Proposal

Physics Simulations to Establish and Refine Detector Requirements and Detector Design for the EIC

Thomas Ullrich, Brookhaven National Laboratory, Upton, NY

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Abstract

We propose to continue compiling a suite of needed *e*A event generators for physics simulations to establish and refine detector requirements and detector design. In the first phase we plan to finalize current efforts on an comprehensive event generator for diffractive physics in *ep* and *e*A and then assemble an *e*A event generator for electro and photo-production in deep inelastic scattering based in an existing generator but augmented to encapsulate all physics aspects relevant for an EIC (energy loss, nuclear breakup etc). In the second phase we plan to put these generators to work using detector simulation packages (currently under development) and conduct studies to improve detector requirements and test proposed detector designs. This proposal aims to provide tools that allows all ongoing R&D projects to rigorously test if proposed detector designs will be able to capture the rich physics program of an EIC.

Background and Motivation

The prospects for a future Electron-Ion Collider (EIC) are closely tied to the strength of the physics case for an *e*A physics program at such a facility [1-4]. Many of the key measurements that provide the motivation for this substantial investment are to come from the *e*A program. The capability of an EIC to collide electrons with heavy ions distinguishes the machine from any existing accelerators and makes it a unique facility. It is in these collisions where one expects new phenomena, such as saturation of the gluon densities, to be unambiguously discovered and studied. These studies will open a window into a regime where deviations from linear QCD, as probed at HERA and JLAB, become pronounced. The EIC's ability to collide high-energy electron beams with high-energy ion beams will provide access to regions in the nuclei where the structure is dominated by gluons. Despite the paramount role played by gluons, their properties in matter remain largely unexplored. It is *terra incognita*.

Electron-ion collisions are more complex than *ep* collisions due to the additional nuclear initial and final state effects, and especially due to the amplification of gluon saturation (non-linear QCD) effects. The latter is a unique feature that makes the study of *e*A collisions extremely compelling. On the other hand, perturbations such as initial state bremsstrahlung, *i.e.* radiation of photons off the scattered electron, that are sufficiently under control in *ep* become large and have the potential to distort the measurements substantially in *e*A. As just recently documented in a report based on a ten-week program on "Gluons and the quark sea at high-energies" at the Institute for Nuclear Theory in Seattle in fall 2010 [1] there is a broad and rich physics program with *e*A collisions ranging from simple inclusive measurements in Deep-Inelastic Scattering (DIS) events to the complex topology of exclusive measurements in diffractive events. The success of each of these challenging measurements depends crucially on the energy and luminosity of the machine as well as the performance of the detector(s).

*e*A event generators are mandatory to test the feasibility and quality of the proposed measurements and to guide the design of the detector (acceptance, tracking and particle identification capabilities) and the machine (energy, luminosity). These generators need to simulate DIS and diffractive events and include all relevant nuclear effects. No such event generator exists at this time.
On January 28 2011, a call for detector R&D proposals addressing relevant issues for an Electron-Ion Collider was put forth from Brookhaven National Laboratory. Early on during the first round of proposals it became clear that there are currently not enough detailed simulations available to establish a set of stringent requirements for an EIC detector. Such simulations must later on be used to establish that measurements of the key observables of the program are in fact possible with any proposed detector design. While simple simulations of electrons run through a detector simulation program such as GEANT or FLUKA might establish the quality of tracking or calorimetry of a given setup, it does not encapsulate the complexity and kinematic correlations of, for example, semi-inclusive and exclusive processes. The situation is very different from that

at the beginning of the RHIC program where detectors were designed to measure uncorrelated identified particle spectra with sufficient momentum resolution in a moderate rapidity range and momentum range. The key observables at an EIC are not simple multiplicity, rapidity, or momentum spectra but complex structure functions, form factor and correlations signals derived from measurements over a broad kinematic range. The lack of kinematic reach or PID in a small region of phase space can have a substantial negative impact on a specific measurement as a whole.

