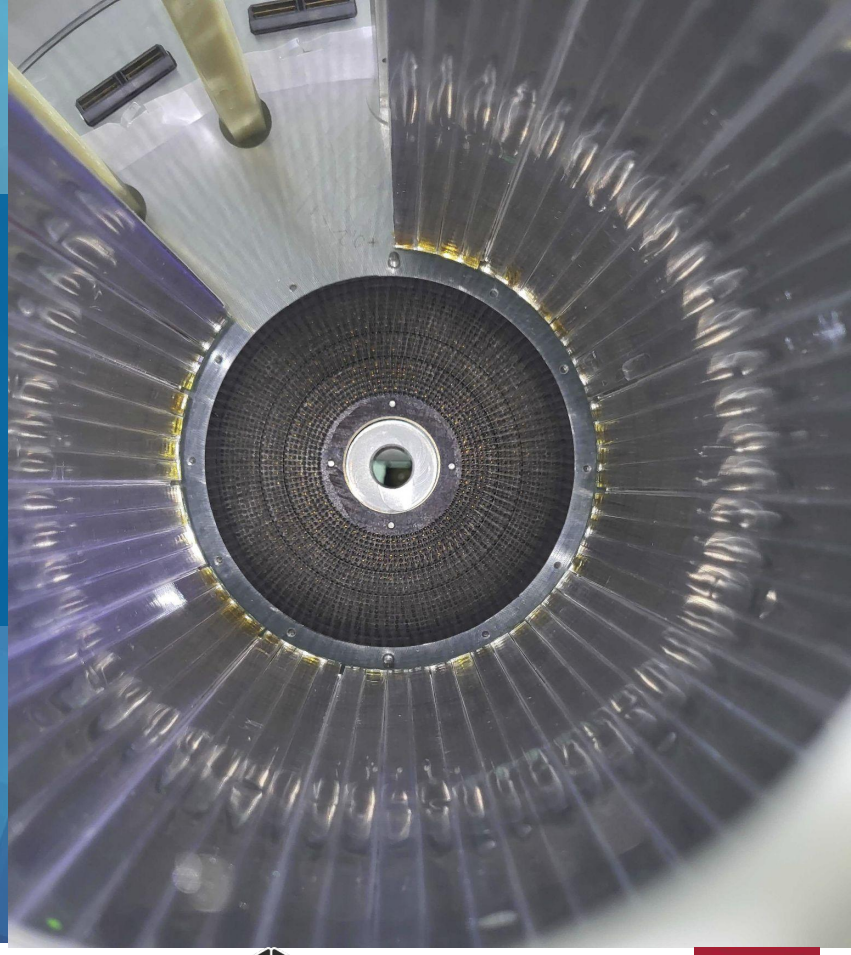
C12-25-004

A Measurement of the Coherent J/ψ Electroproduction Cross Section off ^{4}He



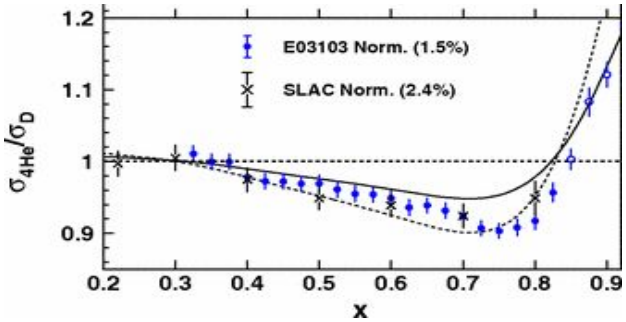
Whitney Armstrong, Sangbaek Lee

CLAS Collaboration Meeting, Online
November 18, 2025

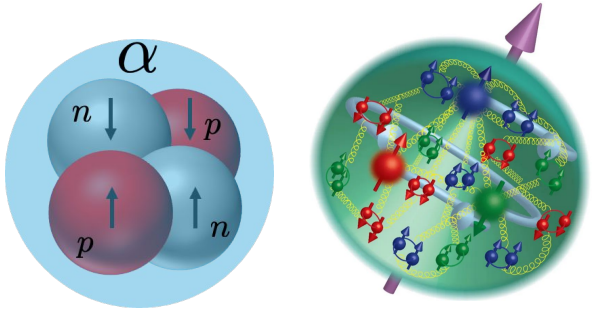
The Alpha Particle and Nuclear Physics

- Since the discovery of the nucleus, the alpha particle plays a special role in nuclear physics
  - Mass: 3.73 GeV/c^2 Spin: 0
  - A tightly bound system: 7.07 MeV per nucleon
  - First closed shell in the nuclear shell model
- ^{4}He is the first possible isoscalar EMC ratio
  - already embodies most of the strength of the EMC effect
  - ^{4}He is ideally suited for studying the quarks and gluons inside the nuclei.
- With elastic scattering, we achieve the model-independent charge (quark) distribution
- But what is the role of QCD in the structure of ^{4}He?

Does the gluon distribution inside the ^{4}He nucleus follow the charge?

