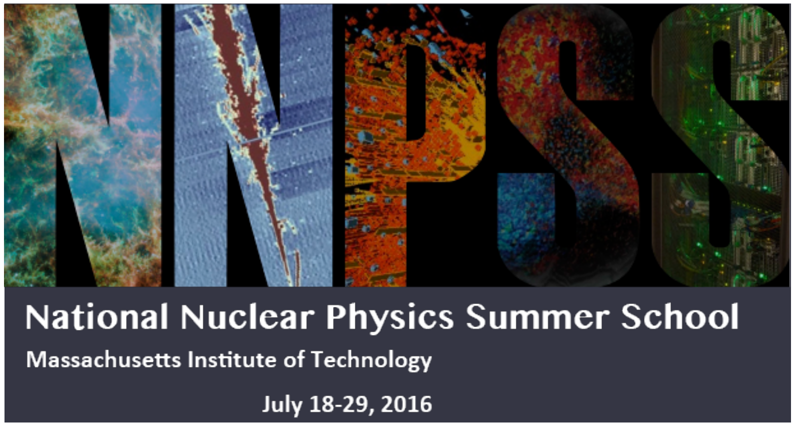


The Electron Ion Collider (EIC)

Abhay Deshpande

Lecture 4:
What else can the EIC address?
How does one design a detector for the EIC?

EIC: how? When?

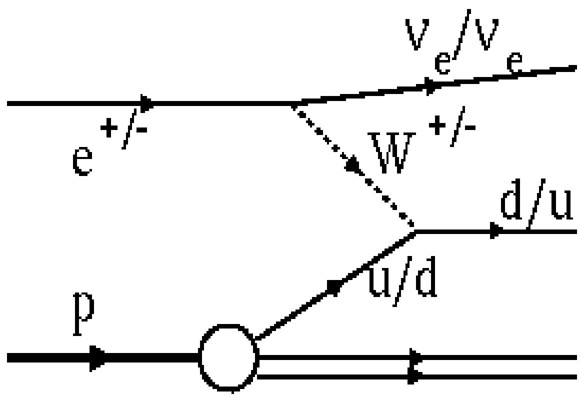
Stony Brook University

QCD Physics at the EIC:

- Pushes the luminosity requirements ~ few x 10^{34} $cm^{-2}s^{-1}$
  - Recall that although lower in luminosity than fixed target experiments, the collider is at (high) 100-140 GeV in CM Energy
- Push the polarimetry and beam quality requirements to the extreme:
  - (dPol/Pol) ~ 1%
  - Ultra low beam divergence for DVCS/Diffraction…

Why not consider using this machine for precision EW & BSM Physics?

Weak probes of nucleon helicity



$$\frac{d^2\sigma}{dx\,dQ^2} \sim \left\{a\left[F_1 - \lambda b F_3\right] + \delta\left[a g_5 - \lambda^2 b g_1\right]\right\}\frac{1}{(Q^2+M_W^2)^2}$$

where

$a = 2(y^2 - 2y + 2)$; $b = y(2-y)$; $\lambda = \pm 1$ for $e^{\pm}$

$\delta = \pm 1$ for $\uparrow\downarrow$ and $\uparrow\uparrow$ spin orientations

Experimental signature is a large asymmetry (due to missing neutrino)

$$A_{cc}^{W^+} = \frac{-2bg_1 + ag_5}{aF_1 - bF_3} \qquad A_{cc}^{W^-} = \frac{+2bg_1 + ag_5}{aF_1 + bF_3}$$

HERA used this to probe xF_3, ➔ combination of quark, anti-quark Distributions, using electron and positron beams

$$g_5^{W^-} = \Delta u + \Delta c - \Delta\bar{d} - \Delta\bar{s}$$
$$g_5^{W^+} = \Delta d + \Delta s - \Delta\bar{u} - \Delta\bar{c}$$

EIC's Polarized beam ➔ $g_5^{W+/-}$

First studied: J. Contreras & A. De Roeck 2002

A more recent study….

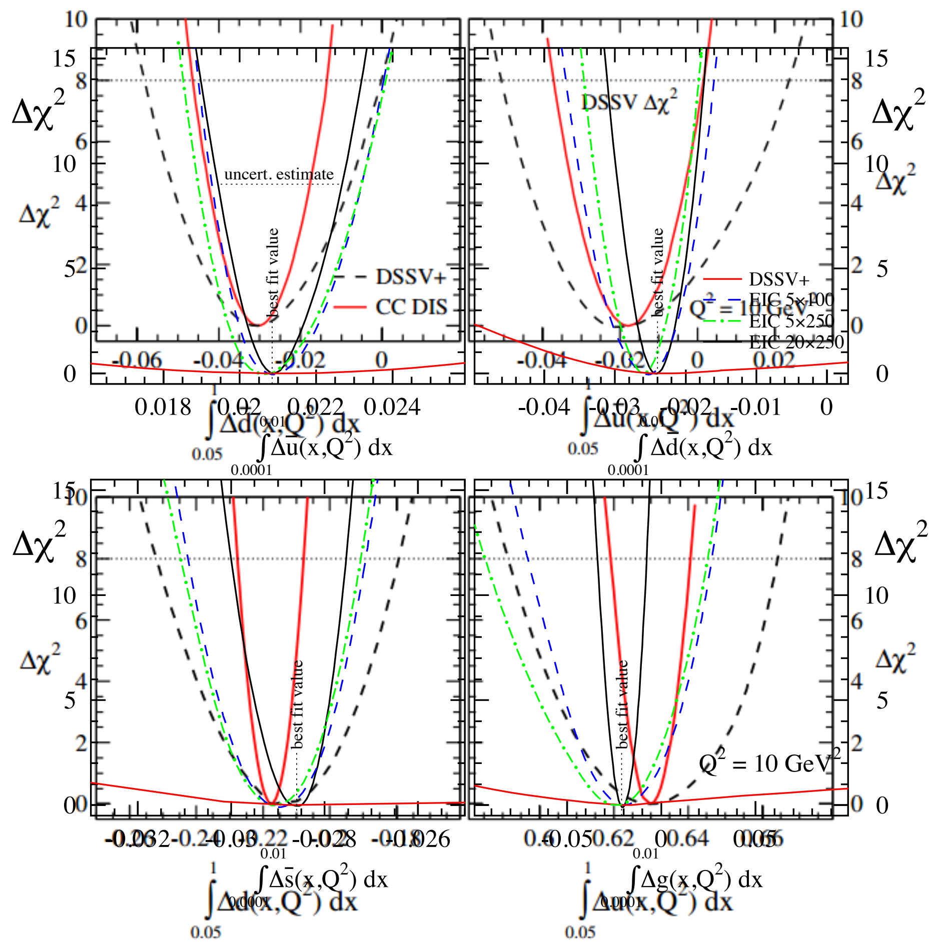
E. Aschanauer et al. PRD 88 114025 (2013)

$$g_1^{W^-,p}(x) = \Delta u(x) + \Delta\bar{d}(x) + \Delta c(x) + \Delta\bar{s}(x),$$

$$g_5^{W^-,p}(x) = -\Delta u(x) + \Delta\bar{d}(x) - \Delta c(x) + \Delta\bar{s}(x)$$

$$g_1^{W^+,p}(x) = \Delta\bar{u}(x) + \Delta d(x) + \Delta\bar{c}(x) + \Delta s(x),$$

$$g_5^{W^+,p}(x) = \Delta\bar{u}(x) - \Delta d(x) + \Delta\bar{c}(x) - \Delta s(x)$$

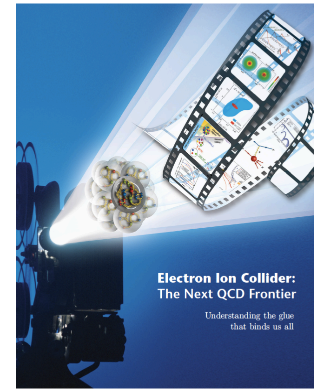


A full unfolding of Q and Qbars will require polarized electron and positron beams at high luminosity.

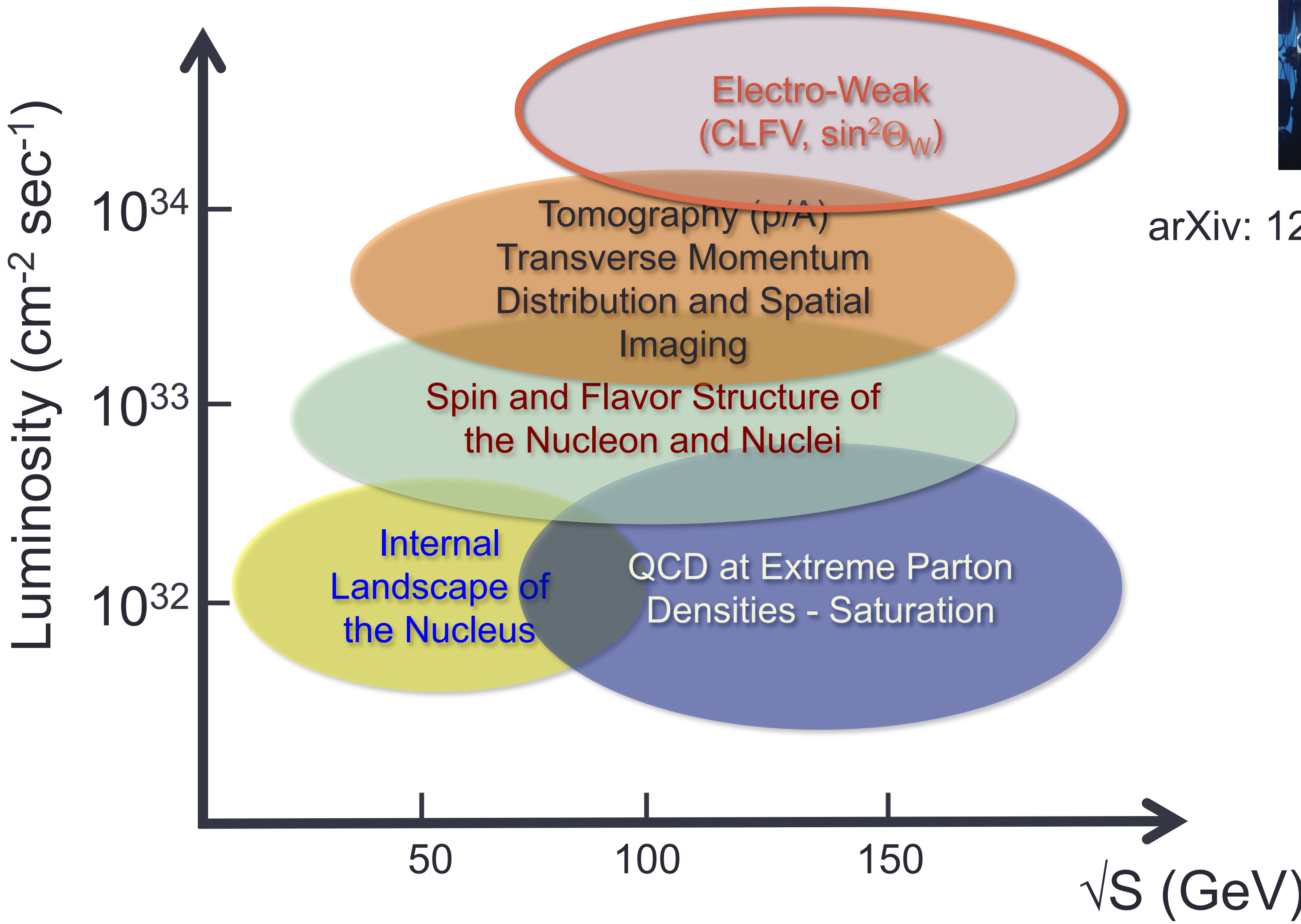
High luminosity positron beams is a challenge

EIC provides independent weak probes of the nucleon spin constitution, Including separation between quarks and anti-quarks

Physics vs. Luminosity & Energy



arXiv: 1212.1701.v3



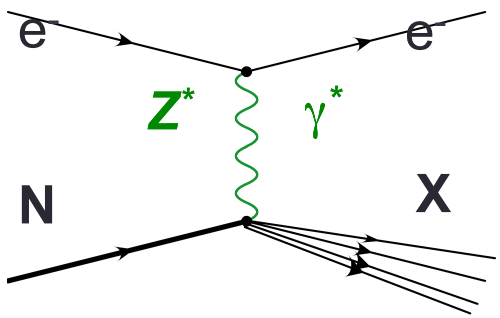
Electroweak & beyond….(?)

BNL LDRD: Deshpande, Marciano, Kumar & Vogelsang

High energy collisions of polarized electrons and protons and nuclei afford a unique opportunity to study

- Electro-weak deep inelastic scattering
  - Electroweak structure functions (including spin)
  - Significant contributions from W and Z bosons which have different couplings with *quarks and anti-quarks*
- Parity violating DIS: a probe of beyond TeV scale physics
  - Measurements at higher Q^2 than the PV DIS 12 GeV at Jlab
  - Precision measurement of $\text{Sin}^2\Theta_W$
- New window for physics beyond SM through LFV search
  M. Gonderinger & M. Ramsey-Musolf, JHEP 1011 (045) (2010); arXive: 1006.5063 [hep-ph] $e^- + p \rightarrow \tau^- + X$

A_{PV} in Deep Inelastic Scattering



A_{PV} in e-N DIS:

$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y)b(x)\right]$$

$$a(x) = \frac{\sum_i C_{1i} Q_i f_i(x)}{\sum_i Q_i^2 f_i(x)} \qquad b(x) = \frac{\sum_i C_{2i} Q_i f_i(x)}{\sum_i Q_i^2 f_i(x)}$$

For a ^{2}H target, assuming charge symmetry, structure functions largely cancel in the ratio

$$a(x) = \frac{3}{10}\left[(2C_{1u} - C_{1d})\right] + \cdots$$

$$b(x) = \frac{3}{10}\left[(2C_{2u} - C_{2d})\frac{u_v(x) + d_v(x)}{u(x) + d(x)}\right] + \cdots$$

$$C_{1u} = (1 - 8\sin^2\theta_W/3)/2 \sim 0.20 \text{ Hadronic}$$
$$C_{1d} = (1 - 4\sin^2\theta_W/3)/2 \sim -0.32 \text{ Hadronic}$$
$$C_{2u} = (1 - 4\sin^2\theta_W)/2 \sim 0.04 \text{ Leptonc}$$
$$C_{2d} = -(1 - 4\sin^2\theta_W)/2 \sim -0.04 \text{ Leptonc}$$

C_{2q} sensitive to RC & New Physics

Measure A_{PV} (C_{2q}) to better than 0.5% (1-2%)

Prospects: near and far future….