I give below two examples to emphasize this point:

1. The measurement of the differential cross-section $d\sigma/dt$ for vector meson production $eA \rightarrow e' + A' + VM$ (VM = ρ, ϕ, J/ψ, or γ) in diffractive events is the only known measurement to provide information on the *spatial* distribution of gluons in the nucleus (see Figure 1). Here $t = (\mathbf{p}_{out} - \mathbf{p}_{in})^2$ is the difference between the incoming (beam) and outgoing scattered hadron. The determination of t with high precision is essential since the Fourier transformation of the cross-section provides the spatial (radial) source distribution, i.e., the gluonic form factor. Diffractive events of this type are characterized by a large rapidity gap between the beam-axis and the produced hadrons, thus requiring hermetic coverage (requirement 1). The main background is incoherent diffractive events which also have a rapidity gap but are characterized by the nucleus breaking up. In the coherent case (nucleus intact) the nucleus has too high longitudinal momentum to leave the beam pipe, possibly not even measurable via Roman Pots. Hence t of the process cannot be measured directly. Obtaining t is a complex task. At very low Q^2 (photoproduction) t can be derived from the p_T of the outgoing vector meson putting stringent constraints on momentum resolution (requirement 2) and particle ID (e, π, K) (requirement 3). As Q^2 increases t can now only be determined if the p_T of the electron can also be measured. This is problematic since the electron is scattered into extreme forward angles (requirement 4). At higher Q^2 the vector meson decay products cannot be measured at mid rapidity any more but are emitted also at extreme forward angles demanding good resolution and PID also in the forward direction (requirement 5). Distinguishing between coherent and incoherent diffractive events is key to this measurement. The breakup products of the nucleus are the only way to detect incoherent events. This was never done at a collider and requires a mix of neutron detectors (requirement 6) in the projected beam direction (before the deflection by the first dipole magnet) as well as Roman Pot detectors along the beamline (requirement 7). This is an example of a very complex measurement where the extraction of the same quantity over a wide kinematic range demands the measurement of different observables in different regions of phase space.
2. One of the golden measurements in *ep* and *e*A is the measurement of the structure functions F_2 and F_L in inclusive reactions. Here only the electron needs to be measured with high accuracy and the rest of the event can typically be ignored. However, the radiation of real and virtual photons of the electron leads to distortion of the kinematic variables and thus obscures the true structure functions. If the photon momentum is large the transverse momentum of the scattered lepton can be shifted to small values, leading to a substantial enhancement of the radiative corrections. Precision measurements of the nucleon structure

functions require a good control of these radiative corrections. One way to avoid radiative distortions is to derive the true kinematic variables x, Q^2, and y from the hadronic final state (Jacquet-Blondel method) where the radiative corrections are large. Here, again, *e*A events are more complicated than *ep* events since the cold nuclear matter the partons traverse distorts the hadronic final states. At the moment it is unknown how it will affect our ability to measure F_2 and F_L and what requirement it imposes on detector and IR design.

These are just two examples to illustrate how the absence of electron-nucleus event generator impedes detector design and requirements studies.

Status of *e*A Event Generators

No dedicated *e*A generator exists that encapsulates all aspects of the EIC physics program. For DIS the current best candidate is DPMJet-III [5]. This Monte Carlo event generator can be used to study particle production in high-energy nuclear collisions including photoproduction and DIS off nuclei. DPMJet is an implementation of the two-component Dual Parton Model for the description of interactions involving nuclei. It is based on the Gribov-Glauber approach and treats both soft and hard scattering processes in a unified way. Soft processes are parametrized according to Regge-phenomenology whereas lowest order perturbative QCD is used to simulate the hard component. Multiple parton interactions in each individual hadron/nucleon/photon-nucleon interaction are described by the PHOJET event generator. The fragmentation of parton configurations is treated by the Lund model PYTHIA [8]. DPMJet-III is currently *not* maintained. It was used in parts for simulation for the LHeC proposal for which it was slightly modified by Nestor Armesto (Santiago de Compostella, Spain). Recent tests here at BNL detected various problems when compared to other (more reliable) generators and data in *ep* mode. Much work is required to update and improve this program to make it usable for us.
An alternative to DPMJet-III is CASCADE [6], which is full hadron level Monte Carlo generator for *ep* and *pp* scattering with focus on small *x*. It is based on the CCFM evolution equation and applicable in *ep* for photo-production and DIS, and for heavy quark production as well as inelastic J/ψ. The author (H. Jung) seems to be interested (given help from our side) to expand CASCADE to simulate eA collisions.

For diffractive *e*A events no generator existed until recently. With the help of a BNL funded LDRD grant (LDRD Project #10-042) a project was started in May 2010 to create such a generator. The development, programming, and testing was and is performed by a postdoctoral fellow (Tobias Toll) hired with funds from the grant and the PI (TU).
Work on a generator for exclusive diffractive vector meson production and DVCS is almost completed (SARTRE [7]) and is currently tested (see Figure 1). The generator is based on the impact parameter dependent bSat dipole model and reproduces HERA data in *ep* mode very well. Within the time frame of the current LDRD it is not possible to expand this Monte Carlo program to also generate inclusive diffractive events (arbitrary final states), which is needed to study diffractive structure function.

