Measurement of $e^+e^- \to \pi\pi\psi(3686)$ at BESIII

Xiaorong Zhou (on behalf of BESIII Collaboration)

State Key Laboratory of Particle Detection and Electronics
University of Science and Technology of China

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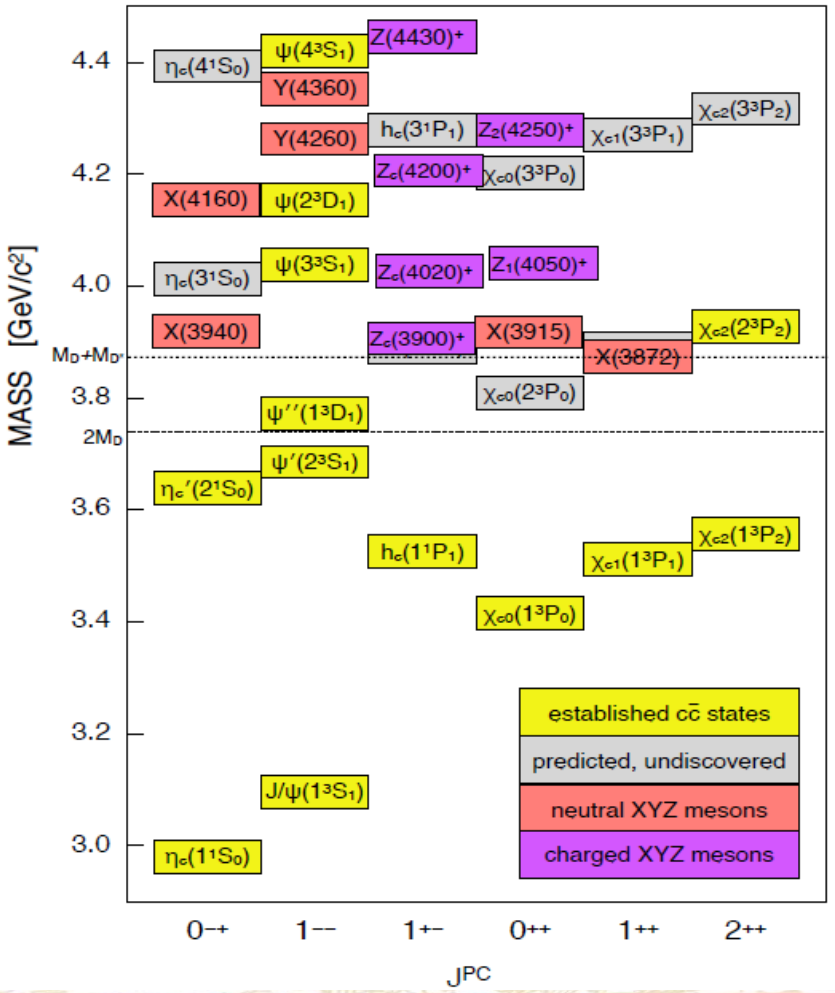
Outline

- **Introduction**
- **Cross section line shape: ‘Y’ states**
- **Intermediate state: ‘Z’ states**
- **Summary**

The Charmonium System

- $c\bar{c}$ bound states can be described using potential models
- All predicted states below the $D\bar{D}$ threshold have been found!
- Properties are in agreement with predictions
- Clean environment to search for exotic states
- Many unpredicted states were reported above the $D\bar{D}$ threshold, called "*XYZ*" states



The Charmonium System

- $c\bar{c}$ bound states can be described using potential models
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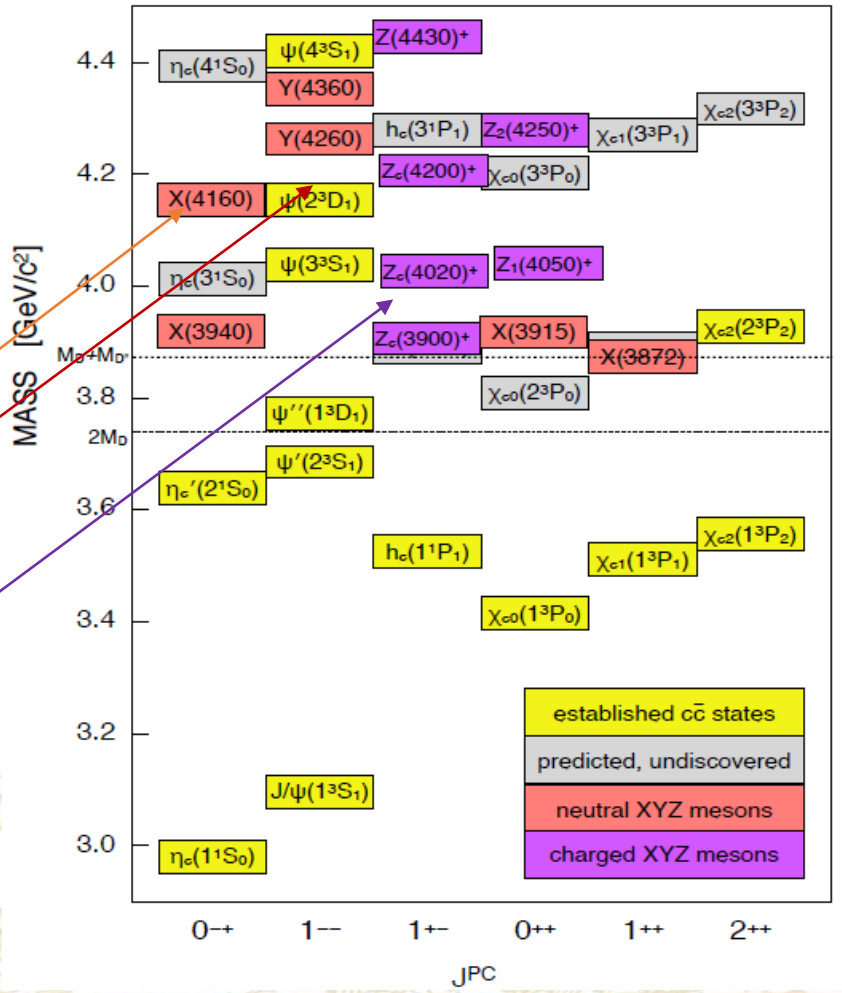
- Properties are in agreement with predictions
- Clean environment to search for exotic states
- Many unpredicted states were reported above the $D\bar{D}$ threshold, called "*XYZ*" states
- "XYZ" states
  - "X": Neutral, $J^{pc} \neq 1^{--}$

    Observed in radiative or hadronic transitions from Y.
  - "Y": Neutral, $J^{pc} = 1^{--}$

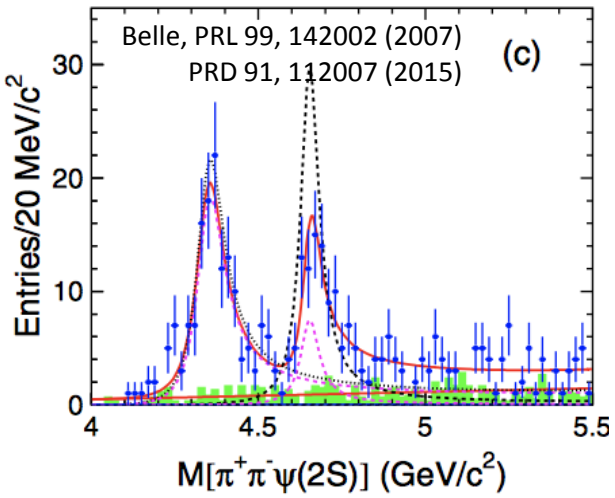
    Direct access in e^+e^-annihilation.
  - "Z": Charged, isospin triplete

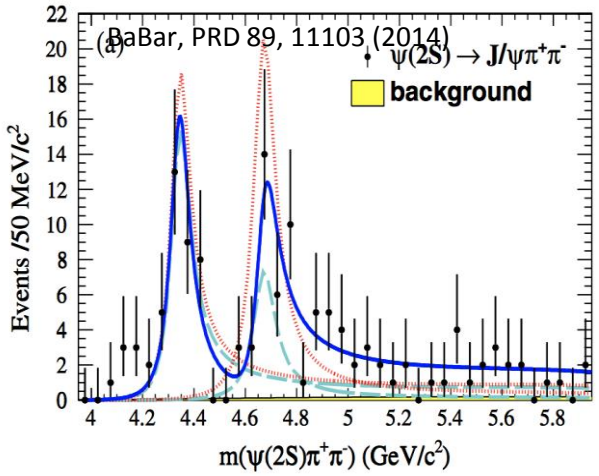
    Observed in hadronic transitions from Y.



