The pole structures of the $X(1840)/X(1835)$ and the $X(1880)$

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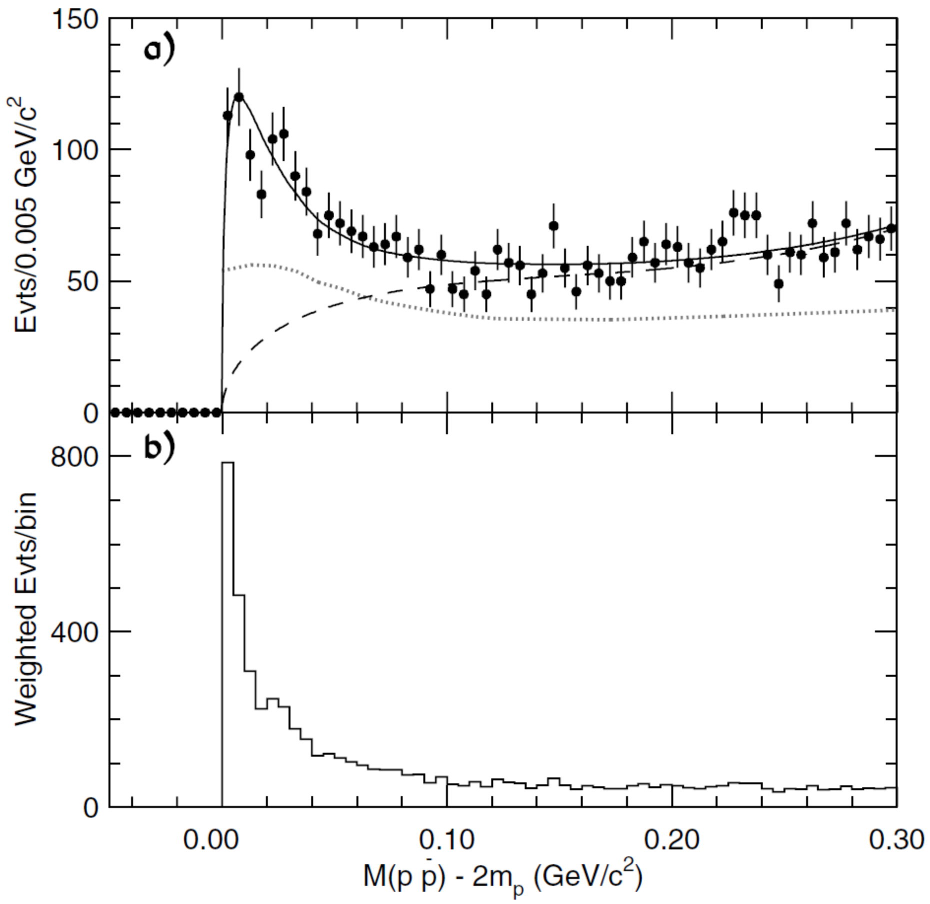
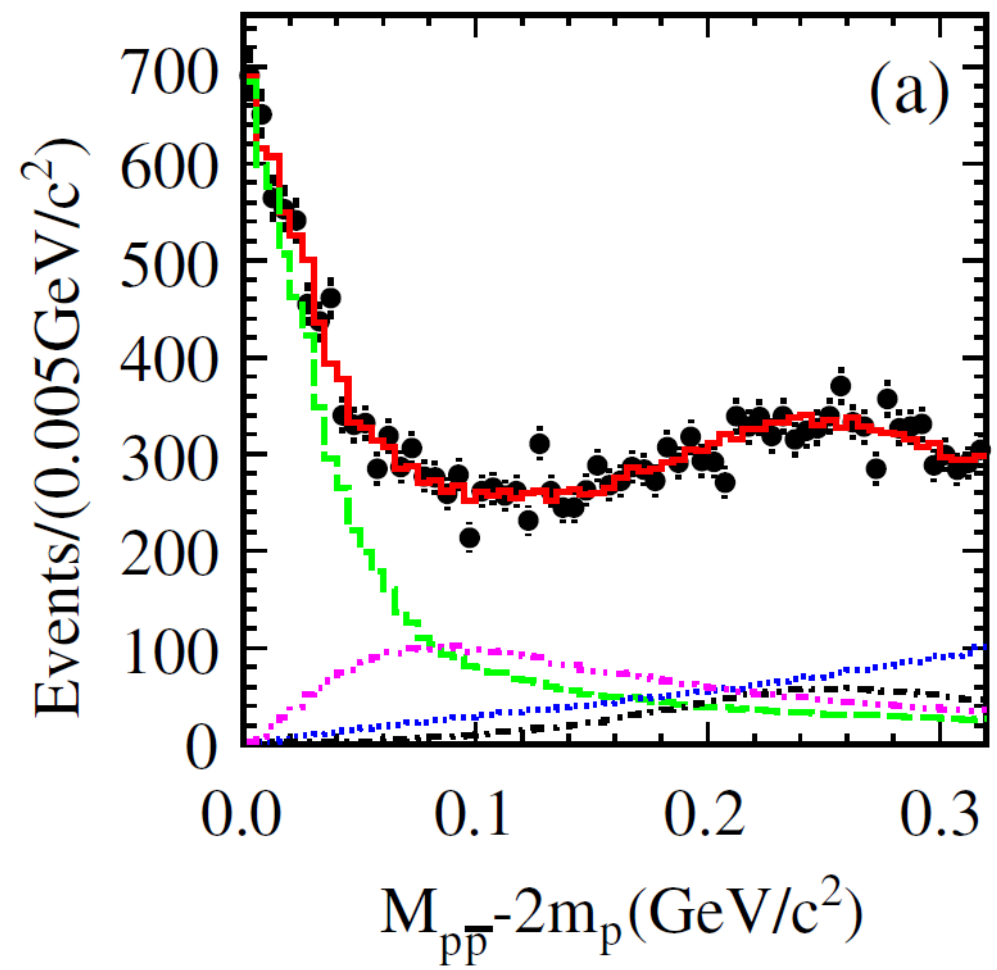
The experimental status

