Theoretical Description of the X(3872) and Y(4260) Decays

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SFB School, Boppard
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SFB 1044
THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

JG|U
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

1 Motivation

X(3872)

- Discovery 2003
  - Belle at KEK - Japan
  - e^+e^- collisions
- Seen by
  - CDF, D0(Fermilab - USA), LHCb, CMS (Cerne-Switzerland), Babar (SLAC - USA), BESIII (IHEP - China)
- 1^{st} exotic in $c\bar{c}$ spectrum

Y(4260)

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  - Babar at SLAC - USA
  - e^+e^- annihilation through initial state radiation
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- Decay into other exotic mesons!

Exotic Mesons

- Mesons that can not be explained by the conventional quark model are called exotic

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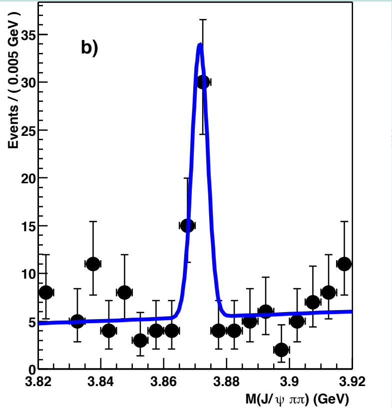

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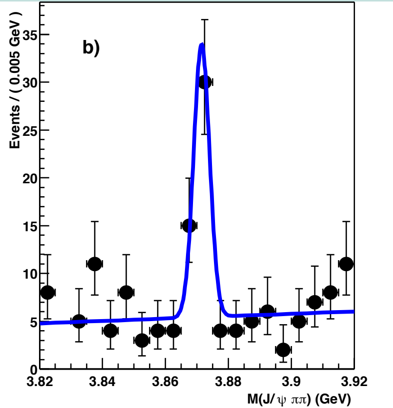

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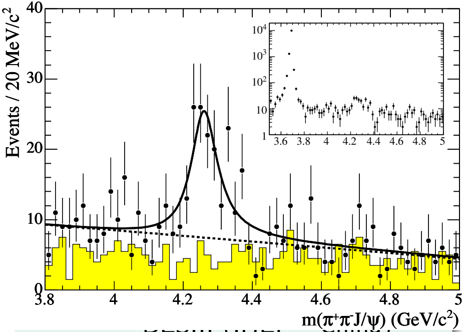

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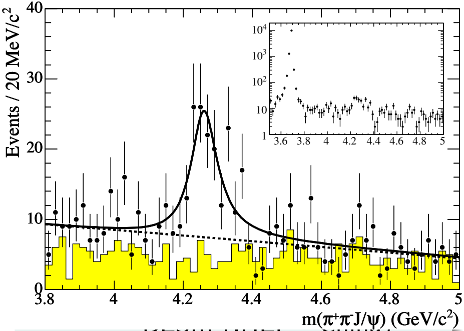

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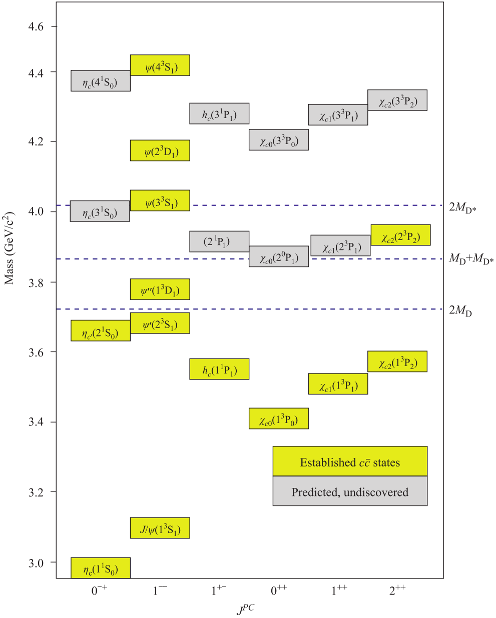
Exotic Mesons

S. L. Olsen *Front.Phys.* *(2015)*



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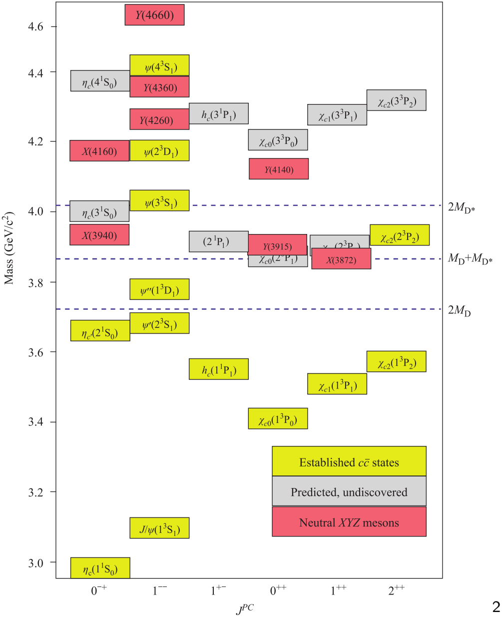

Alternative explanations:

tetraquark, molecular state, hybrids of quarkonium and gluons, quarkonium-glueballs mixtures ...

