

# 2 GeV能区 $\rho$ 介子态的研究

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2026 年 5 月 14日—18 日

# 主要内容

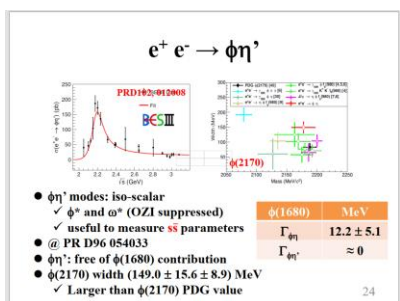
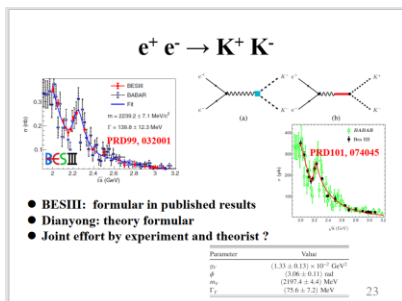
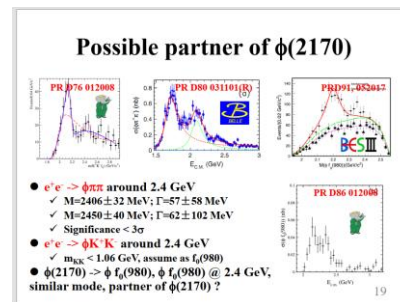
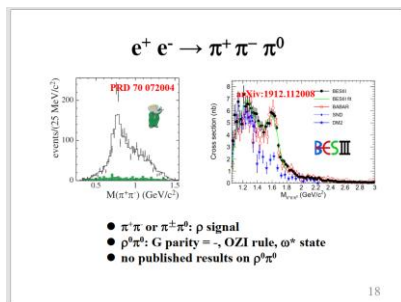
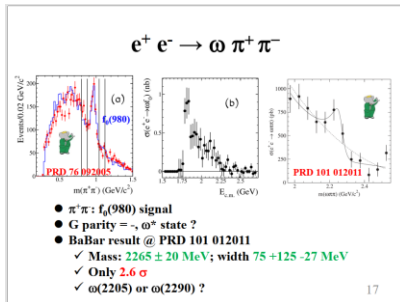
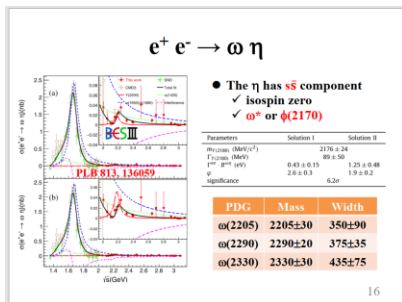
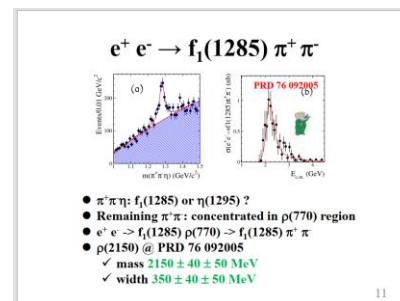
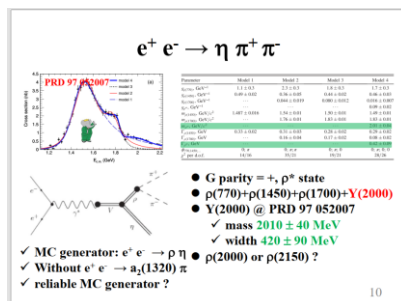
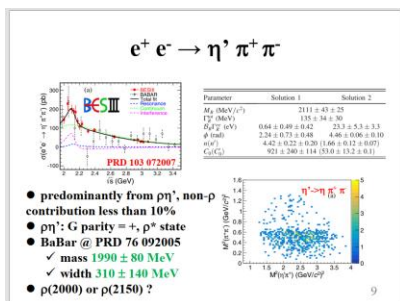
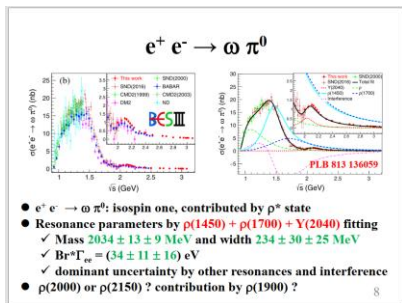
- 研究背景
- 在谱学支撑下对 $\rho$ 介子产生过程的分析
- 总结

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# 研究背景

# $e^+e^-$ 湮灭实验在2GeV能区附近积累了丰富的数据



## $\rho^*$ and $\omega^*$ @ [2.0, 3.0] GeV

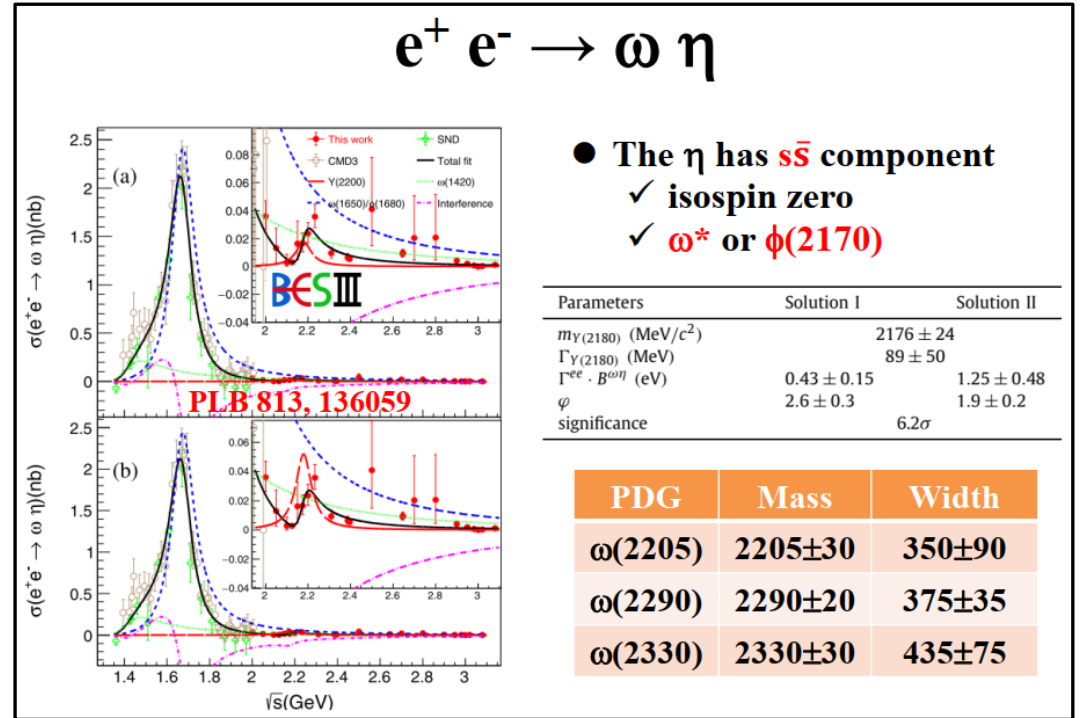
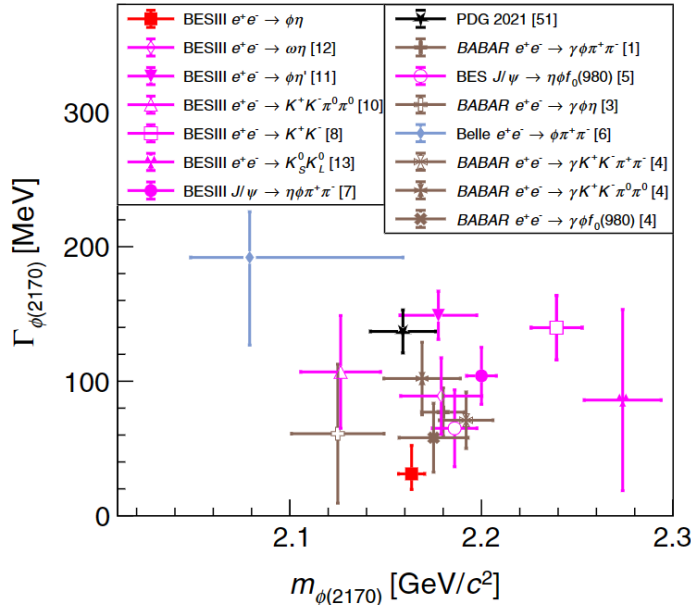
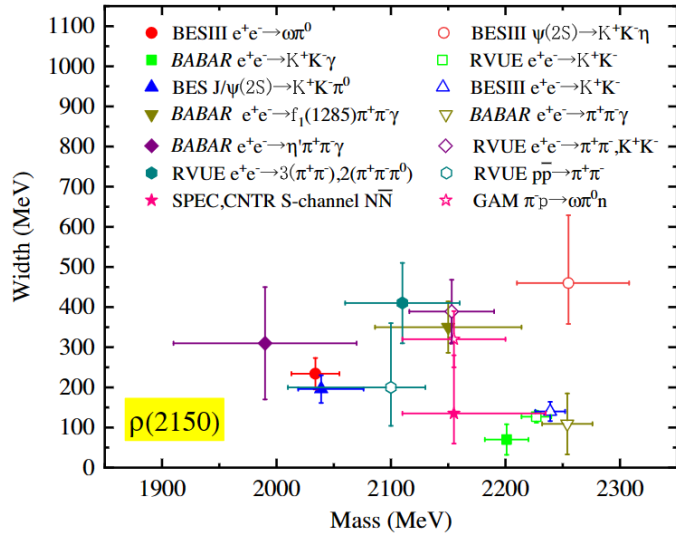
鄢文标 (中国科学技术大学)

