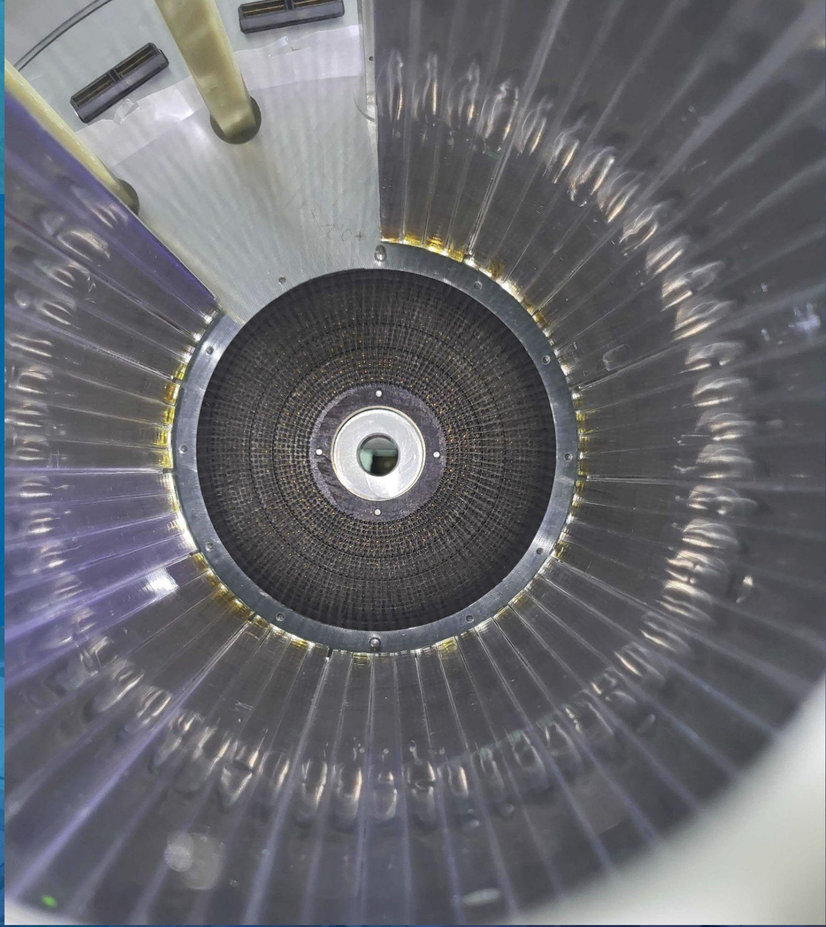
Measurement of the coherent J/ψ electroproduction off ^{4}He with the ALERT at 11 GeV

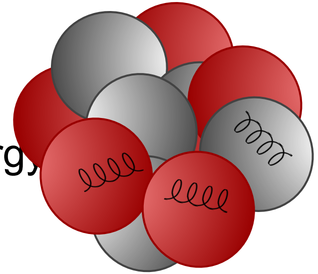


Whitney Armstrong **Sangbaek Lee**

CLAS Collaboration Meeting

Nov. 15 2024

Physics Motivation: QCD in Nuclei



- The Gravitational Form Factors (GFFs) parametrize matrix elements of the Energy Tensor (EMT)
- GFFs related to mechanical properties of hadrons
  - Interpretations of the mass radii, pressure and shear forces densities
  - Gluon GFFs encode matter distribution → Does it mimic the charge in Nuclei?
- Is it possible to determine the gluon gravitational form factors of ^{4}He?
  - ***Main goal of new beamtime proposal***

Gravitational Form Factors

$$\langle p', s' | T^a_{\mu\nu} | p, s \rangle = \bar{u}(p') \Big[\frac{1}{2} \gamma_{\{\mu} P_{\nu\}} A_a(t) + \frac{i P_{\{\mu} \sigma_{\nu\}\rho} q^\rho}{4 M_N} B_a(t) + \frac{q_\mu q_\nu - g_{\mu\nu} q^2}{M_N} C_a(t) + M_N \bar{C}_a(t) g_{\mu\nu} \Big] u(p), \qquad \sum_a \bar{C}_a(t) = 0, \;\; a = g, u, d, \ldots$$

Druck-term $D(t)=4C(t)$ is related to the pressure distribution.

For example, in the Breit Frame,

$$p(r) = \frac{1}{6M} \int \frac{d\mathbf{\Delta}}{(2\pi)^3} e^{i\mathbf{\Delta}\cdot\mathbf{r}} t D(t)$$

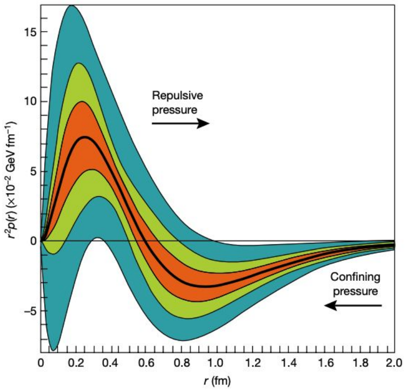
The related radii are (Hatta,et.al. 2023)

$$\langle r^2 \rangle_s = 6 \frac{dA(t)}{dt}\bigg|_{t=0} - \frac{9D(0)}{2M^2} \qquad \langle r^2 \rangle_m = 6 \frac{dA(t)}{dt}\bigg|_{t=0} - \frac{3D(0)}{2M^2} \qquad \langle r^2 \rangle_t = 6 \frac{dA(t)}{dt}\bigg|_{t=0}$$

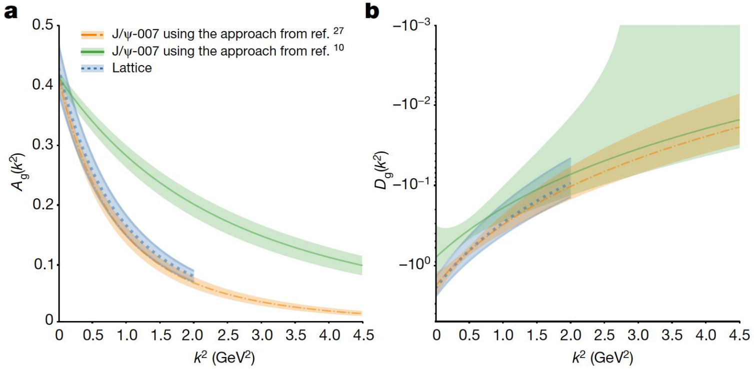
Nucleon Gravitational Form Factor (GFFs)

A recent history

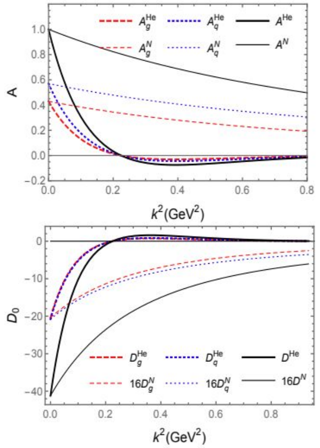
- First extraction of the quarks GFF [$D_q(t)$] using DVCS. Pressure and shear forces in the Breit frame displayed
- First extraction of the gluonic GFFs [$A_g(t)$ and $D_g(t)$] on the proton using near-threshold J/ψ photoproduction off the proton
- The theoretical predictions for **nuclei** GFFs using different models has been recently produced and published
- See earlier talks from **Richard Tyson** and **Mariana Tenorio Pita**



V. Burkert, L. Elouadrhiri & F. X. Girod, Nature 557, 396–399 (2018)



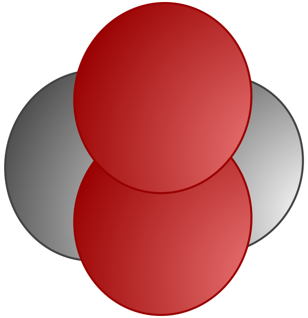
B. Duran et al., Nature 615, 813-816 (2023)



F. He and I. Zahed, arXiv:2310.12315

Gravitational Form Factor (GFFs)

From nucleon to spin zero nuclei



- ^{4}He is
  - a tightly-bound system
  - spin-0 → simpler structure for the electromagnetic and gravitational

$$\langle p', s'|T^a_{\mu\nu}|p, s\rangle = \bar{u}(p')\Big[\frac{1}{2}\gamma_{\{\mu}P_{\nu\}}A_a(t) + \frac{iP_{\{\mu}\sigma_{\nu\}\rho}q^\rho}{4M_N}B_a(t) + \frac{q_\mu q_\nu - g_{\mu\nu}q^2}{M_N}C_a(t) + M_N\bar{C}_a(t)g_{\mu\nu}\Big]u(p)$$

$$= \bar{u}(p')\left[\frac{P_\mu P_\nu}{M_N}A(t) + \frac{iP_{\{\mu}\sigma_{\nu\}\rho}q^\rho}{2M_N}J(t) + \frac{q_\mu q_\nu - g_{\mu\nu}q^2}{4M_N}D(t) + M_N\bar{C}^a(t)\right]u(p)$$

