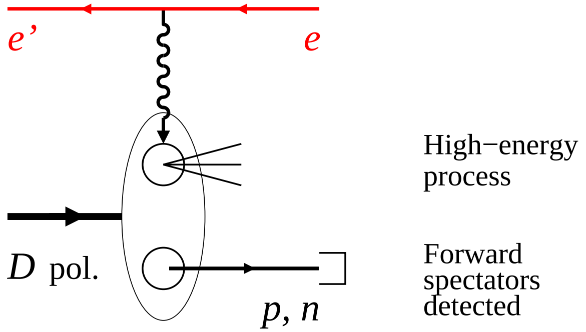
Light-front methods in next-generation nuclear physics at EIC

C. Weiss (JLab), Light Cone 2014, NC State, Raleigh, NC, 28–May–14



Kinematic reach in x, Q^2

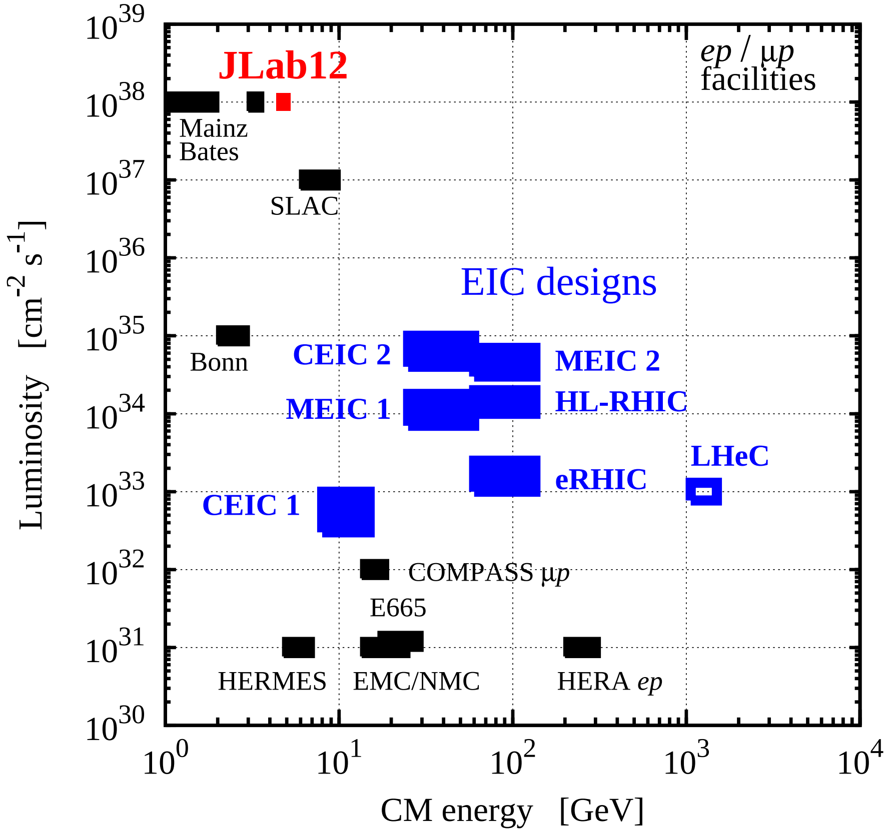
Ion polarization L, T, tensor

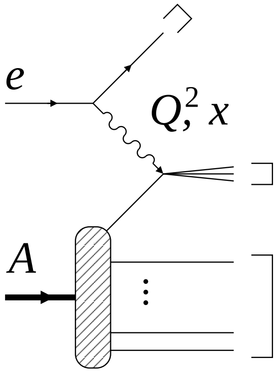
Forward detection of p, n, D

Precision measurements using eD with forward tagging

- Light ion physics with EIC
  - Physics objectives
  - Polarized deuterium
  - Spectator nucleon tagging
- Forward p/n tagging with deuterium
  - Free neutron structure
  - Bound nucleon, correlations
  - Multiple scattering, shadowing, coherence
  - Exclusive processes
- R&D status and prospects
  - Forward detection with JLab MEIC
  - JLab 2014 LDRD project

