# Production of $\Lambda_c(2940)$ at PANDA

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J. He, Z. Ouyang, X. Liu and X. Q. Li, Phys. Rev. D 84 (2011),114010

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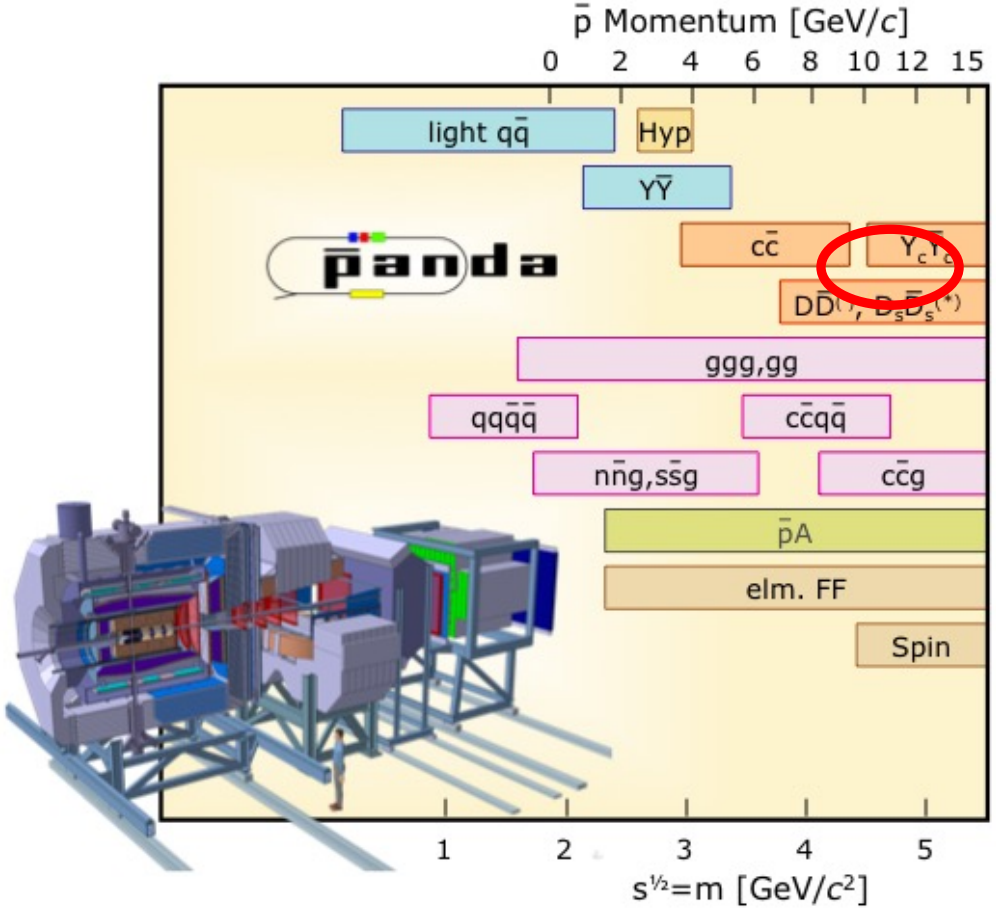
# Outline

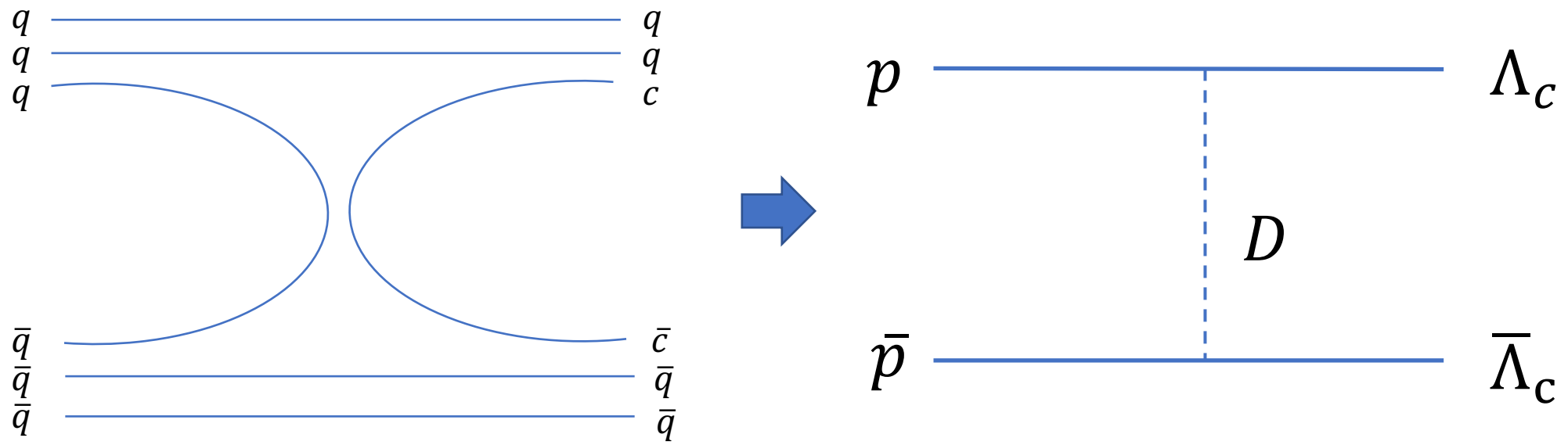
- Introduction
- Production of $\Lambda_c(2940)$
- Daltiz Plot and Background analysis
- Other baryon productions at PANDA
- Summary

# Production of charmed baryon at PANDA

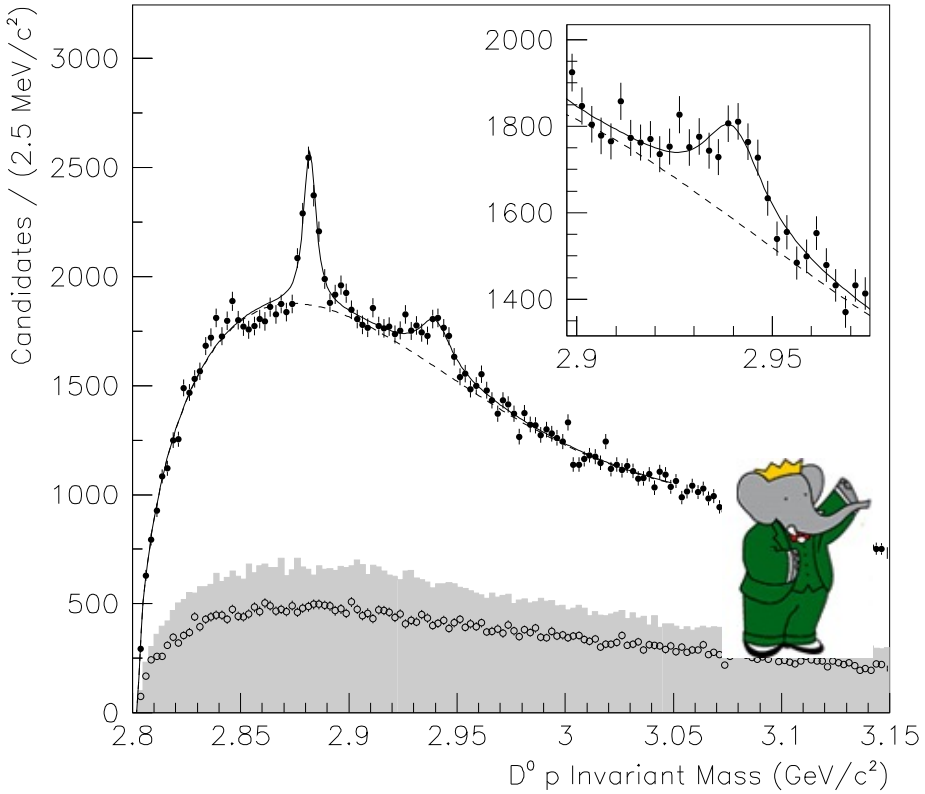


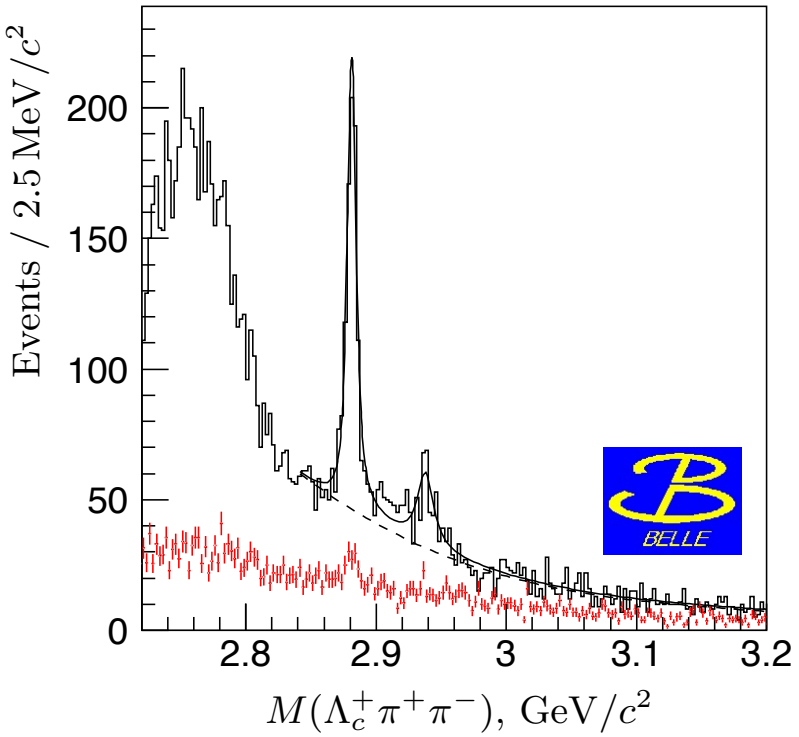

Physics Performance Report for PANDA: Strong Interaction Studies with Antiprotons

# Production of charmed baryon at PANDA



# $\Lambda_c(2940)$




Not find in $D^+p$ invariant mass spectrum: isoscalar

# Conventional charmed baryon?

## mass

- $J^P = 5/2^{\pm}, 3/2^+$:

$M_{5/2^-}$2900 MeV; $M_{5/2^+}$ or $M_{3/2^+}$ 2910 MeV

The potential model

[Capstick, PRD34(1986)2809]

- $\Sigma_c(2S)\ with\ J^P = 3/2^+$: 2912MeV

Relativistic quark-diquark model

[Ebert, PLB659(2008)612]

- $\Lambda_c(L = 3)\ with\ J^P = 5/2^-$: 2935MeV

Mass load flux tube model

[Zhang, CPC33(2009)1327]

- $\Sigma_c(2S)\ with\ J^P = 3/2^+$: 2944MeV

Faddeev method

[Valcarce, EPJA37(2008)217]

## Decay

- $J^P = 5/2^-, 3/2^+$:

The ratio of $\Sigma_c^*\pi/\Sigma_c\pi$ in heavy hadron is useful to distinguish the $J^P$ quantum number of $\Lambda_c(2940)^+$.

