Effective nuclear force, finite (hyper)nuclei and neutron star from quarks: the QMC model

APCTP Focus Program in Nuclear Physics 2019
Nuclear Many-Body Theories: Beyond the Mean Field Approaches

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Kazuo Tsushima

UNICSUL/UNICID (Cruzeiro do Sul University/City University of Sao Paulo), Brazil

1. K. Tsushima, Phys. Rev. D 99, 014026 (2019): propaganda (heavy baryon)

2. G. Krein, A. W. Thomas, K. Tsushima (Quarkonia-A)
Prog. Part. Nucl. Phys. 100, 161 (2018)

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

QMC model: Hadron, Nuclear and Neutron Star Structure from Quarks and Gluons

Kazuo Tsushima

M.K. Cheoun
J.J. Cobos-Martínez
P. Guichon
V. Guzey
G. Krein
D.H. Lu
P.T.P. Hutauruk
J.P.B.C. de Melo
Y. Oh
G. Ramalho
K. Saito
A. Sibirtsev
R. Shyam
A.W. Thomas

Uni. Cruzeiro do Sul
City Uni. of Sao Paulo
Sao Paulo, Brazil

OUTLINE

1. Introduction: Motivations (QMC model)
2. Finite Nuclei: Effective Nuclear Force
3. Hypernuclei (General Introduction)
4. Λ-hypernuclei photoproduction
5. Ξ-hypernuclei production
6. Neutron Star
7. Heavy Baryons in Medium
8. Neutrino reactions and in-medium form factors
9. Pion, N, EMFFs and D.A. in medium,
10. Bound Nucleon GPDs and Incoherent DVCS
11. D (K) meson in medium and J/Ψ-(Φ-)nuclear bound states
12. Other things.......
13. Summary and Future Plans

Introduction, Motivations: QMC model

References:

In-medium properties of the low-lying strange, charm, and bottom baryons in the quark-meson coupling model (Heavy Baryons):
K. Tsushima
Phys. Rev. D 99, 014026 (2019)

Quarkonia-nuclear bindings (QMC model brief summary):
G. Krein, A. W. Thomas, K. Tsushima
Prog. Part. Nucl. Phys. 100, 161 (2018)

QMC model summary:
K. Saito, K. Tsushima and A. W. Thomas
Prog. Part. Nucl. Phys. 58, 1 (2007)

Motivations

- **(Large)** **nuclei**, and **nuclear matter** in terms of **quarks** and **gluons**

(**eventually** by **QCD**) **???!!!**

- **NN**,NNN,NNNN... interactions →

Nucleus ? ← shell model, MF model,...

- **Lattice QCD**: still extracting **NN, NY and YY** interactions, [**Y**=hyperons:**Λ,Σ,Ξ**]
- **Quark model** based description of **nucleus**
- **Hadron** properties **in a nuclear medium**

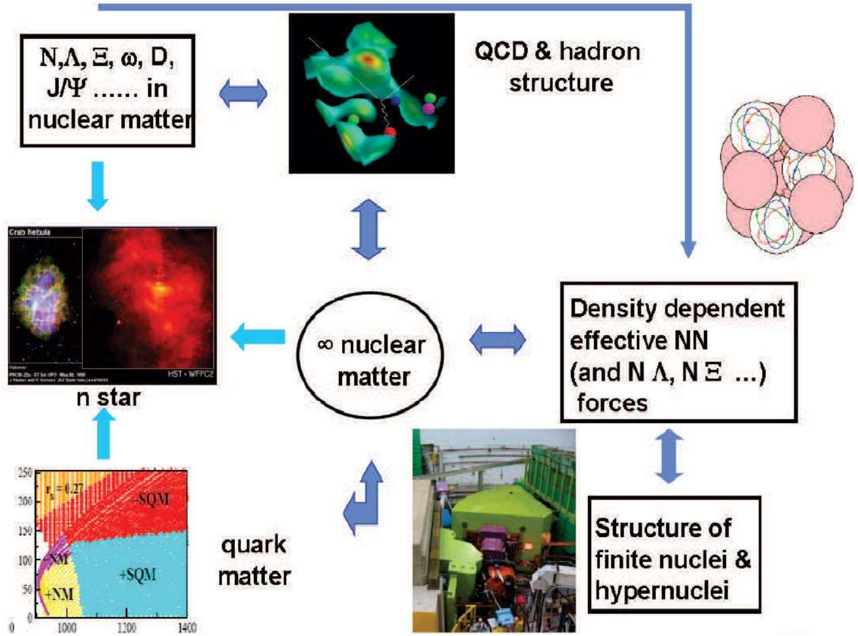
Suggests a different approach : QMC Model

(Guichon, Saito, Tsushima et al., Rodionov et al.
- see Saito et al., Prog. Part. Nucl .Phys. 58 (2007) 1 and
Prog. Part. Nucl. Phys. 100 (2018) 262-297 for reviews)

- Start with quark model (MIT bag/NJL...) for all hadrons
- Introduce a relativistic Lagrangian with σ, ω and ρ mesons coupling to non-strange quarks
- Hence only 3 parameters (4 if σ mass not fixed)

  − determine by fitting to:
  ρ_0 , E/A and symmetry energy
  − same in dense matter & finite nuclei

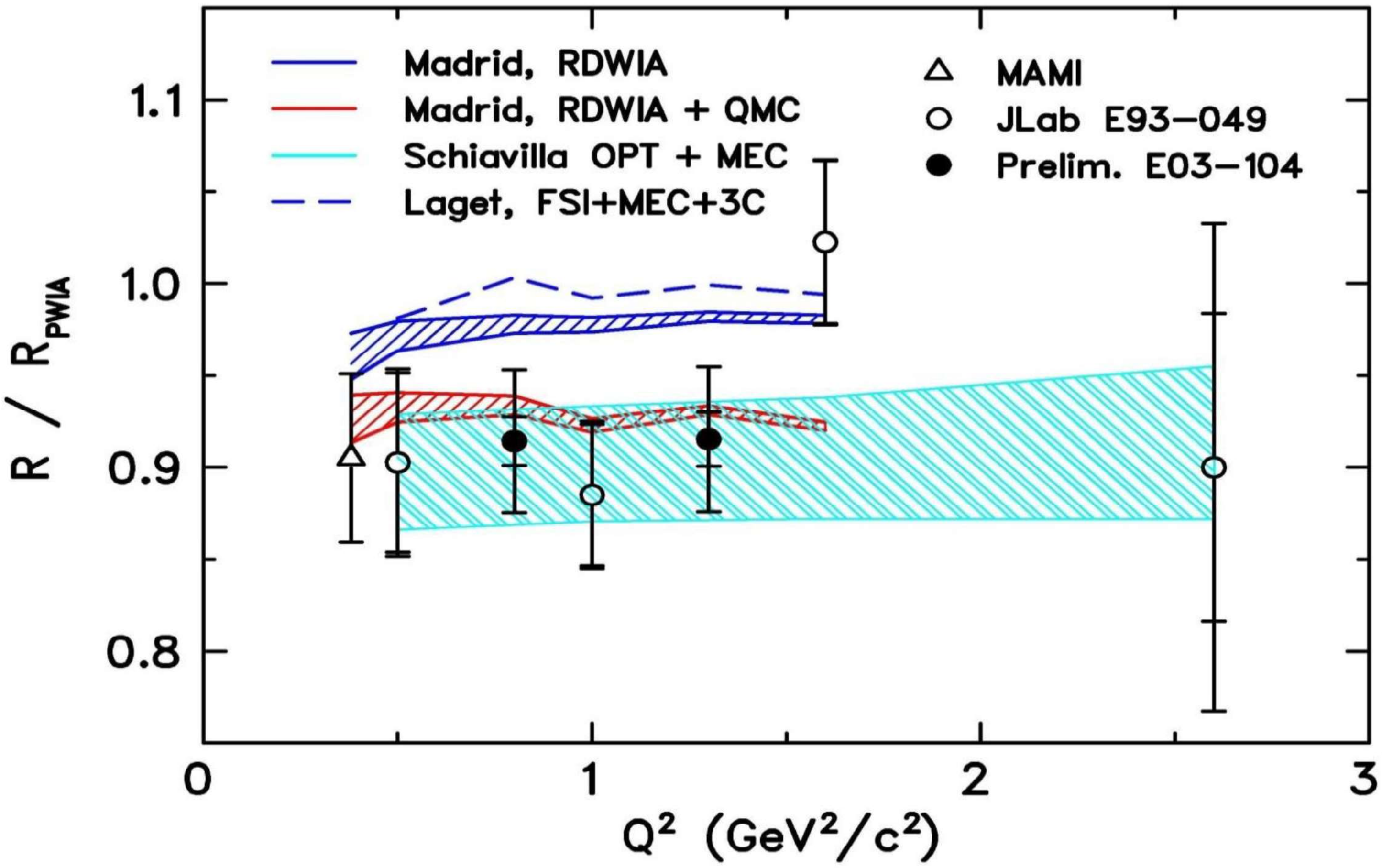
- Must solve self-consistently for the internal structure of baryons in-medium



$R=(p'_x/p'_z)=(G_E^p/G_M^p)$: $^4He/^1H$

S. Malace, M. Paolone and S. Strauch, arXiv:0807.2251 [nucl-ex]

S. Strauch *et al., Phys. Rev. Lett.* ***91, 052301 (2003)***

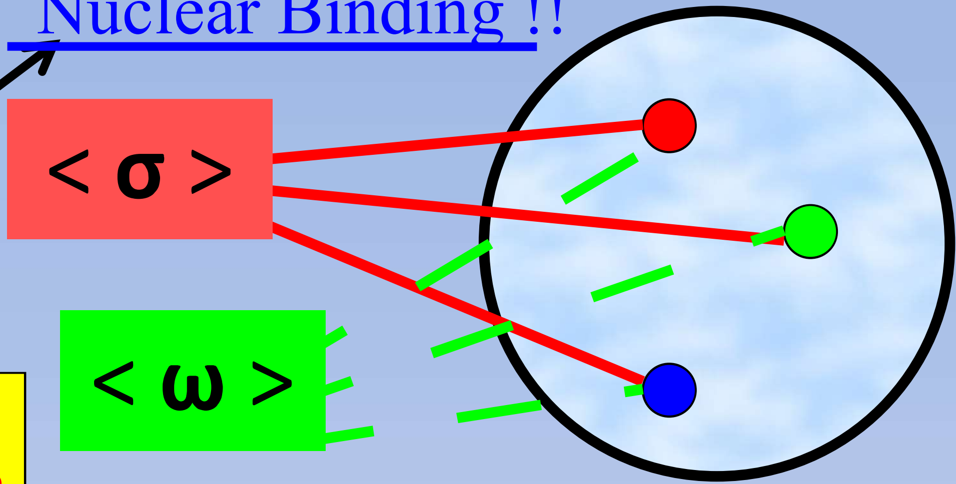


The QMC model P. Guichon, PLB 200, 235 (1988)

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

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

Nuclear Binding !!



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

↓ nonlinear in **σ**

$M^*_N \approx M_N - g^N_\sigma \sigma + \underline{(d/2)\,(g^N_\sigma \sigma)^2}$

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

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

1. Start

$[i\gamma\cdot\partial - M^*_N + \gamma_0 V^N_\omega]\, N = 0$

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

Self-consistent !

(Applied quark model !)

Bound quark Dirac spinor ($1s_{1/2}$)

Quark Dirac spinor in a **bound hadron:**

$$q_{1s}(r) = \begin{pmatrix} U(r) \\ i\sigma\cdot\hat{r}\, L(r) \end{pmatrix} \chi$$

Lower component is **enhanced** !

⇒ $g_A^* < g_A$: ~ $|U|^{**}2 - (1/3)\, |L|^{**}2$,

⇒ **Decrease** of scalar density ⇒

Decrease in Scalar Density

Scalar density (quark): ~ **|U|**2 - |L|**2**,

⇓

M_N*, **N** wave function, **Nuclear** scalar density etc., are **self-consistently modified** due to

the N **internal structure** change !

⇒ **Novel Saturation** mechanism !

At Nucleon Level Response to the Applied Scalar Field is the Scalar Polarizability

Nucleon response to **a chiral invariant scalar field**
is then a nucleon property of great interest…

$$M^*(\vec{R}) \approx M - g_\sigma \sigma(\vec{R}) + (d/2)\,(g_\sigma \sigma(\vec{R}))^{**}2$$

Non-linear dependence **scalar polarizability**
0.22 d**¼ R in original QMC (MIT bag)

Indeed, in nuclear matter at mean-field level (e.g. QMC), this is the **ONLY place the response of the internal structure of the nucleon enters.**

QMC model 1: Hadron level

$$\mathcal{L} = \bar{\psi}[i\gamma \cdot \partial - m_N^*(\sigma) - g_\omega \omega^\mu \gamma_\mu]\psi + \mathcal{L}_{\rm meson},$$

$$m_N^*(\sigma) \equiv m_N - g_\sigma \underline{(\sigma)}\sigma \simeq m_N - g_\sigma \underline{[1 - (a_N/2)(g_\sigma \sigma)]}\sigma$$

$$g_\sigma \equiv g_\sigma(\sigma = 0)$$

$$\mathcal{L}_{\rm meson} = \frac{1}{2}\partial_\mu \sigma \partial^\mu \sigma - m_\sigma^2 \sigma^2 - \frac{1}{2}\partial_\mu \omega_\nu (\partial^\mu \omega^\nu - \partial^\nu \omega^\mu) + \frac{1}{2} m_\omega^2 \omega^\mu \omega_\mu \, ,$$

$$\rho_B = \frac{4}{(2\pi)^3}\int d^3k \, \theta(k_F - |\vec{k}|) = \frac{2k_F^3}{3\pi^2},$$

$$\rho_s = \frac{4}{(2\pi)^3}\int d^3k \, \theta(k_F - |\vec{k}|) \frac{m_N^*(\sigma)}{\sqrt{m_N^{*2}(\sigma) + \vec{k}^2}},$$

QMC model 2: Quark level

$x = (t, \vec{r})$ ($|\vec{r}| \leq$ bag radius)

$$\left[i\gamma\cdot\partial_x - (m_q - V^q_\sigma) \mp \gamma^0\left(V^q_\omega + \frac{1}{2}V^q_\rho\right)\right]\begin{pmatrix}\psi_u(x)\\ \psi_{\bar{u}}(x)\end{pmatrix} = 0$$

$$\left[i\gamma\cdot\partial_x - (m_q - V^q_\sigma) \mp \gamma^0\left(V^q_\omega - \frac{1}{2}V^q_\rho\right)\right]\begin{pmatrix}\psi_d(x)\\ \psi_{\bar{d}}(x)\end{pmatrix} = 0$$

$$[i\gamma\cdot\partial_x - m_Q]\,\psi_Q(x)\ (\text{or } \psi_{\overline{Q}}(x)) = 0$$

$$m^*_h = \sum_{j=q,\bar{q},Q\overline{Q}} \frac{n_j\Omega^*_j - z_h}{R^*_h} + \frac{4}{3}\pi R^{*3}_h B, \quad \left.\frac{\partial m^*_h}{\partial R_h}\right|_{R_h=R^*_h} = 0$$

$$\Omega^*_q = \Omega^*_{\bar{q}} = [x^2_q + (R^*_h m^*_q)^2]^{1/2}, \text{with } m^*_q = m_q - g^q_\sigma\sigma$$

$$\Omega^*_Q = \Omega^*_{\overline{Q}} = [x^2_Q + (R^*_h m_Q)^2]^{1/2} \quad (Q = s, c, b)$$

QMC model 3: From quarks

$$\omega = \frac{g_\omega \rho_B}{m_\omega^2},$$

$$\sigma = \frac{g_\sigma}{m_\sigma^2} C_N(\sigma) \frac{4}{(2\pi)^3} \int d^3k \, \theta(k_F - |\vec{k}|) \frac{m_N^*(\sigma)}{\sqrt{m_N^{*2}(\sigma) + \vec{k}^2}}$$

$$= \frac{g_\sigma}{m_\sigma^2} C_N(\sigma) \rho_s \quad (g_\sigma \equiv g_\sigma(\sigma = 0)),$$

$$C_N(\sigma) = \frac{-1}{g_\sigma(\sigma = 0)} \left[\frac{\partial m_N^*(\sigma)}{\partial \sigma} \right],$$

$$E^{tot}/A - m_N = \frac{4}{(2\pi)^3 \rho_B} \int d^3k \, \theta(k_F - |\vec{k}|) \sqrt{m_N^{*2}(\sigma) + \vec{k}^2}$$

$$+ \frac{m_\sigma^2 \sigma^2}{2\rho_B} + \frac{g_\omega^2 \rho_B}{2 m_\omega^2} - m_N.$$

QMC model 4: Couplings etc.

m_q(MeV)	$g_\sigma^2/4\pi$	$g_\omega^2/4\pi$	m_N^*	K	Z_N	$B^{1/4}$(MeV)
5	5.39	5.30	754.6	279.3	3.295	170
220	6.40	7.57	698.6	320.9	4.327	148

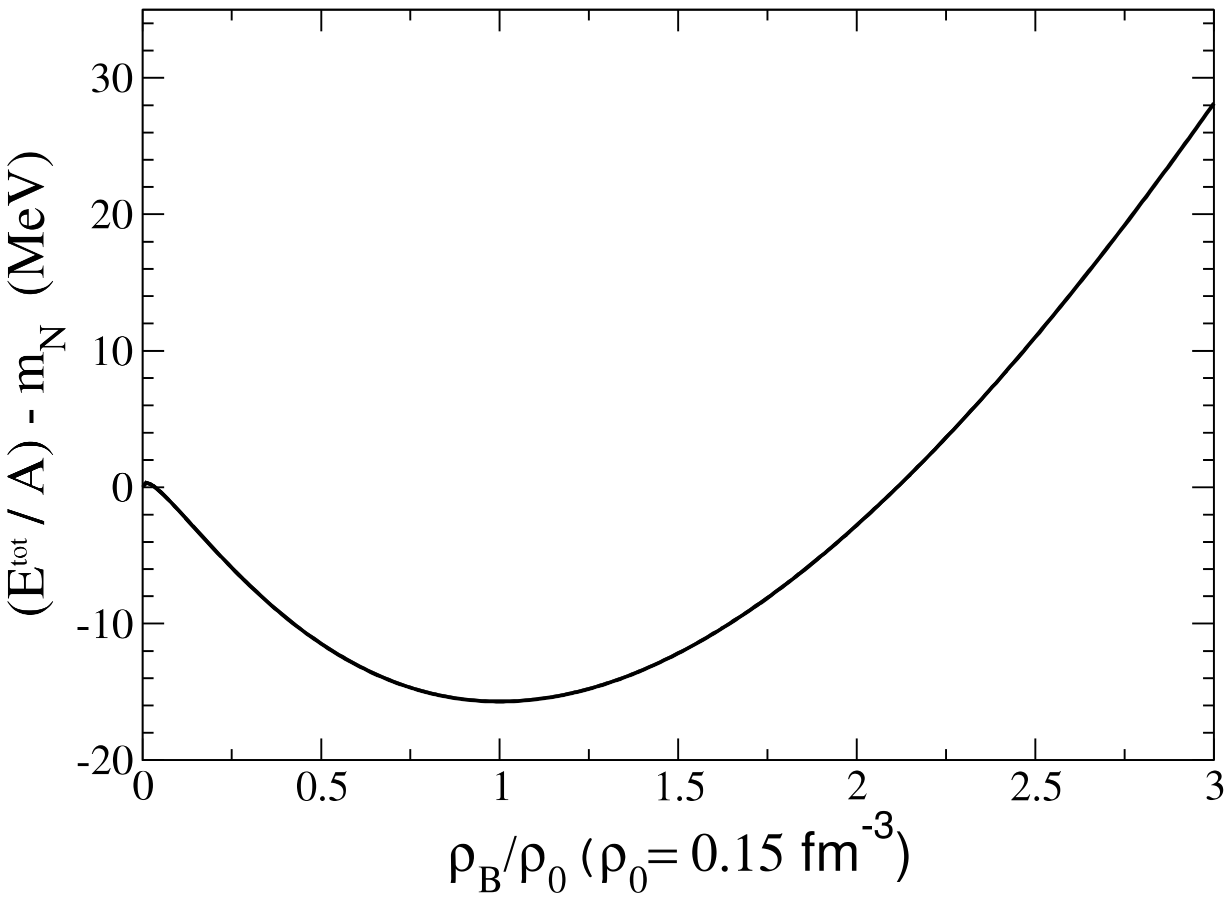
$$\frac{\partial m_N^*(\sigma)}{\partial\sigma} = -3g_\sigma^q \int_{bag} d^3r\, \overline{\psi}_q(\vec{r})\psi_q(\vec{r}) \quad \text{the lowest bag w.f.}$$

$$\equiv -\underline{3g_\sigma^q S_N(\sigma)} = -\frac{\partial}{\partial\sigma}[g_\sigma(\sigma)\sigma],$$

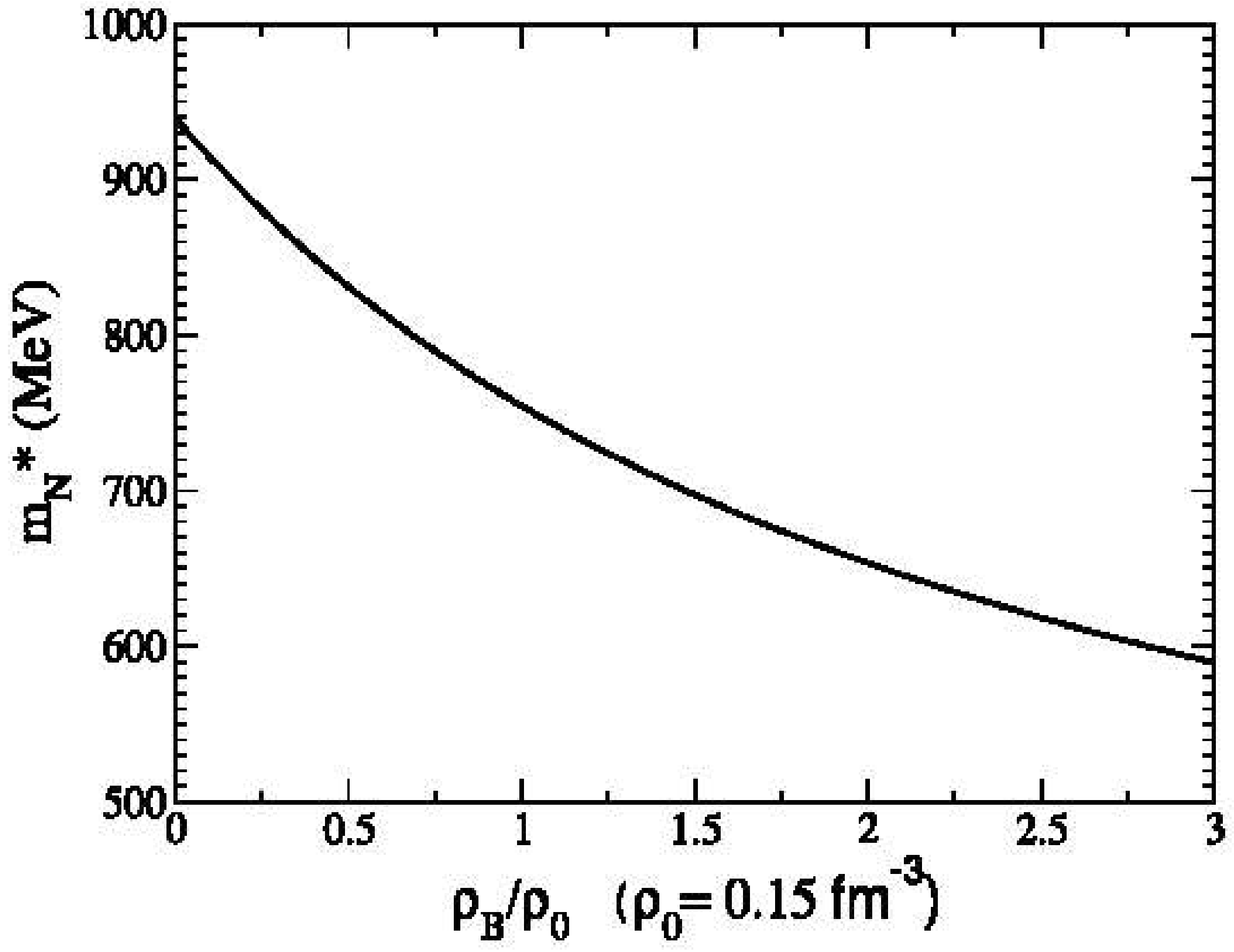
$$C_N(\sigma) = \frac{-1}{g_\sigma(\sigma=0)}\left[\frac{\partial m_N^*(\sigma)}{\partial\sigma}\right],$$

$$g_\sigma \equiv g_\sigma^N \equiv \underline{3g_\sigma^q S_N(\sigma=0)}.$$

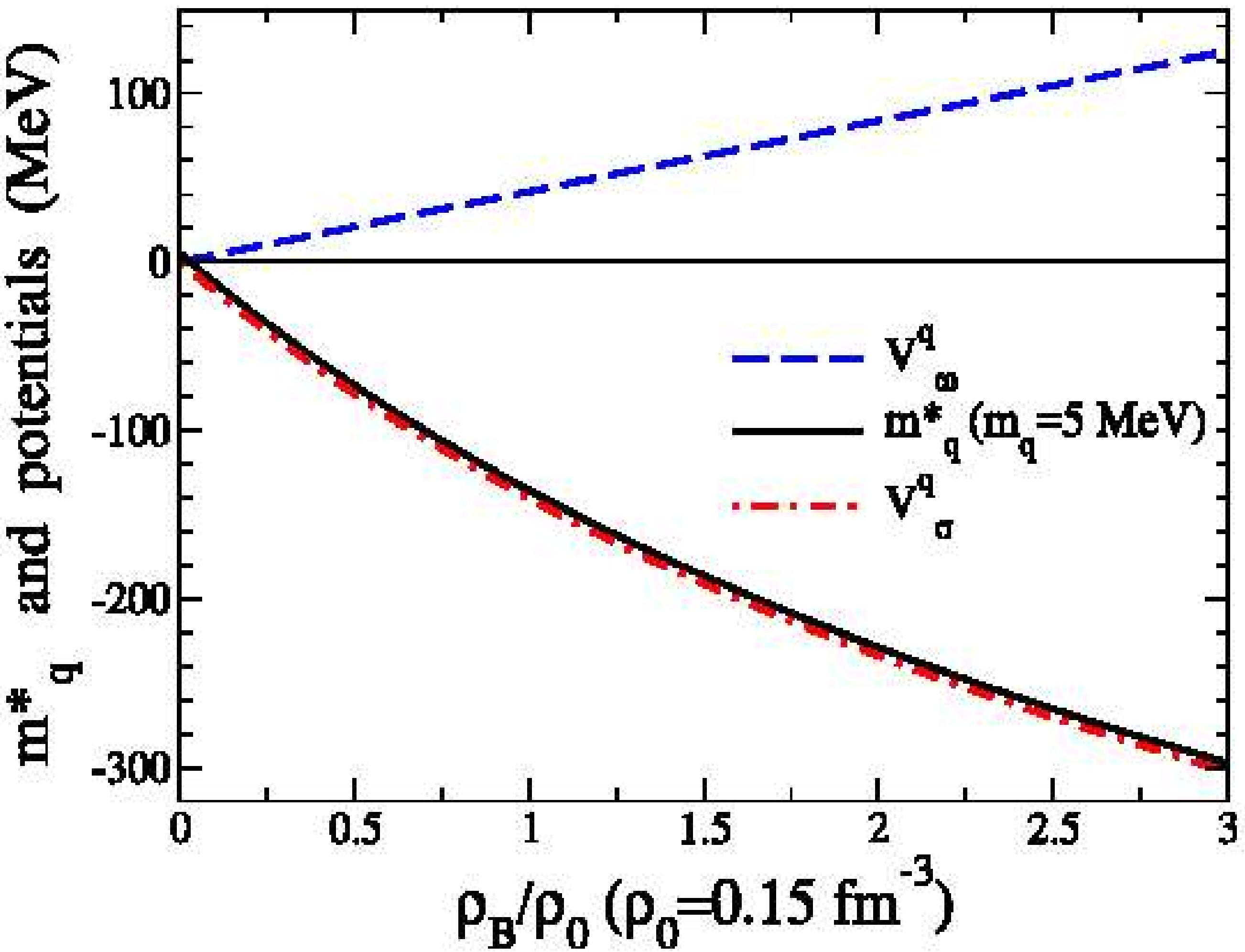
Results: Quark Meson Coupling (Standard)



- Symmetric Nuclear Matter - Binding Energy per Nucleon
- $m_q = 5$ MeV, $K = 279.3$ MeV



- **Nucleon effective mass: $m_q = 5$ MeV**



- Effective mass of constituent quarks: $m_q = 5$ MeV
- All the light-quarks in any hadrons feel the same potentials !!

Standard QMC, π, ρ in LF model parameters comparison

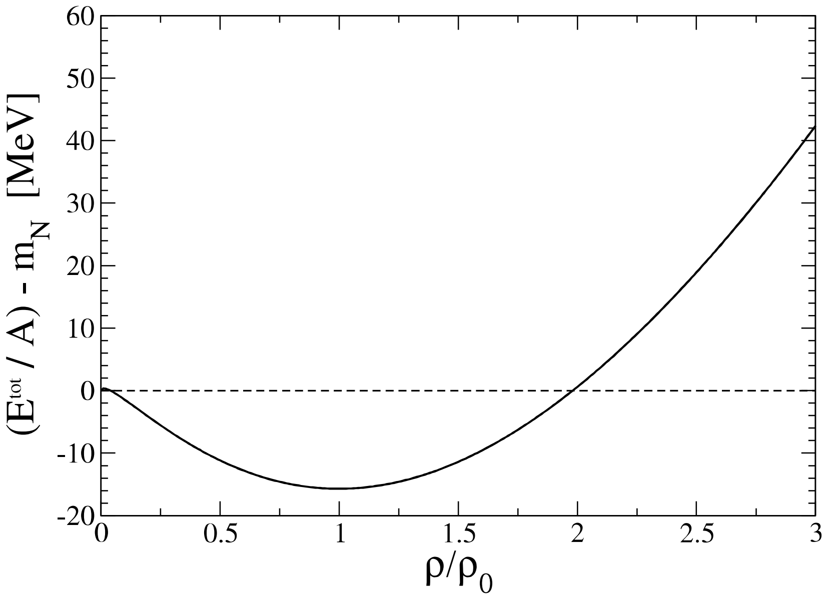
- **Motivation:** The present model works well (Symmetric Vertex)!

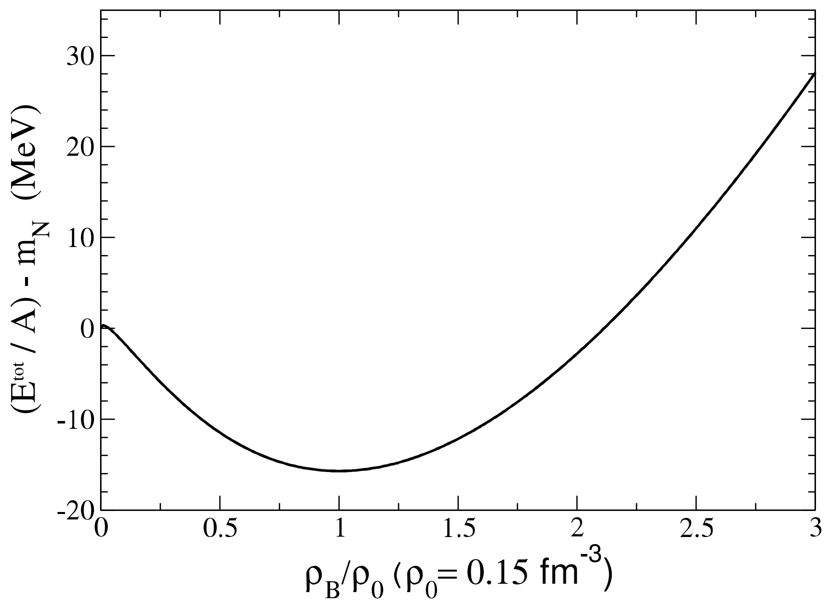
m_q(MeV)	$g_\sigma^2/4\pi$	$g_\omega^2/4\pi$	m_N^*	K	Z_N	$B^{1/4}$(MeV)
5	5.39	5.30	754.6	279.3	3.295	170
220	6.40	7.57	698.6	320.9	4.327	148
430	8.73	11.93	565.25	361.4	5.497	69.75

- **Refs. LF π, ρ model:**

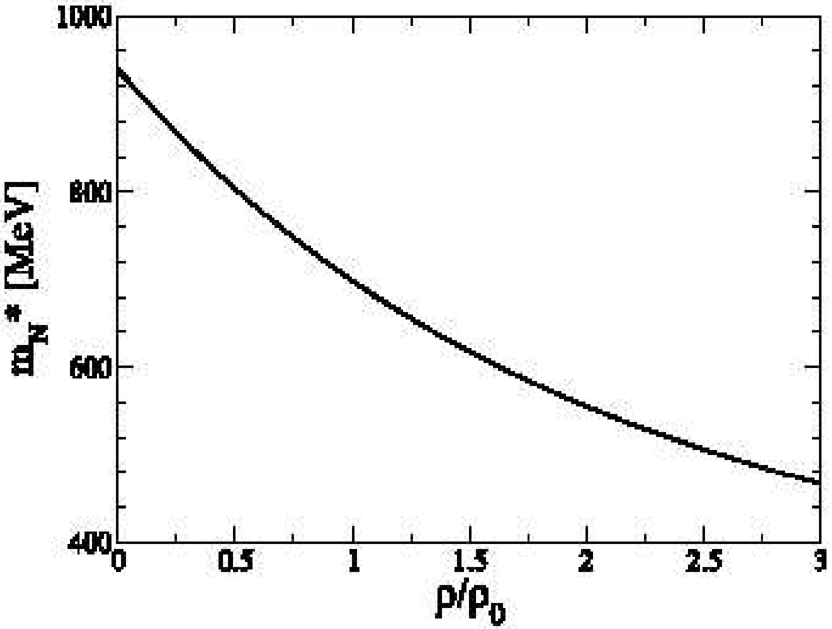
J.P.B.C. de Melo, KT et al.,
LF π model ($m_q = 220$ MeV): Phys.Rev. C90 (2014) no.3, 035201;
Phys.Lett. B766 (2017) 125;
Few Body Syst. 58 (2017) no.2, 85
LF ρ model ($m_q = 430$ MeV): Few Body Syst. 58 (2017) no.2, 82;
arXiv:1802.06096 [hep-ph]

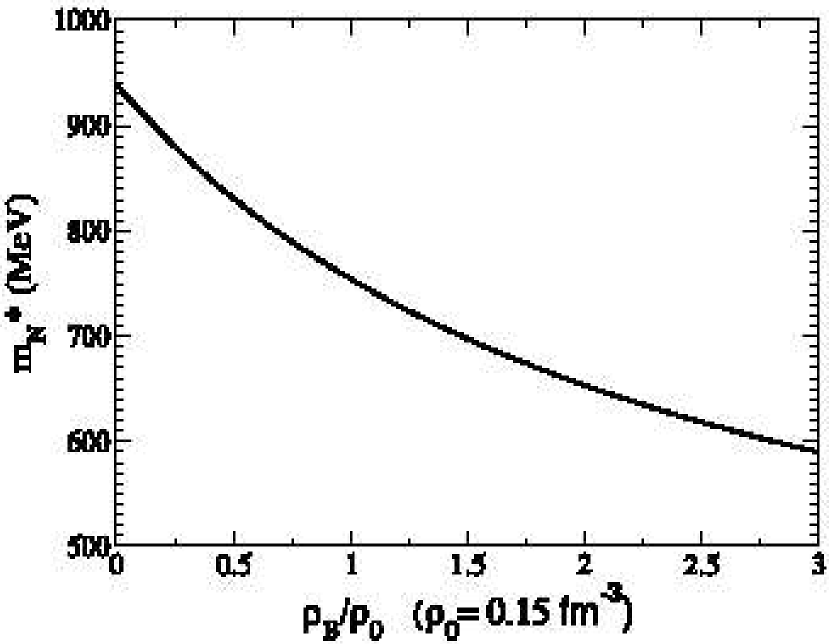
Comparison of Energy/nucleon





- Symmetric Nuclear Matter - Binding Energy per Nucleon (scale !!)
- LF pion model (left): $m_q = 220$ MeV, $K = 320.9$ MeV
- Standard QMC (right): $m_q = 5$ MeV, $K = 279.3$, MeV

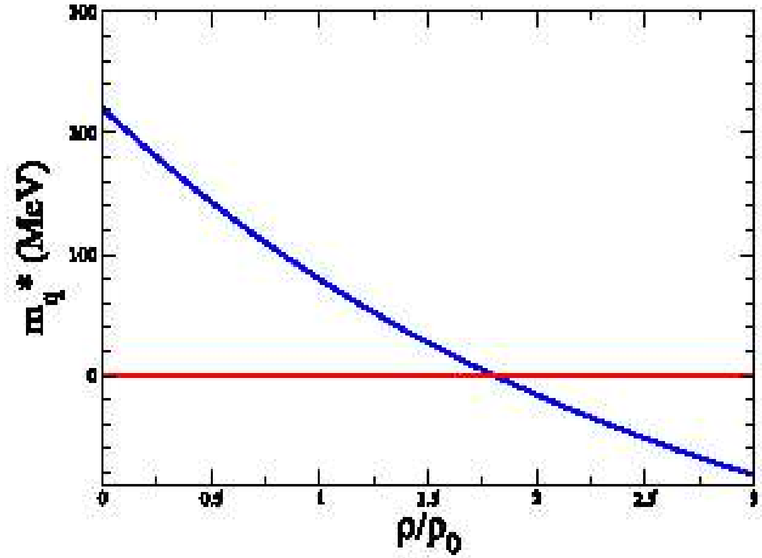


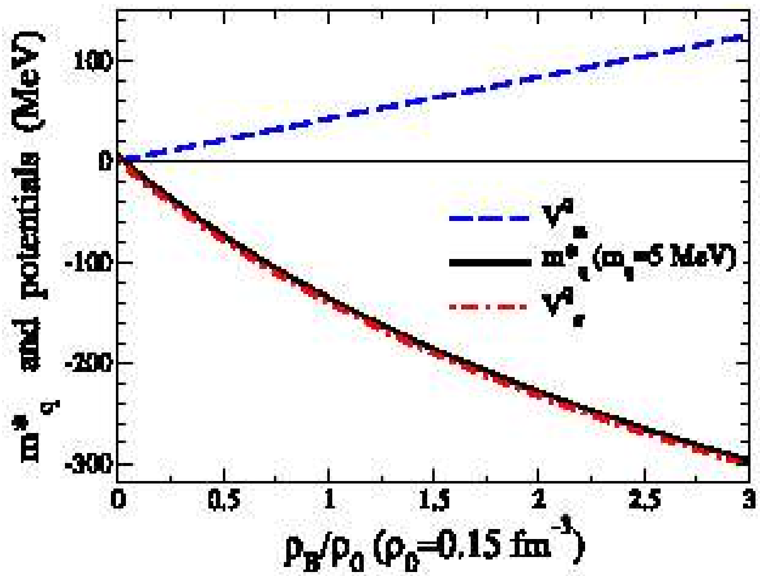


Nucleon effective mass

- **LF pion model** (left: $m_q = 220$MeV)
- **Standard QMC** (right: $m_q = 5$MeV)

LF pion model and Standard QMC: m_q^* (potentials)





- Effective mass of constituent quarks, up and down
- LF pion model: $m_q = 220$ MeV (left)
- Standard QMC $m_q = 5$ MeV (right)

Nuclear (Neutron) matter, E/A-m_N

Novel saturation mechanism !

m_q = 5 MeV (Standard)

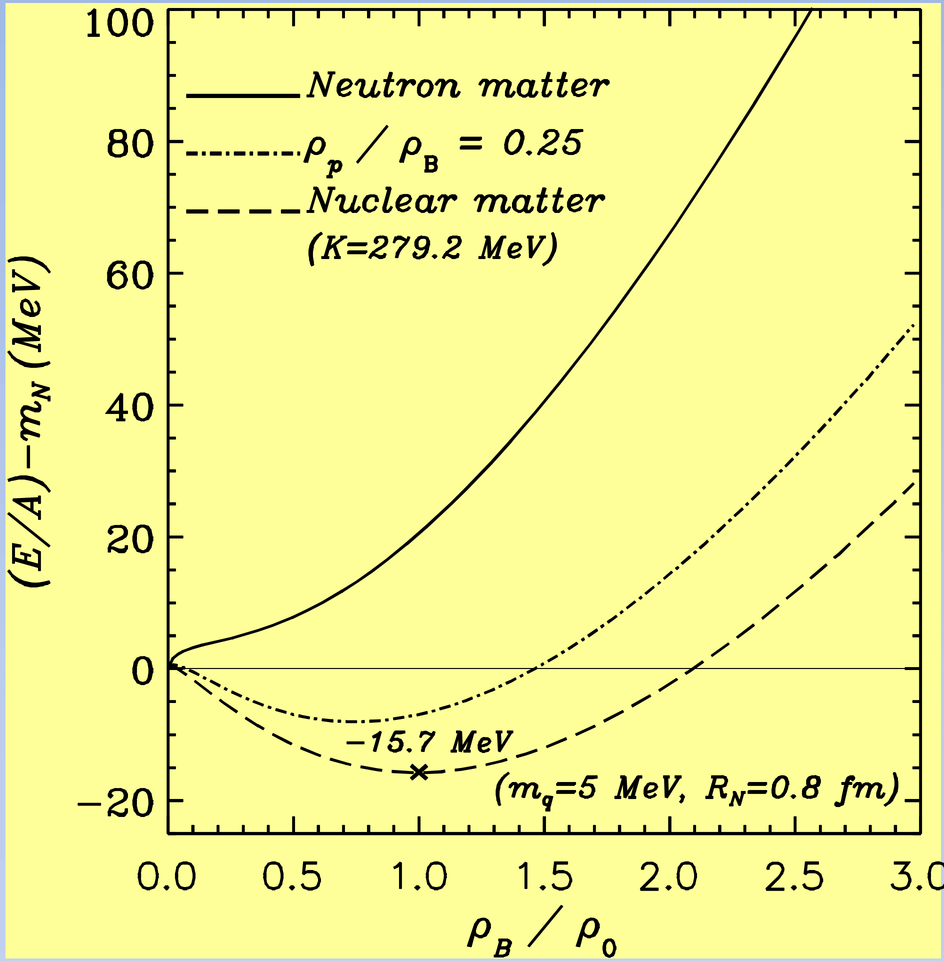
Incompressibility

QHD: K ≈ 500 MeV

QMC: K ≈ 280 MeV

(Exp. 200 ~ 300 MeV)

PLB 429, 239 (1998)



Application to nuclear structure

Finite nuclei (^{208}Pb energy levels)

NPA 609, 339 (1996)

Large mass **nuclei**

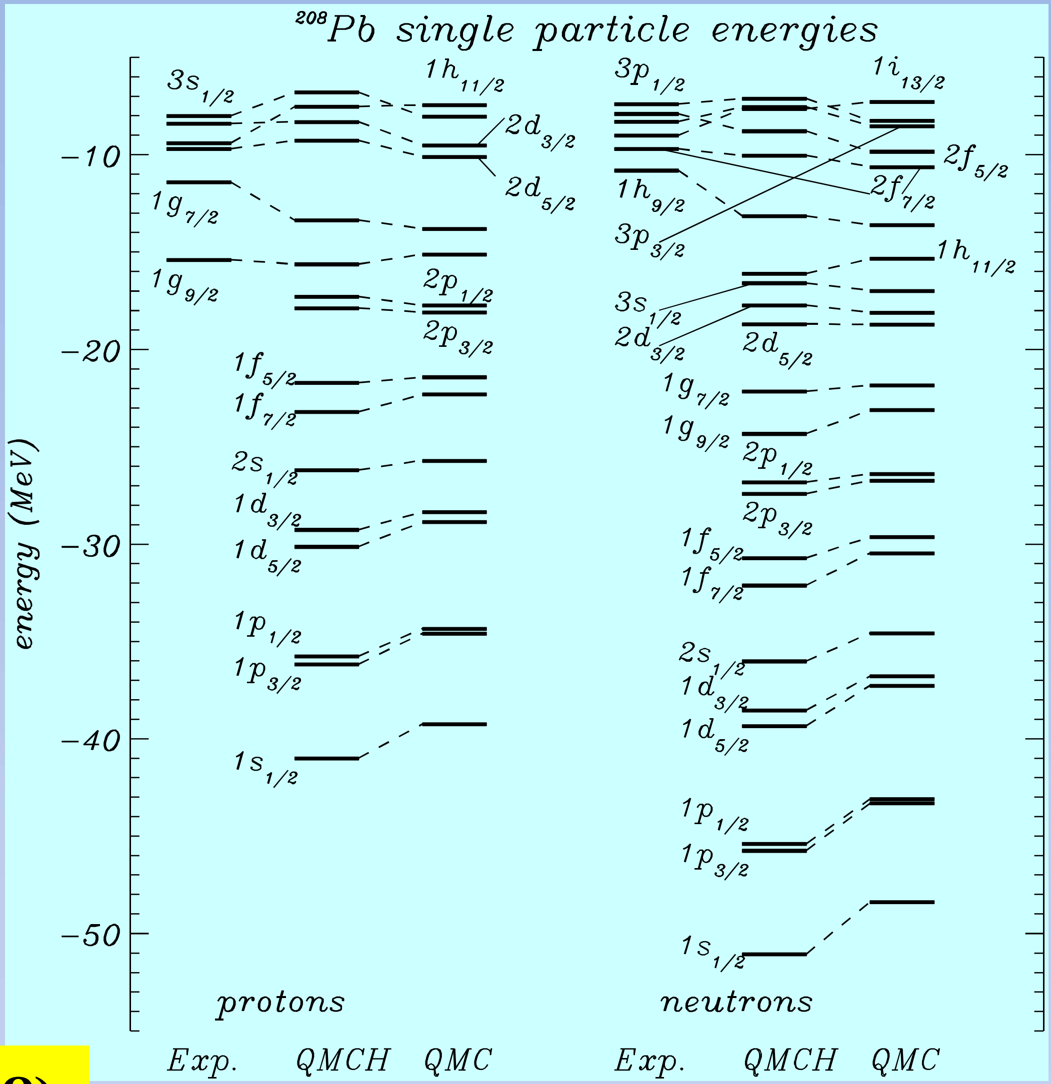
Nuclear matter

<u>Based on **quarks**</u> !

↓

Hadrons

Hypernuclei



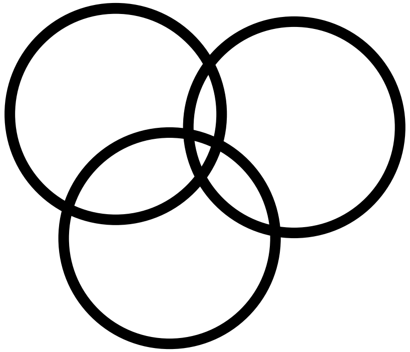
latest QMC, NPA 814, 66 (2008)

Summary : Scalar Polarizability

- Can always rewrite **non-linear coupling** as linear coupling plus non-linear scalar self-coupling – **likely physical origin of <u>non-linear versions of QHD</u>**

- In nuclear matter this is **the only place** the internal structure of the nucleon enters in MFA

- Consequence of **polarizability** in atomic physics is **many-body forces**:



$$V = V_{12} + V_{23} + V_{13} + V_{123}$$

QMC ⟺ QHD

- QHD shows importance of **relativity** :
  mean **σ, ω** and **ρ** fields
- **QMC** goes **far beyond QHD** by incorporating effect of hadron ***internal structure***

- Minimal model couples these mesons to ***quarks*** in relativistic quark model – e.g. MIT bag, or confining NJL

- g_σ^q , g_ω^q, g_ρ^q fitted to ρ_0 , **E/A** and **symmetry energy**

- ***No additional parameters :*** predict change of structure and binding in nuclear matter of **all hadrons**:
  e.g. **ω, ρ, η, J/ψ, N, Λ, Σ, Ξ** ⟹ see later !

Linking QMC to Familiar Nuclear Theory

Since early 70's tremendous amount of work in nuclear theory is based upon **effective forces**

- Used for everything from nuclear astrophysics to collective excitations of nuclei
- **Skyrme Force**: Vautherin and Brink

In Paper : **Guichon and Thomas, Phys. Rev. Lett. 93, 132502 (2004)**

explicitly obtained **effective force**, 2- plus 3- body, of **Skyrme type**

\- **equivalent** to **QMC** model (required expansion around $\boldsymbol{\sigma} = 0$)

Derivation of Density Dependent Effective Force

Physical origin of density dependent forces of Skyrme type within the quark meson coupling model

P.A.M. Guichon [a,*], H.H. Matevosyan [b,c], N. Sandulescu [a,d,e], A.W. Thomas [b]

Nuclear Physics A 772 (2006) 1–19

- **Start with classical theory of MIT-bag nucleons with structure modified in medium to give M_{eff} (σ).**

- **Quantise nucleon motion (non-relativistic), expand in powers of derivatives**

- **Derive equivalent, local energy density functional:**

$$\langle H(\vec{r}\,)\rangle = \rho M + \frac{\tau}{2M} + \mathcal{H}_0 + \mathcal{H}_3 + \mathcal{H}_{\rm eff} + \mathcal{H}_{\rm fin} + \mathcal{H}_{\rm so}$$

Derivation of EDF (cont.)

$$\mathcal{H}_0+\mathcal{H}_3=\rho^2\left[\frac{-3G_\rho}{32}+\boxed{\frac{G_\sigma}{8(1+d\rho G_\sigma)^3}}-\frac{G_\sigma}{2(1+d\rho G_\sigma)}+\frac{3G_\omega}{8}\right]$$
$$+(\rho_n-\rho_p)^2\left[\frac{5G_\rho}{32}+\boxed{\frac{G_\sigma}{8(1+d\rho G_\sigma)^3}}-\frac{G_\omega}{8}\right],$$

$$\mathcal{H}_{\mathrm{eff}}=\left[\left(\frac{G_\rho}{8m_\rho{}^2}-\frac{G_\sigma}{2m_\sigma{}^2}+\frac{G_\omega}{2m_\omega{}^2}+\frac{G_\sigma}{4M_N{}^2}\right)\rho_n+\left(\frac{G_\rho}{4m_\rho^2}+\frac{G_\sigma}{2M_N^2}\right)\rho_p\right]\tau_n$$
$$+p\leftrightarrow n,$$

$$\mathcal{H}_{\mathrm{fin}}=\left[\left(\frac{3G_\rho}{32m_\rho{}^2}-\frac{3G_\sigma}{8m_\sigma{}^2}+\frac{3G_\omega}{8m_\omega{}^2}-\frac{G_\sigma}{8M_N{}^2}\right)\rho_n\right.$$
$$\left.+\left(\frac{-3G_\rho}{16m_\rho{}^2}-\frac{G_\sigma}{2m_\sigma{}^2}+\frac{G_\omega}{2m_\omega{}^2}-\frac{G_\sigma}{4M_N{}^2}\right)\rho_p\right]\nabla^2(\rho_n)+p\leftrightarrow n,$$

$$\mathcal{H}_{\mathrm{so}}=\nabla\cdot J_n\left[\left(\frac{-3G_\sigma}{8M_N{}^2}-\frac{3G_\omega(-1+2\mu_s)}{8M_N{}^2}-\frac{3G_\rho(-1+2\mu_v)}{32M_N{}^2}\right)\rho_n\right.$$
$$\left.+\left(\frac{-G_\sigma}{4M_N{}^2}+\frac{G_\omega(1-2\mu_s)}{4M_N{}^2}\right)\rho_p\right]+p\leftrightarrow n.$$

Spin-orbit force predicted!

