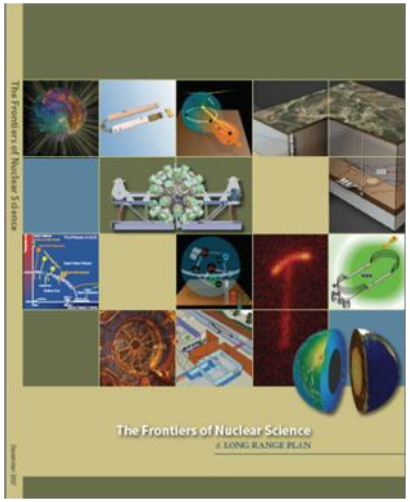
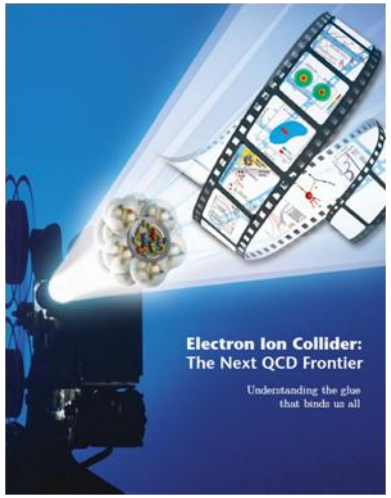
MEIC Physics

Tanja Horn for the MEIC group

THE CATHOLIC UNIVERSITY of AMERICA



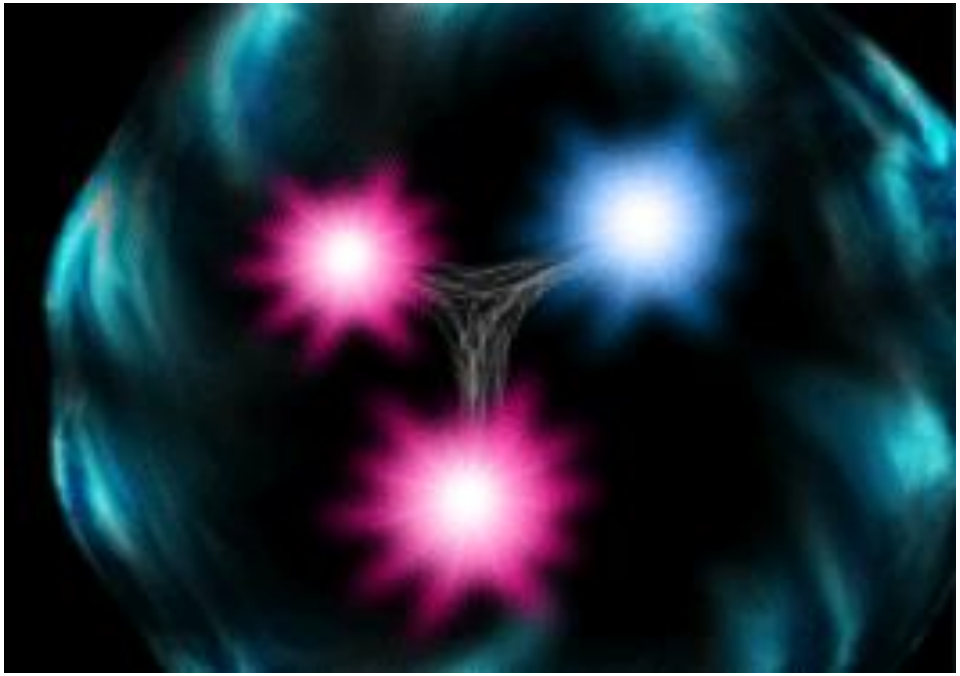


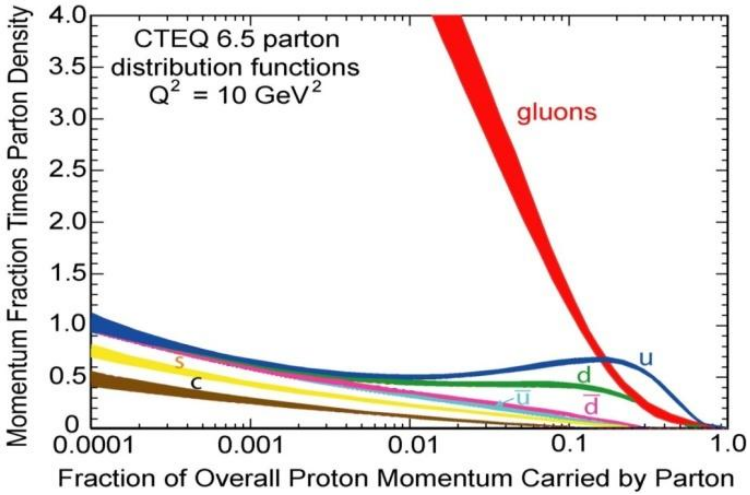
The Structure of the Proton

Naïve Quark Model: proton = uud (valence quarks)

QCD: proton = $uu\bar{d} + u\bar{u} + d\bar{d} + ss + \ldots$

The proton sea has a non-trivial structure: $\bar{u} \neq \bar{d}$ and gluons are abundant

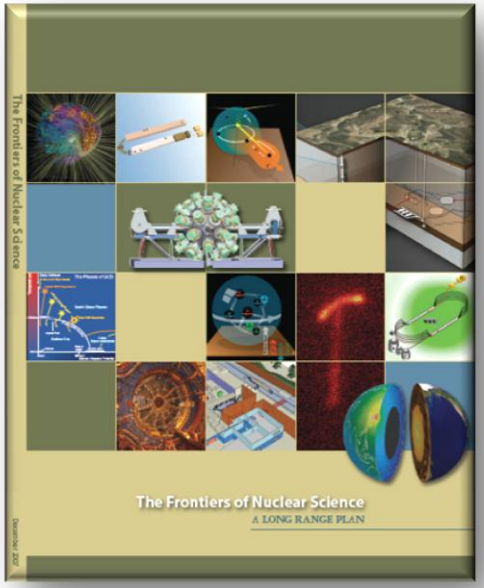




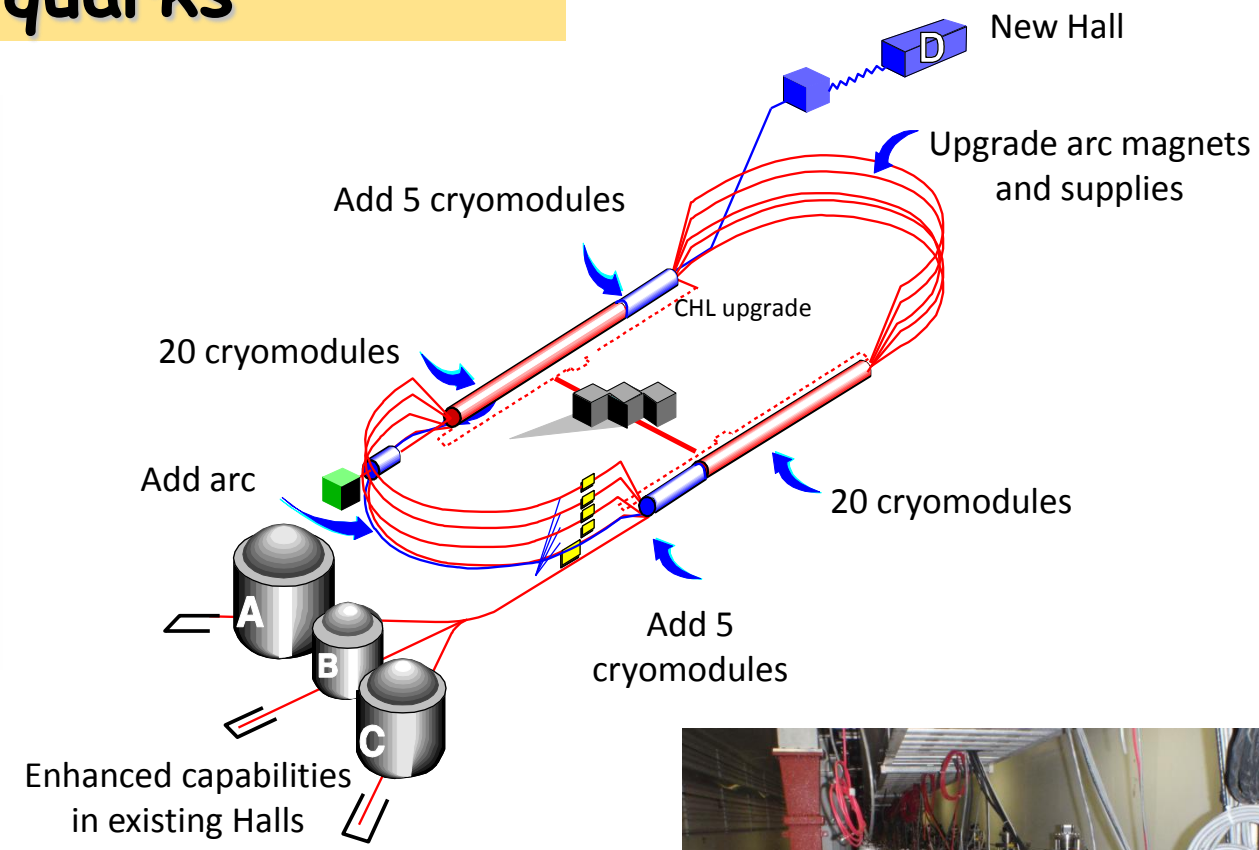
The proton is **far more** than just its up + up + down (valence) quark structure

Nuclear physicists are trying to answer how basic properties like mass, shape, and spin come about from the flood of gluons, quark/anti-quark pairs, and a few ever-present quarks.

Jlab 12 GeV – probing the valence quarks



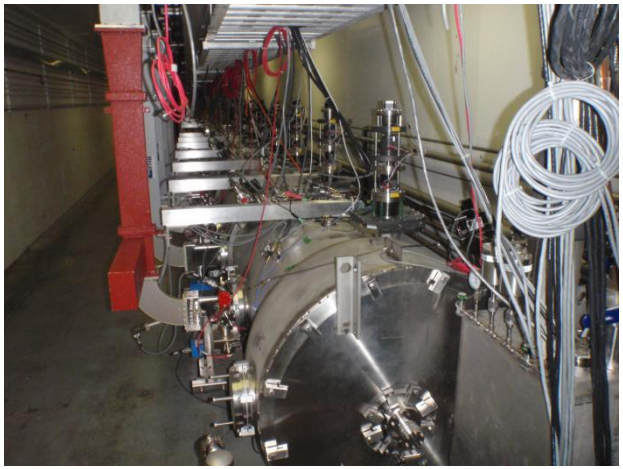
The completion of the 12 GeV Upgrade of CEBAF was ranked the highest priority in the 2007 NSAC Long Range Plan.



