Theoretical study of $N(1535)$ and $\Sigma^*(1/2^-)$ in the Cabibbo-favored process $\Lambda_c^+ \to p\bar{K}^0\eta$

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Background

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- **Low-lying excited baryons with quantum numbers $J^P = 1/2^-$**

$N(1535)$ $J^P = 1/2^-$

- Mass reverse problem

$M_{N(1535)} > M_{N(1440)}$ experimental measurement

$J^P = 1/2^- < J^P = 1/2^+$ constituent quark model

- The strong coupling to channels with strangeness

$N(1535)$ uud $\Leftrightarrow$ ηN $K\Lambda$ $K\Sigma$

- **Theoretical explanations of the $N(1535)$**
  - Pentaquark component:
    PRL96,042002(2006) EPJA35,325(2008)
  - Three-quark core:
    PRD108,094519(2023) PRL116,082004(2016)
  - Dynamically generated state:
    PRD 96,054009 (2017) PRC 98,015201(2018)

- Dynamically generated state:

E. J. Garzon and E. Oset PHYSICAL REVIEW C 91, 025201 (2015)

TABLE IV. Results for the pole position and branching ratios for the different channels of $N^*(1535)J^P = 1/2^-$ and comparison with experimental results.

$N^*(1535)J^P = 1/2^-$	Theory	PDG [34]	Arndt [1]	Cutkosky [35]	Anisovich [24]	Vrana [26]	Thoma [25]
Re(Pole)	1508.1	1490–1530	1502				
2Im(Pole)	90.3	90–250	95				
Channel							
$N\pi(1077)$	58.6	35–55	35.5 ± 0.2				
$N\eta(1487)$	37.0	42 ± 10					
$\Lambda K(1609)$	0.0						
$\Sigma K(1683)$	0.0						
$N\rho(1714)$	1.0	2 ± 1					
$\Delta\pi(1370)$	3.3	0–4					

TABLE III. Coupling constants and decay widths of $N^*(1535)$.

	$K^+\Sigma^-$	$K^0\Sigma^0$	$K^0\Lambda$	π^-p	$\pi^0 n$	ηn	$\pi^0\pi^-p$	$\pi^+\pi^-n$
$\lvert g_i \rvert$	2.12	1.50	0.92	0.56	0.39	1.84	$0.57\ m_\pi^{-2}$	$0.40\ m_\pi^{-2}$
Γ_i (MeV)				14.1	7.0	65.7	4.6	2.4
Branching ratio (%)				15.0	7.4	70.1	4.9	2.5
g_i	−2.36	1.67	−1.28	−0.57	0.39	1.77	$-0.61\ m_\pi^{-2}$	$-0.43\ m_\pi^{-2}$
Γ_i (MeV)				15.0	7.1	60.8	5.4	2.6
Branching ratio (%)				16.5	7.8	66.9	5.9	2.9

T. Inoue, E. Oset, and M. J. Vicente Vacas PHYSICAL REVIEW C, VOLUME 65, 035204

Motivation

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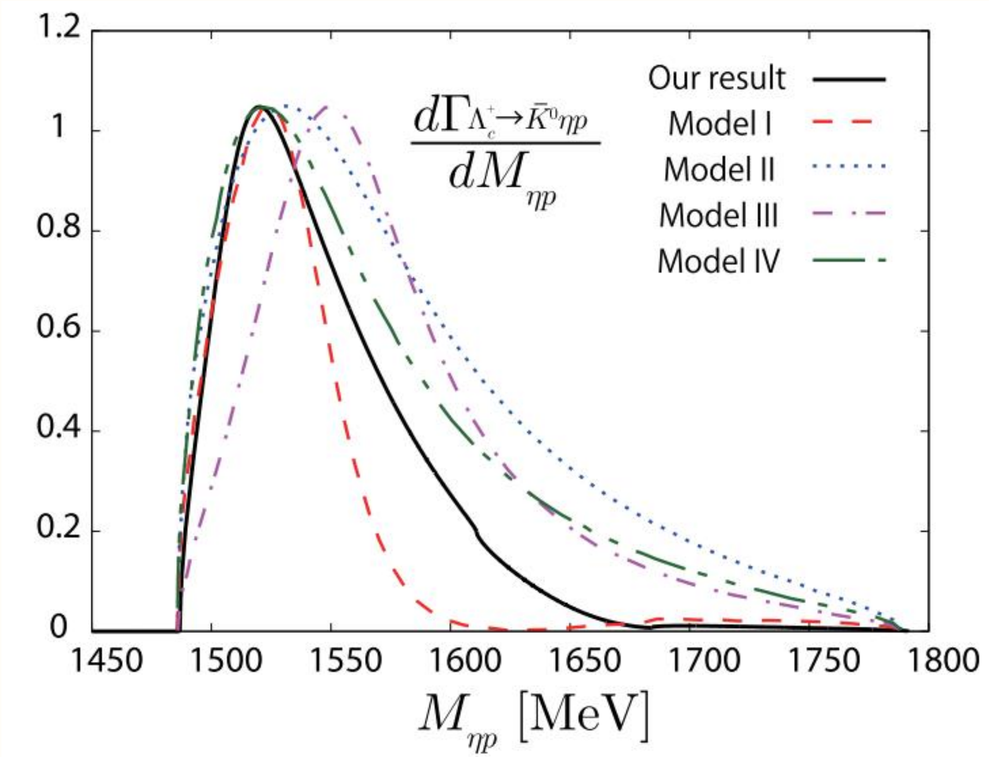
➢ Studying light hadrons in the Λ_c^+ decays