Jefferson Laboratory:

- 6 GeV DIS eD→ eX proceeding
- 12 GeV SoLID experiment at JLab12 in future (2020-2025)
  - Measure C_{2q}'s New Physics, Charge Symmetry violation
  - Effective luminosity (fixed target) 10^{38} $cm^{-2}sec^{-1}$

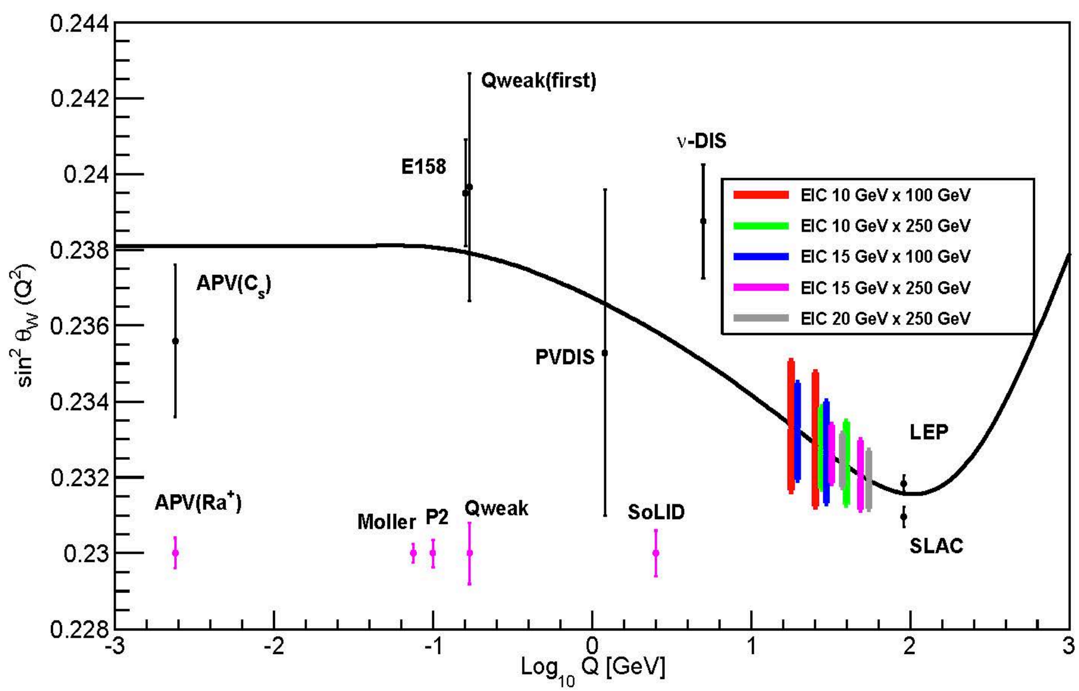
Future ep, eD → Electron Ion Collider:

- Asymmetry: FOM ~ A^2N; **$A \sim Q^2$ & $N \sim 1/Q^2$,** Acceptance
- **Collider: higher Q^2 but luminosity(?)**
- **Need accumulate > 100 fb^{-1} (possible with 10^{34} $cm^{-2}sec^{-1}$)**

Y. Li & W. Marciano studied this at Sqrt(s) = 140 GeV (ep or eD)
Recent: Y. Zhao, A.D. & K. Kumar revisited this….

$Sin^2\Theta_W$ with the EIC: Physics Beyond SM

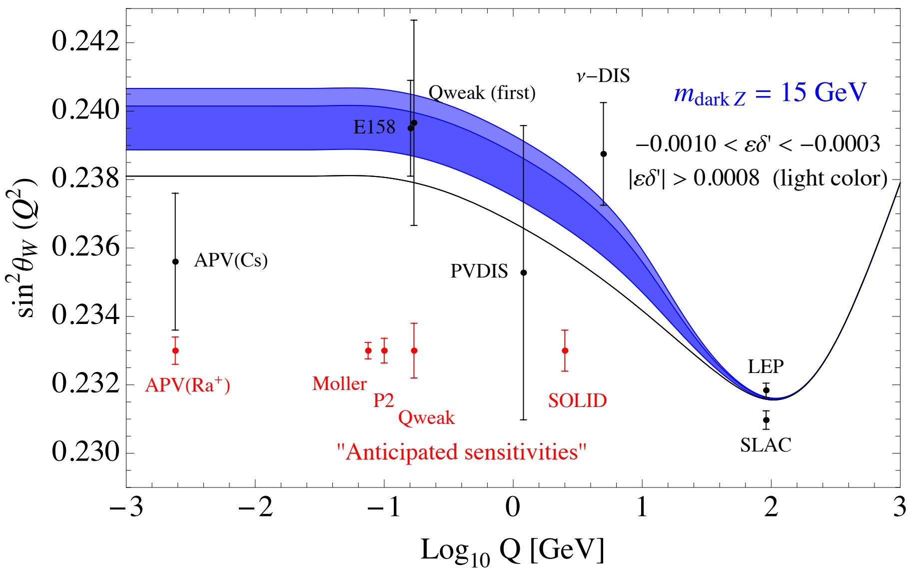
- Precision parity violating asymmetry measurements e/D or e/p
- Deviation from the "curve" may be hints of BSM scenarios including: Lepto-Quarks, RPV SUSY extensions, E_6/Z' based extensions of the SM

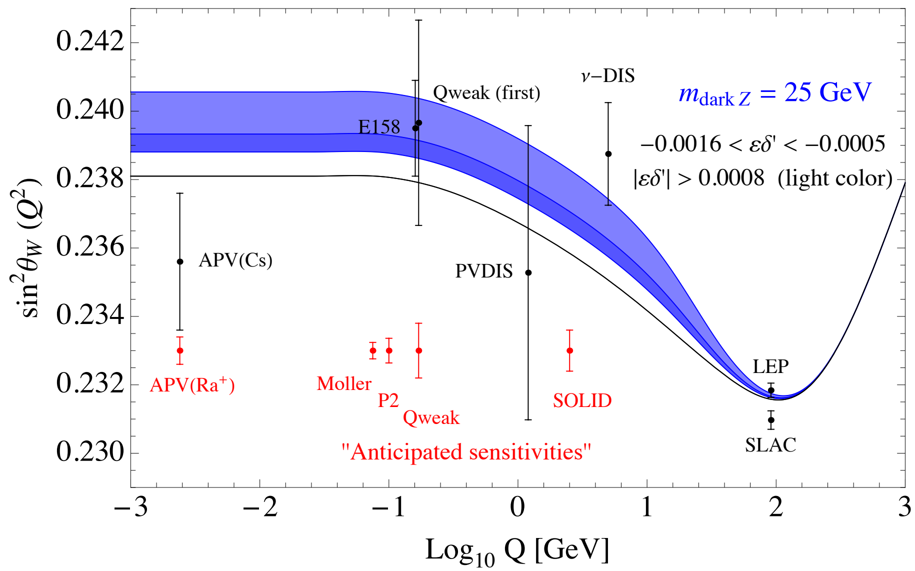


Black: measurements

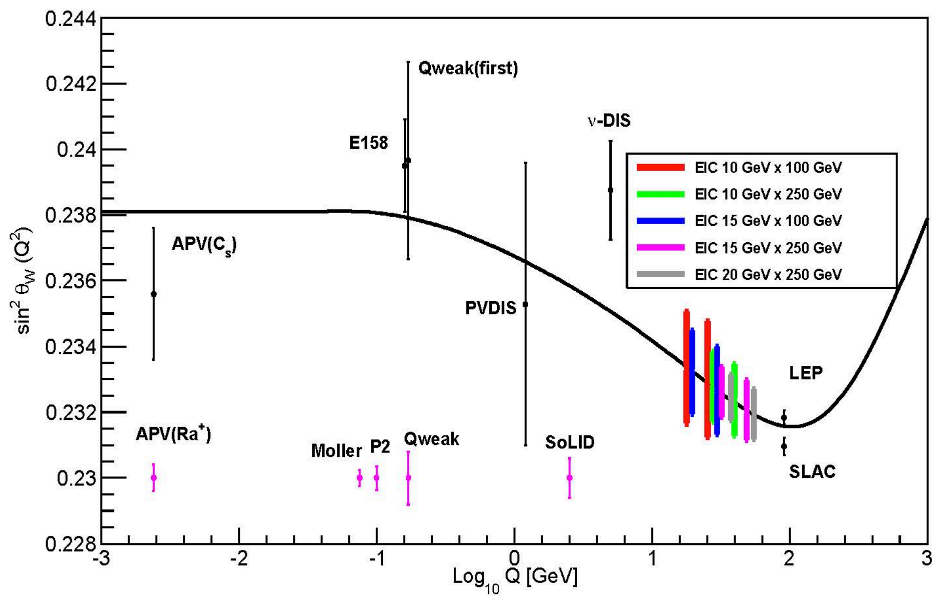
Blue: near future measurements

Red: US EIC projections





Low Q^2 Weak Mixing Angle Measurements and Rare Higgs Decays



and William J. Marciano[1]

Dark Z Study: arXiv:1507.00352

EIC Study .

__Y. Zhao__, A. Deshpande & K. Kumar et al.

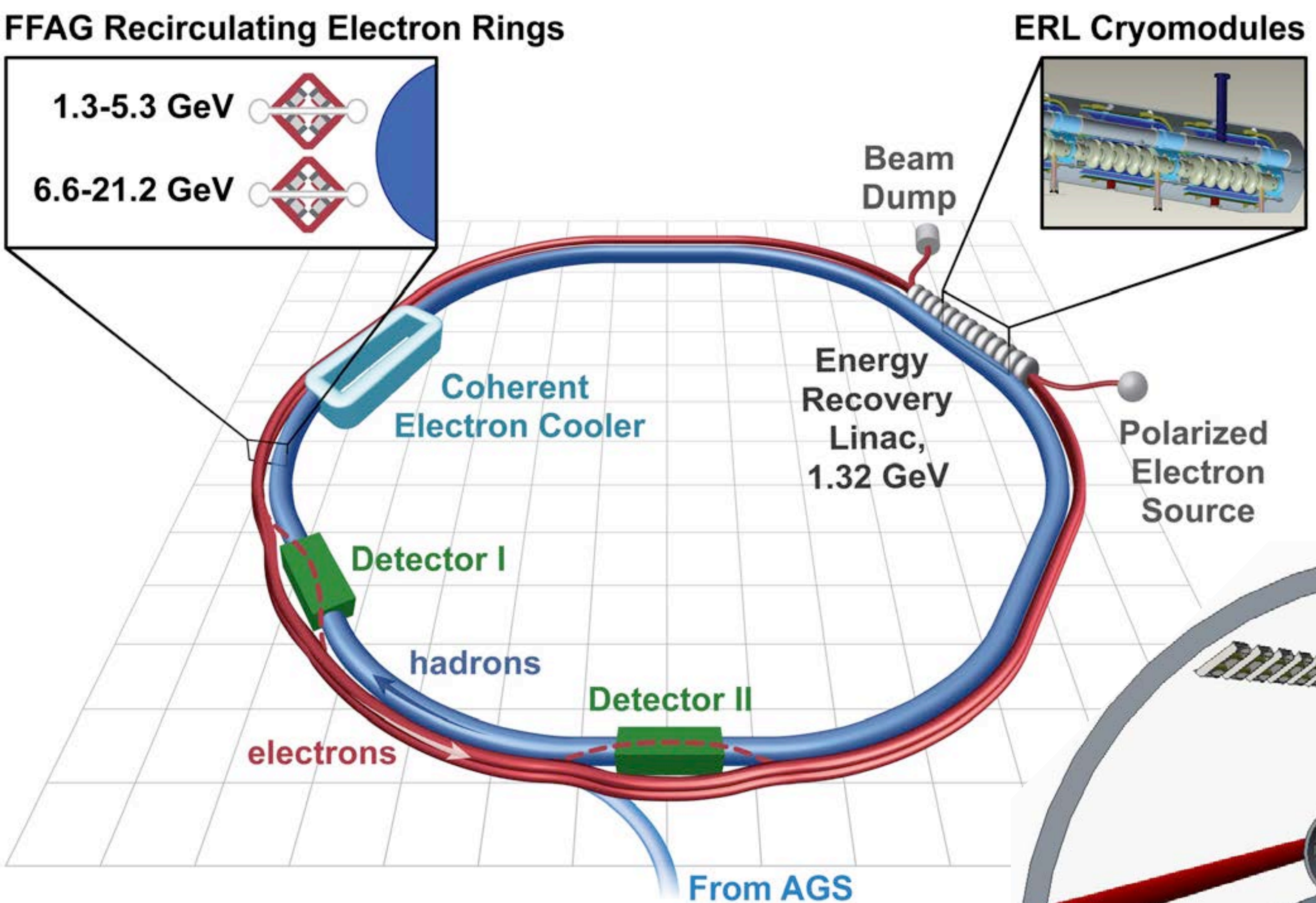
Opportunity for EIC

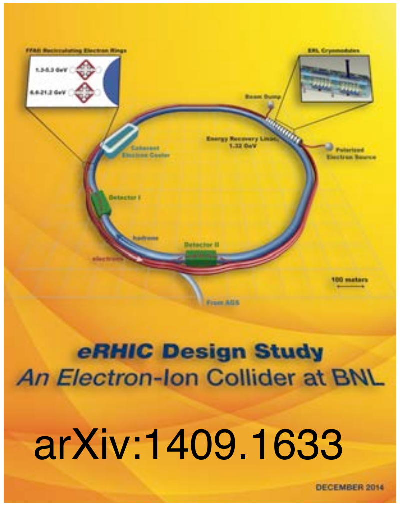
- Limits on **LFV(1,3)** experimental searches are significantly worse than those for LFV(1,2)
- There are BSM models which specifically allow and enhance LFV(1,3) over LFV(1,2)
  - Minimal Super-symmetric Seesaw model:J. Ellis et al. Phys. Rev. D66 115013 (2002)
  - SU(5) GUT with leptoquarks: I. Dorsner et al., Nucl. Phys. B723 53 (2005); P. Fileviez Perez et al., Nucl. Phys. B819 139 (2009)
- M. Gonderinger & M.Ramsey Musolf, JHEP 1011 (045) (2010); arXive: 1006.5063 [hep-ph]
  - 10 fb^{-1} e-p luminosity @ 90 GeV CM would have potential
  - Detector & analysis efficiencies assumed 100%
  - HERA experience: effective efficiencies 5-15%
- Clearly there is an opportunity for EIC: “icing on the cake”

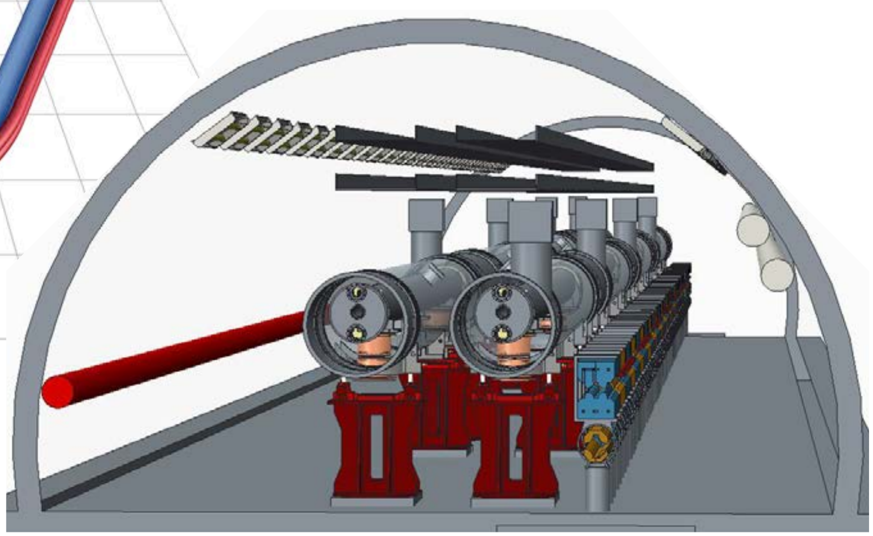
Detector Design:
Some General Considersations

See details about design stretegy, technolgy and integration with accelerator design (IR) in Prof. Aschenauer's lectures tomorrow.

