ΦΨ PHIPSI 2022

13th International Workshop on e^+e^- collisions from Phi to Psi

$\eta_1(1855)$ as a $K\bar{K}_1(1400)$ molecule——Hadronic molecules from meson exchange

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In collaboration with

F.-K. Guo, Y.-H. Lin and B.-S. Zou

16 Aug. 2022, Fudan University, Shanghai

- $K\bar{K}_1(1400)$ and related
  - X.-K. Dong, Y.-H. Lin, B.-S. Zou, Sci.China Phys.Mech.Astron. 65 (2022) 6, 261011
- General threshold behaviors and hadronic molecule spectrum
  - X.-K. Dong, F.-K. Guo, B.-S. Zou, Phys.Rev.Lett. 126 (2021) 15, 152001
  - X.-K. Dong, F.-K. Guo, B.-S. Zou, Progr. Phys. 41 (2021) 65-93
  - X.-K. Dong, F.-K. Guo, B.-S. Zou, Commun.Theor.Phys. 73 (2021) 12, 125201

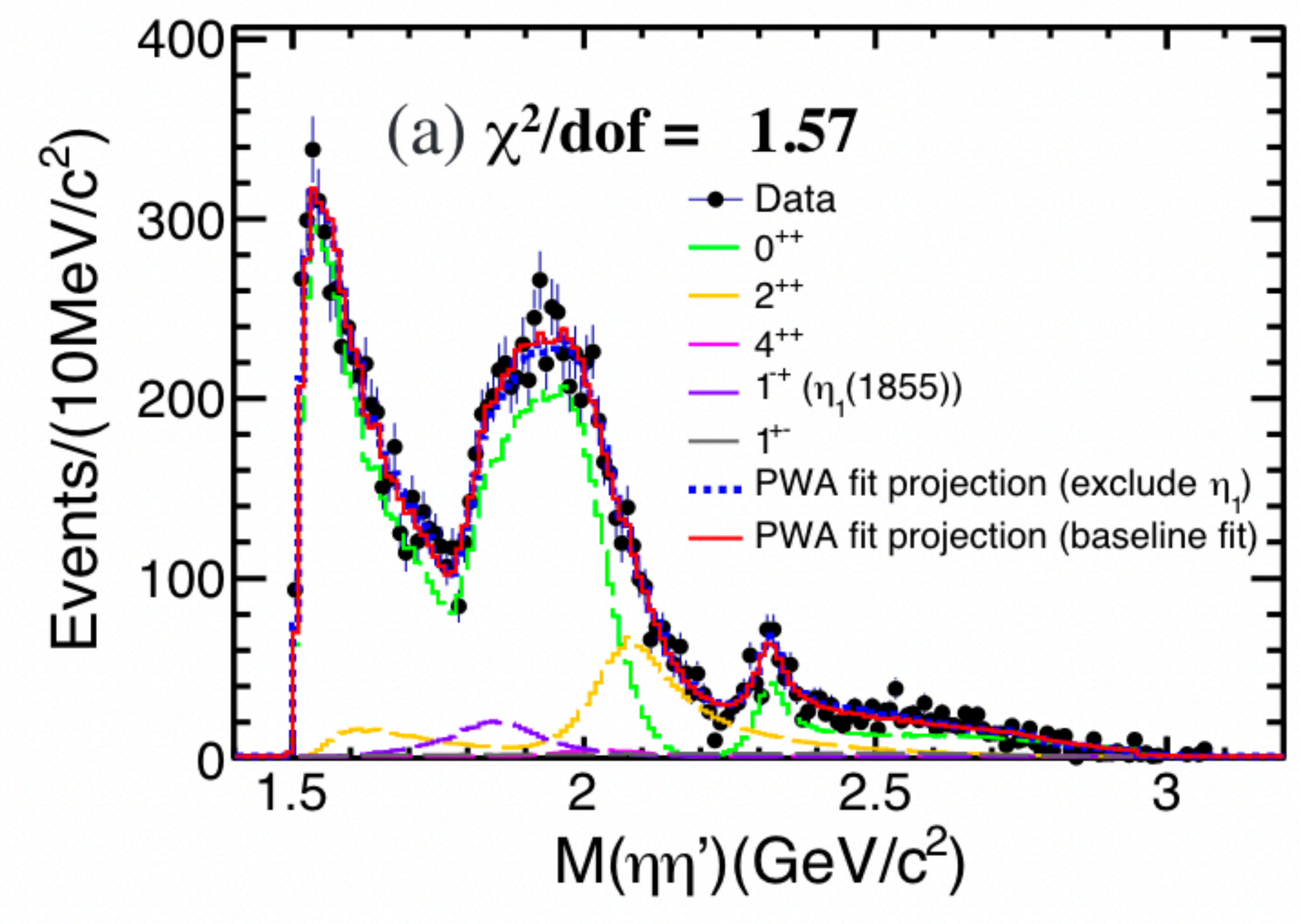
Contents

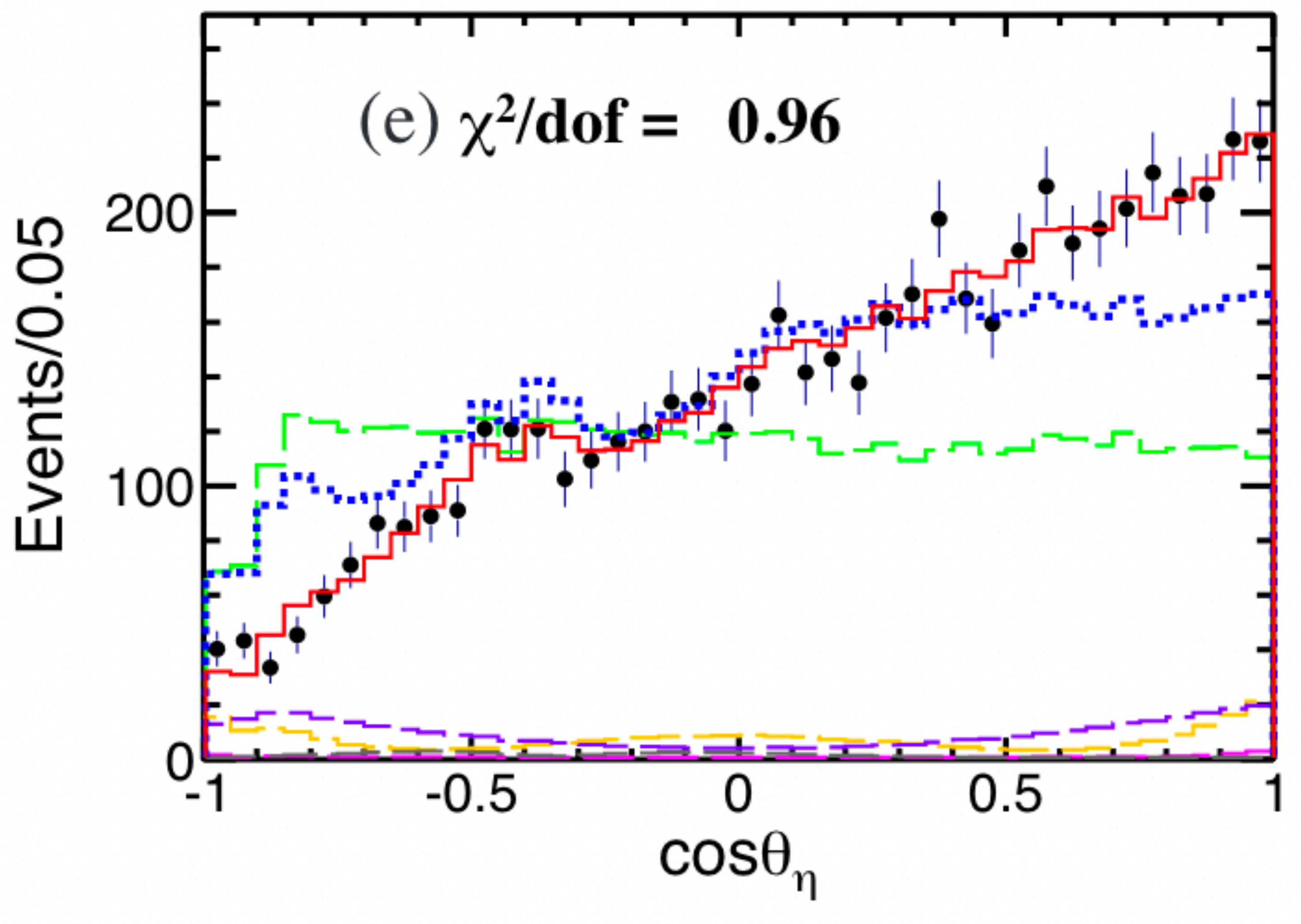
- $\eta_1(1855)$ and related (Hadronic molecules from meson exchange)
- Near threshold structures
- Spectrum of hadronic molecules
  - Charm-anticharm systems
  - Charm-charm systems

$\eta_1(1855)$ and related

- X.-K. Dong, Y.-H. Lin, B.-S. Zou, Sci.China Phys.Mech.Astron. 65 (2022) 6, 261011

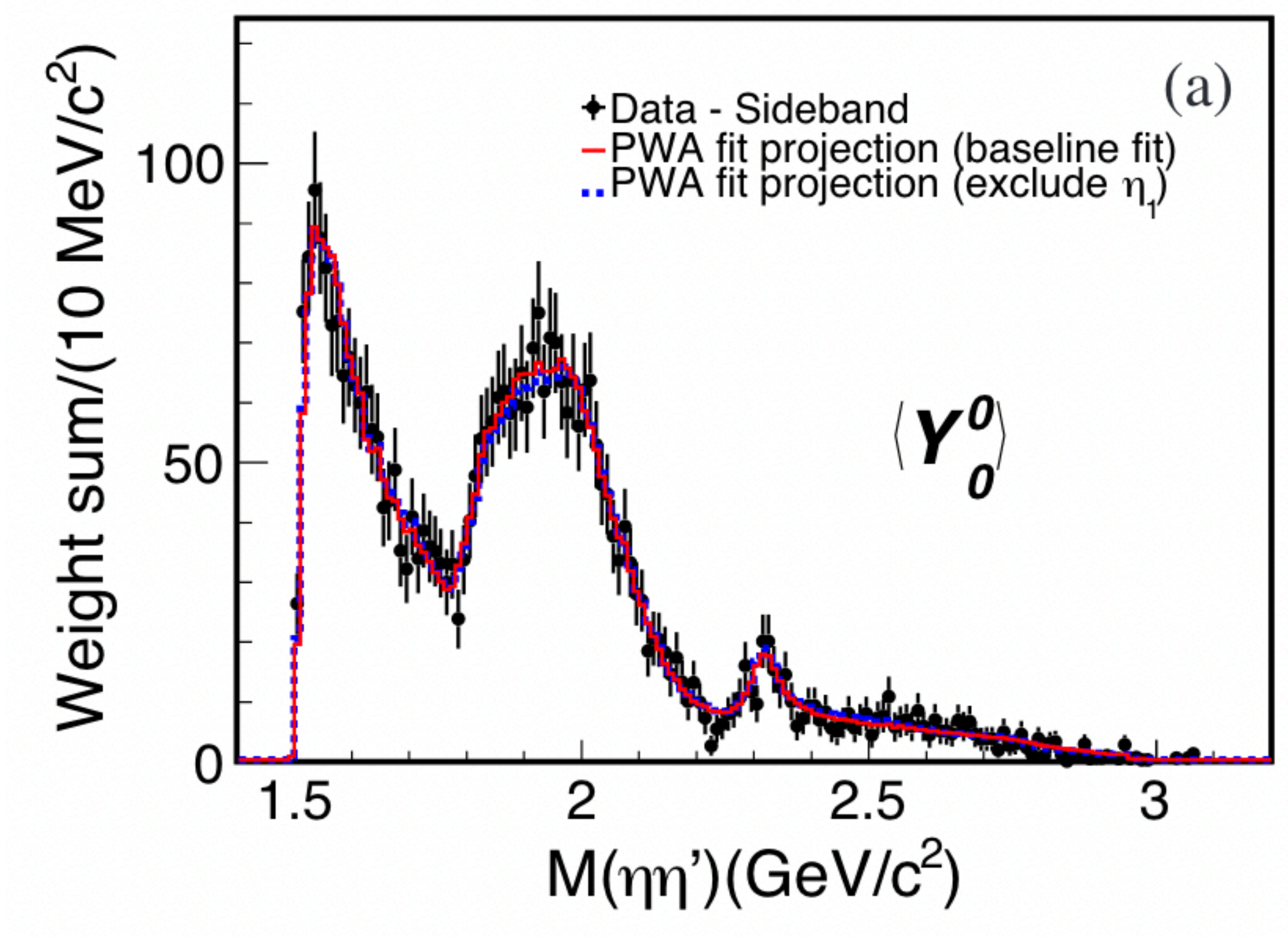
$\eta_1(1855)$

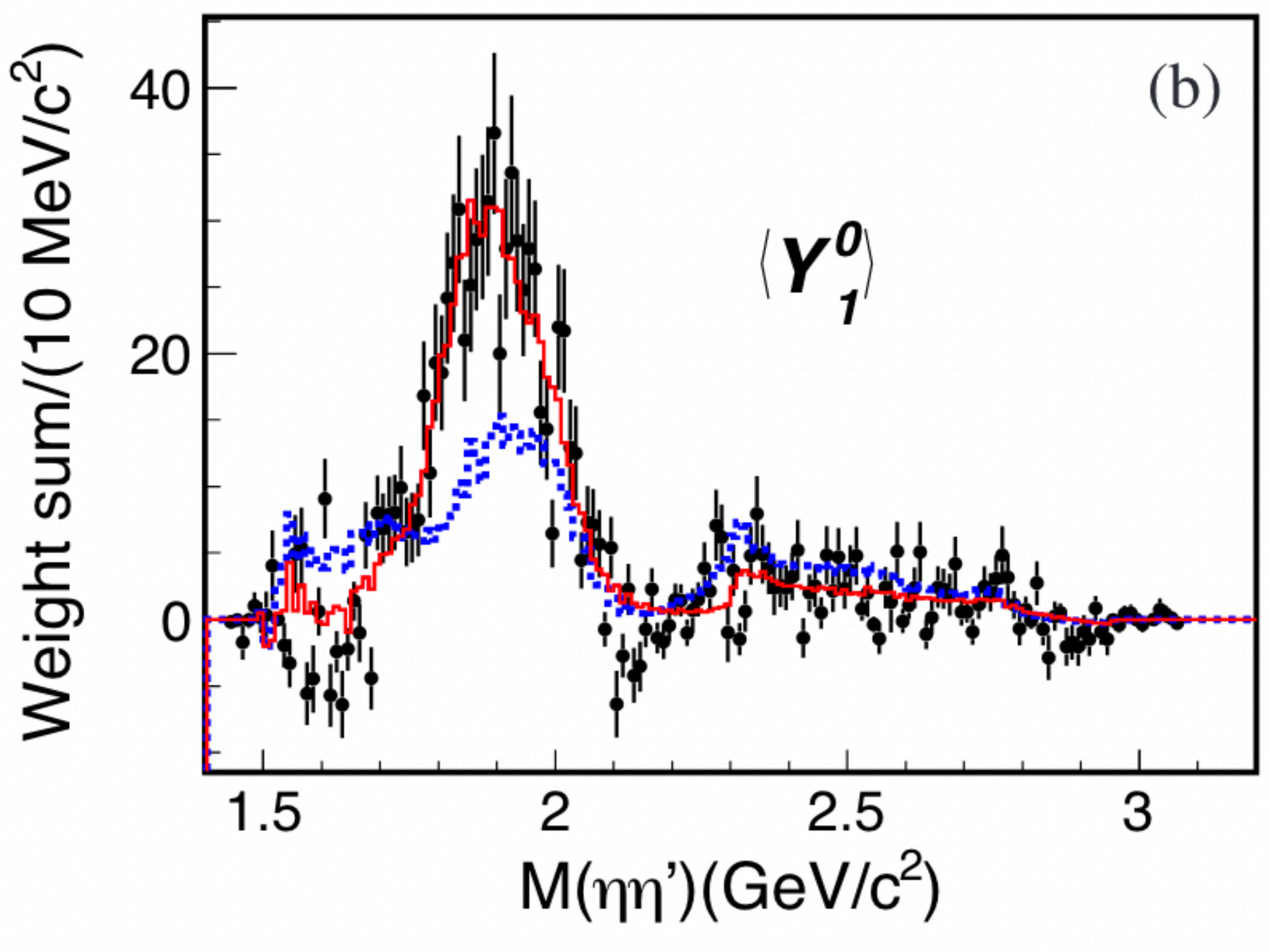




$J/\psi \to \gamma X \to \gamma \eta \eta'$

Resonance	M (MeV/c^2)	Γ (MeV)	B.F.($\times 10^{-5}$)	Sig.
$f_0(1500)$	1506	112	$1.81\pm0.11^{+0.19}_{-0.13}$	$\gg 30\sigma$
$f_0(1810)$	1795	95	$0.11\pm0.01^{+0.04}_{-0.03}$	11.1σ
$f_0(2020)$	$2010\pm6^{+6}_{-4}$	$203\pm9^{+13}_{-11}$	$2.28\pm0.12^{+0.29}_{-0.20}$	24.6σ
$f_0(2330)$	$2312\pm7^{+7}_{-3}$	$65\pm10^{+3}_{-12}$	$0.10\pm0.02^{+0.01}_{-0.02}$	13.2σ
$\eta_1(1855)$	$1855\pm9^{+6}_{-1}$	$188\pm18^{+3}_{-8}$	$0.27\pm0.04^{+0.02}_{-0.04}$	21.4σ
$f_2(1565)$	1542	122	$0.32\pm0.05^{+0.12}_{-0.02}$	8.7σ
$f_2(2010)$	$2062\pm6^{+10}_{-7}$	$165\pm17^{+10}_{-5}$	$0.71\pm0.06^{+0.10}_{-0.06}$	13.4σ
$f_4(2050)$	2018	237	$0.06\pm0.01^{+0.03}_{-0.01}$	4.6σ
0^{++} PHSP	-	-	$1.44\pm0.15^{+0.10}_{-0.20}$	15.7σ
$h_1(1415)$	1416	90	$0.08\pm0.01^{+0.01}_{-0.02}$	10.2σ
$h_1(1595)$	1584	384	$0.16\pm0.02^{+0.03}_{-0.01}$	9.9σ

