对撞物理

第九章 夸克偶素

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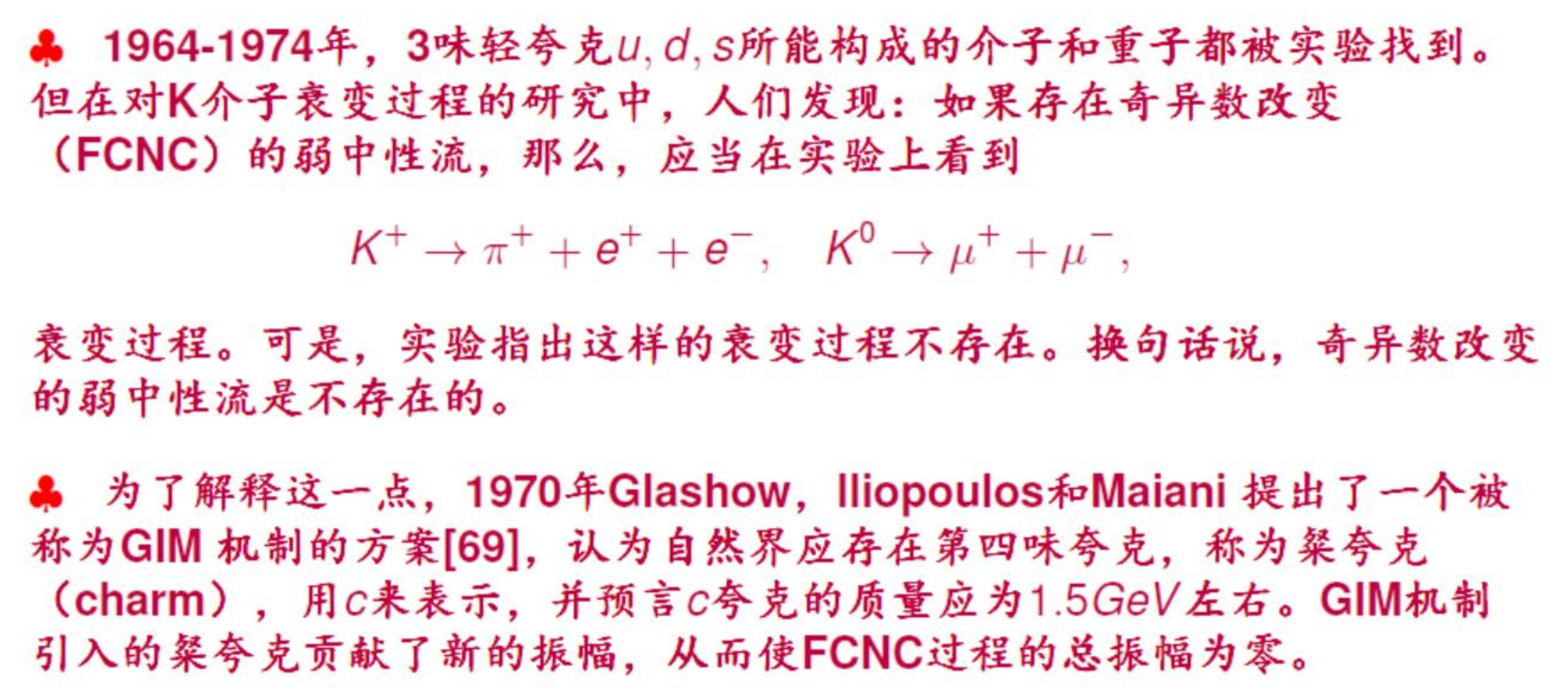
1. 粲夸克偶素：J/ψ的发现与性质



♣ 1964-1974年，3味轻夸克u, d, s所能构成的介子和重子都被实验找到。但在对K介子衰变过程的研究中，人们发现：如果存在奇异数改变（FCNC）的弱中性流，那么，应当在实验上看到

$$K^+ \to \pi^+ + e^+ + e^-, \quad K^0 \to \mu^+ + \mu^-,$$

衰变过程。可是，实验指出这样的衰变过程不存在。换句话说，奇异数改变的弱中性流是不存在的。

♣ 为了解释这一点，1970年Glashow，Iliopoulos和Maiani 提出了一个被称为GIM 机制的方案[69]，认为自然界应存在第四味夸克，称为粲夸克（charm），用c来表示，并预言c夸克的质量应为1.5GeV左右。GIM机制引入的粲夸克贡献了新的振幅，从而使FCNC过程的总振幅为零。

1. 粲夸克偶素：J/ψ的发现与性质

♣ 1974年12月，美国“物理评论快报”(Physical Review Letters) 同时刊登了三篇文章[70] (Phys.Rev.Lett 33 (1974) 1404; *ibid* 33(1974)1406; *ibid* 33 (1974) 1408)，宣布发现粲夸克偶素：J/ψ 粒子。