EIC at BNL: eRHIC

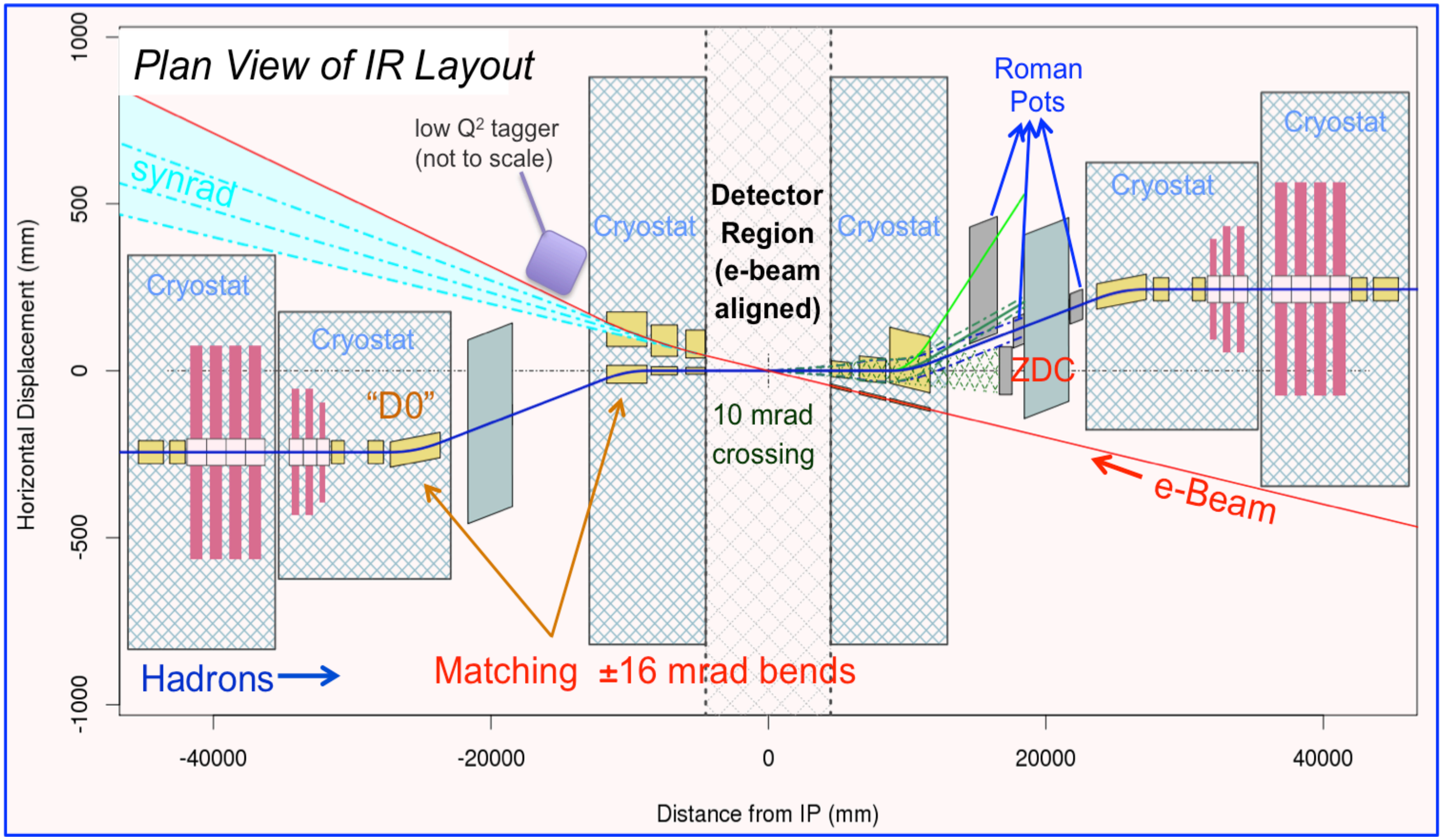




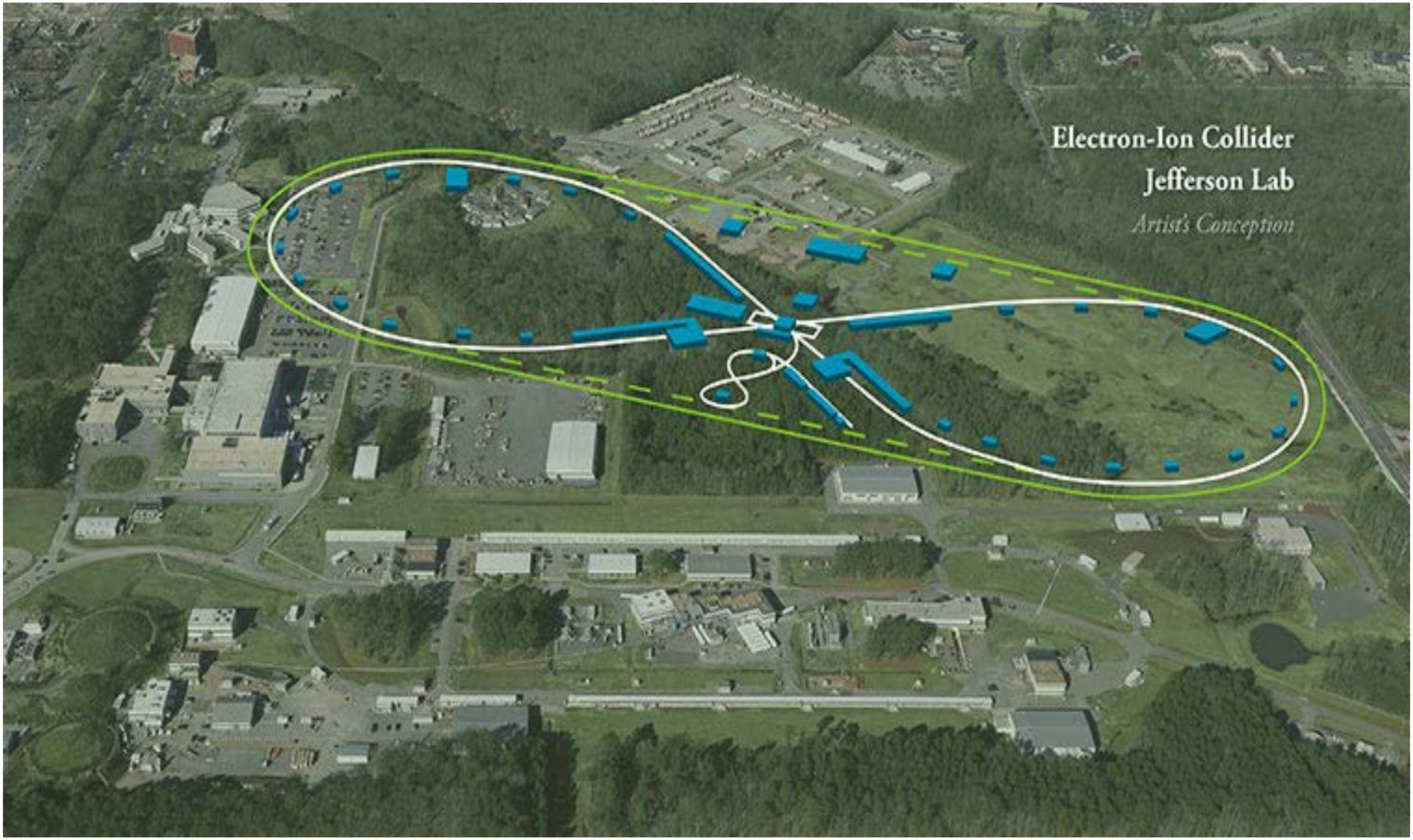


- 4.1×10^{33} cm^{-2} s^{-1} for $\sqrt{s}$ = 126 GeV (15.9 GeV e↑ on 250 GeV p↑)

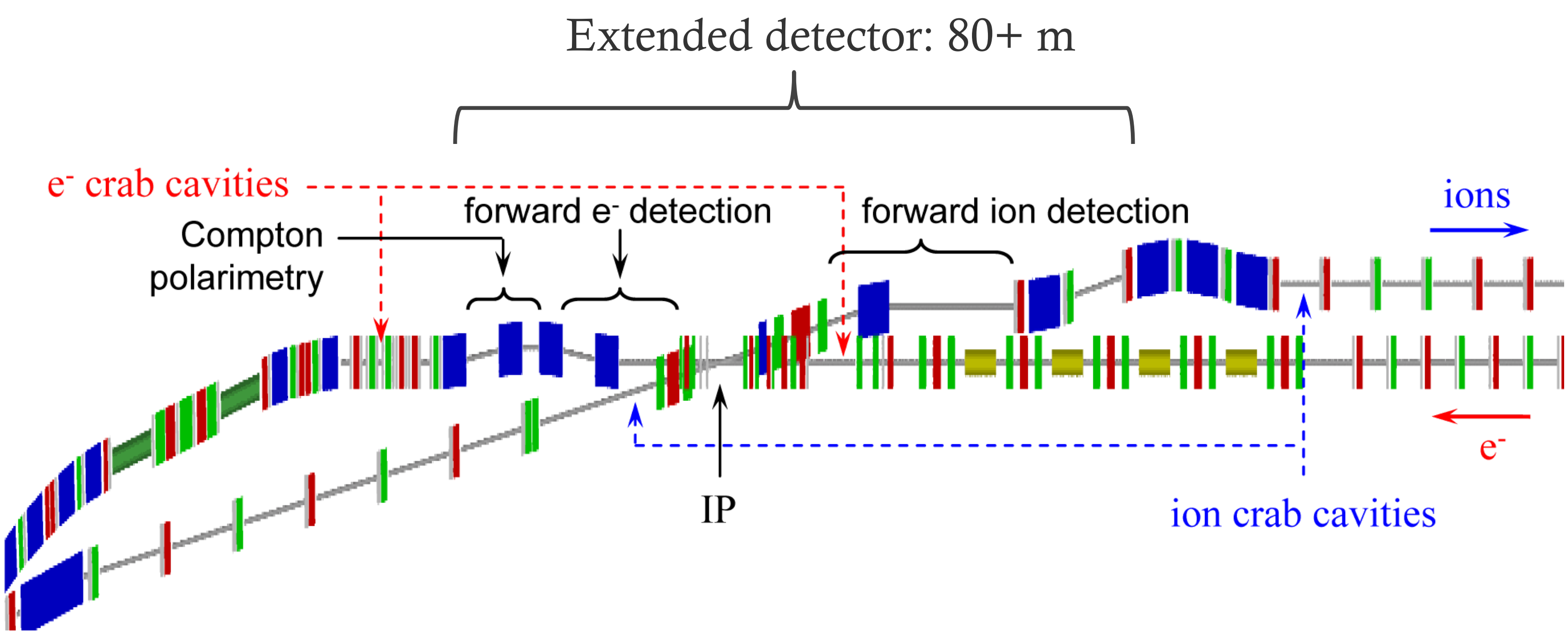
The eRHIC Interaction Region (IR)



EIC at Jlab: JLEIC



JLEIC Interaction Region (IR)

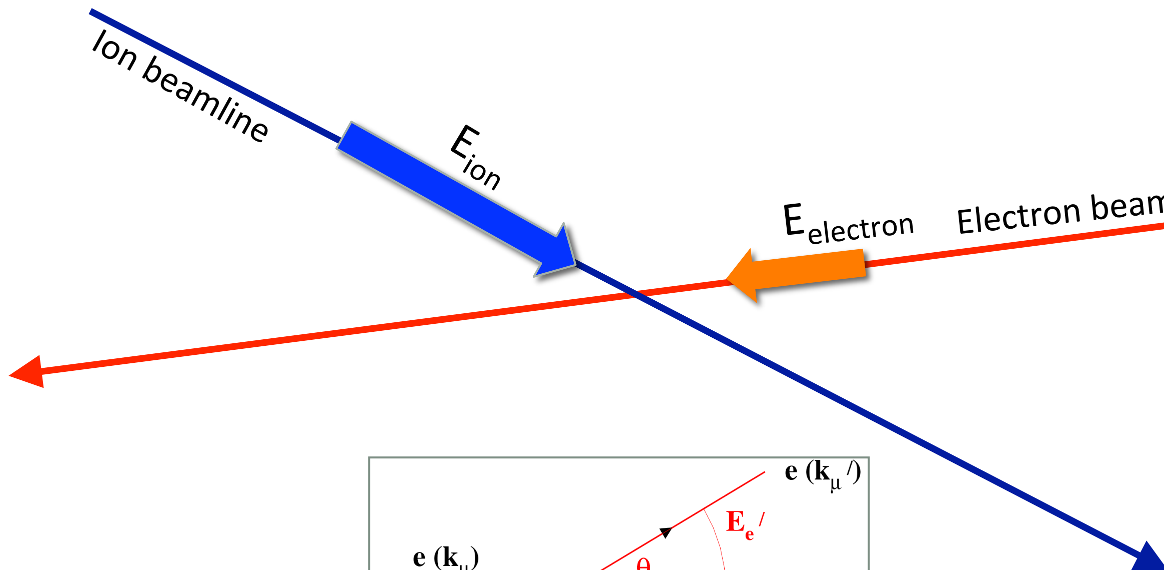


Common characteristics:

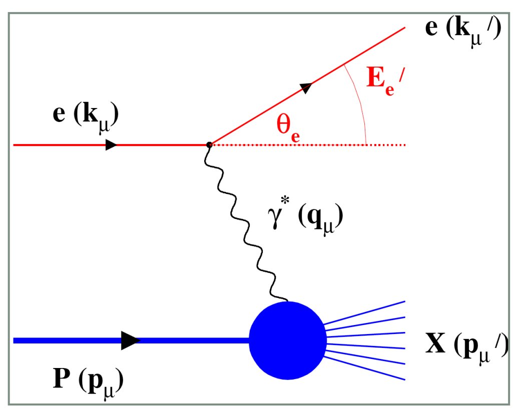
- Both eRHIC and JLEIC are planned to measure the whole event: "Exclusive Measurement" of DIS
  - Measure scattered electron, measure and identify beam and target fragments (remnants)
- Both have beam crossing angles (collisions not head-on)
  - Initially dictated by "lessons from HERA" where e-/e+ beams were brought in and taken out creating a "fan of intense synchrotron radiation" which made detectors difficult (impossible) to operate
  - Electron beam in the EIC era will have no bends before the Interaction Region.
- Many more will be discussed in dedicated lectures….

DIS and Final State Particles

Aim of EIC is nucleon and nuclear structure beyond the longitudinal description. This makes the requirements for the machine and detector different from all previous colliders **including HERA**.



