Measurements for EIC at JLab

Pawel Nadel-Turonski

Jefferson Lab

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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

Note that already 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

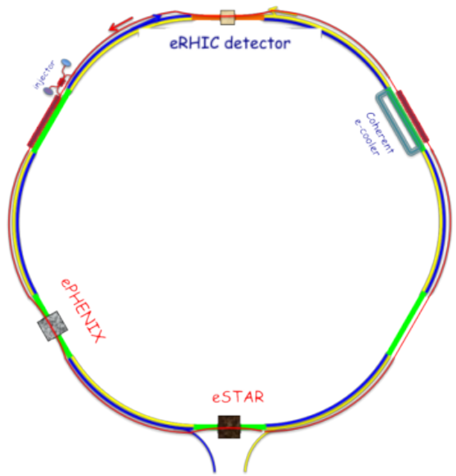
- Polarized electron, nucleon, and light ion beams
  - Electron and nucleon polarization > 70%
  - Transverse polarization at least for nucleons
- Ions from hydrogen to A > 200
- Luminosity reaching 10^{34} $cm^{-2}s^{-1}$
- Stage I energy: $\sqrt{s}$ = 20 – 70 GeV (variable)
- Stage II energy: $\sqrt{s}$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

From base EIC requirements in the INT report

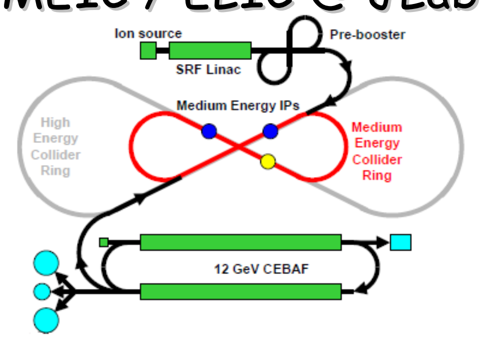
EIC – similar CM energies at BNL and JLab

	Stage I	Stage II
eRHIC @ BNL	$\sqrt{s}$ = 34 – 71 GeV E_e = 3 – 5 (10 ?) GeV E_p = 100 – 255 GeV E_{Pb} = up to 100 GeV/A	$\sqrt{s}$ = 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)

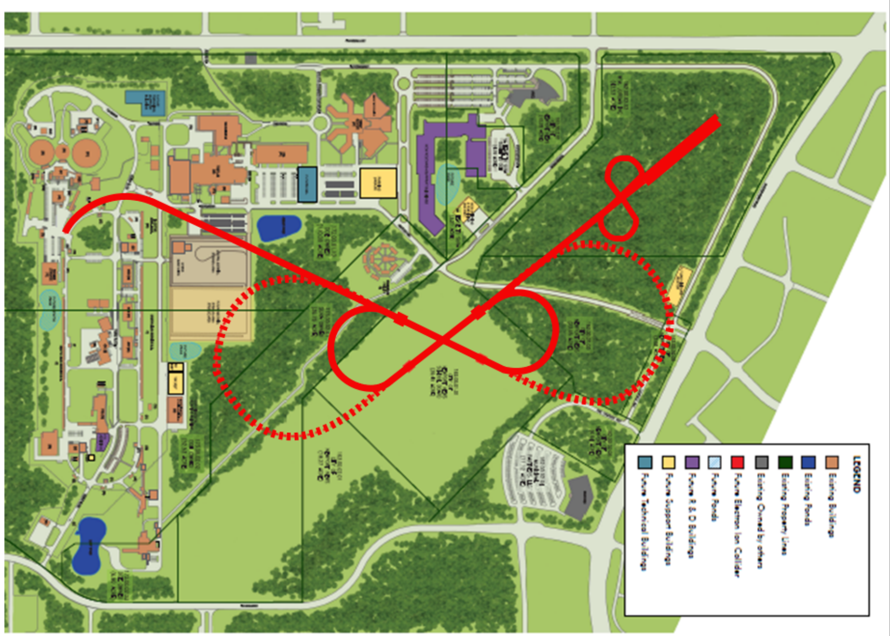
eRHIC @ BNL

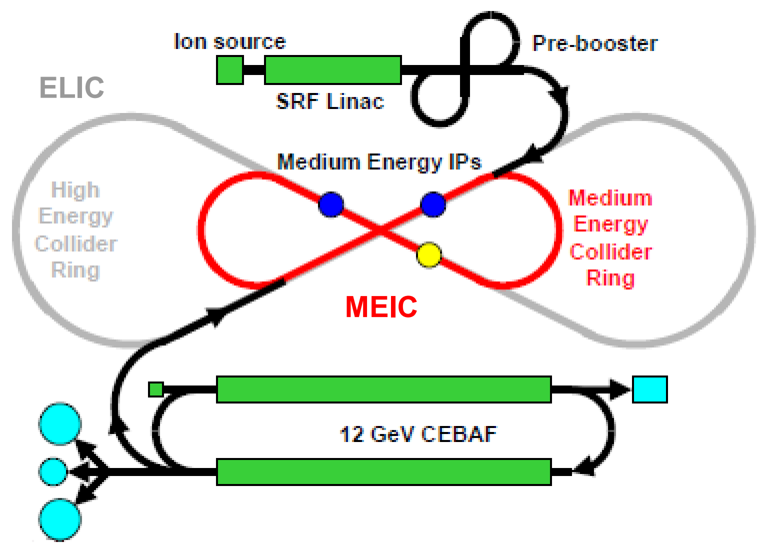


MEIC / ELIC @ JLab



The EIC at JLab – overview of accelerator



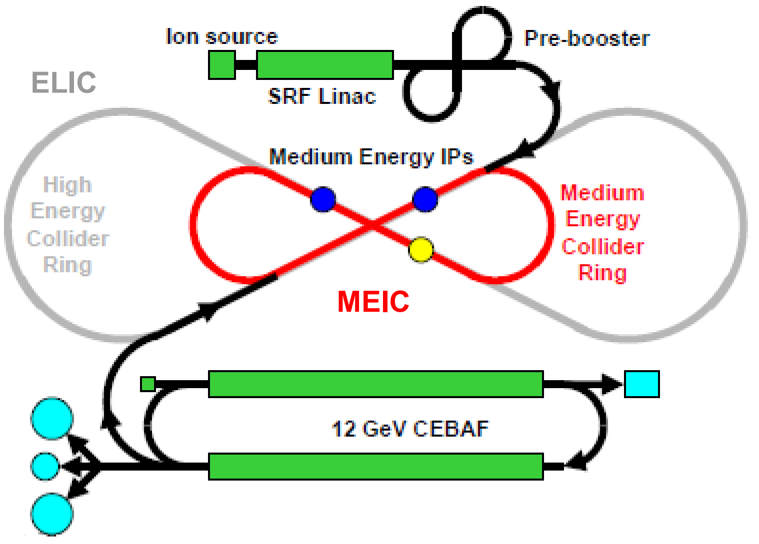


- Stage I (MEIC):
  - 3-11 GeV electrons on 20-100 GeV protons
  - About the same size as the 12 GeV CEBAF accelerator (1/3 of RHIC)
- Stage II (ELIC):
  - ~20 GeV electrons on 250+ GeV protons

MEIC – a figure-8 ring-ring collider

The design makes possible:

- Simultaneous use of both detectors
  - total beam-beam tune shift < 0.03
- 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

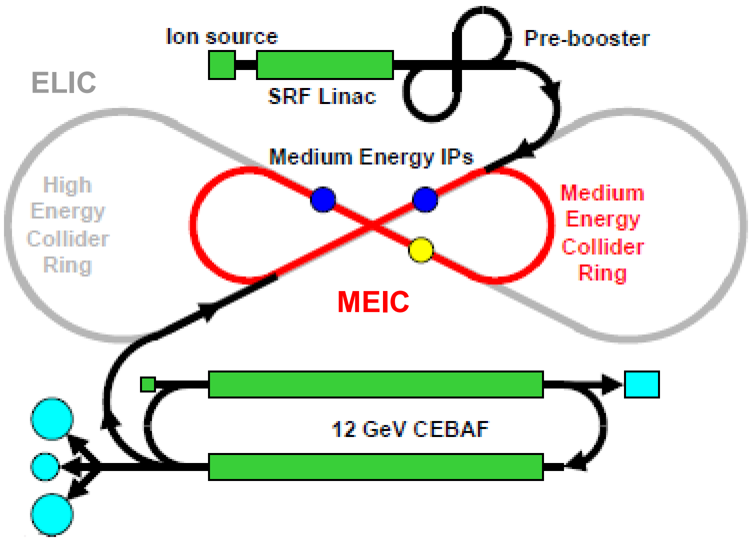


- Reduced R&D challenges
  - Regular electron cooling
  - Regular electron source
  - No multi-pass ERL

MEIC – detectors

Space for 3 Interaction Points (IP)

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



Primary detector (full acceptance)

- 7 m from IP to ion final-focus quads
- $\beta_y^* = 2$ cm, $\beta_x^* = 10\text{-}20$ cm, $\beta^{max} = 2.5$ km

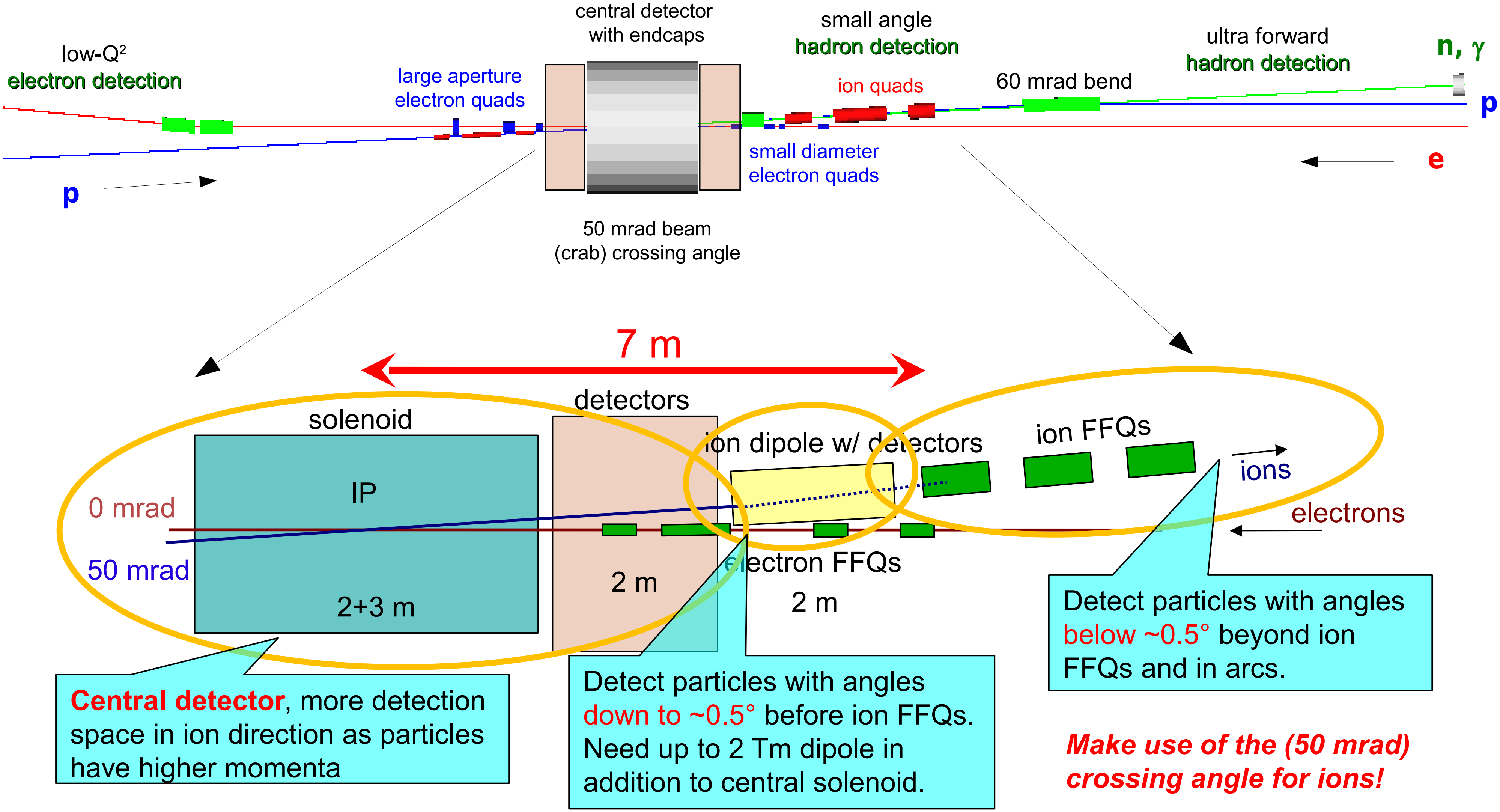
Special IP

- Space reserved for future needs

Secondary detector (can be more limited)

