# Coupled-channel analysis of

# $e^+e^- \to \pi D^* \bar{D},\ J/\psi\pi\pi,\ J/\psi\,\eta$

Satoshi Nakamura

Note: This is an intermediate report.

All results are preliminary and may change later.

Treat results as unpublished data. Keep it within our USTC group.

# Introduction

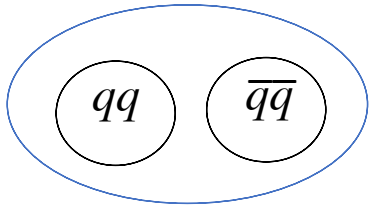
Many exotic hadron candidates (XYZ) discovered by BESIII, Belle, LHCb, … , experiments

Establishing the exotic hadrons (existence & structure) is highly controversial issue !

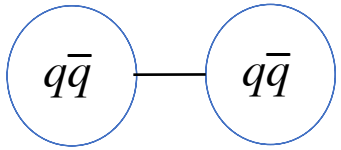
**Exotic picture**

Conventional picture

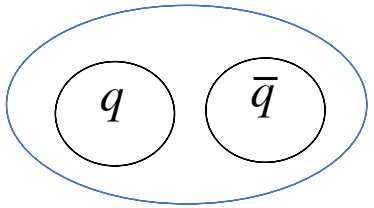
Meson




Diquark-antidiquark

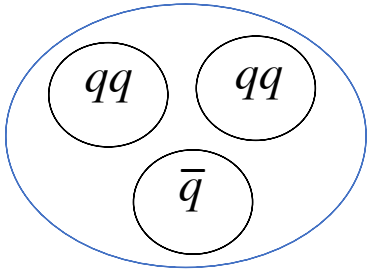



meson-meson molecule

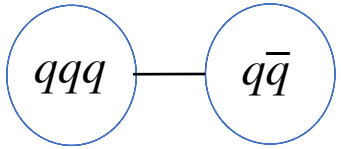



Quark-antiquark

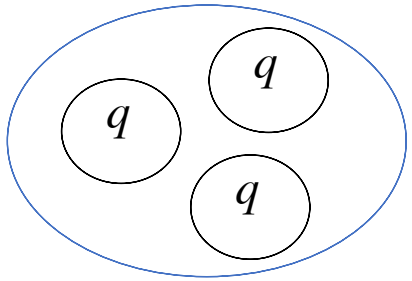
Baryon




Diquark-diquark-antiquark



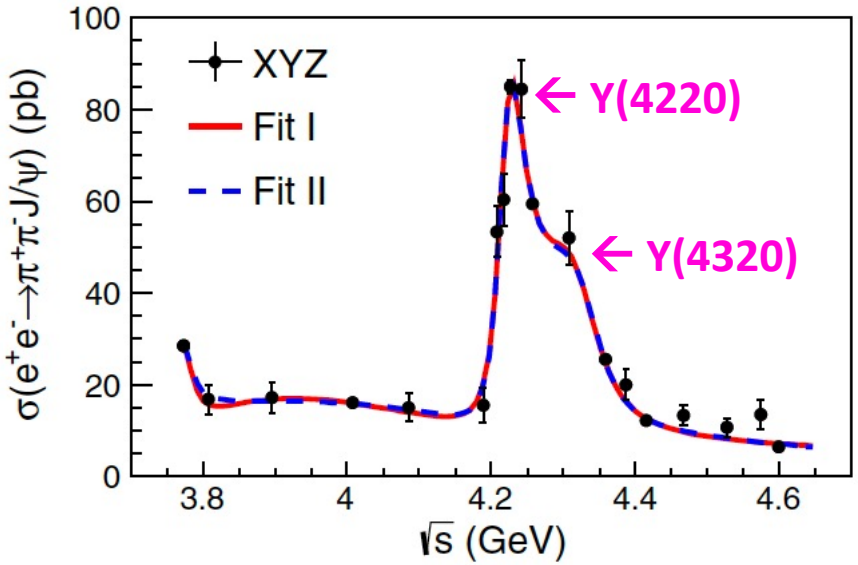

Meson-baryon molecule

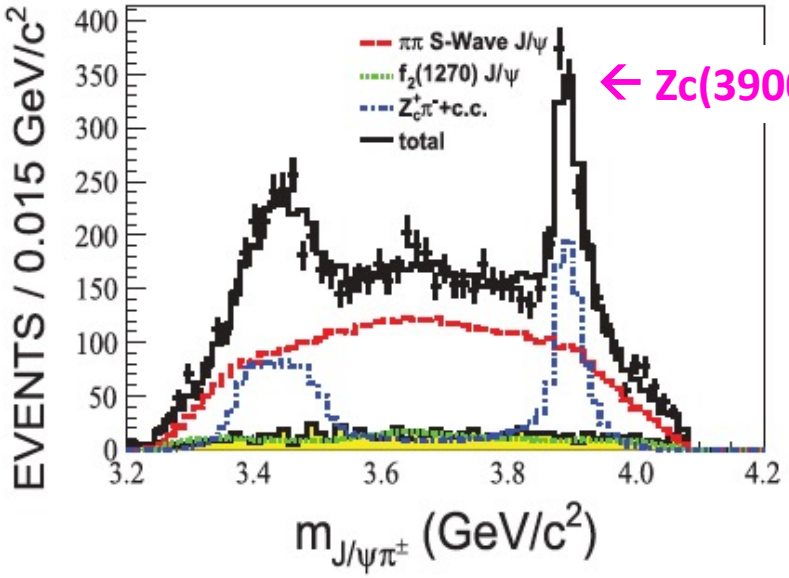



Three-quark

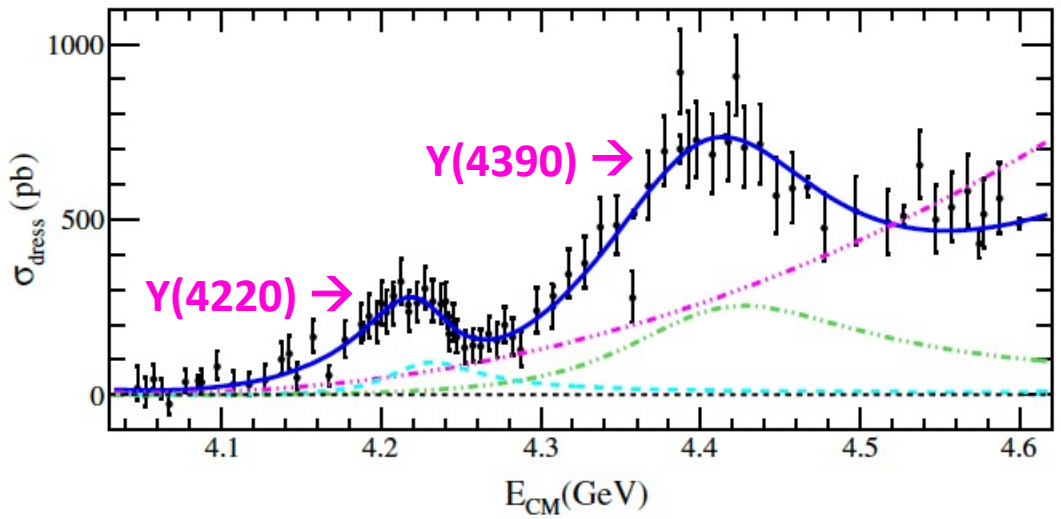
# BESIII data for XYZ physics (only selected ones)

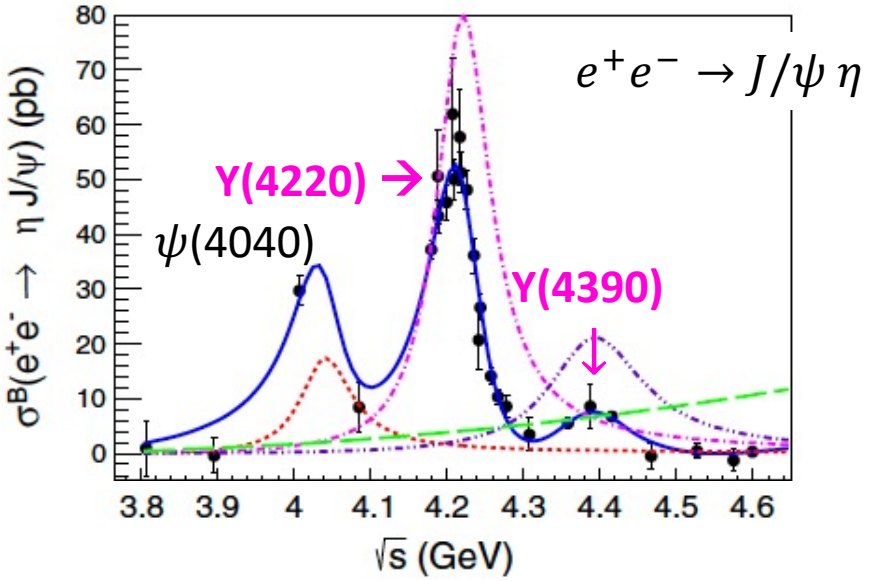
$e^+e^- \to J/\psi\,\pi^+\pi^-$ →




$e^+e^- \to \pi^+ D^0 D^{*-}$

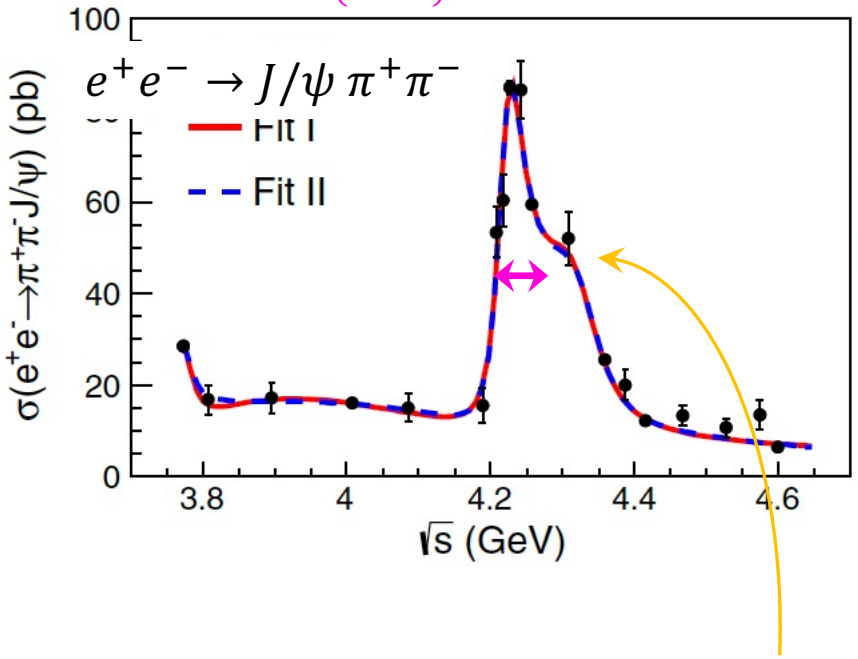


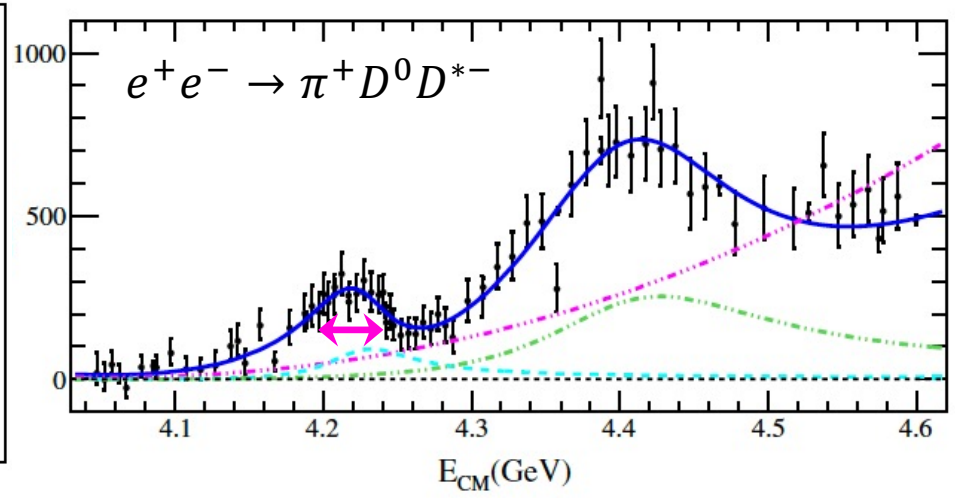
# Outstanding question in XYZ physics : Y puzzle

- Why Y states seem to have different widths for different final states ?

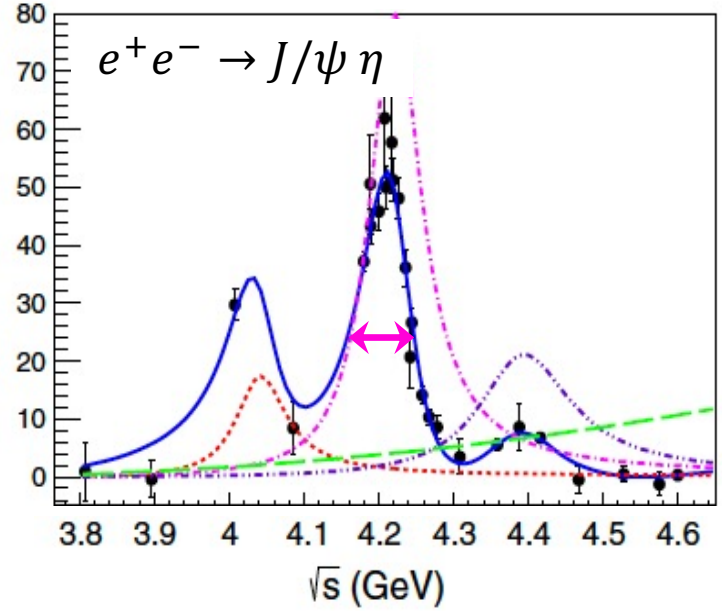
$\Gamma_{Y(4220)}$ ~ 44±4 MeV




$\Gamma_{Y(4220)}$ ~ 77±7 MeV




$\Gamma_{Y(4220)}$ ~ 82±6 MeV




- Why Y(4320) appears only in $e^+e^- \to J/\psi\,\pi\pi$?