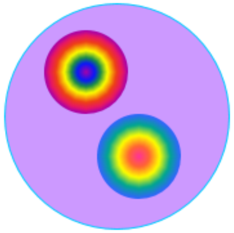
♣ 第一篇是丁肇中实验组的文章(1974年11月12日投稿)。他们宣布，丁肇中教授领导的实验组在美国布鲁克海文国家实验室30GeV的加速器上，利用大型精密双臂谱仪，通过测量高能质子打击铍靶所产生的e^+e^-对有效质量谱，发现了一个质量为3.1 GeV(如图-6.11所示)，寿命比较长（$\sim 10^{-20}s$）的粒子，命名为J粒子。

♣ 同时，B. Richter等人在Stanford直线加速器中心的正负电子对撞实验上，利用磁探测器（MARK-I）测量e^+e^-湮灭产物，发现了同一个重粒子，但他们称之为ψ粒子（第二篇文章，74年11月13日投稿）。第三篇则是意大利Frascadi实验室，在知道美国布鲁克海文国家实验室发现J/ψ粒子的消息后，立即提高了其安东尼加速器的能量，测量了J粒子的性质，并在11 月18日寄出初步结果，赶在同一期快报上发表。

♣ J/ψ粒子的发现给粲夸克的存在给出了直接的实验证据，使强子结构理论的研究展现出新的局面。这一出乎意料的实验发现和其在粒子物理学上的重要意义立即轰动了物理界。由于这一工作，丁肇中教授和Richter教授共同获得了1976年的诺贝尔物理奖。

1. 粲夸克偶素：J/ψ的发现与性质

♣ 1. J/ψ粒子的主要性质：J/ψ粒子是$c\bar{c}$束缚态-粲偶素。与氢原子类似[72]，粲偶素的不同状态可以用主量子数n和总角动量量子数J,轨道角动量L,总自旋S来表示：记为$^{2S+1}L_J$。根据前面的讨论我们知道，粲偶素的宇称和电荷共轭分别为：



$$\mathcal{P} = \mathcal{P}(c\bar{c})(-1)^L = (-1)^{L+1}, \qquad C = (-1)^{L+S}.$$

$J/\psi(1S)$粒子的主要性质如下：

$$\begin{aligned} m(J/\Psi) &= (3096.916 \pm 0.011)\mathrm{MeV}, \\ \Gamma &= (92.9 \pm 2.8)\mathrm{keV}, \ \ \Gamma(e^+e^-) = (5.55 \pm 0.14)\mathrm{keV}, \\ I^G(J^{PC}) &= 0^-(1^{--}). \end{aligned}$$

(6

1. 粲夸克偶素：J/ψ的发现与性质

♣ J/ψ粒子的一个显著特点就是衰变宽度很窄,远小于普通强子的衰变宽度： $\Gamma_\rho \sim 149.1$**MeV**, $\Gamma_\omega \sim 8.49$**MeV**, $\Gamma_\phi \sim 4.26$**MeV**。
但是，J/ψ的轻子衰变宽度$\Gamma(J/\psi \to e^+e^-)$ 和ρ, ω, ϕ介子的轻子衰变宽度的差别不大

$$\begin{aligned}\Gamma(\rho \to e^+e^-) &= 7.04 \pm 0.06\mathrm{keV},\\ \Gamma(\omega \to e^+e^-) &= 0.60 \pm 0.02\mathrm{keV},\\ \Gamma(\phi \to e^+e^-) &= 1.4\mathrm{keV}.\end{aligned}$$

也就是说，电磁衰变在这里没有发生问题。

♣ 2. J/ψ及相近粒子谱： J/ψ是$\bar{c}c$束缚态（**Charmonium**），与电子—正电子偶素的能级结构非常类似。 实验上发现了J/ψ 的径向激发态($\psi(2S)$, ψ')和角动量激发态(χ_{ci})等高激发态。 图-6.12给出了粲偶素衰变的能级图。每一个状态线条的宽度与该状态粒子的衰变宽度成正比。

♣ 我们引入粲量子数“**C**”来描写第四味夸克“**Charm**”。 在强相互作用中，粲数是守恒的。在弱相互作用中，粲数是不守恒的，存在选择定则$\Delta C = 1$。盖尔曼-西岛关系式也改写为：

