



中国科学院近代物理研究所  
Institute of Modern Physics, Chinese Academy of Sciences

# Study of the light baryon states in $\Lambda_c^+$ decays

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# Outline

## Introduction

*Possible  $\Sigma_{1/2-}^*$  (1380) state in  $\Lambda_c^+ \rightarrow \eta\pi^+\Lambda$  decay*

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

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

## Summary

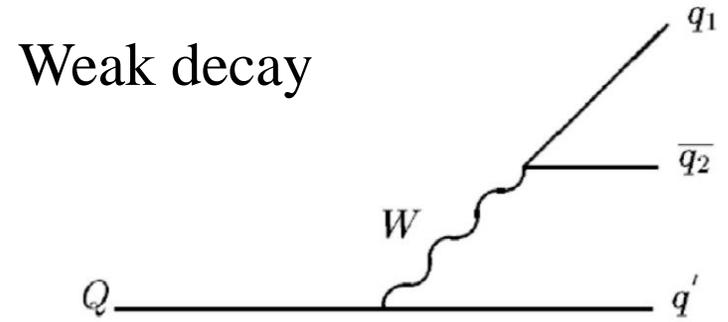
# $\Lambda_c^+$

The lightest charmed baryon



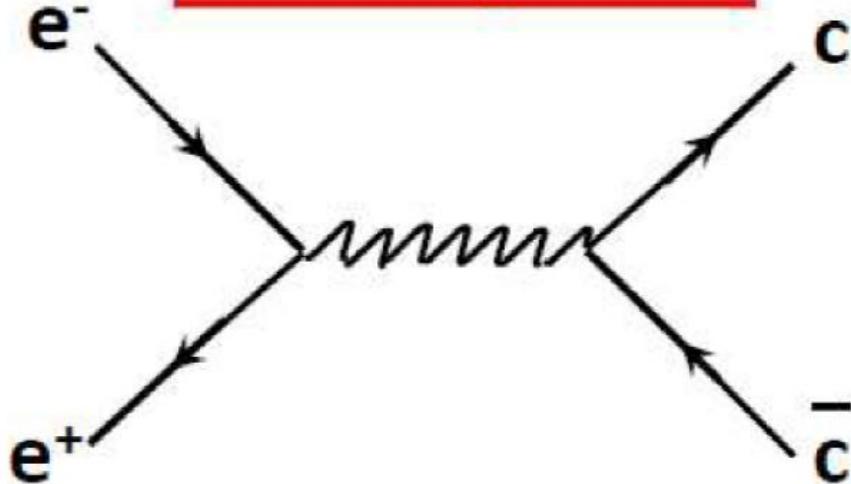
**Strange baryons ( $\Lambda[uds]$ )**  
 $m_u, m_d \approx m_s \rightarrow (qqq)$  uniform

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

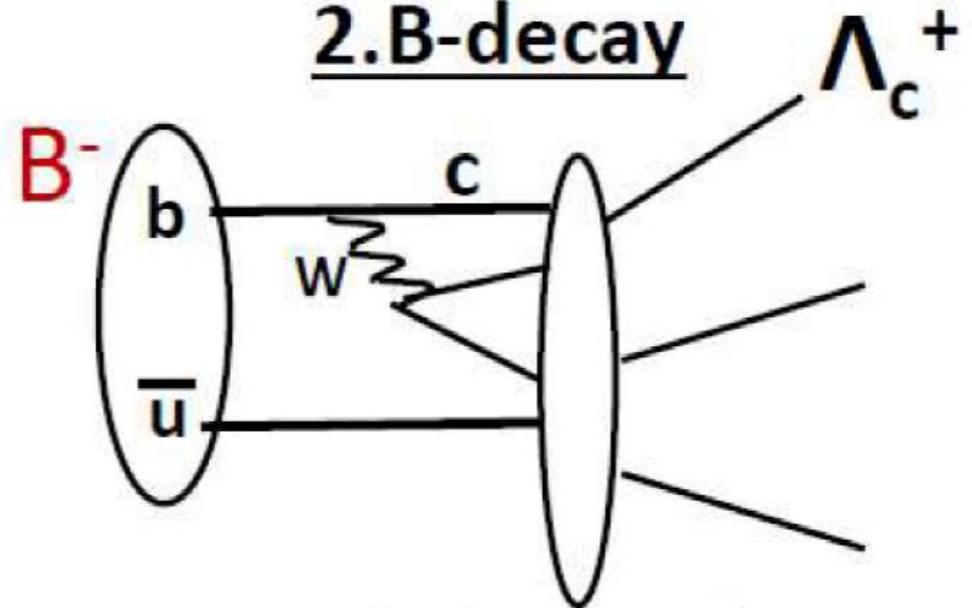


Weak decay

## 1. $e^+e^- \rightarrow c\bar{c}$



## 2. B-decay



# $\Lambda_c^+$ three body decays

PHYSICAL REVIEW D **93**, 056008 (2016)

## Test flavor SU(3) symmetry in exclusive $\Lambda_c$ decays

Cai-Dian Lü,<sup>1,\*</sup> Wei Wang,<sup>2,3,†</sup> and Fu-Sheng Yu<sup>4,‡</sup>

$$\mathcal{A}(\Lambda_c \rightarrow p \bar{K}^0 \pi^0) = \frac{1}{\sqrt{2}} \mathcal{A}^{(1)},$$

$$\mathcal{A}(\Lambda_c \rightarrow p K^- \pi^+) = -\frac{1}{2} \mathcal{A}^{(1)} + \frac{1}{\sqrt{2}} \mathcal{A}^{(2)},$$

$$\mathcal{A}(\Lambda_c \rightarrow n \bar{K}^0 \pi^+) = -\frac{1}{2} \mathcal{A}^{(1)} - \frac{1}{\sqrt{2}} \mathcal{A}^{(2)}.$$

$$\begin{aligned} & \sqrt{2} \mathcal{A}(\Lambda_c \rightarrow p \bar{K}^0 \pi^0) + \mathcal{A}(\Lambda_c \rightarrow p K^- \pi^+) \\ & + \mathcal{A}(\Lambda_c \rightarrow n \bar{K}^0 \pi^+) = 0. \end{aligned}$$

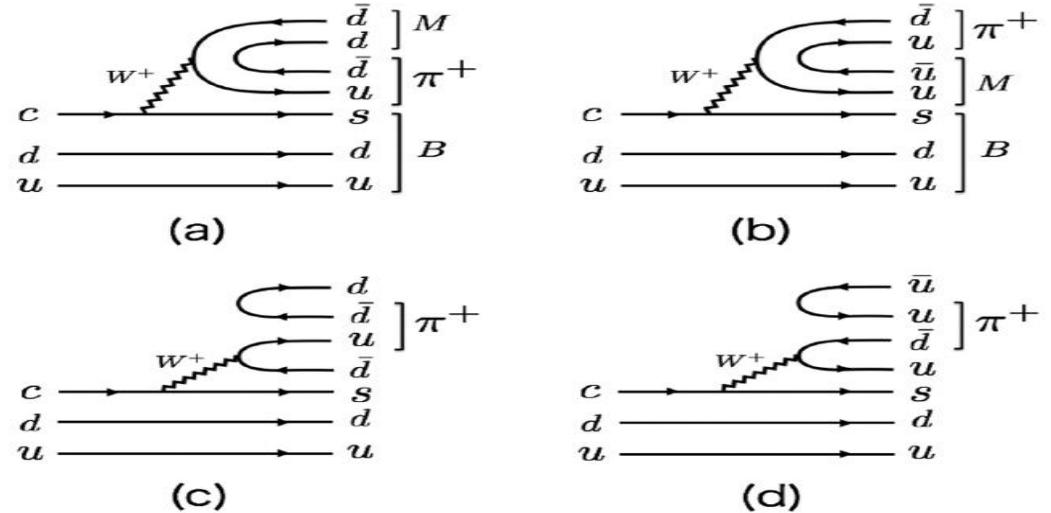
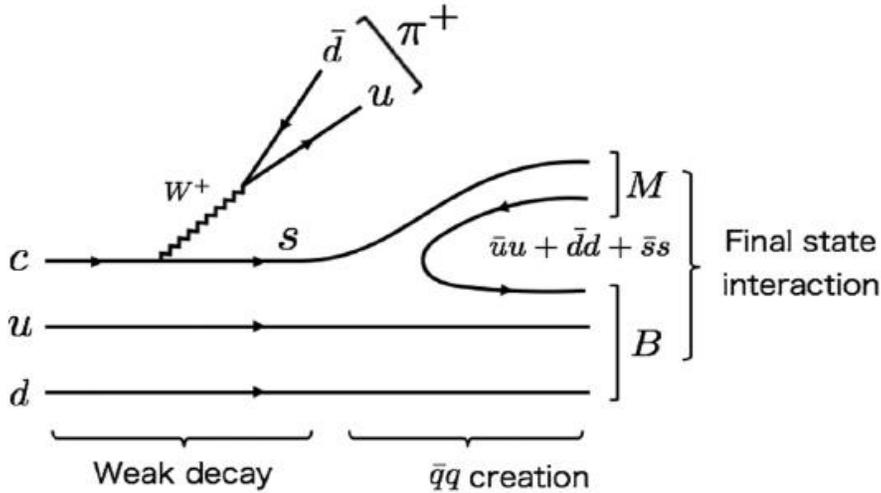
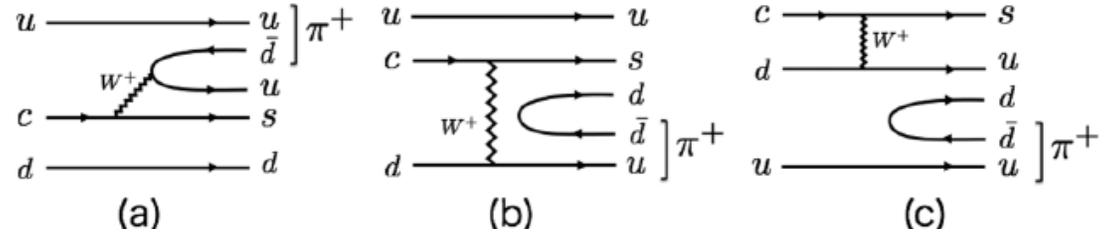


FIG. 1. The dominant diagram for the  $\Lambda_c^+ \rightarrow \pi^+ MB$  decay. The solid lines and the wiggly line show the quarks and the  $W$  boson, respectively.