- Experiment: Λ_c^+ decays

Hadronic decay	
$\Lambda_c^+ \to pK^-\pi^+$ + 11 CF modes	PRL116(2016)052001
$\Lambda_c^+ \to pK^+K^-, p\pi^+\pi^-$	PRL117(2017)232002
$\Lambda_c^+ \to nK_S^0\pi^+$	PRL118(2017)112001
$\Lambda_c^+ \to p\eta, p\pi^0$	PRD95(2017)111102(R)
$\Lambda_c^+ \to \Sigma^-\pi^+\pi^+\pi^0$	PLB772(2017)388
$\Lambda_c^+ \to \Xi^{0(*)}K^+$	PLB783(2018)200
$\Lambda_c^+ \to \Lambda\eta\pi^+$	PRD99(2019)032010
$\Lambda_c^+ \to \Sigma^+\eta, \Sigma^+\eta'$	CPC43(2019)083002
$\Lambda_c^+ \to$ BP decay asymmetries	PRD100(2019)07200
$\Lambda_c^+ \to pK_S\eta$	PLB817(2021)136327
Semi-leptonic decay	
$\Lambda_c^+ \to \Lambda e^+\nu_e$	PRL115(2015)221805
$\Lambda_c^+ \to \Lambda\mu^+\nu_\mu$	PLB767(2017)42
Inclusive decay	
$\Lambda_c^+ \to \Lambda X$	PRL121(2018)062003
$\Lambda_c^+ \to e^+X$	PRL121(2018)251801
$\Lambda_c^+ \to K_S^0X$	EPJC80(2020)935
Production	
$\Lambda_c^+\Lambda_c^-$ cross section	PRL120(2018)132001