Chiral perturbation theory

[Cheng, PRD75(2007)014006]

- D-wave $\tilde{\Lambda}_{c1}^0(1/2^+)$ or $\tilde{\Lambda}_{c1}^0(3/2^+)$:

The first radial excitation of $\Lambda_c(2286)^+$ is fully excluded since $\Lambda_c(2940)^+ \to D^0\,p$ was observed by BaBar

$3P0$ model

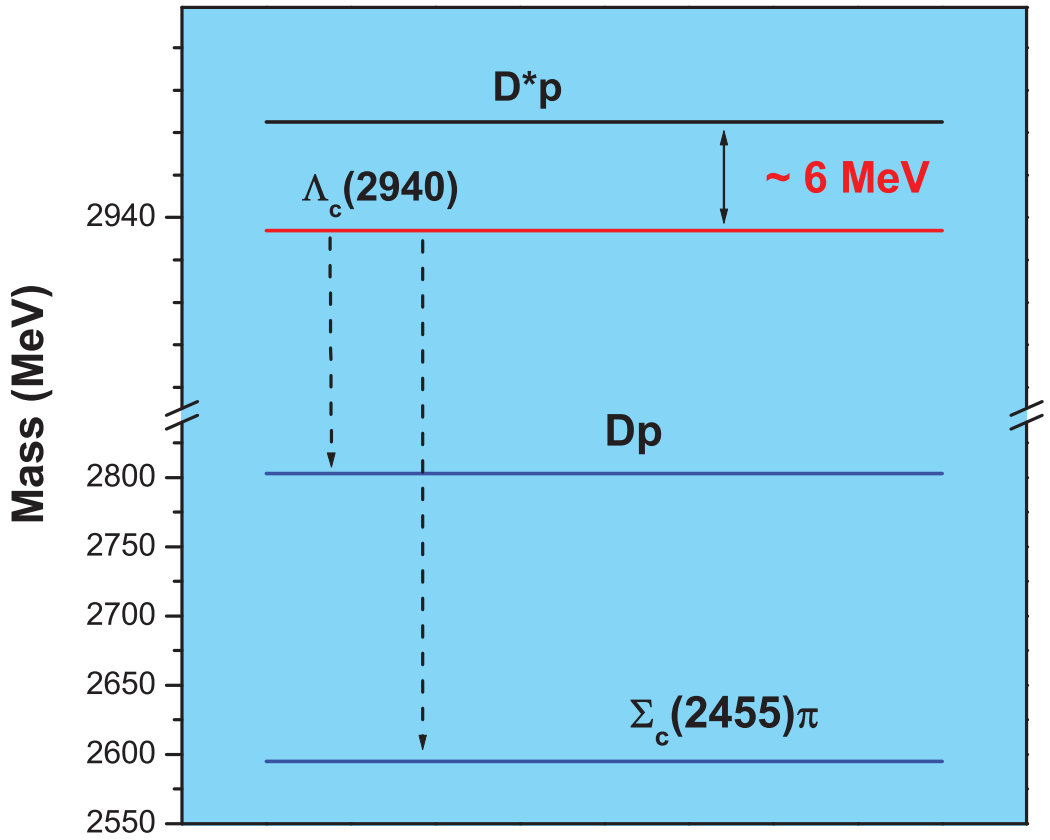
[Chen, PRD75(2007)094017]

- $\Lambda_c,^2 D\_(\lambda\lambda)3/2^+$:

Chiral quark model

[Zhong,PRD77(2007)074008]

# Exotic explanation?




$J^P = 1/2^-$ or $1/2^+$ (S-wave)

The masses of $D^*N$ molecular states were calculated in the potential model.

[He, EPJC51(2007)883]

$J^P = 1/2^+$ (P-wave)

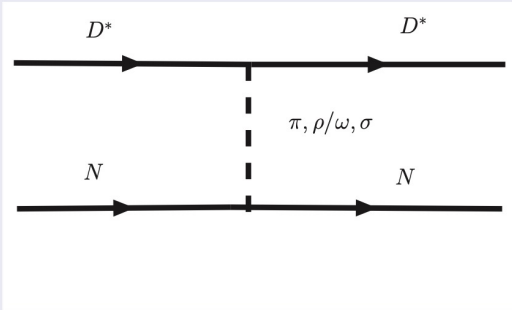
Strong decay; radiative decay

[Dong, PRD82(2009)034035,PRD83(2011)094005]

# The dynamical study of $D^*N$ system

## kinematics of OBE

$$V(\mathbf{q}) = -\frac{1}{\sqrt{\prod_i 2M_i \prod_f 2M_f}}\mathcal{M}(J, J_Z)$$




### $\mathcal{L}_{D^*D^*m}$

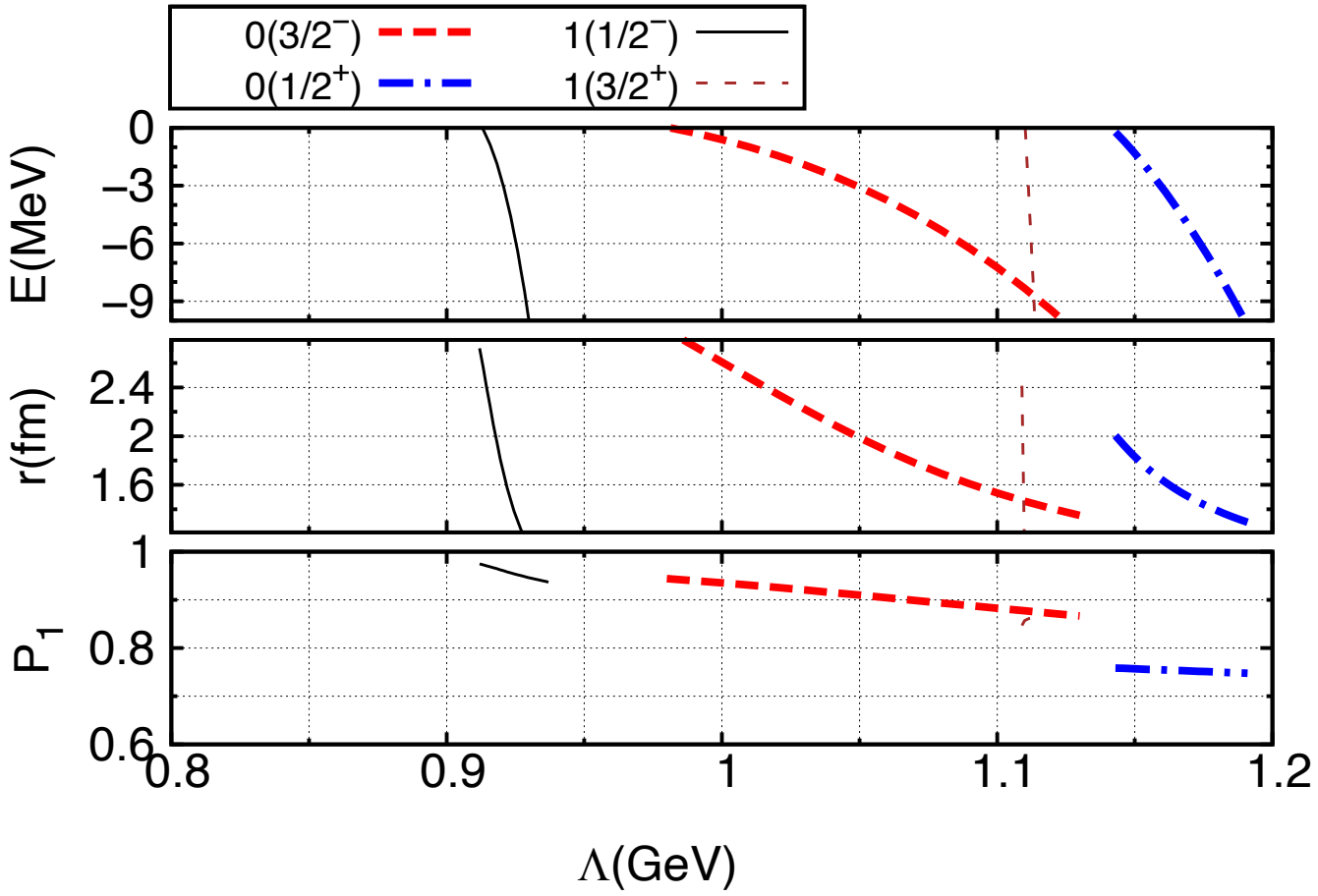
$$\begin{aligned}
\mathcal{L}_{HH\mathbb{P}} &= ig\langle H_b\gamma_\mu A^\mu_{ba}\gamma_5\bar{H}_a\rangle, \\
\mathcal{L}_{HH\mathbb{V}} &= i\beta\langle H_b v_\mu(\mathcal{V}^\mu_{ba} - \rho^\mu_{ba})\bar{H}_a\rangle \\
&\quad + i\lambda\langle H_b\sigma_{\mu\nu}F^{\mu\nu}(\rho)\bar{H}_a\rangle, \\
\mathcal{L}_{HH\sigma} &= g_s\langle H_a\sigma\bar{H}_a\rangle,
\end{aligned}$$

### $\mathcal{L}_{NNm}$

$$\begin{aligned}
\mathcal{L}_{\mathbb{P}NN} &= -\frac{g_{\mathbb{P}NN}}{\sqrt{2}m_N}\bar{N}_b\gamma_5\gamma_\mu\partial_\mu\mathbb{P}_{ba}N_a, \\
\mathcal{L}_{\mathbb{V}NN} &= -\sqrt{2}g_{\mathbb{V}NN}\bar{N}_b\left(\gamma_\mu + \frac{\kappa}{2m_N}\sigma_{\mu\nu}\partial^\nu\right)\mathbb{V}^\mu_{ba}N_a, \\
\mathcal{L}_{\sigma NN} &= g_{\sigma NN}\bar{N}_a\sigma N_a
\end{aligned}$$

