Vector Y states

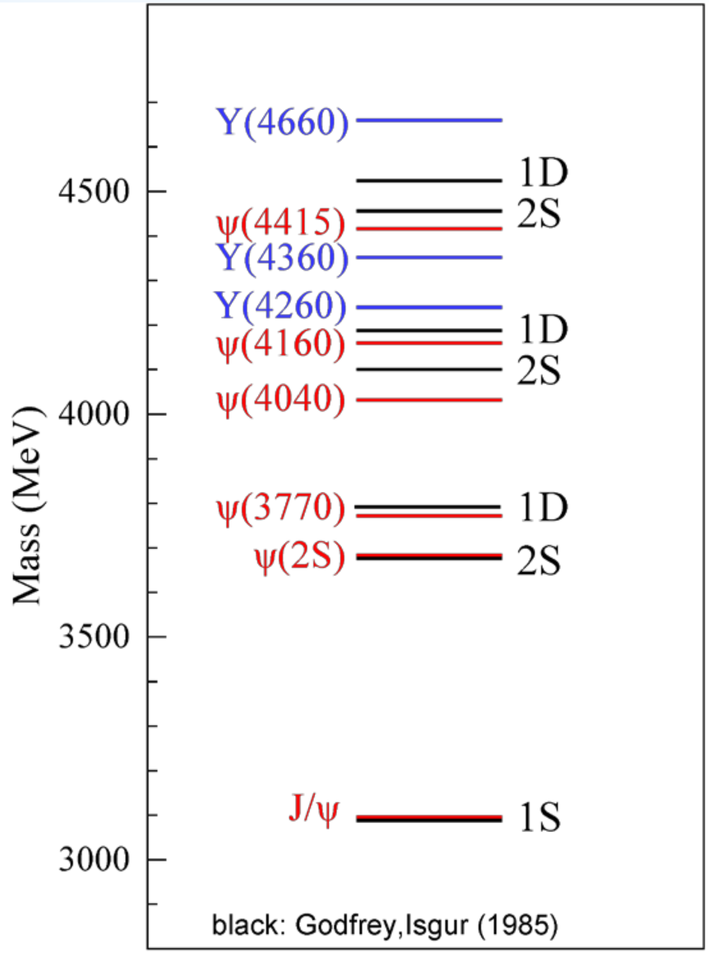
focusing on Y(4260)

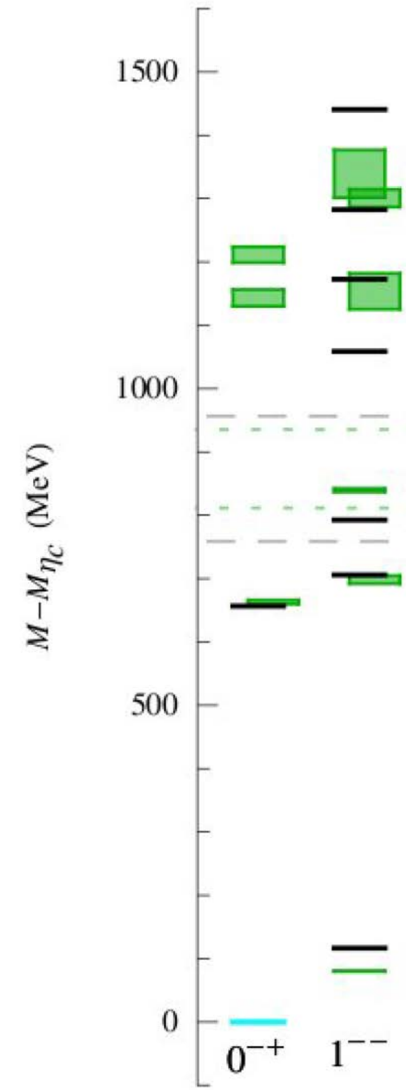
郭奉坤

中国科学院理论物理研究所

第五届XYZ粒子学术研讨会, 郑州, 2018.10.19-10.23

Vector charmonium(-like) states





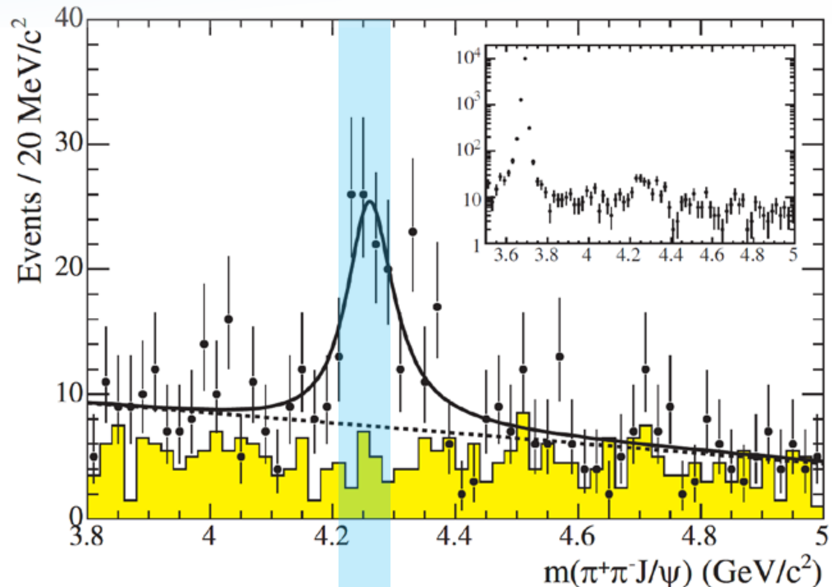
Lattice QCD, L. Liu et al., JHEP1207,126

- 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 $\mathrm{B}(\psi(3770) \to D\bar{D}) = \left(98^{+8}_{-9}\right)\%$

Y(4260)

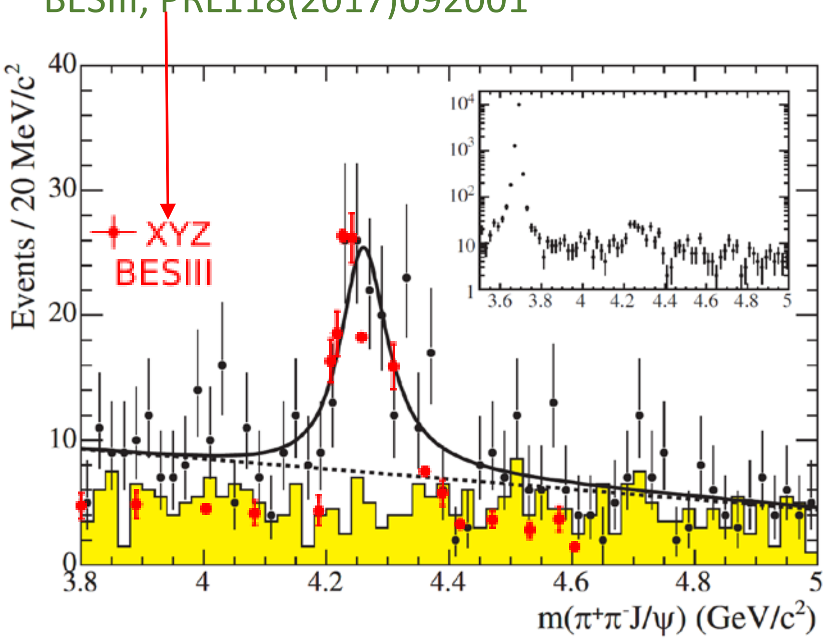
- Discovered in $J/\psi\pi^+\pi^-$

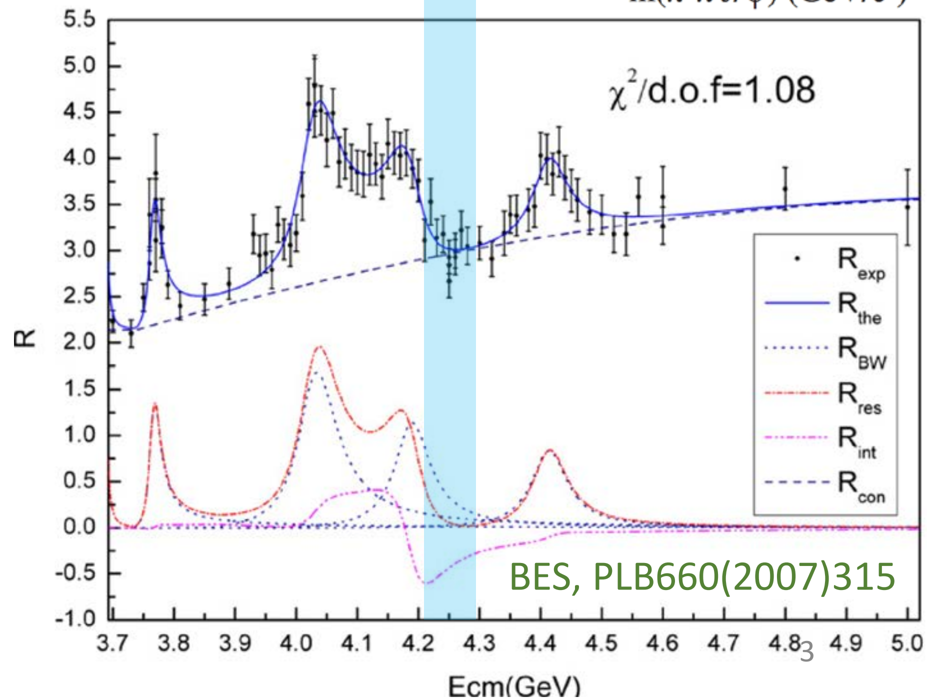
BABAR, PRL95(2005)142001



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

BESIII, PRL118(2017)092001





Y(4260)