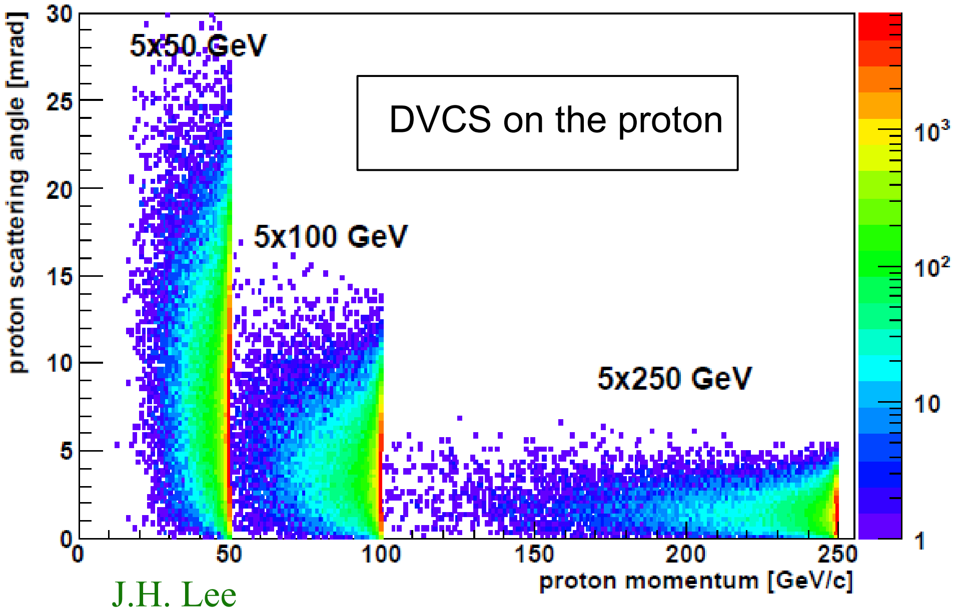
- 4.5 m from IP to ion final-focus quads
  - Same as in BNL design

Full-acceptance detector – strategy

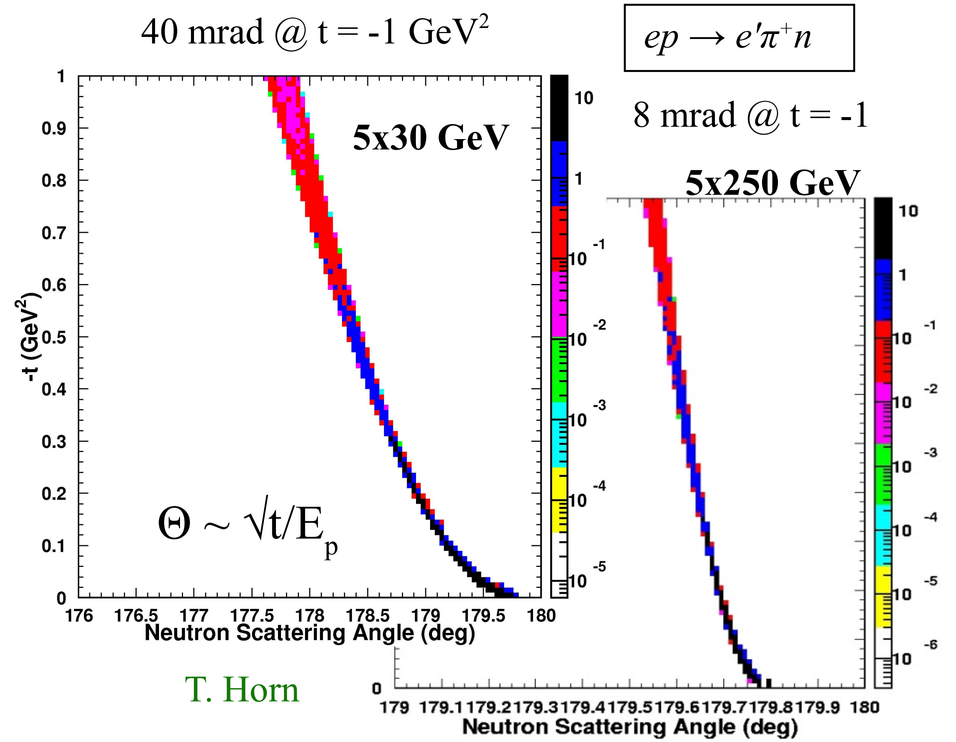


Make use of the (50 mrad) crossing angle for ions!

Recoil baryon detection



J.H. Lee

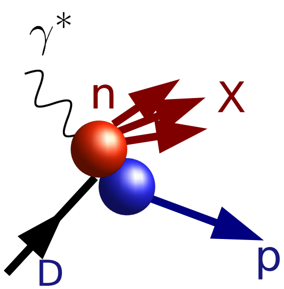


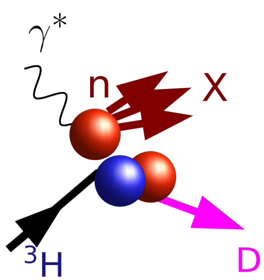
T. Horn

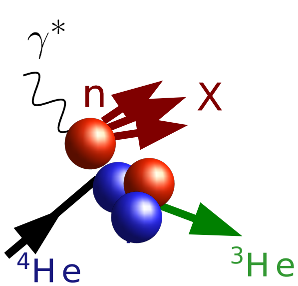
- At high proton energies, recoil baryons are scattered at small angles
  - Lower proton energies give better small-*t* coverage and *resolution* in ***-t***
  - Higher proton energies give better large-*t* acceptance at for a given *maximum* ring energy
    - Lower maximum ring energy gives better acceptance at the *actual* running energy
- Good recoil baryon detection requires
  - Wide range of proton (deuteron) energies
  - Small beam size to reach low -t (relies on highly efficient cooling)

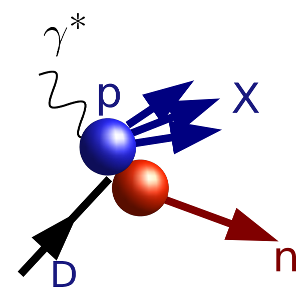
Spectator (and fragment) detection / tagging

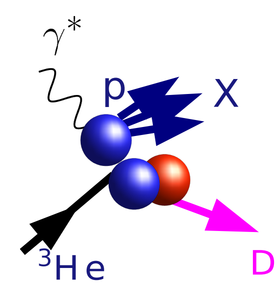
Quasi-free neutron: target	Quasi-free neutron: spect.	(Quasi)-free proton: target	(Quasi)-free proton: spect.
		p	
D	p	D	n
^3H	D		
		^3He	D
^4He	^3He	^4He	^3H

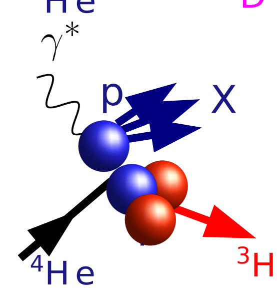












Ultra-forward hadron detection – requirements

1. **Good acceptance for ion fragments** (rigidity different from beam)
   - Large downstream magnet apertures
   - Small downstream magnet gradients (realistic peak fields)

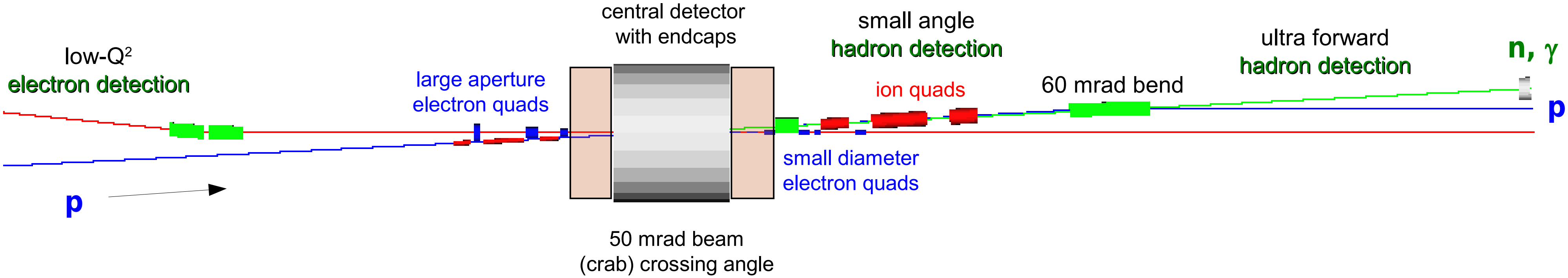
2. **Good acceptance for recoil baryons** (rigidity similar to beam)
   - Small beam size at second focus (to get close to the beam)
   - Large dispersion (to separate scattered particles from the beam)

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

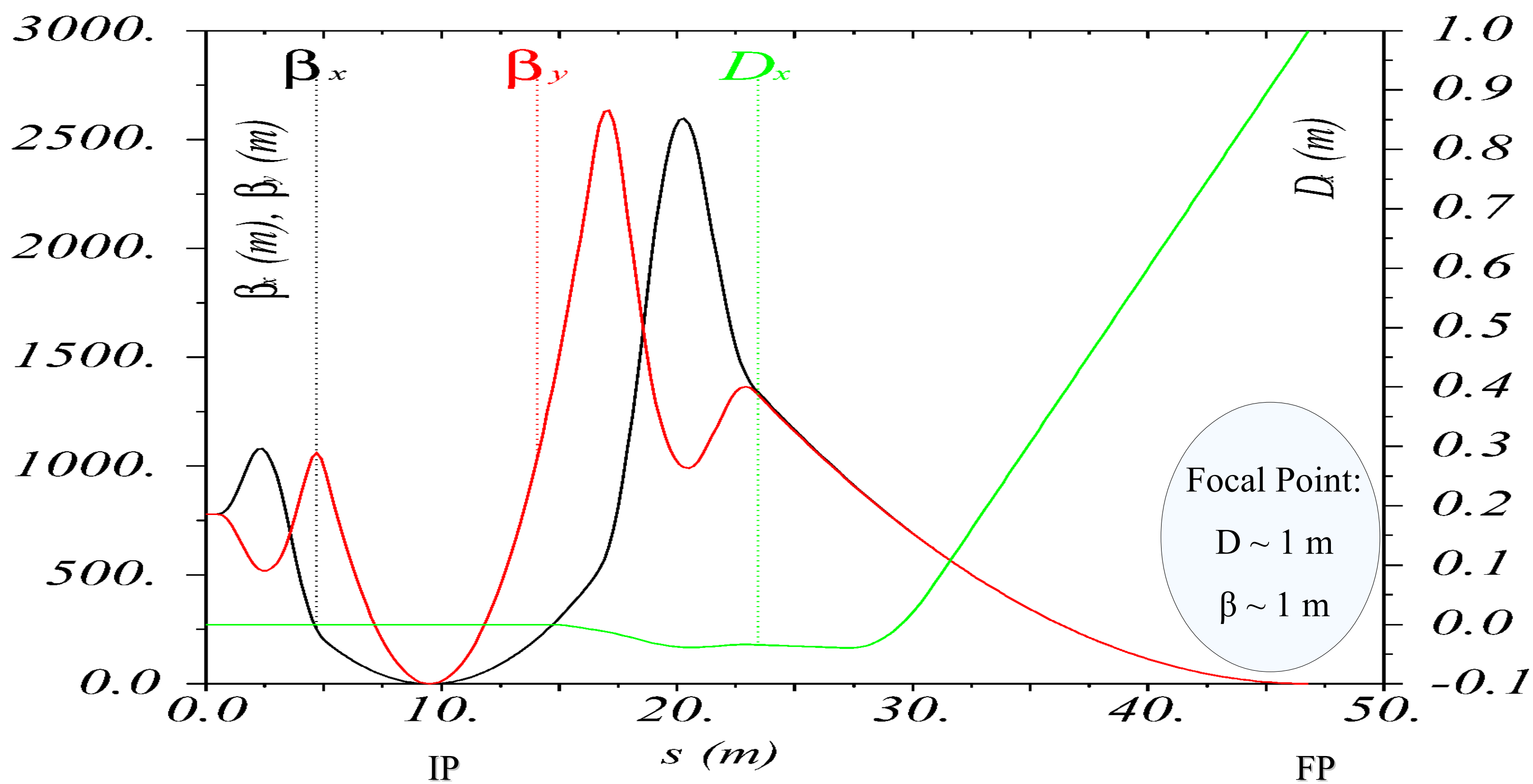
4. Sufficient separation between beam lines (~1 m)

Full-acceptance detector – integration

No other magnets or apertures between IP and FP!

