手征动力学与强子谱和强子衰变

钟显辉
湖南师范大学

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CONTENTS

Part I

Chiral dynamics

Chiral symmetry

QCD Lagrangian:

$$\mathcal{L}_{QCD}^{eff} = -\frac{1}{4}G_{\mu\nu}^{a}G_{a}^{\mu\nu} + \sum_{f=u,d,s}\bar{\psi}_f(i\gamma^\mu D_\mu - m_f)\psi_f + \mathcal{O}(\frac{1}{m_{c,b,t}^2})$$

Written in left and right hand components:

$$q_{L,R} = P_{L,R}\psi \qquad P_L = \frac{1}{2}(1-\gamma_5), P_R = \frac{1}{2}(1+\gamma_5)$$

$$\mathcal{L}_{QCD}^{eff} = \sum_f \left[\bar{q}_{L,f} i\gamma^\mu D_\mu q_{L,f} + \bar{q}_{R,f} i\gamma^\mu D_\mu q_{R,f} - m_f\left(\bar{q}_{L,f}q_{R,f} + \bar{q}_{R,f}q_{L,f}\right)\right] - \frac{1}{4}G_{\mu\nu}^{a}G_{a}^{\mu\nu}$$

Chiral symmetry $\mathrm{SU}(3)_L \times \mathrm{SU}(3)_R$

Chiral transformation: $q_L \to \exp\left(-i\theta_L^i(1+\gamma_5)\frac{\lambda_i}{2}\right) q_L, \quad q_R \to \exp\left(-i\theta_L^i(1-\gamma_5)\frac{\lambda_i}{2}\right) q_R$

For the massless term,

$$\bar{q}_{L,f} i\gamma^\mu D_\mu q_{L,f} + \bar{q}_{R,f} i\gamma^\mu D_\mu q_{R,f}$$

Chiral symmetry is maintained, however for the mass term,

$$m_f \left(\bar{q}_{L,f} q_{R,f} + \bar{q}_{R,f} q_{L,f}\right)$$

Chiral symmetry is broken!

Chiral dynamics

$$\mathrm{SU}(3)_L \times \mathrm{SU}(3)_R \xrightarrow[\text{SSB}]{Q_A^a\,|0\rangle \neq 0} SU(3)_V$$

Goldstone boson: $\xi \to L\xi R^{+}$ $\quad \xi = \exp(i\phi_m/f_m)$

$$\phi_m = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & K^0 \\ K^- & \bar{K}^0 & -\sqrt{\frac{2}{3}}\eta \end{pmatrix},$$

$$M_\pi^2 = \underbrace{(m_u + m_d)}_{\text{显性破缺}}\underbrace{\left(\frac{-\langle 0|\,\bar{u}u\,|0\rangle}{F^2}\right)}_{\text{自发破缺}} + \mathcal{O}(m_q^2)$$

Chiral Lagrangian for chiral quark model (NPB 234, 189(1984)) :

$$\mathcal{L} = \bar{\psi}[\gamma_\mu(i\partial^\mu + V^\mu + \gamma_5 A^\mu) - m]\psi + \cdots,$$

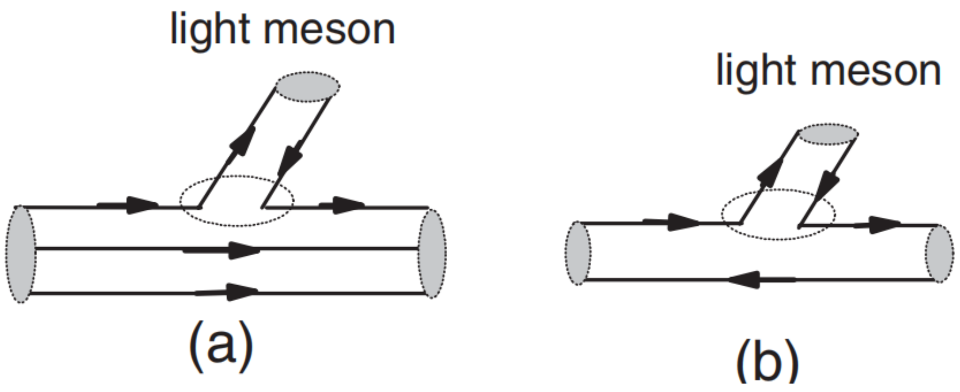
$$V^\mu = \frac{1}{2}(\xi\partial^\mu\xi^\dagger + \xi^\dagger\partial^\mu\xi), \qquad A^\mu = \frac{1}{2i}(\xi\partial^\mu\xi^\dagger - \xi^\dagger\partial^\mu\xi),$$

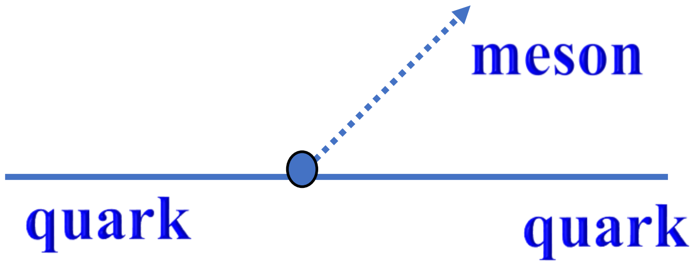
$$\xi = \exp(i\phi_m/f_m)$$

Part II

Strong decay with chiral dynamics

Strong decay within chiral quark model





Light π,η,K mesons are considered as point goldstones

Quark-meson coupling

$$\mathcal{L}_{ps} = \frac{\delta}{\sqrt{2}f_{\mathbb{M}}}\bar{\psi}_j\gamma_\mu\gamma_5\psi_j\vec{I}\cdot\partial^\mu\vec{\phi}_{\mathbb{M}},$$

$$H_m^{nr} = \sum_j\left\{\frac{\omega_m}{E_f+M_f}\boldsymbol{\sigma}_j\cdot\mathbf{P}_f+\frac{\omega_m}{E_i+M_i}\boldsymbol{\sigma}_j\cdot\mathbf{P}_i -\boldsymbol{\sigma}_j\cdot\mathbf{q}+\frac{\omega_m}{2\mu_q}\boldsymbol{\sigma}_j\cdot\mathbf{p}_j'\right\}I_j\varphi_m,$$

Hadron strong decays with chiral dynamics

Strong and radiative decays of the low-lying S- and P-wave singly heavy baryons #4