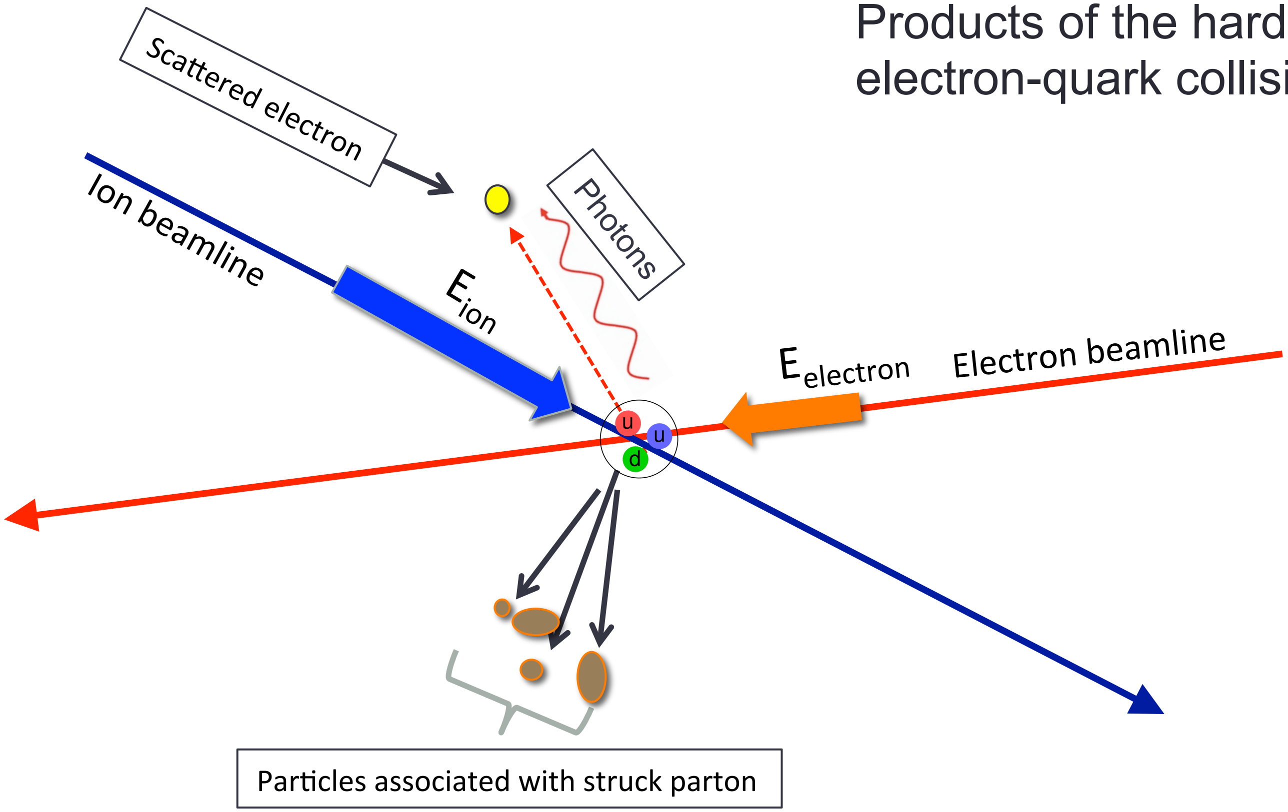
Need more than this



R.Yoshida, EICUG @ ANL

Final State Particles in the Central Rapidity

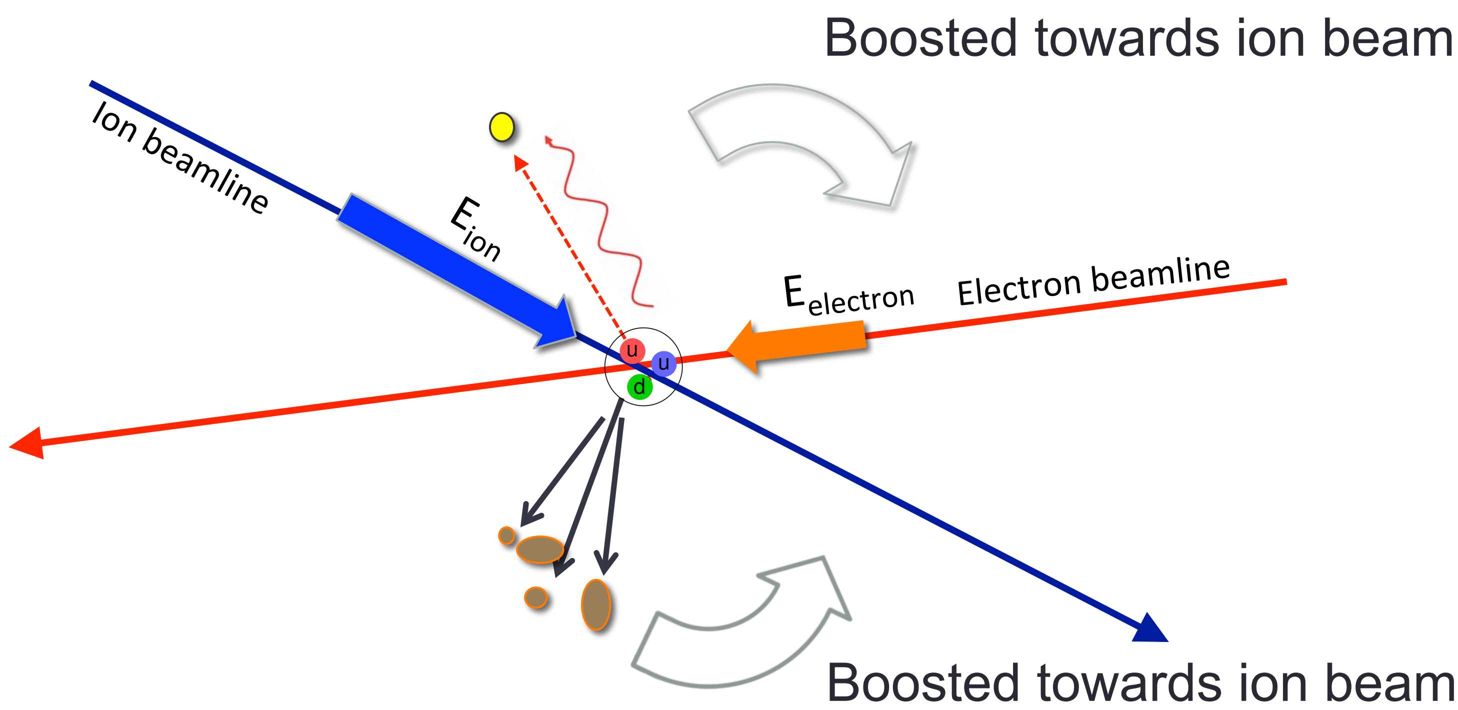
Products of the hard electron-quark collision



Transverse and flavor structure measurement of the nucleon and nuclei:
The particles associated with struck parton must have its species identified and measured.

R.Yoshida, EICUG @ ANL

Final State Particles in the Central Rapidity



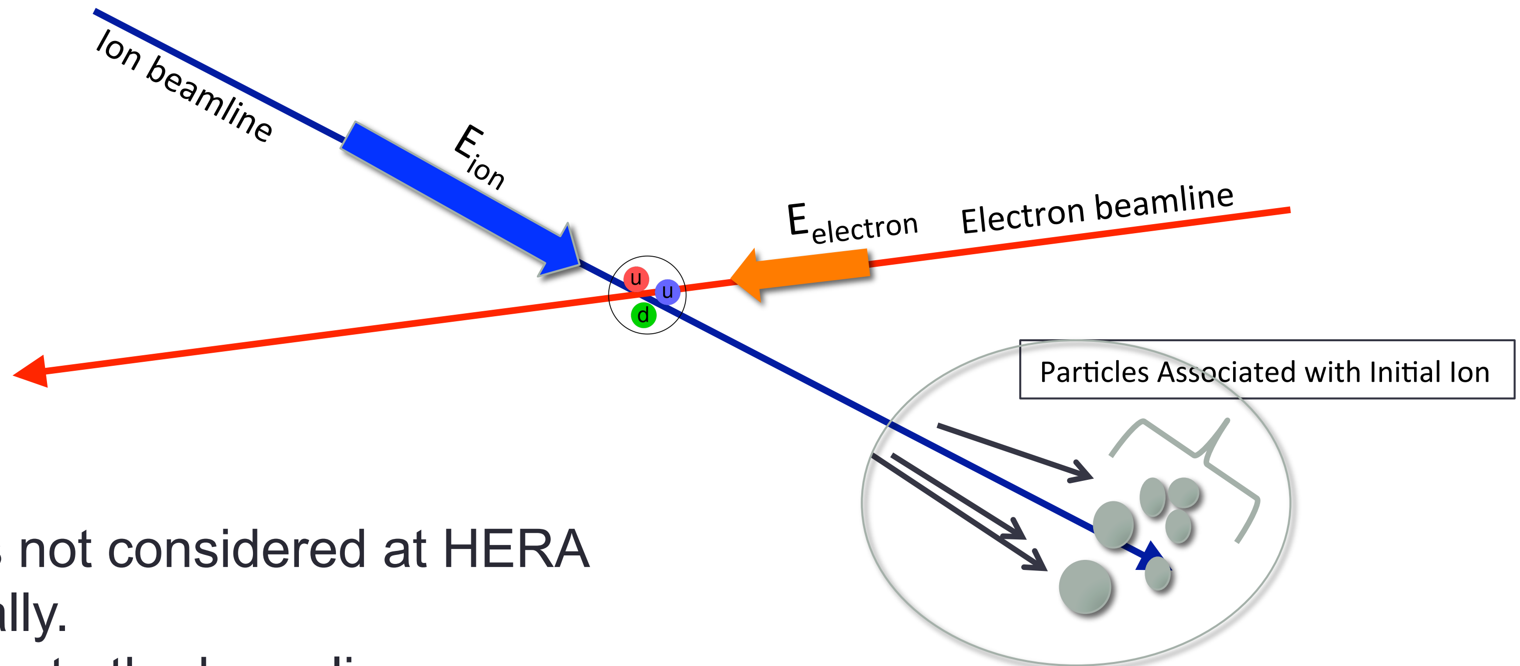
Asymmetric collision energies will boost the final state particles in the ion beam direction:

Detector requirements change as a function of rapidity

R.Yoshida, EICUG @ ANL

Particles Associated with the Initial Ion

For EIC, particles of the "target remnant" is as important as the struck parton



- Was not considered at HERA initially.
- Close to the beamline
- Not analyzed by central solenoid.
- **Aim for ~100% acceptance and good resolution at EIC.**

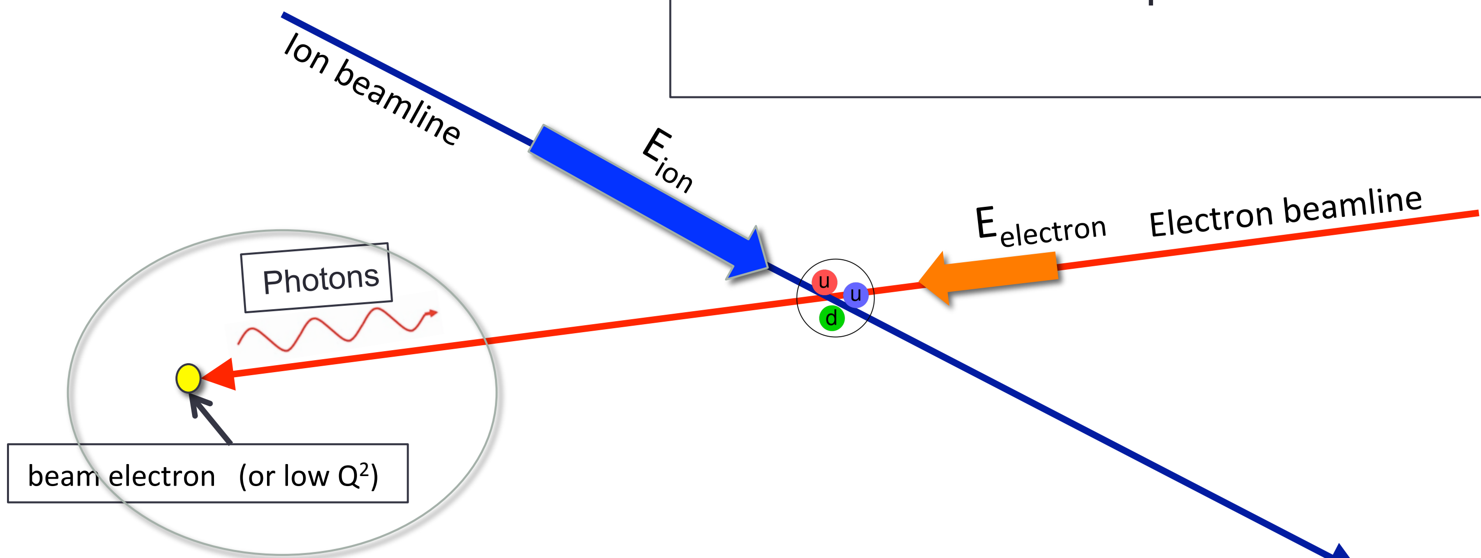
Remember acceptance is equally important as luminosity!

R.Yoshida, EICUG @ ANL

Particles Associated with the Initial Electron

Forward Electron area:

- Tag photoproduction ($Q^2 \approx 0$)
- Measure Luminosity
- Measure electron polarization



Apply lessons from HERA, JLab and elsewhere

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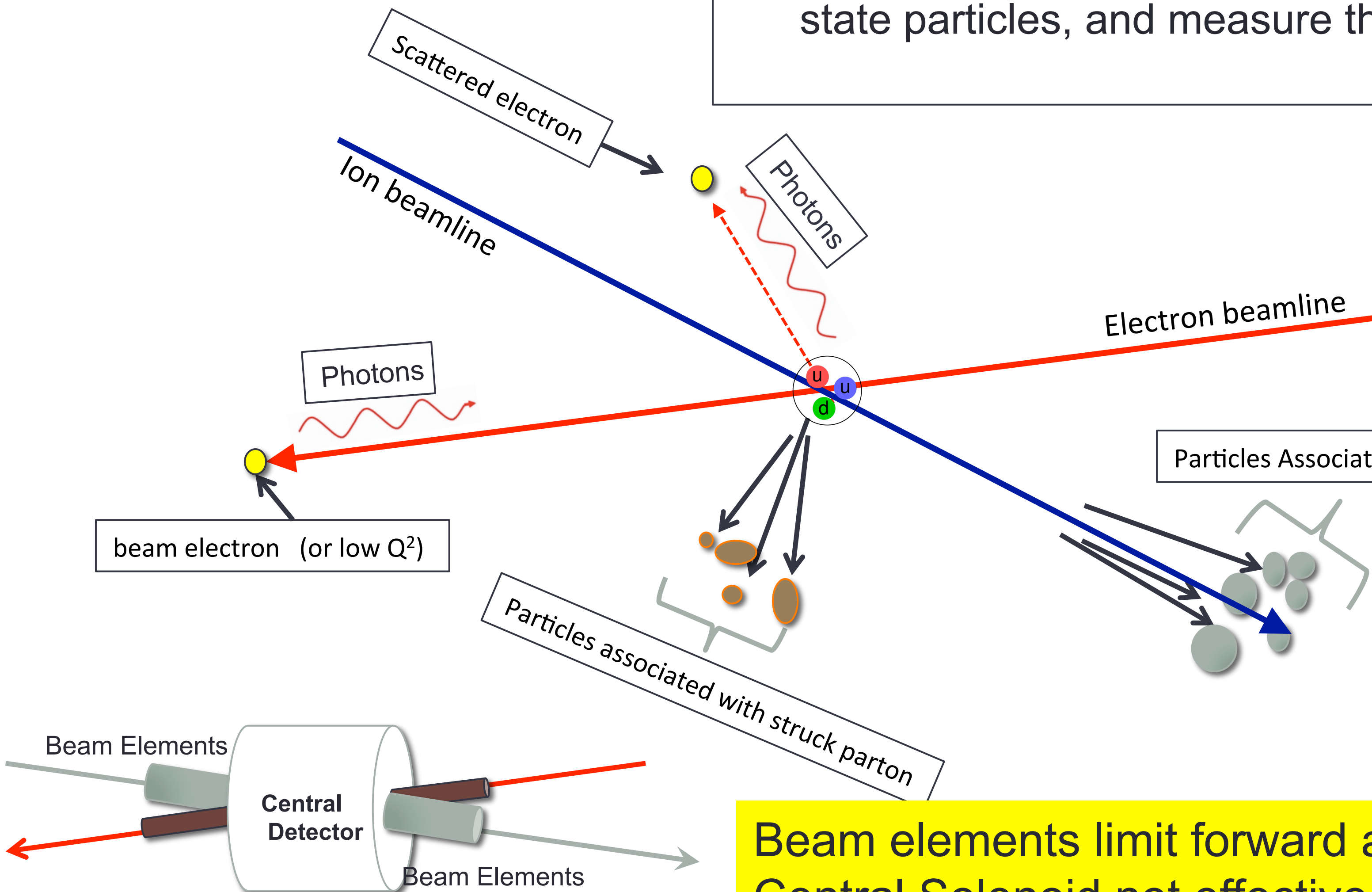
Final State Particles

The aim is to get ~100% acceptance for all final state particles, and measure them with good resolution.



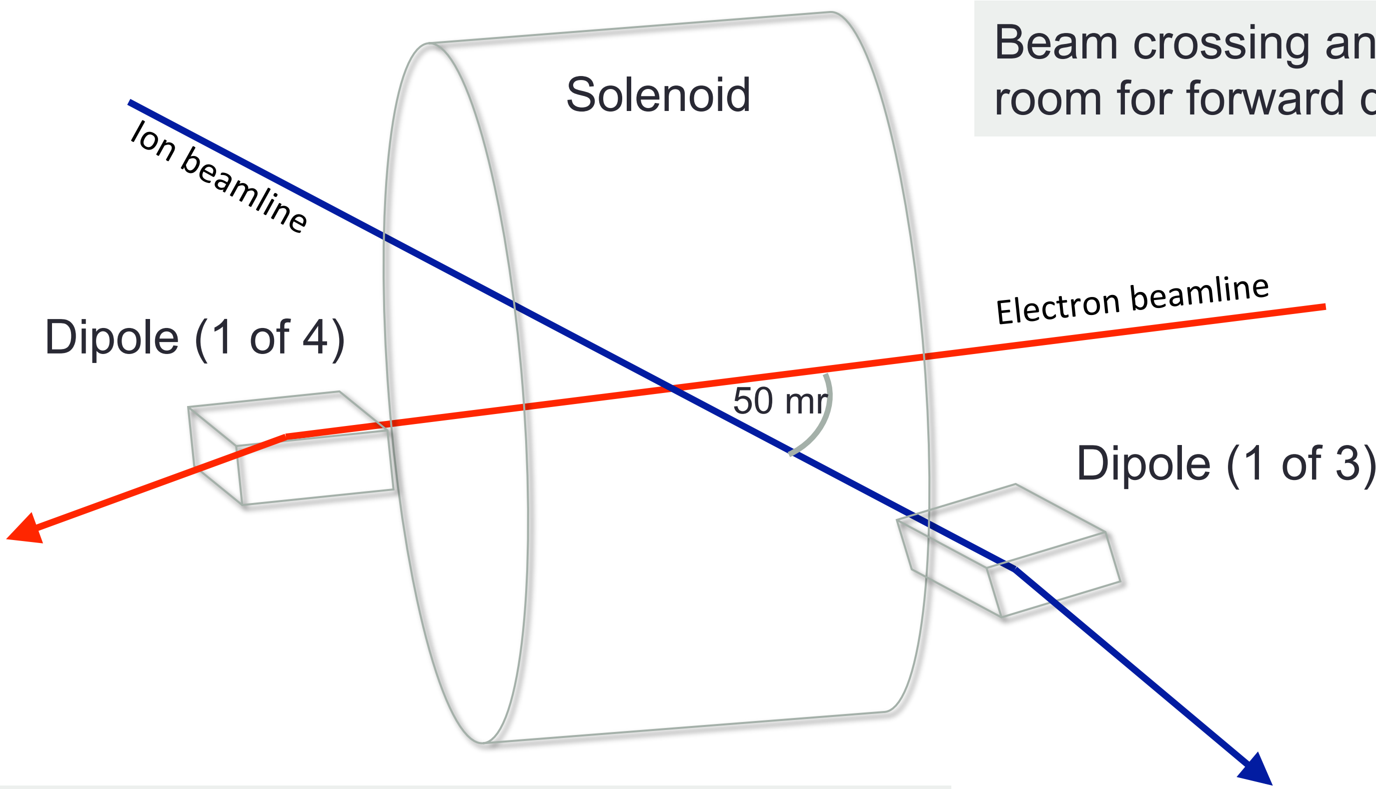
Beam elements limit forward acceptance
Central Solenoid not effective for forward

R.Yoshida, EICUG @ ANL

Interaction Region Concept

NOT TO SCALE!

