北京谱仪上Lambda超子自旋极化理论进展

Jia-Jun Wu (UCAS)
Collaborator: Shu-Ming Wu, Bing-Song Zou

Phys.Rev.D 104 (2021) 5, 054018

第一届Lambda超子自旋极化跨系统研讨会　　2025.03.22.　　合肥，中科大

Content

- 现状和问题
- 利用L-S scheme方法抽取 $\psi \to \bar{B}B$ 过程的L
- 衰变的有效半径
- 小结

现状和问题

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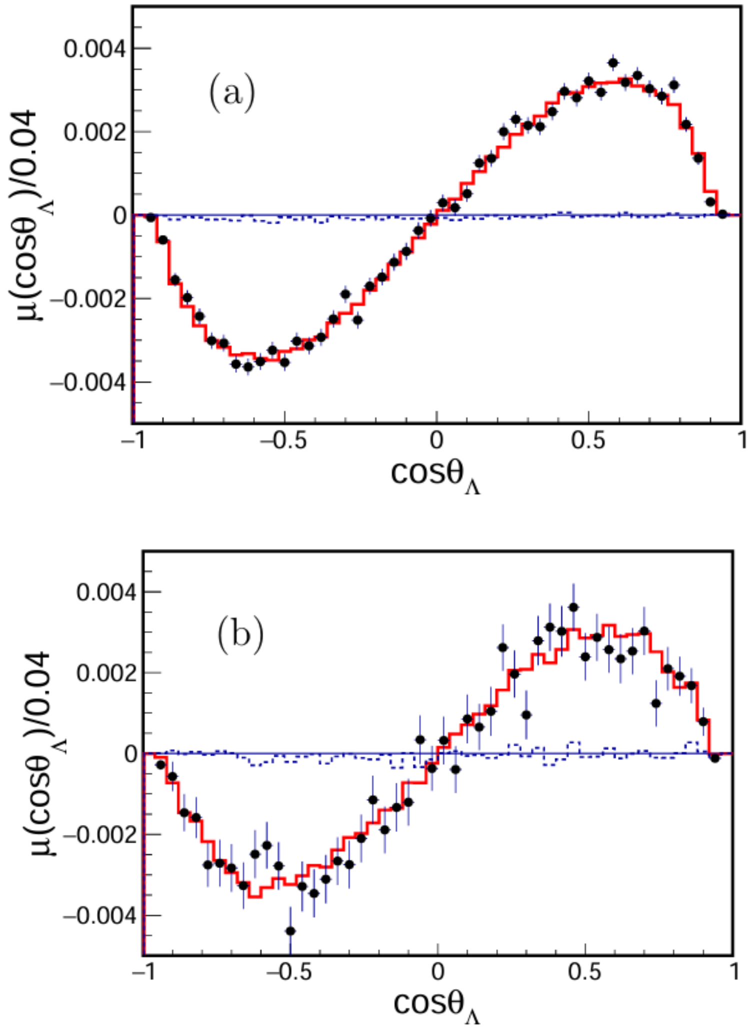
The BESIII Collaboration

