Physics opportunities with tagged deep inelastic scattering on polarized light nuclei at EIC

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On behalf of JLab LDRD project “*Physics potential of polarized light ions with EIC@JLab*”:
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https://eic.jlab.org/forward_tagging/index.php/Main_Page

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Outline:

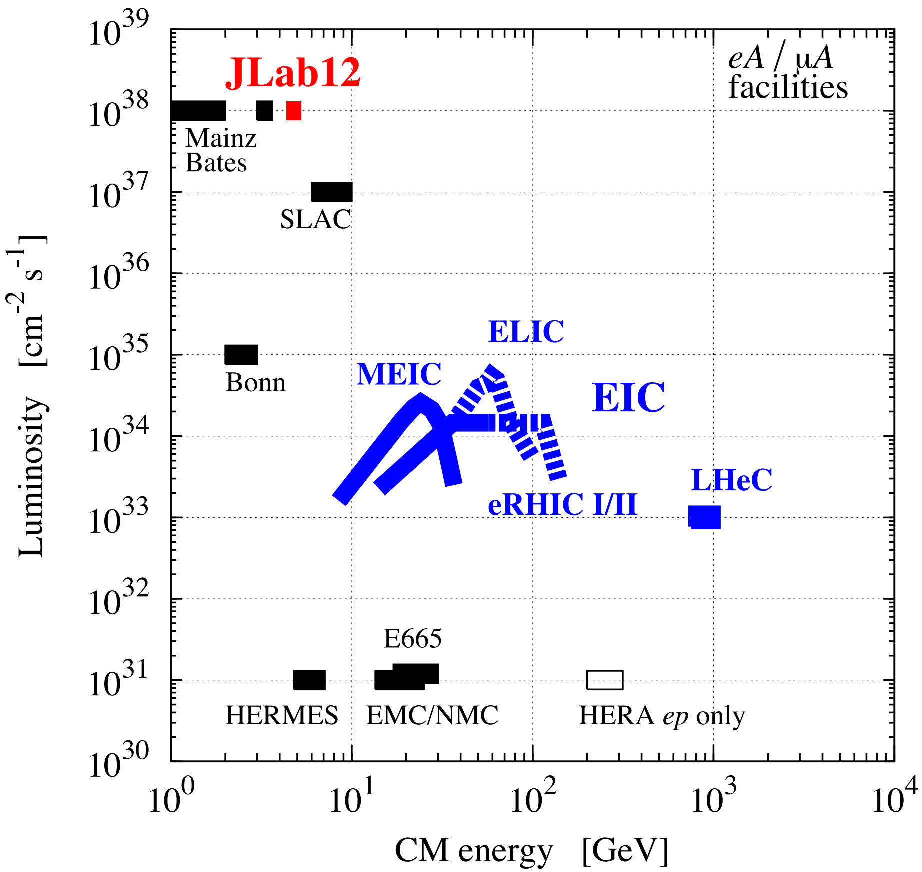
- **Light ion physics with EIC**:
  - Physics objectives
  - Why polarized deuterium
  - Spectator nucleon tagging

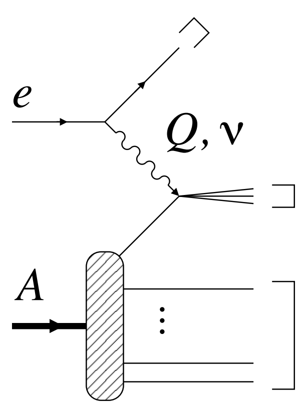
- **MEIC detector/IR design**:
  - Acceptance and resolution for spectator tagging

- **R&D for spectator tagging**:
  - Goals and status
  - Tools: cross section models, MC generators
  - Simulation results: neutron structure, effect of beam momentum spread, acceptance and tracking

- **Next steps**

Light ions: Energy, luminosity, polarization





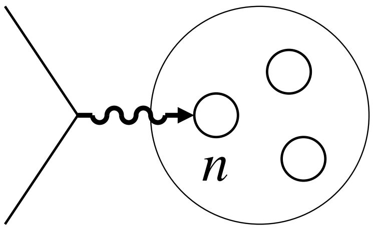
- CM energy 10-40 GeV/nucleon

  eRHIC Stage-1, MEIC. Higher energy upgrades
  - Distances 1/Q << 1 fm
  - Excitation energies ν >> 1 GeV
- Luminosity ~ 10^{34} cm^{-2} s^{-1}

  nucleon luminosity
  - Exceptional configurations in target
  - Multi-variable final states
  - Polarization effects
- Polarized light ions:
  - eRHIC: unpol. D, polarized He-3
  - MEIC: polarized D and He-3

