EIC-related generic detector R&D program, 2022: Exclusive and Semi-inclusive reactions in the muonic channel, and development of muon detectors in the far forward region

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Abstract

The selected detector 1 project for the future EIC doesn't include dedicated muon detectors. However, multiple physics channels, some of which have been deemed critical for the science (quarkonia, open and intrinsic charm...) involve muons. It was claimed over the previous years that the relevant physics can be done using electrons only, neglecting muon in leptonic decay channels. However, several drawbacks prevent numerous reactions to be reconstructed with electrons only. Indeed, scattered beam electrons and decay electrons can't be separated, both from a "physics" and an "analysis" point of view. It is impossible to properly calculate the kinematics of reconstructed events, nor to interpret data in large kinematic regions (additional anti-symmetrization terms, larger background due to misidentification...), if we are restricted into electrons for all leptonic channels.

It is now crucial at this point of the EIC development for the community to put more emphasis on muons, and ensure they can be properly detected in the far forward region. It is essential to ensure that the machine will deliver the physics that was promised. Opening the EIC to study a broad amount of reactions in the muon channel, with proper muon identification and accurate resolutions, is likely to be in the near future an un-avoidable step forward, which was neglected in the earlier design development.

Our project is generic, and can be an extension to the detector 1 or an add-on to the design proposed for another interaction region. We propose to perform physics impact studies with and without muon decay channels, to perform full GEANT4 studies for muons reconstruction with and without dedicated detectors, for the detector 1 and for the potentially upcoming detector 2. Lastly, the proponents will suggest several designs for dedicated muon detectors that can realistically be added into EIC spectrometers, and they will provide physics impact studies with and without muon detectors.

List of Authors and Institutes

Note: more people expressed interest in this proposal, but haven't be given enough time to confirm their authorship or prefer to be included at the stage of hardware development. The authors and collaboration list will be updated in a short term.

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1 Foreword and note to the committee

Due to the short timeline that was given between the initial call for proposal and the deadline of July 25th, this document can be considered by the committee more as an expression of interest or a letter of intent, for an upcoming full proposal at the next call for EIC-generic project. The short timeline didn't allow us to perform extensive simulations, impact studies, and to come now with the final idea for a full muon detector design. We are describing in this document our path forward.

Several reasons however convinced us to submit this proposal this year. First, we would like to emphasize the importance of muons and muon detection for all the physics involving leptonic channels, before a final EIC design is settled down with no possibility for further addition of muon detectors. It is extremely important for exclusive physics and for charmed meson inclusive and exclusive channels to ensure that these whole branches of the EIC physics case are actually feasible, before the machine is being built, and perhaps not able to provide the promised physics.

We will respond to the next call for projects with a full proposal, including a more detailed budget and detector requirements, once we perform further studies. The studies we are proposing to perform this year require a limited, but non zero amount of funding, which we would like to request to the committee. The proponents are also very grateful for any feedback coming from the committee at this stage of our work.

Our project is generic, and can be an extension to detector 1 with muon detectors in the far forward region, or an inclusion of dedicated muon detectors in a potential detector 2.

2 Physics goals

2.1 Exclusive physics with muons

Accessing the so-called Generalized Parton Distributions at the EIC has been deemed a major part of the EIC physics case, in particular for the gluon GPDs. The EIC accessible phase space enable measurements of quarkonia, such as J/Ψ and Υ, for all the proposed beam energies of protons and ions, with an electron beam. In this document, for the hard exclusive production of vector mesons, we are focusing on GPDs of the proton, and partonic interpretations into GPDs only. However, a lot more physics can be accessed via exclusive measurements of quarkonia in the EIC and has been studied by other groups.

J/Ψ and Υ mesons are of particular interest, being vector mesons (as incoming photon) and allowing for accessing gluon GPDs at the leading order. Measuring them will complete an already rich physics program which is possible with lighter vector mesons such as ρ, ω, and Compton-like processes (DVCS, TCS...) for the Compton Form Factors (CFF) extraction and GPD models parametrization. The fact that heavy quarkonia are composed by heavy quarks ensures that we are probing gluon GPDs, without the need of going through Q^2 evolution as for lighter mesons and Compton-like processes.