Hai-Bo-Li-slide-zhengzhou-_2024_IHEP

- Theoretical: the process $\Lambda_c^+ \to p\bar{K}^0\eta$

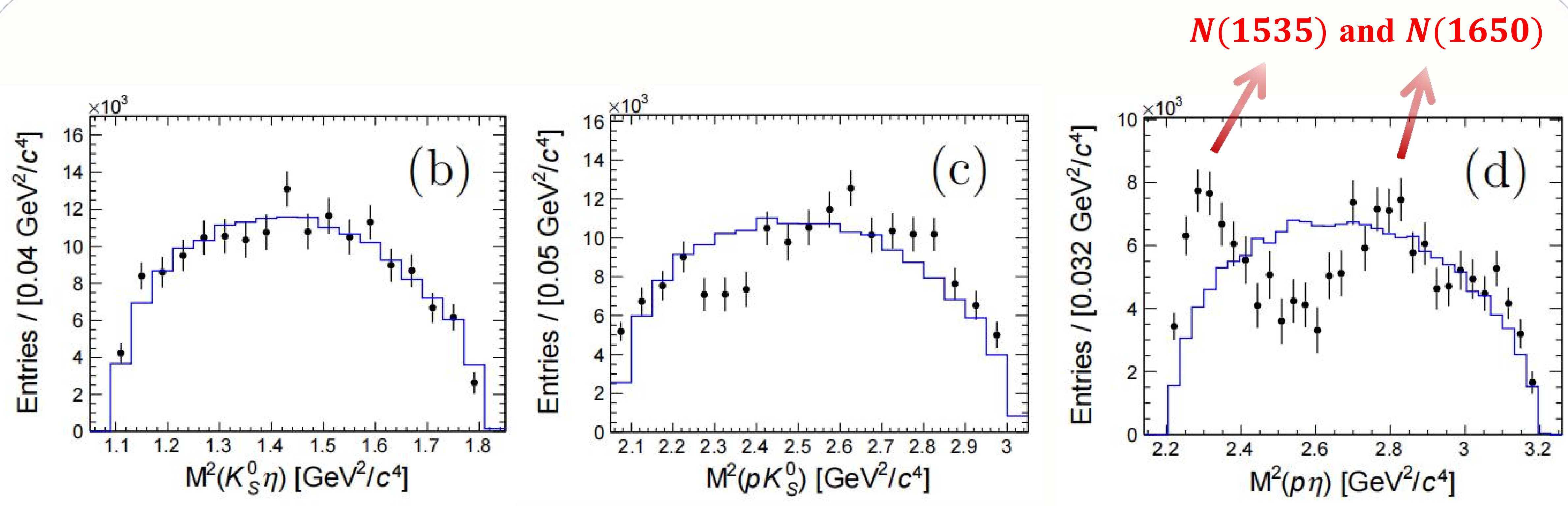


R. Pavao and E. Oset Phys Rev C 98, 015201 (2018)

Motivation

- **The process $\Lambda_c^+ \to p\bar{K}^0\eta$**

- Belle $\mathcal{B}(\Lambda_c^+ \to pK_S^0\eta) = (4.35 \pm 0.10 \pm 0.20 \pm 0.22) \times 10^{-3}$



L. K. Li et al. [Belle], Phys. Rev. D 107 (2023) no.3, 032004

Mechanism of the $\Lambda_c^+ \to p\bar{K}^0\eta$

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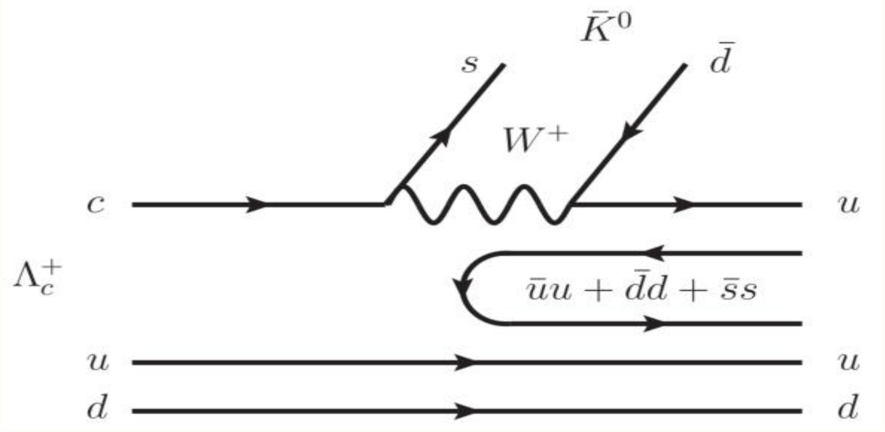
- **$N(1535)$ ---**
  S-wave meson-baryon interaction

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

$$B = \begin{pmatrix} \frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} + \frac{\Lambda_1}{\sqrt{3}} & \Sigma^+ & p \\ \Sigma^- & -\frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} + \frac{\Lambda_1}{\sqrt{3}} & n \\ \Xi^- & \Xi^0 & -\frac{2\Lambda}{\sqrt{6}} + \frac{\Lambda_1}{\sqrt{3}} \end{pmatrix}$$

M, B are the SU(3) pseudoscalar and baryon matrices



The quark-level diagram

$$|MB\rangle = u|(\bar{u}u + \bar{d}d + \bar{s}s)\frac{1}{\sqrt{2}}(ud - du)\rangle$$

$$= \frac{\sqrt{2}}{2}|\pi^0 p\rangle + \frac{\sqrt{3}}{3}|\eta p\rangle + |\pi^+ n\rangle - \frac{\sqrt{6}}{3}|K^+\Lambda\rangle$$

