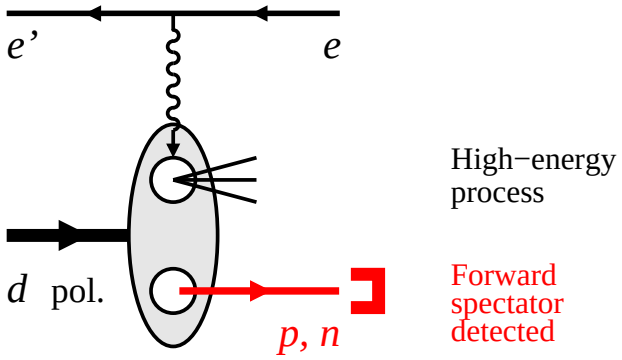
# Opportunities for tagged EMC studies with EIC

C. Weiss (JLab), 2nd SRC/EMC Workshop, MIT, 20-23 Mar 2019



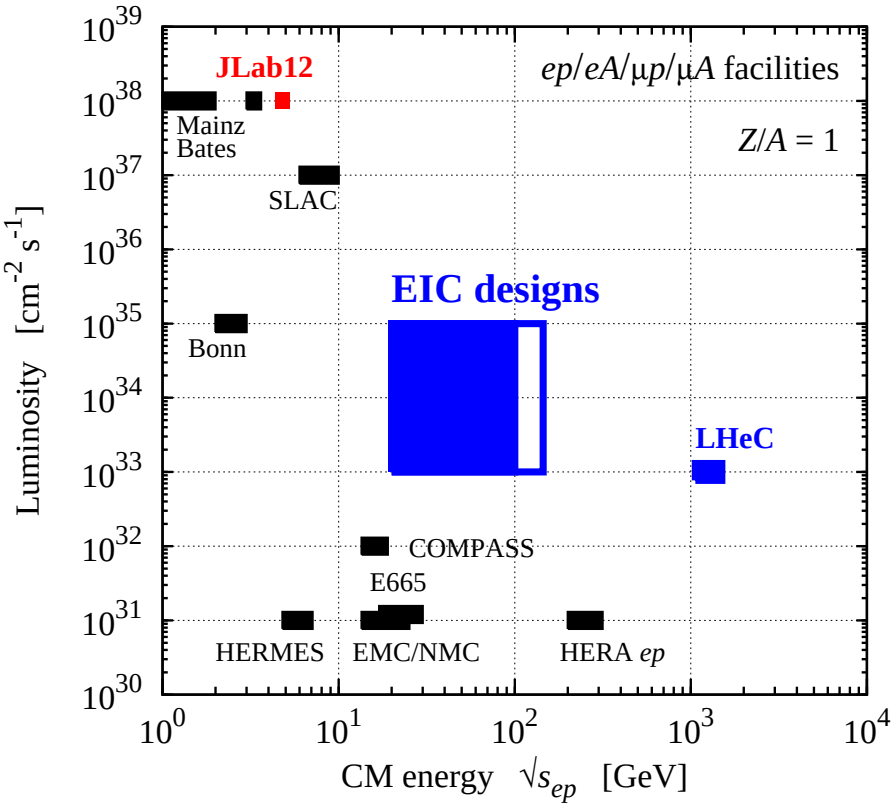

- Light ion physics at EIC
  - Energy, luminosity, polarization, detection
  - Physics objectives
- Deuteron and spectator tagging
  - Theoretical models
  - EIC simulations unpolarized/polarized
- Tagged EMC studies with EIC
  - Proton tagging & momentum dependence
  - Neutron tagging
  - Polarized deuteron vector/tensor
  - $A > 2$ nuclei and breakup
  - Exclusive processes

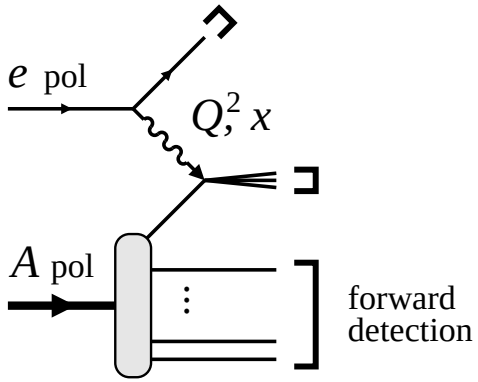
**EIC simulations:** JLab 2014/15 LDRD
W. Cosyn, V. Guzey, D. Higinbotham, Ch. Hyde, K. Park, P. Nadel-Turonski, M. Sargsian, M. Strikman, C. Weiss∗ [Webpage]