- How to study  $J^{PC} = 1^-$  vector states?
- Status of  $J^{PC} = 1^- \ ^3S_1$  &  $\ ^3D_1$   $\rho^*$
- Status of  $J^{PC} = 1^- \ ^3S_1$  &  $\ ^3D_1$   $\omega^*$
- Possible  $\rho^*$ ,  $\omega^*$  and  $\phi^*$  with mass  $> 2.4$  GeV
- What do we want?

共振态参数存在很大差异，  
难以统一解释！

“轻味矢量介子理论与实验研讨会”，2021.07.20，西宁

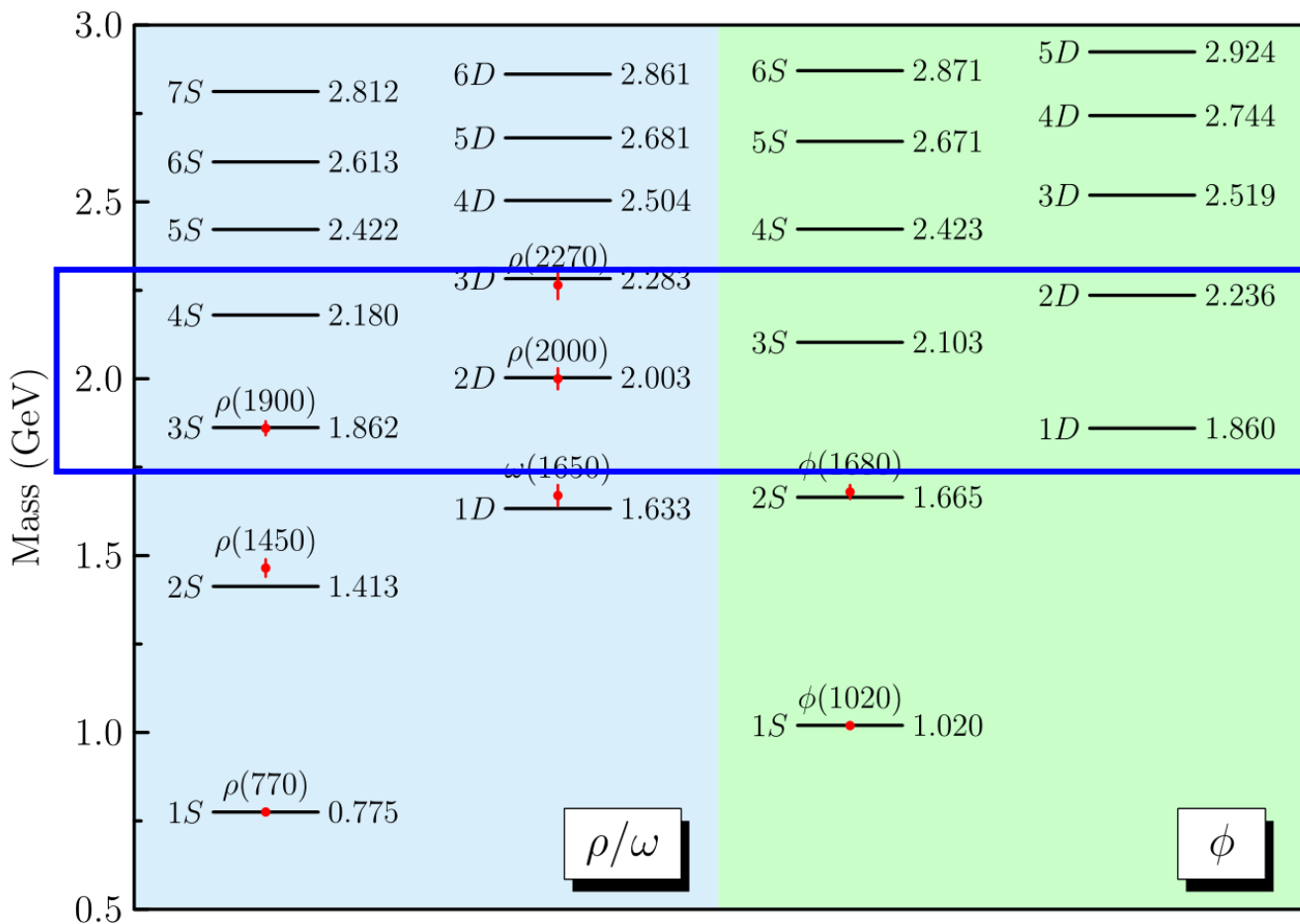
# 2 GeV附近矢量轻介子的态共振态参数测量结果



Chan e l-dependent

通过对比共振态参数的实验和理论结果的方法来建立2 GeV能区的矢量介子态失效了。

# 矢量轻介子质量谱 (MGI)



质量谱重叠

随着能级的增加质量间隔逐渐变小，干涉效应凸显出来，这给实验测量和理论计算的精度都提出了更高的要求。

# $\rho(1450)$ 和 $\rho(1700)$ 的建立

PDG 1976

Nuclear Physics B58 (1973) 31-44

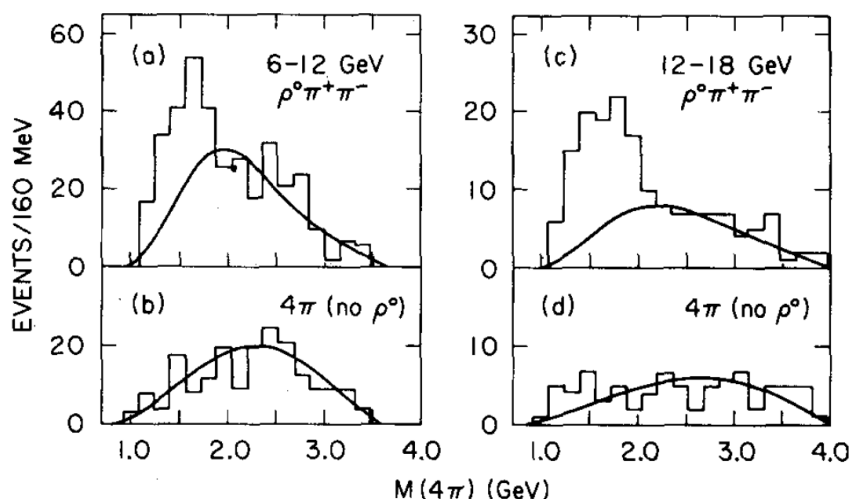


Fig. 7.  $\gamma p \rightarrow \pi^+ \pi^- \pi^+ \pi^- p$ . Four-pion invariant mass distributions with  $\Delta^{++}$  excluded.

Photon energy (GeV)	6-12	12-18
Mass (MeV)	$1622 \pm 20$	$1624 \pm 50$
Width (MeV)	$265 \pm 90$	$433 \pm 100$

Data Card Listings  
For notation, see key at front of Listings.

**$\rho'(1600)$**   
 $\rightarrow 4\pi$

65 RHC PRIME(1600, JPC=1--+) I=1

The  $\rho'$  was first seen in

$\gamma$  (real or virtual)  $\rightarrow \rho^{+0} \rightarrow \rho^0 \pi^+ \pi^-$

with the  $\pi^+ \pi^-$  pair apparently in an S wave  
(BINGHAM 72, DAVIER 73, SCHACHT 74, ALEXANDER 75).

