Physics Opportunities at the MEIC at JLab

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The physics program of an EIC

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

- Sea quark and gluon polarization
- Transverse spatial distributions
- Orbital motion of sea quarks / gluons
- Parton correlations: beyond one-body densities

Discover the collective effects of *gluons in nuclei*

- Color transparency: small-size configurations
- Nuclear gluons: EMC effect, shadowing
- Strong color fields: unitarity limit, saturation
- Fluctuations: diffraction

Understand the emergence of *hadronic matter from color charge*

- Materialization of color: fragmentation, hadron breakup, color correlations
- Parton propagation in matter: radiation, energy loss

EIC Stage I will address all major areas!

EIC – consensus on many global requirements

The EIC project is pursued jointly by BNL and JLab, and both labs work towards implementing a common set of goals

- Polarized electron, nucleon, and light ion beams
  - Electron and nucleon polarization > 70%
  - Transverse polarization at least for nucleons
- Ions from hydrogen to A > 200
- Luminosity reaching 10^{34} $cm^{-2}s^{-1}$
- Stage I energy: $\sqrt{s}$ = 20 – 70 GeV (variable)
- Stage II energy: $\sqrt{s}$ up to about 150 GeV

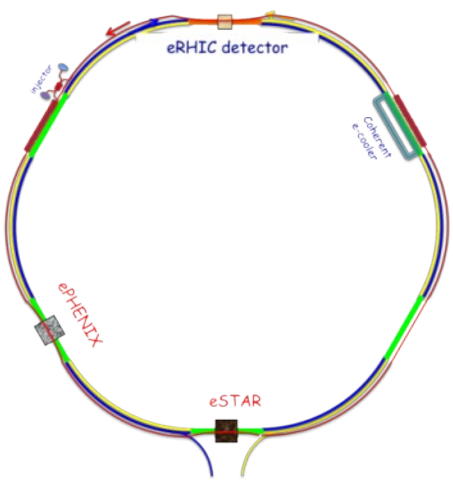
From base EIC requirements in the INT report

(MEIC)

(ELIC)

EIC – similar CM energies at BNL and JLab

eRHIC @ BNL



Stage I

$\sqrt{s}$ = 25 – 71 GeV

E_e = 3 – 5 GeV

E_p = 50 – 250 GeV

E_{Pb} = up to 100 GeV/A

Stage II

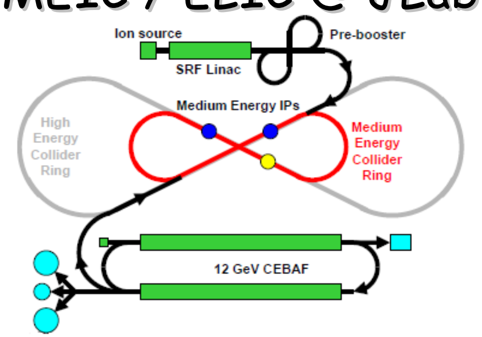
$\sqrt{s}$ = up to ~180 GeV

E_e = up to ~30 GeV

E_p = up to 275 GeV

E_{Pb} = up to 110 GeV/A

MEIC / ELIC @ JLab



$\sqrt{s}$ = 15 – 66 GeV

E_e = 3 – 11 GeV

E_p = 20 – 100 GeV

E_{Pb} = up to 40 GeV/A

(MEIC)

$\sqrt{s}$ = up to ~140 GeV

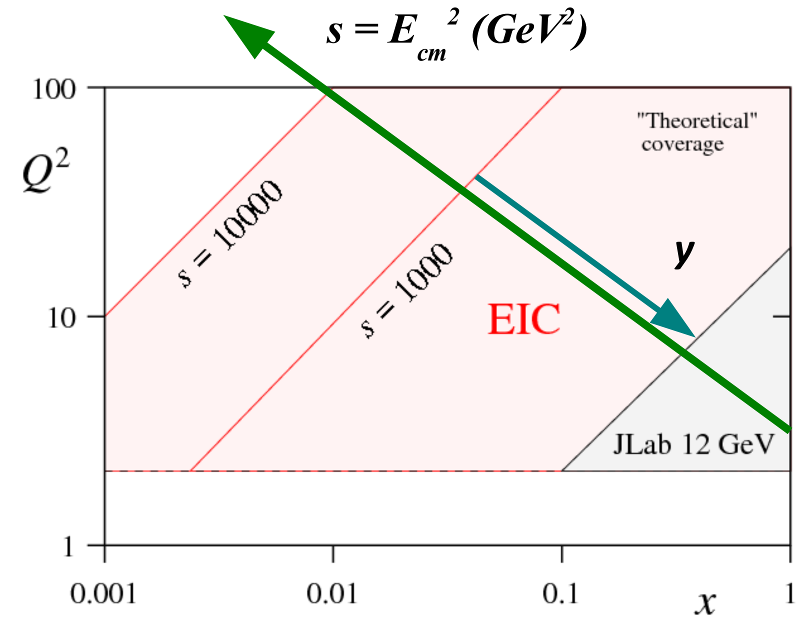
E_e = up to ~20 GeV

E_p = up to at least 250 GeV

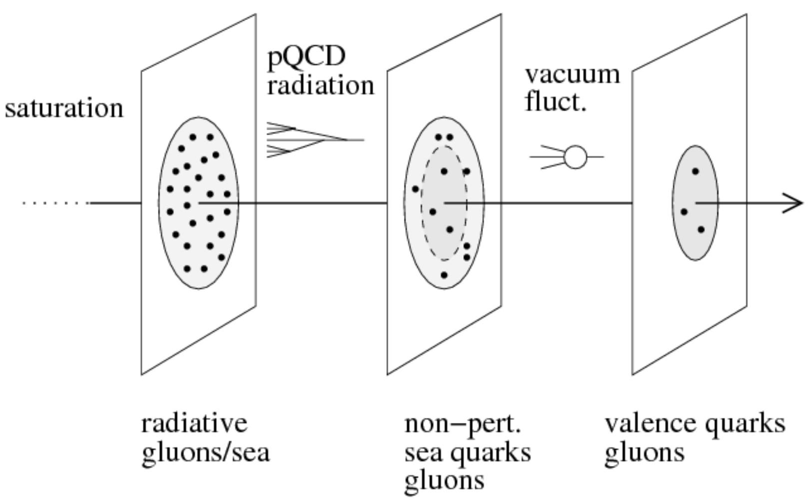
E_{Pb} = up to at least 100 GeV/A

(ELIC)

EIC Stage I – kinematic coverage



C. Weiss



LHeC ?

EIC Stage II (ELIC) **EIC Stage I (MEIC)** **JLab 12 GeV**

$Q^2 \sim ysx$

Medium-energy EIC (Stage I)

- $s_{max} = 4\, E_e E_p = 4 \text{ x } 11 \text{ x } 100 = 4400 \text{ GeV}^2$

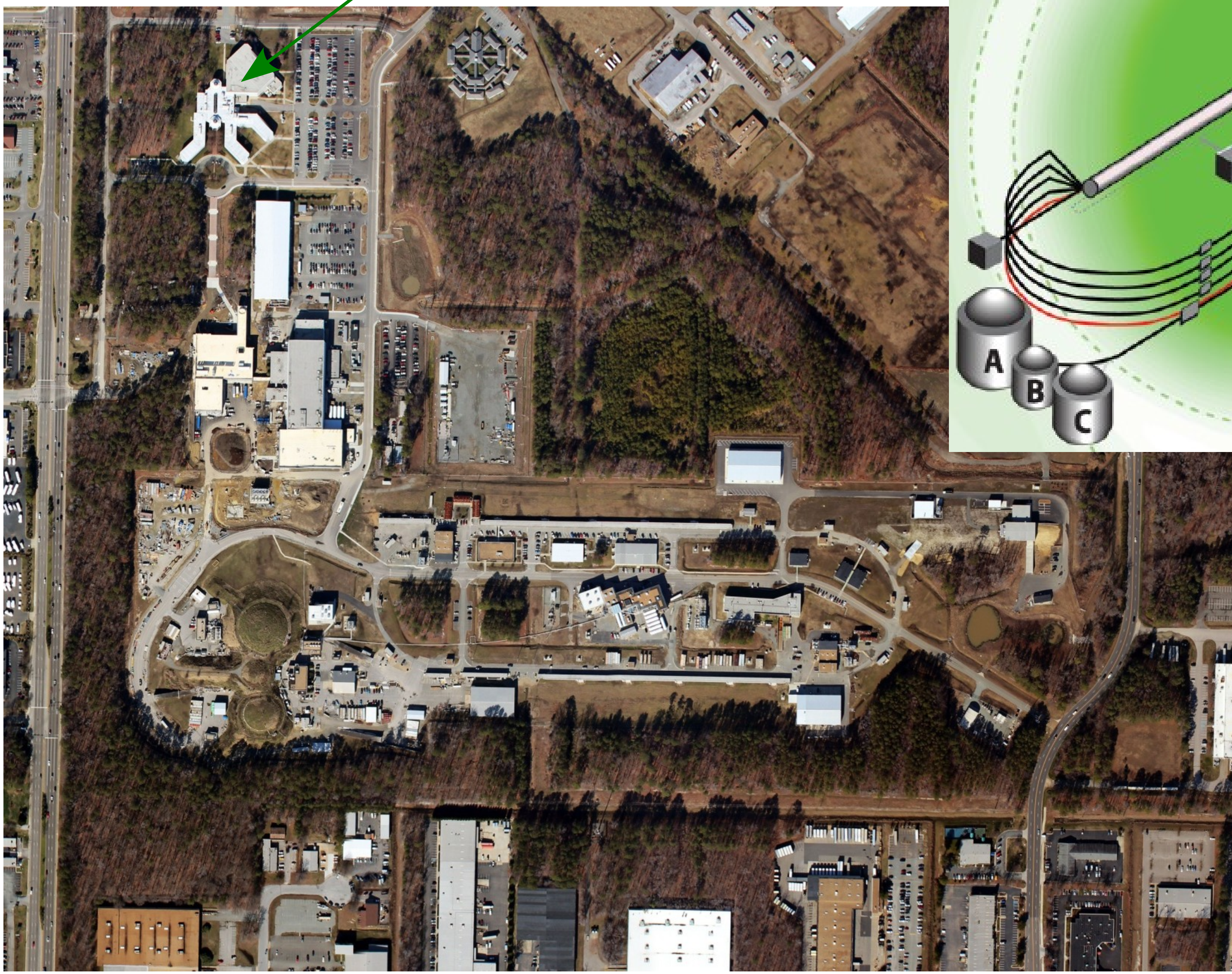
Fixed-target experiments

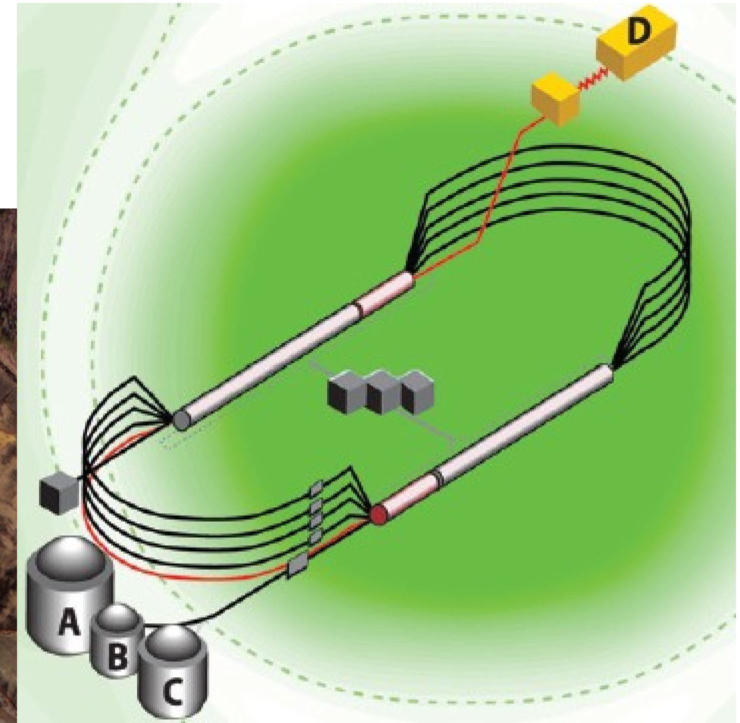
- $s_{max} = 2\, E_e M_p = 2 \text{ x } 11 \text{ x } 0.938 = 20 \text{ GeV}^2$
- $s_{max} = 2\, E_e M_p = 2 \text{ x } 160 \text{ x } 0.938 = 300 \text{ GeV}^2$

LHeC kinematic coverage is entirely complementary to a Stage I EIC

JLab 12 GeV

You are here!

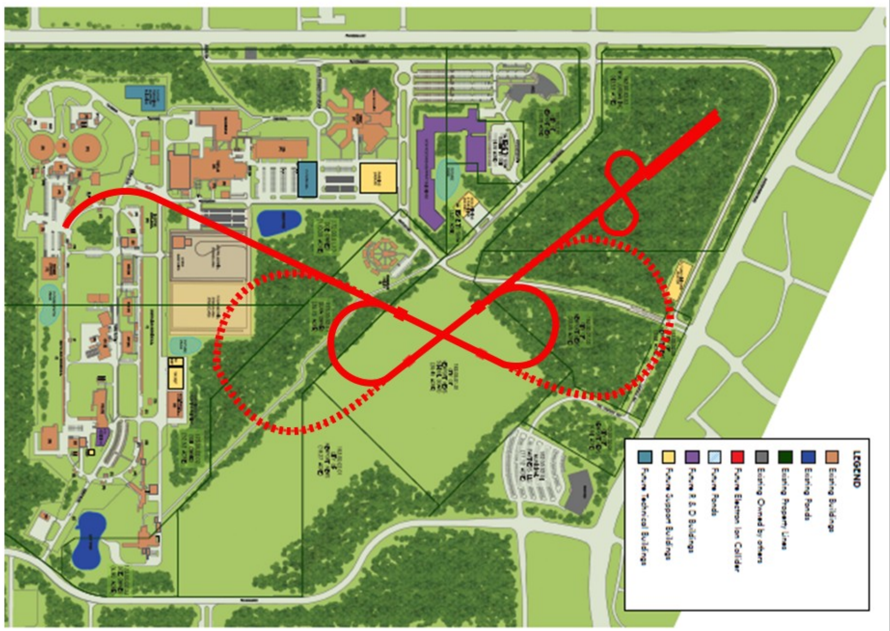


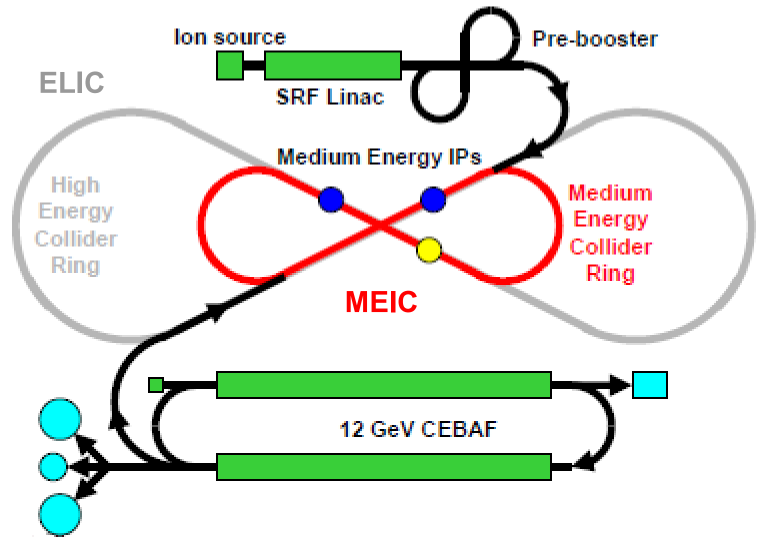


This week concludes more than a decade of successful JLab Stage I (6 GeV) running.

