# From Y to X and Z

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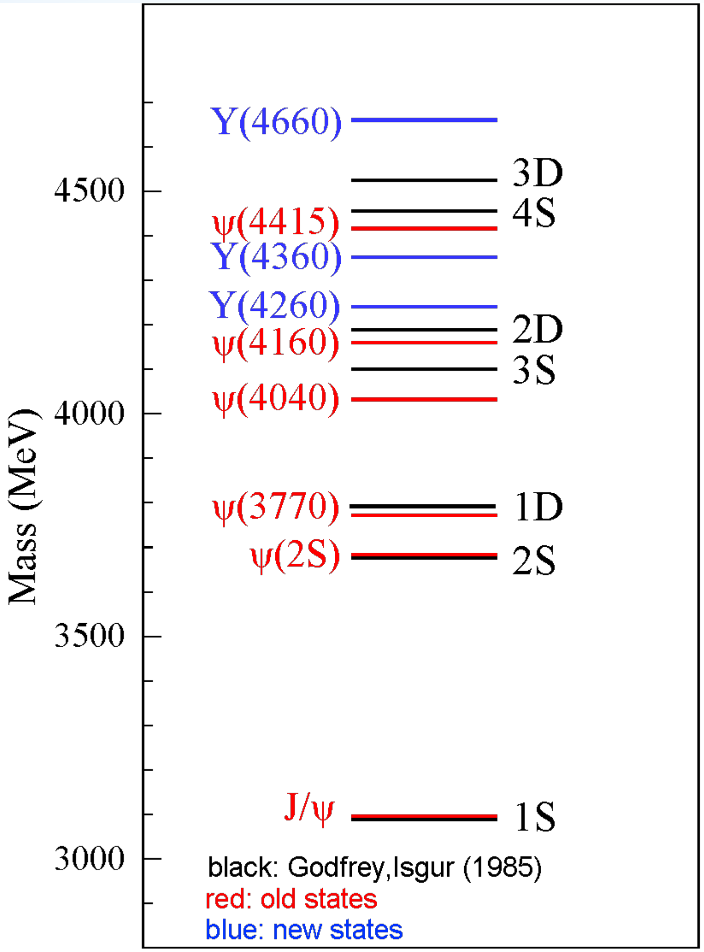
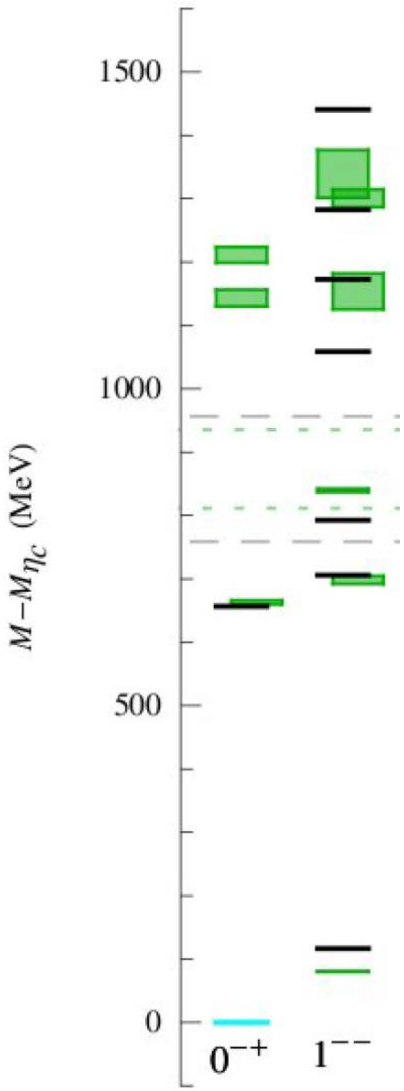
# Vector charmonium(-like) states



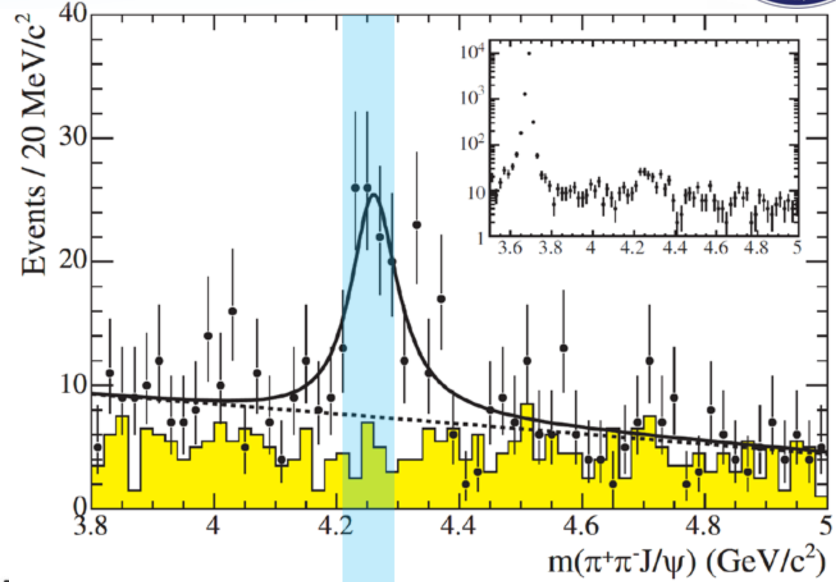

Lattice QCD, L. Liu et al., JHEP1207,126

- Too many vector states (6+3) compared to potential model predictions or lattice QCD results using only $c\bar{c}$ operators
- Not seen in $D\bar{D}$, while $B(\psi(3770) \to D\bar{D}) = \left(98^{+8}_{-9}\right)\%$