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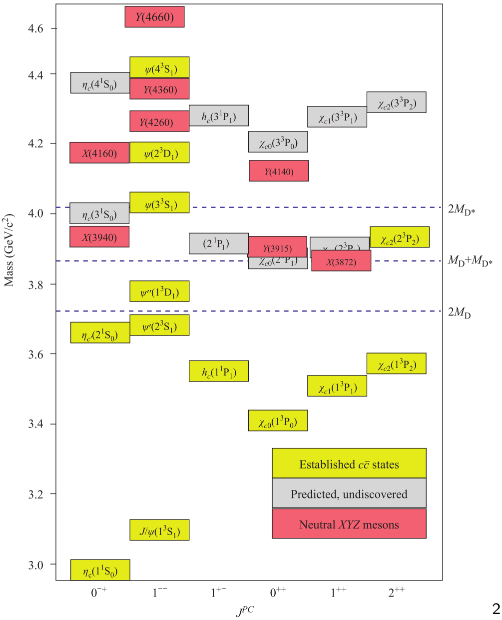

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Charged Exotic Mesons

- Confirmed in 2013 by Belle and BESIII
- $c\bar{c} + q_i\bar{q}_j$ $(i \neq j)$

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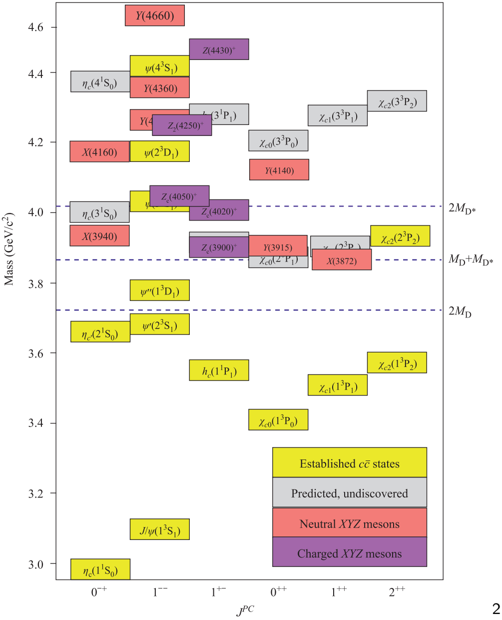

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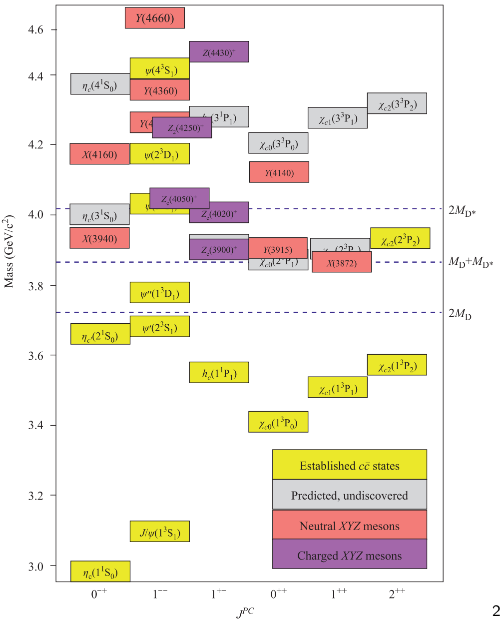
No Unique Structure

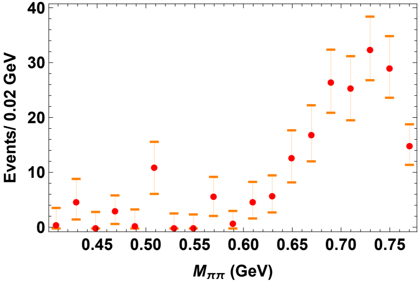
Pure Molecular or tetraquark explanations cannot explain the exotic states

S. L. Olsen *Front.Phys.* (2015)

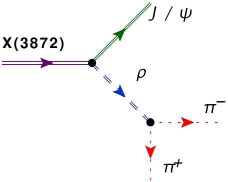


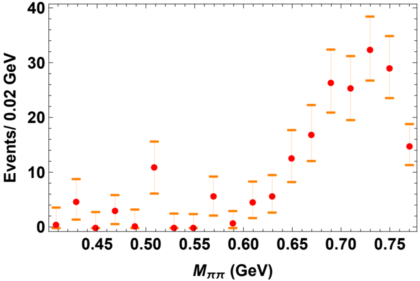
2 X(3872)

Breit-Wigner Method



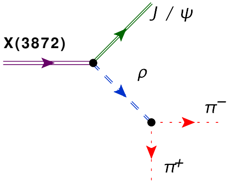
☞ *Belle-2011*


X(3872)
J / ψ
ρ
π−
π+

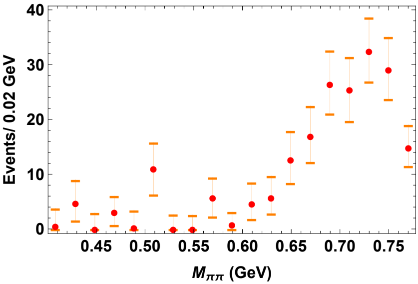

Events/ 0.02 GeV
0
10
20
30
40
0.45
0.50
0.55
0.60
0.65
0.70
0.75
Mππ (GeV)

