Electro- and photo-production of muon pairs with μCLAS12: Double Deeply Virtual Compton Scattering, Timelike Compton Scattering, and J/ψ production

CLAS12 Proposal Review

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Executive Summary

We have reviewed the proposal according to the criteria outlined in the PAC guidelines. The proposal aims to measure double deeply virtual Compton scattering (DDVCS), with the additional opportunity to study timelike Compton scattering (TCS) and threshold J/ψ production, using a modified CLAS detector with enhanced capabilities for muon pair identification and optimized for operation at luminosities of $\geq 10^{37}$ cm^{-2} s^{-1}.

The theoretical motivation and experimental approach are well described, and the proposal presents a comprehensive and coherent overview of the planned measurements. The structure is clear and easy to follow. We find the discussion of the theoretical background and proposed experimental setup to be strong, and the physics case is compelling. The proposed measurements are scientifically well justified.

However, we find that the proposal requires further refinement to fully meet the PAC requirements. While many important elements are addressed, three critical areas warrant stronger emphasis and clarification:

1. **Lack of detailed resource definition** – including institutional responsibilities and associated costs, which the proposal itself acknowledges as needing further development.

The new version has the cost estimate and statements from the collaborating institutions.

2. **Lack of clarity regarding full simulations and end-to-end reconstruction** – it is not clear to what extent full simulations and the complete reconstruction chain have been implemented in the proposed setup. The description leaves open questions about whether all relevant detector effects and reconstruction inefficiencies have been realistically modeled.

Few sentences are added on page 40-41 to clarify this point. But in general, the CLAS12 FD is fully simulated and reconstructed (muons). For wECal we smeared energy by 4%/sqrt(E), assuming the same resolution as for FTCal. For others as well, we assume the same vertex resolution for FVT and the same momentum and PID performance for the recoil detector as in CLAS12 CD.

3. **Limited impact studies and insufficient justification for the requested**

200-day run time

These points are discussed in more detail in the sections below. Additional line-by-line feedback is provided in the “Specific Comments from Reviewers” section.

Equipment and Resources

A dedicated section should be added to summarize institutional responsibilities in a clear and concise manner, ideally in the form of a table. This section should include approximate timelines, estimated costs, and the laboratory facilities that will be used for each component of the proposed upgrade.

The PAC requests a more detailed breakdown of the cost and resources required for each subsystem, as well as a clear definition of the responsibilities assigned to each participating institution. For example, in the discussion of the $PbWO_4$ calorimeter (line 587), it is noted that JLab and Hall B have significant experience with this technology. However, the proposal does not specify the exact resources JLab is expected to contribute, this should be clarified.

The proposal provides a good overview of the experimental setup, including both new and existing equipment, along with a summary of expected performance and some limitations. We recommend explicitly stating the rationale behind the choice of each technology, and clearly outlining the resolution (energy resolution, position resolution, dp/p, etc.) or other performance requirements that each subsystem must meet in order to achieve the stated physics goals. The aspect of expected radiation doses and impact on detectors should be discussed.

Background and Uncertainty Studies/Projections

While the proposal includes background and rate estimates, we recommend providing more details on the realism of the simulations and reconstructions, as well as on the methodology used for uncertainty projections. Several specific areas merit further attention:

- **Realism of Simulations and Reconstructions:** It is not clear whether the presented results are based on a full simulation and end-to-end reconstruction chain.
    - The pion survival rate, muon momentum correction and the missing mass plot has been presented in the proposal. However, it is not clearly stated which effects have been included in the simulations, if the full chain of reconstruction has been incorporated, and how realistic simulation and reconstruction chain is expected to be. Beyond the comparison in Section III.C (page 38), what studies have been performed to benchmark the full reconstruction chain and efficiencies within the proposed setup? Was full tracking and vertexing, as expected in the final experimental configuration with realistic background levels, incorporated? What systematic effects

have been evaluated? We recommend explicitly listing the effects included in the simulations and describing how the realism of the reconstruction has been assessed.

- ○ While momentum corrections are addressed in the proposal, angular corrections are not discussed. Please elaborate on what studies of tracking and vertexing resolution and efficiency have been conducted to support the assumption that: *"It is expected that the reconstructed angles, aided by the FVT, will be sufficiently accurate that no further corrections would enhance the resolution of kinematic variables."* This claim requires more robust justification, supported by quantitative studies.

- **Momentum Corrections and Missing Mass Spectra**

  The momentum corrections for muons are large, on the order of 30–40%, and vary significantly with momentum.

  - ○ The proposed correction method appears to be highly non-linear and possibly non-bijective, which may introduce ambiguities when analyzing correlated observables. Moreover, its reliance on Monte Carlo simulations raises concerns about whether all relevant effects from the absorber are properly captured. These issues should be addressed in greater detail.

