Hypernuclear Physics with Electromagnetic and hadronic Probes

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1. Introduction

A brief review and comparison of production reactions

2. Brief sketch of the theoretical model

3. Results, cross sections, spectroscopy

4. Conclusions

Seminar at Jlab, Oct. 27, 2008

Hypernuclei are systems where one nucleon is replaced by a hyperon

Λ Hypernuclei

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

Number of Baryons (N+Z+Y) → ${}^{B}_{Y}X$ ← Element = Total charge

↑

Number of hyperons

Double Hypernuclei, ${}^{10}_{\Lambda\Lambda}Be$, Σ Hypernuclei

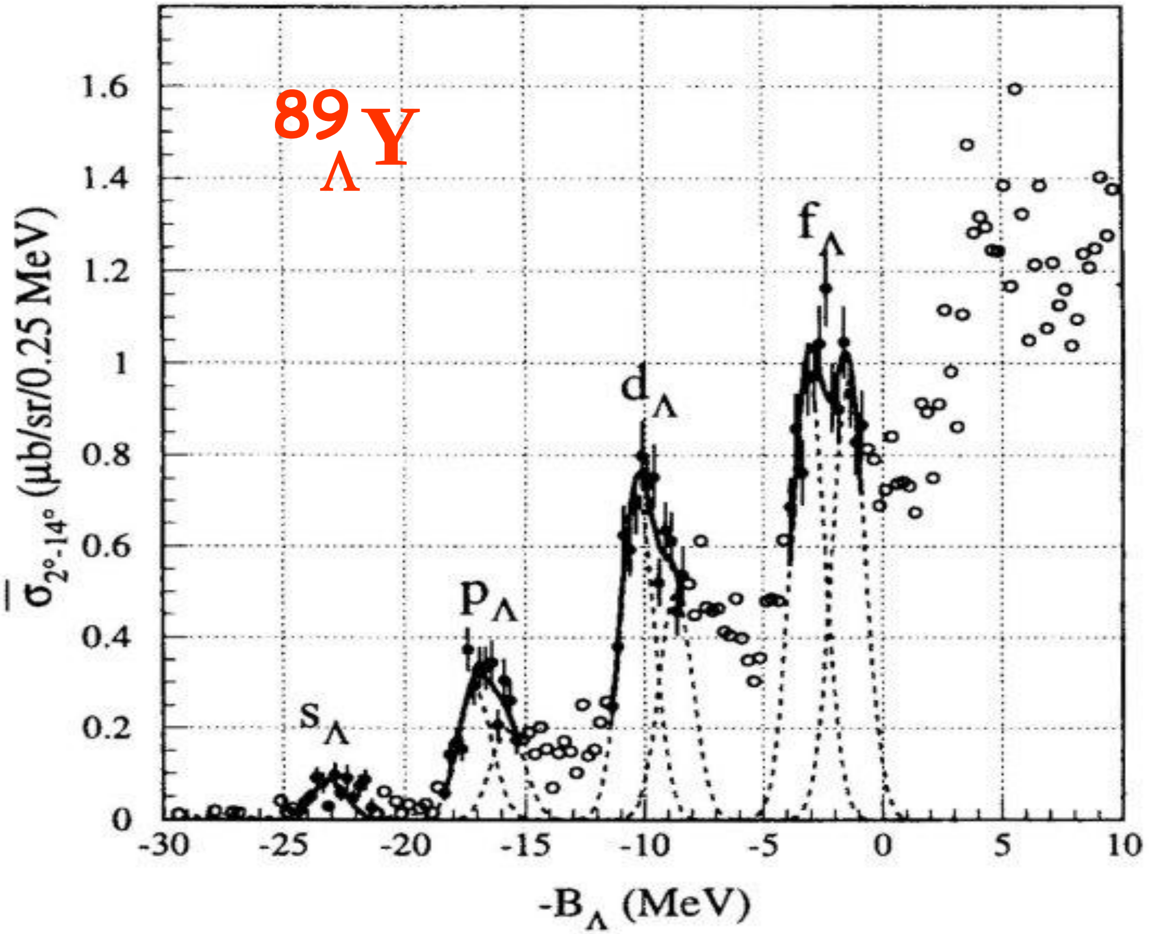
Why are Hypernuclei interesting!

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

Good probe for deeply bound single particle states.

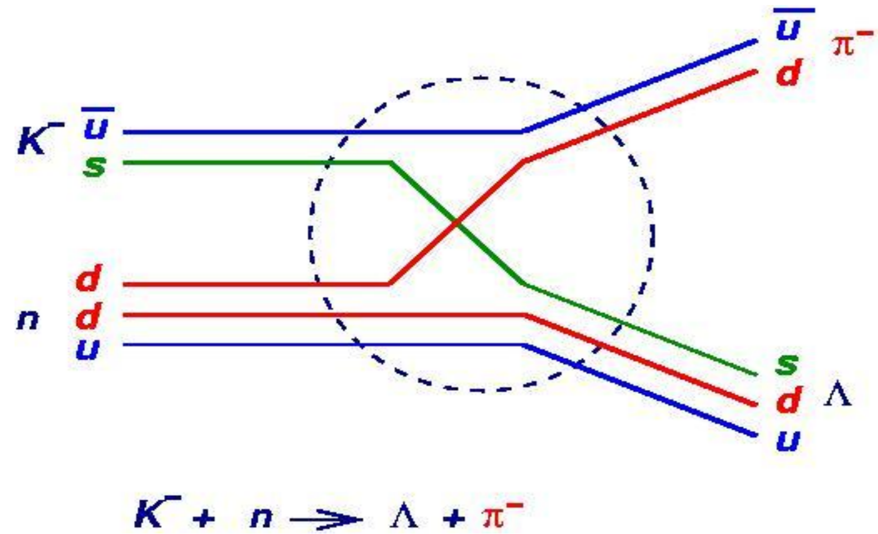


Production of Λ Hypernuclei

MESONIC PROBES

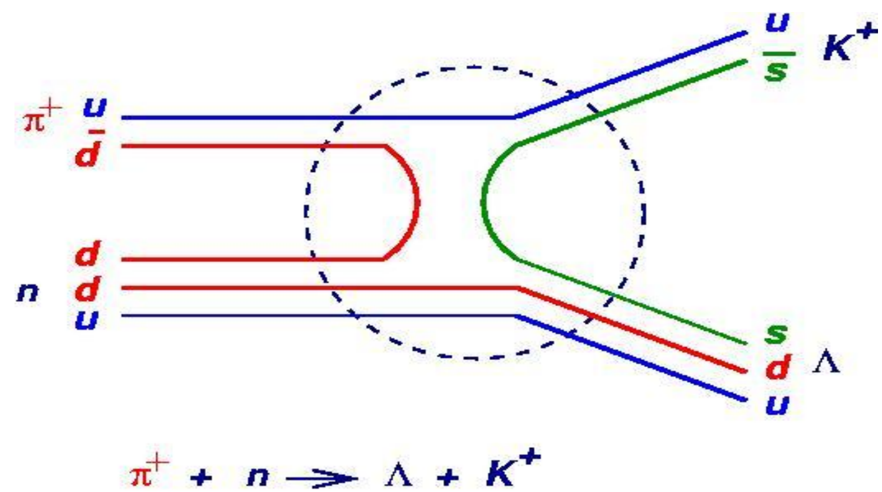
Prog. Part. Nucl. Phys. 57, 564 (2006)

(K^-, π^-) reaction



Strangeness exchange

(π^+, K^+) reaction



Associated strangeness production

Electromagnetic and baryonic Probes

(γ,K^+) reaction $\gamma + p \rightarrow \Lambda + K^+$

H. Yamazaki et al., Phys. Rev. C 52, R1157 (1995)

(e,e' K^+) reaction $\gamma^* + p \rightarrow \Lambda + K^+$

L. Yuan et al. Phys. Rev. C 73, 044607 (2006)
M. Iodice et al, Phys. Rev. Lett. 99, 052501 (2007)
F. Cusanno et al., arXiv: 0810:3853

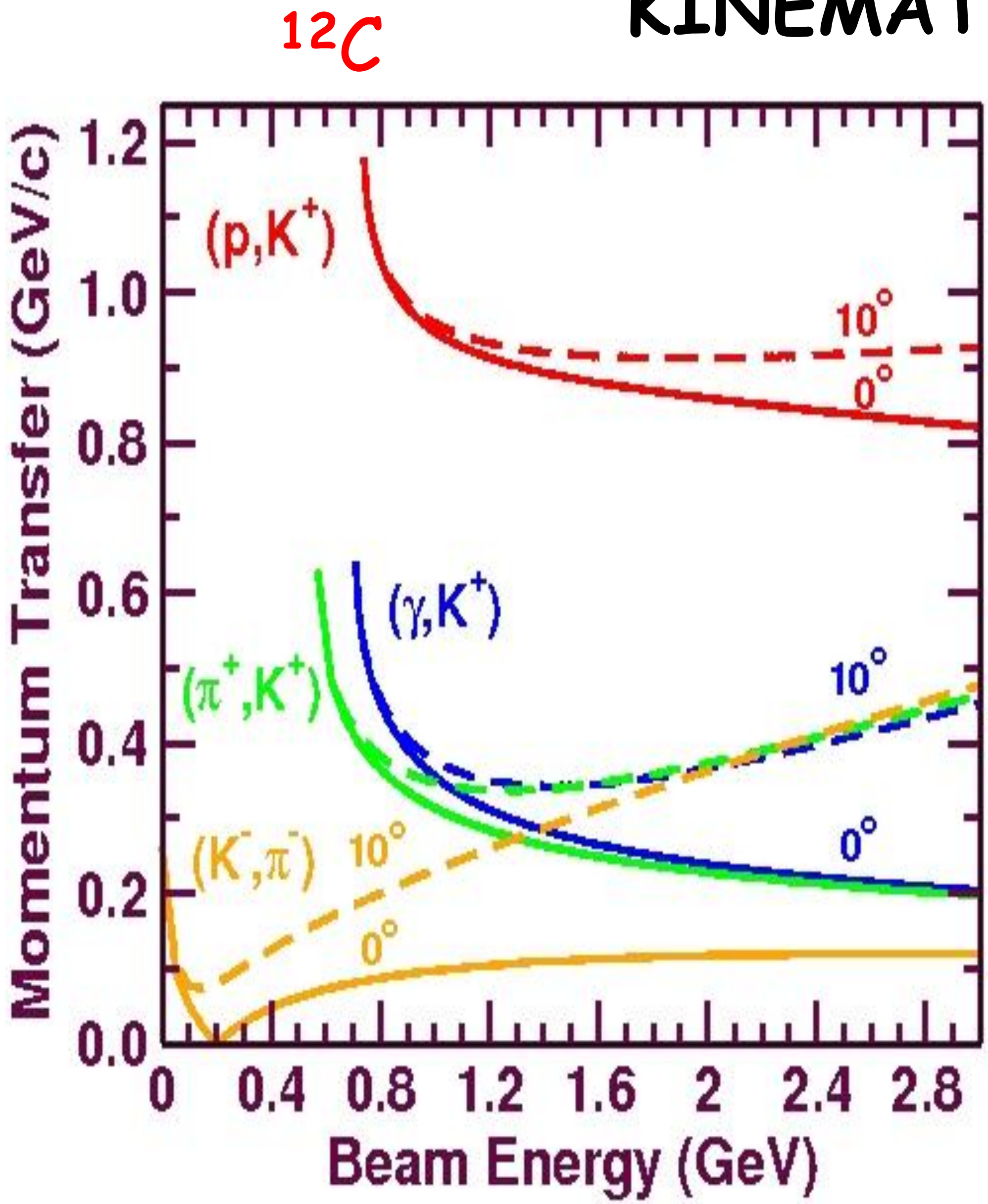
JLab

(p,K^+) reaction $p + p \rightarrow p + \Lambda + K^+$

Heavy Ion reactions $p + p \rightarrow p + \Lambda + K^+$

GSI

KINEMATICS



(p,K^+) reaction

Large Momentum transfers

(π^+,K^+) and (γ,K^+) reactions

Momentum transfer > p_F

(K^-,π^-) reaction

Low momentum transfer

Excitation Energy Spectra

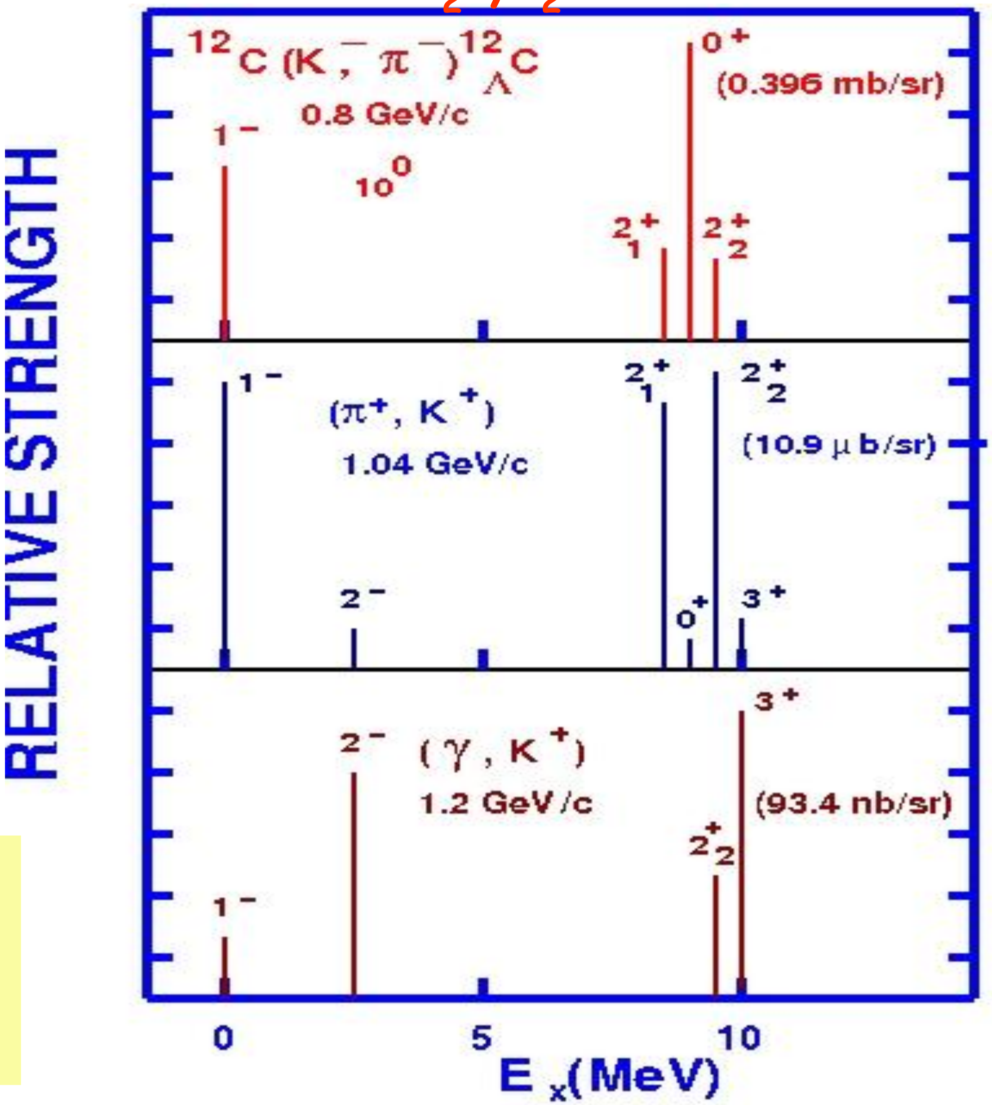
GS: $(p_{3/2}^{-1}, s_{1/2}^{\Lambda})$ $1^-, 2^-$ $(p_{3/2}^{-1}, p_{3/2}^{\Lambda})$ $1_1^+, 2_1^+, 3^+$ $(p_{3/2}^{-1}, p_{1/2}^{\Lambda})$ $1_2^+, 2_2^+$