J/Ψ and Υ have multiple decay channels, the ones favored in past studies in other experiments have been leptonic decays (into electrons or muons pair) and hadronic modes (into pions). The cleanest, and easiest to interpret (limited systematic uncertainties...) is to measure quarkonia decaying into lepton pairs. For the EIC (white paper, yellow report, proto-collaborations...), the emphazis has been put on measuring J/Ψ and Υ into electron pairs. However, from a physics point of view, it is not the most appropriate channel. First, since EIC is using an electron beam, one has to ensure that the kinematic is properly reconstructed without confusion between the beam electron and the decay electron. Second, reconstructing quarkonia into electron pairs means including extra anti-symmetrization terms in amplitudes for the extraction of CFFs, while most of CFF extraction methods are already relying on under-constraints fits. Thus, any way to avoid these extra complications is necessary for GPD interpretations of exclusive quarkonia measurements. Furthermore, using the electrons pair decay mode in these conditions means cutting out large portions of the phase space, in particular at larger rapidity, as it would be impossible to distinguish the 2 electrons from an experimental point of view.

2.2 Example of phase space for J/Ψ into leptonic decay modes: electrons versus muons

The golden decay mode to study these quarkonia appears to be into muon pairs. As an example of limits of studying J/Ψ only in the electron pair decay mode, compared to muons, we are displaying in Fig. 1 the theoretically accessible rapidity and transverse momentum phase space for the decay electron (right panel) after selecting the backward scattering beam electrons only (left panel), which are the only ones we can identify without ambiguity. The figure shows that working with muons greatly enhance the accessible phase space, while being quite restricted in terms of rapidity and larger transverse momenta with electron pairs (red dotted areas on both panels). The colored area (weighted data for exclusive $J/\Psi \to \mu\mu$) corresponds to the theoretically accessible phase space with muons (up to acceptance and magnetic field effects). This exercise was done for 5 GeV electrons off 41 GeV protons.

Fig. 2 is displaying the accessible phase space in decay electrons versus decay positrons rapidity, and the resulting proton rapidity and transverse momentum phase space if only the most symmetric pairs are selected, in a kinematic range where we can "technically" distinguish the decay and beam electrons. This exercise is an example showing the simplest way to stay away from the Bethe-Heitler (BH) peaks: this is another part of the problem one has to be careful at for studying exclusive leptonic decays modes (for quarkonia, Compton-like processes...). We haven't performed yet a full "positioning" of the BH peaks, which will be needed for interpretations of the data and kinematic cuts, but this simple exercise already shows that carefully performing an analysis which selects the electrons from the beam and the from the decaying pair without ambiguity, and adds the requirement of staying away from BH peaks, is drastically limiting the accessible phase space for measuring J/Ψ into its leptonic electron

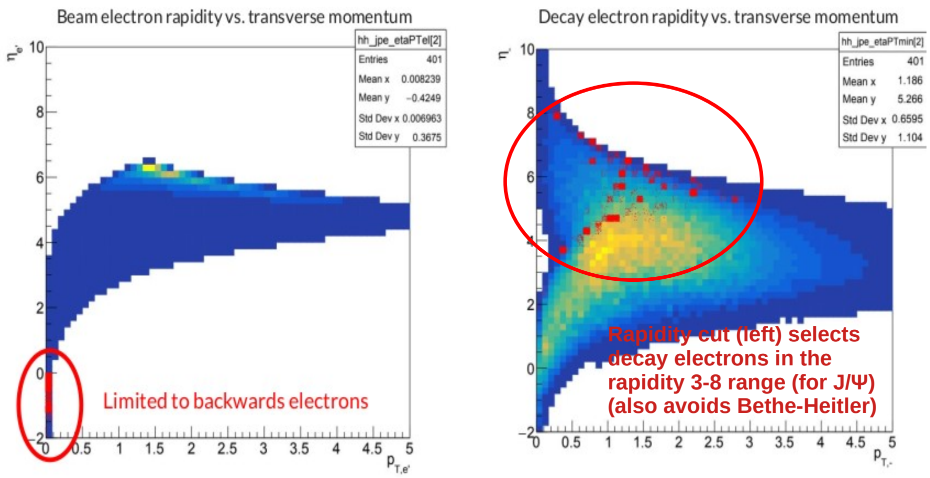

Figure 1: Impact of selecting only backward beam electrons (left panel) on the theoretically accessible rapidity range for the decay electron (right panel). Credit: Tyler Schroeder, VT student

pair decay mode, compared to the other main leptonic mode into a pair of muons. The phase space accessible for decay electrons with these two considerations, is restricted into the largest, and near acceptance limits of rapidity. Note that the impact of magnetic fields is neglected in this conclusion and full Monte-Carlo studies with an updated detector 1 full setup still have to be performed.

