Few-Body Physics with CLAS

G.P. Gilfoyle
(for the CLAS Collaboration)

Outline

1. Scientific Motivation
2. Jefferson Lab and CLAS
3. Short-Range Correlations in Cold Nuclear Matter
4. Three-Body Forces in Nuclei
5. Scaling in Photonuclear Reactions
6. Summary and Conclusions

Scientific Motivation

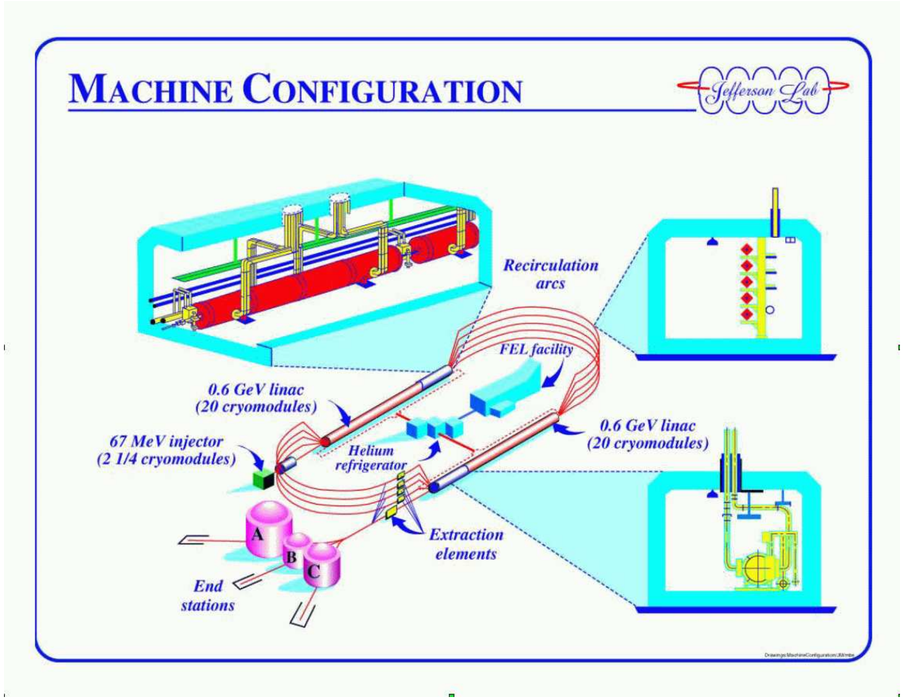
- What are the phases of strongly interacting matter, and what roles do they play in the cosmos?
- What does QCD predict for the properties of strongly interacting matter?
- What governs the transition of quarks and gluons into pions and nucleons?
- What is the role of gluons and gluon self-interactions in nucleons and nuclei?

The Frontiers of Nuclear Science, A Long Range Plan, The DOE/NSF Nuclear Science Advisory Committee, December, 2007.

Similar raised questions in *NuPECC Long Range Plan 2004.*

The Continuous Electron Beam Accelerator Facility at JLab

View of site in Newport News, Va.

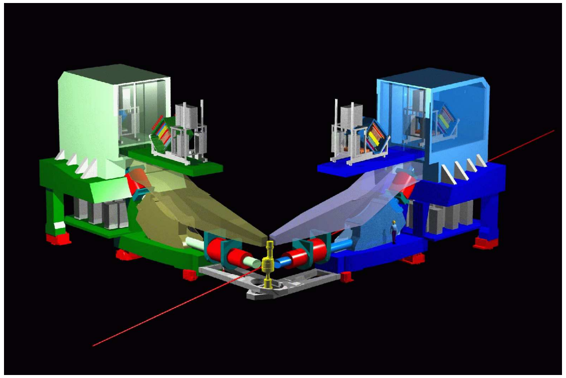


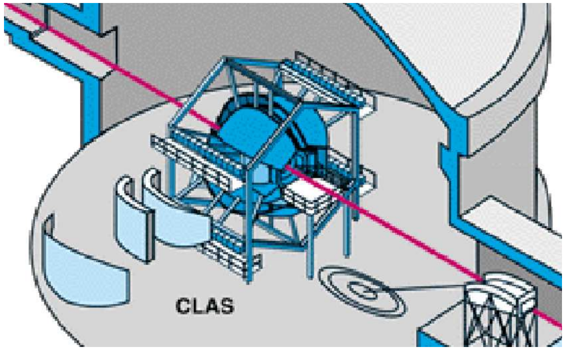
Schematic of accelerator and components.

Superconducting Electron Accelerator (338 cavities), 100% duty cycle, $I_{max} = 200\ \mu A$, $E_{max} = 6\ GeV$, $\Delta E/E = 10^{-4}$, $P_e > 80\%$, 1500 physicists, over 30 countries, operational since end of 1997.

The JLab End Stations

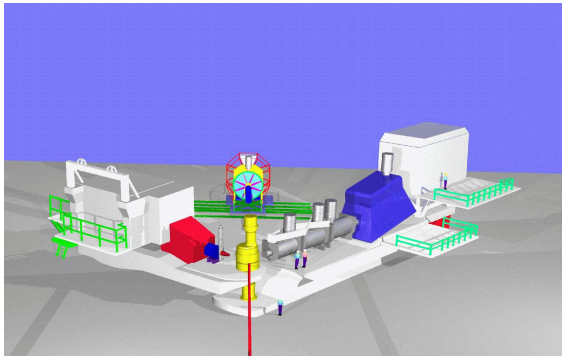
Hall A - Two identical, high-resolution spectrometers ($\Delta p/p < 2 \times 10^{-4}$); luminosity $\approx 10^{38}\ cm^{-2}s^{-1}$.



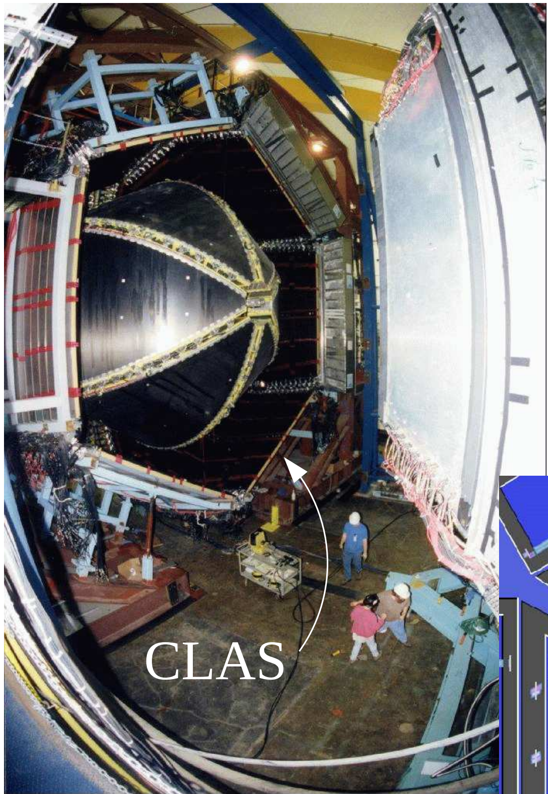


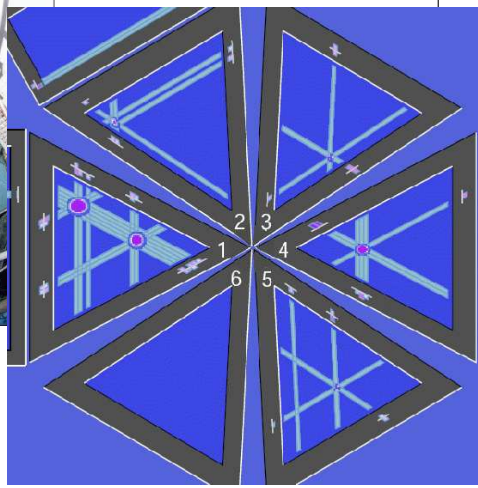
Hall B - The CLAS, nearly 4-π-acceptance spectrometer based on a toroidal magnet ($\Delta p/p = 0.5\%$); luminosity $\approx 10^{34}\ cm^{-2}s^{-1}$.

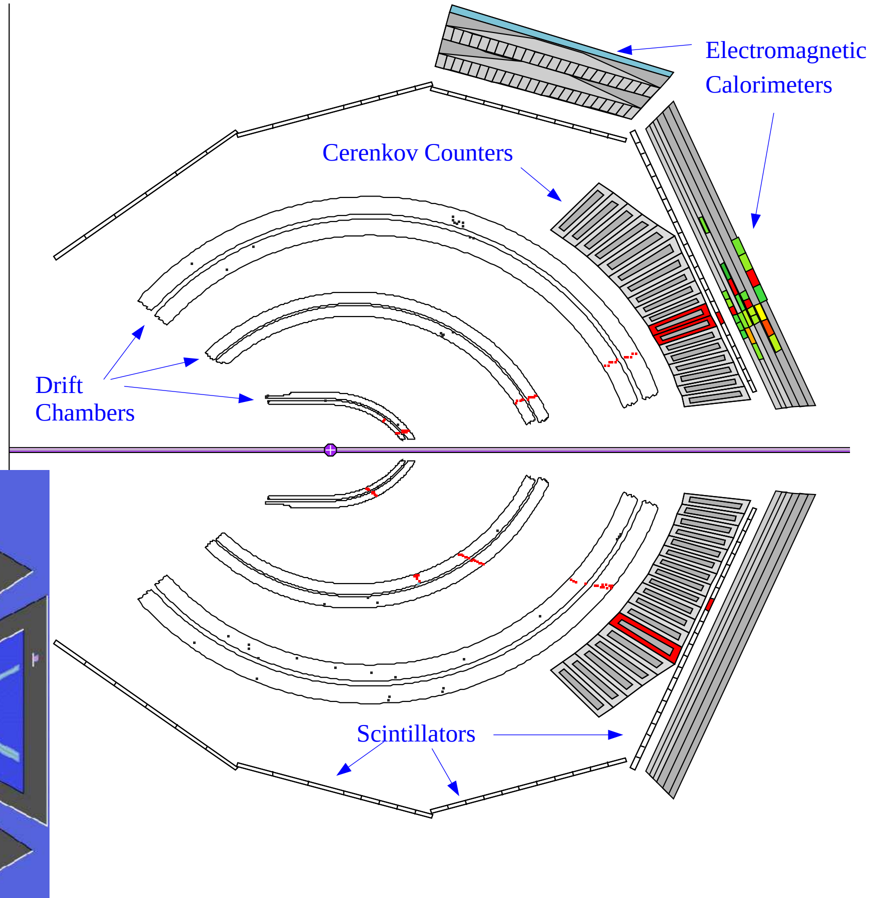
Hall C - Moderate-resolution (10^{-3}), 7-GeV/c High-Momentum Spectrometer (HMS) and the large-acceptance Short-Orbit Spectrometer (SOS) and additional detectors.



The Experiment - CLAS







Six identical mass spectrometers.

Charged particle angles: $8^\circ \; - \; 144^\circ$.

Momentum resolution: $\approx 0.5\%$ (charged).

