Ph.D THESIS AWARD 2025

Study of Form Factors of Several Hadrons at BESIII

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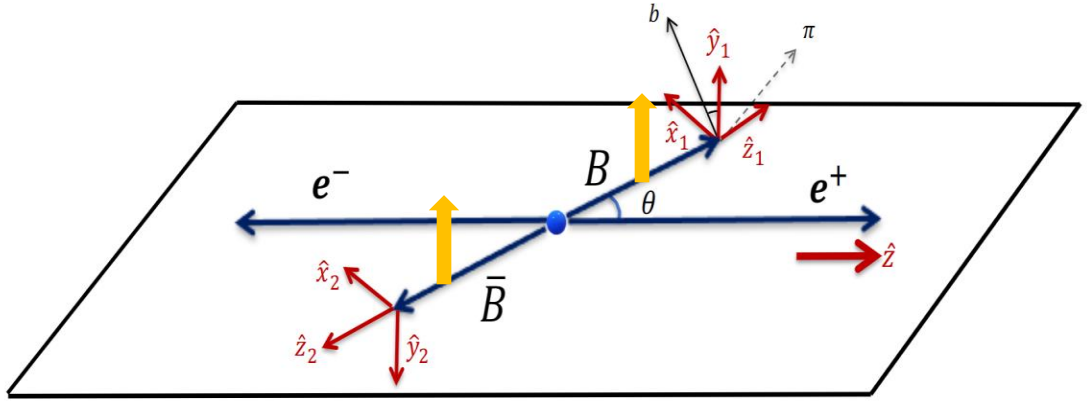
00 Outline

01 Introduction

- Form Factors
  - ✓ Describe the internal charge and magnetization structure of hadrons
  - ✓ Reveal the dynamics of quark-gluon constituents
- Hyperons:
  - ✓ Shorter lifetimes than protons: $e^-Y \to e^-Y$ ❌ $e^+e^- \to Y\bar{Y}$ ✅ **Spin Correlation**

Phys. Lett. B **772**, 16 (2017)

  - ✓ Joint angular distribution of the decay products $\Longrightarrow \alpha_\psi, \Delta\Phi$



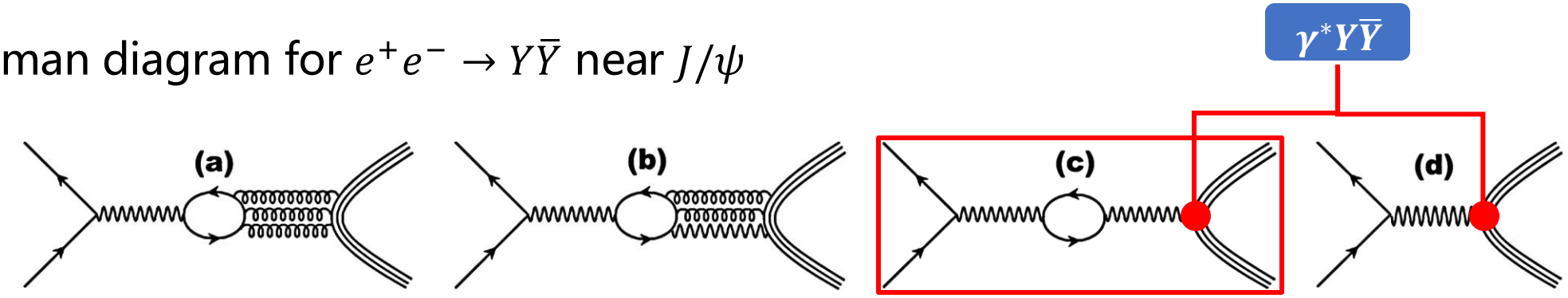
Phys. Rev. D **99**, 056008 (2019)

$$\alpha_\psi = \frac{s|G_M|^2 - 4M_Y^2|G_E|^2}{s|G_M|^2 + 4M_Y^2|G_E|^2}$$

$$\Delta\Phi = \arg\left(\frac{G_E}{G_M}\right) \neq 0 \Rightarrow \text{polarization}$$

02 Study of $J/\psi \to \bar{\Lambda}\Sigma^0 + c.c.$

- Feynman diagram for $e^+e^- \to Y\bar{Y}$ near J/ψ



- Hyperons and antihyperons are distinct particle types
  - ✓ $e^+e^- \to J/\psi \to \bar{\Lambda}\Sigma^0 \Rightarrow$ Isospin Violation ✚ Purely Electromagnetic process Eur. Phys. J. C 80, 903 (2020)
  - ✓ At J/ψ peak, vacuum polarization substantially enhances the $e^+e^- \to J/\psi \to \bar{\Lambda}\Sigma^0$ cross section

    $\Rightarrow$ New method for precision measurement of hyperon form factors

Helicity Amplitude Analysis → Polarization and $\alpha_\psi, \Delta\Phi$ → $R = \left|\frac{G_E}{G_M}\right|$ and $\Delta\Phi = arg\left(\frac{G_E}{G_M}\right)$

CP symmetry: $\Delta\Phi_{CP} = |\pi - (\Delta\Phi_{\bar{\Lambda}\Sigma^0} + \Delta\Phi_{\Lambda\bar{\Sigma}^0})|$

02 Study of $J/\psi \to \bar{\Lambda}\Sigma^0 + c.c.$

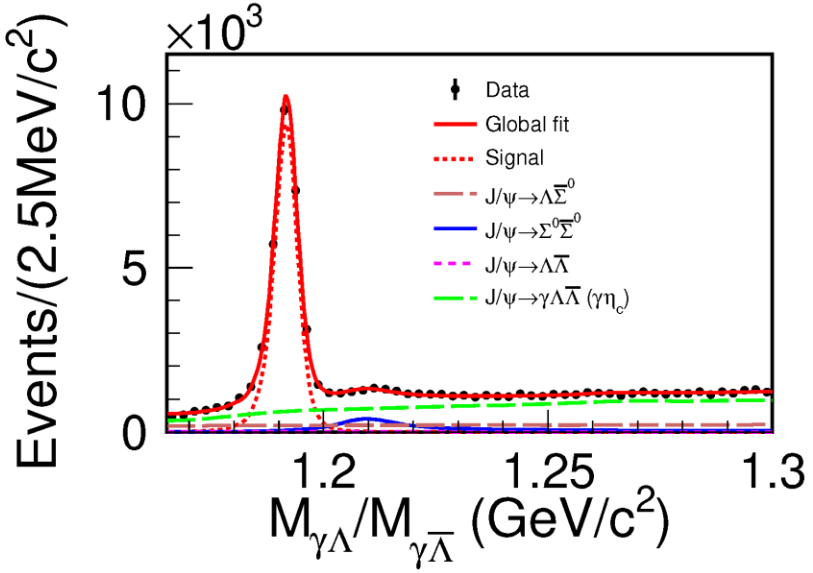
- 10087×10^6 J/ψ events ⇒ 26260 ± 181 $\bar{\Lambda}\Sigma^0 + c.c.$ events
- Helicity Amplitude: $\mathcal{W}(\vec{\xi};\vec{\omega}) = \sum_{\mu,\nu=0}^{3}\sum_{\mu'=0}^{3} C_{\mu\nu} a_{\mu\mu'}^{\Sigma^0} a_{\mu'0}^{\Lambda} a_{\nu0}^{\bar{\Lambda}}$