2.3 Semi-inclusive physics with muons

Most of the semi-inclusive DIS physics proposed for EIC involves hadronic channels. As for the exclusive reactions, selecting muons rather than electrons for the leptonic decays modes prevent a lot of concerns from an experimental and theoretical point of view. Collaborators of this proposal expressed a strong interest in developing further a physics case for semi-inclusive physis, TMD (Transverse Momentum Distributions), and open charmed / intrinsic charm channels.

The proponents don't have projections for this channels at the time of the submission of this proposal, and very few studies have been done so far. It will therefore be included in our full proposal submission at the next call for EIC-generic detector project.

2.4 Why can't we just use electrons?

Using electrons from the decaying particle, covering the same kinematic phase space as scattered beam electrons is very dangerous. First, from an experimental point of view, "choosing" one electron over the other while the physics actually doesn't distinguish similar leptons in the same state, is not something one can do for interpretations of the data. It also can't be done for getting the kinematics of events, as it has been demonstrated in past experiments, where artifacts ("artificial peaks") are so easy to create in an analysis where the mass of the searched meson is used as an input in the analysis.

From an interpretation point of view, one will need to anti-symmetrize the amplitudes, which lead to even more difficult extraction of physics quantities, in a context where data have limited statistics, and extractions are model-dependent, involving multi-parameters fits. Furthermore, to ensure that such studies can be performed and controlled, and that physics quantity can be properly extracted, restricting ourselves to the electron channel, one will have to cross-check the results at all kinematics using the muon channel, which therefore has to be measured in any case.

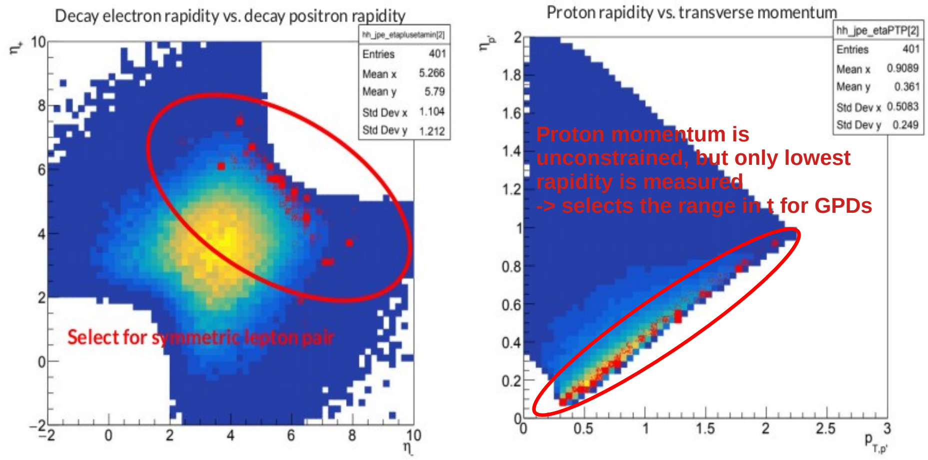

Figure 2: Impact of selecting the most symmetric decay electrons and positrons, i.e. far away from Bethe-Heitler peaks (left panel), on the theoretically accessible phase space in proton rapidity and transverse momentum range (right panel). Credit: Tyler Schroeder, VT student

3 Improvement for EIC

3.1 State of the Art

There is no proper muon identification proposed nor dedicated muon detectors for the EIC. It has to be formally demonstrated that using the end-cap of hadronic calorimeters is enough to ensure proper muon identification, with accurate resolutions and tracking. Studies have been done and proposed as response to the referees when collaborations submitted their proposals in early 2022. However, with the changing design of detector 1 (ECCE collaboration didn't show these studies and provided electron studies only), it still has to be demonstrated that muons can be reconstructed with proper resolution and tracking accuracy, and good PID, for the exclusive and semi-inclusive physics.