The $p\bar{p}$ threshold enhancement in the $J/\psi \to \gamma p\bar{p}$ process



BES, PRL91(2003)022001



BESIII, PRL108(2012)112003

- The first observed enhancement at $p\bar{p}$ thr.
- S-wave BW fit

$M = 1859^{+3}_{-10}(\text{stat})^{+5}_{-25}(\text{syst})$ MeV

$\Gamma < 30$ MeV

- The quantum number $J^{PC} = 0^{-+}$
- The Juelich model analysis

$M = 1832^{+19}_{-5}(\text{stat}) \pm 19(\text{syst})$ MeV

$\Gamma < 76$ MeV

The experimental status

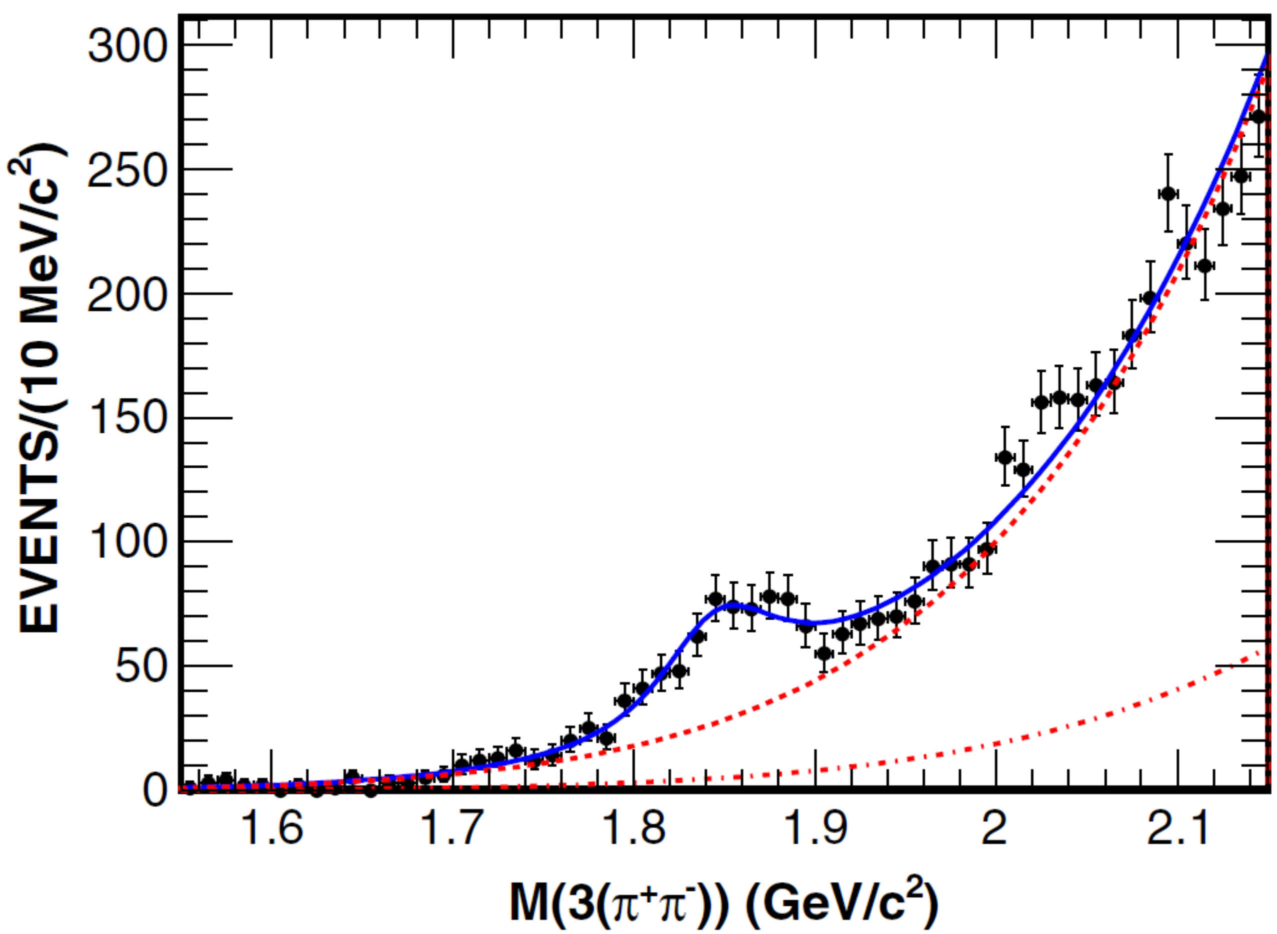
Search for $p\bar{p}$ thre. enhancement in various processes

processes	(Mass width) (MeV)		J^{PC}
$J/\psi \to \gamma p\bar{p}$	(1859,<30)[1]; (1861,<38)[2]; (1837,≈0)[3]; (1832,<76)[5];	X(1835) superposition of two states?	0^{-+} [4]
$J/\psi \to \pi^0 p\bar{p}$	No similar structure [1,5]		-
$J/\psi \to \omega p\bar{p}$	No similar structure [7,8]		-
$J/\psi \to \eta p\bar{p}$	No similar structure [9]		-
$\psi(2S) \to X p\bar{p}$ $(X = \gamma, \pi^0, \eta)$	No similar structure [3]		-
$e^+e^- \to p\bar{p}$	near-threshold enhancement is observed [10]		-
$B \to X p\bar{p}$ $(X = \pi^+, K, K_s, D^{(*)})$	near-threshold enhancement is observed [11-17]		-

[1]BES, PRL91,022001
[2]BESIII, CPC34,421
[3]CLEO, PRD82,092002
[4]BES,PRD80,052004
[5]BESIII,PRL108,112003
[6]BES,PRL95,262001
[7]BES,EPJC53,15
[8]BESIII,PRD87,112004
[9]BES,PLB510,75
[10]BaBar,PRD73,012005
[11]Belle,PRL88,181803
[12]Belle,PLB659,80
[13]BaBar,PRD72,051101
[14]Belle,PLB617,141
[15]Belle,PRL89,151802
[16]BaBar,PRD85,092017
[17]CLEO,PRD82,092002
……

The experimental status

The observation of the $X(1840)$ in $J/\psi \to \gamma 3(\pi^+\pi^-)$



BESIII, PRD88(2013)091502(R)

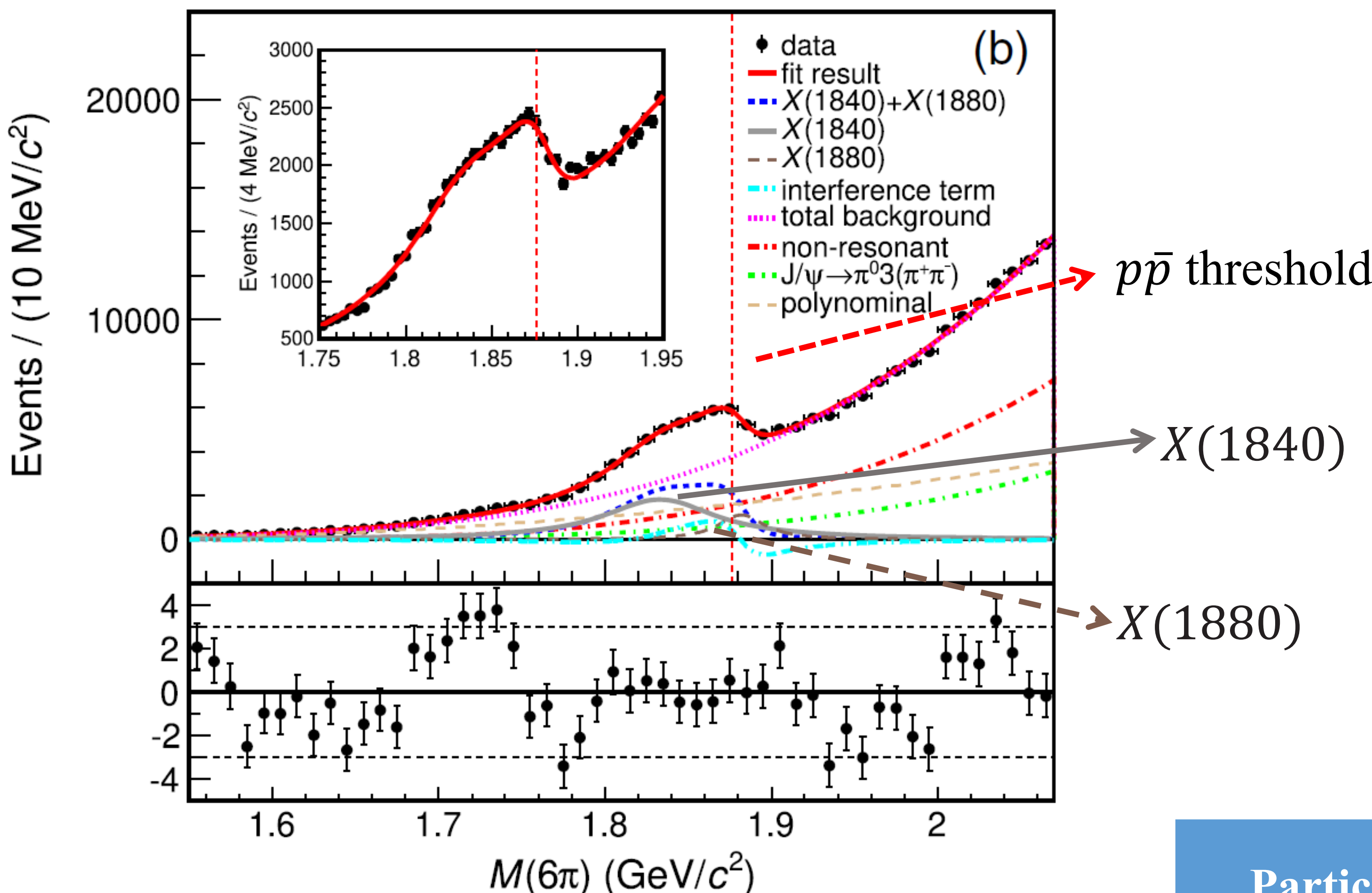
- A structure at 1.84 GeV is observed in the $3(\pi^+\pi^-)$ invariant mass distribution with a statistical significance of 7.6 σ
- Modified BW fit