☞ *Belle-2011*

Breit-Wigner Method



$$(V_{\rho\pi\pi})^{\mu} \underbrace{\frac{\left(-g_{\mu\nu} + q_\mu q_\nu / m_\rho^2\right)}{q^2 - m_\rho^2 + i m_\rho \Gamma_\rho}}_{\text{Breit-Wigner Propagator}} (V_{X\psi\rho})^{\alpha\beta\nu} \epsilon_\alpha(p_X)\epsilon_\beta(p_\psi)$$



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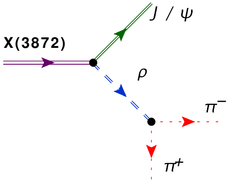

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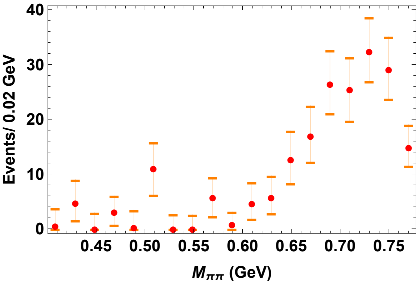


☞ *Belle-2011*

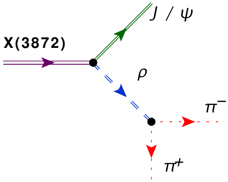
Vertex $V_{x\psi\rho}$

$V_{x\psi\rho} \to$ 3 couplings:
1 longitudinal (helicity $= 0$)
2 transversal (helicity $= \pm 1$)

Vertex $V_{\rho\pi\pi}$

$C_{\rho\pi\pi}$ can be obtained directly from the experimental ρ width:
$\Gamma_{\rho\pi\pi} = 147.8(9)$ MeV
$\Longrightarrow \quad C_{\rho\pi\pi} = 5.98(2)$

Dimensionless Couplings!



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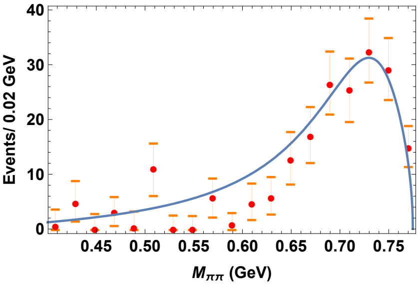

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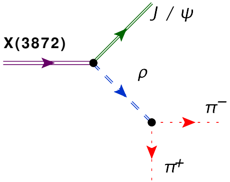

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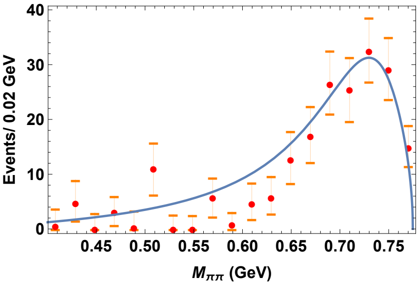

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Fit Parameters

$\chi^2_{red} \simeq 0.73$

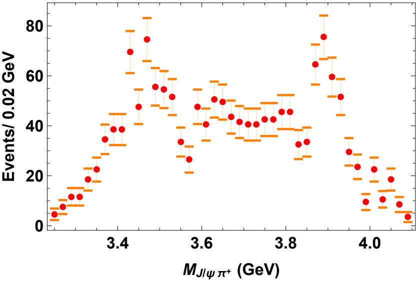
$Norm \simeq 104.08$

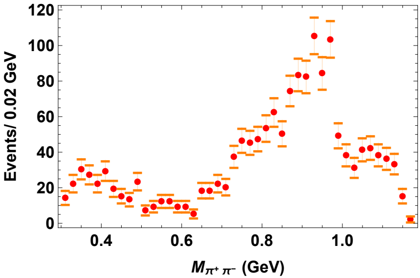
$\frac{Ca^{(1)}_{x\psi\rho}}{C^{(0)}_{x\psi\rho}} \sim 2\cdot 10^{-7}$

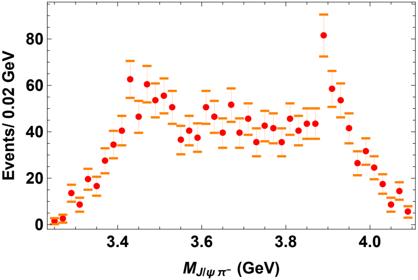
$\frac{Cb^{(1)}_{x\psi\rho}}{C^{(0)}_{x\psi\rho}} \sim 8\cdot 10^{-7}$

3 Y(4260)

☞ *BESIII 2013*


Events/ 0.02 GeV
M_J/ψ π+ (GeV)


Events/ 0.02 GeV
M_π+ π− (GeV)


Events/ 0.02 GeV
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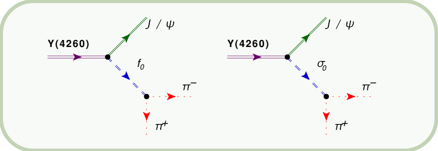
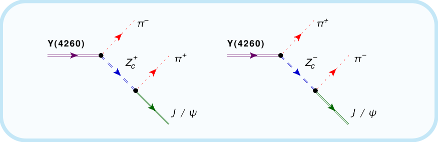
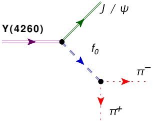
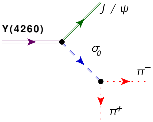
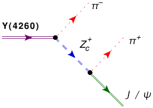

