東南大學·物理学院
SCHOOL OF PHYSICS SOUTHEAST UNIVERSITY

Strong decays of the $\Lambda_c(2910)$ and $\Lambda_c(2940)$ in D^*N molecular picture

Reporter: Zi-Li Yue **2023.12.17**

全国第十二届重味物理和CP破坏研讨会

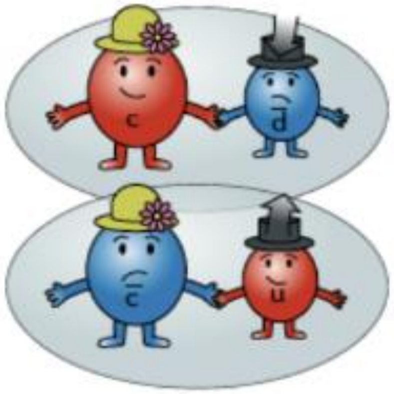
Based on Zi-Li Yue, Dian-Yong Chen, …to appear

止于至善

Outline

- Background
- Molecular Scenario
- The Strong Decay of the Λ_c
- Numerical Results and Discussions
- Summary

Background



Conventional hadrons

Meson($q\bar{q}$), Baryon(qqq)

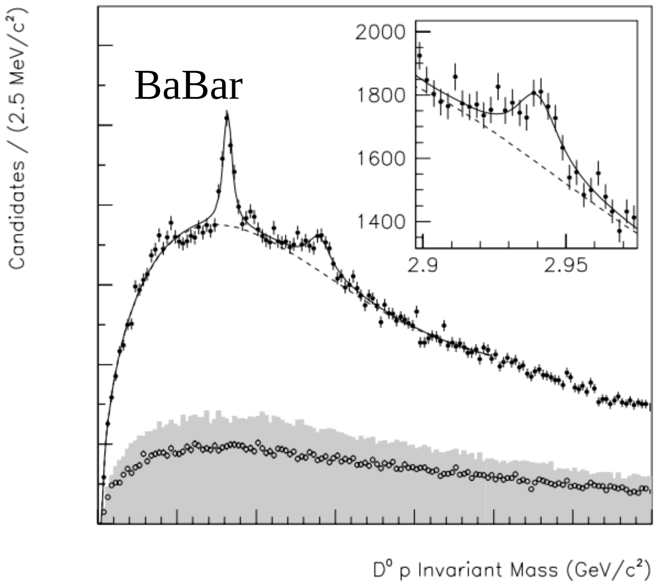
Exotic states

- **Molecular states:** loosely bound states composed of a pair of hadrons, bound by residual interactions of strong interactions.(Candidates: $X(3872), D_{s1}(2460), X(3915)\ldots$)
- Tetraquarks: $qq\bar{q}\bar{q}$
- Pentaquarks: $qqqq\bar{q}$
- Hybrids: $q\bar{q}g$
- Glueballs: gg/ggg

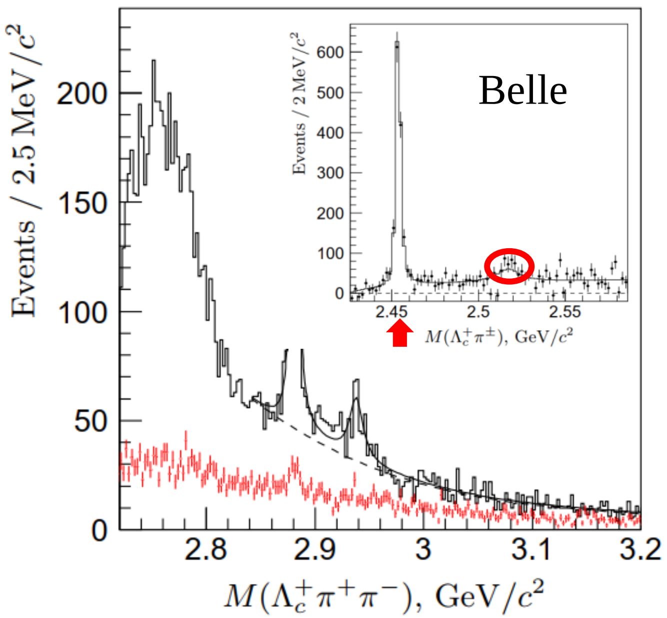
Phys.Lett. 8 (1964) 214-215

Background

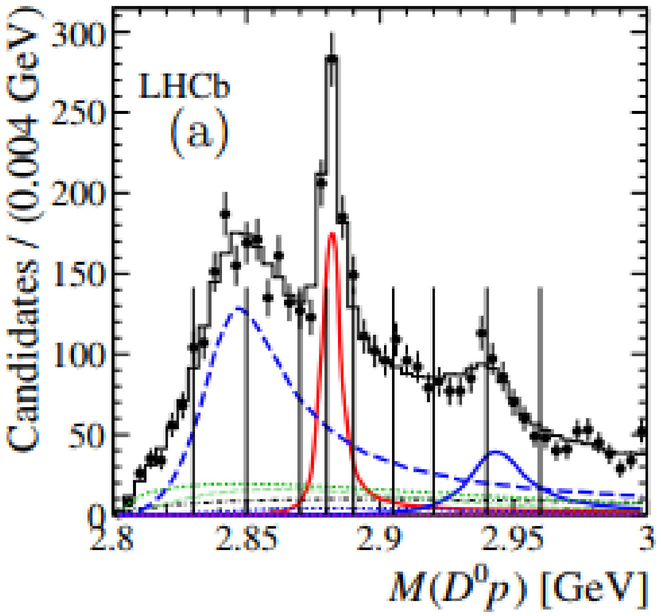
The Discovery of the $\Lambda_c(2940)^+$.