(K^-, π^-) substitutional
0^+ state dominates

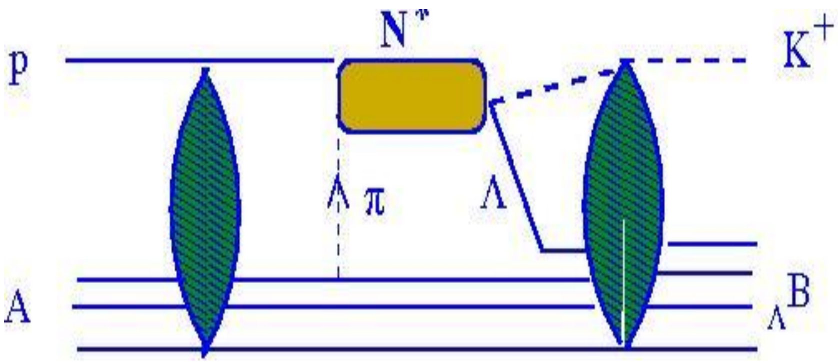
(π^+, K^+) nonsubstitutional
1^- and 2^+ states dominate

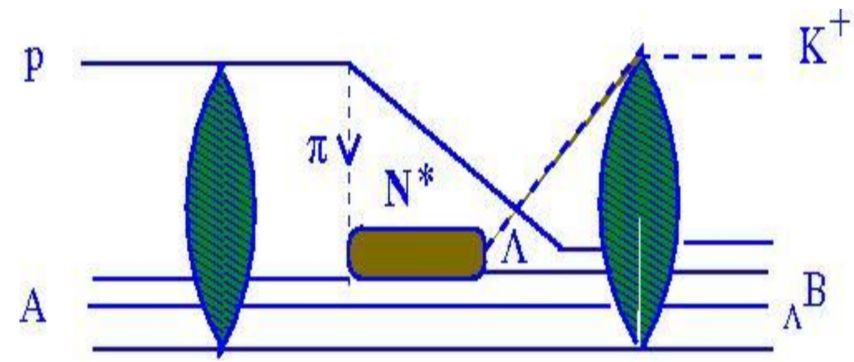
(γ, K^+) unnatural parity states dominate

(γ, K^+) and $(e, e'K^+)$ reactions can also excite unnatural parity stretched states

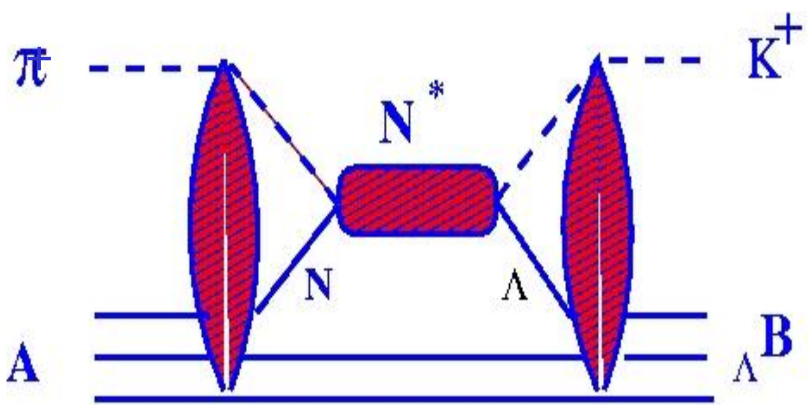


Production processes for various reactions

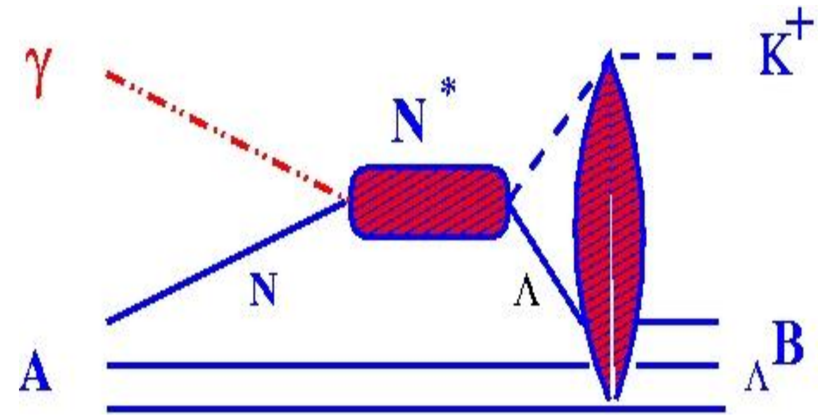




Target emission $A(p,K^+)_\Lambda B$ **Projectile emission**



$A(\pi^+,K^+)_\Lambda B^*$



$A(\gamma,K^+)_\Lambda B'$

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

A Covarient Description of $A(h\gamma,K^+)_\Lambda B$ reaction

Effective Lagrangians at various vertices

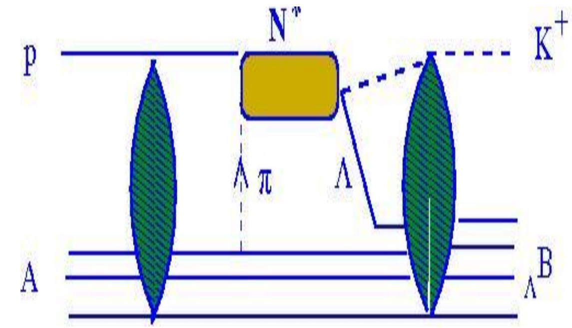
Coupling constants, form-factors

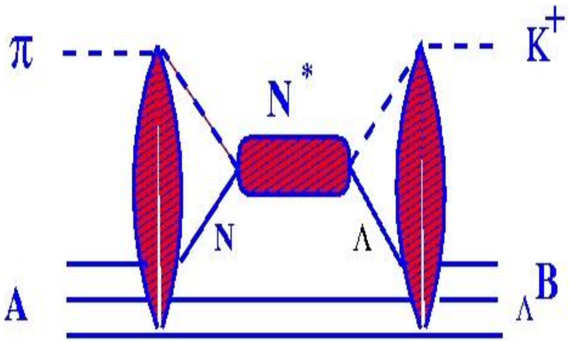
Bound state nucleon and hyperon spinors

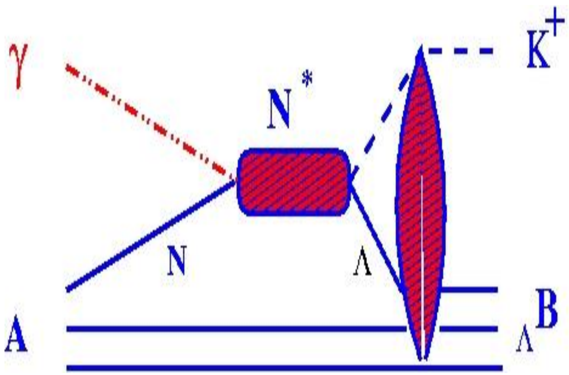
Initial and final state interactions (distorted waves).

Medium modification of N* (also of intermediate mesons in proton induced reactions) self energies.

All calculations in momentum space, so nonlocalities are included.





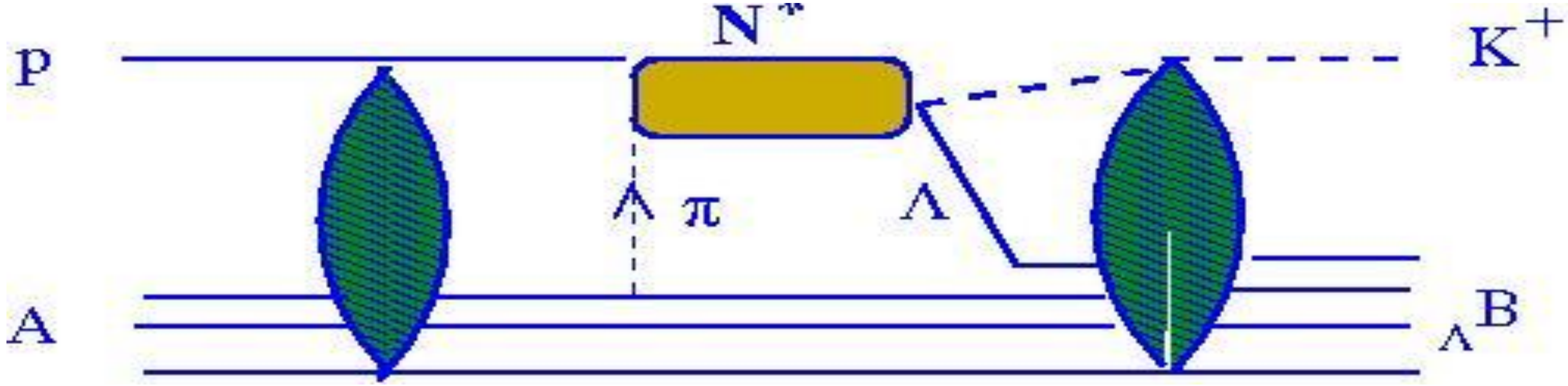


A typical amplitude

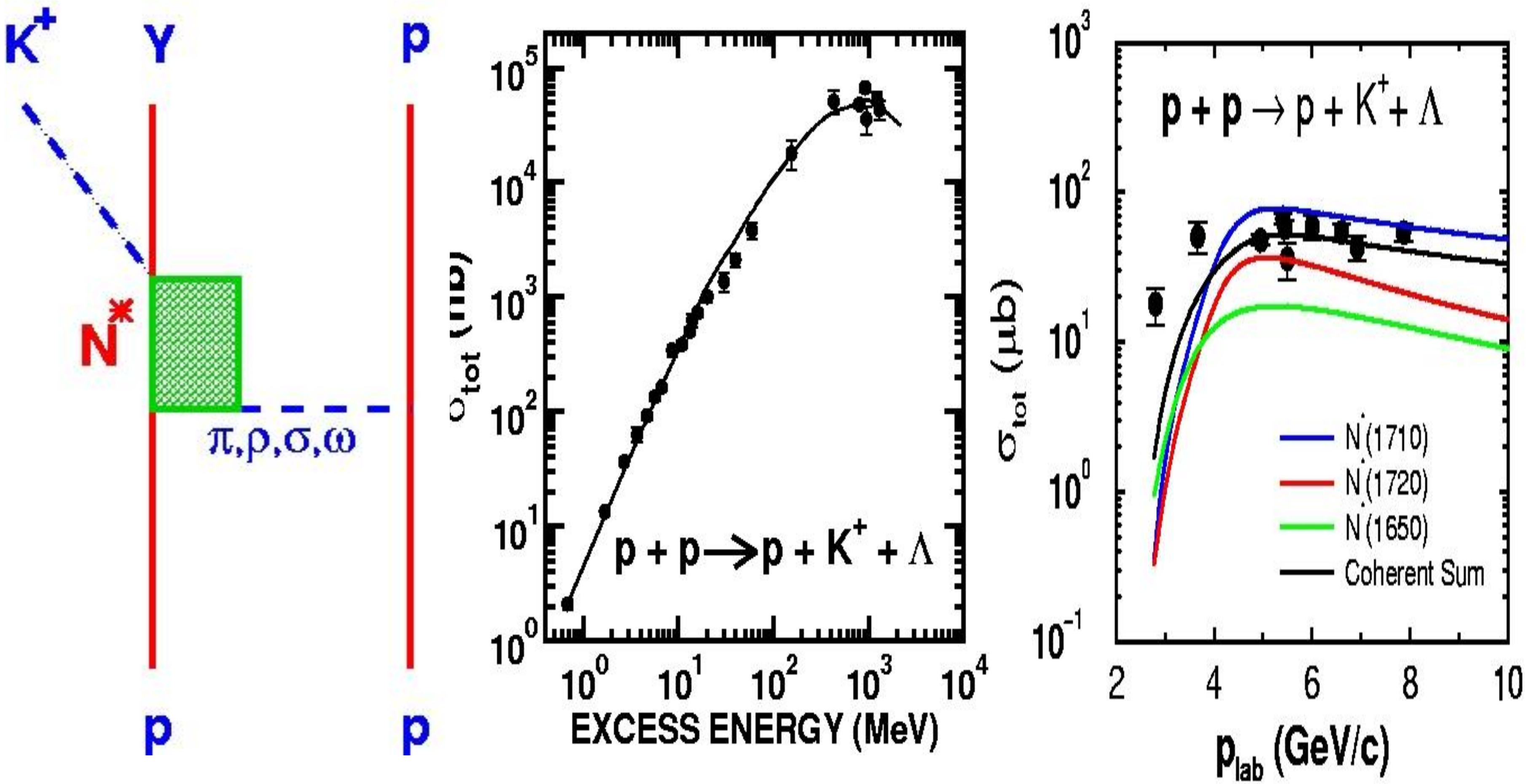
$$M_{2b}(N^*_{1/2}) = C^{2b}_{iso}\left(\frac{g_{NN\pi}}{2m_N}\right)(g_{N^*_{1/2}N\pi})(g_{N^*_{1/2}\Lambda K^+})\bar{\psi}(p_2)\gamma_5\gamma_\mu q^\mu$$