Nature Physics **15**, 631–634 (2019) | Cite this article

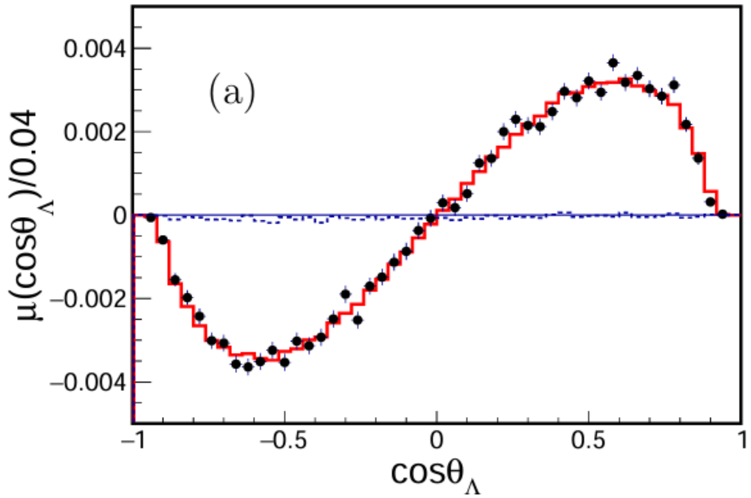


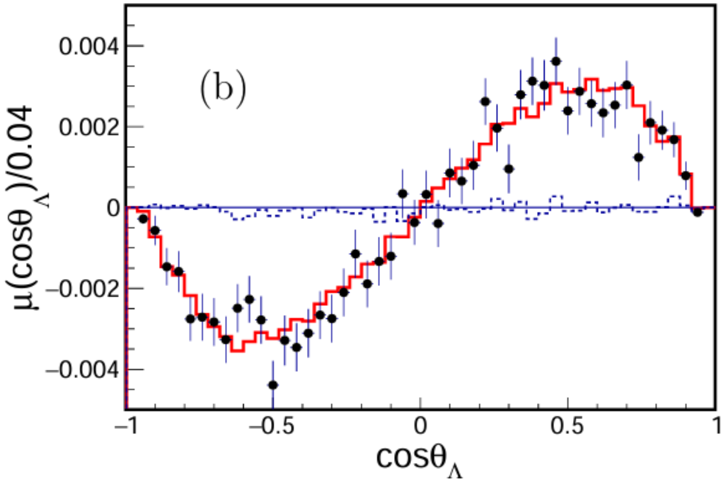
现状和问题

$$e^+e^- \to J/\psi \to \Lambda\bar{\Lambda} \to p\pi^-\ \bar{p}\pi^+\ /\ p\pi^-\bar{n}\pi^0$$

$$\begin{aligned}\mathcal{W}(\boldsymbol{\xi};\alpha_\psi,\Delta\Phi,\alpha_-,\alpha_+) =& 1+\alpha_\psi\cos^2\theta_\Lambda \\ &+\alpha_-\alpha_+\left[\sin^2\theta_\Lambda\left(n_{1,x}n_{2,x}-\alpha_\psi n_{1,y}n_{2,y}\right)+\left(\cos^2\theta_\Lambda+\alpha_\psi\right)n_{1,z}n_{2,z}\right] \\ &+\alpha_-\alpha_+\sqrt{1-\alpha_\psi{}^2}\cos(\Delta\Phi)\sin\theta_\Lambda\cos\theta_\Lambda\left(n_{1,x}n_{2,z}+n_{1,z}n_{2,x}\right) \\ &+\sqrt{1-\alpha_\psi{}^2}\sin(\Delta\Phi)\ \sin\theta_\Lambda\cos\theta_\Lambda\left(\alpha_-n_{1,y}+\alpha_+n_{2,y}\right),\end{aligned}$$

Parameters	This work	Previous results
α_ψ	$0.461 \pm 0.006 \pm 0.007$	0.469 ± 0.027 [25]
$\Delta\Phi$	$(42.4 \pm 0.6 \pm 0.5)^\circ$	–
α_-	$0.750 \pm 0.009 \pm 0.004$	0.642 ± 0.013 [27]
α_+	$-0.758 \pm 0.010 \pm 0.007$	-0.71 ± 0.08 [27]
$\bar{\alpha}_0$	$-0.692 \pm 0.016 \pm 0.006$	–
A_{CP}	$-0.006 \pm 0.012 \pm 0.007$	0.006 ± 0.021 [27]
$\bar{\alpha}_0/\alpha_+$	$0.913 \pm 0.028 \pm 0.012$	–





现状和问题

标准公式，通过末态的衰变来抽取粒子的极化信息。

$$e^+e^- \to J/\psi \to \Lambda\bar{\Lambda} \to p\pi^-\ \bar{p}\pi^+\ /\ p\pi^-\bar{n}\pi^0$$

现状和问题

Zhe Zhang, Rong-Gang Ping, Tianbo Liu，Jiao Jiao Song, Weihua Yang, Ya-jin Zhou PRD 110 034034(2024) $\boldsymbol{e^+e^- \to B_1\bar{B}_2}$

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G. Fäldt, EPJA 52 141(2016)
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Johann Haidenbauer, Ulf-G. Meißner, Ling-Yun Dai PRD 103 (2021) 1, 014028 Study the formfactor
Jian-Ping Dai, Xu Cao, Horst Lenske PLB 846 138192 (2023) isospin assignment and data driven
Prof. He's talk, about CP and EDM

？为什么极化是这样的？
反应的机制是什么？
如何通过极化信息抽取反应的内部信息，从而帮助我们理解强子过程

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$$e^+e^- \to J/\psi \to \Lambda\bar{\Lambda} \to p\pi^- \, \bar{p}\pi^+ \, / \, p\pi^-\bar{n}\pi^0$$