    due to figure-8 design

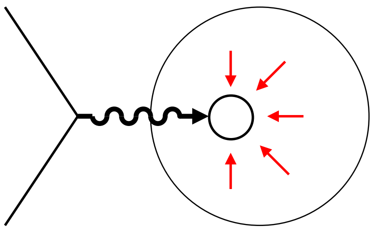
Light ions: Physics objectives



- Neutron structure

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

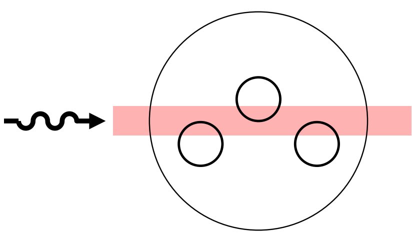
  How to account for binding, polarization, final-state interactions?



- Bound nucleon in QCD

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

  How to control nuclear environment?



- Coherence and saturation:

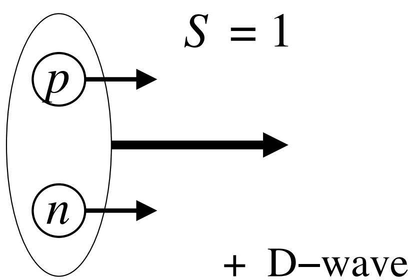
  Interaction of high-energy probe with coherent quark-gluon fields

  How to quantify onset of coherence? Signature of saturations?

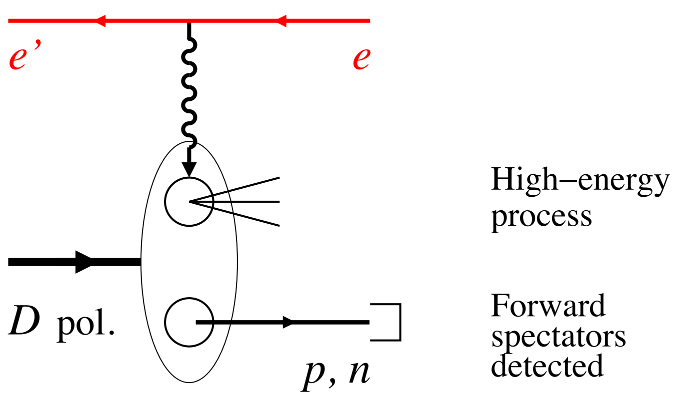
[Nucleus rest frame view]

Challenges to be address by theory and new experimental techniques!

Light ions: Deuteron and spectator tagging



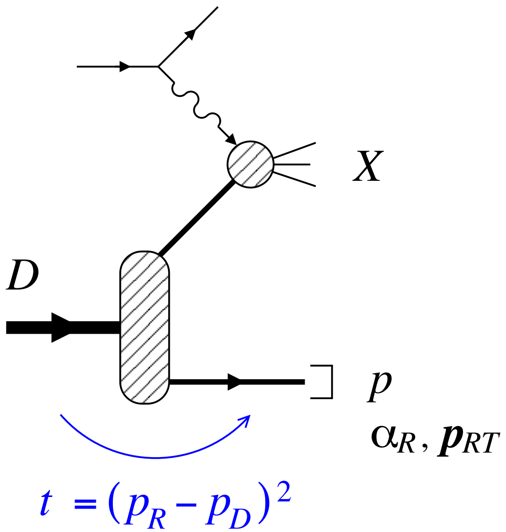
- Polarized deuterium
  - wave function simple and known
    including light-cone wf for high-energy processes
  - neutron spin-polarized
  - limited possibilities for final-state interactions
  - coherent effects at N=2
    complimentary to saturation in heavy nuclei



- 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 particles, polarized ion beams

  Tagging with fixed target: CLAS BONUS, limited to recoil momenta p_R > 100 MeV/c

Spectator tagging: Extracting neutron structure



- Tagged DIS $e + D \to e' + p + X$

  Measure recoil light-cone momentum

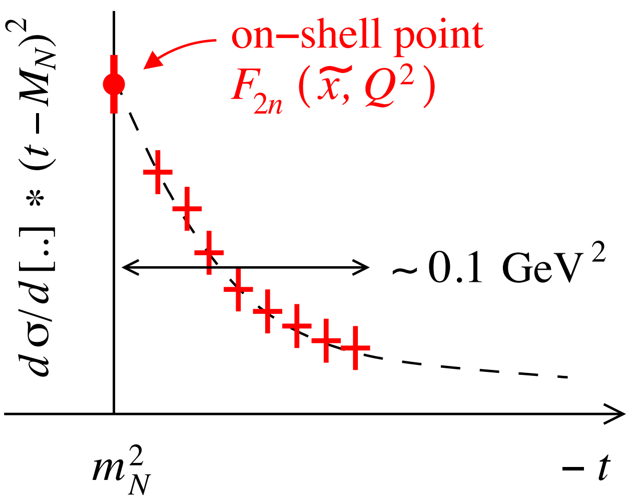
  $$\alpha_R = (E_R + p_{R||})/(E_D + p_{D||}) \text{ and } \mathbf{p}_{RT}$$