Kai-Lei Wang (Hunan Normal U. and Hunan, LDQSQC), Ya-Xiong Yao (Hunan Normal U. and Hunan, LDQSQC), Xian-Hui Zhong (Hunan Normal U. and Hunan, LDQSQC), Qiang Zhao (Hunan Normal U. and Beijing, GUCAS and Beijing, Inst. High Energy Phys.) (Sep 13, 2017)

Published in: *Phys.Rev.D* 96 (2017) 11, 116016 • e-Print: 1709.04268 [hep-ph]

pdf DOI cite claim reference search 128 citations

Charmed baryon strong decays in a chiral quark model #5

Xian-Hui Zhong (Beijing, Inst. High Energy Phys.), Qiang Zhao (Beijing, Inst. High Energy Phys. and Surrey U.) (Nov, 2007)

Published in: *Phys.Rev.D* 77 (2008) 074008 • e-Print: 0711.4645 [hep-ph]

pdf DOI cite claim reference search 127 citations

Strong decays of heavy-light mesons in a chiral quark model #6

Xian-hui Zhong (Beijing, Inst. High Energy Phys.), Qiang Zhao (Beijing, Inst. High Energy Phys. and Surrey U.) (Mar, 2008)

Published in: *Phys.Rev.D* 78 (2008) 014029 • e-Print: 0803.2102 [hep-ph]

pdf DOI cite claim reference search 112 citations

- ✓ **Strong decay properties can be well understood within chiral quark model.**
- ✓ **Most of the predictions are consistent with the observations.**

JP assignments for Ωc(X) are consistent with LHC observations

LHCb ('21) has performed spin analysis based on distribution of helicity angle in the decay $\Omega_b^- \to \Omega_c^{**0}\pi^-$ followed by $\Omega_c^{**0} \to \Xi_c^+ K^-$

	$\Omega_c(3000)^0$	$\Omega_c(3050)^0$	$\Omega_c(3065)^0$	$\Omega_c(3090)^0$	$\Omega_c(3120)^0$
Agaev *et al.*	$1/2^-$	$3/2^-$	$1/2^+$	$1/2^+$	$3/2^+$
Aliev *et al.*	$1/2^-$		$3/2^-$		
B. Chen, X. Liu	$1/2^-$	$3/2^-$	$5/2^-$	$1/2^-$	$3/2^-$
H. Chen *et al.*	$1/2^-$	$1/2^-$	$1/2^-$ or $1/2^+$		$3/2^+$
Cheng, Chiang	$1/2^-$	$3/2^-$	$5/2^-$	$1/2^+$	$3/2^+$
Faustov, Galkin	$3/2^-$	$5/2^-$	$3/2^-$	$1/2^+$	$3/2^+$
Huang *et al.*					$1/2^-$
Jia *et al.*	$1/2^-$	$1/2^-$	$3/2^-$	$3/2^-$	$5/2^-$
Karliner, Rosner : (i)	$1/2^-$	$1/2^-$	$3/2^-$	$3/2^-$	$5/2^-$
(ii)	$3/2^-$	$3/2^-$	$5/2^-$	$1/2^+$	$3/2^+$
Padmanath *et al.*	$1/2^-$	$1/2^-$	$3/2^-$	$3/2^-$	$5/2^-$
Santopinto *et al.*	$1/2^-$	$3/2^-$	$1/2^-$	$3/2^-$	$5/2^-$
K. Wang *et al.*	$1/2^-$	$3/2^-$	$3/2^-$	$5/2^-$	$1/2^+$ or $3/2^+$
W. Wang, R.L. Zhu	$1/2^-$	$1/2^-$	$3/2^-$	$3/2^-$	$5/2^-$
Z. Wang	$1/2^-$	$1/2^-$	$3/2^-$	$3/2^-$	$5/2^-$
Z. Wang *et al.*	$1/2^-$			$3/2^-$ or $1/2^+$	$3/2^+$
Yang, H. Chen	$1/2^-$ or $3/2^-$	$1/2^-$	$3/2^-$	$3/2^-$	$5/2^-$
Z. Zhao *et al.*: (i)	$1/2^+$	$5/2^+$	$3/2^-$	$3/2^-$	$5/2^+$
(ii)	$3/2^+$	$7/2^+$	$5/2^-$	$5/2^-$	$7/2^+$

- **Hypothesis of J=1/2, 1/2, 3/2, 3/2 is rejected by 3.5σ**
- **Spin assignment of four observed peaks is consistent with λ-mode excitations with J=1/2, 3/2, 3/2, 5/2**

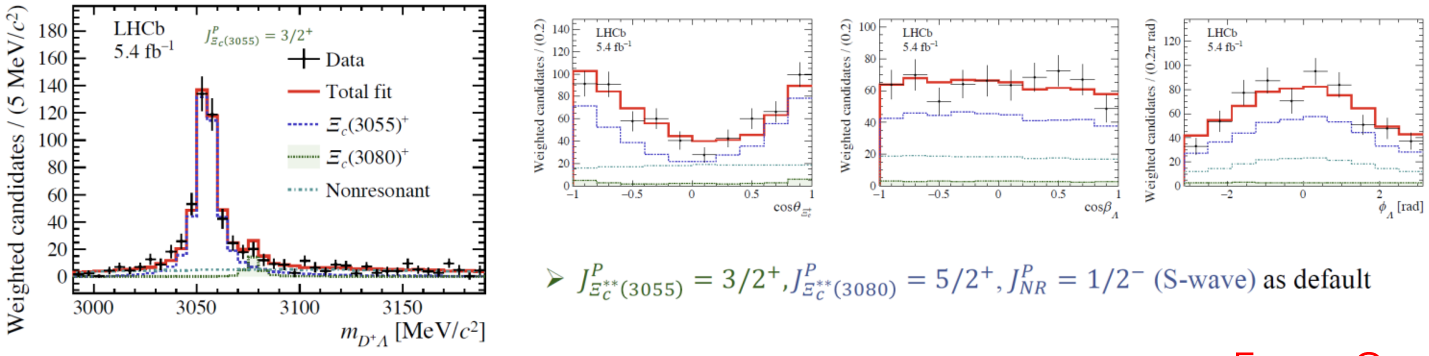
$$J^P[\Omega_c(3000)^0] = 1/2^-, \qquad J^P[\Omega_c(3050)^0] = 3/2^-$$
$$J^P[\Omega_c(3065)^0] = 3/2^-, \qquad J^P[\Omega_c(3090)^0] = 5/2^-$$