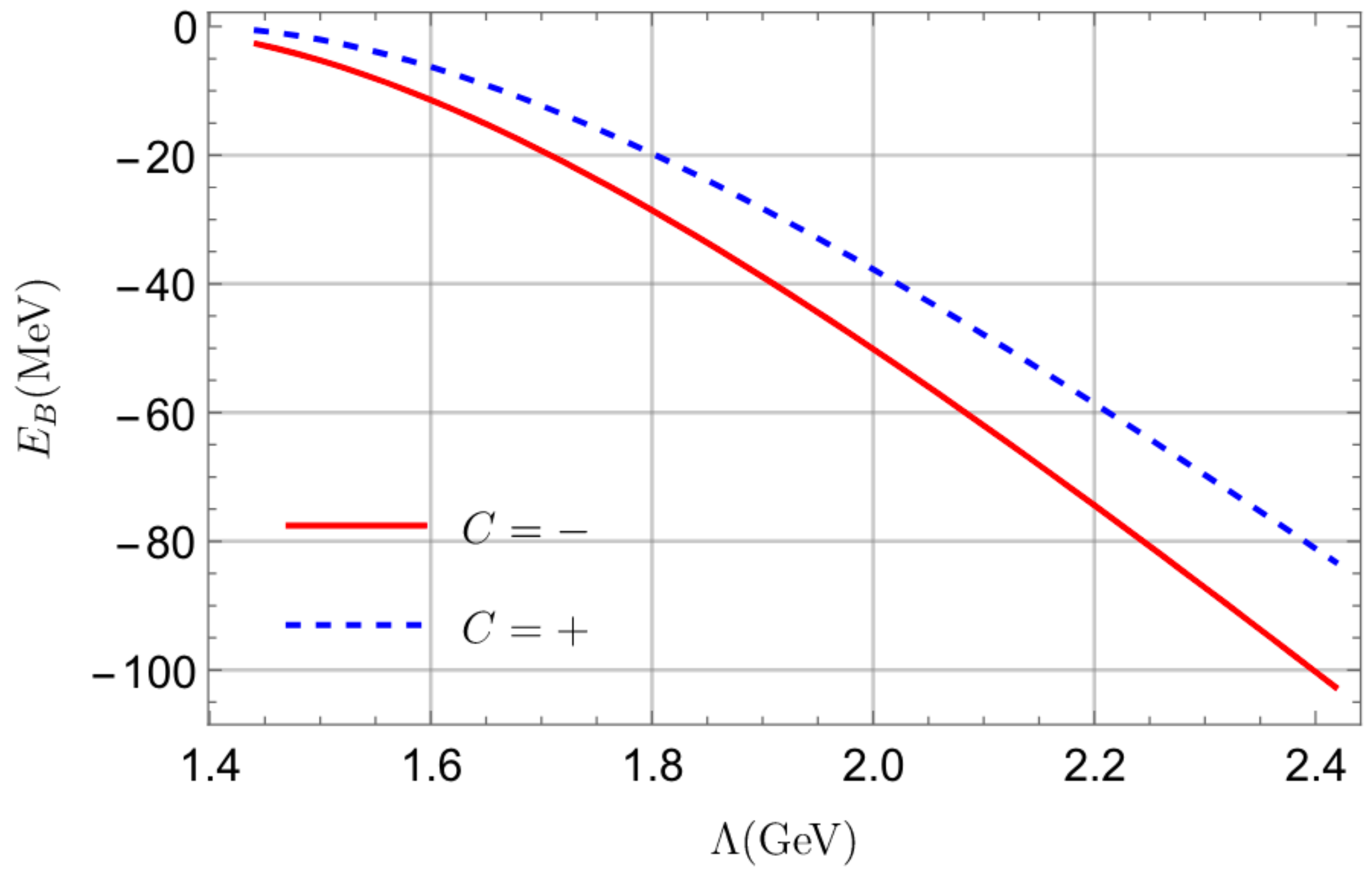




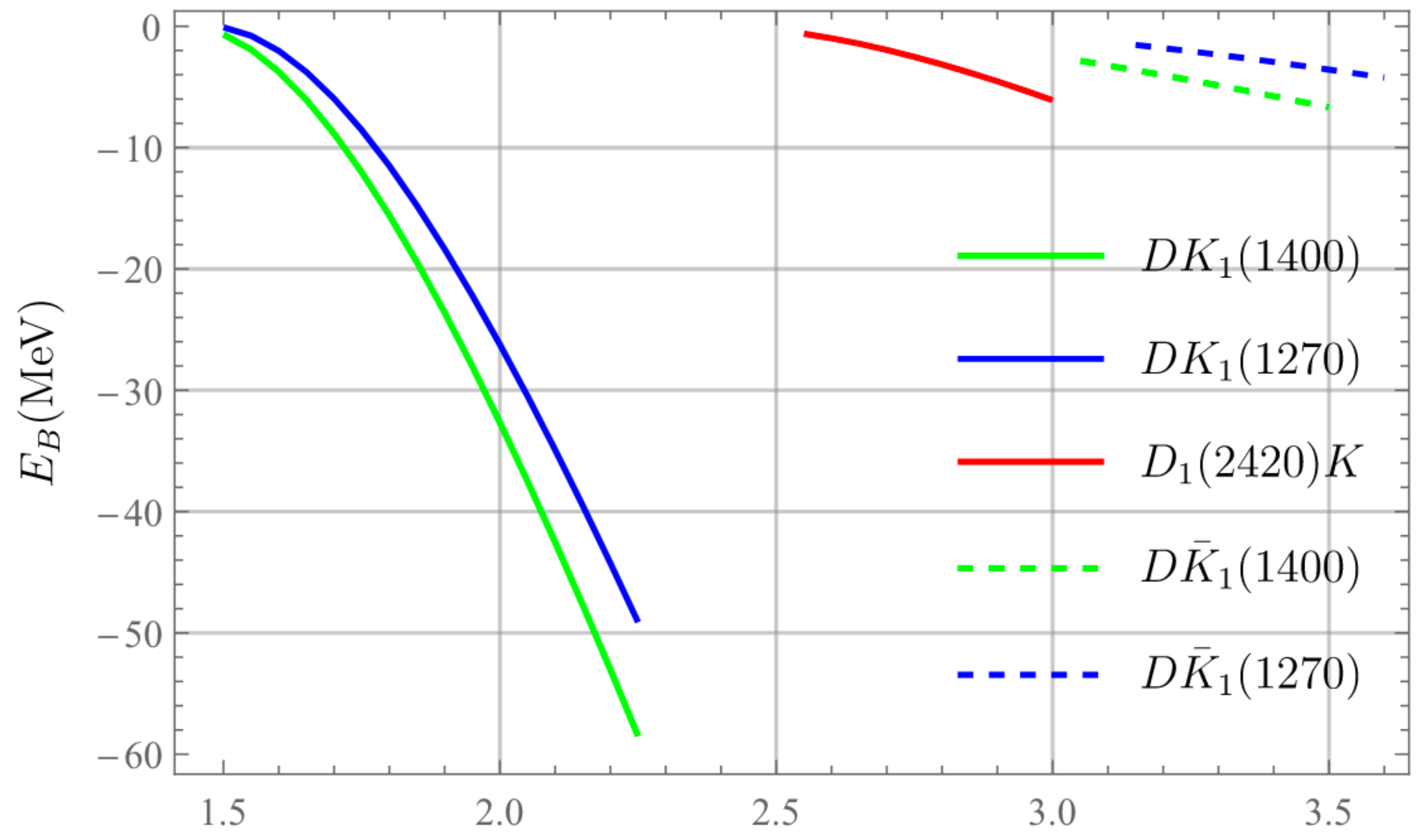
BESIII, arXiv: 2202.00021

$\eta_1(1855)$ - binding

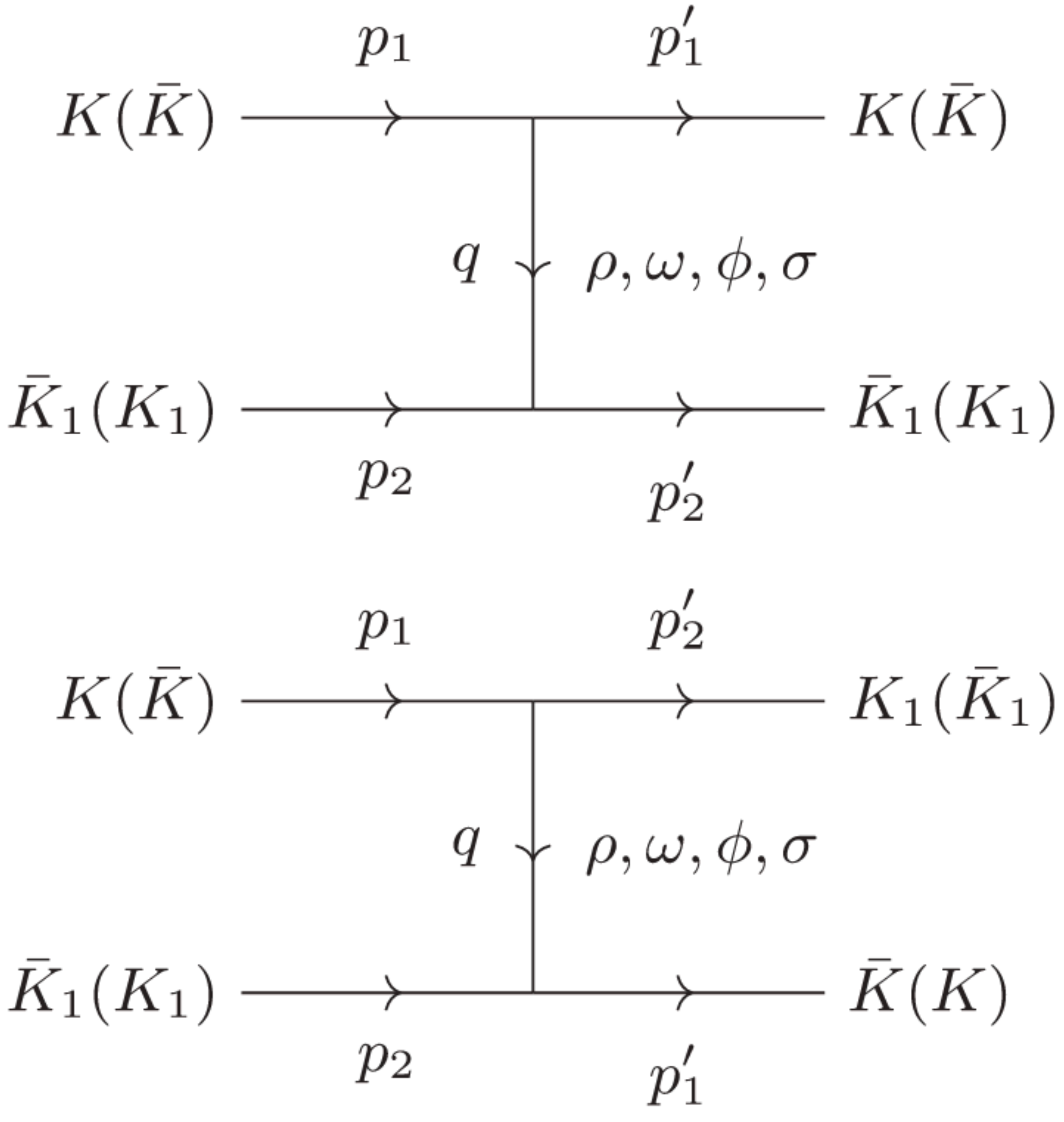
- Interactions between hadrons can be approximately described by meson exchange. (Resonance saturation), e.g.,
  - nuclear force from light meson exchange,
  - vector-meson dominance in the resonance saturation of the low-energy constants in CHPT. G. Ecker, J. Gasser, A. Pich, E. de Rafael, NPB321(1989)311
- $J^{PC} = 1^{-\pm}$ $D\bar{D}_1(2420)$ v.s. $Y(4260)$ and predicted exotic $\chi_{c1}(4240)$ X.-K. Dong, Y.-H. Lin, B.-S. Zou, Phys.Rev.D 101 (2020) 7, 076003
- Some $DK_1(1400)$ states predicted in X.-K. Dong, B.-S. Zou, Eur.Phys.J.A 57 (2021) 4, 139
- Samiliar binding mechanism applied to $K\bar{K}_1(1400)$.



$J^{PC} = 1^{-\pm}$ $D\bar{D}_1(2420)$



$\eta_1(1855)$ - binding



Meson exchange

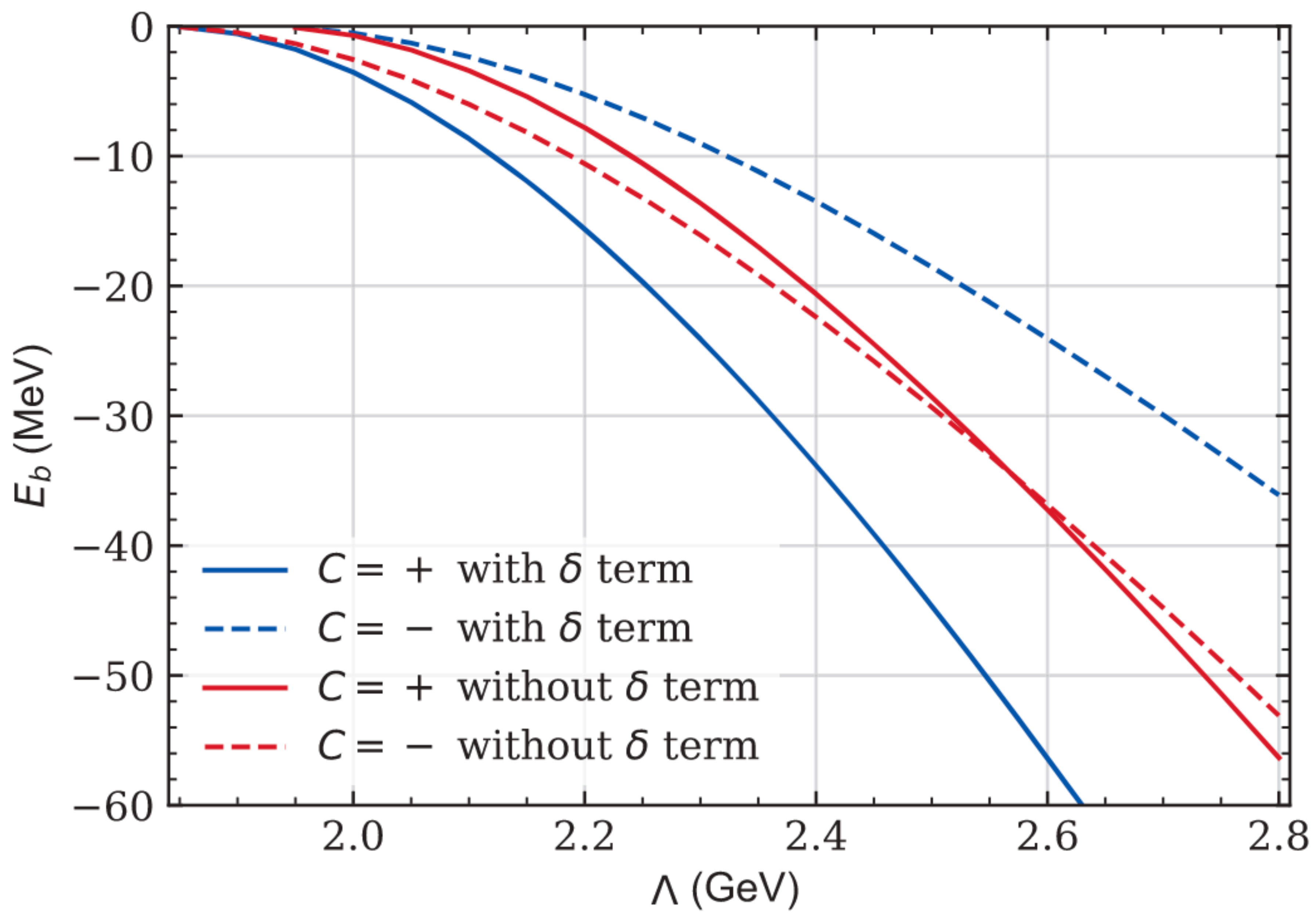
- Mixing of two K_1

$$\begin{pmatrix} |K_1(1270)\rangle \\ |K_1(1400)\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta & -\mathrm{i}\sin\theta \\ -\mathrm{i}\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} |K_{1A}\rangle \\ |K_{1B}\rangle \end{pmatrix},$$