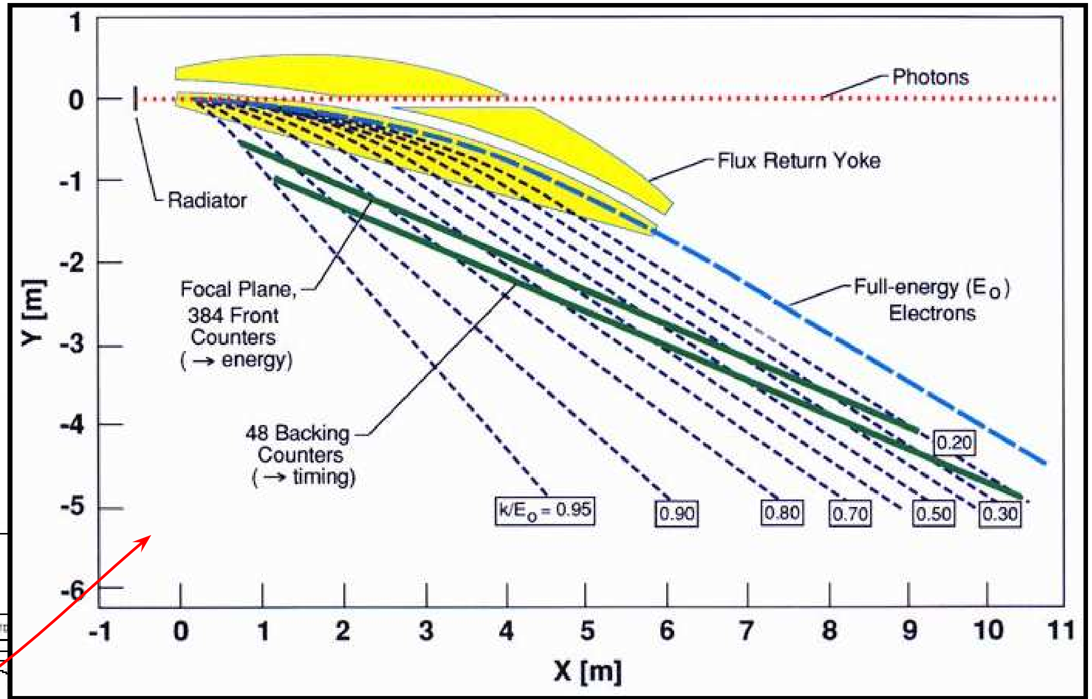
Particle ID: p, π^+/π^-, K^+/K^-, e^+/e^-.

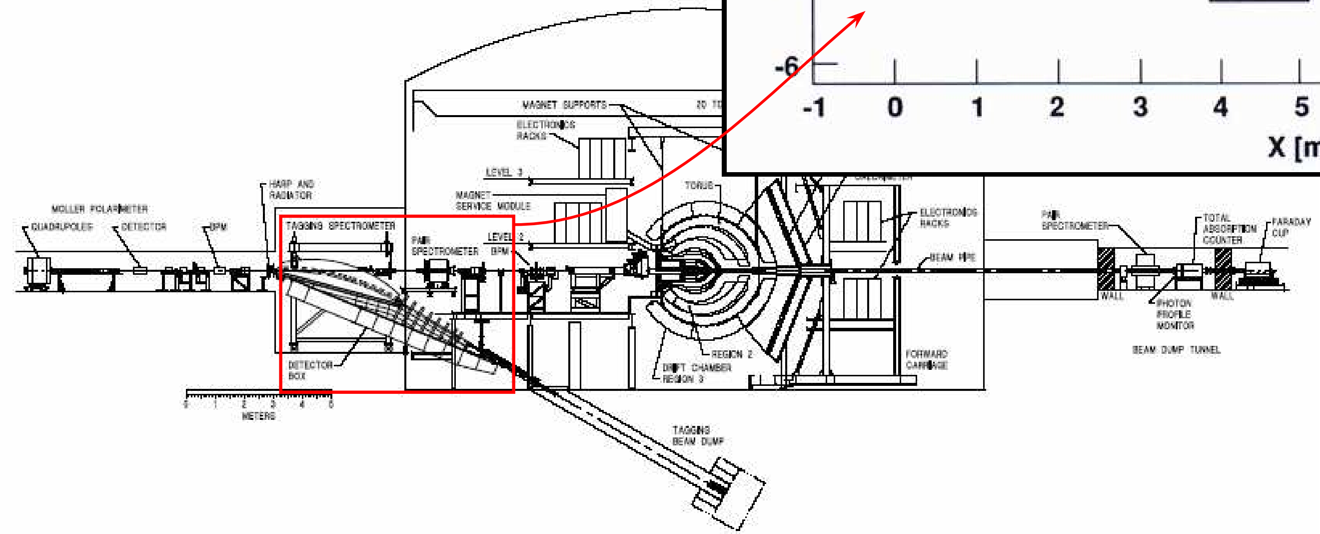
Neutral particle angles: $8^\circ \; - 70^\circ$.

Angular resolution: $\approx 0.5 \; mr$ (charged).

The Experiment - CLAS + Real Photons

- Bremsstrahlung Photon Tagger ($\Delta E/E \approx 10^{-3}$)
- Photon Range: 0.2 - 0.95 of E_{beam} up to 6 GeV.

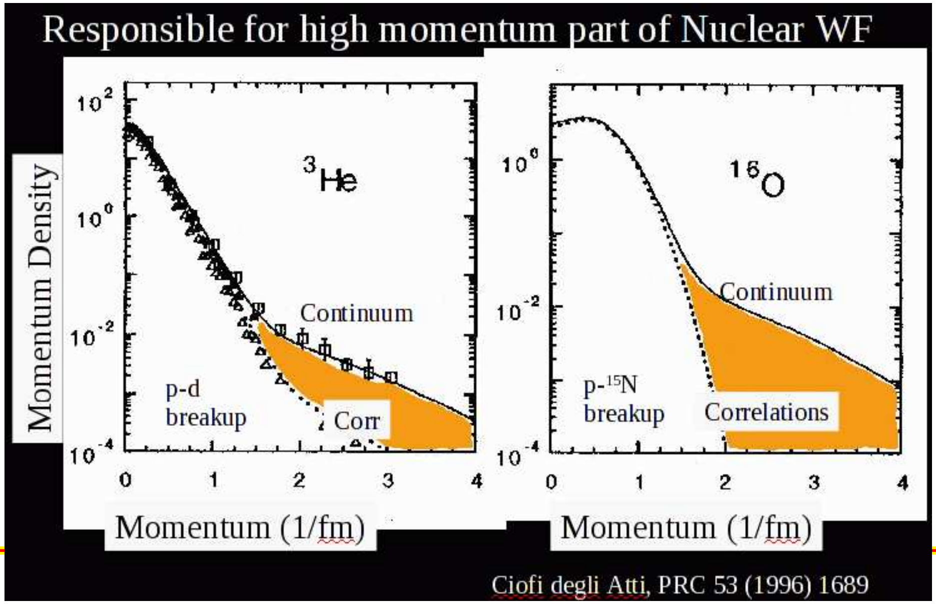




Short-Range Correlations (SRC) in Nuclei

Physics Motivation

- What are they? - High momentum nucleon balanced by one (or two ...) other nucleon.
- Nuclei have been long been approximated as individual nucleons moving in the mean field created by the other nucleons.
- This picture is only good to about 70% (*e.g.* see J.Gao *et al.*, PRL, 84, 3265 (2000)). We get a C^-. The other 30% may be hidden away in the SRCs and ...
- SRCs probe the high-momentum components of the nuclear wave function, cold, dense nuclear matter, the physics of neutron stars, and the EMC effect.



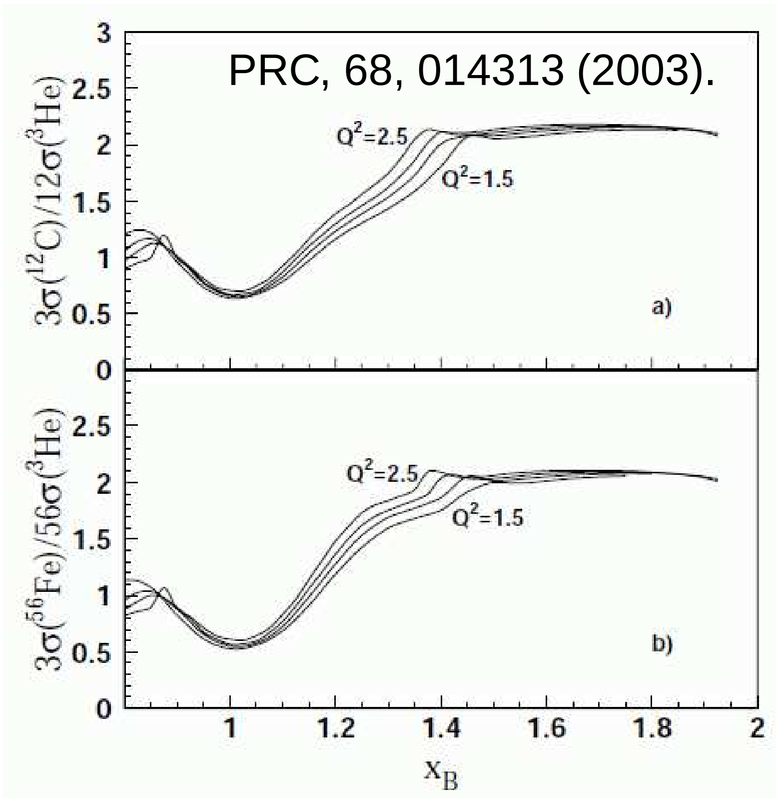
Short-Range Correlations (SRC) in Nuclei

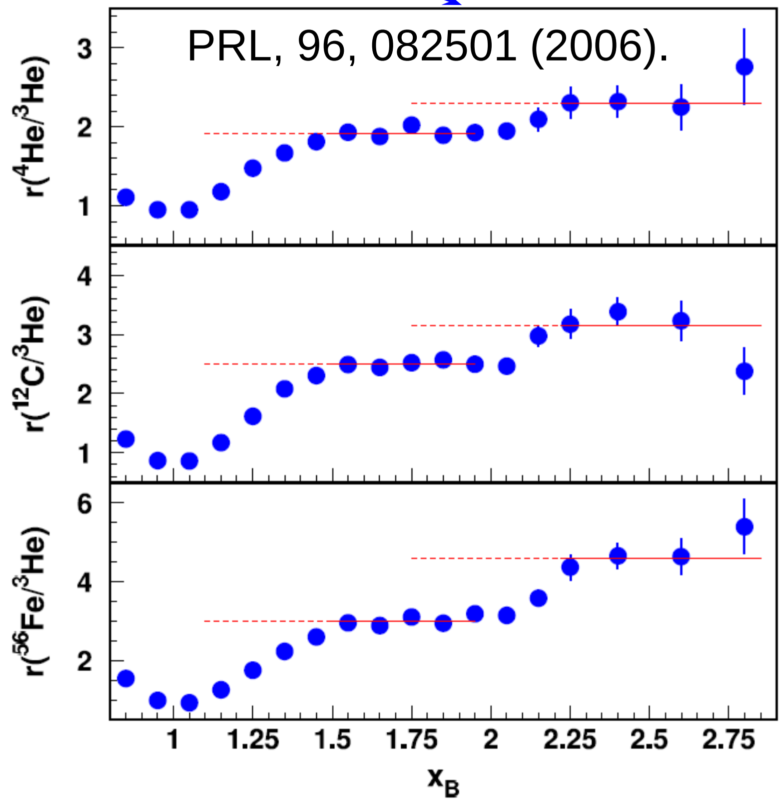
How do we find them?

- SRC expected to exist in quasielastic, inclusive electron scattering, but difficult to extract.
- Signal for SRC in quasielastic exclusive electron scattering obscured by inelastic reactions, final-state interactions (FSI), and quasielastic scattering from low-momentum, uncorrelated nucleons (*e.g.* see J.Arrington *et al.*, PRL, 82, 2056 (1999)).
- Apply new kinematic constraints and exclusive reactions to pull the SRCs out of surrounding noise.
  - Scaling in quasielastic $A(e,e')A-1$.
  - Exclusive knock-out reactions $(e,e'pN)$.

Short-Range Correlations in (e, e')

- High-momentum part of nuclear wave function is similar for different nuclei so the ratio should SCALE!
- Extract the ratio of the cross section in a nucleus to the cross section in $^3\mathrm{He}$ to minimize FSI.