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

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



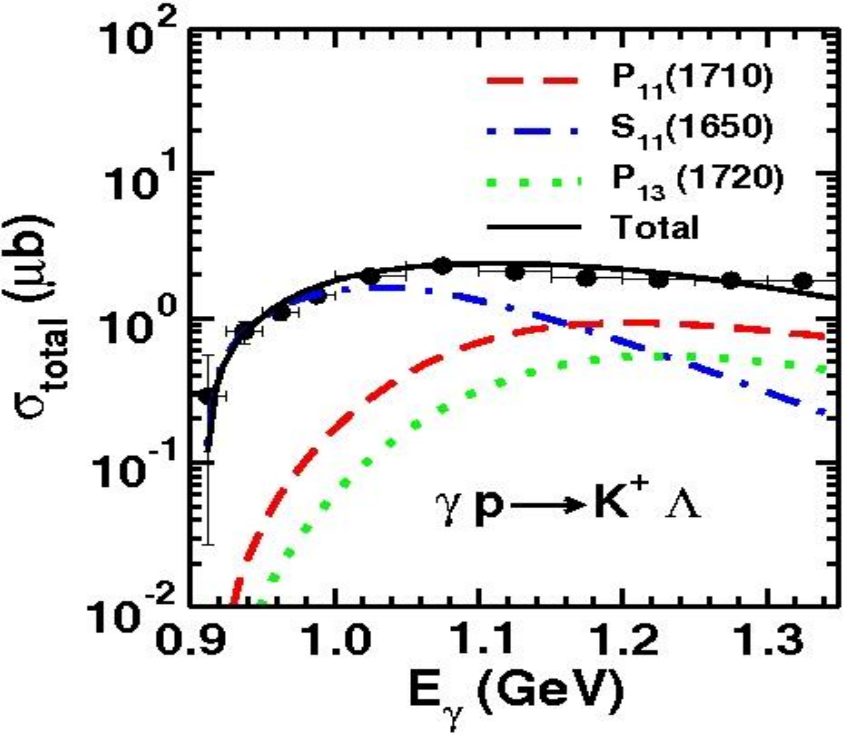
pp → pΛK+ reaction

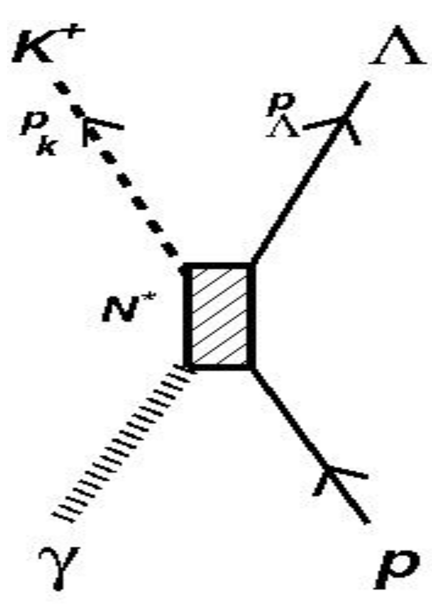


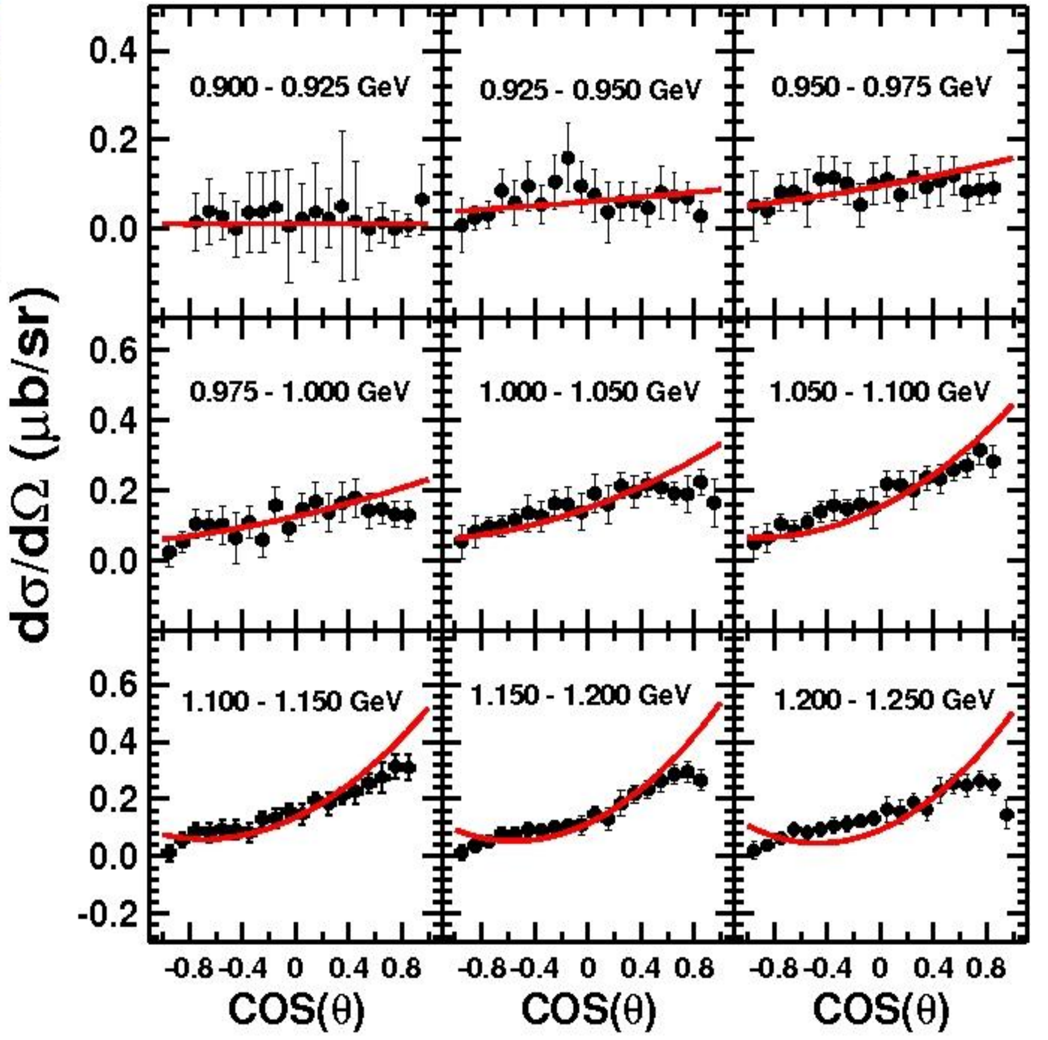
RS, H. Lenske and U. Mosel, Nucl. Phys. 764 (2006) 313

p (γ,K⁺) Λ reaction

RS, K. Tsushima, A.W. Thomas, In prep







Bound state spinors

A mean field approach

Momentum space Dirac Eq.

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

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

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

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

$^{16}O\ (\gamma, K^+)\ ^{16}_{\Lambda}N$, $^{16}O\ (\gamma^*, K^+)\ ^{16}_{\Lambda}N$ Reactions

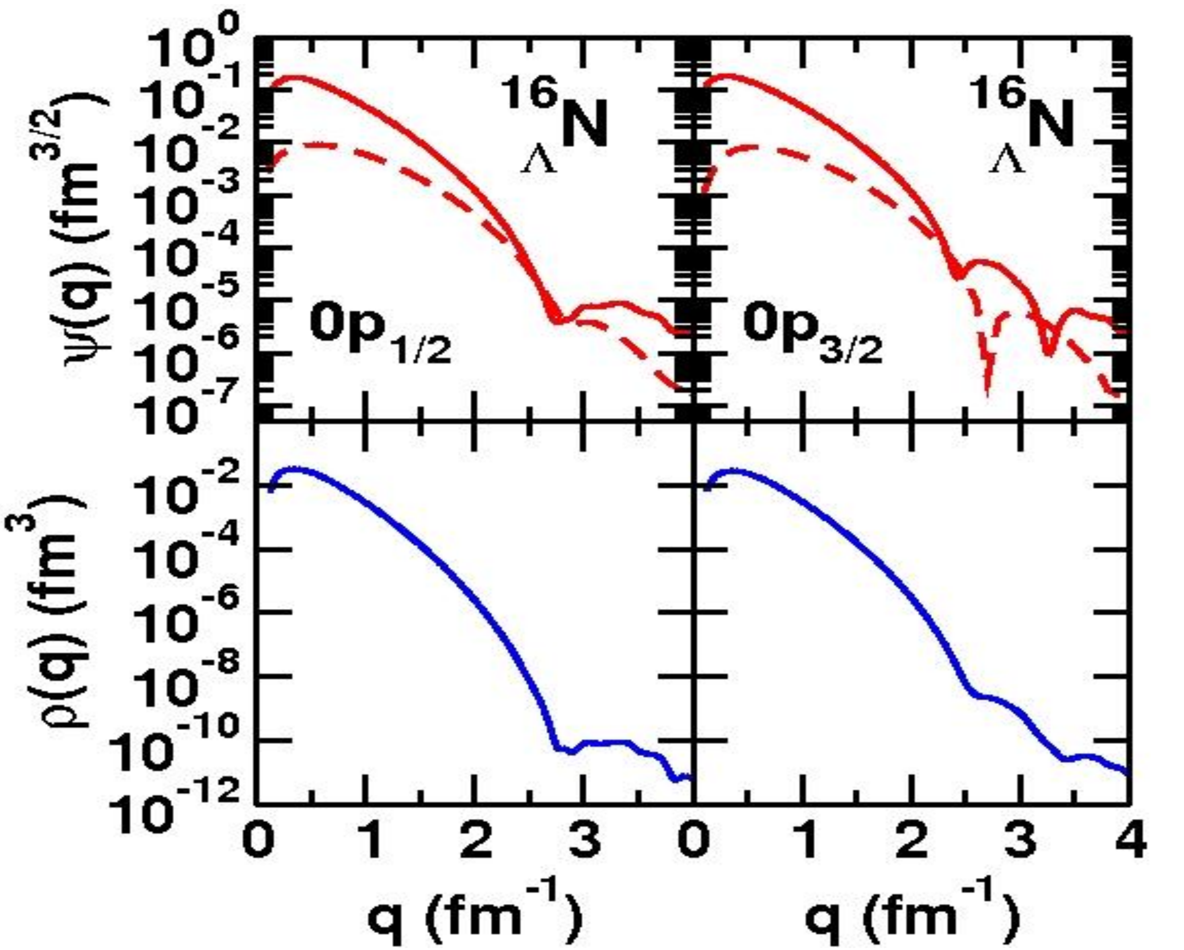
Hole states $B\ (p_{3/2}) - B\ (p_{1/2}) = 6.3$ MeV   Jlab, arXiv: 0810.3852

[$p_{1/2}^{-1}$, s^], [$p_{3/2}^{-1}$, s^], [$p_{1/2}^{-1}$, p^], [$p_{3/2}^{-1}$, p^] $^{16}_{\Lambda}N$ spectrum