# A possible $\Sigma^*$ state with spin-parity $J^P = \frac{1}{2}^-$

	(Y, I)	I <sub>3</sub>	Flavor wave functions	Masses (MeV)
$p_8$	$(1, \frac{1}{2})$	$\frac{1}{2}$	$[su][ud] - \bar{s}$	1460
$n_8$		$-\frac{1}{2}$	$[ds][ud] - \bar{s}$	1460
$\Sigma_8^+$	$(0, 1)$	1	$[su][ud] - \bar{d}$	1360
$\Sigma_8^0$		0	$\frac{1}{\sqrt{2}}([su][ud] - \bar{u} + [ds][ud] - \bar{d})$	1360
$\Sigma_8^-$		-1	$[ds][ud] - \bar{u}$	1360
$\Lambda_8$	$(0, 0)$	0	$\frac{[ud][su] - \bar{u} + [ds][ud] - \bar{d} - 2[su][ds] - \bar{s}}{\sqrt{6}}$	1533
$\Xi_8^0$	$(-1, \frac{1}{2})$	$\frac{1}{2}$	$[ds][su] - \bar{d}$	1520
$\Xi_8^-$		$-\frac{1}{2}$	$[ds][su] - \bar{u}$	1520
$\Lambda_1$	$(0, 0)$	0	$\frac{[ud][su] - \bar{u} + [ds][ud] - \bar{d} + [su][ds] - \bar{s}}{\sqrt{3}}$	1447

TABLE II: Flavor wave functions and masses of the  $\frac{1}{2}^-$  pentaquark octet and singlet.

Ao Zhang, Y. R. Liu, P.Z. Huang, W.Z. Deng, X.L. chen and S.L. Zhu,  
 High Energy Phys. Nucl. Phys. 29, 250 (2005).

## Other Model Predictions

Chiral dynamics in the presence of bound states:  
kaon–nucleon interactions revisited

Physics Letters B 500 (2001) 263–272

J.A. Oller, Ulf-G. Meißner

Chiral dynamics of the two  $\Lambda(1405)$  states

D. Jido<sup>a,c</sup>, J.A. Oller<sup>b,\*</sup>, E. Oset<sup>c</sup>, A. Ramos<sup>d</sup>, U.-G. Meißner<sup>e</sup>

Nuclear Physics A 725 (2003) 181–200

**Phys.Rev. C100 (2019) no.1, 015208**

$z_R$ ( $I = 1$ )	1401 + 40i	
	$g_i$	$ g_i $
$\pi \Lambda$	$0.60 + 0.47i$	0.76
$\pi \Sigma$	$1.27 + 0.71i$	1.5
$\bar{K} N$	$-1.24 - 0.73i$	1.4
$\eta \Sigma$	$0.56 + 0.41i$	0.69
$K \Xi$	$0.12 + 0.05i$	0.13

*Cusp or “resonance” around the  $\bar{K} N$  threshold*

J.A. Oller, Eur. Phys. J. A 28, 63–82 (2006).      Zhi-Hui Guo and J. A. Oller, PRC 87, 035202 (2013) .

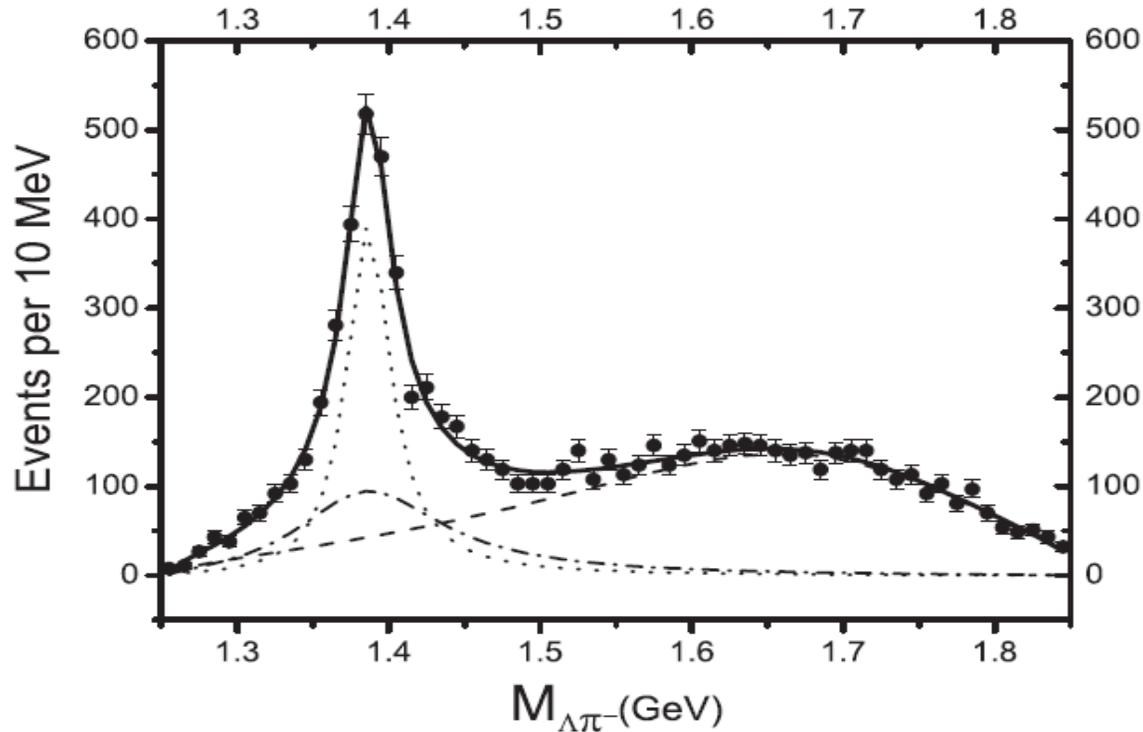
L. Roca and E. Oset, PRC 88, 055206 (2013).

K. P. Khemchandani, A. Martinez Torres, and J. A. Oller, PRC100, 015208 (2019).

in the fit. Two type of fits are found as a result. In both cases, the properties of  $\Lambda(1405)$  are well reproduced. In addition to this, a  $\Sigma$  state is also found with mass around 1400 MeV. Cross sections,

# Evidence for a new $\Sigma^*$ resonance with $J^P = 1/2^-$ in the old data of the $K^- p \rightarrow \Lambda \pi^+ \pi^-$ reaction

Jia-Jun Wu,<sup>1</sup> S. Dulat,<sup>2,3</sup> and B. S. Zou<sup>1,3</sup>



	$M_{\Sigma^*(3/2)}$	$\Gamma_{\Sigma^*(3/2)}$
Fit1	$1385.3 \pm 0.7$	$46.9 \pm 2.5$
Fit2	$1386.1^{+1.1}_{-0.9}$	$34.9^{+5.1}_{-4.9}$
	$M_{\Sigma^*(1/2)}$	$\Gamma_{\Sigma^*(1/2)}$
	$1381.3^{+4.9}_{-8.3}$	$118.6^{+55.2}_{-35.1}$

PHYSICAL REVIEW C **81**, 045210 (2010)

## Possible evidence for the $\Sigma^*$ resonance with $J^P = 1/2^-$ around 1380 MeV

Jia-Jun Wu,<sup>1</sup> S. Dulat,<sup>2,3</sup> and B. S. Zou<sup>1,3</sup>

PHYSICAL REVIEW C **81**, 055203 (2010)

