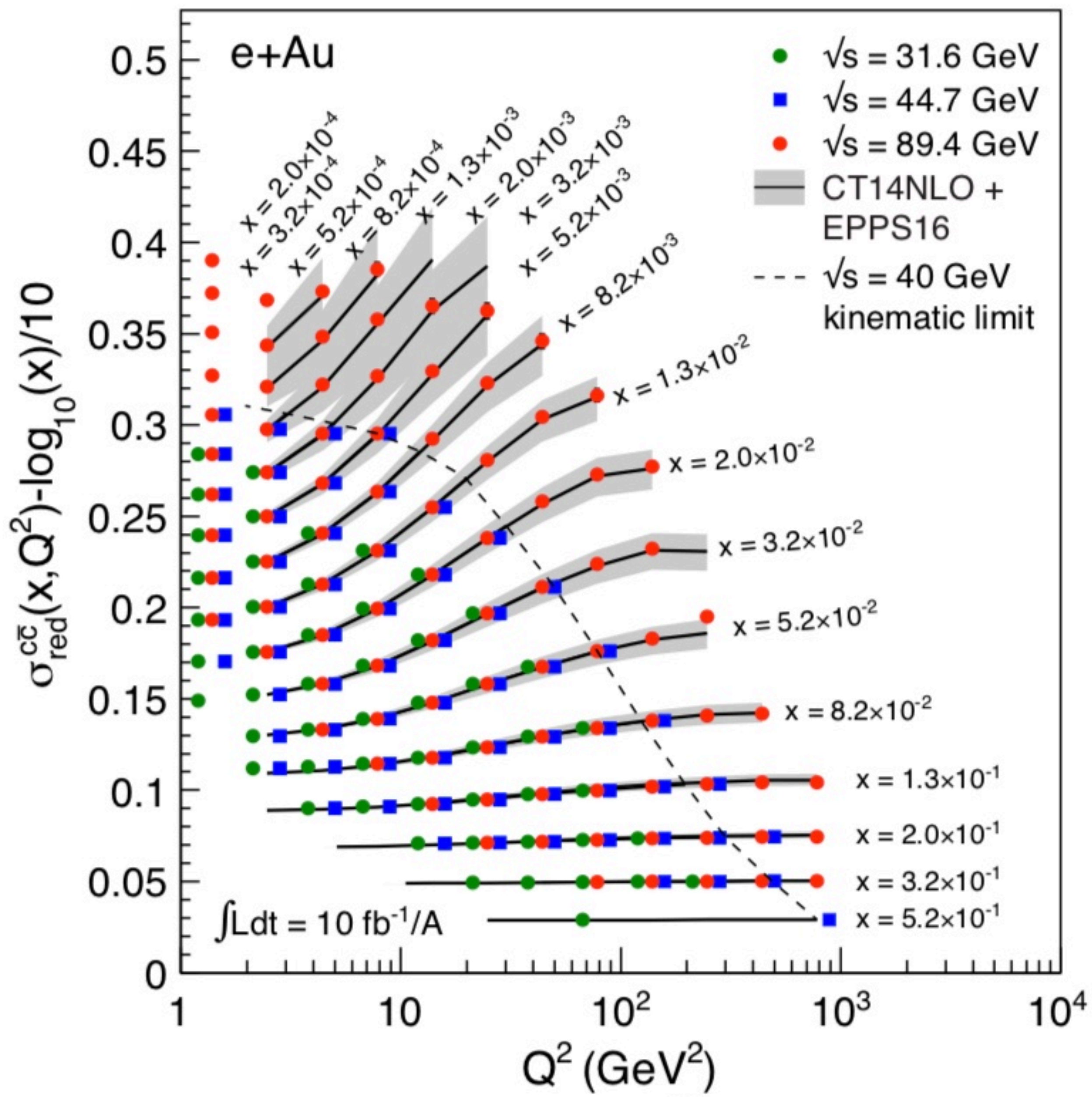
Impactful baseline inclusive measurements.

U.S.-based EIC - The Nuclear Landscape



Rept.Prog.Phys. 82 (2019) 024301

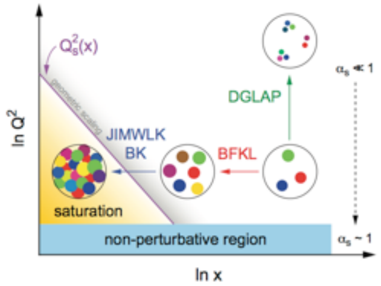


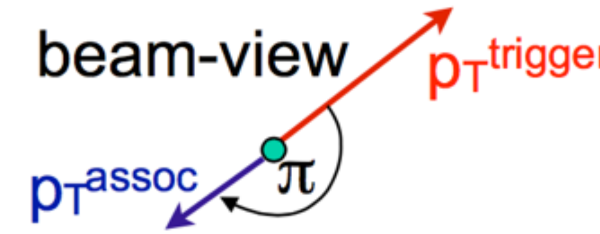


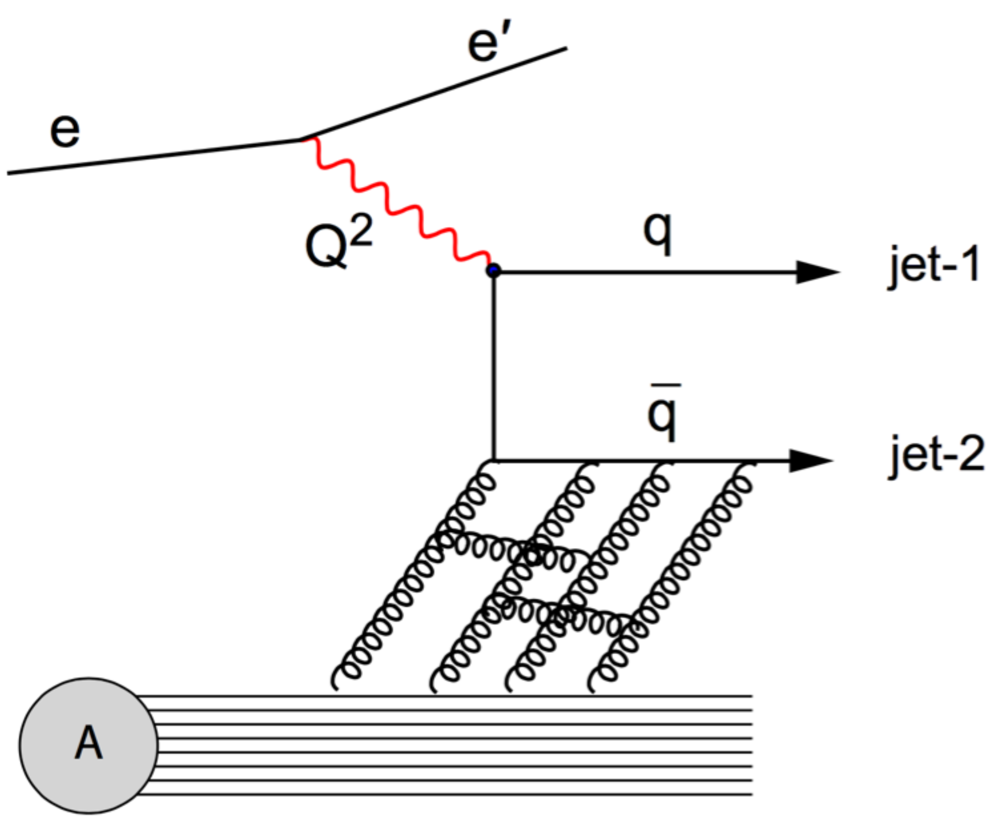
Clearly visible impact also beyond baseline inclusive measurements with “Rosenbluth separation” and semi-inclusive measurements.