A Stage II (12 GeV) upgrade capability was incorporated from the outset

The EIC at JLab – overview of accelerator



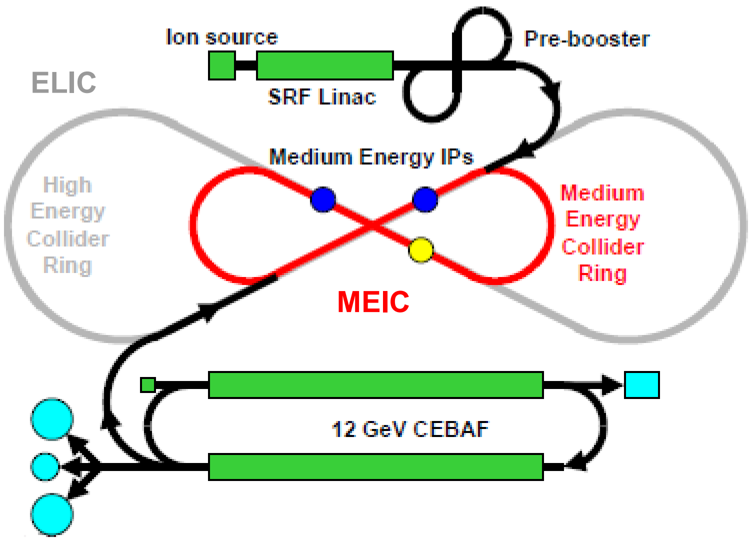


- Stage I (MEIC):
  - 3-11 GeV electrons on 20-100 GeV protons (12-40 GeV/A heavy ions)
  - About the same size as the 12 GeV CEBAF accelerator (1/3 of RHIC)
- Stage II (ELIC):
  - 20 GeV electrons on 250+ GeV protons (100+ GeV/A heavy ions)

MEIC – a figure-8 ring-ring collider

The design makes possible:

- Simultaneous use of multiple detectors
- Longitudinal and *transverse* polarization of light ions
  - protons, ***deuterium***, ^{3}He, ...
- 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 ERL

The EIC will provide unique capabilities

A few examples of what this implies for detection

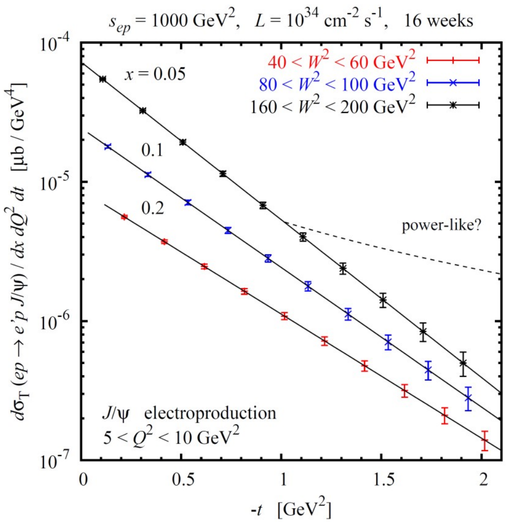
Nuclear beams

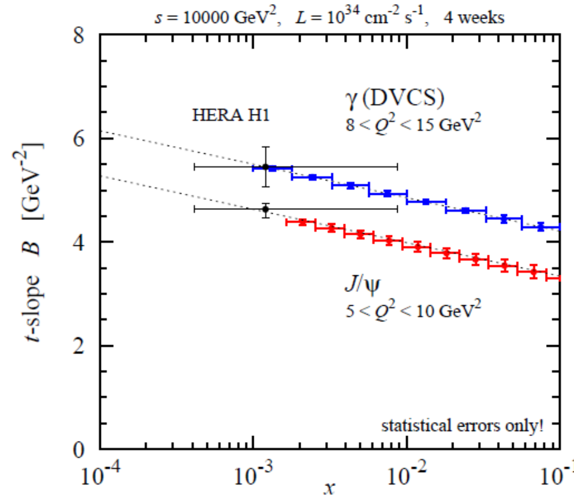
- Nuclear fragments
  - also neutrons and photons
- Spectators
  - protons, neutrons, nuclei

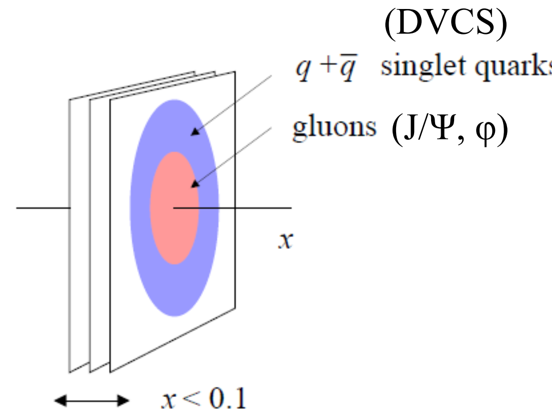
Polarized "targets"

- Recoil baryons from deep exclusive reactions
  - also nuclei from coherent processes
- Current and target fragmentation in SIDIS

Transverse spatial imaging of sea quarks and gluons

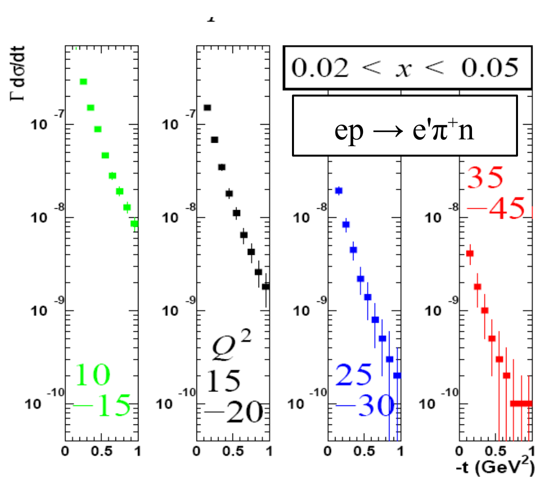


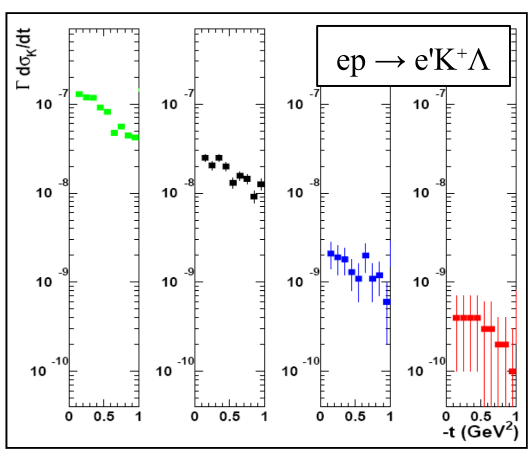


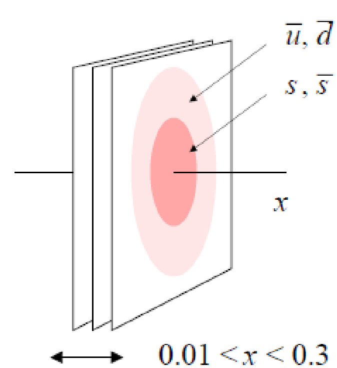


Weiss et al, INT 10-3

- Are the *radii* of quarks and gluons, or strange and light sea quarks, different at a given x?
- Full *image of the proton* can be obtained by mapping t-distributions for different processes.

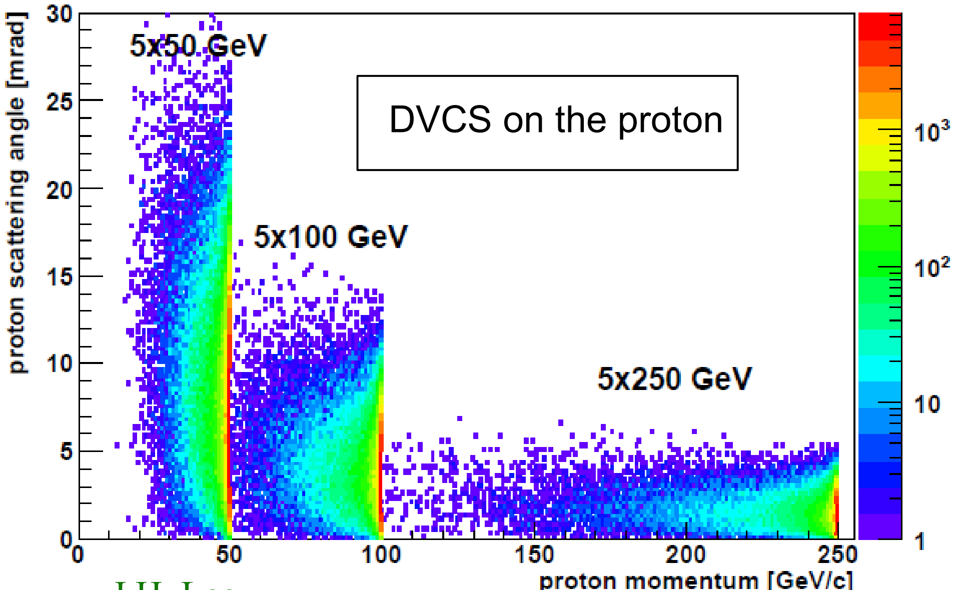




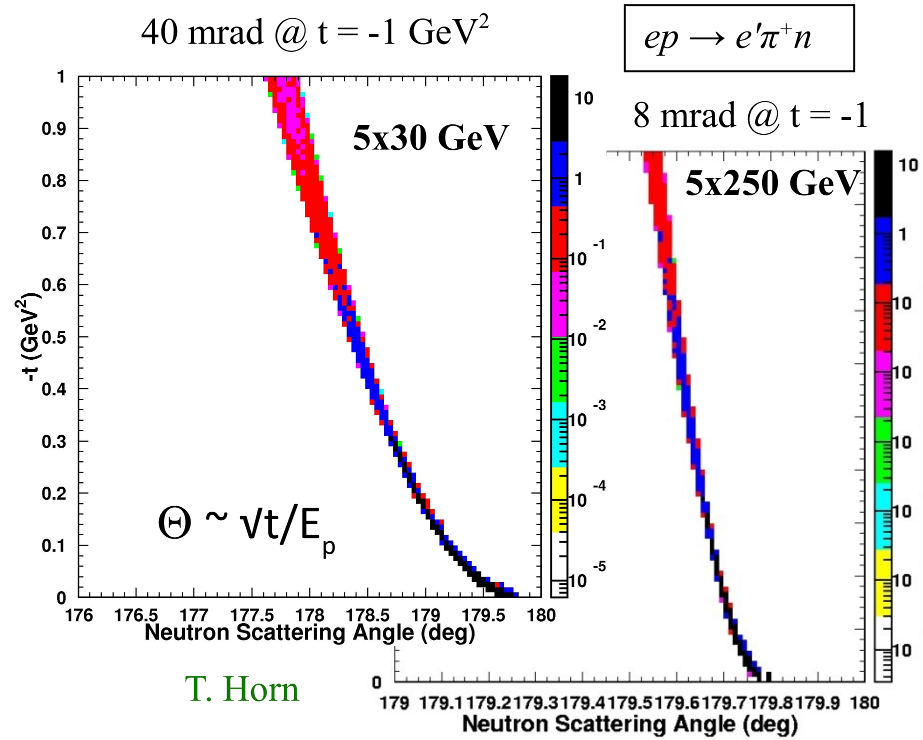


Horn et al. 08+, INT10-3

Recoil baryons



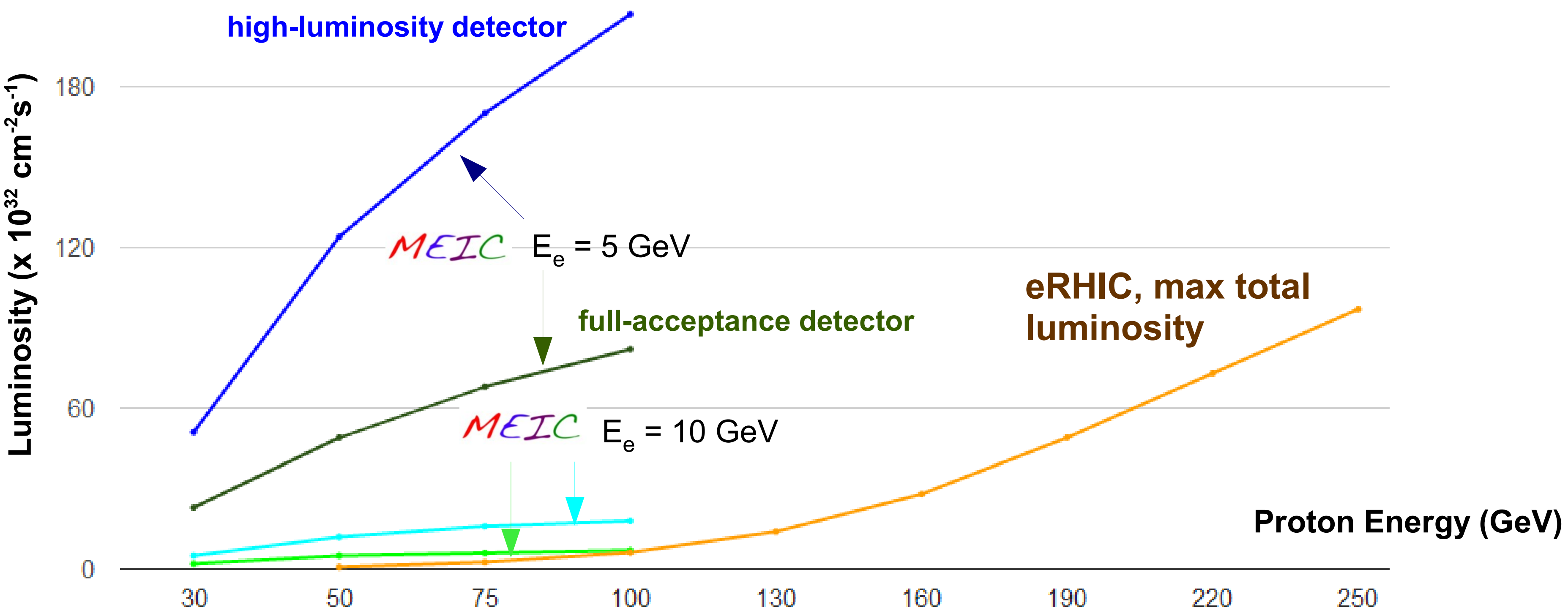
J.H. Lee



T. Horn

- At high proton energies, recoil baryons are scattered at small angles
  - Lower energies give better *resolution* in *-t*
- Taking full advantage of different kinematics requires
  - High luminosity over a wide range of proton (deuteron) energies
  - Excellent small-angle detection

Luminosity as a function of proton energy



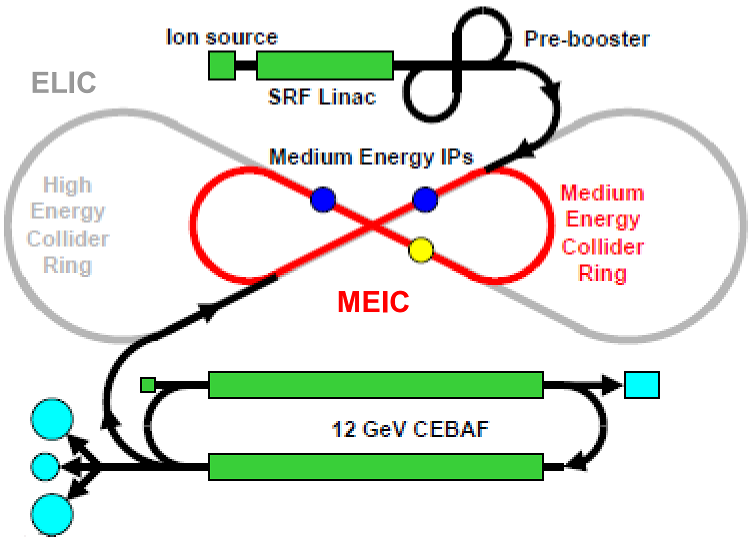
- MEIC luminosity is optimized for mid-range (4-8 GeV) electron energies over a wide range of proton energies.
  - Luminosities are listed *per detector*. All can be used simultaneously.