  - ○ We recommend clarifying whether the missing mass distribution for the $e\,p \to e'\,\mu^-\mu^+\,X$ channel shown in Figure 38 is calculated for a specific momentum range. The narrowness of the black histogram may suggest some potentially unrealistic assumptions. Additionally, the angular dependence of the muon momentum corrections should be studied and documented. How this distribution changfes when realistic experimental backgrounds are included.

  - ○ What is the expected missing mass distribution for the TSC studies ($e\,p \to p\,\mu^-\mu^+\,X$)? We suggest including this in the proposal, along with more detailed results from the RT tracking studies to illustrate the expected performance in an extremely challenging high-background environment. More information on what proton PID efficiency and purity will be achieved in the proposed setup is recommended.

- **Run Time Justification**

  - ○ The proposal would benefit from a more explicit and quantitative discussion of the expected impact of the DDVCS and TCS measurements. At present, it is not clear how these measurements will quantitatively advance our understanding of the underlying physics. As part of the impact studies, it would be important to evaluate, for example, the statistical significance with which different models can be distinguished using the projected DDVCS A_{LU} measurements.

  - ○ We strongly recommend including a more comprehensive discussion of

how systematic uncertainties affect the projected physics outcomes. For example, in the case of azimuthal fits, it is not clear to what extent smearing and bin migration effects, especially those introduced by the absorber, have been incorporated. These effects, and their implications for both statistical and systematic uncertainties, should be clearly discussed.

Discussions on systematics have been added

- Taking all these points into account, we strongly recommend expanding the justification for the proposed 200-day run time, ensuring that it is supported by a detailed evaluation of statistical needs, systematic limitations, detector performance, and physics impact.

Summary Table

A concise summary table of key parameters and requirements is missing and should be added.

Previous Proposal References

PAC requests an explicit description of the previous proposal whenever it's mentioned. In line 33 of the abstract, consider adding one or two sentences to clarify this, and refer to any approved experiments in the body to the proposal. *"The PAC and the Laboratory have specifically asked proponents of new proposals to clearly state how their experimental goals are addressed by other approved experiments at the Laboratory."*

Executive Summary

An executive summary is missing and should be included at the beginning.

Specific Comments from Reviewers:

- Line 33: Should it read "LOI**1**2-16-004"?

DONE

- TOC: Consider adding a paragraph about TCS.

DONE

- TOC, Line 101: Why not mention pentaquarks in the abstract?

Abstract is now called Executive summary and reworked to include this comment

- Line 117: Add "PDFs measured in DIS."

DONe

- Line 128: BH is not a fundamental limitation (in the context of the paragraph), but it is indistinguishable from DVCS even for ideal detector. I think that a dedicated paragraph on its significance in the introduction might be useful.

There is a misunderstanding, the “fundamental limitation” is not about BH, but on DVCS and TCS **observables**. The observables, asymmetries and cross sections are sensitive to two out of three variables GPDs depend on. No change is needed.

- Line 159: Why is the proton called the “recoil”? It participates directly in the scattering.

The only scattered particle in this reaction is the electron. The proton is recoiling, and lepton pairs are produced. There is nothing wrong to call the proton recoil particle.

- Line 186: Change “…is responsible for most of the mass…” to “…visible mass…”.

DONE

- Line 198: “3D structure” is more accurately described as a combination of 2 + 1 dimensions.

DONE

- Line 203: Add a reference to the factorization theorem.

DONE

- Line 216: Light-cone variables are not defined; please define them.

DONE

- Line 236: DVCS and CFF were already defined earlier; remove the redundant definitions.

DONE

- Fig 2: The image is slightly blurred, replace or improve resolution.

Remade

- Line 254: Change “nucleon FFs” to “nucleon GPDs.”

This comment is not applicable

- Fig 3: Does the definition of the φ angle apply to the pure reaction as well as the interference term?

φ is the angle between the lepton and hadron scattering planes. It is the same for all amplitudes in the reaction total, and hence their interferences.

- Fig 4: Instead of “only reachable with a 10 GeV beam,” say “only achievable after

the 12 GeV upgrade."

DONE

- Fig 5: The TCS θ angle is not defined; please define it (analogous to φ).

DONE

- Fig 6 Caption: Change "…to the real art" to "…to the real part."

DONE

- Line 330: When referring to a specific x value in Figure 7, mark it on the figure.

Nothing to do here, it says x=\xi points, \xi values are given on the figures and it is easy to see x-axis for x values.

- Fig 10: The left y-axis label is blurred.

DONE: Figure is replaced

- Fig 20: Some text colors merge with the drawing (especially the drift-chamber labels).

