New results on the X(3872) from BESIII

Xiantao Hou(On behalf of the BESIII Collaboration)

houxiantao@ihep.ac.cn

Institute of High Energy Physics, Chinese Academy of Sciences

QWG-2024 at IISER Mohali

contents

Motivation

Motivation

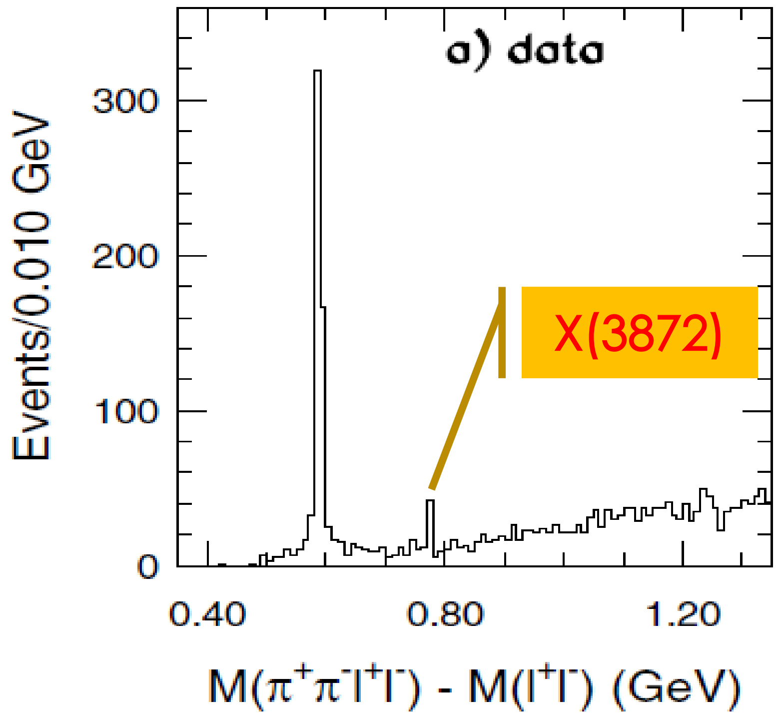
- Important properties:

- The X(3872) (the first unexpected charmonium) was first discovered at the Belle experiment in 2003 during the $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$ process.
  [Belle, Phys. Rev. Lett. 91, 262001 (2003)]

- $Q = m_{X(3872)} - m_{D^{*0}} - m_{\bar{D}^0} = (-0.04 \pm 0.09)$ MeV
  $\Gamma = (1.19 \pm 0.21)$ MeV
  [(Particle Data Group), PTEP 2022, 083C01 (2022)]

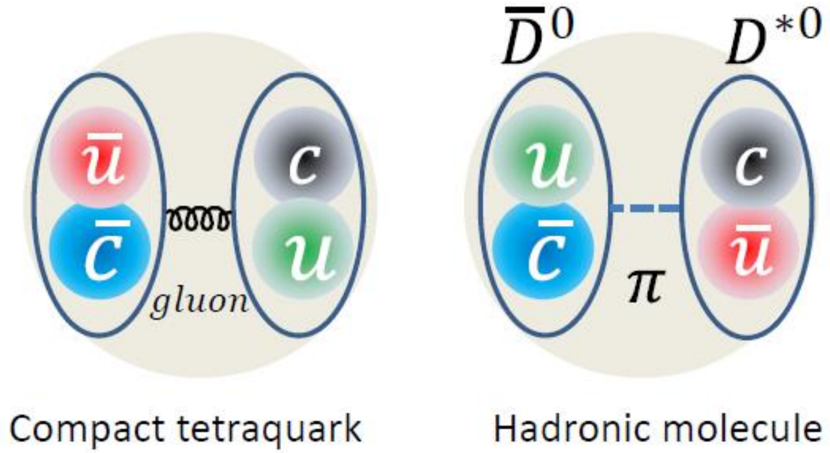
- $B(J/\psi\rho) \approx B(J/\psi\omega)$, isospin break.
  [LHCb, Phys. Rev. D 108 L011103, (2023)]

- Several possible explanations have been proposed to explain the properties of X(3872), including whether it may be a tetraquark or a hadronic molecule.



- Productions:

- $e^+e^- \to \gamma X(3872)$ (BESIII) , $B/B_s \to KX(3872)$ (Belle, Babar, LHCb, CMS), $\gamma\gamma^* \to X(3872)$ (Belle), Λ_b decays (LHCb), pp/p$\bar{\text{p}}$ collision "prompt"(LHCb, CDF, D0, ATLAS, CMS), new production mechanism?



Motivation

- Decays:

- Many experimental measurements have investigated the mass, width, spin-parity and decays of the X(3872). Over 30% decay mode of X(3872) is unknown.

[C. H. Li and C. Z. Yuan, PRD 100, 094003 (2019)]

- Still plenty of room to explore.

Decay mode	Branching fraction
$X(3872) \to \pi^+\pi^- J/\psi$	$(4.1^{+1.9}_{-1.1})\%$
$X(3872) \to D^{*0}\bar{D}^0 + \text{c.c.}$	$(52.4^{+25.3}_{-14.3})\%$
$X(3872) \to \gamma J/\psi$	$(1.1^{+0.6}_{-0.3})\%$
$X(3872) \to \gamma\psi(3686)$	$(2.4^{+1.3}_{-0.8})\%$
$X(3872) \to \pi^0\chi_{c1}$	$(3.6^{+2.2}_{-1.6})\%$
$X(3872) \to \omega J/\psi$	$(4.4^{+2.3}_{-1.3})\%$
$B^+ \to X(3872)K^+$	$(1.9 \pm 0.6) \times 10^{-4}$
$B^0 \to X(3872)K^0$	$(1.1^{+0.5}_{-0.4}) \times 10^{-4}$
$X(3872) \to \text{unknown}$	$(31.9^{+18.1}_{-31.5})\%$

- Search for X(3872) → light hadrons?

- $c\bar{c}$ → light hadrons(annihilate); molecule → light hadrons(?)
- Searching for light hadron final state may tell us more information about X(3872).

- Based on the assumption that X(3872) contains visible components of the $\chi_{c1}(2P)$, we search for the light hadron decay process of $X(3872) \to \pi^+\pi^-\eta$.

[N. Brambilla, S. Eidelman, C. Hanhart, A. Nefediev, C. P. Shen, C. E. Thomas, A. Vairo and C. Z. Yuan, Phys. Rept. 873 (2020), 1-154.]

Motivation

- Spin partner of X(3872)

☐ Degenerated spin partners with quantum numbers 0++, 1++ and 2++ in heavy quark limit.

[P. Colangelo, F. De Fazio and S. Nicotri, Phys. Lett. B 650, 166 (2007)]

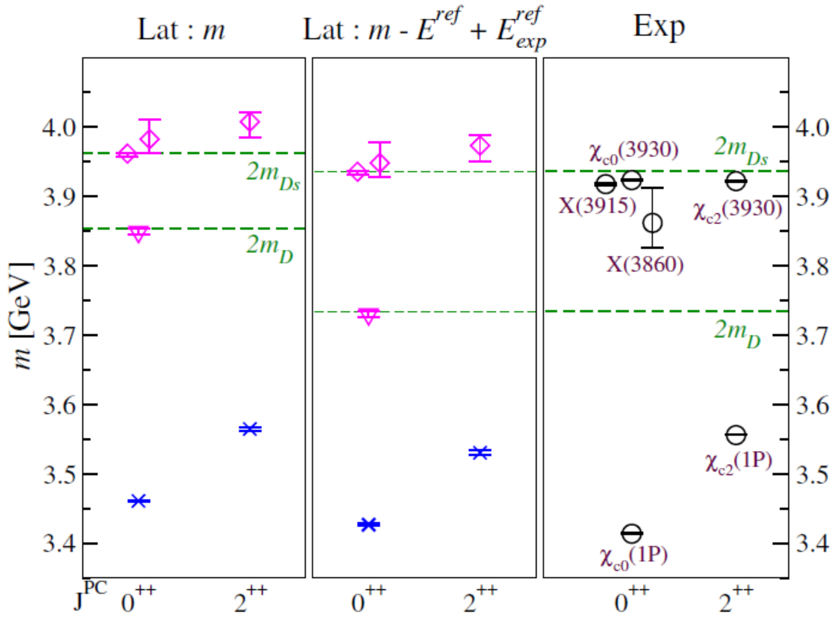
☐ The 0^{++} state(X(3700), a $D\bar{D}$ molecule, mass around 3720 MeV) is expected as a partner of X(3872) via heavy-quark symmetry arguments.

[J. Nieves and M. P. Valderrama, Phys. Rev. D 86, 056004 (2012)]

☐ A shallow $D\bar{D}$ bound state was also found in LQCD in the study of the coupled-channel $D\bar{D} - D_s\bar{D}_s$ scattering. Binding energy : m − $2m_D$ = $-0.4^{+3.7}_{-5.0}$ MeV

☐ Various strategies for the experimental search for the X(3700) in exclusive decays, $\psi(3770) \to \gamma\eta\eta'$(dominant decay), $\psi(3770) \to \gamma D^0\bar{D}^0$ and $B^{0(+)} \to K^{0(+)}D^0\bar{D}^0$.