$$\Rightarrow I = \frac{1}{2}$$

isospin triplet $(-\pi^+, \pi^0, \pi^-)$

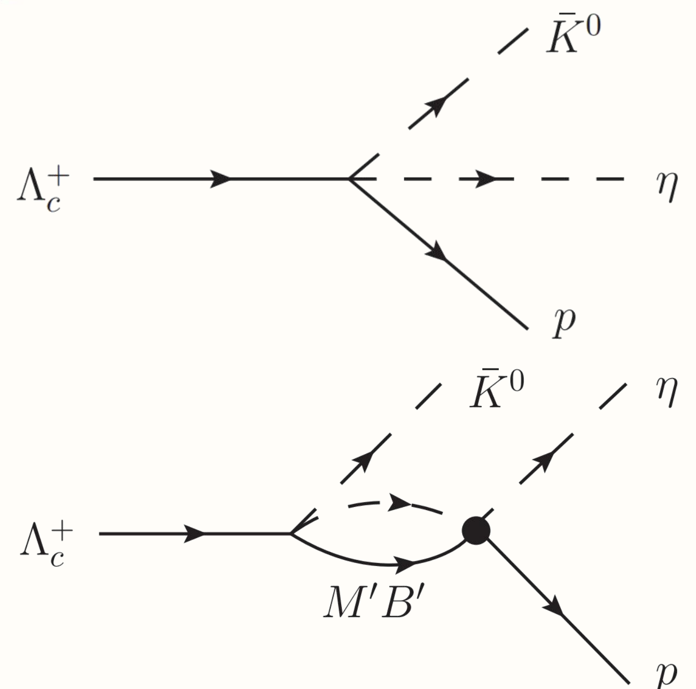
isospin doublet (p, n)

$$= -\frac{\sqrt{6}}{2}|\pi N\rangle + \frac{\sqrt{3}}{3}|\eta N\rangle - \frac{\sqrt{6}}{3}|K\Lambda\rangle$$

Mechanism of the $\Lambda_c^+ \to p\bar{K}^0\eta$

- $N(1535)$ ---

  S-wave meson-baryon interaction



The hadronic-level diagram

- $|MB\rangle = -\frac{\sqrt{6}}{2}|\pi N\rangle + \frac{\sqrt{3}}{3}|\eta N\rangle - \frac{\sqrt{6}}{3}|K\Lambda\rangle$

$$T^{N(1535)} = V_1(h_{\eta N} + h_{\eta N}G_{\eta N}t_{\eta N\to\eta N} + h_{\pi N}G_{\pi N}t_{\pi N\to\eta N} + h_{K\Lambda}G_{K\Lambda}t_{K\Lambda\to\eta N})$$

- $T = [1 - VG]^{-1}V$
- $V_{ij}(s) = -C_{ij}\frac{1}{4f^2}(2\sqrt{s} - M_i - M_j) \times (\frac{M_i+E_i}{2M_i})^{1/2}(\frac{M_j+E_j}{2M_j})^{1/2}$
- $G(s) = \frac{2M}{16\pi^2 s}\{\sigma(arctan\frac{s+\Delta}{\sigma\lambda_1} + arctan\frac{s-\Delta}{\sigma\lambda_2})$

$$-[(s+\Delta)ln\frac{(1+\lambda_1)q_{max}}{m_1}$$

$$+[(s-\Delta)ln\frac{(1+\lambda_2)q_{max}}{m_2}]\}$$

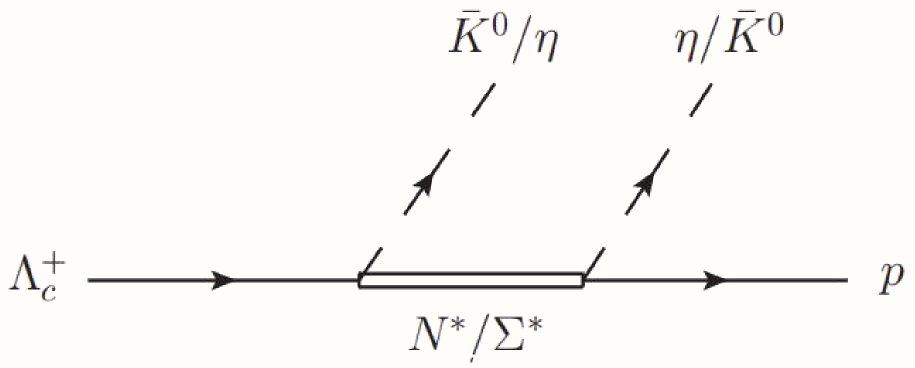
$q_{max} = 1150\text{MeV}$

PDG (pole): (1510, 55i)

Theoretical (pole): (1509, 34i)