# How to find solution to Y puzzle ?

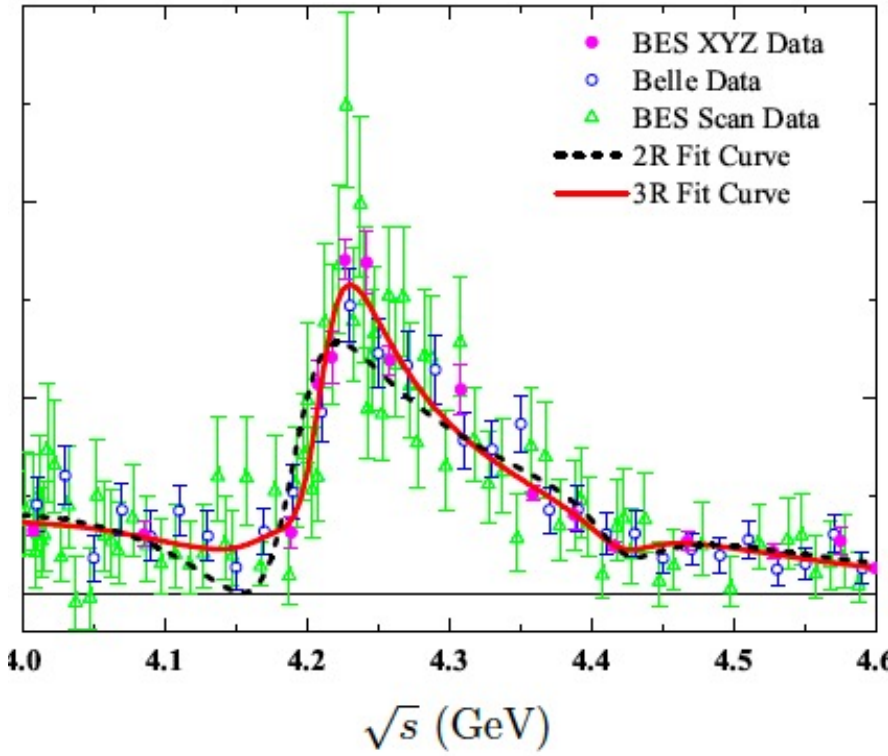
- 🥲 Analyze different final states with different models (usual experimental method)
- 😀 Analyze different final states simultaneously with a unified model

# Previous work on Y puzzle

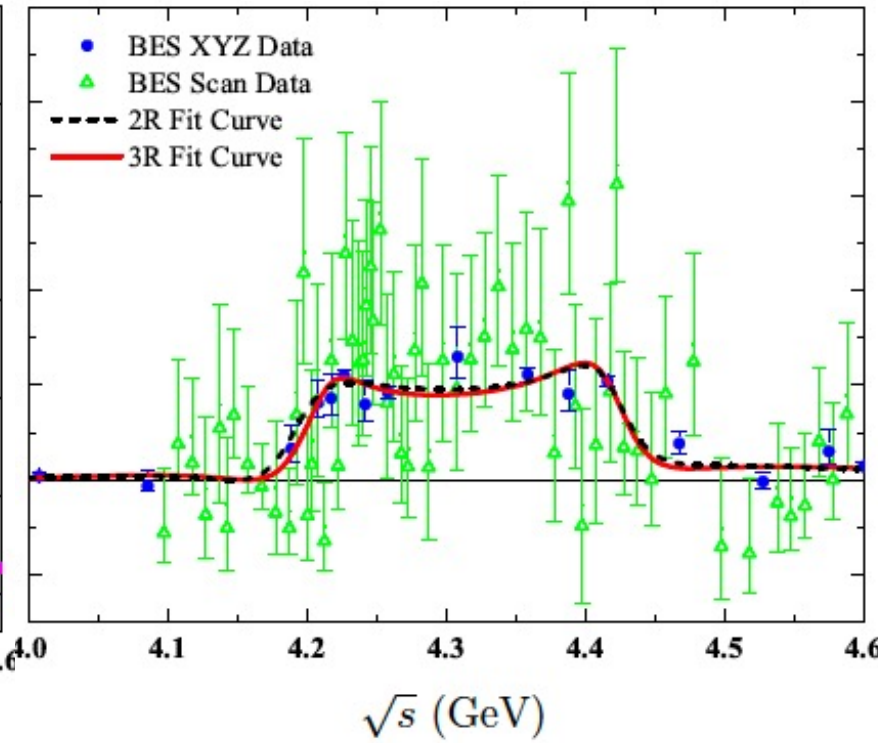
Chen et al., Eur. Phys. J. C 78, 136 (2018)

- $e^+e^- \to J/\psi\,\pi^+\pi^-,\ h_c\,\pi^+\pi^-,\ \pi^+D^0D^{*-}$ total cross section data were simultaneously fitted
- $\psi(4160),\ \psi(4415),\ Y(4220)$, and background are included
- Integrated final three-meson distribution is assumed be proportional to phase-space

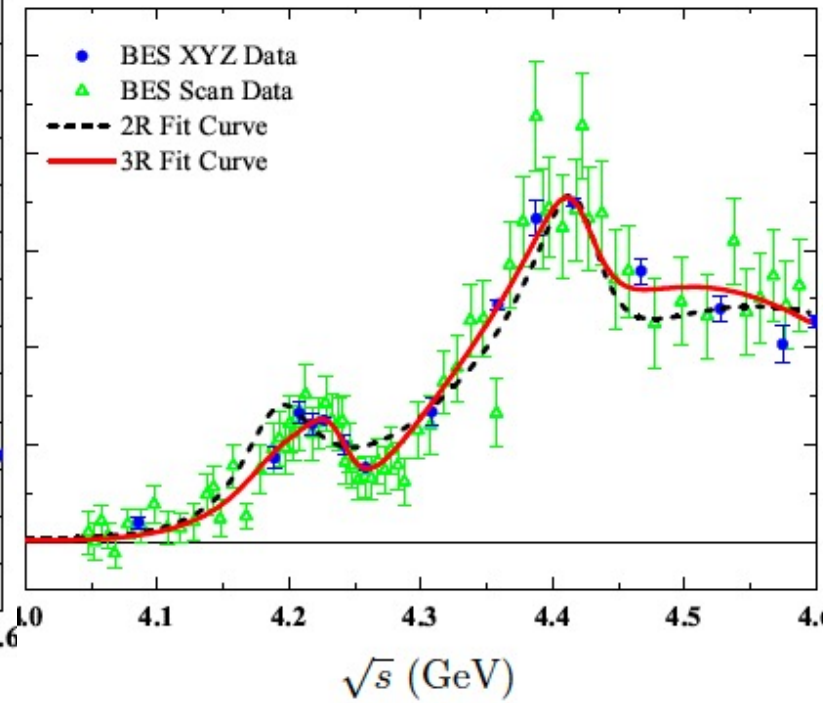
$e^+e^- \to J/\psi\,\pi^+\pi^-$




$e^+e^- \to h_c\,\pi^+\pi^-$




$e^+e^- \to \pi^+D^0D^{*-}$



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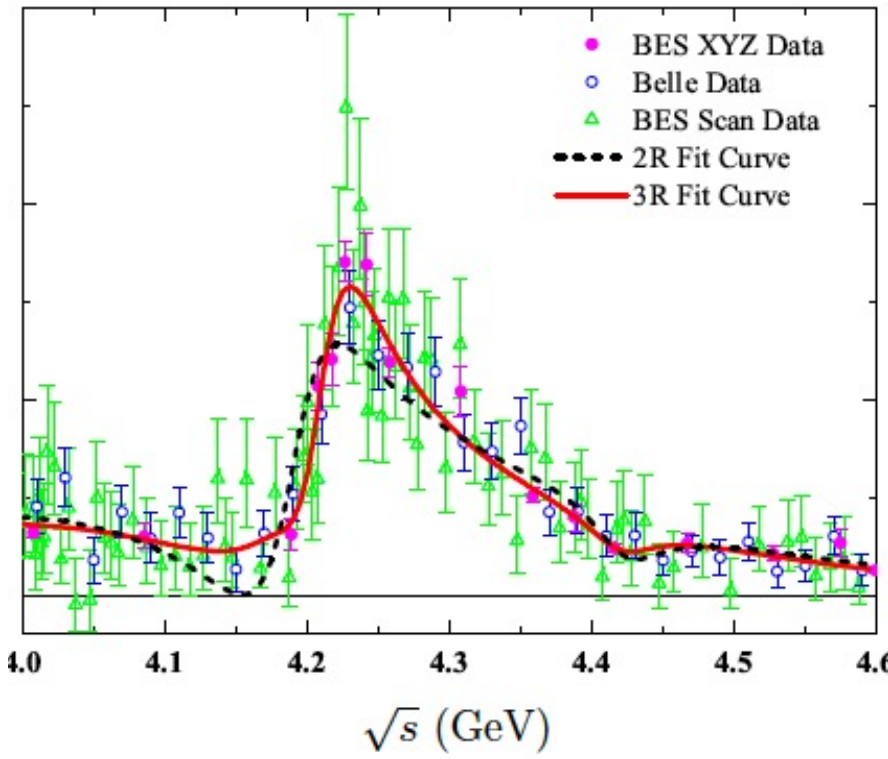


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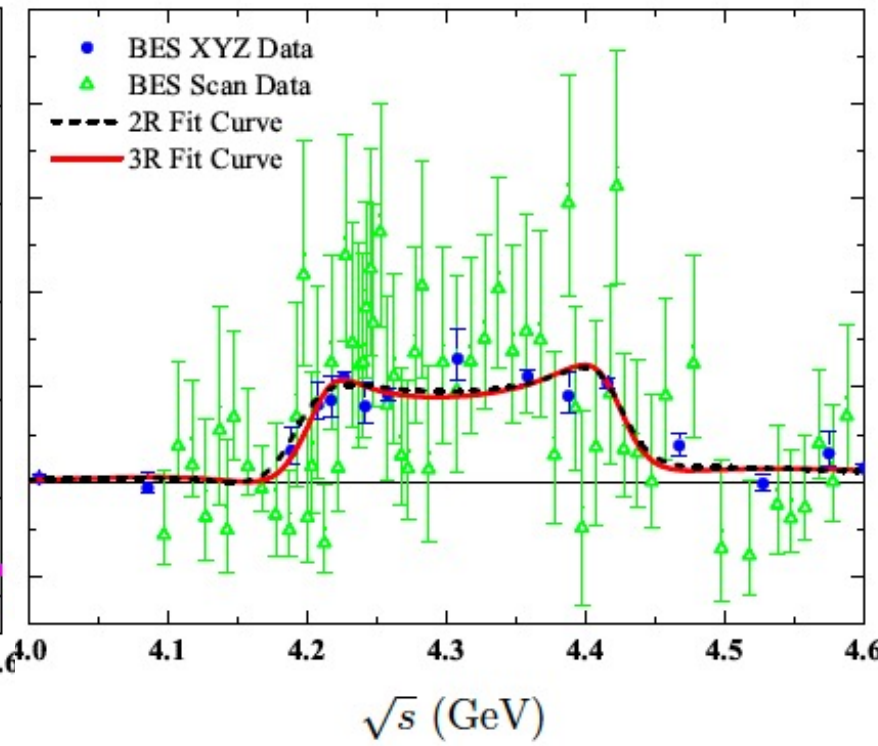
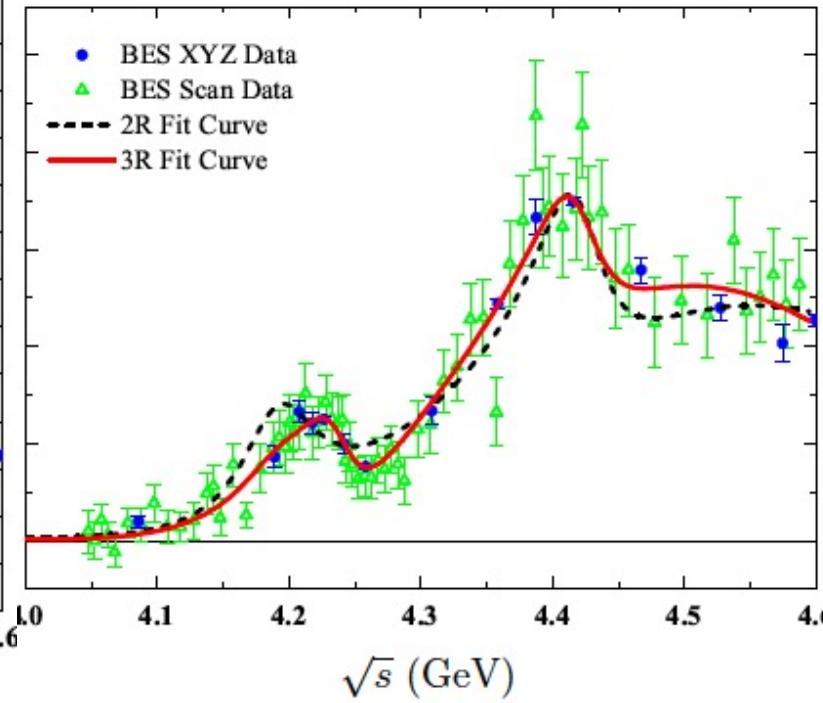



$e^+e^- \to \pi^+D^0D^{*-}$




Conclusions:

- Different Y widths are caused by interference between $\psi(4160)$, $\psi(4415)$, $Y(4220)$, and background
- $Y(4320)$ and $Y(4390)$-like enhancements are from interference

