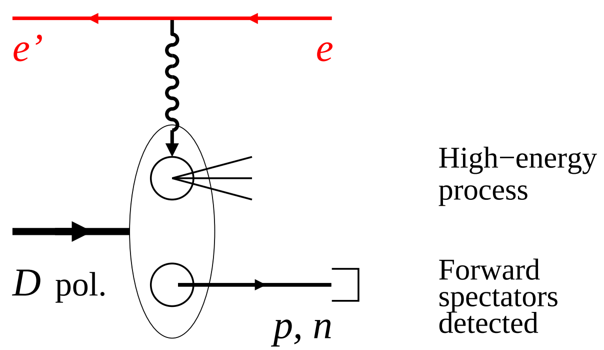
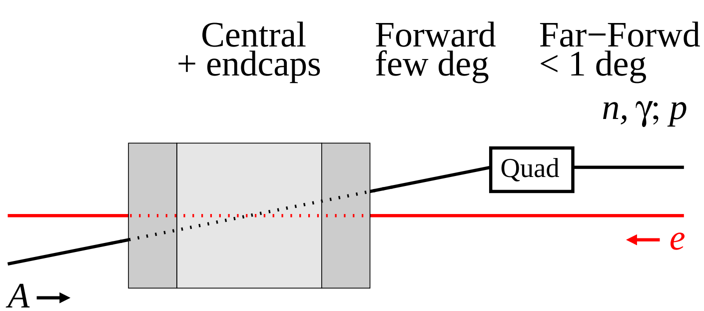
Next-generation nuclear physics with forward p/n detection at MEIC

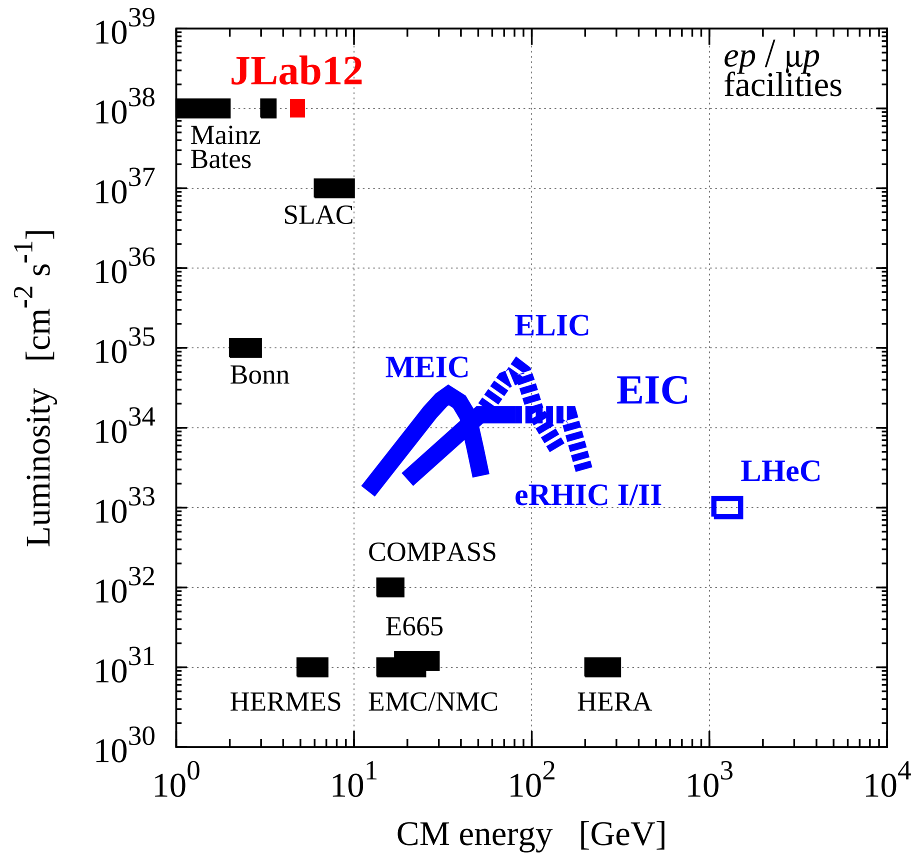
C. Weiss (JLab), EIC14 Workshop on Accelerator Science and Technology, JLab, 20–Mar–14

