Nucleon pair production in Charmonium states

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Workshop of the Baryon Production at BESIII

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IHEP-INFN

1. BESIII Collaboration, PRD 86, 032014 (2012)
2. BESIII Collaboration, PRD 98, 032006 (2018)
3. R.B. Ferroli, A. Mangoni, S. Pacetti, K. Zhu, arXiv:1905.01069

Outline

- Two BESIII measurements
  - $J/\psi \to N\bar{N}$
  - $\psi(3686) \to N\bar{N}$
- Conclusion and conflicts from experimental measurements
  - Relative phase between strong and EM amplitudes
  - G-parity contribution from ggγ exchange

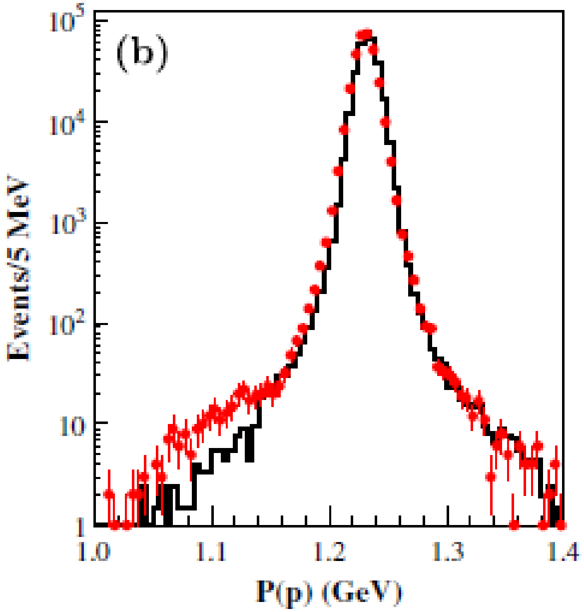
Motivations of $\psi \to N\bar{N}$

- Relative phase between strong and EM amplitudes
  - Strong amplitudes: same for $p\bar{p}$ and $n\bar{n}$ since initial state is iso-spin 0
  - EM amplitudes: (assumed) same magnitude, opposite signs for $p\bar{p}$ and $n\bar{n}$
  - $\frac{B(\psi \to p\bar{p})}{B(\psi \to n\bar{n})}$
- Angular distribution
  - $\frac{dN}{dcos\theta} = A(1 + \alpha \cos^2 \theta)$
  - Reflect the details of baryon structure
- Test of 12% rules
  - $\frac{B(\psi(3686) \to N\bar{N})}{B(J/\psi \to N\bar{N})}$

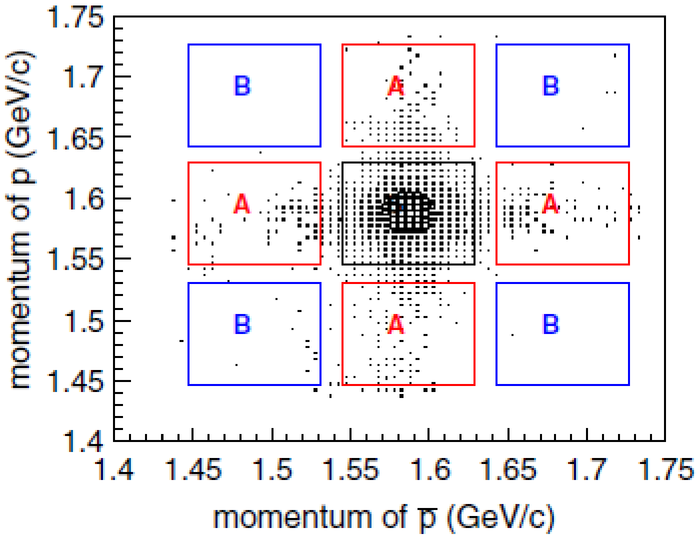
$\psi \to p\bar{p}$ (selection)

- 225×10^6 J/ψ and 107×10^6 $\psi(3686)$ events
- Very simple selection criteria, very low backgrounds
  - Good charged tracks, loose PID, and back-to-back angle cut

