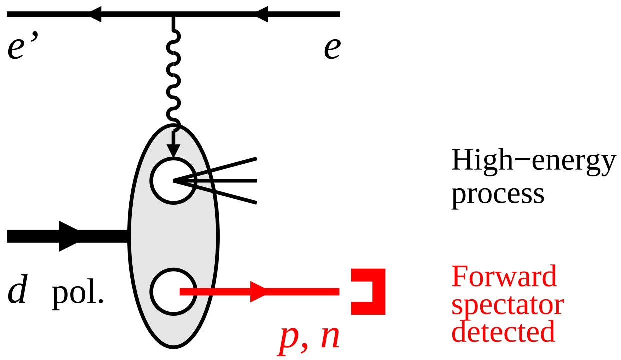
Deuteron and spectator tagging physics with EIC

C. Weiss (JLab), Ad-hoc Meeting "Deuteron Simulations," JLab, 30-Aug-2018



EIC simulations: JLab 2014/15 LDRD
W. Cosyn, V. Guzey, D. Higinbotham, Ch. Hyde, K. Park, P. Nadel-Turonski, M. Sargsian, M. Strikman, C. Weiss∗ [Webpage]

Theory: Continuing effort
Strikman, CW, PRC97 (2018) 035209 [INSP] + in preparation

- Light ion physics at EIC

  Energy, luminosity, polarization, detection

  Physics objectives

- Deuteron and spectator tagging

  Observables and theoretical description

  Free neutron from on-shell extrapolation

  Neutron spin structure

  Applications: Tensor polarization, EMC effect, diffraction and shadowing at small x...

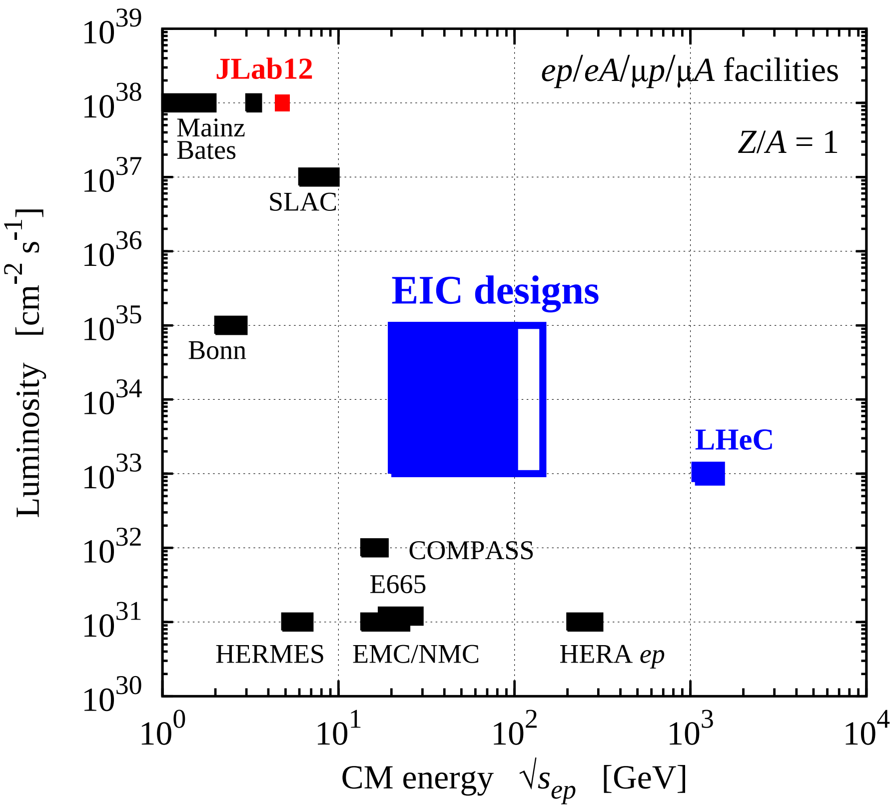
- EIC simulations

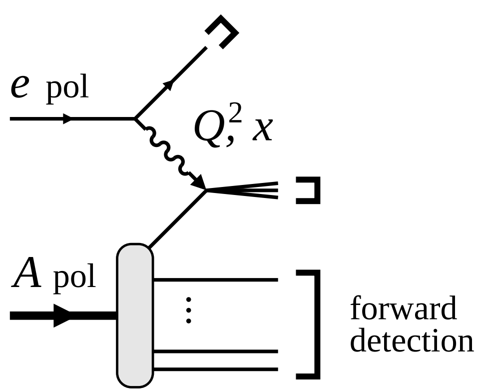
  Forward detection

  Ion beam momentum spread

  Simulation tools

Light ions: EIC capabilities





- CM energy $\sqrt{s_{ep}} \sim$ 20–100 GeV

  Factor $\sqrt{Z/A}$ for nuclei

  DIS at $x \gtrsim 10^{-3}$, $Q^2 \lesssim 10^2$ GeV^2

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

  Exceptional configurations in target
  Multi-variable final states
  Polarization observables

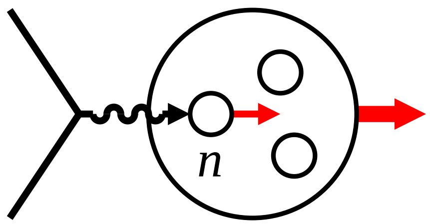
- Polarized protons and light ions

  eRHIC: pol ^{3}He
  JLEIC: pol d and ^{3}He with figure-8

- Forward detection of p, n, A

  Diffractive and exclusive processes
  Nuclear breakup and spectator tagging
  Coherent nuclear scattering

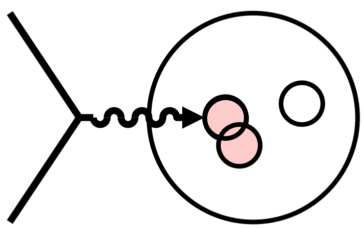
Light ions: Physics objectives



- Neutron structure

  Flavor decomposition of PDFs/GPDs/TMDs,
  singlet vs. non-singlet QCD evolution, polarized gluon

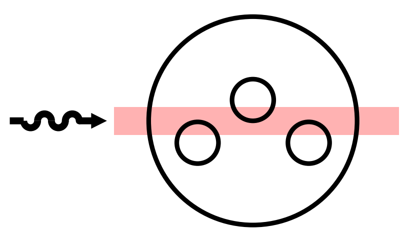
  Eliminate nuclear binding, non-nucleonic DOF!