Mechanism of the $\Lambda_c^+ \to p\bar{K}^0\eta$

- $N(1535)$ ---
  Breit-Wigner decay amplitude



Tree-level diagram accounting for the contribution from the intermediate $N(1535)$, $N(1650)$

$$\widetilde{T}^{N(1535)} = \frac{\widetilde{V}_1 M_{1535}\Gamma^0_{1535}}{S_{\eta p} - M^2_{1535} + iM_{1535}\Gamma_{1535}(s)}$$

$$\Gamma_{1535}(s) = \Gamma^0_{1535}\left(\frac{\rho_{\pi N}(s)}{2\rho_{\pi N}(M^2_{1535})} + \frac{\rho_{\eta N}(s)}{2\rho_{\eta N}(M^2_{1535})}\right)$$

$$\rho_{XN}(s) = \frac{2q_{XN}(s)}{\sqrt{s}}$$

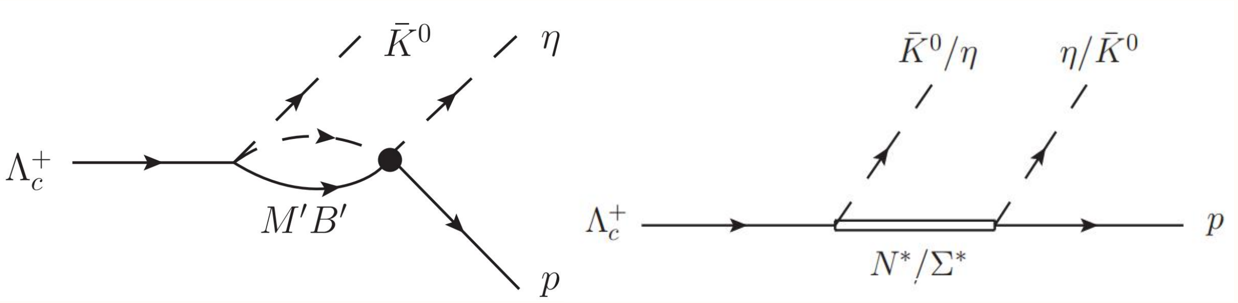
$$= \frac{\sqrt{(s-(M_N+M_X)^2)(s-(M_N-M_X)^2)}}{s}$$

$$M_{1535} = 1530\text{MeV}; \qquad \Gamma^0_{1535} = 150\text{MeV}$$

$$M_{1650} = 1650\text{MeV}; \qquad \Gamma_{1650} = 125\text{MeV}$$

$$T^{N(1650)} = \frac{V_2 M_{1650}\Gamma_{1650}}{S_{\eta p} - M^2_{1650} + iM_{1650}\Gamma_{1650}}$$

Mechanism of the $\Lambda_c^+ \to p\bar{K}^0\eta$



➢ **Double differential widths**

$$\frac{d^2\Gamma}{dM_{\eta p}^2 dM_{p\bar{K}^0}^2} = \frac{1}{(2\pi)^3}\frac{1}{32M_{\Lambda_c^+}^3}|T_{total}|^2$$

$$\frac{d^2\Gamma}{dM_{\eta p}^2 dM_{\eta\bar{K}^0}^2} = \frac{1}{(2\pi)^3}\frac{1}{32M_{\Lambda_c^+}^3}|T_{total}|^2$$

- $T^{N(1535)} = \mathrm{V_P} \sum_i \mathrm{h_i}\, \mathrm{G_i}\, \mathrm{t}_{i\to\eta p}$
- $\widetilde{T}^{N(1535)} = \frac{\widetilde{V}_1 M_{1535}\Gamma_{1535}^0}{S_{\eta p} - M_{1535}^2 + iM_{1535}\Gamma_{1535}(s)}$
- $T^{N(1650)} = \frac{V_2 M_{1650}\Gamma_{1650}}{S_{\eta p} - M_{1650}^2 + iM_{1650}\Gamma_{1650}}$