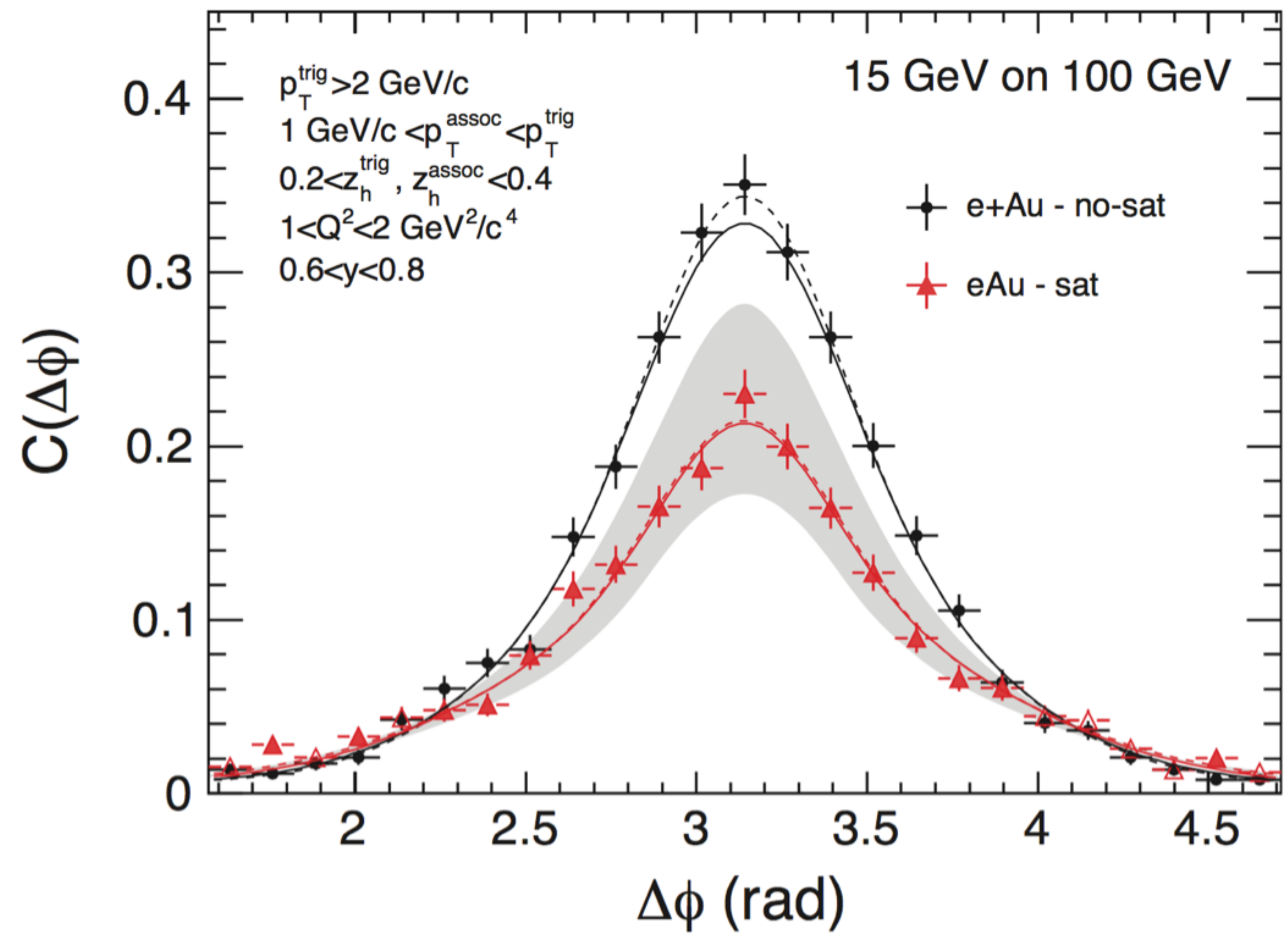
Nuclear gluon will be probed sensitively with complementary channels.

EIC - Dihadrons to probe Saturation







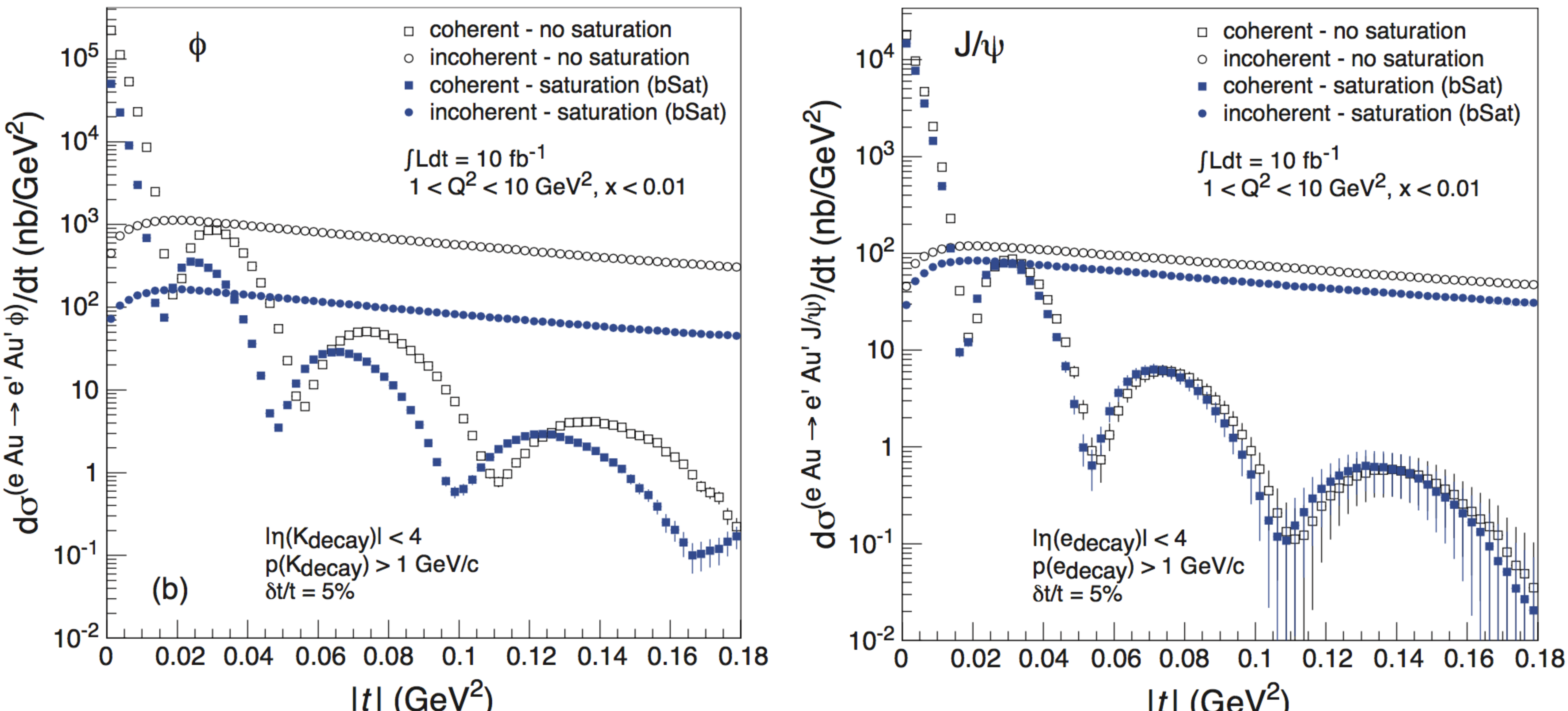


Zheng et al (2014)

Dominguez, Xiao, Yuan (2011)

Suppression of back-to-back hadron or jet correlation directly probes the (un-)saturated gluon distributions in nuclei,

