



Role of the $N^(1535)$ in the $\Lambda_c^+ \rightarrow \bar{K}^0 \eta p$ decay
and possible ϕp state in the $\Lambda_c^+ \rightarrow \pi^0 \phi p$ decay*

Ju-Jun Xie

Institute of Modern Physics, CAS, Lanzhou, China

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Outline

Introduction

Our work:

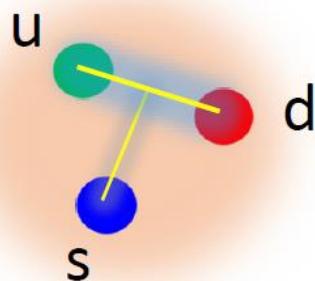
Study of $N^(1535)$ in the $\Lambda_c^+ \rightarrow \bar{K}^0 \eta p$ decay*

Possible ϕp state in $\Lambda_c^+ \rightarrow \pi^0 \phi p$ decay

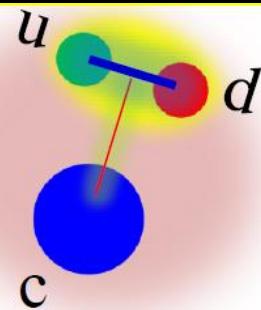
Summary

Λ_c^+

The lightest charmed baryon

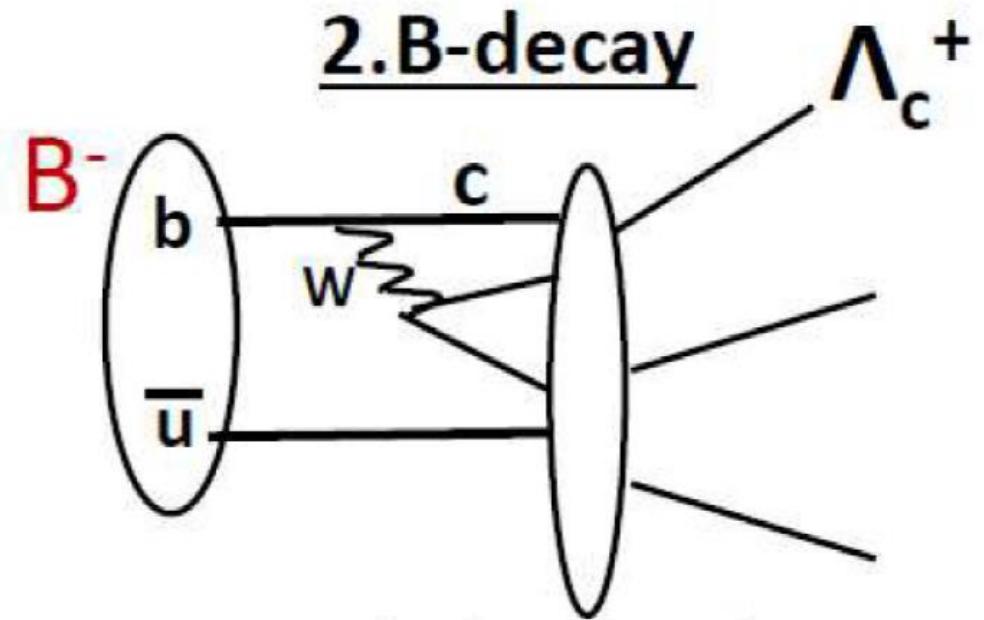
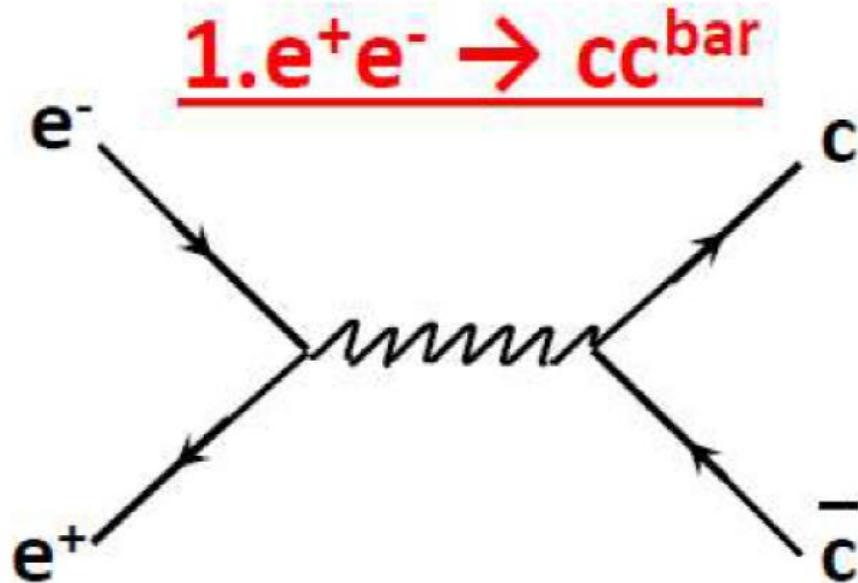
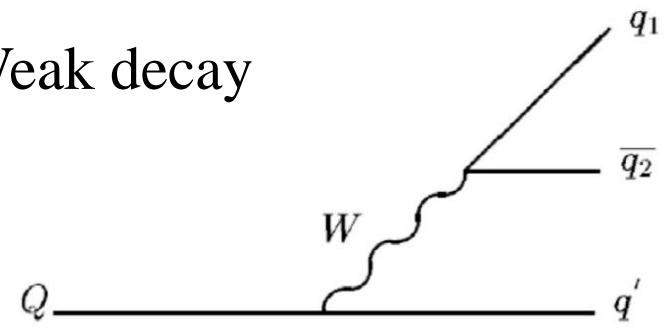


Strange baryons ($\Lambda[\text{uds}]$)
 $m_u, m_d \approx m_s \rightarrow (\text{qqq})$ uniform



Charmed baryon ($\Lambda_c[\text{udc}]$)
 $m_u, m_d \ll m_c \rightarrow \text{diquark} + \text{quark}$
 $(\text{qq}) \quad (\text{Q})$