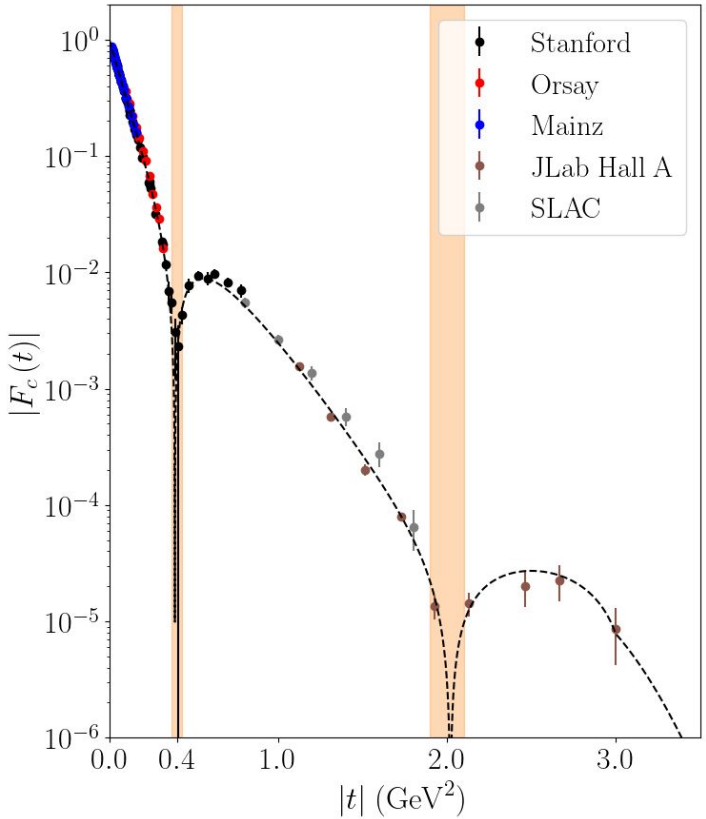


↑ J. Seely, et al., PRL103 (2009), 202301



Charge Distributions inside the ^{4}He Nucleus

- ^{4}He nucleus has one electromagnetic form factor: the charge form factor $F_c(t)$
  - t: Momentum transfer to the nucleus
- Charge form factor $F_c(t)$ is fourier transform of the spatial charge distribution.
- The diffraction minima (yellow regions) show that the charge distribution is flatter at small r compared to the nucleon's exponential-like distribution.
  - The first diffraction minimum is $|t|$=0.4 GeV^2.
  - This corresponds to a length scale of ~0.3 fm.



Can we access similar information for the nuclear gluon distribution?

Exclusive J/ψ Production: A Gluonic Probe

- Exclusive vector meson production probes the gluons inside hadrons via gluon exchange
- Heavy charm quark mass → gluon exchange dominates the interaction

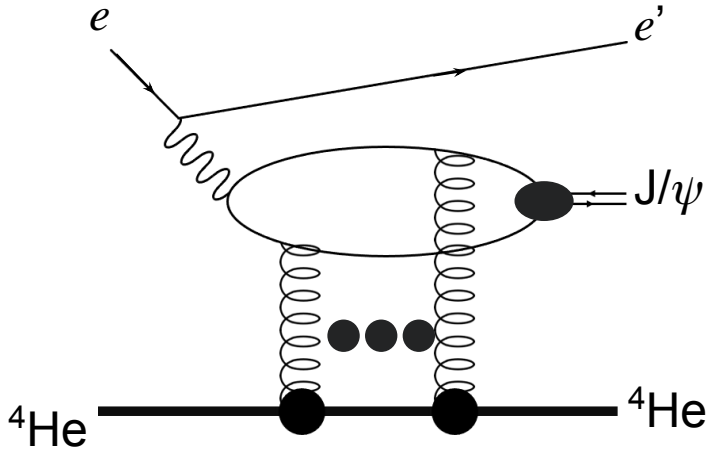
Exclusive J/ψ production provides the best probe of gluon distributions at JLab with a 11 GeV beam.

J/ψ ($c\bar{c}$)

Spin: 1 (Vector meson)

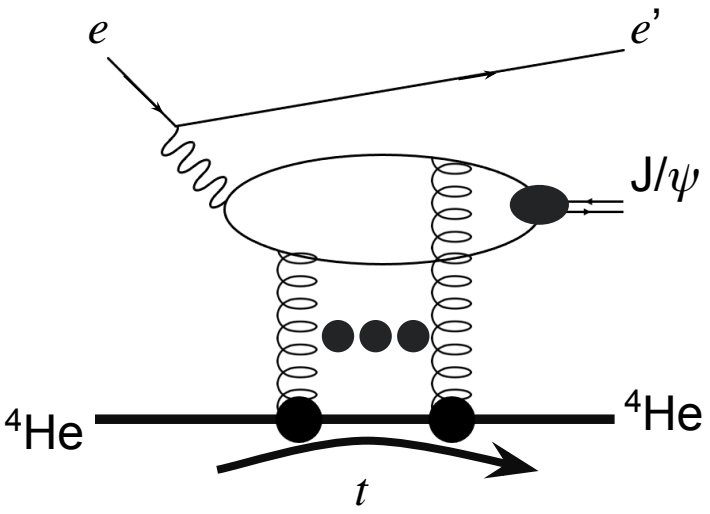
Mass: 3.1 GeV

Decay width: 92.6 keV



Coherent J/ψ Production off ^{4}He

- Exclusive coherent J/ψ production probes gluonic form factor $\frac{d\sigma}{dt} \propto |G_{^4\mathrm{He}}(t)|^2$
- Measure the t-dependence at similar kinematics as first diffraction minimum in $F_c(t)$
- ^{4}He detection simplifies analysis by eliminating incoherent background channels → ^{4}He stays intact