[C. W. Xiao and E. Oset, Eur. Phys. J. A 49, 52 (2013)]
[L. Dai, G. Toledo and E. Oset, Eur. Phys. J. C 80, 510 (2020)]
[L. R. Dai, J. J. Xie and E. Oset, Eur. Phys. J. C 76, 121 (2016)]



[S. Prelovsek, S. Collins, D. Mohler, M. Padmanath and S. Piemonte, JHEP 06, 035 (2021)]

Motivation

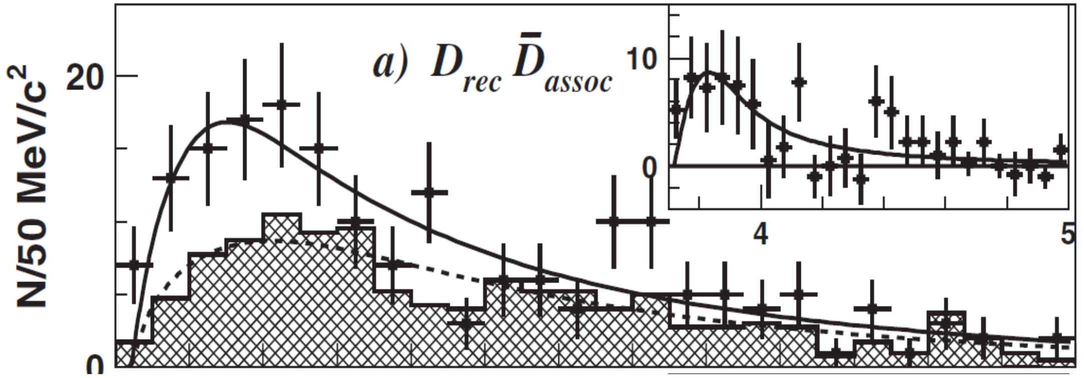
- Experimentally, some hints of the existence of X(3700) have been reported.

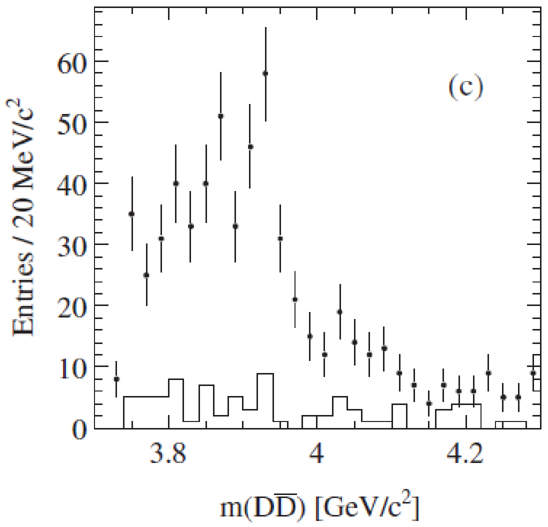
  - In the $e^+e^- \to J/\psi D\bar{D}$ reaction (Belle) indicates that there may be some evidence for such a bound state, with M_X =3723 MeV.

    [Belle, Phys. Rev. Lett. 100, 202001(2008)]
    [D. Gamermann and E. Oset, Eur. Phys. J. A 36, 189 (2008)]

  - A hint of enhancement just above the $D\bar{D}$ threshold was both seen by the BaBar and Belle Collaborations in the reaction $\gamma\gamma \to D\bar{D}$

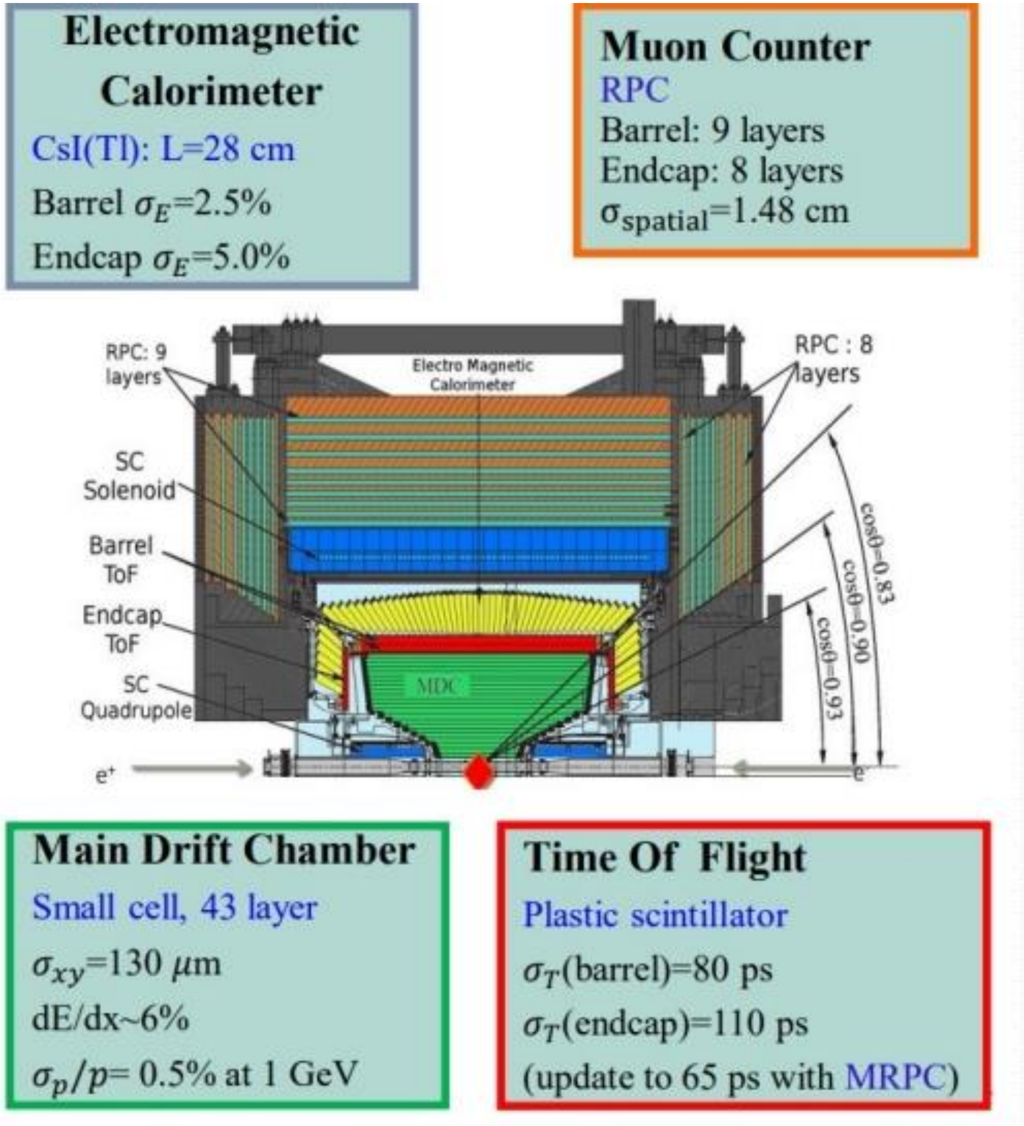
    [BaBar, Phys. Rev. D 81, 092003 (2010)]
    [Belle, Phys. Rev. Lett. 96, 082003 (2006)]

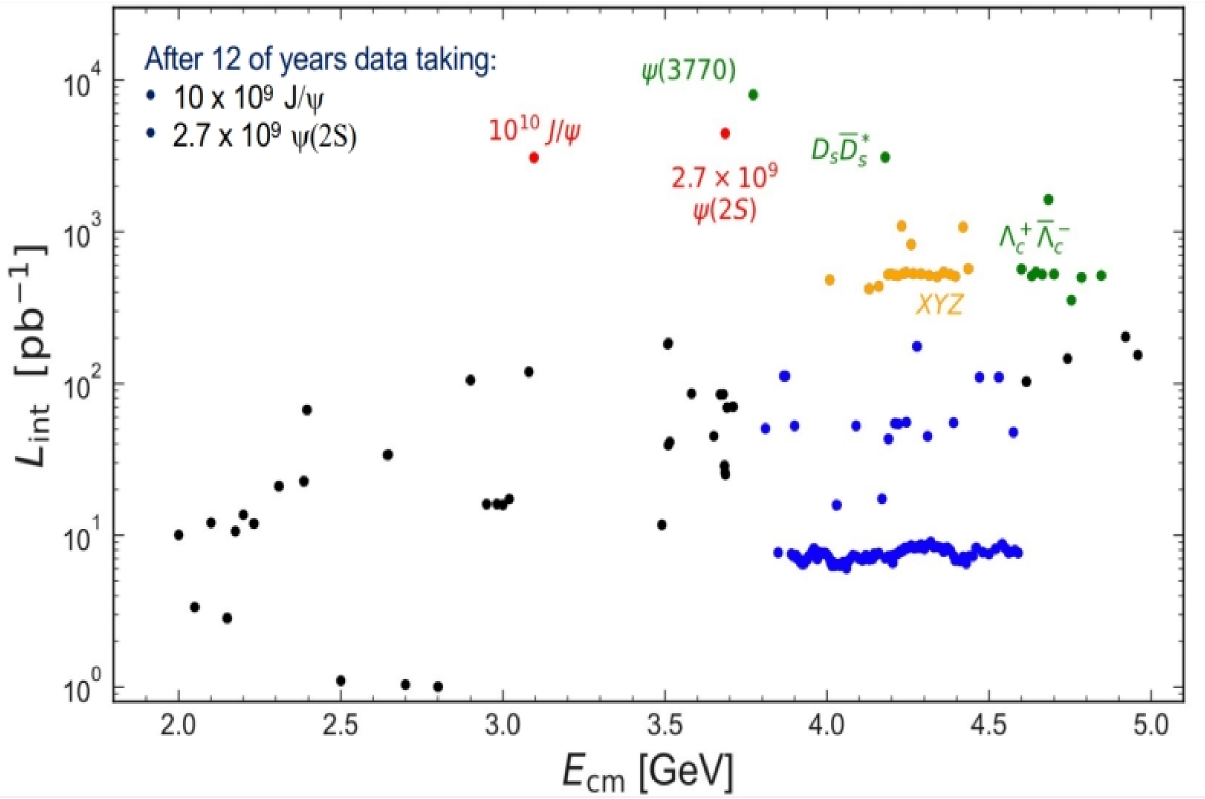




BESIII experiment

BESIII experiment





- ◆ World largest J/ψ, ψ(2S), ψ(3770) data sample
- ◆ More than 37fb^{-1} of data taken between 2 and 4.95GeV

Recent results on the $X(3872)$ from BESIII

A coupled channel analysis of the $X(3872)$ lineshape

arXiv:2309.01502
Submitted to PRL

Two important decay modes:

- $\pi^+\pi^- J/\psi$: Pure charged daughter particles, higher selection efficiency, lower background, narrower peak.
- $D^{*0}\bar{D}^0 + c.c.$: Major decay mode, the opening threshold will strongly distort the lineshape.