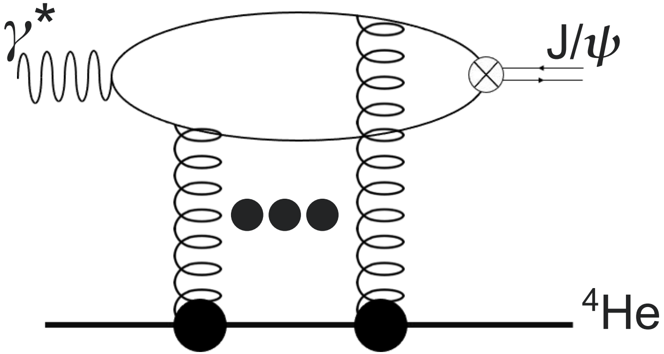
$$\rightarrow \quad \langle p'|T^a_{\mu\nu}(x)|p\rangle = \left[2P_\mu P_\nu A^a(t) + \frac{1}{2}(q_\mu q_\nu - g_{\mu\nu}q^2)D^a(t) + 2M_N^2\bar{C}^a(t)\right]$$

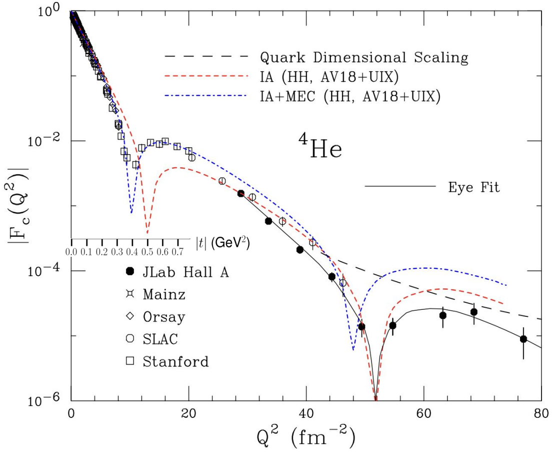
$$\sum_a \bar{C}_a(t) = 0, \;\; a = g, u, d, \ldots$$

  - Helium has a comparable mass to the J/psi
    - ^{4}He: 3.73 GeV, J/ψ: 3.1 GeV

Proposed Measurement

- **Coherent J/ψ** production on **^{4}He** with **CLAS12** and **ALERT.**
  - ALERT will run at high luminosity $L > 10^{35}$ cm^{-2}s^{-1} with a gas target
  - Kinematics will center in $|t|$ around the first minimum of the charge form factor
  - Determine the existence and position of a minimum for the gluonic form factor for ^{4}He.
  - **Measure** the **$|t|$ and E_γ** dependence of the J/ψ production cross section at low Q^2



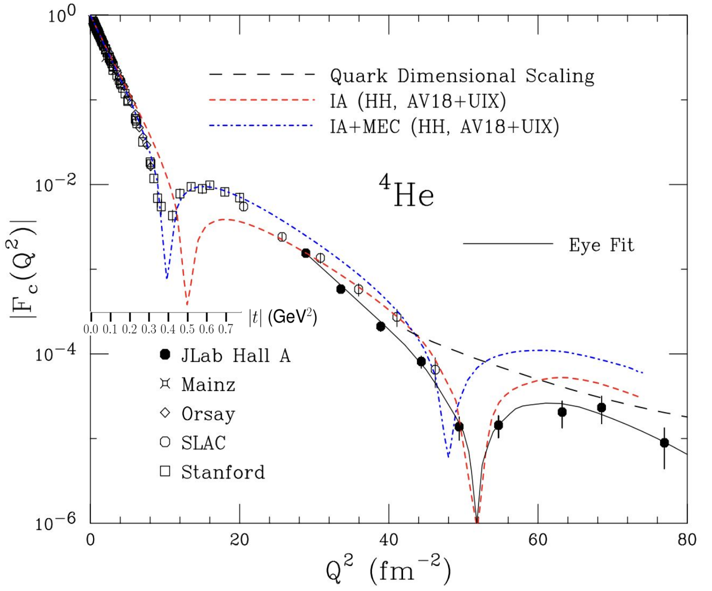


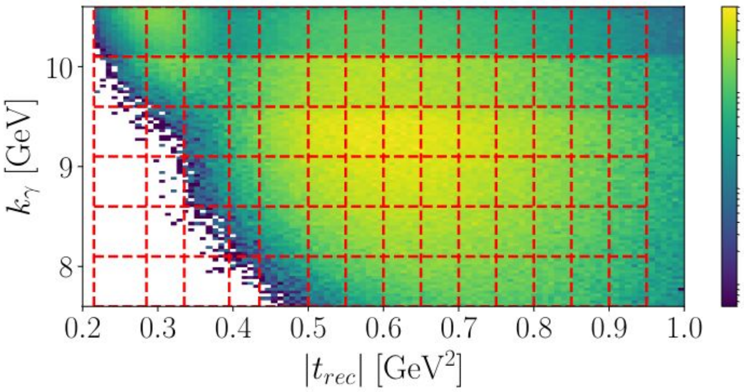
- Hall A charge form factor
  - Phys. Rev. Lett. 112, 132503 (2014)

Objectives of Experiment

1. Determination of the diffraction minimum.
   - Charge form factor has the first diffraction minimum at $|t|\sim 0.4–0.5\ \text{GeV}^2$.
   - **Does the matter distribution of the ^{4}He follow the charge distribution?**

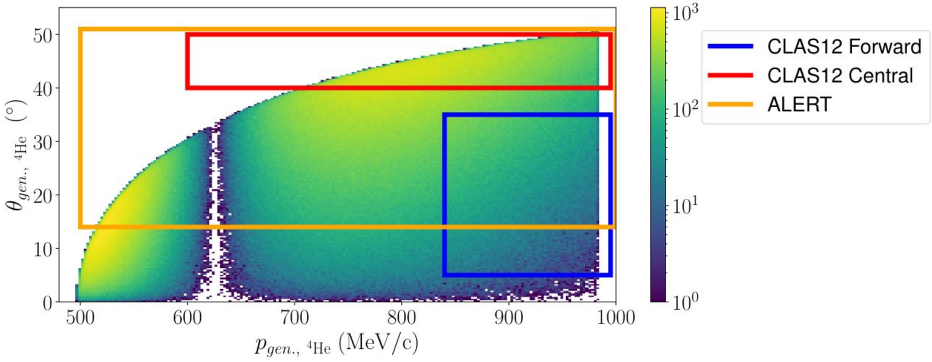
2. Measurement of t-dependent cross sections
   - Extract the GFFs of ^{4}He.
   - We separate the A and D form factor to achieve the pressure distribution using the D form factor.
   - **First extraction of GFFs of the light nuclei**

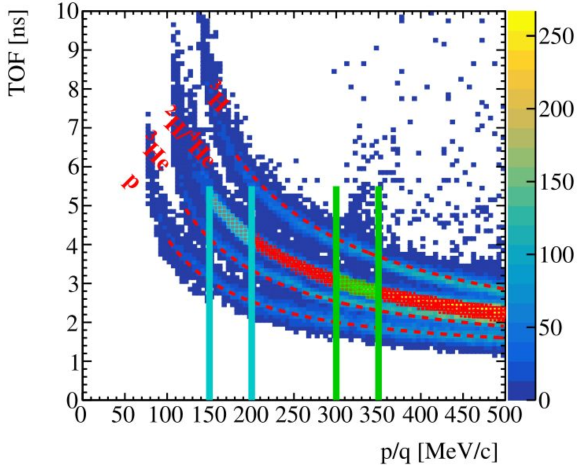


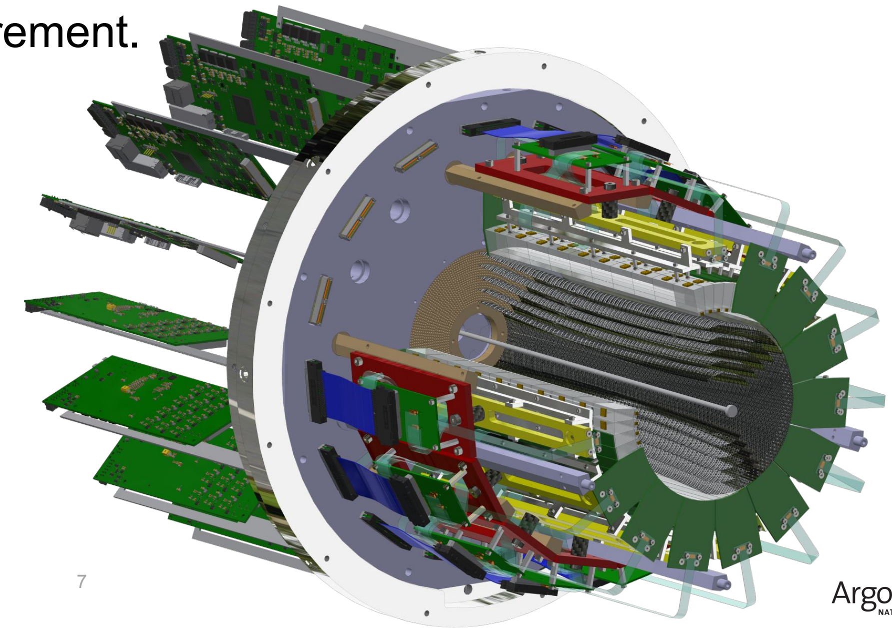


Why ALERT?