$M = 1842.2 \pm 4.2(\mathrm{stat})^{+7.6}_{-2.6}(\mathrm{syst})$ MeV

$\Gamma = 83 \pm 14 \pm 11$ MeV

The experimental status

The observation of the $X(1880)$ in $J/\psi \to \gamma 3(\pi^+\pi^-)$



BESIII, PRL132(2024)151901

Model-I: one resonant structure ($\chi^2/N_{\rm dof}$=317.9/44):

$$A = \left|\frac{1}{M^2 - s - i\sum_j g_j^2 \rho_j}\right|^2$$

Model-II: two resonant structures ($\chi^2/N_{\rm dof}$=155.6/41):

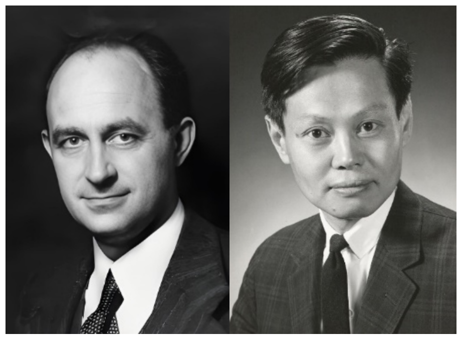
$$A = \left|\frac{1}{M_1^2 - s - iM_1\Gamma_1} + \beta\,\frac{1}{M_2^2 - s - iM_2\Gamma_2}\right|^2$$

- The two BW fit describe the data well

Particle	X(1840)	X(1880)
J^PC	0^(- +)	0^(- +)
Mass (MeV)	1832.5±3.1±2.5	1882.1±1.7±0.7
Width (MeV)	80.7±5.2±7.7	30.7±5.5±2.4

The theoretical status

The study came back to 1949



Are Mesons Elementary Particles?

E. FERMI AND C. N. YANG*
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received August 24, 1949)

The hypothesis that π-mesons may be composite particles formed by the association of a nucleon with an anti-nucleon is discussed. From an extremely crude discussion of the model it appears that such a meson would have in most respects properties similar to those of the meson of the Yukawa theory.

Although a great effort has been put forward, the properties of the resonances in the mass region of [1.8,1.9] GeV is still remain controversial.

Interpretations on the market

- Final state interaction effect

  Chen et al., PRD83, 094029, Chen et al., PLB692,136, Chen et al., PRD78, 054022, Kang et al., PRD91,074003, Milstein et al., NPA966,54,……

- Pseudoscalar glue ball

  Li, PRD74, 034019, Kochelev et al., PRD72, 097502, He et al., EPJC49,731, Hao et al., PLB642, 53, Gui et al., PRD100, 054511,……

- Radial excitations of η'

  Huang et al., PRD73,014023, Yu et al., PRD83, 114007, Wang et al., PRD102,114034, ……

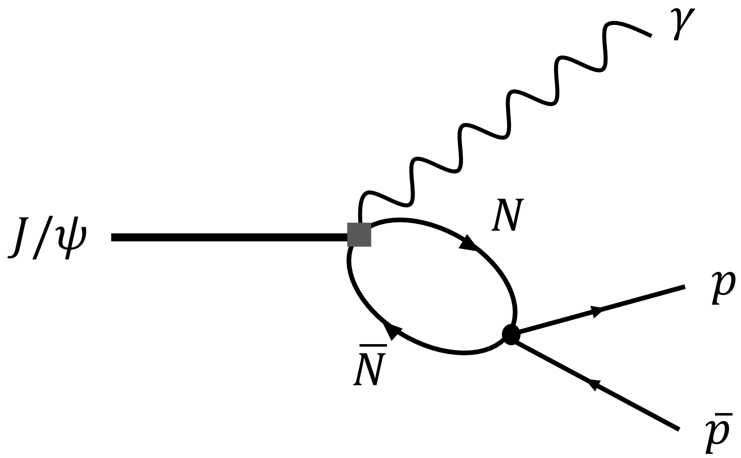
- 3^1S_0 $q\bar{q}$ state

  Li et al., PRD77,074004……

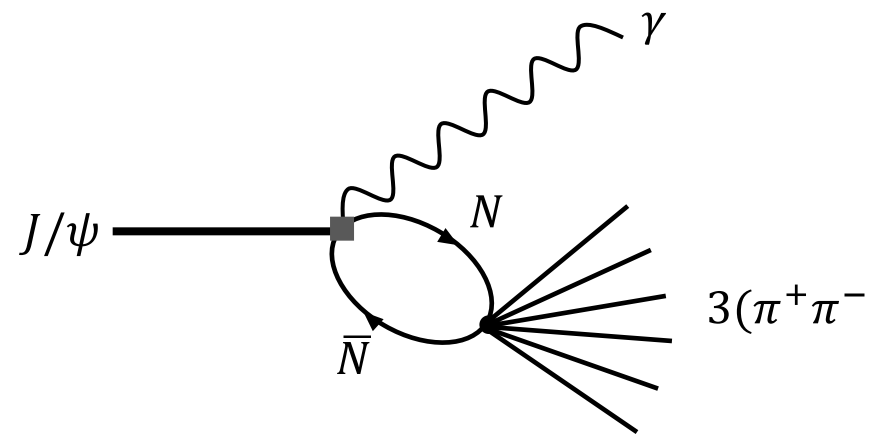
- Several reviews

  Liu et al., Symmetry 8, 14……

A combined analysis of the $J/\psi \to \gamma p\bar{p}$ and $J/\psi \to \gamma 3(\pi^+\pi^-)$ channels



(a)



(b)

- Dynamic channel $N\bar{N}$
- Non-dynamic channel $3(\pi^+\pi^-)$

Niu et al., arXiv:2408.14876 (PRD in press)

Framework

The potential among the dynamic channels

The leading and next-leading order $N\bar{N}$ contact interactions in the chiral effective field theory:

$$L_{N\bar{N}}^{(0)} = C_s + C_T\, \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2\,,$$

$$L_{N\bar{N}}^{(2)} = C_1\boldsymbol{q}^2 + C_2\boldsymbol{k}^2 + (C_3\boldsymbol{q}^2 + C_4\boldsymbol{k}^2)\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 + \frac{i}{2}C_5(\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2)\cdot(\boldsymbol{q}\times\boldsymbol{k}) + C_6(\boldsymbol{q}\cdot\boldsymbol{\sigma}_1)(\boldsymbol{q}\cdot\boldsymbol{\sigma}_2) + C_7(\boldsymbol{k}\cdot\boldsymbol{\sigma}_1)(\boldsymbol{k}\cdot\boldsymbol{\sigma}_2).$$

- The relation between particle basis and isospin basis

The isospin basis and the particle basis:

$$|I=1, I_3=0\rangle = \frac{1}{\sqrt{2}}(|p\bar{p}\rangle + |n\bar{n}\rangle)$$

$$|I=0, I_3=0\rangle = \frac{1}{\sqrt{2}}(|p\bar{p}\rangle - |n\bar{n}\rangle)$$

Niu et al., arXiv:2408.14876 (PRD in press)

