Measurements of Charmonium Decays at BESIII

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on behalf of the BESIII Collaboration

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ICHEP 2024 | PRAGUE

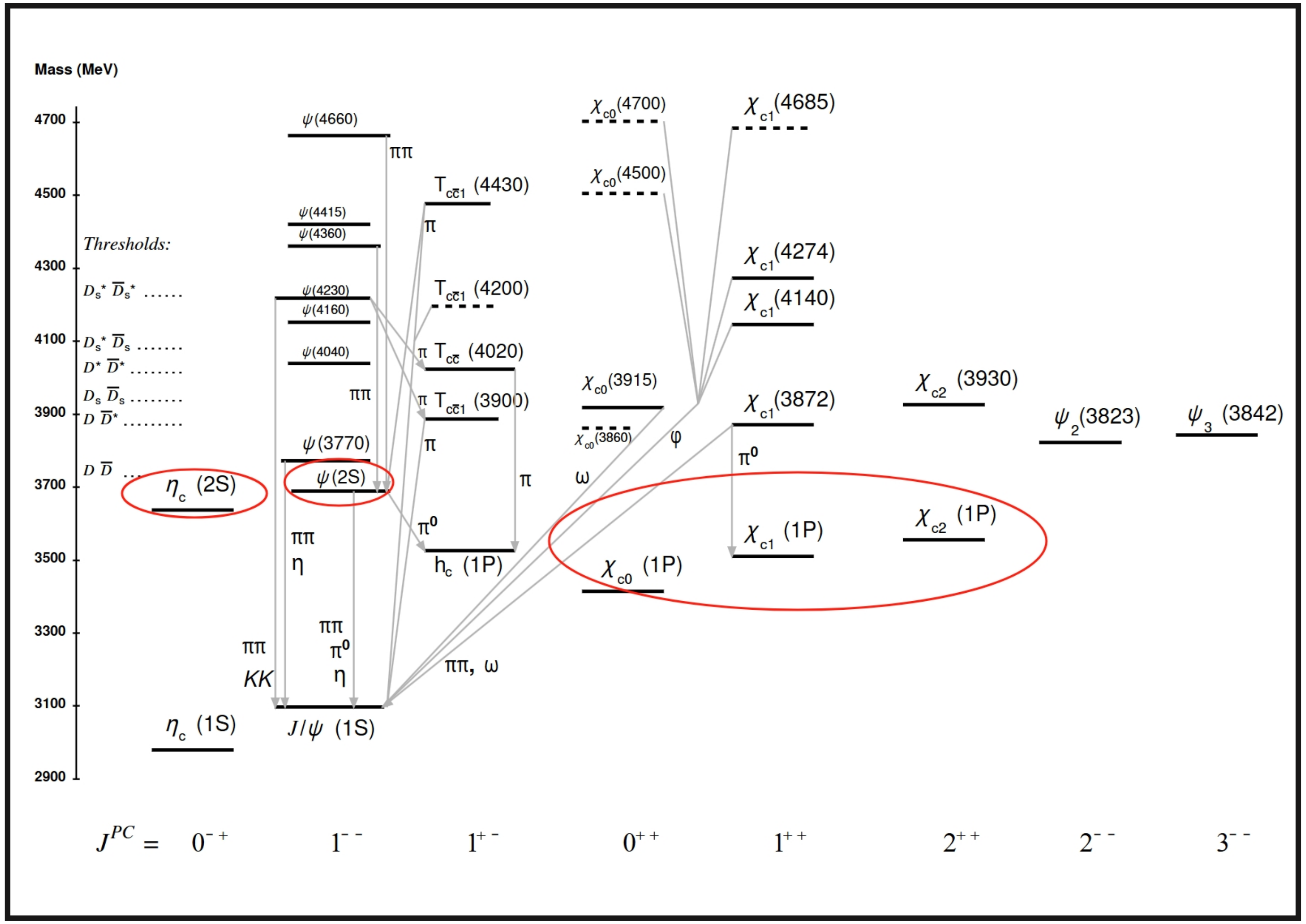
Outline

- **Introduction**
- **BESIII experiment and data sets**
- **The study of $\psi(3686)$ decay**
  - ✓ $\psi(3686) \to \Omega^- K^+ \bar{\Xi}^0 + c.c.$
  - ✓ $\psi(3686) \to \gamma \eta_c(2S)$ **with** $\eta_c(2S) \to K\bar{K}\pi$
- **The study of singlet $\eta_c(2S)$ decay**
  - ✓ $\eta_c(2S) \to \pi^+\pi^-\eta_c / \pi^+\pi^- K_s K^\pm \pi^\mp$
- **The study of χ_{cJ} decay**
  - ✓ $\chi_{cJ} \to 3(K^+K^-)$
- **The nature of $\chi_{c1}(3872)$, 2^3P_1 or not**
  - ✓ $\chi_{c1}(3872) \to \pi^+\pi^-\chi_{c1}$
  - ✓ $\chi_{c1}(3872) \to \pi^+\pi^-\eta$
- **Summary**

DISCLAIMER

This presentation is not an encyclopaedic review of all the charmonium decays at BESIII

Introduction



"Cornell" potential (Coulomb-like potential)

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + kr$$

Charmonium resonances are located in the transition region of perturbative and non-perturbative QCD

Non-vector and above-threshold states are partly unknown

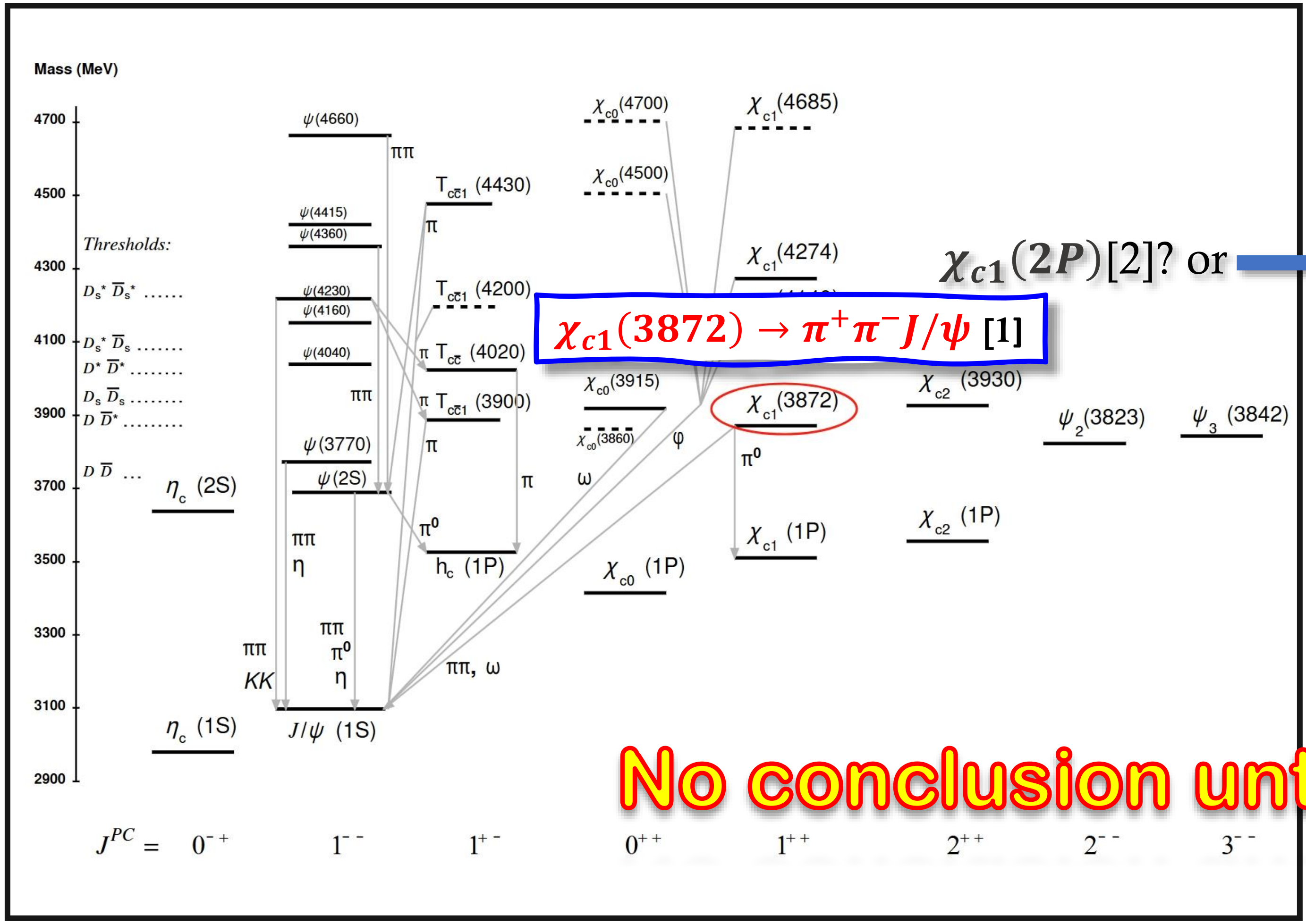
Vector states can be used either to reach non-1^{--} ones or as a way to test pQCD predictions (e.g., 12% rule, $\mathcal{A}$(EM - strong), …)

Gateway to the XYZ exotic states

Another way to probe the SM (via weak decays)

Study the dynamics mechanism of charmonium decays

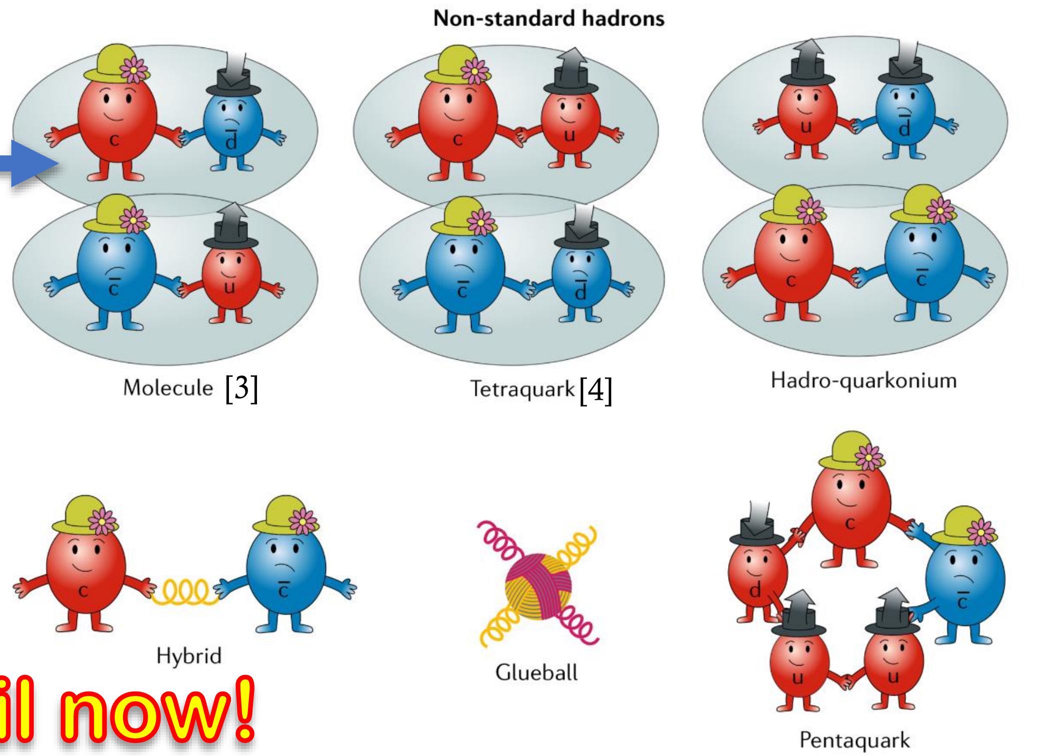
Introduction



$\chi_{c1}(3872) \to \pi^+\pi^- J/\psi$ [1]