From Hai-Yang Cheng's report

JP=3/2+ for Ξc(3055) is consistent with the LHCb observation

Run2, $\Xi_b^0 \to \Xi_c^{**+}\pi^-$ channe

Best fit projections: $J^P_{\Xi_c^{**}(3055)} = 3/2^+$



arXiv:2409.05440

➢ $J^P_{\Xi_c^{**}(3055)} = 3/2^+, J^P_{\Xi_c^{**}(3080)} = 5/2^+, J^P_{NR} = 1/2^-$ (S-wave) as default

From Guanyue Wan's report

Theoretical interpretations of $\Xi_c(3055)$

References	Theoretical model	J^P of $\Xi_c(3055)$
Eur. Phys. J. A 37 (2008) 217–225	Faddeev method	$5/2^+$ (1D)
Phys. Rev. D 78 (2008) 056005	Regge phenomenology	$5/2^+$ (1D)
Phys. Rev. D 84 (2011) 014025	QCD-motivated relativistic quark model	$3/2^+$ (1D)
Phys. Rev. D 86 (2012) 034024	Chiral quark model	$3/2^+$ (1D)
Eur. Phys. J. A 82 (2015) 51	Relativistic flux tube model	$3/2^+$ (1D)
Phys. Rev. D 94 (2016) 114016	QCD sum rules within HQET	$3/2^+$ (1D)
Phys. Rev. D 96 (2017) 114003	3P0 model	$1/2^+(\bar{3}_F), 3/2^+(6_F)$ (2S)
Eur. Phys. J. C 79 (2019)167	Hadron molecular state	$1/2^-$, $3/2^-$ (molecular)

Part II

Mass spectrum with chiral dynamics

Potential model based on OGE: a widely used model

$$H_0 = \sum_{i=1}^{3}\sqrt{\boldsymbol{p}_i^2+m_i^2}+\sum_{i<j}^{3}(V_{ij}+C_{ij}),$$

$$V_{ij} = V_{ij}^{Conf} + V_{ij}^{OGE}$$

$$V^{Conf} = \sum_{i<j}^{3} -\frac{3}{16}(\boldsymbol{\lambda}_i\cdot\boldsymbol{\lambda}_j)b_{ij}r_{ij}.$$

$$V^{OGE} = \sum_{i<j}\left(V_{ij}^{Coul}+V_{ij}^{sd}\right),$$

$$V_{ij}^{Coul} = \sum_{i<j} -\frac{2\alpha_{ij}}{3}\frac{1}{r_{ij}},$$

Spin-dependent potential of OGE:

$$V_{ij}^{ss} = -\frac{\alpha_{ij}}{4}(\boldsymbol{\lambda_i}\cdot\boldsymbol{\lambda_j})\left\{\frac{\pi}{2}\cdot\frac{\sigma_{ij}^3 e^{-\sigma_{ij}^2 r_{ij}^2}}{\pi^{\frac{3}{2}}}\cdot\frac{16}{3m_i m_j}(\boldsymbol{S_i}\cdot\boldsymbol{S_j})\right\},$$

$$V_{ij}^{T} = -\frac{\alpha_{ij}}{4}(\boldsymbol{\lambda_i}\cdot\boldsymbol{\lambda_j})\frac{1}{m_i m_j r_{ij}^3}\left\{\frac{3(\boldsymbol{S_i}\cdot\boldsymbol{r_{ij}})(\boldsymbol{S_j}\cdot\boldsymbol{r_{ij}})}{r_{ij}^2}-\boldsymbol{S_i}\cdot\boldsymbol{S_j}\right\},$$

$$V_{ij}^{so(\nu)} = \sum_{i<j}\frac{1}{r_{ij}}\frac{dV_{ij}^{Coul}}{dr_{ij}}\left(\frac{\boldsymbol{r}_{ij}\times\boldsymbol{p}_i\cdot\boldsymbol{S}_i}{2m_i^2}-\frac{\boldsymbol{r}_{ij}\times\boldsymbol{p}_j\cdot\boldsymbol{S}_j}{2m_j^2}\right.$$
$$\left.-\frac{\boldsymbol{r}_{ij}\times\boldsymbol{p}_j\cdot\boldsymbol{S}_i-\boldsymbol{r}_{ij}\times\boldsymbol{p}_i\cdot\boldsymbol{S}_j}{m_i m_j}\right),$$

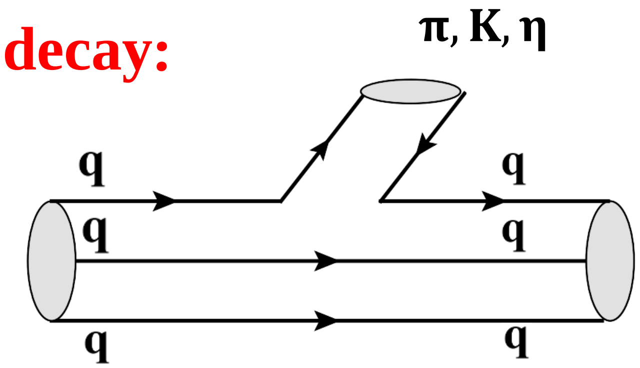
$$V_{ij}^{so(TP)} = \sum_{i<j} -\frac{1}{r_{ij}}\frac{\partial V_{ij}^{Conf}}{\partial r_{ij}}\left(\frac{\boldsymbol{r}_{ij}\times\boldsymbol{p}_i\cdot\boldsymbol{S}_i}{2m_i^2}-\frac{\boldsymbol{r}_{ij}\times\boldsymbol{p}_j\cdot\boldsymbol{S}_j}{2m_j^2}\right).$$

The role of chiral dynamics in mass spectrum

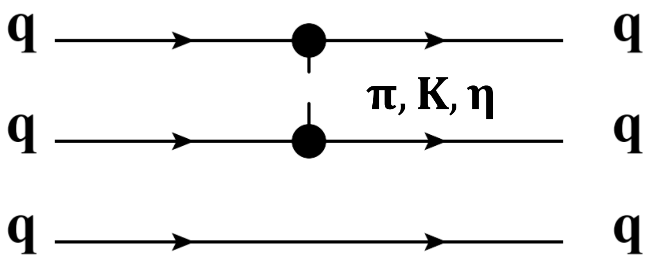
Chiral Lagrangian:

$$\mathcal{L}_{ps} = \frac{\delta}{\sqrt{2}f_{\mathbb{M}}}\bar{\psi}_j\gamma_\mu\gamma_5\psi_j\vec{I}\cdot\partial^\mu\vec{\phi}_{\mathbb{M}},$$

strong decay:



mass spectrum:



$$H_I = \mathcal{H}^{NR} + \mathcal{H}^{RC},$$

$$\mathcal{H}^{NR} = g\sum_j\left(\mathcal{G}\boldsymbol{\sigma}_j\cdot\boldsymbol{q} + \frac{\omega_{\mathbb{M}}}{2\mu_q}\boldsymbol{\sigma}_j\cdot\boldsymbol{p}_j\right)F(\boldsymbol{q}^2)I_j\varphi_{\mathbb{M}},$$

$$\mathcal{H}^{RC} = -\frac{g}{32\mu_q^2}\sum_j[m_{\mathbb{M}}^2(\boldsymbol{\sigma}_j\cdot\boldsymbol{q})$$

