

BES III



兰州大学
LANZHOU UNIVERSITY

Recent advances in hadron production in e^+e^- annihilation at BESIII

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(on behalf of BESIII collaboration)

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Outline

□ Introduction

□ Recent advances @ $\sqrt{s} = 3.5 - 4.9 \text{ GeV}$

$$\checkmark e^+e^- \rightarrow \bar{\Xi}^-\bar{\Xi}^+$$

$$\checkmark e^+e^- \rightarrow \Sigma^+\bar{\Sigma}^-$$

$$\checkmark e^+e^- \rightarrow K_S^0 K_L^0$$

$$\checkmark e^+e^- \rightarrow K^-\bar{\Xi}^+ \Lambda/\Sigma^0 + c. c.$$

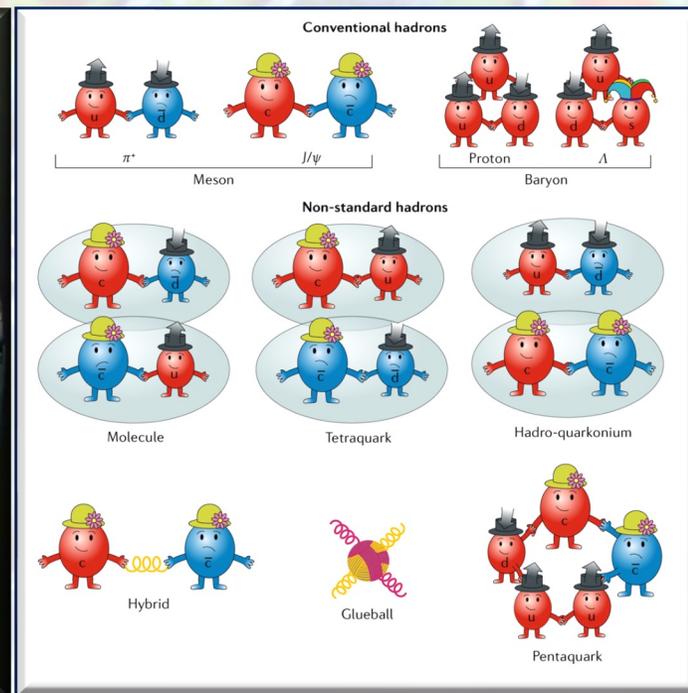
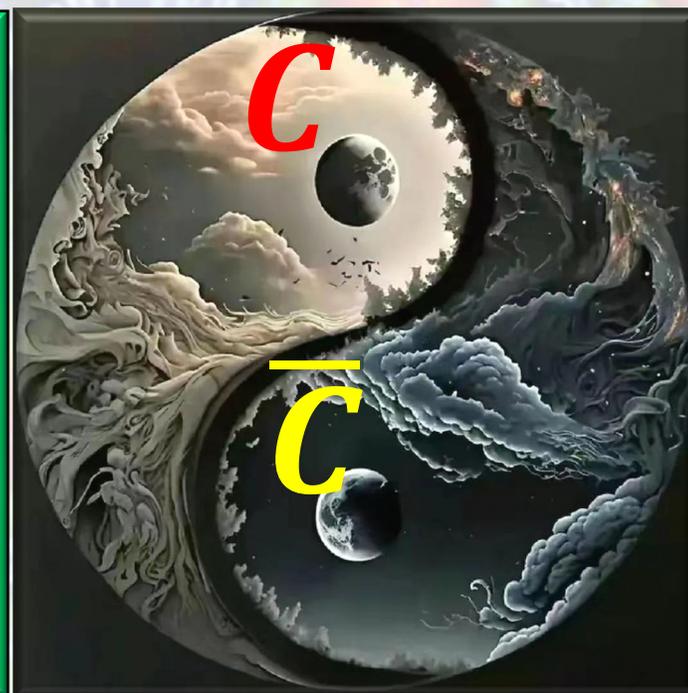
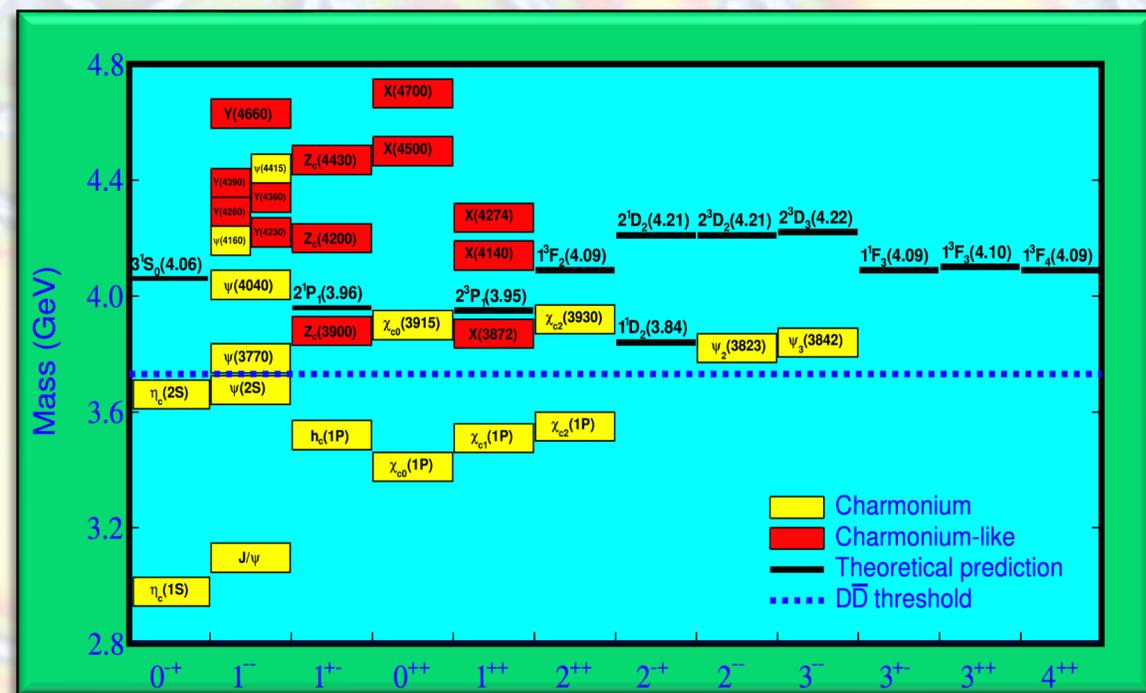
$$\checkmark e^+e^- \rightarrow p p \pi^- \bar{d} + c. c.$$

$$\checkmark e^+e^- \rightarrow p p \bar{p} \bar{n} \pi^- + c. c.$$

□ Summary

XYZ/Charmonium(-like) state

- A series of **XYZ/Charmonium(-like)** states observed since in past decades
- **Conventional Charmonium states**: Nonrelativistic $c\bar{c}$ bound state
- **XYZ/Charmonium(-like) states**: Various scenarios, such as molecule state, hybrid states, tetraquark states, etc., have been proposed

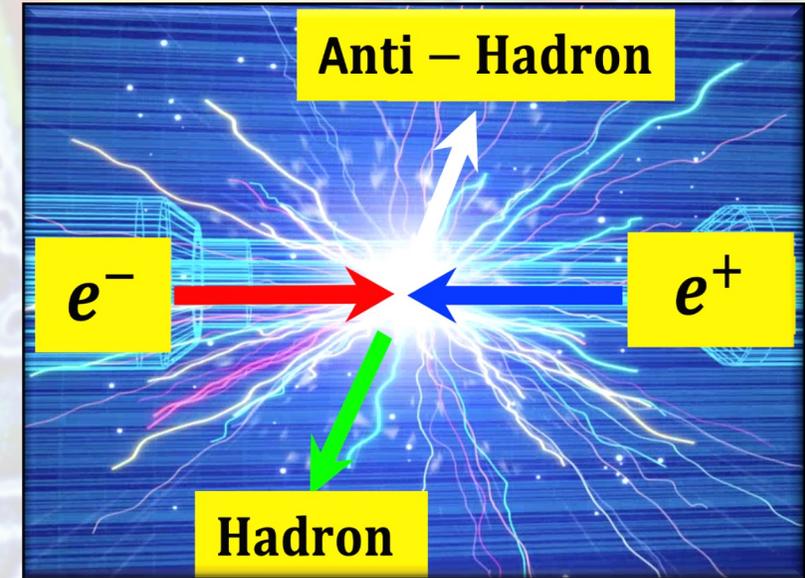
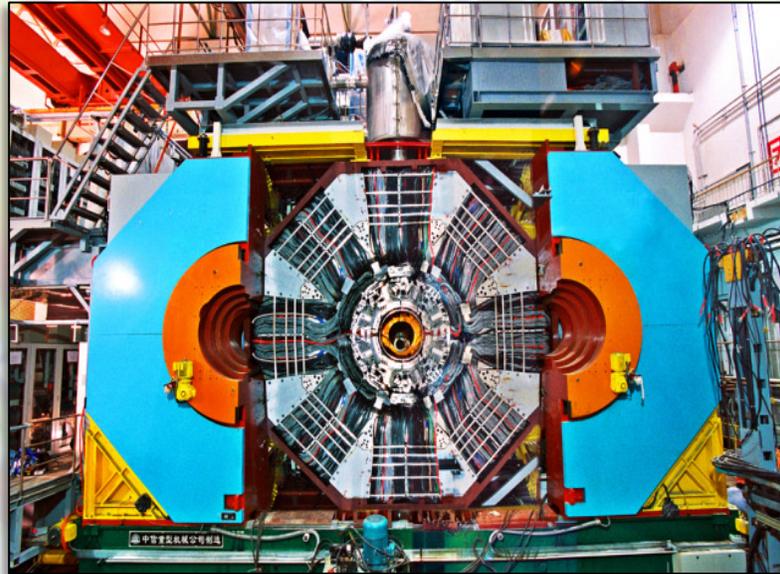
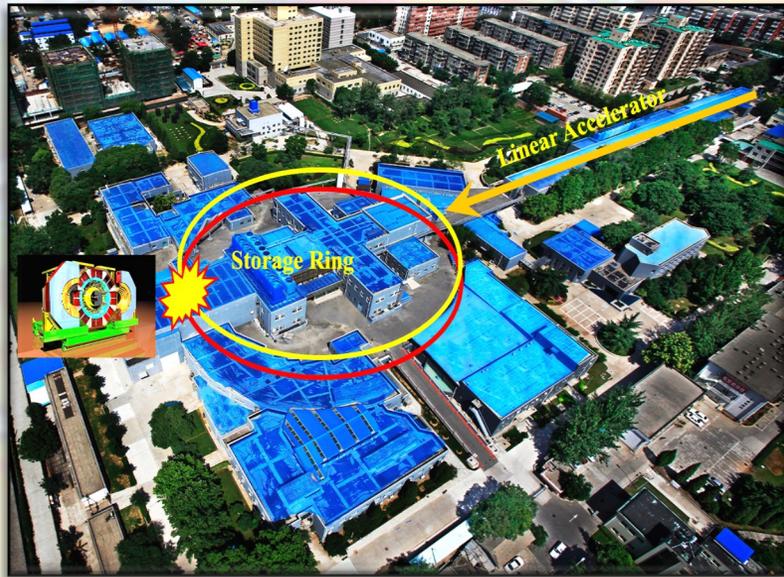