Light ions: Energy, luminosity, polarization





- CM energy 10-40 GeV/nucleon
  MEIC 1. Higher energy upgrade

  $Q^2 \sim$ few 10 GeV^2 for DIS

  $x \sim 10^{-1}$–10^{-3} for sea quarks, gluons

- Luminosity $\sim 10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$
  Nucleon luminosity

  Exceptional configurations in target

  Multi-variable final states

  Polarization effects

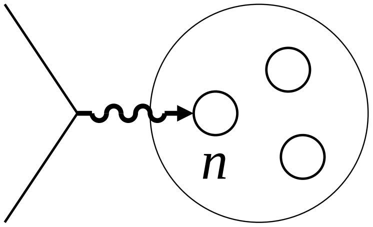
- Polarized light ions

  eRHIC: unpol D, pol ^3He

  MEIC: polarized D and ^3He
  Figure-8 design

- ep physics program
  → 2012 White Paper, reviews

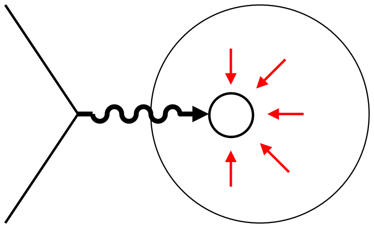
Light ions: Physics objectives



- Neutron structure

  Flavor decomposition of quark spin,
  sea quarks $\Delta\bar{u}$, $\Delta\bar{d}$, gluon polarization Δg

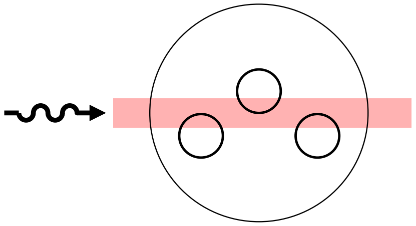
  How to account for binding, polarization,
  final–state interactions?



- Bound nucleon in QCD

  Modification of basic quark/gluon structure by nuclear medium, QCD origin of nuclear forces

  How to control nuclear environment?



[Nucleus rest frame view]

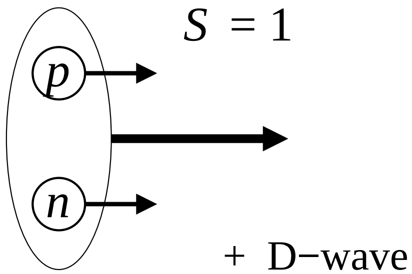
- Coherence and saturation

  Interaction of high–energy probe with coherent quark/gluon fields

  How to quantify onset of coherence?
  Signatures of saturation?

- Challenges to be addressed by theory and new experimental techniques! ←

Light ions: Deuterium and spectator tagging



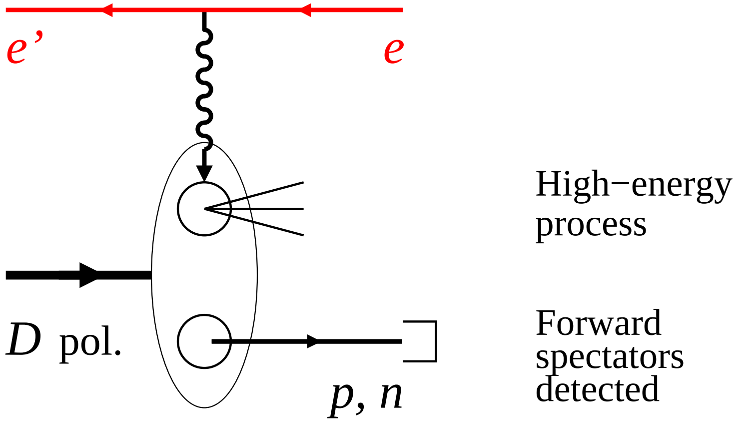
- Polarized deuterium

  Wave function simple, known
  incl. Light-cone wave function for high–energy processes

