Physics with forward processes at EIC

C. Weiss, Yu. Furletova, IR2@EIC: Science and Instrumentation of the 2nd IR for the EIC, 17-Mar-2021

Forward physics with EIC
Processes in ep, eA(light), eA(heavy)
Physics objectives
Forward detection requirements
Interest, novelty, support

Forward detection at IR2
Design considerations and challenges
Complementarity directions
→ V. Morozov, Thu

[This presentation: Basis for discussion/assessment of IR2 options, not specific proposal]
**Forward in ep: Exclusive processes**

**DVCS, TCS and light meson production**

Physics: GPDs, transverse imaging of quarks/gluons, energy-momentum tensor form factors, angular momentum, QCD forces [→ X. Ji, this session]

Detection: Proton $x_L = [0.5, 0.999]$

$p_T = [0, 2 \text{ GeV}], \delta p_T \sim 100 \text{ MeV}$

Neutron detection “as good as possible”

$\Lambda, \Sigma^0$ for strange meson production $K, K^*$

Interest: Major program at JLab12 and EIC, theoretical/computational developments.

Extensive studies for IR1 [A. Jentsch et al]

**Heavy quarkonium production**


Detection: Protons $x_L \sim 0.5$ for large-$x$/near-threshold regime $p_T = [0, 2 \text{ GeV}]$

Interest: Growing community, theoretical developments.

Workshop ANL Jan 2021

EIC YR simulations

[S. Joosten et al → Thu]

**Baryon resonance production**

Physics: DVCS/meson production with $N \rightarrow N^*$ transition, e.g. $N \rightarrow \Delta$.

Transition GPDs, QCD structure of resonances

Detection: Forward $N + \pi$, $N^*$ reconstruction

Interest: EIC Spectroscopy Workshop ECT* 2018 [Webpage]
**Pion/kaon structure**

Physics: Structure of Goldstone bosons of chiral symmetry breaking in QCD → "origin of mass"

Detection: Proton $x_L \sim 0.7-0.99$

$p_T = [0, ~1 \text{ GeV}], \delta p_T \sim 100 \text{ MeV}$

Neutron for $p \rightarrow \pi^+ + n$

$\Lambda, \Sigma^0$ detection for $p \rightarrow K + \Lambda$; large $\Lambda$ decay length

Interest: Sizable community. Workshop CFNS Jun 2020 [Webpage]

YR simulations [T. Horn et al]

**u-channel processes**

Physics: TDAs, baryon Regge trajectories, baryon number transport

Detection: Forward $\pi^+, \pi^-$ and $\pi^0/\gamma$, includes negative charge

Interest: Dedicated group

Workshop JLab Sep 2020 [Webpage]

YR simulations [Wenliang Li et al]

**Nucleon or target fragmentation**

Physics: Multiparton correlations in QCD, hadronization dynamics, diffraction, nuclear final-state interactions

Detection: Forward protons/neutrons/pions: $x_F \sim x_L \sim 0.1-1$

Continuous $\eta$ coverage between forward and central

Interest: Workshop CFNS Sep 2020 [Webpage]

YR topic [C. Weiss et al]

Others apps: Elastic scattering
Spectator tagging with light ions

Physics: Neutron structure PDF/GPD/TMD, spin, flavor

Nuclear interactions: NN short-range correlations, non-nucleonic DoF

Nuclear modifications of partons: EMC effect incl. sea quarks, gluons, spin/flavor; antishadowing; shadowing \([\rightarrow \text{I. Cloet}]\)

Detection: Protons with \(x_L \sim (0.5 - 1.5)/A\), \(p_T = [0, \sim 500 \text{ MeV}]\), \(\delta p_T < 50 \text{ MeV}\)

Neutrons with \(p_T \sim< 500 \text{ MeV}\), “as good as possible”

Interest: Large active community, many events. EIC Workshop CFNS Jan 2020 [Webpage]

Simulations for IR1 and YR: [K. Tu et al, A. Jentsch et al \(\rightarrow\) Thu, Dien Nguyen et al]

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Coherent scattering on light ions

Physics: Imaging nucleus as quark/gluon system, matter vs charge distribution, shadowing and multiple scattering with \(N = 2, 3, \ldots\) nucleons

Detection: Nucleus with \(x_L \sim 0.8-0.999\), \(p_T = [0, \sim 700 \text{ MeV}]\), \(\delta p_T < 50 \text{ MeV}\)

Angular acceptance at \(\theta \rightarrow 0\) much more demanding than in exclusive processes on proton

Interest: Growing community, Meeting March 2020 [Webpage]

Simulation tool development in progress [R. Dupre, S. Scopetta, S. Fucini et al]
**Nuclear breakup in hard processes**

Physics: Interaction of jet/hadrons with nuclei medium, understanding of hard probes for heavy-ion collisions, centrality determination from breakup

Input for neutrino-nucleus interactions
Generation of unstable isotopes (?)