- eRHIC offers a high luminosity at a high proton energy.
  - Luminosity is given for *all detectors*, which share the beam time.

Detectors

Space for 3 Interaction Points (IP)

- Main IPs located close to outgoing ion arc to reduce backgrounds



Full-acceptance detector (primary)

- 7 m from IP to ion final-focus quads

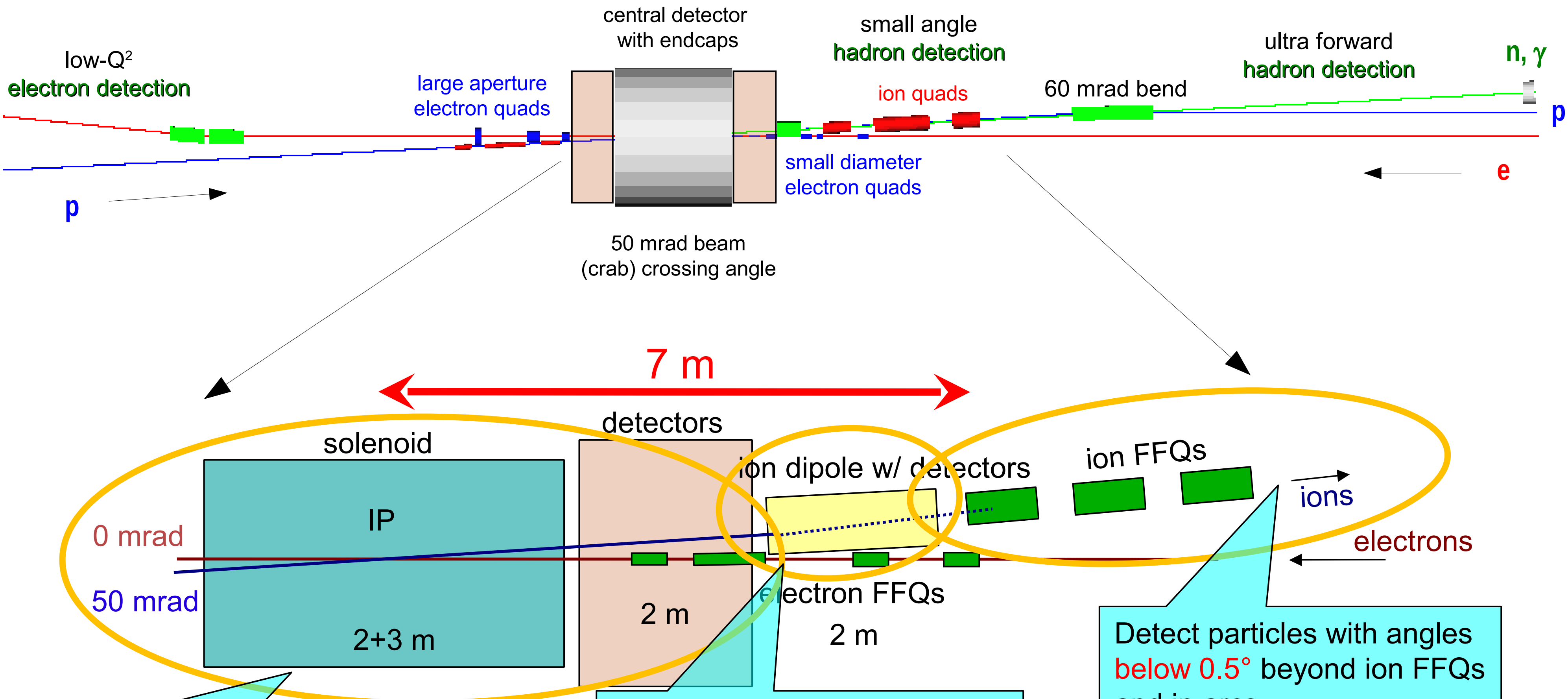
High-luminosity detector (secondary)

- 4.5 m from IP to ion final-focus quads

Special IP

- Space reserved for future needs

Full-acceptance detector – strategy



Central detector, more detection space in ion direction as particles have higher momenta

Detect particles with angles down to 0.5° before ion FFQs. Need up to 2 Tm dipole in addition to central solenoid.

Detect particles with angles below 0.5° beyond ion FFQs and in arcs.

Make use of the (50 mrad) crossing angle for ions!

Ultra-forward hadron detection – requirements

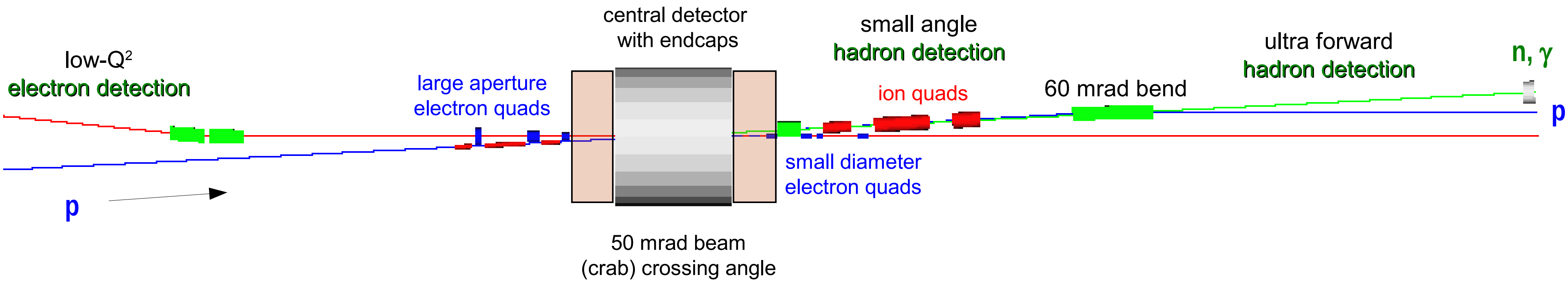
1. Good acceptance for ion fragments (large dp/p or dm/m)

2. Good acceptance for recoil baryons (small dp/p)

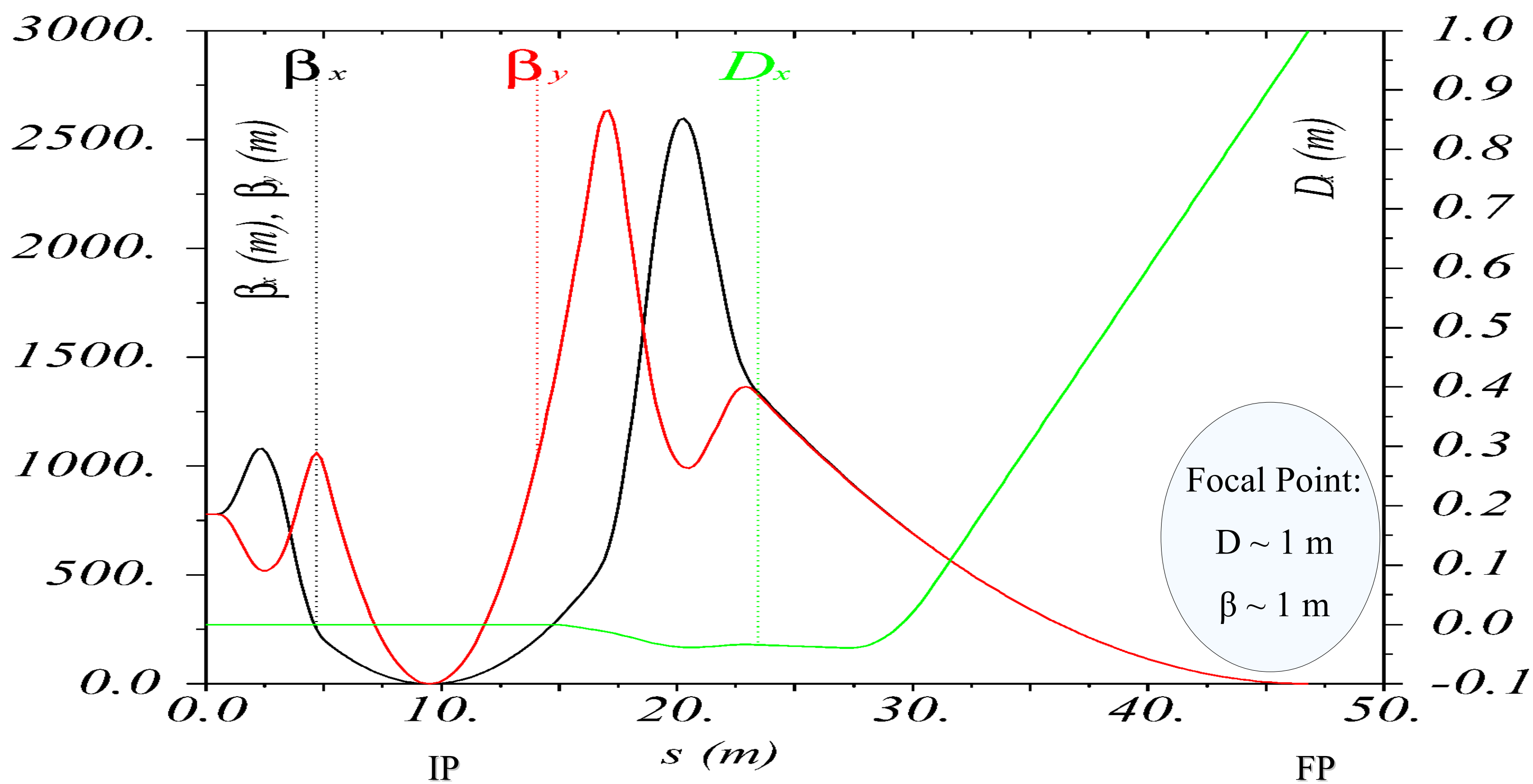
3. Good momentum- and angular resolution

4. Sufficient separation between beam lines (~1 m)

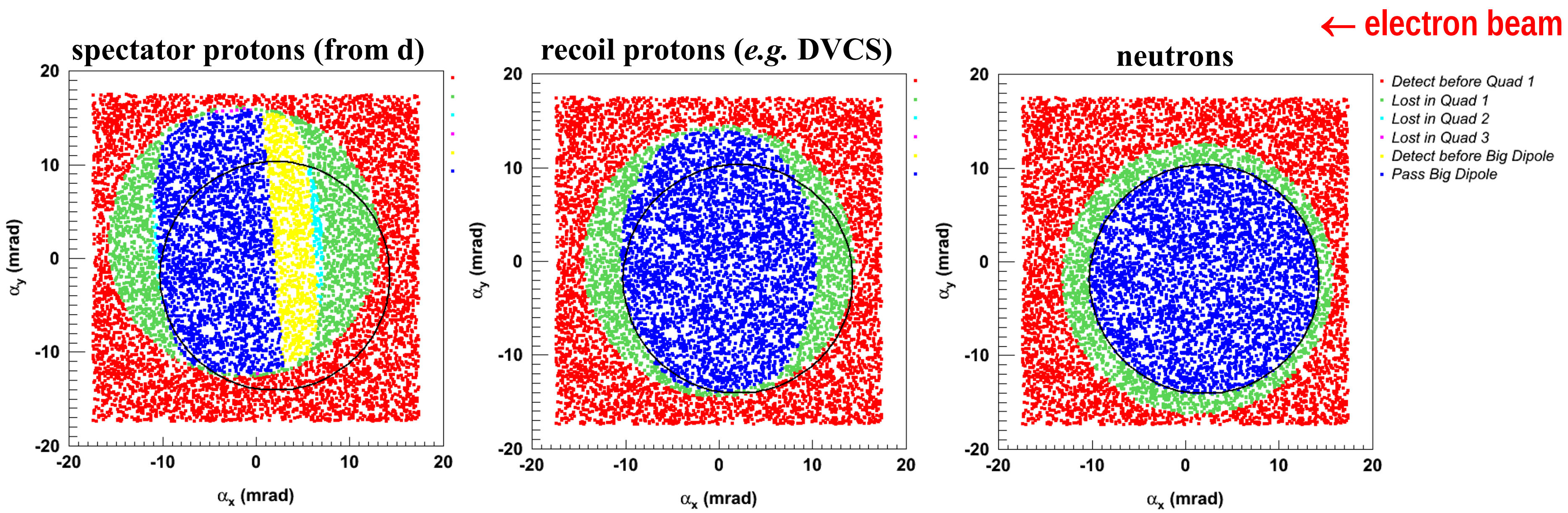
Full-acceptance detector – integration



To achieve all requirements, the accelerator team is designing the MEIC around the detector.



Ultra-forward hadron acceptance from GEANT



Red and Green: Detection between upstream 2 Tm dipole and ion quadrupoles

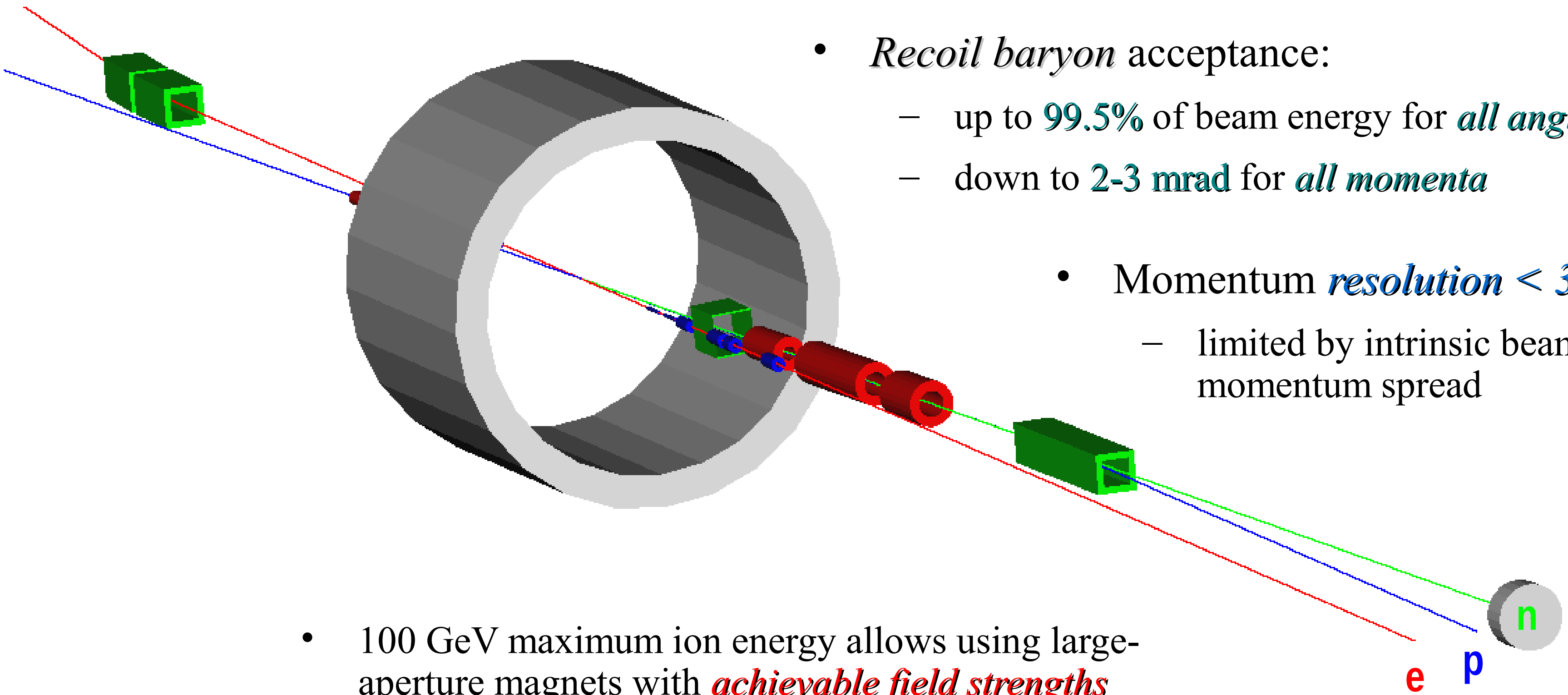
Yellow: Detection between ion quadrupoles and downstream 20 Tm dipole