$\chi_{c1}(2P)$[2]? or

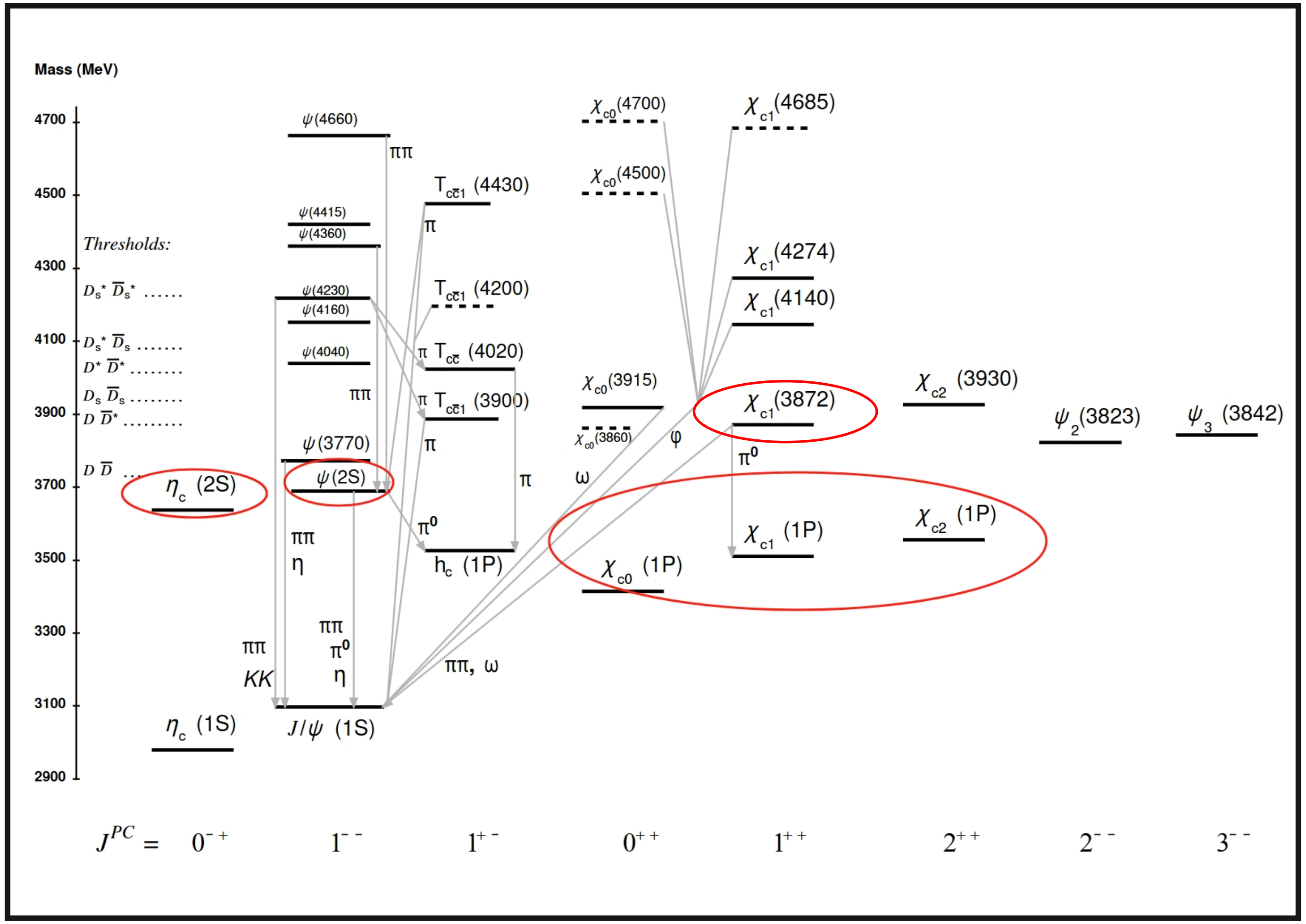
No conclusion until now!



Nature Rev.Phys. 1, 480-494 (2019)

[1] Phys. Rev. Lett. 91, 262001 (2003).
[2] Phys. Rev. D 72, 054026 (2005).
[3] Phys. Rep. 429, 243 (2006).
[4Phys. Rev. D 71, 014028 (2005);

Introduction

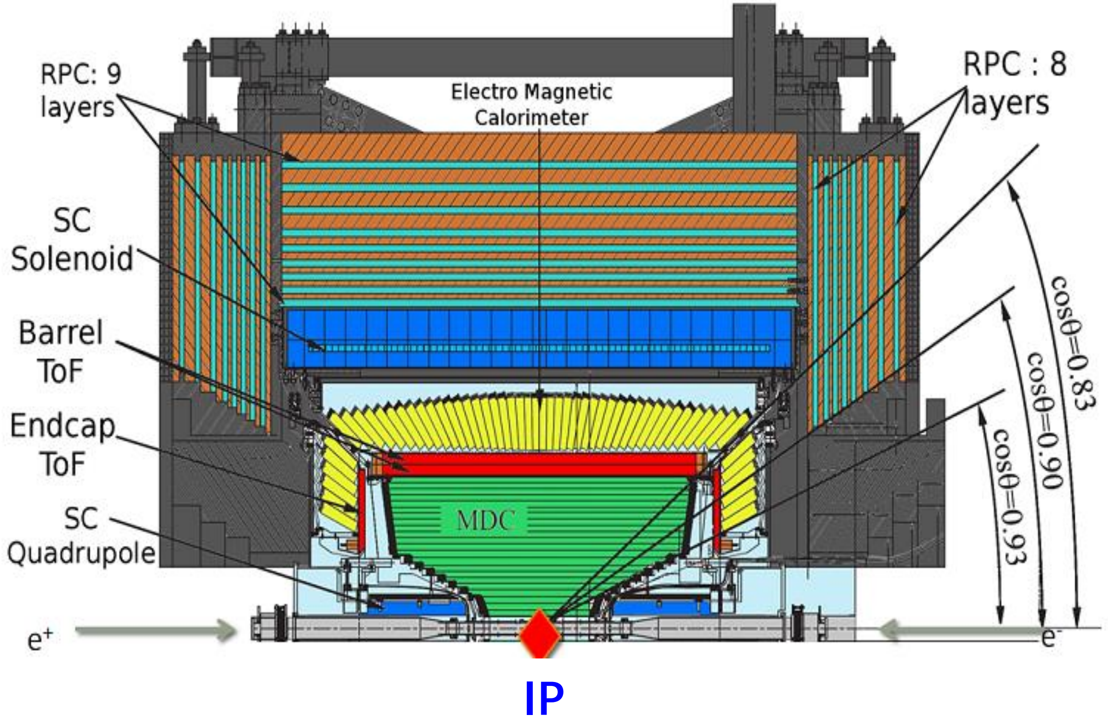


BESIII can perform such studies, and this report focus on the studies of $\eta_c(2S), \psi(2S), \chi_{cJ}(1P), \chi_{c1}(3872)$ decay to expand our knowledge on the charmonium spectrum:

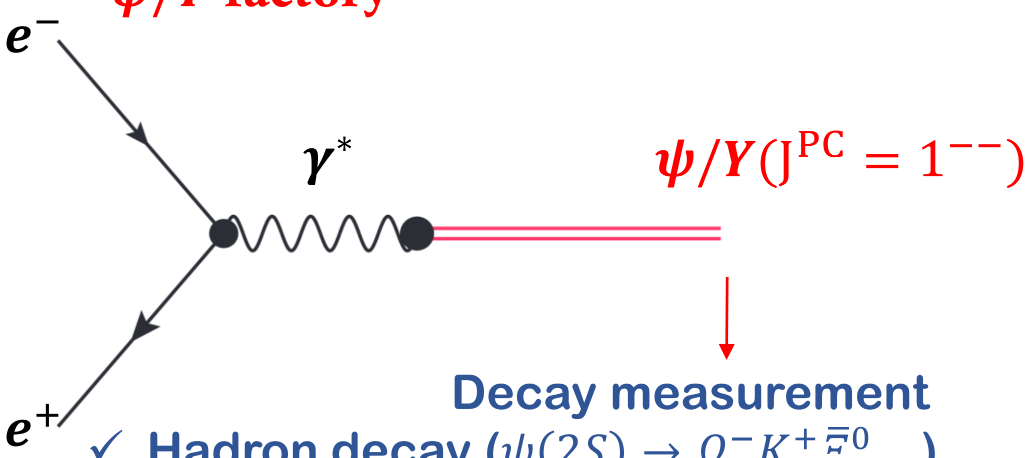
Discussed

1. Observation of $\psi(2S) \to \Omega^- K^+ \bar{\Xi}^0 + c.c.$
2. Updated measurements of the M1 transition $\psi(3686) \to \gamma\eta_c(2S)$ with $\eta_c(2S) \to K\bar{K}\pi$
3. Search for $\eta_c(2S) \to \pi^+\pi^-\eta_c$ and $\eta_c(2S) \to \pi^+\pi^- K_S K^\pm \pi^\mp$ decay
4. Observation of $\chi_{cJ} \to 3(K^+K^-)$
5. Search for the decay $\chi_{c1}(3872) \to \pi^+\pi^-\chi_{c1}$
6. Search for the light hadron decay $\chi_{c1}(3872) \to \pi^+\pi^-\eta$

BESIII experiment



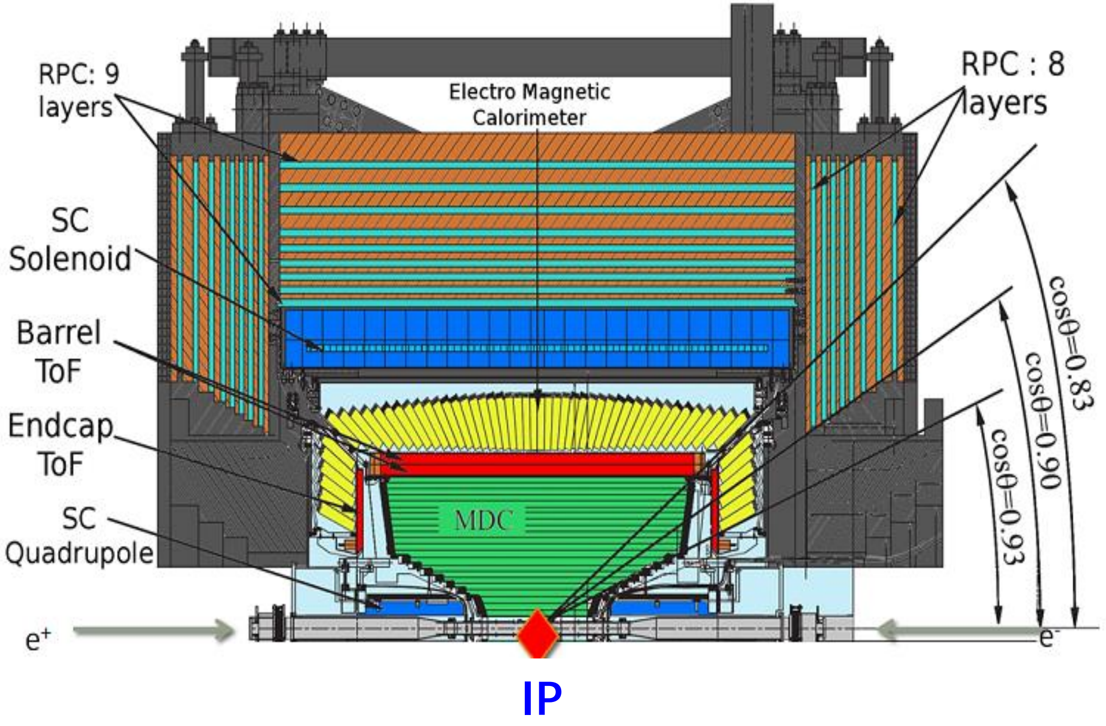
- τ-c region $1.84 < \sqrt{s} < 4.95$ GeV
- Peak luminosity $1.1 \times 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ @ $\sqrt{s} = 3.77$ GeV
- Clean background environment
- **ψ/Υ factory**

