Toward the determination of quantum numbers of Θ^+

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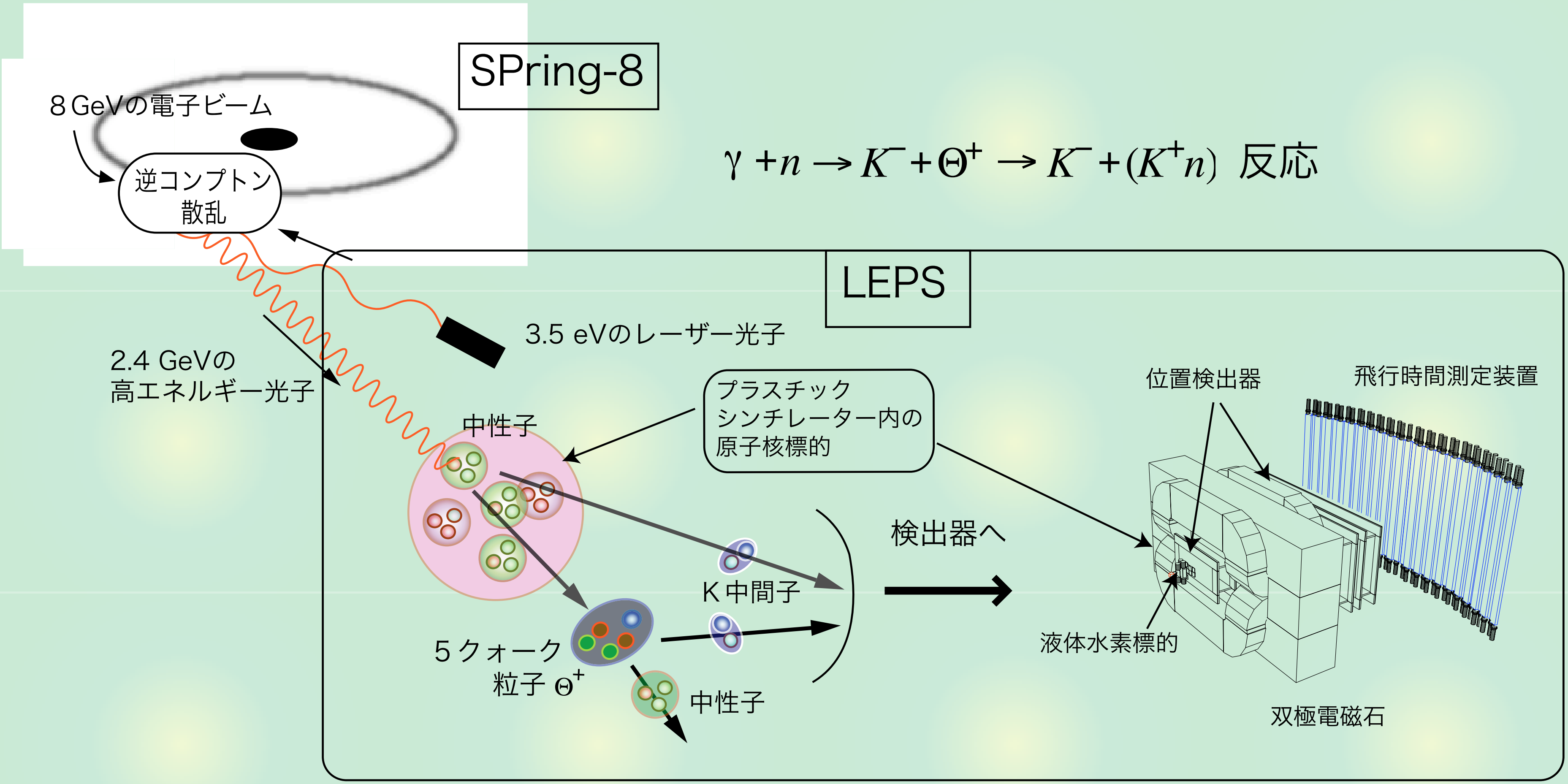
Contents

- Present status of studies
  - Experiments (what do we know?)
  - Model calculations
  - Analysis based on QCD
- Production 1 : $K^+p \longrightarrow \pi^+K^+n$
  - Motivation
  - Chiral model for the reaction
  - Spin and parity
  - Numerical results
- Production 2 : $\vec{p}\vec{p} \longrightarrow \Sigma^+\Theta^+$
  - Model independent analysis
  - Numerical results

Experiment at SPring-8

LEPS, T. Nakano, *et al.*, Phys. Rev. Lett. 91, 012002 (2003)

$\gamma + n \rightarrow K^{-} + \Theta^{+} \rightarrow K^{-} + (K^{+}n)$ 反応



Other experiments

$$K^+ Xe \to K^0 p X e'$$

DIANA, V.V. Barmin, *et al.*, Phys. Atom. Nucl. 66, 1715-1718 (2003)

$$\gamma d \to K^+ K^- p n$$

CLAS, S. Stepanyan, *et al.*, Phys. Rev. Lett. 91, 252001 (2003)

$$\gamma p \to n K^+ K^0_s$$

SAPHIR, J. Barth, *et al.*, Phys. Lett. B 572, 127-132 (2003)

$$\gamma p \to \pi^+ K^- K^+ n$$

CLAS,V. Kubarovsky, *et al.*, Phys. Rev. Lett. 92, 032001 (2004)

- **mass ~ 1540 MeV**
- **width < 9 MeV**
- **S = +1 (Y = 2)**
- **Q = +1 (I_3 = 0)**

Prejudice?

- **Pentaquark state?**
- **It could be 7-, 9-, ... quark state.**
- P. Bicudo, *et al.*, Phys. Rev. D 69, 011503 (2004)
- F. J. Llanes-Estrada, *et al.*, nucl-th/0311020
- T. Kishimoto, *et al.*, hep-ex/0312003
- **Anti-decuplet?**
- **It could be a member of 27, 35, ...**
- $3 \times 3 \times 3 \times 3 \times \bar{3} \sim \{1, 8, 10, \overline{10}, 27, 35\}$
- **Positive parity?**

Not yet determined experimentally.

Model calculations : Prediction?

D. Diakonov, *et al.*, Z. Phys. A 359, 305 (1997)

Chiral quark soliton model : 1/2+, I=0

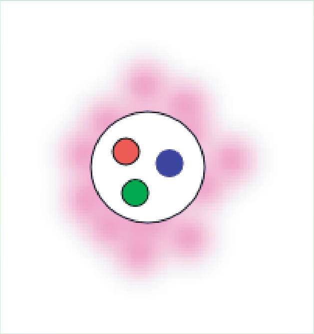
	T	Y	Mass in MeV	Width in MeV	Possible candidate
Z^+	0	2	1530	15	—
$N_{\overline{10}}$	1/2	1	1710 (input)	~ 40	$N(1710)P_{11}$
$\Sigma_{\overline{10}}$	1	0	1890	~ 70	$\Sigma(1880)P_{11}$
$\Xi_{3/2}$	3/2	−1	2070	> 140	$\Xi(2030)?$