- Nucleon interactions in QCD

  Nuclear modification of quark/gluon densities
  Short-range correlations, non-nucleonic DOF
  QCD origin of nuclear forces

  Associate modifications with interactions!



- Coherent phenomena in QCD

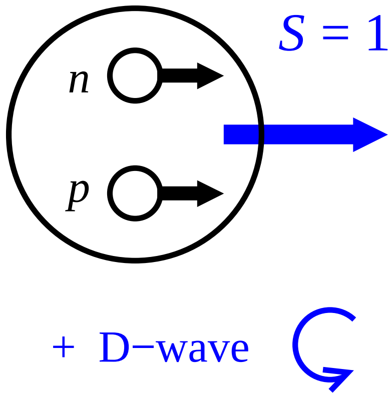
  Coherent interaction of high–energy probe
  with multiple nucleons, shadowing, saturation

  Identify coherent response!

[Nucleus rest frame view]

Common challenge: Many possible nuclear
configurations during high-energy process.
Need to “control” configurations!

Light ions: Deuteron, spectator tagging

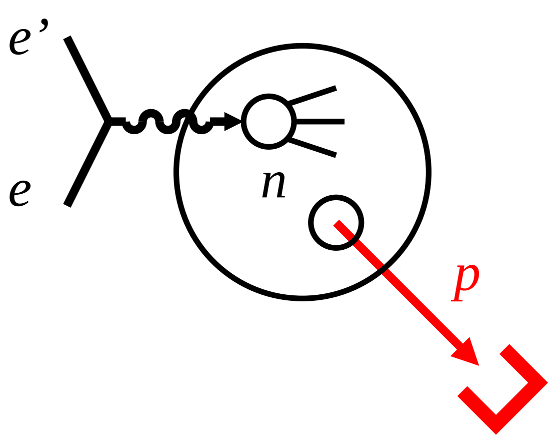


- Polarized deuteron

  pn wave function simple, known well
  incl. light-front WF for high-energy procs

  Neutron spin–polarized

  Intrinsic Δ isobars suppressed by Isospin $= 0$
  $|\text{deuteron}\rangle = |pn\rangle + \epsilon|\Delta\Delta\rangle$ negligible
  3He spin structure distorted by Δ's. Guzey, Strikman, Thomas et al 01



[Nucleus rest frame view]

- Spectator nucleon tagging

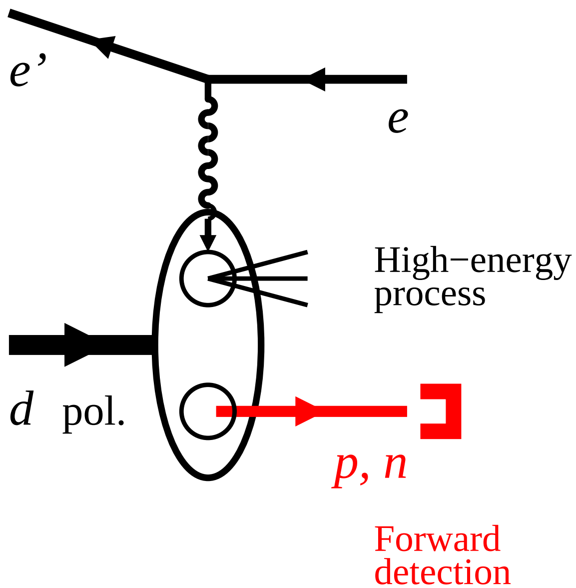
  Identifies active nucleon

  Controls configuration through recoil momentum:
  Spatial size, S $\leftrightarrow$ D wave

  Typical momenta $\sim$ few 10 – 100 MeV (rest frame)

  Tagging in fixed-target experiments
  CLAS6/12 BONUS, recoil momenta $p =$ 70-150 MeV

Light ions: Deuteron, spectator tagging



- Spectator tagging with colliding beams

  Spectator nucleon moves forward
  with approx. $1/2$ beam momentum

  Detection with forward detectors integrated
  in interaction region and beams optics
  LHC $pp/pA/AA$, Tevatron $p\bar{p}$, RHIC pp, ultraperipheral AA

- Advantages over fixed-target

  No target material, $\boldsymbol{p}_p$(rest frame) $\rightarrow 0$ possible

  Potentially full acceptance

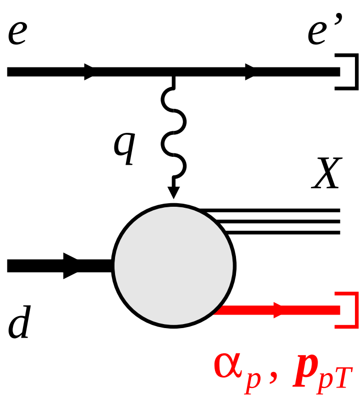
  Resolution $\sim$ 10-20 MeV in $\boldsymbol{p}_p$(rest frame)

  Can be used with polarized deuteron

  Forward neutron detection possible

- Unique physics potential

Tagging: Cross section and observables



$$\frac{d\sigma}{dx\,dQ^2\,(d^3p_p/E_p)} = [\text{flux}]\Big[F_{Td}(x, Q^2; \alpha_p, p_{pT}) + \epsilon F_{Ld}(..)$$

$$+ \sqrt{2\epsilon(1+\epsilon)}\cos\phi_p F_{LT,d}(..) \; + \; \epsilon\cos(2\phi_p) F_{TT,d}(..)$$

$$+ \text{ spin-dependent structures}\Big]$$

- Conditional DIS cross section $e + d \to e' + X + p$

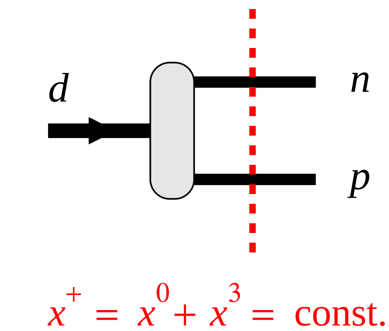
  Proton recoil momentum $p_p^+ = E_p + p_p^z, \; \boldsymbol{p}_{pT}$,
  light-front momentum fraction $p_p^+ = \alpha_p p_d^+/2$,
  simply related to $\boldsymbol{p}_p(\text{restframe})$

  Conditional structure functions

  Special case of semi-inclusive DIS — target fragmentation
  QCD factorization Trentadue, Veneziano 93; Collins 97

  No assumptions re nuclear structure, $A = \sum N$, etc.