Detection: Protons/neutrons with \( x_L \sim 1/A \), \( p_T \sim< 100 \text{ MeV} \)
possibly fragments with \( A' < A \), \( Z' < Z \)

Interest: Diverse community, connections with neutrino and heavy-ion physics. Workshop CFNS Sep 2020 [Webpage]

Simulations: FLUKA, BeAGLE [M. Baker et al]

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**Coherent scattering on heavy ions**

Physics: Transverse gluon profile of nucleus, nuclear shadowing, soft-hard transition

Detection: Veto of protons/neutrons with \( x_L \sim 1/A \)
Photons from nuclear \( \gamma \) decays? Efficiency needed?

Interest: Growing community. Connections with ultraperipheral AA/pA collisions (LHC, RHIC)
Workshop U Kansas/JLab Jan 2020 [Webpage]

Simulations:
IR1 physics program. YR simulations [T. Ullrich et al, S. Klein et al]
Forward detection at IR2: Design, complementarity

Complex design problem
Variable Rigidity(forward)/Rigidity(beam)
Variable beam energies
Tradeoffs with luminosity optimization
Accelerator constraints: Beam return
Space constraints: Hall size, assembly
Engineering constraints: Magnets

[IR1 summary: H. Witte, IP6 meeting]

Potential complementarity to IR1

- Secondary focus at Roman Pot location:
  Substantially improved acceptance at low $p_T$ or $\theta$

- Transition between Roman Pots and B0 detectors:
  Improved $p_T$ - $x_L$ coverage

- Spectrometer optimization at lower CM energies

IR2 and forward detector schematic [V. Morozov et al. → Thu]

Forward cone: ±20-30 mrad before B0, ±5-7 mrad after FFQ
Spectrometer: Dipole magnets, dispersion
Charged detection: Roman Pots, off-momentum
detectors, elements inside B0 dipole
Neutral detection: Zero-degree Calorimeter
Forward detection at IR2: Secondary focus

\[ \sigma(z) = \sqrt{\varepsilon \beta(z)} \]

- Optics with secondary focus at Roman Pot location allows placement of detectors closer to beam
- Substantially improved coverage at pT ~ 0 for xL ~ 1
- Critical for coherent scattering on light ions
- Acceptance simulations on-going

DVCS IR1 18x275 GeV [A. Jentsch]
Forward processes: Summary

• Forward detection is an essential element of exploring hadrons and nuclei as emergent phenomena of QCD. New ideas/processes/methods beyond EIC White Paper and NAS Study are being pursued → Yellow Report, Workshops

• IR2 interaction region and far-forward detector design developing [→ V. Morozov, Thu]

• Clear directions for complementarity to IR1 are emerging, especially the secondary focus and optimization for lower CM energies

• IR2 collaboration(s) should pursue the far-forward detector design both as a necessity and as an opportunity

• The idea of a large-acceptance far-forward detector at EIC is conceptually new and goes beyond all previous collider experiments
Supplementary material
Physics variables

\(x_L\) — longitudinal momentum fraction with respect to proton/ion beam

\(p_T\) — transverse momentum with respect to proton/ion beam \(\Rightarrow\) angle \(\theta\)

\((1 - x_L) \sim x(\text{Bjorken}) \sim 2\xi\) in exclusive processes ("skewness"). Coverage/resolution requirements specified in \((1 - x_L)\).

Connection with detection angle

\[\theta = \frac{p_T}{p_L(\text{forward})}\]

For processes with \((1-x_L) \ll 1\): \(\theta \sim \frac{p_T}{p(\text{beam})}\)

Angle depends on beam momentum and therefore on mass of beam/forward particle

Example: Proton beam 100 GeV: \(p_T = 100\text{ MeV}\) \(\Rightarrow\) \(\theta = 1\text{ mrad}\)

Example: 4He beam with 50 GeV/u: \(p_T = 100\text{ MeV}\) \(\Rightarrow\) \(\theta = 0.5\text{ mrad}\)

