Charged charmoniumlike structures in the $e^+e^- \to \psi(3686)\ \pi^+\ \pi^-$ process based on the ISPE mechanism

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Based on arXiV: 1905.05650 [hep-ph]

Together with Xiang Liu, Dian-Yong Chen, Takayuki Matsuki

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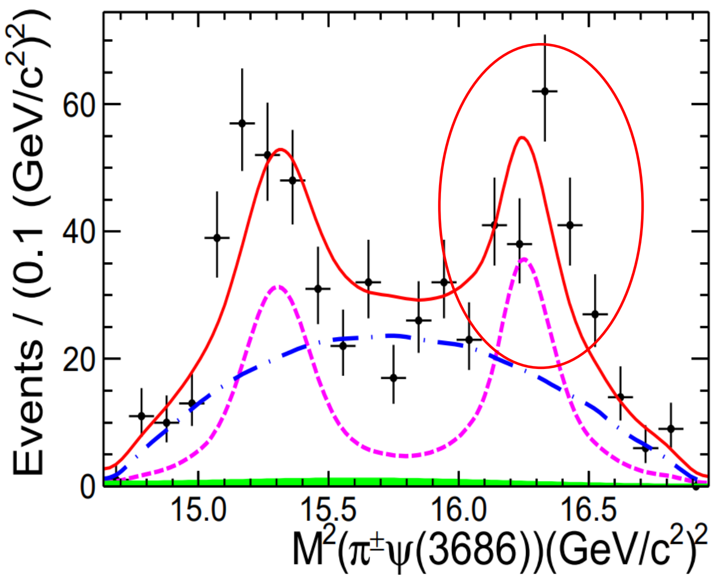
Contents

Experimental results

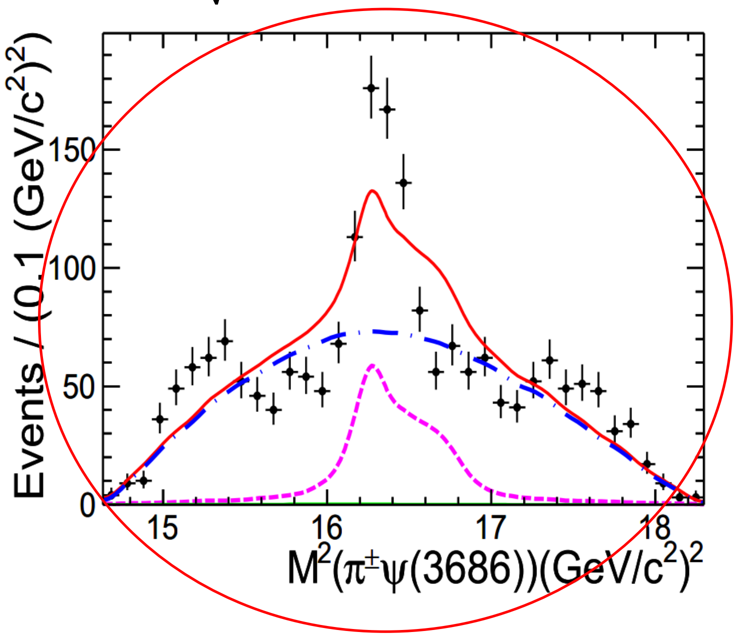
BESIII, Phys. Rev. D 96, 032004 (2017)

$$e^+e^- \to \psi(3686)\pi^+\pi^- \Rightarrow \begin{cases} Cross\ sections\ at\ 16\ different\ energies \\ \psi(3686)\pi^+\ and\ \pi^+\pi^-\ invariant\ mass\ spectrums\ at\ 6\ energies \end{cases}$$

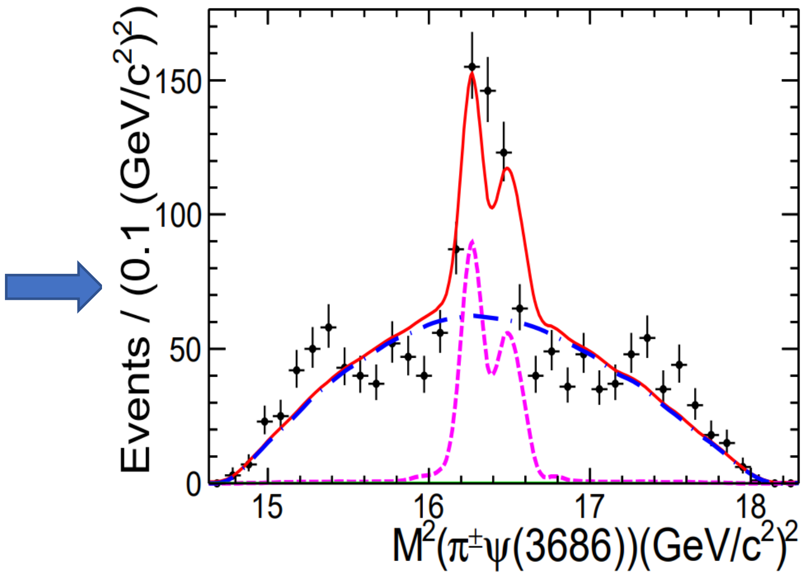
$\sqrt{s} = 4.258$ GeV



$\sqrt{s} = 4.416$ GeV



$M^2(\pi^+\pi^-) > 0.3\ (\mathrm{GeV}/c^2)^2$



Peak @ M=4.032 GeV

A review on ISPE mechanism

Particle	Mass（MeV)	Width (MeV)	Process	Experiment
$Z_b(10610)$	10607.2±2.0	18.4±2.4	$e^+e^- \to \pi^+ \pi^- \Upsilon(nS)/h_b(nP)$	Belle
$Z_b(10650)$	10652.2±1.5	11.5±2.2	$e^+e^- \to \pi^+ \pi^- \Upsilon(nS)/h_b(nP)$	Belle
$Z_c(3900)$	3889.0±3.6±4.9	46±10±20	$e^+e^- \to Y(4260) \to \pi^+ \pi^- J/\psi$	BESIII
$Z_c(3900)$	3894.5±6.6±4.5	63±24±26	$e^+e^- \to Y(4260) \to \pi^+ \pi^- J/\psi$	Belle
$Z_c(3900)$	3886±4±2	37±4±8	$e^+e^- \to \psi(4160) \to \pi^+ \pi^- J/\psi$	CLEO-c
$Z_c(4020)$	4022.9±0.8±2.7	7.9±2.7±2.6	$e^+e^- \to Y(4260) \to \pi^+ \pi^- h_c$	BESIII
$Z_c(3885)$	3882.2±1.1±1.5	26.5±1.7±2.1	$e^+e^- \to Y(4260) \to \pi\,(D\overline{D^*})$	BESIII
$Z_c(4025)$	4026.3±2.6±3.7	24.8±5.6±7.7	$e^+e^- \to Y(4260) \to \pi\,(D^*\overline{D^*})$	BESIII

$$Resonance\ explaination \Rightarrow \begin{cases} Molecular\ state \\ Tetraquark\ state \end{cases}$$

➡

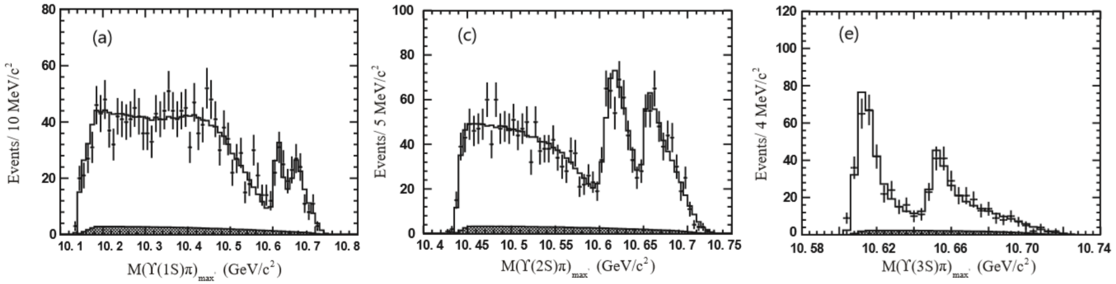
(1). W. Chen, H. X. Chen, X. Liu, et.al., Phys. Rept. 639 (2016) 1-121.
(2). Y. R. Liu, H. X. Chen, X. Liu, et.al., arXiV: 1903.11976 [hep-ph].
。。。。。。

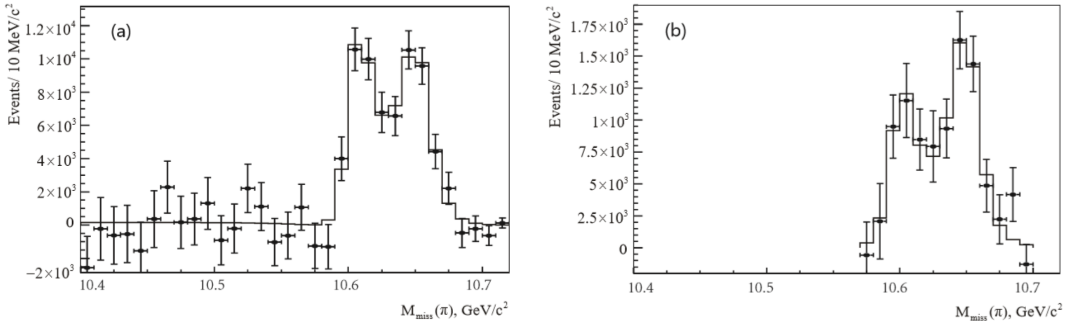
$$Non-Resonance\ explaination \Rightarrow \begin{cases} CUSP\ effect: D.V.Bugg, E.S.Swanson \\ Triangle\ singularity: X.H.Liu, A.P.Szczepaniak \\ ISPE\ mechanism: D.Y.Chen, X.Liu, T.Matsuki \end{cases}$$

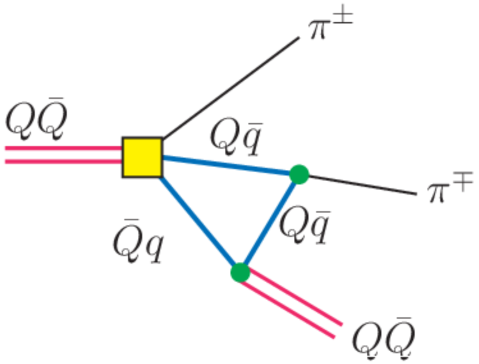
Belle, 2011: $Z_b(10610)$ and $Z_b(10650)$