$$Q = I_3 + \frac{1}{2}(b + S + C).$$

1. 粲夸克偶素：J/ψ的发现与性质

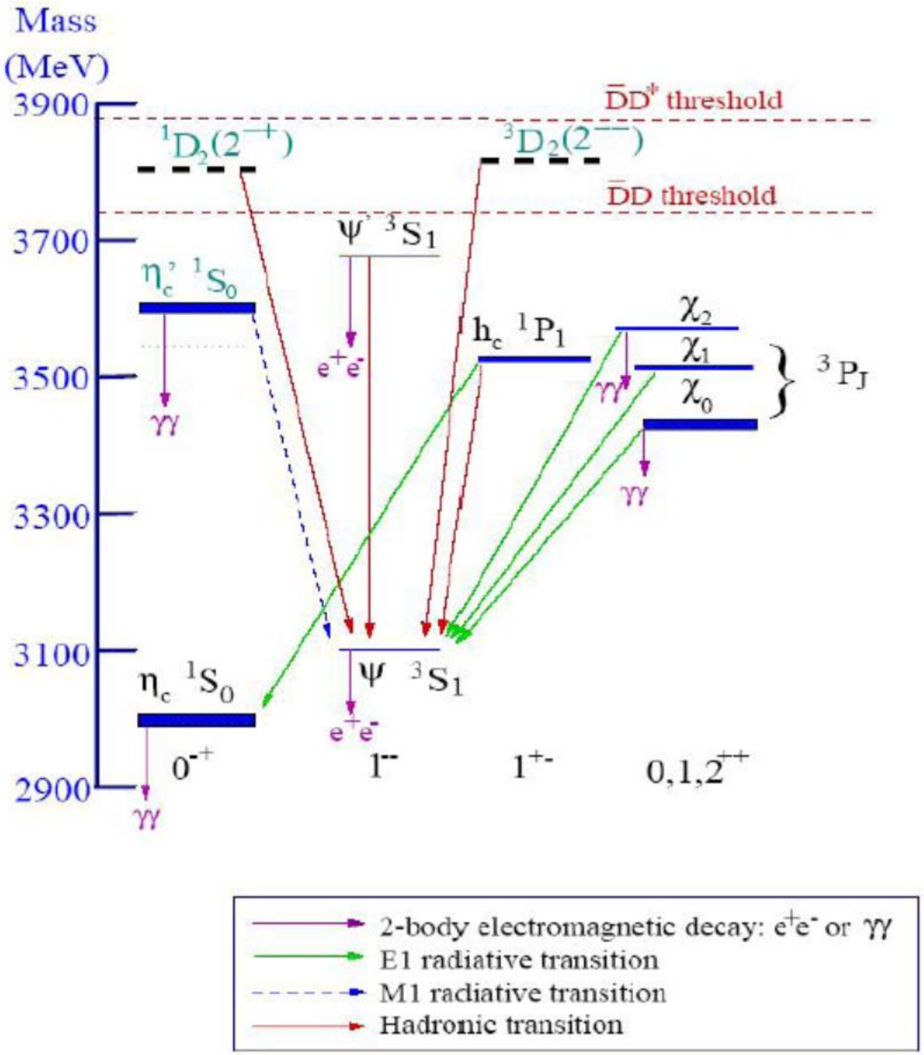


Figure: 6.12 粲偶素衰变的能级图。

1. 粲夸克偶素：J/ψ的发现与性质

♣ 实验测量结果表明，$J/\psi(1S)(0^-(1^{--}))$和其径向激发态ψ′的衰变宽度只有几十个keV，比其它强子的衰变宽度小两个量级：

$$\begin{aligned}\Gamma(J/\Psi(1S)) &= (92.9\pm2.8)\mathrm{keV}, \quad m_{J/\Psi(1S)} = (3096.916\pm0.011)\ \mathrm{MeV},\\ \Gamma(\Psi'(2S)) &= (304\pm9)\mathrm{keV}, \quad m_{\Psi'(2S)} = (3686.109^{+0.012}_{-0.014})\mathrm{MeV}.\end{aligned}$$

♣ $\psi''(3770)$或其它的ψ高激发态的宽度都大于25MeV，

$$\begin{aligned}\Gamma(\Psi(3770)) &= (27.2\pm1.7)\ \mathrm{MeV}, \quad m_{\Psi(3770)} = (3773.15\pm0.33)\ \mathrm{MeV},\\ \Gamma(\Psi(4040)) &= (80\pm10)\ \mathrm{MeV}, \quad m_{\Psi(4040)} = (4039\pm1)\ \mathrm{MeV},\\ \Gamma(\Psi(4160)) &= (103\pm8)\ \mathrm{MeV}, \quad m_{\Psi(4160)} = (4153\pm3)\ \mathrm{MeV},\\ \Gamma(\Psi(4260)) &= (95\pm14)\ \mathrm{MeV}, \quad m_{\Psi(4260)} = (4263^{+8}_{-9})\ \mathrm{MeV},\\ \Gamma(\Psi(4360)) &= (74\pm18)\ \mathrm{MeV}, \quad m_{\Psi(4360)} = (4361\pm13)\ \mathrm{MeV},\\ \Gamma(\Psi(4415)) &= (62\pm20)\ \mathrm{MeV}, \quad m_{\Psi(4415)} = (4421\pm4)\ \mathrm{MeV}.\end{aligned}$$