DONE: Figure is replaced

- Fig 21: Was this implemented in a noise-free environment? How does performance degrade with random background?

This is from RG-A data, do not understand the question.

- Fig 26: The 15% effect is hard to see on the heat map plot.

The point of this figure is to show that our beam induced background is well reproduced in MC. If there is no difference, it is good. The 15% can be seen in the z-axis, for data it goes above 6, for MC itis around 5.5.

- Line 712: Explicitly mark the regions on the plot to improve clarity.

We are going to replace Fig.29 and will take care of it

- Fig 32: Clarify what the different line colors on the left pad represent; rates up to 10 GHz are seen, it is not clear how it affects the rate.

The figure is redone

- Line 829: Energy loss is very large; additional plots showing its effect on angular resolution are important.

DONE: The effect on angles and on angular resolution are shown in Fig.39, the difference between red and green histograms.

- Fig 38: Remove the extra period at the end of the caption.

DONE

- Line 527: Left plot shows M_inv of two MIPs. How are those MIPs selected in this plot? Also with the fECal? Please add a sentence on what is the left plot PID method based on, since you refer later how much the BDT is improving this PID. Is it data/simulation?

DONE. This is data.

- Line 537: How was the 10^2 required suppression factor determined?

DONE: added a footnote about need of 100 times suppression.

- Fig. 22 Explain RT earlier in the text or here

DONE

- Line 559: Explain in a few sentences what energy resolution is required for this measurement and why this technology choice for the calorimeter is optimal. What sensors are you planning to use?

DONE

- Line 572: tungstate?

DONE

- Line 607: For both trackers, what momentum resolution is required to achieve physics goals?

The resolution of the forward tracking is essentially fixed by the DC.
The resolution of the barrel tracking is set to match the one of the CVT. We have added resolution plots for the main kinematic variables to justify these choices

- Fig. 26: Could we present the Data and MC plots at the same z-axis scale so that one can compare the z-color scale directly from those two plots.

It is easier to see the difference (15%) with different scales. With the same z-axis scale one should look for a difference in colors.

- Line 698 From Fig. 27 it's hard to deduce it because of how the muon distribution is normalized.

DONE, hope the change in the caption makes it clear.

- Line 700 How accurately is GEMC describing the showering (non-mip) pions? This is important to correctly access mu/pi and e/pi separations in Calo and W shield.

GEMC reproduces fECal very well, see many CLAS12 analysis that rely on it.

- Line 811 Also pions that shower in the calorimeter leave more energy than MIP, did you also try to impose the MIP energy cut to eliminate pions?

Yes

- Line 819 pion contamination in the muon sample

DONE

- Fig 34. How are those plots normalized? There is no z axis, and it's hard to track changes from one plot to another. Is the left plot for sure only for pions that passed the shield and ended up in the fECAL? I see a huge spike at f_sam = 0.

DONE. Caption is modified.

- Fig 35: Is the enchantment around the last cos theta bin (~0.99-1), close to theta = 0 deg, real or is it an artifact of the overflow bin drawing? If real, where is it coming from? We do not see this in Fig. 36.

DONE, figure corrected

- Line 827-828: Do you mean that the "pion pair contamination in the muon sample is 5 x 10-5"?

DONE: Sentence is changed, it meant to say that pion pairs are suppressed by 5x10-5 times.

- Line 828: Is this number taking into consideration the relative ratio of muon to pion fluxes that you expect in your signal muons and background pions? I.e., is the 5 x 10^5 the actual contamination that you expect in your experiment? It is important to clearly state, because the ratio of mu to pi won't be 1:1.

See above.

- Line 835: How well would one be able to possibly reconstruct the momentum of the particle using the Vertex Tracker planes only?
    - This will be relevant for all electrons and pions that showered and stopped in the w-ecal to measure their momentum for e.g., e/pi separation. I.e., in any of the backgrounds listed in line 863, if there is a pion going in the forward direction and it loses energy in the calo and shielding, it can be mistaken by the electron (that is needed for the Q^2 determination) if the

momentum information is not available to use E/p for e/pi PID. Please estimate the impact of this misidentification in your background studies.

Being done, will be added to the final proposal

- Fig. 48 The expected points with error projections are fixed at the theoretical expectations from one of the models. How would those points look like distributed with stat fluctuations around this curve? Please estimate how well you can separate those two models based on your projected uncertainties.

- Line 1186: TCS Projections are missing.

Projections have been added

We thank the authors for their efforts in preparing this proposal and for their contributions to advancing the CLAS physics program. We hope that the comments and suggestions provided in this review will be helpful in further strengthening the proposal and refining the experimental strategy.