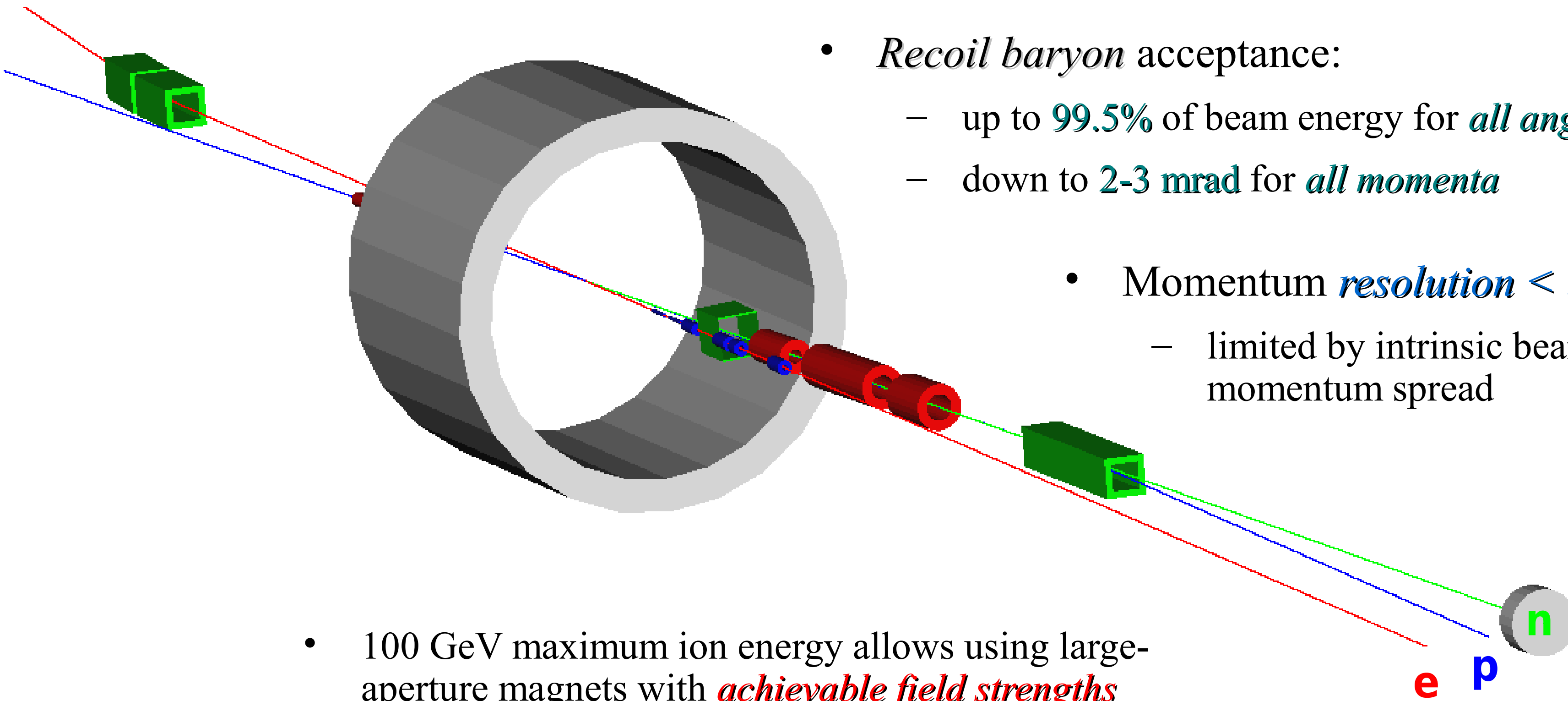


To achieve all requirements, the accelerator team is designing the MEIC around the detector.

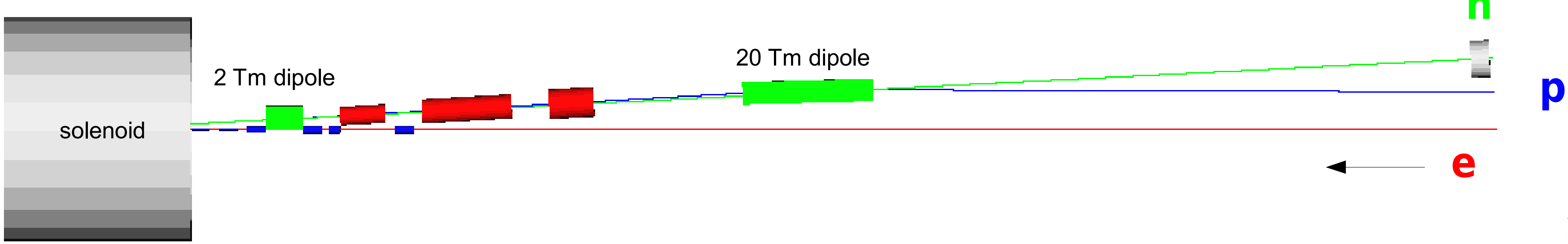


Small-angle hadron detection – summary

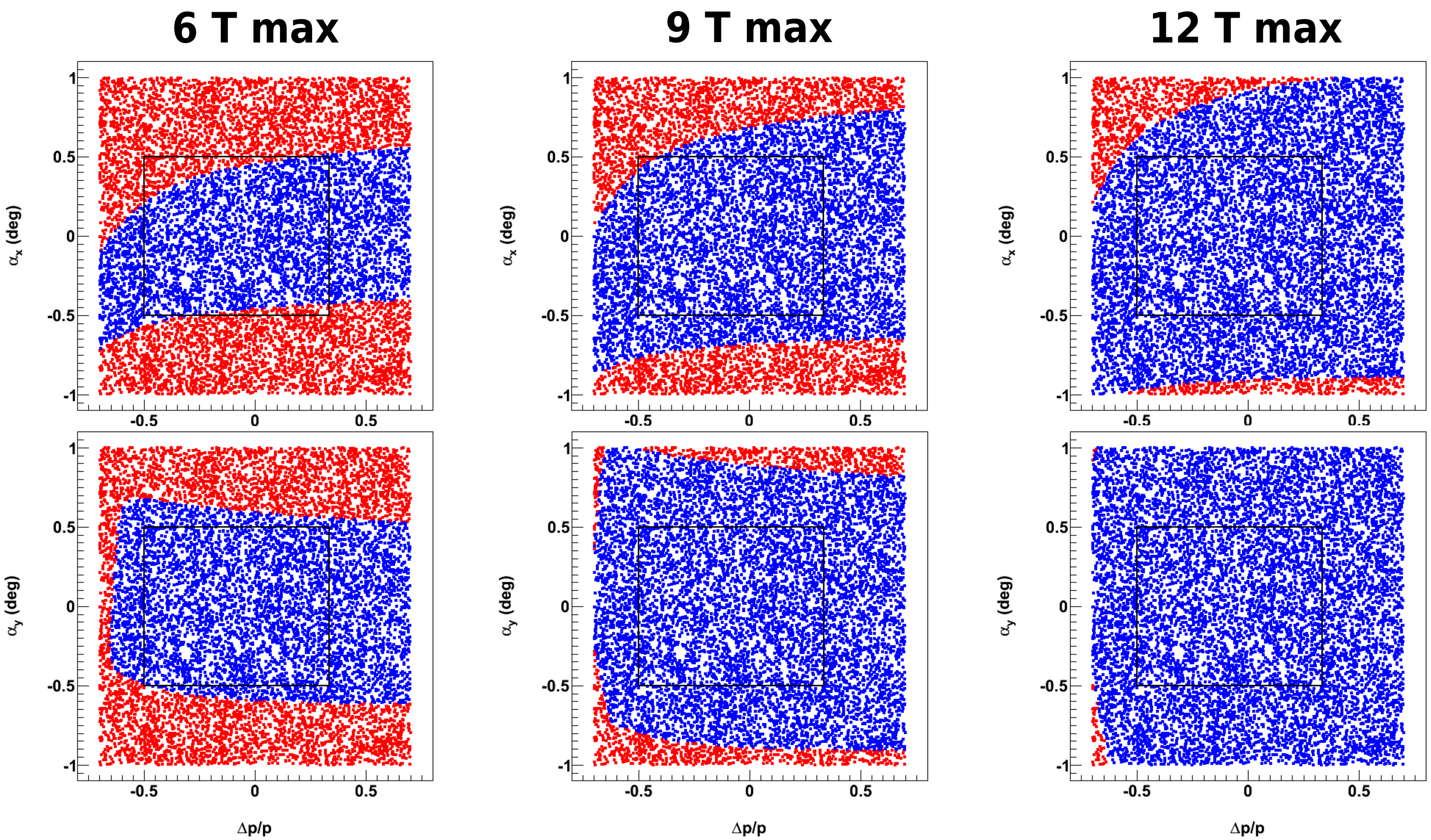
- *Neutron* detection in a 25 mrad cone ***down to zero degrees***
- Excellent acceptance for ***all ion fragments***
- *Recoil baryon* acceptance:
  - up to **99.5%** of beam energy for ***all angles***
  - down to **2-3 mrad** for ***all momenta***
- Momentum ***resolution < 3x10^{-4}***
  - limited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



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



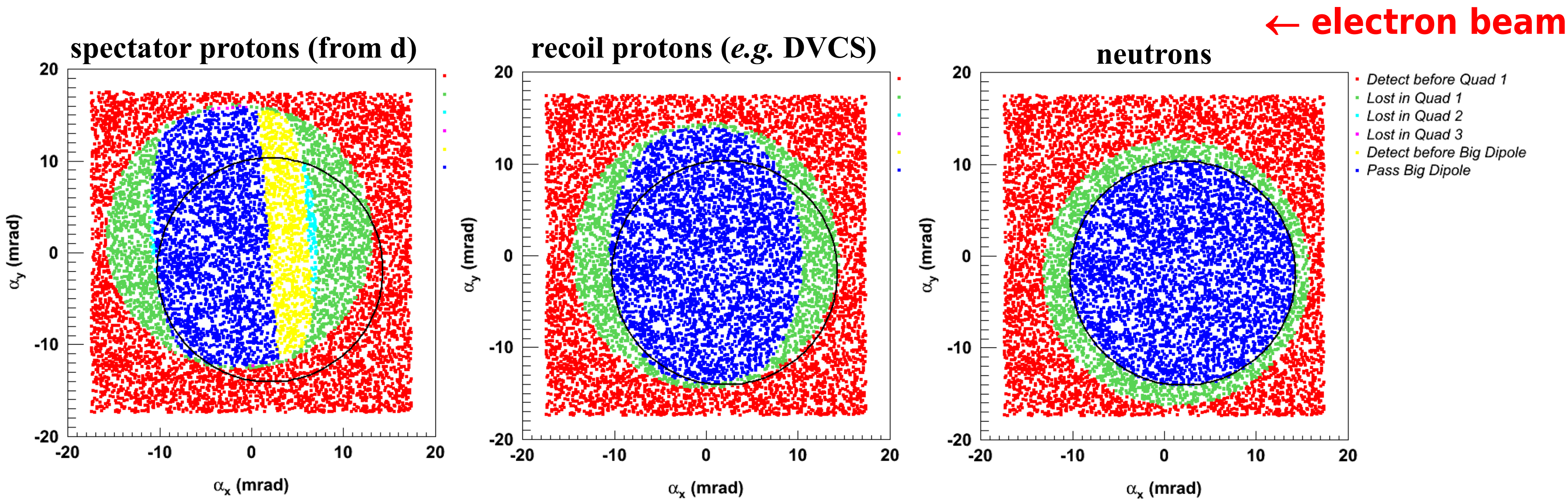
Small-angle hadron acceptance – magnet fields