这些高激发态和其它强子（ρ,ω等）的衰变宽度相当。

1. 粲夸克偶素：J/ψ的发现与性质

♣ 这两类粲偶素介子的宽度差别有两个数量级。这个问题的答案只能在动力学机理上来找。 按照非相对论组分夸克模型(NRCQM)，所有的J/Ψ粒子都是$c\bar{c}$束缚态。D介子是带一个c夸克的介子，例如$D^+ = (c\bar{d})$。因为最轻的D介子的质量是1870 MeV，所以，$J/\psi(1S)$, $\Psi'(2s)$质量均小于$2m_D$，不能衰变到两个D介子，只能通过强湮灭（图6.13a）过程衰变到轻夸克(u,d,s)介子，根据上一节的OZI规则，这些湮灭道是被强烈压低的，因此这两个介子的衰变宽度很窄。

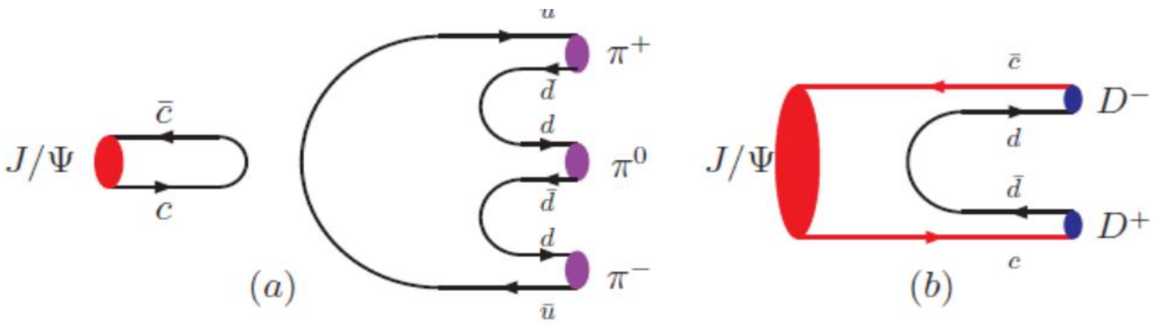


Figure: 6.13 J/Ψ 介子的可能衰变道。(a) 被强烈压低的湮灭衰变道，图中的半椭圆表示可能的高阶QCD和电弱修正，(b) 被OZI 规则允许但相空间不允许的可能衰变道。

1. 粲夸克偶素：J/ψ的发现与性质

♣ 而$\psi''(3770)$或其它的ψ高激发态的质量则大于$2m_D$. 介子中的原有的价夸克c和价反夸克$\bar{c}$都可以直接转化为末态粒子的价夸克，即通过如图-6.13b所示的衰变道衰变到DD对。因此$\psi''(3770)$或其它的ψ高激发态的衰变宽度比较轻的$J/\psi(1S)$, $J/\psi(2S)$大两个量级。从费曼图（图-6.13,图-6.14）上可以看出，经湮灭道衰变的价夸克费曼图实际上断成两个互不相联的部分，需要由至少三个胶子连接两部分。通过图-6.13b衰变的价粒子费曼图是一个整体，初态粒子的价夸克c和$\bar{c}$也是末态D介子的价夸克。

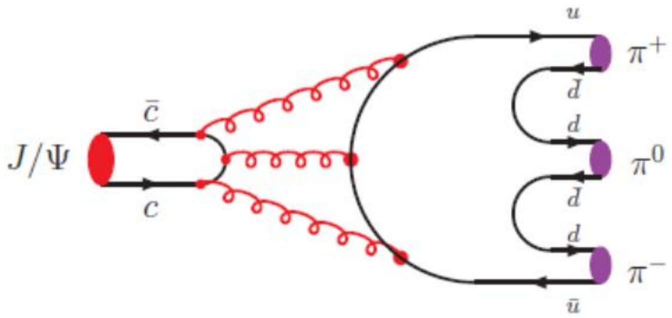


Figure: 6.14 通过3胶子交换实现的$J/\Psi \rightarrow 3\pi$ 湮灭道产生过程。

1. 粲夸克偶素：J/ψ的发现与性质

♣ **量子色动力学的解释：** 胶子是带颜色的，单个胶子不能连接湮灭图。而由于C宇称守恒的限制，矢量介子不能衰变到两个规范粒子、例如两个光子或者两个胶子。 因而如图-6.14所示，只能通过至少三个胶子衰变。这样，领头阶的贡献已经是QCD的高阶图了:$\propto \alpha_s^3$，压低效应明显。