Production: $e^+e^- \to Y(4230) \to \gamma X(3872)$

$J/\psi \to e^+e^-/\mu^+\mu^-$

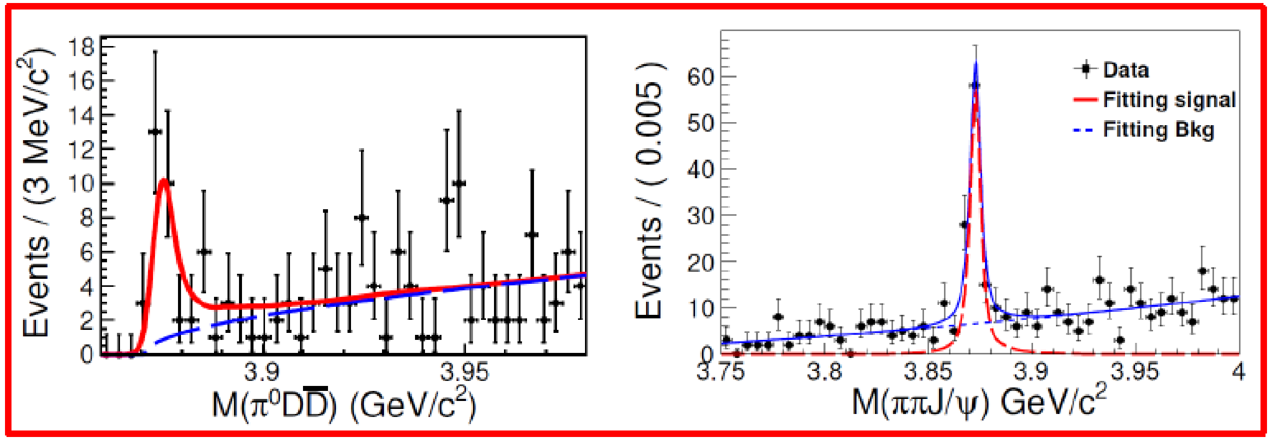
$D^0 \to K^-\pi^+, K^-\pi^+\pi^0, K^-2\pi^+\pi^-$

Mass resolutions

- $\pi^+\pi^- J/\psi$: ~ 2 MeV
- $D^0\bar{D}^0\pi^0$: ~ 0.8 MeV

[Chunhua Li, Chang-Zheng Yuan, PRD 100(2019) 094003]

Parameter index	Decay mode	Branching fraction
1	$X(3872) \to \pi^+\pi^- J/\psi$	$(4.1^{+1.9}_{-1.1})\%$
2	$X(3872) \to D^{*0}\bar{D}^0 + c.c$	$(52.4^{+25.3}_{-14.3})\%$
3	$X(3872) \to \gamma J/\psi$	$(1.1^{+0.6}_{-0.3})\%$
4	$X(3872) \to \gamma\psi(3686)$	(2.[illegible]$^{+1.3}_{-0.8}$)%



[BES III, PRL 122, 232002(2019)], [BES III, PRL 124, 242001(2020)]

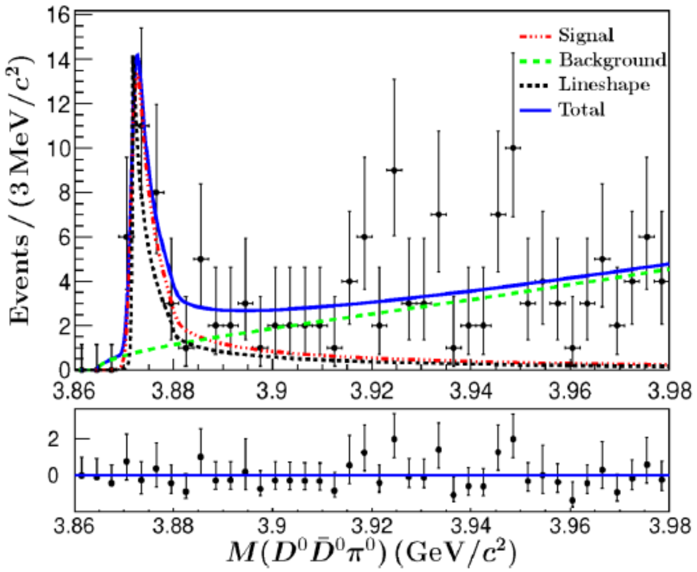
We have well established samples for both modes, we can perform a simultaneous fit

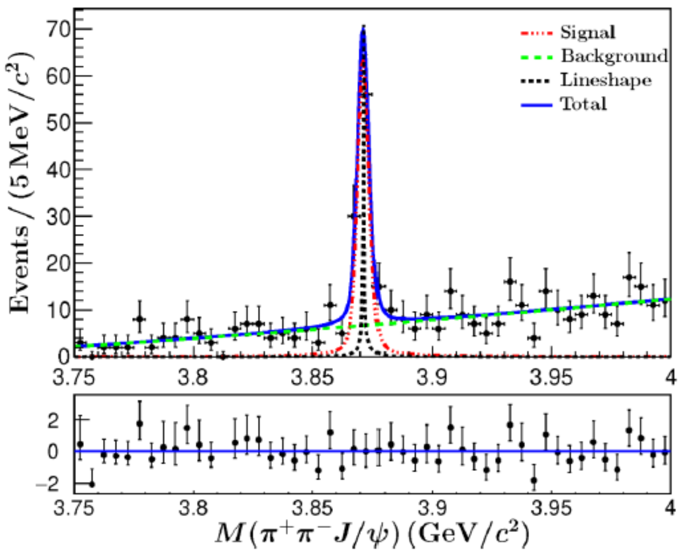
A coupled channel analysis of the $X(3872)$ lineshape

Key features:

- Model independent
- Including the $D^*\bar{D}$ self energy terms
- Including the width of D^*
- Including the coupled channel effect
- **Fit parameters**: g, $\Gamma_{\pi^+\pi^- J/\psi}$, M_X

$$g = 0.16 \pm 0.10^{+1.12}_{-0.11}$$
$$\Gamma_0 = (2.67 \pm 1.77^{+8.01}_{-0.82})\ \text{MeV}$$
$$M_X = (3871.63 \pm 0.13^{+0.06}_{-0.05})\ \text{MeV}$$





Large systematic uncertainty from $\Gamma_{unknow}/\Gamma_{\pi^+\pi^- J/\psi}$

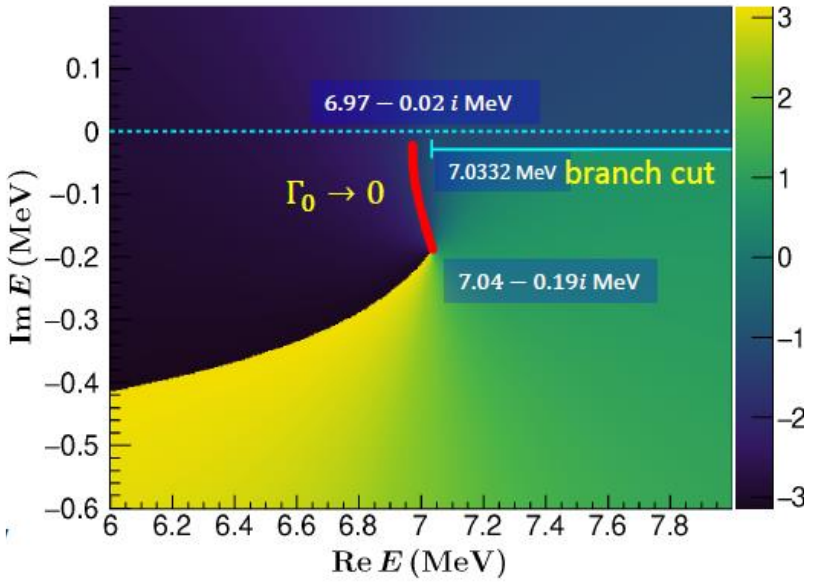
$$\Gamma_0 = \Gamma_{\pi\pi J/\psi} + \Gamma_{known} + \Gamma_{unknown}$$

$\omega J/\psi$, $\gamma J/\psi$, $\gamma\psi'$, $\pi^0\chi_{c1}$

Two poles are found:

$$E_{\text{I}} = (7.04 \pm 0.15^{+0.07}_{-0.08}) + (-0.19 \pm 0.08^{+0.14}_{-0.19})i\ \text{MeV}$$
$$E_{\text{II}} = (0.26 \pm 5.74^{+5.14}_{-38.32}) + (-1.71 \pm 0.90^{+0.60}_{-1.96})i\ \text{MeV}$$

E_{I} is much closer to the threshold, should play a dominant role in the X(3872) confinement mechanism



$M(D^0\bar{D}^{*0}) - M(D^0\bar{D}^0\pi^0) = 7.0332$ MeV $\quad E_X = M_X - (m_{D^0} + m_{\bar{D}^0} + m_{\pi^0})$

A coupled channel analysis of the $X(3872)$ lineshape

- Near the threshold, the scattering amplitude can be expanded as the power series of the momentum $k = \sqrt{2\mu(E - E_R)}$ (Effective Range Expansion, ERE)
- S-Wave $f^{-1}(E) \sim \frac{1}{a} + \frac{r_e}{2}k^2 - ik + \mathcal{O}(k^4)$

- ERE parameters
  - a: scattering length
  - r_e: effective range

In the limit of $\Gamma_0 \to 0$ and stable D^*, the ERE parameters are determined:

- $a = (-16.5^{+7.0}_{-27.6}{}^{+5.6}_{-27.7})$ fm
- $r_e = (-4.1^{+0.9}_{-3.3}{}^{+2.8}_{-4.4})$ fm

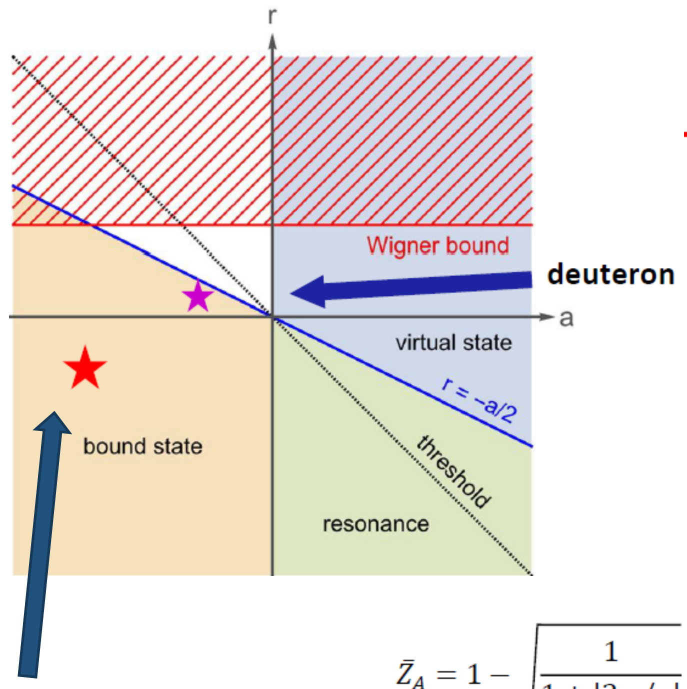
[S. Weinberg, Phys. Rev. 137, B672 (1965)]

$$a = -\frac{2(1-Z)}{(2-Z)}\frac{1}{\gamma} + \mathcal{O}(\beta^{-1})$$
$$r_e = -\frac{Z}{1-Z}\frac{1}{\gamma} + \mathcal{O}(\beta^{-1})$$

Z: field renormalization constant
- $Z = 0$: pure bound (composite) state
- $Z = 1$: pure elementary state

$\beta^{-1} \approx \frac{1}{m_\pi} \approx 1.4$ fm, for both deuteron and the $X(3872)$

$\gamma = \sqrt{2\mu E_b}$



$\bar{Z}_A = 1 - \sqrt{\frac{1}{1 + |2r_e/a|}}$

[Eur.Phys.J.A 57 (2021) 3, 101]

	X(3872)	deuteron
Nearby threshold	$D^{*0}\bar{D}^0$	$p\,n$
a	-16.5 fm	-5.41 fm
r_e	-4.1 fm	1.75 fm
Range correction	negligible	important for r_e
Z	≈ 0.18	-
$\lvert r_e/a \rvert$	0.25	0.32
$\bar{Z}_A$	0.18	0.22

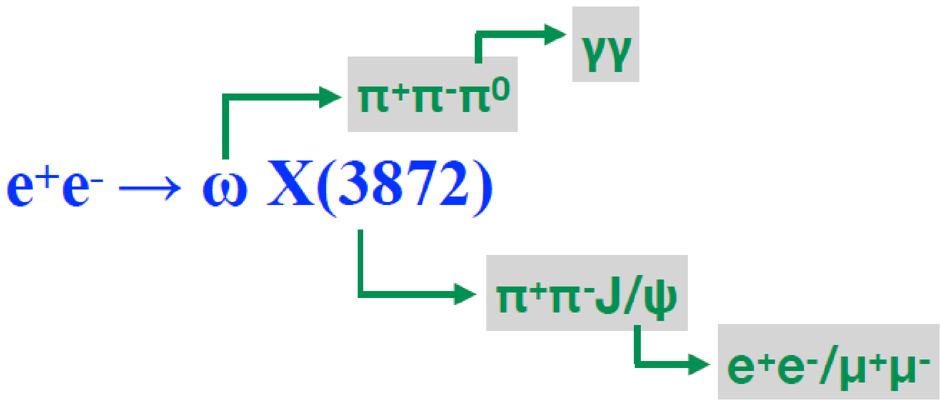
A recent comment from C. Hanhart: The contribution of charged $D^*\bar{D}$ should be subtracted, $r_e \to -2.6$ fm [Phys. Lett. B 833 (2022), 137290]

Different sign, may suggest an elementary $c\bar{c}$ core [A. Esposito PRD 105, L031503]

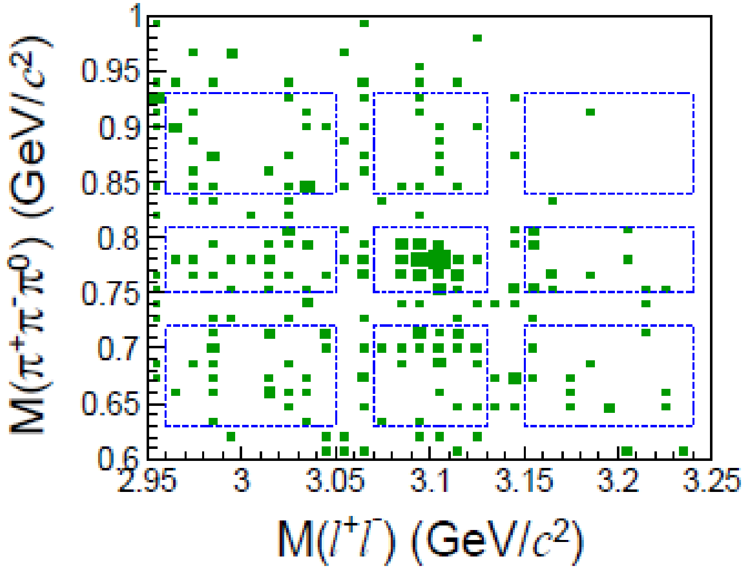
Close to 0 but can not be solved model-independently due to the range correction

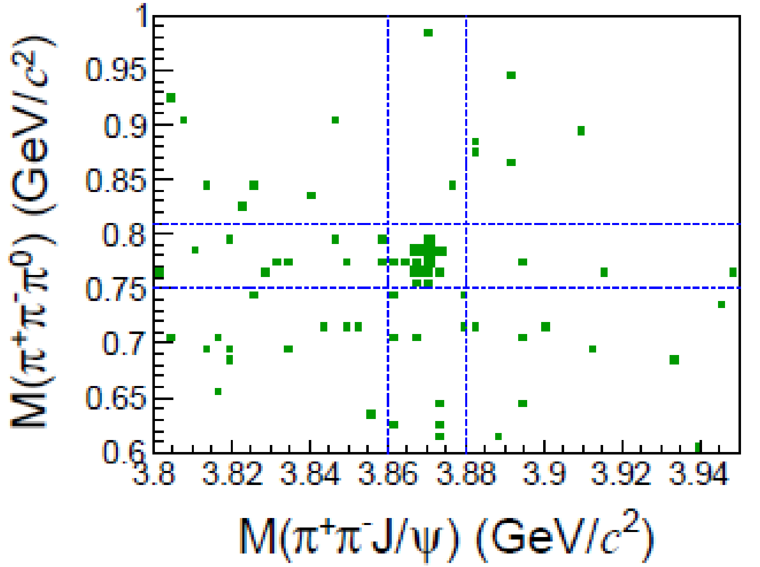
Observation of $e^+e^- \to \omega X(3872)$ at BESIII

arXiv:2212.07291
PRL 130, 151904 (2023)