通过极化信息了解其轨道角动量，然后据此来了解产生端的衰变尺度

Shu-ming Wu, Jia-jun Wu, Bing-song Zou, PRD 104 (2021) 5, 054018

？为什么极化是这样的？
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L-S scheme

$$\psi \to \bar{B}(1/2-)B(1/2+) \xrightarrow{L\text{: S and D wave}} r_{eff} \sim \frac{\bar{L}}{p}$$

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This is a very useful PWA tool

PHYSICAL REVIEW C **67**, 015204 (2003)

Lorentz covariant orbital-spin scheme for the effective *N*NM* couplings

B. S. Zou[1,2,3,*] and F. Hussain[3,†]

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Here I mainly introduce it for $\psi \to \bar{N}N^*$ case

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$$S_{\bar{N}} = \frac{1}{2}, \qquad S_{N^*} = \frac{2n+1}{2}$$

$$\psi \to \bar{N}N^*$$

$$J = S_\psi = S_{\bar{N}N^*} + L_{\bar{N}N^*}$$

$$r = p_{N^*} - p_N$$

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$S_{\bar{N}N^*}$

n: $\psi^{(n)}_{\mu_1,\mu_2,\ldots,\mu_n} = \bar{u}_{\mu_1,\mu_2,\ldots,\mu_n}(p_{N^*}, S_{N^*})\gamma_5 v(p_N, S_N)$

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n+1: $\psi^{(n+1)}_{\mu_1,\mu_2,\ldots,\mu_{n+1}} = \bar{u}_{\mu_1,\mu_2,\ldots,\mu_n}(p_{N^*}, S_{N^*})\left(\gamma_{\mu_{n+1}} - \frac{r_{\mu_{n+1}}}{m_\psi + m_{N^*} + m_N}\right) v(p_N, S_N) + (\mu_i \leftrightarrow \mu_j)$

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$L_{\bar{N}N^*} \sim \tilde{t}^{(L)}_{\mu_1,\mu_2,\ldots,\mu_L}(r, p_\psi)$

$\tilde{t}^{(0)}(r, p_\psi) = 1; \quad \tilde{t}^{(1)}{}_{\mu}(r, p_\psi) = \tilde{r}_\mu \equiv \tilde{g}_{\mu\nu}(p_\psi) r^\nu$

$\tilde{t}^{(2)}{}_{\mu\nu}(r, p_\psi) = \tilde{r}_\mu \tilde{r}_\nu - \frac{1}{3}(\tilde{r} \cdot \tilde{r})\tilde{g}_{\mu\nu}(p_\psi); \quad \cdots$

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S. Dulat, J.-J. Wu, B.S. Zou PRD 83 (2011) 094032

$$\tilde{t}^{(L)}_{\mu_{i_1}\mu_{i_2}\cdots\mu_{i_L}} = \tilde{r}_{\mu_{i_1}}\tilde{r}_{\mu_{i_1}}\cdots\tilde{r}_{\mu_{i_L}} + \sum_{l=1}^{[L/2]}\sum_{i_1<i_2<\cdots<i_{2l}=1}^{L}\frac{(-\tilde{r}\cdot\tilde{r})^l}{(2L-1)(2L-3)\cdots(2L-2l+1)}$$
$$\times\frac{1}{2^l l!}(\tilde{g}_{\mu_{i_1}\mu_{i_2}}\tilde{g}_{\mu_{i_3}\mu_{i_4}}\cdots\tilde{g}_{\mu_{i_{2l-1}}\mu_{i_{2l}}} + \mu_{i_1},\mu_{i_2},\cdots\mu_{i_{2l}}\ permutation, (2l)!\ term)$$
$$\times(\tilde{r}_{\mu_1}\tilde{r}_{\mu_2}\cdots\tilde{r}_{\mu_{i_1-1}}\tilde{r}_{\mu_{i_1+1}}\cdots\tilde{r}_{\mu_{i_2-1}}\tilde{r}_{\mu_{i_2+1}}\cdots\tilde{r}_{\mu_{i_{2l}-1}}\tilde{r}_{\mu_{i_{2l}+1}}\cdots\tilde{r}_{\mu_L}), \qquad (12)$$

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$\psi \to \bar N N^*$ $\qquad J = S_\psi = S_{\bar N N^*} + L_{\bar N N^*}$ $\qquad r = p_{N^*} - p_N$

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$S_\psi = S_{\bar N N^*} + L_{\bar N N^*}$

$\psi^{(S)}_{\mu_1,\mu_2,\ldots,\mu_S}, \quad \tilde t^{(L)}_{\mu_1,\mu_2,\ldots,\mu_L}, \quad \varepsilon_{\mu_1,\ldots\mu_J}(p_\psi, s_\psi)$

