Strangeness Electromagnetic Production on Nucleons and Nuclei

Petr Bydžovský

in collaboration with Miloslav Sotona

Nuclear Physics Institute, Řež near Prague, Czech Republic

10th International Conference on Hypernuclear and Strange Particle Physics,
Tokai, Japan, September 14 - 18, 2009

Outline:

- Introduction
- Photo- and electroproduction of kaons on nucleons
- Photoproduction of K^0 on deuteron
- Electroproduction of hypernuclei
- Summary

Introduction – motivation

I. *Elementary production*

- *The reaction mechanism* – Quark models or effective Lagrangian theory?
- *Nucleon and hyperon resonances* - mass (“missing” resonances), couplings and form factors;
- *Hypernucelus-production calculations* – precise knowledge of the elementary amplitude is important for good predictions of hypernuclear cross sections;

II. *Production of hypernuclei*

- No Pauli blocking for Λ – transparent shell structure - *dynamics of many-body hadronic systems* can be studied (nuclear models);

- *YN interaction in the nuclear medium*

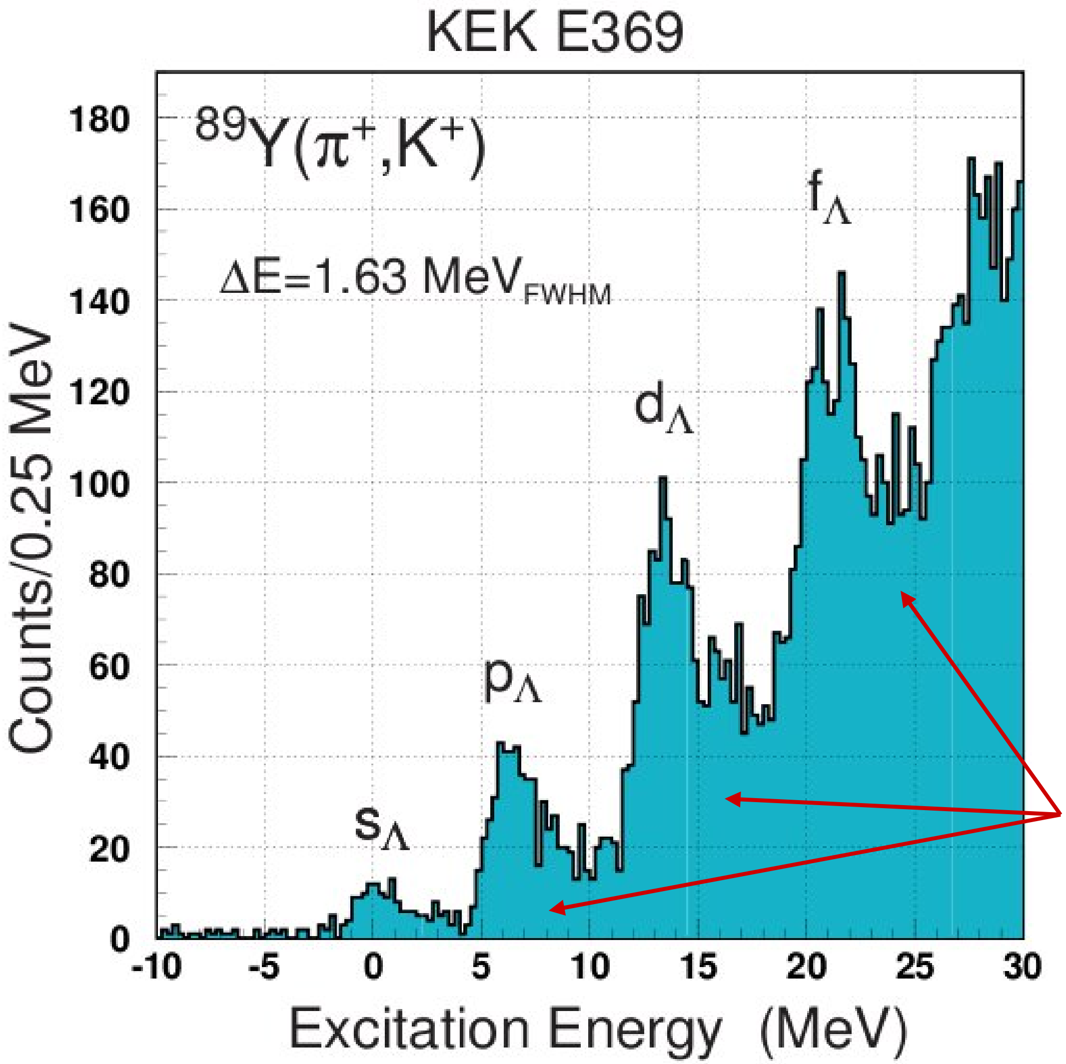
  - spin dependent parts (from ΛN scattering data only averaged s-state interaction is known),

  - Λ–Σ mixing and charge symmetry;

- *Non mesonic weak decays of* Λ : $\Lambda N \rightarrow nN$ (Γ_n/Γ_p)

- *Modifications of* Λ *properties in the nuclear medium* (e.g. magnetic moment)

Λ hyperon occupies *s, p, d,* and *f* shell orbits in $^{89}Y_{\Lambda}$



- Λ single particle states are well defined

- description of the nucleus in terms of baryons is reasonable

multiplets of states

Hotchi et al, Phys. Rev. C 64 (2001) 044302

Photo- and electroproduction of kaons on nucleons

$$e + N \rightarrow e' + K + Y$$

6 channels: $N = p,\ n;\quad Y = \Lambda,\ \Sigma;\quad K = K^{+},\ K^{0}$

One-photon approximation – the electromagnetic and hadron parts can be separated

The unpolarized cross section in lab frame:

$$\frac{d^3\sigma}{dE_{e'}\,d\Omega_{e'}\,d\Omega_K} = \Gamma\left[\frac{d\sigma_T}{d\Omega_K} + \varepsilon\frac{d\sigma_L}{d\Omega_K} + \varepsilon\frac{d\sigma_{TT}}{d\Omega_K}\cos 2\Phi + \sqrt{\varepsilon(\varepsilon+1)}\frac{d\sigma_{TL}}{d\Omega_K}\cos\Phi\right]$$

Models for $\gamma_{(v)} + N \rightarrow K + Y$

- **Isobaric model**;
- Multipole analysis (*T. Mart and A. Sulaksono*);
- Regge formalism (*M. Guidal et al., E_γ > 4 GeV*);
- Quark model (*Zhenping Li et al.*);
- Regge-plus-resonance model (*T. Corthals et al.*);
- Unitary approach (*G. Penner, T. Feuster, and U. Mosel; B. Julia-Diaz et al., A. Usov and O. Scholten*);
- Chiral perturbation theory (*S. Steininger and U.-G. Meissner*);
- Chiral unitary framework (*B. Borasoy et al.).*

Isobaric model for $\gamma_{(v)} + N \rightarrow K + Y$

- *Meson-baryon final-state interaction neglected*: **T = V**

  - violation of unitarity (single-channel calculations),

  - coupling constants absorb a part of the rescattering effects;