- Form factor for the off-shell effects,

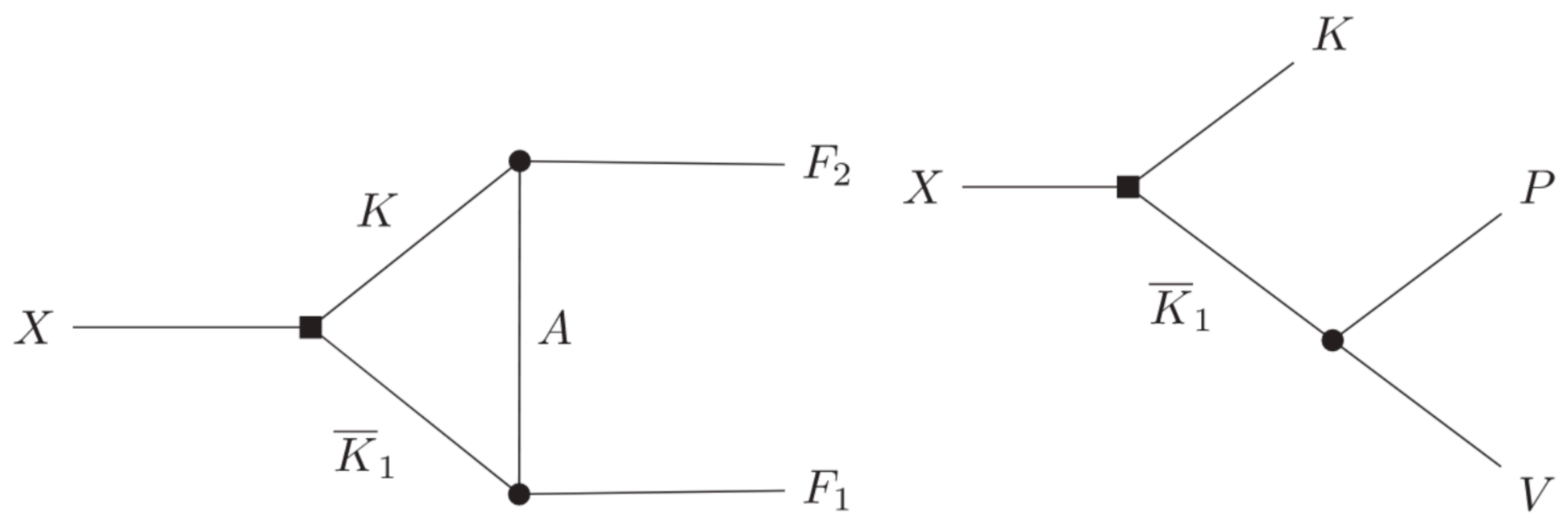
$$F(q, m, \Lambda) = \frac{\Lambda^2 - m^2}{\Lambda^2 - q^2}.$$

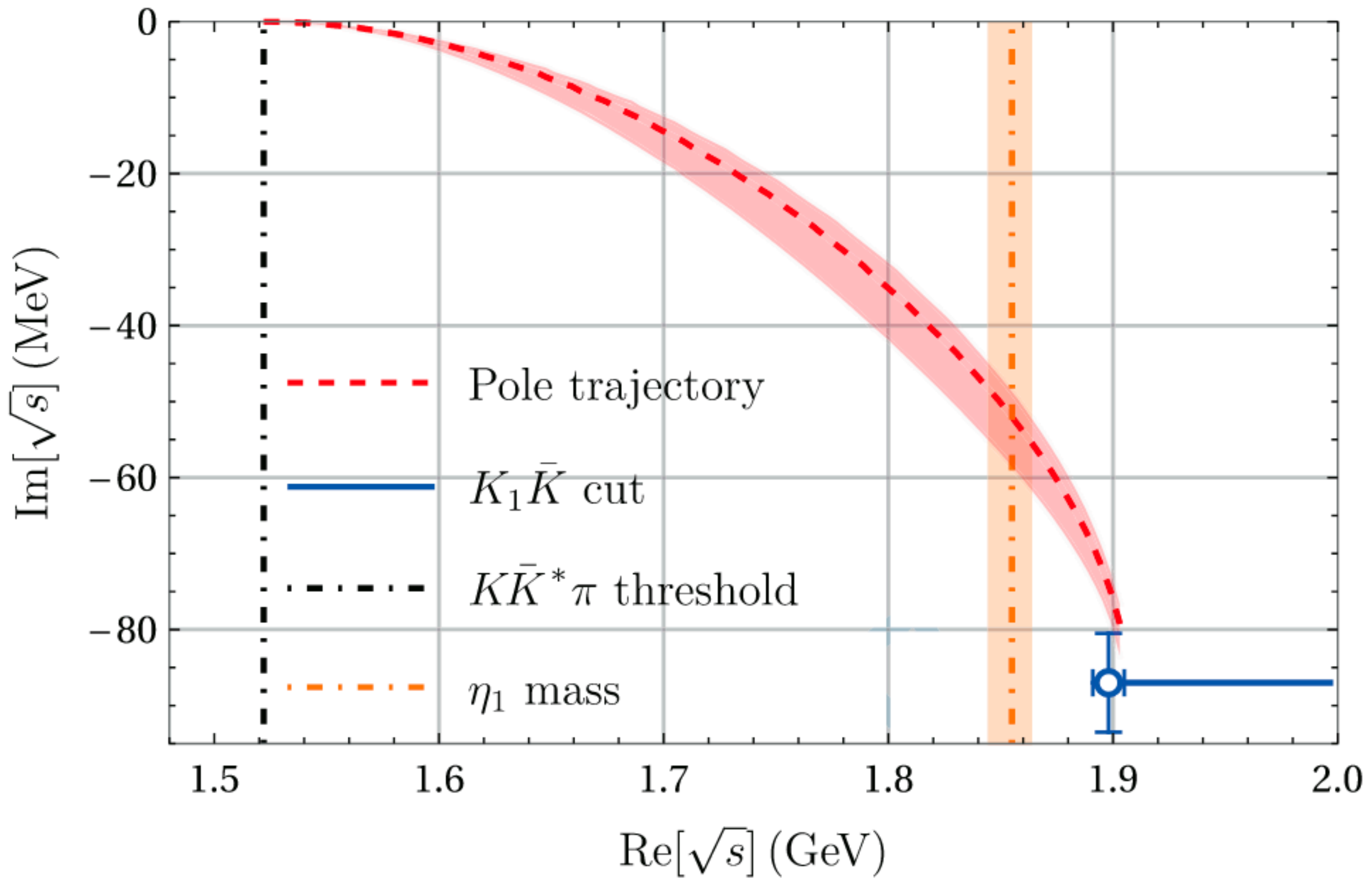
- Fourier transformation of $\dfrac{q^2}{q^2 + m^2}$ leads to δ potential, short-range. We keep or drop such terms to see the effects.



- Coupled-channel effects not included, which may change the binding energy.
- Qualitatively agree with Mao-Jun Yan's results where coupled channels included, details see his report in the poster session.

$\eta_1(1855)$ - width

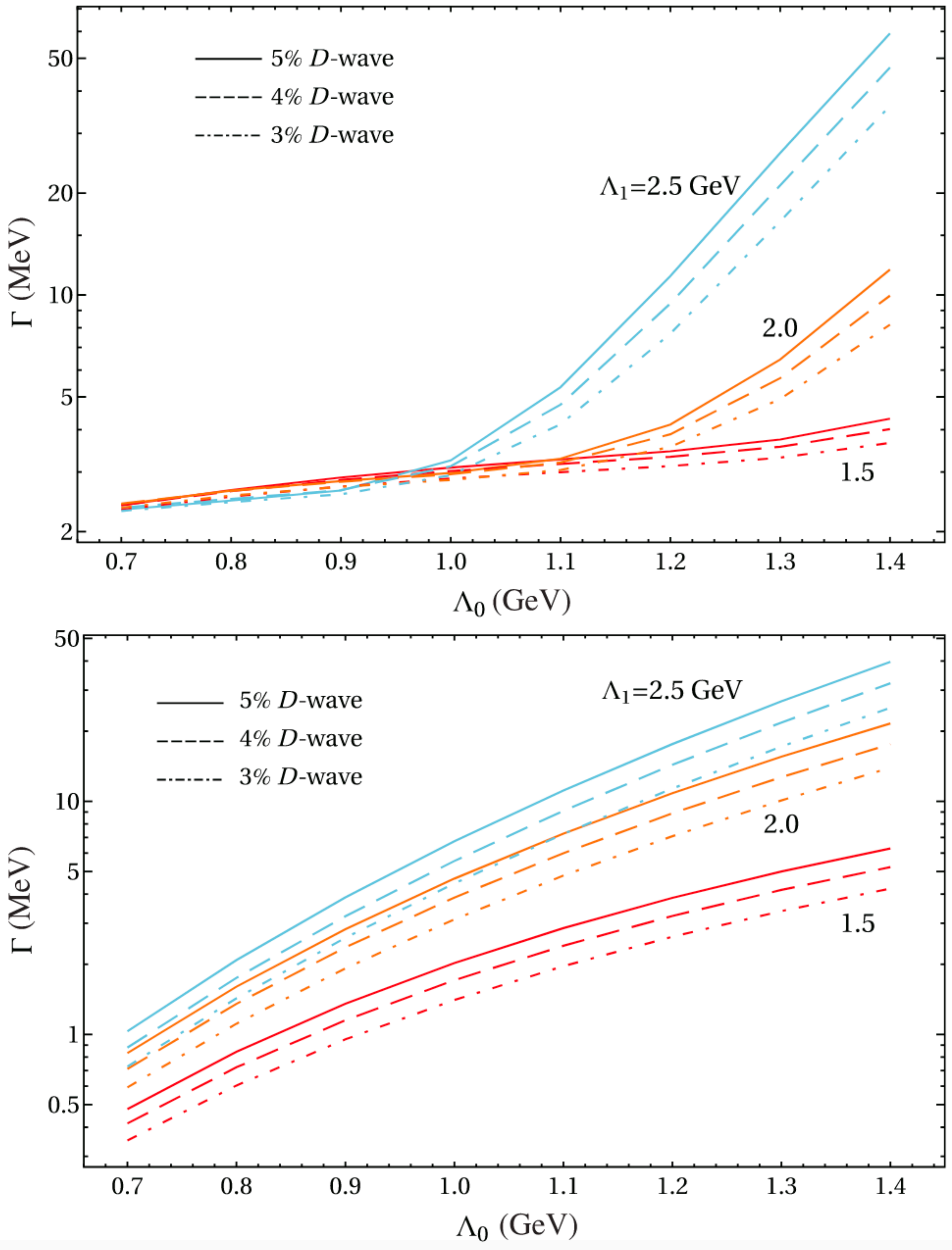




- Coupling between hadronic molecule and its components, $\mathscr{L}_{XKK_1} = yX^\mu K^\dagger K^\dagger_{1\mu} +$ h.c.
- y can be estimated by Weinberg compositeness criterion for loosely bound states with stable components, not applicable here ($\Gamma_{K_1(1400)} = 174$ MeV) .
- Consider the self energy of $K_1(1400)$, assumed dominated by $K^*\pi$ loop (BR($K_1(1400) \to K^*\pi$) $= 94 \pm 6\,\%$)

- Pole from $1 - VG = 0$.
- V assumed constant.
- $$G(s) = \int \frac{d^4 l}{(2\pi)^4} \frac{1}{l^2 - m_K^2 + i\epsilon} \frac{1}{(P-l)^2 - m_{K_1}^2 + i m_{K_1}\Gamma_{K_1}(s)}.$$
- $$\Gamma_{K_1}(s) = g_{K_1}^2 \frac{|\mathbf{q}|}{16\pi m_{K_1}^2}\left(3 + \frac{\mathbf{q}^2}{m_{K^*}^2}\right)$$

$\eta_1(1855)$ - width



Partial width of $\eta_1(1855) \to K^*\bar{K}^*, \eta\eta'$.
$K_1 \to K^*\pi$ has D-wave components

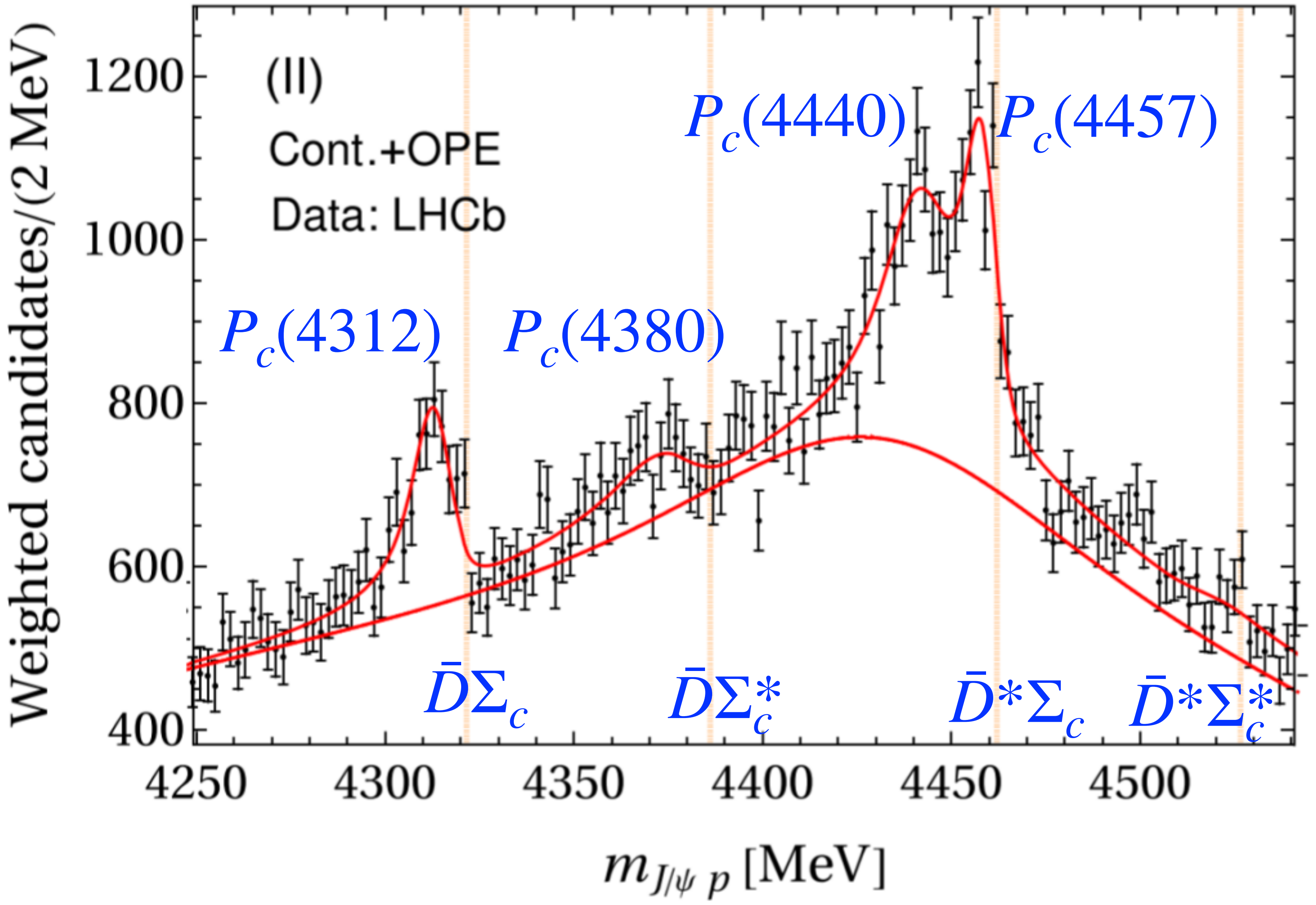
Table 1 Partial widths of the isoscalar $K\bar{K}_1(1400)$ molecular states with quantum numbers 1^{--} and 1^{-+} with $\Lambda_0 = 1.3$ GeV and $\Lambda_1 = 2.5$ GeV. All the decay widths are in unit of MeV. Here, we assume 5% D-wave contribution in the $K_1K^*\pi$ and $K_1K^*\eta$ vertex

Mode	Widths (MeV)	
	1^{--} $E_B = 20$ MeV	1^{-+} $E_B = 40$ MeV
$K^*\bar{K}^*$	38.1	26.3
$K\bar{K}$	0.5	0
$K\bar{K}^*$	1.0	0.9
$a_1\pi$	0	9.2
$f_1\eta$	0	0.2
$\eta\eta'$	0	26.9
$\sigma\omega$	0.2	0
$\rho\rho$	0	0.04
$\pi\rho$	6.4	0
$\eta\omega$	0.4	0
$\omega\omega$	0	0.01
$\omega\phi$	0	0.4
$K\bar{K}^*\pi$	130.0	105.0
2-body	46.5	64.0
Total	176.5	169.0