# Y(4260)

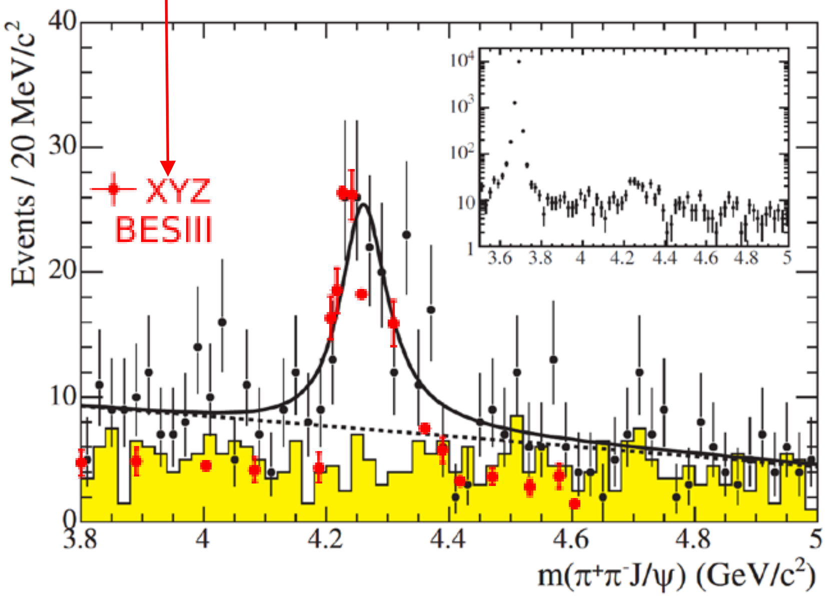
- Discovered in $J/\psi\pi^+\pi^-$

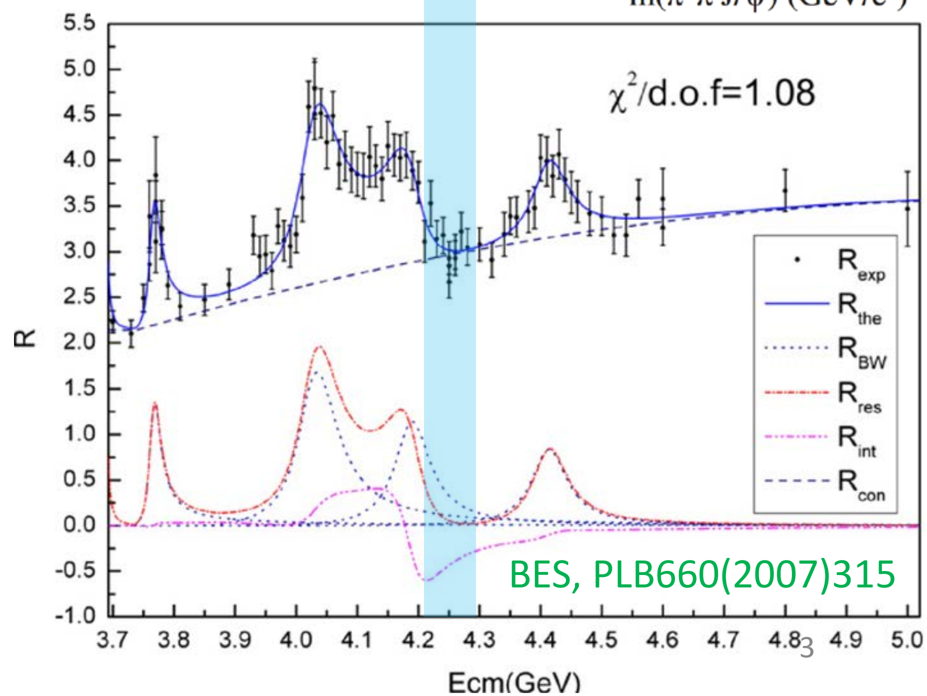
BABAR, PRL95(2005)142001




- Not seen as a peak in R scan
- Much more precise measurement by BESIII

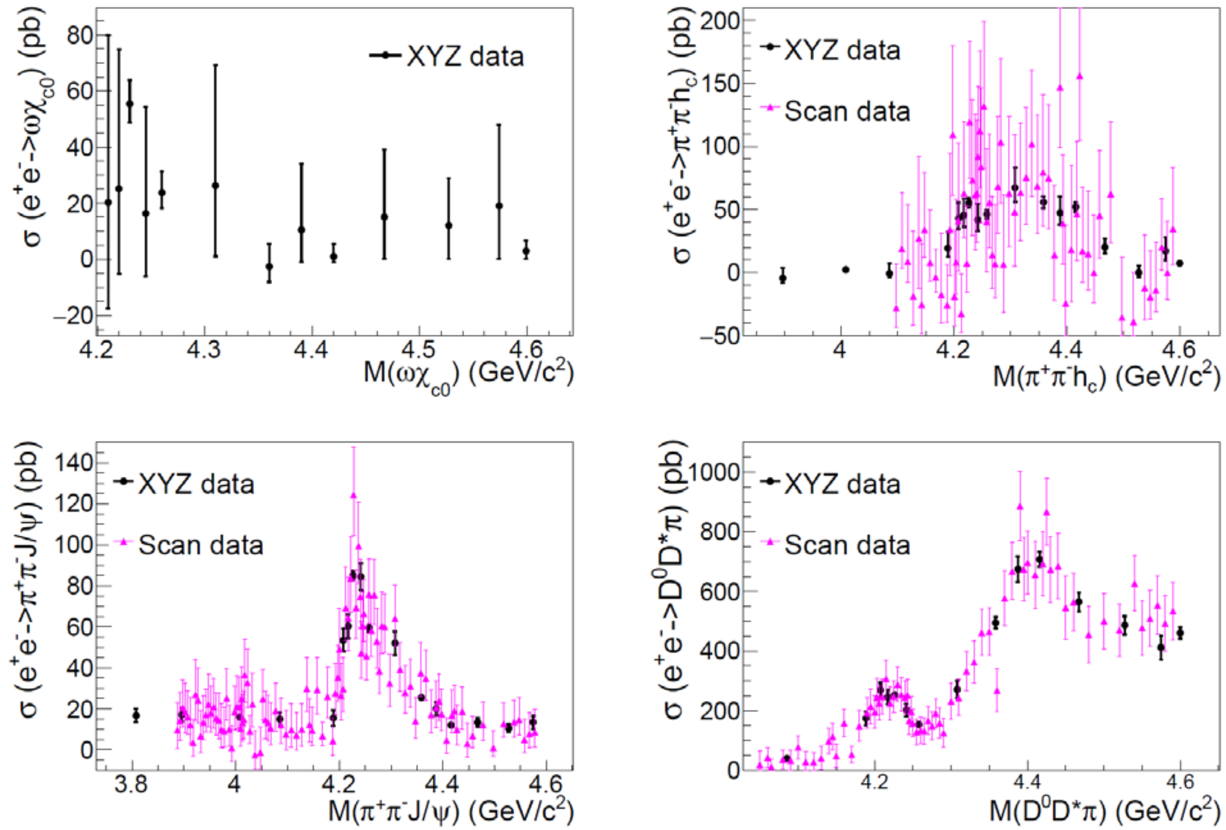
BESIII, PRL118(2017)092001




BES, PLB660(2007)315

# Y(4260): should be called Y(4220)?




A combined fit of $e^+e^- \to \chi_{c0}\omega, J/\psi\pi^+\pi^-, h_c\pi^+\pi^-, D^0D^{*-}\pi^+ + c.c.$ leads to

$M = (4219.6 \pm 3.3 \pm 5.1)$ MeV, $\Gamma = (56.0 \pm 3.6 \pm 6.9)$ MeV

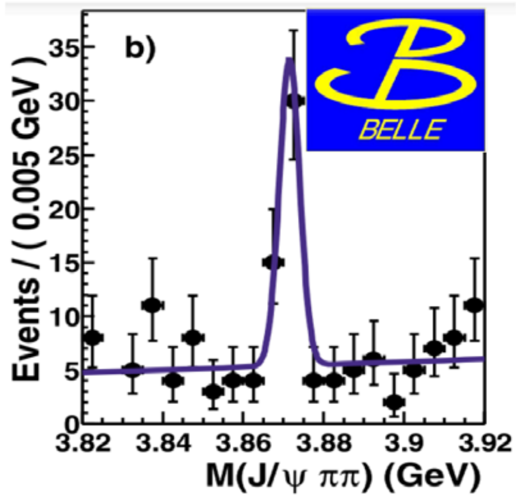
X. Y. Gao, C. P. Shen, C. Z. Yuan, PRD95(2017)092007

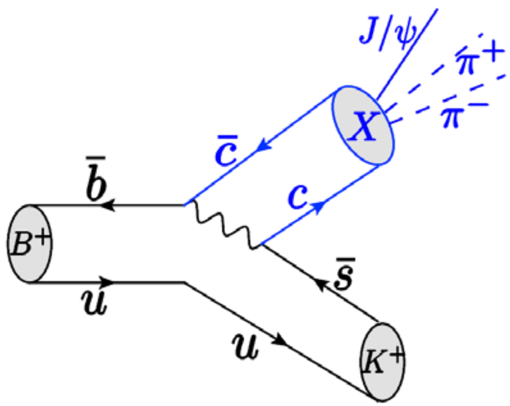
# Y(4260): puzzling features

- No obvious slot in charmonium spectrum in quark model
- Not seen in R-scan
- Not seen in $D\bar{D}$, $D^*\bar{D} + c.c.$, contrary to known $\psi$ states above the $D\bar{D}$ threshold
- The only observed open-charm channel: $D^0 D^{*-}\pi^+ + c.c.$
- Similar cross sections into spin-triplet and spin-singlet final states
  - Spin-triplet: $J/\psi\pi^+\pi^-$, $\chi_{c0}\omega$
  - Spin-singlet: $h_c\pi^+\pi^-$
  - Mixture of spin-triplet and spin-singlet: $D^0 D^{*-}\pi^+ + c.c.$

# X(3872)

Belle, PRL91(2003)262001 [hep-ex/0309032]




- $\Gamma < 1.2$ MeV, $J^{PC} = 1^{++}$

Mysterious properties:

- $M_{D^0} + M_{D^{*0}} - M_X = (0.00 \pm 0.18)$ MeV
- Large coupling to $D^*\bar{D}$:

  $\mathcal{B}(X \to D^0\bar{D}^{*0}) > 30\%$ Belle, PRD81(2010)031103

  $\mathcal{B}(X \to D^0\bar{D}^0\pi^0) > 40\%$ Belle, PRL97(2006)162002

- No isospin partner observed, I=0, but large isospin breaking:

$$\frac{\mathcal{B}(X \to \omega J/\psi)}{\mathcal{B}(X \to \pi^+\pi^- J/\psi)} = 0.8 \pm 0.3$$

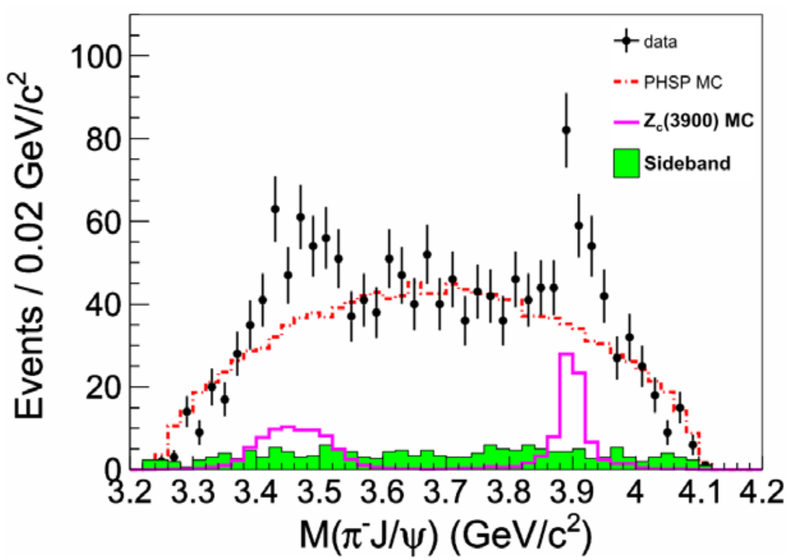
# $Z_c(3900)$: explicitly exotic

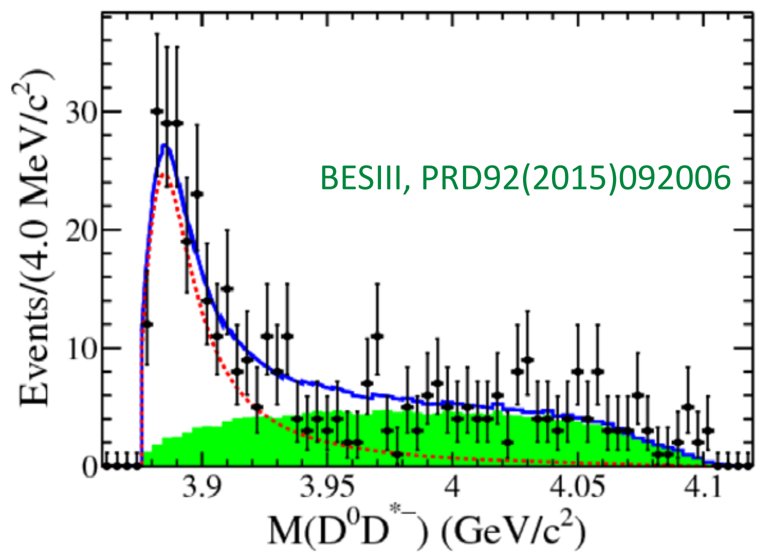
- Discovered by BESIII and Belle in $e^+e^- \to Y(4260) \to J/\psi\pi^+\pi^-$