Y(4260)
J / ψ
f0
π−
π+
Y(4260)
J / ψ
σ0
π−
π+

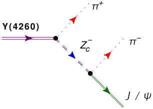

Y(4260)
π−
Zc+
π+
J / ψ
Y(4260)
π+
Zc−
π−
J / ψ

Breit-Wigner Method









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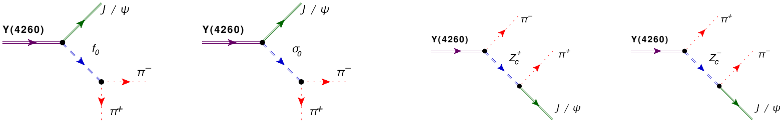
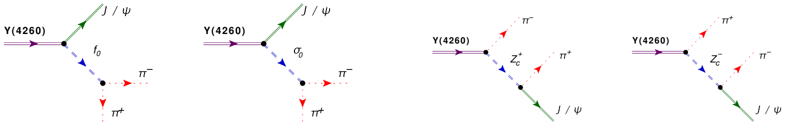


$$\left(\frac{1}{3}\sum_{spin}|\mathcal{M}|^2\right) = \frac{1}{3}\left|\mathcal{M}_{f_0} + \mathcal{M}_{\sigma_0} + \mathcal{M}_{Z_c^+} + \mathcal{M}_{Z_c^-}\right|^2 \left[\underbrace{\epsilon_\alpha(p_Y)\epsilon^*_{\alpha'}(p_Y)}_{-g^{\alpha\alpha'}+\frac{p_Y^\alpha p_Y^{\alpha'}}{m_Y^2}}\right]\left[\underbrace{\epsilon_\beta(p_\psi)\epsilon^*_{\beta'}(p_\psi)}_{-g^{\beta\beta'}+\frac{p_\psi^\beta p_\psi^{\beta'}}{m_\psi^2}}\right]$$

$$\frac{d\Gamma}{dM^2_{\psi\pi}\; dM^2_{\pi\pi}} = \frac{1}{32\,(2\pi\; m_Y)^3}\left(\frac{1}{3}\sum_{spin}|\mathcal{M}|^2\right)$$



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Known Couplings

$\Gamma_{f_0} = 50(15) \Longrightarrow \mathbf{C_{f_0\pi\pi} = 1.32(13)}$

$\Gamma_{\sigma_0} = 552(10) \Longrightarrow \mathbf{C_{\sigma_0\pi\pi} = 7.29(7)}$

$\Gamma_z = \underbrace{4.9(2.2)}_{\text{MeV}} \Longrightarrow \mathbf{C_{Z_c\psi\pi} = 0.41(9)}$

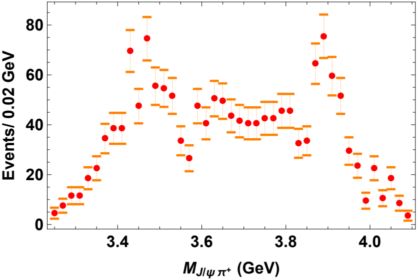
Couplings to fit

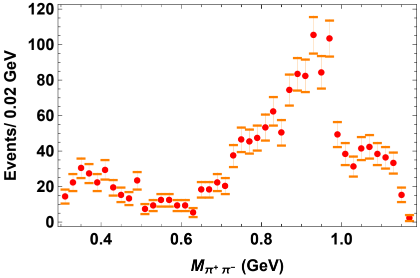
$C^T_{Y\psi f_0}$ $C^L_{Y\psi f_0}$

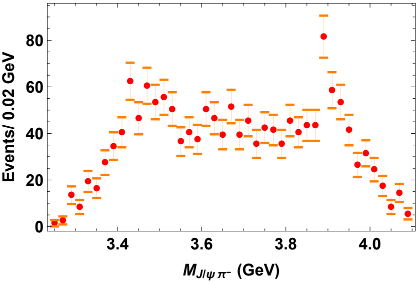
$C^T_{Y\psi\sigma_0}$ $C^L_{Y\psi\sigma_0}$

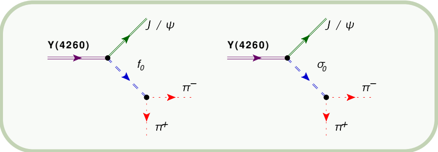
$C_{Y\pi Z_c}$

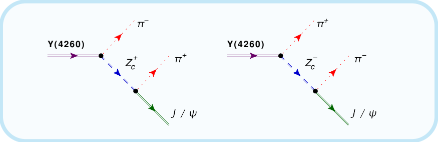
☞ *BESIII 2013*


Events/ 0.02 GeV
$M_{J/\psi\,\pi^+}$ (GeV)

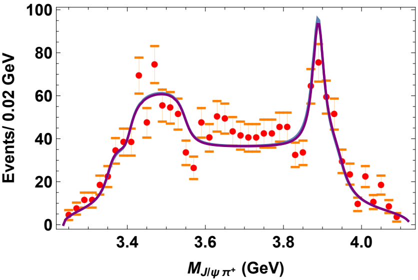

Events/ 0.02 GeV
$M_{\pi^+\pi^-}$ (GeV)

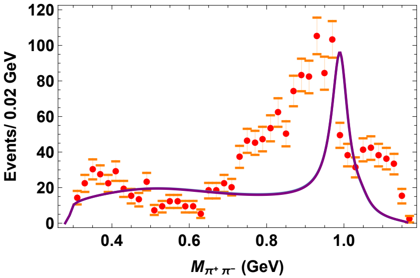

Events/ 0.02 GeV
$M_{J/\psi\,\pi^-}$ (GeV)

