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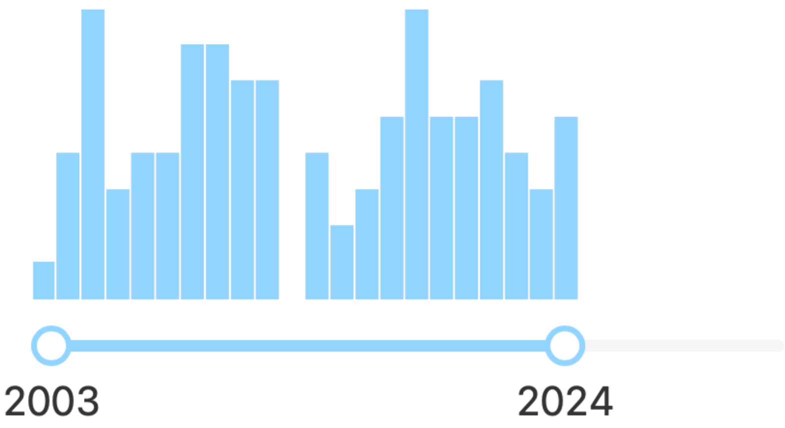

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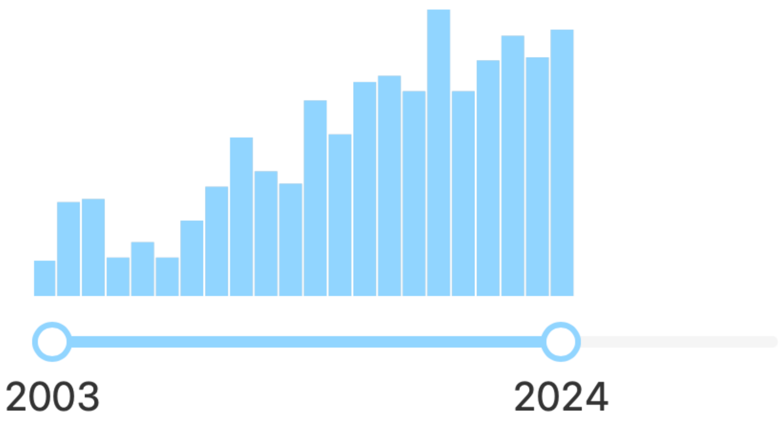

Fei HUANG

2001---2006: PhD student, IHEP

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2013---: UCAS

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Papers	**97**	**74**
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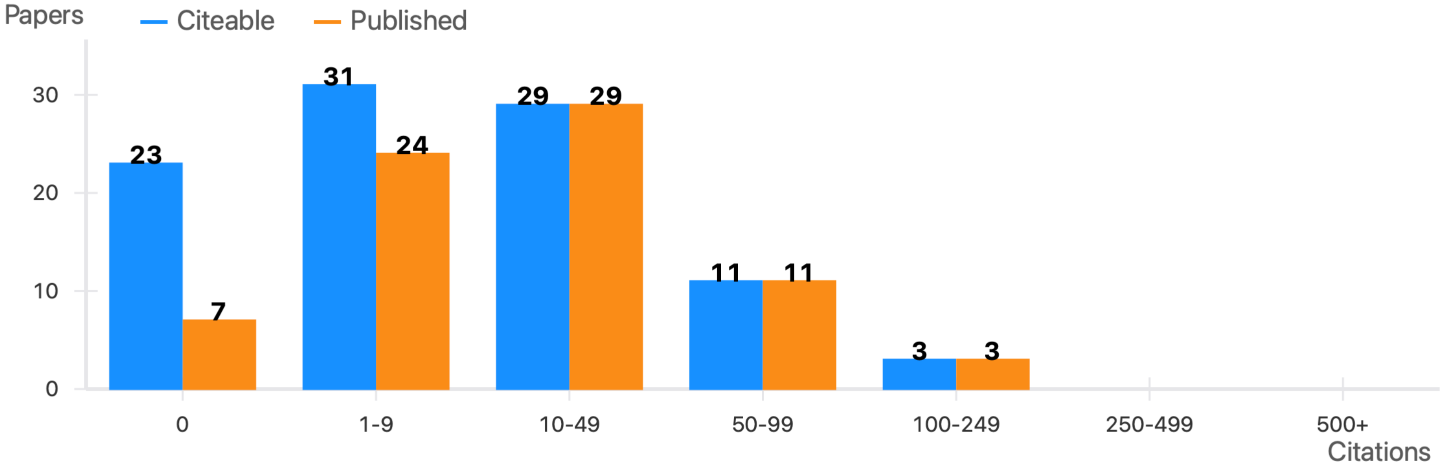
Collaborators

Zongye Zhang	30
Kanzo Nakayama	24
Siegfried Krewald	19
Ai-Chao Wang（王爱超）	17
Peng Nian Shen	17



Outline

- Selected PhD work under supervision of Prof. Zhang
- Work collaborated with Prof. Zhang after PhD
- Recent independent work

Part I

Selected PhD work under supervision of Prof. Z.Y. Zhang

分类号 ______ 密级 ______

UDC ______ 编号 ______

中国科学院研究生院
博士学位论文

重子—介子相互作用和 Θ^+ 粒子结构的研究

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中国科学院高能物理研究所

申请学位级别 博士 学科专业名称 理论物理

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答辩委员会主席 马中玉

发表文章目录

[1] A study of pentaquark Θ state in the chiral SU(3) quark model
F. Huang, Z.Y. Zhang, Y.W. Yu, and B.S. Zou
Phys. Lett. B **586**, 69 (2004)

[2] KN phase shifts in chiral SU(3) quark model
F. Huang, Z.Y. Zhang, and Y.W. Yu
Commun. Theor. Phys. **42**, 577 (2004)

[3] Resonating group method study of kaon-nucleon elastic scattering in the chiral SU(3) quark model
F. Huang, Z.Y. Zhang, and Y.W. Yu
Phys. Rev. C **70**, 044004 (2004)

[4] NK and ΔK states in the chiral SU(3) quark model
F. Huang and Z.Y. Zhang
Phys. Rev. C **70**, 064004 (2004)

[5] A study of pentaquark Θ state in chiral quark model
Z.Y. Zhang, **F. Huang**, Y.W. Yu, and B.S. Zou
原子核物理评论 **21**, 77 (2004)

[6] Further study on $5q$ configuration states in the chiral SU(3) quark model
D. Zhang, **F. Huang**, Z.Y. Zhang, and Y.W. Yu
Nucl. Phys. A **756**, 215 (2005)

[7] Chiral SU(3) quark model study of low energy $N\pi$ scattering phase shifts
F. Huang, Z.Y. Zhang, and Y.W. Yu
High Energy Phys. Nucl. Phys. **29**, 948 (2005)

[8] $NK\pi$ molecular state with $J^\pi = \frac{3}{2}^-$ and $I = 1$
F. Huang, Z.Y. Zhang, and Y.W. Yu
Phys. Rev. C **72**, 065208 (2005)

[9] Coupled-channels study of ΛK and ΣK states in the chiral SU(3) quark model
F. Huang, D. Zhang, Z.Y. Zhang, and Y.W. Yu
Phys. Rev. C **71**, 064001 (2005)

[10] Low-energy $K\pi$ phase shifts in chiral SU(3) quark model
F. Huang, Z.Y. Zhang, and Y.W. Yu
Commun. Theor. Phys. **44**, 665 (2005)

[11] Kaon-nucleon interaction in the extended chiral SU(3) quark model
F. Huang and Z.Y. Zhang
Phys. Rev. C **72**, 024003 (2005)

[12] ΔK, ΛK, and ΣK states in the extended chiral SU(3) quark model
F. Huang and Z.Y. Zhang
Phys. Rev. C **72**, 068201 (2005)

[13] $N\phi$ states in a chiral quark model
F. Huang, Z.Y. Zhang, and Y.W. Yu
Phys. Rev. C **73**, 025207 (2006)

[14] S, P, D, F wave KN phase shifts in the chiral SU(3) quark model[1]
F. Huang, Z.Y. Zhang, and Y.W. Yu
Int. J. Mod. Phys. A **20**, 1884 (2005)

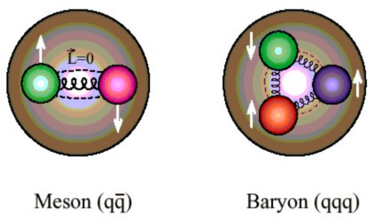
[15] Baryon-meson interactions in chiral quark model[2]
F. Huang, Z.Y. Zhang, and Y.W. Yu
to be published

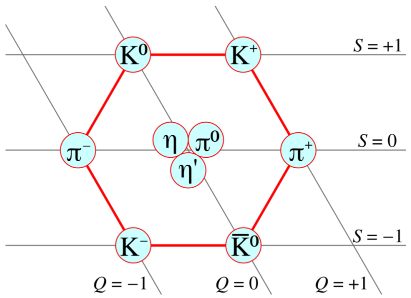
[1] Talk given by F. Huang at 10th International Symposium on Meson-Nucleon Physics and the Structure of the Nucleon (MENU 2004), Beijing, China, 29 Aug - 4 Sep 2004

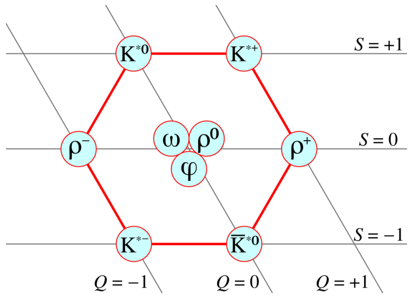
[2] Talk given by F. Huang at 3rd Asia Pacific Conference on Few-Body Problems in Physics (APFB 2005), Korat, Nakhon Ratchasima, Thailand, 26-30 Jul 2005

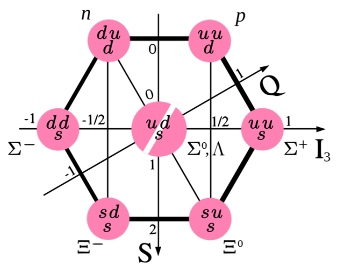
Constituent quark model

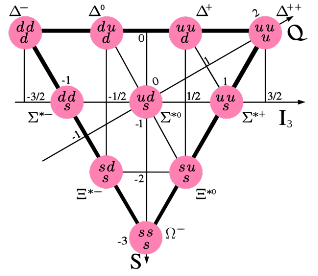
- NPQCD effect is important In light quark systems, but difficult to be exactly solved.
- QCD-inspired models are still needed; CQM is one of the most successful ones.
- Gell-Mann and Zweig model (1964): successful in hadron classification











- Interactions introduced $\Longrightarrow$ magnetic moments, spectrum, scattering data

$$H=\sum_i\left(m_i+\frac{\vec{P}_i^2}{2m_i}\right)-T_{\mathrm{cm}}+V^{\mathrm{conf}}+V^{\mathrm{hyp}}$$

$$V^{\mathrm{hyp}}=\begin{cases}\mathrm{OGE} & \textbf{Isgur–Karl model}\\ \pi, K, \eta, \eta' & \textbf{Glozman–Riska model}\\ \mathrm{OGE}, \pi, \sigma & \textbf{Hybrid model}\end{cases}$$

- OGE — Isgur−Karl model: Lack of medium & long range *NN* attraction
- π, K, η, η' — Glozman−Riska model: Lack of medium range *NN* attraction; tensor force too strong
- OGE, π, σ — Hybrid model: OK for *NN* interaction & *N** spectrum

SU(2) linear σ model

- Nucleon level: Gell-Mann & Lévy, Nuovo Cimento 16, 53 (1960)
  Quark level: Fernández, Valcarce, Straub, & Faessler, J. Phys. G 19, 2013 (1993)
- Lagrangian of SU(2) linear σ model:

$$\mathcal{L} = \bar{\psi} i\gamma^\mu \partial_\mu \psi + \mathcal{L}_I + \mathcal{L}_\Sigma \qquad \mathcal{L}_I = -g\bar{\psi}_L \Sigma \psi_R - g\bar{\psi}_R \Sigma^\dagger \psi_L$$

$$\Sigma = \sigma + i\,\boldsymbol{\tau}\cdot\boldsymbol{\pi} \qquad \mathcal{L}_\Sigma = \frac{1}{2}\left[(\partial_\mu \pi)^2 + (\partial_\mu \sigma)^2\right] - \frac{\lambda}{4}\left[\pi^2 + \sigma^2 - v^2\right]^2$$

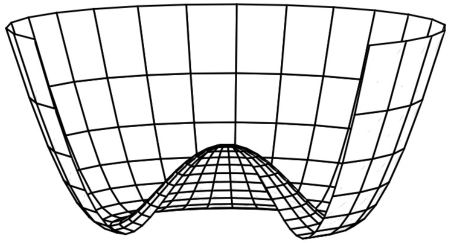
- $\mathcal{L}$ is invariant under chiral SU(2) transformation:

$$\psi_L \to L\psi_L = e^{-iT_a\theta_L^a}\psi_L \qquad \psi_R \to R\psi_R = e^{-iT_a\theta_R^a}\psi_R \qquad \Sigma \to L\Sigma R^\dagger = e^{-iT_a\theta_L^a}\Sigma e^{iT_a\theta_R^a}$$

- Spontaneous symmetry breaking:

$$\mathcal{L} = \bar{\psi} i\gamma^\mu \partial_\mu \psi - gv\bar{\psi}\psi + \frac{1}{2}\left[(\partial_\mu \pi)^2 + (\partial_\mu \sigma')^2\right] - \lambda v^2 (\sigma')^2$$

$$\sigma' = \sigma - v \qquad m_\pi = 0 \qquad m_{\sigma'} = \sqrt{2\lambda v^2} \qquad m_q = gv$$



- None-zero current quark mass $\Longrightarrow$ obvious symmetry breaking $\Longrightarrow$ physical m_π

Chiral SU(3) quark model

- Extend the chiral quark model from SU(2) to SU(3):
  Zhang, Faessler, Straub, & Glozman, Nucl. Phys. A 578, 573 (1994)
  Zhang, Yu, Shen, Dai, Faessler, & Straub, Nucl. Phys. A 625, 59 (1997)

$$\mathcal{L}_I = -g\bar{\psi}_L\Sigma\psi_R - g\bar{\psi}_R\Sigma^\dagger\psi_L$$

$$\Sigma = \sigma + i\,\tau\cdot\pi \quad \Longrightarrow \quad \Sigma = \sum_{a=0}^{8}\lambda_a\sigma_a + i\sum_{a=0}^{8}\lambda_a\pi_a$$

$$\sigma, \sigma', \kappa, \epsilon \qquad \pi, K, \eta, \eta'$$

- $\mathcal{L}$ is invariant under chiral SU(3) transformation:

$$\psi_L \to L\psi_L = e^{-iT_a\theta_L^a}\psi_L \qquad \psi_R \to R\psi_R = e^{-iT_a\theta_R^a}\psi_R \qquad \Sigma \to L\Sigma R^\dagger = e^{-iT_a\theta_L^a}\Sigma e^{iT_a\theta_R^a}$$

- Spontaneous symmetry breaking $\Longrightarrow$ m_q, m_{σ_a}
- Obvious symmetry breaking $\Longrightarrow$ m_{π_a}

Framework of the model

- Hamiltonian

$$H = \sum_i \left(m_i + \frac{\vec{P}_i^2}{2m_i} \right) - T_{\rm cm} + V^{\rm conf} + V^{\rm OGE} + V^{\sigma,\sigma',\kappa,\epsilon} + V^{\pi,K,\eta,\eta'}$$

Chiral SU(3) QM

$$H = \sum_i \left(m_i + \frac{\vec{P}_i^2}{2m_i} \right) - T_{\rm cm} + V^{\rm conf} + V^{\rm OGE} + V^{\sigma,\sigma',\kappa,\epsilon} + V^{\pi,K,\eta,\eta'} + V^{\rho,K^*,\omega,\phi}$$

Ext. chiral SU(3) QM

- Wave functions

$$\psi_B = \psi^{\rm int}(\xi_1, \xi_2)\, Z_{3q}(R_{\rm cm}) \qquad \psi^{\rm int}(\xi_1, \xi_2) = \left(\frac{m_{\xi_1}\omega}{\pi}\right)^{\frac{3}{4}} {\rm Exp}\left[-\frac{m_{\xi_1}\omega}{2}\xi_1^2\right] \left(\frac{m_{\xi_2}\omega}{\pi}\right)^{\frac{3}{4}} {\rm Exp}\left[-\frac{m_{\xi_2}\omega}{2}\xi_2^2\right]$$

$$\psi_{BB} = \psi^{\rm int}(\xi_1, \xi_2)\psi^{\rm int}(\xi_3, \xi_4)\chi(r) Z_{6q}(R_{\rm cm}) \qquad b^2 = 1/(m\omega)$$

$Z_{3q}(R_{\rm cm})$, $Z_{6q}(R_{\rm cm})$: irrelevant

- Single baryon: $E_B = \langle \hat{\psi}_B | H | \hat{\psi}_B \rangle$

- Baryon-Baryon system: $\langle \delta\hat{\psi}_{BB} | H - E | \hat{\psi}_{BB} \rangle = 0$ (RGM equation)

Parameters

- Input parameters:

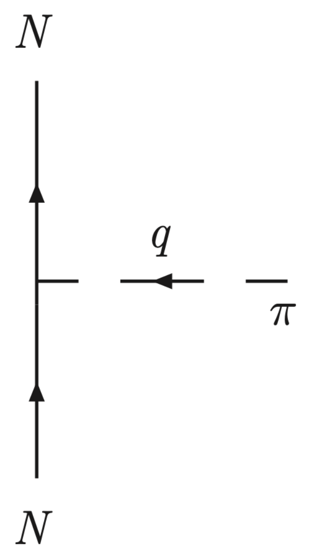
  $m_u = 313$ MeV, $m_s = 470$ MeV, $b_u = 0.5$ fm [SU(3)] or 0.45 fm [Ex. SU(3)]

- Adjustable parameter: m_σ
- Other parameters fixed by physical constraints:
  - Chiral field coupling: $$\frac{g_{\mathrm{ch}}^2}{4\pi} = \frac{9}{25}\frac{m_u^2}{m_N^2}\frac{g_{NN\pi}^2}{4\pi}$$
  - OGE couplings: g_u fixed by $(m_\Delta - m_N)$

    g_s fixed by $(m_\Sigma - m_\Lambda)$
  - Confinement parameters: $$V_{ij}^{\mathrm{conf}} = -(\lambda_i^c \cdot \lambda_j^c)(a_{ij} r_{ij}^2 + a_{ij}^0)$$