- *The driving term*

  - an effective hadron Lagrangian,

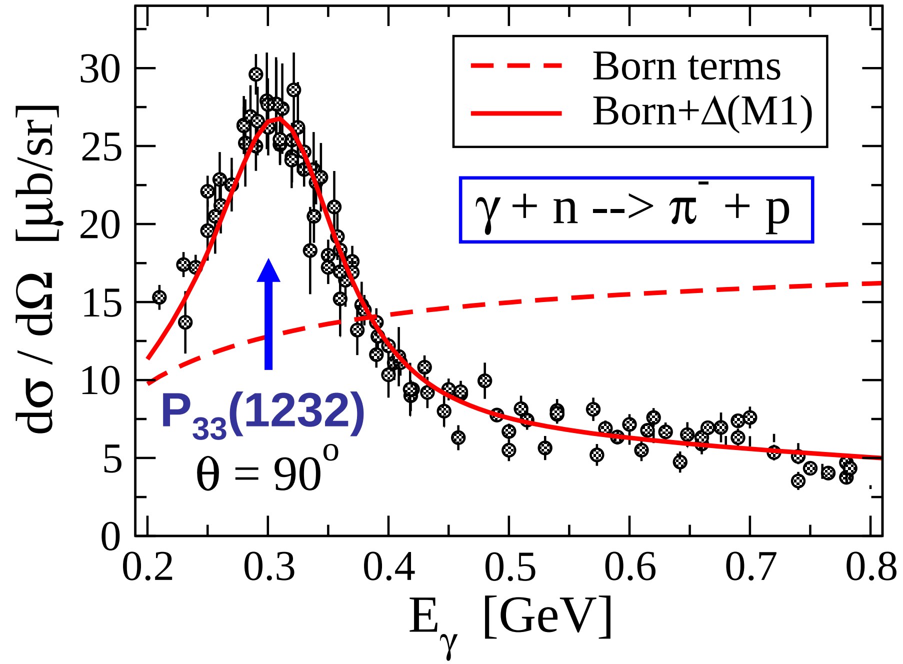
  - the perturbation theory on the tree-level approximation (*s, t,* and *u*-channel Feynman graphs),

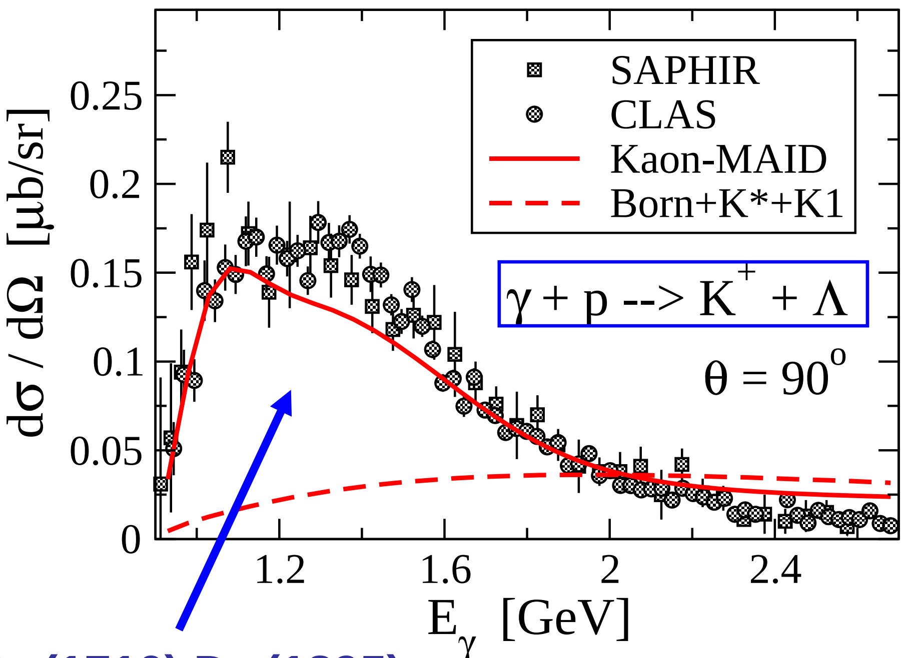
  - coupling constants are fitted to experimental data from JLab (CLAS), ELSA(SAPHIR), SPring-8(LEPS), ESFR(GRAAL), LNS and MAMI ($d\sigma/d\Omega$, σ^{tot}, P, Σ, T)

- No dominant resonance in $p(\gamma,K^+)\Lambda$

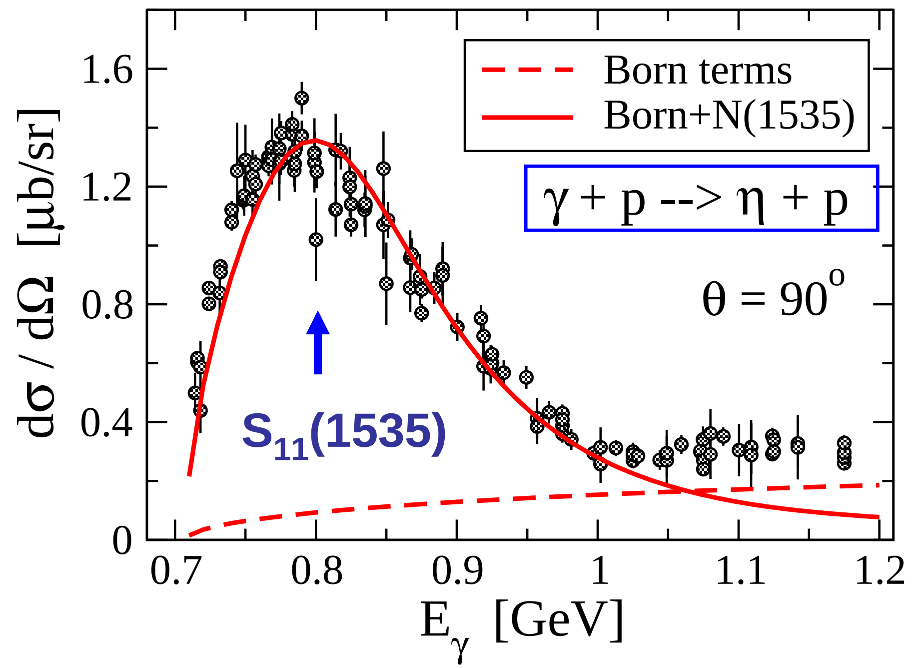
- many resonances (20 - 30) with a reasonable branching ratio to the KΛ channel are assumed