Jun He, Xiang Liu, Phys. Rev. D **82**, 114029

# The dynamical study of $D^*N$ system

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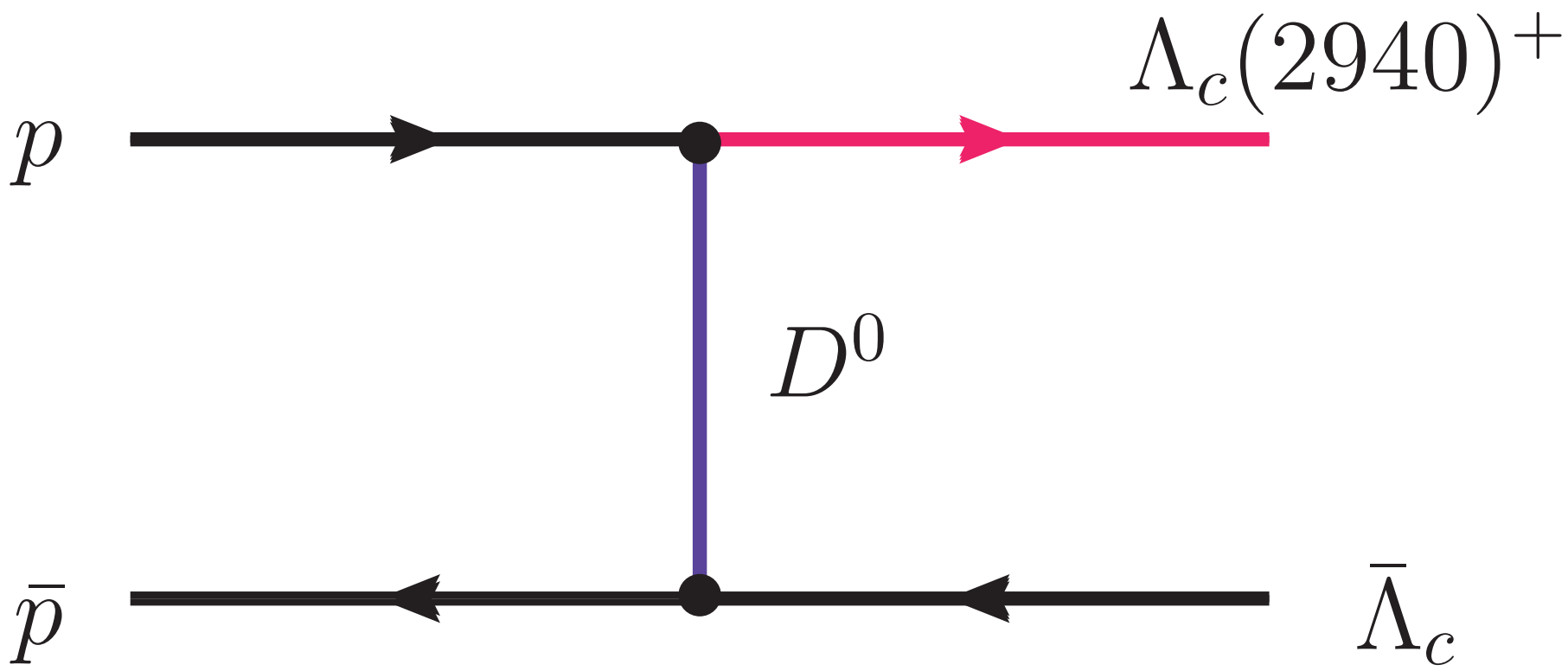
# The possible $J^P$ assignments to the $\Lambda_c(2940)^+$ in the literature

| | | $1/2^+$ | $1/2^-$ | $3/2^+$ | $3/2^-$ | $5/2^+$ | $5/2^-$ |
|---|---|---|---|---|---|---|---|
| He et al. | [3] | | ✓ | | ✓ | | |
| Dong et al. | [5] | $\binom{0.20\pm0.09}{0.95\pm0.37}$ | × | | | | |
| Dong et al. | [6, 7] | ✓ | | | | | |
| He et al. | [4] | ✓ | | | ✓ | | |
| Capstick et al. | [8, 9] | | | ✓ | | ✓ | ✓ |
| Cheng et al. | [12] | | | ✓ | | | ✓ |
| Zhong et al. | [14] | | | | | $\binom{1.08}{1.06}$ | |
| Chen et al. | [13] | $\binom{11}{2.2}$ | | $\binom{11}{0.6}$ | | | |
| Ebert et al. | [10] | | | ✓ | | | |
| Valcarce et al. | [11] | | | ✓ | | | |
| Chen et al. | [15] | | | | | | ✓ |

The upper and lower values in the bracket:
the decay widths for its $D^0p$ and $\Sigma_c^{++}\pi^-$channels.

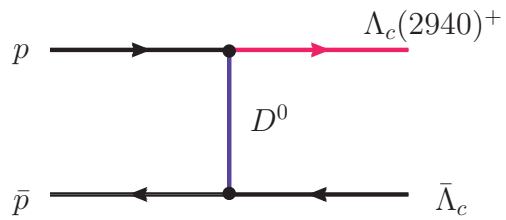
# Production of $\Lambda_c(2940)$




The cross section is suppressed by an additional ISI factor 1/10.

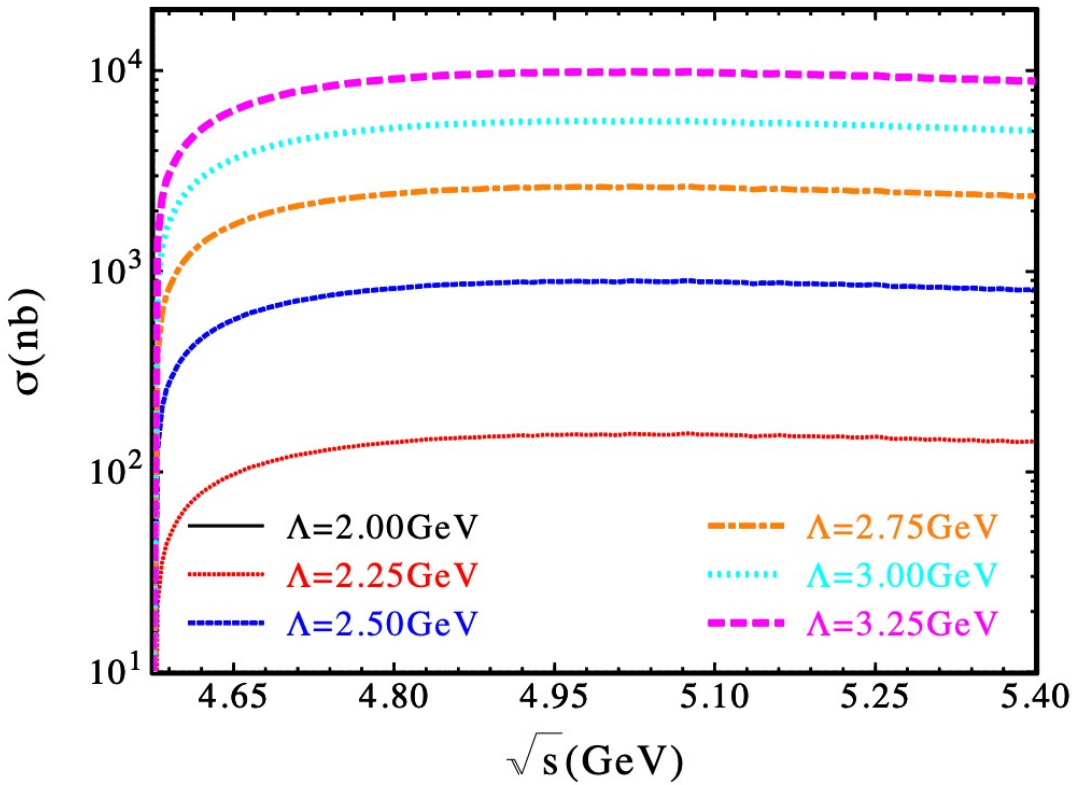
# Lagrangian

$$\mathcal{L}_{\frac{1}{2}^+} = g_{\frac{1}{2}^+}\,\Lambda_c(2940)^+\, i\gamma_5\, p\, D^0,$$
$$\mathcal{L}_{\frac{1}{2}^-} = g_{\frac{1}{2}^-}\,\Lambda_c(2940)^+\, p\, D^0,$$
$$\mathcal{L}_{\frac{3}{2}^+} = g_{\frac{3}{2}^+}\,\Lambda_c^{\mu}(2940)^+\, p\, \partial_\mu D^0,$$
$$\mathcal{L}_{\frac{3}{2}^-} = g_{\frac{3}{2}^-}\,\Lambda_c^{\mu}(1940)^+\, i\gamma_5\, p\, \partial_\mu D^0,$$
$$\mathcal{L}_{\frac{5}{2}^+} = g_{\frac{5}{2}^+}\,\Lambda_c^{\mu\nu}(2940)^+\, i\gamma_5\, p\, \partial_\mu\partial_\nu D^0,$$
$$\mathcal{L}_{\frac{5}{2}^-} = g_{\frac{5}{2}^-}\,\Lambda_c^{\mu\nu}(2940)^+\, p\, \partial_\mu\partial_\nu D^0,$$



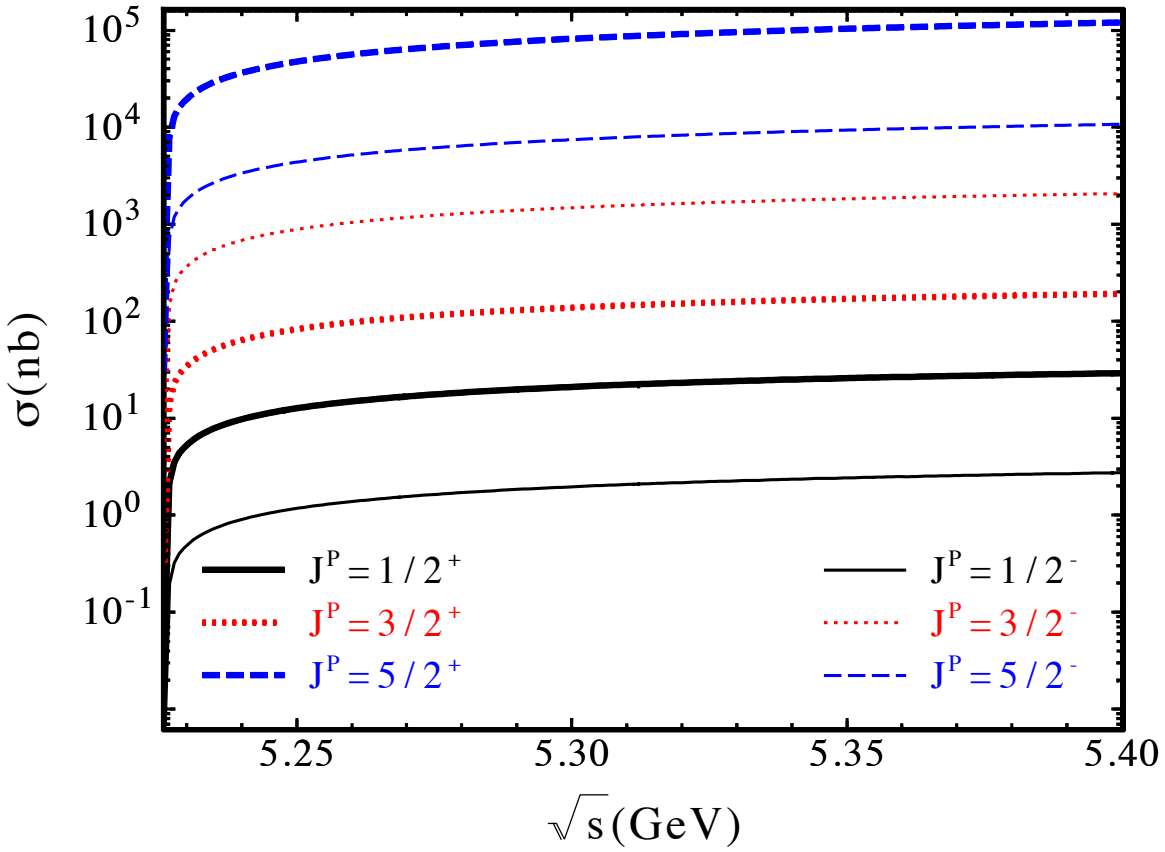

$$\mathcal{F}(k^2) = (\Lambda^2 - m_D^2)/(\Lambda^2 - k^2)$$

$$\frac{\Gamma(\Lambda_c(2940)^+ \to pD^0)}{g^2_{J^P}} = \frac{m_N}{4(2J+1)\pi}\frac{2|\boldsymbol{k}|}{\sqrt{s}} B_S A^J$$