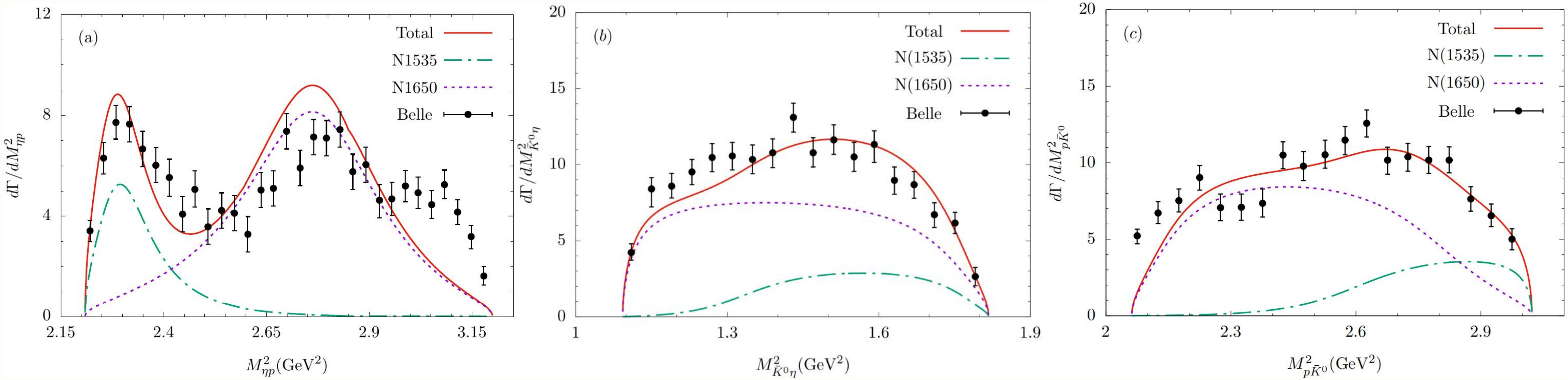
➢ Model A $|T^A| = |T^{N(1535)} + T^{N(1650)}e^{i\phi}|^2$

➢ Model B $|T^B| = |\widetilde{T}^{N(1535)} + T^{N(1650)}e^{i\phi}|^2$

Results

➢ **Model A** $|T^A| = |T^{N(1535)} + T^{N(1650)} e^{i\phi}|^2$

$$T^{N(1535)} = V_1(h_{\eta N} + h_{\eta N} G_{\eta N} t_{\eta N \to \eta N} + h_{\pi N} G_{\pi N} t_{\pi N \to \eta N} + h_{K\Lambda} G_{K\Lambda} t_{K\Lambda \to \eta N})$$



Parameters	$V_1(\widetilde{V}_1)$	V_2	V_3	ϕ	ϕ'	χ^2/d.o.f.
Model A	13939±895	43369±3227	---	(0.98±0.21)π	---	5.67

Results

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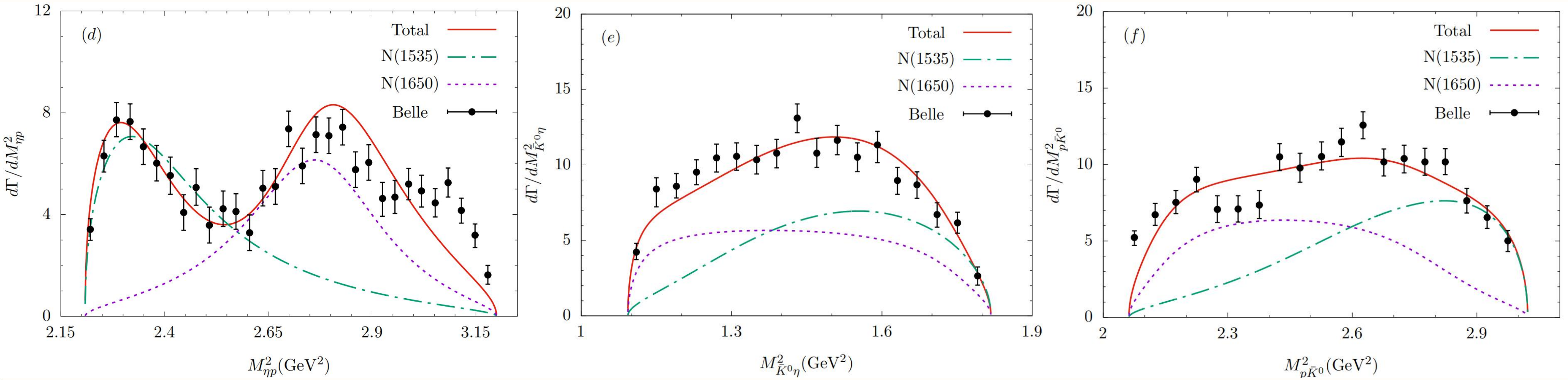
- **Model B** $|T^B| = |\widetilde{T}^{N(1535)} + T^{N(1650)} e^{i\phi}|^2$

$$\widetilde{T}^{N(1535)} = \frac{\widetilde{V}_1 M_{1535} \Gamma^0_{1535}}{S_{\eta p} - M^2_{1535} + i M_{1535} \Gamma_{1535}(s)}$$