=> *large number of models for $p(\gamma,K)\Lambda$ with a good χ^2*





$P_{11}(1710), D_{13}(1895), \ldots$

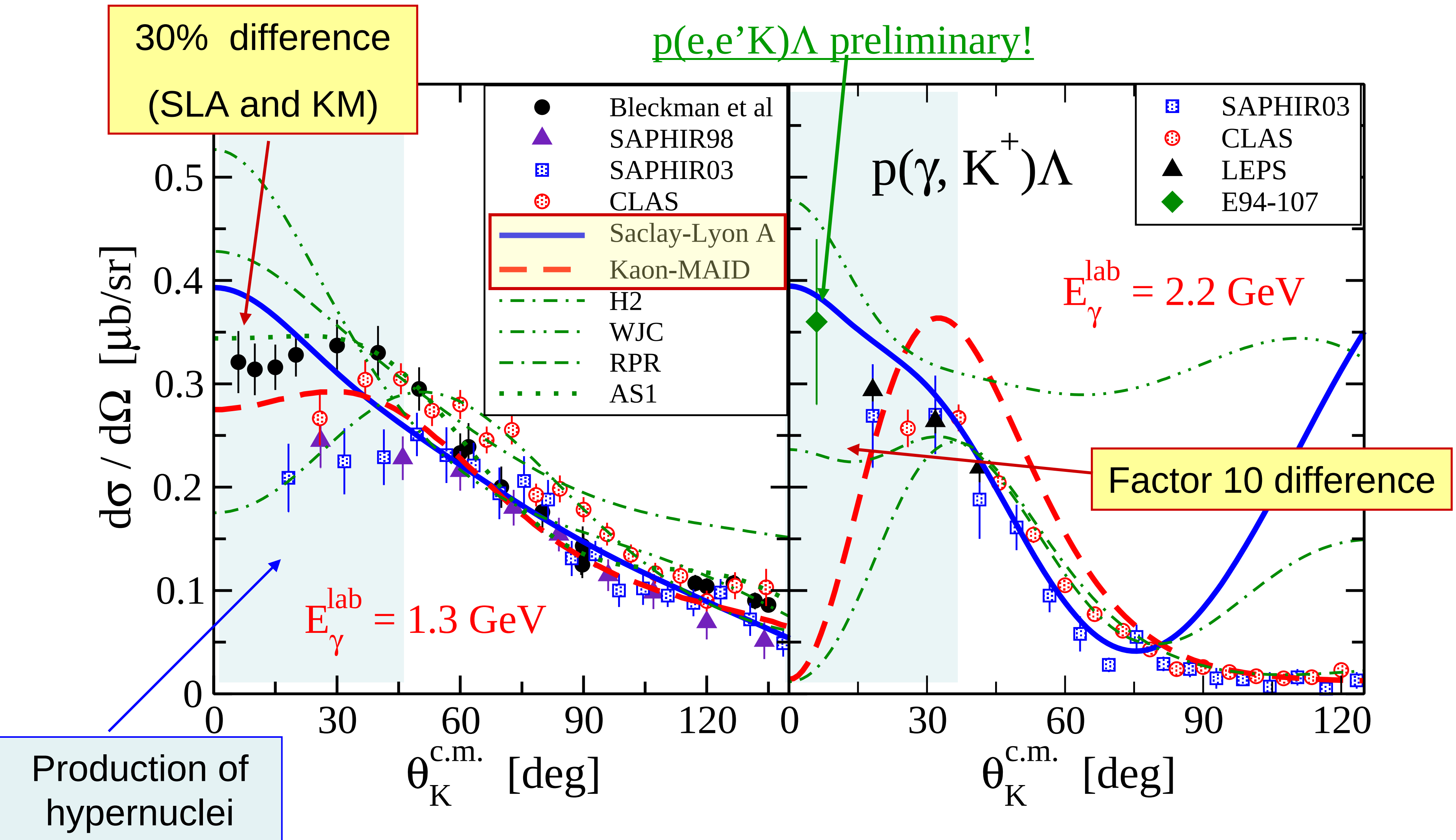


- Constraints on the models
  - SU(3) symmetry ($g_{KN\Lambda}$ and $g_{KN\Sigma}$ are related to $g_{\pi NN}$)
  - crossing symmetry ($\gamma p \to K^+\Lambda \quad \Leftrightarrow \quad K^- p \to \gamma\Lambda$)
  - duality hypothesis
- Form factors
  - electromagnetic vertex (*M.F. Gari and W. Krumpelmann*)
  - hadronic vertex – violation of gauge invariance – a contact term is included to restore the invariance *(H. Haberzettl)*
- Example of isobaric models for the KΛ channel
  - models include: *Born terms (p, Λ, Σ, K), K*(890) and K_1(1270)*

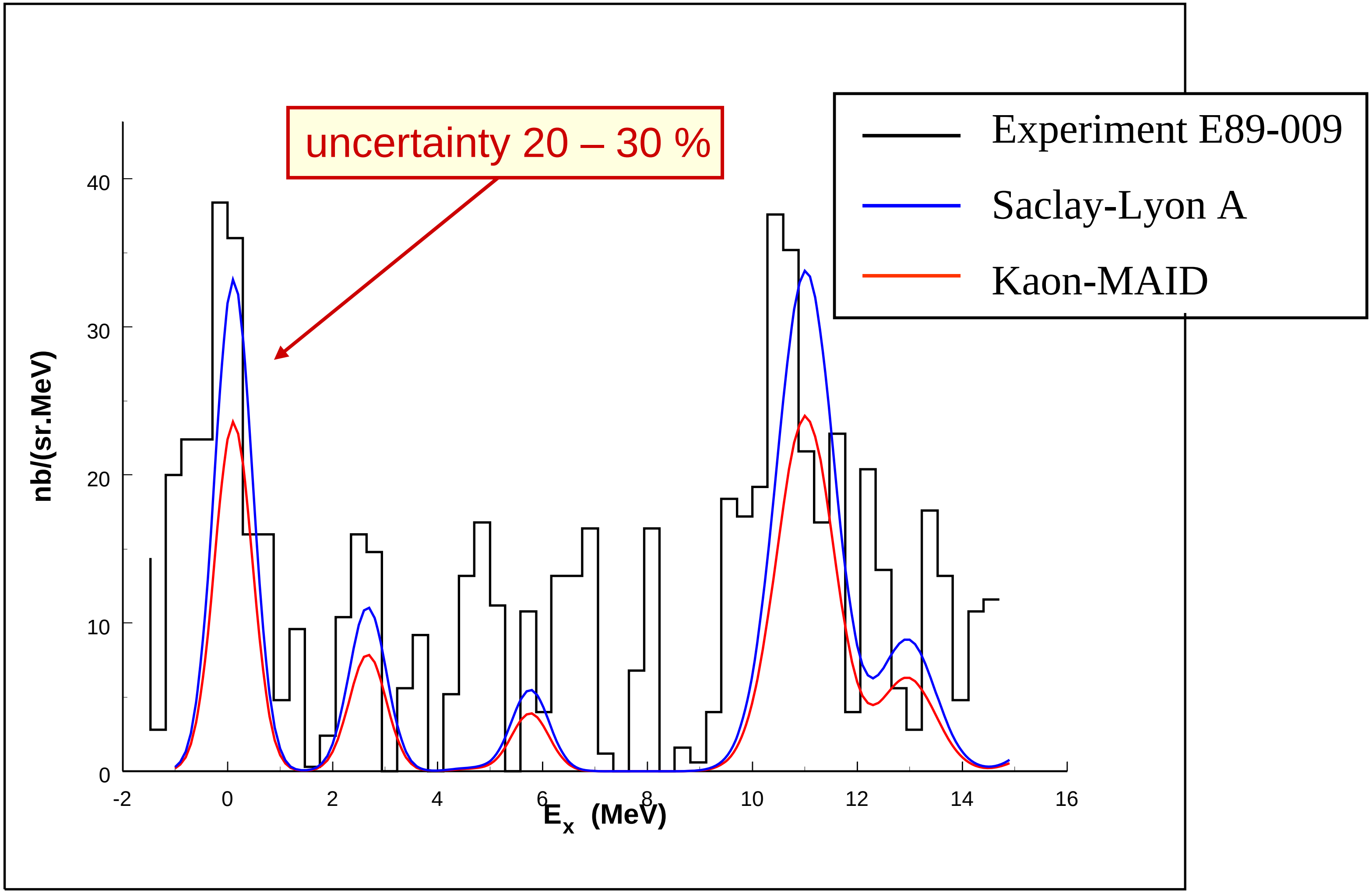
Saclay-Lyon A: no hadronic f. f., SU(3), crossing, many $Y^*(1/2)$ but only $N^*(1720)(3/2^+)$;

Kaon-MAID: hadronic f. f., SU(3), no Y^* but $N^*(1650)(1/2^-)$, $N^*(1710)(1/2^+)$, $N^*(1720)(3/2^+)$, and $N^*(1895)(3/2^-)$

Models give different predictions for the production at small kaon angles – *large uncertainty in calculations of the cross sections for the production of hypernuclei*



Results of DWIA calculation of the cross section for the electroproduction of $^{12}B_{\Lambda}$ at 1.3 GeV (Q^2 is very small)



Photoproduction of K^0 on deuteron

- Relation of the amplitudes for K^+ and K^0 photoproduction

  - isospin symmetry for the strong coupling constants

  - electromagnetic c. c. from the helicity amplitudes and decay widths

- Photoproduction on deuteron target

  (for K_1: $\mathbf{r}_{\mathbf{K1K}\gamma} = g^0/g^+$ is free parameter)

  - PWIA calculations, interaction in the final state (FSI) is neglected

  - $K\Lambda$ FSI is partially absorbed in the coupling constants of the elementary amplitude and KN FSI is weak; ΛN FSI at low energies …?