Dataset at Ecm =4.61-4.95 GeV

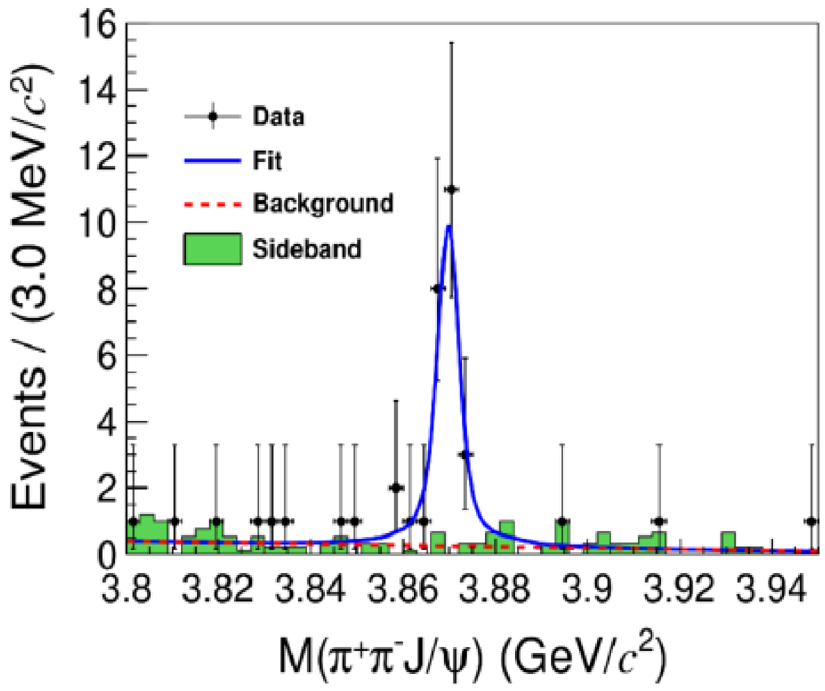


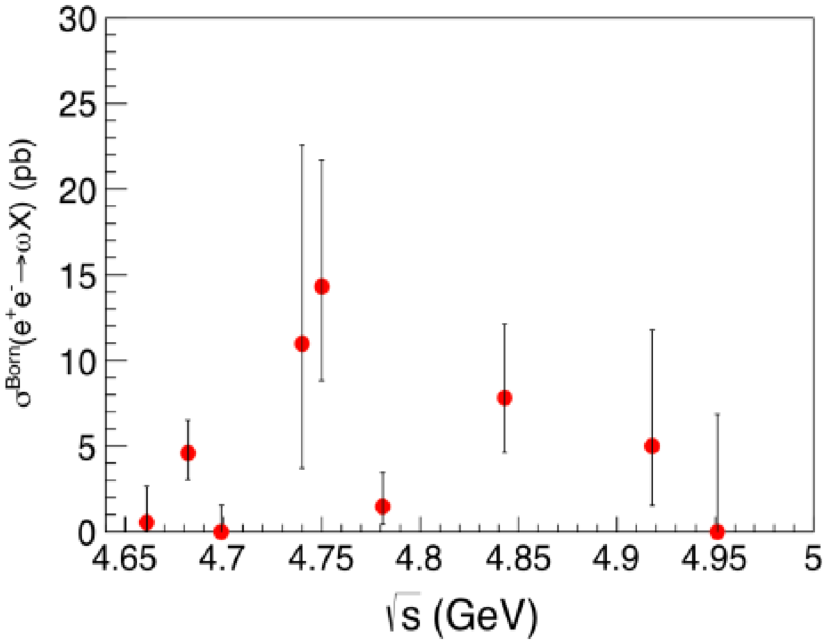


- Signal reconstruction
  - Final state includes six charged particles and two photons
  - Partial reconstruction by missing one pion in kinematic fit is applied to improve the signal efficiency
  - Retain all four $\pi^-\pi^+$ combinations per event

Events accumulation in X(3872) signal regions

Observation of $e^+e^- \rightarrow \omega\, X(3872)$ at BESIII





- Observed the X(3872) new production process $e^+e^- \rightarrow \omega\, X(3872)$ with 7.8σ
- The lineshape of the cross section indicated that $\omega\, X(3872)$ may be from decays of some nontrivial structures.

Search for the light hadron decay $X(3872) \to \pi^+\pi^-\eta$ at BESIII

arXiv: 2308.13980
PRD 109, L011102 (2024)

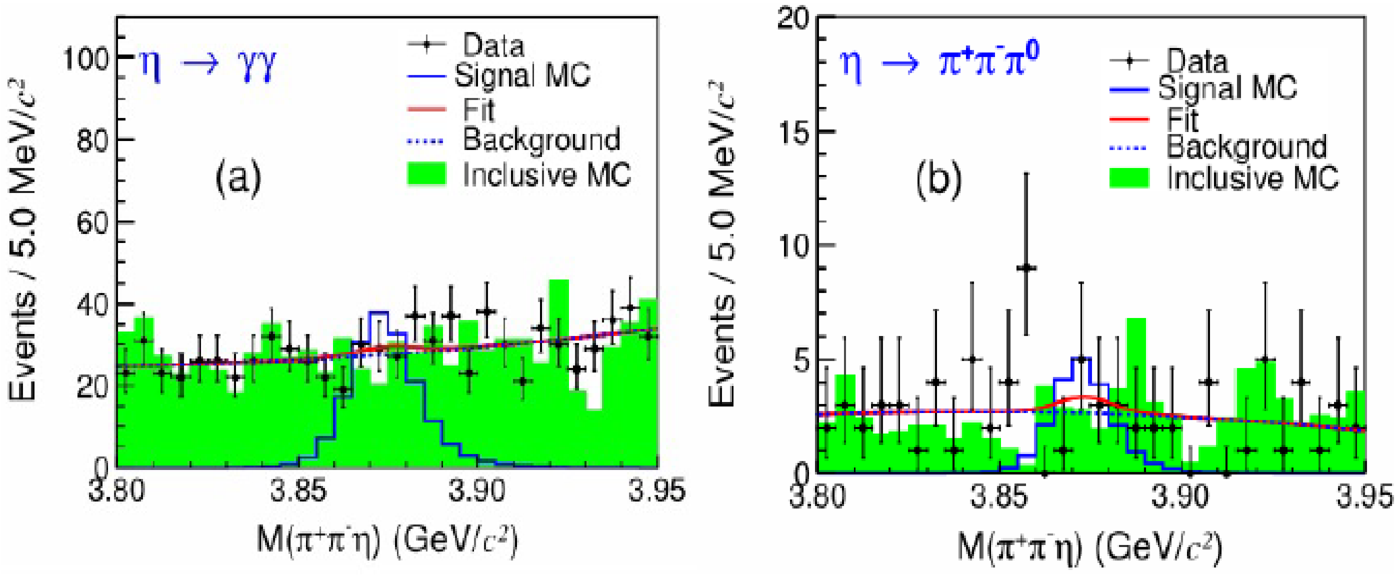
No obvious signal was observed.

☐ For $e^+e^- \to \gamma X(3872) \to \pi^+\pi^-\eta, \eta \to \gamma\gamma$

- $N_{\text{charged tracks}} = 2$, Net Charge $= 0$
- 5C kinematic fit
  - ➢ the four-momentum conservation of the final state particles equal to the initial e^+e^- colliding beams →4C ;
  - ➢ the η mass →1C($\eta \to \gamma\gamma$);

☐ For $e^+e^- \to \gamma X(3872) \to \pi^+\pi^-\eta, \eta \to \pi^+\pi^-\pi^0$

- $N_{\text{charged tracks}} = 4$, Net Charge $= 0$
  - ➢ PID: At least one of the pion candidates is required to satisfy $\mathcal{L}(\pi) > \mathcal{L}(K)$
- 5C kinematic fit:
  - ➢ the four-momentum conservation of the final state particles equal to the initial e^+e^- colliding beams →4C ;
  - ➢ the η mass → 1C($\eta \to \pi^+\pi^-\pi^0$)

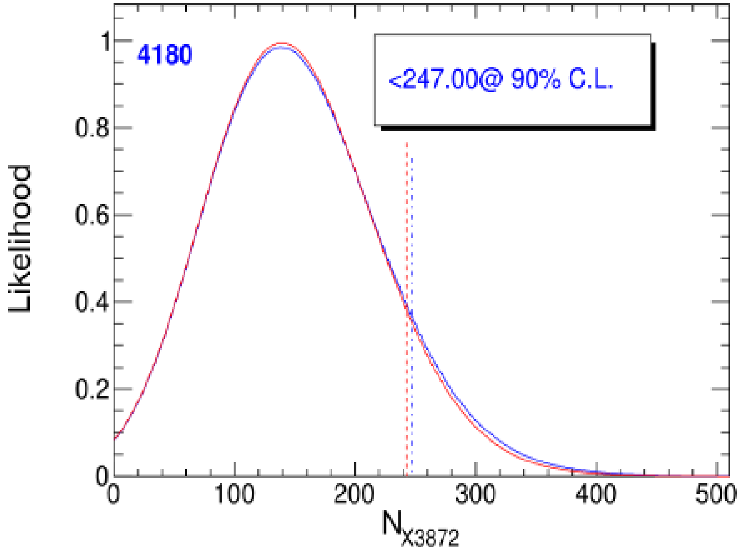


Combine all the data. For the two decay channels of η, a **simultaneous fit to the $M(\pi^+\pi^-\eta)$:**

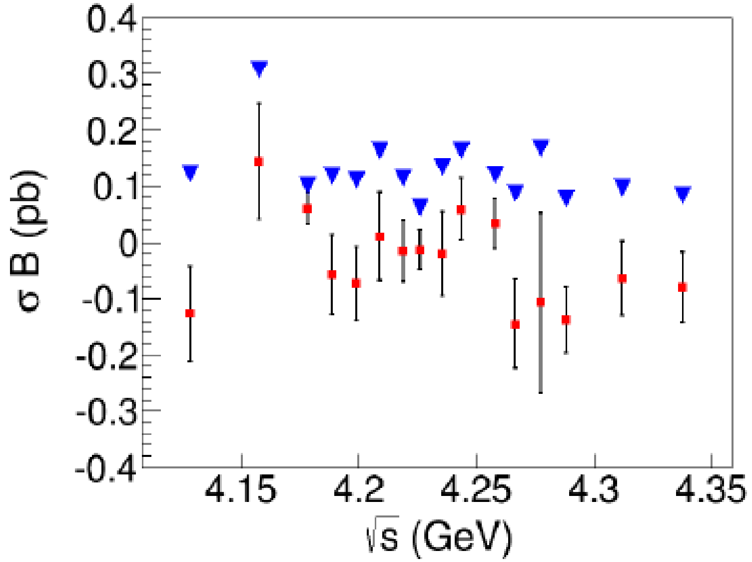
Signal PDF : signa MC ⊗ Gauss function
Background shape : 2nd-order polynomial
Fit result: $\mathbf{N(X(3872)) = 100.31 \pm 148.75}$

Search for the light hadron decay $X(3872) \to \pi^+\pi^-\eta$ at BESIII

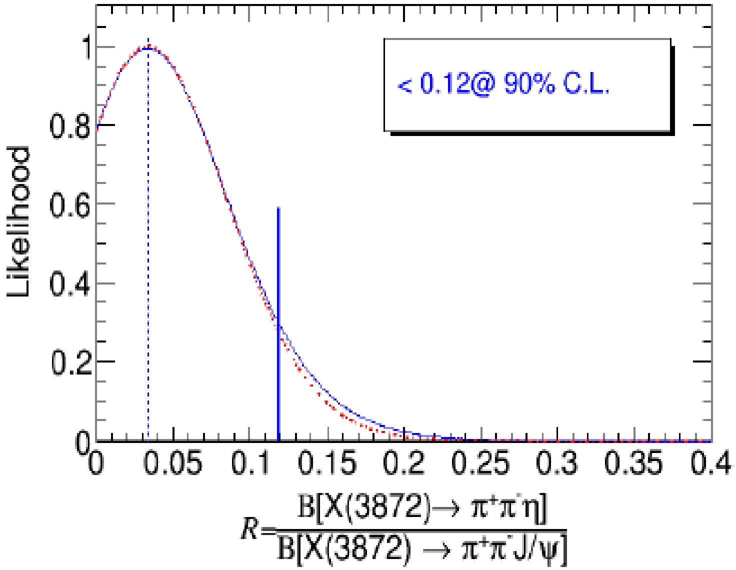
✓ **Blue triangles** are the upper limit for the $(\sigma B)^{up}$ and **red dots with error bars** are the simultaneous fitting result for the (σB).