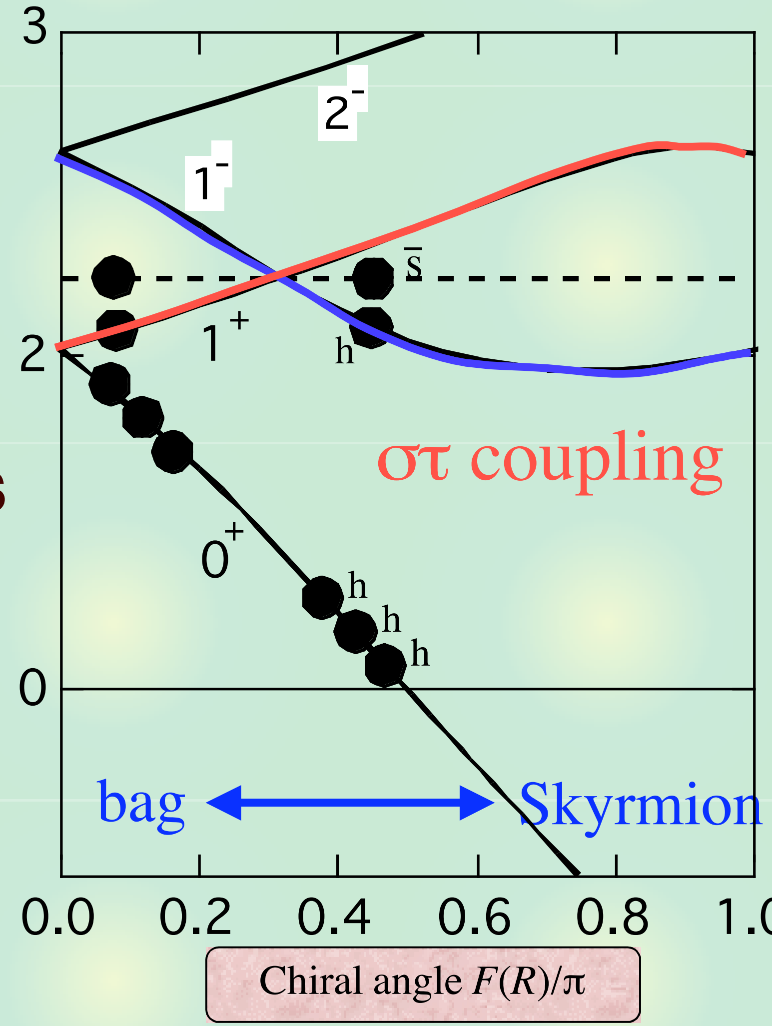
- PDG estimate : $\Gamma_N \sim$ 100 (50 - 250) MeV
  $\Gamma_\Sigma \sim$ 80 - 260
- $\Xi_{3/2}$ resonance : M_Ξ = 1862 MeV, Γ_Ξ < 18 MeV

NA49, C. Alt, *et al.*, Phys. Rev. Lett. 92, 042003 (2004)

Model calculations

☆ Chiral potential





Single particle levels of quarks cross as the strength of pion cloud changes.

Strong π : $1/2^+$

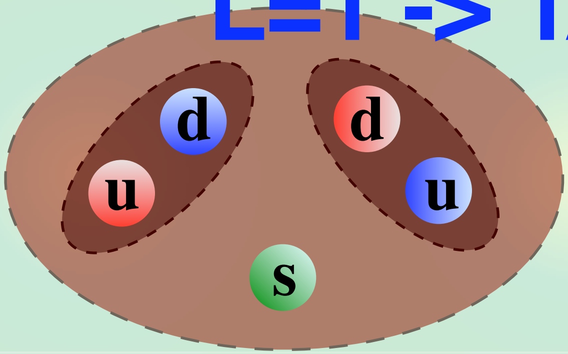
Weak π : $1/2^-$

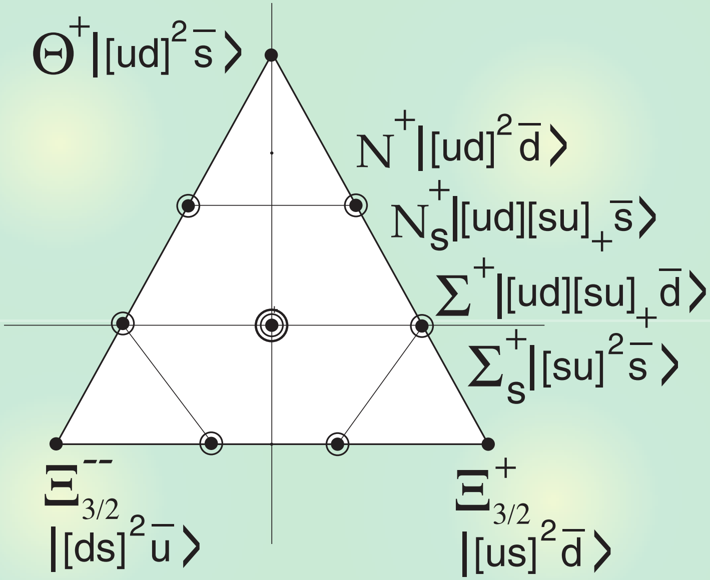
A. Hosaka, Phys. Lett. B 571, 55-60 (2003)

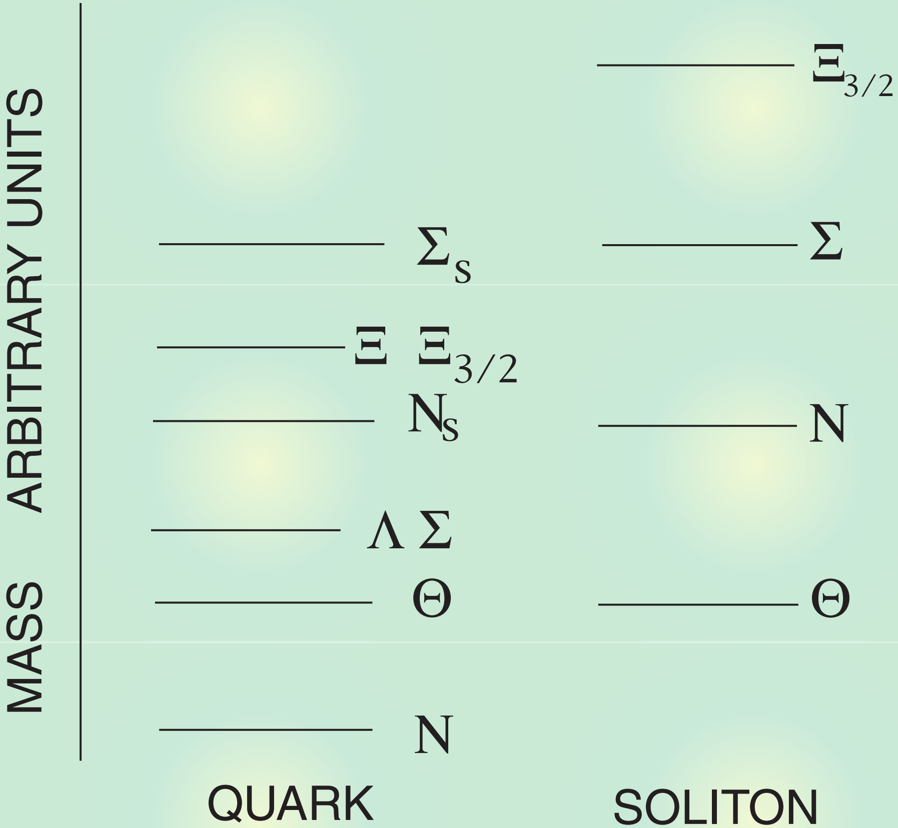
Model calculations

☆ Diquark picture / mixing with octet

L=1 -> 1/2+







[R.L. Jaffe, *et al.*, Phys. Rev. Lett. 91, 232003 (2003)]

Analysis based on QCD

QCD sum rule

no parity projection

S.L. Zhu, Phys. Rev. Lett. 91, 232002 (2003)
R.D. Matheus, *et al.*, Phys. Lett. B 578, 323-329 (2004)

parity projection -> $1/2^-$

J. Sugiyama, *et al.*, Phys. Lett. B 581, 167-174 (2004)

Lattice QCD

parity projection -> $1/2^-$

F. Csikor, *et al.*, JHEP 0311, 070 (2003)
S. Sasaki, hep-lat/0310014
F.X. Lee, K.F. Liu, *et al.*, (Kentucky group)

Motivation : Spin parity determination

No consensus for spin and parity.
It is important to determine the quantum numbers for further theoretical studies.