Tagging: Theoretical description



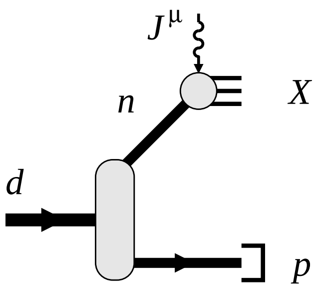
- Light-front quantization

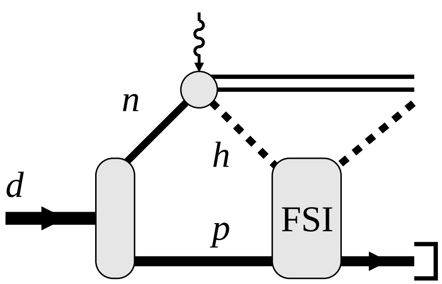
  High-energy scattering probes nucleus at fixed light-front time $x^+ = x^0 + x^3 =$ const.

  Deuteron LF wave function $\langle pn|d\rangle = \Psi(\alpha_p, \boldsymbol{p}_{pT})$

  Permits matching nuclear $\leftrightarrow$ nucleonic structure
  Conserves LF momentum, baryon number
  Frankfurt, Strikman 80's

  Low-energy nuclear structure, cf. non-relativistic theory!



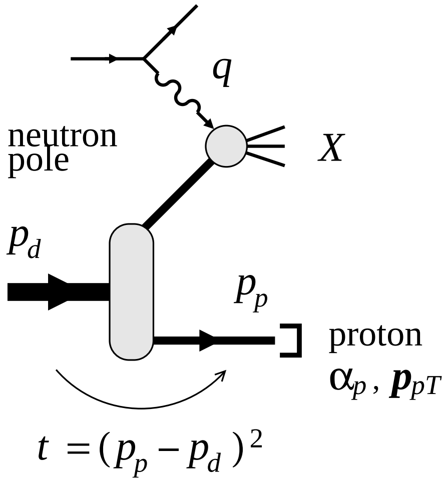


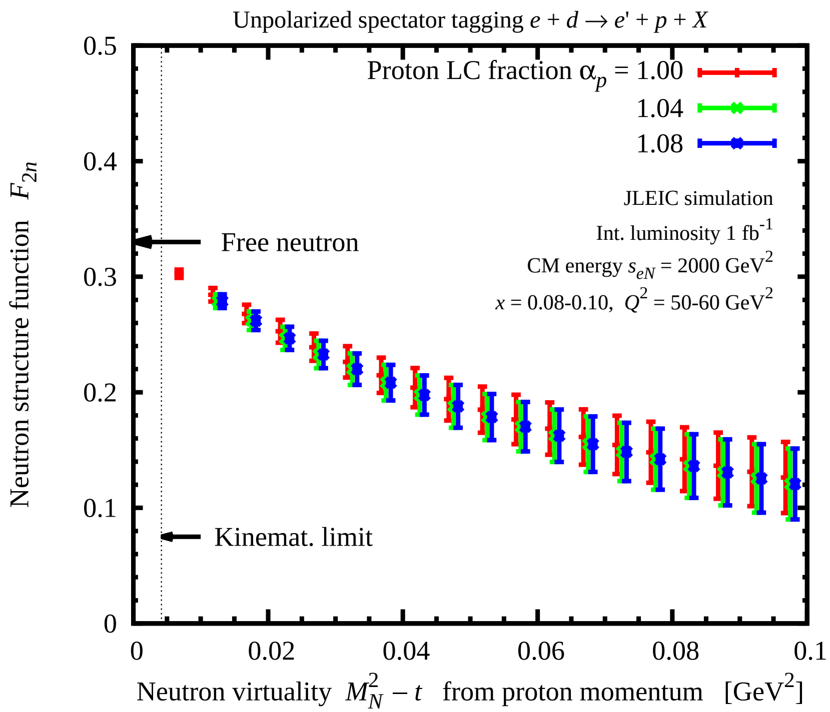
- Composite description

  Impulse approximation: DIS final state and spectator nucleon evolve independently

  Final-state interactions: Part of DIS final state interacts with spectator, transfers momentum

Tagging: Free neutron structure





- Extract free neutron structure

  Proton momentum defines neutron virtuality
  $t - M_N^2 = -2|\boldsymbol{p}_p(\text{rest})|^2 + t_{\min}$

  Free neutron at pole $t - M_N^2 = 0$:
  On-shell extrapolation

  Eliminates nuclear binding effects
  and FSI Sargsian, Strikman 05

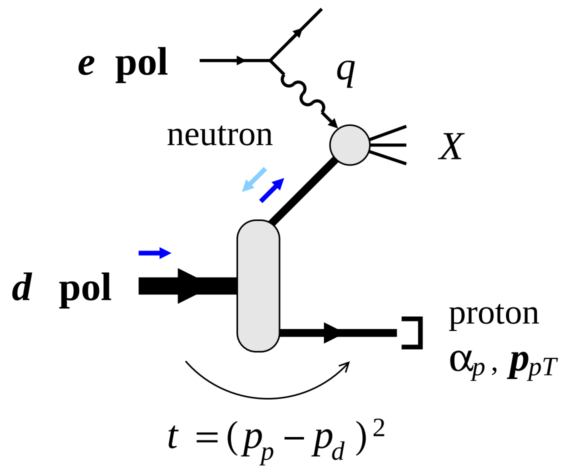
- Precise measurements of F_{2n}

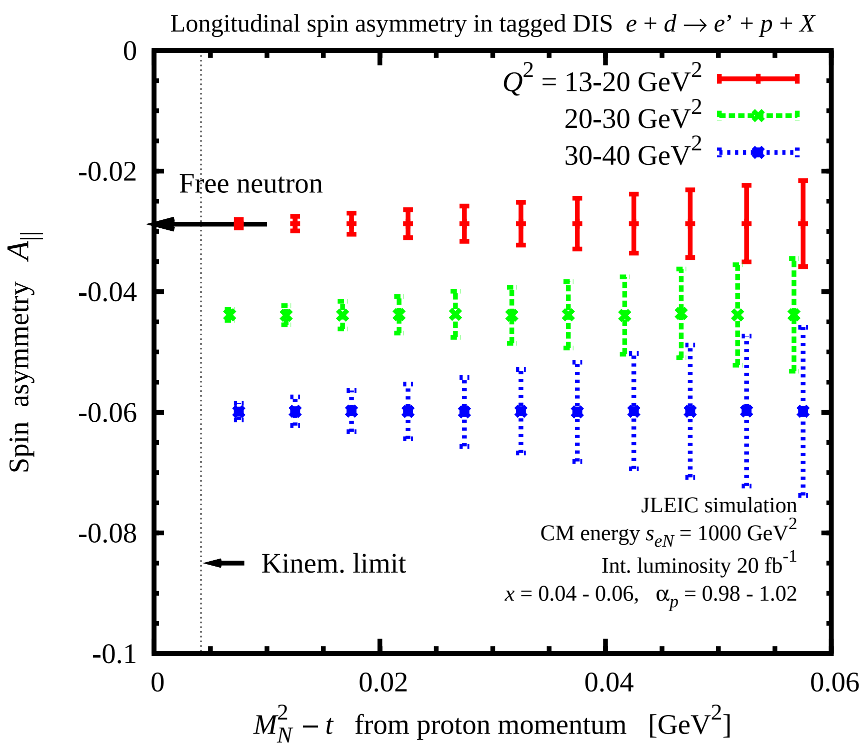
  F_{2n} extracted with few-percent
  accuracy at $x \gtrsim 0.1$