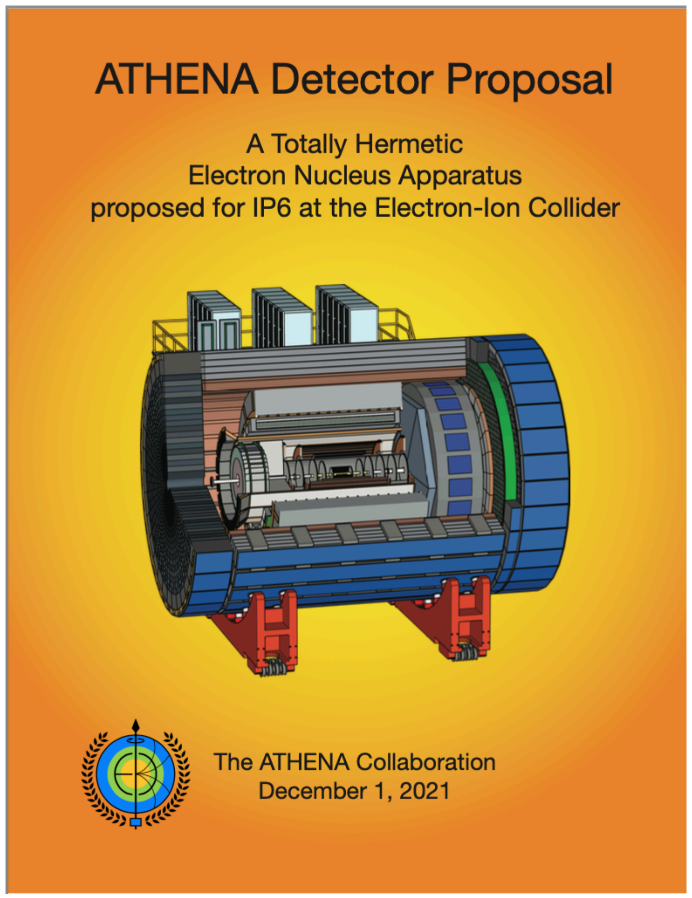
EIC - Diffractive probes of Saturation



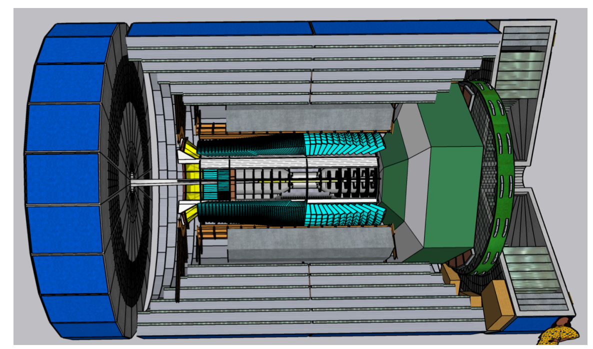
Incoherent and coherent diffraction are both key measurements to saturation,
Exclusive vector meson production is key to (all) imaging,
as is deeply virtual Compton scattering

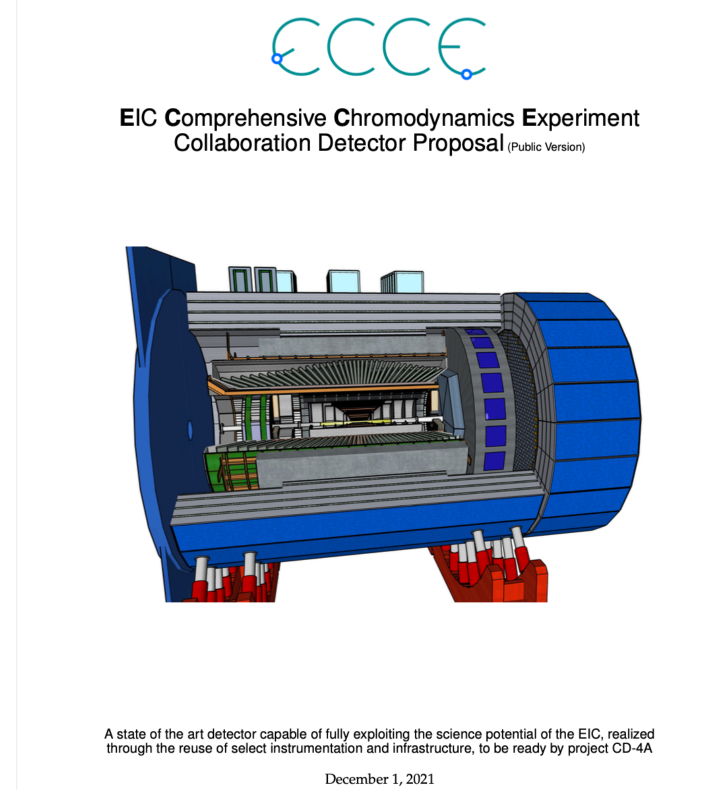
Coherent diffraction in e+A poses <u>very</u> stringent requirements on t resolution,
as well on exclusivity — i.e. <u>very</u> demanding measurements.

Bringing it together — EIC Detector and Collaboration



CORE





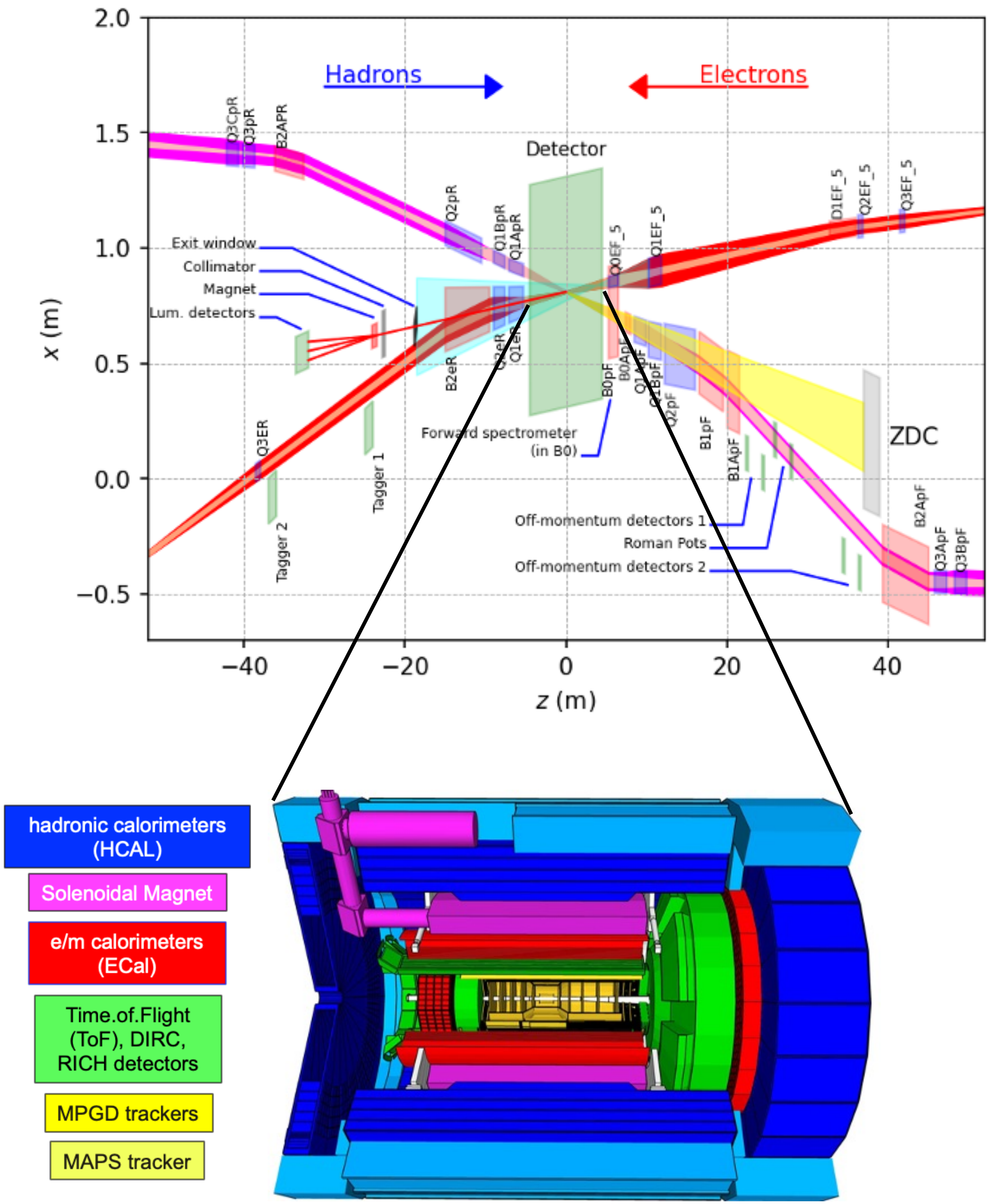
Detector Proposal Advisory Panel (DPAP) reviewed three proposals; ATHENA, CORE, and ECCE,

Finds that ATHENA and ECCE fulfill all requirements for a Detector 1, i.e. NAS science case,
none of the collaborations is strong or large enough to develop Detector 1 for Day 1

Recommended ECCE as Detector 1 in Spring 2022 – adopted by the EIC Project as Reference,
collaborations merged to form ePIC,

“Right language” for *a* Detector 2, but no language on an actual concept, technology, etc.