Note the totally new, subtle density dependence

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Physical Origin of Density Dependent Force of the Skyrme Type within the QMC model

That is, apply new **effective force** directly to calculate nuclear properties using Hartree-Fock (as for usual well known force)

	E_B (MeV, exp)	E_B (MeV, QMC)	r_c (fm, exp)	r_c (fm, QMC)
^{16}O	7.976	7.618	2.73	2.702
^{40}Ca	8.551	8.213	3.485	3.415
^{48}Ca	8.666	8.343	3.484	3.468
^{208}Pb	7.867	7.515	5.5	5.42

» 4% » 1%

- Where analytic form of (e.g. $H_0 + H_3$) piece of energy functional derived from QMC is:

$$\mathcal{H}_0 + \mathcal{H}_3 = \rho^2 \left[\frac{-3\,G_\rho}{32} + \frac{G_\sigma}{8\,(1 + d\,\rho\,G_\sigma)^3} - \frac{G_\sigma}{2\,(1 + d\,\rho\,G_\sigma)} + \frac{3\,G_\omega}{8} \right] + (\rho_n - \rho_p)^2 \left[\frac{5\,G_\rho}{32} + \frac{G_\sigma}{8\,(1 + d\,\rho\,G_\sigma)^3} - \frac{G_\omega}{8} \right],$$

highlights scalar polarizability

Explicit Demonstration of Origin of 3-Body Force

Since early 70's tremendous amount of work in nuclear theory is based upon effective forces

- Used for everything from nuclear astrophysics to collective excitations of nuclei
- Skyrme Force: Vautherin and Brink

$$H_{QMC} = \sum_i \frac{\overleftarrow{\nabla}_i . \overrightarrow{\nabla}_i}{2M} + \frac{G_\sigma}{2M^2} \sum_{i \neq j} \overleftarrow{\nabla}_i \delta(\vec{R}_{ij}) . \overrightarrow{\nabla}_i$$

$$+ \frac{1}{2} \sum_{i \neq j} \left[\nabla_i^2 \delta(\vec{R}_{ij}) \right] \left[\frac{G_\omega}{m_\omega^2} - \frac{G_\sigma}{m_\sigma^2} + \frac{G_\rho}{m_\rho^2} \frac{\vec{\tau}_i . \vec{\tau}_j}{4} \right]$$

$$+ \frac{1}{2} \sum_{i \neq j} \delta(\vec{R}_{ij}) \left[G_\omega - G_\sigma + G_\rho \frac{\vec{\tau}_i . \vec{\tau}_j}{4} \right]$$

$$+ \frac{d G_\sigma^2}{2} \sum_{i \neq j \neq k} \delta^2(ijk) - \frac{d^2 G_\sigma^3}{2} \sum_{i \neq j \neq k \neq l} \delta^3(ijkl)$$

$$+ \frac{i}{4M^2} \sum_{i \neq j} A_{ij} \overleftarrow{\nabla}_i \delta(\vec{R}_{ij}) \times \overrightarrow{\nabla}_i . \vec{\sigma}_i \, ,$$

Guichon and Thomas, Phys. Rev. Lett. 93, 132502 (2004)

Spin-orbit splitting

Element		States	Exp [keV]	QMC [keV]	SV-bas [keV]
O16	proton	$1p_{1/2}$ - $1p_{3/2}$	6.3 (1.3)a)	5.8	5.0
	neutron	$1p_{1/2}$ - $1p_{3/2}$	6.1 (1.2)a)	5.7	5.1
Ca40	proton	$1d_{3/2}$ - $1d_{5/2}$	7.2 [b)]	6.3	5.7
	neutron	$1d_{3/2}$ - $1d_{5/2}$	6.3 [b)]	6.3	5.8
Ca48	proton	$1d_{3/2}$ - $1d_{5/2}$	4.3 [b)]	6.3	5.2
	neutron	$1d_{3/2}$ - $1d_{5/2}$		5.3	5.2
Sn132	proton	$2p_{1/2}$ - $2p_{3/2}$	1.35(27)[a)]	1.32	1.22
	neutron	$2p_{1/2}$ - $2p_{3/2}$	1.65(13)[a)]	1.47	1.63
	neutron	$2d_{3/2}$ - $2d_{5/2}$		2.71	2.11
Pb208	proton	$2p_{1/2}$ - $2p_{3/2}$		0.91	0.93
	neutron	$3p_{1/2}$ - $3p_{3/2}$	0.90(18)[a)]	1.11	0.89

Systematic approach to finite nuclei

J.R. Stone, P.A.M. Guichon, P. G. Reinhard & A.W. Thomas:
(Phys Rev Lett, 116 (2016) 092501)

- Constrain 3 basic quark-meson couplings (g_σ^q, g_ω^q, g_ρ^q) so that nuclear matter properties are reproduced within errors

$-17 < E/A < -15$ MeV
$0.14 < \rho_0 < 0.18$ fm^{-3}
$28 < S_0 < 34$ MeV
$L > 20$ MeV
$250 < K_0 < 350$ MeV

- Fix at overall best description of finite nuclei with 5 parameters (3 for the EDF +2 pairing pars)

- Benchmark comparison: SV-min 16 parameters (11+5 pairing)

Overview of 106 Nuclei Studied – Across Periodic Table

Element	Z	N	Element	Z	N
C	6	6 -16	Pb	82	116 - 132
O	8	4 -20	Pu	94	134 - 154
Ca	20	16 – 32	Fm	100	148 - 156
Ni	28	24 – 50	No	102	152 - 154
Sr	38	36 – 64	Rf	104	152 - 154
Zr	40	44 -64	Sg	106	154 - 156
Sn	50	50 – 86	Hs	108	156 - 158
Sm	62	74 – 98	Ds	110	160
Gd	64	74 -100			

Not fit

N	Z	N	Z
20	10 – 24	64	36 - 58
28	12 – 32	82	46 - 72
40	22 – 40	126	76 - 92
50	28 – 50		

i.e. We look at most challenging cases of p- or n-rich nuclei

Overview

data	rms error %	
	QMC	SV-min
fit nuclei:		
binding energies	0.36	0.24
diffraction radii	1.62	0.91
surface thickness	10.9	2.9
rms radii	0.71	0.52
pairing gap (n)	57.6	17.6
pairing gap (p)	25.3	15.5
ls splitting: proton	15.8	18.5
ls splitting: neutron	20.3	16.3
superheavy nuclei:	0.1	0.3
N=Z nuclei	1.17	0.75
mirror nuclei	1.50	1.00
other	0.35	0.26

Stone et al., PRL 116 (2016) 092501

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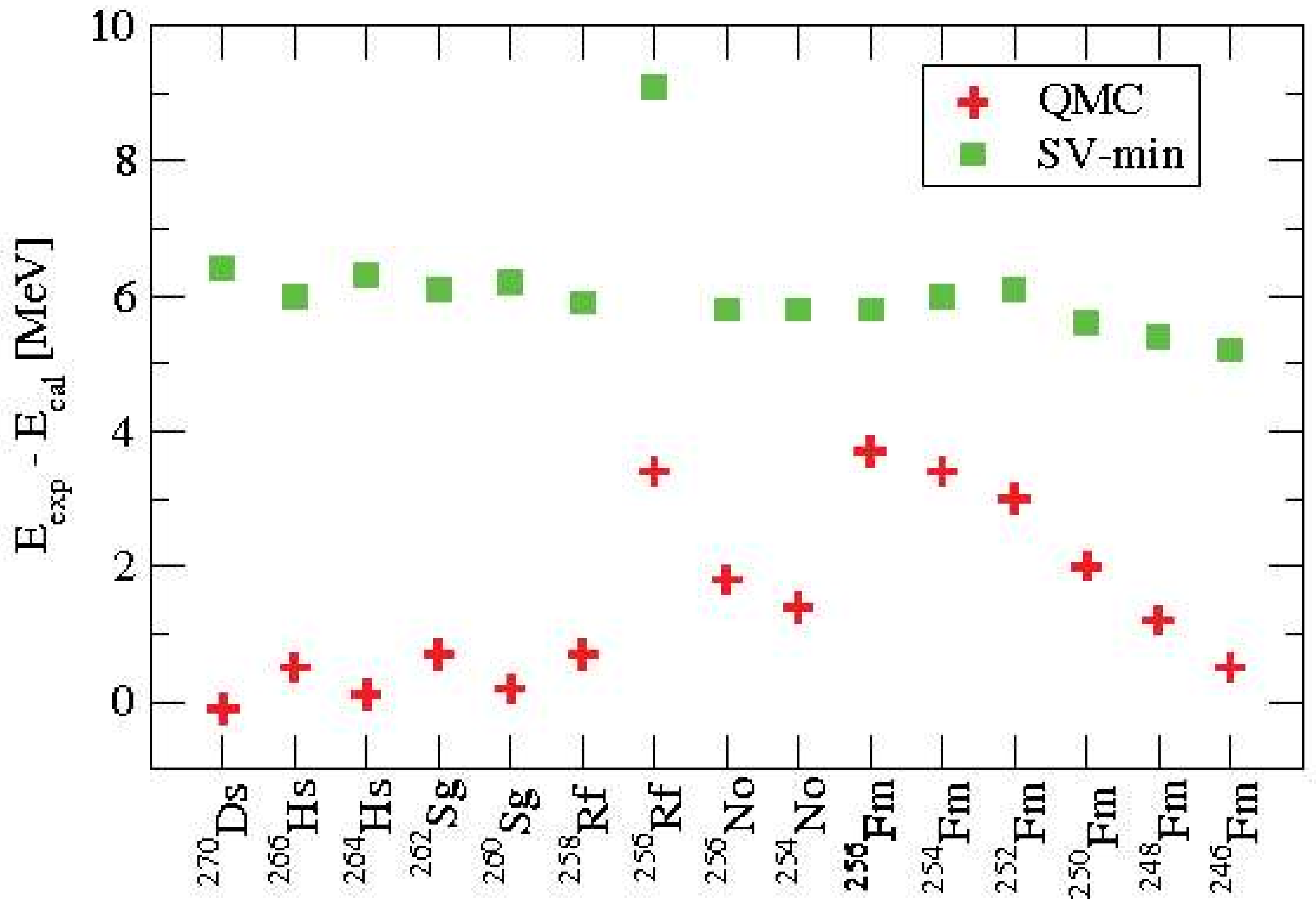
Superheavy Binding : 0.1% accuracy



Stone et al., PRL 116 (2016) 092501

For detailed study of SHE see: arXiv:1901.06064

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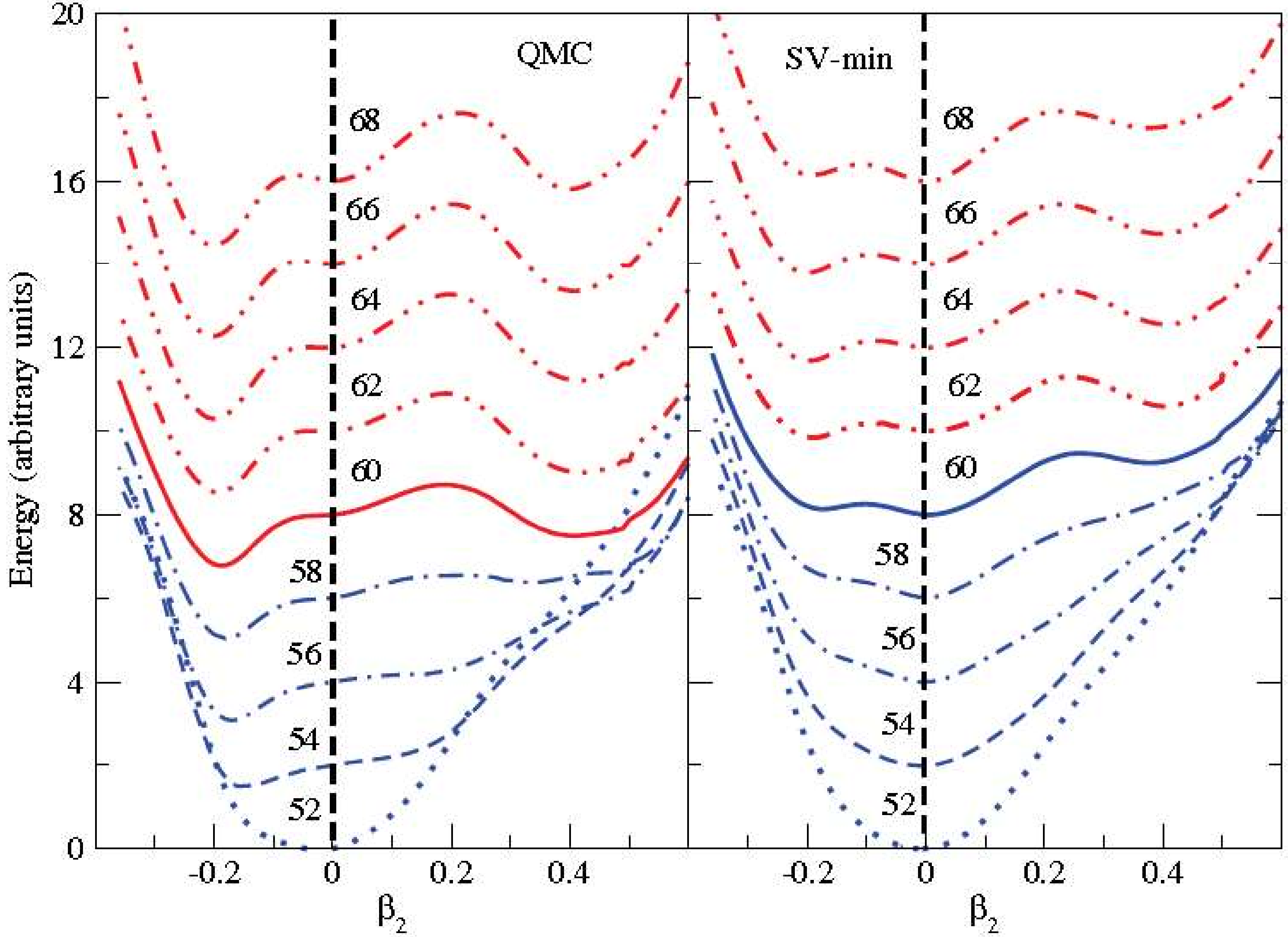
Shape evolution of Zr (Z=40) Isotopes



- Shape co-existence sets in at N=60 – Sotty *et al.*,PRL115 (2015)172501
- Usually difficult to describe
  - – e.g. Mei et al., PRC85, 034321 (2012)

Stone et al., PRL 116 (2016) 092501

Quadrupole deformation in Superheavies

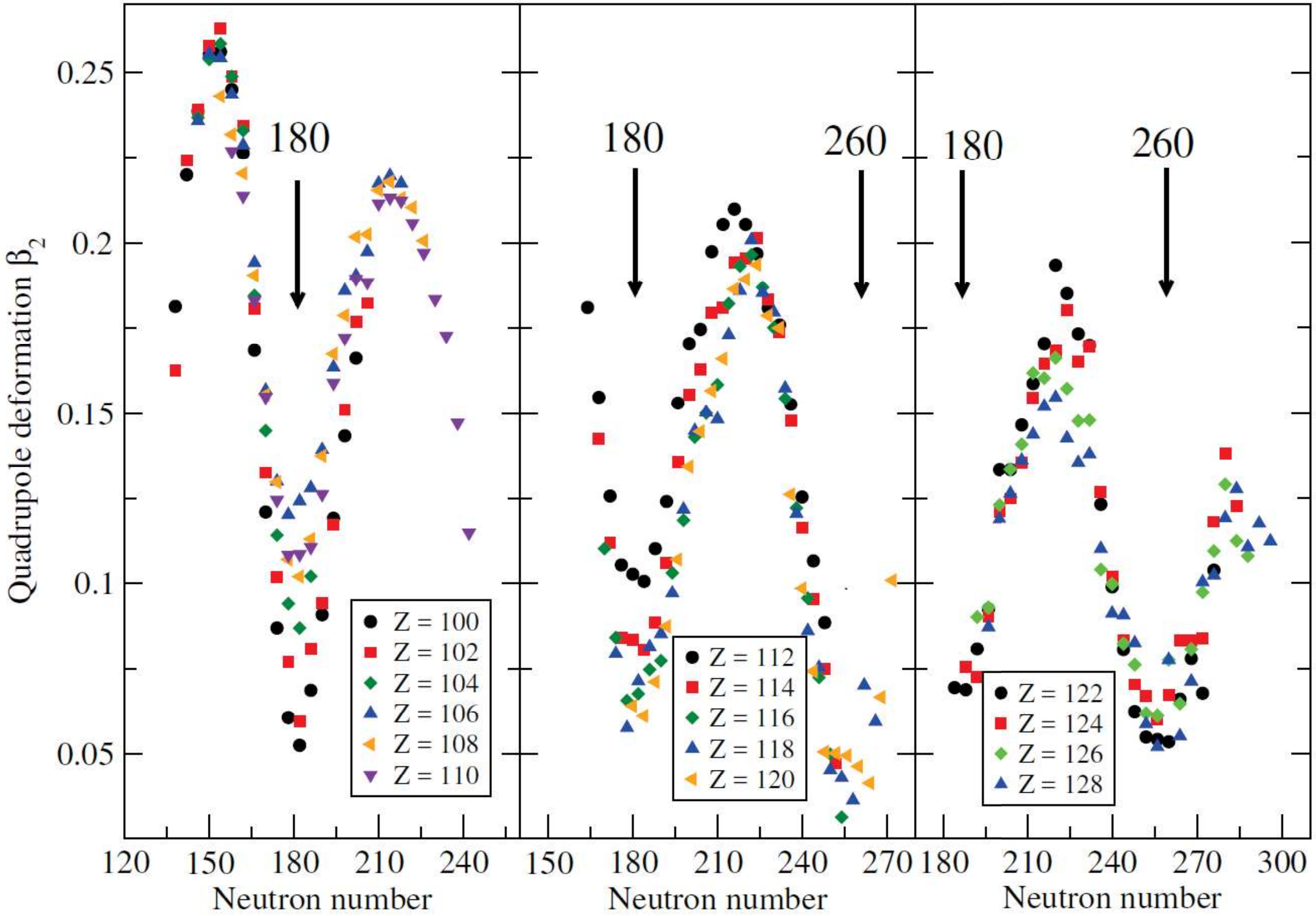


Figure 2. (Color online). Quadrupole deformation calculated in QMCπ for isotopes with proton number $100 < Z < 128$.

Stone *et al.*, E P J Web of Conferences 163 (2017) 00057

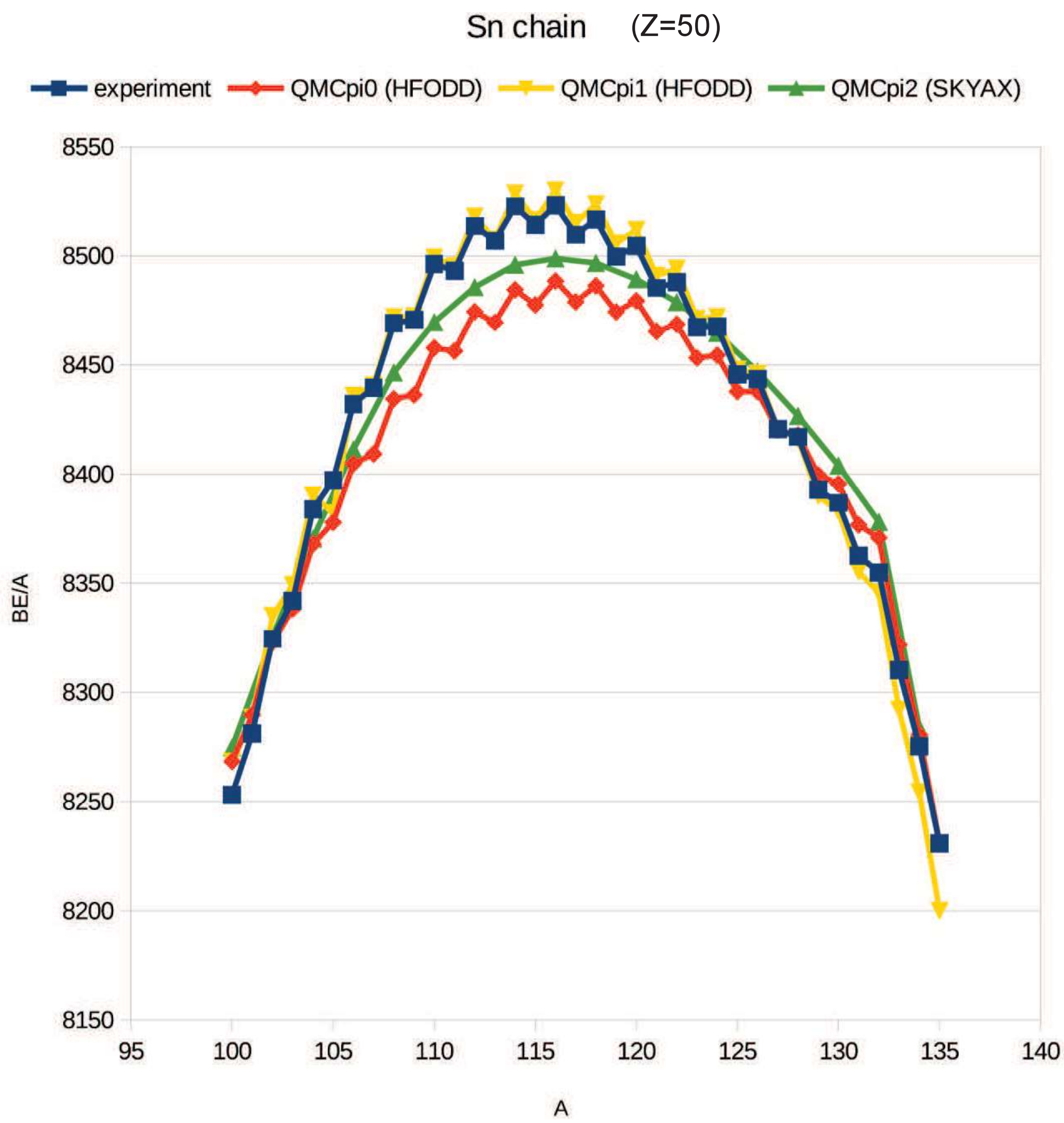
Drip line predictions

Table 1. Neutron numbers corresponding to proton and neutron drip lines, derived from the Fermi energy for isotopes of elements 96 < Z <136

Z	N(p)	N(n)	Z	N(p)	N(n)
96	132	224	118	174	278
98	134	226	120	180	286
100	138	230	122	184	290
102	138	236	124	188	296
104	146	240	126	192	298
106	146	242	128	196	302
108	154	246	130	202	306
110	158	250	132	208	310
112	164	256	134	214	314
114	168	260	136	218	314
116	170	268			

Stone *et al.*, E P J Web of Conferences 163 (2017) 00057

Martinez, Konieczka, Bąszyk *et al.* – *HFODD Implementation*



Publication in preparation….

Summary: Finite Nuclei

- The effective force was *derived* at the quark level *based upon the changing structure of a bound nucleon*

- Has many less parameters but reproduces nuclear properties at a level comparable with the best phenomenological Skyrme forces

- Looks like standard nuclear force

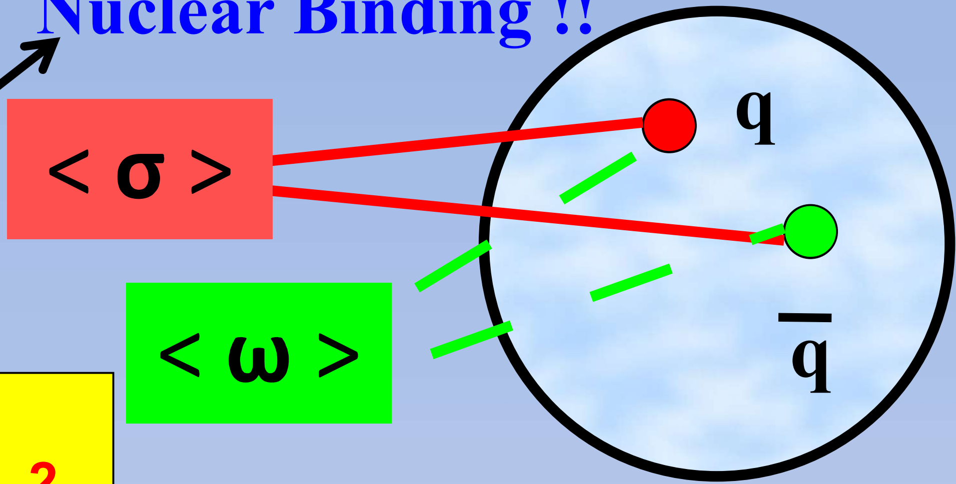
- BUT underlying theory also predicts modified internal structure and hence modified
  - DIS structure functions
  - elastic form factors......

Mesons in nuclear medium in **QMC**

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

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

Nuclear Binding !!



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

↓ **nonlinear** in **σ**

$M^*_M \approx M_M - g^M_\sigma \sigma + (d^M/2)\,(g^M_\sigma \sigma)^2$

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

σ,ω fields: **no couplings** with **s,c,b** quarks!!

QMC model 2: Quark level

$x = (t, \vec{r})$ ($|\vec{r}| \leq$ bag radius)

$$\left[i\gamma\cdot\partial_x - (m_q - V^q_\sigma) \mp \gamma^0\left(V^q_\omega + \frac{1}{2}V^q_\rho\right)\right]\begin{pmatrix}\psi_u(x)\\ \psi_{\bar{u}}(x)\end{pmatrix} = 0$$

$$\left[i\gamma\cdot\partial_x - (m_q - V^q_\sigma) \mp \gamma^0\left(V^q_\omega - \frac{1}{2}V^q_\rho\right)\right]\begin{pmatrix}\psi_d(x)\\ \psi_{\bar{d}}(x)\end{pmatrix} = 0$$

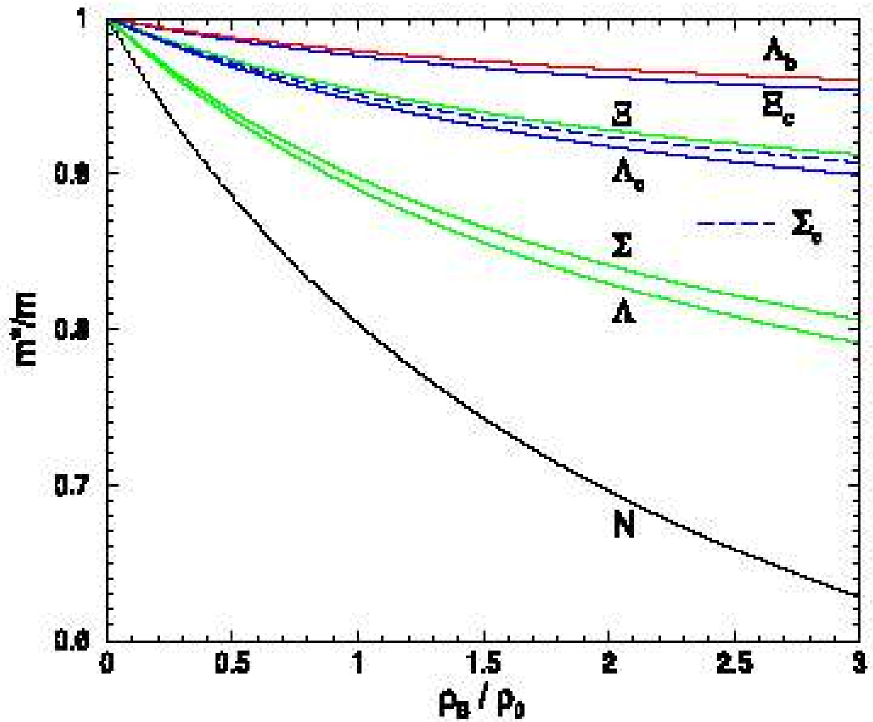
$$[i\gamma\cdot\partial_x - m_Q]\,\psi_Q(x)\ (\text{or}\ \psi_{\overline{Q}}(x)) = 0$$

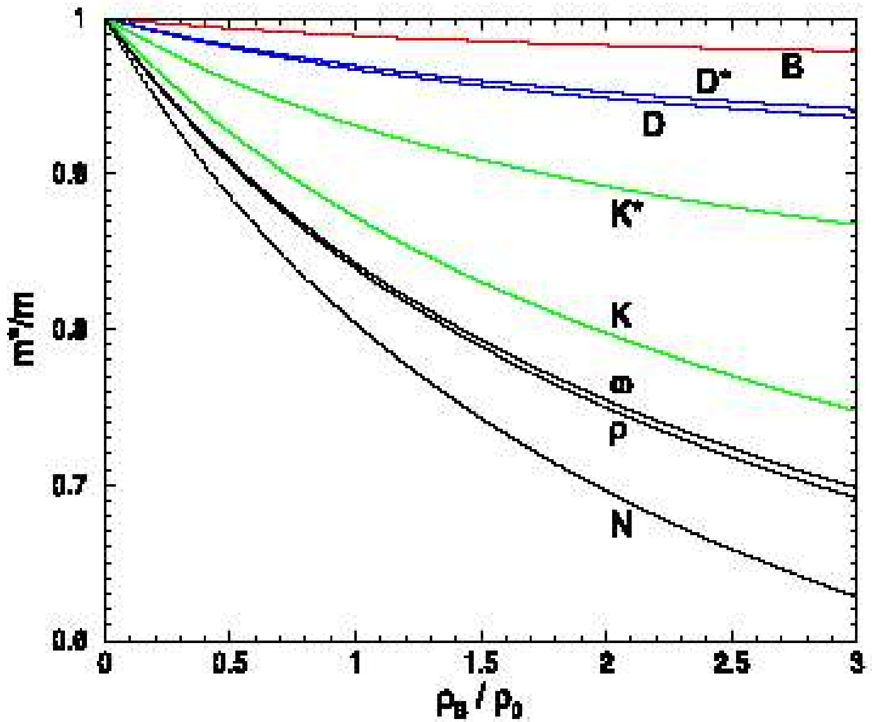
$$m^*_h = \sum_{j=q,\bar{q},Q\overline{Q}} \frac{n_j\Omega^*_j - z_h}{R^*_h} + \frac{4}{3}\pi R^{*3}_h B, \quad \left.\frac{\partial m^*_h}{\partial R_h}\right|_{R_h=R^*_h} = 0$$

$$\Omega^*_q = \Omega^*_{\bar{q}} = [x^2_q + (R^*_h m^*_q)^2]^{1/2}, \text{with } m^*_q = m_q - g^q_\sigma\sigma$$

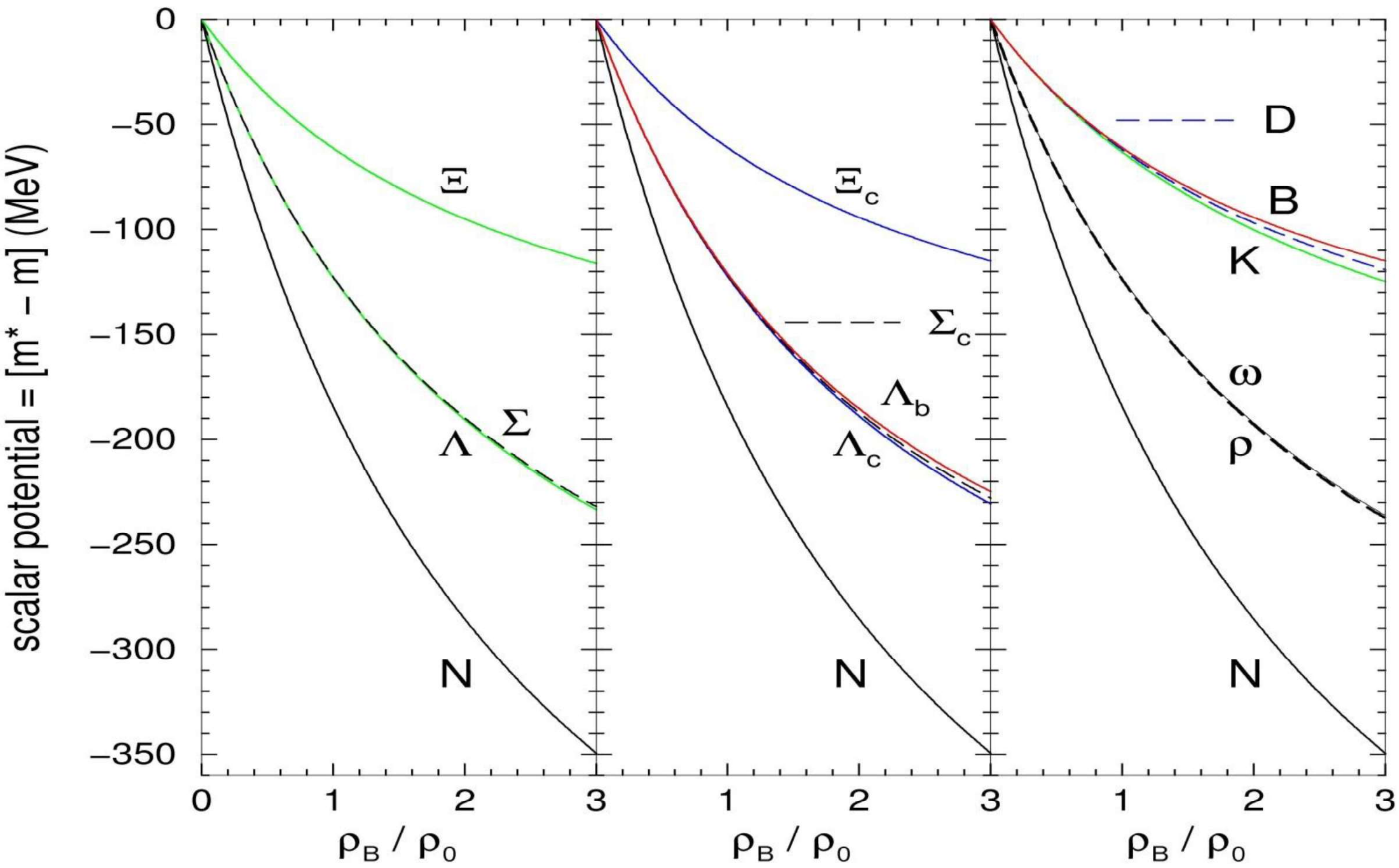
$$\Omega^*_Q = \Omega^*_{\overline{Q}} = [x^2_Q + (R^*_h m_Q)^2]^{1/2} \quad (Q = s, c, b)$$

Hadron masses (ratios) in medium





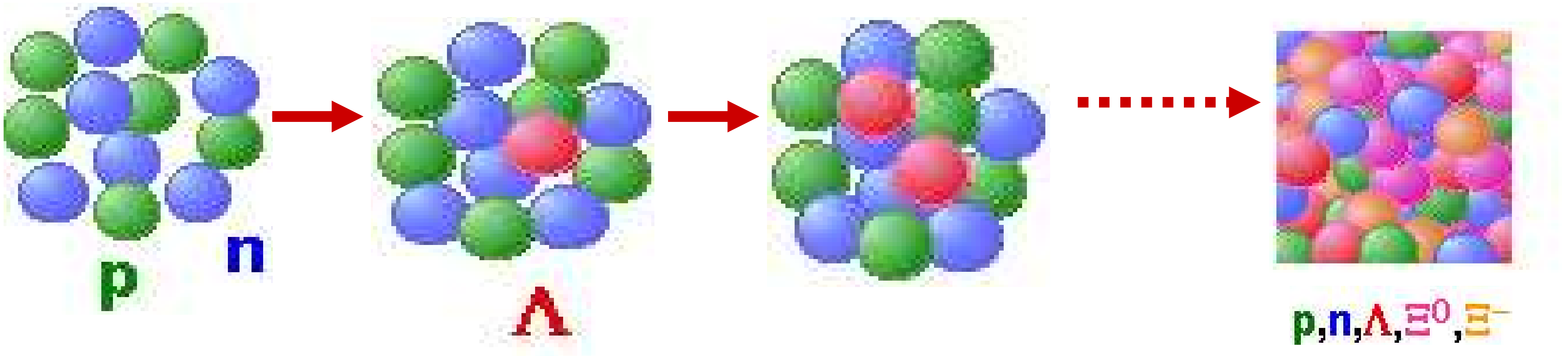
Scalar potentials in **QMC** respects **SU(3)** (**light quark # !**)



Hypernuclei
(Introduction)

What are Hypernuclei ?

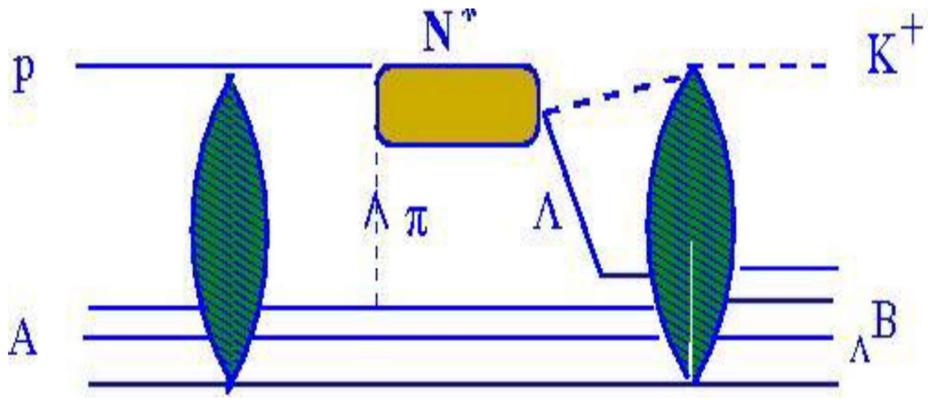
Hypernuclei are nuclear systems where at least one nucleon is replaced by a hyperon (e.g. Λ).

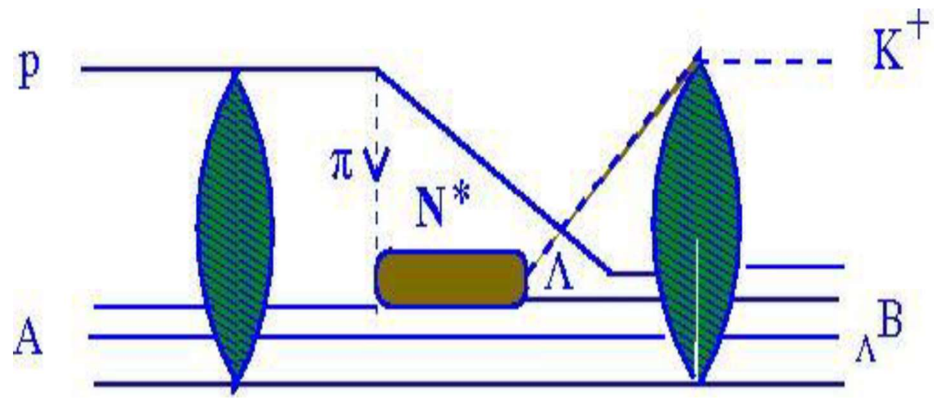


$^{A}_{\Lambda}Z$ is a bound state of Z protons (A-Z-1) neutrons and a Λ hyperon

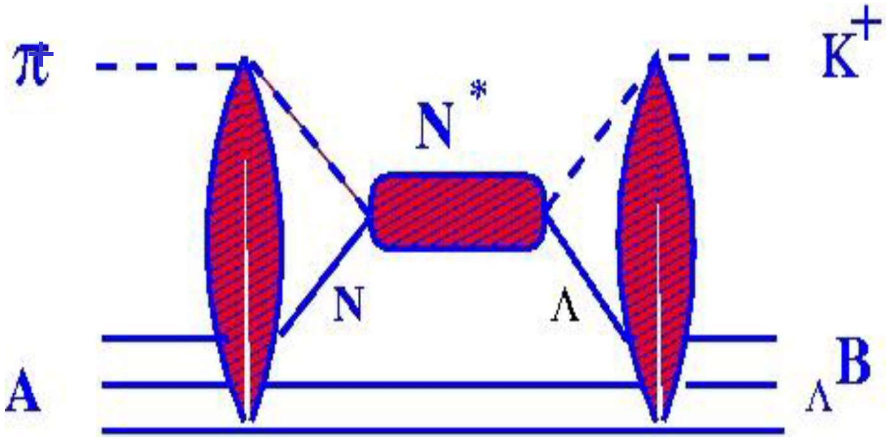
Hypernuclei are a laboratory to study the hyperon-nucleon, Hyperon-hyperon interactions.

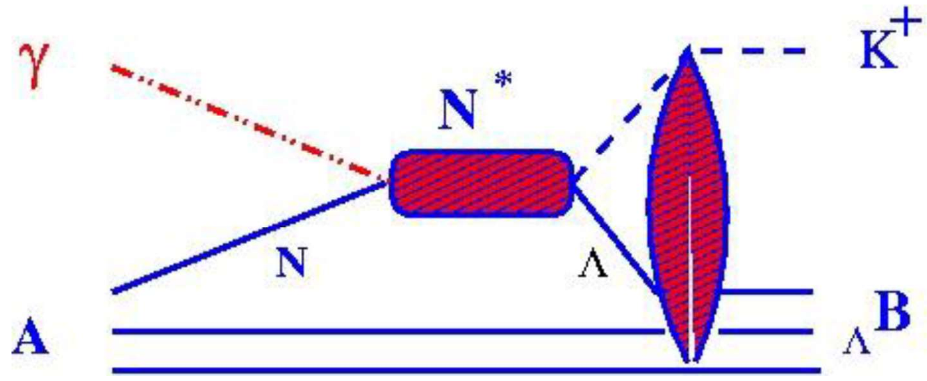
Production processes (e.g.) for reactions leading to S=-1 hypernuclei





Target emission — **$A\,(p,K^+)_{\Lambda}B$** — **Projectile emission**

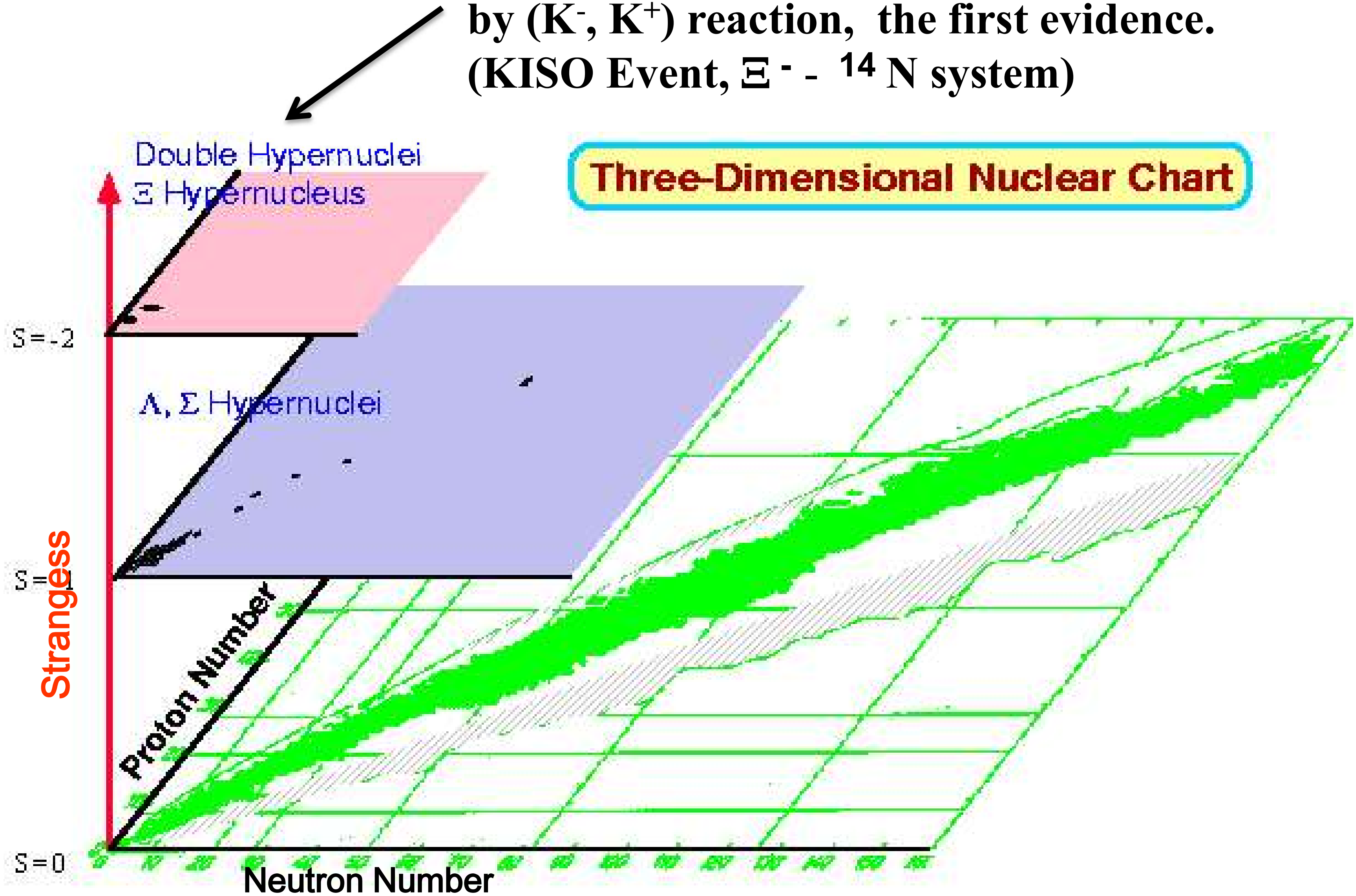


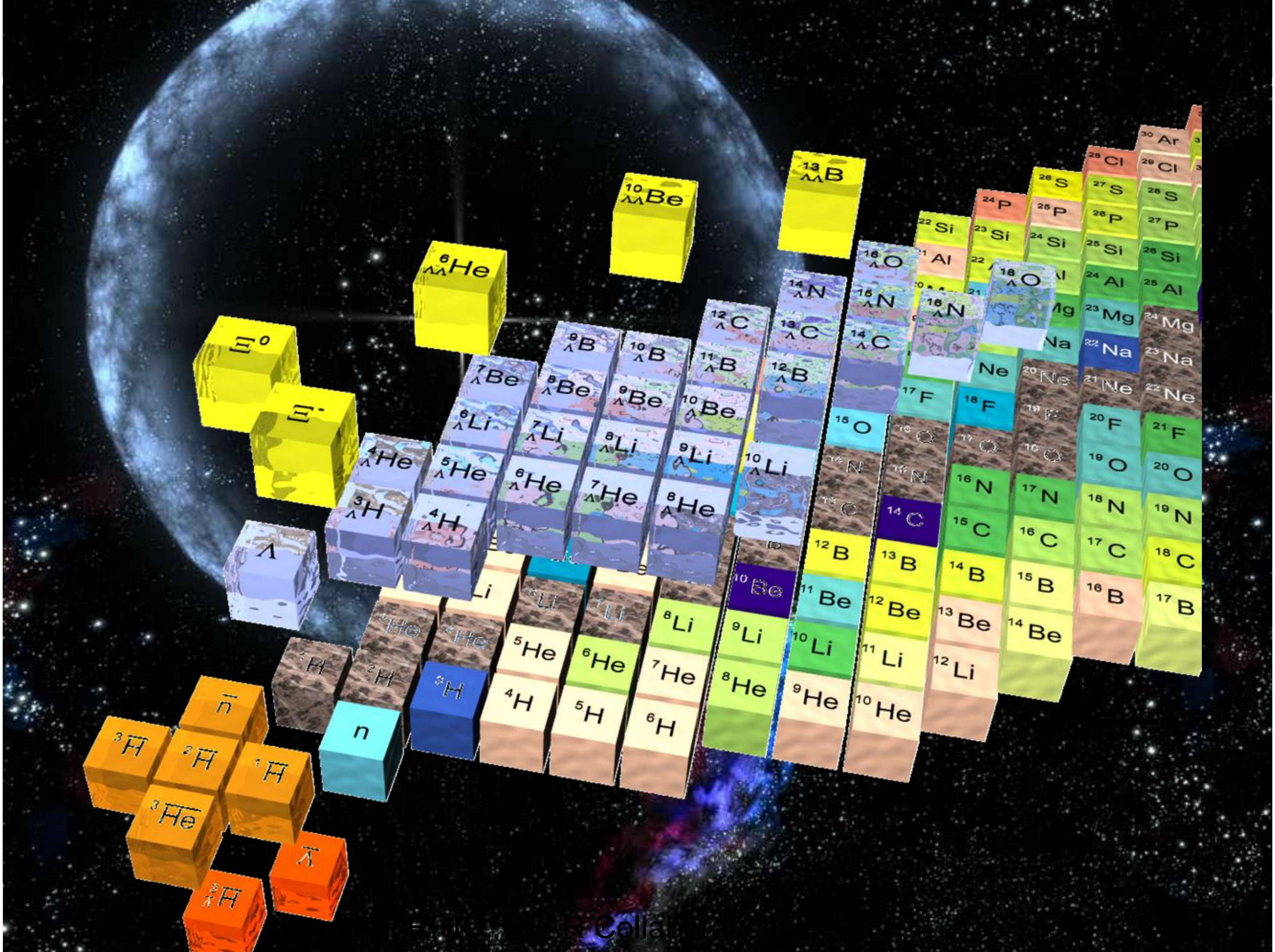


$A\,(\pi^+,K^+)_{\Lambda}B^*$ — **$A\,(\gamma,K^+)_{\Lambda}B'$**

N * (1650), N*(1710), N*(1720) baryonic resonances.