Bound Hypernuclear spinors

Single particle model

It is only for
$q << 1.5\ fm^{-1}$
$|g(q)| << |f(q)|$



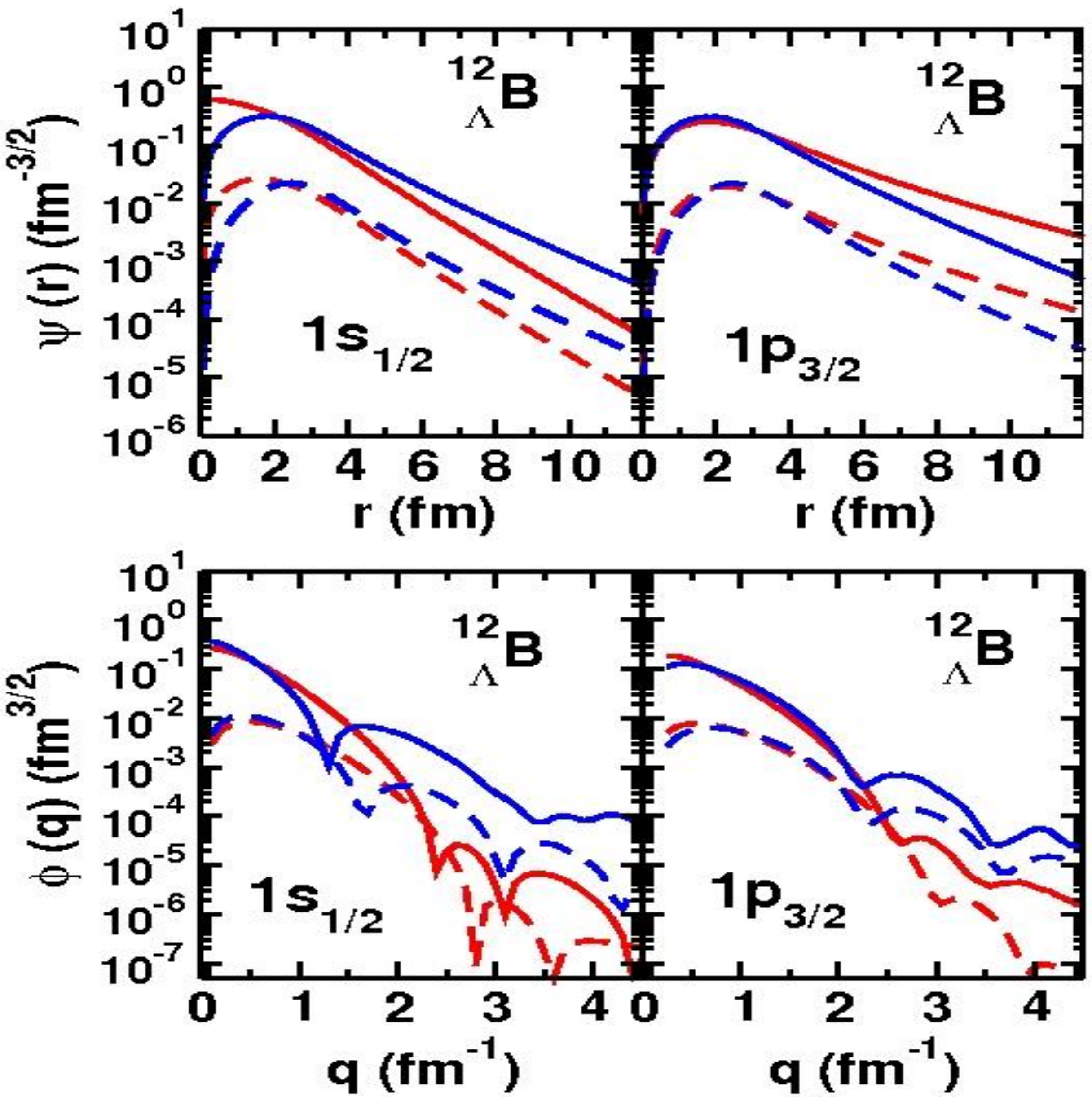
$^{12}C\ (\gamma, K^+)\ ^{12}_{\Lambda}B$, $^{12}C\ (\gamma^*, K^+)\ ^{12}_{\Lambda}B$ Reactions

PRL 99, 052501 (2007)

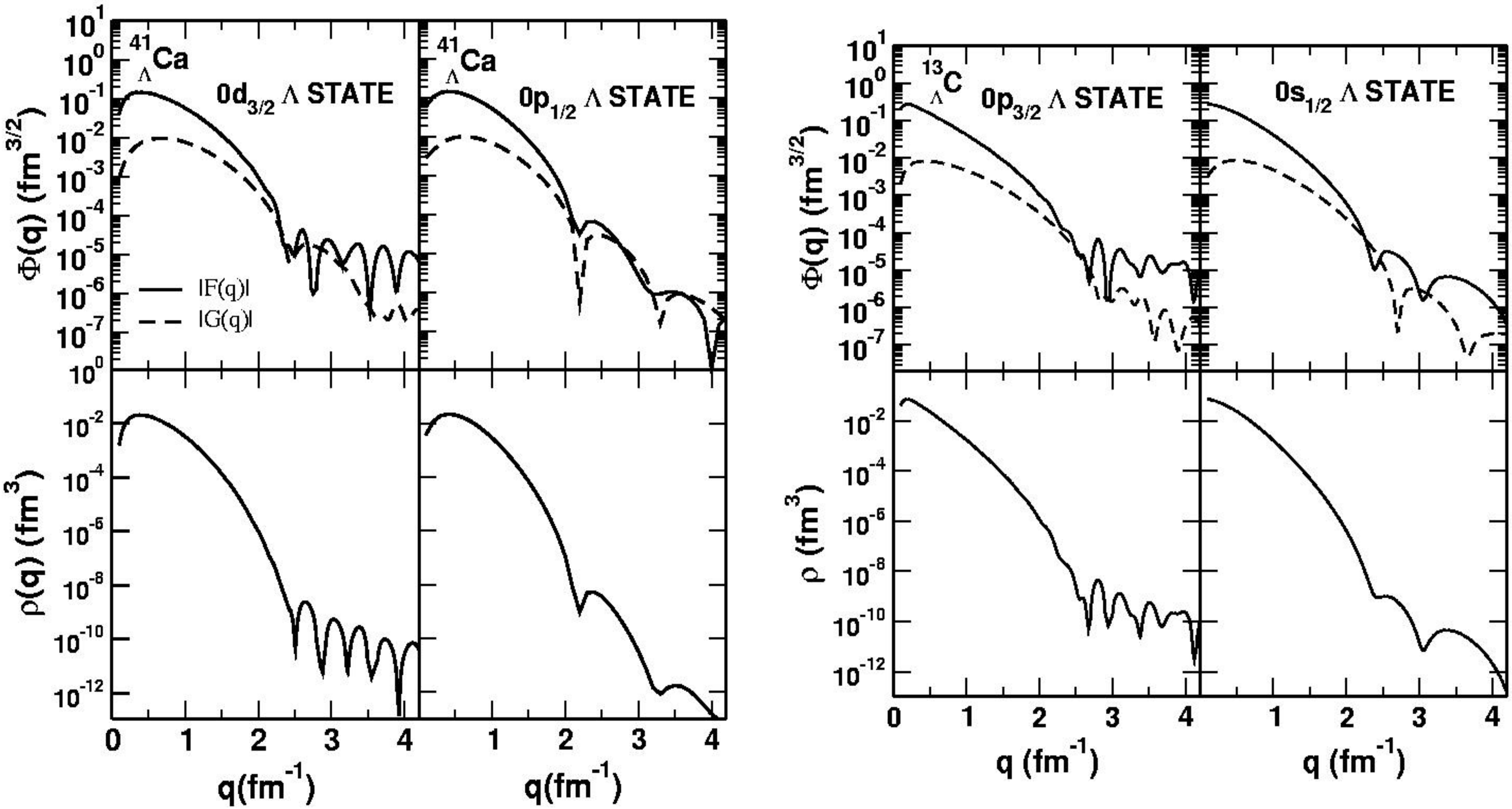
Quark meson Coupling model

Saito, Tsushima, Thomas, Prog. Nucl. Part. Phys. 58, 1-167 (2007).

Single Particle model



Bound Hypernuclear wave spinors



In the region of the momentum transfer of interest, the lower component of the spinor is not negligible.

scattering states

$$\Phi_{pf}(p_K) = \delta(p_K^0 - E_K) \sum_{\ell m} (-)^{\ell} Y_{\ell m}(p_f) Y^*_{\ell m}(p_K) F_\ell(p_K)$$

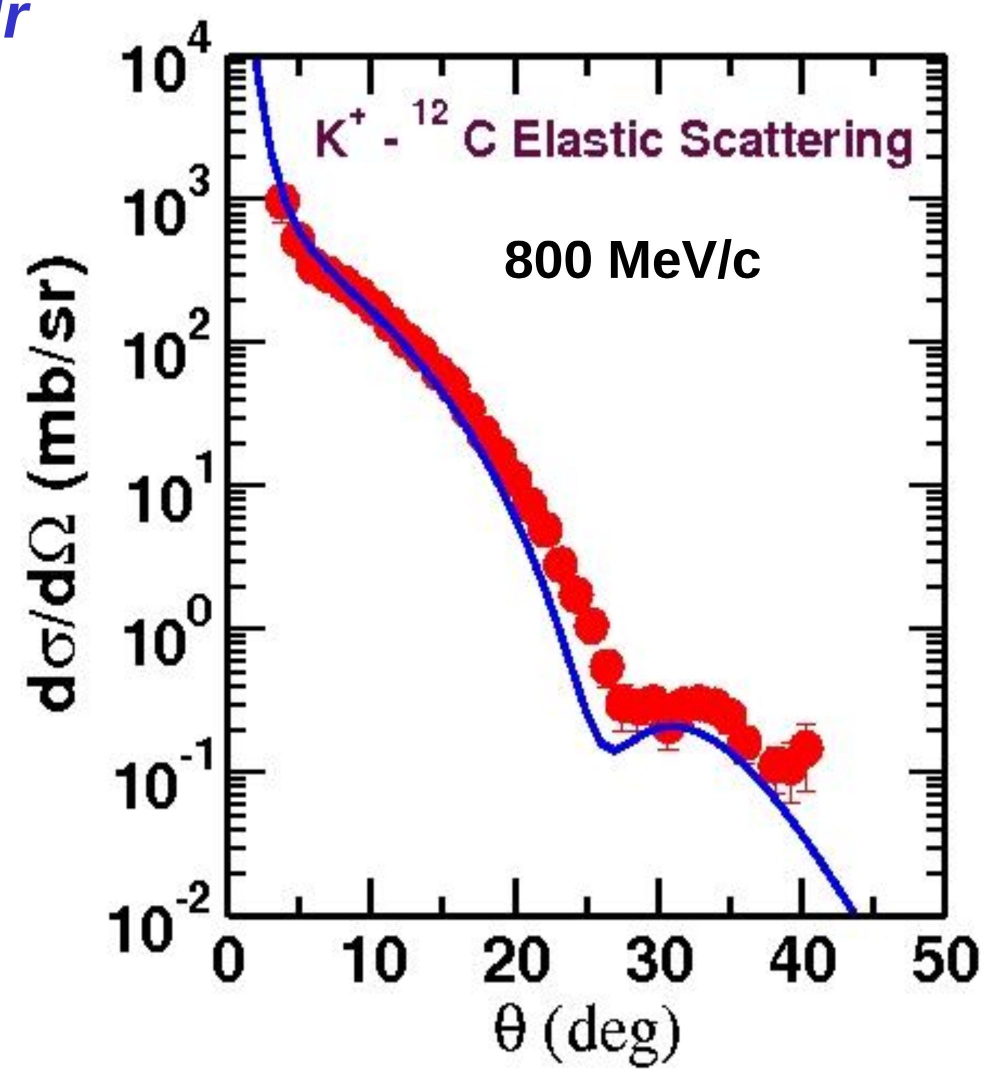
$$F_\ell(p_K) = \int j_\ell(p_K r) f_\ell(p_f, r) r^2 dr$$

Kaon optical potential

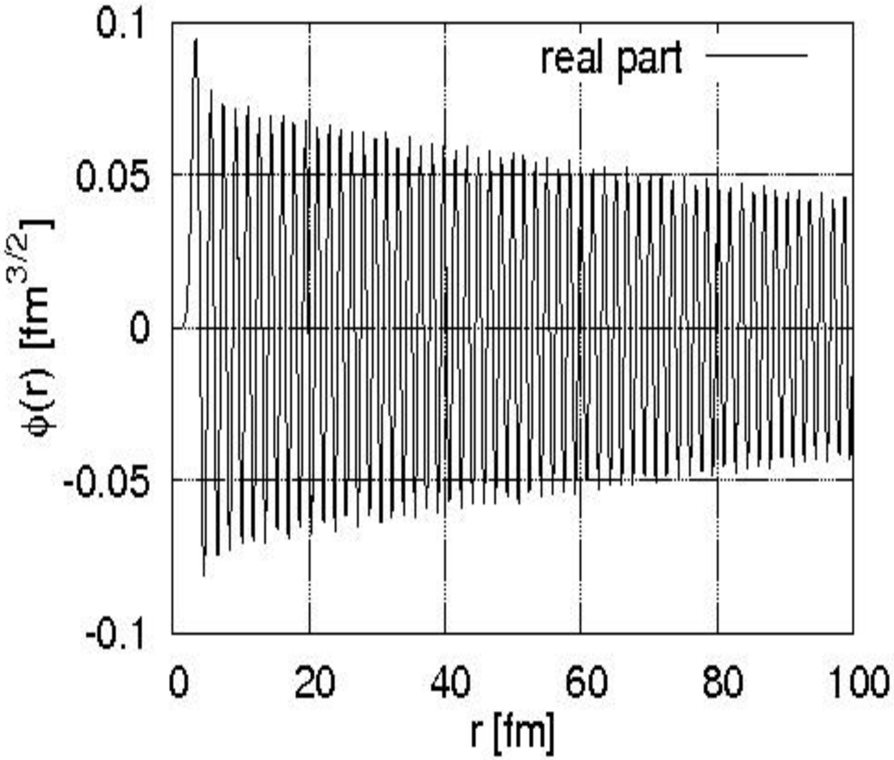
$$2EV_K(r) = -Ab_0 k^2 \rho(r) + Ab_1 \nabla.\rho\nabla$$

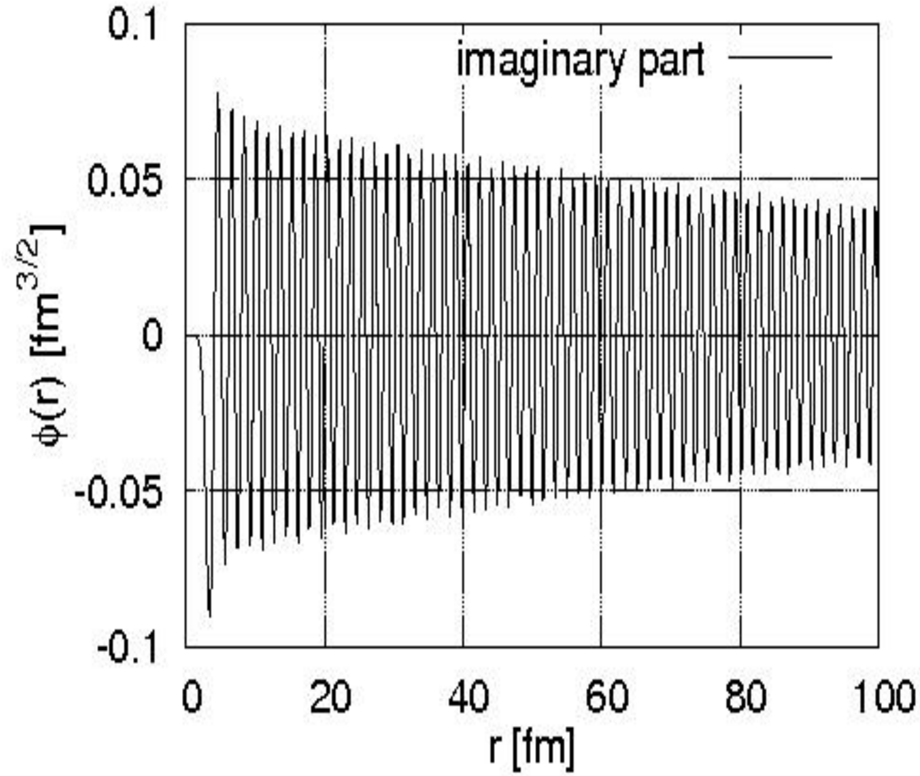
b_0 and b_1 are parameters of the potential