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$$r = p_{N^*} - p_N$$

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$$S_\psi = S_{\bar{N}N^*} + L_{\bar{N}N^*}$$

$$\psi^{(S)}_{\mu_1,\mu_2,\ldots,\mu_S}, \quad \tilde{t}^{(L)}_{\mu_1,\mu_2,\ldots,\mu_L}, \quad \varepsilon_{\mu_1,\ldots\mu_J}(p_\psi, s_\psi)$$

If S+L+J=odd, $M \sim \epsilon^{\alpha\beta\gamma\sigma}\psi^{(S)}_{\mu_i\mu_j,\alpha}\tilde{t}^{(L)}_{\mu_i'\mu_k,\beta}\varepsilon_{\mu_j'\mu_k',\gamma}p_{\psi,\sigma}\, g^{\mu_i\mu_i'}g^{\mu_j\mu_j'}g^{\mu_k\mu_k'}$

If S+L+J=even, $M \sim \psi^{(S)}_{\mu_i\mu_j,}\tilde{t}^{(L)}_{\mu_i'\mu_k,}\varepsilon_{\mu_j'\mu_k'}\, g^{\mu_i\mu_i'}g^{\mu_j\mu_j'}g^{\mu_k\mu_k'}$

We also need to consider Parity conservation.

L-S scheme

$$\psi \to \bar{B}(1/2-)B(1/2+) \xrightarrow{L:\ \text{S and D wave}} r_{eff} \sim \frac{\bar{L}}{p}$$

This is a very useful PWA tool

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$\psi \to \bar{N}^*N^*$
Such as $\Sigma^*\bar{\Sigma}^*$

Here I mainly introduce it for $\psi \to \bar{N}N^*$ case

Update: Recently, we propose a new method based on Group theory to write down covariant partial wave amplitudes within **L-S scheme** for three-particle vertex with any spin. And we also show that it is equivalent with usual helicity amplitude.

Covariant orbital-spin scheme for any spin based on irreducible tensor #43

Hao-Jie Jing (Beijing, GUCAS), Di Ben (Beijing, Inst. Theor. Phys. and Beijing, GUCAS), Shu-Ming Wu (Beijing, GUCAS and Beijing, Inst. Theor. Phys.), Jia-Jun Wu (Beijing, GUCAS), Bing-Song Zou (Beijing, Inst. Theor. Phys. and Central South U., Changsha) (Jan 4, 2023)

Published in: *JHEP* 06 (2023) 039, *JHEP* 06 (2023) 039 • e-Print: 2301.01575 [hep-ph]

Algorithms for partial wave amplitudes in the covariant *L-S* scheme #22

Hao-Jie Jing (Beijing, GUCAS), Shu-Ming Wu (Beijing, GUCAS), Jia-Jun Wu (Beijing, GUCAS and Lanzhou, Inst. Modern Phys.) (May 10, 2024)

Published in: *Phys.Rev.D* 110 (2024) 1, 016014 • e-Print: 2405.06576 [hep-ph]

Two ways for the amplitude of $\psi \to \bar{B}B$

Method 1, using G_E^{ψ} and G_M^{ψ}, the amplitude,

$$M = -ie_g\bar{u}_B\left(G_E^{\psi}\gamma_\mu - \frac{2m_B}{r^2}\left(G_M^{\psi} - G_E^{\psi}\right)r_\mu\right)v_{\bar{B}}\epsilon^{\mu}$$

G. Fäldt, EPJA 52 141(2016)
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$$r^2 = q^2 = \frac{s}{4} - m_B^2$$

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G. Fäldt and A. Kupsc, PLB 772 16(2017)

$$r^2 = q^2 = \frac{s}{4} - m_B^2$$

Method 2, using L-S scheme, the amplitude,

$\psi(1^-) \to \bar{B}(1/2^-)B(1/2^+)$

$$M = \psi_\mu^{(1)}\left(g_S g^{\mu\nu} + g_D e^{i\delta} \tilde{t}^{(2)\mu\nu}\right)\epsilon_\nu = \bar{u}_B \left(\gamma_\mu - \frac{(p_B - p_{\bar{B}})}{m_\psi + 2m_B} \right) v_{\bar{B}} \left(g_S g^{\mu\nu} + g_D e^{i\delta} \tilde{t}^{(2)\mu\nu}\right)\epsilon_\nu$$

$S_\psi = S_{\bar{N}N^*} + L_{\bar{N}N^*}$
$1 = 1 + (0, 2)$
Including S- and D-wave