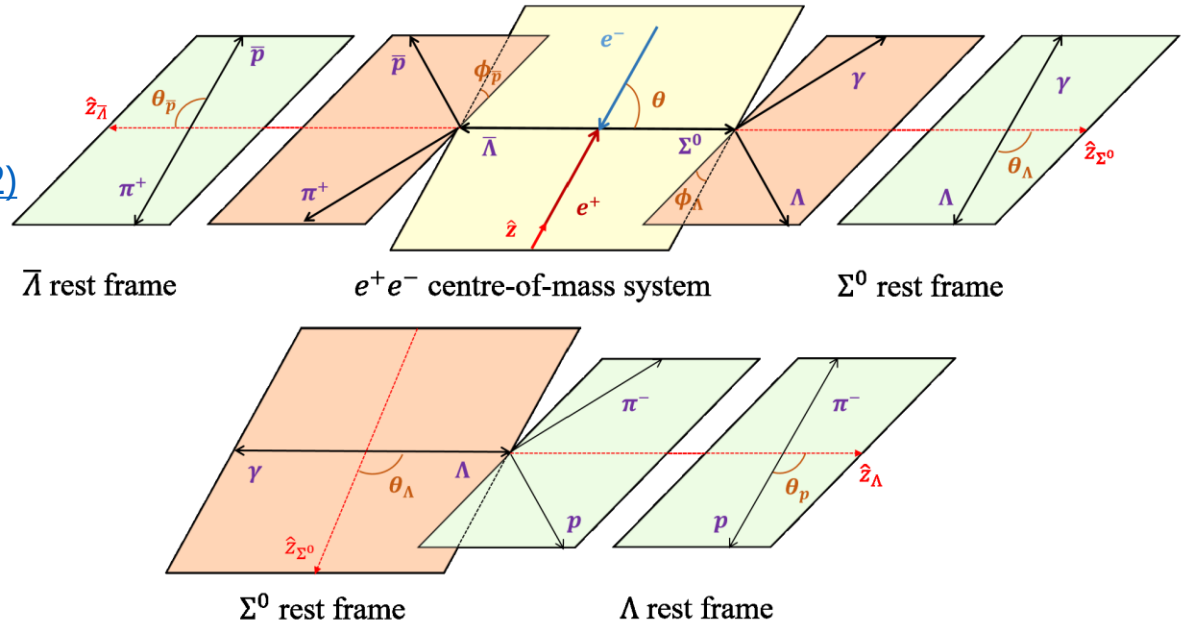
  Phys. Rev. D **99**, 056008 (2019)

  - ✓ Angle variables: $\vec{\xi} = (\theta, \theta_\Lambda, \phi_\Lambda, \theta_p, \theta_{\bar{p}}, \phi_{\bar{p}})$
  - ✓ Parameters: $\vec{\omega} = (\alpha_{J/\psi}, \Delta\Phi, \alpha_{\Sigma^0}, \alpha_\Lambda, \alpha_{\bar{\Lambda}})$
    - Floated: $\alpha_{J/\psi}, \Delta\Phi$
    - Fixed: $\alpha_{\Sigma^0} = 0,\ \alpha_\Lambda = 0.7519,\ \alpha_{\bar{\Lambda}} = -0.7559$

    Phys. Rev. Lett. **129**, 131801 (2022)

  - ✓ Polarization: $P_y = \frac{\sqrt{1-\alpha_{J/\psi}^2}\sin\theta\cos\theta}{1+\alpha_{J/\psi}\cos^2\theta}\sin\Delta\Phi$
  - ✓ Spin-correlation: $C_{xz} = \frac{\sqrt{1-\alpha_{J/\psi}^2}\sin\theta\cos\theta}{1+\alpha_{J/\psi}\cos^2\theta}\cos\Delta\Phi$