3.2 Technology used

No muon detectors have been included in proposed EIC designs.

3.3 Enabling physics programs

Many of the reactions that have been proposed to be measured using electrons will not be available due to the misidentification of the scattered electron and the decay one, both from an experimental and theoretical point of view. All these part of the EIC program will be enabled with the addition of dedicated muon detectors in the far forward region.

Exclusive physics is highly sensitive to the resolution in reconstructed kinematics, it is therefore important to ensure proper tracking for muons. It has to be demonstrated that the addition of muon detectors can improve the measured resolution, in particular in t (transferred momentum squared). Parts of the phase space where all leptons have the same kinematics will be accessible in the muon channel, while it is not with electrons.

Reactions such as Double-Compton like processes (low and high virtuality for incoming and outgoing photons), involving a dilepton continuum can't be accessed without muon detectors. The caveat is it has yet to be demonstrated that these reactions can be measured, from a statistical point of view, due to their low cross sections at high energy. Interpretation of TCS measurements with a quasi-real photons also requires comparison of results from decays into electron and muon pairs, as we have to demonstrate that a quasi-real photon beam (with low virtuality) has the same properties than real photon beam, and that the low, but non-zero virtuality of the photon can be neglected.

4 Tasks, plans and needs

4.1 Most critical needs for the project

Manpower is our most critical need to develop this project. Since our first step is to perform GEANT4 simulations, prior to coming with one or more detector design to test, the first "hardware" cost will be disk to store our Monte Carlo data. Then (expected after about one year), we will also need funding for detector R&D.

Since we are developing new concept and want to perform impact studies with and without an added muon detector, another things that is critical for this project is the complementarity in the skills of the proponents. Regular meetings between theorists and experimentalists, experimentalists developing software and hardware techniques, are necessary. Occasional in-person work may also be required at some point of the project (not in the first 6 months). For this reason, and also to organize an annual meeting to bring the collaboration together, we also need some limited travel funds.

4.2 Distribution of the tasks

Some authors of this project, and people who asked to be included at a later stage, but are supportive and willing to contribute in the future, have interest for complementary tasks. Some groups are very skilled in the technical aspects and already have experience designing muon detectors; other group have extensive software and analysis experience. Several theorists expressed strong interest in this physics and are interested to be included in these studies at a later stage, when their contribution in advising on physics will be relevant.

4.3 Collaborations and future formation of a consortium

Many groups expressed interest in detecting muons with EIC, for various physics goals. In this first "expression of interest" we are submitting, we focused on exclusive physics. We mentioned other reactions, in particular semi-inclusive reactions and heavy flavor physics, meeting the same detector requirements. Since full simulations have not been performed yet (and are one of the goal of this project), we decided to emphasize only one of the physics aspects.

Our goal in the very near future is to bring more collaborators and more physics topics, and share resources, manpower, and technology. In the even of getting positive feedback on this proposal, we anticipate more people and institutes to be willing to join this project.

5 Manpower

5.1 Graduate Students

Two graduate students currently enrolled at the Virginia Tech graduate school, Gyang Chung and Mahmoud Gomina, are identified to be involved in the project. We are requesting a fellowship to transfer the two of them to a research assistantship status rather than a teaching assistantship. It will enable them to spend about 50% of their time each to do research. Each student can dedicated up to 30% of their full time on the project (the rest being formation of the students). The local supervisor (Marie Boër) engages spending at least 10% of a full time equivalent to assist the students in their tasks and doing work such as interfacing event generators with GEANT4 simulations, and hardware testing or analysis methods which will have to be performed after GEANT4 studies. The total full time equivalent research engagement from Virginia Tech is anticipated to be a 70% full time equivalent, split among the group members.

5.2 Postdoctoral Fellows

Due to the risky nature of this project for a postdoc's career, we are not requesting a fellowship for a postdoc at the moment. Postdocs from different institutions may be occasionally involved for some of the studies, and may in the future contribute more significantly.