S = - 2, Ξ-Hypernuclei at J-PARC, JAPAN by (K^-, K^+) reaction, the first evidence. (KISO Event, Ξ^- - ^{14}N system)

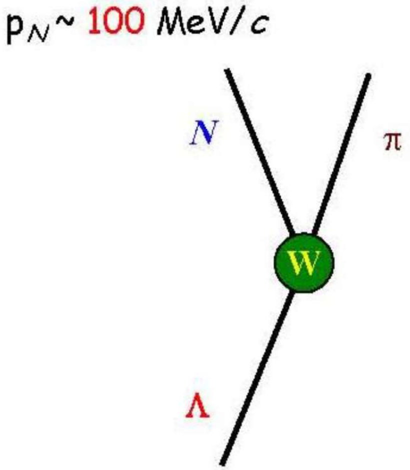




Ξ⁰
Ξ⁻
Λ
n
RHIC,
Collaboration

Λ hyperon can stay in contact with nucleons inside a Nucleus

free Λ decay

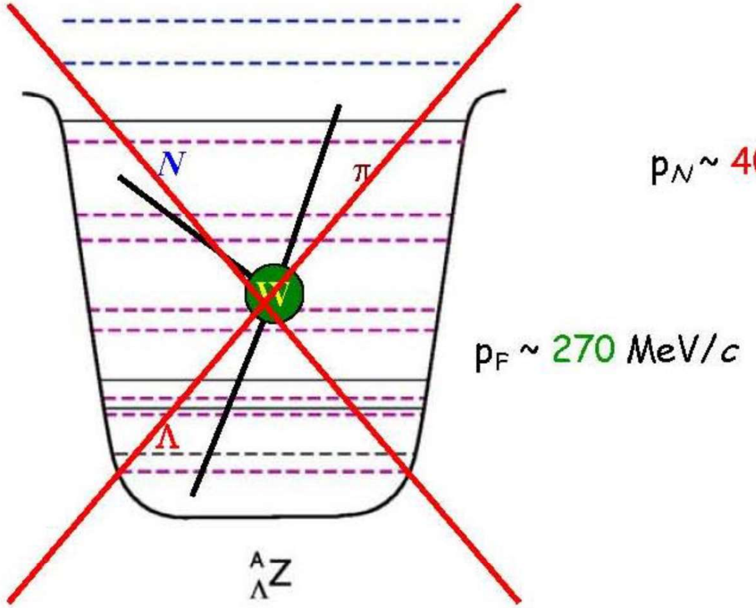


$\Lambda \rightarrow n + \pi^0 + 41$ MeV (36%)

$\Lambda \rightarrow p + \pi^- + 38$ MeV (64%)

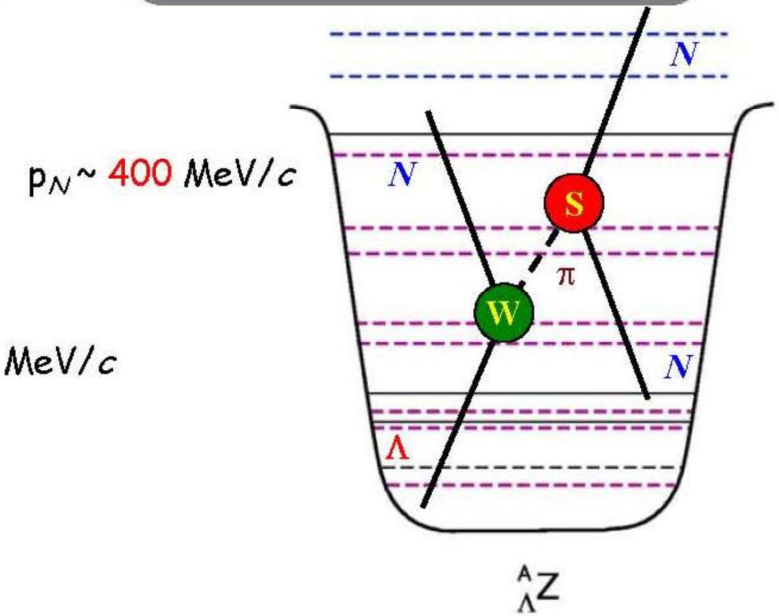
$\tau_\Lambda = 263$ ps

hypernucleus mesonic decay



suppressed by Pauli blocking

hypernucleus non-mesonic decay



$\Lambda + n \rightarrow n + n + 176$ MeV

$\Lambda + p \rightarrow n + p + 176$ MeV

Why are Hypernuclei interesting!

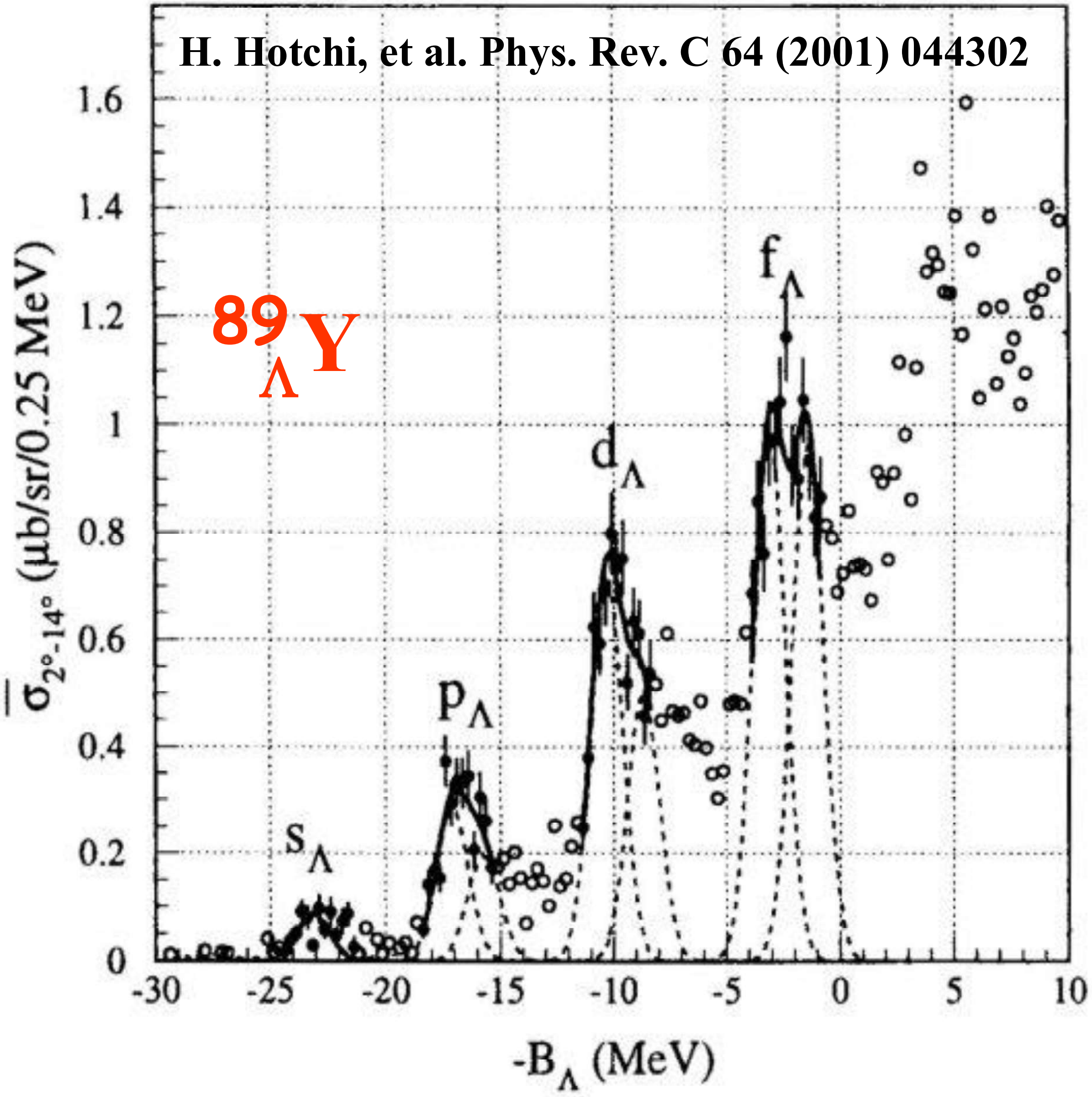
New type of nuclear matter, new symmetries, New selection rules. First kind of flavored nuclei.

Hyperons are free from Pauli principle restrictions

Can occupy quantum states already filled up with nucleons

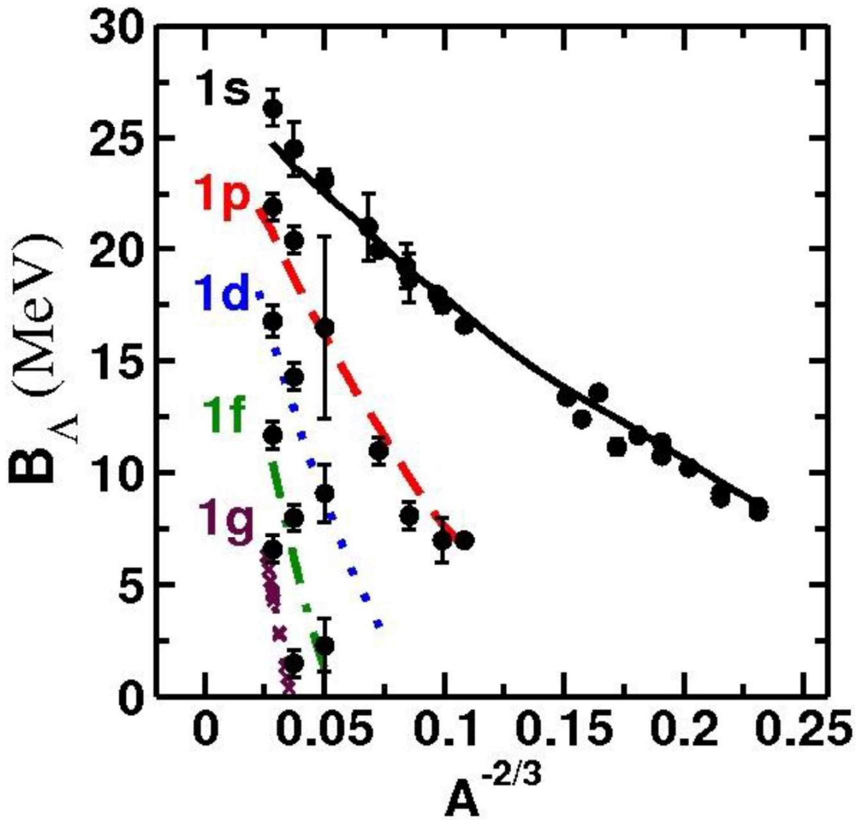
This makes a hyperon embedded in the nucleus a unique tool for exploring the nuclear structure.

Good probe for deeply bound single particle states.



Study of S = -1 hypernuclei (Λ or Σ)

The nuclear structure and the many body nuclear dynamics is extended to new non conventional symmetries, due to the inclusion of an S≠ 0 degree of freedom in the nucleus, YN interaction



The Skyrme type ΛN interaction from the known BE of Λ hypernuclei.

Neelam Guleria, S.K. Dhiman and R. Shyam, Nucl. Phys. A 886, 71 (2012)

The role played by quark degrees of freedom in nuclear phenomena: Quark-Meson coupling model, extended for hypernuclei

Guichon, KT, Saito, Thomas

The study of four fermion, strangeness changing, baryon-baryon weak interaction YN→NN, which can occur only inside hypernuclei

S = -2 systems

➡ **New Physics items**

- **For a detailed understanding of the quark aspect of the baryon-baryon forces in the SU(3) space, information on the YY channel is essential.**

- **Are there S=-2 deeply bound multi $\overline{K}$ states??**

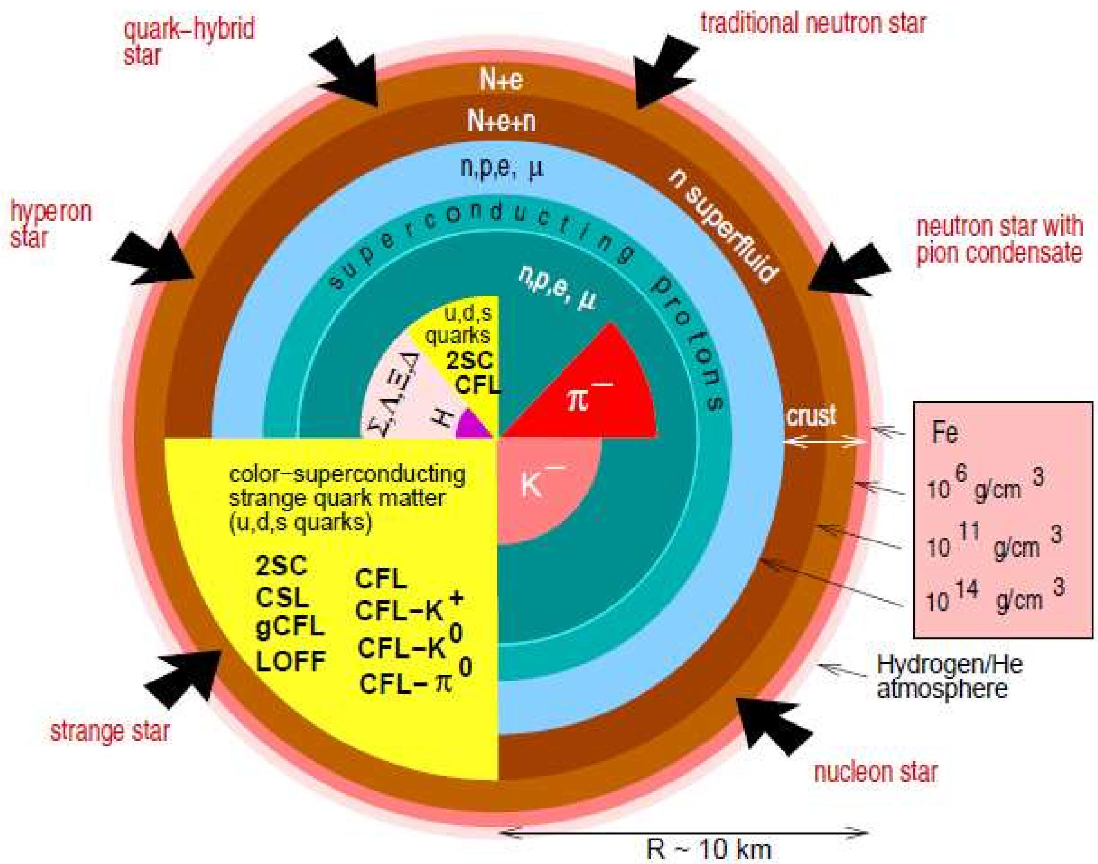
- **Search for *H particle***

six-quark system uuddss

Conjectured composition of a neutron star ➡

Neutron star composition

- **Formation of compact stars depends On the nature of the YY interaction.**



Juergen Schaffner-Bielich, Nucl. Phys. A804 (2008) 309

Experiments

No! Σ-Hypernuclei

Naïve SU(3) based model

yield **Σ**-Hypernuclei !

→ QMC ?

Λ, Σ ⇔ Self-consistent OGE color hyperfine interaction

Λ and Σ hypernuclei are more or less similar (channel couplings) ⇔ **improve !**

Ξ potential: **weaker (~1/2)** of Λ and Σ (**Light quark #**)

Very **small spin-orbit splittings** for Λ hypernuclei ⇔ **SU(6) quark model**

Bag mass and **color mag. HF** int. contribution (**OGE**)

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

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

$$+ \underline{(F_s)}^n \Delta E_M(f) \qquad (f = N, \Delta, \Lambda, \Sigma, \Xi \ldots)$$

$$\Delta E_M = -3\alpha_c \sum_{a,\, i<j} \lambda_i \lambda_j \vec{\sigma}_i \cdot \vec{\sigma}_j \, M(m_i, m_j, R)$$

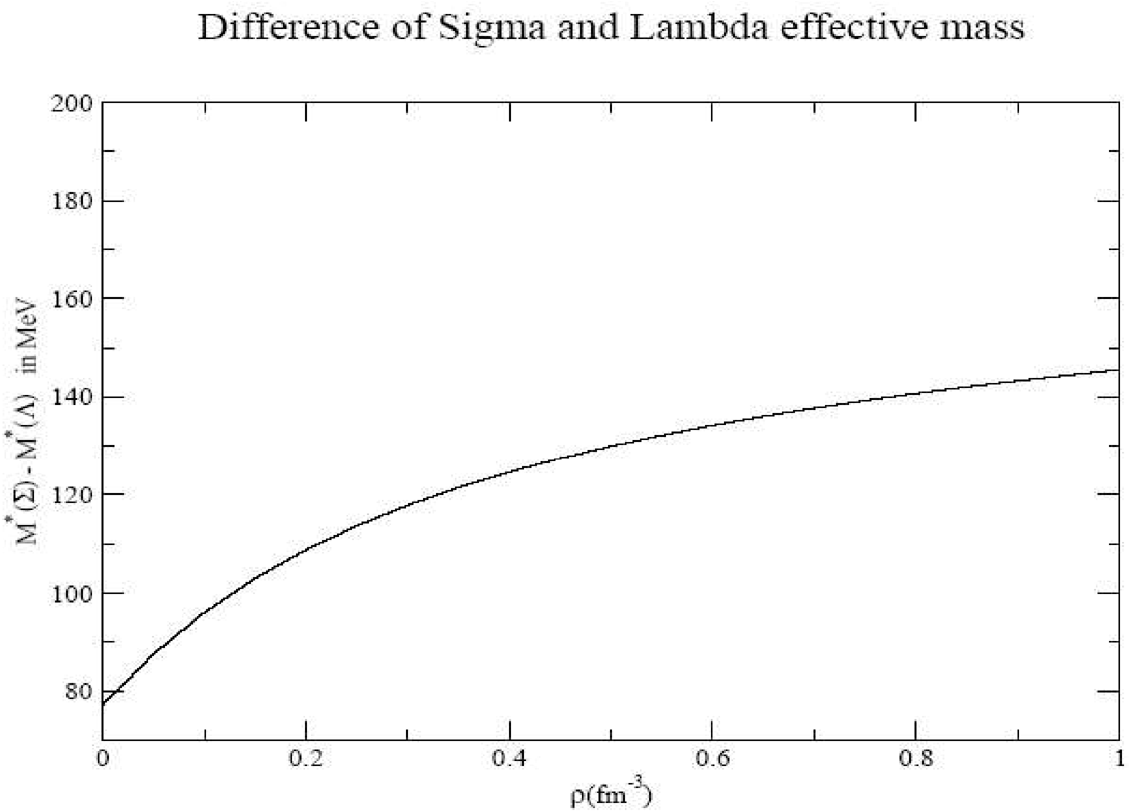
$$\Delta E_M(\Lambda) = -3\alpha_c \, M(m_q, m_q, R), \quad (q = u, d)$$

$$\Delta E_M(\Sigma) = \alpha_c M(m_q, m_q, R)$$

$$-4\alpha_c M(m_q, m_s, R)$$

Latest QMC: Includes Medium Modification of Color Hyperfine Interaction

N - Δ and Σ - Λ splitting arise from **one-gluon-exchange** in MIT Bag Model : as " σ " so does this splitting…



Σ - Λ splitting

→ **Σ-hypernuclei unbound!!**

Guichon, Thomas, Tsushima, Nucl. Phys. A841 (2008) 66

Σ^0 potentials

($1s_{1/2}$)

Repulsion

in center

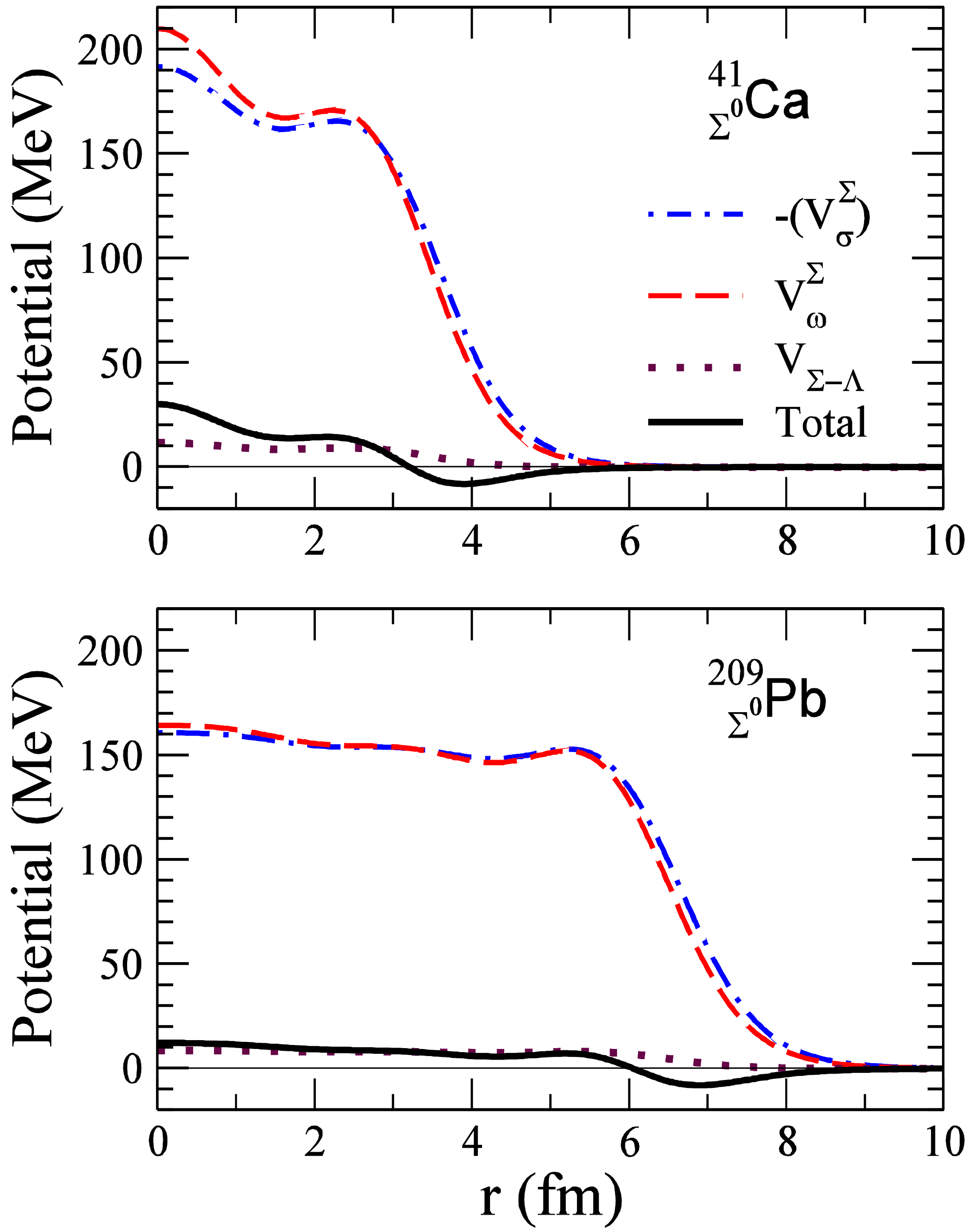
Attraction

in surface

No Σ nuclear bound state!

HF couplings for hyperons ⇔ successful for high density neutron star

(NPA 792, 341 (2007))



Hypernuclei spectra 1

NPA 814, 66 (2008)

	$^{16}_{\Lambda}O$ 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)

	$^{89}_{\Lambda}$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 **hyperfine** interaction included self-consistently in matter) ⇒
- Λ single-particle energy **$1s_{1/2}$ in Pb** is **-26.9** MeV (Exp. **-26.3** MeV) ⇐ **no extra parameter!**
- **Small** spin-orbit splittings for the Λ
- **No Σ nuclear bound state !!**
- Ξ is expected to form nuclear bound state

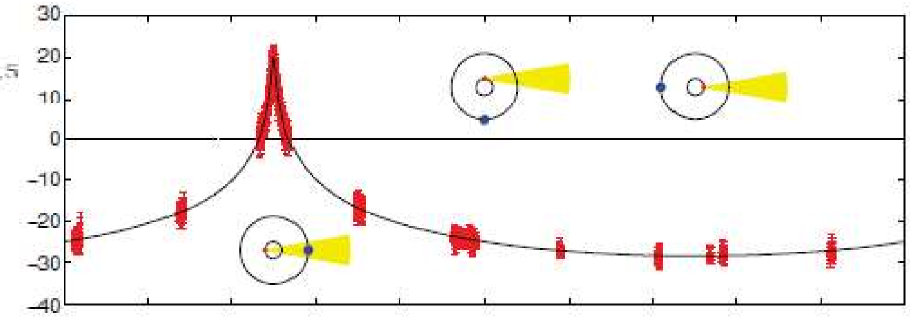
Neutron Stars

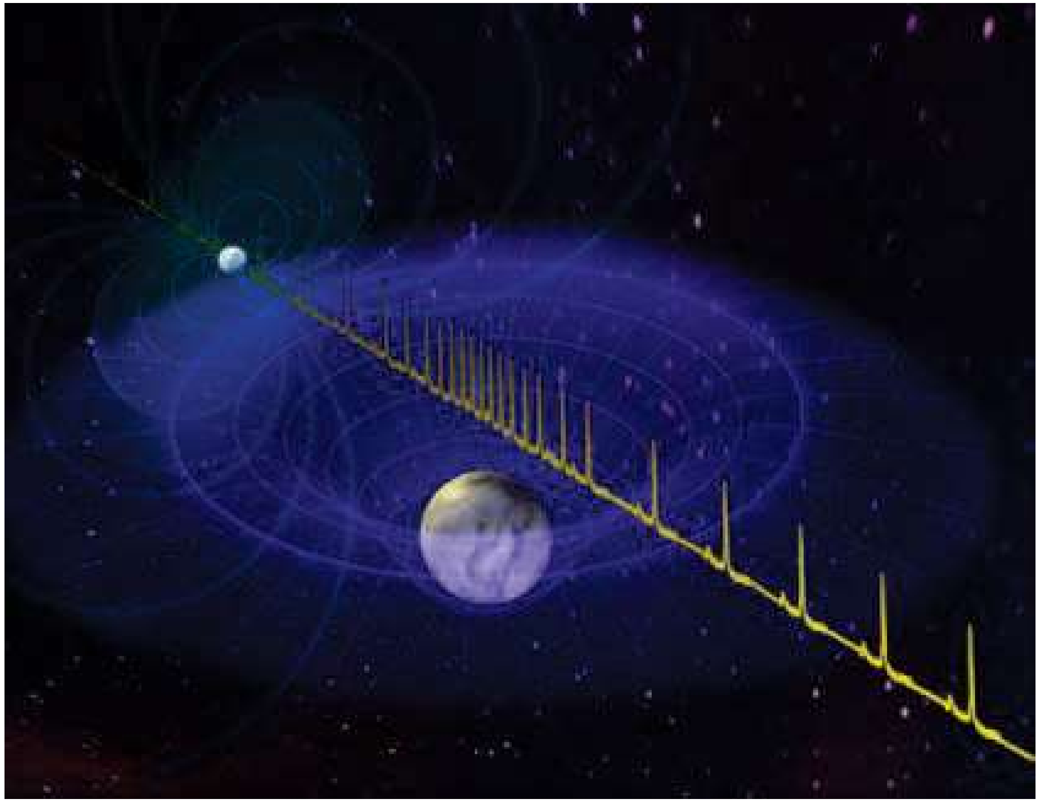
LETTER (2010)

doi:10.1038/nature09466

A two-solar-mass neutron star measured using Shapiro delay

P. B. Demorest[1], T. Pennucci[2], S. M. Ransom[1], M. S. E. Roberts[3] & J. W. T. Hessels[4,5]





Reports a very accurate pulsar mass much larger than seen before : 1.97 ± 0.04 solar mass

Claim: it rules out hyperon occurrence

- ignored our work *published* three years before!

J1614-2230

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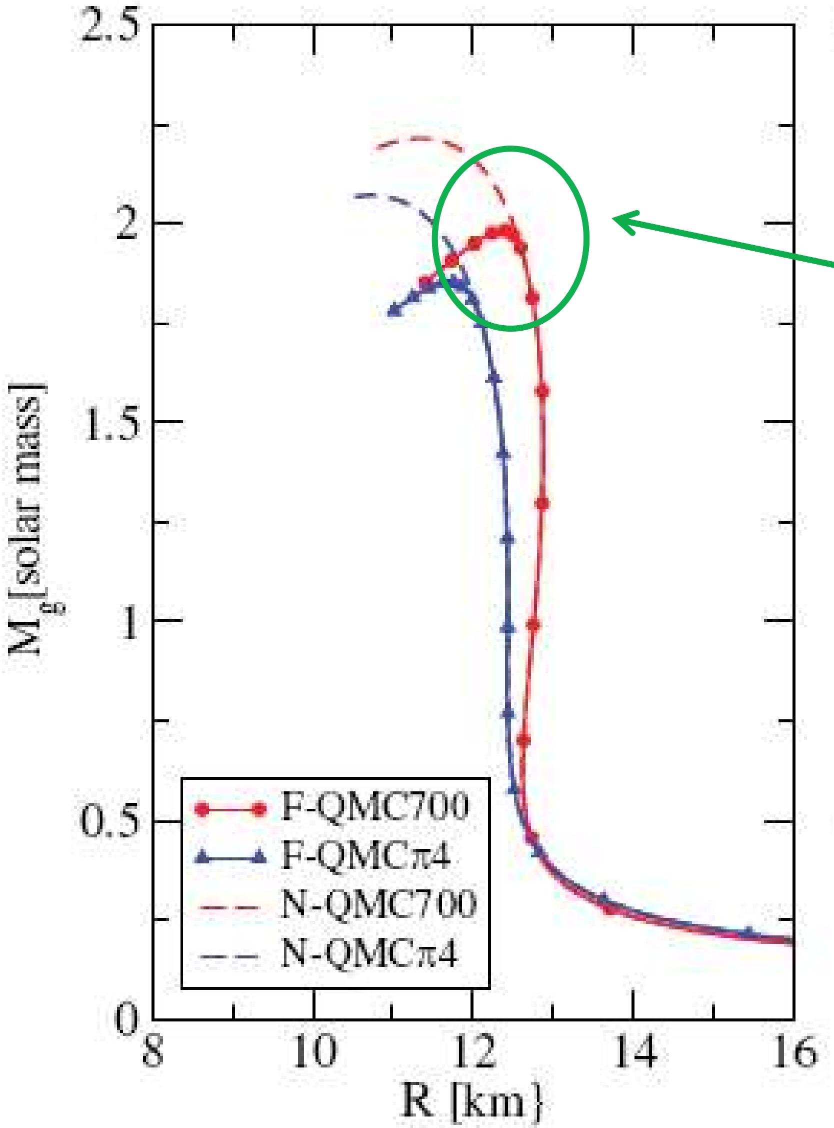
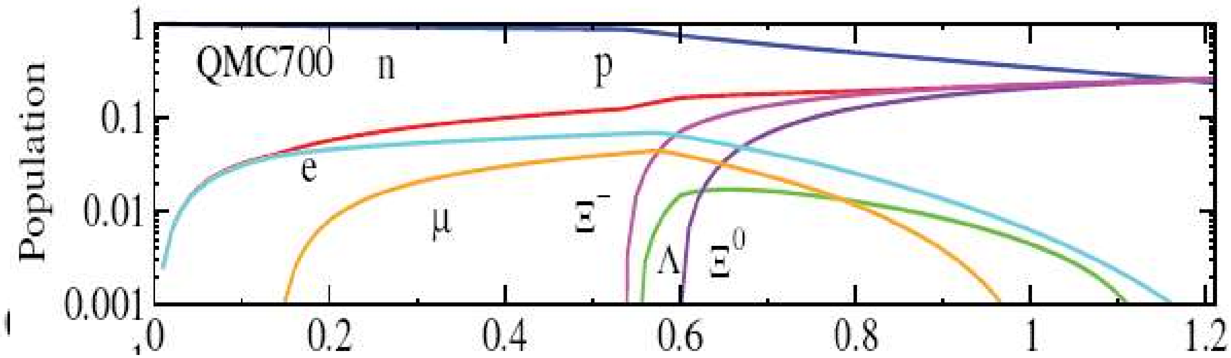
Consequences of QMC for Neutron Star



Rikovska-Stone *et al.*, NP A792 (2007) 341

2 Solar mass stars predicted with hyperons present:



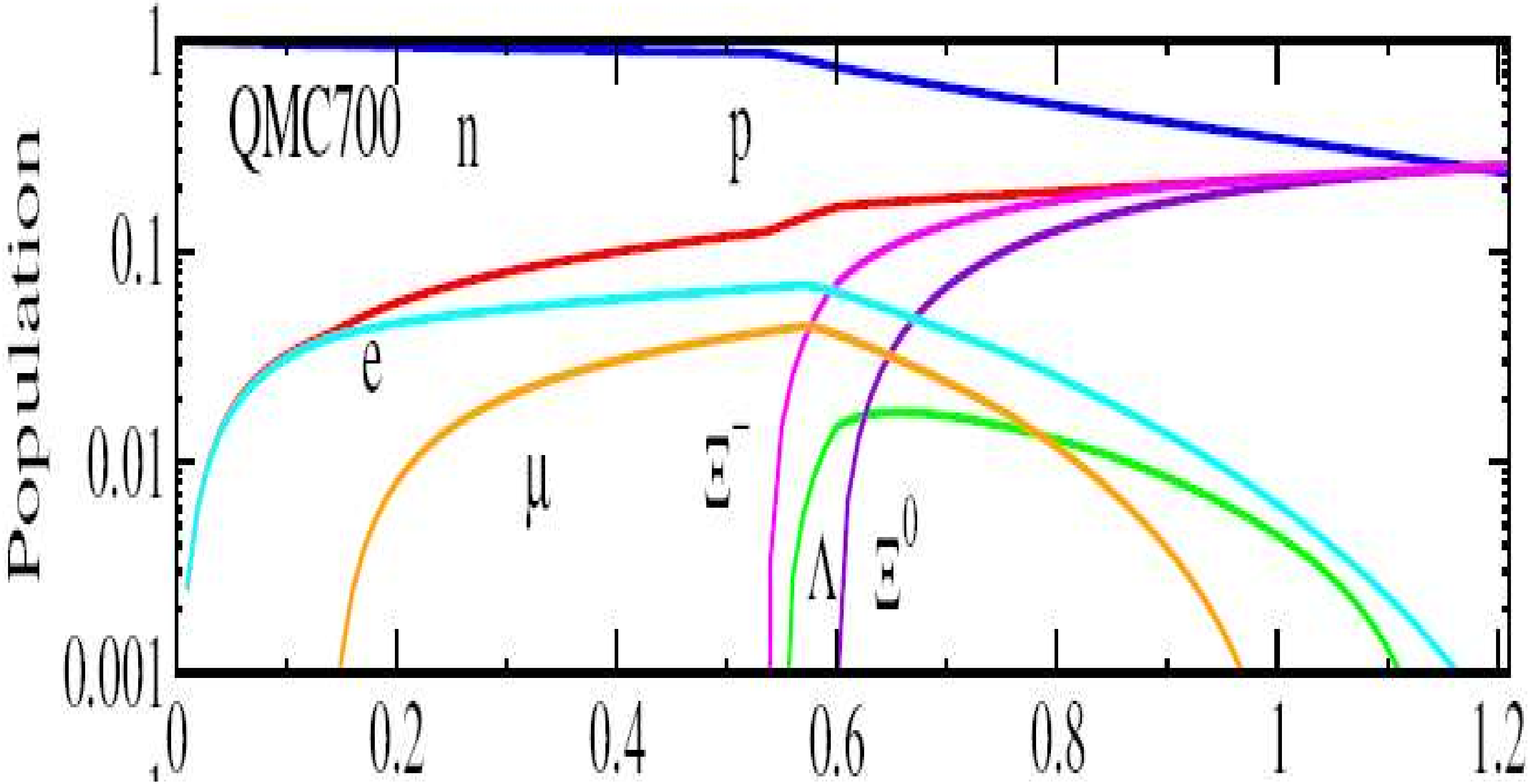
<u>Predicted</u> HNN forces crucial!

Later work: Saito et al., Whittenbury et al.....

Consequences for Neutron Star ⇒

D.L.Whittenbury et.al., Phys.Rev. C89 (2014) 06580

New QMC model, relativistic, Hartree-Fock treatment



Stone et al., Nucl. Phys. A792 (2007) 341

Recent issue: no Δ^- in N.S

- The latest version of QMC (**OGE** color **hyperfine** interaction included self-consistently in matter) ⇒
- Λ single-particle energy **$1s_{1/2}$ in Pb** is **-26.9** MeV (Exp. **-26.3** MeV) ⇐ **no extra parameter!**
- **No Σ nuclear bound state !!**
- **Same interaction of OGE for N and Δ^-**

⇒**No Δ^- in neutron star. arXiv:1906.0549**

(T.F. Motta, A.W. Thomas, P.A.M. Guichon)

In-medium properties of the low-lying Strange, Charm, Bottom baryons

- Effective masses (Σ_b, Ξ_b !!)
- In-medium bag radii
- In-medium bag eigenfrequencies
- Scalar and vector (plus Pauli) potentials
- Excitation (total) energies (Σ_b, Ξ_b !!)

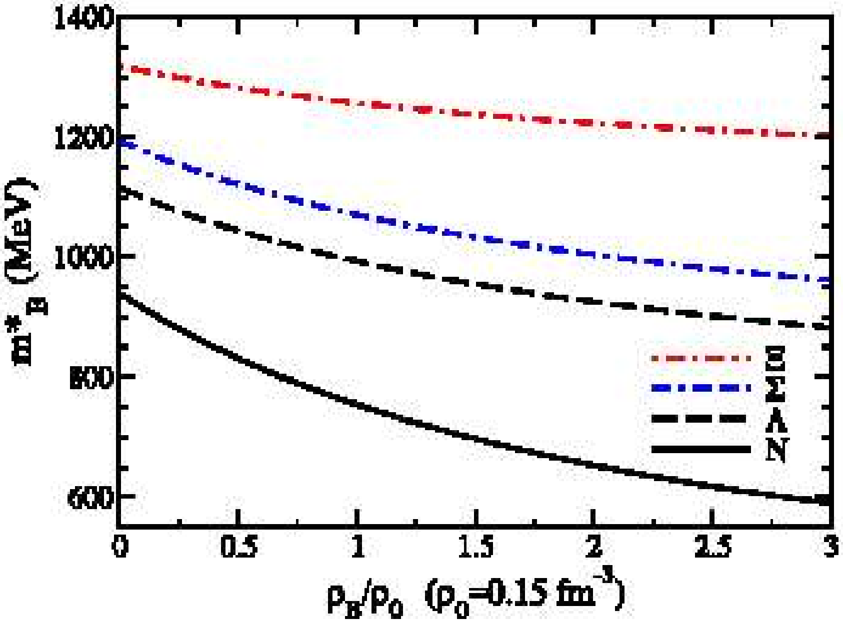
In vacuum (inputs)

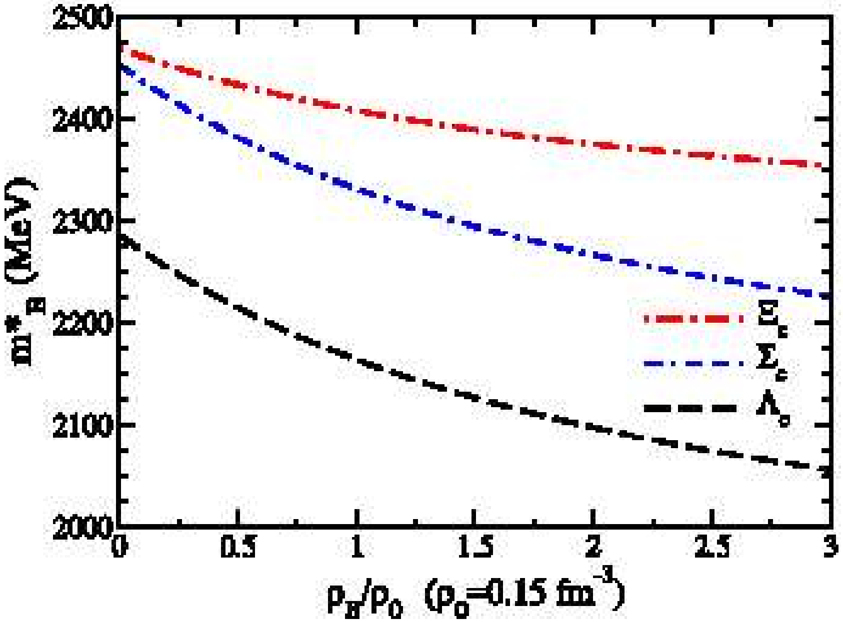
$B(q_1, q_2, q_3)$	z_B	m_B	R_B	x_1	x_2	x_3
N(qqq)	3.295	939.0	0.800	2.052	2.052	2.052
Λ(uds)	3.131	1115.7	0.806	2.053	2.053	2.402
Σ(qqs)	2.810	1193.1	0.827	2.053	2.053	2.409
Ξ(qss)	2.860	1318.1	0.820	2.053	2.406	2.406
Ω(sss)	1.930	1672.5	0.869	2.422	2.422	2.422
Λ_c(udc)	1.642	2286.5	0.854	2.053	2.053	2.879
Σ_c(qqc)	0.903	2453.5	0.892	2.054	2.054	2.889
Ξ_c(qsc)	1.445	2469.4	0.860	2.053	2.419	2.880
Ω_c(ssc)	1.057	2695.2	0.876	2.424	2.424	2.884
Λ_b(udb)	-0.622	5619.6	0.930	2.054	2.054	3.063
Σ_b(qqb)	-1.554	5813.4	0.968	2.054	2.054	3.066
Ξ_b(qsb)	-0.785	5793.2	0.933	2.054	2.441	3.063
Ω_b(ssb)	-1.327	6046.1	0.951	2.446	2.446	3.065

In medium at $\rho_0 = 0.15\ \mathrm{fm}^3$

$B(q_1, q_2, q_3)$	m_B^*	R_B^*	x_1^*	x_2^*	x_3^*
N(qqq)	754.5	0.786	1.724	1.724	1.724
Λ(uds)	992.7	0.803	1.716	1.716	2.401
Σ(qqs)	1070.4	0.824	1.705	1.705	2.408
Ξ(qss)	1256.7	0.818	1.708	2.406	2.406
Ω(sss)	—	—	—	—	—
Λ_c(udc)	2164.2	0.851	1.691	1.691	2.878
Σ_c(qqc)	2331.8	0.889	1.671	1.671	2.888
Ξ_c(qsc)	2408.3	0.859	1.687	2.418	2.880
Ω_c(ssc)	—	—	—	—	—
Λ_b(udb)	5498.5	0.927	1.651	1.651	3.063
Σ_b(qqb)	5692.8	0.966	1.630	1.630	3.066
Ξ_b(qsb)	5732.7	0.931	1.649	2.440	3.063
Ω_b(ssb)	—	—	—	—	—

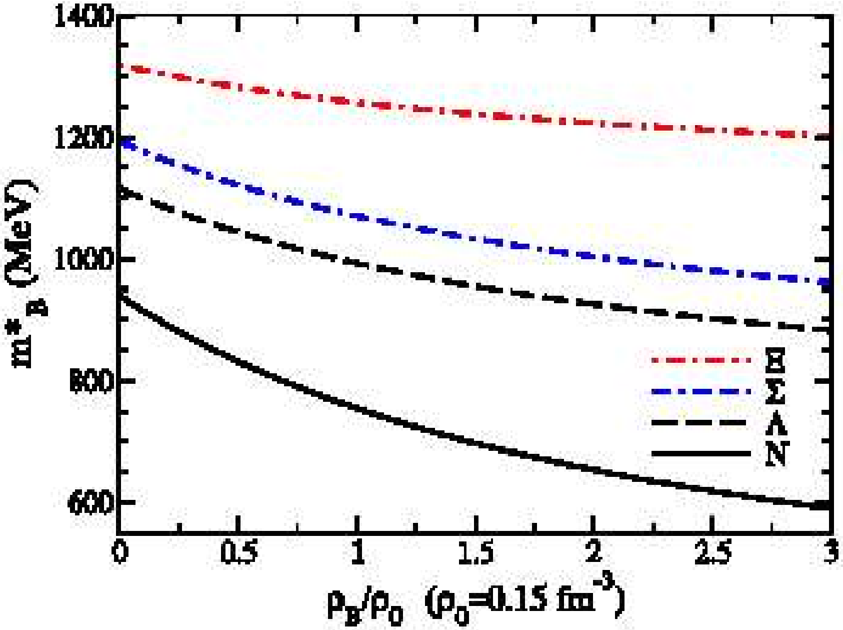
Effective masses:
Strange (left), Charm (right) baryons

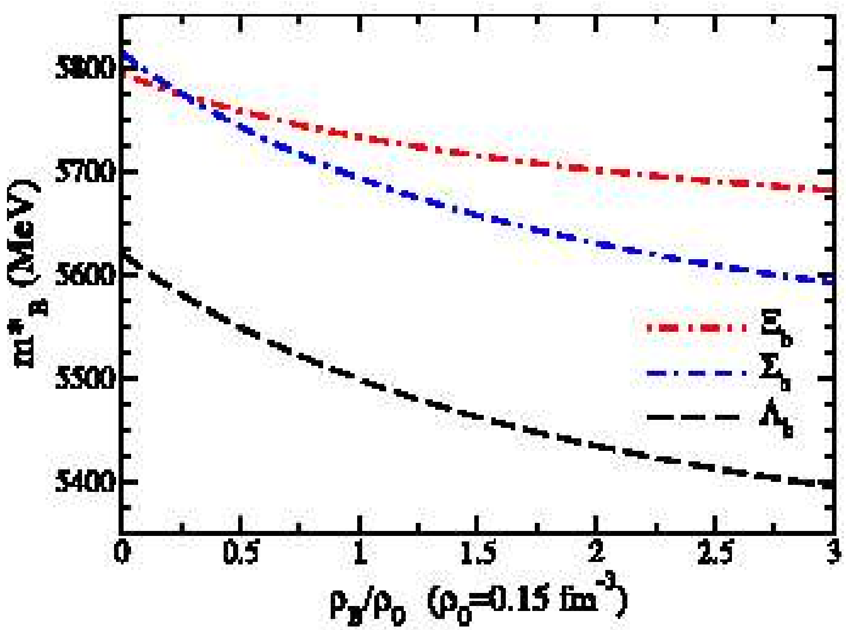




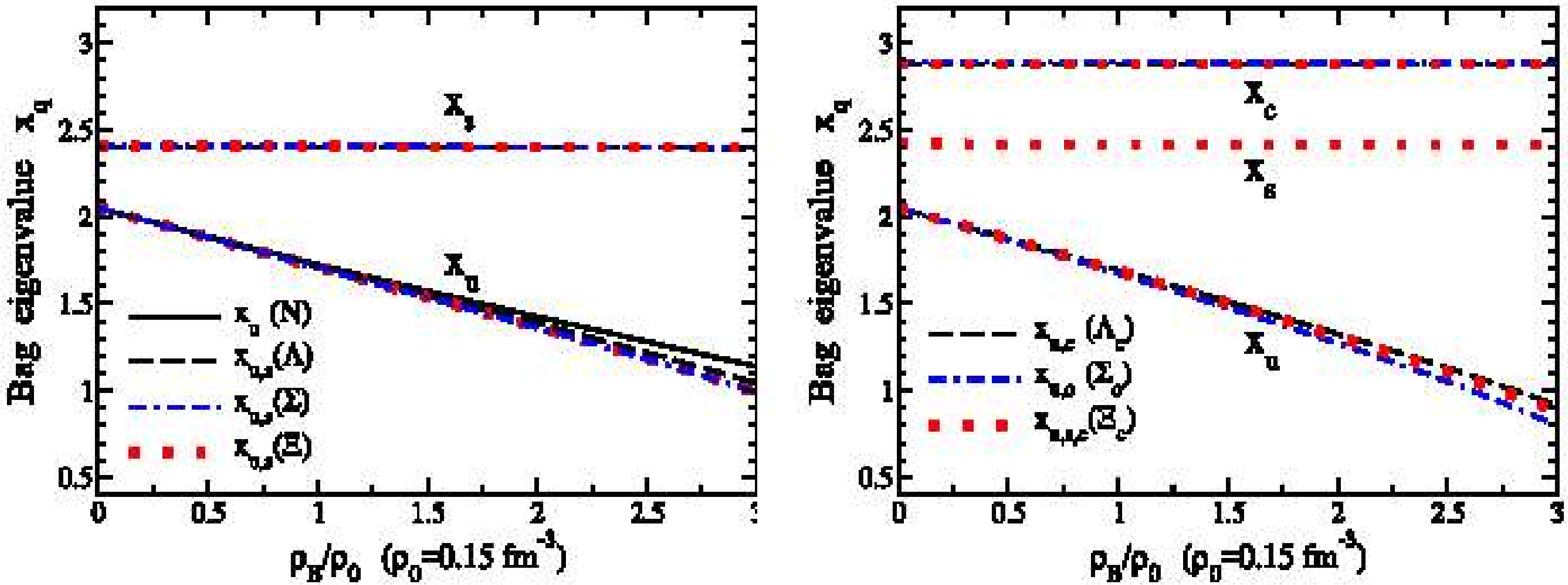
Effective masses:

Strange (left), Bottom (right) baryons

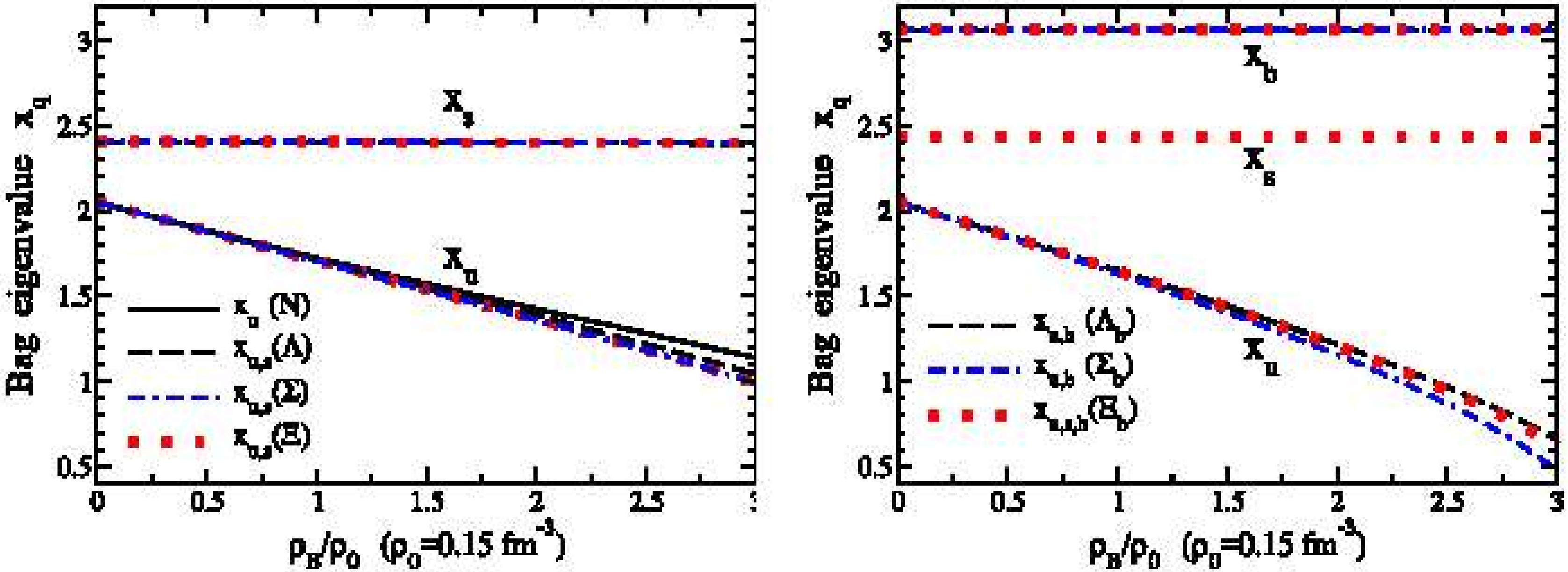




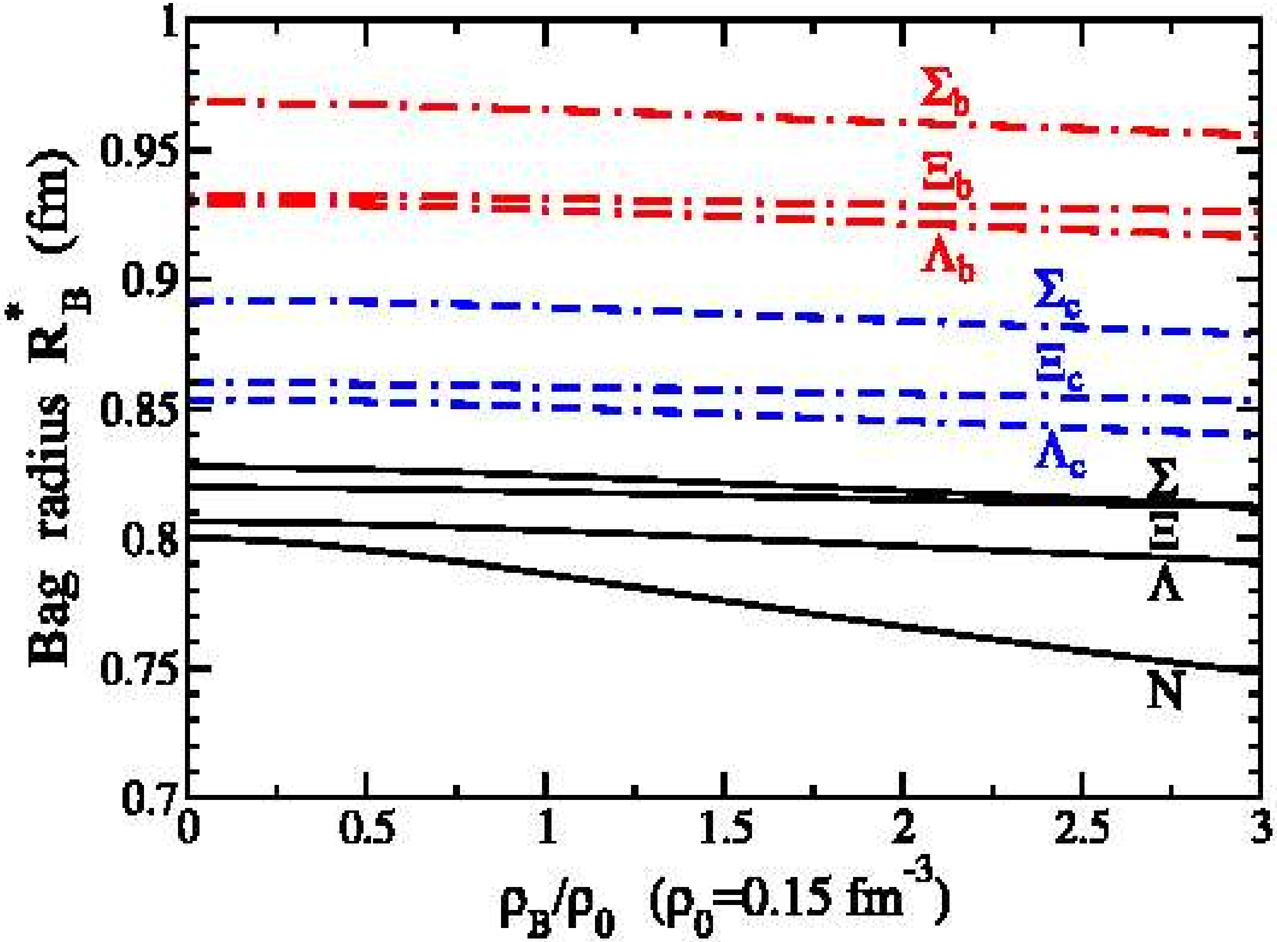
Bag eigenfrequencies: Strange (left), Charm (right) baryons



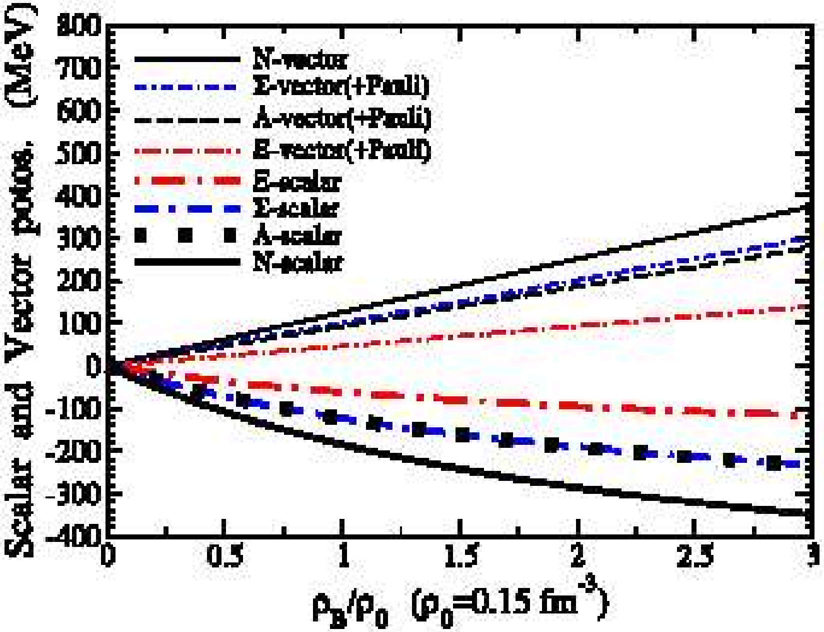
Bag eigenfrequencies:
Strange (left), Bottom (right) baryons

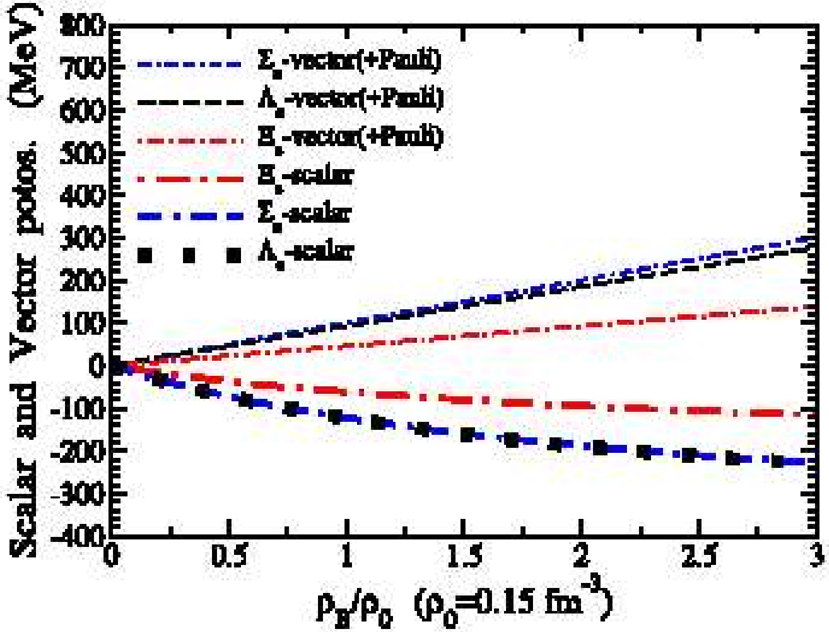


Bag radii: Strange, Charm, Bottom baryons

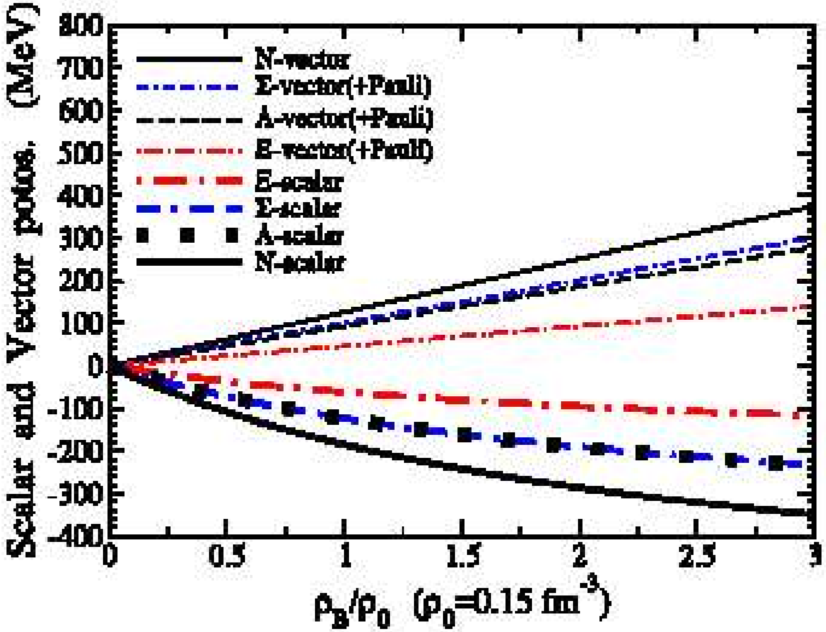


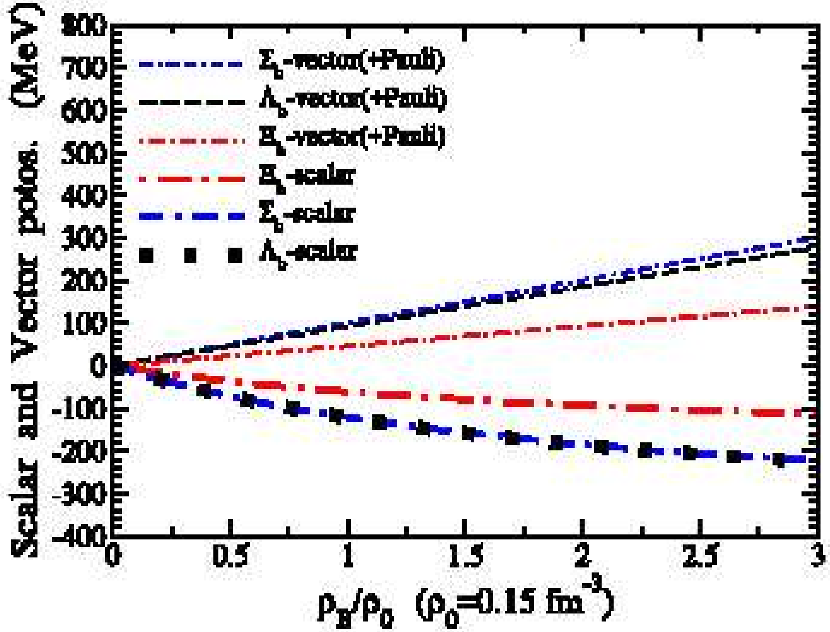
Scalar and (Vector+Pauli) potentials: Strange (left), Charm (right) baryons



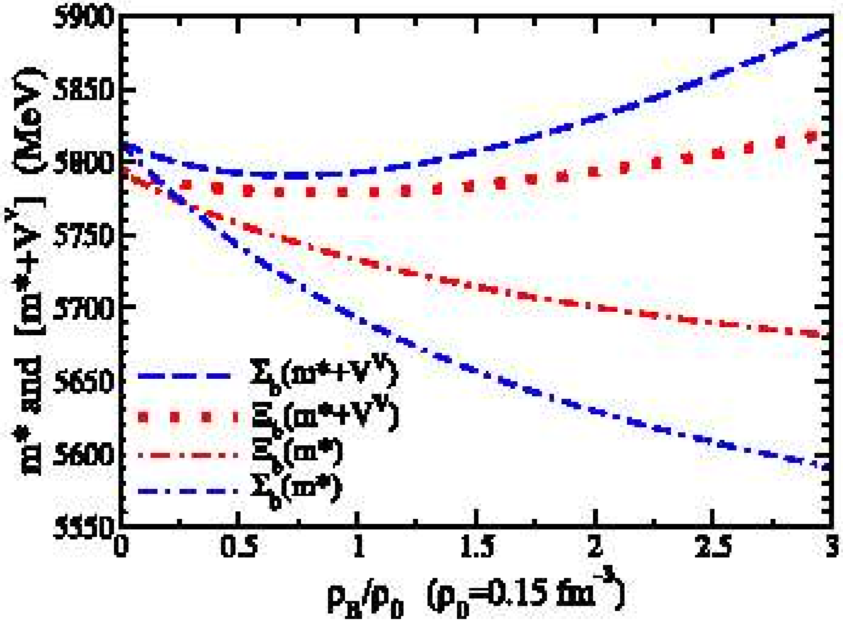


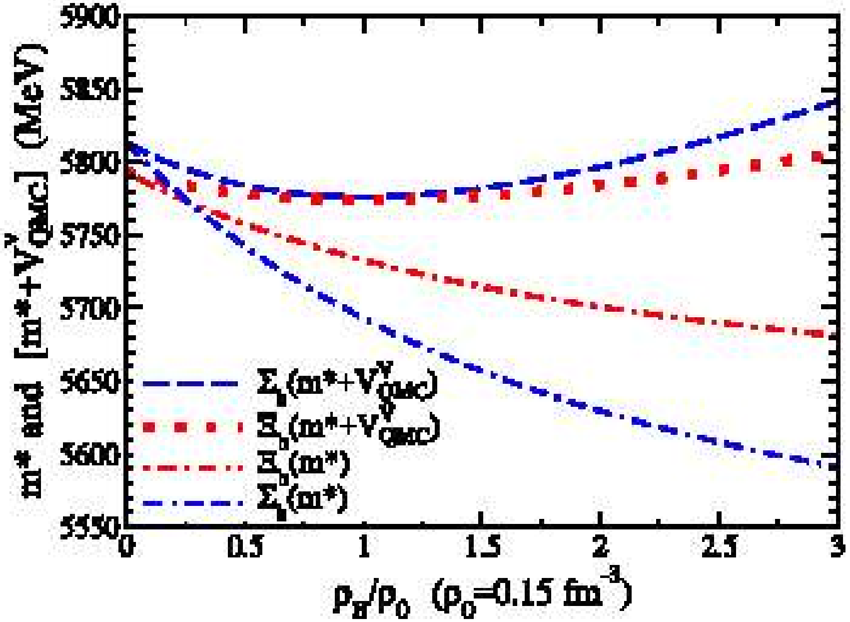
Scalar and (Vector+Pauli) potentials: Strange (left), Bottom (right) baryons





Excitation energies (scalar + vector pots.): Σ_b, Ξ_b
Vector + "Pauli" (left), Vector (right)





Summary, Perspective

•QMC model: In-medium properties of the low-lying Strange, Charm, Bottom baryons (completed) effective masses, bag radii, bag eigenfrequencies, (two different) vector potentials, excitation (total) energies

$\Longrightarrow$• Σ_b, Ξ_b baryon effective masses!! excitation energies !!!

$\Longrightarrow$• EM FFs., Weak-interaction FFs. for heavy baryons in medium

$\Longrightarrow$•in the near future !!

$\Longrightarrow$• Heavy ion collisions involving heavy baryons!!!

$\Longrightarrow$•Other interesting applications ??!! Your Suggestions !!!

Λ-Hypernuclei phtoproduction

Photoproduction of Λ hypernuclei

R. Shyam, KT, A.W. Thomas, PLB 676, 51 (2009)

Λ and K^+ are produced via **s-channel**

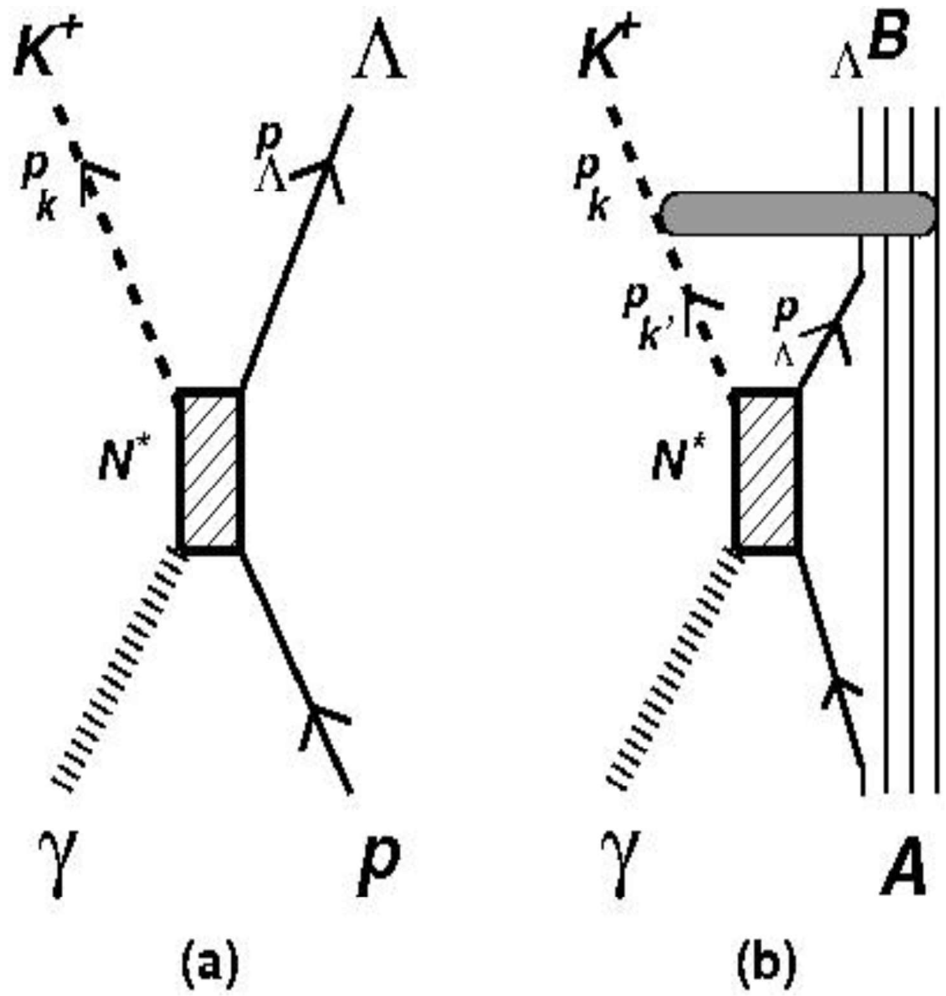
N* excitation (dominant)

S_{11}(1650), P_{11}(1710) P_{13}(1720)

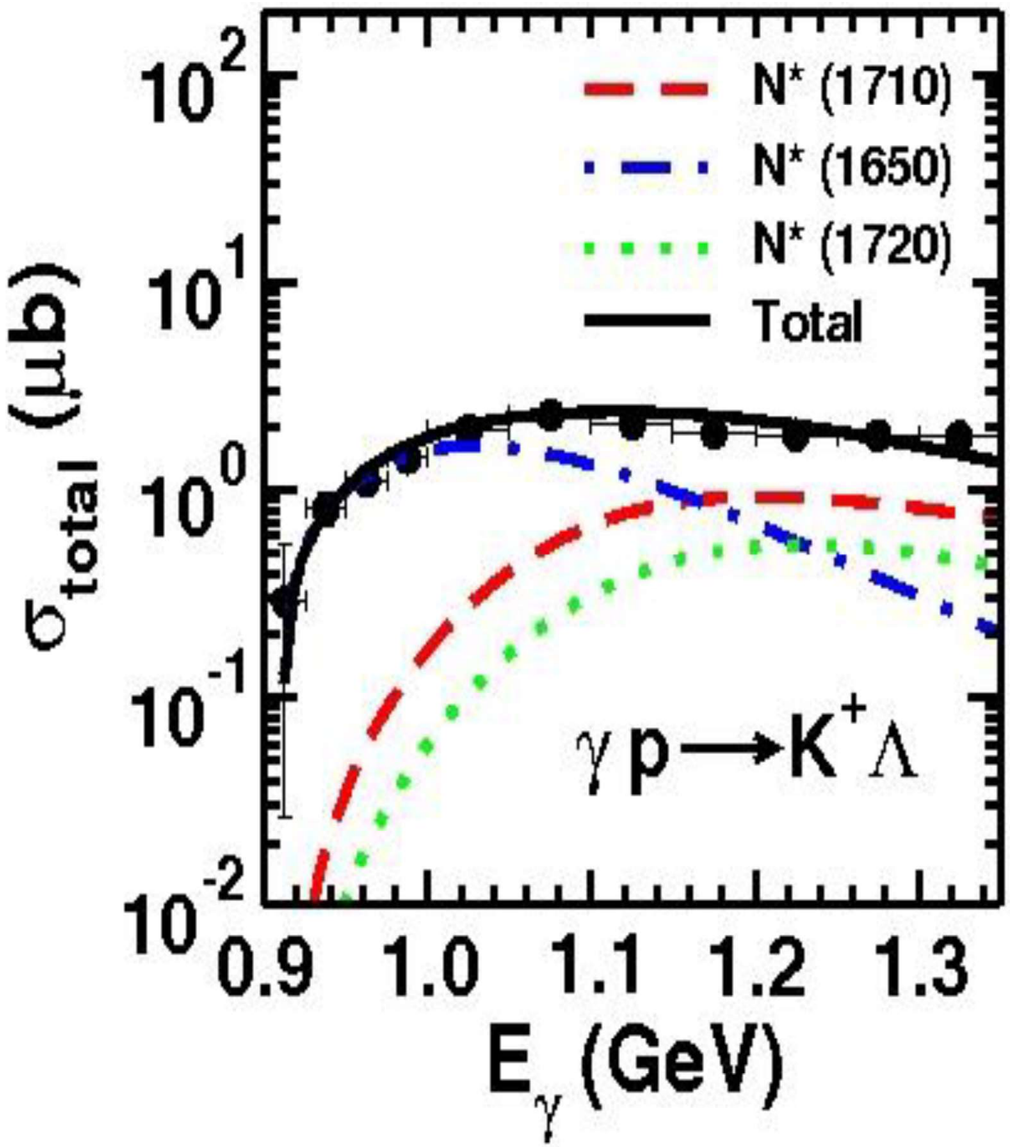
⇓

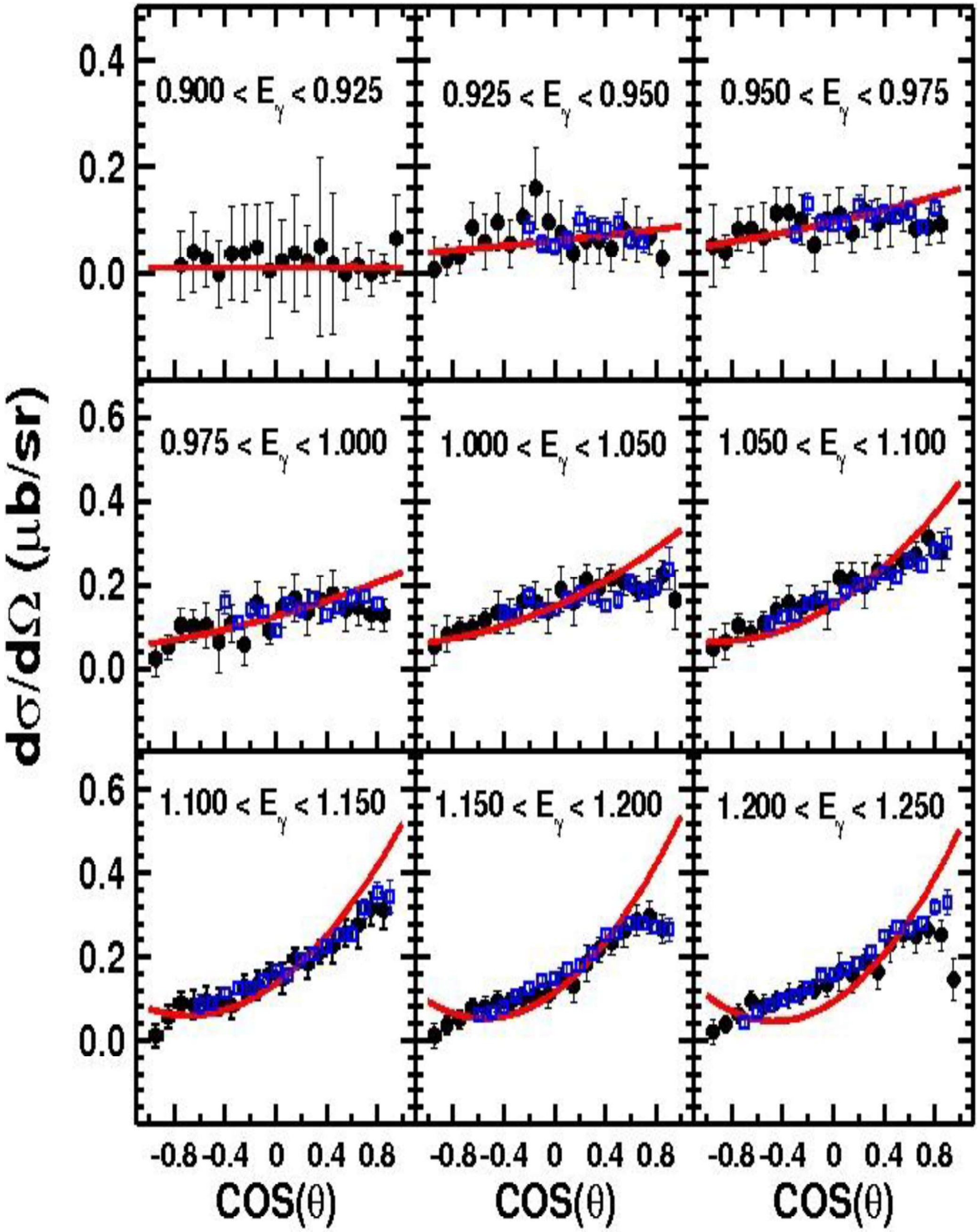
Energy region of interests, hypernuclei production

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



Effective Lagrangian model for $\gamma\, p \rightarrow K\, \Lambda$ reaction





R. Shyam, K. Tsushima, A.W. Thomas, Phys. Lett. B676 (2009) 51

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

State	**Exp.**	**QMC**	V_v (W.S)	V_s (W.S)
${}^{12}_{\Lambda}B\,1s_{1/2}$	**11.37**	**14.93**	171.78	-212.69
${}^{12}_{\Lambda}B\,1p_{3/2}$	**1.73**	**3.62**	204.16	-252.28
${}^{12}_{\Lambda}B\,1p_{1/2}$	**1.13**	**3.62**	227.83	-280.86
$(p1p_{3/2})^{-1}$ ${}^{12}C$	15.96 Sep. energy	(≅OK)	382.60	-472.34

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

PLB 676, 51 (2009)

$E_{th} \sim 695$ MeV

dσ/dΩ at

Kaon angle **θ = 10°**

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

(wave functions!) ⇒

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

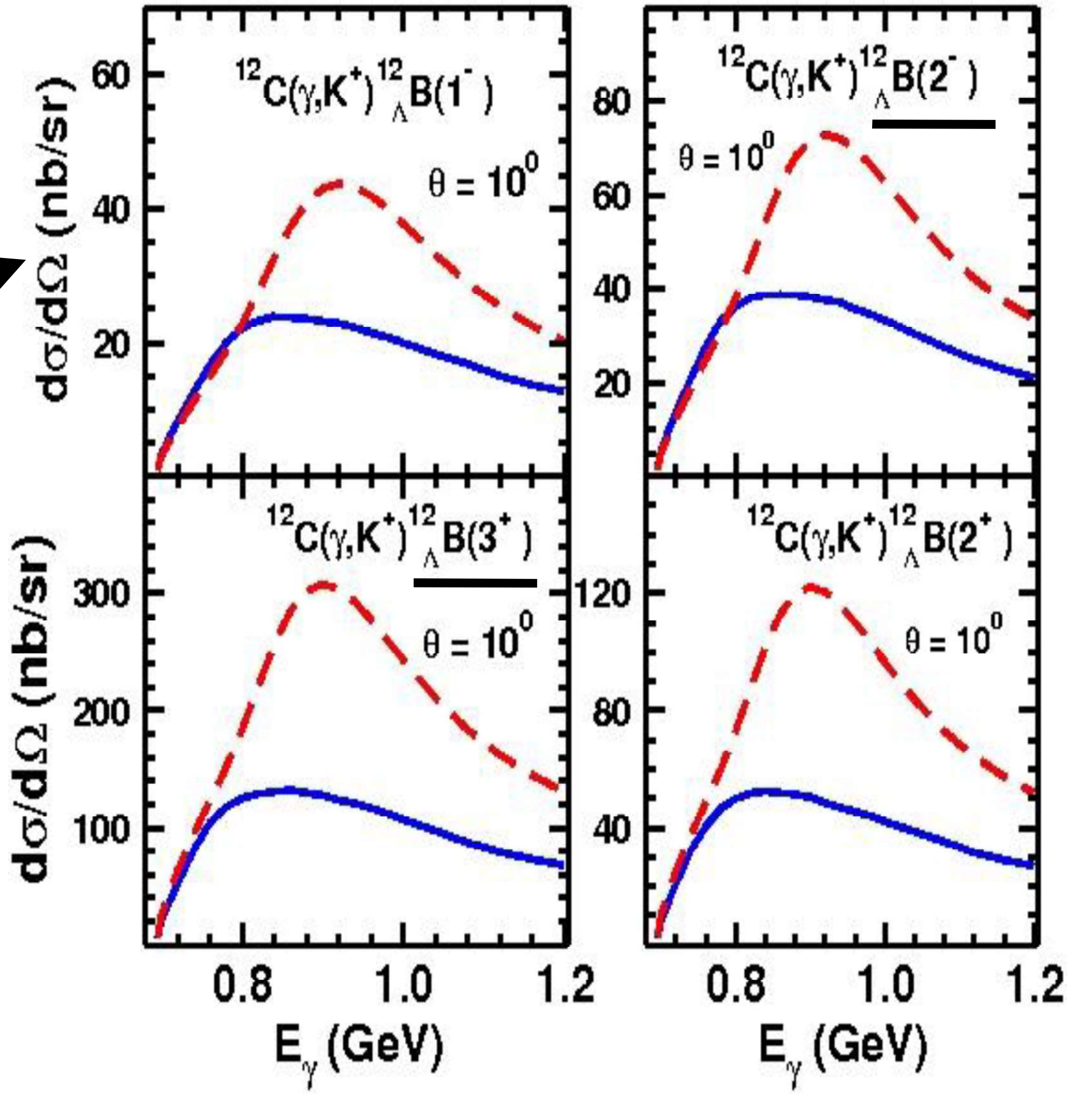
(potentials!) ⇒

Diracp - - - - - -

(phenomenological)

QMC ———

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



Summary: Λ 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. **$d\sigma/d\theta$** at Kaon angle **θ = 10°** shows **distinguishable difference!**
3. **Back ground** inclusion (higher energies)
4. **Heavier Λ** hypernuclei

Discussions

1. Study of Ξ hypernuclei

   ⇑ ⇒ $A(K^-, K^+)_\Xi B$ reaction

2. Elementary $K^- N \to \Xi K^+$ reaction ⟶

3. Heavier Λ hypernuclei **photoproduction**

4. Electroproduction of Λ hypernuclei

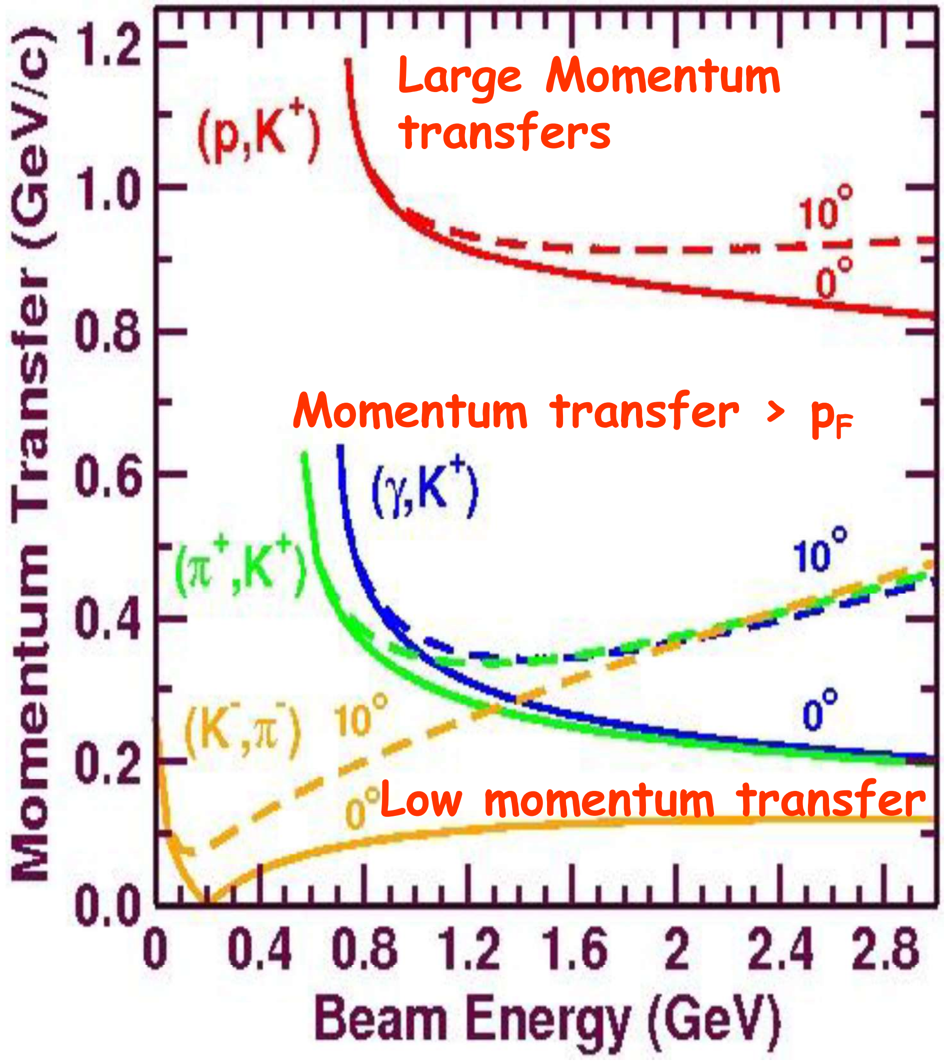
5. Λ_c **and** Λ_b hypernuclei **???!!!**

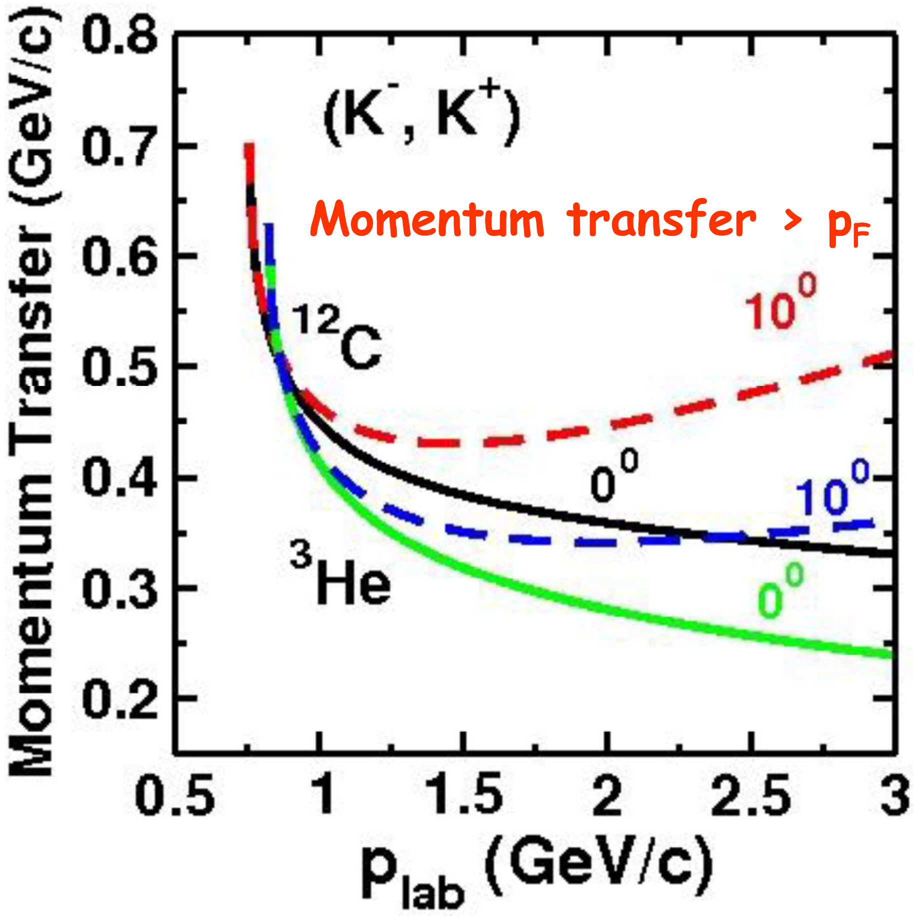
   (**KT, F.C. Khanna, Phys. Rev. C 67, 015211 (2003))**

Ξ^--Hypernuclei

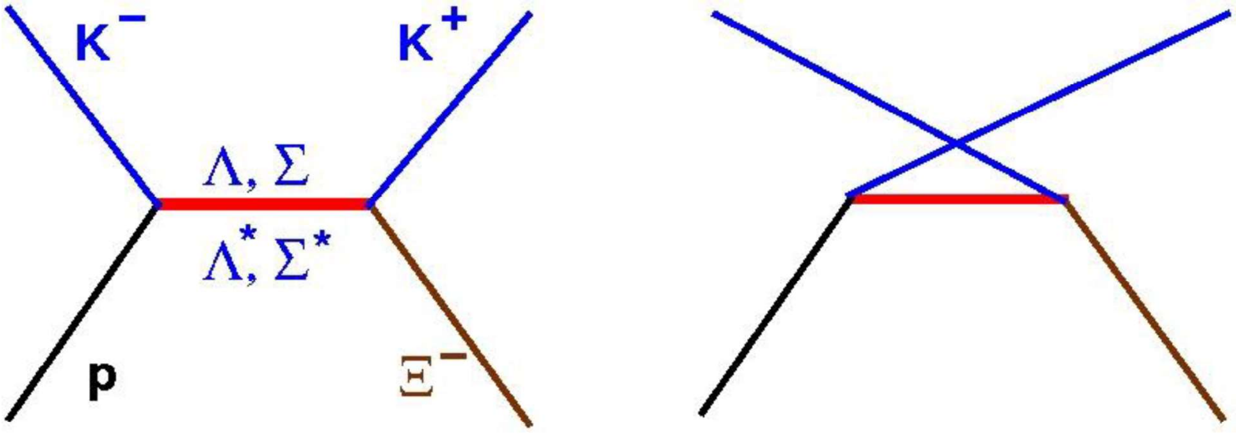
KINEMATICS

^{12}C



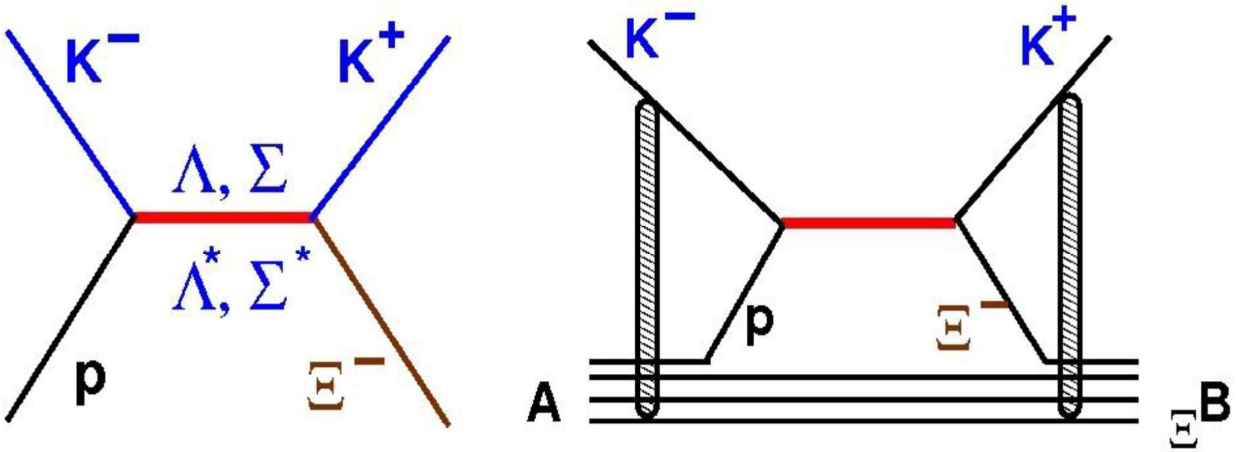


Production process of Cascade (S=-2) hypernuclei



(a) (b)

S-channel and u-channel diagrams for elementary reaction



(a) (b)

Cascade Hypernuclear production in s-channel

Λ(1116), Σ(1189), Λ(1405), Λ(1670), Λ(1180), Λ(1890), Λ(1520), Σ(1750), Σ(1385), Σ(1670)

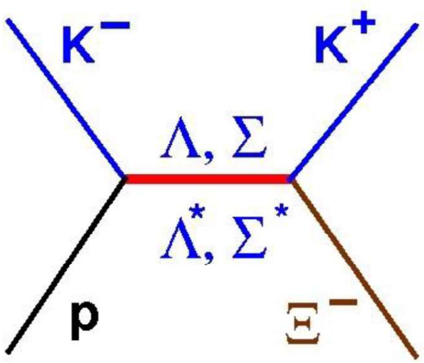
Covarient Description of $A\,(h\gamma,K^{+})\;_{Y}B$ reaction, Effective Lagrangian model

- Effective Lagrangians at Meson-baryon-Resonance vertices

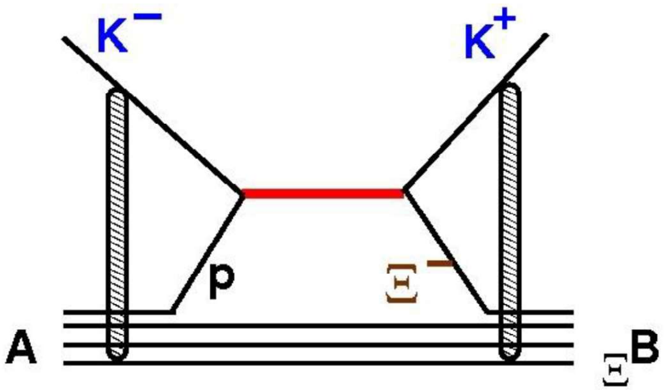
Coupling constants, form-factors (from the description of elementary reaction)

- **Propagators for resonances (spin-1/2, spin-3/2)**
- **Bound state nucleon (hole) and hyperon (particle) spinors**
- Initial and final state interactions (distorted waves).
- Medium effects of Resonances

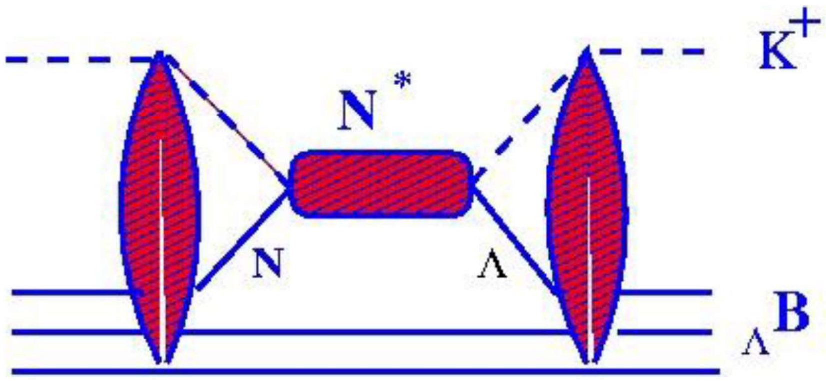
All calculations in momentum space, so nonlocalities are included.