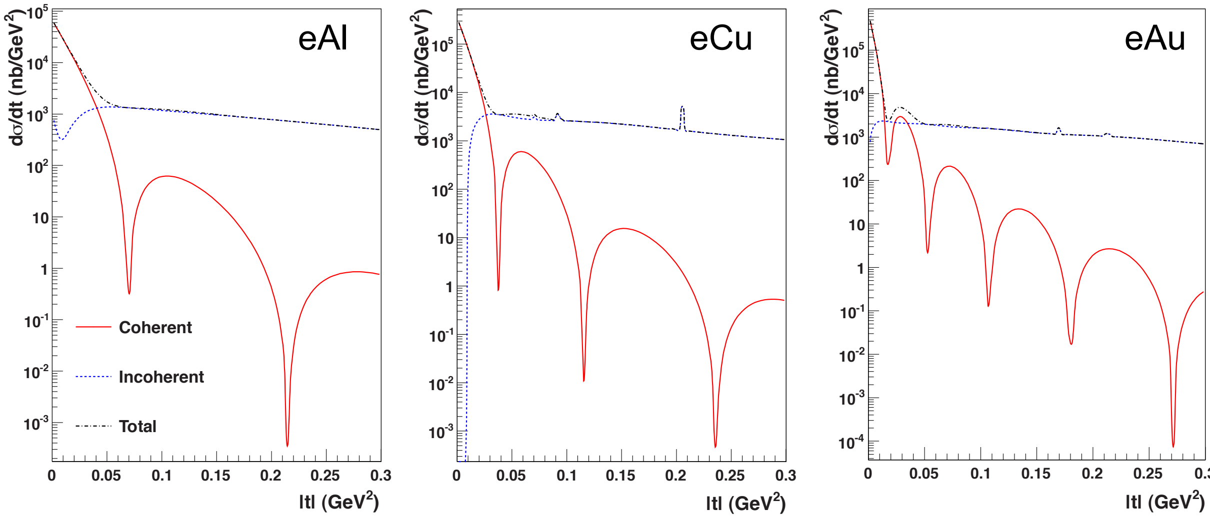

Figure 1: Differential cross-section dσ/d*t* for diffractive exclusive J/ψ production (e + A → e' + J/ψ + A') for three nuclei. The data were produced using the novel Monte Carlo event generator SARTRE [7] currently under development at BNL for the EIC.

Description of Project

We propose work on the realization of a set of *e*A event generators and to conduct physics simulations with focus on *e*A with them. The aim of these simulations is to improve and refine detector requirements and detector design. To conduct this work we propose to hire a postoctoral fellow for 2 years including some moderate funds for travel and visitors to help in the project.

The goals for a comprehensive *e*A generator package are:

- Handling of inclusive DIS as well as semi-inclusive and diffractive final states
- Reflection of the nuclear geometry of various ions from Deuterium up to Uranium
- Simulation of hadronic initial state (e.g. shadowing) and final state (E-loss, color-transparency, medium modified hadronization) nuclear effects
- Simulation of the breakup of the nucleus to allow for studies of the impact parameter sensitivity of various measurements and energy deposition in Zero Degree Calorimeters
- Allowance for the implementation of different models of high energy QCD (e.g., DGLAP) to study the sensitivity to new physics
- Implementation of the relevant QED effects like radiative corrections that may be very significant for large nuclei
- Provision of an event record compatible with current standards [9]
- Integration with EIC detector simulation packages

The complexity of *e*A collisions cannot be encapsulated in a single generator, instead a suite of generators within a common framework will be necessary, *i.e*, the overall generator package will consist of various software packages that provide a common input and output format. This will in part require the integration of code from existing ep generators into a single comprehensive framework/program and modifying it such that the nuclear environment and the related effects and phenomena in an *e*A collision are properly taken into account. They need to be based on recent state-of-the art calculations and will certainly make use of the experiences gained in heavy-ion collisions at RHIC.

We then propose to put these generators to work and study in detail the detector requirements for the key measurement. This would progress in parallel, and in collaboration with, ongoing R&D efforts to help better assess the design of a new detector for the EIC and the possible modifications of existing detectors like STAR and PHENIX at RHIC to enable their *e*A capabilities.