In Ref. [30], the reaction $p\bar{p} \to \Lambda_c\bar{\Lambda}_c$ was supposed to occur via a meson-exchange mechanism, where the cutoff $\Lambda$ was set as 3 GeV. An obvious similarity between $p\bar{p} \to \Lambda_c\bar{\Lambda}_c$ and $p\bar{p} \to \bar{\Lambda}_c\Lambda_c(2940)^+$ suggests that we adopt $\Lambda = 3$ GeV to estimate the cross section of $p\bar{p} \to \bar{\Lambda}_c\Lambda_c(2940)^+$.

# Cross section of production of $\Lambda_c(2940)$



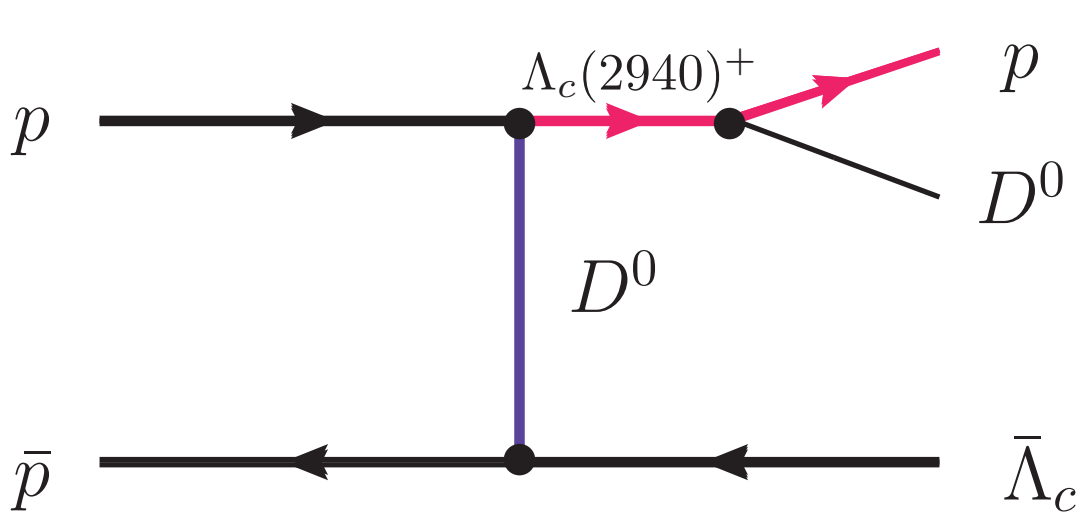

Designed luminosity of PANDA:
$2\times10^{32}\ cm^{-2}/s$,

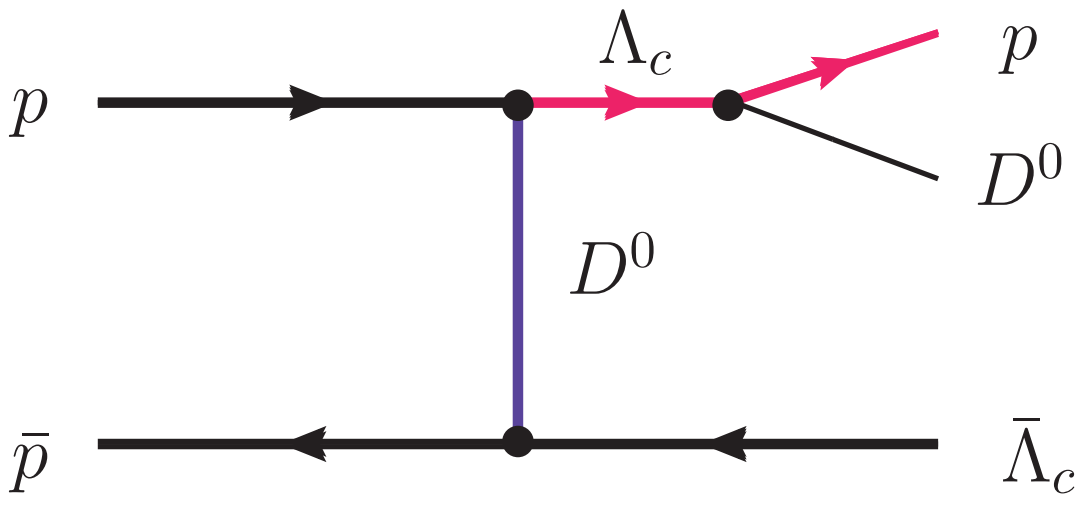
Integrated luminosity in one day run
About $10^4 nb^{-1}$,

50% overall efficiency,

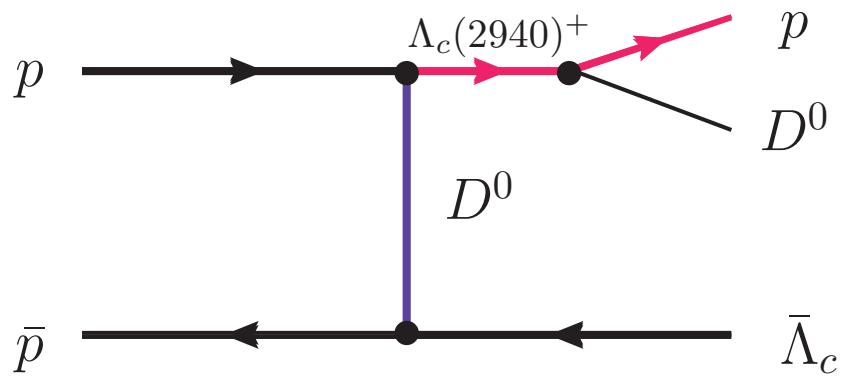
$10^4 \sim 10^8$ events of $\Lambda_c(2940)^+$ per day produced at PANDA.

# Daltiz Plot and background analysis



# Lagrangians




$$G^{n+\frac{1}{2}}(q) = P^{(n+\frac{1}{2})} G_R(q^2) = P^{(n+\frac{1}{2})} \frac{2M_R}{q^2 - M_R^2 + iM_R\Gamma_R}$$

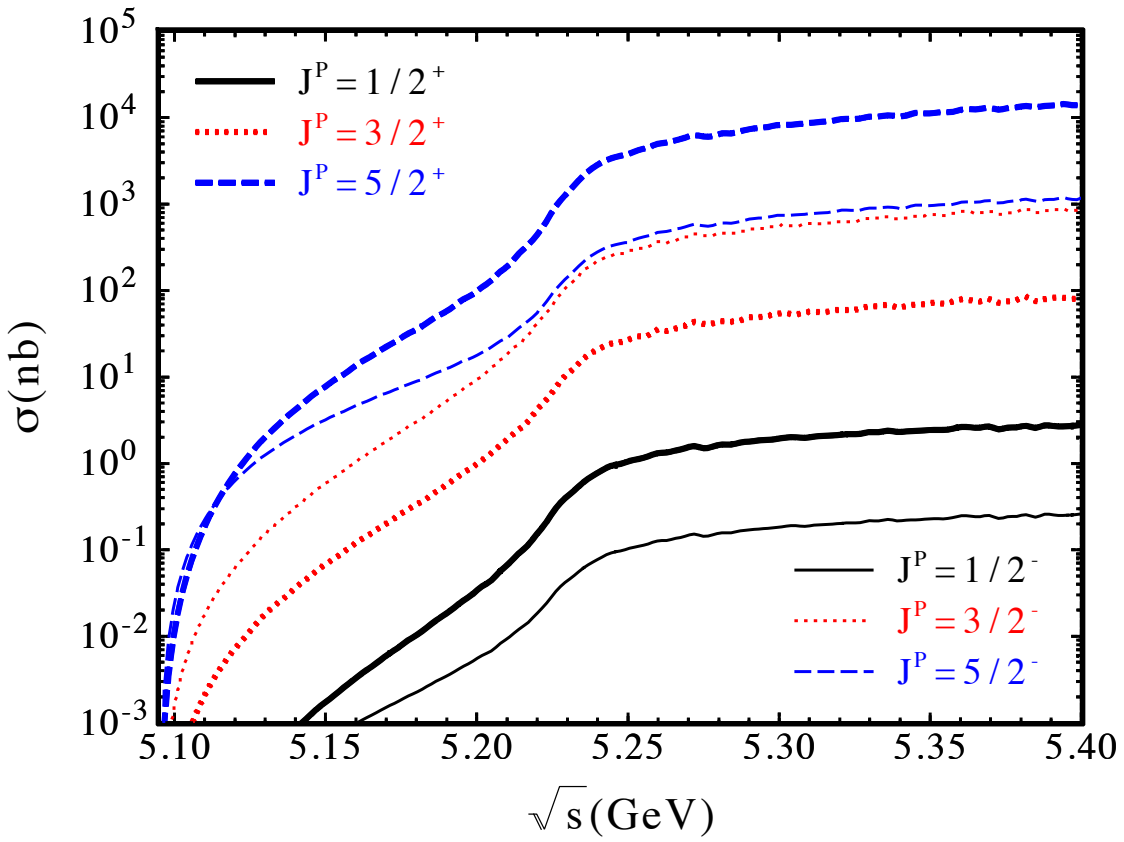
$$P^{\frac{1}{2}}(q) = \frac{\not{q} + M_R}{2M_R}, \tag{9}$$

$$P^{\frac{3}{2}}_{\mu\nu}(q) = \frac{\not{q} + M_R}{2M_R}\left[ -g_{\mu\nu} + \frac{1}{3}\gamma_\mu\gamma_\nu + \frac{1}{3M_R}(\gamma_\mu q_\nu - \gamma_\nu q_\mu) + \frac{2}{3M_R^2} q_\mu q_\nu \right], \tag{10}$$