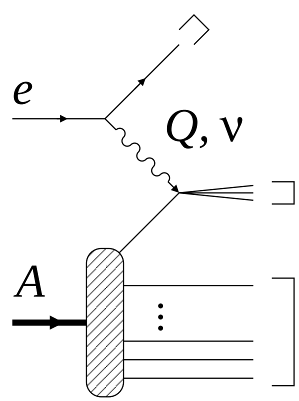




- eA physics with EIC
  - Objectives
  - Importance of light ions $D, {}^3\mathrm{He}$
- Forward p/n tagging with deuterium
  - Neutron spin structure
  - Bound nucleon's quark/gluon structure
  - Coherent effects and shadowing
- Machine requirements
  - Detector coverage and resolution
  - Momentum spread in ion beam
  - Simulations for MEIC
  - JLab 2014 LDRD project

eA physics: Energy, luminosity, polarization





- CM energy 20-70 GeV/nucleon
  eRHIC Stage-1, MEIC. Higher energy upgrades

  Distances $1/Q \ll 1\,\mathrm{fm}$

  Excitation energies $\nu \gg 1\,\mathrm{GeV}$

  Quarks, gluons, coherent QCD fields

- Luminosity $\sim 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

  Exceptional configurations in target

  Multi-variable final states

  Polarization effects

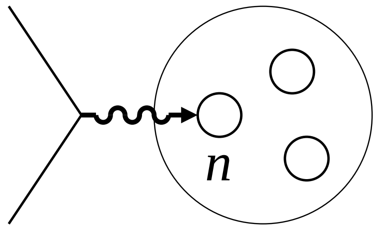
- Polarized light ions

  eRHIC: unpol D, pol $^3\mathrm{He}$

  MEIC: polarized D and $^3\mathrm{He}$
  Figure-8 design

- ep physics program
  $\rightarrow$ Talk Milner, 2012 White Paper, reviews

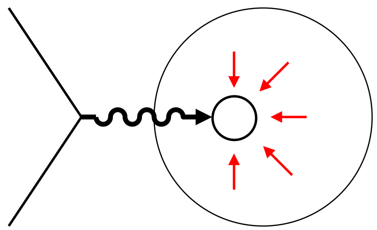
eA physics: Objectives



- Neutron structure

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

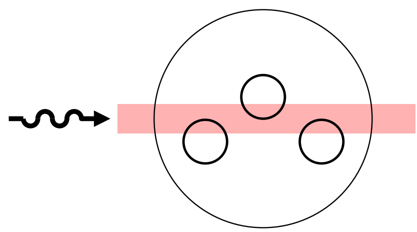
  How to account for binding, polarization,
  final–state interactions?



- Bound nucleon in QCD

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

  How to control nuclear environment?



- Coherence and saturation

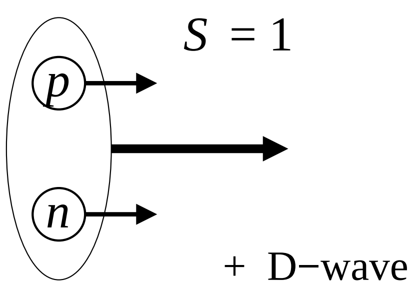
  Interaction of high–energy probe with
  coherent quark/gluon fields

  How to quantify onset of coherence?
  Signatures of saturation?