Resonant structure found in several channels with similar resonance parameters

$\psi(4260)$ MASS

INSPIRE search

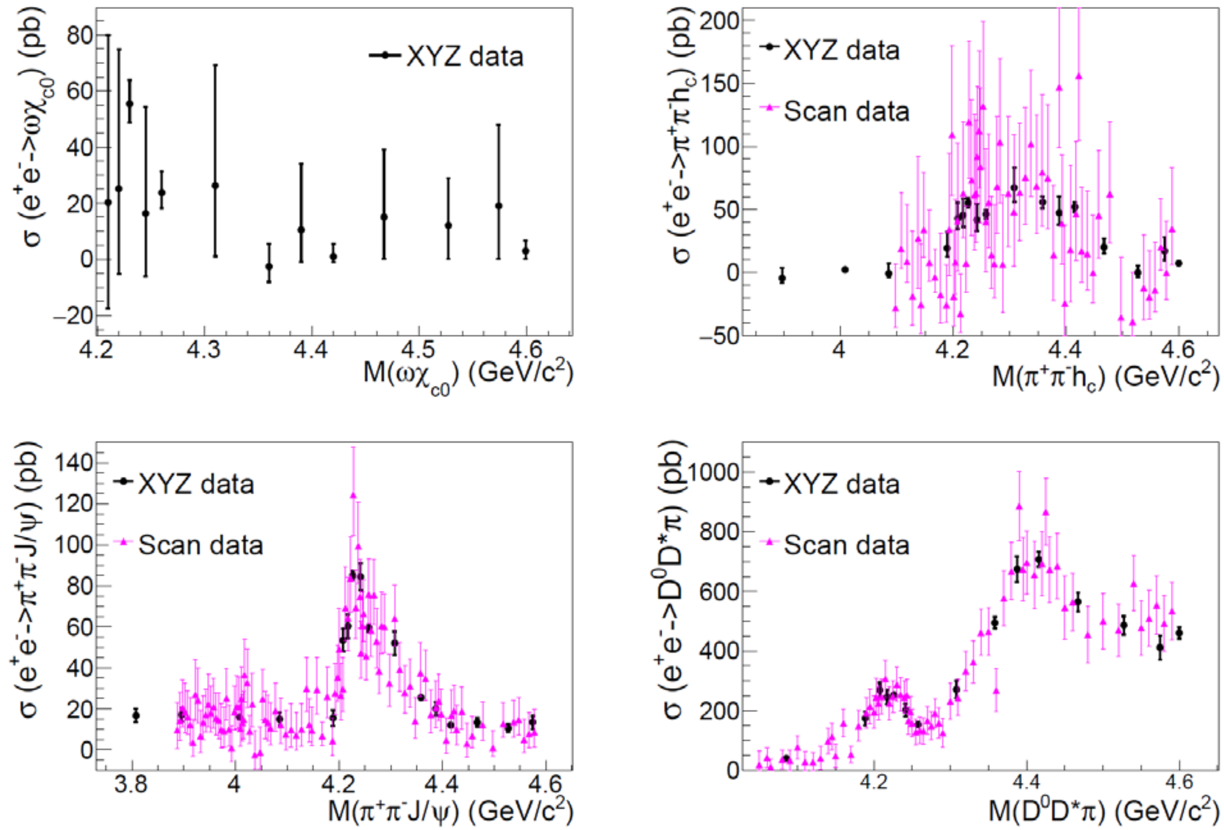
VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$\mathbf{4230 \pm 8}$	**OUR AVERAGE** Error includes scale factor of 2.9.				
$4222.0 \pm 3.1 \pm 1.4$		1 ABLIKIM	2017B	BES3	$e^+ e^- \to \pi^+\pi^- J/\psi$
$4258.6 \pm 8.3 \pm 12.1$		2 LIU	2013B	BELL	$e^+ e^- \to \gamma\pi^+\pi^- J/\psi$
$4245 \pm 5 \pm 4$		3 LEES	2012AC	BABR	10.58 $e^+ e^- \to \gamma\pi^+\pi^- J/\psi$
$4284 ^{+17}_{-16} \pm 4$	13.6	HE	2006B	CLEO	$9.4 - 10.6$ $e^+ e^- \to \gamma\pi^+\pi^- J/\psi$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$4209.1 \pm 6.8 \pm 7.0$		4 ZHANG	2017B	RVUE	$e^+e^- \to \pi^+\pi^-\psi(2S)$
$4223.3 \pm 1.6 \pm 2.5$		5 ZHANG	2017C	RVUE	$e^+ e^- \to \pi^+\pi^- J/\psi$ or $\psi(2S)$
$4247 \pm 12 ^{+17}_{-32}$		6, 2 YUAN	2007	BELL	10.58 $e^+ e^- \to \gamma\pi^+\pi^- J/\psi$
$4259 \pm 8 ^{+2}_{-6}$	125	7 AUBERT,B	2005I	BABR	10.58 $e^+ e^- \to \gamma\pi^+\pi^- J/\psi$

$\psi(4230)$ MASS

INSPIRE search

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$\mathbf{4218^{+5}_{-4}}$	**OUR AVERAGE** Error includes scale factor of 1.2.				
$4218 ^{+5.5}_{-4.5} \pm 0.9$		ABLIKIM	2017G	BES3	$e^+ e^- \to \pi^+\pi^- h_c$
$4209.5 \pm 7.4 \pm 1.4$		1 ABLIKIM	2017V	BES3	$e^+ e^- \to \pi^+\pi^-\psi(2S)$
$4230 \pm 8 \pm 6$	180	2 ABLIKIM	2015C	BES3	$e^+ e^- \to \omega\chi_{c0}$

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

For more experimental observations, see the talk by Xiao-Rui

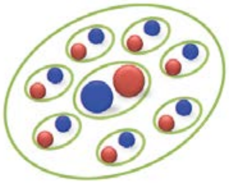
Y(4260): puzzling features

- 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 ψ 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: $D^0 D^{*-}\pi^+ + c.c.$

A very good exotic hadron candidate!

Discuss only a few models here

Y(4260): hadro-charmonium model, assumptions

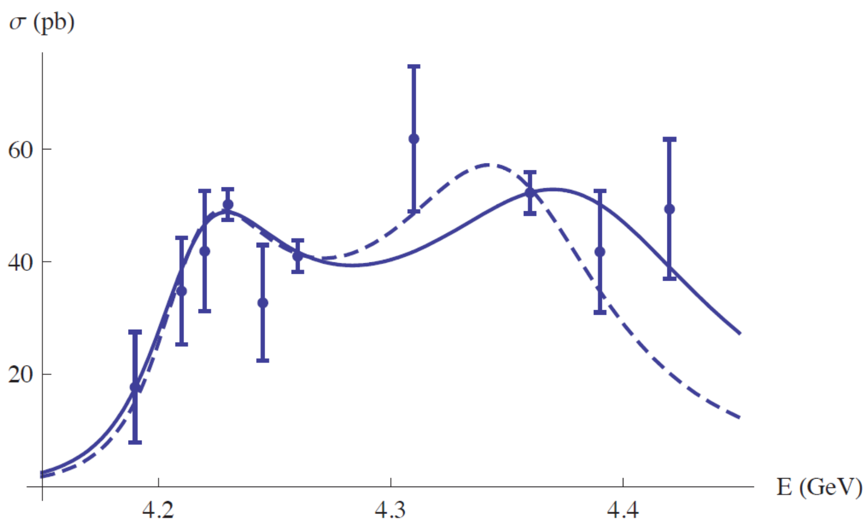


- hadro-charmonium model: M. B. Voloshin, PPNP61(2008)455

  charmonium core embedded inside light-quark matter

- Provided an explanation why the Y(4260) was seen in $J/\psi\pi\pi$ instead of $D\bar{D}$
- The fact that BESIII observed $h_c\pi\pi$ at 4.26 GeV and 4.36 GeV inspired the model for Y(4260) and Y(4360) : X. Li, M. B. Voloshin, MPLA29(2014)1450060

  mixed hadro-charmonia with cores of ψ' and h_c



h_c: $s_{c\bar{c}} = 0$, spin-singlet

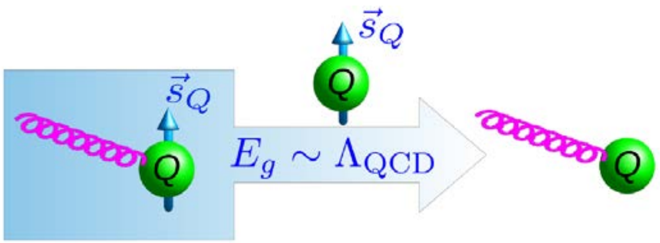
$J/\psi,\psi'$: $s_{c\bar{c}} = 1$, spin-triplet

