The latest results, and photoproduction of hypernuclei in the (latest version) QMC model (and some recent other results)

K. Tsushima (JLab)

P.A.M. Guichon, V. Guzey,

R. Shyam, A.W. Thomas

NPA 814, 66 (2008): (PGTT)

arXiv:0812.1547 [nucl-th]: (STT)

arXiv:0806.3288 [nucl-th]: (VGTT)

The QMC model P.A.M. Guichon, PLB 200, 235 (1988)

(For a review, PPNP 58, 1 (2007))

Light (u,d) quarks interact self-consistently with mean σ and ω fields

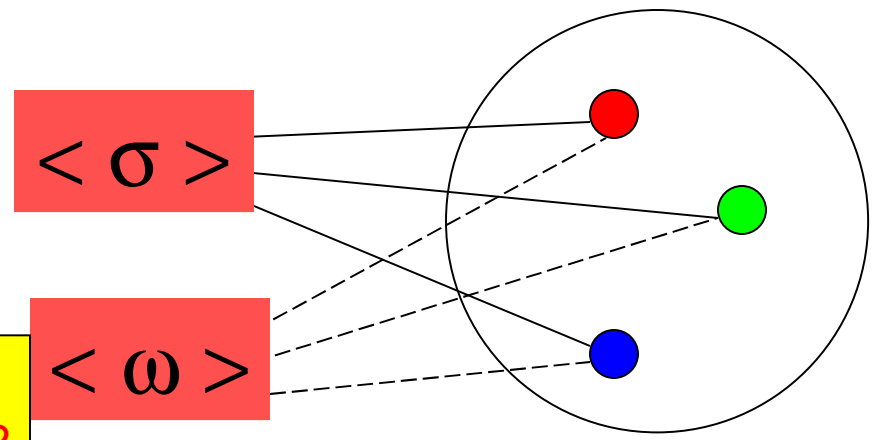
$m^*_q = m_q - g^q_\sigma \sigma = m_q - V^q_\sigma$

$\Downarrow$ nonlinear in σ

$M^*_N \cong M_N - g^N_\sigma \sigma + (d/2)(g^N_\sigma \sigma)^2$

$[i\,\partial\cdot\gamma - (m_q - V^q_\sigma) + \gamma_0 V^q_\omega]\, q = 0$

$[i\,\partial\cdot\gamma - (M_N - V^N_\sigma) + \gamma_0 V^N_\omega]\, N = 0$



$M^*_N = M_N - V^N_\sigma$

$V^N_\omega = 3V^q_\omega$

Outline

- Introduction, the QMC model, finite nuclei
- Hypernuclei in the latest QMC model (Σ,Λ)
- Photoproduction of Λ-hypernuclei
- Discussion, outlook for hypernuclei

5. Medium effect on GPD (informal!)
6. Speculations!!

The QMC model P.A.M. Guichon, PLB 200, 235 (1988)

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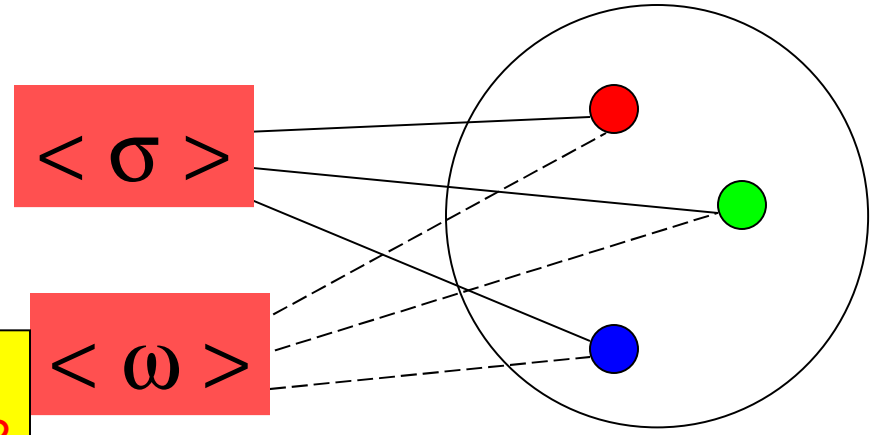

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$[i\,\partial\cdot\gamma - (M_N - V^N_\sigma) + \gamma_0 V^N_\omega]\, N = 0$

$V^N_\omega = 3 V^q_\omega$

Nuclear (Neutron) matter, E/A

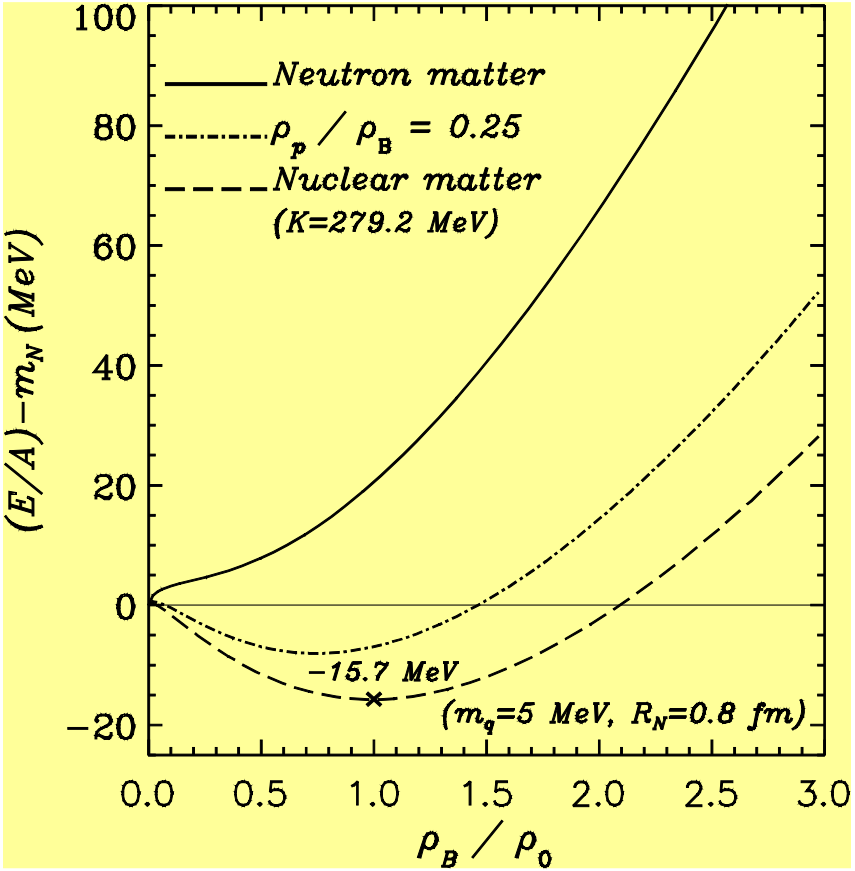
New saturation mechanism !

Incompressibility

K ≈ 280 MeV

(200 ~ 300 MeV)

PLB 429, 239 (1998)



Finite nuclei (^{208}Pb energy levels)

NPA 609, 339 (1996)