[Nucleus rest frame view]

- Challenges to be addressed by theory
  and new experimental techniques! $\longleftarrow$

eA physics: Deuterium and spectator tagging



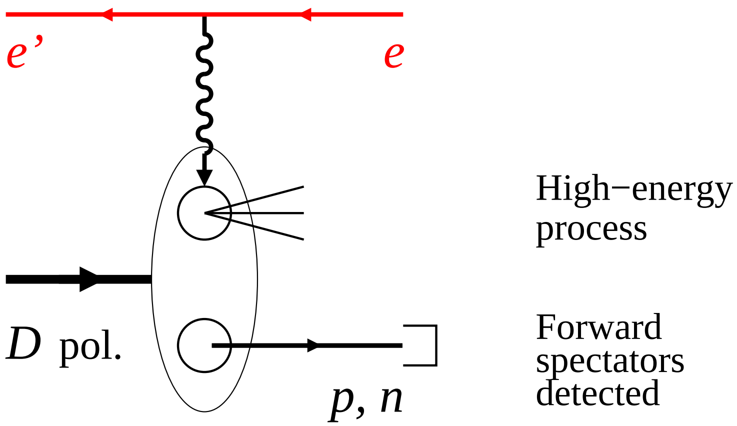
- Polarized deuterium

  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

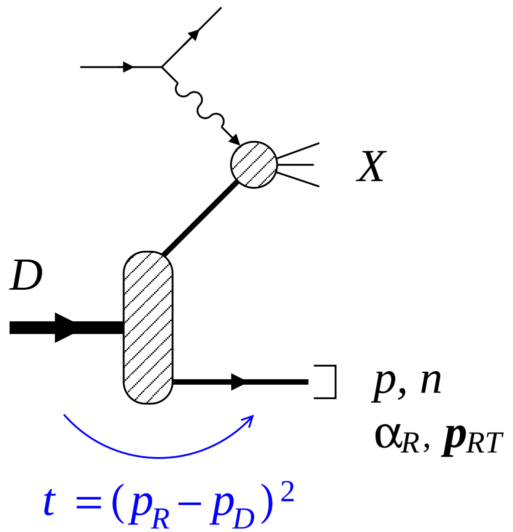
  Detection of forward proton or neutron

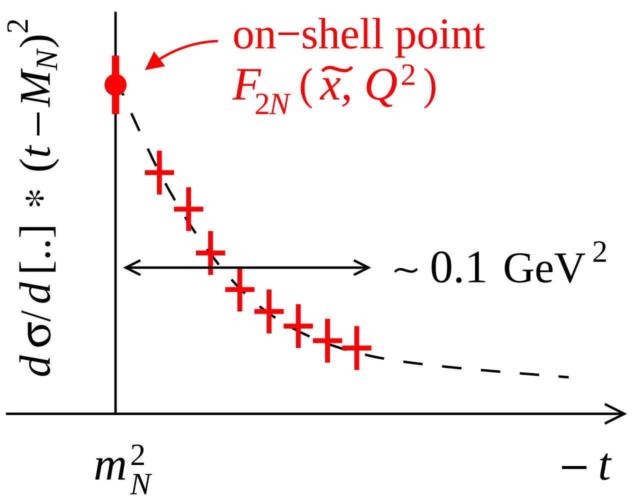
  Identifies active nucleon

  Controls quantum state of active nucleon

  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 nucleon structure





- Tagged DIS $eD \to p/n + X$

  Measure recoil light-cone momentum
  $\alpha_R = (E_R + p_{R\|})/(E_D + p_{D\|})$ and $\boldsymbol{p}_{RT}$

- Cross section in impulse approximation
  Frankfurt, Strikman 81

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

$$\times\; |\psi_D^{\rm LC}(\alpha_R, \boldsymbol{p}_{RT})|^2 \; F_{2N}[x/(2-\alpha_R), Q^2]$$

