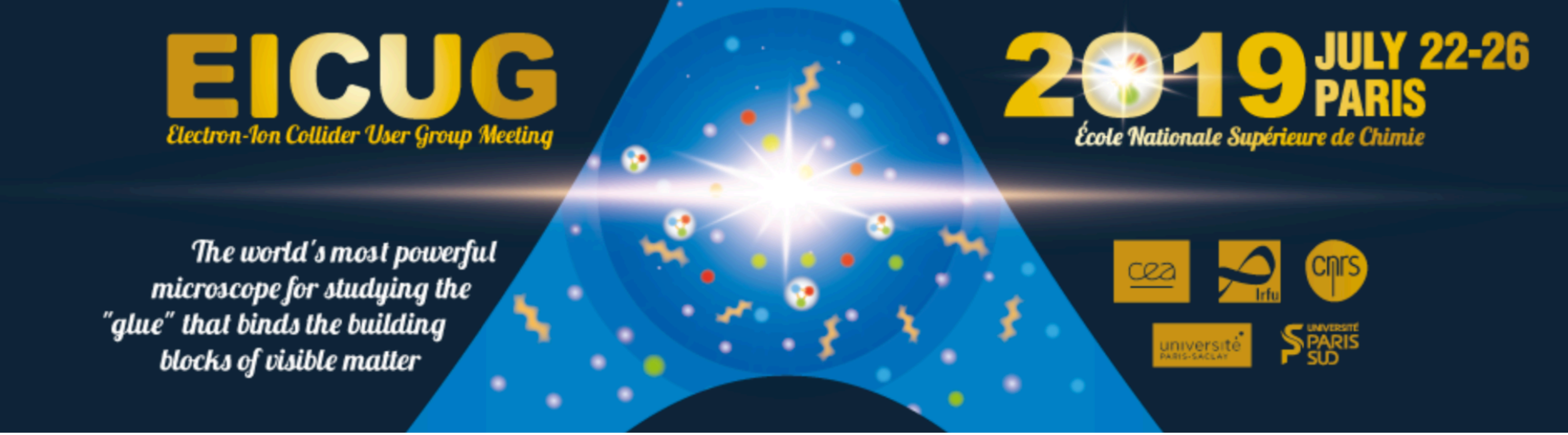
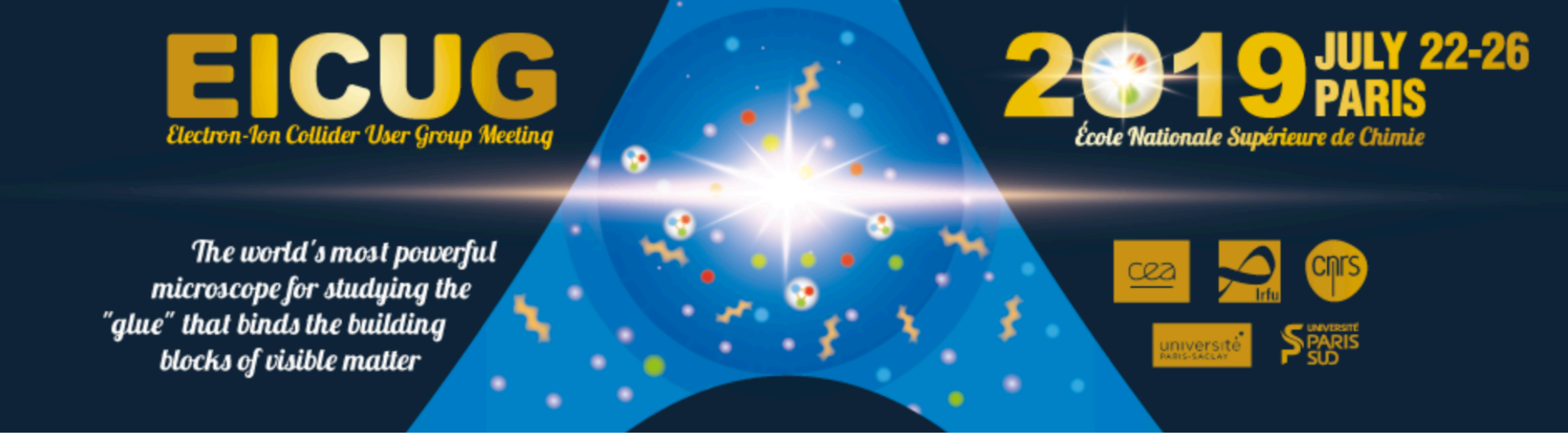


What are we as the EIC User Group missing in our detector R&D?

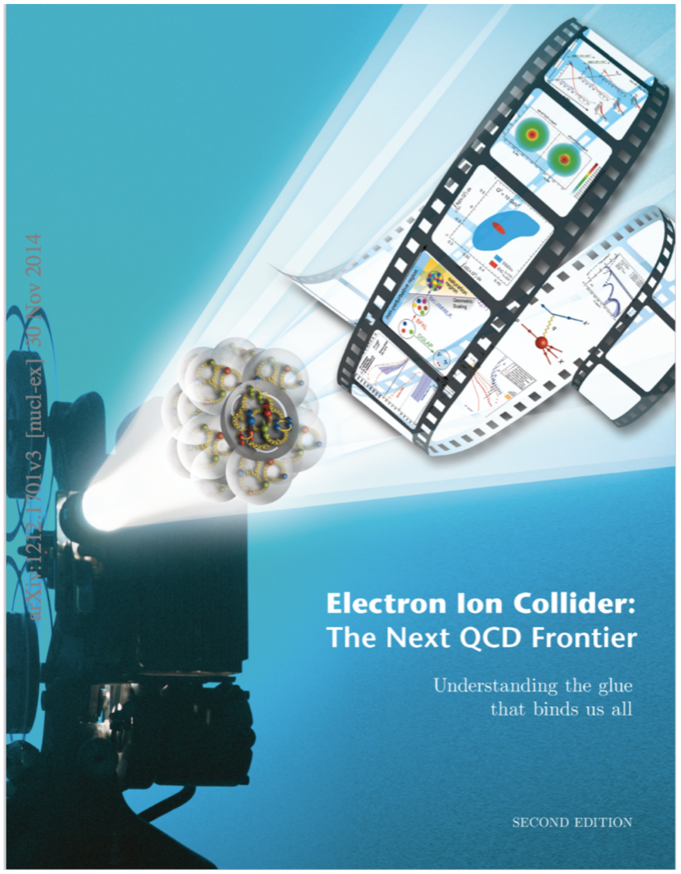
Ernst Sichtermann (LBNL)



What are we as the EIC User Group missing in our detector R&D?

Neither a set of answers, nor a summary, but certainly a worthwhile discussion to have <u>now</u>

U.S.-based EIC - Status


Electron Ion Collider:
The Next QCD Frontier
Understanding the glue
that binds us all
SECOND EDITION

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,

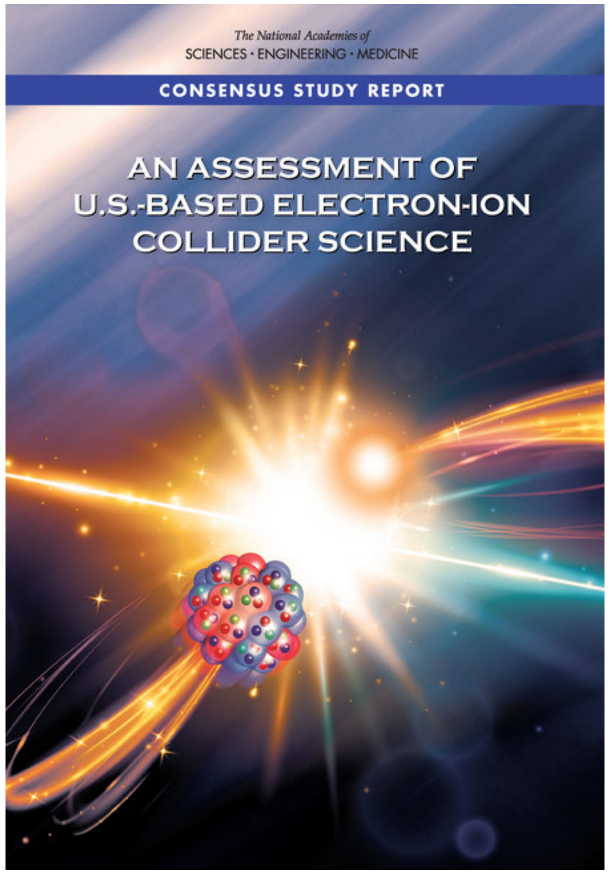
2018 NAS Science Assessment:

EIC is compelling, fundamental, and timely

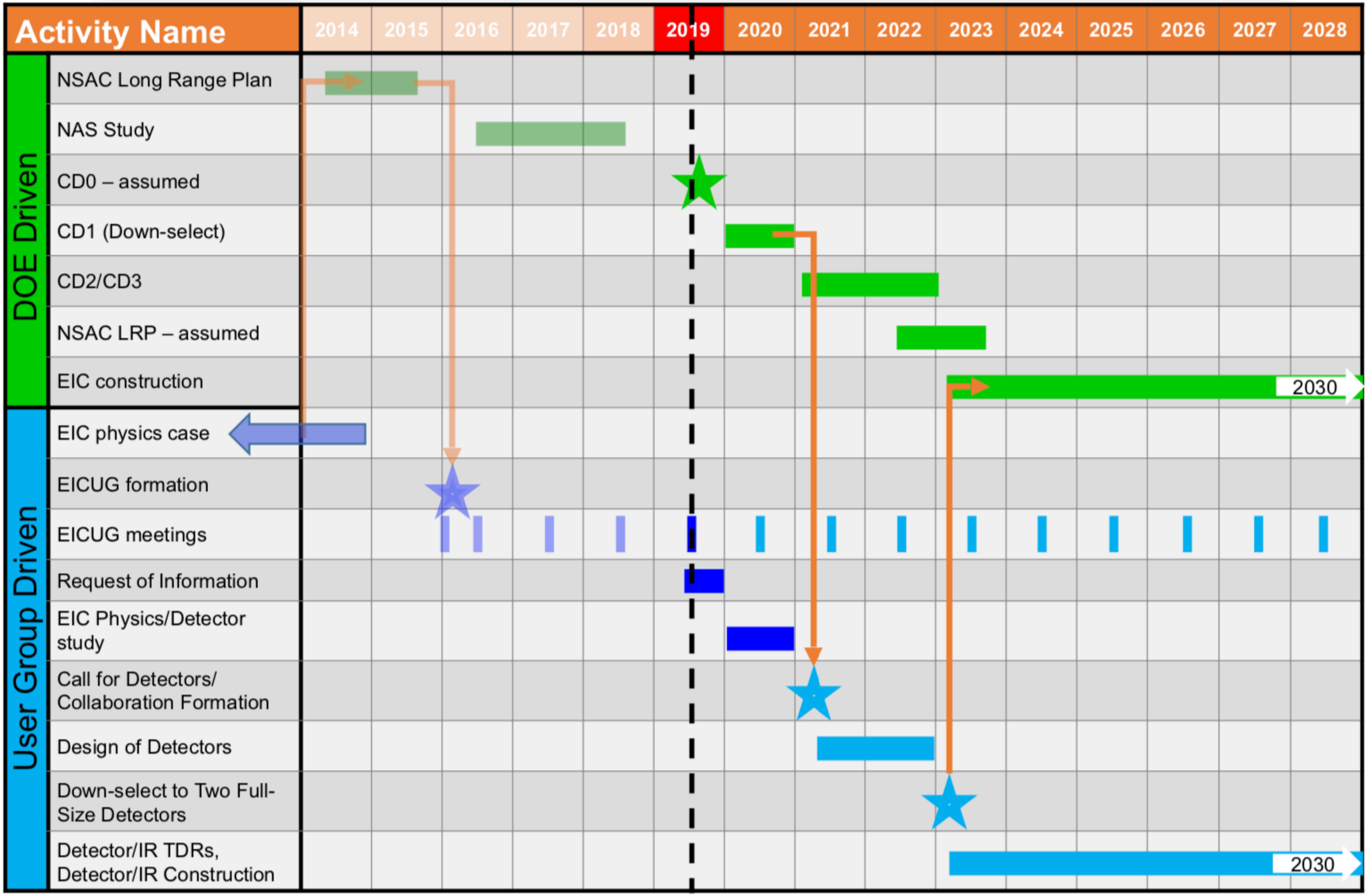
Science case: theory, experiment, *and* accelerator,

U.S. Department of Energy and two candidate host-laboratories are working together towards realizing the project, c.f. T. Hallman's talk on Monday,

Timeline(s) could be "**now,**" c.f. B.Surrow/C.Hyde-Wright's on Tue.


The National Academies of
SCIENCES · ENGINEERING · MEDICINE
CONSENSUS STUDY REPORT
AN ASSESSMENT OF
U.S.-BASED ELECTRON-ION
COLLIDER SCIENCE

EICUG Timeline



DOE Driven

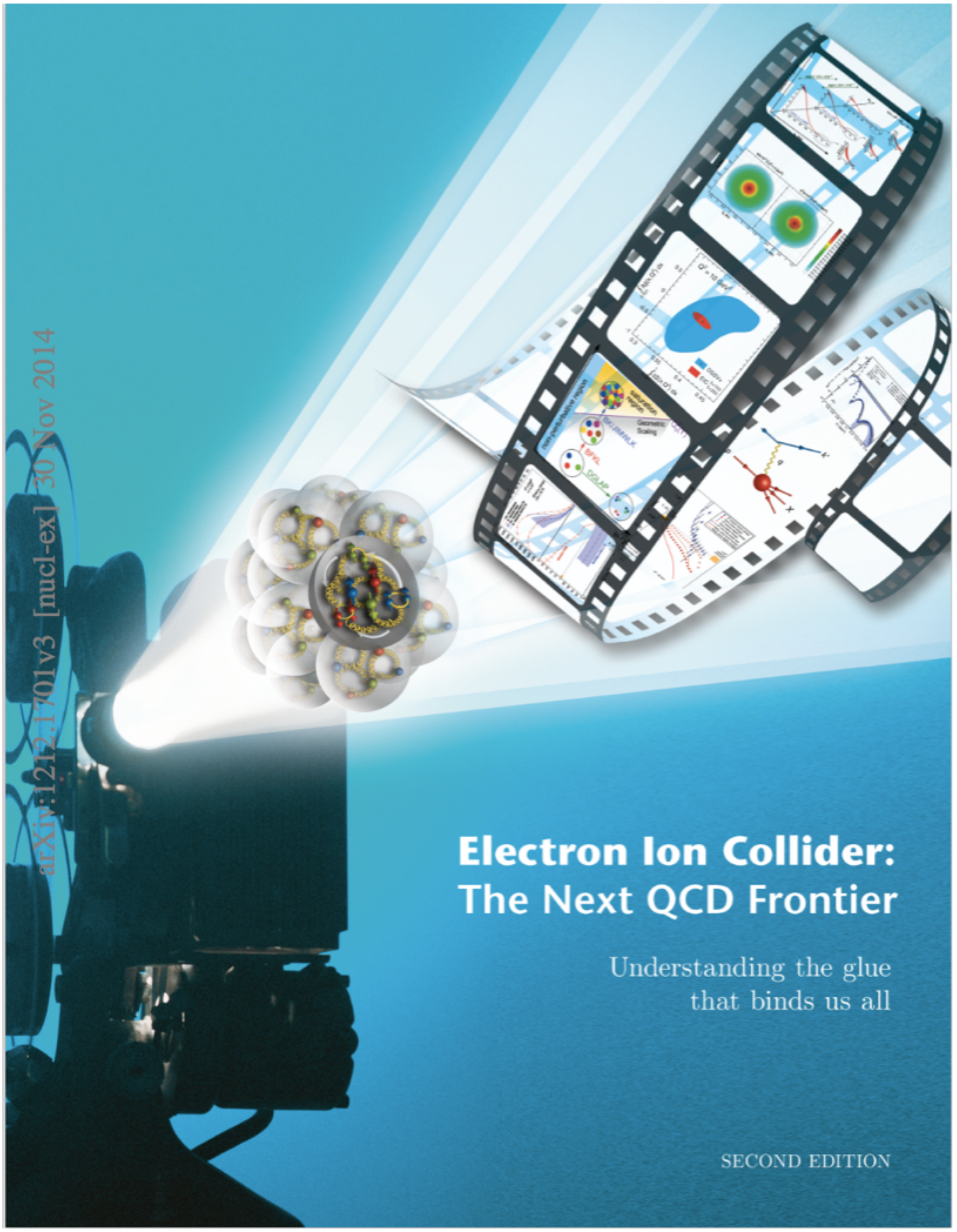
- NSAC Long Range Plan
- NAS Study
- CD0 – assumed
- CD1 (Down-select)
- CD2/CD3
- NSAC LRP – assumed
- EIC construction

User Group Driven

- EIC physics case
- EICUG formation
- EICUG meetings
- Request of Information
- EIC Physics/Detector study
- Call for Detectors/ Collaboration Formation
- Design of Detectors
- Down-select to Two Full-Size Detectors
- Detector/IR TDRs, Detector/IR Construction

c.f. B.Surrow/C.Hyde-Wright - Tuesday morning sessions.