  Neutron spin–polarized

  Limited possibilities for nuclear final–state interaction

  Coherent effects at $N = 2$
  Complementary to saturation in large nuclei



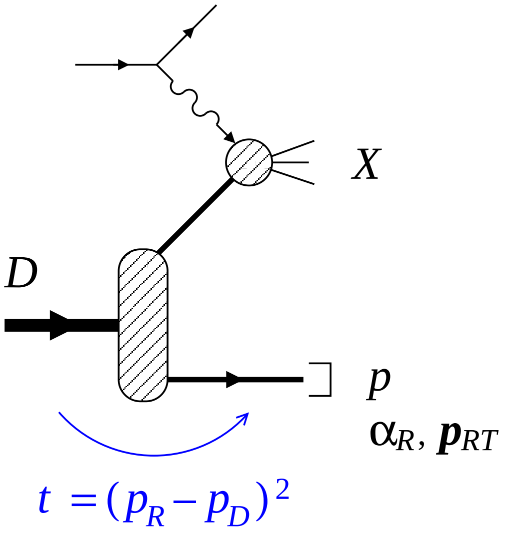
- Spectator nucleon tagging

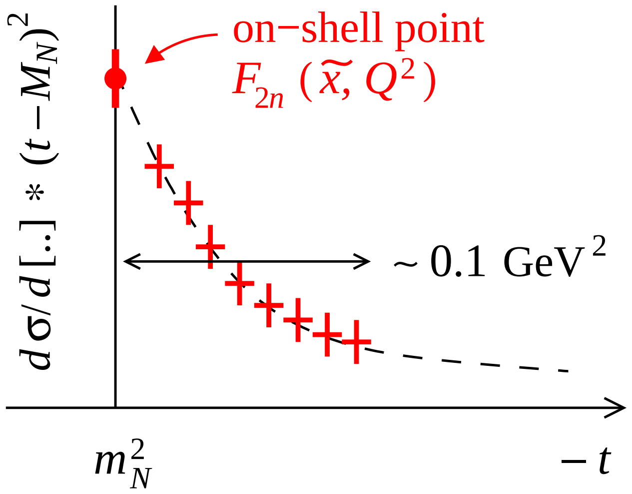
  Detection of forward proton or neutron

  Identifies active nucleon, controls quantum state

  Unique for collider: No target material, forward detection of charged/neutral p's, polarized ion beams
  Tagging with fixed target: CLAS BONUS, limited to recoil momenta $p_R >$ 100 MeV

Spectator tagging: Extracting neutron structure





$$t = \mathrm{function}(\alpha_R, \boldsymbol{p}_{RT})$$

- Light-cone momentum of recoil nucleon

$$\frac{\alpha_R}{2} = \frac{E_R + p_R^z}{E_D + p_D^z} \quad \text{and} \quad \boldsymbol{p}_{RT}$$

- Cross section in impulse approximation
  Frankfurt, Strikman 81

$$\frac{d\sigma}{dx\ dQ^2\ (d\alpha_R/\alpha_R)\ d^2p_{RT}} = \text{flux factor}$$

$$\times\ S_D(\alpha_R, \boldsymbol{p}_{RT})\ \ F_{2n}\left(\frac{x}{2-\alpha_R}, Q^2\right) + \ldots$$

Deuteron LF spectral fn   Neutron structure fn

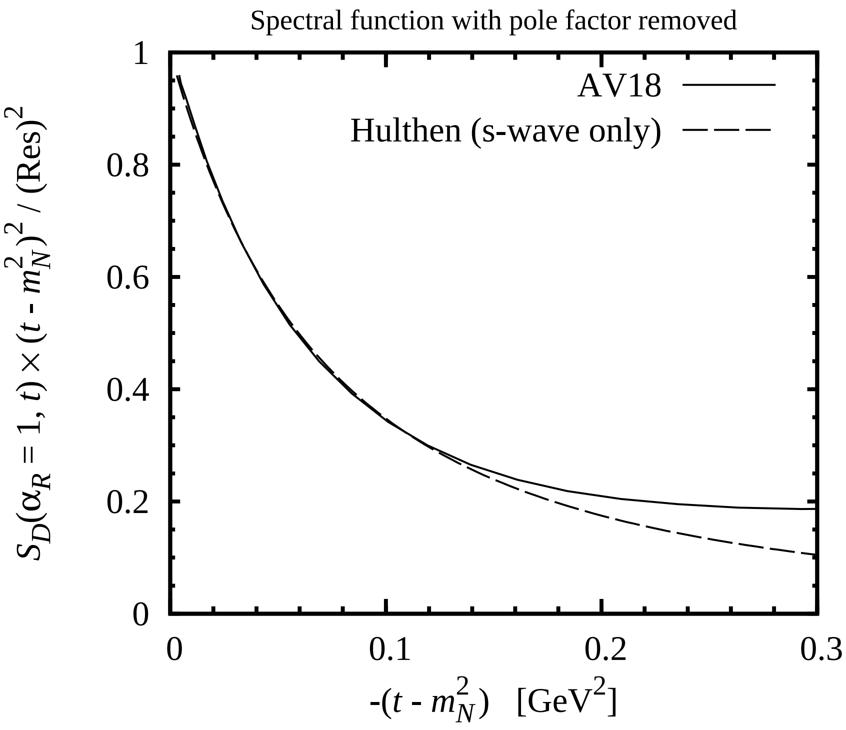
- On-shell extrapolation $t \to M_N^2$
  Cf. Chew–Low extrapolation in πN, NN scattering