Deuteron LCWF   Nucleon SF

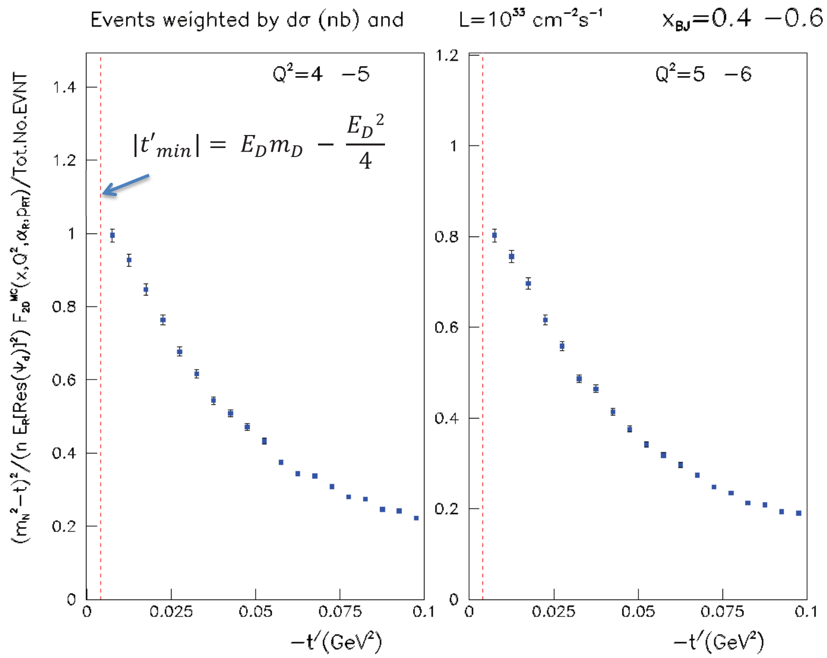
- On-shell extrapolation $t \to M_N^2$
  Cf. Chew–Low extrapolation in πN, NN scattering

  Free nucleon structure at pole

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

  Model–independent method!

Spectator tagging: MEIC



K. Park, based on cross section model by M. Sargsian

- Extract free nucleon structure

  Forward detection down to $p_{RT} \sim 0$ uses most of momentum distribution

  Excellent momentum resolution $\Delta\alpha_R = O(10^{-4}), \ \Delta p_{RT} \sim 15\,\mathrm{MeV}$

  Accuracy limited by intrinsic momentum spread in ion beam

  On-shell extrapolation appears feasible, MC simulations in progress
  JLab LDRD Project "Polarized light ions with EIC@JLab"

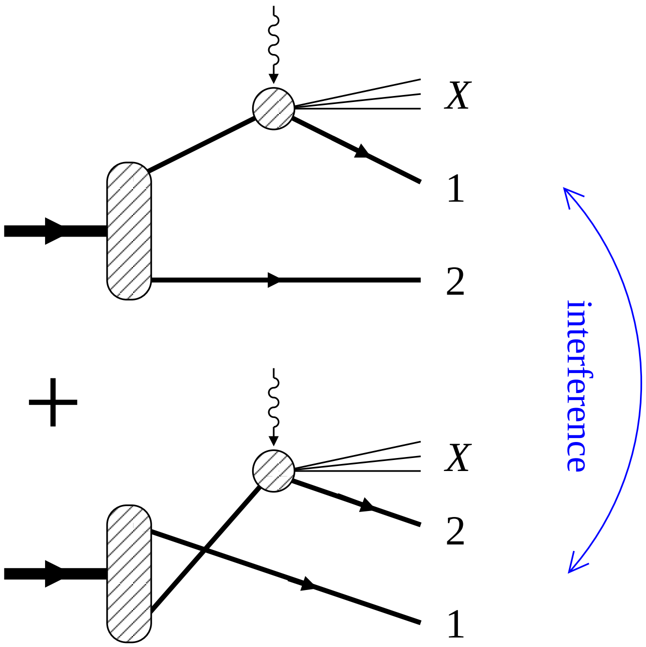
- Great potential

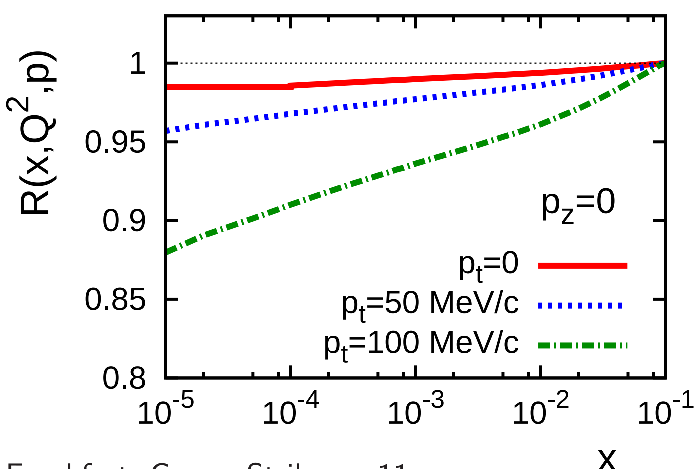
  Neutron structure F_2^n at $x < 10^{-1}$, especially nonsinglet $(p-n) \sim (u-d)$