Blue: Detection after the 20 Tm downstream dipole

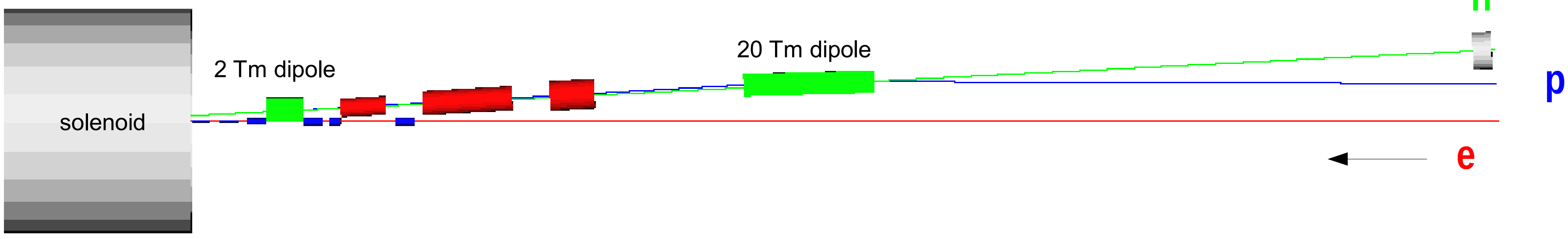
- Reasonable ion quad peak fields at 100 GeV: 9, 9, and 7 T, respectively.
- Aperture of downstream dipole (blue) can be adjusted – shown shifted for illustration
- Angles shown are scattering angles at IP with respect to the ion beam direction

Small-angle hadron detection – summary

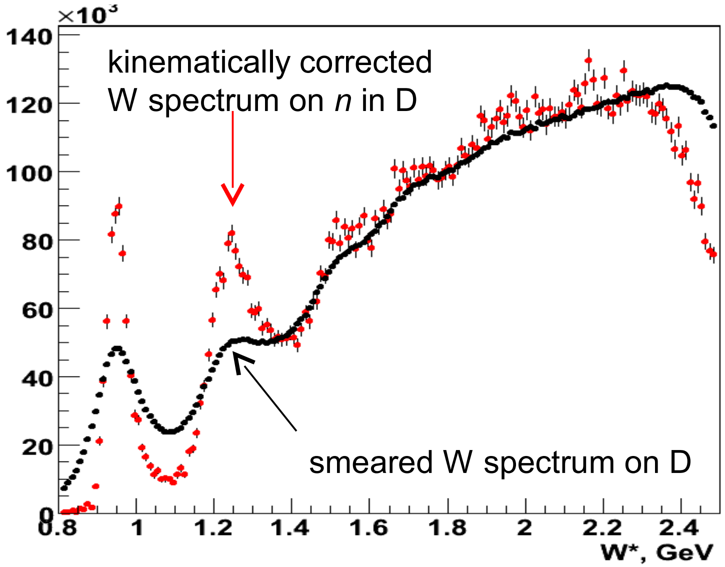
- *Neutron* detection in a 25 mrad cone ***down to zero degrees***
- Excellent acceptance for ***all ion fragments***
- *Recoil baryon* acceptance:
  - up to **99.5%** of beam energy for ***all angles***
  - down to **2-3 mrad** for ***all momenta***
- Momentum ***resolution < 3x10^{-4}***
  - limited by intrinsic beam momentum spread



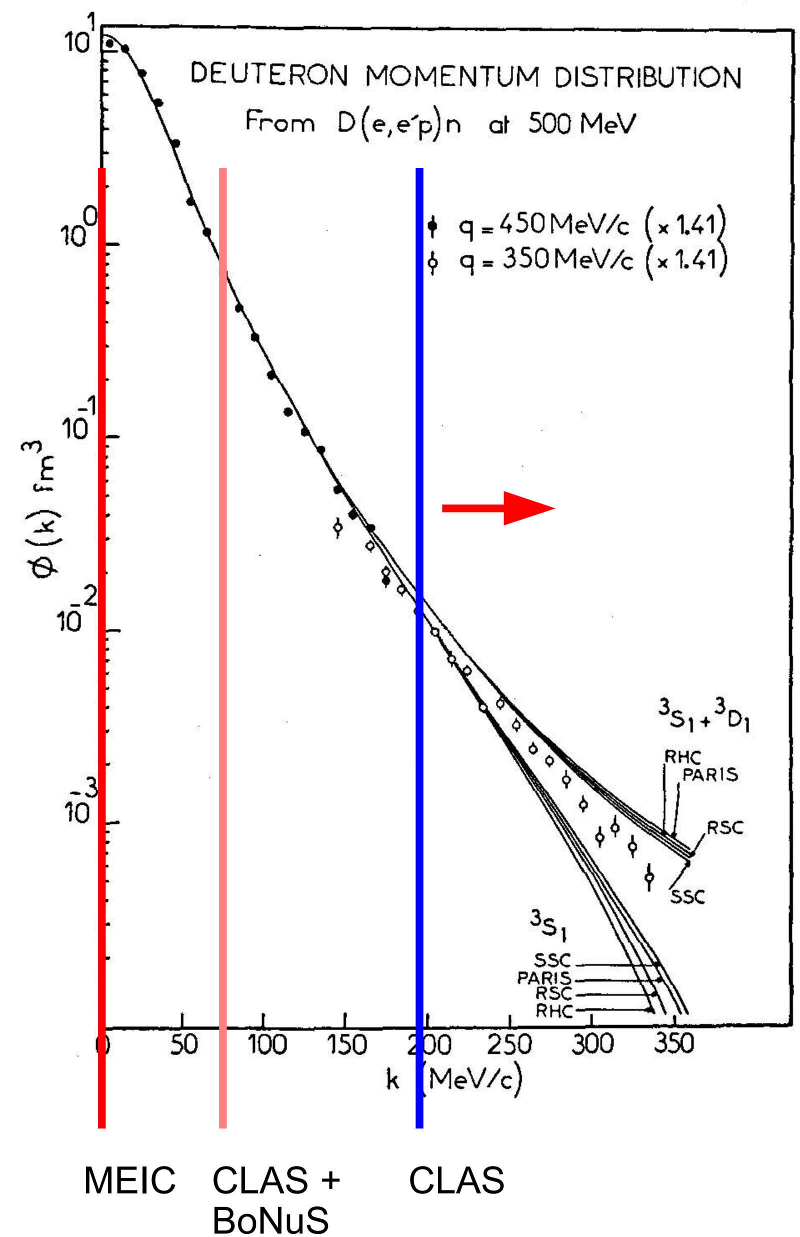
- 100 GeV maximum ion energy allows using large-aperture magnets with ***achievable field strengths***



Neutron structure through spectator tagging

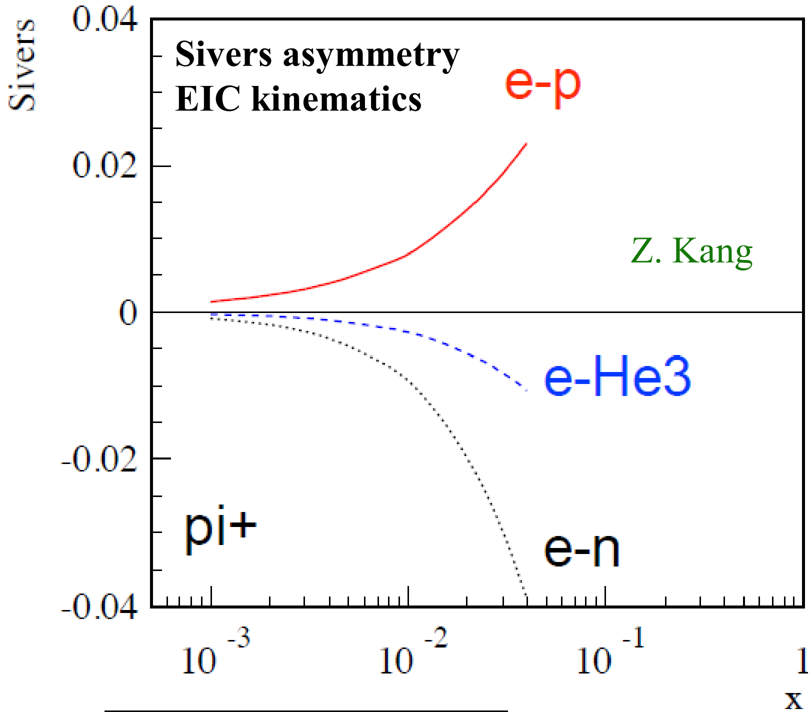


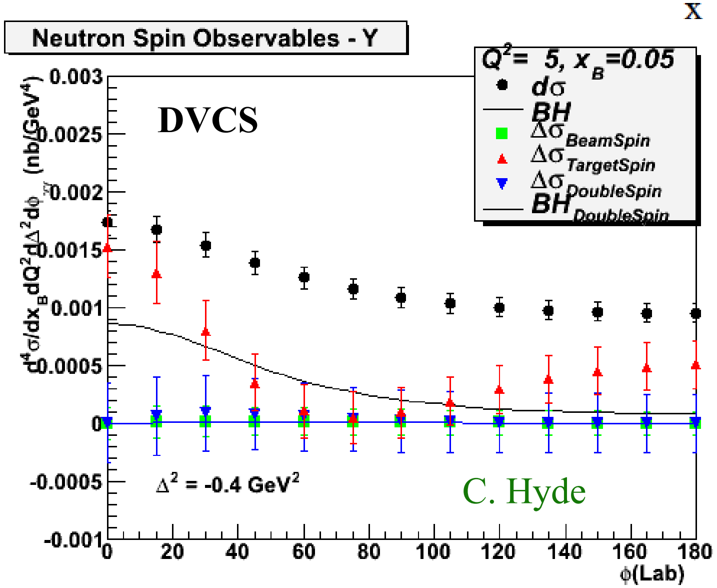
CLAS BoNuS data with tagged spectators



- In fixed-target experiments, scattering on *bound neutrons* is complicated
  - Fermi motion, nuclear effects
  - Low-momentum spectators
- Spectator tagging at the MEIC will allow flavor separation of spin and sea quark distributions

Spectator tagging with polarized deuterium

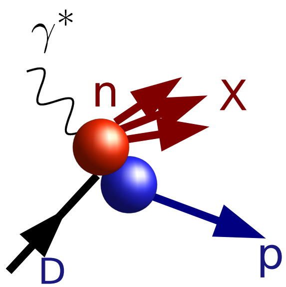


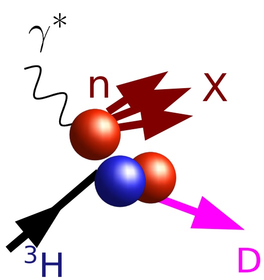


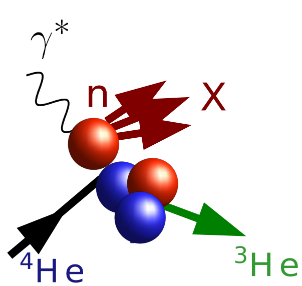
- Longitudinal and *transverse* polarization for deuterium
  - Also for other light ions
- Tagged, quasi-free neutrons give larger asymmetries than ^{3}He and nuclear effects are less of an issue
- Polarized neutrons are important for probing d-quarks through SIDIS
- Polarized *neutrons* are also important for exlusive reactions
  - Access to GPD E

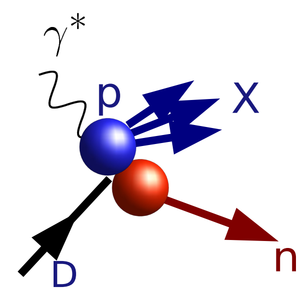
Spectator tagging – understanding nuclear effects

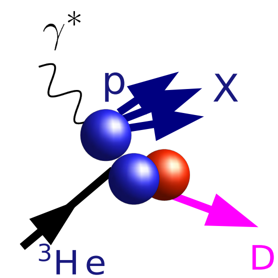
Quasi-free neutron target	spect.	(Quasi)-free proton target	spect.
		p	
D	p	D	n
^{3}H	D		
		^{3}He	D
^{4}He	^{3}He	^{4}He	^{3}H

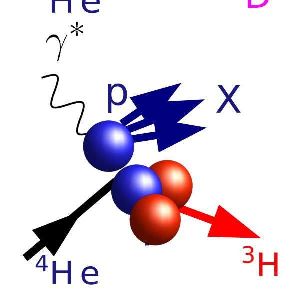




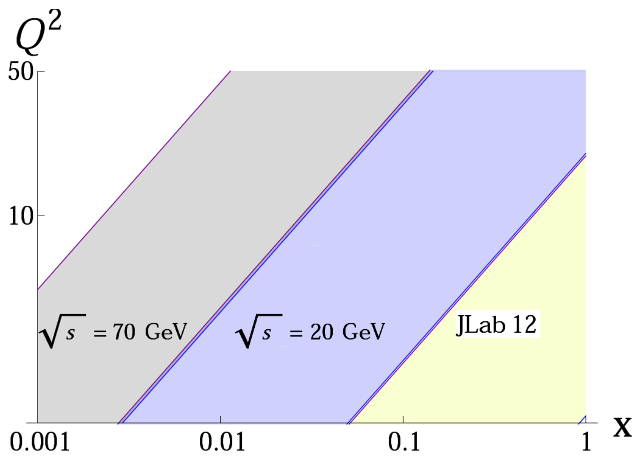


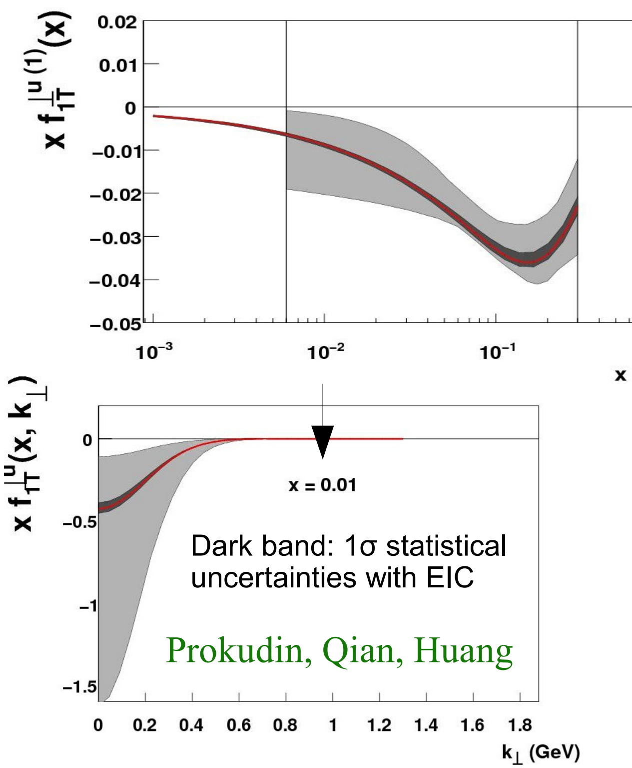






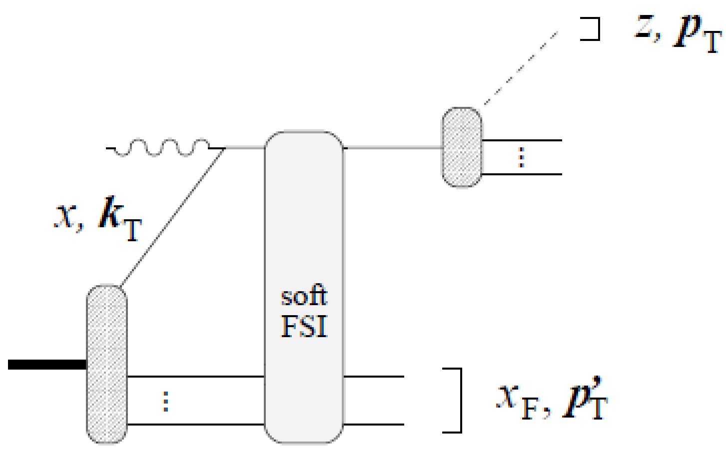
TMDs





- Measure Q^2*-dependence* over a wide range at a *fixed value of x* where asymmetries are significant
  - Ideal for a Stage I EIC (shown)
- Variable CM energy important
  - y-coverage for SIDIS
- Polarized proton and neutron “targets“
- Simulations show very good statistical uncertainties
  - Multi-dimensional binning