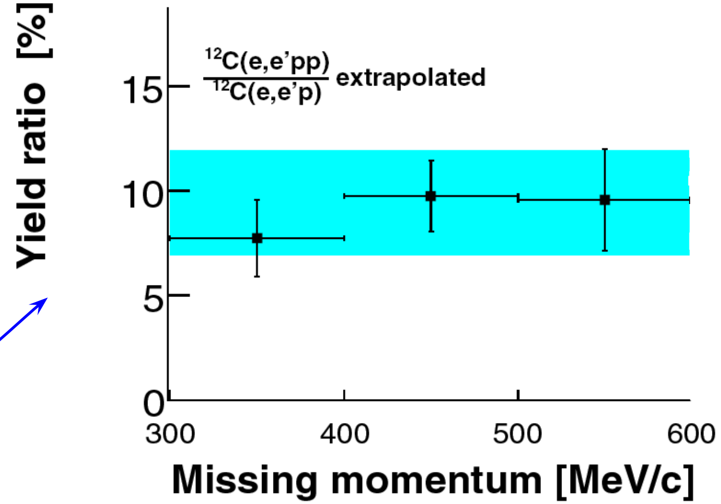


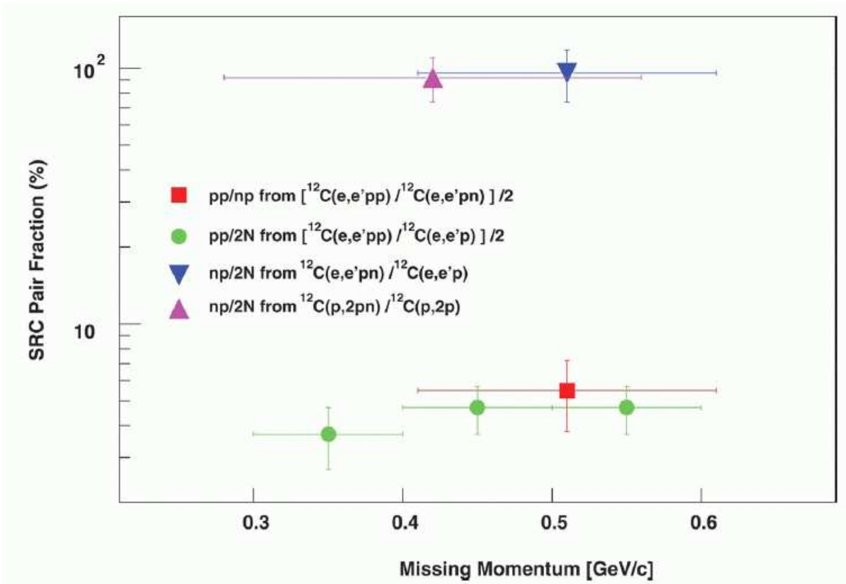
Fraction of SRCs is 8% ($^3\mathrm{He}$) to 23% ($^{56}\mathrm{Fe}$).

Short-Range Correlations in Nuclei

Next-Generation Exclusive Reactions in Hall A at JLab

- Use Hall A, BigBite for protons, and a neutron array; smaller kinematic range, but higher luminosity.
- Use ratios of $^{12}\mathrm{C}(\mathrm{e},\mathrm{e}'\mathrm{p})$ and $^{12}\mathrm{C}(\mathrm{e},\mathrm{e}'\mathrm{pp})$; pp correlations are ≈10% (R. Schneor *et al.*, PRL 99, 072501 (2007)).
- Measure $^{12}\mathrm{C}(\mathrm{e},\mathrm{e}'\mathrm{p})$, $^{12}\mathrm{C}(\mathrm{e},\mathrm{e}'\mathrm{pp})$, and $^{12}\mathrm{C}(\mathrm{e},\mathrm{e}'\mathrm{pn})$; pn SRCs dominate - $\sigma(pn)/\sigma(pp) = 18 \pm 5$ (R.Subedi *et al.*, Science, 320, 1476-1478 (2008)).
- Consistent with BNL results with a proton beam (E. Piasetzky *et al.*, PRL. 97, 162504 (2006)).

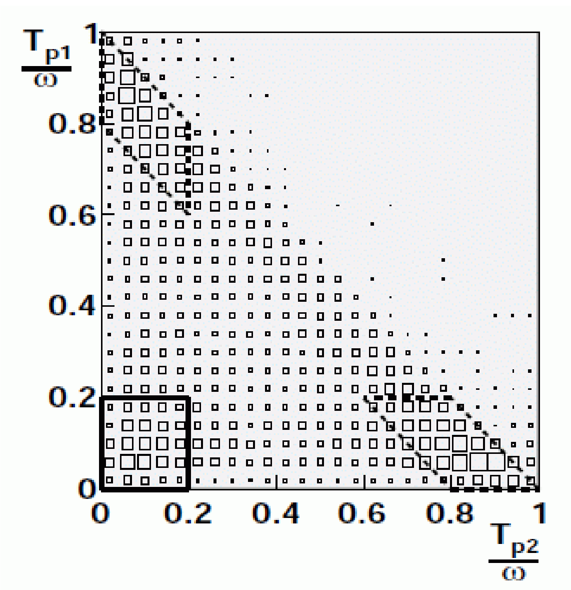


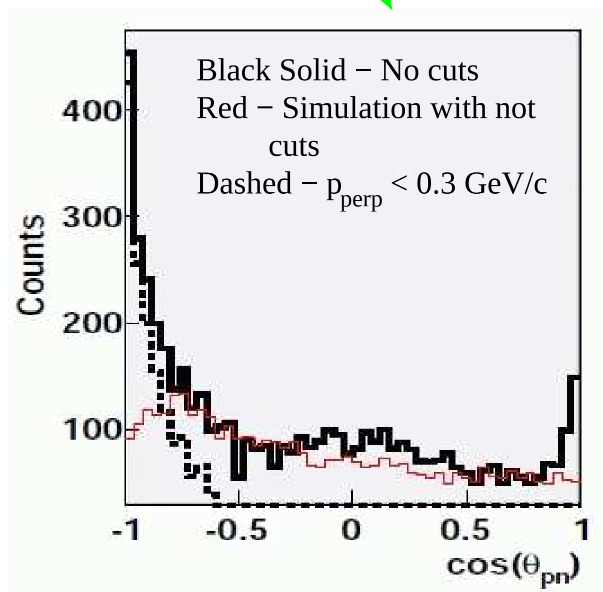


Short-Range Correlations in Nuclei

Next-Generation Exclusive Reactions in CLAS

- Start with the $^3\mathrm{He}(\mathrm{e},\mathrm{e}'\mathrm{pp})\mathrm{n}$ reaction over a broad kinematic range.
  - Use missing mass to select neutron residual.
  - Make cuts on T/ν to select fast nucleons and with an SRC spectator.
  - Require the leading nucleon to be in the direction of $\vec{q}$ to reduce FSI ($p_\perp < 0.3\ GeV/c$).
- Angular distribution will be test for correlated pairs.

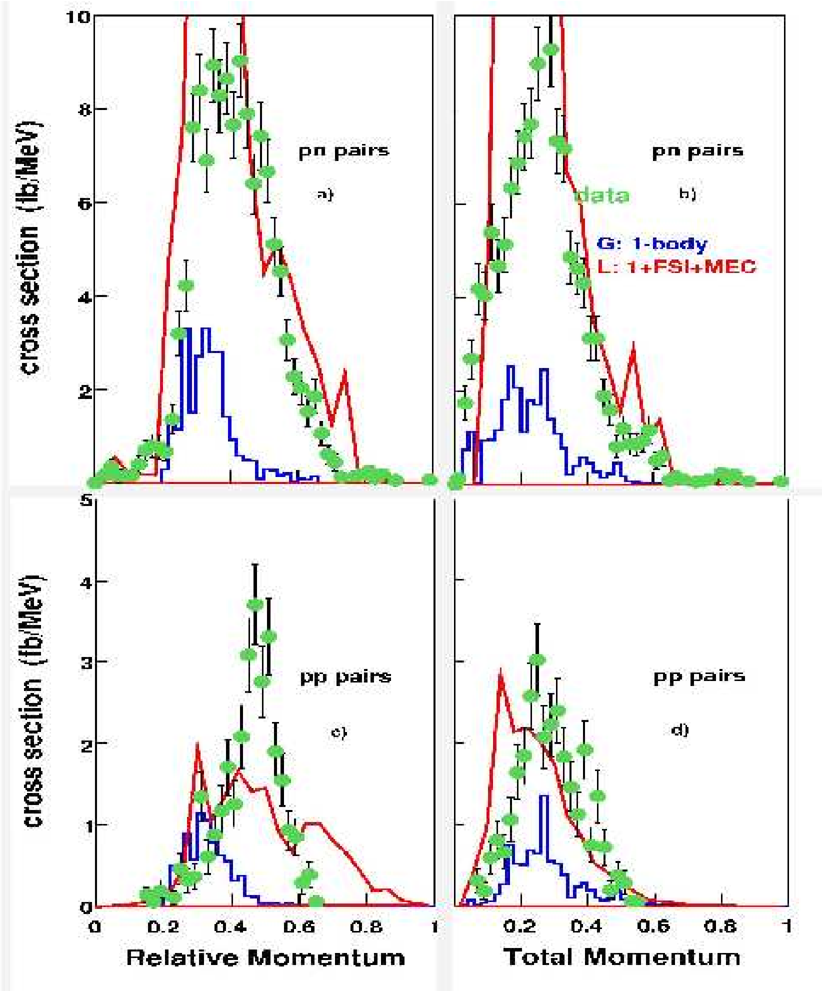




Short-Range Correlations in Nuclei

Next-Generation Exclusive Reactions in CLAS

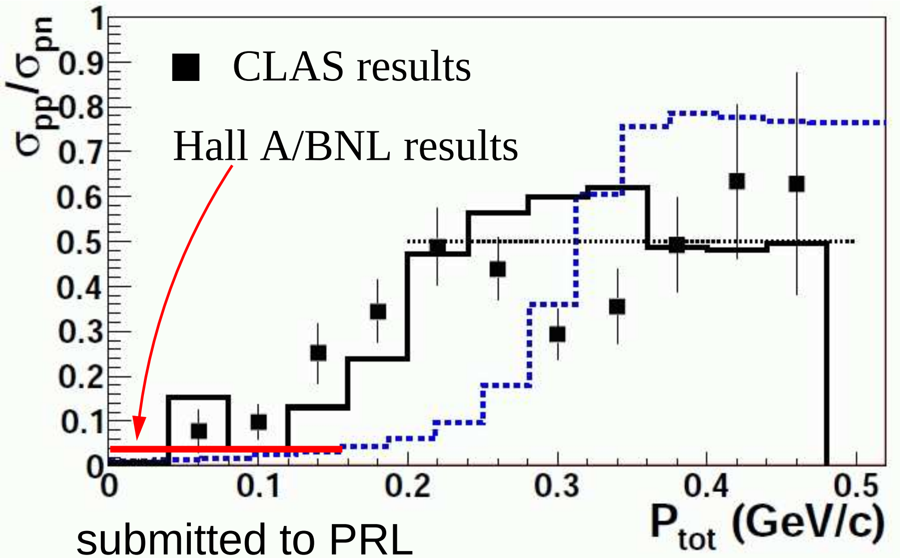
- Measure $^3\mathrm{He}(\mathrm{e},\mathrm{e'pp})\mathrm{n}$ at 4.7 GeV and 2.0 GeV.
- Distributions for pp and np pairs as functions of p_{tot} and p_{rel} are similar (only 4.7-GeV data shown).
  - Blue - Golak single-body calculation (PRC 51, 1638 (1995)).
  - Red - Laget single-body plus MEC and IC.
- Integrated $\sigma(pp)/\sigma(np) \approx 1/4$.
  - consistent with pair counting.
- Contradicts results from Hall A (R.Subedi *et al.*, Science, 320, 1476-1478 (2008)) where $\sigma(pp)/\sigma(np) \approx 1/18$.



Short-Range Correlations in Nuclei

Resolving the difference.

- Hall A results were for $0.3 < p_{rel} < 0.5\ \mathrm{GeV/c}$ and $p_{tot} < 0.3\ \mathrm{GeV/c}$.
- Integrate CLAS results for $\sigma(pp)/\sigma(pn)$ over the same p_{rel} range and plot versus p_{tot}. $\rightarrow$ AGREEMENT!
- Black: Golak one-body.
  Blue-Dashed: Golak pp:pn ratio in bound state.
  Black-Dotted: Pair counting ratio.



submitted to PRL (Baghdasaryan *et al.*)

- The tensor force dominates!
  - *e.g.* Schiavilla *et al.*, PRL 98, 132501 (2007).
  - At low p_{tot} the pn pair is deuteron-like and the tensor force mixes in d wave.
  - At low p_{tot} the pp pair has little d-wave and there is a deep minimum in the momentum distributions so $\sigma(pp) < \sigma(pn)$.
  - As p_{tot} increases the pp tensor force fills in this minimum and $\sigma(pp)/\sigma(pn)$ rises.