Y(4260): hadro-charmonium model, consequences

- Heavy-quark spin symmetry (HQSS)

chromomag. interaction $\propto \dfrac{\boldsymbol{\sigma}\cdot\boldsymbol{B}}{m_Q}$

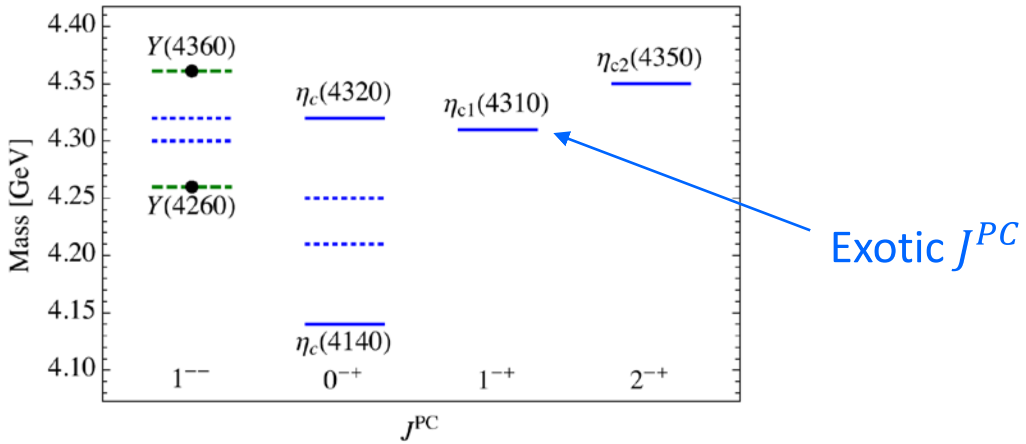
spin of the heavy quark decouples



- HQSS predictions using Li&Voloshin's assumption:

Cleven et al., PRD 92(2015)014005

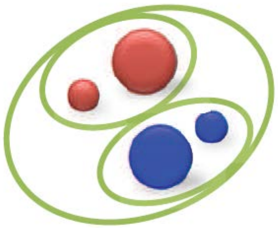
spin partners via $\psi' \to \eta_c'$ and $h_c \to \{\chi_{c0},\ \chi_{c1},\ \chi_{c2}\}$



- Favorite decay modes: $(J/\psi, \psi', h_c)$+light mesons. If the structures ~4.23 GeV in $\chi_{c0}\omega$ and $D\bar{D}^*\pi$ are Y(4260), then the hadro-charmonium model excluded!

Y(4260): tetraquark model, assumptions

- Diquark-antidiquark systems in the model of Maiani et al. PRD89(2014)114010



- Assumption-1: spin-spin interaction only exists within diquarks

$$M = M_{00} + B_c \frac{\boldsymbol{L}^2}{2} - 2a\boldsymbol{L}\cdot\boldsymbol{S} + 2\kappa_{cq}[(\boldsymbol{s}_q\cdot\boldsymbol{s}_c) + (\boldsymbol{s}_{\bar{q}}\cdot\boldsymbol{s}_{\bar{c}})].$$

L: orbital angular mom.; S: total spin, $s_{q,c}$: spin of diquark

$$M = M_{00} + B_c\frac{L(L+1)}{2} + a[L(L+1) + S(S+1) - J(J+1)] + \kappa_{cq}[s(s+1) + \bar{s}(\bar{s}+1) - 3]$$

Parameters: $M_{00}, B_c, a(>0), \kappa_{cq}$

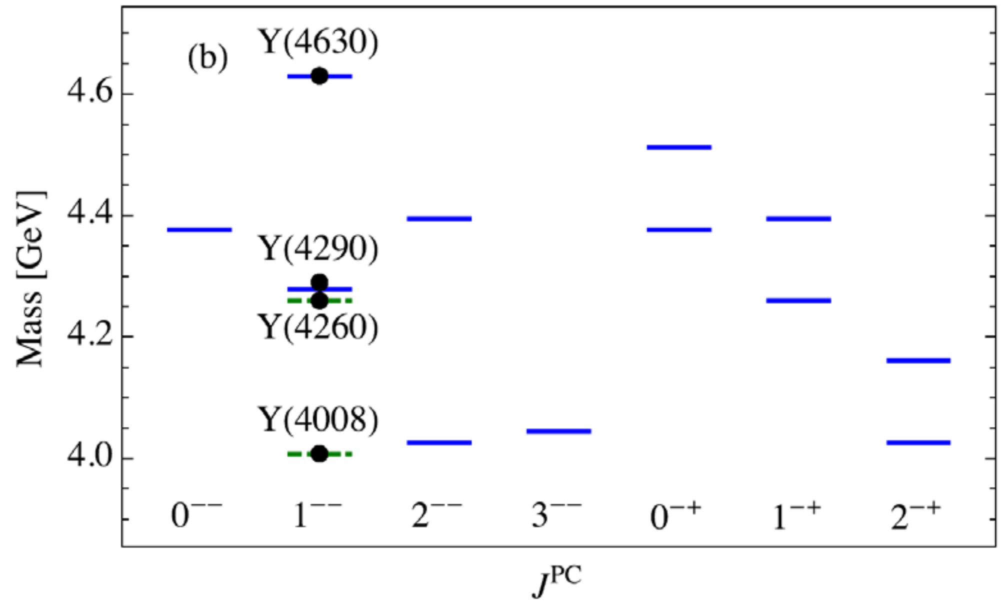
- Assumption-2: assignments in Maiani et al. PRD89(2014)114010

vector P-wave ground states: $Y(4008), Y(4260), Y(4220 \text{ or } 4290), Y(4630)$;

$Y(4360), Y(4660)$: radial excitations of $Y(4008), Y(4260)$

Y(4260): tetraquark model, consequences

- Largest challenge: a very rich spectrum, many more states than observed
- Interaction does not depend on isospin, thus each level corresponds 4 states: iso-singlet and iso-triplet
- thus, 56 P-wave ground states; 112 up to the first radial excitation
- Very light spin-3 states: for given $s, \bar{s}, S, L$, the largest J leads to the smallest mass



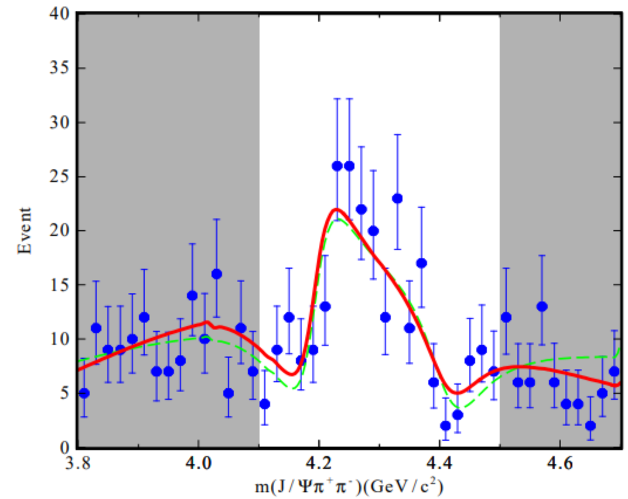
Predictions of ground states in Cleven et al., PRD 92(2015)014005 using inputs of Maiani et al., PRD89(2014)114010

$$M = M_{00} + B_c \frac{L(L+1)}{2} + a[L(L+1) + S(S+1) - J(J+1)] + \kappa_{cq}\left[s(s+1) + \bar{s}(\bar{s}+1) - 3\right]$$

Y(4260): interference model

- Y(4260) as an interference between $\psi(4160)$ and $\psi(4415)$

  D.-Y. Chen, J. He, X. Liu, PRD83(2011)054021



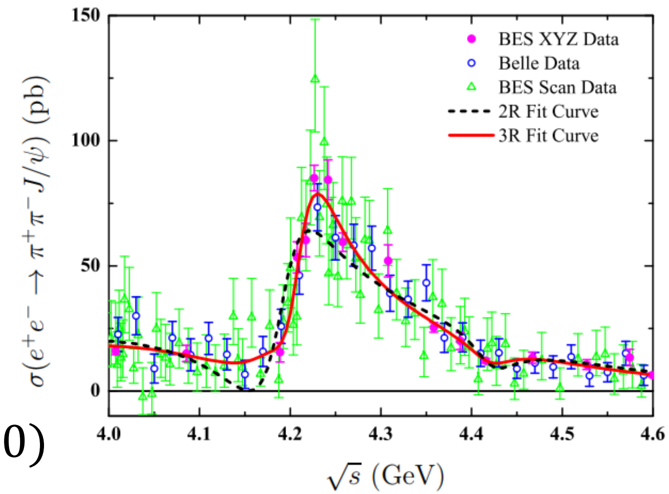
- Y(4220) needed to account for the new BESIII data