C. Z. Yuan, S. L. Olsen, NR1 (2019) 480-494

Nature for XYZ still needs more effort in theory and experiment

BEPCII/BESIII

An excellent experiment platform & Great potential



See more details for BEPCII/BESIII in other BESIII talks

- ❑ Collected a world largest data sample in τ -charm physical region:
 - 10B J/ψ , 2.7B $\psi(3686)$, **20/fb $\psi(3770)$ and ~ 25 /fb for R-scan & XYZ**
- ❑ Provide a rich laboratory in hadron production and probing the nature of Charmonium(-like) states, and has great potential to validate non-pQCD, pQCD, etc.

Outline

□ Introduction

□ Recent advances @ $\sqrt{s} = 3.5 - 4.9 \text{ GeV}$

$$\checkmark e^+e^- \rightarrow \bar{E}^- \bar{E}^+$$

$$\checkmark e^+e^- \rightarrow \Sigma^+ \bar{\Sigma}^-$$

$$\checkmark e^+e^- \rightarrow K_S^0 K_L^0$$

$$\checkmark e^+e^- \rightarrow K^- \bar{E}^+ \Lambda / \Sigma^0 + c. c.$$

$$\checkmark e^+e^- \rightarrow pp\pi^- \bar{d} + c. c.$$

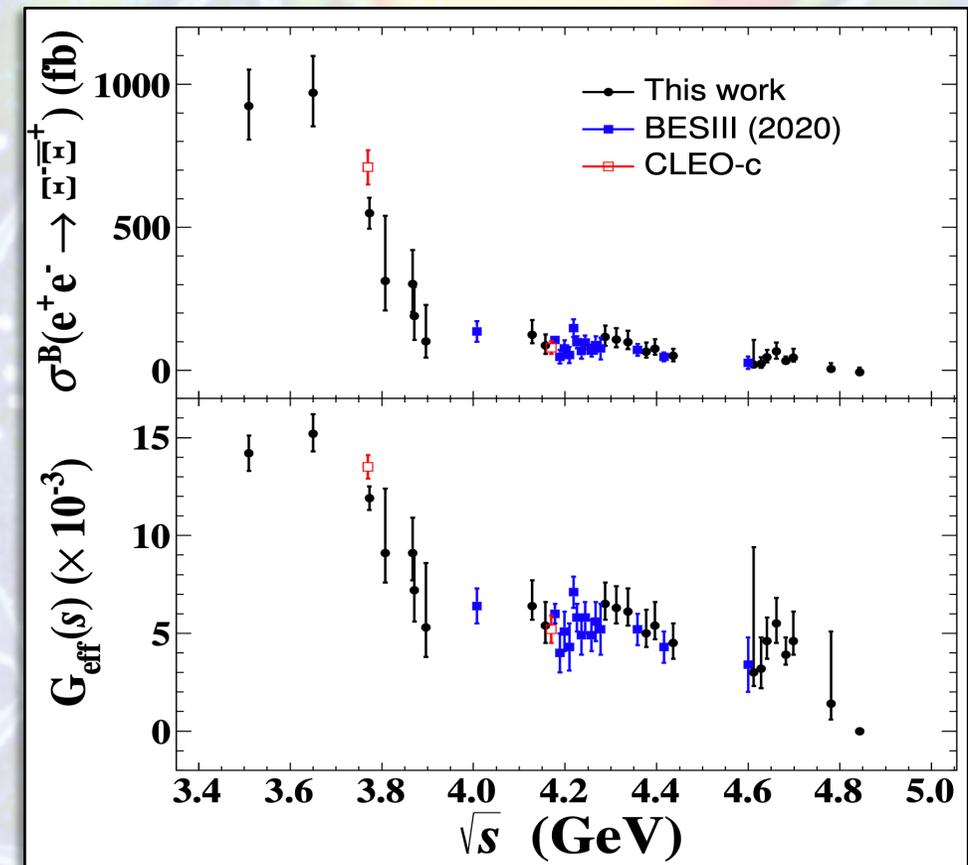
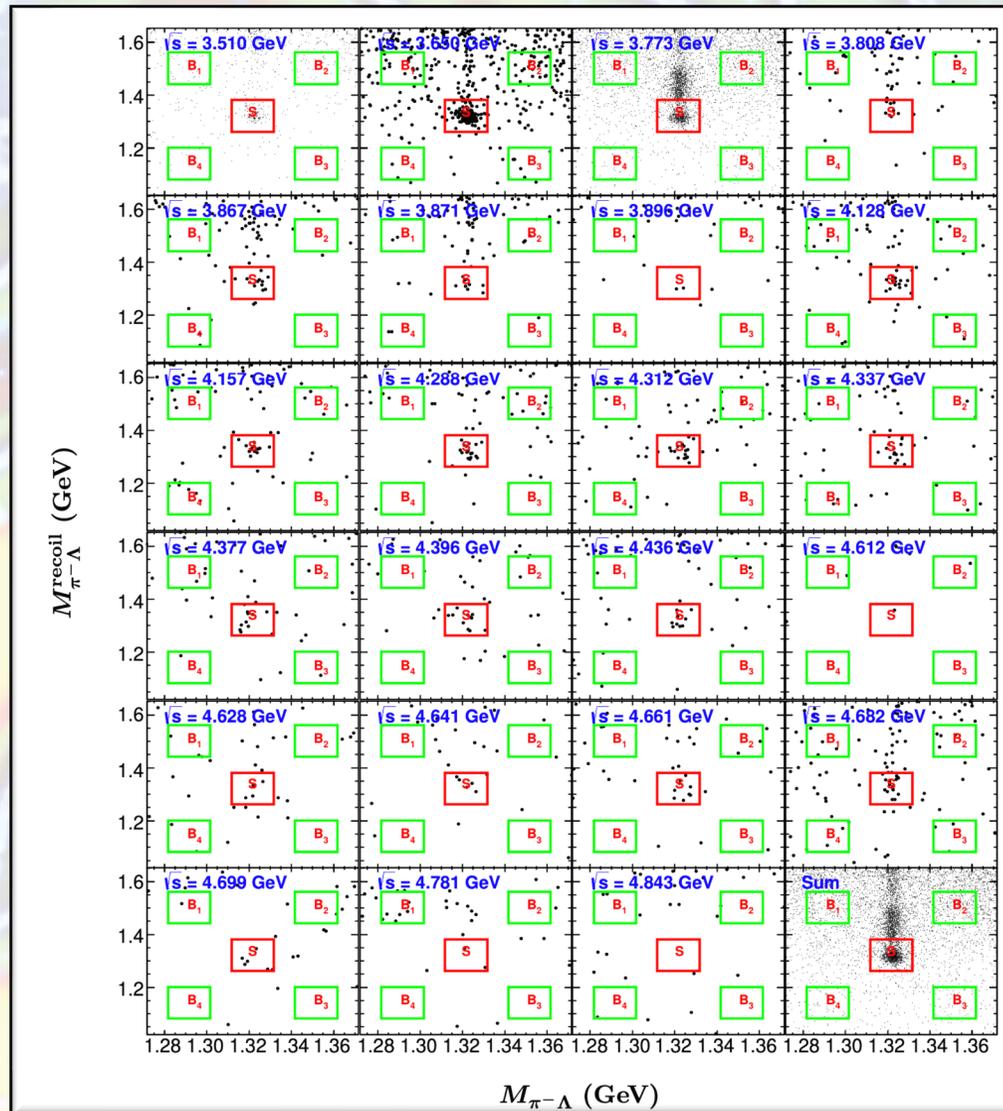
$$\checkmark e^+e^- \rightarrow pp\bar{p}\bar{n}\pi^- + c. c.$$