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$$M = \psi_\mu^{(1)} \left(g_S g^{\mu\nu} + g_D e^{i\delta} \tilde{t}^{(2)\mu\nu} \right) \epsilon_\nu = \bar{u}_B \left(\gamma_\mu - \frac{(p_B - p_{\bar{B}})}{m_\psi + 2m_B} \right) v_{\bar{B}} \left(g_S g^{\mu\nu} + g_D e^{i\delta} \tilde{t}^{(2)\mu\nu} \right) \epsilon_\nu$$

$$S_\psi = S_{\bar{N}N^*} + L_{\bar{N}N^*}$$
$$1 = 1 + (0, 2)$$

Including S- and D-wave

Relationship, there are three free parameters in both cases, we can define them as: an overall coupling constant, $\left|\frac{g_D}{g_S}\right| \left(\left| \frac{G_E^\psi}{G_M^\psi} \right| \right)$, and $\delta \left(\Delta\Phi \equiv Arg\left(\frac{G_E^\psi}{G_M^\psi} \right) \right)$, typically,

$$e^{i\delta} \frac{g_D}{g_S} = -\frac{3}{2r^2} \frac{2m_B - r^2/(m_\psi + 2m_B) - 2m_B \left(G_E^\psi / G_M^\psi \right)}{2m_B - r^2/(m_\psi + 2m_B) + 2m_B \left(G_E^\psi / G_M^\psi \right)}$$

Two ways for the amplitude of $\psi \to \bar{B}B$

Method 1, using G_E^ψ and G_M^ψ, the amplitude, $M = -ie_g\bar{u}_B\left(G_E^\psi\gamma_\mu - \frac{2m_B}{r^2}\left(G_M^\psi - G_E^\psi\right)r_\mu\right)v_{\bar{B}}\epsilon^\mu$

Method 2, using PAW, the amplitude, $M = \bar{u}_B\left(\gamma_\mu - \frac{(p_B - p_{\bar{B}})}{m_\psi + 2m_B}\right)v_{\bar{B}}\left(g_S g^{\mu\nu} + g_D e^{i\delta}\tilde{t}^{(2)\mu\nu}\right)\epsilon_\nu$

Experimently,

(1) an overall coupling constant can be obtained from the partial width Γ.

Two ways for the amplitude of $\psi \to \bar{B}B$

Method 1, using G_E^{ψ} and G_M^{ψ}, the amplitude, $M = -ie_g\bar{u}_B\left(G_E^{\psi}\gamma_\mu - \frac{2m_B}{r^2}\left(G_M^{\psi} - G_E^{\psi}\right)r_\mu\right)v_{\bar{B}}\epsilon^\mu$

Method 2, using PAW, the amplitude, $M = \bar{u}_B\left(\gamma_\mu - \frac{(p_B - p_{\bar{B}})}{m_\psi + 2m_B}\right)v_{\bar{B}}\left(g_S g^{\mu\nu} + g_D e^{i\delta}\tilde{t}^{(2)\mu\nu}\right)\epsilon_\nu$

Experimently,

(1) an overall coupling constant can be obtained from the partial width Γ.

(2) $t = \left|\frac{g_D}{g_S}\right|$ and δ can be determined by angular distribution, $\frac{d\Gamma}{d\cos\theta} \sim \left(1 + \alpha\cos^2\theta\right)$,

and $\Delta\Phi \equiv Arg\left(\frac{G_E^{\psi}}{G_M^{\psi}}\right)$

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Mode	α	$\Delta\Phi$	g_D/g_S	δ	$\Gamma_S/\Gamma_{\mathrm{Total}}$	r_{eff}
$J/\psi \to \Lambda\bar{\Lambda}$	0.461 ± 0.013[23]	0.74 ± 0.019[23]	0.180 ± 0.005	-0.804 ± 0.024	$85.7 \pm 0.6\%$	0.0488 ± 0.0021
$J/\psi \to \Sigma^+\bar{\Sigma}^-$	-0.508 ± 0.010[24]	-0.270 ± 0.021[24]	0.171 ± 0.006	2.67 ± 0.04	$90.9 \pm 0.6\%$	0.0362 ± 0.0024
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Need further decay, such as $\Lambda \to p\,\pi$

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通过这个计算可以发现ψ的有效衰变半径很小。这样就会导致$\psi \to \bar{N}N^*$的轨道角动量很小，即$L = r_{eff} \times p$，那么就很难产生高自旋的N^*. 所以在这类过程中，N^*的分波分析其实只要取到$l = 5/2$就基本足够分析数据了。

当然我们需要更多的数据来确认。

Motivation

Question: How many partial waves does ψ decay need ?