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

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

  Exceptional configurations in target
  Multi-variable final states
  Polarization observables

- Polarized protons and light ions

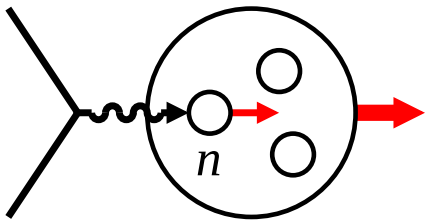
  eRHIC: pol $^3$He
  JLEIC: pol $d$ and $^3$He with figure-8

- Forward detection of $p, n, A$

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

# Light ions: Physics objectives

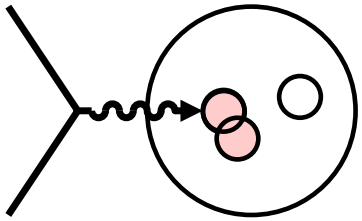





- Neutron structure

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

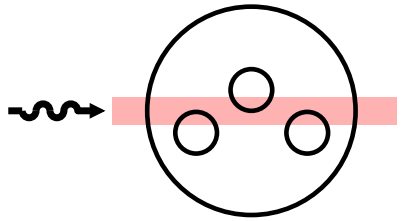
  Eliminate nuclear binding, non-nucleonic DOF!



- 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

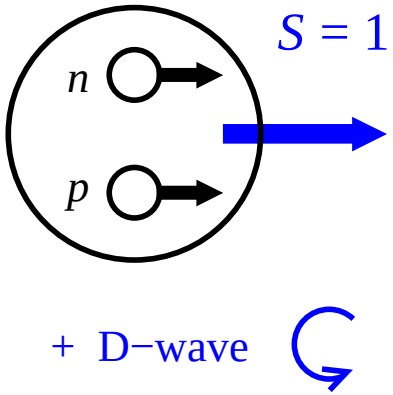
  Identify coherent response!

[Nucleus rest frame view]

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

# Light ions: Deuteron and spectator tagging



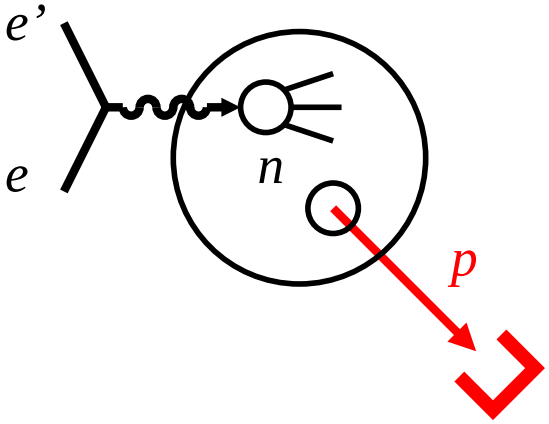



- Deuteron, incl. polarized

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

  Neutron spin–polarized

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




[Nucleus rest frame view]

- Spectator nucleon tagging

  Identifies active nucleon

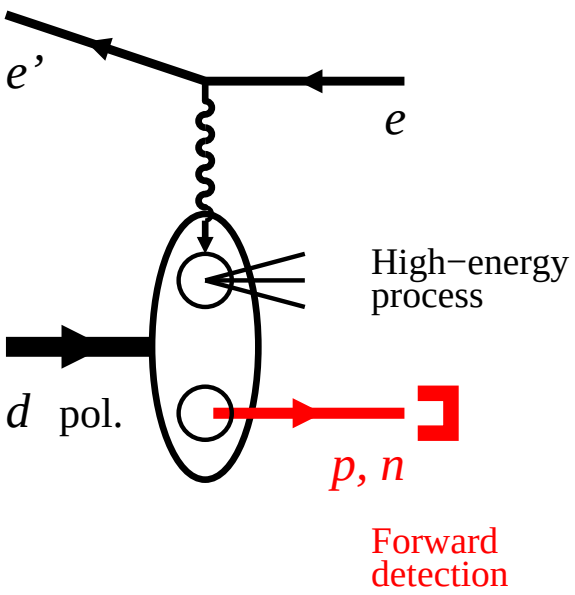
  Controls configuration through recoil momentum:
  Spatial size, S $\leftrightarrow$ D wave