- The partial wave projection

The $N\bar{N}$ interaction in the isospin basis

$$V_{^1S_0}^{I} = C_{I1} + C_{I2}(p^2 + P'^2), \mathrm{I} = 0,1$$

C_{I1}: complex number to take into account the annihilation contribution

The partial wave interaction：

$$L(^1S_0) = C'_{01} + C'_{02}(\boldsymbol{p} + \boldsymbol{p}')$$

$$L(^3S_0) = C'_{11} + C'_{12}(\boldsymbol{p} + \boldsymbol{p}')$$

- Solve LSE numerically

- Potential with χEFT + $N\bar{N}$ scattering

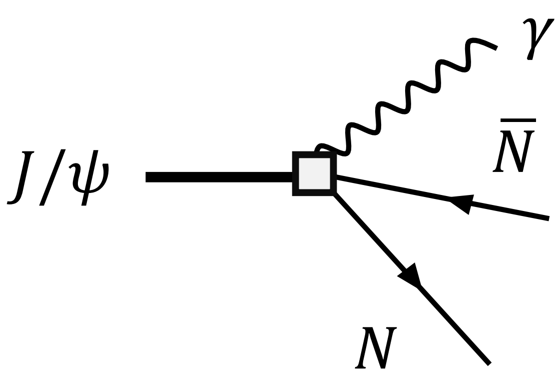
Kang, et al., JHEP02,113

Dai et al., JHEP07, 078

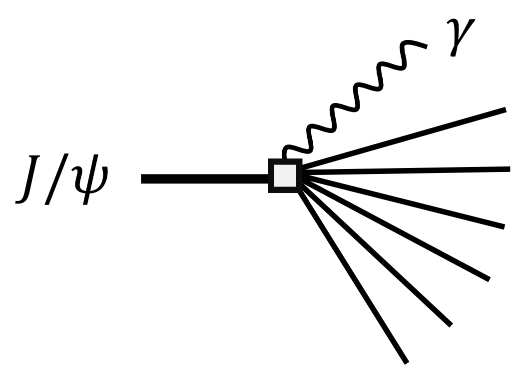
Framework

The bare production amplitudes

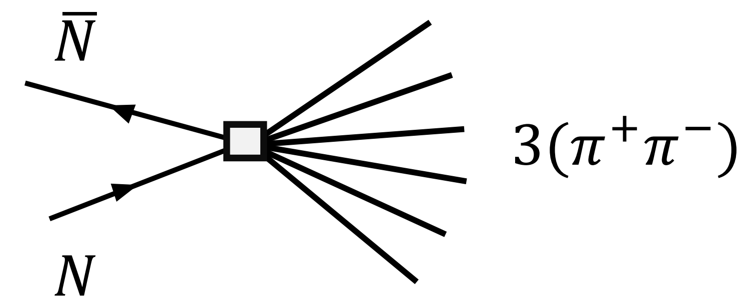
Niu et al., arXiv:2408.14876 (PRD in press)



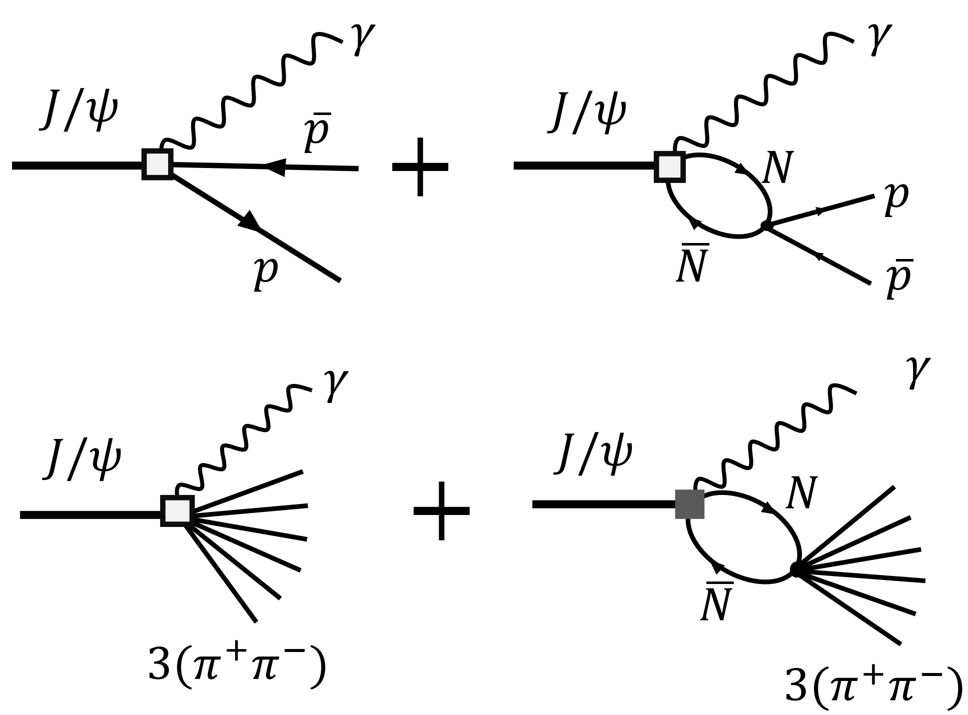
$$A^0_{J/\psi\to\gamma N\bar{N}} = C_{J/\psi\to\gamma N\bar{N}}$$



$$A^0_{J/\psi\to\gamma 3(\pi^+\pi^-)} = C_{J/\psi\to\gamma 3(\pi^+\pi^-)}$$



$$A_{N\bar{N}\to 3(\pi^+\pi^-)} = C_{N\bar{N}\to\gamma 6\pi}$$



The physical decay amplitudes：

$$\widetilde{M}_{J/\psi\to\gamma p\bar{p}} = 8\pi^2\sqrt{E_{J/\psi}E_\gamma E_p E_{\bar{p}}}\, M_{J/\psi\to\gamma p\bar{p}},$$

$$\widetilde{M}_{J/\psi\to\gamma 3(\pi^+\pi^-)} = 32\pi^{7/2}\sqrt{E_{J/\psi}E_\gamma E_2 E_3 E_4}\, M_{J/\psi\to 3(\pi^+\pi^-)},$$

where

$$M_{J/\psi\to\gamma N\bar{N}} = A^0_{J/\psi\to\gamma N\bar{N}} + \int \frac{d^3\boldsymbol{p}}{(2\pi)^3} A^0_{J/\psi\to\gamma N\bar{N}} \cdot G^+ \cdot T_{N\bar{N}\to N\bar{N}},$$

$$M_{J/\psi\to\gamma 3(\pi^+\pi^-)} = A^0_{J/\psi\to\gamma 3(\pi^+\pi^-)} + \int \frac{d^3\boldsymbol{p}}{(2\pi)^3} M_{J/\psi\to\gamma N\bar{N}} \cdot G^+ \cdot A_{N\bar{N}\to 3(\pi^+\pi^-)}.$$

Yang et al., PRD107,034030, Dai et al., PRD98, 014005

Framework

The fitting functions

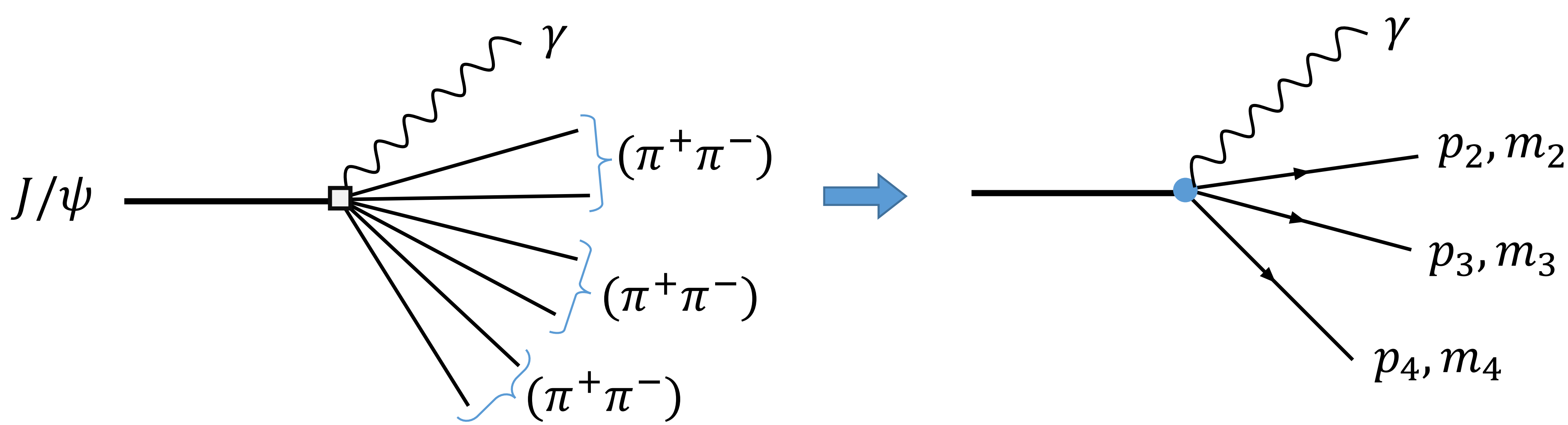
1. Data 2003: $\text{Events}(m_{p\bar{p}}) = \text{fac1}\times\frac{d\Gamma_{J/\psi\to\gamma p\bar{p}}}{dm_{p\bar{p}}}$,
2. Data 2012: $\text{Events}(m_{p\bar{p}}) = \text{fac2}\times\frac{d\Gamma_{J/\psi\to\gamma p\bar{p}}}{dm_{p\bar{p}}}$,
3. Data 2024: $\text{Events}(m_{6\pi}) = \text{fac3}\times\frac{d\Gamma_{J/\psi\to\gamma 3(\pi^+\pi^-)}}{dm_{6\pi}} + \frac{d\Gamma^{\text{bg}}_{J/\psi\to\gamma 3(\pi^+\pi^-)}}{dm_{6\pi}}$.