BESIII, PRL110(2013)252001; Belle, PRL110(2013)252002

- and in $D\bar{D}^*$ by BESIII in $Y(4260) \to \pi^\pm(D\bar{D}^*)^\mp$

BESIII, PRL112(2014)022001



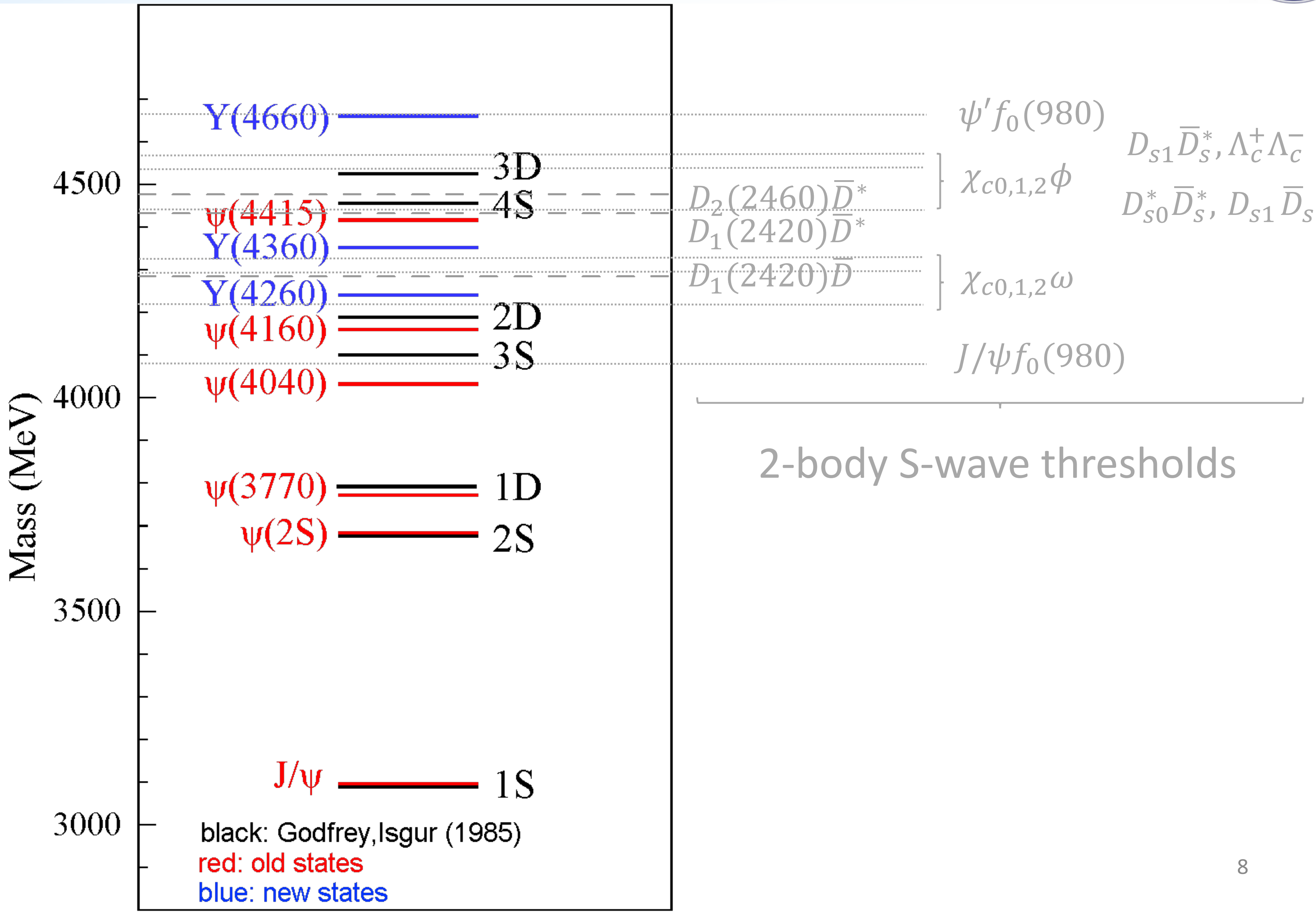

- Nearby the $D\bar{D}^*$ threshold, but still a large branching fraction: strong coupling to $D\bar{D}^*$

$$\frac{\Gamma(Z_c \to D\bar{D}^*)}{\Gamma(Z_c \to J/\psi\pi)} = 6.2 \pm 1.1 \pm 2.7$$

- Evidence in semi-inclusive b-flavored hadron decays via $Y(4260) \to J/\psi\pi^+\pi^-$

D0, PRD98(2018)052010

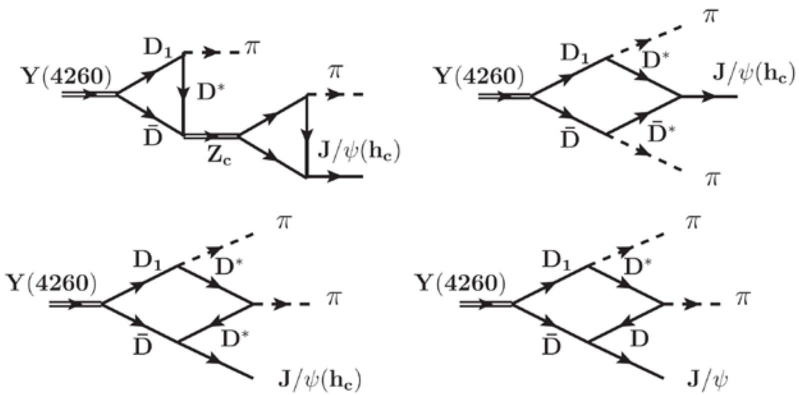
# Y: many thresholds above 4 GeV

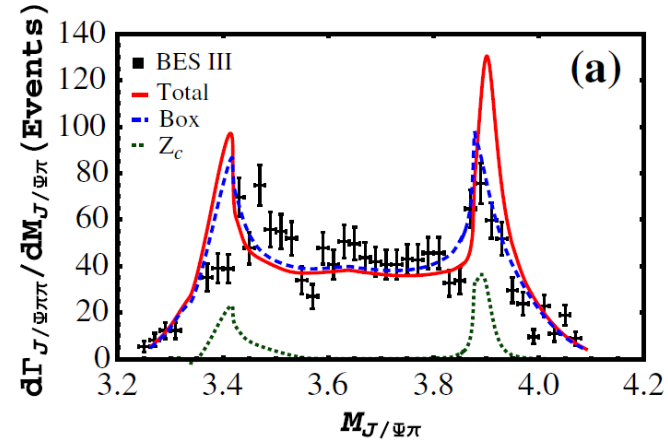


# Y(4260): strong coupling to $D_1\bar{D}$

- Y(4260) as mainly a $D_1(2420)\bar{D}$ hadronic molecule (never purely)

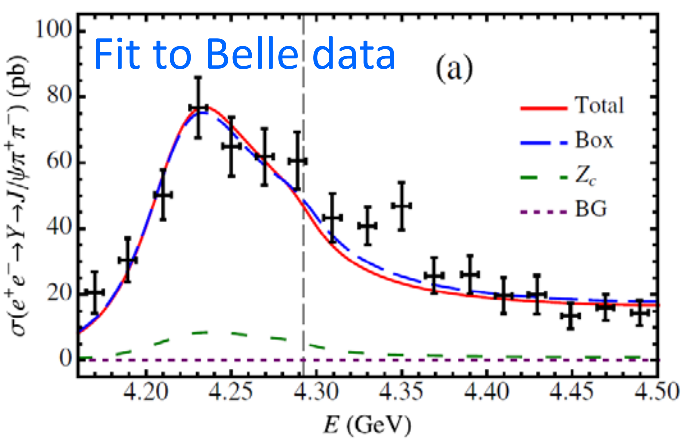
Q. Wang, C. Hanhart, Q. Zhao, PRL111(2013)132003



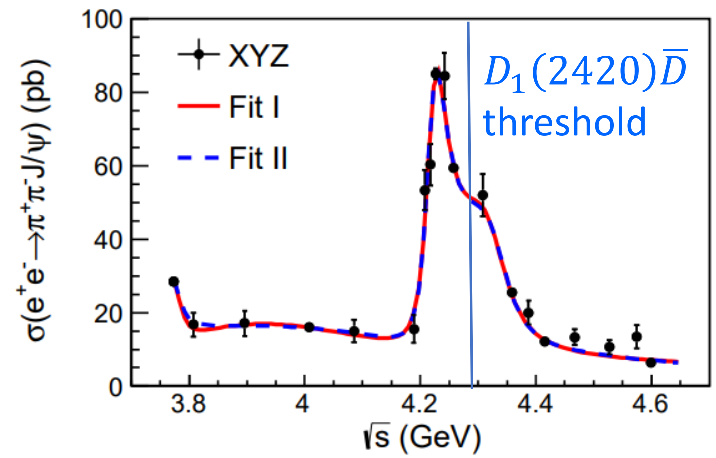




- a large coupling to $D_1\bar{D}$ $\Longrightarrow$ large impact on the line shape

M. Cleven et al., PRD90(2014)074039
see also Qin et al., PRD94(2016)054035




$M_Y = (4217.2 \pm 2.0)$ MeV




BESIII data PRL118(2017)092001

# Cusp at an S-wave threshold

- Unitarity of the $S$-matrix: $S\,S^\dagger = S^\dagger S = \mathbb{1}$, $S_{fi} = \delta_{fi} - i(2\pi)^4\delta^4(p_f - p_i)T_{fi}$

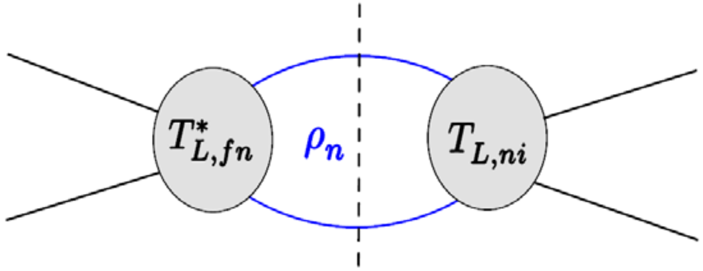
  $T$-matrix: $T_{fi} - T^\dagger_{fi} = -i(2\pi)^4 \underbrace{\sum_n}_{\text{all physically accesible states}} \delta(p_n - p_i) T^\dagger_{fn} T_{ni}$

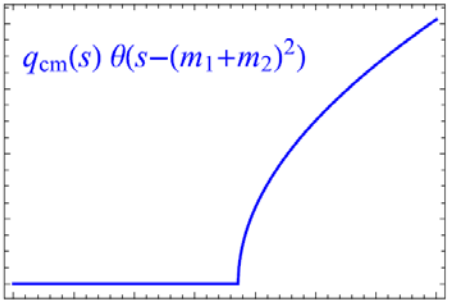
  assuming all intermediate states are two-body, partial-wave unitarity relation:

  $$\text{Im}\, T_{L,fi}(s) = -\sum_n T^*_{L,fn}\,\rho_n(s)\,T_{L,ni}$$

  2-body phase space factor: $\rho_n(s) = q_{\text{cm},n}(s)/(2\sqrt{s})\theta(\sqrt{s} - m_{n1} - m_{n2})$,

  $q_{\text{cm},n}(s) = \sqrt{[s - (m_{n1} + m_{n2})^2][s - (m_{n1} - m_{n2})^2]}/(2\sqrt{s})$