  Bound proton through neutron tagging, comparison with free proton structure
  Validate method. Quantify nuclear binding effect on quark/gluon distributions in proton

  Spin structure function g_1^n for polarized PDF fits
  Cleanest possible extraction of neutron spin structure

Spectator tagging: Coherent effects





Frankfurt, Guzey, Strikman 11

- 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+

  Determines approach to saturation
  in heavy nuclei

- Shadowing in tagged DIS

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

  Clean coherent effect with $N = 2$

  Extend to polarized DIS!
  Tensor polarization also $N = 2$

- Coherent scattering $eD \to e + M + D$
  Exclusive meson production, DVCS, nuclear GPDs

Apparatus: Spectator tagging requirements

Detector

Coverage for forward protons with $0 < p_{RT} \lesssim 300$ MeV and $\Delta p_{R\|}/(p_{\mathrm{beam}}/2) \lesssim 0.2$

Resolution $\Delta p_{RT} \ll 100\,\mathrm{MeV}$ and $\Delta p_{R\|}/p_{R\|} \ll 10^{-2}$

Forward neutron detection with sufficient angular/position resolution

Accelerator

Intrinsic momentum spread in ion beam must not obstruct resolution/interpretation of measured recoil momentum p_{RT} and $p_{R\|}$

Other uses of forward tagging

Diffractive scattering on proton $ep \to e' + p + X$:
Recoil momenta larger $p_{RT} \lesssim 1\,\mathrm{GeV}$
Essential part of proton structure with eRHIC and MEIC

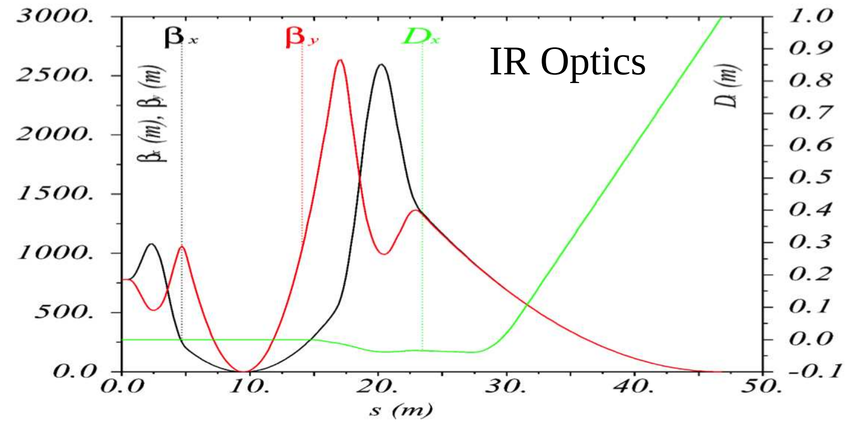
Forward tagging of nuclear fragments with $A > 1$