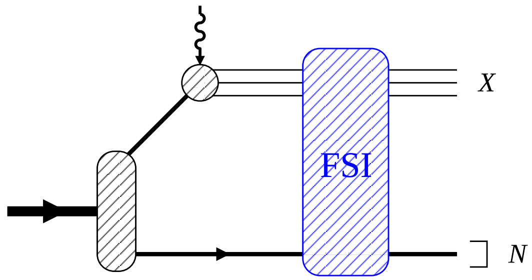
  Free neutron structure at pole

  Pole value not affected by FSI
  Sargsian, Strikman 05: "No-loop theorem"

  Model–independent method!

Spectator tagging: Deuteron spectral function





- Deuteron LF spectral function

$$S_D(\alpha_R, \boldsymbol{p}_{RT}) = \frac{|\psi_{\mathrm{LF}}(\alpha_R, \boldsymbol{p}_{RT})|^2}{2 - \alpha_R}$$

- LF wave function calculable

Weinberg equation in NN sector with phenomenological potential

Correspondence with non-relativistic WF in CM frame through angular condition
Terentev 76; Frankfurt, Strikman 81

$$\widetilde{\psi}_{\mathrm{CM}}(\boldsymbol{k}) \;\longleftrightarrow\; \psi_{\mathrm{LF}}(\alpha_R, \boldsymbol{p}_{RT})$$