Scope of the project includes:

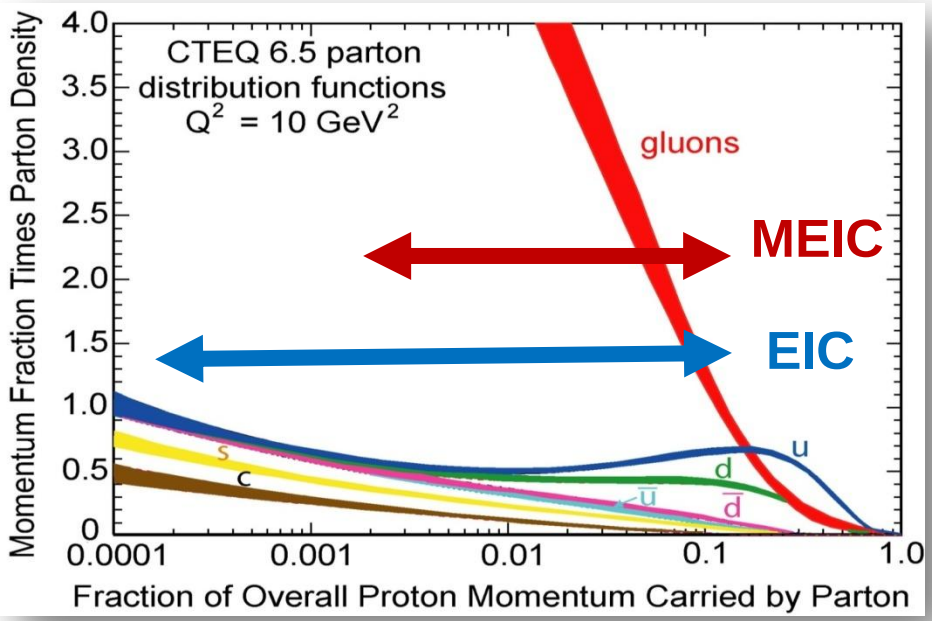
- Doubling the accelerator beam energy
- New experimental Hall and beam line
- Upgrades to existing Experimental Halls

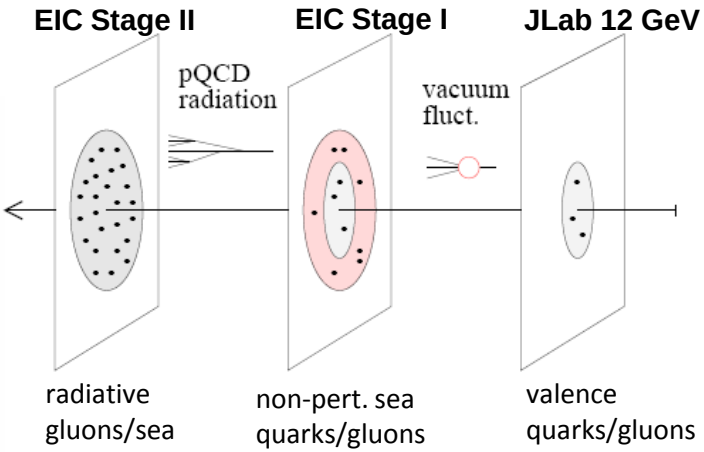
New C100 cryomodules in llinac tunnel

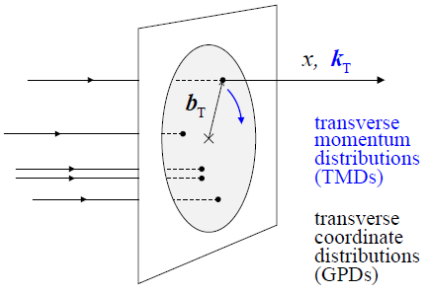


EIC – probing the sea

- ("Medium-Energy") MEIC@JLAB energy choices driven by:
  access to sea quarks and gluons
  - s=few 100- few 1000 GeV^2 allows access to gluons, shadowing



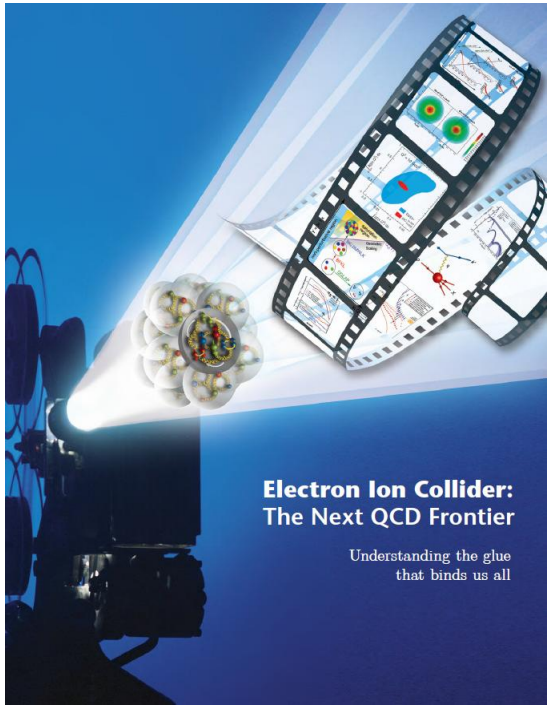




EIC aims to study the sea quark and gluon dominated matter

To cover the physics we need…

arXiv:1212.17010 (v2)

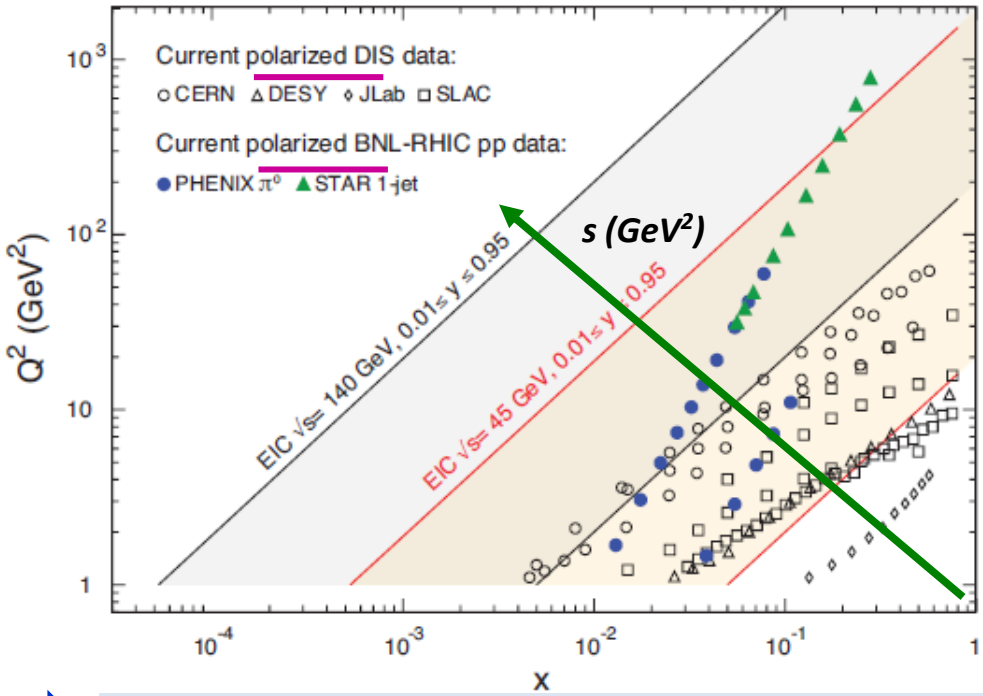


$Q^2 \sim ysx$

(x,Q^2) phase space directly correlated with s ($=4E_eE_p$) :

@ $Q^2 = 1$ lowest x scales like s^{-1}

@ $Q^2 = 10$ lowest x scales as $10s^{-1}$



Two stages:

√s ~ 45 (stage-1)

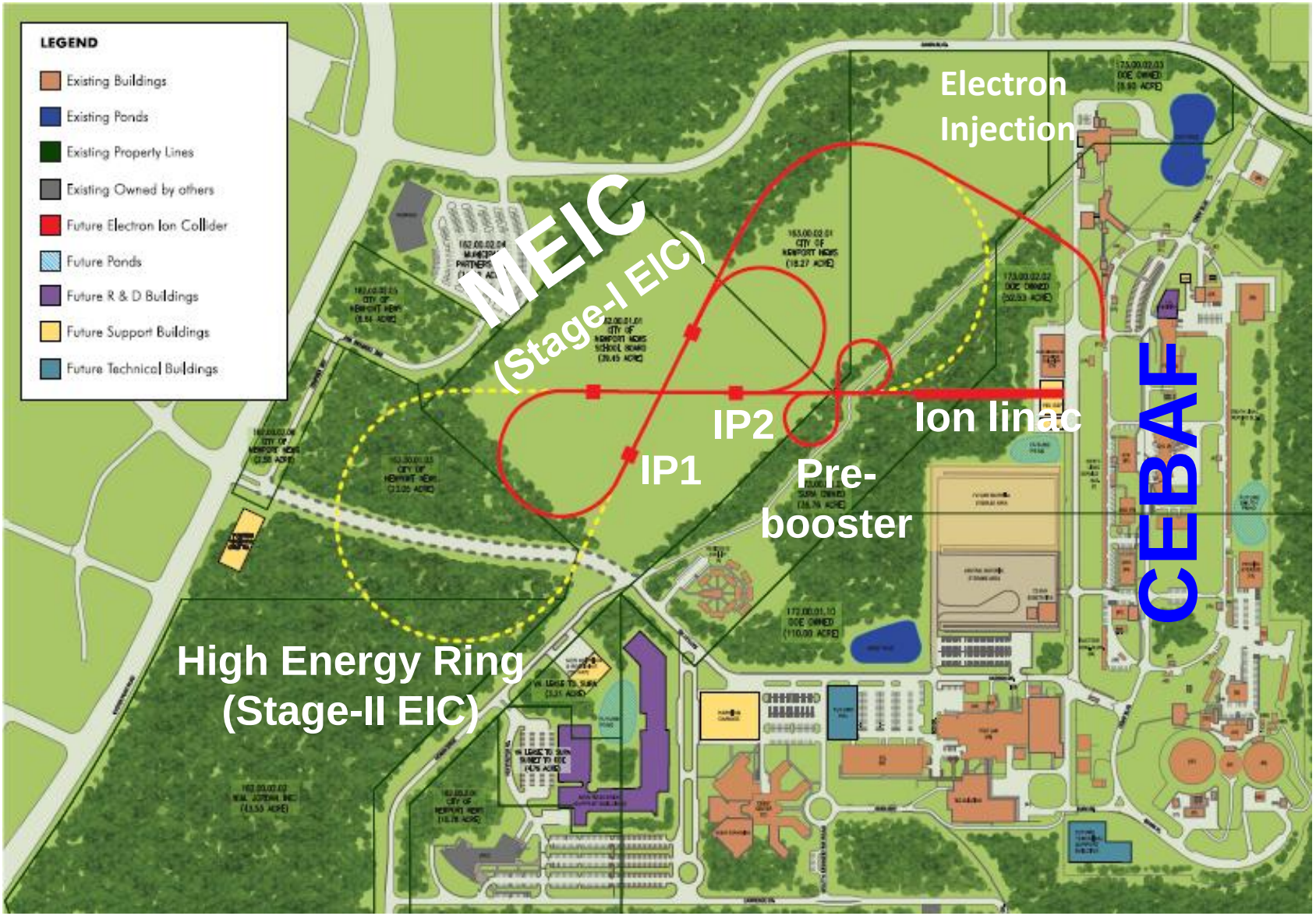
√s ~ 140 (stage-2)