  D.-Y. Chen, X. Liu, T. Matsuki, EPJC78(2018)136

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

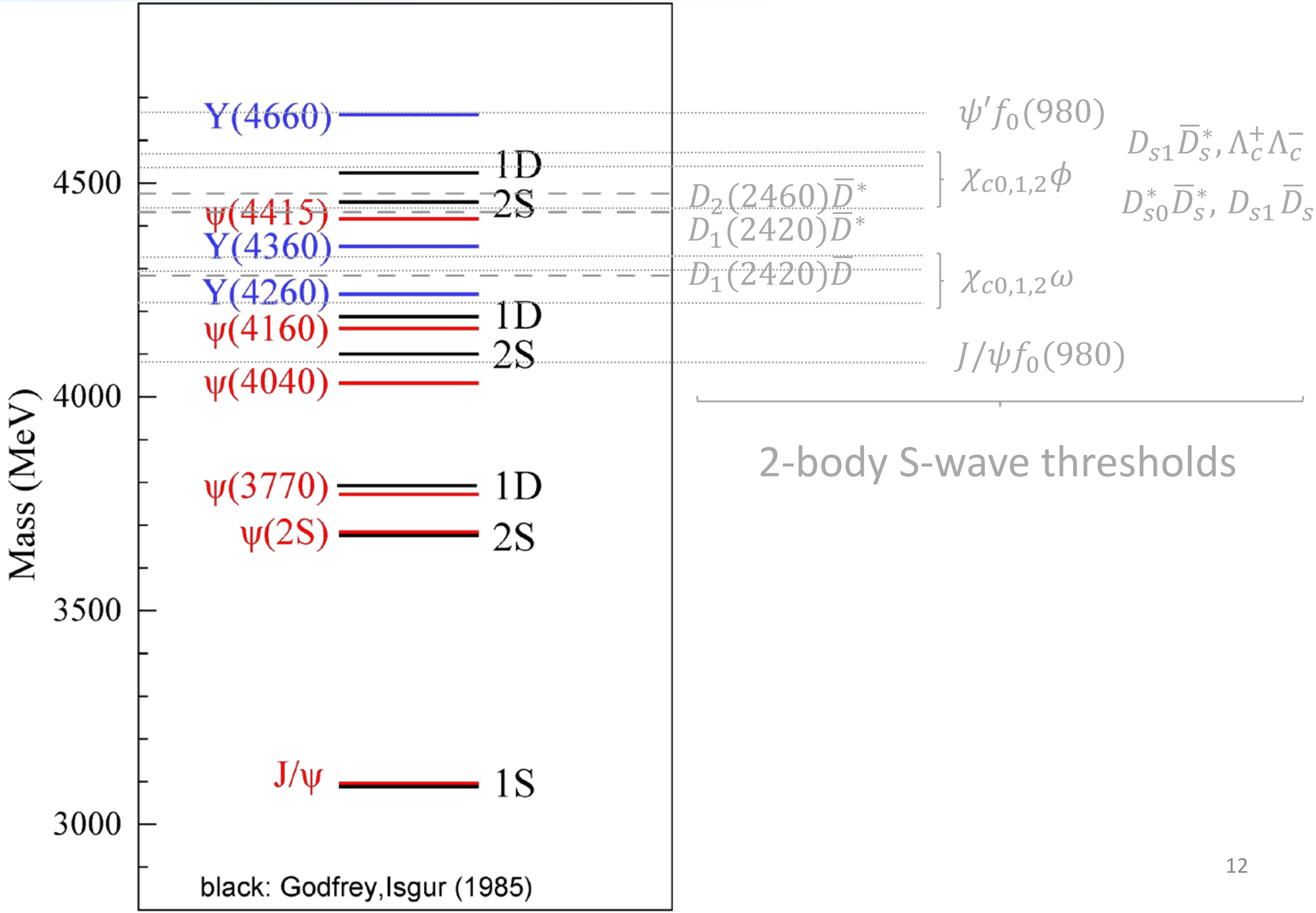
2R: $\text{NoR} + \psi(4160) + \psi(4415)$

3R: $\text{NoR} + \psi(4160) + \psi(4415) + Y(4220)$



- Predictions?

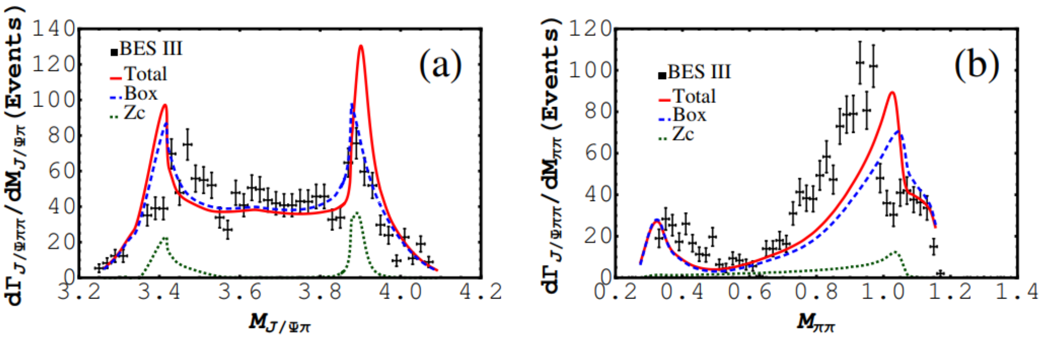
There are many nearby thresholds

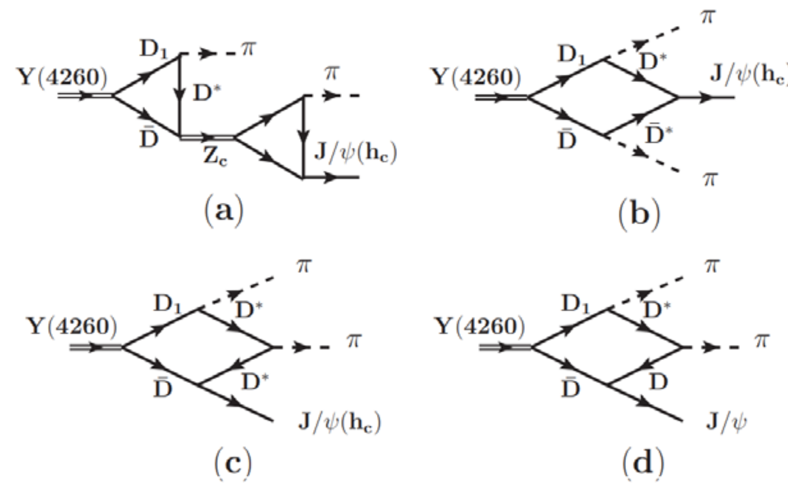


Y(4260): $D_1\bar{D}$ hadronic molecular model

- Y(4260) as mainly a $D_1(2420)\bar{D}$ hadronic molecule

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

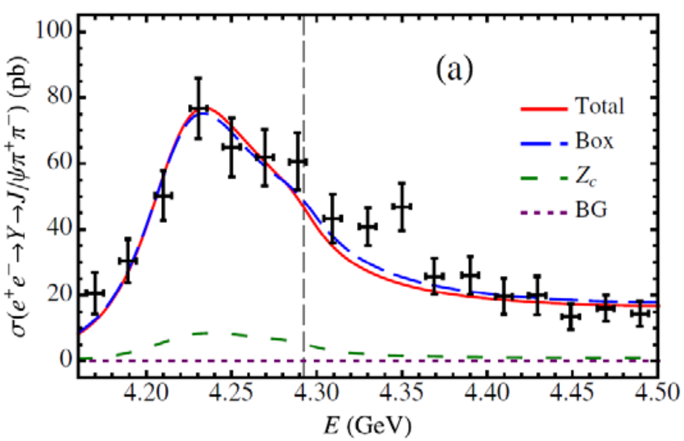




- If the Y(4260) is mainly a $D_1\bar{D}$ molecule $\Longrightarrow$ a large coupling to $D_1\bar{D}$ $\Longrightarrow$ large impact on the line shape

  see also Qin et al., PRD94(2016)054035

- Fit to Belle data



$M = (4217.2 \pm 2.0)$ MeV;

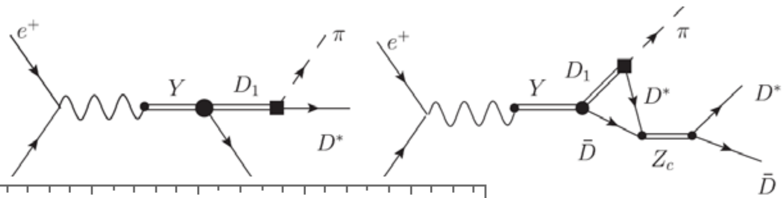
non-$D_1\bar{D}$ width: $\sim$56 MeV $\Longrightarrow$ sizeable non-$D_1\bar{D}$ component