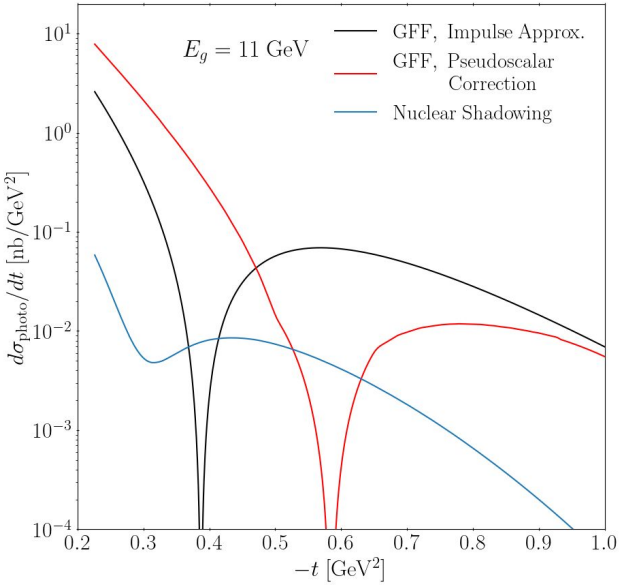


We propose to determine the diffraction minimum of coherent J/ψ production. This is a model-independent measurement to study gluons in comparison to charge inside ^{4}He for the first time.

Cross Section of Coherent J/ψ Production on ^{4}He

- To date, there is no measurement of coherent J/ψ production on ^{4}He to constrain the projection.
- However, a few model predictions for the cross section exist. We will focus on these cases for this talk.
  - Gravitational Form Factor-based prediction
    - $|G(t)|$ is a linear combination of the GFF, parametrizing the matrix elements of the Energy-Momentum Tensor (EMT).
    - This framework was successful for the nucleon and is valid for spin-0 hadrons: **He and Zahed, PRC 112 (2025), 014303**
  - Nuclear Shadowing-based prediction
    - **V. Guzey et al., PRL 129 (2022), 242503**
- Determining the existence (and location) of a diffraction minimum will lead to new insights into the role of QCD in Nuclei

A first glimpse of EIC physics before the EIC!



GFF, IA follows the charge form factor

GFF, PS Correction shifts the minimum location

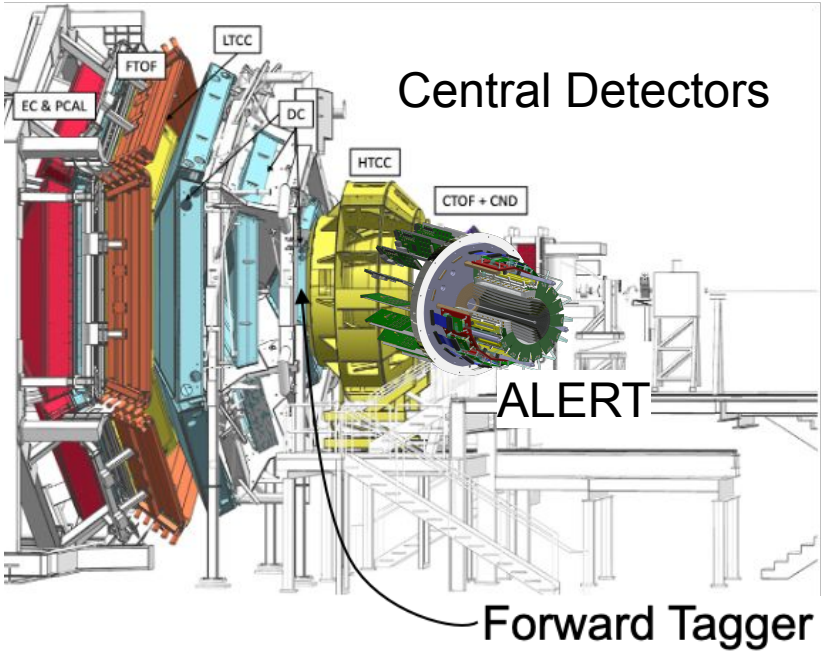
Nuclear shadowing: shifts in (non-zero) minimum location

Overview of the Proposed Measurement Requirements

- Detection of the ^{4}He
  - Requires a Recoil detector
- Detection of the e' at low Q^2
  - Requires a forward electron detector
- Detection of the J/ψ decay products
  - Requires a Large Acceptance detector
- Coincidence trigger with recoil
  - High duty factor beam for low accidentals

***CEBAF Large Acceptance Spectrometer at 12 GeV* (CLAS12) with *A Low Energy Recoil Tracker* (ALERT) and the *Continuous Electron Beam Accelerator Facility* (CEBAF) electron beam is the right place to measure exclusive coherent J/ψ production on ^{4}He.**