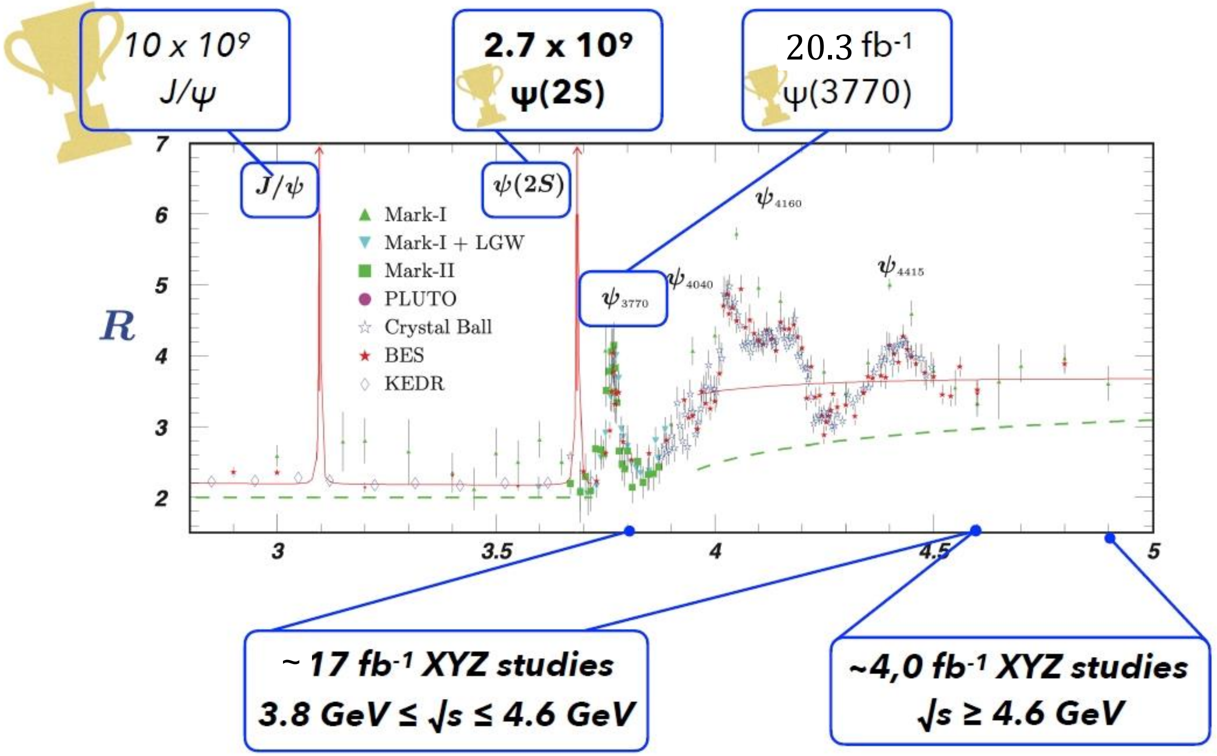


Decay measurement

✓ **Hadron decay** ($\psi(2S) \to \Omega^- K^+ \bar{\Xi}^0 \ldots$)
✓ **Radiative decay** ($\gamma\chi_{cJ}, \gamma\eta_c(2S), \gamma\chi_{c1}(3872) \ldots$)
✓ **Non-1^{--} state decay** ($\chi_{cJ} \to 3(K^+K^-) \ldots$)
✓ **Charmonium-like state decay** ($\chi_{c1}(3872) \to \pi^+\pi^-\chi_{c1} \ldots$)

BESIII experiment



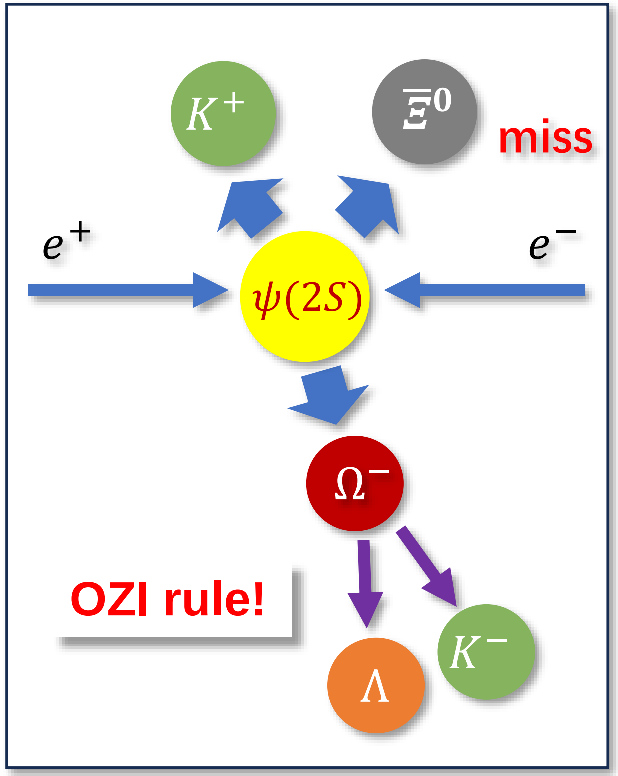


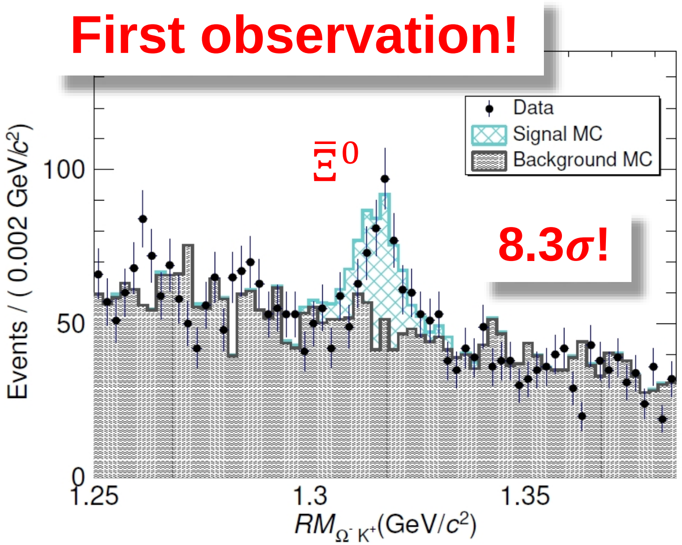
- Precise center-of-mass energies ($\boldsymbol{\sigma_E} < \mathbf{2\ MeV}$)
- $2.7 \times 10^9\ \psi(3686)$ events for charmonium decay study
- High luminosity energy scan ($\sim 500\ \mathrm{pb}^{-1}/10\ \mathrm{MeV}$)
- $\mathbf{22\ fb^{-1}}$ ($4 < \sqrt{s} < 5$ GeV) for XYZ study

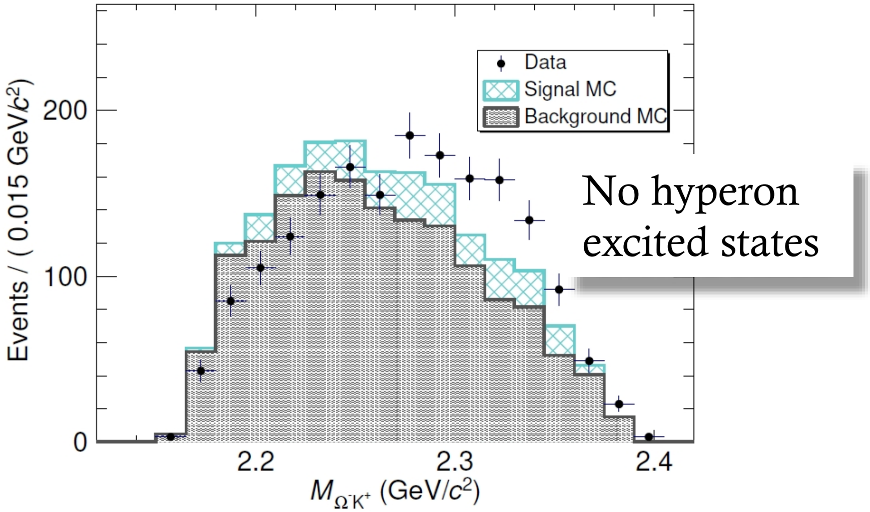
$\psi(3686) \to \Omega^- K^+ \bar{\Xi}^0 + c.c.$

JHEP 04 (2024) 013

Partial reconstruction







$$\mathcal{B}_{\psi(3686)\to\Omega^- K^+ \bar{\Xi}^0 + \mathrm{c.c.}} = \frac{N_{\mathrm{obs.}} - N_{\mathrm{QED}}}{N_{\psi(3686)} \cdot \mathcal{B}_{\Omega^- \to \Lambda K^-} \cdot \mathcal{B}_{\Lambda \to p^+ \pi^-} \cdot \epsilon}$$

$$= (2.78 \pm 0.40 \pm 0.18) \times 10^{-6}$$

Stat. Syst.

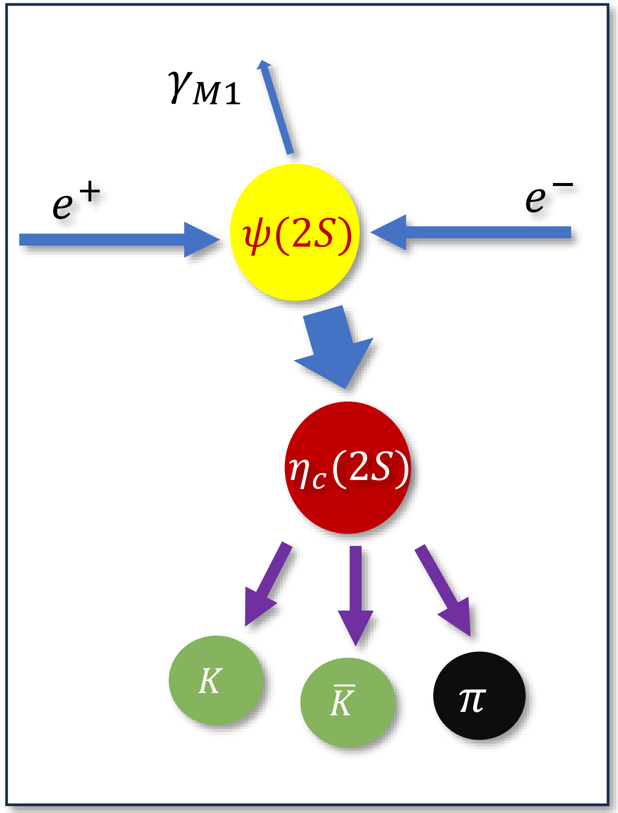
6 s or $\bar{s}$ quark in the final state!