Phys.Rev.Lett. 98 (2007) 012001



Phys.Rev.Lett. 98 (2007) 262001



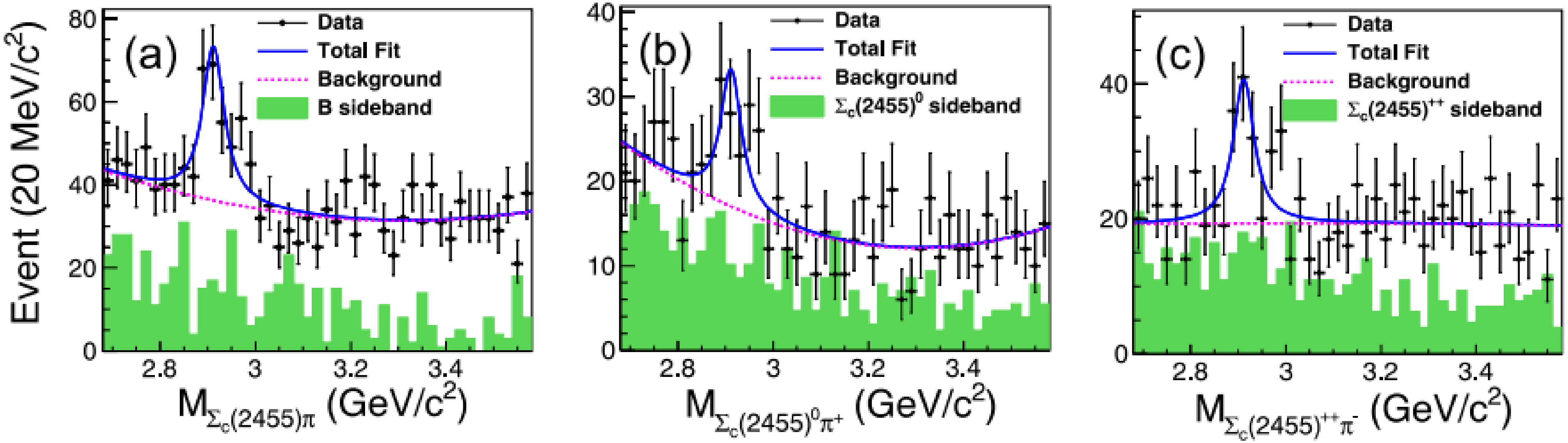
JHEP 05 (2017) 030

Intrinsic parameters: $m_{\Lambda_c(2940)^+} = 2939.6^{+1.3}_{-1.5}$ MeV,

$\Gamma_{\Lambda_c(2940)^+} = 20^{+6}_{-5}$ MeV.

Background

$\Lambda_c(2910)^+$ in $\bar{B}^0 \to \Sigma_c(2455)^{0,++}\pi^{\pm}\bar{p}$ process.



Phys.Rev.Lett. 130 (2023) 3, 031901

Intrinsic parameters: $m_{\Lambda_c(2910)^+} = 2913.8 \pm 5.6 \pm 3.8$ MeV,

$\Gamma_{\Lambda_c(2910)^+} = 51.8 \pm 20. \pm 18.8$ MeV.

Background

Theoretical work on Λ_c states:

$m_{D^*} + m_N - m_{\Lambda_c}(2910) \sim 30$ MeV; $m_{D^*} + m_N - m_{\Lambda_c}(2940) \sim 6$ MeV;

D^*N molecular states:

- Eur.Phys.J.C 51 (2007) 883-889: $\mathrm{D^*N}$ molecular with $\mathrm{J^p} = \frac{1}{2}^-$, decay,
- Phys.Rev.D 81 (2010) 014006,
- Phys.Rev.D 83 (2011) 094005: $\mathrm{D^*N}$ molecular with $\mathrm{J^p} = \frac{1}{2}^+$,decay,
- Phys.Rev.D 107 (2023) 3, 034036: conventional baryons dressed with the $\mathrm{D^*N}$ channel,
- Eur.Phys.J.C 83 (2023) 6, 524: $\Lambda_c(2940)$ composed of $\mathrm{D^*N}$ with $\mathrm{J^p} = \frac{3}{2}^-$ …

Others explaination:

For $\Lambda_c(2910)$:

- Eur.Phys.J.C 82 (2022) 10, 920 $\Lambda_c(2P, 1/2^-)$ state,
- Phys.Rev.D 106 (2022) 7, 074020 Candidate of $\Lambda_c|J^P = 5/2^-\rangle_\rho$…

For $\Lambda_c(2940)$:

- Phys.Rev.D 75 (2007) 094017:D-wave charmed baryon with $J^P = \frac{1}{2}^+$ or $\frac{3}{2}^+$,
- Phys.Lett.B 659 (2008) 612-620: $\Lambda_c(2286)^+$first orbital excitation…

Background

P_c states:

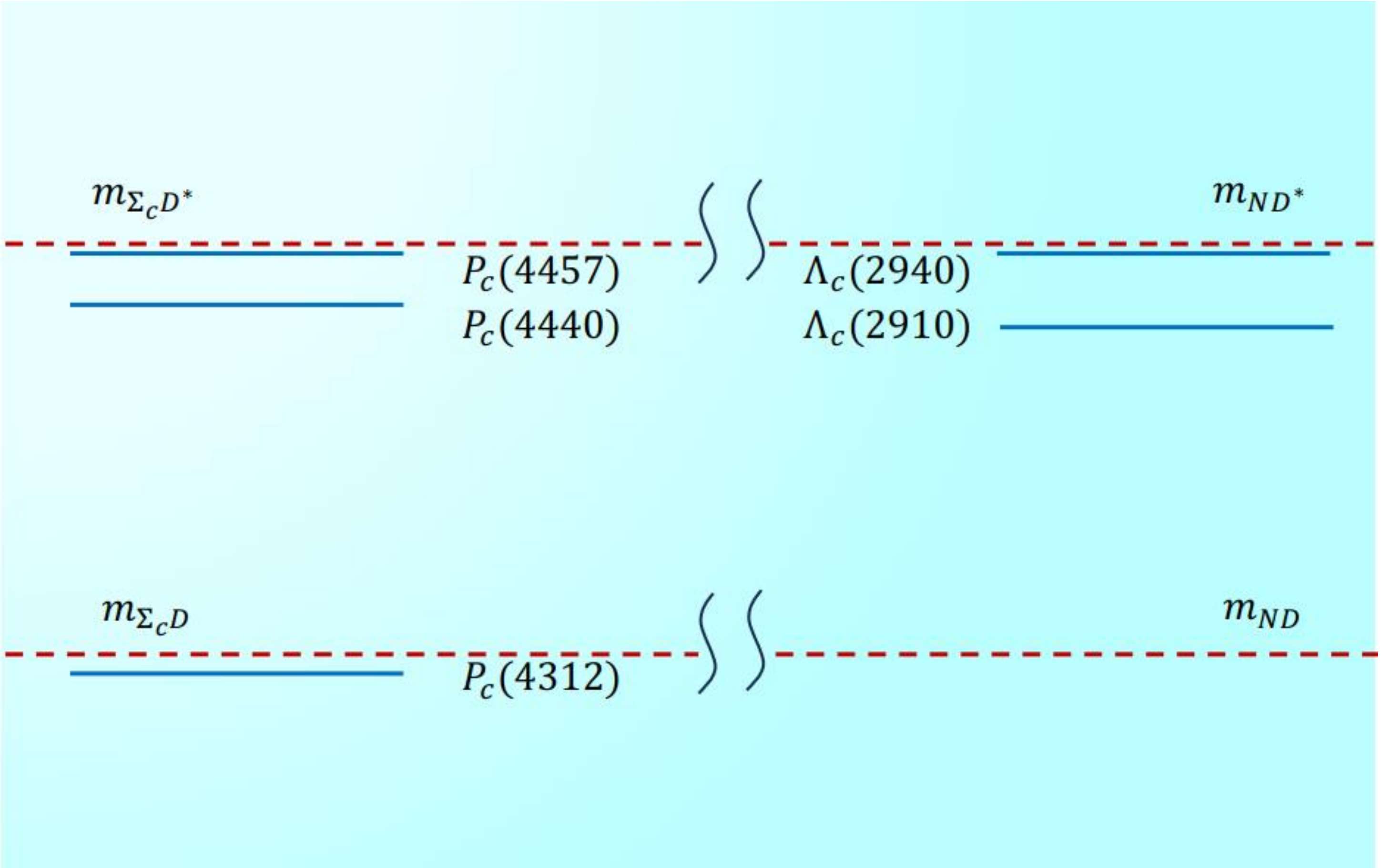
$P_c(4457)$: $\Sigma_c D^*$ molecular, $J^P = \frac{3}{2}^-$;

$P_c(4440)$: $\Sigma_c D^*$ molecular, $J^P = \frac{1}{2}^-$;

$P_c(4312)$: $\Sigma_c D$ molecular, $J^P = \frac{1}{2}^-$;

References:

Phys.Rev.D 100 (2019) 5, 056005,
Phys.Rev.D 100 (2019) 1, 014022,
Phys.Rev.D 100 (2019) 11, 114002,
…



SetA: $\Lambda_c(2910)\ J^P = \frac{1}{2}^-$, $\Lambda_c(2940)\ J^P = \frac{3}{2}^-$.

SetB: $\Lambda_c(2940)\ J^P = \frac{1}{2}^-$, $\Lambda_c(2910)\ J^P = \frac{3}{2}^-$.

The mass spectrum of P_c states and Λ_c states.

Molecular scenario

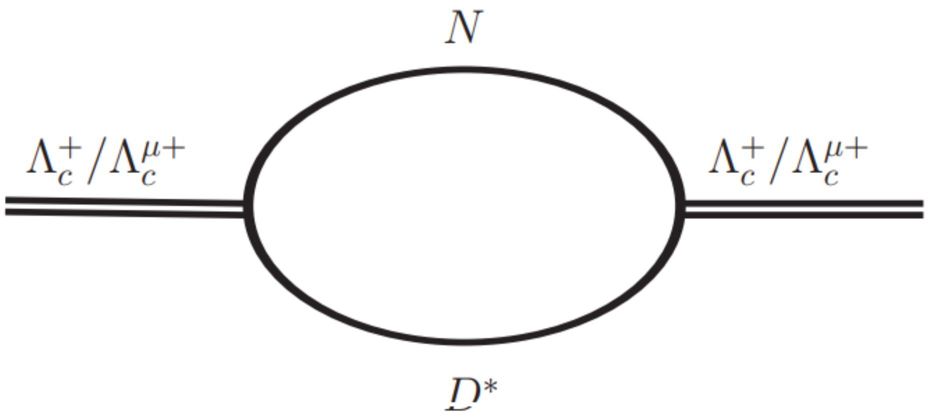
- Effective Lagrangian:

$$\mathcal{L}_{\Lambda_c(1/2^-)} = g^{1/2^-}_{\Lambda_c D^* N} \bar{\Lambda}_c(x)\gamma^\mu\gamma^5 \int dy \boldsymbol{\phi}(\boldsymbol{y}^2)\left[D^{*0}_\mu(x+\omega_{pD^{*0}}y)p(x-\omega_{D^{*0}p}y) + D^{*+}_\mu(x+\omega_{nD^{*+}}y)n(x-\omega_{D^{*+}n}y)\right] + \mathrm{H.c.}$$

$$\mathcal{L}_{\Lambda_c(3/2^-)} = g^{3/2^-}_{\Lambda_c D^* N} \bar{\Lambda}^\mu_c(x) \int dy \boldsymbol{\phi}(\boldsymbol{y}^2)\left[D^{*0}_\mu(x+\omega_{pD^{*0}}y)p(x-\omega_{D^{*0}p}y) + D^{*+}_\mu(x+\omega_{nD^{*+}}y)n(x-\omega_{D^{*+}n}y)\right] + \mathrm{H.c.}$$