PDG 1988

<b><math>\rho(1450)</math></b>	$I^G(J^{PC}) = 1^+(1^{--})$
OMITTED FROM SUMMARY TABLE	
This entry contains claims for vector mesons in the 1250-1500 MeV range. Needs confirmation. See the mini-review under the $\rho(1700)$ .	
<b><math>\rho(1700)</math></b>	$I^G(J^{PC}) = 1^+(1^{--})$
NOTE ON $\rho(1450)$ AND $\rho(1700)$	
Early indications that the 1600 MeV mass region may contain two $1^{--}$ resonances were given by COSME 79 BARBER 80 DIBIANCA 81.	

干涉效应给实验准确抽取共振参数带来很大的困难

# 拟合获得的是数学上的最优解

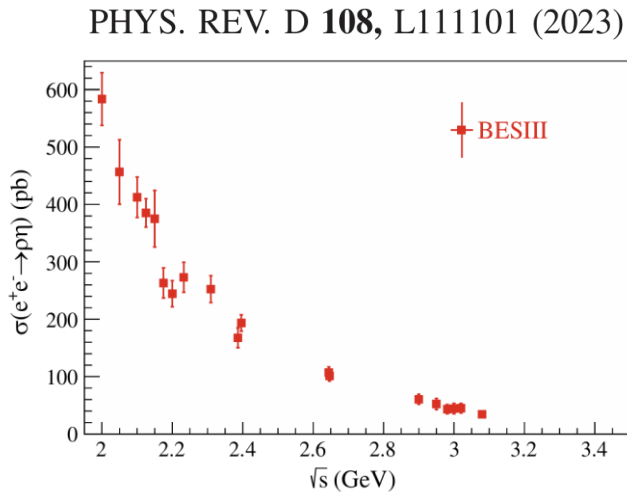
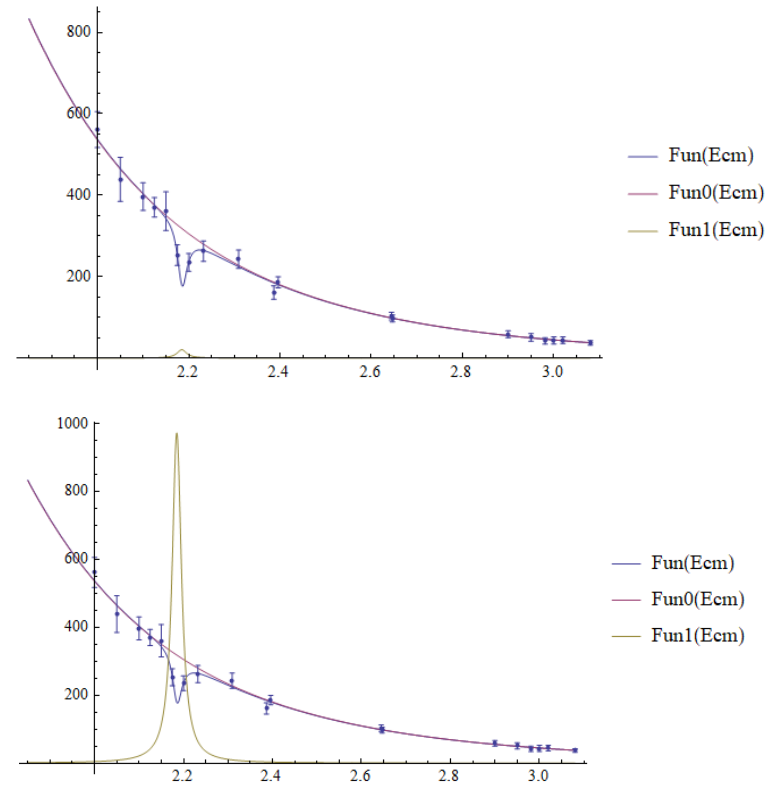


FIG. 4. Cross sections of  $e^+e^- \rightarrow \rho\eta$ . Solid squares with error bars are BESIII data.

$\mathcal{B}_R \cdot \Gamma_{e^+e^-}^R$  are determined to be  $(2044 \pm 31 \pm 4) \text{ MeV}/c^2$ ,  $(163 \pm 69 \pm 24) \text{ MeV}$ , and  $(34.6 \pm 17.1 \pm 6.0)$  or  $(137.1 \pm 73.3 \pm 2.1) \text{ eV}$ , respectively. The observed structure agrees with the properties of the  $\rho(2000)$  resonance observed in  $e^+e^- \rightarrow \omega\pi^0$  [49], which indicates the first observation of the decay  $\rho(2000) \rightarrow a_2(1320)\pi$ . To further understand the dip structure around  $2180 \text{ MeV}/c^2$  observed in the  $e^+e^- \rightarrow \rho\eta$  cross section line shape, it will be necessary to acquire more energy points in order to improve the precision of the cross section measurements in the future.



Parameter	Solution 1	Solution 2
$M_R \text{ (MeV}/c^2)$	$2185^{+6}_{-7} \pm 6$	
$\Gamma_{tot}^R \text{ (MeV)}$	$25^{+53}_{-16} \pm 11$	
$\mathcal{B}_R \Gamma_{e^+e^-}^R \text{ (eV)}$	$0.18^{+0.72}_{-0.02} \pm 0.05$	$8.4^{+20.4}_{-7.1} \pm 3.9$
$\phi \text{ (rad)}$	$4.52^{+0.01}_{-0.12} \pm 0.10$	$4.66^{+0.06}_{-0.05} \pm 0.02$

For  $N$  resonances, solutions with equally good quality:

$$1 + \binom{N-1}{1} + \binom{N-1}{2} + \dots + \binom{N-1}{N-1} = 2^{N-1}$$

东南大学  
物理学院

The multi-solution problem in experimental fitting

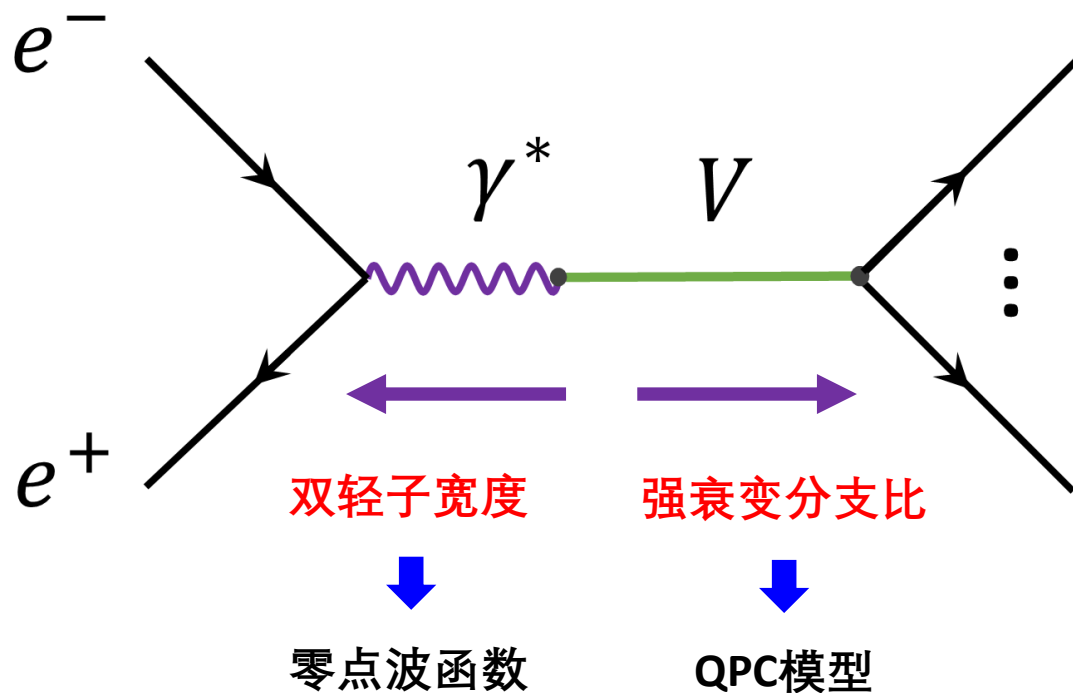
Dian-Yong Chen  
Southeast University

Yu Bai and Dian-Yong Chen, Phys. Rev. D 99, 072007 (2019)  
Yu Bai and Dian-Yong Chen, Preparing