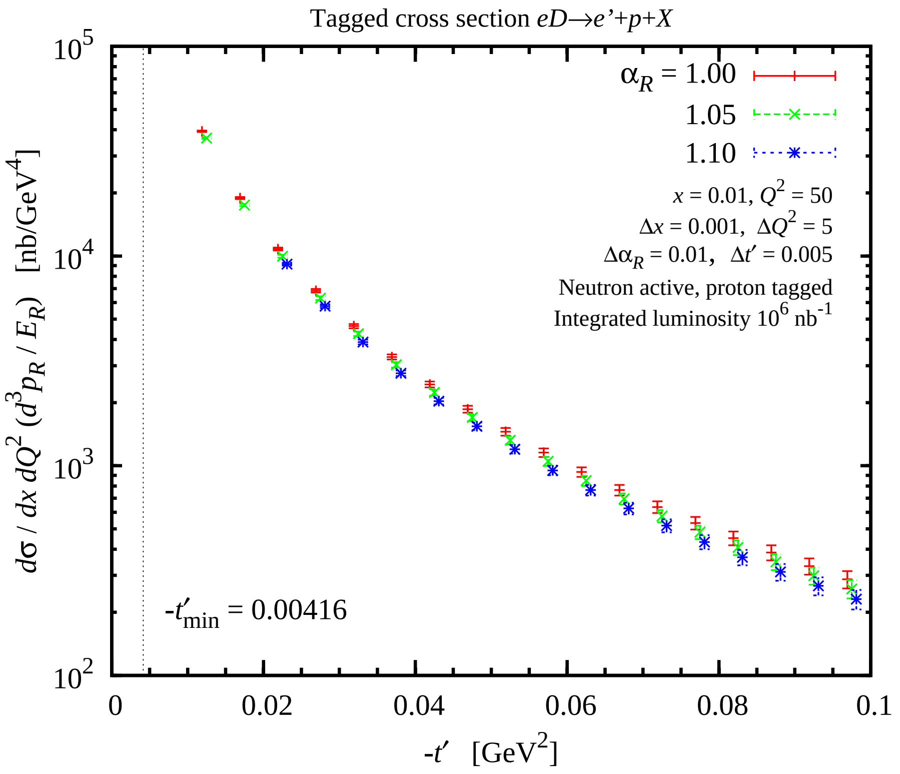
- Final–state interactions

Affect only $t \neq M_N^2$, drop out at pole

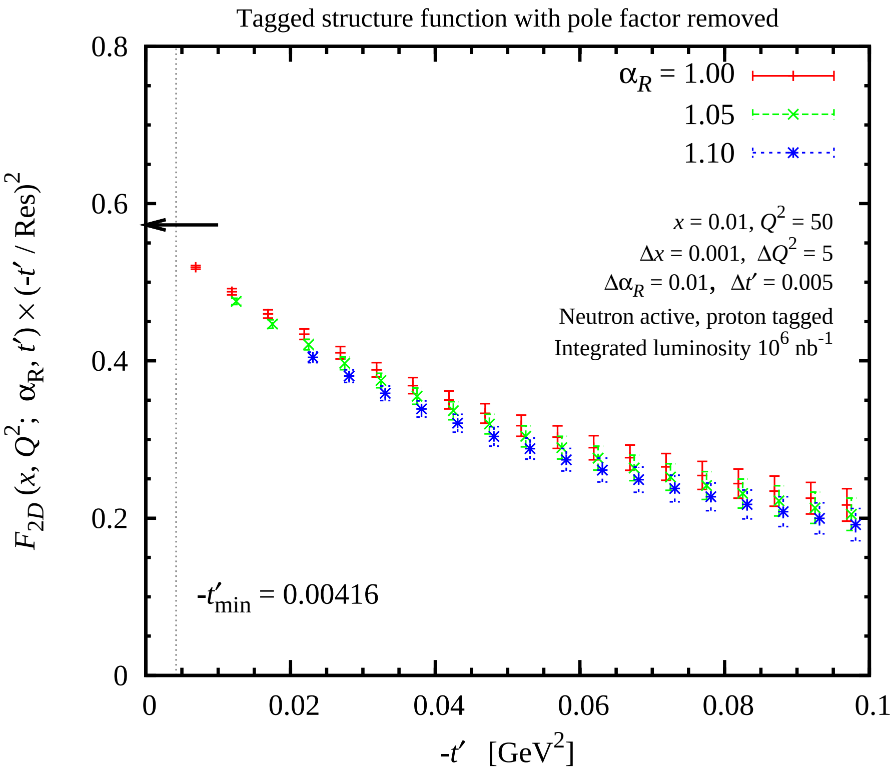
Parametrization at collider energies:
Color transparency at $Q^2 \to \infty$,
coherent scattering at $x \ll 1$
Cosyn, Guzey, Sargsian, CW, LDRD project

Spectator tagging: EIC projections

JLab LDRD project



Tagged cross section $eD \to e' + p + X$



Tagged structure function with pole factor removed

- Stat errors based on integrated lumi $10^6\,\text{nb}^{-1}$ 2 weeks at $10^{33}\,\text{cm}^{-2}\text{s}^{-1}$
  Overall error systematics-dominated, full MC simulation in progress

- On-shell extrapolation appears feasible

  Extrapolation smooth after taking out nucleon pole factor

  Tagged structure function depends mostly on $t' \equiv t - M_N^2$:
  Test universality by measuring/extrapolating at different α_R

  Excellent rates for spin/flavor asymmetries

Spectator tagging: Applications

- Unpolarized neutron structure F_2^n, F_L^n

  Isovector $p - n$ at $x < 10^{-1}$ constrains sea quark flavor asymmetry $\bar{d} - \bar{u}$

- Bound proton through neutron spectator tagging

  Compare tagged SF at $t = m_N^2$ with free proton measurement to validate method

  Quantify nuclear binding effect on quark/gluon distributions through t–dependence:
  Connection with short-range NN correlations?