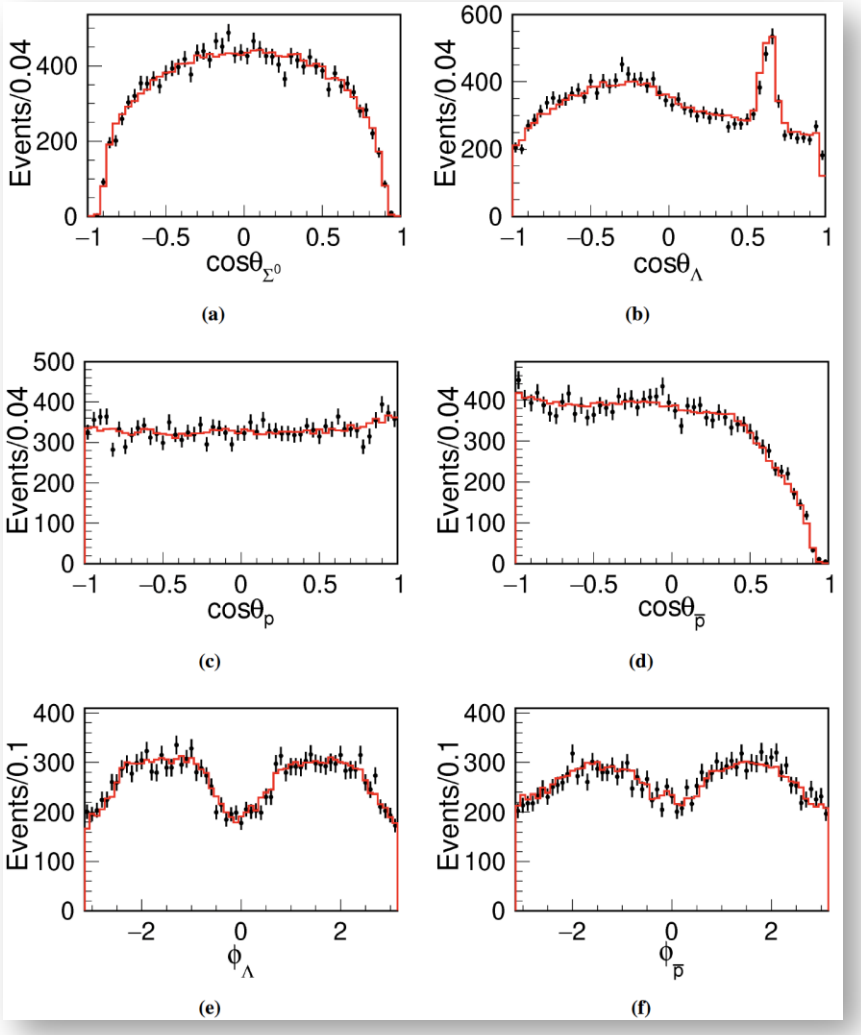


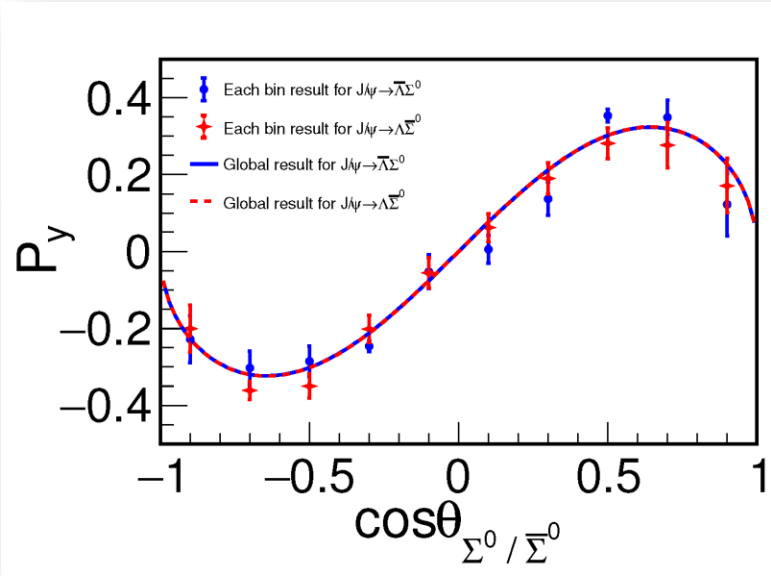


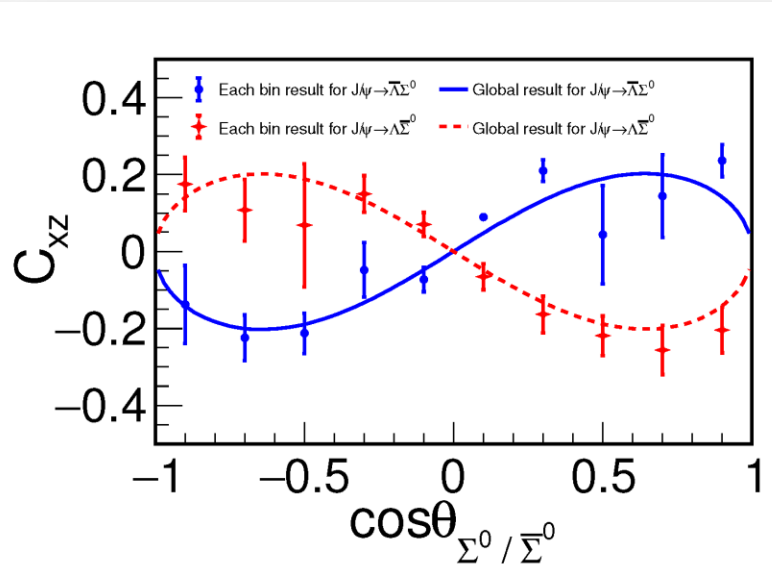
02 Study of $J/\psi \to \bar{\Lambda}\Sigma^0 + c.c.$

Nature Commun. 15, 8812 (2024)

- Unbinned maximum likelihood fit





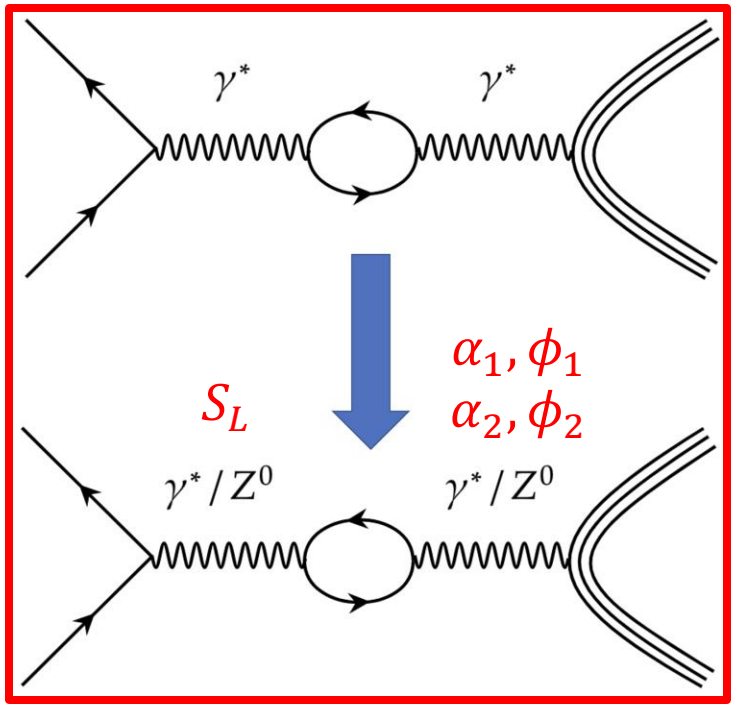


Parameter	Result
$\alpha_{J/\psi}$	$0.418 \pm 0.028(\text{stat.}) \pm 0.014(\text{syst.})$
$\Delta\Phi_{\bar{\Lambda}\Sigma^0}$	$(1.011 \pm 0.094(\text{stat.}) \pm 0.010(\text{syst.}))$ rad
$\Delta\Phi_{\Lambda\bar{\Sigma}^0}$	$(2.128 \pm 0.094(\text{stat.}) \pm 0.010(\text{syst.}))$ rad
R	$0.860 \pm 0.029(\text{stat.}) \pm 0.015(\text{syst.})$
$\Delta\Phi_{\text{CP}}$	$(0.003 \pm 0.133(\text{stat.}) \pm 0.014(\text{syst.}))$ rad

No significant CP violation

02 Study of $J/\psi \to \bar{\Lambda}\Sigma^0 + c.c.$

- Form factors with new CP-violating source ⇒ EDM
  - ✓ $\langle B_1(p_1,s_1)\bar{B}_2(p_2,s_2)|J_\mu(0)|0\rangle = \bar{u}(p_1,s_1)\Gamma_\mu v(p_2,s_2)$
  - ✓ $\Gamma_\mu = \left(F_1\gamma_\mu + F_2\frac{i\sigma_{\mu\nu}q^\nu}{2m}\right) + \left(G_1\gamma_\mu + G_2\frac{i\sigma_{\mu\nu}q^\nu}{2m}\right)\gamma_5$



arXiv:2508.01813

- Helicity amplitude

$A_{1/2\,1/2} = A_{-1/2\,-1/2} \Rightarrow h_1$
$A_{1/2\,-1/2} = A_{-1/2\,1/2} \Rightarrow h_2$

⇒

$A_{1/2\,1/2} \neq A_{-1/2\,-1/2} \Rightarrow h_1, h_3$
$A_{1/2\,-1/2} \neq A_{-1/2\,1/2} \Rightarrow h_2, h_4$

- Parameters scheme
  - ✓ $h_1 = \frac{\sqrt{1-\alpha_{J/\psi}}}{\sqrt{2}}$
  - ✓ $h_2 = \sqrt{1+\alpha_{J/\psi}}e^{-i\Delta\Phi}$
  - ✓ $h_3 = \sqrt{\alpha_1}e^{i\phi_1}$
  - ✓ $h_4 = \sqrt{2\alpha_2}e^{i\phi_2}$