The conclusions are still not excluded by the current data

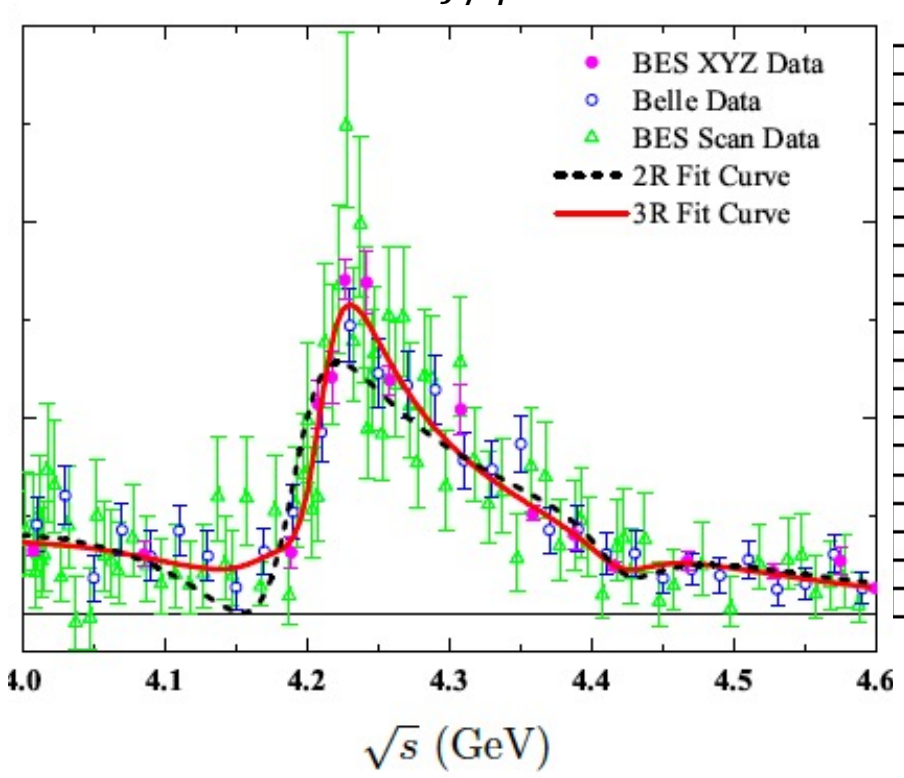
# Previous work on Y puzzle

Chen et al., Eur. Phys. J. C 78, 136 (2018)

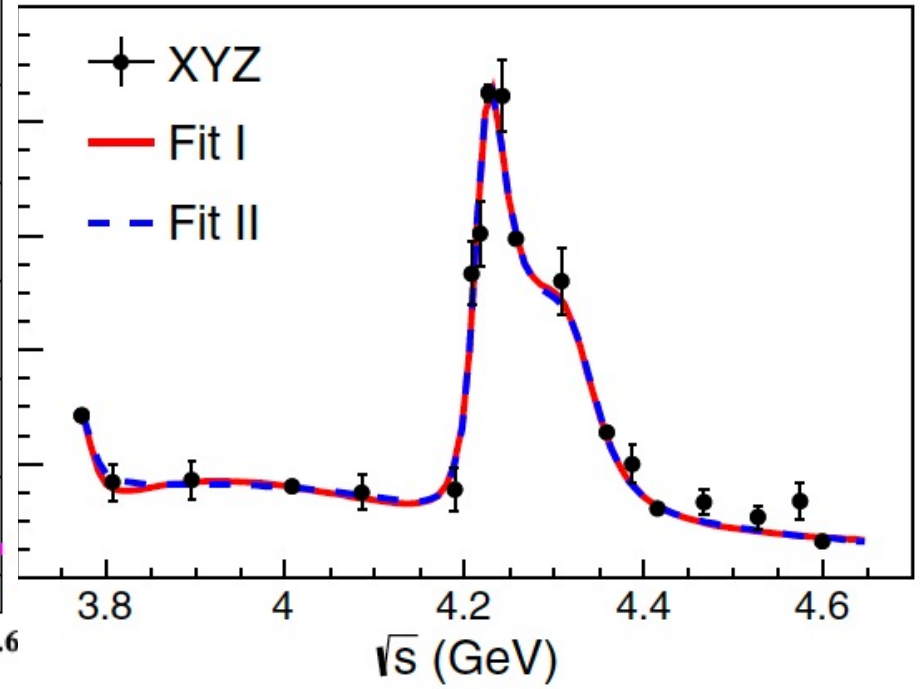
Criticism 1 : $J/\psi\pi\pi$ lineshape seems qualitatively different from high-precision data

(even though barely consistently within errors)

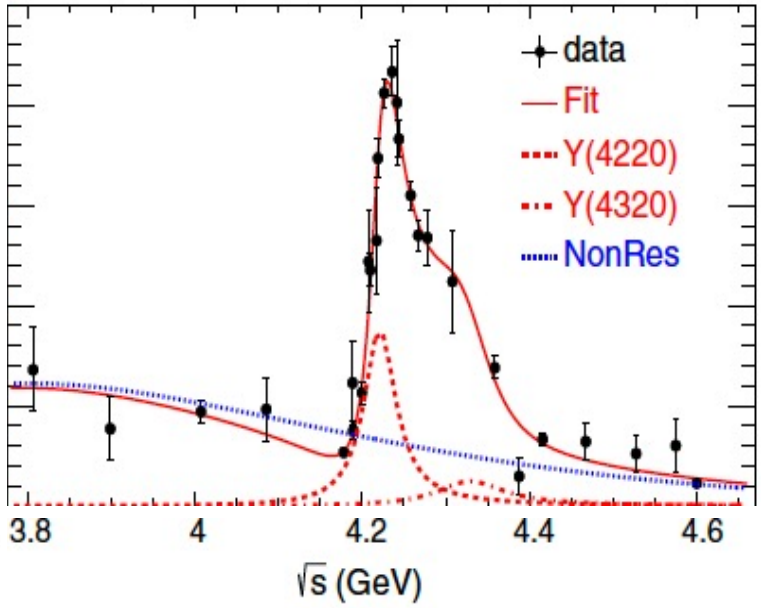
$e^+e^- \to J/\psi\,\pi^+\pi^-$




$e^+e^- \to J/\psi\,\pi^+\pi^-$




$e^+e^- \to J/\psi\,\pi^0\pi^0$

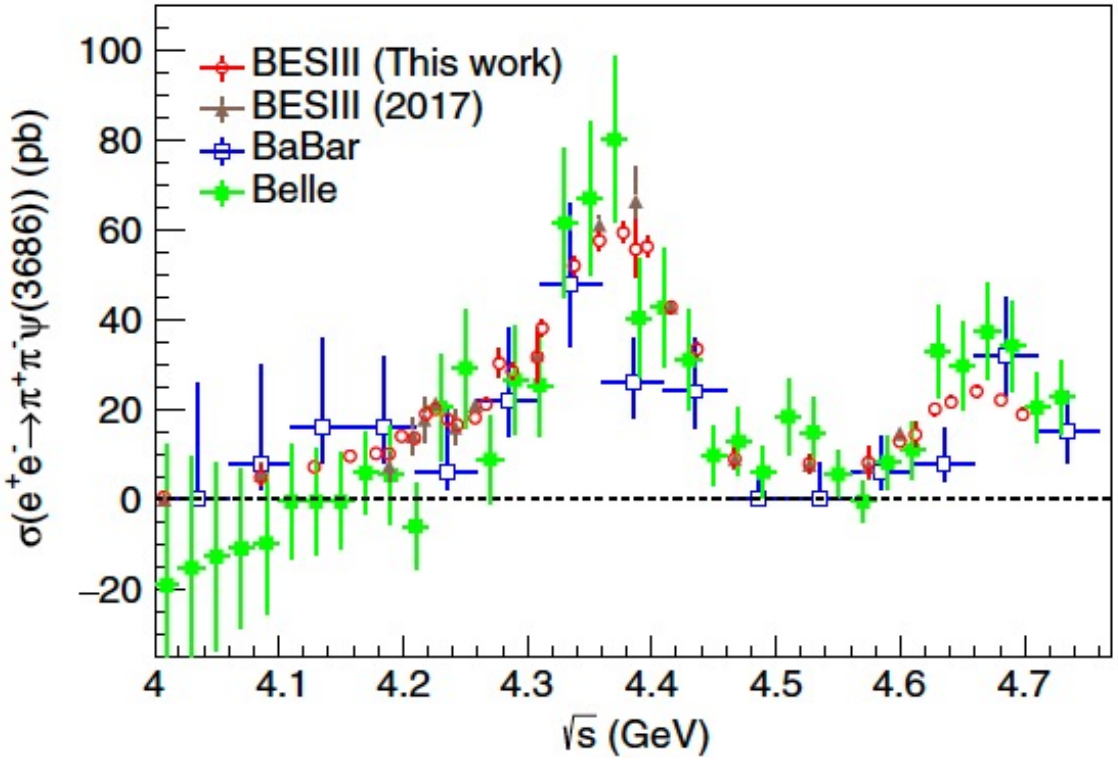


# Previous work on Y puzzle

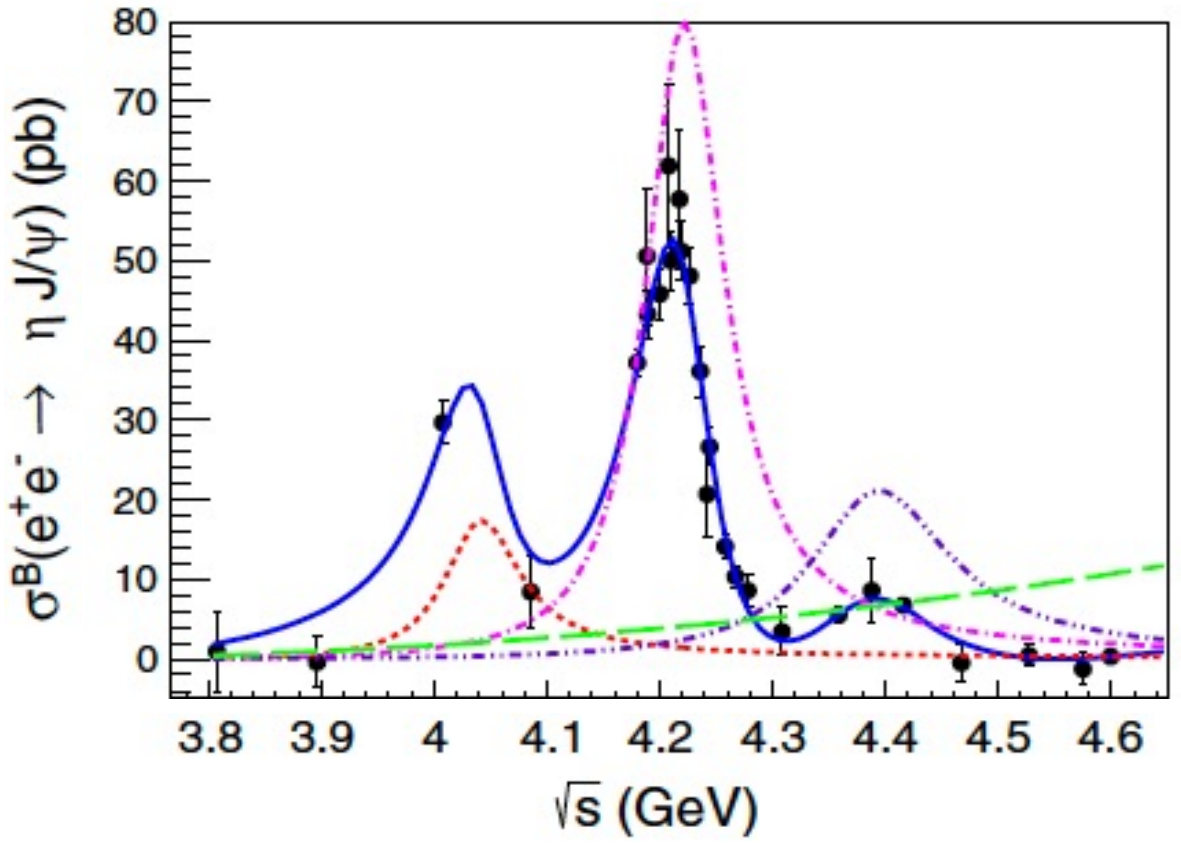
Chen et al., Eur. Phys. J. C 78, 136 (2018)

Criticism 2 : seems difficult to explain Y(4390) in other data not fitted (why didn't they include $\psi'\,\pi^+\pi^-$ data ?)

$e^+e^- \to \psi'\,\pi^+\pi^-$




$e^+e^- \to J/\psi\,\eta$ (BESIII, 2020)



# Previous work on Y puzzle

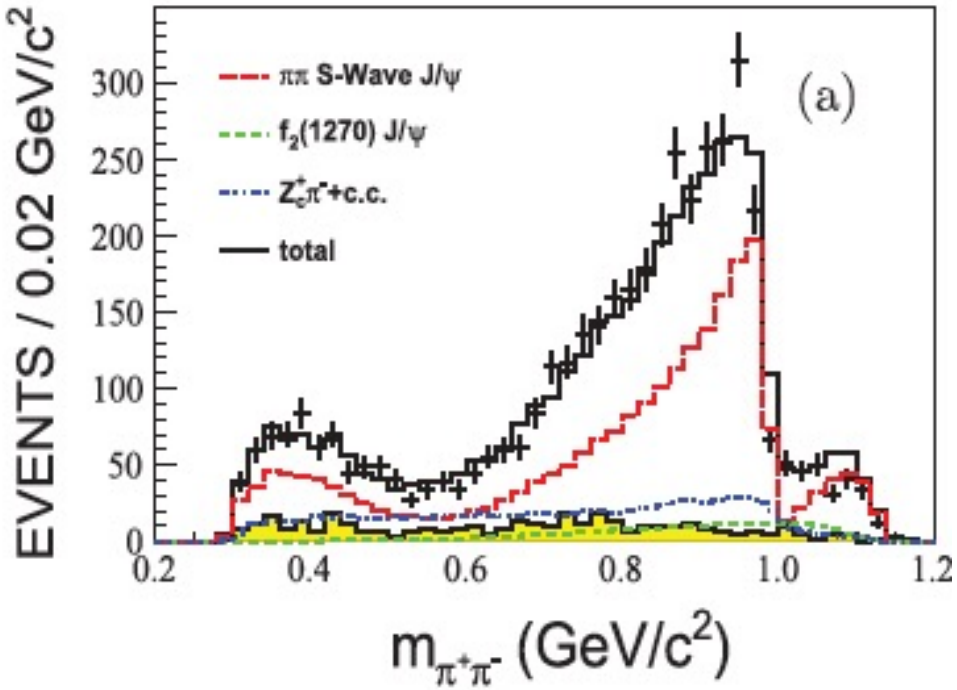
Chen et al., Eur. Phys. J. C 78, 136 (2018)