Need for:

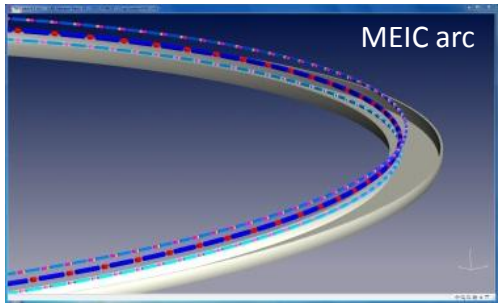
- ❑ variable energies
- ❑ polarized luminosity over full range of energies

Fixed target equivalent: $s = 2\,E_e M_p = 2 \times 1066 \times 0.938 = 2000\ \mathrm{GeV}^2$

MEIC Accelerator Layout at JLab

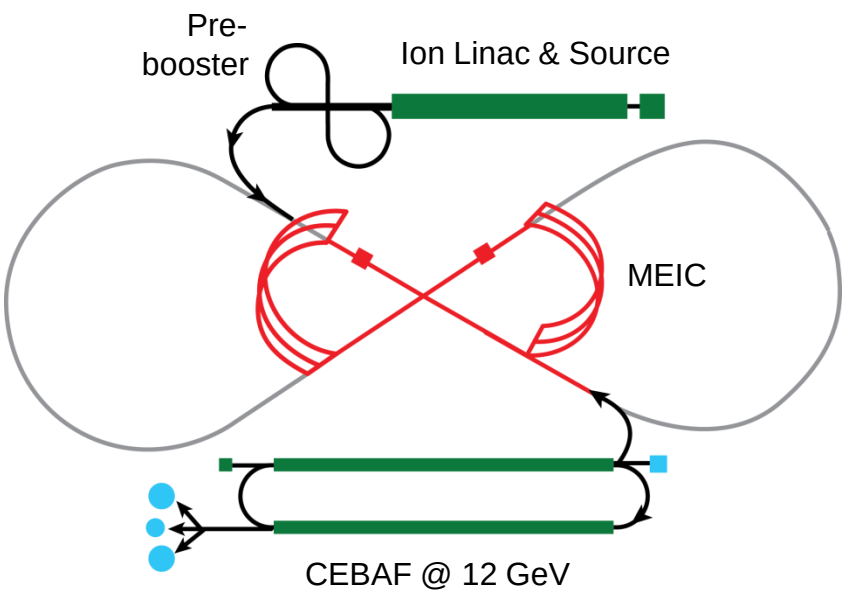


MEIC – a Figure-8 Ring-Ring Collider



Design allows for:

- *Simultaneous* use of *two* full acceptance detectors
- Longitudinal and *transverse* polarization of light ions
  - Proton, *deuterium*, ^{3}He, *etc.*
- Longitudinally *polarized* leptons
  - Electrons and *positrons*
- Running fixed-target experiments in parallel with collider



Reduced R&D challenges

- Regular electron cooling
- Regular electron source
- No multi-pass Energy-Recovery Linac (ERL)
- No space-charge compensation

MEIC Design Report

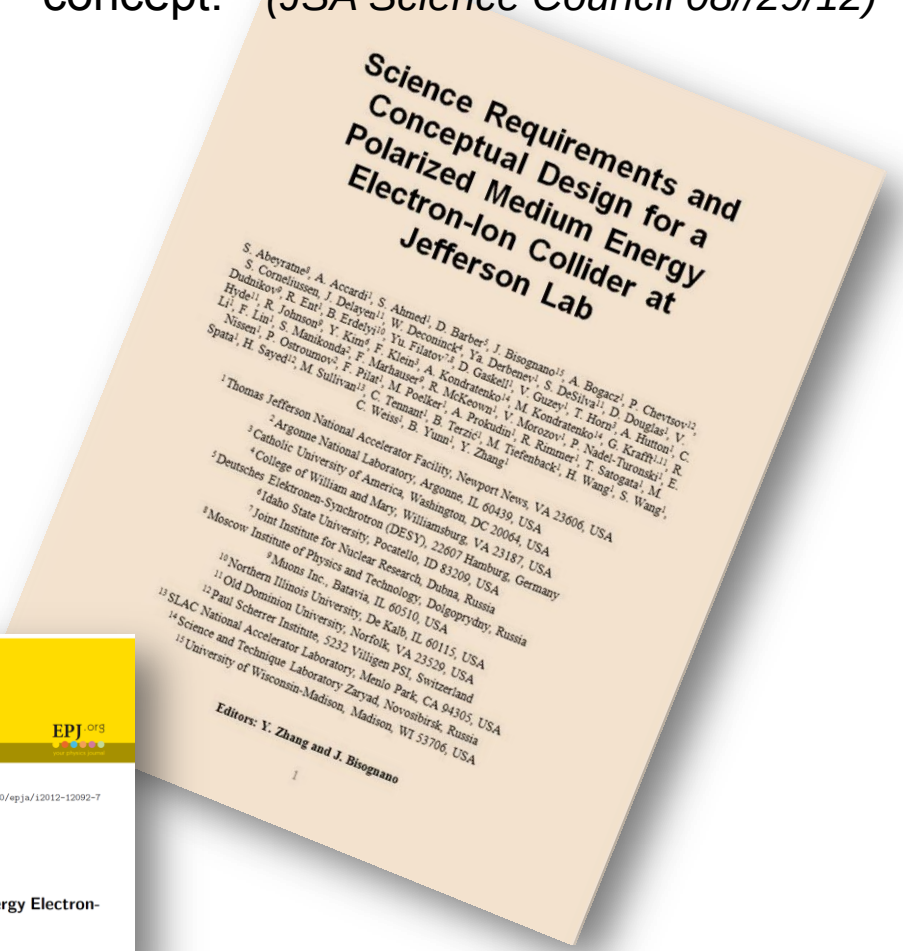
- **Posted: arXiv:1209.0757**
- **Stable concept for 3 years**

"world's first polarized e-p collider and world's first e-A collider"

"… was impressed by the outstanding quality of the present MEIC design"
"The report is an excellent integrated discussion of all aspects of the MEIC concept." *(JSA Science Council 08//29/12)*

Overall MEIC design features:

- **Highly polarized (including D)** →
- **Full acceptance & high luminosity**
- **Minimize technical risk and R&D**



Science Requirements and Conceptual Design for a Polarized Medium Energy Electron-Ion Collider at Jefferson Lab

S. Abeyratne[8], A. Accardi[1], S. Ahmed[1], D. Barber[5], J. Bisognano[15], A. Bogacz[1], P. Chevtsov[12], S. Corneliussen, J. Delayen[11], W. Deconinck[4], Ya. Derbenev[1], S. DeSilva[11], D. Douglas[1], V. Dudnikov[9], R. Ent[1], B. Erdelyi[10], Yu. Filatov[7,8], D. Gaskell[1], V. Guzey[1], T. Horn[3], A. Hutton[1], C. Hyde[11], R. R. Johnson[9], Y. Kim[5], F. Klein[3], A. Kondratenko[14], M. Kondratenko[14], G. Krafft[1,11], R. Li[1], F. Lin[1], S. Manikonda[2], F. Marhauser[9], R. McKeown[1], V. Morozov[1], P. Nadel-Turonski[1], E. Nissen[1], P. Ostroumov[2], F. Pilat[1], M. Poelker[1], A. Prokudin[1], R. Rimmer[1], T. Satogata[1], M. Spata[1], H. Sayed[12], M. Sullivan[13], C. Tennant[1], B. Terzić[1], M. Tiefenback[1], H. Wang[1], S. Wang[1], C. Weiss[1], B. Yunn[1], Y. Zhang[1]

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Editors: Y. Zhang and J. Bisognano

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EPJ A Hadrons and Nuclei

EPJ org

Eur. Phys. J. A (2012) **48**: 92 DOI 10.1140/epja/i2012-12092-7

Nuclear physics with a medium-energy Electron-Ion Collider

A. Accardi, V. Guzey, A. Prokudin and C. Weiss

EPJA article by JLab theory on MEIC science case (arXiv:1110.1031; EPJ A48 (2012) 92)

Physics Program of an EIC

Map the spin and spatial structure of quarks and gluons in nucleons

- How much spin is carried by gluons?
- Does orbital motion of sea quarks contribute to spin?
  - Generalized Parton Distribution (GPDs)
  - Transverse Momentum Distributions (TMDs)
- What do the partons reveal in transverse momentum and coordinate space

Needs high luminosity and range of energies

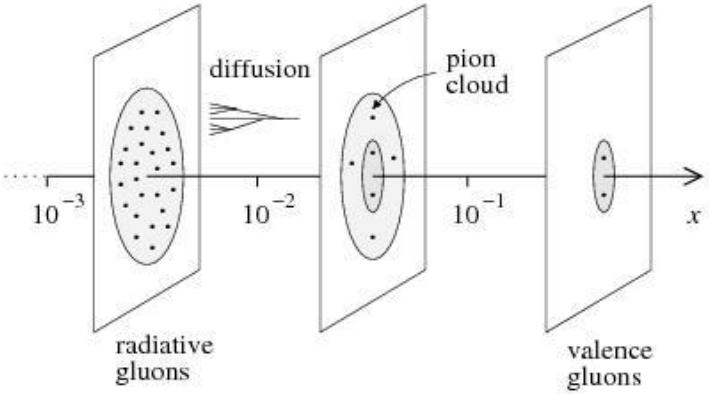
Discover the collective effects of gluons in atomic nuclei

- What is the distribution of glue in nuclei?
- Are there modifications as for quarks?
- Can we observe gluon saturation effects?

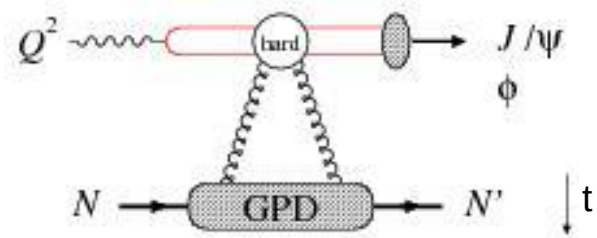
Understand the emergence of hadronic matter from color charge

- How do color charges evolve in space and time?
- How do partons propagate in nuclear matter?
- Can nuclei help reveal the dynamics of fragmentation?