Weak decay



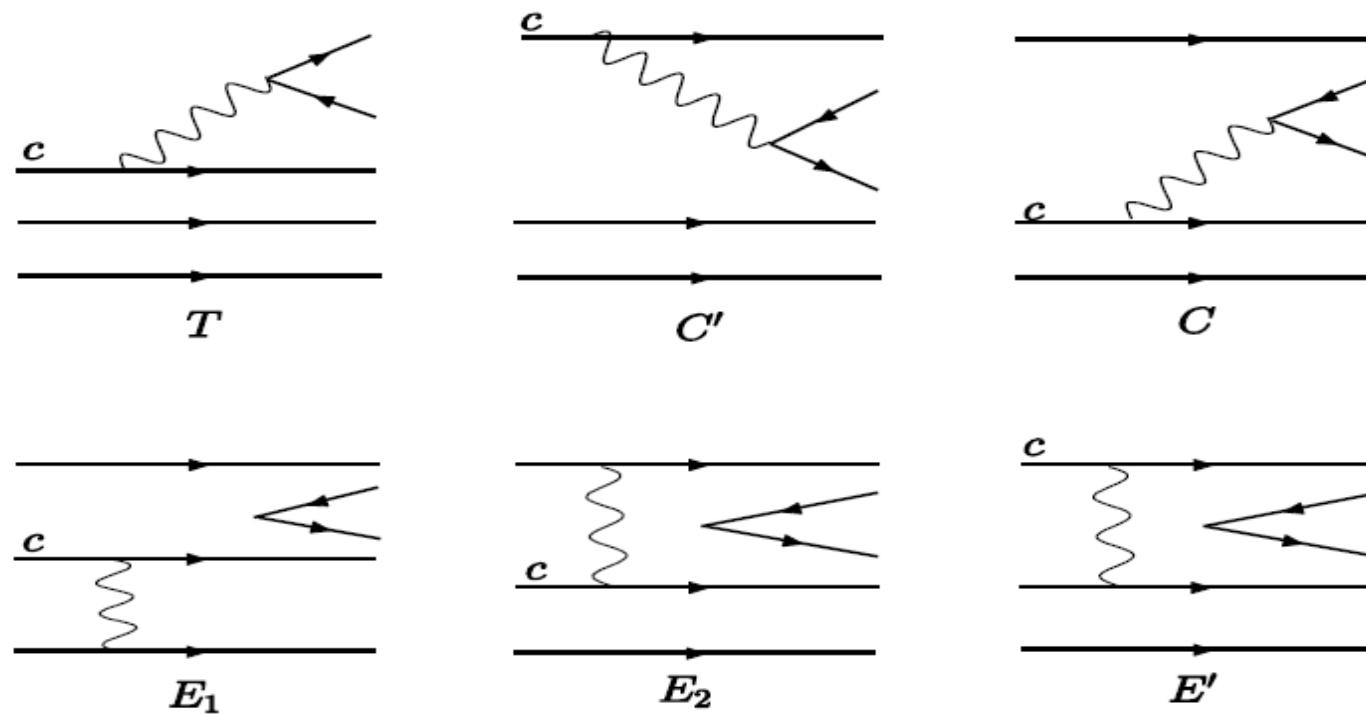
Theory

Λ_c^+ two body decays

Non-leptonic two-body weak decays of $\Lambda_c(2286)$

C.Q. Geng ^{a,b,*}, Y.K. Hsiao ^{a,b}, Yu-Heng Lin ^b, Liang-Liang Liu ^a

Physics Letters B 776 (2018) 265–269



[11] H.Y. Cheng, B. Tseng, Phys. Rev. D 48 (1993) 4188.

[23] K.K. Sharma, R.C. Verma, Phys. Rev. D 55 (1997) 7067.

[24] K.K. Sharma, R.C. Verma, Eur. Phys. J. C 7 (1999) 217.

Λ_c^+ two body decays

Singly Cabibbo suppressed decays of Λ_c^+ with SU(3) flavor symmetry

Chao-Qiang Geng ^{a,b,c,*}, Chia-Wei Liu ^b, Tien-Hsueh Tsai ^b

Physics Letters B 790 (2019) 225–228

Branching ratios for the Cabibbo allowed and singly Cabibbo suppressed decays of Λ_c^+ .

Decay branching ratio	This work	Data	$SU(3)_F$ [22]	CKX [17]
$10^3 \mathcal{B}(\Lambda_c^+ \rightarrow \Sigma^+ \pi^0)$	12.6 ± 2.1	12.4 ± 1.0	12.8 ± 2.3	–
$10^3 \mathcal{B}(\Lambda_c^+ \rightarrow \Sigma^+ \eta)$	5.4 ± 1.0	7.0 ± 2.3	7.1 ± 3.8	[22] C.Q. Geng, Y.K. Hsiao, C.W. Liu, T.H. Tsai, – Phys. Rev. D 97 (7) (2018) 073006.
$10^3 \mathcal{B}(\Lambda_c^+ \rightarrow \Sigma^0 \pi^+)$	12.6 ± 2.1	12.9 ± 0.7	12.8 ± 2.3	–
$10^3 \mathcal{B}(\Lambda_c^+ \rightarrow \Xi^0 K^+)$	5.9 ± 1.0	5.9 ± 0.9	5.5 ± 1.4	–
$10^3 \mathcal{B}(\Lambda_c^+ \rightarrow p \bar{K}^0)$	31.3 ± 1.6	31.6 ± 1.6	32.7 ± 1.5	–
$10^3 \mathcal{B}(\Lambda_c^+ \rightarrow \Lambda^0 \pi^+)$	13.1 ± 1.6	13.0 ± 0.7	12.8 ± 1.7	–
$10^4 \mathcal{B}(\Lambda_c^+ \rightarrow \Sigma^+ K^0)$	11.4 ± 2.0	–	8.0 ± 1.6	14.4
$10^4 \mathcal{B}(\Lambda_c^+ \rightarrow \Sigma^0 K^+)$	5.7 ± 1.0	5.2 ± 0.8	4.0 ± 0.8	7.18
$10^4 \mathcal{B}(\Lambda_c^+ \rightarrow p \pi^0)$	1.3 ± 0.7	< 2.7	5.7 ± 1.5	0.8
$10^4 \mathcal{B}(\Lambda_c^+ \rightarrow p \eta)$	13.0 ± 1.0	12.4 ± 3.0	$12.5^{+3.8}_{-3.6}$	12.8
$10^4 \mathcal{B}(\Lambda_c^+ \rightarrow n \pi^+)$	6.1 ± 2.0	–	11.3 ± 2.9	2.7
$10^4 \mathcal{B}(\Lambda_c^+ \rightarrow \Lambda^0 K^+)$	6.4 ± 0.9	6.1 ± 1.2	4.6 ± 0.9	10.6

[17] H.Y. Cheng, X.W. Kang, F. Xu, Phys. Rev. D 97 (7) (2018) 074028.

coefficient a_2 for naive color-suppressed modes and the effective number of color N_c^{eff} . We rely on the current-algebra approach to evaluate W -exchange and nonfactorizable internal W -emission amplitudes, that is, the commutator terms for the S wave and the pole terms for the P wave. Our prediction for $\Lambda_c^+ \rightarrow p \eta$ is in

Λ_c^+ three body decays

PHYSICAL REVIEW D 93, 056008 (2016)

Test flavor SU(3) symmetry in exclusive Λ_c decays

Cai-Dian Lü,^{1,*} Wei Wang,^{2,3,†} and Fu-Sheng Yu^{4,‡}

$$\begin{aligned} \mathcal{A}(\Lambda_c \rightarrow p \bar{K}^0 \pi^0) &= \frac{1}{\sqrt{2}} \mathcal{A}^{(1)}, \\ \mathcal{A}(\Lambda_c \rightarrow p K^- \pi^+) &= -\frac{1}{2} \mathcal{A}^{(1)} + \frac{1}{\sqrt{2}} \mathcal{A}^{(2)}, \\ \mathcal{A}(\Lambda_c \rightarrow n \bar{K}^0 \pi^+) &= -\frac{1}{2} \mathcal{A}^{(1)} - \frac{1}{\sqrt{2}} \mathcal{A}^{(2)}. \end{aligned} \quad \xrightarrow{\hspace{1cm}} \quad \begin{aligned} &\sqrt{2} \mathcal{A}(\Lambda_c \rightarrow p \bar{K}^0 \pi^0) + \mathcal{A}(\Lambda_c \rightarrow p K^- \pi^+) \\ &+ \mathcal{A}(\Lambda_c \rightarrow n \bar{K}^0 \pi^+) = 0. \end{aligned}$$