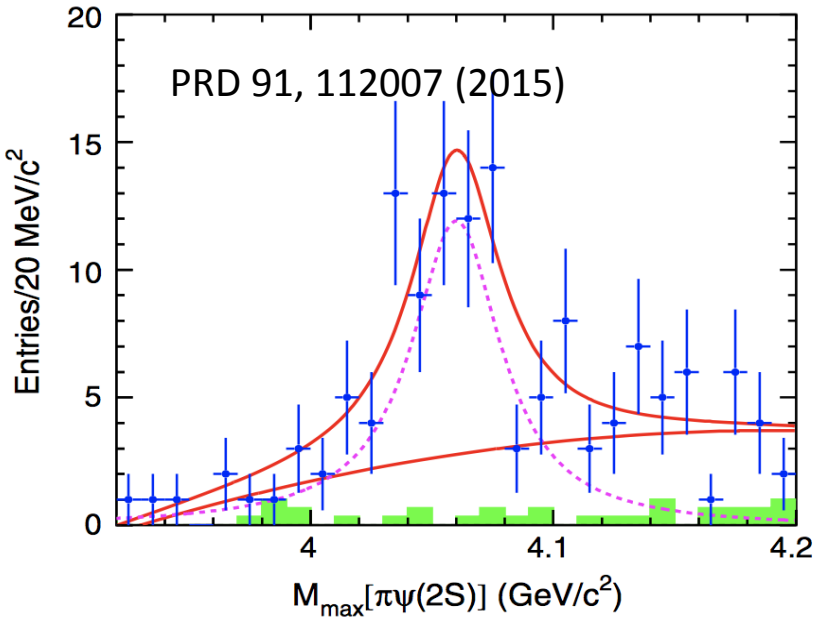
History on $e^+e^- \to \pi^+\pi^-\psi(3686)$

- Y(4360), Y(4660) in $e^+e^- \to \pi^+\pi^-\psi(3686)$
  - Discovery in ISR process by Belle
  - Confirmed by Babar.
  - No evidence for the Y(4260).





- A possible charmoniumlike structure in $M_{\pi^\pm\psi(3686)}$:
  - An excess at 4.05 GeV/c^2 in the Y(4360) decays
  - 3.6σ significance



Analysis strategy

- Data samples:
  - 16 energy points from $\sqrt{s} = 4.008$ to 4.600 GeV
  - The total integrated luminosity is 5.1 fb^{-1}
- Reconstructed modes:
  - Charged channel: $e^+e^- \to \pi^+\pi^-\psi(3686)$

    Mode I: $\psi(3686) \to \pi^+\pi^- J/\psi, J/\psi \to l^+l^-$

    Mode II: $\psi(3686) \to neutrals + J/\psi, J/\psi \to l^+l^-$

    $neutrals = (\pi^0\pi^0, \pi^0, \eta$ and $\gamma\gamma)$
  - Neutral channel: $e^+e^- \to \pi^0\pi^0\psi(3686)$

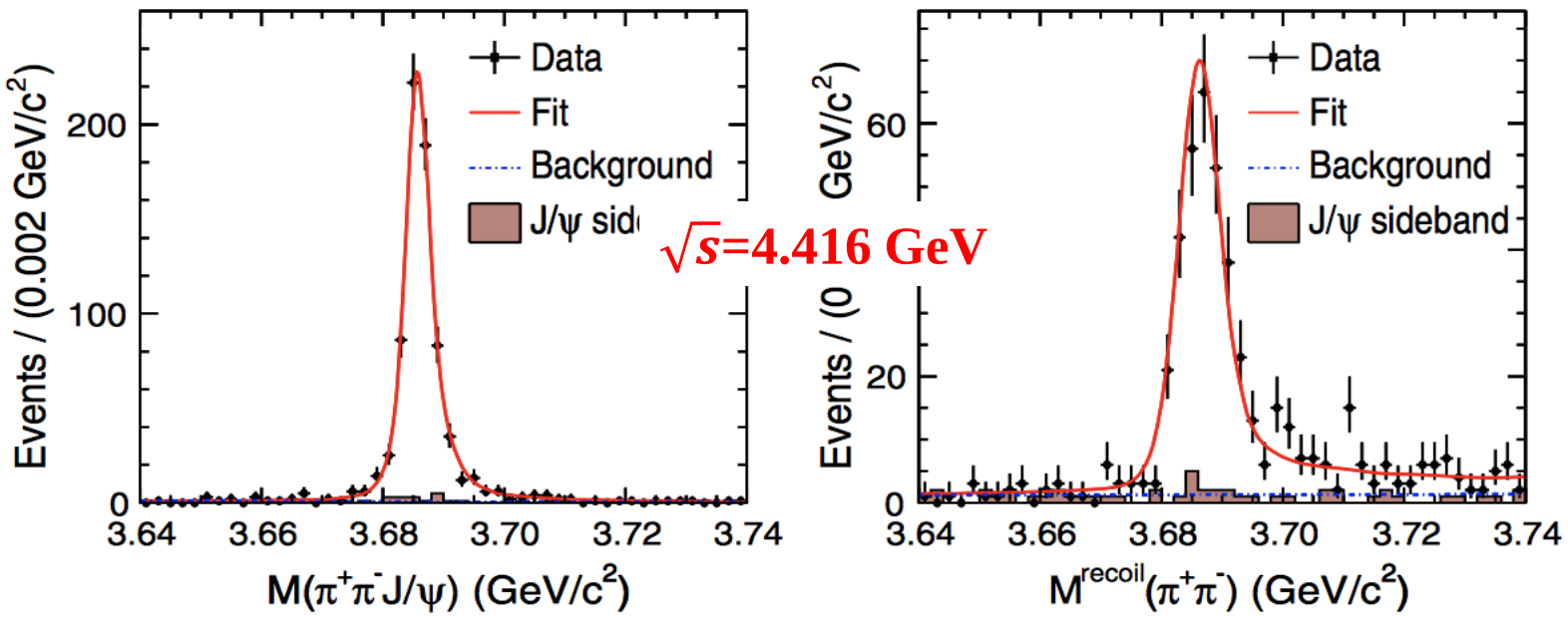
    $\psi(3686) \to \pi^+\pi^- J/\psi, J/\psi \to l^+l^-$

Event selection: charged channel

- Topologies: $\pi^+\pi^-\pi^+\pi^- l^+l^-$
- Track level:
  - Pions: $p < 0.65$ GeV/c
  - Leptons: $p > 1.0$ GeV/c (electrons: E/p>0.7 ; muons: E<0.45 GeV)
  - For $J/\psi \to \mu^+\mu^-$, $N_{hits} \geq 5$
- Event level
  - 5 or 6 good charged tracks
  - 4C/1C kinematic fit for 6/5 tracks
  - 5C/2C kinematic fit to get better M($\psi(3686)$) resolution

- Topologies: $\pi^+\pi^- l^+l^- + \mathrm{N}\gamma(N \geq 2)$
- Event level:
  - 4 good charged tracks
  - $\geq$ 2 photon candidates
  - Veto $e^+e^- \to neutrals + \psi(3686)$ ($\psi(3686) \to \pi^+\pi^- J/\psi$), $|M_{\pi^+\pi^- J/\psi} - M_{\psi(3686)}| > 8$ MeV/c^2
  - Veto $e^+e^- \to \eta$ J/$\psi(\eta \to \pi^+\pi^-\pi^0)$, $|M_{\gamma\gamma\pi\pi} - M_\eta| > 50$ MeV/c^2
  - Veto Bhabha and dimuon, $cos\theta_{\pi^+\pi^-} < 0.9$

Signals in data: charged channel

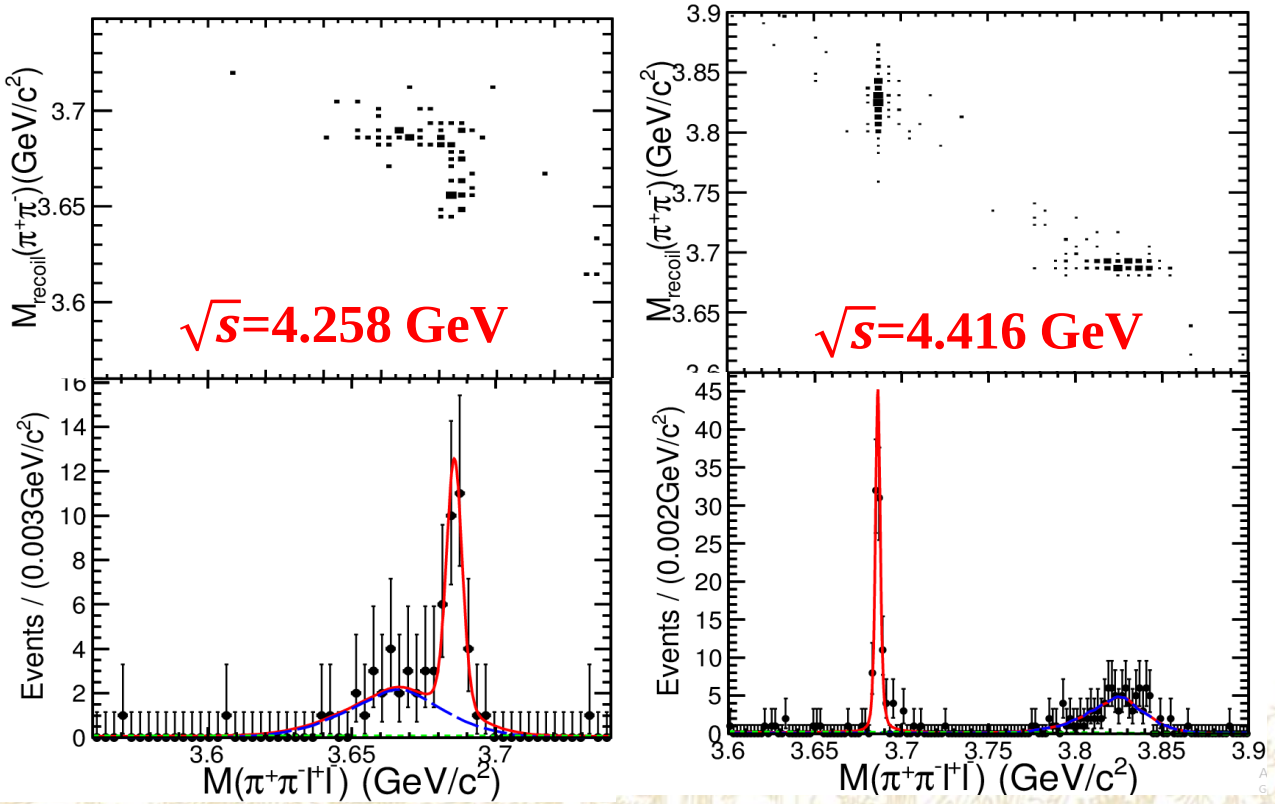


- Number of signals are extracted from $\pi^+\pi^- J/\psi$ invariant mass (mode I) and $\pi^+\pi^-$ recoiled mass spectrum (mode II)
- Signals are described with MC simulated shape convoluted with a Gaussian function

Event selection: neutral channel

- Topologies: $\pi^+\pi^-l^+l^-\gamma\gamma\gamma\gamma$
- Track level:
  - Same as charged channel
- Event level:
  - 4C kinematic fit is applied, photons are selection from minimum χ^2_{4C}.
  - Minimizing $(M_{\gamma_1\gamma_2} - M_{\pi^0})^2 + (M_{\gamma_3\gamma_4} - M_{\pi^0})^2$ to select π^0s.
  - 7C kinematic fit (two π^0 and J/ψ masses) is applied.