Transverse Spatial Imaging of Sea quark and gluons



EIC: Gluon size from J/Ψ and ϕ electroproduction ($Q^2 > 10$ GeV^2)



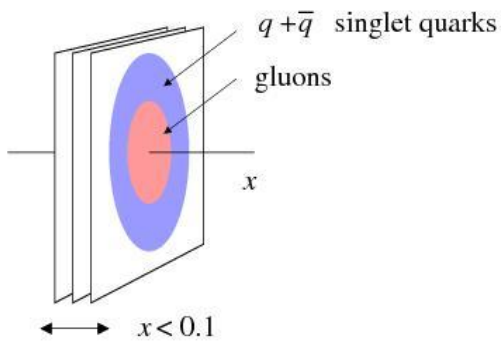
[Transverse distribution derived directly from t dependence]

Hints from HERA:

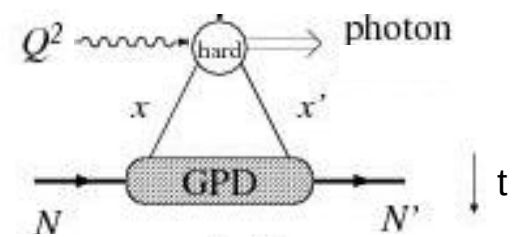
Area ($q + \bar{q}$) > Area (g)

Dynamical models predict difference:

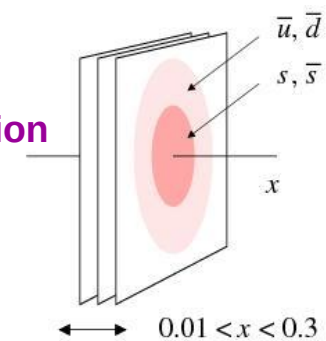
pion cloud, constituent quark picture



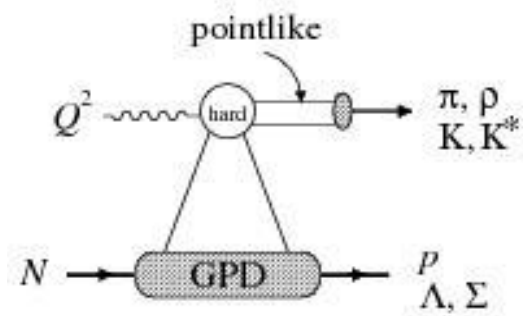
Are radii of quarks and gluons different at a given x? – DVCS and J/Ψ



- **$Q^2 > 10$ GeV^2 for factorization**
- **Statistics hungry at high Q^2!**

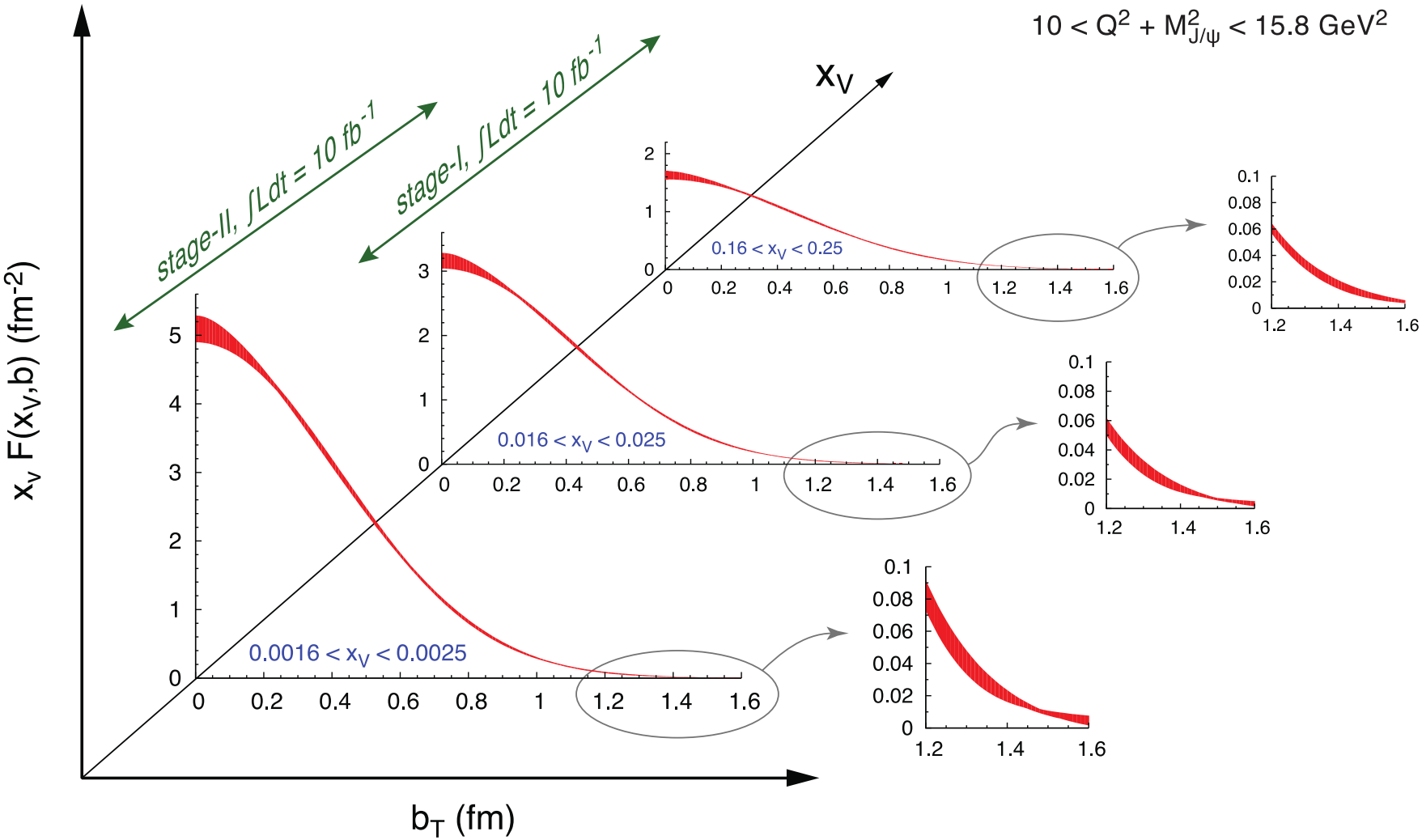


Are strange and non-strange (light sea) quark sizes different at given x? - π and K production

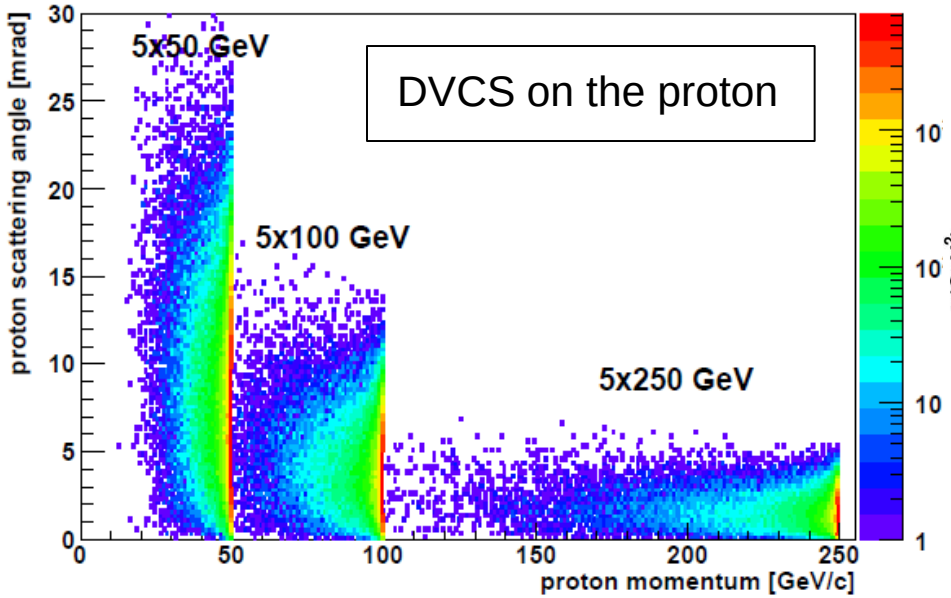


Full image of the proton can be obtained by mapping t-distributions for different processes.

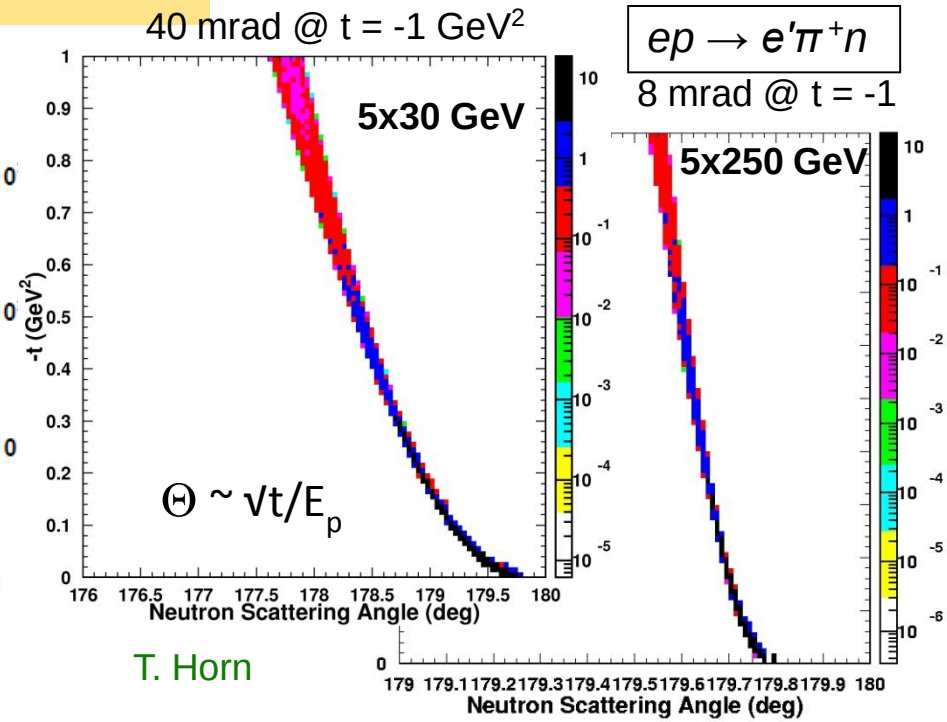
Example: Transverse Spatial Distribution of Gluons from J/Ψ