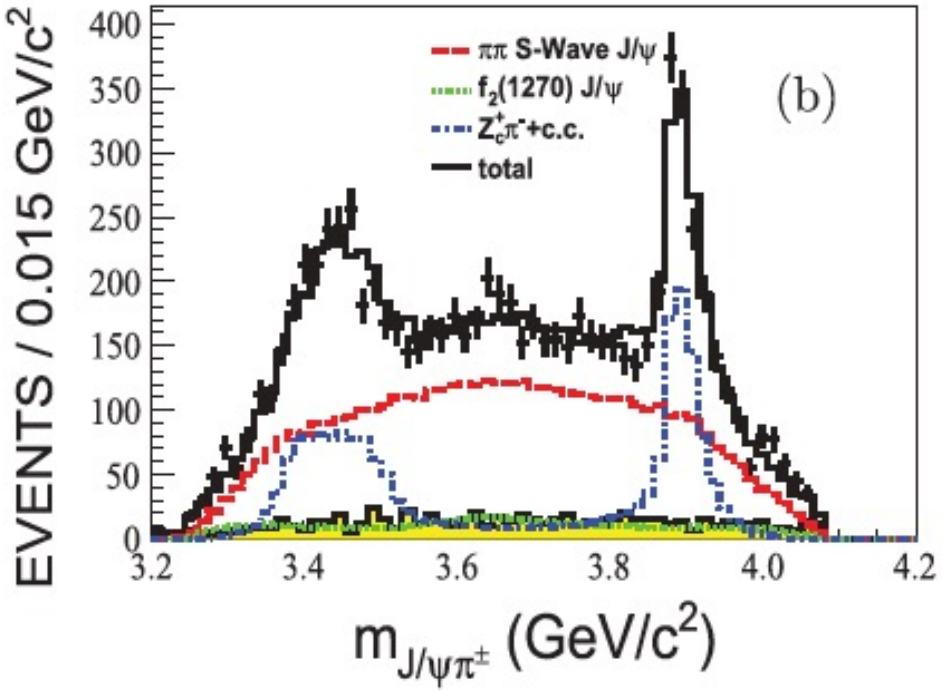
Criticism 3 : Integrated final three-meson distribution is assumed be proportional to phase-space

← final three-meson distributions are very different from phase-space shape

assumption may be bad

$e^+e^- \to J/\psi\,\pi^+\pi^-$




My opinion: the interferences could play some role, but is inconclusive solution to Y puzzle

# This work addresses the Y problem

**Method**

Analyze $e^+e^- \to \pi D^* \bar{D},\ J/\psi\pi\pi,\ J/\psi\,\eta$ BESIII data simultaneously with a unified coupled-channel model

Both total and differential cross section data are fitted

Nature of Zc(3900) and $Y(4320)$ is also studied

# MODEL

# Model

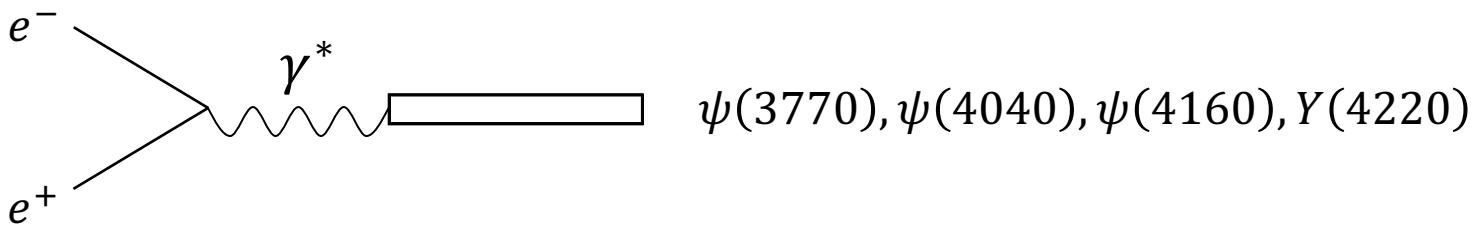
Analyze BESIII data in $3.8 \leq \sqrt{s} \leq 4.5$ GeV region

Charmonia included in model : $\psi(3770),\ \psi(4040),\ \psi(4160),\ Y(4220)$

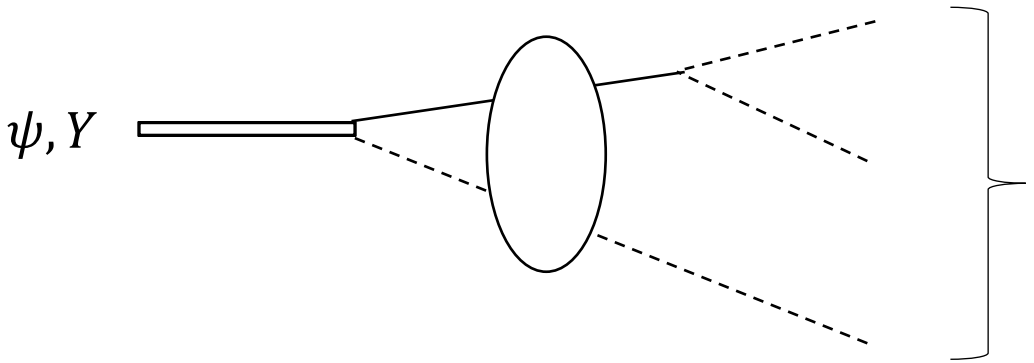
Well-established $c\bar{c}$ Exotic candidate

$D_1\bar{D}$ molecule

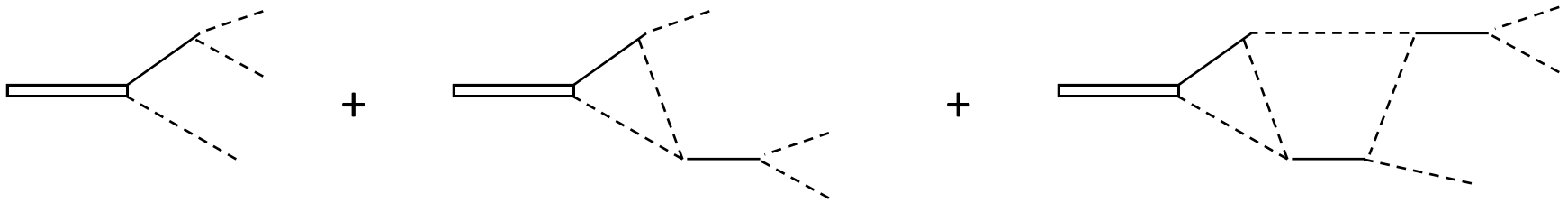
$c\bar{c}g$ hybrid



# Decay processes of $\psi$ and Y




$\pi D^* \bar{D}$, $J/\psi\pi\pi$, $J/\psi\,\eta$, etc.



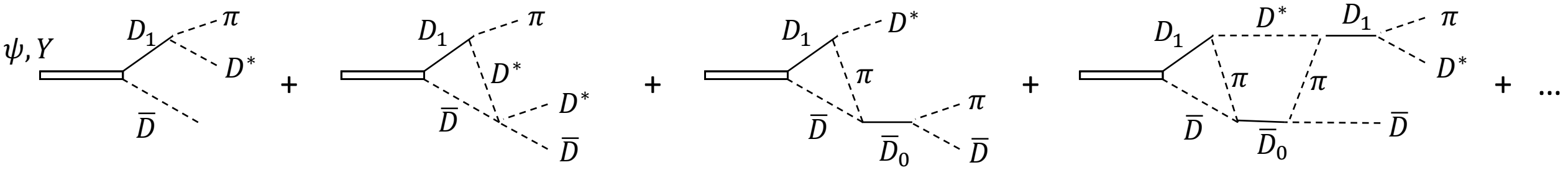
+ + + … (until infinite loops)

Coupled-channels and unitarity (conservation of probability) are taken into account

# Decay processes of $\psi$ and Y

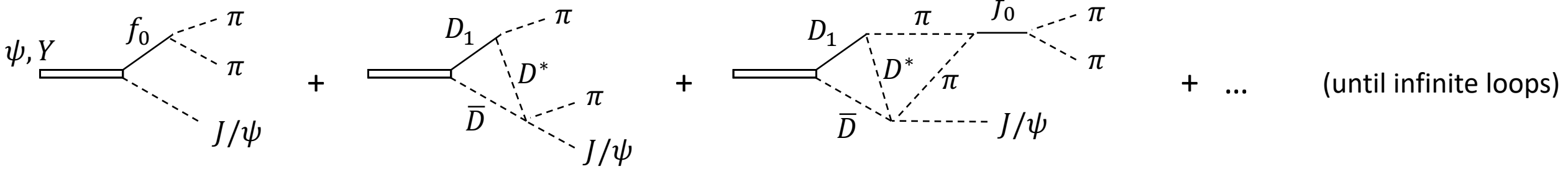
(selected important diagrams; diagrams with more loops are usually more suppressed)

$e^+e^- \to \pi D^* \bar{D}$

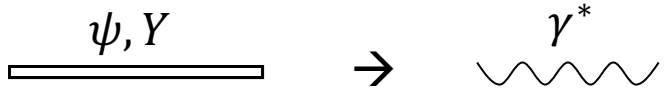



(until infinite loops)

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



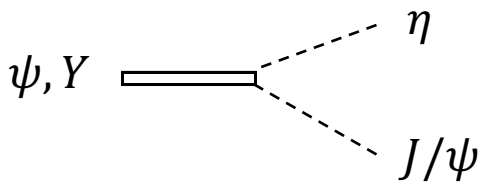

(until infinite loops)

Non-resonant amplitudes are also considered in the model 

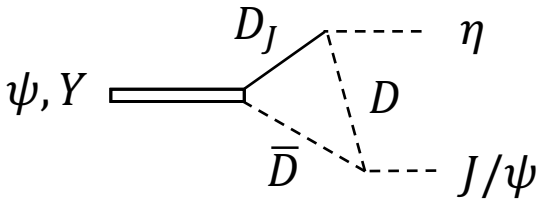
# Decay processes of $\psi$ and Y

$e^+e^- \to J/\psi\,\eta$

We consider only



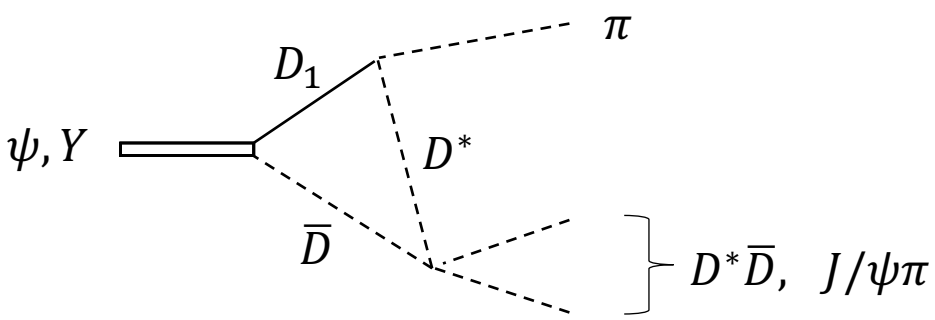

We do NOT consider




- $D_J D\eta$ coupling is unknown,

  and difficult to determine by fitting data
- This mechanism should be smaller than tree graph

# Triangle singularity (TS)




Kinematical condition for TS

Energy-momentum is conserved everywhere as classical process

→ amplitude is significantly enhanced at

$\sqrt{s} \sim m_{D_1} + m_{\bar{D}}$ (4.3 GeV) and $M_{D^*\bar{D}} \sim m_{D^*} + m_{\bar{D}}$ (3.88 GeV)
$M_{J/\psi\pi}$

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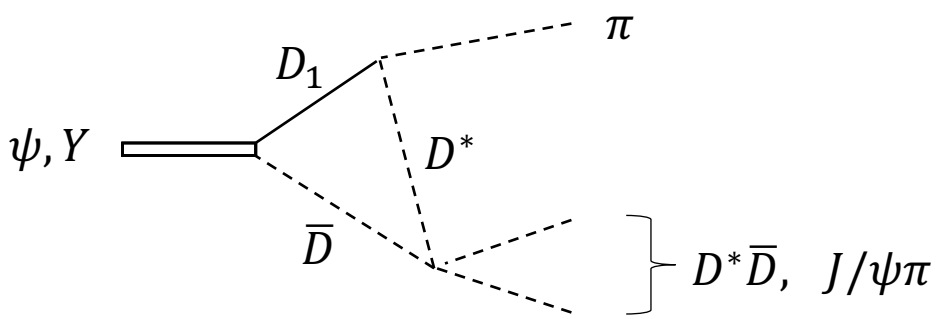


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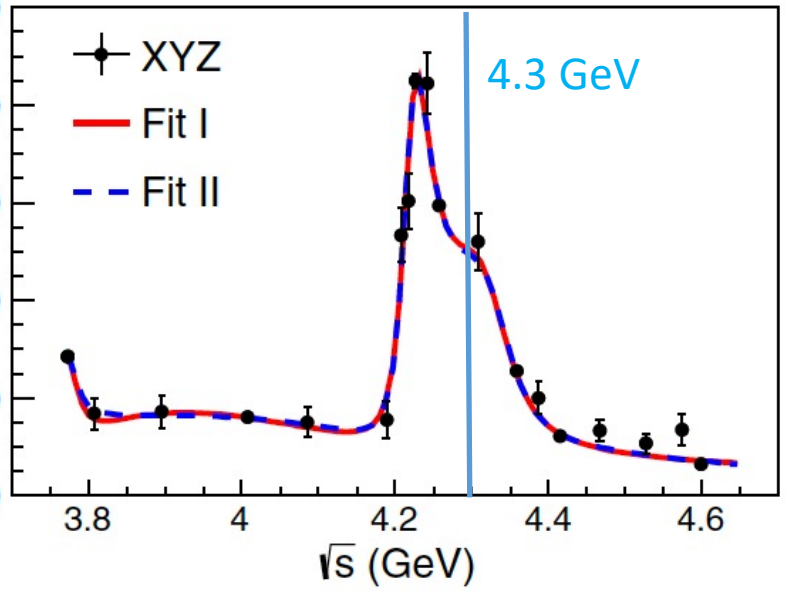