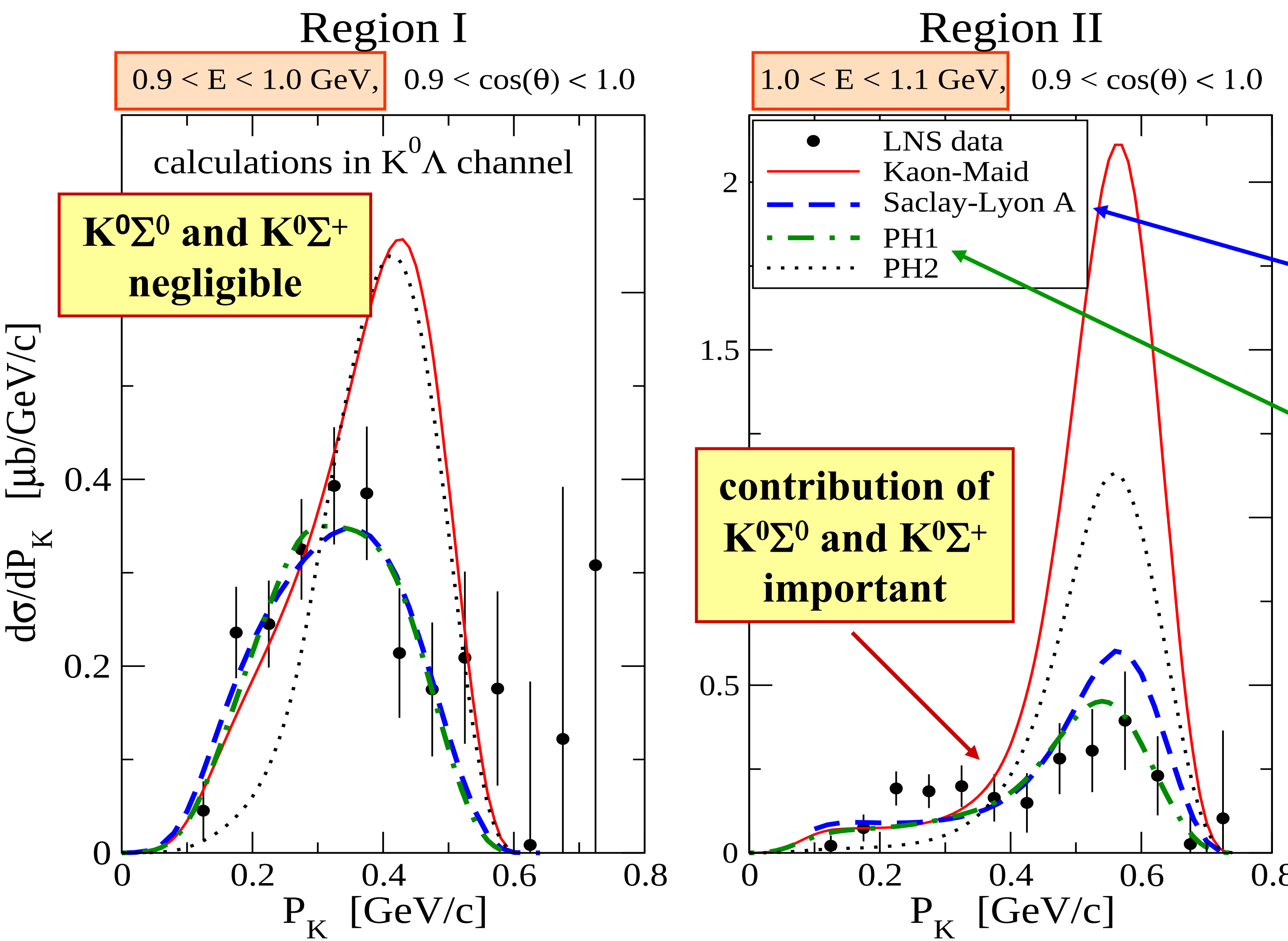
  - effects of FSI in *the inclusive cross section* are small below 1.1 GeV *(A. Salam et al. Phys. Rev. C 74 (2006) 044004)*

  - inclusive cross sections in the $K^0\Lambda$ channel are calculated – contributions of the Σ-channels are very small in the threshold region

Data on inclusive cross section $d(\gamma,K^0)YN$ $Y=\Lambda$, Σ^0 and Σ^+

from LNS, Tohoku Uni. *K. Tsukada et al, Phys.Rev. C 78 (2008) 014001*

Energy-averaged and kaon-angle-integrated momentum distributions



Fits to data in Region I

$r_{K1K\gamma}$ = -2.09

χ^2_{ndf} = 0.88

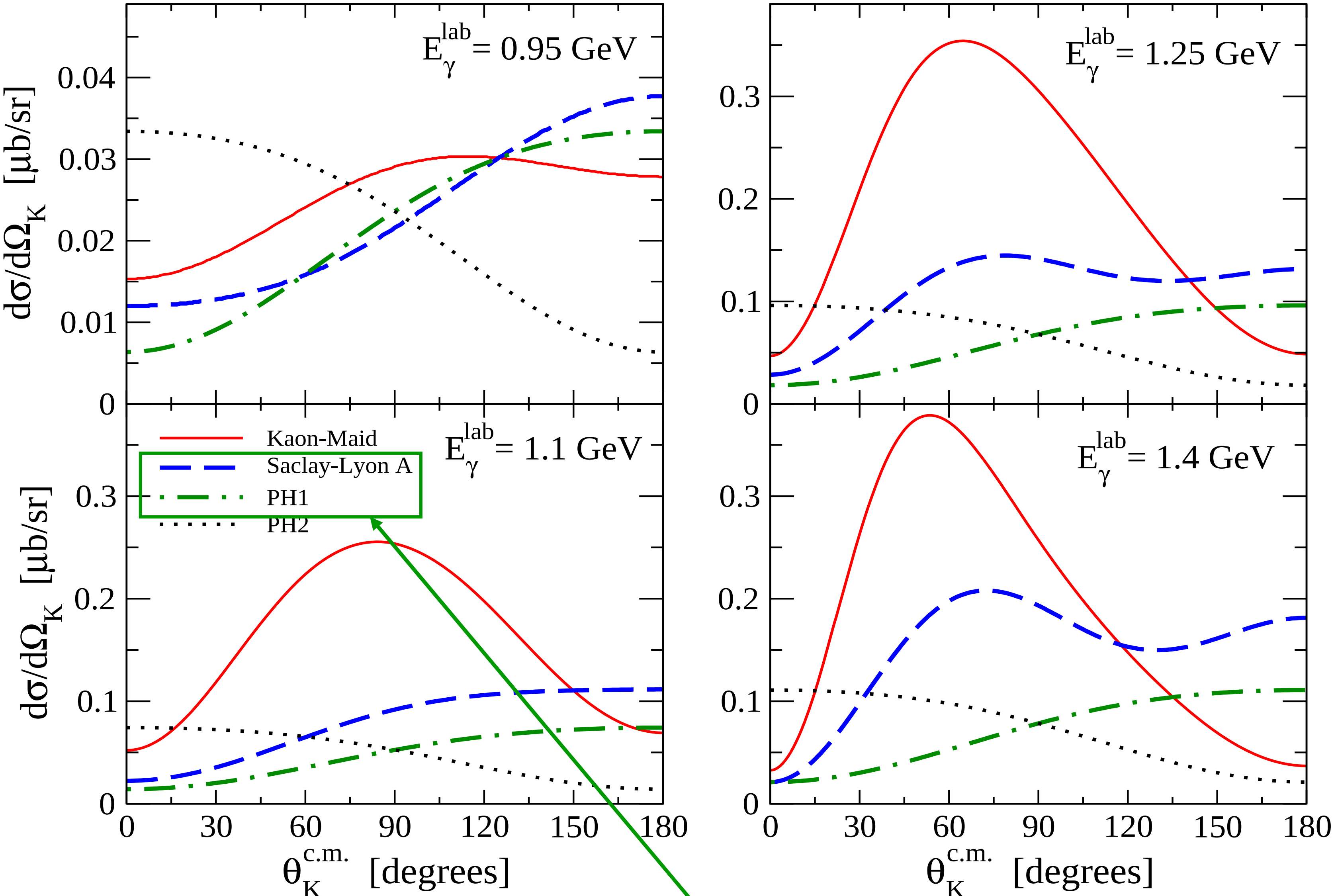
χ^2_{ndf} = 1.19

If Kaon-MAID is fitted:

χ^2_{ndf} = 3.64

$r_{K1K\gamma}$ = -2.34

differential cross section of $\gamma + n \rightarrow K^0 + \Lambda$ in c.m. frame



the best description of $d(\gamma,K^0)\Lambda p$

Electroproduction of Hypernuclei

$$e + A \rightarrow e' + K^{+} + H^{*}$$ - spectrum of states for

$H:\ {}^{12}\mathrm{B}_{\Lambda},\ {}^{16}\mathrm{N}_{\Lambda} \ldots$

Many-body matrix element in **DWIA**

$$\left\langle \psi_{H} \left| \sum_{i=1}^{Z} \chi_{\gamma} \chi_{K}^{*} J^{\mu}(i) \right| \psi_{A} \right\rangle$$

$J^{\mu}(i)$ – elementary hadron current in lab frame *(frozen-nucleon approx.)*

χ_{γ} – virtual-photon wave function *(one-photon approx.)*

χ_{K} – distorted kaon wave f. *(eikonal approx., 1st order optical potential)*

$\Psi_{A} (\Psi_{H})$ - target nucleus (hypernucleus) nonrelativistic wave functions

Shell model description of *p*-shell nuclei and hypernuclei

Ψ_A - *Cohen-Kurath* NN *interaction* in s^4p^{A-4} model space

Ψ_H - *phenomenological effective* ΛN *interaction* (*John Millener*)

$$V_{\Lambda N}(r) = V_0(r) + V_\sigma(r)\,\vec{s}_\Lambda \cdot \vec{s}_N + V_\Lambda(r)\,\vec{\ell}_{\Lambda N} \cdot \vec{s}_\Lambda + V_N(r)\,\vec{\ell}_{\Lambda N} \cdot \vec{s}_N + V_T(r)\,S_{12}$$

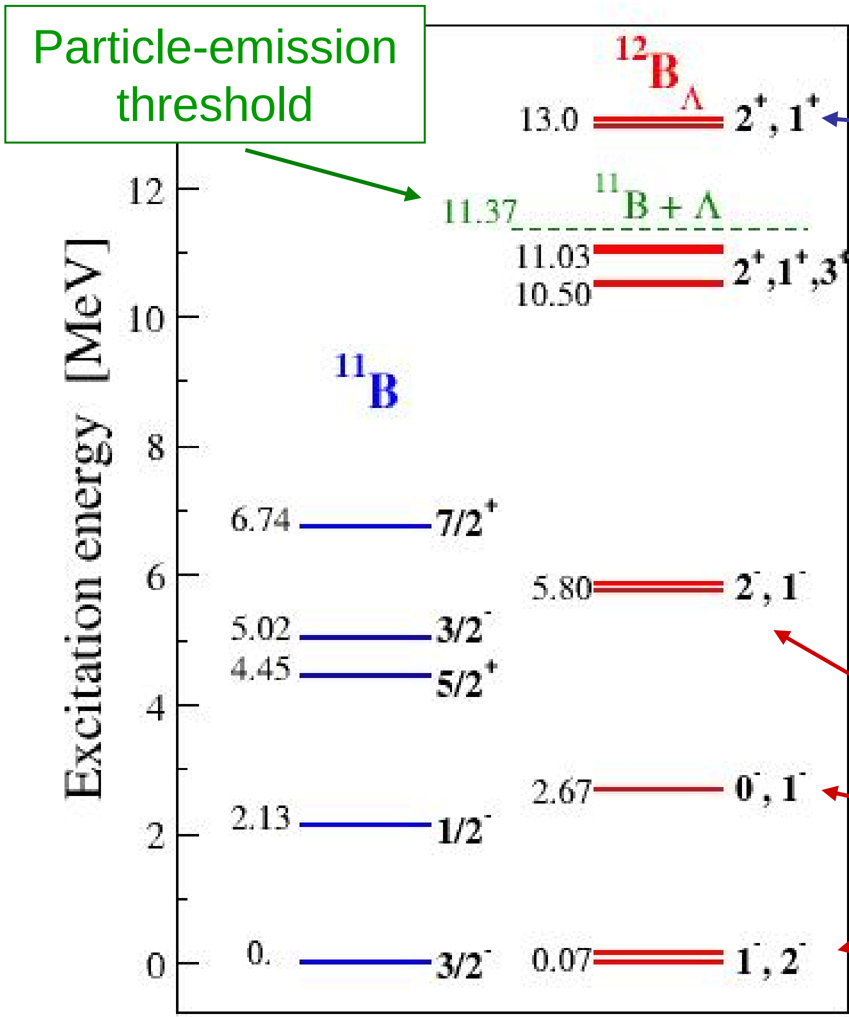
radial integrals are parameterized (Λ in *s*-shell):

$$V_{\Lambda N} = \overline{V} + \Delta\,\vec{s}_\Lambda \cdot \vec{s}_N + S_\Lambda\,\vec{\ell}_{\Lambda N} \cdot \vec{s}_\Lambda + S_N\,\vec{\ell}_{\Lambda N} \cdot \vec{s}_N + T\,S_{12}$$

parameters **Δ, S_Λ, S_N**, and **T** fitted to γ-ray spectra of $^7Li_\Lambda$, $^9Be_\Lambda$, and $^{16}O_\Lambda$
(e.g., $\Delta = 0.33$, $S_\Lambda = -0.015$, $S_N = -0.35$, $T = 0.024$ all in MeV)

Λ–Σ mixing ($\Lambda N \leftrightarrow \Sigma N$) included ($s_N^4\, p_N^{A-5}\, s_\Lambda + s_N^4\, p_N^{A-5}\, s_\Sigma$)

ΛN is weaker than NN => hypernucleus states can be build up on the states of the core nucleus (weak coupling model)



Λ in *p*-states (*$p_{1/2}$ or $p_{3/2}$*)

Example:

$$\left|{}^{12}_{\Lambda}\mathrm{B}(E,J)\right\rangle =$$

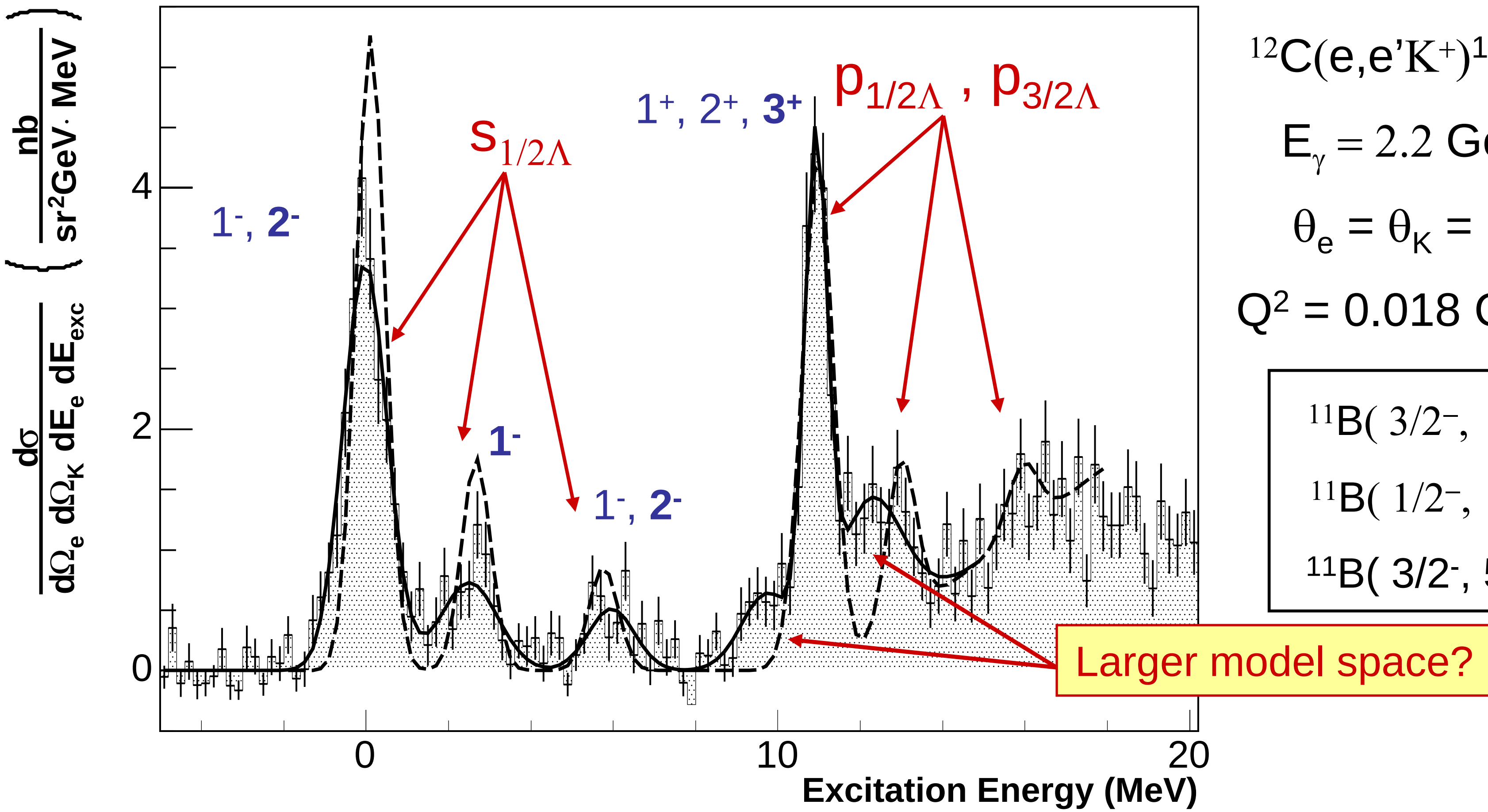
$$\left|{}^{11}\mathrm{B}(E_c,J_c)\otimes s^{\Lambda}_{1/2}, J=J_c \pm 1/2\right\rangle$$

doublet of states

Results for p-shell hypernuclei: spectrum of $^{12}B_\Lambda$

Theoretical prediction: elementary operator – Saclay-Lyon A model

(dashed line) ΛN interaction from γ-ray spectra of $^{7}Li_\Lambda$



$^{12}C(e,e'K^+)^{12}B_\Lambda^*$

$E_\gamma = 2.2$ GeV

$\theta_e = \theta_K = 6^o$

$Q^2 = 0.018$ GeV^2

$^{11}B(3/2^-$, g. s.)

$^{11}B(1/2^-$, 2.12)

$^{11}B(3/2^-$, 5.02)

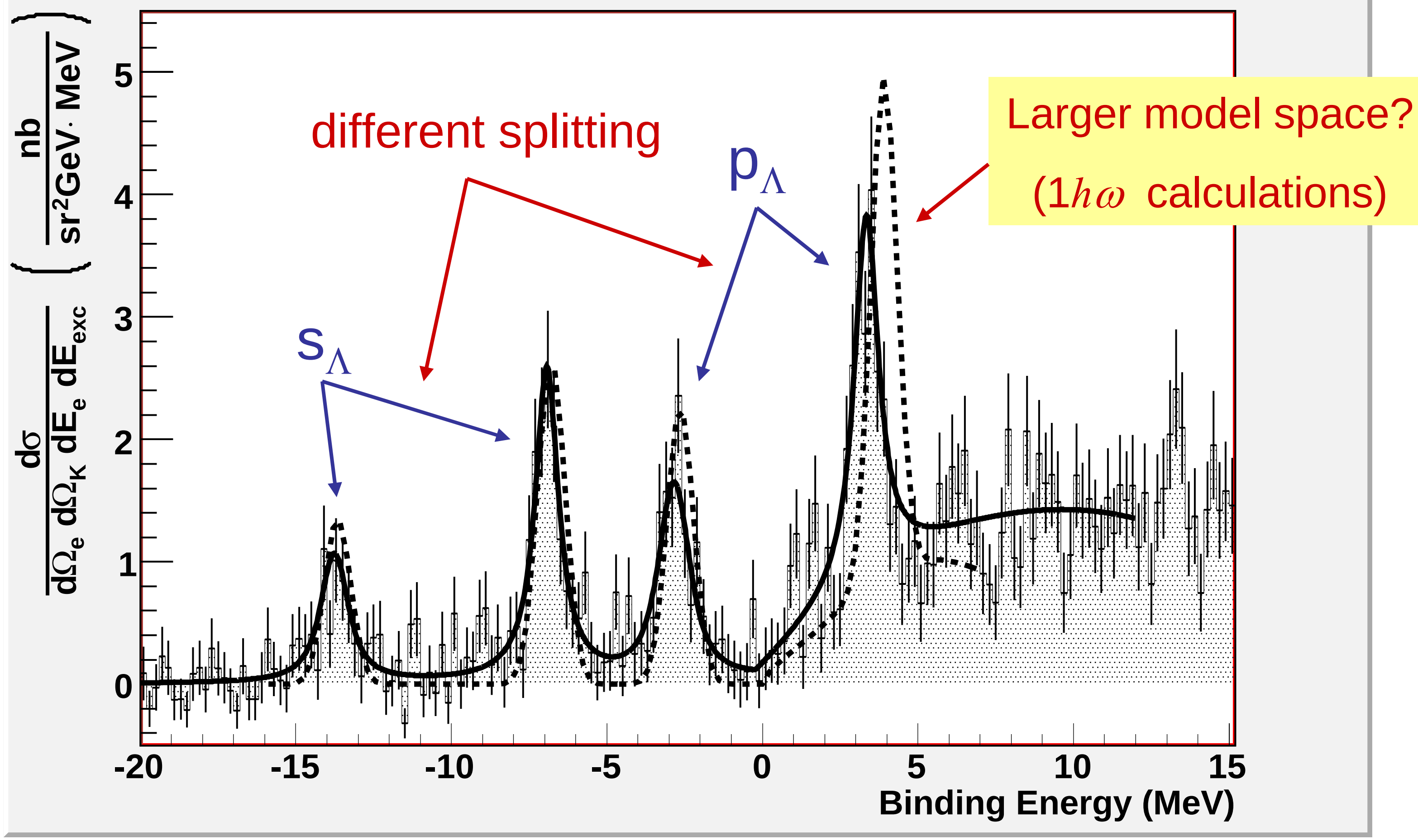
data: E94-107, JLab Hall A, M. Iodice et al, Phys. Rev. Lett. 99 (2007) 052501

Spectrum of $^{16}N_{\Lambda}$

Theoretical prediction: elementary operator – Saclay-Lyon A model

(dashed line) ΛN interaction fitted to $^{16}O_{\Lambda}$ and $^{15}N_{\Lambda}$ spectra

Data: the E94-107 experiment in JLab, Hall A (*F. Cusanno et al*)