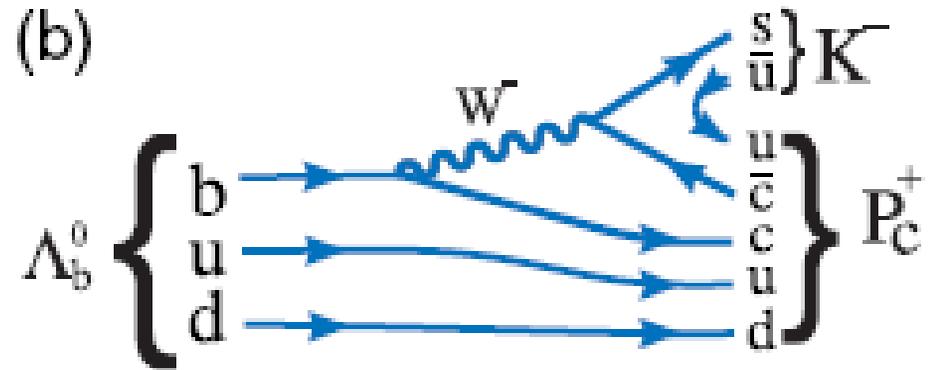
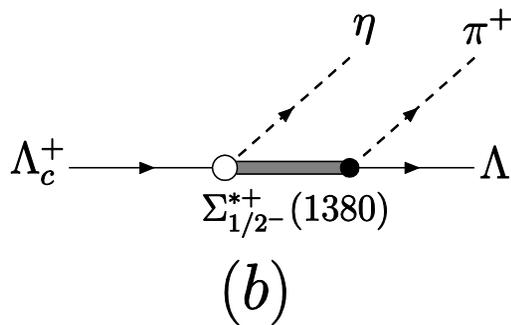
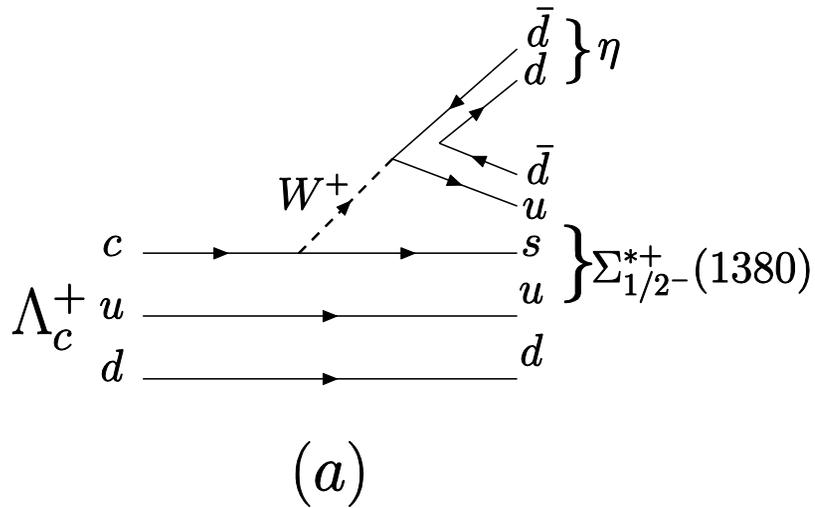
## Possible $\Sigma(\frac{1}{2}^-)$ under the $\Sigma^*(1385)$ peak in $K \Sigma^*$ photoproduction

Puze Gao, Jia-Jun Wu, and B. S. Zou

Yun-Hua Chen and B. S. Zou, PRC **88**, 024304 (2013).

Ju-Jun Xie, Jia-Jun Wu, and Bing-Song Zou, PRC **90**, 055204 (2014).

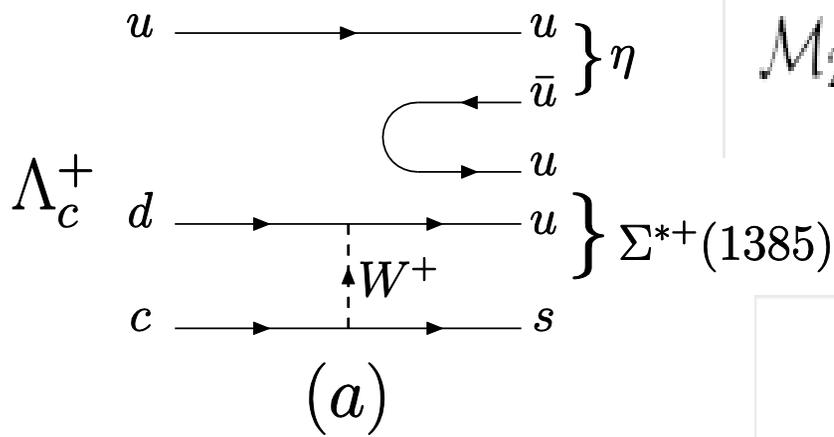
# $\Sigma(1380)$ in $\Lambda_c^+ \rightarrow \eta \pi^+ \Lambda$ decay



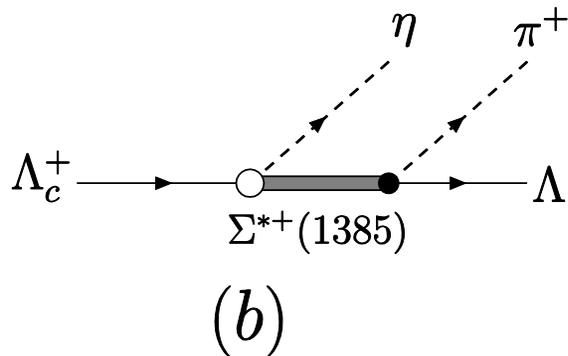
$$\mathcal{M}_1 = ig_{\pi\Lambda\Sigma_1^*} \bar{u}(p_3) G^{\Sigma_1^*}(q) (A_1 + B_1 \gamma_5) u(p),$$

$$G^{\Sigma_1^*}(q) = i \frac{\not{q} + M_{\Sigma_1^*}}{q^2 - M_{\Sigma_1^*}^2 + iM_{\Sigma_1^*}\Gamma_{\Sigma_1^*}},$$

# $\Sigma(1385)$ in $\Lambda_c^+ \rightarrow \eta \pi^+ \Lambda$ decay



$$\mathcal{M}_2 = \frac{i g_{\pi \Lambda \Sigma_2^*}}{m_\eta m_\pi} \bar{u}(p_3) p_2^\mu G_{\mu\nu}^{\Sigma_2^*}(q) p_1^\nu (A_2 + B_2 \gamma_5) u(p),$$



$$G_{\mu\nu}^{\Sigma_2^*}(q) = i \frac{\not{q} + M_{\Sigma_2^*}}{q^2 - M_{\Sigma_2^*}^2 + i M_{\Sigma_2^*} \Gamma_{\Sigma_2^*}} P_{\mu\nu},$$

with

$$P^{\mu\nu} = -g^{\mu\nu} + \frac{1}{3} \gamma^\mu \gamma^\nu + \frac{2q^\mu q^\nu}{3M_{\Sigma_2^*}^2} + \frac{\gamma^\mu q^\nu - \gamma^\nu q^\mu}{3M_{\Sigma_2^*}}.$$

# Invariant mass distributions

$$\frac{d\Gamma}{dM_{\pi+\Lambda}} = \frac{m_{\Lambda}}{32\pi^3 M_{\Lambda_c^+}} \int \sum |\mathcal{M}|^2 |\vec{p}_1| |\vec{p}^*| d\cos\theta^*$$

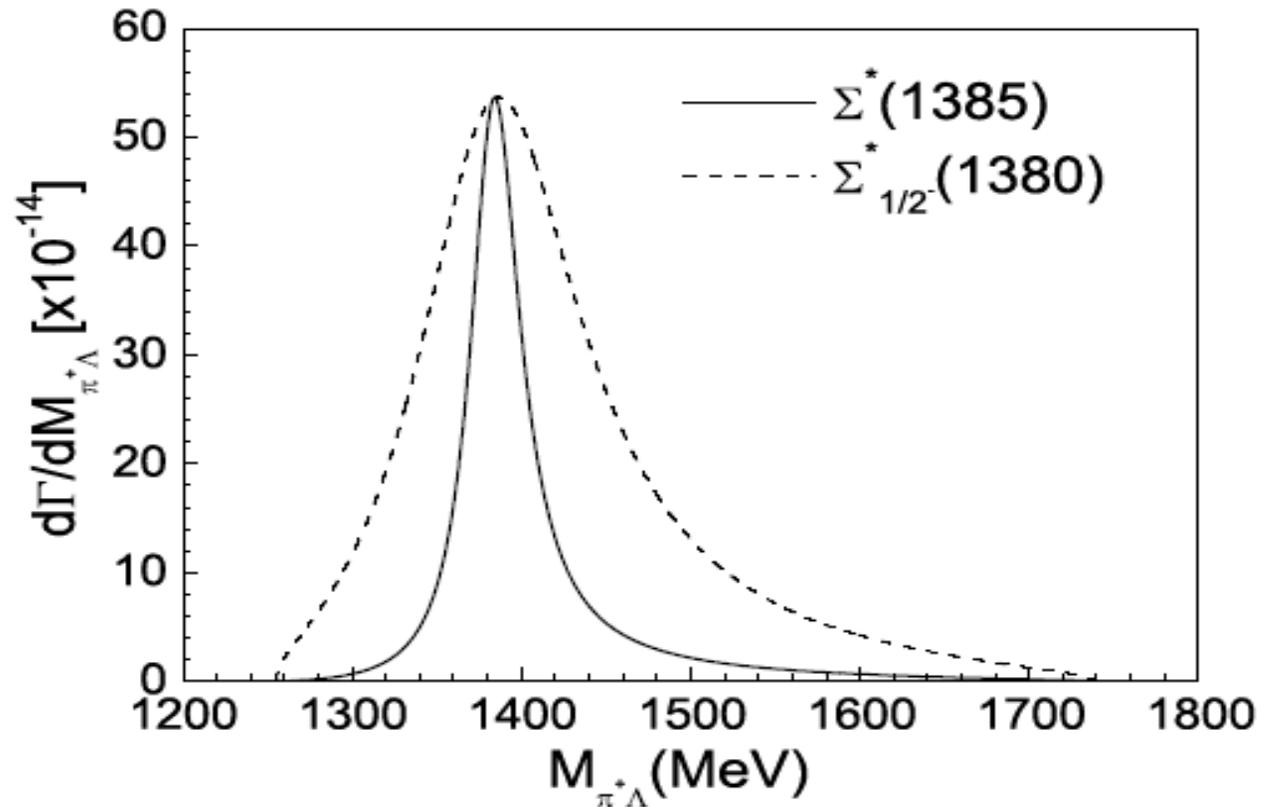


FIG. 5: Invariant mass distributions  $d\Gamma/dM_{\pi+\Lambda}$  as a function of  $M_{\pi+\Lambda}$ .