⇒

- Helicity amplitudes with Z^0 boson contributions:
  - ✓ $\mathcal{W}(\vec{\xi};\vec{\omega}') = \sum_{\mu,\nu=0}^{3}\sum_{\mu'=0}^{3} S_{\mu\nu}a_{\mu\mu'}^{\Sigma^0}a_{\mu'0}^{\Lambda}a_{\nu0}^{\bar{\Lambda}}$
  - ✓ $\vec{\omega}' = (\alpha_{J/\psi}, \Delta\Phi, \alpha_1, \phi_1, \alpha_2, \phi_2, S_L, \alpha_{\Sigma^0}, \alpha_\Lambda, \alpha_{\bar{\Lambda}})$
  - ✓ $\alpha_1, \phi_1, \alpha_2, \phi_2$: CP violation of $J/\psi \to \bar{\Lambda}\Sigma^0$
  - ✓ S_L: polarization of J/ψ

02 Study of $J/\psi \to \bar{\Lambda}\Sigma^0 + c.c.$

BAM-875

- Fit results with the same fit strategy of the extraction of the electromagnetic form factors

Parameter	Result	Parameter	Result
$\alpha_{J/\psi}$	$0.41 \pm 0.03(\text{stat.}) \pm 0.01(\text{syst.})$	–	–
$\Delta\Phi_{\bar{\Lambda}\Sigma^0}$	$(1.02 \pm 0.10(\text{stat.}) \pm 0.02(\text{syst.}))$ rad	$\Delta\Phi_{\Lambda\bar{\Sigma}^0}$	$(2.11 \pm 0.10(\text{stat.}) \pm 0.02(\text{syst.}))$ rad
$\alpha_1^{\bar{\Lambda}\Sigma^0}$	$(0.50 \pm 0.98(\text{stat.}) \pm 0.34(\text{syst.})) \times 10^{-3}$	$\alpha_1^{\Lambda\bar{\Sigma}^0}$	$(4.67 \pm 4.07(\text{stat.}) \pm 0.24(\text{syst.})) \times 10^{-3}$
$\phi_1^{\bar{\Lambda}\Sigma^0}$	$(2.73 \pm 4.45(\text{stat.}) \pm 0.42(\text{syst.}))$ rad	$\phi_1^{\Lambda\bar{\Sigma}^0}$	$(1.36 \pm 0.34(\text{stat.}) \pm 0.12(\text{syst.}))$ rad
$\alpha_2^{\bar{\Lambda}\Sigma^0}$	$(4.37 \pm 3.71(\text{stat.}) \pm 0.47(\text{syst.})) \times 10^{-3}$	$\alpha_2^{\Lambda\bar{\Sigma}^0}$	$(1.11 \pm 1.71(\text{stat.}) \pm 0.07(\text{syst.})) \times 10^{-3}$
$\phi_2^{\bar{\Lambda}\Sigma^0}$	$(-2.49 \pm 0.20(\text{stat.}) \pm 0.04(\text{syst.}))$ rad	$\phi_2^{\Lambda\bar{\Sigma}^0}$	$(-1.88 \pm 0.68(\text{stat.}) \pm 0.06(\text{syst.}))$ rad
$S_L^{\bar{\Lambda}\Sigma^0}$	$(-3.57 \pm 2.64(\text{stat.}) \pm 0.31(\text{syst.})) \times 10^{-2}$	$S_L^{\Lambda\bar{\Sigma}^0}$	$(-2.44 \pm 2.64(\text{stat.}) \pm 0.36(\text{syst.})) \times 10^{-2}$
α_{Σ^0}	$(-1.35 \pm 1.74(\text{stat.}) \pm 0.12(\text{syst.})) \times 10^{-2}$	$\alpha_{\bar{\Sigma}^0}$	$(0.08 \pm 1.78(\text{stat.}) \pm 0.04(\text{syst.})) \times 10^{-2}$

Consistent with those without Z^0 contribution

Consistent with CP conservation

Consistent with theoretical prediction

No polarization in $\Sigma^0 \to \gamma\Lambda$

03 Study of $\Lambda(1520/1690) \to \gamma\Lambda(\Sigma^0)$

- Further study of the properties of Λ and Σ^0 excited states
  - ✓ Analyze mass spectrum of $\gamma\Lambda$ and $\gamma\Sigma^0$

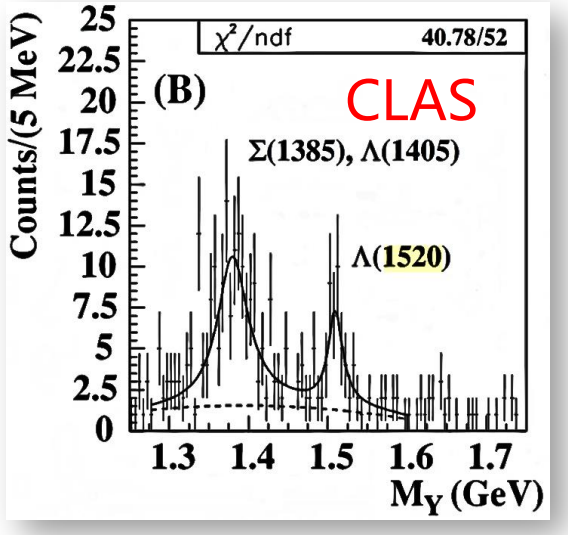
- $\Lambda(1520) \to \gamma\Lambda(\Sigma^0)$
  - ✓ Significant discrepancies among theoretical predictions
  - ✓ SU(3) symmetry prediction: $\mathcal{R} \equiv \frac{\mathcal{B}(\Lambda(1520)\to\gamma\Lambda)}{\mathcal{B}(\Lambda(1520)\to\gamma\Sigma^0)} \approx 2.5$

- $\Lambda(1520)$ and $\Lambda(1690) \to \gamma\Sigma^0$ have not been observed

Phys. Rev. D **73**, 114001 (2006)