Shanghai 2026-05-15

# 质量谱和衰变性质支撑下对截面数据的研究

在质量谱和衰变质性的支撑下，中间态贡献大小被确定



从质量谱、衰变性质和产生过程全方位地认识，  
避免盲人摸象带来的理解偏差！

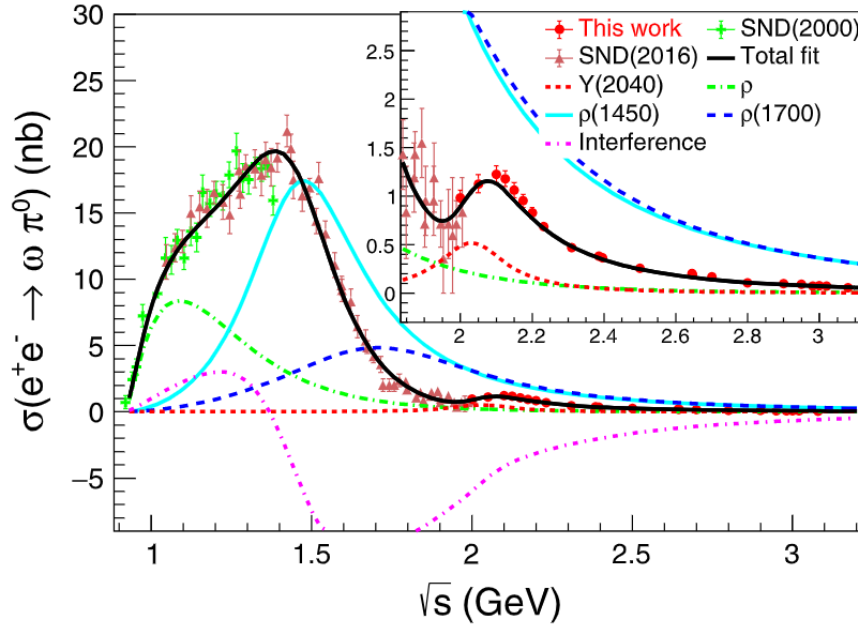
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# 2

谱学支撑下对 $\rho$ 介子产生过程的分析

# $e^+e^- \rightarrow \omega\pi^0$ 和 $\eta'\pi\pi$ 的截面测量结果

BESIII: Physics Letters B 813 (2021) 136059



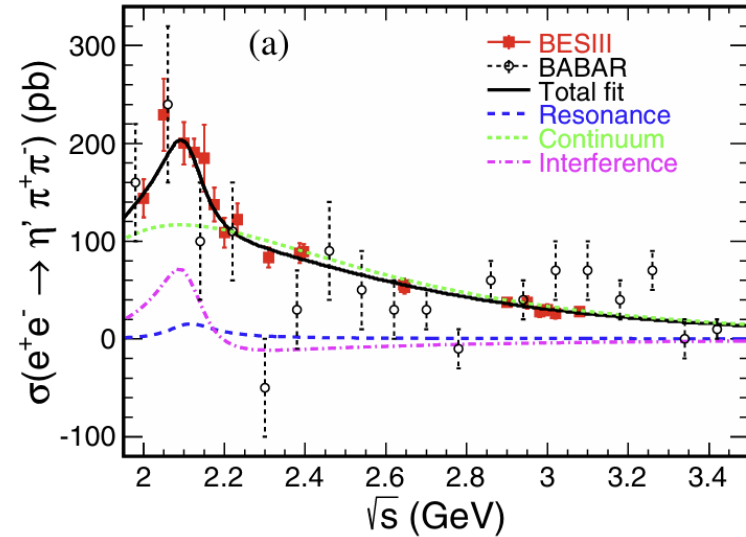
$$M = 2034 \pm 13 \text{ MeV},$$

$$\Gamma = 234 \pm 30 \text{ MeV},$$

$$\Gamma_{ee} B(\omega\pi^0) = 34 \pm 11 \text{ eV}$$

Another structure is observed in the  $\omega\pi^0$  cross section with a significance of more than  $10\sigma$  and with a mass of  $m = (2034 \pm 13 \pm 9) \text{ MeV}/c^2$ , width of  $\Gamma = (234 \pm 30 \pm 25) \text{ MeV}$  and  $\Gamma_{ee} \cdot B\omega\pi^0$  of  $(34 \pm 11 \pm 16) \text{ eV}$ . This structure could either be the  $\rho(2000)$  or the  $\rho(2150)$  state. However, the mass and width of the observed resonance is closer to the  $\rho(2000)$  resonance, which is suggested to be the  $2^3D_1$  state [41].

BESIII: Phys. Rev. D 103, 072007 (2021)



$$M = 2111 \pm 43 \pm 25 \text{ MeV},$$

$$\Gamma = 135 \pm 34 \pm 30 \text{ MeV},$$

$$\Gamma_{ee} B(a_2\pi) = 0.64 \pm 0.49 \pm 0.42$$

$$(23.3 \pm 5.3 \pm 3.3) \text{ eV}$$

the second systematic. The mass and width measured in this work agree with those of the  $Y(2040)$  resonance found in  $e^+e^- \rightarrow \omega\pi^0$  by BESIII ( $M = 2034 \pm 13 \pm 9 \text{ MeV}/c^2$ ,  $\Gamma = 234 \pm 30 \pm 25 \text{ MeV}$ ) [17] and with those of the  $\rho(2150)$  resonance found in  $e^+e^- \rightarrow \eta'\pi^+\pi^-$  by BABAR ( $M = 1990 \pm 80 \text{ MeV}/c^2$ ,  $\Gamma = 310 \pm 140 \text{ MeV}$ ) [16] within two standard deviation.

### The ground states and the first radially excited states of D-wave vector $\rho$ and $\phi$ mesons

#27

Guo-Liang Yu (North China Electric Power U., Baoding), Zhi-Gang Wang (North China Electric Power U., Baoding), Xiu-Wu Wang (North China Electric Power U., Baoding), Hui-Juan Wang (North China Electric Power U., Baoding) (Feb 22, 2021)

Published in: *Int.J.Mod.Phys.A* 36 (2021) 27, 2150197, *Int.J.Mod.Phys.A* 36 (2021) 2150197 • e-Print: 2102.11078 [hep-ph]

pdf DOI cite claim

reference search citations

### Assignments of the $Y(2040)$ , $\rho(1900)$ , and $\rho(2150)$ in the quark model

Zheng-Ya Li (Zhengzhou U.), De-Min Li (Zhengzhou U.), En Wang (Zhengzhou U.), Wen-Cheng Yan (Zhengzhou U.), Qin-Tao Song (Zhengzhou U.) (Feb 10, 2021)

Published in: *Phys.Rev.D* 104 (2021) 3, 034013 • e-Print: 2102.05356 [hep-ph]

pdf DOI cite claim

reference search 13 citations

Y(2034) =  $\rho(2^3D_1)$

TABLE IV. Decay widths of  $Y(2040)$  as the  $\rho(2^3D_1)$  (in MeV), the initial mass is set to be 2034 MeV and the masses of all the final states are taken from PDG [2].