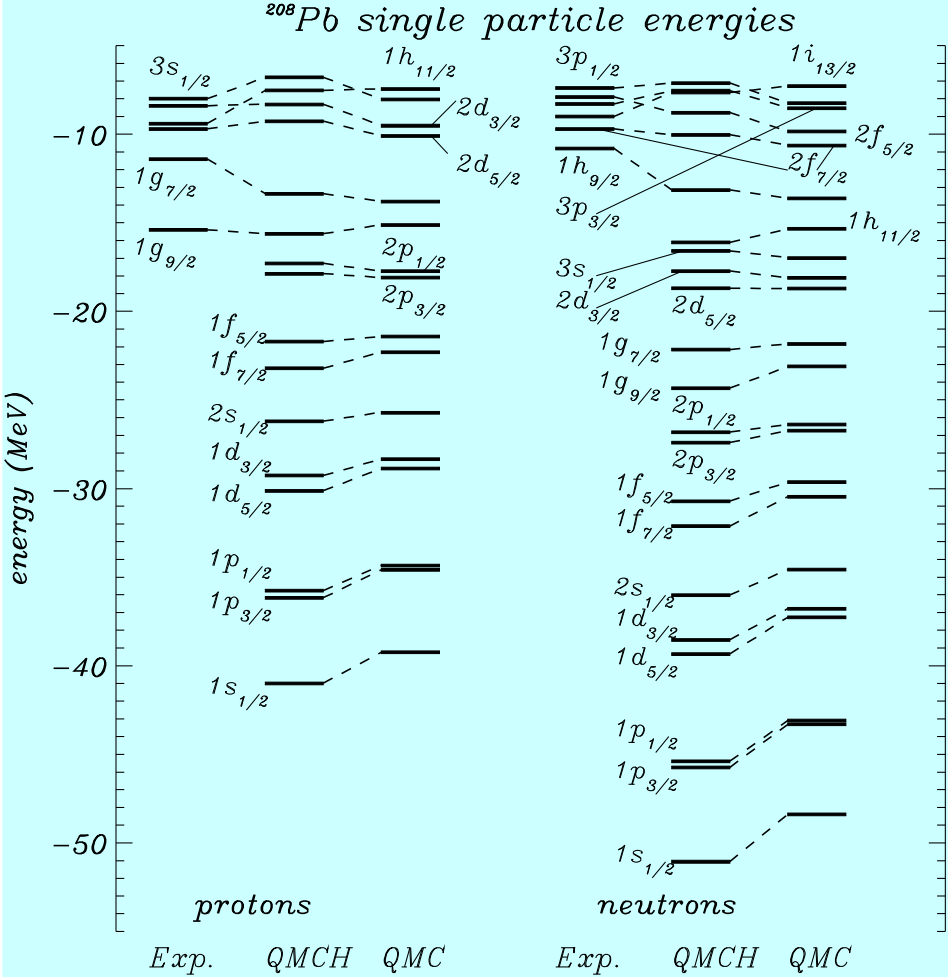
Large mass nuclei

Based on the quarks !

↓

Hypernuclei

(the latest version of QMC)



The latest QMC model

NPA 814, 66 (2008) (arXiv:0712.1925 [nucl-th])

- Color "Coulomb-spike" effect on OGE hyperfine interaction (s-quark different)
  (T. Barnes, PRD 30, 1961 (1984))
- $\Longrightarrow$ Smaller α_c in the MIT bag model (PRD 12, 2060 (1976): 0.55 $\rightarrow$ ~0.45)
- Self-consistent inclusion in matter

  $\Longrightarrow$ extra repulsion for Σ relative to Λ

  $\Longrightarrow$ No Σ nuclear bound state!!

Bag mass and mag. HFC contribution (OGE)

T. DeGrand *et al.*, PRD 12, 2060 (1975)

$$M = [N_q\Omega_q + N_s\Omega_s]/R - Z_0/R + 4\pi BR^3/3$$

$$+ \Delta E_M(f) \qquad (f=N,\Delta,\Sigma,\Lambda,\Xi\ldots)$$

$$\Delta E_M = -3\alpha_c \sum_{a,\, i<j} \lambda_i \lambda_j \vec{\sigma}_i \cdot \vec{\sigma}_j [(\mu_i \mu_j)/R^3]\, I_{ij}$$

$\mu_i(R)$, I_{ij} $\longrightarrow$ T. DeGrand *et al.*, PRD 12, 2060 (1975)

(typos !)

Octet and Decuplet masses (GeV)

NPA 814, 66 (2008) (arXiv:0712.1925 [nucl-th])

Fs	ms	Λ	Σ	Ξ	Σ^*	Ξ^*	Ω
1	0.341	1.135	1.176	1.355	1.416	1.599	1.784
0.726	0.297	1.107	1.189	1.325	1.368	1.507	1.654
Exp.		1.116	1.193	1.318	1.385	1.533	1.672

R_N=0.8 fm, N, Δ masses $\rightarrow$ B=0.5541 fm^{-1}, Z_0=2.6422,

α_c=0.4477, (0.55), Less enhanced the "Coulomb-spike" for s quark

$\Longrightarrow$independent, Fs,ms: fit to Λ,Σ, Ξ masses (predictions)

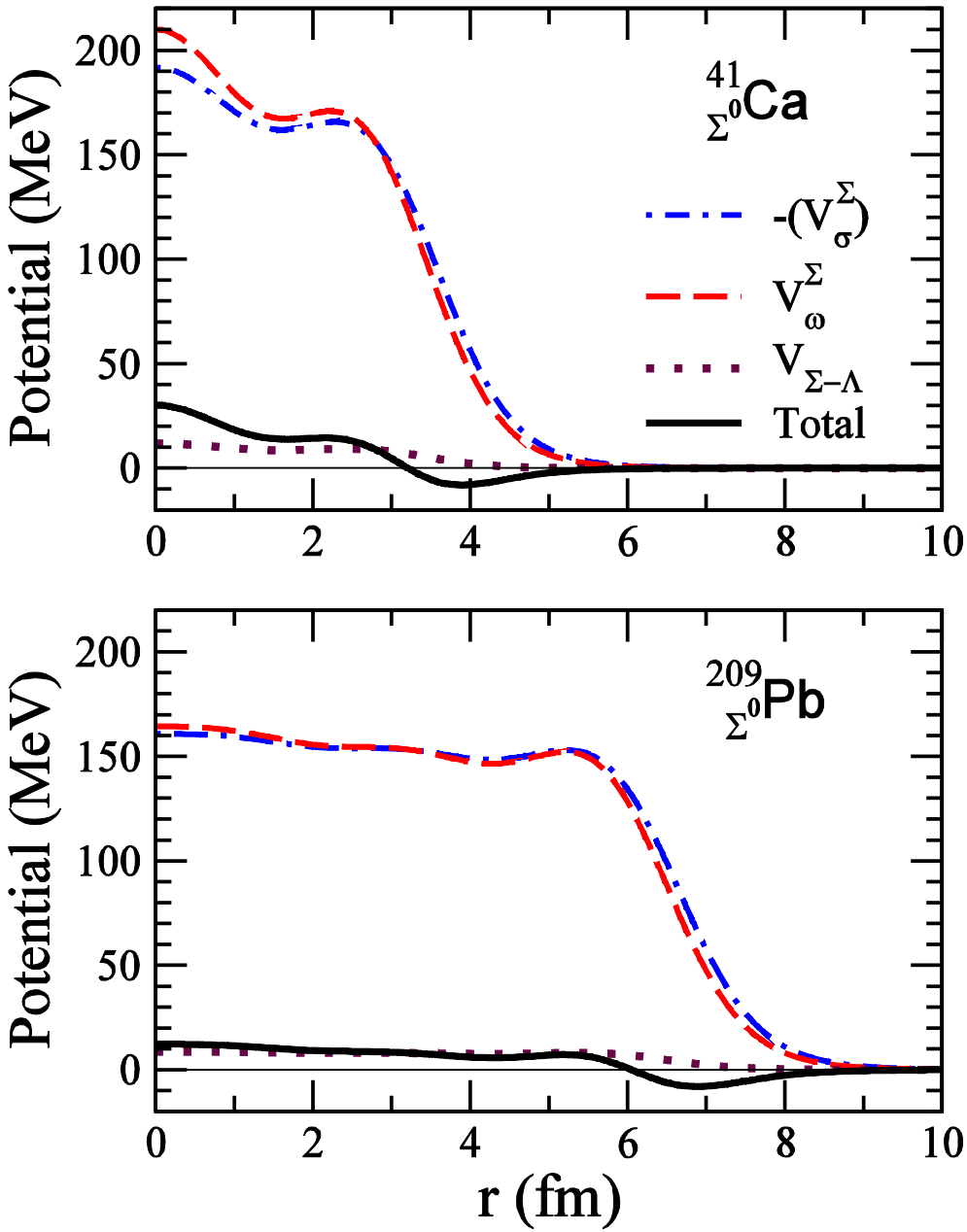
Σ^0 potentials ($1s_{1/2}$)

Repulsion
in center

Attraction
in surface

No Σ nuclear
bound state!