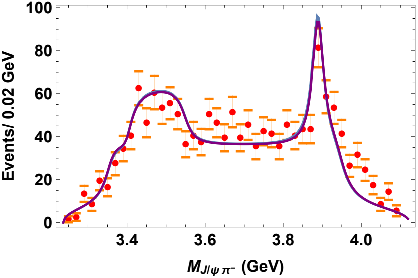

Y(4260)
J / ψ
f_0
π^-
π^+
Y(4260)
J / ψ
σ_0
π^-
π^+

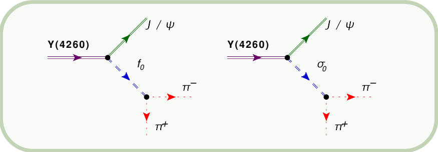

Y(4260)
π^-
Z_c^+
π^+
J / ψ
Y(4260)
π^+
Z_c^-
π^-
J / ψ

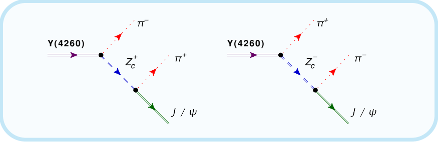
☞ *BESIII 2013*


Events/ 0.02 GeV
$M_{J/\psi\,\pi^+}$ (GeV)
0
20
40
60
80
100
3.4
3.6
3.8
4.0


Events/ 0.02 GeV
$M_{\pi^+\,\pi^-}$ (GeV)
0
20
40
60
80
100
120
0.4
0.6
0.8
1.0


Events/ 0.02 GeV
$M_{J/\psi\,\pi^-}$ (GeV)
0
20
40
60
80
100
3.4
3.6
3.8
4.0


Y(4260)
J / ψ
f_0
π^-
π^+
Y(4260)
J / ψ
σ_0
π^-
π^+


Y(4260)
π^-
Z_c^+
π^+
J / ψ
Y(4260)
π^+
Z_c^-
π^-
J / ψ

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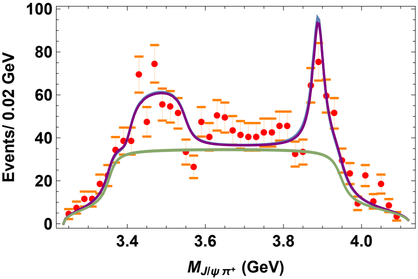
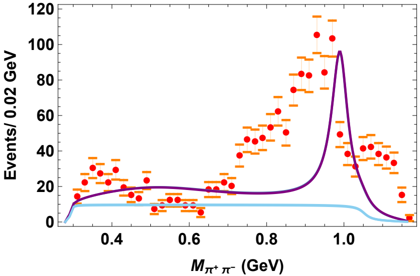
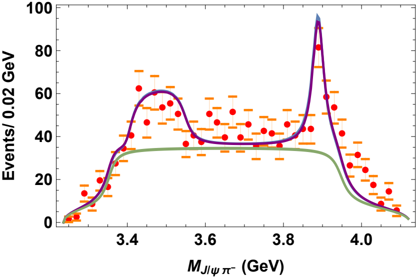
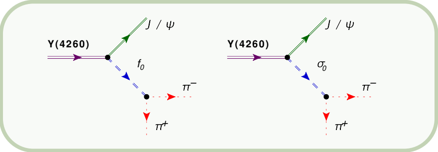

Events/ 0.02 GeV
$M_{J/\psi\,\pi^+}$ (GeV)


Events/ 0.02 GeV
$M_{\pi^+\pi^-}$ (GeV)


Events/ 0.02 GeV
$M_{J/\psi\,\pi^-}$ (GeV)


Y(4260)
J/ψ
f_0
π^-
π^+
Y(4260)
J/ψ
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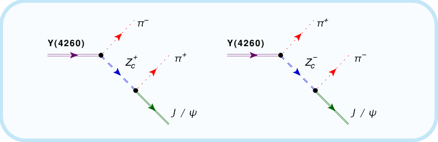
π^-
π^+


Y(4260)
π^-
Z_c^+
π^+
J/ψ
Y(4260)
π^+
Z_c^-
π^-
J/ψ

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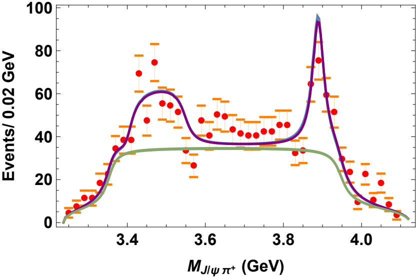
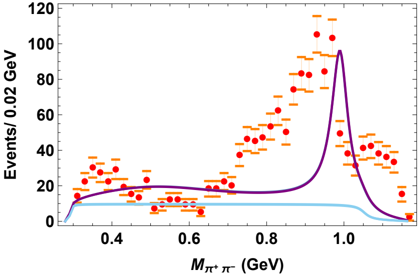
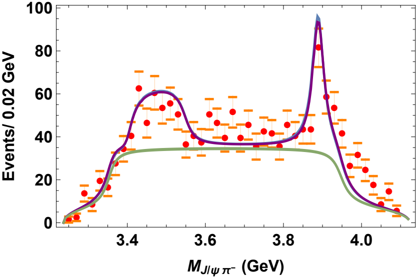