The EIC White Paper - Three Science Questions



arXiv:1212.1701v3 [nucl-ex] 30 Nov 2014

Electron Ion Collider:
The Next QCD Frontier

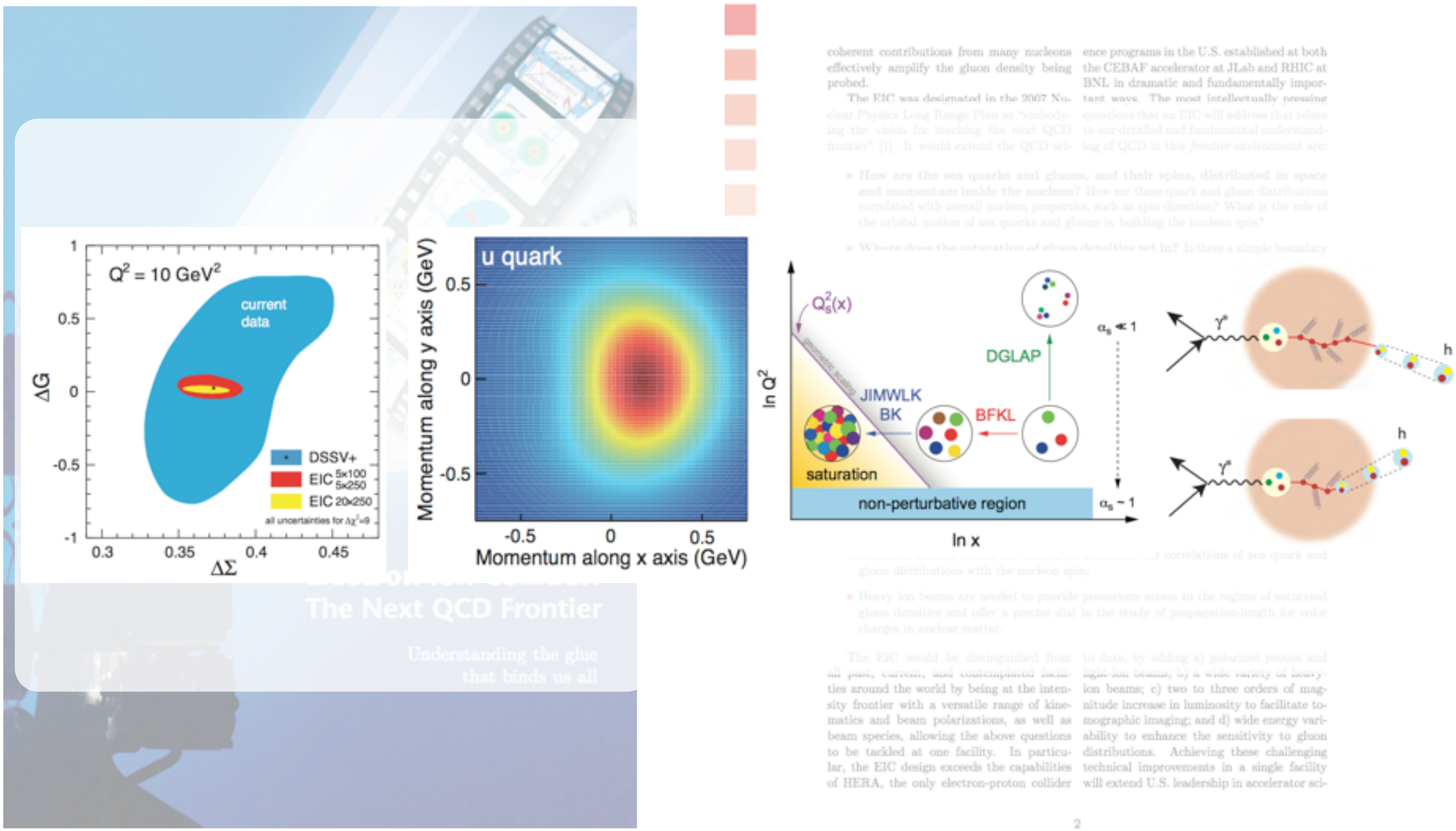
Understanding the glue
that binds us all

SECOND EDITION

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

- *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?*

The EIC White Paper - Core Science



The Next QCD Frontier

Understanding the glue that binds us all

coherent contributions from many nucleons effectively amplify the gluon density being probed.

The EIC was designated in the 2007 Nuclear Physics Long Range Plan as "embodying the vision for reaching the next QCD frontier" [1]. It would extend the QCD science programs in the U.S. established at both the CEBAF accelerator at JLab and RHIC at BNL in dramatic and fundamentally important ways. The most intellectually pressing questions that an EIC will address that relate to our detailed and fundamental understanding of QCD in this *frontier* environment are:

- How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon? How are these quark and gluon distributions correlated with overall nucleon properties, such as spin direction? What is the role of the orbital motion of sea quarks and gluons in building the nucleon spin?
- Where does the saturation of gluon densities set in? Is there a simple boundary

correlations of sea quark and gluon distributions with the nucleon spin;

- Heavy ion beams are needed to provide precocious access to the regime of saturated gluon densities and offer a precise dial in the study of propagation-length for color charges in nuclear matter.

The EIC would be distinguished from all past, current, and contemplated facilities around the world by being at the intensity frontier with a versatile range of kinematics and beam polarizations, as well as beam species, allowing the above questions to be tackled at one facility. In particular, the EIC design exceeds the capabilities of HERA, the only electron-proton collider to date, by adding a) polarized proton and light-ion beams; b) a wide variety of heavy-ion beams; c) two to three orders of magnitude increase in luminosity to facilitate tomographic imaging; and d) wide energy variability to enhance the sensitivity to gluon distributions. Achieving these challenging technical improvements in a single facility will extend U.S. leadership in accelerator sci-

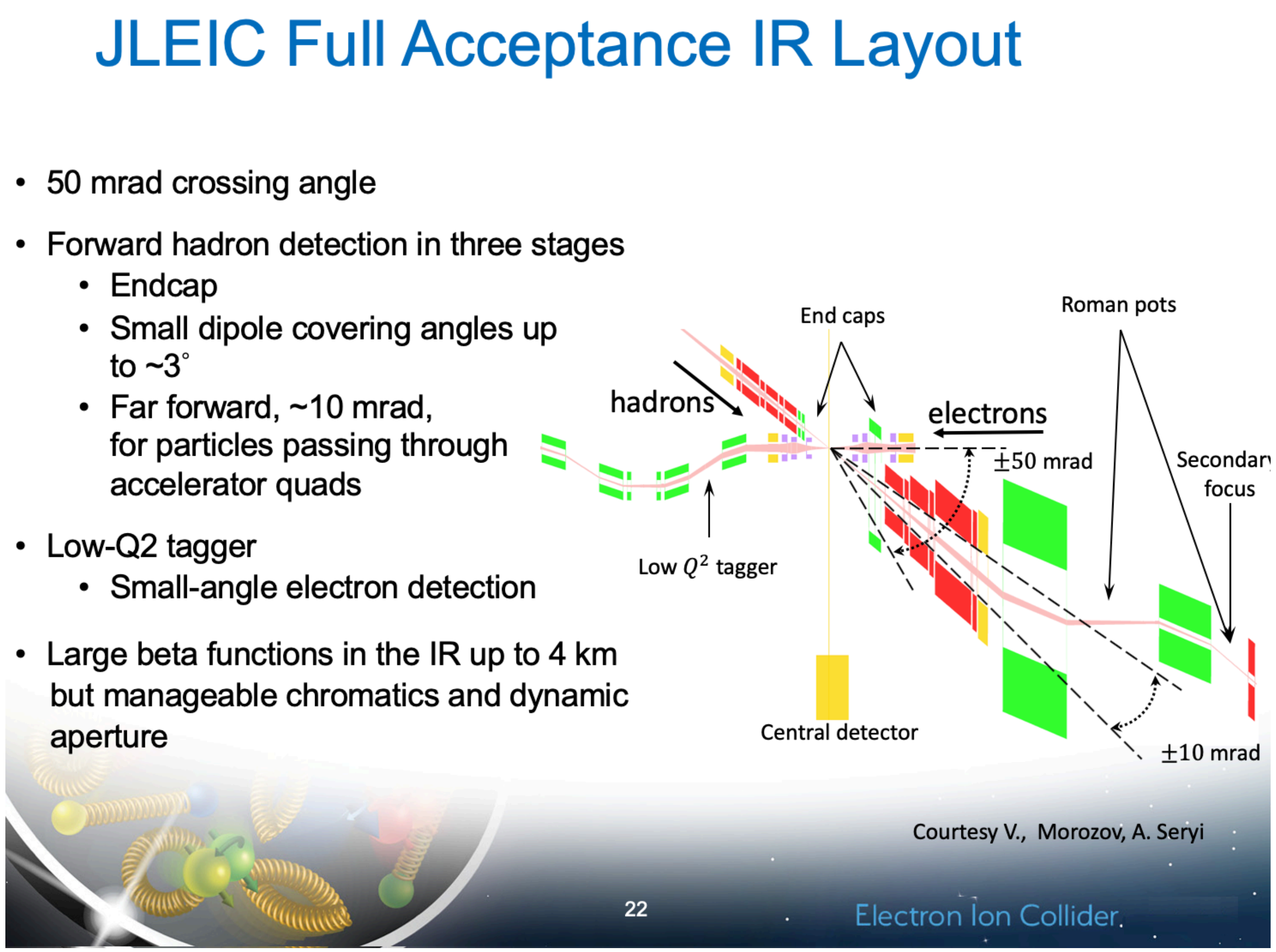
2

Nuclear Physics enabled by EIC **beam** energy, intensity, polarization, and species, **detector** capabilities,

Theory

The EIC White Paper - Two facility concepts

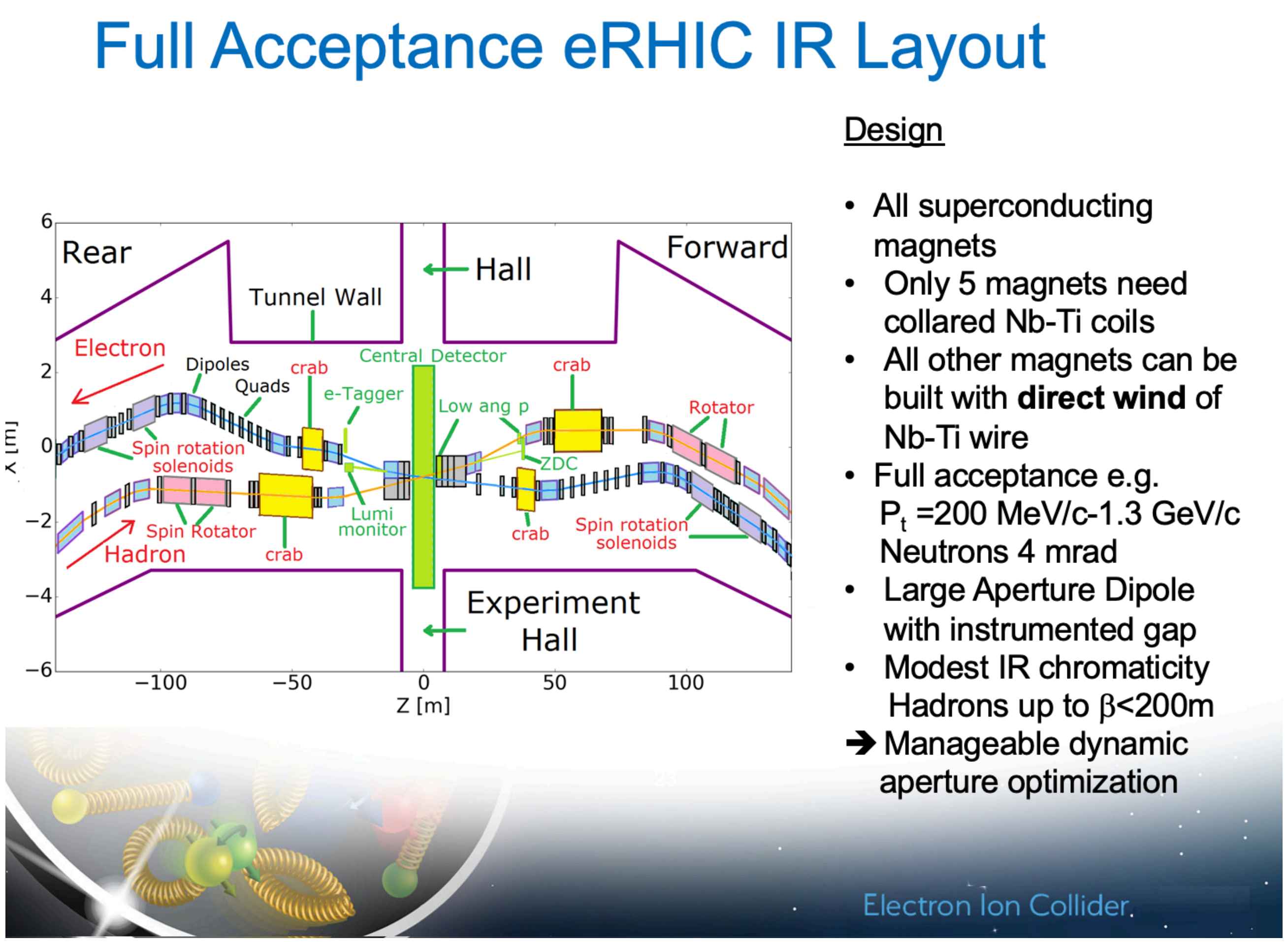
See F. Willeke on Monday - science cases by themselves requiring, for example, tight integration with detectors



JLEIC Full Acceptance IR Layout

- 50 mrad crossing angle
- Forward hadron detection in three stages
  - Endcap
  - Small dipole covering angles up to ~3˚
  - Far forward, ~10 mrad, for particles passing through accelerator quads
- Low-Q2 tagger
  - Small-angle electron detection
- Large beta functions in the IR up to 4 km but manageable chromatics and dynamic aperture

Courtesy V., Morozov, A. Seryi



Full Acceptance eRHIC IR Layout

Design

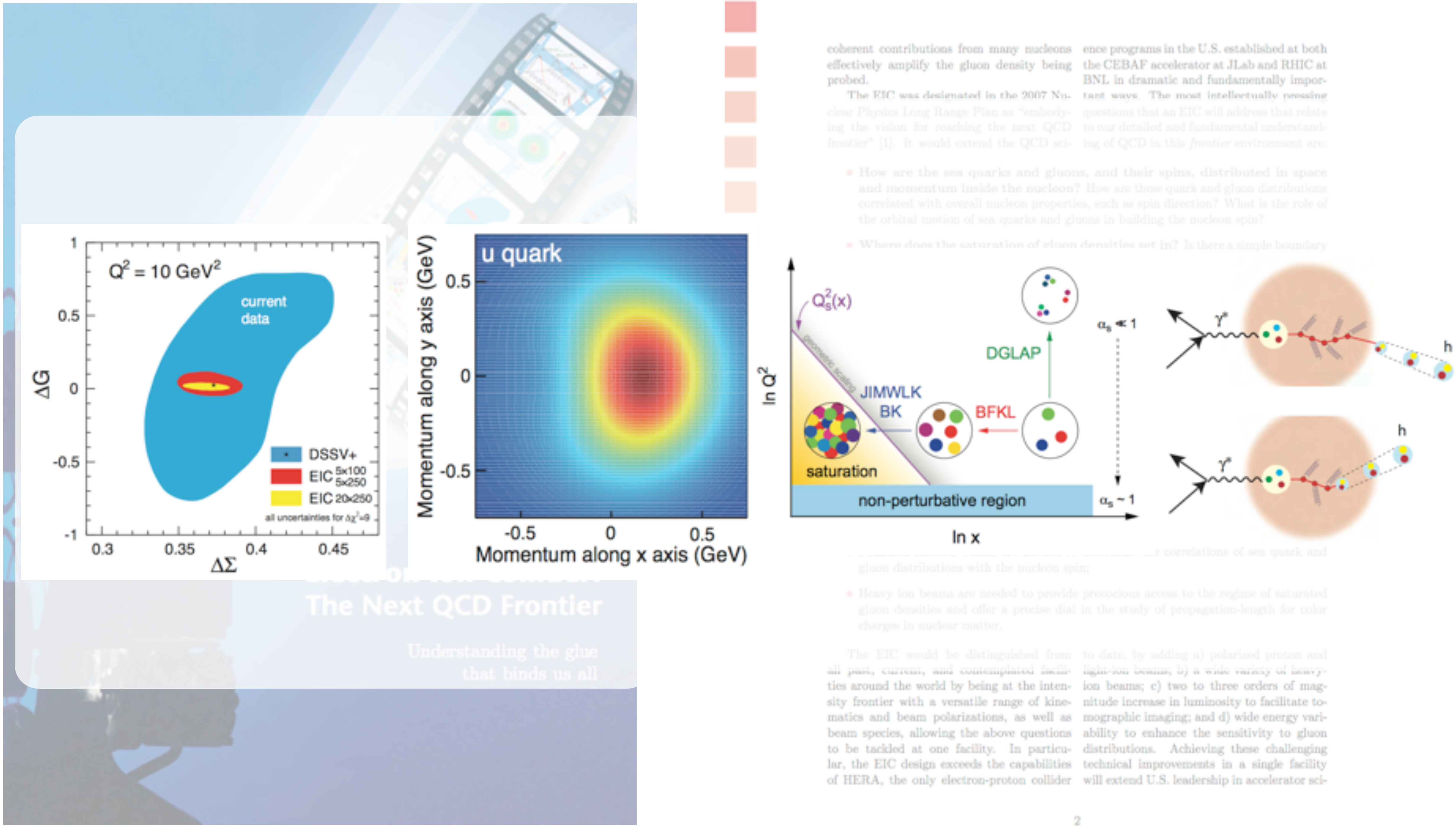
- All superconducting magnets
- Only 5 magnets need collared Nb-Ti coils
- All other magnets can be built with **direct wind** of Nb-Ti wire
- Full acceptance e.g. P_t =200 MeV/c-1.3 GeV/c Neutrons 4 mrad
- Large Aperture Dipole with instrumented gap
- Modest IR chromaticity Hadrons up to β<200m

➔ Manageable dynamic aperture optimization

7—9 m linear space available for both general purpose detectors,

Machine-Detector-Interface discussion this afternoon.

The EIC White Paper - Core Science



coherent contributions from many nucleons effectively amplify the gluon density being probed.