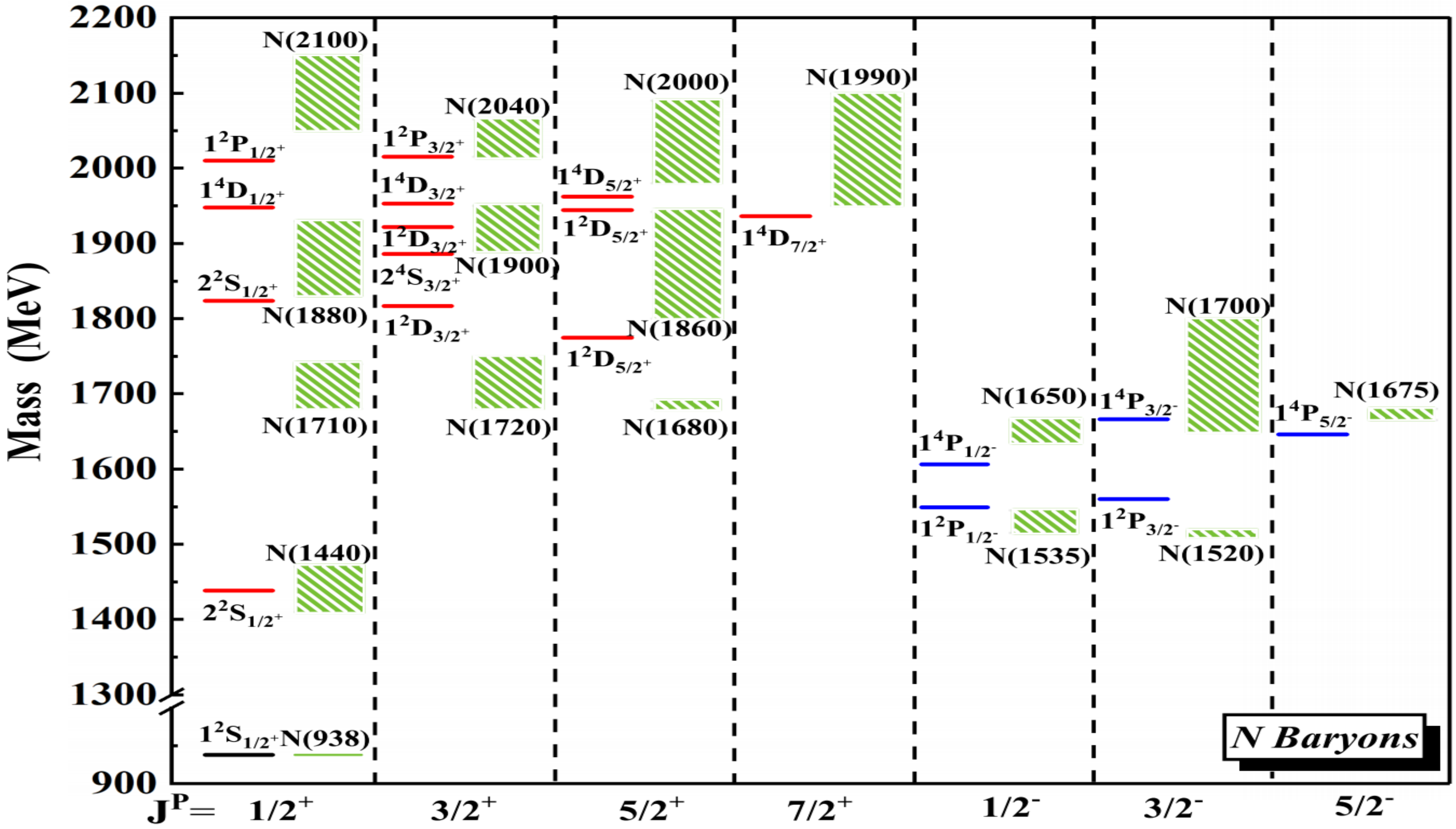
$$+2\boldsymbol{\sigma}_j\cdot(\boldsymbol{q}-2\boldsymbol{p}_j)\times(\boldsymbol{q}\times\boldsymbol{p}_j)]F(\boldsymbol{q}^2)I_j\varphi_{\mathbb{M}}$$