Red: Detection between the small upstream dipole and ion quadrupoles

Blue: Detection after the large downstream dipole

Small-angle hadron acceptance @ 9 T (100 GeV)



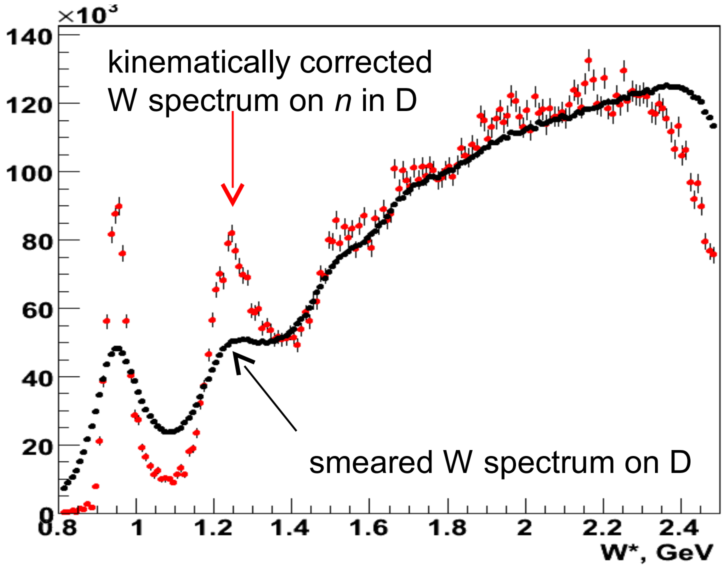
Red and Green: Detection between upstream 2 Tm dipole and ion quadrupoles

Yellow: Detection between ion quadrupoles and downstream 20 Tm dipole

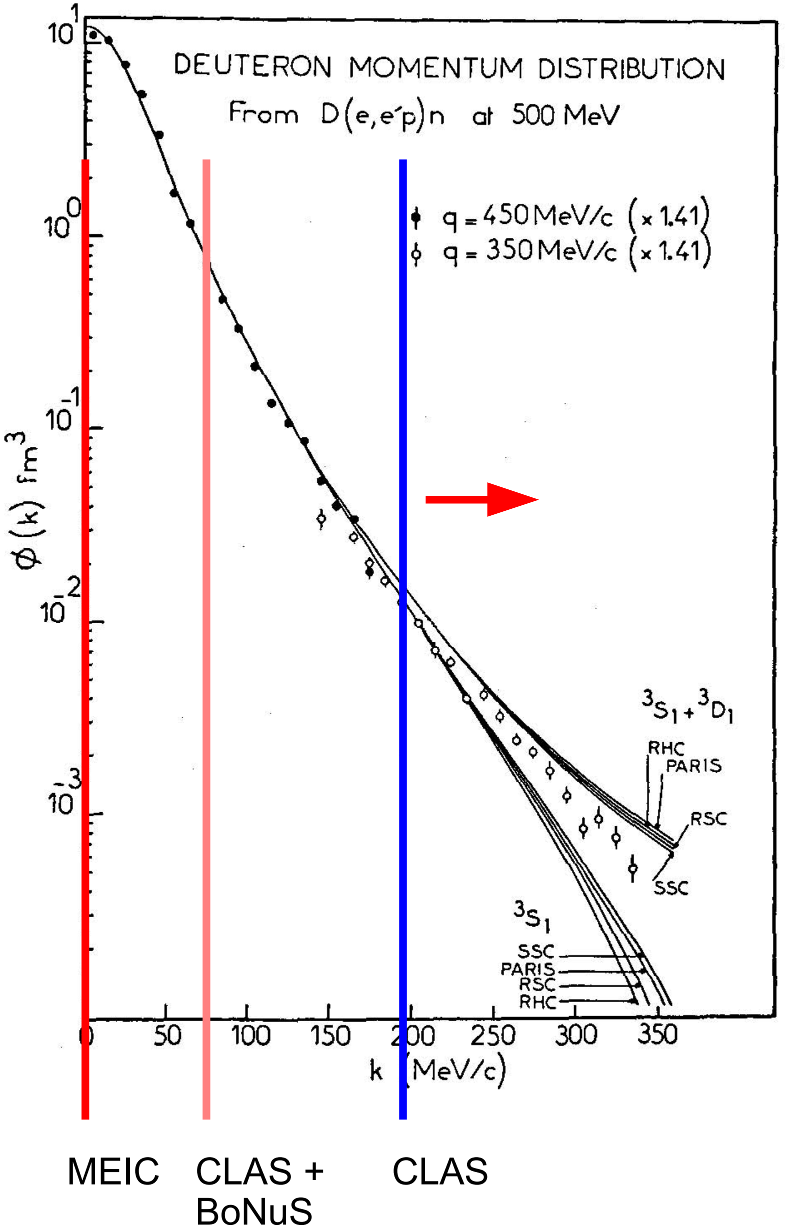
Blue: Detection after the 20 Tm downstream dipole

- 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

Neutron structure through spectator tagging

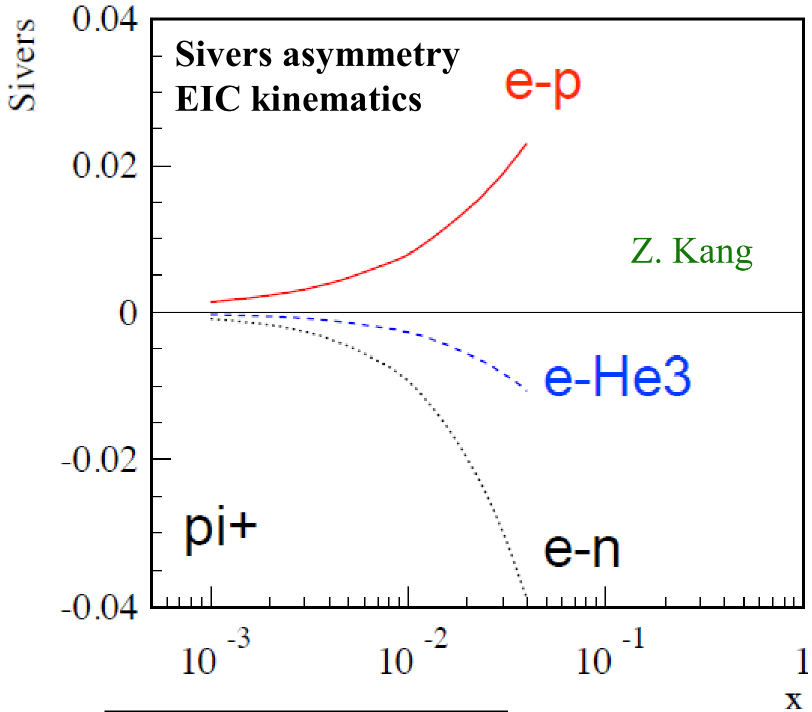


CLAS BoNuS data with tagged spectators



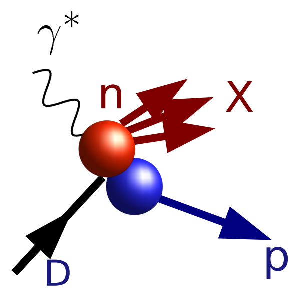
- In fixed-target experiments, scattering on *bound neutrons* is complicated
  - Fermi motion, nuclear effects
  - Low-momentum spectators
- Spectator tagging at the MEIC will allow flavor separation of spin and sea quark distributions

Spectator tagging with polarized deuterium

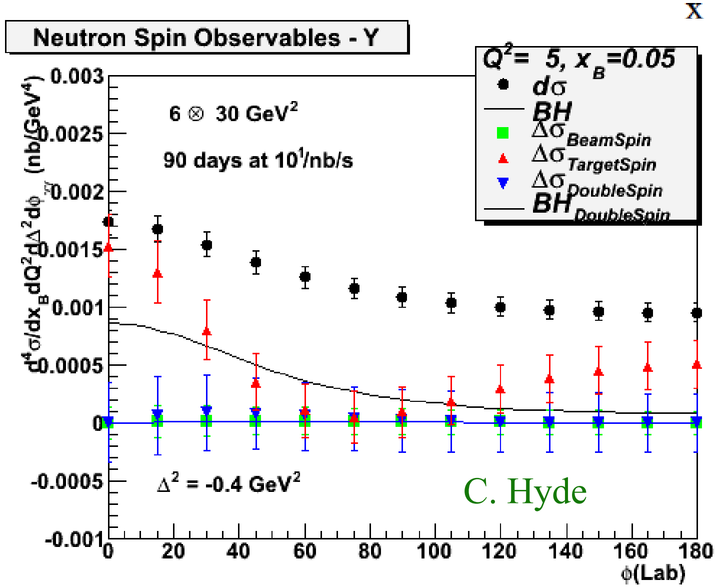


„If one could tag neutron, it typically leads to larger asymmetries“

Z. Kang



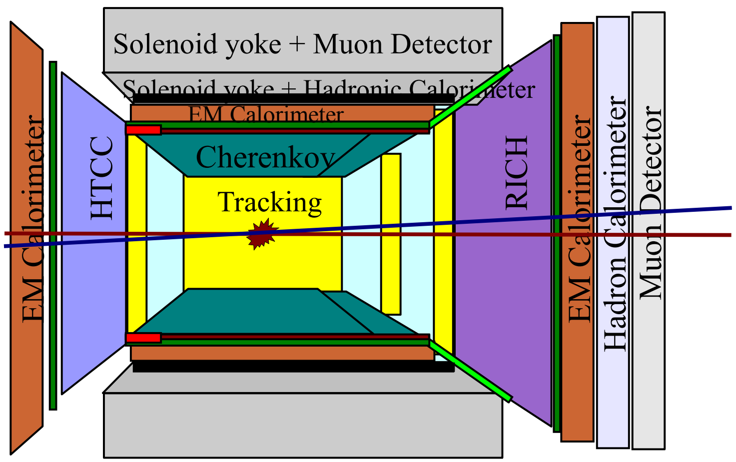
- Longitudinal and *transverse* polarization for d, ^{3}He, and other light ions



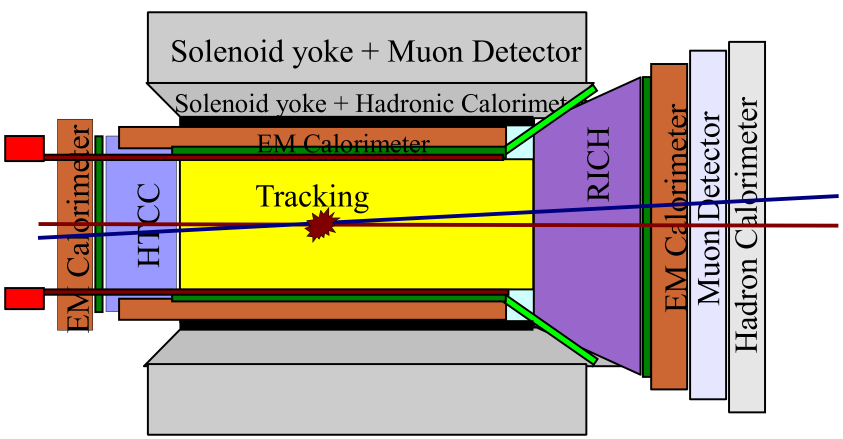
- Polarized neutrons are important for probing d-quarks through **SIDIS**

- Polarized *neutrons* are also important for **exclusive reactions**

Particle identification and central 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

- The importance of Stage I cannot be overemphasized since this is the machine that is actually going to be built and operated for at least a decade before there is any chance for a Stage II to materialize.