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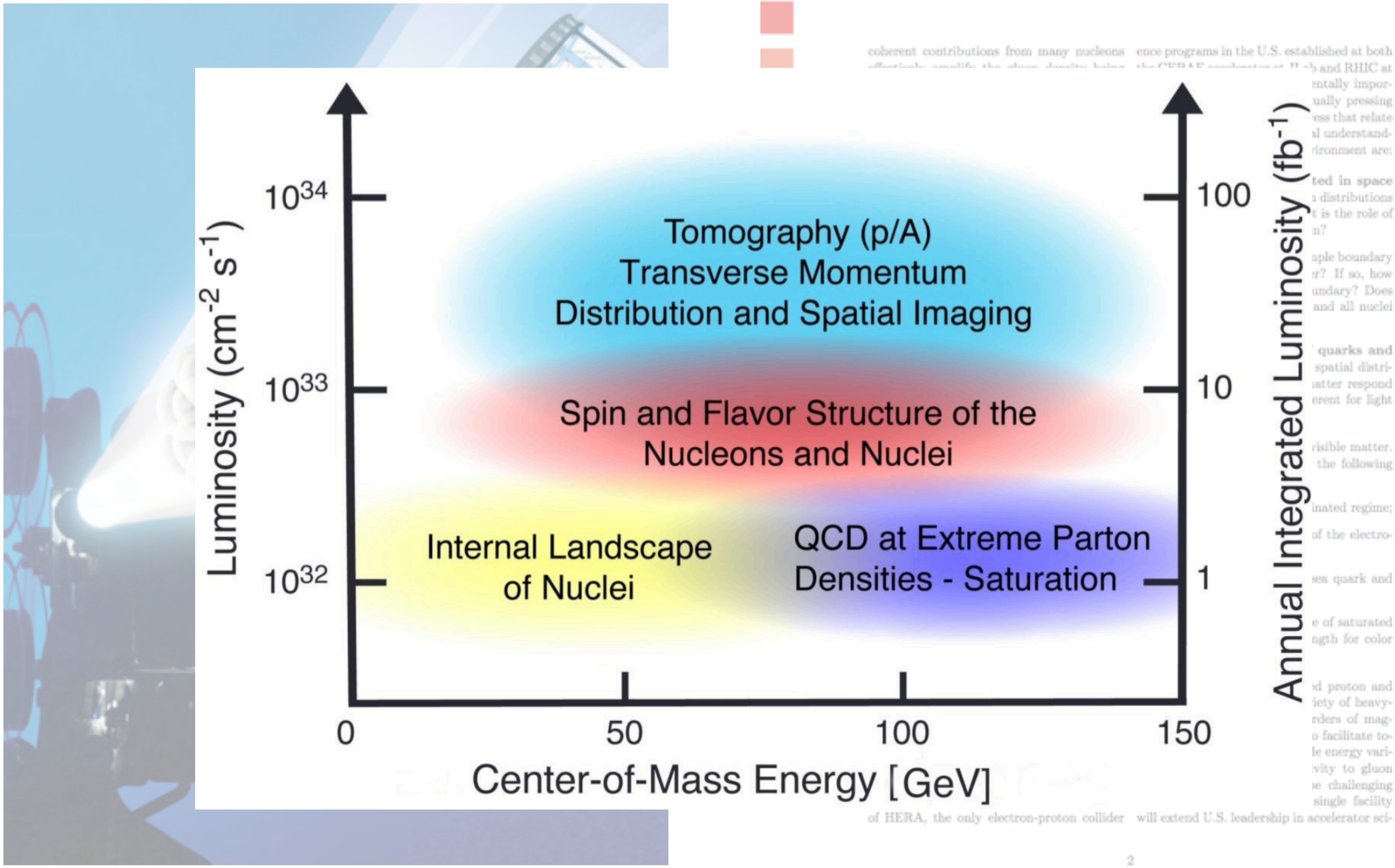
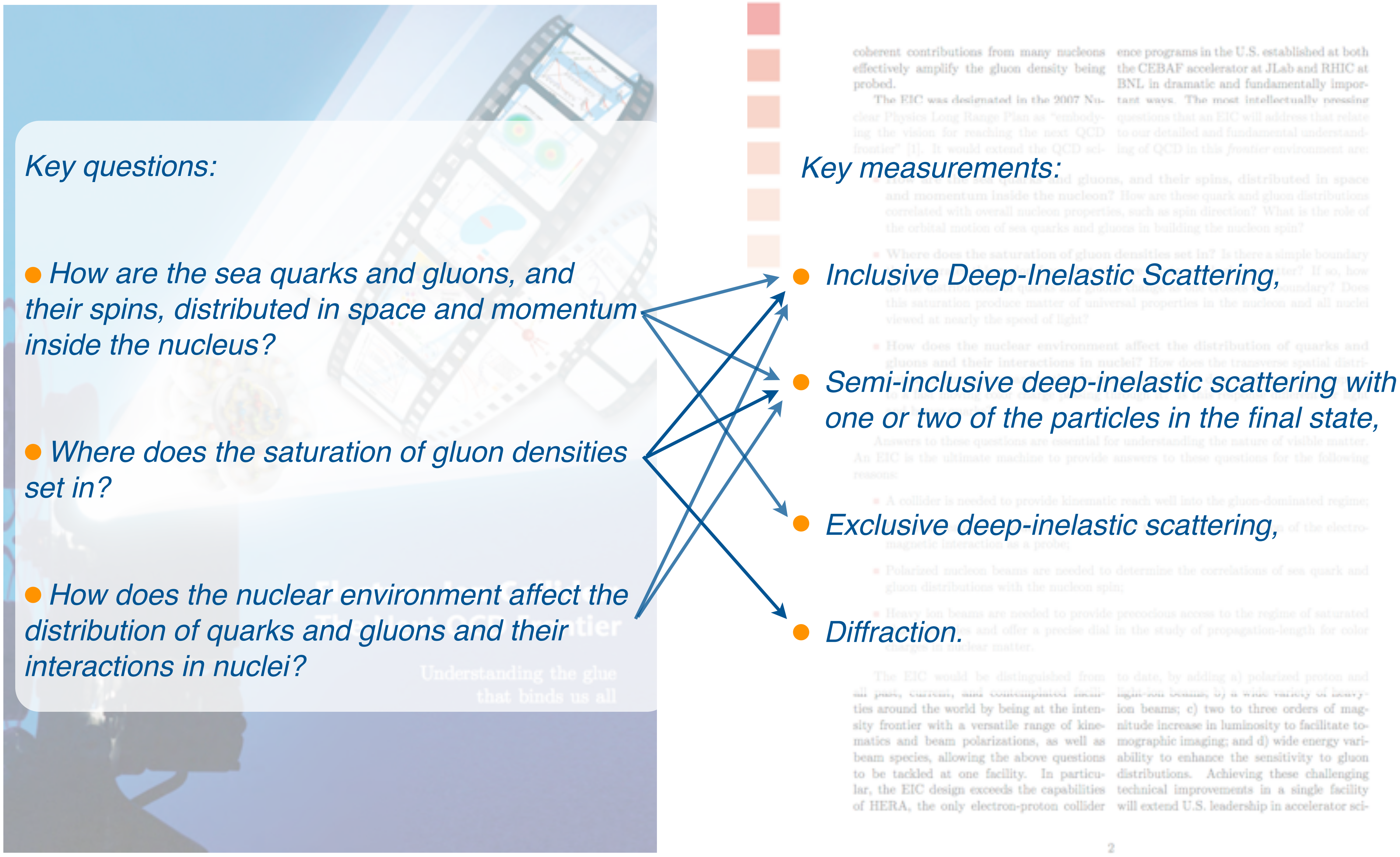
Theory

The EIC White Paper - Core Science



Many measurements will be systematics limited; c.f. this afternoon’s talks by
C. Hyde on the luminosity and IR working group,
E. Aschenauer on the polarimetry working group, and also
R. Yoshida’s talk on complementarity in measurement/experiment techniques.

The EIC White Paper - Core Science



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?*

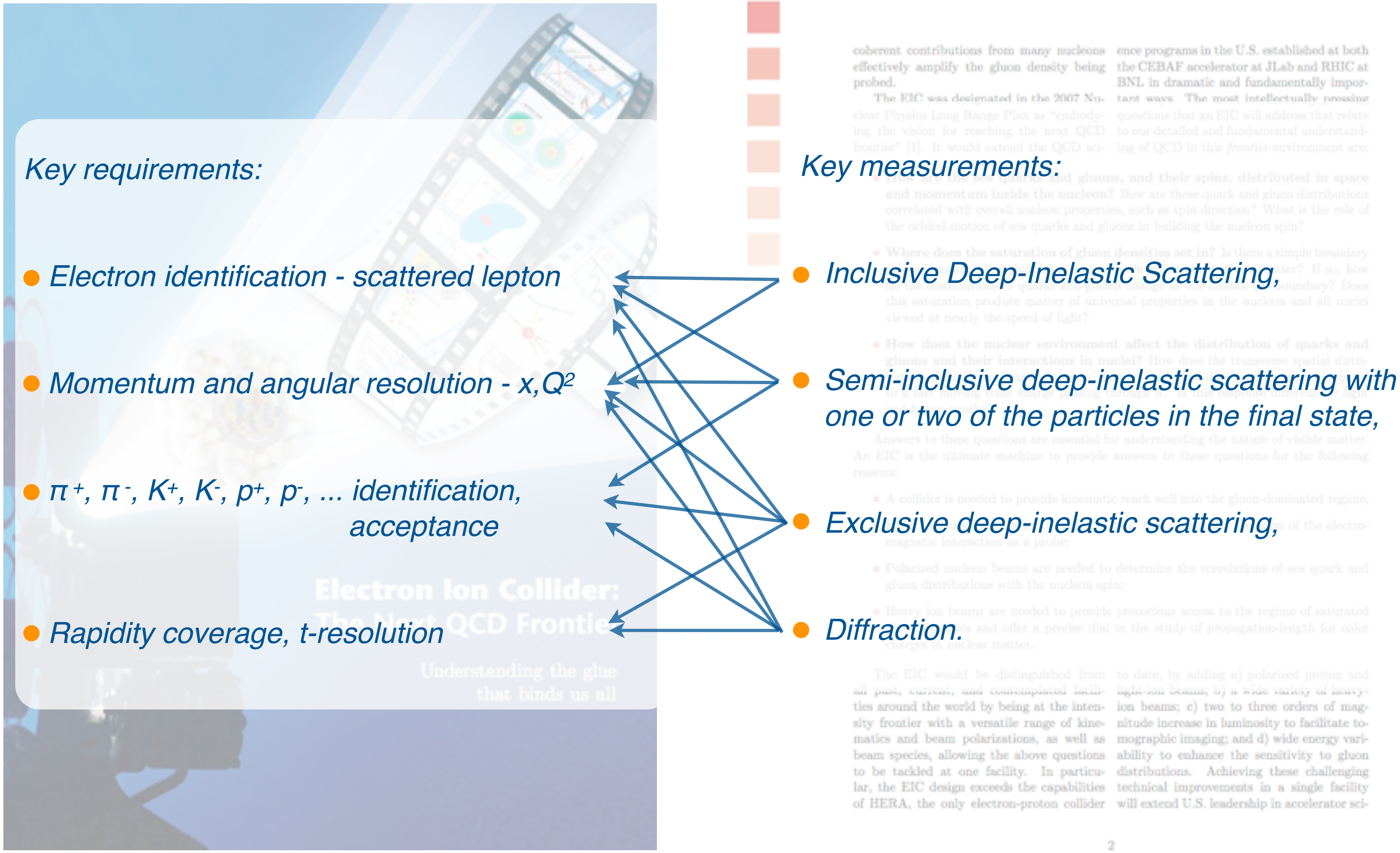
Key measurements:

- *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.*

Nuclear Physics enabled by EIC **beam** energy, intensity, polarization, and species, **detector** capabilities,

Theory

The EIC White Paper - Core Measurements



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*

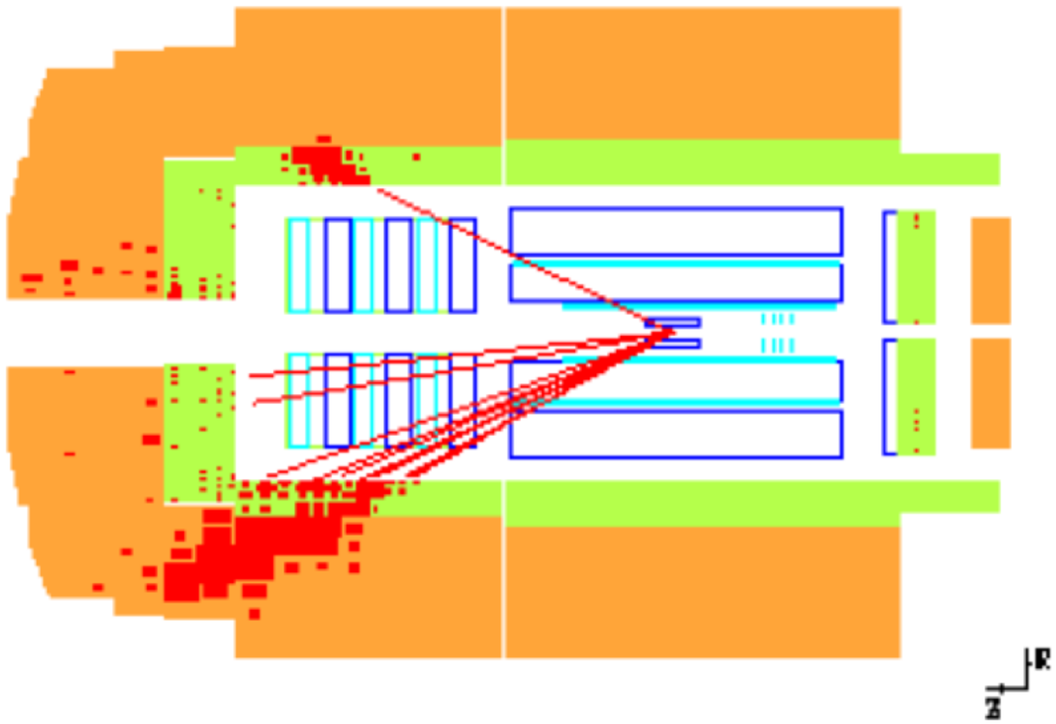
Key measurements:

- *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.*

Electron-Ion Collider Detector Requirements and R&D Handbook,
Eds. T. Ullrich and A. Kiselev, v1.1 January 2019, c.f. www.eicug.org

U.S.-based EIC - Preliminaries

H1, neutral-current candidate event



coherent contributions from many nucleons effectively amplify the gluon density being probed.

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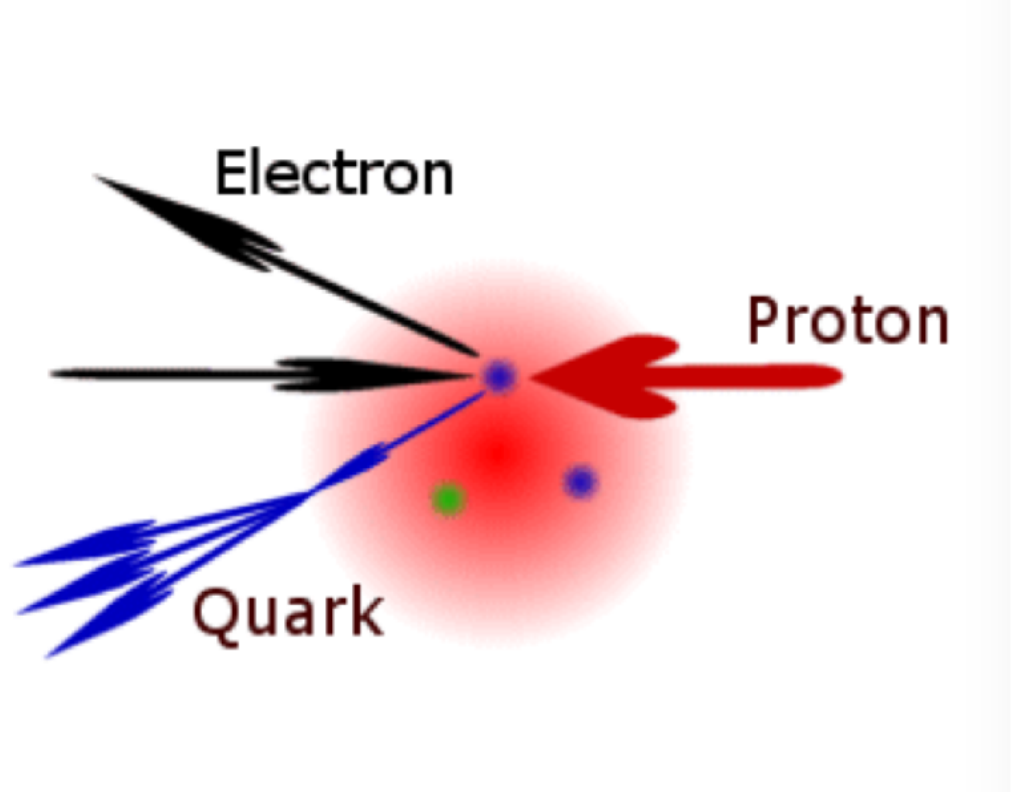


courtesy J. Meyer, DESY 2005

ties around the world by being at the intensity frontier with a versatile range of kinematics and beam polarizations, as well as beam species, allowing the above questions to be tackled at one facility. In particular, the EIC design exceeds the capabilities of HERA, the only electron-proton collider