□ Summary

Update of $e^+e^- \rightarrow \Xi^- \bar{\Xi}^+$ @ $\sqrt{s}=3.5-4.9$ GeV

JHEP11(2023)228

□ Update for $\Xi^- \bar{\Xi}^+$ pair production above open charm threshold

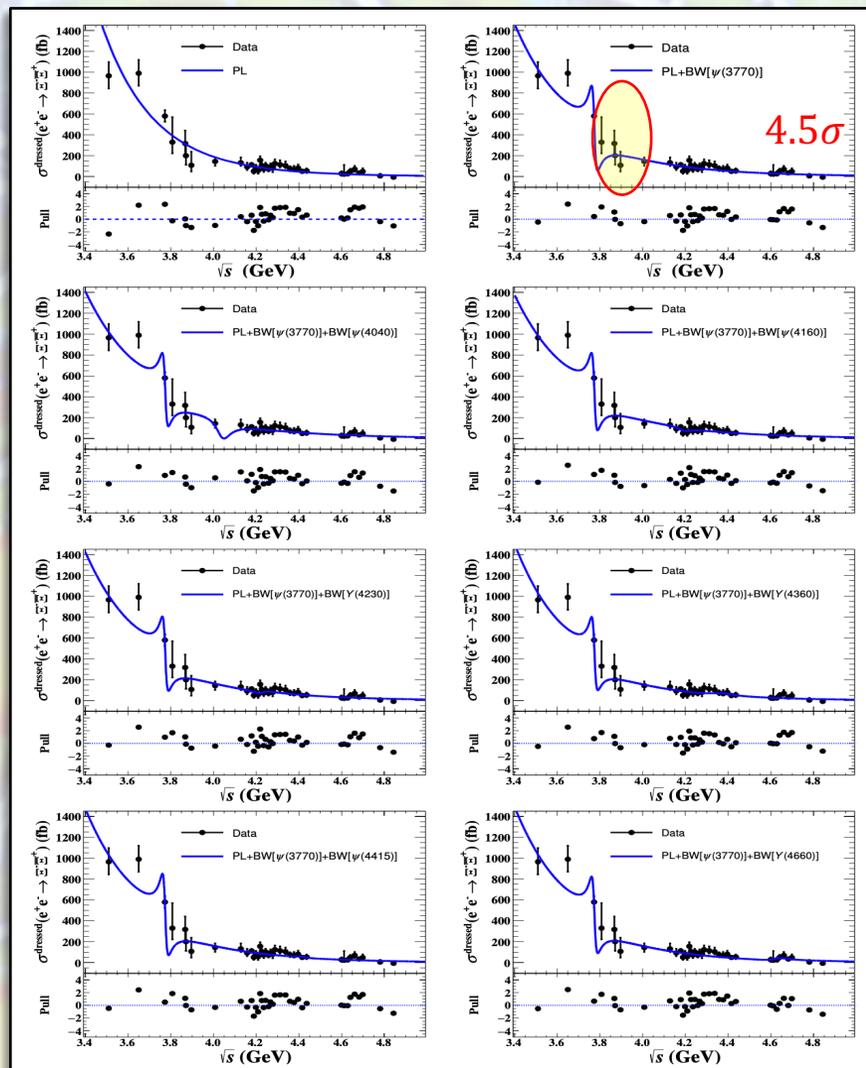


■ Improved measurements for the Born cross section and effective form factor with more 32 energy points

Update of $e^+e^- \rightarrow \Xi^- \bar{\Xi}^+$ @ $\sqrt{s}=3.5-4.9$ GeV

JHEP11(2023)228

□ Search for Charmonium(-like) states decaying into the $\Xi^- \bar{\Xi}^+$ pair



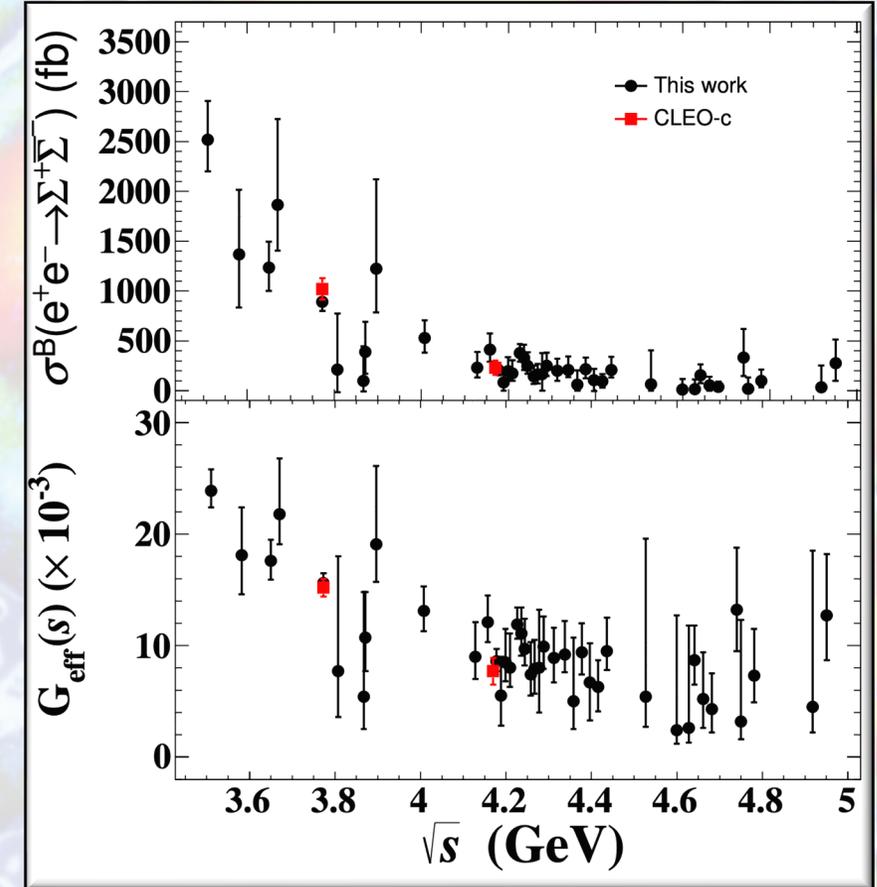
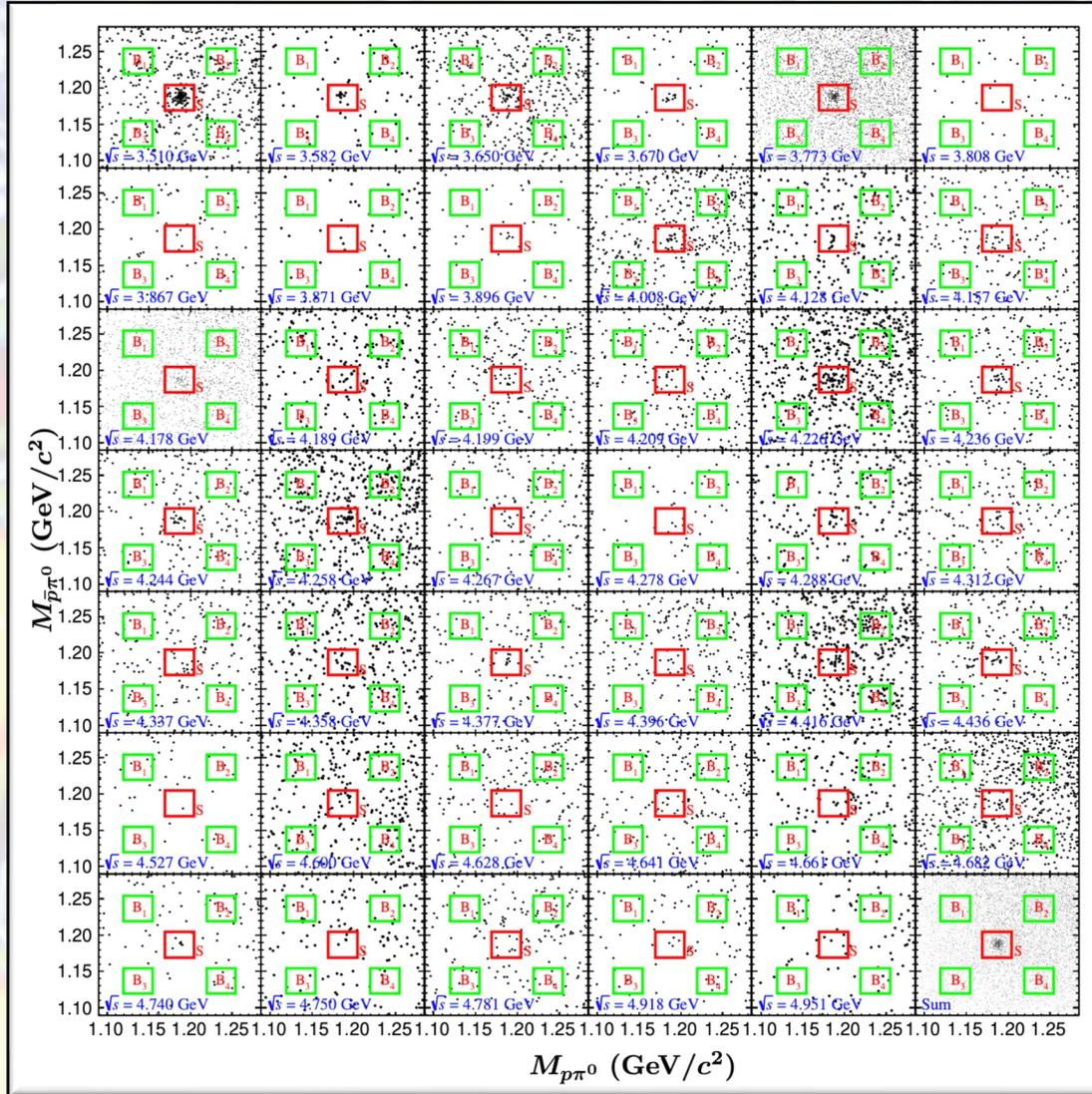
Mass and width are fixed by PDG