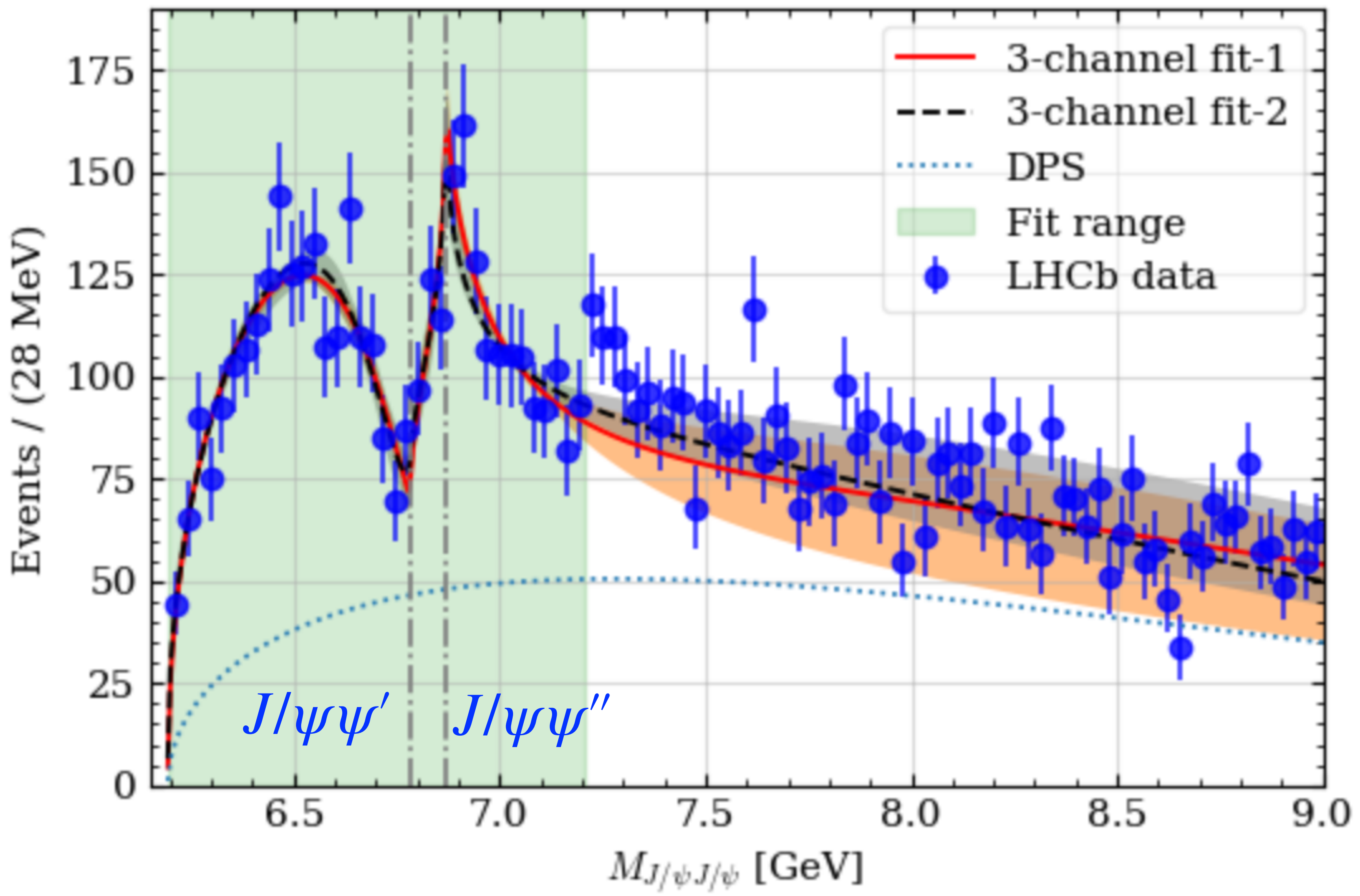
Near threshold structures

- General threshold behaviors
  - X.-K. Dong, F.-K. Guo, B.-S. Zou, Phys.Rev.Lett. 126 (2021) 15, 152001

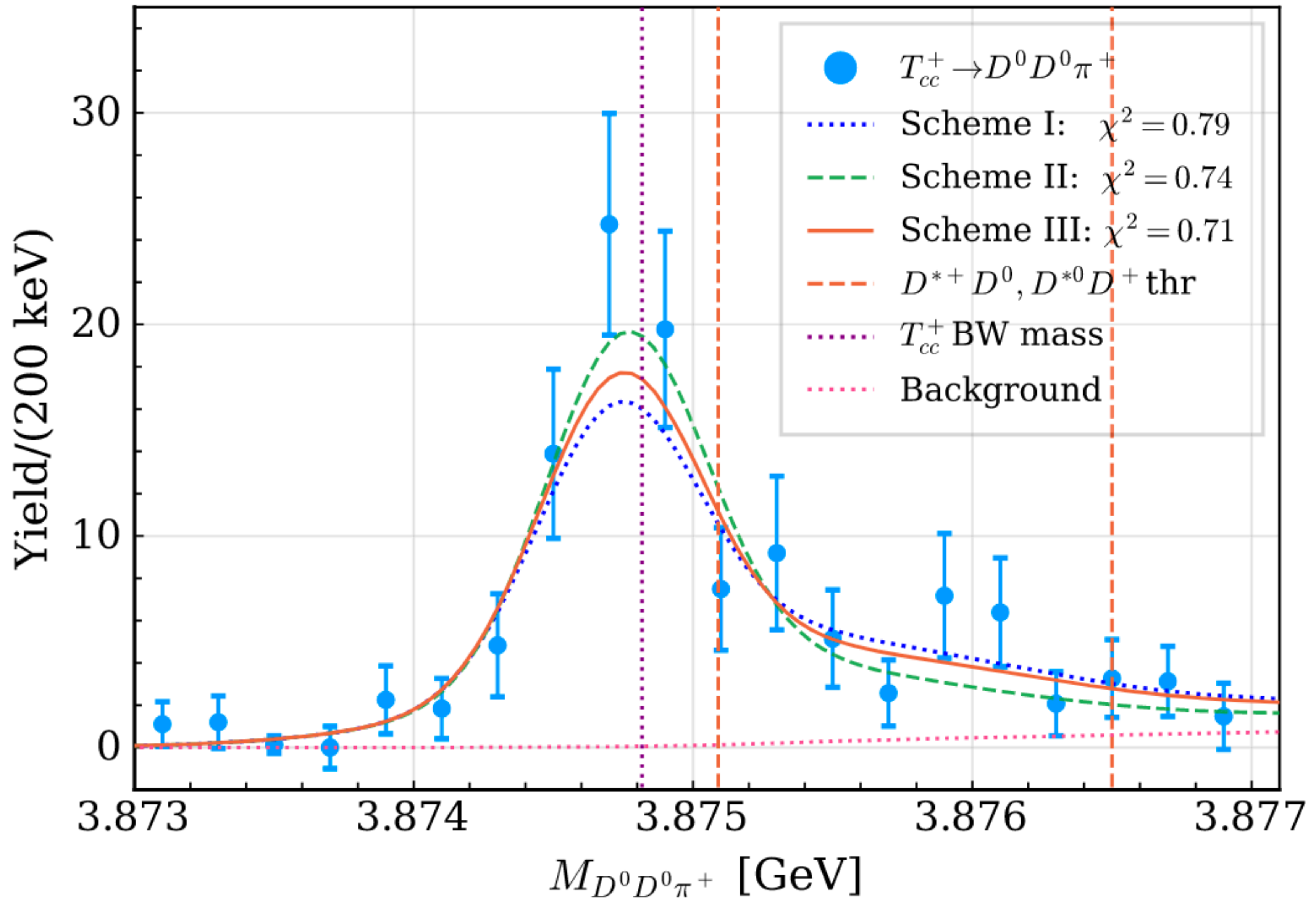
Near threshold structures



data from LHCb,
PRL122,222001(2019)
fit from M.-L. Du et al.,
PRL124,072001(2020)



data from LHCb,
Sci.Bull.65,1983(2020)
fit from X.-K. Dong et al.,
*PRL*126,132001(2021)



data from LHCb,
NaturePhys. 18 (2022) 7, 751-754
fit from M.-L. Du et al.,
PRD105,014024(2022)

$X(3872)$, $Y(4260)$, $Z_c's$, $Z_b's$, Z_{cs}, ⋯

Many new structures are near thresholds of a pair of hadron hadrons.

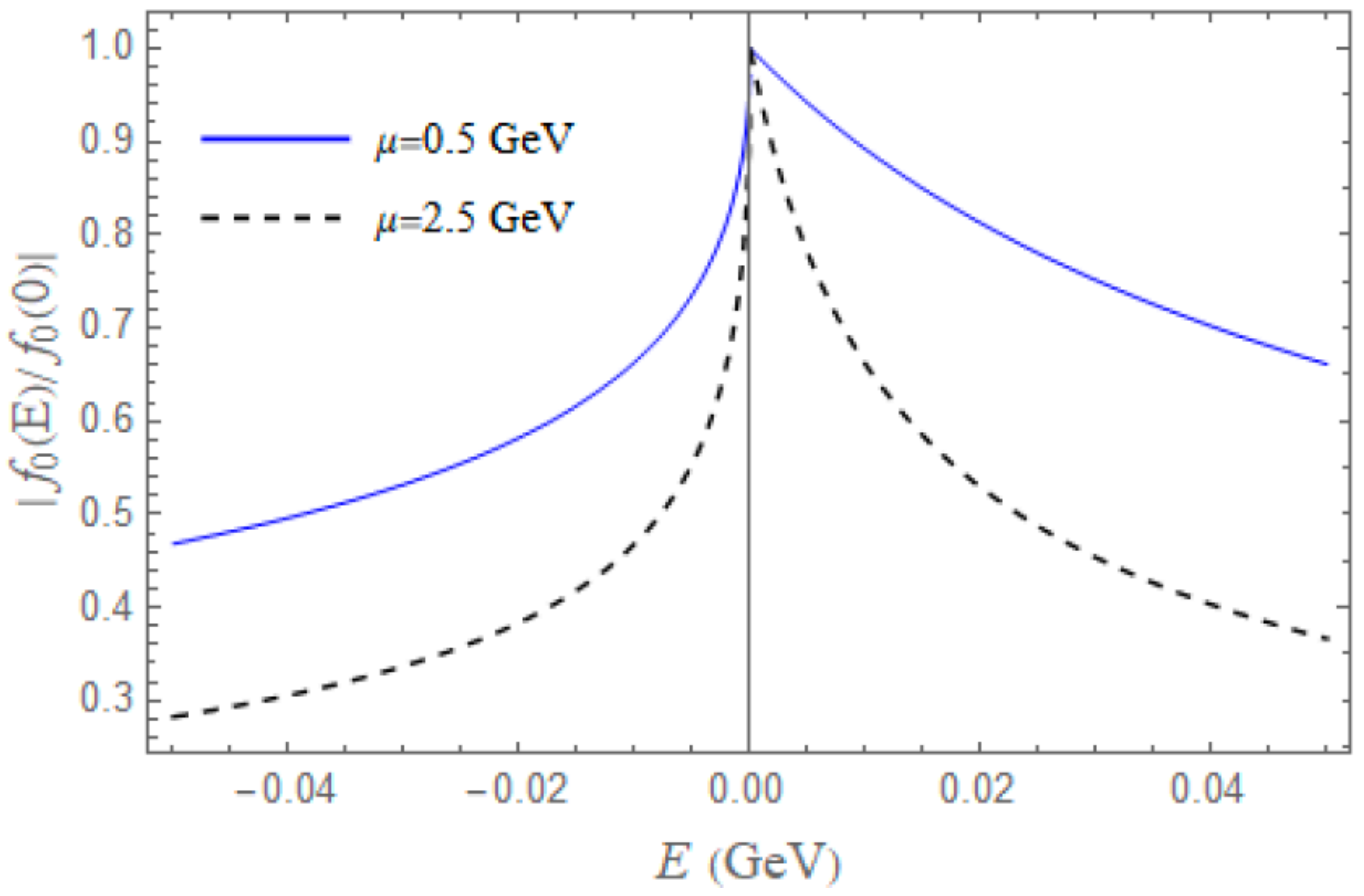
Why? What is the pattern?

Threshold cusp

- There is always a cusp at the threshold due to the Unitarity of S-matrix for S-wave scattering amplitude.
- Single channel, S-wave, ERE

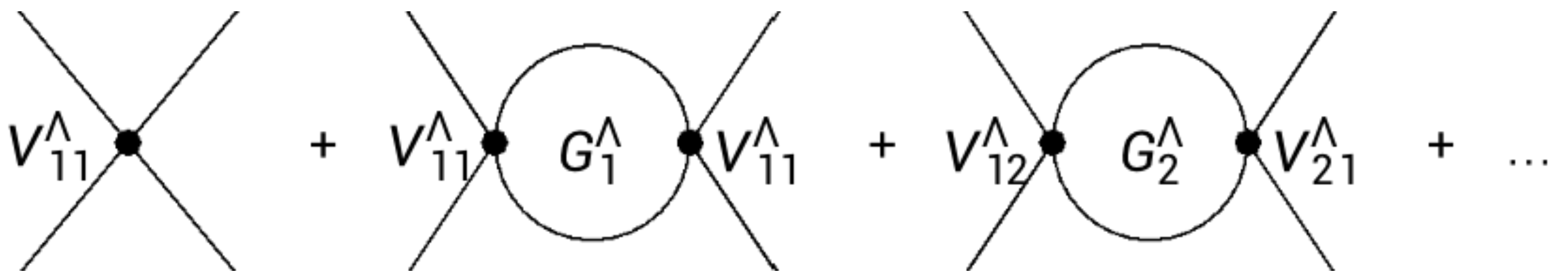
$$f_0^{-1}(k) = \frac{1}{a_0} + \frac{1}{2} r_0 k^2 - ik + \mathcal{O}\left(k^4/\beta^4\right) .$$

- Close to threshold, scattering length approximation
    - Cusp at threshold.
    - Maximal at threshold for positive a_0 (attractive but no bound state).
    - Half-maximum width $2/(\mu a_0^2)$; Virtual state pole at $E = -1/(2\mu a_0^2)$.
    - Increasing attraction, $a_0 > 0$, bound state, peak below threshold.



Coupled channels

- Consider a two-channel system, construct a nonrelativistic effective field theory (NREFT).
    - Energy region around the higher threshold Σ_2,
    - Expansion in powers of $E = \sqrt{s} - \Sigma_2$,
    - Λ-dependence absorbed by V.



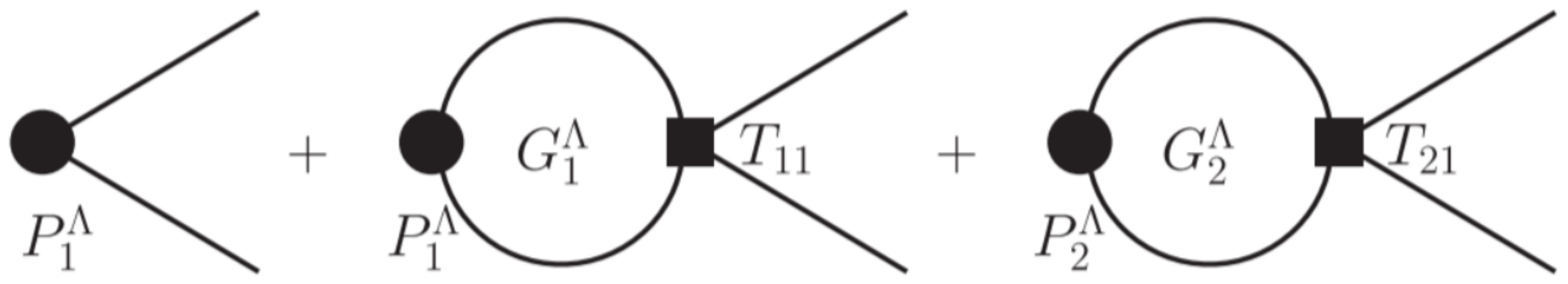
$$T = V + VGV + VGVGV = (1 - VG)^{-1}V$$

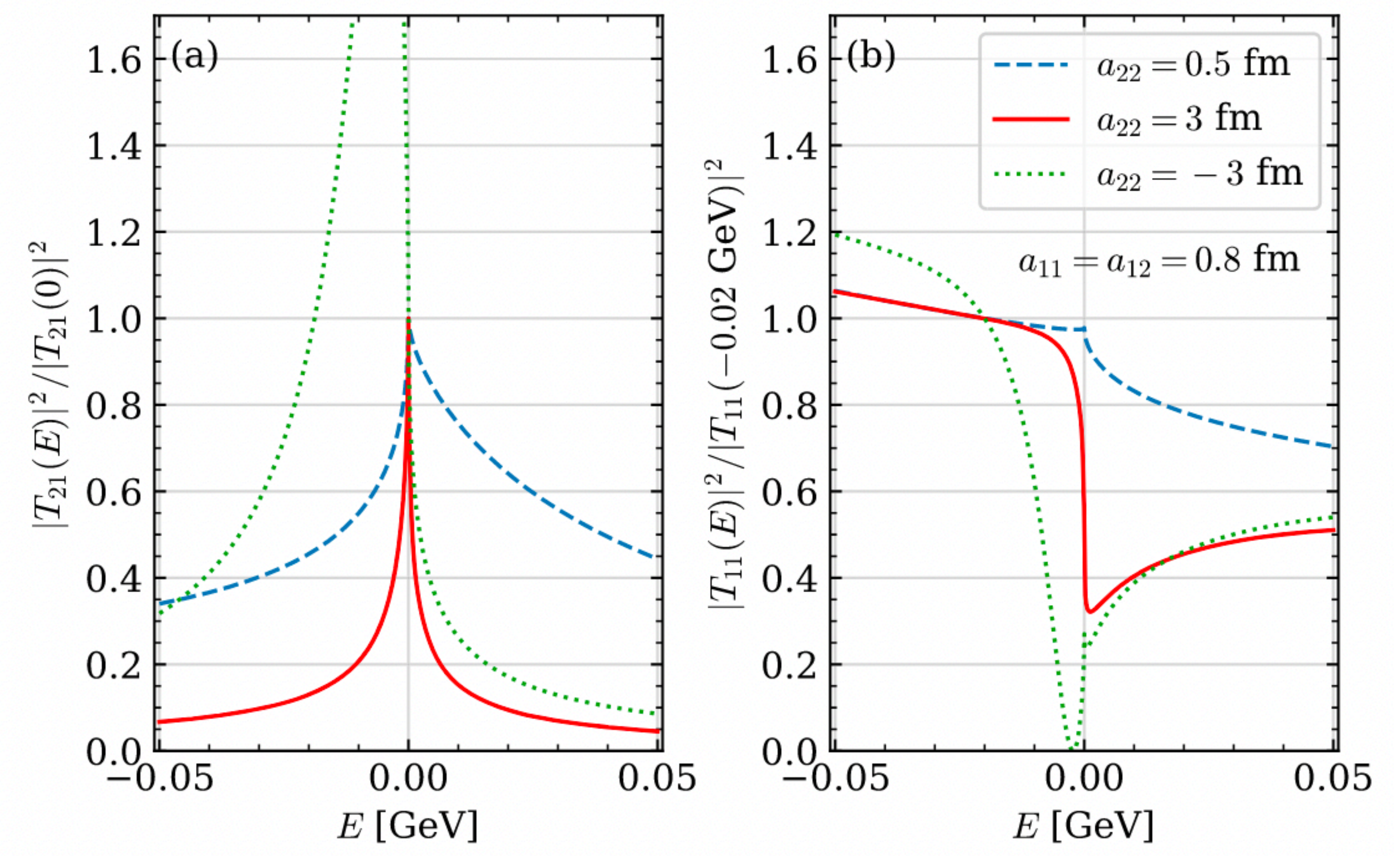
$$G_1^{\Lambda}(E) = R(\Lambda_1) - i\frac{k_1}{8\pi\sqrt{s}},$$