This provides $f_\ell(p_f, r)$



$$F_\ell(p_K) = \int_0^\infty j_\ell(p_K r)\, f_\ell(p_f, r)\, r^2\, dr$$





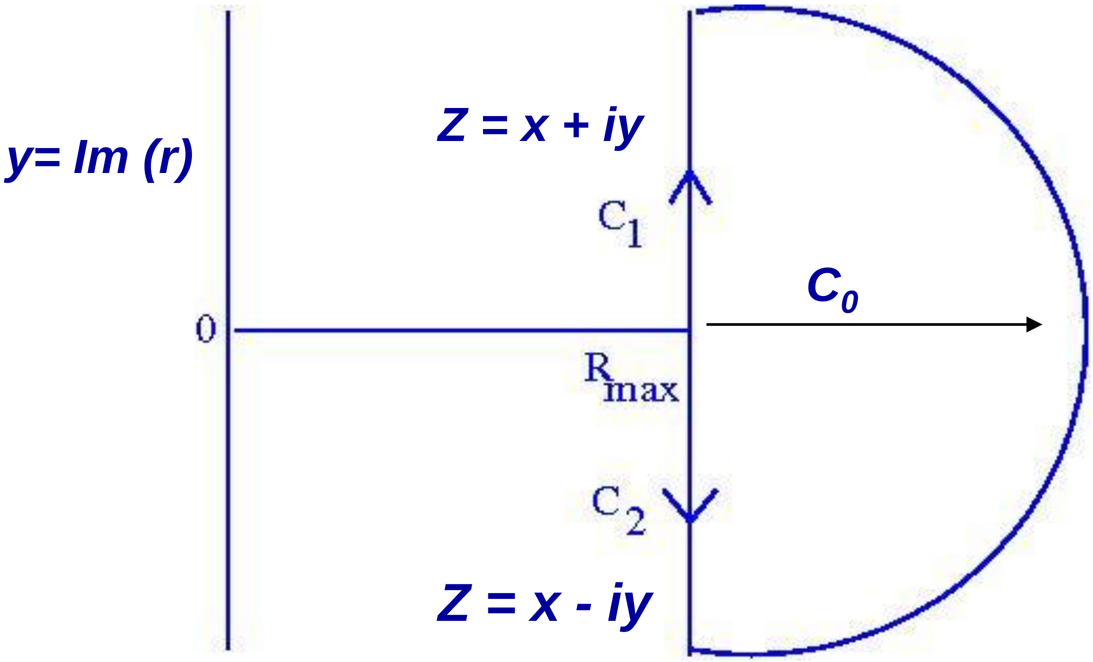
Scattering wave function in momentum space

$$F_\ell(p_K) = \int_0^\infty j_\ell(p_K r)\, f_\ell(p_f, r)\, r^2\, dr$$

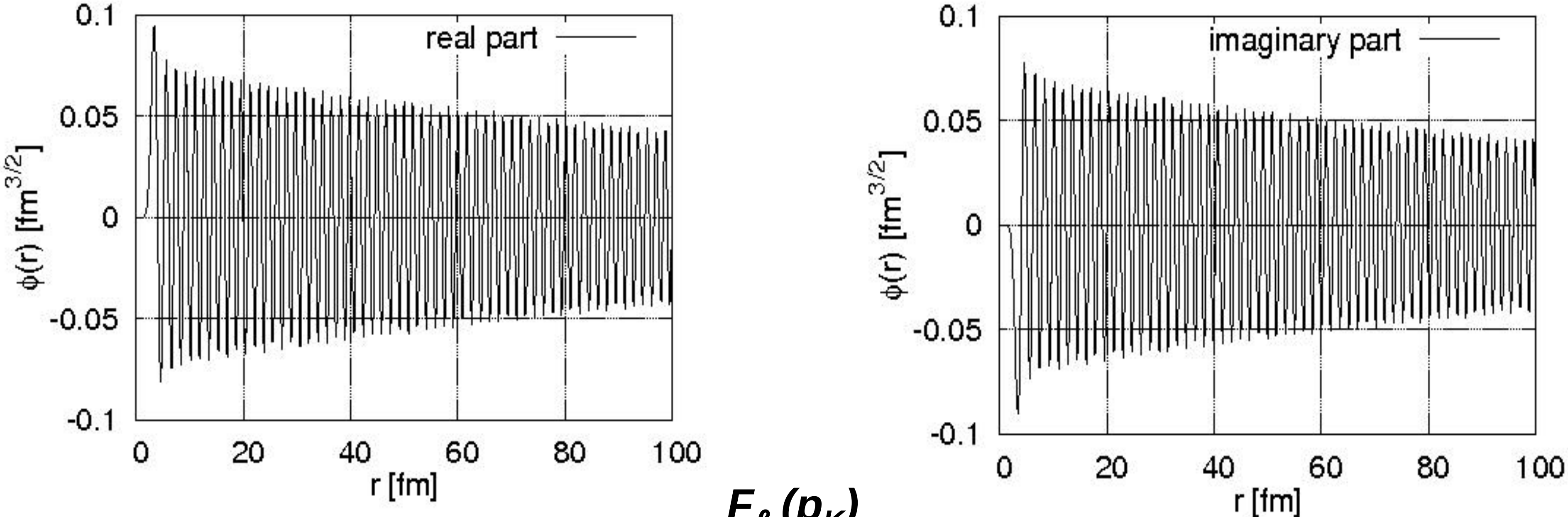
$$= \int_0^{R_{max}} j_\ell(p_K r)\, f_\ell(p_f, r)\, r^2\, dr + \int_{R_{max}}^\infty j_\ell(p_K r)\, f_\ell(p_f, r)\, r^2\, dr$$

$$h^1_\ell(p_K r) + h^2_\ell(p_K r) \qquad H^-_\ell(p_f r) - S_\ell H^+_\ell(p_f r)$$

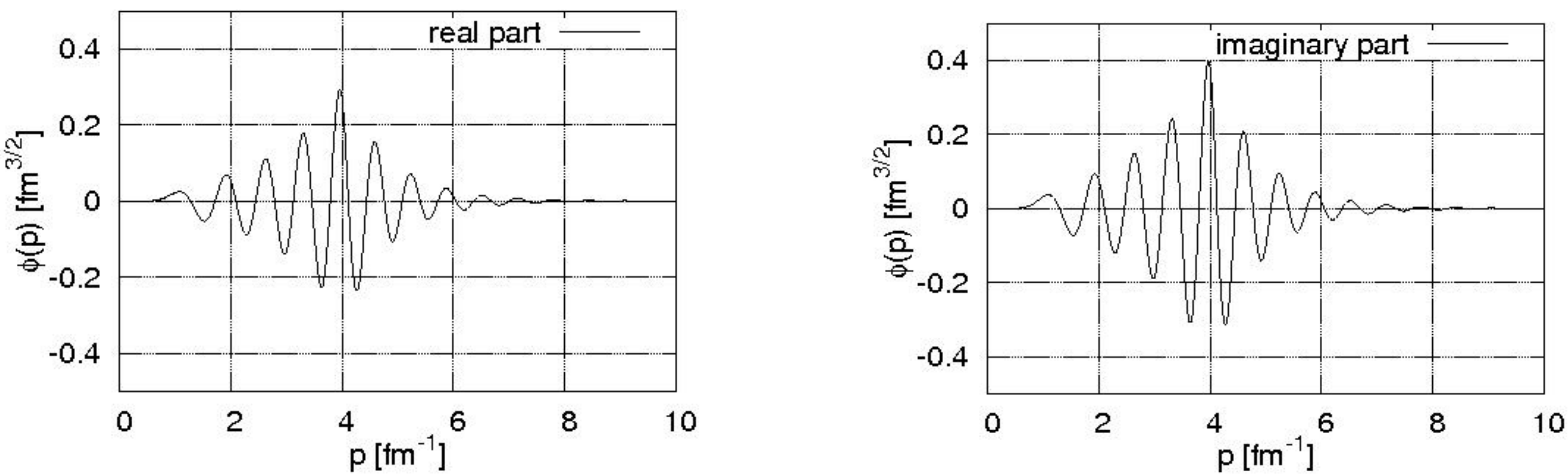
$$I_2 = \exp[\pm i(p_K \mp p_f) r]$$



$f_\ell (p_f ,r)$ $\ell = 15$



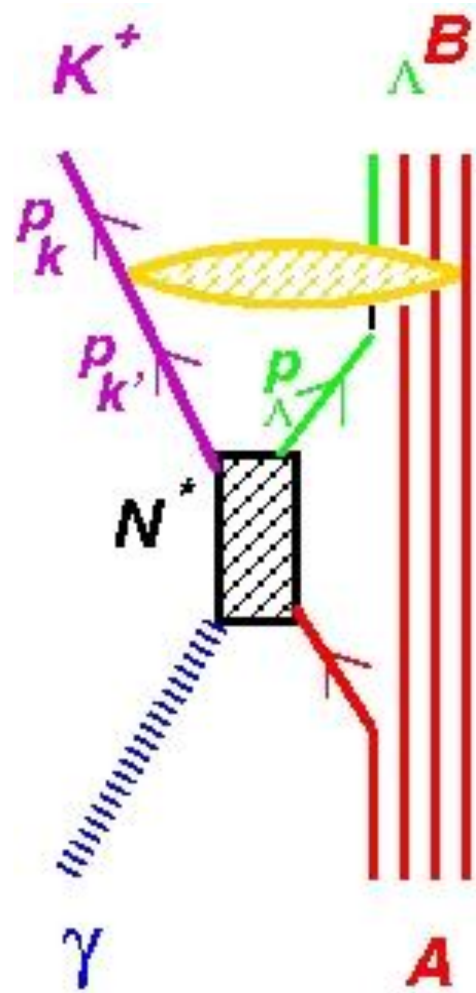
$F_\ell (p_K)$



(γ,K$^+$) reaction on Nuclei

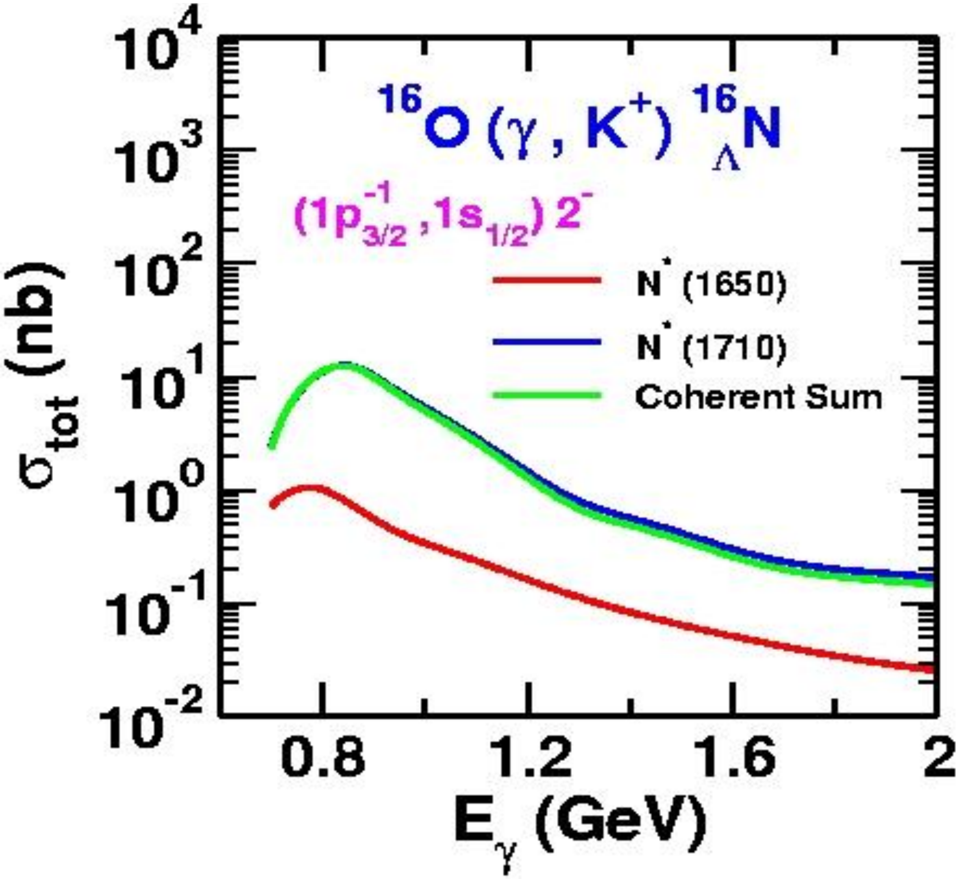
- K$^+$ is weakly absorbing so reaction occurs deep in the nuclear interior.
- *A proton is converted into a Λ, produces neutron rich hypernuclei.*
- Unnatural parity states strongly excited
- $\gamma p \rightarrow \Lambda K^+$ reaction well understood within an effective Lagrangian picture

Excitations of N*(1650), N*(1710), N*(1720) resonances.