(a)



(b)

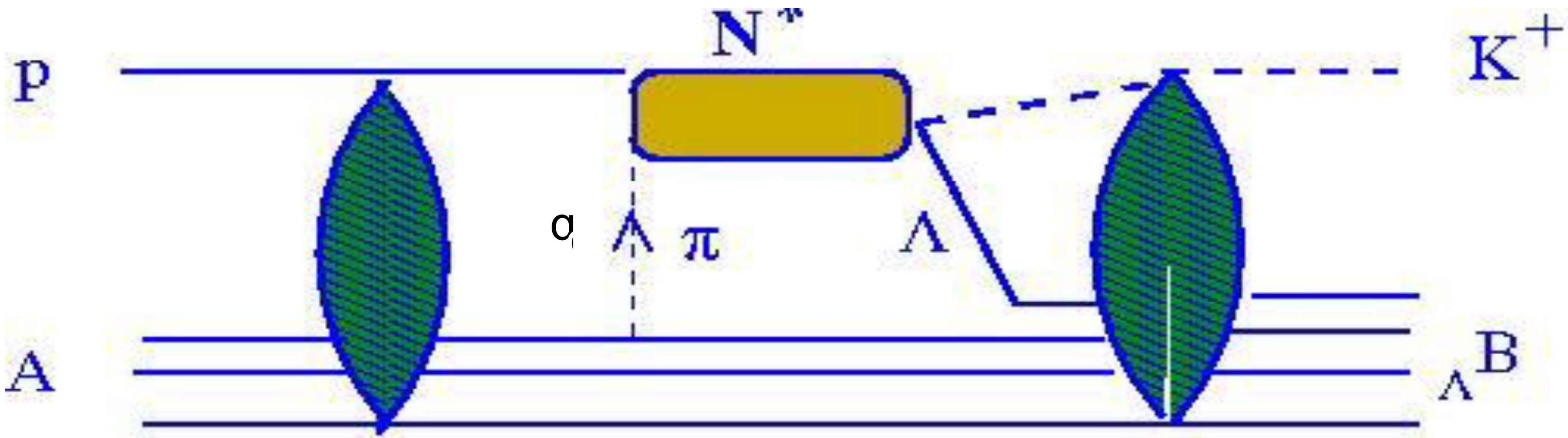


A typical amplitude

$$M_{2b}(N^*_{1/2}) = C^{2b}_{iso}\left(\frac{g_{NN\pi}}{2m_N}\right)(g_{N^*_{1/2}N\pi})(g_{N^*_{1/2}\Lambda K^+})\bar{\psi}(p_2)\gamma_5\gamma_\mu q^\mu$$

$$\times\,\psi(p_1)D_\pi(q)\bar{\psi}(p_\Lambda)\gamma_5 D_{N^*_{1/2}}(p_{N^*})\gamma_5$$

$$\times\,\Phi_K^{(-)*}(p'_K, p_K)\Psi_i^{(+)}(p'_i, p_i),$$



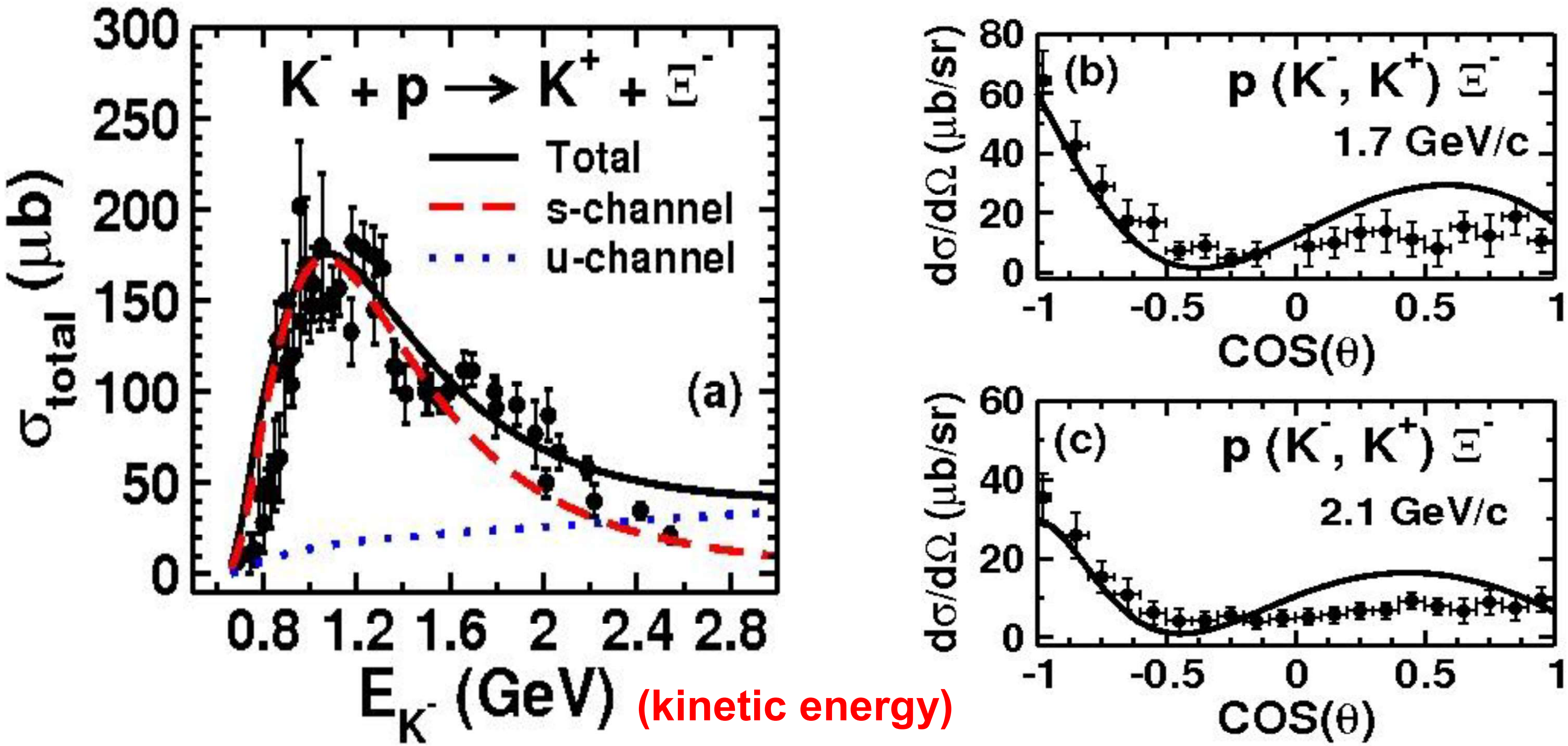
Effective Lagrangian model for the p $(K^-, K^{+,0})$ Ξ^- (Ξ^0)

Λ(1116), Λ(1180), Λ(1405), Λ(1520), Λ(1670), Λ(1890), Σ(1189), Σ(1385), Σ(1670), Σ(1750)

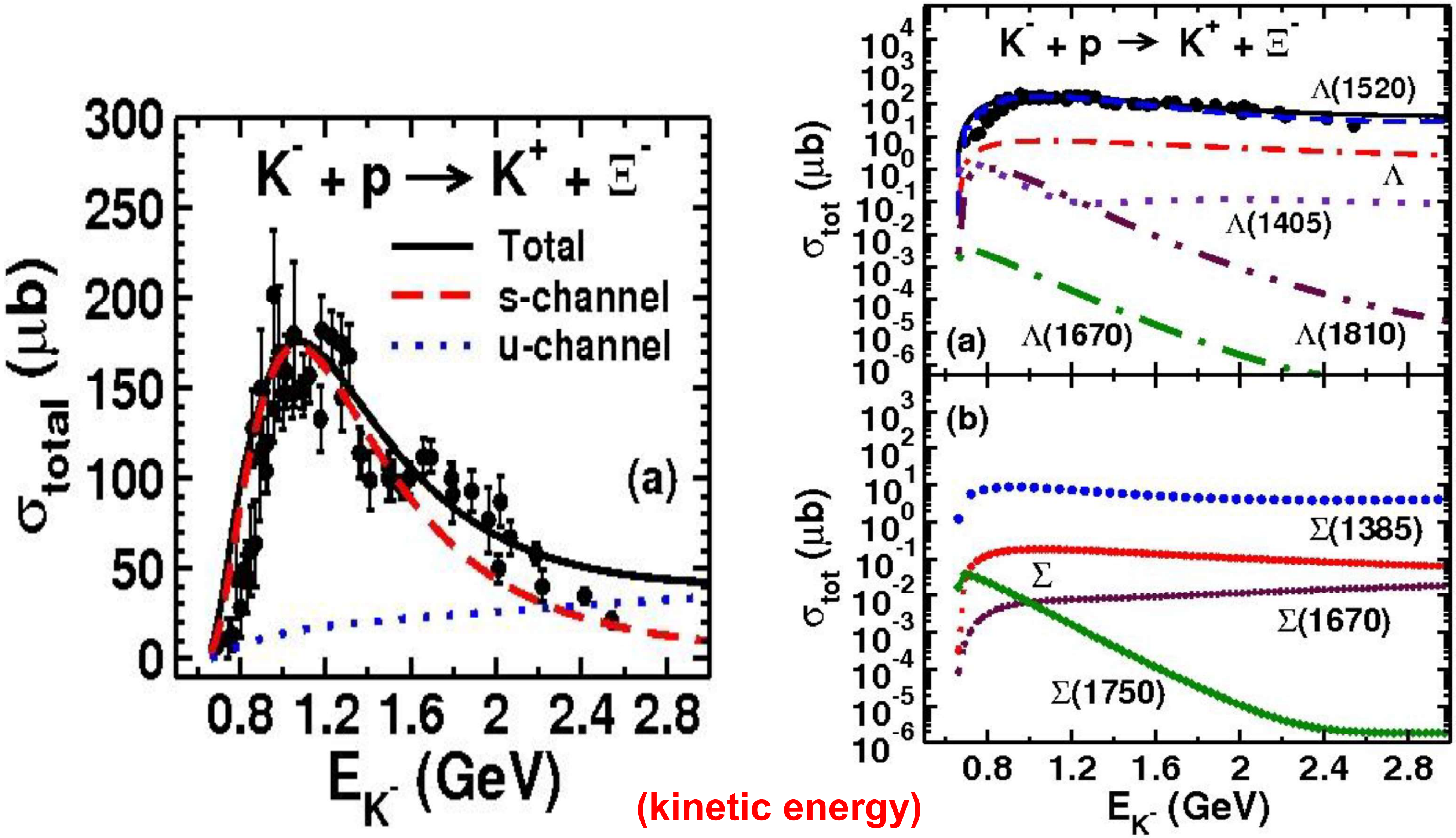
The information about the coupling constants is very scanty

From SU(3) model, old experimental determinations

R. Shyam, Olaf Scholten and A.W. Thomas, Phys. Rev. C84 (2011) 042201(R)



Elementary reactions for Ξ^- production, Role of resonances



(kinetic energy)

R .Shyam , O. Scholten, A. W. Thomas, Phys. Rev. C 84 (2011) 042201

Bound state spinors

A mean field approach, Phenomenological, or QMC

Momentum space Dirac Eq.

$$\not{p}\psi(p) = m_N\psi(p) + F(p),$$

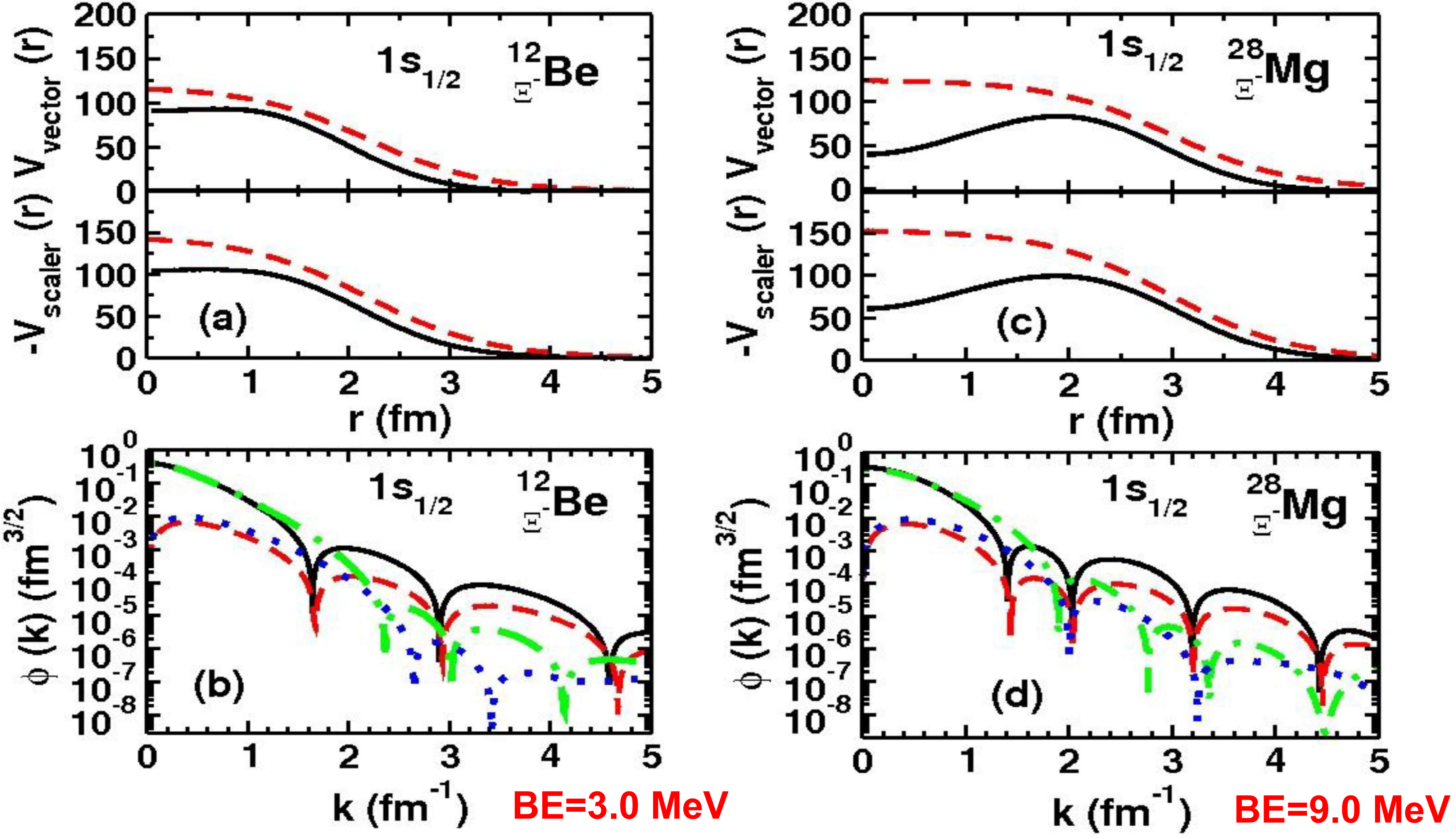
$$F(p) = \delta(p_0 - E)\Big[\int d^3p' V_s(-\mathbf{p}')\psi(\mathbf{p}+\mathbf{p}') - \gamma_0 \int d^3p' V_v^0(-\mathbf{p}')\psi(\mathbf{p}+\mathbf{p}')\Big].$$

$$\psi(p) = \delta(p_0 - E)\begin{pmatrix} f(k)\mathscr{Y}^{m_j}_{\ell 1/2 j}(\hat{p}) \\ -ig(k)\mathscr{Y}^{m_j}_{\ell' 1/2 j}(\hat{p}) \end{pmatrix},$$

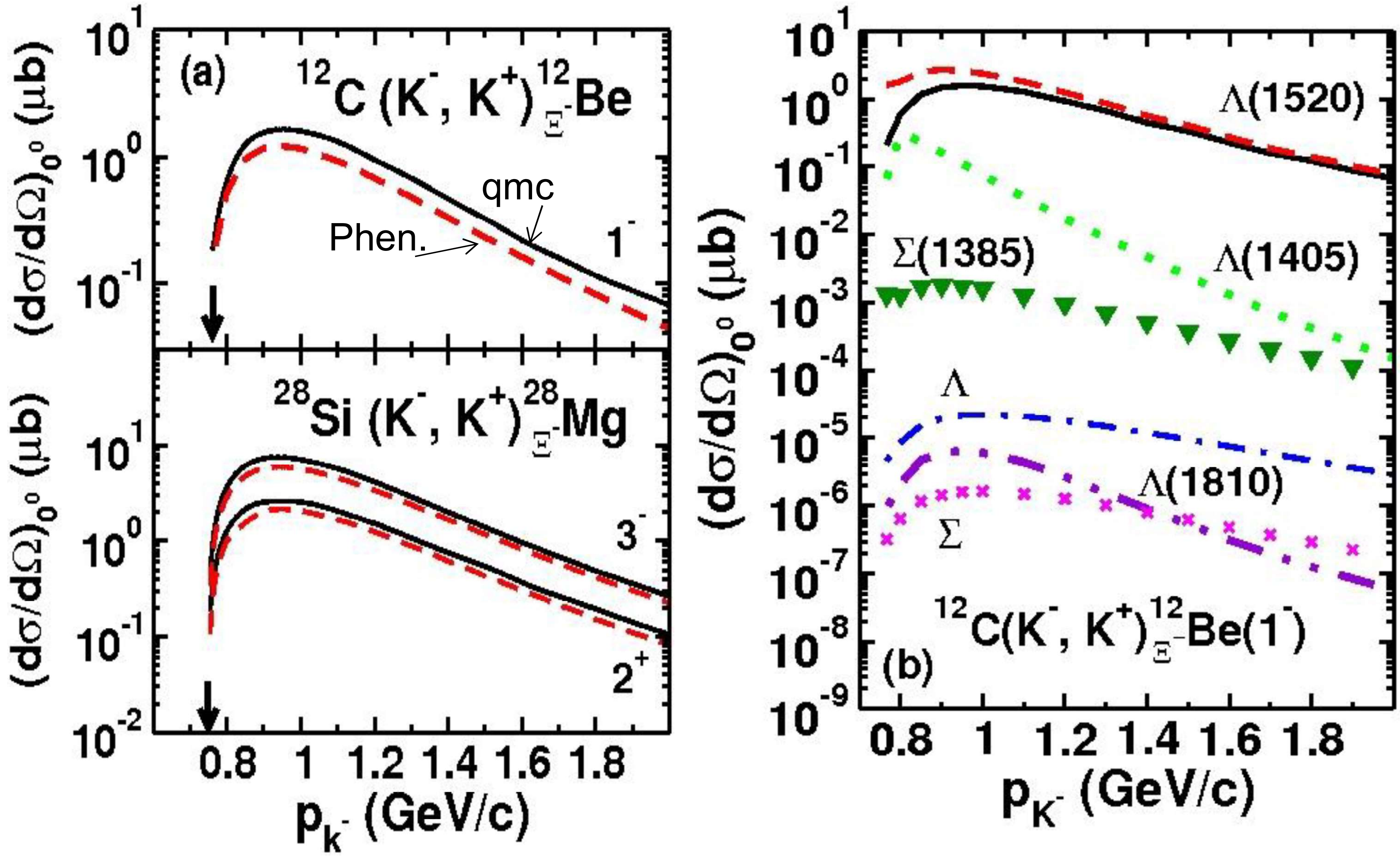
$$F(p) = \delta(p_0 - E)\begin{pmatrix} \zeta(k)\mathscr{Y}^{m_j}_{\ell 1/2 j}(\hat{p}) \\ -i\zeta'(k)\mathscr{Y}^{m_j}_{\ell' 1/2 j}(\hat{p}) \end{pmatrix},$$

Cascade bound states

Phenomenological and QMC model

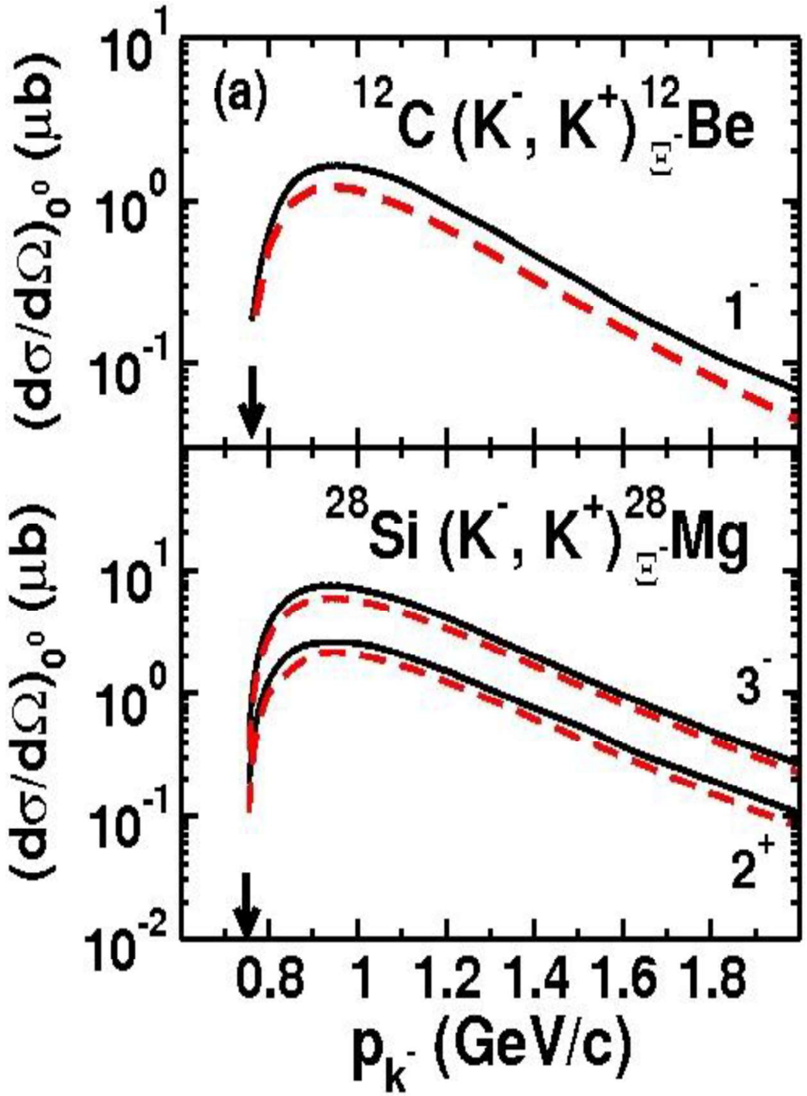


Cross section for Ξ^- hypernuclear production

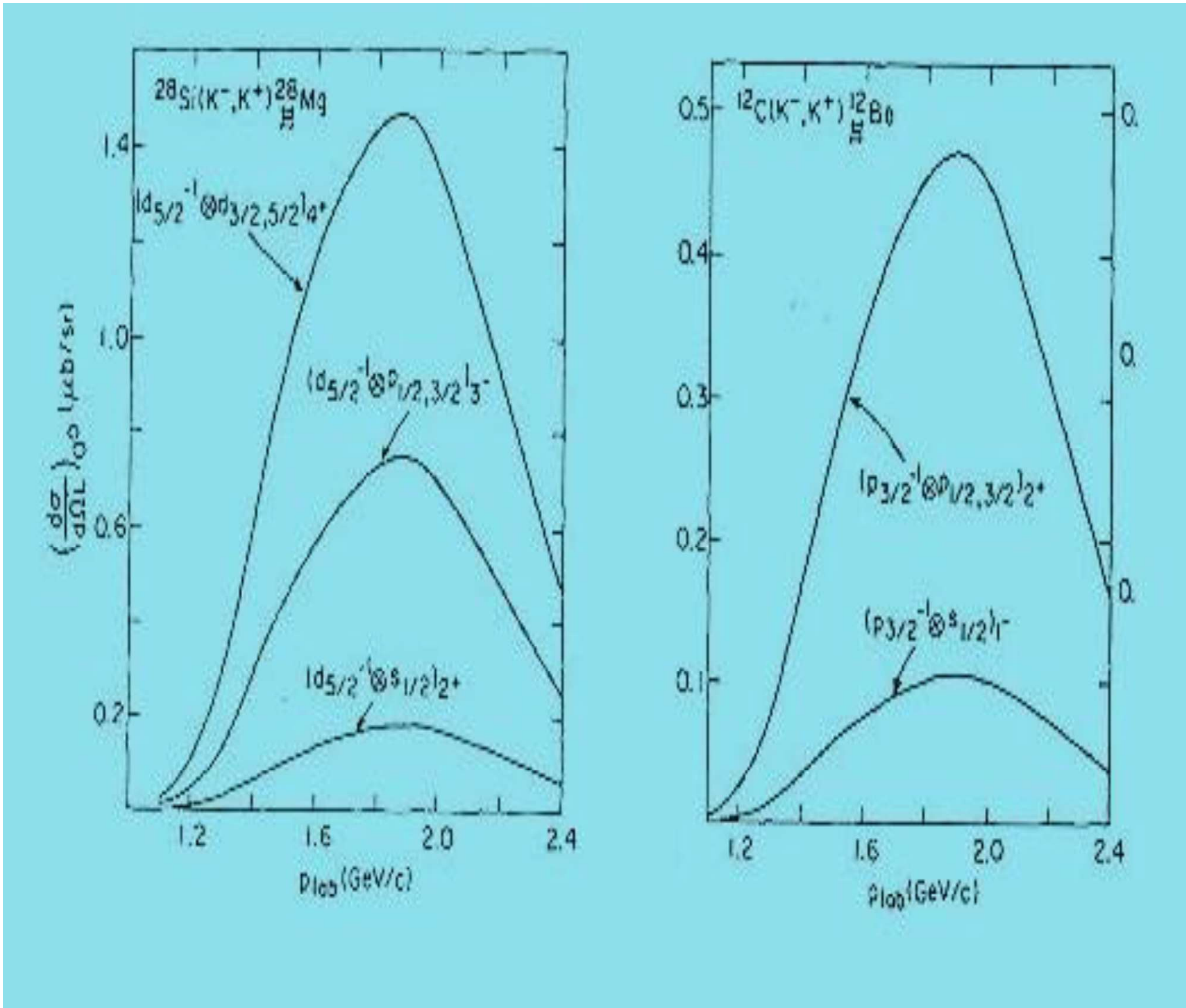


R. Shyam, K. Tsushima and A.W. Thomas, Nucl. Phys. A 881, 255 (2012)

Cross section for Ξ-hypernuclear production

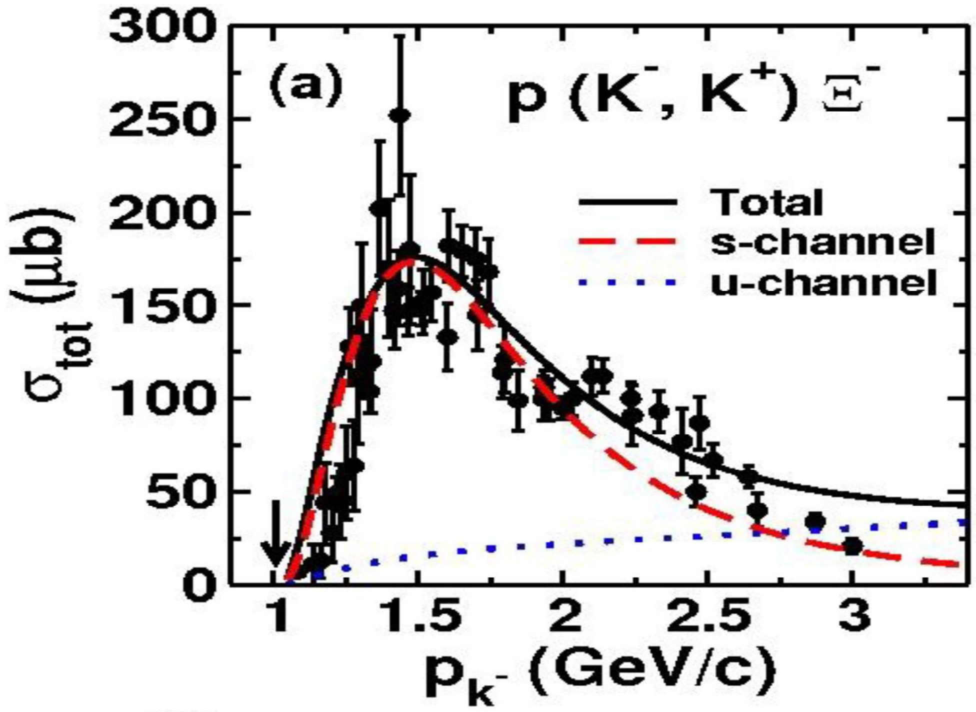


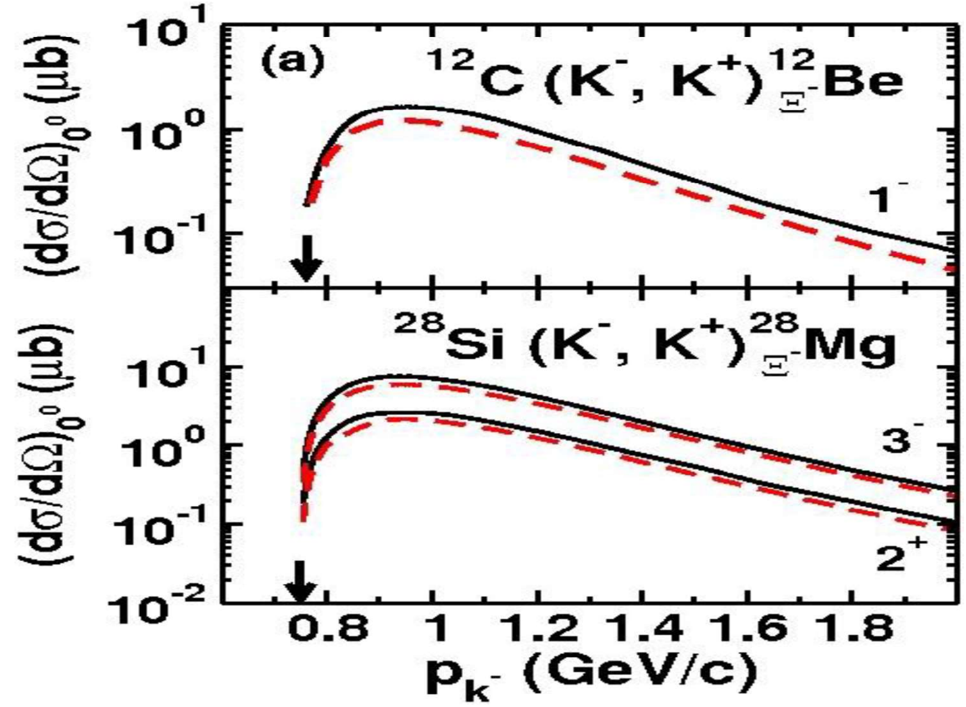
R. Shyam, K. Tsushima and A.W. Thomas, Nucl. Phys. A 881, 255 (2012)

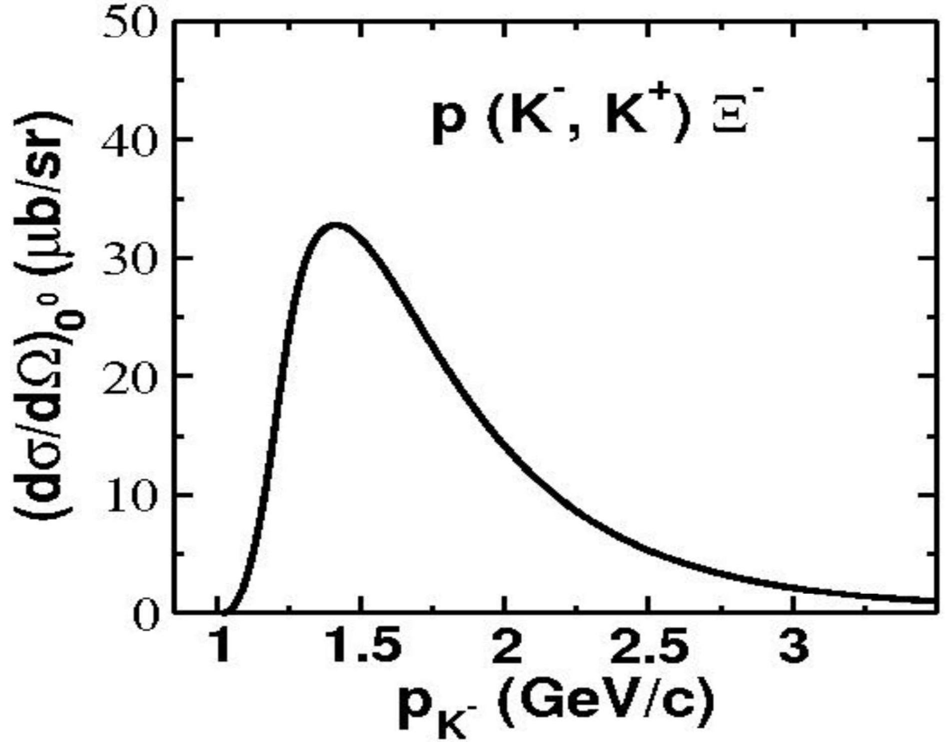


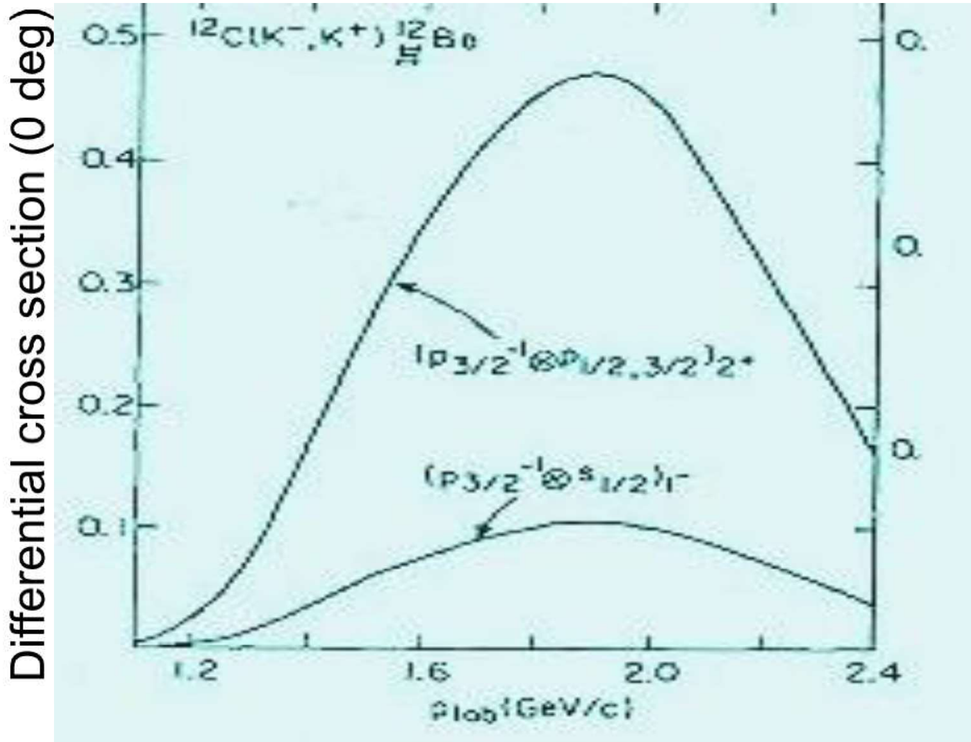
Dover and Gal, Ann. Phys. 146 (1983) 256

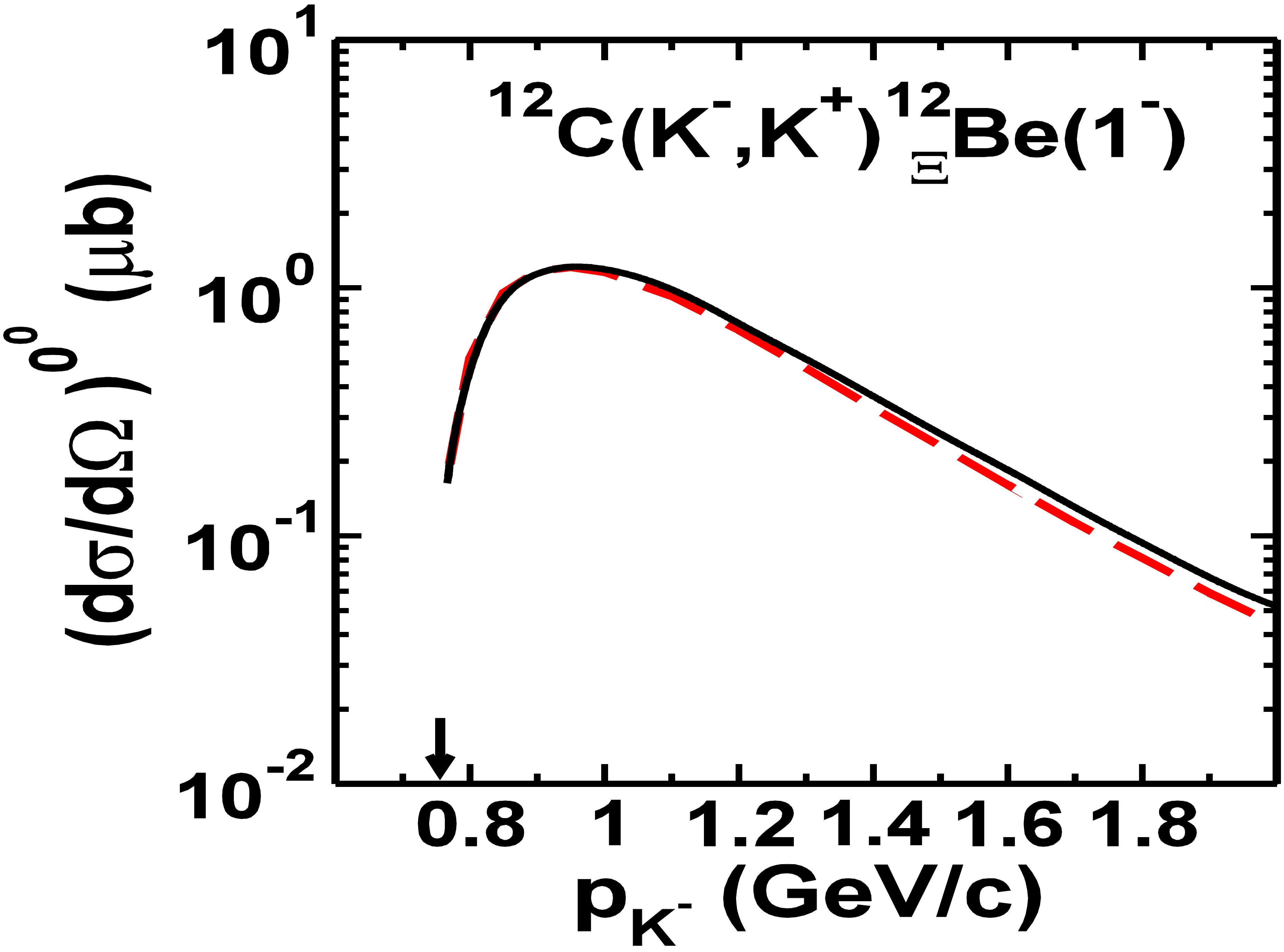
Difference between Old and our New results











$^{12}C(K^-,K^+)^{12}_{\Xi}Be(1^-)$
10^1
10^0
10^{-1}
10^{-2}
0.8
1
1.2
1.4
1.6
1.8
$(d\sigma/d\Omega)^{0^0}$ (μb)
p_{K^-} (GeV/c)

SUMMARY AND OUTLOOK

We developed a new description of the Ξ^- hypernuclear production via (K^-, K^+) reaction that is based on the mechanism of hyperon resonance excitation and decay. New calculations differ significantly from the older one.

A covariant description of the reaction is desirable and is possible.

Bound state spinors from the QMC model (quark-based) and phenomenological model

New Measurements are needed for some key quantities to resolve the differences between the old calculations. J-PARC facility should be ideal for this purpose. (E.g., elementary cross section.)

Neutrino Reactions, MFP
(ν, $\bar{\nu}$ asymmetry)

M.K. Cheoun, K.S. Choi, K.S. Kim,

K. Saito, T. Kajino, T. Maruyama, KT,

P.T.P. Hutauruk, Y. Oh

Phys. Lett. B 723, 464 (2013)

Phys. Rev. C 87, 065502 (2013)

arXiv: 1802.01749 [nucl-th]

Medium effect on CC weak form factors

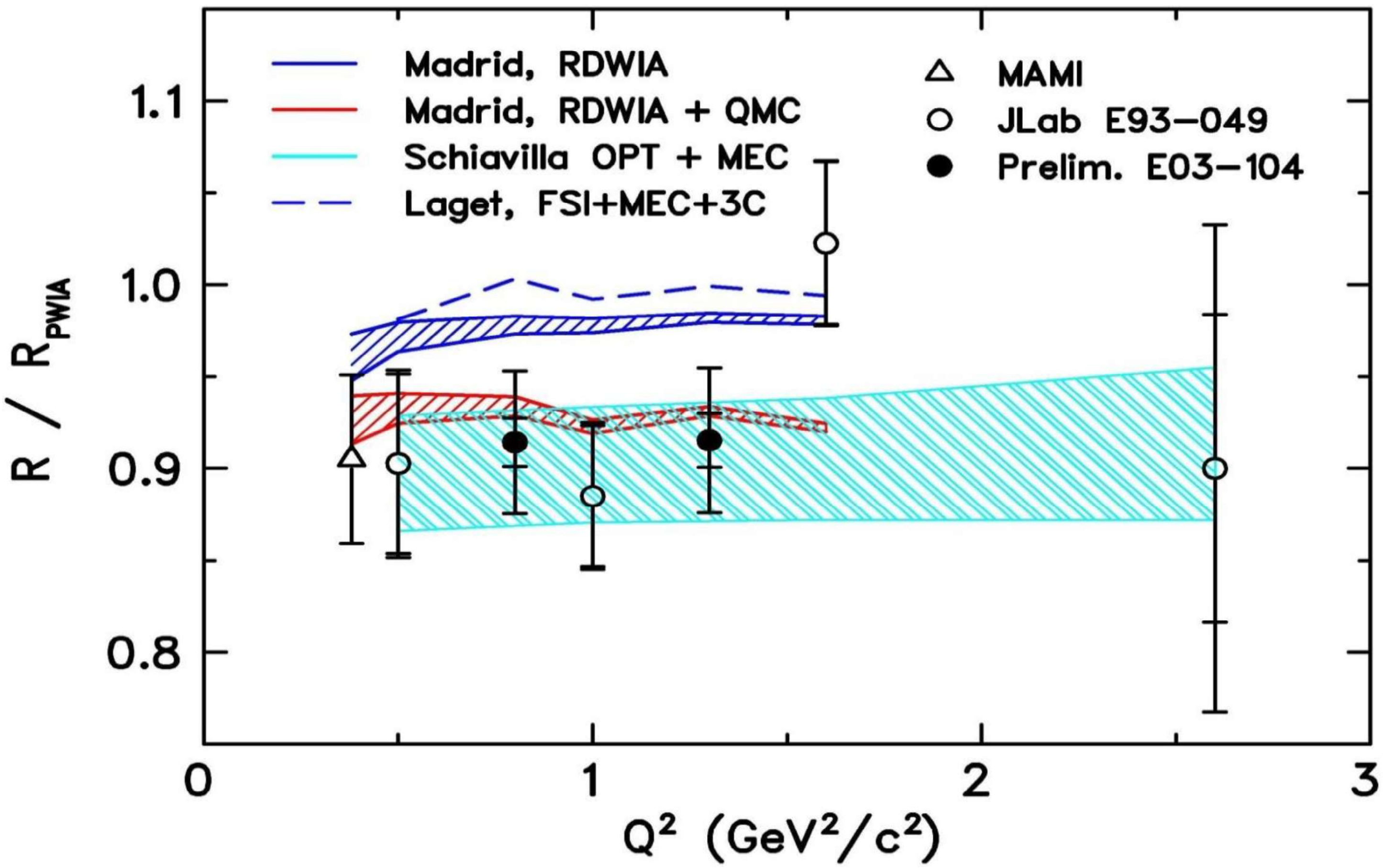
(Octet baryon EM ffs.

G. Ramalho, KT, J. Phys. G 40, 015102 (2013))

$R=(p'_x/p'_z)=(G_E^p/G_M^p)$: $^4He/^1H$ (reminder)

S. Malace, M. Paolone and S. Strauch, arXiv:0807.2251 [nucl-ex]

S. Strauch *et al., Phys. Rev. Lett.* ***91, 052301 (2003)***



$$W^{\mu} = F_1(Q^2)\gamma^{\mu} + iF_2(Q^2)\sigma^{\mu\nu}q_{\nu}/2M_N + F_A(Q^2)\gamma^{\mu}\gamma_5 + F_P(Q^2)\, q^{\mu}\gamma_5/2M_N$$

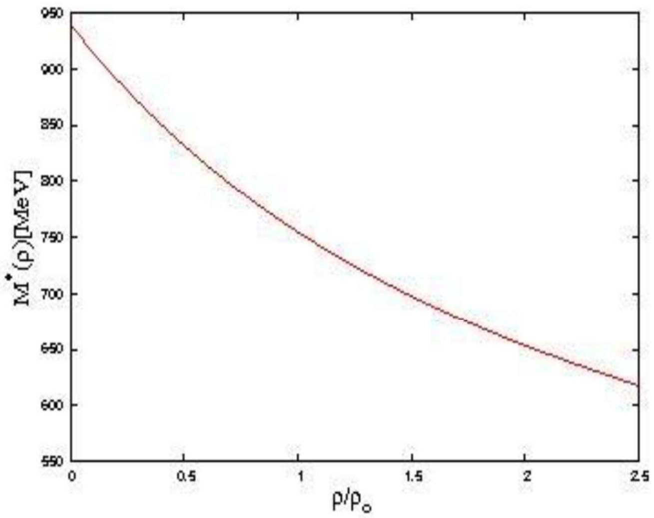
$$F_A(Q^2) = G_A(Q^2) = -g_A / (1+Q^2/M_A^2)^2$$

$$F_i = F_i^p - F_i^n \quad (i=1,2)$$

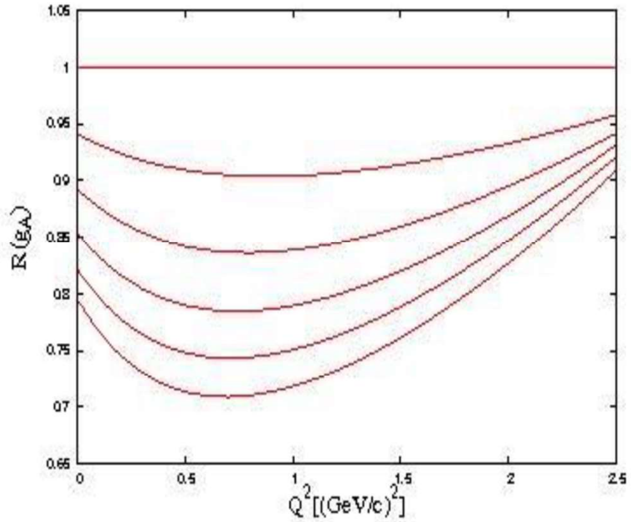
$$G_E = F_1 - Q^2 F_2/4M_N$$

$$G_M = F_1 + F_2$$

M_N* - ρ (density)
$\rho_0 = 0.15\ fm^{-3}$



g_A*/g_A – Q^2 and
ρ (density): $0.5\rho_0$
Increase top to bottom



F_1*/F_1 – Q^2 and

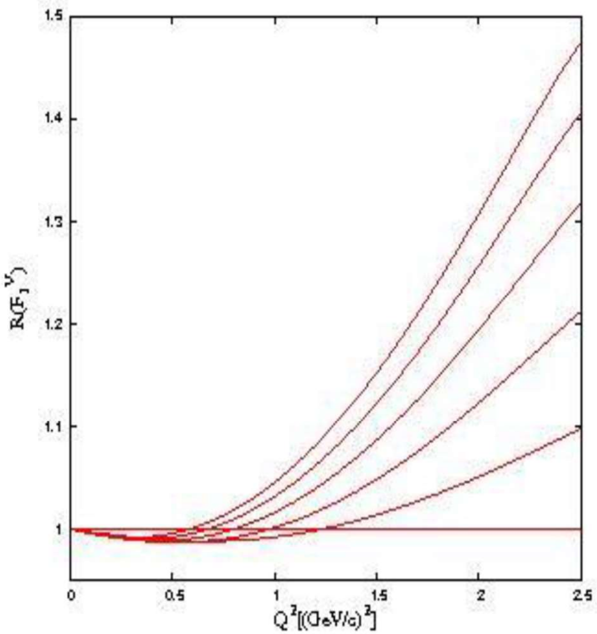
ρ (density): $0.5\rho_0$

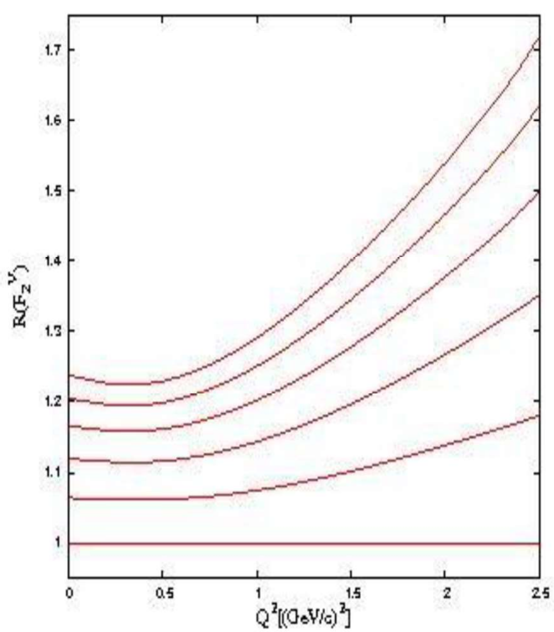
Increase bottom to top

F_2*/F_2 – Q^2 and

ρ (density): $0.5\rho_0$

Increase bottom to top





$\sigma(\bar{\nu}_e)$ – E and

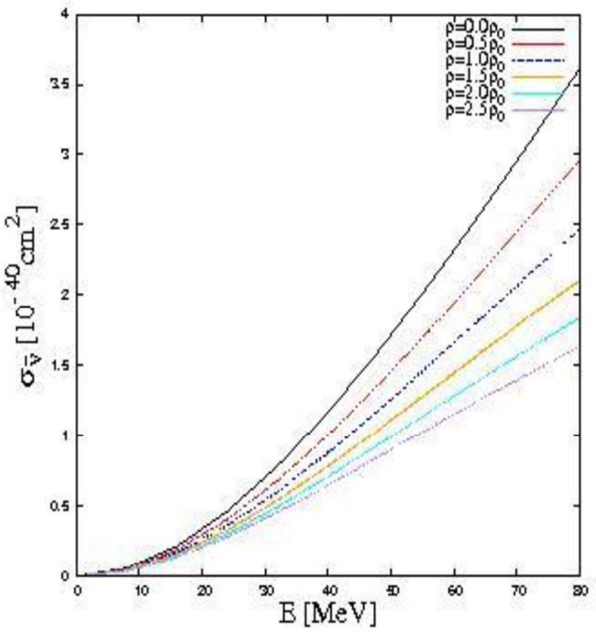
ρ (density): $0.5\rho_0$

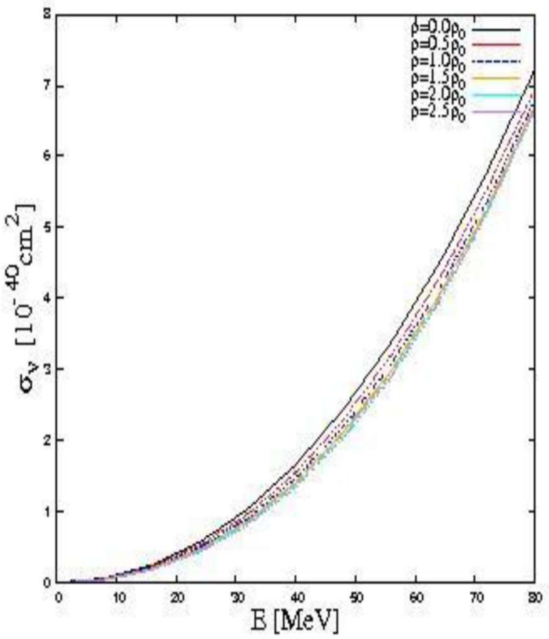
Increase top to bottom

$\sigma(\nu_e)$ – E and

ρ (density): $0.5\rho_0$

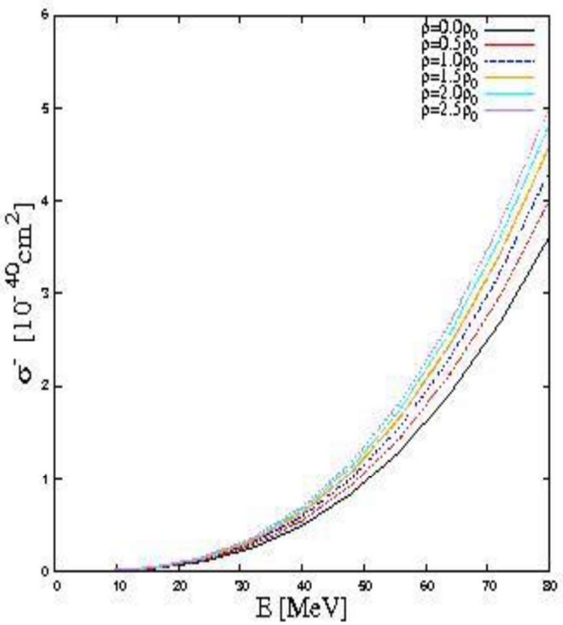
Increase top to bottom

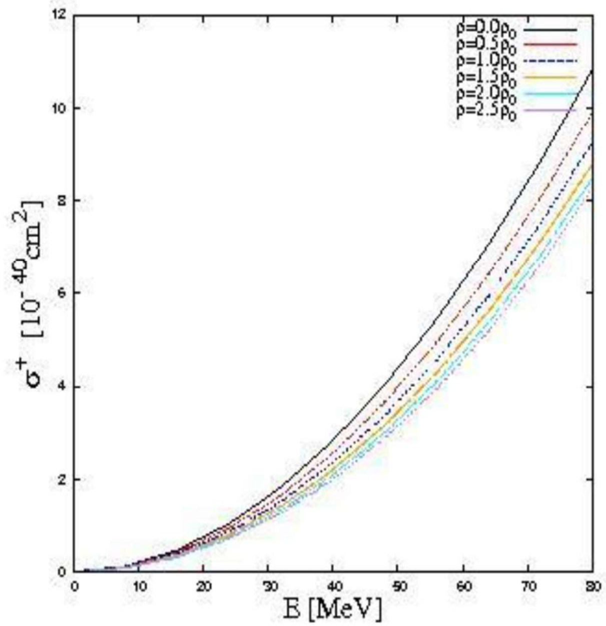




$\sigma(\nu_e) - \sigma(\bar{\nu}_e)$: **E and**
ρ (density): $0.5\rho_0$
Increase bottom to top

$\sigma(\nu_e) + \sigma(\bar{\nu}_e)$: **E and**
ρ (density): $0.5\rho_0$
Increase top to bottom