Nonanalyticity only from here

$$G_2^{\Lambda}(E) = \frac{1}{8\pi\Sigma_2}\left[-\frac{2\Lambda_2}{\pi} + \sqrt{-2\mu_2 E - i\epsilon} + \mathcal{O}\left(\frac{k_2^2}{\Lambda_2}\right)\right]$$

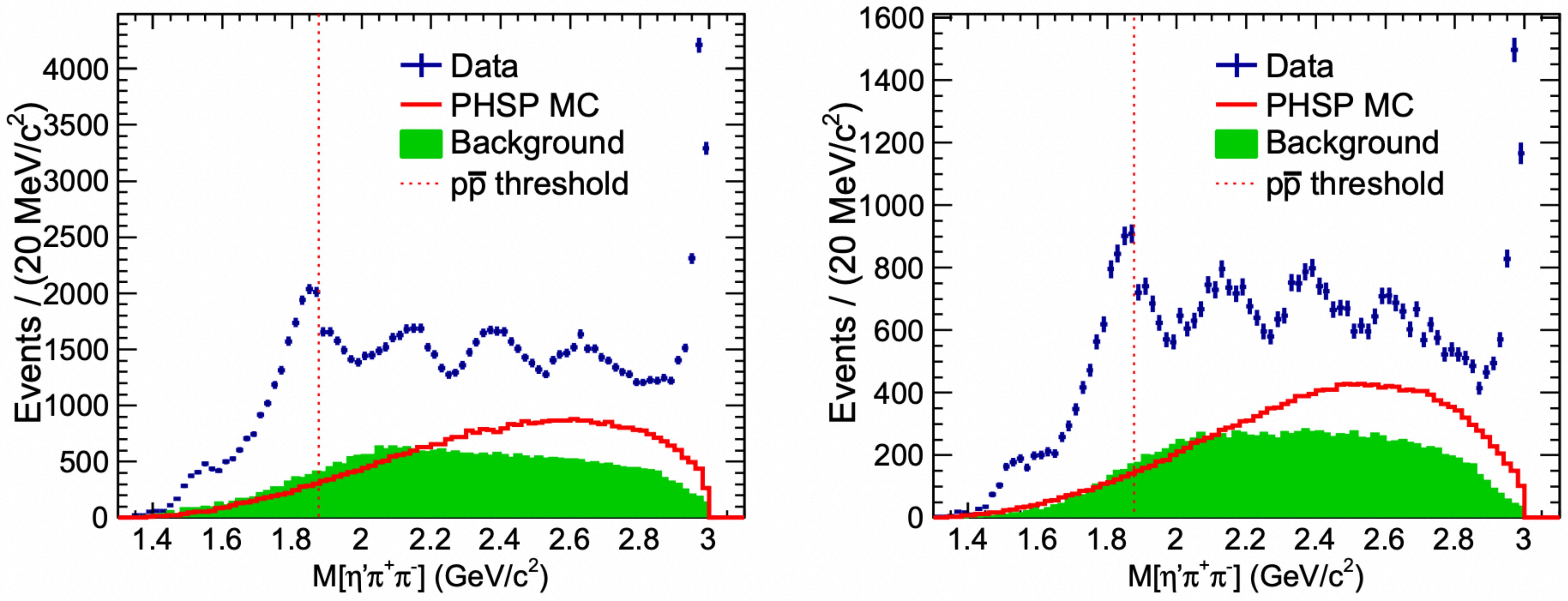
- Consider a production process, must go through final-state interaction (unitarity)





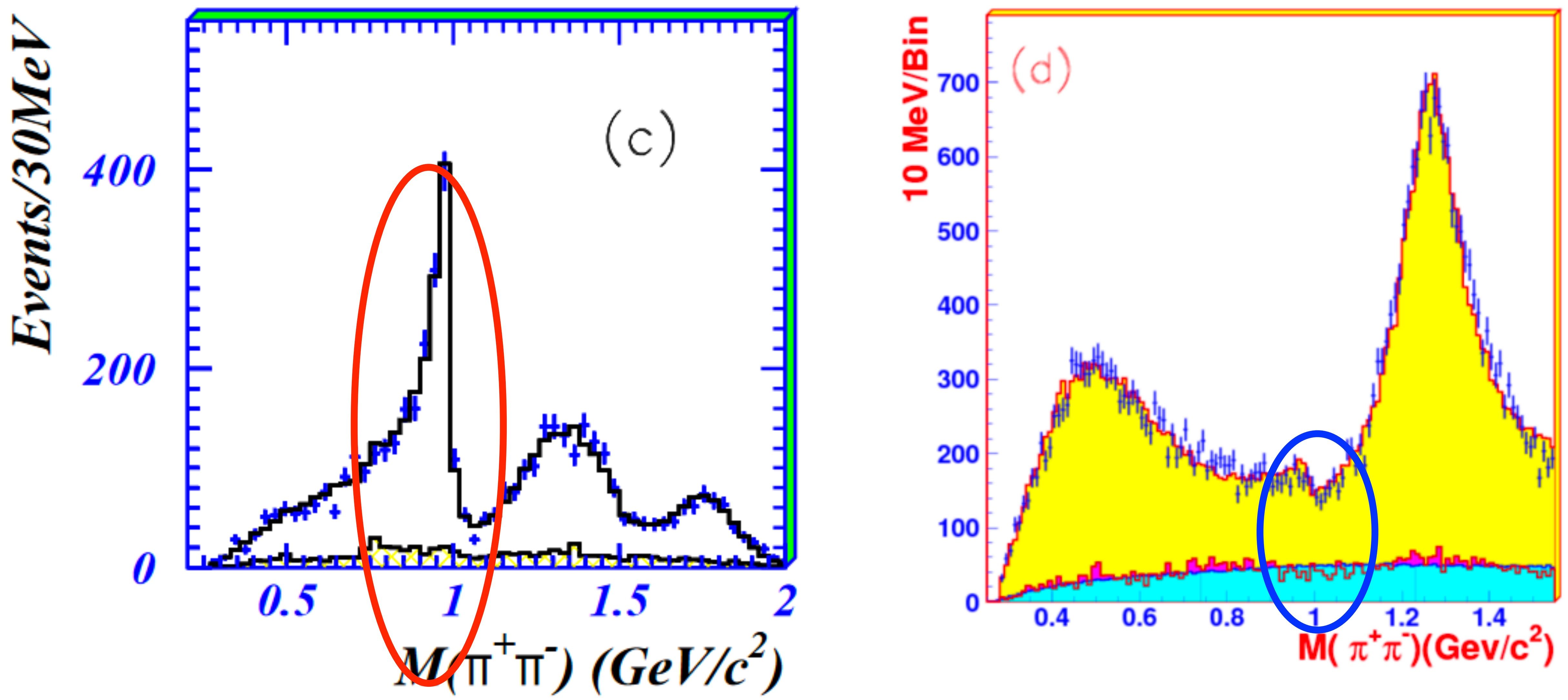
Phenomenology

- $p\bar{p}$ threshold in $J/\psi \to \gamma\eta'\pi^+\pi^-$
  - Clear abrupt drop.



BESIII PRL117(2016)042002

- $f_0(980)$ in
  - $J/\psi \to \phi\pi^+\pi^-$ (left)
  - Driving channel: $K\bar{K}$.
  - $J/\psi \to \omega\pi^+\pi^-$ (right)
  - Driving channel: $\pi\pi$.

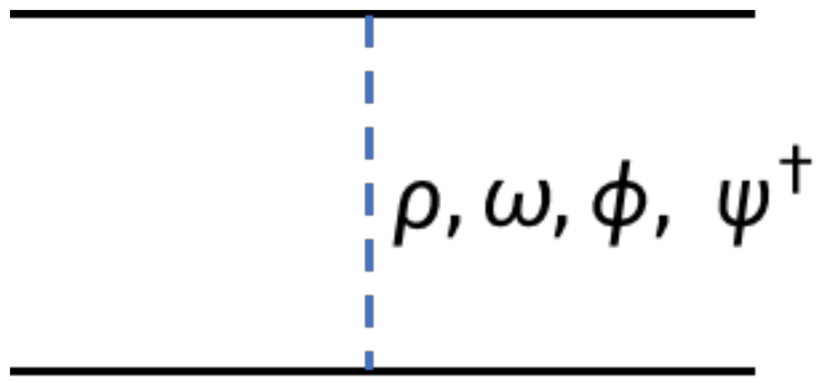


BES, PLB607(2005)243

BES, PLB598(2004)149

Phenomenology

- Production of states with hidden-charm and hidden-bottom
  - open-flavor much easier than $Q\bar{Q}$ + light hadrons,
  - peaks around threshold of a pair of open-flavor hadrons for attractive interaction.
- Threshold structures should be more pronounced in bottom than in charm.
- Resonance saturation
  - vector meson dominance

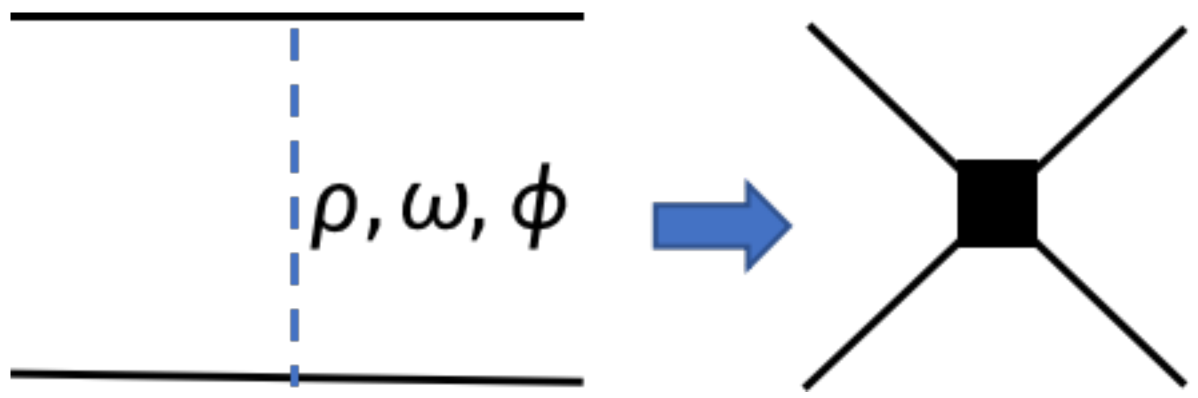


$H\bar{H}$	$D^{(*)}\bar{D}^{(*)}\,[0,1^{\dagger}]$;	$D_s^{(*)}\bar{D}^{(*)}\,[\frac{1}{2}^{\dagger}]$;	$D_s^{(*)}\bar{D}_s^{(*)}\,[0]$
	$X(3872), Z_c(3900,4020)$	$Z_{cs}(3985)$	$X(4140)$
	$Z_b(10610,10650)$		$X(3960)$
$\bar{H}T$	$\bar{D}^{(*)}\Xi_c\,[0]$;	$\bar{D}_s^{(*)}\Lambda_c\,[0^{\dagger}]$	
	$P_{cs}(4459)$ $P_{cs}(4338)$		
$\bar{H}S$	$\bar{D}^{(*)}\Sigma_c^{(*)}\,[\frac{1}{2}]$;	$\bar{D}_s^{(*)}\Sigma_c^{(*)}\,[1^{\dagger}]$;	$\bar{D}^{(*)}\Xi_c^{\prime(*)}\,[0]$;
	$P_c(4312,4440,4457)$		
	$\bar{D}^{(*)}\Omega_c^{(*)}\,[\frac{1}{2}^{\dagger}]$		
$T\bar{T}$	$\Lambda_c\bar{\Lambda}_c\,[0]$;	$\Lambda_c\bar{\Xi}_c\,[\frac{1}{2}]$;	$\Xi_c\bar{\Xi}_c\,[0,1]$
$T\bar{S}$	$\Lambda_c\bar{\Sigma}_c^{(*)}\,[1]$;	$\Lambda_c\bar{\Xi}_c^{\prime(*)}\,[\frac{1}{2}]$;	$\Lambda_c\bar{\Omega}_c^{(*)}\,[0^{\dagger}]$;
	$\Xi_c\bar{\Sigma}_c^{(*)}\,[\frac{3}{2}^{\dagger},\frac{1}{2}]$;	$\Xi_c\bar{\Xi}_c^{\prime(*)}\,[1,0]$;	$\Xi_c\bar{\Omega}_c^{(*)}\,[\frac{1}{2}]$
$S\bar{S}$	$\Sigma_c^{(*)}\bar{\Sigma}_c^{(*)}\,[2^{\dagger},1,0]$;	$\Sigma_c^{(*)}\bar{\Xi}_c^{\prime(*)}\,[\frac{3}{2}^{\dagger},\frac{1}{2}]$;	$\Sigma_c^{(*)}\bar{\Omega}_c^{(*)}\,[0^{\dagger}]$;
	$\Xi_c^{\prime(*)}\bar{\Xi}_c^{\prime(*)}\,[1,0]$;	$\Xi_c^{\prime(*)}\bar{\Omega}_c^{(*)}\,[\frac{1}{2}]$;	$\Omega_c^{(*)}\bar{\Omega}_c^{(*)}\,[0]$

Spectrum of hadronic molecules

- Hadronic molecule spectrum
  - X.-K. Dong, F.-K. Guo, B.-S. Zou, Progr. Phys. 41 (2021) 65-93
  - X.-K. Dong, F.-K. Guo, B.-S. Zou, Commun.Theor.Phys. 73 (2021) 12, 125201