Upper limit at 90% C.L. for 4.18 GeV



Cross section measurement



Upper limit of the branching fraction ratio

$$\sigma[e^+e^- \to \gamma X(3872)]B[X(3872) \to \pi^+\pi^-\eta] = \frac{N_i^{obs}}{\mathcal{L}_{int}(1+\delta)(\varepsilon_{\eta\to\gamma\gamma}B_{\eta\to\gamma\gamma} + \varepsilon_{\eta\to\pi^+\pi^-\pi^0}B_{\eta\to\pi^+\pi^-\pi^0})} = \frac{N_i^{sig}}{\mathcal{L}_{int}(1+\delta)}$$

$$\mathcal{R} = \frac{N_{\rm total}}{N'_{\rm total}} \frac{\sum_i \mathcal{L}_i\sigma_i(1+\delta_i)}{\sum_i \mathcal{L}_i\sigma_i(1+\delta_i)} \frac{\epsilon'_i\mathcal{B}(J/\psi \to \ell^+\ell^-)}{\epsilon_i^{\gamma\gamma}\mathcal{B}_1 + \epsilon_i^{\pi^+\pi^-\pi^0}\mathcal{B}_2}$$

N_{total}: the total number of X(3872) signal events;
$L_i, \sigma_i, (1+\delta_i)$ are the same for both process.

Search for $X(3872)$ spin partner in $\psi(3770)$ radiative decay

arXiv:2305.11682
PRD 108, 052012 (2023)

- $\psi(3770) \to \gamma X(3700),\ X(3700) \to \eta\eta'$(dominant decay)
- $\Gamma_{\psi(3770)\to\gamma X, X\to\eta\eta'}$= 0.293 keV, based on 2.9 fb^{-1} $\psi(3770)$ data, we can test the theoretical prediction.
- The new 20 fb^{-1} $\psi(3770)$ data will be able to improve the sensitivity further.

[C. W. Xiao and E. Oset, Eur. Phys. J. A 49, 52 (2013)]

Channel	Re(g_X) [MeV]	Im(g_X) [MeV]	$\lvert g_X\rvert$ [MeV]
$\pi^+\pi^-$	9	83	84
K^+K^-	5	22	22
D^+D^-	5962	1695	6198
$\pi^0\pi^0$	6	83	84
$K^0\bar{K}^0$	5	22	22
$\eta\eta$	1023	242	1051
$\eta\eta'$	1680	368	1720
$\eta'\eta'$	922	-417	1012

gx: Coupling of the pole at (3722 − *i*18)MeV to the channels

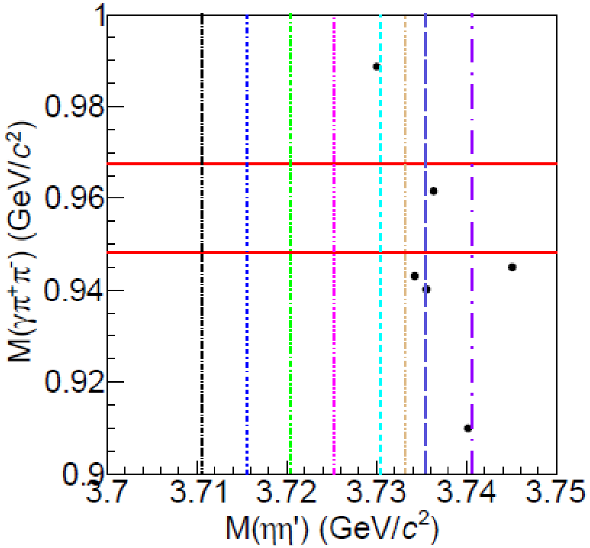
- $\psi(3770) \to \gamma X(3700), X(3700) \to \pi^+\pi^- J/\psi$
- Since the X(3700) decay might have a large isospin violation similar to X(3872) $\to \pi^+\pi^- J/\psi$.
- There is no theoretical prediction of this process, which can provide input information for the theoretical prediction.

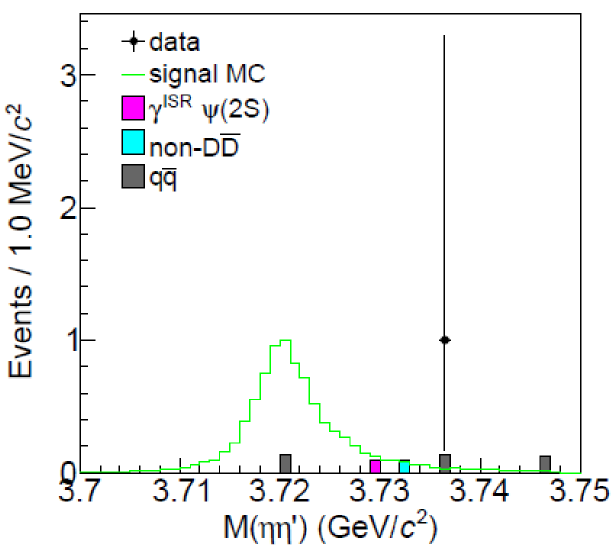
[N. A. Tornqvist, Phys. Lett. B 590, 209 (2004)]

Search for $X(3872)$ spin partner in $\psi(3770)$ radiative decay

- Study of $\psi(3770) \to \gamma\eta\eta'$

No obvious signal was observed.

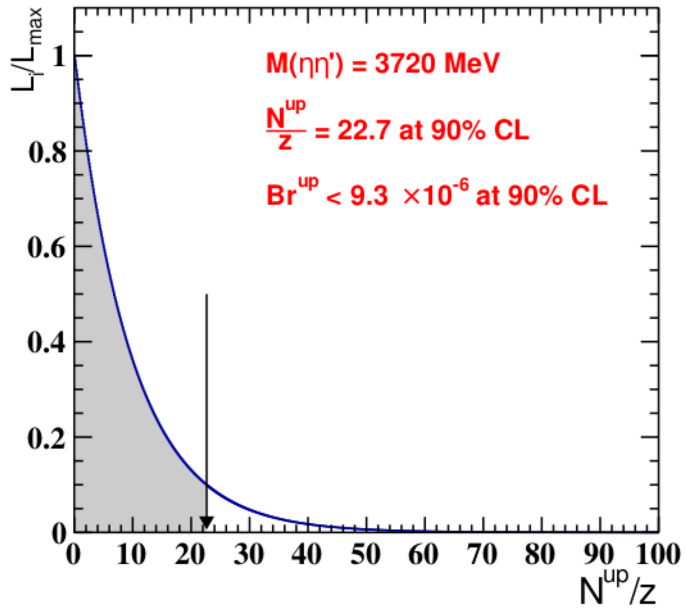




- The upper limit we get (0.9 - 1.9($\times 10^{-5}$))mostly lower than the theoretical prediction (1.8×10^{-5})
- Disfavor that $\psi(3770) \to \gamma\eta\eta'$ is the dominant channel for X(3700) decay

- Upper limit at 90% C.L.:

$$L(\mu, \epsilon, b \mid x, y, z) = \frac{(\epsilon\mu + b)^x}{x!} e^{-(\epsilon\mu+b)} \times \frac{1}{\sqrt{2\pi}\sigma_\epsilon} e^{-\frac{(\epsilon-z)^2}{2\sigma_\epsilon^2}} \times \frac{(\tau b)^y}{y!} e^{-\tau b}$$



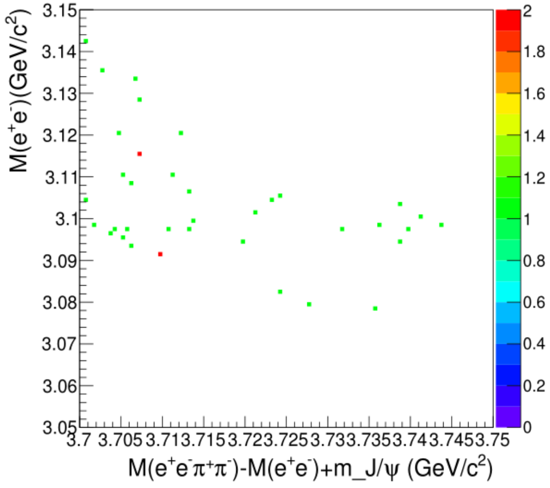
$$B(\psi(3770) \to \gamma X(3700) \times X(3700) \to \eta\eta') < \frac{N^{up}_{sig}}{L \times \sigma \times z \times Br(\eta \to \gamma\gamma) \times Br(\eta' \to \gamma\pi^+\pi^-)}$$

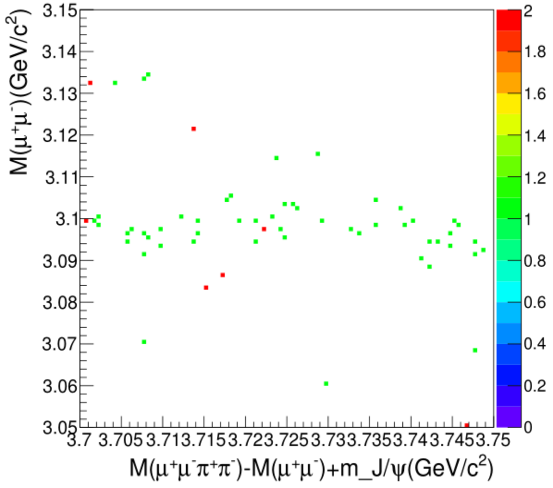
$M(X(3700))$ (MeV$/c^2$)		3710	3715	3720	3725	3730	3733	3735	3740
$\psi(3770) \to \gamma\eta\eta'$	ε_0 (%)	10.56	10.50	10.14	9.77	9.31	8.99	8.70	8.15
	$\mathcal{B}^{\rm up}(\times 10^{-6})$	8.9	9.0	9.3	9.7	10	18	18	19