1. **3-body decays study of charmoniums is difficult for theory**
2. **Available experimental results are limited now [5]**
3. **Provide important information for strong interaction**
4. **Help understand the dynamics of $\psi(3686)$ decays**

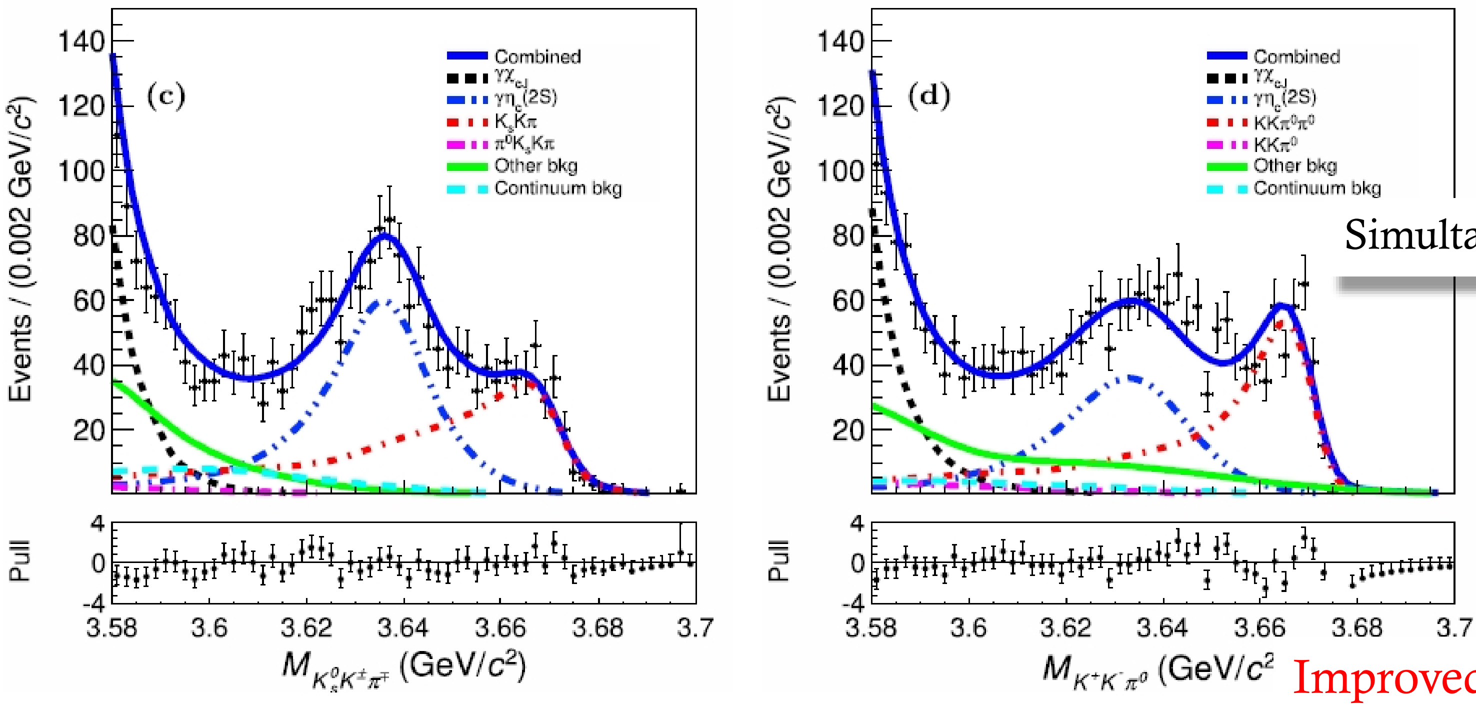
[5] Prog. Theor. Exp. Phys. 2022 (2022)083C01.

$\psi(3686) \to \gamma\eta_c(2S)$ with $\eta_c(2S) \to K\bar{K}\pi$

PRD 109, 032004(2024)



$\eta_c(2S) \to K_S^0 K^{\pm}\pi^{\mp}$ $\eta_c(2S) \to K^+K^-\pi^0$



Simultaneous fit

Improved precision

	Mass (MeV/c^2)	Width (MeV)	$\mathcal{B}(\psi(3686) \to \gamma\eta_c(2S))(\times 10^{-4})$	$\Gamma(\psi(3686) \to \gamma\eta_c(2S))$ (keV)
This work	$3637.8 \pm 0.8 \pm 0.2$	$10.5 \pm 1.7 \pm 3.5$	$5.2 \pm 0.3 \pm 0.5^{+1.9}_{-1.4}$	$0.15^{+0.06}_{-0.04}$
BESIII (2012)	$3637.6 \pm 2.9 \pm 1.6$	$16.9 \pm 6.4 \pm 4.8$	$6.8 \pm 1.1 \pm 4.5$	0.20 ± 0.14
World average	3637.6 ± 1.2	$11.3^{+3.2}_{-2.9}$	7 ± 5	0.21 ± 0.15

From $\mathcal{B}(\eta_c(2S) \to K\bar{K}\pi) = (1.86^{+0.68}_{-0.49})\%$ [6]

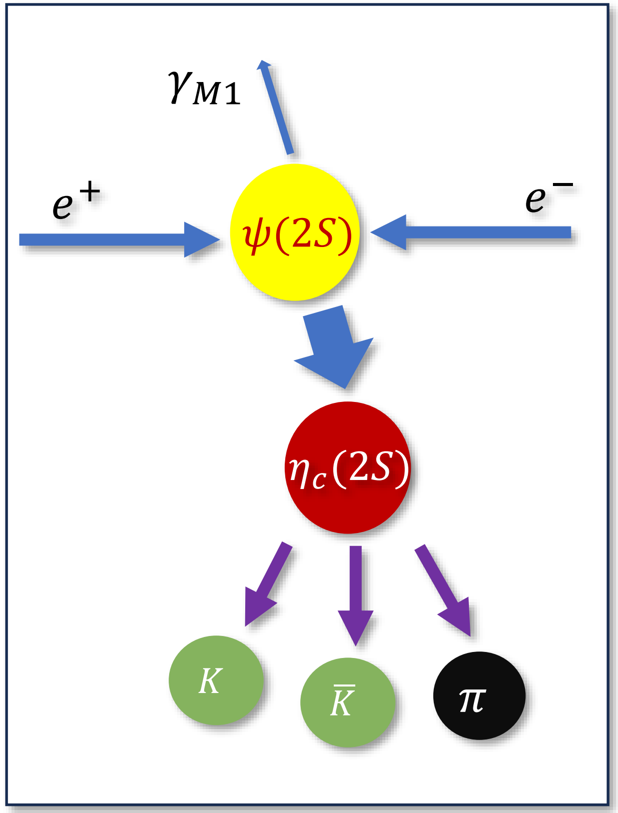
1. Different theoretical model give different $Br(\psi(2S) \to \gamma\eta_c(2S))$

2. Ref[6] give $Br(\psi(2S) \to \gamma\eta_c(2S)) = (7^{+3.4}_{-2.5}) \times 10^{-4}$ but difficult to validate theoretical calculation

[6] Chin. Phys. C 46 071001 (2022)

$\psi(3686) \to \gamma\eta_c(2S)$ with $\eta_c(2S) \to K\bar{K}\pi$

PRD 109, 032004(2024)



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Improved precision

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Comparison with theoretical expectations…

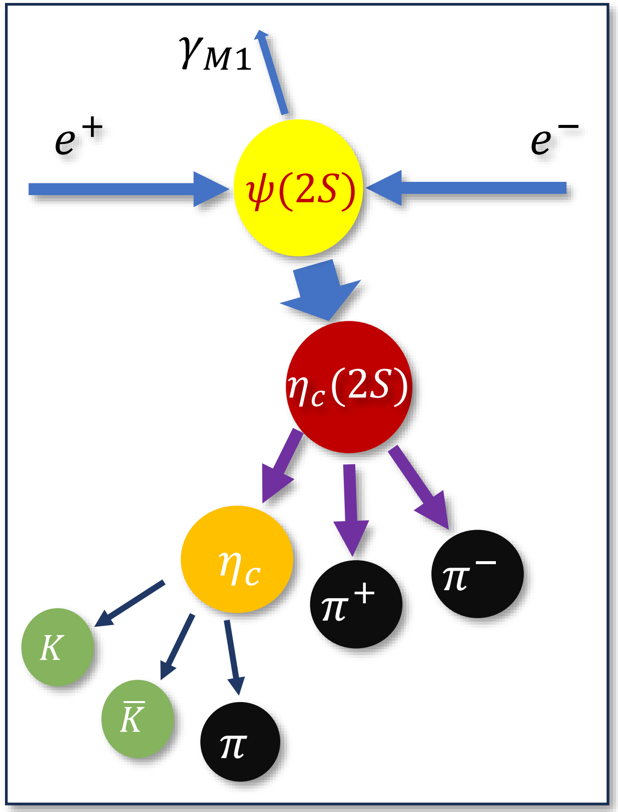
	Mass (MeV/c^2)	$\mathcal{B}(\psi(3686) \to \gamma\eta_c(2S))$($\times 10^{-4}$)	$\Gamma(\psi(3686) \to \gamma\eta_c(2S))$ (keV)
NR model [7]	3630	7.14 ± 0.19	0.21
GI model [7]	3623	5.80 ± 0.16	0.17
Meson loop correction[8]	N/A	2.72 ± 1.00	0.08 ± 0.03
Light-front quark model[9]	3637	3.9	0.11
Other models [10]	N/A	0.6–36.0	N/A

1. **Favor all model within 2σ**
2. **$Br(\eta_c(2S) \to K\bar{K}\pi)$ limit the precision and more precise result is needed!**

[6] Chin. Phys. C 46 071001 (2022)
[7] Phys. Rev. D 72,054026 (2005)
[8] Phys. Lett. B 670, 55 (2008)
[9] Eur. Phys. J. A 48, 66 (2012).
[10] arXiv:0909.2812.