- Cross section in impulse approximation

  Frankfurt, Strikman 81

$$\frac{d\sigma}{dx\, dQ^2\, (d\alpha_R/\alpha_R)\, d^2 p_{RT}} \propto |\psi_D^{LC}(\alpha_R, p_{RT})|^2 F_{2n}[x/(2-\alpha_R), Q^2]$$

Deuteron LCWF Neutron SF



- On-shell extrapolation $t \to M_N^2$

  Cf. Chew-Low extrapolation in piN, NN scattering

  - free neutron structure at pole
  - pole value not affected by FSI

    Sargsian, Strikman (2005): “no-loop” theorem
  - model independent method!

Spectator tagging: Potential

- Unpolarized neutron structure F_2^n, F_L^n

  Isovector p-n at x < 0.1 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 result to validate method

  Quantify nuclear binding effect on quark/gluon distribution via t-dependence

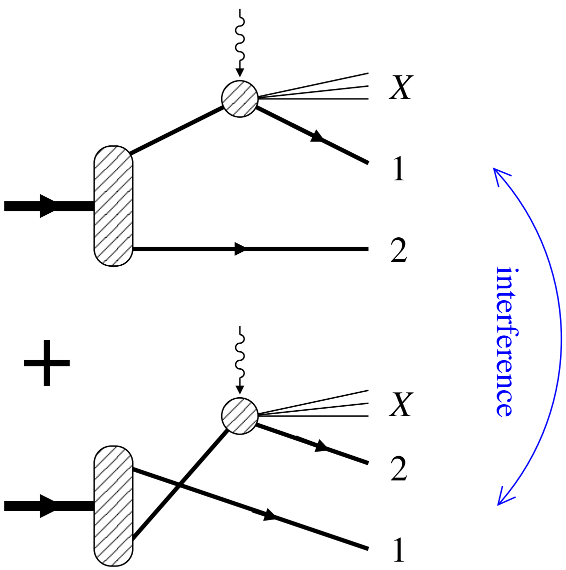
- Neutron spin structure function g_1^n

  - Isoscalar p+n for ΔG , especially at large x
  - Isovector p-n for $\Delta u - \Delta d$
  - Definitive measurement of Bjorken sum rule: fundamental, tests higher-order QCD calculations

Cleanest possible extraction of neutron spin structure!

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

Spectator tagging: Coherent effects



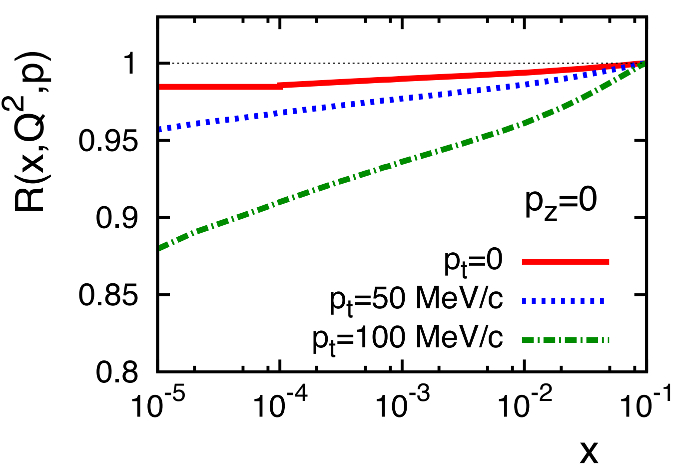
- Shadowing in inclusive DIS x << 0.1

  - Interference between diffractive scattering on nucleons 1 and 2: Leading twist effect seen at HERA

  - Nuclear effect calculable in terms of nucleon diffractive structure functions

    Gribov 70's, Frankfurt, Strikman '98, Frankfurt, Guzey, Strikman '02+

  - Determines approach to saturation in heavy nuclei



Frankfurt, Guzey, Strikman 11

- Shadowing in tagged DIS
  - Recoil momentum dependence as exper. test

    Guzey, Strikman, CW; in progress
  - Clean coherent effect with N=2
  - Essential for systematics in p-n

    Also polarized. Needs to be controlled.