HF couplings for hyperons $\Leftrightarrow$ successful for high density neutron star (NPA 792, 341 (2007))



Hypernuclei spectra 1

NPA 814, 66 (2008) (arXiv:0712.1925 [nucl-th])

	${}^{16}_{\Lambda}O$ Exp.	${}^{17}_{\Lambda}O$	${}^{17}_{\Xi^0}O$	${}^{40}_{\Lambda}Ca$ Exp.	${}^{41}_{\Lambda}Ca$	${}^{41}_{\Xi^0}Ca$	${}^{49}_{\Lambda}Ca$	${}^{49}_{\Xi^0}Ca$
$1s_{1/2}$	-12.4	-16.2	-5.3	-18.7	-20.6	-5.5	-21.9	-9.4
$1p_{3/2}$		-6.4			-13.9	-1.6	-15.4	-5.3
$1p_{1/2}$	-1.85	-6.4			-13.9	-1.9	-15.4	-5.6
$1d_{5/2}$					-5.5		-7.4	
$2s_{1/2}$					-1.0		-3.1	
$1d_{3/2}$					-5.5		-7.3	

Hypernuclei spectra 2

NPA 814, 66 (2008) (arXiv:0712.1925 [nucl-th])

	${}^{89}_{\Lambda}$Yb Exp.	${}^{91}_{\Lambda}$Zr	${}^{91}_{\Xi^0}$Zr	${}^{208}_{\Lambda}$Pb Exp.	${}^{209}_{\Lambda}$Pb	${}^{209}_{\Xi^0}$Pb
$1s_{1/2}$	-23.1	-24.0	-9.9	-26.3	-26.9	-15.0
$1p_{3/2}$		-19.4	-7.0		-24.0	-12.6
$1p_{1/2}$	-16.5	-19.4	-7.2	-21.9	-24.0	-12.7
$1d_{5/2}$	-9.1	-13.4	-3.1	-16.8	-20.1	-9.6
$2s_{1/2}$		-9.1	–		-17.1	-8.2
$1d_{3/2}$	(-9.1)	-13.4	-3.4	(-16.8)	-20.1	-9.8

Summary: hypernuclei

- The latest version of QMC (OGE color Coulomb "spike" effect included self-consistently in matter) $\Longrightarrow$

$\forall\ \Lambda$ single-particle energy $1s_{1/2}$ in Pb is -26.9 MeV (Exp. -26.3 MeV) $\Longleftarrow$ no extra parameter!

- Small spin-orbit splittings for the Λ
- No Σ nuclear bound state !!

$\forall\ \Xi$ is expected to form nuclear bound state

Photoproduction of Λ Hypernuclei

R. Shyam, KT, A.W. Thomas, arXiv:0812.1547 [nucl-th]

Λ and K^+ are produced via s-channel

N* excitation (dominant)

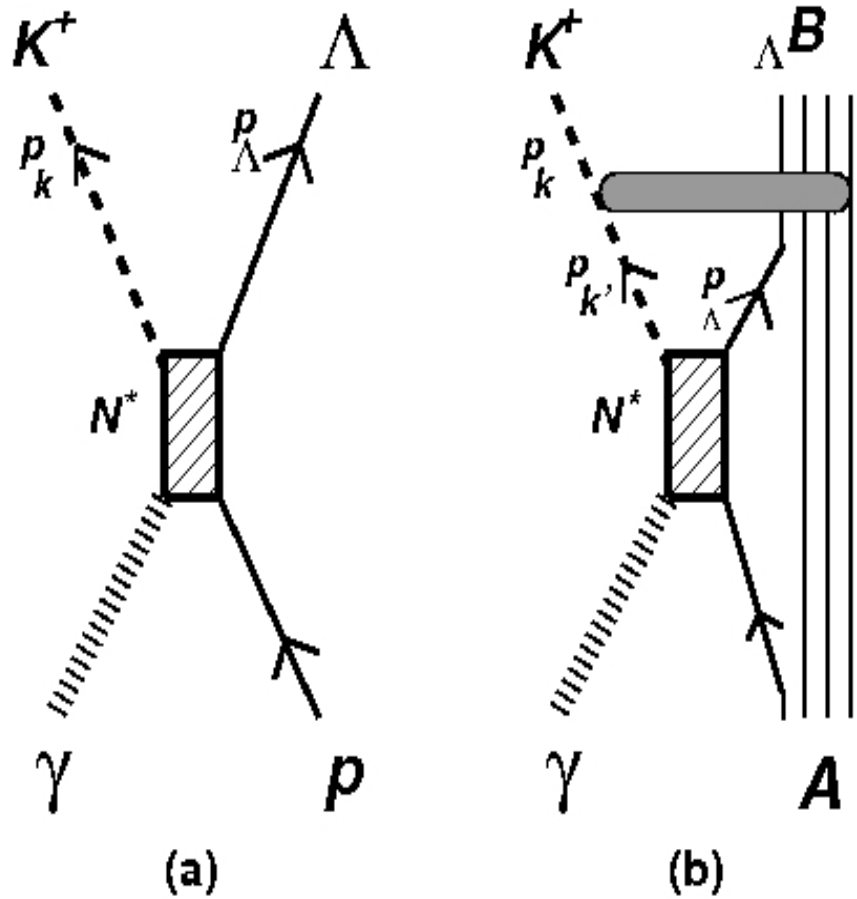
$S_{11}(1650)$, $P_{11}(1710)$

$P_{13}(1720)$

⇕

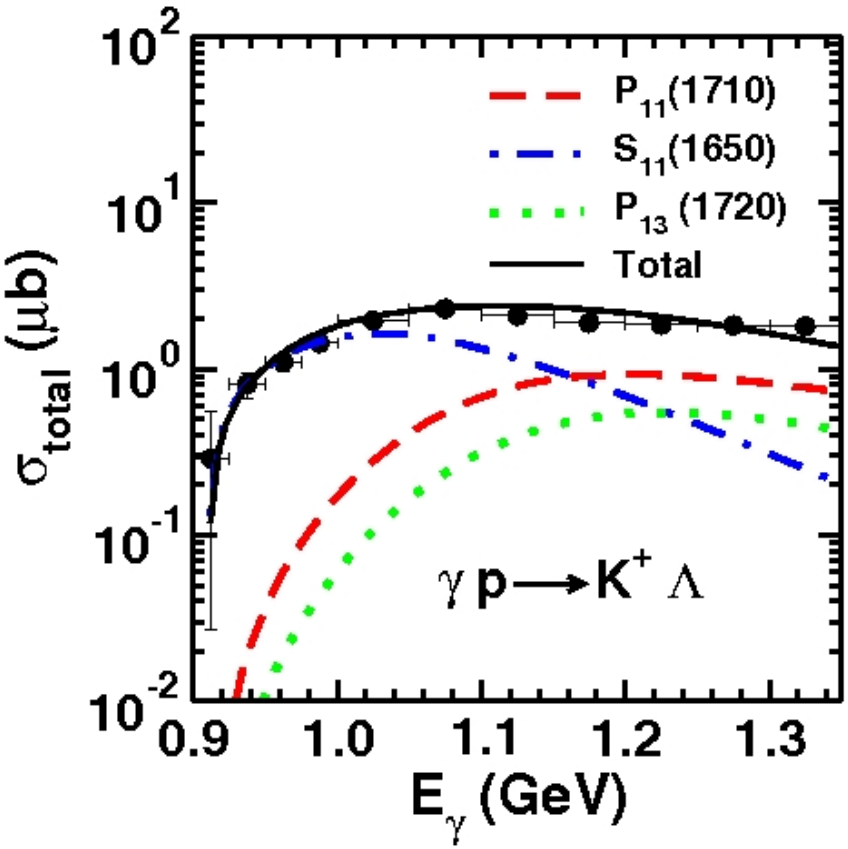
Energy region of interests, hypernuclei production

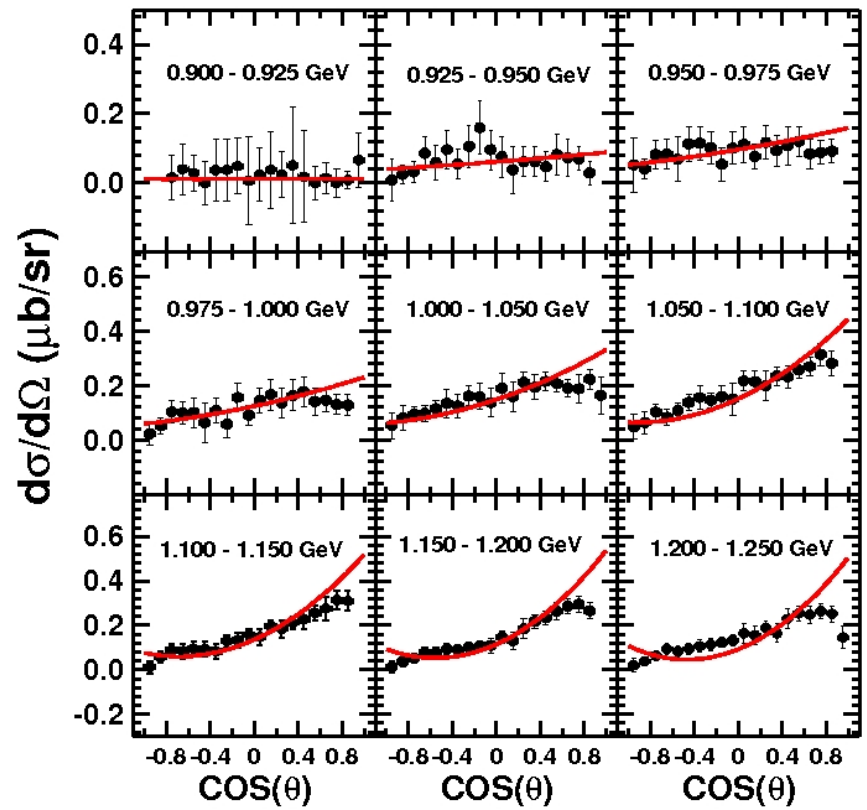
(~ 10 % ambiguity due to the other background ⇒)