  Uncertainty mainly systematic
  LDRD project: Detailed estimates

  Non-singlet $F_{2p} - F_{2n}$,
  sea quark flavor asymmetry $\bar{d} - \bar{u}$

Tagging: Neutron spin structure





- Neutron spin structure with pol deuteron and proton tagging

  On-shell extrapolation of asymmetry

  D-wave suppressed at $\boldsymbol{p}_p(\text{rest}) = 0$: Neutron 100% polarized

- Systematic uncertainties cancel

  Weak off-shell dependence of asymmetry

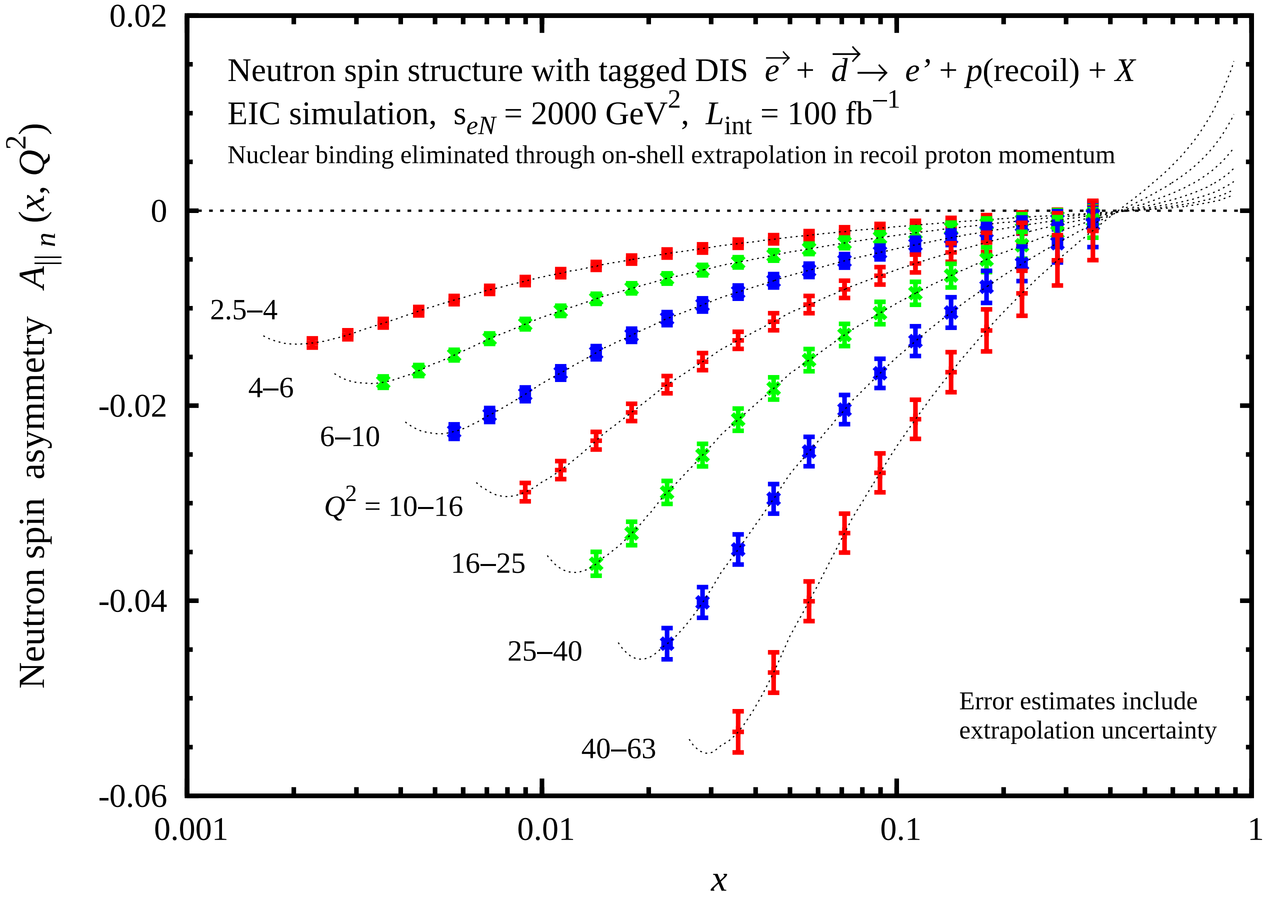
  Momentum smearing/resolution effects largely cancel in asymmetry

- Statistics requirements

  Physical asymmetries $\sim$ 0.05-0.1, effective polarization $P_e P_D \sim 0.5$

  Possible with int lumi $\sim$ few 10 fb^{-1}

Tagging: Neutron spin structure II



$$A_{\parallel n} = \frac{\sigma(+-) - \sigma(++)}{\sigma(+-) + \sigma(++)}$$

$$= D\,\frac{g_1}{F_1} + \ldots$$

$$D = \frac{y(2-y)}{2 - 2y + y^2}$$

depolarization factor

$$y = \frac{Q^2}{x s_{eN}}$$

- Precise measurement of neutron spin structure

  Wide kinematic range: Leading $\leftrightarrow$ higher twist, nonsinglet $\leftrightarrow$ singlet QCD evolution

  Parton density fits: Flavor separation $\Delta u \leftrightarrow \Delta d$, gluon spin ΔG