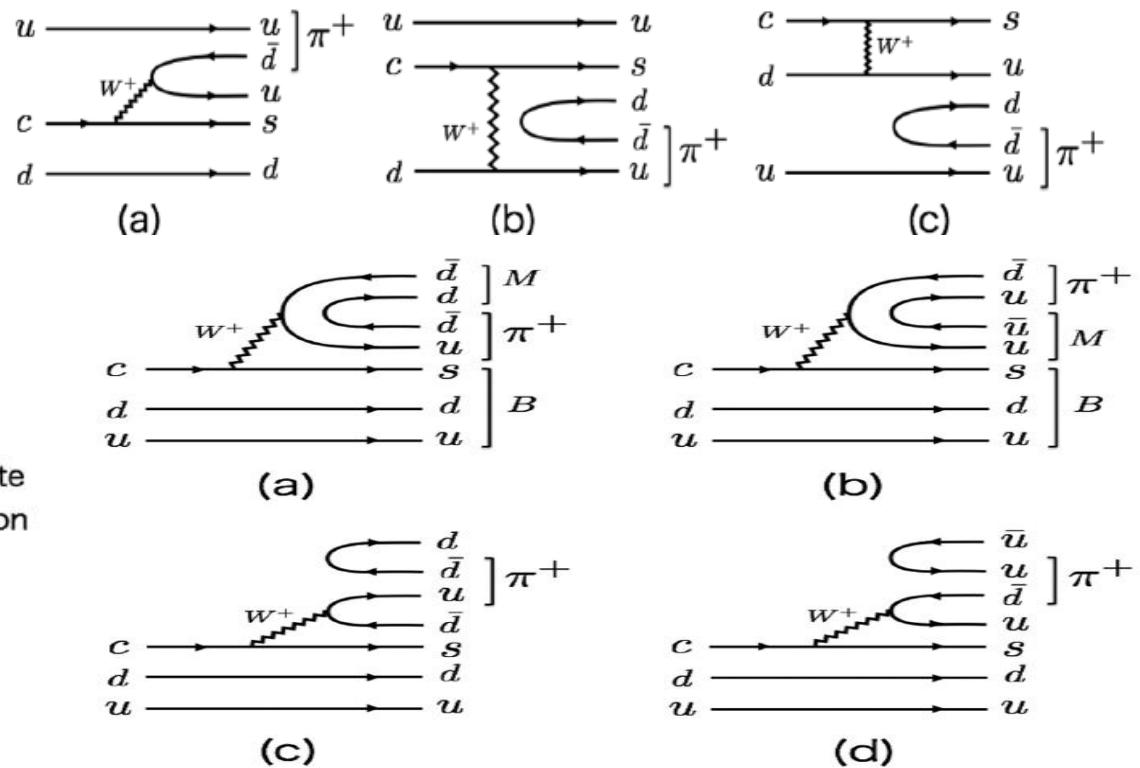
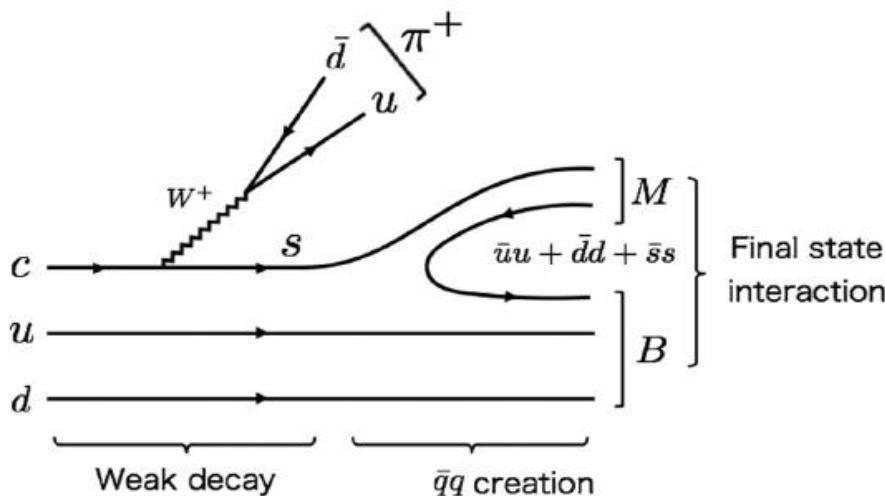


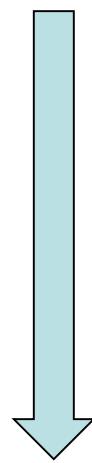
FIG. 1. The dominant diagram for the $\Lambda_c^+ \rightarrow \pi^+ MB$ decay. The solid lines and the wiggly line show the quarks and the W boson, respectively.

K. Miyahara, T. Hyodo, and E. Oset, Phys. Rev. C 92, 055204 (2015).

Weak decay of Λ_c^+ for the study of $\Lambda(1405)$ and $\Lambda(1670)$

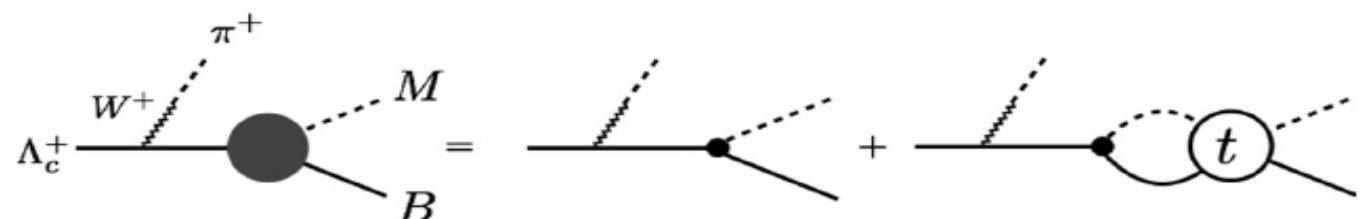
$$|MB\rangle = \frac{1}{\sqrt{2}} |s(\bar{u}u + \bar{d}d + \bar{s}s)(ud - du)\rangle \\ = \frac{1}{\sqrt{2}} \sum_{i=1}^3 |P_{3i} q_i (ud - du)\rangle,$$

$$q \equiv \begin{pmatrix} u \\ d \\ s \end{pmatrix}, \quad P \equiv q\bar{q} = \begin{pmatrix} u\bar{u} & u\bar{d} & u\bar{s} \\ d\bar{u} & d\bar{d} & d\bar{s} \\ s\bar{u} & s\bar{d} & s\bar{s} \end{pmatrix}.$$



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

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

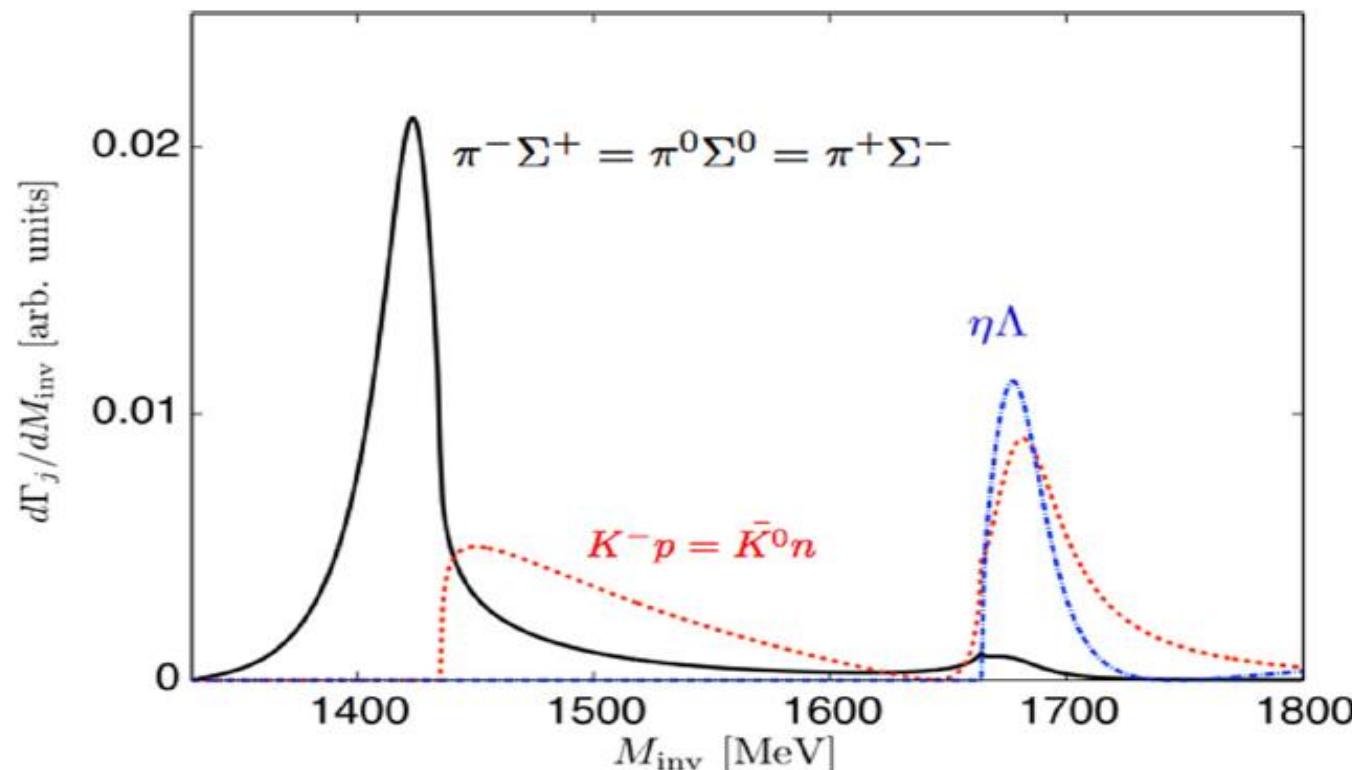


$$\mathcal{M}_j = V_P \left[h_j + \sum_i h_i G_i(M_{\text{inv}}) t_{ij}(M_{\text{inv}}) \right],$$