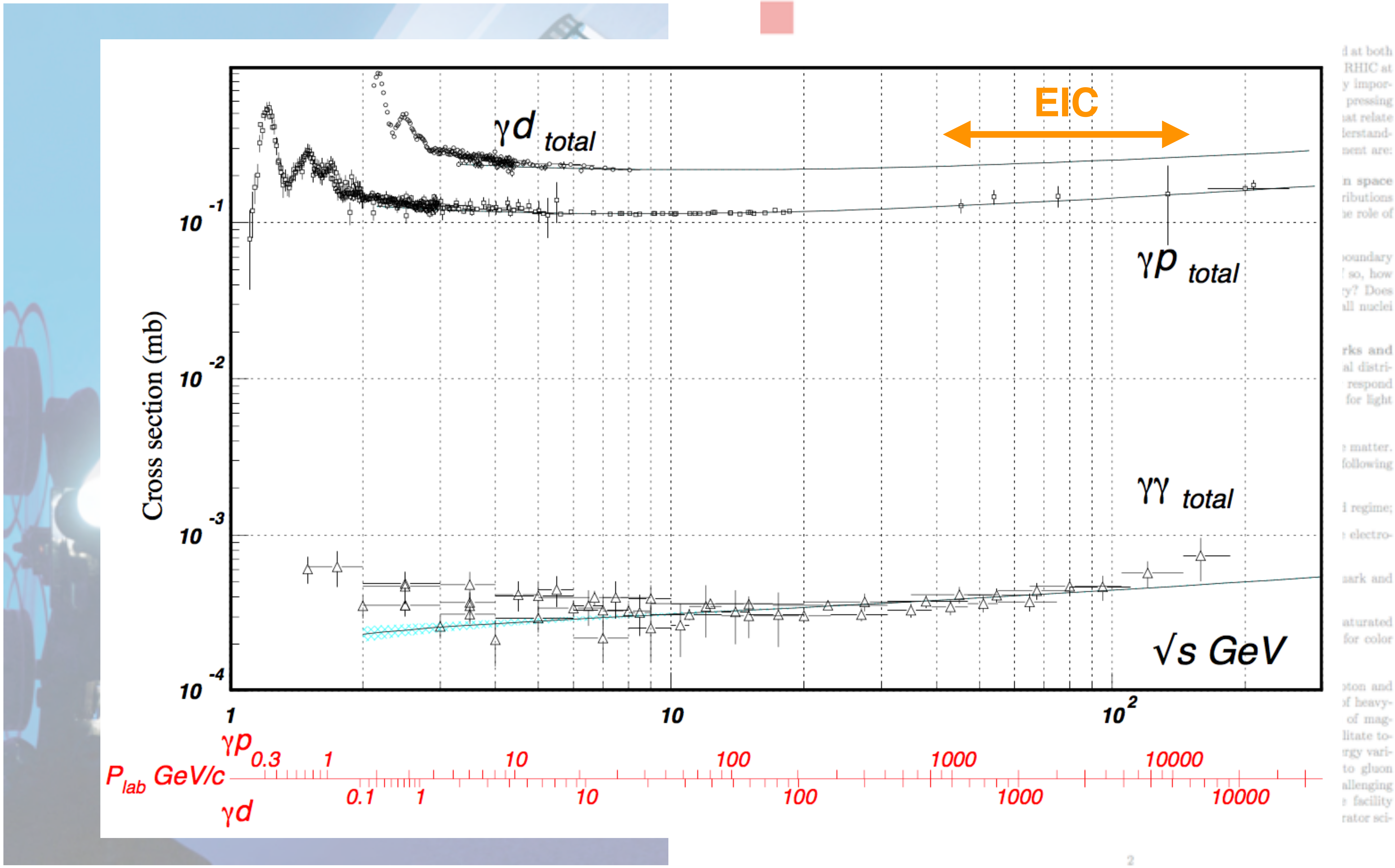
ion beams; c) two to three orders of magnitude increase in luminosity to facilitate tomographic imaging; and d) wide energy variability to enhance the sensitivity to gluon distributions. Achieving these challenging technical improvements in a single facility will extend U.S. leadership in accelerator sci-

2

HERA went before: event topologies are well known, and *many* (other) insights gained.

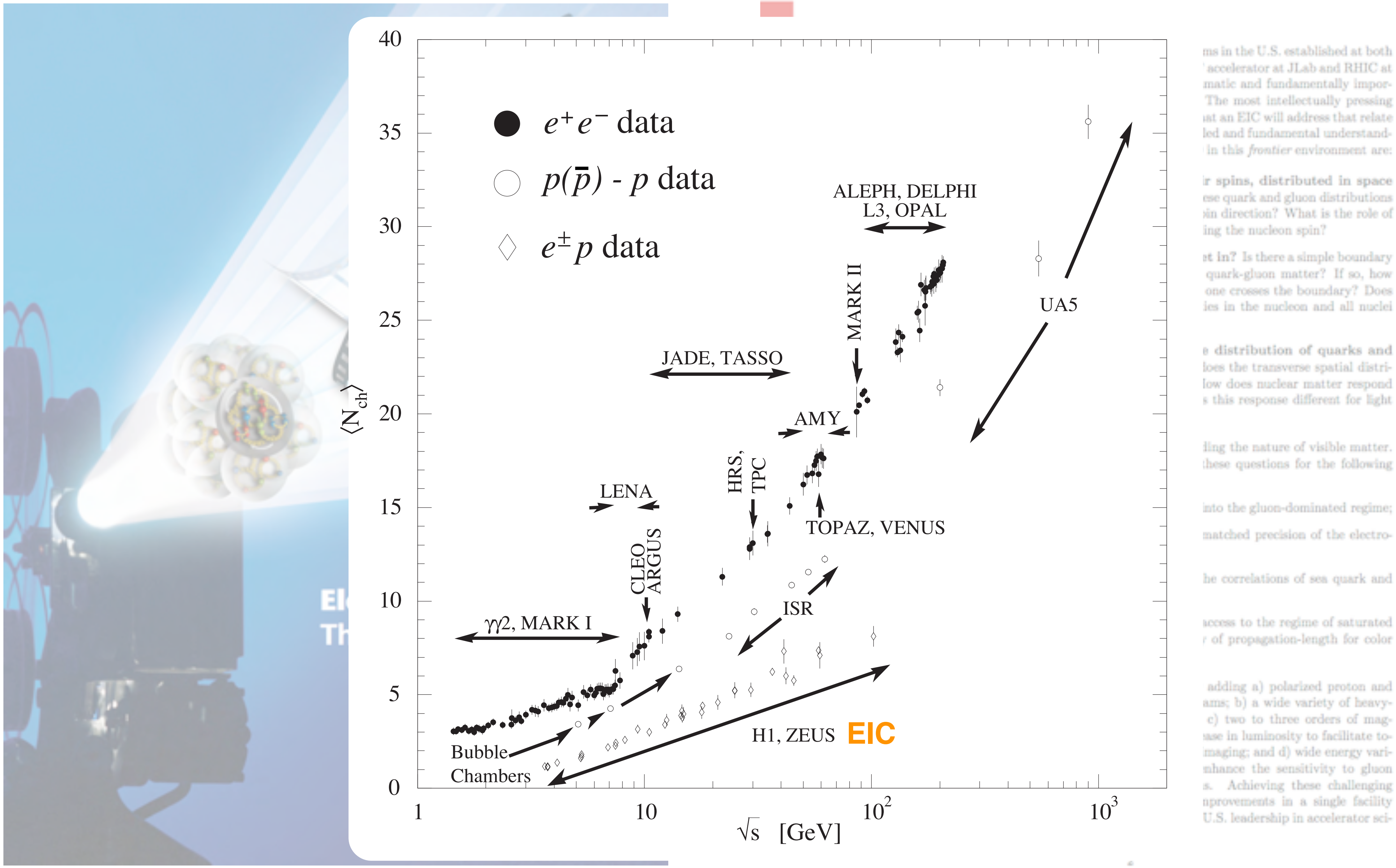
In hindsight, it is of course easy to name a few missing capabilities of H1 and ZEUS…

U.S.-based EIC - Preliminaries



Photoproduction is the dominant cross-section; well known, 2 orders below RHIC, LHC

U.S.-based EIC - Preliminaries



ms in the U.S. established at both
accelerator at JLab and RHIC at
matic and fundamentally impor-
The most intellectually pressing
at an EIC will address that relate
led and fundamental understand-
in this *frontier* environment are:

r spins, distributed in space
ese quark and gluon distributions
in direction? What is the role of
ing the nucleon spin?

et in? Is there a simple boundary
quark-gluon matter? If so, how
one crosses the boundary? Does
ies in the nucleon and all nuclei

e distribution of quarks and
loes the transverse spatial distri-
low does nuclear matter respond
s this response different for light

ding the nature of visible matter.
these questions for the following

into the gluon-dominated regime;

matched precision of the electro-

he correlations of sea quark and

access to the regime of saturated
of propagation-length for color

adding a) polarized proton and
ams; b) a wide variety of heavy-
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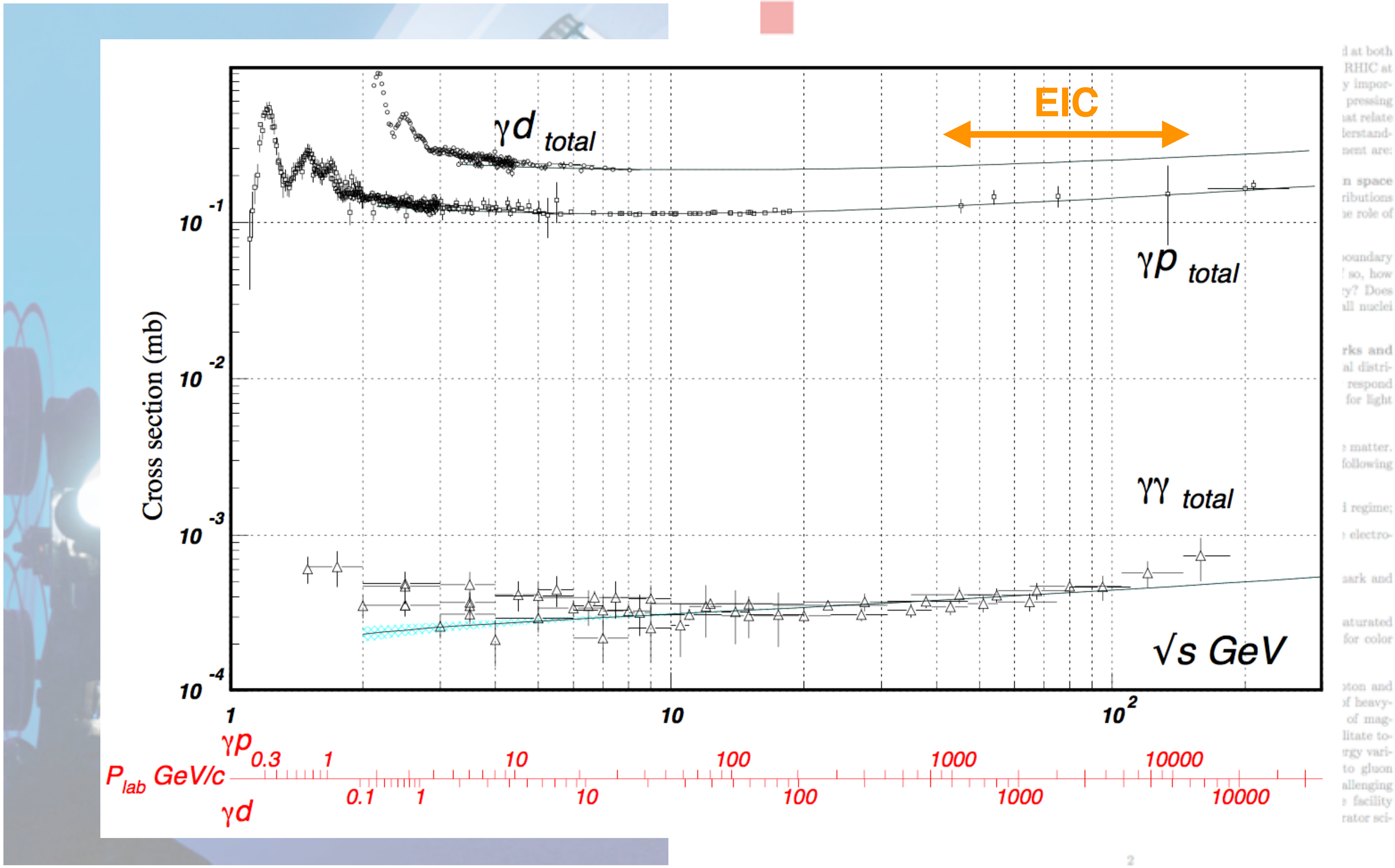
U.S. leadership in accelerator sci-

Photoproduction is the dominant cross-section; well known, 2 orders below RHIC, LHC

Likewise, particle multiplicities are well below those at the hadron colliders,

Backgrounds, e.g. hadronic beam-gas interactions must be studied/quantified.

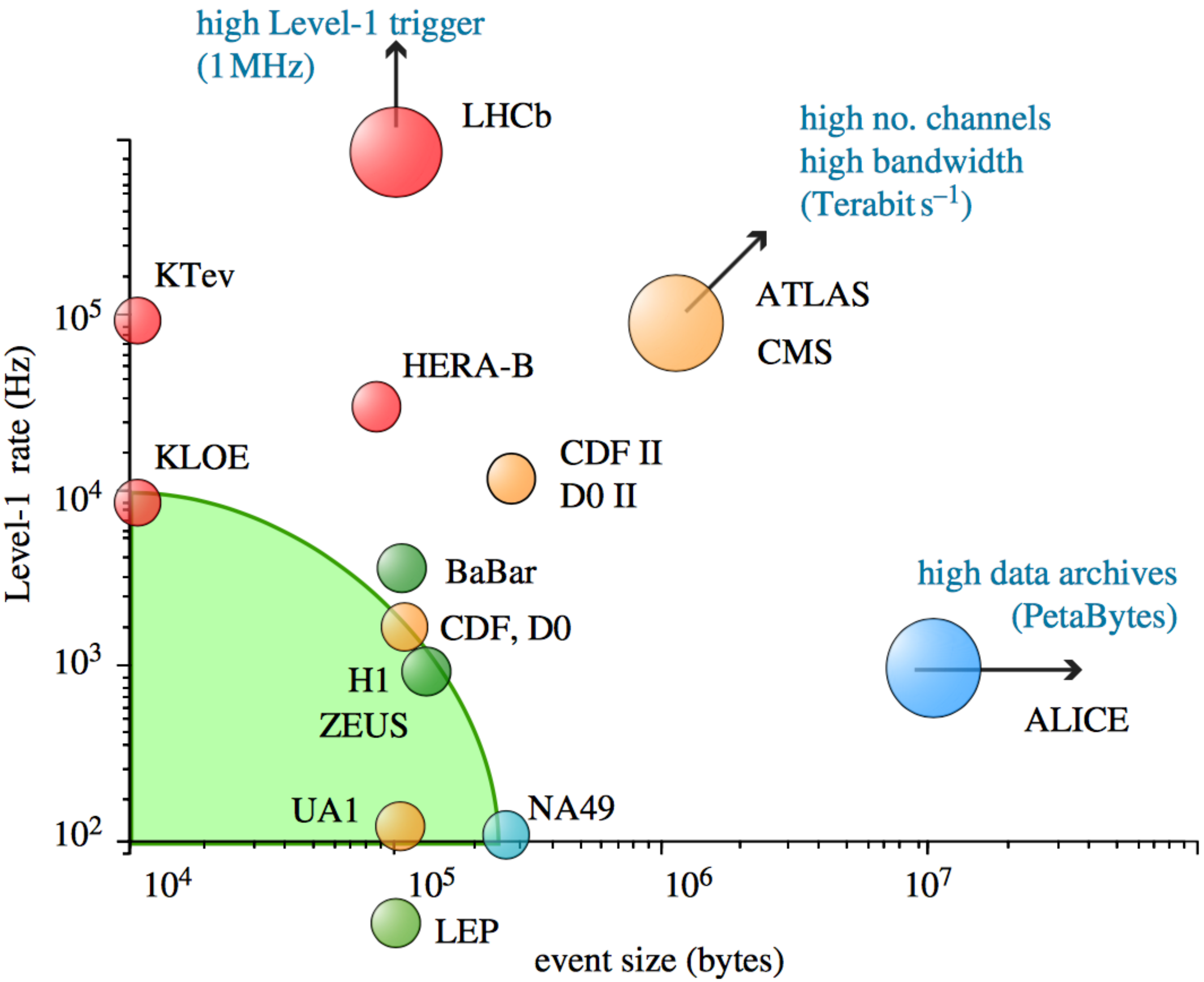
U.S.-based EIC - Preliminaries



L ~ $10^{33(34)}$cm^{-2}s^{-1} implies a ~50 (500) kHz collision-event rate,

<< EIC bunch cross crossing rate
~ similar to μs integration times

U.S.-based EIC - Computing context



LHC: a sounding success of bold extrapolations and numerous technological breakthroughs,

40 MHz beam bunch crossing rates with multiple collisions per crossing,

*"Big Data" by size and rate, **and** analysis speed,*

S. Cittolin, Phil. Trans. R. Soc. A (2012) 370, 954

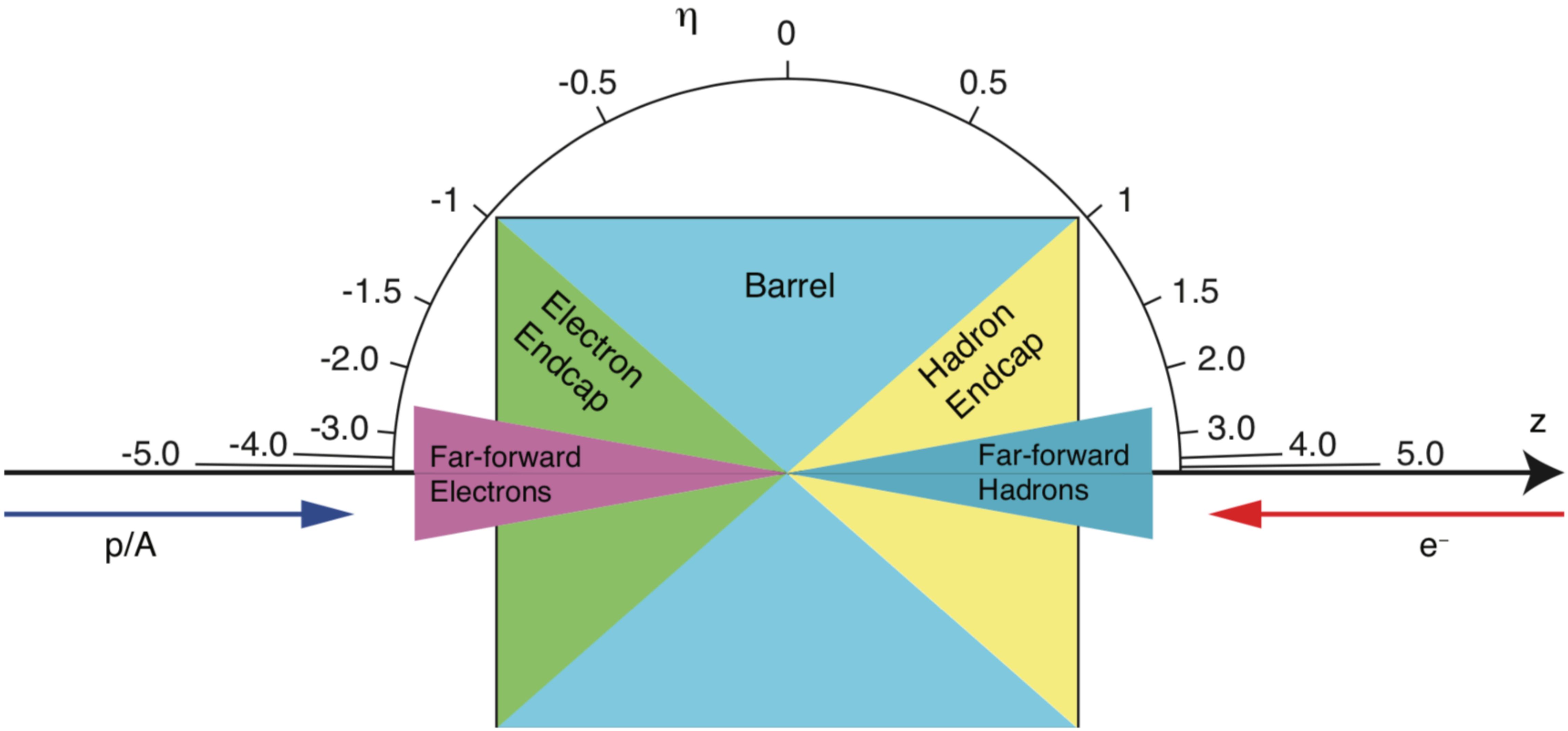
Note, the above figure is from ca. 2012… almost prehistoric,

High-Intensity LHC is on its way; LHCb, for example, will move to a triggerless-readout system for LHC run 3 (2021-2023, prior to EIC), and will process 5TB/s in real time on the CPU farm (M. Williams at the Future Trends in NP Computing),

Possibility of qualitatively new analysis paradigm(s) for EIC?