- Neutron spin structure functions g_1^n, g_2^n **in progress**

  Isoscalar $p + n$ for ΔG, especially at large x

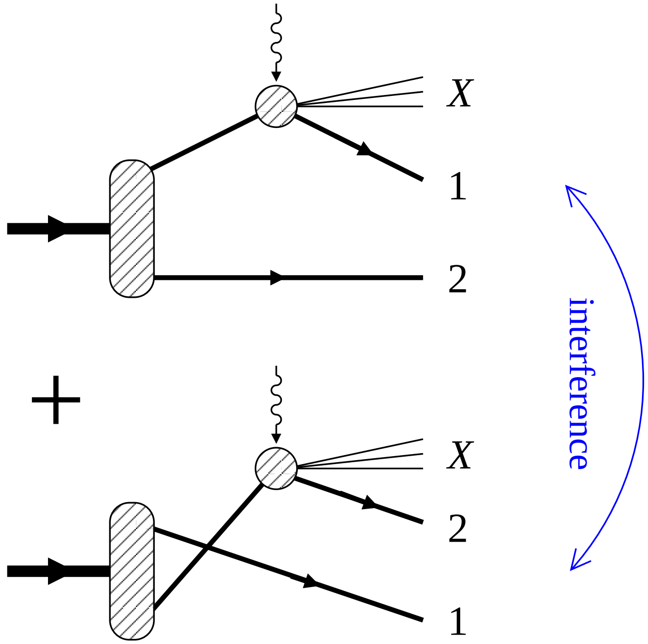
  Isovector $p - n$ for $\Delta u - \Delta d$

  Bjorken sum rule: Fundamental quantity, tests high-order pQCD calculations

  Cleanest possible extraction of neutron spin structure!

- Other DIS final states: Semi-inclusive, exclusive, DVCS

Spectator tagging: Coherent effects

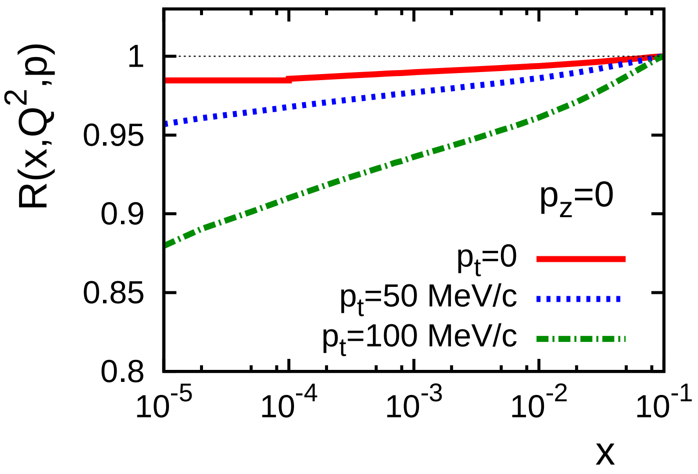


- Shadowing in inclusive DIS $x \ll 10^{-1}$

  Diffractive scattering on single nucleon
  Leading-twist effect! Seen at HERA

  Interference between scattering on nucleons 1 and 2

  Nuclear effect calculable in terms of nucleon's diffractive structure functions
  Gribov 70's. Frankfurt, Guzey, Strikman 02+



Frankfurt, Guzey, Strikman 11. Guzey LDRD 2014

- Coherence in tagged DIS

  Recoil momentum dependence as exp test
  Guzey, Strikman, CW; in progress

  Clean coherent effect with $N = 2$

  Essential for systematics in $p - n$
  Also polarized. Needs to be controlled!

  Strong low-energy FSI between p and n distorts p_T spectrum, spin/isospin dep.
  Guzey, Strikman, CW; in progress

Spectator tagging: Requirements

- Detection

  Acceptance for forward protons with
  transverse momenta $0 < p_{RT} \lesssim 300\,\mathrm{MeV}$
  longitudinal momenta $\Delta p_{R\|}/(p_{\mathrm{beam}}/2) \lesssim 0.2$

  Momentum resolution
  transverse $\Delta p_{RT} \ll 100\,\mathrm{MeV}$,
  longitudial $\Delta p_{R\|}/p_{R\|} \ll 10^{-2}$

  Forward neutron detection with sufficient angular/position resolution

- Beams

  Intrinsic momentum spread in ion beam sufficiently small to allow for resolution/interpretation of measured recoil momentum p_{RT} and $p_{R\|}$