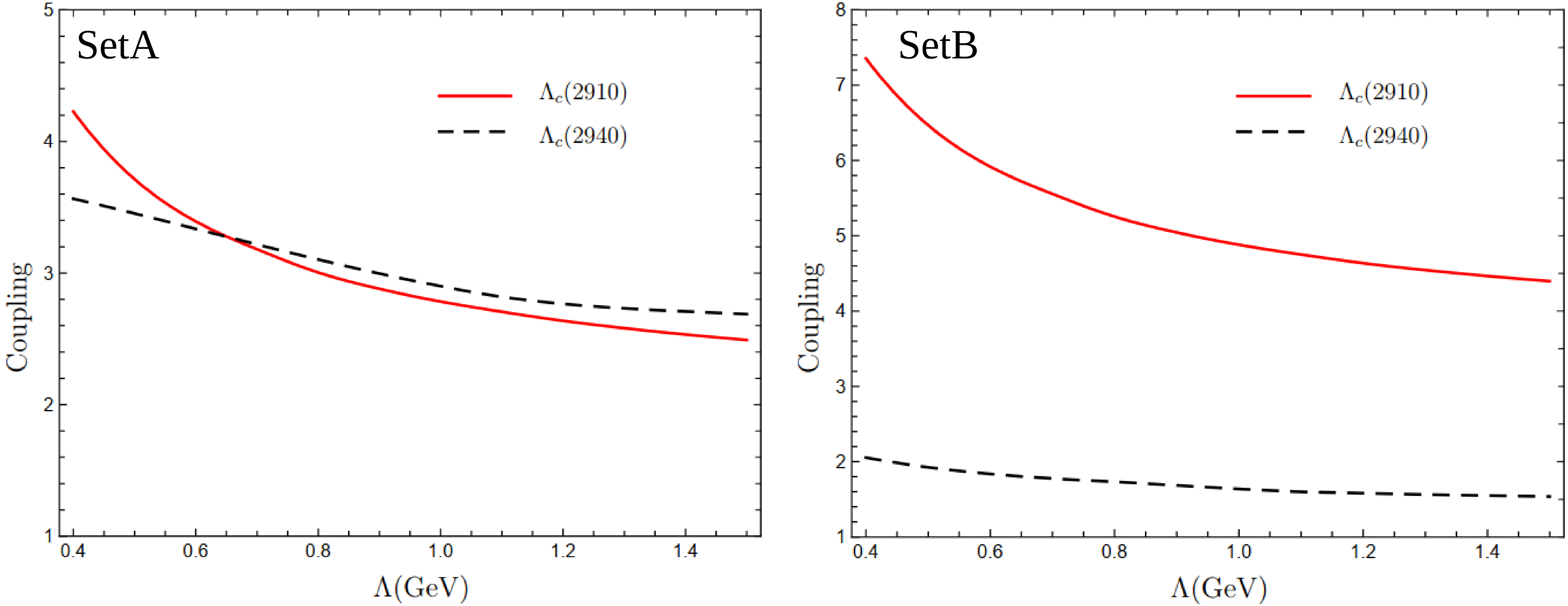
Correlation function:

- ✓ Fourier transformation: $\phi(y^2) = \int \frac{d^4p}{(2\pi)^4} e^{-ipy}\, \tilde{\phi}(-p^2)$,
- ✓ describe the interior structure of the molecular state,
- ✓ fall fast enough in the ultraviolet region,
- ✓ Gaussian form: $\tilde{\phi}(p_E^2) = \exp(-p_E^2/\Lambda^2)$.



Molecular scenario

- Compositeness condition: $Z = \langle Bare|Phys\rangle = 0, Z = 1 - \Pi'\left(m^2_{T^0_{c\bar{s}0}}\right) = 0 \Rightarrow g_{\bar{\Lambda}_c}$.



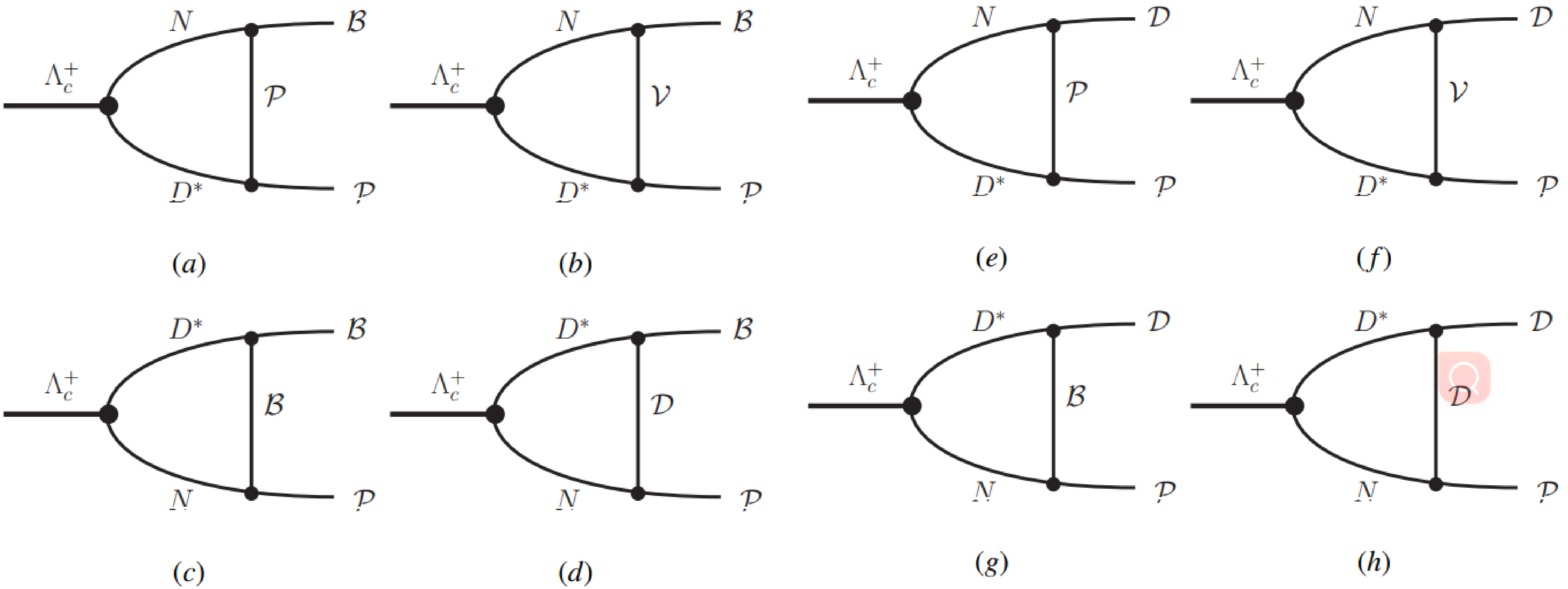
The strong decay of the Λ_c

The possible decay mode:

- $\boldsymbol{\Lambda_c \to (c\bar{u})(uud), (u\bar{u})(cud), (\bar{u}d)(cuu), (u\bar{d})(cdd)\ldots}$

	Final states	process	
$\frac{1}{2}^-$	ND	$1/2^- \to 0^- + 1/2^+$	$S - wave$
	$\Sigma_c\pi$	$1/2^- \to 0^- + 1/2^+$	$S - wave$
	$\Sigma_c^*\pi$	$1/2^- \to 0^- + 3/2^+$	$D - wave$
$\frac{3}{2}^-$	ND	$3/2^- \to 0^- + 1/2^+$	$D - wave$
	$\Sigma_c\pi$	$3/2^- \to 0^- + 1/2^+$	$D - wave$
	$\Sigma_c^*\pi$	$3/2^- \to 0^- + 3/2^+$	$S - wave$

The strong decay of the Λ_c



All the decay mode of the Λ_c at the hadron level.

The strong decay of the Λ_c

All the possible specific decay channels of the Λ_c

J^P	Final states	loops
$\frac{1}{2}^-$	ND	$[ND^*\pi]$, $[ND^*\eta]$, $[ND^*\rho]$, $[ND^*\omega]$
	$\Sigma_c^{(*)+}\pi^0$	$[pD^{*0}\bar{D}^0]$, $[pD^{*0}\bar{D}^{*0}]$, $[nD^{*+}D^-]$, $[nD^{*+}D^{*-}]$,$[D^{*0}p\bar{\Delta}^+]$, $[D^{*0}p\bar{p}]$, $[D^{*+}n\bar{\Delta}^0]$, $[D^{*+}n\bar{n}]$
	$\Sigma_c^{(*)++}\pi^-$	$[pD^{*0}D^-]$, $[pD^{*0}D^{*-}]$,$[D^{*+}n\bar{\Delta}^+]$, $[D^{*+}n\bar{p}]$,$[D^{*0}p\bar{\Delta}^{++}]$
	$\Sigma_c^{(*)0}\pi^+$	$[nD^{*+}\bar{D}^0]$, $[nD^{*+}\bar{D}^{*0}]$,$[D^{*0}p\bar{\Delta}^0]$, $[D^{*0}p\bar{n}]$,$[D^{*+}n\bar{\Delta}^-]$
$\frac{3}{2}^-$	ND	$[ND^*\pi]$, $[ND^*\eta]$, $[ND^*\rho]$, $[ND^*\omega]$
	$\Sigma_c^{(*)+}\pi^0$	$[pD^{*0}\bar{D}^0]$, $[pD^{*0}\bar{D}^{*0}]$, $[nD^{*+}D^-]$, $[nD^{*+}D^{*-}]$,$[D^{*0}p\bar{\Delta}^+]$, $[D^{*0}p\bar{p}]$, $[D^{*+}n\bar{\Delta}^0]$, $[D^{*+}n\bar{n}]$
	$\Sigma_c^{(*)++}\pi^-$	$[pD^{*0}D^-]$, $[pD^{*0}D^{*-}]$,$[D^{*+}n\bar{\Delta}^+]$, $[D^{*+}n\bar{p}]$,$[D^{*0}p\bar{\Delta}^{++}]$
	$\Sigma_c^{(*)0}\pi^+$	$[nD^{*+}\bar{D}^0]$, $[nD^{*+}\bar{D}^{*0}]$,$[D^{*0}p\bar{\Delta}^0]$, $[D^{*0}p\bar{n}]$,$[D^{*+}n\bar{\Delta}^-]$

The strong decay of the Λ_c

- Effective Lagrangian:

  $SU(4)$ symmetry:

$$\mathcal{L}_{\mathcal{BBP}} = -\frac{g_{\mathcal{BBP}}}{m_p}\bar{\mathcal{B}}\gamma^{\mu}\gamma_5\partial_{\mu}\mathcal{P}\mathcal{B}$$

$$\mathcal{L}_{\mathcal{BBV}} = -g_{\mathcal{BBV}}\bar{\mathcal{B}}\gamma_{\mu}\mathcal{V}^{\mu}\mathcal{B}$$

$$\mathcal{L}_{\mathcal{BDP}} = \frac{g_{\mathcal{BDP}}}{m_{\mathcal{P}}}(\bar{\mathcal{D}}^{\mu}\mathcal{B} - \bar{\mathcal{B}}\mathcal{D}^{\mu})\partial_{\mu}\mathcal{P}$$

$$\mathcal{L}_{\mathcal{BDV}} = -i\frac{g_{\mathcal{BDV}}}{m_{\mathcal{V}}}\left(\bar{\mathcal{D}}^{\mu}\gamma^5\gamma^{\nu}\mathcal{B} - \bar{\mathcal{B}}\gamma^5\gamma^{\nu}\mathcal{D}^{\mu}\right)\left(\partial_{\mu}\mathcal{V}_{\nu} - \partial_{\nu}\mathcal{V}_{\mu}\right)$$

$$\mathcal{L}_{\mathcal{BDV}} = \bar{\mathcal{D}}_{\alpha}\gamma^{\nu}\mathcal{V}_{\nu}\mathcal{D}^{\alpha}$$

$$\mathcal{L}_{\mathcal{PPV}} = -ig_{\mathcal{PPV}}(\mathcal{P}\partial_{\mu}\mathcal{P} - \partial_{\mu}\mathcal{P}\mathcal{P})\mathcal{V}^{\mu}$$

$$\mathcal{L}_{\mathcal{VVP}} = g_{\mathcal{VVP}}\epsilon_{\mu\nu\alpha\beta}\partial^{\mu}\mathcal{V}^{\nu}\partial^{\alpha}\mathcal{V}^{\beta}\mathcal{P}$$