Resonance parameter	Solution I	Solution II	$\chi^2/n.d.f$
$\phi_{\psi(3770)}$ (rad)	-2.1 ± 0.2	—	
$\Gamma_{ee} \mathcal{B}_{\psi(3770)}$ (10^{-3} eV)	35.5 ± 9.2	—	45.0/(38 - 4)
$\mathcal{B}[\psi(3770) \rightarrow \Xi^- \bar{\Xi}^+]$ (10^{-6})	136.0 ± 35.2	—	
$\phi_{\psi(4040)}$ (rad)	-1.9 ± 0.2	-2.5 ± 0.1	
$\Gamma_{ee} \mathcal{B}_{\psi(4040)}$ (10^{-3} eV)	$15.2 \pm 27.6 (< 44.0)$	$19.7 \pm 30.9 (< 51.9)$	37.1/(38 - 6)
$\mathcal{B}[\psi(4040) \rightarrow \Xi^- \bar{\Xi}^+]$ (10^{-6})	$17.8 \pm 32.2 (< 51.4)$	$23.0 \pm 36.1 (< 60.6)$	
$\phi_{\psi(4160)}$ (rad)	-1.7 ± 0.1	-2.3 ± 0.1	
$\Gamma_{ee} \mathcal{B}_{\psi(4160)}$ (10^{-3} eV)	$29.8 \pm 2.5 (< 32.9)$	$33.9 \pm 2.7 (< 37.2)$	38.1/(38 - 6)
$\mathcal{B}[\psi(4160) \rightarrow \Xi^- \bar{\Xi}^+]$ (10^{-6})	$61.7 \pm 5.2 (< 68.1)$	$70.2 \pm 5.6 (< 77.0)$	
$\phi_Y(4230)$ (rad)	-1.7 ± 0.1	-2.2 ± 0.1	
$\Gamma_{ee} \mathcal{B}_{Y(4230)}$ (10^{-3} eV)	$19.4 \pm 1.9 (< 22.3)$	$22.0 \pm 2.1 (< 25.1)$	39.5/(38 - 6)
$\mathcal{B}[Y(4230) \rightarrow \Xi^- \bar{\Xi}^+]$ (10^{-6})	—	—	
$\phi_Y(4360)$ (rad)	-1.8 ± 0.1	-2.1 ± 0.1	
$\Gamma_{ee} \mathcal{B}_{Y(4360)}$ (10^{-3} eV)	$36.0 \pm 3.2 (< 41.2)$	$39.4 \pm 3.3 (< 44.8)$	41.7/(38 - 6)
$\mathcal{B}[Y(4360) \rightarrow \Xi^- \bar{\Xi}^+]$ (10^{-6})	—	—	
$\phi_{\psi(4415)}$ (rad)	-1.7 ± 0.1	-2.2 ± 0.1	
$\Gamma_{ee} \mathcal{B}_{\psi(4415)}$ (10^{-3} eV)	$16.5 \pm 1.9 (< 19.8)$	$18.3 \pm 2.0 (< 21.7)$	44.5/(38 - 6)
$\mathcal{B}[\psi(4415) \rightarrow \Xi^- \bar{\Xi}^+]$ (10^{-6})	$28.3 \pm 3.3 (< 34.0)$	$31.4 \pm 3.4 (< 37.2)$	
$\phi_Y(4660)$ (rad)	-1.6 ± 0.1	-2.2 ± 0.1	
$\Gamma_{ee} \mathcal{B}_{Y(4660)}$ (10^{-3} eV)	$13.6 \pm 2.0 (< 18.0)$	$15.3 \pm 2.2 (< 19.9)$	41.1/(38 - 6)
$\mathcal{B}[Y(4660) \rightarrow \Xi^- \bar{\Xi}^+]$ (10^{-6})	—	—	

- An evidence of $\psi(3770) \rightarrow \Xi^- \bar{\Xi}^+$ ($\sim 4.5\sigma$)
- No significant other ones are found
- Upper limits of $\Gamma_{ee} \mathcal{B}(Y \rightarrow \Xi^- \bar{\Xi}^+)$ are determined
- Provide more information for charmless decay of Charmonium(-like) states

$$e^+ e^- \rightarrow \Sigma^+ \bar{\Sigma}^- @ \sqrt{s} = 3.5 - 4.9 \text{ GeV}$$

□ First study of $\Sigma^+ \bar{\Sigma}^-$ production above open charm threshold

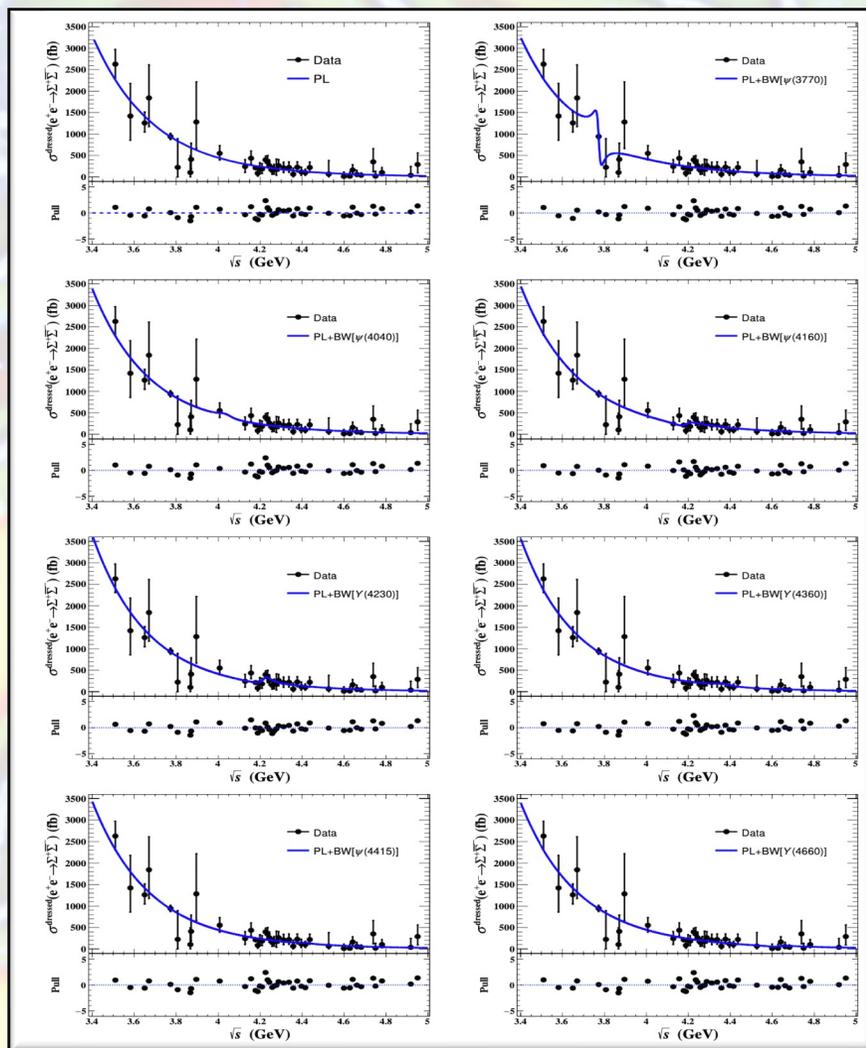


■ A total of 41 energy points measurement for the Born cross section and effective form factor

$$e^+e^- \rightarrow \Sigma^+\bar{\Sigma}^- @ \sqrt{s} = 3.5 - 4.9 \text{ GeV}$$

JHEP05(2024)022

Search for Charmonium(-like) states decaying into the $\Sigma^+\bar{\Sigma}^-$ pair