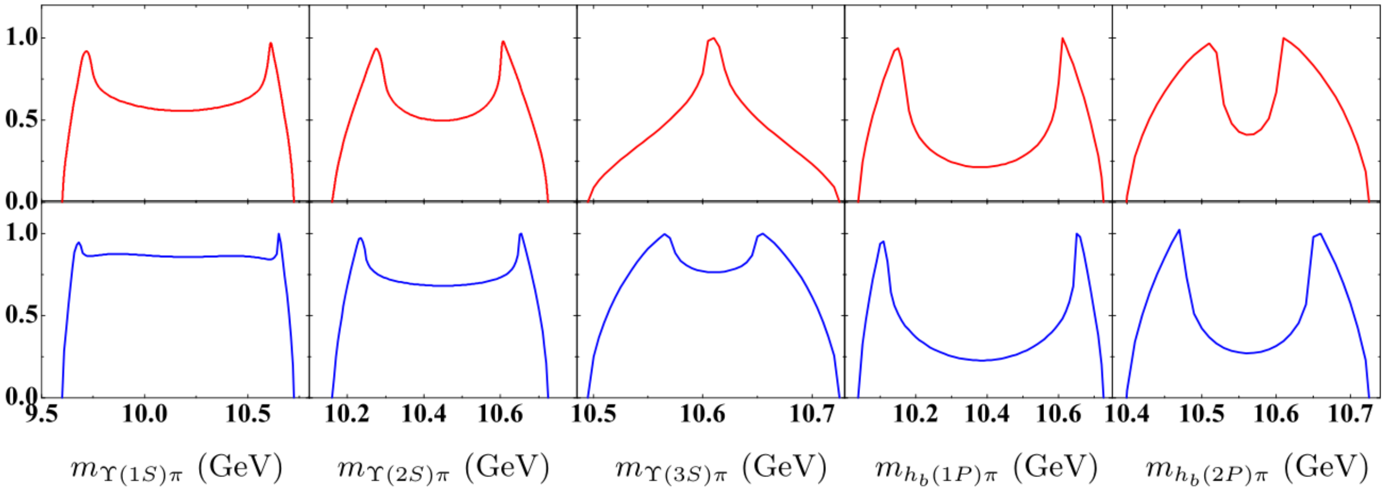
D.-Y. Chen, Xiang Liu, Phys. Rev. D84: 074016, (2011)

$\Upsilon(5S) \to \pi^+ \pi^- \Upsilon(nS)$
$\Upsilon(5S) \to \pi^+ \pi^- h_b(nP)$



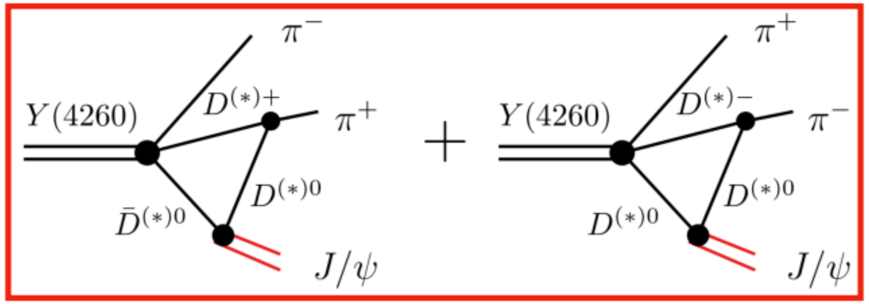


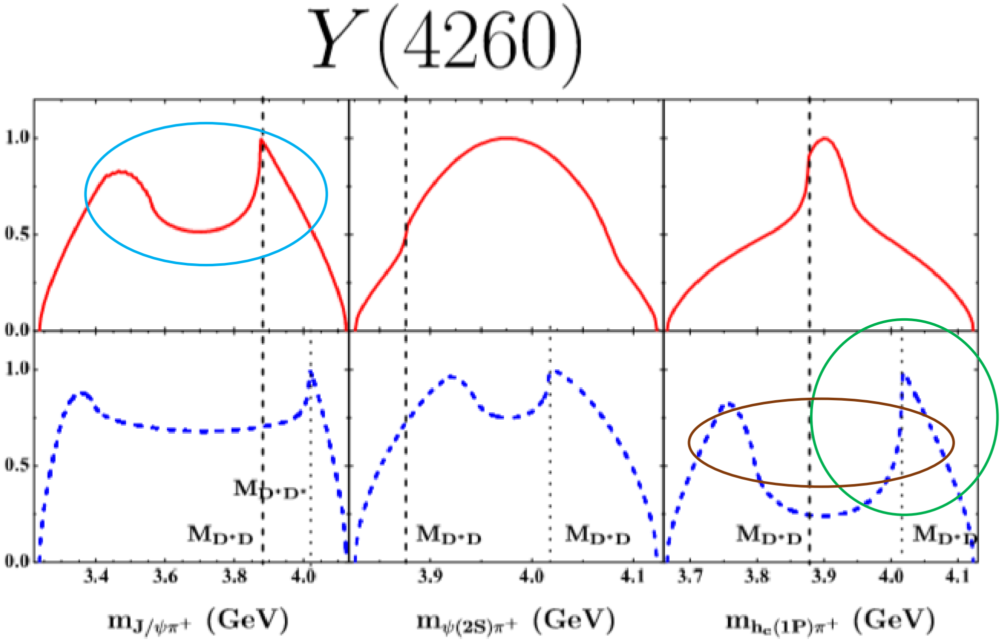




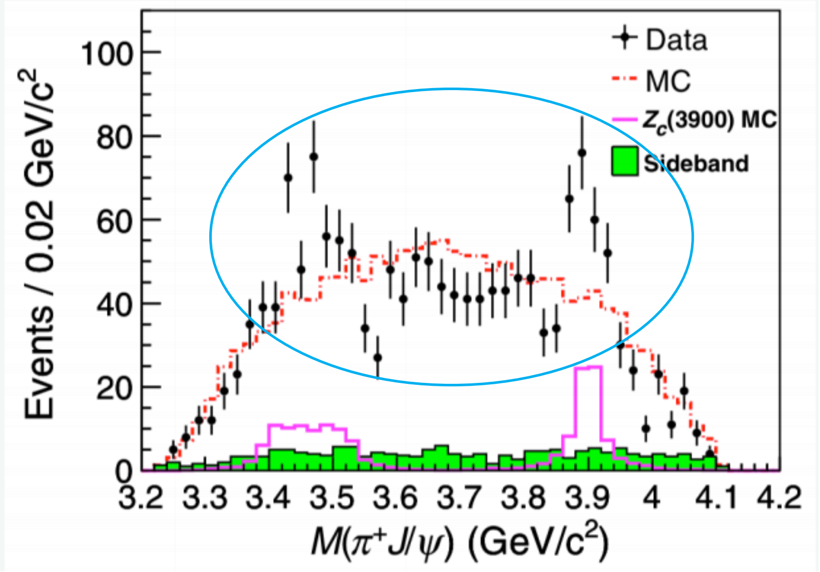
Dian-Yong Chen, Xiang Liu: $Z_c(3900)$ and $Z_c(4020)$

Phys. Rev. D84: 034032, (2011):

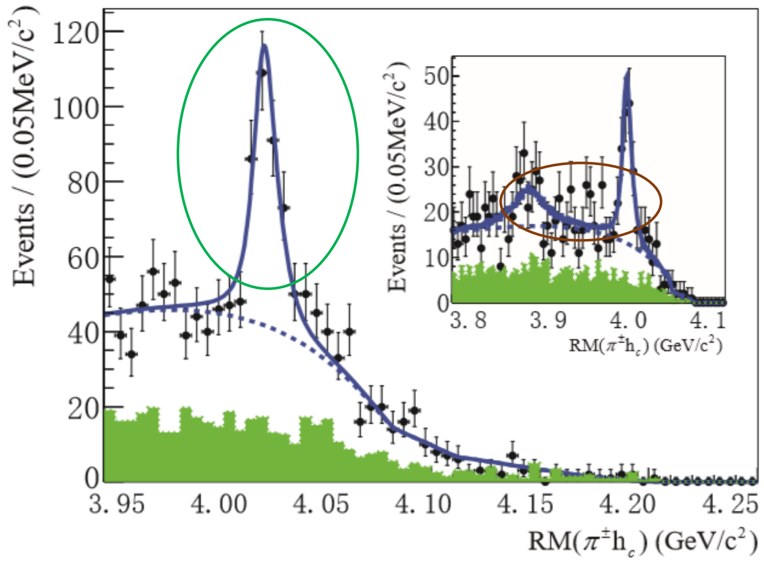




BESIII, Phys. Rev. Lett., 110, 252001, (2013)



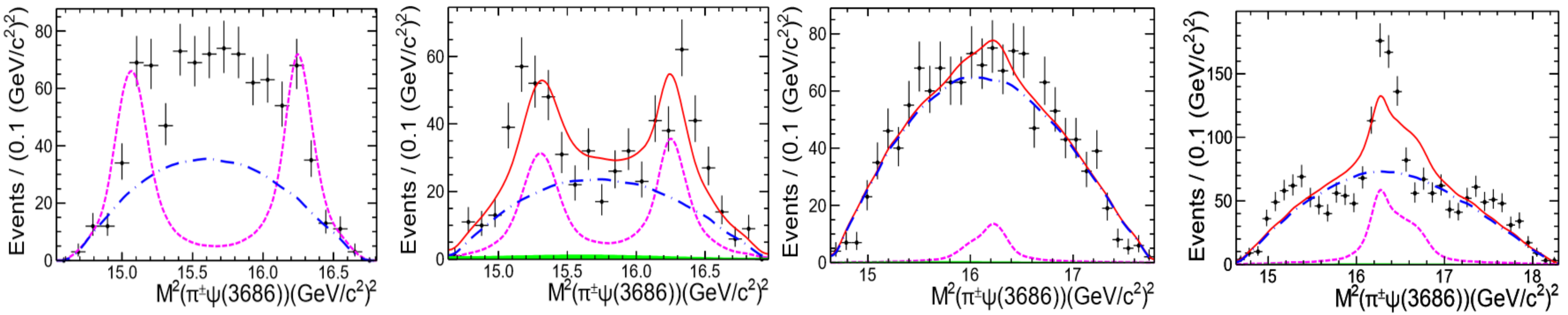
BESIII, Phys. Rev. Lett., 111, 242001, (2013)



Motivation

BESIII, Phys. Rev. D96: 032004, (2017)

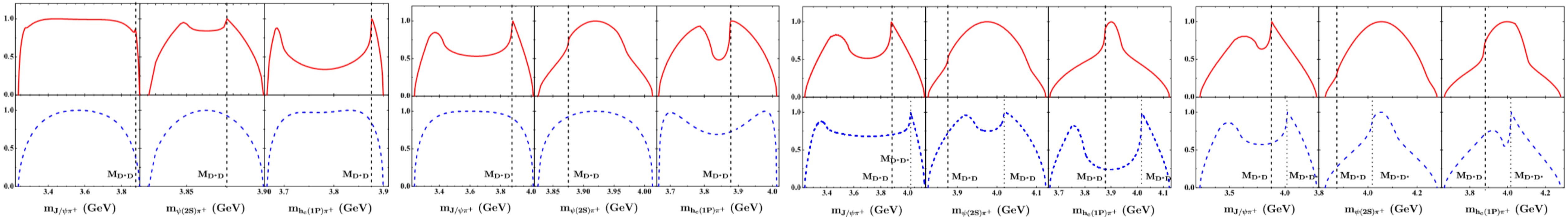
$\sqrt{s} = 4.226$ GeV | $\sqrt{s} = 4.258$ GeV | $\sqrt{s} = 4.358$ GeV | $\sqrt{s} = 4.416$ GeV



ISPE mechanism: Phys. Rev. D84: 034032, (2011)

