PR12-25-004

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

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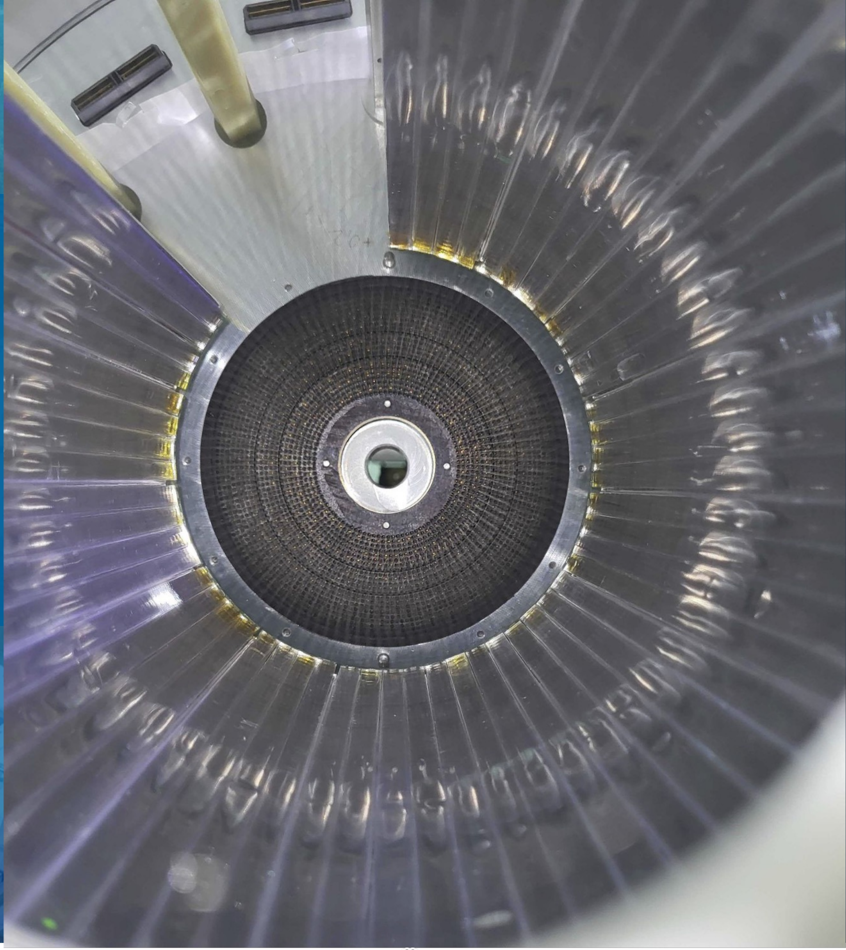
Sangbaek Lee (Speaker)
Chao Peng
and CLAS Collaboration

A Proposal to PAC 53



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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**

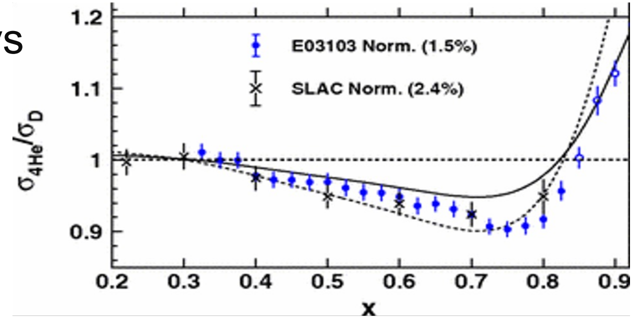
→ already embodies most of the strength of the EMC effect

→^{4}He is ideally suited for studying the quarks and gluons inside the nuclei.

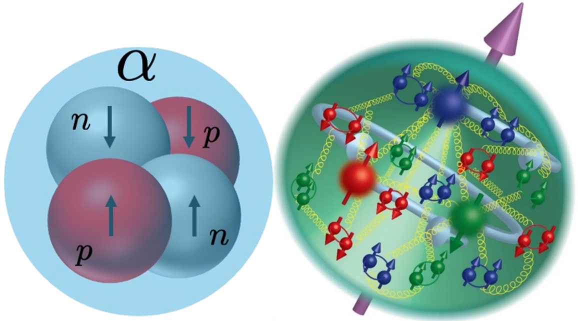
Electromagnetic form factor from elastic scattering

→ model independent (quark) charge distribution

But what is the role of QCD in the structure of ^{4}He?



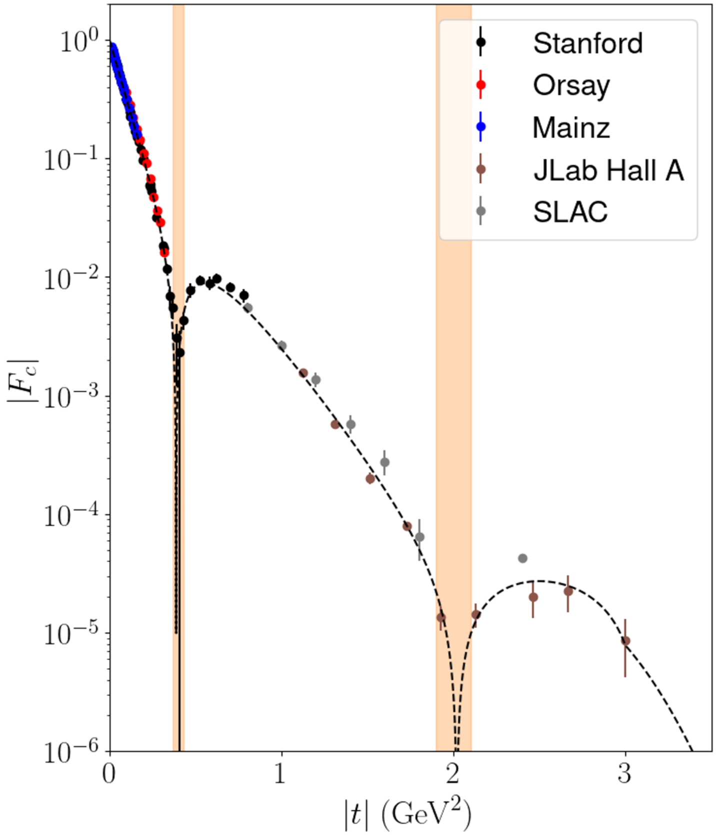
↑ J. Seely, et al., PRL103 (2009), 202301