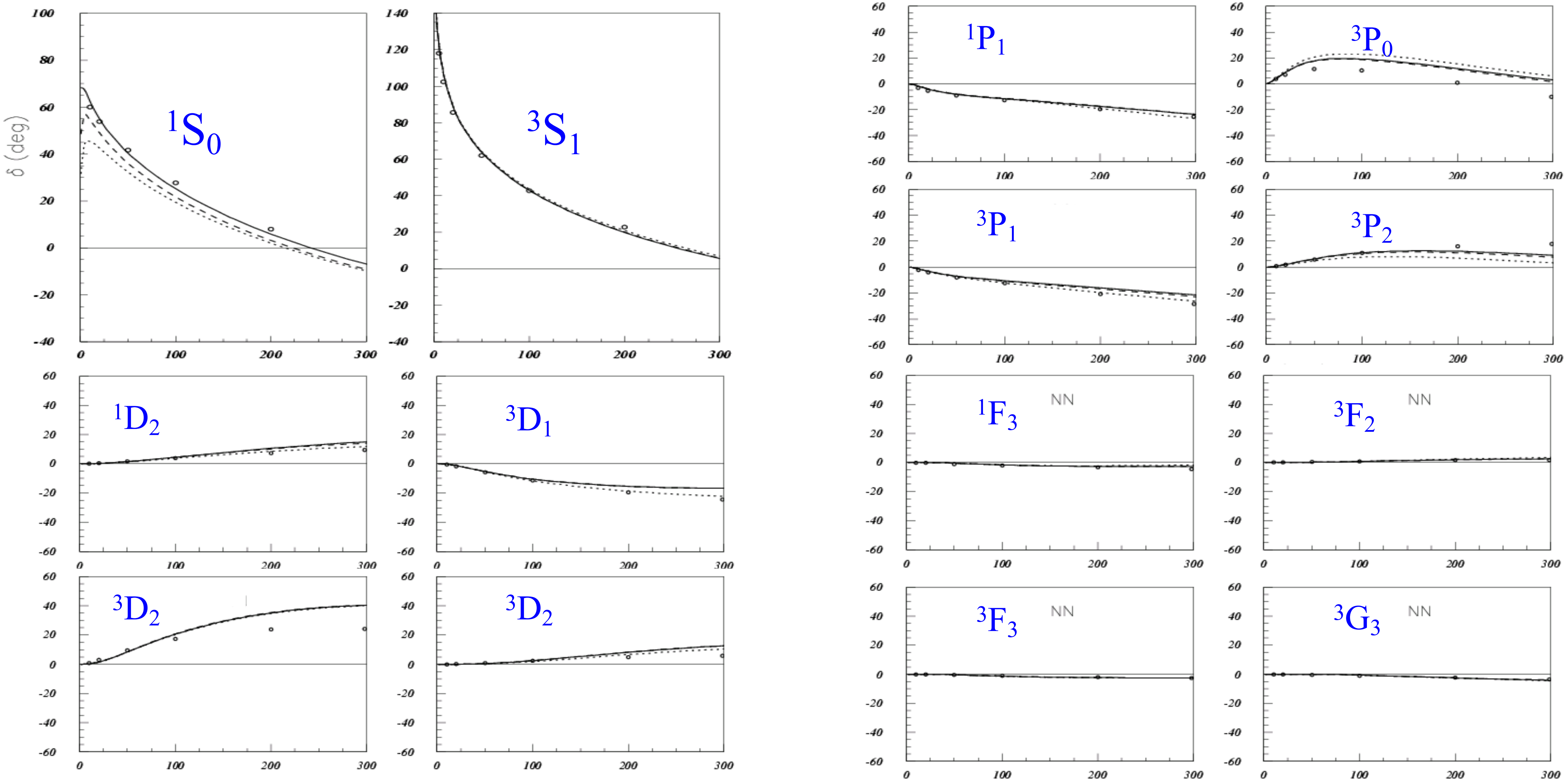
    a_{uu}, a_{us}, a_{ss} fixed by $\partial M_{N,\Lambda,\Xi}/\partial b = 0$

    $a_{uu}^0, a_{us}^0, a_{ss}^0$ fixed by $M_N, M_\Sigma, M_\Xi + M_\Omega$



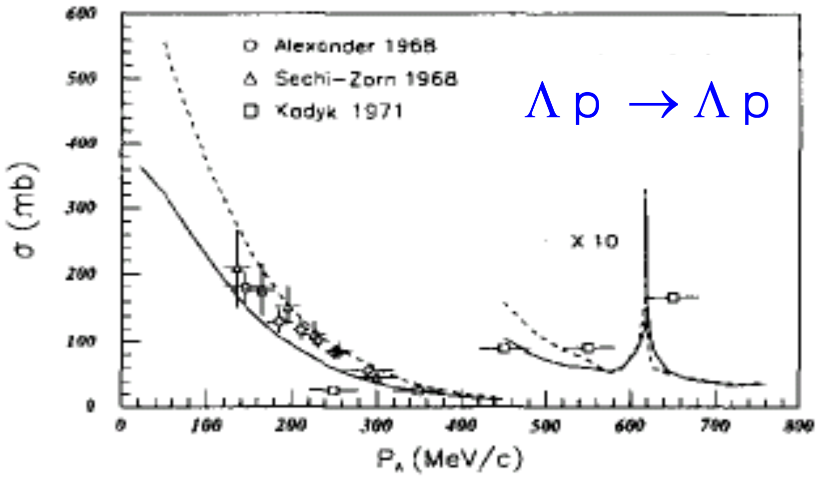
NN phase shifts

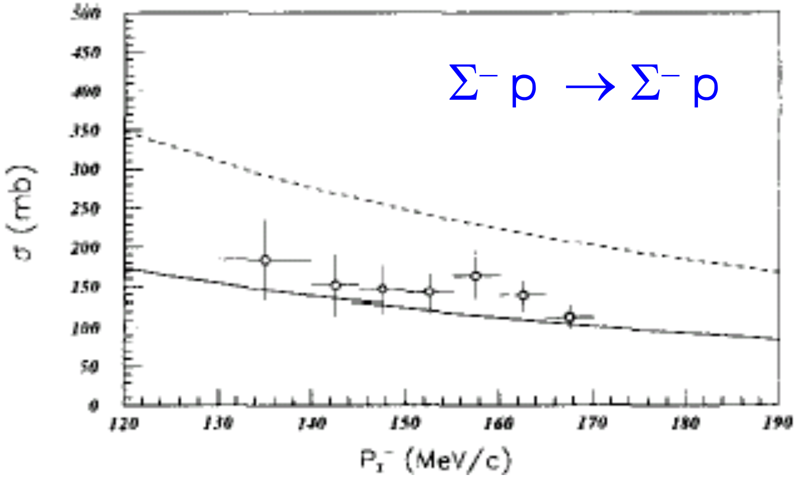
Zhang, Yu, Shen, Dai, Faessler, & Straub, Nucl. Phys. A 625, 59 (1997)

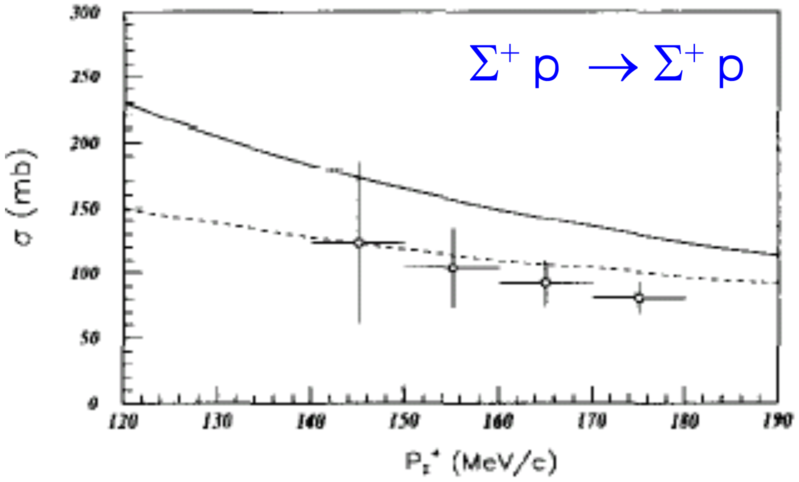


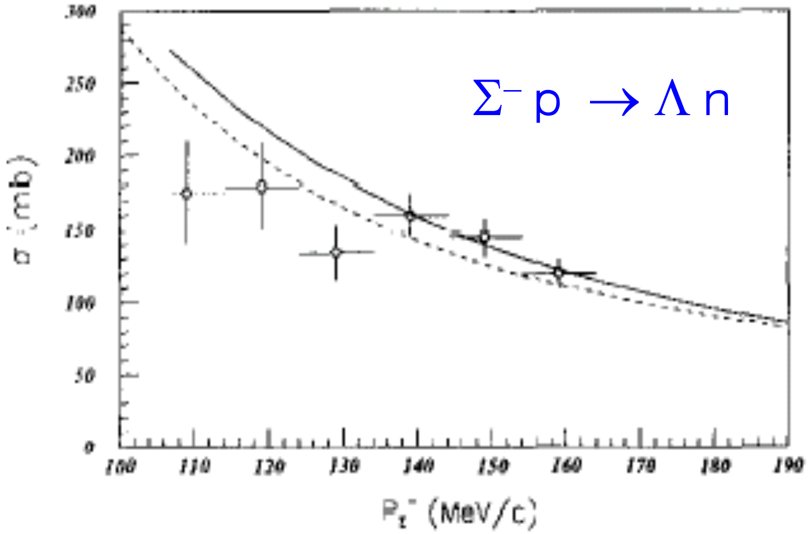
NY cross sections

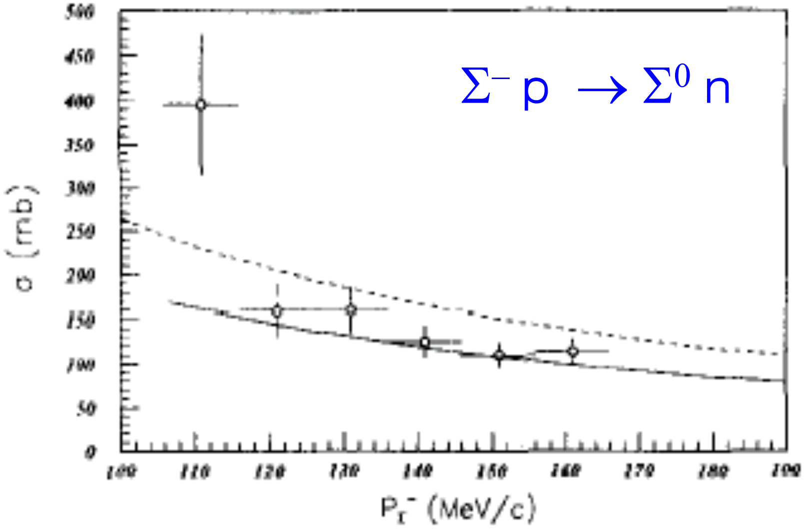
Zhang, Yu, Shen, Dai, Faessler, & Straub, Nucl. Phys. A 625, 59 (1997)







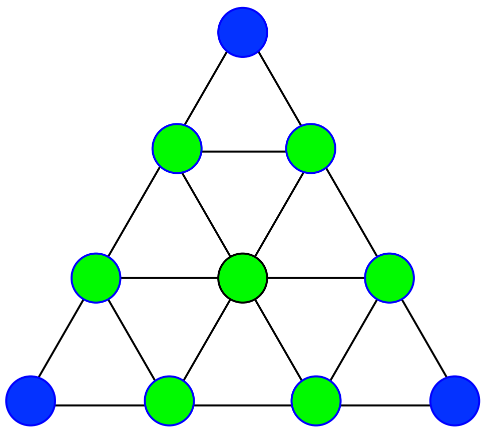




$\Theta^+(1540)$

Theoretical prediction in chiral soliton model:

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



$\Theta(1530)$

$N(1710)$

$\Sigma(1890)$

$\Xi(2070)$

$\Theta(1530) \quad J^{\pi} = \frac{1}{2}^{+} \quad S = 1 \quad B = 1$

表 6.1: 发现五夸克态 Θ^+ 的实验。

Group	Reaction	Mass (MeV)	Width (MeV)	σ's	Ref.
LEPS	$\gamma C \to K^+K^-X$	1540 ± 10	< 25	4.6	[110]
DIANA	$K^+Xe \to K^0 p X$	1539 ± 2	< 9	4.4	[111]
CLAS	$\gamma d \to K^+K^- p(n)$	1542 ± 5	< 21	5.2	[112]
SAPHIR	$\gamma d \to K^+K^0(n)$	1540 ± 6	< 25	4.8	[113]
ITEP	$\nu A \to K_s^0 p X$	1533 ± 5	< 20	6.7	[114]
CLAS	$\gamma p \to \pi^+K^+K^-(n)$	1555 ± 10	< 26	7.8	[115]
HERMES	$e^+d \to K_s^0 p X$	1528 ± 3	13 ± 9	~ 5	[116]
ZEUS	$e^+p \to e^+K_s^0 p X$	1522 ± 3	8 ± 4	~ 5	[117]
COSY-TOF	$pp \to K^0 p \Sigma^+$	1530 ± 5	< 18	4-6	[118]
SVD	$pA \to K_s^0 p X$	1526 ± 5	< 24	5.6	[119]
LEPS	$\gamma d \to K^+K^-X$	~ 1530			[120]
ITEP	$\nu A \to K_s^0 p X$	1532 ± 2	< 12	7.1	[121]
NOMAD	$\nu A \to K_s^0 p X$	1529 ± 3	< 9	4.3	[122]
JINR	$p(C_3H_8) \to K_s^0 p X$	1545 ± 12	16 ± 4	5.5	[123]
JINR	$CC \to K_s^0 p X$	1532 ± 6	< 26		[124]
LPI	$np \to np K^+K^-$	1541 ± 5	< 11	4.5	[125]

Our work on $\Theta^+(1540)$

F. Huang, Z.Y. Zhang, Y.W. Yu, and B.S. Zou, Phys. Lett. B 586 (2004) 69

$$[4]_{\rm orb}[31]^{\sigma f}_{ts=01}\bar{s},\quad LST=0\frac{1}{2}0,\quad J^\pi=\frac{1}{2}^-,$$
$$[4]_{\rm orb}[31]^{\sigma f}_{ts=10}\bar{s},\quad LST=0\frac{1}{2}1,\quad J^\pi=\frac{1}{2}^-,$$
$$[4]_{\rm orb}[31]^{\sigma f}_{ts=11}\bar{s},\quad LST=0\frac{1}{2}1,\quad J^\pi=\frac{1}{2}^-,$$
$$[4]_{\rm orb}[31]^{\sigma f}_{ts=21}\bar{s},\quad LST=0\frac{1}{2}2,\quad J^\pi=\frac{1}{2}^-.$$

$$[31]_{\rm orb}[4]^{\sigma f}_{ts=00}\bar{s},\quad LST=1\frac{1}{2}0,\quad J^\pi=\frac{1}{2}^+,$$
$$[31]_{\rm orb}[4]^{\sigma f}_{ts=11}\bar{s},\quad LST=1\frac{1}{2}1,\quad J^\pi=\frac{1}{2}^+,$$
$$[31]_{\rm orb}[4]^{\sigma f}_{ts=11}\bar{s},\quad LST=1\frac{3}{2}1,\quad J^\pi=\frac{1}{2}^+,$$
$$[31]_{\rm orb}[4]^{\sigma f}_{ts=22}\bar{s},\quad LST=1\frac{3}{2}2,\quad J^\pi=\frac{1}{2}^+.$$

Table 1
Energies (in MeV) of pentaquark states in various chiral quark models with b_u the size parameter. I and II for cases with and without annihilation interactions

Configuration	Chiral $SU(3)$ quark model $b_u=0.50$ fm		Ex. chiral $SU(3)$ quark model $b_u=0.45$ fm	
$J^\pi=\frac{1}{2}^-$	I	II	I	II
$[4]_{\rm orb}[31]^{\sigma f}_{ts=01}\bar{s}$	1801	1957	1843	2091
$[4]_{\rm orb}[31]^{\sigma f}_{ts=10}\bar{s}$	2049	2128	2089	2170
$[4]_{\rm orb}[31]^{\sigma f}_{ts=11}\bar{s}$	2117	2190	2115	2193
$[4]_{\rm orb}[31]^{\sigma f}_{ts=21}\bar{s}$	2323	2369	2314	2334
$J^\pi=\frac{1}{2}^+$	I	II	I	II
$[31]_{\rm orb}[4]^{\sigma f}_{ts=00}\bar{s}$	2271	2185	2270	2253
$[31]_{\rm orb}[4]^{\sigma f}_{ts=11}\bar{s}$ $(S=\frac{1}{2})$	2308	2235	2296	2310
$[31]_{\rm orb}[4]^{\sigma f}_{ts=11}\bar{s}$ $(S=\frac{3}{2})$	2362	2282	2367	2337
$[31]_{\rm orb}[4]^{\sigma f}_{ts=22}\bar{s}$	2426	2367	2412	2435

T=0, $J^P=1/2^-$ is the lowest one; 250 MeV higher than M_Θ; 1/4 KN component.

High mass & large width in our chiral quark model!

CLAS negative evidence of $\Theta^+(1540)$

B. McKinnon et al. (CLAS), Phys. Rev. Lett. 96 (2006) 212001

PRL **96,** 212001 (2006) PHYSICAL REVIEW LETTERS week ending 2 JUNE 2006

Search for the Θ^+ Pentaquark in the Reaction $\gamma d \to pK^- K^+ n$

(CLAS Collaboration)

A search for the Θ^+ in the reaction $\gamma d \to pK^- K^+ n$ was completed using the CLAS detector at Jefferson Lab. A study of the same reaction, published earlier, reported the observation of a narrow Θ^+ resonance. The present experiment, with more than 30 times the integrated luminosity of our earlier measurement, does not show any evidence for a narrow pentaquark resonance. The angle-integrated upper limit on Θ^+ production in the mass range of 1.52–1.56 GeV$/c^2$ for the $\gamma d \to pK^- \Theta^+$ reaction is 0.3 nb (95% C.L.). This upper limit depends on assumptions made for the mass and angular distribution of Θ^+ production. Using $\Lambda(1520)$ production as an empirical measure of rescattering in the deuteron, the cross section upper limit for the elementary $\gamma n \to K^- \Theta^+$ reaction is estimated to be a factor of 10 higher, i.e., $\sim$3 nb (95% C.L.).