- Feasible with MEIC beam & forward detector design

- Other uses of forward tagging

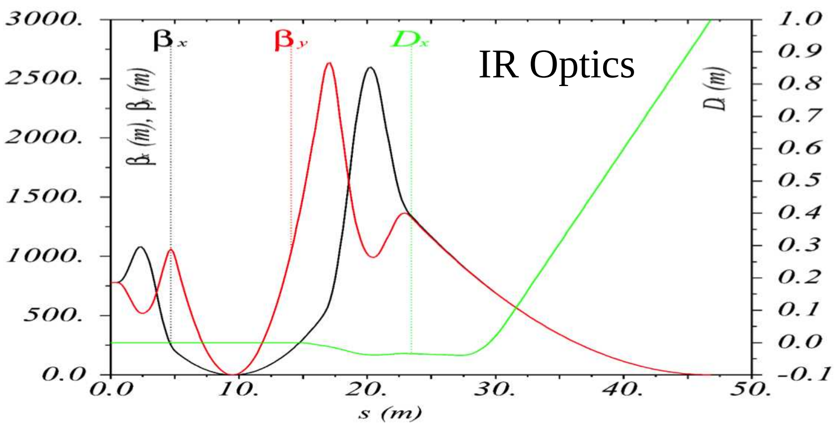
  Diffractive scattering on proton $ep \rightarrow e' + p + X$
  Essential part of proton structure with EIC

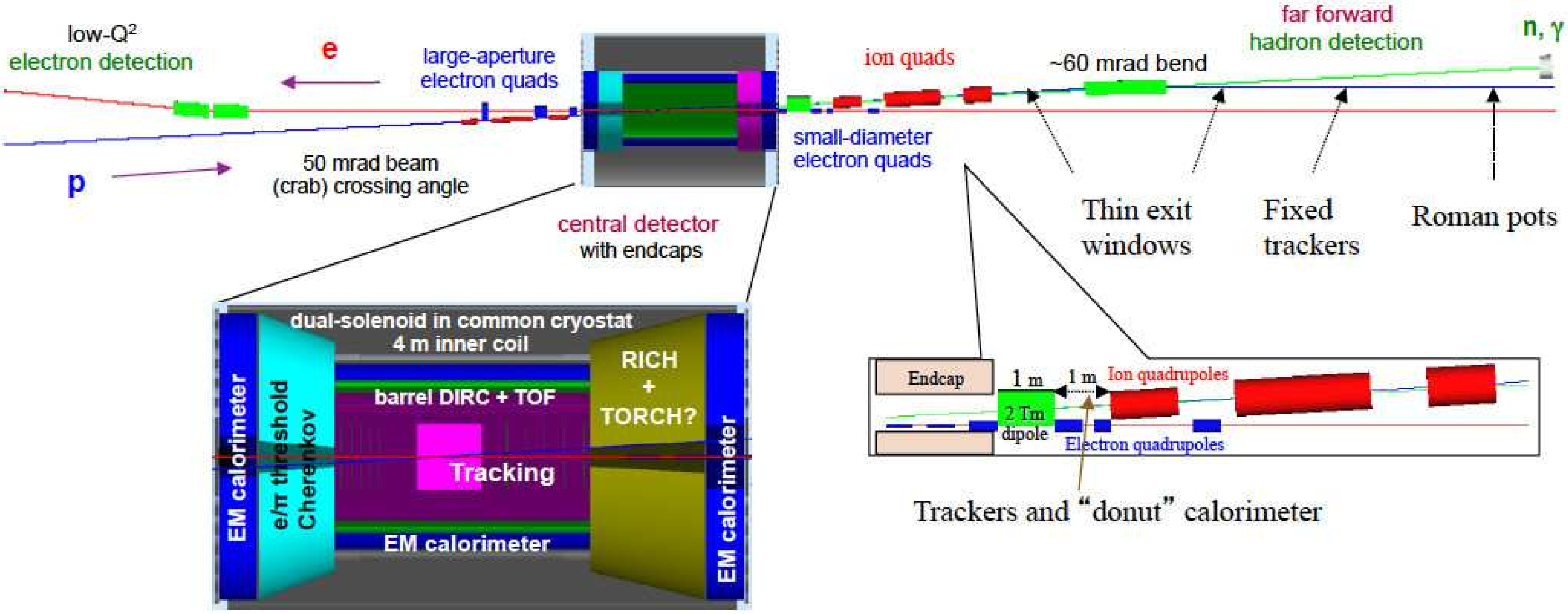
  Forward tagging of nuclear fragments with $A > 1$