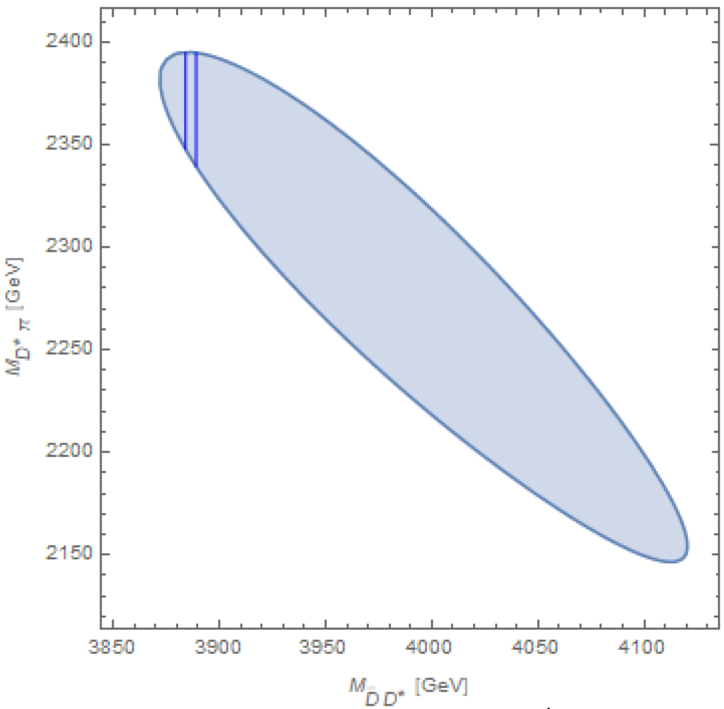
M. Cleven et al., PRD90(2014)074039

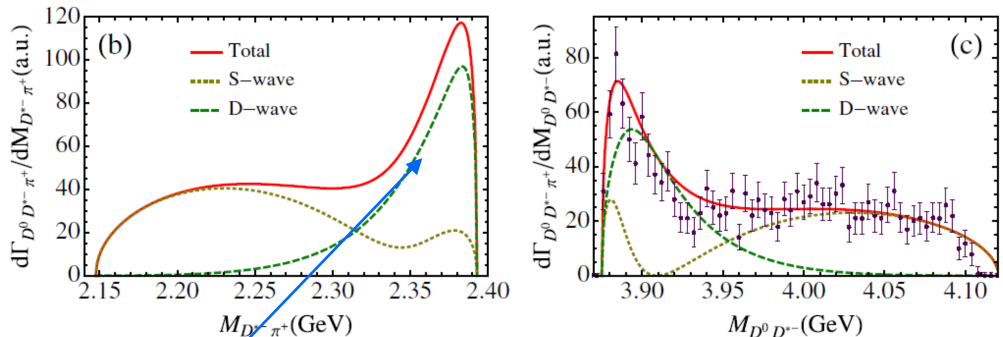
Y(4260): $D_1\bar{D}$ hadronic molecular model

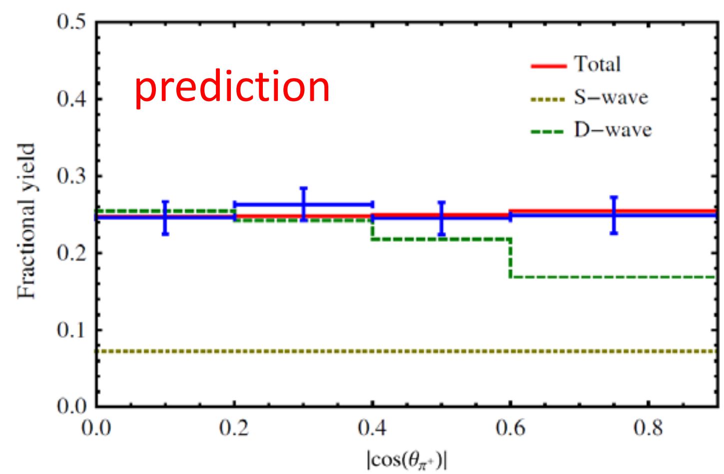
- Natural decay channel in this picture: $\bar{D}D^*\pi + c.c.$

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









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

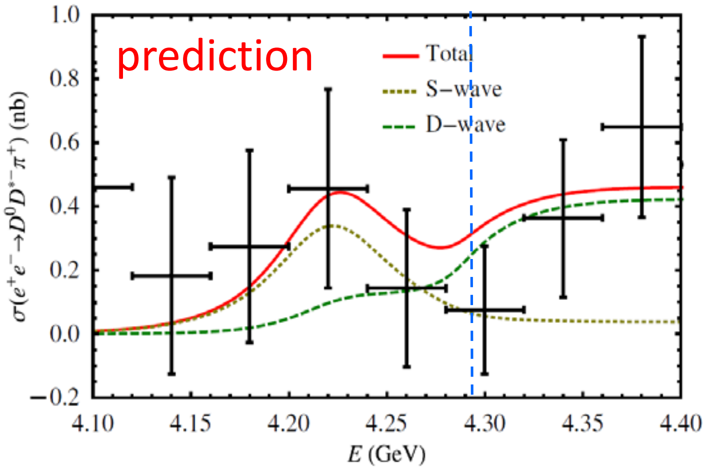
$D_1(2420)$ and Z_c's projection;

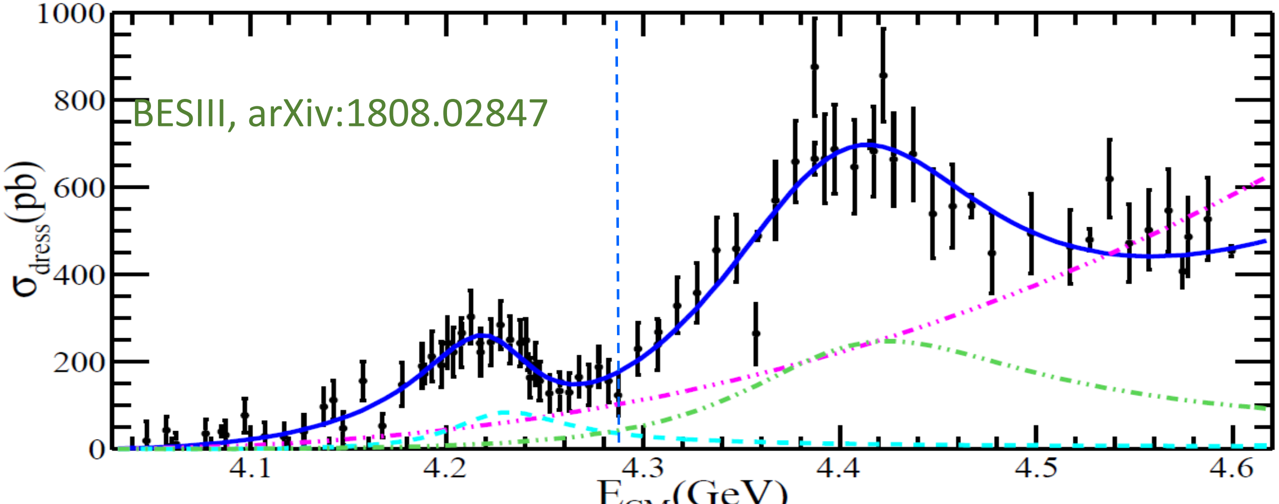
Dalitz plot analysis

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



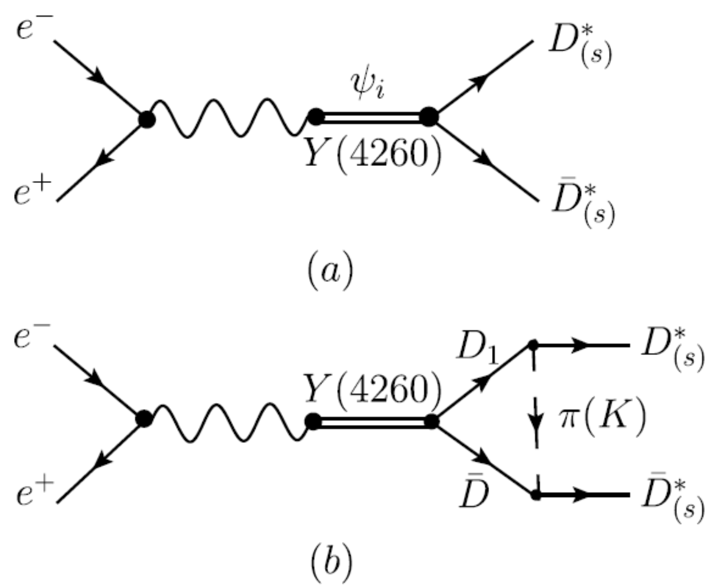


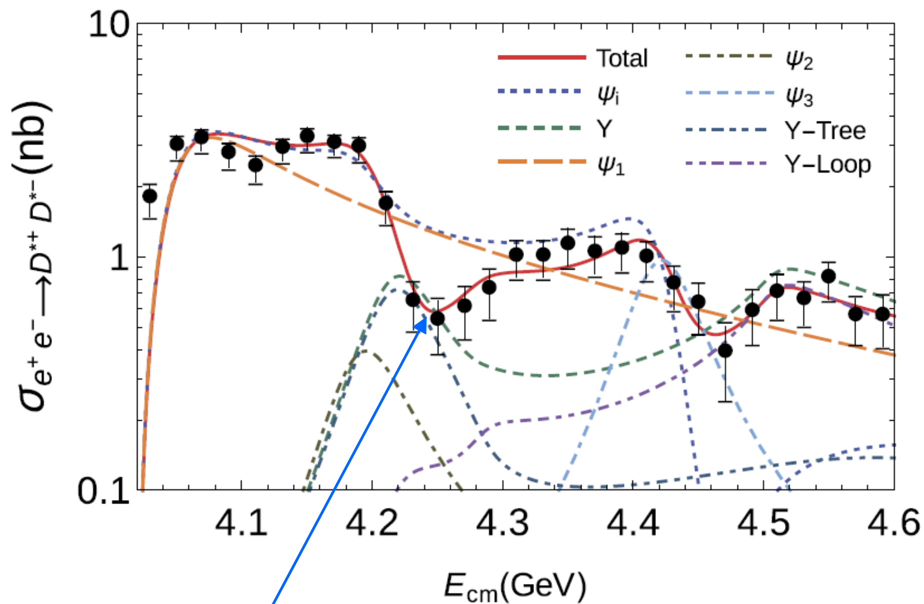
new analysis with more thresholds is ongoing