Common framework for JLab and BNL implementations

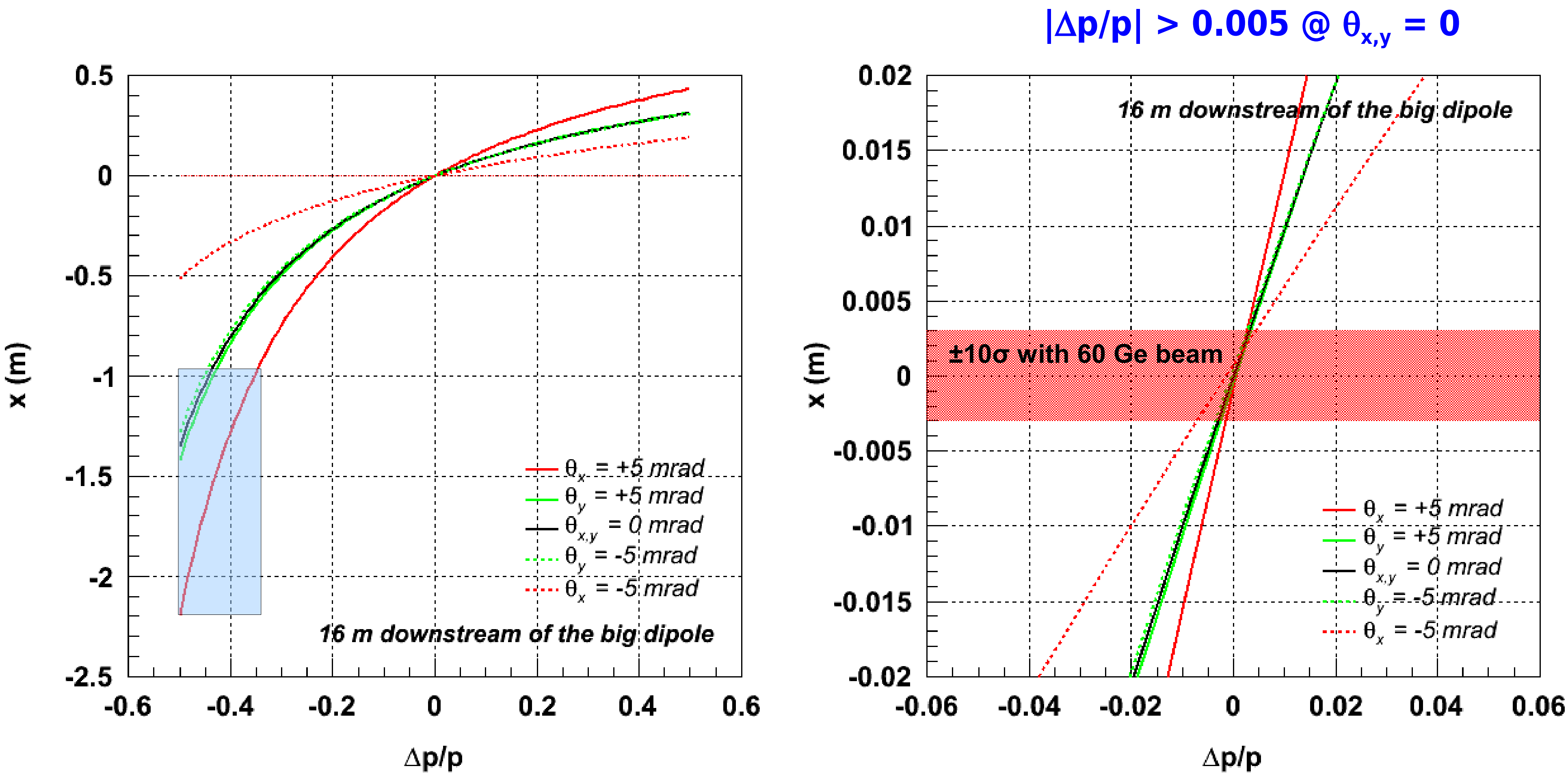
- Global design parameters (energies, staging, etc) follow INT consensus

MEIC at JLab offers many attractive capabilities

- Wide range of proton (ion) energies
- Polarized deuterons and positrons
- Excellent detection of recoil baryons, spectators, and target fragments

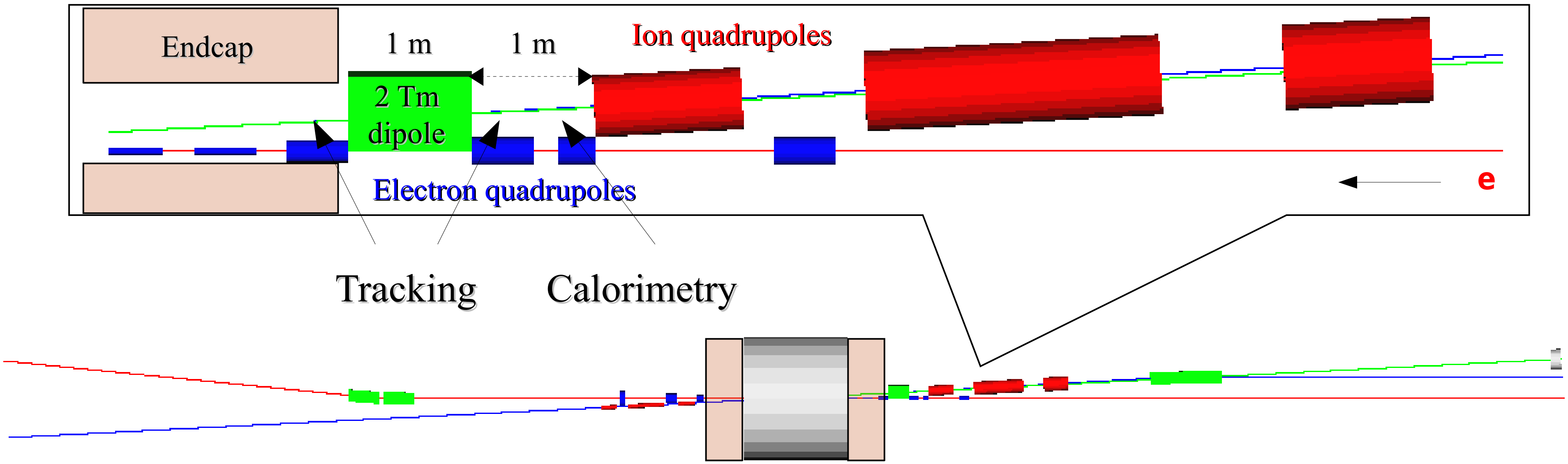
Backup

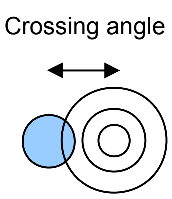
Momentum resolution at the focal point



- Momentum resolution is given by the slope of the line
- Large deflections and long drift space allows precise tracking
  - Particles with deflections > 1 m will be detected closer to the large dipole

Hadron detection prior to ion quadrupoles

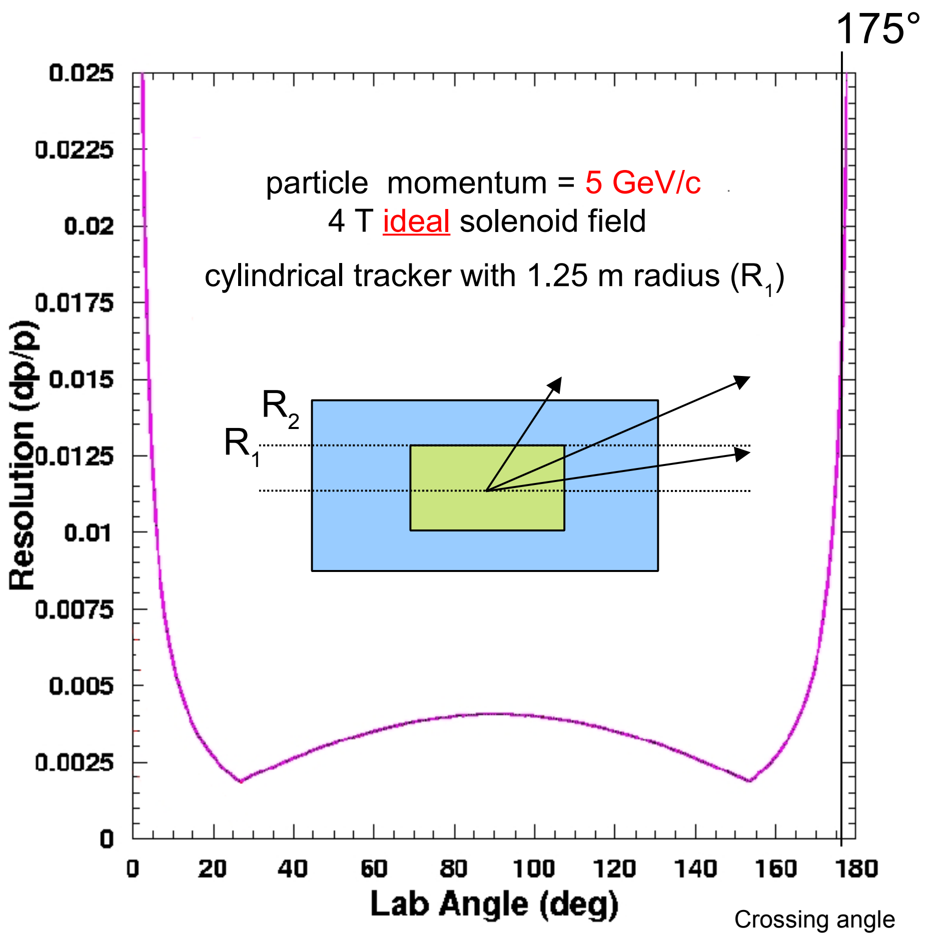


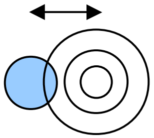


- Large crossing angle (50 mrad)
  - Moves spot of poor resolution along solenoid axis into the periphery
  - Minimizes shadow from electron FFQs

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

Tracking: momentum resolution in a solenoid field

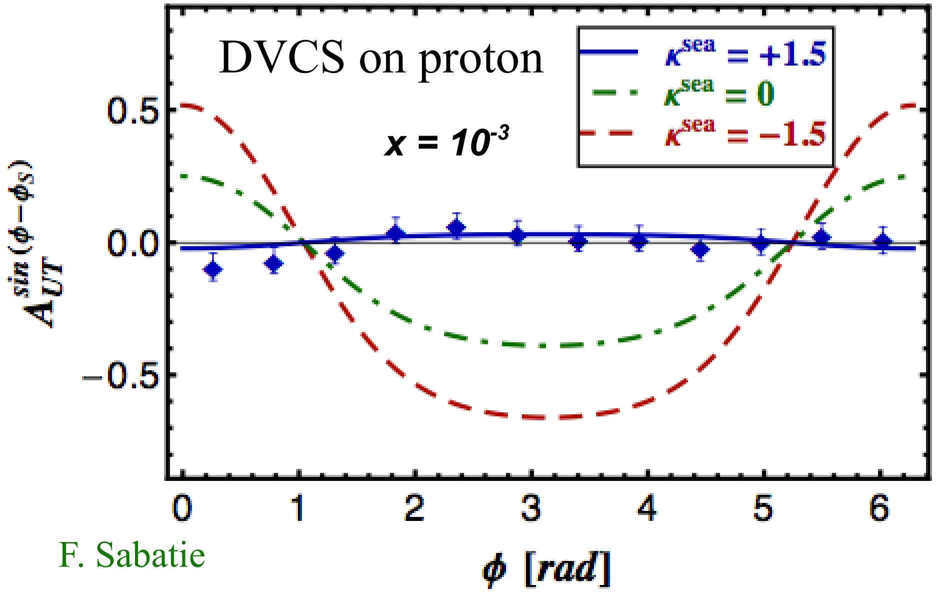




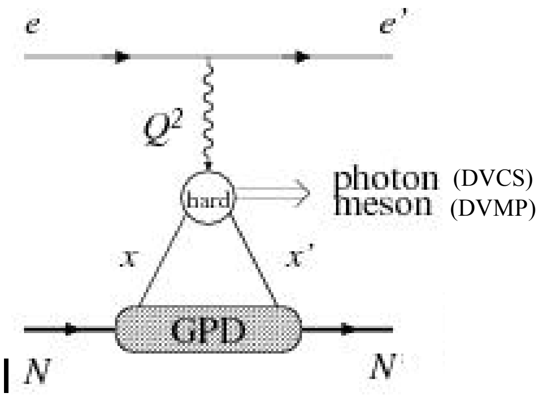
$\Delta p/p \sim \sigma p / BR^2$

- 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!

