Intermediate Energy Nuclear Reactions

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Plenary Talk at Nucleus-Nucleus 2015, Catania, Italy

HIC for FAIR
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OUTLINE

1. **Introduction**
   Theoretical methods for describing the Intermediate energy nuclear reactions. The Effective Lagrangian Model.

2. **Photon induced meson production on nucleons within a Coupled Channels K-matrix method.**

3. **Strangeness production in K^- induced reactions on proton and heavier nuclei leading to production of free or bound cascade (S = -2) hyperon.**

4. **Charm baryon and meson production in antiproton-proton annihilation reactions at energies of interest to $\bar{\text{P}}$ANDA experiments.**

5. **Summary**

Introduction

- **Quantum Chromodynamics (QCD) is supposed to describe all of Nuclear Physics in terms of quarks and gluons.**

Quarks and Gluons — QCD — Nucleons and Mesons — Nuclear Physics — Nuclei

- **Hadron-hadron and hadron-photon and lepton interactions have played a major role in understanding of QCD.**

Two distinct regimes of QCD

High momentum transfer (reactions at very high energies):

Due to the Asymptotic freedom pQCD works remarkably well.

Low momentum transfer (reactions at intermediate energies):

Quarks are confined into colorless Hadrons, Large α_s, pQCD does not work.

Intermediate Energy Nuclear Reactions

- **Studies of hadronic reactions in this region provide opportunity to learn more about the nature of confinement and its transition to the asymptotic freedom.**
- **Because of confinement effective theories where degrees of freedom are mesons and baryons are expected to be useful.**

Strategy

1 **Lattice QCD: solve equations of motion (of the fields) on a space time lattice by Monte-Carlo simulation.**

Experimental data

2 **Effective Field Theory methods where degrees of freedom are nucleons and meson instead of quarks and gluons.**

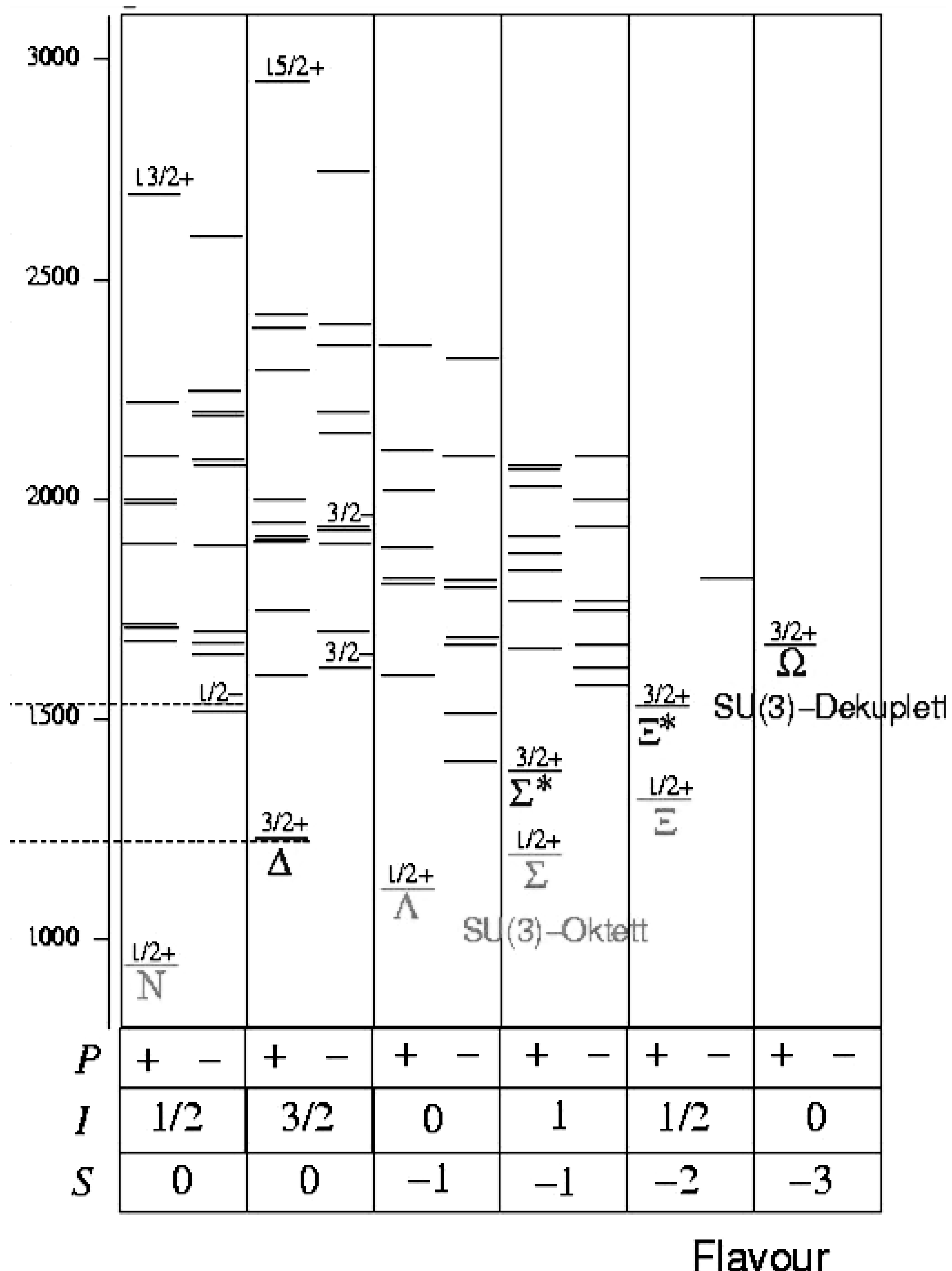
Effective Lagrangian model

2. Meson production in photon-nucleon collisions

Rich excitation spectrum of nucleons: Complex multi-quark inner dynamics, mechanism of Confinement.

Importance of the determination of baryonic resonance properties from the experimental data.

Effective methods include baryonic resonances, and determine their properties by comparing prediction of the theory with the data.



The effective theoretical method should

- describe simultaneously all the reaction channels using a single Lagrangian.

- satisfy the symmetries of the fundamental theory QCD while using only meson and baryon degrees of freedom.

- relativistic invariance, Unitarity, gauge invariance, analyticity

K-matrix method provides one such approach

$$S = 1 + 2iT$$

$$T = K/(1-iK)$$
$$= K + iKK + i^2KKK + \ldots$$

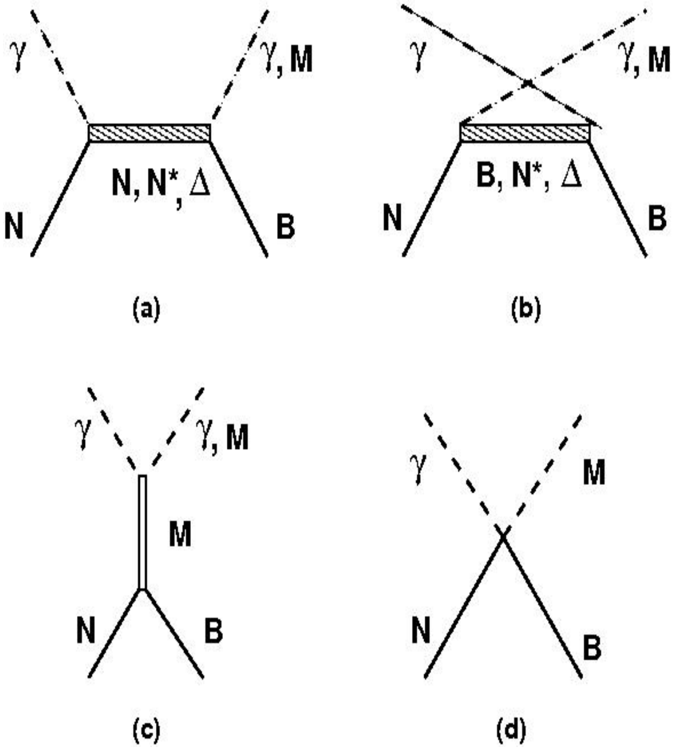
T is the solution of the Bethe-Saltpeter Eq.

If K is Hermitian, then S is unitary.

K-matrix starting from effective Lagrangians that describe coupling between all the channels included in the model space

Model Space (two-body final channels)

$(N+\gamma)$, $(N+\pi)$, $(N+\eta)$, $(N+\varphi)$, $(N+\rho)$, $(\Lambda+K)$, $(\Sigma+K)$



s- and u-channels

N, Λ, Σ, S_{11} (1535), S_{11}(1650), S_{31}(1620), P_{11}(1440), P_{11}(1710), P_{13} (1720), P_{33}(1232), P_{33}(1600), D_{13}(1520), D_{13}(1700), D_{33}(1700)

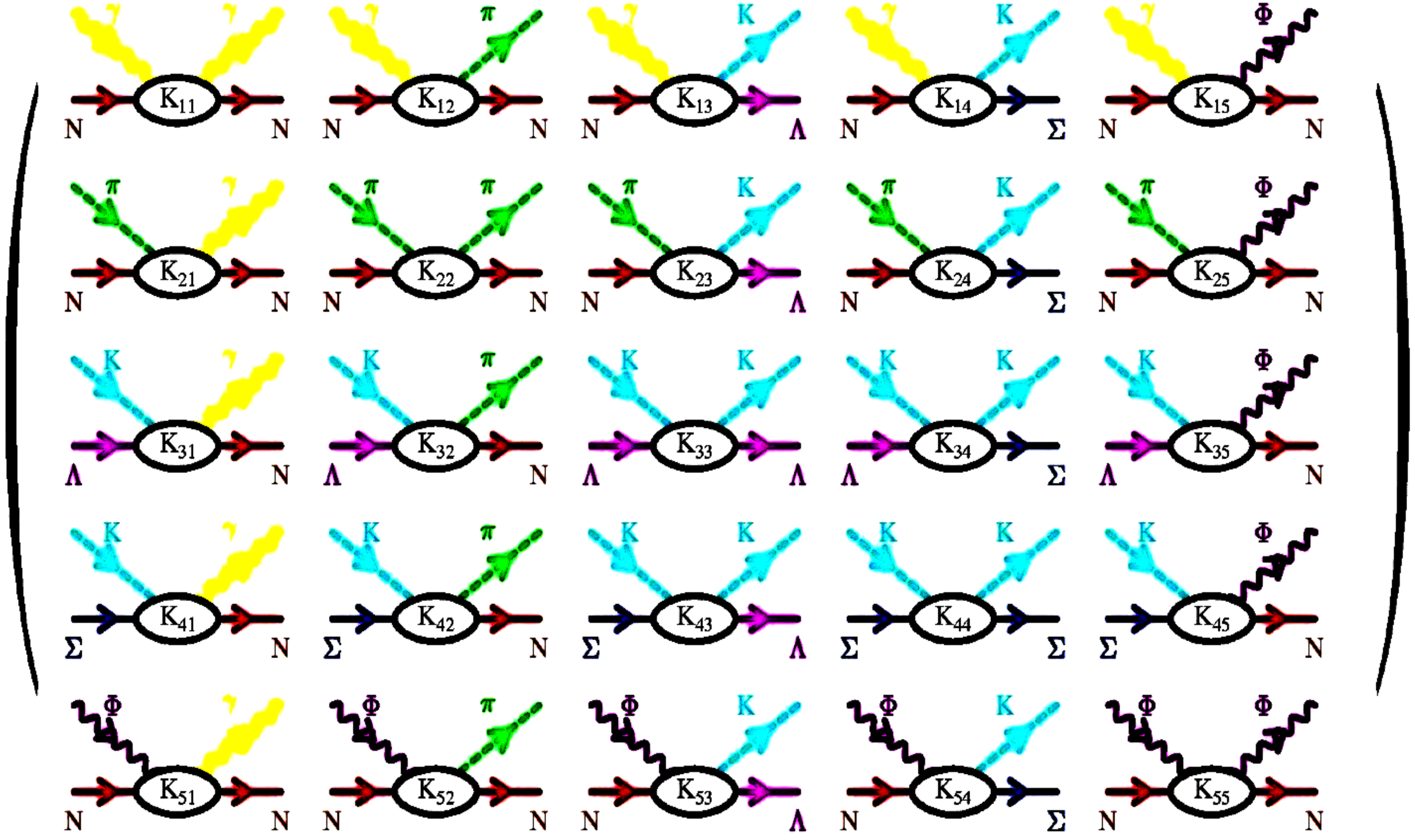
t-channels

π, η, ρ, ω, σ, φ, K, K* mesons

t-channel Contact terms ➡ Gauge invariance

Background contributions are created dynamically, no additional parameters.