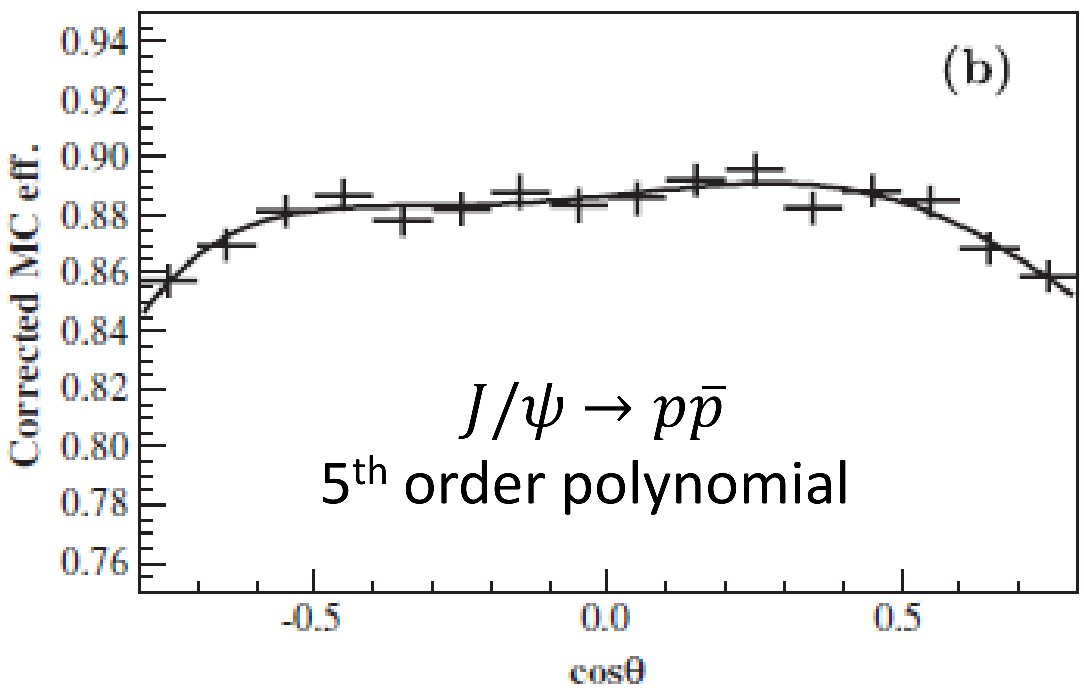
$J/\psi \to p\bar{p}$
314651 candidates

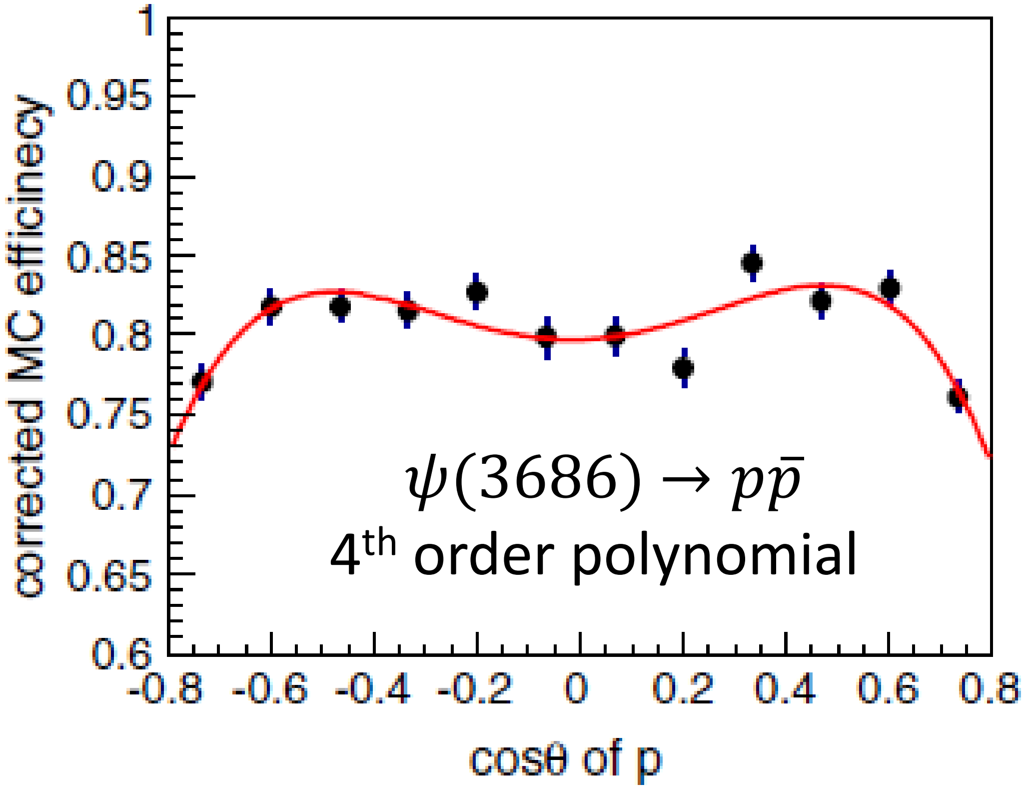


$\psi(3686) \to p\bar{p}$
18984 candidates

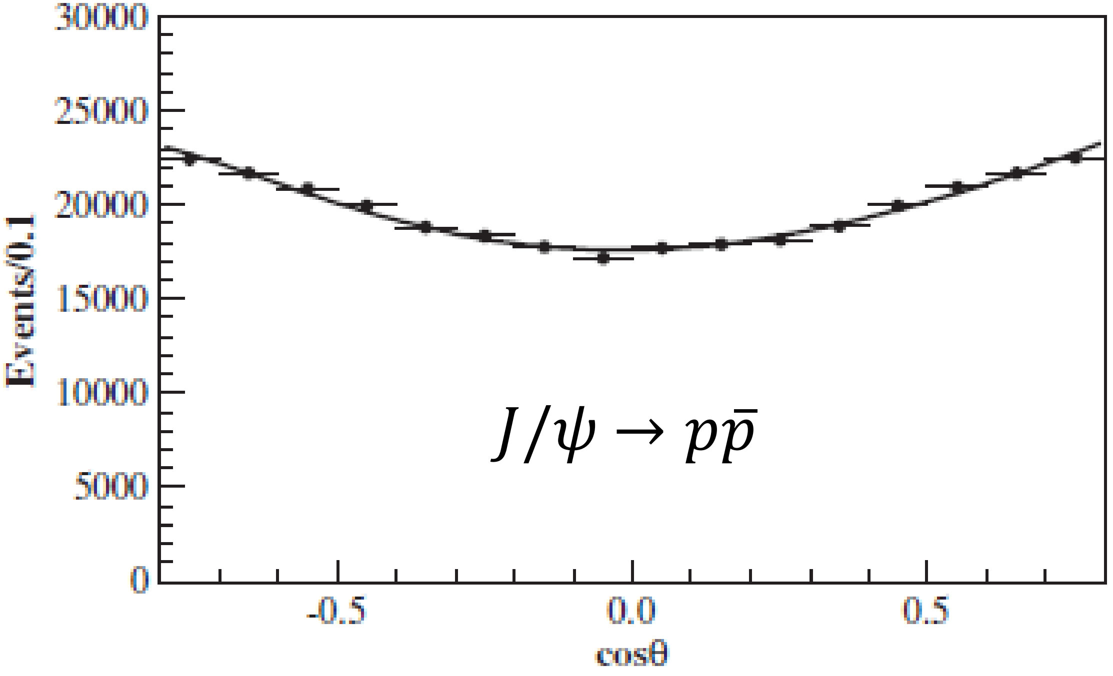


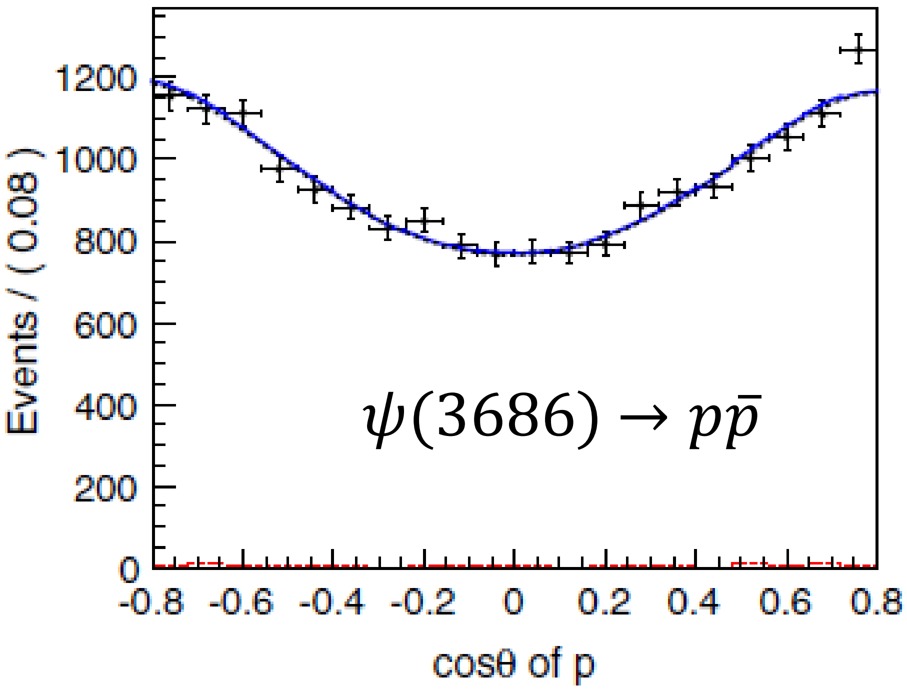
$\psi \to p\bar{p}$ (efficiency correction: tracking and PID)