$$h_{\pi^0\Sigma^0} = h_{\pi^-\Sigma^+} = h_{\pi^+\Sigma^-} = h_{\pi^0\Lambda} = 0,$$

$$h_{K^-p} = h_{\bar{K}^0n} = 1, \quad h_{\eta\Lambda} = -\frac{\sqrt{2}}{3}, \quad \frac{d\Gamma_j}{dM_{\text{inv}}} = \frac{1}{(2\pi)^3} \frac{p_{\pi^+}\tilde{p}_j M_{\Lambda_c^+} M_j}{M_{\Lambda_c^+}^2} |\mathcal{M}_j|^2,$$

$$h_{\eta\Sigma^0} = h_{K^+\Xi^-} = h_{K^0\Xi^0} = 0,$$

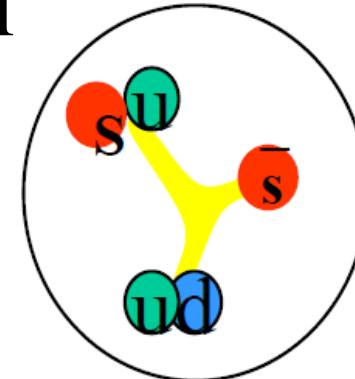


$N^*(1535)$: strangeness component

Couples strongly to strangeness channel

$$uud \text{ (L=1) } 1/2^- \sim N^*(1535) \sim [ud][us] \bar{s}$$

Mode	Fraction (Γ_i/Γ)	
$\Gamma_1 N\pi$	32–52 %	Larger $[ud][us] \bar{s}$ component
$\Gamma_2 N\eta$	30–55 %	in $N^*(1535)$ makes it coupling strong to $N\eta$ & $K\Lambda$.



$$J/\psi \rightarrow \bar{p}N^* \rightarrow \bar{p}(K\Lambda)/\bar{p}(p\eta) \rightarrow \text{large } g_{N^* K\Lambda}$$

Liu&Zou, PRL96 (2006) 042002; Geng,Oset,Zou&Doring, PRC79 (2009) 025203

$$\gamma p \rightarrow p\eta' \& pp \rightarrow pp\eta' \rightarrow \text{large } g_{N^* N\eta'}$$

M.Dugger et al., PRL96 (2006) 062001; Cao&Lee, PRC78(2008) 035207

$$\pi^- p \rightarrow n\phi \& pp \rightarrow pp\phi \& pn \rightarrow d\phi \rightarrow \text{large } g_{N^* N\phi}$$

Xie, Zou & Chiang, PRC77(2008)015206; Cao, Xie, Zou & Xu, PRC80(2009)025203

$N^*(1535)$: dynamically generated state

- Pole position $z_R = [(1490 \sim 1530) - i(45 \sim 125)]\text{MeV}$
PDG 2018  $(M_R, \Gamma_R) = (\simeq 1510, \simeq 170)\text{MeV}$

PHYSICAL REVIEW C, VOLUME 65, 035204

Chiral unitary approach to S-wave meson baryon scattering in the strangeness $S=0$ sector

T. Inoue,* E. Oset, and M. J. Vicente Vacas

Departamento de Física Teórica and IFIC, Centro Mixto Universidad de Valencia-CSIC, Institutos de Investigación de Paterna,
Apartado Correos 22085, E-46071 Valencia, Spain

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Chiral dynamics of the $S_{11}(1535)$ and $S_{11}(1650)$ resonances revisited

Peter C. Bruns^a, Maxim Mai^{b,*}, Ulf-G. Meißner^{b,c}

Physics Letters B 697 (2011) 254–259

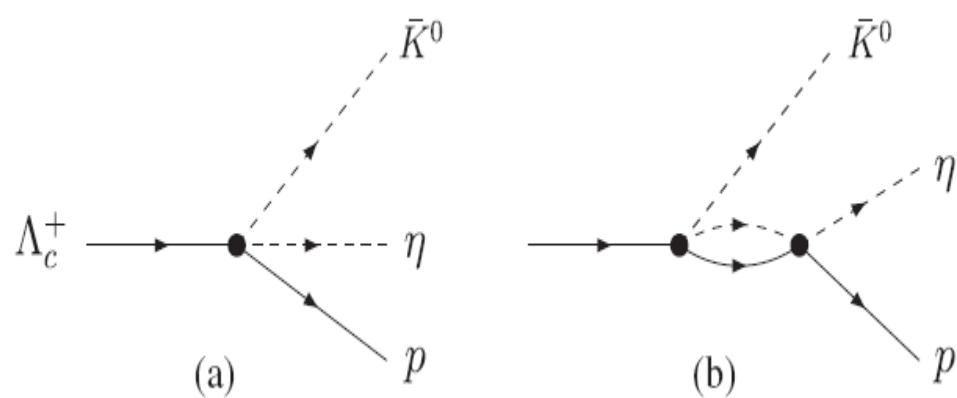
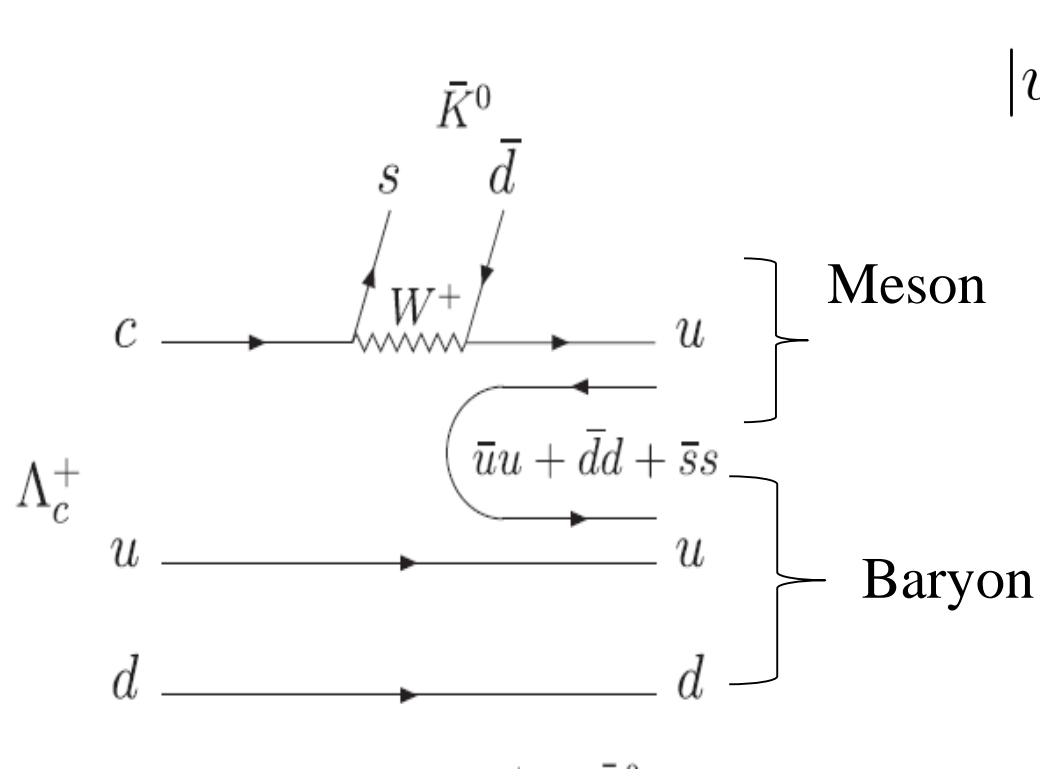
- Breit-Wigner parameterization

$$(M_R, \Gamma_R) = (1525 \sim 1545, 125 \sim 175)\text{MeV} = (\simeq 1535, \simeq 150)\text{MeV}$$