See e.g. J. Huang's talk Thursday morning on ePHENIX DAQ

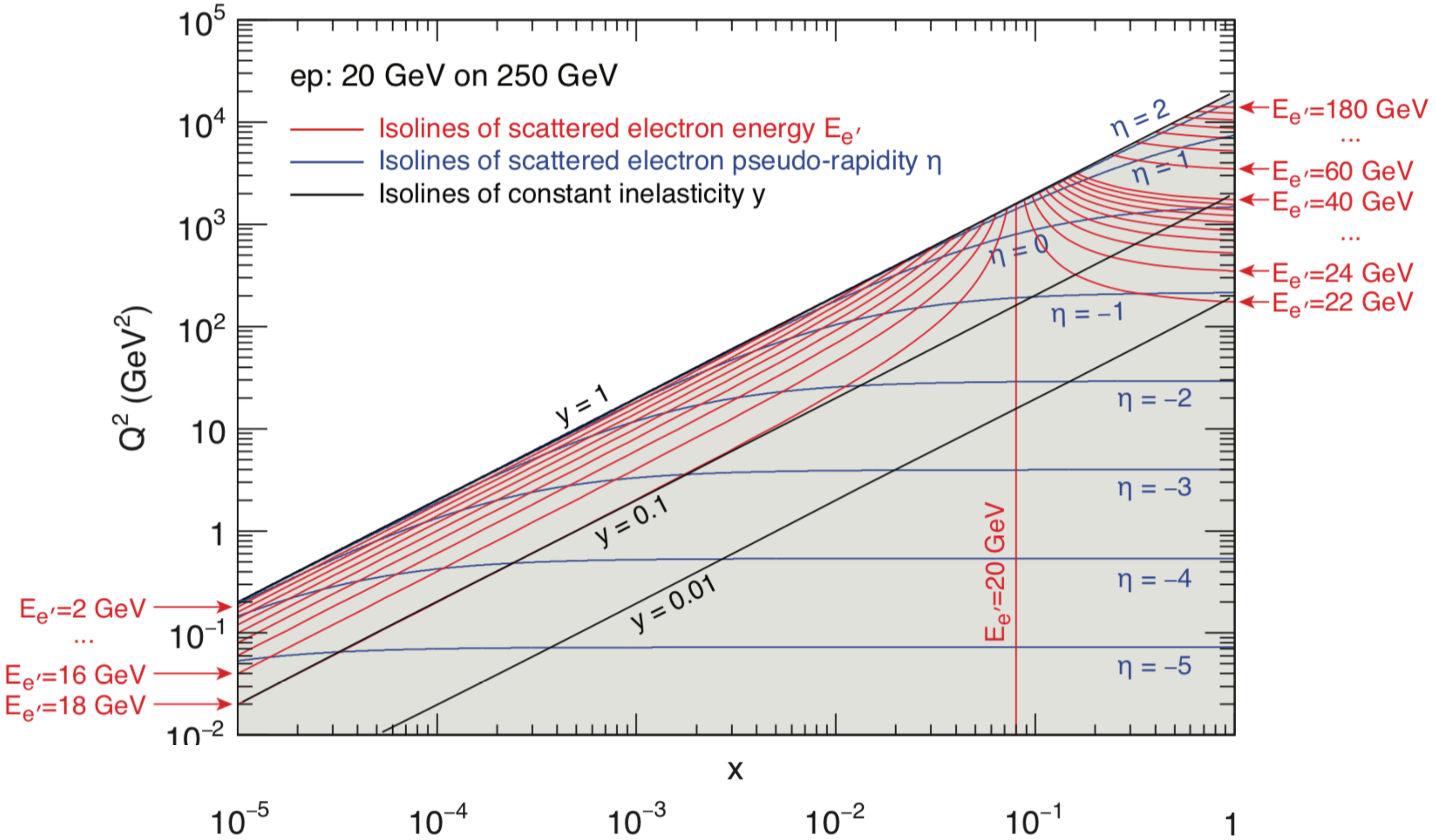
U.S.-based EIC - Coordinate Conventions

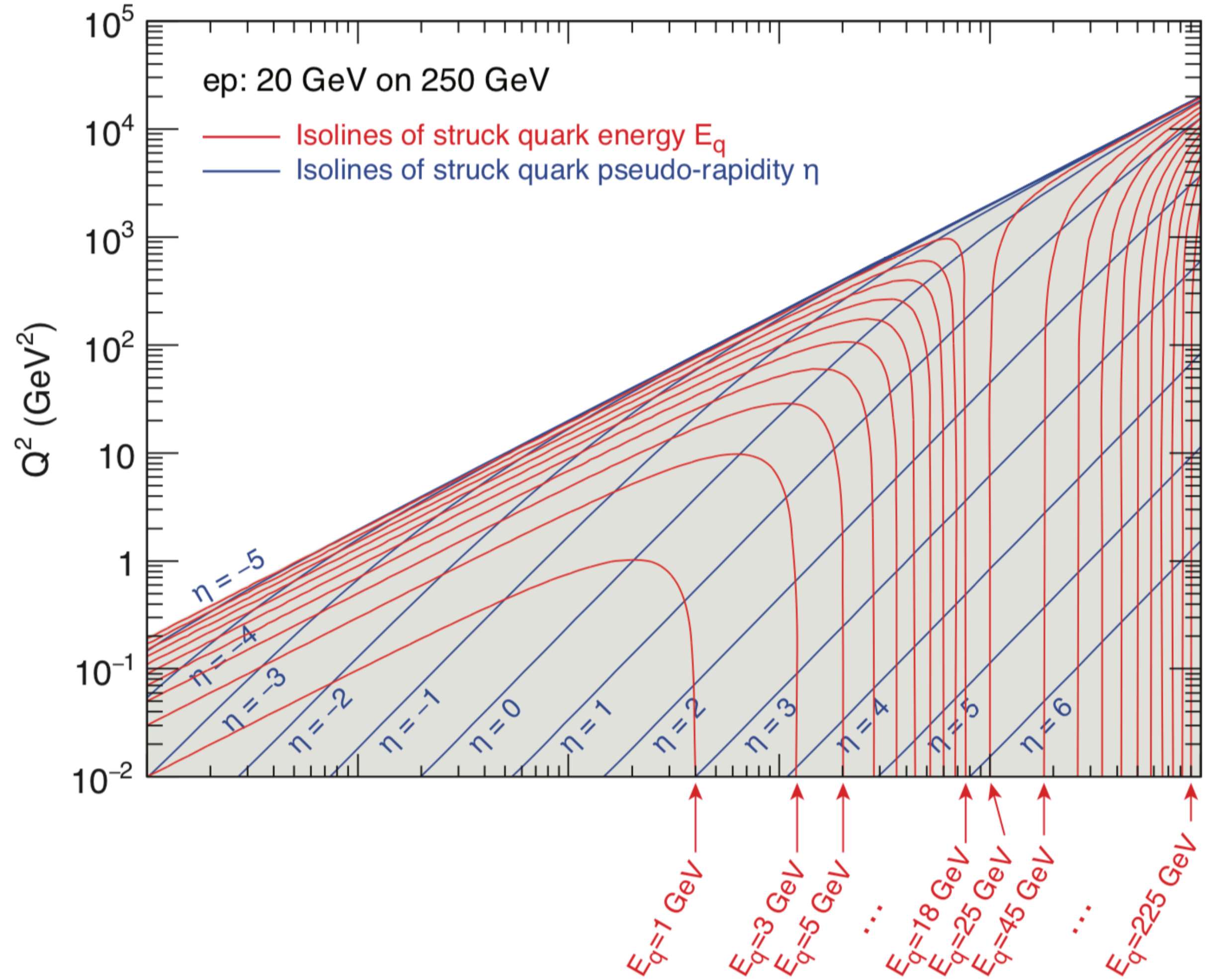


EIC detector Handbook, figure 2

Angles and pseudorapidities are defined with respect to the hadron beam-momentum, following the HERA conventions.

U.S.-based EIC - Kinematic considerations





There is a lot in these plots:

Large acceptance and good electron ID are musts,

Scattered electron angle is a good estimator of Q^2, except at high y,

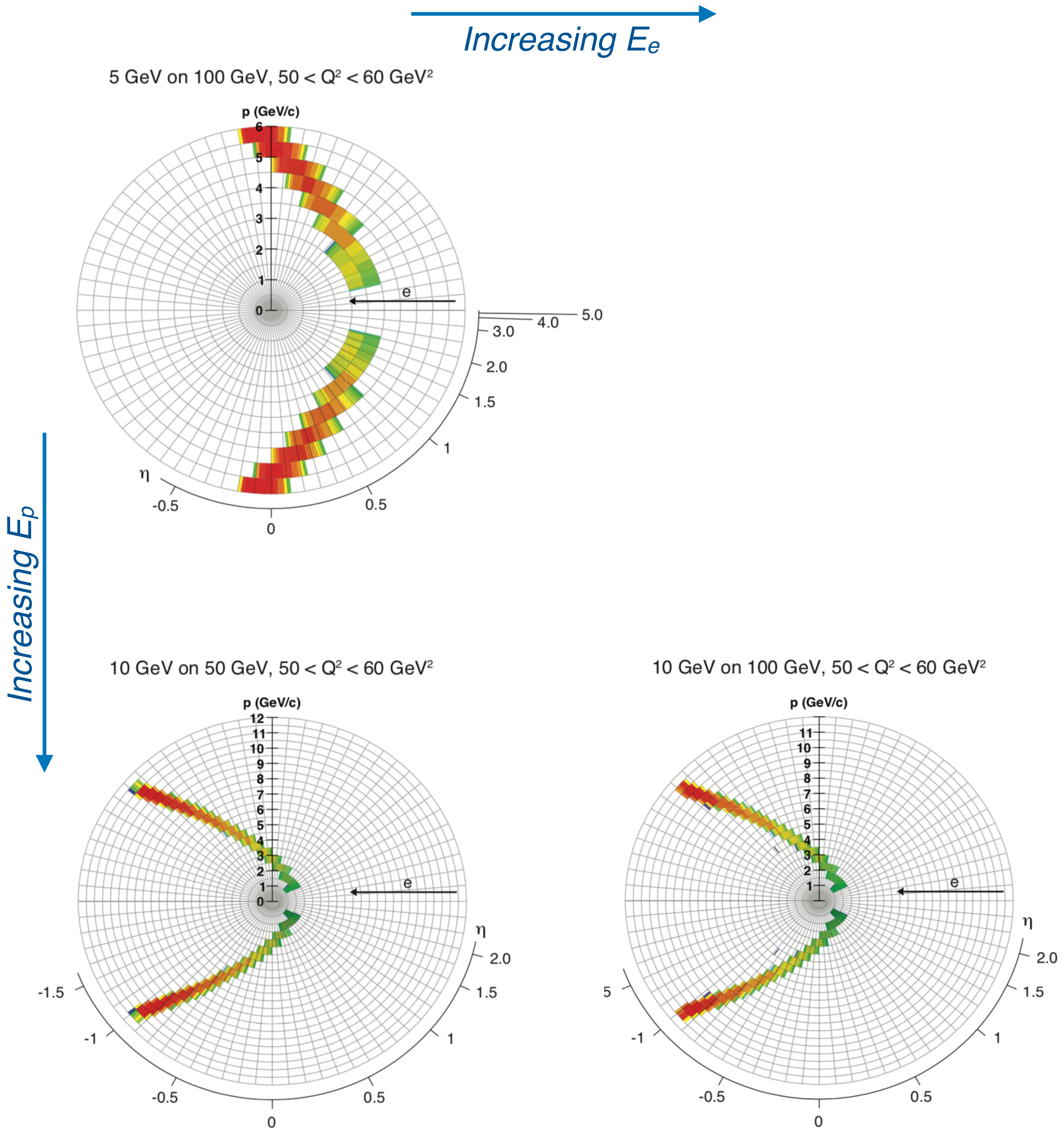
Scattered electron energy, combined with angle, is a good estimator of x, except at low y,

At low y, quark (-jet) energy is a good estimator of x in NC SIDIS,

Many combinations of electron and quark (-jet) can determine x and Q^2

Figures 3 and 4 from the EIC detector Handbook

U.S.-based EIC - Kinematic considerations


Increasing E_e

Increasing E_p

5 GeV on 100 GeV, $50 < Q^2 < 60$ GeV^2

10 GeV on 50 GeV, $50 < Q^2 < 60$ GeV^2

10 GeV on 100 GeV, $50 < Q^2 < 60$ GeV^2

There is a lot in these plots:

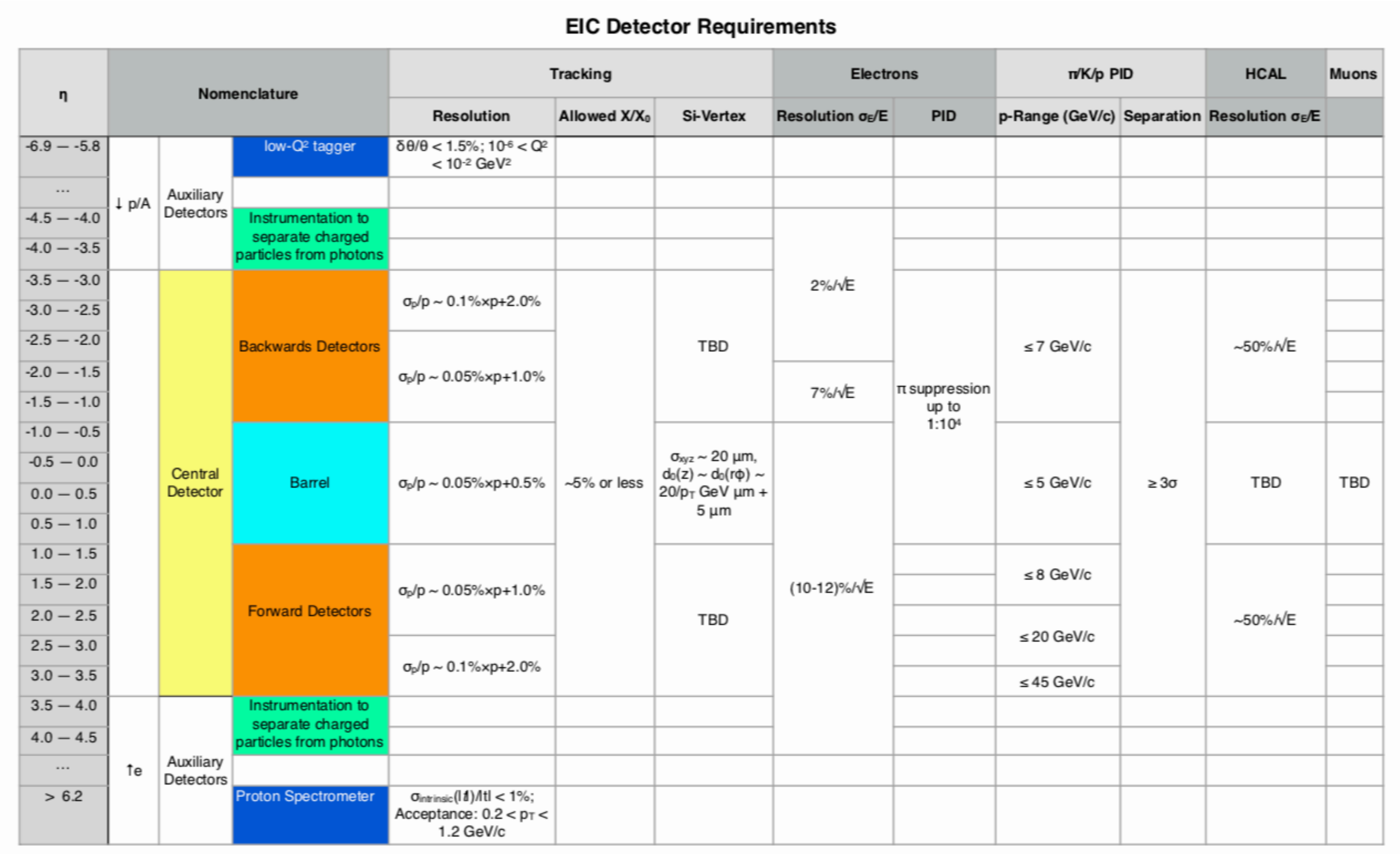
Increased in electron beam energy typically boosts the scattered electron more in the backward direction (HERA convention),

Increased hadron beam energy has almost no effect on the scattered electron,

The ability to vary $\sqrt{s} = 2\sqrt{E_e E_p}$ is essential to part of the physics program; how to do best do it can be different for different measurements/ experiments.