K =:



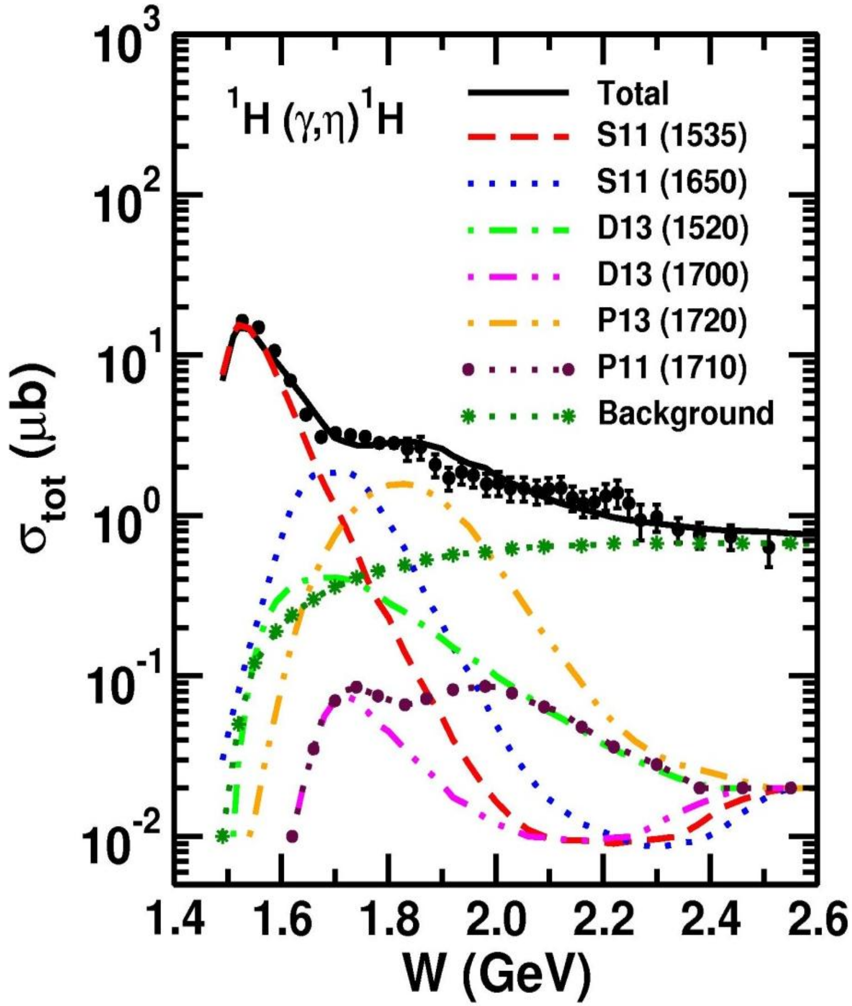
Because of channel coupling resonances generate widths compatible with their decays to channels included in the model space.

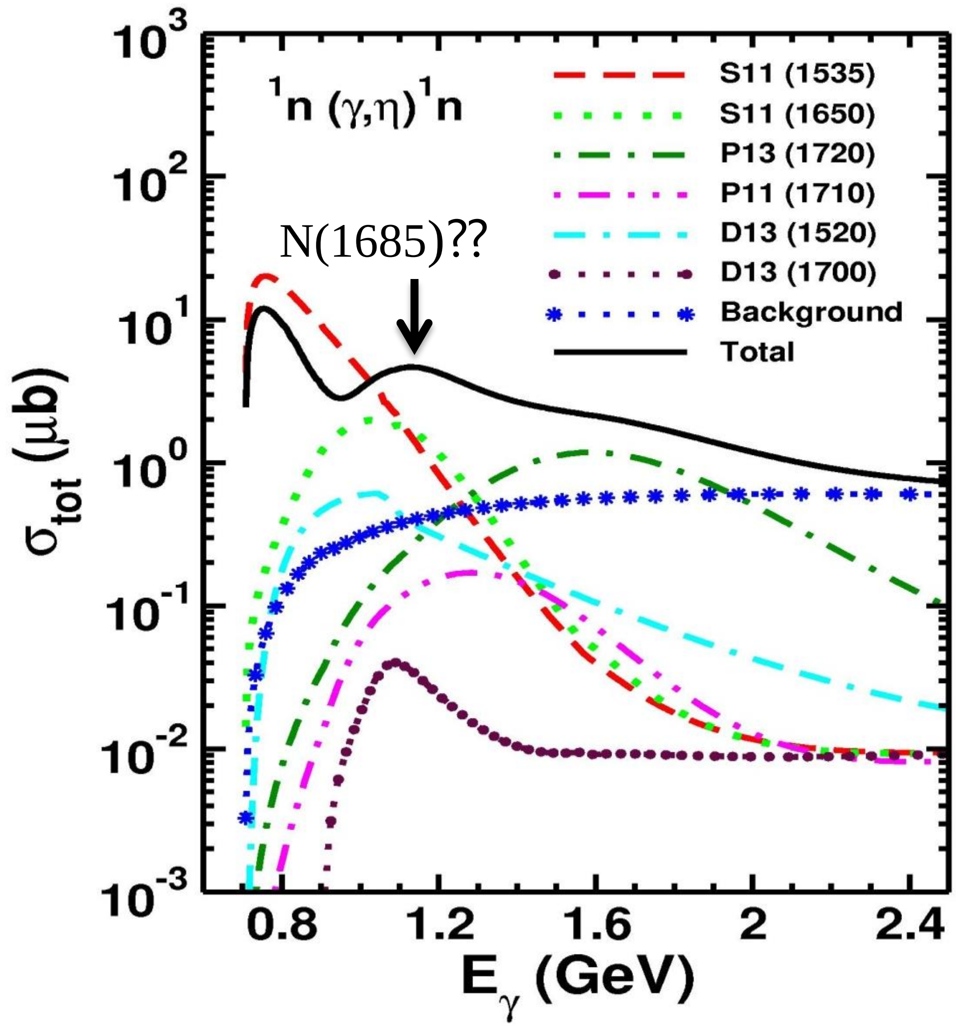
Strength of the K matrix method

- **Full coupled channels in large model space**
- **Non-perturbative**
- **Unitary**
- **Gauge invariant**
- **Covariant**
- **Crossing symmetric (s- and u-channel)**