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Find a reaction where the qualitatively different results depending on the quantum numbers are observed.

Motivation : Photo-production?

- **Easy to handle the experiments**

W. Liu, *et al.*,	Phys. Rev. C 68, 045203 (2003)
S. I. Nam, *et al.*,	Phys. Lett. B 579, 43-51 (2004)
W. Liu, *et al.*,	nucl-th/0309023
Y. Oh, *et al.*,	Phys. Rev. D 69, 014009 (2004)
Q. Zao, *et al.*,	hep-ph/0310350
W. Liu, *et al.*,	nucl-th/0310087
K. Nakayama, *et al.*,	hep-ph/0310350
Y. Oh, *et al.*,	hep-ph/0312229
B. Yu, *et al.*,	nucl-th/0312075
Q. Zao, *et al.*,	hep-ph/0312348

- **Model (mechanism) dependence**

  Initial cm energy ~ 2 GeV (p_{cm} ~ 750 MeV)
  not low energy -> linear or nonlinear?
  N* resonances, K* exchange, κ exchange, …

- **Form factor dependence**

  Monopole, dipole, … , value of Λ, …

- **Unknown parameters**

  $\gamma\Theta\Theta$ coupling, $K^*p\Theta$ coupling, …

Motivation : Advantage of hadronic process

We propose

$$K^+p \to \pi^+\Theta^+ \to \pi^+K^+n(K^0p)$$

- Low energy model is sufficient (p_{cm} ~ 350 MeV)
- Decay is considered -> background estimation
  -> Width independent
- Hadronic process : clear mechanism

to extract a qualitative behavior which depends on the quantum numbers of Θ^+.

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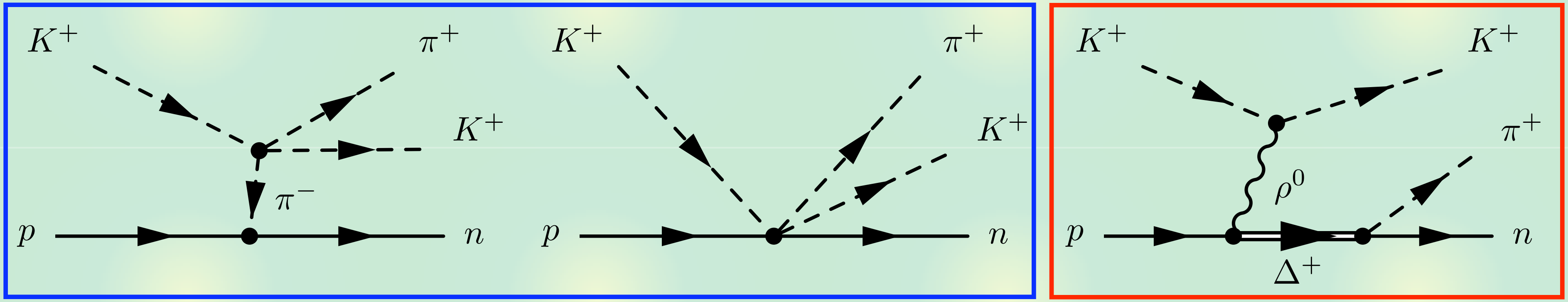
Determination of quantum numbers