Transverse spatial imaging – recoil baryons



J.H. Lee

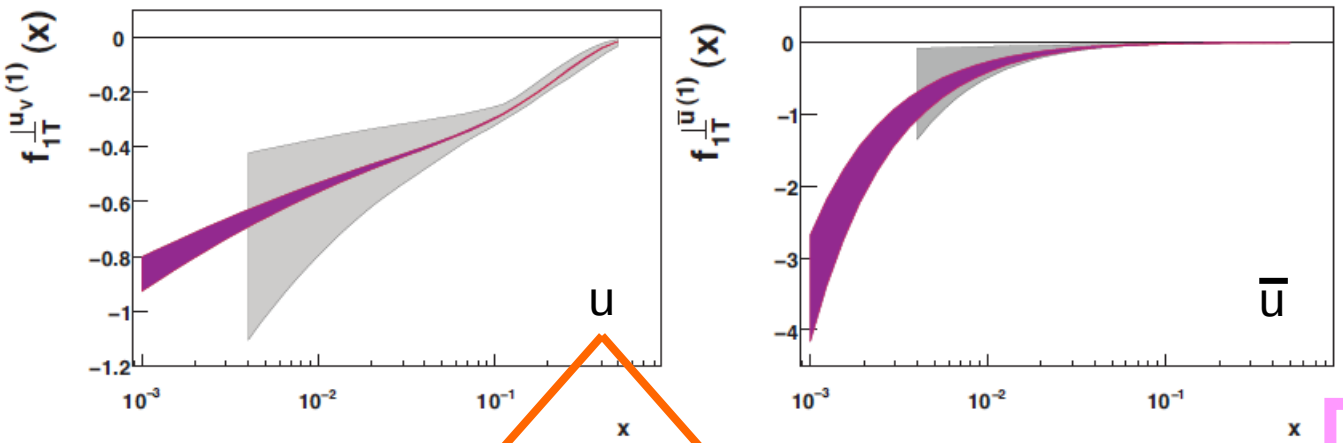


T. Horn

- Colliders allow straightforward detection of recoil baryons, making it (in principle) possible to map the t-distribution down to very low values of *–t*
- At very high proton energies, recoil baryons are all scattered at small angles
  - Moderate proton energies give the best resolution
- High luminosity at intermediate proton energies and *excellent* small-angle detection make the MEIC a perfect tool for imaging of the proton

TMDs: Imaging the Transverse Momentum of the Quarks

- TMDs encode the 3D partonic picture in momentum space

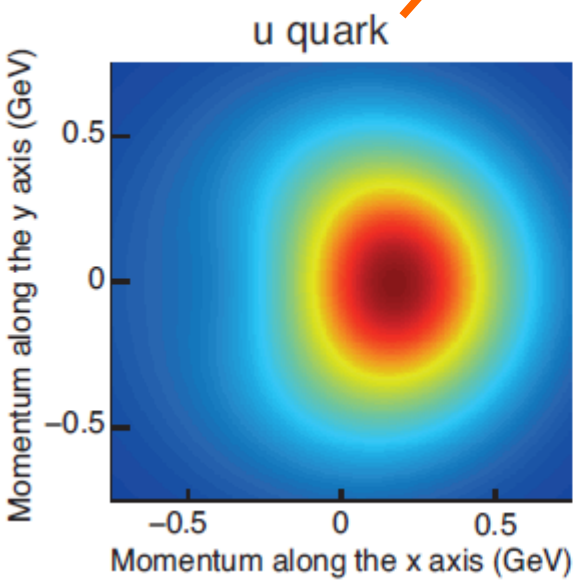


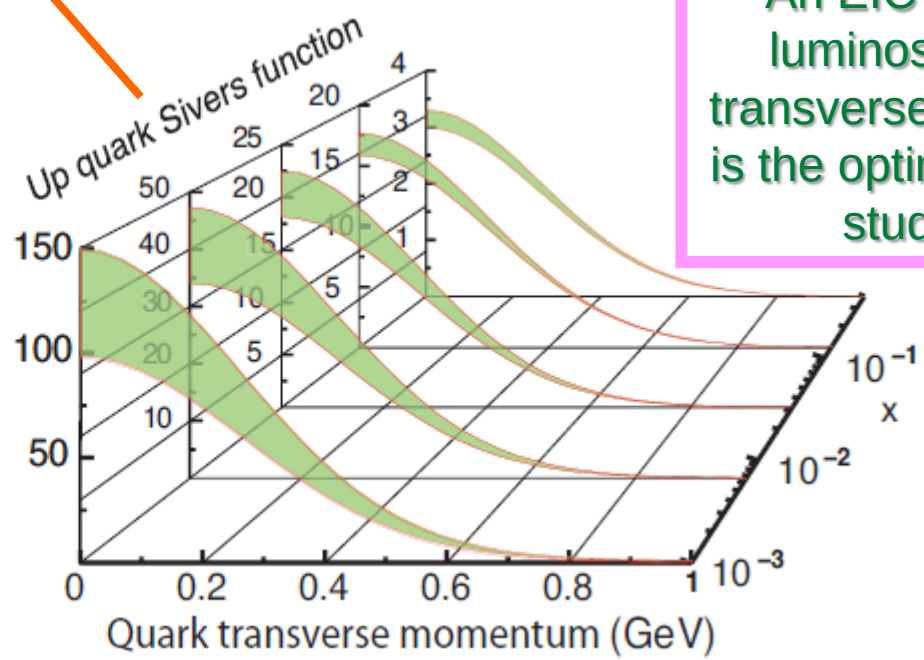
- Only a small subset of the (x,Q^2) landscape has been mapped here: **terra incognita**

Gray band: present "knowledge"

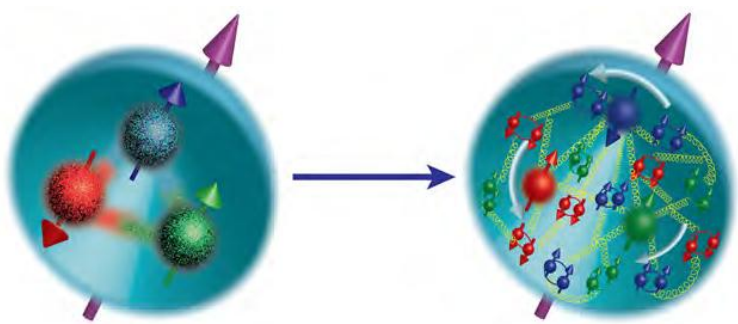
Purple band: EIC (2σ)

An EIC with good luminosity & high transverse polarization is the optimal tool to to study this!





The Spin Puzzle of the Proton



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + J_g$$

- $\Delta\Sigma \sim 0.25$ (world DIS)
- ΔG small (RHIC+DIS)
- L_q? J_g?

If we do not understand proton spin from QCD, we do not understand QCD!

- It is more than the number ½! It is the interplay between the intrinsic properties and interactions of quarks and gluons

Spin = intrinsic (parton spin) + motion (orbital angular momentum)

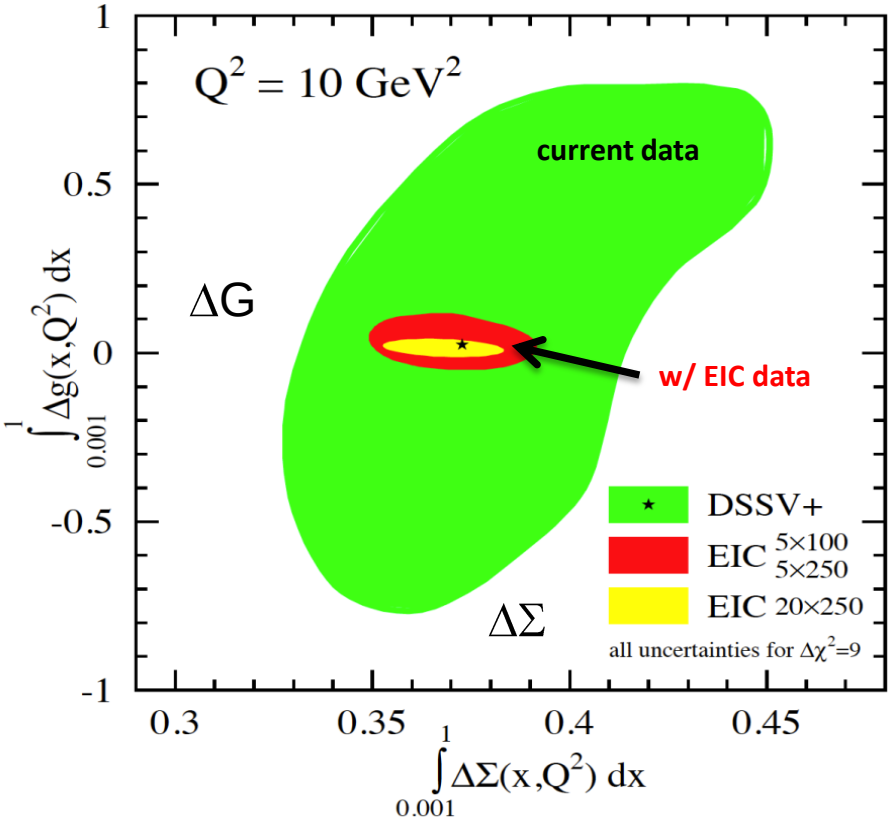
- Two complementary approaches to resolve proton spin puzzle

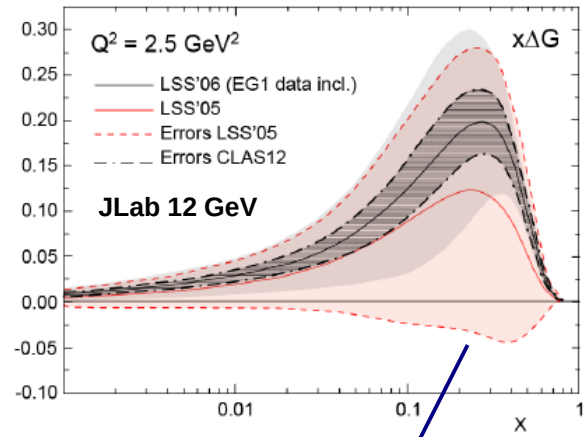
Measure Δg - Explore the "full" gluon and sea quark contribution

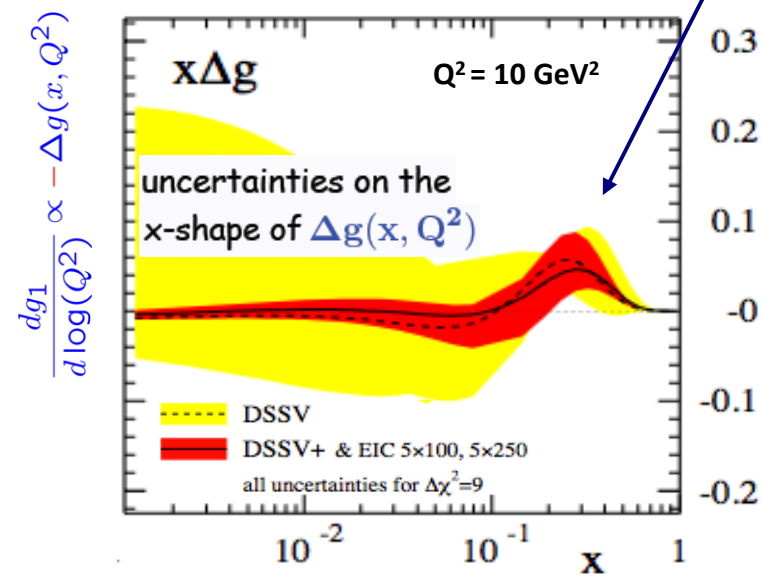
Measure TMD and GPDs - quantify the role of orbital motion