Elementary γ p $\longrightarrow$ K$^+\Lambda$ reaction

R. Shyam, KT, A.W. Thomas, arXiv:0812.1547 [nucl-th]

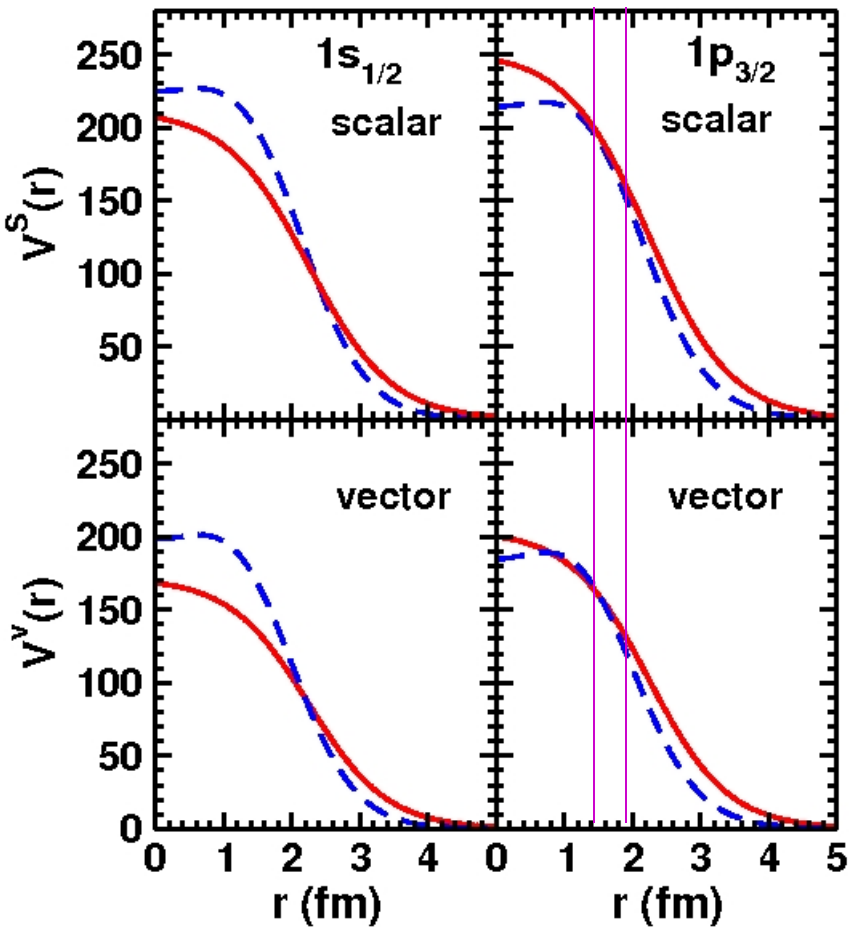


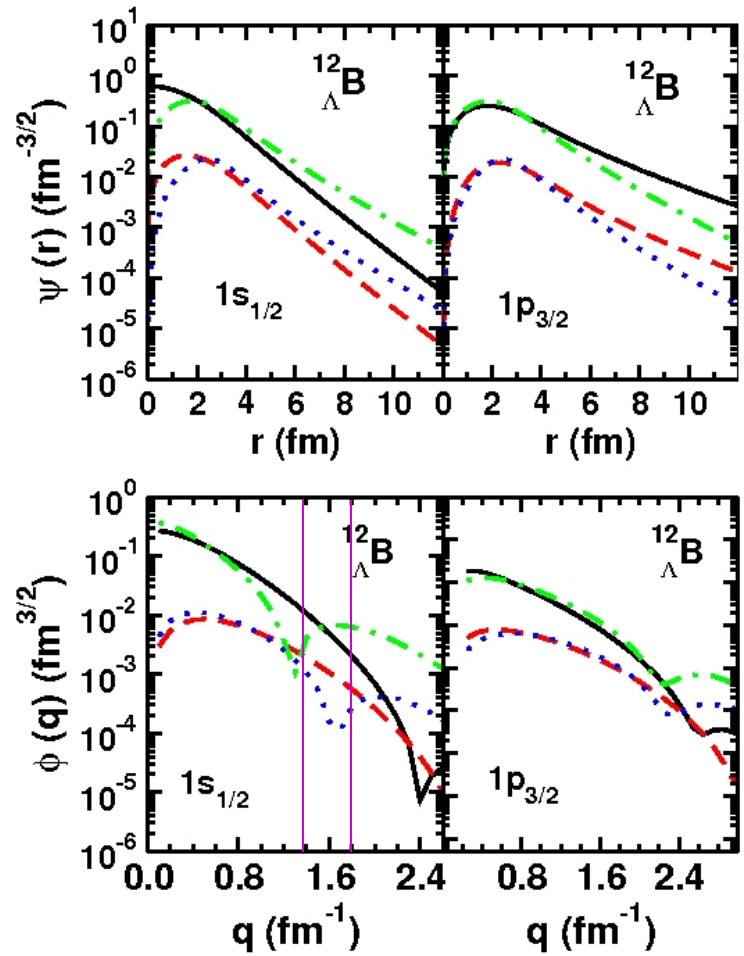


$^{12}_{\Lambda}$B hypernuclei (MeV)

State	Exp.	QMC	V_V (W.S)	V_S (W.S)
$^{12}_{\Lambda}$B1s$_{1/2}$	11.37	14.93	171.78	-212.69
$^{12}_{\Lambda}$B1p$_{3/2}$	1.73	3.62	204.16	-252.28
$^{12}_{\Lambda}$B1p$_{1/2}$	1.13	3.62	227.83	-280.86
(p1p$_{3/2}$)$^{-1}$ ^{12}C	15.96 Sep. energy	(≅OK)	382.60	-472.34

Potentials and wave functions





QMC, W.S. type

|QMCU|, |QMCL|, |DiracpU|, |DiracpL|

Differential cross sections: $^{12}C(\gamma,K^+)^{12}_{\Lambda}B$

arXiv:0812.1547 [nucl-th]