Photon induced η production on nucleon

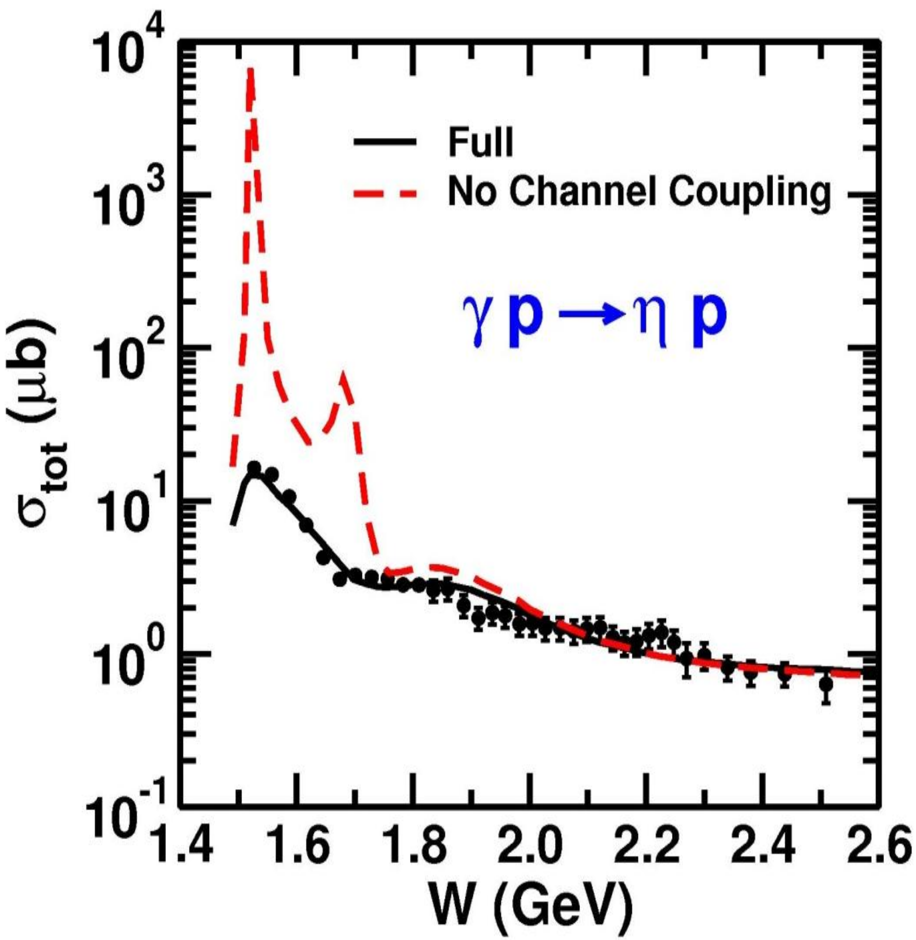
CB-ELSA data

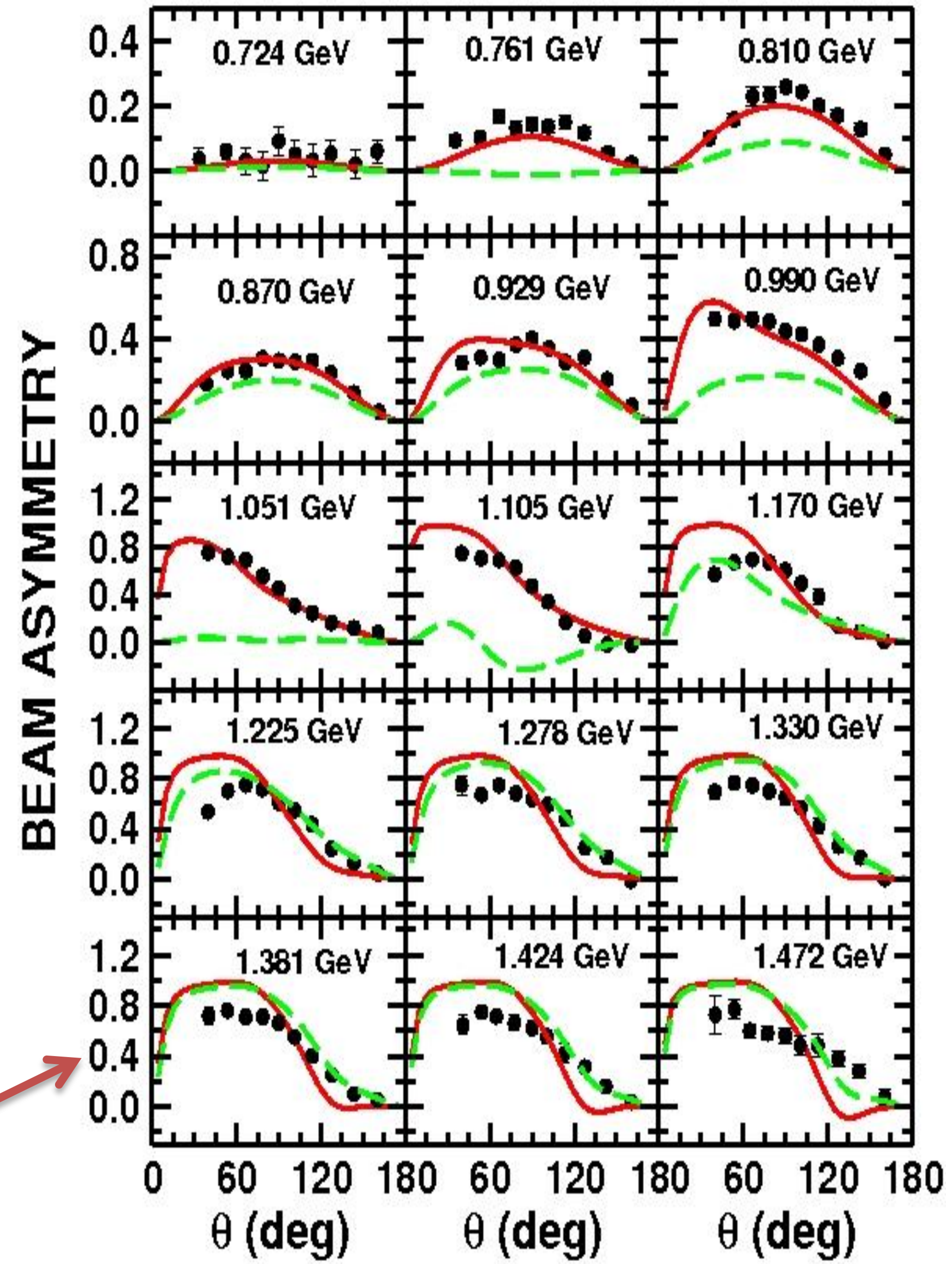




R. S. AND O. Scholten., PHYS REV C **78**, 065201 (2008)

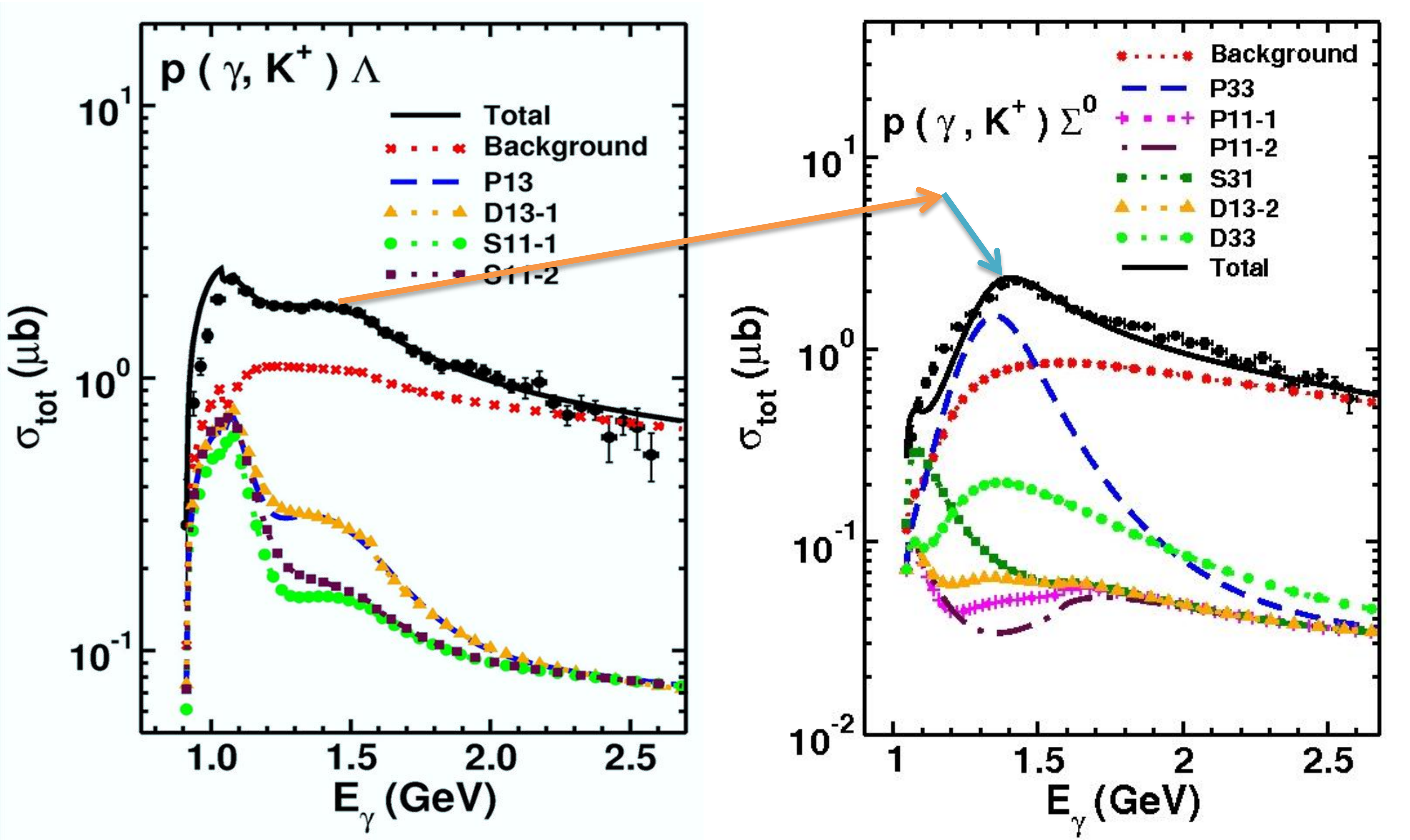
Photon induced η production: effect of coupled channels





green dashed lines: No CC

Photon induced K+Λ and K+Σ production on proton



RS, O. Scholten, H. Lenske, Phys. Rev. C **81**, 015201 (2010)

3. Strangeness production:

(K^-,K^+) Reaction

(K^-,K^+) reaction leads to the transfer of two units of charge and strangeness. Most promising way of studying the S = -2 systems.

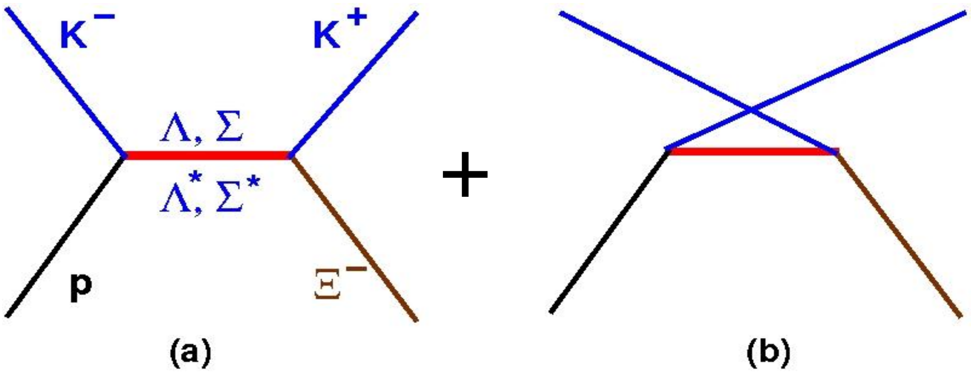
Caveat

The currently available data in the $K\Xi$ channel are scarce and of Low quality. So full coupled channel treatment is not feasible.

We use the single channel effective Lagrangian model for calculations in this section.

Ξ Production in elementary (K⁻,K⁺) reaction on proton.

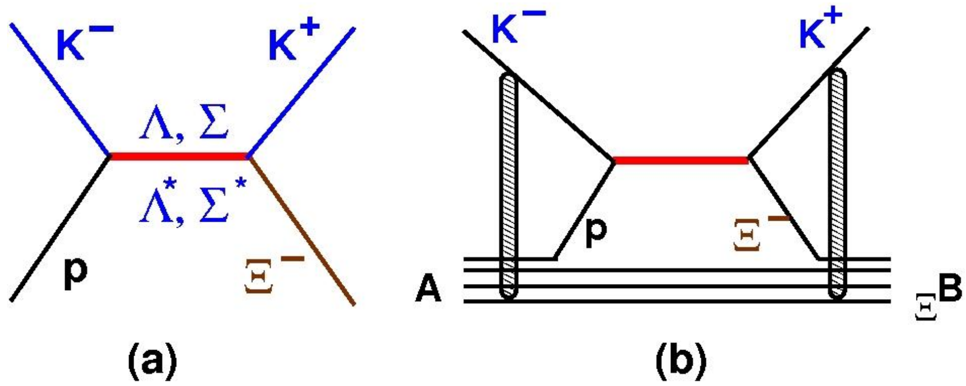
Hyperon resonances S = -1



Production of Ξ hypernuclei

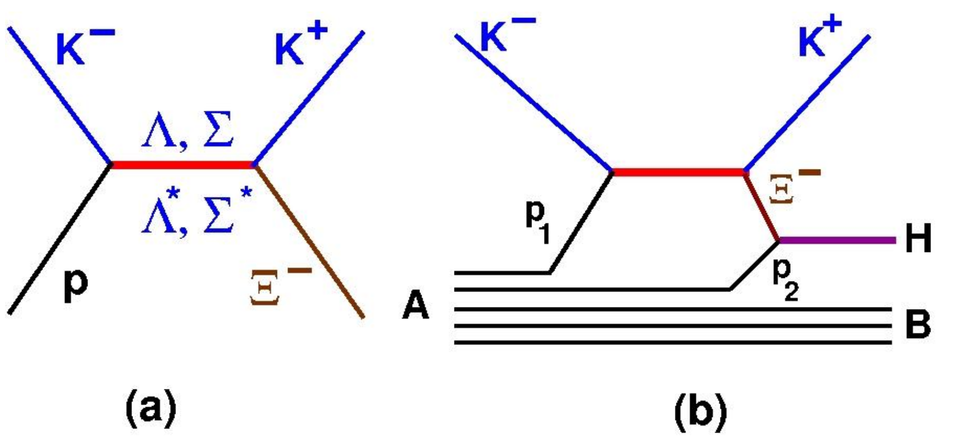
BE and widths determine the strengths of Ξ N and Ξ N → ΛΛ interactions, respectively.

Potential depths control the composition in the core of neutron star.



Production of H dibaryon

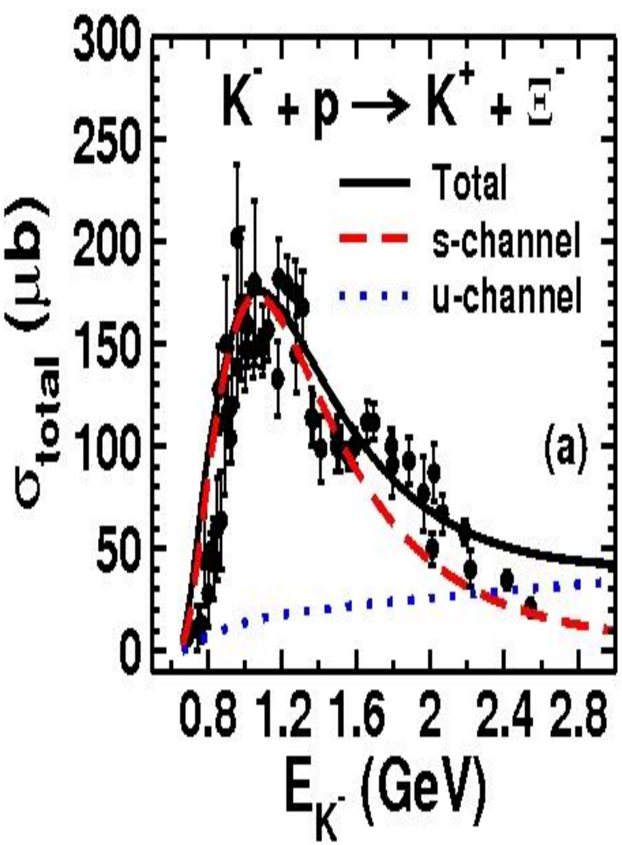
Renewed interest in the search for dibaryonic (H) resonance by the (K^-, K^+) reaction on nuclei.