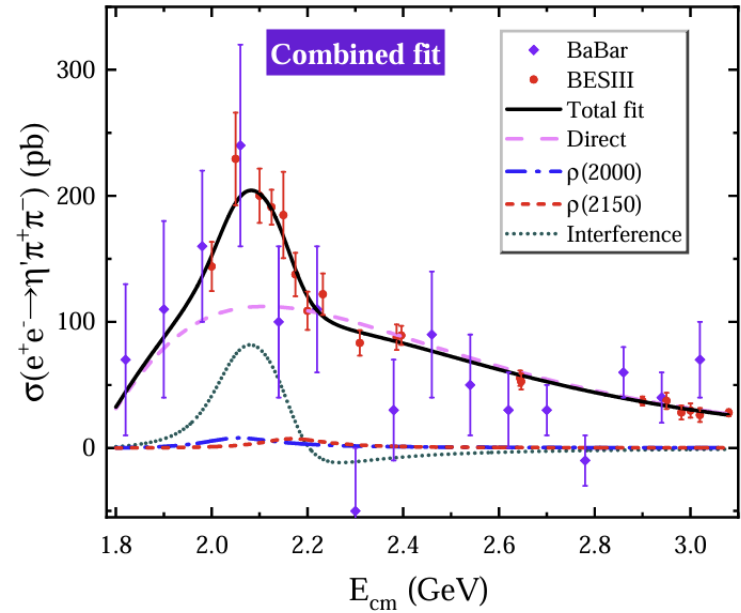
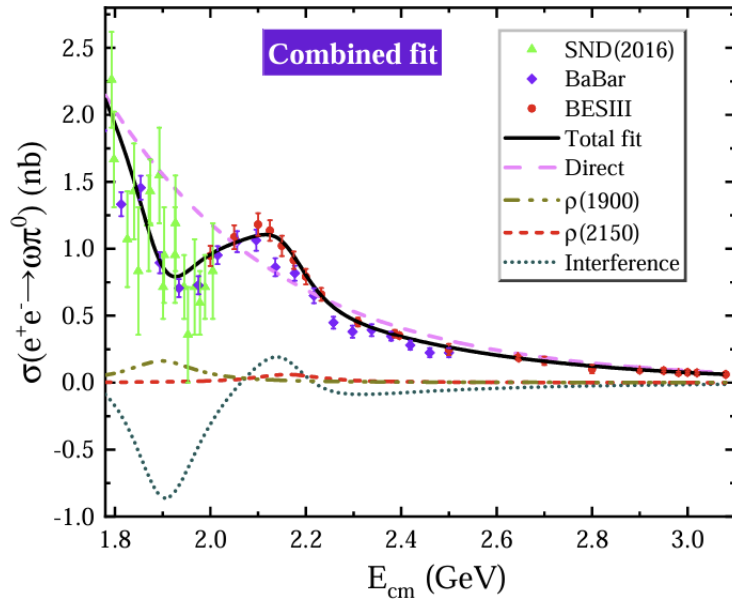
Channel	Mode	$\rho(2^3D_1)$	Mode	$\rho(2^3D_1)$
$1^- \rightarrow 0^-0^-$	$\pi\pi$	19.77	$KK$	0.32
	$\pi\pi(1300)$	14.81	$KK(1460)$	0.30
	$\pi\pi(1800)$	1.28		
$1^- \rightarrow 0^-1^-$	$\pi\omega$	6.31	$\rho\eta'$	0.013
	$\rho\eta$	2.17	$KK^*$	0.015
	$\omega(1420)\pi$	6.68	$\omega(1650)\pi$	0.14
	$KK^*(1410)$	0.57	$\rho(1450)\eta$	0.51
$1^- \rightarrow 1^-1^-$	$\rho\rho$	36.38	$K^*K^*$	0.13
$1^- \rightarrow 0^-1^+$	$a_1(1260)\pi$	26.60	$h_1(1170)\pi$	35.20
	$KK_1(1400)$	0.098	$b_1(1235)\eta$	6.23
	$KK_1(1270)$	0.19		
$1^- \rightarrow 0^-2^+$	$a_2(1320)\pi$	9.76	$KK_2^*(1430)$	0.027
$1^- \rightarrow 0^-2^-$	$\pi\pi_2(1670)$	39.15		
$1^- \rightarrow 0^-3^-$	$\pi\omega_3(1670)$	0.19		
$1^- \rightarrow 1^-1^+$	$b_1(1235)\rho$	15.86	$a_1(1260)\omega$	5.20
Total width		227.91		
Experiment		$234 \pm 30 \pm 25$ [1]		

State	$\rho(1900)$	$\rho(2150)$	$\rho(2000)$
Mass (MeV)	$1890 \pm 20$ [3]	2160 [11]	2040 [11]
$R$ ( $\text{GeV}^{-1}$ ) [11, 20]	$3.8 \sim 4.3$	$4.5 \sim 5.0$	$4.3 \sim 4.8$
$\Gamma_{e^+e^-}$ (eV) [20]	$166.31 \sim 213.91$	$78.72 \sim 96.80$	$28.74 \sim 16.74$
$\mathcal{B}(\omega\pi^0)$ ( $10^{-3}$ ) [11]	$0.18 \sim 24.79$	$18.22 \sim 88.76$	$15.01 \sim 19.65$
$\mathcal{B}(\rho\eta')$ ( $10^{-3}$ ) [11]	$6.85 \times 10^{-4} \sim 2.73$	$0.94 \sim 2.65$	$5.55 \sim 15.78$
$\Gamma_{e^+e^-}\mathcal{B}(\omega\pi^0)$ (eV)	$0.03 \sim 5.31$	$1.76 \sim 6.99$	$0.23 \sim 0.38$
$\Gamma_{e^+e^-}\mathcal{B}(\rho\eta')$ (eV)	$0.01 \times 10^{-2} \sim 0.45$	$0.10 \sim 0.20$	$0.11 \sim 0.24$

联合分支比的理论预言预实验结果存在量级差异，为什么没有 $\rho(4S)$ 的信号

**Identifying the contribution of higher  $\rho$  mesons around 2 GeV in the  $e^+e^- \rightarrow \omega\pi^0$  and  $e^+e^- \rightarrow \rho\eta'$  processes**

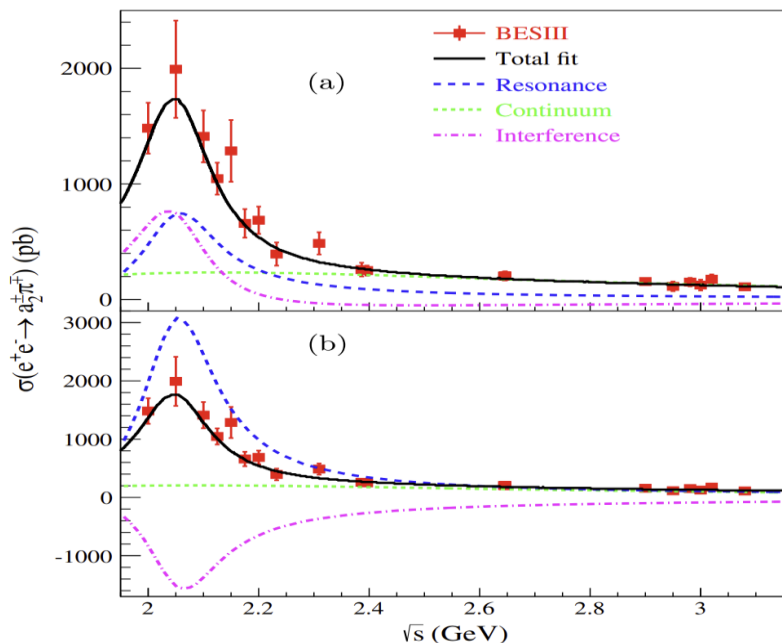
Qin-Song Zhou,<sup>1,2,\*</sup> Jun-Zhang Wang,<sup>1,2,†</sup> Xiang Liu<sup>1,2,3,4,‡</sup> and Takayuki Matsuki<sup>5,§</sup>



**$Y(2040)$ 是 $\rho(3S)$ 和 $\rho(4S)$ 干涉的结果**

# $e^+e^- \rightarrow a_2(1320)\pi$ 的截面测量结果

BESIII: Phys. Rev. D 108, L111101 (2023)



PHYS. REV. D 102, 034037

State	$M_{\text{exp}}$ (MeV)	$R$ ( $\text{GeV}^{-1}$ ) [6]	$\Gamma_{e^+e^-}$ (keV)
$\rho(1900)$	$1909 \pm 17 \pm 25$ [16]	$3.85 \sim 4.28$	$0.1958 \sim 0.1578$
$\rho(2150)$	$2150 \pm 17$ [6]	$4.74 \sim 4.98$	$0.0888 \sim 0.0806$
$\rho(2000)$	$2000 \pm 30$ [38]	$4.34 \sim 4.80$	$0.0204 \sim 0.0160$
$\rho(2270)$	$2265 \pm 40$ [31]	$4.40 \sim 4.80$	$0.0163 \sim 0.0129$

TABLE II. Resonant parameters from the fit to  $e^+e^- \rightarrow a_2(1320)\pi$  cross sections. The first uncertainty is statistical, and the second one is systematic.

Parameter	Solution 1	Solution 2
$M_R$ ( $\text{MeV}/c^2$ )	$2044 \pm 31 \pm 4$	
$\Gamma_{\text{tot}}^R$ (MeV)	$163 \pm 69 \pm 24$	
$\mathcal{B}_R \Gamma_{e^+e^-}^R$ (eV)	$34.6 \pm 17.1 \pm 6.0$	$137.1 \pm 73.3 \pm 2.1$
$\phi$ (rad)	$1.95 \pm 0.97 \pm 0.06$	$4.35 \pm 0.48 \pm 0.43$

( $137.1 \pm 73.3 \pm 2.1$ ) eV, respectively. The observed structure agrees with the properties of the  $\rho(2000)$  resonance observed in  $e^+e^- \rightarrow \omega\pi^0$  [49], which indicates the first observation of the decay  $\rho(2000) \rightarrow a_2(1320)\pi$ . To further

$\rho(2^3D_1)$ 态的双轻子宽度约为20 eV, 且远小于 $\rho(4^3S_1)$ 的双轻子宽度

如果  $Y(2034) \equiv Y(2044) \equiv \rho(2D) \Rightarrow Br(\rho(2D) \rightarrow \omega\pi^0/a_2(1320)\pi) > 100\%$  !