E_{th} ~ 695 MeV

$d\sigma/d\Omega$ at

Kaon angle $\theta = 10°$

$1^-, 2^- \Leftrightarrow (1p^{-p}_{3/2}, 1s^{\Lambda}_{1/2})$

(wave functions!) ⇒

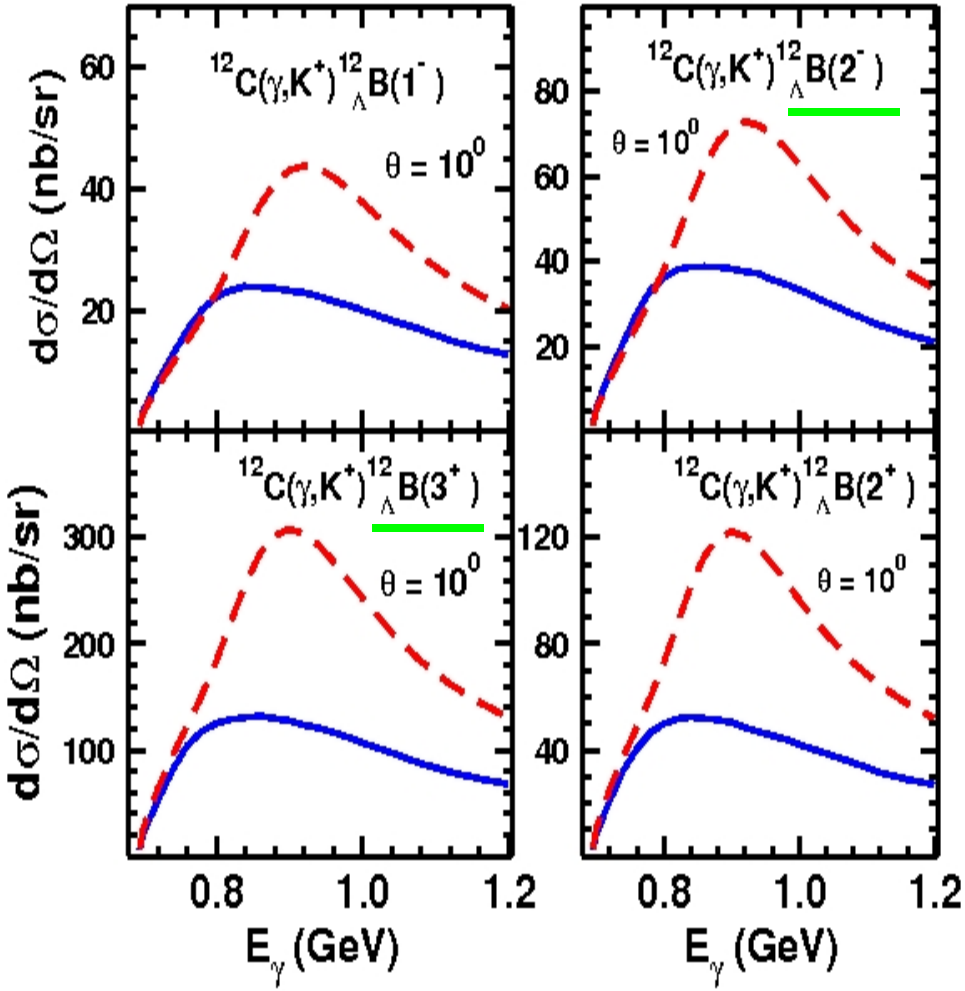
$2^+, 3^+ \Leftrightarrow (1p^{-p}_{3/2}, 1p^{\Lambda}_{3/2})$

(potentials!) ⇒

Diracp (phenomenological)

QMC

$|q| \cong [1.4, 1.7]$ fm $^{-1}$



Summary: Hypernuclei photoproduction

1. First attempt to study photoproduction of Λ-hypernuclei ($^{12}C(\gamma,K^+)^{12}_{\Lambda}B$ reaction) via quark-based model (QMC)
2. $d\sigma/d\Omega$ at Kaon angle $\theta = 10^\circ$ shows distinguishable difference!
3. Back ground inclusion for higher energies
4. Heavier hypernuclei?

Discussions, outlook

1. Study of Ξ-hypernuclei

   $\Uparrow$ $\Rightarrow$ $A(K^-,K^+)\,{}_{\Xi}B$ reaction

2. Elementary $K^- p \longrightarrow \Xi K^+$ reaction

3. Heavier Λ-hypernuclei photoproduction

4. Electroproduction of Λ-hypernuclei

Bound Nucleon GPDs and Incoherent DVCS

V. Guzey, A.W. Thomas, KT

arXiv:0806.3288 [hep-ph],

to be published in PLB

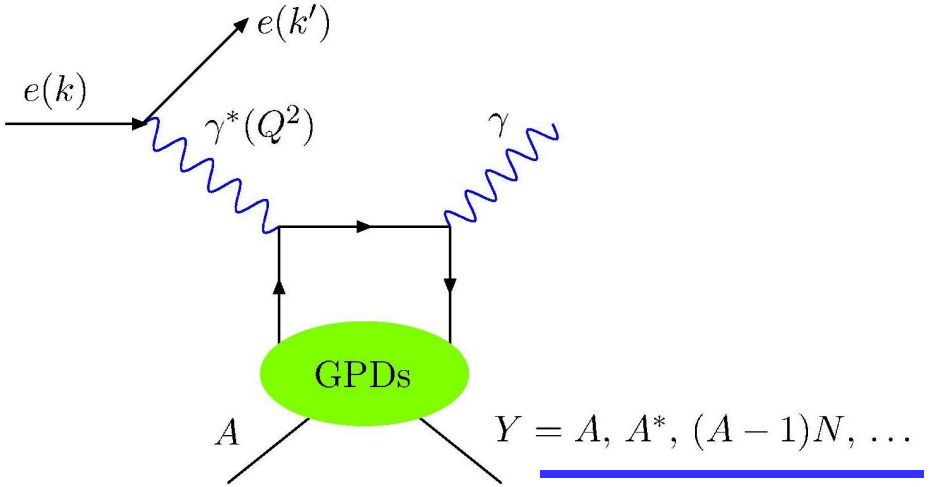
Medium effect on Generalized Parton Distributions

$\longrightarrow$ Deeply Virtual Compton Scattering

on a ^{4}He nucleus

Introduction

eply Virtual Compton ttering (DVCS) is the cleanest mple of hard exclusive process.



The QCD factorization theorem for hard exclusive reactions (DVCS, electroproduction of mesons) allows to interpret the measurements in terms of universal generalized parton distributions (GPDs) of the target.

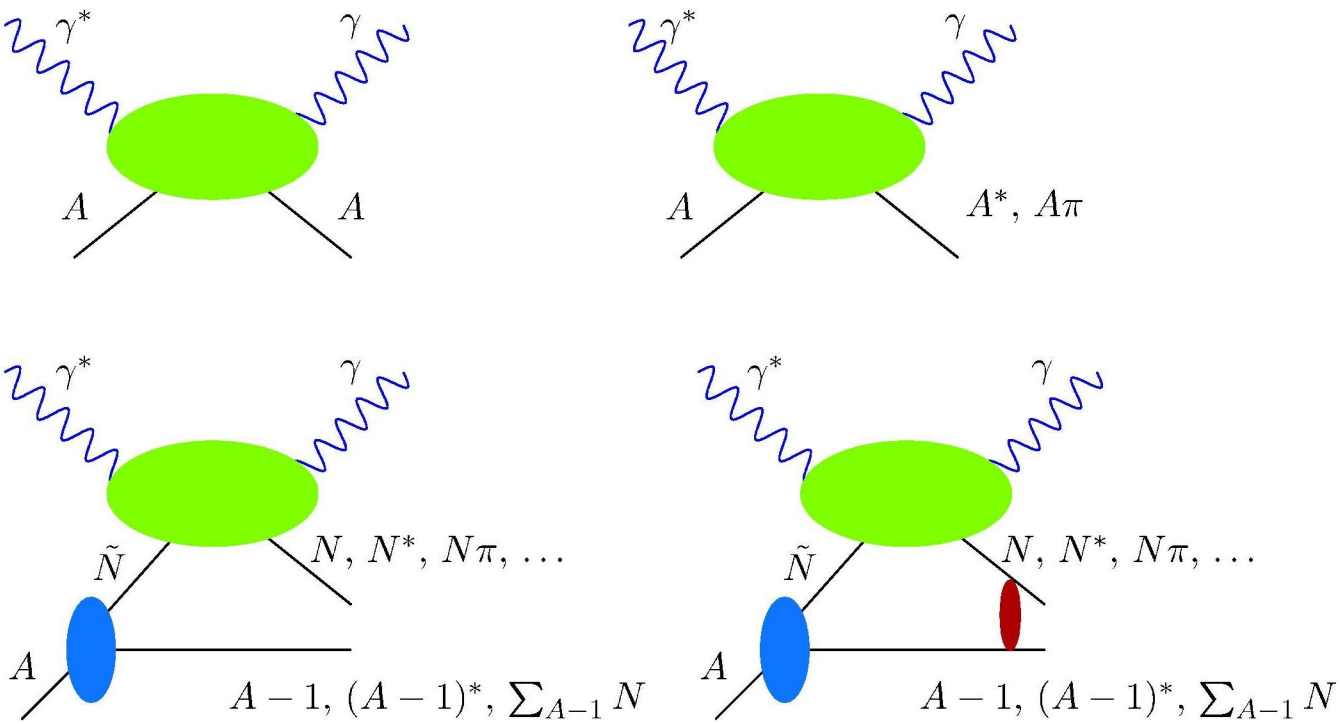
The GPDs generalize and interpolate between form factors and structure functions and encode information on 3D distributions of quarks and gluons in the target.