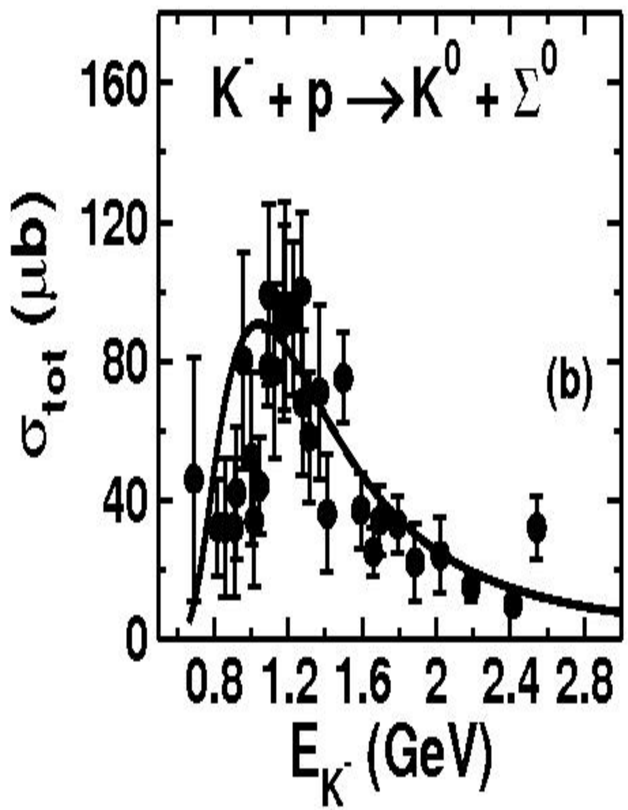


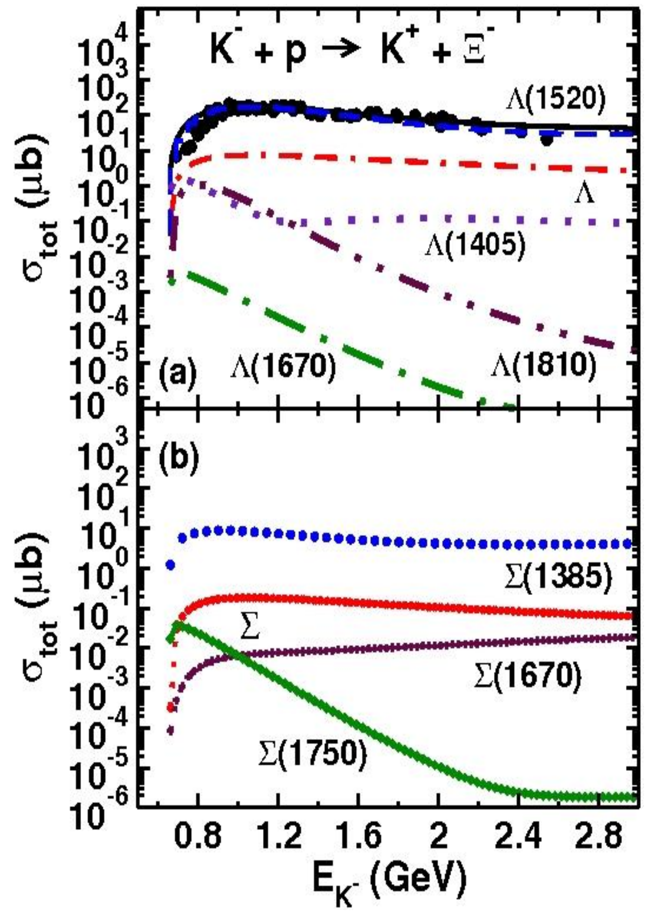
Elementary (K^-,K^+) reaction on a proton target

Effective Lagrangians at Hyperon-nucleon-resonances (spin-1/2 and spin -3/2) vertices, Coupling constants, form factors

Λ(1116), Λ(1405), Λ(1520), Λ(1670), Λ(1810), Λ(1890), Σ(1189), Σ(1385), Σ(1670), Σ(1750)