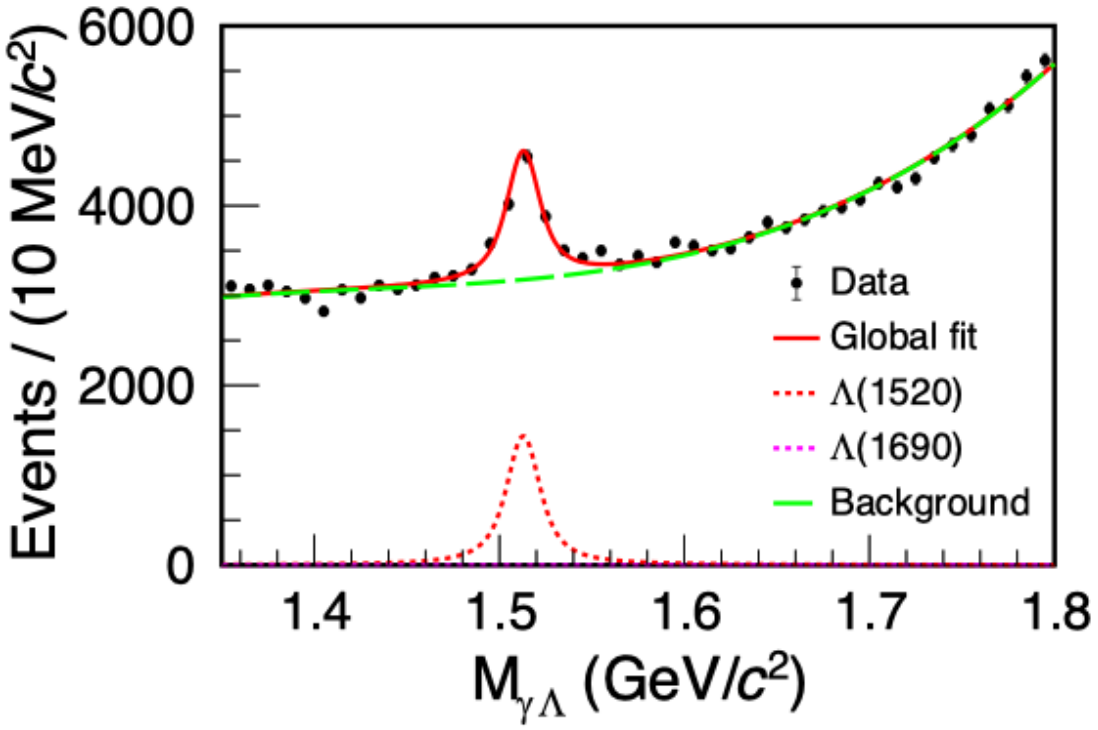
$B_i \to B_f + \gamma$	$\Lambda(1520) \to \gamma\Lambda$	$\Lambda(1520) \to \gamma\Sigma^0$
χQM [3]	134	92
NRQM	156 [6],96 [7]	55 [6], 74 [7]
RCQM[8]	215	293
MIT Bag[6]	46	17
Chiral Bag[9, 10]	32	51
Algebraic model[11]	85.1	180.4
CLAS [5]	$167 \pm 43^{+26}_{-12}$	

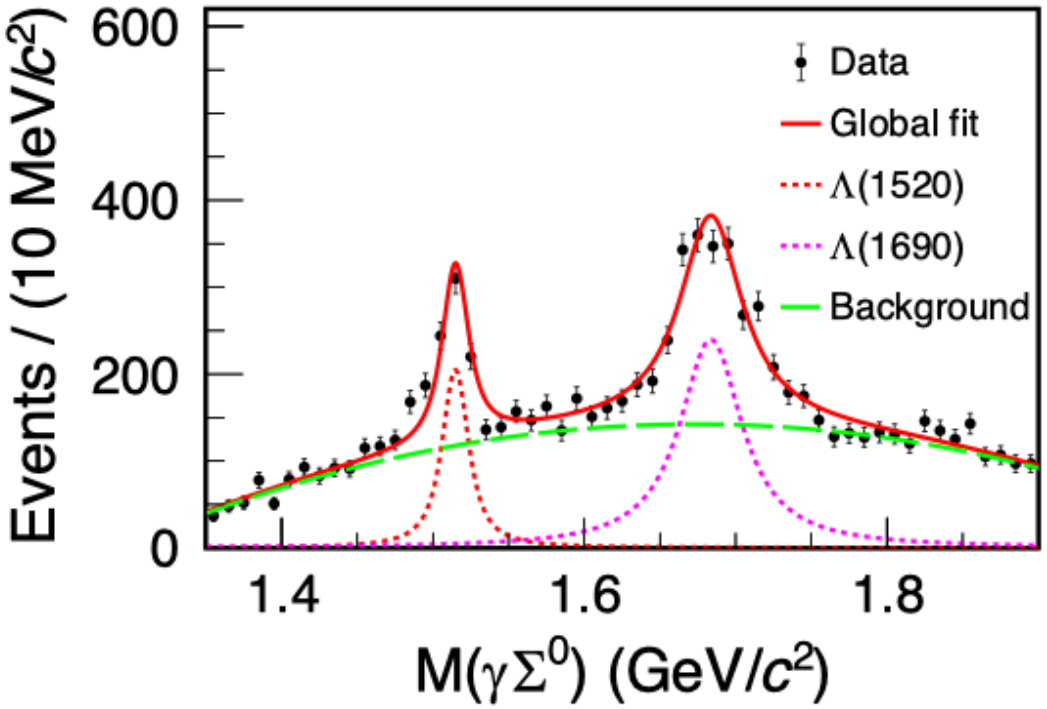
Phys. Rev. C **71**, 054609 (2005)



03 Study of $\Lambda(1520/1690) \to \gamma\Lambda(\Sigma^0)$

- 10087×10^6 J/ψ events ⇒ Study resonant structure in $J/\psi \to \gamma\Lambda\bar{\Lambda}$ and $\gamma\bar{\Lambda}\Sigma^0$ processes
- Clear $\Lambda(1520)$ in **both** $M(\gamma\Lambda)$ and $M(\gamma\Sigma^0)$
- $\Lambda(1690)$ **only** in $\gamma\Sigma^0$ channel





03 Study of $\Lambda(1520/1690) \to \gamma\Lambda(\Sigma^0)$

arXiv:2507.11145

- $\Lambda(1520) \to \gamma\Lambda(\Sigma^0)$
  - ✓ 4043 ± 247 $\Lambda(1520) \to \gamma\Lambda$ and 621 ± 53 $\Lambda(1520) \to \gamma\Sigma^0$
  - ✓ $\mathcal{R} \equiv \frac{\mathcal{B}(\Lambda(1520)\to\gamma\Lambda)}{\mathcal{B}(\Lambda(1520)\to\gamma\Sigma^0)} = \frac{N^{obs}_{\gamma\Lambda}}{N^{obs}_{\gamma\Sigma^0}} \cdot \frac{\epsilon_{\gamma\Sigma^0}}{\epsilon_{\gamma\Lambda}} = 3.19 \pm 0.34(\text{stat.}) \pm 0.19(\text{syst.}) \Rightarrow$ Consistent with SU(3)
  - ✓ $\mathcal{B}(\Lambda(1520) \to \gamma\Sigma^0) = (2.66 \pm 0.28(\text{stat.}) \pm 0.50(\text{syst.})) \times 10^{-3} \Rightarrow$ First observation
  - ✓ $\Gamma(\Lambda(1520) \to \gamma\Sigma^0) = \left(46.8 \pm 6.6(\text{stat.}) \pm 9.0(\text{syst.})\right)$ keV

    ⇒ ~6 times smaller than RCQM and ~3-4 times smaller than Algebraic model

    ⇒ RCQM and Algebraic model are unlikely to serve as suitable representations

Decay Mode	N_{obs}	$\epsilon(\%)$	$\mathcal{R}$	$\mathcal{B}(\Lambda(1520) \to \gamma\Sigma^0)(\times 10^{-3})$	$\Gamma(\Lambda(1520) \to \gamma\Sigma^0)(\text{keV})$
$\Lambda(1520) \to \gamma\Lambda$	4043 ± 247	18.91%	$3.19 \pm 0.34(\text{stat.}) \pm 0.19(\text{syst.})$	$2.66 \pm 0.28(\text{stat.}) \pm 0.50(\text{syst.})$	$46.8 \pm 6.6(\text{stat.}) \pm 9.0(\text{syst.})$
$\Lambda(1520) \to \gamma\Sigma^0$	621 ± 53	9.28%			