Short-Range Correlations in Nuclei

Conclusions.

- Short-Range Correlations are an important next step in fully describing nuclei; they account for 10-20% of the ground state cross sections.
- Proton-neutron pairs are far more prevalent at low p_{tot}, but pp pairs rise to the same level at $p_{tot} > 0.25\ \mathrm{GeV/c}$.
- The tensor force is essential for understanding SRCs and the nuclear ground state.

The Future.

- With CLAS: data mining proposal has been submitted to DOE.
  - More detailed study of 2N-SRC and the deuteron system.
  - A search for non-nucleonic decays of the SRC via Δ-isobar production.
  - A search for 3N SRC.
- In Hall A:
  - Experiment E03-101 investigated the photodisintegration of pp pairs in $^3\mathrm{He}$.
  - Experiment E08-014 is scheduled to search for three-nucleon SRCs in May, 2011.

Two- and Three-Body Forces in Light Nuclei

- The NN force has significant two- and three-body components; the break-up of light nuclei is a path to understand these components.
- The balance between two- and three- body forces could reveal the fundamental features of the NN force, (*e.g.* the range) and the effect of the nuclear medium.
- We can study the transition from soft (hadronic) physics to hard (constituent-quark).
- Reactions being analyzed:

$^3\mathrm{He}(\gamma, \mathrm{dp})$ (2-body breakup)	$^3\mathrm{He}(\gamma, \mathrm{pp})\mathrm{n}$ (helicities)
$^3\mathrm{He}(\gamma, \mathrm{tp})$ (2-body breakup)	$^3\mathrm{He}(\gamma, \mathrm{pp})$ (hard/2-body breakup)
$^4\mathrm{He}(\gamma, \mathrm{dd})$ (2-body breakup)	$^3\mathrm{He}(\gamma, \mathrm{p}\pi^+)\mathrm{nn}$ (Δ^{++} knockout)
$^3\mathrm{He}(\gamma, \mathrm{t}\pi^+)$ (coherent)	$^{3,4}\mathrm{He}(\gamma, \pi^+\pi^+)$ (ρ production)

Two- and Three-Body Forces in Light Nuclei

- The NN force has significant two- and three-body components; the break-up of light nuclei is a path to understand these components.
- The balance between two- and three- body forces could reveal the fundamental features of the NN force, (*e.g.* the range) and the effect of the nuclear medium.
- We can study the transition from soft (hadronic) physics to hard (constituent-quark).
- I also want to recognize the many contributions to this field from Barry Berman, a valued member of our CLAS Collaboration.

/ breakup)

ιockout)

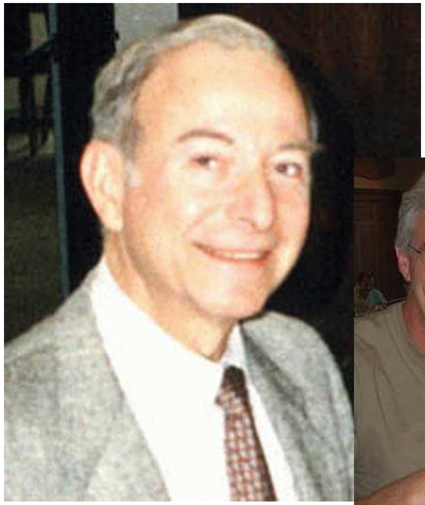
ιction)

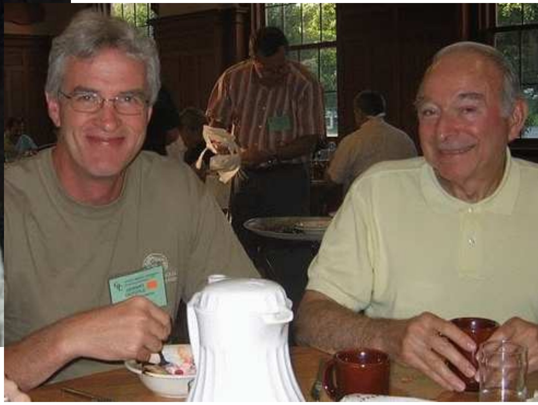
$^3\mathrm{He}(\gamma, t\pi^+)$ (coherent)

Two- and Three-Body Forces in Light Nuclei

- The NN force has significant two- and three-body components; the break-up of light nuclei is a path to understand these components.
- The balance between two- and three- body forces could reveal the fundamental features of the NN force, (*e.g.* the range) and the effect of the nuclear medium.
- We can study the transition from soft (hadronic) physics to hard (constituent-quark).
- I also want to recognize the many contributions to this field from Barry Berman, a valued member of our CLAS Collaboration.

$^3\mathrm{He}(\gamma, t\pi^+)$ (coherent)

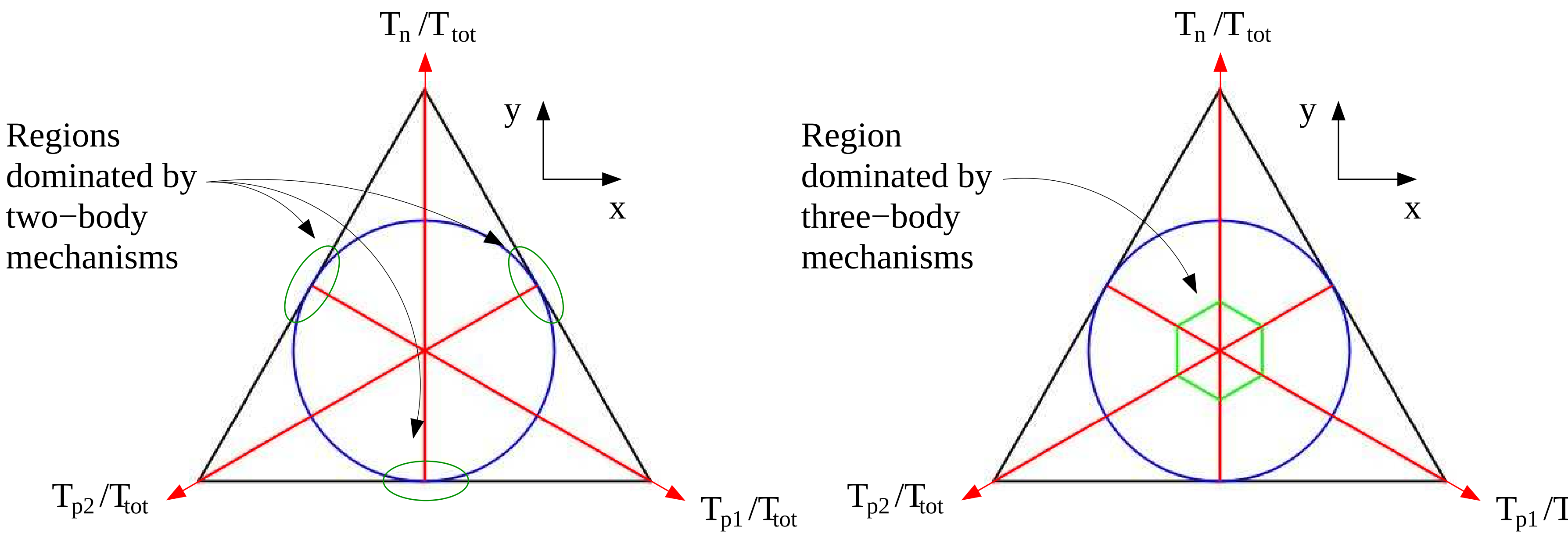




Two- and Three-Body Forces in $^3\mathrm{He}(\gamma, \mathrm{pp})\mathrm{n}$

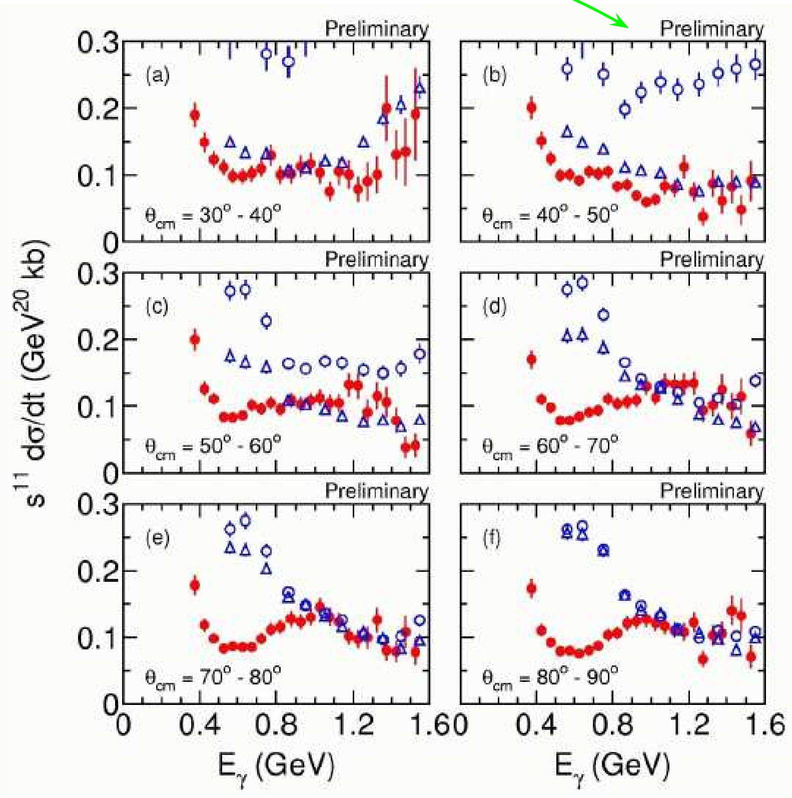
- Selecting two- and three-body events using the Dalitz plot.

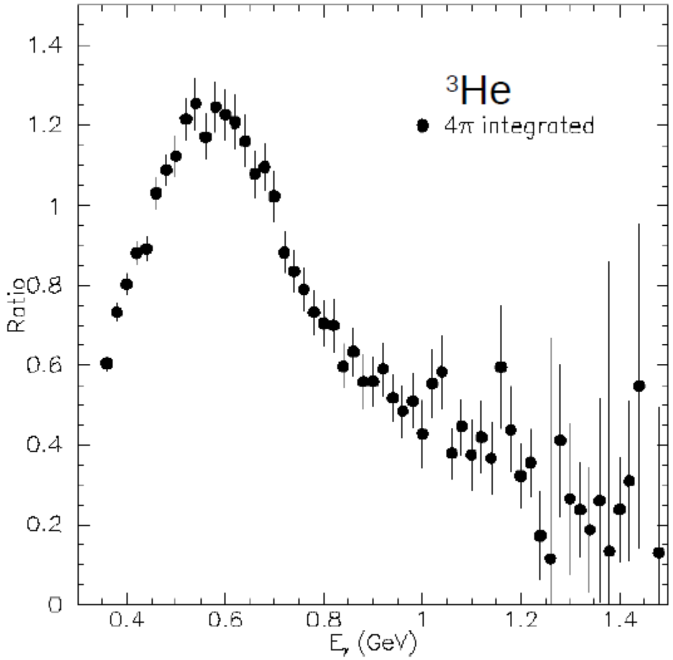
$$x = \frac{T_{p1} - T_{p2}}{\sqrt{3}T_{tot}} \quad y = \frac{T_n}{T_{tot}}$$



Two- and Three-Body Forces in $^3\mathrm{He}(\gamma, \mathrm{pp})\mathrm{n}$

- Extract ratio of three- to two-body cross sections; peak corresponds to three-body range scale?
- E_γ dependence with neutron spectator by angle bin (red).





- Blue - Deuteron photodisintegration.
  - Mirazita *et al.*, PRC 70, 014005 (2004).
  - Scaled by $\frac{1}{4}$.
  - ◯ - forward; △ - back angles.
- Evidence of scaling?