Background for the $J/\psi \to \gamma 3(\pi^+\pi^-)$:

$$bg_{J/\psi\to\gamma 3(\pi^+\pi^-)} = a + bQ + cQ^2.$$

Discussed with Shuang-Shi Fang

The reduction of 7-body phase space to 4-body phase space

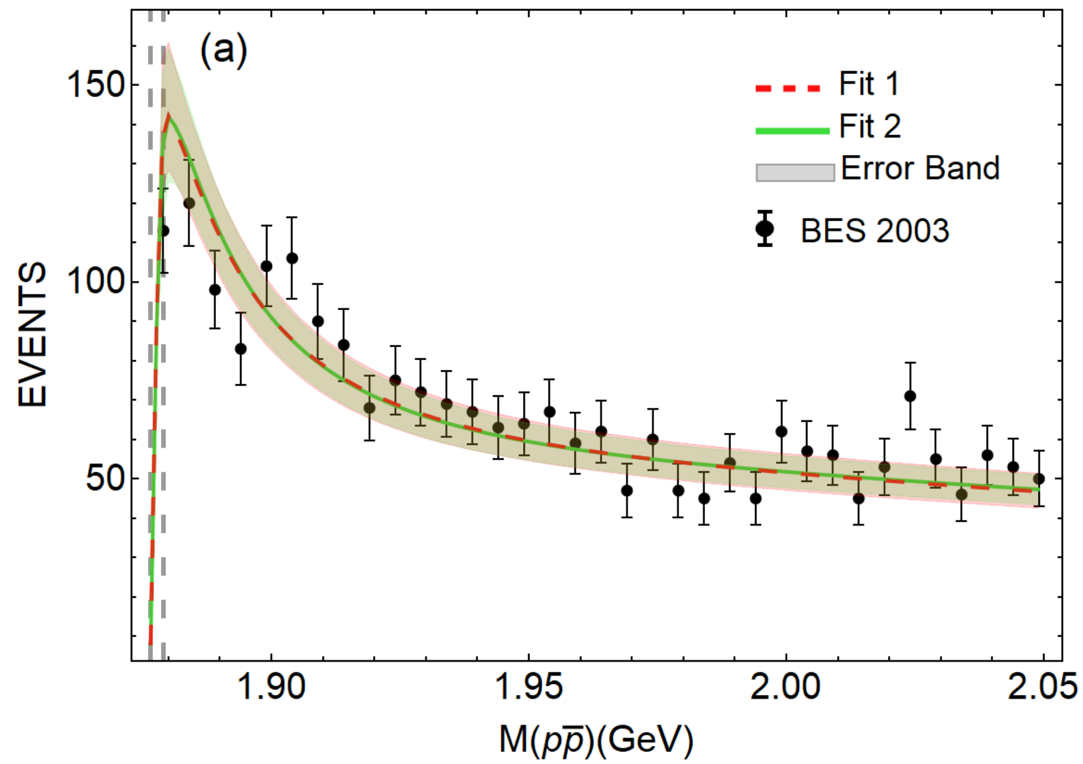


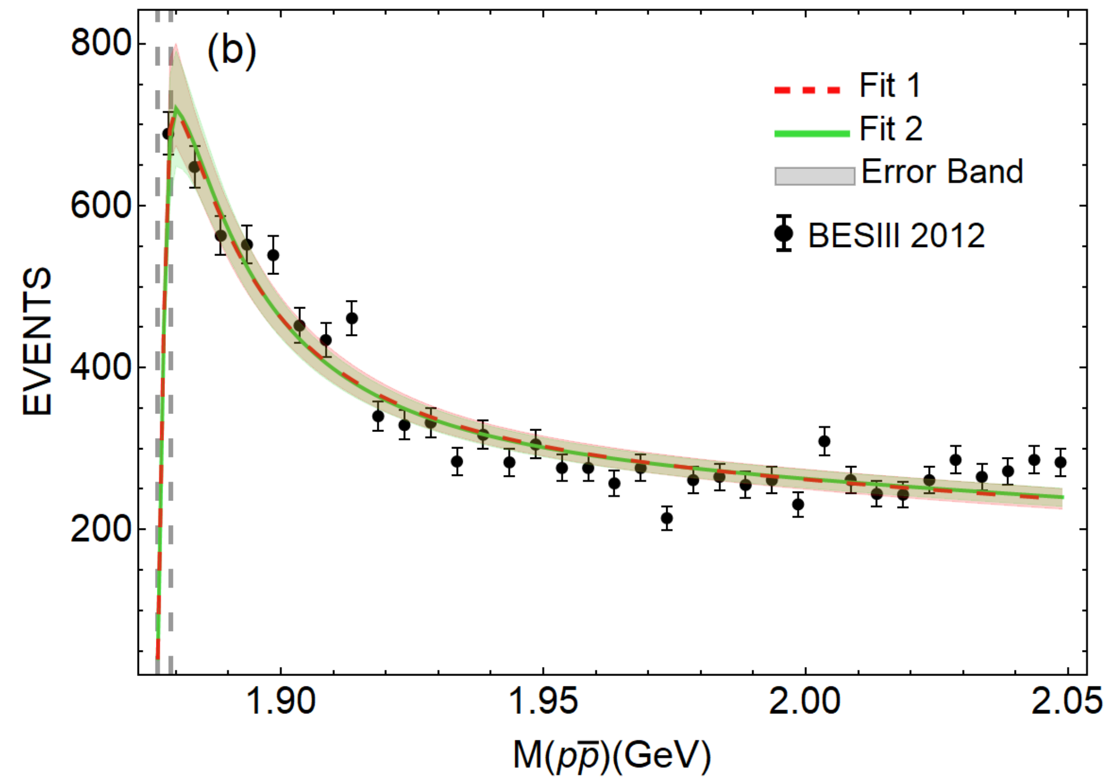
Niu et al., arXiv:2408.14876 (PRD in press)