Bringing it together — EIC IR and Detector



IR design integral to the science,

incorporates e.g. Roman Pots,
low Q^2 tagger,
(ZDC, B0, off-mom.)

luminosity drives compactness of the central detector

Central detector "just" ~ 9.5 m,

Combines tracking and vertexing, PID, and EM and hadronic calorimetry,

Asymmetric beam energies lead to very different electron and hadron endcaps,

1.7 T solenoidal field with ~2.8 m bore,

Streaming readout approach.

Bringing it together — EIC Central Detector

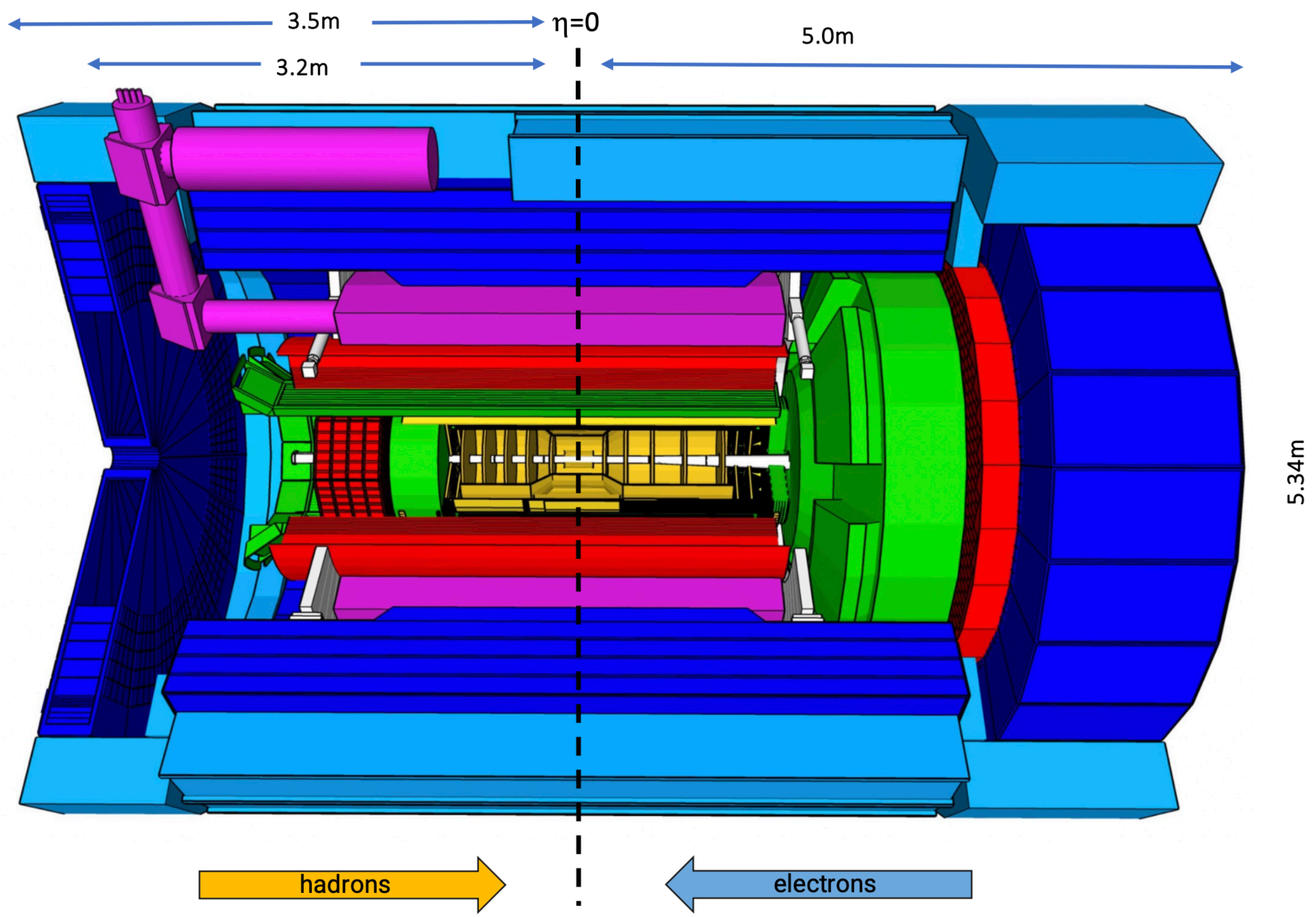
Magnet
- New 1.7 T SC solenoid, 2.8 m bore diameter

Tracking
- Si Vertex Tracker MAPS wafer-level stitched sensors (ALICE ITS3)
- Si Tracker MAPS barrel and disks
- Gaseous tracker: MPGDs (μRWELL, MMG) cylindrical and planar

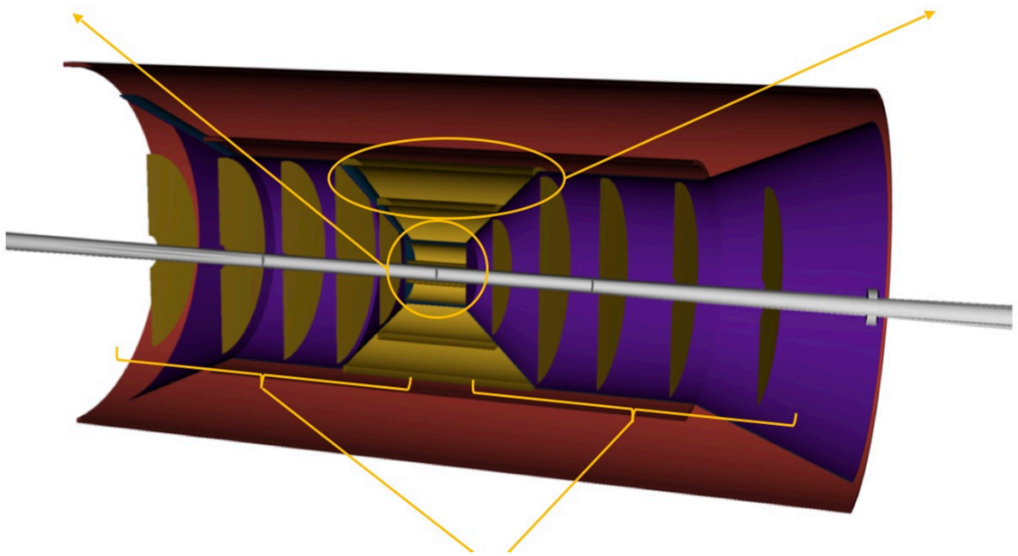
PID
- high performance DIRC (hpDIRC)
- dual RICH (aerogel + gas) (forward)
- proximity focussing RICH (backward)
- ToF using AC-LGAD (barrel+forward)