# Decay angle and energy distributions

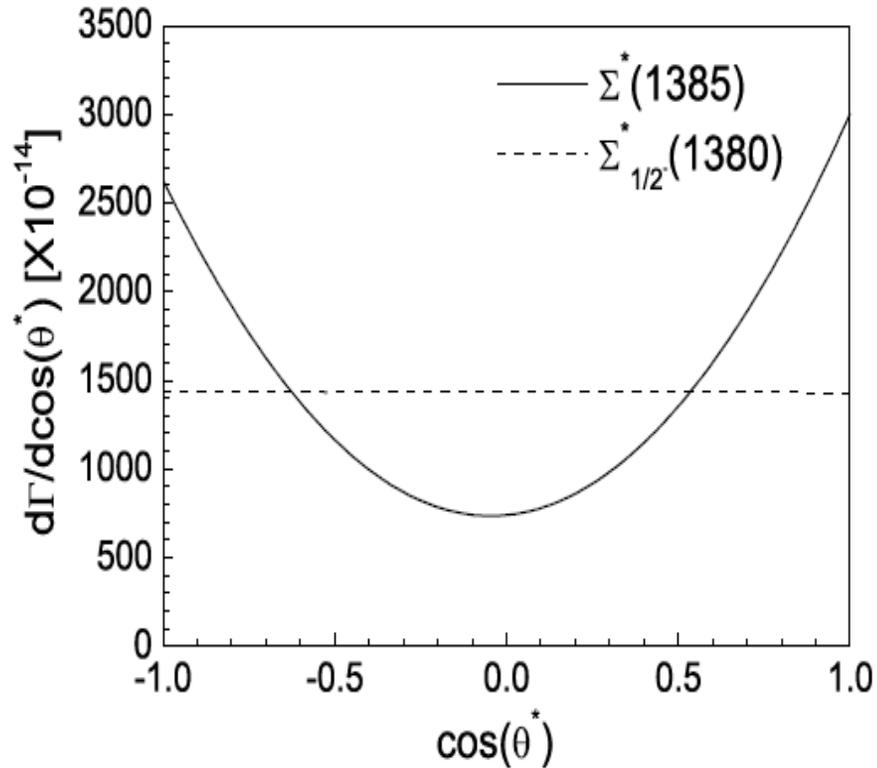


FIG. 6: Angle distributions  $d\Gamma/d\cos\theta^*$  in the c.m. frame of  $\pi^+\Lambda$  system as a function of  $\cos\theta^*$ .

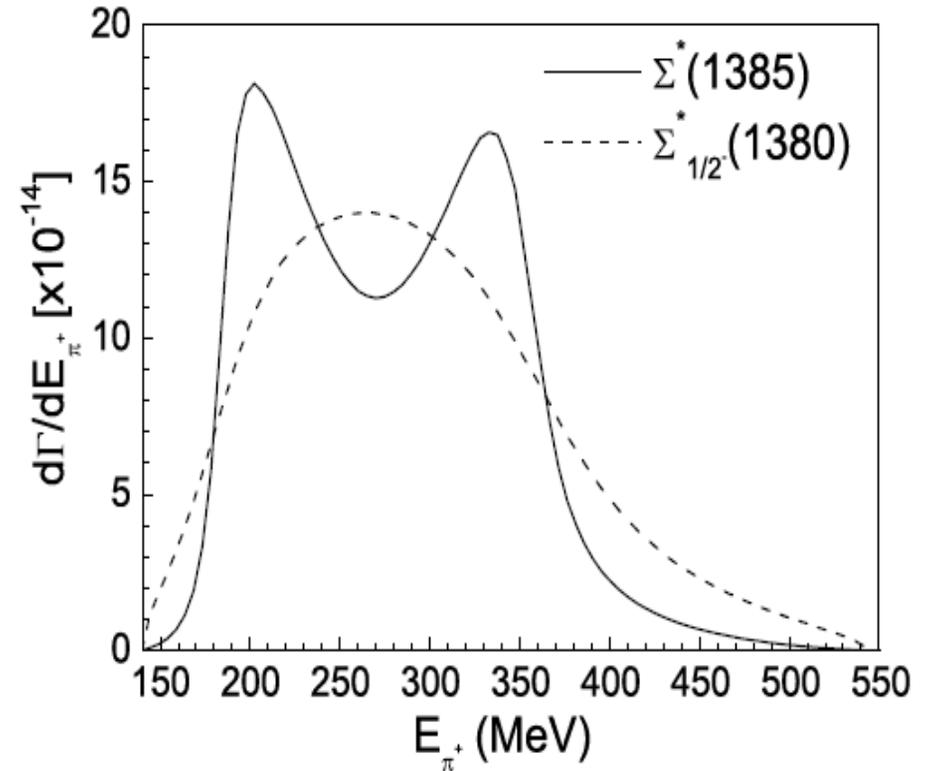
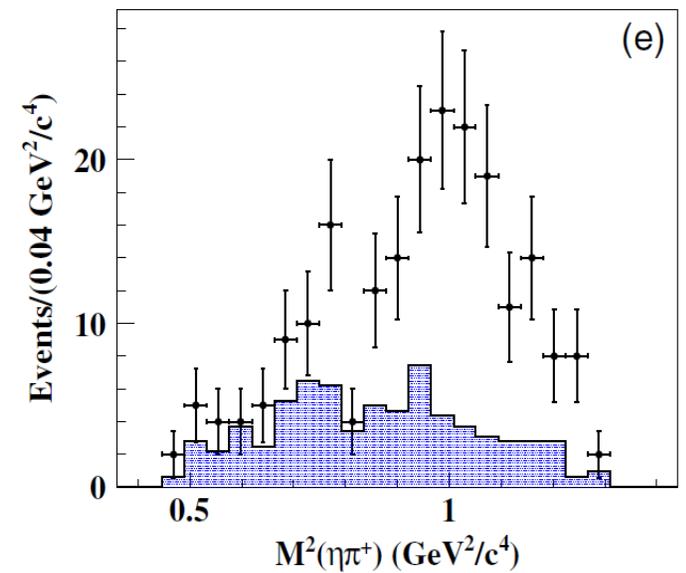
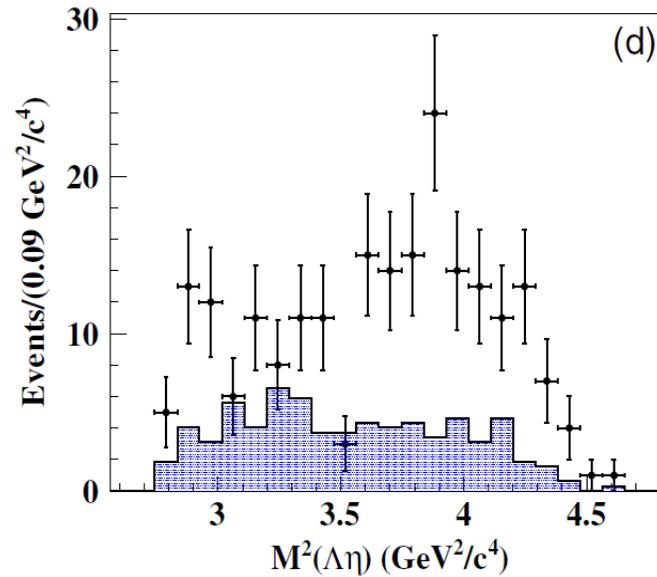
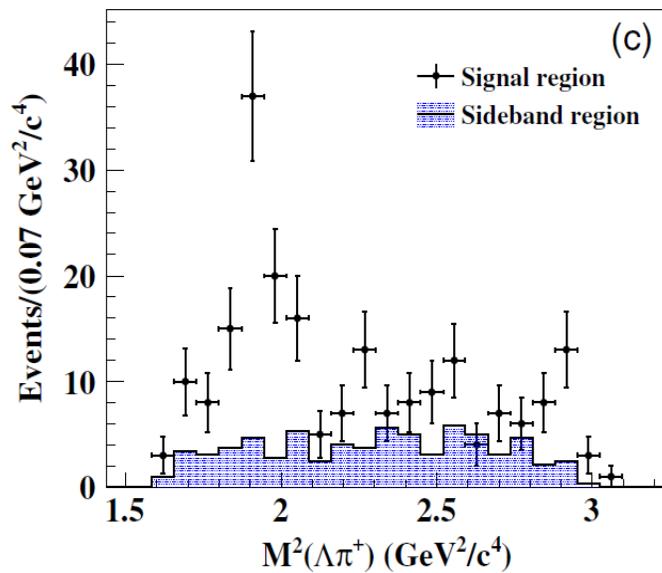
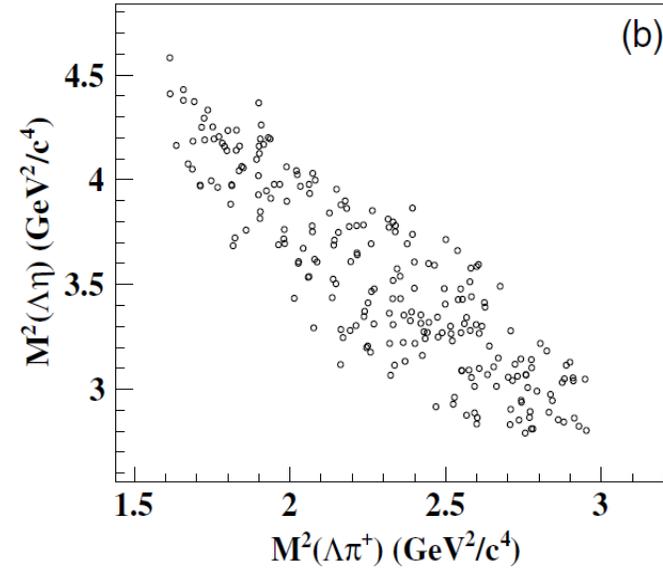
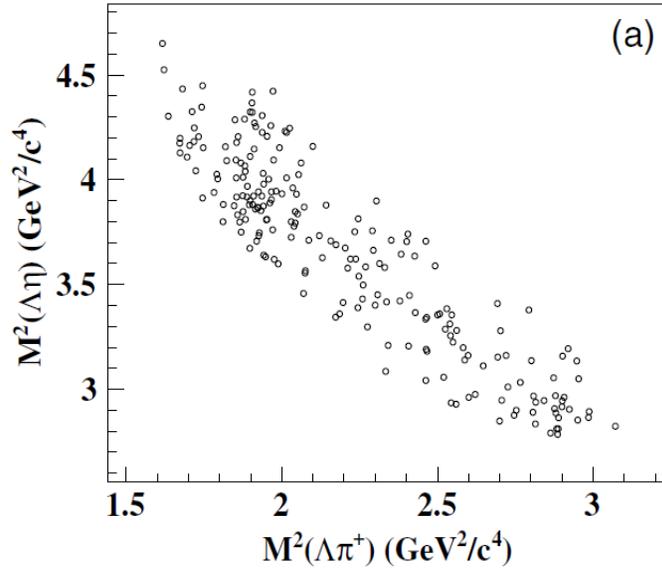