$\psi \rightarrow p\bar{p}$ (fit to extract α)





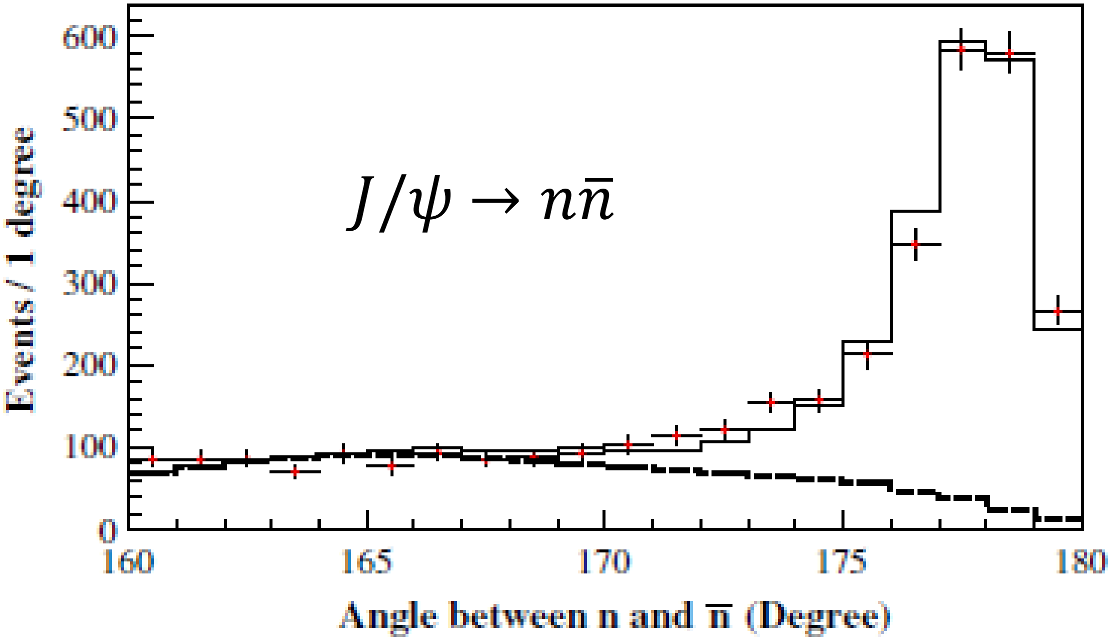
$\psi \to n\bar{n}$ (selection)

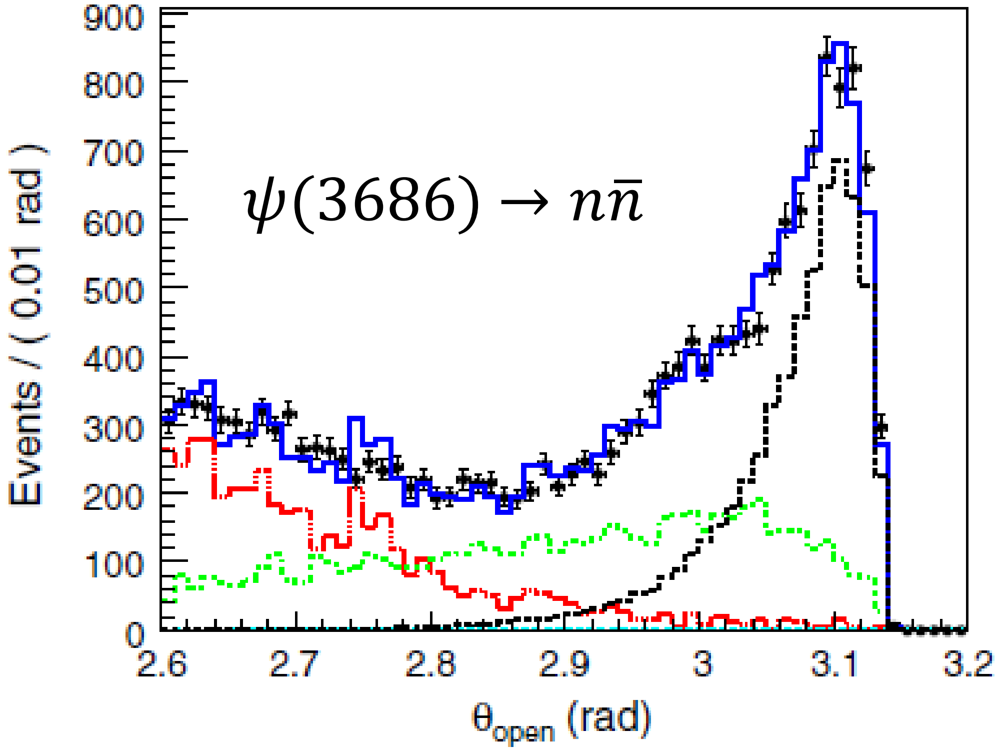
- Much more complex than $p\bar{p}$ final states
- Many EMC shower characters are exploited
- For $\psi(3686)$ decay, a machine learning method (BDT) is applied