Target and current fragmentation in SIDIS



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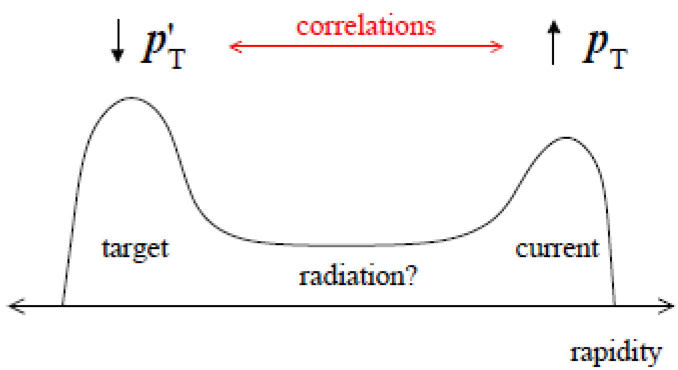
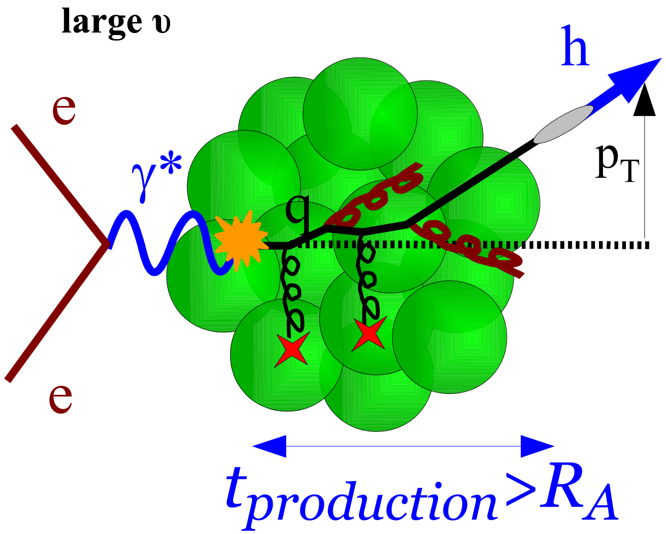
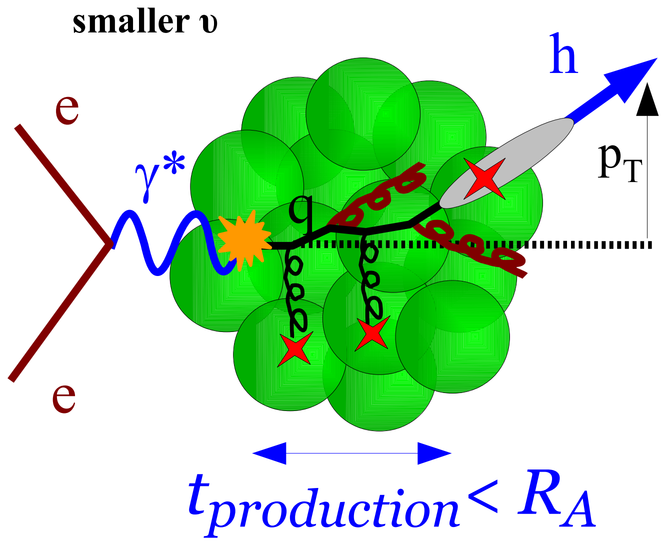


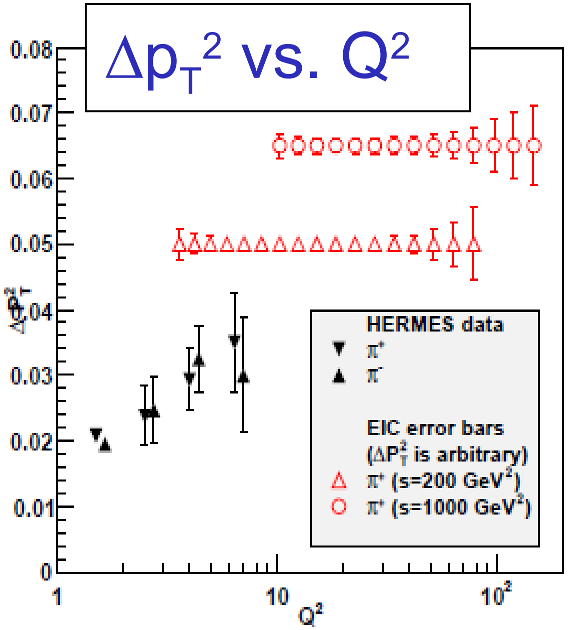
- Cannot separate intrinsic k_T from soft FSI and fragmentation
- New insight from p'_T of target fragments?
  - Origin of FSI? QCD radiation?
- EIC: current-target correlation measurements over wide range in p_T

Hadronization – parton propagation in matter

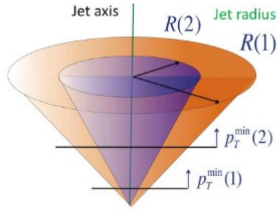




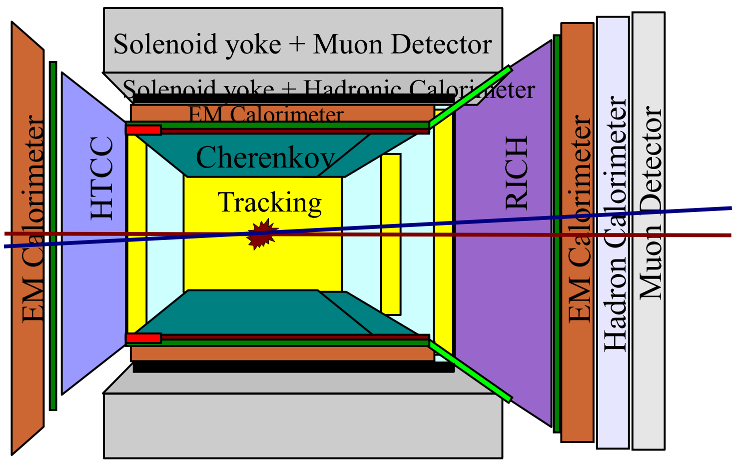
Accardi, Dupre

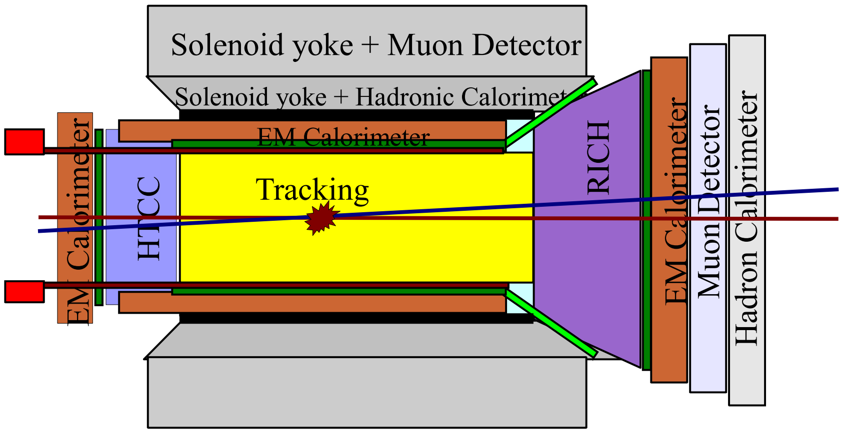


- p_T broadening
- Fragmentation functions
- Heavy flavors: B, D mesons, J/Ψ ...
- Jets at s > 1000 GeV²
  - „real" pQCD, IR safe



Particle identification and detector design





- Small differences in the desired range of π/K separation has huge impact on detector layout
- What range in p_{lab} (not p_T or k_T) do you need?
- If you need 8-9 GeV, the detector may look like on the left (1 m radial space for PID)
- If 5-6 GeV is enough, the detector may look like this instead (0.1 m radial space for PID)

- TOF
- DIRC bar
- DIRC expansion volume

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

Common framework for JLab and BNL implementations

- Global design parameters (energies, staging, etc)
- Funds for detector and accelerator R&D have been allocated

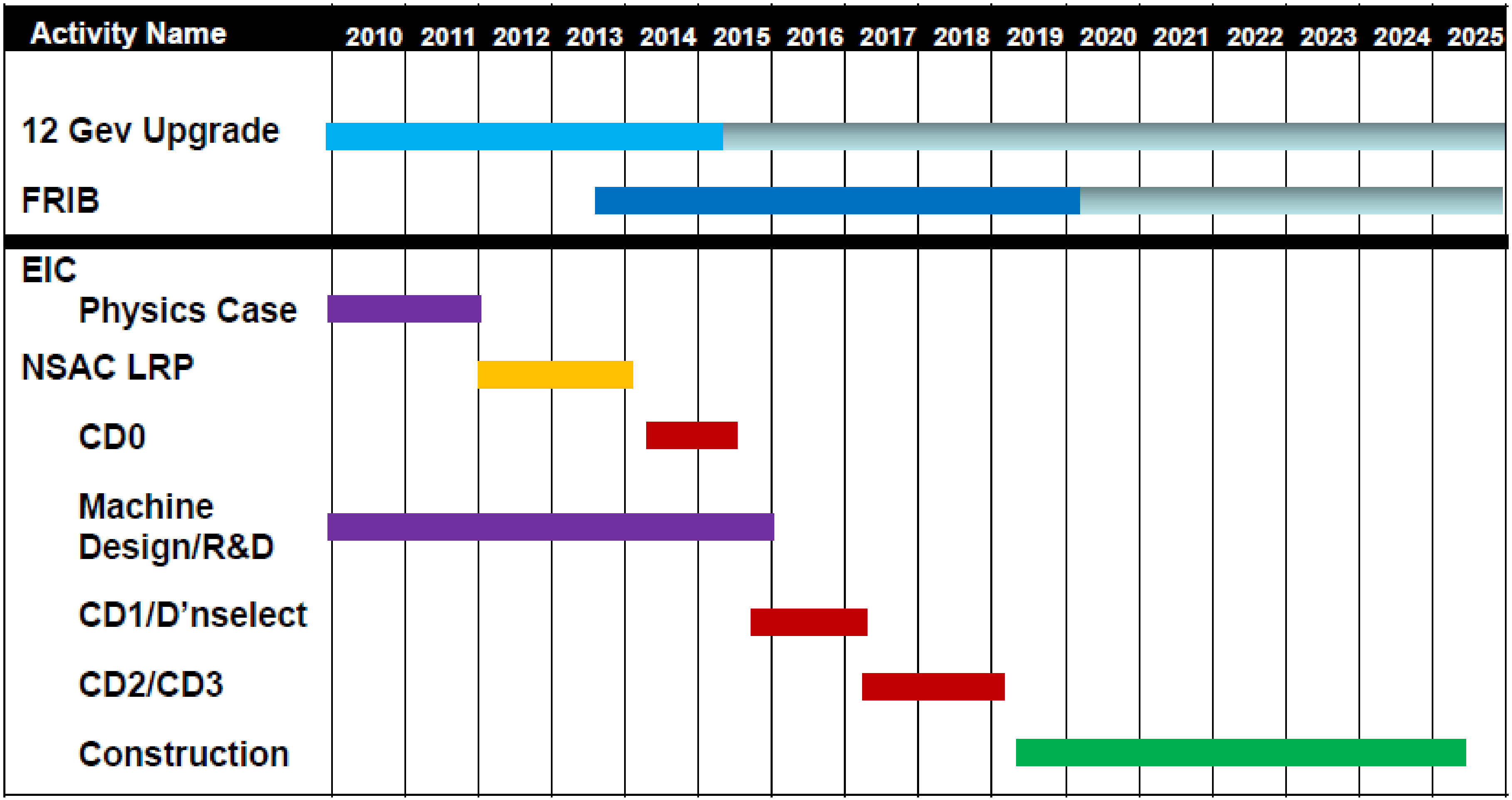
MEIC at JLab offers many attractive capabilities

- Luminosity profile
- Positrons and polarized deuterium
- Excellent detection of recoil baryons, spectators, and target fragments