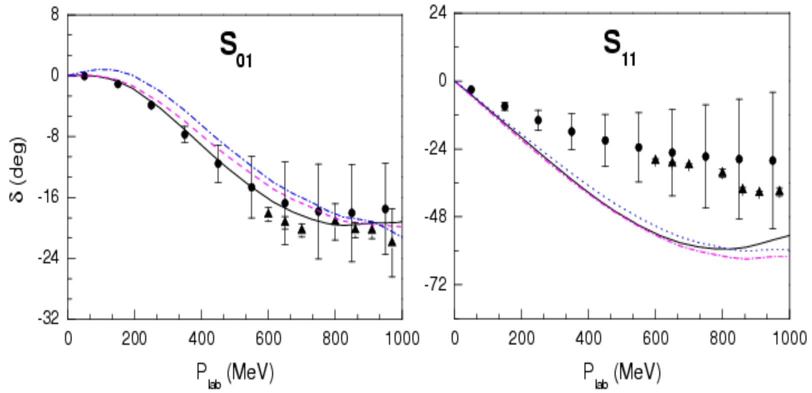
DOI: 10.1103/PhysRevLett.96.212001 PACS numbers: 12.39.Mk, 13.60.Rj, 14.20.Jn, 14.80.−j

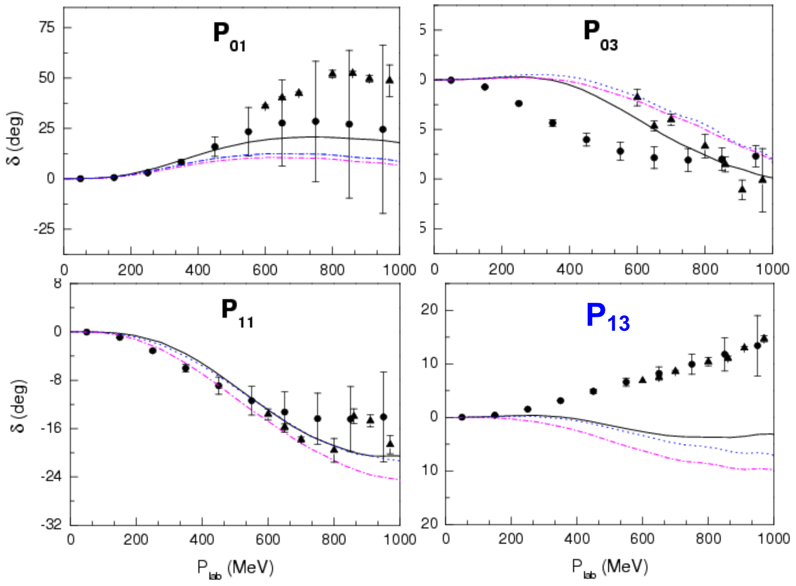
KN scattering

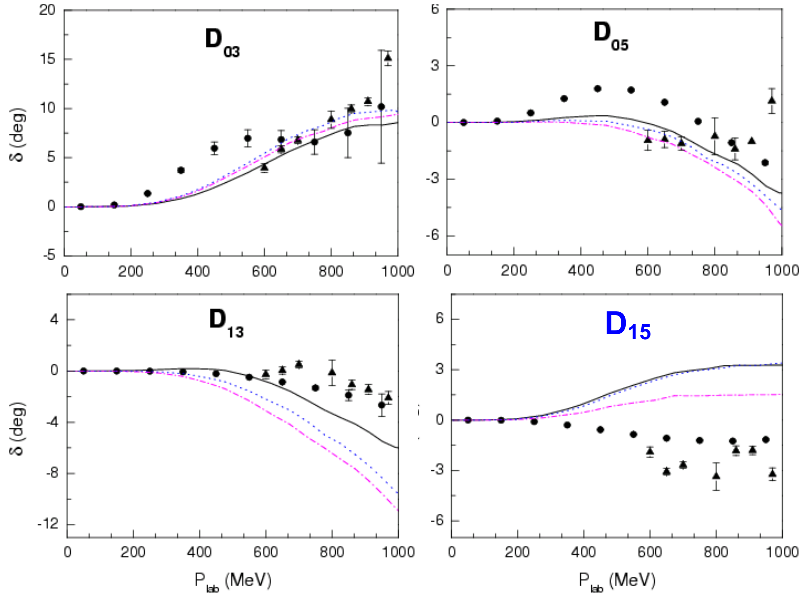
F. Huang, Z.Y. Zhang, and Y.W. Yu, Phys. Rev. C 70 (2004) 044004
F. Huang and Z.Y. Zhang, Phys. Rev. C 70 (2004) 064004

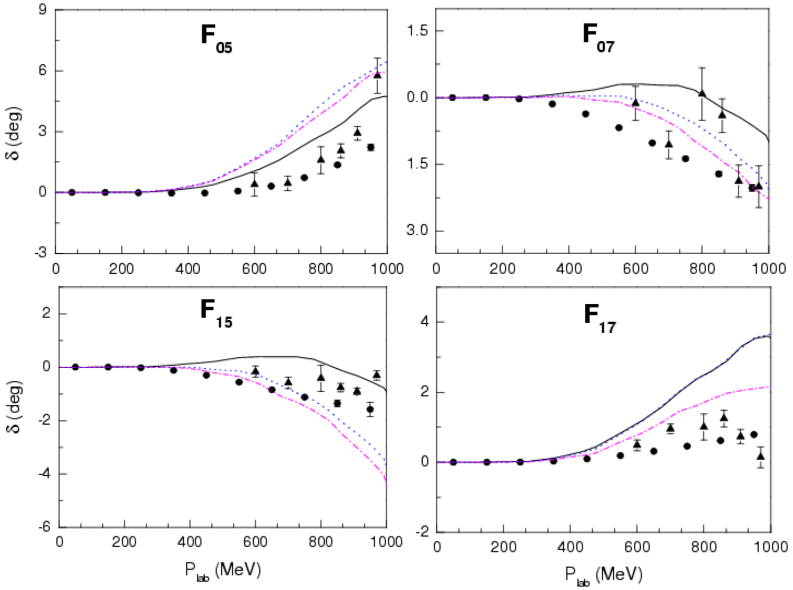
Motivations: Is there KN resonance state?
Does our model work for KN?

Results: No KN bound or resonance state;
Overall description is satisfactory.









Part II

Work collaborated with Prof. Z.Y. Zhang after PhD

$\Sigma_c\bar{D} - \Lambda_c\bar{D}$

W.L. Wang, F. Huang, Z.Y. Zhang, and B.S. Zou, Phys. Rev. C 84 (2011) 015203

PHYSICAL REVIEW C **71**, 064001 (2005)

Coupled-channels study of ΛK and ΣK states in the chiral SU(3) quark model

F. Huang,[1,2,3] D. Zhang,[2,3] Z. Y. Zhang,[2] and Y. W. Yu[2]
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[2]*Institute of High Energy Physics, P.O. Box 918-4, Beijing 100049, People's Republic of China**
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(Received 12 January 2005; published 16 June 2005)

PHYSICAL REVIEW C **72**, 068201 (2005)

ΔK, ΛK, and ΣK states in the extended chiral SU(3) quark model

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(Received 11 October 2005; published 30 December 2005)

TABLE III. Binding energy of ΣK.

Model	$B_{\Sigma K}$ (MeV)	Attraction
I	18	OGE + σ
II	44	$\sigma + \rho + \phi$
III	33	$\sigma + \rho + \phi$

PHYSICAL REVIEW C **84**, 015203 (2011)

$\Sigma_c\bar{D}$ and $\Lambda_c\bar{D}$ states in a chiral quark model

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(Received 2 January 2011; published 8 July 2011)

The S-wave $\Sigma_c\bar{D}$ and $\Lambda_c\bar{D}$ states with isospin $I = 1/2$ and spin $S = 1/2$ are dynamically investigated within the framework of a chiral constituent quark model by solving a resonating group method equation. The results show that the interaction between Σ_c and $\bar{D}$ is attractive, which consequently results in a $\Sigma_c\bar{D}$ bound state with a binding energy of about 5–42 MeV, unlike the case of the $\Lambda_c D$ state, which has a repulsive interaction and thus is unbound. The channel-coupling effect of $\Sigma_c\bar{D}$ and $\Lambda_c\bar{D}$ is found to be negligible owing to the fact that the gap between the $\Sigma_c\bar{D}$ and $\Lambda_c\bar{D}$ thresholds is relatively large and the $\Sigma_c\bar{D}$ and $\Lambda_c\bar{D}$ transition interaction is weak.

DOI: 10.1103/PhysRevC.84.015203 PACS number(s): 12.39.−x, 11.30.Rd, 14.20.Gk, 24.85.+p

TABLE III. The binding energy of $\Sigma_c\bar{D}$ (in MeV) in models I, II, and III, respectively.

	m_c (GeV)	r confinement	r^2 confinement
I	1.43	9.3	4.5
	1.55	10.9	6.4
	1.87	15.3	11.0
II	1.43	28.3	9.3
	1.55	31.8	10.3
	1.87	41.6	10.0
III	1.43	19.7	7.3
	1.55	22.2	8.9
	1.87	28.6	11.3

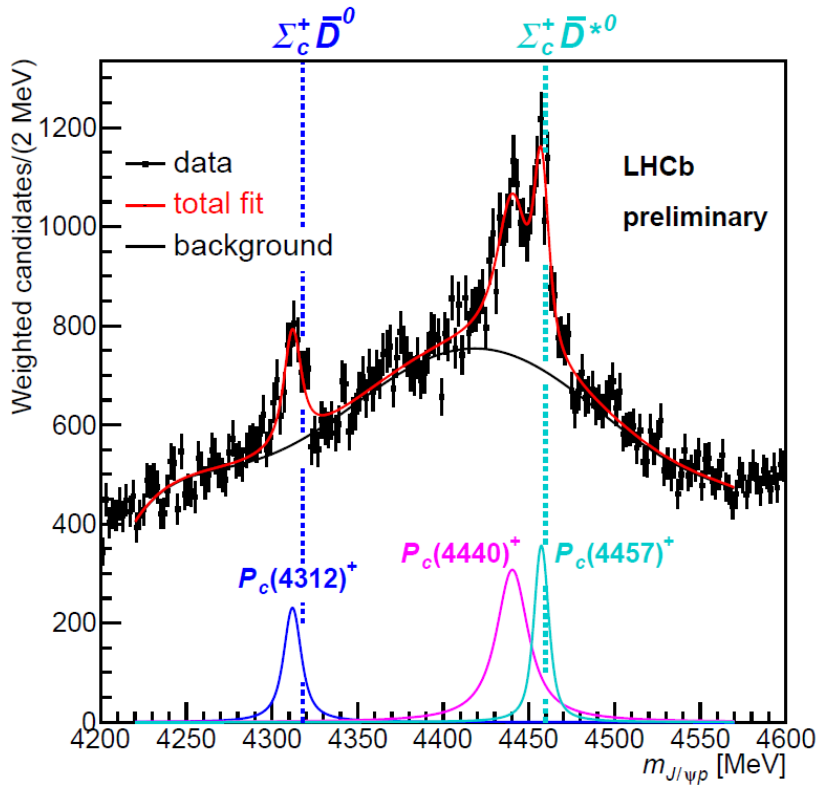
LHCb results in 2019

PHYSICAL REVIEW LETTERS **122**, 222001 (2019)

Editors' Suggestion | Featured in Physics

Observation of a Narrow Pentaquark State, $P_c(4312)^+$, and of the Two-Peak Structure of the $P_c(4450)^+$

R. Aaij *et al.*[*]
(LHCb Collaboration)



$P_c(4312)$: 9 MeV below $\Sigma_c \bar{D}$ threshold

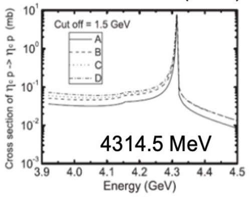
Slide of Tomasz Skwarnicki, Moriond QCD, Mar 26, 2019

Moriond QCD, Tomasz Skwarnicki, Mar 26, 2019 — 15

Comparison to numerical predictions

- Many theoretical predictions for $\Sigma_c^+ \bar{D}^{(*)0}$ published before 2015, **some in quantitative agreement with the LHCb data**
  - Wu,Molina,Oset,Zou, PRL105, 232001 (2010),
  - **Wang,Huang,Zhang,Zou, PR C84, 015203 (2011),**
  - **Yang,Sun,He,Liu,Zhu, Chin. Phys. C36, 6 (2012),**
  - **Wu,Lee,Zou, PR C85 044002 (2012),**
  - Karliner,Rosner, PRL 115, 122001 (2015)

PR C85 044002 (2012)



ΔE – binding energy

Example:

Nucleon resonances with hidden charm in coupled-channels models

Jia-Jun Wu, T.-S. H. Lee, and B. S. Zou
Phys. Rev. C **85**, 044002 – Published 17 April 2012

arXiv:1202.1036

TABLE III: The pole position ($M - i\Gamma/2$) and "binding energy" ($\Delta E = E_{thr} - M$) for different cut-off parameter Λ and spin-parity J^P. The threshold E_{thr} is 4320.79 MeV of $\bar{D}\Sigma_c$ in PB system and 4462.18 MeV of $\bar{D}^*\Sigma_c$ in VB system. The unit for the listed numbers is MeV.

		PB System		VB System	
$J^p = \frac{1}{2}^-$	Λ	$M - i\Gamma/2$	ΔE	$M - i\Gamma/2$	ΔE
	650	-	-		
	800		-	4462.178 − 0.002i	0.002
	1200	4318.964 − 0.362i	1.826	4459.513 − 0.417i	2.667
	1500	4314.531 − 1.448i	6.259	4454.088 − 1.662i	8.092
	2000	4301.115 − 5.835i	19.68	4438.277 − 7.115i	23.90
$J^p = \frac{3}{2}^-$					
	650	-	-	-	-
	800	-	-	4462.178 − 0.002i	0.002
	1200	-	-	4459.507 − 0.420i	2.673
	1500	-	-	4454.057 − 1.681i	8.123
	2000	-	-	4438.039 − 7.268i	23.14

$\Delta E(4312) = 5.8^{+1.0}_{-6.8}$ MeV

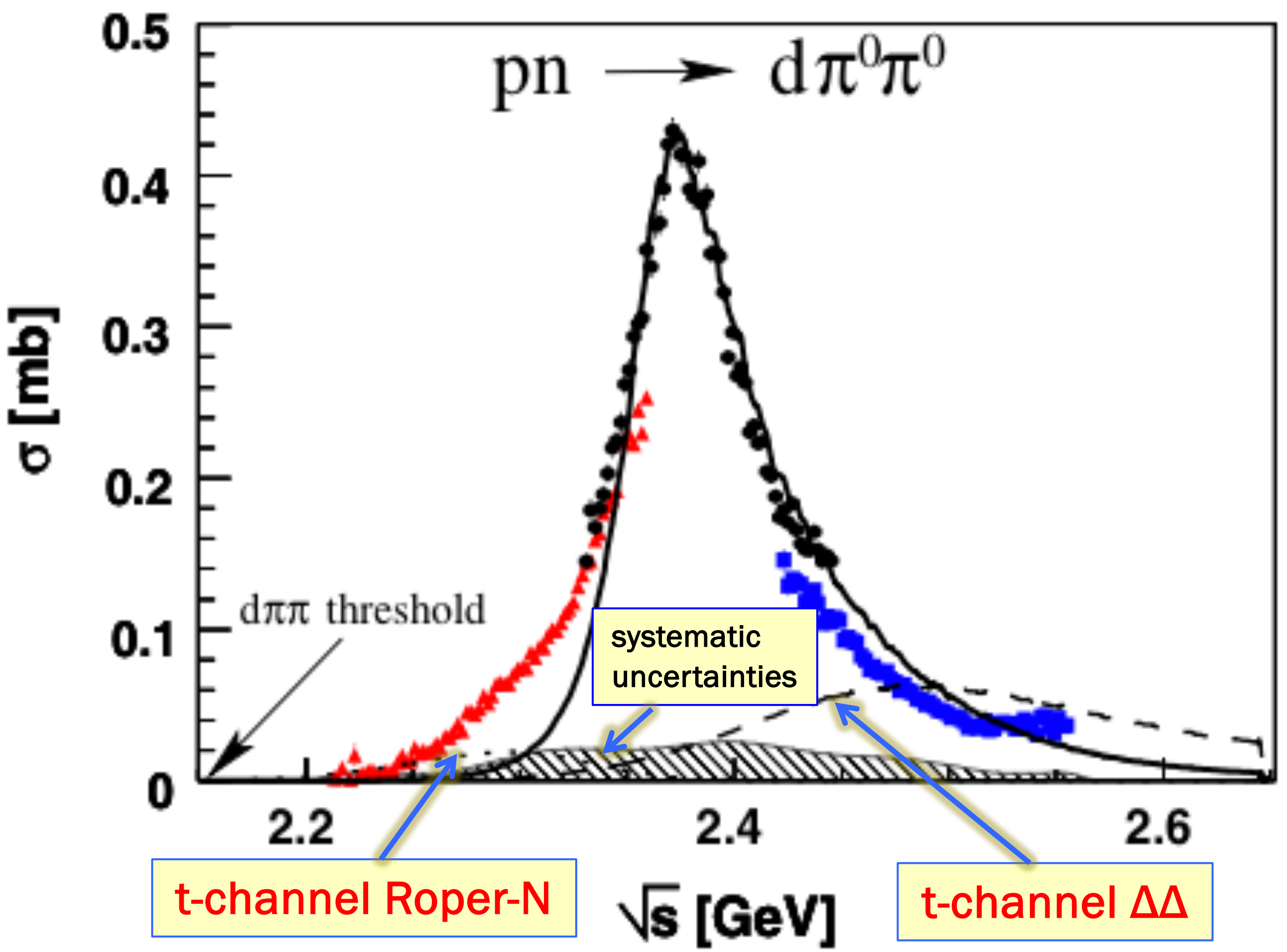
$\Delta E(4457) = 2.5^{+4.3}_{-4.1}$ MeV

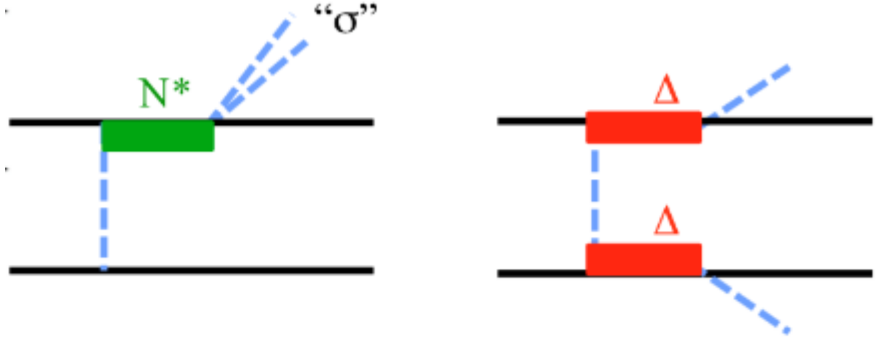
$\Delta E(4440) = 19.5^{+4.9}_{-4.3}$ MeV

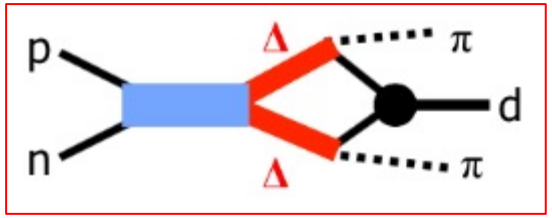
Λ - cut off on exchanged meson mass.