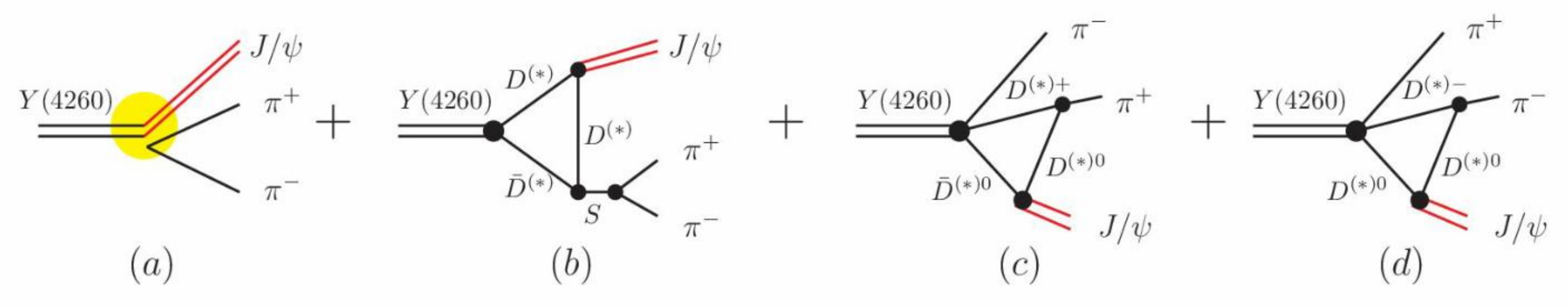
Similar phenomena

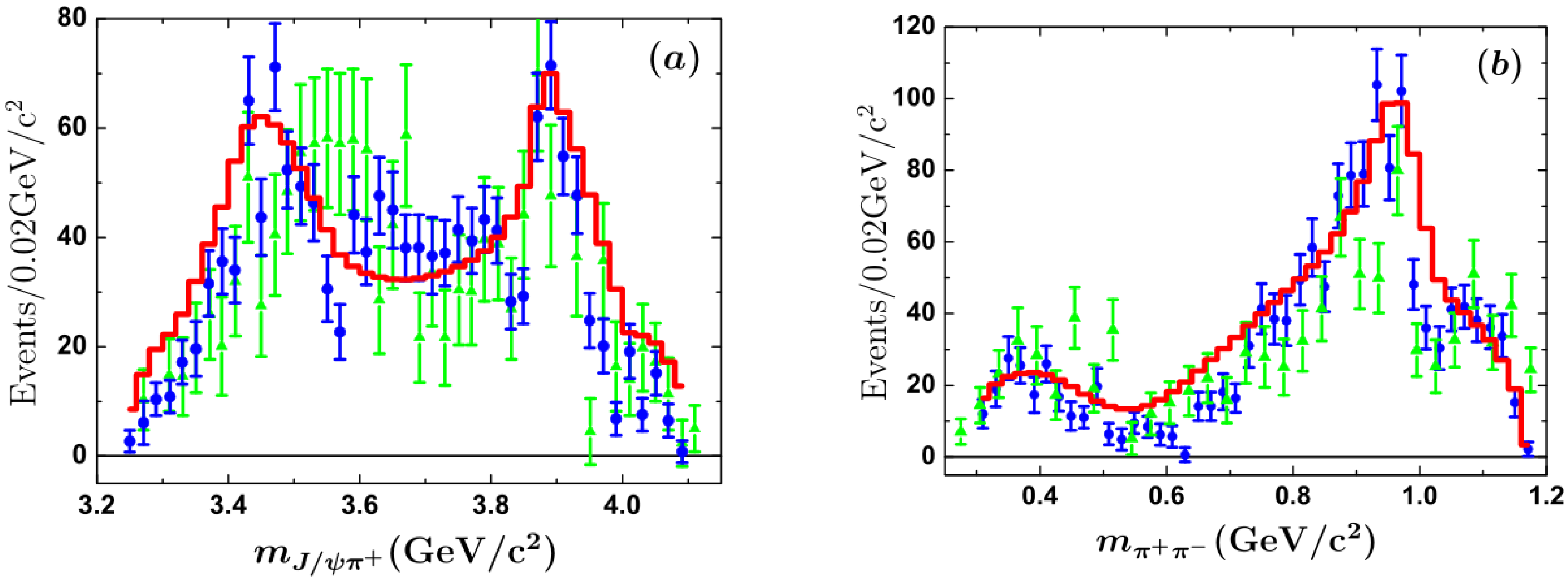
$\psi(4040)$ | $\psi(4160)$ | $Y(4260)$ | $\psi(4415)$



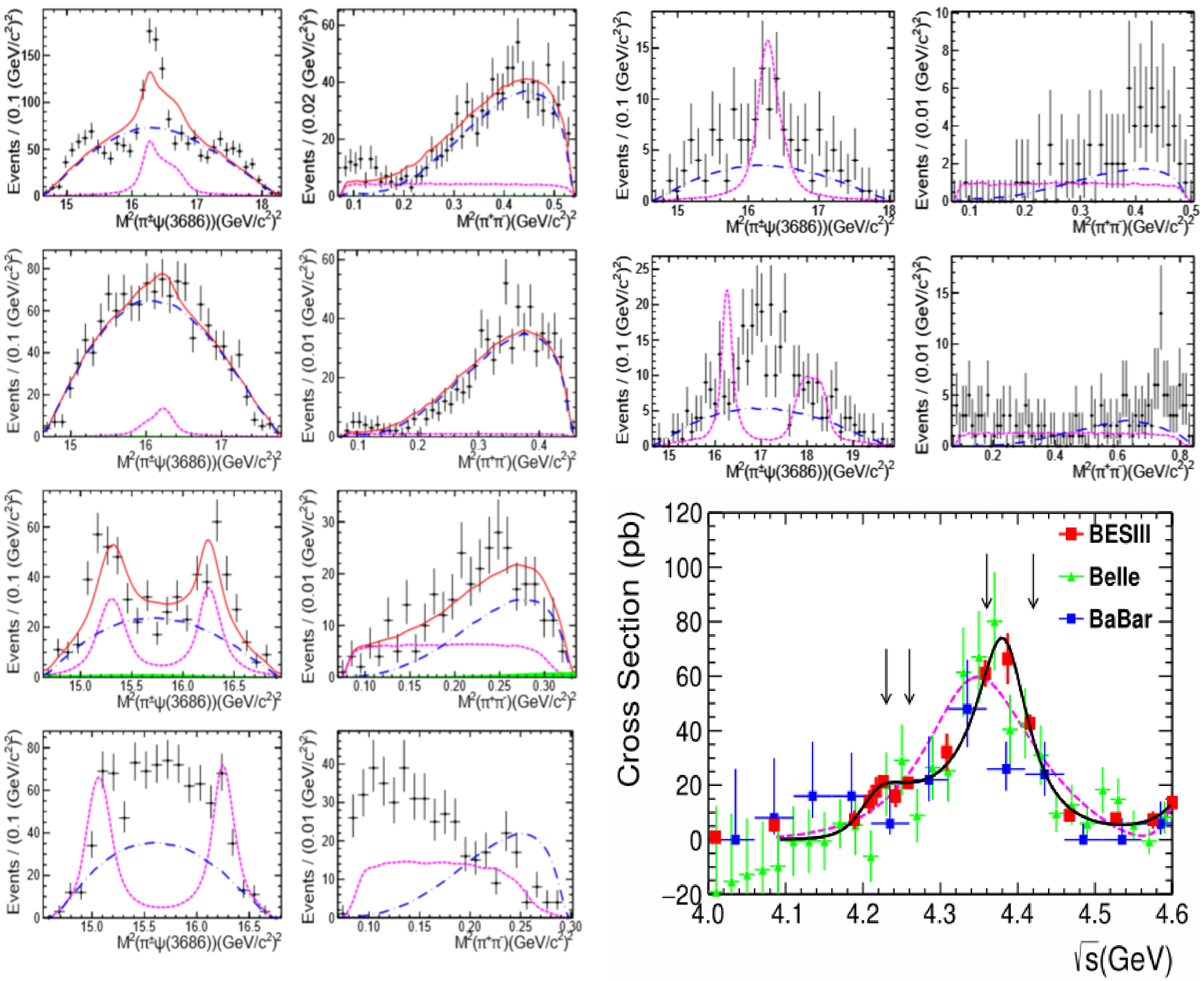
Dian-Yong Chen, Xiang Liu, Phys. Rev. D88: 036008, (2013)

2013, BESIII, Belle : $e^+e^- \to Y(4260) \to \pi^+ \pi^- J/\psi$, $Z_c(3900)$





BESIII, Phys. Rev. D 96, 032004 (2017):



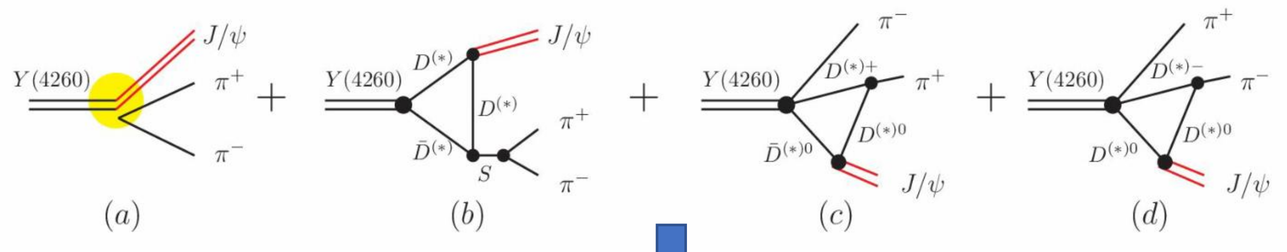
Doing a combined fit on the cross section in addition with all the invariant mass spectrums.