Exclusive reactions with transverse “target“



F. Sabatie



Model

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

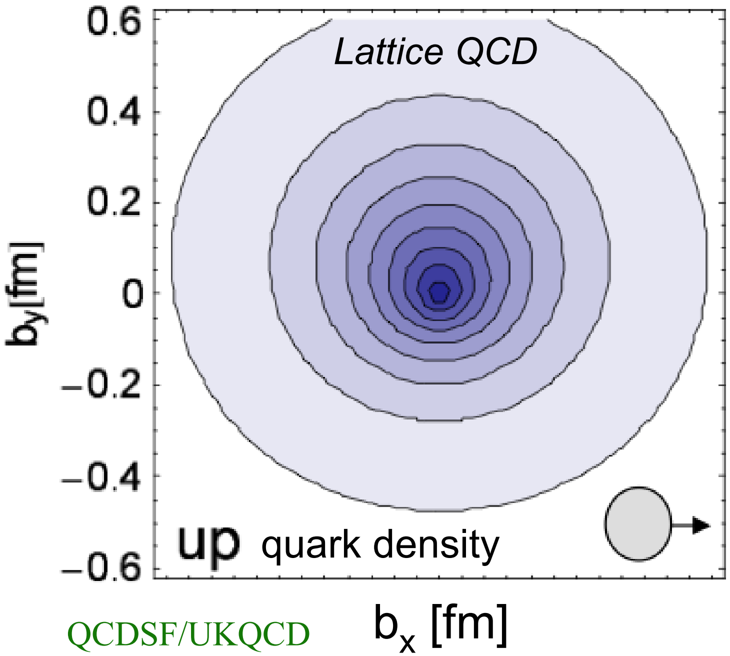
Error bars shown only for $\kappa^{sea} = +1.5$

- 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

<u>GPDs</u>

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

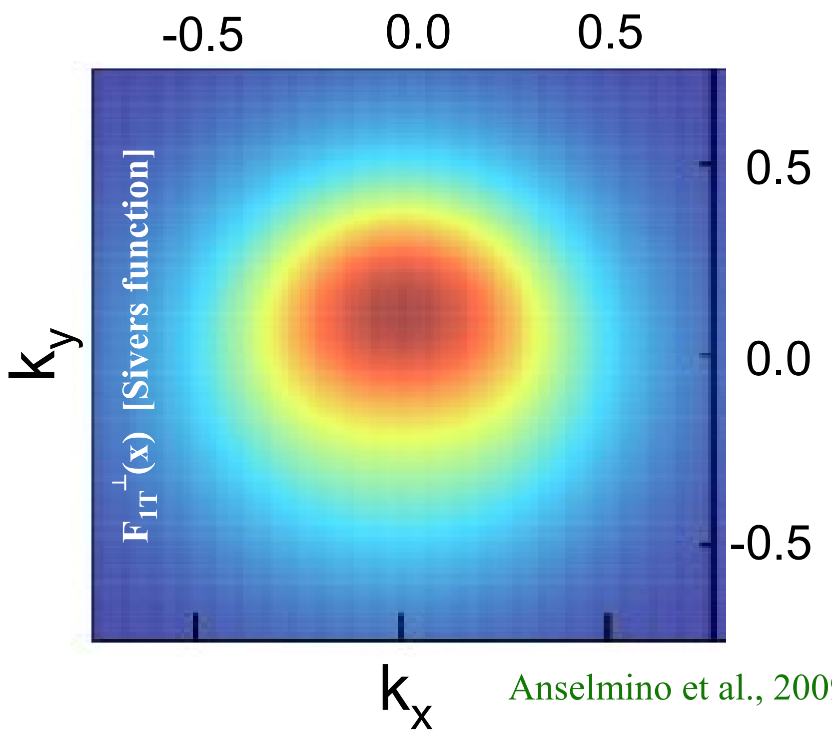


QCDSF/UKQCD Coll., 2006

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

<u>TMDs</u>

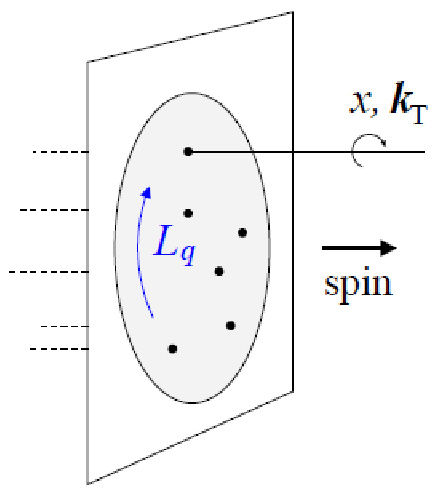
2+1 D picture in **momentum space**



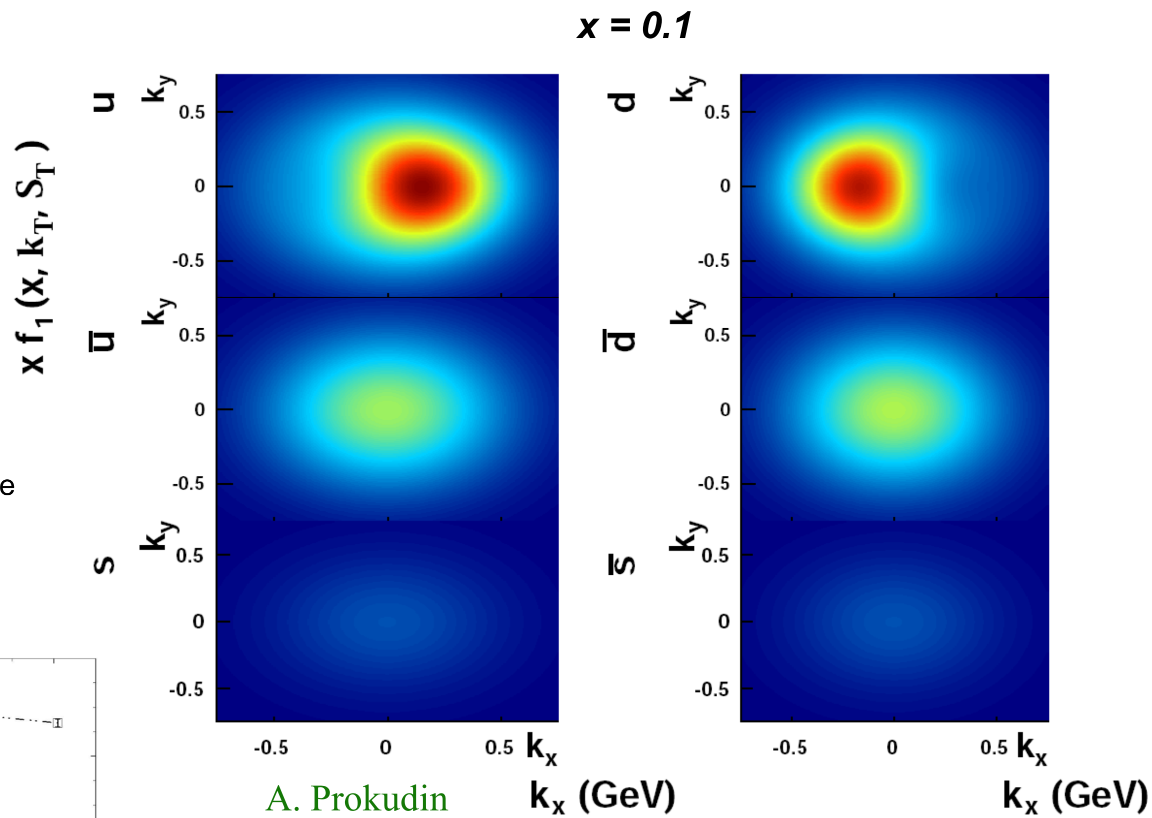
Anselmino et al., 2009

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

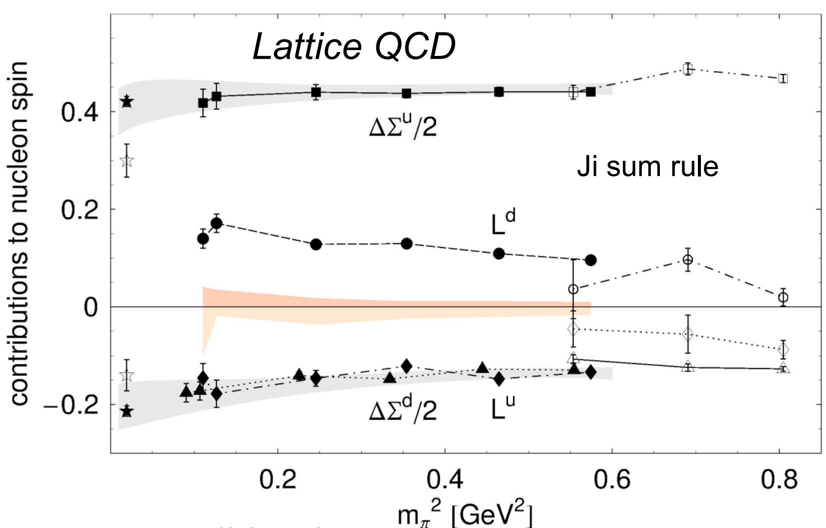
TMDs and Orbital Angular Momentum (OAM)