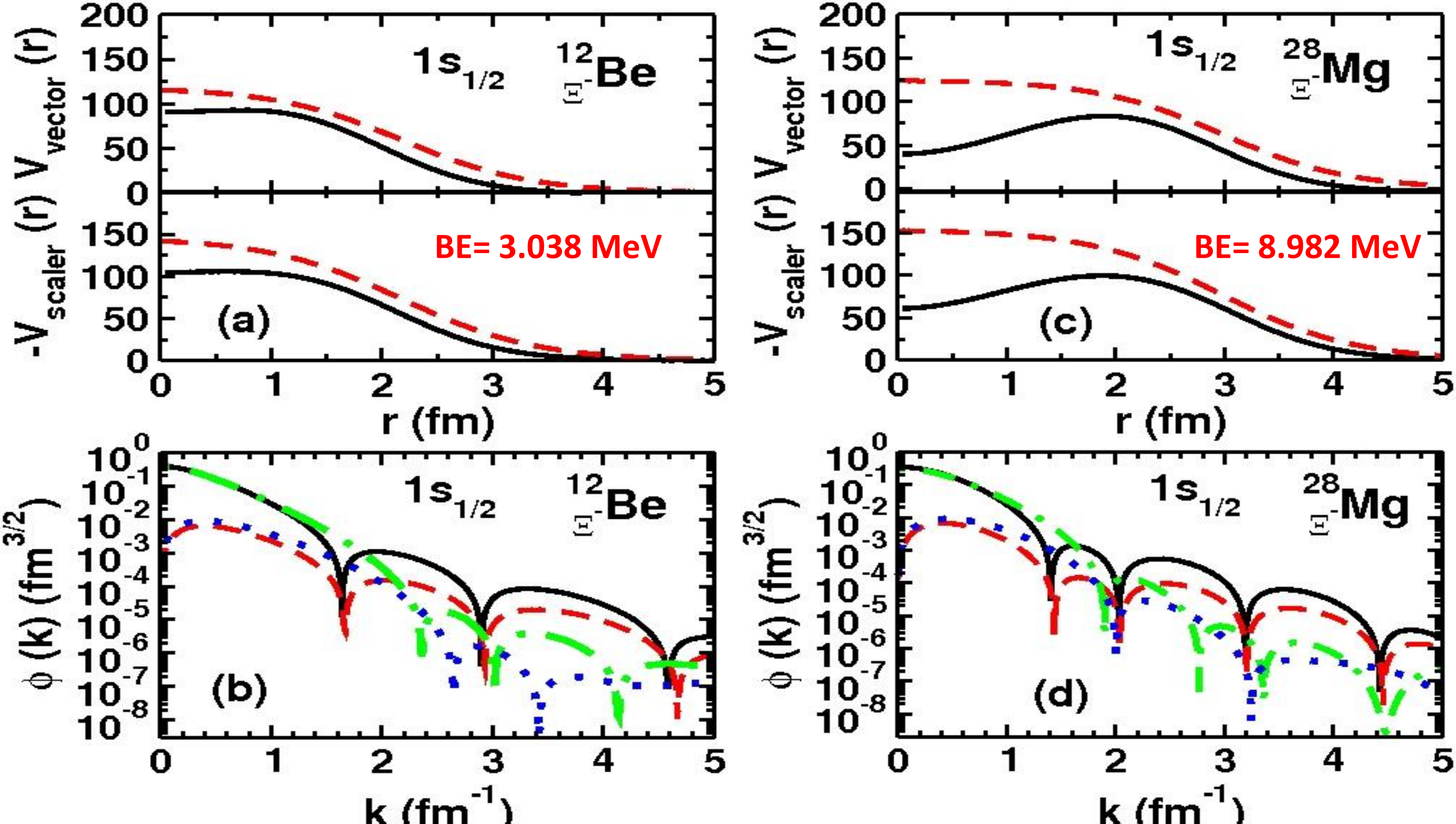




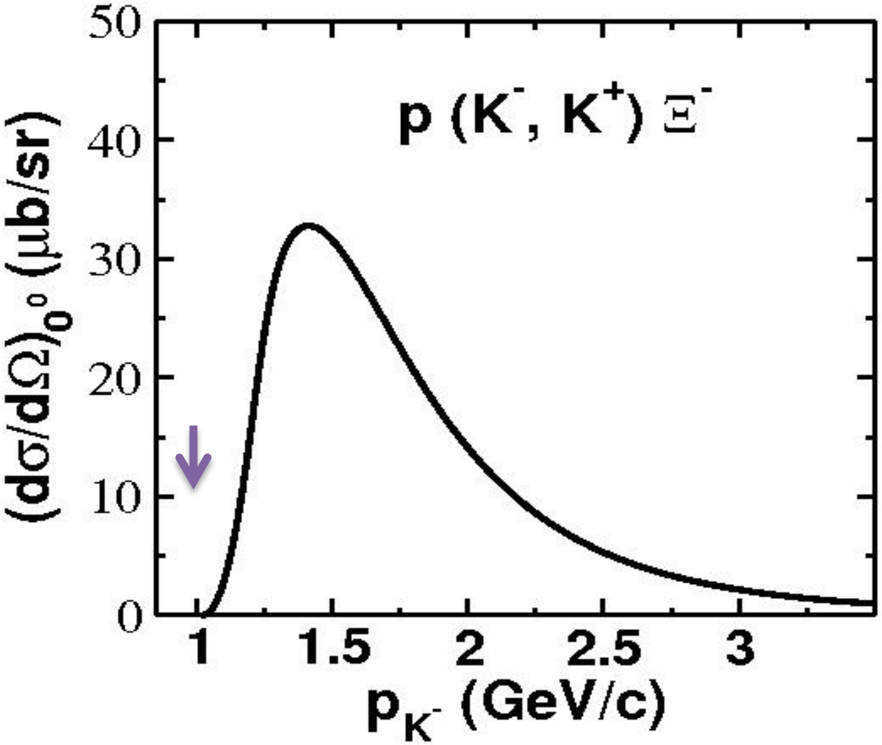


Cascade bound states

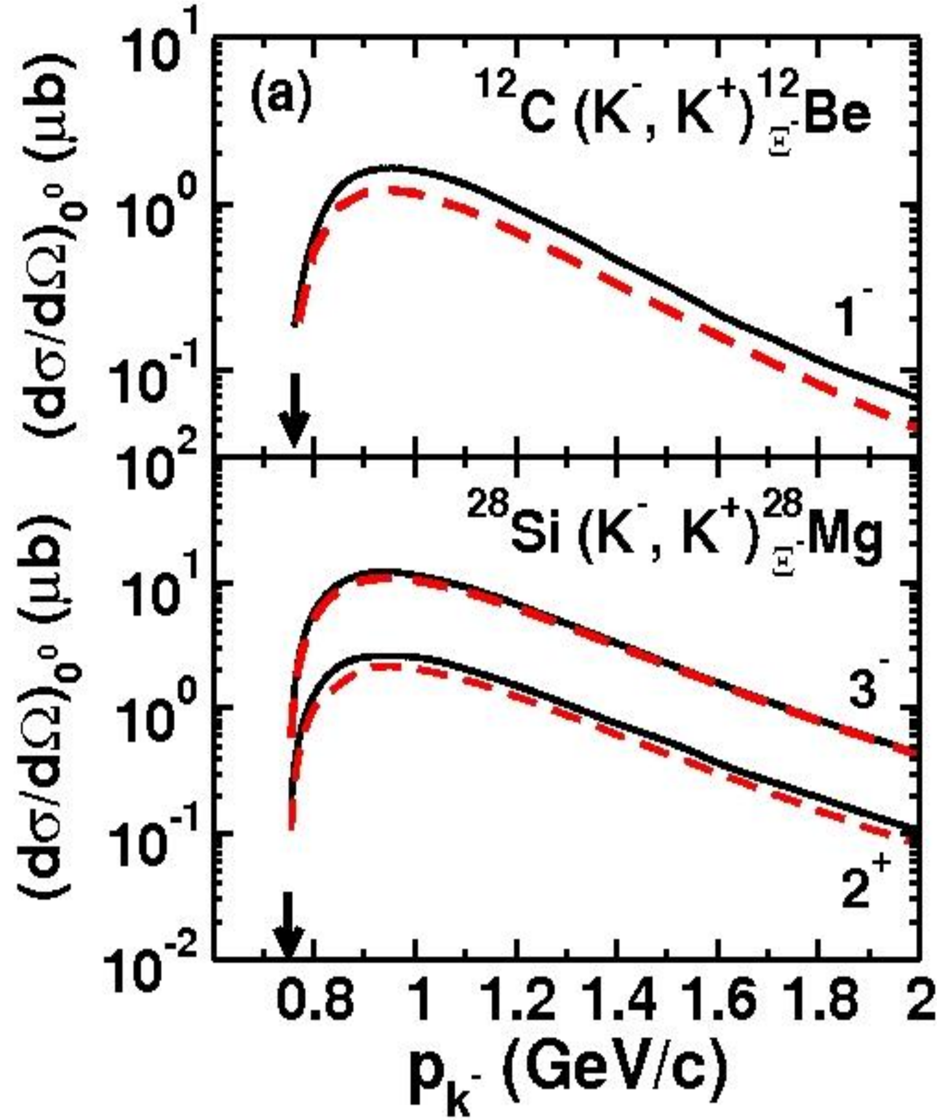
Quark-meson Coupling (QMC) Model —— Dirac Single particle model ----



Cross section for Ξ^- hypernuclear production



Single particle-single-hole ($\Xi\ p^{-1}$) structure.



Threshold to peak energy difference almost similar.

Peak in hypernuclear production cross sections ≈ 1.0 GeV

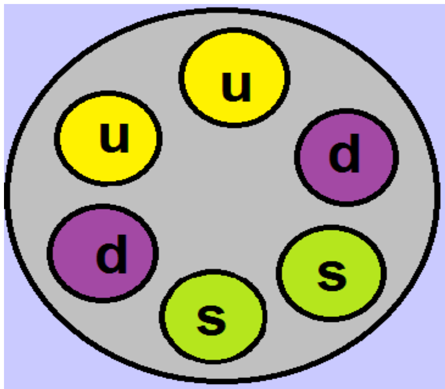
Peak cross sections are between 1-10 μb.

The H dibaryon

Perhaps a Stable Dihyperon*

R. L. Jaffe†

PRL 38 (1977) 195



Stable, flavor-singlet 6q object (single hadron) , S = -2, Spin-parity 0^+, and isospin 0.

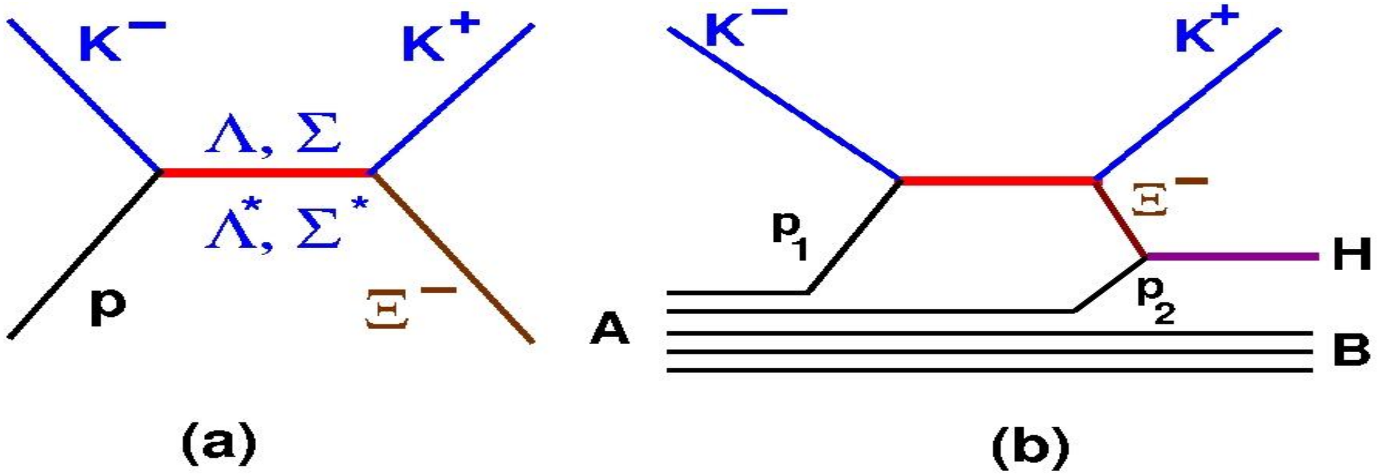
BE = 80 MeV (2150 MeV, ($m_\Lambda + m_\Lambda$ - 80 MeV)

- **Center-of-mass motion, pionic-cloud corrections to this model predicted this system to be much less bound or even unbound.**

- **A definite lower limit on the binding energy of H in the KEK experiment where the $^{6}_{\Lambda\Lambda}He$ observed with a double Λ BE of 6.9 MeV. $M_H > 2\,m_\Lambda - B_{\Lambda\Lambda}$**

Nakazawa, Nucl. Phys. A 835 (2010) 207

H dibaryon production by (K^-,K^+) reaction



Factorization approximation Aerts and Dover, Phys. Rev. D28 (1983) 450

$$A \propto [\Sigma_{Y*} M\,(K^- + p_1 \rightarrow K^+ + \Xi^-)]\; F(\Xi^- + p_2 \rightarrow H)$$

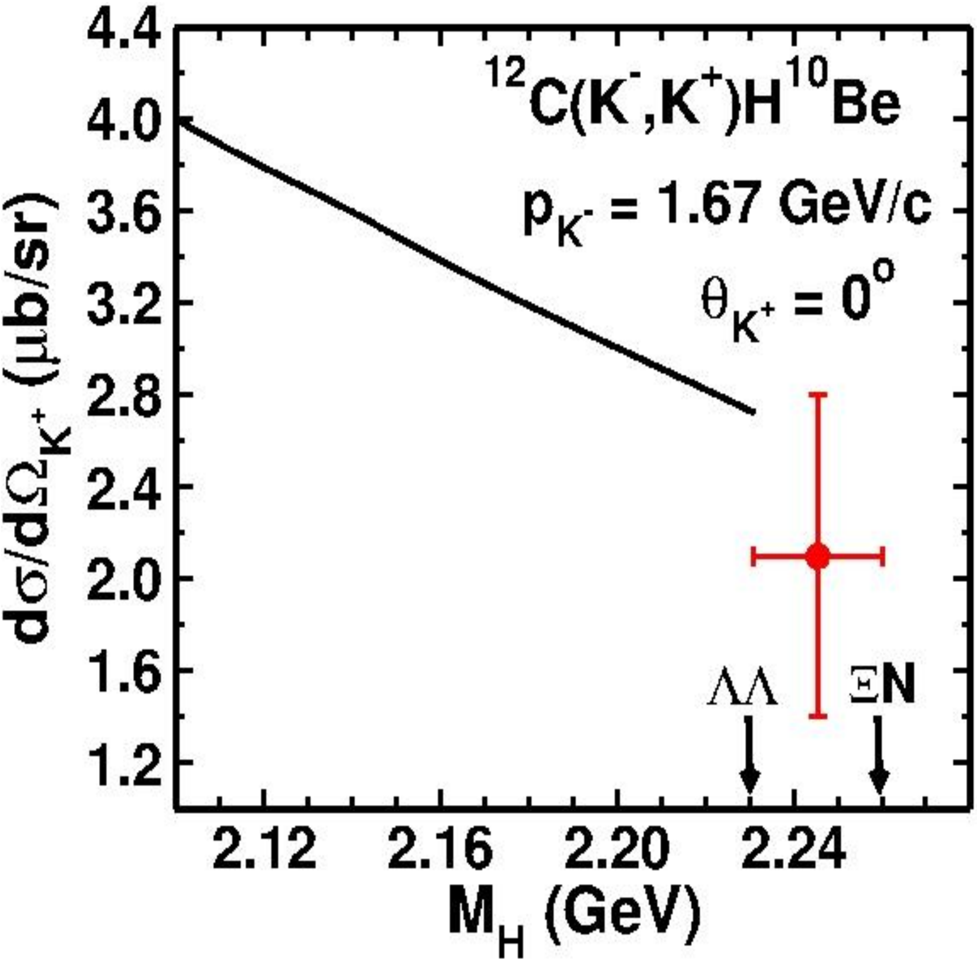
Proper three-body phase space.

Ξ production from effective Lagrangian model.

F function from the overlap of the internal wave functions of three particles invoking their quark structures.

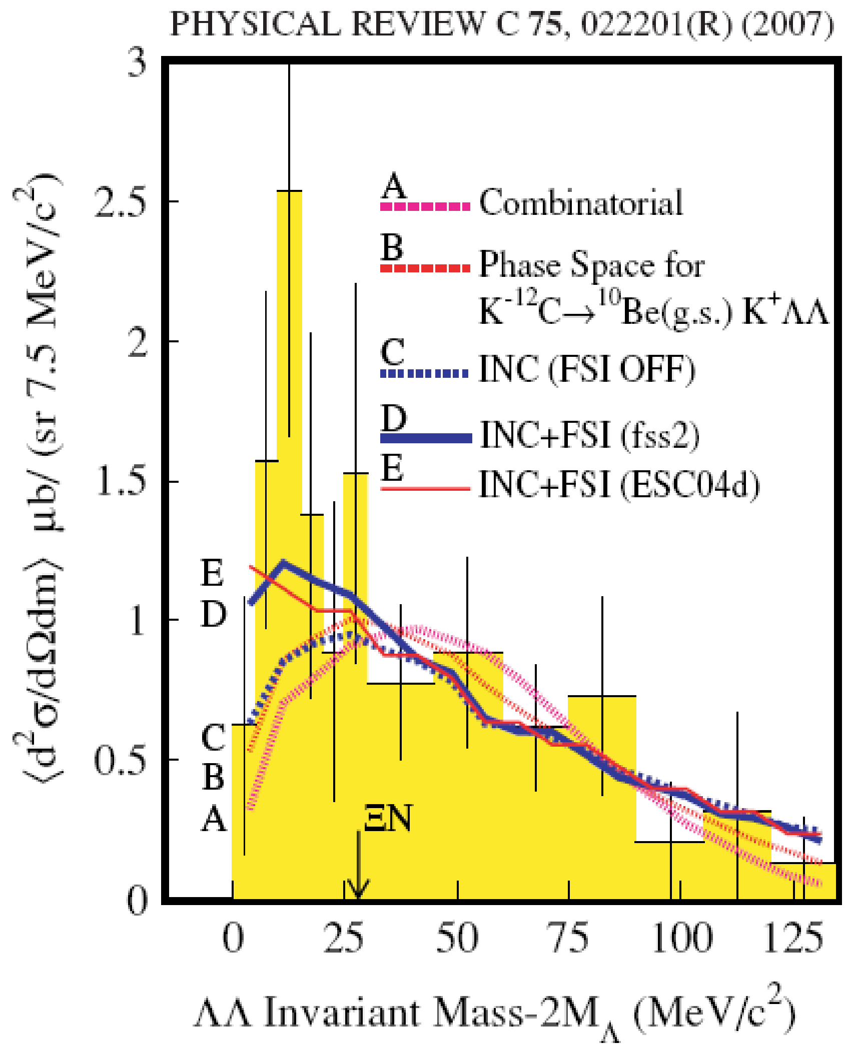
R.S. , O. Scholten and A.W. Thomas, Phys. Rev. C 88 (2013) 025209