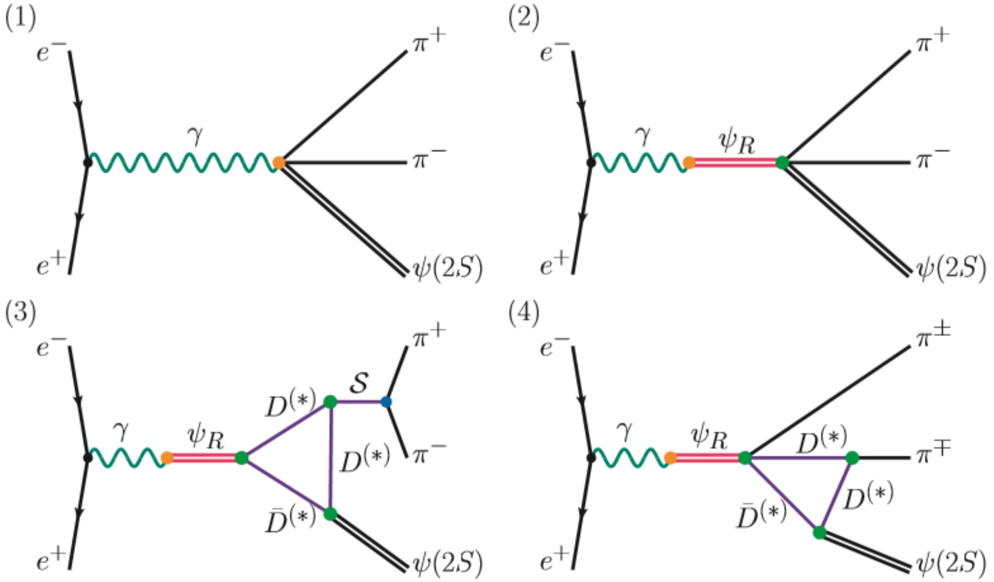
1. Reproducing the structure on the $\psi(3686)\ \pi^+$ mass spectrum

2. Testifying the ISPE mechanism

Model

Dian-Yong Chen, Xiang Liu, Phys. Rev. D88: 036008, (2013)





(1). Decay directly: background

$$\mathcal{M}^{(1)}_{\rm NoR} = \bar{v}(k_2)\gamma^{\mu}u(k_1)g_{\rm NoR}e\frac{-g_{\mu\nu}}{s}\epsilon^{*\nu}_{\psi'}\mathcal{F}_{\rm NoR}(s),$$

$$\mathcal{F}_{\rm NoR}(s) = e^{-a_{\rm NoR}(\sqrt{s}-\Sigma m_f)^2},$$

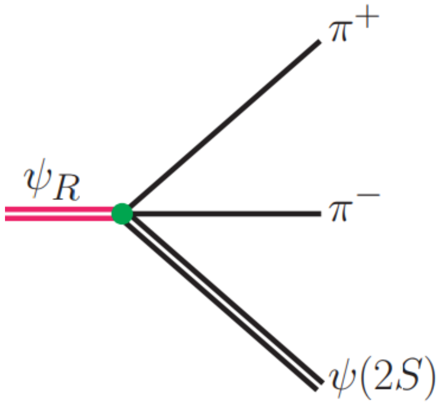
(2)-(4). Decay with intermediate ψ_R

$$\mathcal{M}^{(i)}_{R} = \bar{v}(k_2)\gamma^{\alpha}u(k_1)e\frac{-g_{\alpha\beta}}{s}\frac{em_R^2}{f_R}\frac{1}{s-m_R^2+im_R\Gamma_R} \times\left(-g^{\beta\mu}+\frac{p_0^{\beta}p_0^{\mu}}{m_R^2}\right)\mathcal{A}^{(i)}_{\mu\zeta}\epsilon^{*}_{\psi'}(p_3)^{\zeta}\mathcal{F}_R(s),$$

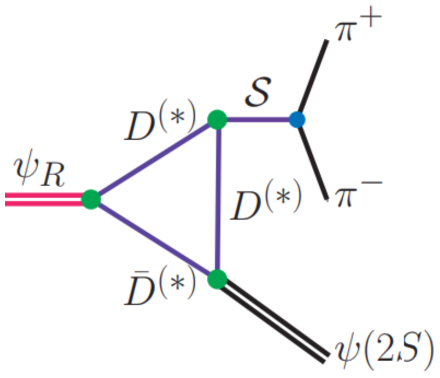
$$\mathcal{F}_R(s) = e^{-a_R[\sqrt{s}-m_R]}$$

Decay amplitudes

Decay amplitudes



$$\mathcal{A}^{(2)}_{\mu\nu} = \frac{F_{\rm Dir}}{f_\pi^2} g_{\mu\nu} \Big\{ \Big[m_{\pi\pi}^2 - \kappa_{\rm Dir}(\Delta M)^2 \Big(1 + \frac{2m_\pi^2}{m_{\pi\pi}^2}\Big)\Big]_{\rm S-wave} + \Big[\frac{3}{2}\kappa_{\rm Dir}\left((\Delta M)^2 - m_{\pi\pi}^2\right)\Big(1 - \frac{4m_\pi^2}{m_{\pi\pi}^2}\Big) \times \Big(\cos^2\alpha - \frac{1}{3}\Big)\Big]_{\rm D-wave}\Big\},$$

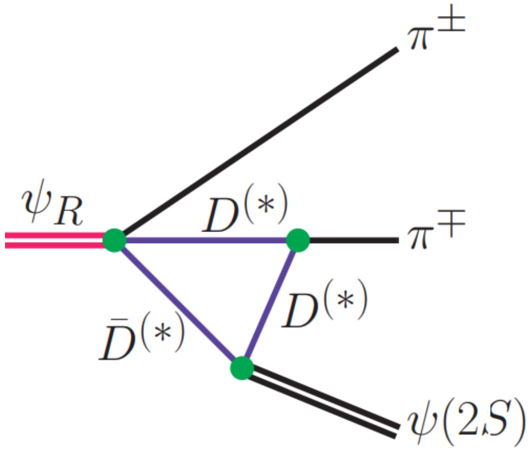


$$\mathcal{A}^{(3)}_{\mu\nu} = \frac{1}{m_{\pi\pi}^2 - m_\sigma^2 + i m_\sigma \Gamma_\sigma}\left(f_\sigma g_{\mu\nu} + e^{i\varphi_\sigma} g_\sigma p_{0\nu} p_{3\mu}\right),$$

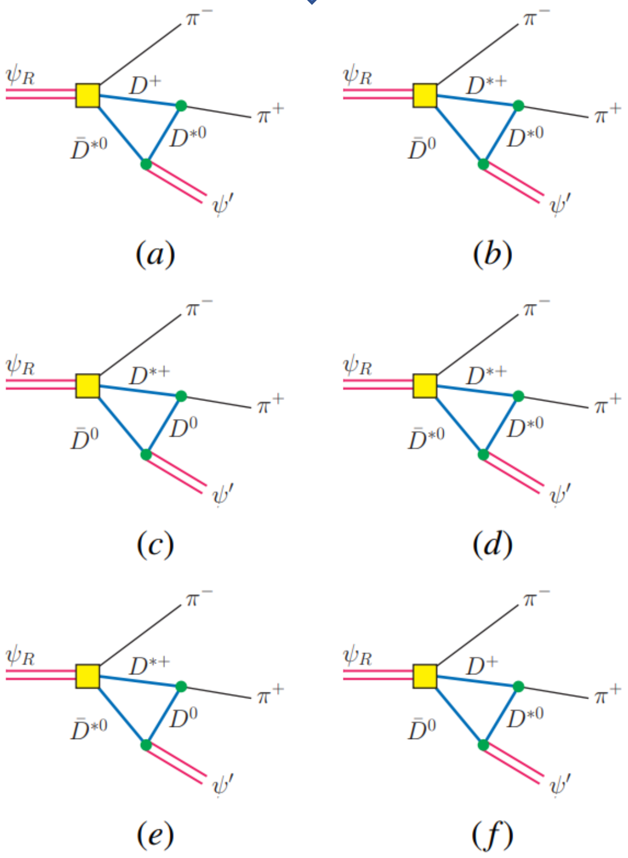
Form of parametrization,
Reduce the parameters.

$$\Gamma_\sigma(m_{\pi\pi}) = \Gamma_\sigma \frac{m_\sigma}{m_{\pi\pi}} \frac{\left|\vec{P}(m_{\pi\pi})\right|}{\left|\vec{P}(m_\sigma)\right|}$$

The effect caused by the width of σ



$$
\begin{aligned}
\mathcal{A}^{(4)}_{\mu\nu} &= C_{00}g_{\mu\nu} + C_{12}p_{1\mu}p_{2\nu} + C_{13}p_{1\mu}p_{3\nu} \\
&\quad + C_{22}p_{2\mu}p_{2\nu} + C_{23}p_{2\mu}p_{3\nu} \\
&\quad + C_{32}p_{3\mu}p_{2\nu} + C_{33}p_{3\mu}p_{3\nu},
\end{aligned}
$$



$$
\mathcal{A}_{\mu\zeta} = 2\sum_{i=a}^{f}\left(\mathcal{A}^{(i)}_{\mu\zeta} + \mathcal{A}^{(i)}_{\mu\zeta[p_2\rightleftharpoons p_3]}\right),
$$

$$
\begin{aligned}
&\mathcal{L}_{\psi D^{(*)}D^{(*)}\pi} \\
&= -ig_{RDD\pi}\varepsilon^{\mu\nu\alpha\beta}\psi_\mu\partial_\nu D\partial_\alpha\pi\partial_\beta\bar{D} + g_{RD^*D\pi}\psi^\mu(D\pi\bar{D}^*_\mu + D^*_\mu\pi\bar{D}) \\
&\quad -ig_{RD^*D^*\pi}\varepsilon^{\mu\nu\alpha\beta}\psi_\mu D^*_\nu\partial_\alpha\pi\bar{D}^*_\beta - ih_{RD^*D^*\pi}\varepsilon^{\mu\nu\alpha\beta}\partial_\mu\psi_\nu D^*_\alpha\pi\bar{D}^*_\beta.
\end{aligned}
$$

$$
\begin{aligned}
&\mathcal{L}_{D^*D^{(*)}\pi} \\
&= ig_{D^*D\pi}(D^*_\mu\partial^\mu\pi\bar{D} - D\partial^\mu\pi\bar{D}^*_\mu) - g_{D^*D^*\pi}\varepsilon^{\mu\nu\alpha\beta}\partial_\mu D^*_\nu\pi\partial_\alpha\bar{D}^*_\beta.
\end{aligned}
$$

$$
\begin{aligned}
&\mathcal{L}_{\psi D^{(*)}D^{(*)}} \\
&= ig_{\psi DD}\psi_\mu(\partial^\mu D\bar{D} - D\partial^\mu\bar{D}) - g_{\psi D^*D}\varepsilon^{\mu\nu\alpha\beta}\partial_\mu\psi_\nu(\partial_\alpha D^*_\beta\bar{D} \\
&\quad + D\partial_\alpha\bar{D}^*_\beta) - ig_{\psi D^*D^*}\{\psi^\mu(\partial_\mu D^{*\nu}\bar{D}^*_\nu - D^{*\nu}\partial_\mu\bar{D}^*_\nu) \\
&\quad + (\partial_\mu\psi_\nu D^{*\nu} - \psi_\nu\partial_\mu D^{*\nu})\bar{D}^{*\mu} + D^{*\mu}(\psi^\nu\partial_\mu\bar{D}^*_\nu - \partial_\mu\psi^\nu\bar{D}^*_\nu)\}.
\end{aligned}
$$

Parameters

Parameter	Source
g_{NoR}, a_{NoR}	Background
Φ_{Dir}, F_{Dir}, κ_{Dir}	Multipole expansion
Φ_{σ}, f_{σ}, g_{σ}, φ_{σ}	Triangle loop
Φ_{ISPE}, $g_{R\,D^{(*)}\,D^{(*)}\pi}$	ISPE mechanism
a_R	Form factor

a_R : *a parameter in the resonance form factor,*

ϕ_{Dir} : *a phase angle of the direct production amplitude,*

F_{Dir}, κ_{Dir} : *parameters in the direct production amplitude,*

ϕ_{σ} : *a phase angle of the σ meson production amplitude,*

f_{σ}, g_{σ} : *S and D wave coupling constants in the σ meson production amplitude,*