Forward Detectors

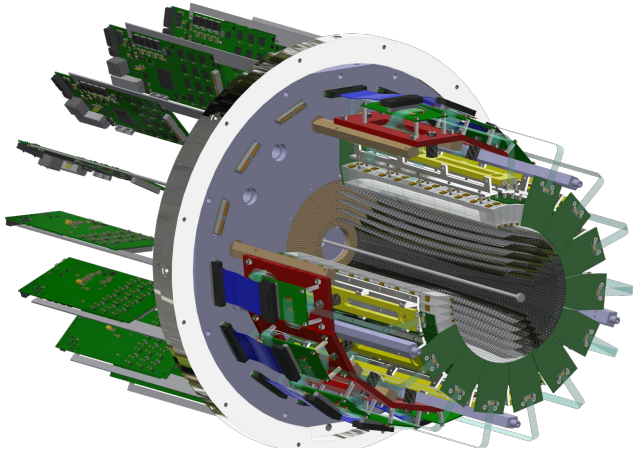


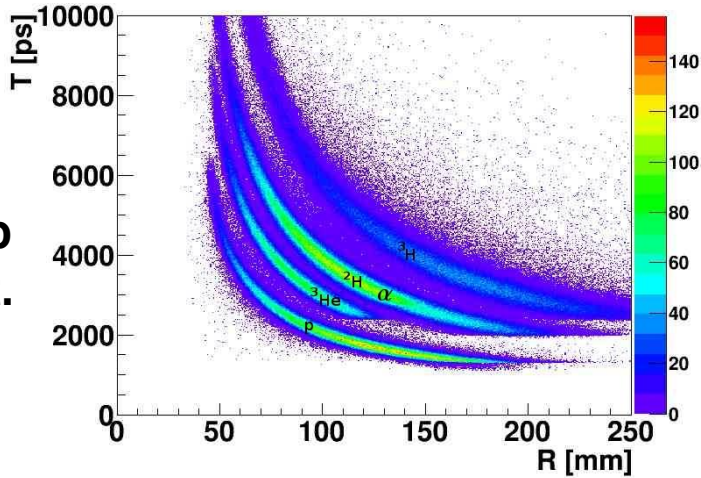
↑ V. Burkert et al. (CLAS Collaboration), Nucl. Instr. Meth. A 959 (2020), 163419

Equipment for the Proposed Measurement

- ALERT consists of the Drift Chamber (tracker) and the Time-of-Flight detector (particle identification) to detect the recoil from a high pressure gas target.
  1. Large detector acceptance
  2. PID to reject the incoherent background
  3. Reconstruction of recoil momentum to determine $|t|$

- ALERT Run Group (RG-L) successfully ran with 65 psi target pressure, 18% reduced from the nominal pressure.

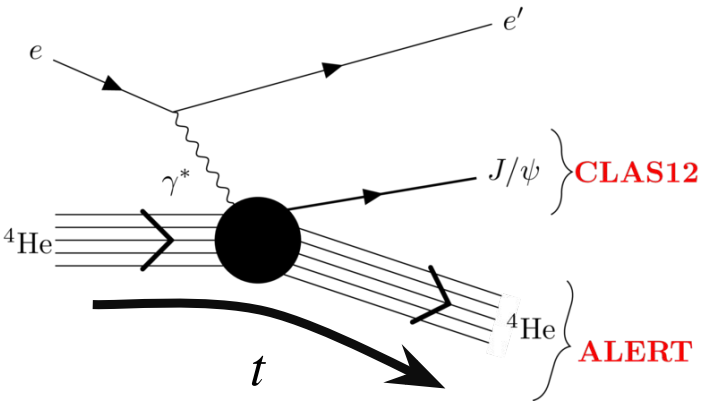




Except for the proposed coincidence trigger, the same configuration used for the ALERT Run Group (RG-L) will be used for the proposed measurement.

Technical Challenges for the Proposed Measurement

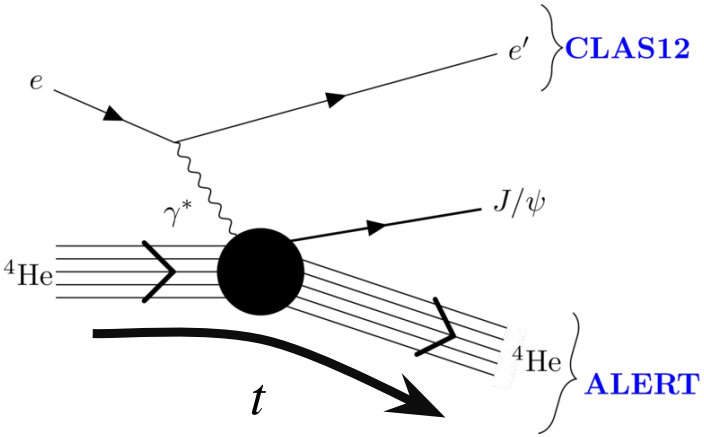
- Owing to the narrow J/ψ decay width, the leptonic decay products have been a popular choice to select the J/ψ events at Jefferson Lab.
- However, the 6% branching ratio for di-electrons (and di-muons) **limits the statistics**.
- Without also detecting e', E_γ resolution suffers. With full final state detection the statistics further suffers.



It is important to pursue alternative techniques for measuring the exclusive coherent J/ψ production on ^{4}He. How can we identify J/ψ events with ^{4}He recoil and the good E_γ resolution?

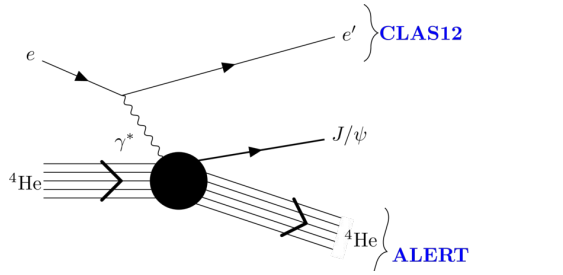
Coincidence Trigger for the Proposed Measurement