- ALERT offers
  1. Large detector acceptance
  2. PID to reject the incoherent background
  3. Reconstruction of recoil momentum to determine $|t|$
- ALERT-CLAS12 coincidence trigger is essential component of this measurement.

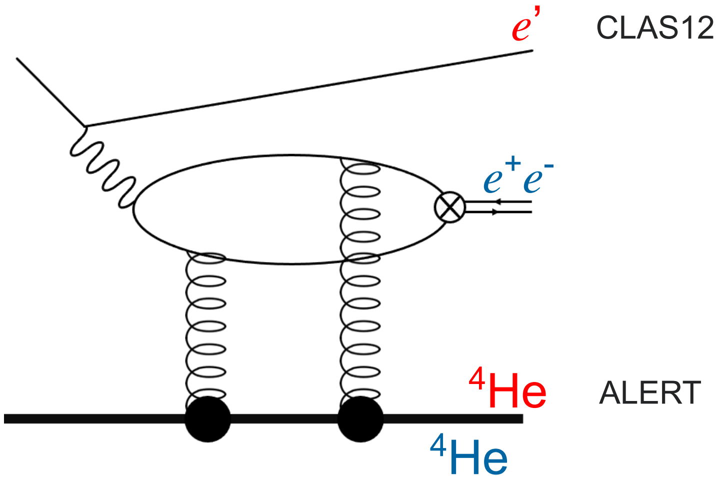


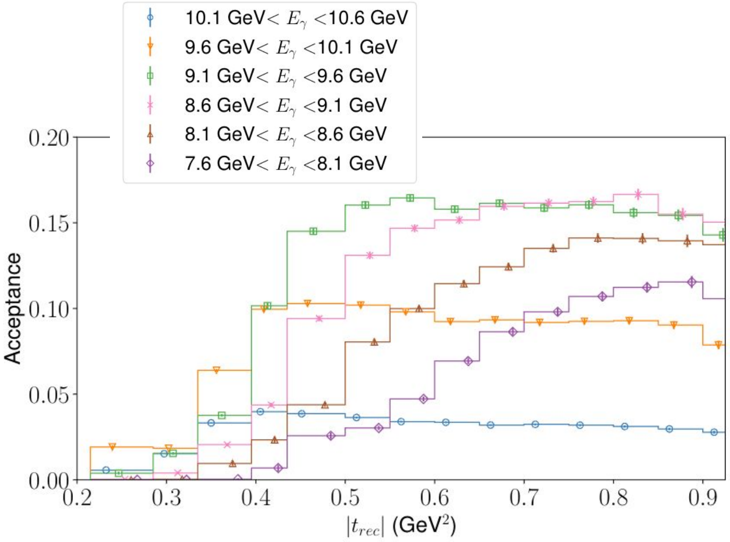




Detector Acceptance

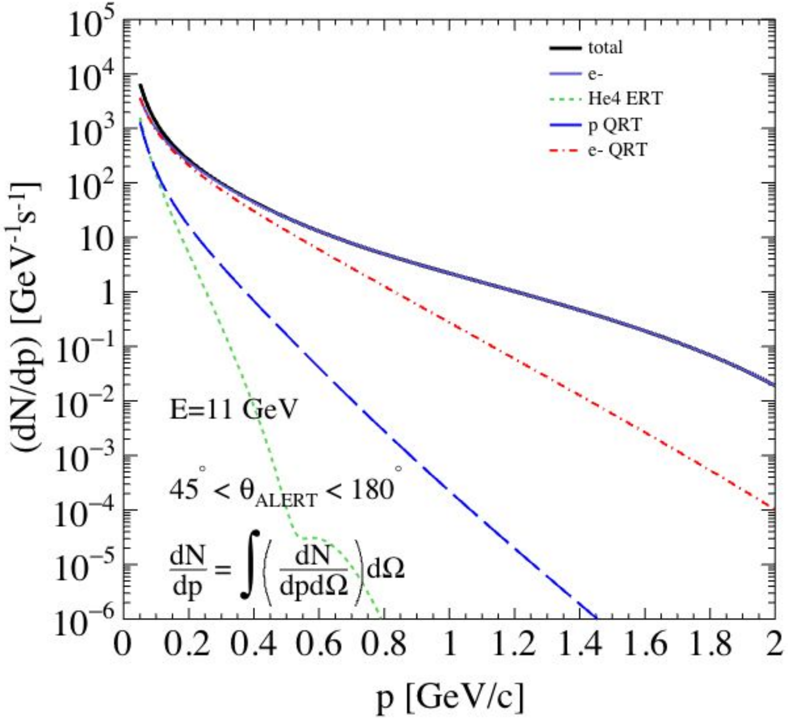
Topology	Particle	Detector	Condition
1	e'	Forward Tagger	p > 0.5 GeV/c 2.5°<θ<4.5°
		Forward Detectors	p > 1 GeV/c CLAS12 FastMC
	^{4}He	ALERT	r > 8 cm (ATOF)
2	l^+l^-	Forward Detectors	p > 1 GeV/c CLAS12 FastMC
	^{4}He	ALERT	r > 8 cm (ATOF)

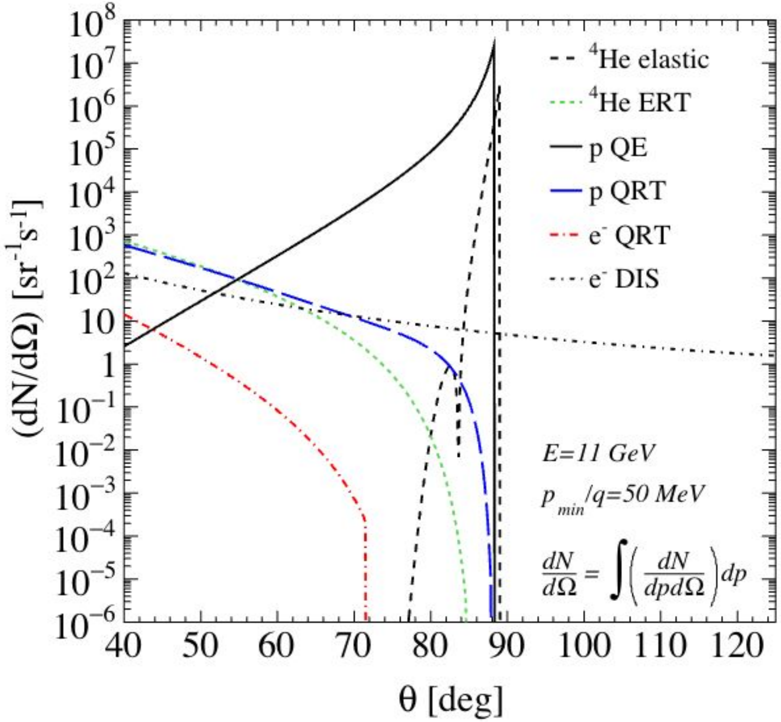




- ^{4}He p was smeared out with 5% resolution.
- Topology 2 has higher geometrical acceptance
  - Caveat) BR($J/\psi \to e^+e^-$) = 5.971%
    BR($J/\psi \to \mu^+\mu^-$)= 5.961%

Background Channel





- Sources of main background
  - Topology 1: Accidental coincidence of any e’ in FT and radiative tail ^{4}He
  - Topology 2: Accidental coincidence of any l^+l^- and ^{4}He

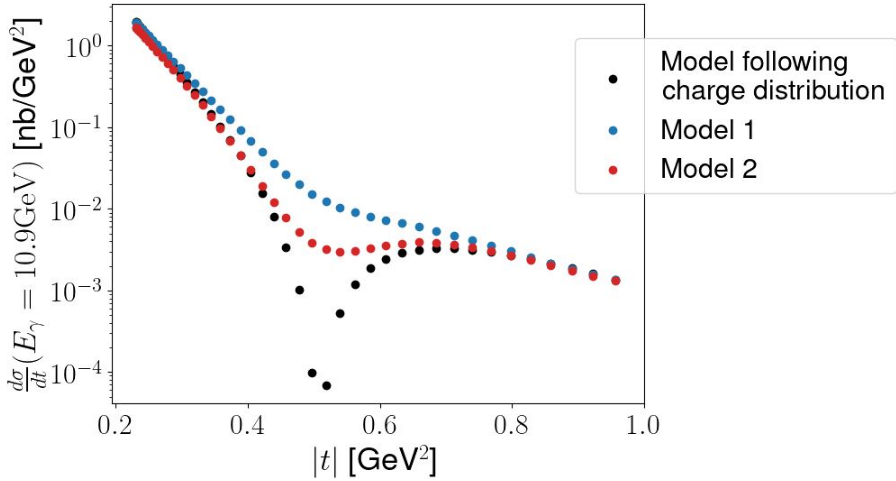
Looking towards ALERT Run Group (RG-L)