Chiral model for the reaction: Background

E. Oset and M. J. Vicente Vacas, PLB386, 39 (1996)

Vertices <- chiral Lagrangian



Proportional to $S \cdot p_{\pi^+}$

Dominant

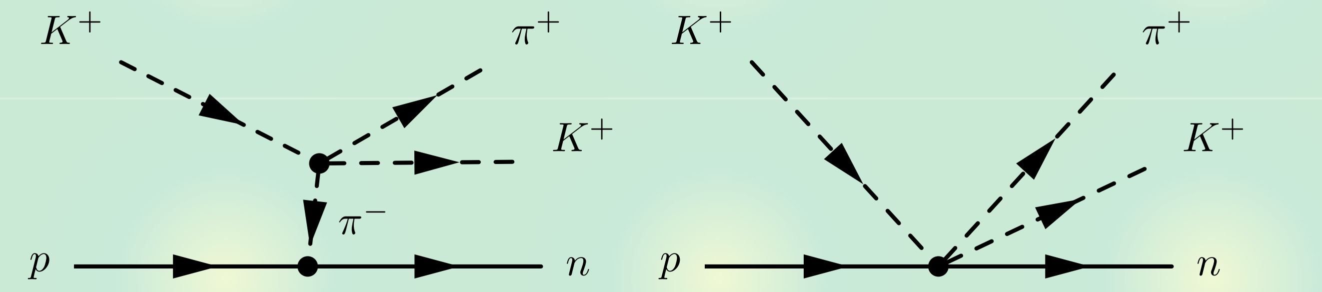
vanishes

Assume the final π^+ is almost at rest

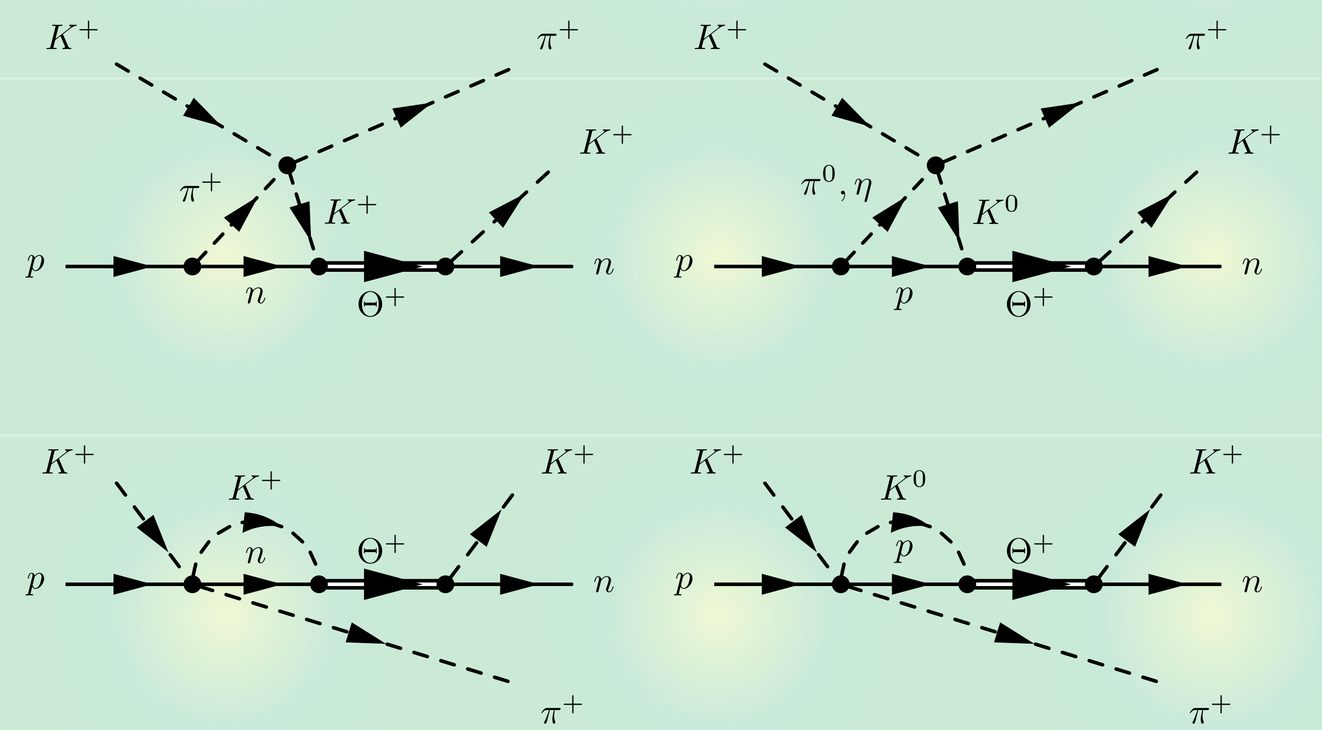
Production 1 : $K^+ p \to \pi^+ K^+ n$

Chiral model for the reaction: Resonance term

Background (tree level)



Resonance (one loop)



Production 1 : $K^+ p \to \pi^+ K^+ n$

Spin and parity : KN -> Θ -> KN

- M_R = 1540 MeV
- Γ_R = 20 MeV

$1/2^-$ (KN s-wave resonance)

$1/2^+$, $3/2^+$ (KN p-wave resonance)

$$t^{(s)}_{K^+n(K^0p)\to K^+n} = \frac{(\pm) g^2_{K^+n}}{M_I - M_R + i\Gamma/2},$$

$$t^{(p,1/2)}_{K^+n(K^0p)\to K^+n} = \frac{(\pm) \bar{g}^2_{K^+n} (\boldsymbol{\sigma}\cdot\boldsymbol{q}')(\boldsymbol{\sigma}\cdot\boldsymbol{q})}{M_I - M_R + i\Gamma/2},$$

$$t^{(p,3/2)}_{K^+n(K^0p)\to K^+n} = \frac{(\pm) \tilde{g}^2_{K^+n} (\boldsymbol{S}\cdot\boldsymbol{q}')(\boldsymbol{S}^\dagger\cdot\boldsymbol{q})}{M_I - M_R + i\Gamma/2},$$

$$g^2_{K^+n} = \frac{\pi M_R \Gamma}{M q}, \quad \bar{g}^2_{K^+n} = \frac{\pi M_R \Gamma}{M q^3}, \quad \tilde{g}^2_{K^+n} = \frac{3\pi M_R \Gamma}{M q^3}.$$

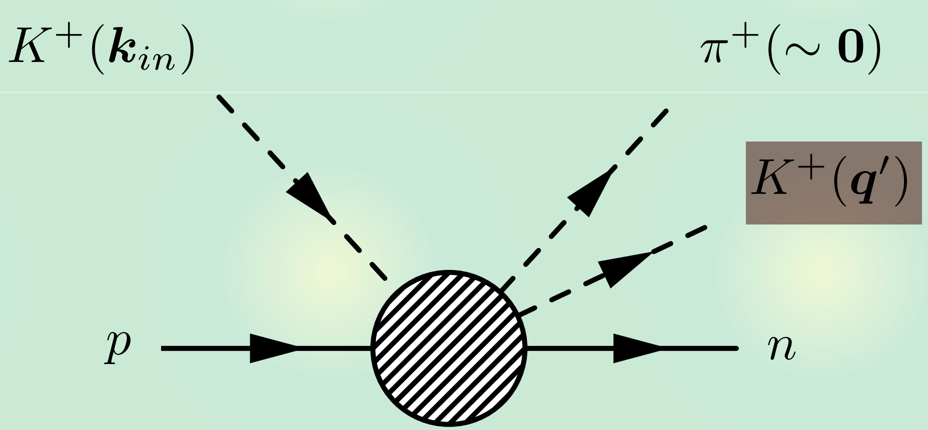
Spin and parity : Resonance amplitude

Resonance term for $K^+p \to \pi^+K^+n$

$$-i\tilde{t}_i^{(s)} = \frac{g^2_{K^+n}}{M_I - M_R + i\Gamma/2}\left\{G(M_I)(a_i + c_i) - \frac{1}{3}\bar{G}(M_I)b_i\right\}\boldsymbol{\sigma}\cdot\boldsymbol{k}_{in}S_I(i) \ ,$$

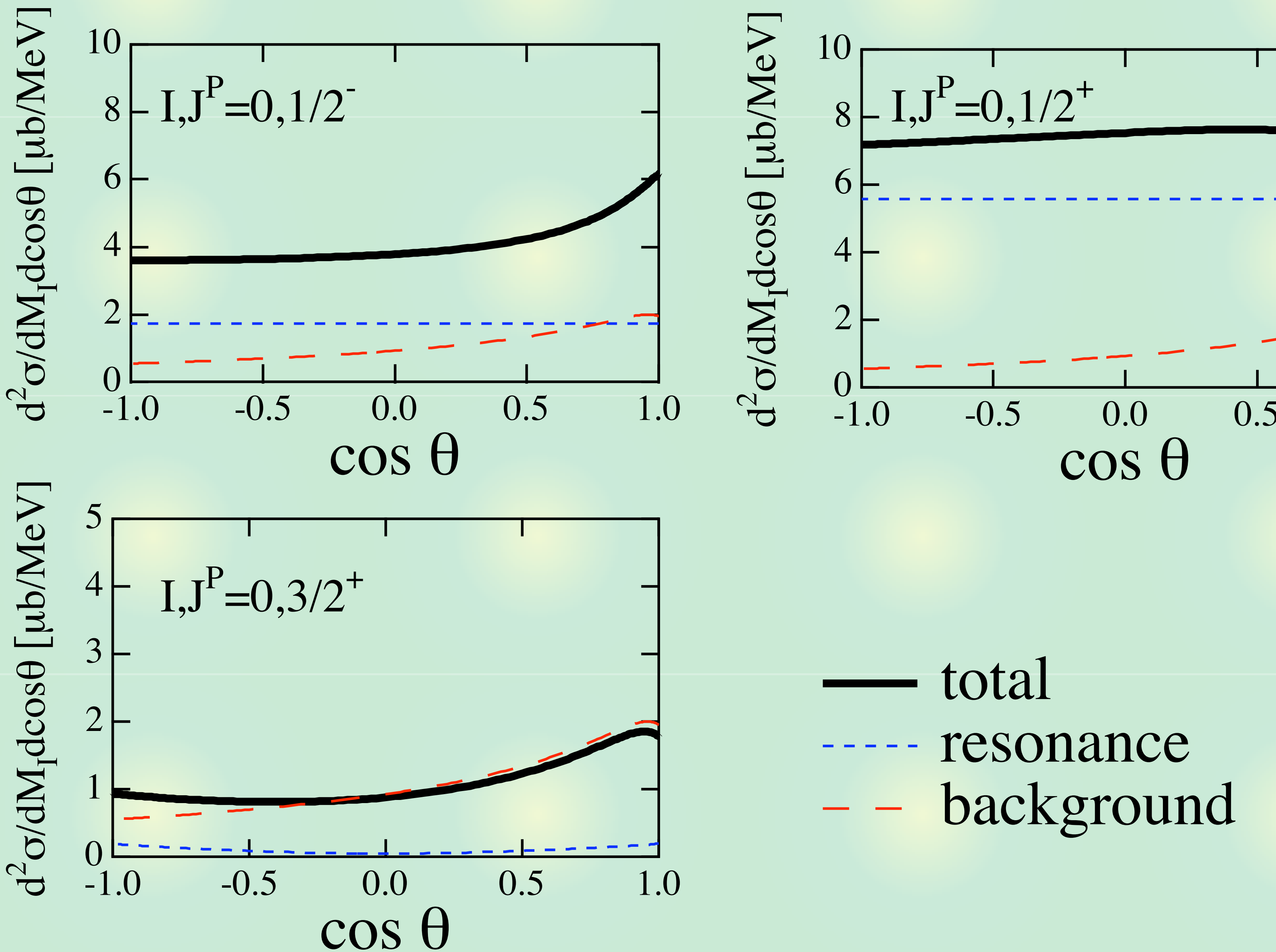
$$-i\tilde{t}_i^{(p,1/2)} = \frac{\bar{g}^2_{K^+n}}{M_I - M_R + i\Gamma/2}\bar{G}(M_I)\left\{\frac{1}{3}b_i\boldsymbol{k}^2_{in} - a_i + d_i\right\}\boldsymbol{\sigma}\cdot\boldsymbol{q}'S_I(i) \ ,$$