Helicity PDFs at an EIC

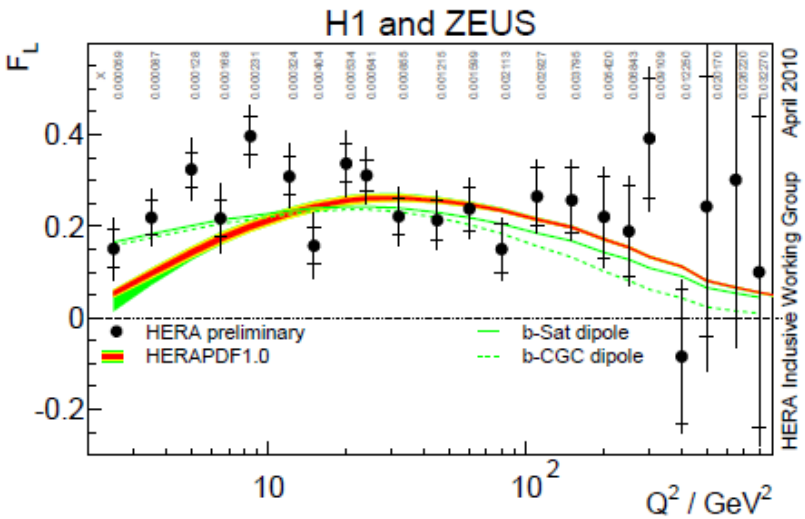
- Precision measurement of *Δg*:
  - stage I will greatly improve our understanding
  - stage II will further reduce uncertainty

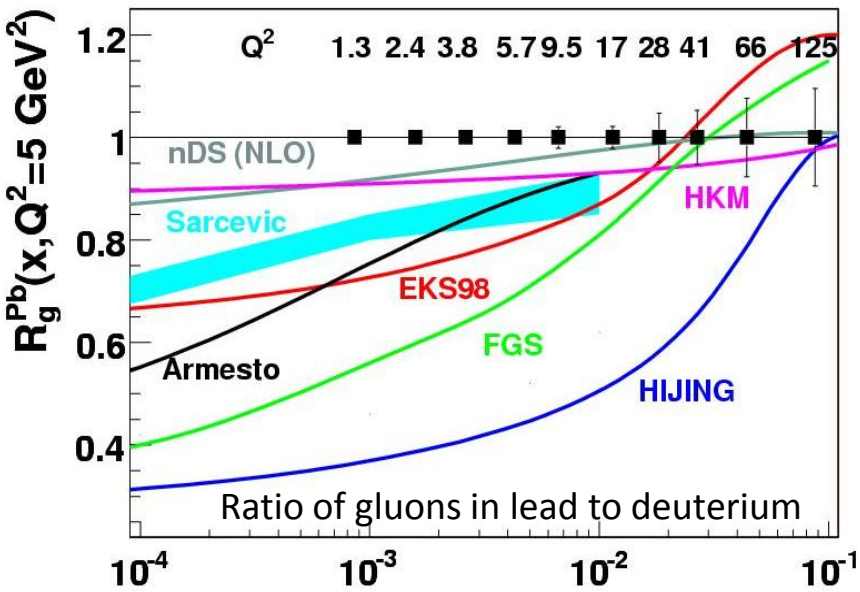






Gluons in nuclei

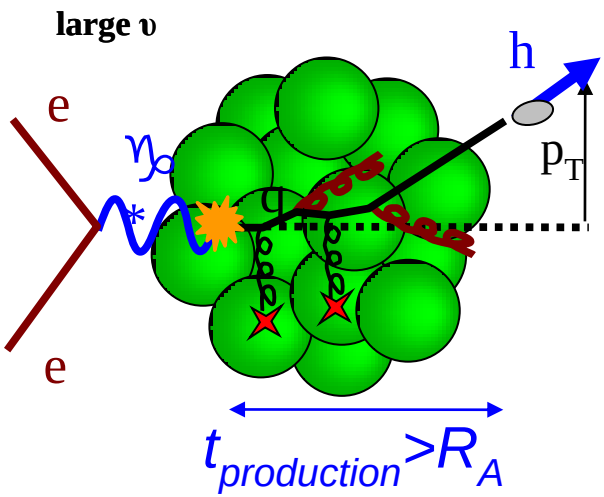


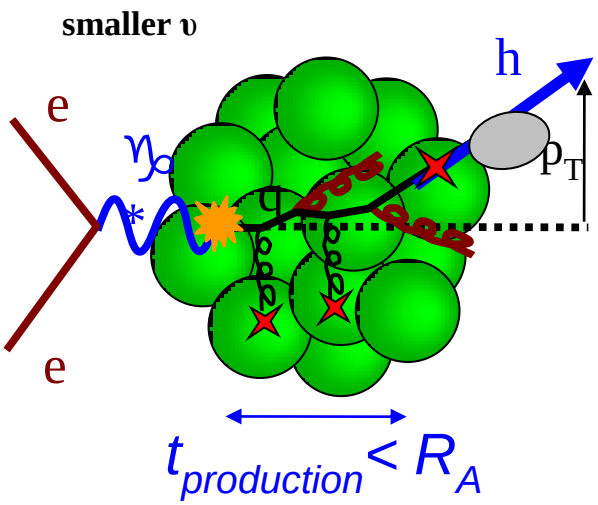


Guzey et al., Phys.Rept. 512 (2012) 255-393

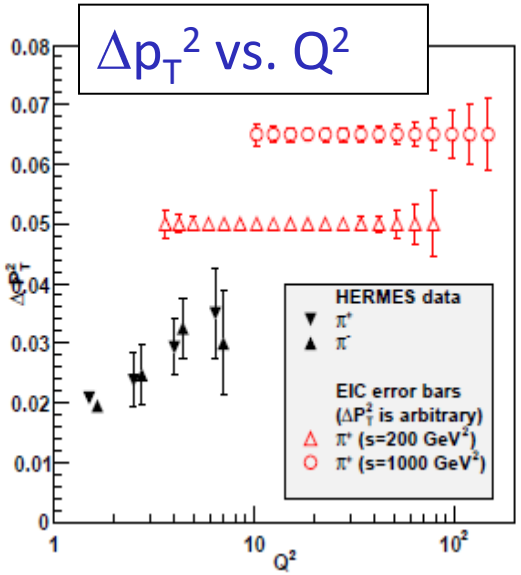
- HERA measured the longitudinal gluon distributions in the *nucleon*
  - F_L and $dF_2/dln(Q^2)$
- Very little is known about gluons in ***nuclei***
- EIC: access gluons through F_L (needs variable energy) and $dF_2/dln(Q^2)$
- Knowledge of gluon PDF essential for quantitative studies of onset of saturation

Hadronization – parton propagation in matter

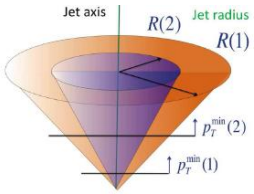




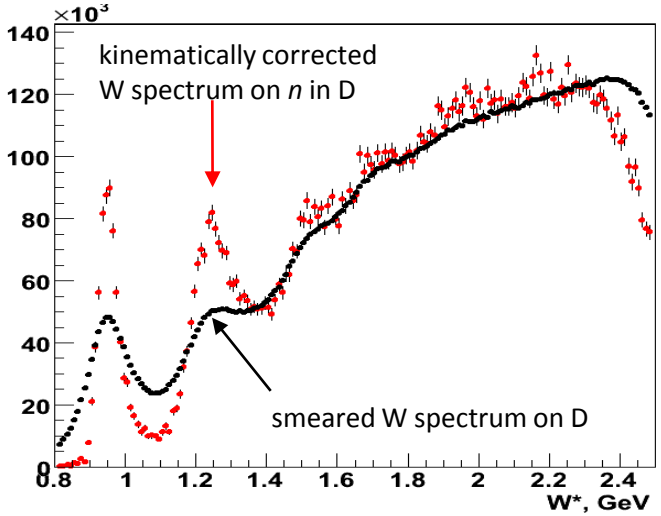
Accardi, Dupre



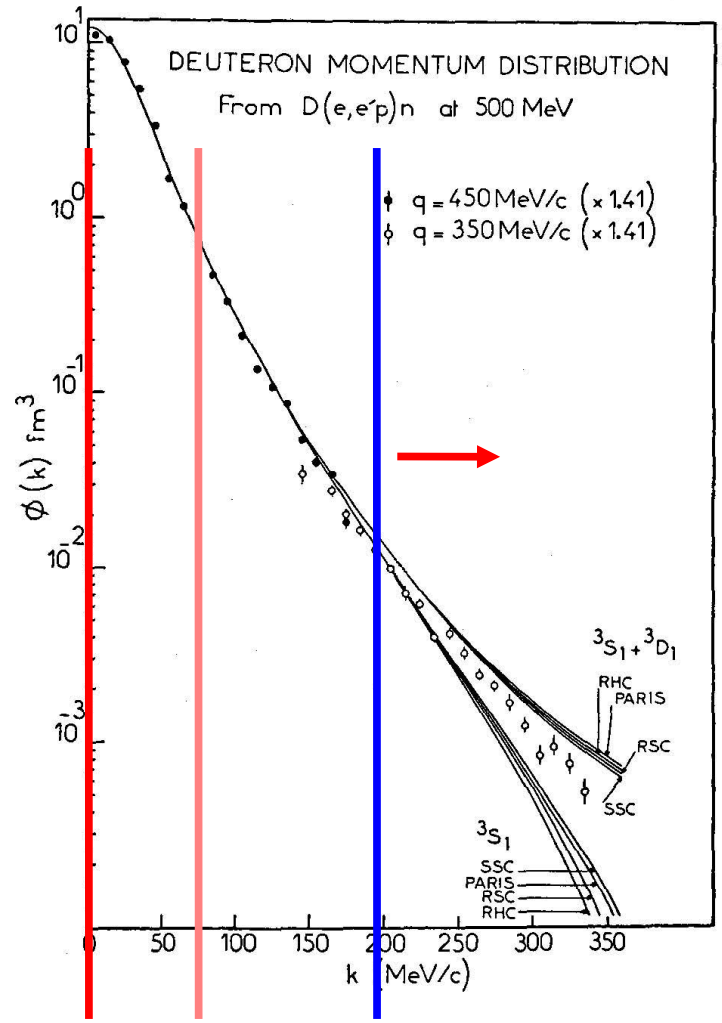
- p_T broadening strongly constrains theory
- Large range in υ at a collider allows
  - Isolation of pQCD energy loss (large υ)
  - Study of (pre)hadronization (smaller υ)
- Heavy flavors: B, D mesons, J/Ψ ...
- Jets above s = 1000 GeV^2
  - „real“ pQCD, IR safe