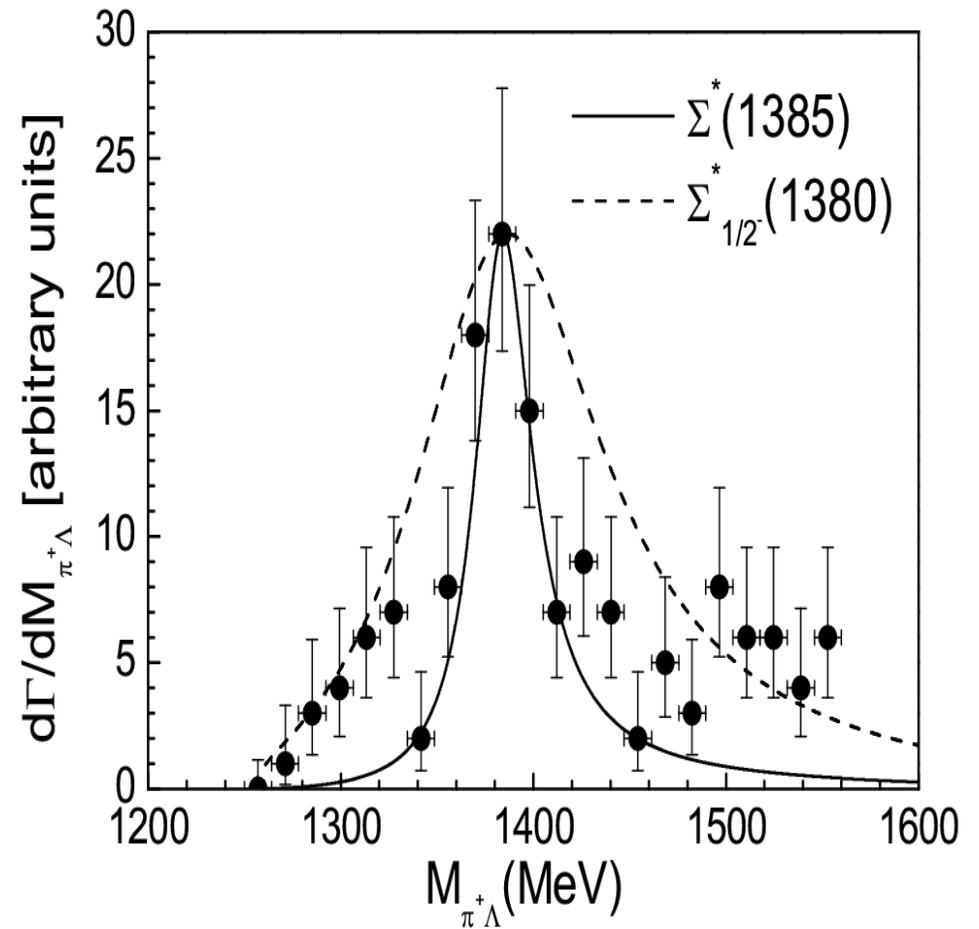
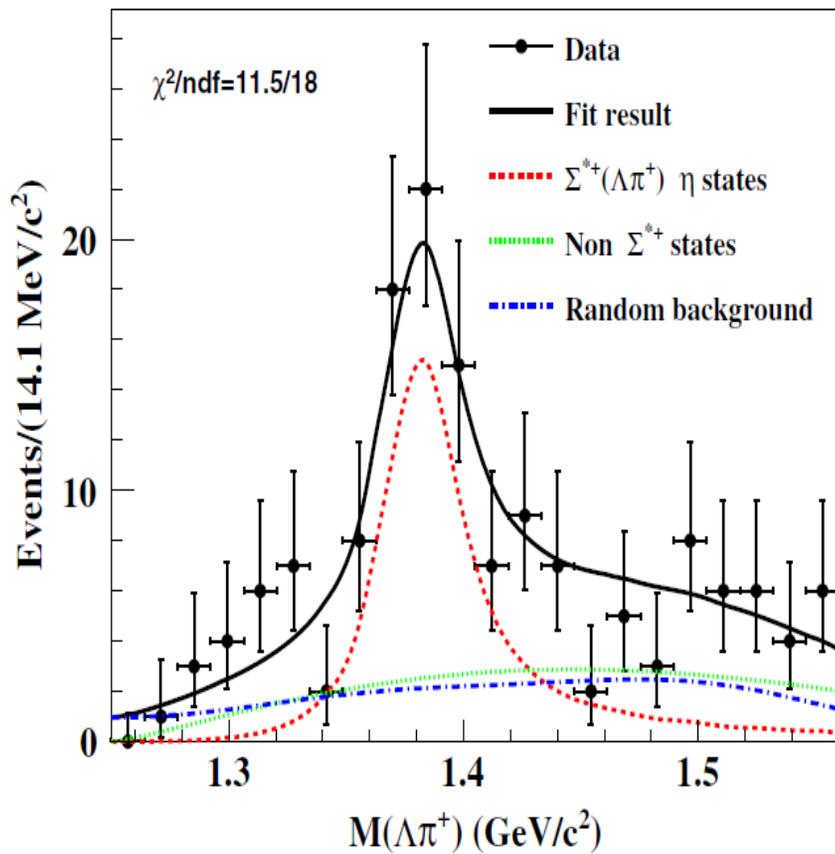
FIG. 7: Energy distributions  $d\Gamma/dE_{\pi^+}$  in the rest frame of  $\Lambda_c^+$  as a function of  $E_{\pi^+}$ .

# Measurement of the absolute branching fractions $\Lambda_c^+ \rightarrow \Lambda\eta\pi^+$ and $\Sigma(1385)^+\eta$ (BESIII Collaboration)

PRD 99, 032010 (2019).



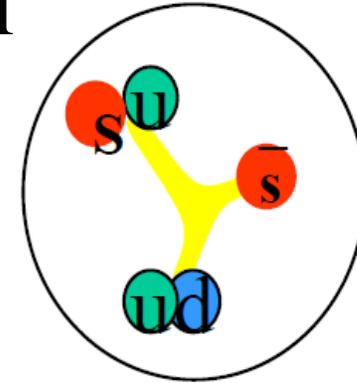
# $\pi^+\Lambda$ invariant mass distributions at low energies



# $N^*(1535)$ : strangeness component

Couples strongly to strangeness channel

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



	Mode	Fraction ( $\Gamma_i/\Gamma$ )
$\Gamma_1$	$N\pi$	32-52 %
$\Gamma_2$	$N\eta$	30-55 %

Larger  $[ud][us] \bar{s}$  component 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

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

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

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

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,<sup>\*</sup> 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*

(Received 31 October 2001; published 14 February 2002)

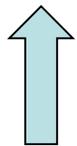
Chiral dynamics of the  $S_{11}(1535)$  and  $S_{11}(1650)$  resonances revisited

Peter C. Bruns<sup>a</sup>, Maxim Mai<sup>b,\*</sup>, Ulf-G. Meißner<sup>b,c</sup>