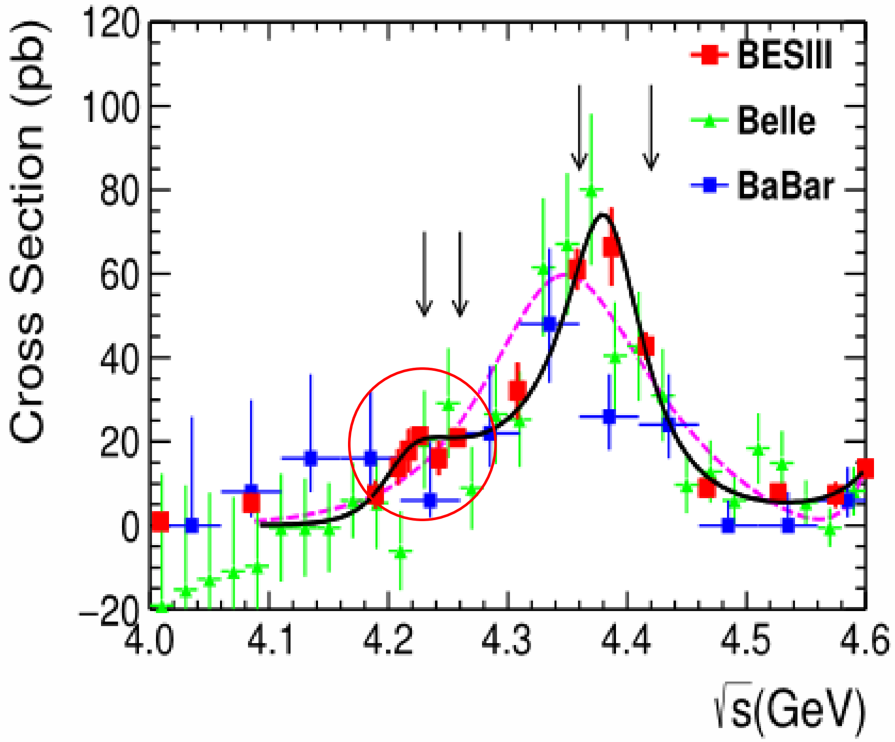
φ_{σ} : *a relative phase angle between S and D wave terms in the σ meson production amplitude,*

ϕ_{ISPE} : *a phase angle of the* ISPE *amplitude,*

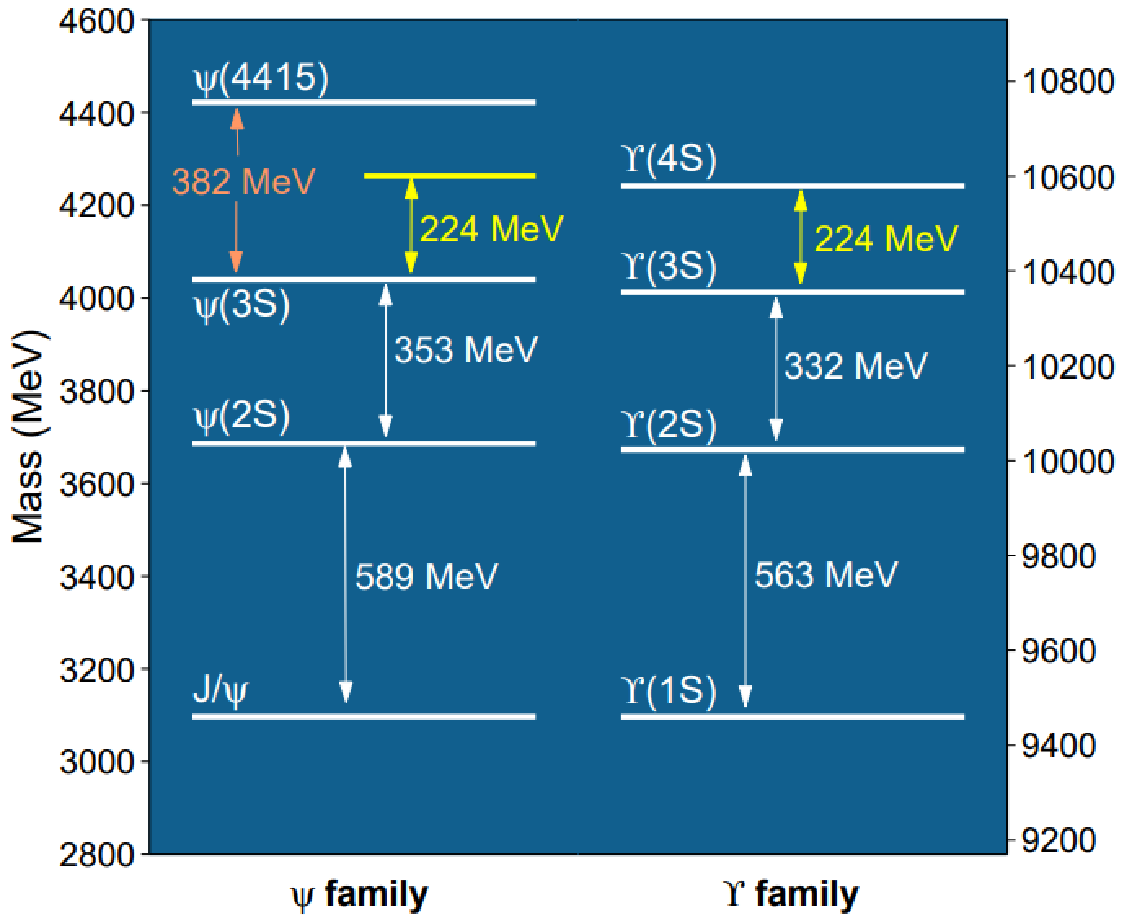
$g_{RD^{(*)}\bar{D}^{(*)}\pi}$: *coupling constants of the four-particle interactions in the* ISPE *mechanism.*

Fit by three resonances

ψ(nS) between 4.1 and 4.6 GeV:
$\psi(4160), \psi(4415)$

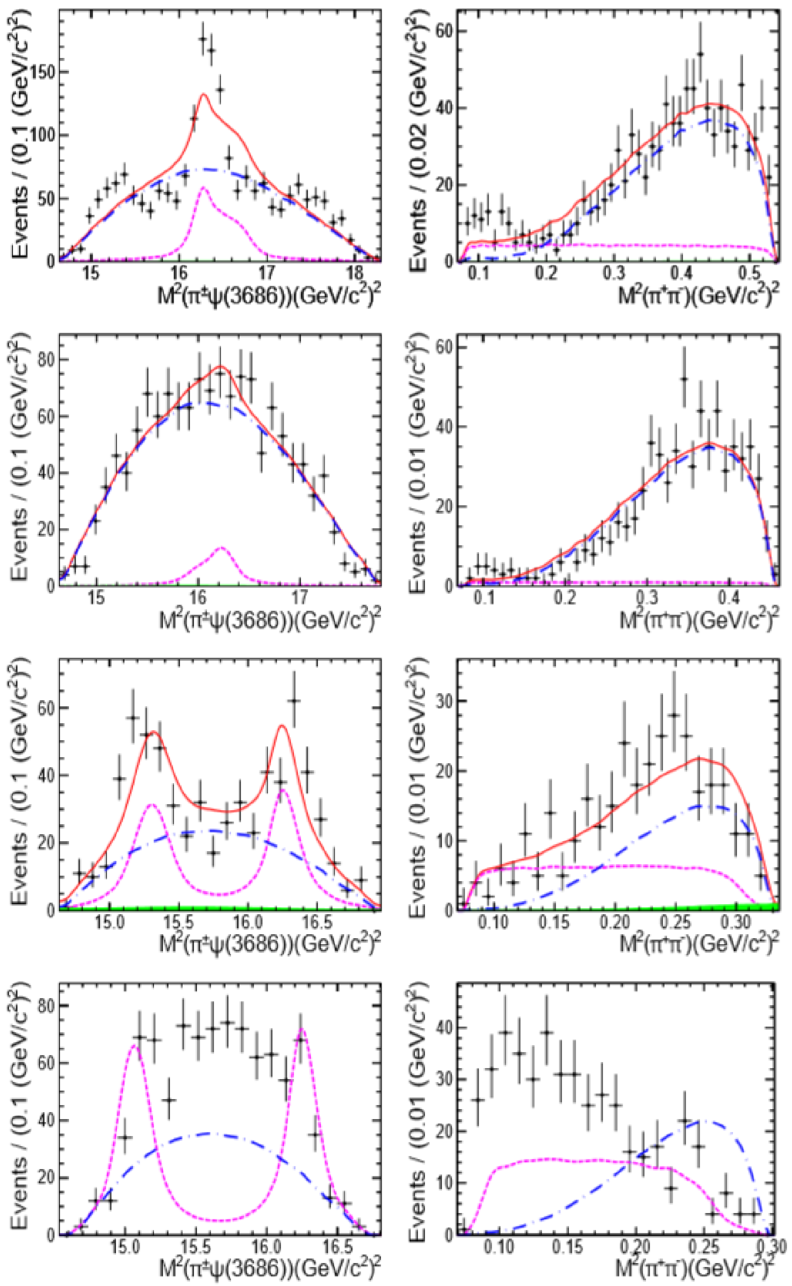


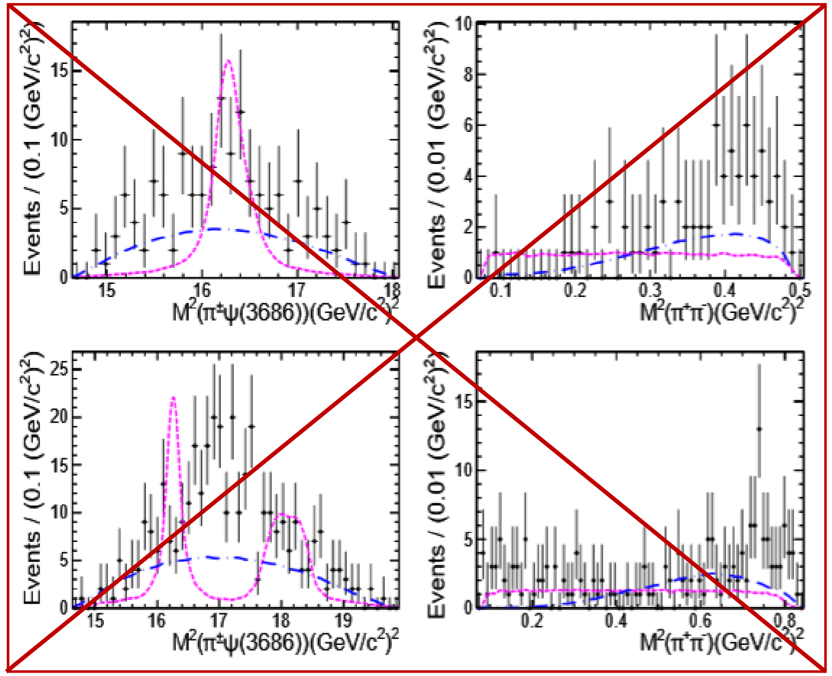
Enhancement around 4.22 GeV ⇒ missing $\psi(4S)$ [1-4]