$$-i\tilde{t}_i^{(p,3/2)} = \frac{\tilde{g}^2_{K^+n}}{M_I - M_R + i\Gamma/2}\bar{G}(M_I)\frac{1}{3}b_i\left\{(\boldsymbol{k}_{in}\cdot\boldsymbol{q}')(\boldsymbol{\sigma}\cdot\boldsymbol{k}_{in}) - \frac{1}{3}\boldsymbol{k}^2_{in}\boldsymbol{\sigma}\cdot\boldsymbol{q}'\right\}S_I(i) \ ,$$



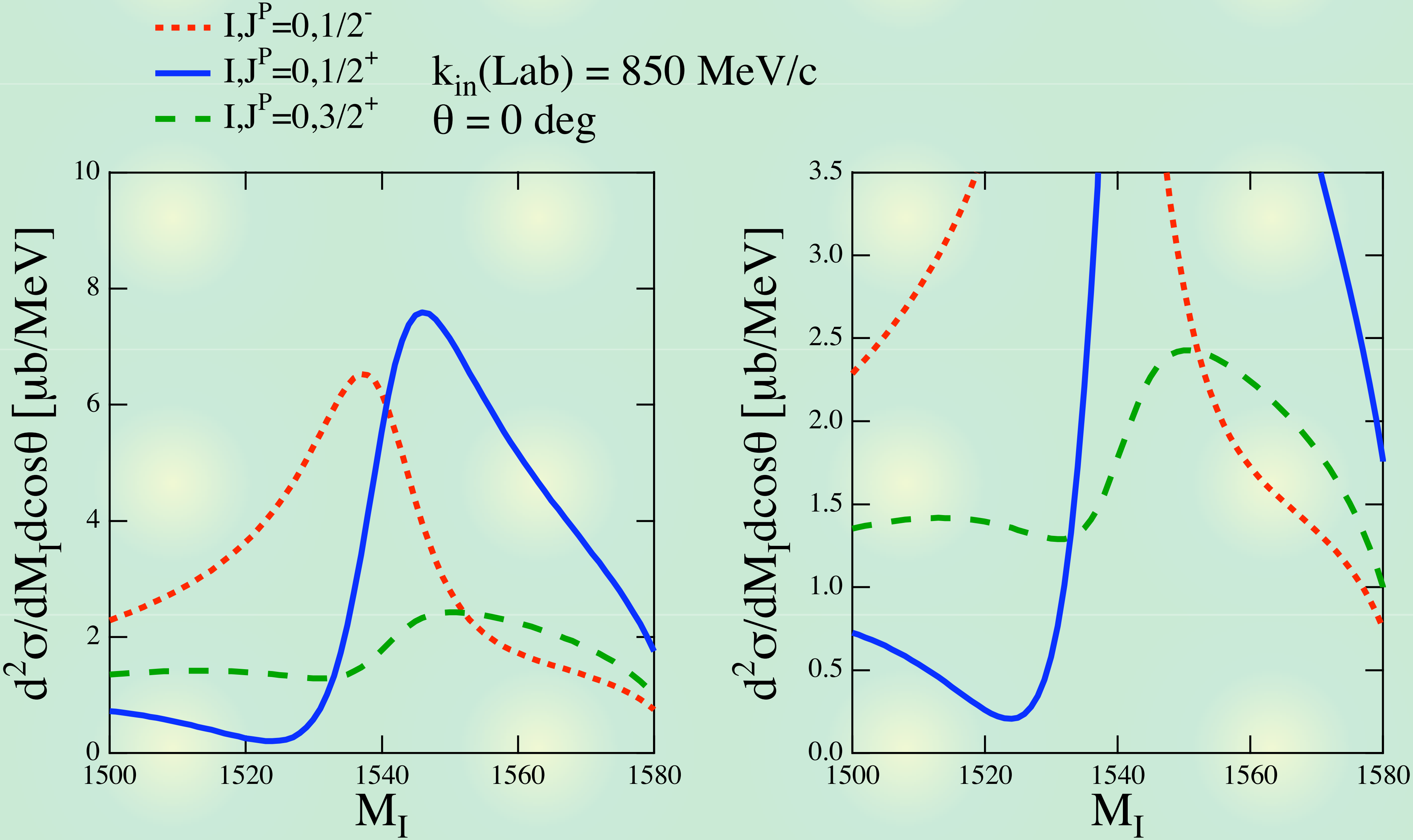
Production 1 : $K^+ p \rightarrow \pi^+ K^+ n$