H production as a function of H mass

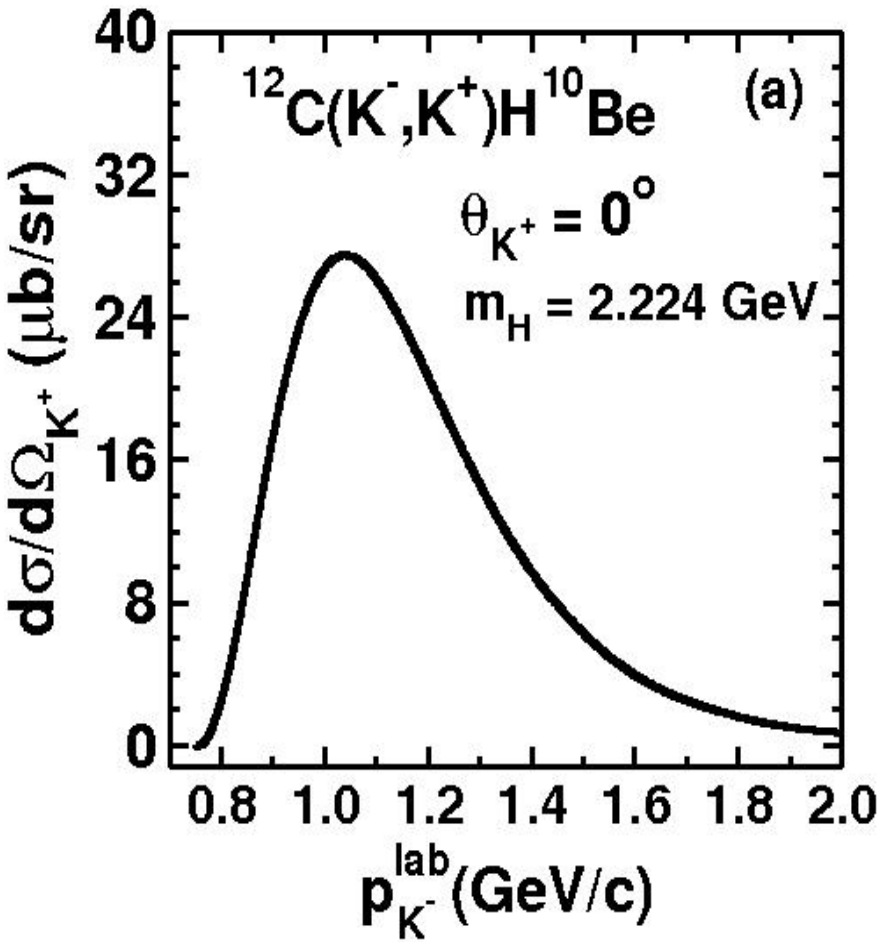


We stop calculations at $M_H = 2m_\Lambda$

$^{12}C(K^-,K^+\Lambda\Lambda X)$

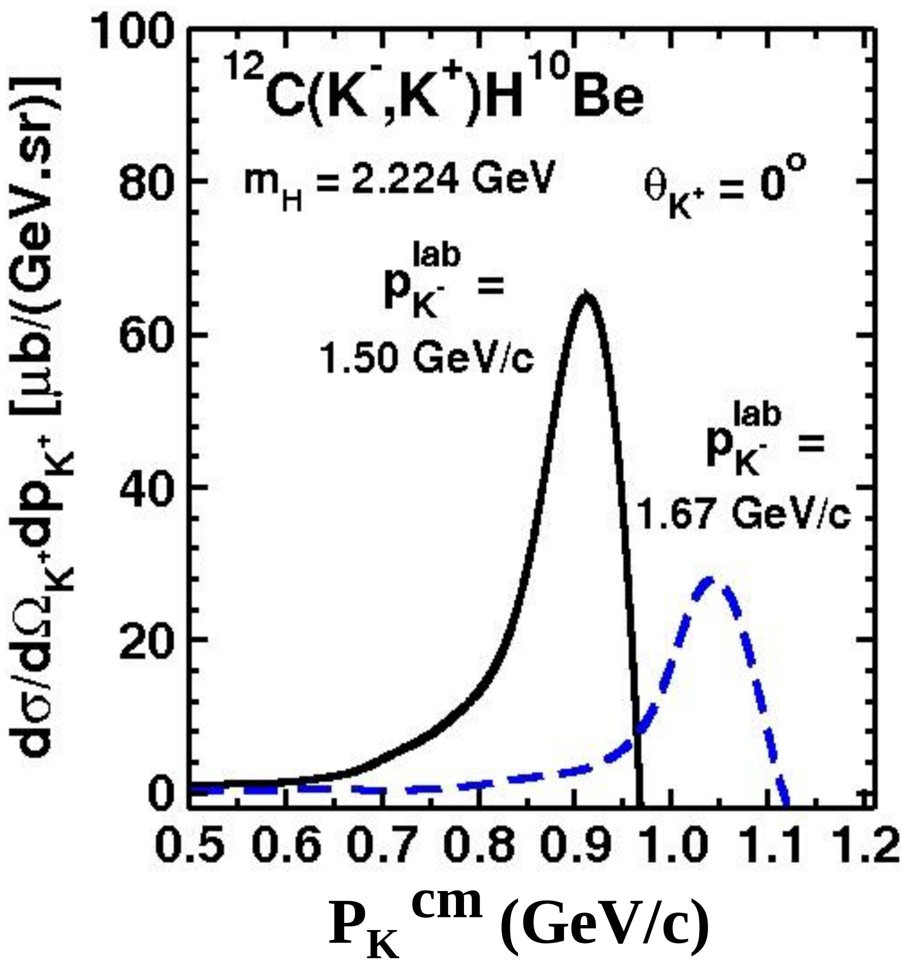


Beam momentum dependence



Follows closely the trends of the elementary Ξ production, just like the hypernuclear production

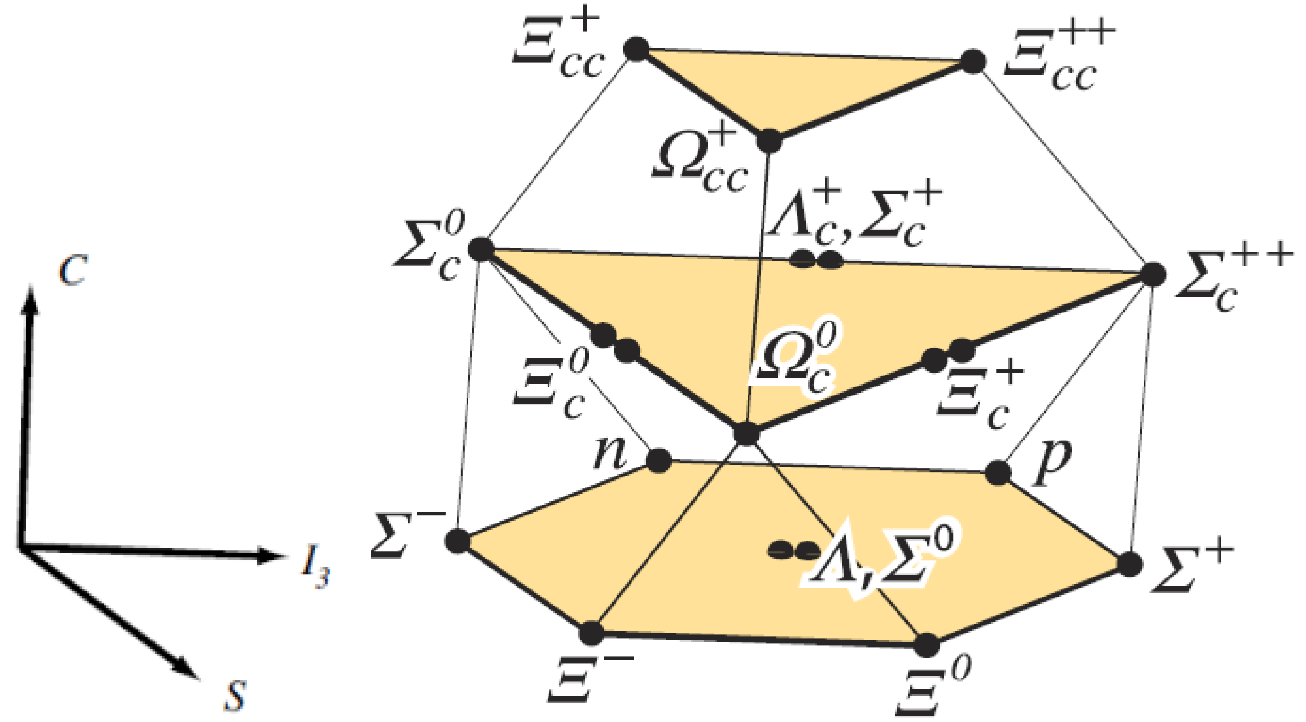
Momentum spectrum of K^+



Peak very close to the kinematically allowed $p_K^{CM,max}$. Width 90 MeV

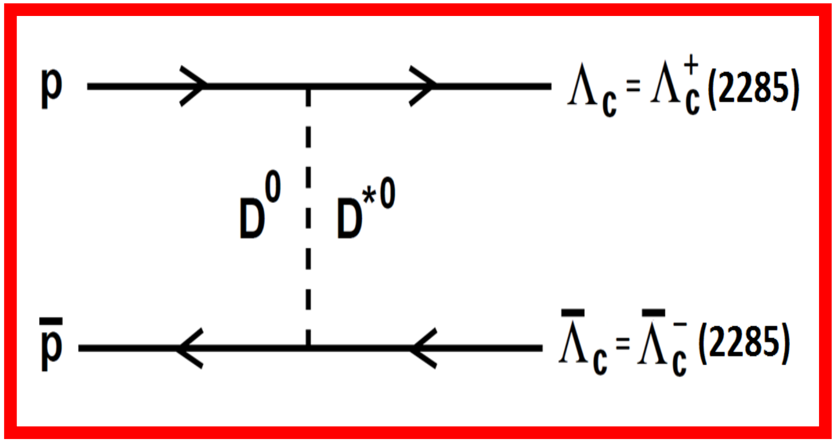
4. Production of charmed baryons and mesons in proton-antiproton annihilation

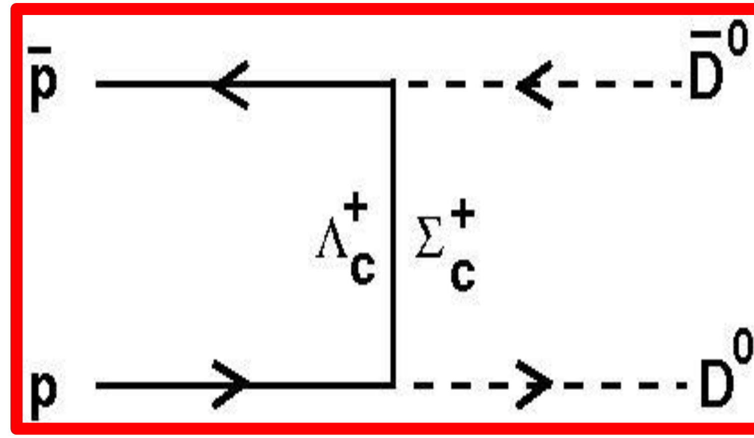
...from isospin and strangeness to flavor physics:



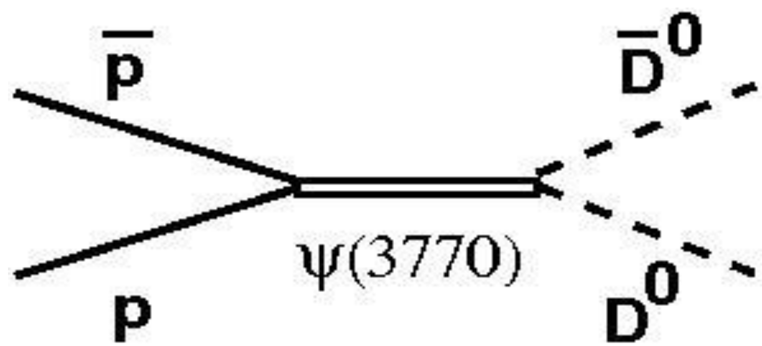
SU(4) baryon 20-plet in the (u,d,s,c) quark-sector

Λ_c^+ (udc) and D^0 ($c\bar{u}$) production in Proton-Antiproton Annihilation:





RS and H. Lenske, Phys. Rev. D 90 (2014) 014017, and to be published



$$\mathcal{L}_{D^0BN} = ig_{BD^0N}\bar{\psi}_B i\gamma_5\psi_N\phi_{D^0} + h.c.$$

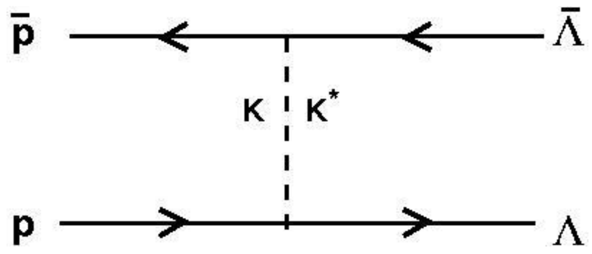
$$F(q) = \frac{\lambda^2 - m_D^2}{\lambda^2 - q_D^2},$$

$$\mathcal{L}_{D^{*0}BN} = g_{D^{*0}BN}\bar{\psi}_B\gamma_\mu\psi_N\theta^\mu_{D_{*0}} + \frac{f_{D^{*0}BN}}{4M}\bar{\psi}_B\sigma_{\mu\nu}\psi_N F^{\mu\nu}_{D^{*0}} + h.c.,$$

$$F^{\mu\nu}_{D^{*0}} = \partial^\mu\theta^\nu_{D_{*0}} - \partial^\nu\theta^\mu_{D_{*0}}$$

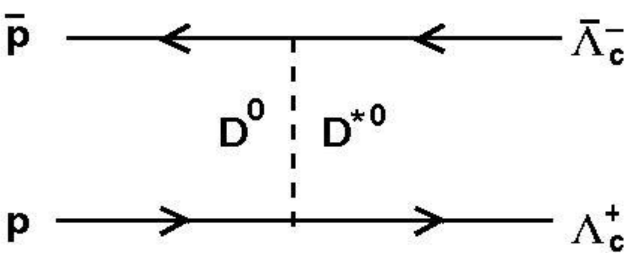
Reactions near the thereshold beam momenta

Threshold = 1.43 GeV/c



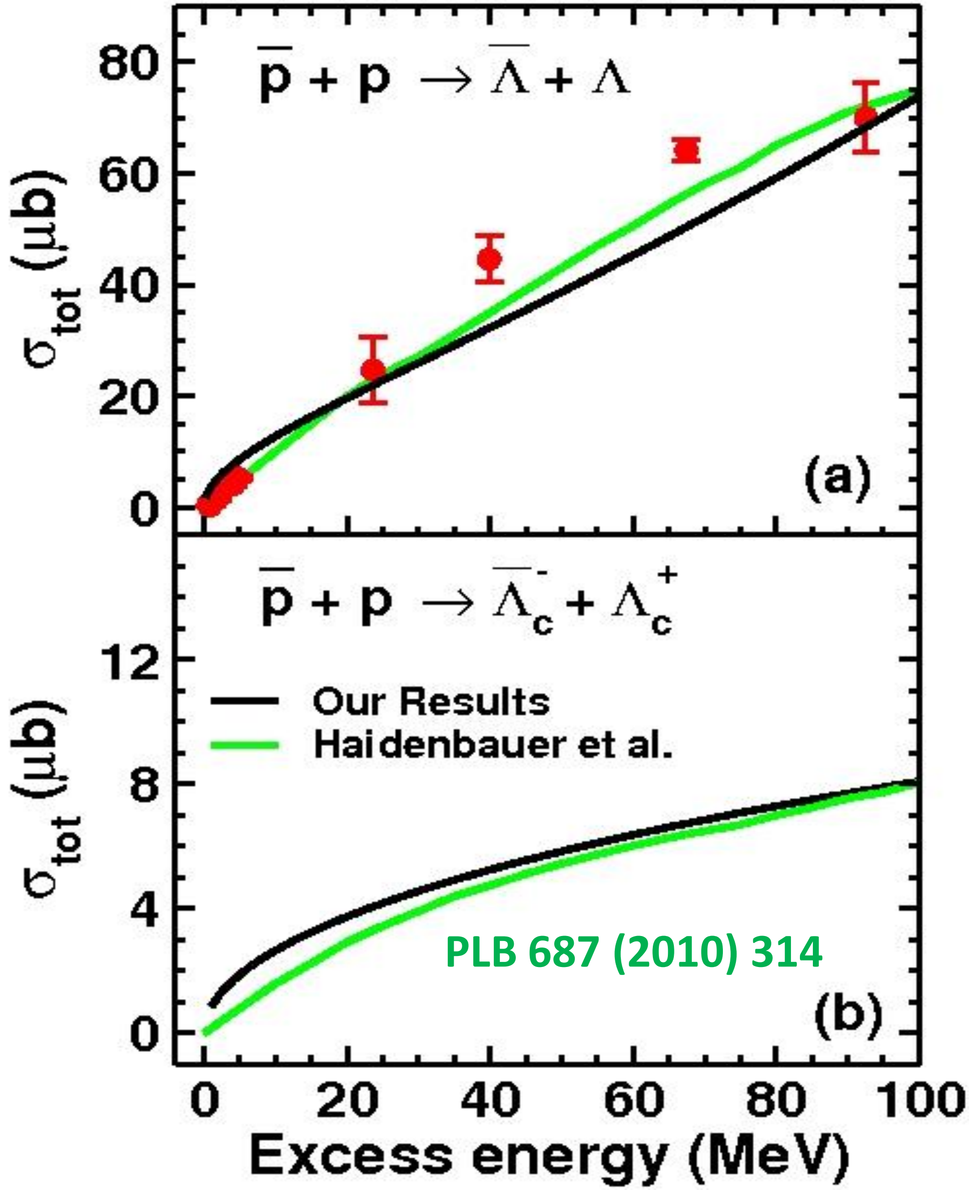
ISI is included in a coupled channels model

Threshold = 10.16 GeV/c



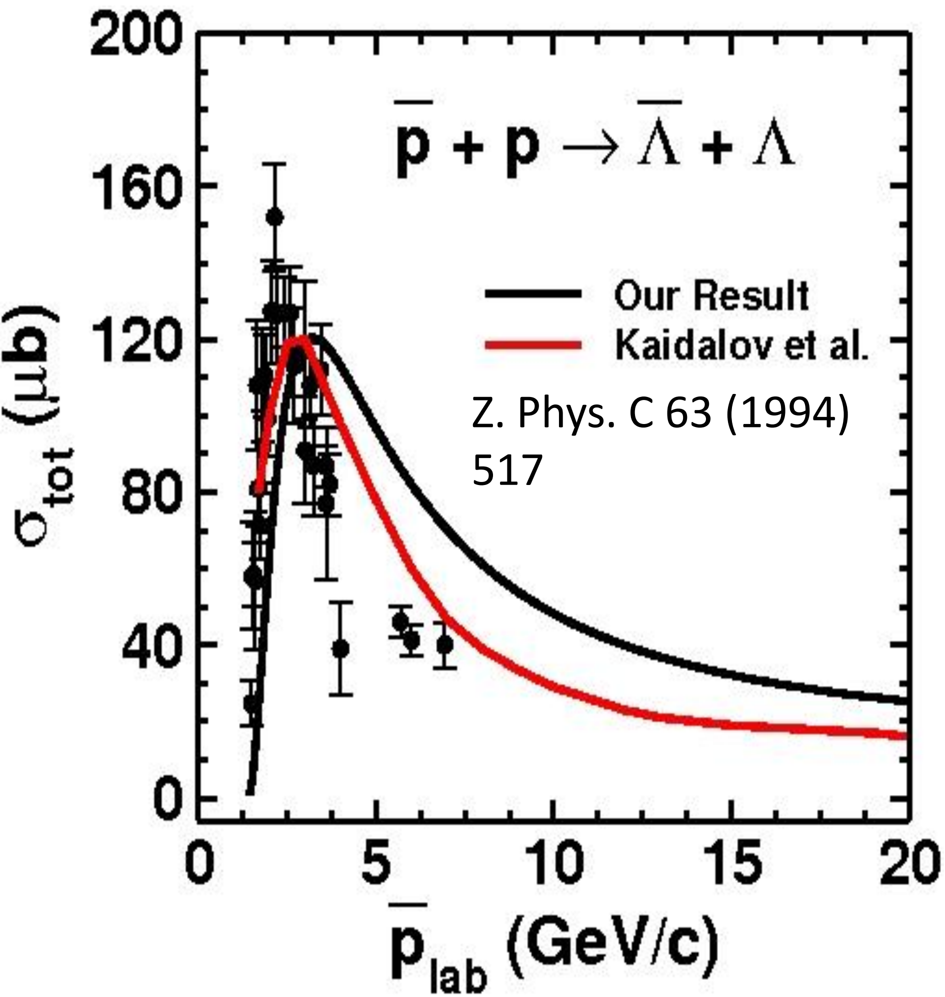
Same coupling constants and the form factor at the vertices, SU(4) symmetry