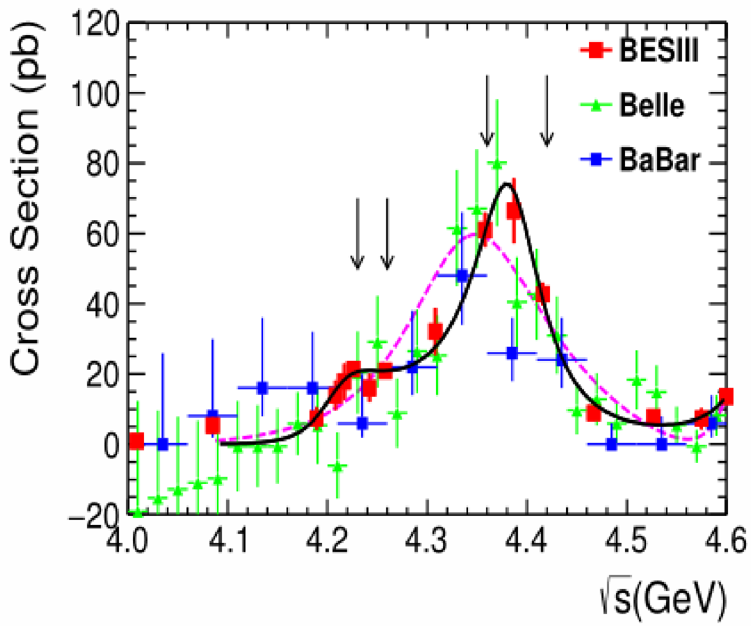


[1]. L. P. He, X. Liu, et.al., Eur. Phys. J. C74, 3208 (2014).
[2]. D. Y. Chen, X. Liu, et.al., Phys. Rev. D91, 094023 (2015).
[3]. D. Y. Chen, X. Liu, et.al., Phys. Rev. D93, 034028 (2016).
[4]. J. Z. Wang, X. Liu, et.al., Phys. Rev. D99, 114003 (2019).

BESIII, Phys. Rev. D 96, 032004 (2017):







The events are relatively small, the errors are relatively large.

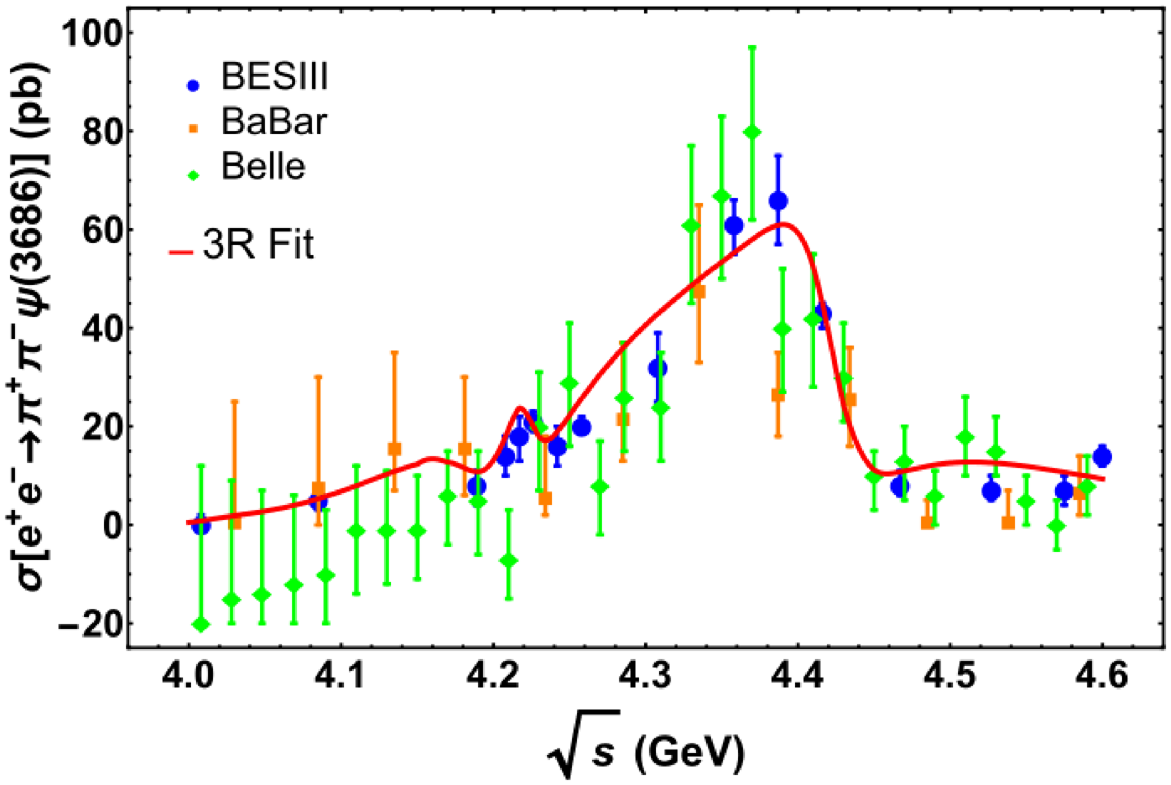
Fit one cross section in addition with 8 invariant mass spectrums

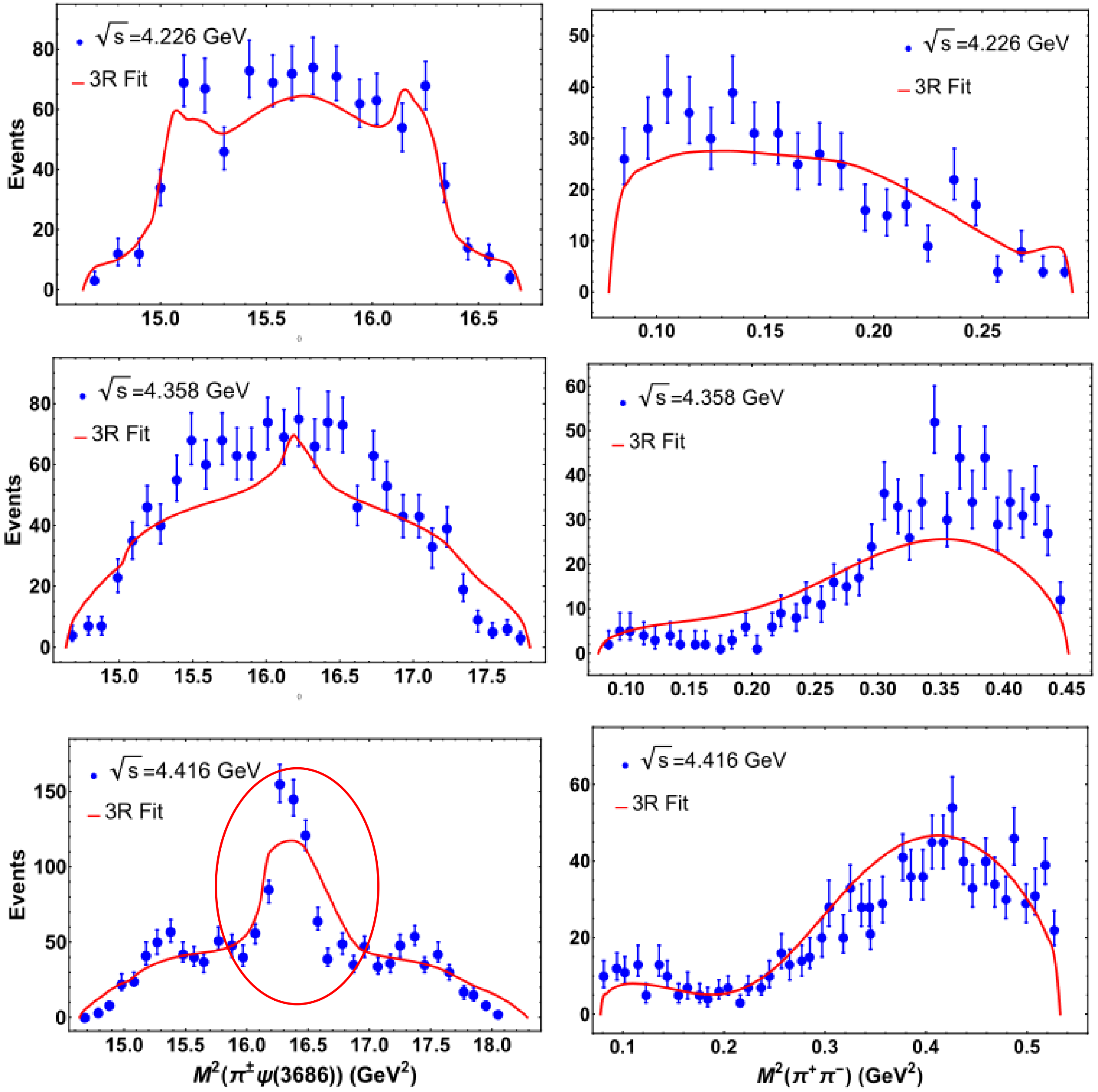
3R Fit: ψ(4160), ψ(4220), ψ(4415)

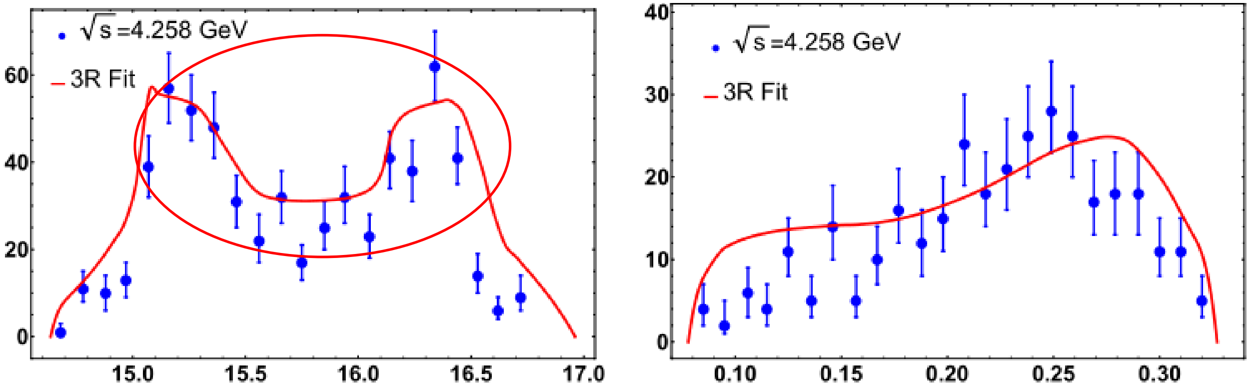
3R Fit: 38 parameters

Prameters	$\psi(4160)$	$\psi(4220)$	$\psi(4415)$
a_R (GeV^{-1})	6.0	5.0	4.0
$\phi_{\rm Dir}$	-1.631	-1.506	1.762
$F_{\rm Dir}$	-3.477	5.881	0.982
κ_{Dir}	-1.829	-0.025	-0.918
ϕ_σ	1.130	2.009	2.241
f_σ (GeV^2)	7.562	5.785	-3.971
g_σ	77.498	21.803	-1.920
φ_σ	1.186	-2.426	-1.923
$\phi_{\rm ISPE}$	-1.320	2.980	-2.813
$g_{RD\bar{D}\pi}$ (GeV^{-3})	1.717	1.574	0.002
$g_{RD^*\bar{D}\pi}$	-1.834	-0.670	0.025
$g_{RD^*\bar{D}^*\pi}$ (GeV^{-1})	0.120	-0.096	0.105
$g_{\rm NoR}$=18.940 GeV	$a_{\rm NoR}$=4.702 GeV^{-2}		