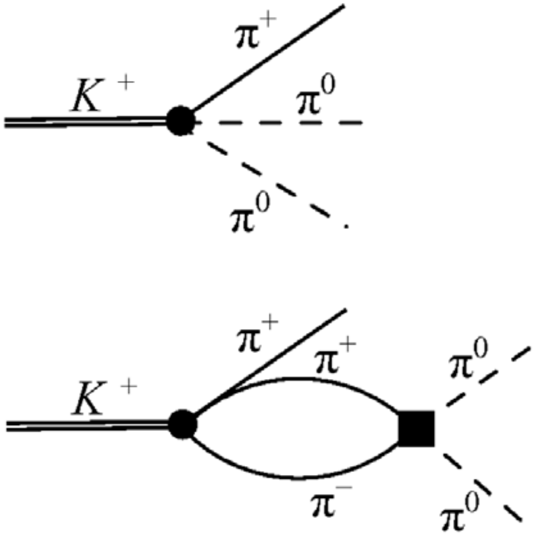



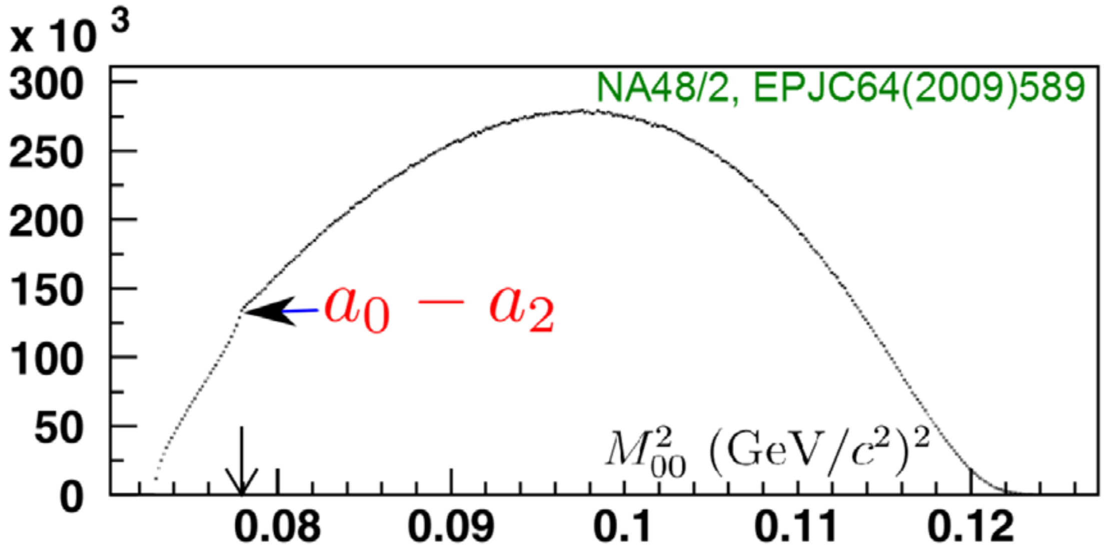

- There is always a cusp at an $S$-wave threshold

# Cusp measures interaction strength

- Cusp effect as a useful tool for precise measurement:
  - ☞ example of the cusp in $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$
  - ☞ strength of the cusp measures the interaction strength!

Meißner, Müller, Steininger (1997); Cabibbo (2004); Colangelo, Gasser, Kubis, Rusetsky (2006); . . .




$\sim$ threshold, only sensitive to scattering length, $(a_0 - a_2)M_{\pi^+} = 0.2571 \pm 0.0056$

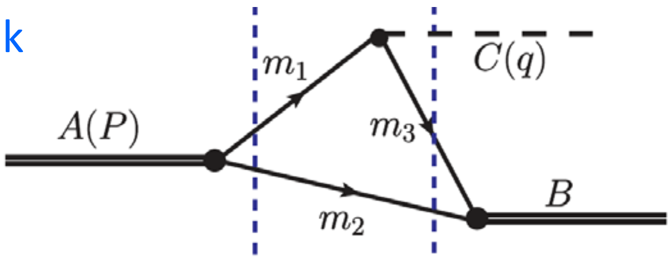
- Very prominent cusp $\Rightarrow$ large scattering length $\Rightarrow$ likely a nearby pole

  effective range expansion (ERE): $f(k) = \frac{1}{1/a + rk^2/2 - ik}$

# Triangle singularity

Rescattering in Steve's talk

Logarithmic singularity ⇒ peak




$$\frac{1}{2m_A}\sqrt{\lambda(m_A^2, m_1^2, m_2^2)} \equiv \boxed{p_{2,\text{left}} = p_{2,\text{right}}} \equiv \gamma\,(\beta\, E_2^* - p_2^*)$$

on-shell momentum of $m_2$ at the left and right cuts in the $A$ rest frame

$\beta = |\vec{p}_{23}|/E_{23},\, \gamma = 1/\sqrt{1-\beta^2}$

Bayar et al., PRD94(2016)074039

- $p_2 > 0,\, p_3 = \gamma\,(\beta\, E_3^* + p_2^*) > 0 \Rightarrow$ $m_2$ and $m_3$ move in the same direction
- velocities in the $A$ rest frame: $v_3 > \beta > v_2$

$$v_2 = \beta\,\frac{E_2^* - p_2^*/\beta}{E_2^* - \beta\, p_2^*} < \beta\,, \qquad v_3 = \beta\,\frac{E_3^* + p_2^*/\beta}{E_3^* + \beta\, p_2^*} > \beta$$

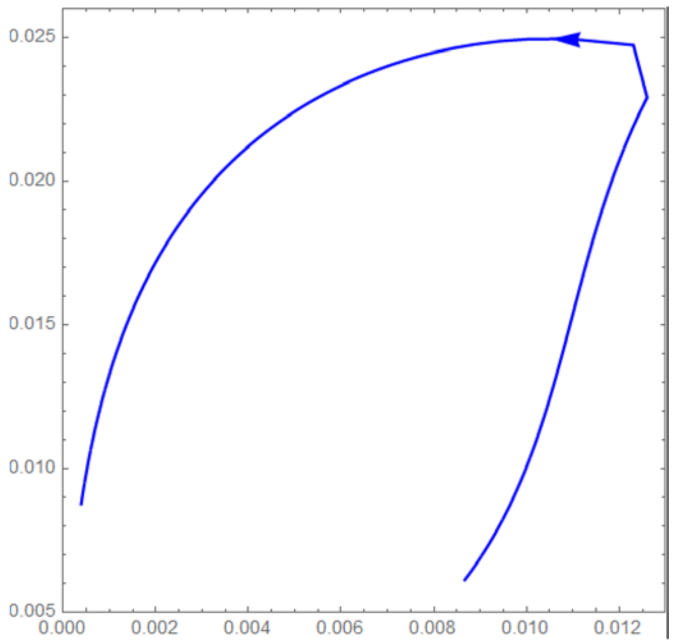
- Conditions (Coleman–Norton theorem):

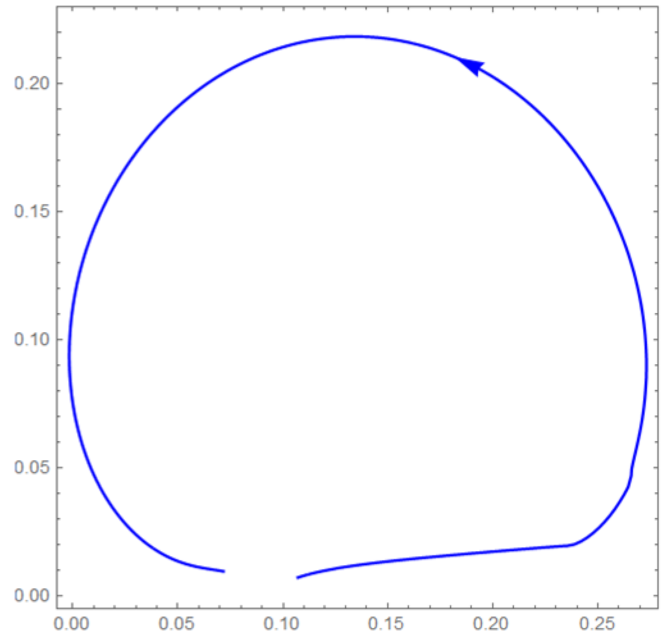
  Coleman, Norton (1965); Bronzan (1964)

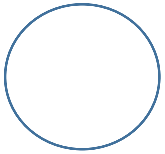
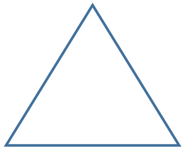
  ☞ all three intermediate particles can go on shell simultaneously

  ☞ $\vec{p}_2 \parallel \vec{p}_3$, particle-3 can catch up with particle-2 (as a classical process)
- needs very special kinematics ⇒ process dependent! (contrary to pole position)

# Triangle singularity



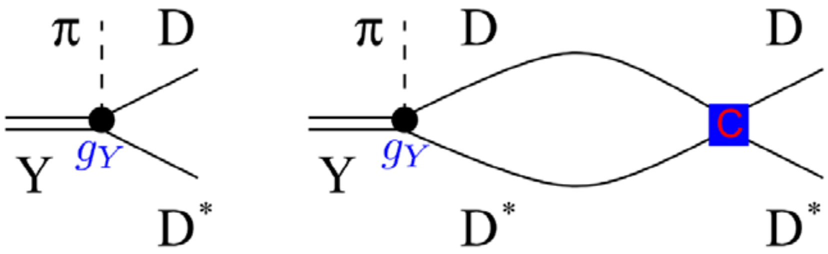



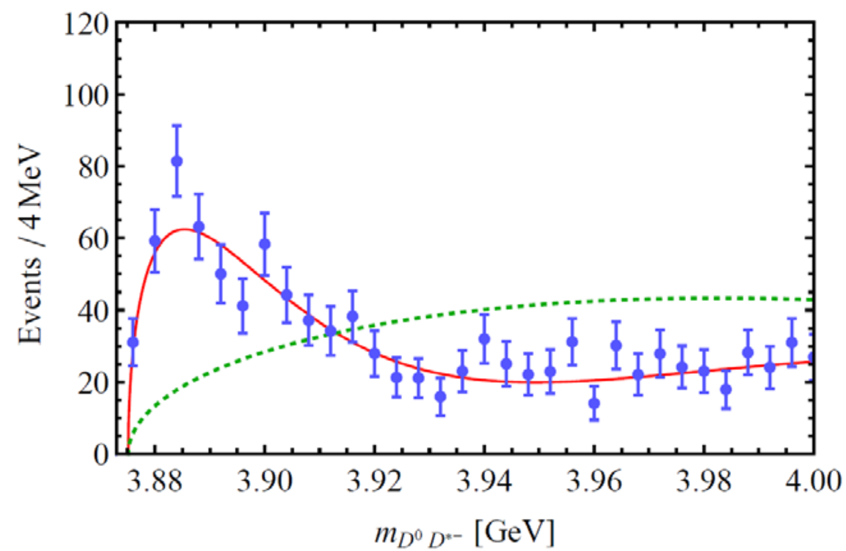

- Left: Argand plot for a triangle diagram with a TS: also counter-clockwise, not a circle, but
- Right: constant +  + 

# $Z_c$: just a threshold cusp?

- But $Z_c(3900)[Z_b]$ as a narrow peak in $D\bar{D}^*[B\bar{B}^*]$ distribution cannot be only due to cusp: prominent cusp $\Rightarrow$ strong int. $\Rightarrow$ pole!