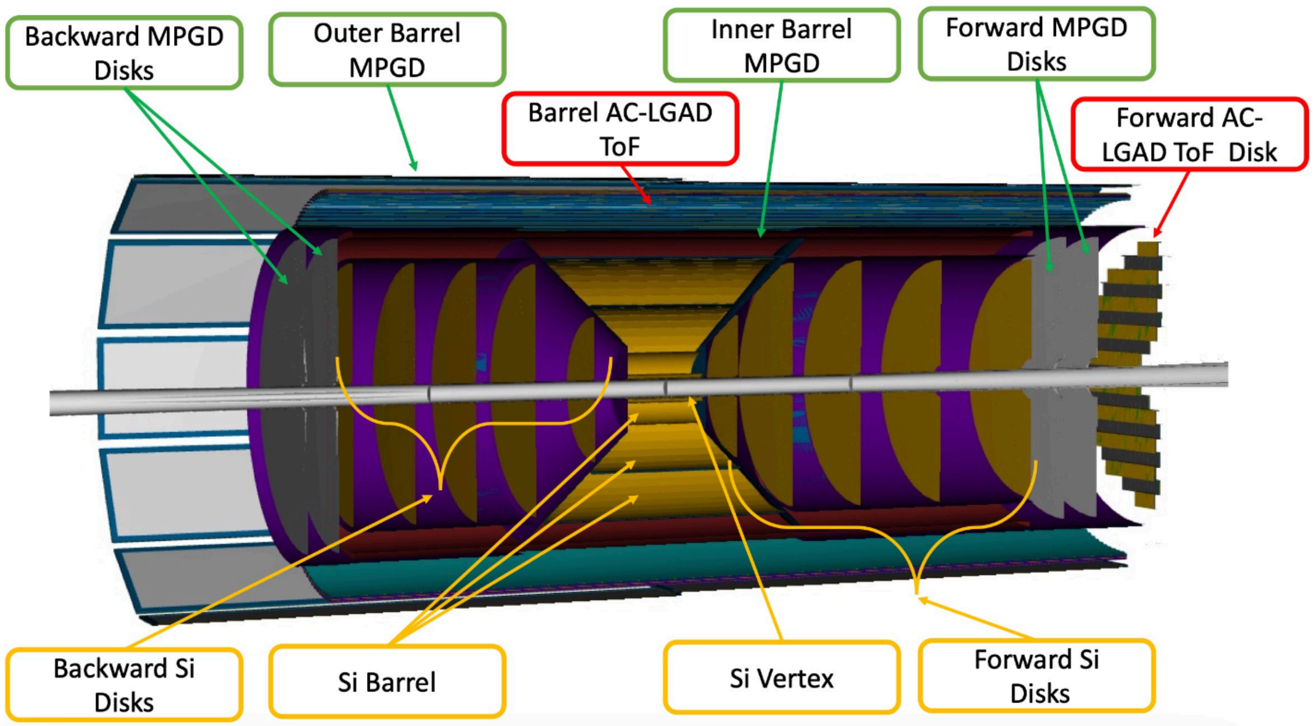
EM Calorimetry
- imaging EMCal (barrel)
- W-powder/SciFi (forward)
- $PbWO_4$ crystals (backward)

Hadron calorimetry
- FeSc (barrel, re-used from sPHENIX)
- Steel/Scint – W/Scint (backward/forward)



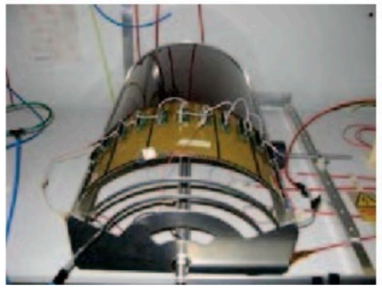
EIC Central Detector — Tracking





- one technology: MAPS @ 65 nm (ALICE ITS3)
- IB: First layer @ R ~ 3.6 cm - Material: 0.05% X/X_0 / layer
- OB: Material: 0.55% X/X_0 / layer
- EE/EH Material: 0.24% X/X_0 / layer
- pixel size O(10x10 μm^2)
- Total area 8.5 m^2

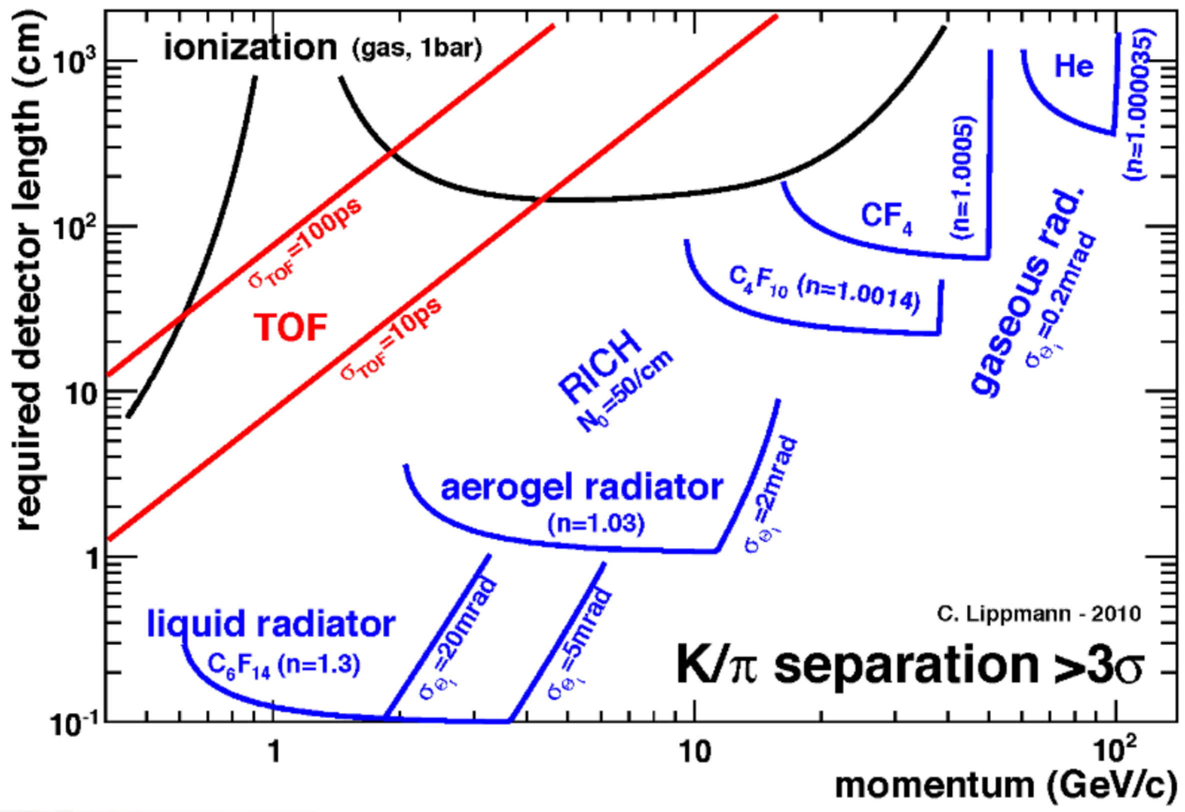
- additional hit points for track reconstruction (~150 μm)
- fast timing hits for background rejection (~10-20 ns)
- provide hit point over large angular range for PID
- new ASIC SALSA for readout (derived from ALICE SAMPA for TPC



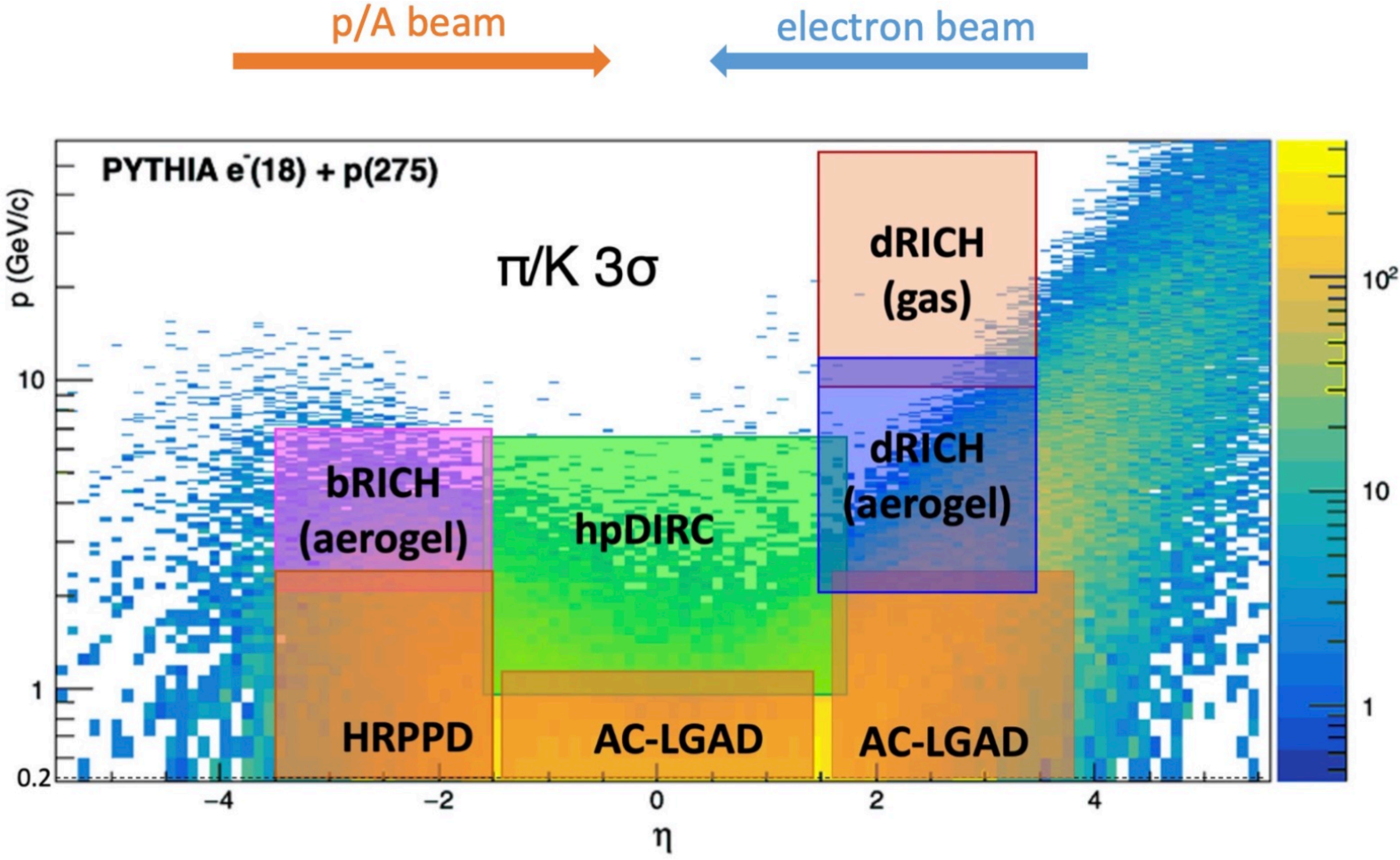
EIC Central Detector — Particle Identification