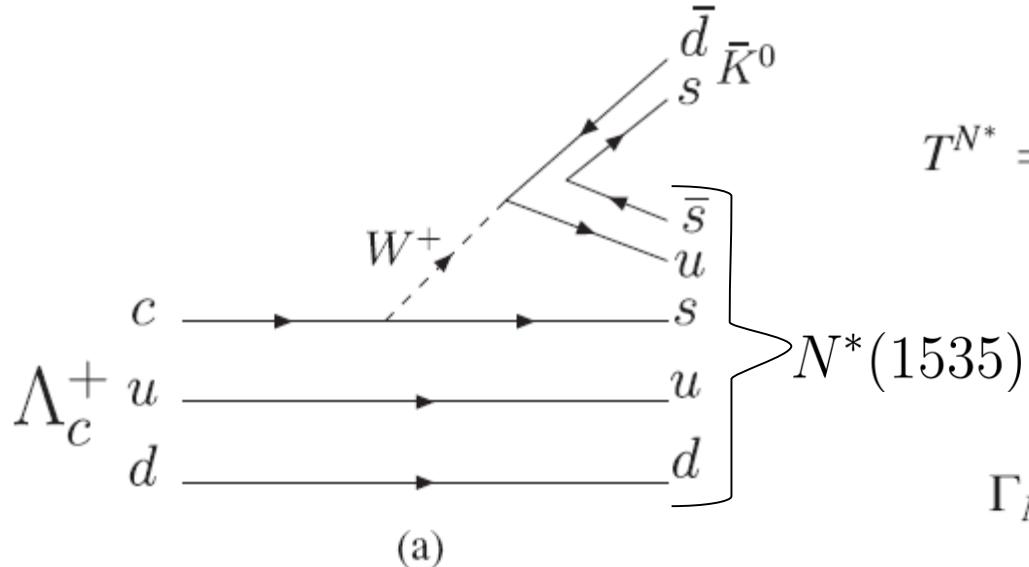
PDG 2018

The $N^*(1535)$ as a dynamically generated state



$$\begin{aligned}
 |uud\rangle &\rightarrow \frac{1}{\sqrt{2}}|u(u\bar{d}-d\bar{u})\rangle \\
 &+ |\bar{u}u + \bar{d}d + \bar{s}s\rangle \\
 |MB\rangle &= \frac{\sqrt{3}}{3}|\eta p\rangle + \frac{\sqrt{2}}{2}|\pi^0 p\rangle + |\pi^+ n\rangle - \frac{\sqrt{6}}{3}|K^+ \Lambda\rangle, \\
 T^{MB} &= V_P \left(\frac{\sqrt{3}}{3} + \frac{\sqrt{3}}{3}G_{\eta p}(M_{\eta p})t_{\eta p \rightarrow \eta p}(M_{\eta p}) \right. \\
 &+ \frac{\sqrt{2}}{2}G_{\pi^0 p}(M_{\eta p})t_{\pi^0 p \rightarrow \eta p}(M_{\eta p}) \\
 &+ G_{\pi^+ n}(M_{\eta p})t_{\pi^+ n \rightarrow \eta p}(M_{\eta p}) \\
 &\left. - \frac{\sqrt{6}}{3}G_{K^+ \Lambda}(M_{\eta p})t_{K^+ \Lambda \rightarrow \eta p}(M_{\eta p}) \right),
 \end{aligned}$$

Effective Lagrangian approach and the $N^*(1535)$ resonance as a Breit-Wigner resonance

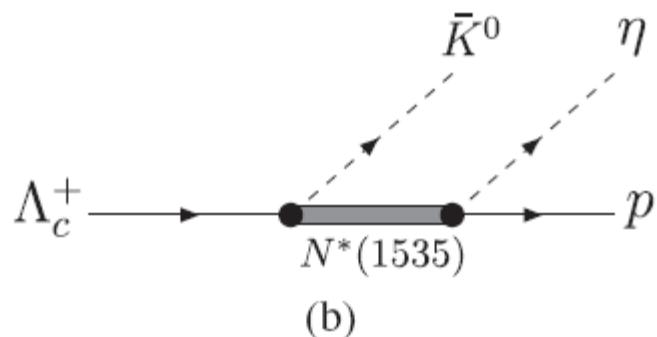


$$T^{N^*} = ig_{N^*\eta}\bar{u}(p_3, s_p)G_{N^*}(q)(A + B\gamma_5)u(p, s_{\Lambda_c^+}),$$

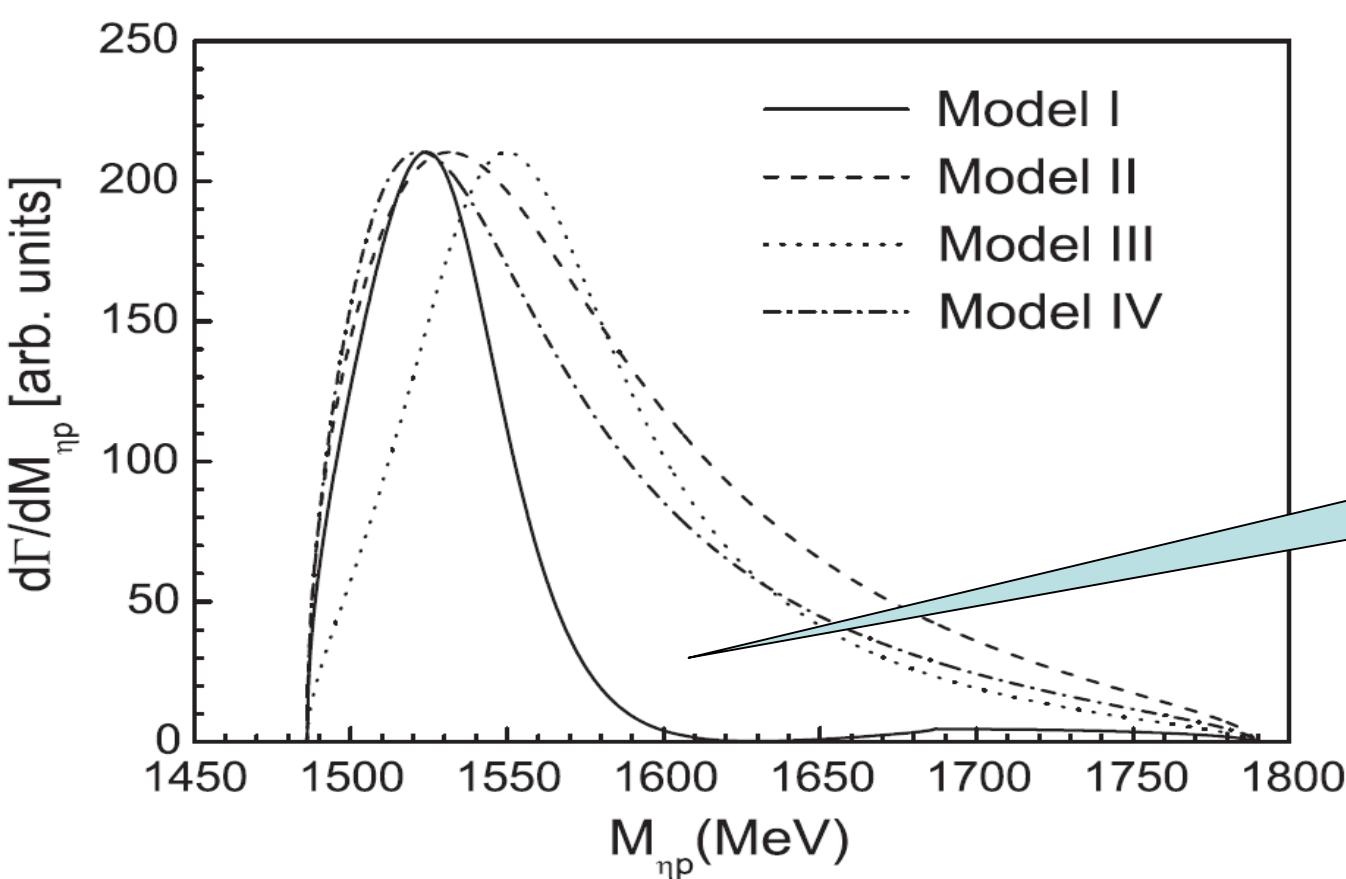
$$G_{N^*}(q) = i \frac{\not{q} + M_{N^*}}{q^2 - M_{N^*}^2 + iM_{N^*}\Gamma_{N^*}(q^2)},$$