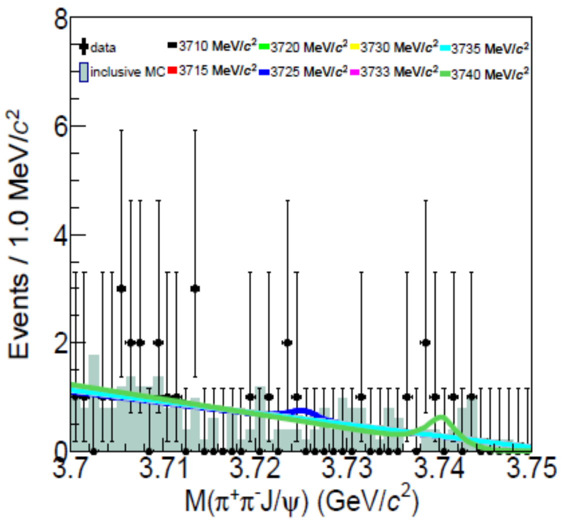
Search for $X(3872)$ spin partner in $\psi(3770)$ radiative decay

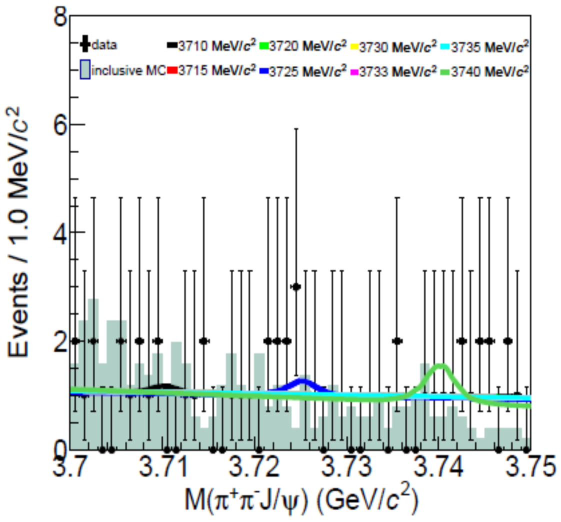
- Study of $\psi(3770) \to \gamma\pi^+\pi^- J/\psi$

No obvious signal was observed.









- Simultaneous fit of $M(\pi^+\pi^- l^+ l^-)$ distribution with different masses of the X(3700)

Signal : signal MC shape
Background:1st-order Chebyshev polynomial

- Upper limit at 90% C.L.:

$$B(\psi(3770) \to \gamma X(3700) \times X(3700) \to \pi^+\pi^- J/\psi) < \frac{N^{up}_{sig}}{L \times \sigma \times \epsilon \times Br(J/\psi \to l^+ l^-)}$$

$M(X(3700))$ MeV/c^2	3710	3715	3720	3725	3730	3733	3735	3740
$\mathcal{L}(\text{pb}^{-1})$	2931.8							
$\mathcal{B}(J/\psi \to \ell^+\ell^-)$	5.97%							
σ(pb)	7150							
ε_0^{ee}	15.68%	15.59%	15.88%	15.50%	15.38%	15.32%	14.83%	13.76%
$\varepsilon_0^{\mu\mu}$	24.10%	23.97%	24.02%	23.93%	23.67%	23.54%	23.16%	21.80%
$\mathcal{B}^{up}_{90\% C.L.}(\times 10^{-5})$	2.2	1.2	1.8	3.0	0.86	1.0	1.3	3.4

- The upper limit we get from 0.9 to 3.4 ($\times 10^{-5}$).
- This result can provide a constraint for the theoretical calculation of X(3700)

Summary

A set of interesting and important results on the X(3872) from BESIII achieved:

- ✓ A coupled channel analysis of the X (3872) lineshape with $D^0\bar{D}^0\pi^0$ and $\pi^+\pi^-J/\psi$ samples was performed for the first time. The result is consistent with the molecular picture. Due to the uncertainty, the presence of a compact component can not be excluded.
- ✓ We observed new production mechanisms of X(3872), $e^+e^- \to \omega\ X(3872)$, which provide a window to peer into the internal structure of the X(3872).
- ✓ We searched for the decay $X(3872) \to \pi^+\pi^-\eta$ associated with the radiative production $e^+e^- \to \gamma\ X(3872)$. No obvious signal was found and the upper limits for the product of the production cross section and branching fraction have been given.
- ✓ We searched for the X(3872) spin partner X(3700) in $\psi(3770)$ radiative decay for the first time. No signal events were observed, the upper limits of combined branching fraction have been given. The branching fraction we get is inconsistent with current theoretical predictions.

With the largest $\psi(3770)$ data sample (20/fb) and the upgrade of BEPCII in both luminosity (*3 times at 4.8 GeV) and the maximum energy (~5.6 GeV), the more extensive and intensive investigation is ongoing, looking forward to new results in the near future.

Thank you for the attention!

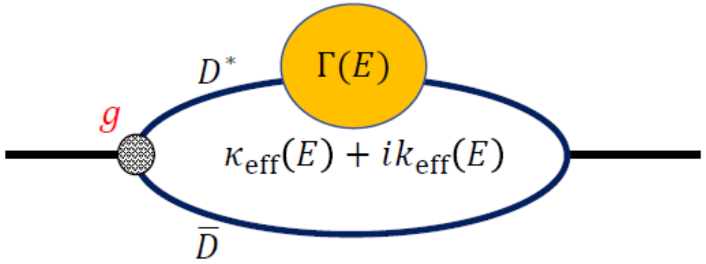
Backups

Parameterization

$$\frac{d\mathrm{Br}(D^0\bar{D}^0\pi^0)}{dE} = \boldsymbol{B}\,\frac{1}{2\pi} \times \frac{g * k_{\mathrm{eff}}(E)}{|D(E)|^2} \times \mathrm{Br}(D^{*0} \to D^0\pi^0)$$

$$\frac{d\mathrm{Br}(\pi^+\pi^- J/\psi)}{dE} = \boldsymbol{B}\,\frac{1}{2\pi} \times \frac{\Gamma_{\pi^+\pi^-\,J/\psi}}{|D(E)|^2}$$

[C. Hanhart, PRD 81, 094028]



Composite particle with one unstable constituent

$$D(E) = E - E_X + \frac{1}{2} g * \left(\kappa_{\mathrm{eff}}(E) + ik_{\mathrm{eff}}(E) + \kappa^c_{\mathrm{eff}}(E) + ik^c_{\mathrm{eff}}(E)\right) + \frac{i}{2}\Gamma_0$$

$$k_{\mathrm{eff}}(E) = \sqrt{\mu_p}\sqrt{\sqrt{(E-E_R)^2 + \Gamma^2/4} + E - E_R}$$

$$\kappa_{\mathrm{eff}}(E) = -\sqrt{\mu_p}\sqrt{\sqrt{(E-E_R)^2 + \Gamma^2/4} - E + E_R} + \sqrt{\mu_p}\sqrt{\sqrt{(E_X-E_R)^2 + \Gamma_X^2/4} - E_X + E_R}$$

$$\sqrt{\sqrt{(E-E_R)^2 + \Gamma^2/4} - E + E_R} - i\sqrt{\sqrt{(E-E_R)^2 + \Gamma^2/4} + E - E_R} = \sqrt{-2(E - E_R + i\Gamma/2)}$$

$$\Gamma_0 = \Gamma_{\pi^+\pi^- J/\psi} + \Gamma_{known} + \Gamma_{unknown}$$

$$E_X = M_X - (m_{D^0} + m_{\bar{D}^0} + m_{\pi^0})$$

⋆ Due to the limited statistics, $\boldsymbol{\Gamma_{unknown}/\Gamma_{\pi^+\pi^- J/\psi}}$ is fixed [Chunhua Li, Chang-Zheng Yuan, PRD 100(2019) 094003]

⋆ It brings us the largest uncertainty

$D^0\bar{D}^{*0} + D^+\bar{D}^{*-}$ effective self energy

$$\Gamma(E) = \Gamma_R\left(\mathrm{Br}(D^{*0} \to D^0\pi^0)\left(\frac{E}{E_R}\right)^{\frac{3}{2}} + \mathrm{Br}(D^{*0} \to D^0\gamma)\right)$$

$\Gamma_R = 55.9$ keV

For the effect of D^{*0} width, we fit to $M(D^0\bar{D}^0\pi^0)$ without mass constraint

Partial width of the other decay channels

$$\Gamma_0 = \Gamma_{\pi\pi J/\psi} + \Gamma_{known} + \Gamma_{unknown}$$

$\omega J/\psi$, $\gamma J/\psi$, $\gamma\psi'$, $\pi^0\chi_{c1}$

Key features:

- Model independent
- Including the $D^*\bar{D}$ self energy terms
- Including the width of D^*
- Including the coupled channel effect
- **Fit parameters**: g, $\Gamma_{\pi^+\pi^- J/\psi}$, M_X

Parameterization

$$2\,Im[D(E)] = g * (k_{\text{eff}} + k^{c}_{\text{eff}}) + \Gamma_{\pi^+\pi^- J/\psi} + \Gamma_{known} + \Gamma_{unknown}$$