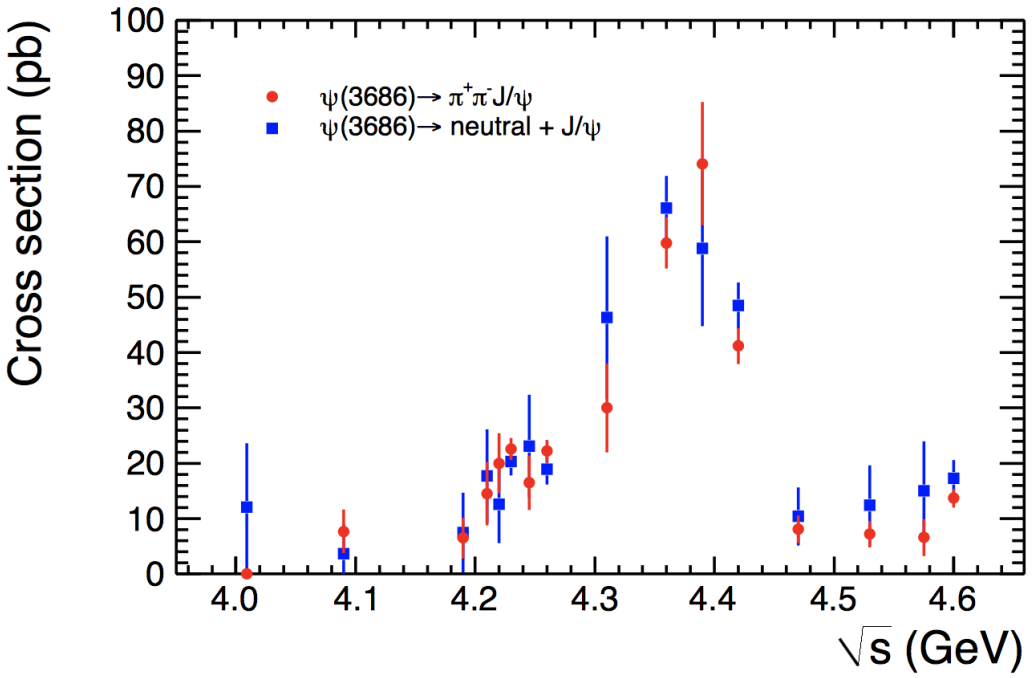
Signals in data: neutral channel



- Number of signals are extracted from $\pi^+\pi^- J/\psi$ invariant mass.
- Signals are described with MC simulated shape convoluted with a Gaussian function.
- Dominant background from $e^+e^- \rightarrow \pi^+\pi^-\psi(3686)$

Determination of cross section: charged channel

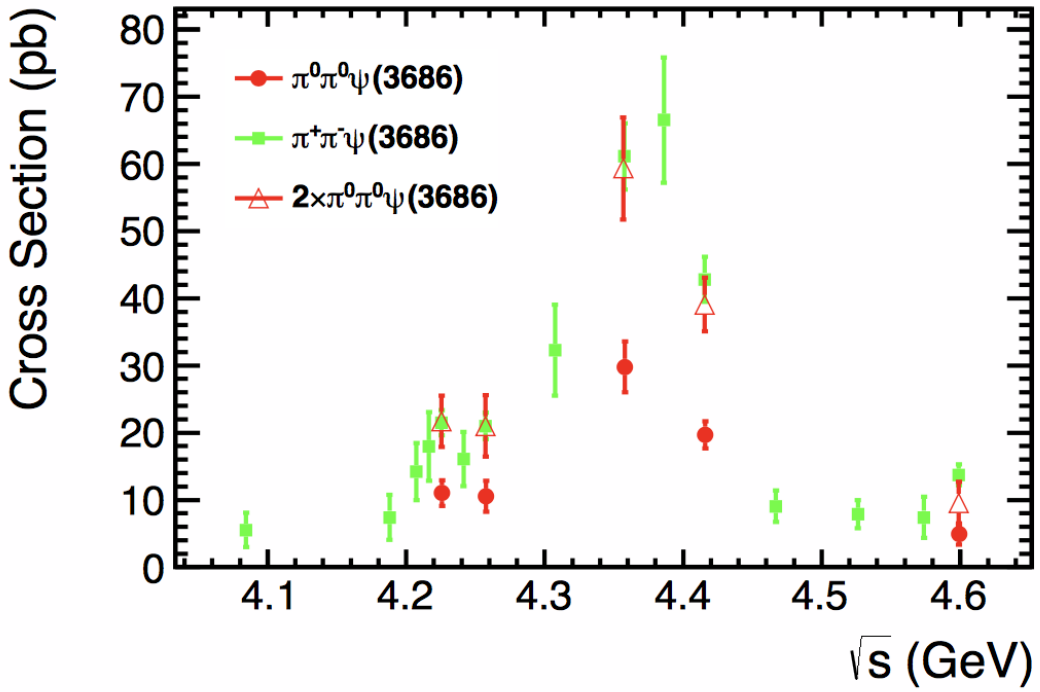
$$\sigma_i^B = \frac{N_i^{obs}}{L_{int}(1+\delta^r)(1+\delta^v)Br_i\varepsilon_i}(i = 1,2)$$



- Cross section for charged channel
- The two modes are combined by considering the correlated and uncorrelated uncertainties.

Determination of cross section: neutral channel

$$\sigma^B = \frac{N^{obs}}{\mathcal{L}_{int}(1+\delta^r)(1+\delta^v)B \cdot \varepsilon}$$



- The cross section of neutral channel is found to be half of those for charged channel.
- Consistent with expectation from isospin symmetry.

Fit to the cross section

- **A binned χ^2 fit is applied, with the PDF parameterized as:**

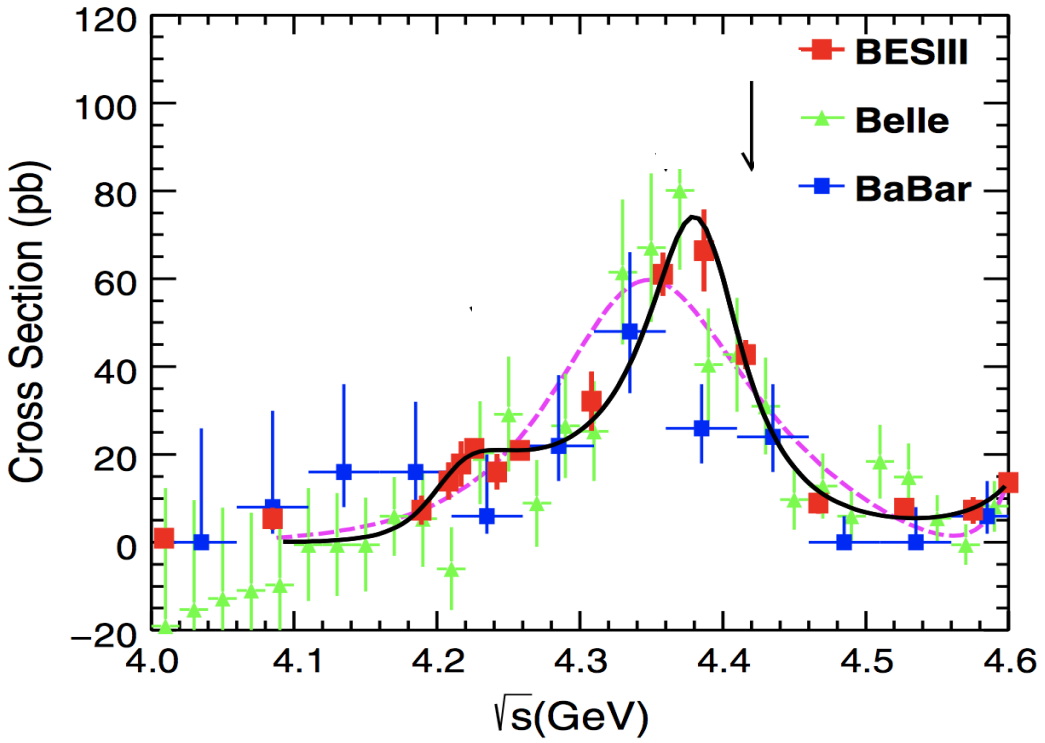
$$\mathcal{A} = f_1 e^{i\phi_1} + f_2 + f_3 e^{i\phi_2}$$

  - f_1 for Y(4220), f_2 for Y(4390), f_3 for Y(4660)
  - The amplitude for each resonance is:

$$f_i = \frac{M_i}{M} \frac{\sqrt{12\pi \mathcal{B}_i \Gamma_i^{e^+e^-} \Gamma_i}}{M^2 - M_i^2 + iM_i\Gamma_i} \sqrt{\frac{\phi(M)}{\phi(M_i)}}$$