The goals here are:

- DIS
  - Study the feasibility of jet measurements (is hadronic calorimetry needed?)
  - Optimize detector design for dihadron measurements and establish requirements
  - Optimize detector design for measurement of the structure functions F_2 and F_L
  - Investigate the possibilities of measuring the charm structure functions
  - Study the impact of cold matter energy loss on the reconstruction of x,Q^2 using the hadronic final state
- Diffractive Collisions
  - Optimize detector design for measurement of the diffractive structure functions F_2^D and F_L^D
  - Optimize detector design to measure $d\sigma/dt$ for exclusive diffractive events
  - Study in detail how the nuclear breakup can be detected and which detectors are required

Necessary resources

The realization of an *e*A generator package requires a full time FTE with experience in event generators and *ep*/*e*A physics as well as a basic understanding of detectors and detector simulations. While no person exists that meets all requirements one can consider Tobias Toll the top candidate. He was originally hired using the LDRD grant discussed above and currently works with the PI on testing/debugging the diffractive event generator SARTRE for eA. Tobias did his Ph.D. in H1 at HERA where he worked extensively on Monte Carlo generators. He was supervised by Hannes Jung, *the* event generator expert at DESY. He studied in Lund, Sweden and knows many of the event generator experts known from Lund who authored PYTHIA [8] and many other HEP generators. Tobias's two year term ends in May 2012. Extending his term by two years appears the most efficient way achieving the goals laid out in this proposal. In addition the PI of this proposal will dedicate ~40% of his time on the effort as well.

Since a young candidate like Tobias does not yet have enough experience in all relevant topics, it will be necessary to support his or her efforts by inviting experts in specific areas to BNL to work in collaboration with him and the PI on the program. These can be short (few days) or long term visitors (2-3 weeks), depending on the complexity of the problem at hand. We estimate the need to cover the expenses for visitors on the order of four 1-2 week visits per year.

Budget

Budget Plan Dept Code: PO
Revision Id: CURRENT REVISION 1
Budget Plan Id: EIC ULLRICH R AND D

Description	*FY 2012*	*FY 2013*	*FY 2014*	*TOTAL*
NEW FUNDING	74,500	143,000	101,500	319,000
COST PLAN	74,493	143,000	101,500	318,993
051 - Base Salary - Research Assoc	27,292	64,836	38,697	130,825
SALARY	**27,292**	**64,836**	**38,697**	**130,825**
185 - Per diem 4 short term visitors	3,276	3,378	3,482	10,136
PUR-LABOR	**3,276**	**3,378**	**3,482**	**10,136**
212 - Car rentals	3,384	3,489	3,597	10,470
290 - Domestic Travel	8,000	12,407	12,779	33,186
300 - PO Purchases	3,000	3,093	3,189	9,282
MSTC-LV	**14,384**	**18,989**	**19,565**	**52,937**
161 - Housing - 4 short term visitors dorm h	3,360	3,463	3,570	10,393
251 - Electric - Distributed	524	1,245	743	
OTH-EXEMPT	**3,884**	**4,708**	**4,313**	**10,393**
700 - Organizational Burden	3,439	8,169	4,876	16,484
DEPT-CHRGS	**3,439**	**8,169**	**4,876**	**16,484**
705 - LDRD Burden	2,466	4,830	3,395	10,691
710 - G&A Burden	4,069	7,970	5,601	17,641
720 - Common Support	14,748	28,885	20,300	63,933
725 - IGPP Burden	-	-	-	-
745 - Procurement	935	1,234	1,272	3,441
LABWIDE-OH	**22,219**	**42,920**	**30,567**	**95,706**
051 - RA2 - 24505 - TOLL ,TOBIAS	0.35	0.80	0.46	1.61
TOTAL POST DOCS	**0.35**	**0.80**	**0.46**	**1.61**

Summary

The EIC will be the first electron-ion collider in the world. The benchmark for every proposed detector design is its capability to capture the rich and complex *e*A physics that becomes available at such a machine. We propose to assemble a suite of *e*A event generators that are mandatory for physics simulations and to establish and refine detector requirements and detector design. In the first phase we plan to finish current efforts on writing a comprehensive event generator for diffractive physics in *ep* and *e*A followed by assembling an *e*A event generator for electro and photo-production in deep inelastic scattering based in an existing generator but augmented to encapsulate all physics aspects (energy loss, nuclear breakup etc). In the second phase we plan to put these generators to work using detector simulation packages (currently under development) and conduct studies to improve detector requirements and test proposed detector designs.

References:

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