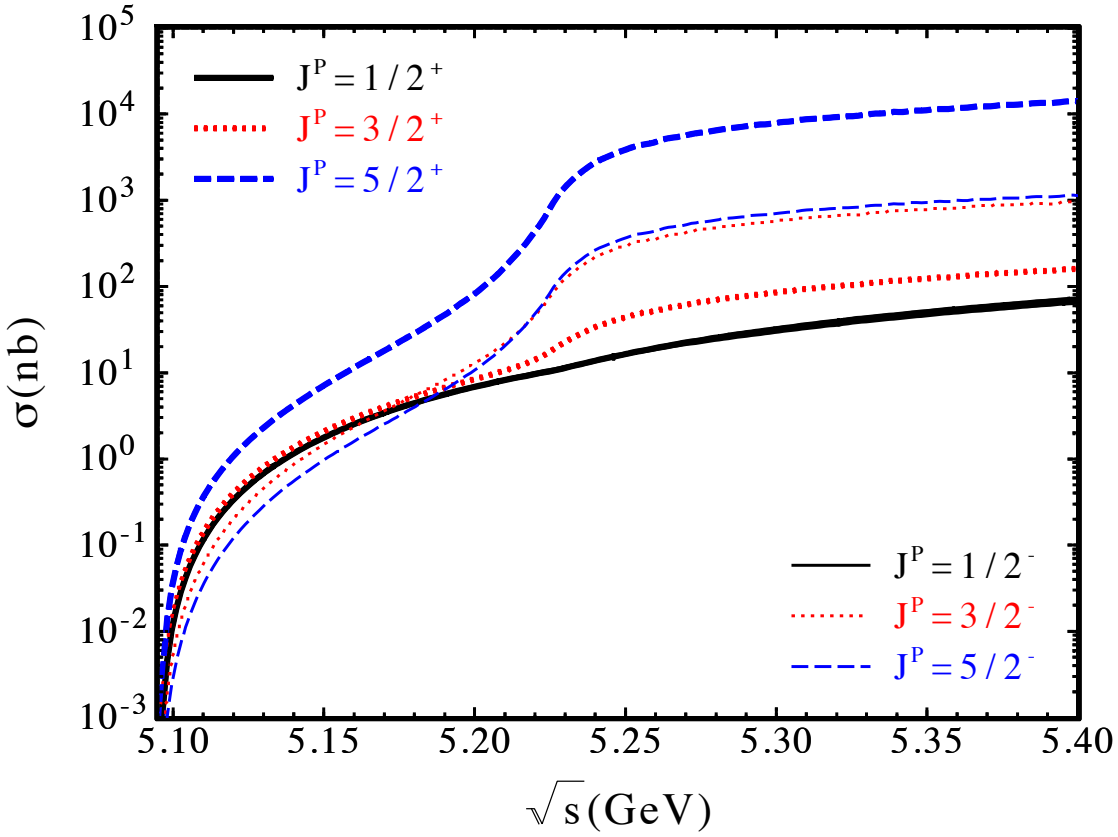
$$P^{\frac{5}{2}}_{\mu_1\mu_2\nu_1\nu_2}(q) = \frac{\not{q} + M_R}{2M_R}\left[ \frac{1}{2}(\widetilde{g}_{\mu_1\nu_1}\widetilde{g}_{\mu_2\nu_2} + \widetilde{g}_{\mu_1\nu_2}\widetilde{g}_{\mu_2\nu_1}) - \frac{1}{5}\widetilde{g}_{\mu_1\mu_2}\widetilde{g}_{\nu_1\nu_2} - \frac{1}{10}(\widetilde{\gamma}_{\mu_1}\widetilde{\gamma}_{\nu_1}\widetilde{g}_{\mu_2\nu_2} + \widetilde{\gamma}_{\mu_1}\widetilde{\gamma}_{\nu_2}\widetilde{g}_{\mu_2\nu_1} + \widetilde{\gamma}_{\mu_2}\widetilde{\gamma}_{\nu_1}\widetilde{g}_{\mu_1\nu_2} + \widetilde{\gamma}_{\mu_2}\widetilde{\gamma}_{\nu_2}\widetilde{g}_{\mu_1\nu_1}) \right], \tag{11}$$

# Cross section

## Without background




## With background



# Daltiz Plot and invariant mass spectrum

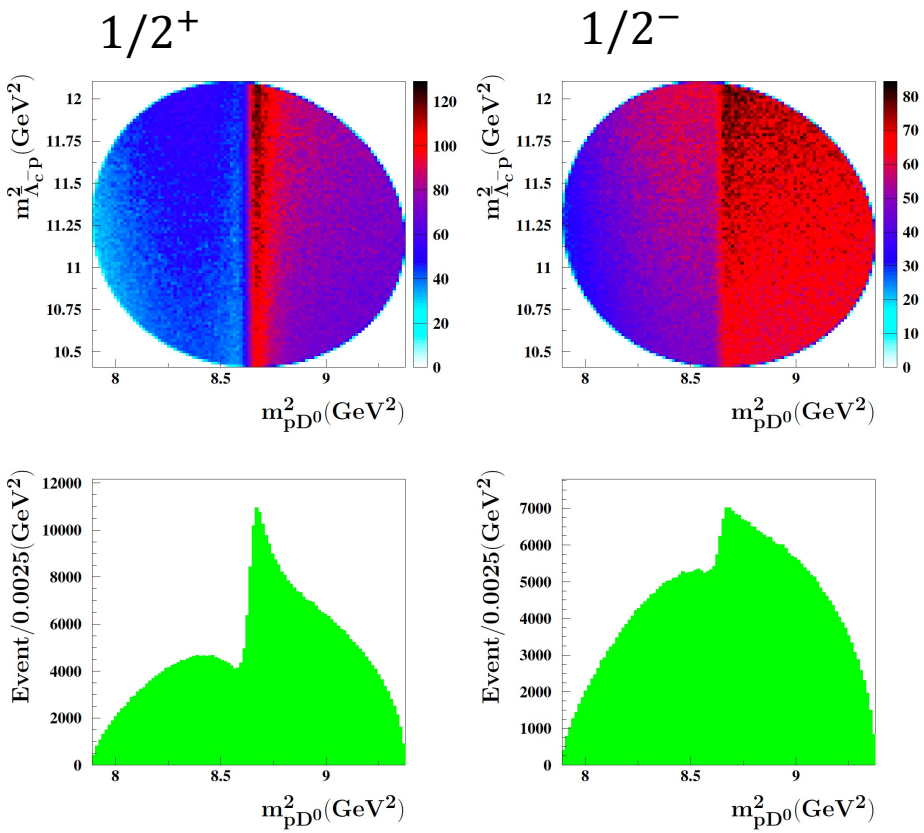



FIG. 7: The Dalitz plot and invariant mass spectra for $p\bar{p} \to \bar{\Lambda}_c D^0 p$ at $\sqrt{s} = 5.32$ GeV and with $J = 1/2$ assignment to $\Lambda_c(2940)^+$. Here, the left or right column corresponds to the numerical result of the production of $\Lambda_c(2940)^+$ with positive or negative parity.

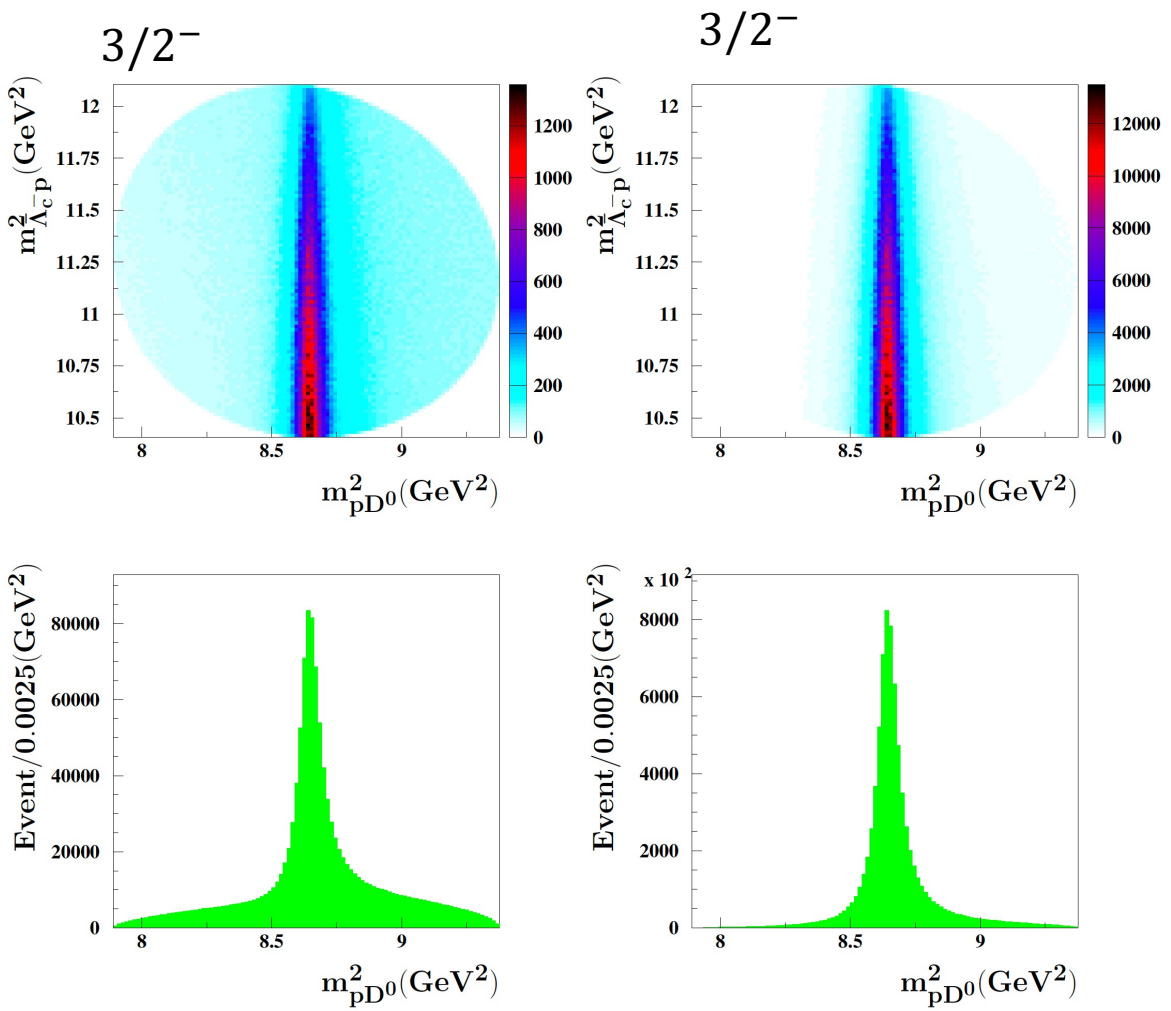



FIG. 8: The Dalitz plot and invariant mass spectra for $p\bar{p} \to \bar{\Lambda}_c D^0 p$ at $\sqrt{s} = 5.32$ GeV and with $J = 3/2$ assignment to $\Lambda_c(2940)^+$. Here, the left or right column corresponds to the numerical result of the production of $\Lambda_c(2940)^+$ with positive or negative parity.