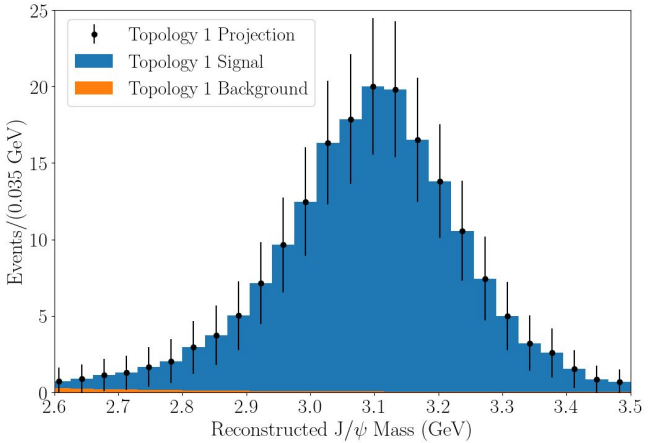
- **We solve this challenge by introducing a new detection mode, a coincidence of *e*' and ^{4}He.**
- Detecting *e*' provides excellent photon energy determination
- Detecting the recoil determines t
- The invariant mass resolution of the J/ψ suffers but this is not a problem because of the very low background in this topology.
  - Far above threshold using the ^{4}He target
  - The narrow J/ψ peak, far from elastic radiative tail minimizes accidentals



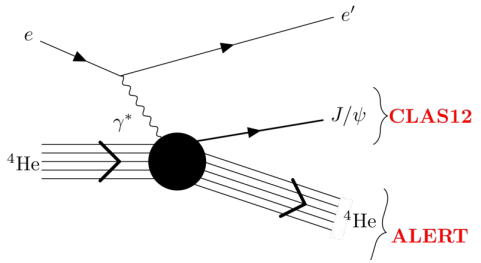
Event Selection with the J/ψ Peak

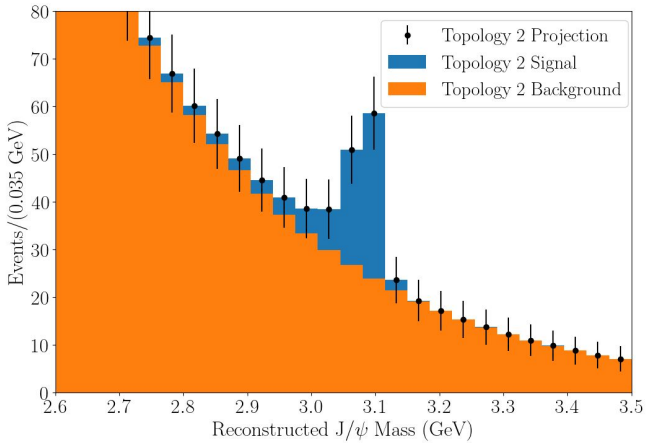
- Trigger 1 (Topology 1)





- Trigger 2 (Topology 2)

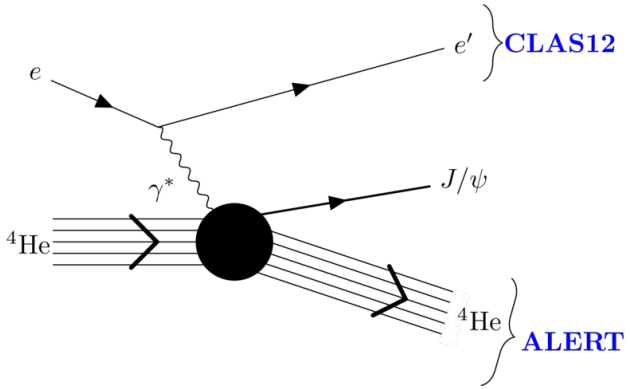




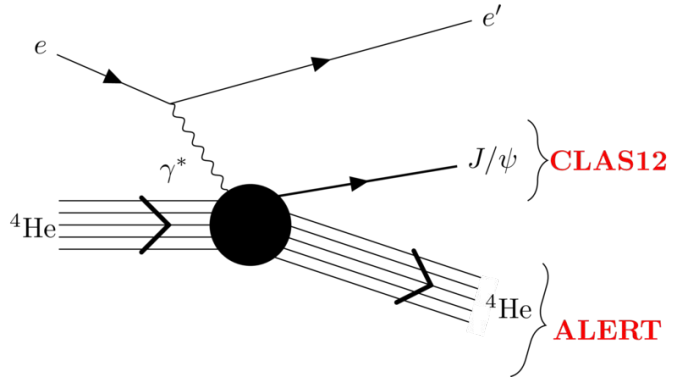
Two methods with different systematics should produce the same cross-section. This is a powerful way to build confidence in the result and improve understanding.

Singles and Coincidence Rates

- Trigger 1 (Topology 1)
  - Singles
    - e': ~200 kHz @ the proposed luminosity
    - ^{4}He candidate: ~1 kHz
  - Coincidence
    - Coincidence timing window < 1 μs
    - Trigger rate: ~200 Hz.



- Trigger 2 (Topology 2)
  - Singles
    - J/$\psi\rightarrow\mu^+\mu^-$ trigger already ran at the RG-L!
    - Rate ~ 10 kHz
  - Coincidence will further reduce the rate.