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

- Contribution of Y(4260) to $e^+e^- \to D^*\bar{D}^*$

S.-R. Xue et al., PLB779(2018)402





- If Y(4260) not included, the description around the dip becomes worse

$\Rightarrow \quad \Gamma(Y(4260) \to D^*\bar{D}^*) = (10.8 \pm 7.9)$ MeV

Y(4260): a light quark perspective

Yun-Hua Chen, L.-Y. Dai et al., arXiv:181x.abcde

- Idea:

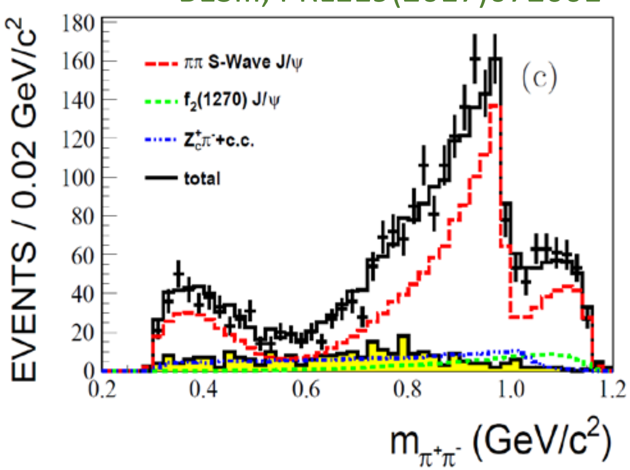
if Y(4260) is a charmonium/hybrid, then light-flavor SU(3) singlet;

if Y(4260) is a $D_1\bar{D} + c.c.$ molecule, then the light quark part is

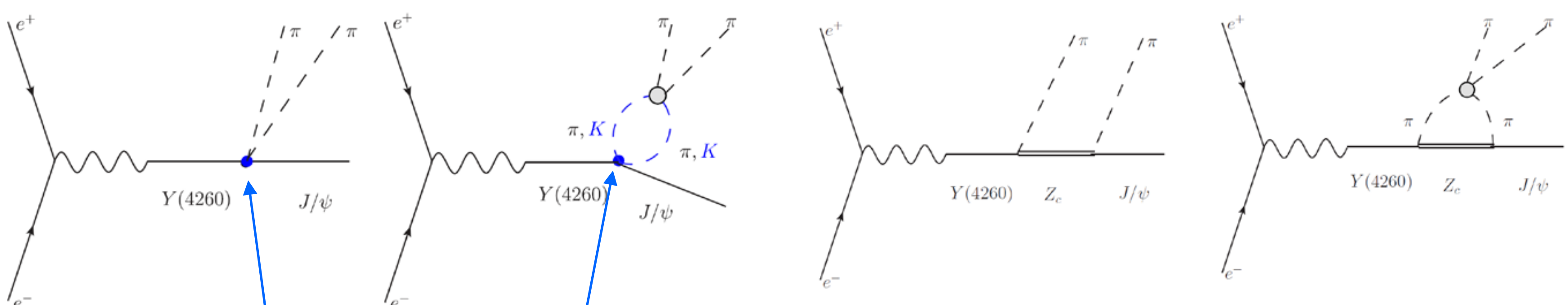
$$|u\bar{u} + d\bar{d}\rangle \propto \sqrt{2}|\text{singlet}\rangle + |\text{octet}\rangle$$

The $\pi\pi$ distribution of $\mathrm{Y}(4260) \to J/\psi\pi^+\pi^-$ contains information about the SU(3) content of the Y(4260)

BESIII, PRL119(2017)072001



- Mechanism:

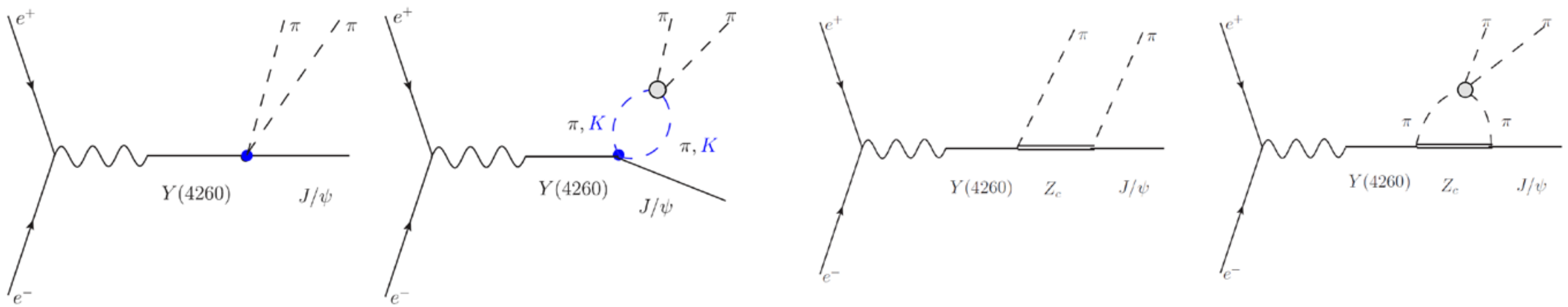


determined by SU(3) symmetry

Y(4260): a light quark perspective

Yun-Hua Chen, L.-Y. Dai et al., arXiv:181x.abcde

- Mechanism:

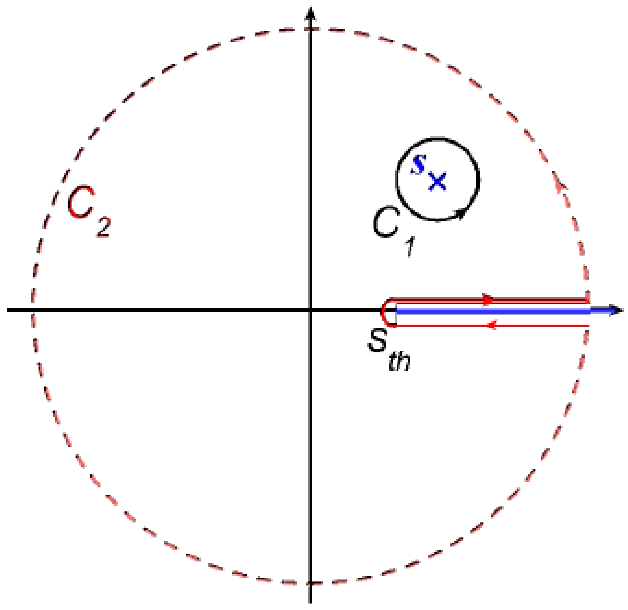


- Method:
  - $\pi\pi$ FSI from dispersion relation: unitarity + analyticity; model independent, consistent with well-known $\pi\pi$ scattering observables
  - t-channel $Z_c(3900)$ exchange included as left-hand cut
  - SU(3) content in the $Y\psi\pi\pi$, $Y\psi K\bar{K}$ vertices, can be described with a chiral effective Lagrangian

Dispersion relation in a nutshell

- Cauchy's theorem $\Rightarrow$ dispersion relation:

$$\begin{aligned} f(s) &= \frac{1}{2\pi i}\oint_{C_1} dz \frac{f(z)}{z-s} \\ &\to \frac{1}{2\pi i}\int_{s_{\text{th}}}^{\infty} dz \frac{\text{disc} f(z)}{z-s} \end{aligned}$$



discontinuity along the cut:

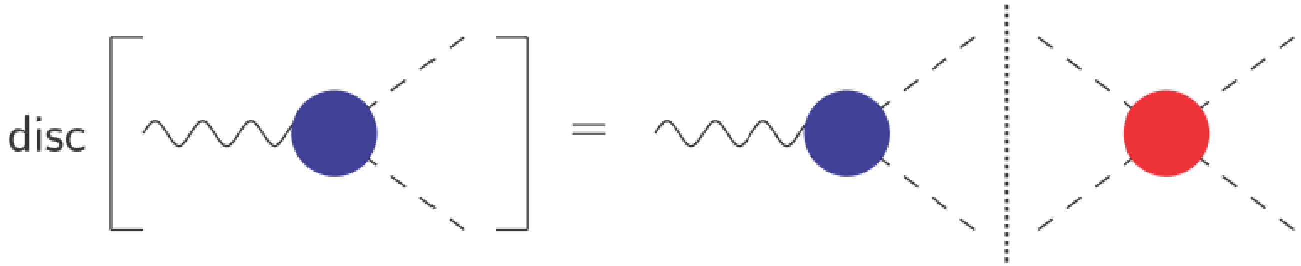
$$\begin{aligned} \text{disc} f(z) &= f(z+i\epsilon) - f(z-i\epsilon) \\ &= 2i\,\text{Im} f(z+i\epsilon) \end{aligned}$$