$$\Gamma_{N^*}(q^2) = \Gamma_{N^*\rightarrow\pi N}(q^2) + \Gamma_{N^*\rightarrow\eta N}(q^2) + \Gamma_0,$$

$$\Gamma_0 = 19.5 \text{ MeV} \quad \text{for} \quad \Gamma_{N^*}(\sqrt{q^2} = 1535 \text{ MeV}) = 150 \text{ MeV}.$$



Invariant ηp mass distributions



$$\frac{d\Gamma}{dM_{\eta p}} = \frac{1}{16\pi^3} \frac{m_p p_{\bar{K}^0} p_\eta^*}{M_{\Lambda_c^+}} |T|^2,$$

Model I : $T = T^{MB}$

Different line shapes

Model II : $T = T^{N^}$, $M_{N^*} = 1535$ MeV, $\Gamma_{N^*} = \Gamma_{N^*}(q^2)$*

Model III : $T = T^{N^}$, $M_{N^*} = 1543$ MeV, $\Gamma_{N^*} = 92$ MeV*

Model IV : $T = T^{N^}$, $M_{N^*} = 1500$ MeV, $\Gamma_{N^*} = 110$ MeV*

Other contributions

$N^*(1650) \rightarrow \eta p$

Σ^* resonances

$\rightarrow \bar{K}^0 p$

$\Sigma^*(1660)1/2^+ :$ $p - wave$

$\Sigma^*(1670)3/2^- :$ $d - wave$

$\Sigma^*(1750)1/2^- :$ $s - wave, but,$

very small phase space

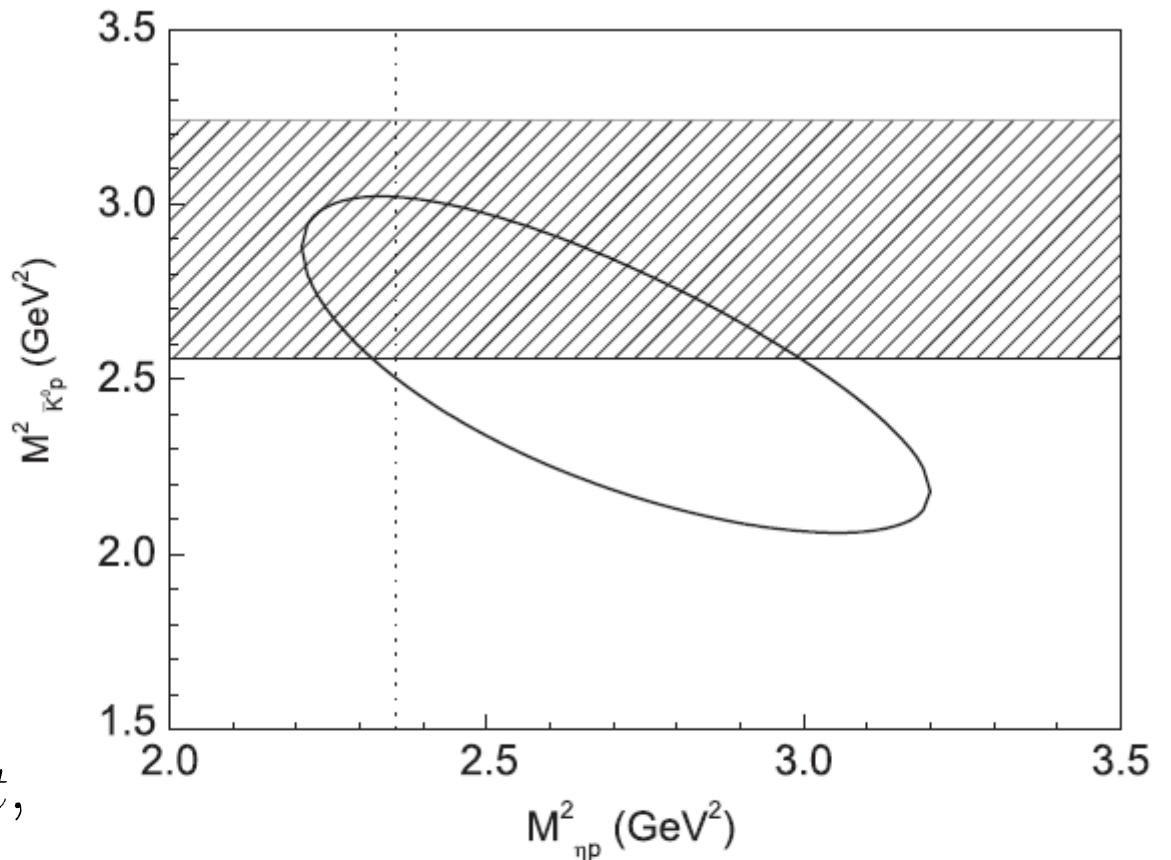
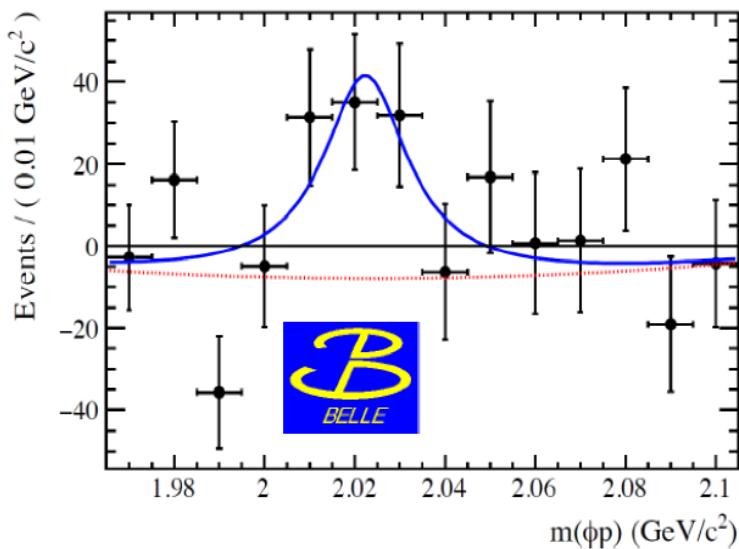
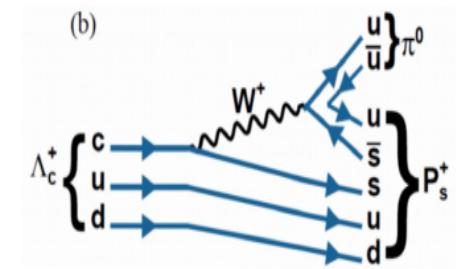
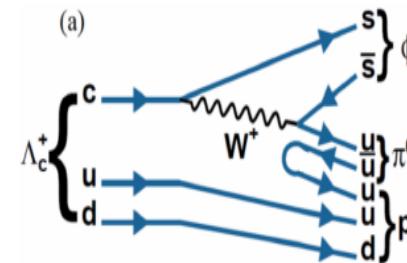
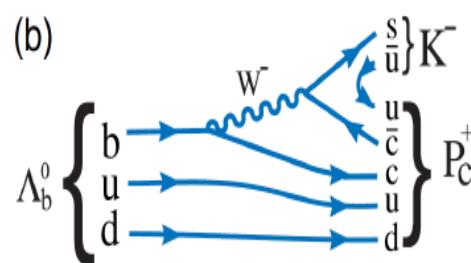
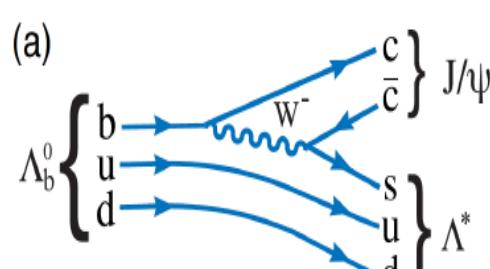


FIG. 7. Dalitz plot for $M_{\eta p}^2$ and $M_{\bar{K}^0 p}^2$ in the $\Lambda_c^+ \rightarrow \bar{K}^0 \eta p$ decay. The $N^*(1535)$ energy is shown by the vertical dotted line, and the horizontal band represents the masses of Σ^* states from 1600 to 1800 MeV.