- Coherent scattering $e + D \to e' + M + D$

  Exclusive meson production, DVCS, nuclear GPDs

Spectator tagging: Requirements

- **Detector**
  - Acceptance for spectator protons with $0 < p_{RT} < 300$ MeV/c and $\Delta p_{R||}/(p_{\rm beam}/2) \leq 0.2$
    - Resolution $\Delta p_{RT} << 100$ MeV/c and $\Delta p_{R||}/p_{R||} << 0.01$
    - Forward neutron detection with sufficient angular/position resolution
- **Beam**

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

- **Other uses of forward tagging**
  - Diffractive scattering on proton: $e + p \rightarrow e' + p + X$

    Recoil momenta larger $p_{RT} < 1$ GeV.

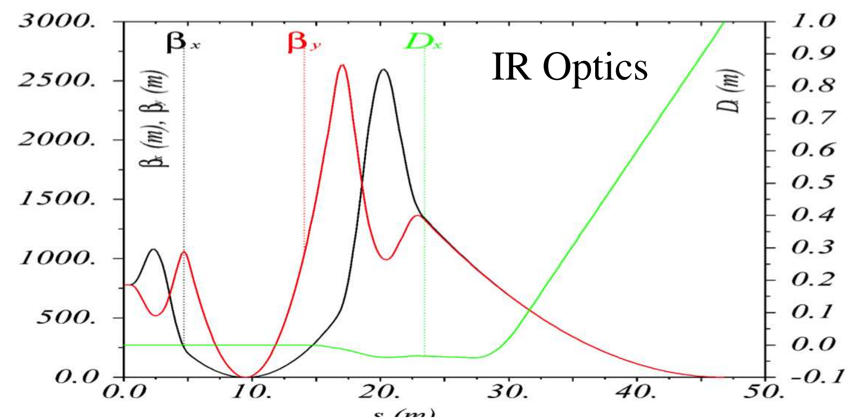
    Essential part of proton structure with eRHIC and MEIC
  - Forward tagging on nuclear fragments with A > 1
  - Neutron evaporation from heavy ions as break-up veto

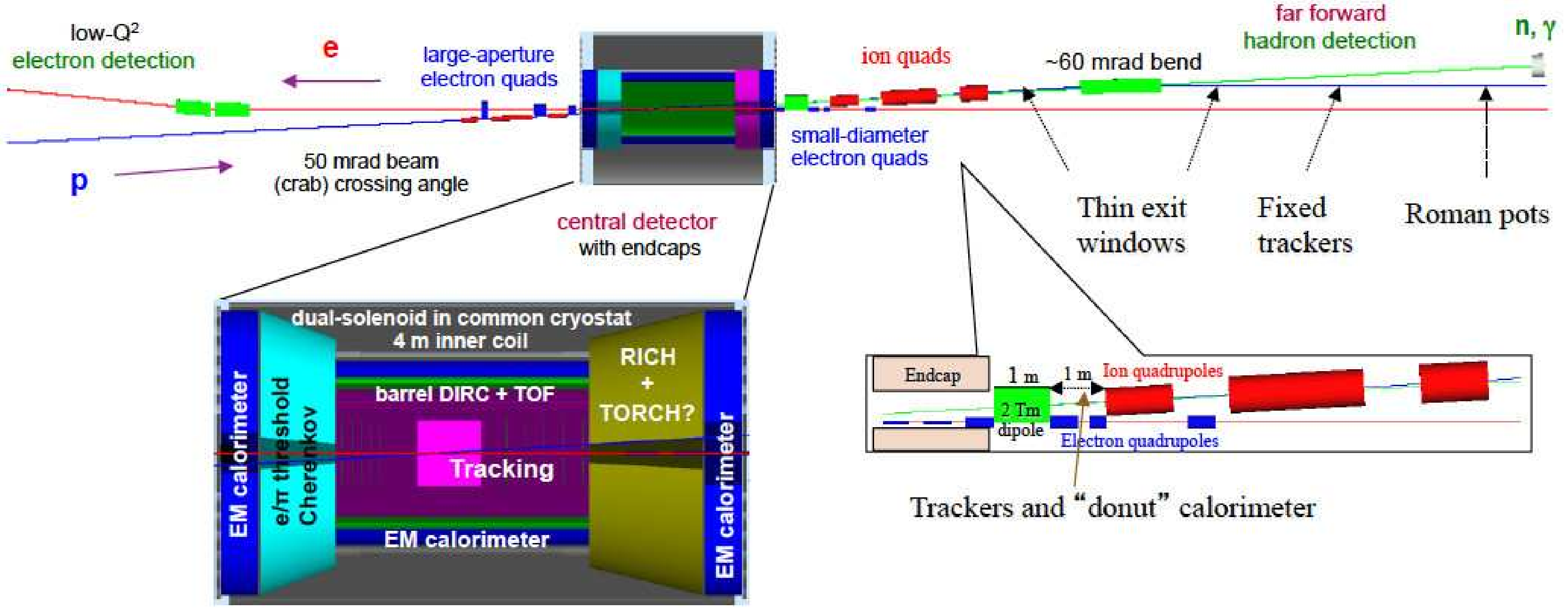
    Ultraperipheral collisions at RHIC and LHC; diffraction on heavy nuclei at eRHIC and MEIC