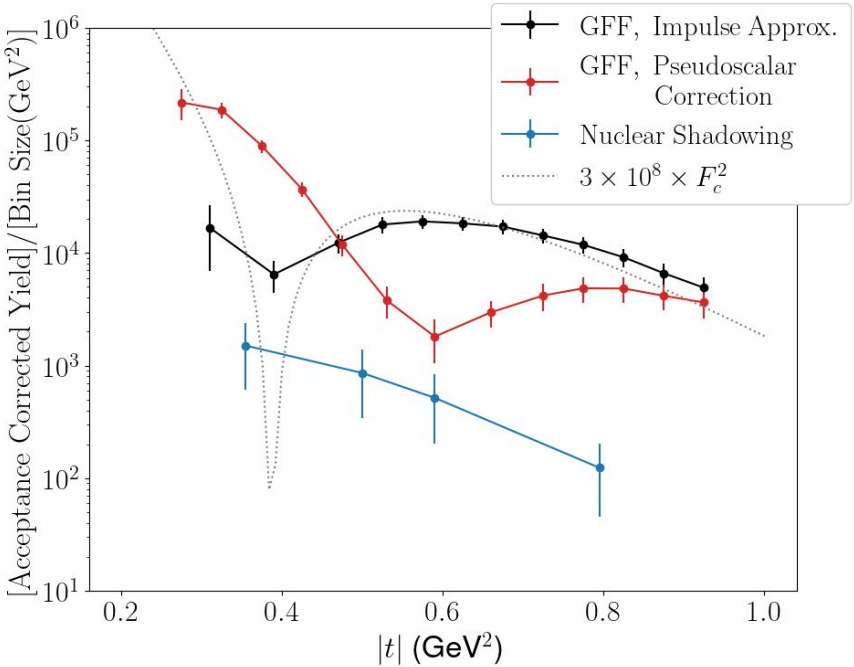
Both triggers are compatible with the CLAS12 DAQ rate limit of 20 kHz.

Projected Results and Requested Beamtime

- **We will determine if a diffraction minimum exists in the gluonic form factor between $|t|$=0.3 GeV^2 and 0.9 GeV^2**
- If it exists, **we will precisely determine its $|t|$ location**
- Direct comparison of **gluonic FF** and **charge FF** begins to shed light on the fundamental question:

How are gluons distributed in ^{4}He relative to the quark charges?

97 days of production



GFF, IA follows the charge form factor

GFF, PS Correction shifts the diffraction minimum

Nuclear shadowing shifts in (non-zero) minimum location

Theory Report

- *This proposal … is **a very interesting and important idea** for exploring the internal matter distribution of bound nuclei.*
- ***the first diffractive minimum** in the cross section's t-dependence can allow us to explore and learn how gluon distributed inside a light and tightly bound nucleus*
- ***the absence of any diffraction minimum** for a $|t|$ as close to 1 GeV^2, the range that can be covered by JLab energies, would provide **new challenges and opportunities to think differently** on how gluon could be distributed inside a bound light nucleus.*

Strong support by JLab Theory Group!

PR12-25-004: *A Measurement of the Coherent J/psi Electronprouction Cross Section off 4He*

J. Qiu and T. Rogers

This proposal aims to measure the location of the first diffraction minimum in the cross section for coherent J/ψ electroproduction off a ^{4}He target and compare the corresponding gluonic form factor to the charge form factor to gain insight into the distribution of matter relative to the quark charge, which is a very interesting and important idea for exploring the internal matter distribution of bound nuclei. The diffractive minima off ^{4}He from its elastic electromagnetic current interaction as a function of its momentum transfer square $t = (p_{^4\mathrm{He}} - p'_{^4\mathrm{He}})^2$ are sensitive to the spatial electric charge distribution of ^{4}He. The first minimum was found near $|t| = 0.4\mathrm{GrV}^2$.

The proposed key measurement is the exclusive differential cross section for coherent J/ψ electroproduction off ^{4}He in Hall B using CLAS12 and ALERT detectors, using 100 days of total beam time, consisting of 97 days of production data and 3 days for calibration of the detectors and commission of a new coincidence trigger. However, at JLab energy, the proposed exclusive differential cross section for coherent J/ψ electroproduction (or the approximated coherent J/ψ photoproduction) off a hadron or a light nucleus, is near and not too far away from the threshold. Theory for describing and calculating such a cross section in this kinematic regime is not well-established due to potential final-state interactions between the produced $c\bar{c}$ pair before it forms a physical J/ψ and the quark/gluon content that emerge into the measured hadron (the ^{4}He in this case). Consequently, theoretical predictions for the location of the first diffractive minimum is allover the places as indicated in Fig. 2.

The simulation based on existing theoretical model calculations, with 100 fb^{-1} integrated luminosity, seems to indicate that it is feasible for the proposed experiment to search for the location of the first diffraction minimum in $t-$dependence of the exclusive differential cross section of coherent J/ψ electroproduction off ^{4}He. A precise measurement of the cross section for coherent J/ψ electroproduction off a ^{4}He target and the discovery of the location of the first diffractive minimum in the cross section's t-dependence can allow us to explore and learn how gluon distributed inside a light and tightly bound nucleus as well as J/ψ production mechanism. On the other hand, the absence of any diffraction minimum for a $|t|$ as close to 1 GeV^2, the range that can be covered by JLab energies, would provide new challenges and opportunities to think differently on how gluon could be distributed inside a bound light nucleus.

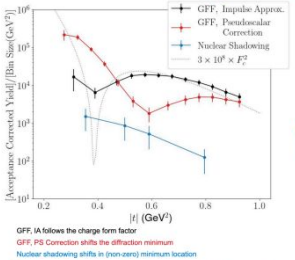
PAC53 Report

- PAC conditionally approved (C2) the proposal.
  - PAC recognized that the physics case is important and the result would deliver useful information on the gluon structure of ^{4}He, whether the diffractive minimum is found or not found.
  - However, recommended to analyze the RG-L data to get some first insights based on real data rather than on model predictions.
  - We will submit the updated proposal with answers to the PAC questions based on the RG-L data without coincidence triggers.