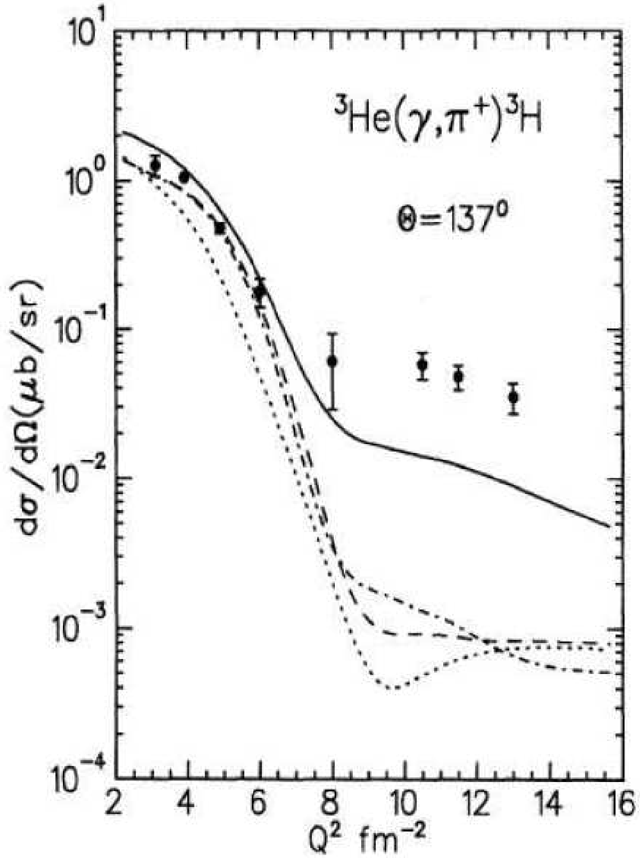
Two- and Three-Body Forces in $^3\mathrm{He}(\gamma, \pi^+ \mathrm{t})$

Motivation

- Compare elementary process on a free nucleon ($\gamma p \to \pi^+ n$) with the same reaction in the nucleus.
- Probe the NN force, the pion cloud, and mesonic degrees of freedom.
- The triton and $^3\mathrm{He}$ are the lightest nuclei with coherent photoproduction with charge exchange and a well-defined final state.

Previous work

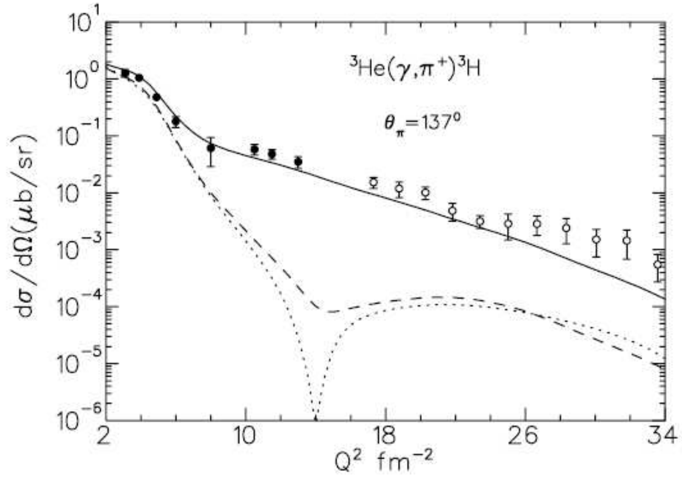
- Previous data at low Q^2 could be explained by including one- and two-body effects.
- Failed to account for all the cross section at higher momentum transfer.



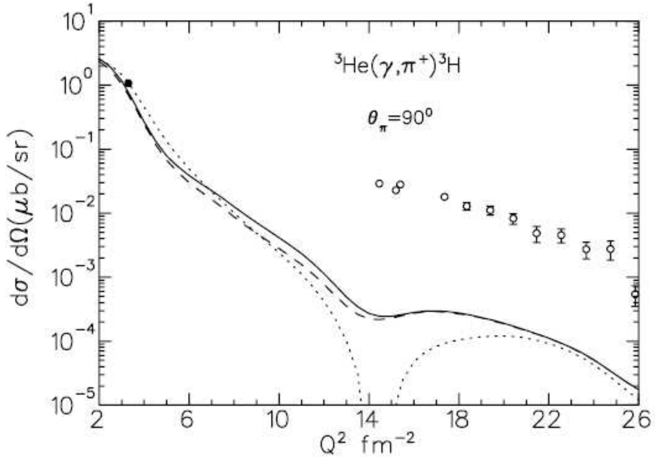
S. Kamalov *et al.* PRL 75, 1288 (1995).

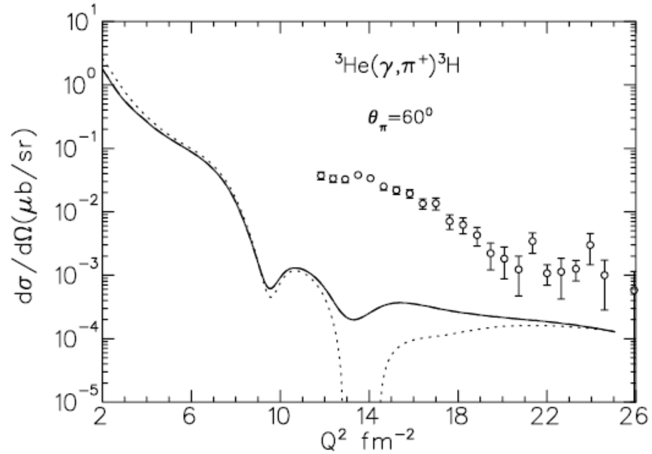
Two- and Three-Body Forces in $^3\mathrm{He}(\gamma,\pi^+\mathrm{t})$

- Measured $d\sigma/d\Omega$ for $^3\mathrm{He}(\gamma,\pi^+\mathrm{t})$ at higher photon energy ($E_\gamma = 0.5 - 1.55$ GeV) and more π^+ angles θ_π.
- Good agreement with CLAS results and previous data (D. Bachelier *et al.*, PLB 44, 44 (1973) and D.Bachelier *et al.*, NP A251, 433 (1975)) with updated 2-body calculation.
- Major deviations between previous calculations and CLAS results at smaller θ_π!



Serious need for new calculations to study three-body effects, preformed Δs,....





Two- and Three-Body Forces in Light Nuclei

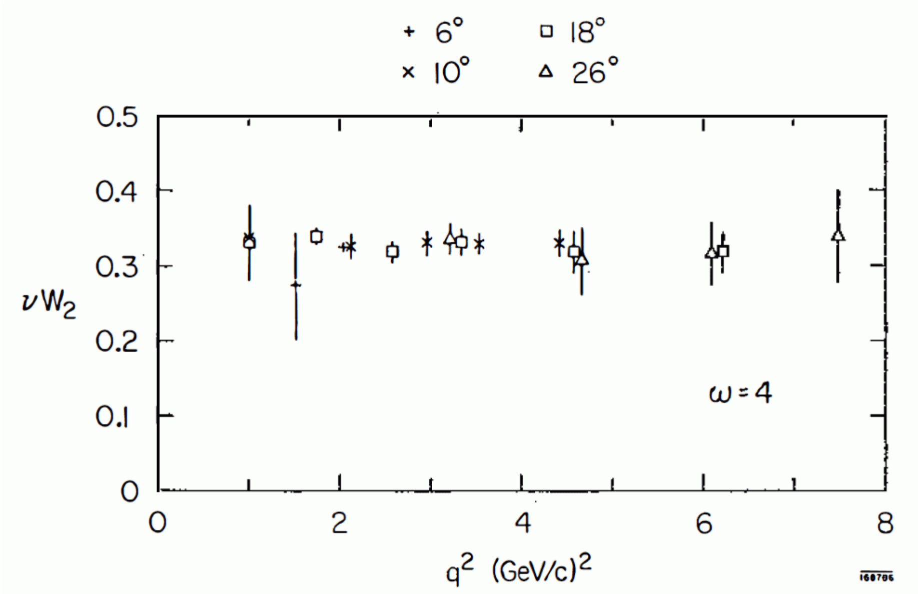
Conclusions

- Active program focused on helium nuclei with a variety of physics topics.
- Three body forces are an essential ingredient for understanding these nuclei.
  - For example, three-body calculations from Laget do well for some reactions (*e.g.* $^{4}\mathrm{He}(\gamma, \mathrm{pt})$), but miss others ($^{4}\mathrm{He}(\gamma, \mathrm{pd})$).
- Testing ground for nuclear medium effects like $^{3}\mathrm{He}(\gamma, \pi^{+}\mathrm{t})$.
- Signs of scaling.
- Need for contributions from theorists!!

Scaling in Photodisintegration of Nuclei

Physics Motivation

- Signature of scattering from individual partons inside the nucleus; sign that we have reached territory beyond the hadronic model.
- Central goal of JLab; a laboratory for the study of QCD.
- Identifying scaling has been elusive; the geography of the transition from hadronic to quark-gluon degrees of freedom is rugged.



Friedman and Kendall, Ann. Rev. Nucl. Sci. 22, 203 (1972).

Scaling in Photodisintegration of Nuclei

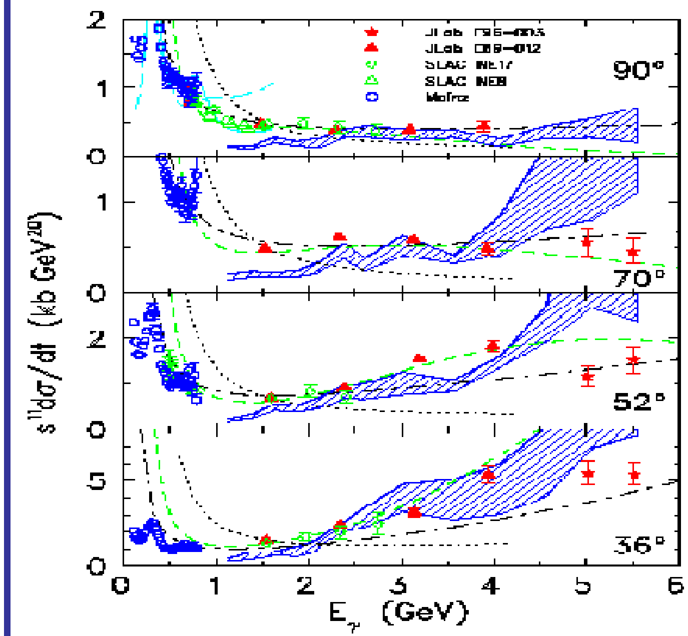
How do we find it?

- Brodsky and Farrar (PRL 31, 1153 (1973)) predict constituent counting rules (CCR)

$$\frac{d\sigma}{dt}_{AB\rightarrow CD} \approx s^{2-n} f(t/s)$$

where t and s are the Mandelstam variables (total energy and 4-momentum transfer squared) for $s \rightarrow \infty$ and t/s fixed. The number n is the total number of leptons, photons, and quark components.

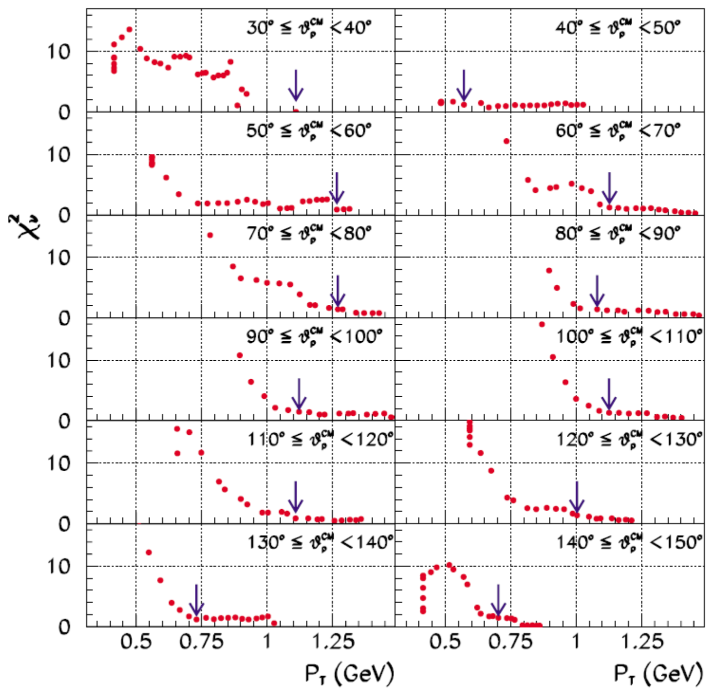
- Deuteron photodisintegration ($n = 13$).
  - large momentum transfers can be reached at relatively low energy.
- Hall A and C results.
  - Schulte *et al.*, PRC 66, 042201 (2002). Hall A green points.
  - Bochna *et al.*, PRL 81, 4576 (1998); Schulte *et al.* PRL 87, 102302 (2001). Hall C red points.