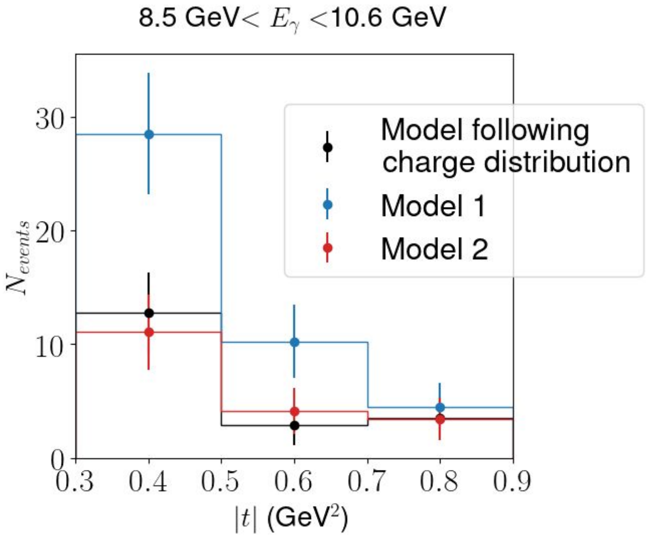
Using ALERT Data (RG-L)

Is there a minimum in $\frac{d\sigma}{dt}$?

- ALERT uses the gaseous 4He target
- RG-L approved beam time:
  - ~26 fb^{-1} integrated luminosity for the nuclei (coherent process)
- **Enough to rule out a minimum** with a few t-bins?

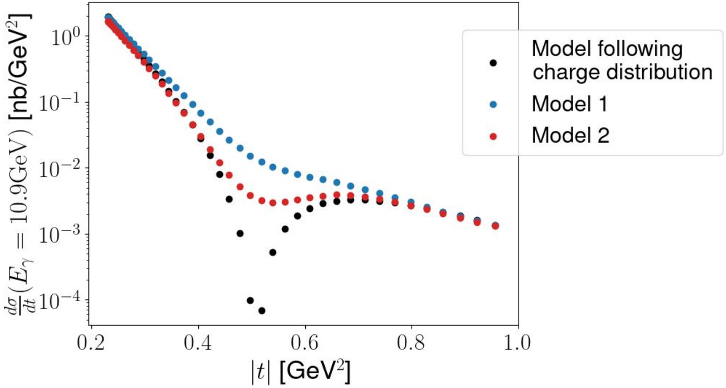
Does the charge distribution follow the gluon distribution?



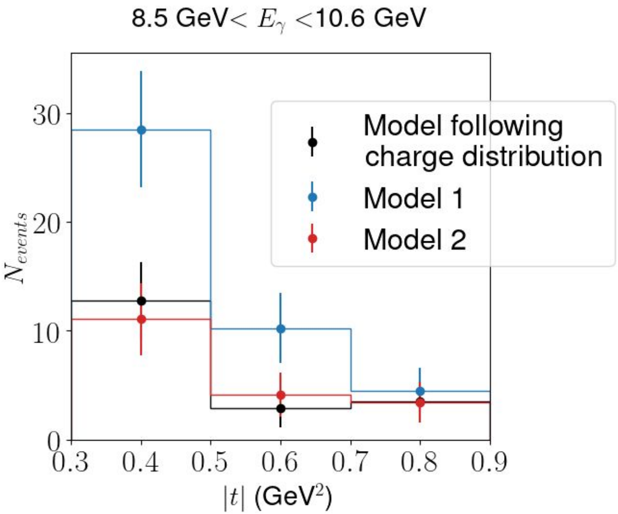


Lessons from the RG-L

- With the ALERT Run Group Data
  - Verify and/or update estimates of cross section
  - Tune the proposal beam request with updated estimates
  - Possibly identify a minimum in differential cross section (or hints therein)?



- The ALERT run will provide important feedback for improvements to the new proposal
  - Efficiencies, acceptance, etc.
  - Possible detector changes for improved kinematic coverage
  - Refine projected statistical and systematic uncertainties

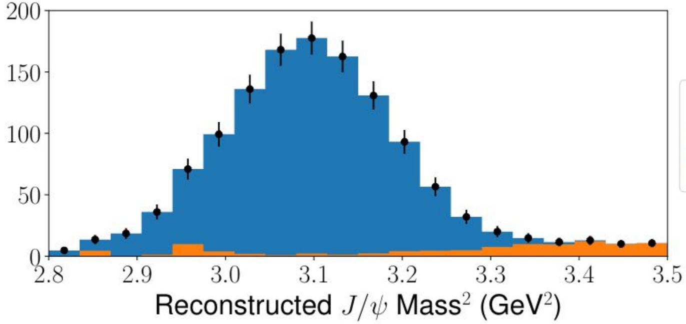


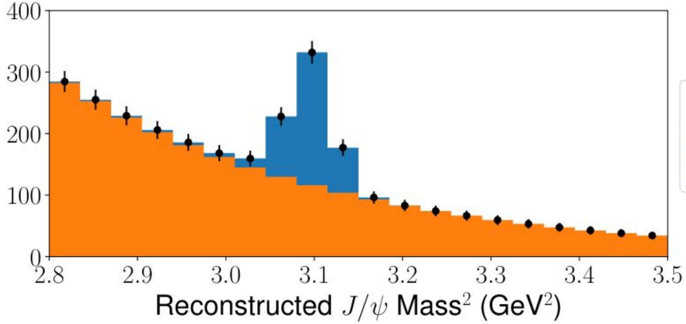
New beam time proposal

Estimated Signal/Background and Requested Beamtime

Topology	Particle	Detector	Condition
1	e'	Forward Tagger	p > 0.5 GeV/c 2.5°<θ<4.5°
		Forward Detectors	p > 1 GeV/c CLAS12 FastMC
	^4He	ALERT	r > 8 cm (ATOF)
2	l^+l^-	Forward Detectors	p > 1 GeV/c CLAS12 FastMC
	^4He	ALERT	r > 8 cm (ATOF)

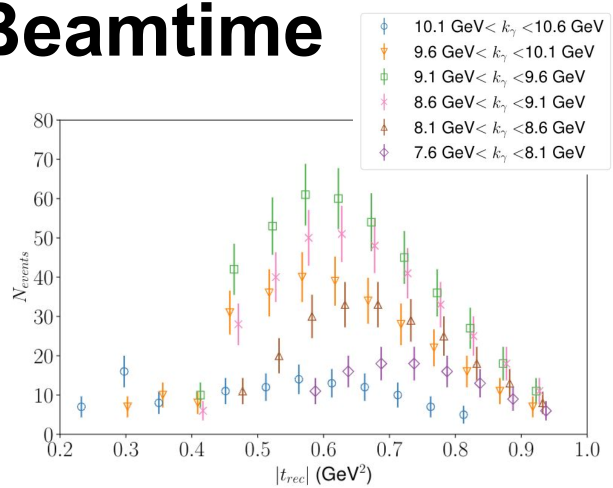
- Signal (blue) is copious compared to Background (orange) for both Topology 1 (top) and Topology 2 (bottom).

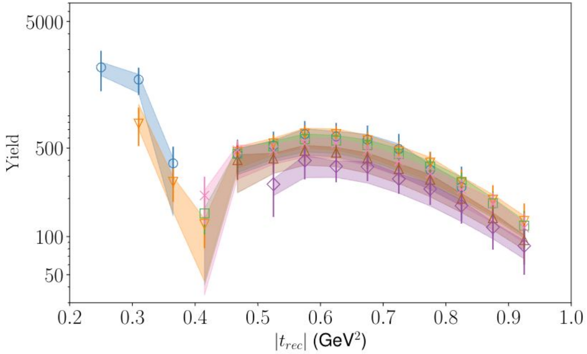




Projected Results and Requested Beamtime

- To ensure that each bin has more than 10 counts, 450 fb^{-1} is the nominal integrated luminosity for coherent processes.
  - RG-L approved: 26 fb^{-1}
- With ALERT and a factor of 2 luminosity upgrade, a luminosity of $L = 5x10^{34}\ cm^{-2}s^{-1}$ is possible for the coherent process at a beam current 1.16 μA
  - the beam blocker limit: 1.3 μA
    (R. Paremuzyan, https://indico.ijclab.in2p3.fr/event/9131/contributions/28948/attachments/20755/28907/Paris_Workshop_2023.pdf)
- We currently plan to request **100 days of beam** with ALERT and ^{4}He target in CLAS12





Responses to the LOI

- We received the collaboration endorsement for the LOI and submitted it to the PAC52.
  - Thank you for the review!