S on nuclear targets is more complex and versatile than DVCS on the free on since:

any more final states can be excited

he reaction mechanism is more complex

fferent spin and isospin of the target are available.



Important roles of nuclear DVCS:

Nuclear DVCS gives the information on the nucleon GPDs complimentary to DVCS on the free proton:

- theoretical description of nuclear GPDs requires GPDs of the (bound) proton and neutron as input
  VG and Strikman '03, VG '08;S. Scopetta '04; S. Liuti and S.K. Taneja '05

- incoherent DVCS on deuteron accesses almost-on-shell neutron GPDs
  M. Mazouz *et al.* (Hall A), Phys. Rev. Lett. **99**, 242501 (2007)

- DVCS on polarized ^{3}He will probe GPDs of the neutron

- electroduction of pseudoscalar mesons on deuteron is sensitive to non-pole contribution to the GPD $\tilde{E}$
  F. Cano and B. Pire, Eur. Phys. J. A **19**, 423 (2004)

  $\Downarrow$???!!!

- electroproduction of pseudoscalar mesons on ^{3}He at small t probes GPDs of the neutron ($\gamma^*_{\rm L}+{}^3{\rm He}\to\pi^0+{}^3{\rm He}$) or proton ($\gamma^*_{\rm L}+{}^3{\rm He}\to\pi^++{}^3{\rm H}$)
  L. Frankfurt *et al.*, Phys. Rev. D **60**, 014010 (1999)

ear DVCS is interesting in its own right:

light access novel nuclear effects not present in DIS and elastic scattering on uclear targets:

- contribution of non-nucleon (meson) degrees of freedom to the real part of the DVCS amplitude
  M.V. Polyakov, Phys. Lett. B **555**, 57 (2003); VG and M. Siddikov, J. Phys. G **32**, 251 (2006)

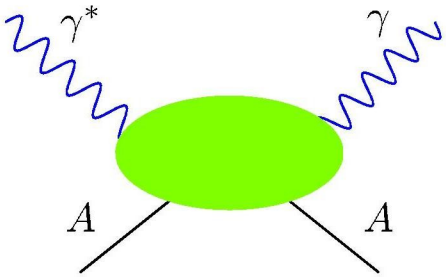
- unexpected pattern of nuclear shadowing for the real part of the DVCS amplitude at high-energies
  A. Freund and M. Strikman, Phys. Rev. C **69**, 015203 (2004)

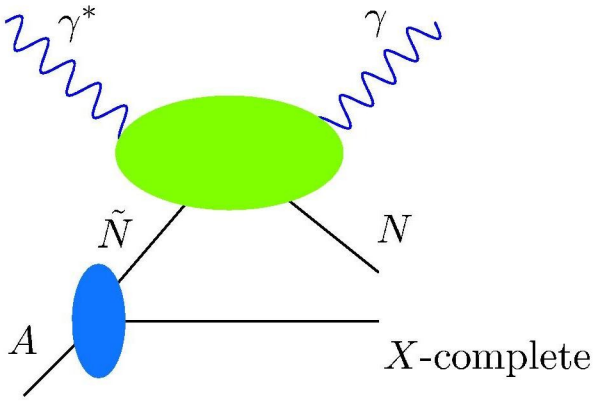
Vill put stringent constaints on theoretical models of the nuclear structure: ovariant description is more important than for nuclear DIS and nuclear form ctors

t high energies, nuclear DVCS is more sensitive to the physics of high parton ensities and the parton saturation than inclusive scattering
.V.T. Machado, arXiv:0810.3665 [hep-ph]

Incoherent and coherent nuclear DVCS

eoretical analysis of nuclear DVCS, the analysis is simplest when the final state
mple: elastic or complete set of final nuclear states.





Coherent nuclear DVCS:

- dominates at small t
- $\mathcal{A} \propto A\, F_A(t)$

Incoherent nuclear DVCS:

– dominates at large t
– $\mathcal{A} \propto F_N(t)$

n the final nuclear state is not detected (summed over), both coherent and
herent contributions are present.

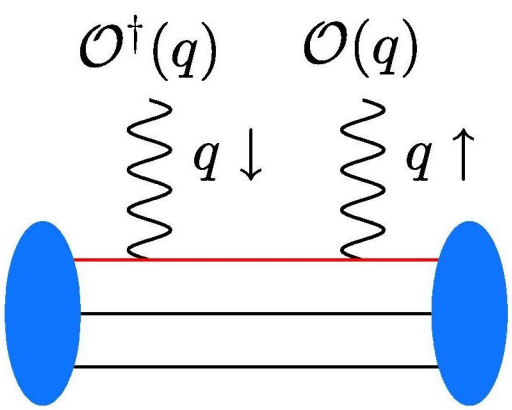
S amplitude: $\mathcal{T}^A_{\rm DVCS} = -\bar{u}(k')\gamma_\mu u(k)\frac{1}{Q^2}H^{\mu\nu}\epsilon^*_\nu$

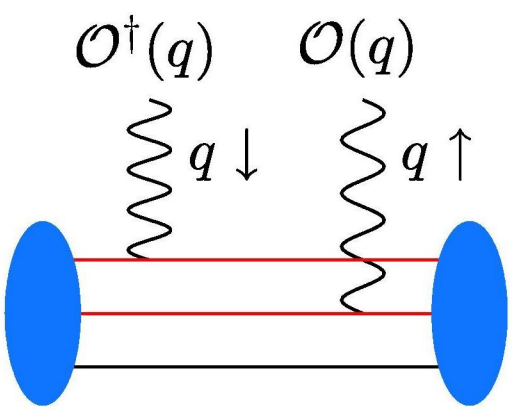
ronic tensor: $H^{\mu\nu} = -\int d^4x e^{-iqx}\langle X|T\{J^\mu(x)J^\nu(0)\}|A\rangle \equiv \langle X|\mathcal{O}(q)|A\rangle$

S amplitude squared:

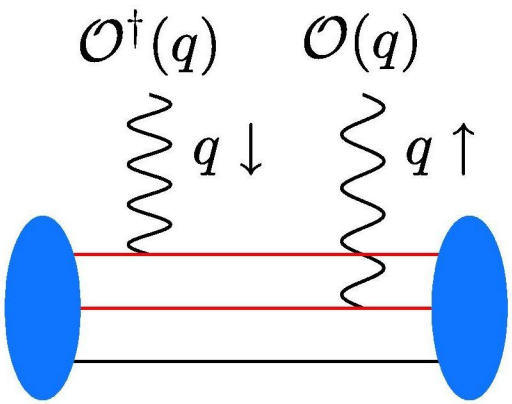
$$
\begin{aligned}
{}_{\rm CS}|^2 &\propto \langle A|\mathcal{O}^\dagger(q)|X\rangle\langle X|\mathcal{O}(q)|A\rangle = \langle A|\mathcal{O}^\dagger(q)\mathcal{O}(q)|A\rangle \\
&= \sum_{i,j}\langle A|N_i\rangle\langle N_i|\mathcal{O}^\dagger(q)\mathcal{O}(q)|N_j\rangle\langle N_j|A\rangle \\
&= \sum_i |\langle A|N_i\rangle|^2\langle N_i|\mathcal{O}^\dagger(q)\mathcal{O}(q)|N_i\rangle + \sum_{i\neq j}\langle A|N_i\rangle\langle N_i|\mathcal{O}^\dagger(q)\mathcal{O}(q)|N_j\rangle\langle N_j|A\rangle \\
&= A|\mathcal{T}^N_{\rm DVCS}|^2 + A(A-1)F_A^2(t' = A/(A-1)t)|\mathcal{T}^{A,\rm coh.enr.}_{\rm DVCS}|^2
\end{aligned}
$$

ankfurt, G.A. Miller and M.Strikman, Phys. Rev. D **65**, 094015 (2002)

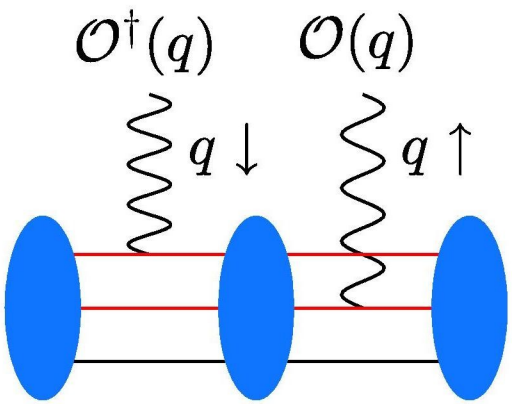




e the difference between the coherent-enriched and purely coherent contributions



$A(A-1)F_A^2(t')$



$A^2F_A^2(t)$

ral important comments:

he assumption of the completeness of final nuclear states (closure approximation) justified at sufficiently large t so that many final states are possible.