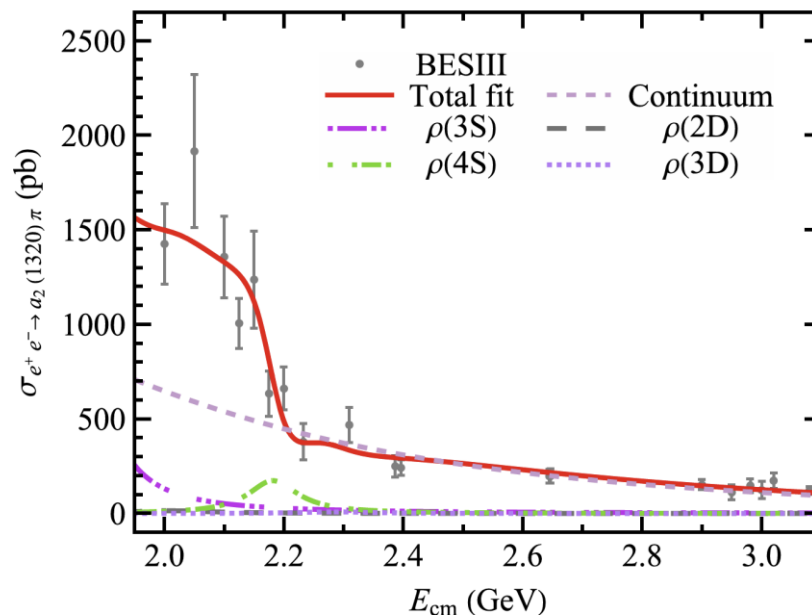
# 在Fano干涉的框架下理解Y(2044)

$$\sigma(s) = |\mathcal{M}^{\text{Dir}} + \sum_k e^{i\phi_k} \mathcal{M}_k^{\rho^*}|^2$$

$$\mathcal{M}^{\text{Dir}} = C_0 \cdot s^{-n} \sqrt{\Phi_2(s)}$$

$$\mathcal{M}^{\rho^*} = \frac{\sqrt{12\pi\Gamma_{e^+e^-}^{\rho^*} \mathcal{B}_{a_2(1320)\pi}^{\rho^*} \Gamma_{\rho^*}^{\text{tot}}}}{s - M_{\rho^*}^2 + iM_{\rho^*}\Gamma_{\rho^*}^{\text{tot}}} \sqrt{\frac{\Phi_2(s)}{\Phi_2(M_{\rho^*}^2)}}$$

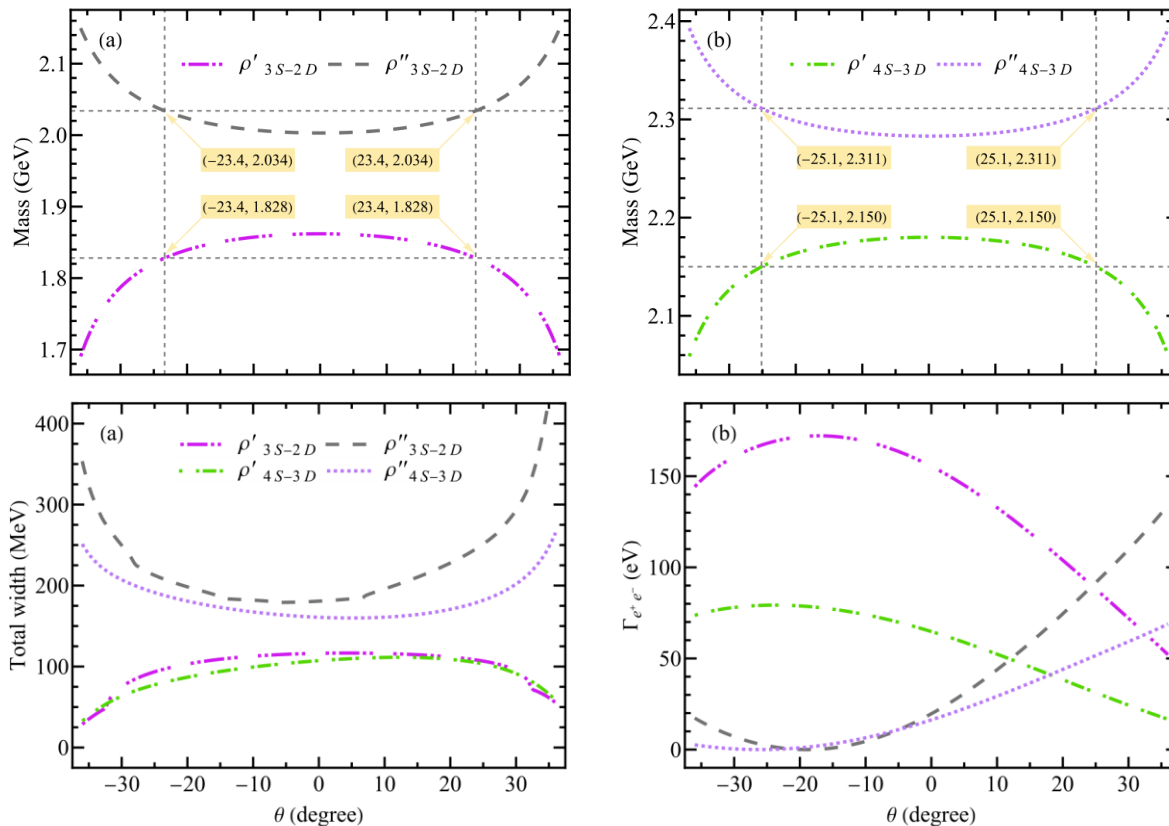
Parameters	$\rho(3S)$	$\rho(2D)$	$\rho(4S)$	$\rho(3D)$
$M_{\rho^*}$ (MeV)	1862	2003	2180	2283
$\Gamma_{\rho^*}^{\text{tot}}$ (MeV)	115	179	102	158
$\Gamma_{\rho^*}^{e^+e^-}$ (eV)	156	20	63	16
$\mathcal{B}_{\rho^*}^{\omega\pi^0}$ ( $10^{-2}$ )	19.75	0.34	3.31	0.12
$\mathcal{B}_{\rho^*}^{a_2(1320)\pi}$ ( $10^{-2}$ )	18.1	0.40	5.52	0.29