Parameters	$V_1(\widetilde{V}_1)$	V_2	V_3	ϕ	ϕ'	χ^2/d.o.f.
Model B	45763±3421	37691±2817	---	$(0.805\pm0.158)\pi$	---	3.15

Mechanism of the $\Lambda_c^+ \to p\bar{K}^0\eta$

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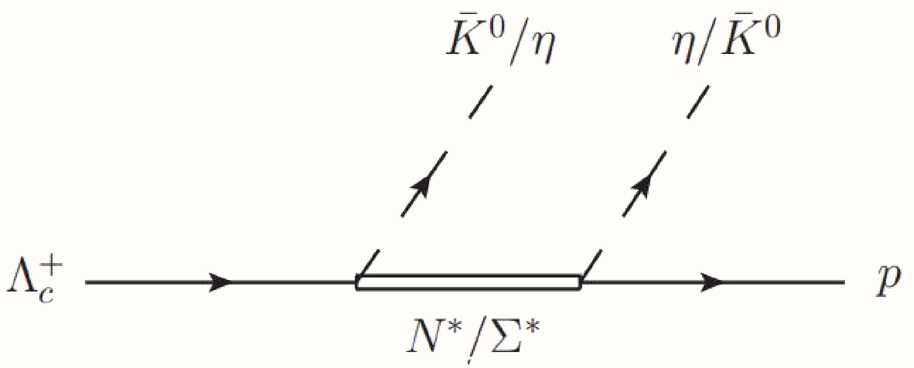
- $\Sigma^*(1/2^-)$ ---
  Breit-Wigner decay amplitude



Tree-level diagram accounting for the contribution from the intermediate $\Sigma^*(1/2^-)$

$$T^{\Sigma^*(1/2^-)} = \frac{V_3 M_{\Sigma^*(1/2^-)} \Gamma_{\Sigma^*(1/2^-)}}{S_{pK} - M^2_{\Sigma^*(1/2^-)} + iM_{\Sigma^*(1/2^-)}\Gamma_{\Sigma^*(1/2^-)}}$$

$$M_{\Sigma^*(1/2^-)} = 1380\text{MeV}; \quad \Gamma_{\Sigma^*(1/2^-)} = 120\text{MeV}$$

E. Wang, L. S. Geng, J. J. Wu, J. J. Xie, B. S. Zou arXiv:2406.07839

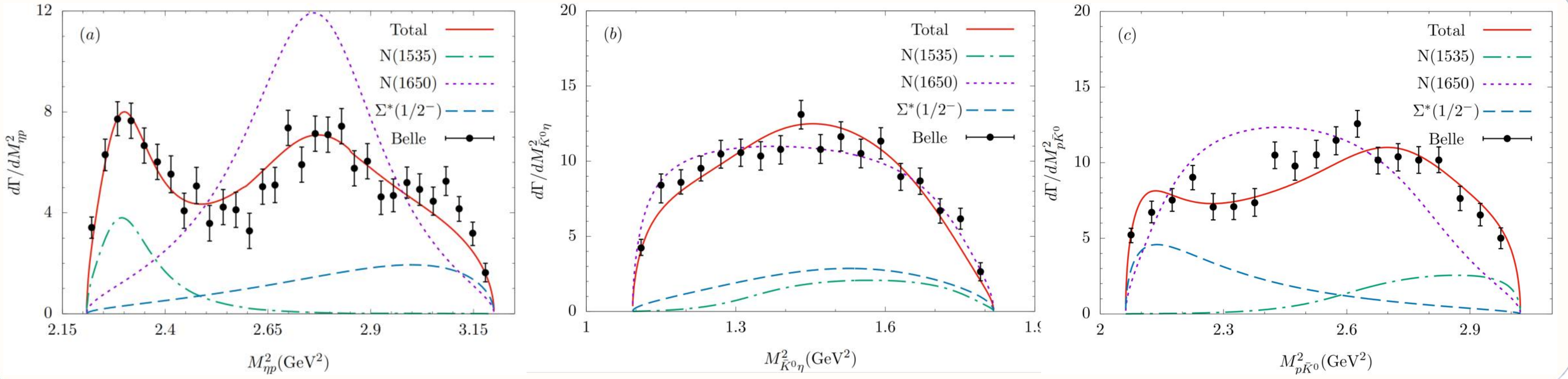
- Model A $|T^A| = |T^{N(1535)} + T^{N(1650)}e^{i\phi}|^2$
- Model B $|T^B| = |\widetilde{T}^{N(1535)} + T^{N(1650)}e^{i\phi}|^2$