e-π separation
Cherenkov PID complements ECAL effort, especially at low momenta/backward region

C. Lippmann, NIM A 666 (2012), 148

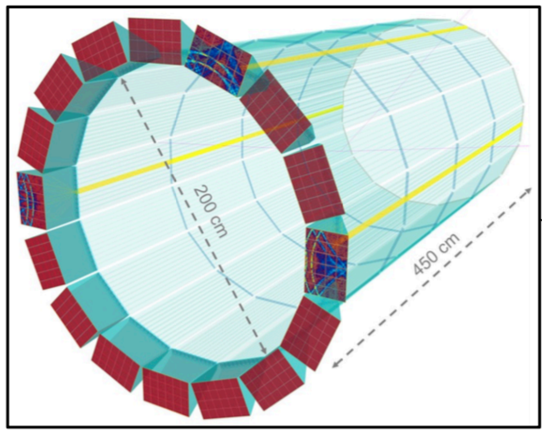


hadron identification: SIDIS (→ TMD) , heavy flavour
ToF complements Cherenkov PID

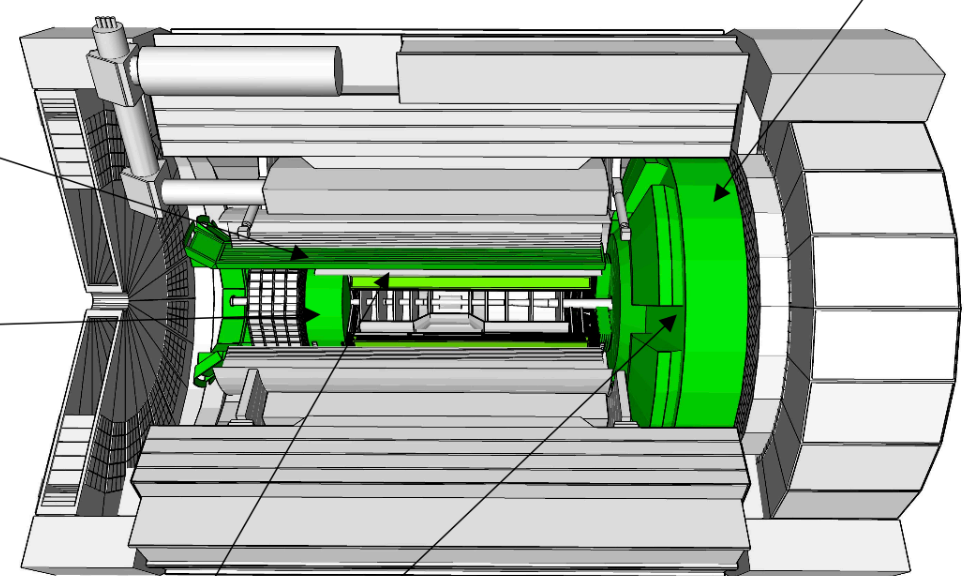


more than one technology needed to cover the entire momentum ranges at different rapidities

EIC Central Detector — Particle Identification



hpDIRC (High Performance DIRC)
- Quartz bar radiator → Reuse of BaBAR DIRC bars
- photosensor: MCP-PMTs
- p/K 3s sep. at 6 GeV/c



dual radiator Forward RICH: dRICH

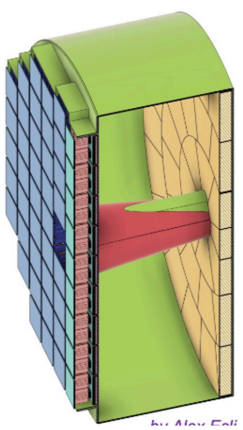
Aerogel z: 4cm
radius: 110 cm
0.3 mm acrylic filter

Spherical Mirrors
6 Azimuthal Sectors

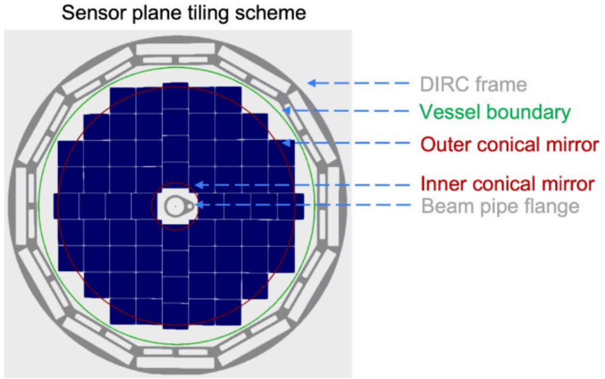
C_2F_6 Gas Volume
120 cm length
radius: 185 cm

Photosensor: **SiPMs**

Backward RICH: pfRICH
- Aerogel Cherenkov Det.
- e, π, K, p separation → π/K 3σ sep. at 10 GeV/c
- Photosensor:: **HRPPDs** to include TOF
- RICH with long proximity gap (~30 cm)

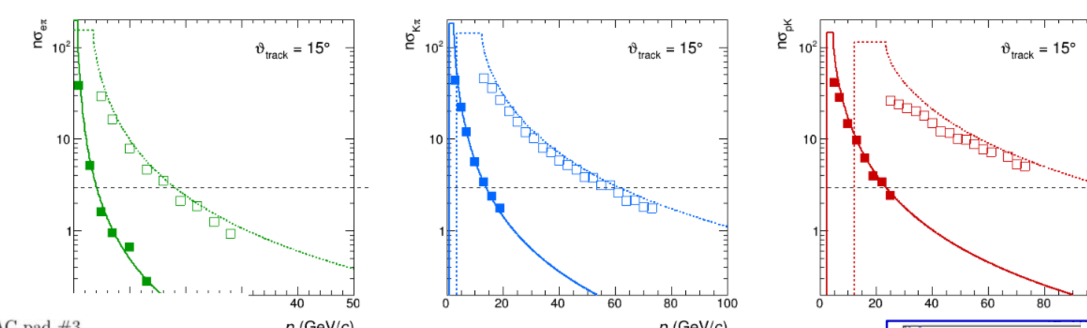


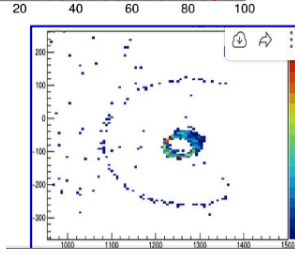
Sensor plane tiling scheme



π/K 3σ sep. at 50 GeV/c–

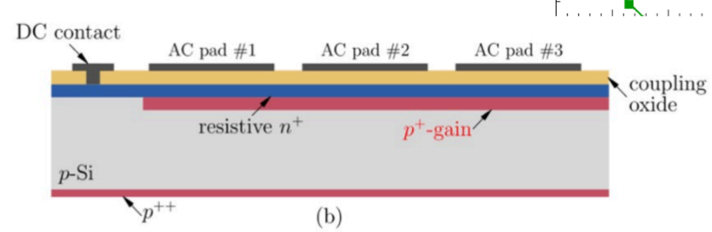
dRICH sim.