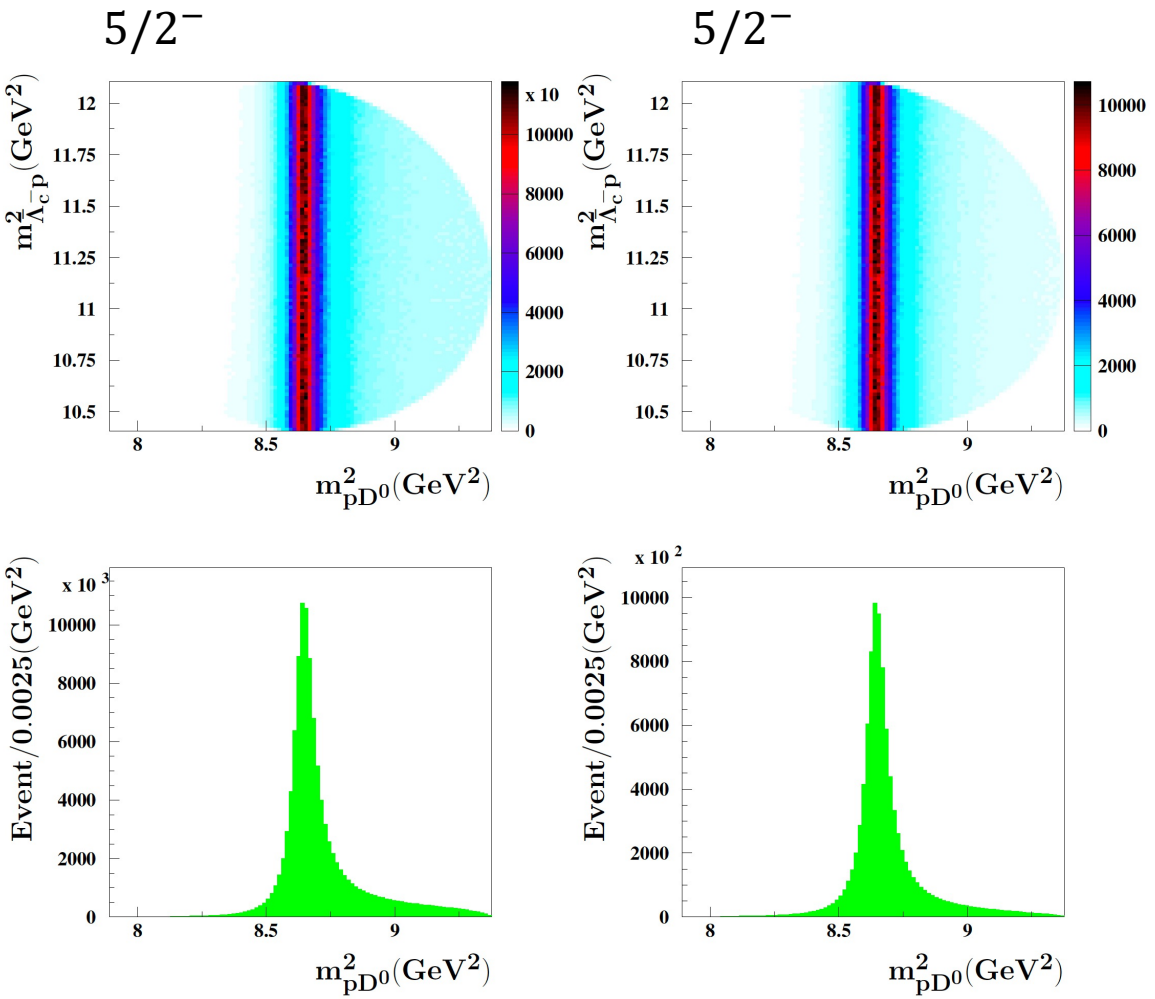
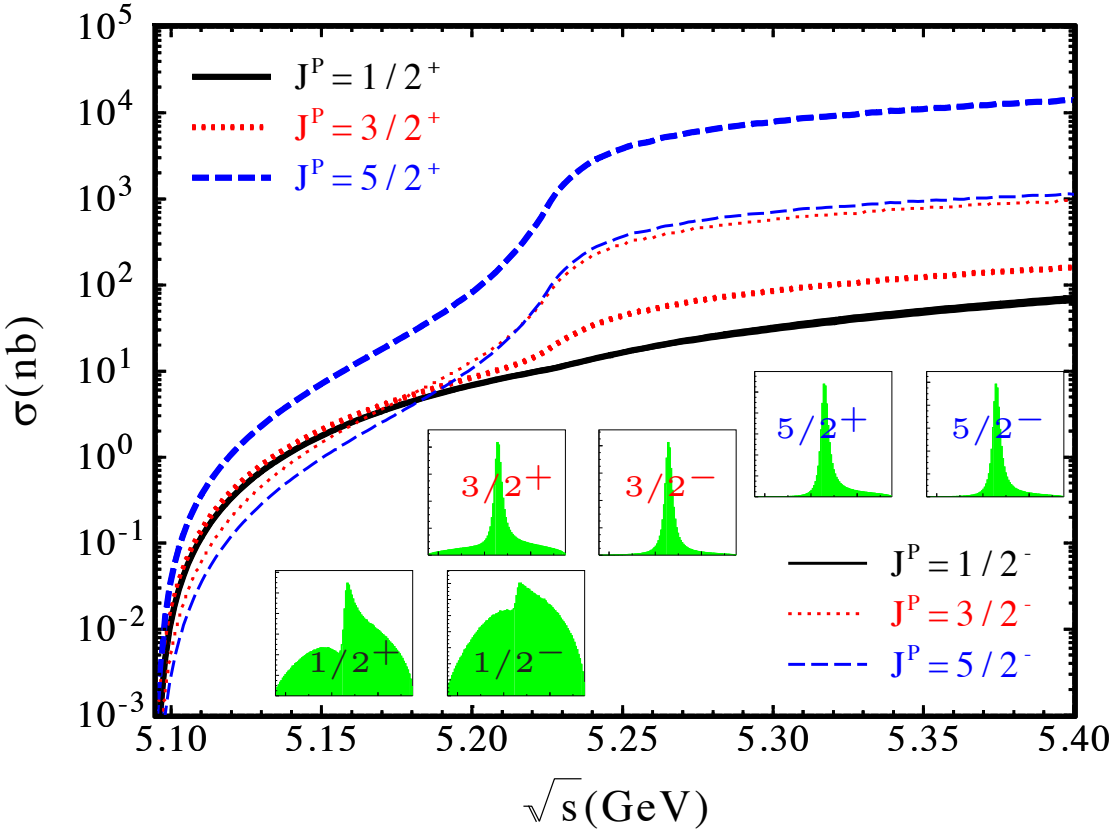


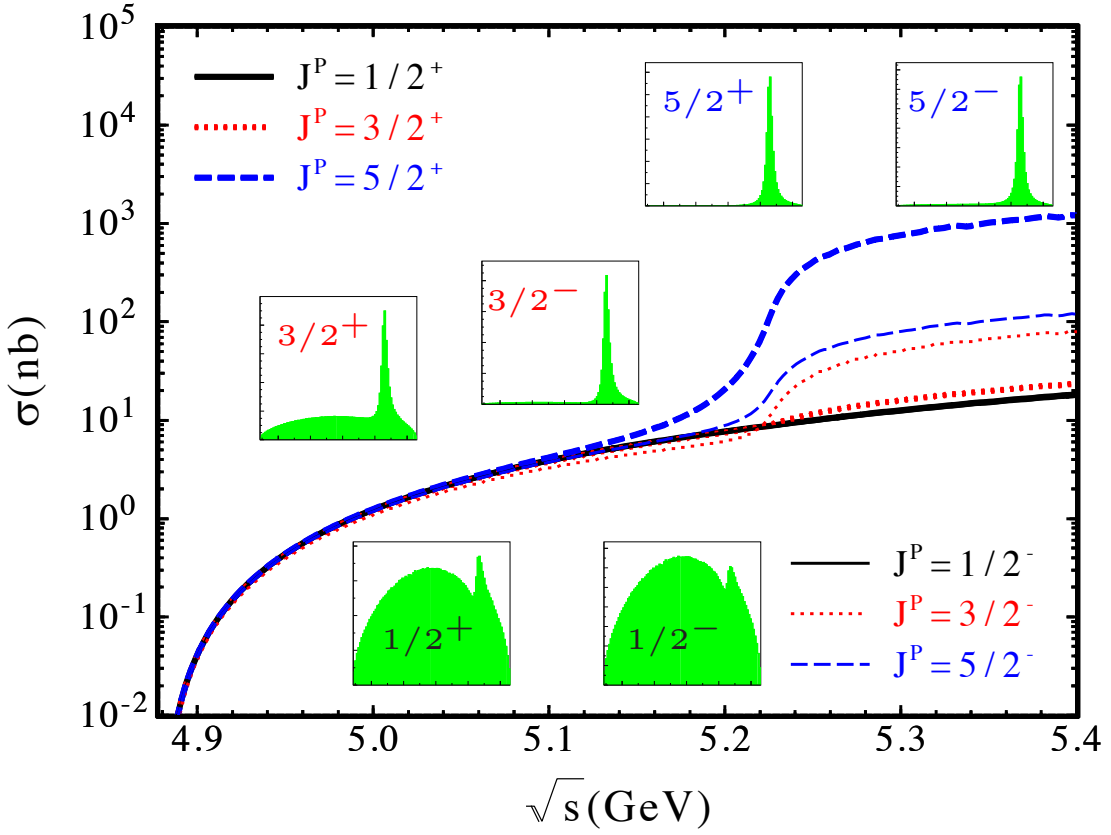

FIG. 9: The Dalitz plot and invariant mass spectra for $p\bar{p} \to \bar{\Lambda}_c D^0 p$ at $\sqrt{s} = 5.32$ GeV and with $J = 5/2$ assignment to $\Lambda_c(2940)^+$. Here, the left or right column corresponds to the numerical result of the production of $\Lambda_c(2940)^+$ with positive or negative parity.