Numerical results : Angular dependence

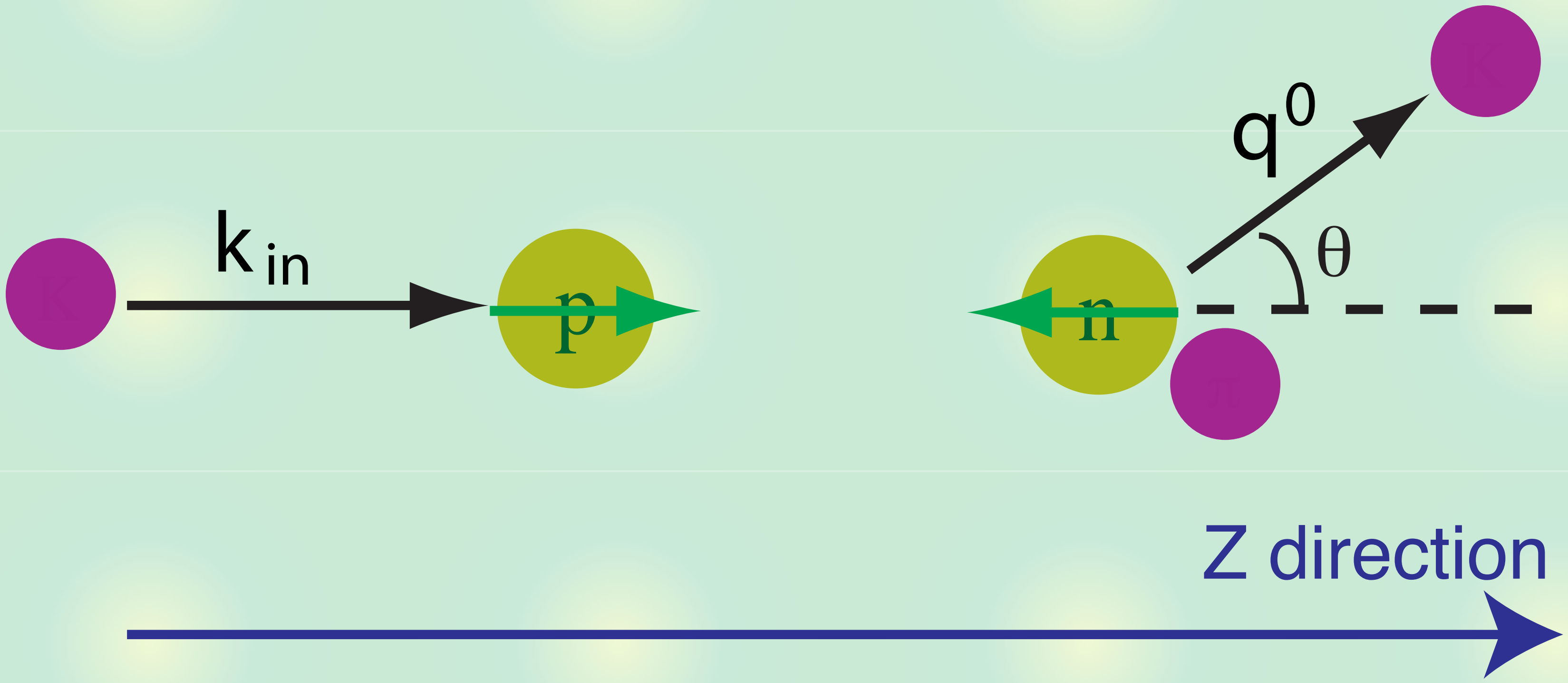


Production 1 : $K^+ p \rightarrow \pi^+ K^+ n$

Numerical results : Mass distributions



Numerical results : Polarization test



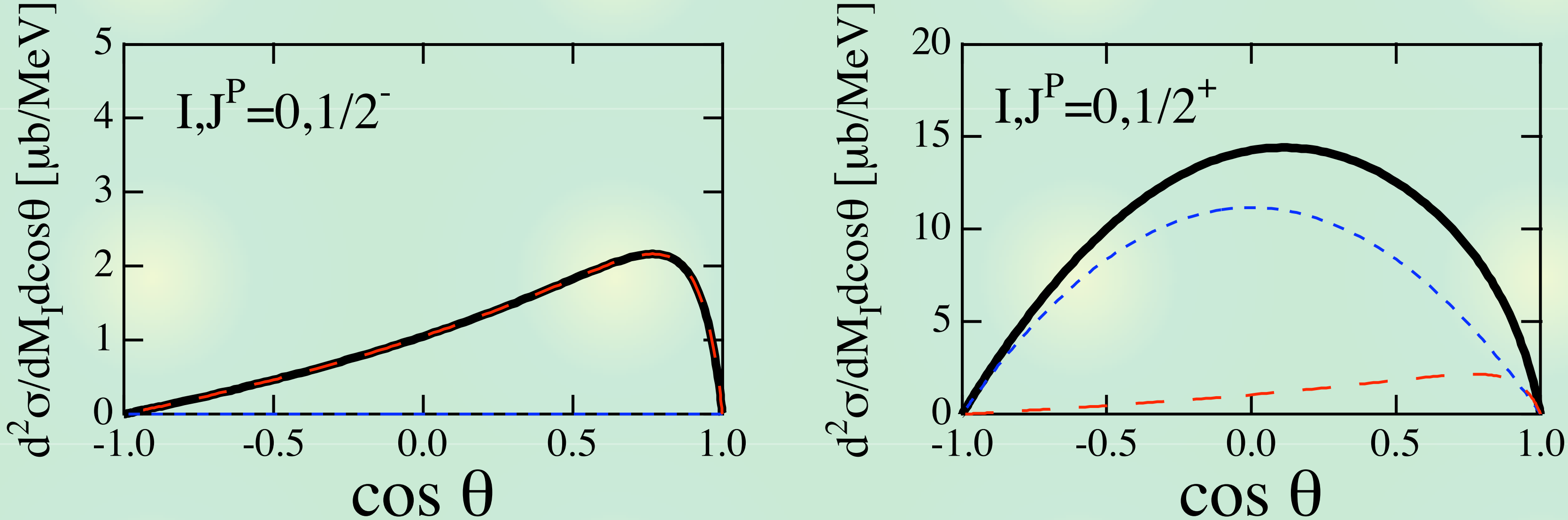
$$\langle -1/2|\boldsymbol{\sigma}\cdot\boldsymbol{k}_{in}|1/2\rangle = 0$$

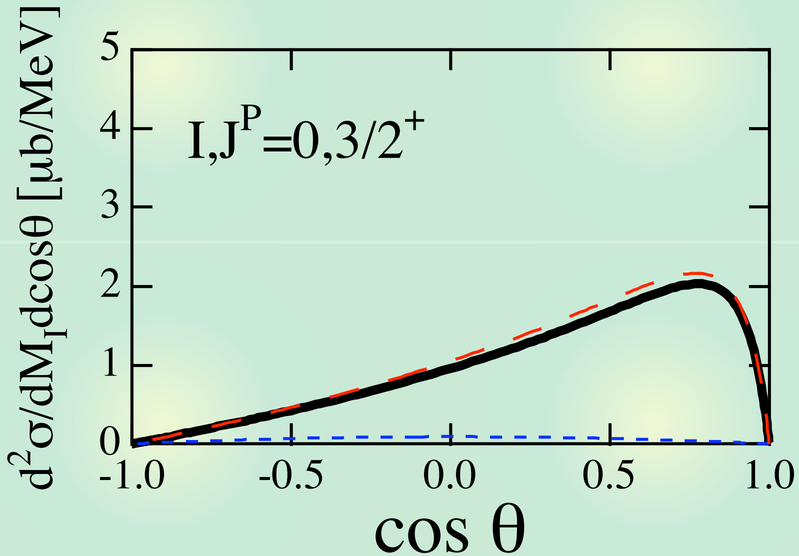
$$\langle -1/2|\boldsymbol{\sigma}\cdot\boldsymbol{q}'|1/2\rangle \propto q'\sin\theta$$

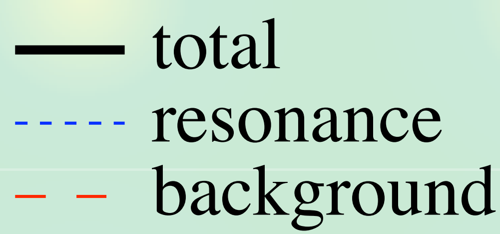
 # Same result is obtained for final pK^0