MEIC: Full–acceptance detector [Slide P. Nadel-Turonski]

Design goals

- Detection/identification of complete final state
- Recoil p_T resolution $\ll$ Fermi momentum
- Low–Q^2 electron tagger for photoproduction





MEIC: Far-forward detection [Slide P. Nadel-Turonski]

- Good acceptance for all ion fragments – rigidity different from beam ←

  Large magnet apertures (small gradients at a fixed maximum peak field)

  Roman pots not needed for spectators and high-p_T fragments

- Good acceptance for low–p_T recoils – rigidity similar to beam

  Small beam size at detection point (downstream focus, efficient cooling)

  Large dispersion (generated after the IP, $D = D' = 0$ at the IP)

  With 10σ beam size cut, the low–p_T recoil proton acceptance is
  Energy up to 99.5% of the beam for all angles
  Angular down to 2 mrad for all energies

- Good momentum and angular resolution

  Should be limited only by initial state (beam)

  Longitudinal dp/p: 4×10^{-4} ←
  Angular in θ, for all ϕ: 0.2 mrad
  $p_{RT} \sim 15\,\mathrm{MeV}/c$ resolution for tagged 50 GeV/A deuterium beam ←

  Long, instrumented drift space (no apertures, magnets, etc.)

- Sufficient beam line separation ($\sim$ 1 m)

LDRD: Polarized light ions with EIC@JLab

JLab FY14 LDRD Project

D. Higinbotham, W. Melnitchouk, P. Nadel–Turonski, K. Park, C. Weiss (JLab),
Ch. Hyde (ODU), M. Sargsian (FIU), V. Guzey (PNPI),
with collaborators W. Cosyn (Ghent), S. Kuhn (ODU), M. Strikman (PSU), Zh. Zhao (JLab)

Objectives

Develop physics models for DIS processes on polarized light ions (D, 3He) with spectator tagging
Develop event generators for MC simulations of inclusive, diffractive and exclusive final states
Simulate processes with schematic modeling of EIC beam/detector/IR characteristics
Analyze pseudodata and quantify physics output of spectator tagging

Resources

50% FTE experimental physics postdoc, shared with ODU: Kijun Park
Theory collaborators as long-term visitors in Summer 2014: Sargsian, Guzey, Cosyn
10% FTE of JLab Staff: Weiss, Higinbotham

Collaboration

Open for collaboration with Users!
Physics models and generators to be made available
Extension to other processes of interest possible

More information on Wiki

`https://eic.jlab.org/forward_tagging/`

LDRD: Status and next steps

Physics models

Unpolarized $eD \rightarrow e' + N + X$ with nuclear binding, final-state interactions
theory+codes ready, testing/documentation in progress

Unpolarized $eD \rightarrow e' + pn + X$ with diffraction/shadowing
theory+code ready, low-energy final-state interaction in progress

Polarized $eD \rightarrow e' + N + X$ theory+code developing,
Polarized $e^3\mathrm{He} \rightarrow N + X$ scheduled (summer 14)

MC generators

FSGEN-based generator (nucleus rest frame) adapted from fixed-target code

New generator developed for collider kinematics (detector frame),
including intrinsic momentum spread of beam particles

Codes available on github, testing/documentation in progress

Polarized beams, diffractive final state $eD \rightarrow e' + pn + X$ scheduled (summer 14)

Process simulations

On-shell extrapolation in $eD \rightarrow e' + N + X$
Effect of intrinsic momentum spread
Hookup to GEMC detector MC to study tracking, acceptance

Physics extraction from pseudodata, extension to polarized eD (summer 14)

Summary

- Next-generation nuclear DIS measurements enabled by

$$\left.\begin{array}{l}\text{Polarized deuterium beam}\\ \text{Forward } p, n \text{ detection}\\ \text{EIC kinematic reach}\end{array}\right\}\quad\text{Unique combination!}$$

- R&D to establish forward tagging as standard method

  Theory: Polarization, final–state interactions, . . .

  Simulations: Acceptance, tracking, systematic errors, . . .

- Light-front methods as essential tool

  Spectral functions: $D \to p + n$, 3He $\to N+$ fragments
  Correspondence with non-relativistic NMBT

  Final-state interaction models

  High-energy processes in LF time x^+