TABLE II. The variables used in the MVA. The second moment is defined as $\sum_i E_i r_i^2 / \sum_i E_i$, and the lateral moment is defined as $\sum_{i=3}^n E_i r_i^2 / (E_1 r_0^2 + E_2 r_0^2 + \sum_{i=3}^n E_i r_i^2)$. Here, $r_0 = 5$ cm is the average distance between crystal centers in the EMC, r_i is the radial distance of crystal i from the cluster center, and E_i is the crystal energy in decreasing order.

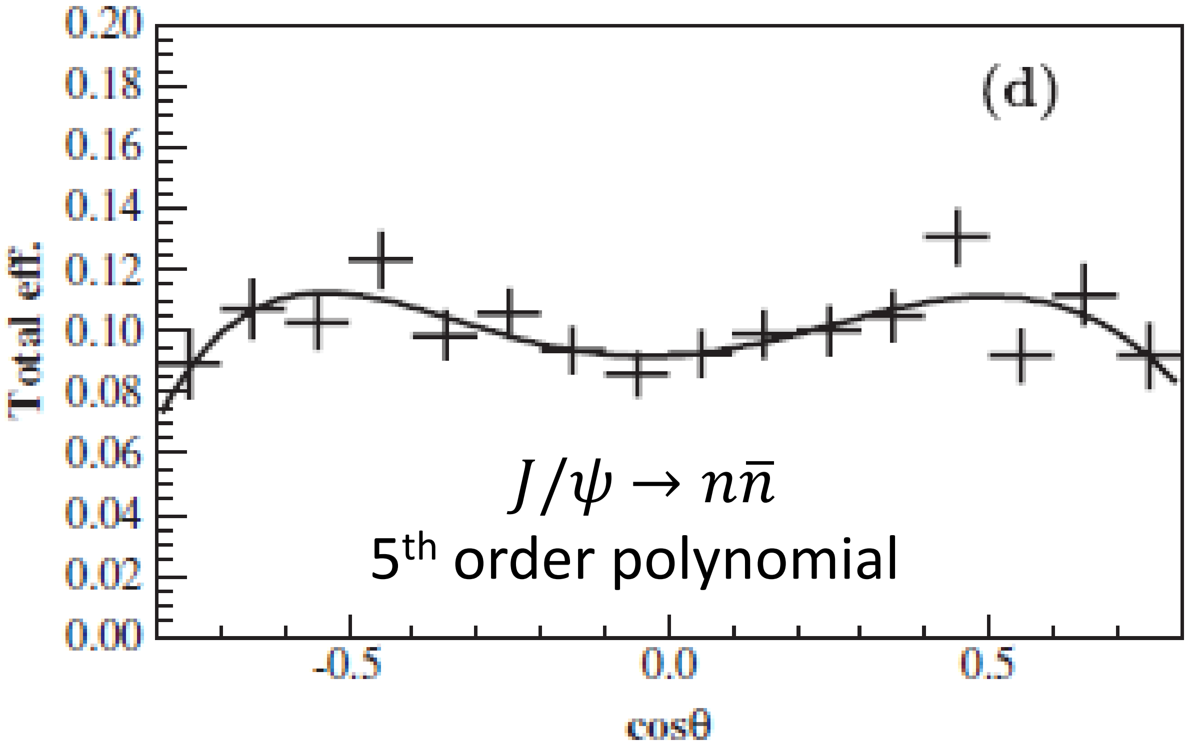
Names	Definitions	Importance
numhit1	Number of hits in the first SG	0.09
numhit2	Number of hits in the second SG	0.06
ene1	Energy of the first SG	0.10
ene2	Energy of the second SG	0.21
secmom1	Second moments of the first SG	0.06
secmom2	Second moments of the second SG	0.06
latmom1	Lateral moments of the first SG	0.09
latmom2	Lateral moments of the second SG	0.05
bbang1	Largest opening angle in the first SG	0.04
bbang2	Largest opening angle in the second SG	0.05
numshow1	Number of showers in the first SG	0.04
numshow2	Number of showers in the second SG	0.04
numrem	Number of remaining showers	0.06
enerem	Energy of remaining showers	0.07