Jaffe sum rule



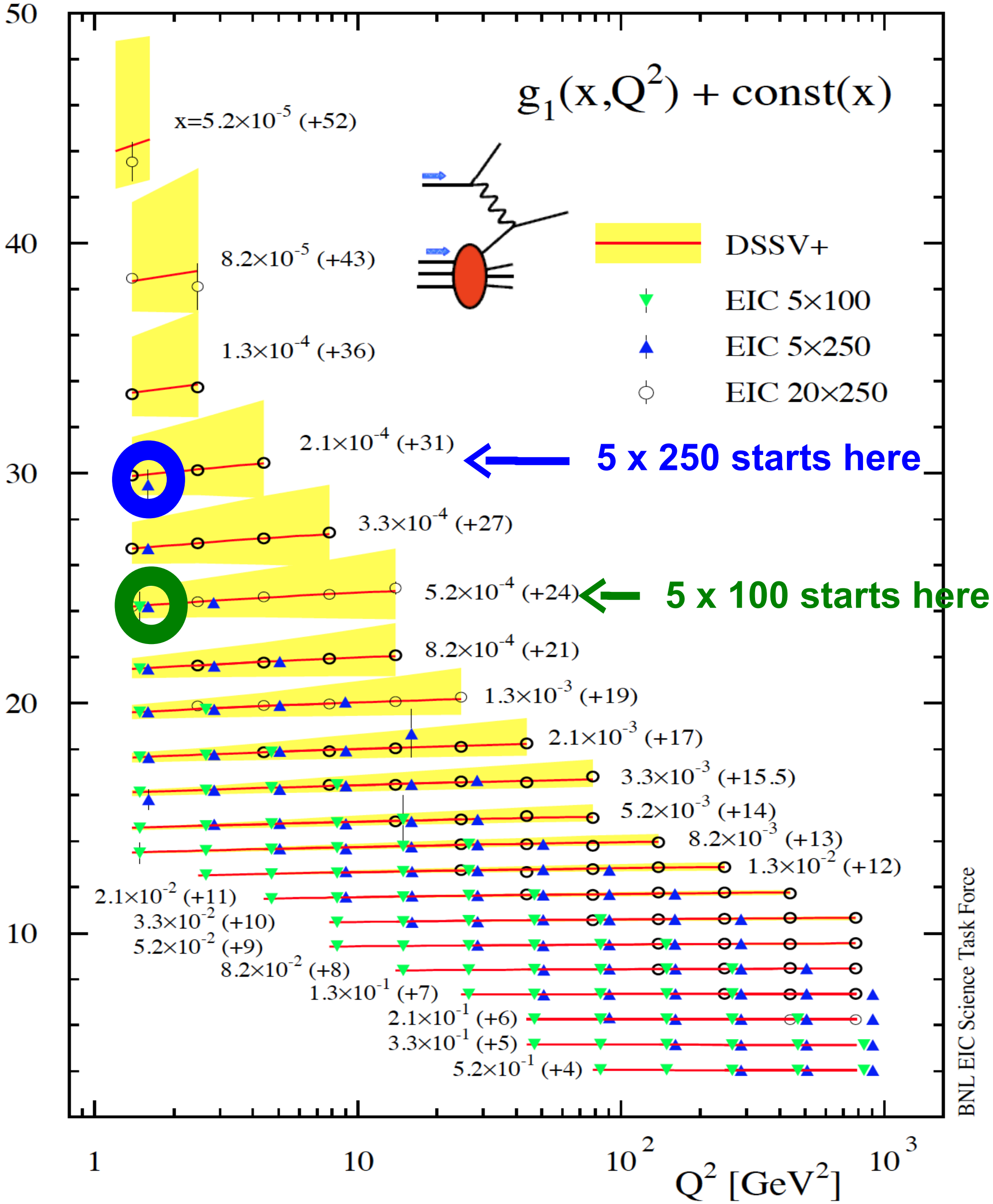
A. Prokudin

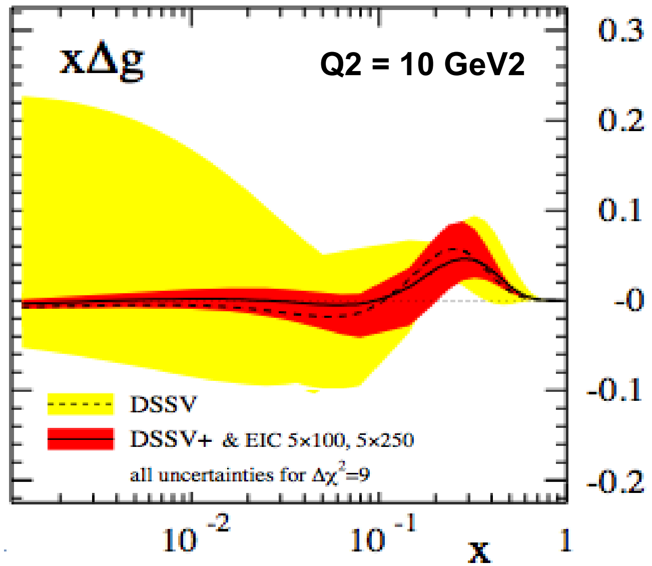


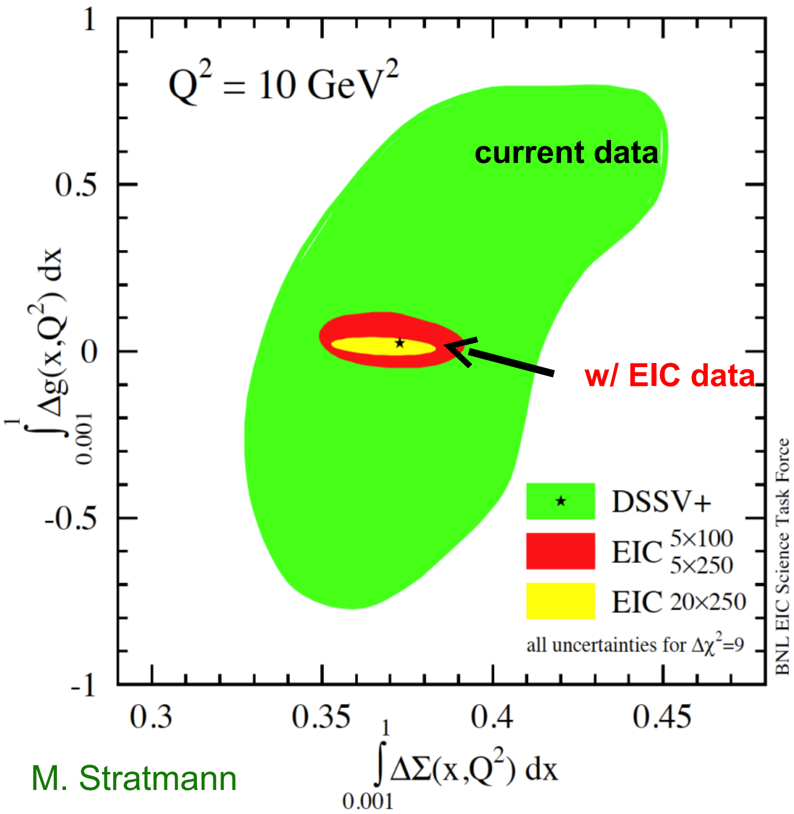
LHPC Collaboration

- 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

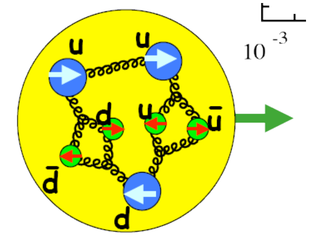






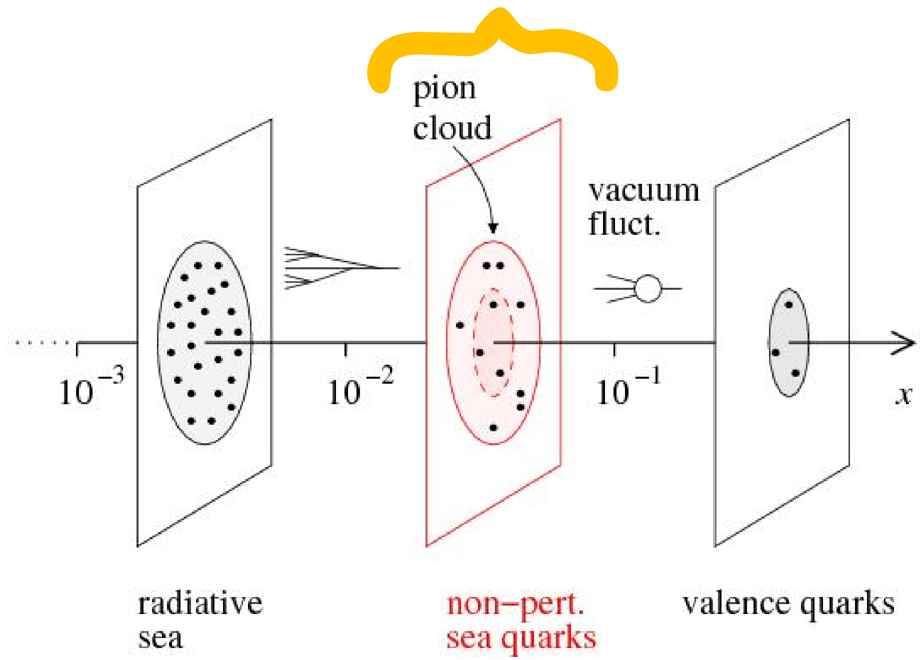
M. Stratmann

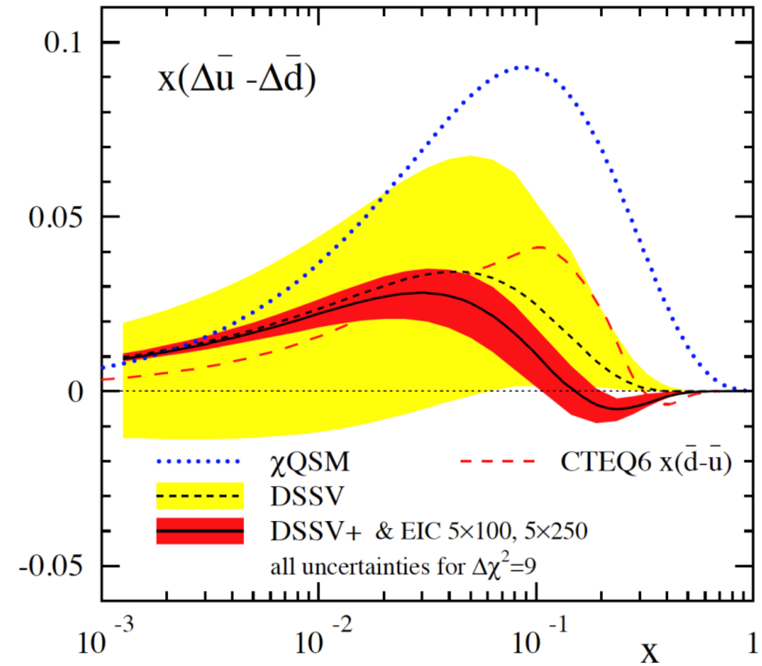
Sea quark polarization



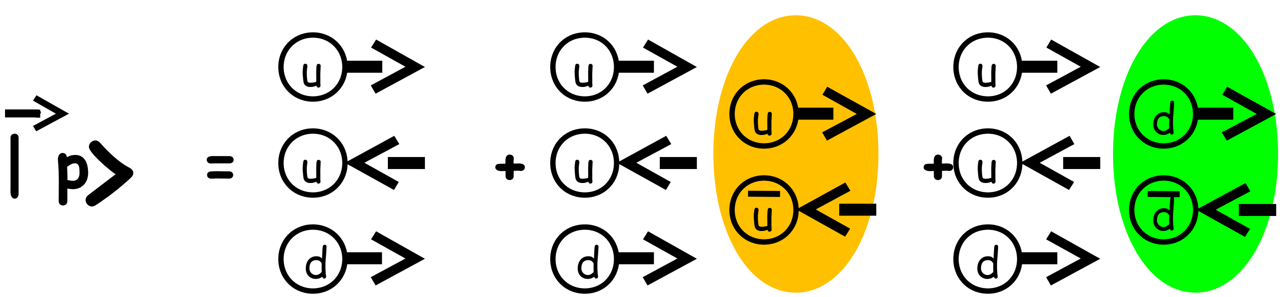
- Spin-Flavor Decomposition of the Light Quark Sea

Needs intermediate √s ~ 30 (and good luminosity)