MEIC: Full-acceptance detector

Design goals:

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





MEIC: Far-forward detection

- 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, 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)

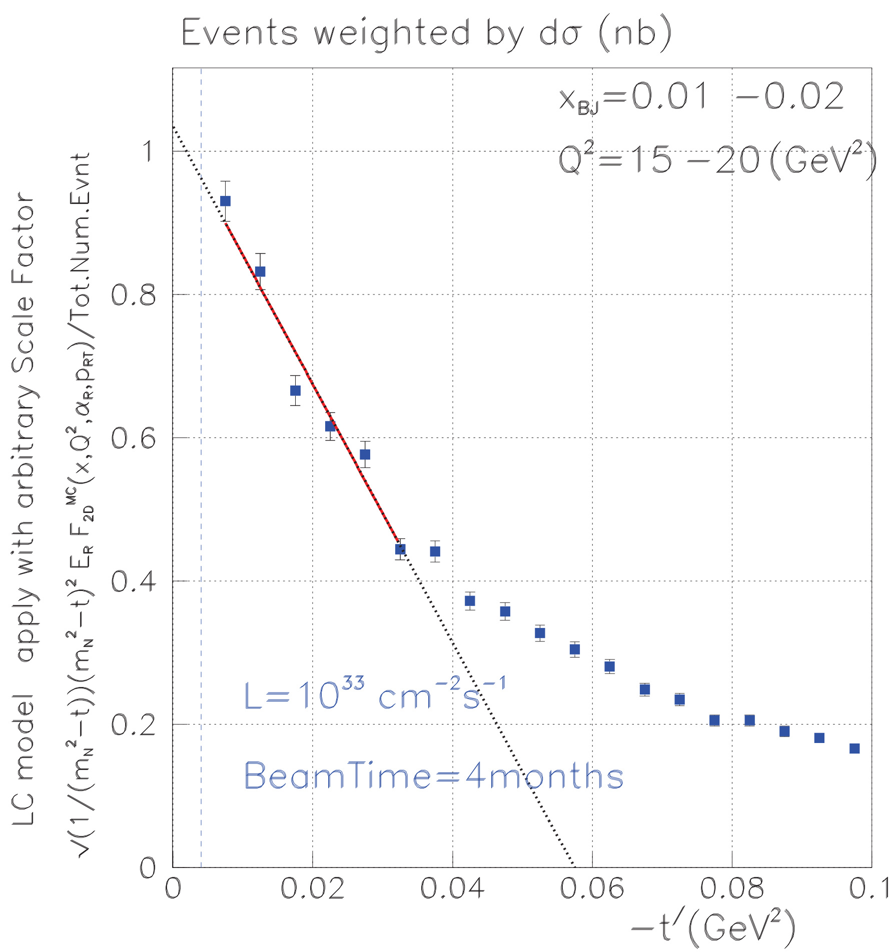
  Longitudinal dp/p: 4×10^{-4} ; Angular in Θ, for all ϕ: 0.2 mrad;
  p_T ~ 15 MeV/c resolution for tagged 50 GeV/A deuteron beam
  Long, instrumented drift space (no apertures, magnets, etc.)

- Sufficient beam line separation (~ 1 m)

R&D: Status and next steps

- Physics models
  - Unpolarized $e + D \to e' + N + X$ with nuclear binding, final-state interac.
    theory+codes ready, testing/documentation in progress
  - Unpolarized $e + D \to e' + pn + X$ with diffraction/shadowing
    theory+codes ready, low-energy final-state interaction in progress
  - Polarized $e + D \to e' + N + X$ theory+code developing,
    Polarized $e +^3 \mathrm{He} \to e' + N + X$ scheduled (Summer 2014)
- MC generators
  - FSGEN-based generator (nucleus rest frame) adapted from fixed target
  - New generator developed for collider kinematics (detector frame), including intrinsic momentum spread of beam particles
  - Polarized beams, diffractive final states $e + D \to e' + pn + X$ scheduled
- Process simulations
  - On-shell extrapolation in $e + D \to e' + N + X$
  - Effect of intrinsic momentum spread; Hookup to GEMC detector, etc.
  - Physics extraction from pseudodata, extension to polarized eD

R&D: Extracting neutron structure



Here: Full acceptance, no smearing.

Error bars do not reflect experimental statistics – to be updated!