$d^*(2380)$ from COSY

WASA-at-COSY, PRL 106 (2011) 242302







$I(J^p) = 0(3^+)$

$M \approx 2380$ MeV $\Gamma \approx 70$ MeV

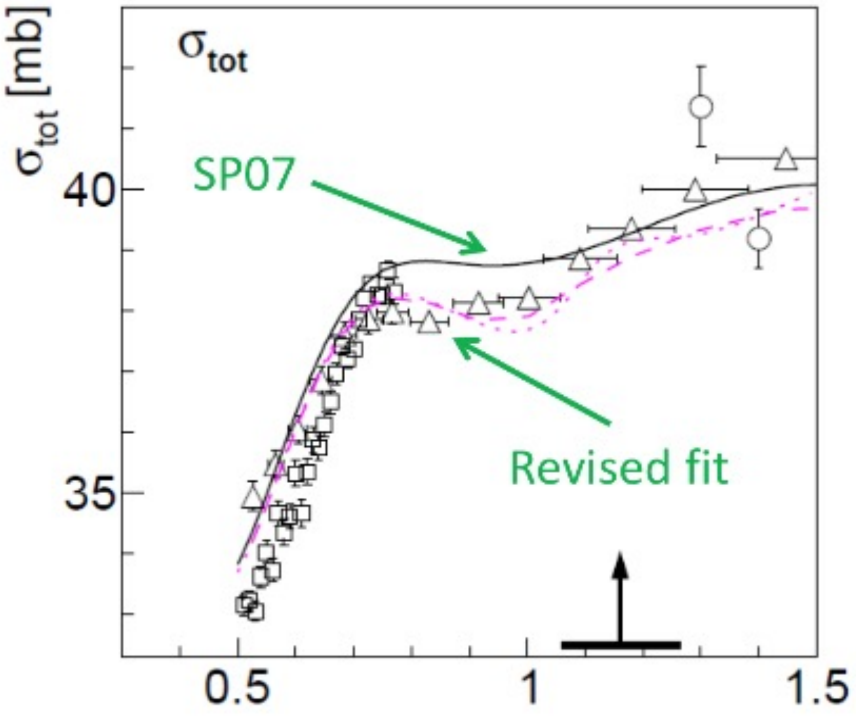
$d^*(2380)$

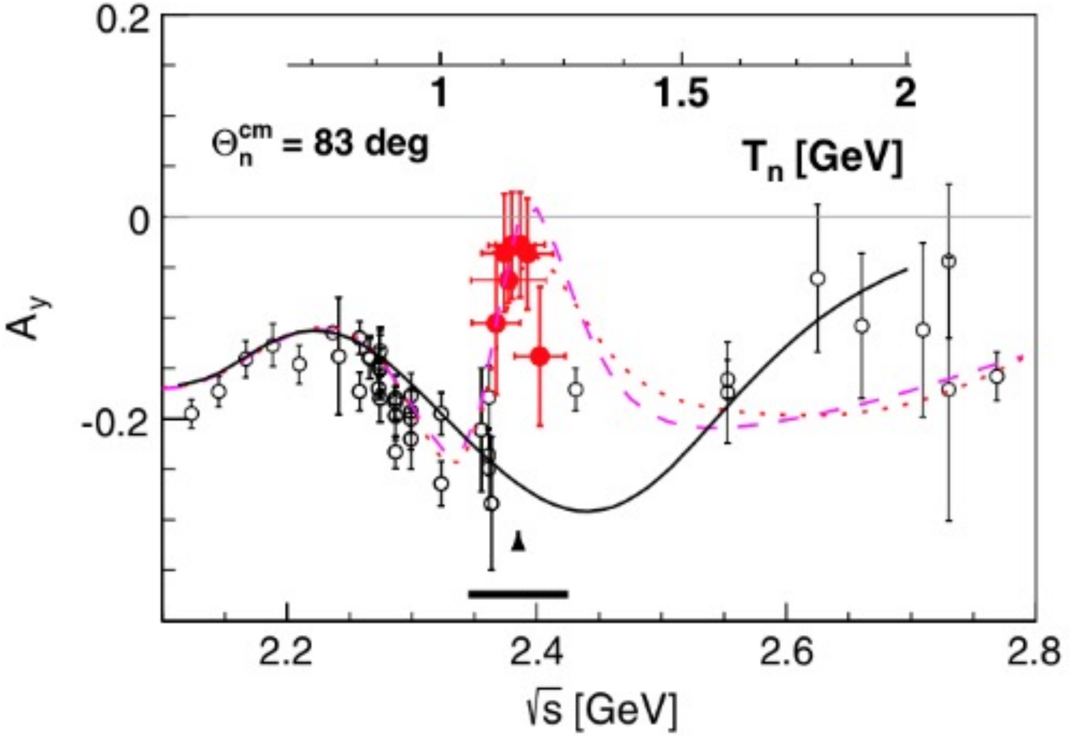
Evidence from $\vec{n}p$ scattering

WASA-at-COSY & SAID DAC, PRL 112 (2014) 202301

$\vec{d}p \rightarrow np + p_{spectator}$

M = (2380±10) – *i* (40±5)

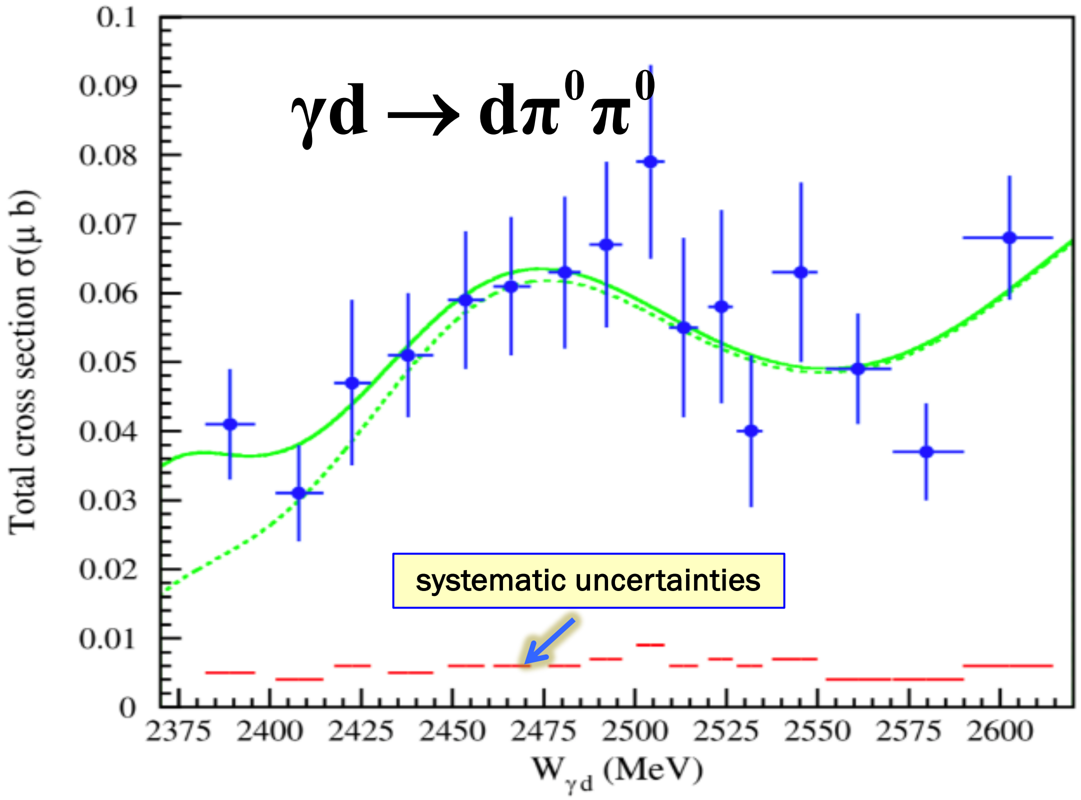




Colored lines: new fits with inclusion of new data (red symbols)

Experiments @ ELPH, MAMI

FOREST-at-ELPH, PLB 772 (2017) 398

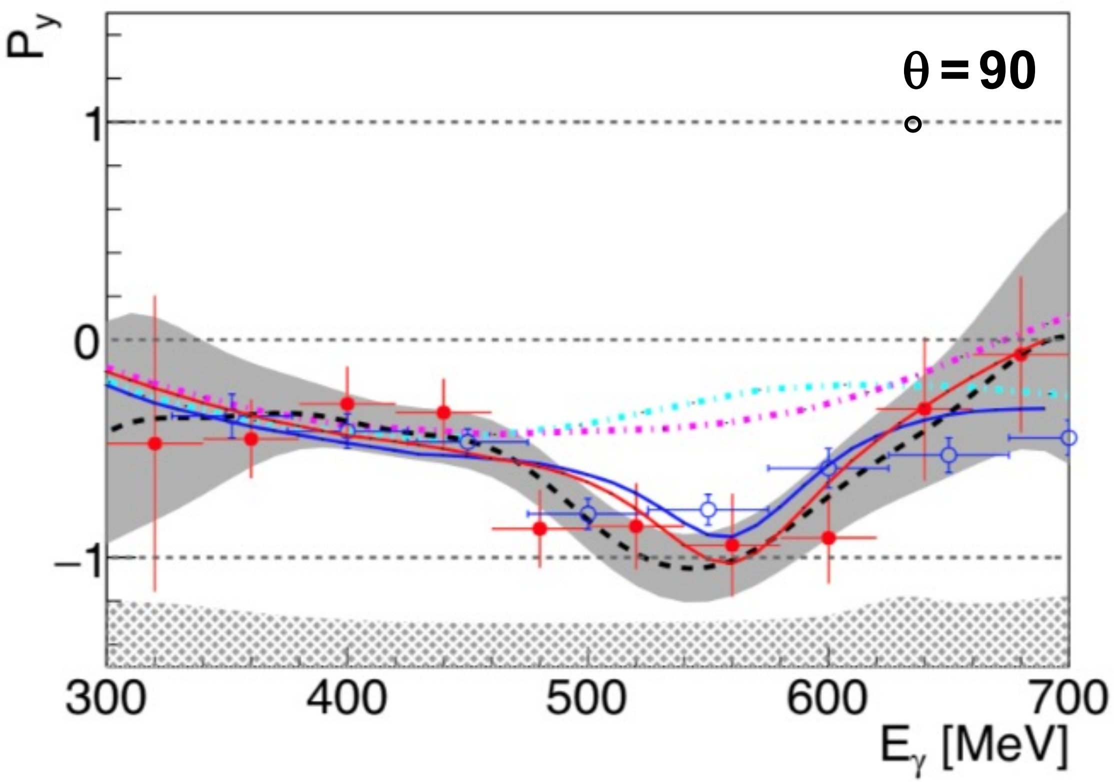


- - - W/o d*(2380)

Fix & Arenhovel, EPJA25(2005)115

— With d*(2380)

A2-at-MAMI, PRL 124 (2020) 132001



P_y^n fit without d*(2380)

P_y^p fit without d*(2380)

P_y^n fit with d*(2380)

P_y^p fit with d*(2380)

Unusual narrow width of d*

2464 — ΔΔ

2380 — d*

2309 — ΔNπ

2154 — NNππ

1878 — NN

$M_{d*} \approx 2380$ MeV

$\approx 2M_{\Delta} - 84$ MeV

$> M_{\Delta N\pi}$

$> M_{NN\pi\pi}$

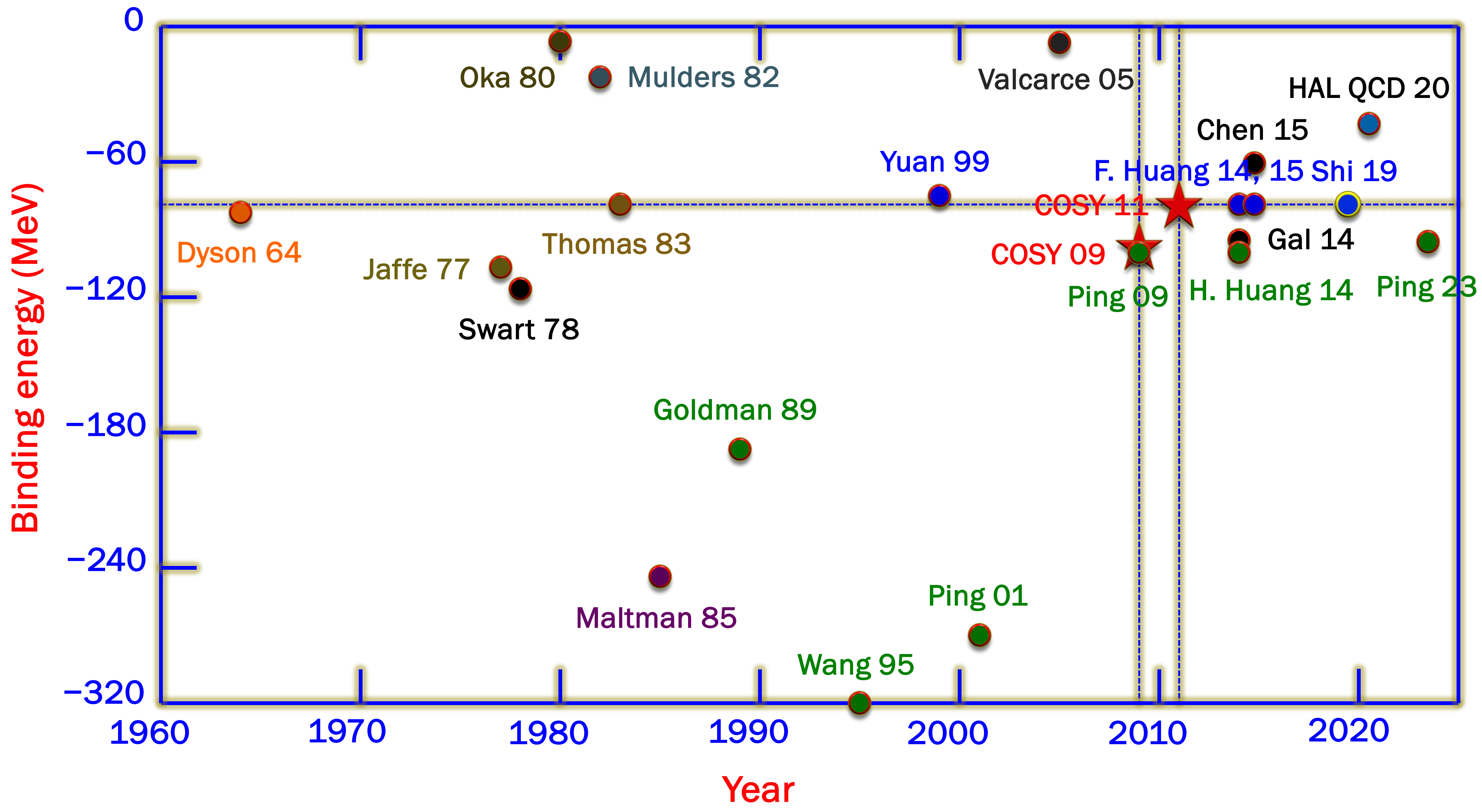
$> M_{NN}$

$\Gamma_{\Delta} \approx 115$ MeV

$\Gamma_{d*} \approx 70$ MeV

$< 1/3 \times 2\Gamma_{\Delta}$?

Overview of theoretical investigations



Prediction by Yuan et al. in 1999

X. Q. Yuan, Z. Y. Zhang, Y. W. Yu, & P. N. Shen, Phys. Rev. C 60, 045203 (1999).

TABLE II. Binding energy B and rms $\bar{R}$ of the deltaron $B=-(E_{\text{deltaron}}-2M_{\Delta})$, $\bar{R}=\sqrt{\langle r^2\rangle}$.

		$\Delta\Delta(L=0)$	$\Delta\Delta\binom{L=0}{+2}$	$\Delta\Delta$ CC $(L=0)$	$\Delta\Delta$ CC $\binom{L=0}{+2}$
OGE	B (MeV)	29.8	29.9	41.0	42.0
	$\bar{R}$ (fm)	0.92	0.92	0.87	0.87
OGE+π,σ	B (MeV)	50.2	62.6	68.6	79.7
	$\bar{R}$ (fm)	0.87	0.86	0.84	0.83
OGE+SU(3)	B (MeV)	18.4	22.5	31.7	37.3
	$\bar{R}$ (fm)	1.01	1.00	0.92	0.92

30-60

40-80

- Binding energy: 40 ~ 80 MeV
- CC: 10 ~ 20 MeV increase in binding energy

Results in chiral SU(3) QM, revisited

Structures & wave functions

- F. Huang, Z.Y. Zhang, P.N. Shen, W.L. Wang, Chin. Phys. C 39 (2015) 071001
- F. Huang, P.N. Shen, Y.B. Dong, Z.Y. Zhang, Sci. China-Phys. Mech. Astron. 59 (2016) 622002

Decay widths & charge distributions

- Y.B. Dong, P.N. Shen, F. Huang, Z.Y. Zhang, Phys. Rev. C 91 (2015) 064002
- Y.B. Dong, F. Huang, P.N. Shen, Z.Y. Zhang, Phys. Rev. C 94 (2015) 014003
- Y.B. Dong, F. Huang, P.N. Shen, Z.Y. Zhang, Phys. Lett. B 769 (2017) 223
- Y.B. Dong, F. Huang, P.N. Shen, Z.Y. Zhang, Phys. Rev. D 96 (2017) 094001
- Y.B. Dong, F. Huang, P.N. Shen, Z.Y. Zhang, Chin. Phys. C 41 (2017) 101001

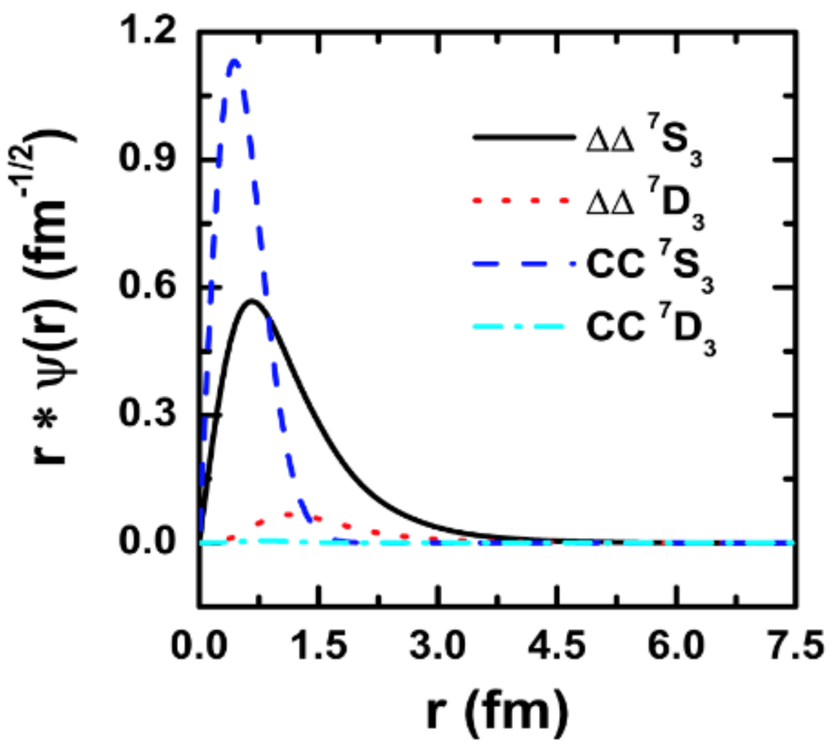
Calculated d* mass and wave functions

Without CC: BE ≈ 29 – 62 MeV

	ΔΔ (L = 0, 2)		
	SU(3)	Ext. SU(3) (f/g=0)	Ext. SU(3) (f/g=2/3)
B (MeV)	28.96	62.28	47.90
RMS (fm)	0.96	0.80	0.84