$^{12}C(\bar{\nu}_e, e^+)^{12}B_{g.s(1+)}$

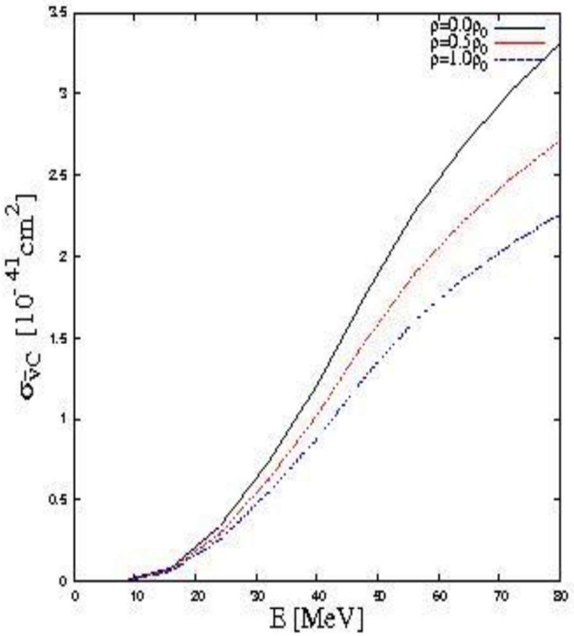
ρ/ρ_0: 0, 0.5, 1.0

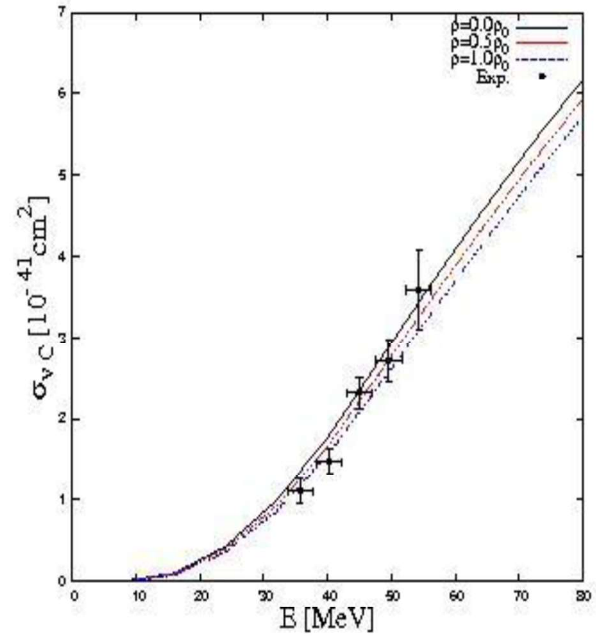
Increase top to bottom

$^{12}C(\nu_e, e^-)^{12}B_{g.s(1+)}$

ρ/ρ_0: 0, 0.5, 1.0

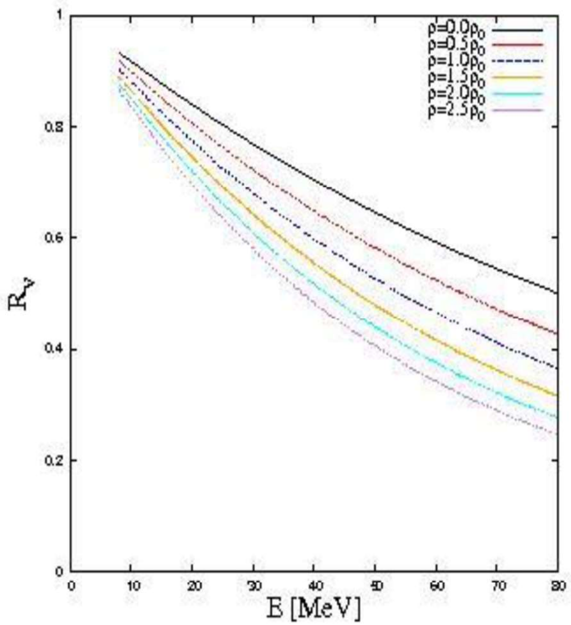
Increase top to bottom

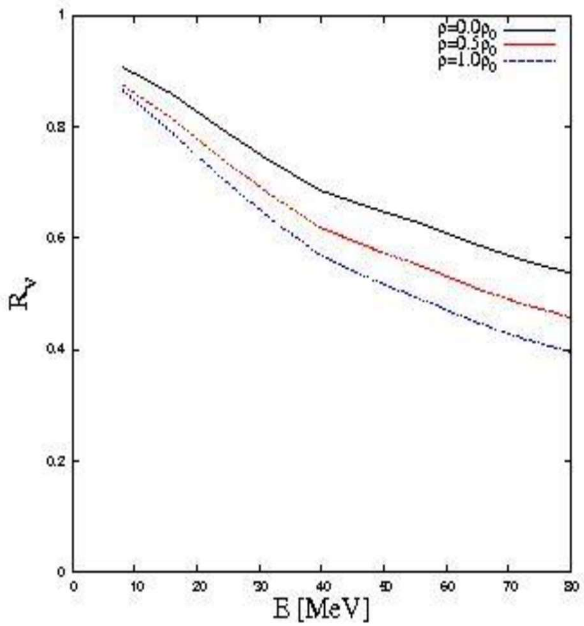




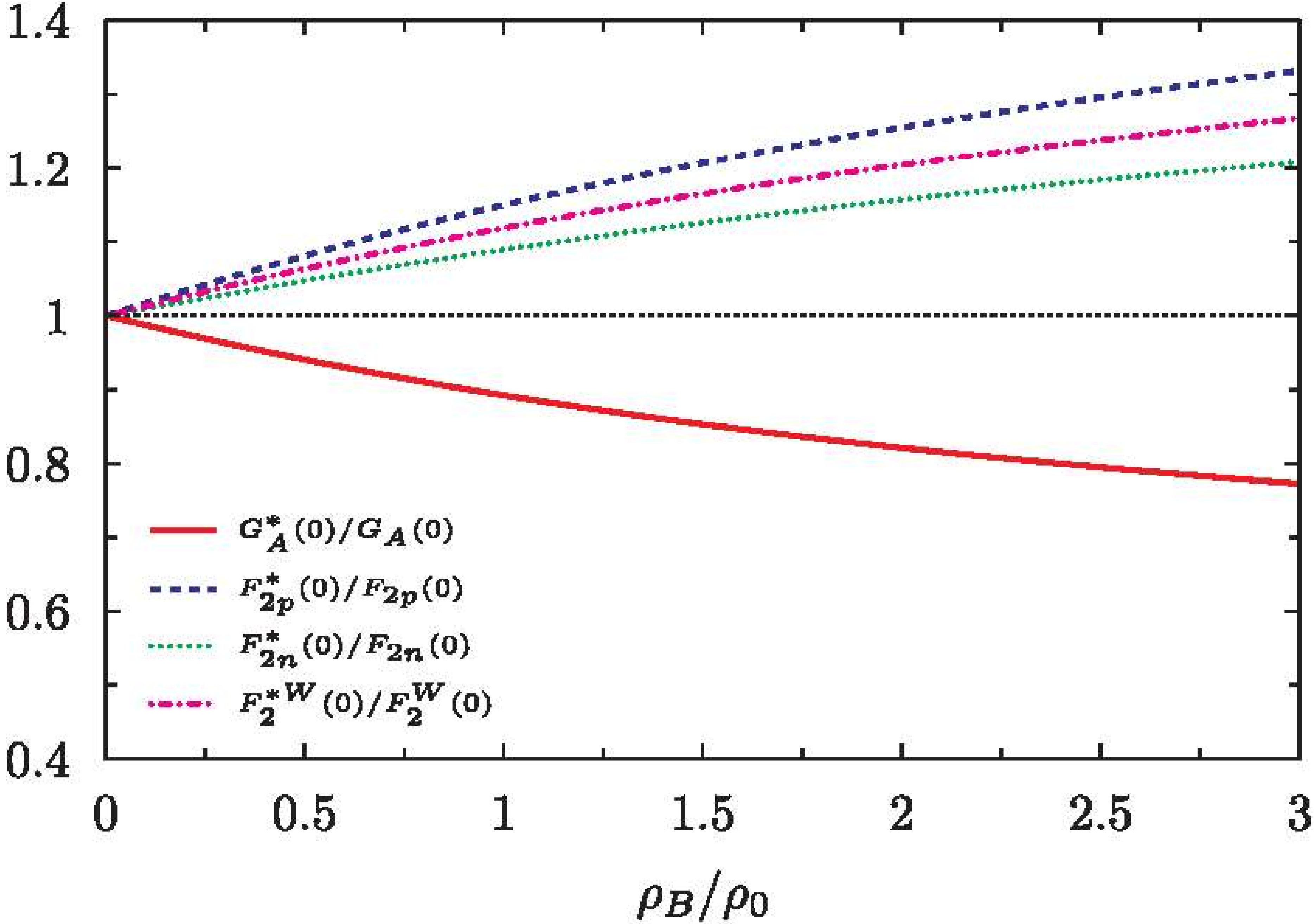
$\sigma(\bar{\nu}_e)/\sigma(\nu_e)$: E and
ρ (density): $0.5\rho_0$
Increase top to bottom

$\sigma(\bar{\nu}_e)/\sigma(\nu_e)$ in ^{12}C
E and ρ (density): $0.5\rho_0$
Increase top to bottom

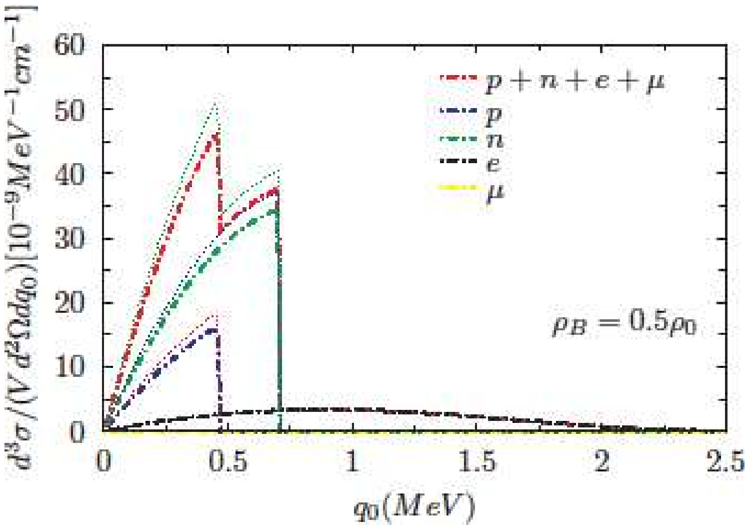


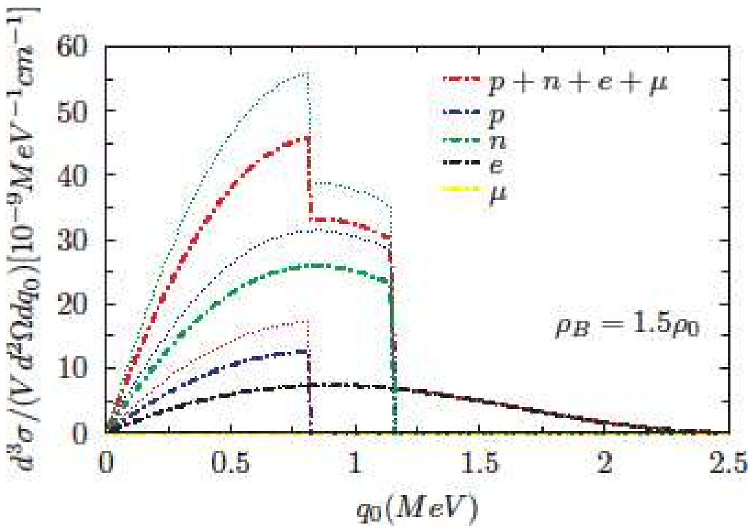


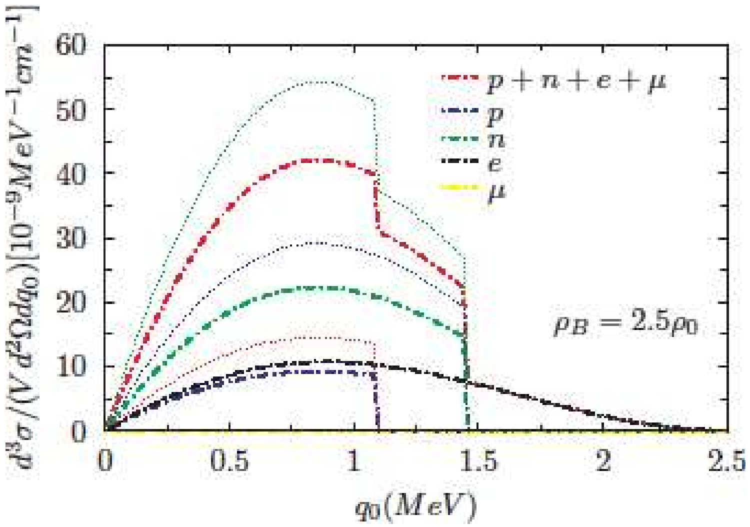
Neutrino Mean Free Path
Weak FFs. In medium (QMC)

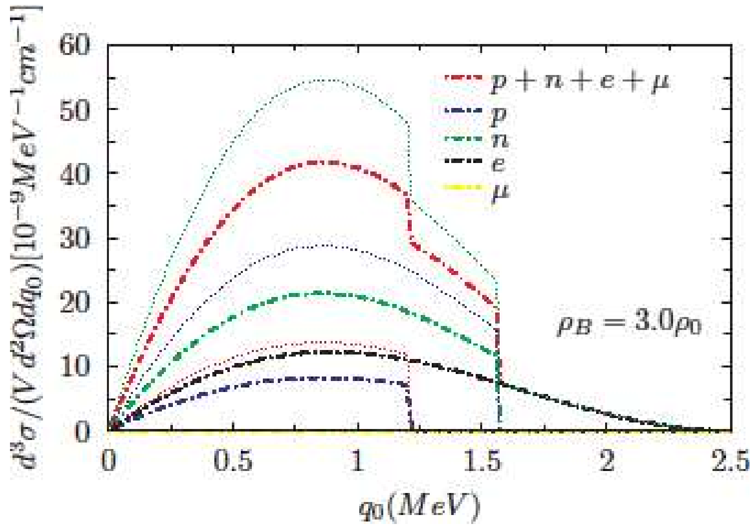


Neutrino Mean Free Path
Cross Sections

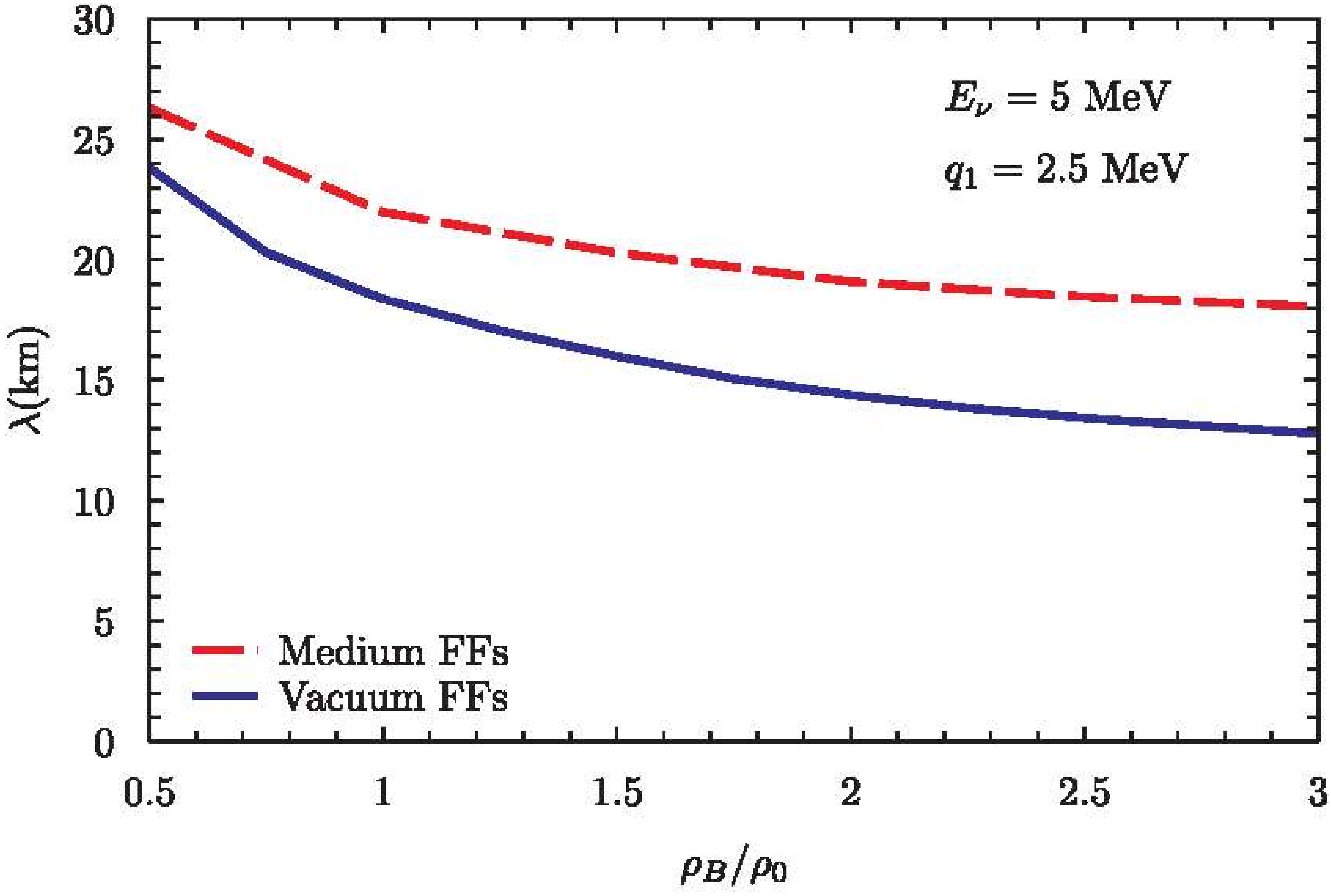








Neutrino Mean Free Path



Conclusions, Interests

Effects of density dependent FFs.

ν_e and $\bar{\nu}_e$ cross section asymmetry

Asymm. enhanced by the in-medium FFs.

Neutrino MFP increases 10 – 40 %

$\Rightarrow$ Neutron Star Cooling Enahnced !!

Pion, N, EMFFs and D.A. in medium

J.P.B.C. de Melo et al,

Phys.Rev. C90 (2014) no.3, 035201

Phys.Lett. B766 (2017) 125

Nucl.Phys. A970 (2018) 325 (W.R.B. Aráujo et al)

Medium effect on pion and N EMFFs

and pion Distribution Amplitude

with the Light Front Constituent Quark Model

Pion, N, properties in medium

Light-Front Coordinates

Four-Vector $\Longrightarrow$ $x^\mu = (x^0, x^1, x^2, x^3) \rightarrow (x^+, x^-, \vec{x}_\perp)$

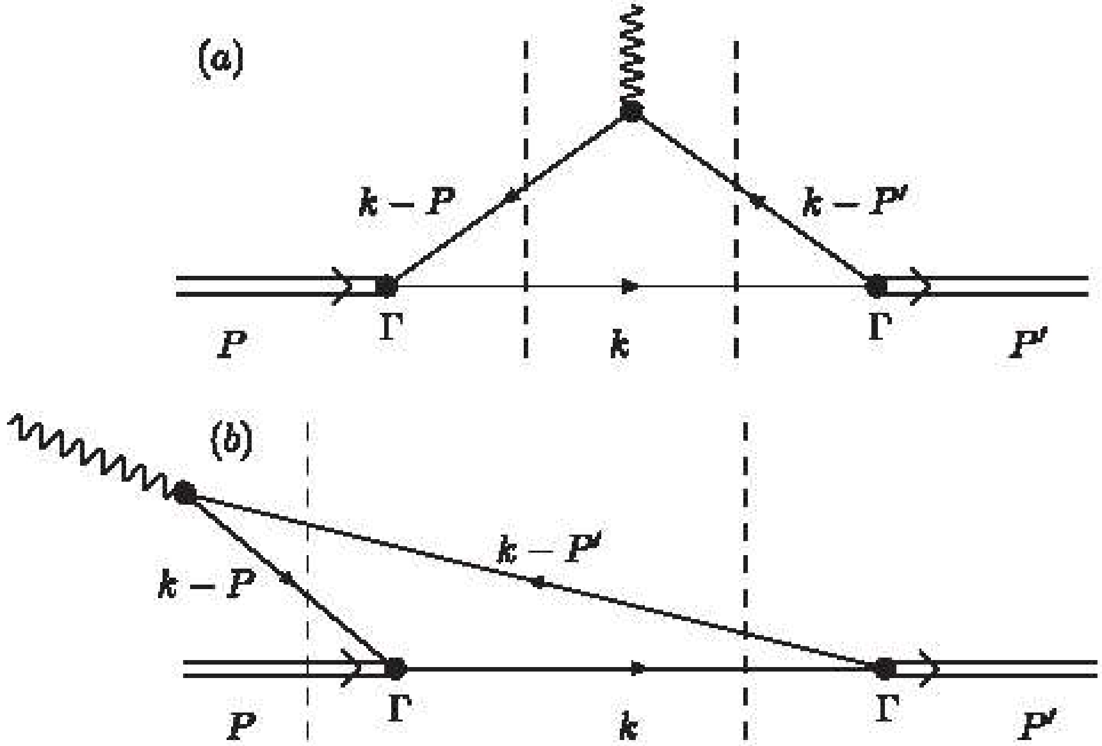
$x^+ = t + z$ $\quad x^+ = x^0 + x^3$ $\Longrightarrow$ Time

$x^- = t - z$ $\quad x^- = x^0 - x^3$ $\Longrightarrow$ Position

Metric Tensor and Scalar product

$$x \cdot y = x^\mu y_\mu = x^+ y_+ + x^- y_- + x^1 y_1 + x^2 y_2 = \frac{x^+ y^- + x^- y^+}{2} - \vec{x}_\perp \vec{y}_\perp$$

$p^+ = p^0 + p^3$, $p^- = p^0 - p^3$, $\vec{p}_\perp = (p^1, p^2)$



(a) ⇒ Valence Component of the Electromagnetic Current

(b) ⇒ Non-Valence Component of the Electromagnetic Current

Ref.: de Melo and Frederico, PRC (1997) , de Melo, Naus, Frederico and Sauer, PRC(1999)

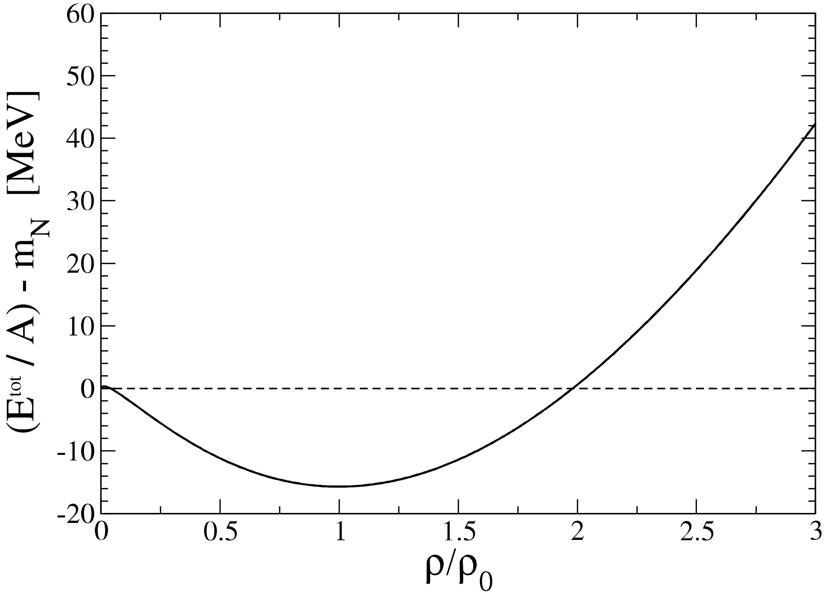
- **Motivation:** The present model works well (Symmetric Vertex)!

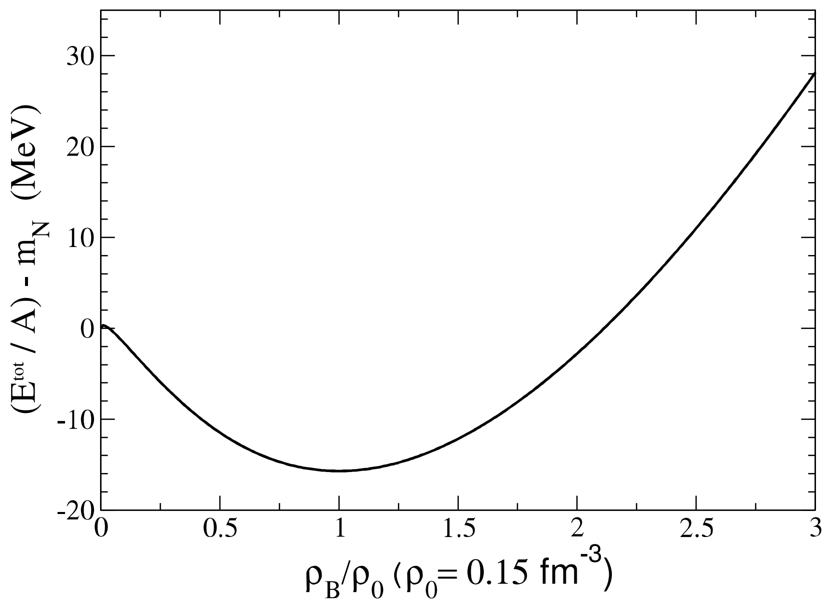
Observables: Decay constant and charge radius						
	f_{0^-} (MeV)	r_{0^-}	m_u (π^-)	m_d (π^+)	m_d (K^+)	$m_{\bar{s}}$ (K^+)
Pion	93.12	0.736	220	220		
	101.85	0.670	250	250		
Kaon	101.81	0.754			220	440
	113.74	0.687			250	440

m_R = 600 MeV, (all masses in MeV and radius in fm)
Ex.(Pion): $f_\pi = 92.4 \pm 0.021$ MeV, $r_\pi = 0.672 \pm 0.08$ fm (PDG)
Ex.(Kaon): $f_{k^+} = 110.38 \pm 0.1413$ MeV, $r_{k^+} = 0.560 \pm 0.031$ (PDG)

- Ref.: de Melo, Frederico, Pace and Salmè, NPA707, 399 (2002); ibid., Braz. J. Phys. 33, 301 (2003)
- Yabusaki, Ahmed, Paracha, de Melo, El-Bennich, PRD92 (2015) 034017.

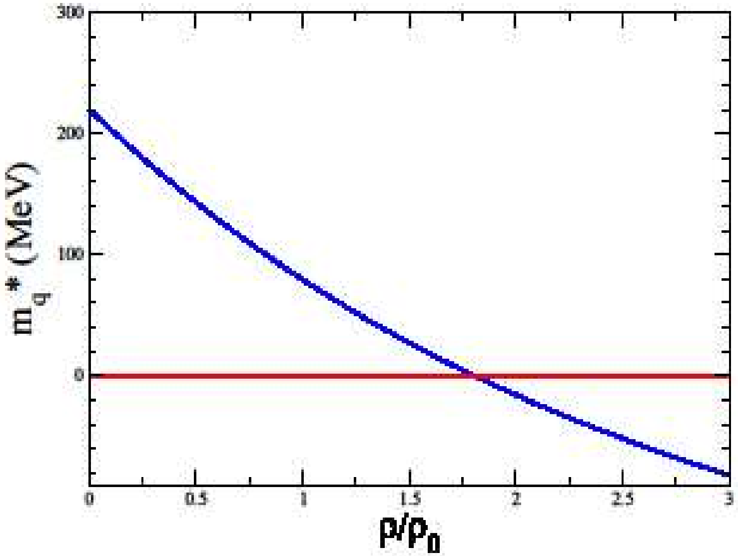
Comparison of Energy/nucleon

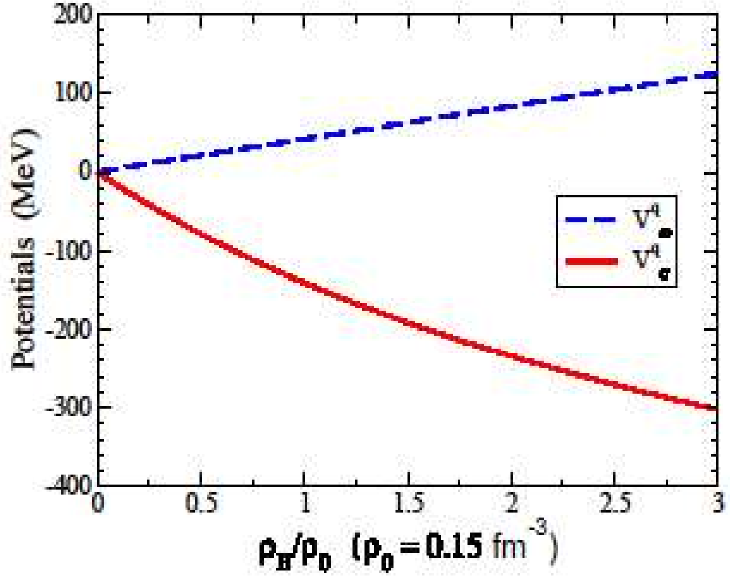




- Symmetric Nuclear Matter - Binding Energy per Nucleon (scale !!)
- LF pion model (left): $m_q = 220$ MeV, $K = 320.9$ MeV
- Standard QMC (right): $m_q = 5$ MeV, $K = 279.3$, MeV

Standard QMC and Pion: m_q^* (potentials)





- Effective mass of constituent quarks, up and down
- Pion, Nucleon: $m_q = 220$ MeV (left)
- Standard QMC $m_q = 5$ MeV (right)

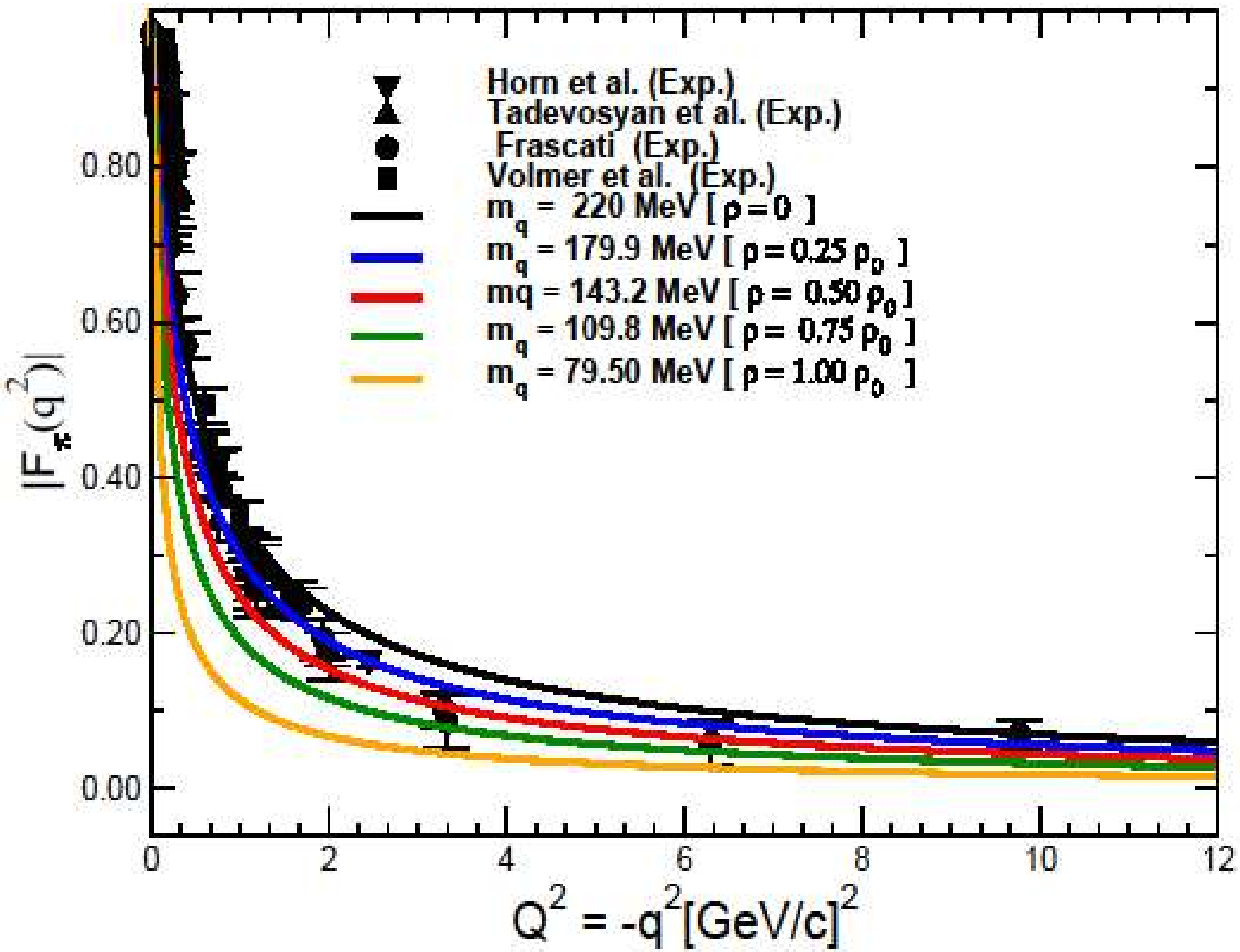
Valence Light-front wave function in Medium (Symm. Nuclear Matter)

$$\Phi^*(k^+,\vec{k}_\perp;P^+,\vec{P}_\perp) = \frac{P^+}{m_\pi^{*2} - M_0^2} \left[\frac{N^*}{(1-x)(m_\pi^{*2} - \mathcal{M}^2(m_q^{*2}, m_R^2))} + \frac{N^*}{x(m_\pi^{*2} - \mathcal{M}^2(m_R^2, m_q^{*2}))} \right]$$

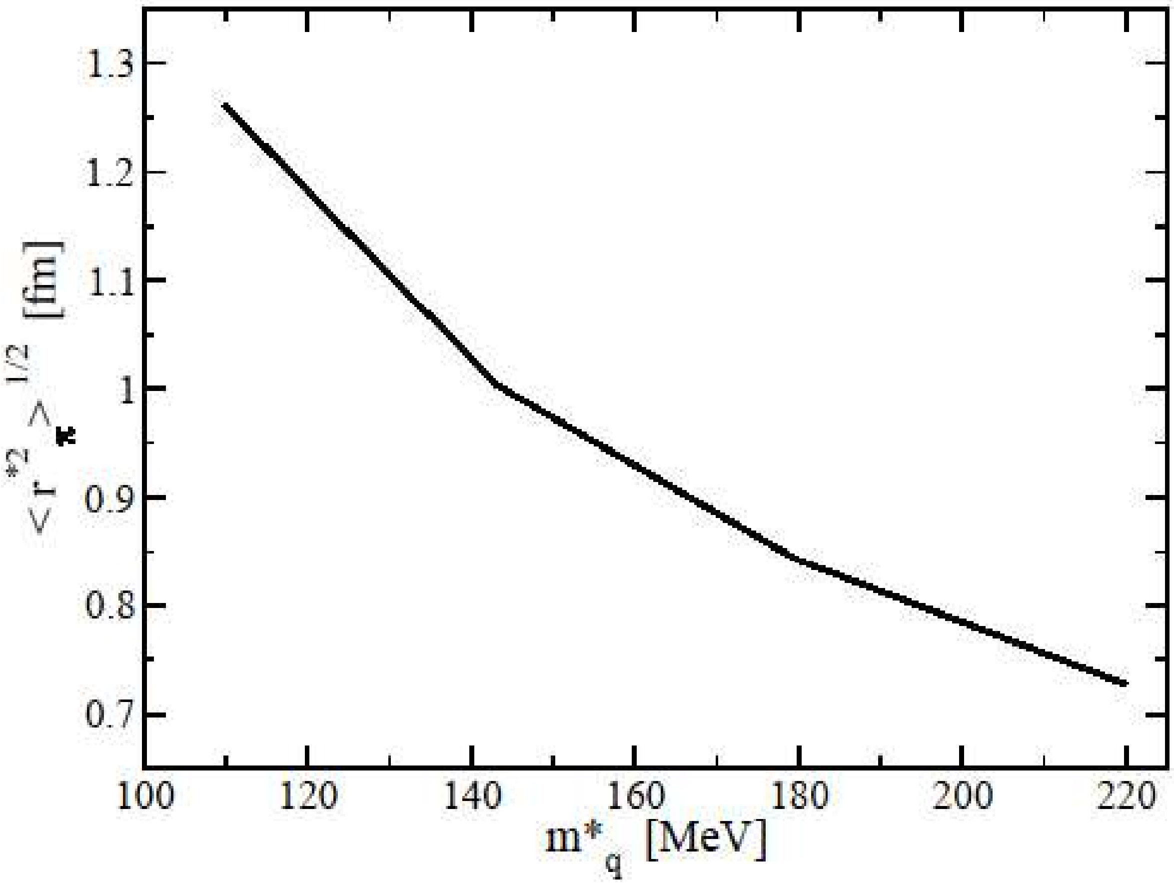
- $x = k^+/P^+$, with $0 \leq x \leq 1$, $m_\pi^* \simeq m_\pi$
- $\mathcal{M}^2(m_a^2, m_b^2) = \frac{k_\perp^2 + m_a^2}{x} + \frac{(P-k)_\perp^2 + m_b^2}{1-x} - P_\perp^2$
- **Free Square Mass operador:** $M_0^2 = \mathcal{M}^2(m_q^{*2}, m_q^{*2})$.

Pion properties in medium. η^* is the probability of the valence component in the pion. ($\rho_0 = 0.15$ fm^{-3})

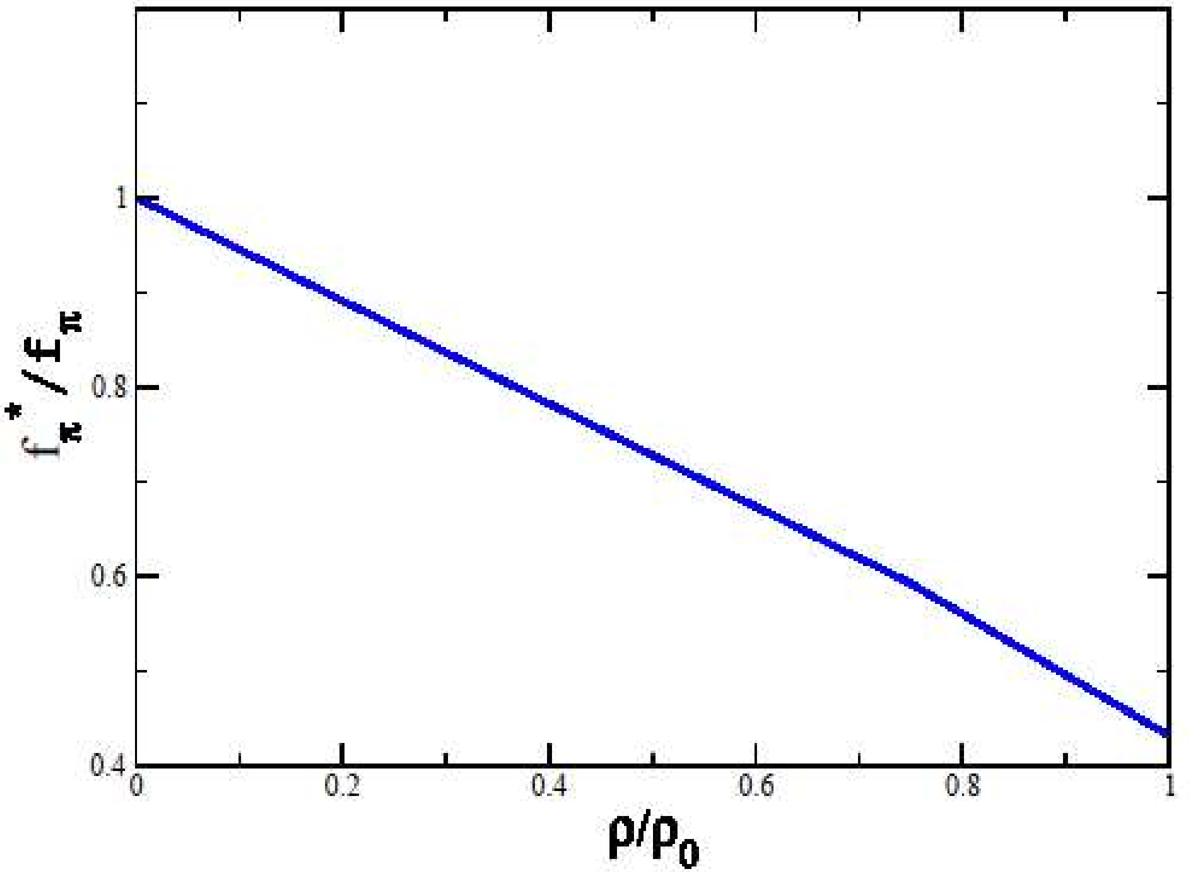
ρ/ρ_0	m_q^* [MeV]	f_π^* [MeV]	$< r_\pi^{*2} >^{1/2}$ [fm]	η^*
0.00	220	93.1	0.73	0.782
0.25	179.9	80.6	0.84	0.812
0.50	143.2	68.0	1.00	0.843
0.75	109.8	55.1	1.26	0.878
1.00	79.5	40.2	1.96	0.930



- **Exp. Data (in Vacuum!!)**



- **Pion Electromagnetic Radius**



- **Pion Decay Constant**

Distribution Amplitude (normalized with f_{ps} !!!)

Def.: DAs

$$\phi_{DA}(x) = \int \frac{d^2k_\perp}{(16\pi^3)} \Psi_{ps}(x, \vec{k}_\perp)$$

$$\int_0^1 dx \int \frac{d^2k_\perp}{16\pi^3} \Psi_{ps}(x, \vec{k}_\perp) = \frac{f_{ps}}{2\sqrt{6}}$$

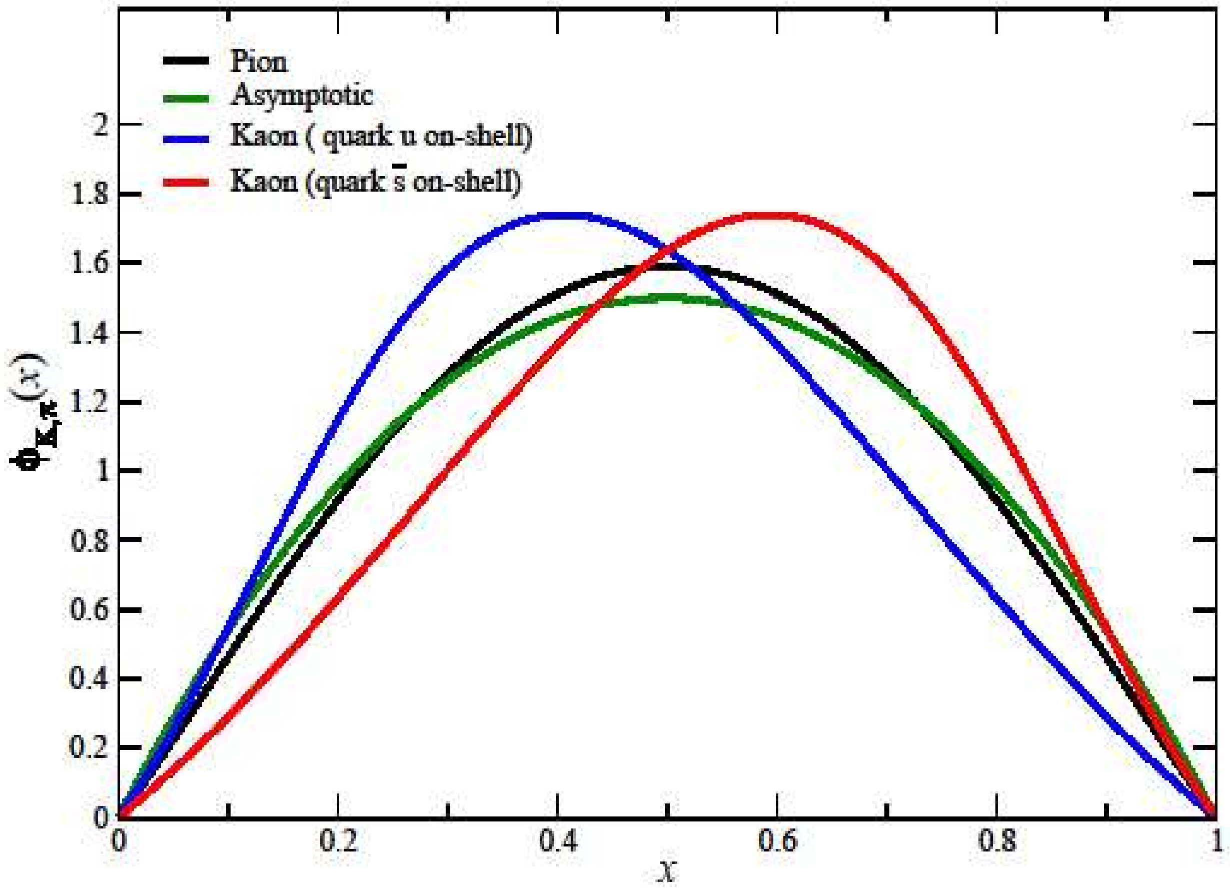
Def.: NDA (normalized to unity)

$$\phi(x) = \frac{2\sqrt{6}}{f_{ps}} \int \frac{d^2k_\perp}{(16\pi^3)} \Psi_{ps}(x, \vec{k}_\perp) \ .$$

- **Pion Asymptotic**

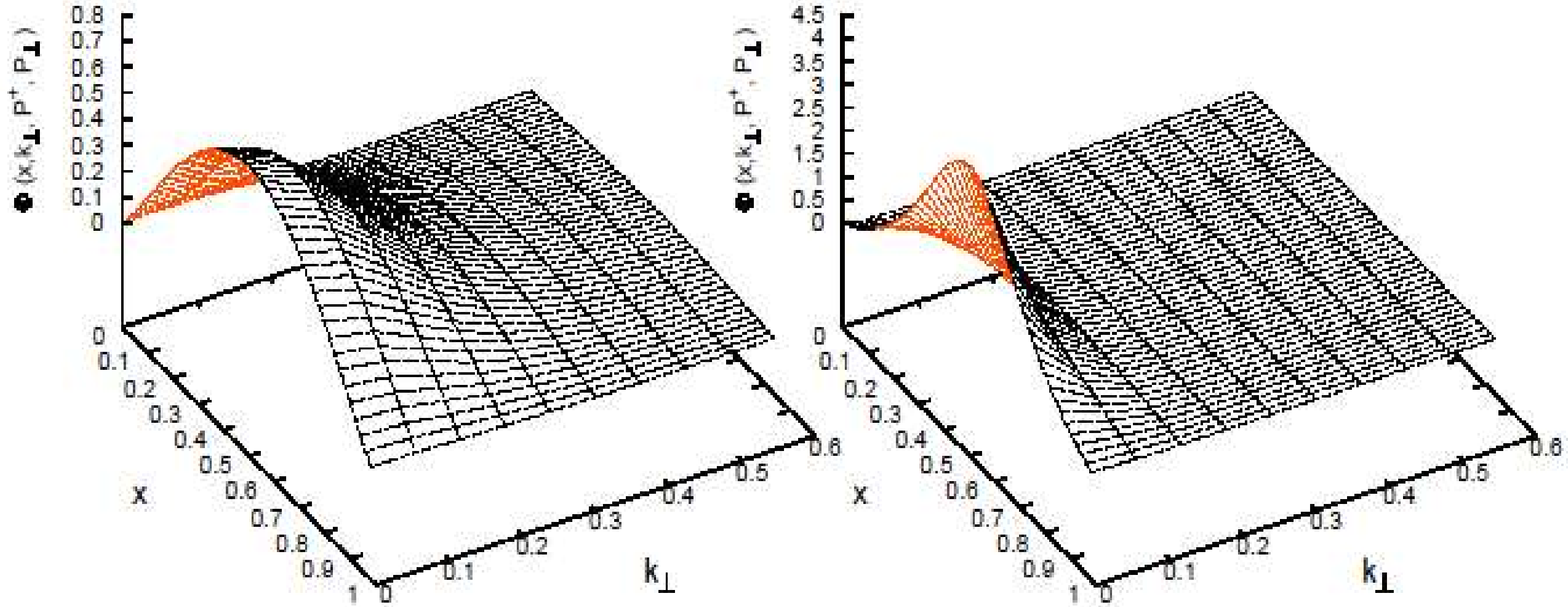
$$\phi_\pi^{as}(x, \mu^2) \propto 6x(1-x)$$

NDAs vacuum

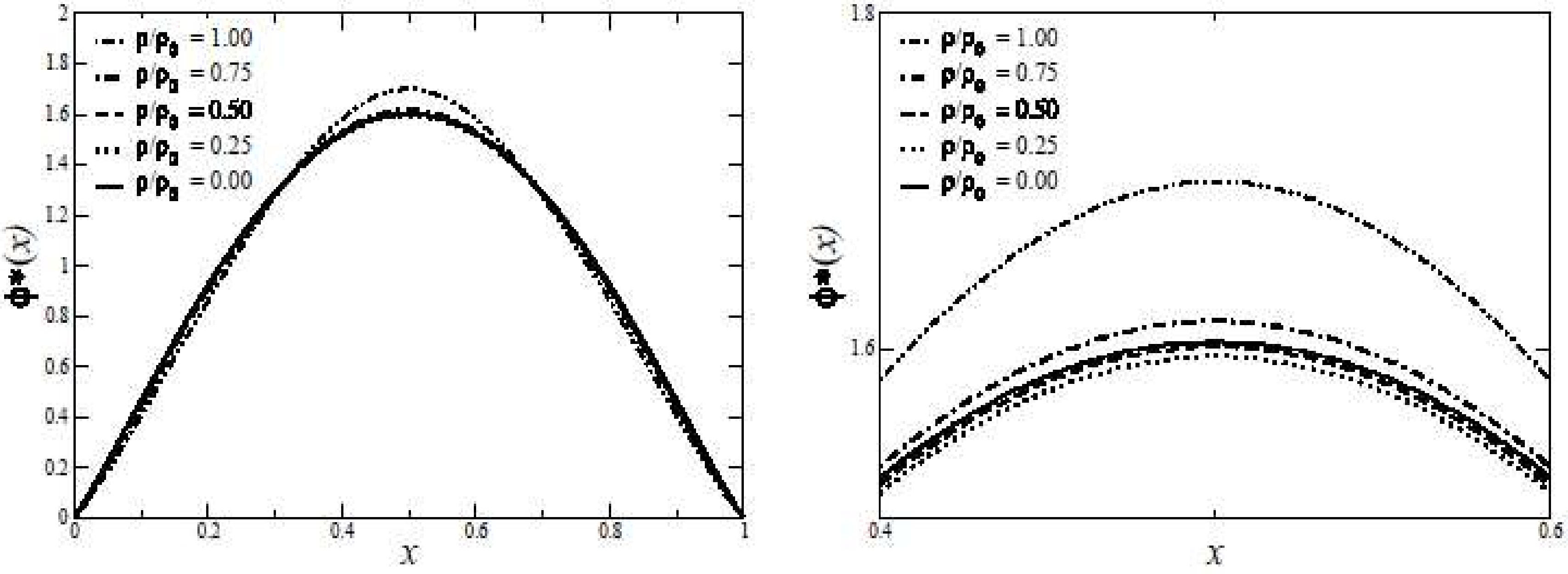

Pion
Asymptotic
Kaon (quark u on-shell)
Kaon (quark $\bar{s}$ on-shell)
$\phi_{K,\pi}(x)$
x
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

Pion (Valence) W. Func.: Vacuum (left) ρ_0 (right)