$$V_{OBE}^C(r_{ij}) = V_\pi^C(r_{ij}) + V_K^C(r_{ij}) + V_\eta^C(r_{ij}).$$

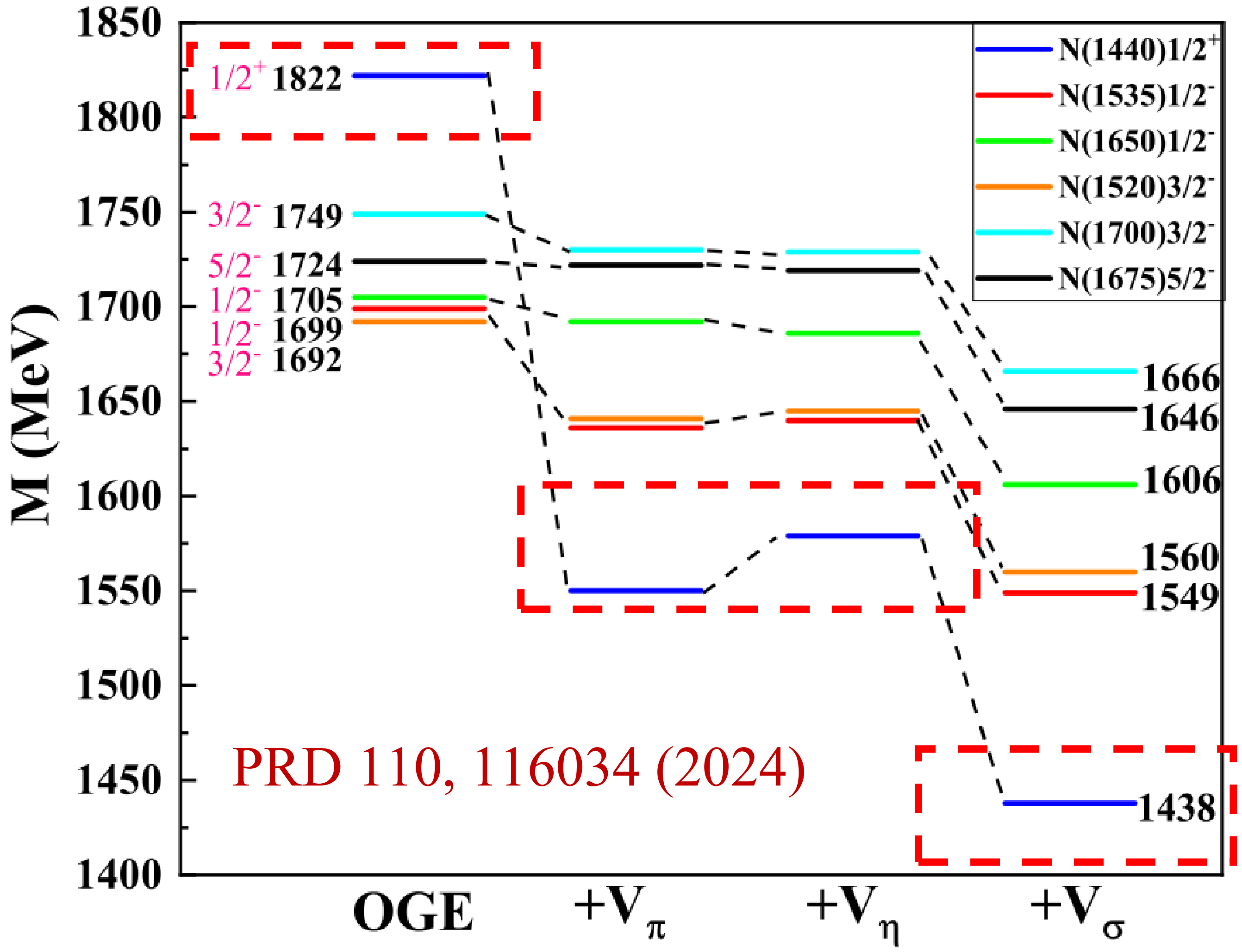
$$V_{OBE}^T(r_{ij}) = V_\pi^T(r_{ij}) + V_K^T(r_{ij}) + V_\eta^T(r_{ij}),$$

Nucleon spectrum

H.H. Zhong et al., PRD 110, 116034 (2024)



Mass inversion mechanism of $N(1440)$

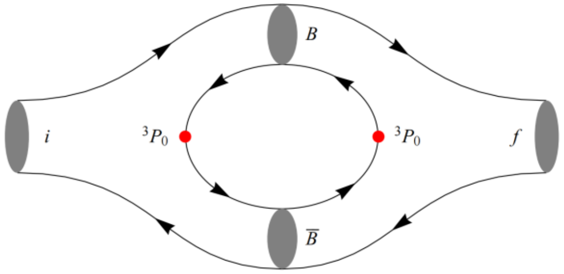


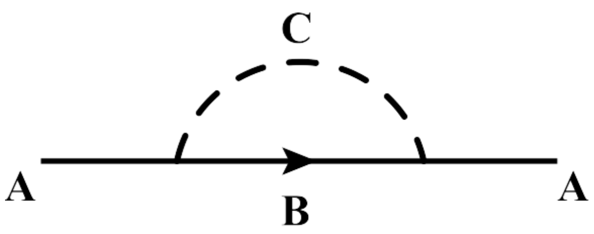
The OBE (pion exchange) palys a crucial role: the mass shift down ~ 500 MeV.

For light quark systems, we may need OGE+OBE! More evidences need to be found.

Coupled channel effects with chiral dynamics

PRD 109, 116006 (2024)





$$|\Psi\rangle = c_A|A\rangle + \sum_{BC}\int c_{BC}(\mathbf{p})d^3\mathbf{p}|BC,\mathbf{p}\rangle,$$

$$\begin{pmatrix} H_0 & H_I \\ H_I & H_c \end{pmatrix}\begin{pmatrix} c_A|A\rangle \\ \sum_{BC}\int c_{BC}(\mathbf{p})d^3\mathbf{p}|BC,\mathbf{p}\rangle \end{pmatrix} = M\begin{pmatrix} c_A|A\rangle \\ \sum_{BC}\int c_{BC}(\mathbf{p})d^3\mathbf{p}|BC,\mathbf{p}\rangle \end{pmatrix},$$