Mass and width are fixed by PDG

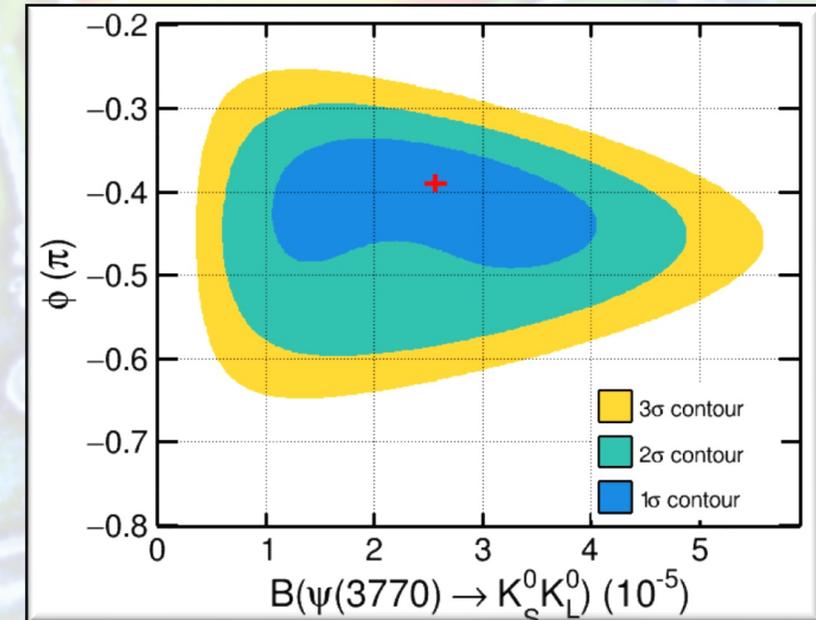
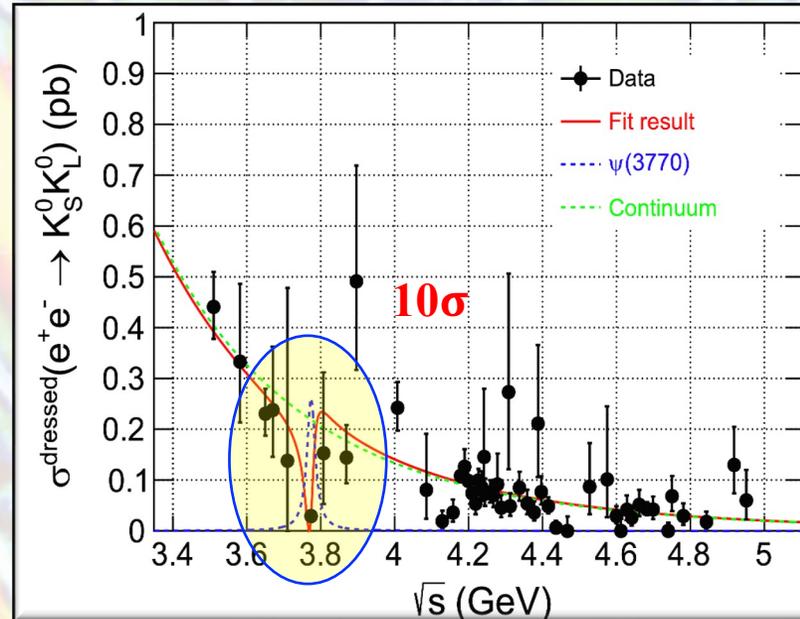
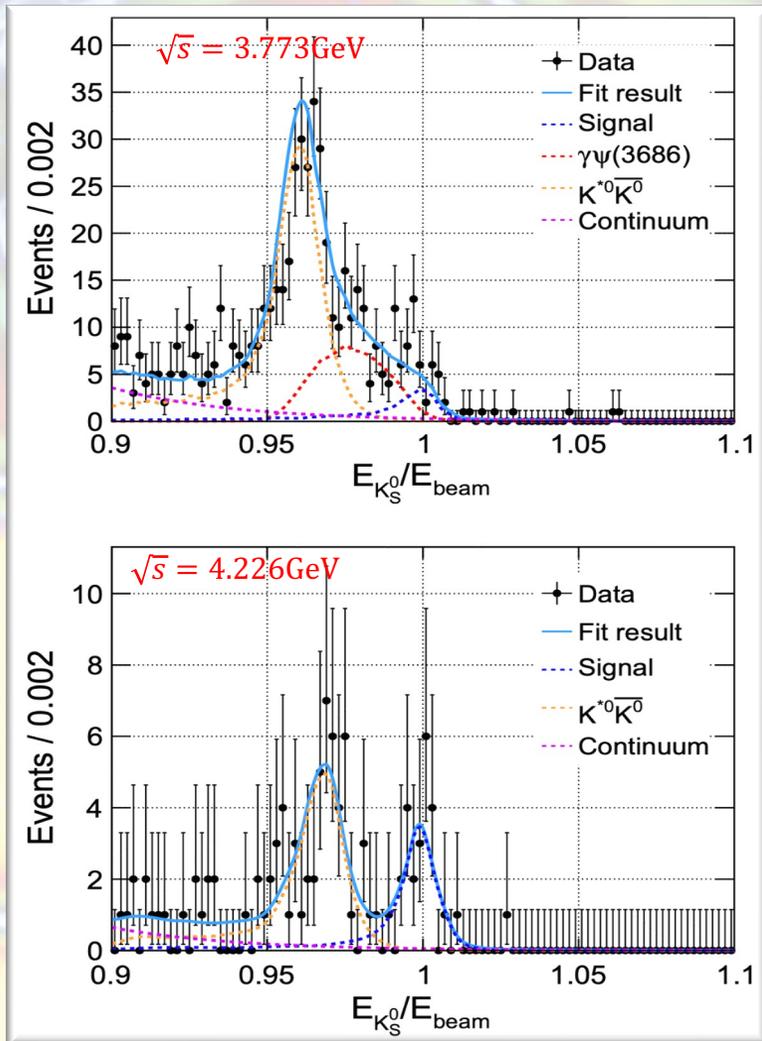
Resonance parameters	Solution I	Solution II	$\chi^2/n.d.f$
$\phi_{\psi(3770)}$ (rad)	-2.6 ± 0.4	-2.0 ± 0.4	28.8/(41 - 4)
$\Gamma_{ee}\mathcal{B}_{\psi(3770)}$ (10^{-3}eV)	19.5 ± 29.1	$73.8 \pm 32.7 (< 101.5)$	
$\phi_{\psi(4040)}$ (rad)	2.0 ± 0.6	-1.7 ± 0.1	30.5/(41 - 4)
$\Gamma_{ee}\mathcal{B}_{\psi(4040)}$ (10^{-3}eV)	0.2 ± 1.3	$154.6 \pm 29.0 (< 216.6)$	
$\phi_{\psi(4160)}$ (rad)	-0.6 ± 0.5	-1.5 ± 0.1	27.9/(41 - 4)
$\Gamma_{ee}\mathcal{B}_{\psi(4160)}$ (10^{-3}eV)	0.8 ± 0.7	$82.1 \pm 5.6 (< 94.6)$	
$\phi_{\psi(4230)}$ (rad)	0.4 ± 0.4	-1.5 ± 0.1	26.5/(41 - 4)
$\Gamma_{ee}\mathcal{B}_{\psi(4230)}$ (10^{-3}eV)	1.2 ± 0.8	$60.1 \pm 5.0 (< 72.4)$	
$\phi_{\psi(4360)}$ (rad)	1.7 ± 0.7	-1.7 ± 0.1	30.1/(41 - 4)
$\Gamma_{ee}\mathcal{B}_{\psi(4360)}$ (10^{-3}eV)	0.5 ± 1.0	$98.4 \pm 10.4 (< 118.8)$	
$\phi_{\psi(4415)}$ (rad)	0.8 ± 0.6	-1.6 ± 0.1	30.5/(41 - 4)
$\Gamma_{ee}\mathcal{B}_{\psi(4415)}$ (10^{-3}eV)	0.1 ± 0.5	$47.7 \pm 6.8 (< 62.1)$	
$\phi_{\psi(4660)}$ (rad)	-0.3 ± 0.5	-1.5 ± 0.2	30.6/(41 - 4)
$\Gamma_{ee}\mathcal{B}_{\psi(4660)}$ (10^{-3}eV)	0.2 ± 1.6	$31.1 \pm 9.3 (< 49.6)$	

- No significant signals are found
- Upper limits of $\Gamma_{ee}\mathcal{B}(Y \rightarrow \Sigma^+\bar{\Sigma}^-)$ are determined
- provide more information for Charmonium(-like) states coupling to the $\Sigma^+\bar{\Sigma}^-$ final states

$$e^+e^- \rightarrow K_S^0 K_L^0 @ \sqrt{s} = 3.5 - 4.9 \text{ GeV}$$

PRL132(2024)131901

□ First study of $K_S^0 K_L^0$ production above open charm threshold



■ Observation of $\psi(3770) \rightarrow K_S^0 K_L^0$ ($\sim 10\sigma$)

$$\text{Br}[\psi(3770) \rightarrow K_S^0 K_L^0] = (2.63_{-1.59}^{+1.40}) \times 10^{-5}$$

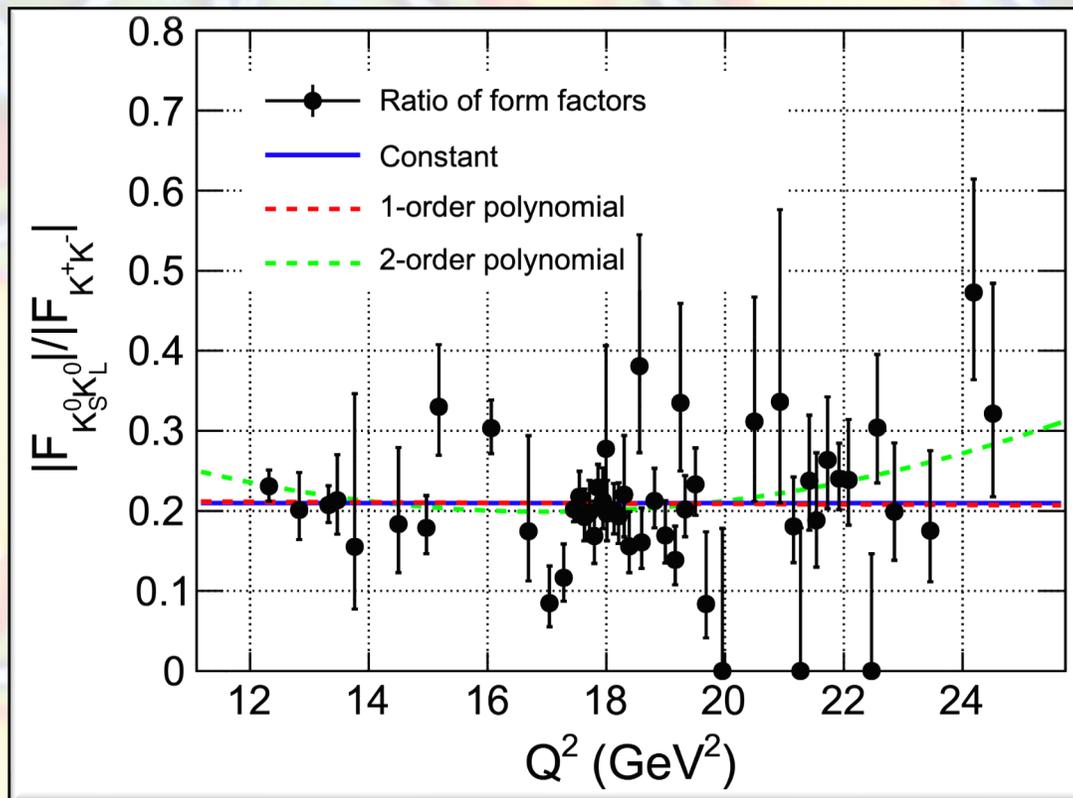
■ Agree with the prediction of the S-and D-wave charmonia mixing model developed to interpret the “ $\rho\pi$ puzzle” between J/ψ and $\psi(3686)$ decays

$$e^+ e^- \rightarrow K_S^0 K_L^0 @ \sqrt{s} = 3.5 - 4.9 \text{ GeV}$$

PRL132(2024)131901

■ Determine ratio of neutral-to-charged kaon form factors at large momentum

transfers ($12 < Q^2 < 25 \text{ GeV}^2$): $\left| \frac{F_{K_S^0 K_L^0}}{F_{K^+ K^-}} \right| = 0.21 \pm 0.01$