- **In the fit, M_i, Γ_i, the product $\mathcal{B}_i\Gamma_i^{e^+e^-}$ and the relative phase angle $\phi_i (i = 1, 2)$ are free parameters.**
- **The parameters of the Y(4660) are fixed to Belle's latest results.**

Fit to the cross section



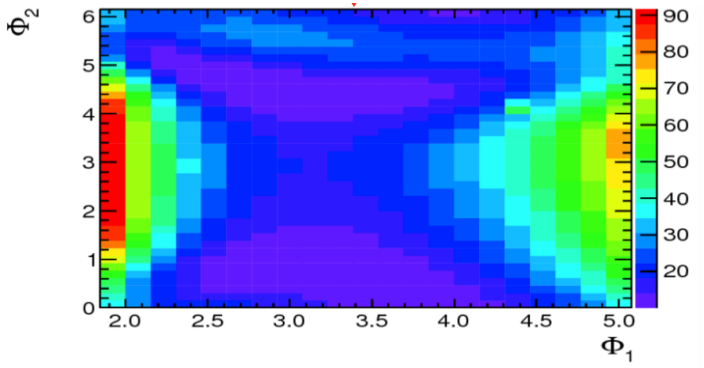
- Black solid curve: with three resonances χ^2/ndf=9.98/7
- Pink dashed curve: without $Y(4220)$, χ^2/ndf=54.54/11
- Significance of $Y(4220)$ is 5.8σ
- $Y(4220)$ observed in $e^+e^- \to \pi^+\pi^-\psi(3686)$ for the first time !

$M_1 = 4209.5 \pm 7.4 \pm 1.4\ \mathrm{MeV/c^2}$, $\Gamma_1 = 80.1 \pm 24.6 \pm 2.9\ \mathrm{MeV}$

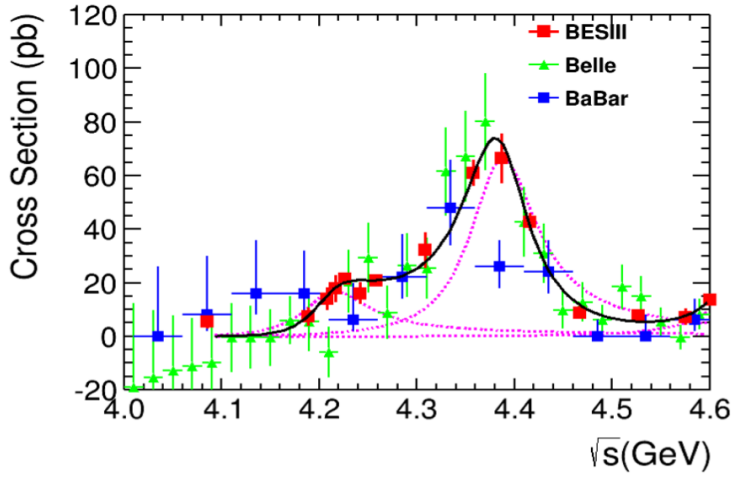
$M_2 = 4383.8 \pm 4.2 \pm 0.8\ \mathrm{MeV/c^2}$, $\Gamma_2 = 84.2 \pm 12.5 \pm 2.1\ \mathrm{MeV}$

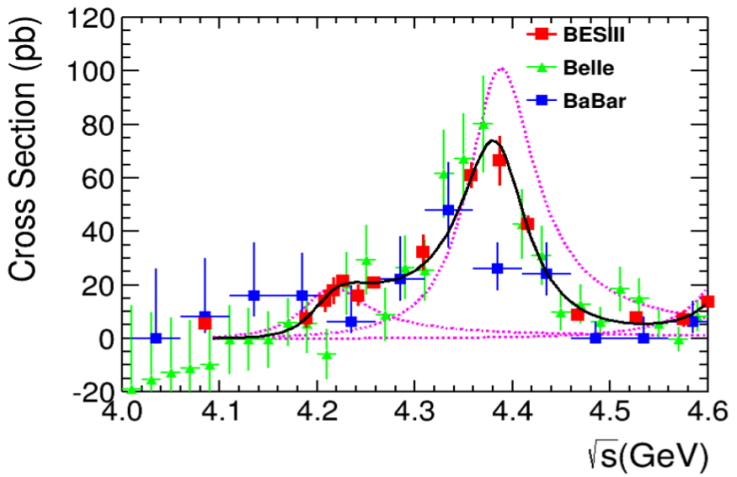
- Systematic uncertainty includes: Energy scale, Energy spread, Fit range, Y(4660) parameters

Discussion on two fitting results



Parameters	Solution I	Solution II
$M(Y4220)$ (MeV/c^2)	4209.5 ± 7.4	
$\Gamma(Y(4220))$ (MeV)	80.1 ± 24.6	
$\mathcal{B}\Gamma^{e^+e^-}(Y(4220))$ (eV)	0.8 ± 0.7	0.4 ± 0.3
$M(Y4390)$ (MeV/c^2)	4383.8 ± 4.2	
$\Gamma(Y(4390))$ (MeV)	84.2 ± 12.5	
$\mathcal{B}\Gamma^{e^+e^-}(Y(4390))$ (eV)	3.6 ± 1.5	2.7 ± 1.0
ϕ_1 (rad)	3.3 ± 1.0	2.8 ± 0.4
ϕ_2 (rad)	0.8 ± 0.9	4.7 ± 0.1

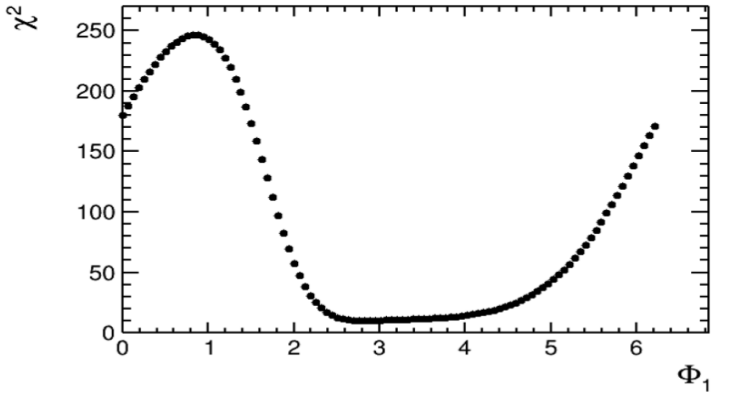


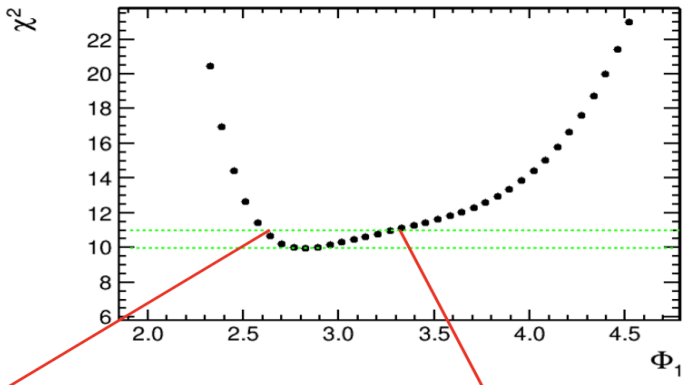


- Y(4390) has constructive and destructive interference
- Two solutions from constructive interference from Y(4220) are missing

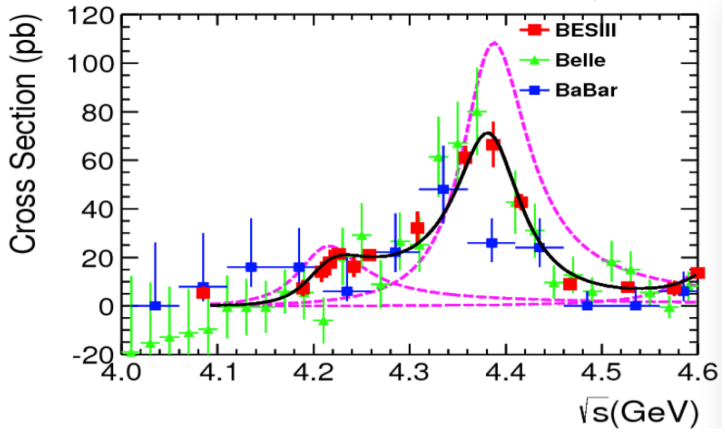
Discussion on two fitting results

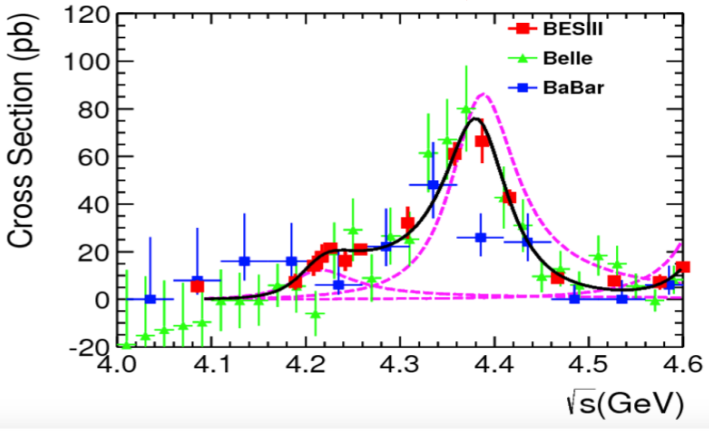
- Scan of ϕ_1(fixing $\phi_2 = 4.7$)