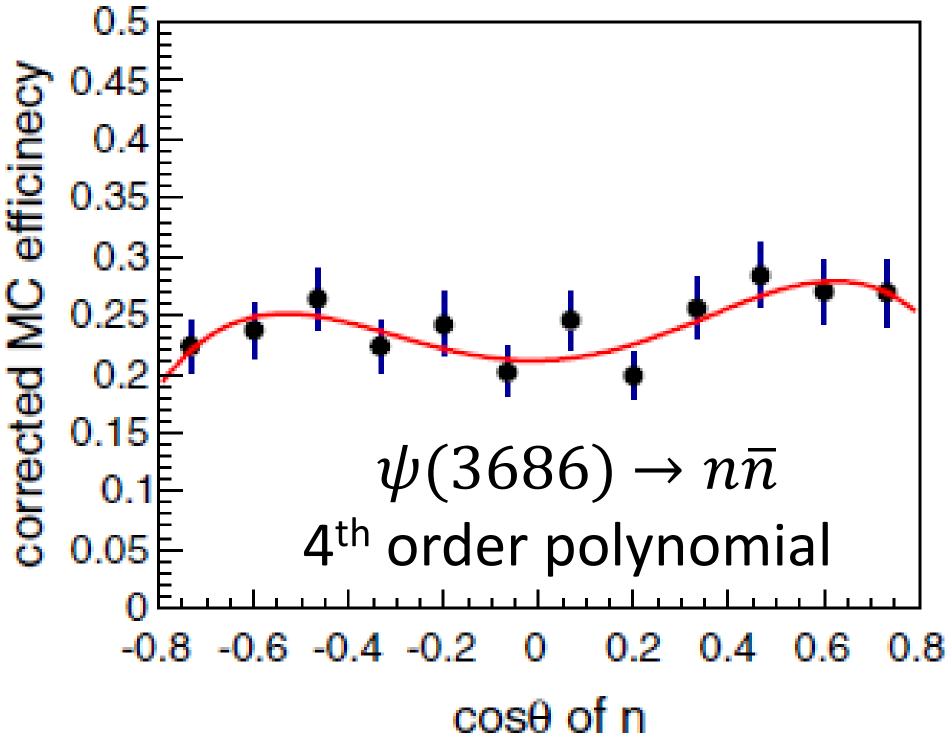
$\psi \to n\bar{n}$ (fit open-angle to extract yields)



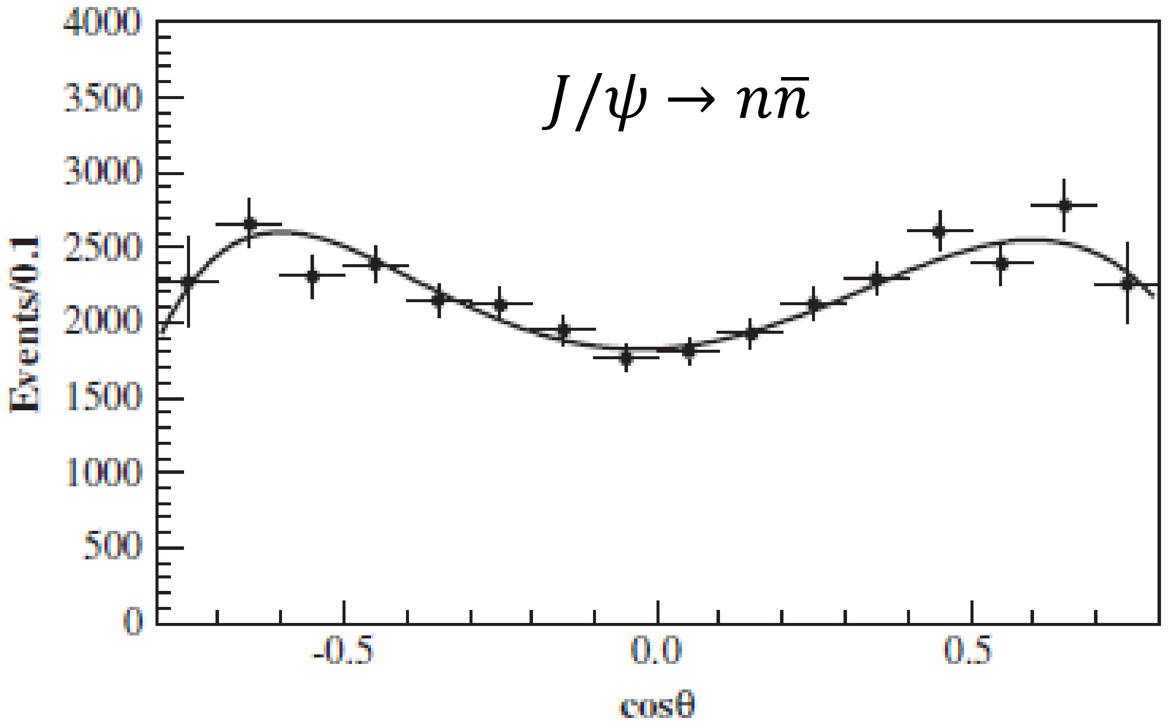


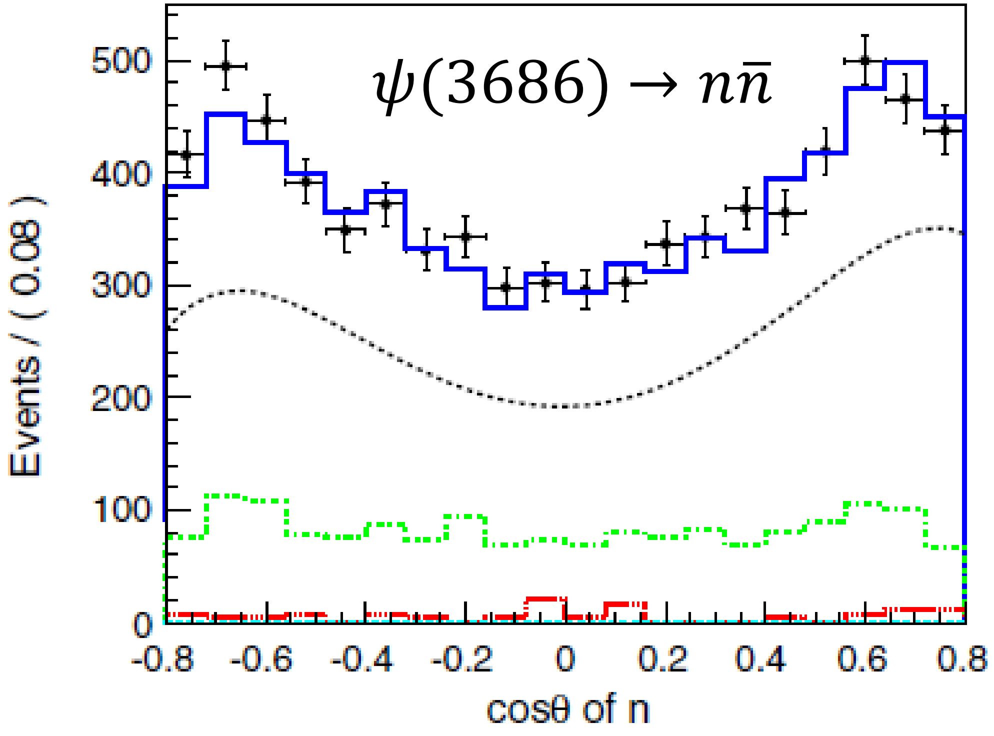
$\psi \to n\bar{n}$ (efficiency correction)