- Well received by JLab theory group, theory report by J.W. Qiu and R. Edwards sent to contact person privately.
  - *“Such measurement could address important questions concerning the respective distributions of quarks and gluons inside a nucleus, such as does the gluonic form factor have a similar minimum as the charge form factor?”*

- PAC report is public. Assigned reader was F. Yuan (LBNL).
  - Gluon radius measurement is well-received.
    - *“The diffraction minimum for light nuclei target is an interesting subject, as it can be compared to the relevant charge form factor measurements.”*
  - Phenomenological concern about small skewness for GFF extraction and interpretation of the result
  - To be discussed at the full proposal

Impact of this work

- First measurement for the differential cross section of coherent J/ψ production on ^{4}He.
  - Top: quote from T. Toll and T. Ullrich, PRC 87 (2013)

- Lots of fruitful theory discussions about nuclear GFF is ongoing with new publications from independent groups, especially this year.
  - 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).

- A partial answer to PAC52's question can be found in F. He and I. Zahed's preprint (arXiv:2407.09991).
  - Careful approach to the interpretation? Yes.
  - No show-stopper for the measurement.

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

Threshold photo-production of J/Ψ off light nuclei

Fangcheng He[1,2,*] and Ismail Zahed[1,†]

We note that the value of the center of mass energy used $W = 10\,\mathrm{GeV}$ implies a low value of the skewness parameter from Fig. 2, suggesting that higher corrections in ξ to (14) maybe needed. However, we recall that for the nucleon case, dual gravity arrives at a similar result (in the large N_c limit) without assuming large skewness [21].

Summary

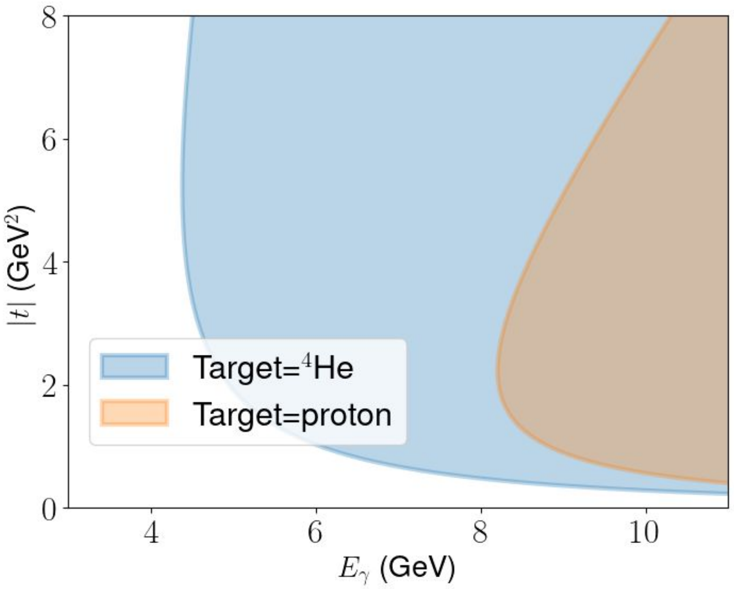
- We propose to use CLAS12 and ALERT to study QCD in nuclei
  - Coherent J/psi electroproduction on ^4He at 11 GeV
  - First extraction of GFFs for ^4He

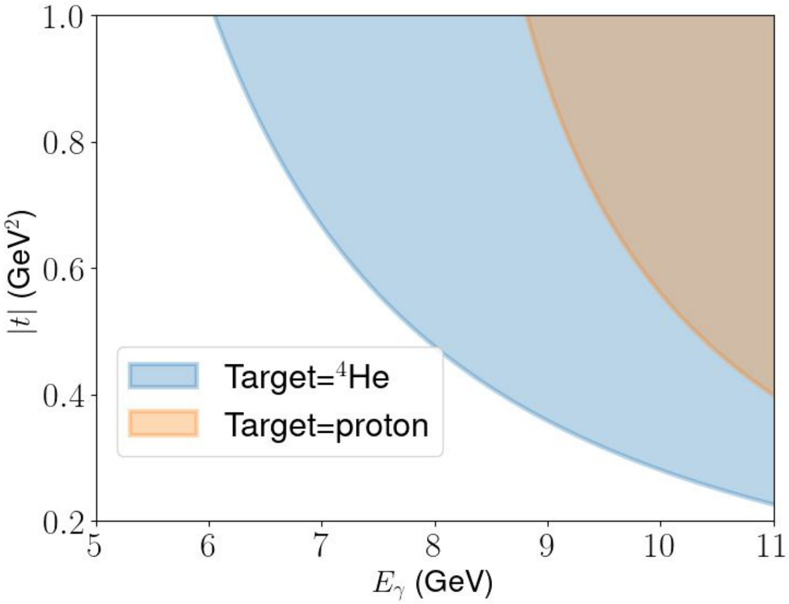
- Next steps towards the proposal
  - Careful investigation of all backgrounds with simulation
  - Update the projection of the latest cross section models
  - Refine measured cross-section binning for the optimal GFF extraction
  - Perform the impact study on the GFFs using detailed simulation data

- We invite more CLAS collaborators to the full proposal for this high impact experiment

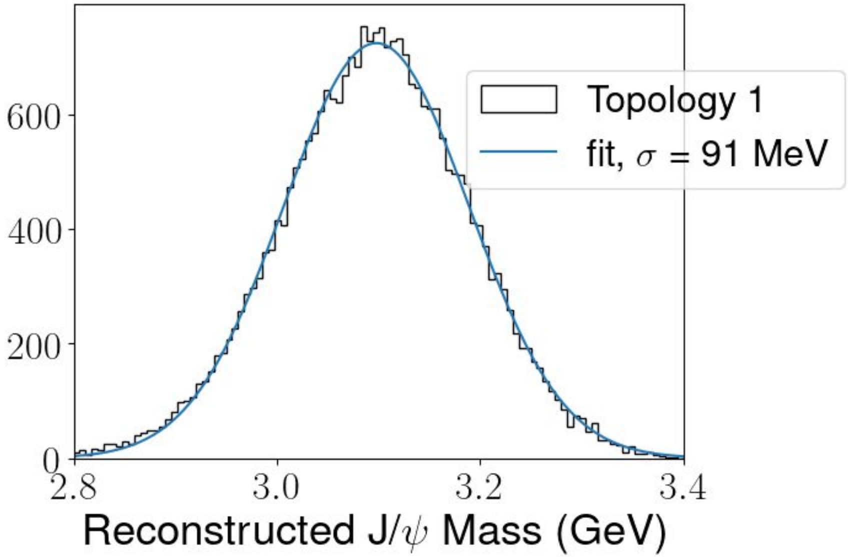
Backup

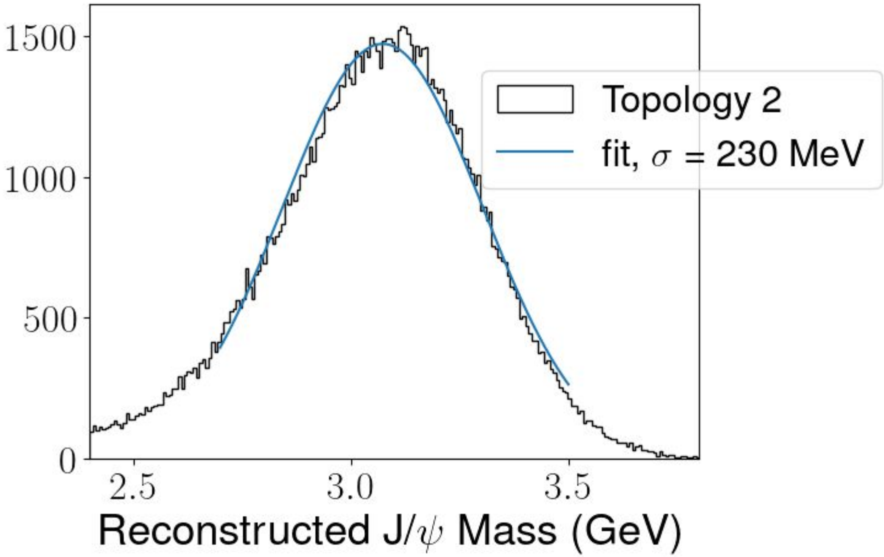
Allowed Phase Space



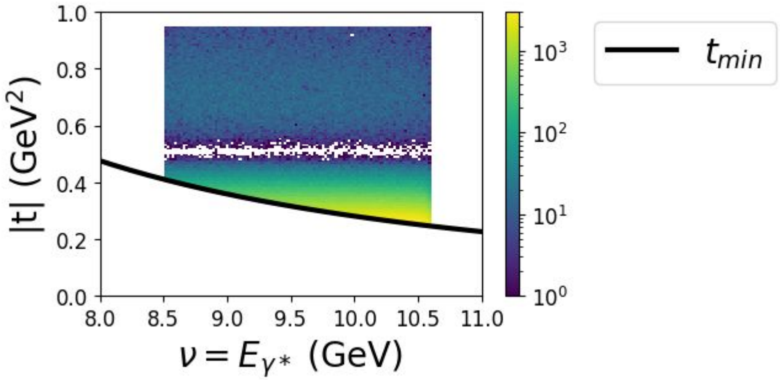


Resolutions in J/ψ Mass





MC Simulation



Event Generator

2M events with Lager (E_{beam} = 10.6 GeV) (https://eicweb.phy.anl.gov/monte_carlo/lager/)

