Hadron states in e^+e^- annihilation and subthreshold resonance

Xu CAO

Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou, China

Workshop of the Baryon Production at BESIII
University of Science and Technology of China
14-16 Sep. 2019, Hefei

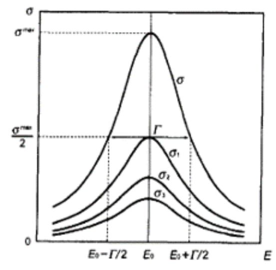
中国科学技术大学
University of Science and Technology of China
中国科学院近代物理研究所
Institute of Modern Physics, Chinese Academy of Sciences

Outline

Introduction

Hadron spectrum

1. Hadron in ground state: objects with internal components
2. Hadron spectrum: excitation of internal freedom



Breit-Wigner resonances $\frac{M\Gamma}{s-M^2+iM\Gamma}$

$\Gamma \Longrightarrow$ decaying more or less to other hadrons ....

3. however, Reality is much more complicated because of background:

   non-resonant contribution

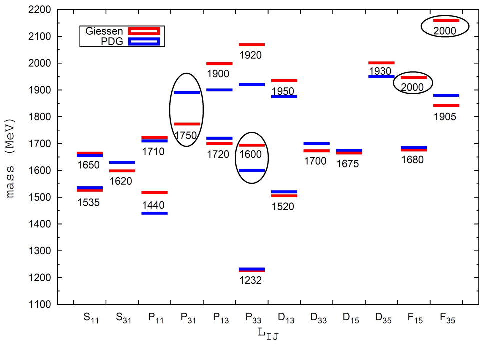
   near-by resonances & thresholds

Introduction

e.g. Baryon spectrum - N^* and Δ^*

1. Nucleon: objects with internal components and structure.
2. Baryon spectrum: excitation of internal freedom
   $\Longrightarrow$ must be wide > 100 MeV (coupled strongly to πN, ηN ....)

In a coupled-channel model H. Lenske, M. Dhar, T. Gaitanos, X.C., PPNP98(2018)119



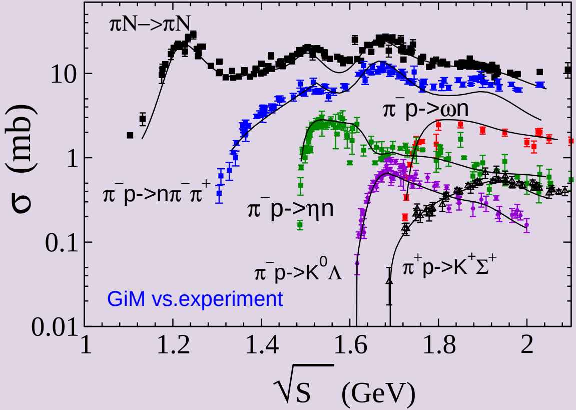
PDG update: $F_{15}(2060)$ & $F_{35}(2000)$ in $K\Lambda$ & $K\Sigma$

Philip COLE's talk

Introduction

Reaction in Reality: Multiple peaks X.C.& H.Lenske,PRC88(2013)055204;PLB772(2017)274

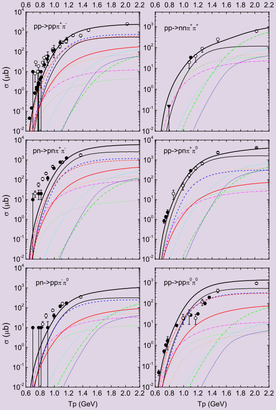
- The measured πN (also γN) reactions *versus* CC model

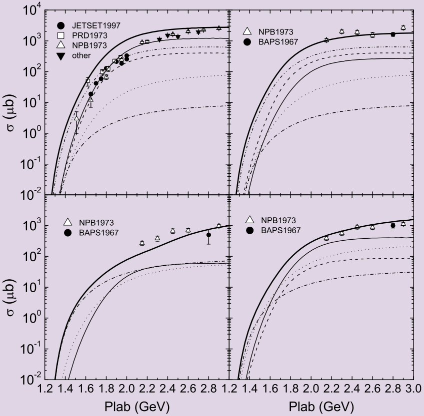


Introduction

Reaction in Reality: complementary reactions IJMPA26(2011)505

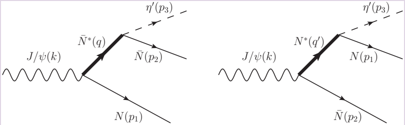
- COSY, HADES: $NN \to NN\pi\pi$, X. C., Bing-Song Zou, Hu-Shan Xu, PRC81(2010)065201
- PANDA: $N\bar{N} \to N\bar{N}\pi\pi$, X. C., Ju-Jun Xie, Bing-Song Zou, Hu-Shan Xu, NPA861(2011)23