3R Fit: ψ(4160), ψ(4220), ψ(4415)

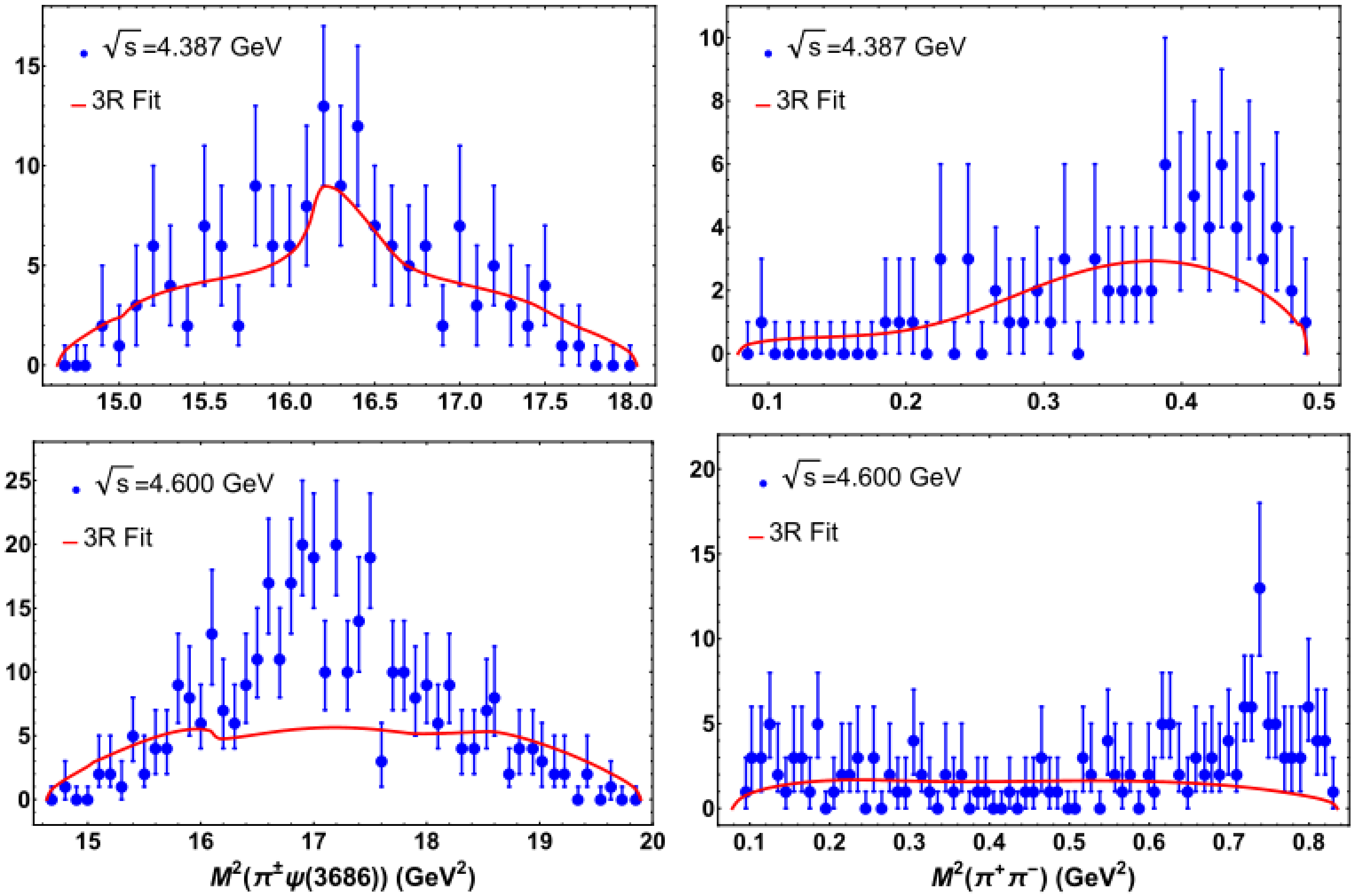






(1). The cross section in addition with all the invariant mass spectrums can be reproduced well by one set of parameters.

(2). The structure around 4.032 GeV can be explained by our model that based on the ISPE mechanism



When $\sqrt{s} = 4.387$ GeV, the invariant mass spectrums are plotted directly, and they are consistent with the experimental data.

More precise data will be helpful ~

We know little about the mass spectrum of charmonia near or above 4.6 GeV until now.

Add another ψ(4380)

J. Z. Wang, X. Liu, et.al., Phys. Rev. D99, 114003 (2019)

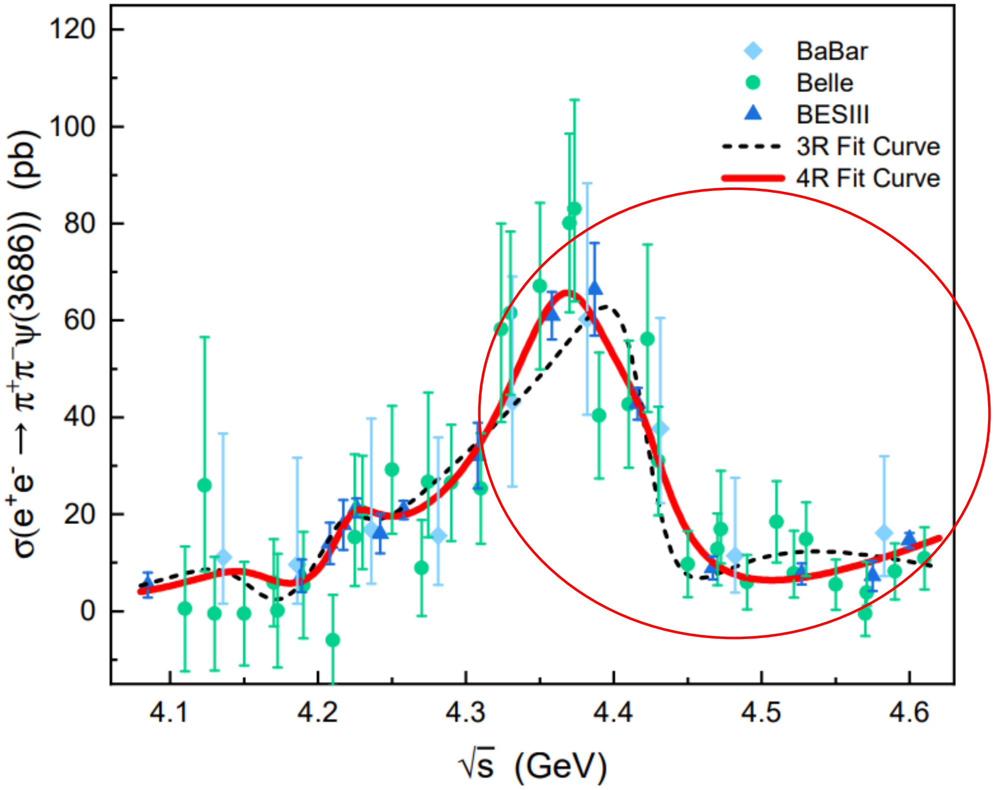
Y(4220)
- *Scarling Point* ⇒ *Charmonia spectrum*
- *Charmonia with* 4S − 3D *mixing*
- *Predict* a ψ(4380) *as the partner of* Y(4220)

Fano interference

$$\mathcal{M}_{\rm NoR} = g u^2 e^{-a u^2}$$

$$M_R(\psi) = \frac{\sqrt{12\pi\Gamma_\psi^{e^+e^-} \times \mathcal{B}(\psi \to \pi^+\pi^-\psi(3686))\Gamma_\psi}}{s - m_\psi^2 + i m_\psi \Gamma_\psi} \times \sqrt{\frac{\Phi_{2\to3}(s)}{\Phi_{2\to3}(m_\psi^2)}},$$

$$\mathcal{M}^{\rm Total} = \mathcal{M}_{\rm NoR} + \sum_k e^{i\phi_k} \mathcal{M}_R(\psi_k),$$



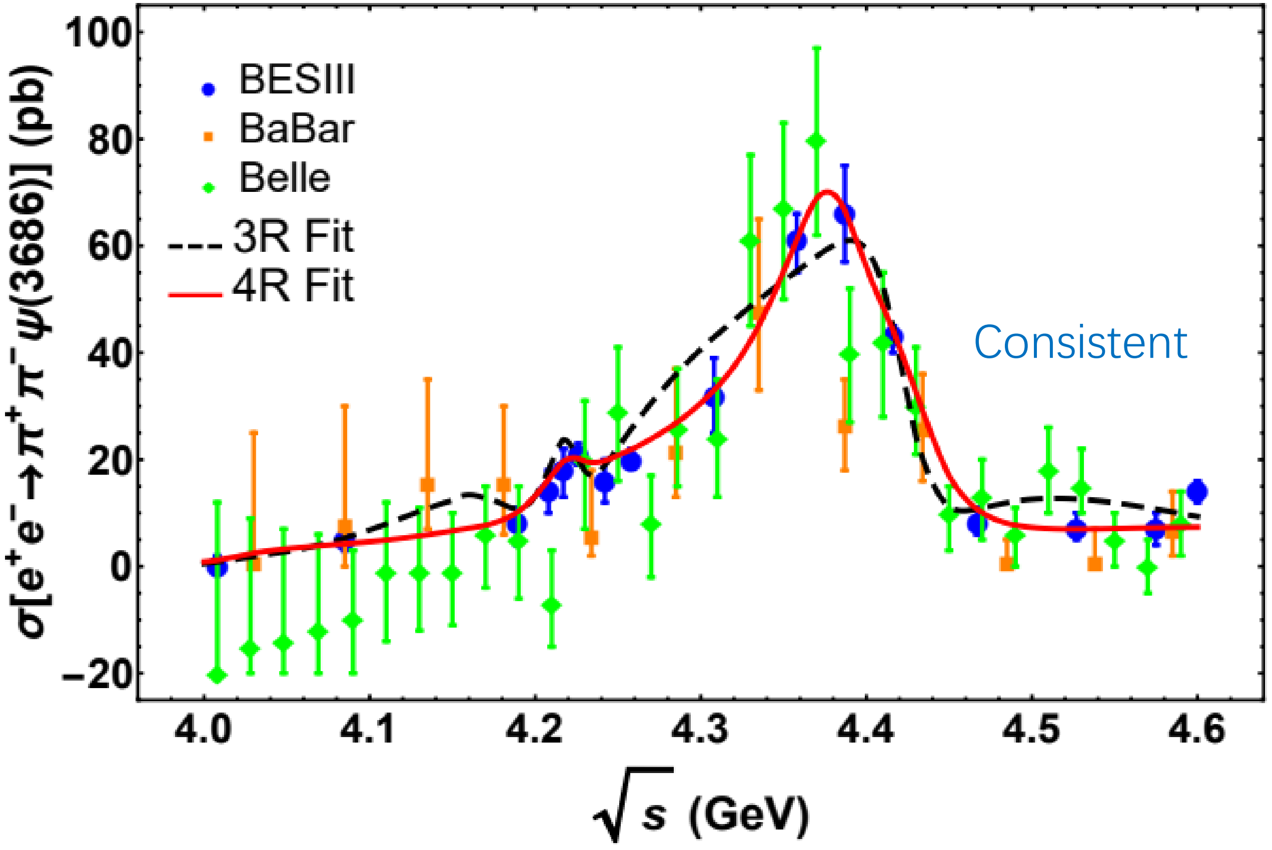
4R Fit: ψ(4160), ψ(4220), ψ(4415), ψ(4380)