Model

Based on T-S. H. Lee's calculation for E_{beam} = 11 GeV

$E_{\gamma*}$ > 8.5 GeV

Final states

A. Scattered electron
B. Recoil He4
C. $J/\psi \rightarrow e^+e^-$

Possible detection scenarios

A-B, A-C, B-C, A-B-C

Total cross sections

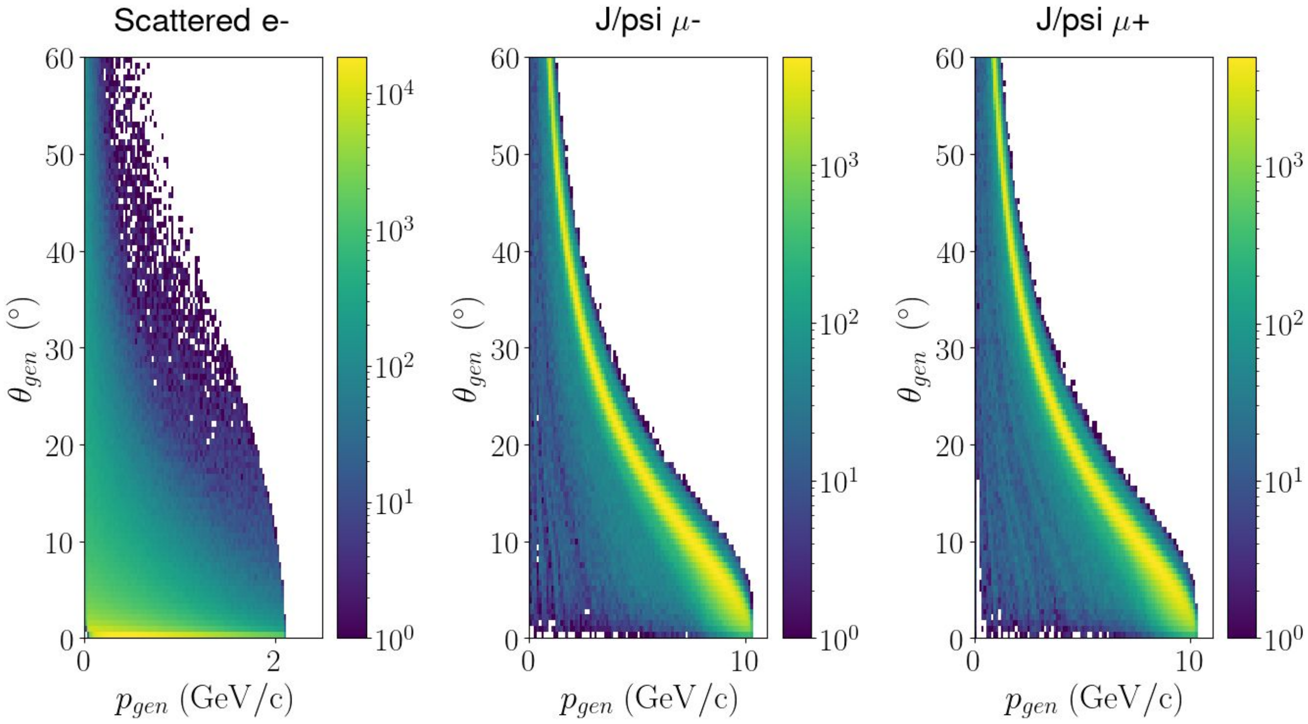
σ ($E_{\gamma*}$ > 8.5 GeV) = 4.7 $\times 10^{-5}$ nb

σ ($E_{\gamma*}$ > 8.5 GeV, $J/\psi \rightarrow e^+e^-$) = 2.6 $\times 10^{-6}$ nb

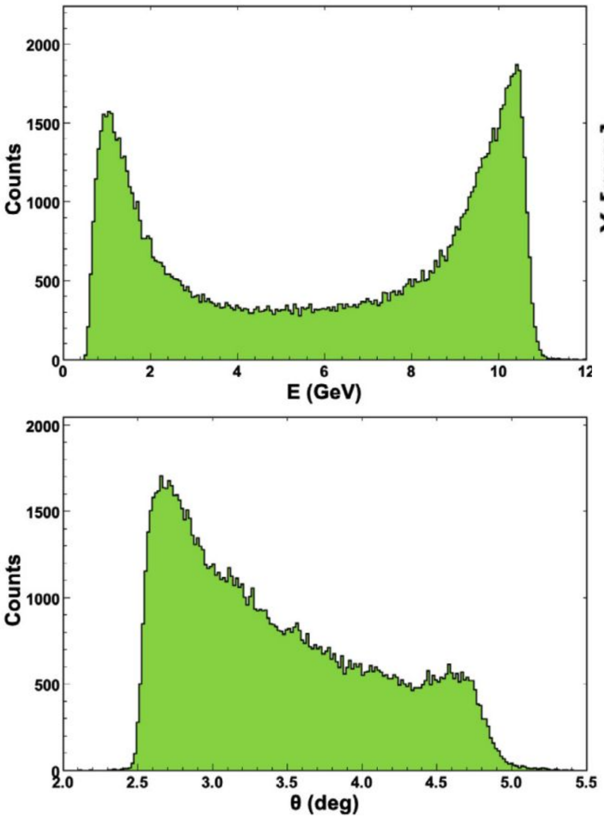
Pro of detecting C) Clear sign of J/ψ

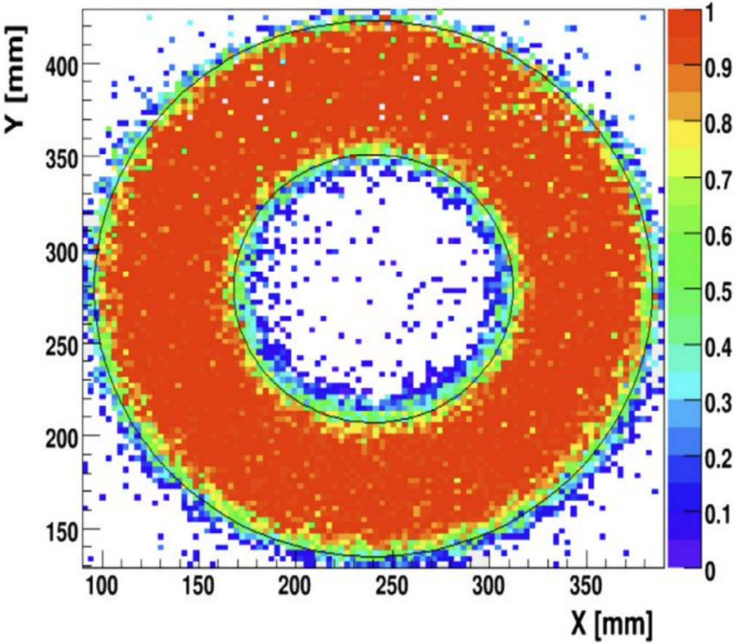
Con of detecting C) 6% BR and reduced overall acceptance