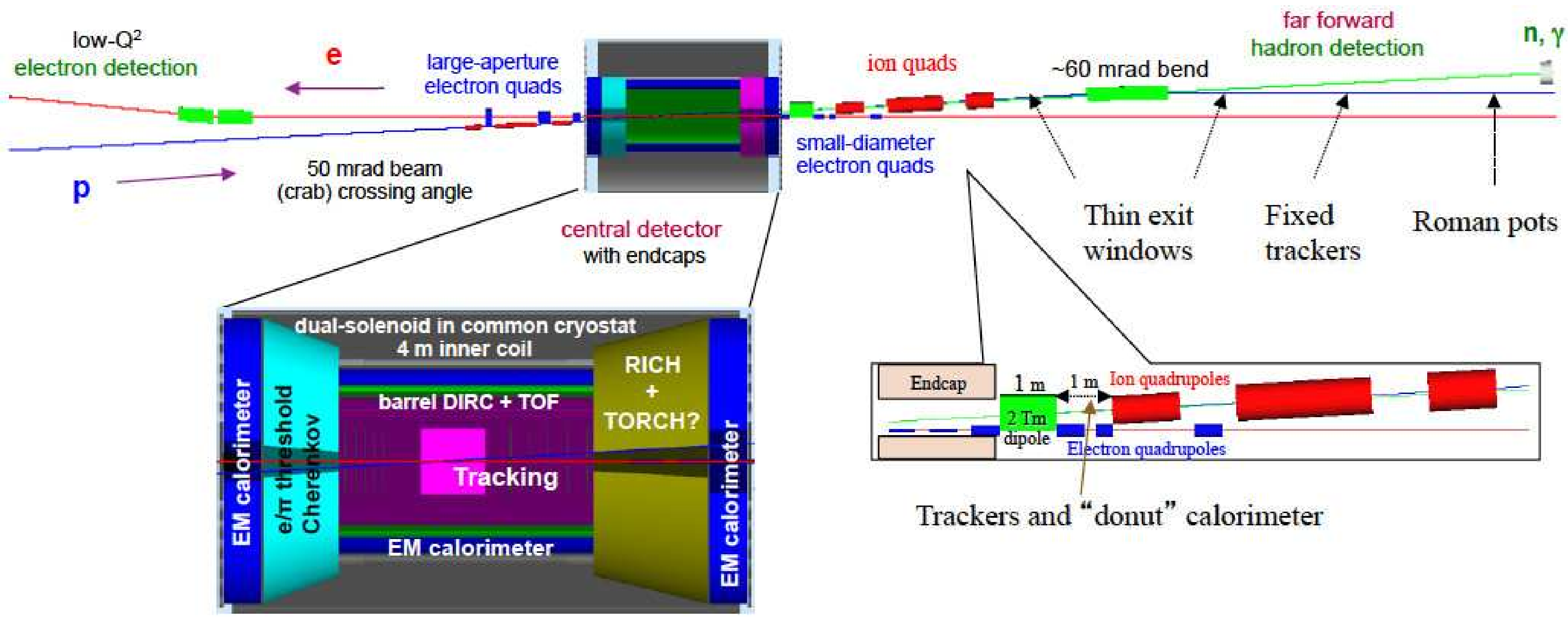
Neutron evaporation from heavy ions as break-up veto
Ultraperipheral collisions at RHIC; diffraction on heavy nuclei at eRHIC and MEIC

Apparatus: 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





Apparatus: 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

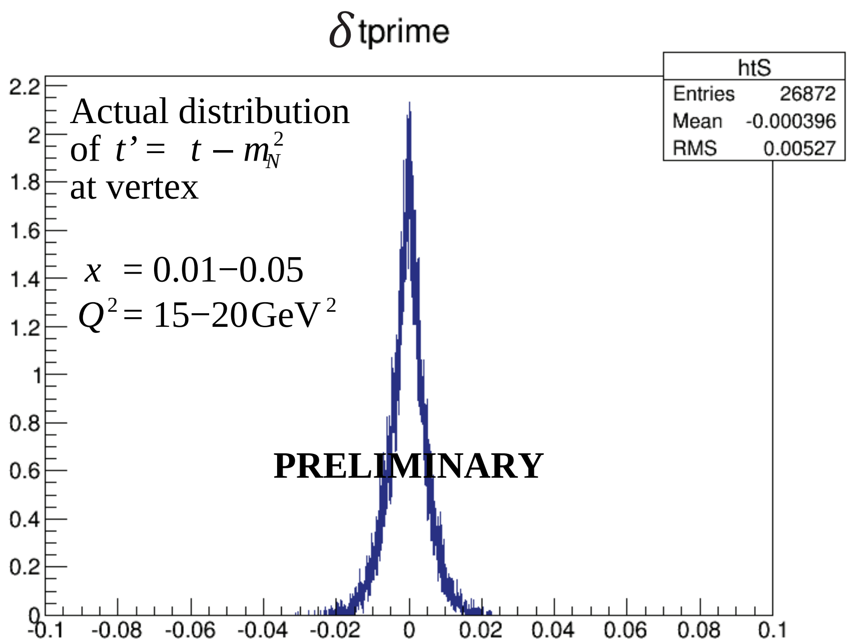
  Should be limited only by initial state (beam)