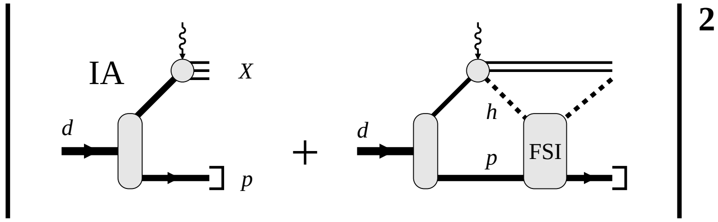
  Nonsinglet $g_{1p} - g_{1n}$ and Bjorken sum rule

Tagging: Theoretical results

- Final-state interactions in tagged DIS at $x \gtrsim 0.1$ — Strikman, CW, PRC97 (2018) 035209

  Induced by slow hadrons in DIS final state

  Vanishes at on-shell point



- Polarized deuteron tagging — Cosyn, CW, in preparation

  SIDIS cross section for general spin-1 target

  Vector and tensor-polarized structures

  Polarized deuteron light-front structure with S+D waves

- Diffraction and shadowing in tagging at $x \ll 0.1$ — Guzey, Strikman, CW, in preparation

  Coherent interaction with both nucleons

  Stringent tests through recoil momentum dependence

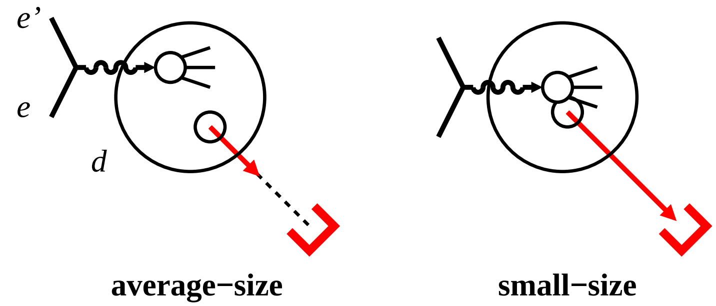
Tagging: Applications and extensions

- Tagged EMC effect

  What momenta/distances cause modification?

  Connection with NN short-range correlations?

  Modified gluonic structure in SRC?
  Miller, Sievert, Venugopalan 17



- Tensor polarization from tagging

  Certain ϕ_p harmonics specific to tensor polarization – unique signal Cosyn, CW, in preparation

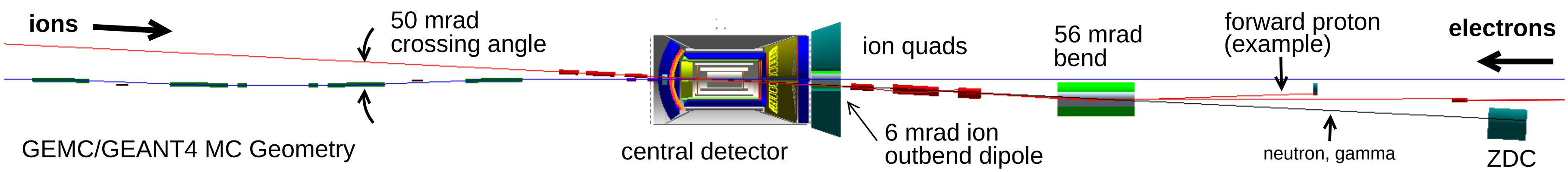
  Complements inclusive b_1 structure function measurements

- Tagging with complex nuclei $A > 2$

  Could test isospin dependence and/or universality of bound nucleon structure

  $(A - 1)$ ground state recoil, e.g. 3He (e, e' d) X Ciofi, Kaptari, Scopetta 99; Kaptari et al. 2014
  Theoretically challenging, cf. experience with quasielastic breakup JLab Hall A

EIC simulations: Forward detection



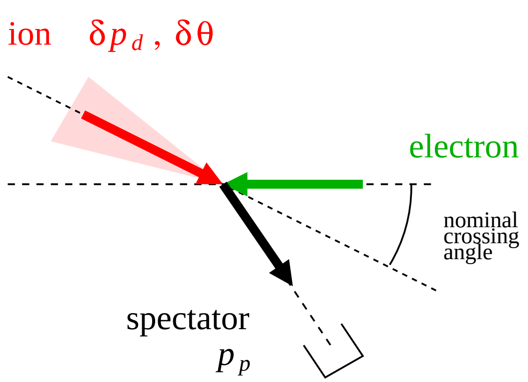
- Forward detector integrated in IR and beam optics

  Protons/neutrons/fragments travel through ion beam quadrupole magnets

  Dispersion generated by dipole magnets

  Detection using forward detectors — Roman pots, ZDCs

  Tagging studies: Full acceptance, proton momentum resolution longit $\delta p/p \sim 10^{-3}$, angular $\delta\theta \sim 0.2$ mrad P. Nadel-Turonski, Ch. Hyde et al.



- Intrinsic momentum spread in ion beam

  Transverse momentum spread $\sigma \sim$ few 10 MeV

  Smearing effect $\boldsymbol{p}_{pT}(\text{vertex}) \neq \boldsymbol{p}_{pT}(\text{measured})$, partly corrected by convolution

  Dominant systematic uncertainty in tagged neutron structure measurements. Correlated, x and Q^2-indpendent. JLab LDRD

EIC simulations: Tools

- Cross section models

  Unpolarized $e + d \to e' + N + X$: Nuclear binding in impulse approximation.
  Final-state interaction theory available, could be implemented

  Longitudinally polarized $e + d \to e' + N + X$: Minimal implementation.
  General deuteron polarization (transverse, tensor) in progress.

  Diffractive $e + d \to e' + p + X(\text{diff})$: Minimal implementation including
  diffraction/shadowing at $x \ll 0.1$. Theory development in progress.

  FORTRAN/C++ codes and documentation. Available at: `https://www.jlab.org/theory/tag/`

- Event generators and analysis tools

  $e + d \to e' + p + X$ event generator: 4–vectors generated in collider frame.
  Includes crossing angle and intrinsic momentum spread in ion beam.
  Output in GEMC format, used for studies of tracking, acceptance.
  Fixed-target applications possible; tested against FSGEN-based generator. K. Park, Ch. Hyde

  Analysis tools: Neutron structure, on-shell extrapolation

  Codes and docu available at: `https://github.com/JeffersonLab/LightIonEIC`

- Forward detector model → Discussion

Summary

- Light-ion physics program with EIC has great potential, should be developed & articulated at same level as ep and eA(heavy)

- Polarized deuteron uniquely suited for neutron spin structure: Clean pn system (up to few 100 MeV momenta), Δ isobars suppressed

- Spectator tagging overcomes main limiting factor of nuclear DIS: Control of nuclear configurations during high-energy process

- Interesting theoretical challenges

  Intersection of low-energy nuclear structure and high-energy scattering
  Workshop "Polarized light ion physics with EIC", 5-9 Feb 2018, Ghent U, Belgium [webpage]

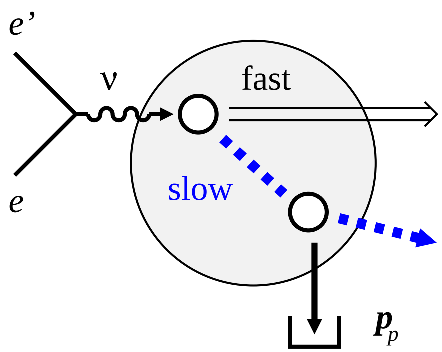
  Progress with final-state interactions, polarized deuteron, diffraction and shadowing

- Ready for simulations with next-generation physics models
  JLab 2014/15 LDRD project. Physics model codes publicly available at [webpage]. Open for collaboration!