Backup

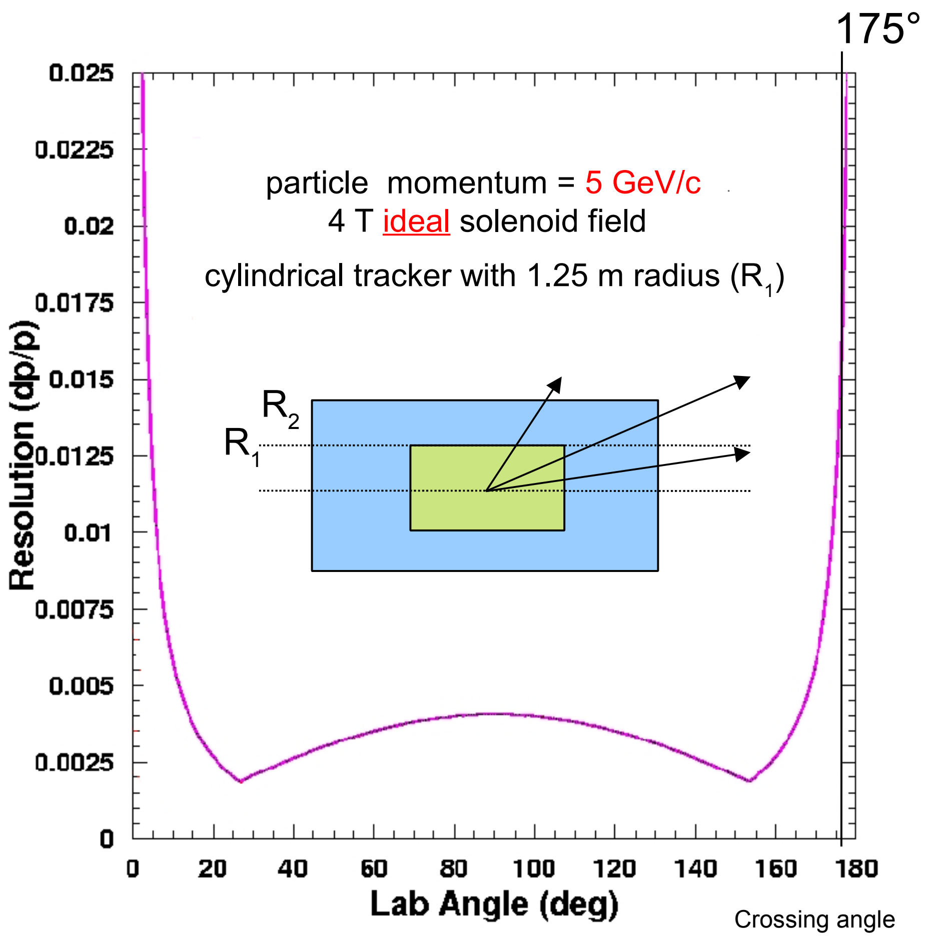
EIC – timeline

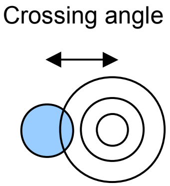
Mont, INT-10-03



The EIC project will be a pursued jointly by BNL and JLab in the Long Range Plan

Tracking: momentum resolution in a solenoid field

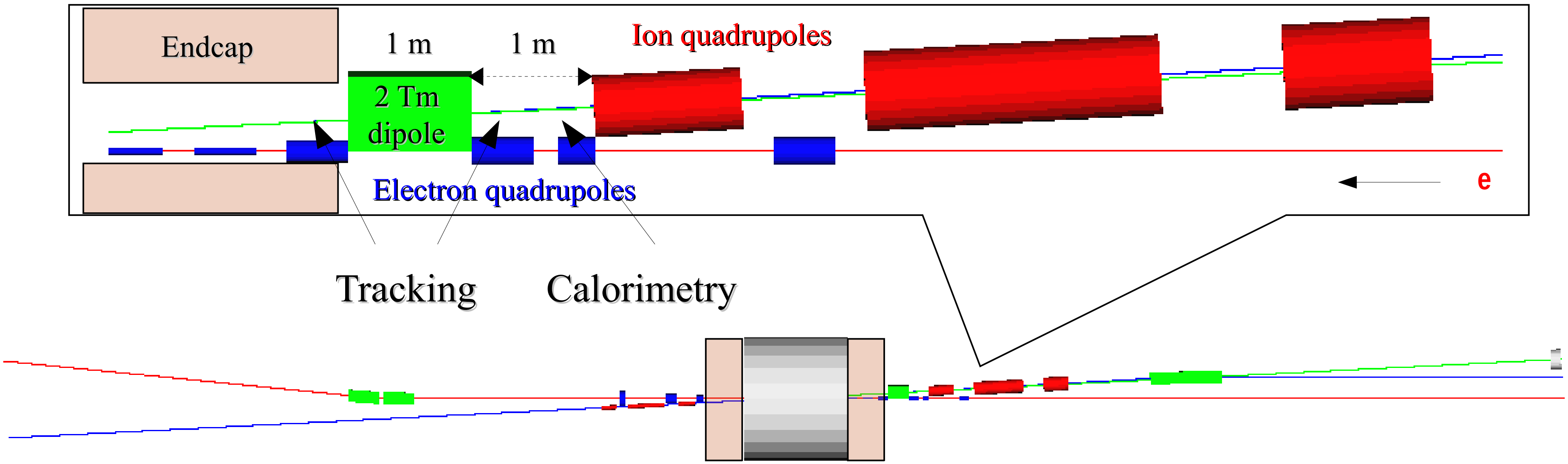


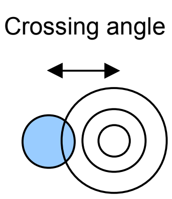


$$\Delta p/p \sim \sigma p / BR^2$$

- Tracker (not magnet!) radius R is important at central rapidities
- Only solenoid field B matters at forward rapidities
- A 2 Tm dipole covering 3-5° can eliminate divergence at small angles
- A beam crossing angle moves the region of poor resolution away from the ion beam center line.
  - 2D problem!

Hadron detection prior to ion quadrupoles

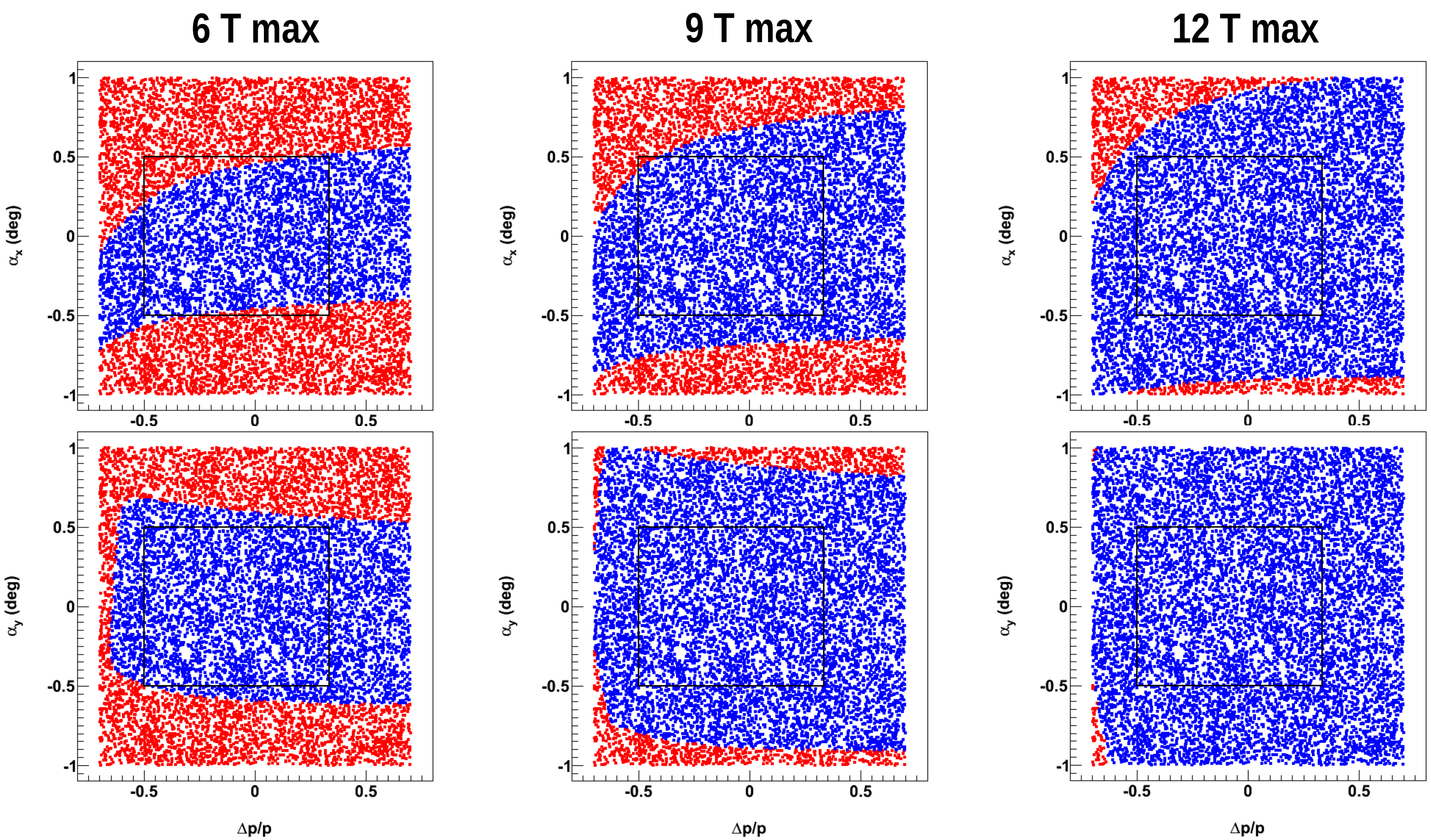




- Large crossing angle (50 mrad)
  - Moves spot of poor resolution along solenoid axis into the periphery
  - Minimizes shadow from electron FFQs

- Large-acceptance dipole further improves resolution in the few-degree range

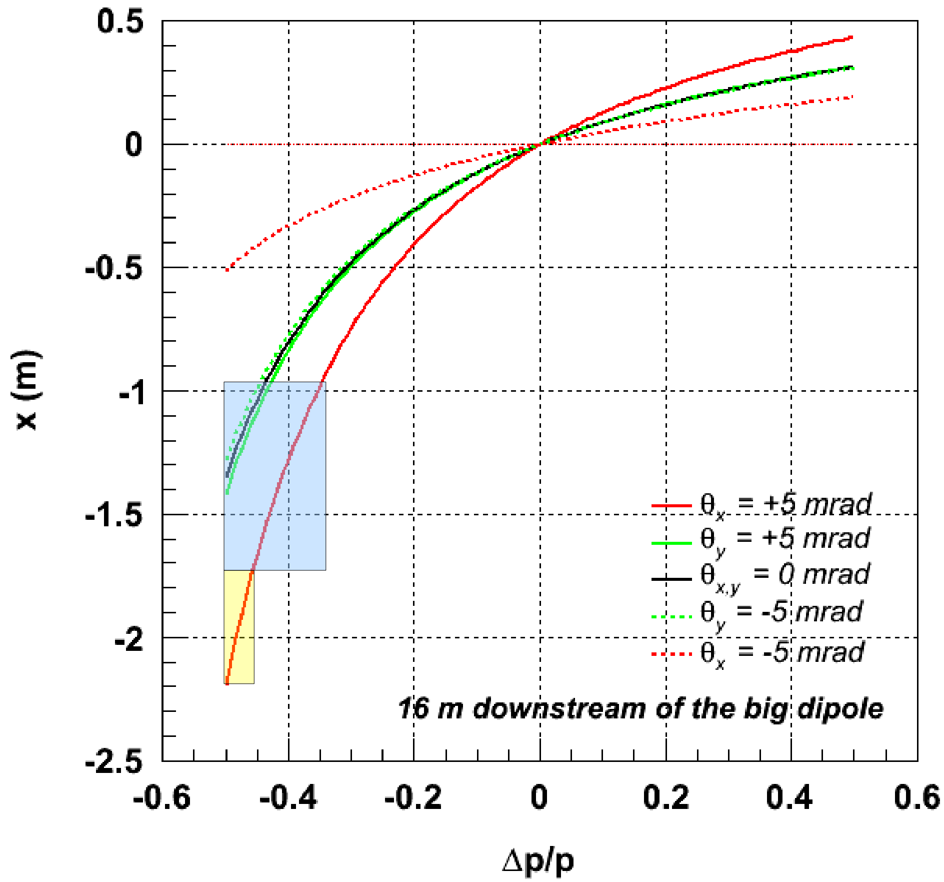
Small-angle hadron acceptance – quad peak fields

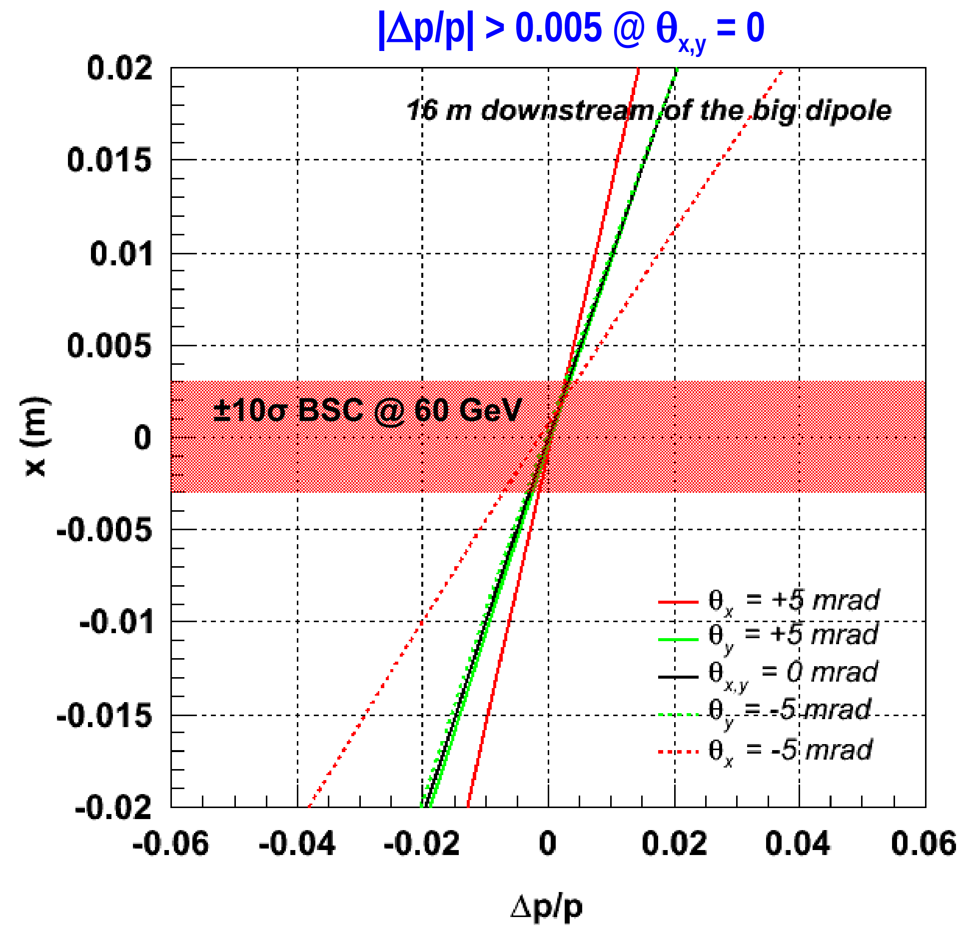


Red: Detection between the 2 Tm upstream dipole and ion quadrupoles

Blue: Detection after the 20 Tm downstream dipole

Hadron acceptance and resolution at the focal point

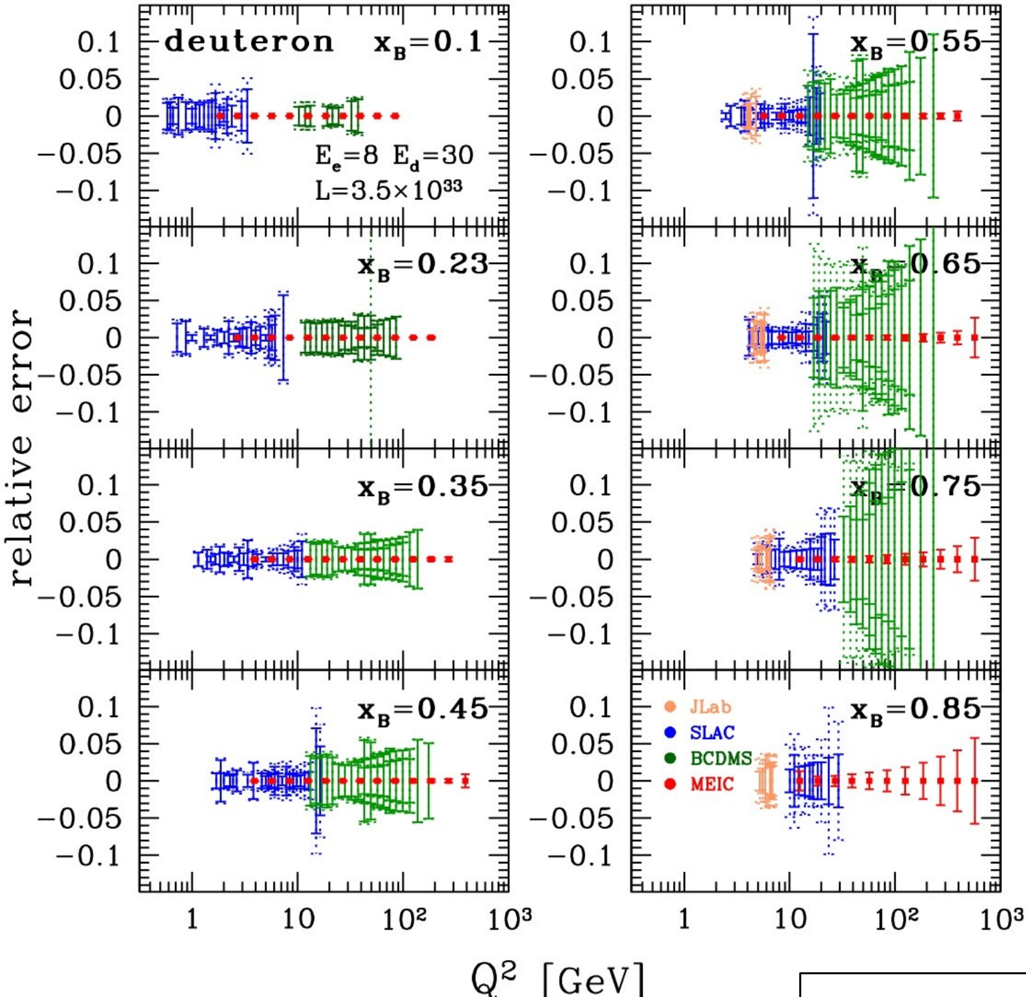




- Momentum resolution is given by the slope of the line
- Recoil baryons do not gain $\Delta p/p$ (or $\Delta m/m$)
- Large deflections allow precisce tracking over long distances with cheaper detectors
  - Particles with deflections > 1 m will be detected closer to the dipole