With CC: BE ≈ 47 – 84 MeV

	ΔΔ – CC (L = 0, 2)		
	SU(3)	Ext. SU(3) (f/g=0)	Ext. SU(3) (f/g=2/3)
B (MeV)	47.27	83.95	70.25
RMS (fm)	0.88	0.76	0.78
$(\Delta\Delta)_{L=0}$ (%)	33.11	31.22	32.51
$(\Delta\Delta)_{L=2}$ (%)	0.62	0.45	0.51
$(CC)_{L=0}$ (%)	66.25	68.33	66.98
$(CC)_{L=2}$ (%)	0.02	0.00	0.00

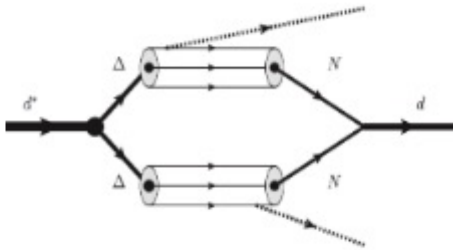


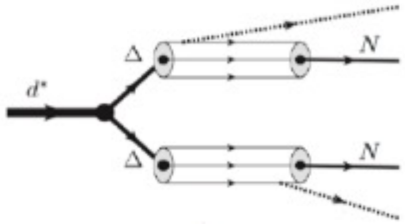
$$\frac{|\chi_{CC}|^2}{|\chi_{\Delta\Delta}|^2 + |\chi_{CC}|^2} \approx \frac{2}{3}$$

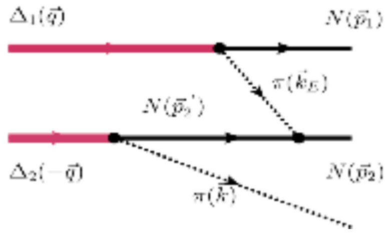
Partial decay widths

Y.B. Dong, P.N. Shen, F. Huang, Z.Y. Zhang, PRC 91 (2015) 064002

Y.B. Dong, F. Huang, P.N. Shen, Z.Y. Zhang, PRC 94 (2015) 014003; PLB 769 (2017) 223







	Theor. (MeV)	Expt. (MeV)
$d^* \to d\pi^+\pi^-$	16.8	16.7
$d^* \to d\pi^0\pi^0$	9.2	10.2
$d^* \to pn\pi^+\pi^-$	20.6	21.8
$d^* \to pn\pi^0\pi^0$	9.6	8.7
$d^* \to pp\pi^0\pi^-$	3.5	4.4
$d^* \to nn\pi^0\pi^+$	3.5	4.4
$d^* \to pn$	8.7	8.7
$d^* \to nn\pi^0\pi^+$	0.67	< 6.7
Total	72.6	74.9

Part III

Recent independent work

New developments in Chiral QM

Nucleon-nucleon interaction in a chiral SU(3) quark model revisited,
F. Huang and W.L. Wang, Phys. Rev. D 98, 074018 (2018)

- NN interaction: OGE is important for short-range repulsion
  - ⟶ A credible determination of g_u & g_s is essential
- Earlier studies: size parameter b predetermined

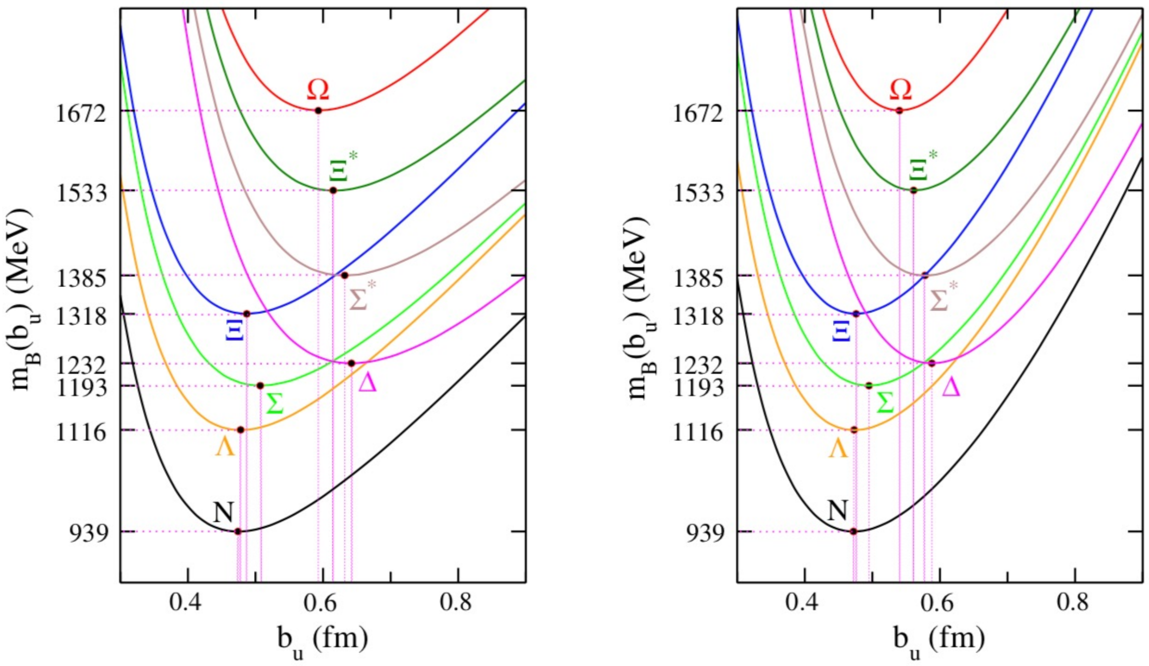
$$M_B = \langle T \rangle + \left\langle V^{\mathrm{conf}} \right\rangle + \left\langle V^{\mathrm{OGE}} \right\rangle + \left\langle V^{\mathrm{ch}} \right\rangle$$

$$M_\Delta - M_N \;\Longrightarrow\; g_u \qquad M_\Sigma - M_\Lambda \;\Longrightarrow\; g_s$$

- Problem: why different baryons have same sizes?
- Consequence: non-physical channels might be needed to change the internal wave functions of the single baryons
  - ⟶ Be careful in explaining the structure of bound BB states

Single baryon masses

F. Huang and W.L. Wang, Phys. Rev. D 98, 074018 (2018)



linear confinement quadratic confinement

TABLE II. Resulted mass and size parameter of octet and decuplet baryon ground states.

	N	Λ	Σ	Ξ	Δ	Σ^*	Ξ^*	Ω
Expt. [MeV]	939	1116	1193	1318	1232	1385	1533	1672
Theo. [MeV]	939	1116	1193	1318	1232	1385	1533	1672
b_u [fm] (r conf.)	0.474	0.478	0.507	0.487	0.642	0.632	0.615	0.593
(r^2 conf.)	0.472	0.473	0.495	0.476	0.588	0.578	0.561	0.540

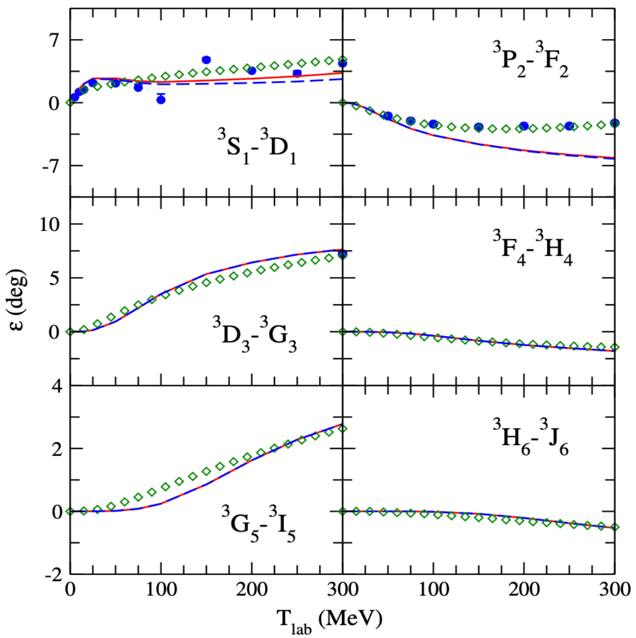
TABLE III. Binding energy of deuteron (in MeV).

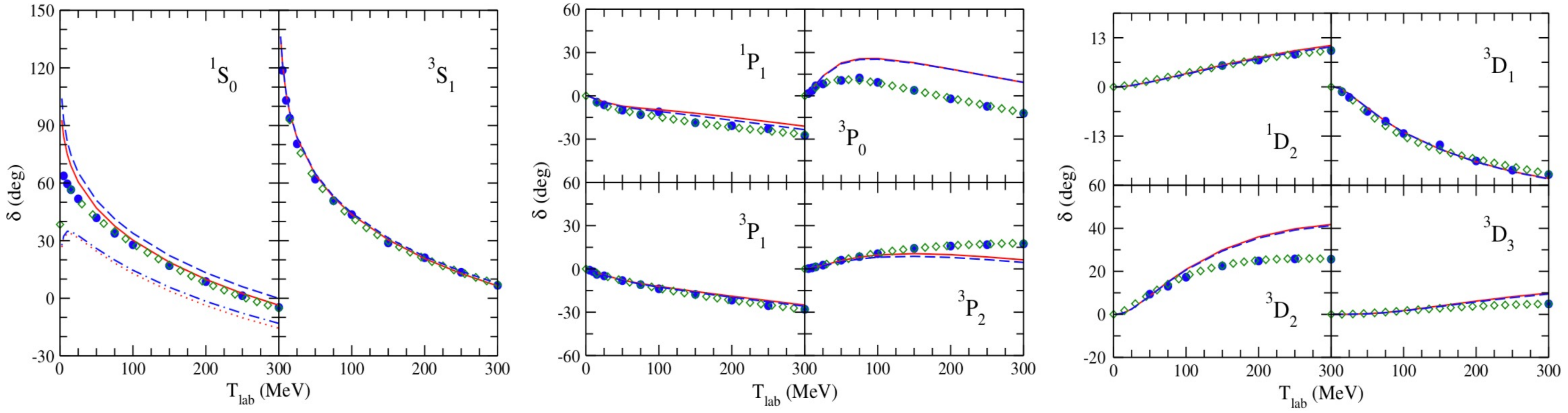
Model I (r conf.)	Model II (r^2 conf.)	Expt.
−2.215	−2.218	−2.224

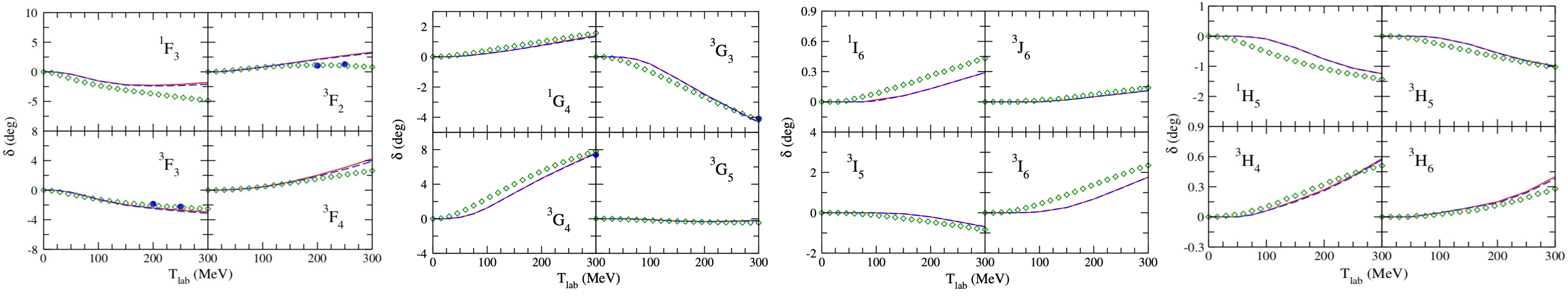
- Sizes of octet baryons are close
- Sizes of decuplet baryons are close
- Sizes of decuplet baryons are distinct from those of octet baryons
- When same sizes are used, be careful if decuplet baryon is involved

NN interaction revisited

F. Huang and W.L. Wang, Phys. Rev. D 98, 074018 (2018)





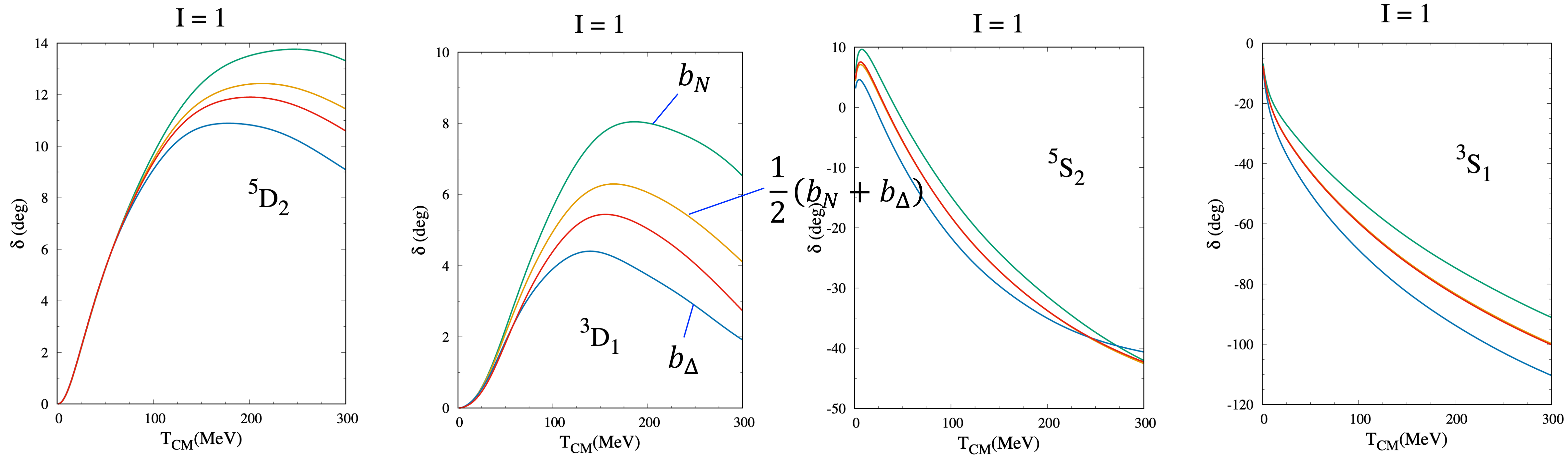


New RGM formula & NΔ interaction

$$Z_{6q}(\boldsymbol{R}, \boldsymbol{S}_G; \boldsymbol{r}, \boldsymbol{S}) = \left(\frac{1}{\pi b'^2_{AB}}\right)^{\frac{3}{4}} \exp\left[-\frac{1}{2b'^2_{AB}}\left((\boldsymbol{R}-\boldsymbol{S}_G)-\gamma(\boldsymbol{r}-\boldsymbol{S})\right)^2\right]$$

$$\int d\boldsymbol{S}_G Z_{6q}(\boldsymbol{R}, \boldsymbol{S}_G; \boldsymbol{r}, \boldsymbol{S}) = (4\pi b'^2_{AB})^{\frac{3}{4}}$$

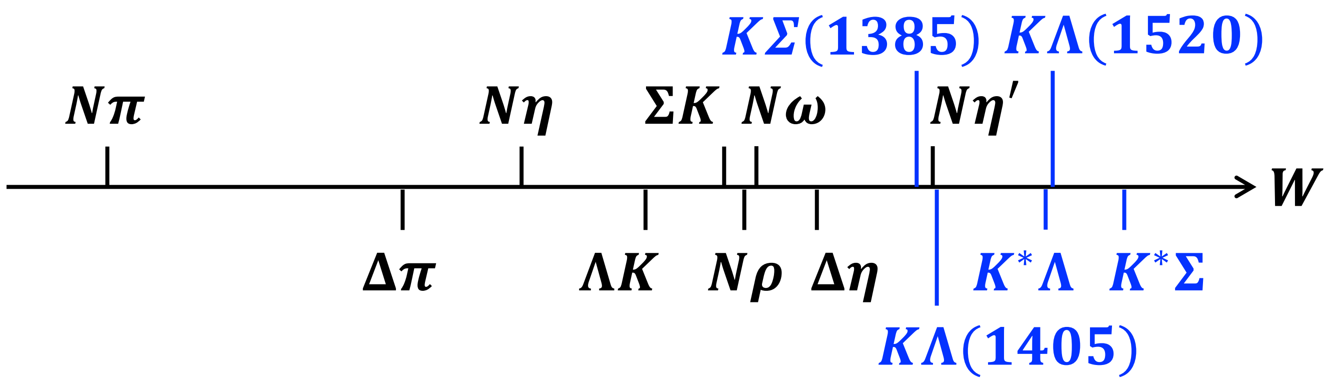
$$O_{ij} \equiv \langle \varphi_A(\boldsymbol{\xi}_1, \boldsymbol{\xi}_2, \omega_A)\varphi_B(\boldsymbol{\xi}_3, \boldsymbol{\xi}_4, \omega_B)\chi_i(\boldsymbol{r})|\hat{O} \times |\mathcal{A}[\varphi_A(\boldsymbol{\xi}_1, \boldsymbol{\xi}_2, \omega_A)\varphi_B(\boldsymbol{\xi}_3, \boldsymbol{\xi}_4, \omega_B)\chi_j(\boldsymbol{r})]\rangle = (4\pi b'^2_{AB})^{-\frac{3}{2}} \times \int d\boldsymbol{S}_G \langle \Phi_{6q}(\boldsymbol{S}_i, \boldsymbol{S}_G)|\hat{O}|\mathcal{A}[\Phi_{6q}(\boldsymbol{S}_j, 0)]\rangle.$$



K^*Y & KY^* production reactions

Particle	J^P	overall	Status as seen in									
			$N\gamma$	$N\pi$	$\Delta\pi$	$N\sigma$	$N\eta$	ΛK	ΣK	$N\rho$	$N\omega$	$N\eta'$
N	$1/2^+$	****										
$N(1440)$	$1/2^+$	****	****	****	****	***						
$N(1520)$	$3/2^-$	****	****	****	****	**	****					
$N(1535)$	$1/2^-$	****	****	****	***	*	****					
$N(1650)$	$1/2^-$	****	****	****	***	*	****	*				
$N(1675)$	$5/2^-$	****	****	****	****	***	*	*	*			
$N(1680)$	$5/2^+$	****	****	****	****	***	*	*	*			
$N(1700)$	$3/2^-$	***	**	***	***	*	*			*		
$N(1710)$	$1/2^+$	****	****	****	*		***	**	*	*	*	
$N(1720)$	$3/2^+$	****	****	****	***	*	*	****	*	*	*	
$N(1860)$	$5/2^+$	**	*	**		*	*					
$N(1875)$	$3/2^-$	***	**	**	*	**	*	*	*	*	*	
$N(1880)$	$1/2^+$	***	**	*	**	*	*	**	**		**	
$N(1895)$	$1/2^-$	****	****	*	*	*	****	**	**	*	*	****
$N(1900)$	$3/2^+$	****	****	**	**	*	*	**	**		*	**
$N(1990)$	$7/2^+$	**	**	**			*	*	*			
$N(2000)$	$5/2^+$	**	**	*	**	*	*				*	
$N(2040)$	$3/2^+$	*		*								
$N(2060)$	$5/2^-$	***	***	**	*	*	*	*	*	*	*	
$N(2100)$	$1/2^+$	***	**	***	**	**	*	*		*	*	**
$N(2120)$	$3/2^-$	***	***	**	**	**		**	*		*	*
$N(2190)$	$7/2^-$	****	****	****	****	**	*	**	*	*	*	
$N(2220)$	$9/2^+$	****	**	****			*	*	*			
$N(2250)$	$9/2^-$	****	**	****			*	*	*			
$N(2300)$	$1/2^+$	**		**								
$N(2570)$	$5/2^-$	**		**								
$N(2600)$	$11/2^-$	***		***								
$N(2700)$	$13/2^+$	**		**								