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

  Tagging in fixed-target experiments
  CLAS6/12 BONUS, recoil momenta $p$ = 70-150 MeV
  JLab12 ALERT, Hall A

# Light ions: Deuteron and spectator tagging






$$p_{p\parallel} = \frac{1}{2}\left[1 + \mathcal{O}\left(\frac{p_p[\text{rest}]}{m}\right)\right]$$

[Collider frame view]

- Spectator tagging with colliding beams

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

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

- Advantages over fixed-target

  No target material, $\boldsymbol{p}_p[\text{rest}] \to 0$ possible

  Potentially full acceptance, good resolution

  Can be used with polarized deuteron

  Forward neutron detection possible

- Unique physics potential

# Tagging with EIC: Tools and results



## Theoretical models for tagged DIS $e + d \to e' + N + X$

- Unpolarized: Light-front impulse approximation with realistic wave funtions, final-state interactions $x \gtrsim 0.1$ Strikman, CW, PRC97 (2018) 035209 → Talk Thursday
- Vector-polarized deuteron: Light-front impulse approximation with deuteron spin structure, polarization observables Frankfurt, Strikman NPA405, 557 (1983). Cosyn, CW, arXiv:1902.03678; in progress
- Tensor-polarized deuteron: General structure of response including azimuthal-angle dependence, polarization observables Cosyn, Sargsian, CW, in progress
- Diffractive scattering $x \ll 0.1$: Theory of diffractive deuteron breakup including shadowing and low-momentum FSI Guzey, Strikman, CW, in progress

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

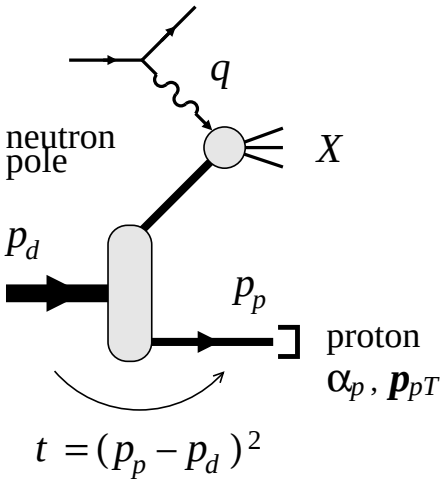
## Event generators and analysis tools

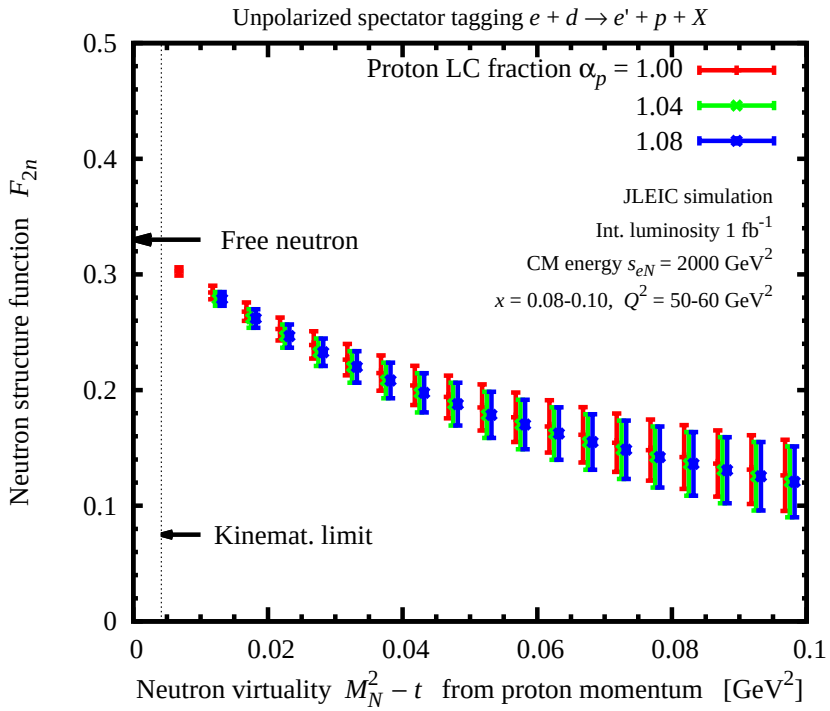
- e + d → e' + p + X event generator: 4-vectors generated in collider frame. Includes crossing angle and intrinsic momentum spread in ion beam. Fixed-target applications possible K. Park, Ch. Hyde
- Analysis tools: Neutron structure, on-shell extrapolation