The produced numbers of events in a fitting range $(E_{min},\ E_{max})$ are:

$$\mu^{prod}_{X(3872)} = \int_{E_{min}}^{E_{max}} dE\, \frac{B}{2\pi} * \frac{2\,Im[D(E)]}{|D(E)|^2}$$

$$\mu^{prod}_{D^0\bar{D}^0\pi^0} = \mathrm{Br}(D^{*0} \to D^0\pi^0) \times \int_{E_{min}}^{E_{max}} dE\, \frac{B}{2\pi} * \frac{g * k_{\text{eff}}}{|D(E)|^2}$$

$$\mu^{prod}_{\pi^+\pi^- J/\psi} = \int_{E_{min}}^{E_{max}} dE\, \frac{B}{2\pi} * \frac{\Gamma_{\pi^+\pi^- J/\psi}}{|D(E)|^2}$$

$$\mu_{D^0\bar{D}^0\pi^0} = \epsilon_{D^0\bar{D}^0\pi^0} \times R_{D^0\bar{D}^0\pi^0} \times \mu^{prod}_{X(3872)}$$

$$\mu_{\pi^+\pi^- J/\psi} = \epsilon_{\pi^+\pi^- J/\psi} \times R_{\pi^+\pi^- J/\psi} \times \mu^{prod}_{X(3872)}$$

ϵ : efficiency and branching fractions correction

$$R_{D^0\bar{D}^0\pi^0} = \mathrm{Br}(D^{*0} \to D^0\pi^0) \times \frac{\int_{E_{min}}^{E_{max}} dE\, \frac{g * k_{\text{eff}}}{|D(E)|^2}}{\int_{E_{min}}^{E_{max}} dE\, \frac{2\,Im[D(E)]}{|D(E)|^2}}$$

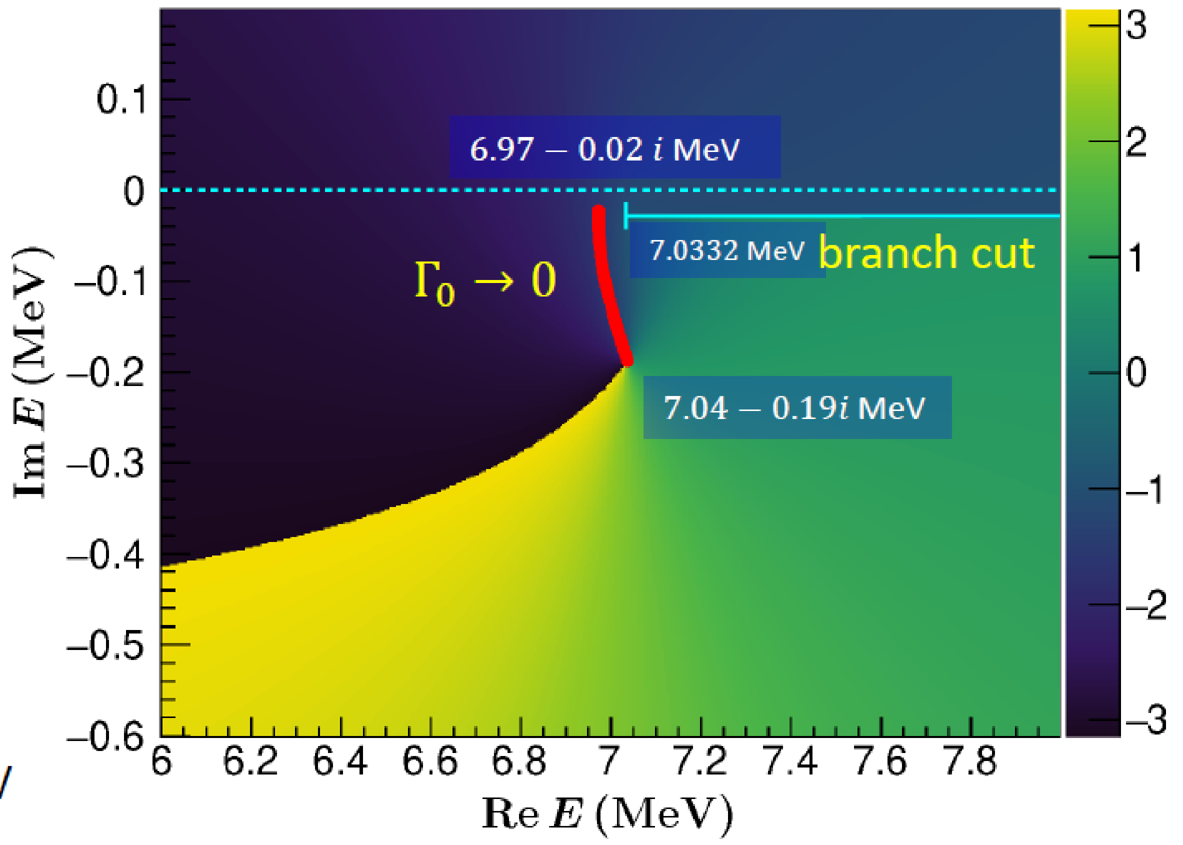
$$R_{\pi^+\pi^- J/\psi} = \frac{\int_{E_{min}}^{E_{max}} dE\, \frac{\Gamma_{\pi^+\pi^- J/\psi}}{|D(E)|^2}}{\int_{E_{min}}^{E_{max}} dE\, \frac{2\,Im[D(E)]}{|D(E)|^2}}$$

Only one new parameter $\mu^{prod}_{X(3872)}$

Pole search

- Due to causality, the scattering amplitude should be analytic over the complex energy plane, up to poles and branch cuts
- The pole locations can reveal the intrinsic properties of the particle
- Two sheets with respect to $D^{*0}\bar{D}^0$ branch cut
  - Sheet I: $E - E_X - g\sqrt{-2\mu(E - E_R + i\Gamma/2)}$
  - Sheet II: $E - E_X + g\sqrt{-2\mu(E - E_R + i\Gamma/2)}$

- $E_{\mathrm{I}} = (7.04 \pm 0.15^{+0.07}_{-0.08}) + (-0.19 \pm 0.08^{+0.14}_{-0.19})i$ MeV
- $E_{\mathrm{II}} = \left(0.26 \pm 5.74^{+5.14}_{-38.32}\right) + (-1.71 \pm 0.90^{+0.60}_{-1.96})i$ MeV
- E_{I} is much closer to the threshold, should play a dominant role in the X(3872) confinement mechanism



Comparison

	LHCb	Belle	This work
g	$0.108 \pm 0.003^{+0.005}_{-0.006}$	$0.29^{+2.69}_{-0.15}$	$0.16 \pm 0.10^{+1.12}_{-0.11}$
$Re[E_I]$ [MeV]	7.10	7.12	$7.04 \pm 0.15^{+0.07}_{-0.08}$
$Im[E_I]$ [MeV]	-0.13	-0.12	$-0.19 \pm 0.08^{+0.14}_{-0.19}$
$Re[k^+]$ [MeV]	-13.9	-15.3	$-12.6 \pm 5.5^{+6.6}_{-6.2}$
$Im[k^+]$ [MeV]	8.8	7.7	$12.3 \pm 6.8^{+6.0}_{-6.4}$
a (fm)	-27.1	-31.2	$-16.5^{+7.0}_{-27.6}{}^{+5.6}_{-27.7}$
r_e (fm)	-5.3	$-3.0^{+1.3}_{-1.5}$	$-4.1^{+0.9}_{-3.3}{}^{+2.8}_{-4.4}$
$\bar{Z}_A$	0.15 (0.33)	$0.08^{+0.04}_{-0.03}$	$0.18^{+0.06}_{-0.17}{}^{+0.19}_{-0.16}$

Estimation of the width of D^{*0}

The Lagrangian for $D^* \to D + \pi$ under HQSS is

$$\mathcal{L} = -\frac{g}{f_\pi} < \overline{H_a} H_b \gamma^\mu \gamma^5 > \partial_\mu M_{ba},$$

Where H is the heavy meson fields and the M is the matrix of pseudoscalar mesons. The partial width of $D^{*+} \to D^0 \pi^+$ reads

$$\Gamma_c = \frac{|p_\pi|}{8\pi M_{D^{*+}}^2} \times \frac{1}{3} \frac{4g^2}{f_\pi^2} |p_\pi^2| M_{D^{*+}} M_{D^0} \ .$$

For $D^{*0} \to D^0 \, \pi^0$,

$$\Gamma_0 = \frac{|p'_\pi|}{8\pi M_{D^{*0}}^2} \times \frac{1}{3} \frac{2g^2}{f_\pi^2} |p'_\pi|^2 M_{D^{*0}} M_{D^0} = \frac{|p'_\pi|^3 M_{D^{*+}}}{2|p_\pi|^3 M_{D^{*0}}} \times \Gamma_c$$

One obtains the strong decay partial width $\Gamma_0 = 35.8$ keV, the total width of D^{*0} is estimated to be

$$\Gamma_{D^{*0}} = \frac{\Gamma_0}{64.7\%} \approx 55.4 \text{ keV}$$

Combine the systematic uncertainties between two η decay modes

- **A weighted average is taken as:**

$$\Delta_{\text{tot}}^2 = \sum_{i=1}^{2} \omega_i^2 \Delta_i^2 + 2 \sum_{i \neq j}^{2} \text{cov}(i,j),$$

$$\omega_i = \frac{\epsilon_i \mathcal{B}_i}{\sum_{i=1}^{2} \epsilon_i \mathcal{B}_i}, \quad \text{cov}(i,j) = \rho_{ij} \omega_i \omega_j \Delta_i \Delta_j,$$

- ✓ Δ_{tot} is the combined total systematic uncertainty for each source;
- ✓ ω_i and Δ_i are the corresponding weight and systematic uncertainty;
- ✓ ϵ_i and $\mathcal{B}_i$ are the efficiency and branching fractions for the i-th decay mode of η
- ✓ ρ_{ij} is the correlation coefficient between them.
- We take $\rho_{ij} = 1$ for the same systematic source,otherwise $\rho_{ij} = 0$.