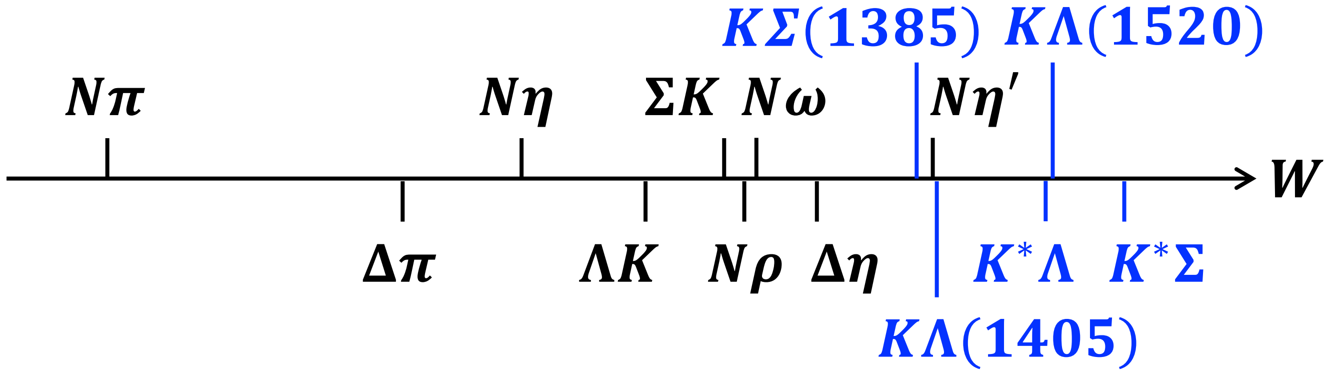
PDG (2024)



- **Most N^* & Δ^* come from $\gamma N, \pi N \to \pi N, \pi\Delta, N\eta, K\Lambda, K\Sigma$**
- **No N^* or Δ^* information on K^*Y & KY^***
- **K^*Y & KY^*: suitable to study N^* & Δ^* with higher masses**

Research method

$$T_{fi} = V_{fi} + \sum \int V_{fm} G_m T_{mi}$$



Step 1: tree level $T_{fi} = V_{fi}$ done

Step 2: K^*Y & KY^* intermediate channels

$$T_{fi} = V_{fi} + \sum_{KY^*, K^*Y} \int V_{fm} G_m T_{mi}$$

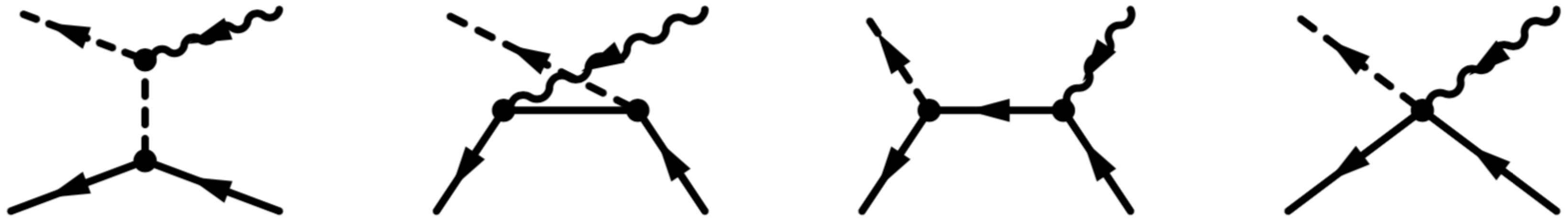
underway; meson-beam data needed

Step 3: all channels

$$T_{fi} = V_{fi} + \sum \int V_{fm} G_m T_{mi}$$

long future plan

Effective Lagrangian approach



$$M = M_t + M_u + M_s + M_{int}$$

- t channel: κ, K, K^*
- u channel: Λ, Σ, Λ^*, Σ^*
- s channel: N, Δ, N^*, Δ^*

SU(3) relations & decay widths used to fix couplings.

Others left as fit parameters.

Resonance: Introduce N^*'s & Δ^*'s as few as possible.

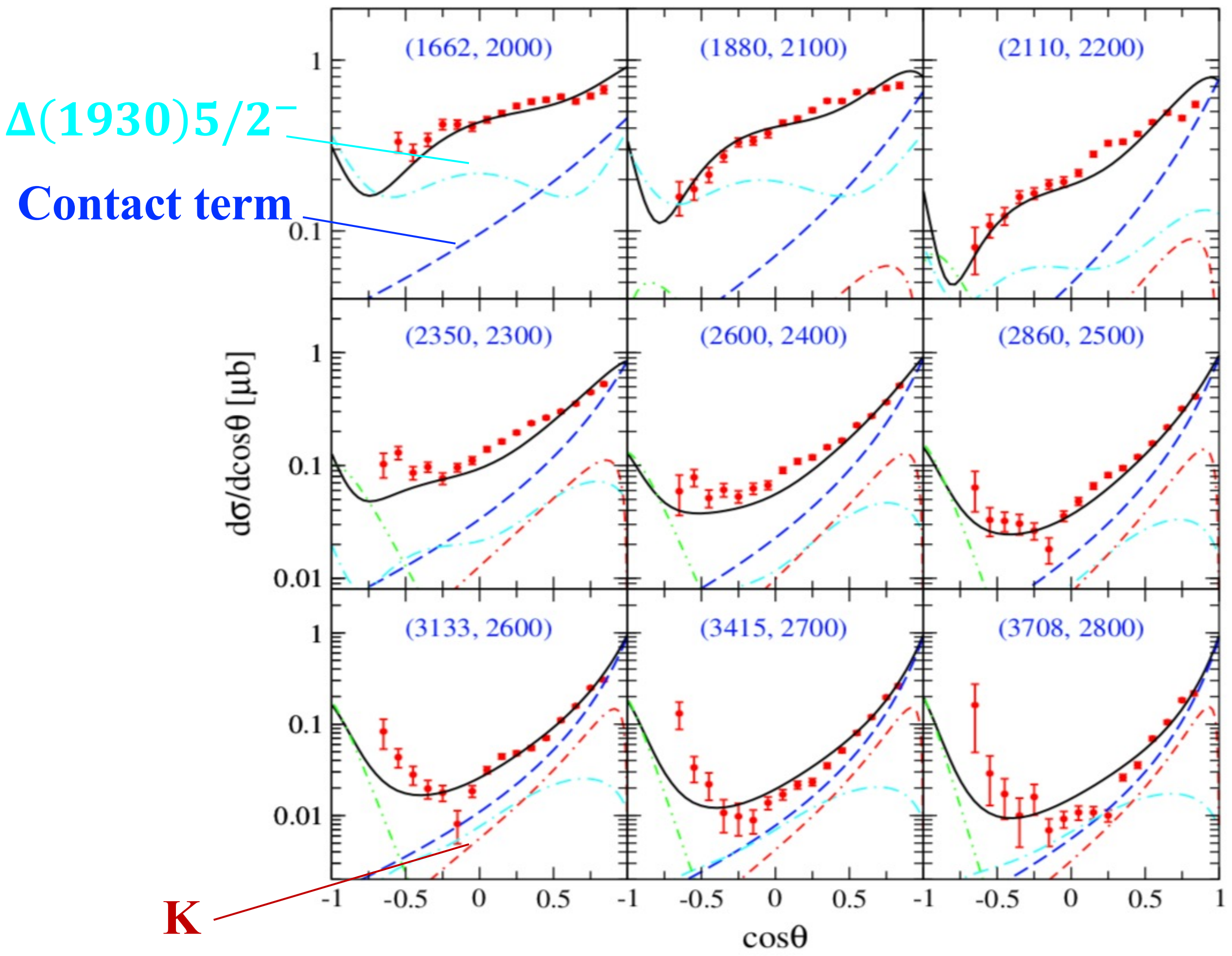
Gauge invariance strictly reserved.

$K\Sigma(1385)$ production reactions

A.C. Wang et al., PRD 101 (2020) 074025; 105 (2022) 034017

- Combined analysis of
  $$\gamma p \to K^+\Sigma^0(1385)$$
  $$\gamma n \to K^+\Sigma^-(1385)$$
  $$\pi^+ p \to K^+\Sigma^+(1385)$$
- All data are considered
- $\Delta(1930)5/2^-$ needed
- Photoproduction: $\Delta(1930)5/2^-$ (M & Γ from PDG), interaction current, and K dominate
- $\pi^+ p$ reaction: Λ dominates, $\Delta(1930)5/2^-$ considerable