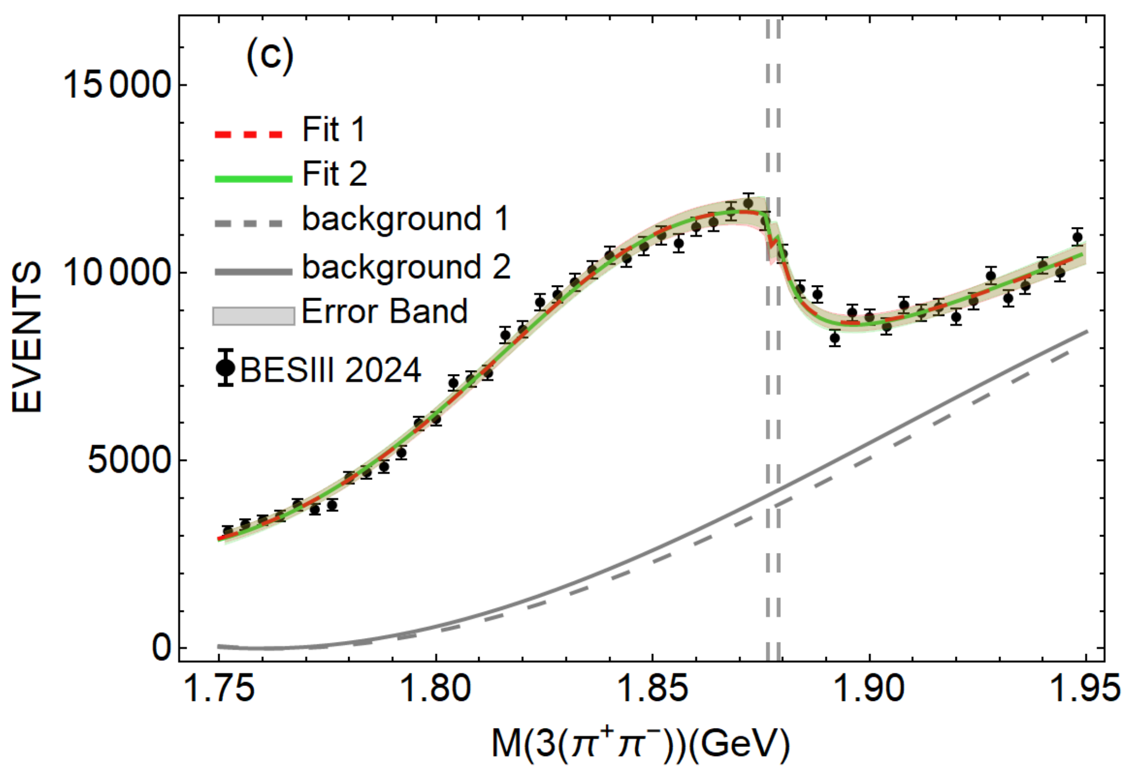
The fitting results

The fitting functions

Niu et al., arXiv:2408.14876 (PRD in press)







- Fit parameters:

Dynamic potential: $C_{01}, C_{02}, C_{11}, C_{12}$

Non-dynamic potential: $C_{p\bar{p}\to 6\pi}, C_{n\bar{n}\to 6\pi}$

Production amplitudes: $C_{J/\psi\to\gamma p\bar{p}}, C_{J/\psi\to\gamma n\bar{n}}$

Background: a, b, c

Normalization factors: fac1,fac2,fac3

- Two solutions

The pole positions and effective couplings

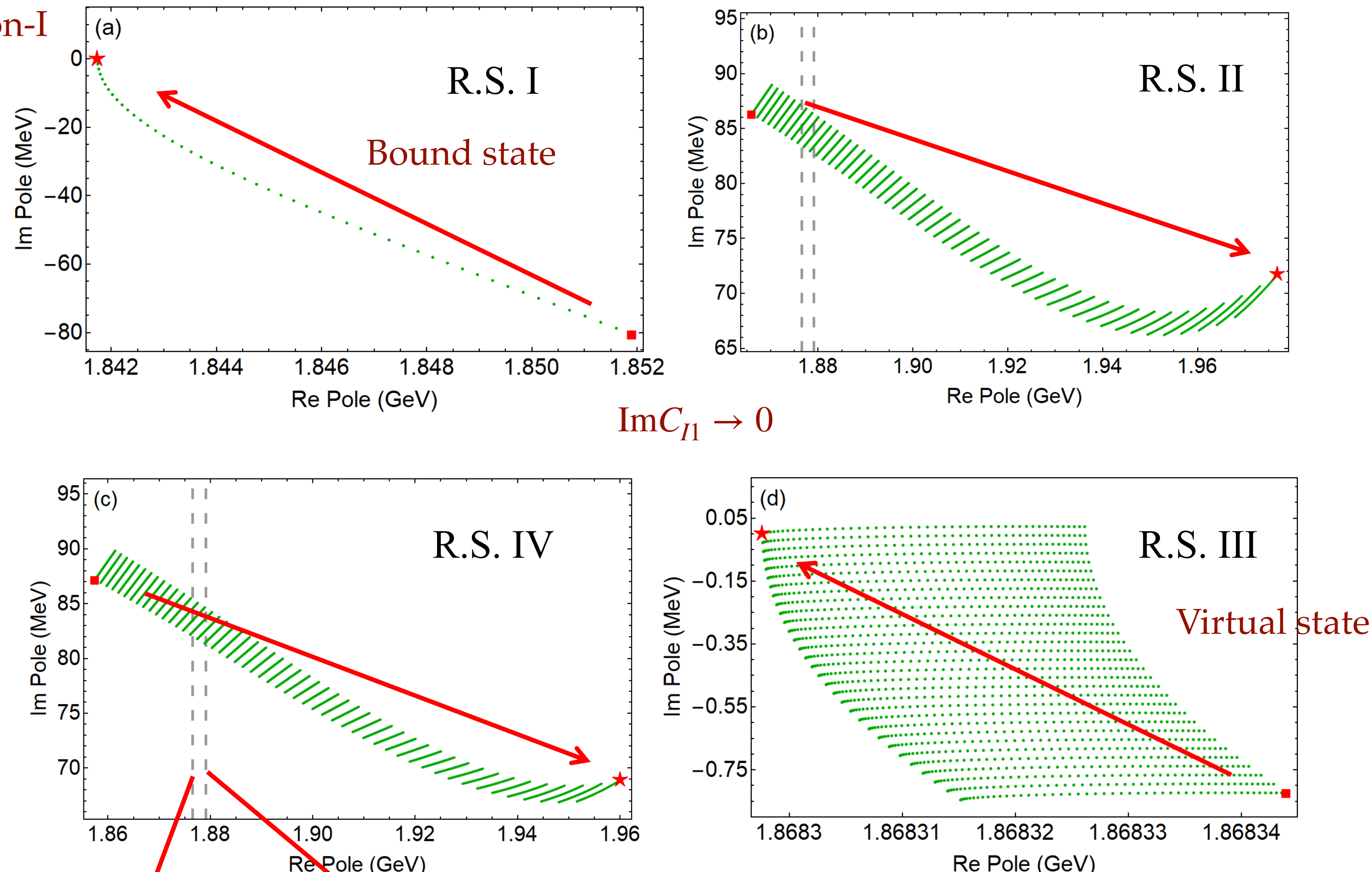
R. S.	I	IV	II	III
Solution-I (MeV)	$1851.90^{+3.02}_{-2.71} - 80.49^{+1.68}_{-1.63}i$	$1866.07^{+22.41}_{-7.20} + 86.34^{+8.65}_{-12.76}i$	$1875.46^{+20.61}_{-6.60} + 87.20^{+9.45}_{-12.92}i$	$1868.34^{+1.66}_{-0.55} - 0.82^{+1.17}_{-1.41}i$
$(g_{pp}, g_{nn})(\mathrm{GeV}^{-1/2})$	(1.61, 1.64)	(3.42, 2.22)	(2.16, 3.42)	(0.98, 0.94)
(g_1, g_0) $(\mathrm{GeV}^{-1/2})$	(0.017, 2.37)	(3.32, 2.36)	(3.31, 2.32)	(1.35,0. 032)
Solution-II (MeV)	$1852.90^{+3.57}_{-3.31} - 82.35^{+2.45}_{-2.80}i$	$1860.31^{+8.77}_{-8.34} + 61.23^{+6.18}_{-5.38}i$	$1855.23^{+8.49}_{-8.07} + 62.01^{+6.02}_{-5.29}i$	$1868.92^{+1.13}_{-1.48} - 2.58^{+1.70}_{-1.86}i$
(g_{pp}, g_{nn}) $(\mathrm{GeV}^{-1/2})$	(1.85, 1.88)	(2.82, 1.80)	(1.76, 2.82)	(0.94, 0.90)
(g_1, g_0) $(\mathrm{GeV}^{-1/2})$	(0.013, 2.89)	(2.68, 1.99)	(2.67, 1.98)	(1.30, 0.033)

- Almost the same two fit results
- All the poles are below the lowest threshold
- C_{01} and C_{11} are set to be complex values
- Only pole on the physical sheet strongly couples to isospin singlet