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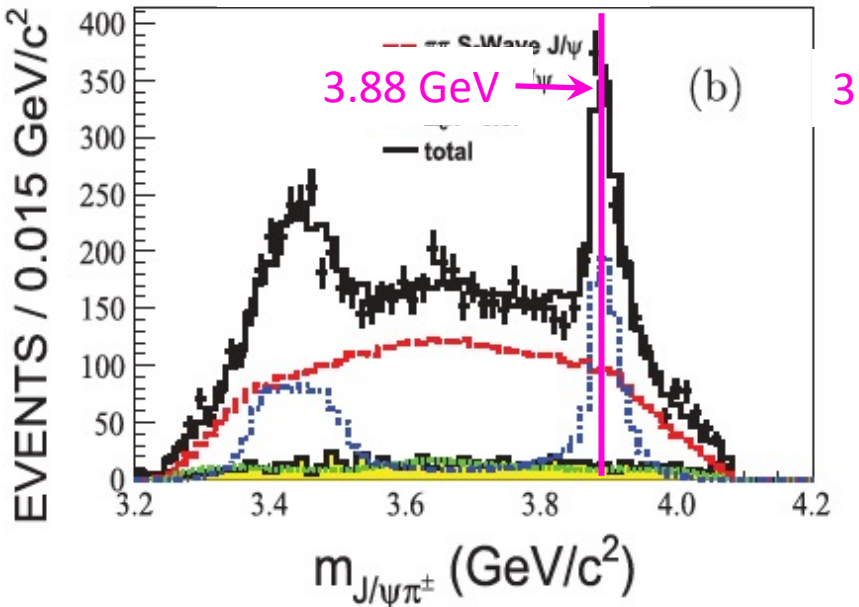
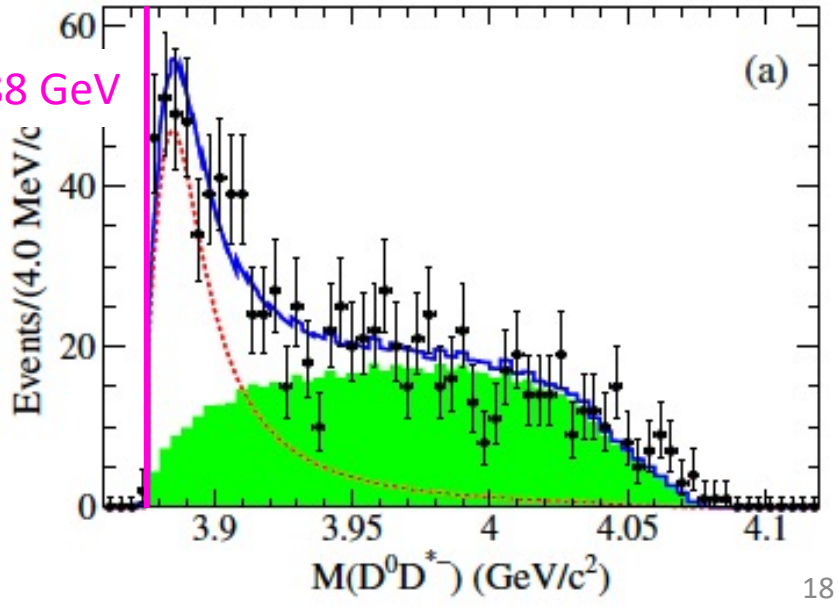



$e^+e^- \to \pi^+D^0D^{*-}$

3.88 GeV



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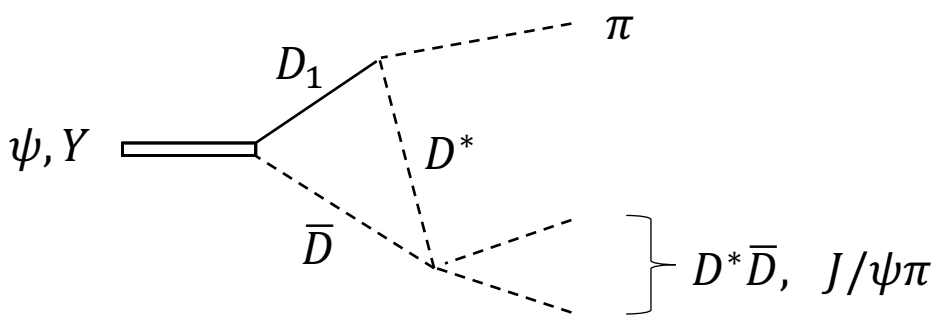


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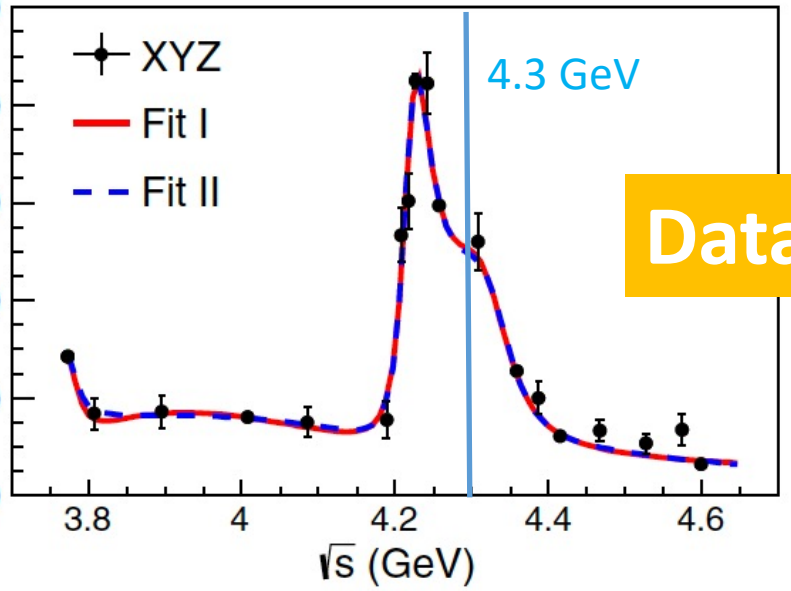
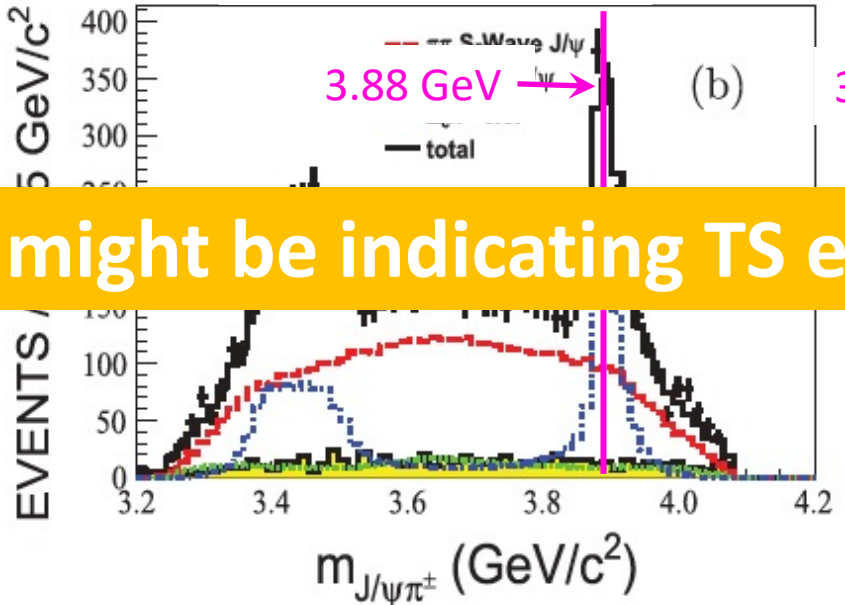
$M_{J/\psi\pi}$

$e^+e^- \to J/\psi\,\pi^+\pi^-$



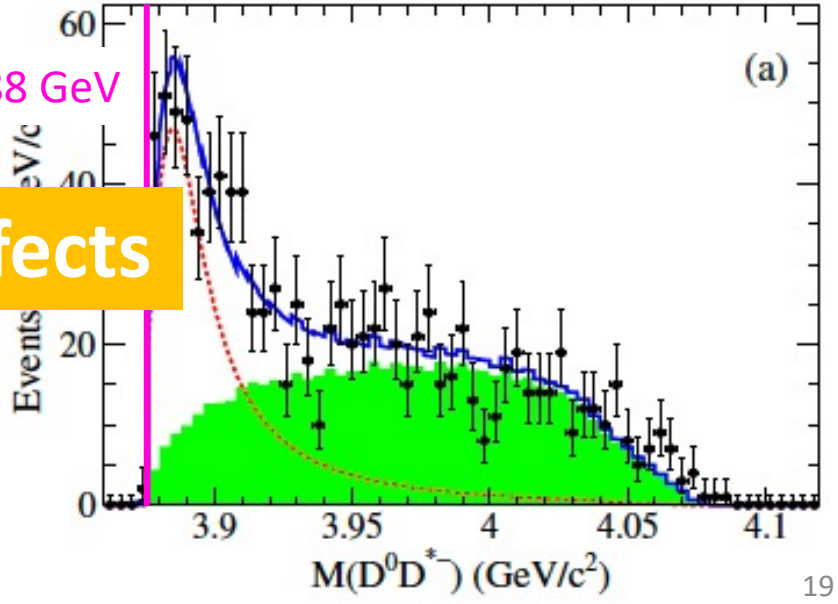

$e^+e^- \to J/\psi\,\pi^+\pi^-$



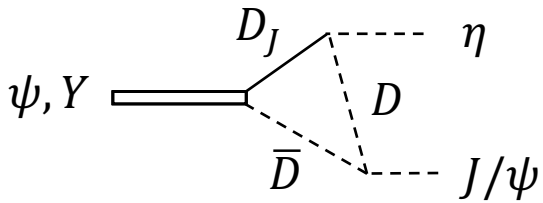

**Data might be indicating TS effects**

$e^+e^- \to \pi^+D^0D^{*-}$

3.88 GeV



# No TS in $e^+e^- \to J/\psi\,\eta$

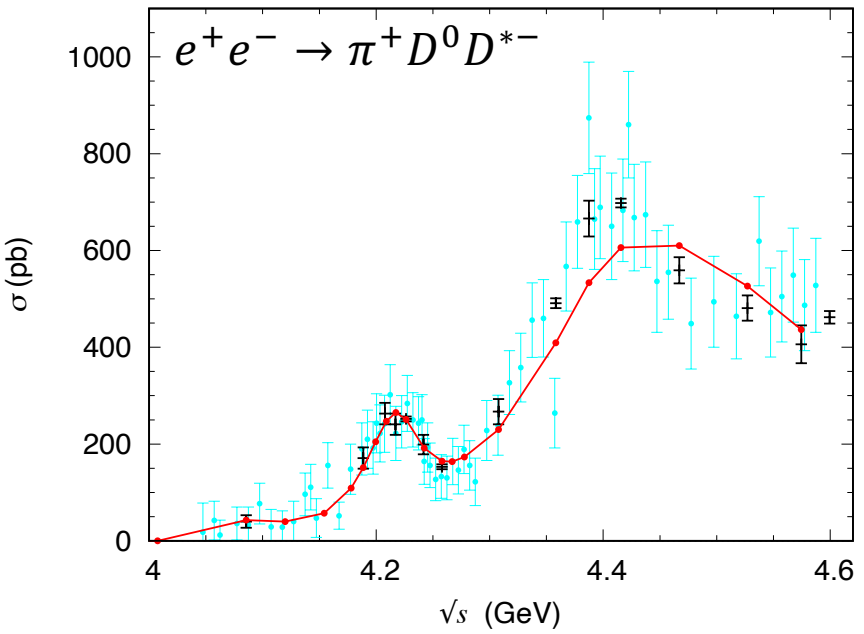


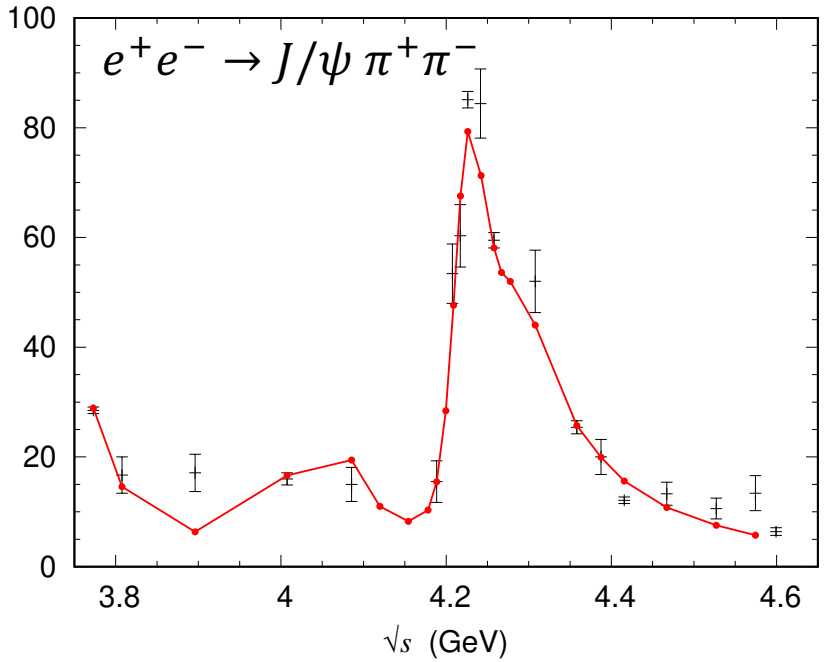

This triangle diagram does not satisfy TS condition

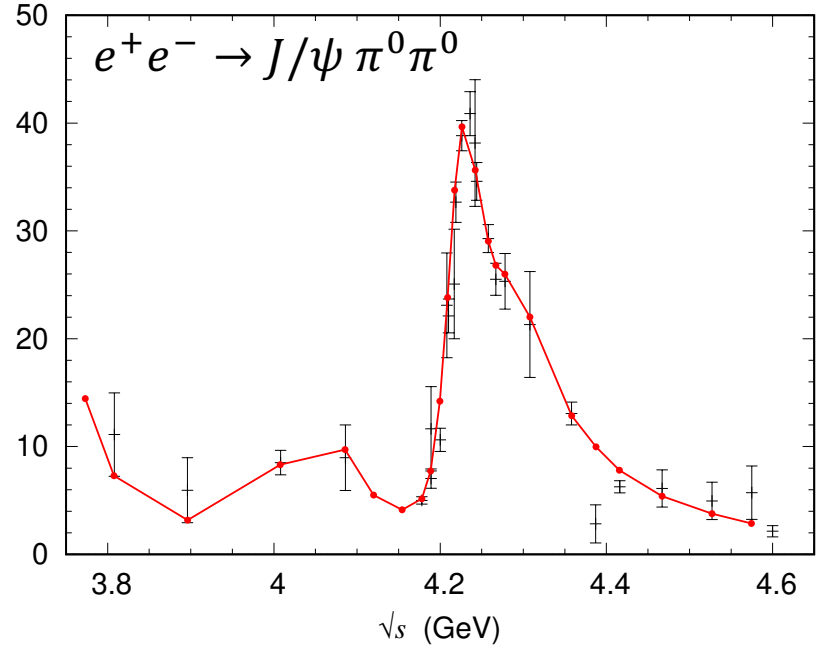
$J/\psi \leftrightarrow D\overline{D}$ does not occur at on-shell