N(2190) 7/2−	πN and γN
N(2220) 9/2+	πN and γN
N(2250) 9/2−	πN and γN
N(2300) 1/2+	ψ(2S) decay
N(2570) 5/2−	ψ(2S) decay
N(2600) 11/2−	πN
N(2700) 13/2+	πN

$$L = r_{eff} \times p$$

πN and γN

$$E \sim 2\ \text{GeV} \rightarrow p \sim 1\ \text{GeV}$$

$$r_{eff} \sim r_N \sim 1\text{fm}$$

$$L \sim 1\ \text{fm} \times 1\ \text{GeV} \sim 5$$

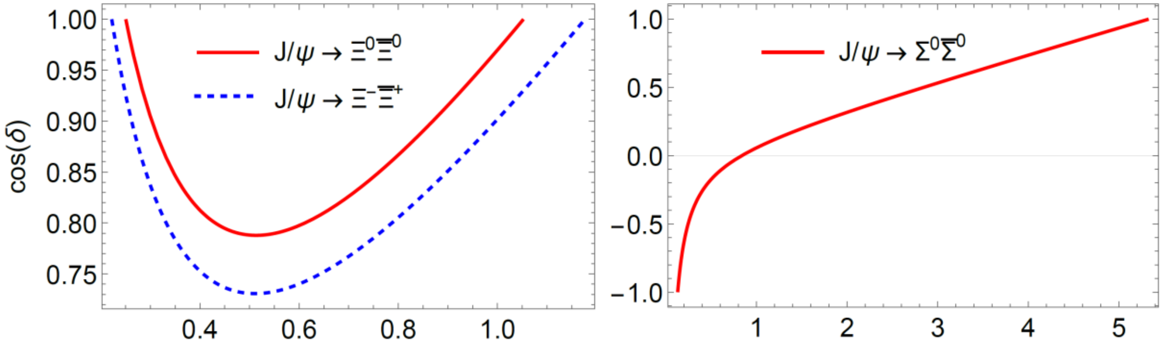
$$J_{N^*} \sim \left[5 - \frac{3}{2}, 5 + \frac{3}{2}\right] \sim \left[\frac{7}{2}, \frac{13}{2}\right]$$

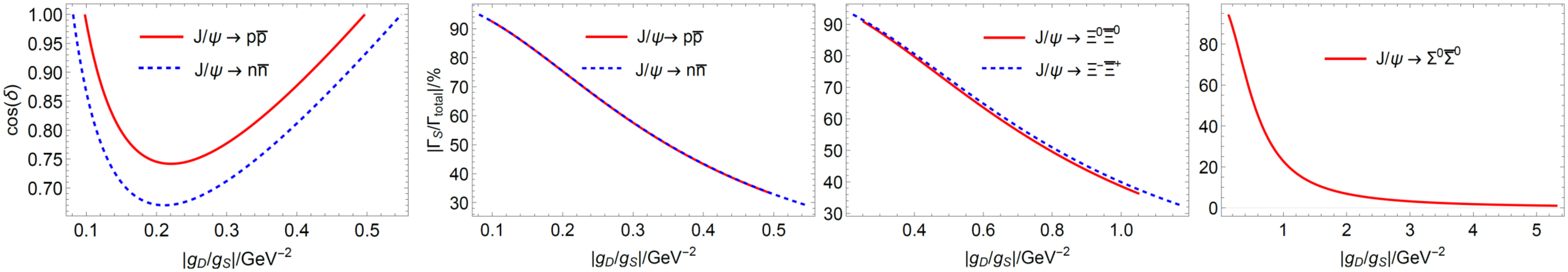
How to estimate the effective radius of the ψ decay ???

$$\psi \rightarrow \bar{B}(1/2-)B(1/2+) \longrightarrow r_{eff} \sim \frac{\bar{L}}{p}$$