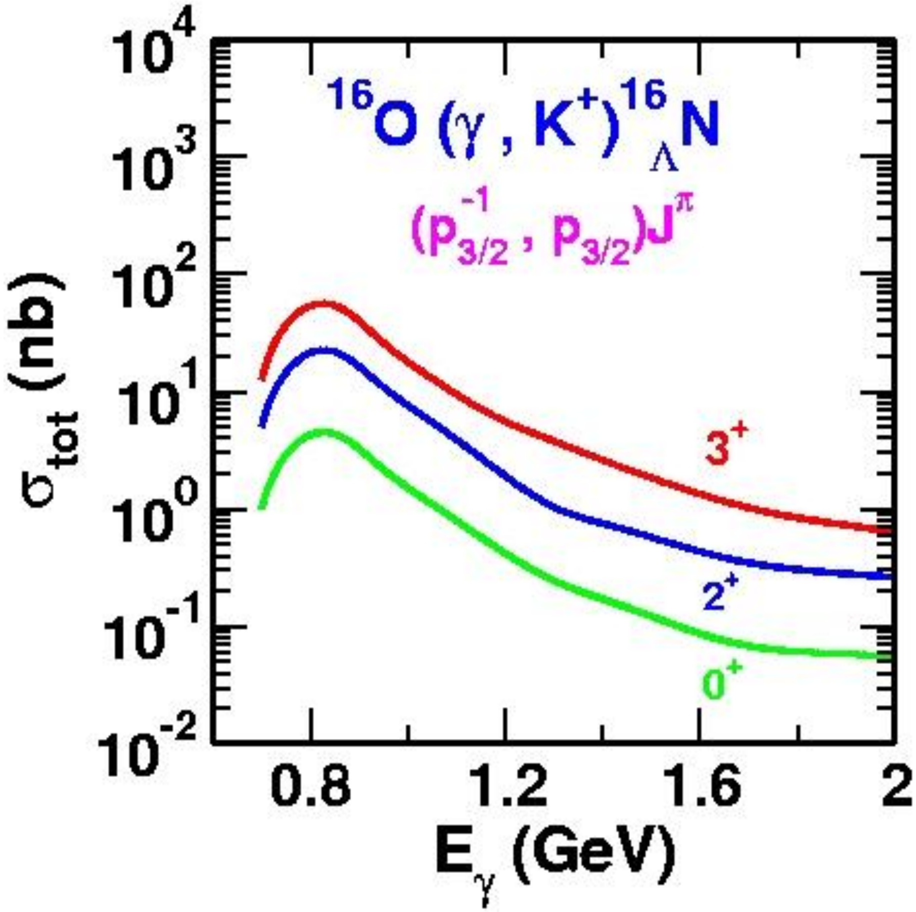


^{16}O (γ,K^+) ^{16}N Reaction

Relative Contribution of Various resonances



Different J excitation



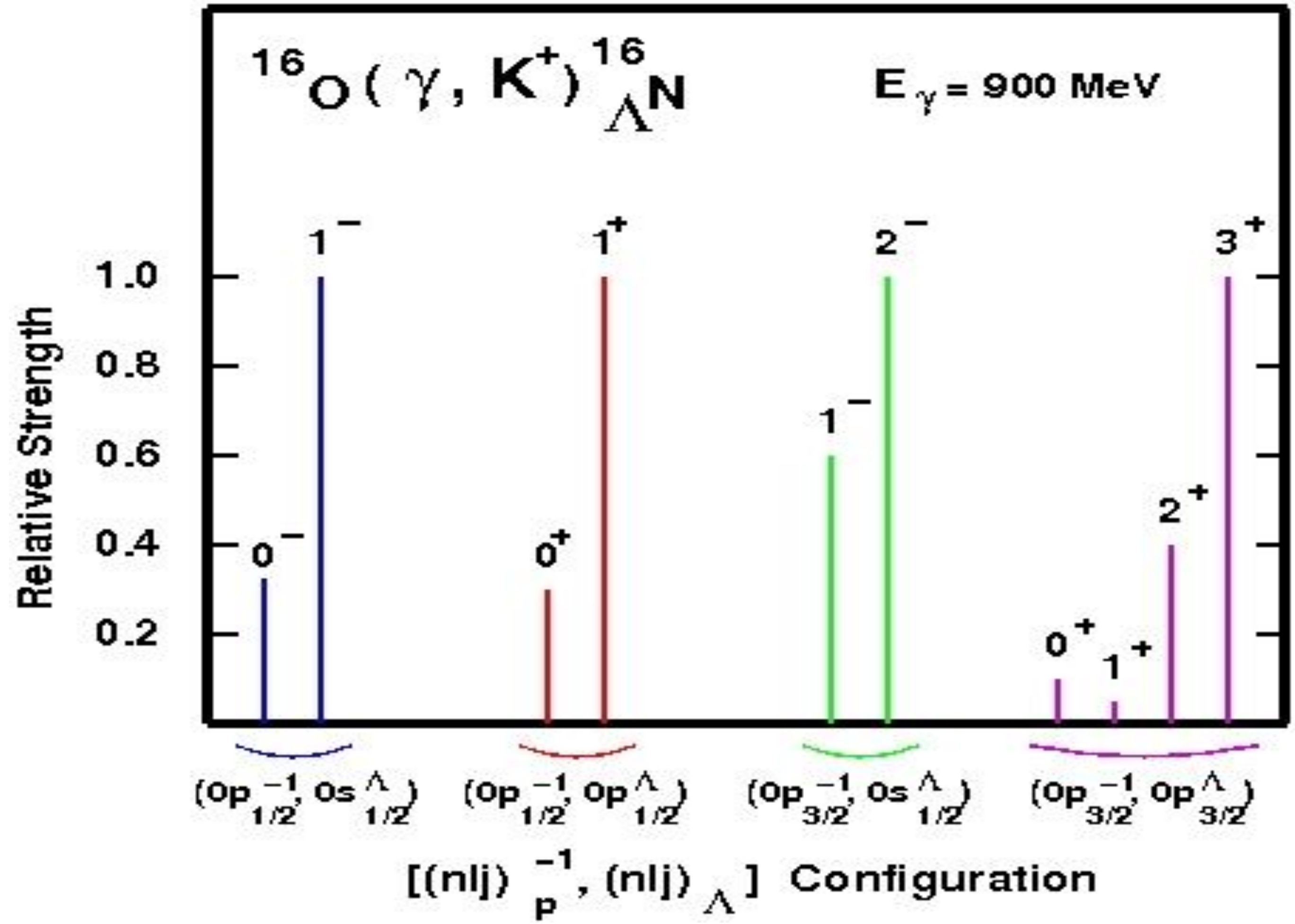
N*(1720) weaker by 3-4 orders of magnitude

Largest J state is dominant

Jlab results from (γ*,K^+)

RS, H. Lenske and U. Mosel, PRC77, 052201 (2008)

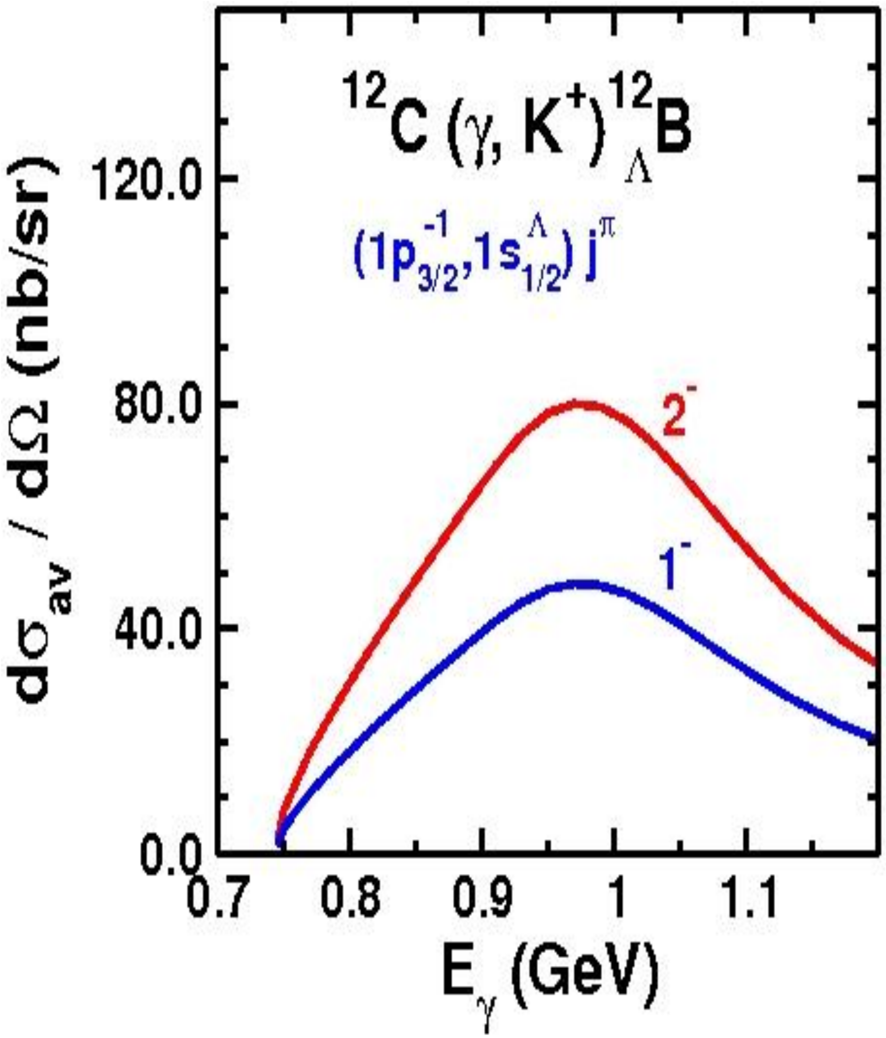
Excitation spectrum of 4 groups of (p^{-1},Λ) states

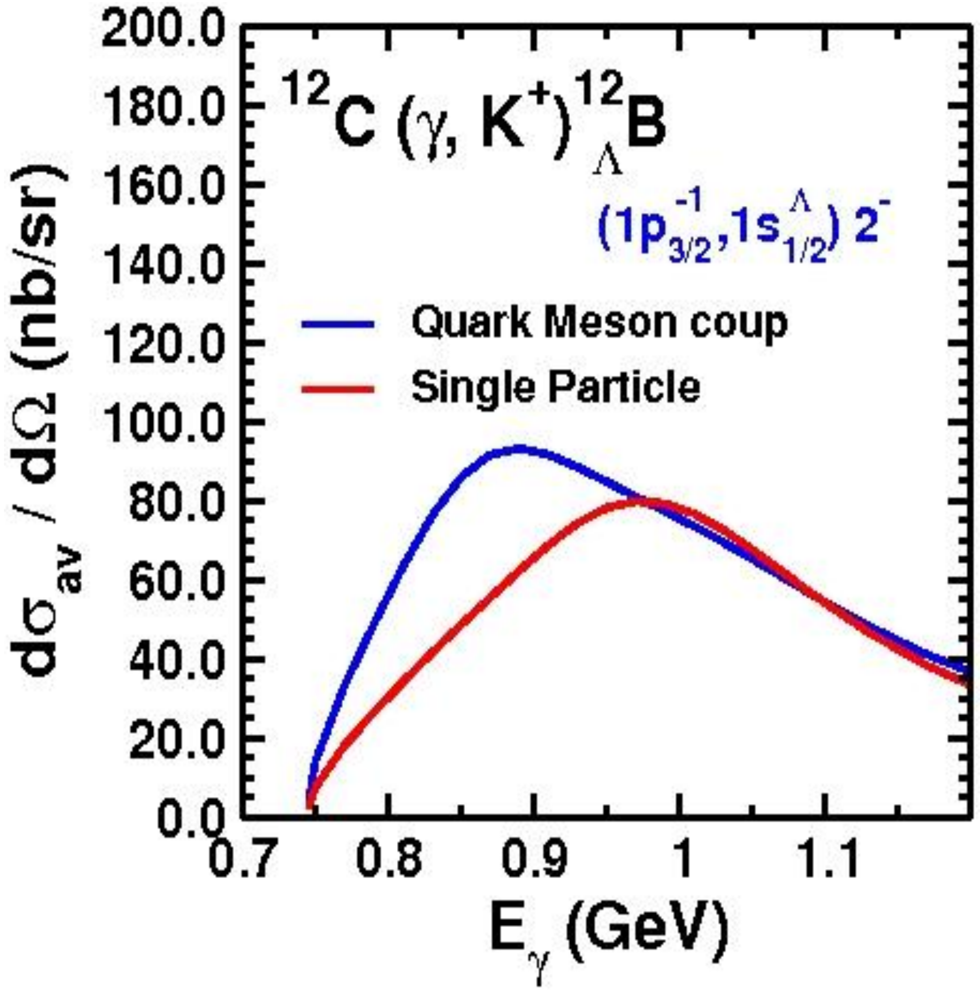


In each group highest *J* is most strong.

Unnatural Parity states dominate.