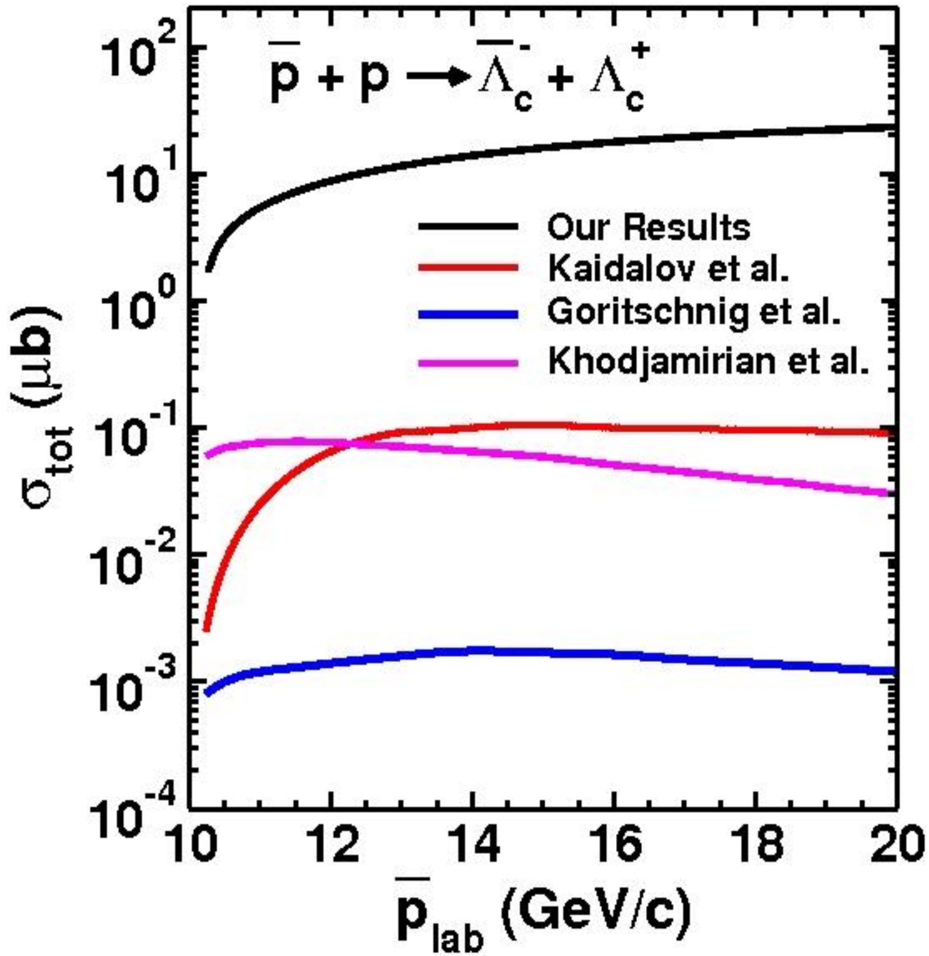
ISI in included within an eikonal model



Excess energy = $\sqrt{s} - m_1 - m_2$

Reactions at higher beam momenta

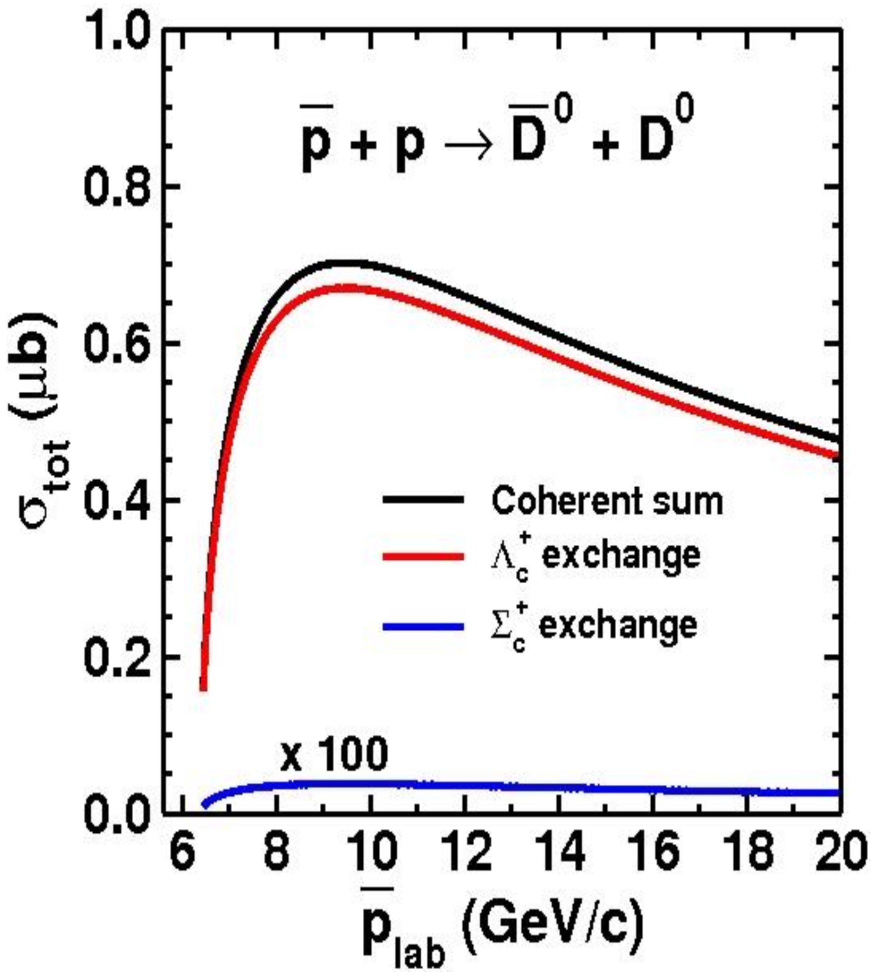


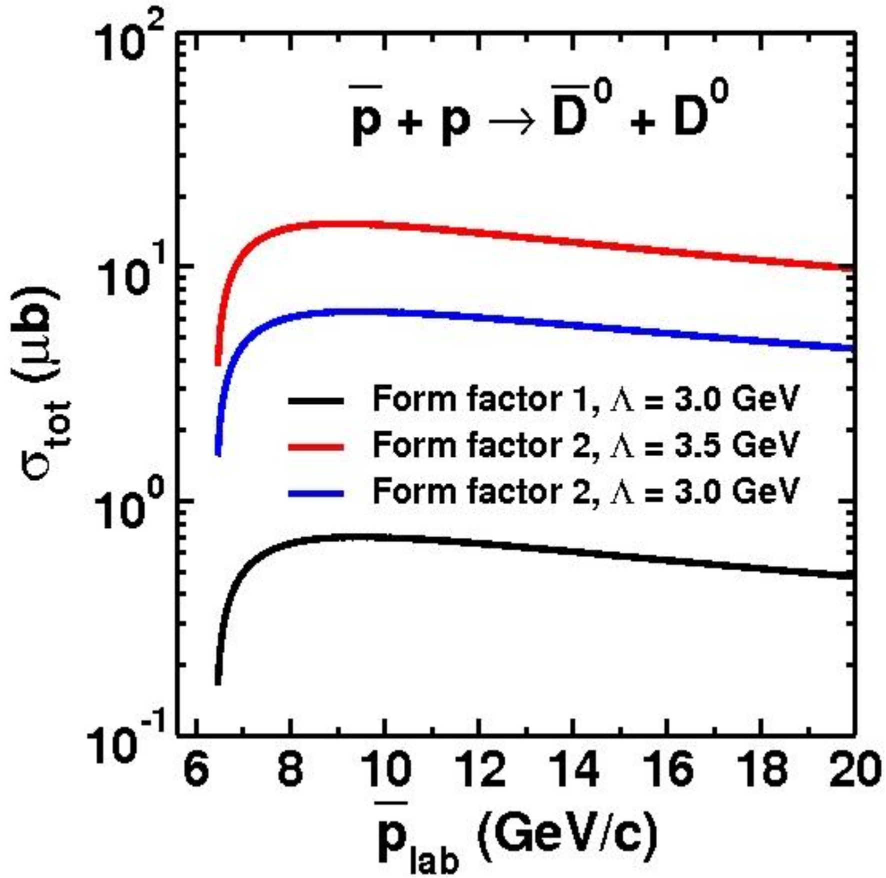


At 15 GeV/c σ_{tot} = 32 μb,
19 μb

At 15 GeV/c σ_{tot} = 18 μb

D^0-$\bar{D}^0$ production in antiproton-proton annihilation





Form factor 1 $F(q) = \dfrac{\lambda^2 - m_D^2}{\lambda^2 - q_D^2}$

At 15 GeV/c $\sigma_{tot} = 0.55$ **μb**

Haidenbauer and Grein, PRD 89 (2014) 114003

Form factor 2 $F(q) = \dfrac{\lambda^4}{\lambda^4 + (q^2 - m^2)^2}$

Estimation of the $p\,\bar{p} \to \psi(3770) \to D^0\,\bar{D}^0$ cross section in a resonance production and decay model

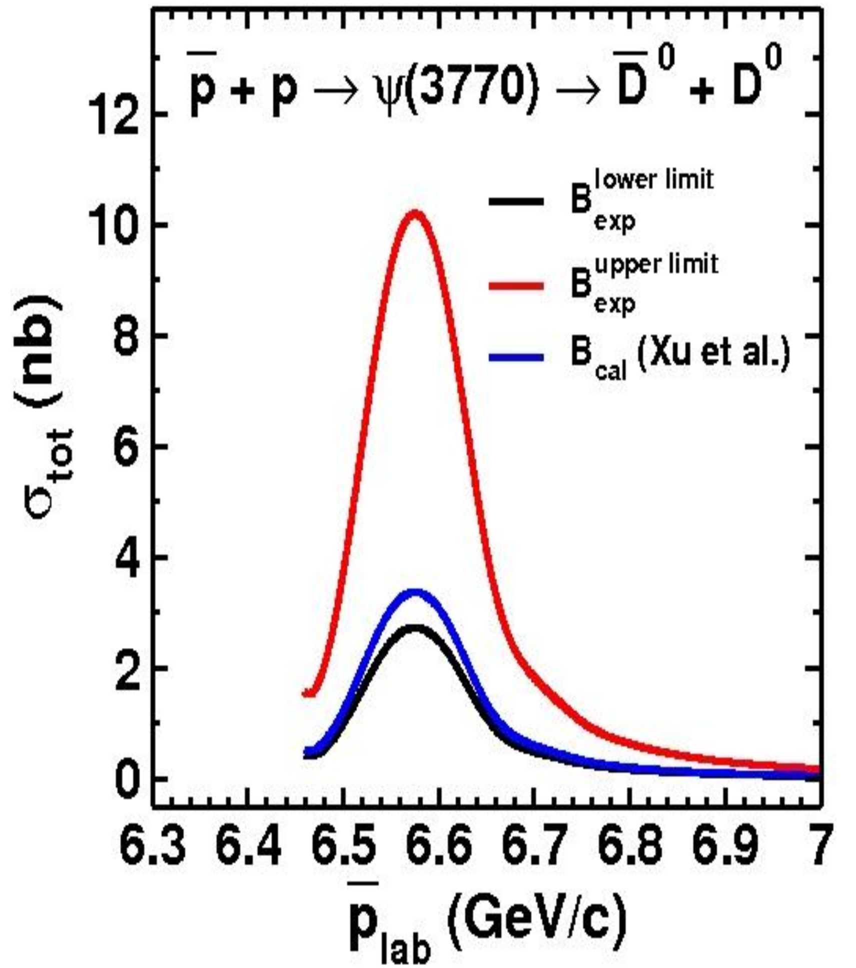
$$\sigma_{\bar{p}p\to\psi(3770)\to\bar{D}^0D^0} = \frac{2J_R+1}{(2j_{\bar{p}}+1)(2j_p+1)}\,\frac{4\pi}{q^2_{\bar{p}p}}\,\frac{s\Gamma_{\psi(3770)\to\bar{p}p}\,\Gamma_{\psi(3770)\to\bar{D}^0D^0}}{(s-M^2_{\psi})+s\Gamma^2_{tot}}$$

$B(\psi \to p\bar{p}) = (7.1^{+8.6}_{-2.9})\text{x}10^{-6}$

BESSIII collaboration, Phys. Lett. B 735 (2014) 101

Calculated value, Xu et al., arXiv:1505.04571

$B(\psi \to p\bar{p}) = (3.5 \pm 1.7)\text{x}10^{-6}$



Summary

1

The coupled channels effective Lagrangian approach based on the K- matrix method provides a good description of the meson production in photon nucleon reactions.

It is indeed possible to fit the data for many channels simultaneously with a single parameter set within a coupled-channels method.

2

A description of the cascade hypernuclear production reactions based on the mechanism of resonance excitation and decay has been developed.

Cross section of H dibaryon production around 1.0 GeV/c beam momentum is expected to be an order of magnitude larger than that at 1.8 GeV/c.

3

Effective Lagrangian model is developed to describe the Λ_c^+ baryon and D^0 meson production in proton-antiproton annihilation. The cross sections are found to be larger than old Regge model calculations at the beam momentum of interest to the PANDA experiment.