The strong decay of the Λ_c

- Form factor:

$$\mathcal{F}\left(m_q, \Lambda_1\right) = \frac{\Lambda_1^4}{(m^2-q^2)^2+\Lambda_1^4},$$

- Loop Integral:

$$C_0 = \int \frac{d^4q}{(2\pi)^4} \widetilde{\Phi} \frac{1}{[p_1^2 - m_1^2][p_2^2 - m_2^3][q^2 - m_q^2]}$$

Schwinger parametrization:

$$\frac{1}{m^2 - k^2} = \int_0^\infty d\alpha e^{-\alpha(m^2-k^2)}$$

- Decay width:

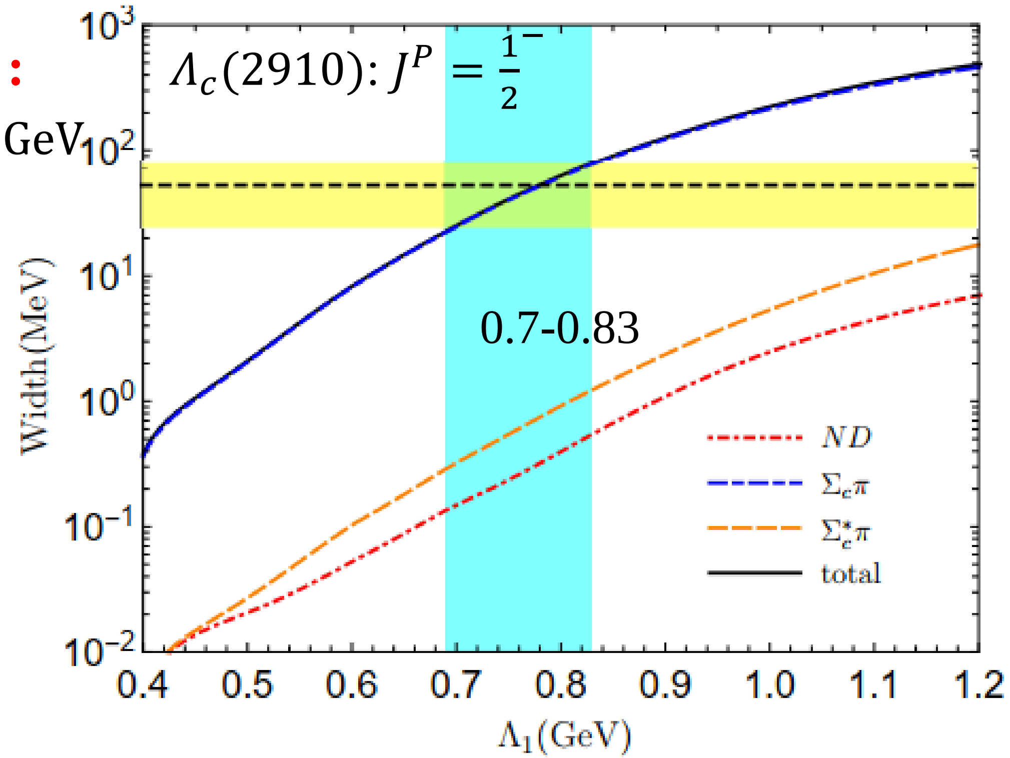
$$\Gamma_{\Lambda_c \to \cdots} = \frac{1}{(2J+1)8\pi} \frac{|\vec{p}|}{m_{\Lambda_c}^2} \left|\overline{\mathcal{M}_{\Lambda_c} \to \cdots}\right|^2$$

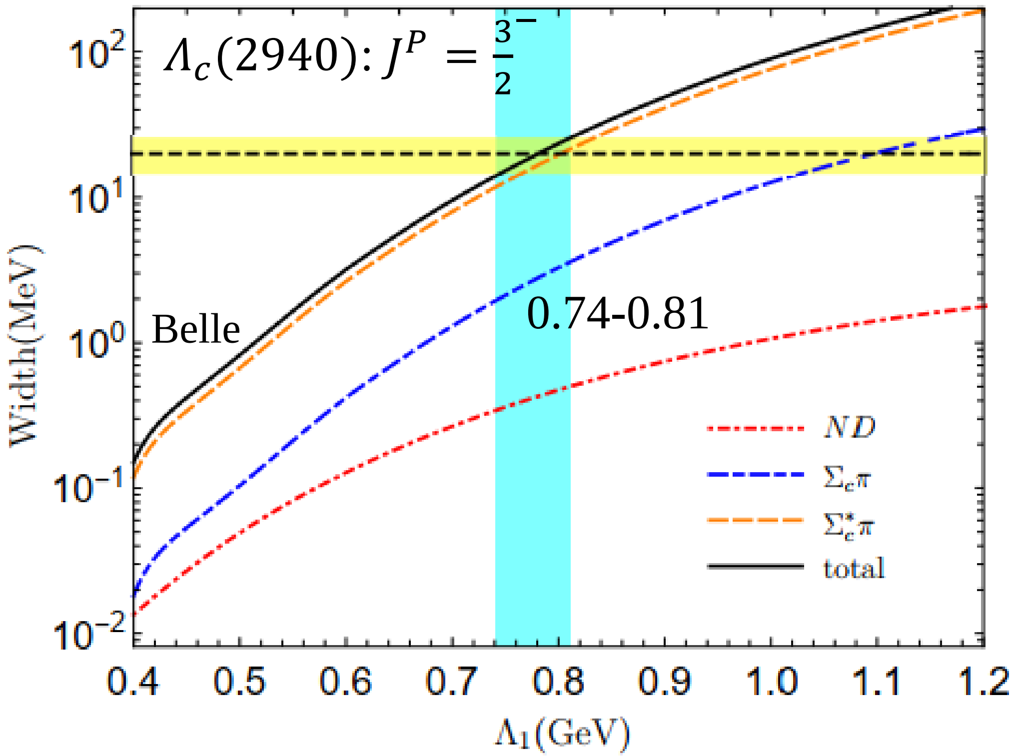
Numerical Results and discussions

东南大學 · 物理学院
SCHOOL OF PHYSICS SOUTHEAST UNIVERSITY

Set A :