♣ **考虑$\eta_c(2980)$介子。** 该粒子的量子数为$I^G(J^{PC}) = 0^+(0^{-+})$，是赝标量介子。其质量为$m(\eta_c) = 2981.0 \pm 1.1$ MeV。$\eta_c(2980)$ 介子质量比J/ψ 粒子还低，因而也不能衰变到两个D介子。也是OZI禁戒的过程。但它的宽度是$\Gamma = (29.7 \pm 1.0)$ MeV，虽然没有达到100 多MeV的量级，却比J/ψ的宽度大得多。原因就是，η_c是赝标量介子，它能衰变到两个胶子，也就是说可以通过两个胶子衰变。没有需要通过三个胶子衰变的J/ψ压低效应强。

♣ **同样地，$\chi_{c0}(3415)$也是OZI禁戒的过程。** 由于是标量介子$[0^+(0^{++})]$，可以通过两个胶子衰变，$\Gamma = (10.4 \pm 0.6)$ MeV，压低的不厉害。$\chi_{c0}(3511)$也是OZI禁戒的过程。由于是轴矢量介子$[0^+(1^{++})]$，只可以通过三个胶子衰变，$\Gamma = (0.86 \pm 0.05)$ MeV，虽质量大，却宽度窄。

♣ OZI规则最早是在ϕ和ω介子到$\pi^+\pi^-\pi^0$道的衰变中总结出来的。而且在许多衰变过程中都成立。在现已发现的不稳定粒子中，有十几种粒子的强衰变都是OZI禁戒过程。

2. 底夸克偶素：Υ的发现与性质

♣ 1977年，由L.M. Lederman领导的费米实验室E288实验组在400GeV质子-原子核对撞实验中发现了一个长寿命的重粒子，命名为Υ粒子[$0^-(1^{--})$][73]。前3个Υ共振态的主要性质如下：

$$\Upsilon(1S):\quad m=(9460.30\pm0.26)\ \mathrm{MeV},\quad \Gamma=(54.02\pm1.25)\ \mathrm{keV},$$
$$\Upsilon(2S):\quad m=(10.0233\pm0.0003)\ \mathrm{GeV},\quad \Gamma=(31.98\pm2.63)\ \mathrm{keV},$$
$$\Upsilon(3S):\quad m=(10.3552\pm0.0005)\ \mathrm{GeV},\quad \Gamma=(20.32\pm1.85)\ \mathrm{keV},$$

$\Upsilon(1S,2S,3S)$粒子也是衰变宽度很窄(20 – 50 KeV)，寿命长。$\Upsilon=(b\bar{b})$ 是由一对正反底夸克作为价夸克的介子，底夸克的质量约为4.6GeV左右。含b夸克的最轻粒子是$B^+=(u\bar{b})$和$B^0=d\bar{b}$粒子，$m_B=5279MeV$，因此$\Upsilon(1S)-\Upsilon(3S)$介子不可能衰变为一对正反B 介子。

♣ 对前3个Υ共振态，$2B$衰变道没有打开，强衰变道都是OZI禁戒的，分支比最大的衰变道也是二级电磁衰变的l^+l^-，宽度很窄。它们只能通过湮灭道做强衰变，所以衰变概率被严重压低，表现出明显的“重质量，窄宽度”性质。 但对$\Upsilon(4S)$以及更高质量的Υ高激发态，则有：

$$\Upsilon(4S):\quad m=10.5794(12)\ \mathrm{GeV},\quad \Gamma=(20.5\pm2.5)\ \mathrm{MeV},$$
$$\Upsilon(5S):\quad m=10.876(11)\ \mathrm{GeV},\quad \Gamma=(55\pm28)\ \mathrm{MeV},$$
$$\Upsilon(11020):\quad m=11.019(8)\ \mathrm{GeV},\quad \Gamma=(79\pm16)\ \mathrm{MeV}.$$