Adapted from the EIC detector Handbook, fig. 5.

U.S.-based EIC - Detector Requirements

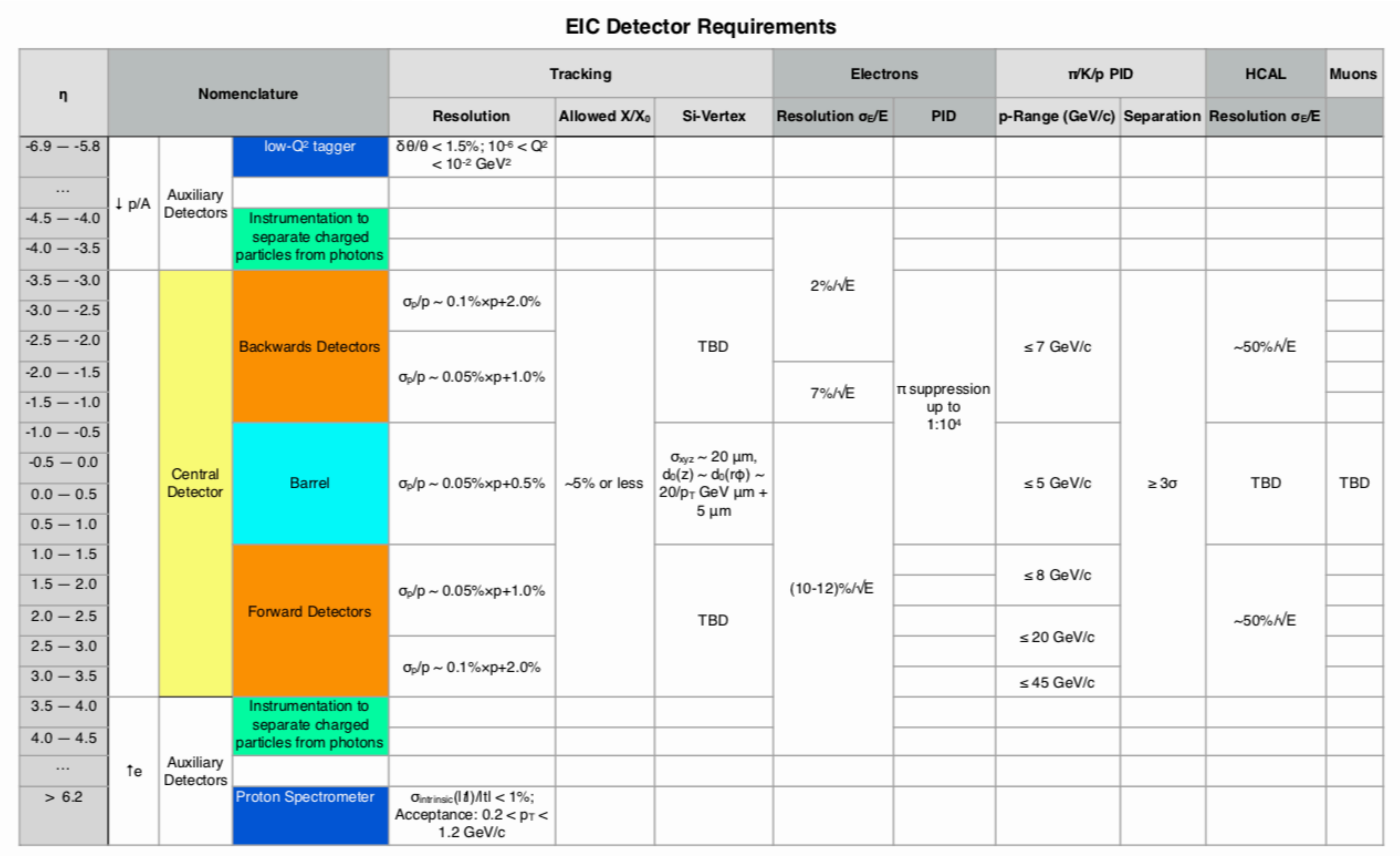


EIC Detector Requirements

η	Nomenclature			Tracking			Electrons		π/K/p PID		HCAL	Muons
				Resolution	Allowed X/X_0	Si-Vertex	Resolution σ_E/E	PID	p-Range (GeV/c)	Separation	Resolution σ_E/E	
-6.9 — -5.8	↓ p/A	Auxiliary Detectors	low-Q^2 tagger	$\delta\theta/\theta < 1.5\%$; $10^{-6} < Q^2 < 10^{-2}$ GeV^2								
…												
-4.5 — -4.0			Instrumentation to separate charged particles from photons				2%/√E					
-4.0 — -3.5												
-3.5 — -3.0		Central Detector	Backwards Detectors	$\sigma_p/p \sim 0.1\% \times p + 2.0\%$	~5% or less	TBD		π suppression up to 1:10^4	≤ 7 GeV/c	≥ 3σ	~50%/√E	
-3.0 — -2.5												
-2.5 — -2.0				$\sigma_p/p \sim 0.05\% \times p + 1.0\%$								
-2.0 — -1.5							7%/√E					
-1.5 — -1.0												
-1.0 — -0.5			Barrel	$\sigma_p/p \sim 0.05\% \times p + 0.5\%$		$\sigma_{xyz} \sim 20$ µm, $d_0(z) \sim d_0(r\phi) \sim 20/p_T$ GeV µm + 5 µm	(10-12)%/√E		≤ 5 GeV/c		TBD	TBD
-0.5 — 0.0												
0.0 — 0.5												
0.5 — 1.0												
1.0 — 1.5			Forward Detectors	$\sigma_p/p \sim 0.05\% \times p + 1.0\%$		TBD			≤ 8 GeV/c		~50%/√E	
1.5 — 2.0												
2.0 — 2.5									≤ 20 GeV/c			
2.5 — 3.0				$\sigma_p/p \sim 0.1\% \times p + 2.0\%$								
3.0 — 3.5									≤ 45 GeV/c			
3.5 — 4.0	↑e	Auxiliary Detectors	Instrumentation to separate charged particles from photons									
4.0 — 4.5												
…												
> 6.2			Proton Spectrometer	$\sigma_{intrinsic}(\lvert t\rvert)/\lvert t\rvert < 1\%$; Acceptance: $0.2 < p_T < 1.2$ GeV/c								

EIC detector Handbook, Table 2.

U.S.-based EIC - Detector Requirements



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…												
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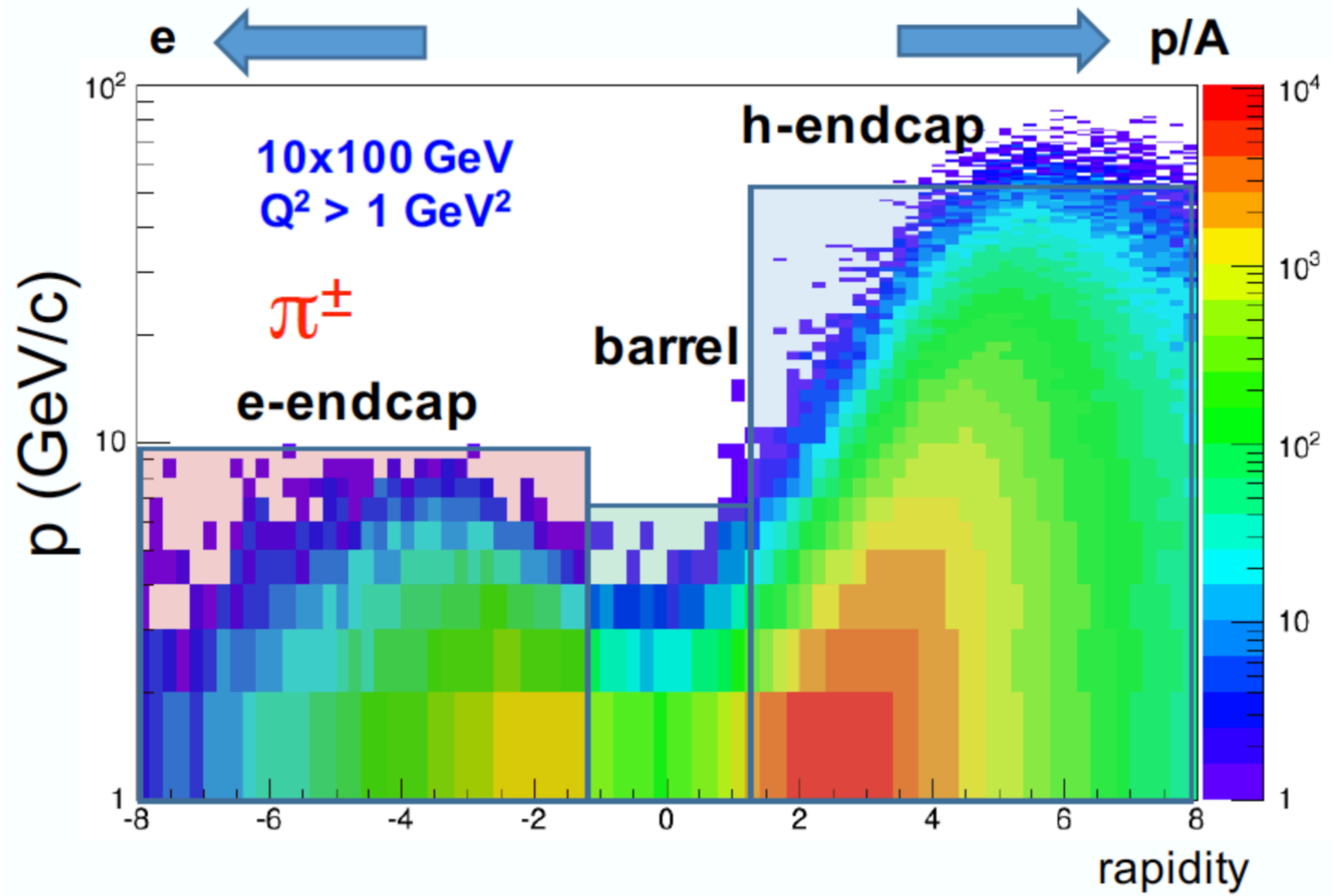
-3.0 — -2.5												
-2.5 — -2.0				$\sigma_p/p \sim 0.05\% \times p + 1.0\%$								
-2.0 — -1.5							7%/√E					
-1.5 — -1.0												
-1.0 — -0.5			Barrel	$\sigma_p/p \sim 0.05\% \times p + 0.5\%$		$\sigma_{xyz} \sim 20\ \mu m$, $d_0(z) \sim d_0(r\phi) \sim 20/p_T$ GeV μm + 5 μm	(10-12)%/√E		≤ 5 GeV/c		TBD	TBD
-0.5 — 0.0												
0.0 — 0.5												
0.5 — 1.0												
1.0 — 1.5			Forward Detectors	$\sigma_p/p \sim 0.05\% \times p + 1.0\%$		TBD			≤ 8 GeV/c		~50%/√E	
1.5 — 2.0												
2.0 — 2.5									≤ 20 GeV/c			
2.5 — 3.0				$\sigma_p/p \sim 0.1\% \times p + 2.0\%$								
3.0 — 3.5									≤ 45 GeV/c			
3.5 — 4.0	↑e	Auxiliary Detectors	Instrumentation to separate charged particles from photons									
4.0 — 4.5												
…												
> 6.2			Proton Spectrometer	$\sigma_{intrinsic}(\lvert t\rvert)/\lvert t\rvert < 1\%$; Acceptance: $0.2 < p_T < 1.2$ GeV/c								

Well, so much for a table…. PID is a key challenge.

EIC detector Handbook, Table 2.

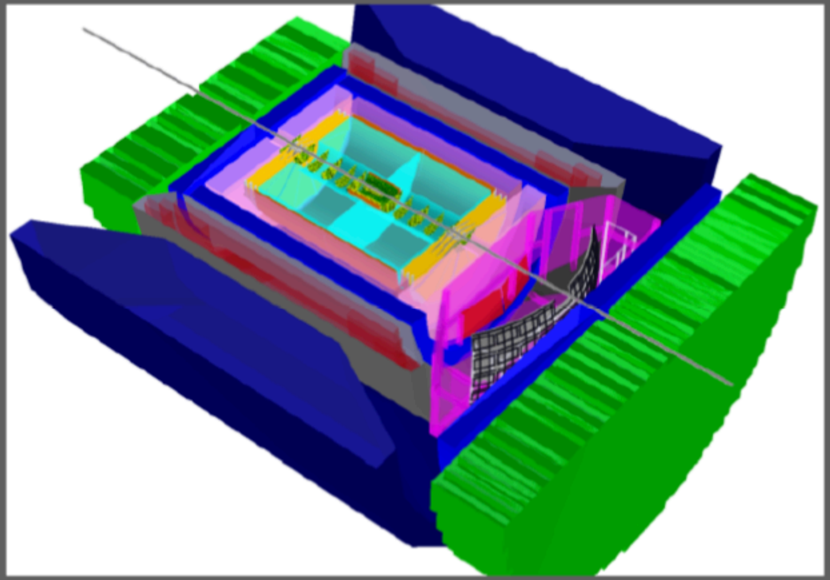
U.S.-based EIC - Detector Requirements



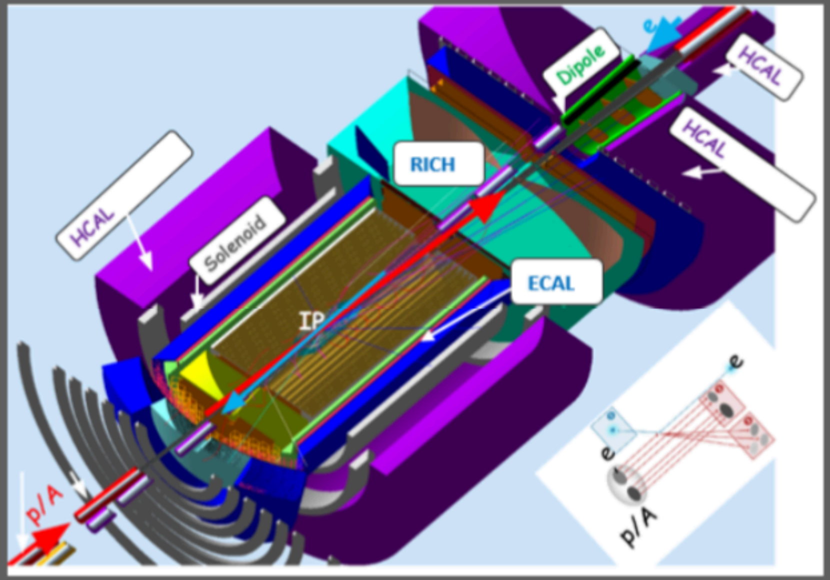
Well, so much for a table…. PID is a key challenge: need positive ID for 1—50 GeV/c

U.S.-based EIC - Current General Purpose Detector Concepts

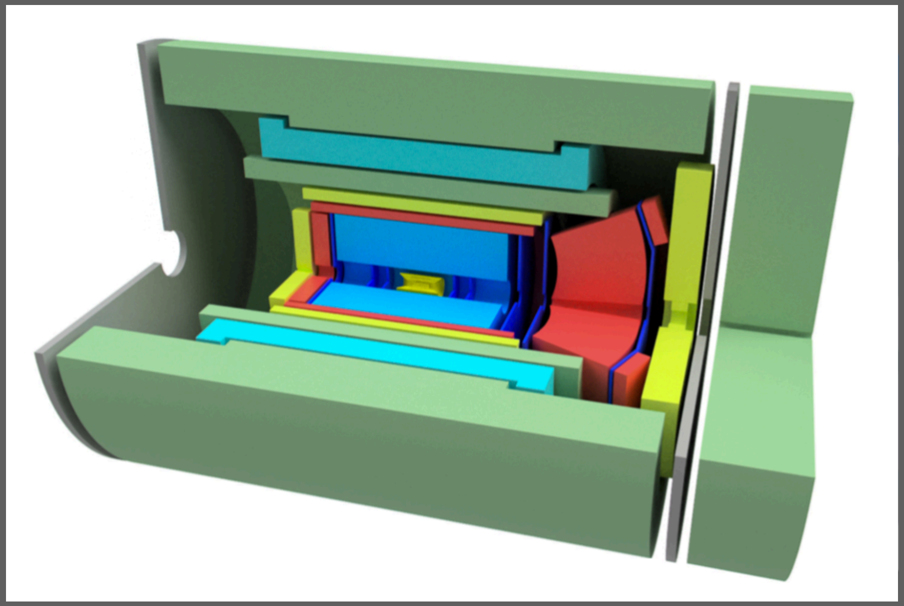
Brookhaven concept: BEAST



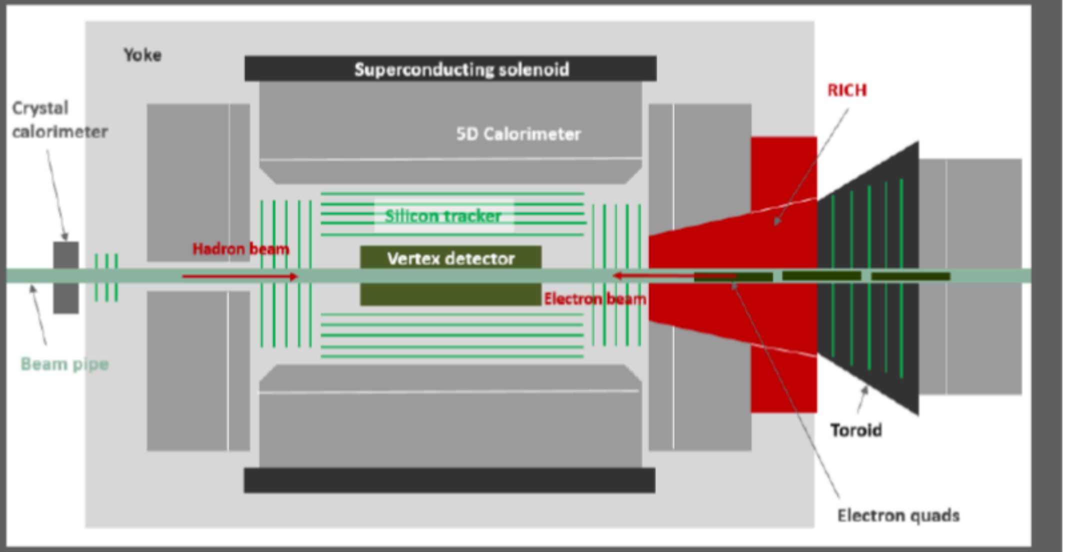
Jefferson lab concept: JLEIC



sPhenix → ePhenix



Argonne concept: TOPSiDE



Commonalities and differences….