$\eta_c(2S) \to \pi^+\pi^-\eta_c/\pi^+\pi^-K_sK^\pm\pi^\mp$

PRD 109, 072017 (2024)

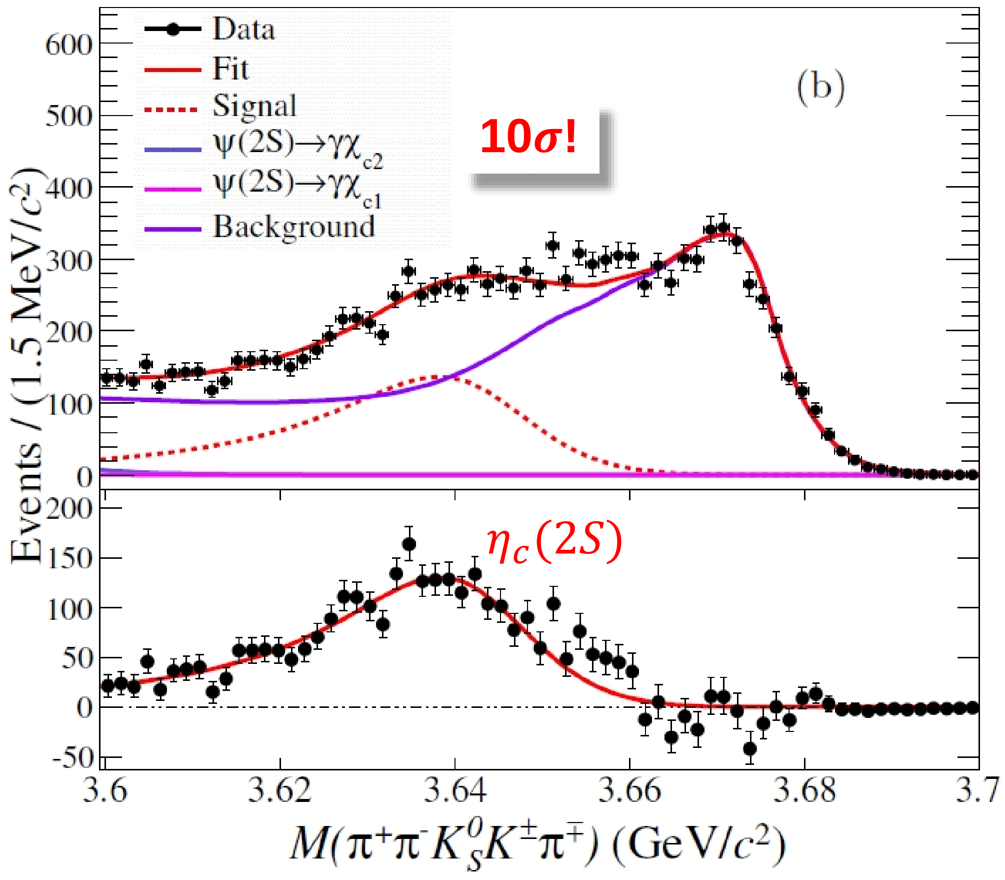


1. Assuming same linear dependence q^2 (squared mass of pion pair) between $\psi(2S) \to \pi^+\pi^- J/\psi$ and $\eta_c(2S) \to \pi^+\pi^-\eta_c$, Refs.[11] estimate $B(\psi(2S) \to \gamma\eta_c(2S)) \times B(\eta_c(2S) \to \pi^+\pi^-\eta_c) \sim 3.5 \times 10^{-5}$

2. Additional suppression for $Br(\eta_c(2S) \to \pi^+\pi^-\eta_c)$ from stronger chromo-magnetic interaction may exist [12].

3. Experient result is important to test theories and $B(\psi(2S) \to \gamma\eta_c(2S)) \times B(\eta_c(2S) \to \pi^+\pi^-\eta_c)$ is determined to be 2.21×10^{-5} @ 90% C.L..

First observation!



For the first time

$\mathcal{B}(\eta_c(2S) \to \pi^+\pi^- K_S^0 K^\pm\pi^\mp) = (1.33 \pm 0.11 \pm 0.4 \pm 0.95)$ %

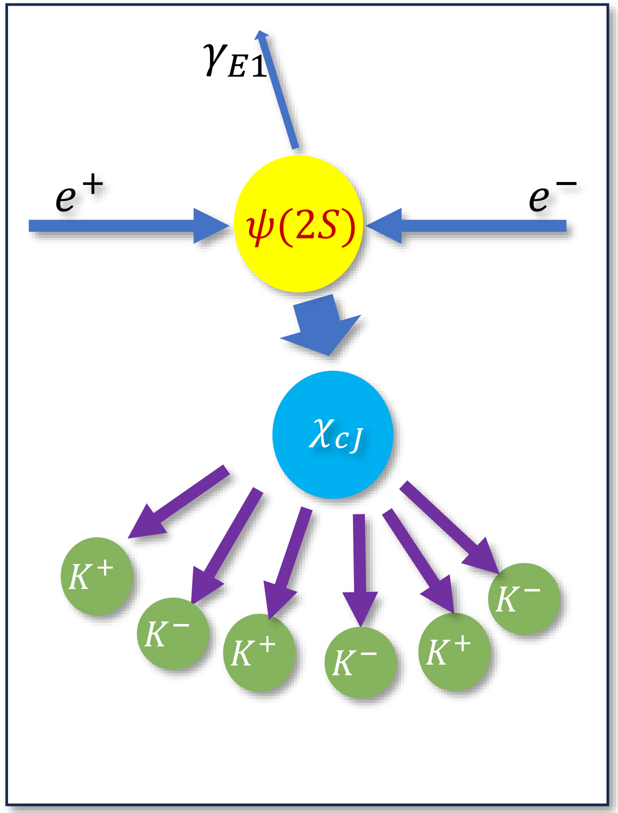
1. Our result favor these two theories.
2. New decay channel of $\eta_c(2S)$ hepl us understand it better.

NB The sum of $Br(\eta_c(2S))$ is ~ 6%!

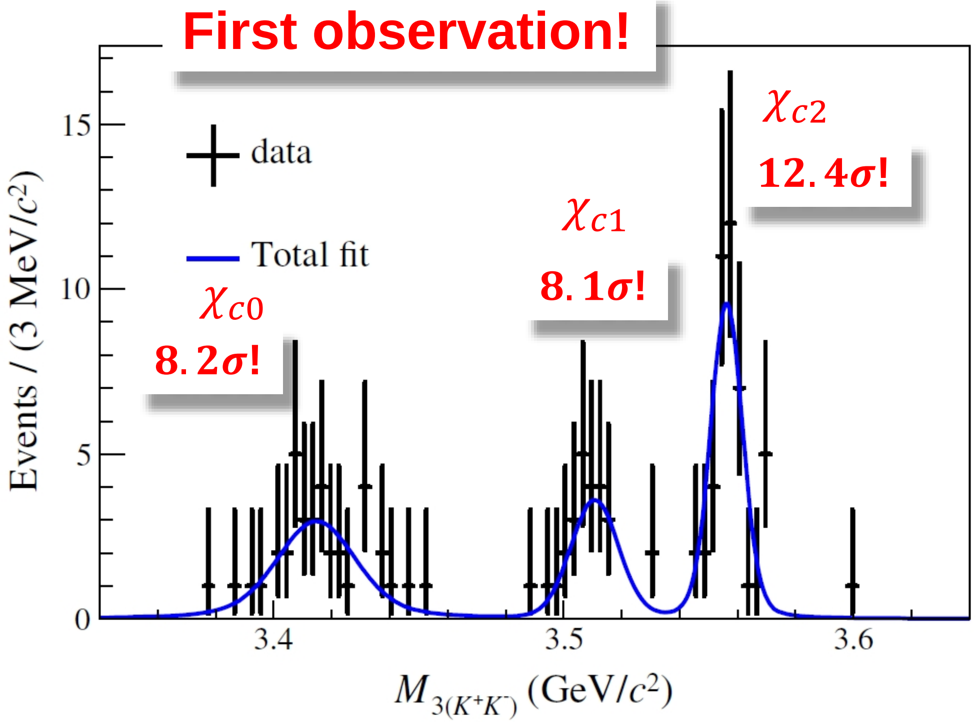
[11] Mod. Phys. Lett. A 17, 1533 (2002)
[12] Phys. Rev. D 74, 054022 (2006)

$\chi_{cJ} \to 3(K^+K^-)$

PRD 109, 072016 (2024)



6 s or $\bar{s}$ quark in the final state!



For the first time

- ✓ $Br(\chi_{c0} \to 3(K^+K^-)) = (10.7 \pm 1.8 \pm 1.1) \times 10^{-6}$
- ✓ $Br(\chi_{c1} \to 3(K^+K^-)) = (4.2 \pm 0.9 \pm 0.5) \times 10^{-6}$
- ✓ $Br(\chi_{c2} \to 3(K^+K^-)) = (7.2 \pm 1.1 \pm 0.8) \times 10^{-6}$

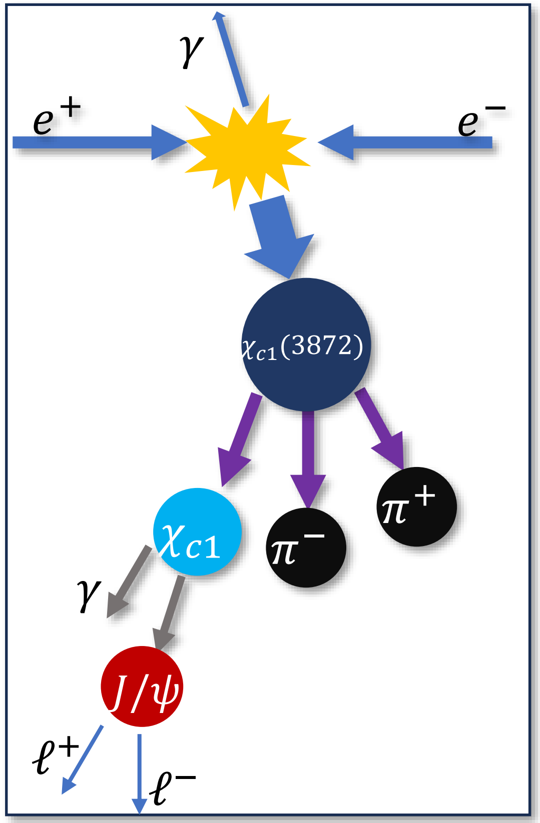
1. **Discrepancies between theory and experiment are observed [13-15].**
2. **Exclusive χ_{cJ} hadronic decays are desirable.**
3. **Deepen the understanding about the decay mechanisms of χ_{cJ}.**

[13] Eur. Phys. J. A 23,129 (2005).
[14] Phys. G 38, 035007 (2011).
[15] Eur. Phy. J. C 14, 643 (2000).