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

Charge Distributions inside the ^{4}He Nucleus

- ^{4}He nucleus (spin 0) has one electromagnetic form factor – the charge form factor $F_c(t)$
  - t: Momentum transfer to the nuclei
- 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 Gaussian-like distribution.
  - The first diffraction minimum is $|t|$=0.4 GeV^2.
  - Corresponds to distance scales 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, as demonstrated in the JLab experiments with nucleons

Heavy charm quark mass →gluon exchange dominates the interaction

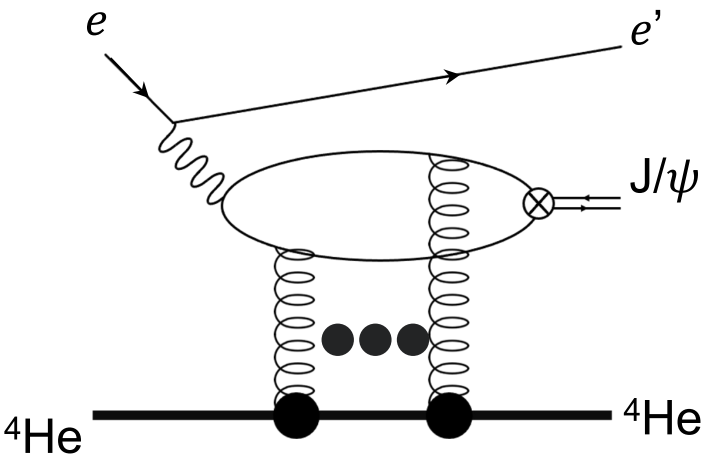
Exclusive J/ψ production provides the best probe of nuclear gluon distributions at JLab with a 11 GeV beam.

J/ψ (c cbar)

Spin: 1 (Vector meson)

Mass: 3.1 GeV

Decay width: 92.6 keV



Coherent J/ψ Production off ^{4}He

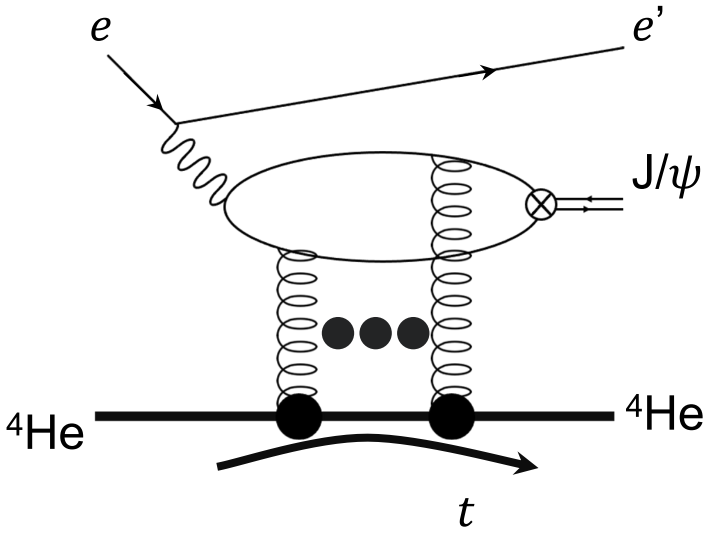
Exclusive coherent J/ψ production on ^{4}He

$$\frac{d\sigma}{dt} \propto |G_{^4\mathrm{He}}|^2$$

Measure the $|t|$ dependence of the J/ψ production cross section around the first diffraction minimum, when the ^{4}He stays intact

^{4}He detection simplifies analysis by eliminating incoherent channels

This is a model-independent measurement used to study gluon dynamics in comparison to charge inside ^{4}He for the first time.



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

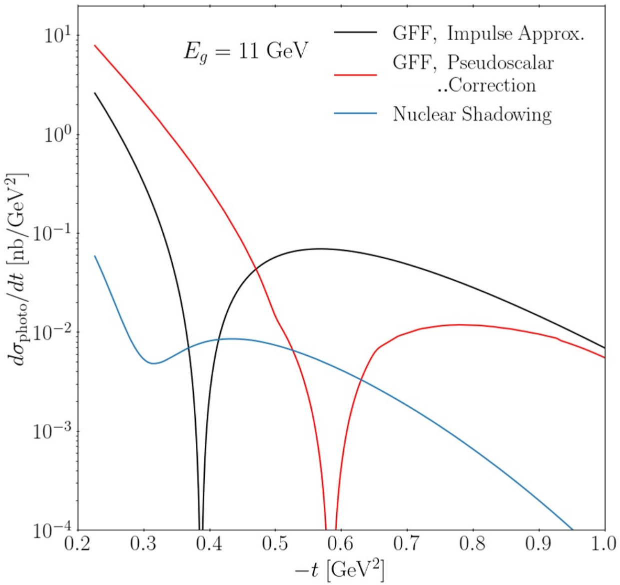
To date, there is no measurement of coherent J/ψ production on ^{4}He.

However, a few model predictions for the cross section exist. We will focus on these cases for this talk.

- Gravitational Form Factor-based prediction
  - The threshold J/ψ production cross section can be parametrized by the GFF, a form factor of Energy-Momentum Tensor (EMT).
  - This framework was a success 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 does not follow the charge

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

Overview of the Proposed Measurement Requirements

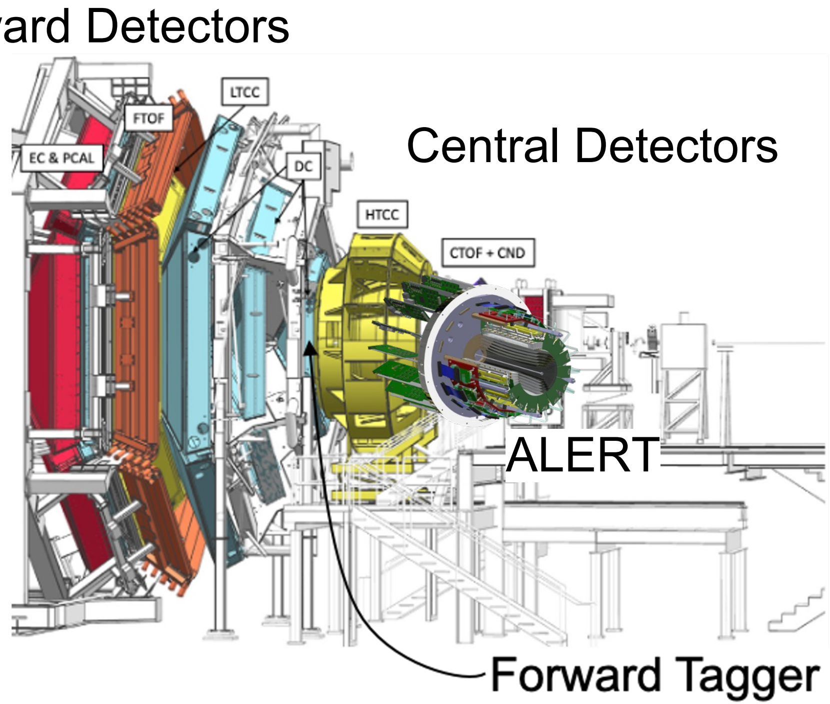
Detection of the ^{4}He
- Requires a Recoil detector