$^{12}C\ (\gamma, K^+)\ ^{12}_{\Lambda}B$ Reaction

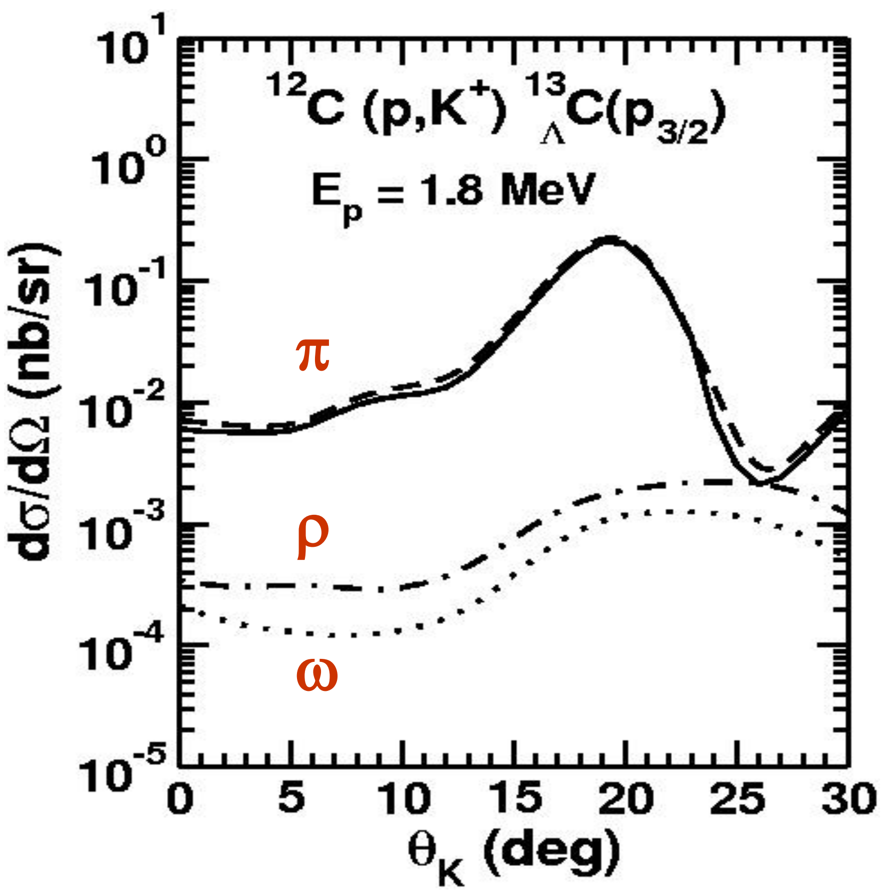


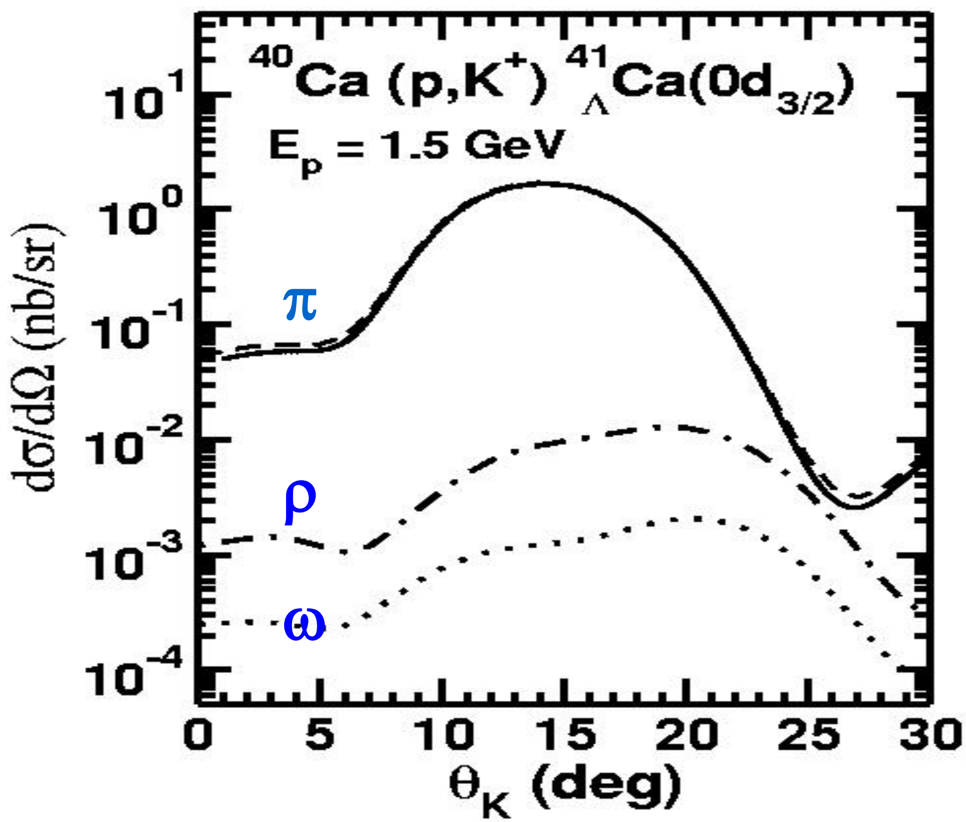


RS, K. Tsushima and A.W. Thomas, In preparation

$A\ (p,K^+)_\Lambda B$

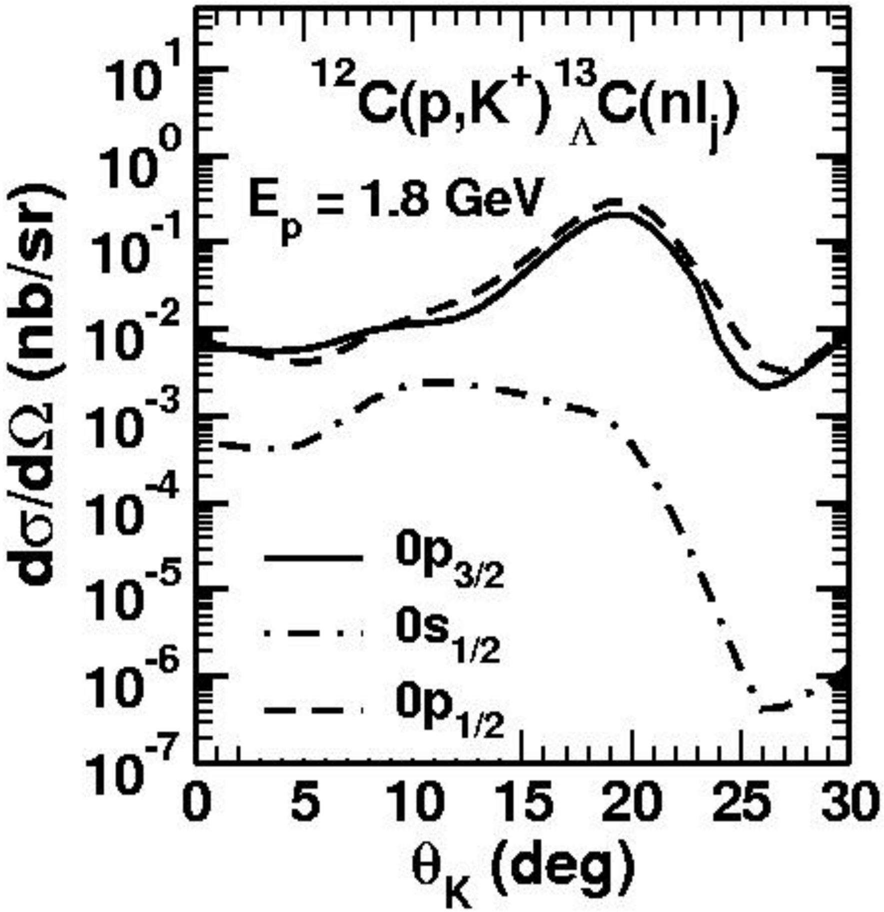
Contributions of Various Meson Exchange Processes

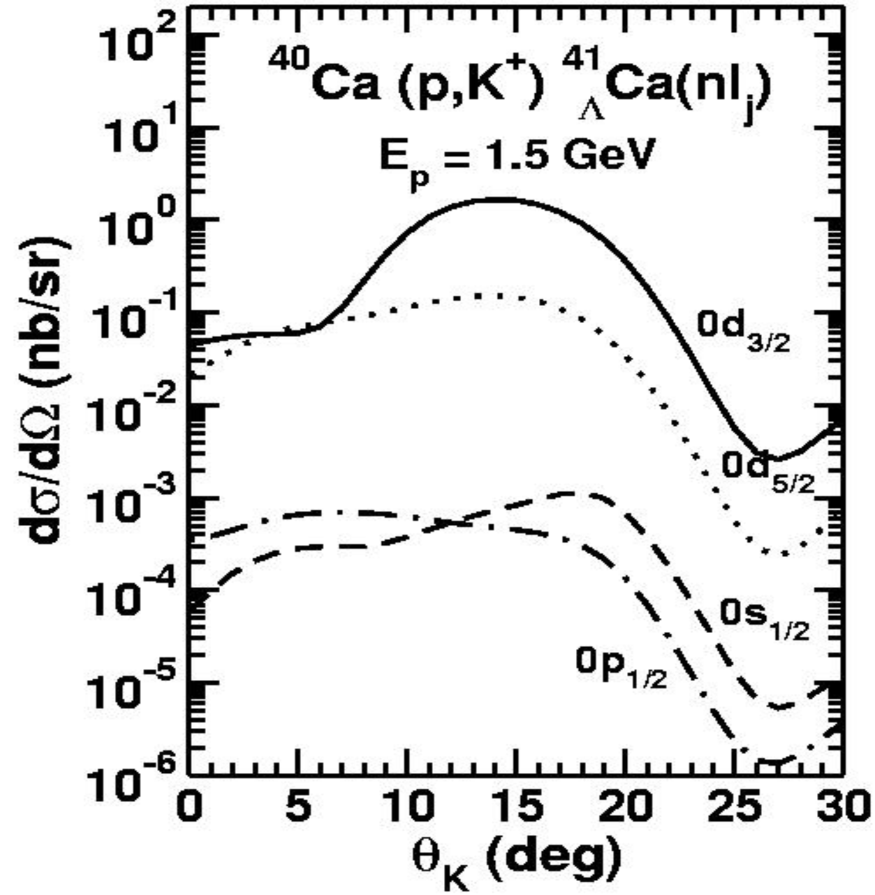




Π exchange dominates, ρ and ω exchange more important at back angles due to large momentum transfers.

Binding energy selectivity





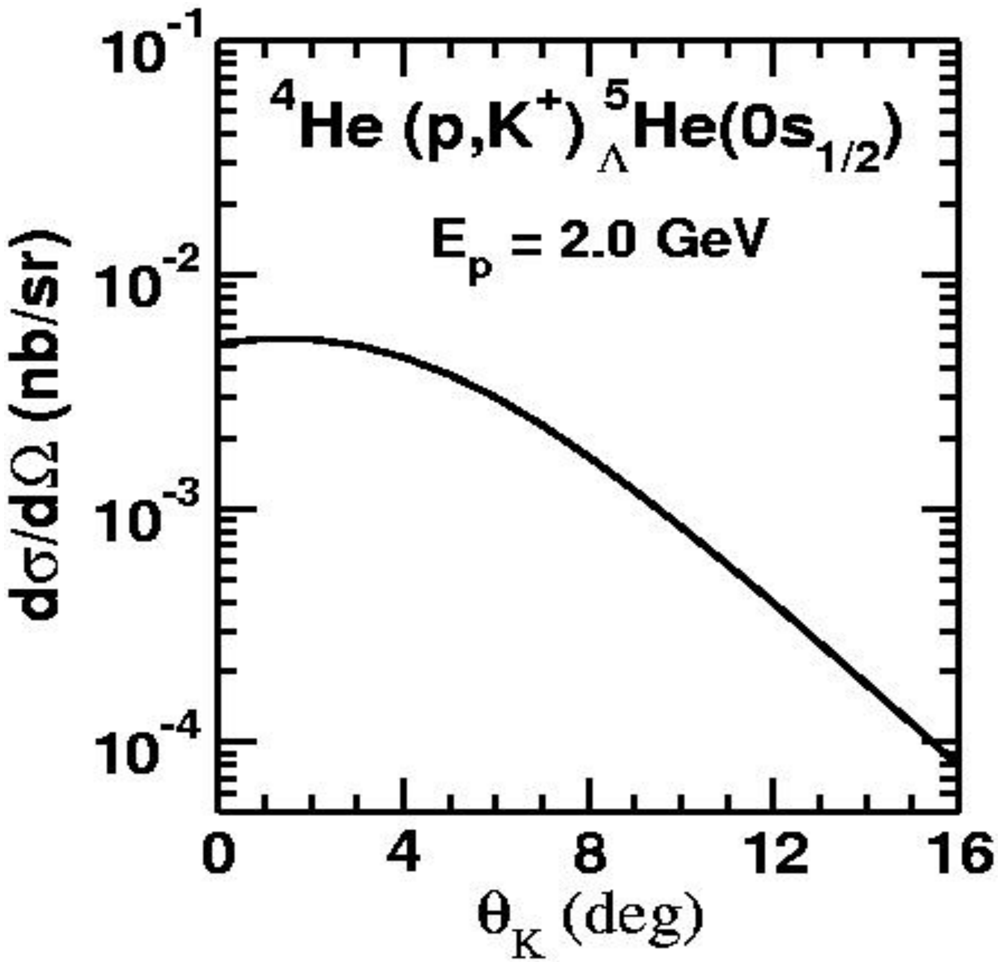
$B_\Lambda(^{13}_{\Lambda}C)$

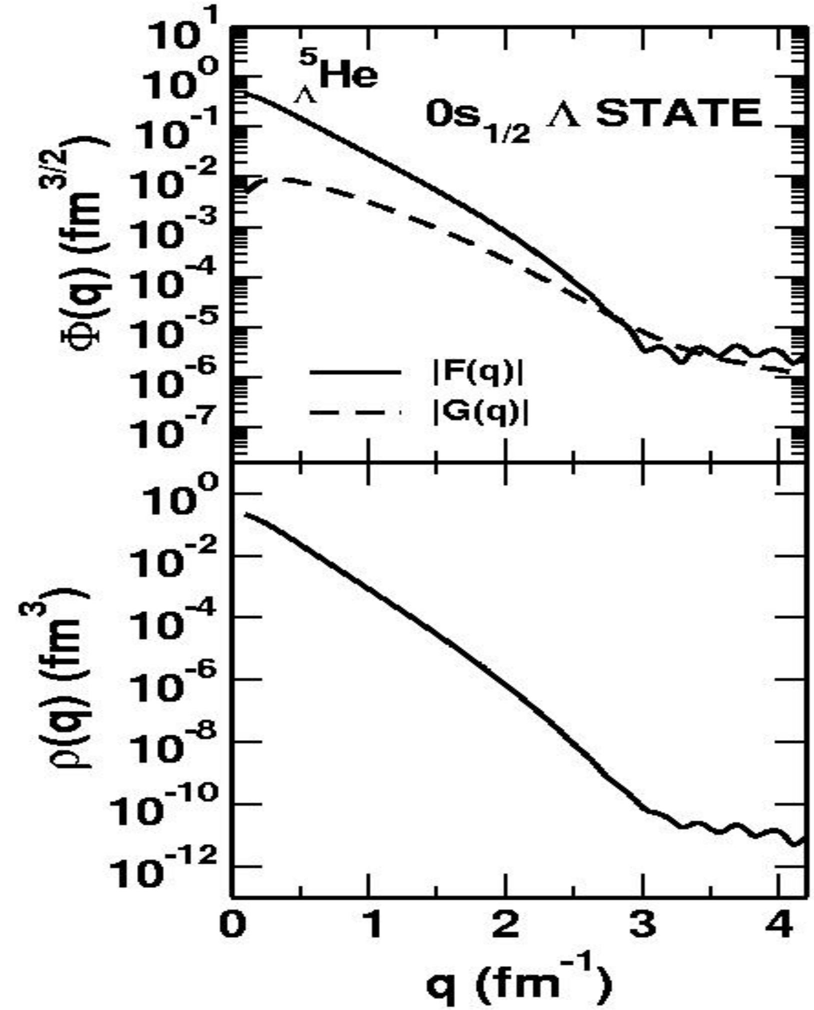
$0p_{1/2}$	0.708 MeV
$0p_{3/2}$	0.860
$0s_{1/2}$	11.690