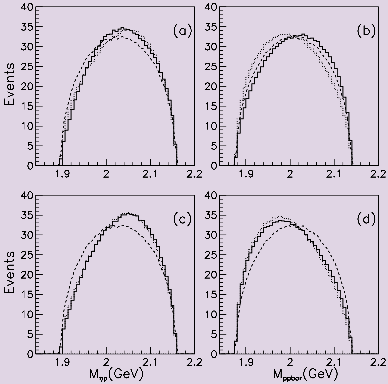


Reaction in Reality: No peaks X. C.,& Ju-Jun Xie, CPC40(2016)083103

- Baryon spectrum in $J/\psi \to p\bar{p}\eta'$ (with small phase space)
- We know little about states coupling to $\eta' N$ (also ωN & ϕN)
- Higher charmonium ($\psi(3686)$, $\psi(3770)$)? BESIII,PRD99(2019)032006



$S_{11}(1535)$, $P_{11}(1710)$,
$P_{13}(1900)$, $S_{11}(2090)$, $P_{11}(2100)$



Formula: Beyond Breit-Wigner resonance

$$\frac{M\sqrt{\Gamma_{tot}\Gamma_{i(s)}}}{s - M^2 + \mathrm{i}\sqrt{s}\sum_i \Gamma_{i(s)}}$$

1. the Flatté formula Flatté,PLB63(1976)224

$$\Gamma_{i(s)} = \Gamma_0 \left(\frac{p_{(s)}}{p_{(M^2)}}\right)^{2L+1} \frac{M}{\sqrt{s}} \left(\frac{F_L(p_0, p_{(s)})}{F_L(p_0, p_{(M^2)})}\right)^2$$

with $F_L(p_0, p_{(M^2)})$ being (Blatt-Weisskopf) form factor.

2. E.G. energy dependent width in p-wave: $\Gamma_{i(s)} = g_i \frac{p^3}{s(1+r^2p^2)}$

$p_{(s)}$: c.m. momenta of final particles
pure imaginary below threshold

Formula: Fano resonance

$$|F_{bg}|^2 \frac{|q+\varepsilon|^2}{1+\varepsilon^2} \qquad \text{with} \qquad \varepsilon = \frac{-s+M^2}{M\Gamma}$$

1. interplay of discrete states with continua Fano,PhysRev124(1961)1866

$$|\Psi\rangle = z_r|r\rangle + \sum_c \int_0^\infty dk_c z_c(k_c)|c\rangle$$

 is the wave function of the system.

2. After solving the coupled Schödinger equations Z.G.Xiao&Z.Y.Zhou PRD94(2016)076006:

$$q = \frac{\langle b'|T|i\rangle}{\langle r'|T|i\rangle}$$

 determined by the wave functions of resonance and continuum.

3. producing a dip in line shape at the position of $q = -\varepsilon\big|_{s=s_0}$

F_{bg}? AND q?

1. We can construct models to calculate them!
2. q: energy dependent, but can be regraded as a constant in limited energy range of interest.
3. The form of background:

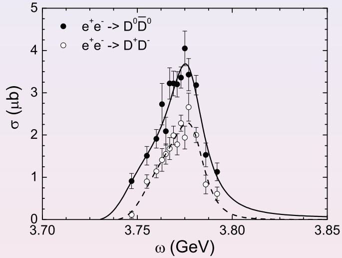
$$F_{bg} = \begin{cases} \text{Breit Wigner of } \psi(3686) & \text{for } \psi(3770) \\ \frac{A_B}{\tau^2 \ln^2(s/\Lambda^2_{QCD})} & \text{for } \Lambda \text{ EFF} \end{cases}$$

which is the main uncertainties!

Results: $\psi(3770)$

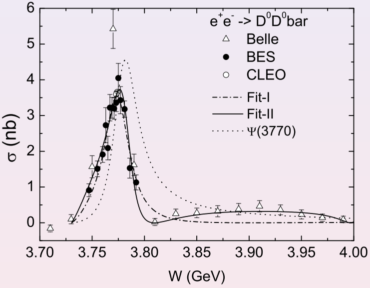
- non-resonant background:
$$\psi(2S) = \psi(3686)$$
- main difference is from q, $\psi(3770)$ is the same in both channels.

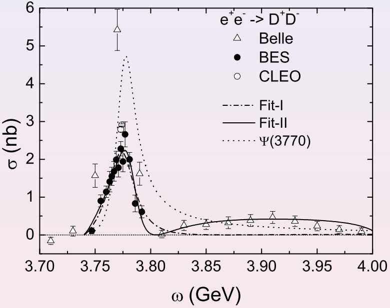
X. C., H. Lenske, arXiv:1410.1375; 1408.5600.