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

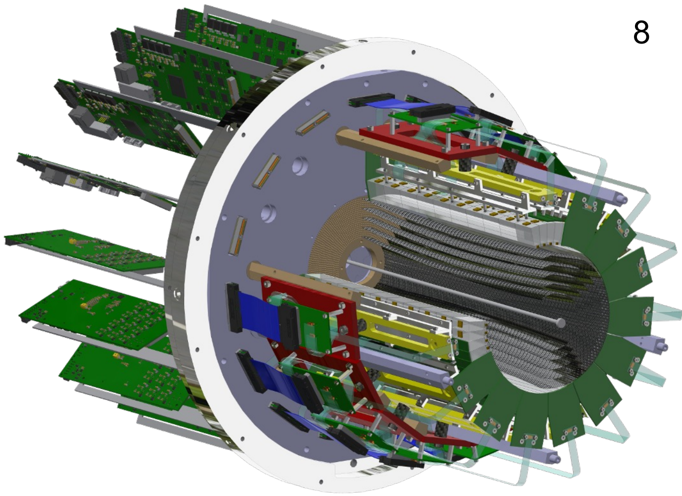
Coincidence trigger with recoil
- High duty factor beam for low accidental coincidence

***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 Coherent J/ψ production on ^{4}He.



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

Recoil Detection with the ALERT

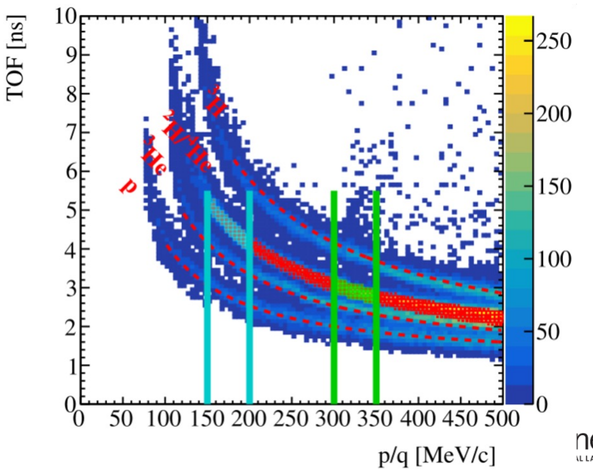


The ALERT consists of the Drift Chamber (tracker) and the Time-of-Flight detector (particle identification) to detect the recoil from a high pressure gas target

1. Large detector acceptance
2. PID to reject the incoherent background
3. Reconstruction of recoil momentum to determine $|t|$

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

RG-L currently running with 65 psi target pressure instead of nominal 82 psi in proposal.

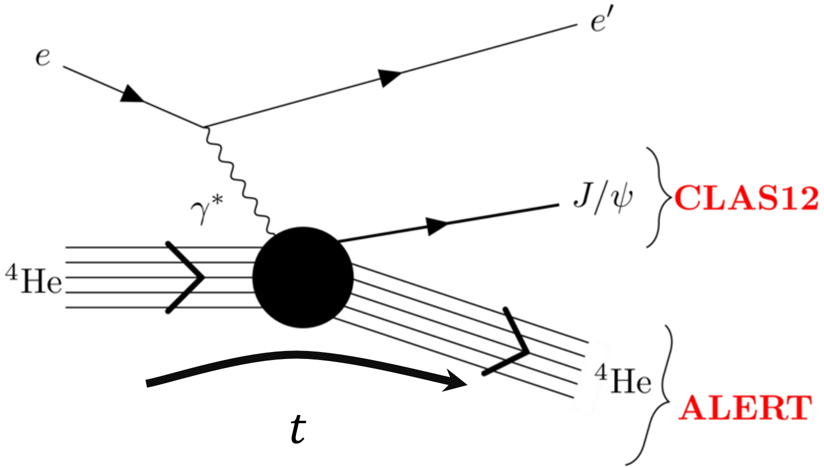


Technical Challenges for the Measurement

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 electrons (and muons) **limits the statistics**.

Without also detecting e’, E_γ resolution suffers. With full final state detection the statistics further suffers.



Coincidence Trigger for the Measurement

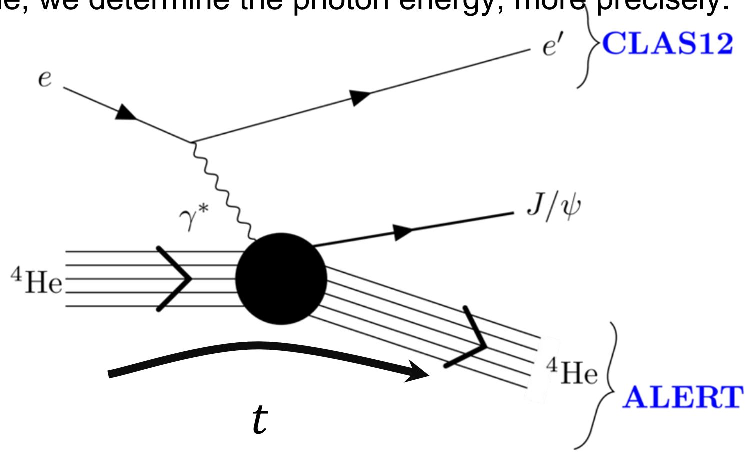
We solve this challenge by introducing a new detection mode, a coincidence of e' and ^{4}He.

Detecting e' provides excellent photon energy determination

Detecting the recoil determines t

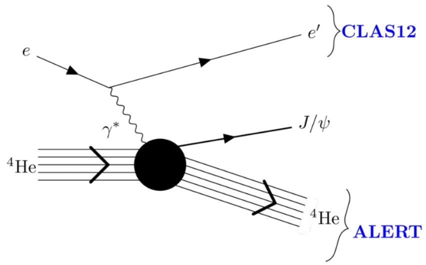
The invariant mass of the J/psi suffers but this is not a problem because of the very low background in this topology.