显然，这些Υ 高激发态均可以衰变到两个B介子，因而具有几十个MeV 的衰变宽度。

2. 底夸克偶素：Υ的发现与性质

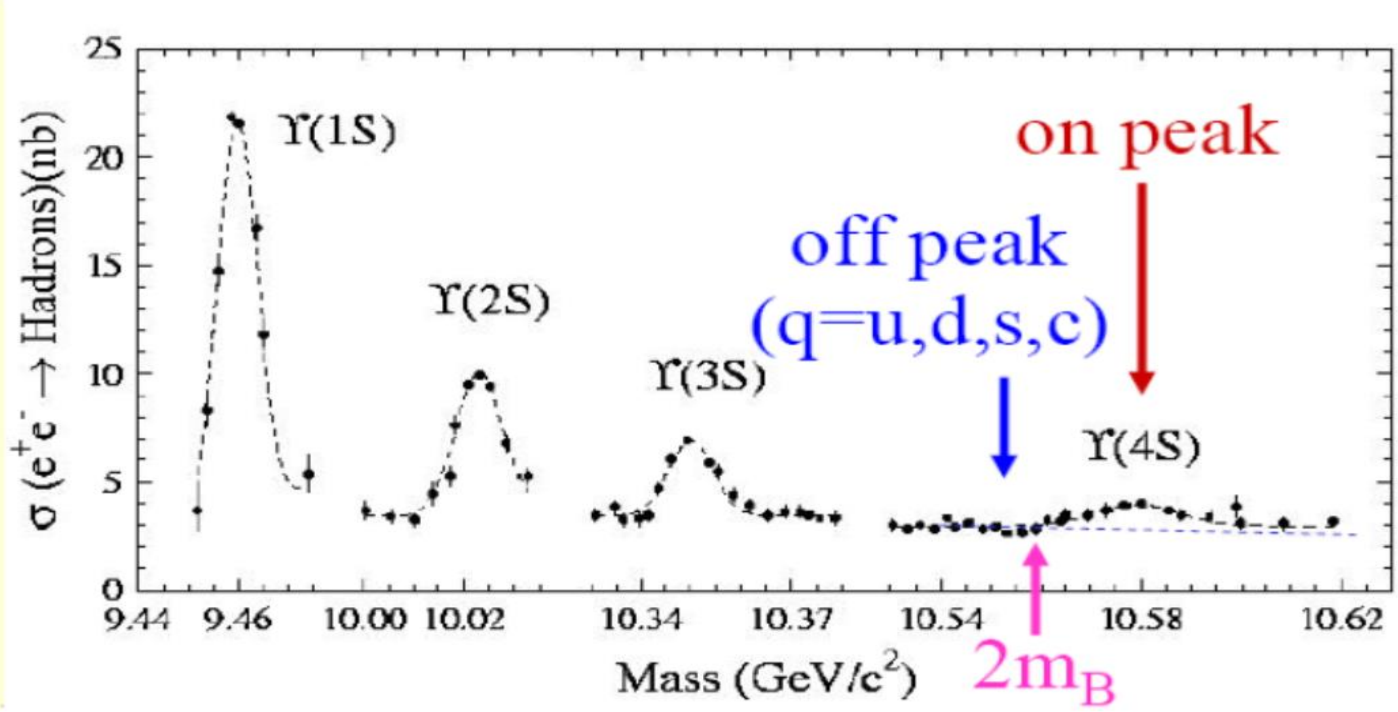


Figure: 6.15 $\Upsilon(NS)$ 共振态($N = 1, 2, 3, 4$).

2. 底夸克偶素：ϒ的发现与性质

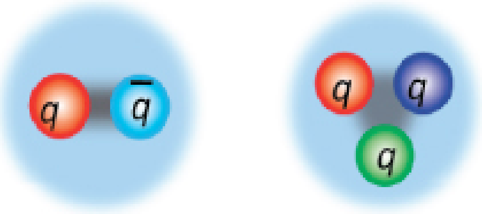
- 量子力学给出，通过散射所能分辨的空间间隔与散射时的动量成反比，即低能散射时分辨间隔大，高能散射时分辨间隔小。低能散射时，由于分辨间隔大，分辨率低，对于强子内部结构不可能观察得很细致，只能看到强子作为一个整体。 在高能散射时，由于分辨间隔小，分辨率高，对于强子内部结构就可以观察得很细致，看到内部结构的具体细节。

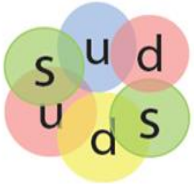
- J/ψ粒子和ϒ粒子是质量很重的粒子，研究它们的结构性质时所涉及的散射过程能量动量变化尺度是GeV量级，这对应于分辨间隔小于0.2fm，因此人们可以对J/ψ粒子和ϒ粒子的内部结构进行比轻介子细致得多的实验研究。

- 另一方面，由于粲夸克和底夸克很重，它们和相应的反夸克组成J/ψ, ϒ粒子时可以近似地按非相对论性运动来处理。这在理论处理上大大简化，并能得到足够好的精确度，只有在精确讨论某些特殊性质时，才需要进一步考虑相对论性的修正。

- 一对正反夸克作为价粒子的介子称为夸克偶素。考虑到上述实验和理论两方面的因素，尽管重夸克偶素发现得很晚，对它们内部结构性质的研究要比对轻介子内部结构性质的研究细致深入得多。