Production 1 : $K^+ p \to \pi^+ K^+ n$

Numerical results : Angular dependence 2



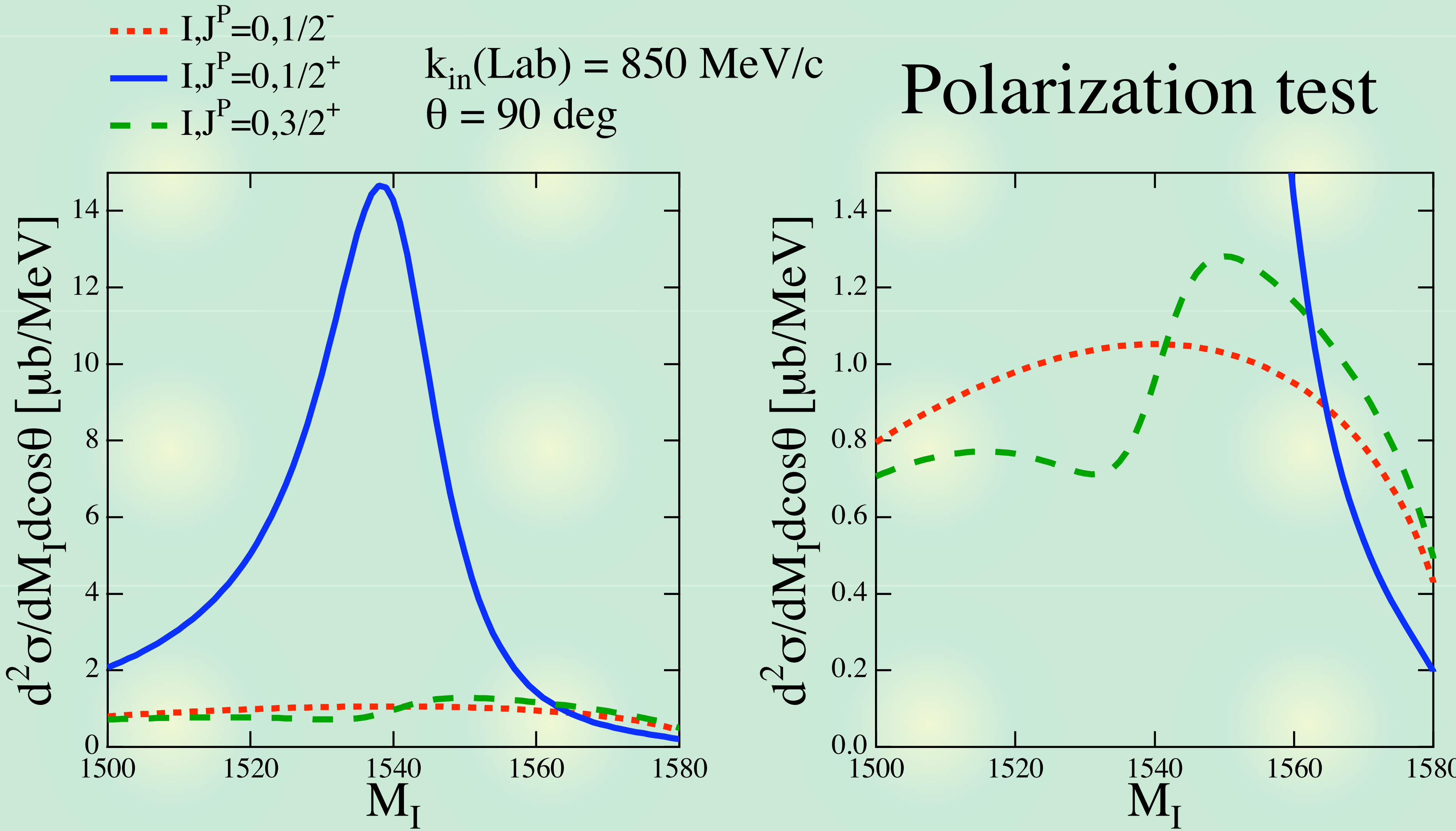




Polarization test

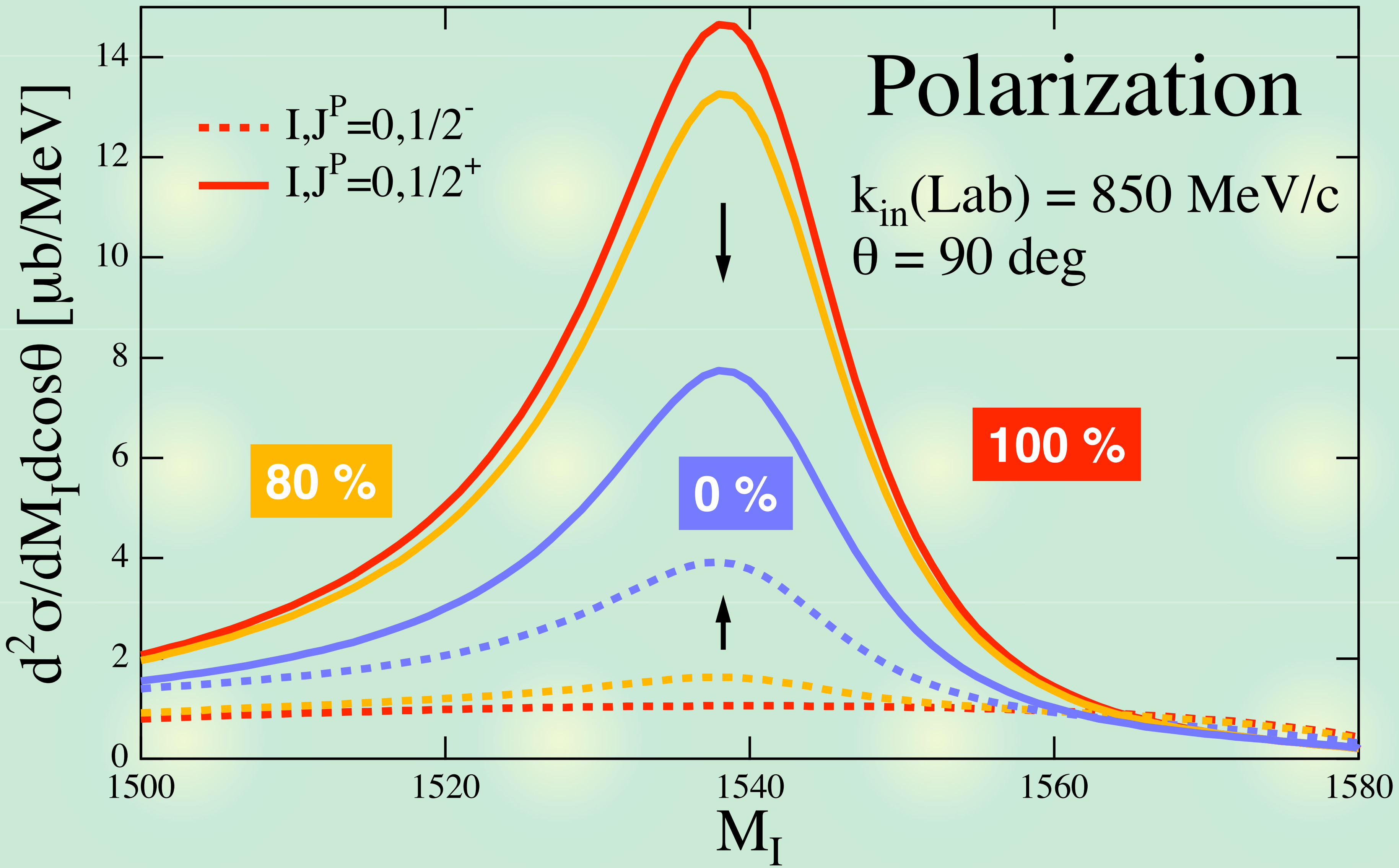
Production 1 : $K^+ p \to \pi^+ K^+ n$

Numerical results : Mass distributions 2



Production 1 : $K^+ p \rightarrow \pi^+ K^+ n$

Numerical results : Incomplete polarization



Conclusion

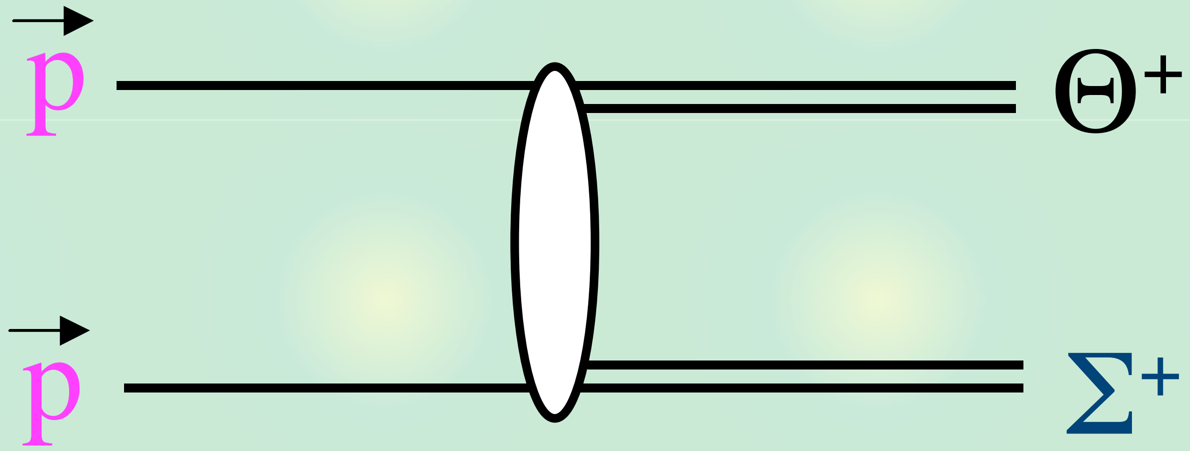
We calculate the $K^+p \longrightarrow \pi^+K^+n$ reaction using a chiral model, assuming the possible quantum numbers of Θ^+ baryon.

If we find the resonance in the polarization test, the quantum numbers of Θ^+ can be determined as $I=0$, $J^P=1/2^+$