FKG, Hanhart, Wang, Zhao, PRD91(2015)051504




Black curve: up to 1 loop with $C_\Lambda\, G_\Lambda(E_{\text{th}}) = -1/2$,
no narrow peak any more!

$g_Y\,[1 + C_\Lambda\, G_\Lambda(E) + C_\Lambda\, G_\Lambda(E) C_\Lambda\, G_\Lambda(E) + \ldots]$ produces a pole

- so far, triangle diagrams not considered (see next slides)

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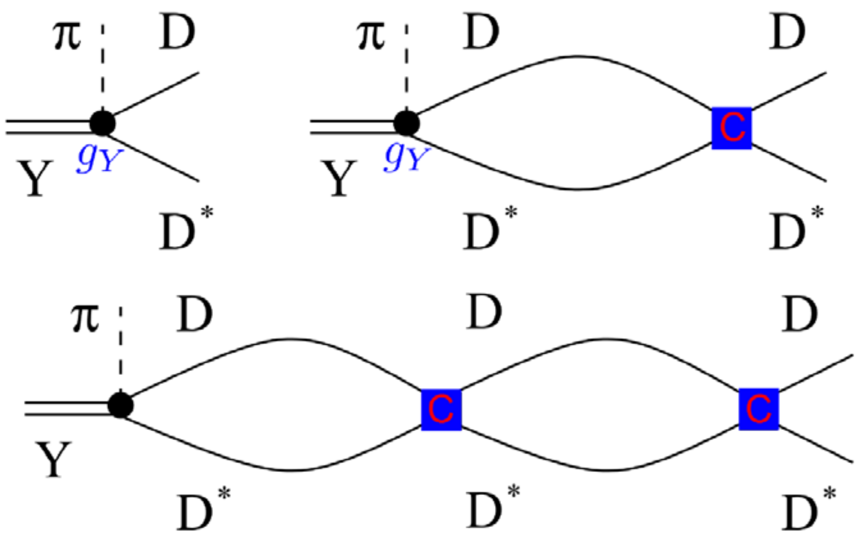


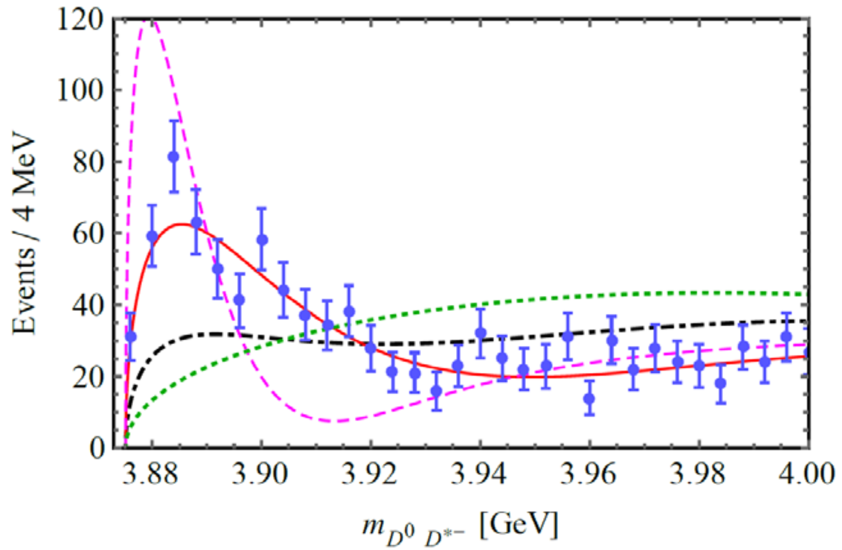


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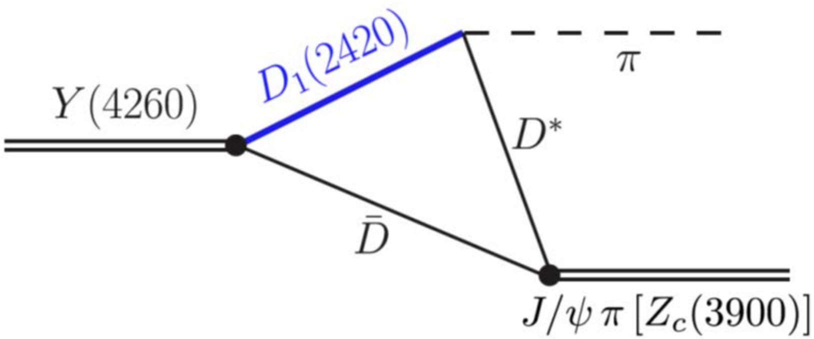
# From Y to Z

- Strong S-wave coupling of $Y(4260)$ to $D_1\bar{D}+c.c.$
- Strong S-wave coupling of $Z_c(3900)$ to $D^*\bar{D}+c.c.$
- Natural production mechanism of $Z_c(3900)$ :




- Enhancement due to closeness to thresholds

$$\mathcal{A}\sim\frac{v^5}{(v^2)^3}\mathrm{Vertex}_{D_1D^*}(p_\pi)=\frac{1}{v}\mathrm{Vertex}_{D_1D^*}(p_\pi)$$

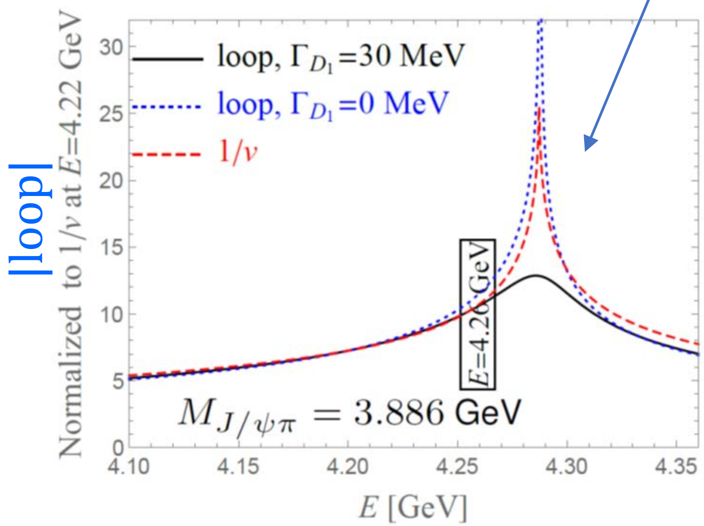
Intermediate mesons are nonrelativistic, $v\sim 0.1 \ll 1$

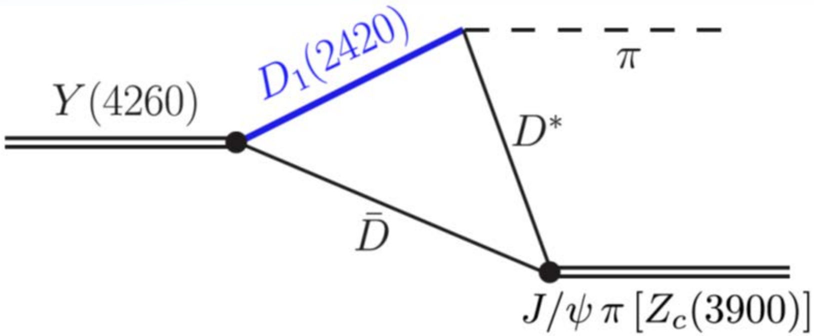
Power counting: 3-momentum $\sim\mathcal{O}(v)$, energy $\sim\mathcal{O}(v^2)$

loop integral measure $\sim\mathcal{O}(v^5)$, propagator $\sim\mathcal{O}(v^{-2})$

# From Y to Z

NR power counting works very well:

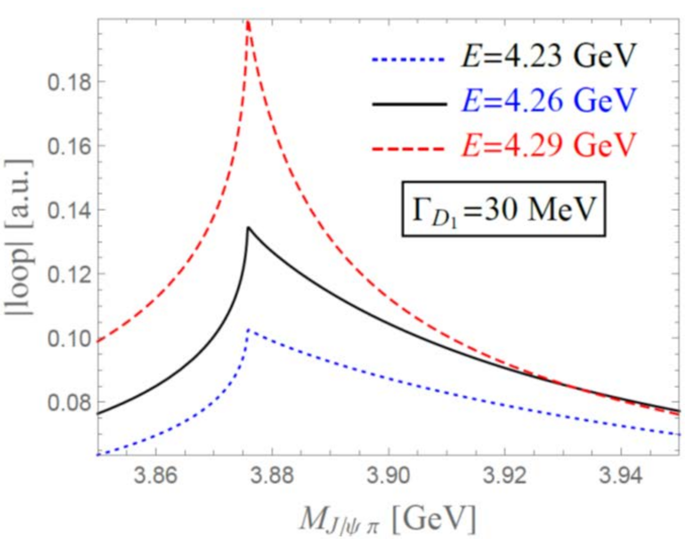


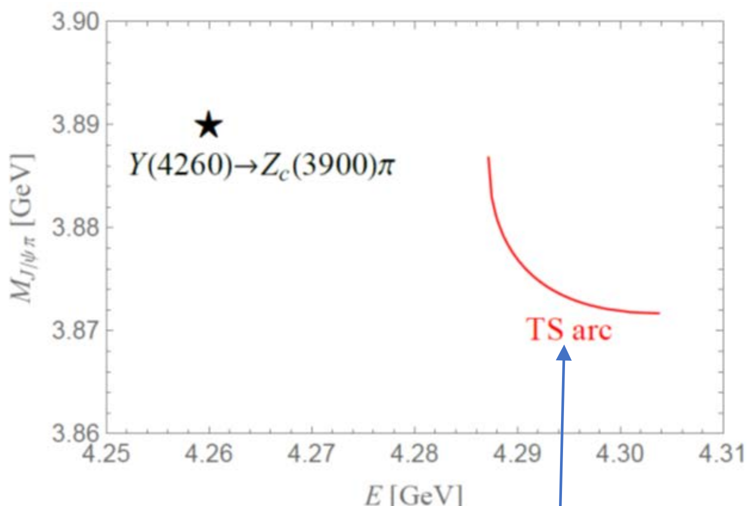




Reason for the sharp peak: triangle singularity (TS)