$\psi \to n\bar{n}$ (fit to extract α)





Results of $\psi \to N\bar{N}$

- $B(J/\psi \to p\bar{p}) = (2.112 \pm 0.004 \pm 0.031) \times 10^{-3}$
- $B(J/\psi \to n\bar{n}) = (2.07 \pm 0.01 \pm 0.17) \times 10^{-3}$
- $\alpha_{p\bar{p}} = 0.595 \pm 0.012 \pm 0.015$
- $\alpha_{n\bar{n}} = 0.50 \pm 0.04 \pm 0.21$

- $B(\psi(3686) \to p\bar{p}) = (3.05 \pm 0.02 \pm 0.12) \times 10^{-4}$
- $B(\psi(3686) \to n\bar{n}) = (3.06 \pm 0.06 \pm 0.14) \times 10^{-4}$
- $\alpha_{p\bar{p}} = 1.03 \pm 0.06 \pm 0.03$
- $\alpha_{n\bar{n}} = 0.68 \pm 0.12 \pm 0.11$

Conclusions and conflicts (I)

- Consistent with the 12% rule

$$\frac{\mathcal{B}(\psi(3686) \to p\bar{p})}{\mathcal{B}(J/\psi \to p\bar{p})} = (14.4 \pm 0.6)\%$$

$$\frac{\mathcal{B}(\psi(3686) \to n\bar{n})}{\mathcal{B}(J/\psi \to n\bar{n})} = (14.8 \pm 1.2)\%,$$

Conclusions and conflicts (II)

Following four slides is a revision of Rinaldo's talk in BESIII P&S workshop, Guangzhou, 2017

- Close branching fractions suggest interference between strong and EM decay is small
  - i.e. the relative phase $\phi \sim 90°$

- $B(J/\psi \rightarrow p\bar{p}) = (2.112 \pm 0.004 \pm 0.031) \times 10^{-3}$
- $B(J/\psi \rightarrow n\bar{n}) = (2.07 \pm 0.01 \pm 0.17) \times 10^{-3}$

- $B(\psi(3686) \rightarrow p\bar{p}) = (3.05 \pm 0.02 \pm 0.12) \times 10^{-4}$
- $B(\psi(3686) \rightarrow n\bar{n}) = (3.06 \pm 0.06 \pm 0.14) \times 10^{-4}$

Conclusions and conflicts (III)

- In the case of $J/\psi \to N\bar{N}$
  - $\alpha_{p\bar{p}} = 0.595 \pm 0.012 \pm 0.015, \quad \alpha_{n\bar{n}} = 0.50 \pm 0.04 \pm 0.21$
  - consistent with $\phi \sim 90^{\circ}$
- So far, so good

Conclusions and conflicts (III)

- In the case of $J/\psi \to N\bar{N}$
  - $\alpha_{p\bar{p}} = 0.595 \pm 0.012 \pm 0.015, \quad \alpha_{n\bar{n}} = 0.50 \pm 0.04 \pm 0.21$
  - consistent with $\phi \sim 90°$
- So far, so good
- However, in $\psi(3686) \to N\bar{N}$
  - $\alpha_{p\bar{p}} = 1.03 \pm 0.06 \pm 0.03,\ \alpha_{n\bar{n}} = 0.68 \pm 0.12 \pm 0.11$, i.e. $p\bar{p}$ and $n\bar{n}$ angular distribution are quite different, in spite of similar branching fractions
  - BTW, no evidence of a $cos\theta$ term: no forward/backward asymmetry, i.e. no evidence of a 2γ contribution in $e^+e^- \to \psi(3686)$.

Conclusions and conflicts (IV)

- Conclusion (after some derivation)
  - no chance to find a proper solution with only three-gluon and one-photon exchange amplitudes
  - Therefore, additional to the strong amplitude S, there might be a G parity violating amplitude T in the $\psi(3686)$ decays
- That amplitude T might contribute to J/ψ decays too
  - In addition to the $\pi\pi$ final states [PRD 95, 034038 (2017)], we shall discuss the baryon final states following