  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)

Apparatus: Beam momentum spread



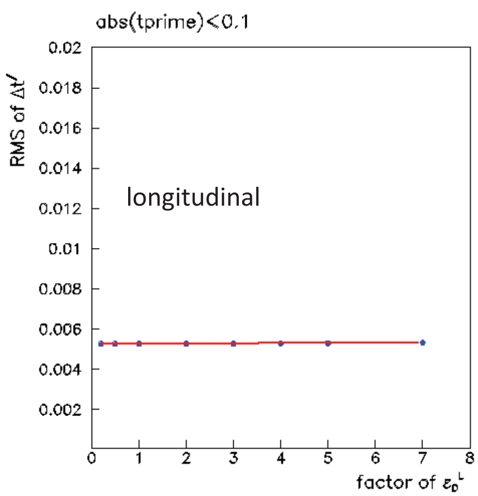
- Intrinsic momentum spread in ion beam "smears" recoil momentum

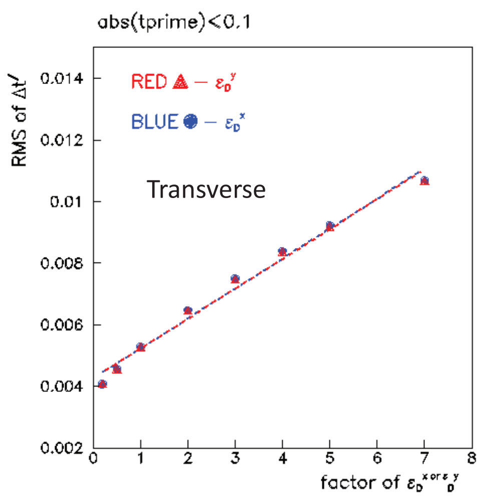
$$p_R\,(\text{measured}) \neq p_R\,(\text{vertex})$$

Dominant uncertainty for MEIC

Larger than detector resolution. Different for eRHIC!

At nominal MEIC emittance
momentum spread $\delta p_D / p_D = 3 \times 10^{-4}$
angular spread $\delta\theta = 2 \times 10^{-4}$





- MC simulation of smearing of $t' = t - M_N^2$

Smearing width $\lesssim$ bin size

Extrapolation appears safe!

Dominant effect from ion transverse emittance

JLab LDRD project: Ch. Hyde, K. Park et al.

LDRD project: Polarized light ions with EIC

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 tagged nucleons
Implement in MC generator with schematic modeling of EIC beam/detector characteristics
Simulate processes and demonstrate feasibility of physics extraction

- Project started Dec 2013

- 50% FTE experimental physics postdoc (shared with ODU): Kijun Park
  Senior theory collaborators as long-term visitors in Summer 2014

- Cross section model for unpolarized D available (Sargsian)
  Shadowing model being developed (Guzey)
  MC generator development in progress (Park, Higinbotham, Hyde, Nadel-Turonski)
  Simulations of extraction of unpolarized F_2^p, F_2^n with forward tagging
  Next steps: Final-state interactions, polarized g_1^p, g_1^n, DVCS

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

Summary

- Precise nuclear physics measurements enabled by

  Polarized deuterium beam
  Forward p, n detection
  EIC kinematic reach

  } Unique combination!

- Excellent coverage and resolution for forward p, n, fragments with MEIC detector design

- Main limitations likely to come from intrinsic momentum spread in ion beam

- R&D in progress to establish forward tagging as standard method

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

  Simulations: Tracking, systematic errors, . . .