- Need forward detector implementation

Supplementary material

Tagging: Final-state interactions



- Spectator can interact with DIS final state

  Changes recoil momentum distributions in tagging

  No effect on total cross section – closure

- Nucleon DIS final state has two components

"Fast" $E_h = O(\nu)$		hadrons formed outside nucleus interact weakly with spectators
"Slow" $E_h = O(\mu_{\text{had}}) \sim 1$ GeV		formed inside nucleus interacts with hadronic cross section dominant source of FSI

- FSI effects calculated $x \sim 0.1$–0.5 — Strikman, CW, PRC97 (2018) 035209

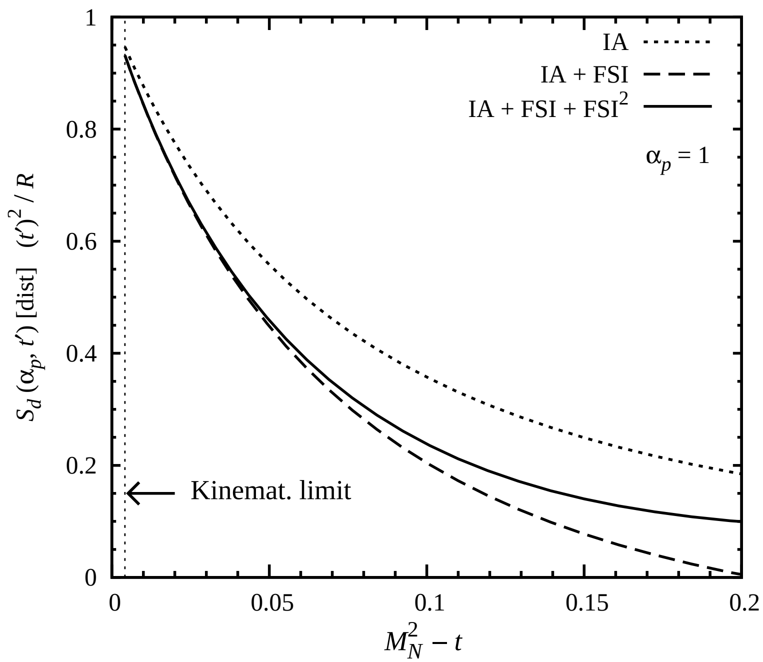
  Experimental slow hadron multiplicity distributions — Cornell, EMC, HERA

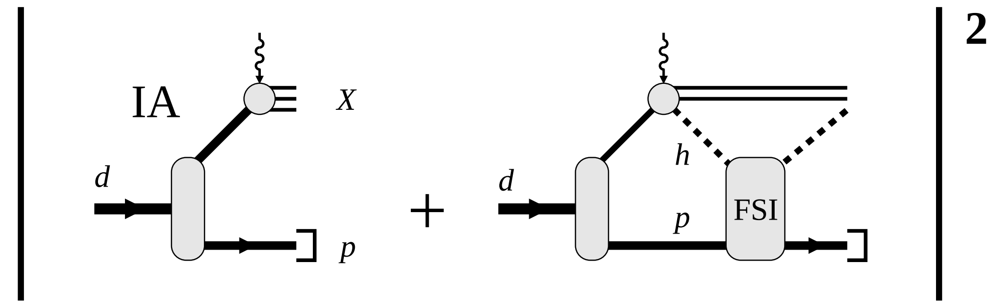
  Hadron-nucleon low-energy scattering amplitudes

  Light-front QM: Deuteron pn wave function, rescattering process — Frankfurt, Strikman 81

  QCD factorization theorem for target fragmentation — Trentadue, Veneziano 93; Collins 97

Tagging: Final-state interactions II





Strikman, CW 18

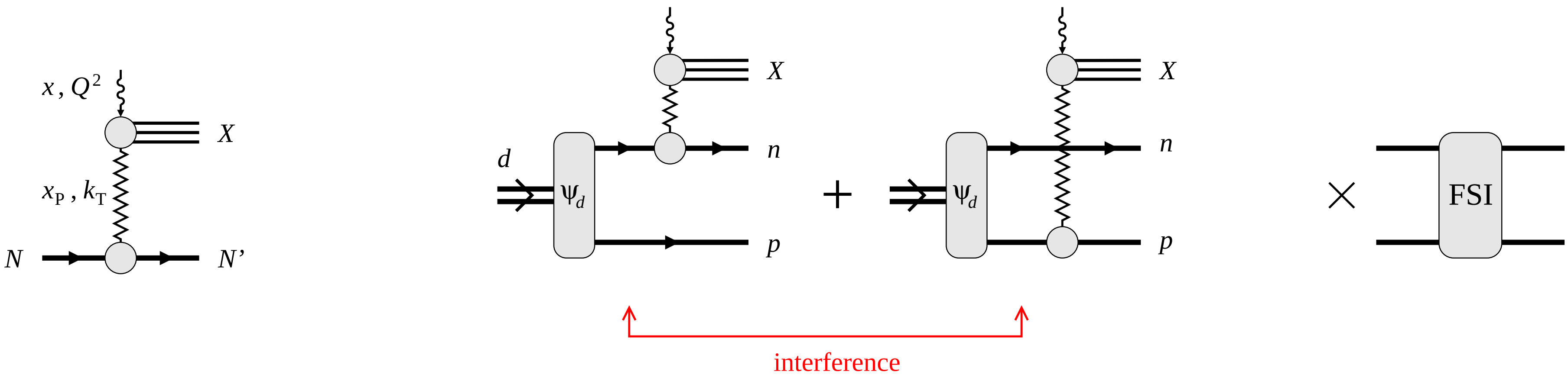
- FSI reduces IA cross section at $|t - M_N^2| \neq 0 \quad (\lesssim 0.2\,\mathrm{GeV}^2)$
- FSI vanishes at $t - M_N^2 \to 0$; on-shell extrapolation not affected
- Other interesting aspects