- Model C $|T^C| = |T^{N(1535)} + T^{N(1650)}e^{i\phi} + T^{\Sigma^*(1/2^-)}e^{i\phi'}|^2$
- Model D $|T^D| = |\widetilde{T}^{N(1535)} + T^{N(1650)}e^{i\phi} + T^{\Sigma^*(1/2^-)}e^{i\phi'}|^2$

Results

$$T^{N(1535)} = V_1(h_{\eta N} + h_{\eta N} G_{\eta N} t_{\eta N \to \eta N} + h_{\pi N} G_{\pi N} t_{\pi N \to \eta N} + h_{K\Lambda} G_{K\Lambda} t_{K\Lambda \to \eta N})$$

- **Model C** $|T^C| = |T^{N(1535)} + T^{N(1650)} e^{i\phi} + T^{\Sigma^*(1/2^-)} e^{i\phi'}|^2$

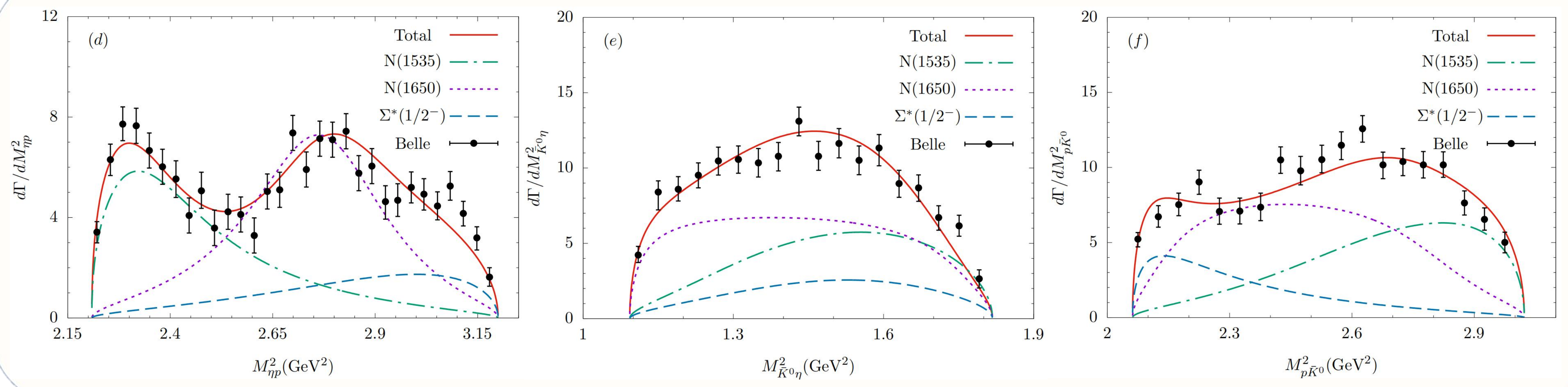


Parameters	$V_1(\tilde{V}_1)$	V_2	V_3	ϕ	ϕ'	χ^2/d.o.f.
Model C	11848±813	52495±3938	56230±4019	(1.35±0.43)π	(1.83±0.35)π	1.55

Results

➢ **Model D** $|T^D| = |\widetilde{T}^{N(1535)} + T^{N(1650)}e^{i\phi} + T^{\Sigma^*(1/2^-)}e^{i\phi'}|^2$

$$\widetilde{T}^{N(1535)} = \frac{\widetilde{V}_1 M_{1535}\Gamma^0_{1535}}{S_{\eta p} - M^2_{1535} + iM_{1535}\Gamma_{1535}(s)}$$



Parameters	$V_1(\widetilde{V}_1)$	V_2	V_3	ϕ	ϕ'	χ^2/d.o.f.
Model D	41614±2506	41026±2910	53264±3248	(1.049±0.309)π	(1.597±0.260)π	1.49

Summary

- In this work, we have investigated the process $\Lambda_c^+ \to p\bar{K}^0\eta$ by considering the contributions from the $N(1535)$, $N(1650)$, and $\Sigma^*(1/2^-)$.
- We have adopted two models for the contribution of the N(1535); one is the molecular picture and the other one is the Breit-Wigner form.
- The current experimental data cannot distinguish the two descriptions of $N(1535)$.
- The present experimental data support the existence of the $\Sigma^*(1/2^-)$.

Thank you very much!