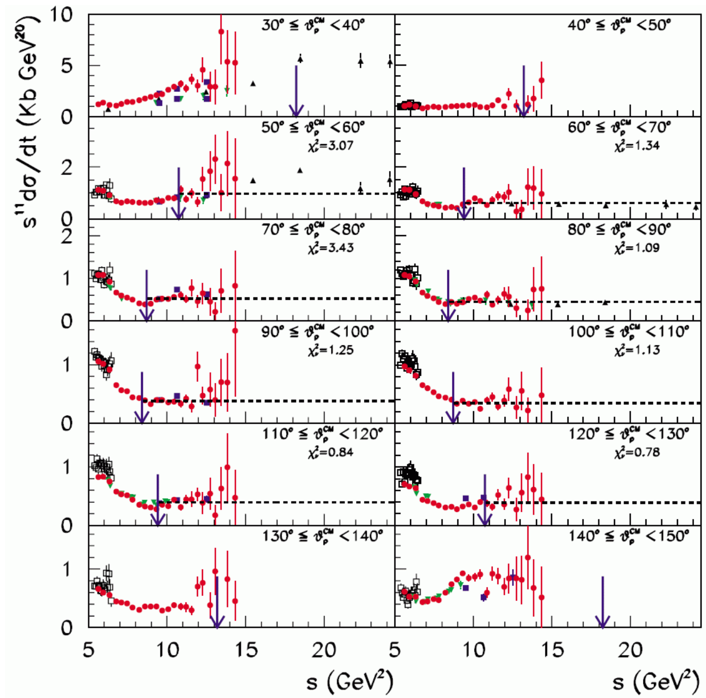


Scaling in Photodisintegration of Nuclei

CLAS results (Rossi *et al.*, PRL 94, 012301 (2005))

- Measure $d\sigma/dt$ at fixed proton angle θ_p^{cm} and in terms of the center-of-mass proton transverse momentum $P_T = \sqrt{\frac{1}{2}E_\gamma M_d \sin^2\theta_p^{cm}}$ where M_d is the deuteron mass.
- Combine CLAS data and other measurements and use fits to s^{-11} to determine the minimum P_T where the scaling begins (at $P_T > 1.1\ \mathrm{GeV/c}$).
- Now fit remaining data for $P_T >\ 1.1\mathrm{GeV/c}$ to s^{-11}. $\rightarrow$ Consistent with CCR!

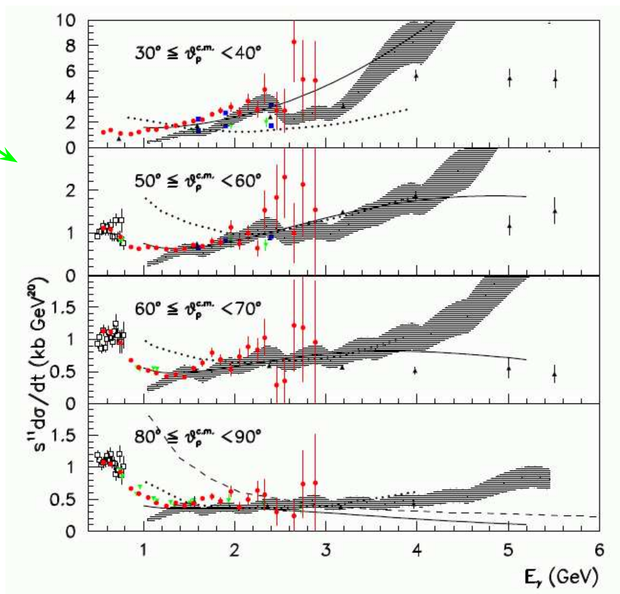


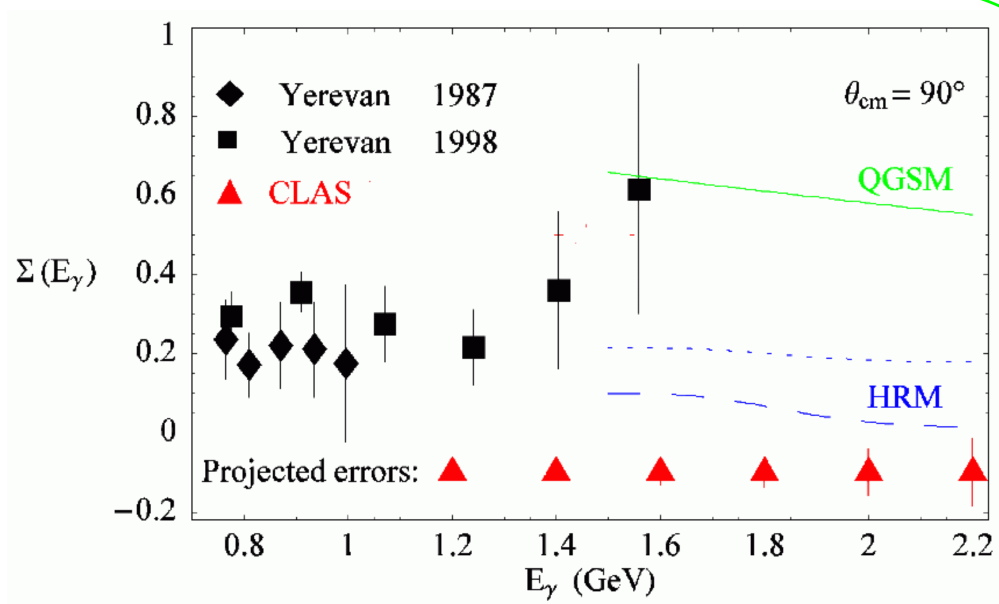


Scaling in Photodisintegration of Nuclei

But....

- CCR is valid for $t \approx s >> m^2$ and not expected to work in the few-GeV region.
- Several competing, quark-gluon theories describe the unpolarized data: QGSM (Grishina *et al.* Eur. Phys. J. A 10, 355 (2001)), RNA (Brodsky and Hiller, PRC 30 412(E) (1984)), AMEC (Diepernik and Nagorny, PLB 456, 9 (1999)), and HRM (Frankfurt *et al.* PRL 84 3045 (2000)).
- Analysis of existing CLAS data (CAA-NP07-01) on the azimuthal asymmetry hold the promise of differentiating among the different approaches.

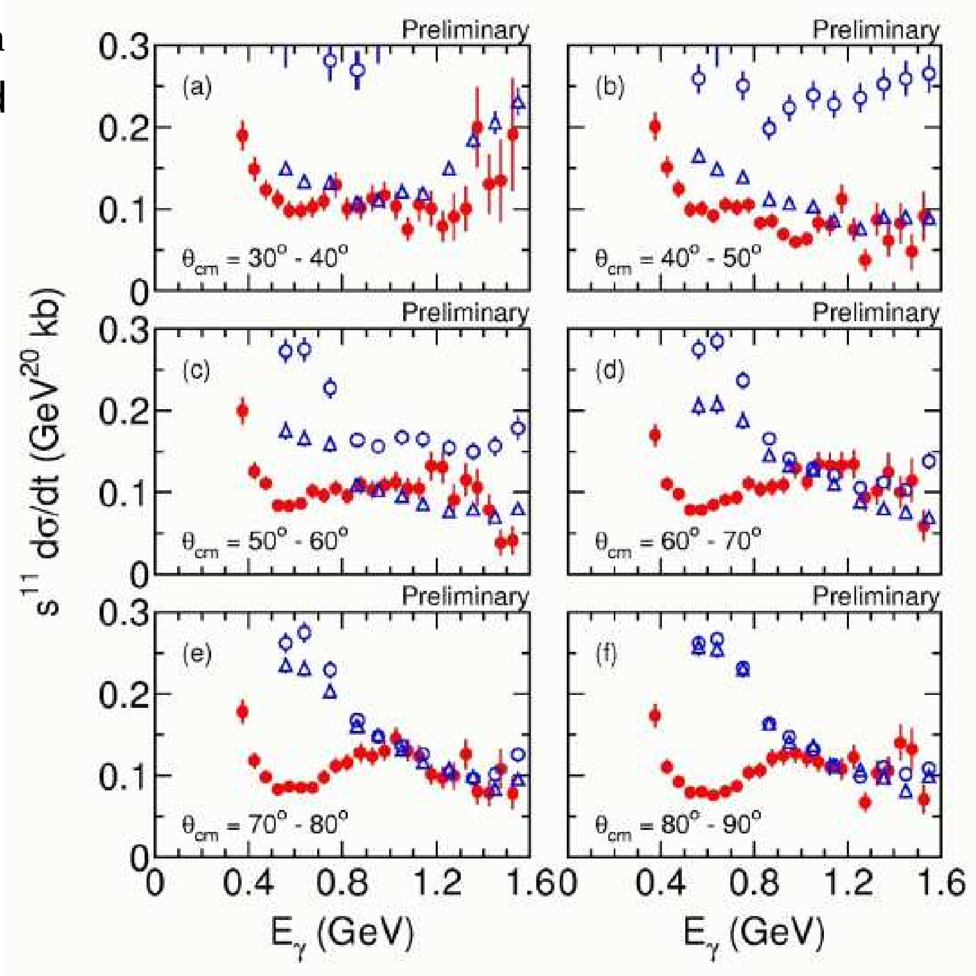




Scaling in Photodisintegration of Nuclei

Other exclusive reactions

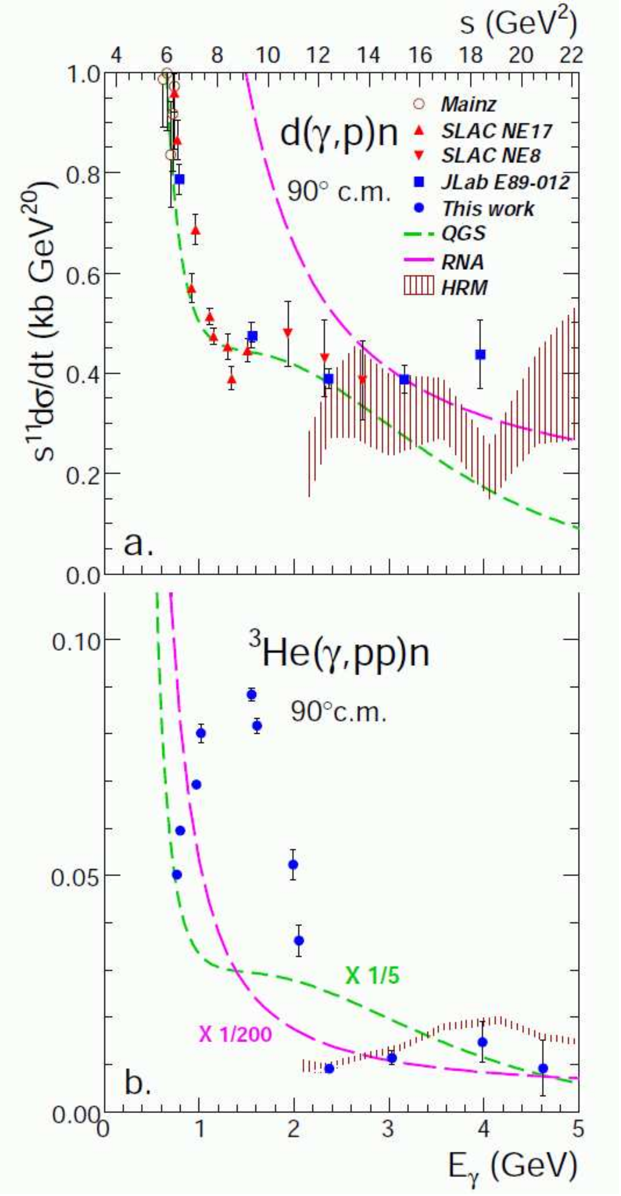
- Brodsky *et al.* (Phys.Lett. B578, 69 (2004).) suggest that $^3\mathrm{He}(\gamma,\mathrm{pp})\mathrm{n}$ could be a testing ground for hard processes.
  - pp breakup not much smaller than the pn breakup.
  - energy-dependent oscillations seen in pp could appear.
- Recall $^3\mathrm{He}(\gamma,\mathrm{pp})\mathrm{n}$ (red points).
  - Blue points from deuteron photodisintegration.
  - Mirazita *et al.*, PRC 70, 014005 (2004).
  - Scaled by $\frac{1}{4}$.
  - $\bigcirc$ - forward; $\triangle$ - back angles.