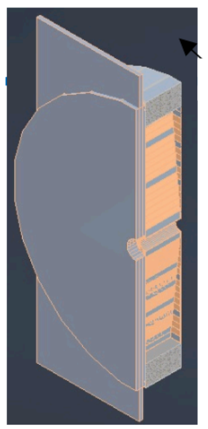
TOF

AC-LGAD (Low Gain Avalanche Detector)
- 20-35 psec / σ=30 μm
- Accurate space point for tracking
- forward disk and central barrel

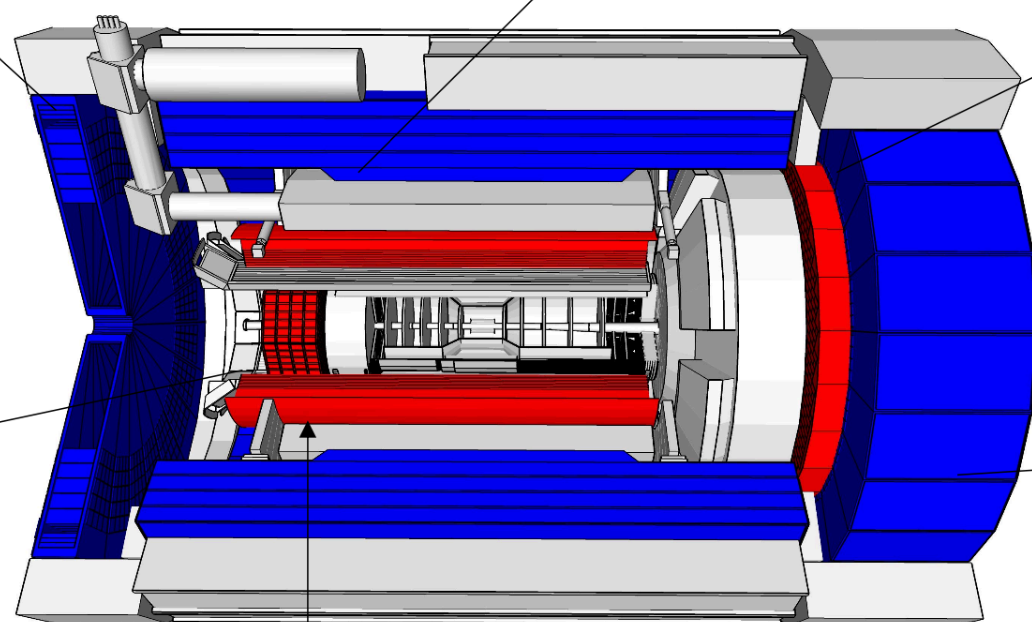


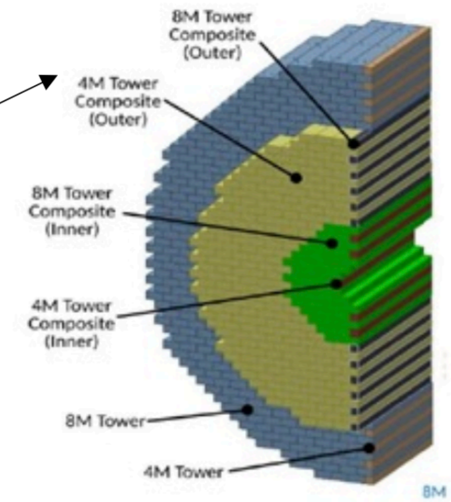
EIC Central Detector — Calorimetry

Backwards HCal
Steel/Scint Sandwich (10 layers)
(STAR re-use of scint. tiles)



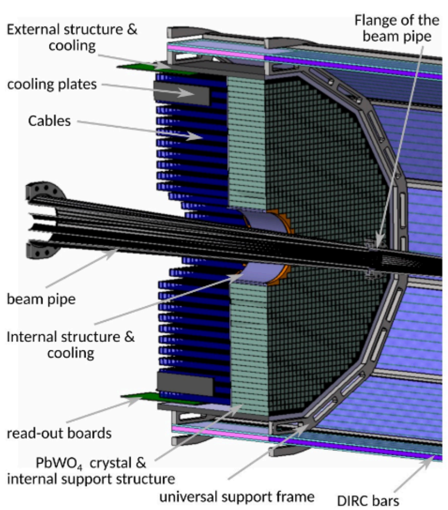
Barrel HCAL
sPHENIX re-use
new SiPM



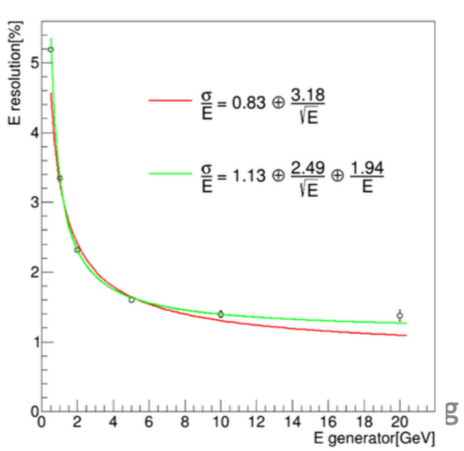


High granularity
W-powder/SciFi EMCal:) keeps
em energy resolution
at ~10%/√ E + 2%

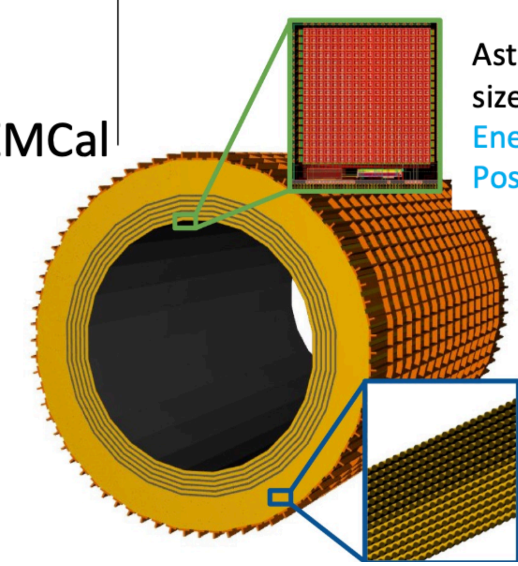
Longitudinally separated HCAL
Steel/Sc & W/Sc sandwich
with SiPMs embedded in
Scintillator



Backwards EMCal. $PbW0_4$ crystals



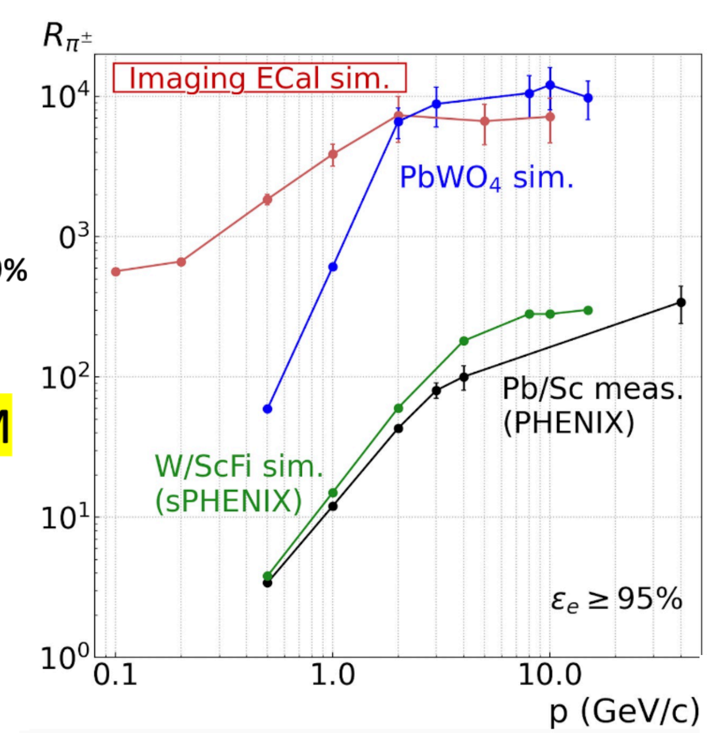
Barrel EMCal



AstroPix: silicon sensor with 500x500 μm2 size (NASA design). 4(+2) layers
Energy resolution - SciFi/Pb Layers: **5.3% /√E ⊕ 1.0%**
Position resolution: O(pixel size)