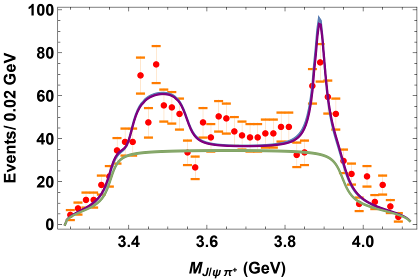
Fit Parameters

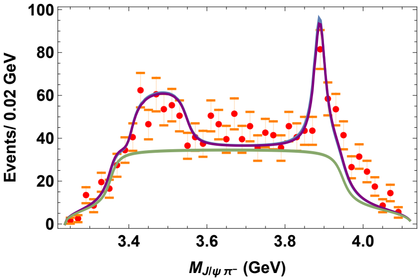
$$\chi^2_{red} \simeq 9.5$$

$$N1 \simeq 3280 \quad N2 \simeq 25931$$

$$\frac{C^T_{Y\psi f_0}}{C_{Y\pi Z_c}} \simeq 0.21 \qquad \frac{C^T_{Y\psi\sigma_0}}{C_{Y\pi Z_c}} \simeq -0.7\cdot 10^{-2}$$

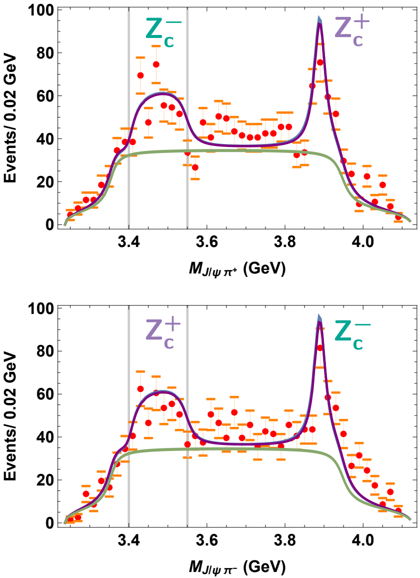
$$\frac{C^L_{Y\psi f_0}}{C_{Y\pi Z_c}} \simeq -0.11 \qquad \frac{C^L_{Y\psi\sigma_0}}{C_{Y\pi Z_c}} \simeq 0.4\cdot 10^{-1}$$





Mandelstam Variables

$$\underbrace{M_{\pi\pi}^2}_{s} + \underbrace{M_{\psi\pi^+}^2}_{t} + \underbrace{M_{\psi\pi^-}^2}_{u} = \sum_{i}^{all\ part.} m_i^2$$



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$$\underbrace{M^2_{\pi\pi}}_{s} + \underbrace{M^2_{\psi\pi^+}}_{t} + \underbrace{M^2_{\psi\pi^-}}_{u} = \sum_i^{all\ part.} m_i^2$$

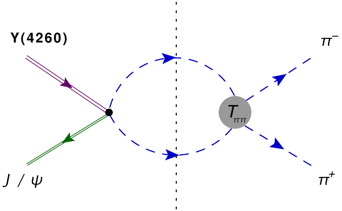
$$M_{\psi\pi^\pm} \rightarrow M_{Z_c^\pm}$$

$$\Longrightarrow \; 3.40 < M_{\psi\pi^\mp} < 3.55$$

Mirror Partner (Z_c^+, Z_c^-)

The bump in this region is due to the kinematic reflection of the mirror partner!

Omnes Method



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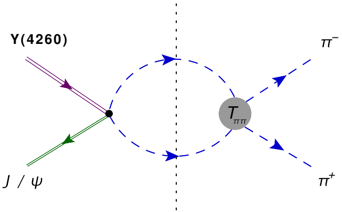
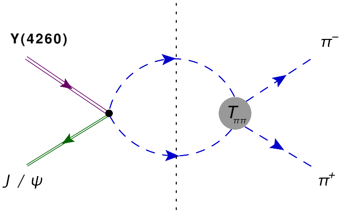


Analyticity: Dispersion Relation

$$\mathcal{M} = \frac{1}{\pi} \int_{4m_\pi^2}^{\infty} ds' \, \frac{Im\,(\mathcal{M})}{s' - s}$$

Omnes Method



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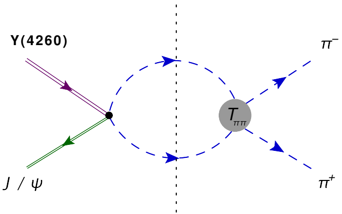
Cutskovsky (Cutting) Rule:

$$\frac{1}{p^2 - m^2 + i\epsilon} \rightarrow (-2\pi i)\,\delta(p^2 - m^2)$$

Imaginary Part $\rightarrow$ Propagators On-Shell

Omnes Method



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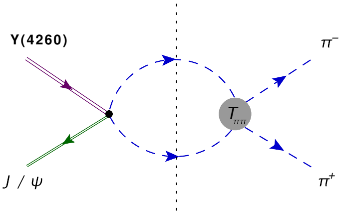
Imaginary Part $\to$ Propagators On-Shell

Unitarity: p. w. Amplitude

$$Im\mathcal{M}_j(s) = \rho_j(s)\mathcal{M}_j(s) t^{*\,I}_{\pi\pi\,j}\,\theta(s > 4\pi^2)$$

Omnes Method



Analyticity: Dispersion Relation

$$\mathcal{M} = \frac{1}{\pi}\int_{4m_\pi^2}^{\infty} ds' \, \frac{Im\,(\mathcal{M})}{s'-s}$$