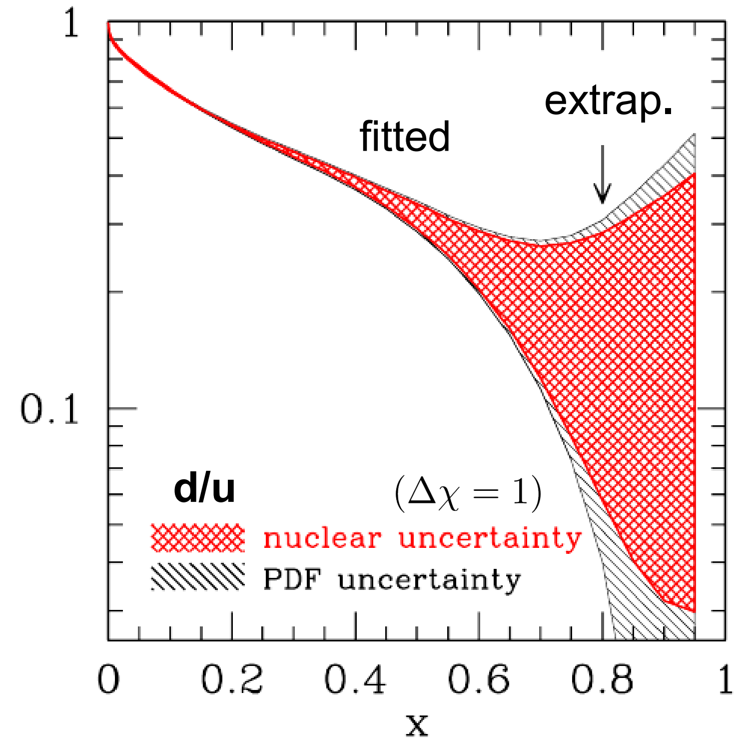
$F_2^{d/n}$

F_2^d



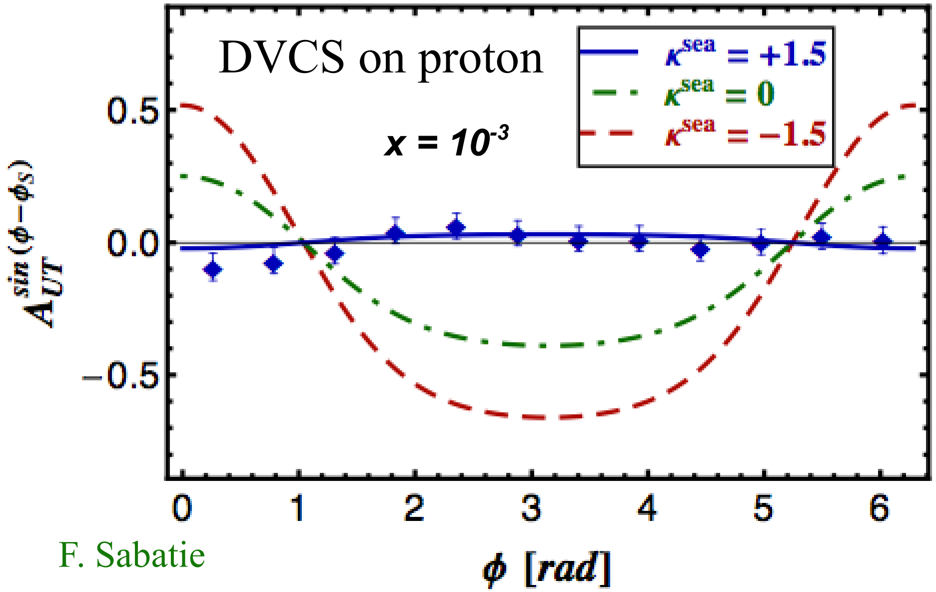
CTEQ-JLab collaboration

$$Q^2 \sim ysx$$



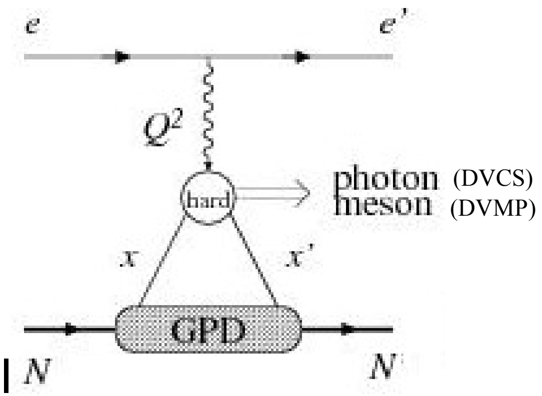
- Spectator tagging reduces nuclear uncertainties
  - F_2^n measured directly

Exclusive reactions with transverse “target“



F. Sabatie

Model



$$E^i(x, \xi, t) = \kappa^i(t)\, H^i(x, \xi, t)$$

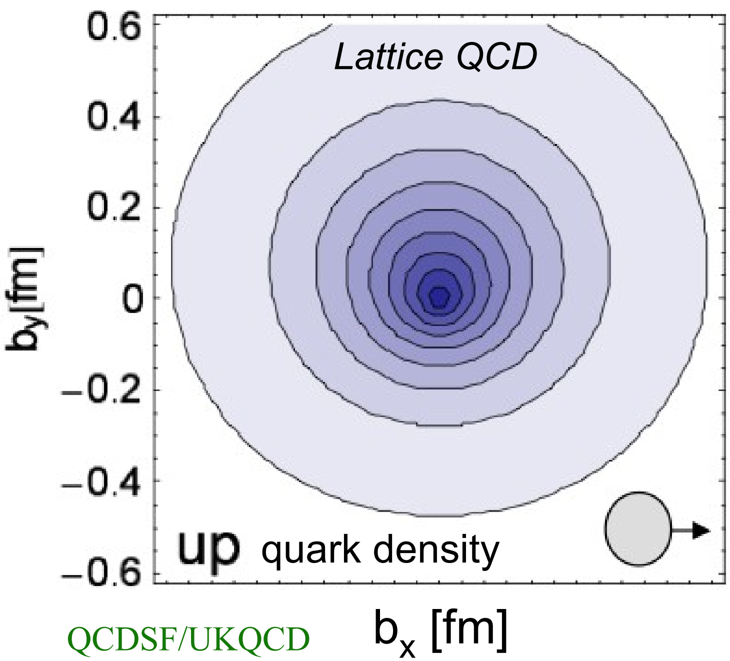
Error bars shown only for $\kappa^{sea} = +1.5$

- DVCS on a transversely polarized target is sensitive to the ***GPD E***
  - GPD H can be measured through the beam spin asymmetry
- Meson production is more selective: J/Ψ sensitive to corresponding ***gluon GPDs***
- Colliders provide an excellent Figure-Of-Merit (FOM)
  - ***FOM*** = Cross section x Luminosity x Acceptance x ***(Polarization)^2 x (Target dilution)^2***

Imaging in coordinate and momentum space

GPDs

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

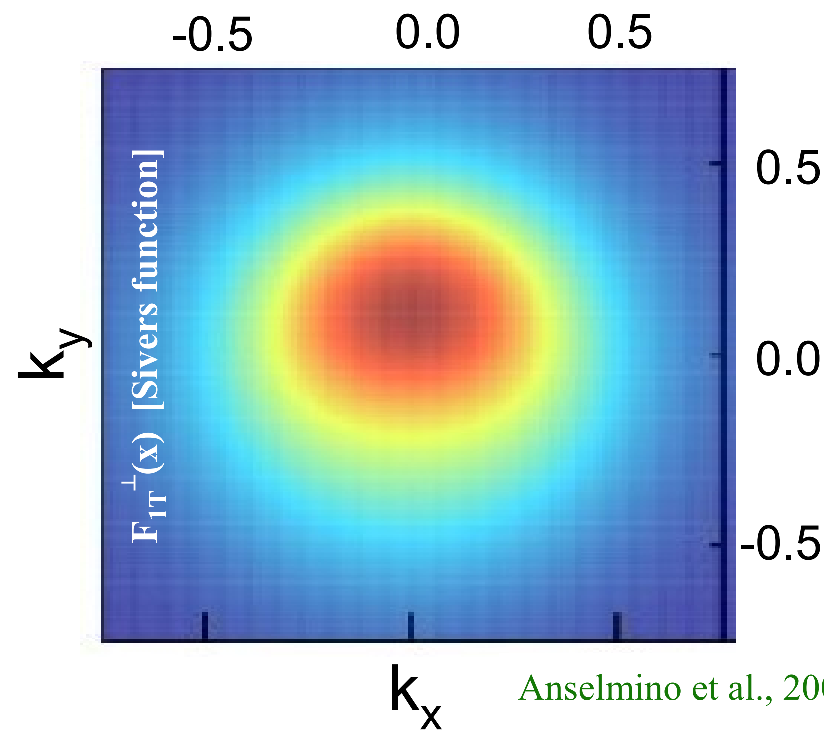


QCDSF/UKQCD Coll., 2006

- Accessed through *exclusive* processes
- Existing factorization theorems
- Ji sum rule for nucleon spin

TMDs

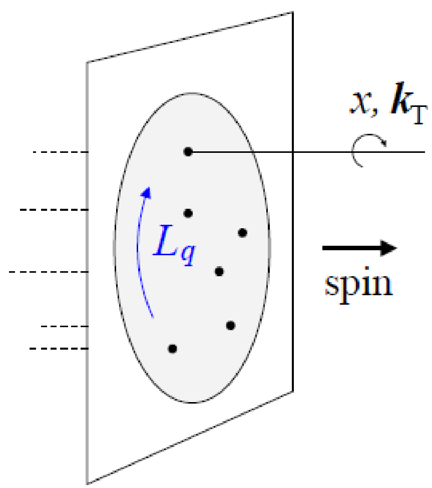
2+1 D picture in **momentum space**



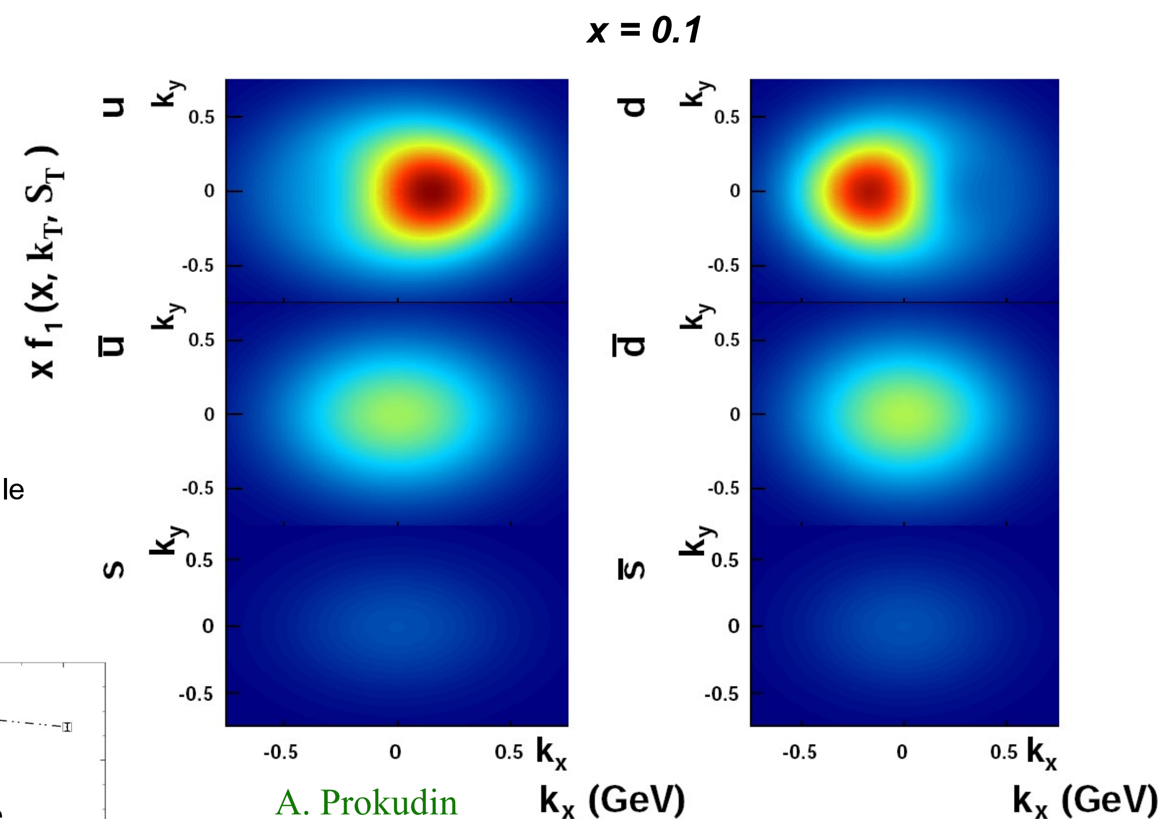
Anselmino et al., 2009

- Accessed through *Semi-Inclusive* DIS
- Non-trivial factorization
- OAM through spin-orbit correlations?