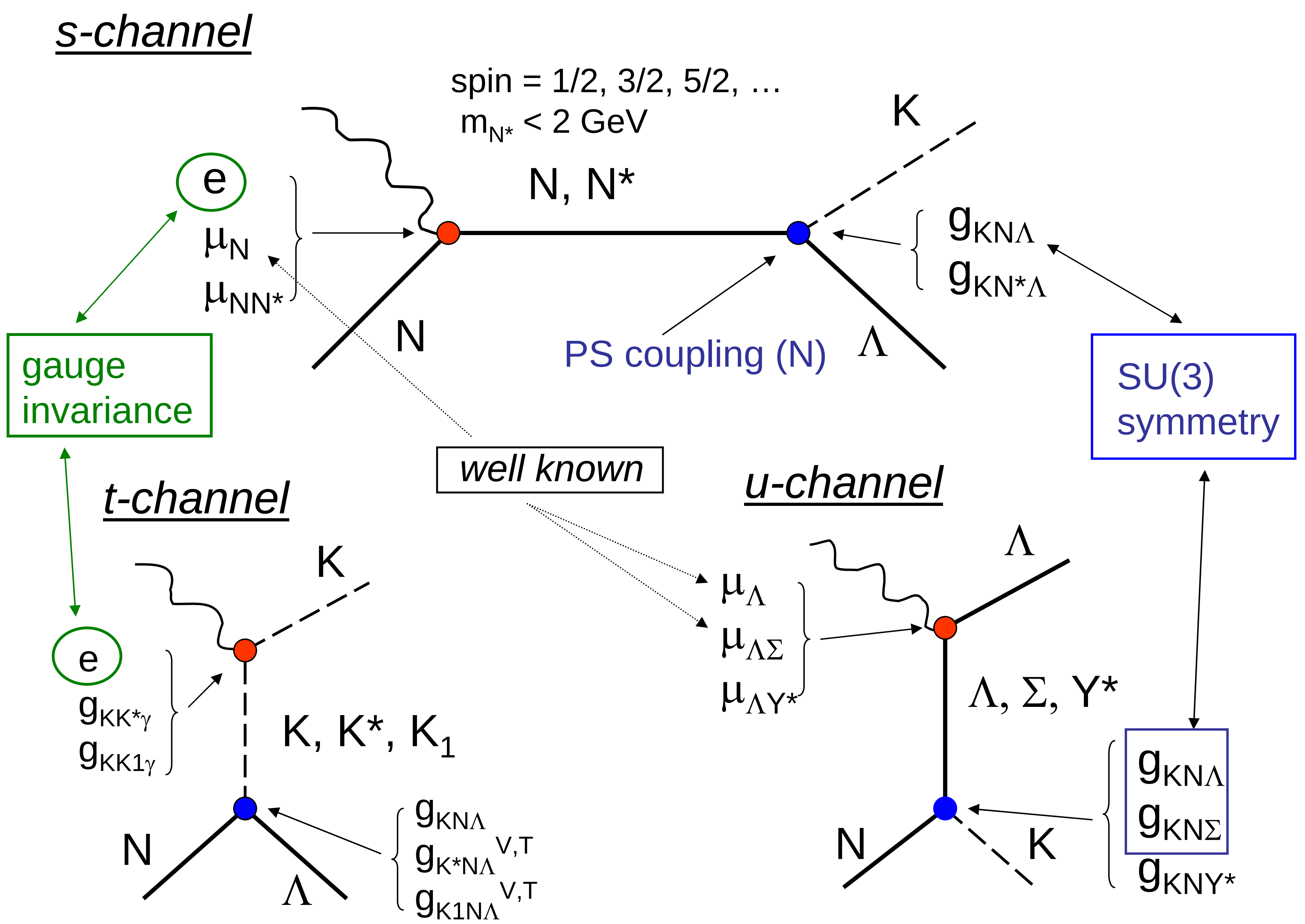
Summary

Elementary process $N(\gamma,K)\Lambda$

- *data at very small θ_K are needed to fix the models for K^+ production at forward angles (necessary for reliable hypernuclear calculations);*
- *the first data on K^0 photoproduction near threshold prefer the models which give enhancement of the cross section at the backward angles;*

Hypernucleus electroproduction

- *predictions of the DWIA shell-model calculations agree well with the spectra of $^{12}B_\Lambda$ and $^{16}N_\Lambda$ for Λ in s-state;*
- *in the p_Λ region more elaborate calculations (core-nucleus $1h\omega$ states) are needed to fully understand the data;*
- *the Saclay-Lyon model for the elementary process gives reasonable cross sections – good behaviour at small θ_K?*


s-channel
spin = 1/2, 3/2, 5/2, …
m_{N^*} < 2 GeV
K
N, N*
e
μ_N
μ_{NN^*}
N
$g_{KN\Lambda}$
$g_{KN^*\Lambda}$
PS coupling (N)
Λ
gauge invariance
SU(3) symmetry
well known
t-channel
u-channel
K
Λ
e
$g_{KK^*\gamma}$
$g_{KK1\gamma}$
K, K*, K_1
μ_Λ
$\mu_{\Lambda\Sigma}$
$\mu_{\Lambda Y^*}$
Λ, Σ, Y*
N
Λ
$g_{KN\Lambda}$
$g_{K^*N\Lambda}^{V,T}$
$g_{K1N\Lambda}^{V,T}$
N
K
$g_{KN\Lambda}$
$g_{KN\Sigma}$
g_{KNY^*}

How to produce hypernuclei?

(K^-, π^-) – small momentum transfer (below 100 MeV/c)

(stopped / inflight) – non spin-flip dominates ($\Delta S = \Delta L = 0$)

– predominantly substitutional states populated (poor spectrum)

– σ : mb/sr *(strangeness exchange)*

(π^+, K^+) – larger momentum transfer than in (K^-, π^-) (300 MeV/c)

– $\Delta S = 0$, $\Delta L = \Delta J = 1, 2$ natural-parity states populated

– σ : μb/sr *(associated production of strangeness)*

– rich series of Λ single-particle states – γ-ray spectroscopy

$(e,e'K^+)$ – momentum transfer as in (π^+, K^+) (350 MeV/c)

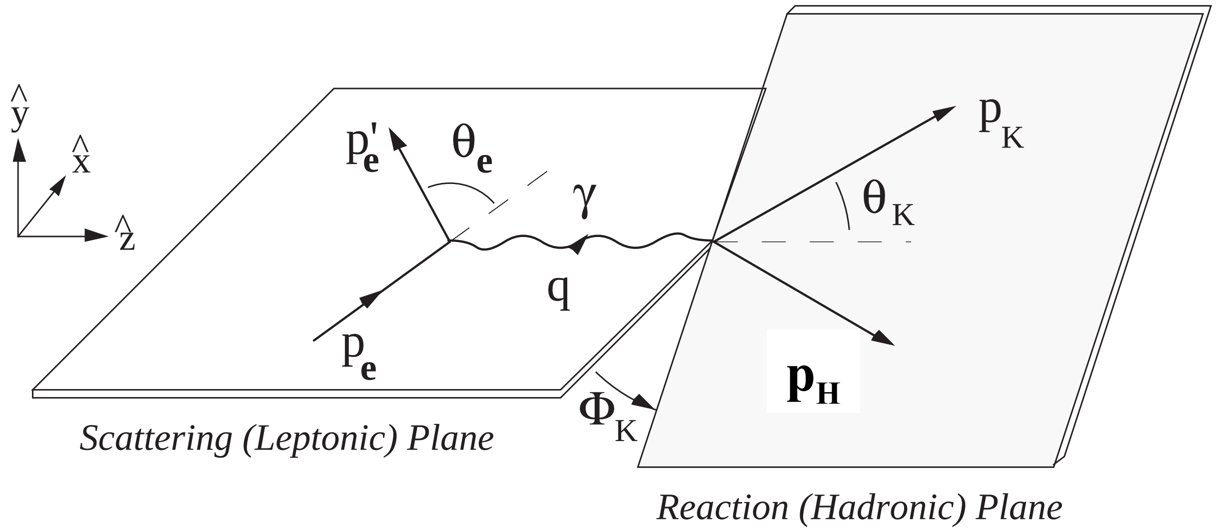
– spin-flip dominates: $\Delta S = 1$, $\Delta L = 1, 2$, $\Delta J = 1, 2, 3$

– wide variety of Λ single-particle states are populated

– σ : nb/sr *(production of strangeness in the electromagnetic process)*

– production on proton – other hypernuclei than in (π,K)

Kinematics



Detection of e' and K^+ at very forward angles (θ_e: 0 – 6°, θ_K: 6°)