$f_\pi^*/2\sqrt{6}$ normalization



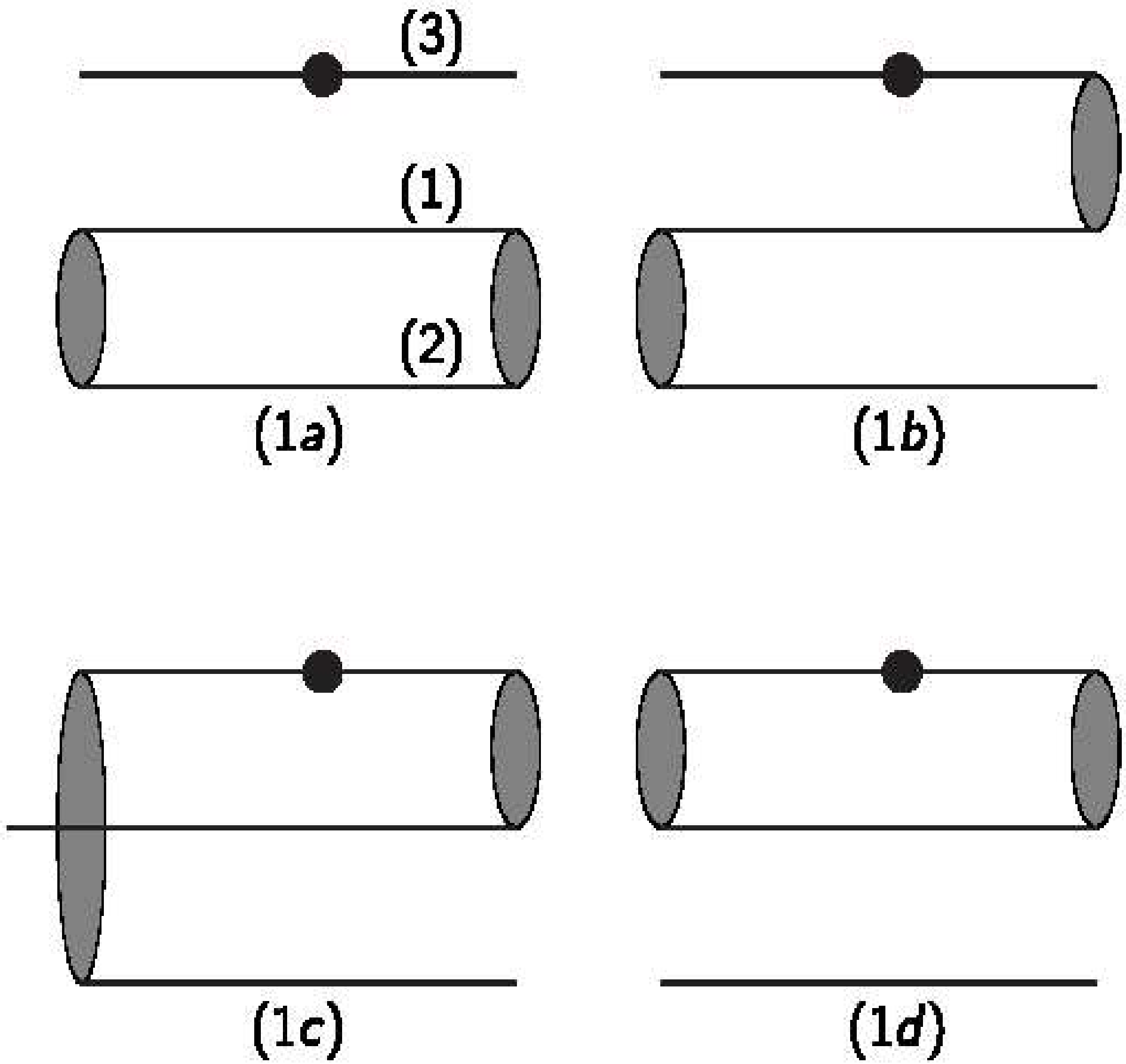
In-Medium NDA



In-Medium Nucleon EMFFs in LF spin-coupling model

- W.R.B. de Aráujo et al.,
  Nucl. Phys. A970 (2018) 325
  Eur.Phys.J. A29 (2006) 227
  Phys.Lett. B478 (2000) 86

Nucleon EM form factors



N wave function, EM form factors

$$\mathcal{L}_{\mathrm{N-3q}} = m_N \epsilon^{lmn} \overline{\Psi}_{(l)} i\tau_2\gamma_5 \Psi^C_{(m)} \overline{\Psi}_{(n)} \Psi_N + H.C.$$

$$\Psi_{\mathrm{Power}} = N_{\mathrm{Power}} \left[(1 + M_0^2/\beta^2)^{-p} + \lambda (1 + M_0^2/\beta_1^2)^{-p} \right]$$

$$\lambda = \left[(1 + M_H^2/\beta_1^2)/(1 + M_H^2/\beta^2) \right]^p$$

$$F_{1N}(Q^2) = \frac{1}{\sqrt{1+\eta}} \langle N \uparrow | J_N^+(Q^2) | N \uparrow \rangle$$

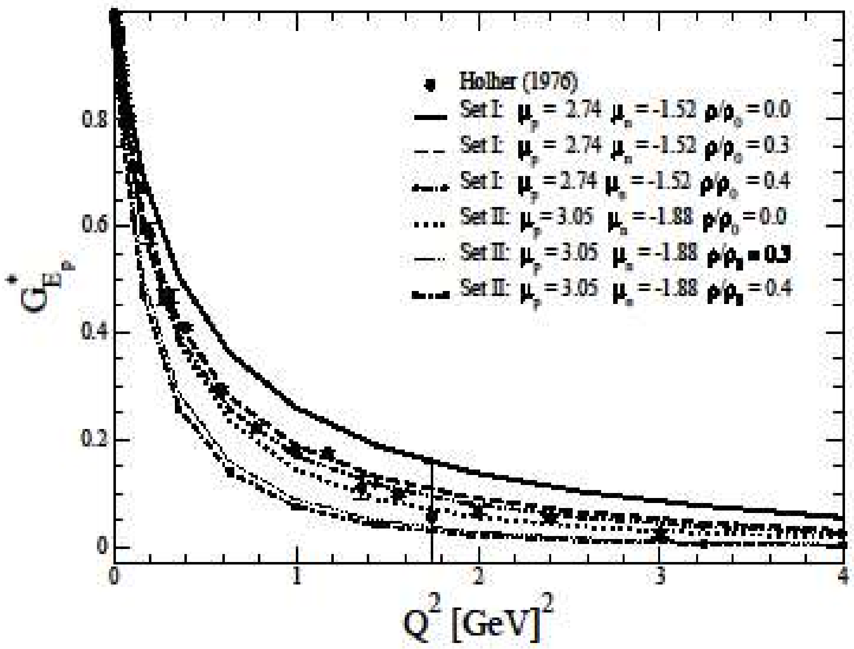
$$F_{2N}(Q^2) = \frac{1}{\sqrt{\eta}\sqrt{1+\eta}} \langle N \uparrow | J_N^+(Q^2) | N \downarrow \rangle$$

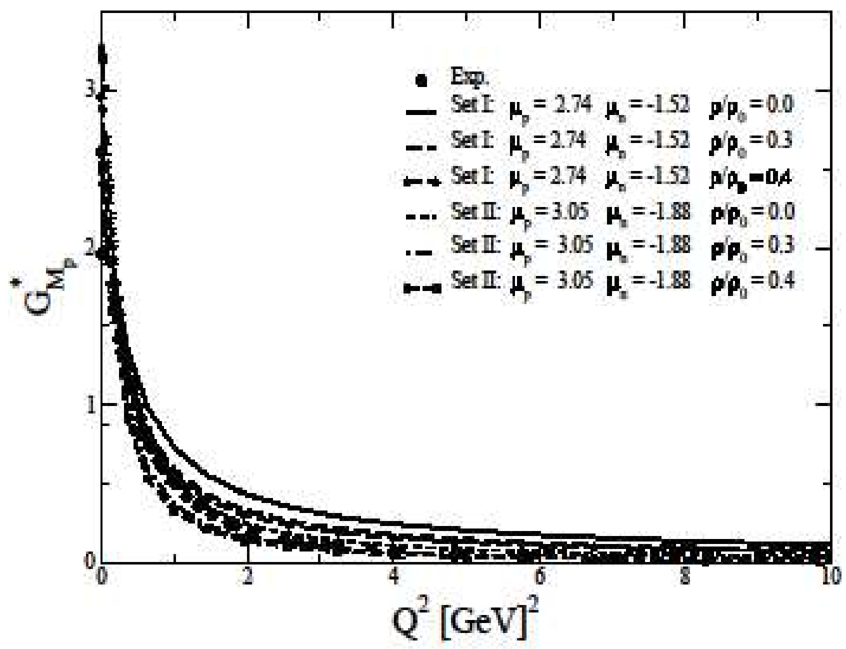
$$G_{EN}(Q^2) = F_{1N}(Q^2) - \frac{Q^2}{4m_N^2} F_{2N}(Q^2)$$

$$G_{MN}(Q^2) = F_{1N}(Q^2) + F_{2N}(Q^2$$

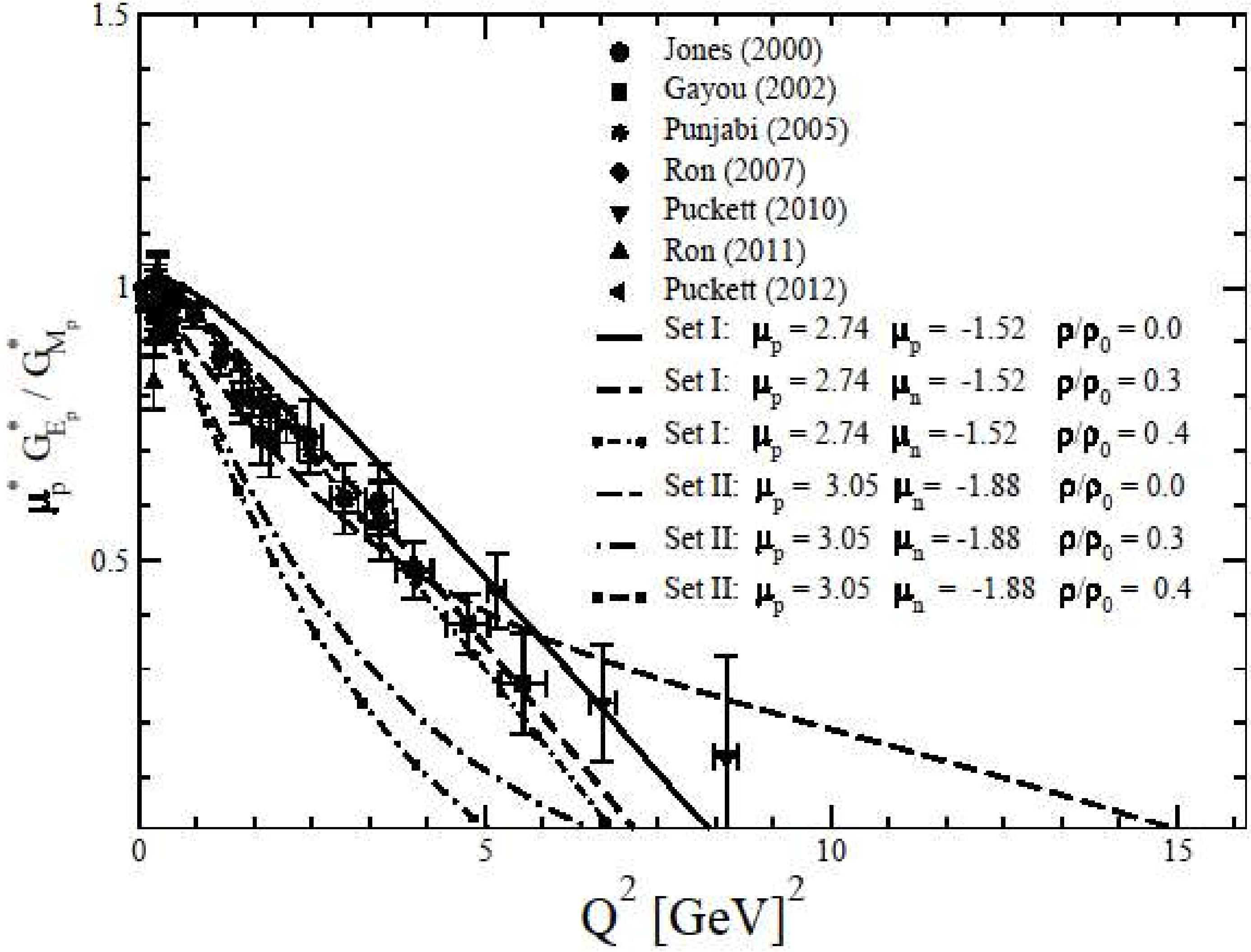
$$\eta = -q^2/4m_\rho^2 = Q^2/4m_\rho^2$$

Proton EM form factors in medium

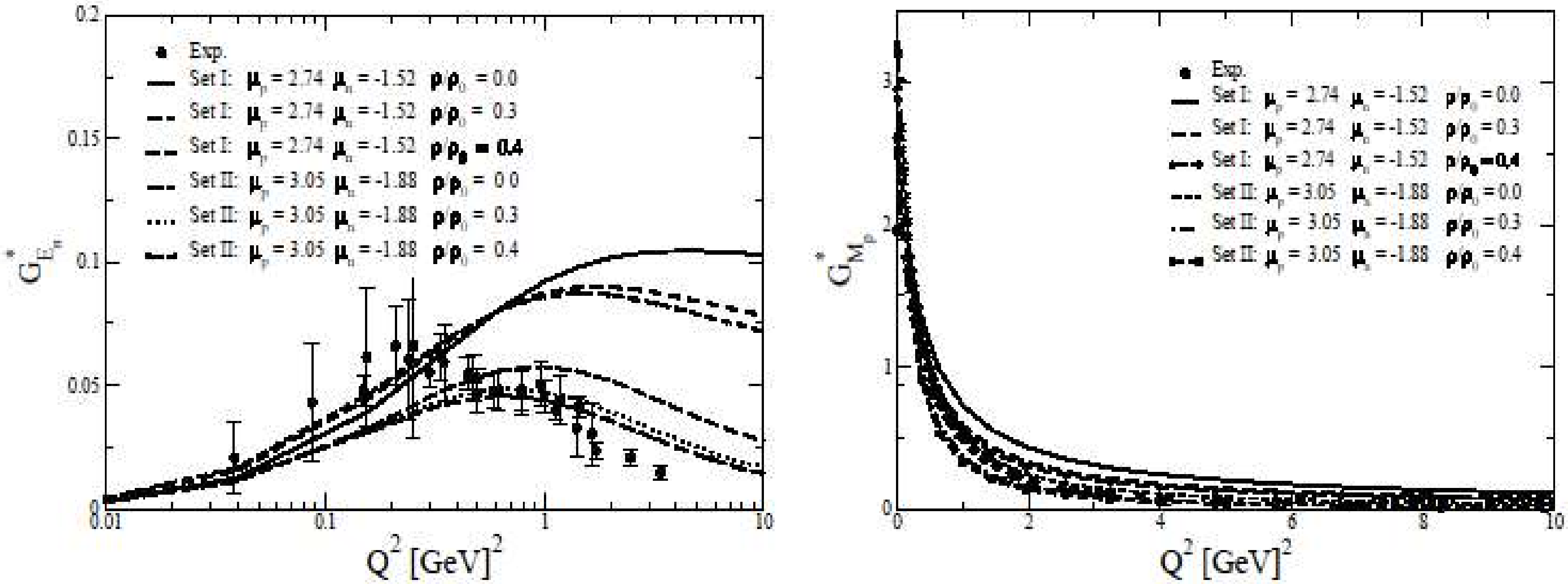




Proton EM form factor ratio in medium

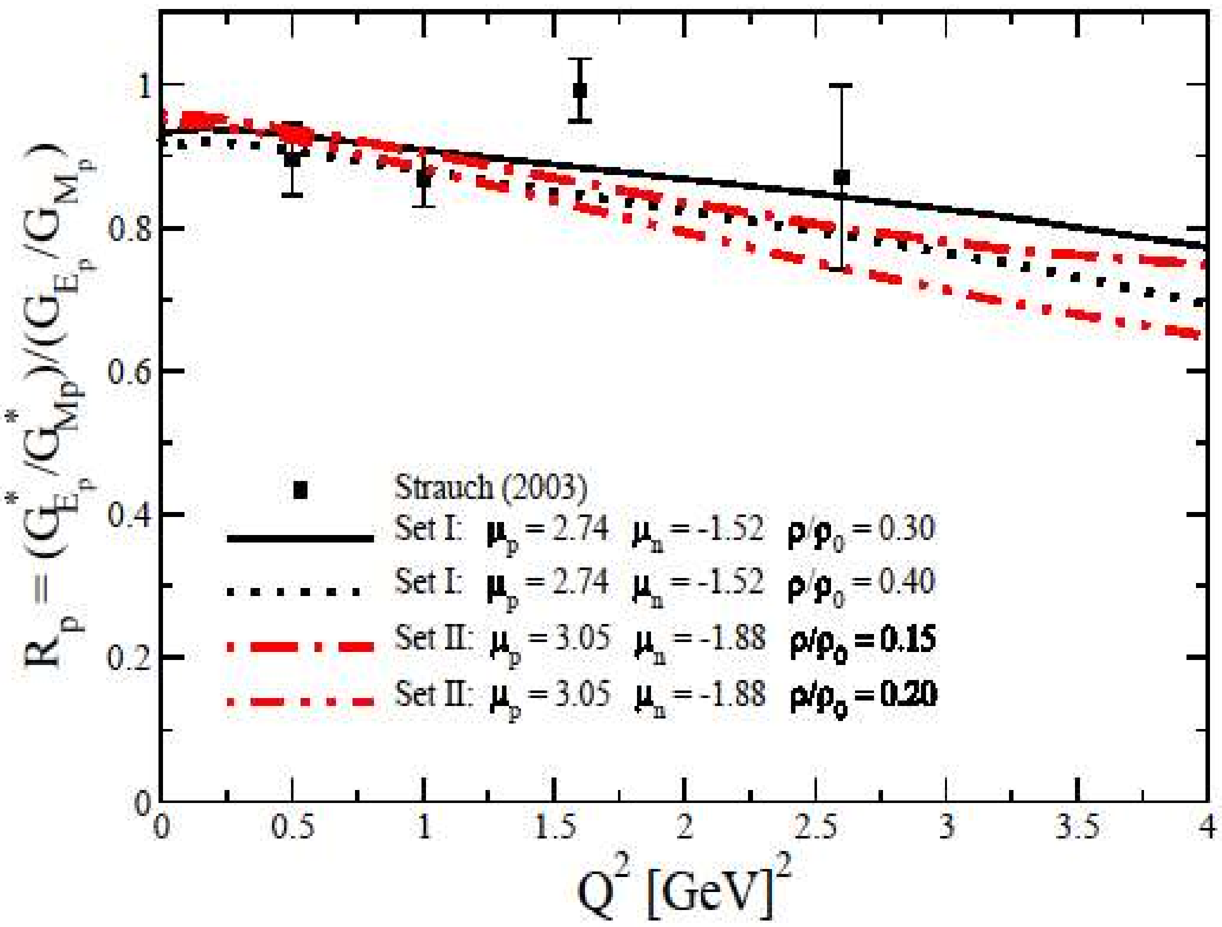


Neutron EM form factors in medium

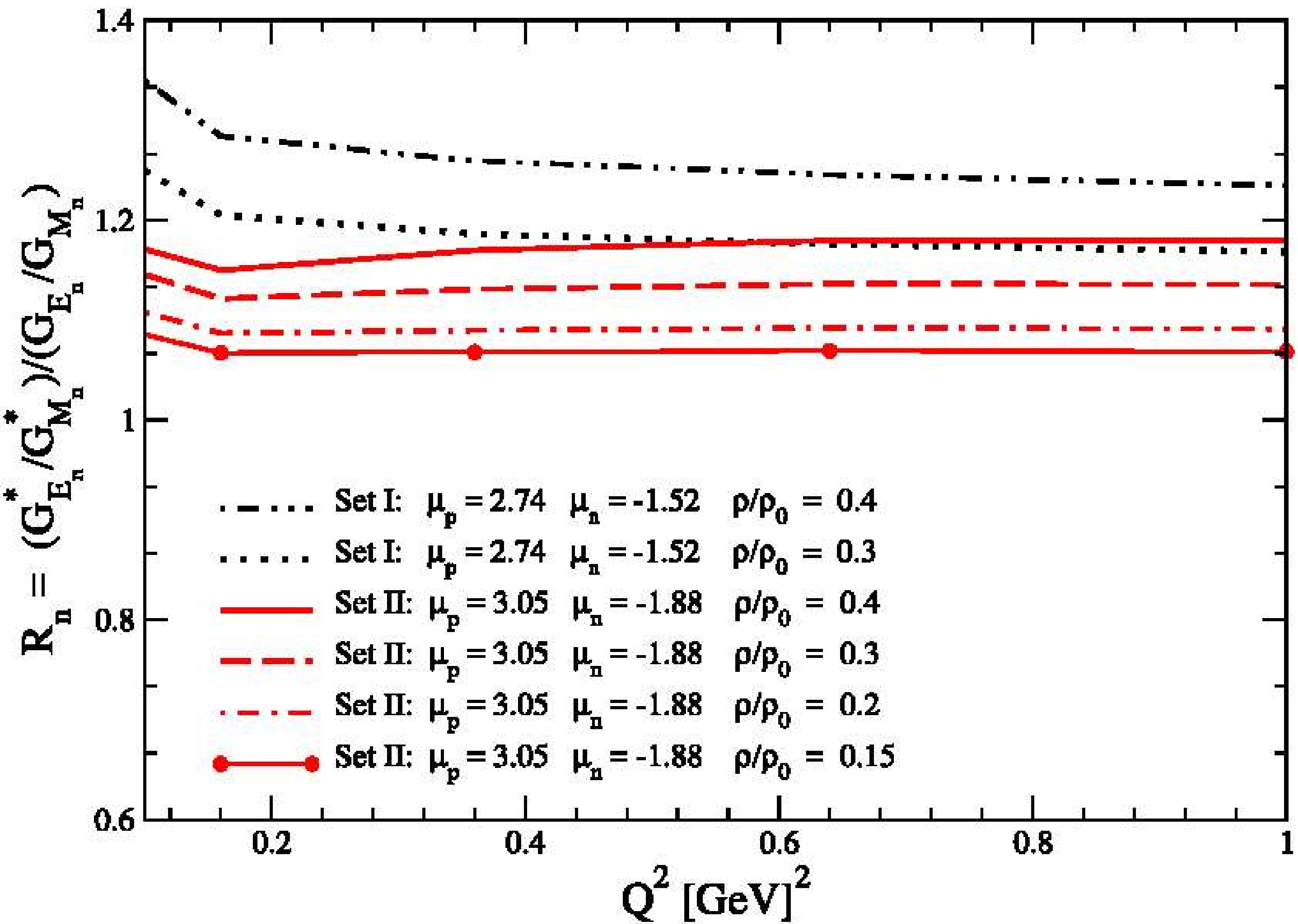


JLab data: double ratio (in medium)

$[G_{Ep}^{^4\mathrm{He}}(Q^2)/G_{Mp}^{^4\mathrm{He}}(Q^2)]/[G_{Ep}^{^1\mathrm{H}}(Q^2)/G_{Mp}^{^1\mathrm{H}}(Q^2)]$



Neutron EMFFs double ratio !!



Bound Nucleon GPDs and Incoherent DVCS

V. Guzey, A.W. Thomas, KT

Phys. Lett. B 673, 9 (2009)

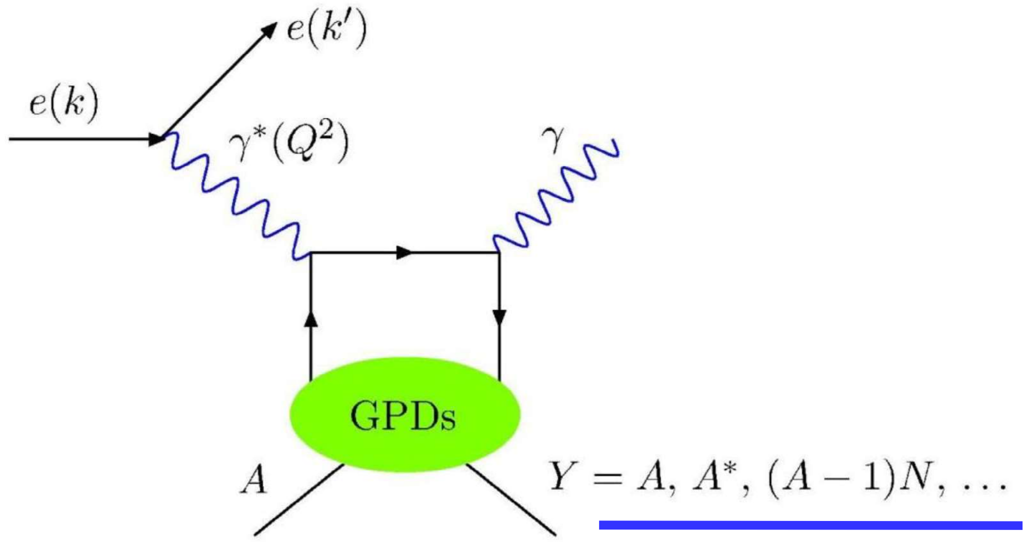
Phys. Rev. C 79, 055205 (2009)

Medium effect on **G**eneralized **P**arton **D**istributions and **D**eeply **V**irtual **C**ompton **S**cattering

on a ^{4}He nucleus

Introduction

eply Virtual Compton ıttering (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.

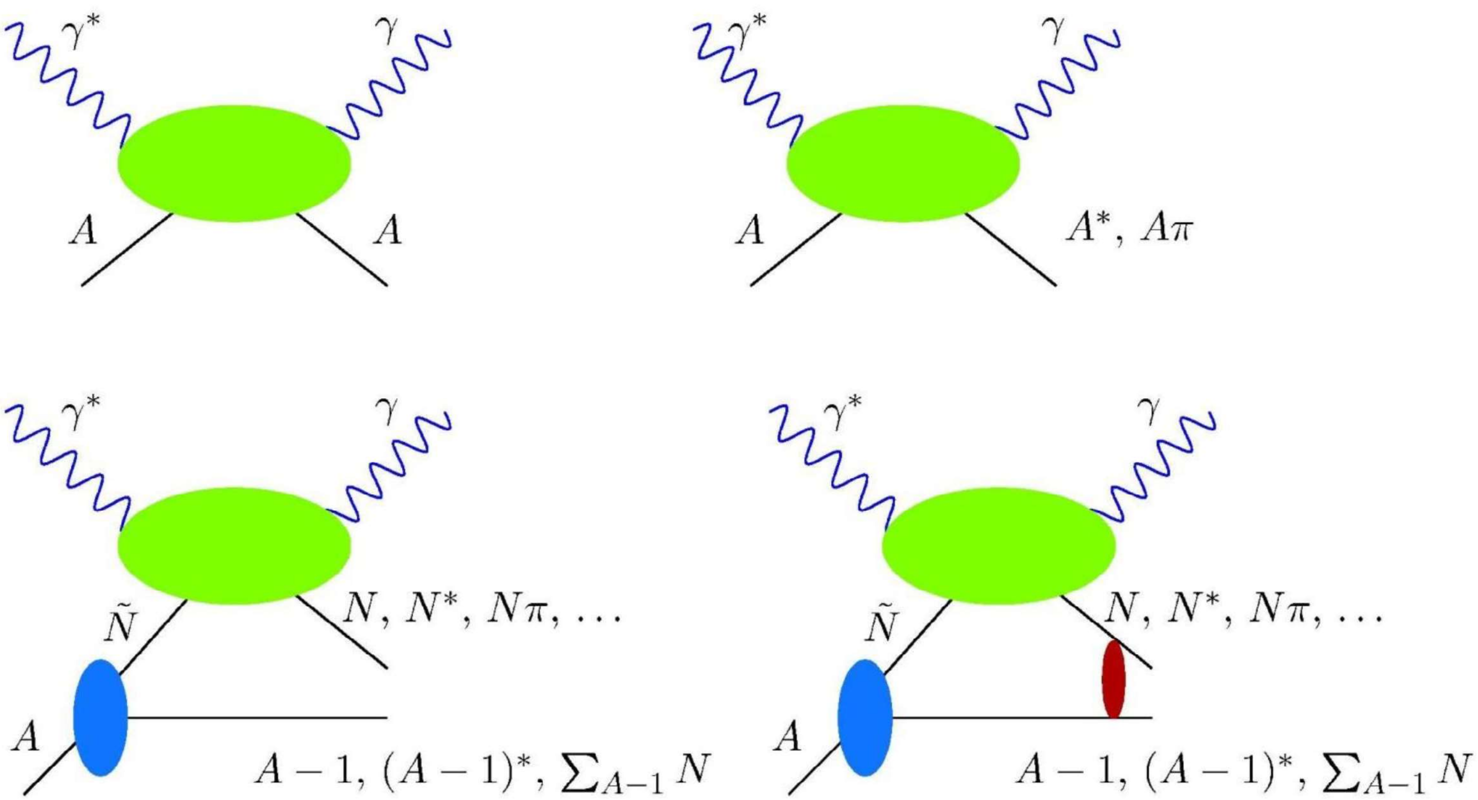
The GPDs generalize and interpolate between form factors and structure functions and encode information on 3D distributions of quarks and gluons in the target.

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

any more final states can be excited

e 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 ($\gamma_L^* + {}^3$He$\to \pi^0 + {}^3$He) or proton ($\gamma_L^* + {}^3$He$\to \pi^+ + {}^3$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 ıclear 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)

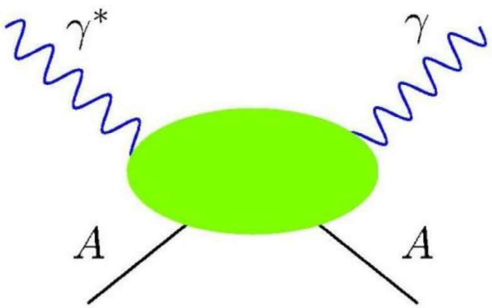
/ill put stringent constaints on theoretical models of the nuclear structure: ›variant description is more important than for nuclear DIS and nuclear form ctors

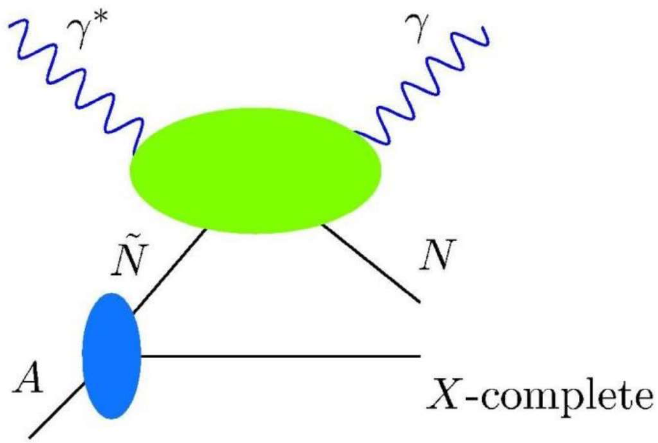
t high energies, nuclear DVCS is more sensitive to the physics of high parton ensities and the parton saturation than inclusive scattering

.V.T. Machado, arXiv:0810.3665 [hep-ph]

Incoherent and coherent nuclear DVCS

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





:oherent 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
ierent contributions are present.

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

onic 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:

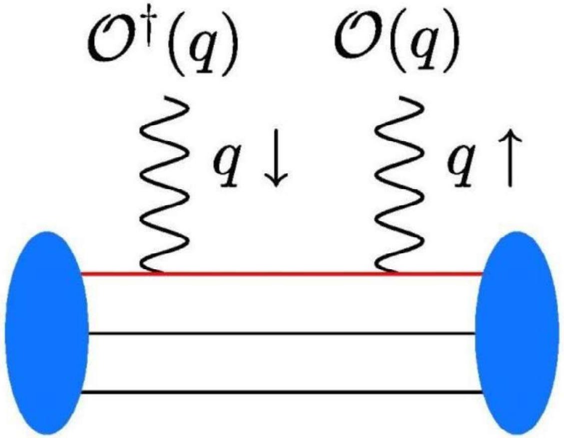
$$\text{CS}|^2 \propto \langle A|\mathcal{O}^\dagger(q)|X\rangle\langle X|\mathcal{O}(q)|A\rangle = \langle A|\mathcal{O}^\dagger(q)\mathcal{O}(q)|A\rangle$$

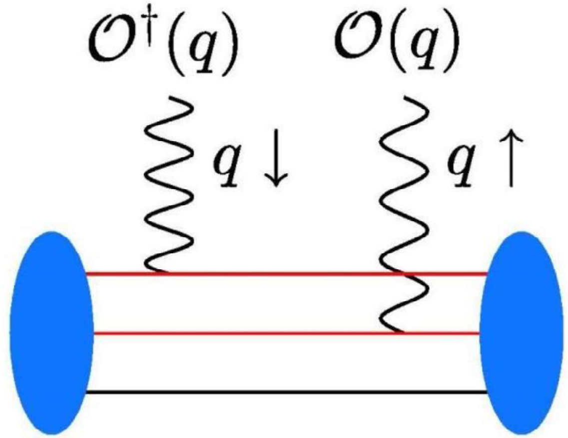
$$= \sum_{i,j}\langle A|N_i\rangle\langle N_i|\mathcal{O}^\dagger(q)\mathcal{O}(q)|N_j\rangle\langle N_j|A\rangle$$

$$= \sum_i |\langle A|N_i\rangle|^2\langle N_i|\mathcal{O}^\dagger(q)\mathcal{O}(q)|N_i\rangle + \sum_{i\neq j}\langle A|N_i\rangle\langle N_i|\mathcal{O}^\dagger(q)\mathcal{O}(q)|N_j\rangle\langle N_j|A\rangle$$

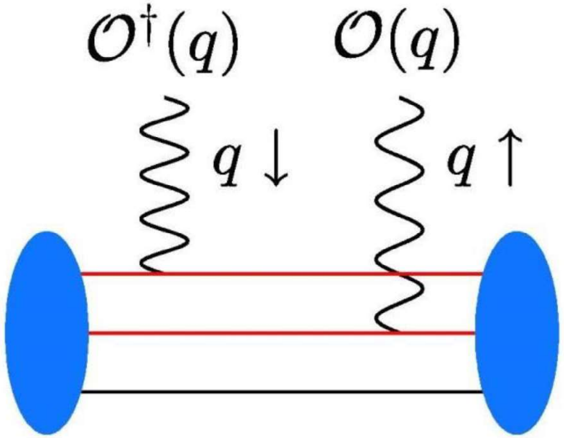
$$= A|\mathcal{T}^N_{\rm DVCS}|^2 + A(A-1)F^2_A(t' = A/(A-1)t)|\mathcal{T}^{A,\text{coh.enr.}}_{\rm DVCS}|^2$$

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

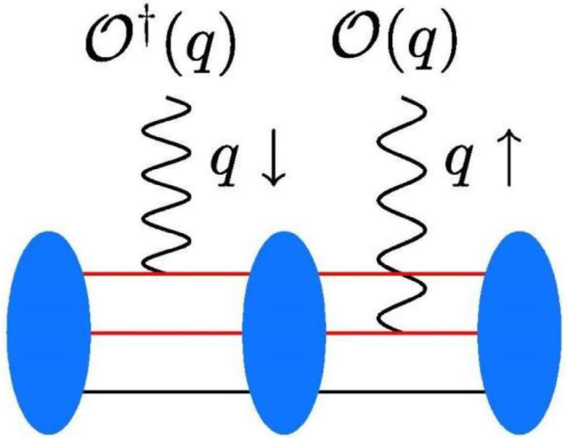




the difference between the coherent-enriched and purely coherent contributions



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



$A^2F_A^2(t)$

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:

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

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

$$A|\mathcal{T}_{\rm DVCS}^{N}|^2 = Z|\mathcal{T}_{\rm DVCS}^{p}|^2 + N|\mathcal{T}_{\rm DVCS}^{n}|^2$$

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

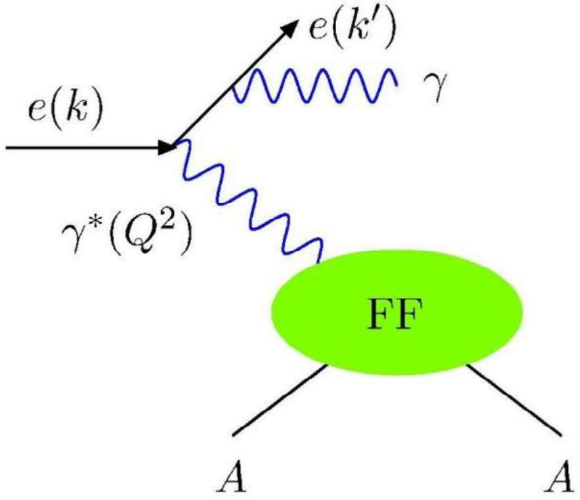
S cross section at the photon level (keeping only the GPD H):

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

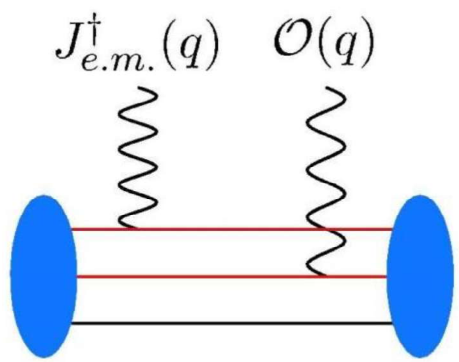
S beam-spin asymmetry $A_{LU}(\phi)$:

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

e-Heitler process



"Counting" for coherent-enriched interference



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

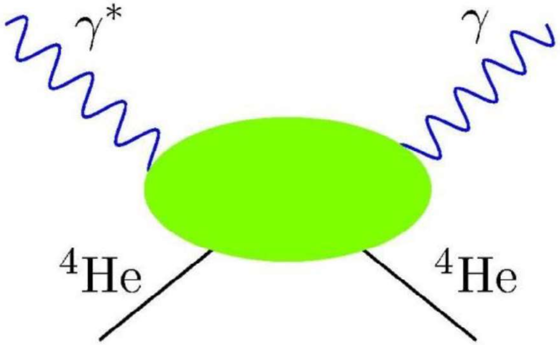
/ledium modifications and incoherent nuclear DVCS

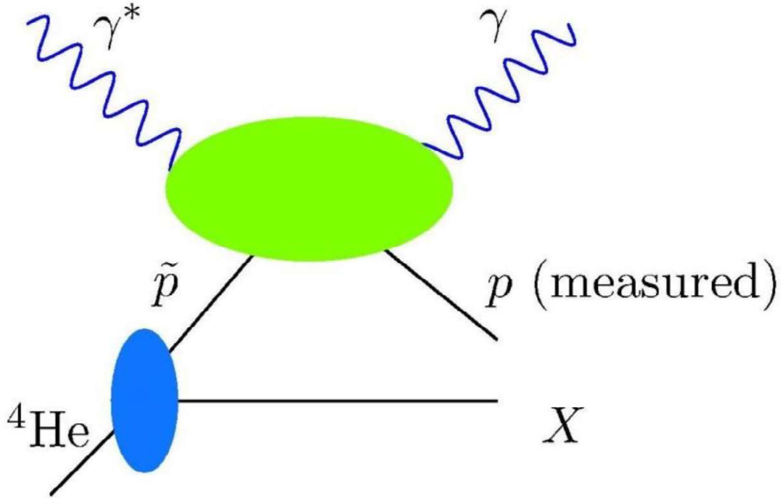
new Jefferson Lab (CLAS collaboration) experiment on DVCS on ^{4}He will
sure

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)

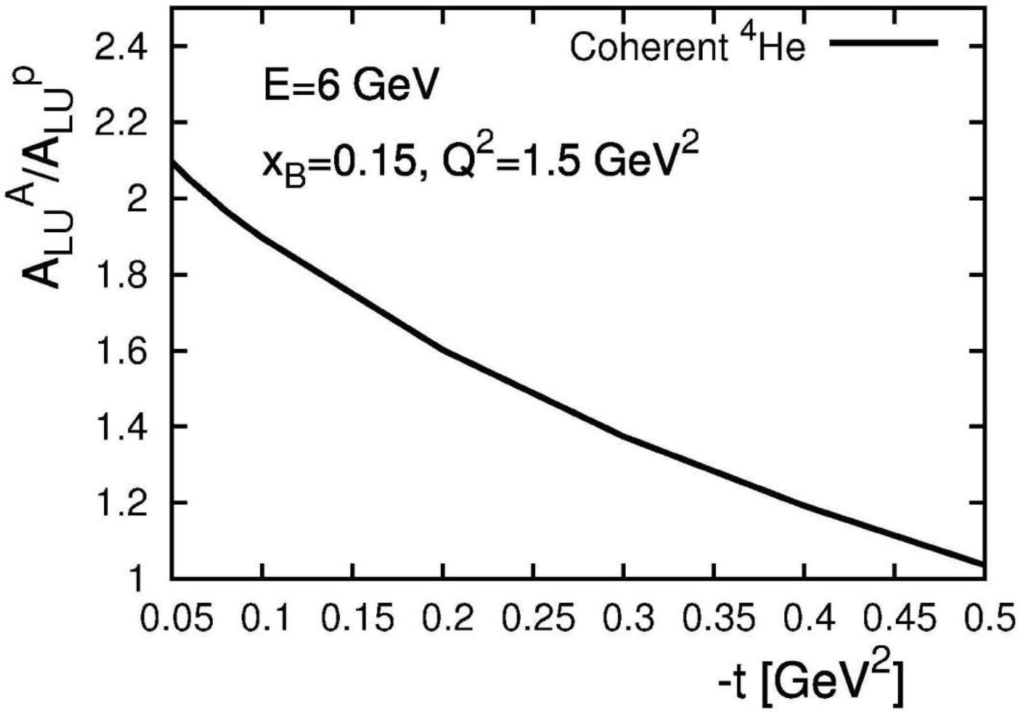
coherent DVCS on the bound proton (the final proton is detected)





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

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



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

$$\frac{A^{p^*}_{LU}}{A^{p}_{LU}} = 1$$

However !! ⇒

ɜ 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.

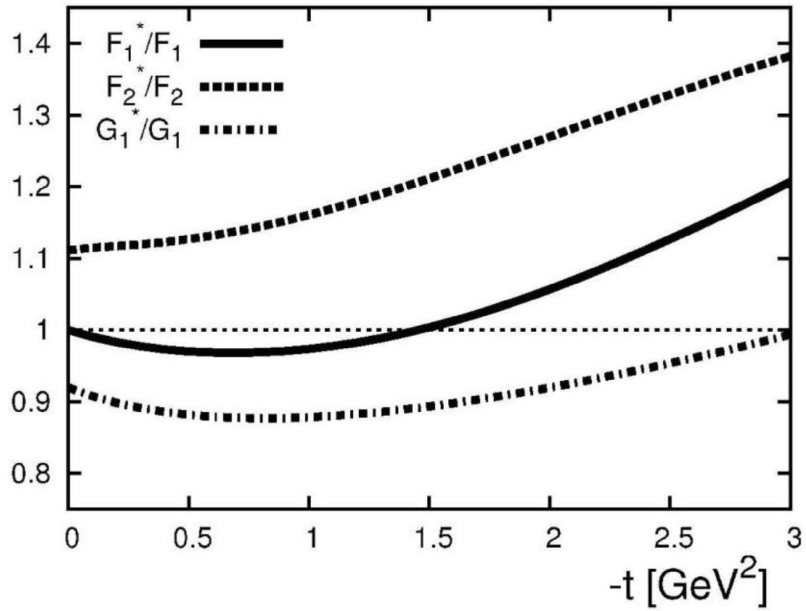
A.W. Thomas and K. Tsushima, arXiv:0806.3288

Model, assumption !