Neutron Structure through Spectator Tagging



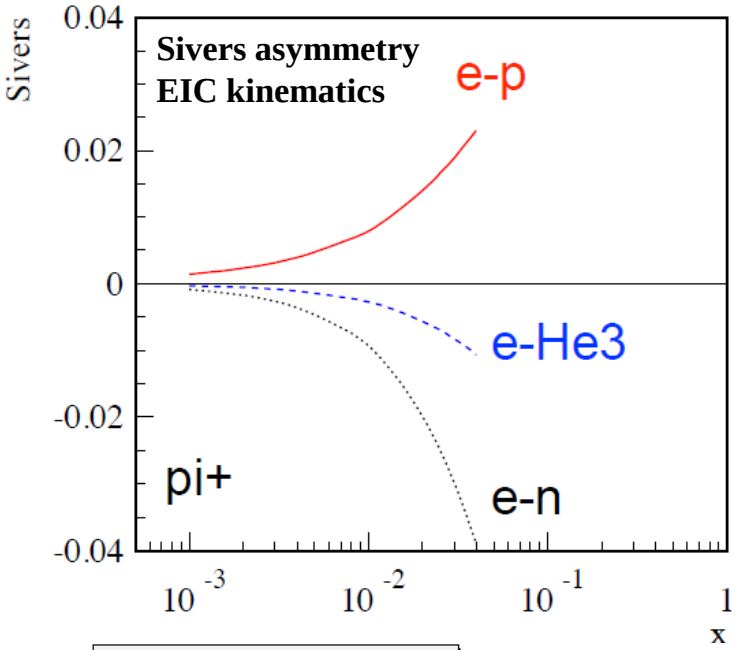
BoNuS data with tagged spectators

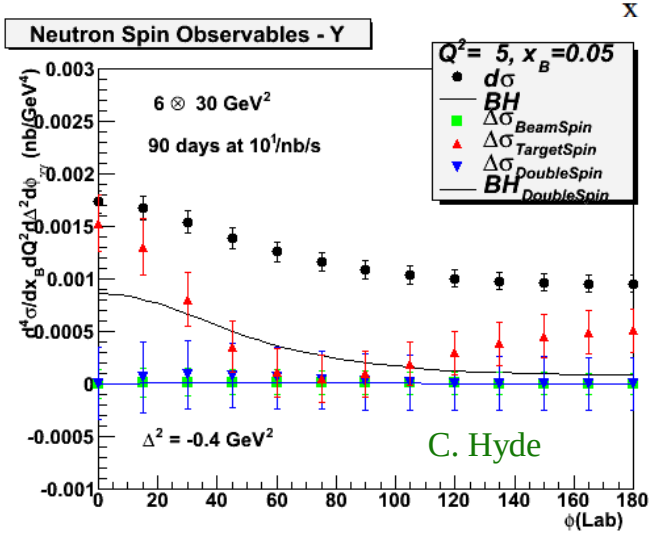


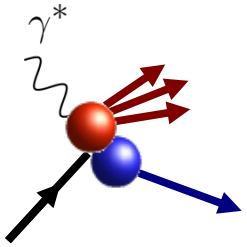
MEIC CLAS + BoNuS CLAS

- In fixed target experiments, scattering on bound neutrons is complicated
  - Fermi motion, nuclear effects
  - Low-momentum spectators
  - No polarization
- The MEIC is designed to tag spectators, and all nuclear fragments

Spectator Tagging with Polarized Deuterium







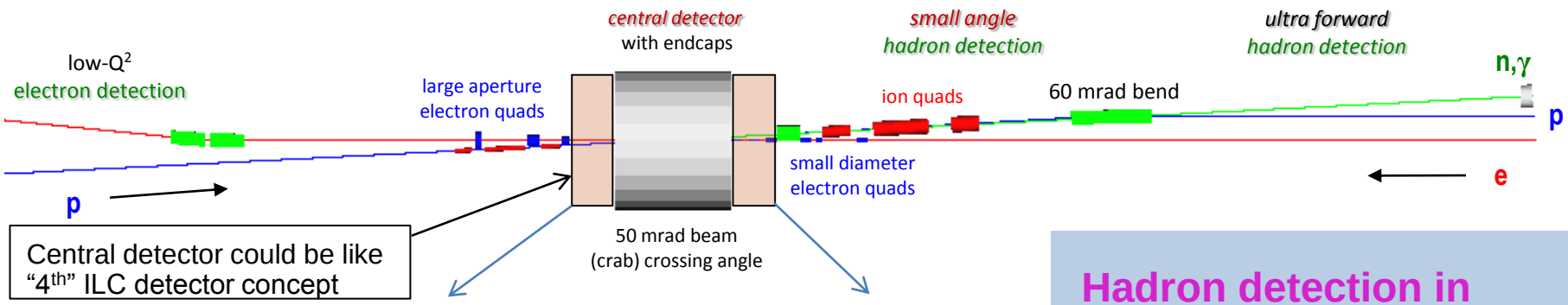
„If one could tag neutron, it typically leads to larger asymmetries“ Z. Kang

- MEIC will provide longitudinal and transverse polarization for d, ^{3}He, and other light ions
- Polarized neutrons are important for probing d-quarks through SIDIS
- Measurements of exclusive reactions like DVCS also greatly benefit from polarized neutron “targets“
  - *c.f.* Hall A and B programs at JLab

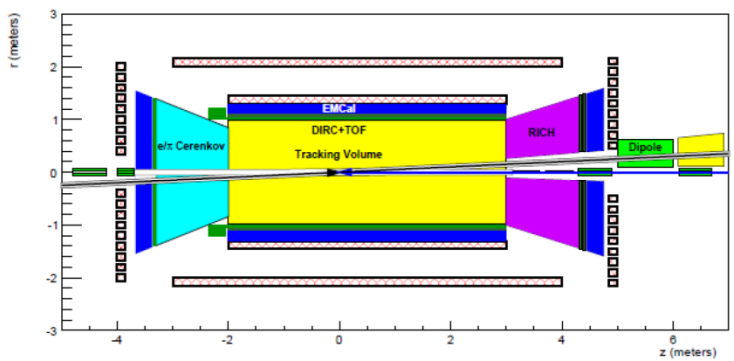
LDRD for polarized light nuclei at the EIC

Full-Acceptance Detector

In general, e-p and e-A colliders have a large fraction of their science related to the detection of what happens to the ion beams… spectator quark or struck nucleus remnants will go in the forward (ion) direction → this drives the **integrated** detector/interaction region design



Central detector could be like "4th" ILC detector concept



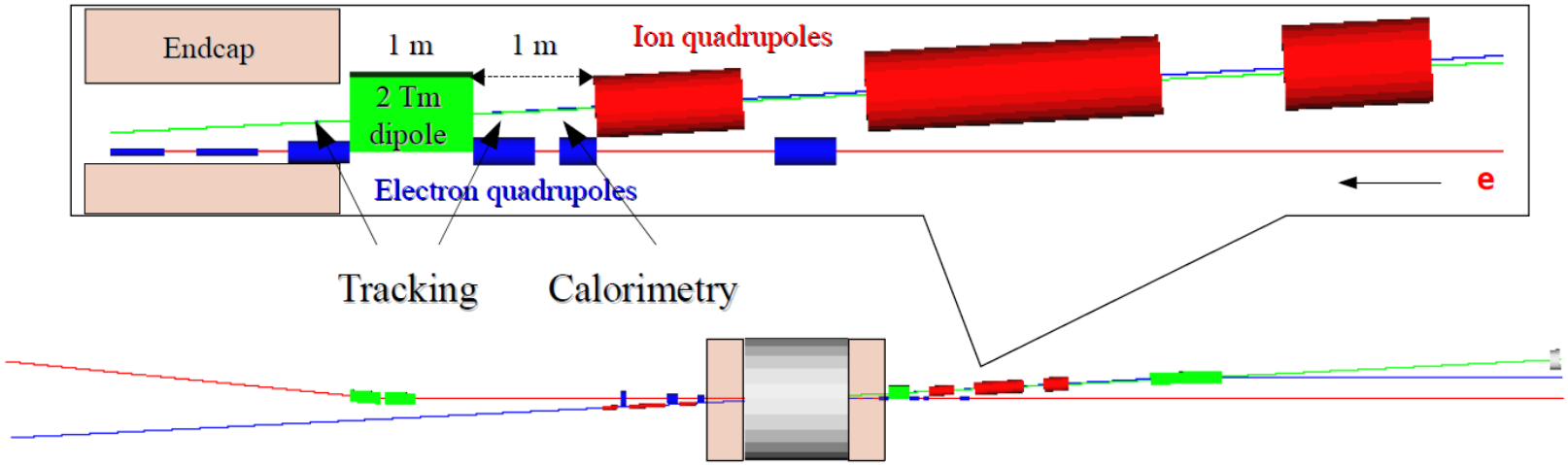
Dual-solenoid allows for a compact, low mass detector

- Easy end-cap integration (line of sight) and good access
- Easy integration with small-angle detectors on outgoing ion side (right)

Hadron detection in three stages

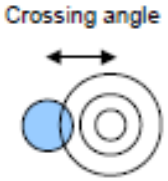
- ❑ Endcap with 50 mrad crossing angle
- ❑ Small dipole covering angles to a few degrees
- ❑ Ultra-forward up to one degree, for particles passing the accelerator quads

Forward Hadron detection with crossing angle



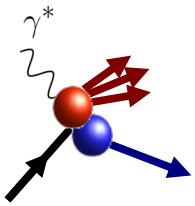
Large crossing angle (50 mrad)

- Moves spot of poor resolution along solenoid axis into the periphery
- Minimizes shadow from electron FFQ

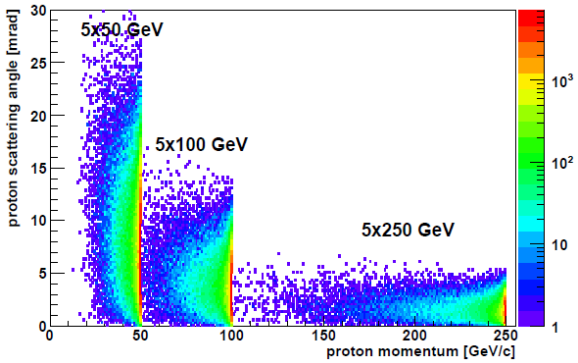


Ultra-forward Hadron detection requirements

- **Good acceptance for ion fragments (different rigidity from beam)**
  - Large downstream magnet apertures
  - Small downstream magnet gradients (realistic peak fields)
  - Roman pots not needed



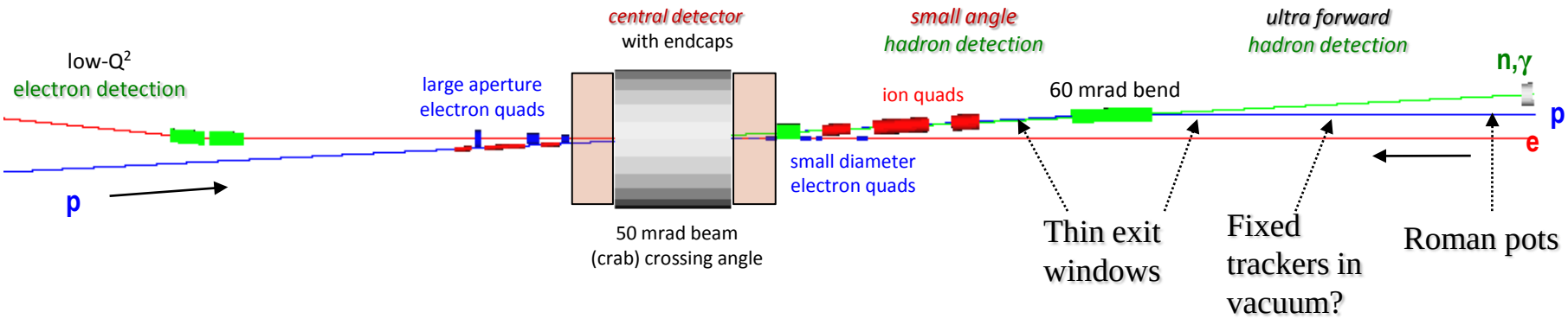
- **Good acceptance for recoil baryons (rigidity similar to beam)**
  - Small beam size at second focus (to get close to the beam)
  - Large dispersion (to separate scattered particles from the beam)
  - Roman pots important