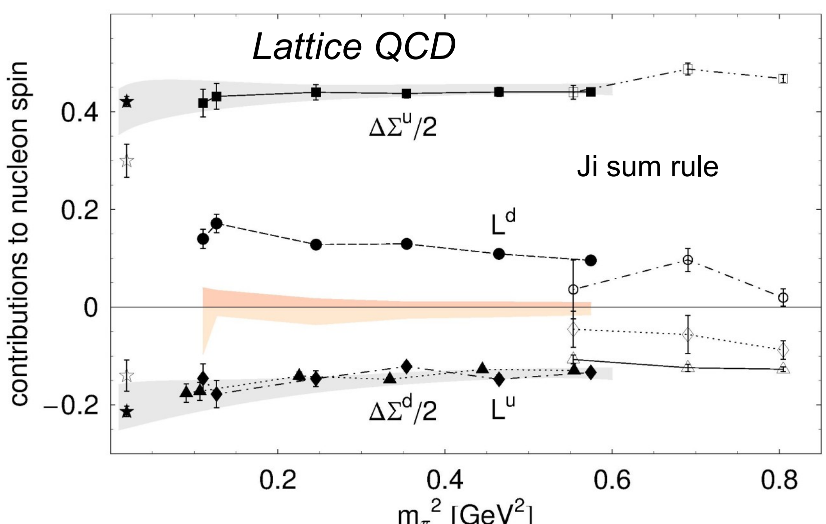
TMDs and Orbital Angular Momentum (OAM)



Jaffe sum rule



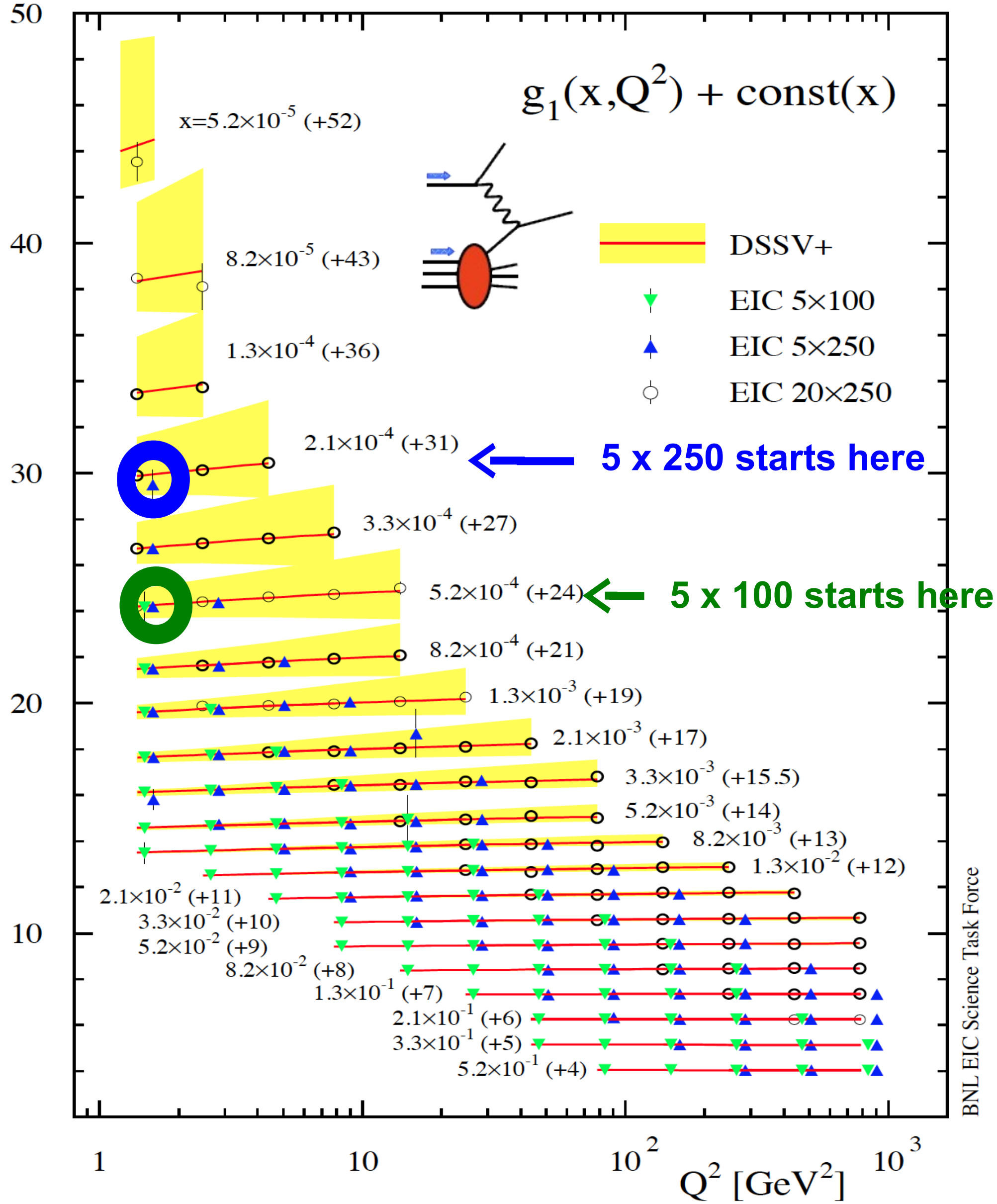
A. Prokudin

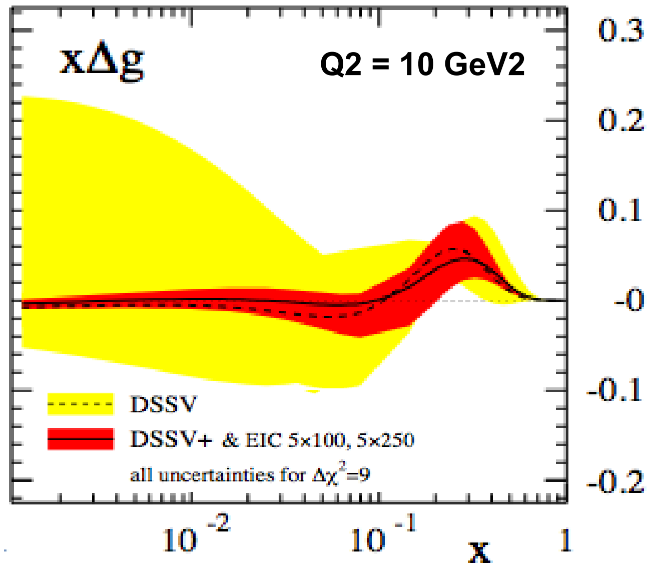


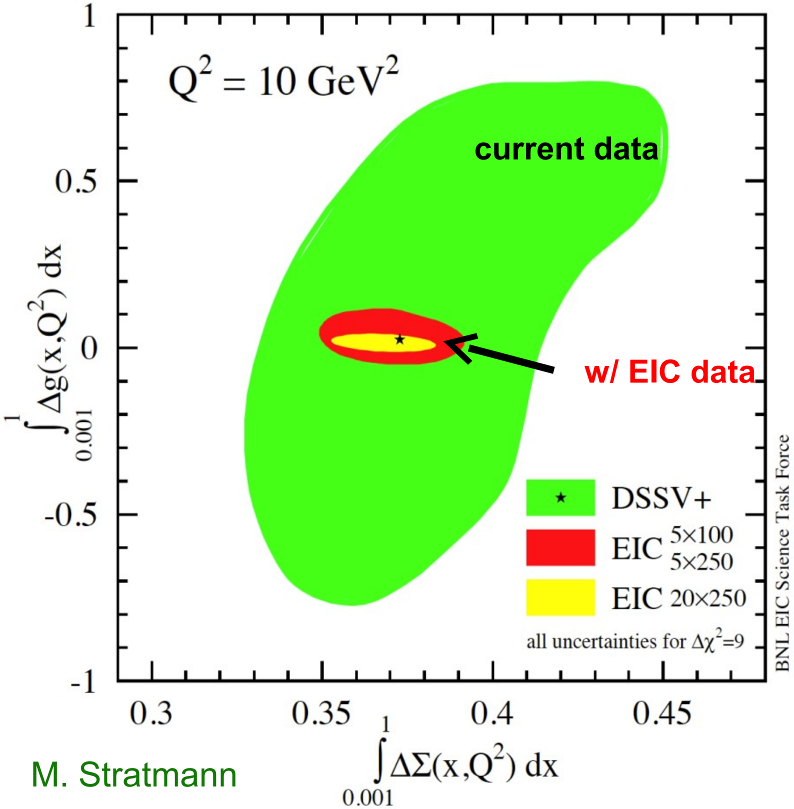
LHPC Collaboration

- Do valence u and d quarks have opposite signs of their OAM?
- TMD data and Lattice calculations suggestive (despite different sum rules)
- What about sea quarks?

Helicity PDFs at an EIC

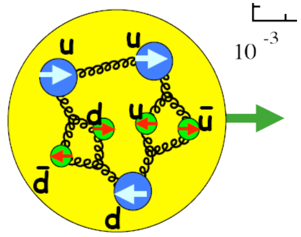






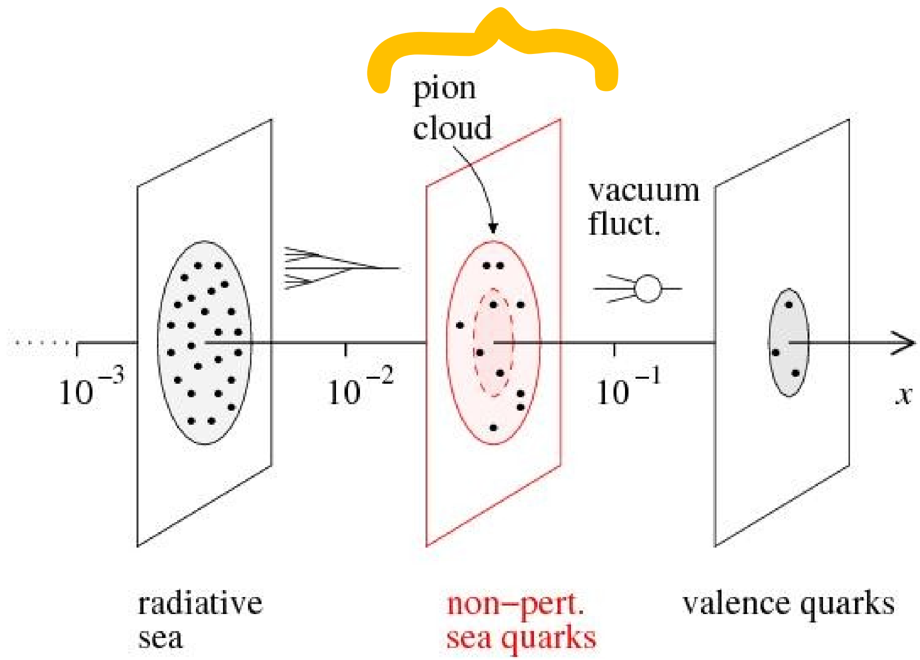
M. Stratmann

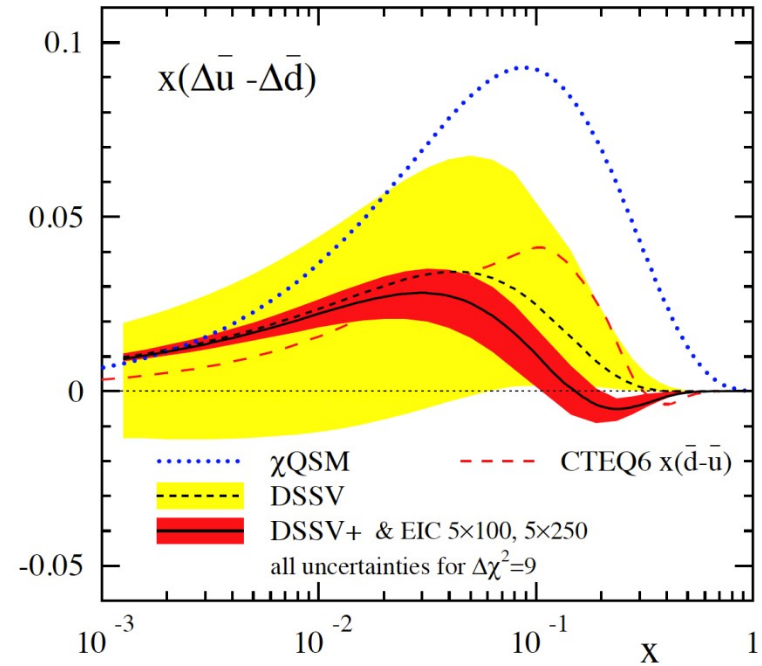
Sea quark polarization



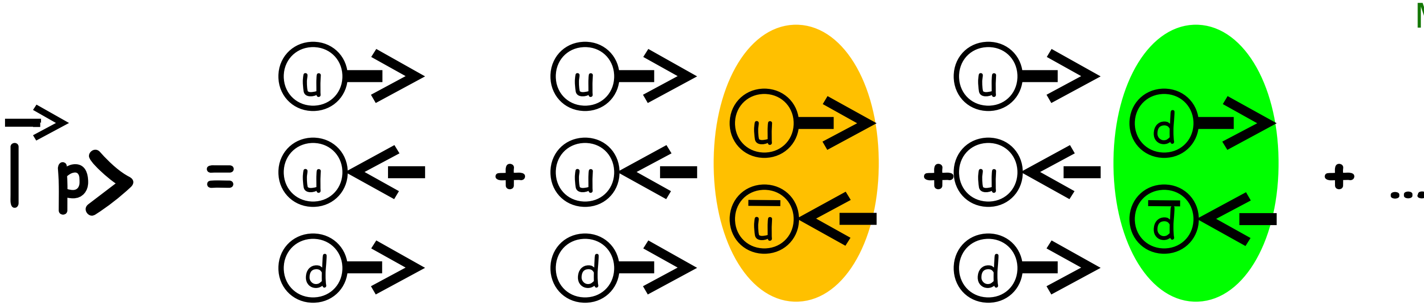
- Spin-Flavor Decomposition of the Light Quark Sea

Needs intermediate √s ~ 30 (and good luminosity)





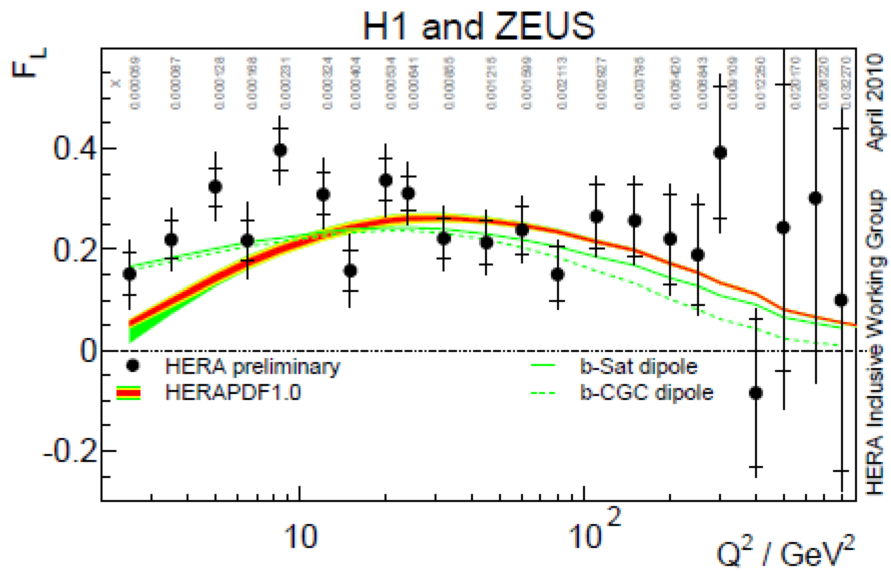
M. Stratmann

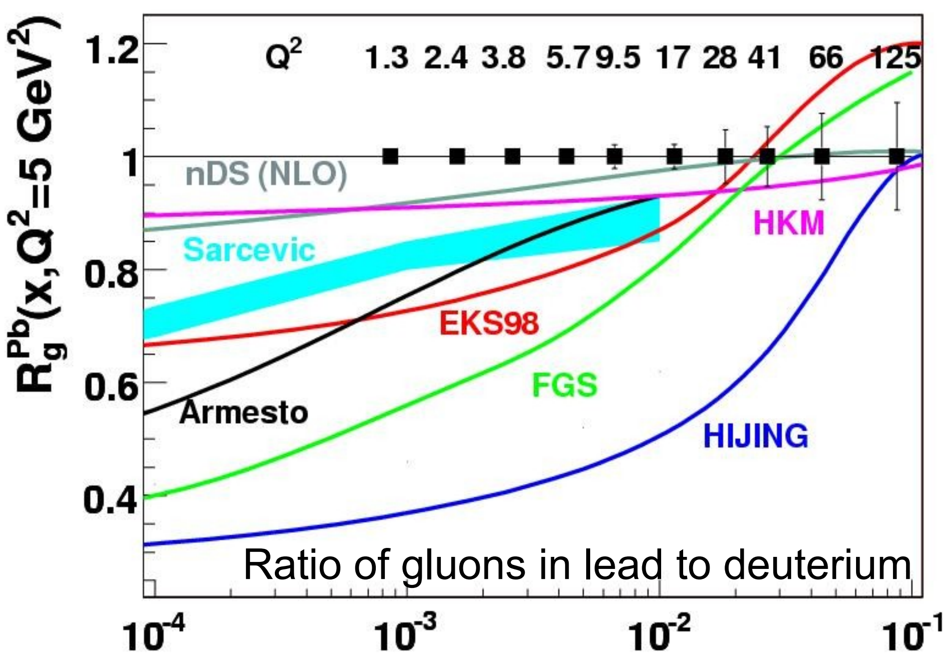


Many models predict

$\Delta\bar{u} > 0$, $\Delta\bar{d} < 0$

Gluons in nuclei





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

- HERA measured the longitudinal gluon distributions in the *nucleon*
  - F_L and $dF_2/d\ln(Q^2)$

- Very little is known about gluons in *nuclei* for all x