- one or more subtractions might be necessary:

$$f(s) - f(s_0) = \frac{s-s_0}{2\pi i}\int_{s_{\text{th}}}^{\infty} dz \frac{\text{disc} f(z)}{(z-s)(z-s_0)}$$

Dispersion relation in a nutshell

- Two-body final state interaction below inelastic threshold, unitarity $\Rightarrow$



$$\frac{1}{2i}\mathrm{disc}\, f_l(s) = \mathrm{Im}\, f_l(s) = f_l(s)\,\theta\,(s - s_{\mathrm{th}})\,\sin\delta_l(s)\exp[-i\delta_l(s)]$$

l: partial wave

☞ Watson's FSI theorem:

the phase of $f_l(s)$ is given by $\delta_l(s)$ (modulo $n\pi$) Watson (1953,1954)

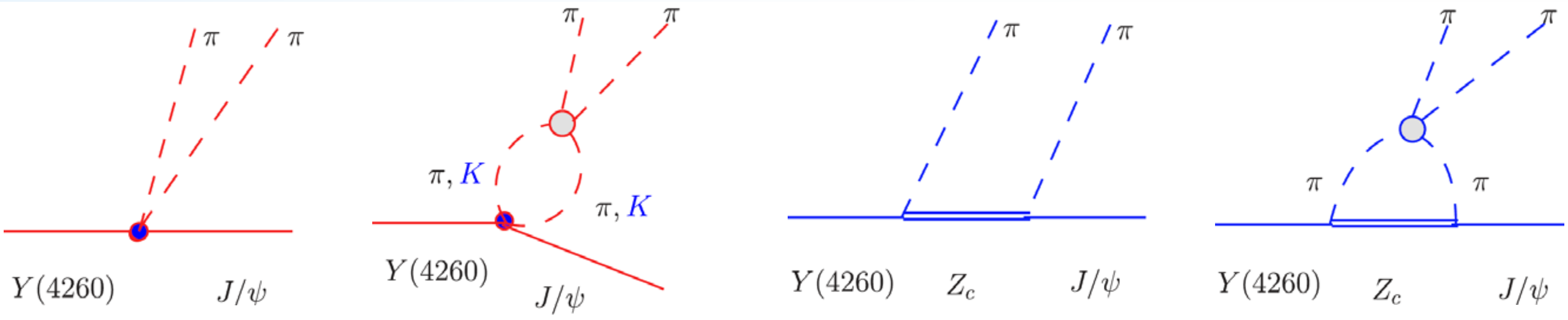
☞ $\mathrm{disc}\,[\log f_l(s)] = 2i\delta_l\,\theta\,(s - s_{\mathrm{th}})$ $\Rightarrow$ dispersion relation for $\log f_l(s)$ gives

- Omnès representation Omnès (1958)

$$f_l(s) = P_l(s)\Omega_l(s), \qquad \Omega_l(s) = \exp\left[\frac{s}{\pi}\int_{s_{\mathrm{th}}}^{\infty} dz\,\frac{\delta_l(z)}{z(z-s)}\right]$$

$P_l(s)$: polynomial

FSI including Z_c-exchange



- Single-channel case:

$$\frac{1}{2i}\text{disc}\, M_l(s) = \left[M_l(s) + \hat{M}_l(s)\right]\theta\left(s - s_{\text{th}}\right)\sin\delta_l^0(s)e^{-i\delta_l^0(s)}$$

Solution: Anisovich, Leutwyler, PLB375(1996)335

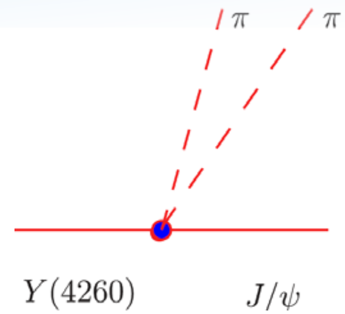
$$M_l(s) = \Omega_l(s)\left\{P_l^{n-1}(s) + \frac{s^n}{\pi}\int_{4M_\pi^2}^{\infty} dz \frac{\hat{M}_l(z)\sin\delta_l(z)}{|\Omega_l(z)|z^n(z-s)}\right\}$$

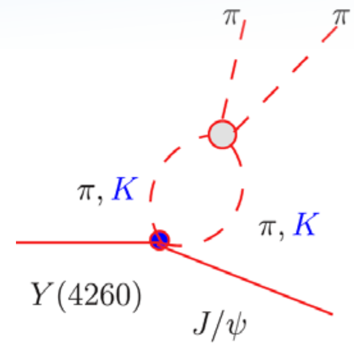
- Coupled-channel case: more complicated, but still solvable

inputs: $\pi\pi, K\bar{K}$ scattering phase shifts, inelasticity, precisely known from Roy(-Steiner) equation analyses

Both *S*-wave and *D*-wave, mesons $f_0(500), f_0(980), f_2(1270)$ automatically included; BW parameterization avoided

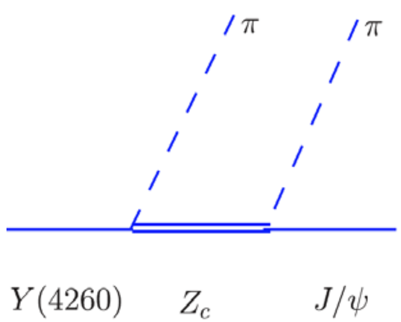
Parameters





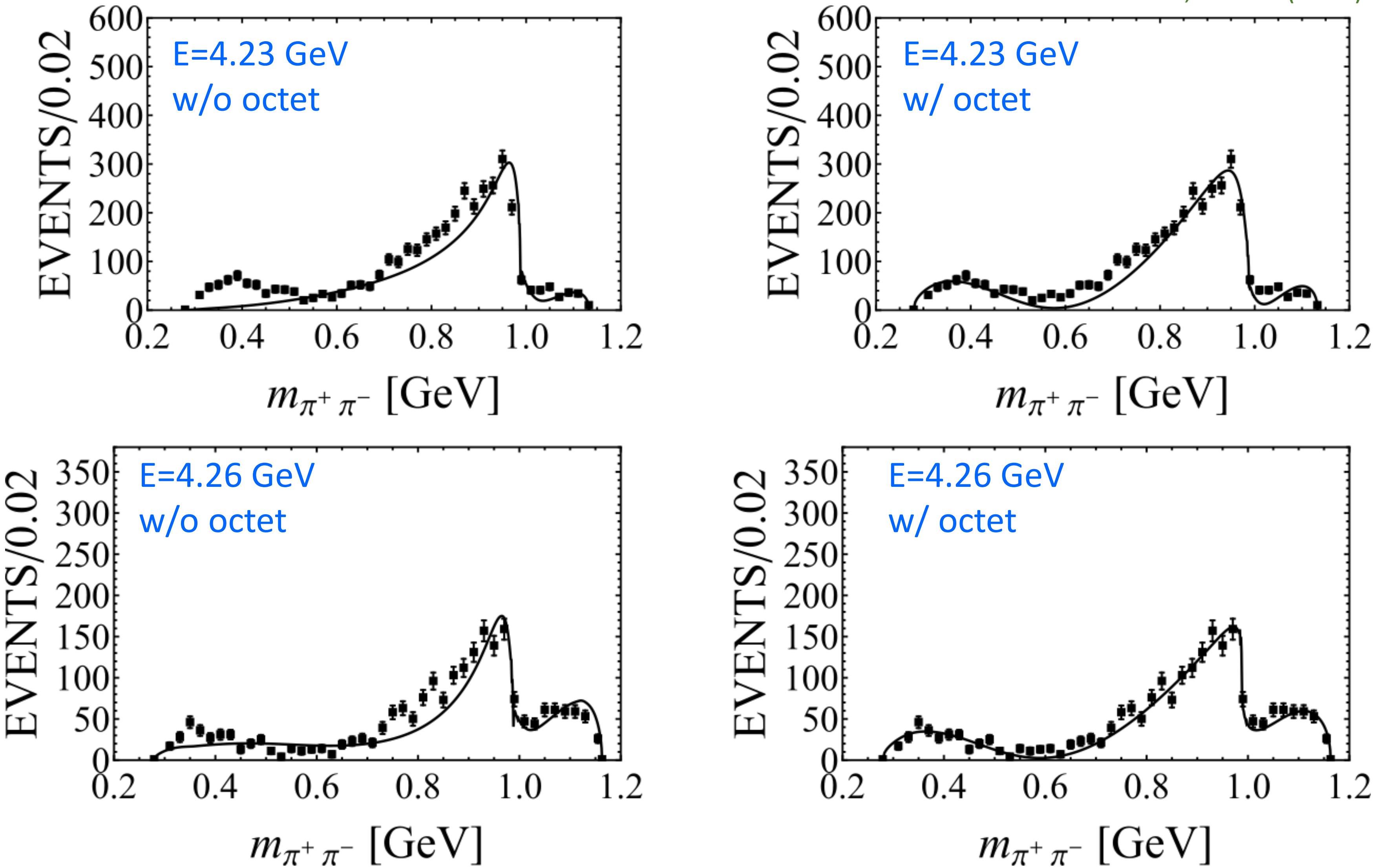
$$\mathscr{L}_{Y\psi\Phi\Phi} = \underbrace{g_1\langle V_1^\alpha J_\alpha^\dagger\rangle\langle u_\mu u^\mu\rangle + h_1\langle V_1^\alpha J_\alpha^\dagger\rangle\langle u_\mu u_\nu\rangle v^\mu v^\nu}_{\text{SU(3) singlet terms}} + \underbrace{g_8\langle J_\alpha^\dagger\rangle\langle V_8^\alpha u_\mu u^\mu\rangle + h_8\langle J_\alpha^\dagger\rangle\langle V_8^\alpha u_\mu u_\nu\rangle v^\mu v^\nu}_{\text{SU(3) octet terms}} + \text{h.c.}$$