Synergies with ALICE R&D, PANDA R&D, ILC R&D, COMPASS, STAR, sPHENIX…

Further development relies, crucially, on generic EIC Detector R&D program.

EIC - Generic Detector R&D Program

In January 2011 Brookhaven National Laboratory, in association with Jefferson Lab and the DOE Office of Nuclear Physics, announced a generic detector R&D program to address the scientific requirements for measurements at a future Electron Ion Collider (EIC). The primary goals of this program are to develop detector concepts and technologies that have particular importance for experiments in an EIC environment, and to help ensure that the techniques and resources for implementing these technologies are well established within the EIC user community.

This program is supported through R&D funds provided to BNL by the DOE Office of Nuclear Physics. It is not intended to be specific to any proposed EIC site, and is open to all segments of the EIC community. Proposals should be aimed at optimizing detection capability to enhance the scientific reach of polarized electron-proton and electron-ion collisions up to center-of-mass energies of 50-200 GeV and e-p equivalent luminosities up to a few times 10^{34} $cm^{-2}s^{-1}$*. Funded proposals will be selected on the basis of peer review by a standing EIC Detector Advisory Committee consisting of internationally recognized experts in detector technology and collider physics. This committee meets approximately twice per year, to hear and evaluate new proposals, and to monitor progress of ongoing projects. The program will be administered by the BNL Physics Department.*
This program is funded at an annual level of $1.0M - $1.5M, subject to availability of funds from DOE NP.

https://wiki.bnl.gov/conferences/index.php/EIC_R%25D

EIC - Generic Detector R&D Program

Current and ~recently completed projects:

*eRD1: Calorimeter Development - see also **V. Berdnikov**, Tuesday afternoon*

eRD2: Magnetic-Field Cloaking Device

*eRD6: The EIC Tracking and PID Consortium - see also **F. Tessarotto**, Thursday morning*

eRD12: Polarimeter, Luminosity Monitor and Low Q^2-Tagger for Electron Beam

eRD14: An Integrated Program for Particle Identification for an EIC Detector

eRD15: R&D for a Compton Electron Detector

eRD16: Forward Silicon Tracking

eRD17: BEAGLE: A tool to Refine Detector Requirements for eA Collisions

*eRD18: Precision Central Silicon Tracking and Vertexing for the EIC - c.f. **H.Wennlöf**, Thu m.*

*eRD20: Developing Simulation and Analysis Tools for the EIC - c.f. **software tutorial** Tue a.*

eRD21: EIC Background Studies and Impact on the IR and Detector design

eRD22: GEM based Transition radiation detector and tracker

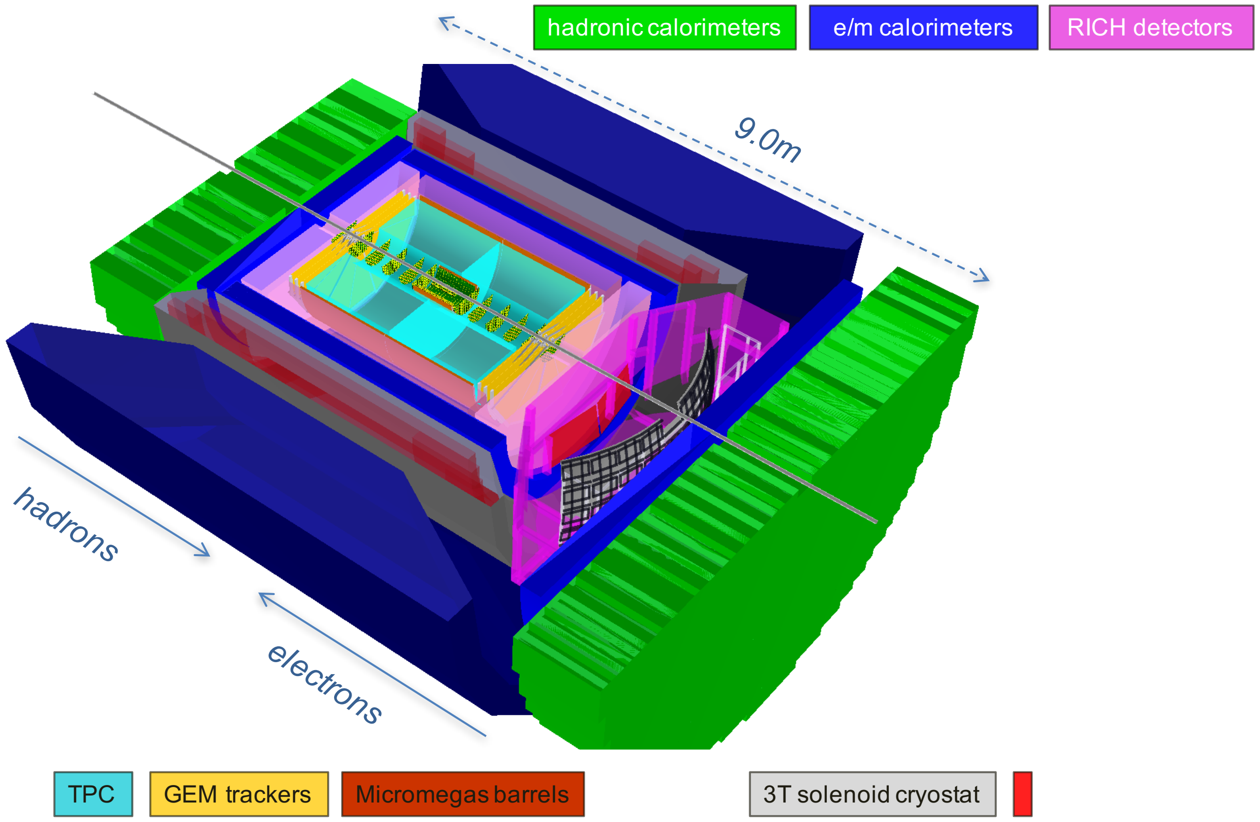
*eRD23: Streaming readout for EIC detectors - c.f. **J. Bernauer**, Thursday Morning*

New: Silicon Detectors with high Position and Timing Resolution as Roman Pots at EIC

Generic detector technologies that could be applied both at eRHIC and at JLEIC.

See e.g. Y. Ilieva at the 2018 DIS conference for a summary.

Current General Purpose Detector Concepts - BeAST

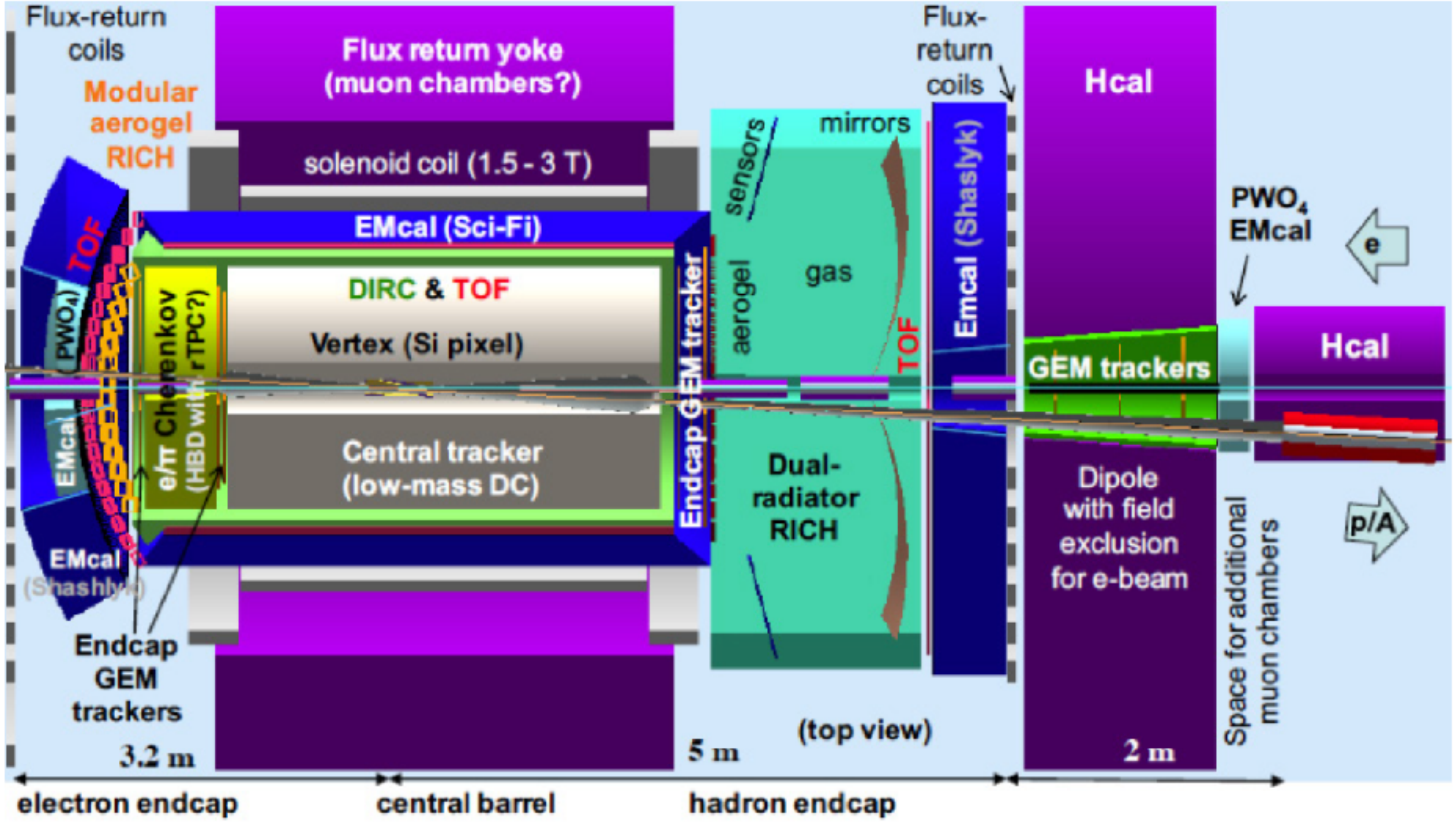


Compact design

3T solenoidal magnetic field,
Minimal effect(s) on electron beam,
No material in inner acceptance,
Sufficient for forward tracking,
Uniform in inner (TPC) region,
High-ish momentum threshold,
Field needs to be shaped for gaseous RICH,
Most photosensors don't like fields, 3T being a lot of field,

Central tracking with a compact TPC, possibly complemented with micromegas layers,
Forward tracking with Si-disks and large-area GEM disks,
ALICE-inspired inner vertex tracker,
E.M. calorimetry based on newly developed W-powder + scintillating fiber calorimeter, complemented with high-resolution $PbWO_4$ crystals at very backward angles,
Hadronic calorimetry in the forward region, modular lead-scintillator design,
PID: (dE/dx w. TPC), barrel DIRC (detection of internally reflected light), dual RICH in forward hadron region,
Not shown e.g. very forward Roman Pots,

Current General Purpose Detector Concepts - JLEIC



Emphasis on forward detectors, additional bending field,

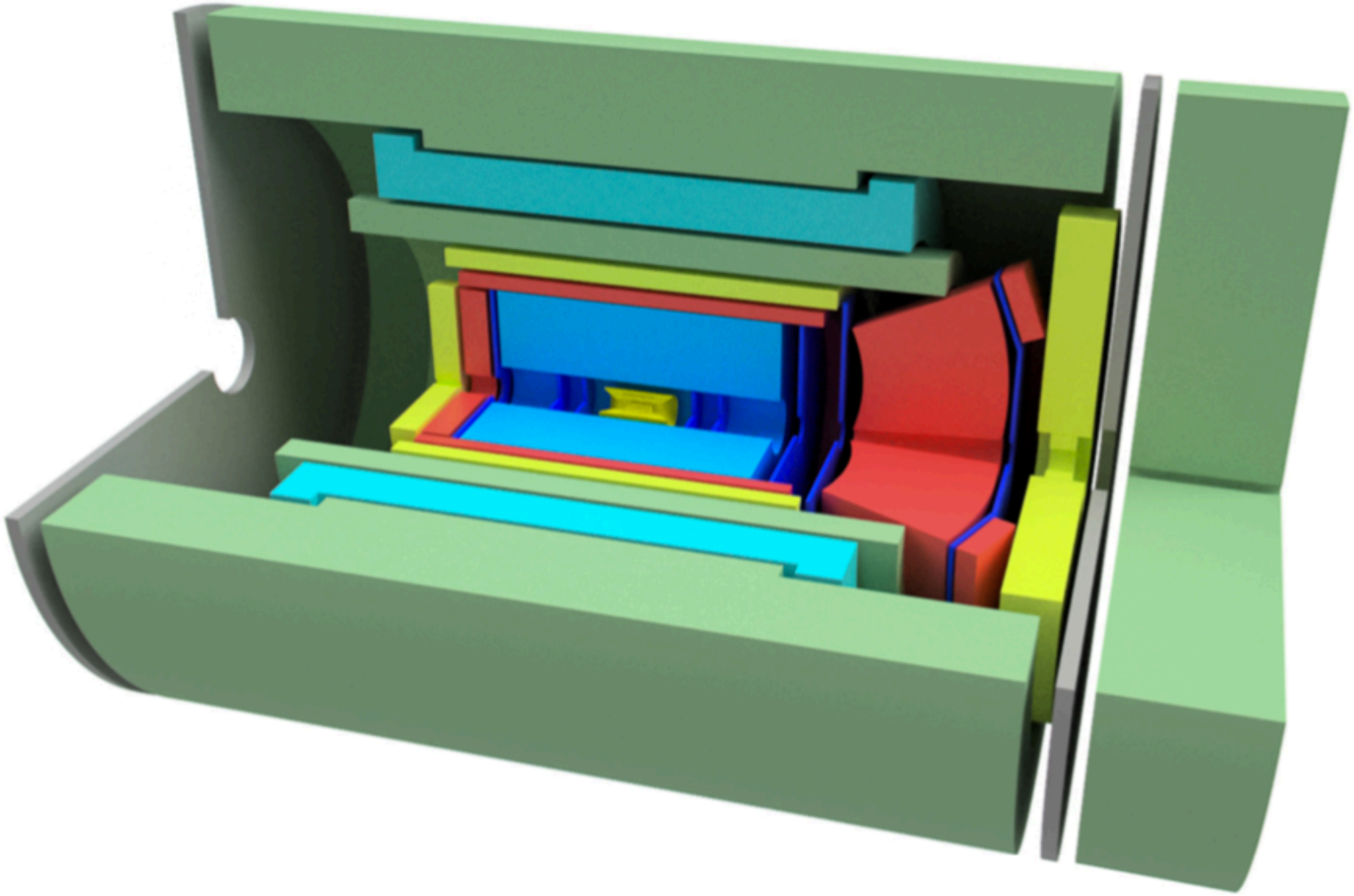
Relies on magnetic cloaking, de monstrated to ~0.5T

Can be carried over to other concepts if/as needed.