  FSI depends on recoil momentum angle in rest frame: forward-sideways-backward regions

  Analogy with FSI in quasi-elastic deuteron breakup

  FSI suppressed for $x \to 1$: Minimum momentum of DIS hadrons grows

Tagging: Diffraction and shadowing



- Diffraction in nucleon DIS at $x \ll 0.1$

  Nucleon remains intact, recoils with $k \sim$ few 100 MeV (rest frame)

  10-15% of events diffractive. Detailed studies at HERA: QCD factorization, diffractive PDFs

- Shadowing in deuteron DIS

  Diffraction can happen on neutron or proton: QM interference

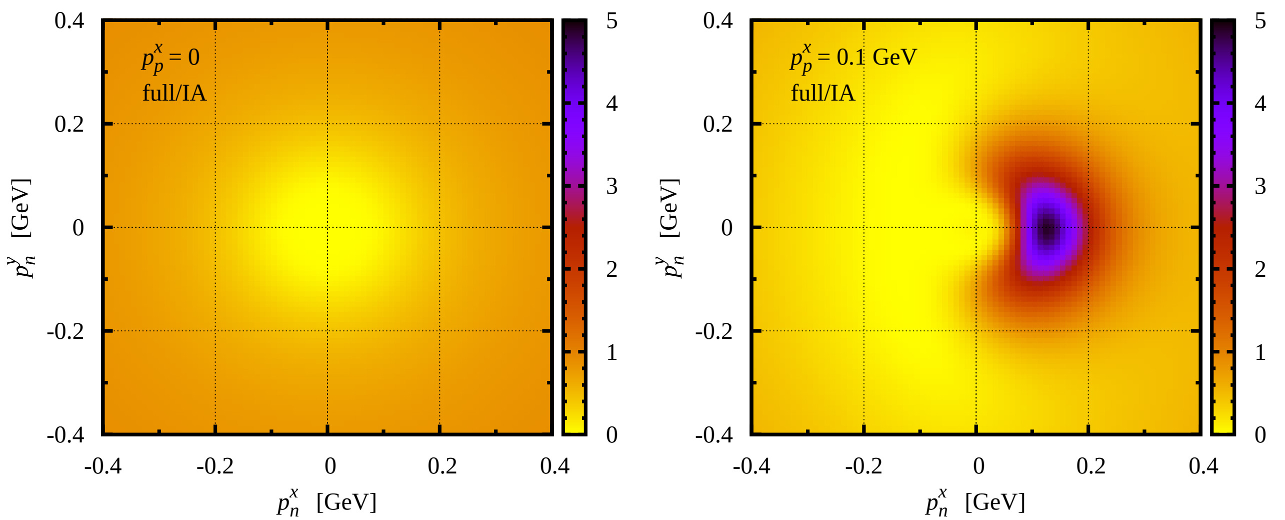
  Reduction of cross section compared to IA — shadowing. Leading-twist effect.
  Frankfurt, Strikman, Guzey 12. Hints seen in J/ψ production in UPCs at LHC ALICE.

- Diffraction and shadowing in tagged DIS

  Differential studies as function of recoil momentum!

  FSI: Outgoing pn scattering state must be orthogonal to d bound state
  Guzey, Strikman, CW, in preparation

Tagging: Diffraction and shadowing



$$R = \frac{d\sigma(\text{full})}{d\sigma(\text{IA})}$$ as function of neutron $\boldsymbol{p}_{nT}$ for fixed proton $\boldsymbol{p}_{pT}$

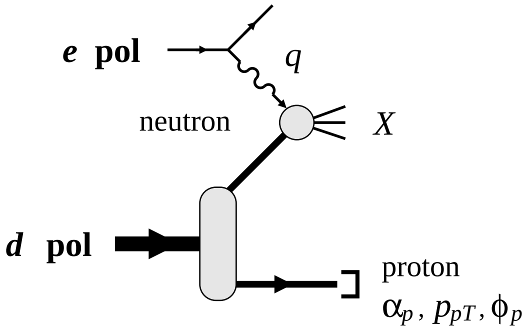
- Final-state interactions in diffractive tagged DIS $e + d \rightarrow e' + X + n + p$

  Large FSI effects due to orthogonality

  Shadowing effects calculated Guzey, Strikman, CW, in preparation

  Other application: High-p_T deuteron breakup and gluonic structure of small-size pn configuration Miller, Sievert, Venugopalan 17

Tagging: Polarized deuteron



- Deuteron spin density matrix $\rho_{\lambda\lambda'}(S,T)$

  3 vector parameters, 5 tensor parameters

  Fixed by polarization measurements
  cf. Stokes' parameters for photon

- Polarized tagged cross section

Cosyn, Sargsian, CW 17

$$\frac{d\sigma}{dx\,dQ^2(d^3p_p/E_p)} = [\text{flux}](\mathsf{F}_U + \mathsf{F}_S + \mathsf{F}_T) \qquad \mathsf{F}_I = \text{functions}(x, Q^2, \alpha_p, p_{pT}, \phi_p)$$

$$F_U = F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_h F_{UU}^{\cos\phi_h} + \epsilon\cos 2\phi_h F_{UU}^{\cos 2\phi_h} + h\sqrt{2\epsilon(1-\epsilon)}\sin\phi_h F_{LU}^{\sin\phi_h}$$

$$\begin{aligned}
F_S = S_L & \left[\sqrt{2\epsilon(1+\epsilon)}\sin\phi_h F_{US_L}^{\sin\phi_h} + \epsilon\sin 2\phi_h F_{US_L}^{\sin 2\phi_h}\right] \\
& + S_L h\left[\sqrt{1-\epsilon^2}F_{LS_L} + \sqrt{2\epsilon(1-\epsilon)}\cos\phi_h F_{LS_L}^{\cos\phi_h}\right] \\
& + S_\perp\left[\sin(\phi_h-\phi_S)\left(F_{US_T,T}^{\sin(\phi_h-\phi_S)} + \epsilon F_{US_T,L}^{\sin(\phi_h-\phi_S)}\right) + \epsilon\sin(\phi_h+\phi_S)F_{US_T}^{\sin(\phi_h+\phi_S)}\right. \\
& \left. +\epsilon\sin(3\phi_h-\phi_S)F_{US_T}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\left(\sin\phi_S F_{US_T}^{\sin\phi_S} + \sin(2\phi_h-\phi_S)F_{US_T}^{\sin(2\phi_h-\phi_S)}\right)\right] \\
& + S_\perp h\left[\sqrt{1-\epsilon^2}\cos(\phi_h-\phi_S)F_{LS_T}^{\cos(\phi_h-\phi_S)} + \right. \\
& \left.\sqrt{2\epsilon(1-\epsilon)}\left(\cos\phi_S F_{LS_T}^{\cos\phi_S} + \cos(2\phi_h-\phi_S)F_{LS_T}^{\cos(2\phi_h-\phi_S)}\right)\right],
\end{aligned}$$