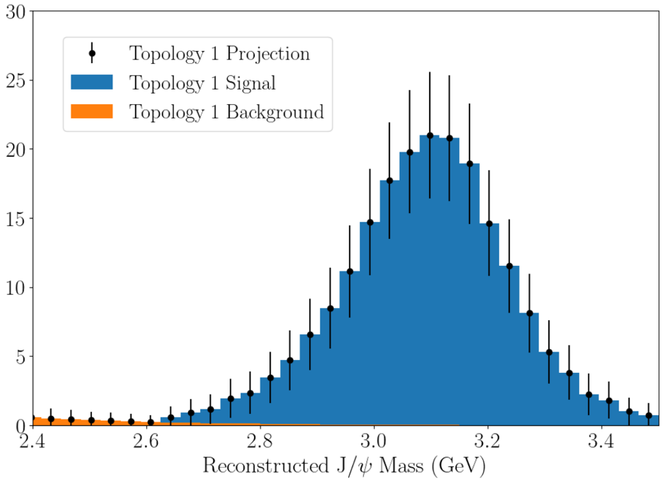
- The narrow J/ψ peak, far from the radiative tail ensures the event selection.
- In this mode, we determine the photon energy, more precisely.



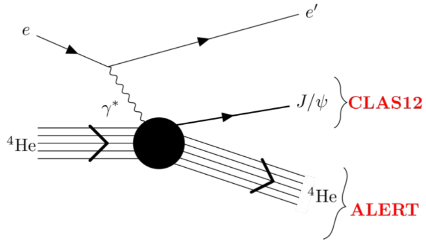
Event Selection: J/ψ peak

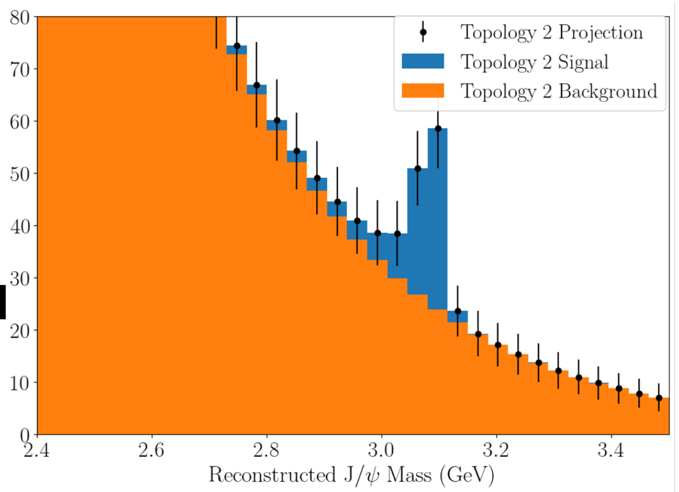
Trigger 1 (Topology 1)





Trigger 2 (Topology 2)

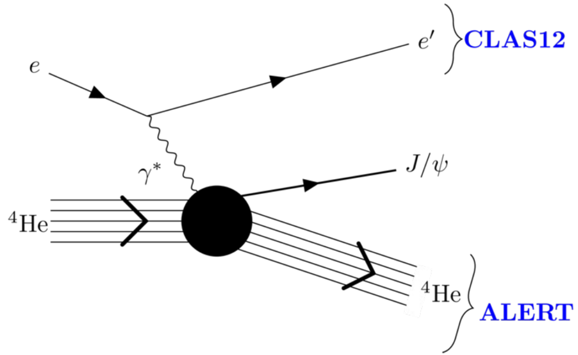




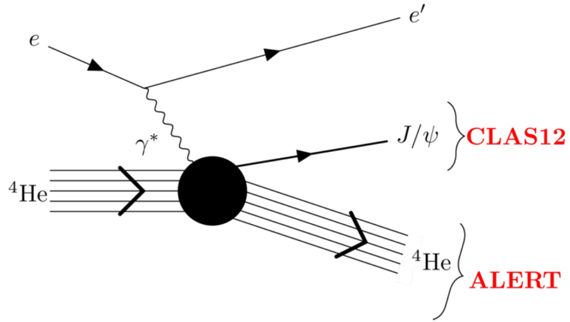
These are two methods with different systematics that should produce the same cross-section. This is a powerful way to build confidence in the result and improve understanding.

Singles and Coincidence Rates

Trigger 1
- Singles
  - e': less than 120 MHz
  - ^{4}He candidate: ~1 kHz
- Coincidence
  - Coincidence time window ~ 100 ns
  - Trigger rate:12 kHz.
  - The current DAQ can handle the rate.



Trigger 2
- $J/\psi \rightarrow \mu^+\mu^-$ trigger already runs at the RG-L!



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

Projected Results and Requested Beamtime

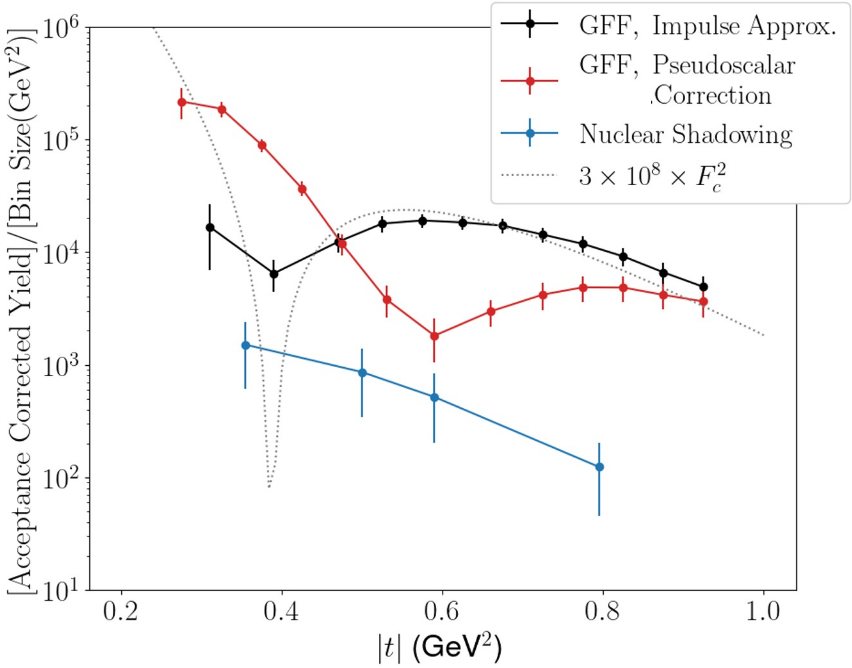
How are gluons distributed in ^{4}He relative to the quark charges?

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 above.

97 days of production



GFF, IA follows the charge form factor

GFF, PS Correction does not follow the charge

Nuclear shadowing: shifts in non-zero minimum location

Theory Report

Strong support by JLab Theory Group

*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 GeV2, 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.*

PR12-25-004

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.