# Cross section and invariant mass spectrum

$p\bar{p} \rightarrow D^0 p \bar{\Lambda}_c^-$




$p\bar{p} \rightarrow \pi^- \Sigma^{++} \bar{\Lambda}_c^-$



# Other baryon productions:

# Production of $\boldsymbol{\Lambda_c(2940)}$ at PANDA

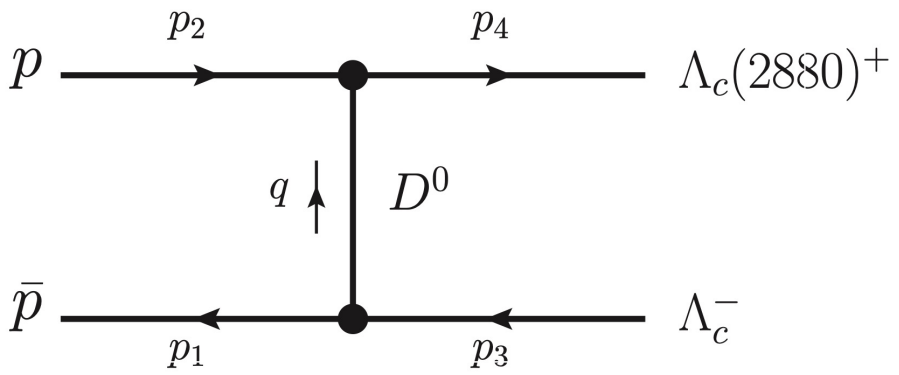



FIG. 1: The diagram describing the $p\bar{p} \to \Lambda_c^- \Lambda_c(2880)^+$ process.

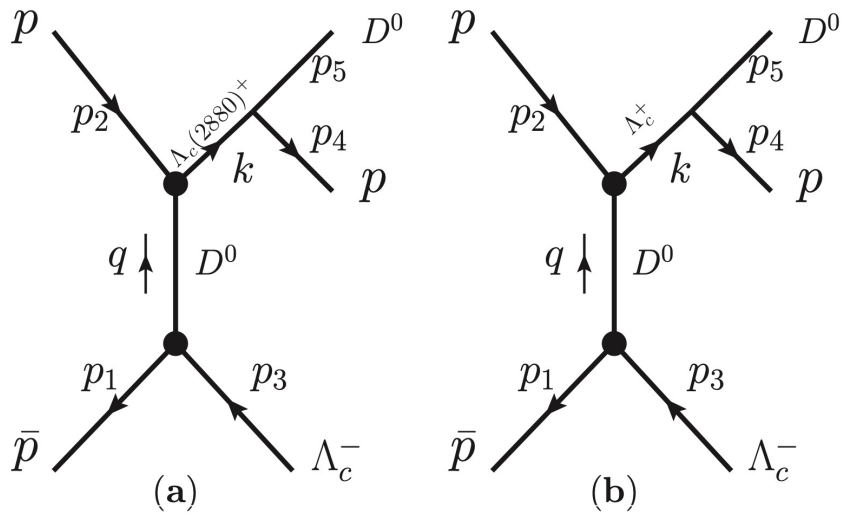



FIG. 7: The diagrams for $p\bar{p} \to D^0 p\bar{\Lambda}_c$ with the intermediate $\Lambda_c(2880)^+$ (a) and $\Lambda_c^+$ (b) contributions.

Qing-Yong Lin, Xiang Liu, Hu-Shan Xu, Phys. Rev. D 90, 014014 (2014)

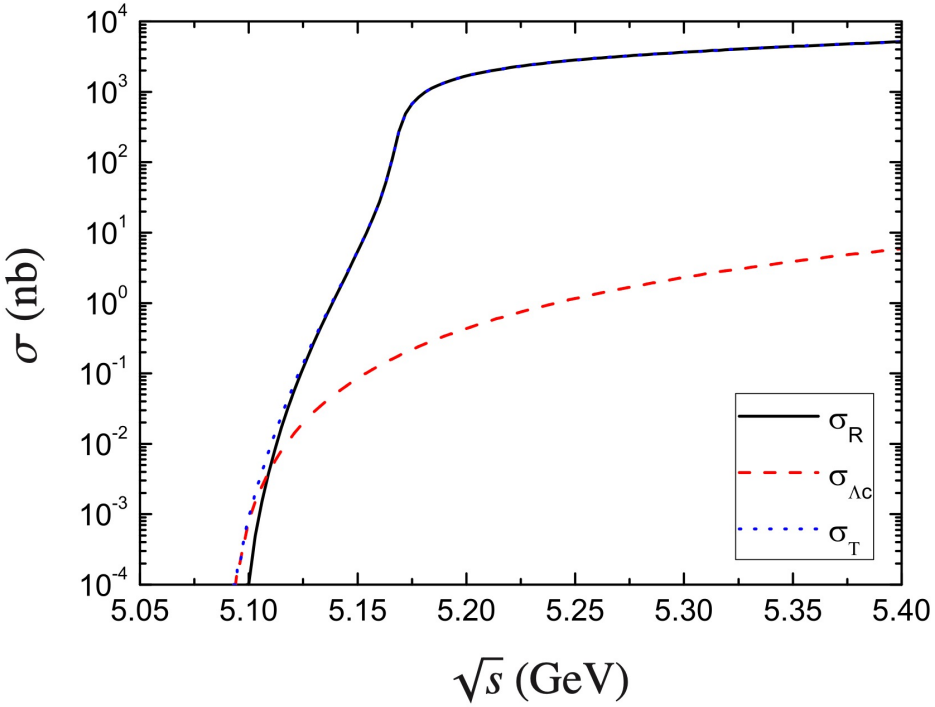



FIG. 8: (color online) The obtained total cross section for $p\bar{p} \to \Lambda_c^- p D^0$. Here, $\sigma_R$ and $\sigma_{\Lambda_c}$ are the results via the exchanged $\Lambda_c(2880)^+$ and $\Lambda_c^+$, respectively, while $\sigma_T$ denotes the total cross section.

When $10^7$ events are generated in the Monte Carlo simulation, the signal event can reach up to about $10^4$ events/0.005 GeV .

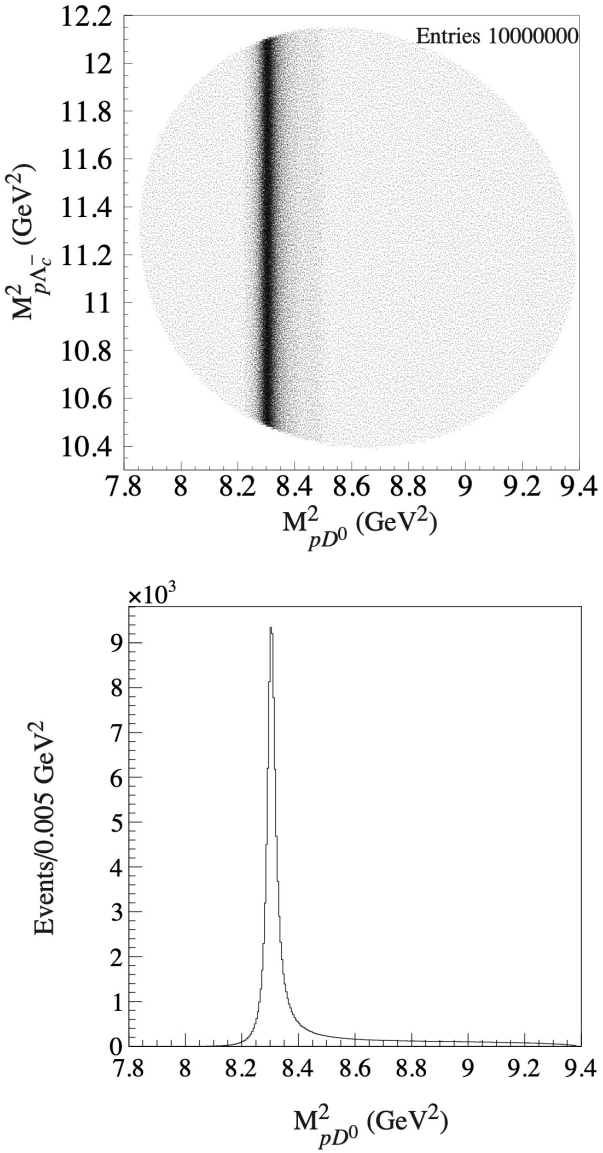



FIG. 9: The Dalitz plot (top) and the invariant mass spectrum distribution (bottom) for $p\bar{p} \to \Lambda_c^- p D^0$ at $\sqrt{s}$ = 5.35 GeV.