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

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

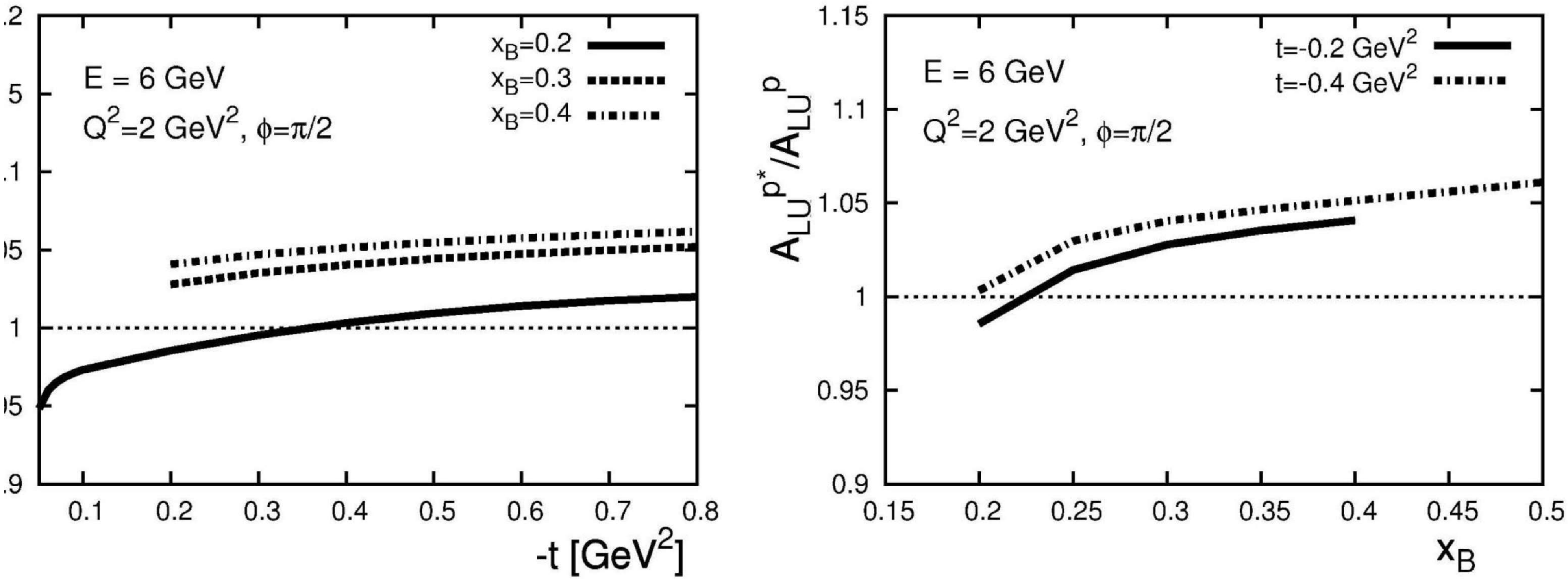
$$\tilde{H}^{q/p^*} = \frac{G_1^{p^*}(t)}{G_1^p(t)} \tilde{H}^{q/p}$$



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}He
.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**, 4902 (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 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) $J_q+J_G=(\Delta q+L_q)+J_G=1/2$

- $g_A^* < g_A \Rightarrow \Delta q^* < \Delta q$
- $F_1^* = F_1$ $(F_1^*(0) = F_1(0) = 1)$, $F_2^* > F_2$
- $H_q^* \cong H_q$, $E_q^* > E_q$ $(\mu_p^* > \mu_p)$

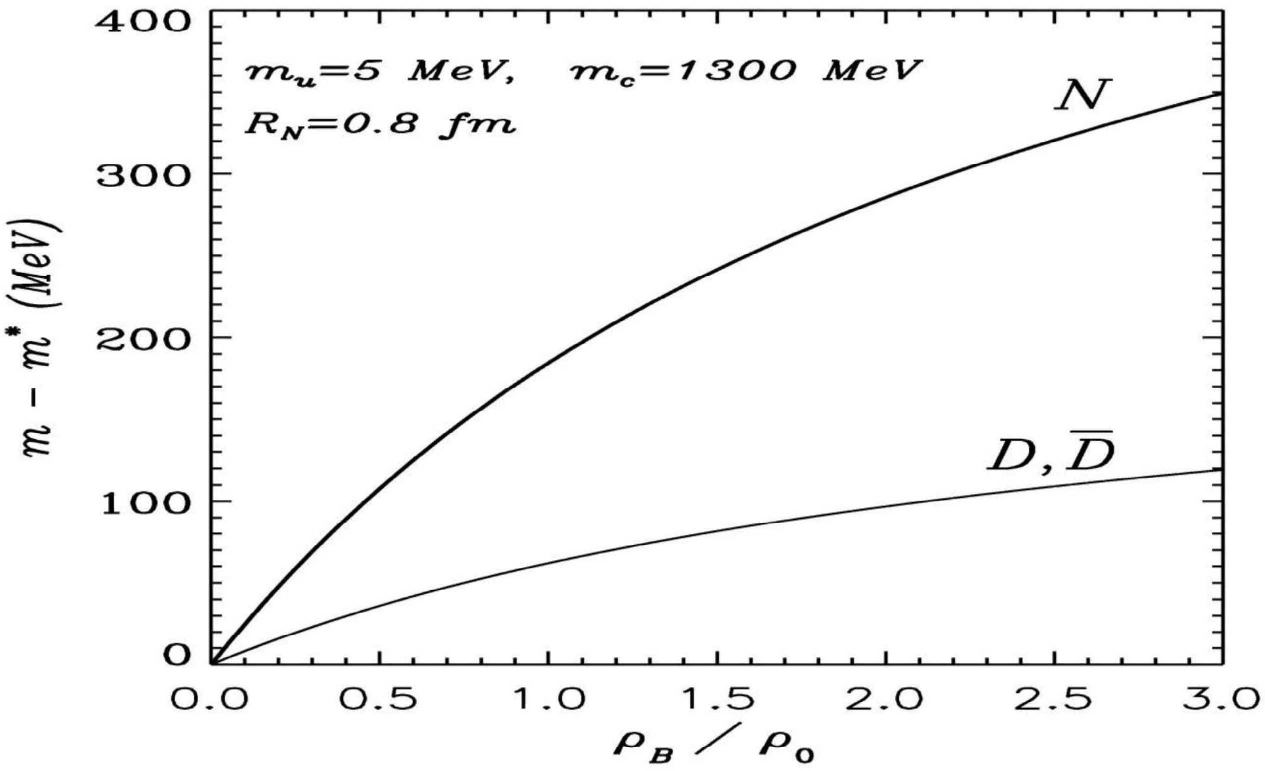
$J_q^* = ½ - J_G^* = (\Delta q^* + L_q^*)$

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

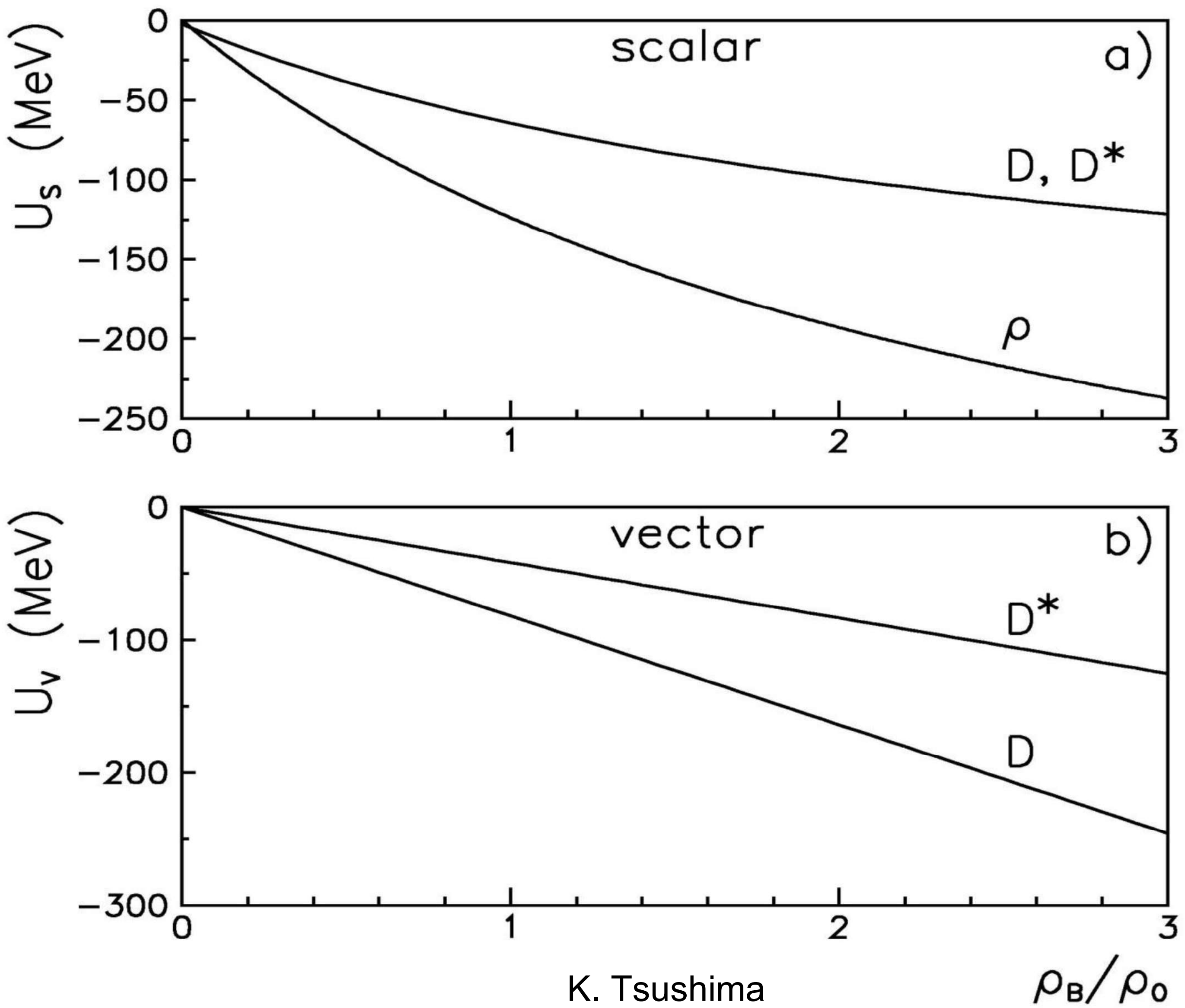
$= (\Delta q + L_q) = ½ - J_G = J_q$

- $J_q^* > J_q$ $(J_G^* < J_G$ or $L_q^* > L_q)$

D meson **scalar** potential



D and **D*** potentials in **nuclear matter**



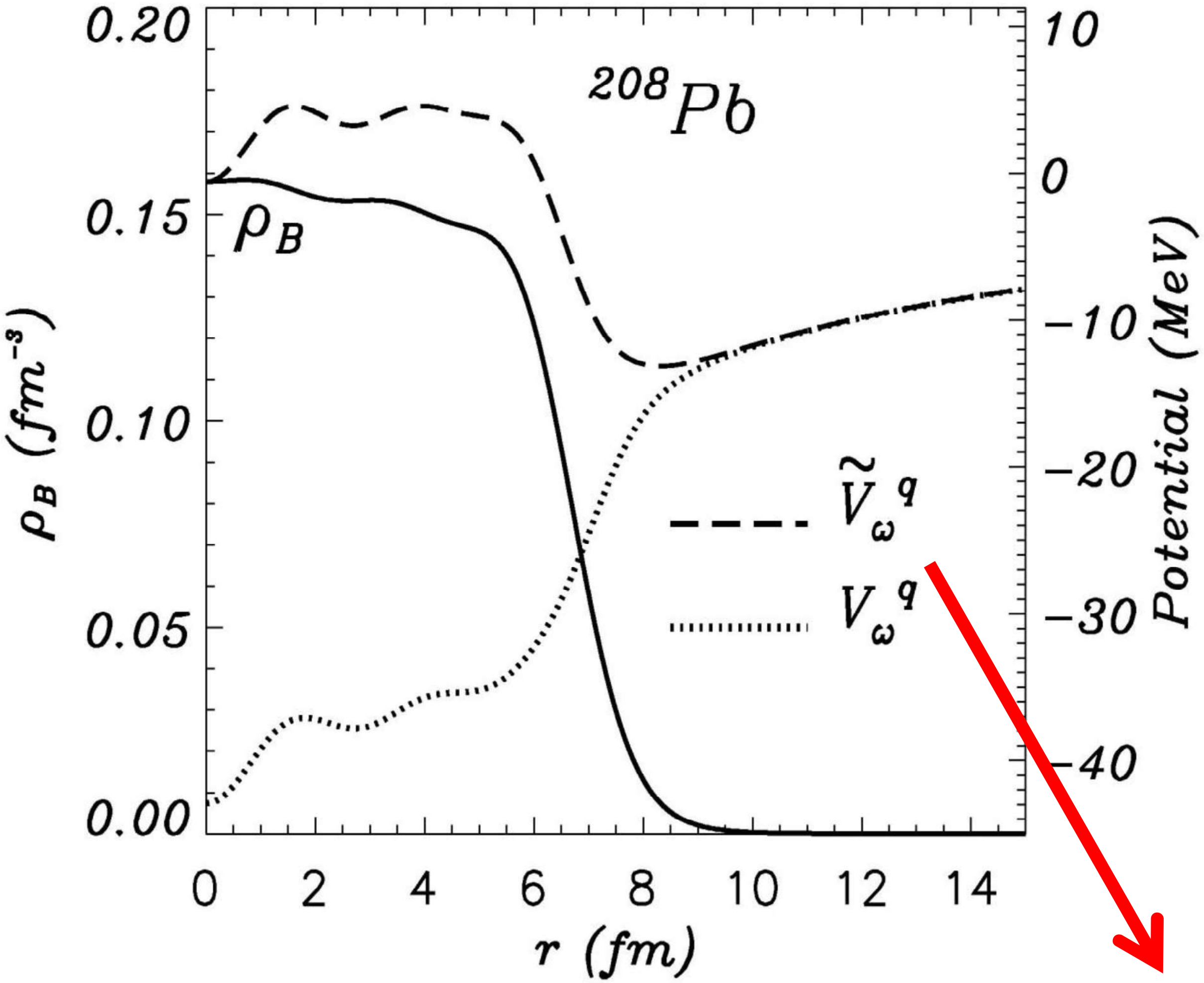
K. Tsushima

$1.96{*}V_\omega^q$

$D^+ = c\,\bar{d}$

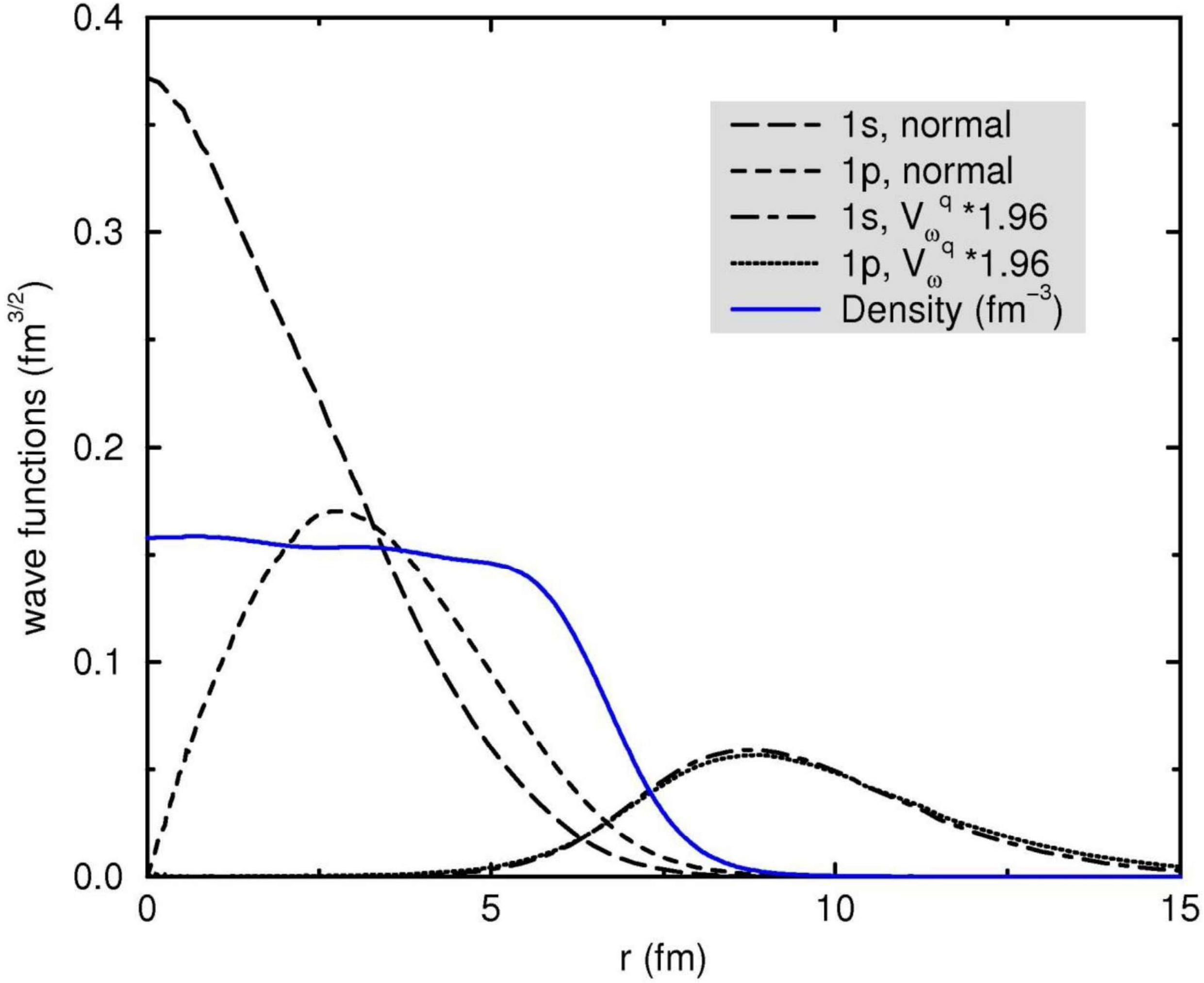
$D^0 = c\,\bar{u}$

D^- ($\bar{c}d$) **total** potential in **Pb**



$1.96*V_\omega^q$

D^- ($\bar{c}d$) bound state wave functions in Pb



$\bar{D}$ bound state energy in Pb

state	D^- 1.96 *V$q\omega$	D^- V$q\omega$	D^- V$q\omega$ No Coulomb	$\bar{D}^0$ 1.96 *V$q\omega$	$\bar{D}^0$ V$q\omega$	D^0 V$q\omega$
1s	-10.6	-35.2	-11.2	unbound	-25.4	-96.2
1p	-10.2	-32.1	-10.0	unbound	-23.1	-93.0
2s	-7.7	-30.0	-6.6	unbound	-19.7	-88.5

J/Ψ in nuclei (historical)

S. J. Brodsky, I. Schmidt, Guy F. de Téramond:

QCD van der Waals potential

A=9, η_c binding energy **~ 400** [MeV] **!!!**

PRL 64, 1011 (1990)

↓

Corrected by folding nuclear density dist.

D. A. Wasson:

at most ~ 30 [MeV] **!!!** **PRL 67, 2237 (1991)**

J/Ψ pot. at ρ_0 (color octet)

$\alpha_\psi/2 \langle N| \vec{E}_a \cdot \vec{E}_a |N\rangle$

M.B. Voloshin: chromo-polarizability

at ρ_0, $V < -21$ ($\alpha_\psi/2$ GeV^{-3}) [MeV],

Prog. Part. Nucl. Phys. 61, 455 (2008)

S.H. Lee, C.M. Ko: QCD Stark effect

V = - 8 + 3 (D-loop) [MeV], PRC 67, 038202 (2003)

M. Luke, A.V. Manohar, M.J. Savage: EFT

V = -11 ~ - 8 [MeV], PLB 288, 355 (1992)

QCD sum rules

Klingl et. al, PRL 82, 3396 (1999), Err-ibid 83, 4224 (1999).

A. Hayashigaki, Prog. Theor. Phys. 101, 923 (1999).

S. Kim and S. H. Lee, NPA 679, 517 (2001).

(mass shift)

V = - 4 ~ - 7 [MeV]

Recent A=2,3 few-body calculations

V.B. Belyaev et. al, NPA 780, 100 (2006)

η_c - d and η_c - ^3He (local Yukawa type pot.)

E_B = a few ~ ten [MeV]

Lattice (quenched)

T. Kawanai, S. Sasaki, PRD 82, 09151 (2010)

Equal-time BS amplitudes → potential

η_c - N and J/Ψ - N potentials: attraction !

V = - 30 ~ - 40 [MeV] at **r ~ 0.2** fm

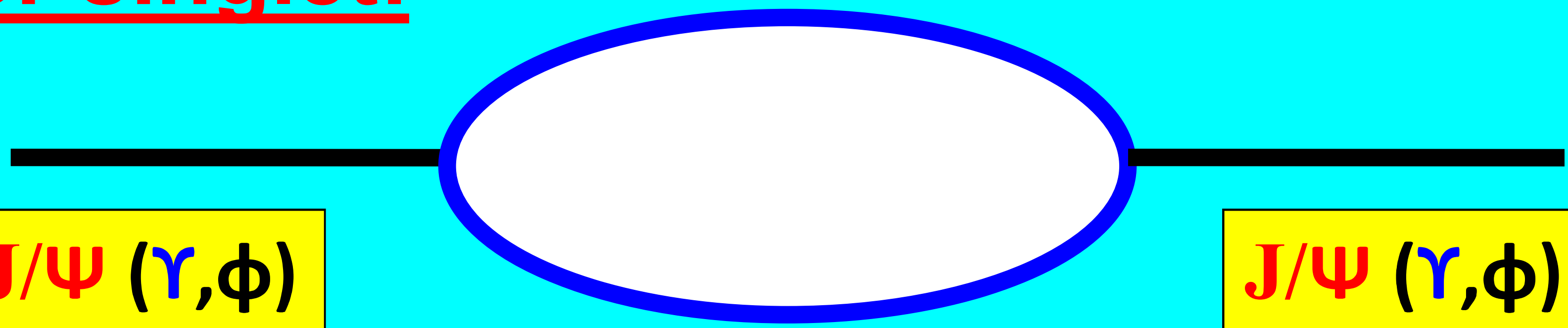
K. Tsushima

J/Ψ (ϒ,ϕ) mass in **medium** (loop!)

J/Ψ **bound** in large nuclei ?

D, B, K (also vector mesons in medium!)

Color singlet!



J/Ψ (ϒ,ϕ)

J/Ψ (ϒ,ϕ)

$\bar{D}$, $\bar{B}$, $\bar{K}$ (also vector mesons in medium!)

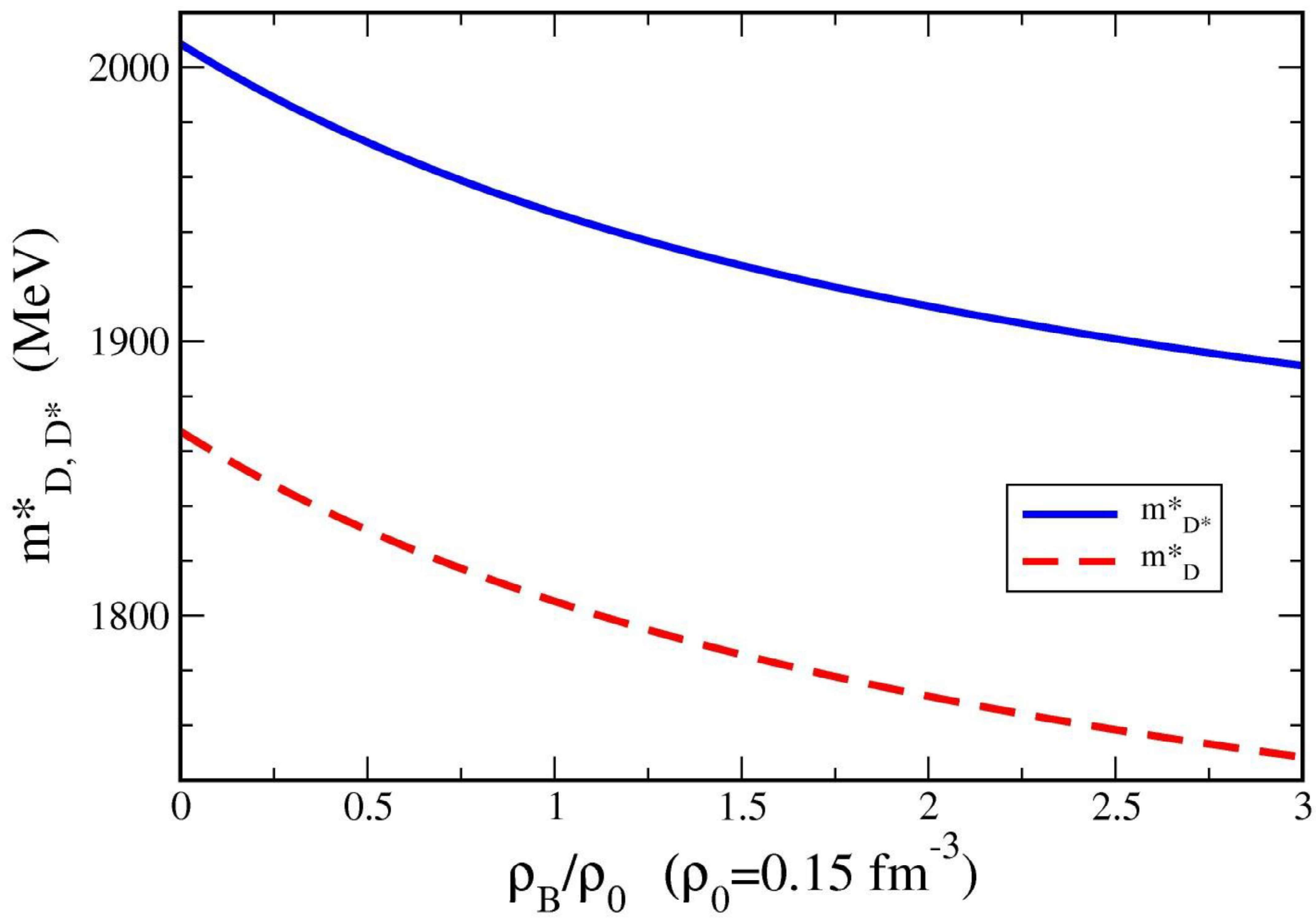
Lagrangian (updated! only D,$\bar{D}$ included)

$$\mathcal{L}_{\psi DD} = i g_{\psi DD}\, \psi^{\mu} \left[\bar{D}\,(\partial_{\mu} D) - (\partial_{\mu}\bar{D})\, D\right]$$

$$\mathcal{L}_{\psi DD^*} = \frac{g_{\psi DD^*}}{m_{\psi}}\, \varepsilon_{\alpha\beta\mu\nu}\, (\partial^{\alpha}\psi^{\beta}) \left[(\partial^{\mu}\bar{D}^{*\nu})\, D + \bar{D}\,(\partial^{\mu} D^{*\nu})\right]$$

$$\begin{aligned} \mathcal{L}_{\psi D^* D^*} &= i g_{\psi D^* D^*} \left\{\psi^{\mu} \left[(\partial_{\mu}\bar{D}^{*\nu})\, D^*_{\nu} - \bar{D}^{*\nu}\,(\partial_{\mu} D^*_{\nu})\right]\right. \\ &+ \left[(\partial_{\mu}\psi^{\nu})\, \bar{D}^*_{\nu} - \psi^{\nu}\,(\partial_{\mu}\bar{D}^*_{\nu})\right] D^{*\mu} + \left.\bar{D}^{*\mu} \left[\psi^{\nu}\,(\partial_{\mu} D^*_{\nu}) - (\partial_{\mu}\psi^{\nu})\, D^*_{\nu}\right]\right\} \end{aligned}$$

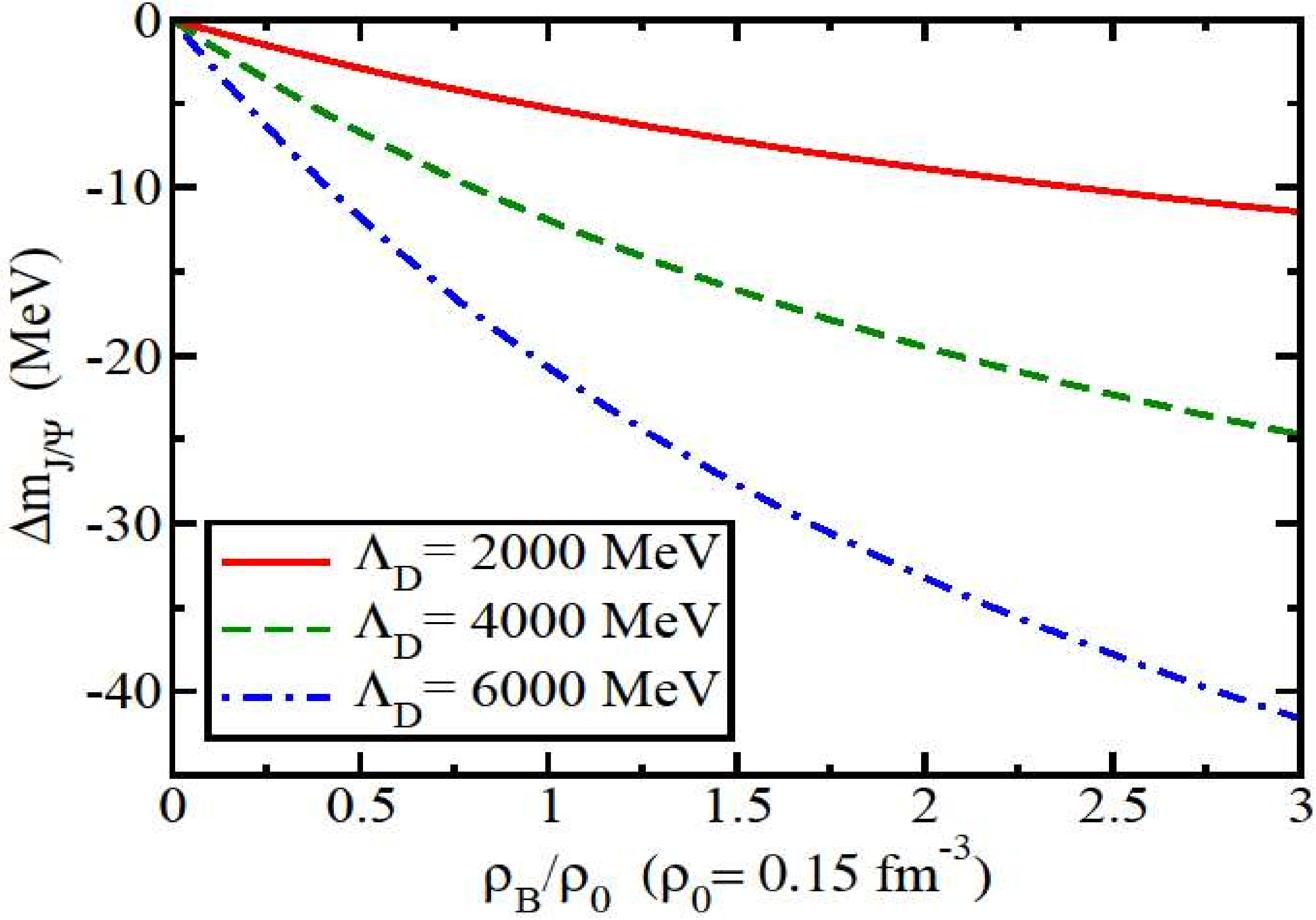
D and D* masses in matter



Vertex form factor

- $$U_{D,D*}(\vec{q}^2) = \left[\frac{\Lambda^2{}_{D,D*} + m^{*2}{}_{J/\Psi}}{\Lambda^2{}_{D,D*} + 4\omega^{*2}{}_{D,D*}(\vec{q}^2)}\right]^2$$

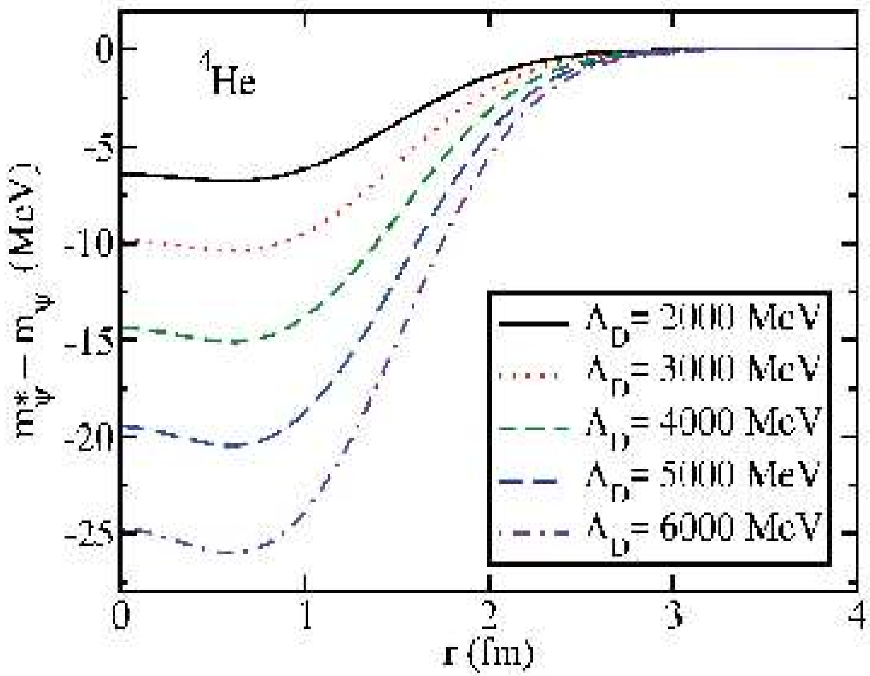
D-$\bar{D}$ loop: J/Ψ potential in matter

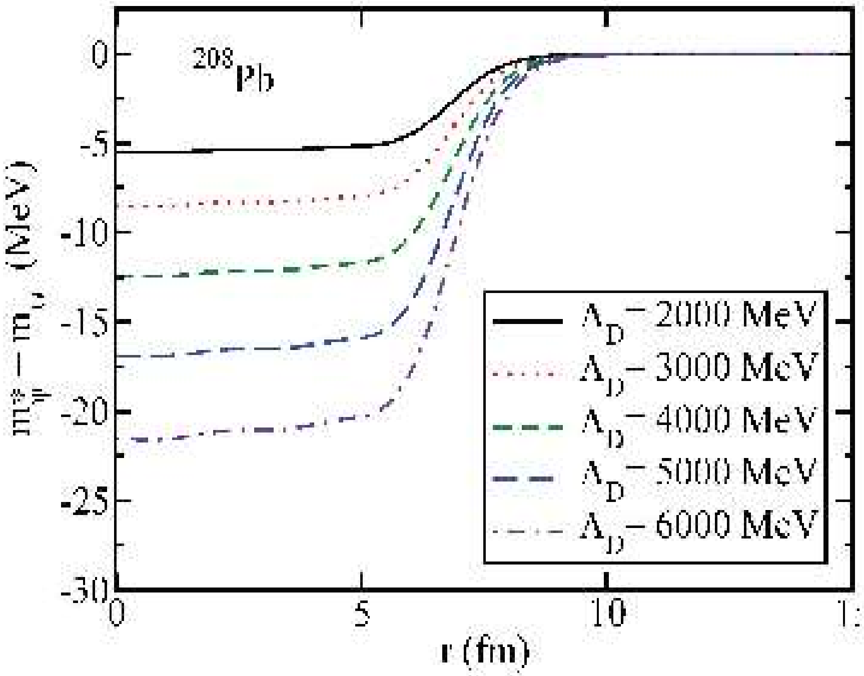


J/Ψ binding in finite nuclei

Potentials and single-particle energies in ^{4}He and ^{208}Pb

J/Ψ potentials in ^{4}He and ^{208}Pb





Proca (Klein-Gordon) equation

Lorentz condition ⇒ T and L modes similar

$$\left[\nabla^2 + E^2 - \mu^2 - 2\mu(m(r)^* - m)\right] \Phi(r) = 0$$

$$\mu = mM_A/(m+M_A)$$

m: J/Ψ mass, M_A: nucleus mass

Possible width

$$\left[p^2 - m^2 + i\, m\, \Gamma\right] = \left[p^2 - m^2 - \Sigma\right]$$

$$\Gamma = -\frac{Im(\Sigma)}{m}$$

$= \mathbf{(p/E)\ (0.5\rho\ \ )}\ \sigma$

≈ 1.1 MeV (p=3 GeV)

Γ **:** F. Riek *et al.*, PRC 82, 015202 (2010)

σ **:** A. Sibirtsev *et al*., PRC 63, 044906 (2001)

J/Ψ Bound state energies: Schrödinger (KG) Eq.

		Bound state energies				
		$\Lambda_D = 2000$	$\Lambda_D = 3000$	$\Lambda_D = 4000$	$\Lambda_D = 5000$	$\Lambda_D = 6000$
$^{4}_{J/\psi}\mathrm{He}$	1s	n	n	-0.70	-2.70	-5.51
$^{12}_{J/\psi}\mathrm{C}$	1s	0.52	1.98	4.47	7.67	11.26
	1p	n	n	n	-1.38	-3.84
$^{16}_{J/\psi}\mathrm{O}$	1s	-1.03	-2.87	-5.72	-9.24	-13.09
	1p	n	n	-0.94	-3.48	-6.60
$^{40}_{J/\psi}\mathrm{Ca}$	1s	-2.78	-5.44	-9.14	-13.50	-18.12
	1p	0.38	2.32	5.43	9.32	13.56
	1d	n	n	-1.52	-4.74	-8.49
	2s	n	n	-1.27	-4.09	-7.60
$^{48}_{J/\psi}\mathrm{Ca}$	1s	-2.96	-5.62	-9.28	-13.55	-18.08
	1p	-0.73	-2.83	-6.03	-9.95	-14.18
	1d	n	n	-2.46	-5.87	-9.73
	2s	n	-0.07	-1.90	-5.00	-8.65
$^{90}_{J/\psi}\mathrm{Zr}$	1s	-3.64	-6.40	-10.12	-14.41	-18.92
	1p	-1.93	-4.42	-7.92	-12.03	-16.40
	1d	-0.03	-2.13	-5.31	-9.18	-13.37
	2s	-0.02	-1.56	-4.51	-8.26	-12.37
	2p	n	n	-1.52	-4.71	-8.45
$^{208}_{J/\psi}\mathrm{Pb}$	1s	-4.25	-7.08	-10.82	-15.11	-19.60
	1p	-3.16	-5.86	-9.52	-13.74	-18.18
	1d	-1.84	-4.38	-7.90	-12.01	-16.37
	2s	-1.41	-3.81	-7.25	-11.30	-15.61
	2p	0.07	1.95	5.10	8.97	13.14

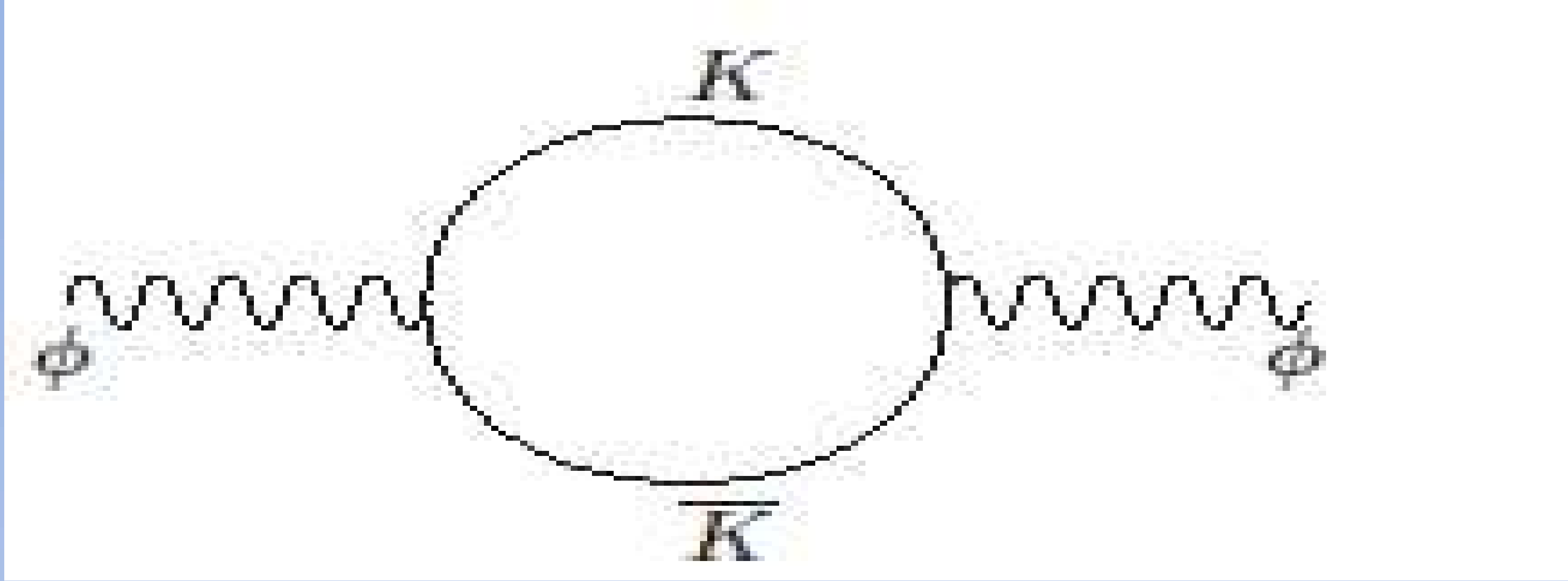
J/Ψ-nuclear bound states Summary, outlook

- **J/Ψ** potential in nuclear matter
  Color **octet**, **QCD Stark** → **attraction!**
  Color **singlet**, **DD loop**
  → all give **attraction!** (**non**gauged **J/Ψ**)
- **J/Ψ** will be **bound** in (large mass) nuclei
  (nearly **stopped** production of **J/Ψ**)
- **Widths** of **D** and **D*** **?!**
- **Φ** **(next)** and **Υ** in future **?!**

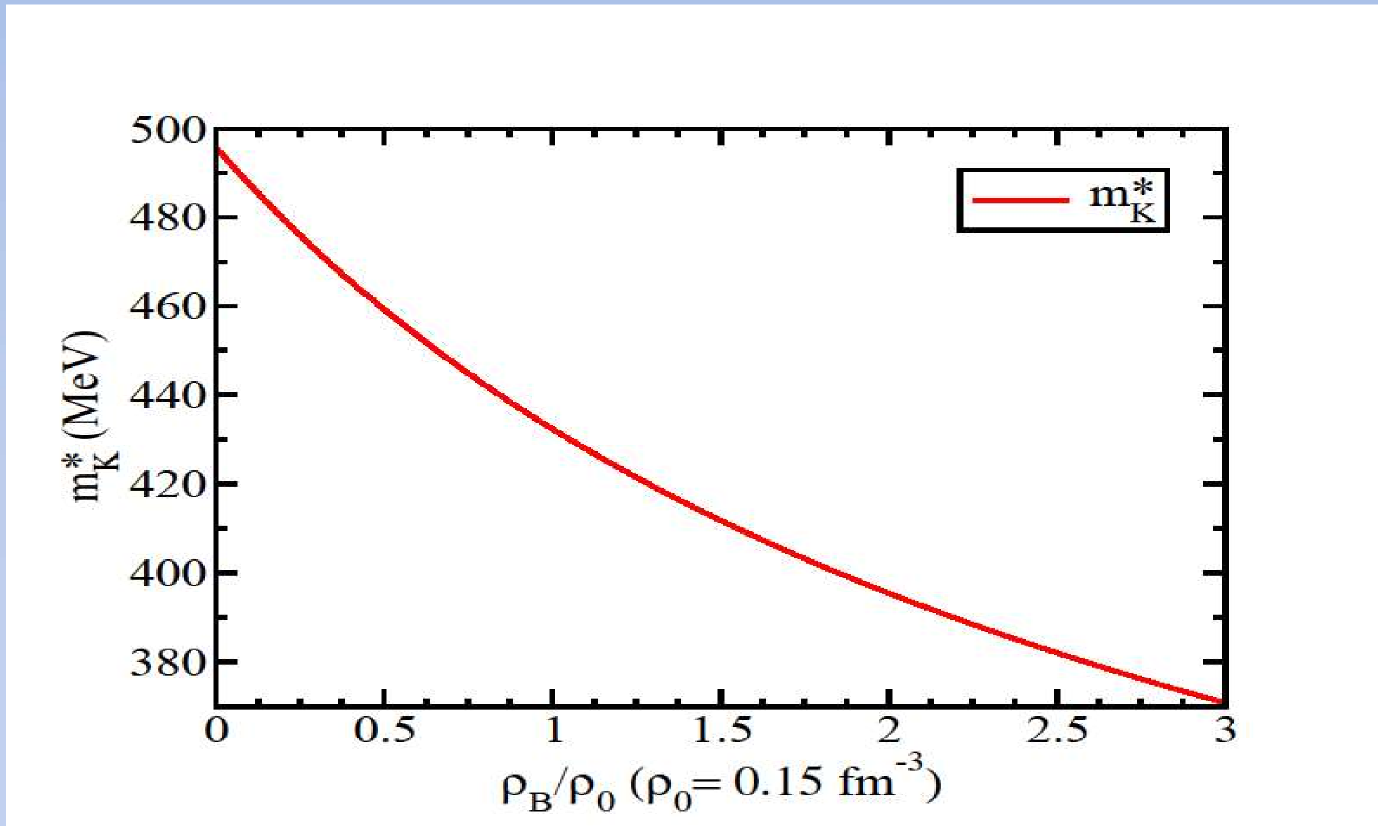
Φ-meson nuclear bound states

- J.~J.~Cobos-Martínez, et al.

- Phys.Lett. B771 (2017) 113-118
- Phys.Rev. C96 (2017) 035201
- J.Phys.Conf.Ser. 912 (2017) 012009
- PoS Hadron2017 (2018) 209



K
φ
φ
$\overline{K}$



m_K^*
m_K^* (MeV)
500
480
460
440
420
400
380
0
0.5
1
1.5
2
2.5
3
ρ_B/ρ_0 (ρ_0= 0.15 fm^{-3})

Φ-meson nuclear bound states

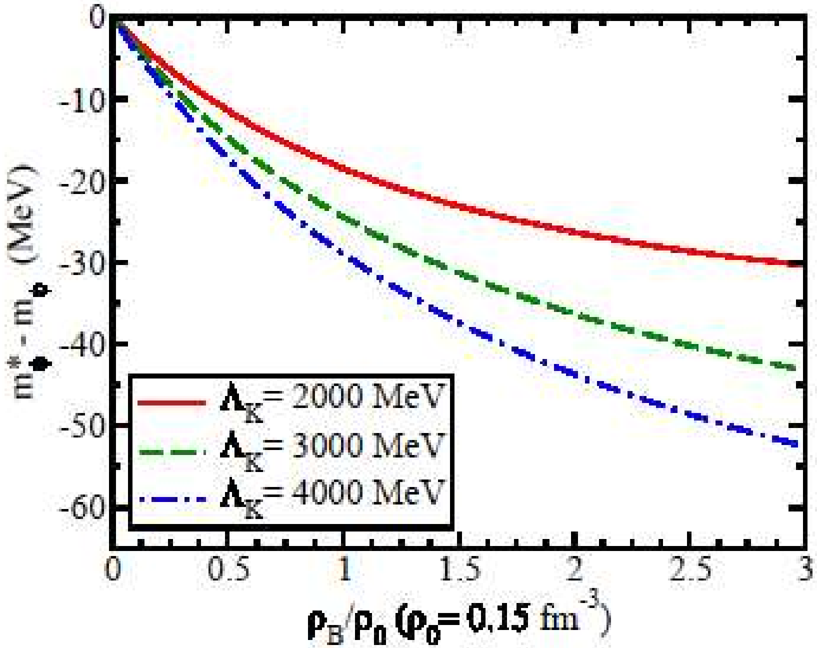
ϕ-meson: at normal nucl. matt. density ρ_0

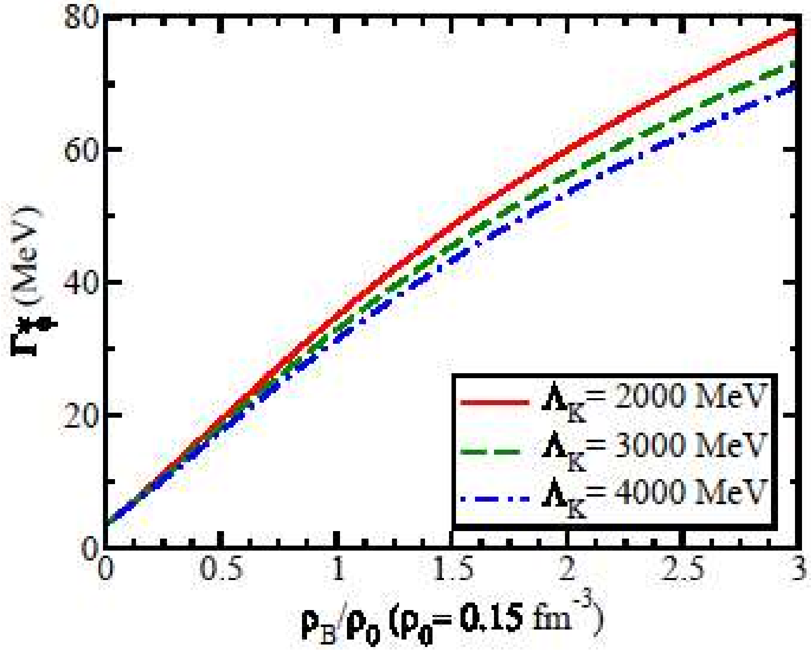
	$\Lambda_K = 1000$	$\Lambda_K = 2000$	$\Lambda_K = 3000$	$\Lambda_K = 4000$
m^*_ϕ	1009.3	1000.9	994.9	990.5
Γ^*_ϕ	37.7	34.8	32.8	31.3

Form Factor at ϕKK vertex

$$u_K(\vec{q}^2) = \left(\frac{\Lambda_K^2 + m_\phi^2}{\Lambda_K^2 + 4E_K^2(\vec{q})} \right)^2$$

m^*_ϕ and width in symm. nucl. matter (non-gauged)



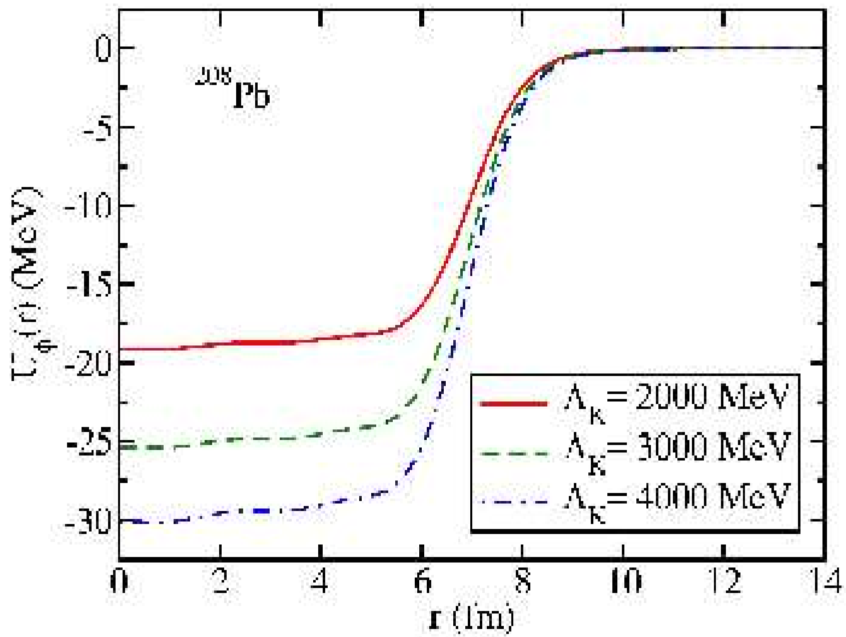


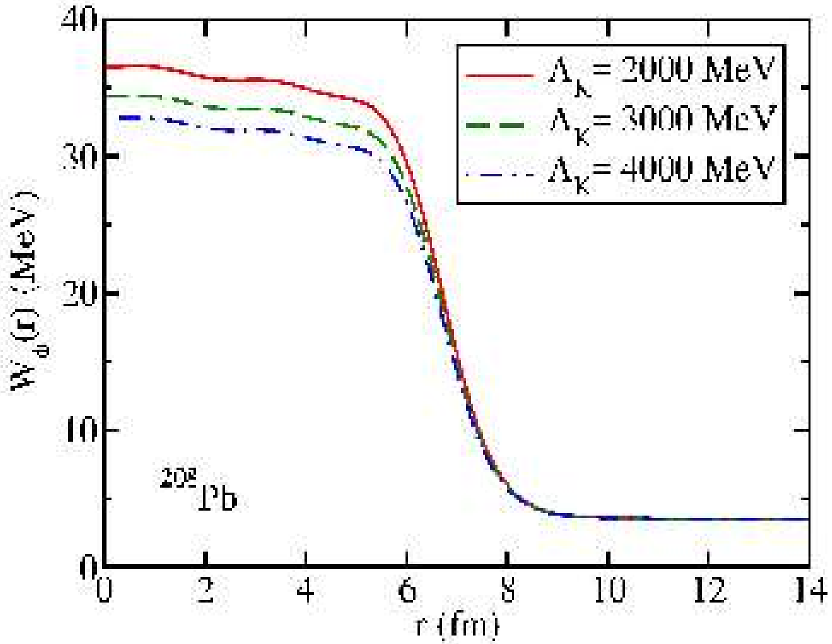
Complex Potential and KG equation

$$V_{\phi A}(r) = \Delta m_\phi^*(\rho_B(r)) - (\mathrm{i}/2)\Gamma_\phi^*(\rho_B(r)),$$
$$\equiv U_\phi(r) - \frac{i}{2}W_\phi(r)$$

$$\left(-\nabla^2 + \mu^2 + 2\mu V(\vec{r})\right)\phi(\vec{r}) = \mathcal{E}^2\phi(\vec{r})$$
$$\mu = m_\phi m_A/(m_\phi + m_A)$$

m^*_ϕ and width: ^{208}Pb





Bound state energies

		$\Lambda_K = 2000$		$\Lambda_K = 3000$		$\Lambda_K = 4000$	
		E	$\Gamma/2$	E	$\Gamma/2$	E	$\Gamma/2$
$^4_\phi$He	1s	n (-0.8)	n	n (-1.4)	n	-1.0 (-3.2)	8.3
$^{12}_\phi$C	1s	-2.1 (-4.2)	10.6	-6.4 (-7.7)	11.1	-9.8 (-10.7)	11.2
$^{16}_\phi$O	1s	4.0 (5.9)	12.3	8.9 (10.0)	12.5	12.6 (13.4)	12.4
	1p	n (n)	n	n (n)	n	n (-1.5)	n
$^{40}_\phi$Ca	1s	9.7 (11.1)	16.5	15.9 (16.7)	16.2	20.5 (21.2)	15.8
	1p	-1.0 (-3.5)	12.9	-6.3 (-7.8)	13.3	-10.4 (-11.4)	13.3
	1d	n (n)	n	n (n)	n	n (-1.4)	n
$^{48}_\phi$Ca	1s	-10.5 (-11.6)	16.5	-16.5 (-17.2)	16.0	-21.1 (-21.6)	15.6
	1p	-2.5 (-4.6)	13.6	-7.9 (-9.2)	13.7	-12.0 (-12.9)	13.6
	1d	n (n)	n	n (0.8)	n	2.1 (3.6)	11.1
$^{90}_\phi$Zr	1s	-12.9 (-13.6)	17.1	-19.0 (-19.5)	16.4	-23.6 (-24.0)	15.8
	1p	-7.1 (-8.4)	15.5	-12.8 (-13.6)	15.2	-17.2 (-17.8)	14.8
	1d	-0.2 (-2.5)	13.4	-5.6 (-6.9)	13.5	-9.7 (-10.6)	13.4
	2s	n (-1.4)	n	-3.4 (-5.1)	12.6	-7.4 (-8.5)	12.7
	2p	n (n)	n	n (n)	n	n (-1.1)	n
$^{208}_\phi$Pb	1s	-15.0 (-15.5)	17.4	-21.1 (-21.4)	16.6	-25.8 (-26.0)	16.0
	1p	-11.4 (-12.1)	16.7	-17.4 (-17.8)	16.0	-21.9 (-22.2)	15.5
	1d	-6.9 (-8.1)	15.7	-12.7 (-13.4)	15.2	-17.1 (-17.6)	14.8
	2s	-5.2 (-6.6)	15.1	-10.9 (-11.7)	14.8	-15.2 (-15.8)	14.5
	2p	n (-1.9)	n	-4.8 (-6.1)	13.5	-8.9 (-9.8)	13.4
	2d	n (n)	n	n (-0.7)	n	-2.2 (-3.7)	11.9

Summary and Future Plans

1. **QMC model:** Quark-based in-medium hadron properties and nuclear model (phenomenological)

2. Hypernuclei, Λ- and Ξ-hypernuclei (Λ_c, Λ_b)

3. Heavy Baryons in nuclear medium

4. Neutrino reactions and in-medium form factors, MFP

5. Pion, N, EMFFs, pion D.A., bound Nucleon GPDs and Incoherent DVCS

6. D meson in nuclear medium and J/Ψ(Φ-)-nuclear bound states

7. **Plans:** In-medium gA and weak-transitions, heavy baryons