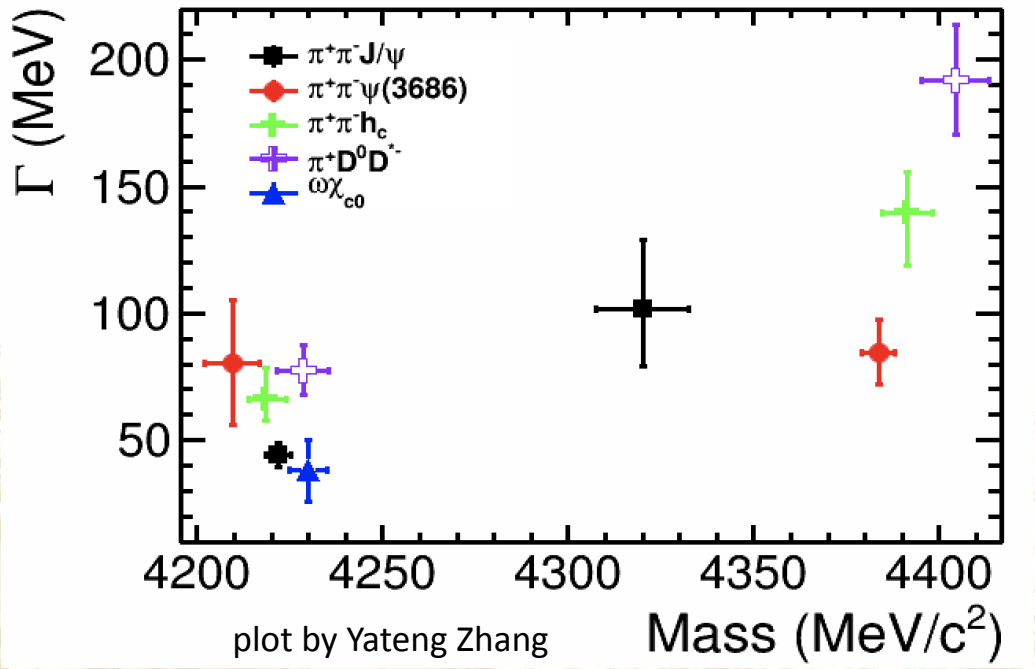
constructive interference for Y(4220) is in 1sigma errors of Phi1





Y states observed at BESIII

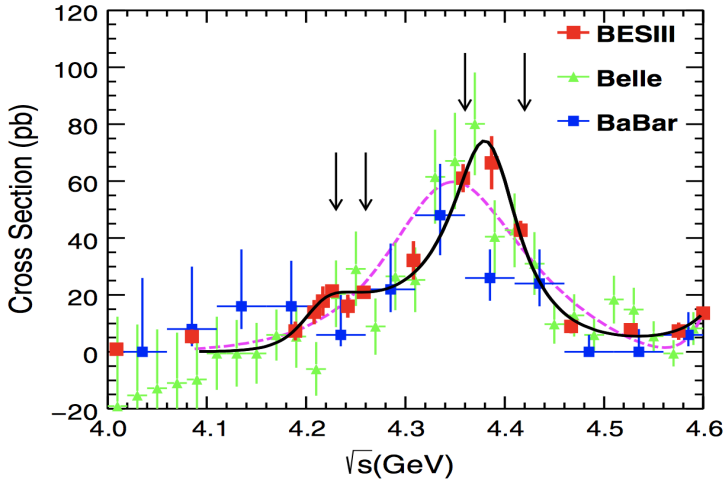
Process	M_1 (MeV/c^2)	Γ_1 (MeV)	M_2 (MeV/c^2)	Γ_2 (MeV)
$e^+e^- \to \omega\chi_{c0}$	$4230 \pm 8 \pm 6$	$38 \pm 12 \pm 2$ [37]		
$e^+e^- \to \pi^+\pi^- J/\psi$	$4220.0 \pm 3.1 \pm 1.4$	$44.1 \pm 4.3 \pm 2.0$	$4320.0 \pm 10.4 \pm 7.0$	$101.4^{+25.3}_{-19.7} \pm 10.2$ [9]
$e^+e^- \to \pi^+\pi^- h_c$	$4218.4^{+5.5}_{-4.5} \pm 0.9$	$66.0^{+12.3}_{-8.3} \pm 0.4$	$4391.5^{+6.3}_{-6.8} \pm 1.0$	$139.5^{+16.2}_{-20.6} \pm 0.6$ [10]
$e^+e^- \to \pi^+ D^0 D^{*-} + c.c$	$4224.8 \pm 5.6 \pm 4.0$	$72.3 \pm 9.1 \pm 0.9$	$4400.1 \pm 9.3 \pm 2.1$	$181.7 \pm 16.9 \pm 7.4$ [38]
$e^+e^- \to \pi^+\pi^-\psi(3686)$	$4209.5 \pm 7.4 \pm 1.4$	$80.1 \pm 24.6 \pm 2.9$	$4383.8 \pm 4.2 \pm 0.8$	$84.2 \pm 12.5 \pm 2.1$

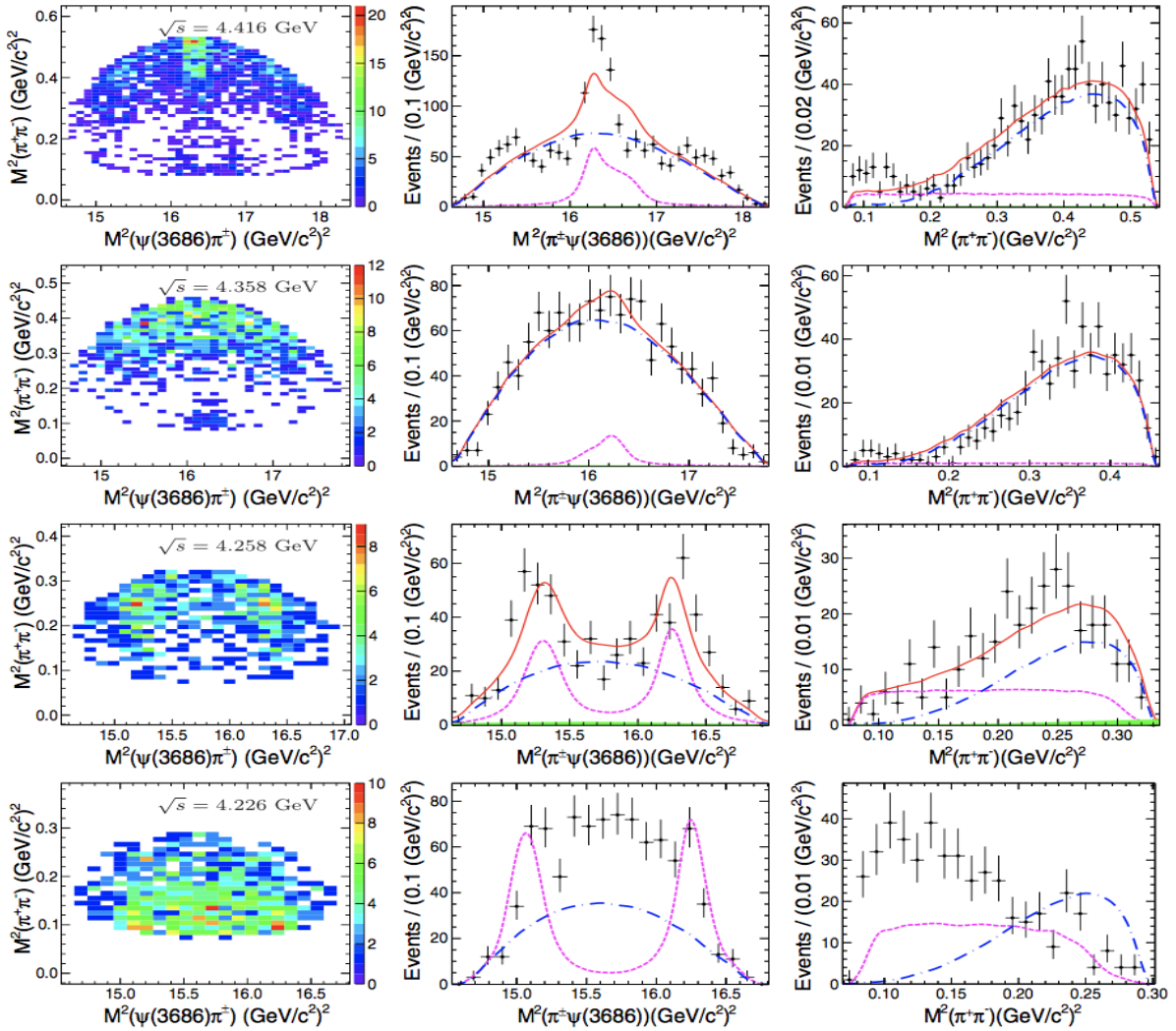


plot by Yateng Zhang

Intermediate states: charged channel

- Dalitz plot for data samples at 4.416, 4.358, 4.258 and 4.226 GeV
  - **At 4.416 GeV, a narrow structure observed around 4.03 GeV/c^2 in $M(\pi^{\pm}\psi(3686))$**
  - **At 4.358 GeV, no obvious structure observed.**
  - At 4.258 GeV, two bumps around 3.9 and 4.03 GeV/c^2 are visible
  - At 4.226 GeV, no structure clearly seen in $M(\pi^{\pm}\psi(3686))$ and a different $M(\pi^{+}\pi^{-})$.