The effective radius of the decay reaction

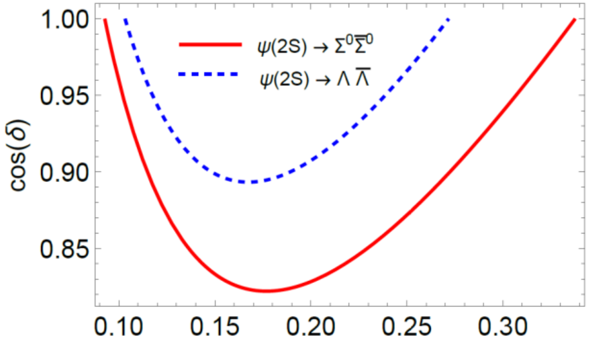
Mode	α	$r_{\text{eff}}(\text{fm})$
$J/\psi \to p\bar{p}$	0.595 ± 0.027[26]	$[0.023 - 0.214]$
$J/\psi \to n\bar{n}$	0.50 ± 0.25[26]	$[0.016 - 0.228]$
$J/\psi \to \Sigma^0\bar{\Sigma}^0$	-0.449 ± 0.028[25]	$[0.022 - 0.396]$
$J/\psi \to \Xi^0\bar{\Xi}^0$	0.66 ± 0.08[28]	$[0.044 - 0.308]$
$J/\psi \to \Xi^-\bar{\Xi}^+$	0.58 ± 0.12[29]	$[0.034 - 0.331]$

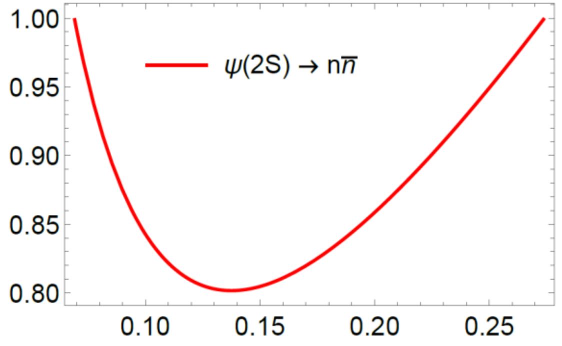


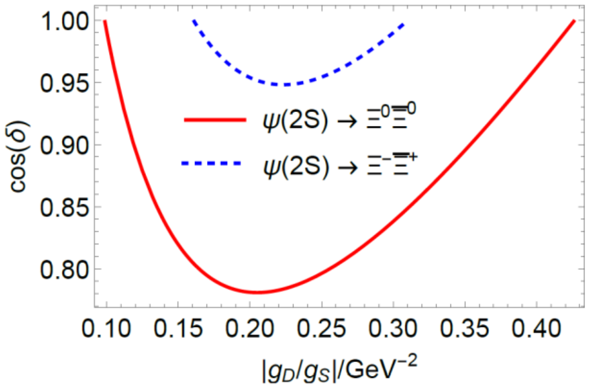


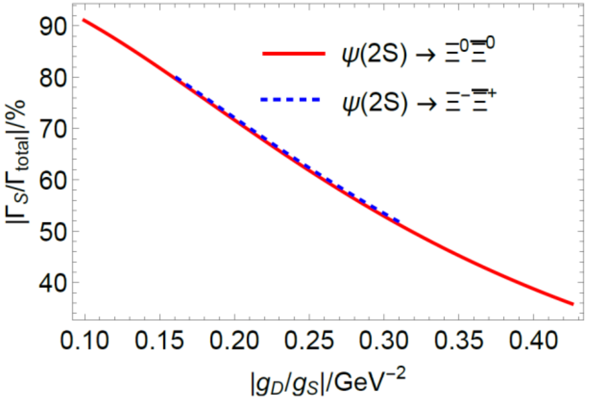
The effective radius of the decay reaction

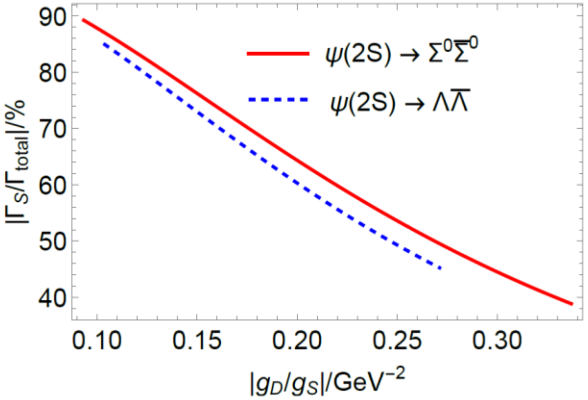
Mode	α	$r_{\text{eff}}(\text{fm})$
$\psi_{2S} \to \Lambda\bar{\Lambda}$	0.82 ± 0.10[25]	$[0.040 - 0.148]$
$\psi_{2S} \to p\bar{p}$	1.03 ± 0.09[27]	**???**
$\psi_{2S} \to n\bar{n}$	0.68 ± 0.23[27]	$[0.024 - 0.156]$
$\psi_{2S} \to \Sigma^0\bar{\Sigma}^0$	0.71 ± 0.15[25]	$[0.030 - 0.172]$
$\psi_{2S} \to \Xi^0\bar{\Xi}^0$	0.65 ± 0.23[28]	$[0.027 - 0.196]$
$\psi_{2S} \to \Xi^-\bar{\Xi}^+$	0.91 ± 0.27[29]	$[0.061 - 0.148]$