Unitarity: p. w. Amplitude

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$$\Longrightarrow \text{ S-wave and Isospin} = 0$$

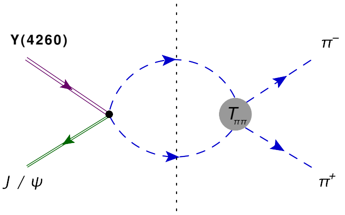
$$t^* = \frac{e^{i\delta(s)}\sin\delta(s)}{\rho(s)}$$

$$\mathcal{M}(s) = |\mathcal{M}(s)|e^{i\delta(s)}$$

Watson Final State Theorem

$$Arg[\mathcal{M}(s)] = \delta(s)$$

Omnes Method



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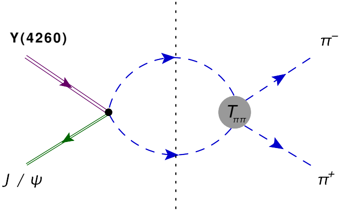

$$\Longrightarrow V_{Y\psi\pi\pi} \cdot \Omega(s)$$

Omnes Function

$$\Omega(s) = exp\left[\frac{s}{\pi}\int_{4m^2}^{\infty}\frac{ds'}{s'}\frac{\delta(s')}{s'-s}\right]$$

One subtraction and normalization

$$\Omega(0) = 1$$

Analyticity: Dispersion Relation

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$\pi\pi$ Rescattering

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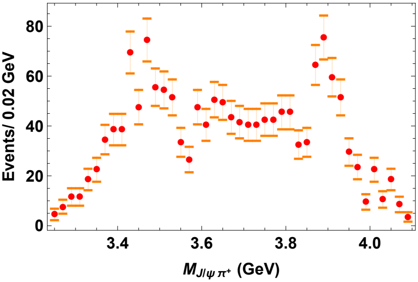

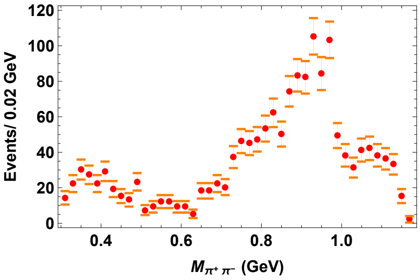

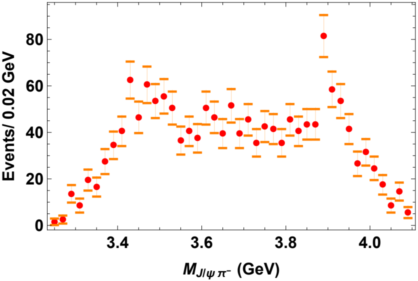

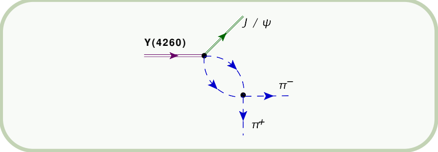

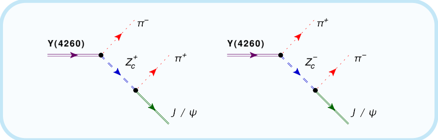

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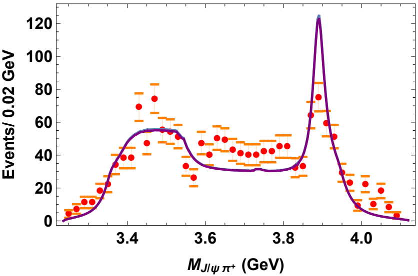

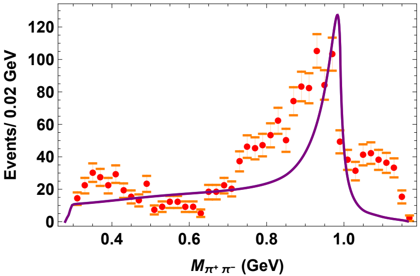

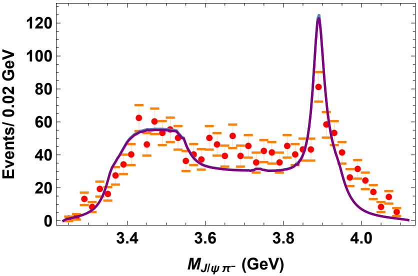

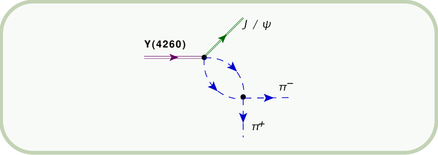

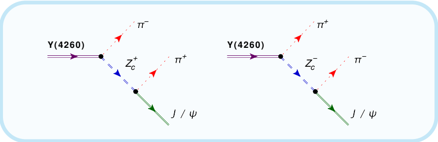

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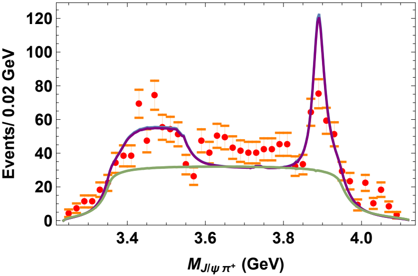