Physics Letters B 697 (2011) 254–259

- **Breit-Wigner parameterization**

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

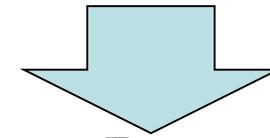


PDG 2018

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

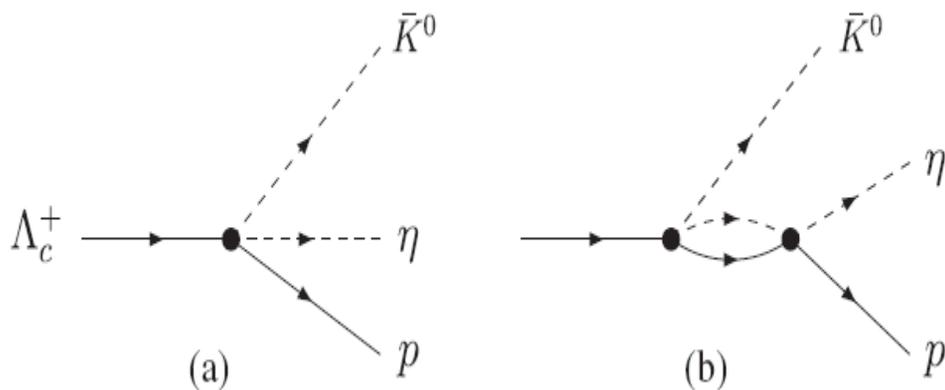
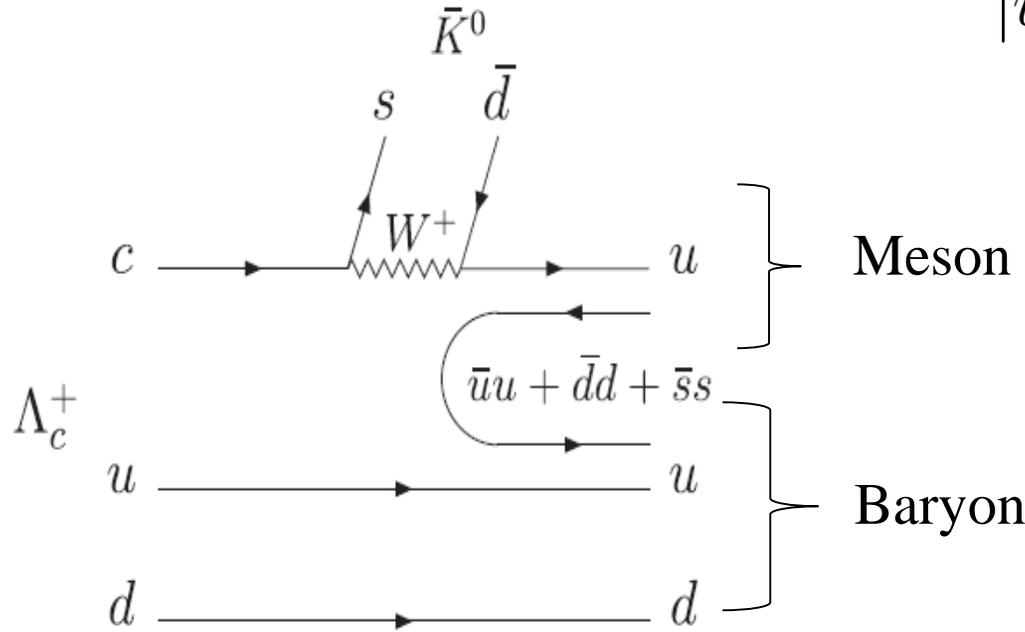
$$|uud\rangle \rightarrow \frac{1}{\sqrt{2}}|u(ud - du)\rangle$$

$$\bar{u}u + \bar{d}d + \bar{s}s$$

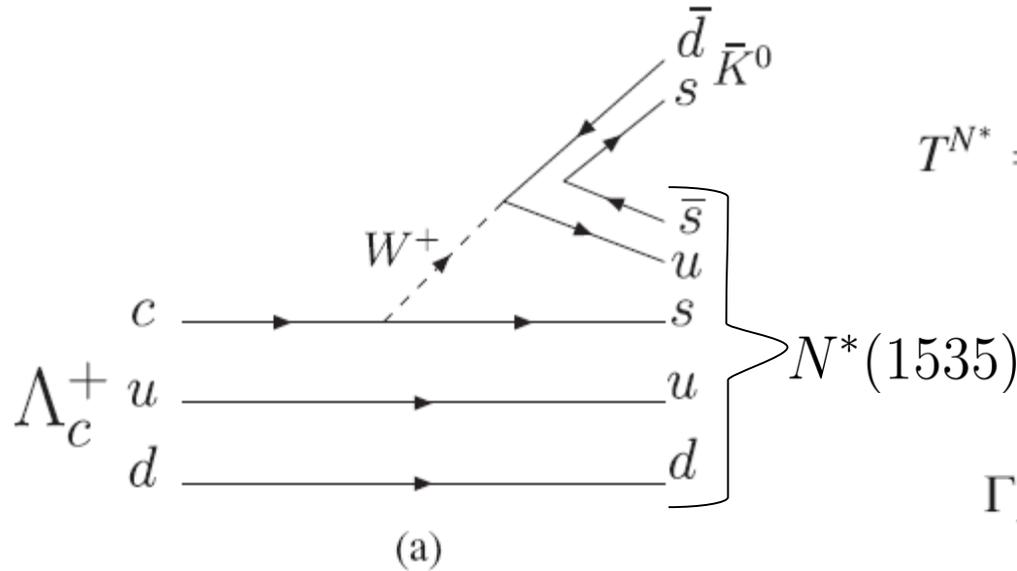


$$|MB\rangle = \frac{\sqrt{3}}{3}|\eta p\rangle + \frac{\sqrt{2}}{2}|\pi^0 p\rangle + |\pi^+ n\rangle - \frac{\sqrt{6}}{3}|K^+\Lambda\rangle,$$

$$T^{MB} = V_P \left( \frac{\sqrt{3}}{3} + \frac{\sqrt{3}}{3} G_{\eta p}(M_{\eta p}) t_{\eta p \rightarrow \eta p}(M_{\eta p}) \right. \\ \left. + \frac{\sqrt{2}}{2} G_{\pi^0 p}(M_{\eta p}) t_{\pi^0 p \rightarrow \eta p}(M_{\eta p}) \right. \\ \left. + G_{\pi^+ n}(M_{\eta p}) t_{\pi^+ n \rightarrow \eta p}(M_{\eta p}) \right. \\ \left. - \frac{\sqrt{6}}{3} G_{K^+\Lambda}(M_{\eta p}) t_{K^+\Lambda \rightarrow \eta p}(M_{\eta p}) \right),$$



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

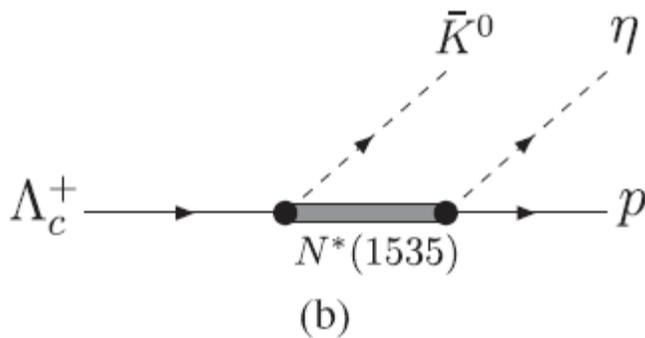


$$T^{N^*} = ig_{N^*N\eta} \bar{u}(p_3, s_p) G_{N^*}(q) (A + B\gamma_5) u(p, s_{\Lambda_c^+}),$$

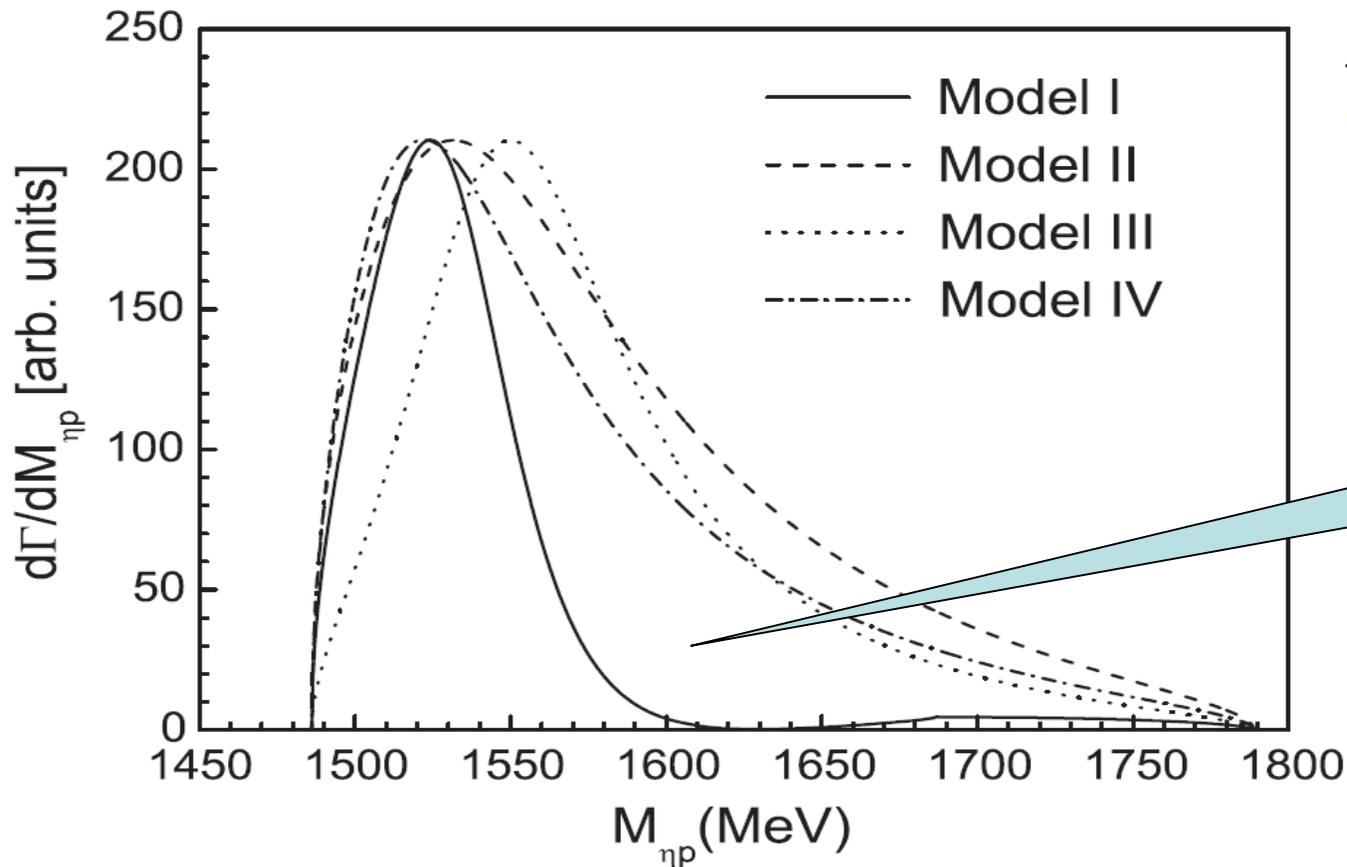
$$G_{N^*}(q) = i \frac{\not{q} + M_{N^*}}{q^2 - M_{N^*}^2 + iM_{N^*}\Gamma_{N^*}(q^2)},$$