Beam crossing angle creates room for forward dipoles

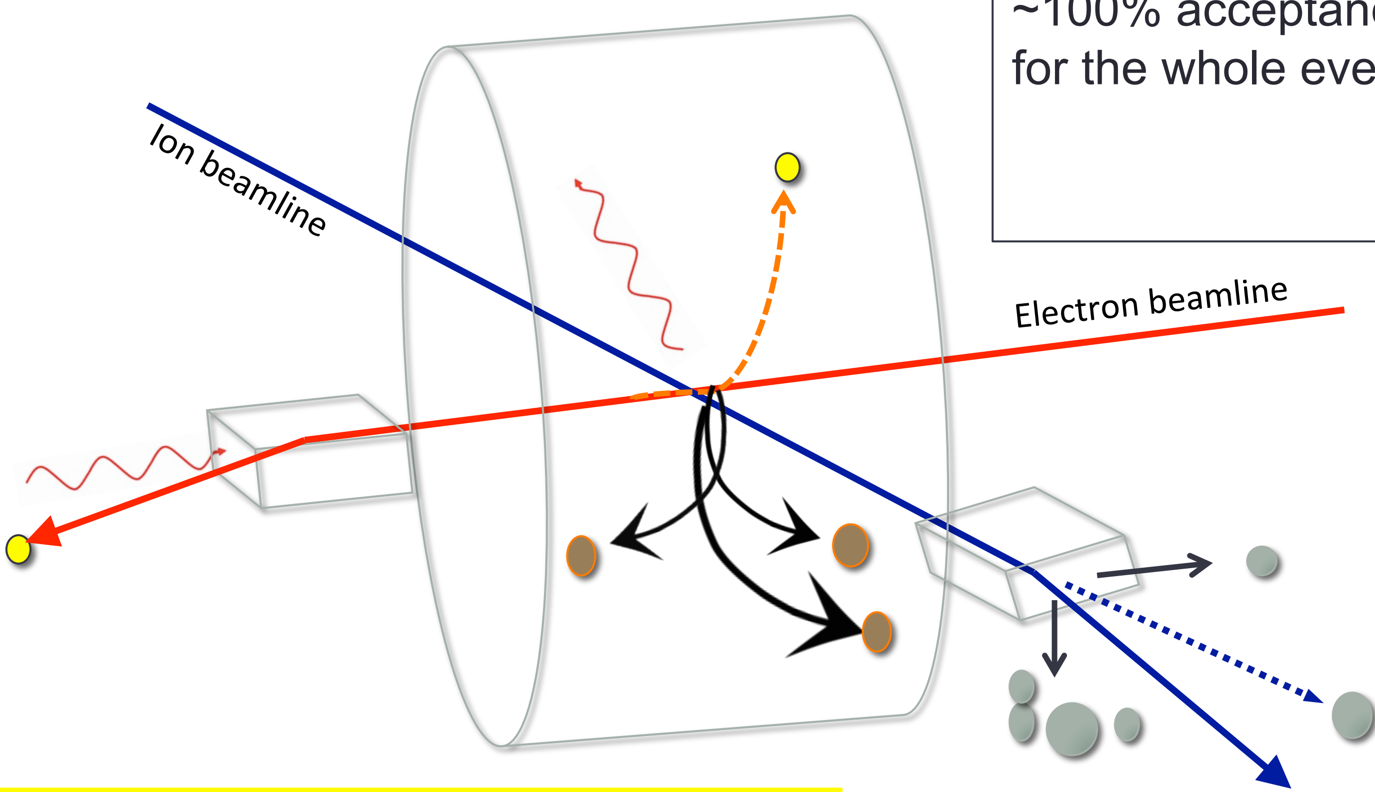


Dipoles analyze the forward particles and create space for detectors in the forward direction

R.Yoshida, EICUG @ ANL

Interaction Region Concept

Possible to get ~100% acceptance for the whole event



Total acceptance detector (and IR)

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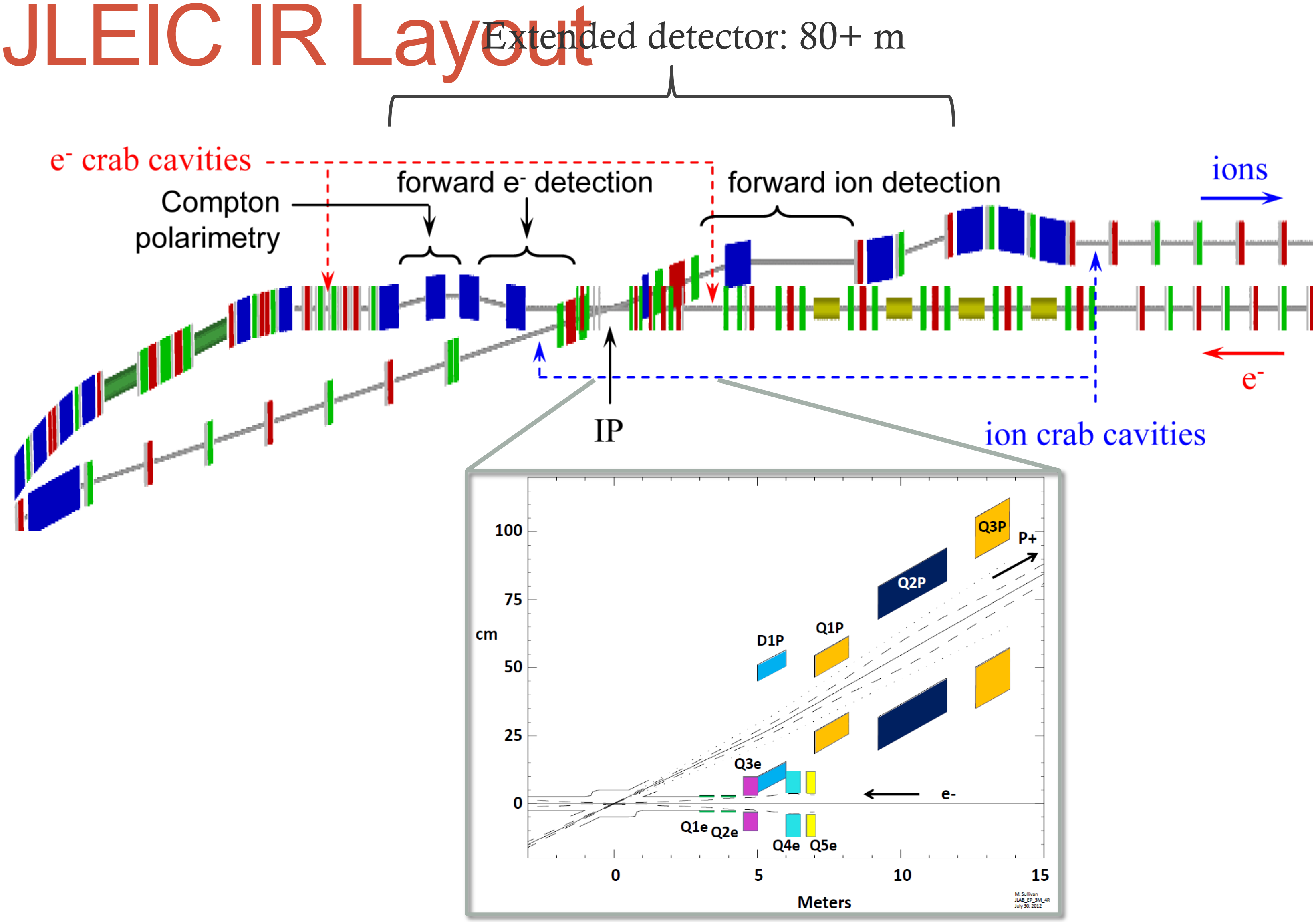
JLEIC IR Layout



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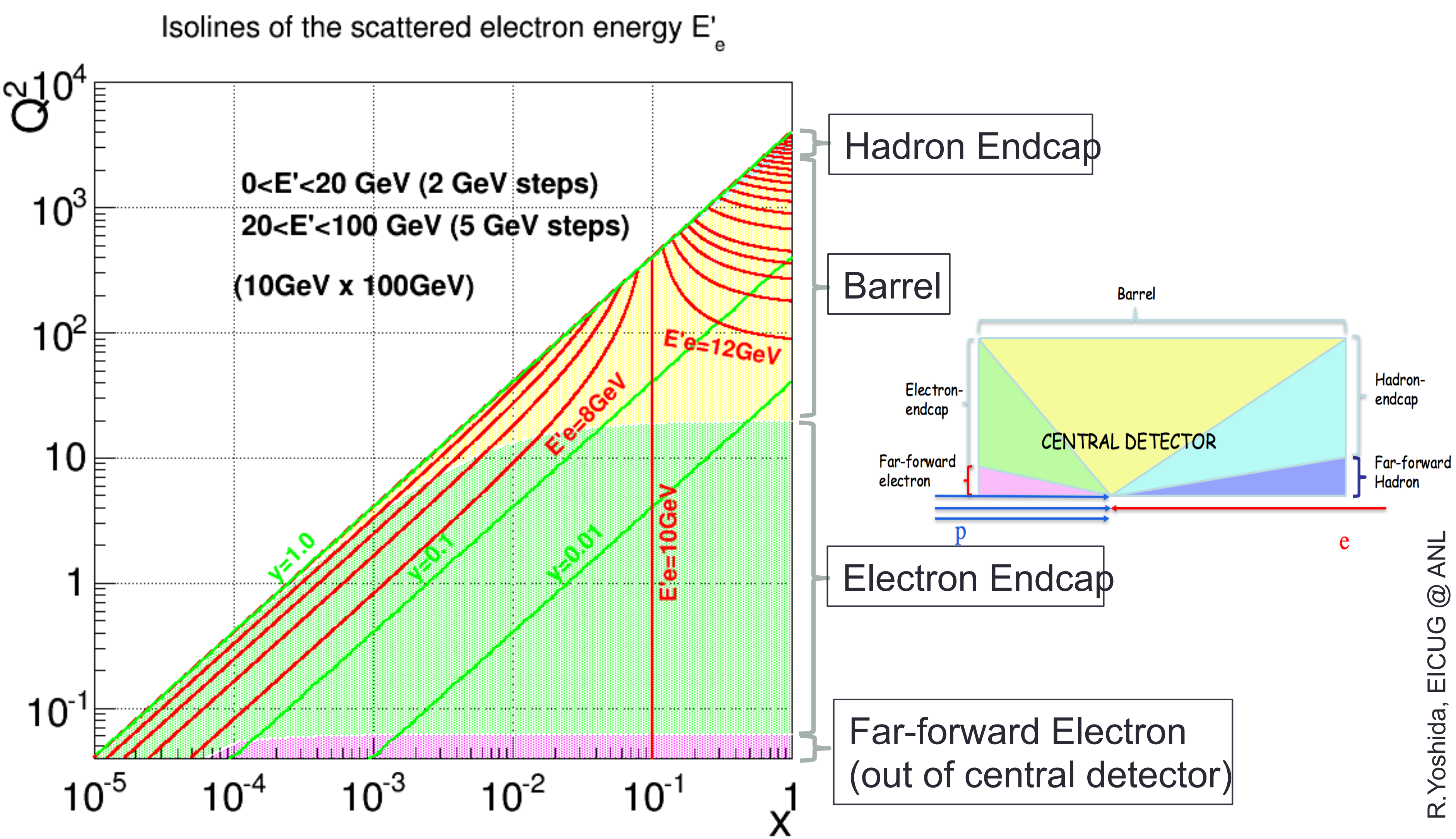
Electron Isoline Plot



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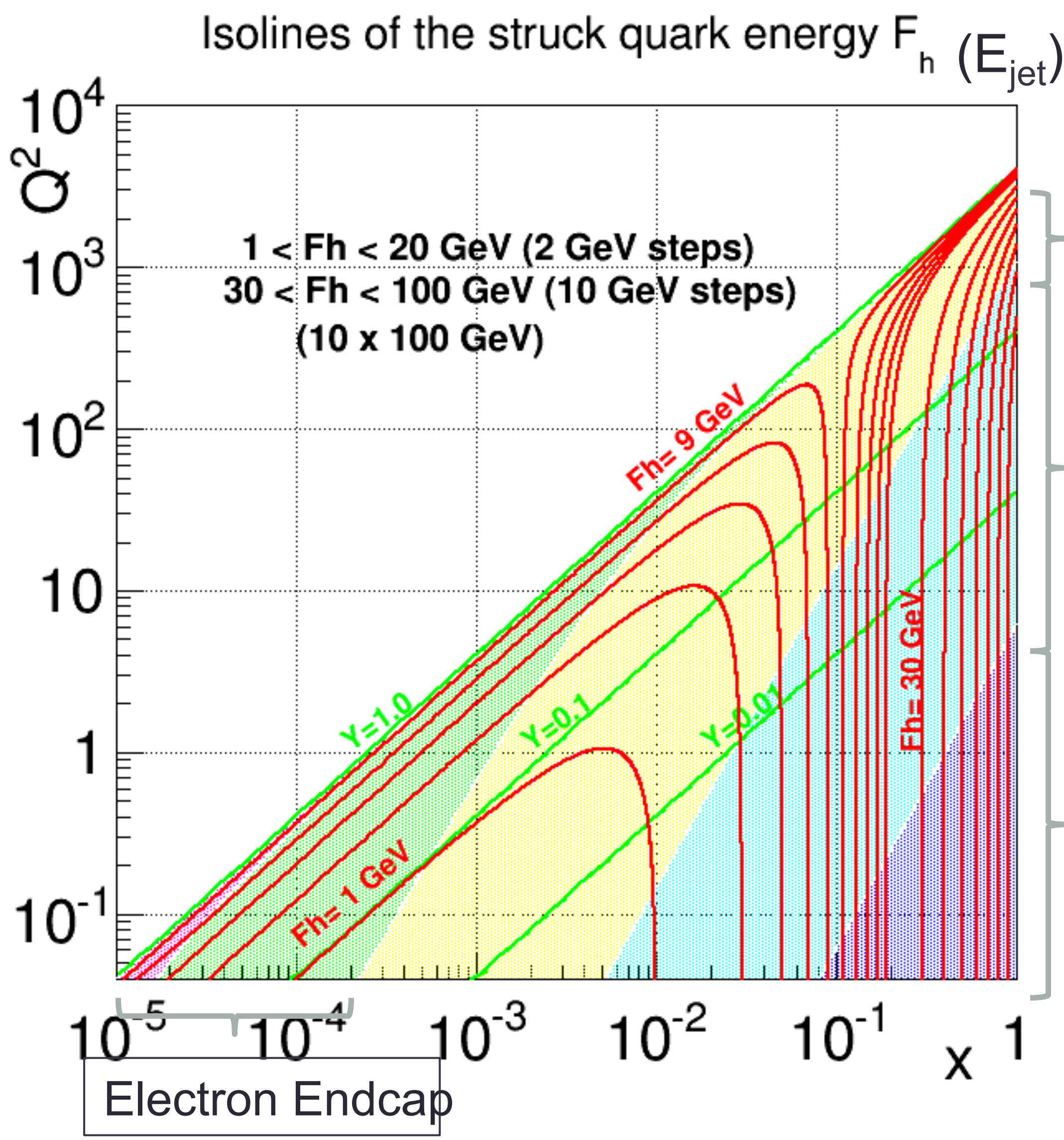
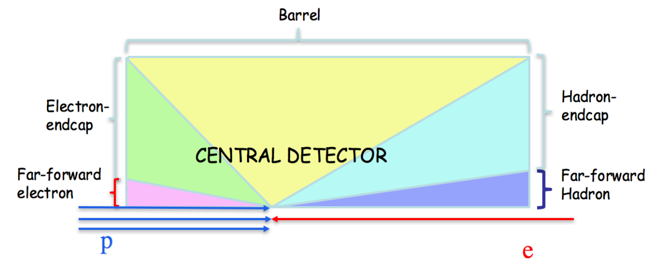
Quark(Jet) Isoline Plot