Three possible contributions

R.B. Ferroli, A. Mangoni, S. Pacetti, K. Zhu, arXiv:1905.01069

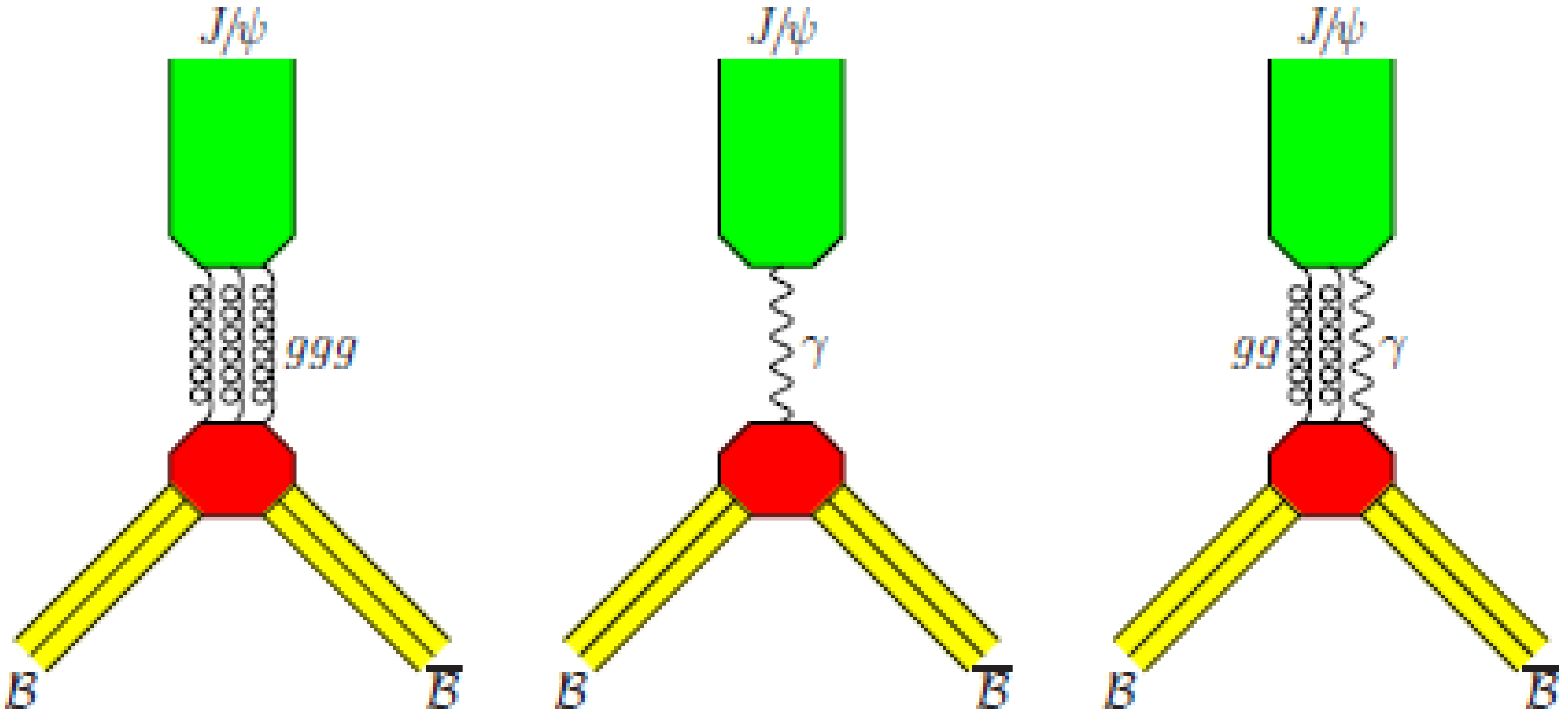


Figure 1: Feynman diagrams of the the purely strong, purely EM and strong-EM contributions.

Effective Lagrangian

$$S_m = \frac{g_m}{3}\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}$$

$$\mathcal{B} = \begin{pmatrix} \Lambda/\sqrt{6} + \Sigma^0/\sqrt{2} & \Sigma^+ & p \\ \Sigma^- & \Lambda/\sqrt{6} - \Sigma^0/\sqrt{2} & n \\ \Xi^- & \Xi^0 & -2\Lambda/\sqrt{6} \end{pmatrix}.$$

$$S_e = \frac{g_e}{3}\begin{pmatrix} 2 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix}$$

$$\begin{aligned} \mathcal{L} \quad = \quad & g\,\mathrm{Tr}(\mathcal{B}\overline{\mathcal{B}}) + d\,\mathrm{Tr}\left(\{\mathcal{B}, \overline{\mathcal{B}}\}S_e\right) + f\,\mathrm{Tr}\left([\mathcal{B}, \overline{\mathcal{B}}]S_e\right) \\ & + d'\,\mathrm{Tr}\left(\{\mathcal{B}, \overline{\mathcal{B}}\}S_m\right) + f'\,\mathrm{Tr}\left([\mathcal{B}, \overline{\mathcal{B}}]S_m\right), \qquad (1) \end{aligned}$$

Amplitudes parameterization

$B\overline{B}$	$\mathcal{A}_{B\overline{B}} = \mathcal{A}^{ggg}_{B\overline{B}} + \mathcal{A}^{gg\gamma}_{B\overline{B}} + \mathcal{A}^{\gamma}_{B\overline{B}}$
$\Sigma^0\overline{\Sigma}^0$	$(G_0 + 2D_m)e^{i\varphi} + D_e$
$\Lambda\overline{\Lambda}$	$(G_0 - 2D_m)e^{i\varphi} - D_e$
$\Lambda\overline{\Sigma}^0$+ c.c.	$\sqrt{3}\, D_e$
$p\overline{p}$	$(G_0 - D_m + F_m)(1 + R)e^{i\varphi} + D_e + F_e$
$n\overline{n}$	$(G_0 - D_m + F_m)e^{i\varphi} - 2\, D_e$
$\Sigma^+\overline{\Sigma}^-$	$(G_0 + 2D_m)(1 + R)e^{i\varphi} + D_e + F_e$
$\Sigma^-\overline{\Sigma}^+$	$(G_0 + 2D_m)(1 + R)e^{i\varphi} + D_e - F_e$
$\Xi^0\overline{\Xi}^0$	$(G_0 - D_m - F_m)e^{i\varphi} - 2\, D_e$
$\Xi^-\overline{\Xi}^+$	$(G_0 - D_m - F_m)(1 + R)e^{i\varphi} + D_e - F_e$

$$R = \frac{\mathcal{A}^{gg\gamma}_{B\overline{B}}}{\mathcal{A}^{ggg}_{B\overline{B}}}$$

- ϕ is the relative phase angle between strong and EM amplitudes
- Assume there is no relative phase between ggg and $gg\gamma$

In particular, G_0 is related to the coupling constant g, D_e, F_e to d, g, which refer to the EM breaking effects, and D_m, F_m to d', g', describing to the mass difference breaking effects.