Scaling in Photodisintegration of Nuclei

Complementary results from Hall A

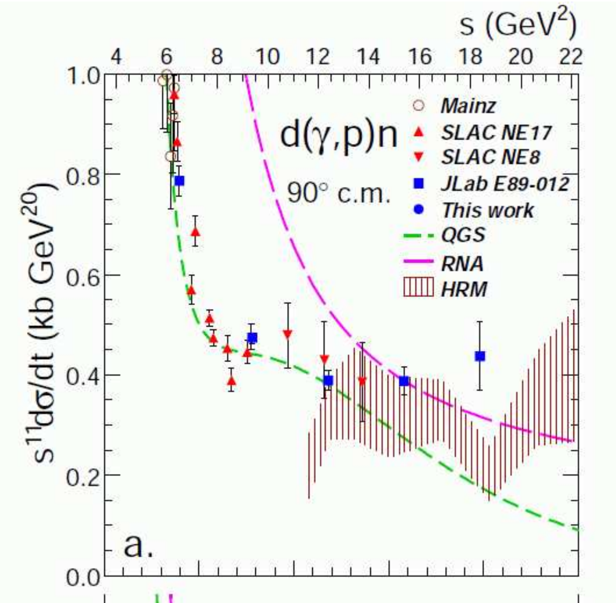
- Experiment E03-101 measured $^3\mathrm{He}(\gamma, \mathrm{pp})\mathrm{n}$ at $\theta_p^{cm} = 90^\circ$ and for $E_\gamma = 0.8 - 4.7$ GeV (Pomerantz, PLB 684, 106 (2010)).
- Scaling observed for $E_\gamma > 2$ GeV and σ_{pp} is about 20 times smaller than σ_{pn} measured in deuteron photodisintegration.
- Hard rescattering model (Frankfurt *et al.* PRL, 84, 3045 (2000)) reproduces scaling.
- Results could be due to scaling but the tensor force effects seen in the SRC studies by Baghdasaryan *et al.* offer an alternative explanation.
- Large structure in $E_\gamma = 1 - 2$ GeV may be due to γN or γNN resonances reminiscent of pion photoproduction.
- Consistent with preliminary results from CLAS.

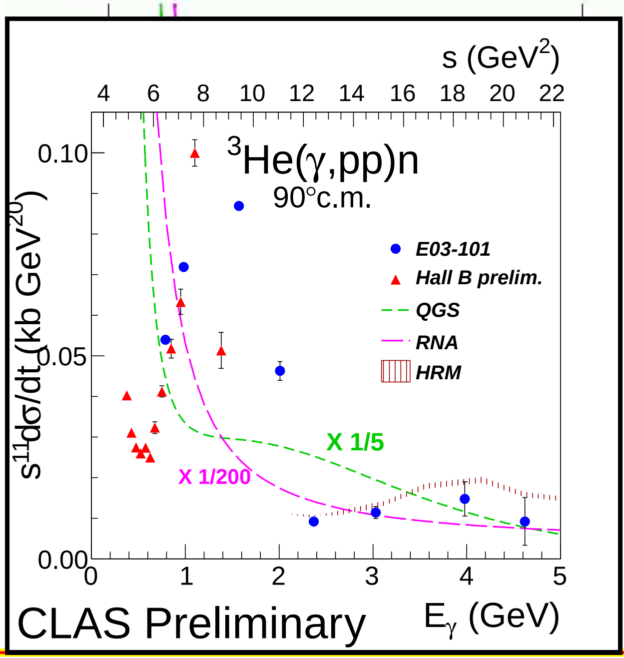


Scaling in Photodisintegration of Nuclei

Complementary results from Hall A

- Experiment E03-101 measured $^3\mathrm{He}(\gamma,\mathrm{pp})\mathrm{n}$ at $\theta_p^{cm} = 90^\circ$ and for $E_\gamma = 0.8 - 4.7\ \mathrm{GeV}$ (Pomerantz, PLB 684, 106 (2010)).
- Scaling observed for $E_\gamma > 2\ \mathrm{GeV}$ and σ_{pp} is about 20 times smaller than σ_{pn} measured in deuteron photodisintegration.
- Hard rescattering model (Frankfurt *et al.* PRL, 84, 3045 (2000)) reproduces scaling.
- Results could be due to scaling but the tensor force effects seen in the SRC studies by Baghdasaryan *et al.* offer an alternative explanation.
- Large structure in $E_\gamma = 1 - 2\ \mathrm{GeV}$ may be due to γN or γNN resonances reminiscent of pion photoproduction.
- Consistent with preliminary results from CLAS.





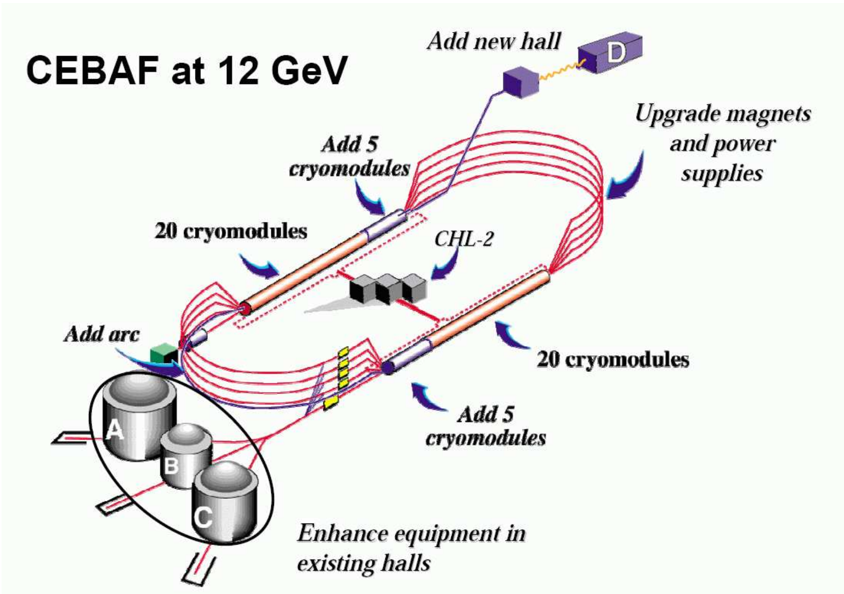
Scaling in Photodisintegration of Nuclei

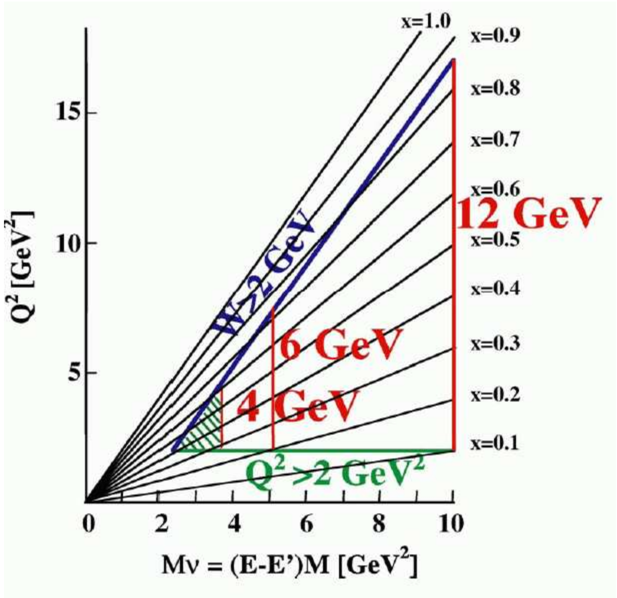
Conclusions

- We have seen the transition, but it's complicated. Alternative explanations remain.
- Future measurements (*e.g.* asymmetry measurements of $^3\mathrm{He}(\gamma,\mathrm{pp})\mathrm{n}$) may help untangle things.
- Wonderful example of the interplay of experiments in different halls at JLab.

JLab 12-GeV Upgrade

- The electron beam energy at JLab (CEBAF) will be doubled from 6 GeV to 12 GeV.
- Halls A, B and C will be upgraded to accommodate the new physics opportunities.
- A new hall (Hall D) will house a large-acceptance detector built around a solenoidal magnet for photon beam experiments.
- All of the physics discussed here will be extended to 12 GeV.
- Specific proposals have already been approved for running during the first five years to study SRC (PR12-06-105) and other few-body phenomena like color transparency (PR12-06-106 and PR12-06-107).





Conclusions

- SRCs improve our understanding of the NN force and the ground state structure of nuclei.
- The study of two- and three-body forces still needed to understand the range of physics in helium nuclei.
- Scaling is an important phenomenon that points to the quark-gluon substructure, but alternative explanations have to be reconciled.
- MORE TO COME at 6 GeV and 12 GeV!!

Additional Slides

Short-Range Correlations in (e,e')

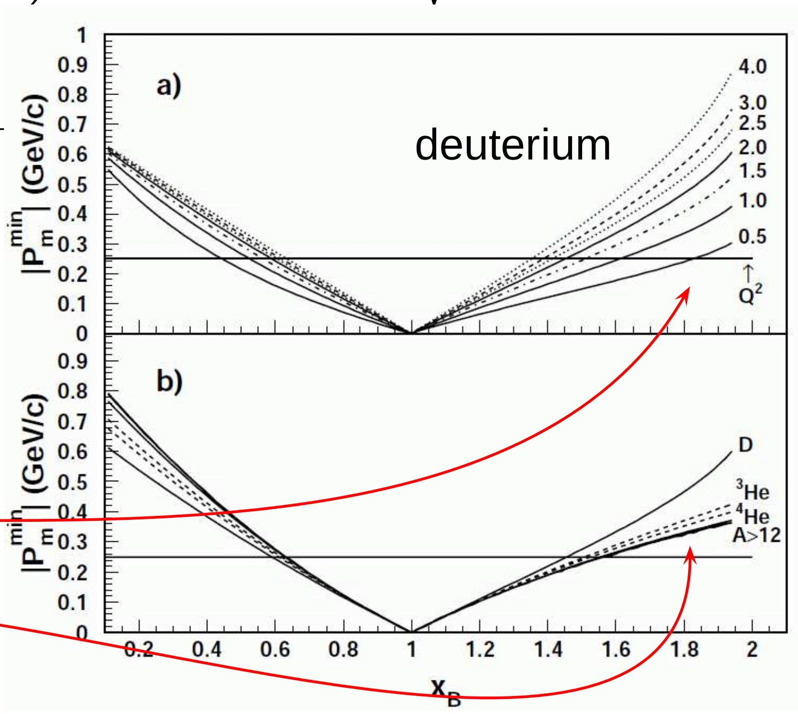
Selecting SRCs in Quasielastic (e,e') on Nuclei with CLAS

- Use broad kinematic coverage of the reaction $A(e,e')A-1$ to isolate the SRCs.
- Momentum and energy conservation lead to

$$\Delta M^2 - Q^2 + \frac{Q^2}{m_N x_B}\left(M_A - \sqrt{M_{A-1}^2 + p_m^2}\right) - 2\vec{q}\cdot\vec{p}_m - 2M_A\sqrt{M_{A-1}^2 + p_m^2} = 0$$

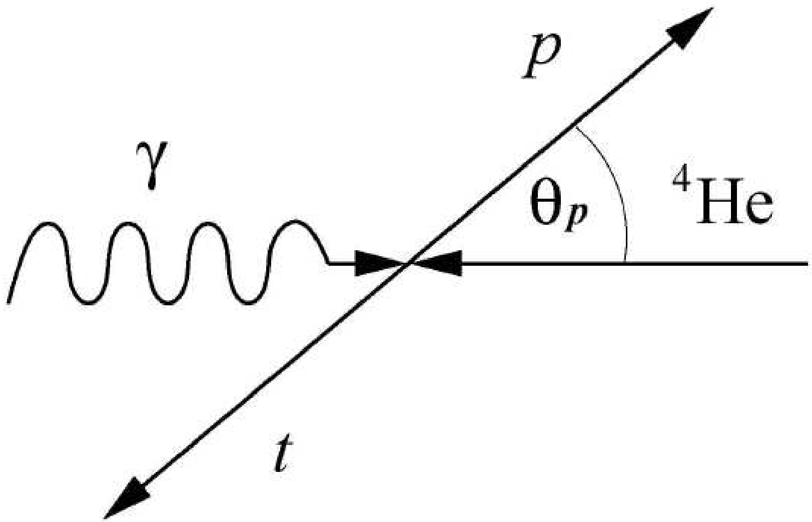
where $x_B = Q^2/2m_N\nu$, $\Delta M^2 = M_A^2 + M_{A-}$ $\vec{p}_m = \vec{p}_f - \vec{q} = -\vec{p}_{A-1}$ (see K. Egiyan PRC, 68, 014313 (2003)).