Method

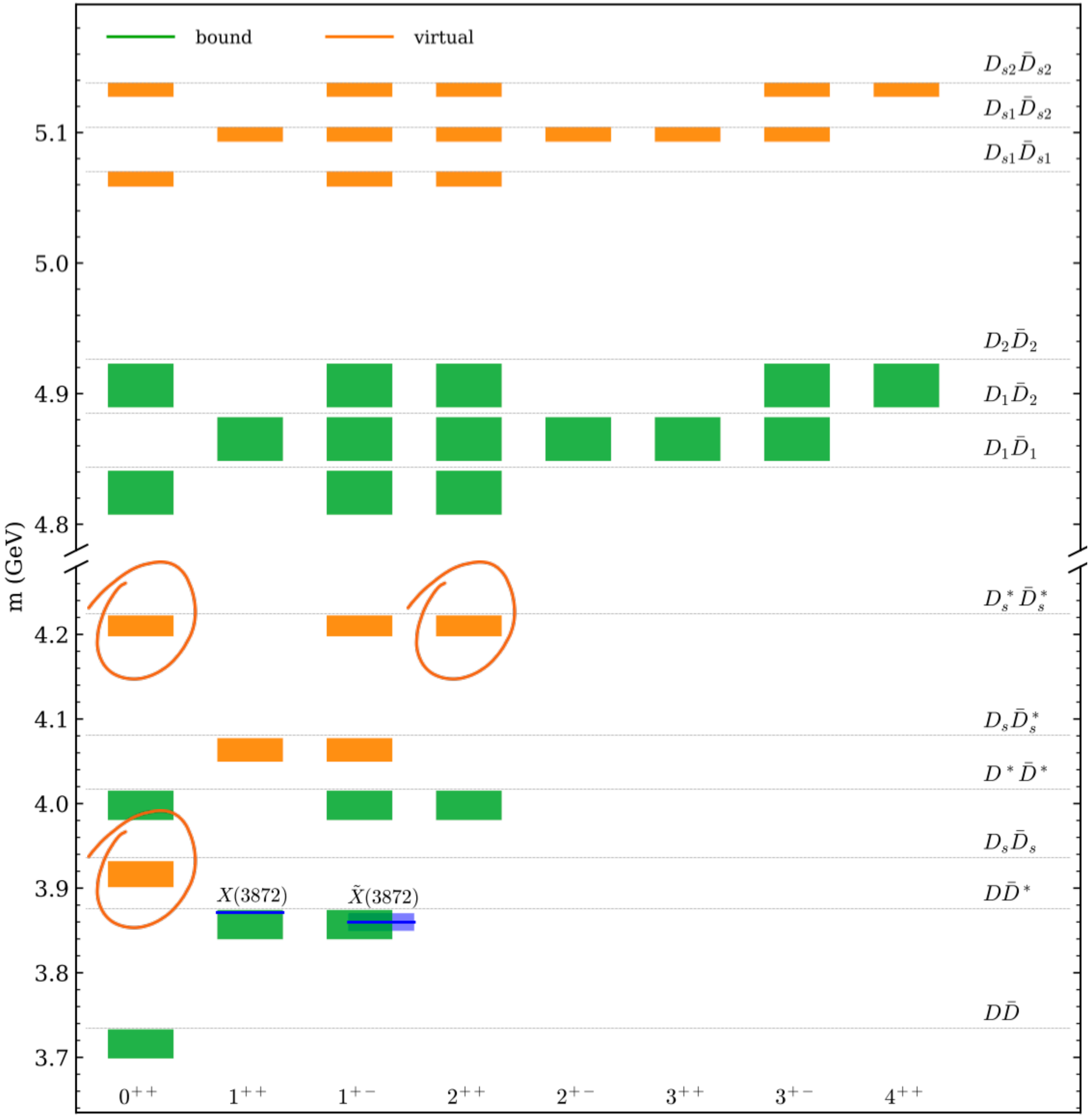


- Approximations:
  - Constant contact terms (V) saturated by light-vector-meson exchange,
  - Similar to the vector-meson dominance in the resonance saturation of the low-energy constants in CHPT. G. Ecker, J. Gasser, A. Pich, E. de Rafael, NPB321(1989)311
- Single channels.
- Neglecting mixing with normal charmonia.
- Resummation using the Bethe-Salpether equation $T = (1 - VG)^{-1}V$.
  - G: two-point scalar loop integral regularized using dim.reg. with a subtraction constant matched to a Gaussian regularized G at threshold

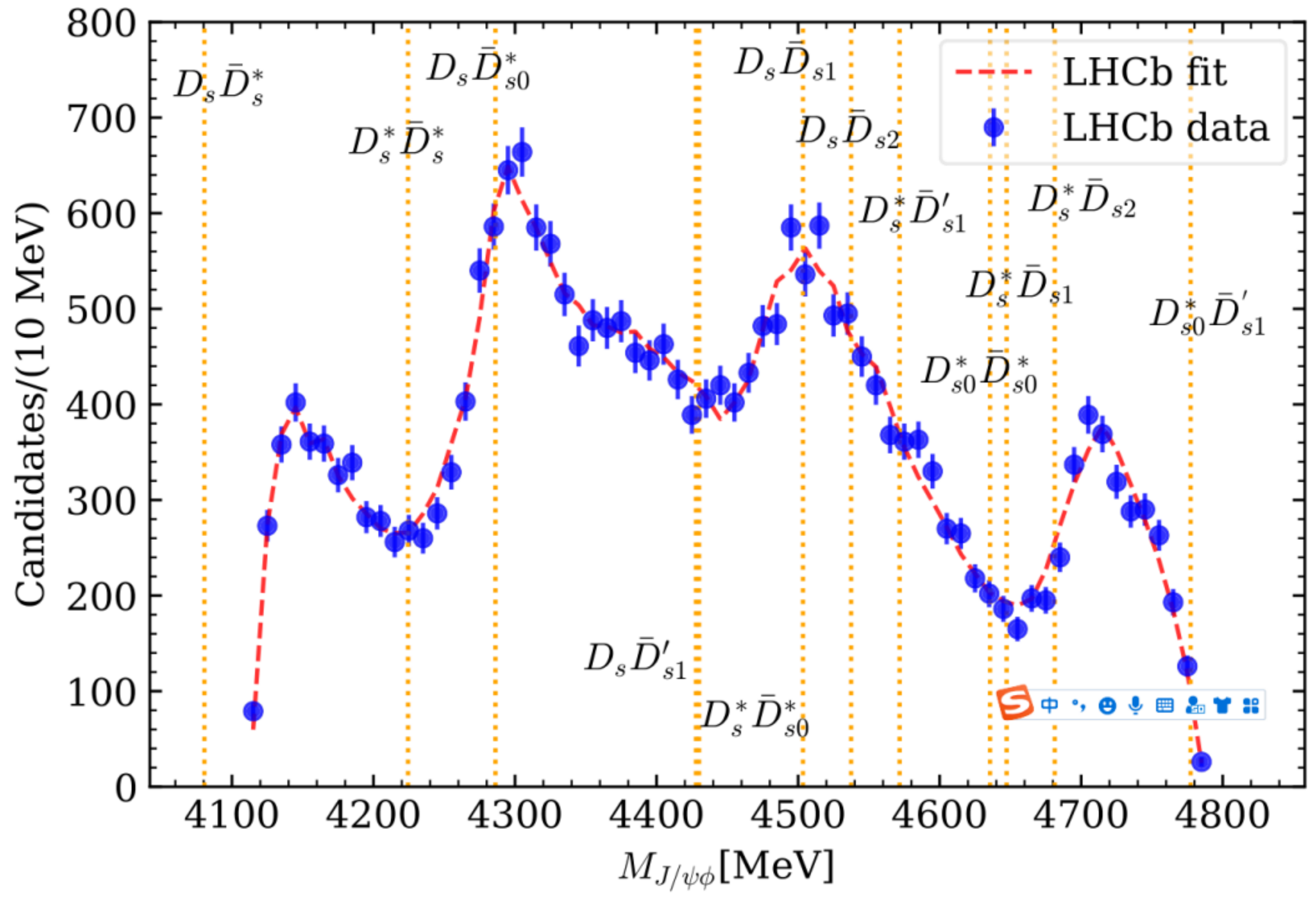
$$G(E) = \frac{1}{16\pi^2}\left\{a(\mu) + \log\frac{m_1^2}{\mu^2} + \frac{m_2^2 - m_1^2 + s}{2s}\log\frac{m_2^2}{m_1^2} + \frac{k}{E}[\log(2kE + s + \Delta) + \log(2kE + s - \Delta) - \log(2kE - s + \Delta) - \log(2kE - s - \Delta)]\right\}$$

- Hadronic molecules appear as bound or virtual state poles of the T matrix.

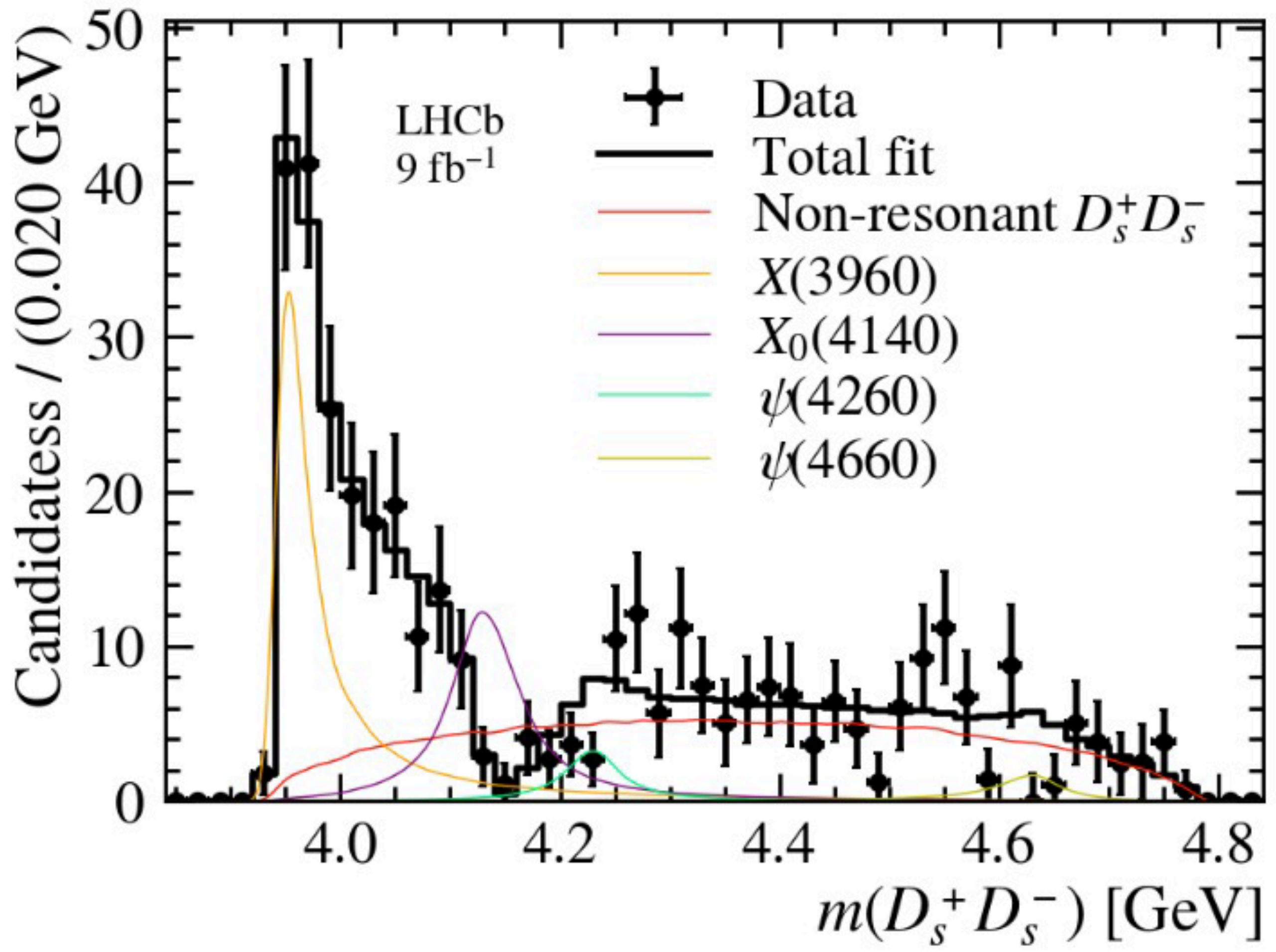
X(3872) and related states



- X(3872) as a $\bar{D}D^*$ bound state.
- Negative-C parity partner observed by COMPASS.
  PLB783(2018)334
- $\bar{D}D$ bound state predicted with lattice.
  Prelovsek et al., *JHEP* 06 (2021) 035
- Evidence for $\bar{D}_s^* D_s^*$, $\bar{D}_s D_s$ virtual state in LHCb data?