5.3 Undergraduate students

Talented undergraduate students will occasionally be involved in the project. We are not counting them in our manpower.

6 Work locations

6.1 Hardware labs

The first steps of the project don't require lab space. Once the project, after about half a year, moves towards technical R&D developments, the proponents will benefit from the lab area present at their main work location. National labs have access to more resources. Virginia Tech has a spacious lab with limited availability of local technicians.

6.2 Other work locations

Students will be performing most of their work at their local university, with occasional trips to the partnering national labs. Postdocs, faculty members and staff scientists will perform most of their work (this year) at their local institution with potential longer trips to a different location (depending our needs) in a partner institution.

6.3 Remote work

Our meetings are anticipated to take place remotely, to minimize travelling and costs. Most of the work will be done in small groups communicating remotely, with an annual in-person meeting.

7 Our commitments

7.1 Diversity, Equity, Inclusion

Two students who are identified at Virginia Tech to work on the project are from Nigeria. The African continent as a whole is sadly (almost) missing from the map of institutions involved in the future EIC, such as it is for most of major physics experiments. We would like to contribute overturning this situation, and benefit from bringing talents from all over the world, by involving these students in priority. It has short and long term goals: in the short term, these students, coming with already a thorough scientific experience will help the rest of the collaboration by bringing a different culture and a different approach to solve scientific problems. In the long term, we can't more emphasize the importance of training a new generation which can bridge the Western world to an increasing number of countries, and particularly in the one cruelly missing from the map, such as African countries. By training students from the entire world, and ensuring they are treated fairly by their pairs in the supporting institutions, we are contributing to building a more diverse field in high energy physics. Furthermore, if the proponents of this proposal are sensitive to all of the aspects mentioned above, this is thanks to being an already very diverse and culturally non-homogeneous group of individuals, from various countries, continents, national origins, genders, etc. If we are writing such a detailed paragraph in response to the question on diversity in this call for proposal, it is not only because we are asked to do so, but also thanks to the personal trajectory of the proponents, being very conscious of the importance of ensuring a diverse and inclusive environment in our field and of ensuring that everybody can benefit from a welcoming environment. The institution involved in the project are equal opportunity employers and have strict rules, with code of conducts in application. The proponents engage to go further by refusing to close their eyes should they observe any form of discrimination in the context of this work.

7.2 Cost effectiveness: Our budget

Groups involved have other projects for various experiment involving muons, and/or experience with the potential detector technology. There is no need to buy much material for this first year of development. Our budget request is very small, since it mostly involve manpower and computing material.

7.3 Environment impact

Even thought computing and remote meetings have an impact on the environment, it is quite unavoidable these days. We propose to meet in person once a year to facilitate contact and informal discussions to advance the project. However, for any travel that may be required, the proponents will optimize their travel and tasks, and they will stay at the visited institution for extended periods of time, rather than multiplying short trips, to avoid the unnecessary transportation costs and environmental impacts.

8 Achievement goals

8.1 One year achievement goals (this proposal)

1. We anticipate 2 months of work to refine our physics case together with theorists and experimentalists to identify the most critical physics channels requiring muon detection, and the scientific limit (limited impact) of what can be achieved in an EIC with and without proper muon detections, with an without muonic channels.
2. We estimate 6 months of work with GEANT4 simulations and analysis for the impact studies and come with one or more potential detectors design
3. We estimate 3 months of R&D for one or two of the proposed muon detector designs, if the GEANT4 and physics impact studies conclude on the importance of developing a muon detector in addition to the proposed detector 1 design and/or in addition to a potential detector 2.
4. We estimate 3 months of developing analysis technique for improved muon PID if the GEANT4 and physics impact studies conclude that we can't include a muon detector in any of the proposed full EIC spectrometer designs and/or if the our conclusion is that muons can be detected and identified with an accurate resolution for the channels of interest, without dedicated muon detectors.

Part of the work can be done in parallel. The development of the third or forth tasks requires the completion of the second one.

8.2 Two years achievement goals (anticipated continuation of this project)

If a muon detector is to be developed and build, we will need to work a second year on this project and perform extensive R&D for a best muon detector design. Several groups expressed interest in our project, however due to the short timeline of this call for proposal, we didn't had time to engage in further collaborations with other groups. We anticipate having more manpower, and more needs in terms of hardware in a potential second year for this project.