Lepton kinematic variables



Forward Tagger Coverage



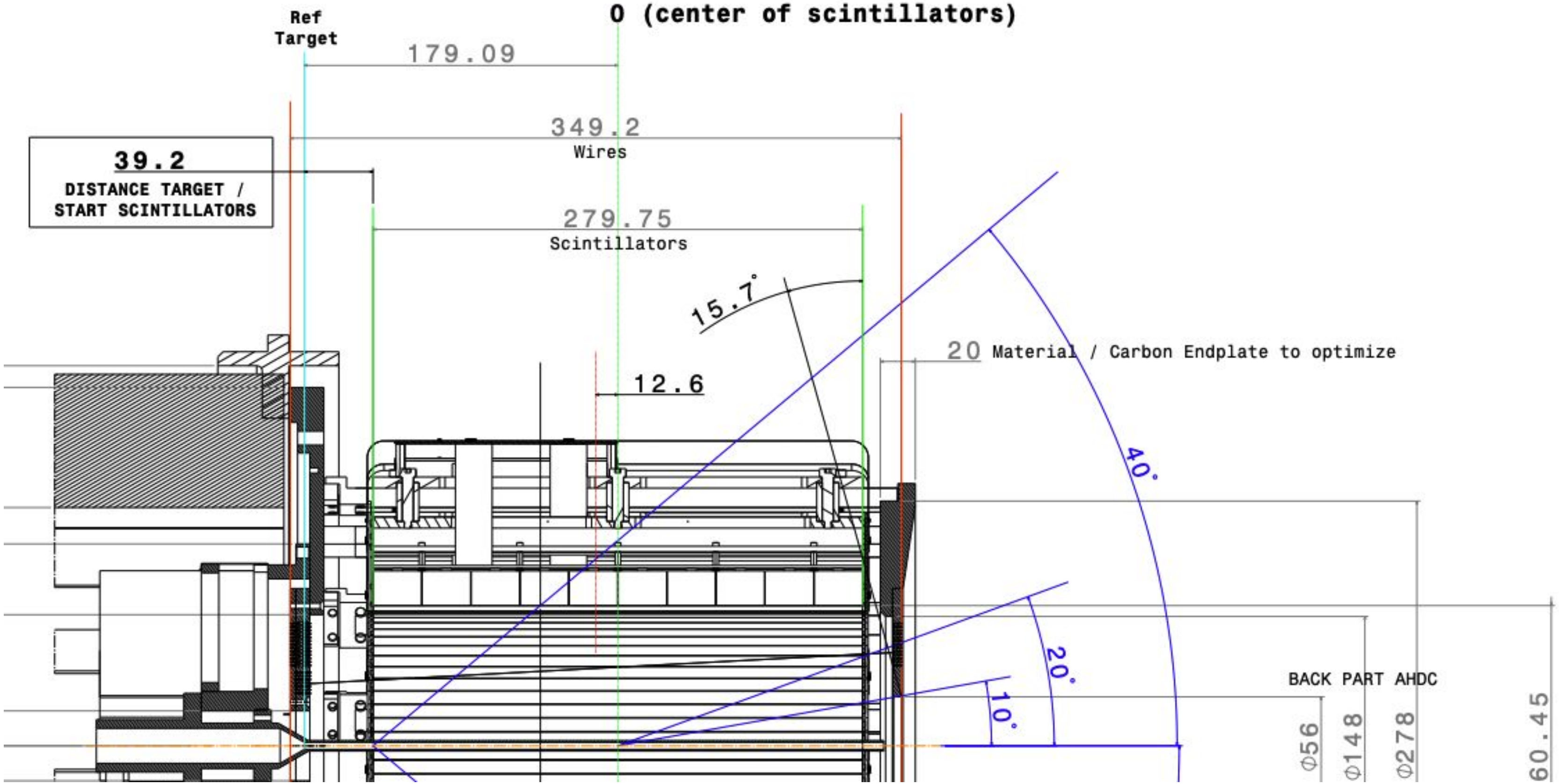


$$p > 500\ \mathrm{MeV/c}$$

$$2.5^\circ < \theta < 4.5^\circ$$

From A. Acker et al, The CLAS12 Forward Tagger (NIM A 959, 163475 (2020))

ALERT - Extend upstream target for low |t|



ALERT Beamtime and Luminosity

Configurations	Proposals	Targets	Beam time request days	Beam current nA	Luminosity* n/cm²/s
Commissioning	All†	^{1}H, ^{4}He	5	Various	Various
A	Nuclear GPDs	^{4}He	10	1000	6×10^{34}
B	Tagged EMC & DVCS	^{2}H	20	500	3×10^{34}
C	All†	^{4}He	20	500	3×10^{34}
TOTAL			**55**		

The beam current is lowered with thicker target

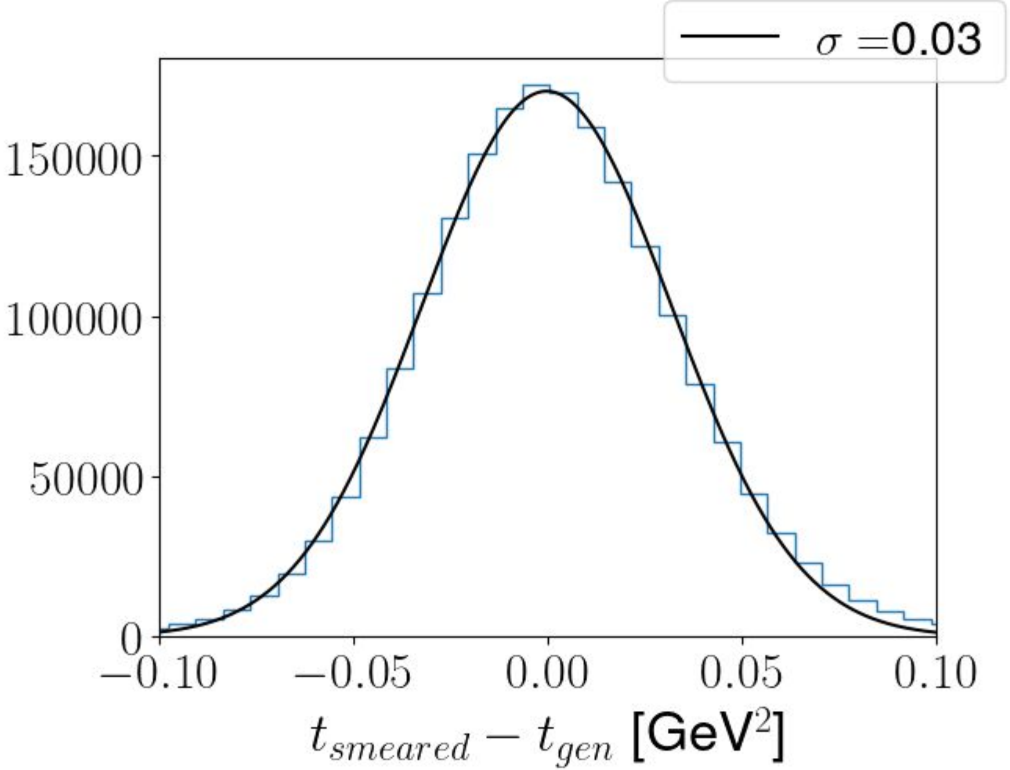
Luminosity remains the same

Total 30 days, 10 days of 60 nb^{-1}/s and 20 days of 30 nb^{-1}/s for the nucleon.

This is 104/4 = 26 fb^{-1} for the nuclei.

Resolution in $|t|$

- ^{4}He p was smeared out with 5% resolution.



Background channels

Incoherent channel background

- ex) DIS
- Should be suppressed by detecting the ^4He

ISR + elastic scattering

- Distinguished by the missing mass

Accidentals

- Møller background, especially at the Forward Tagger
  - https://www.ge.infn.it/~batta/jlab/ft-tdr.2.2.pdf

Accessing the GFFs and Binning

$$\frac{d\sigma}{dt} = \text{Kinematic Factor}(E_\gamma, t) \times |A(t) + \xi^2 D(t)|^2$$

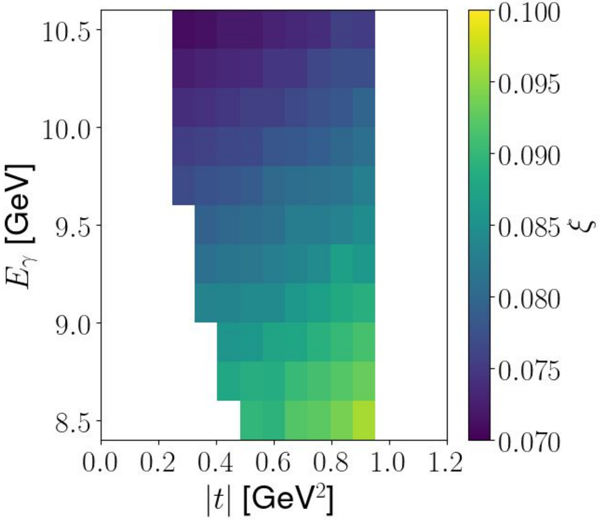
$$\xi = \frac{t - M_{J/\psi}^2}{2M_{^4He}^2 + M_{J/\psi}^2 - 2W^2 - t}$$