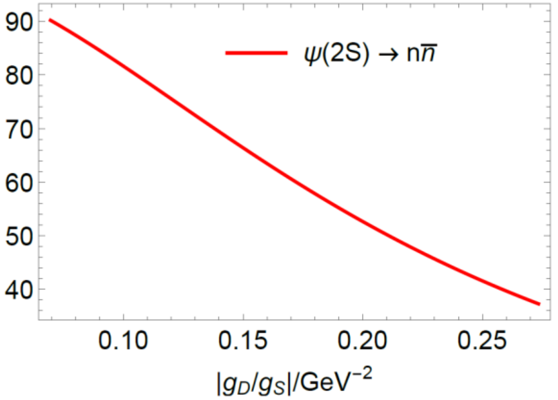












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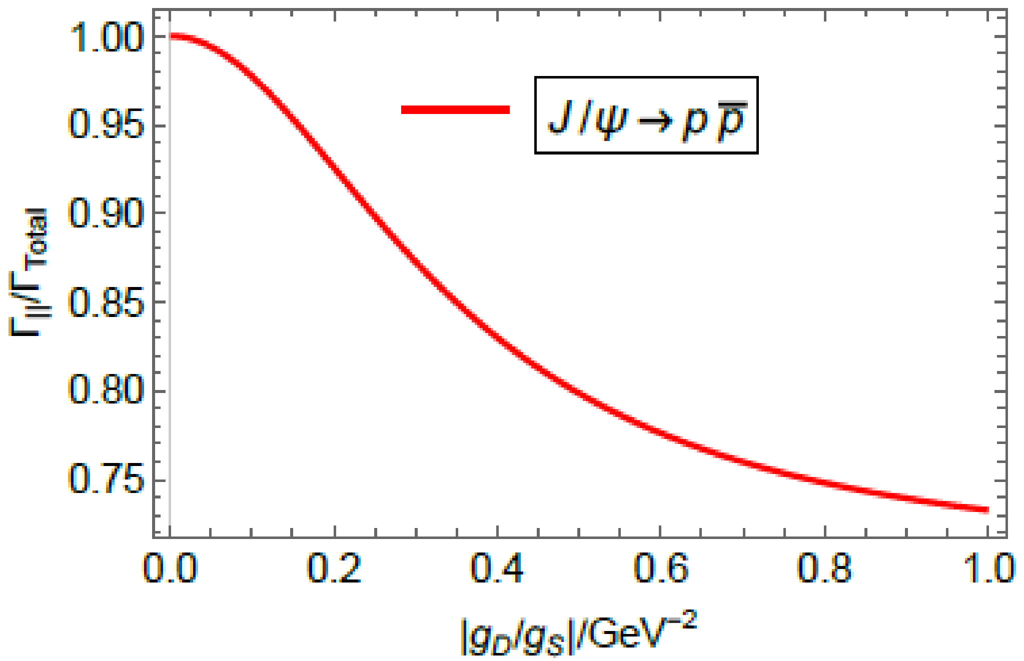

Since $p(n)$ can not further decay, thus $\Delta\Phi$ cannot be measured. We need new observable, such as $\Gamma_{//}$ to stand for the decay width of the process where $p(n)$ and $\bar{p}(\bar{n})$ have the same polarization,

$$\Gamma_{//} = \frac{|\vec{p}_B|}{32\pi^2 m_\psi^2} \int \frac{1}{2} \sum_{S_\psi, S_B = S_{\bar{B}}} \left|M(S_\psi, S_B, S_{\bar{B}})\right|^2 d\Omega = \Gamma_S + 0.7\Gamma_D$$

Summary

- Introduction of L-S scheme
- Through $\psi \to \bar{B}(1/2-)B(1/2+)$ to estimate the effective radius of ψ decay, around 0.05fm.
- It leads to low spin N^* dominate in the $\psi \to \bar{N}N^*$, thus, highest partial wave analysis require the total J of N^* with $l = 5/2$.
- It provides a unique window to search low spin baryon resonances with masses above 2 GeV in ψ decay.
- We need more experimental data to confirm it.

Thanks Very Much !