- Simulated on-shell extrapolation in $e + D \to e' + p + X$

Cross section model based on deuteron LC wave function, M. Sargsian

MC simulation using collider generator Ch. Hyde, K. Park

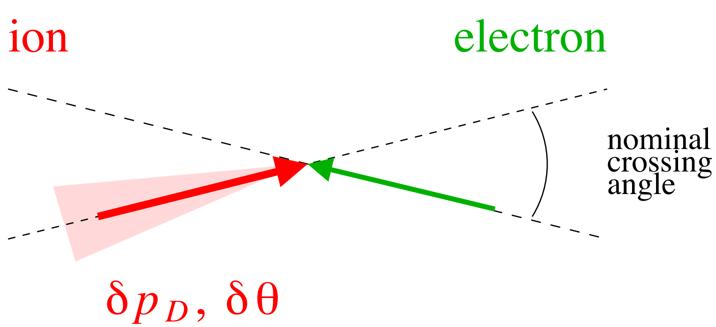
- Forward detection with MEIC

Forward detection down to p_{RT}~0 uses most of momentum distribution

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

Accuracy limited by intrinsic mom. spread

R&D: Momentum spread in beam



- Intrinsic momentum spread in ion beam “smears” recoil momentum

p_R (measured) ≠ p_R (vertex)

Dominant uncertainty for MEIC

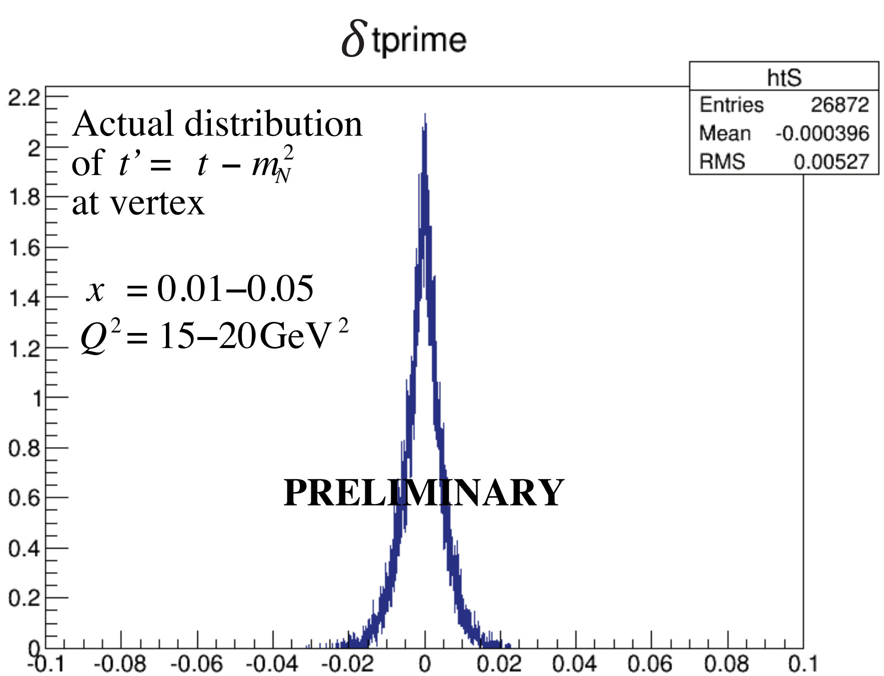
Larger than detector resolution. Different for eRHIC!

At nominal MEIC emittance:

$$\delta p_D / p_D = 3 \times 10^{-4}$$

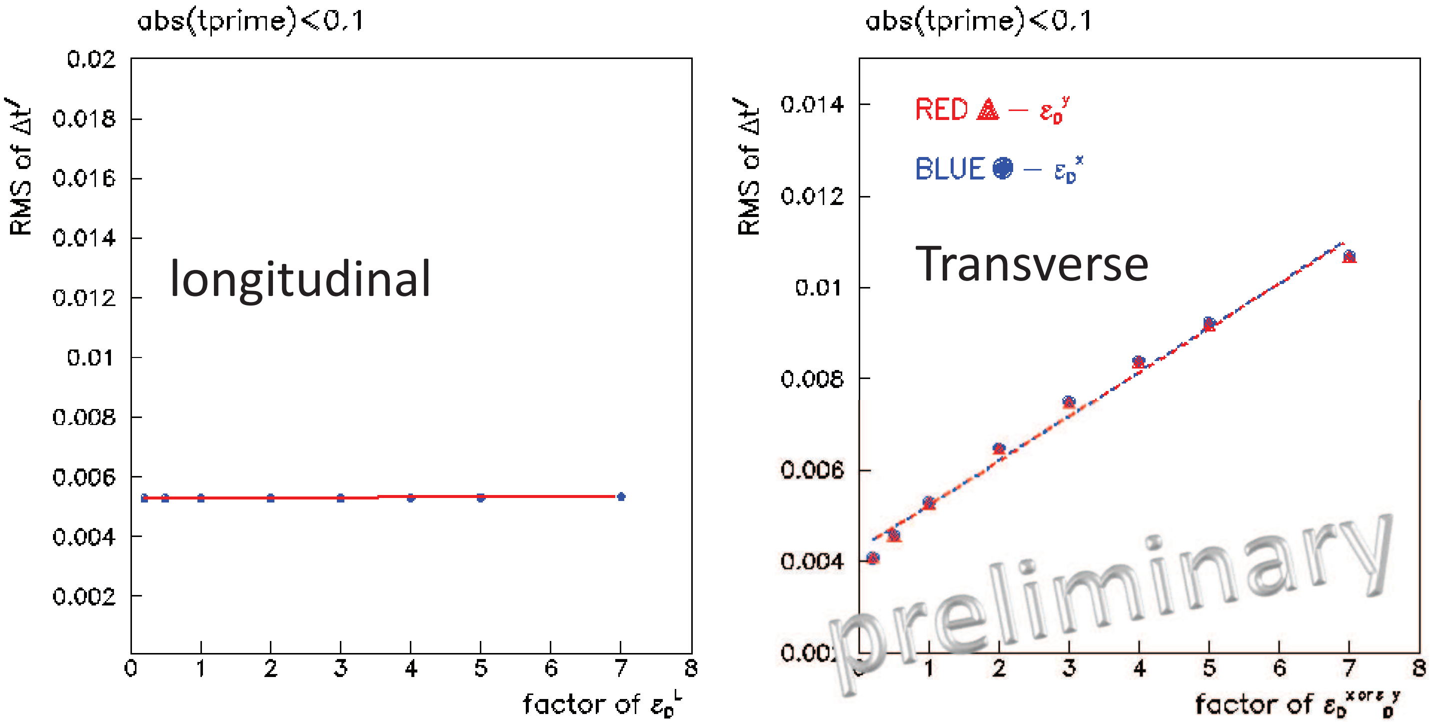
$$\delta\theta = 2 \times 10^{-4}$$

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



- Smearing width < bin size
- Extrapolation arrears safe!
- Dominant effect from ion transverse emittance.

R&D: Scaling with beam emittance



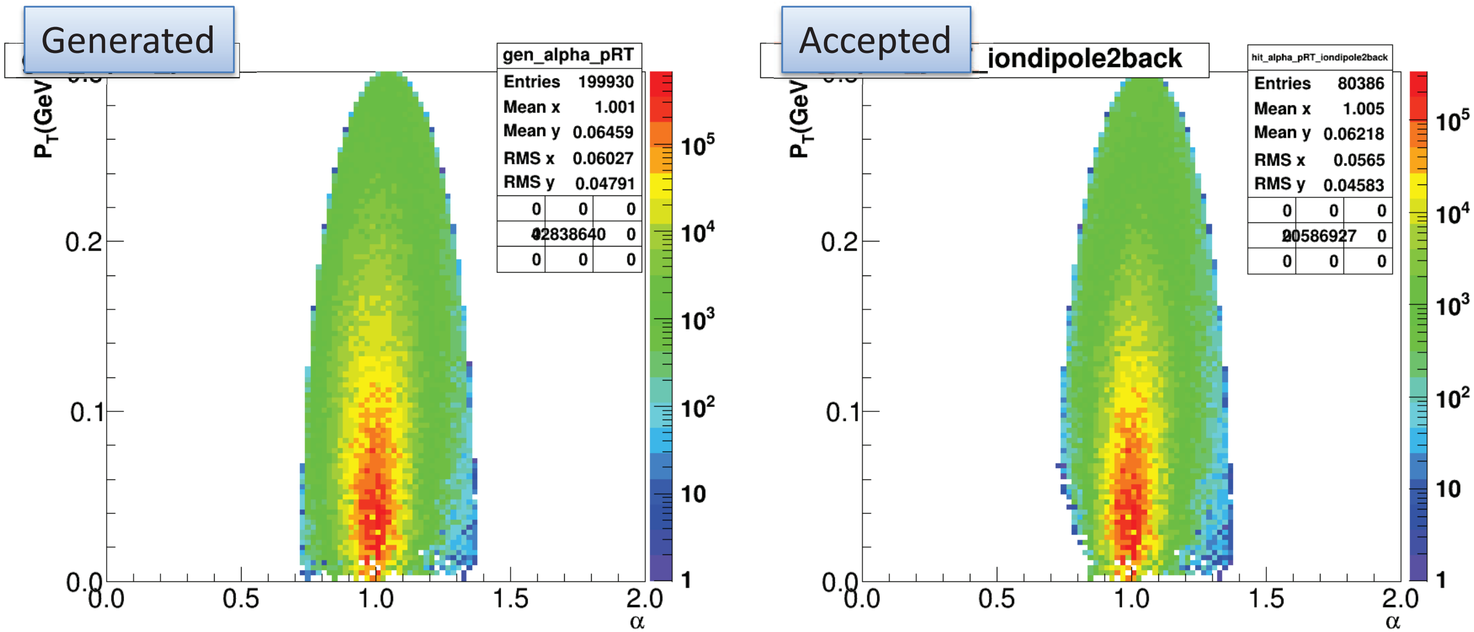
- Scaling of δt' width with ion beam emittance: Longitudinal, transverse
- Nominal values for MEIC:

$$\epsilon^*_{||} = 3 \times 10^{-4}$$

$$\epsilon^*_x = 0.35 \times 10^{-6}$$

$$\epsilon^*_y = 0.07 \times 10^{-6}$$

R&D: Acceptance with GEMC MC



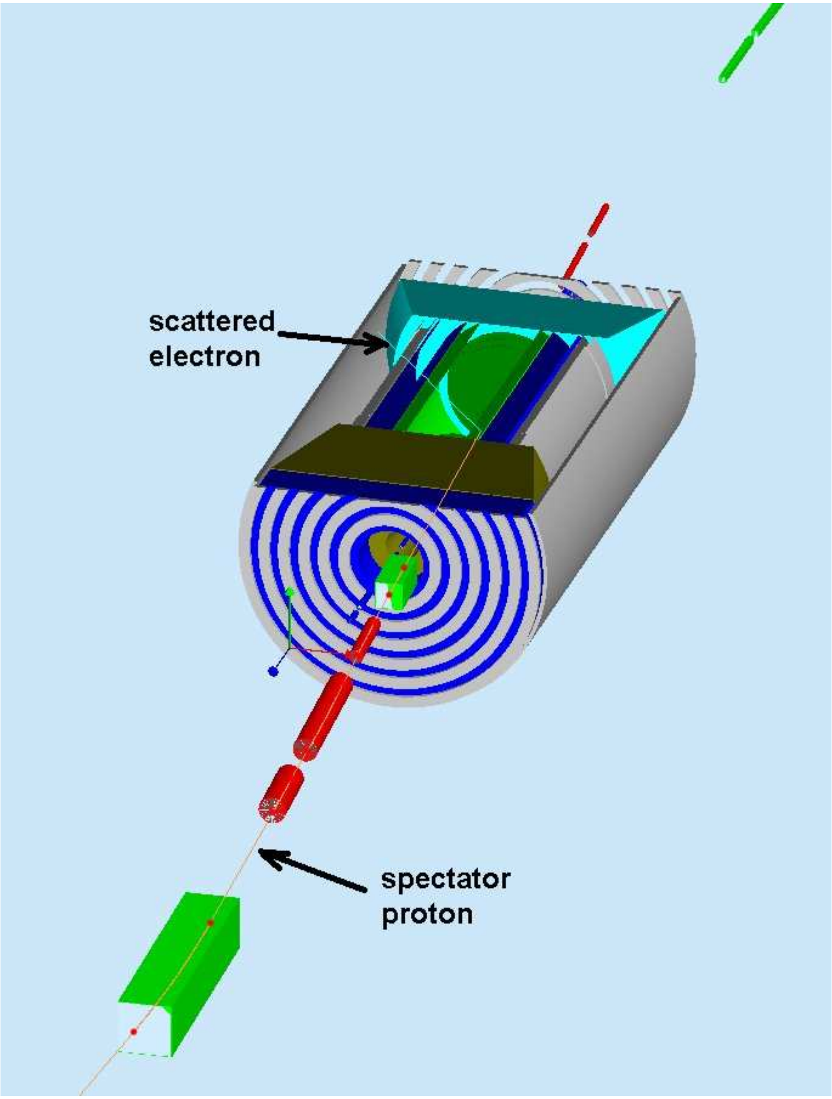
- $e + D \to e' + p + X$ events run through MEIC detector

Forward tagging generator → FastMC GEMC → plot Zh. Gao

- First assessment of acceptance:

  Here: α_R and p_{TR} distribution
  "Cut corner" due to dipole — present configuration, not optimized

R&D: Tracking with GEMC MC



- Particle tracking of $e + D \rightarrow e' + p + X$ events with GEMC, Zh. Gao

  - Events from forward tagging generator

  - Input to full detector simulations beyond LDRD project

Summary

- Precise nuclear physics measurements enabled by
  - Polarized deuterium beam
  - Forward p, n detection
  - EIC kinematic reach

- 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 project aims to establish forward tagging as standard method

  - Theory: Polarization, final-state interactions
  - Simulations: Acceptance, tracking, systematic errors

R&D: Enabling spectator tagging

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/`