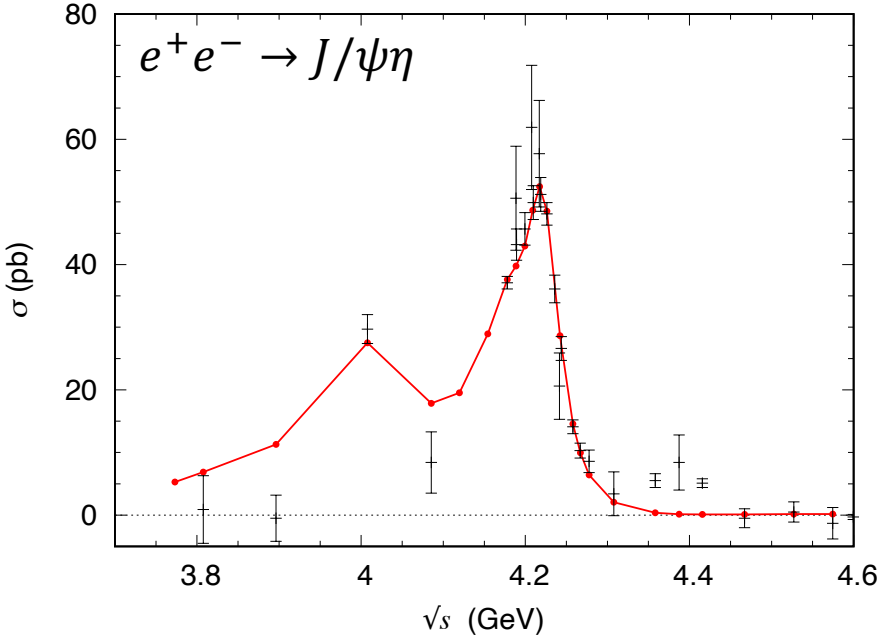
Most triangle diagrams do not satisfy TS condition

# Results



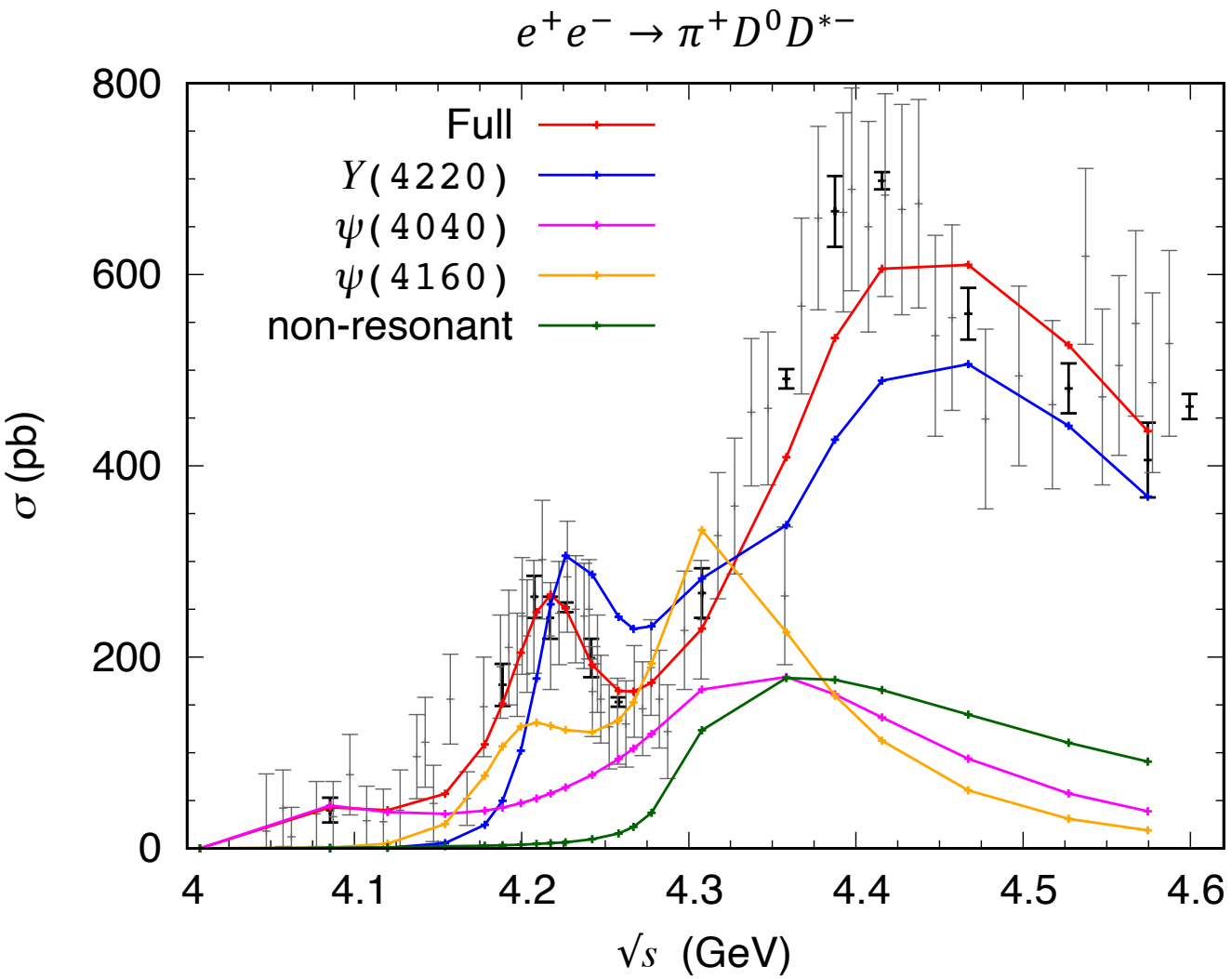



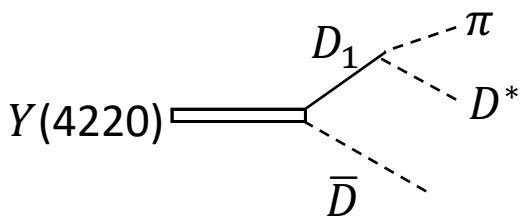




- $e^+e^- \to \pi D^* \bar{D},\ J/\psi\pi\pi,\ J/\psi\eta$ total cross section data are fitted simultaneously with coupled-channel model
- $\sqrt{s} \leq 4.35$ GeV region is well fitted (maybe improvable more)
- $\sqrt{s} > 4.35$ GeV region would need $Y(4390)$ and $\psi(4415)$ for further improvements

# Addressing Y puzzle




- Y(4220) structure is formed by Y(4220), $\psi(4160)$, and their interference (similar result as Chen et al.)
- Large bump at $\sqrt{s} \sim 4.4$ GeV is mostly from tree mechanism of




← suppressed in $\sqrt{s} < m_{D_1} + m_{\bar{D}} = 4.3$ GeV, but rapidly increasing phase-space above threshold

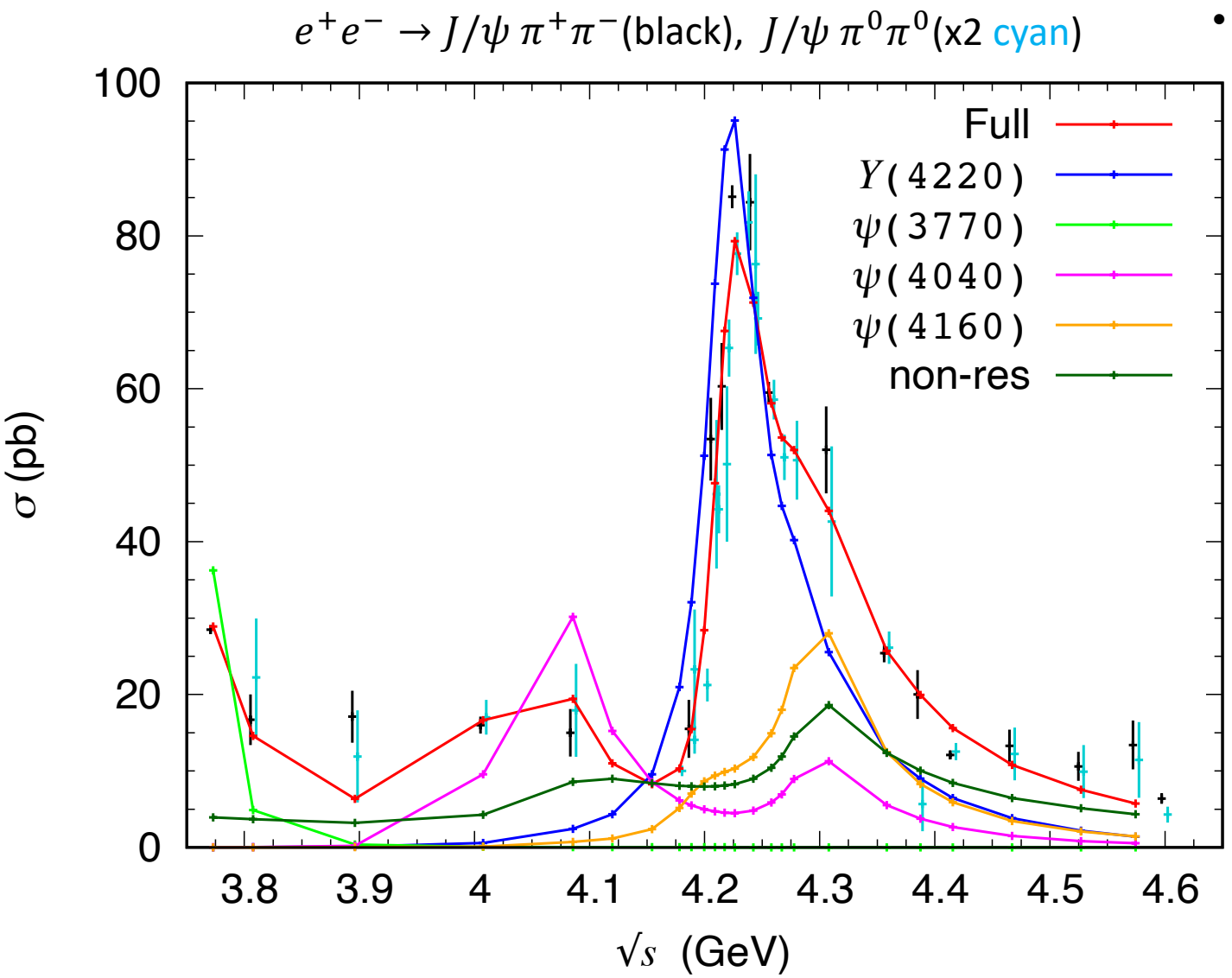
(Different result from Chen et al. who did not consider $\psi$ decays through $D_1\bar{D}$)

- TS-induced enhancements at $\sqrt{s} \sim 4.3$ GeV

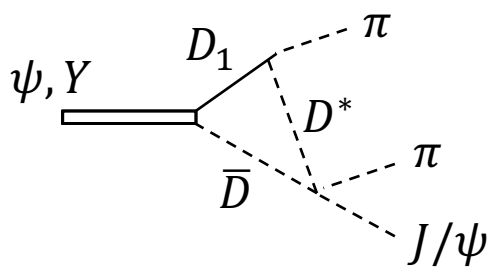
  Clear in $\psi(4160)$ decay

- Fit is further improvable by adding $\psi(4415), Y(4390)$

# Addressing Y puzzle



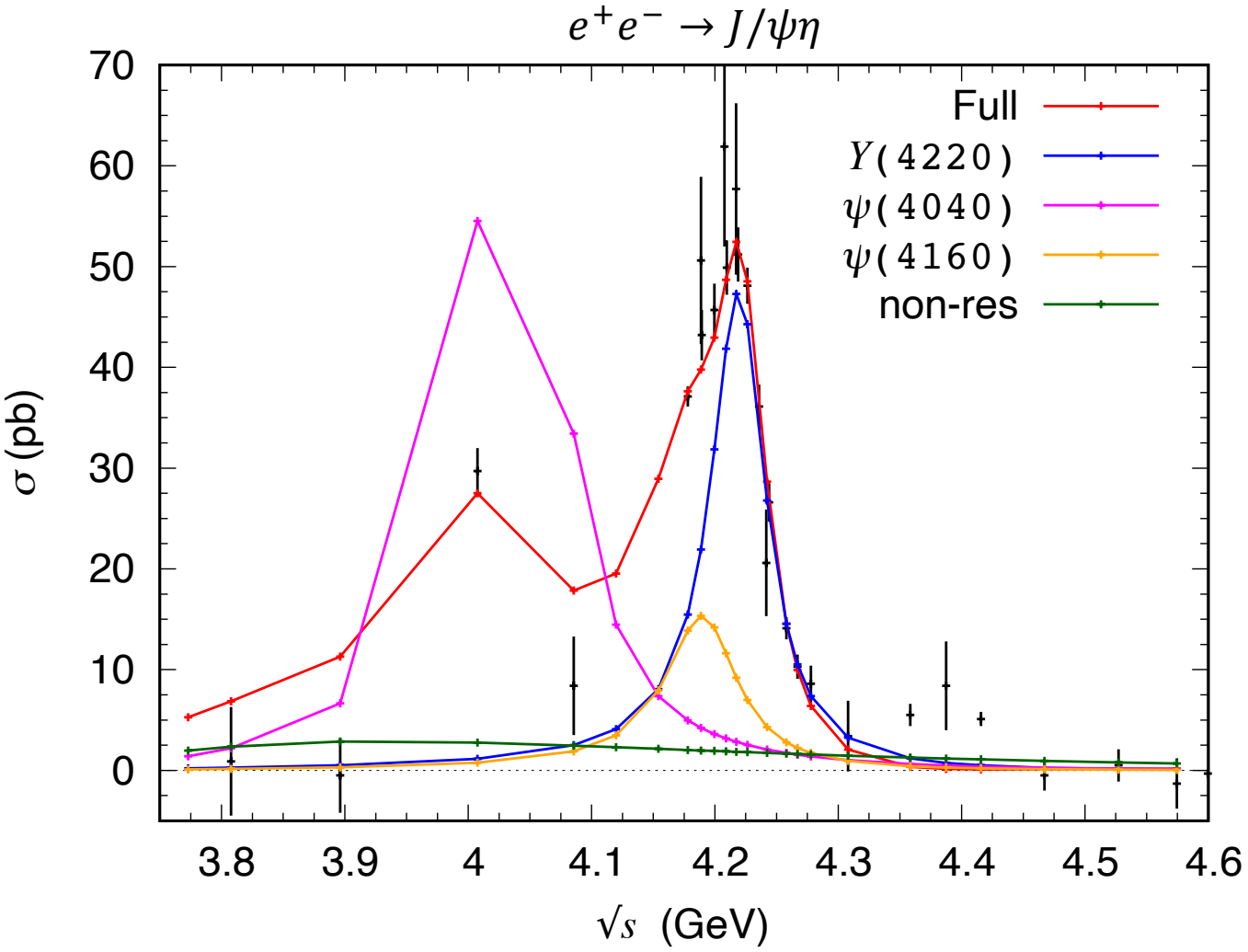

- Y(4220) structure is formed by Y(4220), $\psi(4040)$, TS, and their interference
- TS-induced enhancements at $\sqrt{s} \sim 4.3$ GeV