	$D^0\bar{D}^0$	D^+D^-
$m_{\psi'}$ (MeV)	3782.1 ± 1.6	3784.0 ± 2.0
$g_{\psi' D\bar{D}}$	11.8 ± 0.9	10.7 ± 1.3
q	-2.1 ± 0.3	-1.6 ± 0.3
m_{bg} (MeV)	3743.0 ± 5.4	3753.3 ± 3.9
Γ_{bg} (MeV)	34.1 ± 5.2	33.3 ± 5.6
$\chi^2/d.o.f$	0.83	0.90

Results: $\psi(3770)$

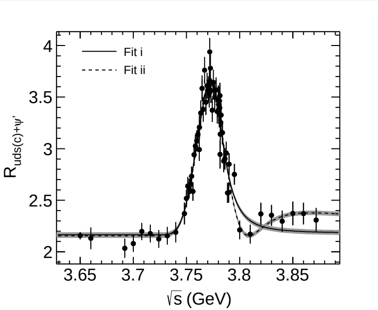


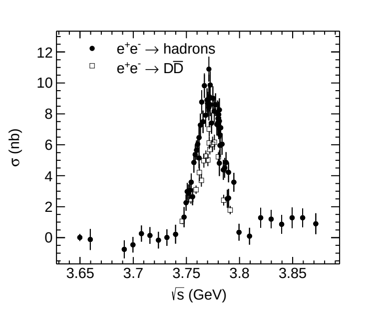


- in a parameterized coupled-channel formalism
- Fit-I: $\psi(3686)$ and $D\bar{D}$ channel
- Fit-II: $\psi(4040)$ and $D^*\bar{D} + h.c.$ channel also added

X. C., H. Lenske, arXiv:1410.1375; 1408.5600.

Results: $\psi(3770)$





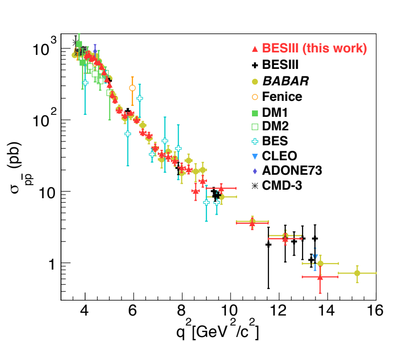
- R_{uds} value in the vicinity of $\psi(3770)$ state
- $R_{uds} = 2.156 \pm 0.022$ after correction of line shape
- Fit-I: $g_{\psi(3770)\gamma}$ fixed
- Fit-II: $g_{\psi(3770)\gamma}$ non-fixed

- Extracted $e^+e^- \to hadrons$ Versus $e^+e^- \to D\bar{D}$
- non-$D\bar{D}$ decay of $\psi(3770)$?

Rong Wang, X. C., Xurong Chen, PLB747(2015)321

Results: Λ electromagnetic form factor (EFF)

- proton EFF: follows pQCD expectation:
  $$\frac{A_B}{\tau^2 \ln^2(s/\Lambda^2_{QCD})}$$
  BESIII, PRD99(2019)092002
- Some small structures:
  resonances?
  thresholds opening?
- threshold enhancement



Results: Λ electromagnetic form factor (EFF)

- non-resonant background:
  $\phi(2170)$ and pQCD
- The second errors are obtained by varying the mass and width of $\phi(2170)$

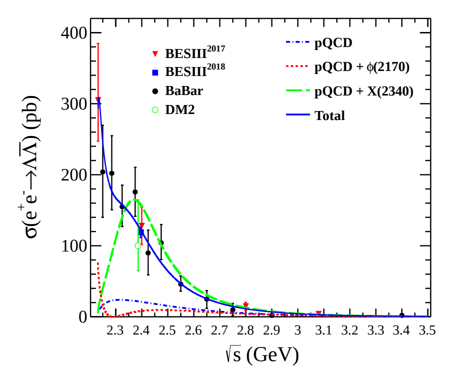
X. C., Jian-Ping Dai, Ya-Ping Xie, PRD98(2018)094006

- A vector meson as in $p\bar{p} \to \Lambda\bar{\Lambda}$?

D. V. Bugg, EPJC 36(2004)161

$M = 2.338 \pm 0.046 \pm 0.030$

$\Gamma = 257 \pm 159 \pm 41$



q_1^0	q_2^0	A_Λ
$6.32 \pm 2.22 \pm 2.95$	$-2.53 \pm 0.93 \pm 0.35$	$1.19 \pm 0.46 \pm 0.09$

Relative phase $\Delta\Phi$ of FFs would vary dramatically with c.m. energies!

$$\Delta\Phi = 37 \pm 12 \pm 6 @ 2.396 \text{ GeV}, \ 42.4 \pm 0.6 \pm 0.5 @ J/\psi$$

Conclusion

- A parameterization originated from Fano resonance is discussed
  - easy to use for both theoretical and experimental purposes
  - directly connected to underlying nature of resonance
- We use it to study line shape of states in e^+e^- annihilation
- The role of subthreshold resonance
  - significant for the $\psi(3770)$ line shape and [illegible]
- Other interesting cases?
- Combined analysis of different reactions in realistic amplitudes!
- Thanks for the attention!!!

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  - close-to-threshold enahncement of Λ EFF: $\phi(2170)$?
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