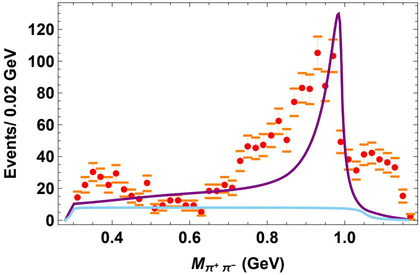

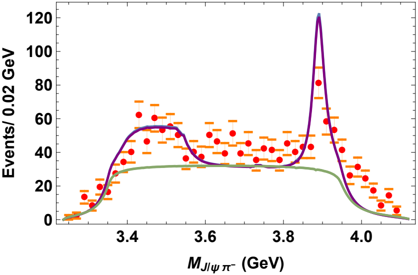

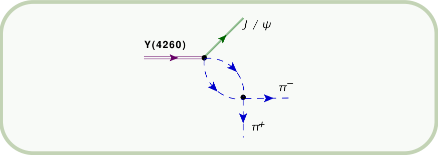

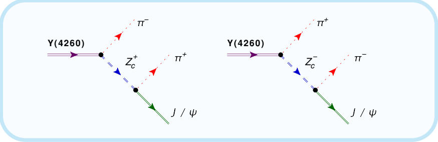

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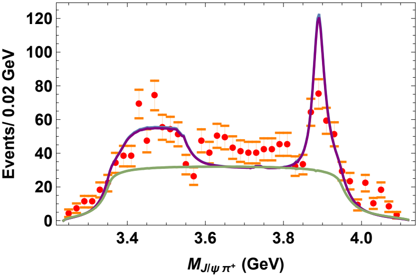
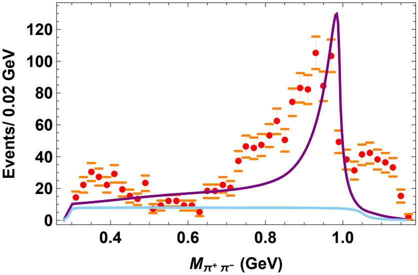
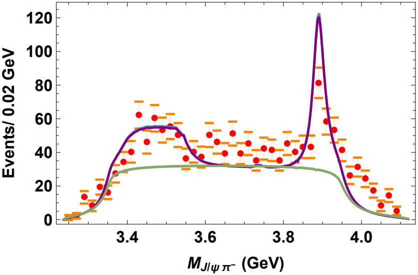






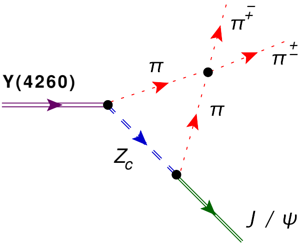
Fit Parameters

$$\chi^2_{red} \simeq 6.9$$

$$N1 \simeq 2691 \quad N2 \simeq 17445.5$$

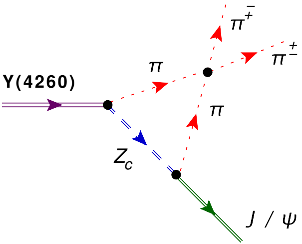
$$\frac{C^T_{Y\psi\pi\pi}}{C_{Y\pi Z_c}} \simeq 0.68 \quad \frac{C^L_{Y\psi\pi\pi}}{C_{Y\pi Z_c}} \simeq 0.57$$

4 Perspectives



Triangle Loop

- Analytic structure of the process with t and u channel diagrams
- As important as the others diagrams
- Inclusion of neutral Z_c^0
- Development of the formalism in progress



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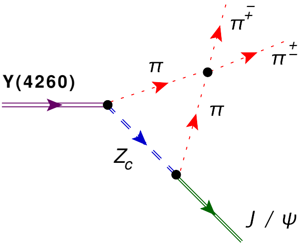

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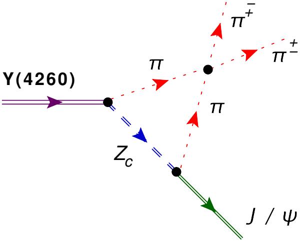

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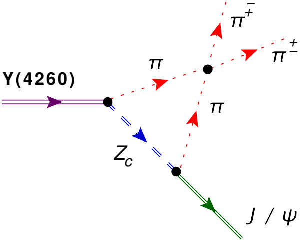

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5 Conclusions

X(3872)

- Simple Breit-Wigner method explain the dynamics of the decay:
- Meaning that $X \to \rho^0 + J/\psi$, then $\rho^0 \to \pi^- + \pi^+$
- $C_{X\psi\rho}$ longitudinal dominates the transverse one, and can be determined as soon as the absolute mass spectra are known.

Y(4260)

- Breit-Wigner Method:
  - $J/\psi\pi^{\pm}$ invariant mass distribution can be (well) explained!
  - First step: approximate estimate for f_0 and σ_0
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  - $J/\psi\pi^\pm$ invariant mass distribution can be (well) explained!
  - First step: approximate estimate for f_0 and σ_0
- $\pi\pi$ rescattering (via Omnes method):
  - Number of fitting couplings is reduced (only 3)
  - Implemented mechanism $\mathrm{I} \to \pi\pi$ rescattering in the S-channel

X(3872)

- Simple Breit-Wigner method explain the dynamics of the decay:
- Meaning that $X \to \rho^0 + J/\psi$, then $\rho^0 \to \pi^- + \pi^+$
- $C_{x\psi\rho}$ longitudinal dominates the transverse one, and can be determined as soon as the absolute mass spectra are known.

Y(4260)

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Thank you for listening!

THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

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