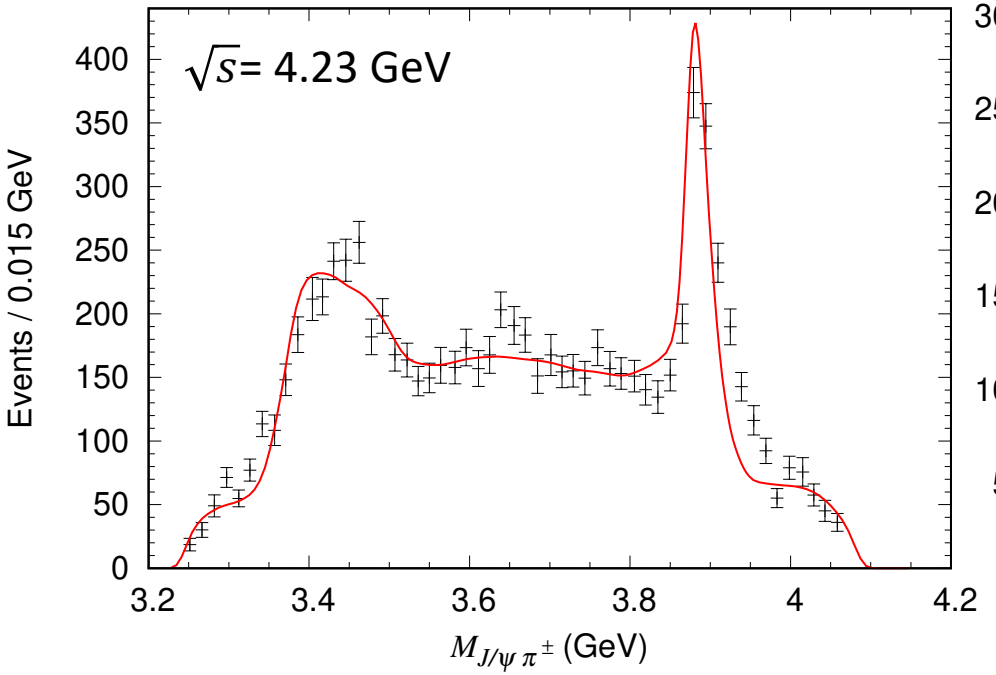

$Y(4320)$-like structure is well described by TS

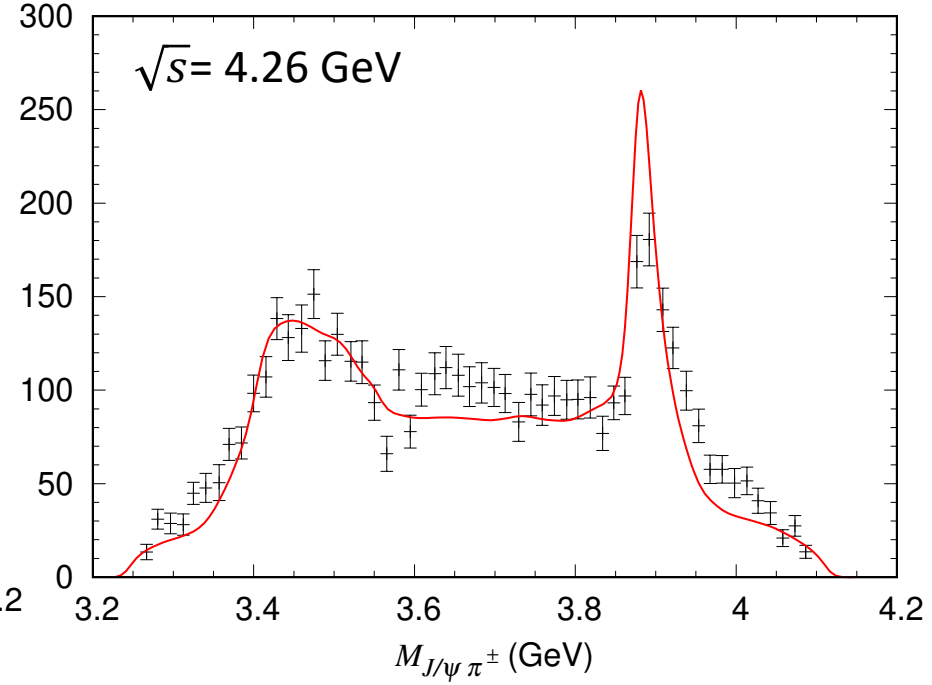
Different conclusion from Chen et al. (interference) who did not consider TS

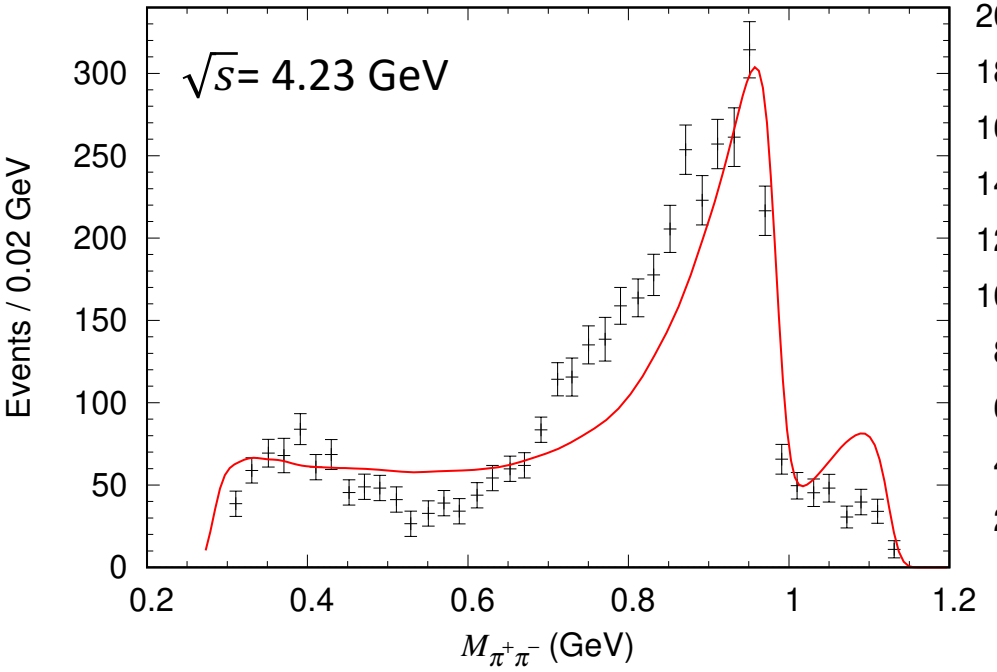
# Addressing Y puzzle

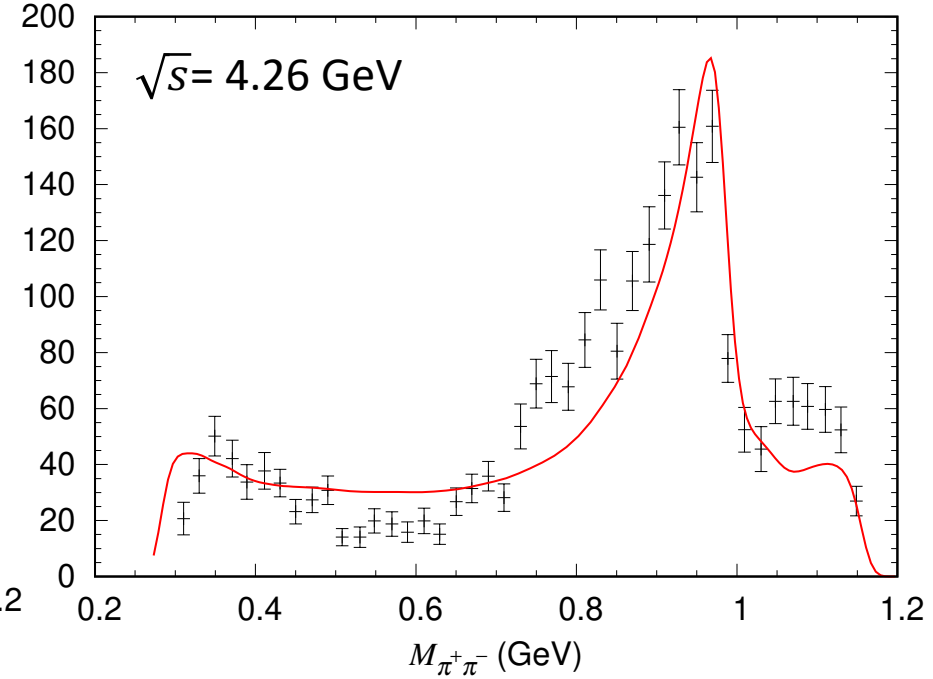



- Y(4220) structure is formed by Y(4220), $\psi(4160)$, and their interference
- No TS exists → No Y(4320)
- $Y(4390)$ would be needed to fit peak at $\sqrt{s} \sim 4.38$ GeV



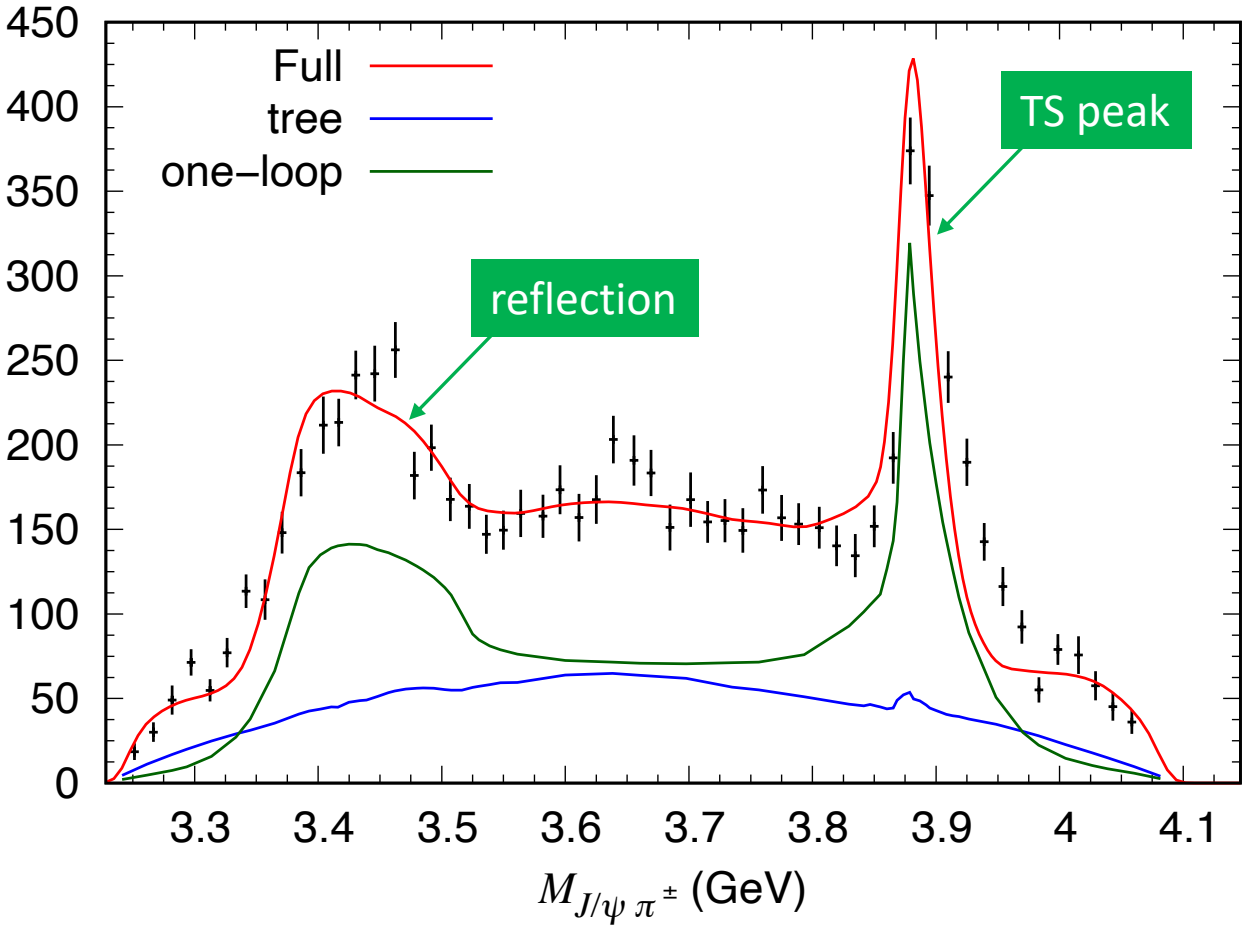

# Differential cross sections

$e^+e^- \to J/\psi\,\pi^+\pi^-$

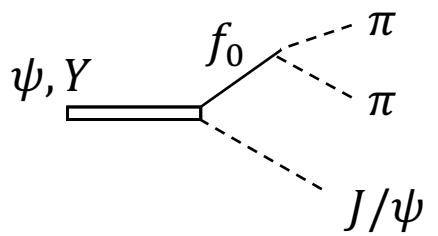
- Overall, fit is good
- Zc(3900)-like peak overshoots data for $\sqrt{s}$= 4.26 GeV
  ← to be improved
- Good fits of differential cross sections support our solution of Y puzzle