3.类粲（底）夸克偶素



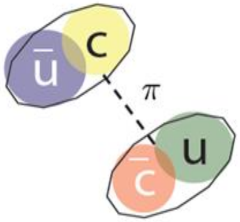


dibaryon

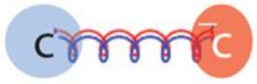
pentaquark

glueball

diquark + di-antiquark



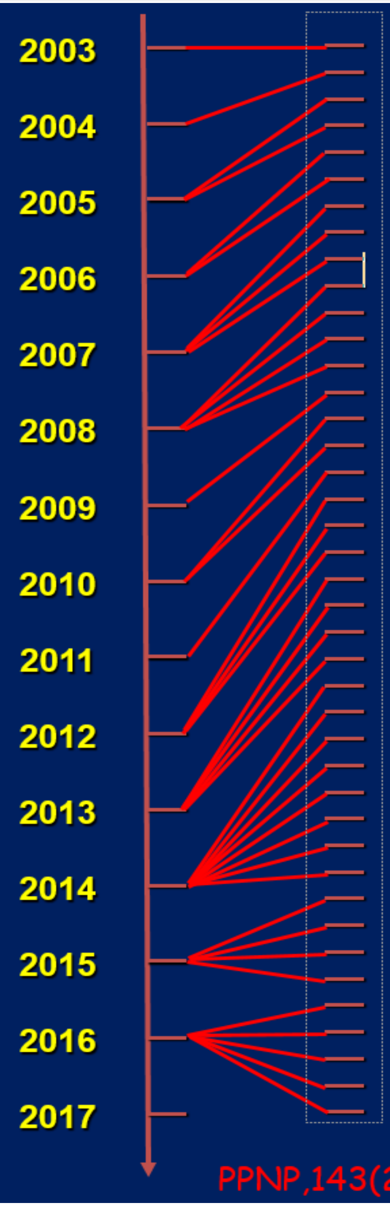
dimeson molecule



$q\,\bar{q}\,g$ hybrid

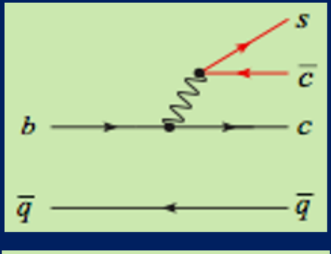
近年来实验上陆续发现了一些奇特的粒子，它们都含有 $c\bar{c}$ 或者是 $b\bar{b}$ 的组分，但又不具备粲偶素或底夸克偶素的特征，不能将其归入粲偶素或底夸克偶素的粒子谱，因此被称之为类粲偶素或类 b 夸克偶素。我们这里主要讨论类粲偶素，通常以 XYZ 标记它们。X 粒子的自旋一般为 0，Y 粒子指 $J^{PC}=1^{--}$ 的中性粒子态，其余自旋为 1 的粒子态则归入 Z 粒子一类，

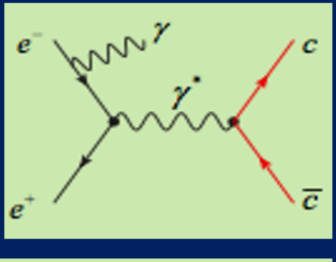
3.类粲（底）夸克偶素

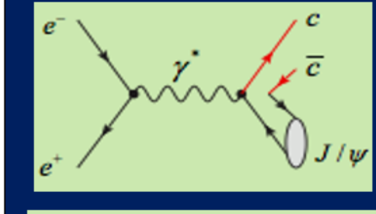


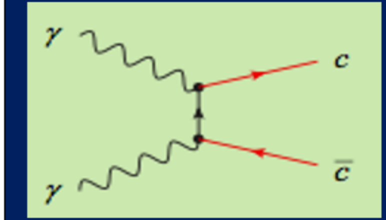
	Observed	Confirmed
X(3872)	Belle	
X(3872)		CDF, D0
X(3915) [as Y(3940)]		Belle
Y(4260)		BaBar
$\chi_{c2}(2P)$ [as Z(3930)]	Belle	
Y(4260)		CLEO-c
X(3940), Y(4008), Y(4660)	Belle	
Y(4360)	BaBar	
Y(4360)		Belle
X(3915) [as Y(3940)]		BaBar
X(3940)		Belle
$Z^+(4050)$, X(4160), $Z^+(4250)$,		
$Z^+(4430)$, X(4630)	Belle	
Y(4140)		CDF
X(3915), X(4350), $Y_b(10888)$	Belle	
$\chi_{c2}(2P)$ [as Z(3930)]		BaBar
Y(4274)	CDF	
X(3915)		BaBar
$Z_b^+(10610)$		Belle
$Z_b^+(10650)$		Belle
X(3823), $Z_b^0(10610)$	Belle	
$Z_c^+(3900)$, $Z_c^+(4020)$	BESIII	
$Z_c^+(3900)$		Belle
$Z_c^0(3900)$	CLEO-c	
$Z_c^0(4020)$	BESIII	
Y(4140)		D0, CMS
Y(4274)		CMS
Y(4660)		BaBar
$Z_c^+(4020)$	BESIII	
$Z^+(4200)$		Belle
$Z^+(4240)$		LHCb
$Z^+(4430)$		LHCb
X(3823), $Z_c^0(3900)$, $Z_c^0(4020)$		BESIII
$Z_c^+(4055)$	Belle	
Y(4230)	BESIII	
$P_c^+(4380)$, $P_c^+(4450)$	LHCb	
$Y_b(10880)$		NOT Belle
$X^+(5568)$	D0	
$X^+(5568)$		NOT LHCb
Y(4140), Y(4274)		LHCb
X(4500), X(4700)	LHCb	