- This result relates a minimum p_m (p_m^{min}) to Bjorken x_B and Q^2.
- For a given Q^2 we can select a value of x_B such that the $p_m^{min} > p_{Fermi}$.
- We can do this for different nuclei.



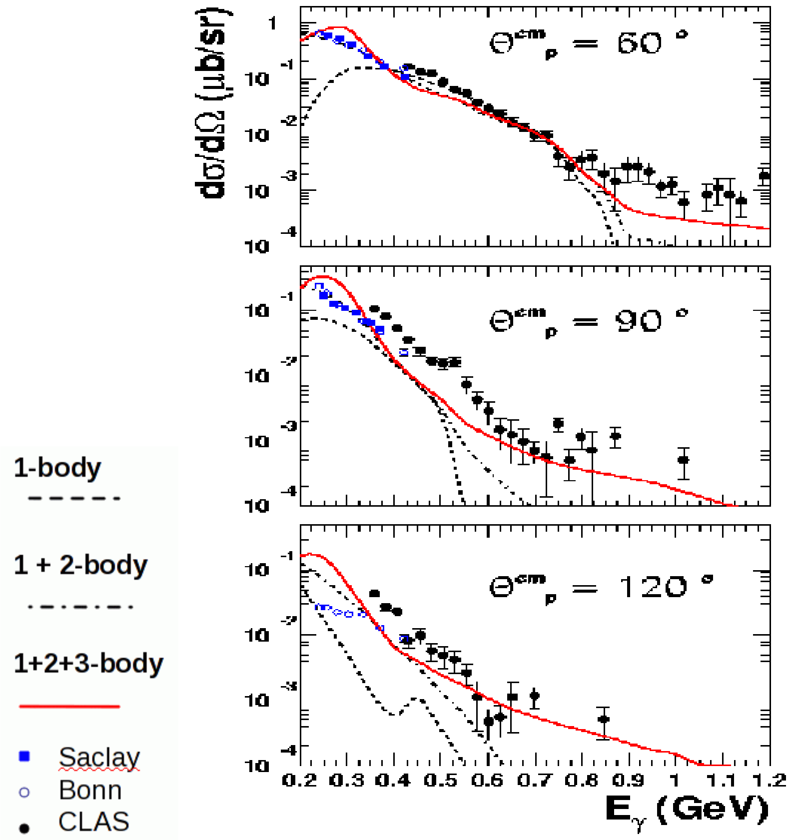
Two- and Three-Body Forces in $^4\mathrm{He}(\gamma, \mathrm{tp})$

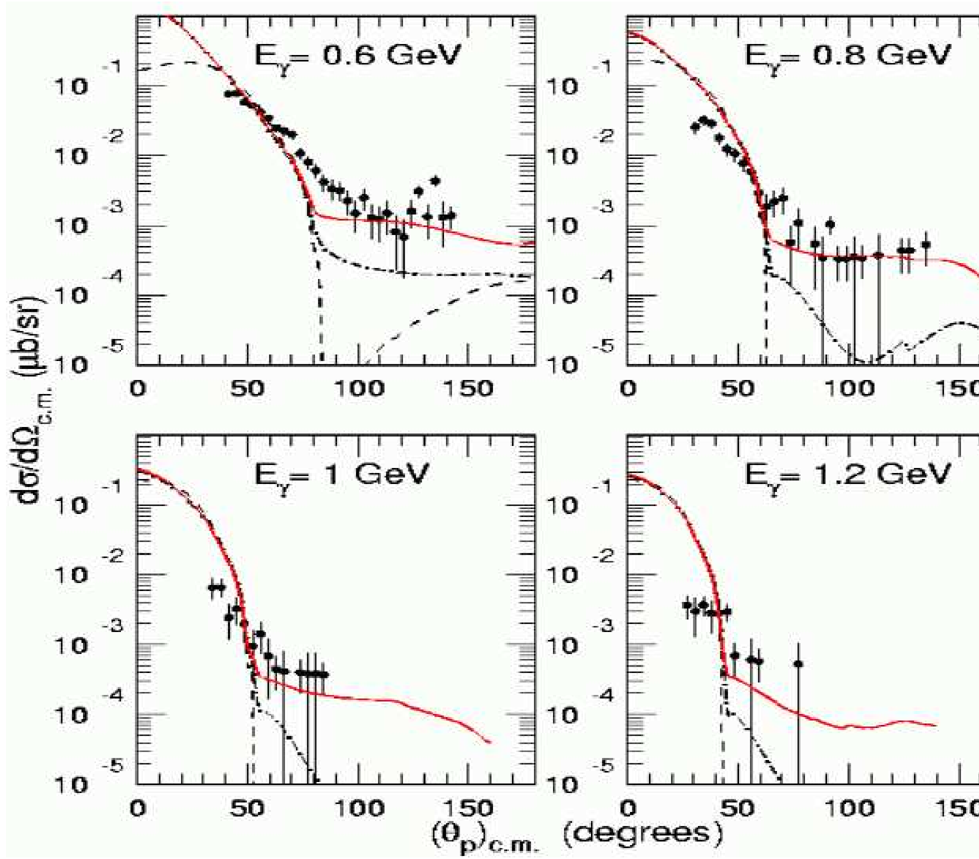
- Complementary reaction to $^3\mathrm{He}(\gamma, \mathrm{pp})\mathrm{n}$; different kinematics probes different elementary amplitudes.
- Investigate the contribution of 3-body mechanisms to the reactions and to further constrain the theoretical calculations.
- Investigate the possible transition from soft (hadronic) physics to hard (constituent-quark) physics in the energy range of the g3 experiment (up to 1.5 GeV).
- Part of a bigger program using JLab/CLAS g3 data on $^{3,4}\mathrm{He}$ including $^3\mathrm{He}(\gamma, \mathrm{dp})$, $^3\mathrm{He}(\gamma, \mathrm{pp})\mathrm{n}_{\mathrm{spect}}$(hard), polarization measurements, and 3-body breakup and other channels.



Two- and Three-Body Forces in $^4\mathrm{He}(\gamma, \mathrm{tp})$

- Results:

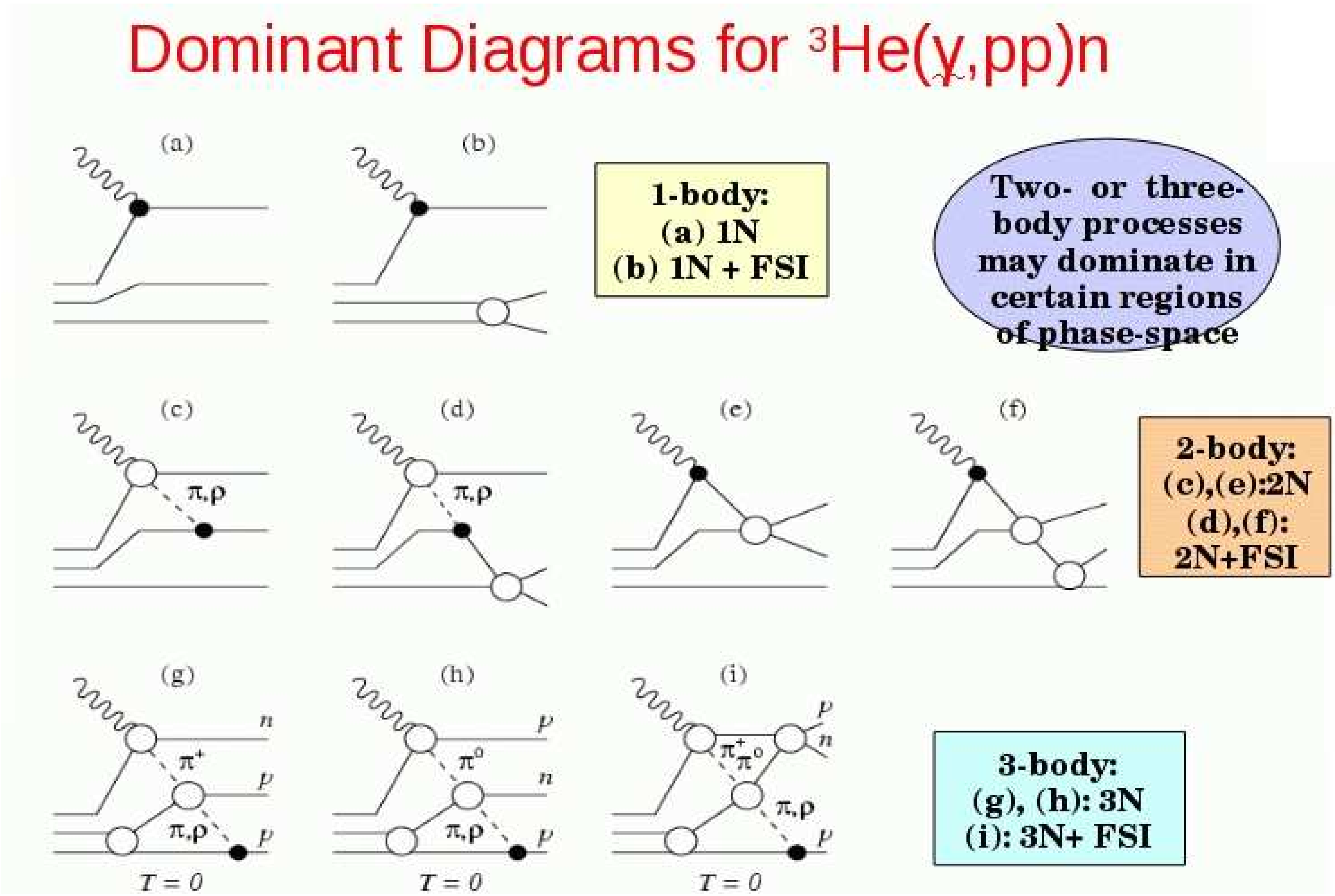




Three-body forces are essential for Helium nuclei at $E_\gamma > 0.40\ \mathrm{GeV/c}$; Laget diagrammatic approach works reasonably well.

Two- and Three-Body Forces in $^3\mathrm{He}(\gamma, \mathrm{pp})\mathrm{n}$

- Use diagrammatic approach of Laget.



Two- and Three-Body Forces in $^{3,4}\mathrm{He}$

- Scaling! Have we reached the transition from hadronic to quark-gluon degrees of freedom?

$^{4}\mathrm{He}(\gamma, \mathrm{pt})$ $^{3}\mathrm{He}(\gamma, \mathrm{pp})\mathrm{n}$