Production of $N^*(1535)$ and $N^*(1650)$ in $\Lambda_c \rightarrow \bar{K}^0 \eta p$ (πN) decay

Possible ϕp state in $\Lambda_c^+ \rightarrow \pi^0 p \phi$ decay

R. Lebed, PRD92(2015)114030



$\Sigma^+ \rightarrow p \pi^0$ vetoed

- No significant P_s signal
- Best fit yields a peak at $M = (2025 \pm 5) \text{ MeV}/c^2$ and $\Gamma = (22 \pm 12) \text{ MeV}$

[PRD96, 051102\(R\) \(2017\)](#); 915 fb^{-1}

Number of candidate $\Lambda_c \rightarrow P_s \pi^0 \rightarrow \phi p \pi^0$ events: 77.6 ± 28.1

$B(\Lambda_c \rightarrow P_s \pi^0) \times B(P_s \rightarrow \phi p) < 8.3 \times 10^{-5}$ @ 90% C.L.

From Cheng-Ping Shen

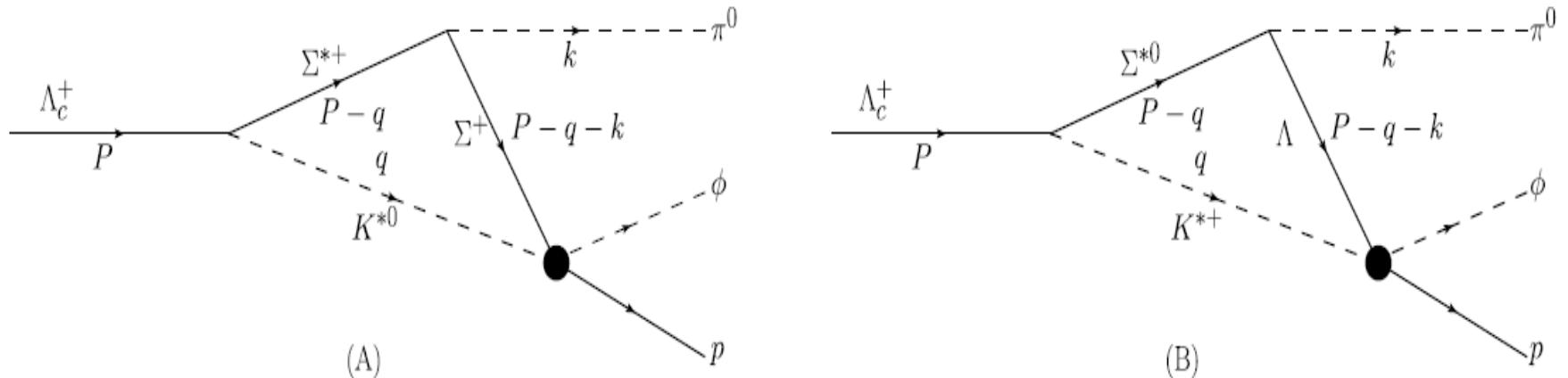


Fig. 1. Triangle diagrams for the $\Lambda_c^+ \rightarrow \pi^0 p \phi$ decay. (A): Σ^+ -exchange. (B): Λ -exchange. The definitions of the kinematical variables (P, q, k) are also shown.

$$\begin{aligned}
 t = & \frac{g_{\Lambda_c \Sigma^* K^*} g_{\phi \cdot k}}{m_\pi} \vec{\epsilon}_\phi \cdot \vec{k} \sum_{i=\Sigma, \Lambda} C_i \int \frac{d^4 q}{(2\pi)^4} \\
 & \times \frac{i 2 m_{\Sigma^*}}{(P - q)^2 - m_{\Sigma^*}^2 + i m_{\Sigma^*} \Gamma_{\Sigma^*}} \frac{i}{q^2 - m_{K^*}^2 + i m_{K^*} \Gamma_{K^*}} \\
 & \times \frac{i 2 m_i}{(P - q - k)^2 - m_i^2 + i \epsilon}, \tag{4}
 \end{aligned}$$

where we have defined $C_\Sigma = \frac{\sqrt{6}}{3} t_{K^* \Sigma^+ \rightarrow \phi p}$ and $C_\Lambda = -t_{K^* \Lambda \rightarrow \phi p}$,

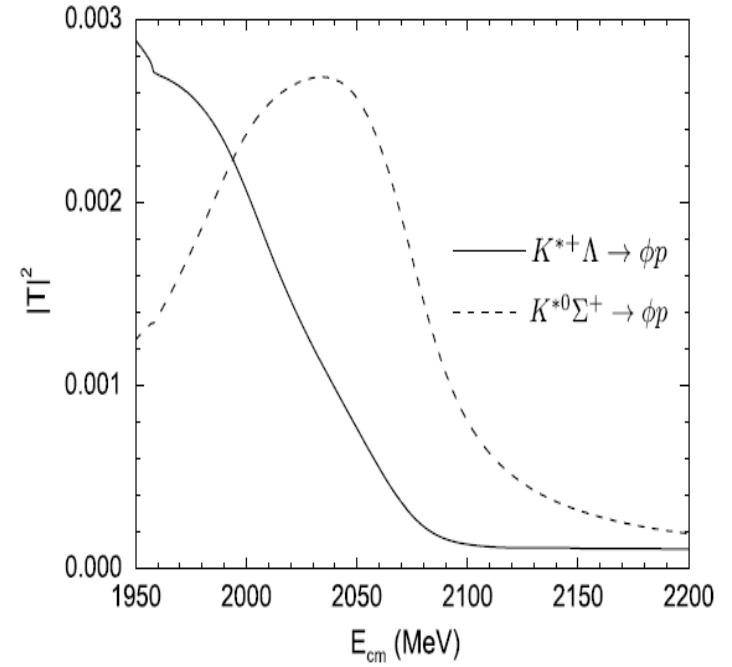


Fig. 3. The squared norm of the T -matrix elements for $K^* \Lambda \rightarrow \phi p$ and $K^* \Sigma^+ \rightarrow \phi p$ as a function of the meson-baryon invariant mass E_{cm} in the model of Ref. [72].