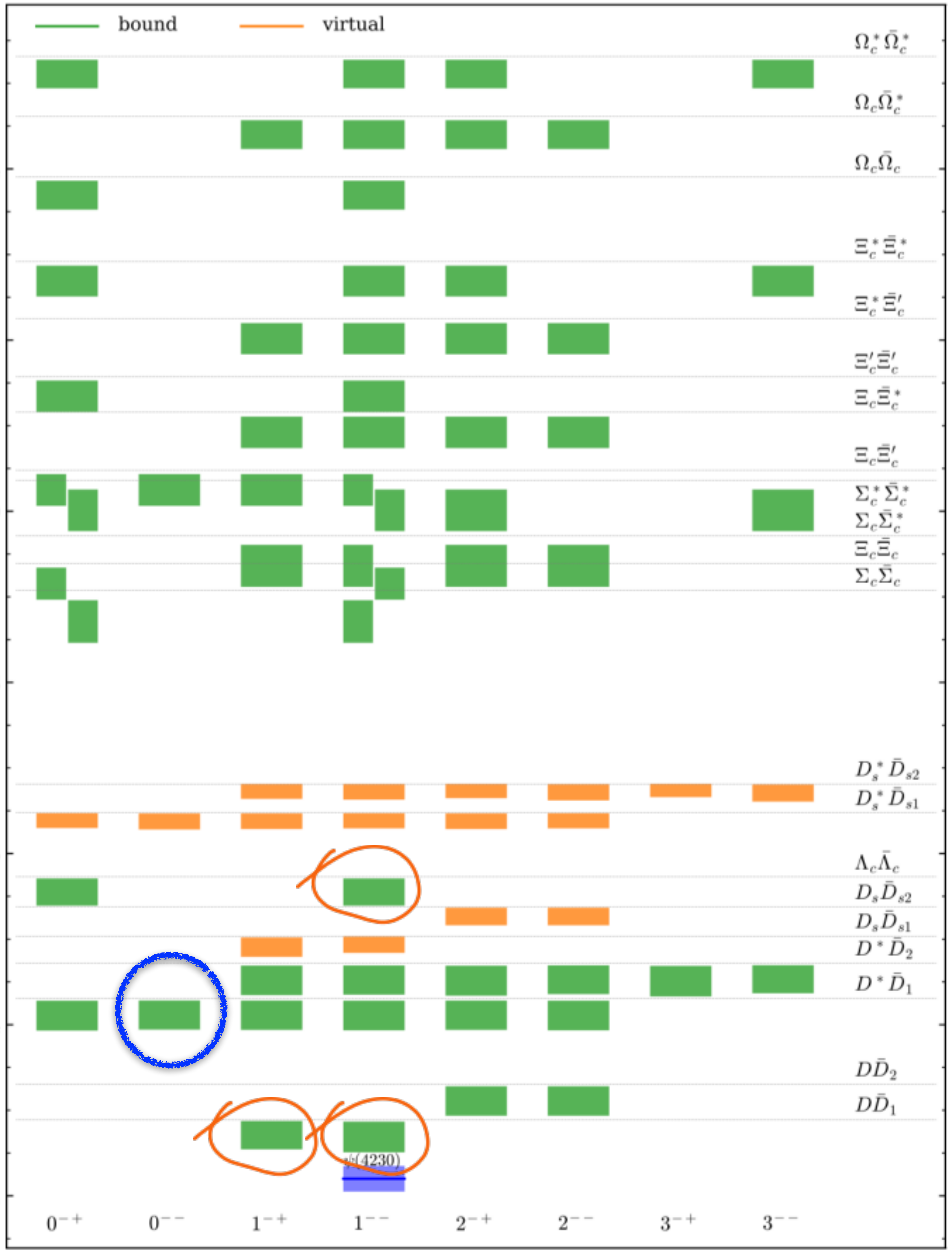


Data taken from PRL118(2017)022003

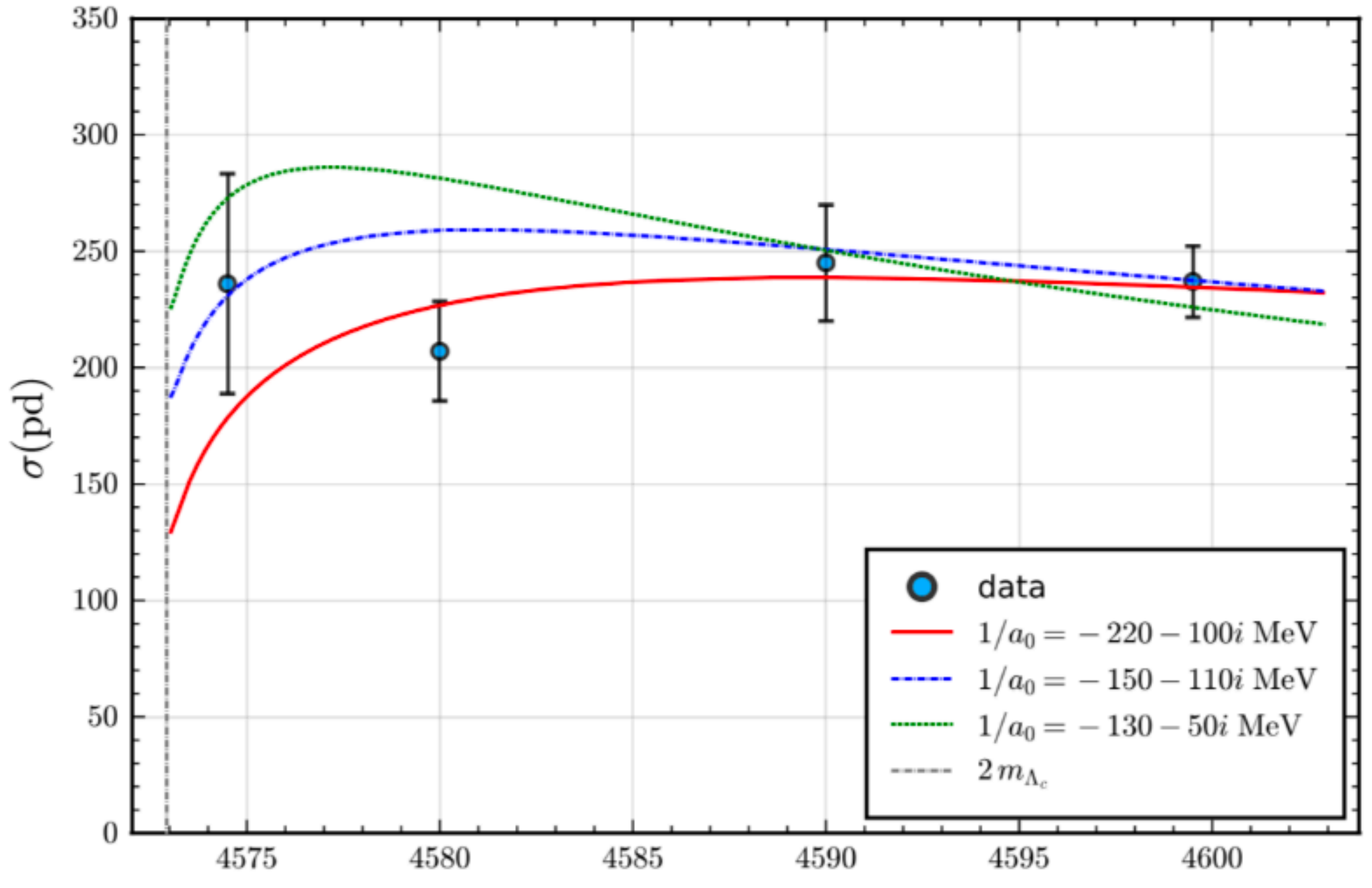


CERN Seminar
5th July, 2022

Isoscalar vectors and related states



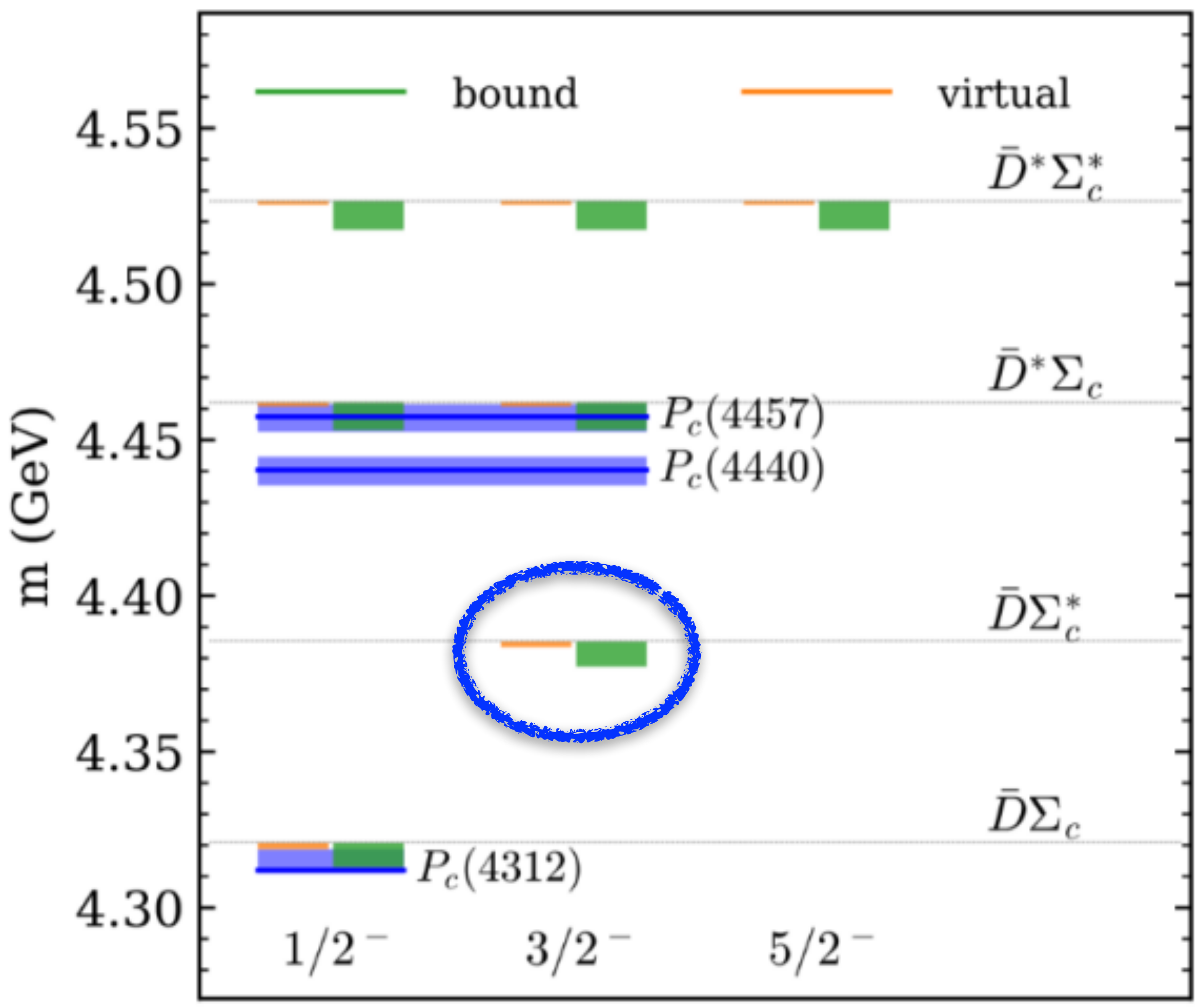
- Y(4260)/ψ(4230) as a $\bar{D}D_1(2420)$ bound state.
- Vector charmonia around 4.4 GeV unclear.
- Evidence for 1^{--} $\Lambda_c\bar{\Lambda}_c$ bound state in BESIII data. Sommerfeld factor & Near-threshold pole.
- Many 1^{--} states above 4.8 GeV, for Super Tau-Charm Facility (STCF).

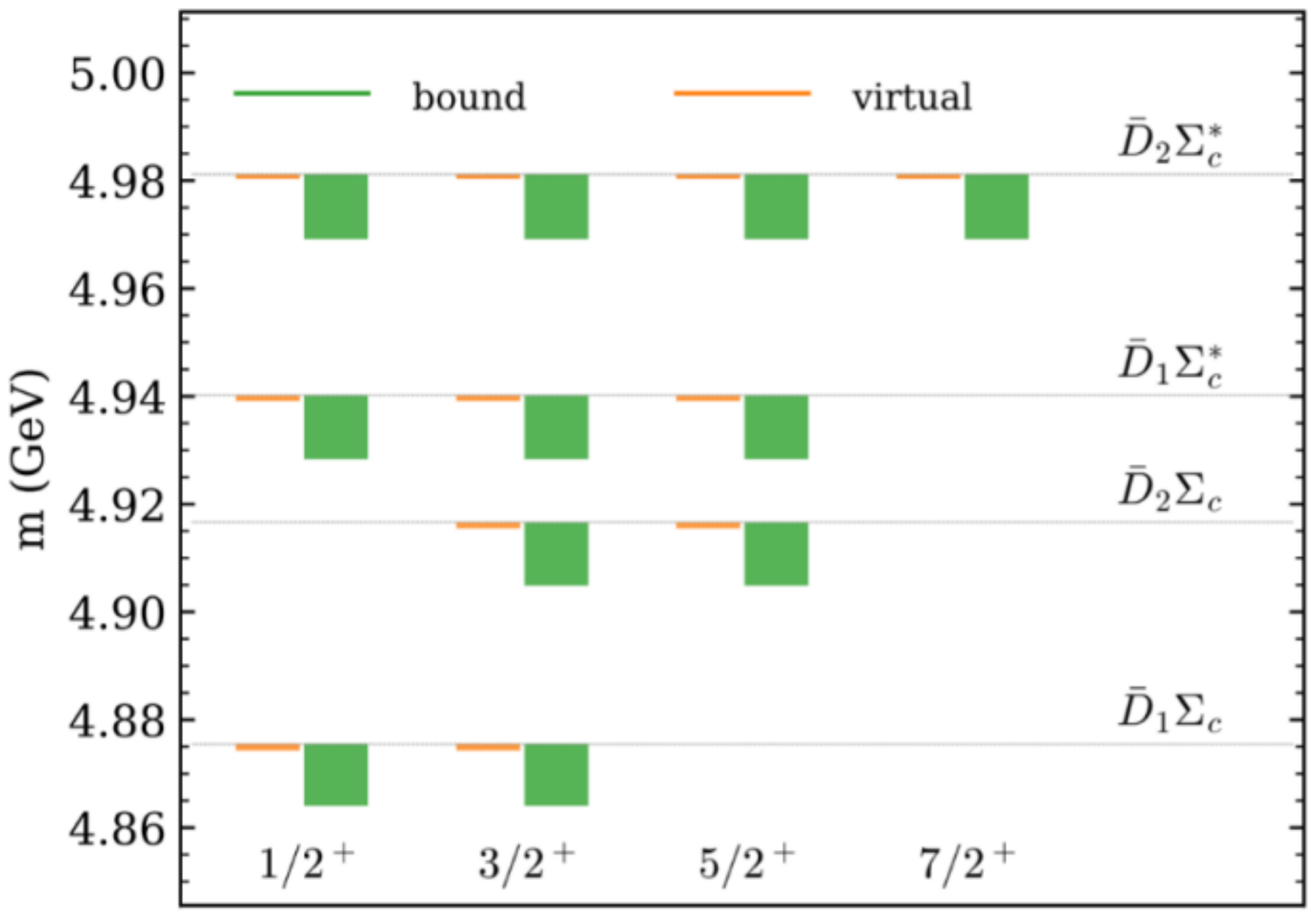


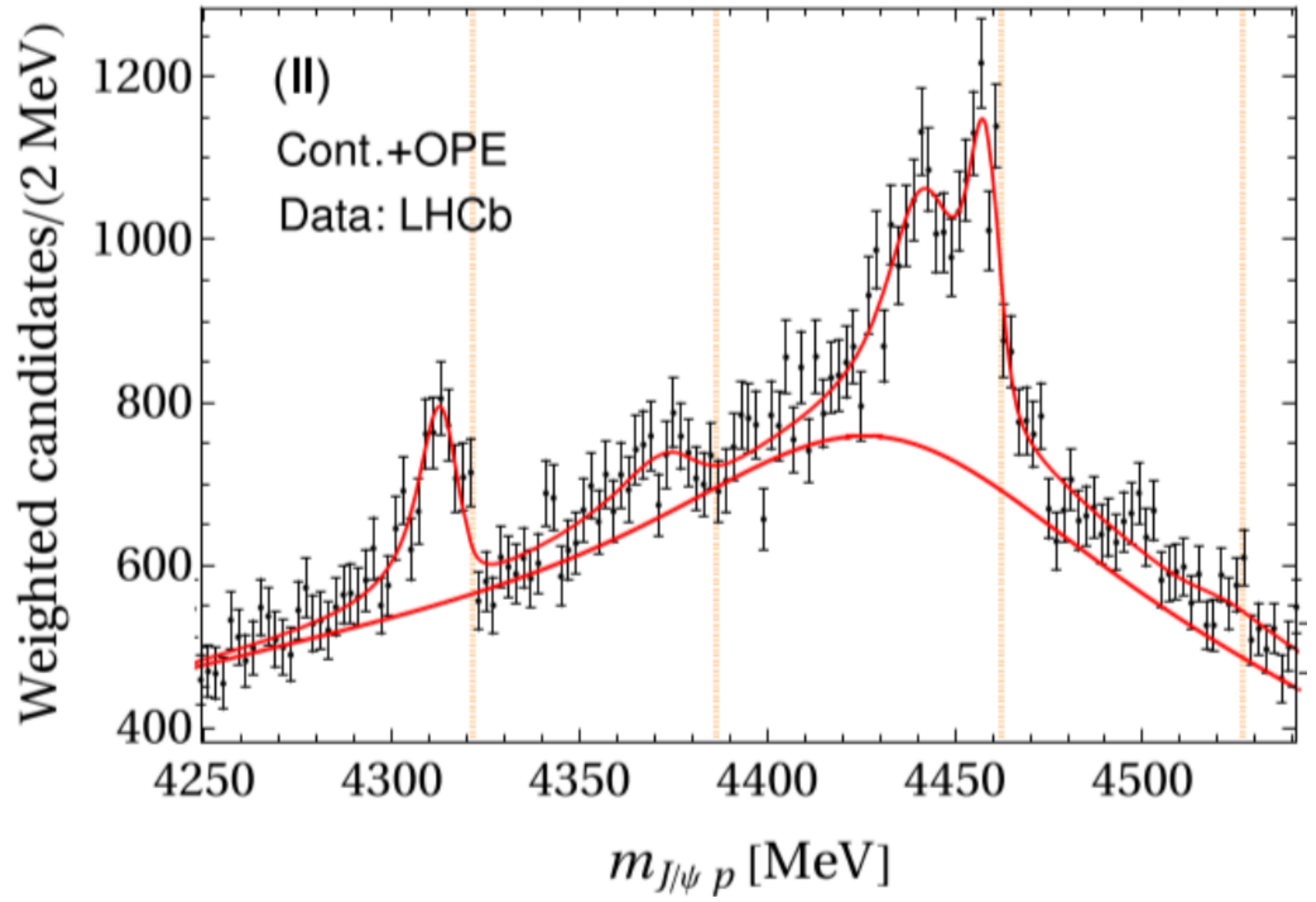
- $\psi_0(4360)$ as a $D^*\bar{D}_1$ molecule
  - only one with exotic $J^{PC} = 0^{--}$ nearby in hadronic picture.
  - More accurate treatments in arXiv: 2205.10994 (accepted by PRL) including coupled channel and 3-body effects.
  - Robust prediction in hadronic picture.
  - Details see the report in the poster session.