Tagging: Polarized deuteron II

$$
\begin{aligned}
F_T = T_{LL} \Big[& F_{UT_{LL},T} + \epsilon F_{UT_{LL},L} + \sqrt{2\epsilon(1+\epsilon)} \cos\phi_h F_{UT_{LL}}^{\cos\phi_h} + \epsilon \cos 2\phi_h F_{UT_{LL}}^{\cos 2\phi_h} \Big] \\
& + T_{LL} h \sqrt{2\epsilon(1-\epsilon)} \sin\phi_h F_{LT_{LL}}^{\sin\phi_h} \\
& + T_{L\perp} [\cdots] + T_{L\perp} h [\cdots] \\
& + T_{\perp\perp} \Big[\cos(2\phi_h - 2\phi_{T_\perp}) \Big(F_{UT_{TT},T}^{\cos(2\phi_h - 2\phi_{T_\perp})} + \epsilon F_{UT_{TT},L}^{\cos(2\phi_h - 2\phi_{T_\perp})} \Big) \\
& + \epsilon \cos 2\phi_{T_\perp} F_{UT_{TT}}^{\cos 2\phi_{T_\perp}} + \epsilon \cos(4\phi_h - 2\phi_{T_\perp}) F_{UT_{TT}}^{\cos(4\phi_h - 2\phi_{T_\perp})} \\
& + \sqrt{2\epsilon(1+\epsilon)} \Big(\cos(\phi_h - 2\phi_{T_\perp}) F_{UT_{TT}}^{\cos(\phi_h - 2\phi_{T_\perp})} + \cos(3\phi_h - 2\phi_{T_\perp}) F_{UT_{TT}}^{\cos(3\phi_h - 2\phi_{T_\perp})} \Big) \Big] \\
& + T_{\perp\perp} h [\cdots]
\end{aligned}
$$

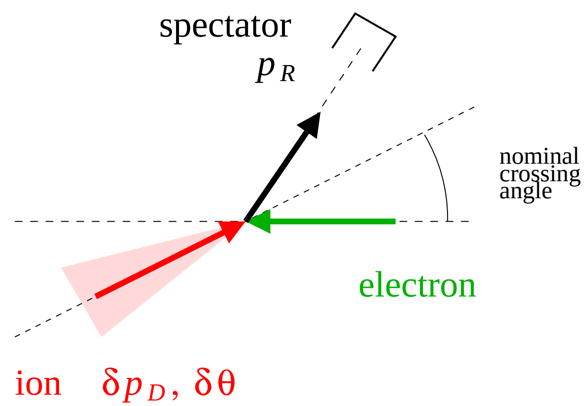
- U + S cross sections identical to spin-1/2 target — Bacchetta et al. 07

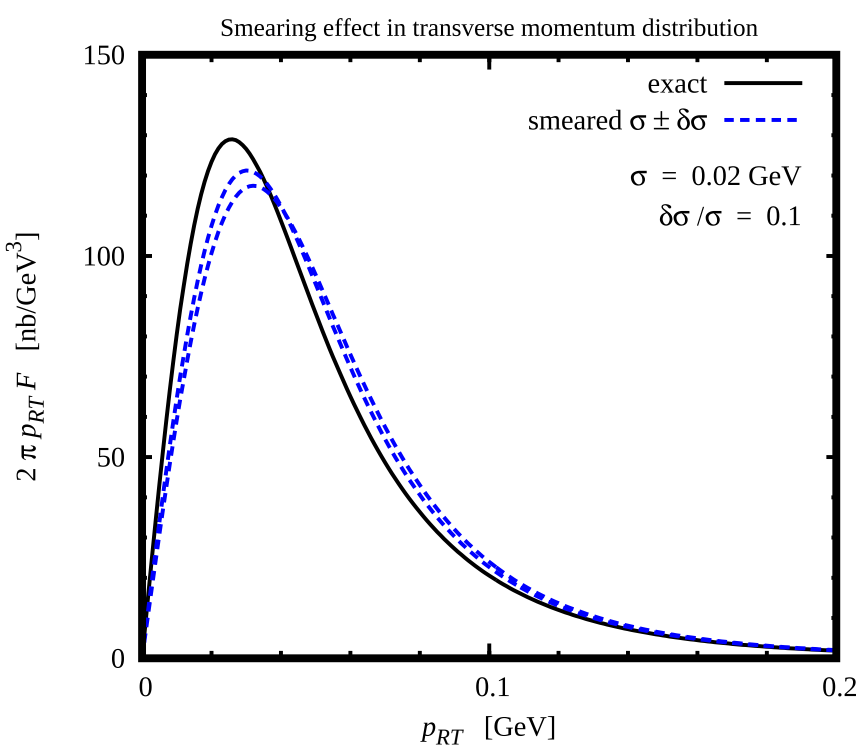
- T cross section has 23 new tensor structure functions specific to spin-1
  4 structure functions survive in inclusive DIS, cf. $b_1 - b_4$ — Hoodbhoy, Jaffe, Manohar 88

  ϕ-harmonics specific to tensor polarization — new handle

- T-odd structures vanish in impulse approximation,
  provide sensitive tests of FSI

EIC simulations: Ion beam momentum spread





- Intrinsic momentum spread in ion beam

  Ion beam has transverse momentum spread with width $\sigma \approx 20$ MeV

  Smearing effect $\boldsymbol{p}_{pT}(\text{vertex}) \neq \boldsymbol{p}_{pT}(\text{measured})$

  Width known only to $\delta\sigma/\sigma \sim 10\%$

  Results in systematic uncertainty: Correlated, x and Q^2–indpendent

  Does not compromise PDF fits! Cf. normalization uncertainty

- Dominant syst error in neutron structure measurements at JLEIC

  Detector resolution higher than beam momentum spread
  Might be different for eRHIC