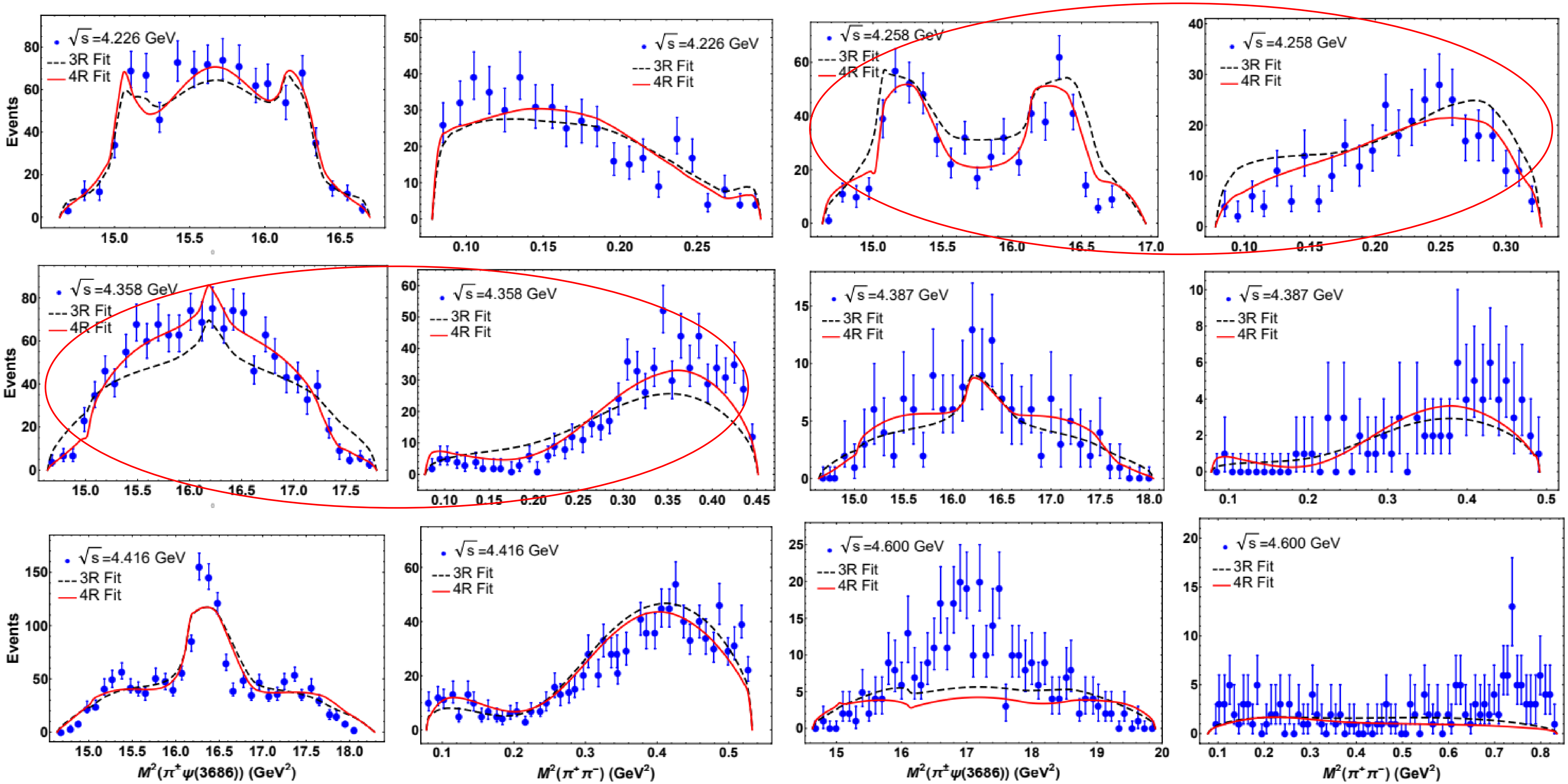
4R Fit: 50 parameters

Parameter	$\psi(4160)$	$\psi(4220)$	$\psi(4415)$	$\psi(4380)$
a_R (GeV^{-1})	5.5	4.0	3.3	3.0
ϕ_{Dir}	-0.146	1.661	-0.423	-0.345
F_{Dir}	-12.243	3.361	0.504	1.523
κ_{Dir}	-0.151	-0.215	-1.190	-0.463
ϕ_σ	0.517	-0.950	2.910	-0.328
f_σ (GeV^2)	11.953	1.813	1.832	-5.940
φ_σ	-1.680	0.287	-0.838	-1.455
g_σ	58.717	-6.612	-7.864	-25.906
ϕ_{ISPE}	-1.759	2.875	1.396	-5.475
$g_{RD\bar{D}\pi}$ (GeV^{-3})	-2.223	-1.736	-0.257	0.276
$g_{RD^*\bar{D}\pi}$	1.646	0.353	-0.470	1.249
$g_{RD^*\bar{D}^*\pi}$ (GeV^{-1})	0.323	0.131	0.133	-0.022

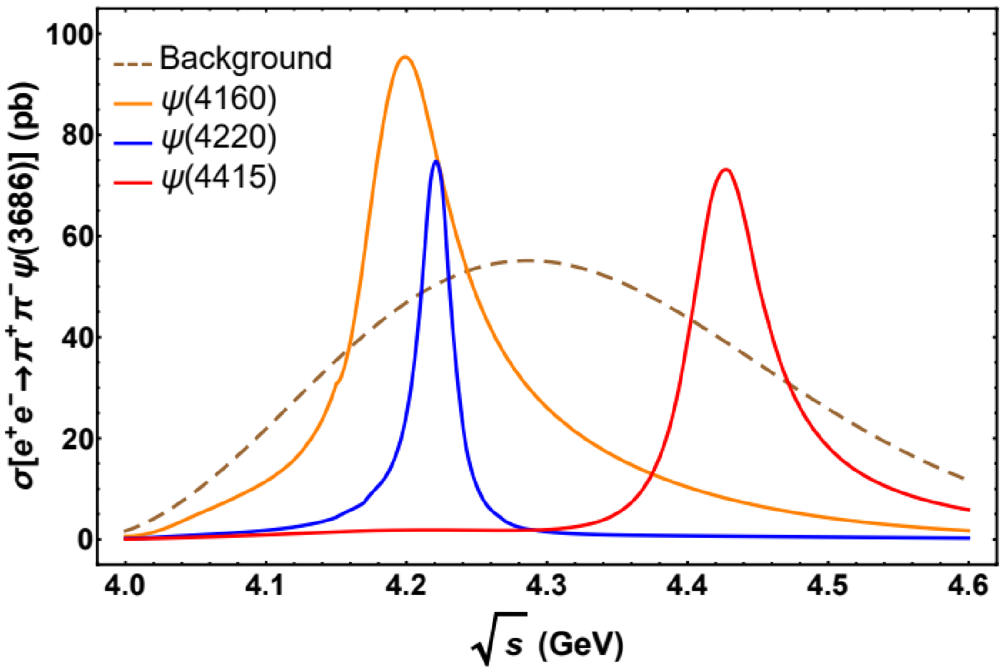
g_{NoR}=-4.847 GeV a_{NoR}=2.058 GeV^{-2}

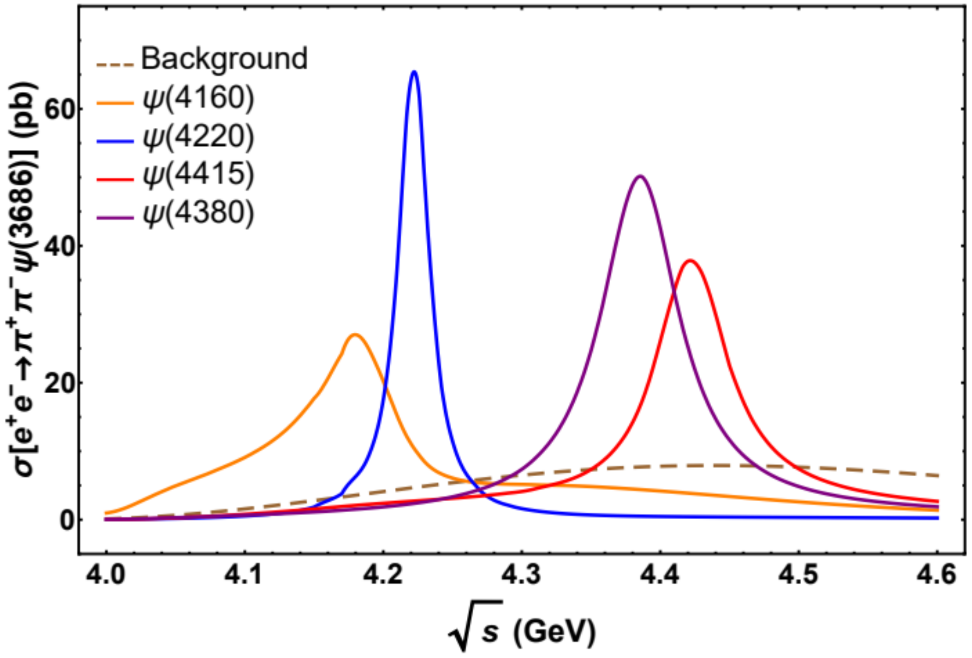
4R Fit: ψ(4160), ψ(4220), ψ(4415), ψ(4380)




√s =4.226 GeV
3R Fit
4R Fit
√s =4.258 GeV
√s =4.358 GeV
√s =4.387 GeV
√s =4.416 GeV
√s =4.600 GeV
Events
M²(π⁺ψ(3686)) (GeV²)
M²(π⁺π⁻) (GeV²)

Contributions of intermediate states





The Breit-Wigner distribution can be approximately hold

Branching ratios of $\psi_R \rightarrow \pi^+\pi^-\psi(3686)$ (x10^{-3})

	$\psi(4160)$	$\psi(4220)$	$\psi(4415)$	$\psi(4380)$
3R Fit	15.711	8.101	9.65	-
4R Fit	4.389	7.370	5.368	17.285

Consistent with experimental experience

Our parameters are reasonable

Summary

- We do a combined fit on the data of $e^+e^- \to \psi(3686)\,\pi^+\,\pi^-$ process given by BESIII.
- Our model can explain BESIII's data in a unified framework, and the given parameters are reasonable.
- The charged structure appeared on the $\psi(3686)\,\pi^+$ invariant mass spectrum can be explained by ISPE mechanism without introducing any new charmonium-like states.
- After adding $\psi(4380)$, our result are consistent with the conclusion given by Phys. Rev. D99, 114003 (2019).

Thank you ~