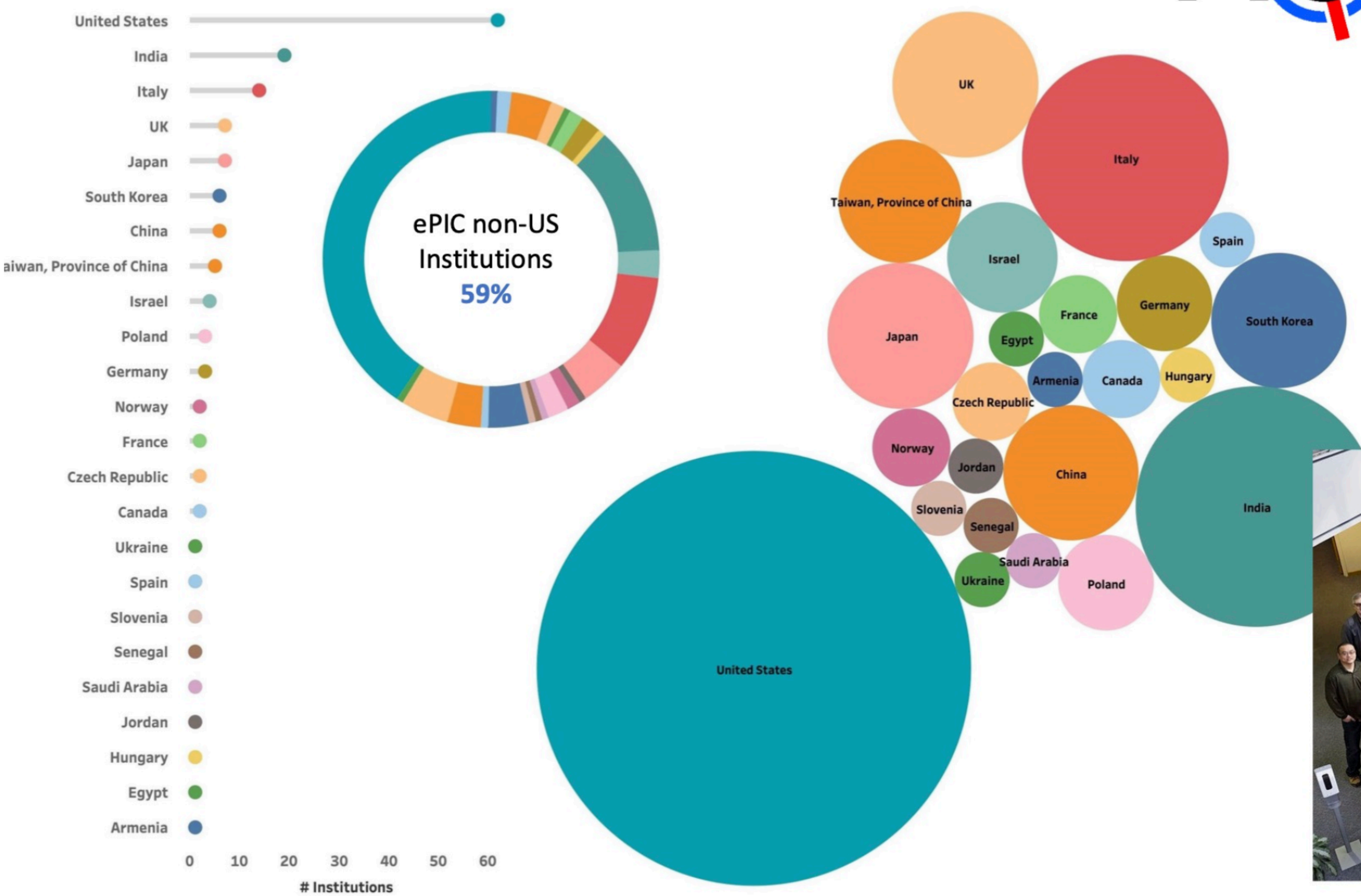
All calorimeters read with SiPM

SciFi layers in Pb (GlueX design)
with two-sided SIPM readout



Bringing it together — Collaboration

The ePIC Collaboration



171 institutions
24 countries

500+ participants

A truly global pursuit for a new experiment at the EIC!

Closing Comments

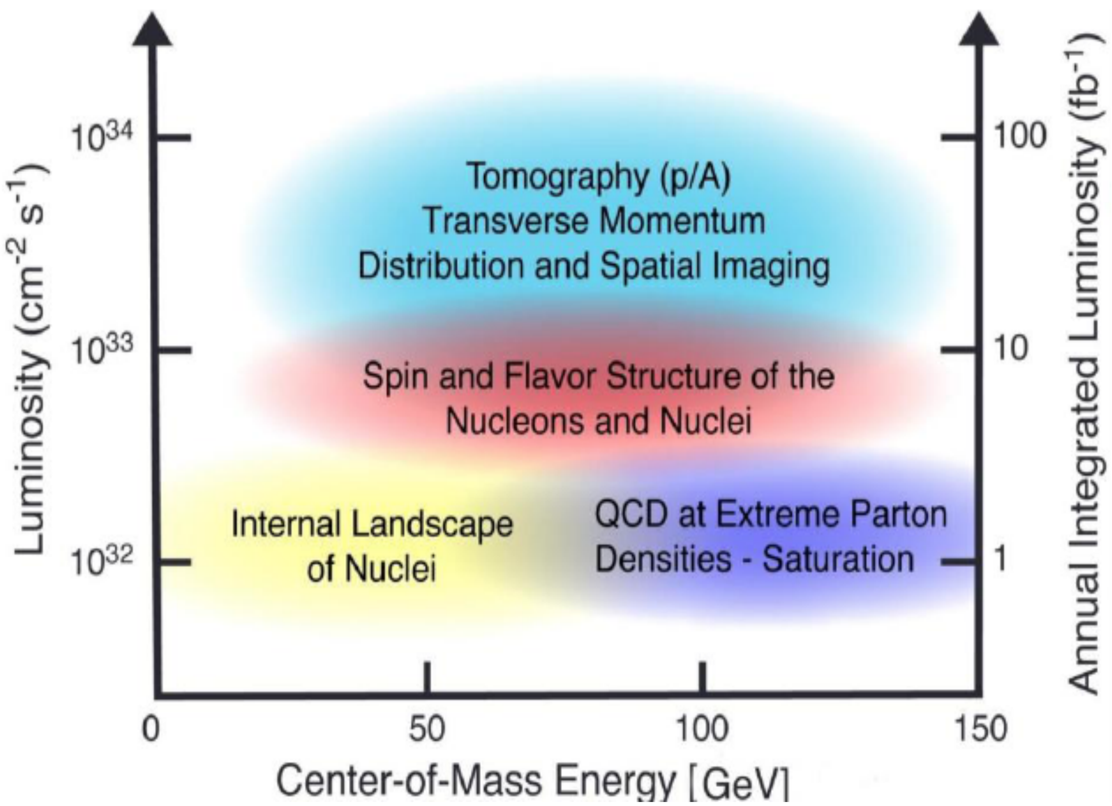
EIC project is well on track,

Project includes both collider and (one) detector,

Current focus on long-lead-time items,

Technical Design Report is next,

~2030 is closer than it may appear…



EIC offers exciting, if not challenging, processes and observables in addition to the (semi-)inclusive structure functions in DIS — jets, near-photo production, …

ePIC as a detector is increasingly defined (locked in),

In a glass is (just over) half full world, we should consider the scientific merits and complementarity of a second detector — muons, (near-) photo-production, spin transfer to final state…

If the glass is a paper cup, it is not untimely to consider e.g. run scenarios,

Hard to overstate the importance of Monte Carlo Event Generators,

Thank you — I very much look forward to the (other) talks and discussions at this workshop.