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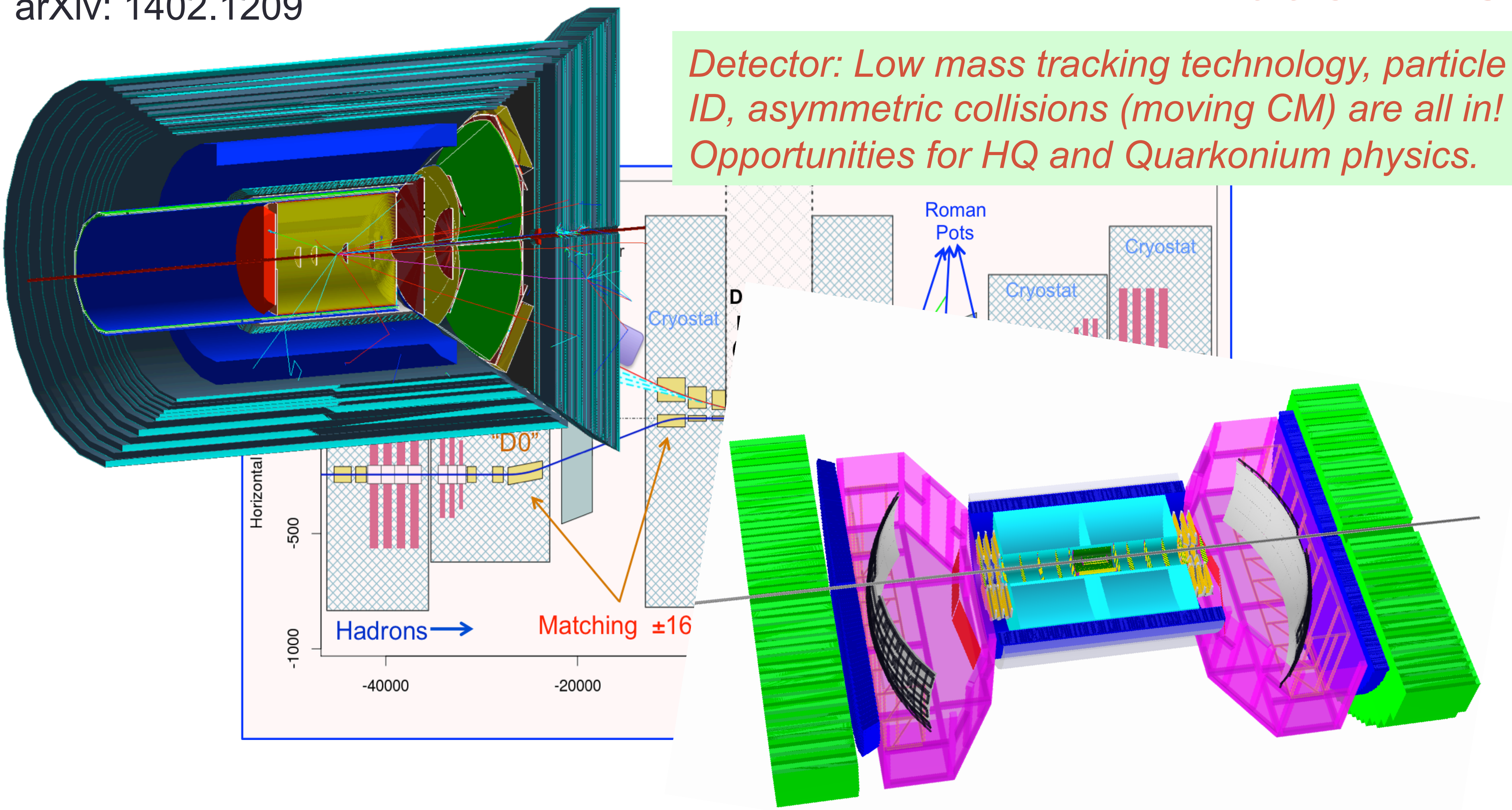
EIC IR & Detector Ideas at eRHIC

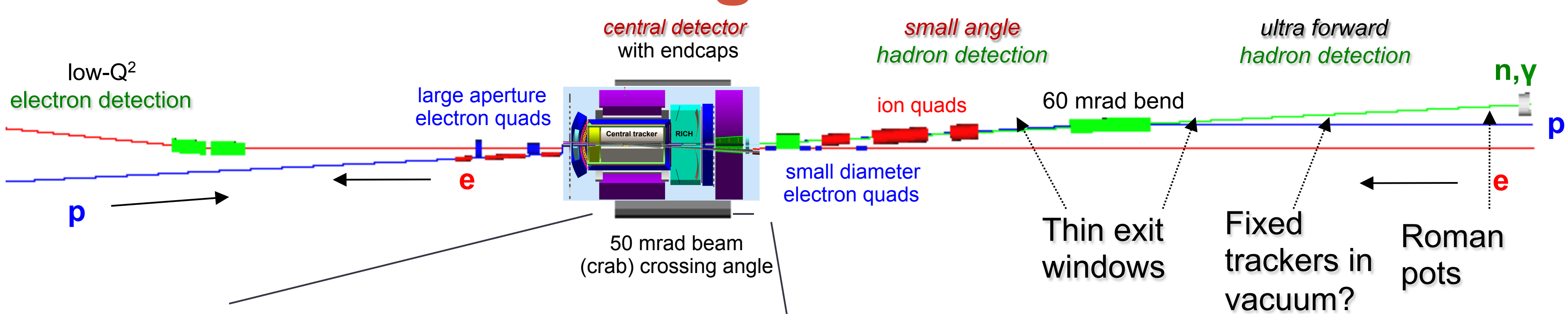
Day-1 Detector: CELESTE
A.K.A. “ePHENIX” with BaBar Solenoid
arXiv: 1402.1209

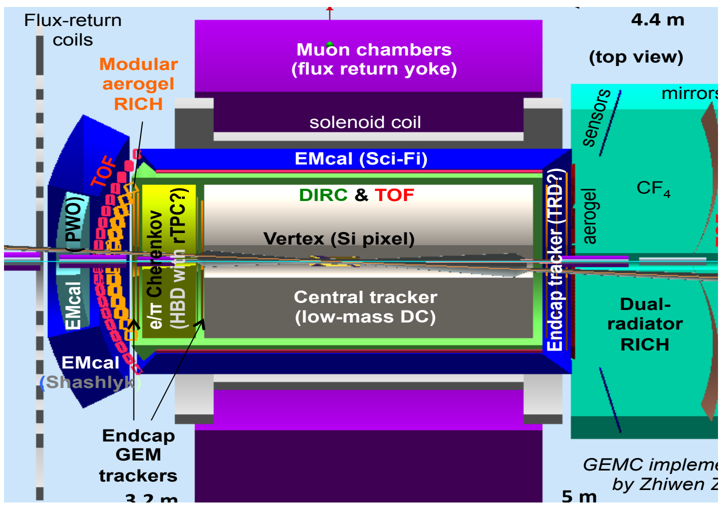
Detector: Low mass tracking technology, particle ID, asymmetric collisions (moving CM) are all in! Opportunities for HQ and Quarkonium physics.



BEAST by BNL’s EIC Task Force
arXiv: 1409.1633

EIC at JLab: Integrated IR & Detector

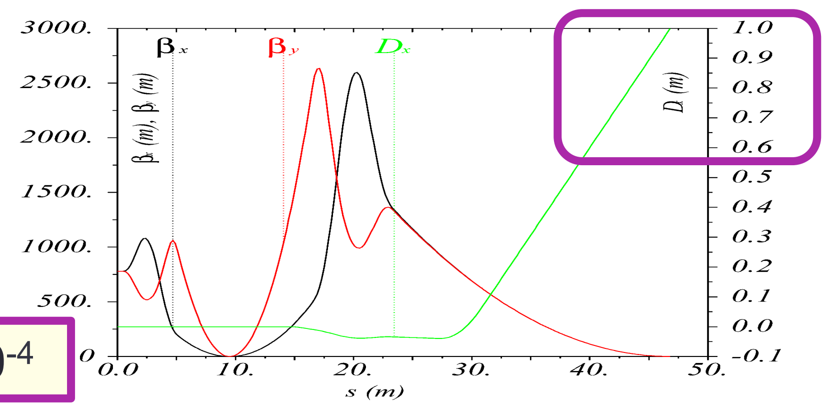




Cartoon of central detector based on dual solenoid a la ILC4 detector, but using the previous iteration interaction region design.

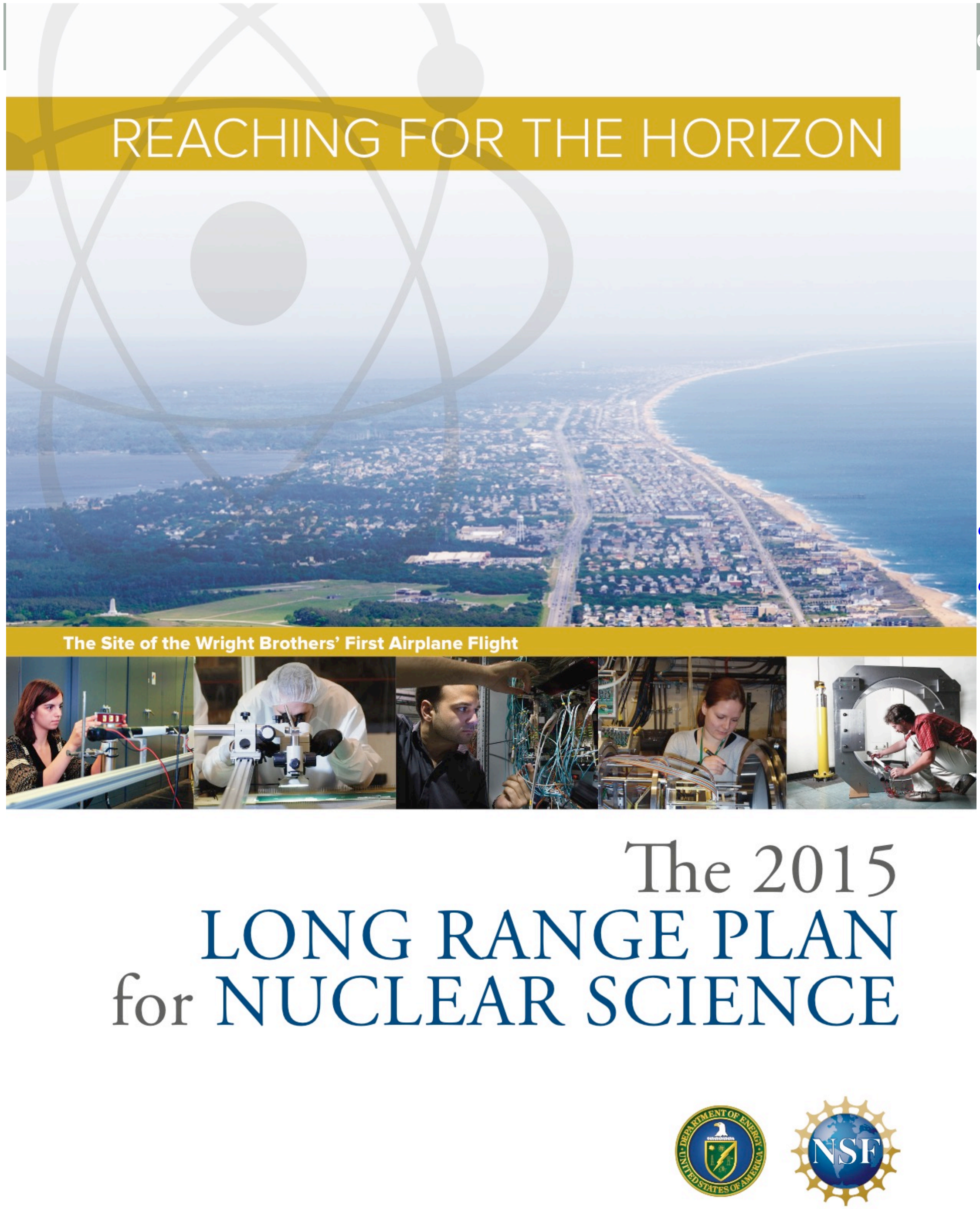
Hadron/Ion detection in 3 stages

- Endcap with 50 mrad crossing angle
- Small dipole covering angles to a few degrees
- Ultra-forward up to one degree, for particles passing accelerator quads



Beamline functions as spectrometer: $dp/p < 3\times10^{-4}$

EIC Realization Time Line And Planning



RECOMMENDATION:

We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.

Initiatives:

Theory

Detector & Accelerator R&D

http://science.energy.gov/np/reports

T. Hallman, Office of NP at the NSAC meeting March 23, 2016

Next Formal Step on the EIC Science Case

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

Summary

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

Mail reviews received; proposal approved for funding in PAMS; PR package in PAMS being processed.

Progress is also being made on a second Joint NAS study on Space Radiation Effects Testing

Innovative Accelerator Science

On going R&D on accelerator concepts and technologies:

- High current polarized electron gun
- High current Energy Recovery Linac (ERL)
- Coherent electron cooling
- Fixed Field Acceleration Gradient beam transport
- High gradient crab cavities
- Super-ferric magnets
- Figure-8 shaped e/h rings to aid polarization of beams

eRHIC R&D (first five items)

JLEIC R&D (items from Fixed Field Acceleration Gradient beam transport to Figure-8 shaped e/h rings)

Most of these are of global interest!

Realizing these for the US EIC requires *cutting edge accelerator science*

T. Hallman, Office of NP at the NSAC meeting March 23, 2016

Seeding the Possibility of a Future Electron Ion Collider

NP Planning for EIC Accelerator R&D

In view of Recommendation III in the 2015 LRP report on the realization of an EIC, NP is fomenting a plan in discussion with EIC stakeholders:

18 months NAS study:	US-BASED ELECTRON ION COLLIDER SCIENCE ASSESSMENT
March - July 2016:	Competitive FOA published this month, proposals due May 2 to select and fund accelerator R&D for Next Generation NP Facilities for 1 year only.
Summer 2016	Conduct an NP community EIC R&D panel (EIC-R&D) Review charged with generating a report as basis for FY17-FY20+ EIC accelerator R&D funding. NP to appoint Chair of the panel
Late Fall 2016:	Use the EIC panel report from the panel to publish a new Accelerator R&D FOA for FY2017 funding.

Funding amount and source for EIC accelerator R&D in FY17 and beyond:

Funding level:	Aiming for $7M, exact amount to be guided by EIC-R&D Review's report
Funding sources:	~$1.9M from NP competitive pot, the rest generated by percentage tax to RHIC and CEBAF Accelerator Operations budgets (~2.6% FY17 president request for each Lab).

Community/Collaboration building:

EIC User Group → eicug.org (contact me!)

Ample opportunities for contributions & participation!

EICUG Today: 651 Users, 142 Institutes, 27 Countries

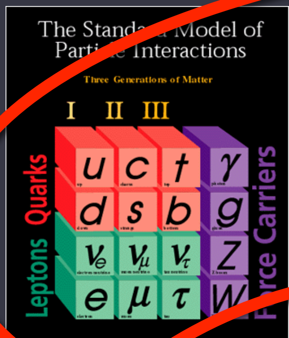
350 experimentalists, 111 theorists, 141 accelerator-physicists, 43 unknowns

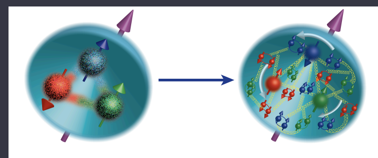
What's in the immediate future for EIC?