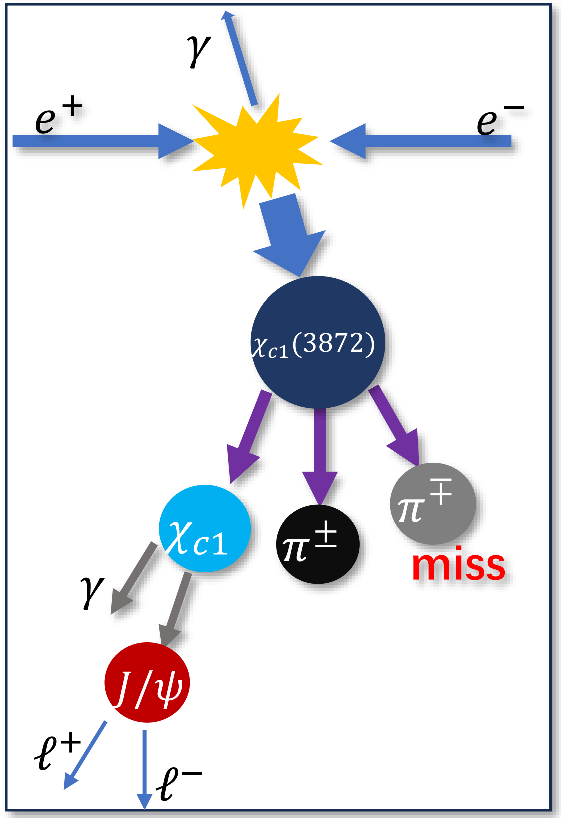
$\chi_{c1}(3872) \to \pi^+\pi^-\chi_{c1}$

PRD 109, L071101 (2024)

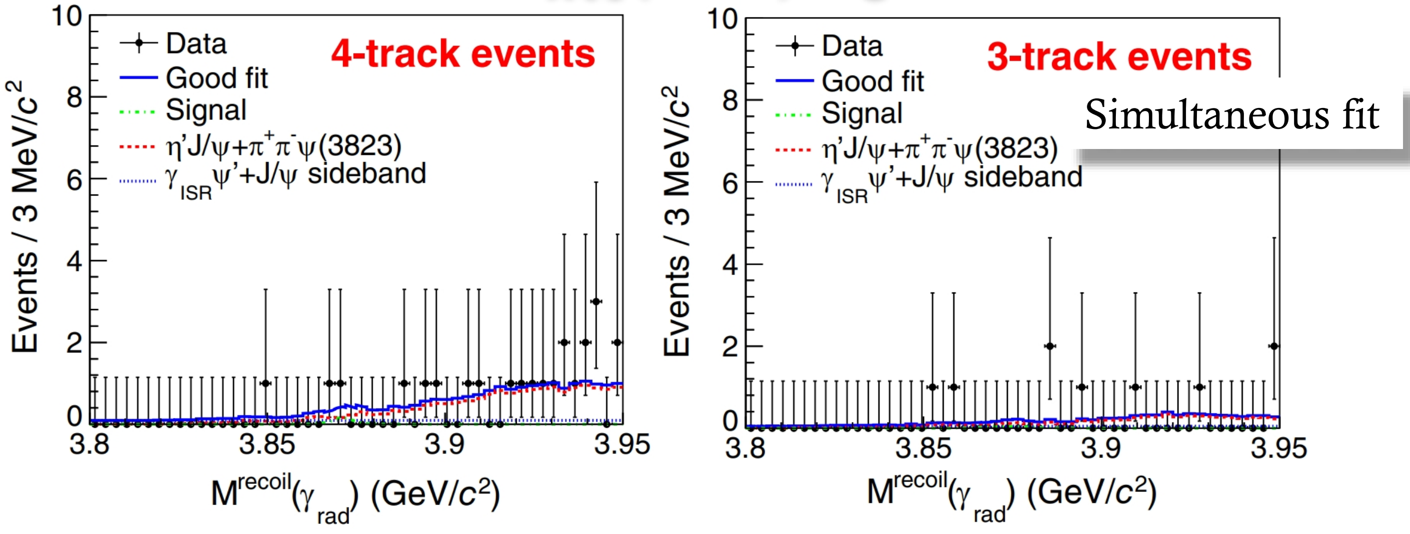
1. Full reconstruction



2. Partial reconstruction



No $\chi_{c1}(3872)$ signal!



Our result

$$\frac{\Gamma[\chi_{c1}(3872)\to\chi_{c1}\pi^0]}{\Gamma[\chi_{c1}(3872)\to\chi_{c1}\pi^+\pi^-]} > 5$$

Theoretical prediction:

$\chi_{c1}(2P)$:

$$\frac{\Gamma(2^3P_1\to\chi_{c1}\pi^0)}{\Gamma(2^3P_1\to\chi_{c1}\pi^+\pi^-)} \approx 0.04\ [17]$$

$\bar{D}^0 D^{*0}$ bound state: **Favor!**

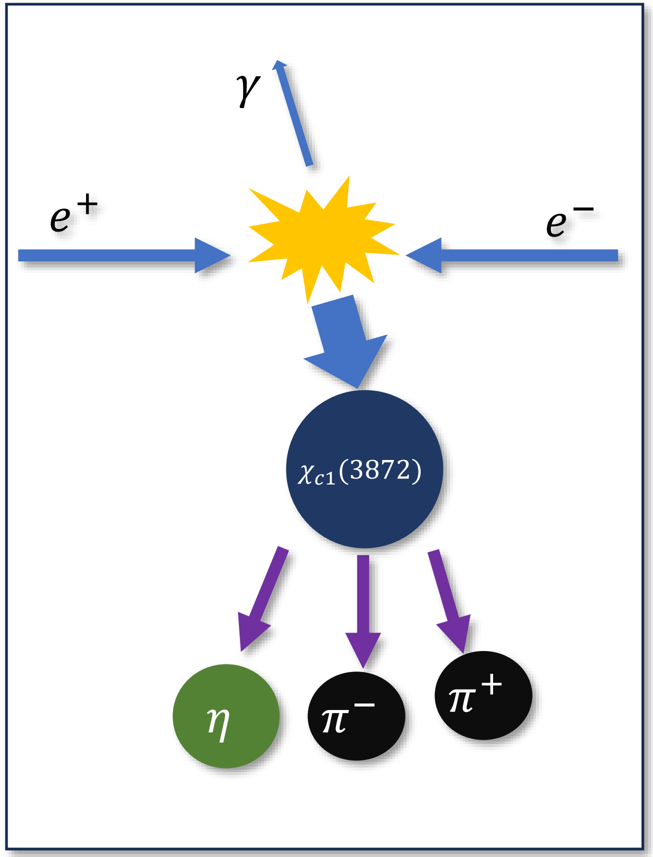
$$\left(\frac{\mathrm{Br}[X(3872)\to\chi_{c1}\pi^+\pi^-]}{\mathrm{Br}[X(3872)\to\chi_{c1}\pi^0]}\right)_{\mathrm{LO}} \approx \mathcal{O}(10^{-3}).\ [18]$$

1. $\chi_{c1}(3872) \to \pi^0\chi_{c1}$ **have been observed at BESIII [16]**
2. **Favoring the non-conventional charmonium [18]**

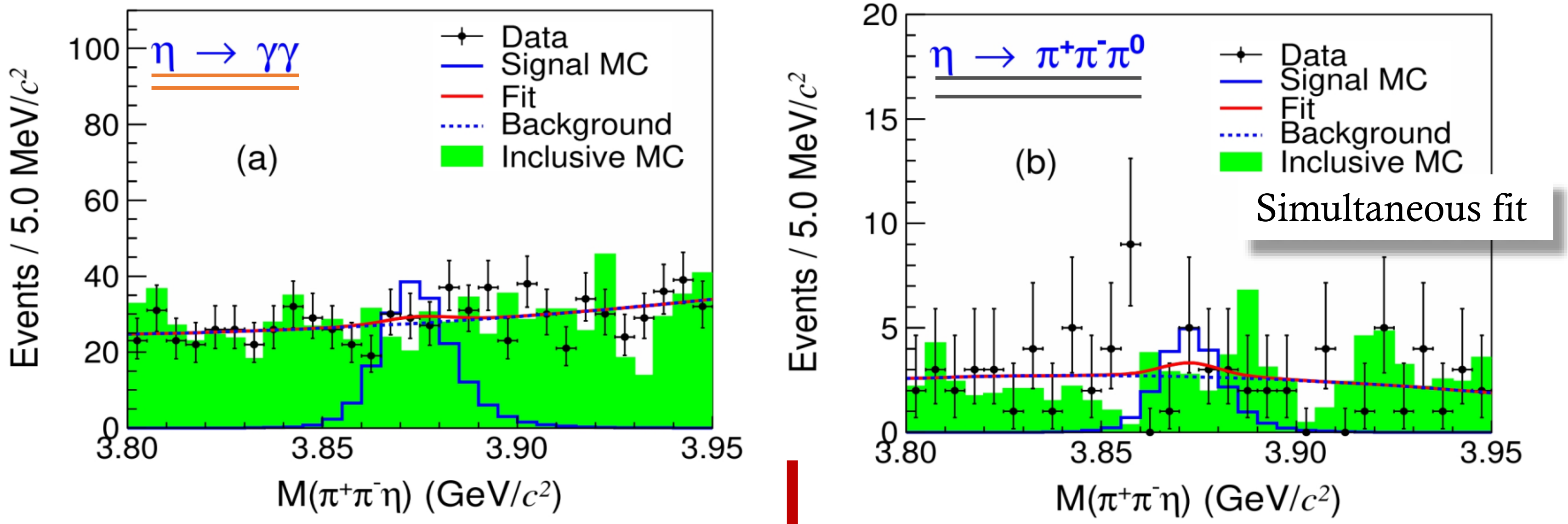
[16] Phys. Rev. Lett. 122, 202001 (2019).
[17] Phys. Rev. D 77, 014013 (2008).
[18] Phys. Rev. D 78, 094019 (2008).

$\chi_{c1}(3872) \to \pi^+\pi^-\eta$

PRD 109, L011102 (2024)



No $\chi_{c1}(3872)$ signal!



$$R = \frac{Br[\chi_{c1}(3872) \to \pi^+\pi^-\eta]}{Br[\chi_{c1}(3872) \to \pi^+\pi^- J/\psi]} < 0.12$$

$$Br[\chi_{c1}(3872) \to \pi^+\pi^-\eta] < 0.6\%$$

Assuming $\chi_{c1}(3872)$ is a $\bar{D}D^*$ molecule state, theoretical calculations show the light hadron decay BF ~(1-10)%[19] (our result <1%).

[19] Phys. Rev. D 106, 074015 (2022).

Summary

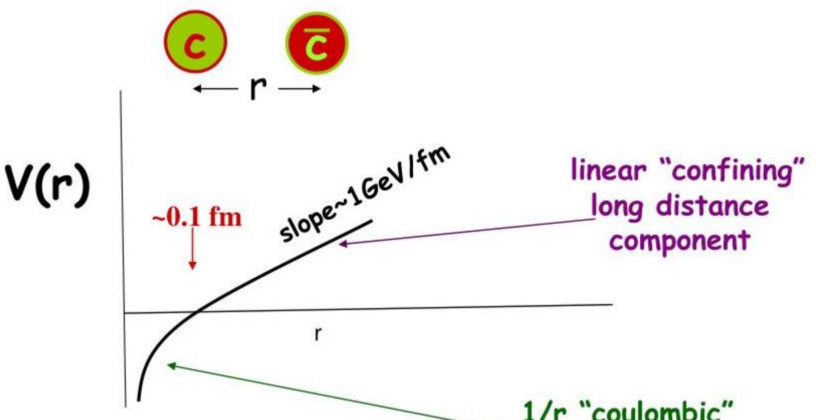
- BESIII has achieved significant progress in the study of charmonium(-like) decay
  - ※ First observation of $\psi(2S) \to \Omega^- K^+ \bar{\Xi}^0 + c.c$
  - ※ Update the precision of $\psi(2S) \to \gamma\eta_c(2S)$ with $\eta_c(2S) \to K\bar{K}\pi$
  - ※ First observation of $\eta_c(2S) \to \pi^+\pi^- K_s K^\pm \pi^\mp$ and give the upper limit of $\eta_c(2S) \to \pi^+\pi^-\eta_c$
  - ※ First observation of $\chi_{cJ} \to 3(K^+K^-)$
  - ※ Give the upper limits of $\chi_{c1}(3872) \to \pi^+\pi^-\chi_{c1}$ and $\chi_{c1}(3872) \to \pi^+\pi^-\eta$
- The largest datasets of $\boldsymbol{c\bar{c}}$ vector states collected by BESIII provide the power to study the $\psi(2S), \eta_c(2S)$, $\chi_{cJ}(1P)$ states and their decays with unprecedented precision.
- Also datasets above the $\boldsymbol{D\bar{D}}$ threshold can shed new light on charmonium-like state decays and hint at possible connections between XYZ states and the conventional charmonium.