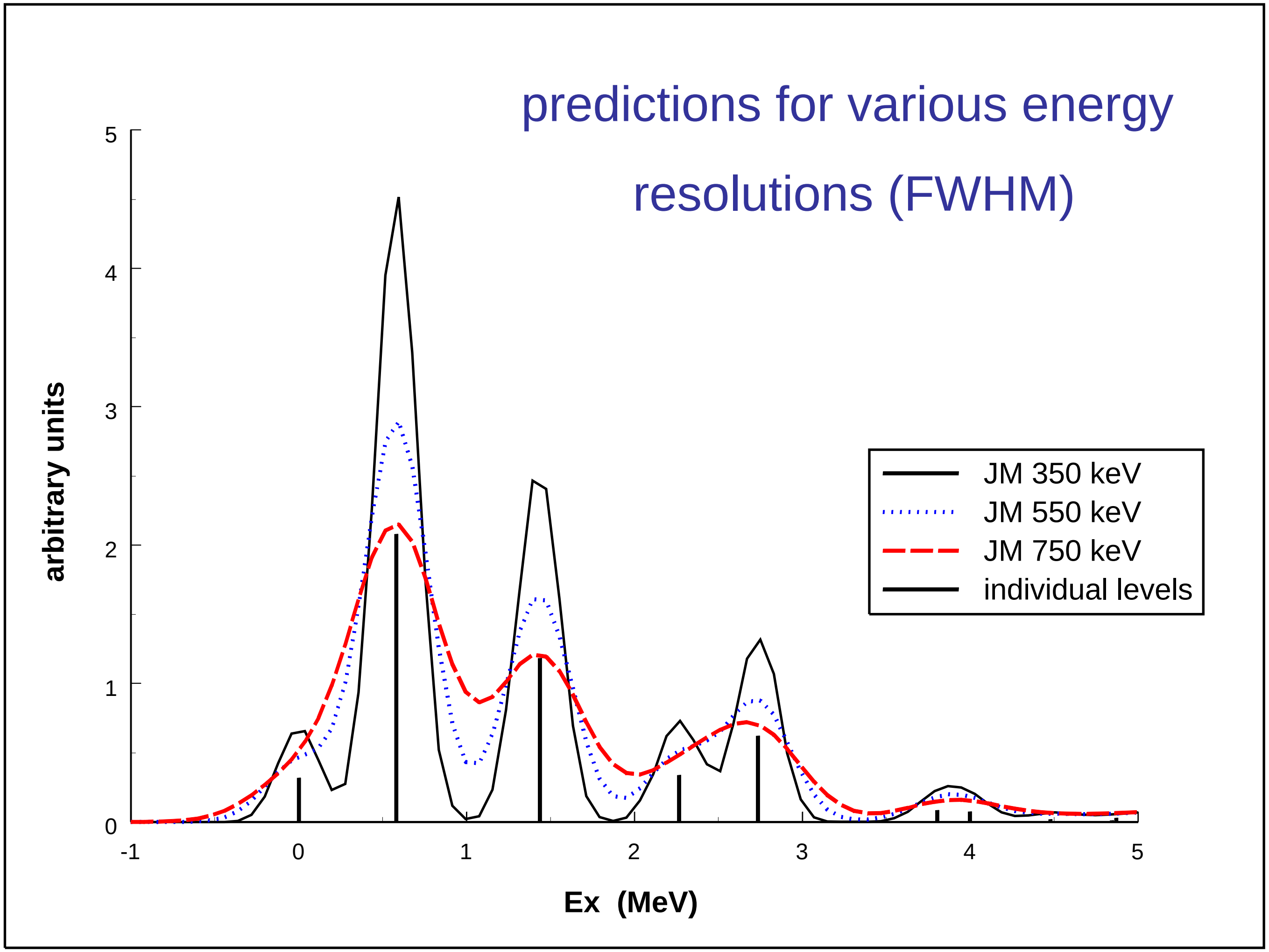
due to a steeply decreasing angular dependence of the virtual-photon flux and nucleus-hypernucleus transition form factors.

Hypernuclear production cross section is measured as a function of hypernucleus excitation energy.

^{9}Be target - Hypernuclear Spectrum of $^{9}Li_{\Lambda}$

Theoretical calculation: elementary operator – Saclay-Lyon A model,

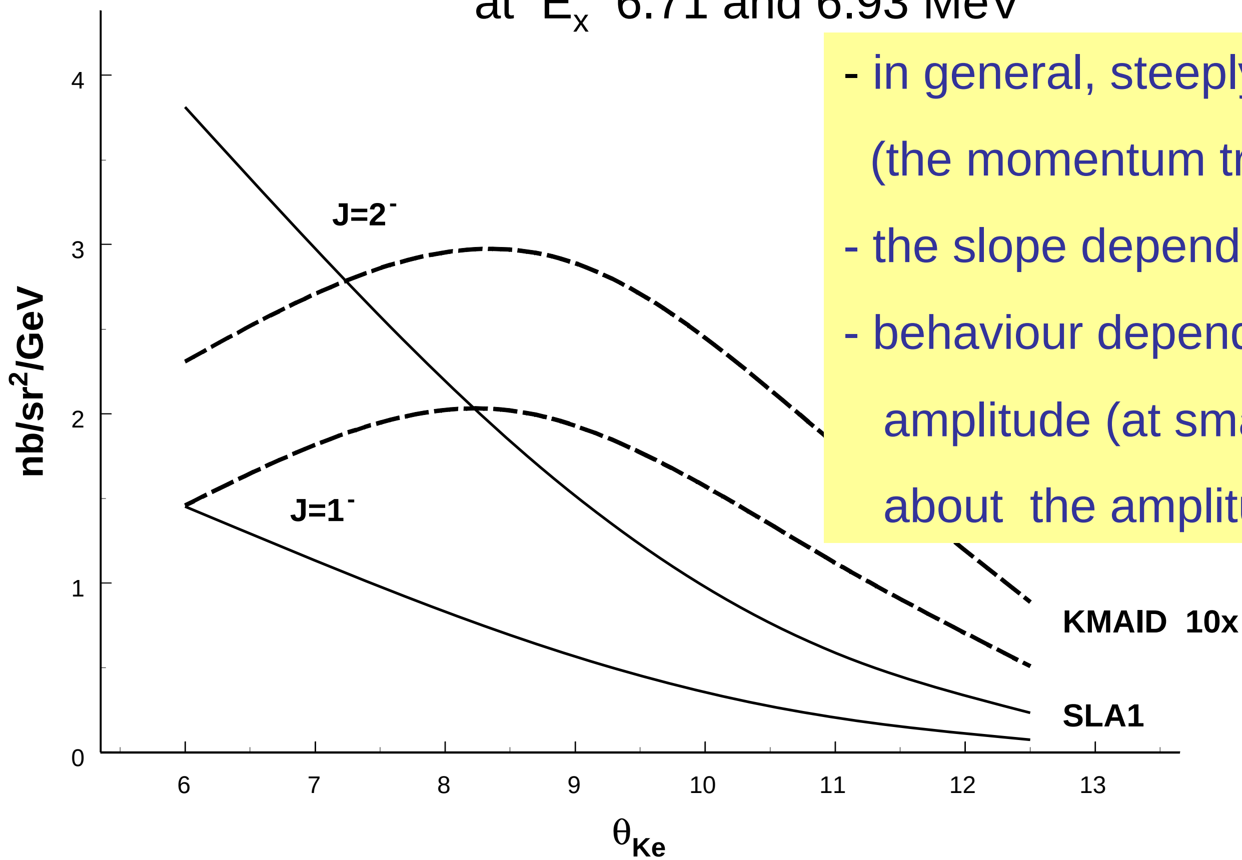
wave functions by John Millener (fitted to γ-ray spectroscopy data)



Angular dependence of the cross section

for electroproduction of $^{16}N_{\Lambda}$ at E_{γ}= 2.21 GeV and θ_e = 6^o

Cross sections in lab frame for doublet J = 1^- , 2^- at E_x 6.71 and 6.93 MeV



- in general, steeply decreasing dependence (the momentum transfer changes rapidly);
- the slope depends on the spin (J);
- behaviour depends on the elementary amplitude (at small θ_K) – information about the amplitude at small angles.

θ_{Ke} is kaon lab angle with respect to beam