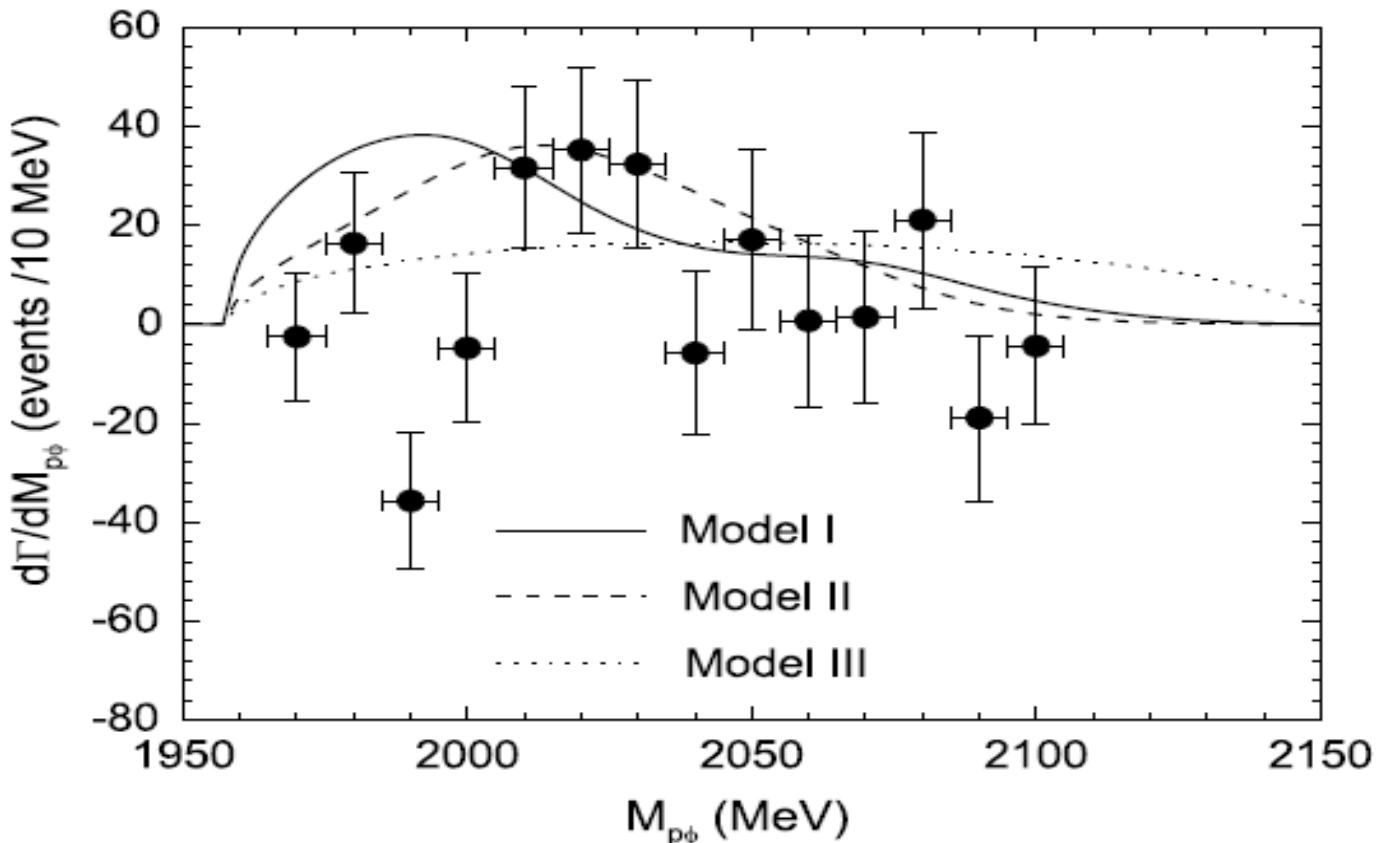


Fig. 2. Invariant mass distribution of the $\Lambda_c^+ \rightarrow \pi^0 p\bar{\phi}$ decay. The experimental data are taken from Ref. [47].

Model I: the BV interaction model (P_s generated) of A. Ramos, E. Oset, PLB727(2013)287

Model II: no resonance, constant interaction; Model III: phase space

Summary

The $\Lambda_c^+ \rightarrow \bar{K}^0 \eta p$ decay can be used to study the $N^(1535)$ resonance*

Possible ϕp state, P_s , in the $\Lambda_c^+ \rightarrow \pi^0 \phi p$ decay

TS produces a bump at around 2.02 GeV

Ps, if exists, could distort the line shape, but difficult to be distinguished from TS in this process

We need more efforts, both on theoretical and experimental sides.

Thank you very much for your attention!

$$\frac{d\Gamma}{dM_{\eta p}} = f_1 A^2 + f_2 B^2.$$

$$R = \frac{f_2 B^2}{f_1 A^2} = \frac{f_2}{f_1}.$$

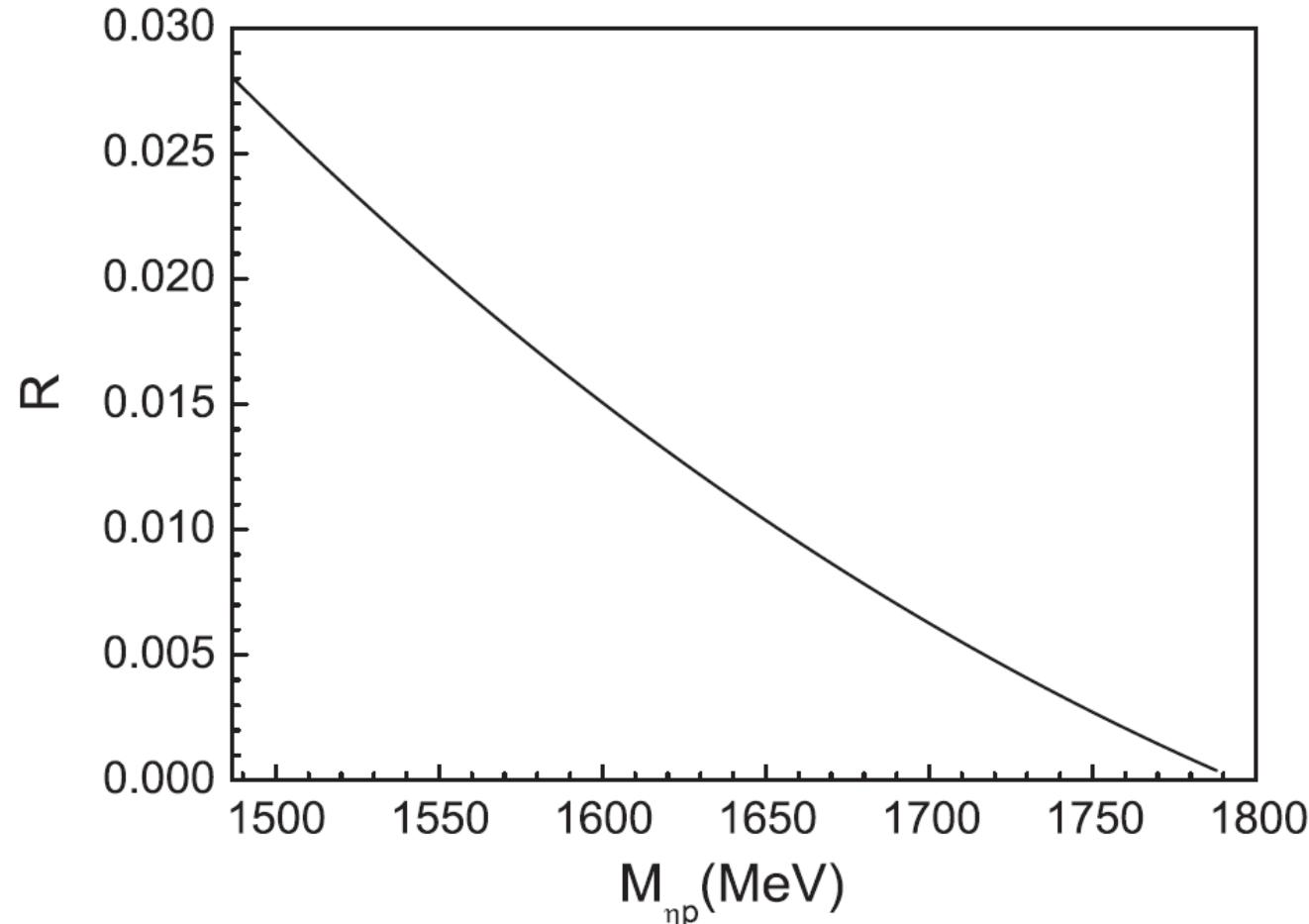


FIG. 6. Ratio R of the B and A terms as a function of the ηp invariant mass.