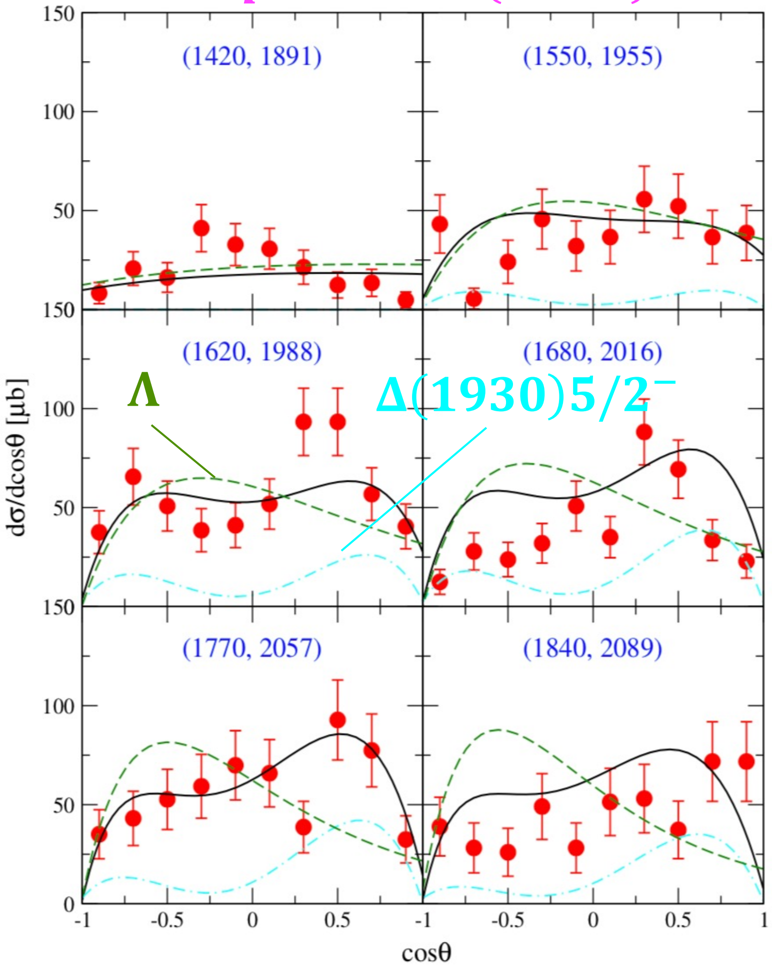
$\gamma p \to K^+\Sigma^0(1385)$



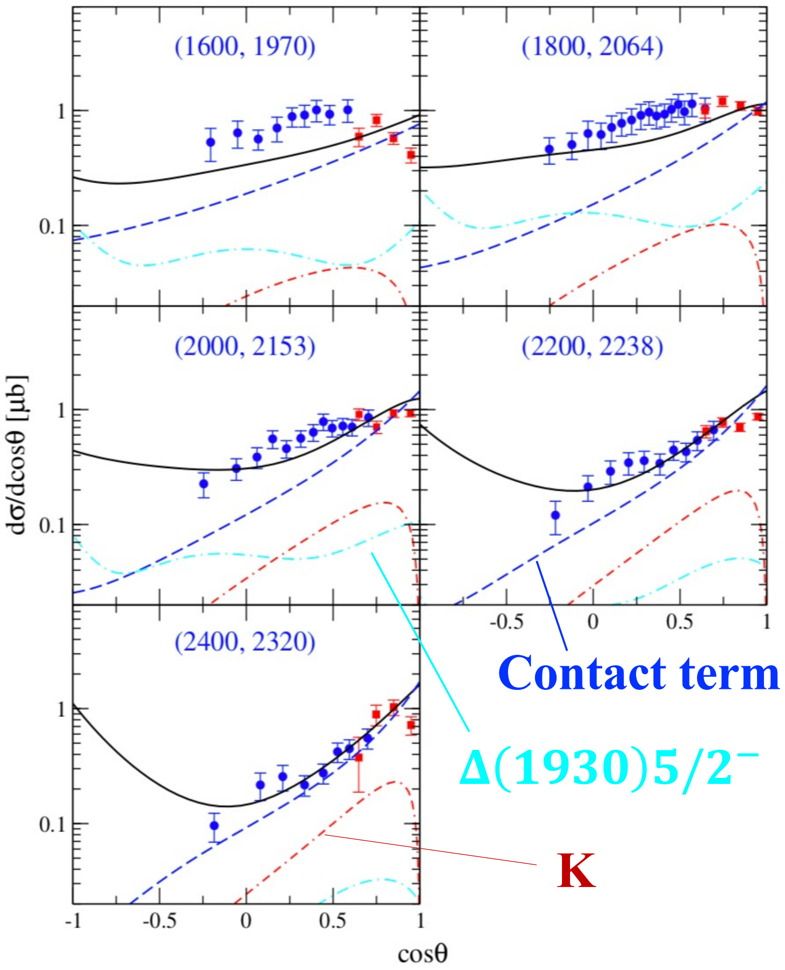
$K\Sigma(1385)$ production reactions

A.C. Wang et al., PRD 101 (2020) 074025; 105 (2022) 034017

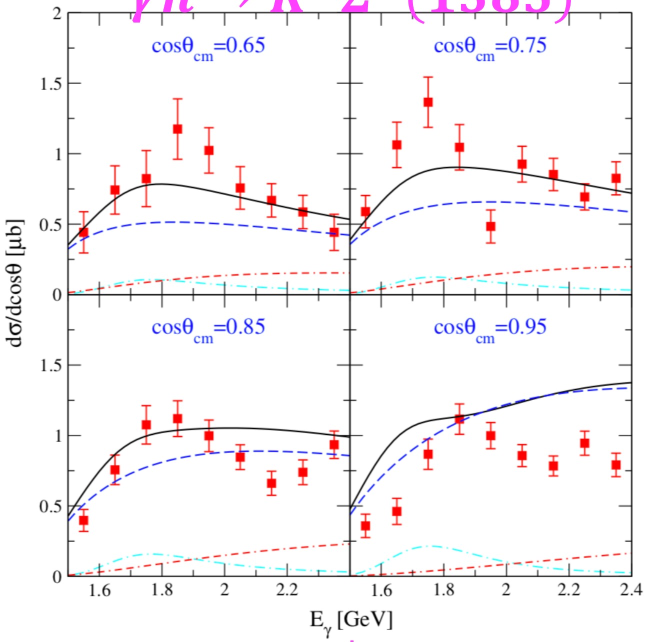
$\pi^+ p \to K^+ \Sigma^0(1385)$



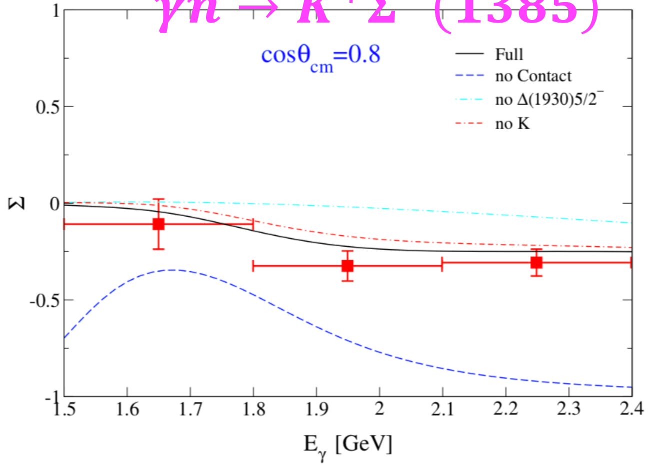
$\gamma n \to K^+ \Sigma^-(1385)$



$\gamma n \to K^+ \Sigma^-(1385)$



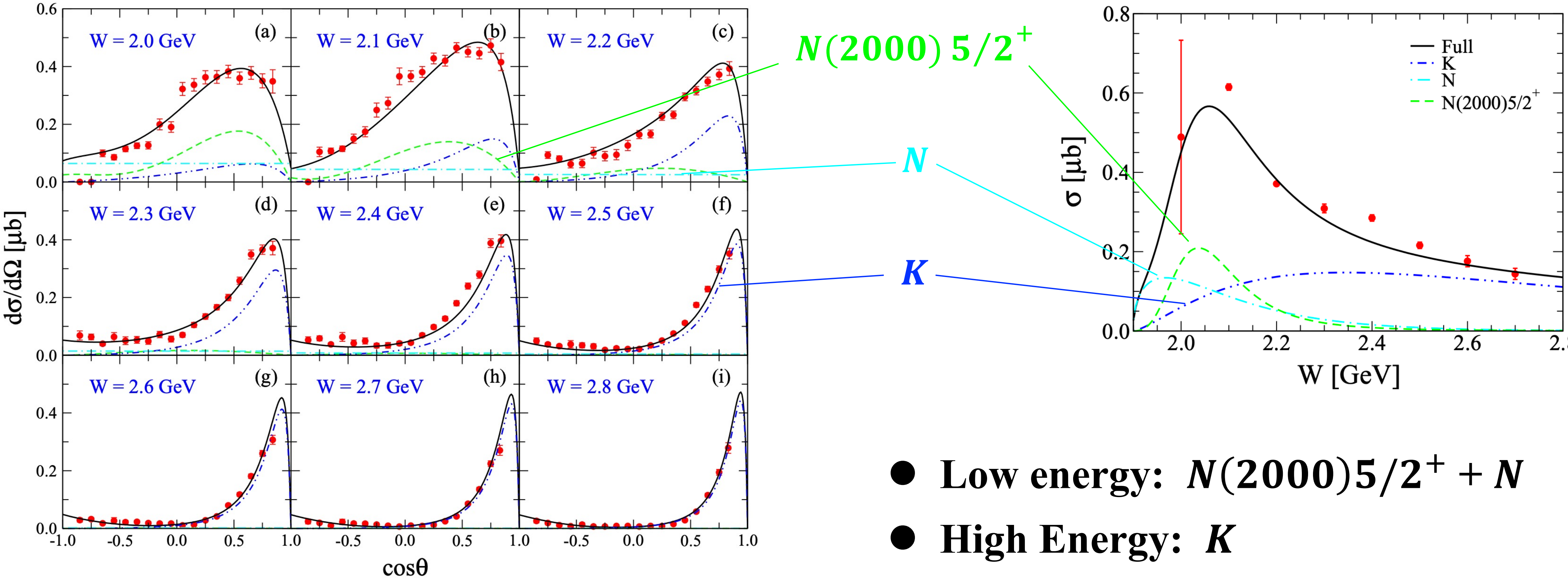
$\gamma n \to K^+ \Sigma^-(1385)$



$K\Lambda(1405)$ photoproduction

Y. Zhang and F. Huang, PRC 103 (2021) 025207

$\gamma p \to K^+\Lambda(1405)$

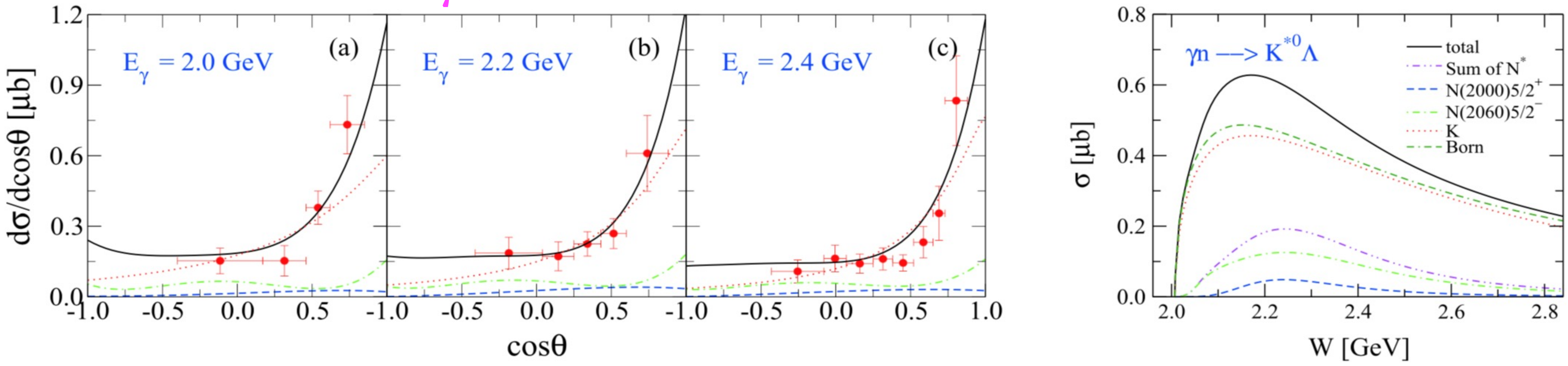


- **Low energy:** $N(2000)5/2^+ + N$
- **High Energy:** K

$K^*\Lambda$ photoproduction

A.C. Wang et al., PRC 96 (2017) 035206; N.C. Wei et al., PRC 101 (2020) 014003; N.C. Wei et al., CPC 46 (2022) 023106

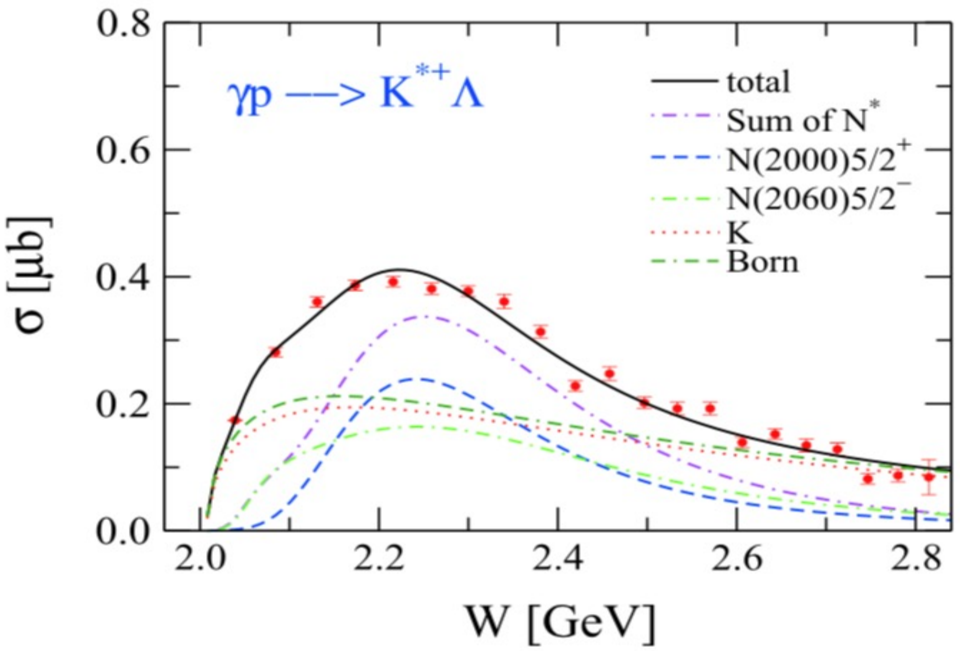
$\gamma n \to K^{*0}\Lambda$



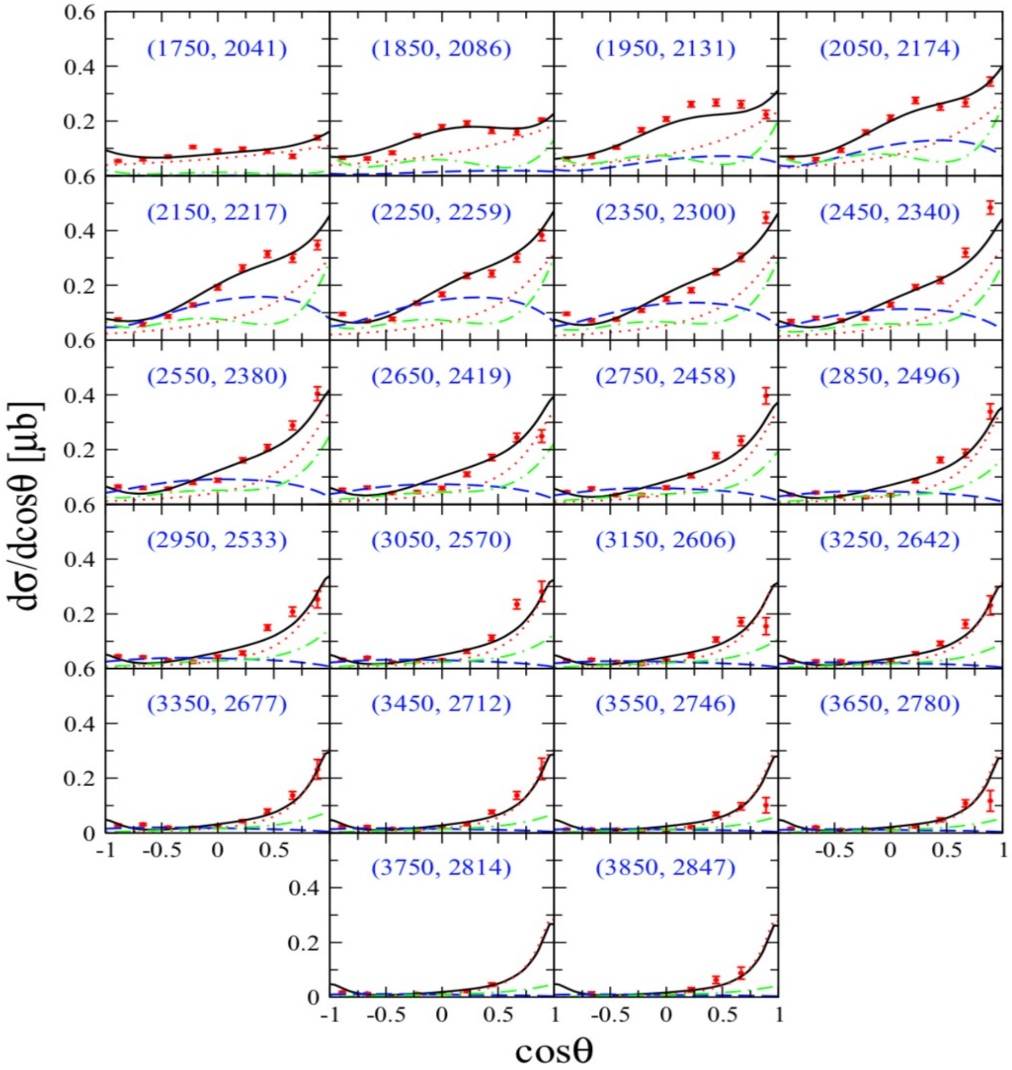
- Combined analysis of all data for both $\gamma p \to K^{*+}\Lambda$ & $\gamma n \to K^{*0}\Lambda$
- $N(2060)5/2^-$ & $N(2000)5/2^+$ needed
- γn reaction: K dominates, resonances significant

$K^*\Lambda$ photoproduction

A.C. Wang et al., PRC 96 (2017) 035206;
N.C. Wei et al., PRC 101 (2020) 014003.



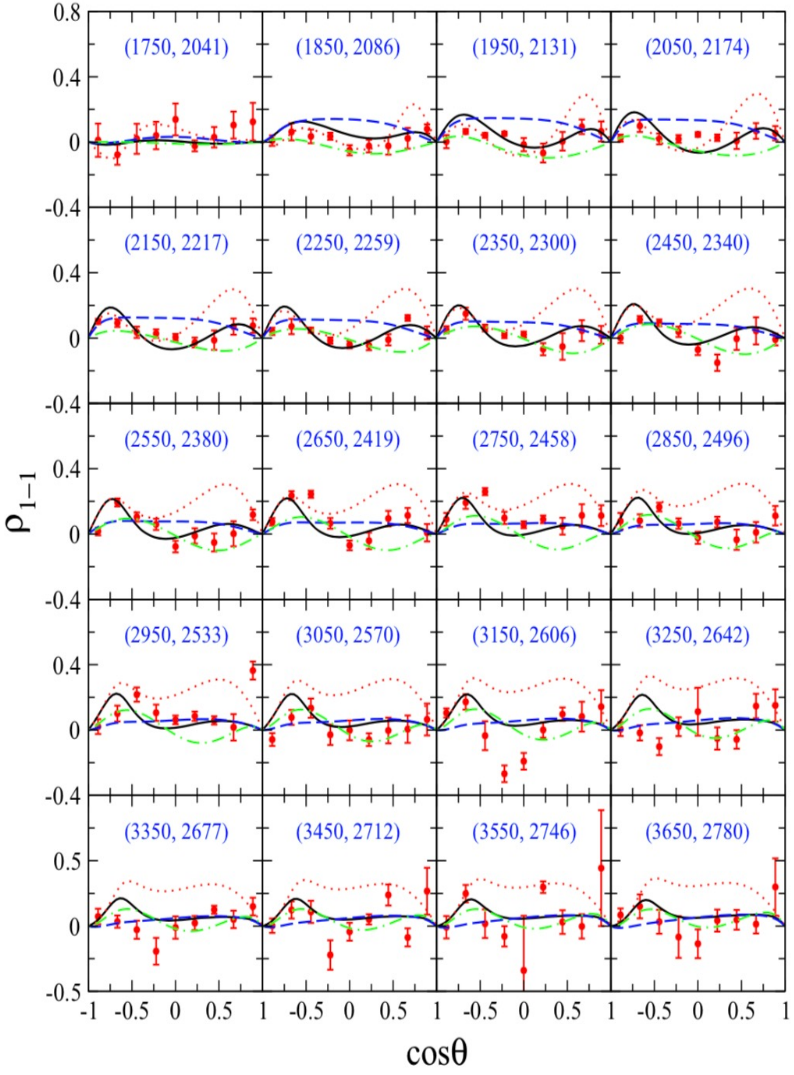
$\gamma p \rightarrow K^{*+}\Lambda$



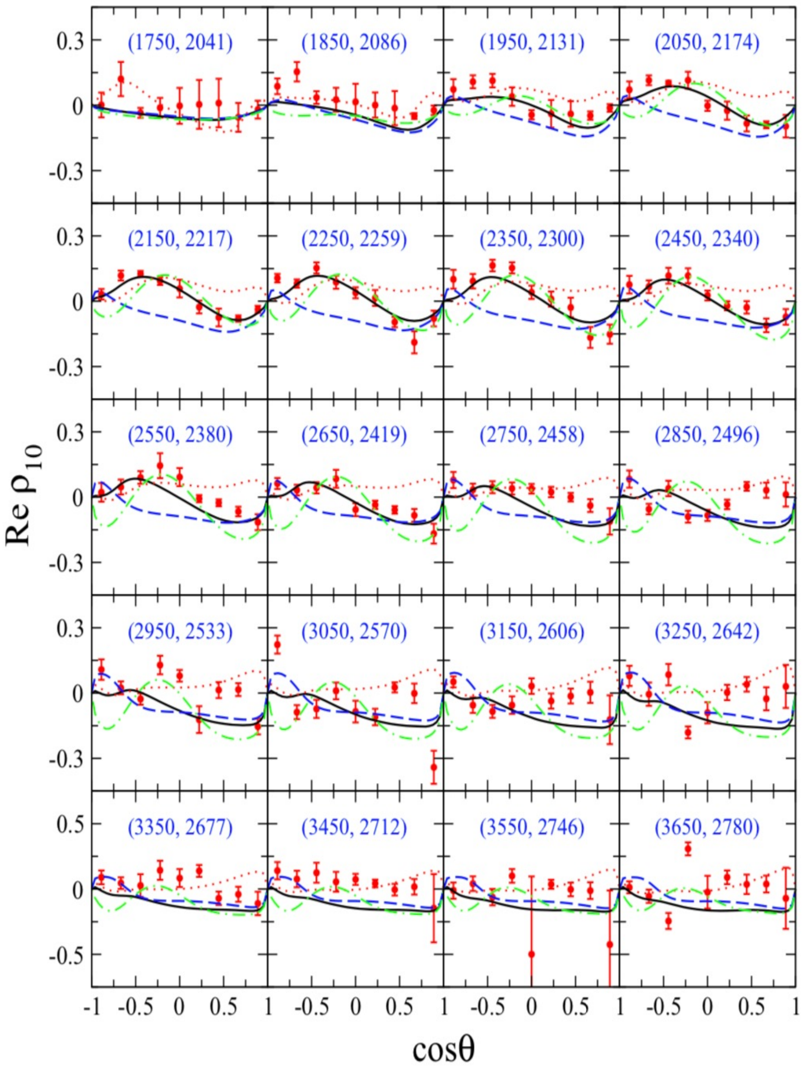
- ***γp* reaction: *K* & resonances both are important**