Data taken from BESIII, PRL120(2018)132001

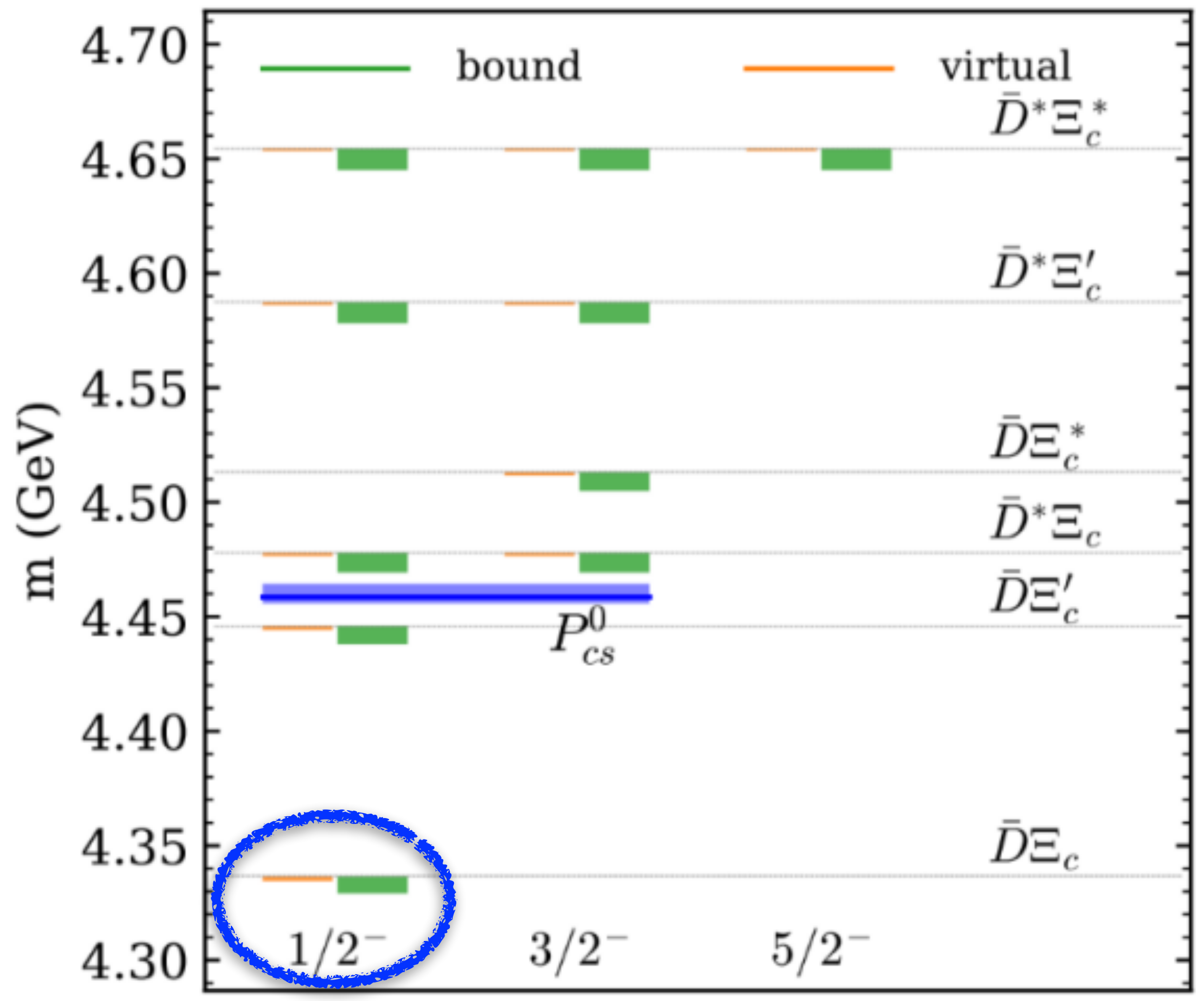
Hidden-charm pentaquarks

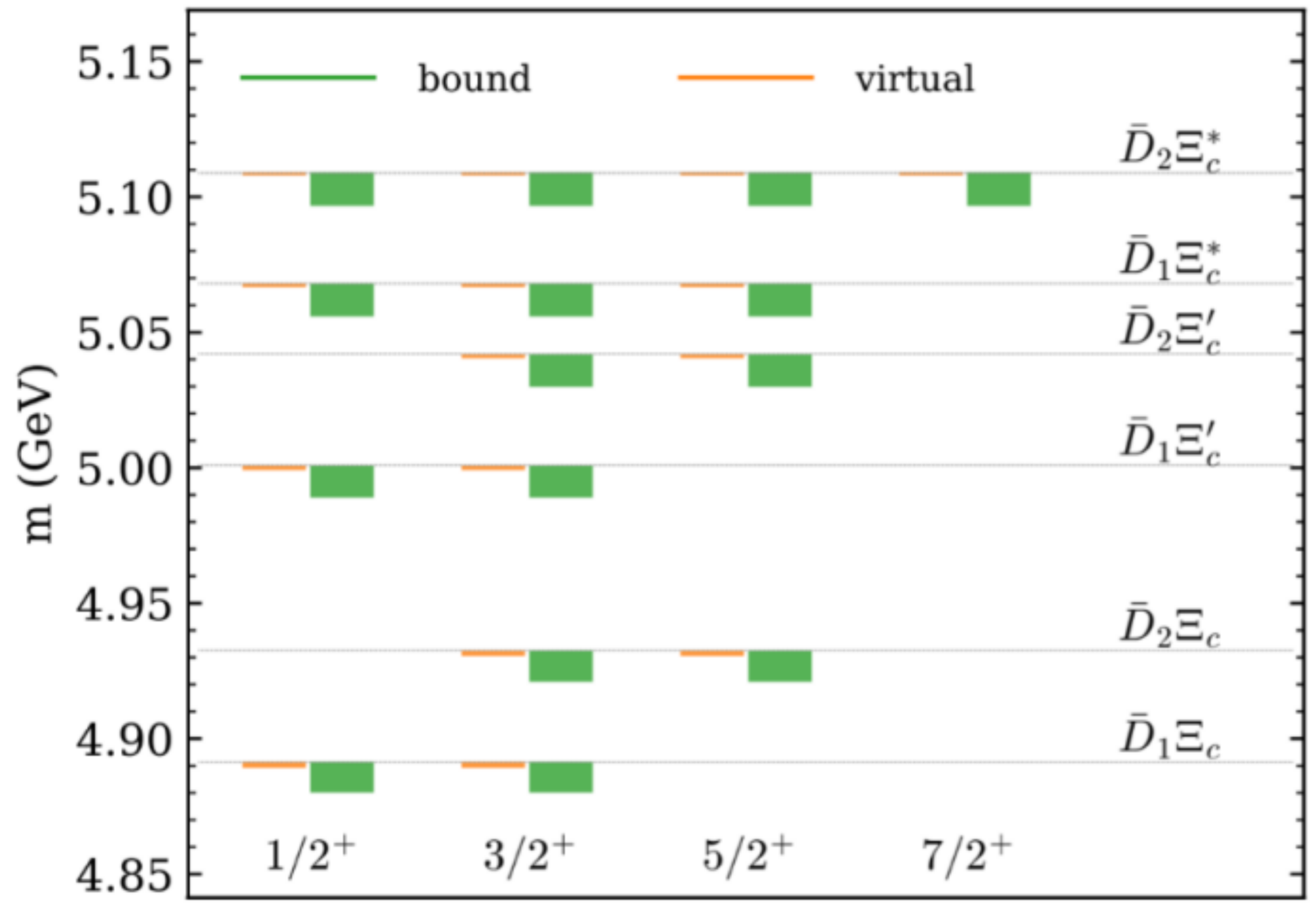


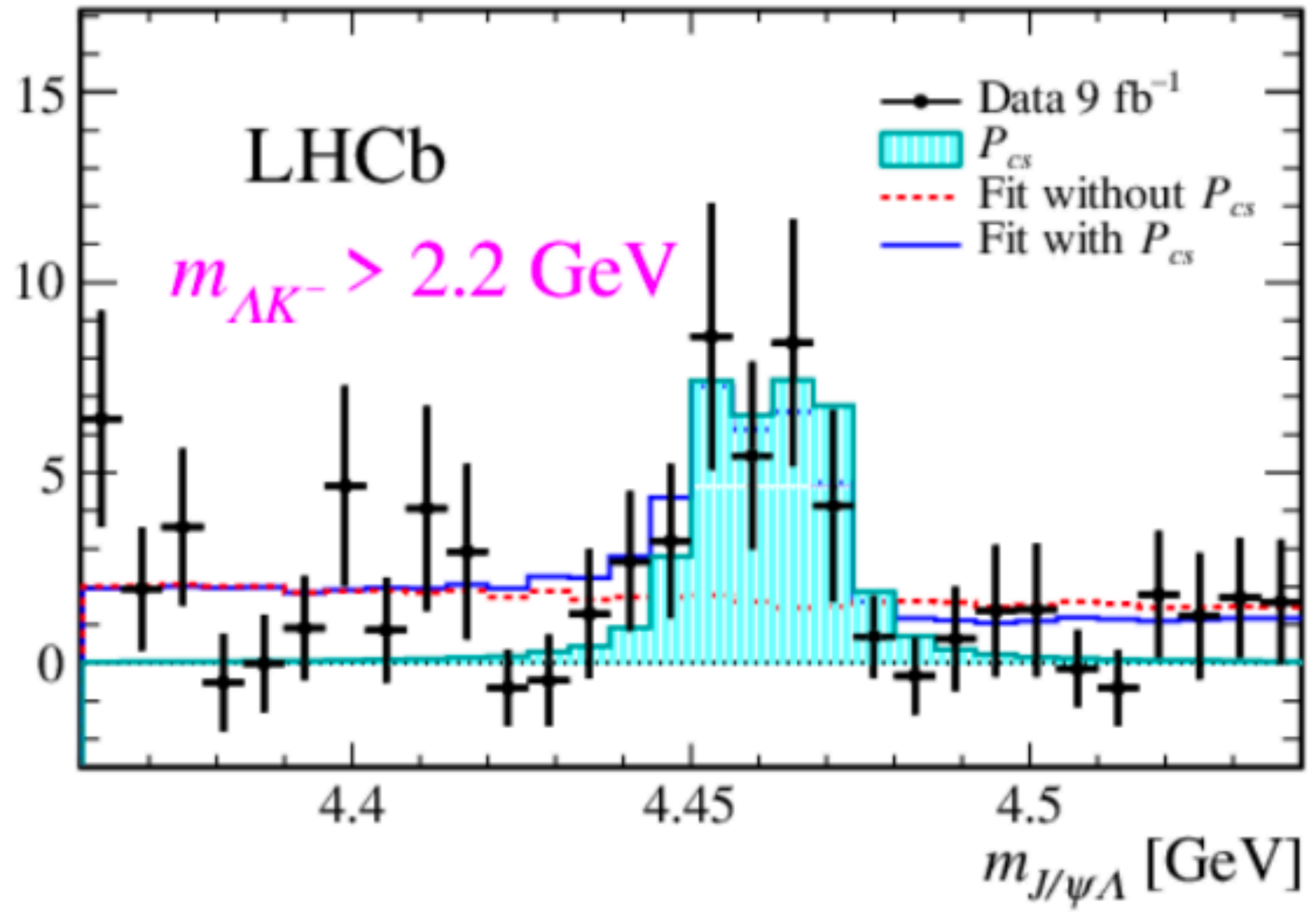




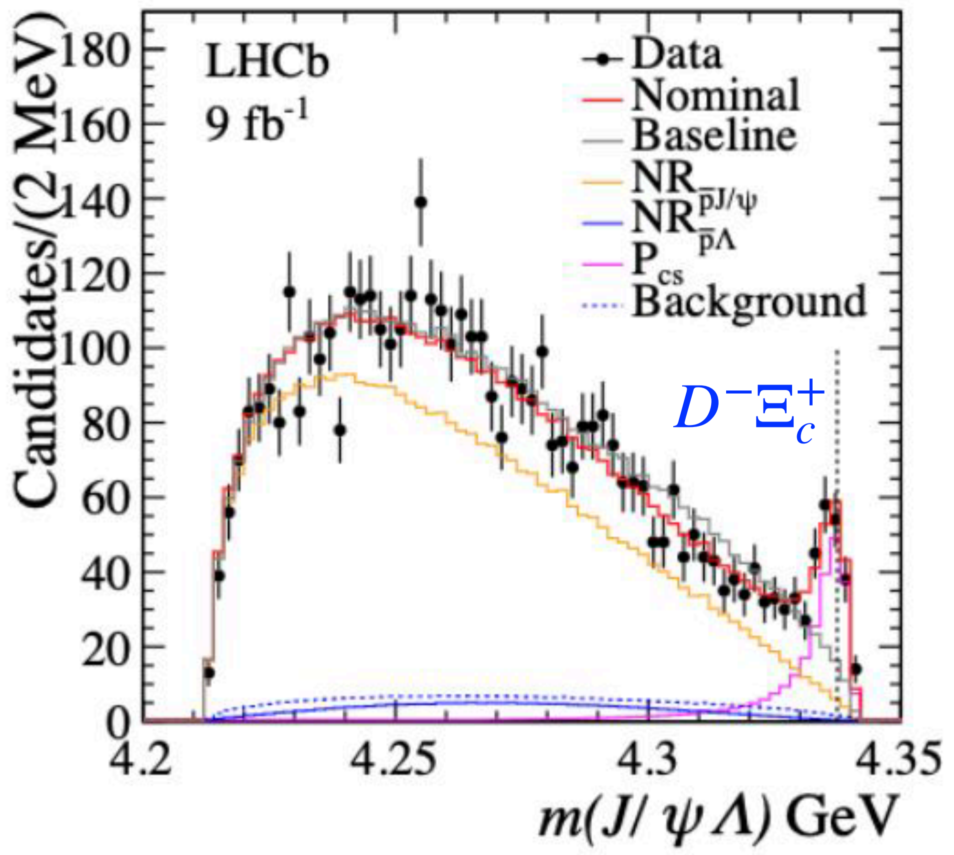
Du et al., PRL124(2020)072001





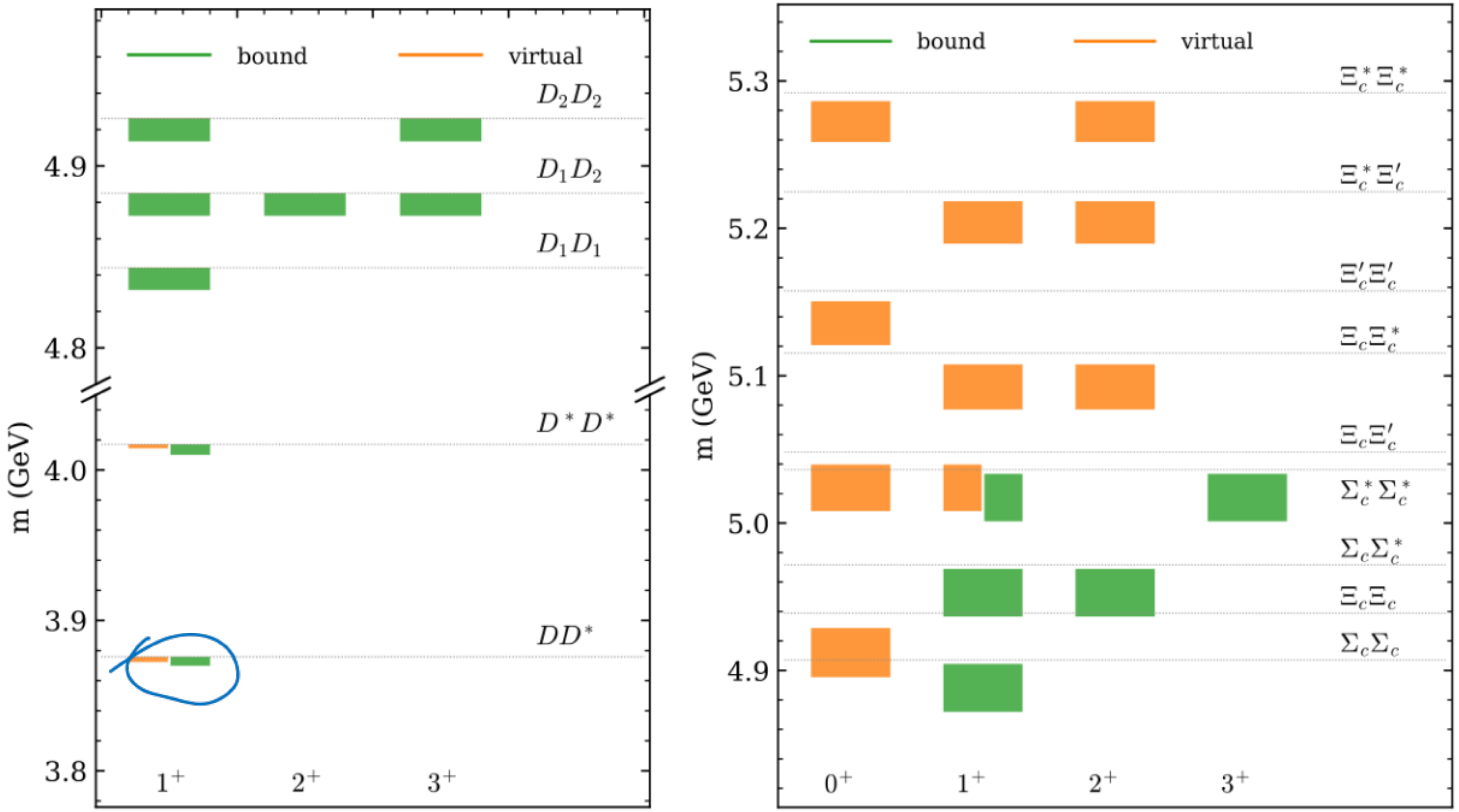


LHCb,
Sci.Bull. 66 (2021) 1278-1287



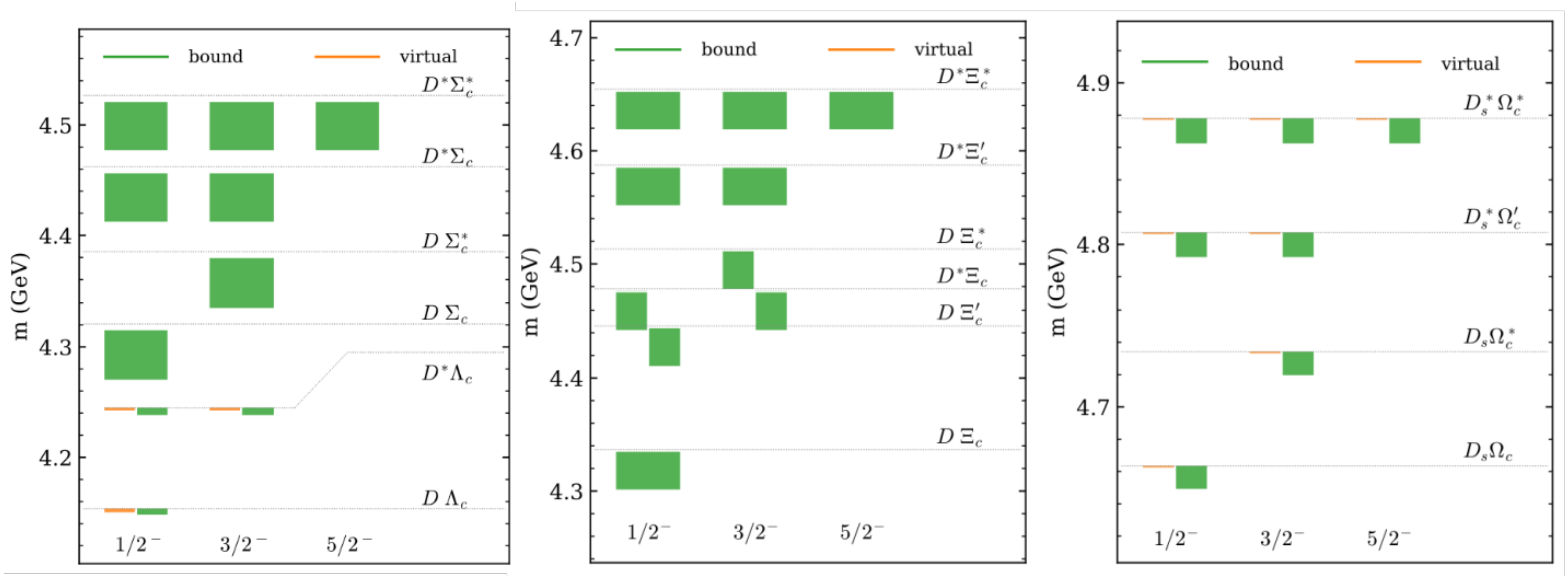
CERN Seminar
5th July, 2022

double-charm systems



- $T_{cc}^+(3875)$ as an isoscalar DD^* bound or virtual state.
- D^*D^* predicted to be similar.
- Similar in $P = -$ sector.
- Isoscalar $\Sigma_c^{(*)}\Sigma_c^{(*)}$ dibaryons very likely bound.

double-charm partners of P_c & P_{cs}



- For isoscalar, more attractive in double charm systems than in hidden charm ones.
- Similar when $D_{(s)}^{(*)}$ is replaced by $D_{1,2(s)}^{(*)}$.

States in other channels not shown

Summary

- The recently observed $\eta_1(1855)$ interpreted as a $K\bar{K}_1(1400)$ molecule.
- Threshold structures (threshold cusp or near-threshold peak) are generally expected for a pair of heavy hadrons with attractive interaction.
  - strong attraction, then hadronic molecules below threshold.
  - otherwise threshold cusps.
- Structures should be more prominent in bottom than in charm.
- Hundreds of hidden-charm and double-charm hadronic molecules predicted.
  - consistent with present experimental data.

Thanks for your attention