03 Study of $\Lambda(1520/1690) \to \gamma\Lambda(\Sigma^0)$

arXiv:2507.11145

- $\Lambda(1690) \to \gamma\Lambda(\Sigma^0)$
  - ✓ < 341 $\Lambda(1690) \to \gamma\Lambda$ and 1754 ± 122 $\Lambda(1690) \to \gamma\Sigma^0$
  - ✓ $\mathcal{B}(J//\psi \to \bar{\Lambda}\Lambda(1690)) \times \mathcal{B}(\Lambda(1690) \to \gamma\Sigma^0) = (6.05 \pm 0.42(\text{stat.}) \pm 0.39(\text{syst.})) \times 10^{-6}$

    ⇒ First observation
  - ✓ $\mathcal{B}(J/\psi \to \bar{\Lambda}\Lambda(1690)) \times \mathcal{B}(\Lambda(1690) \to \gamma\Lambda) < 5.08 \times 10^{-7}$ (90% C.L.) ⇒ No evidence
  - ✓ $\mathcal{R}_{UL} \equiv \frac{\mathcal{B}_{UL}(\Lambda(1690)\to\gamma\Lambda)}{\mathcal{B}_{UL}(\Lambda(1690)\to\gamma\Sigma^0)} < 0.08$ (90% C.L.) ⇒ Significant decay mode difference in $\Lambda(1690)$
    - ⇒ Partial wave analysis of $J/\psi \to \bar{\Lambda}\Sigma^0\pi^0$ may provide a new perspective

Decay Mode	N_{obs}	$\epsilon(\%)$	$\mathcal{B}(J\psi \to \bar{\Lambda}\Lambda(1690)) \times \mathcal{B}(\Lambda(1690) \to \gamma\Lambda(\Sigma^0))$	$\mathcal{R}$
$\Lambda(1690) \to \gamma\Lambda$	< 341	16.20%	$< 5.08 \times 10^{-7}$	< 0.08
$\Lambda(1690) \to \gamma\Sigma^0$	1754 ± 122	7.00%	$(6.05 \pm 0.42(\text{stat.}) \pm 0.39(\text{syst.})) \times 10^{-6}$	

04 Study of meson decay

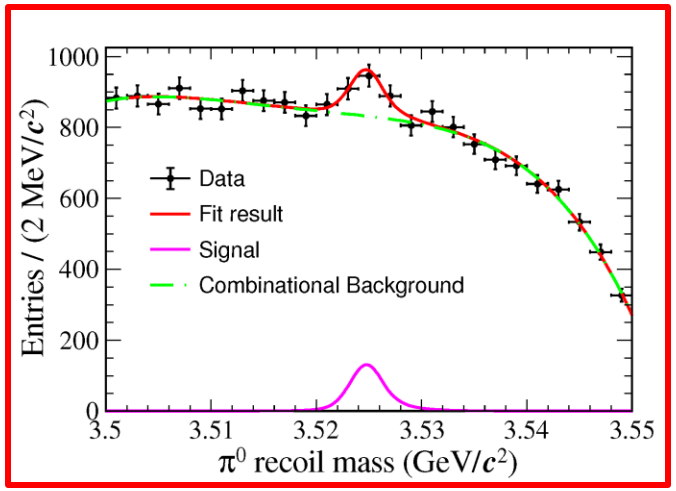
- Charmonium system: h_c ($J^{PC} = 1^{+-}$)
  - ✓ Main decay mode: $\mathcal{B}(h_c \to \gamma\eta_c) = (60 \pm 4)\%$
  - ✓ Others: $\mathcal{B}(h_c \to others) < 6\%$
  - ✓ $h_c \to e^+e^-\eta_c$?

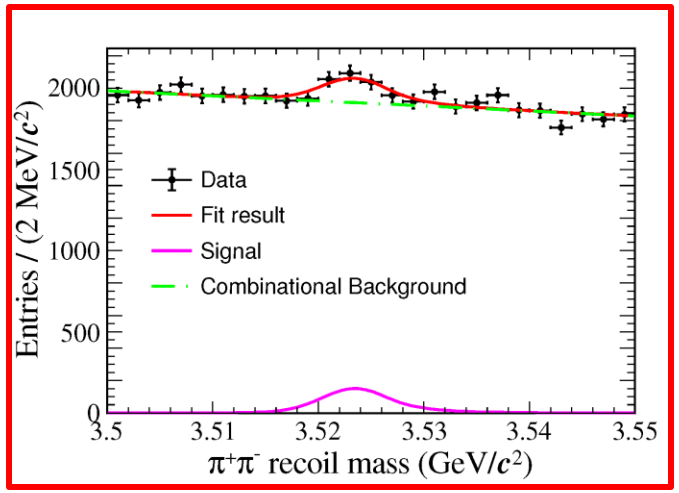
Decay Mode	$N^{obs}_{e^+e^-\eta_c}$	$N^{obs}_{\gamma\eta_c}$
$\psi(3686) \to \pi^0 h_c$	298 ± 76	95564 ± 1340
$e^+e^- \to \pi^+\pi^- h_c$	663 ± 136	99260 ± 1792

- Combined analysis of $\psi(3686) \to \pi^0 h_c$ and $e^+e^- \to \pi^+\pi^- h_c$

Phys. Rev. D 110, L111101 (2024)

$\Rightarrow$ First observation of $h_c \to e^+e^-\eta_c (5.4\sigma) \Rightarrow \mathcal{R} \equiv \frac{\mathcal{B}(h_c \to e^+e^-\eta_c)}{\mathcal{B}(h_c \to \gamma\eta_c)} = (0.59 \pm 0.10(\text{stat.}) \pm 0.04(\text{syst.}))\%$





04 Study of meson decay

Phys. Rev. D 109, 032006 (2024)

- Axial anomaly : $\eta' \to 4\pi \Rightarrow \pi\pi - \gamma^*\gamma^*$ coupling ⇒ Hadronic Light-by-Light (HLbL)

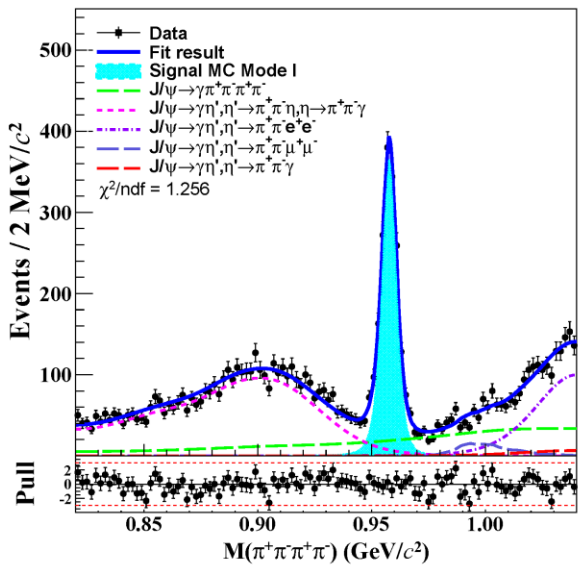
10 billion J/ψ events $J/\psi \to \gamma\eta'$