PR12-25-004 A Measurement of the Coherent J/psi Electroproduction Cross Section off 4He

Hall-B 100

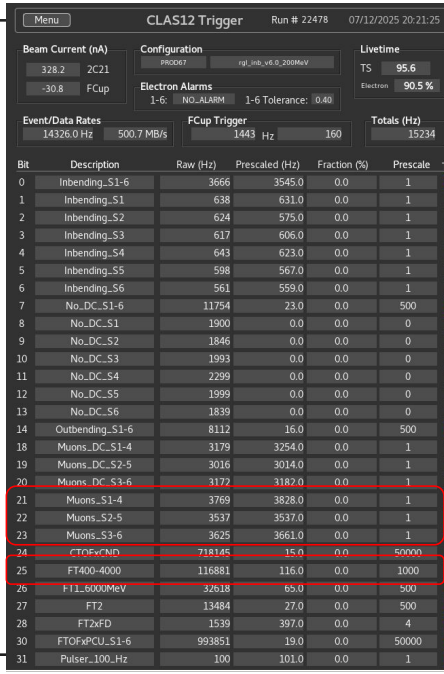
The proposal aims at checking if there is a difference between the charge radius and matter (gluonic) radius of ^{4}He, similar to what existing data suggest about the proton



Searching for a diffraction minimum in the gluonic form factor for $|t|$=0.3-0.9 GeV^2

Although the theoretical formalism is not well founded, the PAC recognizes that the physics case is important.
Take advantage of data from ALERT Run Group and get first insights based on real data (e.g. electroproduction cross section+background)

Approved C2



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2	Inbending_S2	624	575.0	0.0	1
3	Inbending_S3	617	606.0	0.0	1
4	Inbending_S4	643	623.0	0.0	1
5	Inbending_S5	598	567.0	0.0	1
6	Inbending_S6	561	559.0	0.0	1
7	No_DC_S1-6	11754	23.0	0.0	500
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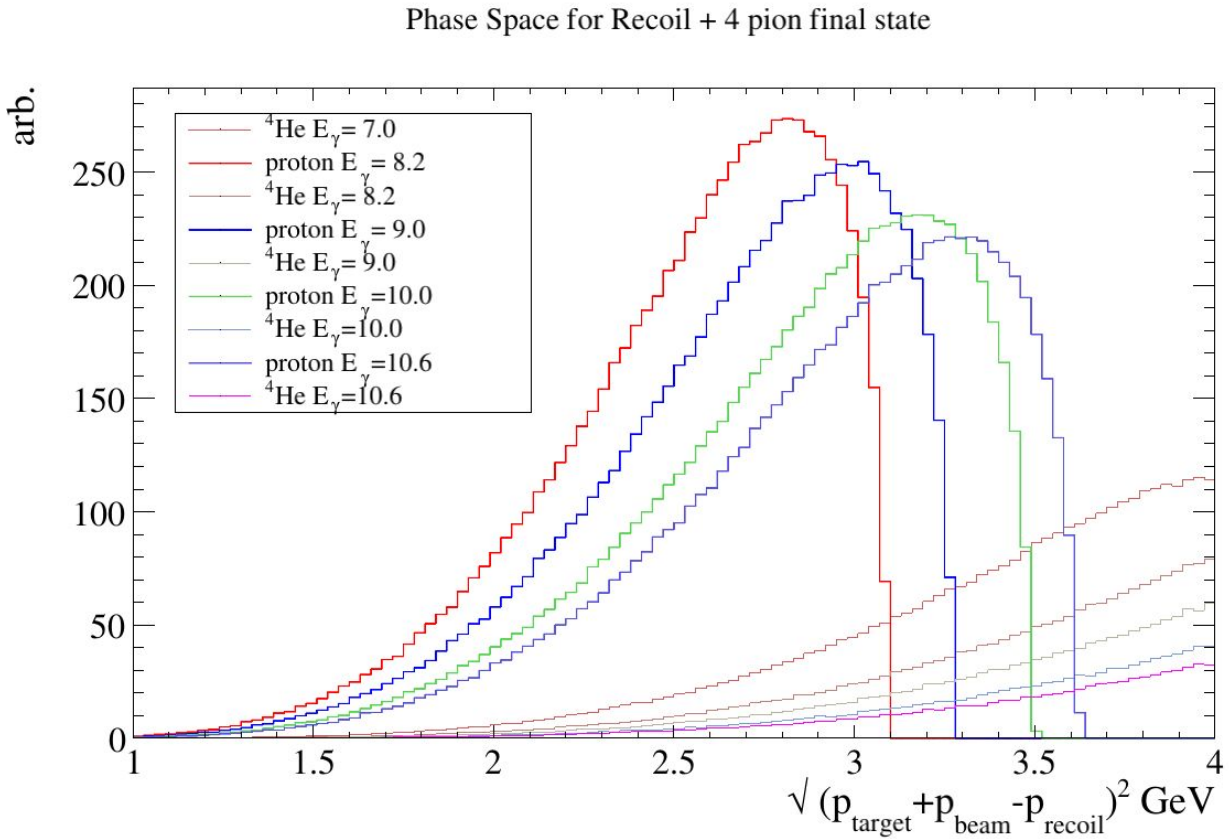
9	No_DC_S2	1846	0.0	0.0	0
10	No_DC_S3	1993	0.0	0.0	0
11	No_DC_S4	2299	0.0	0.0	0
12	No_DC_S5	1999	0.0	0.0	0
13	No_DC_S6	1839	0.0	0.0	0
14	Outbending_S1-6	8112	16.0	0.0	500
18	Muons_DC_S1-4	3179	3254.0	0.0	1
19	Muons_DC_S2-5	3016	3014.0	0.0	1
20	Muons_DC_S3-6	3172	3182.0	0.0	1
21	Muons_S1-4	3769	3828.0	0.0	1
22	Muons_S2-5	3537	3537.0	0.0	1
23	Muons_S3-6	3625	3661.0	0.0	1
24	CTOFxCND	718145	15.0	0.0	50000
25	FT400-4000	116881	116.0	0.0	1000
26	FT1_6000MeV	32618	65.0	0.0	500
27	FT2	13484	27.0	0.0	500
28	FT2xFD	1539	397.0	0.0	4
30	FTOFxPCU_S1-6	993851	19.0	0.0	50000
31	Pulser_100_Hz	100	101.0	0.0	1