- **Good momentum and angular resolution**
  - Large dispersion (e.g., 60 mrad bending dipole)
  - Long, instrumented magnet-free drift space

- Sufficient separation between beam lines (~1m)

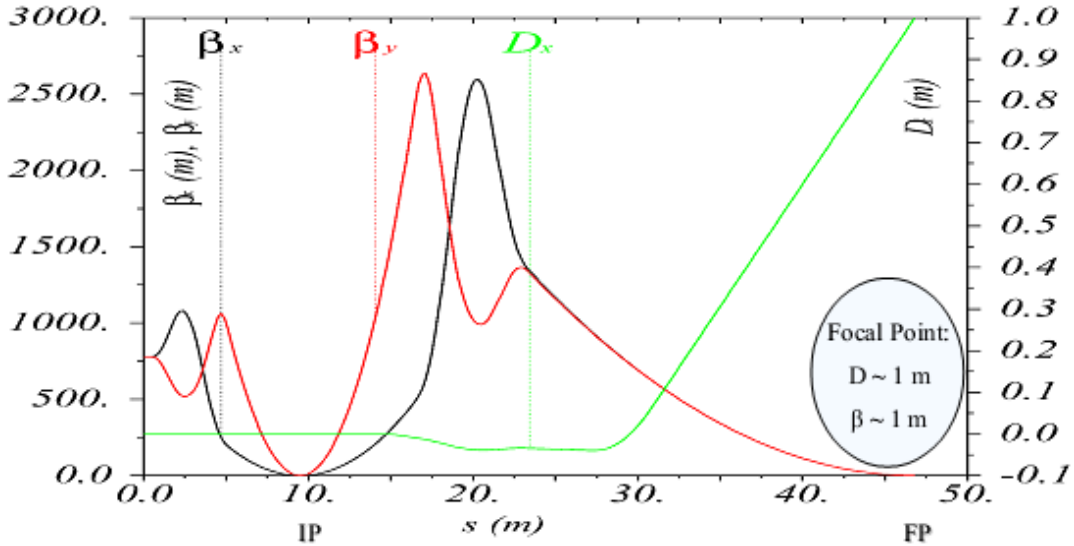
IR Optics for Ultra-Forward Particles



- Recoil baryon detection:

➢ Small beam size (β function) and large dispersion at the secondary focal point give excellent resolution and great acceptance at small angles

➢ **Excellent t-coverage at all kinematics**

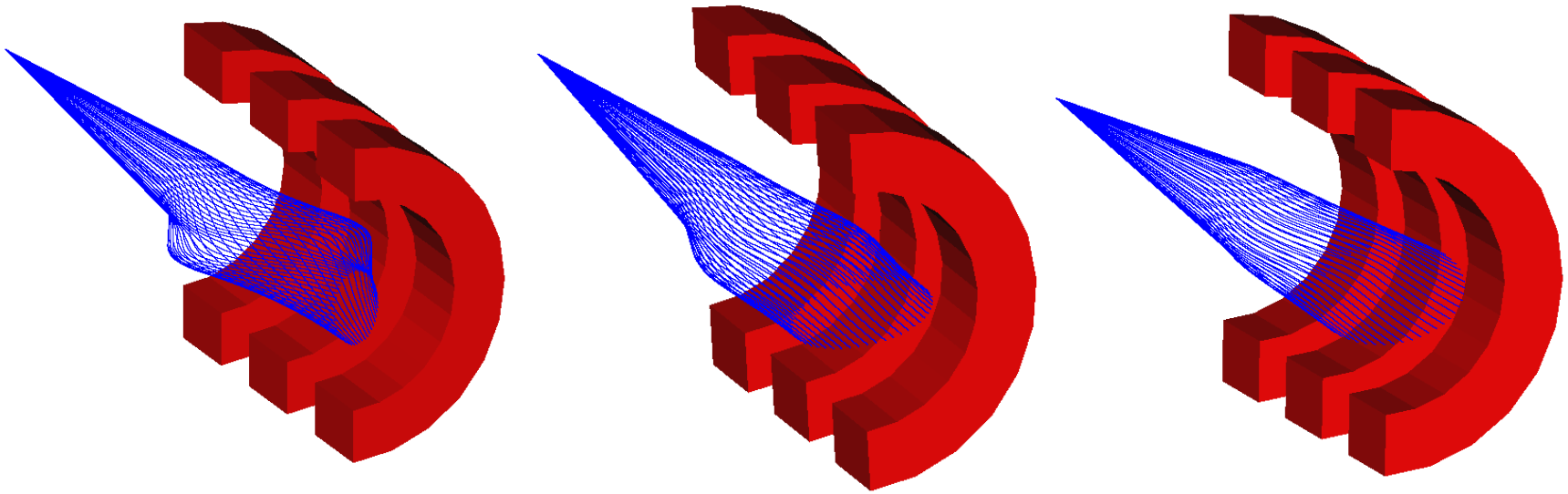


Tracking of ultra-forward charged particles

Δp/p = -0.5
(spectator protons from deuterium)

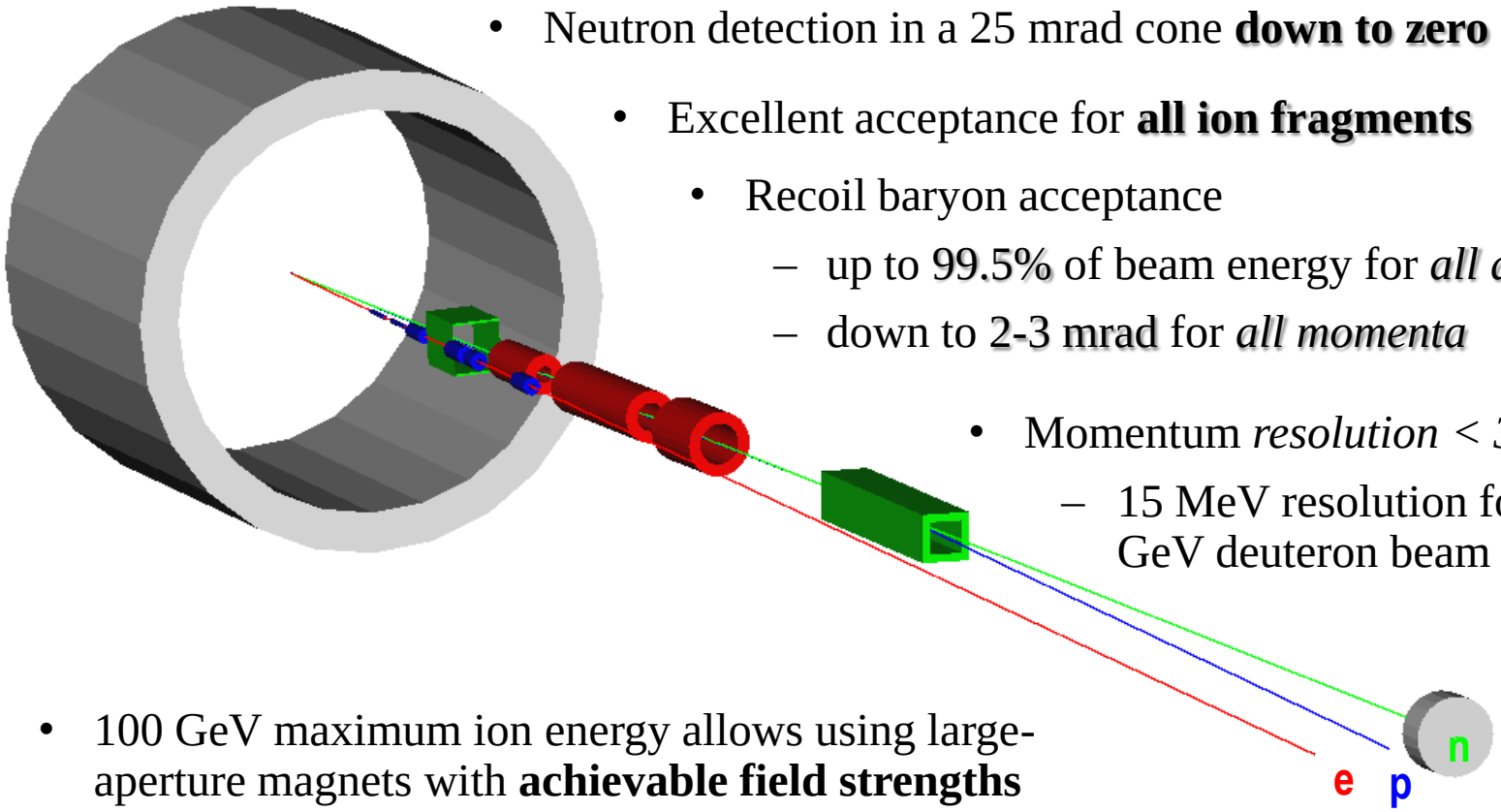
Δp/p = 0.0
(exclusive / diffractive recoil protons)

Δp/p = 0.5
(neutron-rich nuclear fragments)



- Design provides full acceptance for *all* nuclear fragments
  - Low gradient quads make possible the necessary large apertures
  - Can be achieved with realistic peak fields (= gradient * aperture radius)
    - Easier with lower maximum energy – benefits from JLab two-ring staging

Ultra-forward detection concept



- Neutron detection in a 25 mrad cone **down to zero degrees**
  - Excellent acceptance for **all ion fragments**
    - Recoil baryon acceptance
      - up to 99.5% of beam energy for *all angles*
      - down to 2-3 mrad for *all momenta*
    - Momentum *resolution* < $3x10^{-4}$
      - 15 MeV resolution for 50 GeV deuteron beam

- 100 GeV maximum ion energy allows using large-aperture magnets with **achievable field strengths**

Summary

EIC is the ultimate tool for studying sea quarks and gluons

- An EIC is required to fully understand nucleon structure and the role of gluons in nuclei

MEIC offers a fully integrated interaction region

- Straightforward detection of recoil baryons, spectators, and target fragments
- Promising collaboration on central detector with HEP

EIC is a maturing project

- Designs ongoing at JLab and BNL
- Funds for joint detector R&D projects and accelerator R&D have been allocated
- Physics effort for polarized light nuclei and forward tagging ongoing