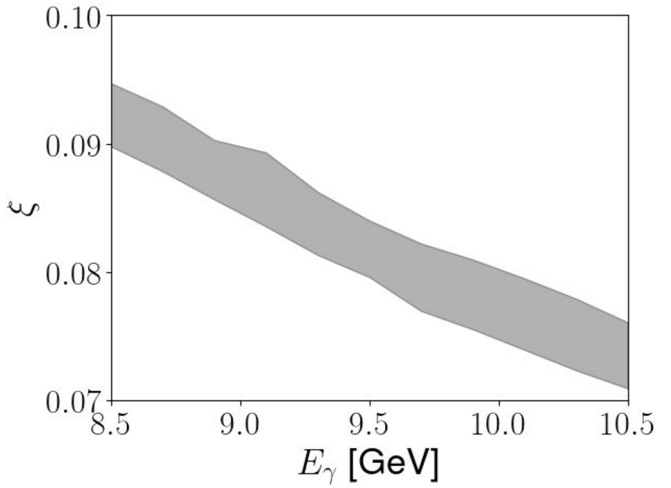
$$\begin{cases} A(t) + \xi_1^2 D(t) = F[\sqrt{\frac{d\sigma}{dt}}_1, \xi_1; t] \\ A(t) + \xi_2^2 D(t) = F[\sqrt{\frac{d\sigma}{dt}}_2, \xi_2; t] \end{cases}$$

- 2 bins in $E\gamma$

  Bin 1: [8.5, 9 .5] GeV
  Bin 2: [9.5, 10.6] GeV

- 9 bins in $|t|$





Model Dependence

$$\left(\frac{d\sigma}{dt}\right) = 2 \times \frac{e^2}{64\pi(s-m_N^2)^2} \times \left(\frac{f_V}{M_V}\right)^2 \times \mathbb{V}_{h\gamma V} \times 2\kappa^2 \times \left[A(K,\kappa_T) + \eta^2 D(K,\kappa_T,\kappa_S)\right]^2 \times \tilde{F}(s) \times \frac{8m_N^2}{m_N^2},$$

$$= \mathcal{N}^2 \times \frac{e^2}{64\pi(s-m_N^2)^2} \times \frac{\left[A(K,\kappa_T) + \eta^2 D(K,\kappa_T,\kappa_S)\right]^2}{A^2(0)} \times \tilde{F}(s) \times 8\,, \qquad \text{(III.31)}$$

K. Mamo and I. Zahed, PRD 106, 086004 (2022)

F. He and I. Zahed, arXiv 2310.12315

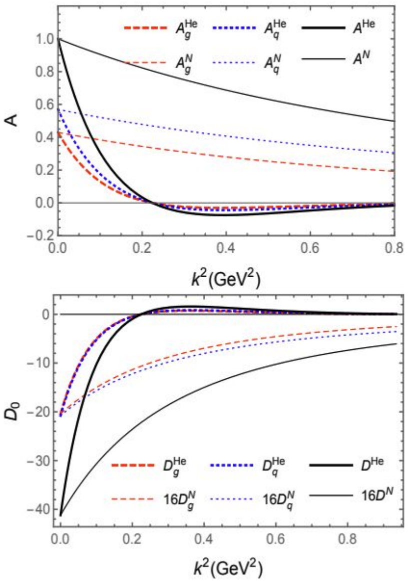


FIG. 8: A- and D-form factors for Helium-4 obtained using K-harmonic method.

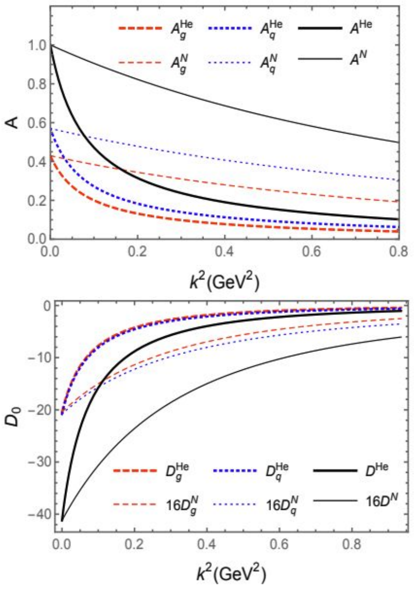


FIG. 9: A- and D-form factors for Helium-4 obtained using Woods-Saxon potential.

A. G. Martín-Caro, M. Huidobro, and Y. Hatta, PRD 108, 034014 (2023)

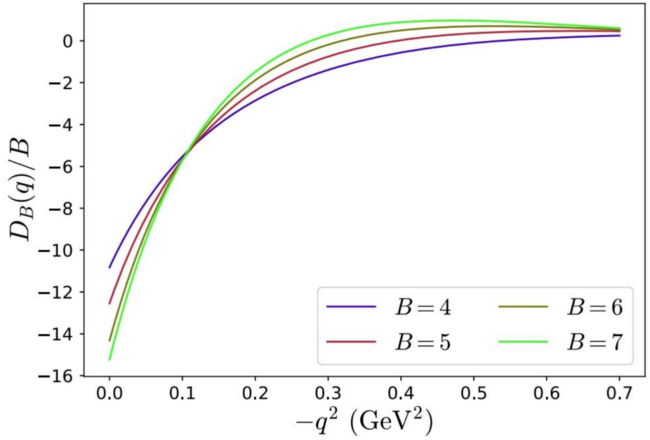


FIG. 3. The D gravitational form factor of the skyrmions with $B = 4$, 5, 6, and 7, normalized by B, for the $\lambda = 0$ case.

Model Dependence

Caveat: this is for the EIC kinematics.

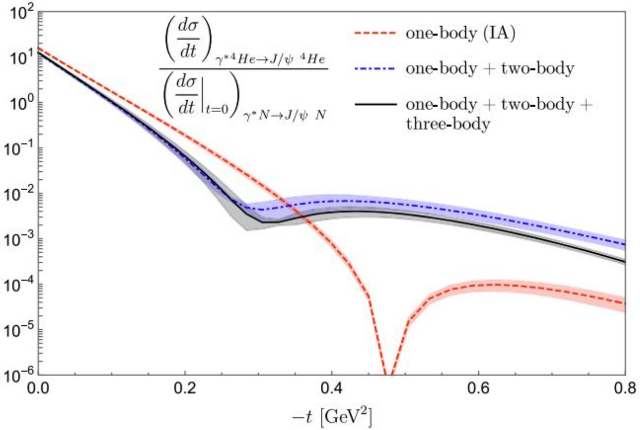


FIG. 3. Ratio of the differential cross section for J/ψ coherent production on ^{4}He to the same quantity for the nucleon target at $t = 0$ as a function of $-t$ at $x = 10^{-3}$. Relative errors of 10% and 15% have been considered on the quantities B_0 and σ_2, respectively (see text and the Supplemental Material [31]).

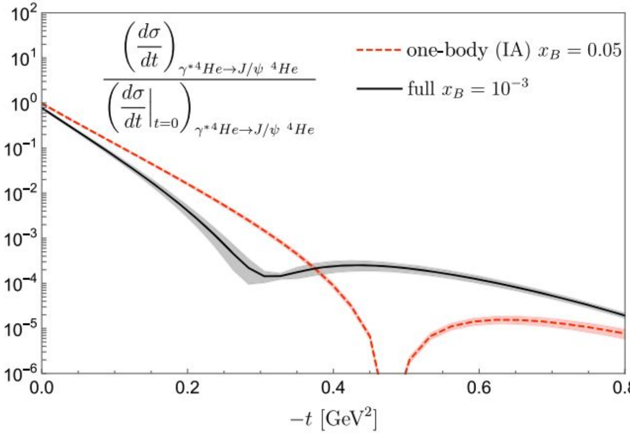


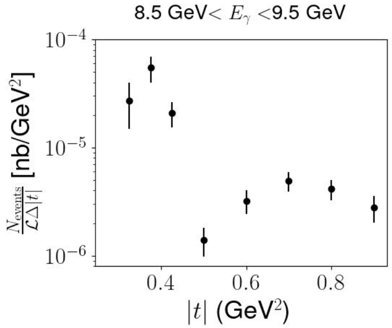
FIG. 4. Ratio of the differential cross section for J/ψ coherent production on ^{4}He to the same quantity at $t = 0$ as a function of $-t$: the IA result at $x = 0.05$ is compared with the full one at $x = 10^{-3}$. Relative errors of 10% and 15% have been considered on the quantities B_0 and σ_2, respectively (see text and the Supplemental Material [31]).

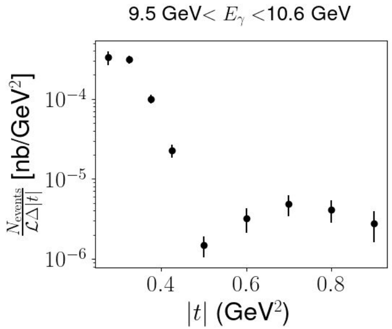
V. Guzey, M.Rinaldi, S.Scopetta, M. Strikman, and M. Viviani, PRL 129, 242503 (2022)

VMD Model Framework

From the photoproduction to electroproduction,

$$\sigma_{elec.} = \sigma_{photo.} \times \left(\frac{M_V^2}{Q^2 + M_V^2} \right)^m \times (1 + \epsilon R(Q^2))$$





ex) A. Airapetian et al, "Exclusive Leptoproduction of rho0 Mesons on Hydrogen at Intermediate W Values", EPJ C 17 (2000) 389-398