$$\mathcal{H} = \mathcal{H}_0 + \mathcal{H}_c + \mathcal{H}_I.$$

Potential model

chiral dynamics

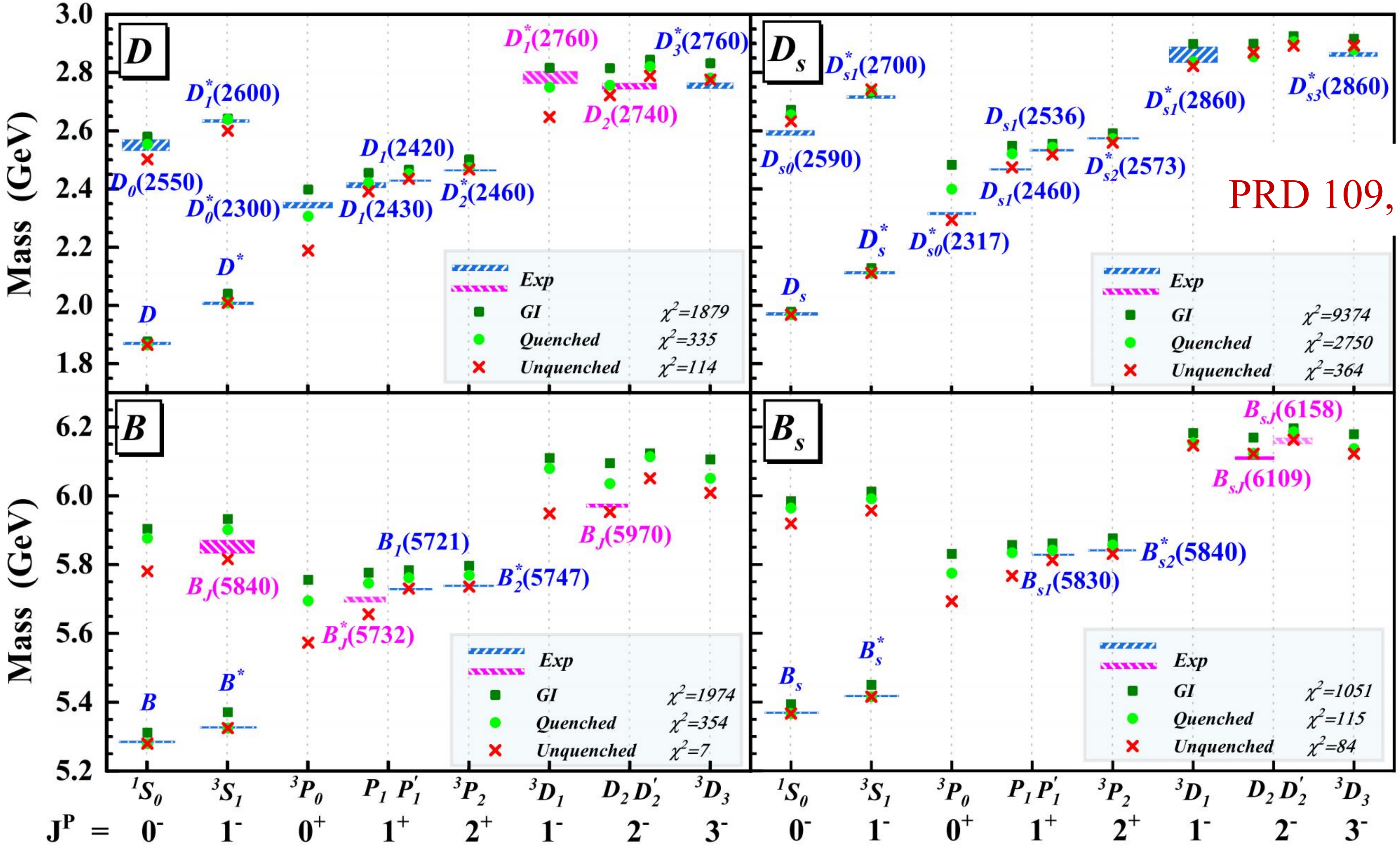
$$M = M_A + \Delta M(M)$$

$$\mathcal{H}_I^{NR} = g\sum_j\left[\mathcal{G}\boldsymbol{\sigma}_j\cdot\boldsymbol{q} + \frac{\omega_m}{2\mu_q}(\boldsymbol{\sigma}_j\cdot\boldsymbol{p}_j)\right]I_j\varphi_m,$$

$$\mathcal{H}_I^{RC} = -\frac{g}{32\mu_q^2}\sum_j[m_{\mathbb{P}}^2(\boldsymbol{\sigma}_j\cdot\boldsymbol{q}) + 2\boldsymbol{\sigma}_j\cdot(\boldsymbol{q}-2\boldsymbol{p}_j)\times(\boldsymbol{q}\times\boldsymbol{p}_j)]I_j\varphi_m.$$

$$\Delta M(M) = \mathrm{Re}\sum_{BC}\int_0^\infty \frac{|\langle BC,\mathbf{p}|H_I|A\rangle|^2}{(M-E_{BC})}p^2dpd\Omega_p, = \mathrm{Re}\sum_{BC}\int_0^\infty \frac{\overline{|\mathcal{M}_{A\to BC}(\mathbf{p})|^2}}{(M-E_{BC})}p^2dp.$$

Heavy–light meson spectrum with coupled channel effects



PRD 109, 116006 (2024)

The spectra are **largely improved by including coupled effects** with chiral dynamics

Part III

Production processes with chiral dynamics

Pseudoscalar meson photoproduction process: model

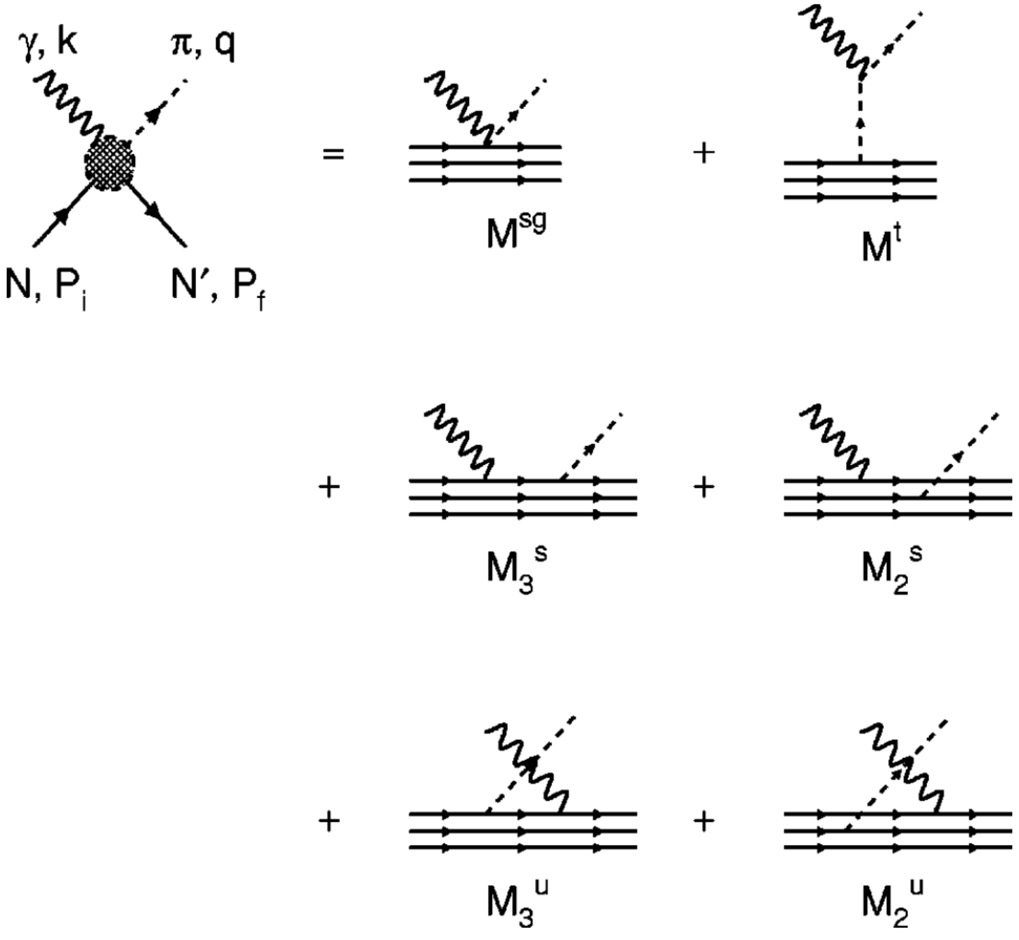


FIG. 1. Tree level diagrams calculated in this model.