Summary

We propose the first measurement of coherent J/ψ electroproduction cross section off ^{4}He with CLAS12 and ALERT

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 is currently installed inside of CLAS12 in Hall B for Run Group L.

Beam Energy (GeV)	Beam Current (uA)	Beam Requirements	Target Material	Material Thickness (mg/cm^2	Beamtime (days)
2.2	< 0.5	Unpolarized	^{4}He	45	3
10.6	0.5	Unpolarized	^{4}He	45	97
Total Time					100

Backup Slides

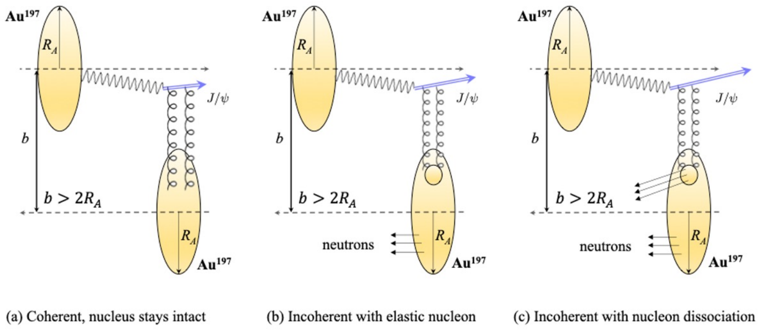
Importance of ^{4}He Detection

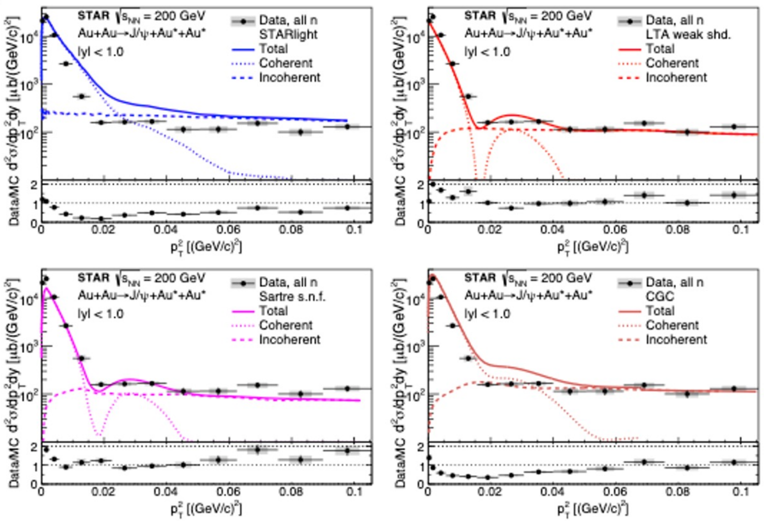
The ^{4}He should stay intact to compare the gluons to the charge.

Assigned readers asked if it's useful to consider the proposed incoherent J/ψ production for the Hall D.

- Some UPC measured the $|t|$ distributions of J/ψ production off the nuclei.
  - Pb+Pb from the ALICE and CMS
  - d+Au and Au+Au from STAR

^{4}He detection eliminates model dependence when distinguishing between coherent and incoherent processes and solidifies the goal of the measurement.





↑ STAR Collaboration, PRC 110 (2024), 014911

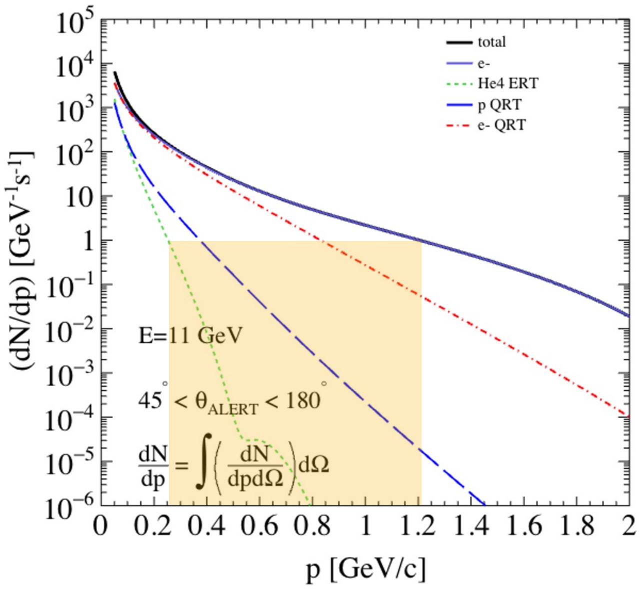
Impacts

Heavy mass of J/ψ prevents contamination in the invariant mass peak by the radiative tail

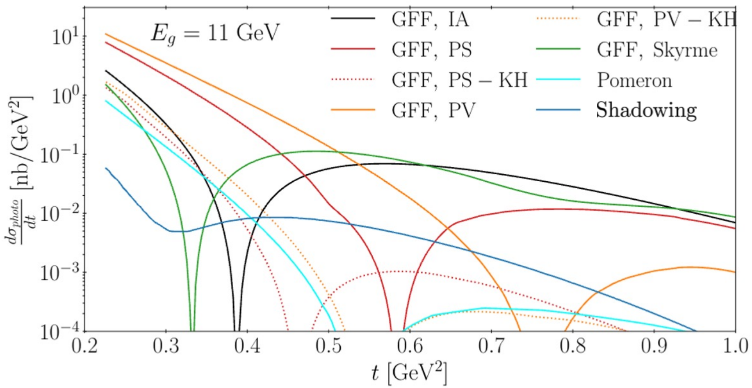
Narrow decay width of J/ψ defines the event selection