oth incoherent and coherent nuclear DVCS take place on medium-modified, ff-shell nucleons that are subject to Fermi motion.
or incoherent nuclear DVCS:

$$A|\mathcal{T}^N_{\rm DVCS}|^2 \to \int_{\alpha_{\rm min}}^1 \frac{d\alpha}{\alpha}\rho^N_A(\alpha)|\mathcal{T}^{N^*}_{\rm DVCS}(\xi_N(\alpha)|^2$$

my numerical results shown below, these effects are neglected. I only distinguish etween protons and neutrons:

$$A|\mathcal{T}^N_{\rm DVCS}|^2 = Z|\mathcal{T}^p_{\rm DVCS}|^2 + N|\mathcal{T}^n_{\rm DVCS}|^2$$

$$A\mathcal{T}^{A,\rm coh.enr.}_{\rm DVCS} = F_A(t')(Z\mathcal{T}^p_{\rm DVCS} + N\mathcal{T}^n_{\rm DVCS}) \equiv AF_A(t')\mathcal{T}^{N/A}_{\rm DVCS}$$

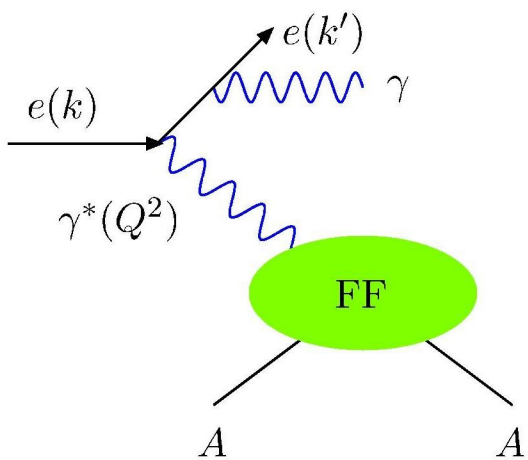
S cross section at the photon level (keeping only the GPD H):

$$\frac{d\sigma}{dt} \approx \frac{\pi \alpha_{\rm em}^2 x_B^2}{Q^4} \left[A(A-1) F_A^2(t') |\mathcal{H}_{N/A}|^2 + Z|\mathcal{H}_p|^2 + N|\mathcal{H}_n|^2 \right]$$

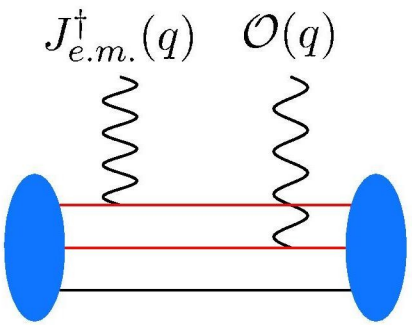
S beam-spin asymmetry $A_{LU}(\phi)$:

$$A_{LU}(\phi) = \frac{\overrightarrow{\sigma} - \overleftarrow{\sigma}}{\sigma^{\rm unp}} = \frac{(A-1) Z F_A^2(t') \Delta\mathcal{I}_{N/A} + Z\Delta\mathcal{I}_p + N\Delta I_n}{Z(Z-1) F_A^2(t') |\mathcal{T}_{N/A}^{\rm BH}|^2 + Z|\mathcal{T}_p^{\rm BH}|^2 + N|\mathcal{T}_n^{\rm BH}|^2 + \ldots}$$

e-Heitler process



"Counting" for coherent-enriched interference



$Z(A-1)F_A^2(t')$

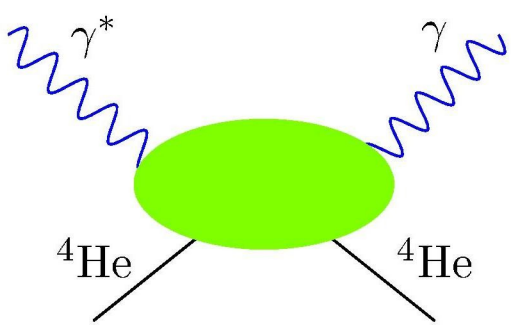
Medium modifications and incoherent nuclear DVCS

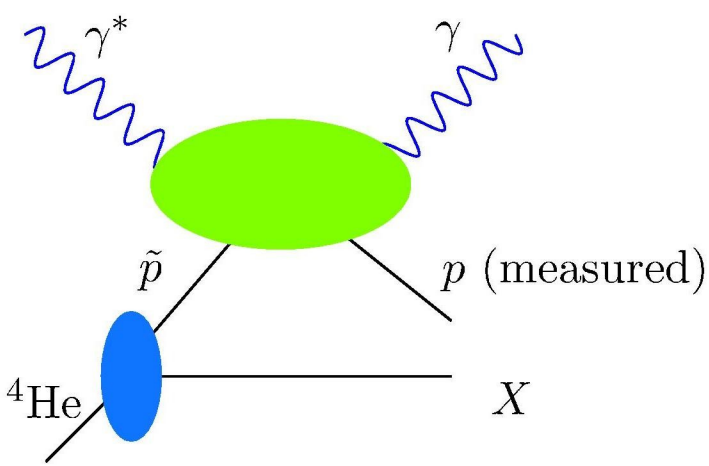
new Jefferson Lab (CLAS collaboration) experiment on DVCS on ^{4}He will sure

giyan, F.-X. Girod, K. Hafidi, S. Liuti, E. Voutier *et al.*, Jefferson Lab Experiment E08-024)

urely coherent DVCS on ^{4}He (the final nucleus will be detected using BoNuS etector)

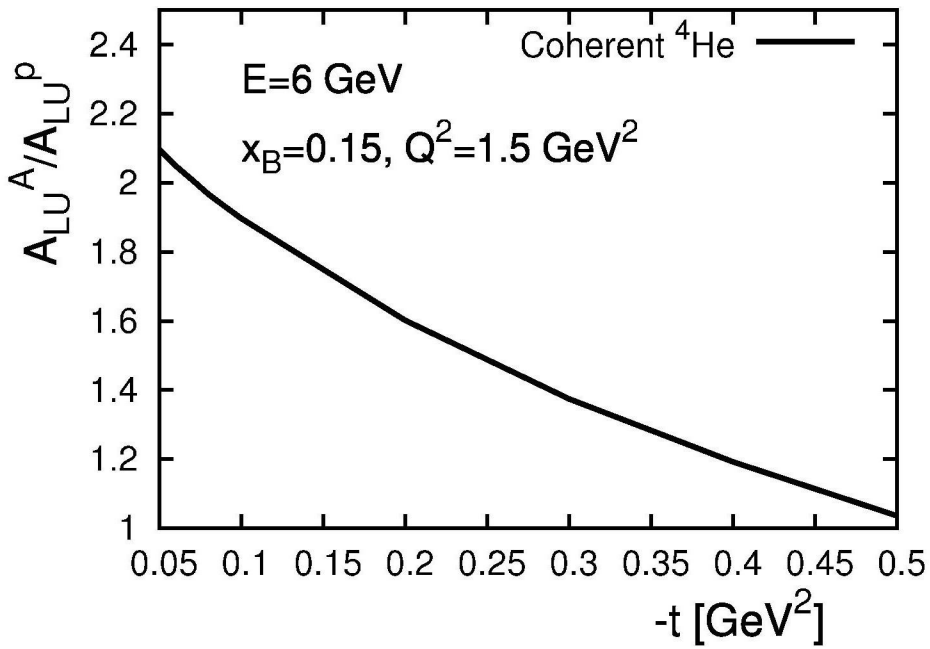
coherent DVCS on the bound proton (the final proton is detected)





ictions for A_{LU}^{A}/A_{LU}^{p} for coherent DVCS on ^{4}He ($\phi = 90^0$)

uzey, Phys. Rev. C **78**, 025211 (2008)



ictions for the incoherent DVCS on bound proton in ^{4}He

$$\frac{A_{LU}^{p^*}}{A_{LU}^{p}} = 1$$

However !! ⇒

e Fermi motion, off-shellness and medium-modification effects are not taken into unt.

ncluded the effect of medium-modifications of the bound nucleon assuming that edium nucleon GPDs are modified in proportion to the bound nucleon elastic factors.