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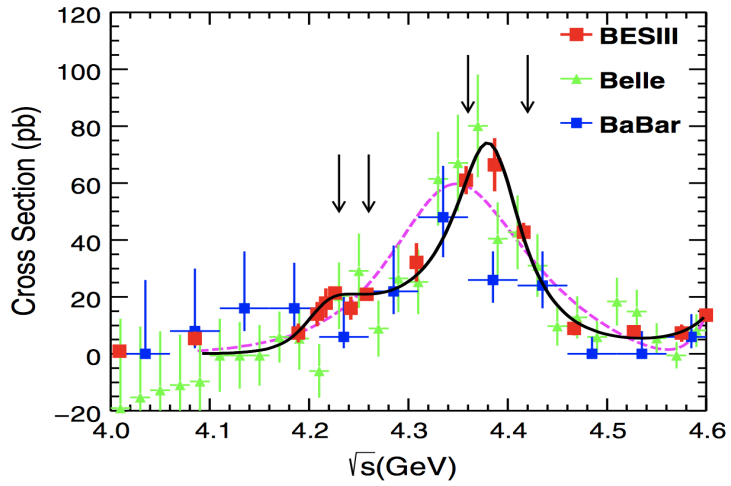

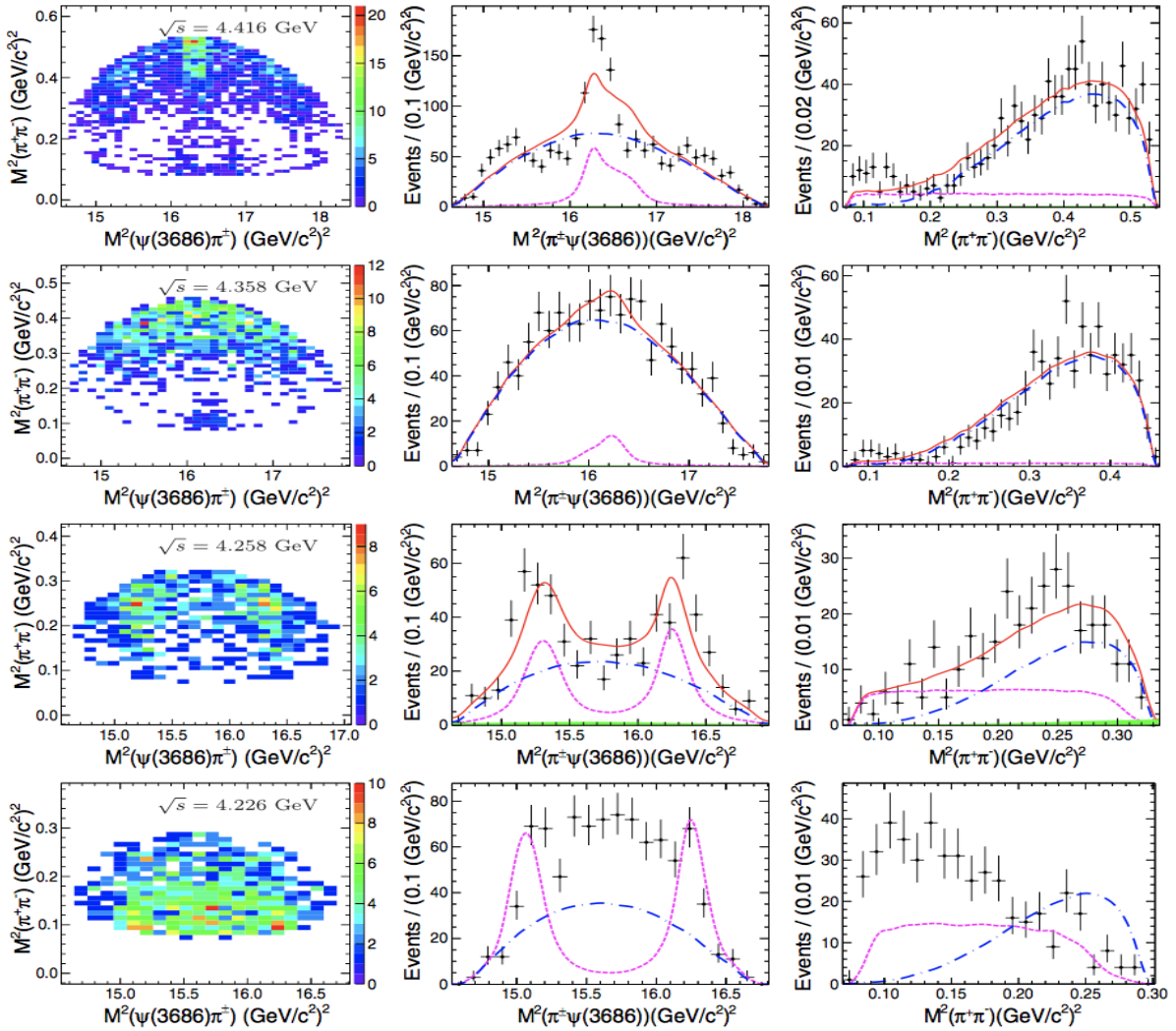

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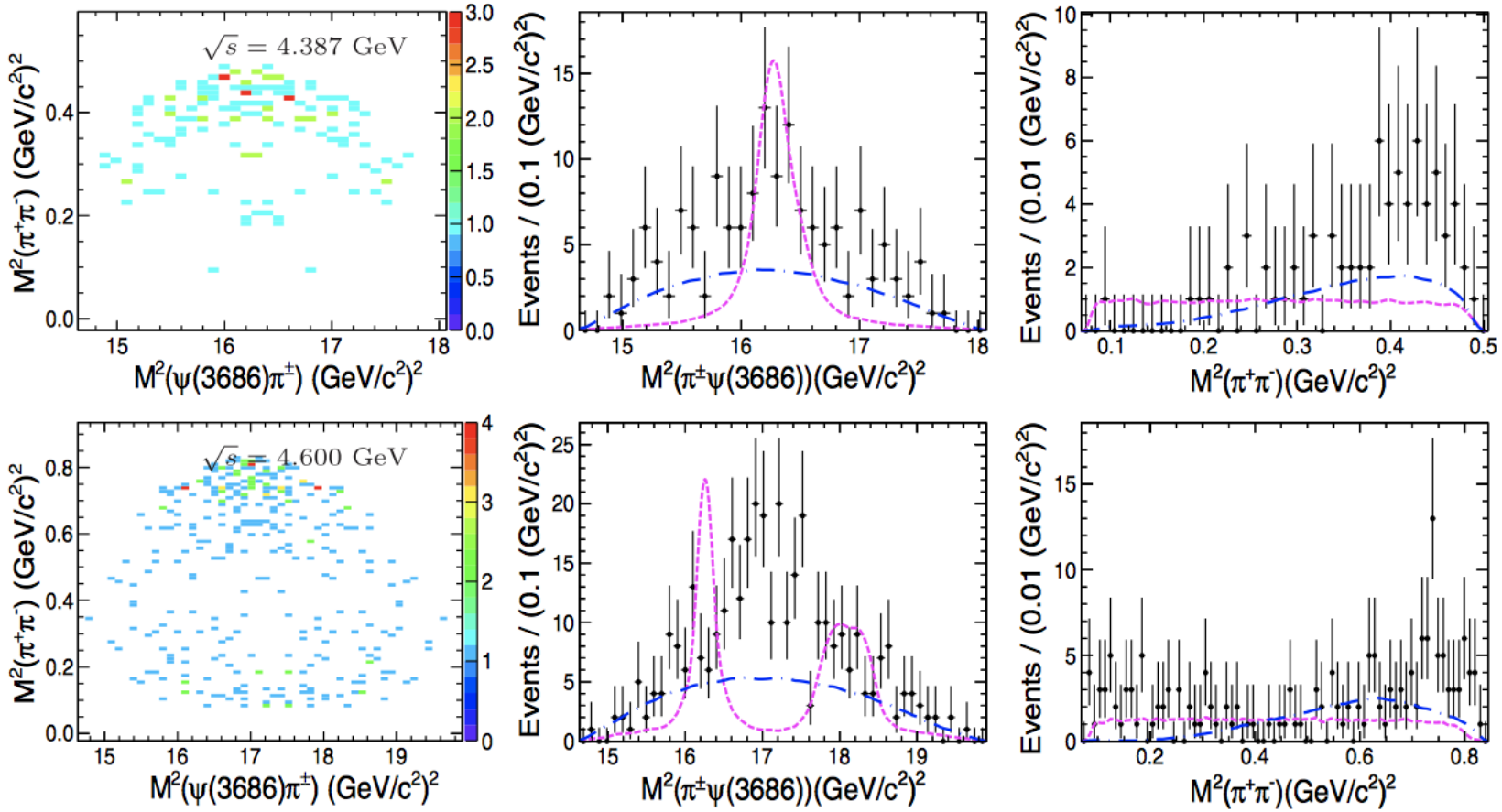
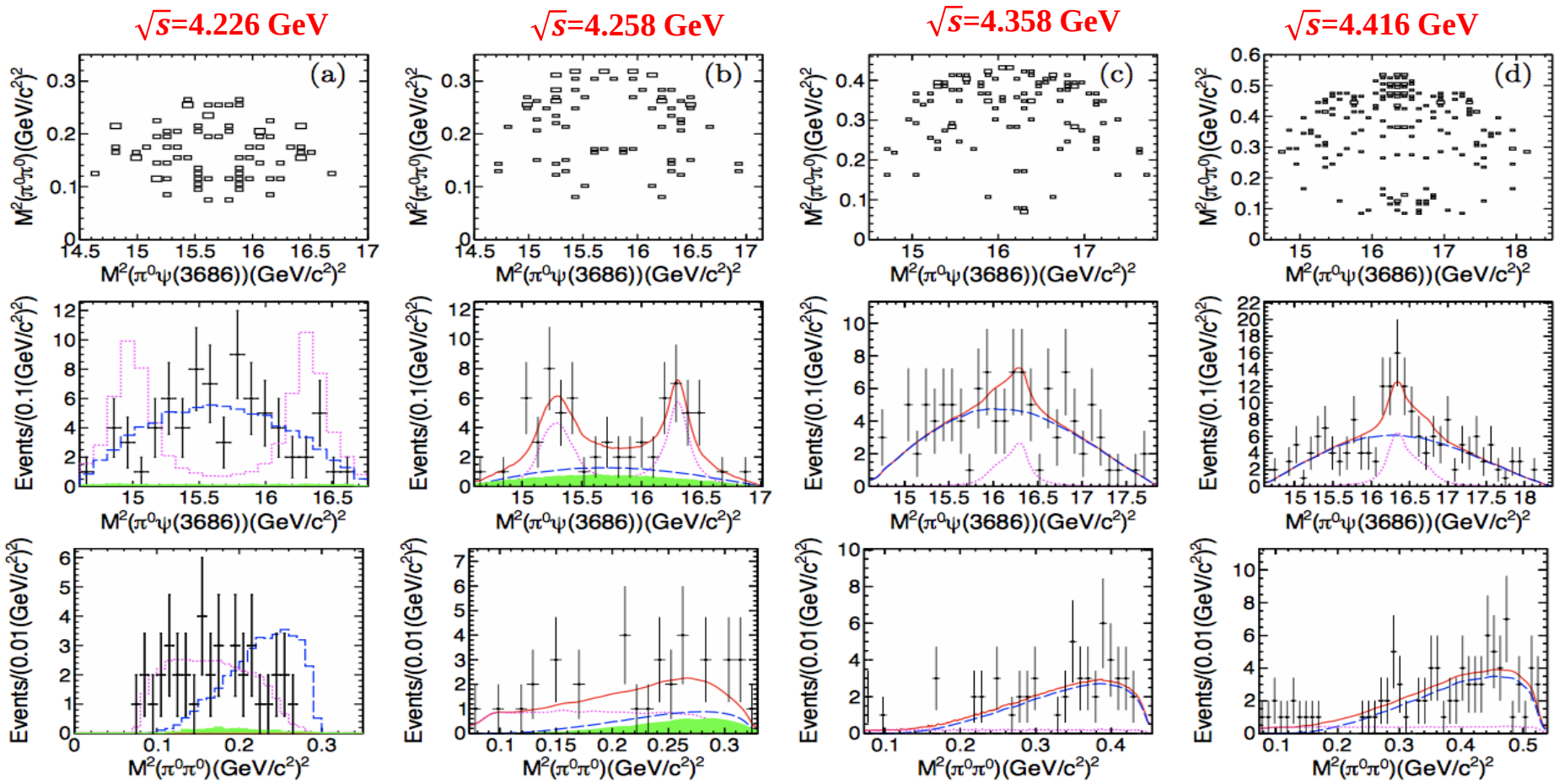