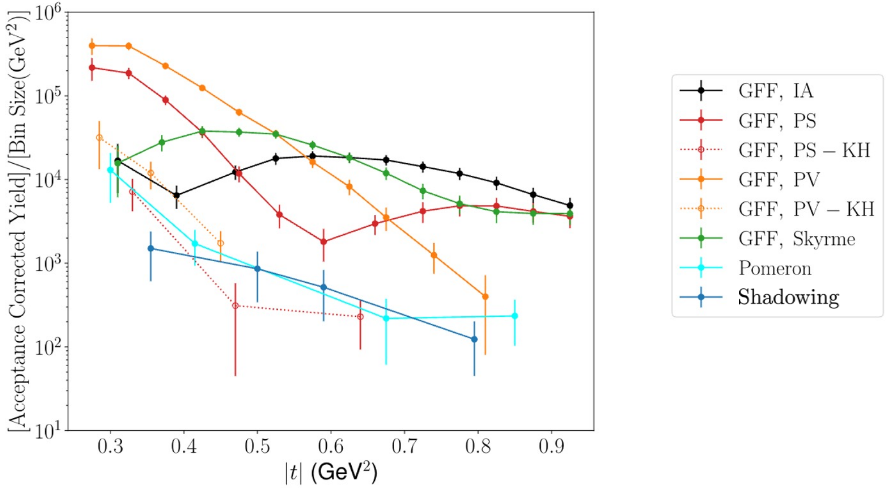
Reasoning of Recoil Rate Estimates

Integrate the rate from 0.3 GeV/c to 1.1 GeV/c -> 1 kHz

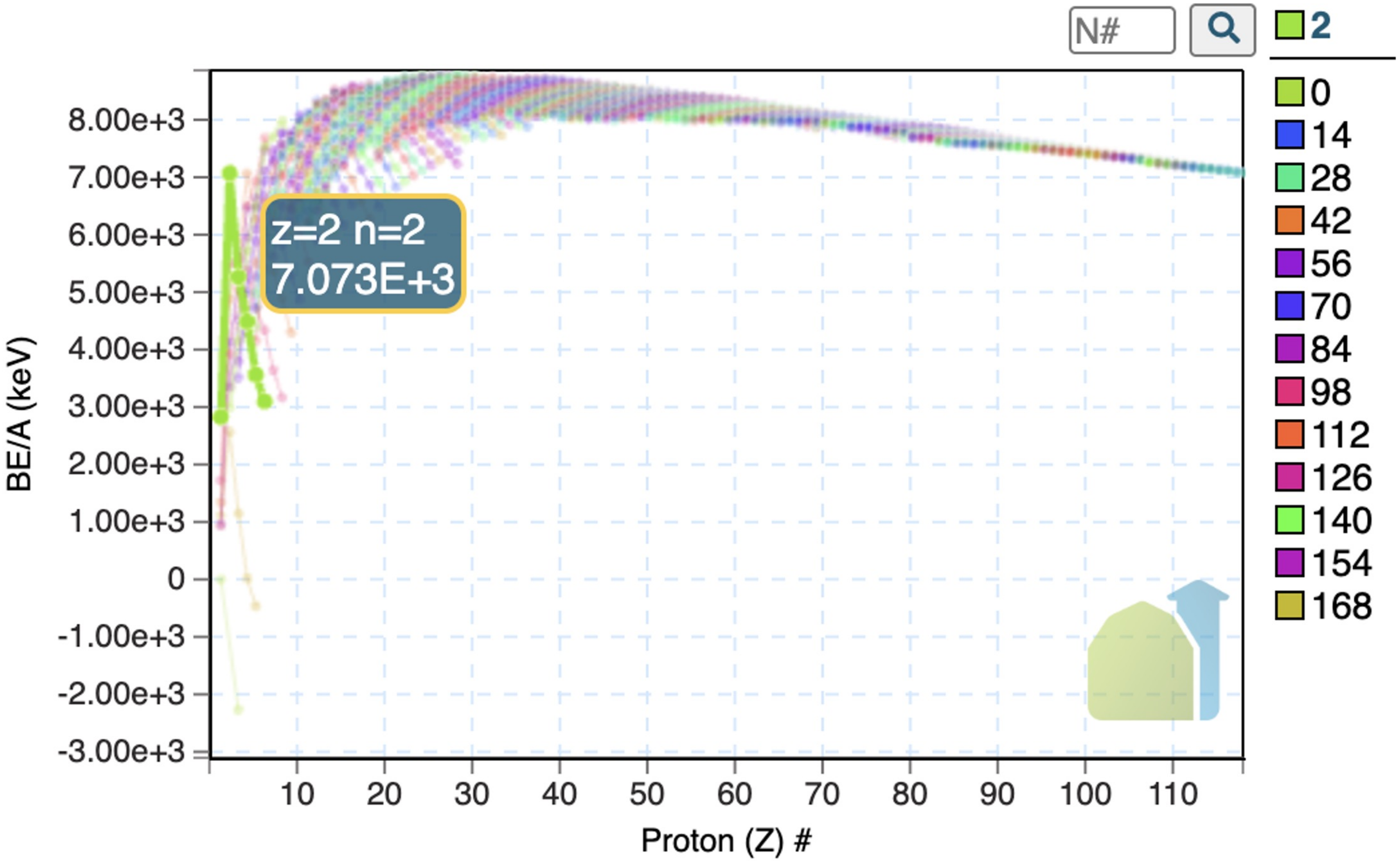


All cross section models



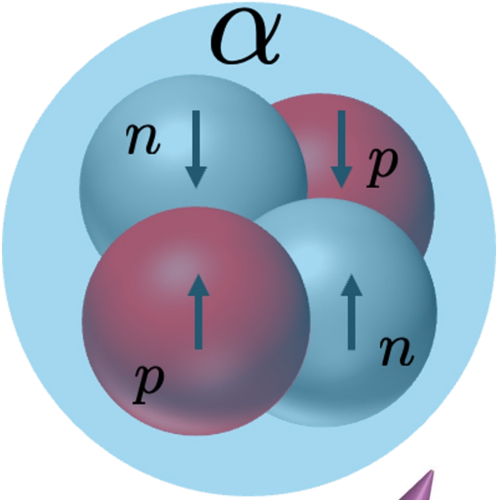


Binding Energy per Nucleons

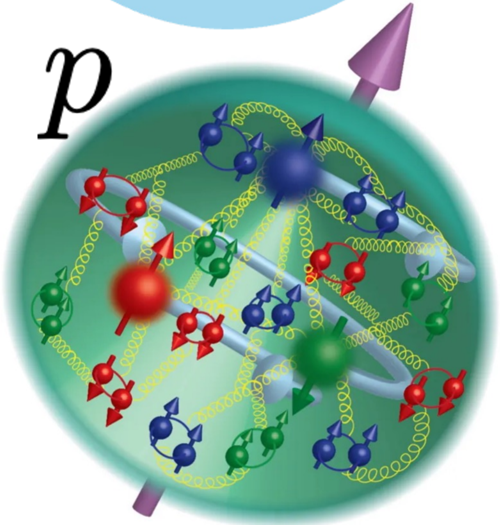


From NNDC

Motivation of the Proposed Measurement



The alpha particles are approximately two protons and two neutrons. The net charge is explained by the two protons.