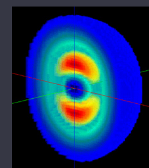
- Science Review by National Academy of Science (& Engineering & Arts) (National Research Council)

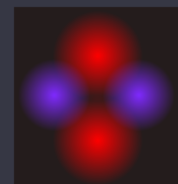
- Positive NAS review will trigger the DOE's CD process
  - CD0 (acceptance of the critical need for science by DOE) FY18
  - EIC-Proposal's Technical & Cost review → FY19 (site selection)
  - CD2 requires site selection
  - Major Construction funds ("CD3") by 2022/23"
  - Assuming 1.6% sustained increase over inflation of the next several years (Long Range Plan)

21st Century Nuclear Science: Probing nuclear matter in all Its forms & exploring their potential for applications



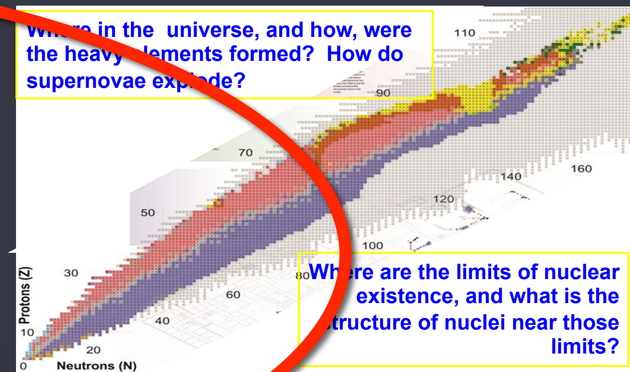




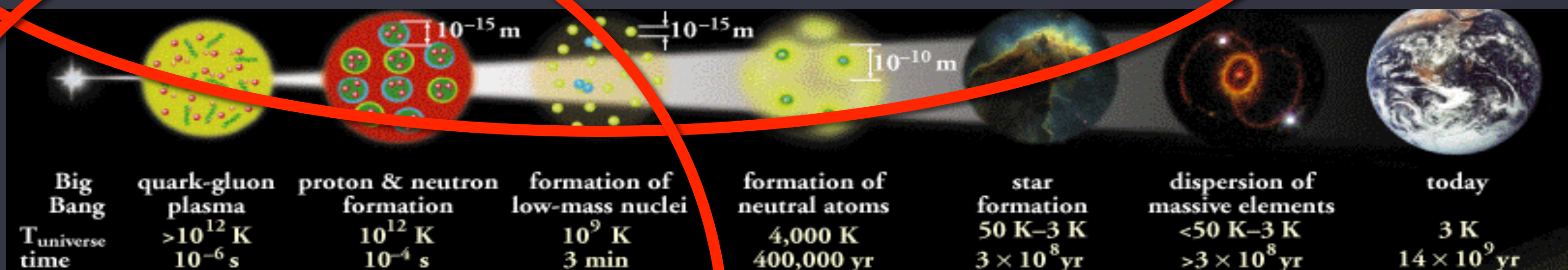


How are the properties of protons and neutrons, and the force between them, built up from quarks, antiquarks and gluons? What is the mechanism by which these fundamental particles materialize as hadrons?

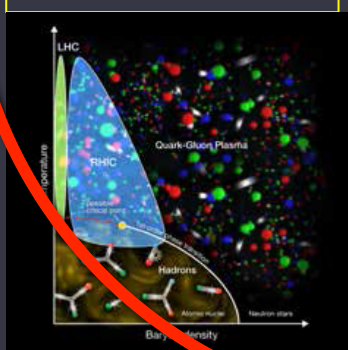
Where in the universe, and how, were the heavy elements formed? How do supernovae explode?



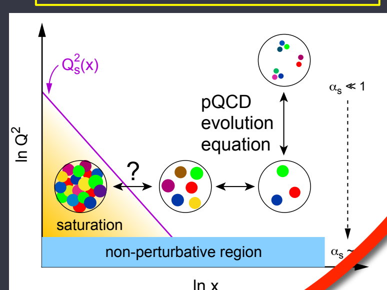
Where are the limits of nuclear existence, and what is the structure of nuclei near those limits?



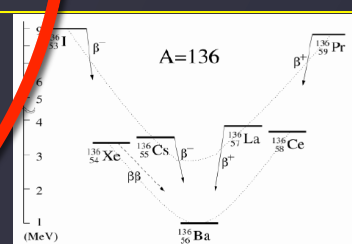
What is the nature of the different phases of nuclear matter through which the universe has evolved?



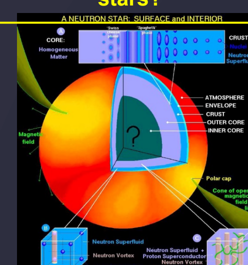
Do nucleons and all nuclei, viewed at near light speed, appear as walls of gluons with universal properties?



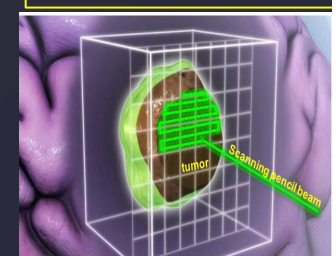
How can the properties of nuclei be used to reveal the fundamental processes that produced an imbalance between matter and antimatter in our universe?



How are the nuclear building blocks manifested in the internal structure of compact stellar objects, like neutron stars?



How can technologies developed for basic nuclear physics research be adapted to address society's needs?



Summary:

The EIC will profoundly impact our understanding of the **structure of nucleons and nuclei in terms of sea quarks & gluons** (SM of Physics).

→ ***The bridge between sea quark/gluons to Nuclei***

The EIC will enable **IMAGES** of **yet unexplored regions of phase spaces in QCD** with its high luminosity/energy, nuclei & beam polarization

→ ***High potential for discovery***

Outstanding questions raised by world wide experiments at CERN, BNL and Jeff Lab, have **naturally led us to the science and design parameters of the EIC:**
World wide interest and opportunity in collaborating on the EIC

Accelerator scientists at RHIC, Jlab in collaboration with **many from outside accelerator experts** will provide the **intellectual and technical leadership for to realize the EIC** -- *a frontier accelerator facility.*

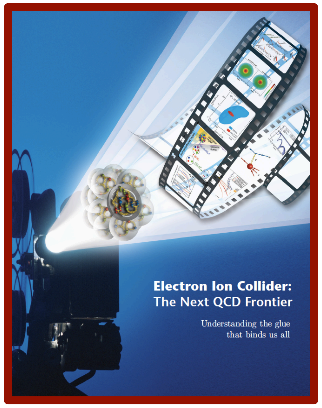
Future QCD studies, particularly for Gluons, demands an Electron Ion Collider

NSAC Agrees nad we are moving forward!

THANK YOU

Thanks to many of my EIC Collaborators and Enthusiasts who led many of the studies presented in this talk
See: **arXiv:1108.1713**, D. Boer et al.

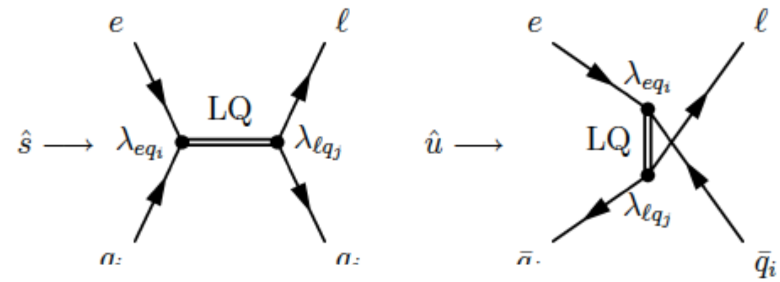
Without the EIC White Paper Writing Group the EIC White Paper would not have existed.
Special thanks to Dr. Jian-Wei Qiu and Prof. Zein-Eddine Meziani, my Co-Editors for the EIC White Paper
See: **arXiv:1212.1701.v3**



The eRHIC and JLEIC machine design teams

Also gratefully acknowledge recent input from: E. Aschenauer, M. Diefenthaler, R. Ent, R. McKeown, B. Mueller, R. Milner, R. Yoshida

LFV phenomenology



$$\frac{d^2\sigma_s}{dxdy} = \underbrace{\frac{1}{32\pi\hat{s}}}_{\text{phase space}} \cdot \underbrace{\frac{\lambda_{eq}^2\lambda_{\ell q}^2\hat{s}^2}{(\hat{s}^2 - m_{\mathrm{LQ}}^2)^2 + m_{\mathrm{LQ}}^2\Gamma_{\mathrm{LQ}}^2}}_{\text{Breit-Wigner LQ propagator term}} \cdot \underbrace{q_i(x,\hat{s})}_{\text{parton density}} \times \begin{cases} \frac{1}{2} & \text{scalar LQ} \\ 2(1-y)^2 & \text{vector LQ} \end{cases}$$

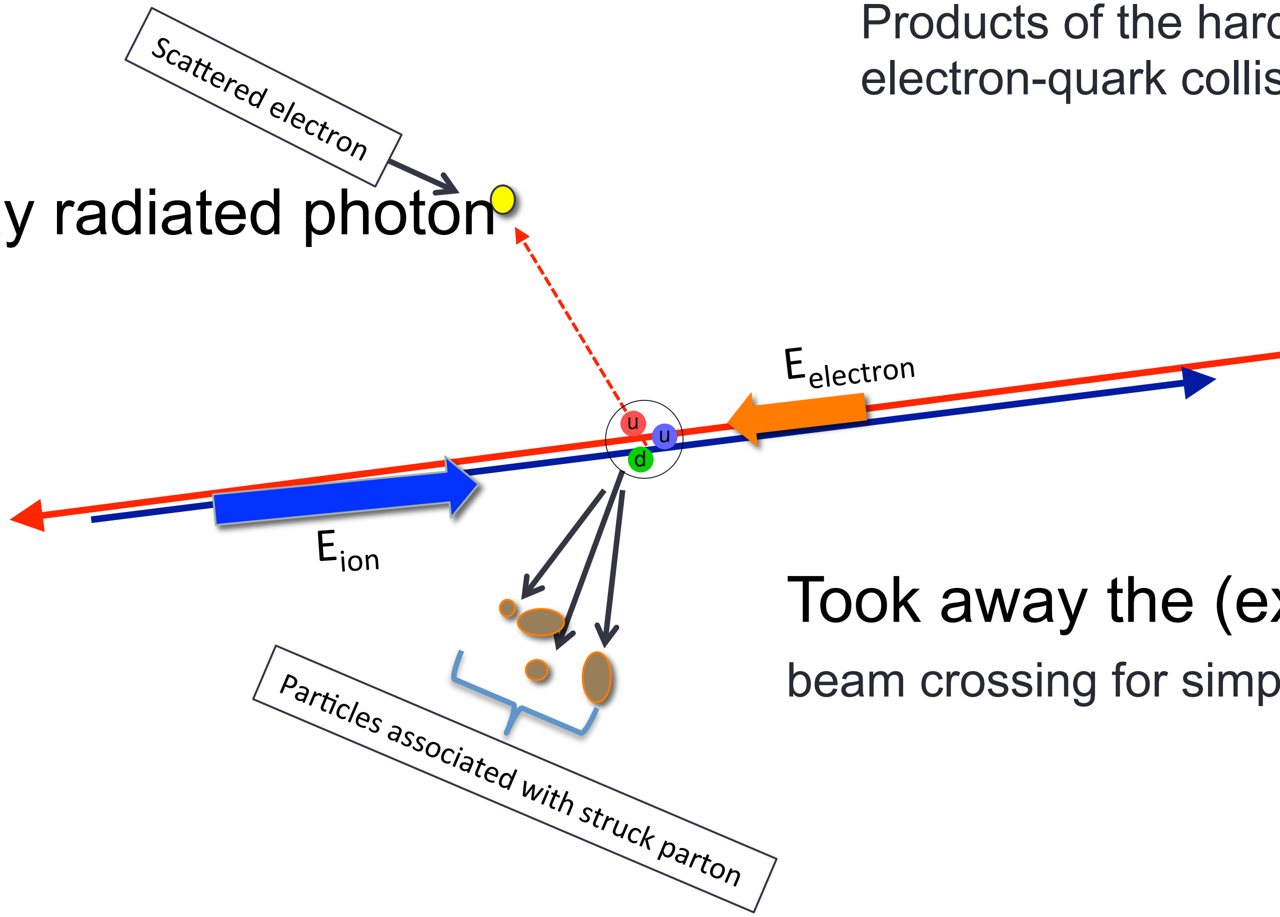
- Leptoquark (LQ) event topologies studied with:
  - LFV MC generator: LQGENEP (L. Bellagamba, Comp. Phys. Comm. 141, 83 (2001)
  - LQ generator for e-p processes using BRW effective model
- In this study to increase efficiency: BW-LO propagator replaced with a constant.
  - m_{LQ} = 200 GeV, $\lambda = 0.3$ (for example one particular LQ…)
  - **Then go over various values of M_{LQ} i.e. ratios: $z = \lambda i \lambda j / M_{LQ}^2$**
- τ has a clean characteristic decay signature:
  - 3π decay in a **narrow pencil like jet**
  - Leptonic decays with neutrinos (missing mom.) with **different angular correlations** in SM vs. LQ

CENTRAL DETECTOR

Final State Particles in the Central Detector

Products of the hard electron-quark collision

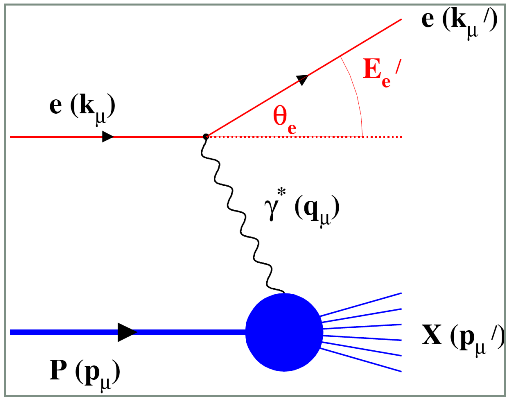
Took away radiated photon
for simplicity



Took away the (exaggerated)
beam crossing for simplicity

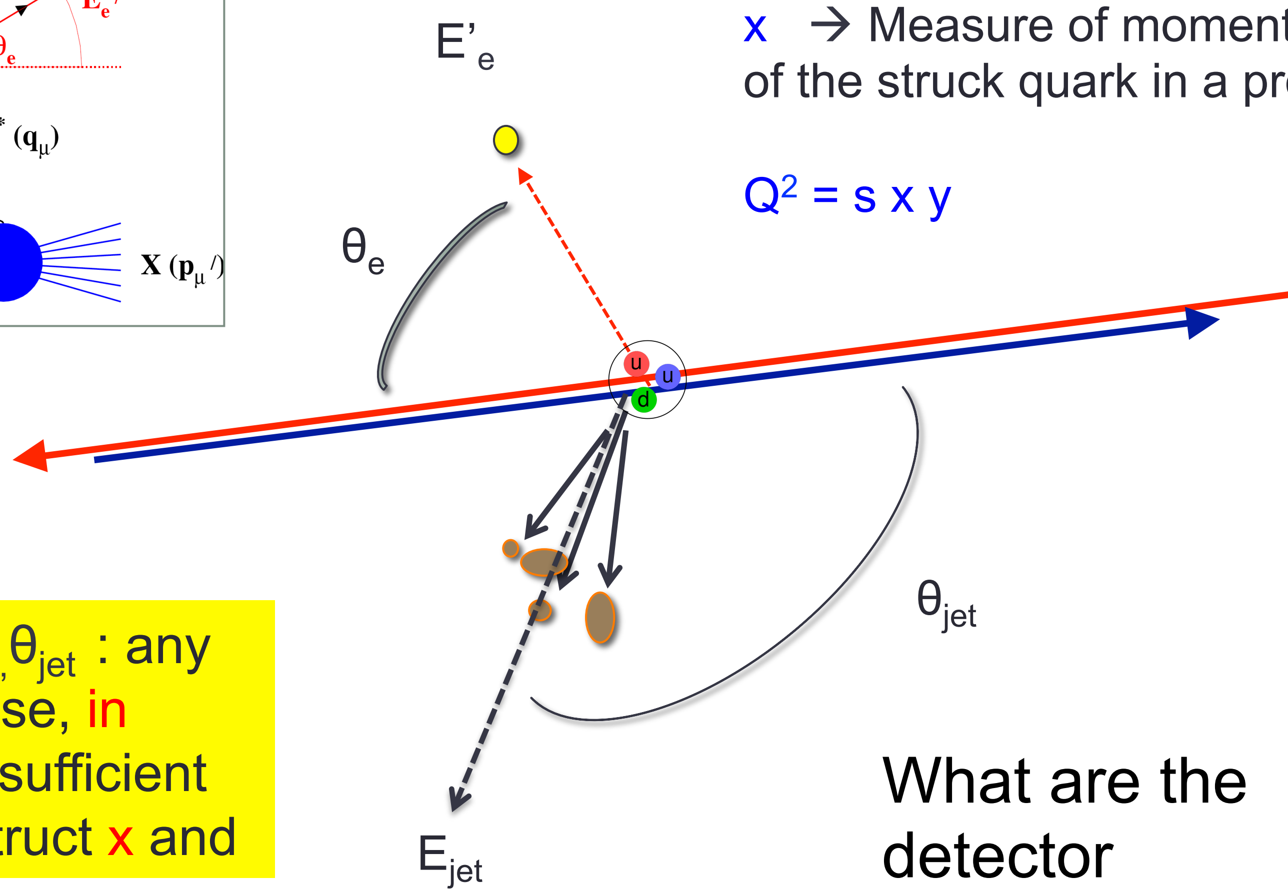
R.Yoshida, EICUG @ ANL

Basic Kinematic Reconstruction



Q^2 → Measure of resolution
y → Measure of inelasticity
x → Measure of momentum fraction of the struck quark in a proton