$K^*\Lambda$ photoproduction

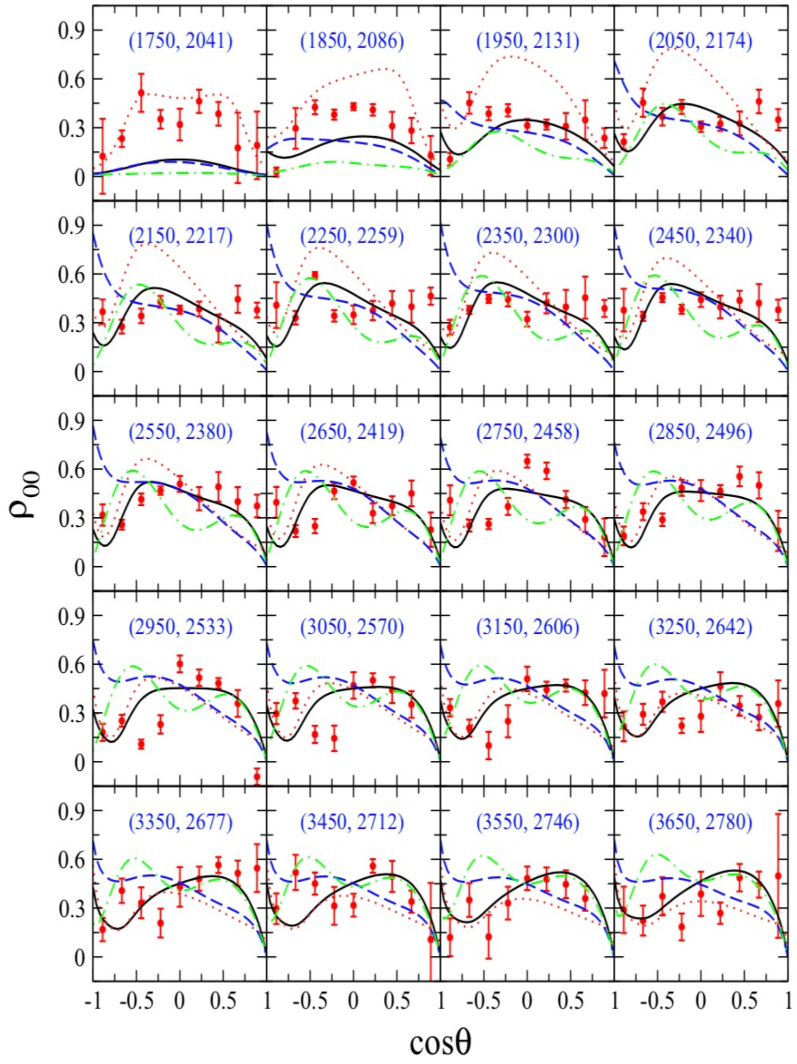
$\gamma p \rightarrow K^{*+}\Lambda$



$\gamma p \rightarrow K^{*+}\Lambda$

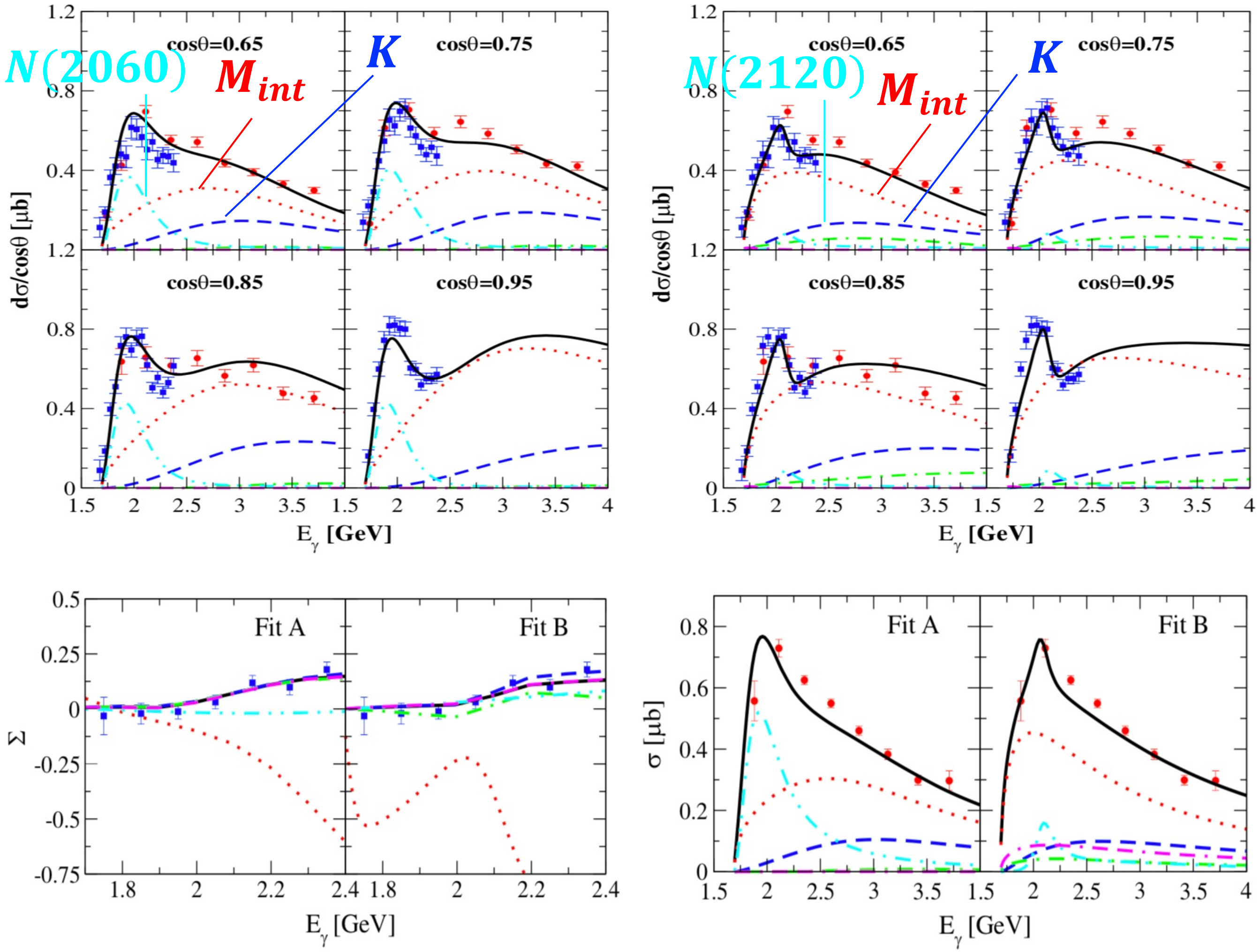


$\gamma p \rightarrow K^{*+}\Lambda$



$K^+\Lambda(1520)$ photoproduction

N.C. Wei, Y. Zhang, F. Huang, and D.M. Li, PRD 103 (2021) 034007

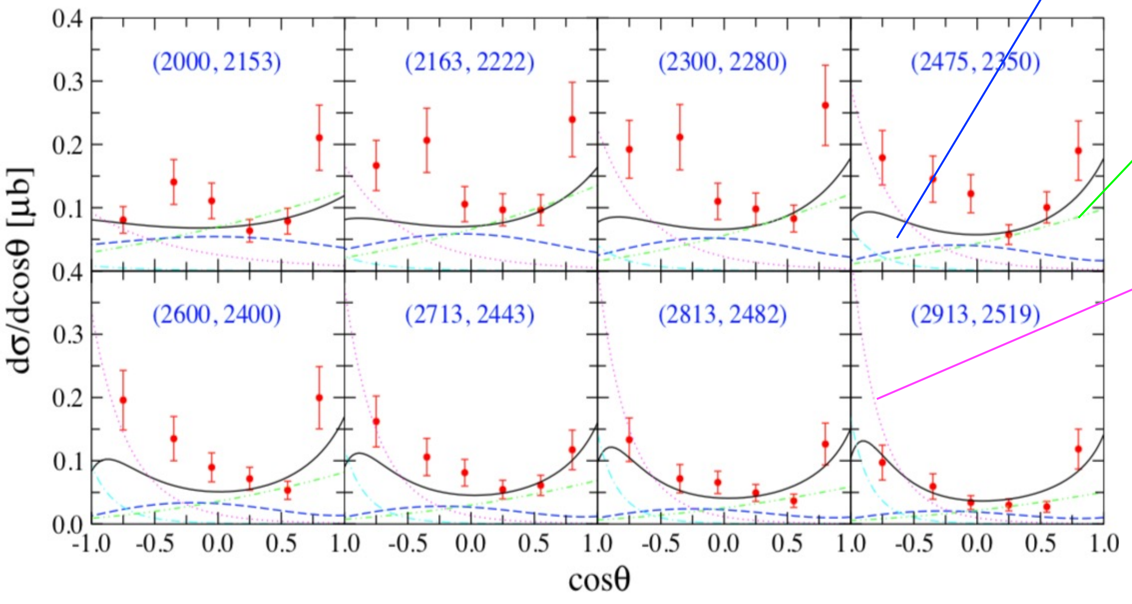


- **All data are well described**
- **One of the $N(2060)5/2^-$ and $N(2120)3/2^-$ is needed**
- **Background: M_{int} & K**
- **Fit A: $N(2060)5/2^-$ dominate**
  Fit B: $N(2120)3/2^-$ small

$K^*\Sigma$ photoproduction

A.C. Wang, W.L. Wang, & F. Huang, PRC 98 (2018) 045209;
A.C. Wang et al., in preparation

$\gamma p \to K^{*0}\Sigma^+$

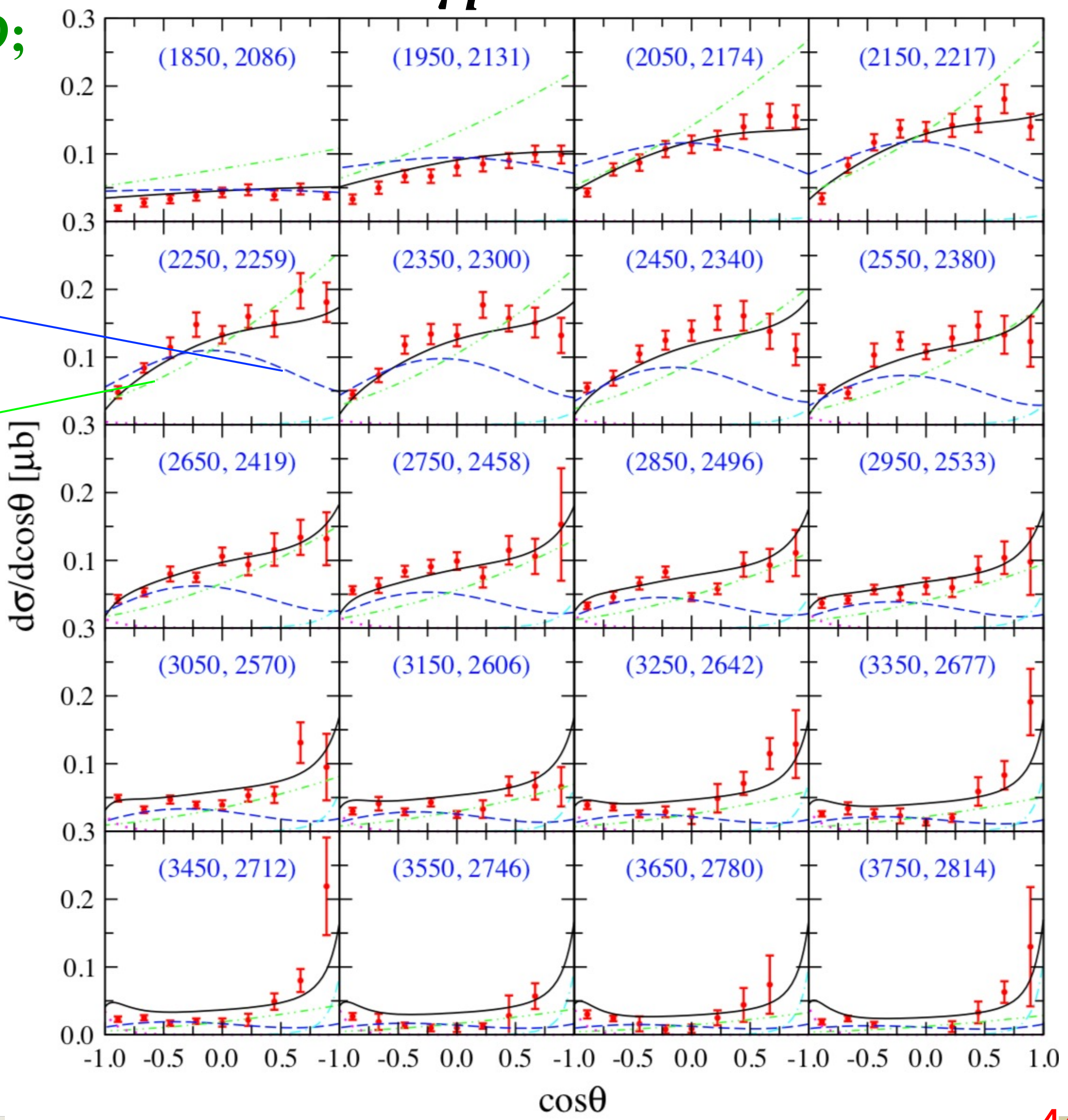


$\Delta(1905)\,5/2^+$

Δ

Σ

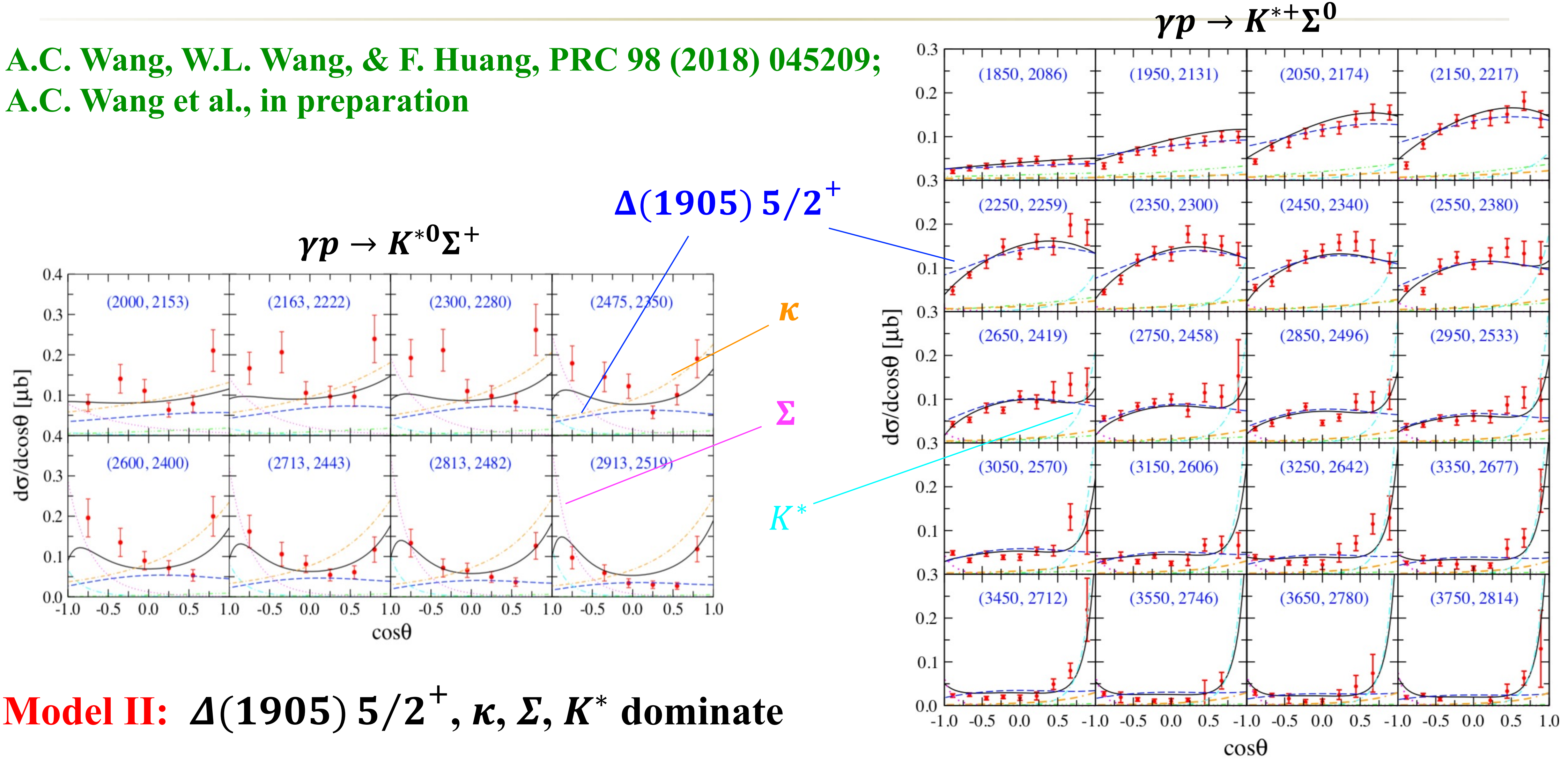
$\gamma p \to K^{*+}\Sigma^0$



Model I: $\Delta(1905)\,5/2^+$, Δ, Σ **dominate**

$K^*\Sigma$ photoproduction

A.C. Wang, W.L. Wang, & F. Huang, PRC 98 (2018) 045209;
A.C. Wang et al., in preparation



Model II: $\Delta(1905)\ 5/2^+$, κ, Σ, K^* dominate

κ exchange in $\gamma p \to K^{*0}\Sigma^+$

For t-channel meson exchanges,

$$T^N\text{: natural parity } P = (-1)^J$$

$$T^U\text{: unnatural parity } P = (-1)^{J+1}$$

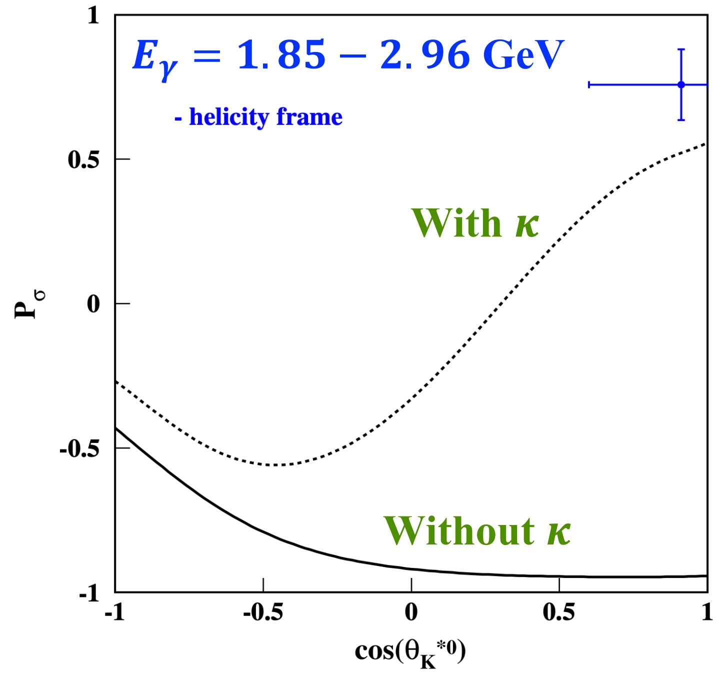
Spin-parity asymmetry:

$$P_\sigma = 2\rho^1_{1-1} - \rho^1_{00} = \frac{\sigma^N - \sigma^U}{\sigma^N + \sigma^U}$$

In the high energy limit at forward angles:

$$P_\sigma \to \begin{cases} -1: & K \text{ exchange} \\ 1: & \kappa \text{ exchange} \end{cases}$$

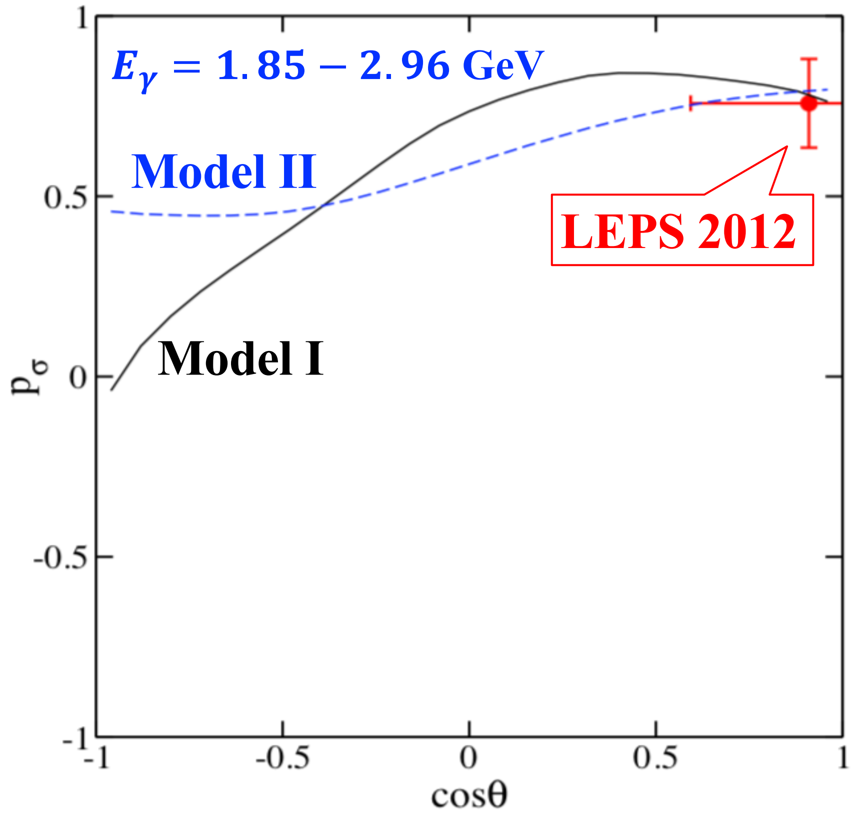
LEPS, PRL 108 (2012) 092001



"The measured parity spin asymmetry shows that natural-parity exchange is dominant. This result clearly indicates the need for t-channel exchange of the $\chi(800)$ scalar meson"

κ exchange in $\gamma p \to K^{*0}\Sigma^+$

A.C. Wang et al., in preparation



Model I: no κ
Model II: significant κ

- Either with or without dominant χ, LEPS P_σ data can be well reproduced
- $W \sim 2 - 2.5$ GeV: s-channel exchanges also contribute

  $P_\sigma \sim 1$: not necessarily caused by χ
- At $E_\gamma \approx 8.5$ GeV, $W \sim 4$ GeV:

  model with dominant κ: $P_\sigma \sim 1$

  model without dominant κ: small P_σ
- Data on P_σ at high energies are needed to confirm the role of χ exchange

Summary

- Selected PhD work under supervision of Prof. Zhang
  - Negative results for $\Theta(1540)$ [CLAS confirmed 2 years later]
  - Successful description of KN data
- Work collaborated with Prof. Zhang after PhD
  - Prediction of $\Sigma_c\bar{D}$ bound state in 2011 [LHCb confirmed in 2019]
  - Understanding of the structure & decay of $d^*(2380)$
- Recent independent work
  - New developments in chiral SU(3) quark model
    Consistent description of single baryon & baryon-baryon interaction
    New formula for RGM equation with different sizes of two baryons
  - K^*Y & KY^* production reactions
    Systematic investigation, resonance information extracted
    $\gamma p \to K^*\Sigma$: LEPS P_σ data not sufficient to claim dominant κ exchange