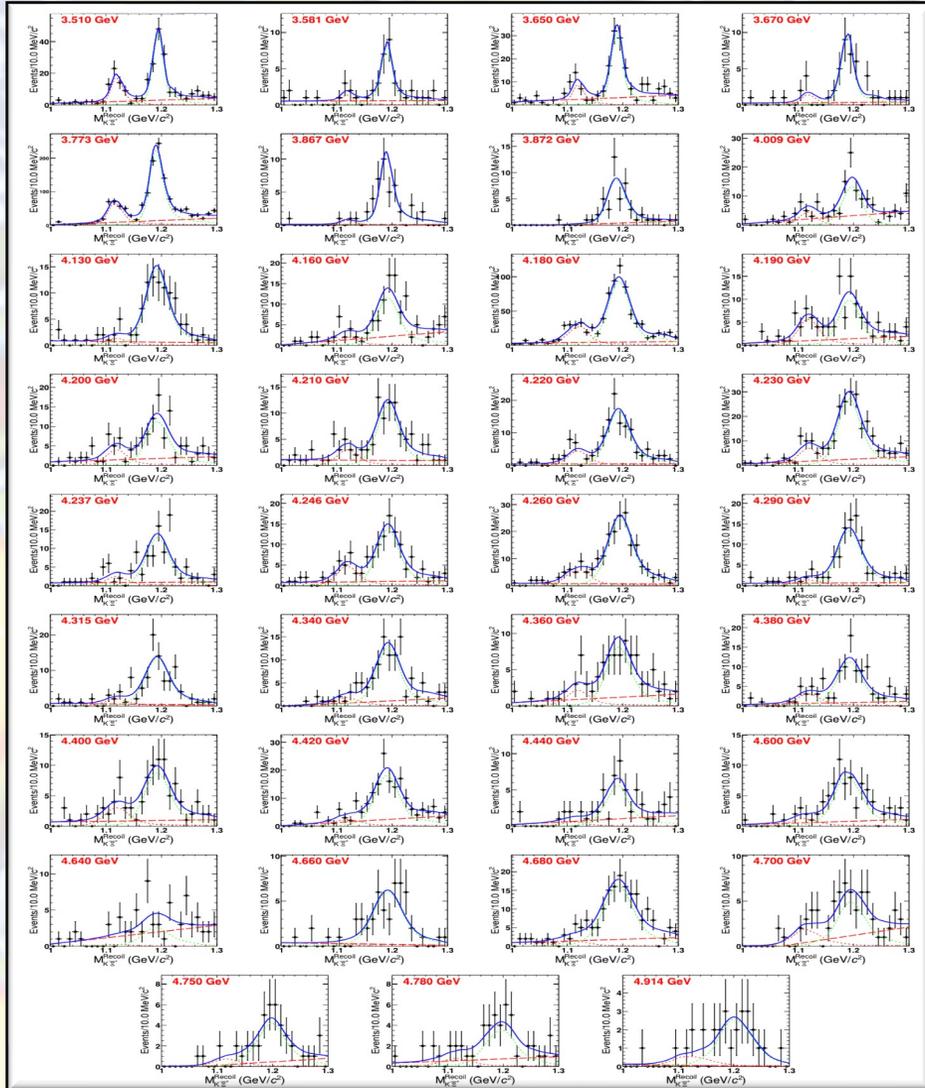


- **Indicating** a small but significant effect of flavor-SU(3) breaking in the kaon wave function (< 1 , and close to 0)
- **Excluding** flavor-SU(3) breaking is the primary possibility for the large deviation between the pQCD prediction^[PRD922(1980)2157] and the CLEO-c result^[PRL110(2013)022002]
- **Disagreeing with** the predicted trend using a single bound-state interaction kernel^[PRD96(2017)034024]
- **Provide more information for studying the internal structure of neutral kaons**

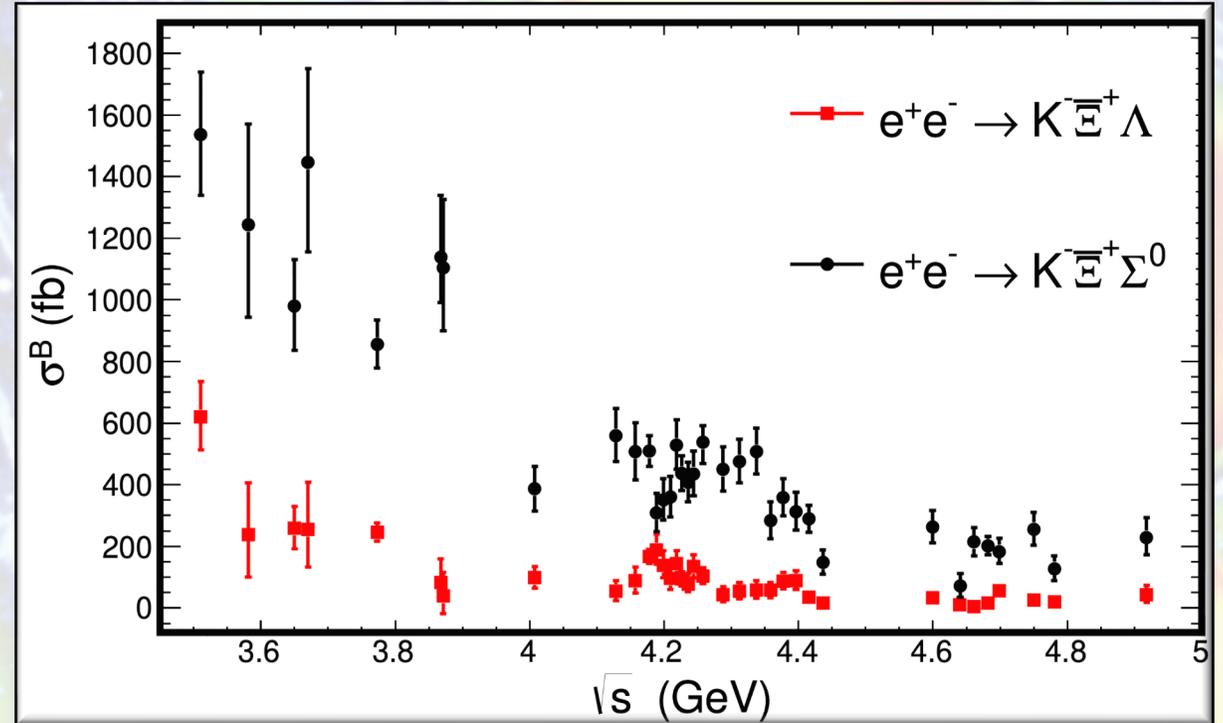
$$e^+e^- \rightarrow K^- \bar{E}^+ \Lambda/\Sigma^0 + c.c. @ \sqrt{s} = 3.5 - 4.9 \text{ GeV}$$

[arXiv:2406.18183](https://arxiv.org/abs/2406.18183)

□ First study of $K^- \bar{E}^+ \Lambda/\Sigma^0 + c.c.$ production above open charm threshold