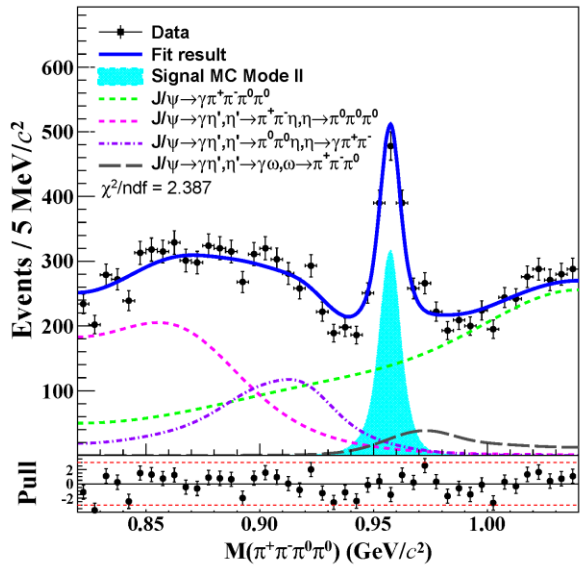
Decay Mode	N_{sig}	ϵ (%)	$\mathcal{B}(\eta' \to X) \times 10^{-5}$	Previous Results [94,95] ($\times 10^{-5}$)
$\eta' \to \pi^+\pi^-\pi^+\pi^-$	1650±48	36.4	$8.56 \pm 0.25(\text{stat.}) \pm 0.23(\text{syst.})$	$8.53 \pm 0.69(\text{stat.}) \pm 0.64(\text{syst.})$
$\eta' \to \pi^+\pi^-\pi^0\pi^0$	865±49	7.8	$21.2 \pm 1.2(\text{stat.}) \pm 1.0(\text{syst.})$	$18.2 \pm 3.5(\text{stat.}) \pm 1.8(\text{syst.})$
$\eta' \to \pi^0\pi^0\pi^0\pi^0$	< 10	1.6	< 1.24	< 4.94

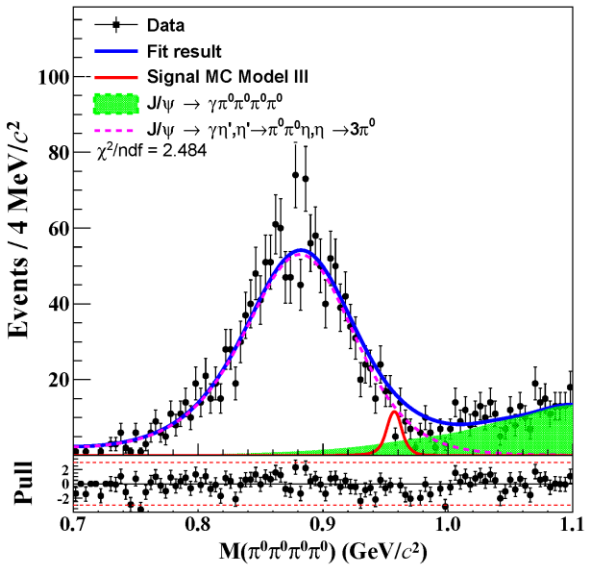
- Consistent with earlier results.
- Precision improved by a factor of 3-4.

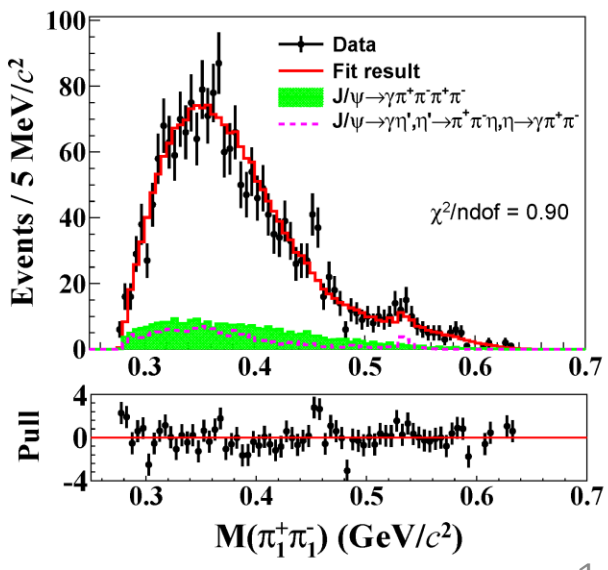
- First measurement of the TFF ($\eta' \to \pi^+\pi^-\pi^+\pi^-$): $\alpha = 1.22 \pm 0.33 \pm 0.04$