$\Lambda = 0.7$ GeV





Conclusions:

- The estimations is consistent with the experiment measurement in parameter Λ_1 from $0.74 - 0.81$;
- In this assignment, the dominant decay channel for $\Lambda_c(2910)$ is $\Sigma_c\pi$ and for $\Lambda_c(2940)$ is $\Sigma_c^*\pi$;
- Branching ratio: $\mathrm{Br}(AB) = \Gamma_{AB}/\Gamma_{tot}$;

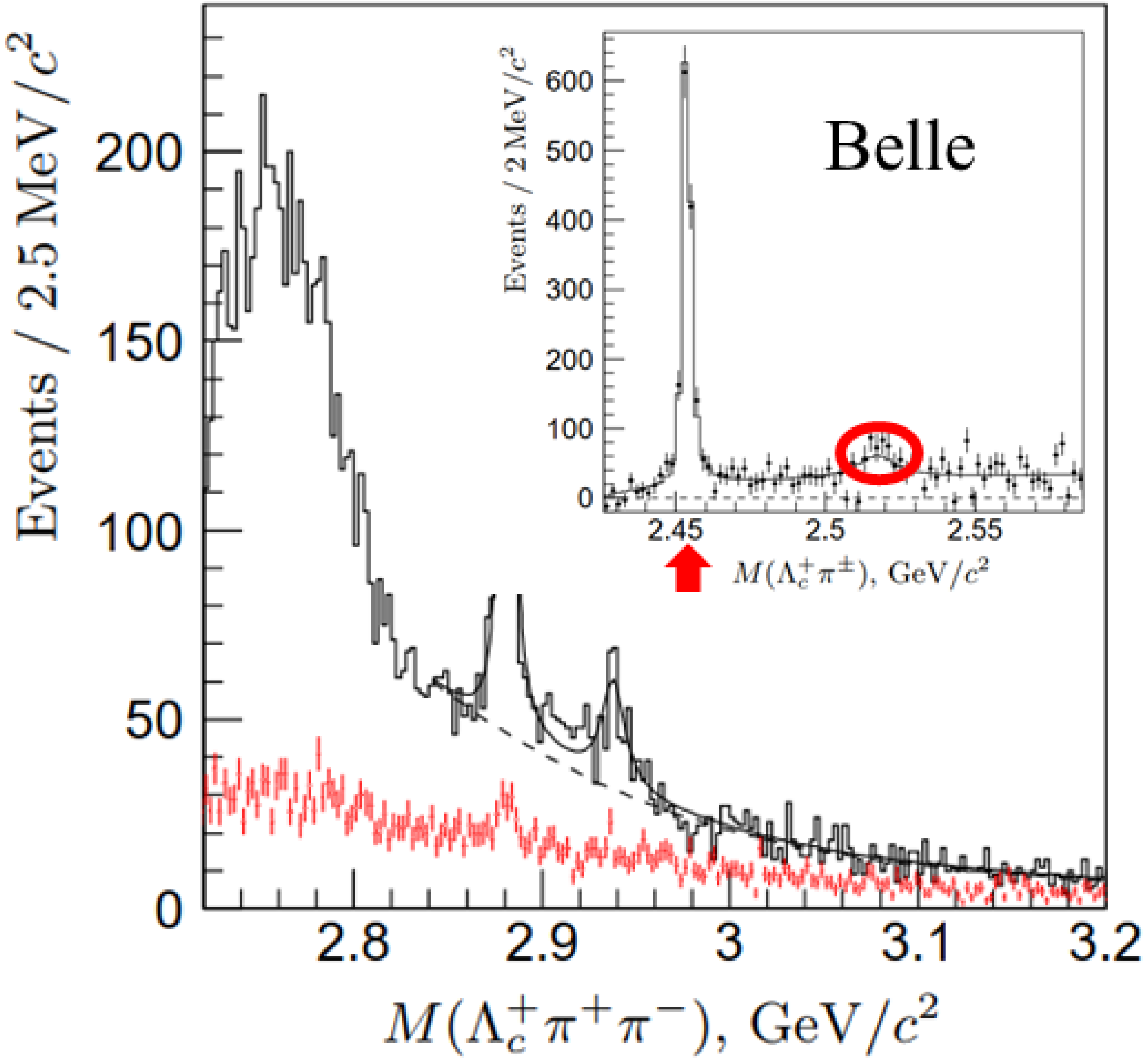
For $\Lambda_c(2910)$: $\mathrm{Br}(ND) = 0.39 - 0.56\%$, $\mathrm{Br}(\Sigma_c\pi) = 97.9 - 98.2\%$, $\mathrm{Br}(\Sigma_c^*\pi) = 1.35 - 1.53\%$;
For $\Lambda_c(2940)$: $\mathrm{Br}(ND) = 1.9 - 2.4\%$, $\mathrm{Br}(\Sigma_c\pi) = 13.8 - 14\%$, $\mathrm{Br}(\Sigma_c^*\pi) = 83.7 - 84\%$.