If it is shown that muon detectors are not needed, we will keep working on the software development for muon identification and exploring new physics channels involving leptonic decays into muons. In that event, the anticipated cost of the project will shrink to purely manpower, and partial support for CPU time on a computing farm.

Achievement goals for a second year will be either providing and make public a software method for improved muon identification, or coming with a prototype of a muon detector, which can start to be tested in an about 2 years term from now.

9 Funding request

Our funding request can split in the following subcategories:

1. Manpower
2. Computing Material
3. Travel
4. Organization of an annual meeting

9.1 Manpower

We would like to request partial support for 2 graduate students of Virginia Tech to be moved from their status of teaching assistant to research assistant. We need $30k annual funding for each of the students, who will in exchange dedicate half of their time to this project. Our request includes the partial funding for only one of the students, and we are looking for other sources to pay the other student on a RA. If we are given the opportunity to finance the two students, Virginia Tech engages that they will be spending their research time this year on this project. The two students are not engaged in other research projects at the moment.

Marie Boër would like to include one month of summer salary (out of 3) to dedicate more time into this project during next year summer break ($10k).

9.2 Computing material

The work involve running extensive simulations. We would like to buy good laptops for the students of the project ($2k per laptop). We also need to buy disks for storage and shared time on the Virginia Tech computing farm. Our estimate for data storage, CPU time cost and computing farm equipment is $15k for detailed studies of 3 to 4 physics channels. Our priority is to study the exclusive electron- and photo-production of $J\Psi$ and Υ into leptonic modes (electron and muons), with and without muon detectors, with a realistic GEANT4 for the full detector 1 setup, and then for a potential detector 2 (second stage of our studies).

9.3 Travel

Proponents will need to travel to various workplace locations to meet their colleagues in-person for some of the tasks. We would like to request $6k for domestic travel for all the proponents. In addition, we would like to request $5k to allow the students presenting their work in a conference.

9.4 Annual meeting

If an annual meeting is to be hosted at one of the proponent's institution, the cost will be partial travel support for those who can't come in person otherwise. We would like to request $5k for travel support for an annual meeting.

9.5 Funding request summary

With a cut on budget of 20 to 45%, we will prioritize cutting on travel support and on the annual meeting (-$16k), then on cutting on computing (which means we will have to run on other machines such as JLab farm, but it will be much slower) (-$7k if we keep data storage, -$10k if we cut half of it). Then, we can cut on faculty summer salary (-$10k). Please note that manpower is the critical aspect of our project, as well as computing resources, and any financial cut may impact the speed of achieving our goals. We can however start working on this project with a cut on our proposed budget of no more than 45%.

Category	details	cost
Manpower	student's RA support	$30k
	summer salary (M. Boer, 1 month)	$10k
Computing	storage disk	$10k
	CPU and shared farm access	$5k
	2 laptop with enough RAM to run GEANT4	$4k
Travel support	technical work in-person	$6k
	Conference support for 2 students	$5k
Annual meeting	travel support	$5k
TOTAL		$75k

Table 1: Detailed funding request

Please note that at this stage of the project, the funding request is to be allocated to Virginia Tech, as the university will provide the manpower and take care of the funds. In the future, we would like to share funding and costs between collaborating institutions.

10 Summary

Our project has been triggered by the fact that none of the 2021 EIC "proto-collaborations" implemented muon detector in their preliminary design, and this despite the community is fully aware that major parts of the EIC physics case can't be achieve without muons. Arguments of the proponents range from doing physics with electrons only (which proved in the past to be not possible with such example as analysis artifact being seen as new particles) and reconstructing muons without dedicated detectors. While it is very easy to dismantle the first argument, we would like to study the performance of the proposed detector 1, and the potentially upcoming detector 2, should a muon detector be added or not in the design in the far forward region.

Our studies will start with simulations using the proposed setup (without muon detector) for the reconstruction of muonic channels, then impact studies will be performed without and with an "ideal" muon detector. If it proves to be useful to include a muon detector in one of the EIC spectrometer design, we will move forward to propose, as a collaboration, an appropriate design for a dedicated muon detector in the far forward region.