# Other baryon productions:

## $\Lambda^*$ resonances in the $p\bar{p} \to \Lambda\bar{\Lambda}\eta$ reaction

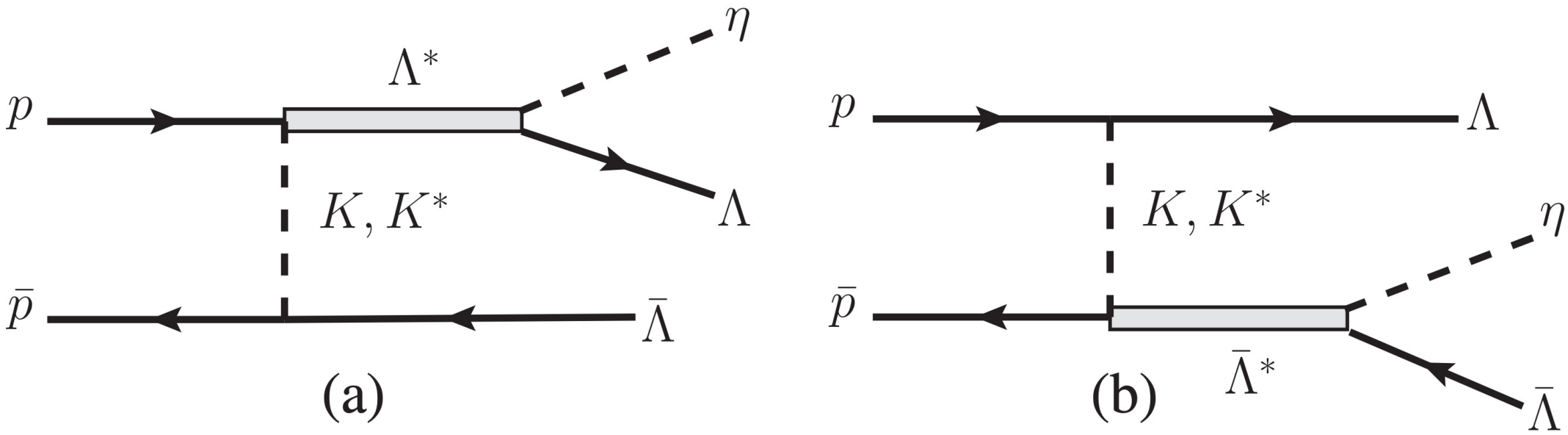
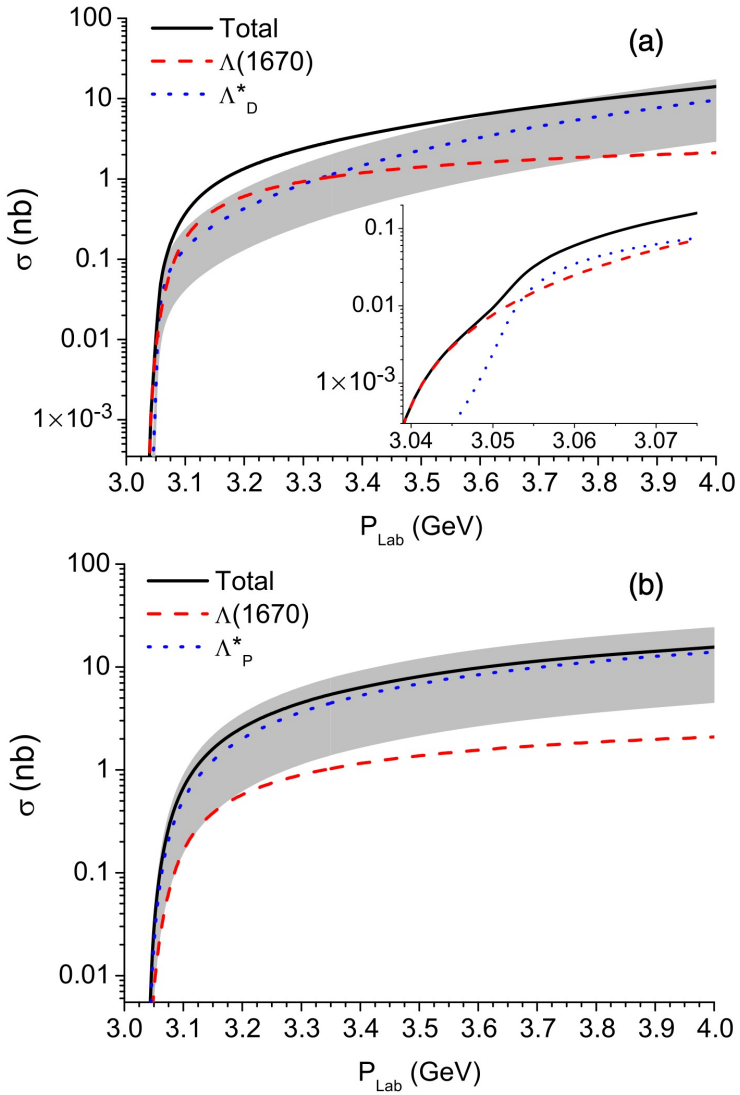



FIG. 1. Model for the reaction $p\bar{p} \to \Lambda\bar{\Lambda}\eta$.



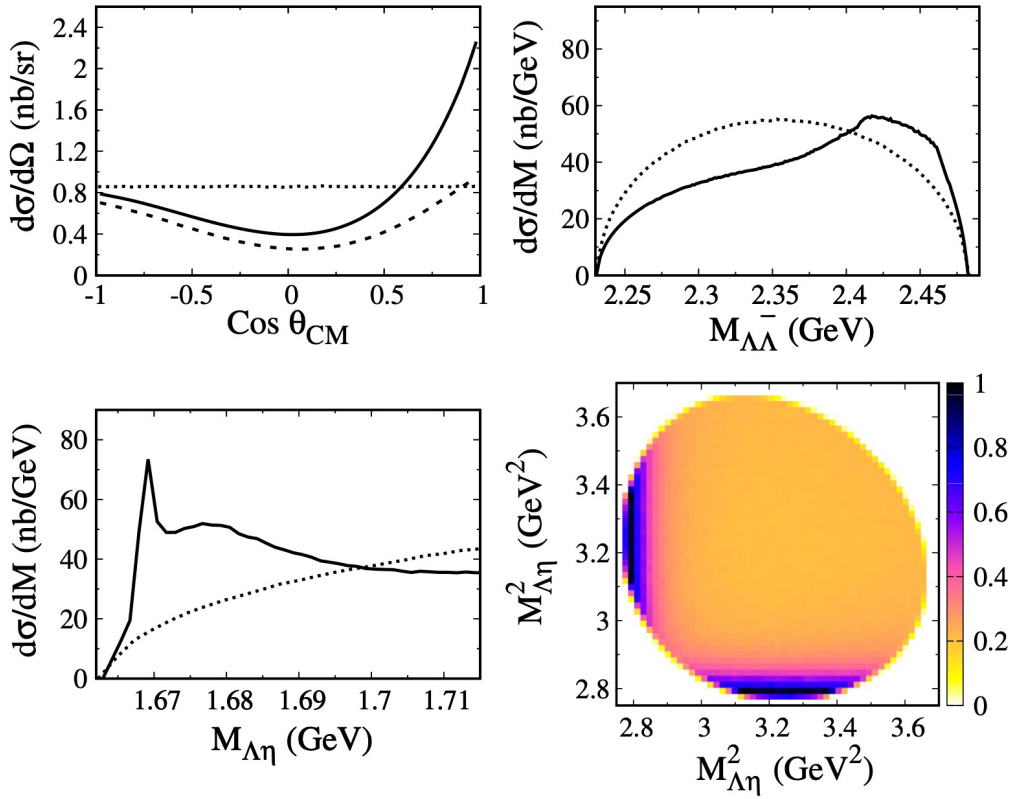
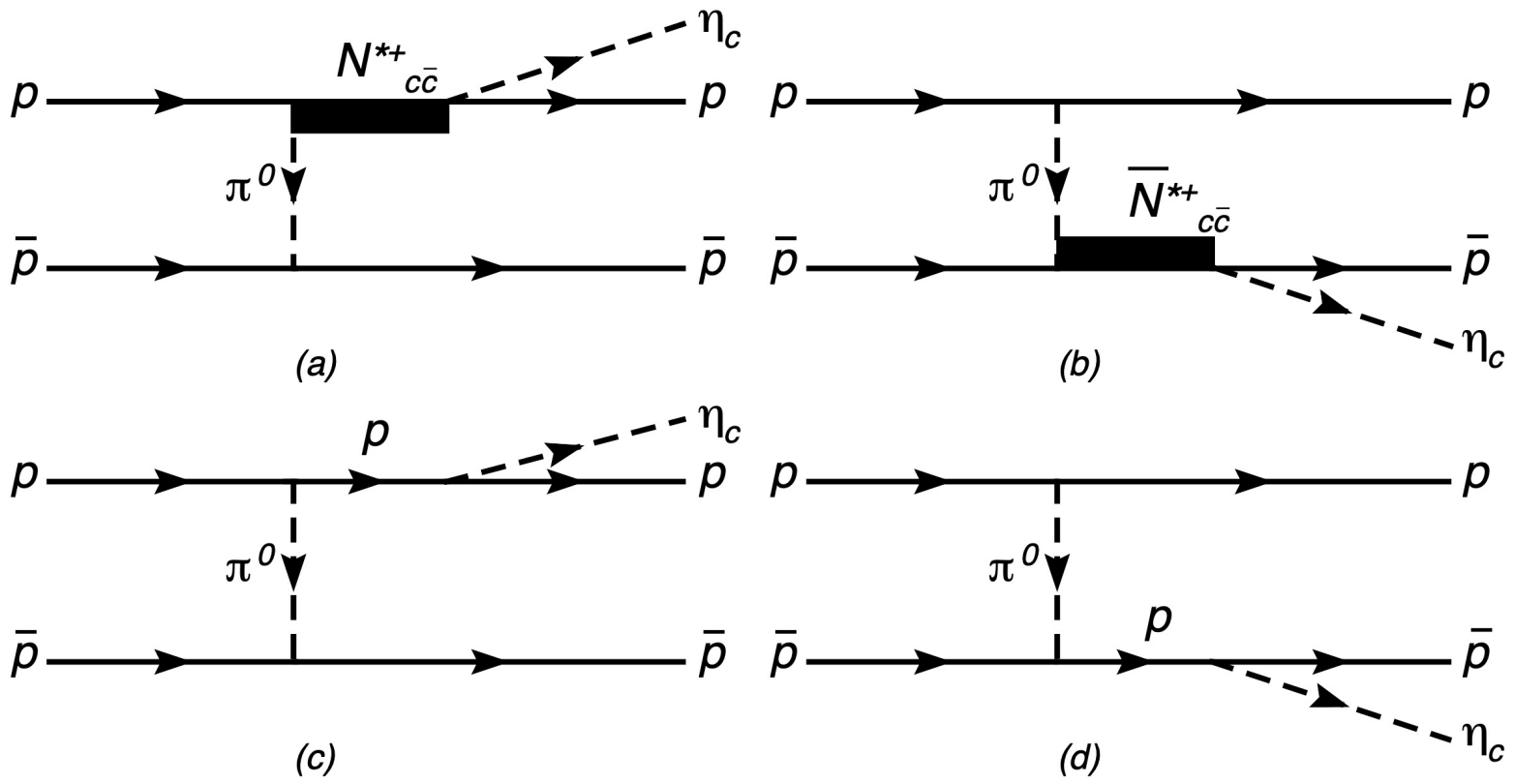




FIG. 3. Predictions for the angular distribution of $\eta$ in the $\Lambda\eta$ rest frame, the spectrum of $M_{\Lambda\bar{\Lambda}}$, the spectrum of $M_{\Lambda\eta}$ and Dalitz plot for Scenario I at $P_{\rm lab} = 3.84$ GeV. The predicted results are shown by the solid lines and compared with the phase space distribution (dotted lines). The dashed line of the $\eta$ angular distribution represents the results with imposing a cut $M_{\bar{\Lambda}\eta} > 1.75$ GeV on the invariant mass of $\bar{\Lambda}\eta$.

# Other baryon productions:

## Pentaquark in the $p\bar{p} \to p\bar{p}\eta_c$ reaction




Jia-Jun Wu, R.Molina, E.Oset, B.S.Zou, Phys.Rev.Lett.105:232001,2010

# Summary

- PANDA is a good platform to study the heavy and strange baryon.
- Take the $\Lambda_c(2940)^+$ as example, about $10^4 \sim 10^8$ events of $\Lambda_c\,(2940)^+$ per day produced at PANDA.
- If the two channel, $p\bar{p} \rightarrow D^0 p\overline{\Lambda}_c^-$ and $p\bar{p} \rightarrow \pi^-\Sigma^{++}\overline{\Lambda}_c^-$ are considered, the signals of $\Lambda_c(2940)^+$ should be seen with any spin-parity assignment.