$B_\Lambda(^{41}_{\Lambda}Ca)$

$0d_{3/2}$	0.753
$0d_{5/2}$	1.544
$0p_{1/2}$	9.140
$0s_{1/2}$	17.882

Results for ^4He target

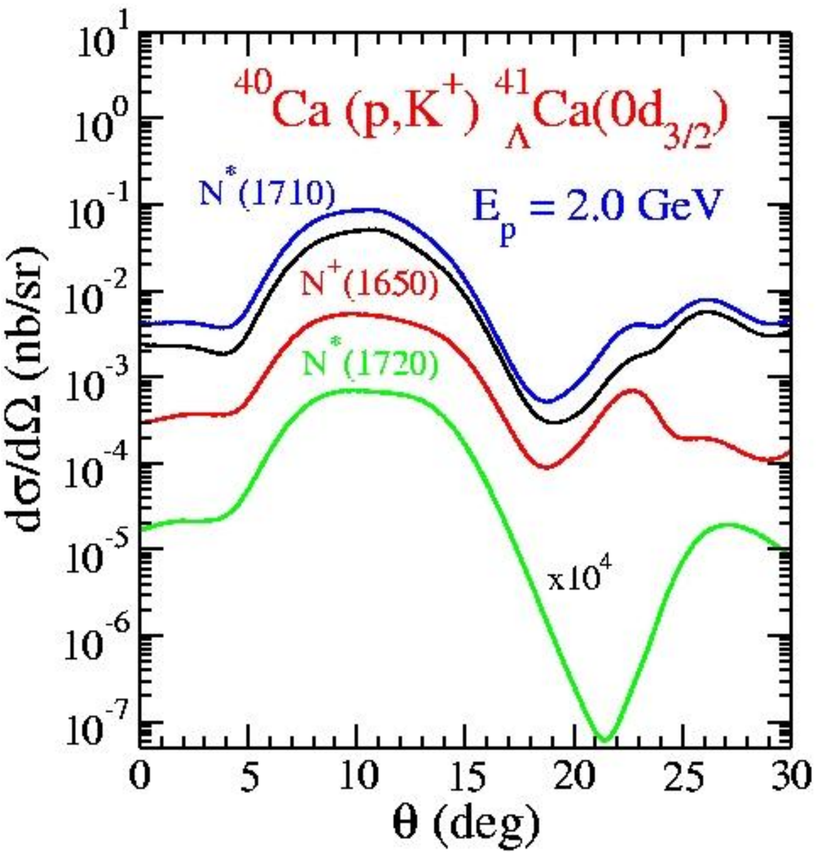




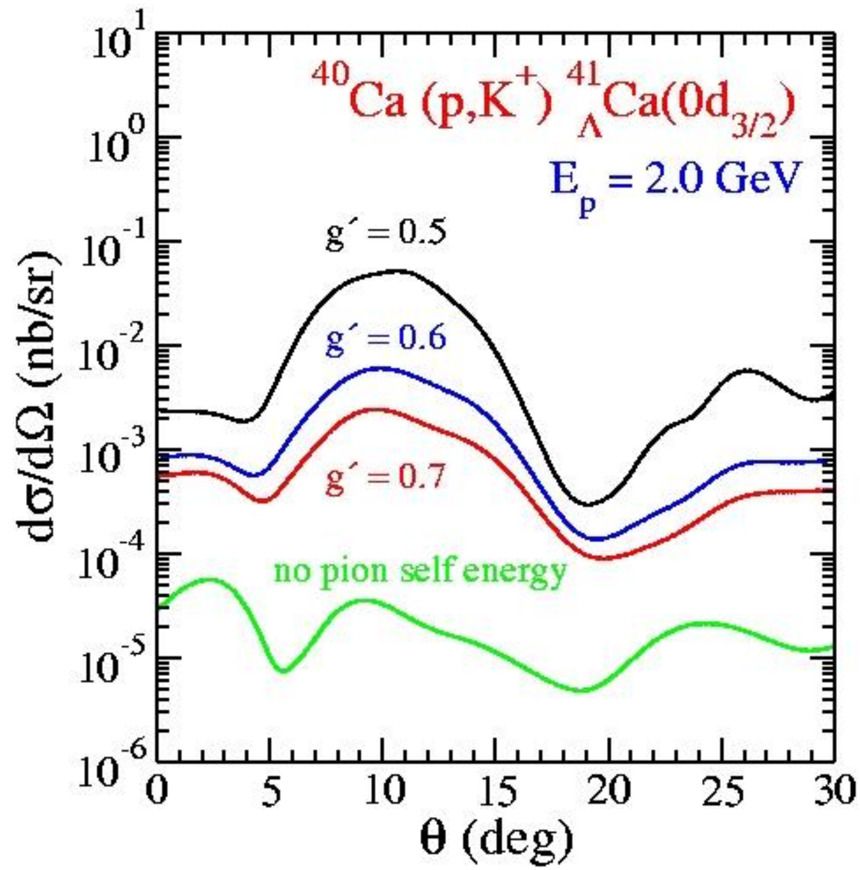
For momentum transfers of interest, Dirac spinors smoothly varying, and are devoid of structures.

$A(p,K^+)_\Lambda B$

Relative Contribution of Various resonances

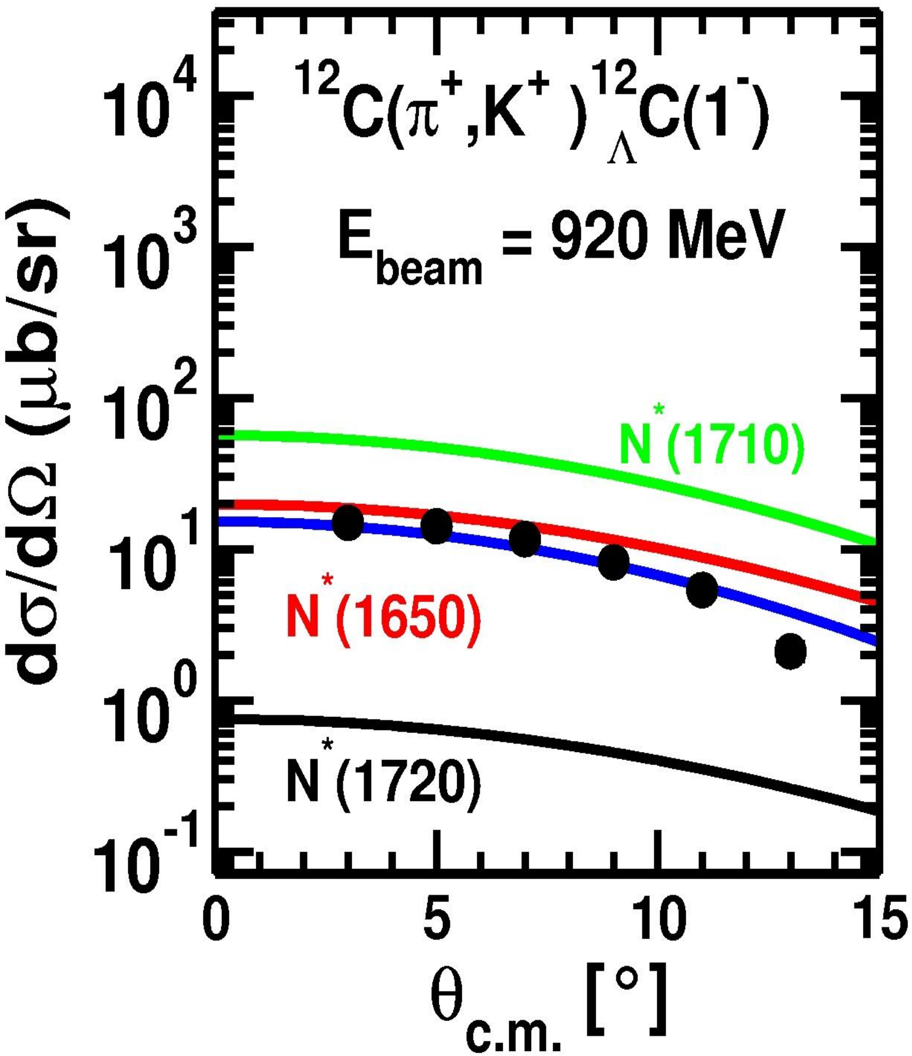


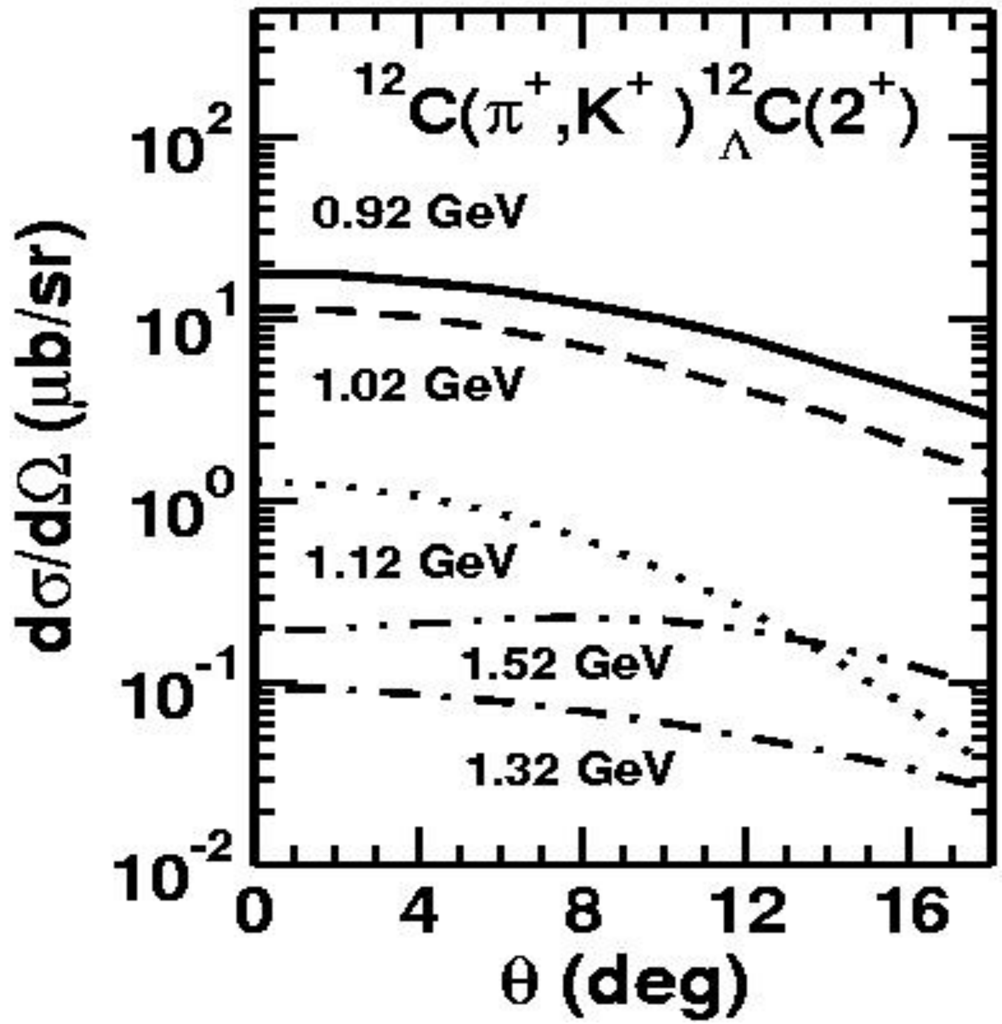
Role of pion self energy



RS, H. Lenske and U. Mosel, Phys. Rev.C 69 (2004) 065205

(π^+, K^+) reaction





N*(1710) dominates in his case too.

S. Bender

SUMMARY AND OUTLOOK

$A(h\gamma, K^+)_\Lambda B$ reactions provide mutually complimentary information about the hypernuclear spectrum.

A fully covariant description of these reactions is desirable and is possible.

Hypernuclear states with largest angular momentum are dominant, typical of large momentum trasfer reactions.

(γ, K^+), (γ^*, K^+) strongly excites also the unnatural parity states.

Tighter constraints on the models of Λ-N interaction

In-medium Chiral Dynamics, orxiv:0709.2298 (Weise)
Quark Meson Coupling Model (Tsushima, A.W. Thomas, Saito, Guichon)

Coll: H. Lenske, U. Mosel, K. Tsushima and A.W. Thomas