T. Hyodo, *et al.*, Phys. Lett. B579, 290-298 (2004)
E. Oset, *et al.*, nucl-th/0312014, Hyp03 proceedings

Production 2 : $\vec{p}\vec{p} \rightarrow \Sigma^+\Theta^+$

Model independent analysis



At the threshold (final state : s-wave),

S=0 (Spin aligned) →→ : $1/2^+$

S=1 (Spin anti-aligned) →← : $1/2^-$

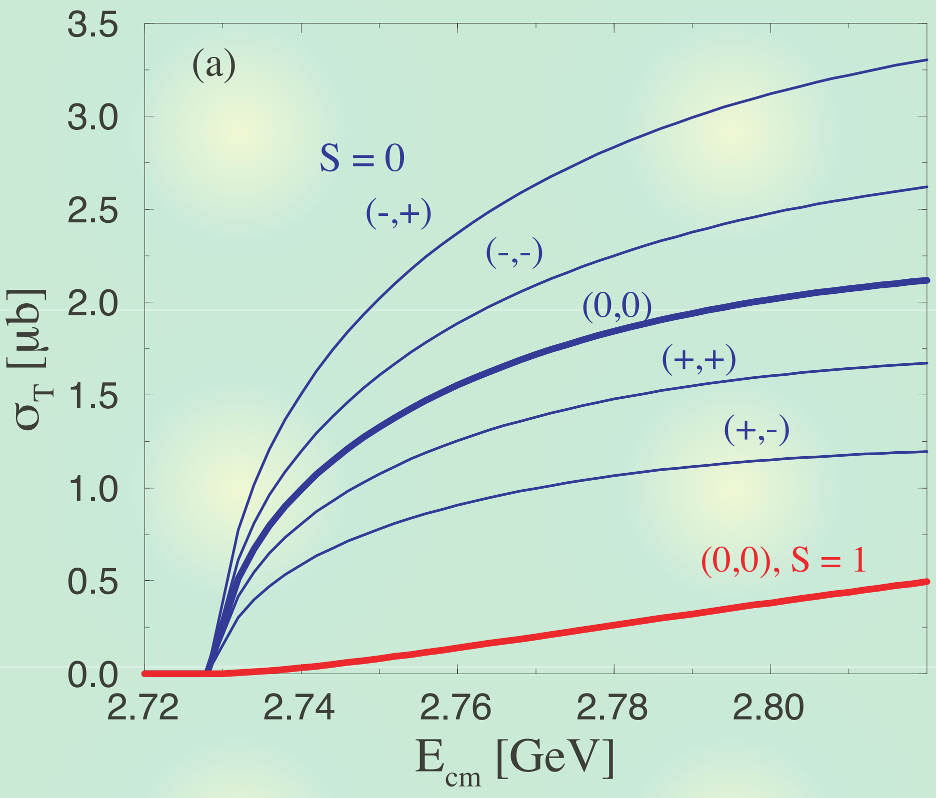
<- P and J conservations

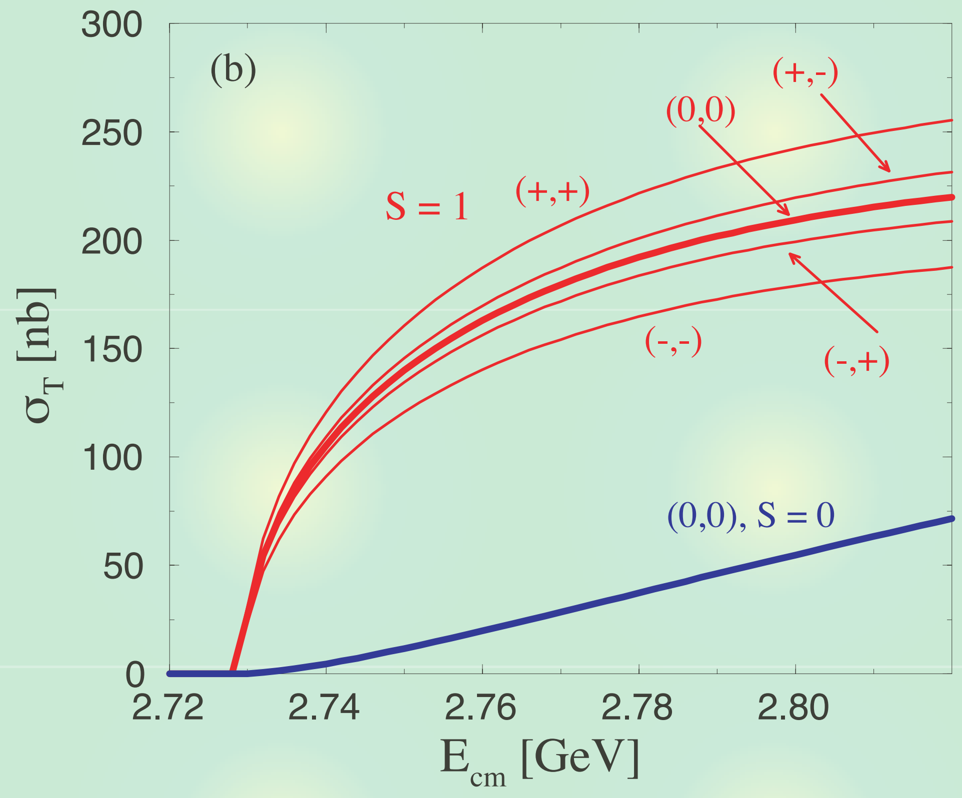
A.W. Thomas, *et al.*, hep-ph/0312083

Production 2 : $\vec{p}\vec{p} \longrightarrow \Sigma^{+}\Theta^{+}$

Numerical results

Positive parity $1/2^{+}$ Negative parity $1/2^{-}$





S.I. Nam, *et al.*, hep-ph/0401074