Very sensitive to kinematics (energy, masses)

|loop| as a function of the mass of Y



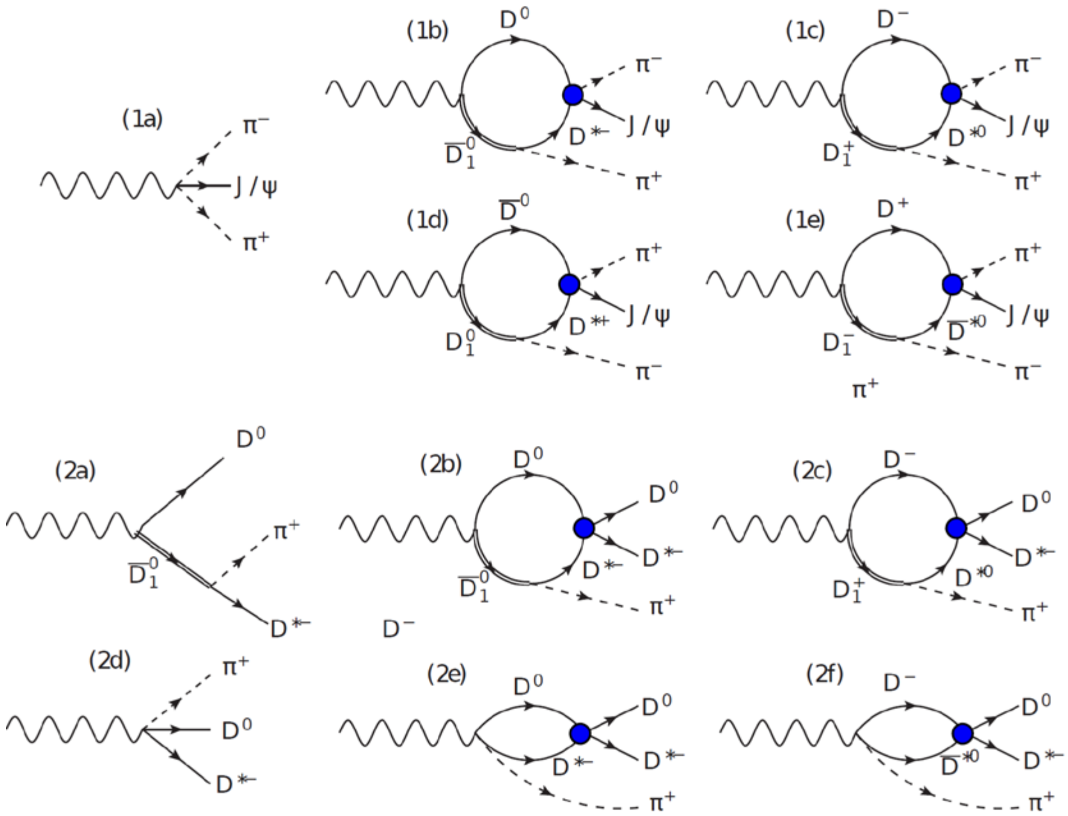




TS is on the physical boundary on along this arc

# From Y to Z

- Coupled-channel analysis with both FSI and triangle diagrams

Albaladejo, FKG, Hidalgo-Duque, Nieves, PLB755(2016)337



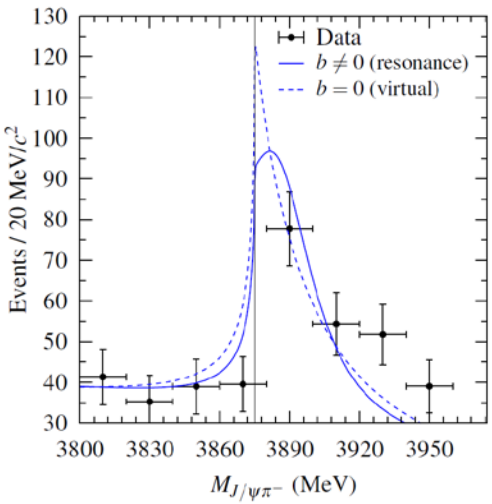

Blue bulbs: FSI T-matrix, it may or may not have a near-threshold pole ($Z_c$);
data will tell

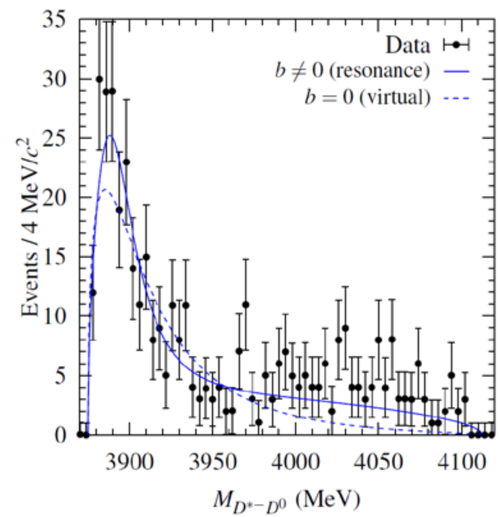
Kinematical singularities (threshold cusp, TS) and resonances are NOT exclusive

# From Y to Z

Fit to BESIII data at 4.26 GeV                Albaladejo, FKG, Hidalgo-Duque, Nieves, PLB755(2016)337

$Z_c(3900)$ is needed: either a resonance or a virtual state, more precise line shape data needed




| $M_{Z_c}$ (MeV) | $\Gamma_{Z_c}/2$ (MeV) | Ref. | Final state |
|---|---|---|---|
| $3899 \pm 6$ | $23 \pm 11$ | [1] (BESIII) | $J/\psi\ \pi$ |
| $3895 \pm 8$ | $32 \pm 18$ | [2] (Belle) | $J/\psi\ \pi$ |
| $3886 \pm 5$ | $19 \pm 5$ | [3] (CLEO-c) | $J/\psi\ \pi$ |
| $3884 \pm 5$ | $12 \pm 6$ | [4] (BESIII) | $\bar{D}^* D$ |
| $3882 \pm 3$ | $13 \pm 5$ | [5] (BESIII) | $\bar{D}^* D$ |
| $3894 \pm 6 \pm 1$ | $30 \pm 12 \pm 6$ | $\Lambda_2 = 1.0$ GeV | $J/\psi\ \pi,\ \bar{D}^* D$ |
| $3886 \pm 4 \pm 1$ | $22 \pm 6 \pm 4$ | $\Lambda_2 = 0.5$ GeV | $J/\psi\ \pi,\ \bar{D}^* D$ |
| $3831 \pm 26^{+7}_{-28}$ | virtual state | $\Lambda_2 = 1.0$ GeV | $J/\psi\ \pi,\ \bar{D}^* D$ |
| $3844 \pm 19^{+12}_{-21}$ | virtual state | $\Lambda_2 = 0.5$ GeV | $J/\psi\ \pi,\ \bar{D}^* D$ |

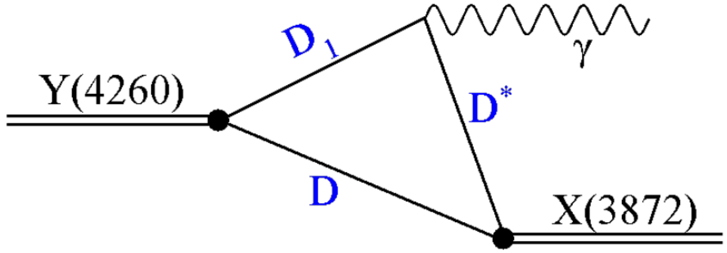
resonance pole $\chi^2/\mathrm{dof} = 1.09$

or virtual state $\chi^2/\mathrm{dof} = 1.36$

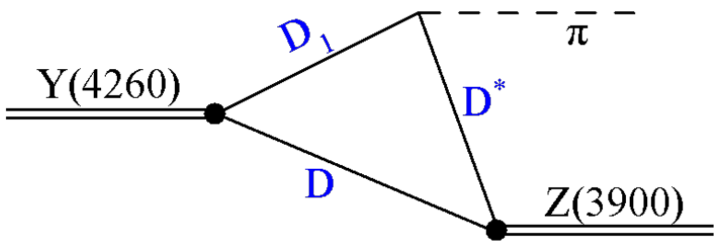
# From Y to X

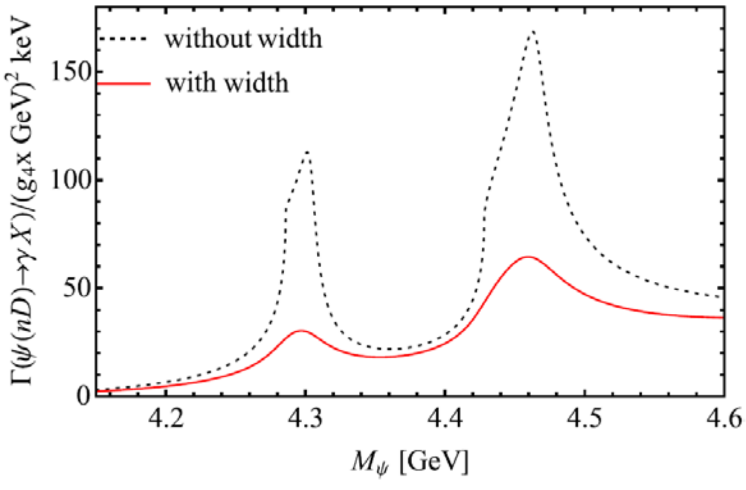
- Strong S-wave coupling of $Y(4260)$ to $D_1\bar{D} + c.c.$
- Strong S-wave coupling of $X(3872)$ to $D^*\bar{D} + c.c.$
- Method of producing X(3872) in $e^+e^-$:

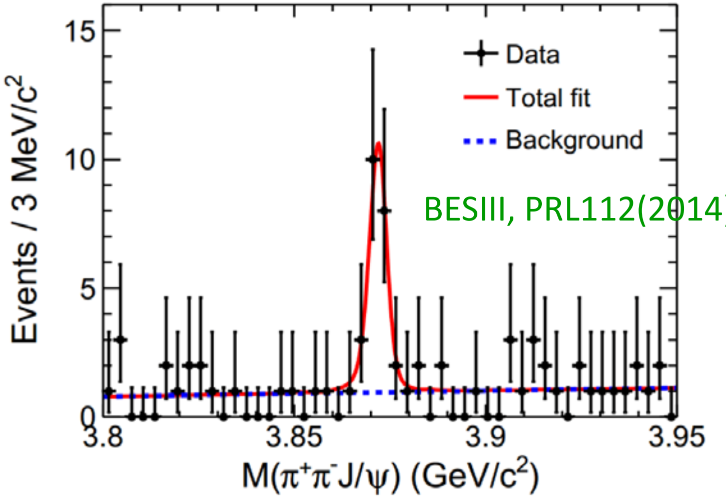
FKG et al., PLB725(2013)106




similar to




BESIII, PRL112(2014)092001

BESIII observed $e^+e^- \to \gamma X(3872)$ at $E = 4.26$ GeV

# From Y to $X_2$?

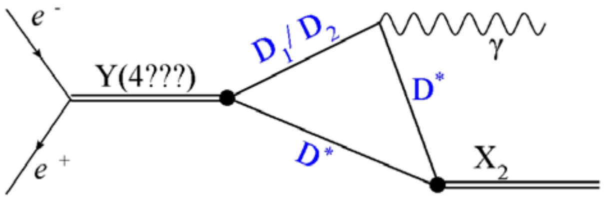
- $X_2$: $2^{++}, M \approx 4$ GeV, $D^*\bar{D}^*$, spin partner of $X(3872)$ in hadronic molecular model

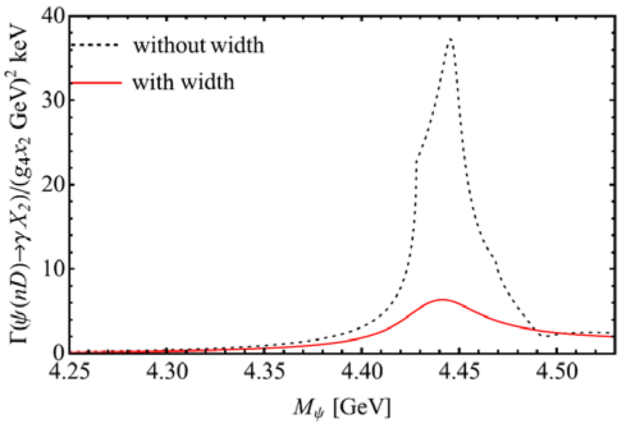
  Nieves, Pavon Valderrama, PRD86(2012)056004

- Small width $\lesssim 50$ MeV    Albaladejo et al., EPJC75(2014)547; Baru et al., PLB763(2016)20

- Method of producing $X_2$ in $e^+e^-$:
  - $e^+e^- \to \gamma X_2$, $X_2 \to D\bar{D}, D\bar{D}^*$

    FKG, Meißner, Yang, PLB740(2015)42

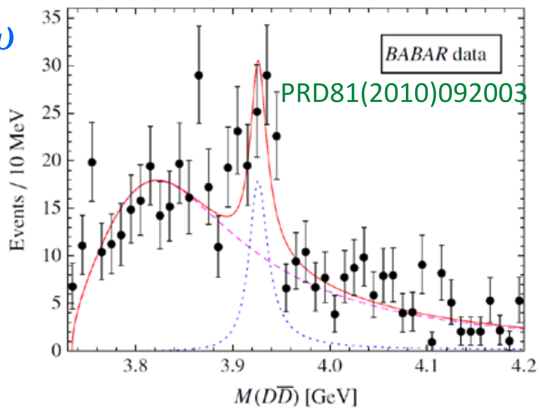


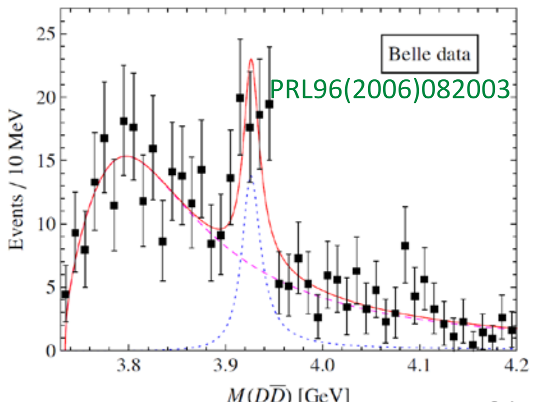




$$\sqrt{s} \sim 4.26\ \text{GeV} + \left(M_{D_1/D_2} + M_{D^*}\right) - \left(M_{D_1} + M_D\right) \sim [4.4, 4.5]\ \text{GeV}$$

  - $\gamma\gamma \to X_2 \to D\bar{D}, D\bar{D}^*, J/\psi\omega$

    No signal in existing data for $\gamma\gamma \to D\bar{D}$

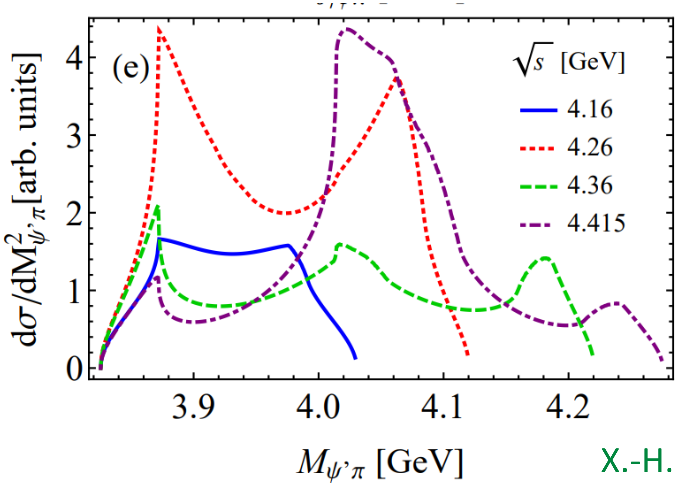


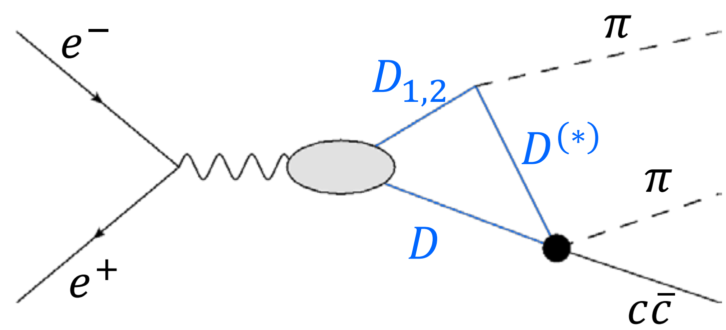




FKG, Meissner, PRD86(2012)091501

# Nontrivial energy dependence

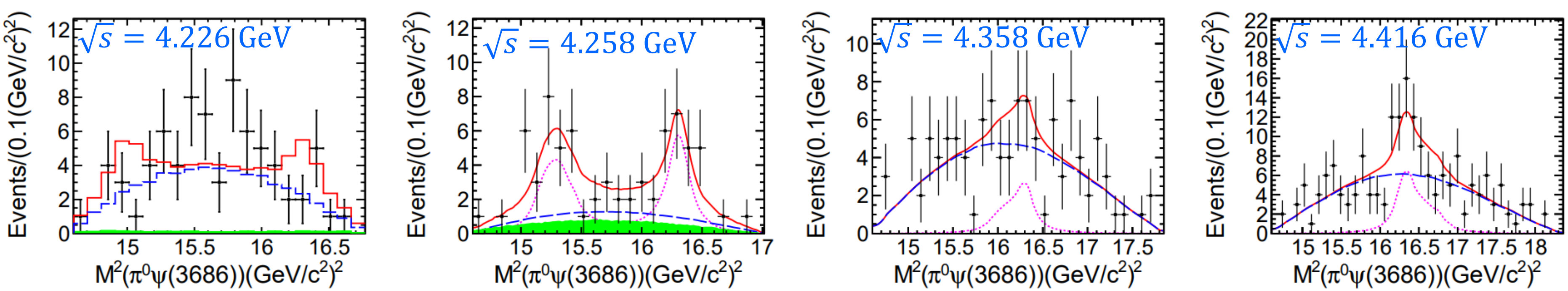
Highly nontrivial energy dependence expected, e.g. $e^+e^- \to \psi'\pi^+\pi^-$




X.-H. Liu, PRD90(2014)074004

Difficulty/opportunity of identifying $Z_c$




BESIII measurement of $e^+e^- \to \psi'\pi^0\pi^0$ BESIII, PRD97(2018)052001

# Biased selection

Y and relatives:

- Y(4260): source of $Z_c$ and X(3872); consequence of strong coupling of Y(4260) to $D_1\bar{D}$ ?
- Structures around 4.4 GeV need to be studied together in more detail:

  Y(4360), $\psi$(4415); nearby thresholds: $D_{1,2}\bar{D}^*$, $D_{s0}^*\bar{D}_s^*$, $D_{s1}\bar{D}_s$, $\chi_{c0}\phi$

X and relatives:

- $\Gamma(X \to D^0\bar{D}^0\pi^0)$: measuring the probability of $D^0\bar{D}^{*0}$ in $X(3872)$
- $X(3860)$: $\chi_{c2}(3930)$ not included in Belle fit PRD95(2017)112003;