Intermediate states: neutral channel

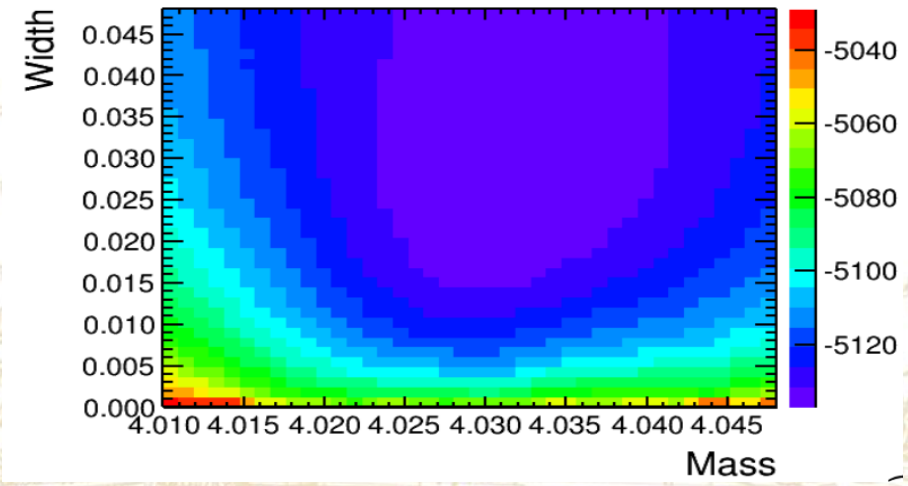


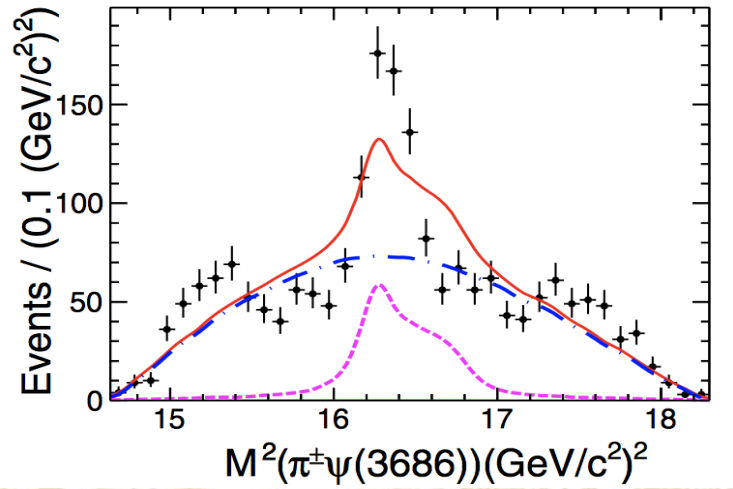
Fit of intermediate states

- A prominent narrow structure is observed in $\pi\psi(3686)$ mass spectrum for data at $\sqrt{s} = 4.416$ GeV.
- An S-wave Breit-Wigner fit function is performed on the Dalitz plot of $M^2(\pi^+\psi(3686))$ versus $M^2(\pi^-\psi(3686))$.

$$\epsilon(x,y)\cdot\left(\frac{p\cdot q}{(M_R^2-x)^2+M_R^2\cdot\Gamma^2}+\frac{p\cdot q}{(M_R^2-y)^2+M_R^2\cdot\Gamma^2}\right)\otimes\sigma(x,y)$$

- The fit yields a mass of **M=4032.1±2.4 MeV/c^2** and a width of **Γ=26.1±5.3 MeV**, with a significance of 9.2σ.





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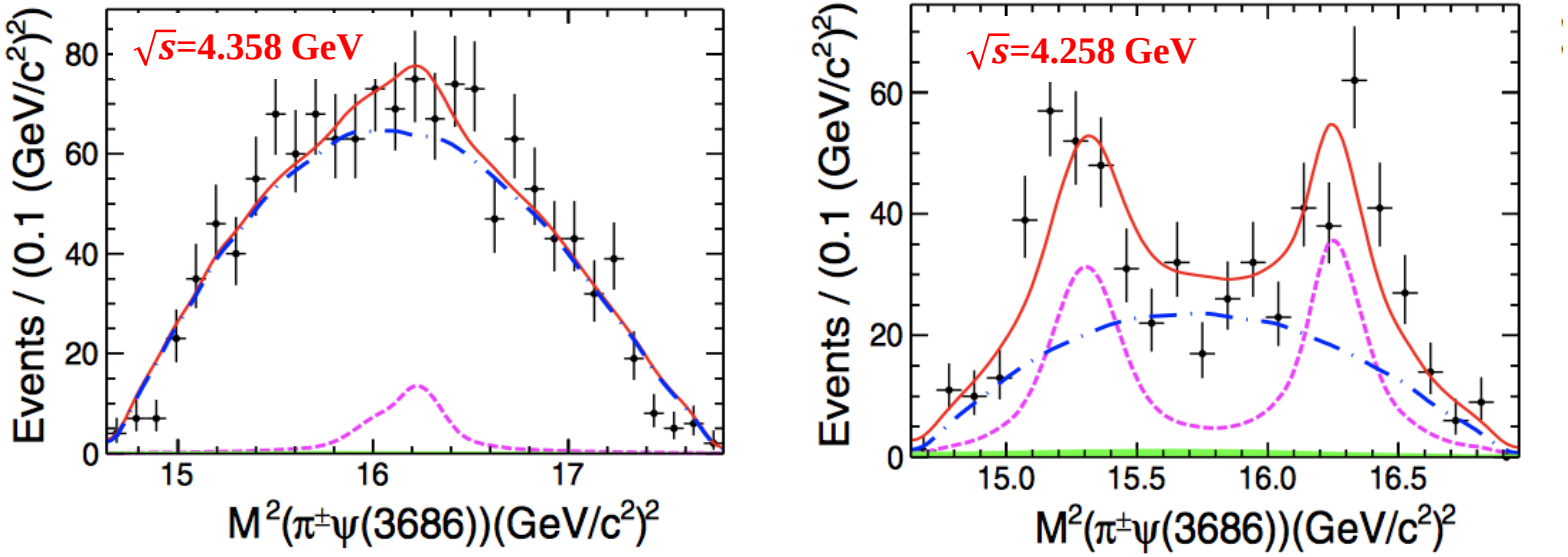
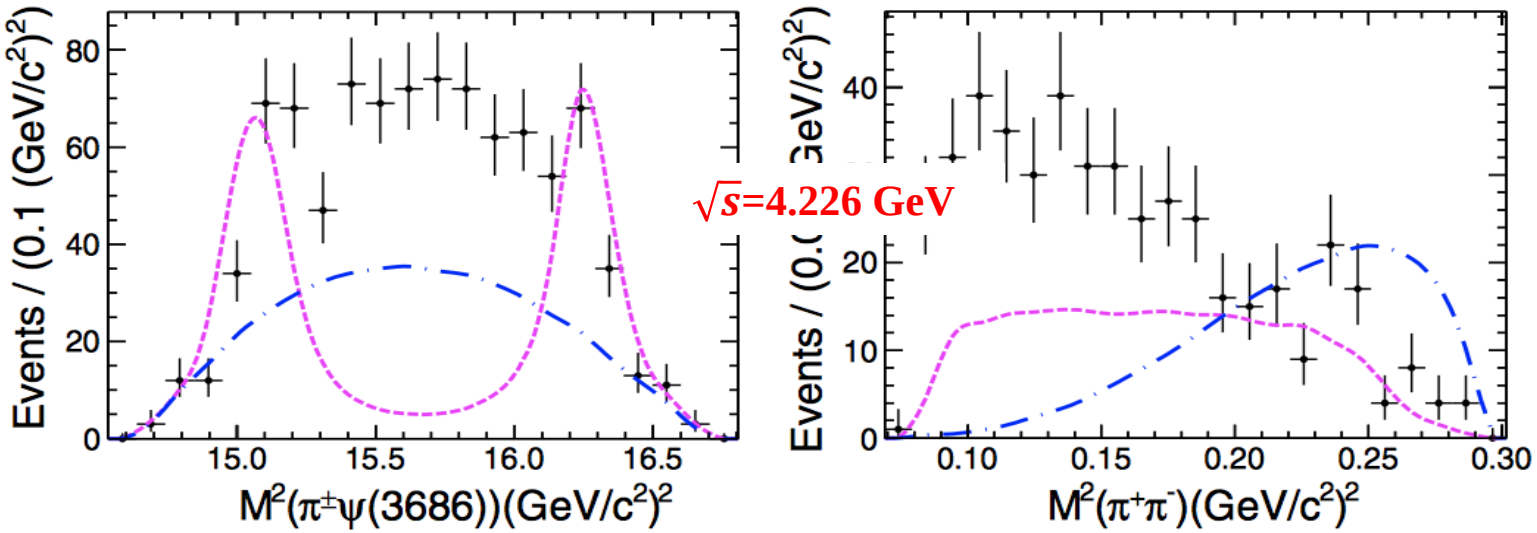