## Forward detector model → Following

# Tagging with EIC: Unpolarized






- Measure tagged structure functions

  Recoil momentum dependence $\alpha_p$, $\boldsymbol{p}_T$

  Uncertainty mainly systematic:
  Steep recoil momentum dependence,
  beam momentum spread
  LDRD project: Detailed estimates

- Extract free neutron structure

  On-shell extrapolation in $t - m^2 \leftrightarrow |\boldsymbol{p}_{pT}|^2$

  Eliminates nuclear binding and FSI
  Sargsian, Strikman 05

  $F_{2n}$ extracted with few-percent accuracy

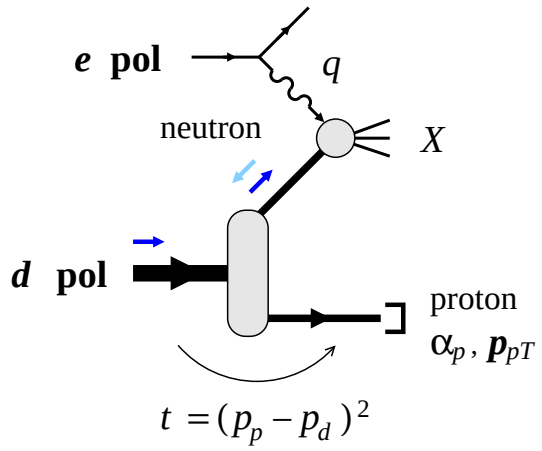
- Same measurements could be used to study tagged EMC effect

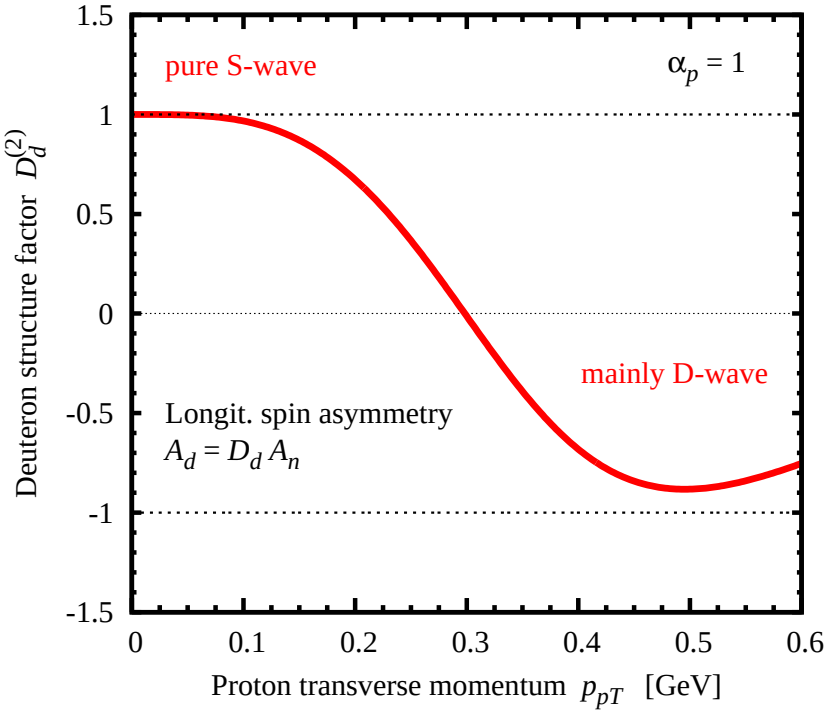
  Finite $|\boldsymbol{p}_{pT}| \sim$ few 100 MeV

  Theoretical interpretation, EMC $\leftrightarrow$ FSI?