Thanks for your attention!

Back up

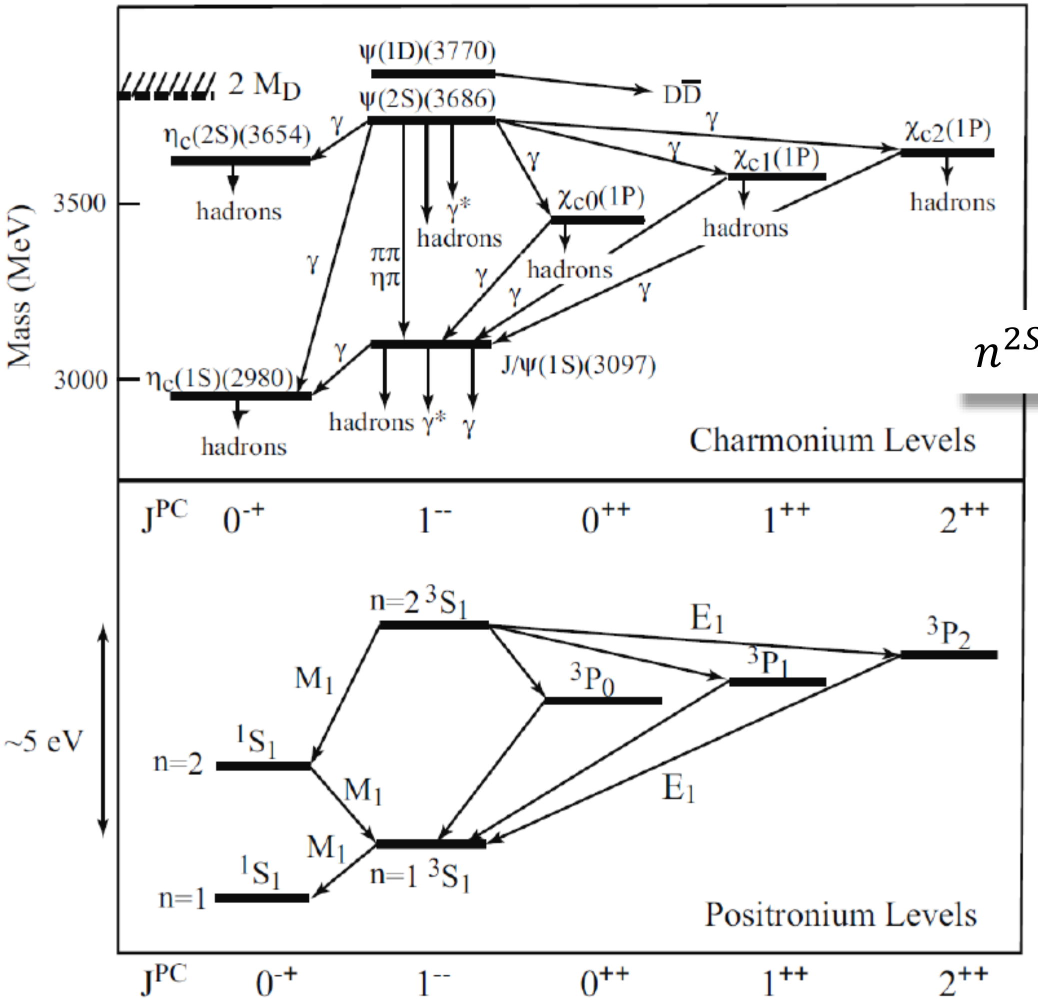
Introduction

"Cornell" potential (Coulomb-like potential)



2 parameters:
slope & intercept

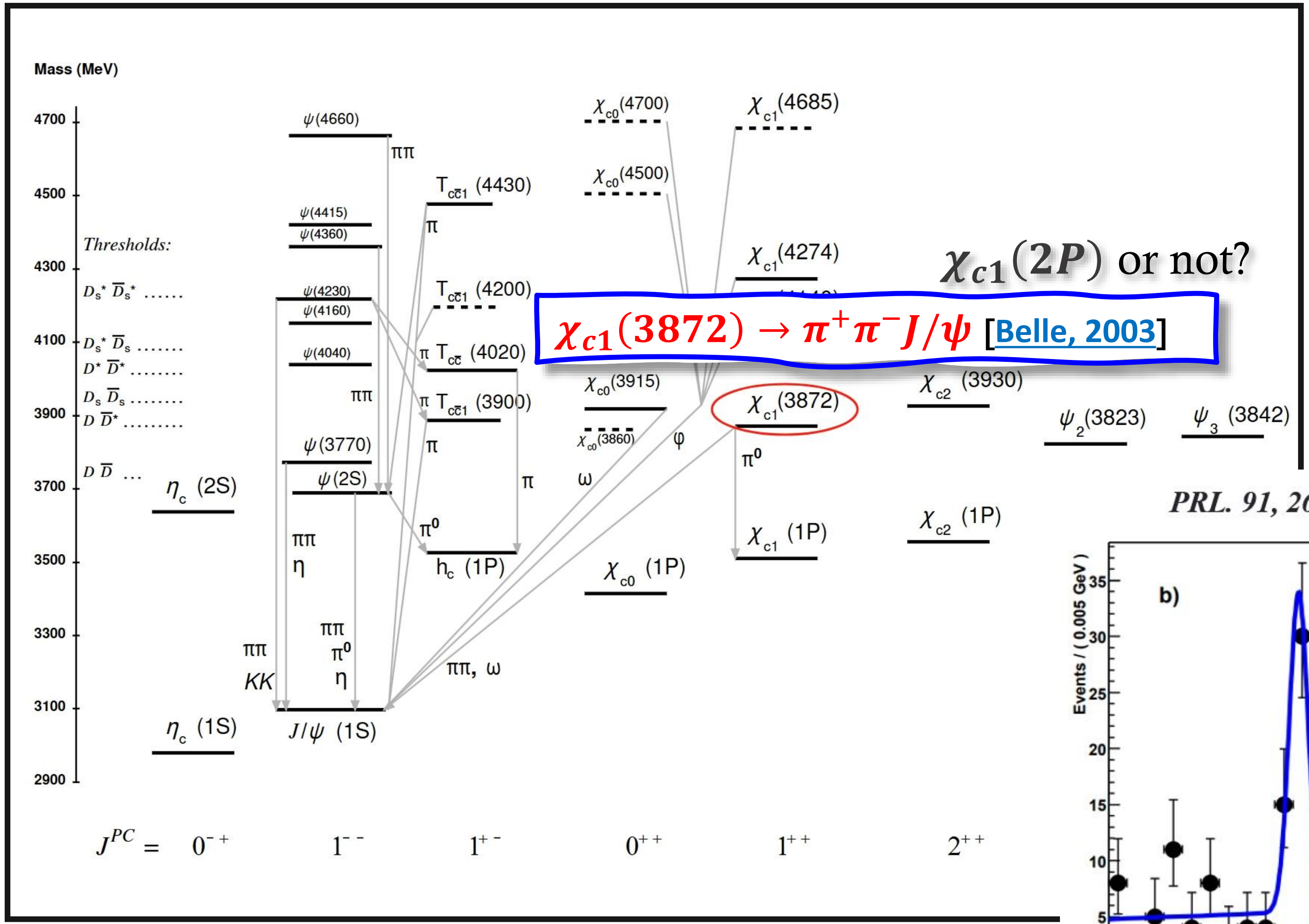
$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + kr$$

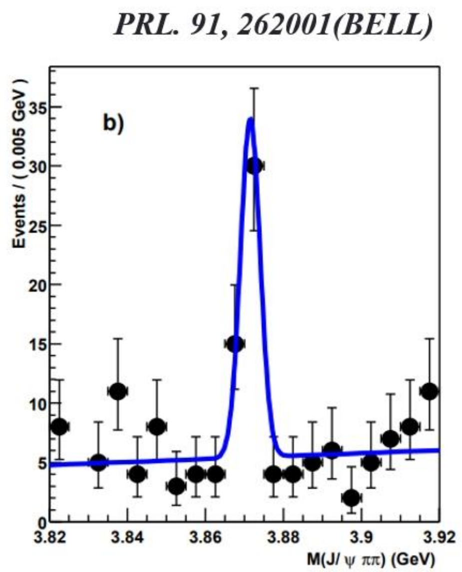


$n^{2S+1}L_J$

Charmoniumlike $\chi_{c1}(3872)$

PTEP 2022, 083C01





Main features:

1. Narrow width ($\Gamma = 1.19 \pm 0.21$ MeV)
2. Mass is close to $D^0\bar{D}^{*0}$ threshold
3. $J^{PC} = 1^{++}$
4. Obvious isospin-violation effect ($\chi_{c1}(3872) \to \rho J/\psi$)

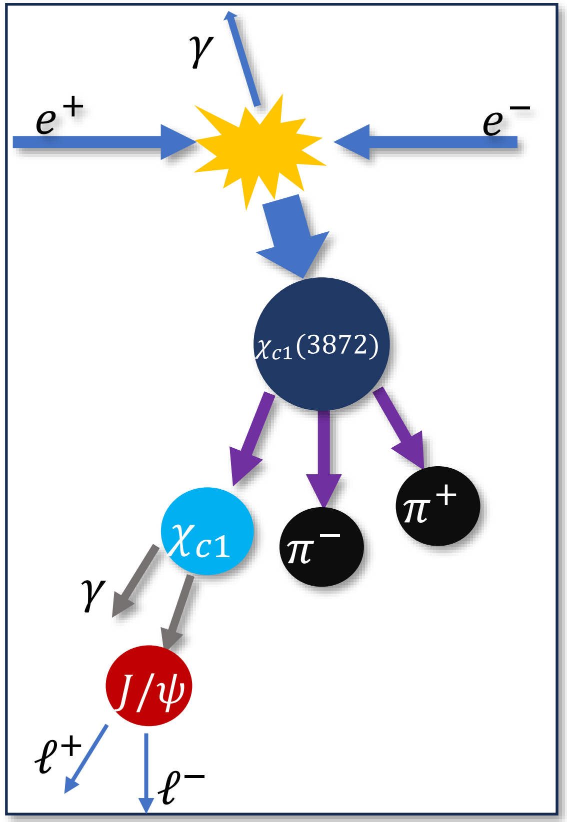
Well-established decay channels

1. $\chi_{c1}(3872) \to \pi^+\pi^- J/\psi$
2. $\chi_{c1}(3872) \to D^0\bar{D}^{*0}$
3. $\chi_{c1}(3872) \to \gamma J/\psi$
4. $\chi_{c1}(3872) \to \pi^0 \chi_{c1}$
5. $\chi_{c1}(3872) \to \omega J/\psi$