# Zc(3900) as TS

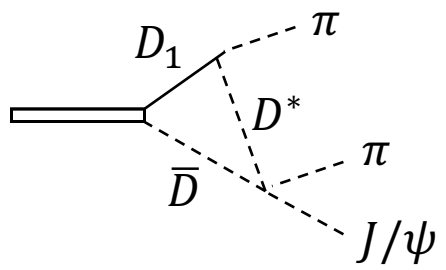
$e^+e^- \to J/\psi\,\pi^+\pi^-$ at $\sqrt{s}$= 4.23 GeV




Tree




One-loop

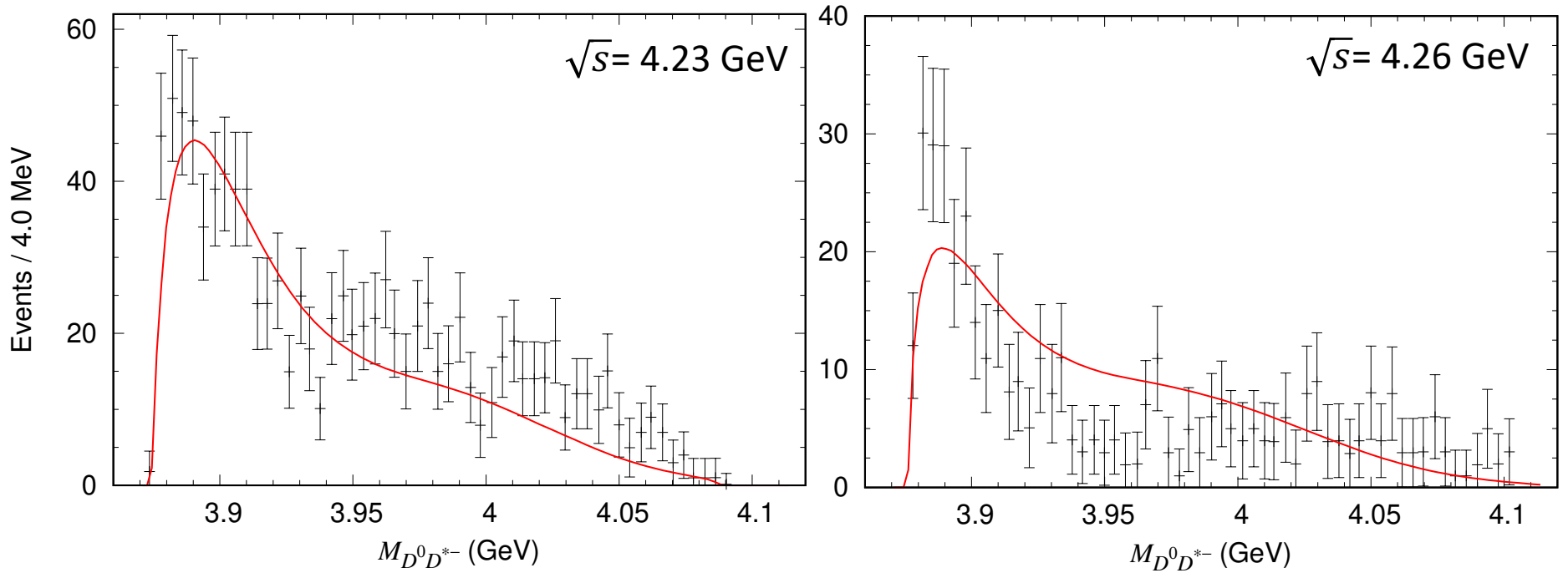



Because of TS, one-loop amplitude is enhanced significantly at $M_{J/\psi\pi} \sim m_{D^*} + m_{\overline{D}}$ (3.88 GeV)

→ Good fit to data

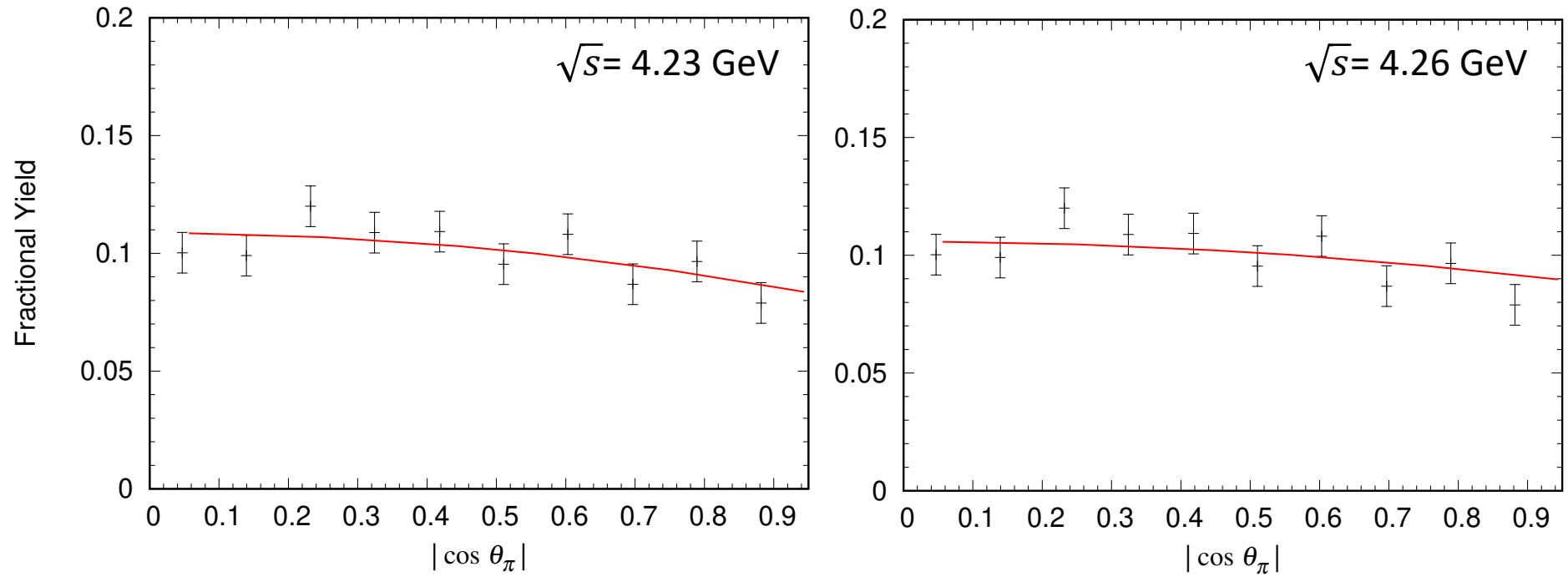
This interpretation has been discussed since the discovery of Zc(3900); not conclusive yet.

Combined analysis of total and differential cross sections may be important to address the nature of Zc(3900)









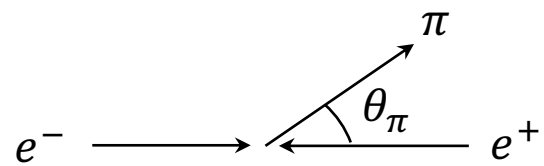




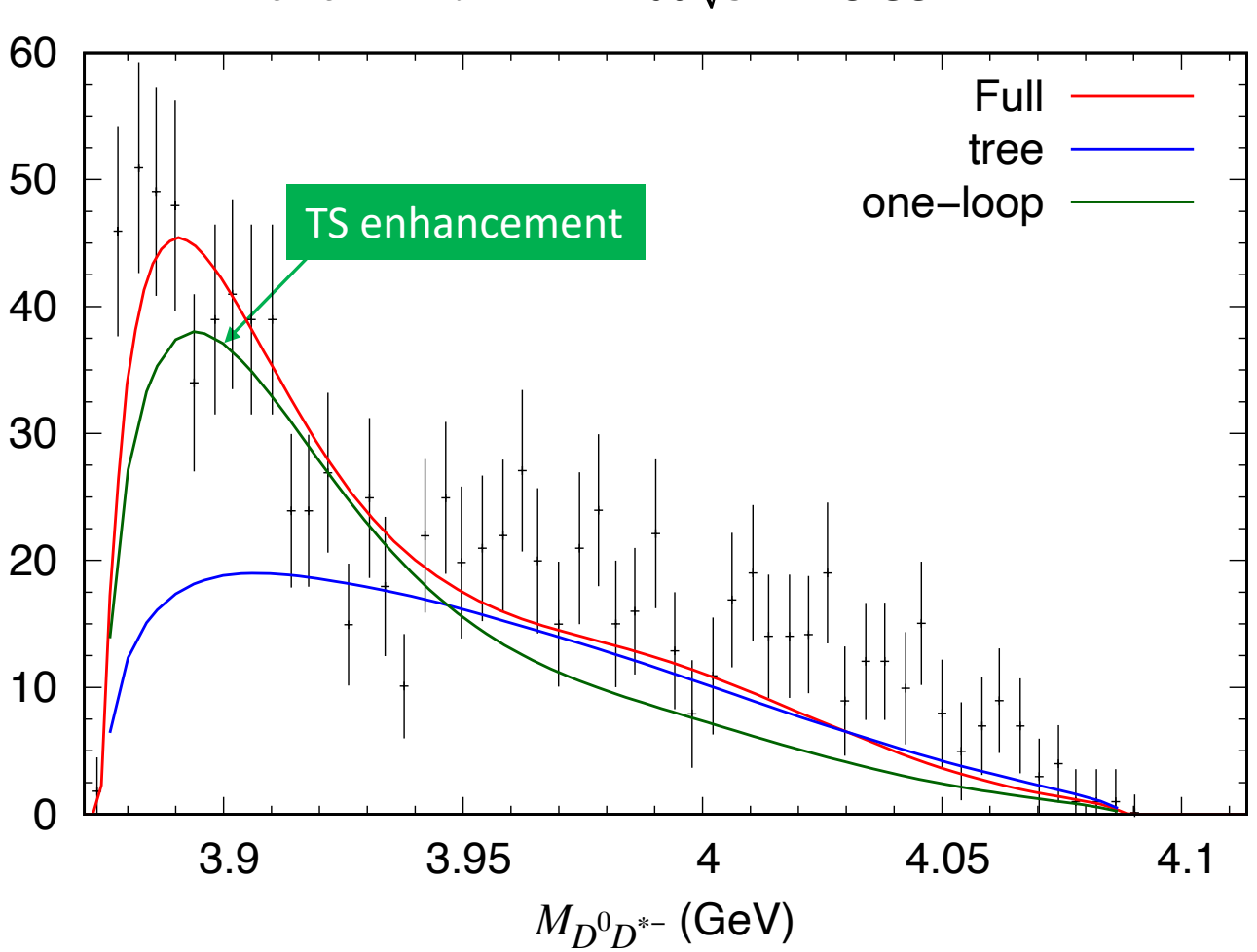
# Differential cross sections

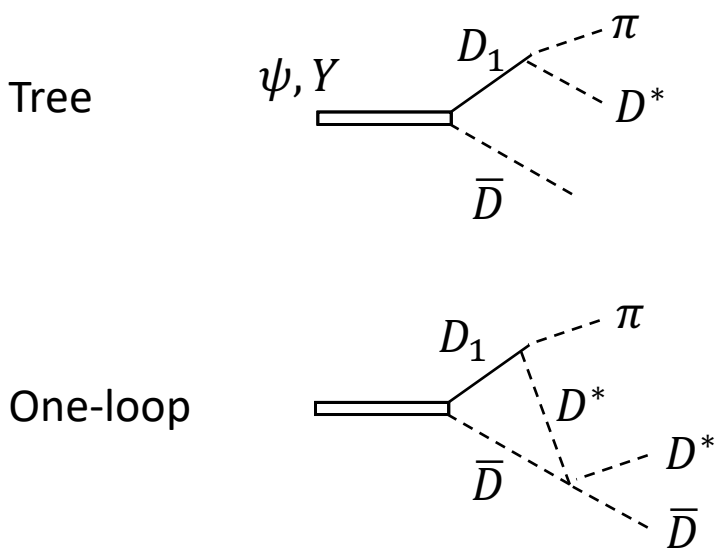
$e^+e^- \to \pi^+ D^0 D^{*-}$

- Overall, fit is good
- Zc(3900)-like peak near $M_{D^*\bar{D}} \sim m_{D^*} + m_{\bar{D}}$ (TS effect)
- Fits will be improved more
- Good fits of differential cross sections support our solution of Y puzzle



# Zc(3900) as TS




Because of TS, one-loop amplitude is enhanced significantly at $M_{D^*\overline{D}} \sim m_{D^*} + m_{\overline{D}}$ (3.88 GeV)

# Summary

# The Y problem is addressed

By analyzing $e^+e^- \to \pi D^*\bar{D},\ J/\psi\pi\pi,\ J/\psi\,\eta$ BESIII data simultaneously with a coupled-channel model

Both total and differential cross section data were fitted

**(Tentative) Conclusion 1 : Y puzzle can be solved as follows:**

| | Y(4220)-like width is mainly from: | Y(4390)-like structure is mainly from: |
|---|---|---|
| $e^+e^- \to \pi^+ D\bar{D}^*$ | Y(4220), $\psi(4160)$, and their interference | Rapidly increasing phase-space for $D_1\bar{D}$ |
| $e^+e^- \to J/\psi\pi\pi$ | Y(4220), $\psi(4040)$, TS, and their interference | No structure |
| $e^+e^- \to J/\psi\eta$ | Y(4220), $\psi(4160)$, and their interference | Seems Y(4390) resonance |

**(Tentative) Conclusion 2 : Y(4320) and Zc(3900) are consistent with TS enhancements**

# Remaining tasks

- Improve fits
- Write a paper

Maybe another paper

- Include $\psi(4415), Y(4390)$ to better describe higher $\sqrt{s}$ region
- Include $\psi'\pi\pi$ and $h_c\pi\pi$ final state data in the fits
- Include more coupled-channels, such as $D_1\overline{D}^*$