Fit to $M_{K^- \bar{E}^+}^{Recoil}$

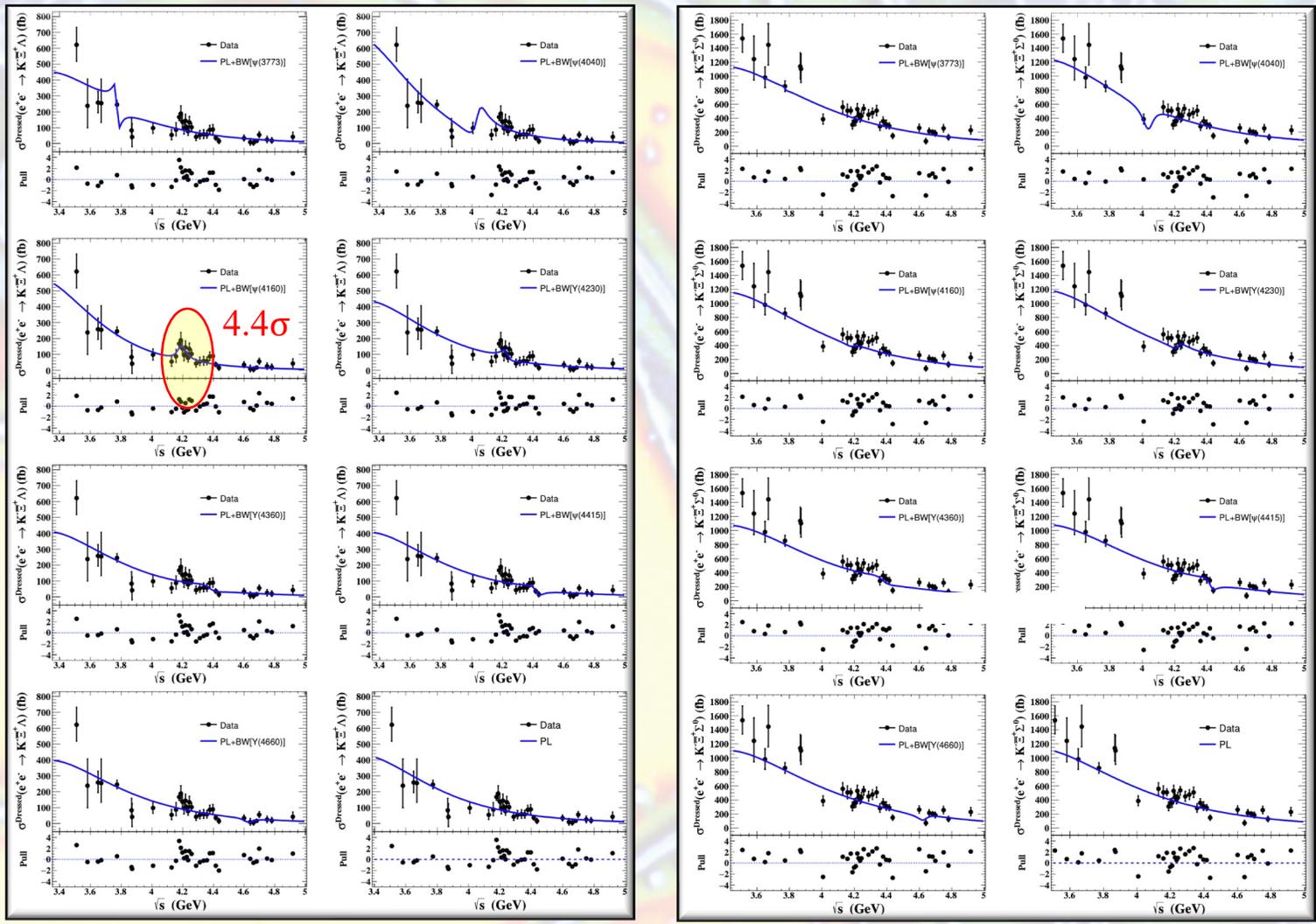


■ A total of 35 energy points measurement for the Born cross section for both modes

$$e^+e^- \rightarrow K^- \bar{\Xi}^+ \Lambda / \Sigma^0 + c.c. @ \sqrt{s} = 3.5 - 4.9 \text{ GeV}$$

arXiv:2406.18183

□ Search for charmonium(-like) states in the $K^- \bar{\Xi}^+ \Lambda / \Sigma^0 + c.c.$ final states



Fitted resonance parameters

$e^+e^- \rightarrow K^- \bar{\Xi}^+ \Lambda$						
Resonance	$\Gamma_{ee} B (10^{-3} \text{ eV})$		$\phi \text{ (rad)}$		$\chi^2/n.d.f$	$S (\sigma)$
	I	II	I	II		
$\psi(3770)$	$21.0 \pm 3.7 (< 25.0)$	1.7 ± 0.5	-1.9 ± 0.3	-2.8 ± 0.2	1.8	0.5
$\psi(4040)$	$45.0 \pm 6.3 (< 62.0)$	5.1 ± 2.3	-1.3 ± 0.1	-1.3 ± 0.1	1.4	2.8
$\psi(4160)$	2.1 ± 0.2	1.5 ± 0.4	-1.6 ± 0.1	-1.3 ± 0.2	1.1	4.4
$\psi(4230)$	$21.3 \pm 1.5 (< 24.9)$	0.6 ± 0.3	-1.8 ± 0.1	2.5 ± 0.3	1.5	2.8
$\psi(4360)$	$28.9 \pm 2.7 (< 35.8)$	0.6 ± 0.1	-1.8 ± 0.1	-2.9 ± 0.1	1.6	1.7
$\psi(4415)$	$9.3 \pm 2.3 (< 14.3)$	1.7 ± 1.1	-1.9 ± 0.1	-2.3 ± 0.2	1.6	1.2
$\psi(4660)$	$6.8 \pm 3.5 (< 13.0)$	0.8 ± 1.5	-1.6 ± 0.1	-1.6 ± 0.1	1.7	1.2
$e^+e^- \rightarrow K^- \bar{\Xi}^+ \Sigma^0$						
Resonance	$\Gamma_{ee} B (10^{-3} \text{ eV})$		$\phi \text{ (rad)}$		$\chi^2/n.d.f$	$S (\sigma)$
	I	II	I	II		
$\psi(3770)$	$83.1 \pm 3.2 (< 89.5)$	0.3 ± 3.3	-1.6 ± 0.2	-2.7 ± 1.7	2.2	1.5
$\psi(4040)$	$5.3 \pm 2.5 (< 12.5)$	4.2 ± 2.3	-1.3 ± 0.3	-1.1 ± 0.3	2.0	2.0
$\psi(4160)$	$0.4 \pm 0.7 (< 1.5)$	0.1 ± 0.9	-0.1 ± 0.5	0.1 ± 0.4	2.3	0.9
$\psi(4230)$	$0.6 \pm 0.2 (< 1.6)$	0.2 ± 0.1	0.2 ± 0.3	0.3 ± 0.3	2.3	0.9
$\psi(4360)$	$1.1 \pm 0.6 (< 2.8)$	0.9 ± 0.4	2.9 ± 0.3	2.9 ± 0.3	2.0	1.0
$\psi(4415)$	$77.0 \pm 4.5 (< 87.0)$	1.8 ± 0.8	-1.7 ± 0.2	-2.5 ± 0.2	2.0	2.7
$\psi(4660)$	$62.5 \pm 6.2 (< 77.3)$	0.6 ± 1.0	-1.6 ± 0.2	-1.3 ± 0.2	2.2	1.5

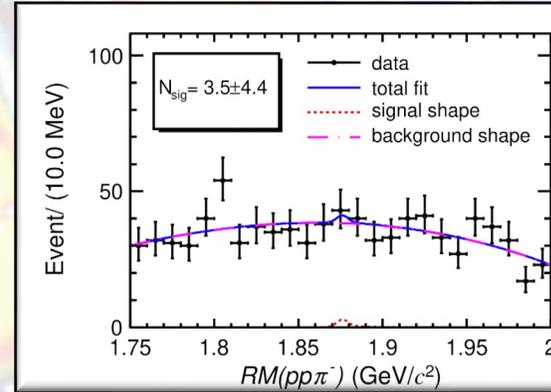
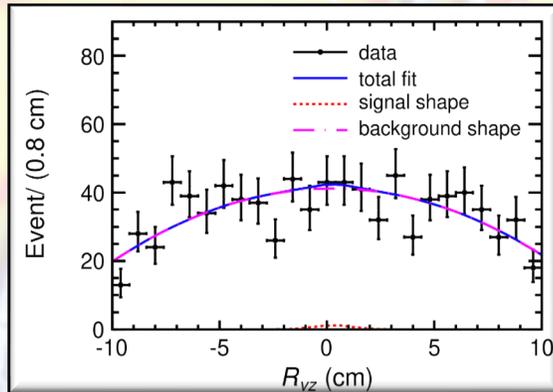
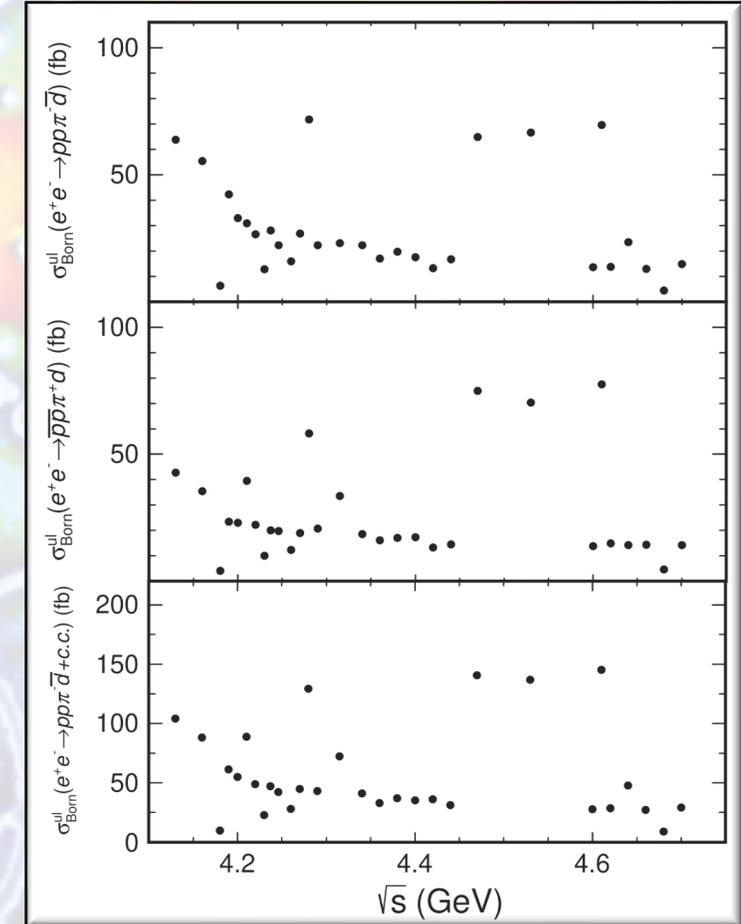
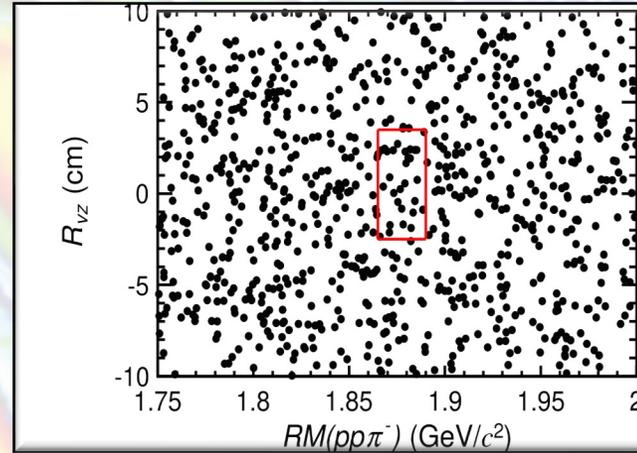
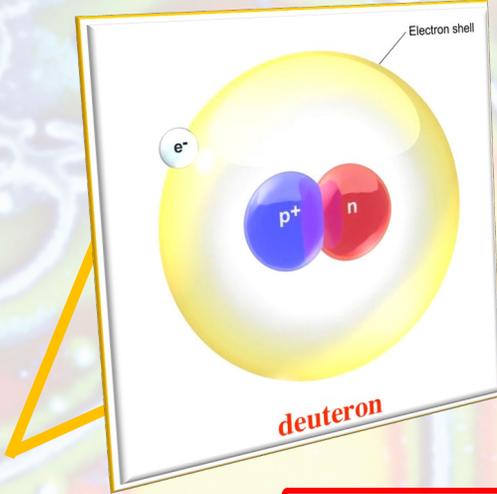
- Evidence of $\psi(4160) \rightarrow K^- \bar{\Xi}^+ \Lambda$ ($\sim 4.4\sigma$)
- No significant other resonances are observed
- Upper limits on $\Gamma_{ee} B$ are determined
- More information for charmonium(-like) states