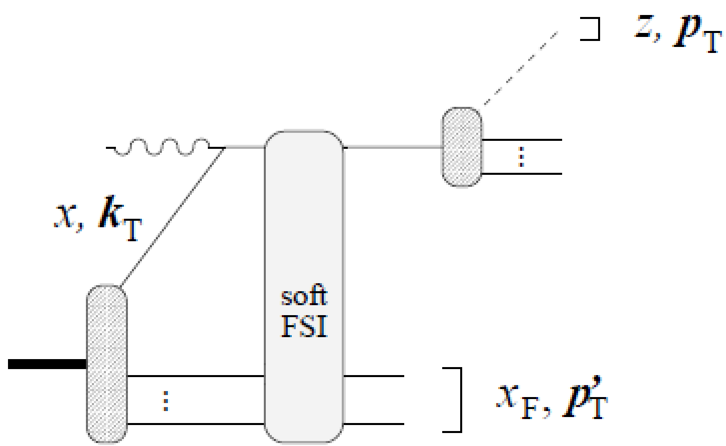
M. Stratmann

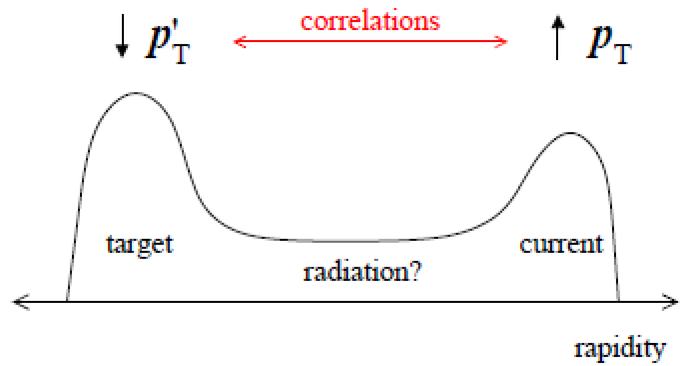


Many models predict

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

Target and current fragmentation in SIDIS

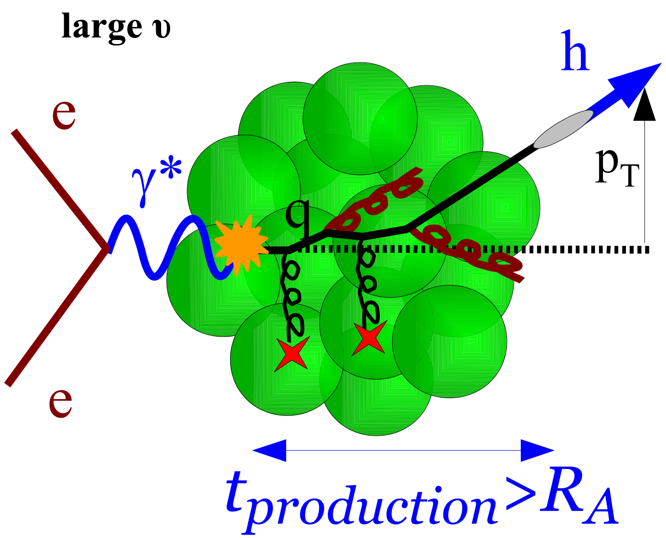


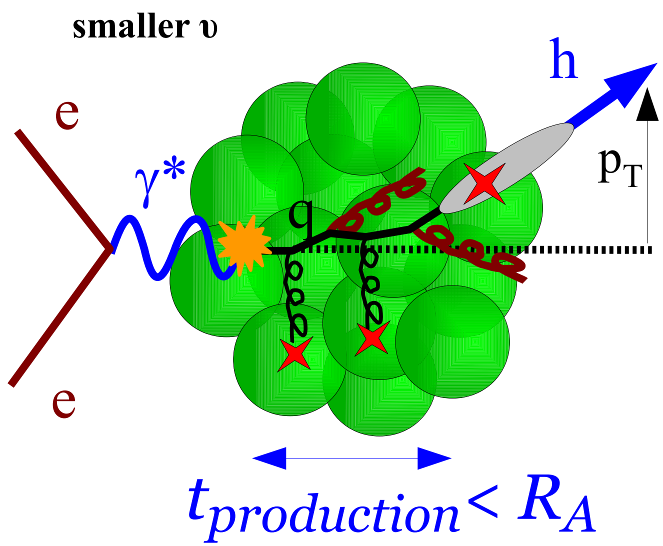


C. Weiss

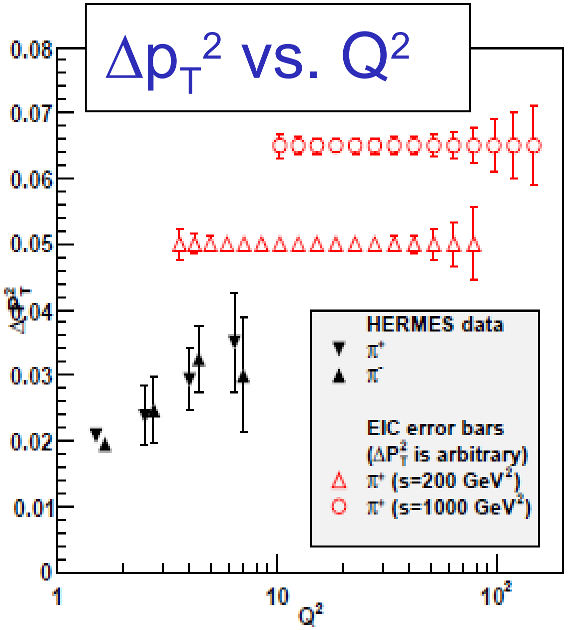
- Cannot separate intrinsic k_T from soft FSI and fragmentation
- New insight from p'_T of target fragments?
  - Origin of FSI? QCD radiation?
- EIC: current-target correlation measurements over wide range in p_T

Hadronization – parton propagation in matter

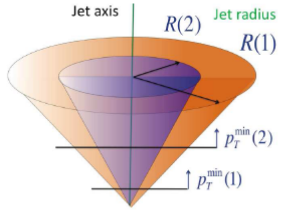




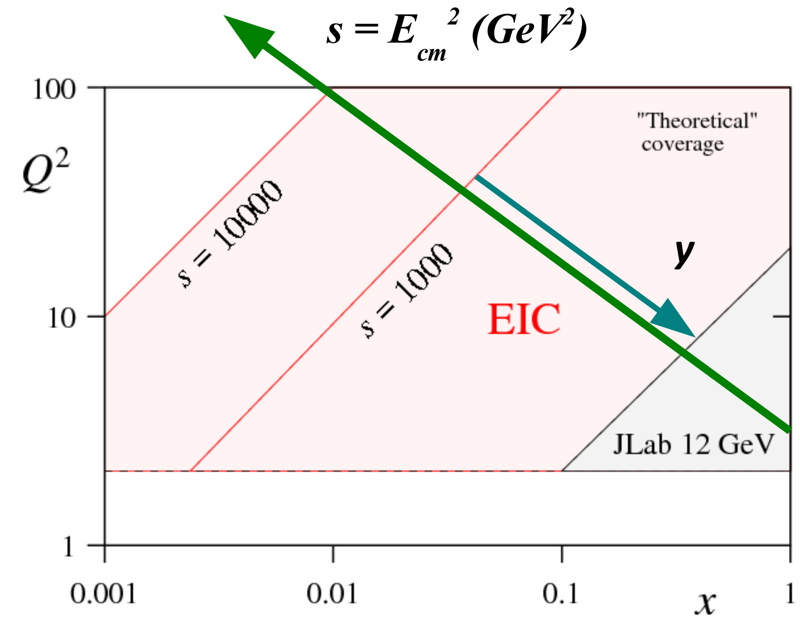
Accardi, Dupre



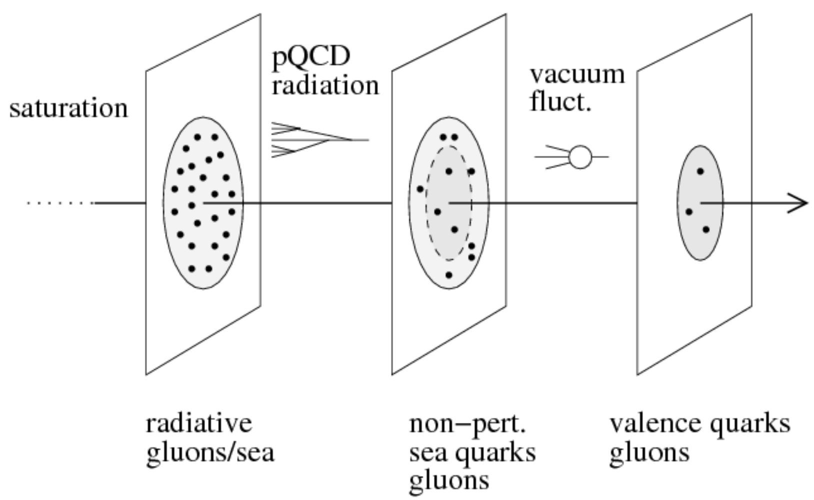
- p_T broadening
- Fragmentation functions
- Heavy flavors: B, D mesons, J/Ψ …
- Jets at s > 1000 GeV^2
  - „real“ pQCD, IR safe



EIC Stage I



C. Weiss



LHeC

EIC Stage II (ELIC)

EIC Stage I (MEIC)

JLab 12 GeV

$Q^2 \sim ysx$

Medium-energy EIC (Stage I)

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

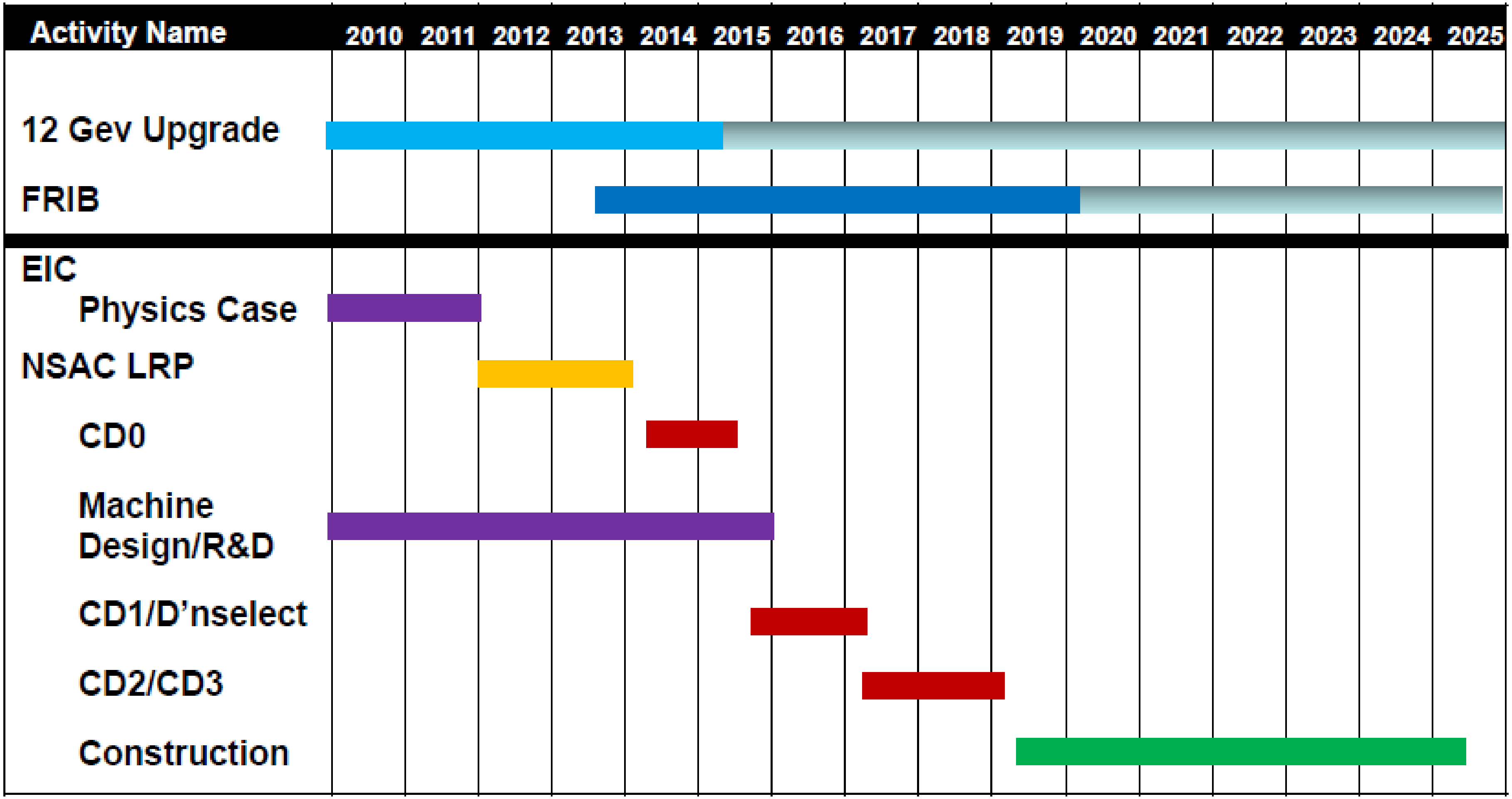
Fixed-target experiments

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

LHeC kinematic coverage is entirely *complementary* to a **Stage I EIC**

EIC – timeline

Mont, INT-10-03



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