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

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



# Invariant $\eta p$ mass distributions



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

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

Different line shapes

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

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

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

# Other contributions

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

$\Sigma^*$  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*

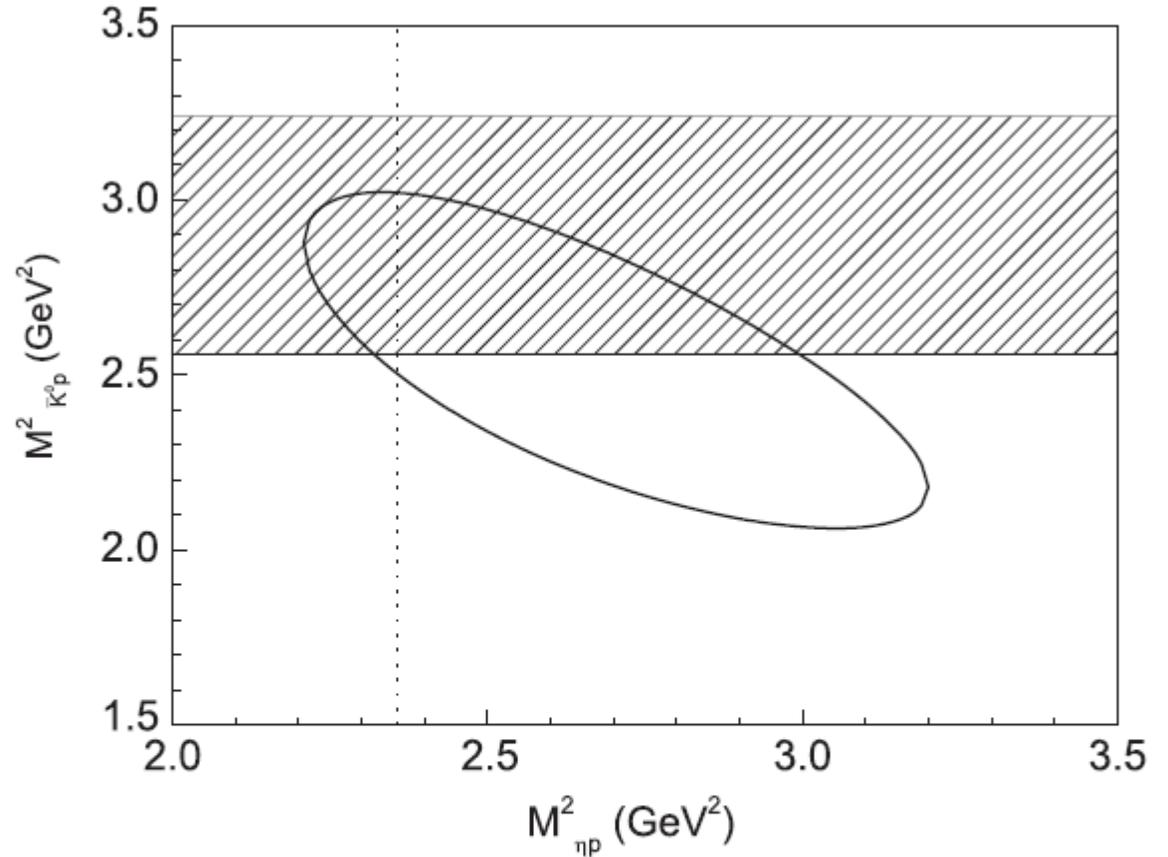


FIG. 7. Dalitz plot for  $M_{\eta p}^2$  and  $M_{\bar{K}^0 p}^2$  in the  $\Lambda_c^+ \rightarrow \bar{K}^0 \eta p$  decay. The  $N^*(1535)$  energy is shown by the vertical dotted line, and the horizontal band represents the masses of  $\Sigma^*$  states from 1600 to 1800 MeV.

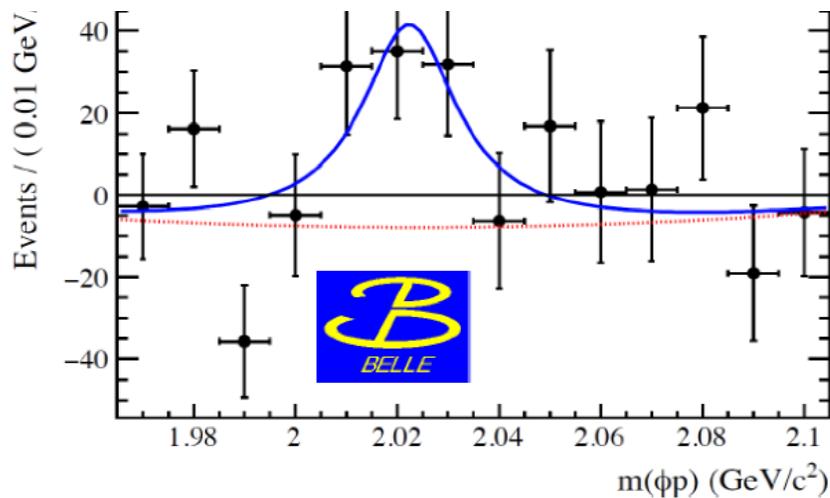
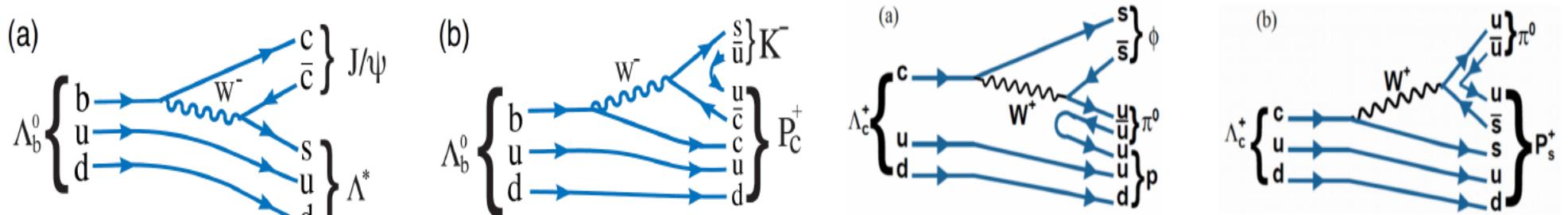
PRC 98, 015201 (2018).

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

See also the talk by  
Shuntaro SAKAI,  
Aug. 20, 17:20—17:40

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

R. Lebed, PRD92(2015)114030



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

From Cheng-Ping Shen

- **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\(R\) \(2017\); 915fb<sup>-1</sup>](#)

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

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

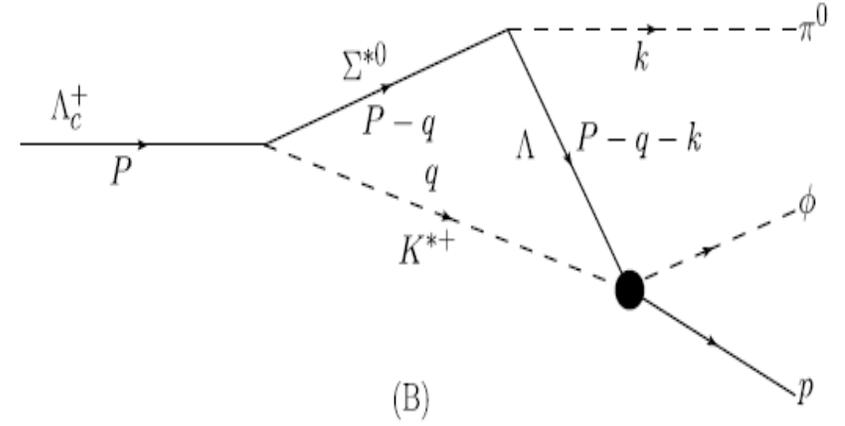
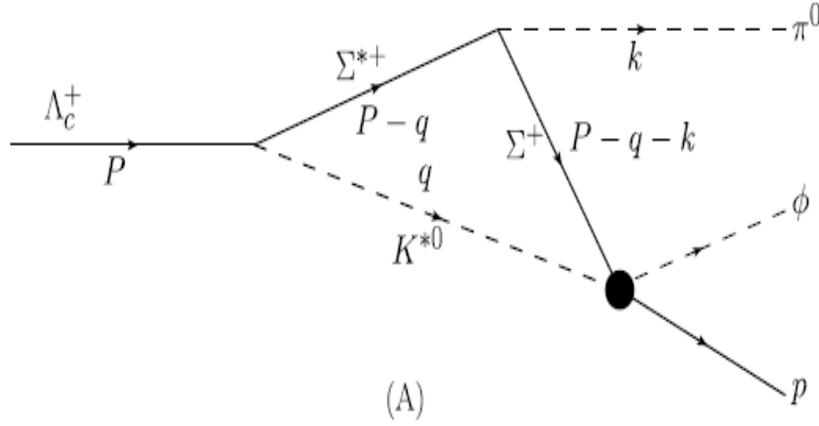


Fig. 1. Triangle diagrams for the  $\Lambda_c^+ \rightarrow \pi^0 p \phi$  decay. (A):  $\Sigma^+$ -exchange. (B):  $\Lambda$ -exchange. The definitions of the kinematical variables ( $P, q, k$ ) are also shown.