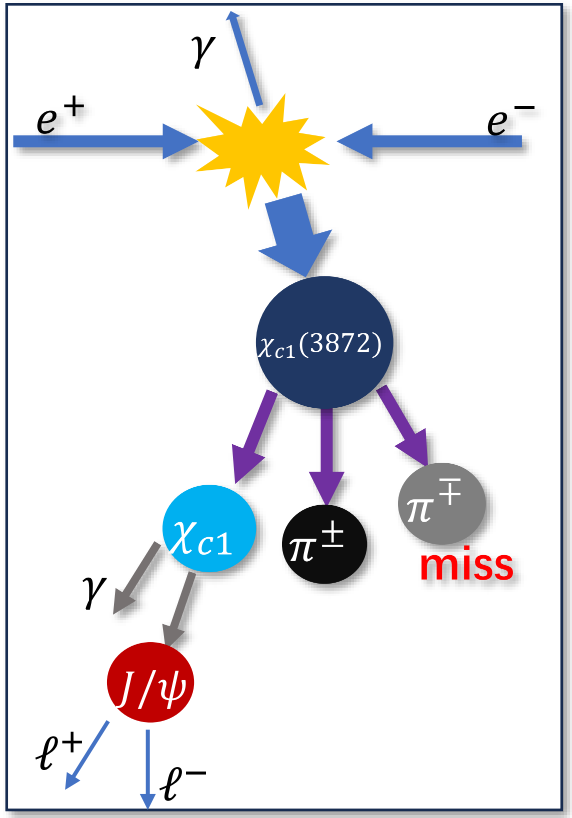
$\chi_{c1}(3872) \to \pi^+\pi^-\chi_{c1}$

PRD 109, L071101 (2024)

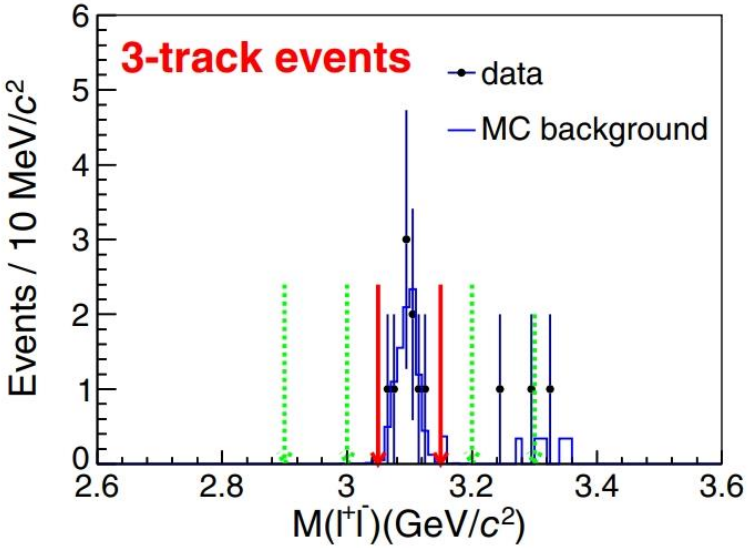
1. Full reconstruction

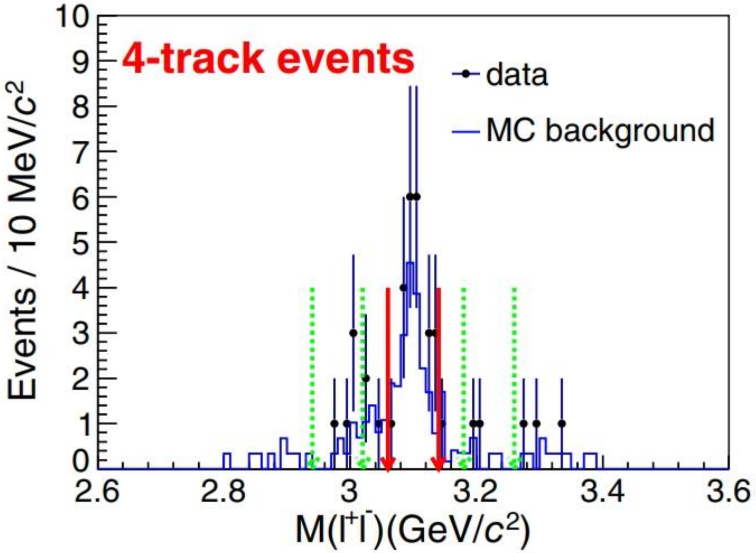


2. Partial reconstruction



- Kinematic constraint
- Well controlled background
- Improved statistic & precision



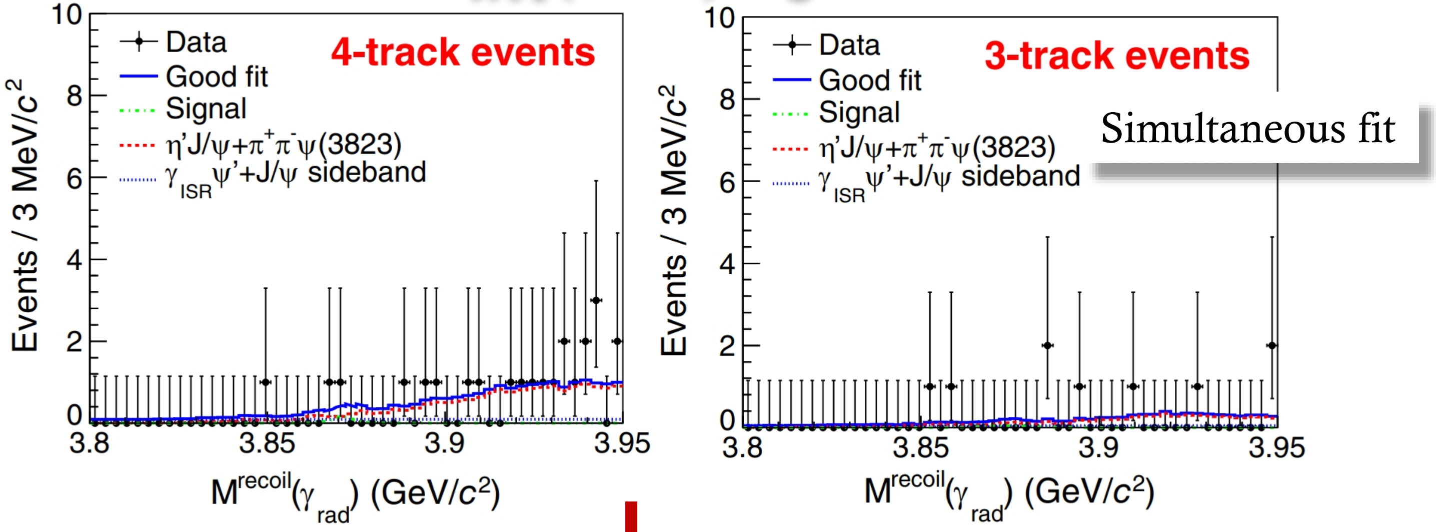


Clean J/ψ signal but mainly from expected background

$\chi_{c1}(3872) \to \pi^+\pi^-\chi_{c1}$

PRD 109, L071101 (2024)

No $\chi_{c1}(3872)$ signal!



$$\mathcal{R} := \frac{\mathcal{B}(\chi_{c1}(3872) \to \pi^+\pi^-\chi_{c1})}{\mathcal{B}(\chi_{c1}(3872) \to \pi^+\pi^- J/\psi)} < 0.18$$

$$\frac{\Gamma[\chi_{c1}(3872) \to \chi_{c1}\pi^0]}{\Gamma[\chi_{c1}(3872) \to \chi_{c1}\pi^+\pi^-]} > 5$$

Push new theoretical result!

More interaction between theory and experiment needed!

Theoretical prediction:

$\chi_{c1}(2P)$:

No $\chi_{c1}(3872)$ signal! [9]

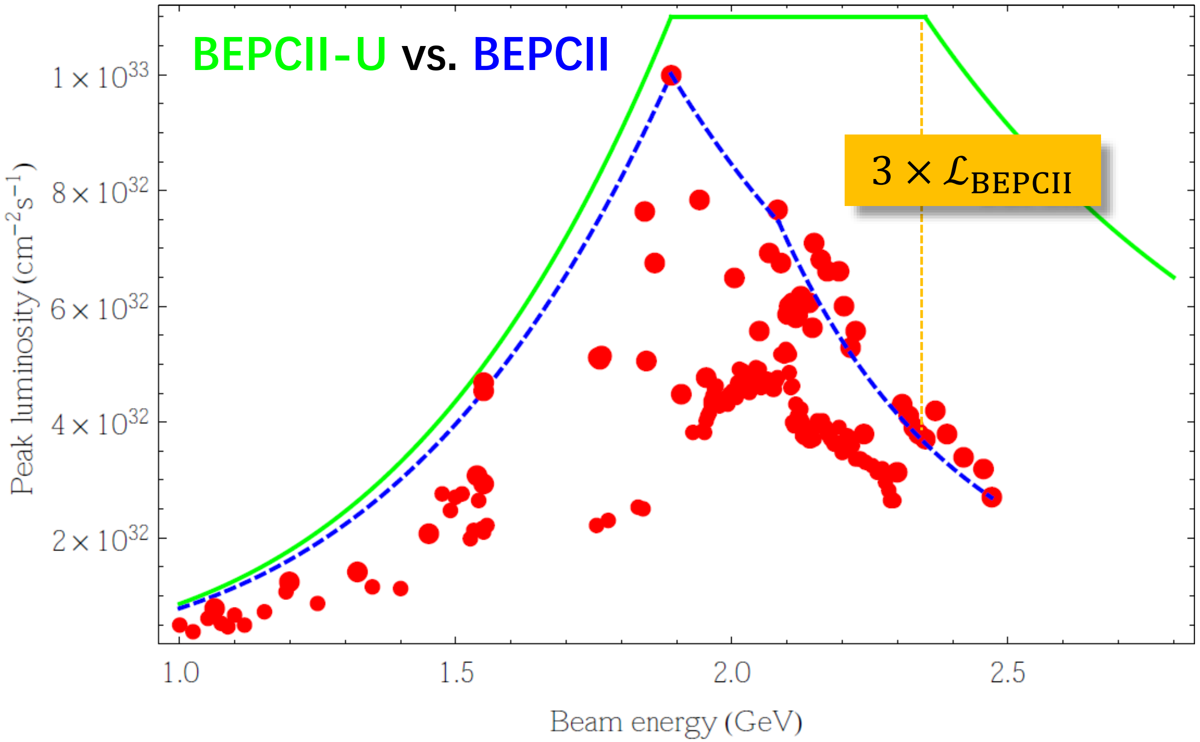
$\bar{D}^0 D^{*0}$ bound state: **Favor!**

$$\left(\frac{\mathrm{Br}[X(3872) \to \chi_{c1}\pi^+\pi^-]}{\mathrm{Br}[X(3872) \to \chi_{c1}\pi^0]}\right)_{\mathrm{LO}} \approx \mathcal{O}(10^{-3}).$$ [10]

1. Pionic transitions of the spin-2 partner of X(3872) to χ_{cJ} [11]
2. Tentative estimates of $B(X(3872) \to \pi^0\pi^0\chi_{c1})$ and $B(X(3872) \to \pi^+\pi^-\chi_{c1})$[12]
3. Predicting isovector charmonium-like states from X(3872) properties [13]

[9] S. Dubynskiy and M. B. Voloshin, Phys. Rev. D 77, 014013 (2008).
[10]S. Fleming and T. Mehen, Phys. Rev. D 78, 094019 (2008).
[11] arxiv:2406.01874
[12] arXiv:2405.09228
[13] arXiv:2404.11215

Summary & Prospect



- The BEPCII-U scheduled in the coming summer of this year
- Luminosity of BEPCII-U increased by a factor of 3 @ $\sqrt{s}$ = 4.7 GeV enabling efficient collection of XYZ data; $\sqrt{s}$ extends to 5.6 GeV; Commissioning in 2025
- Stay tuned for more exciting results from BESIII! BESIII is still Charming :)