- Similar fits are carried out at $\sqrt{s} = 4.358$ and 4.258 GeV,
- Parameters of the intermediate states are fixed to results at $\sqrt{s} = 4.416$ GeV
- At $\sqrt{s} = 4.258$ GeV, the fit result is shifted from the peak obviously
- Significance is 3.6σ and 9.6σ for 4.358 and 4.258 GeV, respectively.

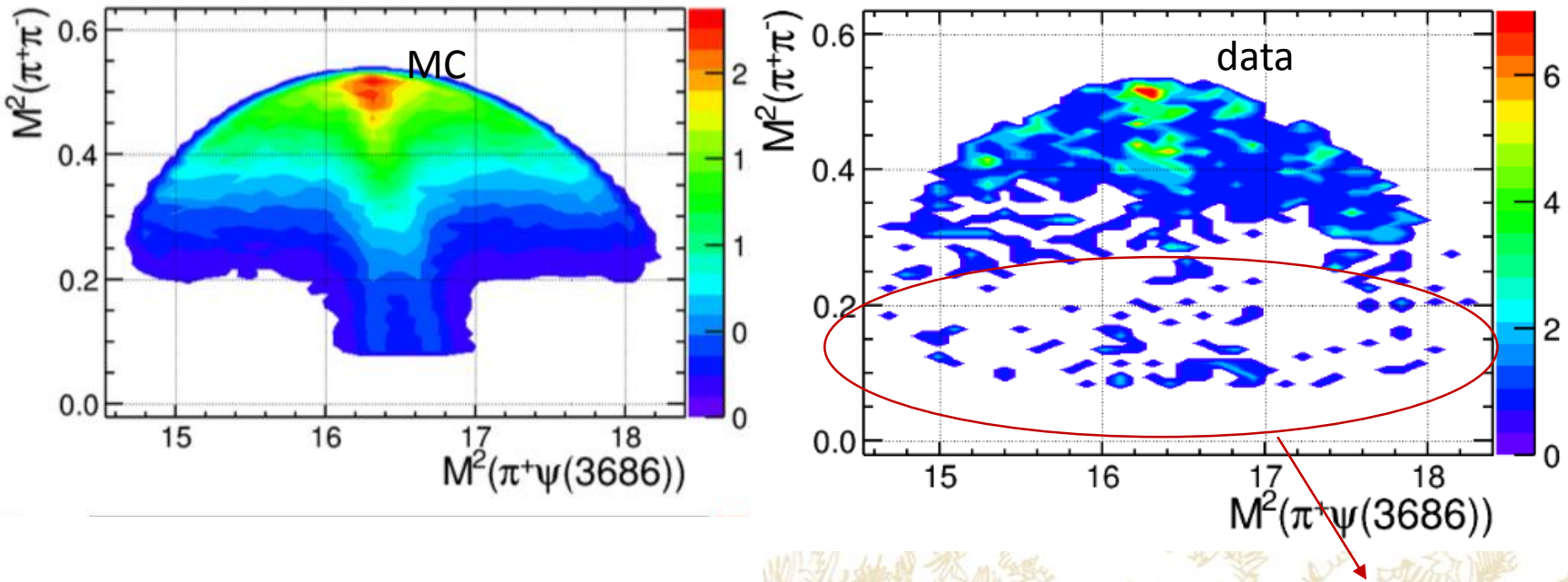
Fit of intermediate states



- No structure is observed in $M(\pi^{\pm}\psi(3686))$ at $\sqrt{s} = 4.226$ GeV
- The behavior of $M(\pi^{+}\pi^{-})$ is different with that at other energy points
- A possible interpretation might be found in the **triangle singularity mechanism** (Phys. Rev. D **51**, 4619 (1995)).

Some discussion

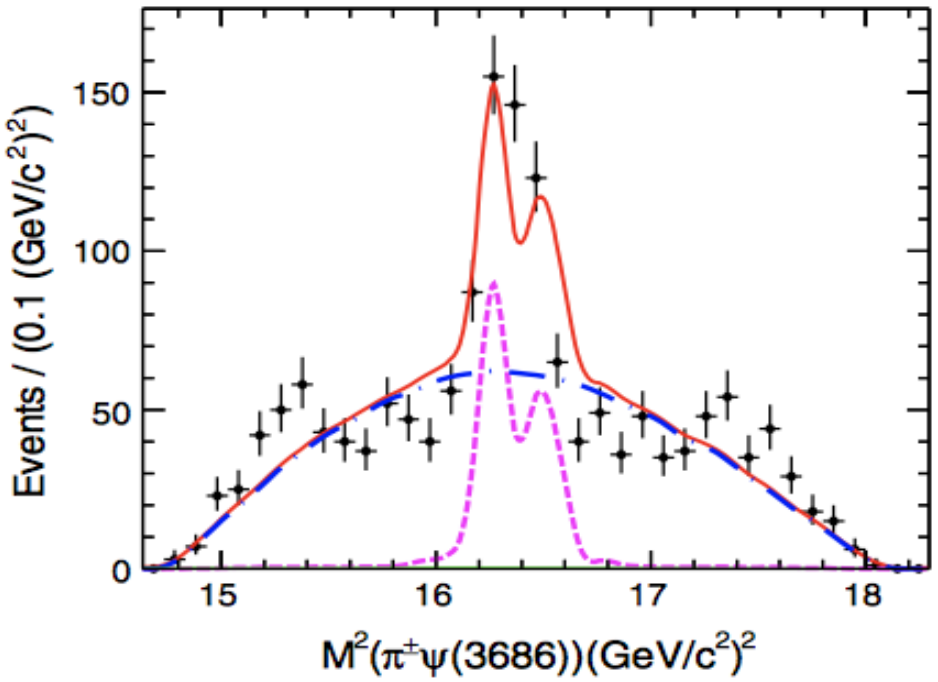
- Poor fit quality in full PHSH region at 4.416 GeV, P≈8%
- Different behaviors between high and low $M^2(\pi^+\pi^-)$ in data



Difference performance on $M^2(\pi^+\pi^-)$ region

Some discussion

- A fit with additional requirement $M^2(\pi^+\pi^-) > 0.3\ (\mathrm{GeV}/c^2)^2$ at $\sqrt{s} = 4.416$ GeV, yields M=4030.3±0.1 MeV/c^2, $\Gamma = 5.1 \pm 0.2$ MeV. P>50%.



Summary

- 'Y' states from line shape of $e^+e^- \to \pi^+\pi^-\psi(3686)$
  - Improved precision compare with Babar and Belle
  - Observation of Y(4220) in this process for the first time with 5.8σ
  - Large uncertainty on mass/width of Y(4220), Y(4390).

- 'Z' states in the $\pi\psi(3686)$ mass spectrum
  - Different production ratios and different distributions under the same 'Y' state.
  - Mass and width of Z_c determined from a simple 2D fit on Dalitz plot at $\sqrt{s} = 4.416$ GeV.

- A new XYZ data sample with more statistics is undergoing.
  - Improve the precision of mass/width of Y(4220), Y(4390).
  - Determine the parameters of Z_c from PWA.
  - Extraction line shape of πZ_c.