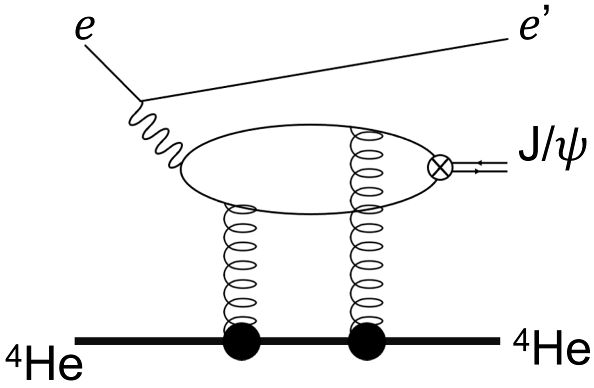
The charge inside the nuclei are fundamentally carried by the quarks.

Does the gluon inside the nuclei follow the charge? If not, why?

Other Advantages of ^{4}He Detection

Detection of ^{4}He has many advantages.

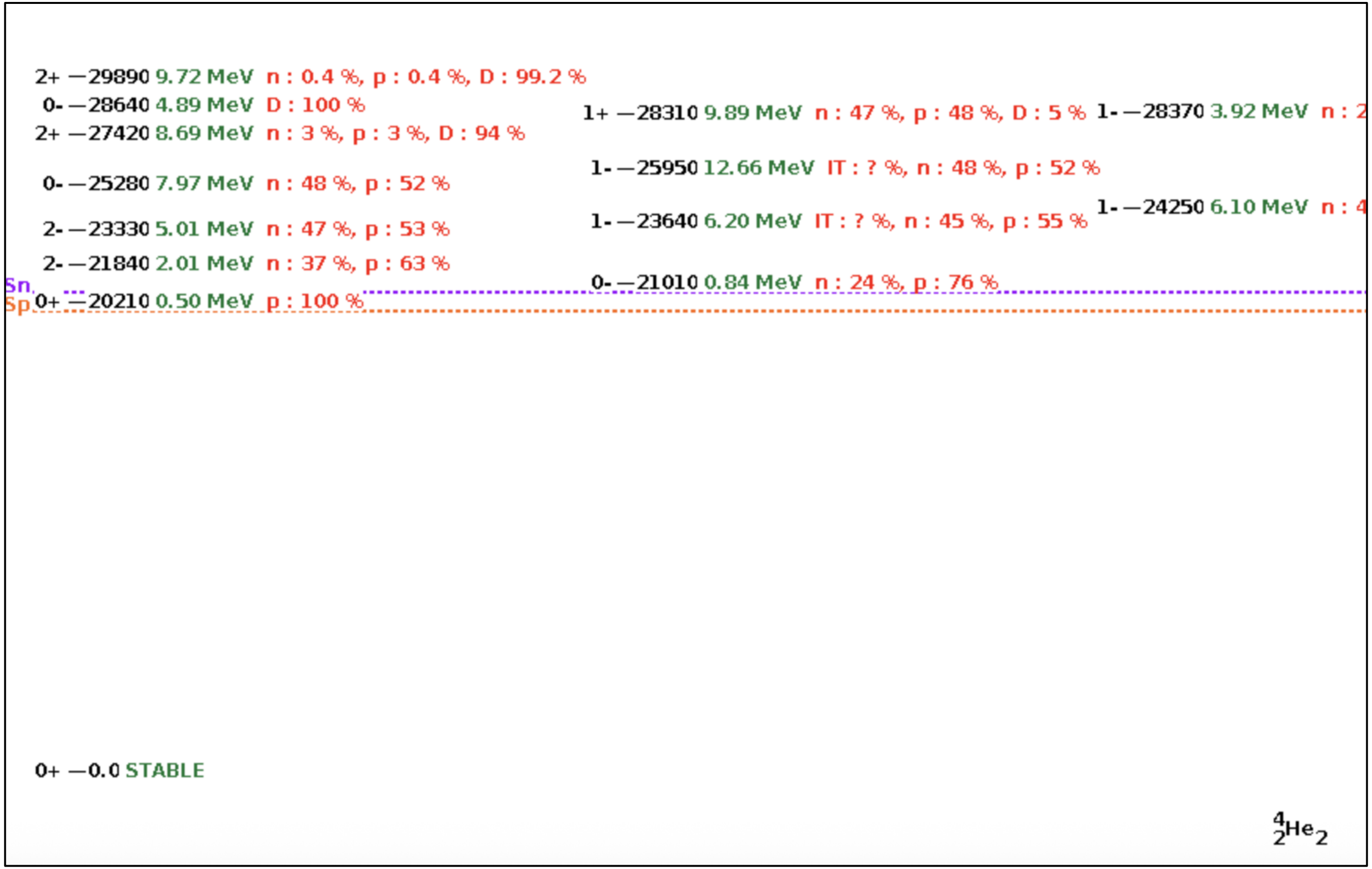
- It vetoes the accidentals from nucleon/ deuteron recoils.
- It guarantees that ^{4}He stays in the ground state, because there is no gamma de-excitation from the excited states of ^{4}He.



The momentum transfer t can be determined.

Detecting the ^{4}He nucleus ensures proper event selection for the analysis.