BeAST and JLEIC detectors are conceptually similar,

- *Solenoidal magnetic field, 1.5—3T*
- *Similar mid-rapidity (vertex) trackers, PID and E.M. calorimetry*
- *Dual RICH and modular RICH in forward and backward regions, respectively,*
- *Possibly a GEM TRD behind the forward dual RICH,*
- *Hadronic calorimetry only in the forward region,*

Current General Purpose Detector Concepts - ePHENIX



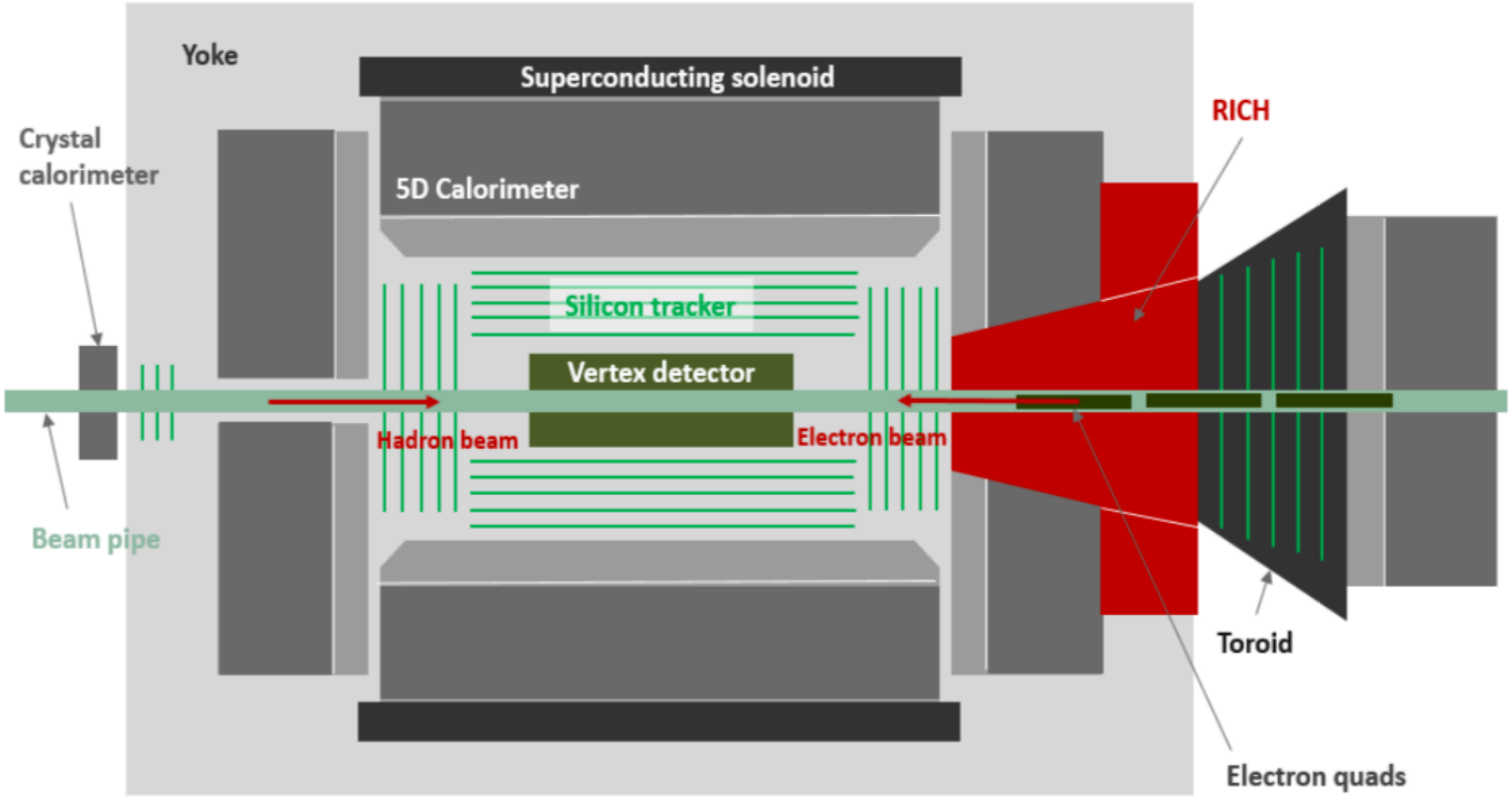
Again conceptually similar,

Re-use of magnet and possibly several other sPHENIX subsystems,

Not shown Roman Pots, ZDCs, etc.

Phenix -> sPhenix -> ePHENIX
Re-uses the sPHENIX/BaBar solenoid —1.5T
Compact TPC, complemented with barrel-DIRC, mRICH or dual-RICH,
Full barrel hadronic calorimeter in addition to a forward hadronic calorimeter,
E.M. calorimeters a combination of Sci similar to BeAST and JLEIC
sPHENIX-note sPH-eQCD-2018-001

Current General Purpose Detector Concepts - TopSide



See J. Repond et al, at 2019 DIS conference

3T solenoidal magnetic field,

Silicon pixel vertex tracker, complemented with a strip tracker,

Imaging electromagnetic and hadronic calorimeters, c.f. CALICE

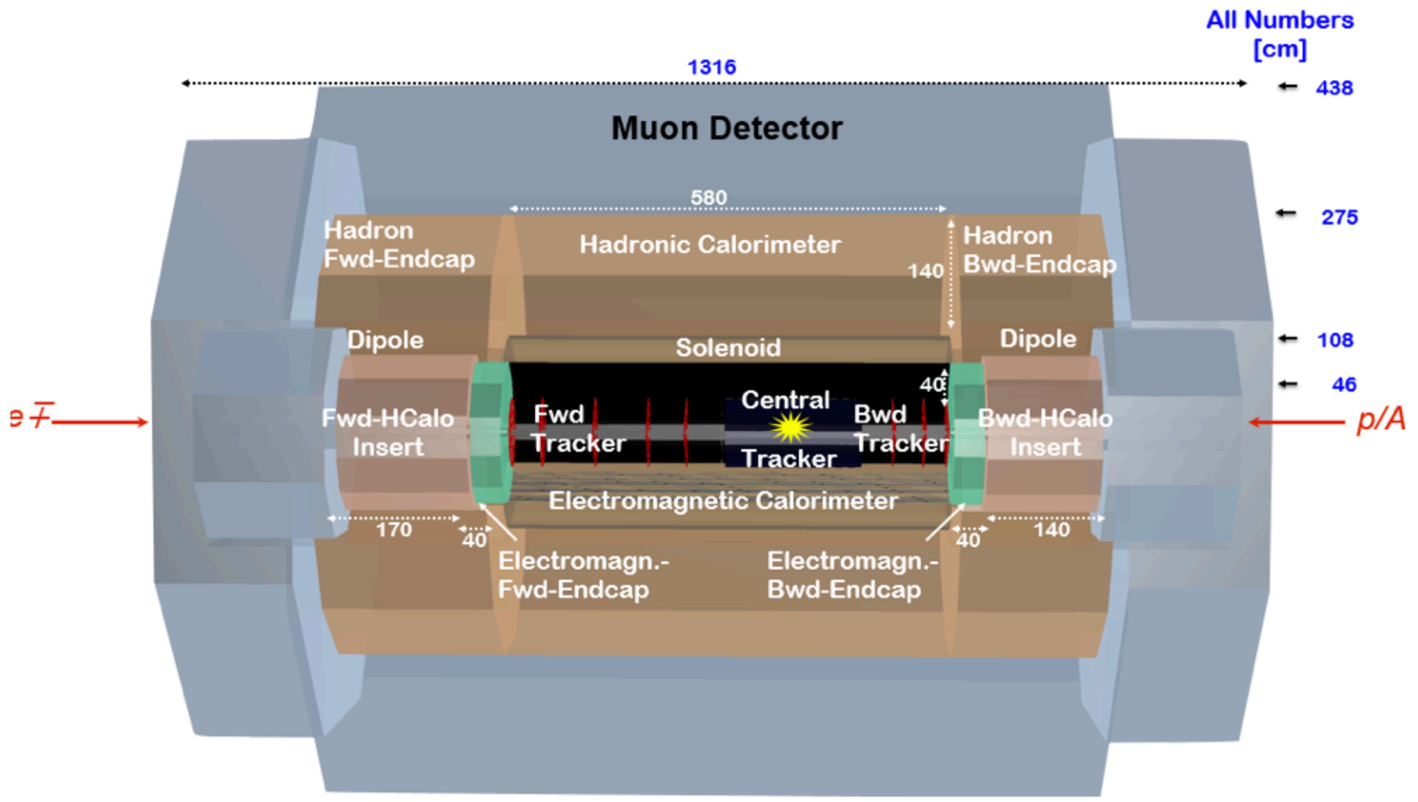
F. Sefkow et al. arXiv:1507.05893

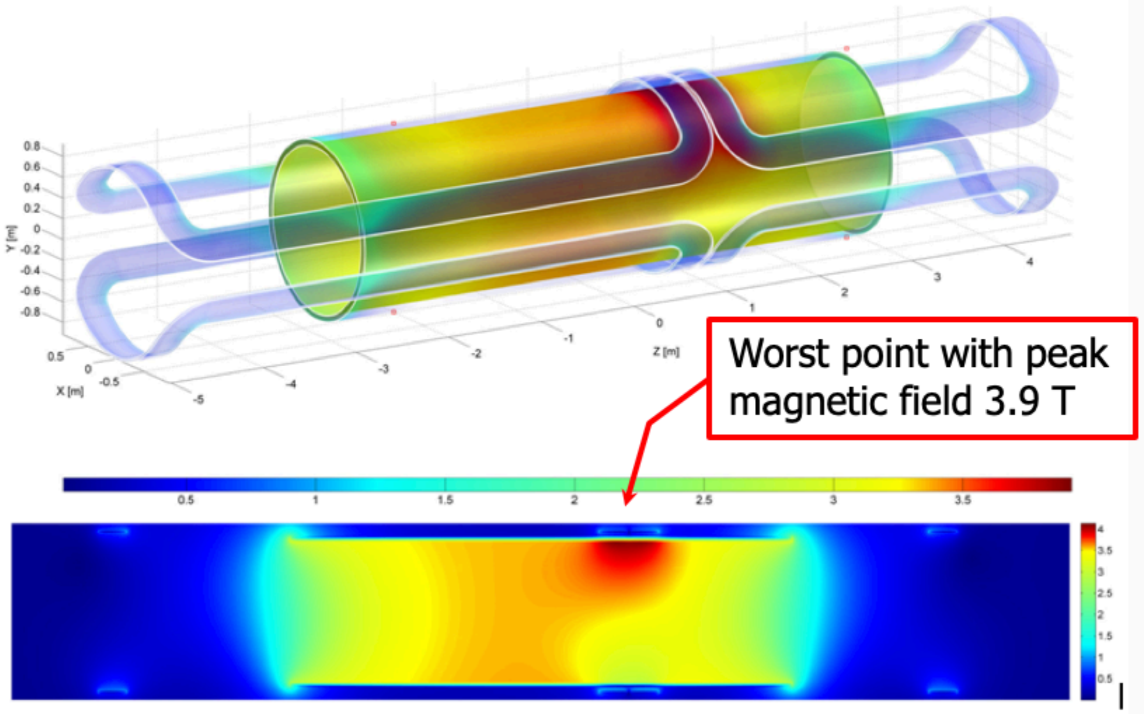
Forward gaseous RICH and a forward toroid, instrumented

PID relies on ultra-fast silicon sensors, < ~10ps <u>for the system</u> (start and stop)

Intermezzo - LHeC

LHeC Detector Magnet layout, CDR baseline



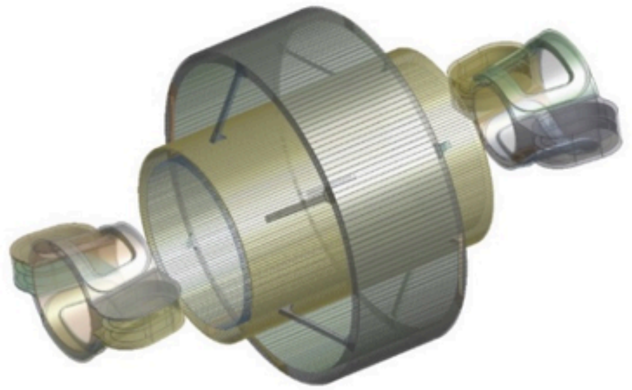


Worst point with peak magnetic field 3.9 T

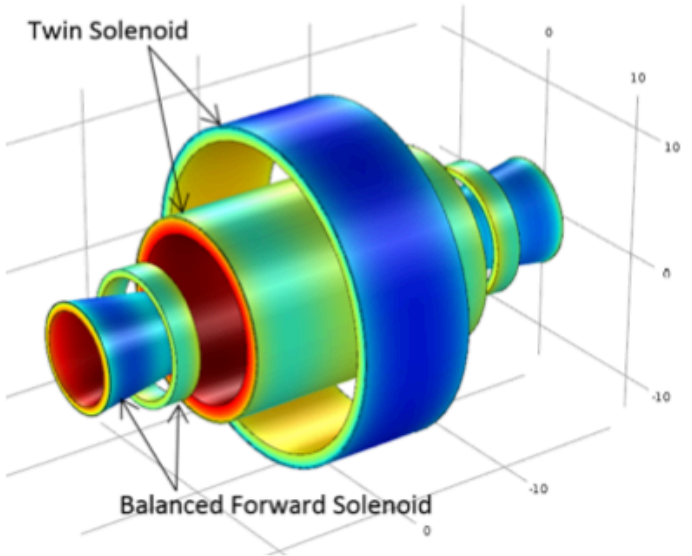
- Design concept: minimum cost, R&D and risk, relies on present technology for detectors magnets
- **3.5 T Solenoid & 2 Dipoles** in same cryostat around EMC, Muon tagging chambers in outer layer
- **Solenoid and dipoles have a common support cylinder in a single cryostat**; free bore of 1.8 m; extending along the detector with a length of 10 m.

H. ten Kate, for working group 8, March 2018 EP R&D workshop

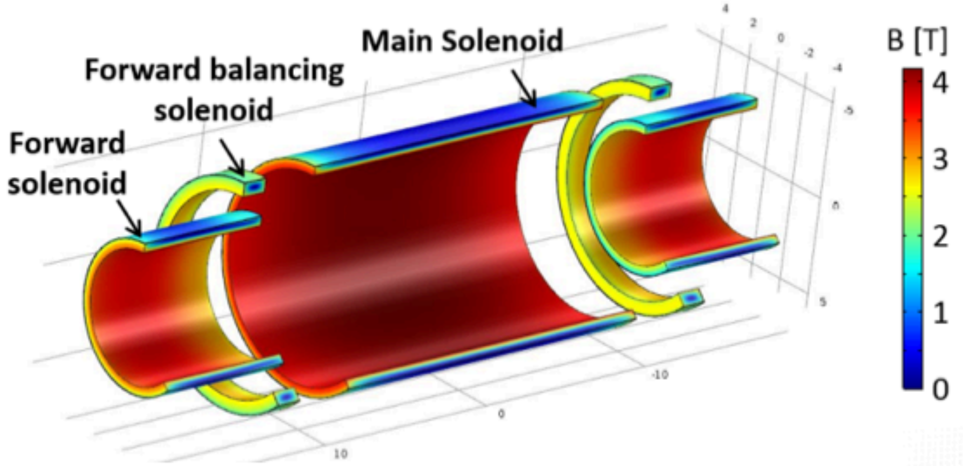
Intermezzo - FCC



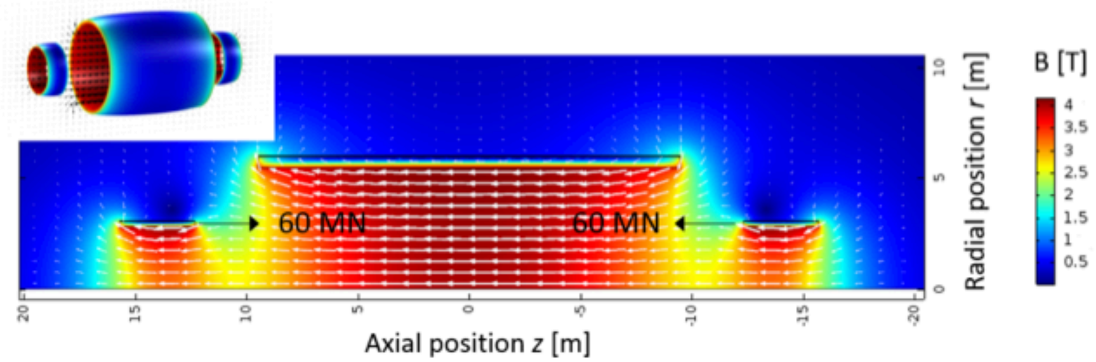
6T/12m bore Twin Solenoid + Balanced Forward Dipoles



Twin Solenoid + Balanced Forward Solenoids



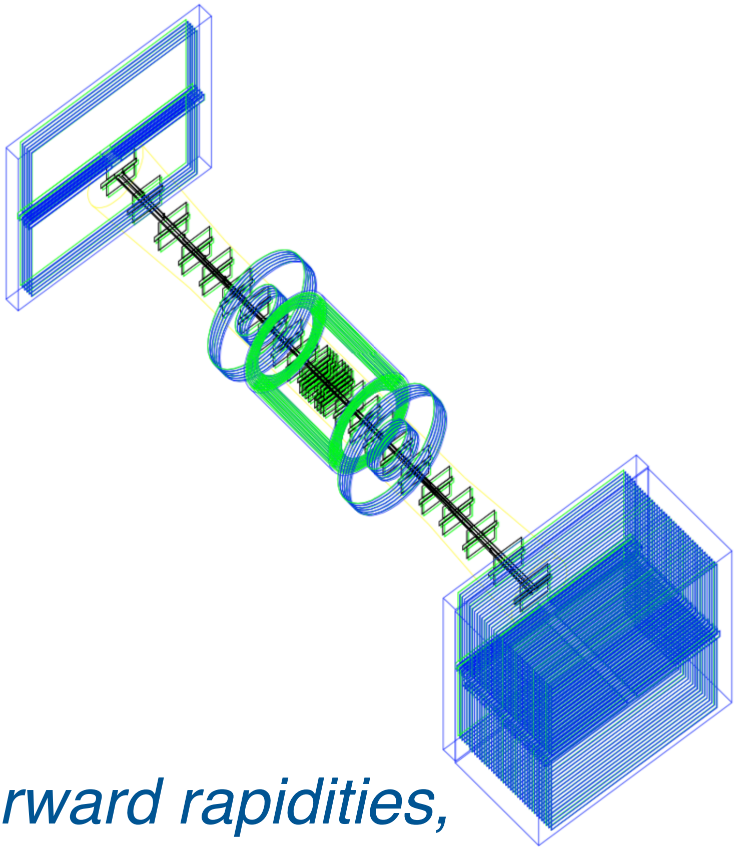
Solenoid + Balanced Forward Solenoids



4T/10m bore Solenoid + Forward Solenoids

H. ten Kate, for working group 8, March 2018 EP R&D workshop

Closing Comments



EIC relies on a new generation of experiment, in addition to accelerator and theory.

All current concepts are general-purpose concepts,

Are we missing one or more dedicated-purpose concepts?
c.f. A.Caldwell et al., arXiv:0407053

All general purpose concepts rely on a solenoidal field;
this imposes conflicting demands at central and forward rapidities,

Most forward fields appear, to me, “add-ons” rather than designed-in upfront,

Change of field will have wide-ranging implications and could take considerable time,

More space for central-rapidity PID would seem welcome; a high-resolution central tracker may be a worthwhile pursuit (irrespective of technology)

We appear to not yet to be giving due consideration to cooling, integration, mechanical support, despite our acceptance and X_0 needs, as well as calibration

Muons?   Target fragmentation region?

This is/was not a summary of ongoing R&D effort, nor is/was it intended to be,

It was intended to provide some pointers and induce some discussion;

Thank you — I will take notes now…