- Matching the dispersion representation w/o FSI to the chiral contact terms give the subtraction polynomials, 4 parameters: h_1, g_1, h_8, g_8
- One more parameter: product of $YZ\pi$ and $\psi Z\pi$ couplings



Fit to BESIII data

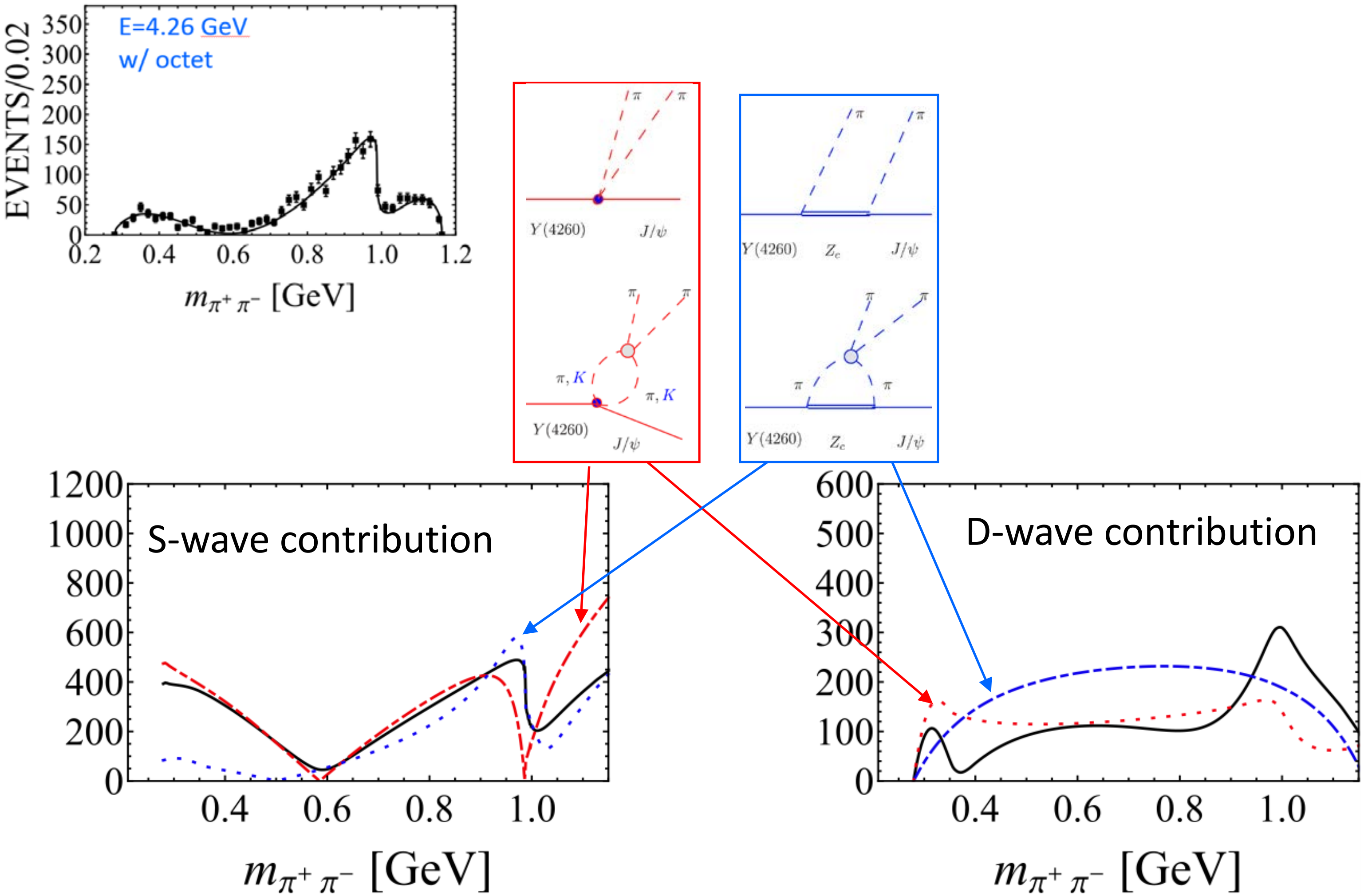
Data taken from: BESIII, PRL119(2017)072001



The octet contribution is necessary!

$g_8/g_1 \approx h_8/h_1 \sim -10$, a large component containing light quarks (from $D_1\bar{D}$?)

Fit to BESIII data



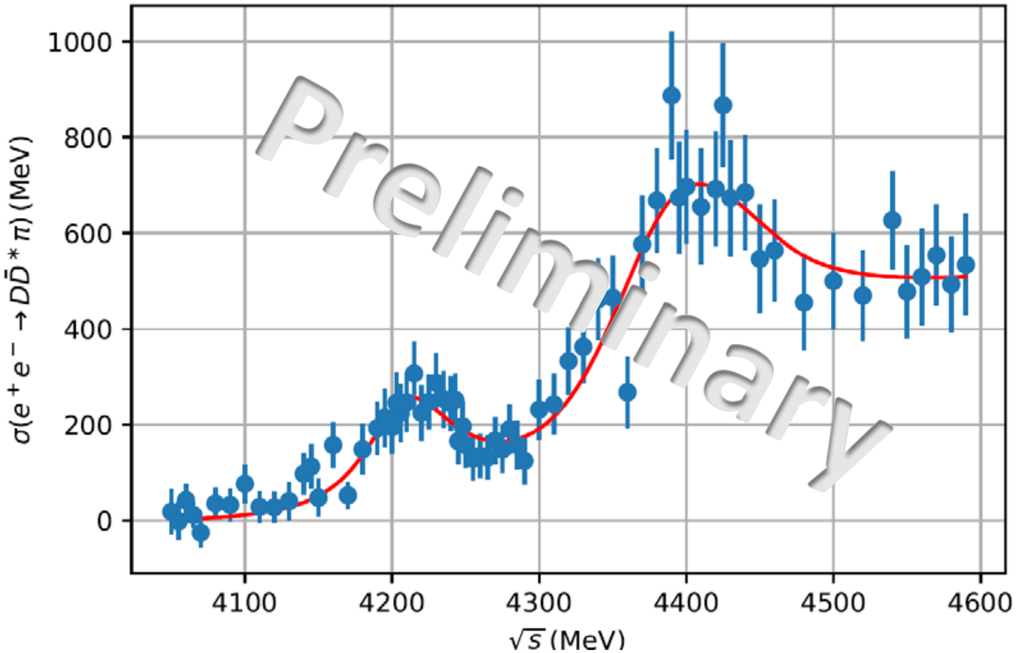
A large D-wave contribution, consistent with the analysis in the picture with a large $D_1\bar{D}$ component in M. Cleven et al., PRD90(2014)074039

Summary

- BESIII has observed structures related to Y(4260) in several channels; much more information about Y(4260)
- Hadro-charmonium model for Y(4260) unlikely; tetraquark model a la Maiani et al. leads to too many states; so far data are consistent with a strong coupling of Y(4260) to $D_1\bar{D}$+c.c.
- A new analysis of the $\pi\pi$ distribution of $\mathrm{Y}(4260) \to J/\psi\pi^+\pi^-$ shows about Y(4260) contains a large SU(3) octet component
- More complicated at around 4.4 GeV: Y(4360), ψ(4415); nearby thresholds: $D_{1,2}\bar{D}^*$, $D_{s0}^*\bar{D}_s^*$, $D_{s1}\bar{D}_s$, $\chi_{c0}\phi$
- Looking forward to improved line shape measurements in more channels

Thank you for your attention!

Y(4260)



K. Olschewsky, Master thesis, Bonn Uni.