$Q^2 = s\,x\,y$



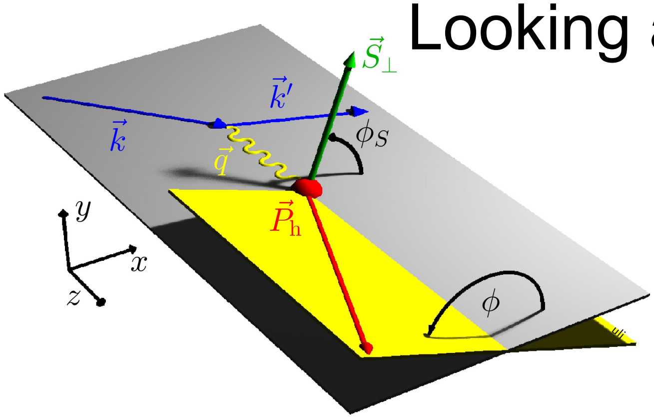
$E'_e, \theta_e, E_{jet}, \theta_{jet}$: any two of these, in principle, sufficient to reconstruct x and Q^2.

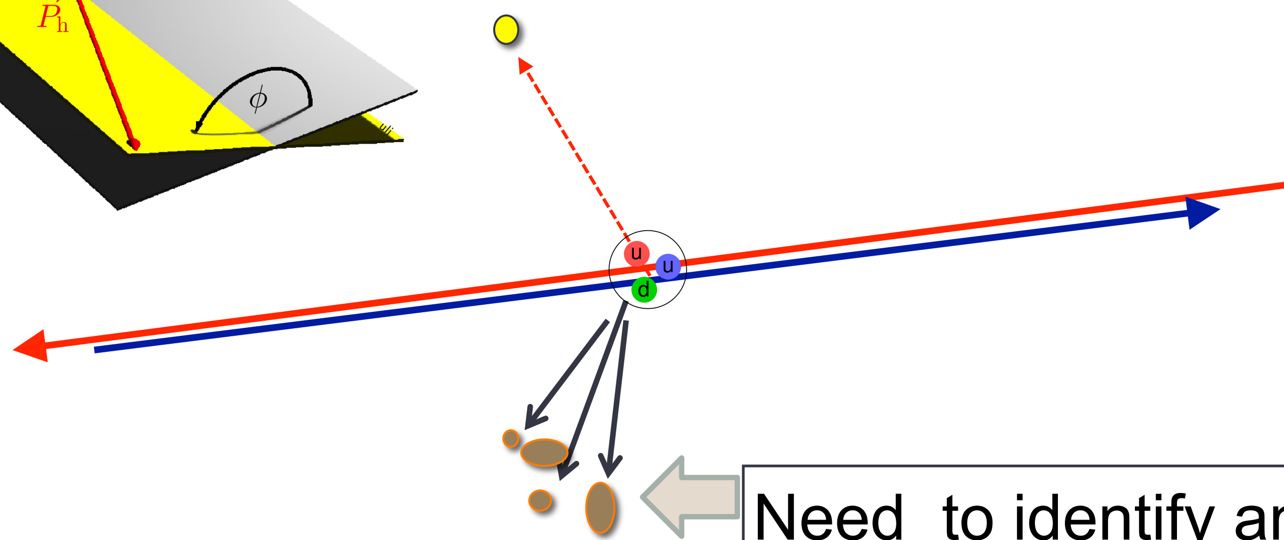
What are the detector requirements?

R.Yoshida, EICUG @ ANL

Reconstruction for Transvers Structure

Looking at out-of –plane component in the final sta





Need to identify and measure
these particles

What are the detector requirements?

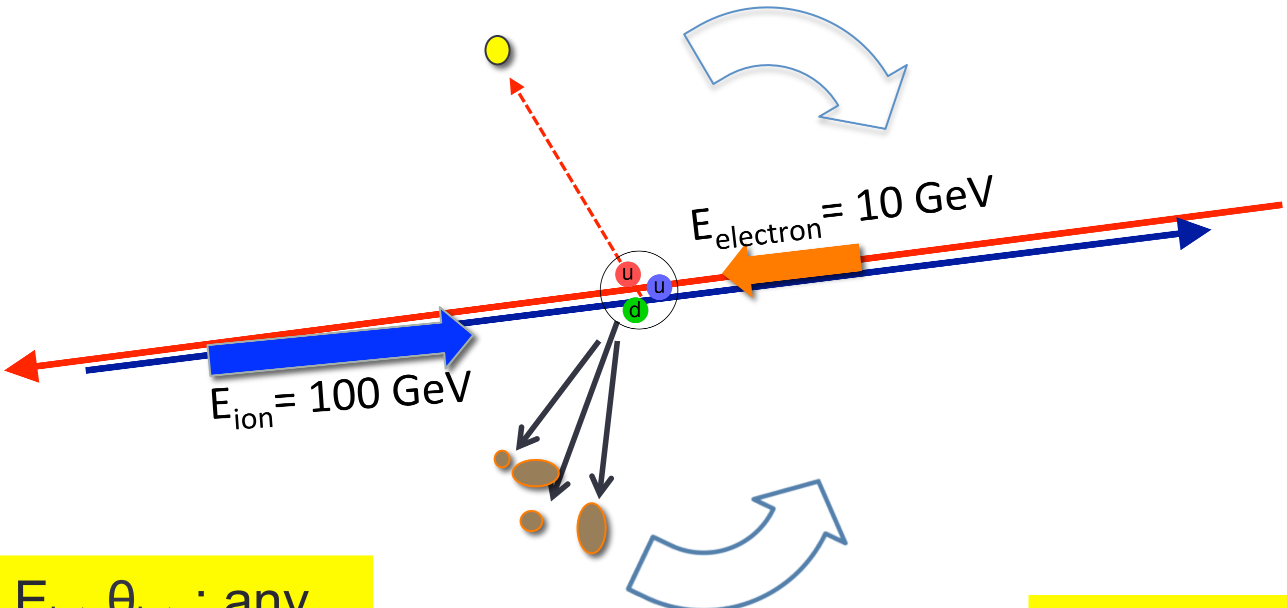
Note: multiplicities are low (~20 for ep)
Cross-sec x Lumi < 0.01 x HLLHC
< 0.1 interaction/crossing

R.Yoshida, EICUG @ ANL

How Boosted is the Final State?

No Monte Carlo needed to Determine

Boosted towards ion beam



$E'_e, \theta_e, E_{jet}, \theta_{jet}$: any two of these, in principle, sufficient to reconstruct x and Q^2.

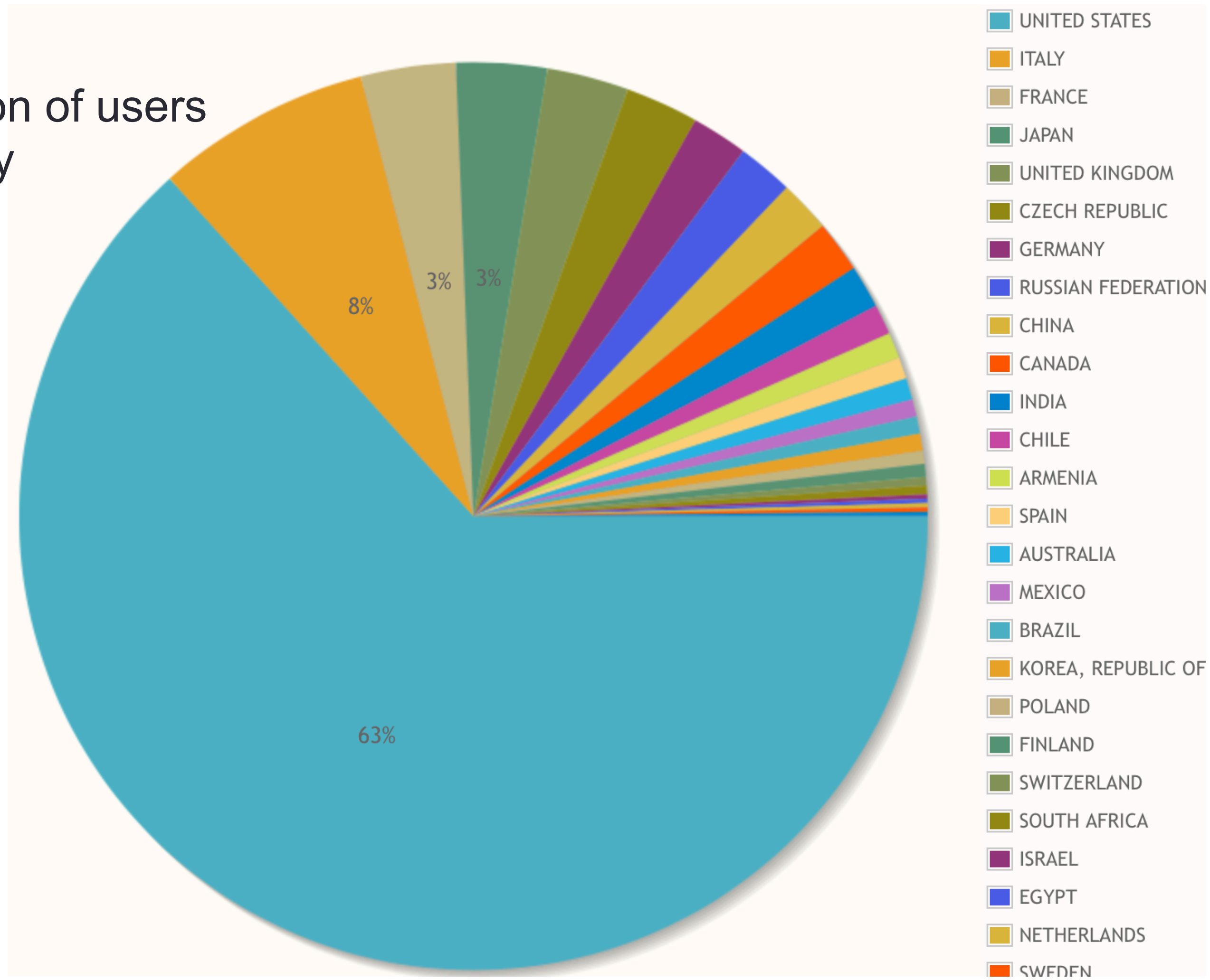
Given x and Q^2, **$E'_e, \theta_e, E_{jet}, \theta_{jet}$** are all fixed

R.Yoshida, EICUG @ ANL

EICUG Today: 651 Users, 142 Institutes, 27 Countries

350 experimentalists, 111 theorists, 141 accelerator-physicists, 43 unknowns

Distribution of users by country



Assumption: "Modest Growth" ➔ 1.6% growth/year above constant effort

The 2015 Long Range Plan for Nuclear Science

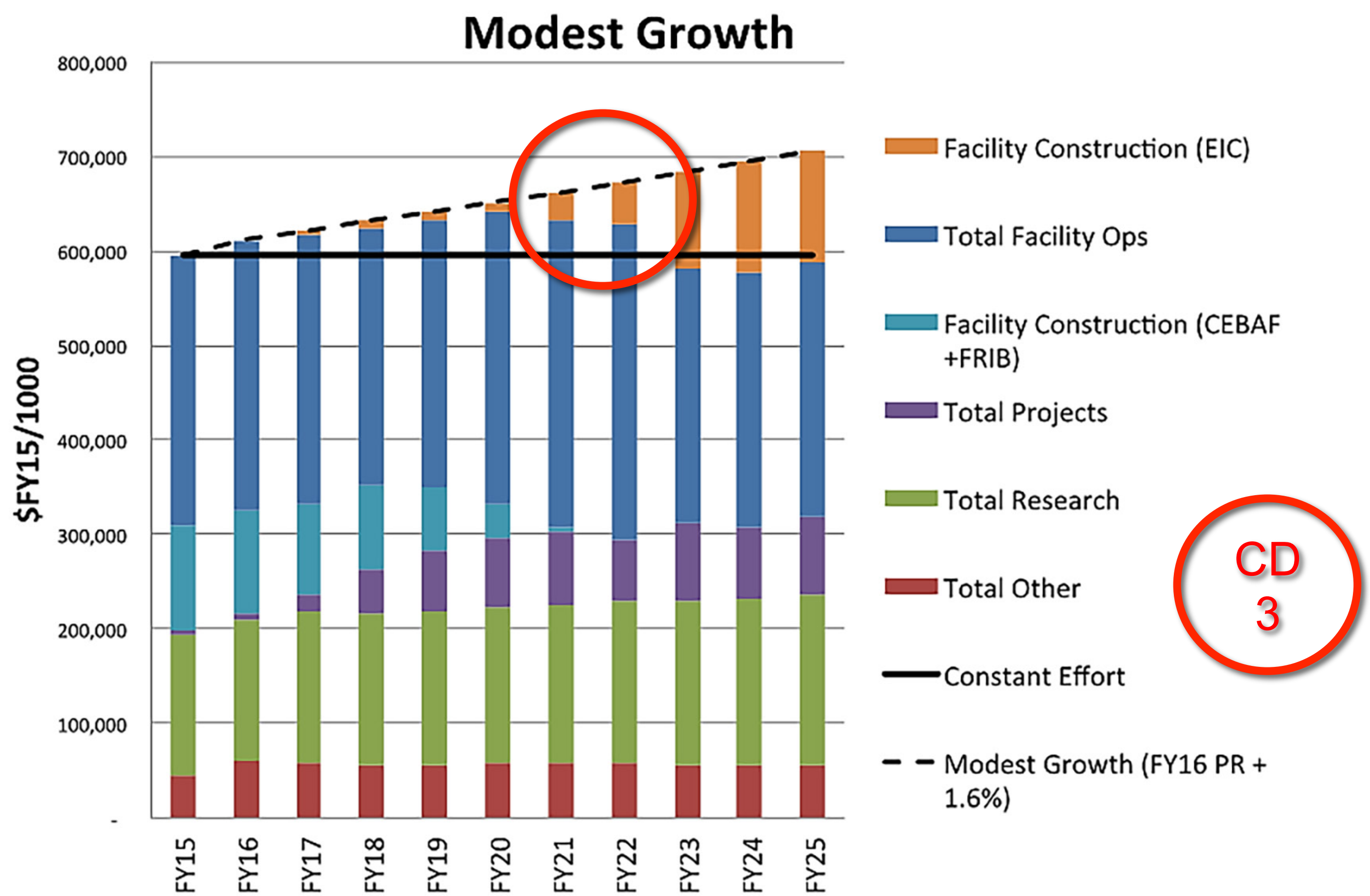


Figure 10.4: *DOE budget in FY 2015 dollars for the Modest Growth scenario.*