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

where we have defined  $C_\Sigma = \frac{\sqrt{6}}{3} t_{K^{*0} \Sigma^+ \rightarrow \phi p}$  and  $C_\Lambda = -t_{K^{*+} \Lambda \rightarrow \phi p}$ ,

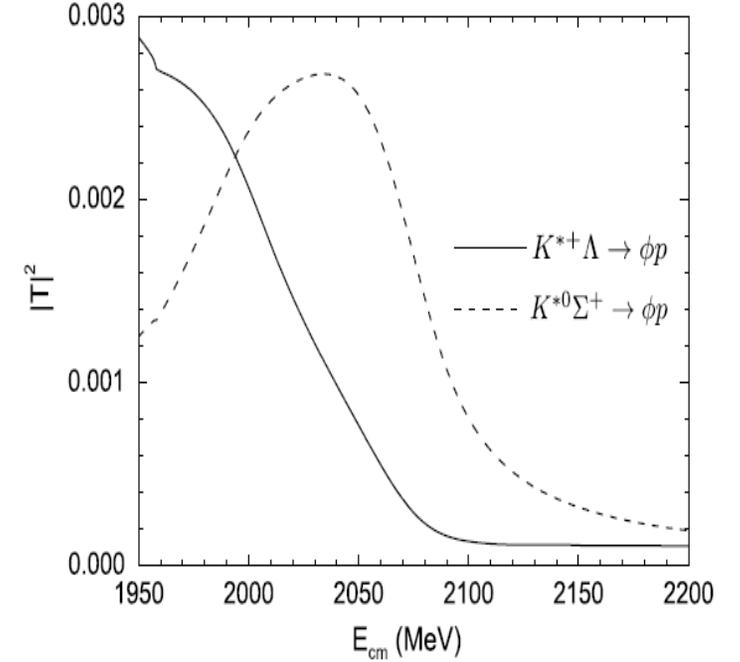
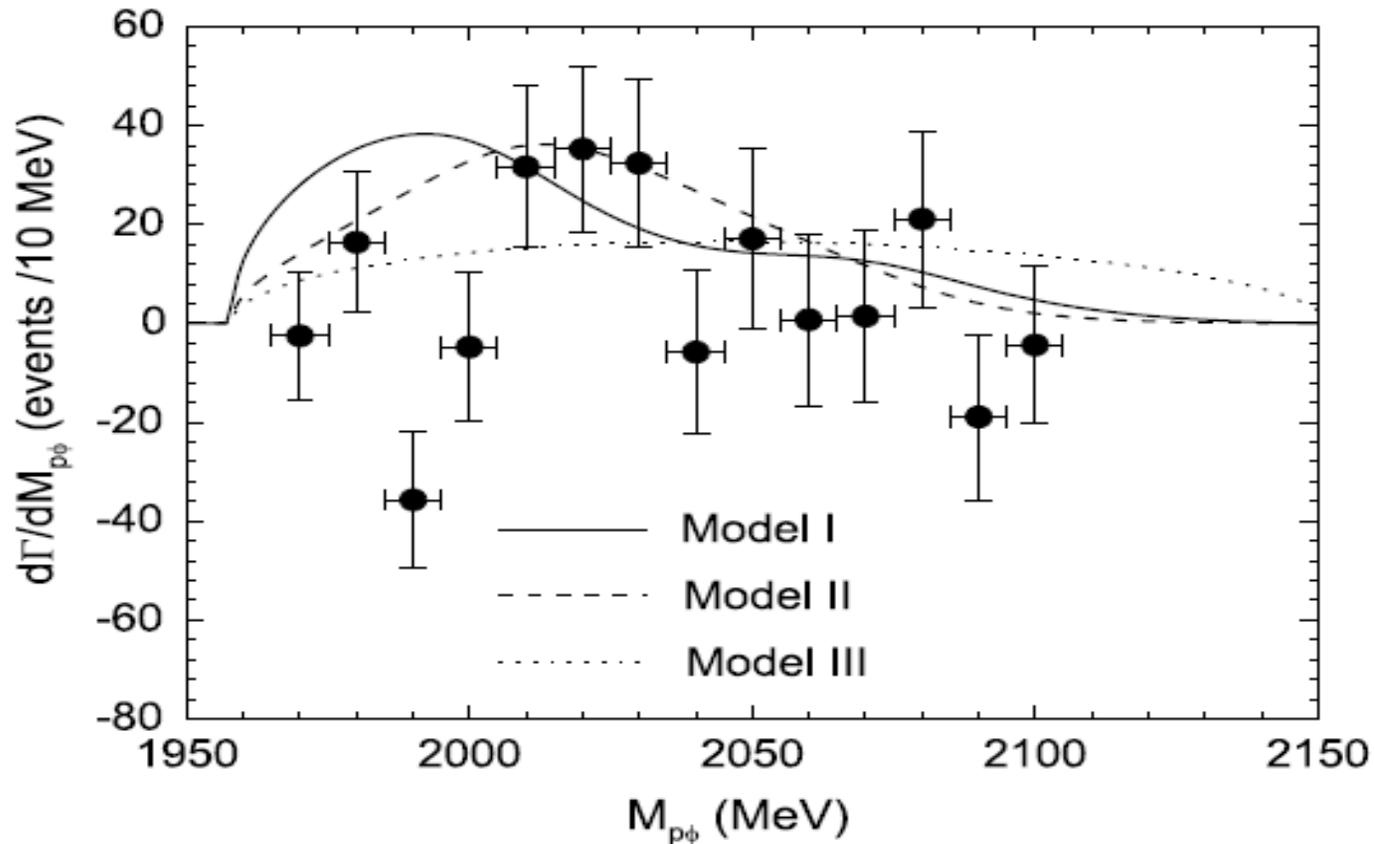


Fig. 3. The squared norm of the  $T$ -matrix elements for  $K^{*+} \Lambda \rightarrow \phi p$  and  $K^{*0} \Sigma^+ \rightarrow \phi p$  as a function of the meson-baryon invariant mass  $E_{cm}$  in the model of Ref. [72].



**Fig. 2.** Invariant mass distribution of the  $\Lambda_c^+ \rightarrow \pi^0 p \phi$  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  $\Lambda_c^+ \rightarrow \eta\pi^+\Lambda$  decay can be used to study the  $\Sigma_{1/2}^*$  resonance*

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

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

TS produces **a bump at around 2.02 GeV**

$P_s$ , 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!*

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

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

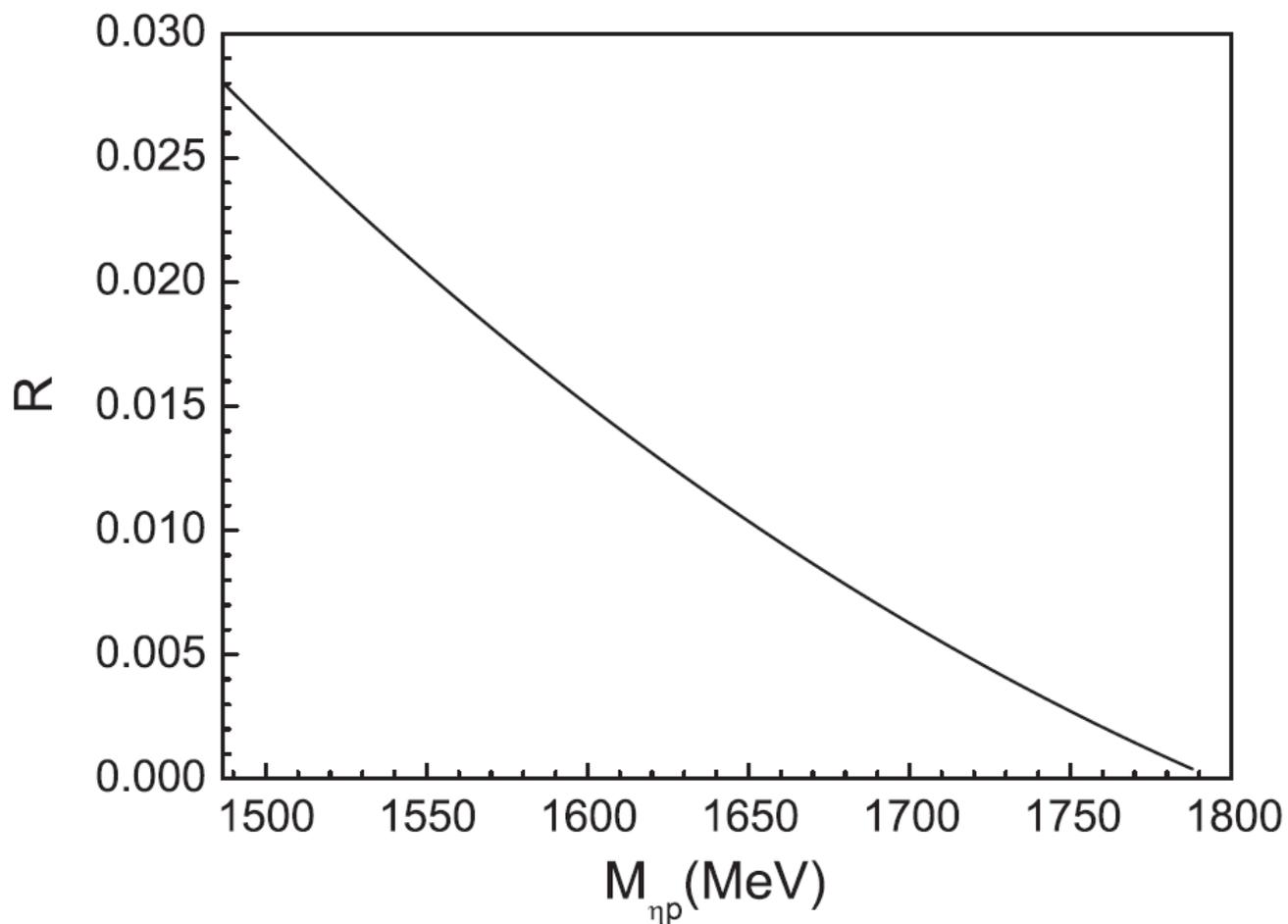


FIG. 6. Ratio  $R$  of the  $B$  and  $A$  terms as a function of the  $\eta p$  invariant mass.