*Same angular acceptance limit has different impact on processes with forward protons and ions!*
<table>
<thead>
<tr>
<th>Processes</th>
<th>Beam -&gt; Fwd</th>
<th>Rigidity Fwd/Beam</th>
<th>Coverage</th>
<th>Resolution (Charged)</th>
<th>Neutrals</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exclusive &amp; diffractive scattering on proton</td>
<td>p -&gt; p, n</td>
<td>1</td>
<td>pT = [0, ~2 GeV]</td>
<td>ΔpT ~ 50 MeV</td>
<td>n</td>
<td>Inelastic diffraction physics &amp; background</td>
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<td></td>
<td></td>
<td></td>
<td>xL = [~0.5, ~0.999]</td>
<td>ΔxL/xL &lt;&lt; 0.1</td>
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<tr>
<td></td>
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<td></td>
<td>1-xL = [~1E-3, ~0.3]</td>
<td>Δ(1-xL)/(1-xL) &lt; 0.1</td>
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<td></td>
</tr>
<tr>
<td>Coherent scattering on light nuclei</td>
<td>A -&gt; A</td>
<td>1</td>
<td>pT = [0, ~700 MeV]</td>
<td>ΔpT ~20 MeV</td>
<td>none</td>
<td>Ion beam divergence (pT spread) significant</td>
</tr>
<tr>
<td>(A = D, He)</td>
<td></td>
<td></td>
<td>1-xL = [~1E-3, ~1E-1]</td>
<td>Δ(1-xL)/(1-xL) &lt; 0.1</td>
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</tr>
<tr>
<td>Spectator tagging in deuteron</td>
<td>D -&gt; p (n)</td>
<td>1/2</td>
<td>pT = [0, ~500 MeV]</td>
<td>ΔpT ~ 10-20 MeV</td>
<td>(n)</td>
<td>Ion beam divergence (pT spread) significant</td>
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<td></td>
<td></td>
<td></td>
<td>xL = [~0.25, ~0.75]</td>
<td>ΔxL/xL &lt;&lt; 0.1</td>
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<td></td>
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<td></td>
<td>xL relative to 1/2 deuteron beam momentum</td>
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</tr>
<tr>
<td>Breakup of light and heavy nuclei</td>
<td>A -&gt; p, n, A-1</td>
<td>various</td>
<td>pT = [0, ~500 MeV]</td>
<td>?</td>
<td>multiple n</td>
<td>Veto detection for heavy nuclei</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>xL various</td>
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</tbody>
</table>

Schematic classification of processes with estimated coverage/resolution requirements
Used in IR2 planning
Approximate numbers, to be updated through simulations, evolving
Physics: Forward acceptance for protons at IR1

Exclusive scattering on proton
\[ e + p \rightarrow e' + M + p \] (M = meson, photon, X)

Physics objectives and kinematics
- GPDs/Quark-gluon imaging, \( p_T = [0, \sim 1.5 \text{ GeV}] \), \( 1-x_L \sim 10^{-3} - 10^{-1} \)
- Diffractive scattering \( p_T = [0, \sim 2 \text{ GeV}] \), \( 1-x_L < 10^{-2} \)

Forward acceptance requirements
- Detection down to \( p_T \sim 100 \text{ MeV} \)

Limitations from IR1 and baseline detector
- IR1 acceptance limit \( \theta > O(1 \text{ mrad}) \) from RP 10\( \sigma \) distance implies \( p_T > 100 \text{ MeV} \) for 100 GeV protons
- Combination of high-acceptance and high-divergence modes
- IR2 limits -> V. Morozov

DVCS on 100 GeV proton
A. Jentsch, Zero-Degree Physics Workshop, Stony Brook, Sep 2019
Coherent scattering on light ions

\[ e + A \rightarrow e' + M + A, \quad (A = d, 3He, 4He) \]

**Physics objectives and kinematics**

- Quark/gluon imaging of nucleus, \( p_T = [0, \sim 500 \text{ MeV}], \quad 1-x_L \sim 10^{-3} - 10^{-1} \)
- Double scattering, nuclear shadowing, \( p_T = [0, \sim 700 \text{ MeV}] \)
  (Strikman et al 2020)

**Forward acceptance requirements**

- Detection down to \( p_T = 0 \) essential on scale of \( \sim 50-100 \text{ MeV} \)
- Example: 4He form factor \( F^2 \sim \exp(-p_T^2/\Lambda^2) \), \( \Lambda \sim 200 \text{ MeV} \)

**Limitations from angular acceptance**

- Acceptance limit \( \theta > O(1 \text{ mrad}) \) [IR1 baseline detector + 10\( \sigma \) RP] would imply \( p_T > 200 \text{ MeV} \) for 4He at 50 GeV/u
- *Not sufficient for coherent scattering physics*
- Need angular acceptance down to \( \sim 0.25-0.5 \text{ mrad} \) [IR2 secondary focus]
Complementarity: Transition B0 - Roman Pots

Complementarity option: Transition between Roman Pots and off-momentum detectors in B0

Alter beam pipe size in IR2 B0 off-momentum detector to change the kinematic gap between B0 and RP coverage (currently theta ~ 5mrad). Should not affect apertures for smaller pipe in first dipole.

IP1 B0 coverage (5.5 < θ < 20.0 mrad)
IP1 RP coverage 0.0* (10σ cut) < θ < 5.0 mrad

(DVCS) 5 GeV x 41 GeV
10 GeV x 100 GeV (DVCS)

Need both detector systems together here!