需要存在一个质量在2044 MeV左右，且在该过程有较大贡献的  $\rho$ -like 态。

# $S$ - $D$ 混合框架下 $\rho$ 介子态的质量谱和衰变性质

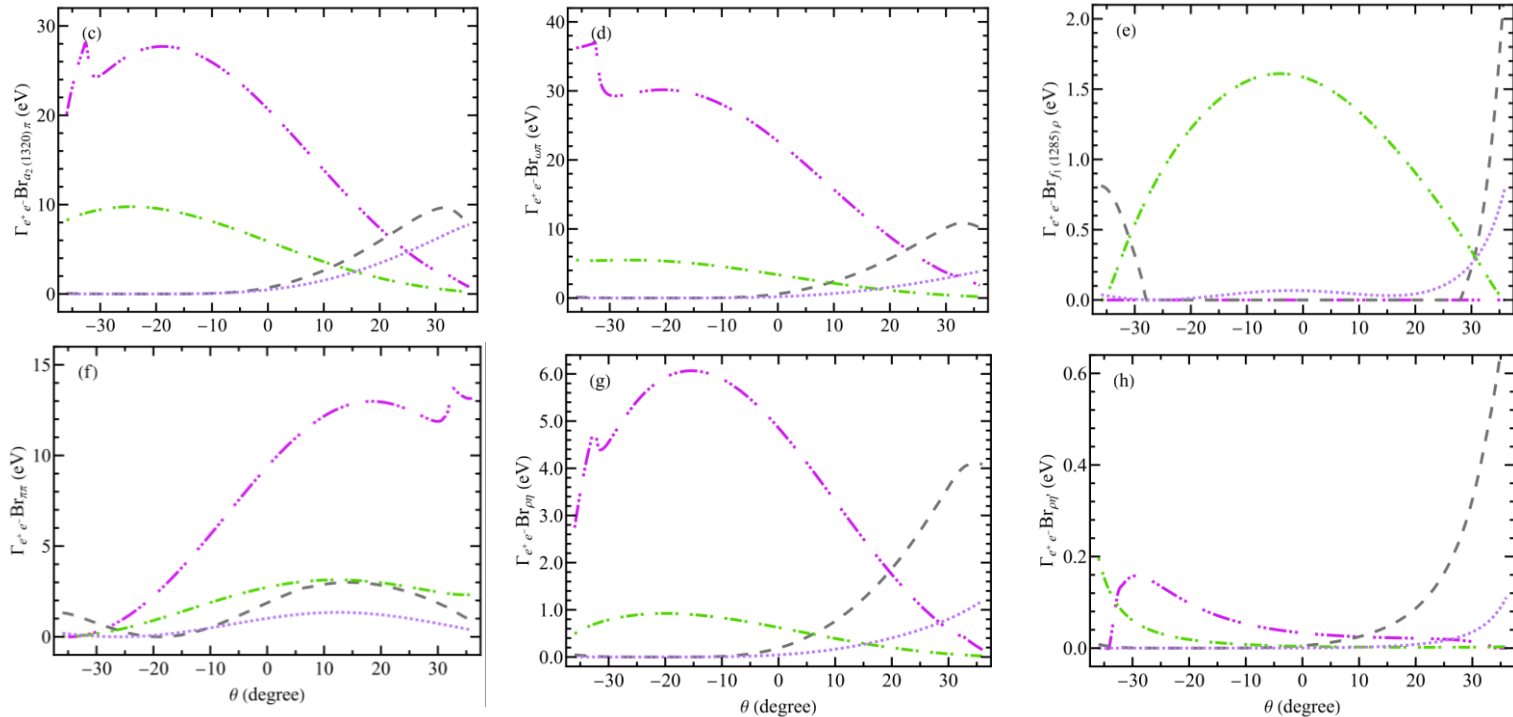
$$\begin{pmatrix} |\rho'_{nS-(n-1)D}\rangle \\ |\rho''_{nS-(n-1)D}\rangle \end{pmatrix} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} |\rho(nS)\rangle \\ |\rho((n-1)D)\rangle \end{pmatrix}$$



- $\rho''_{nS-(n-1)D}$  的  $\Gamma_{e^+e^-}$  相较于纯的  $\rho((n-1)D)$  可能会显著增大,  $Y(2044)$  有可能是来自  $\rho''_{3S-2D}$  的贡献;
- 混合角需要特征衰变道确定。

# $S$ - $D$ 混合框架下 $\rho$ 介子态的质量谱和衰变性质

- · - · -  $\rho'_{3S-2D}$    
 - - -  $\rho''_{3S-2D}$    
 - · - · -  $\rho'_{4S-3D}$    
 - · - · -  $\rho''_{4S-3D}$



□  $e^+e^- \rightarrow a_2(1320)\pi$ :  $\rho''_{3S-2D}$  在该过程有较大贡献  $\Rightarrow \theta_{3S-2D} > 0$ ;

□  $e^+e^- \rightarrow \omega\pi^0$ :  $Y(2034) \equiv \rho''_{3S-2D} \Rightarrow \theta_{3S-2D} = +23.4^\circ$ ;

□  $e^+e^- \rightarrow f_1(1285)\pi^+\pi^-$ :  $\rho(2150) \equiv \rho'_{4S-3D} \Rightarrow \theta_{4S-3D} = \pm 25.1^\circ$ .

# $S$ - $D$ 混合框架下 $\rho$ 介子态的质量谱和衰变性质

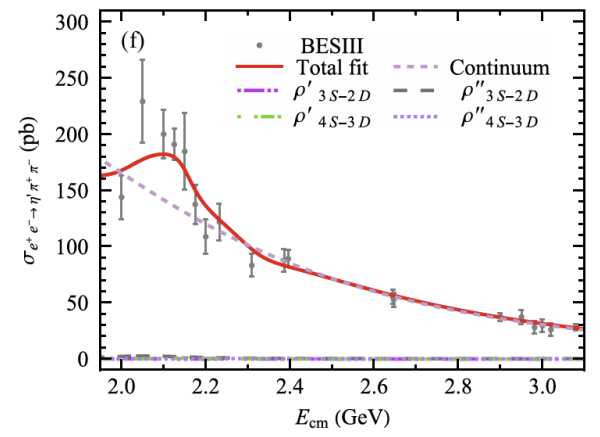
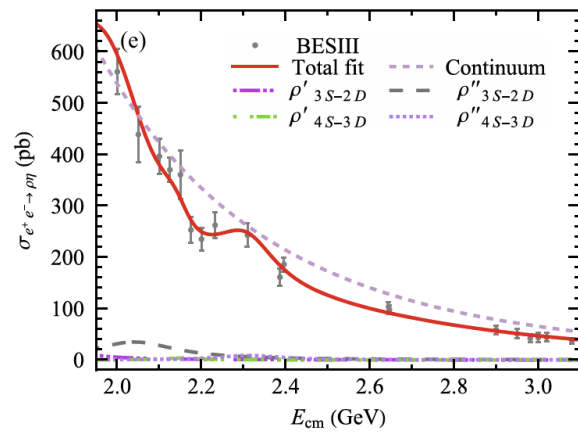
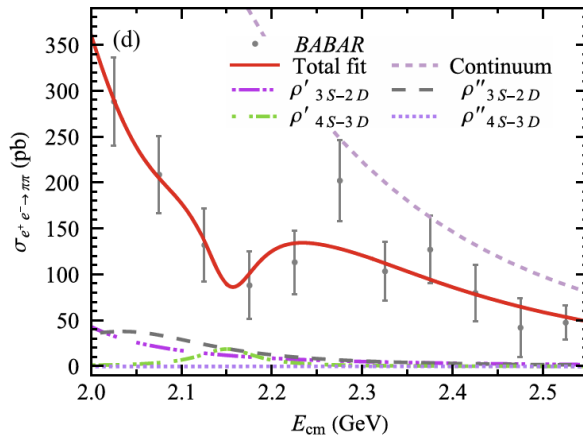
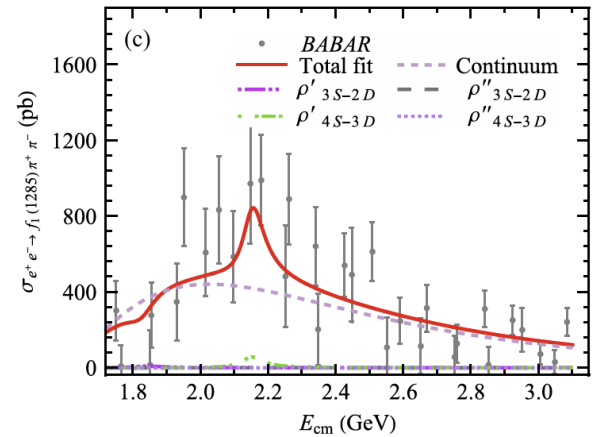
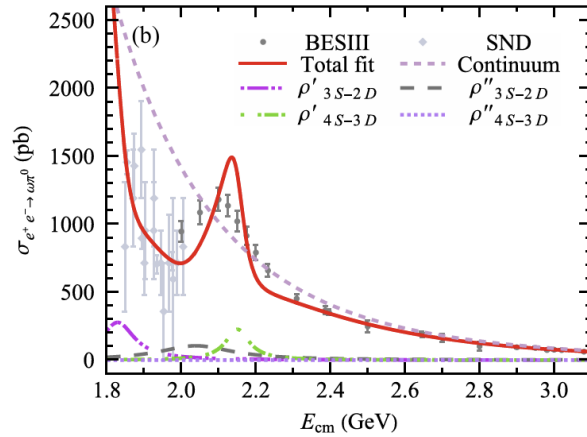
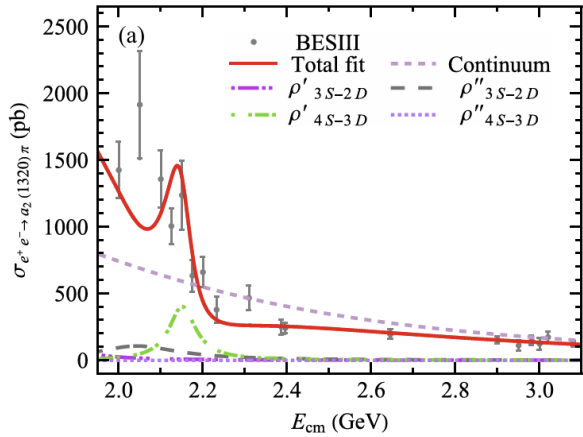
TABLE III: Masses and decay properties of  $\rho'_{3S-2D}$ ,  $\rho''_{3S-2D}$ ,  $\rho'_{4S-3D}$ , and  $\rho''_{4S-3D}$ . Here, mixing angles for  $3S$ - $2D$  wave and  $4S$ - $3D$  wave admixtures are taken as  $\pm 23.4^\circ$  and  $\pm 25.1^\circ$ , respectively.