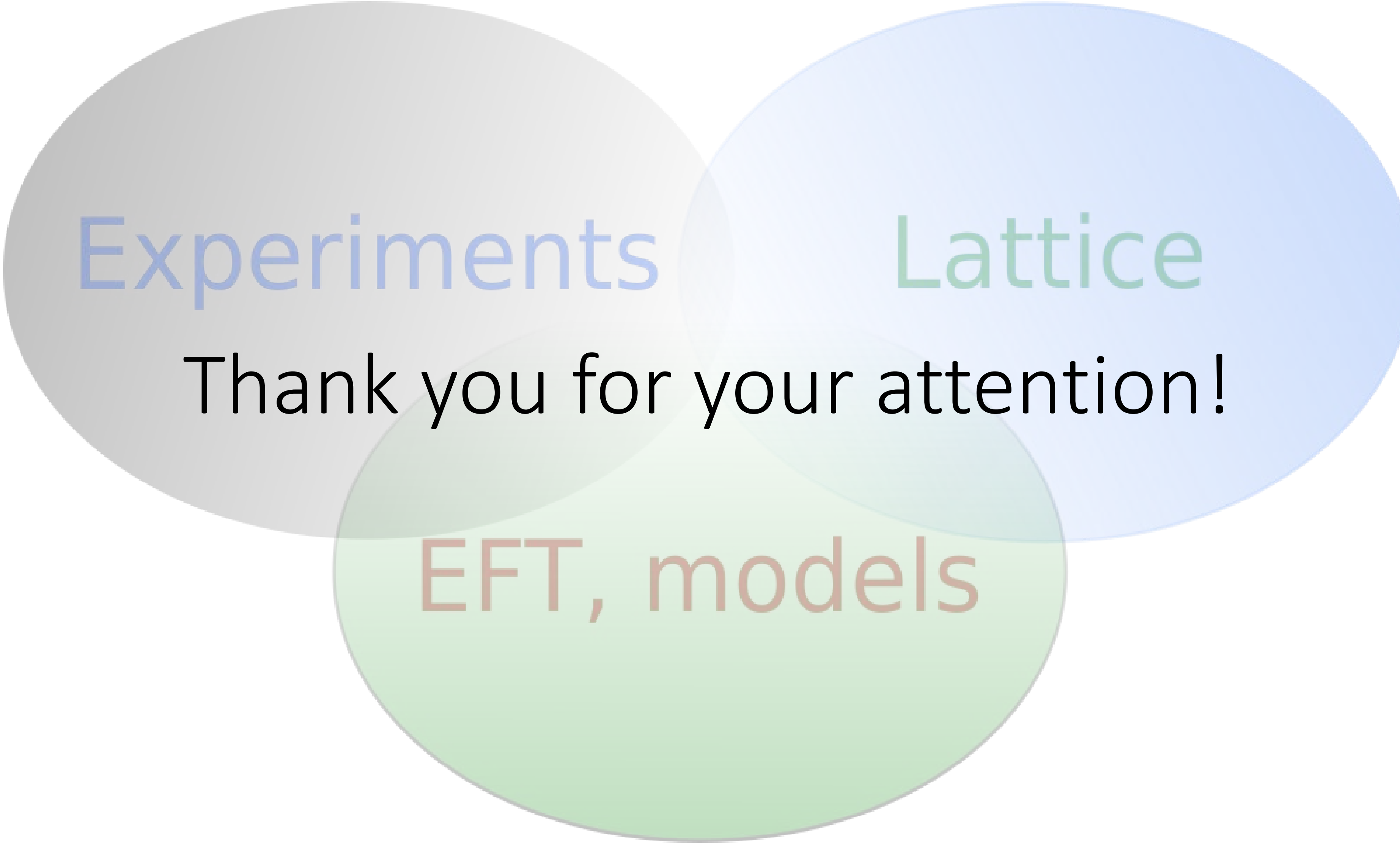
  $M = 3838 \pm 12$ MeV FKG, Meissner, PRD86(2012) 091501
- X(3915)
- Searching for additional (likely broad) $\chi_{c1}$and $h_c$ at $\gtrsim$ 3.9 GeV
- Searching for $X_2(\to D\bar{D}, D^*\bar{D})$ around 4 GeV

$Z_c$(3900,4020):

- Can they be found in B decays?

Precise line shape measurements for all of them!

# Looking forward to new discoveries

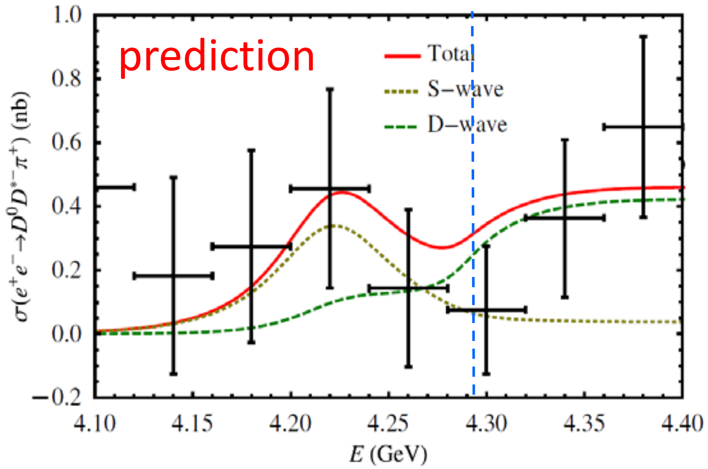


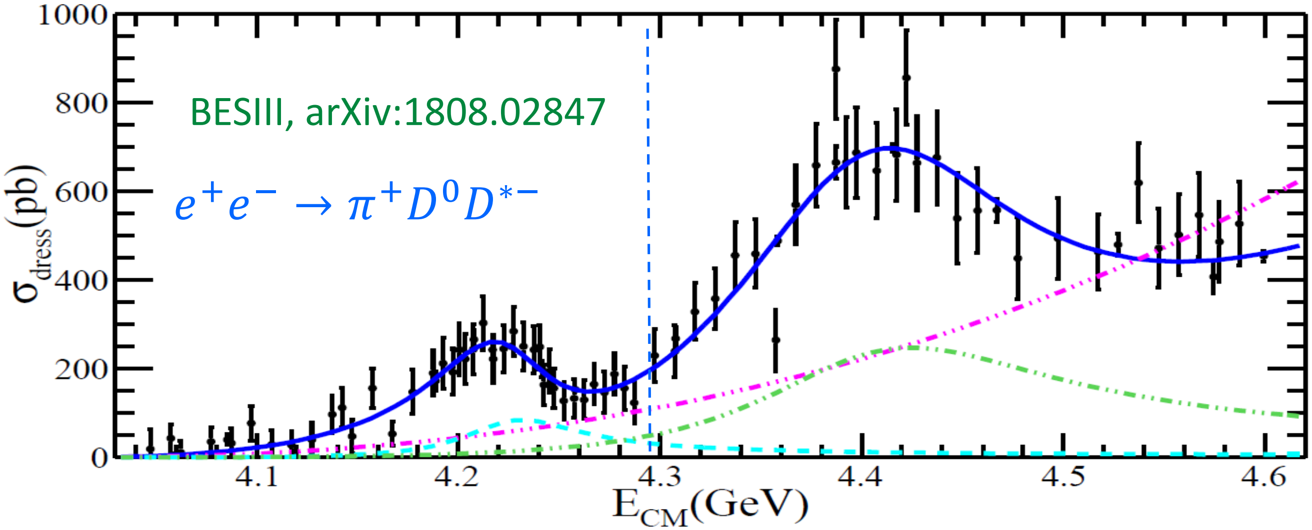

Thank you for your attention!

# Y(4260): $D_1\bar{D}$ hadronic molecular model

- Natural decay channel in this picture: $\bar{D}D^{*}\pi + c.c.$

M. Cleven et al., PRD90(2014)074039

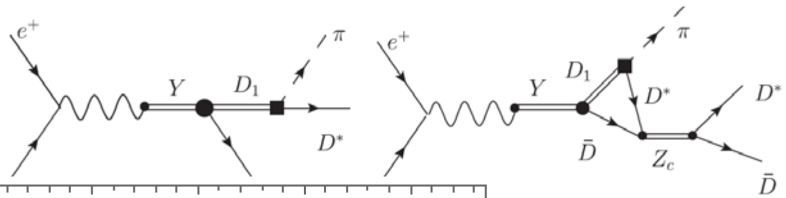


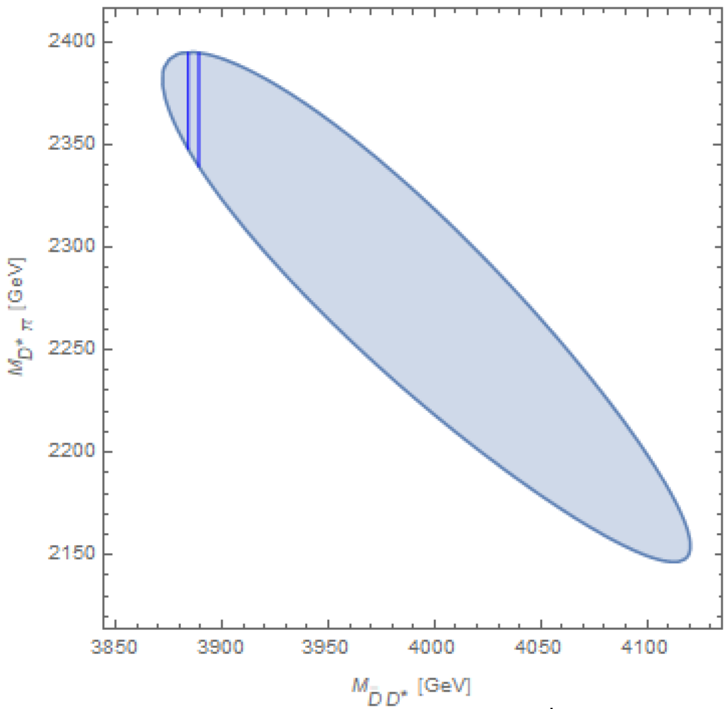



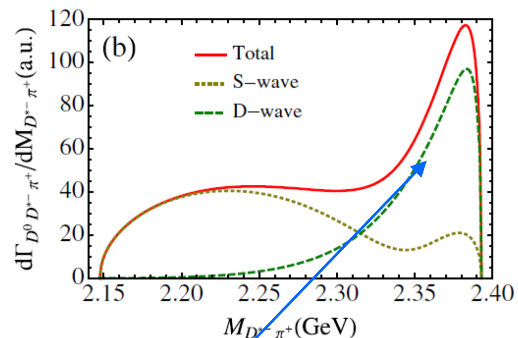
# Y(4260): $D_1\bar{D}$ hadronic molecular model

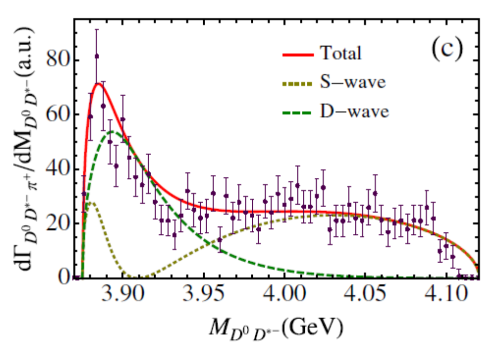
- Natural decay channel in this picture: $\bar{D}D^*\pi + c.c.$

M. Cleven et al., PRD90(2014)074039




The end-point peak in $D^*\pi$ comes from

$D_1(2420)$ and $Z_c$'s projection;

Dalitz plot analysis