Niu et al., arXiv:2408.14876 (PRD in press)

The pole trajectories on the complex energy plane

Solution-I



thr_2=1879.13 MeV

thr_1=1876.54 MeV

Niu et al., arXiv:2408.14876 (PRD in press)

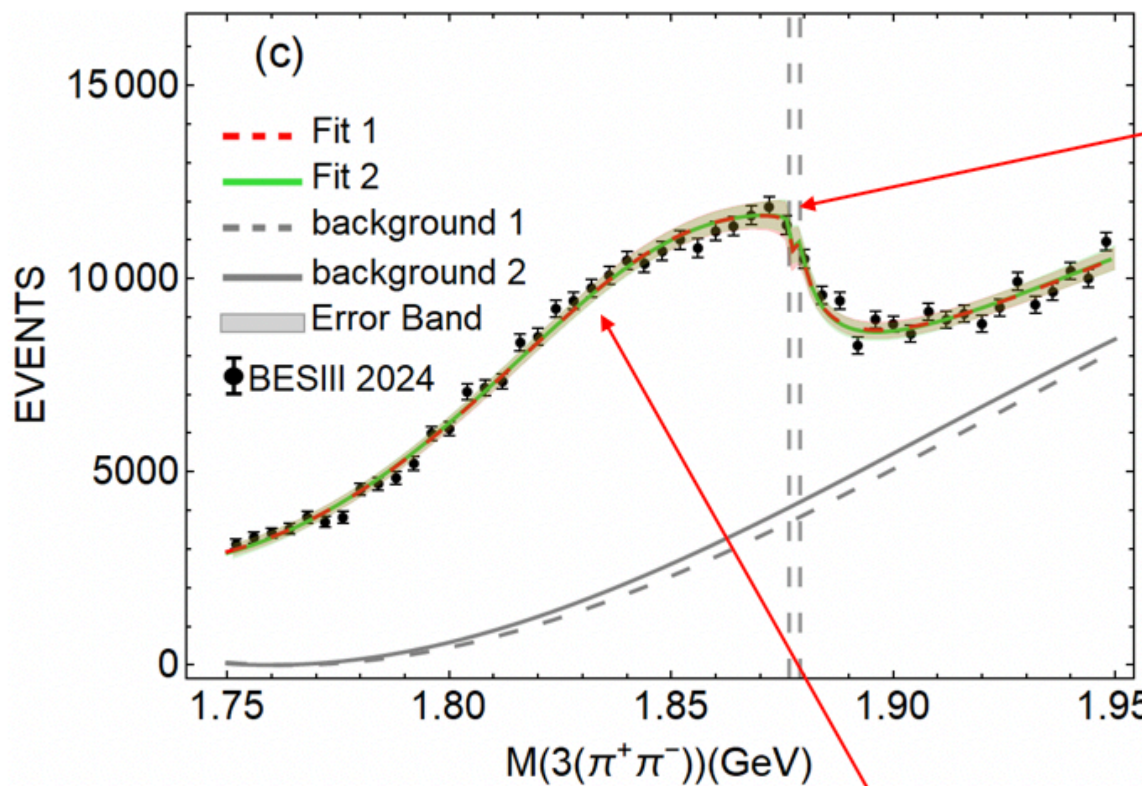
The pole structures of the $X(1840)\,/\,X(1880)$

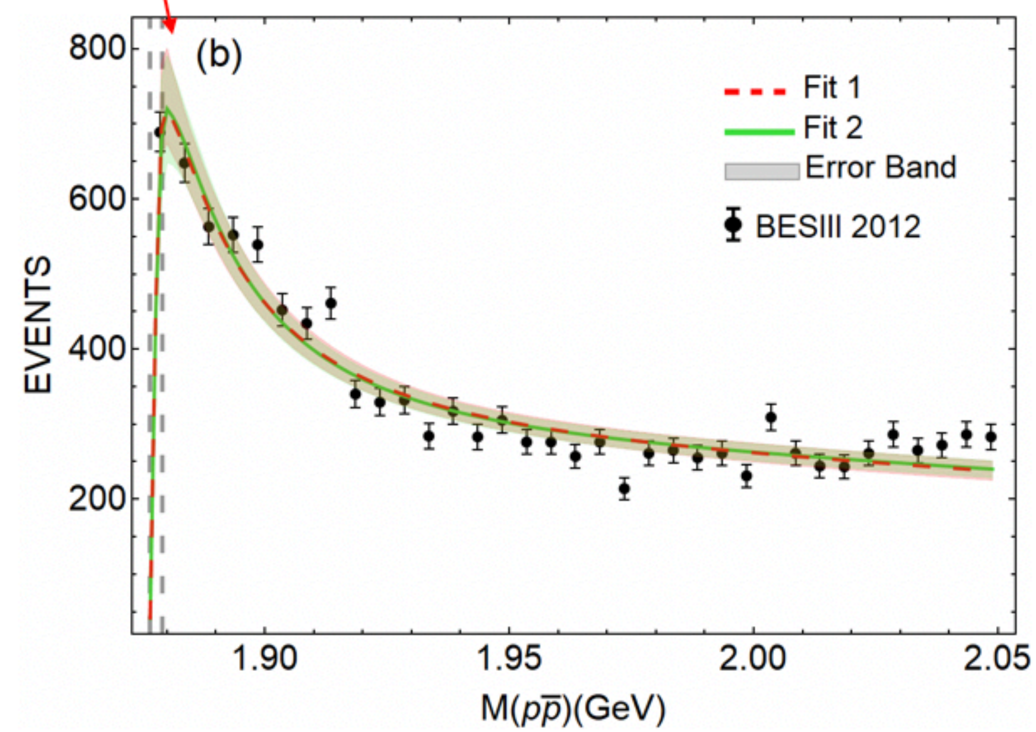
- Further suggested channel $J/\psi \to \rho^0 p\bar{p}$

$(g_1, g_0) = (1.35, 0.032)$

$1868.34^{+1.66}_{-0.55} - 0.82^{+1.17}_{-1.41}i$

On the third R. S. of $T_{N\bar{N}}$(virtual state)





$1851.90^{+3.02}_{-2.71} - 80.49^{+1.68}_{-1.63}i$

On the first R. S. of $T_{N\bar{N}}$ (bound state)

$(g_1, g_0) = (0.0017, 2.37)$

- Further suggested channel $J/\psi \to \omega p\bar{p}$

Niu et al., arXiv:2408.14876 (PRD in press)

The compositeness

Niu et al., arXiv:2408.14876 (PRD in press)

Effective-Range-Expansion：

$$T^{-1}(k) = -\frac{\mu}{2\pi}\left[-\frac{1}{a_0} + \frac{1}{2}r_0k^2 - ik + \mathcal{O}(k^4)\right]$$

$\Rightarrow$

scattering length: $a_0 = \frac{2\pi}{\mu}T(k)|_{k\to 0}$,

effective range: $r_0 = -\frac{2\pi}{\mu^2}\mathrm{Re}\left[\frac{dT^{-1}(E)}{dE}\right]$,

correction from isospin breaking effect:

$$r_0' = r_0 + \sqrt{\frac{1}{2\,\mu\,\Delta}}$$

Baru et al., PLB833,137290, Du et al., PRD105,014024

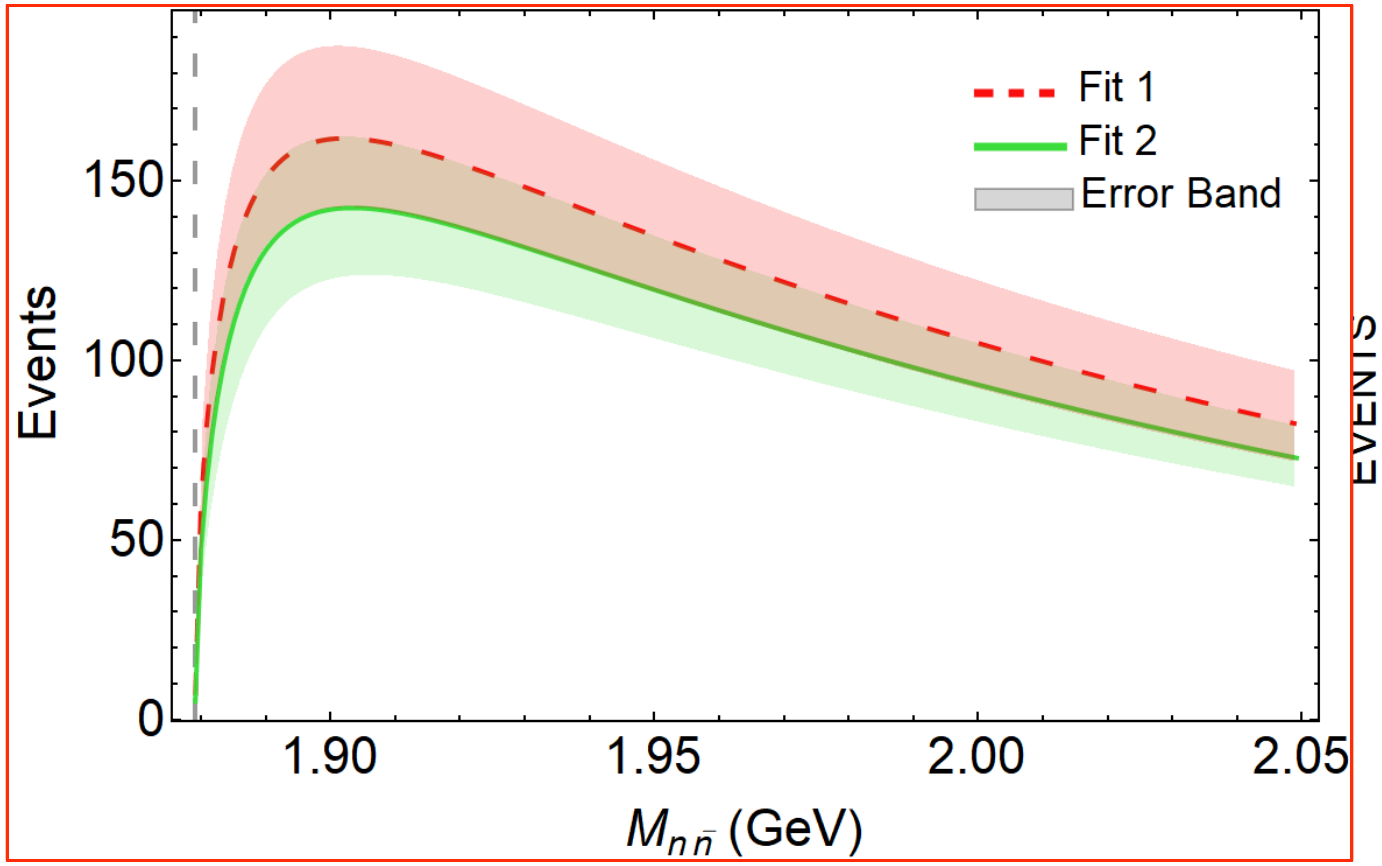
Compositeness: $\bar{X} = \frac{1}{\sqrt{1+2\left|\frac{r_0'}{\mathrm{Re}[a_0]}\right|}}$

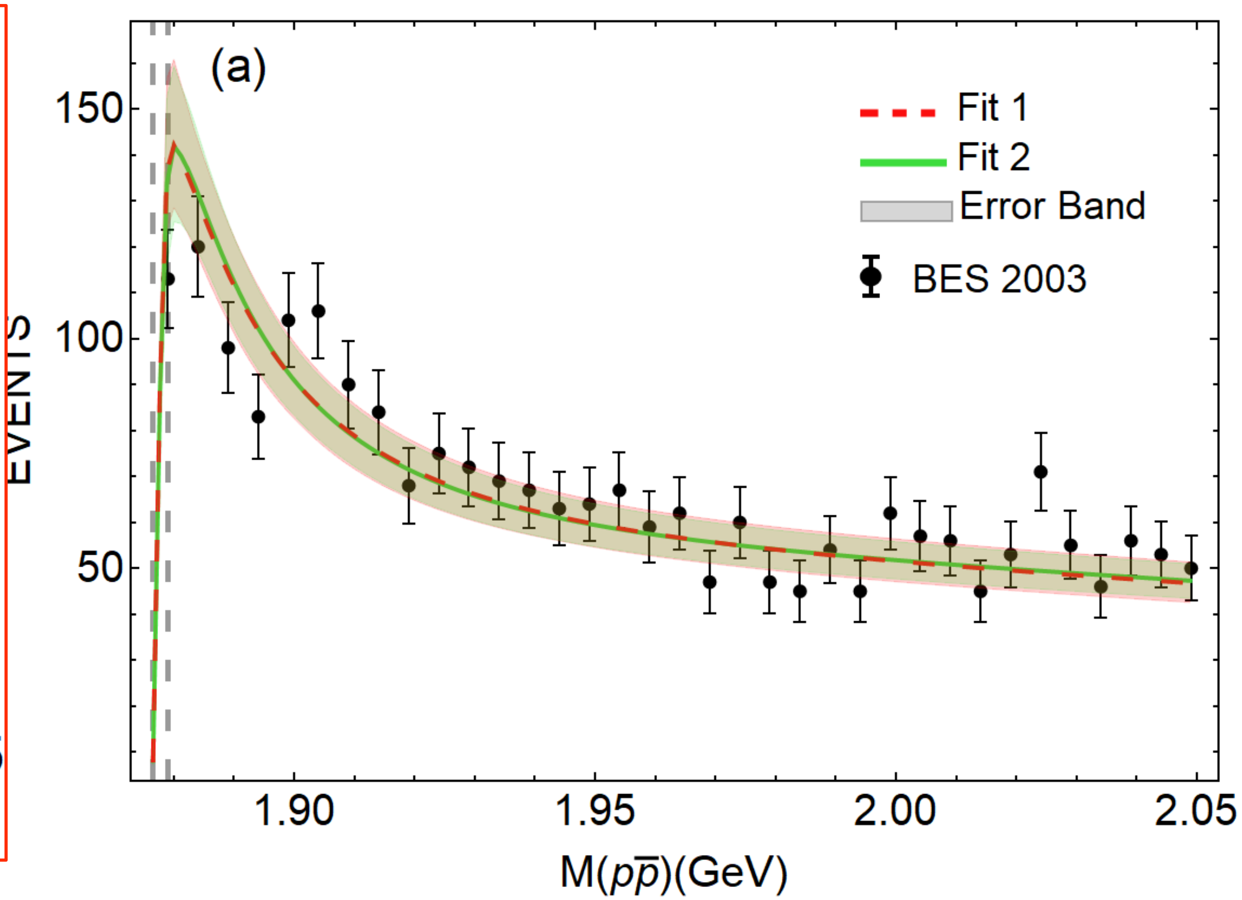
	r_0 (fm)	r_0' (fm)	a_0(fm)	$\bar{X}$
Solution-I	-2.30	1.70	-65.46-31.94i	0.98
Solution-II	1.50	5.50	-56.52-27.16i	0.91

There exists $p\bar{p}$ dynamical generated states.

The predicted $n\bar{n}$ line shapes

Niu et al., arXiv:2408.14876 (PRD in press)





- A clear threshold enhancement, but not as significant as that in $p\bar{p}$ channel
- Can be used to compare with the further measurement

Summary and outlook

- Construct contact $N\bar{N}$ respecting chiral symmetry
- Describe the line shapes in both $J/\psi \to \gamma p\bar{p}$, $J/\psi \to \gamma 3(\pi^+\pi^-)$ simultaneously
- The annihilation contribution is important
- Extract the pole positions of the two X states
- There exists a $p\bar{p}$ dynamic generated state

$\mathrm{RS-I}: m = 1852\ \mathrm{MeV},\ \Gamma = 160\ \mathrm{MeV}$ (bound state)

$\mathrm{RS-III}: m = 1868\ \mathrm{MeV},\ \Gamma = 2\ \mathrm{MeV}$ (virtual state)

Thank you very much for your attention!

Thank the organizers for organizing the nice workshop in such a nice place!