Parameters	Positive angle				Negative angle			
	$\rho'_{3S-2D}$	$\rho''_{3S-2D}$	$\rho'_{4S-3D}$	$\rho''_{4S-3D}$	$\rho'_{3S-2D}$	$\rho''_{3S-2D}$	$\rho'_{4S-3D}$	$\rho''_{4S-3D}$
Mass (MeV)	1828	2034	2150	2311	1828	2034	2150	2311
$\Gamma_{\text{tot}}$ (MeV)	109	243	103	182	97	207	77	192
$\Gamma_{e^+e^-}$ (eV)	93.35	85.94	31.03	51.81	169.59	1.14	79.21	0.02
$\Gamma_{e^+e^-} \mathcal{B}_{a_2(1320)\pi}$ (eV)	5.51	7.25	1.11	4.75	27.15	$3.67 \times 10^{-4}$	9.76	$5.52 \times 10^{-7}$
$\Gamma_{e^+e^-} \mathcal{B}_{\omega\pi^0}$ (eV)	6.87	7.17	0.72	2.20	30.01	$5.96 \times 10^{-7}$	5.49	$2.90 \times 10^{-6}$
$\Gamma_{e^+e^-} \mathcal{B}_{f_1(1285)\rho}$ (eV)	...	...	0.63	0.11	...	...	0.92	$3.28 \times 10^{-4}$
$\Gamma_{e^+e^-} \mathcal{B}_{\pi\pi}$ (eV)	12.70	2.61	2.74	1.00	1.38	0.14	0.46	$2.01 \times 10^{-3}$
$\Gamma_{e^+e^-} \mathcal{B}_{\rho\eta}$ (eV)	1.29	2.39	0.12	0.58	5.63	$1.01 \times 10^{-6}$	0.89	$7.35 \times 10^{-7}$
$\Gamma_{e^+e^-} \mathcal{B}_{\rho\eta'}$ (eV)	0.02	0.13	0.02	0.02	0.12	$1.76 \times 10^{-6}$	0.03	$2.62 \times 10^{-7}$

Parameters	$\Gamma_{e^+e^-} \mathcal{B}_{f_1(1285)\pi^+\pi^-}$ (eV)	$\Gamma_{e^+e^-} \mathcal{B}_{\eta'\pi^+\pi^-}$ (eV)
$\rho'_{3S-2D}$	0.20 (0.21)	0.03 (0.19)
$\rho''_{3S-2D}$	0.02 (0.04)	0.18 ( $2.52 \times 10^{-6}$ )
$\rho'_{4S-3D}$	0.93 (1.38)	0.03 (0.04)
$\rho''_{4S-3D}$	0.20 (0.0006)	0.03 ( $4.3 \times 10^{-7}$ )

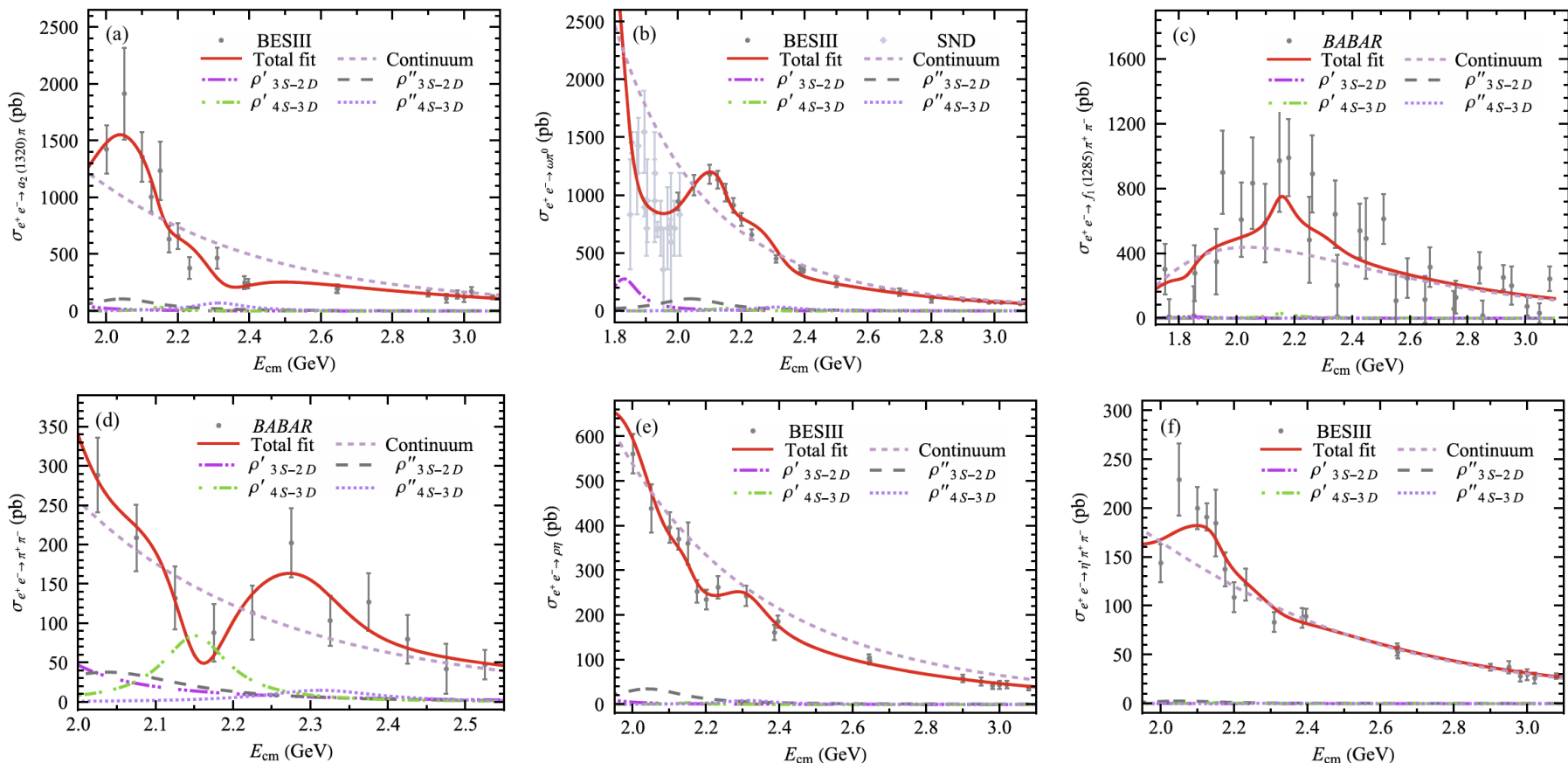
在 $e^+e^- \rightarrow f_1(1285)\pi^+\pi^-$ 过程中，  
 $\rho'_{3S-2D}$ 和 $\rho''_{3S-2D}$ 是压低的。

# $\theta_{4S-3D} = -25.1^\circ$ 的拟合结果



$\theta_{4S-3D} = -25.1^\circ$  不能描述好截面数据

# $\theta_{4S-3D} = +25.1^\circ$ 的拟合结果



□  $\theta_{4S-3D} = +25.1^\circ$  可以较好地描述截面数据；

□ 在误差范围内可认为  $Y(2044)$  与  $Y(2034)$  是同一个态；

□  $Y(2034)$  是  $\rho''_{3S-2D}$  的一个很好的候选态。

# 总结

- 基于谱学研究对截面数据的分析可能会提供更丰富的信息，从而帮助我们构建2 GeV能区矢量轻介子态；
- S-D混合效应在理解2 GeV能区矢量轻介子态的性质时可能是需要考虑的，混合角需要结合实验对一些特征衰变道的测量结果来确定；
- S-D混合的来源和混合角的大小（势模型中的张量项对混合角的贡献不会太大）还需要从动力学角度（耦合道效应？）进一步探索。

谢谢大家！