Numerical Results and discussions

- $\mathrm{Br}(\Sigma_c^* \pi) = 83.7 - 84\%$

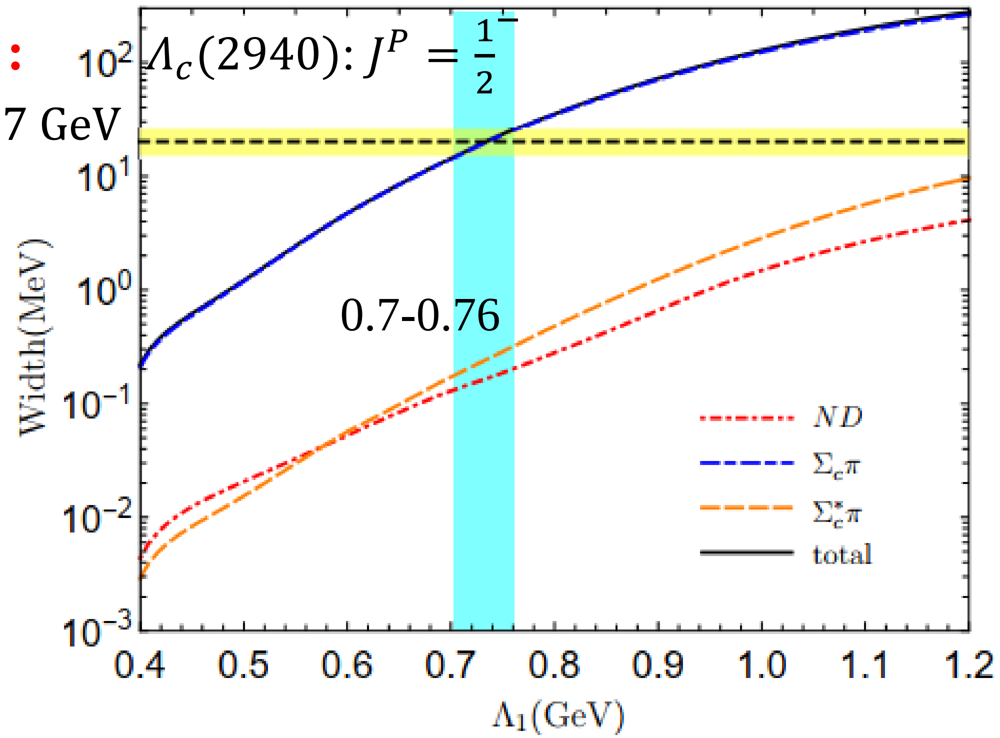
Large branching ratio for $\boldsymbol{\Lambda_c(2940)}$!

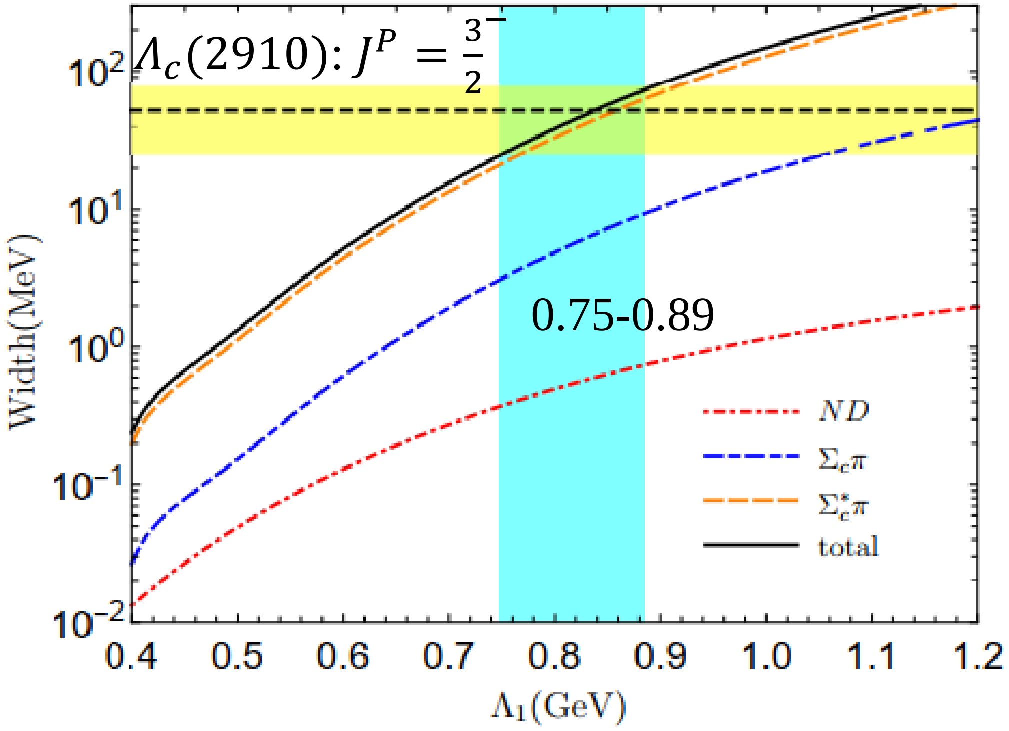
- Experiment could look for $\Lambda_c(2940)$ in the $\Sigma_c^* \pi$ invariant mass spectrum.



Numerical Results and discussions

Set B :
$\Lambda = 0.7$ GeV





Conclusions:

- The estimations is consistent with the experiment measurement in parameter Λ_1 from $0.75 - 0.76$;
- In this assignment, the dominant decay channel for $\Lambda_c(2910)$ is $\Sigma_c^*\pi$ and for $\Lambda_c(2940)$ is $\Sigma_c\pi$;
- Branching ratio: $\mathrm{Br}(AB) = \Gamma_{AB}/\Gamma_{tot}$;

For $\Lambda_c(2910)$: $\mathrm{Br}(ND) = 1.44 - 1.49\%$, $\mathrm{Br}(\Sigma_c\pi) = 12.4 - 12.5\%$, $\mathrm{Br}(\Sigma_c^*\pi) = 0.86\%$;
For $\Lambda_c(2940)$: $\mathrm{Br}(ND) = 0.34 - 0.38\%$, $\mathrm{Br}(\Sigma_c\pi) = 98.3\%$, $\mathrm{Br}(\Sigma_c^*\pi) = 1.26 - 1.27\%$.

Summary

1. The present work investigate the strong decay behavior the $\Lambda_c(2940)$ and $\Lambda_c(2910)$ in D^*N molecular scenario by using the effective Lagrangian approach;
2. We estimate the partial decay width of $\Lambda_c \to ND$ and $\Lambda_c \to \Sigma_c^{(*)}\pi$;
3. By comparing our calculations with experiment measurements, the J^P for $\Lambda_c(2910)$ prefers $\frac{1}{2}^-$ and for $\Lambda_c(2940)$, the $J^P = \frac{3}{2}^-$ is weakly favored.

Thank you for your attention!