Fit to experimental measurements

$$\chi^2(C;R,\varphi) = \sum_{B\bar{B}}\left(\frac{\mathrm{BR}^{\mathrm{th}}_{B\bar{B}}-\mathrm{BR}^{\mathrm{exp}}_{B\bar{B}}}{\delta\mathrm{BR}^{\mathrm{exp}}_{B\bar{B}}}\right)^2 + \left(\frac{\mathrm{BR}^{\gamma,\mathrm{th}}_{p\bar{p}}-\mathrm{BR}^{\gamma,\mathrm{exp}}_{p\bar{p}}}{\delta\mathrm{BR}^{\gamma,\mathrm{exp}}_{p\bar{p}}}\right)^2$$

G_0	$(5.73511 \pm 0.0059) \times 10^{-3}$ GeV
D_e	$(4.52 \pm 0.19) \times 10^{-4}$ GeV
D_m	$(-3.74 \pm 0.34) \times 10^{-4}$ GeV
F_e	$(7.91 \pm 0.62) \times 10^{-4}$ GeV
F_m	$(2.42 \pm 0.12) \times 10^{-4}$ GeV
φ	$1.27 \pm 0.14 = (73 \pm 8)^\circ$
R	$(-9.7 \pm 2.1) \times 10^{-2}$

Two remarks

$$\frac{\chi^2\left(C^{\text{best}}; R^{\text{best}}, \varphi^{\text{best}}\right)}{N_{\text{dof}}} = 1.33 \qquad \frac{\chi^2\left(C'^{\text{best}}; R = 0, \varphi'^{\text{best}}\right)}{N_{\text{dof}}} = \frac{16.44}{3} = 5.48$$

$$p(2.65; 2) = 0.266\,, \qquad p(16.44; 3) = 9.21 \times 10^{-4}$$

The contribution from $gg\gamma$ is significant!

$$\varphi \qquad 1.27 \pm 0.14 = (73 \pm 8)^\circ$$

The strong amplitude is orthogonal to the EM one, consistent with previous studies

Further results & predictions

$B\overline{B}$	$\lvert\mathcal{A}^{\gamma}_{B\overline{B}}/\mathcal{A}^{ggg}_{B\overline{B}}\rvert$	$\lvert\mathcal{A}^{gg\gamma}_{B\overline{B}}/\mathcal{A}^{ggg}_{B\overline{B}}\rvert$
$\Sigma^0\overline{\Sigma}^0$	~ 0.09	0
$\Lambda\overline{\Lambda}$	~ 0.07	0
$p\overline{p}$	~ 0.20	~ 0.1
$n\overline{n}$	~ 0.14	0
$\Sigma^+\overline{\Sigma}^-$	~ 0.25	~ 0.1
$\Sigma^-\overline{\Sigma}^+$	~ 0.07	~ 0.1
$\Xi^0\overline{\Xi}^0$	~ 0.15	0
$\Xi^-\overline{\Xi}^+$	~ 0.06	~ 0.1

$e^+e^- \to B\overline{B}$	Cross section at the $q^2 = M^2_{J/\psi}$
$e^+e^- \to \Sigma^0\overline{\Sigma}^0$	(1.37 ± 0.12) pb
$e^+e^- \to \Lambda\overline{\Lambda}$	(1.49 ± 0.13) pb
$e^+e^- \to (\Lambda\overline{\Sigma}^0 + \text{c.c.})$	(4.30 ± 0.36) pb
$e^+e^- \to p\overline{p}$	(12.9 ± 1.4) pb
$e^+e^- \to n\overline{n}$	(6.84 ± 0.58) pb
$e^+e^- \to \Sigma^+\overline{\Sigma}^-$	(10.4 ± 1.1) pb
$e^+e^- \to \Sigma^-\overline{\Sigma}^+$	(0.79 ± 0.30) pb
$e^+e^- \to \Xi^0\overline{\Xi}^0$	(4.54 ± 0.38) pb
$e^+e^- \to \Xi^-\overline{\Xi}^+$	(0.65 ± 0.24) pb

Summary

- BESIII measurements of $\psi \to N\bar{N}$ provide crucial information for studies of the charmonium decay mechanism, baryon structure, and other issues.
  - Additional channels and more precise measurements are expected.
  - Will the scan of J/ψ and $\psi(3686)$ help?
- G-parity violation process is found significantly contributed to the $J/\psi \to B\bar{B}$ decays.
  - The relative phase between strong and EM is found $90°$, again.
- The angular distribution has not been explored thoroughly, yet.

Thanks for your attention!

Backup

A new attempt to explain the anomalous J/ψ strong decay phase Exploiting $\alpha_S(s_{tl})$ Imaginary Part

- $\mu^2 \approx \Lambda^2 \quad \delta(M) \approx -3/2 \, \mathrm{arctg}\{\pi/[2\ln(M/(3\Lambda)]\}$

  $i\pi$ in denominator-> δ always negative

  no arctg ambiguity

  $\alpha_S{}^3$ -> x3, Amplitude -> x 1/2

QQ_{bar}	$\|\delta(M)\|_{exp}$	$\mu^2 \approx \Lambda^2$	$\mu^2 \approx M_\Phi{}^2$
Φ	$\|163 \pm 7\|^0 - \delta_\omega$	-170.	-170.
J/ψ	$\|85 \pm 4\|^0$	-66.	**-84.**
$\psi(3686)$	(?)	-61.	-81.
$\Upsilon(1S)$	~ $\|64\|^0$	-44.	-68.

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Changsha, March 2019