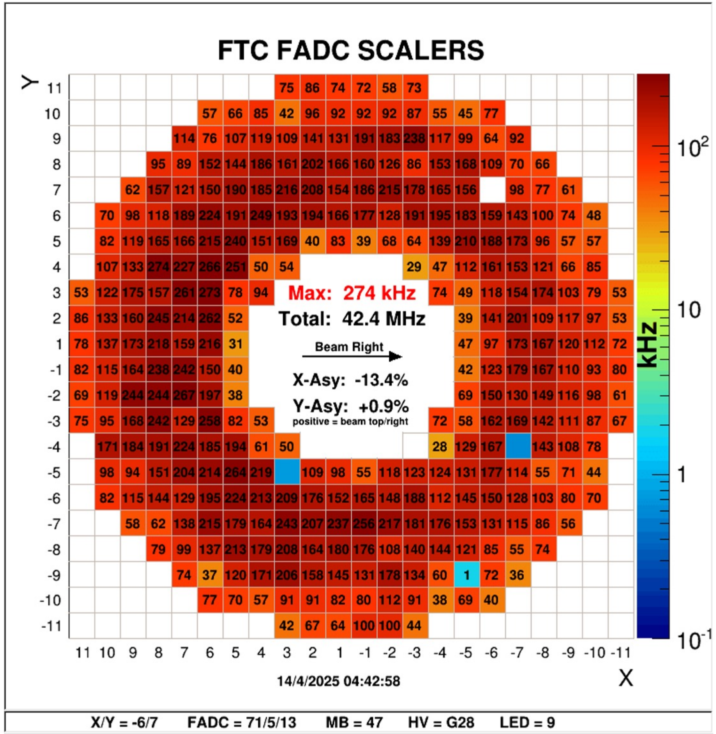
4He Level Scheme, From NNDC



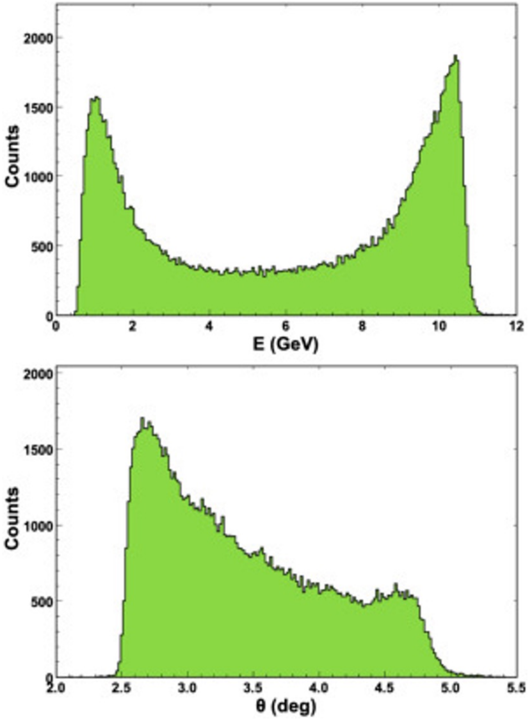
From NNDC

FT Rates with the ALERT

Rates @ 500 nA: 42.4 MHz
https://logbooks.jlab.org/entry/4355908



Profile A. Acker et al., The CLAS12 Forward Tagger, NIM A



Impact of the proposed measurement

- The proposed measurement in the first measurement for the differential cross section of exclusive coherent J/ψ production on ^{4}He.
  - Quote from T. Toll and T. Ullrich, PRC 87 (2013)

> Exclusive diffractive processes in electron-ion collisions
>
> Tobias Toll and Thomas Ullrich
> Phys. Rev. C **87**, 024913 – Published 26 February 2013
>
> **A. Predictions for *e*A collisions**
>
> To date, there exist no experimental data on diffractive vector meson production in *e*A. However, these measurements

  - To be fair, a couple of UPC results on heavy ion have been published, but there's no direct, exclusive diffraction minimum measurement.
- Lots of fruitful theory discussions about nuclear GFF is ongoing with new publications from independent groups. It is timely to perform the measurement at JLab 12 GeV.
  - **F. He** and **I. Zahed** PRC 109, 110 (2024).
  - A. G. Martín-Caro, M. Huidobro, **Y. Hatta** PRD 110 (2024)
  - **R. Wang**, **C. Hang** and **X. Chen** PRC 109 (2024).
  - Bold: theory support for the proposal

ALERT Hardware Status

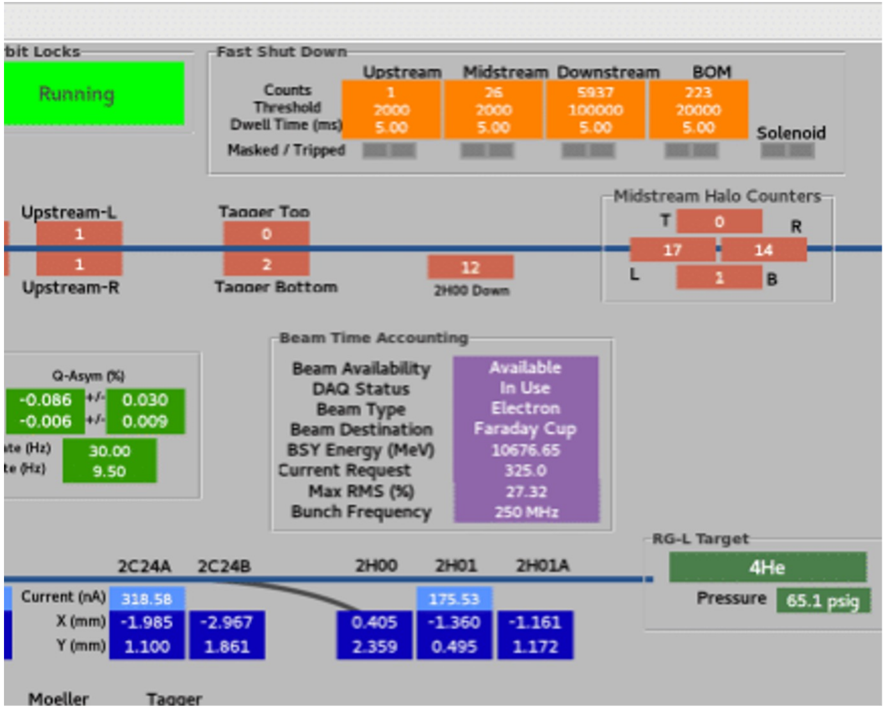
The current RG-L have been collecting the data stably with the ALERT and the 65 psig gas ^{4}He target.

Responses to the TAC

Q) Requested target pressure (82 psig) is higher than the RG-L target

A) **The 82 psig target is technically possible.**

ex) Double walls on the kapton tubing.

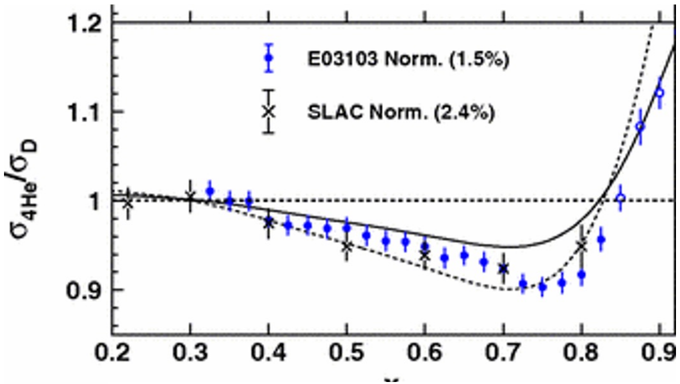


↑ Jefferson Lab, Hall B Logbook, 07/08/2025

The Alpha Particle

Basic facts about the ^{4}He nucleus

- Mass: 3.73 GeV/c^2
- Spin: 0
- A tightly bound system
  - Binding energy per nucleons are 7.07 MeV
  - Maximum BE/A is approximately 8.8 MeV (^{56}Fe)
- First closed shell.



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

The EMC effect, the suppression of high momentum quarks, is comparable for ^{4}He to the heavier nuclei, owing to the isoscalar EMC ratio.

^{4}He is ideally suited for studying the quarks and gluons inside the nuclei.