# Tagging with EIC: Polarized






Cosyn, CW arXiv:1902.03678

- Measure tagged spin asymmetries

  Momentum smearing/resolution effects largely cancel in asymmetry

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

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

- Extract neutron spin structure

  D-wave drops out at $\boldsymbol{p}_{pT} = 0$: Neutron 100% polarized

  Asymmetry depends weakly on off-shellness $t - m^2 \sim |\boldsymbol{p}_{pT}|^2$

  On-shell extrapolation of asymmetry

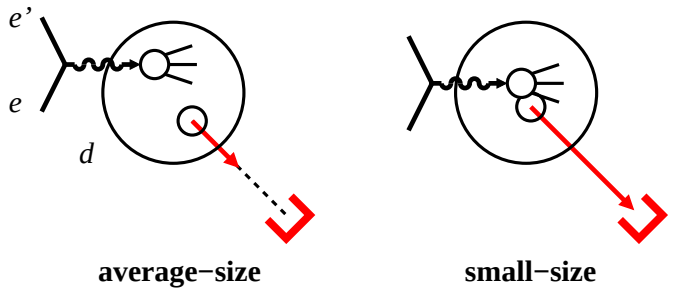
- Same measurements can be used to study spin-dep EMC effect

# Tagged EMC studies with EIC*



- Recoil momentum dep of tagged structure fns

  What momenta/distances cause modification?
  Connection with $NN$ short-range correlations?
  Separate EMC $\leftrightarrow$ FSI?




- Neutron tagging and modified proton structure

  Free proton structure known, serves as reference point
  Should be possible with forward neutron detectors.

- Vector-polarized tagged structure functions

  S vs. D waves, polarization observables.
  Spin-orbit effects in $\phi_p$ dependence.

- Tensor-polarized tagged structure functions

  Certain $\phi_p$ harmonics specific to tensor polarization, provide unique signal.
  Pure N $= 2$ effect. Complements inclusive $b_1$ structure function measurements.

$*$ EIC will also enable non-tagged EMC measurements. Opportunities, specific challenges, need for discussion!

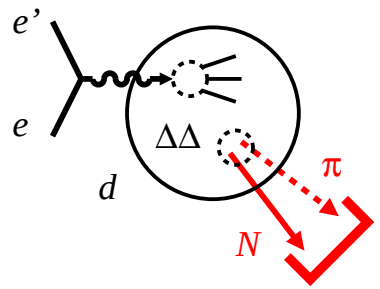
# Tagged EMC studies with EIC II



- Tagging $\Delta$ isobars

  Tagged DIS $e + d \to e' + \pi + N$, reconstruct $\Delta$ from $\pi N$

  Direct demonstration of non-nucleonic degrees of freedom
  → Talk Strikman




- 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

  Theoretically challenging, cf. experience with quasielastic breakup

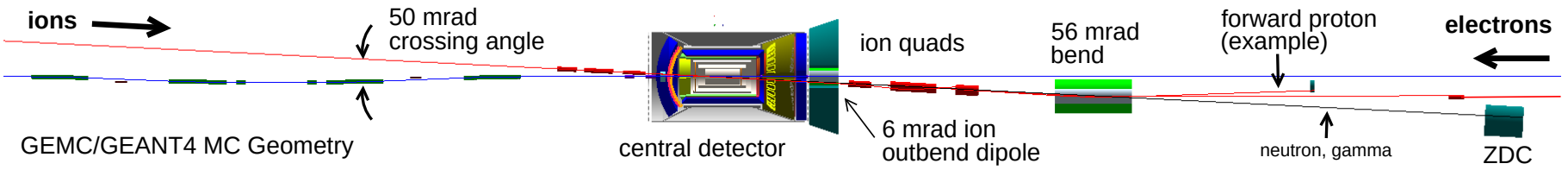
- Tagged exclusive processes — meson production, DVCS

  Nuclear generalized parton distributions (GPDs).
  Measurements benefit from simpler final state, constrained kinematics ($\to$ FSI).

  Includes nuclear coherent processes $A \to A$

# EIC simulations: Forward detection





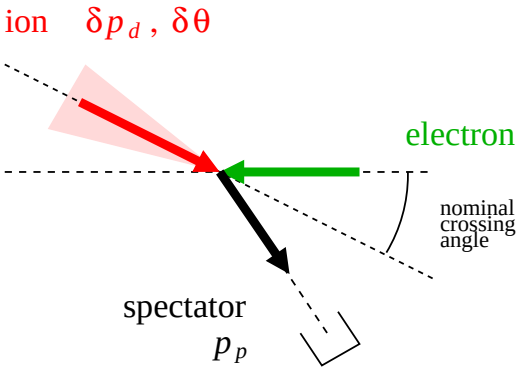

- Forward detector integrated in IR and beam optics

  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

# Summary



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

- Spectator tagging permits nuclear DIS in controled nuclear configuration:
  Neutron structure, EMC effect, coherent phenomena

- 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!

- Needs further development/model implementation of forward detector