Mass and width are fixed by PDG

$$e^+ e^- \rightarrow pp\bar{d}(\bar{p}\bar{n})\pi^- + c.c. @ \sqrt{s} = 4.13 - 4.70 \text{ GeV}$$

PRD109(2024)092013

Search for the production of deuterons/antideuterons

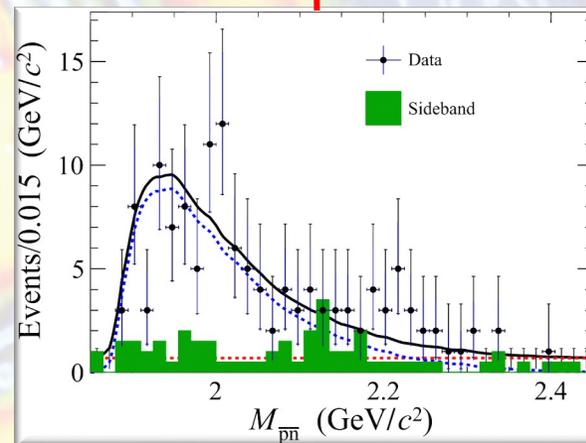
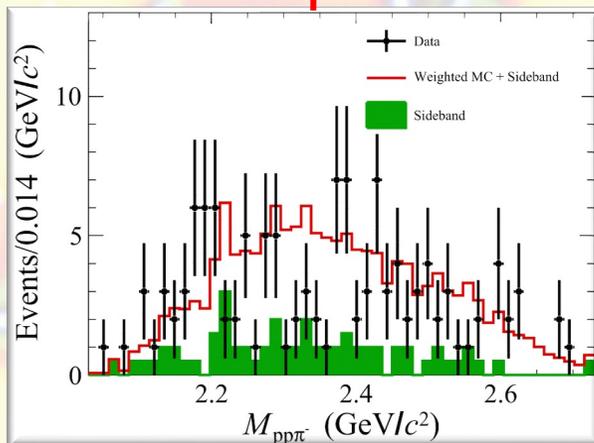
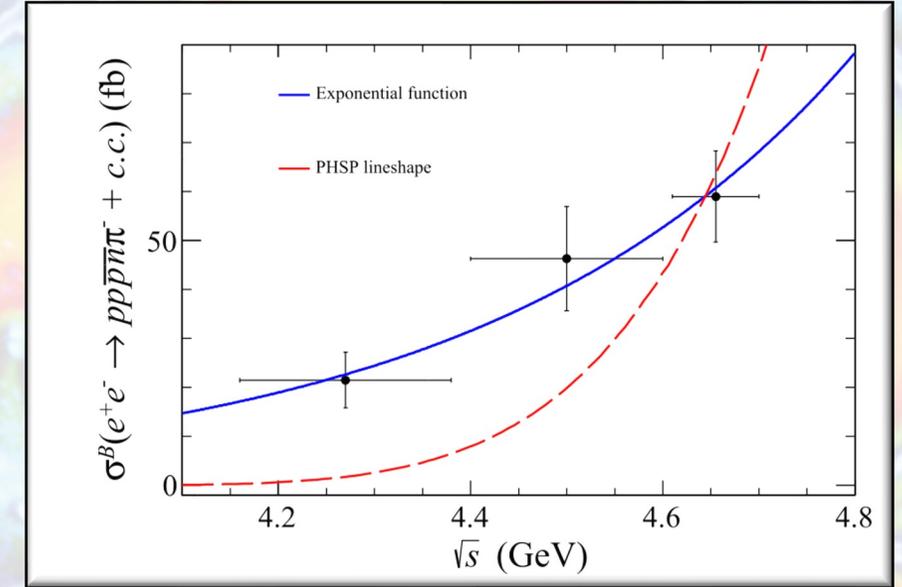
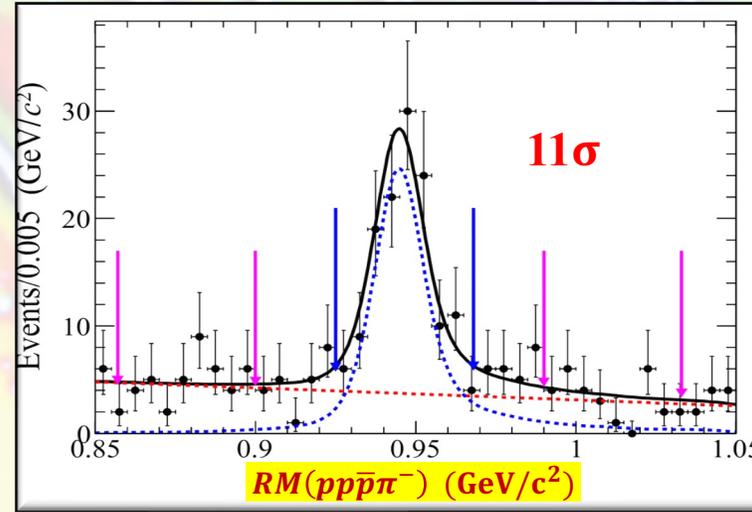
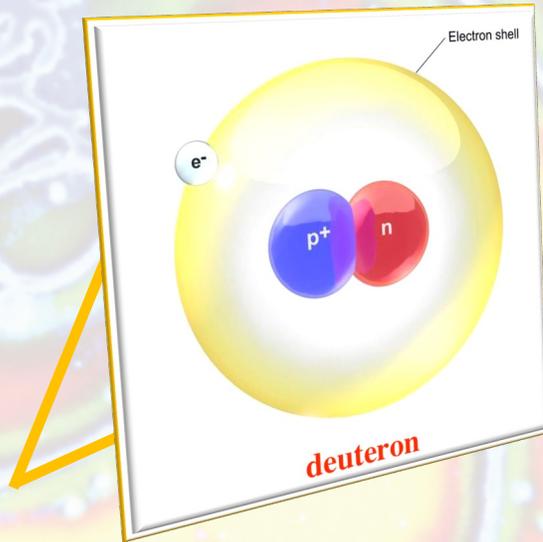


- No significant (anti-)deuteron signal is observed, and upper limit on Born cross section is determined
- This study may unravel the production mechanisms and properties of these light nuclei, shedding light on the dynamics of hadronization and quark-gluon interactions.

$$e^+ e^- \rightarrow p p \bar{p} \bar{n} \pi^- + c. c. @ \sqrt{s} = 4.16 - 4.7 \text{ GeV}$$

CPC47, 043001 (2023)

□ Search for the production of deuterons/antideuterons, hexaquark, di-baryon states



- The $e^+ e^- \rightarrow p p \bar{p} \bar{n} \pi^- + c. c.$ is observed for first time (11σ)
- No significant deuteron, hexaquark, di-baryon, etc. are observed
- Born cross sections at three sub-samples are determined

Summary

- Many advances in hadron production in e^+e^- annihilation at BESIII achieved
 - ✓ Study of $\Xi^- \bar{\Xi}^+ / \Sigma^- \bar{\Sigma}^+$, $K_S^0 K_L^0$ production
 - ✓ Evidence of $\psi(3770) \rightarrow \Xi^- \bar{\Xi}^+$
 - ✓ Observation of $\psi(3770) \rightarrow K_S^0 K_L^0$
 - ✓ Search for deuterons/antideuterons, hexaquark, di-baryon states
- More new results are on the way

Thanks for your attention!