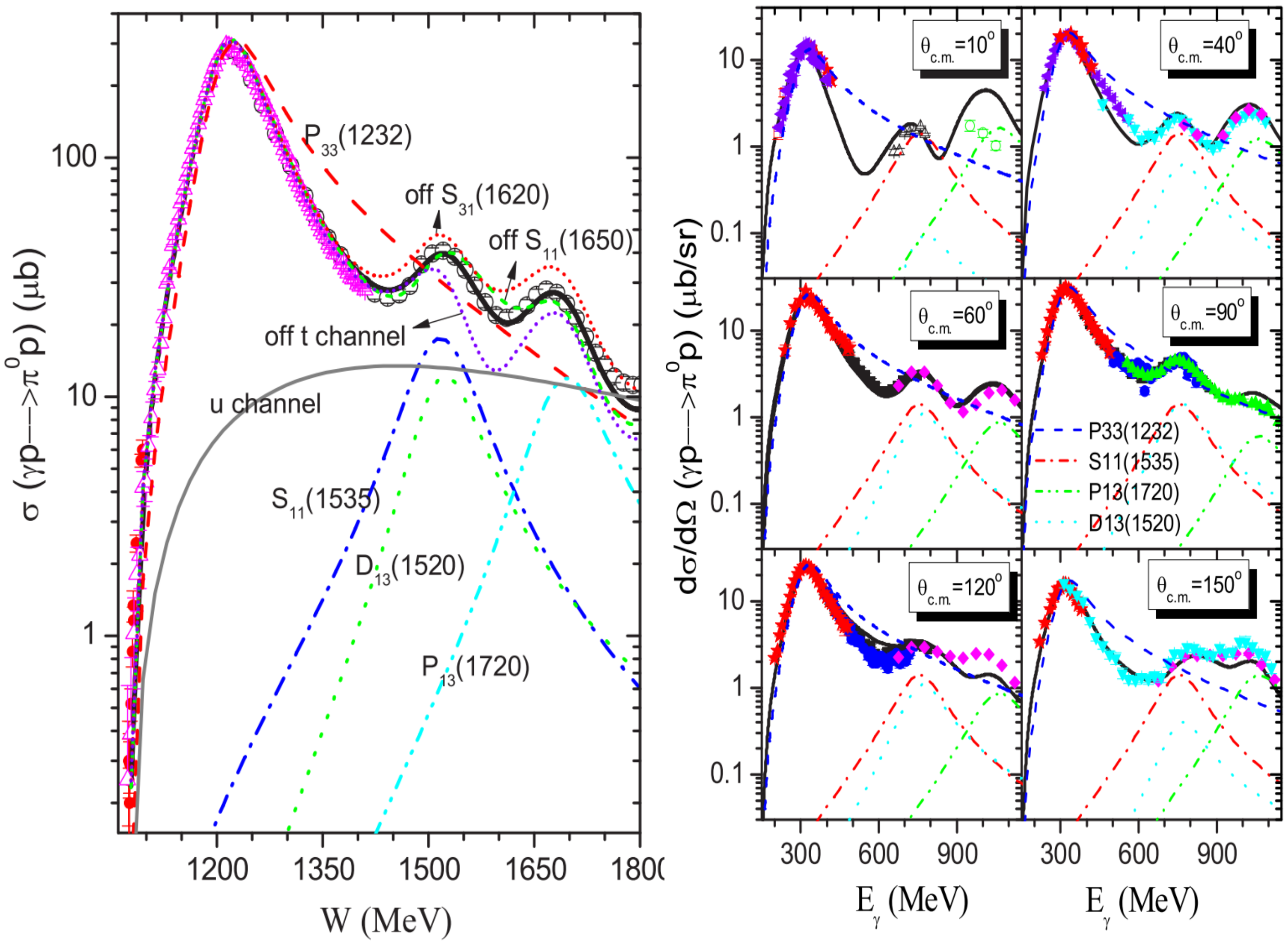
$$H_m = \sum_j \frac{1}{f_m} \overline{\psi_j} \gamma_\mu^j \gamma_5^j \psi_j \partial^\mu \phi_m ,$$

$$H_e = -\sum_j e_j \gamma_\mu^j A^\mu(\mathbf{k}, \mathbf{r}),$$

$$H_{m,e} = \sum_j \frac{e_m}{f_m} \phi_m(\mathbf{q}, \mathbf{r}_j) \overline{\psi_j} \gamma_\mu^j \gamma_5^j \psi_j A^\mu(\mathbf{k}, \mathbf{r}_j)$$

Qiang Zhao et al, PRC 65, 065204 (2002)

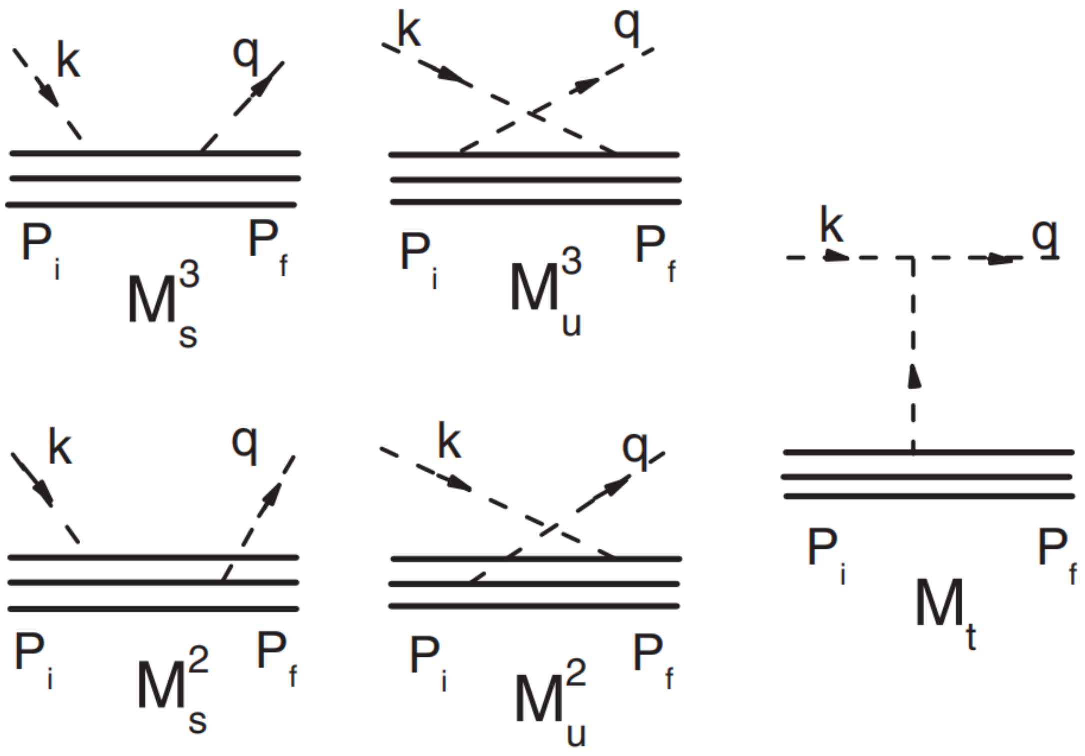
pion0 photoproduction within chiral quark model