⇒ Consistent with ChPT and VMD predictions





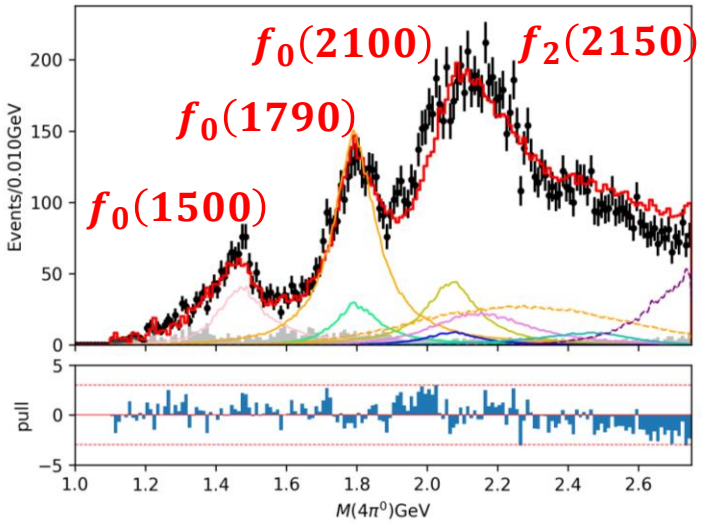


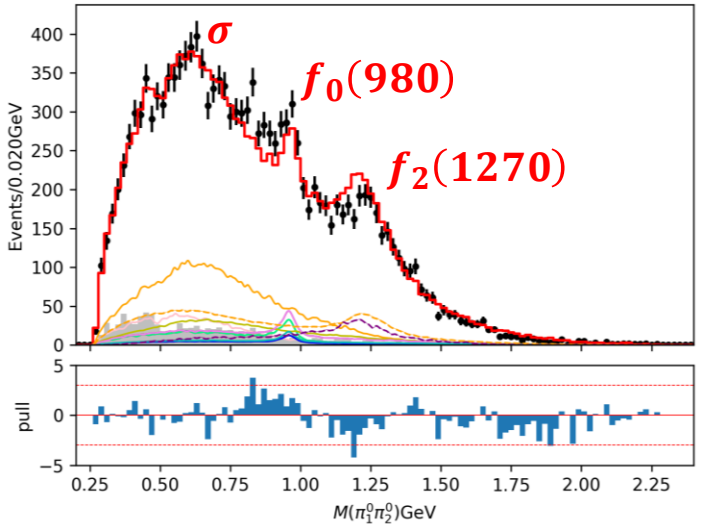


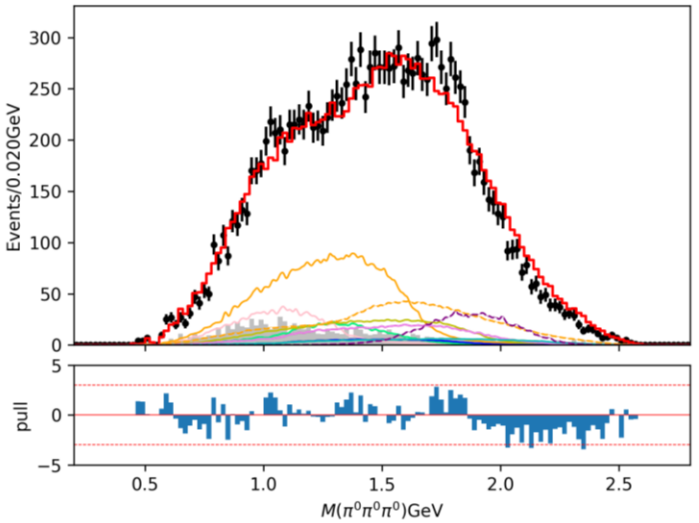
04 Study of meson decay

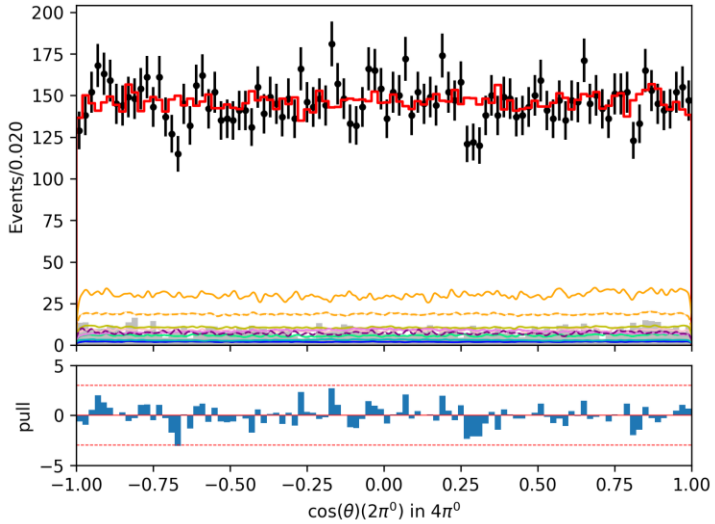
Parallel talk in Collaboration Meeting in Winter(2024)

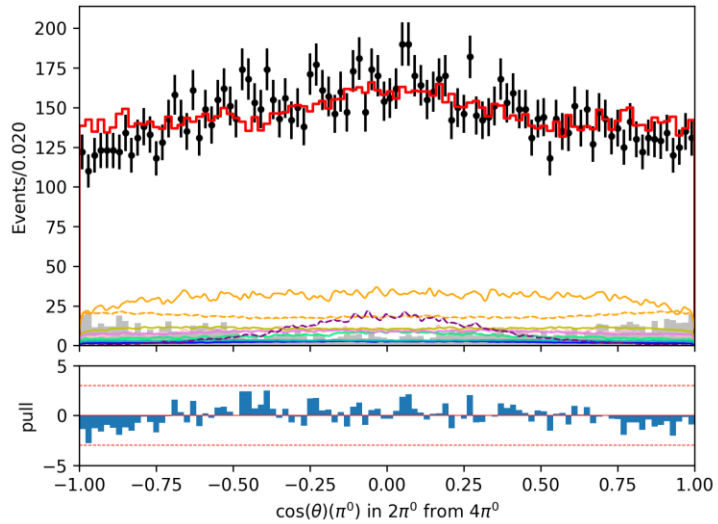
- 1312.5×10^6 J/ψ events (2009 and 2012) $\Rightarrow \approx$ 10k $J/\psi \to \gamma 4\pi^0$ events
- Amplitude analysis (TF-PWA)

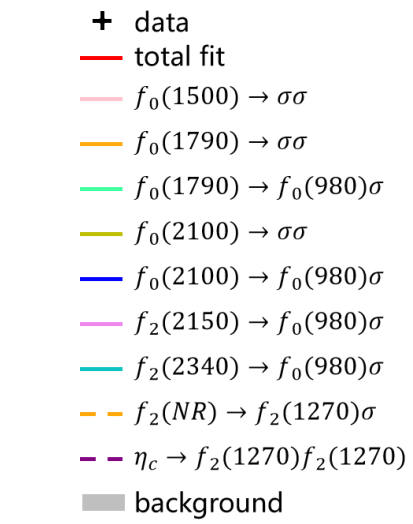












04 Summary

- Hyperon decay
  - ✓ Study of $J/\psi \to \overline{\Lambda}\Sigma^0 + c.c.$
    - New method for precision measurement of hyperon FFs via vacuum polarization effect
    - Examine CP symmetry ⇒ No significant CP violation
    - Measure EDM-related parameters ⇒ No significant CP violation
  - ✓ Study of $\Lambda(1520/1690) \to \gamma\Lambda(\Sigma^0)$
    - First observation of $\Lambda(1520) \to \gamma\Sigma^0$ and $\Lambda(1690) \to \gamma\Sigma^0$
    - Result of $\frac{\mathcal{B}(\Lambda(1520)\to\gamma\Lambda)}{\mathcal{B}(\Lambda(1520)\to\gamma\Sigma^0)}$ is consistent with SU(3)
    - No signal of $\Lambda(1690) \to \gamma\Lambda$

04 Summary

- Meson decay
  - ✓ Study of $h_c \to e^+e^-\eta_c$
    - First observation of $h_c \to e^+e^-\eta_c$ $(5.4\sigma) \Rightarrow \frac{\mathcal{B}(h_c \to e^+e^-\eta_c)}{\mathcal{B}(h_c \to \gamma\eta_c)} = (0.59 \pm 0.10 \pm 0.04)\%$
  - ✓ Study of $J/\psi \to \gamma X, X \to 4\pi$
    - Precision measurement of $\mathcal{B}(\eta' \to 4\pi) \Rightarrow$ Precision improved by a factor of 3-4
    - First measurement of TFF($\eta' \to \pi^+\pi^-\pi^+\pi^-$) ⇒ Consistent with ChPT and VMD predictions
    - PWA of $J/\psi \to \gamma\pi^0\pi^0\pi^0\pi^0$

      ⇒ Clear peaks such as $f_0(1500)$, $f_0(1790)$, $f_0(2100)$, and $f_2(2150)$ in $M(4\pi^0)$
- Outlook
  - ✓ Further physics analysis and development work on CGEM software are ongoing during my post-doc

Thank you for your attention!