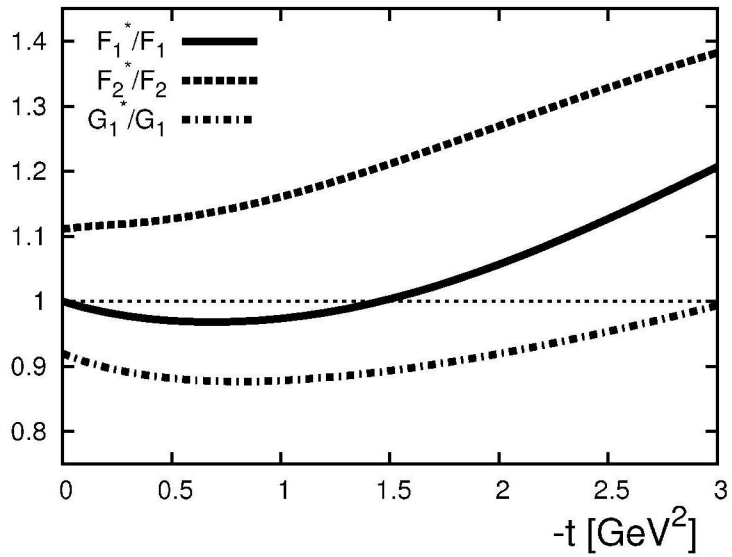
A.W. Thomas and K. Tsushima, arXiv:0806.3288

Model, assumption !

$$H^{q/p^*} = \frac{F_1^{p^*}(t)}{F_1^p(t)} H^{q/p}$$

$$E^{q/p^*} = \frac{F_2^{p^*}(t)}{F_2^p(t)} E^{q/p}$$

$$\tilde{H}^{q/p^*} = \frac{G_1^{p^*}(t)}{G_1^p(t)} \tilde{H}^{q/p}$$

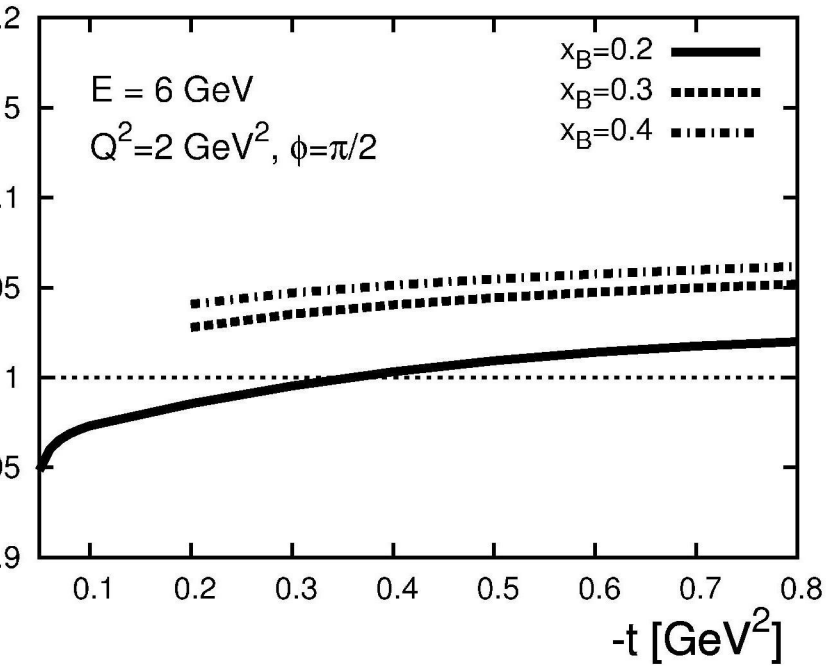


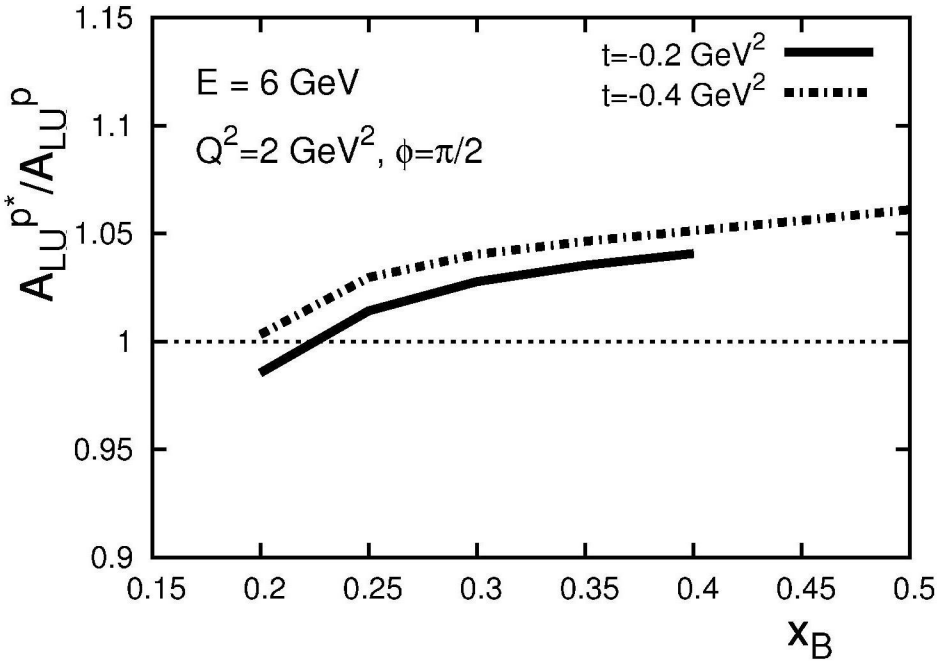
K. Saito, K. Tsushima and A.W. Thomas, Prog. Part. Nucl. Phys. **58**, 1 (2007)

medium-modified elastic form factors are taken from the Quark-Meson Coupling el whose predictions are consistent with the polarization transfer measurement $(\vec{e}, e'\vec{p})^3\mathrm{H}$ (Hall A JLab): S. Malace, S. Strauch, arXiv:0807.2252 (Actually, MM+FM+FSI)

ictions for the ratio of the bound to free proton DVCS beam-spin asymmetries, $/A^p_{LU}$, for incoherent DVCS on $^4\mathrm{He}$

A.W. Thomas and K. Tsushima, arXiv:0806.3288.





he deviation of $A^{p^*}_{LU}/A^p_{LU}$ from unity is as large as 6%

ur predictions are much smaller in size and different in shape (x_B-dependence) om the predictions of S. Liuti and S.K. Taneja, Phys. Rev. C **72**, 032201 (2005); C **72**, 34902 (2005)

Conclusions and Discussion

sing the completeness of the final nuclear states, one can derive an expression r nuclear DVCS that interpolates between the coherent-enriched and incoherent uclear DVCS

or the coherent-enriched and purely coherent nuclear DVCS, we predict the combinatoric" enhancement at small t, $A_{LU}^{A}/A_{LU}^{p} = 1.65 - 2$.

or the incoherent nuclear DVCS at large t, $A_{LU}^{A}/A_{LU}^{p} < 1$ due to the neutron ontribution.

he effect of medium-modifications of the bound nucleon GPDs are modelled sing results of the Quark-Meson coupling model; the deviation of $A_{LU}^{p^*}/A_{LU}^{p}$ is t most 6%.

the above results, we neglected the effects of the Fermi motion and the final ate interactions.

uture work (personal plans): final state interactions for incoherent DVCS on euteron; DVCS on polarized ^{3}He.

Speculations !!! (bound proton spin)

$J_q + J_G = (\Delta q + L_q) + J_G = 1/2$

- $g_A^* < g_A \longrightarrow \Delta q^* < \Delta q$
- $F_1^* \cong F_1$ ($F_1^*(0) = F_1(0) = 1$), $F_2^* > F_2$

$\longrightarrow H_q^* \cong H_q$, $E_q^* > E_q$ ($\mu_p^* > \mu_p$)

$J_q^* = ½ - J_G^* = (\Delta q^* + L_q^*)$

$= ½\int dx\, x(H_q^* + E_q^*) > ½\int dx\, x(H_q + E_q)$

$= (\Delta q + L_q) - J_G = ½ - J_G = J_q$

$\longrightarrow$ $J_q^* > J_q$ ($J_G^* < J_G$ or $L_q^* > L_q$)