- ✓ Can well explain the scattering data in the resonance region.
- ✓ Can reasonably understand the roles of the nucleon excitations.
- ✓ Less parameters
- ✓ Quark level

Li−Ye Xiao, Xu Cao, XH, PRC 92, 035202 (2015)

Pseudoscalar meson-baryon scattering



$$H_m = \sum_j \frac{1}{f_m} \overline{\psi_j} \gamma_\mu^j \gamma_5^j \psi_j \partial^\mu \phi_m \,,$$

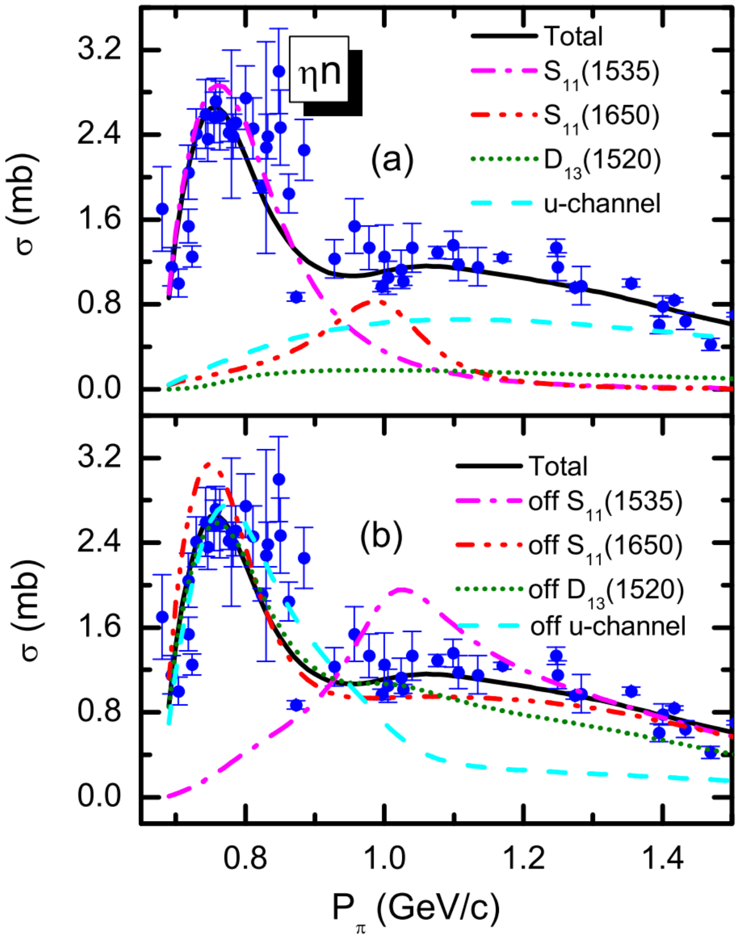
XH, Qiang Zhao et al,

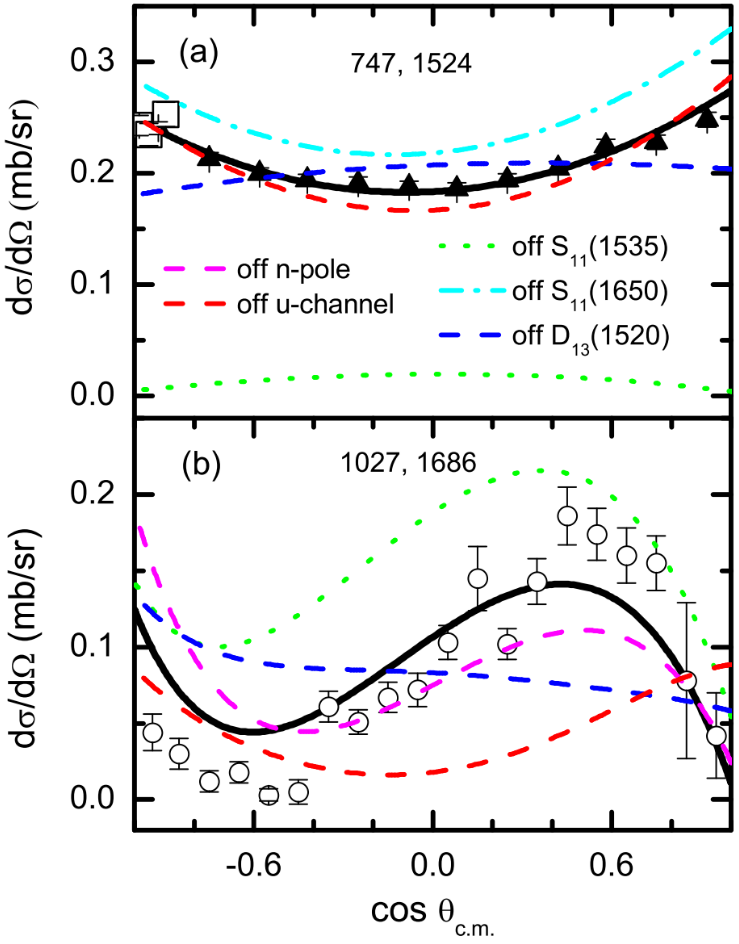
PRC76, 065205 (2007)

PRC 88, 015208 (2013)

PRC94, 035202 (2016)

eta production with πN scattering within chiral quark model





- ✓ Giving a clear picture for the reaction process.
- ✓ Can reasonably understand the roles of the nucleon excitations.
- ✓ Less parameters
- ✓ Quark level

Li−Ye Xiao et al, PRC 94, 035202 (2016)

Summary

» **Chiral dynamics plays crucial roles in hadrons.**

» **Hadron masses, strong decays, scattering processes, …, are related to chiral dynamics**

» **More and further studies with chiral dynamics are carrying out.**

Thanks