Summary

- We proposed the first measurement of coherent J/ψ electroproduction cross section off ^{4}He with CLAS12 and ALERT for the PAC53.
  - The main physics goal is to identify the existence of diffractive minimum and determine the value of momentum transfer at which the minimum occurs.
  - Its position in momentum transfer t relative to the diffraction minimum of the ^{4}He charge form factor will provide **a first glimpse at the shape of the gluon distribution in light nuclei**.
  - The experiment will utilize the existing CLAS12 forward detector and forward tagger, along with the ALERT detector, which successfully ran with CLAS12 in Hall B for Run Group L.
- The PAC conditionally approved (C2) the proposal, and recommended analyzing the RG-L data to estimate the upper bound of the J/ψ yield and the background profile.
- To perform this scientifically important first-of-its-kind experiment, we will submit the updated proposal in either 2026 or 2027 in coordination with the RG-L and CLAS collaboration.
- Thank you so much for collaboration efforts for helping the PAC presentation, proposal writing/ review, and helpful comments!

Backup – Multiparticle final state phase space



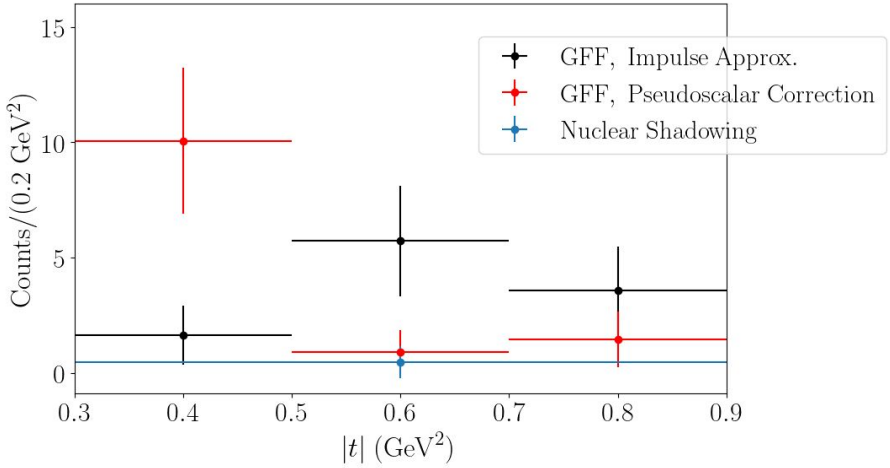
Coherent J/psi using existing ALERT Data (RG-L)

RG-L has only topology 2 in the trigger

- In most optimistic scenario, we expect 20 events, however,
- Very **Low statistics** and **high background** in topology 2 make identification of Jpsi peak very difficult

→ Very little constraint on cross section due to large statistical and systematic uncertainties.

Note: having topology 1 and 2 in our proposal reduces the systematic uncertainties associated with each reconstruction channel.



Backup – PAC53 Report

Motivation: This proposal aims to measure the location of the first diffractive minimum in the cross section for coherent exclusive J/ψ electroproduction off a ^{4}He target and compare the corresponding gluonic form factor to the charge form factor. A similar comparison in photoproduction of J/ψ on proton target suggests that the proton charge radius may be different from its matter (gluonic) radius. This proposal aims at checking if this holds also in ^{4}He. Even if no diffractive minimum will be found, the measurement will be an opportunity to gain insight into the distribution of matter inside the nucleus, relative to the quark charge.

Measurement and Feasibility: Measurement of coherent exclusive J/ψ electroproduction off ^{4}He is proposed to be conducted in Hall B with a 10.6 GeV electron beam with currents of 0.5 μA incident on a 5.6 atm gaseous ^{4}He target. The experiment proposes to use the ALERT detector and the Forward Detectors (FD) and Forward Tagger (FT) of CLAS12, but it requires the development of a new coincidence trigger using ALERT and CLAS12 FT to accumulate most of the J/ψ statistics. The experiment asks for 100 days of total beam time, consisting of 97 days of production data and 3 days for calibration of the detector and commissioning of the new coincidence trigger. It has been approved by the CLAS Collaboration.

Backup – PAC53 Report (Cont'd)

Issues: ALERT is planned to work with a current (500 nA) and target pressure (82 psig) higher than nominal target working conditions. Further studies about target stability in these conditions and the background generated by higher pressure are required. Similarly, a more careful investigation is needed to estimate the uncertainty in localizing the diffractive minimum, which depends on detector t-resolution and statistics. A strategy should be devised to optimize the finding of its location, if it exists, which may vary according to model predictions.

Summary: Although the theoretical formalism is not well-founded and largely model dependent, the PAC recognizes that the physics case is important and the result would deliver useful information on the gluon structure of ^{4}He, whether the diffractive minimum is found or not found. However, the proponents should take advantage of data from the ALERT Run Group (CLAS12 Run Group L), that are being accumulated in summer 2025 and get some first insights based on real data rather than on model predictions. Data may yield an upper limit on the electroproduction cross section for J/ψ and provide an estimate of the background. This may allow to tune the beam time request and the experimental parameters more accurately. The PAC encourages the proponents to submit an updated proposal.