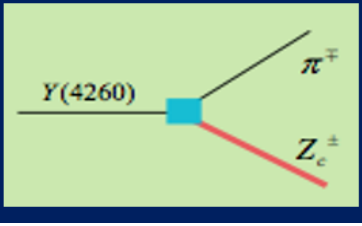
PPNP,143(2017), Phys.Rept.1(2016)





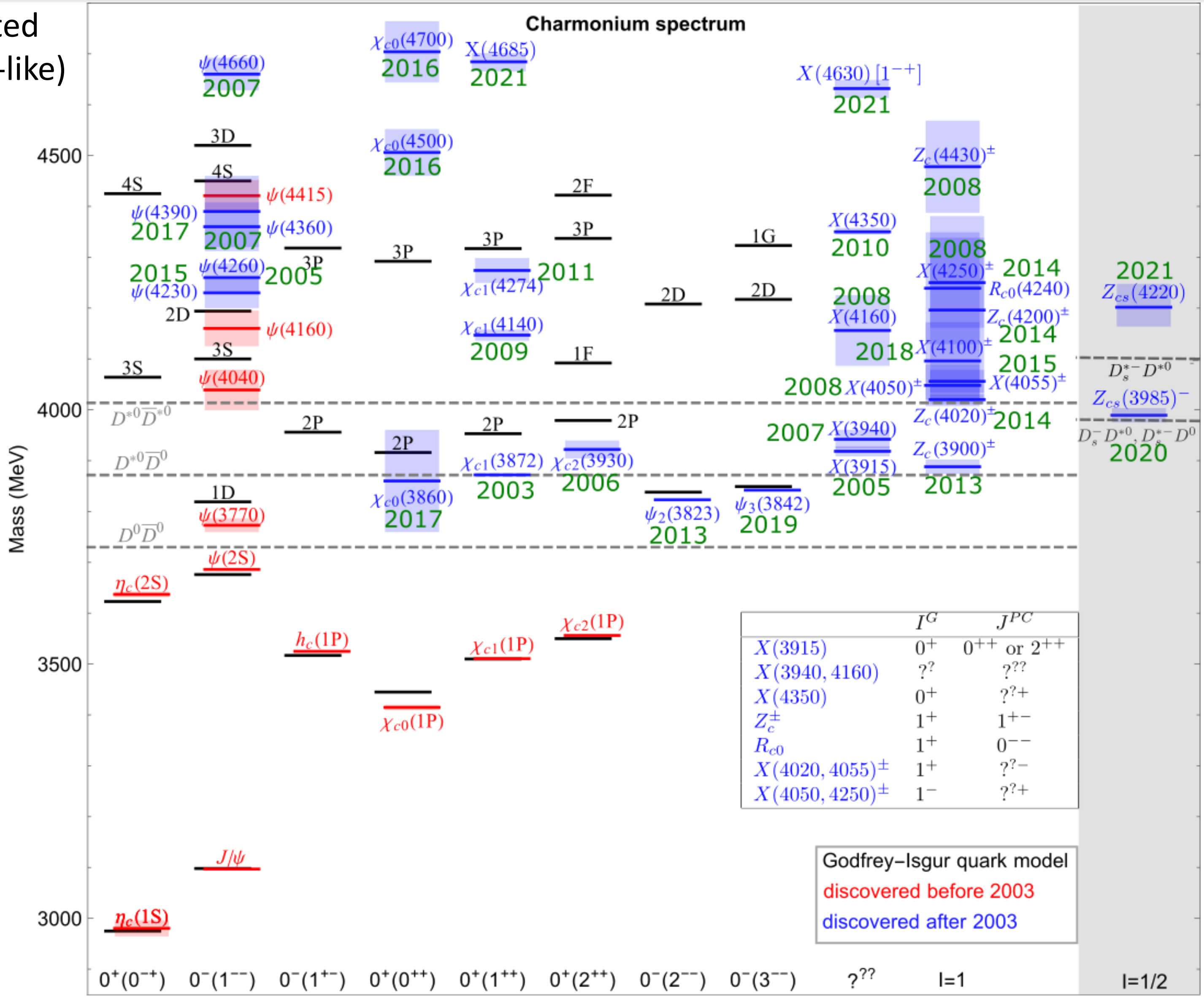






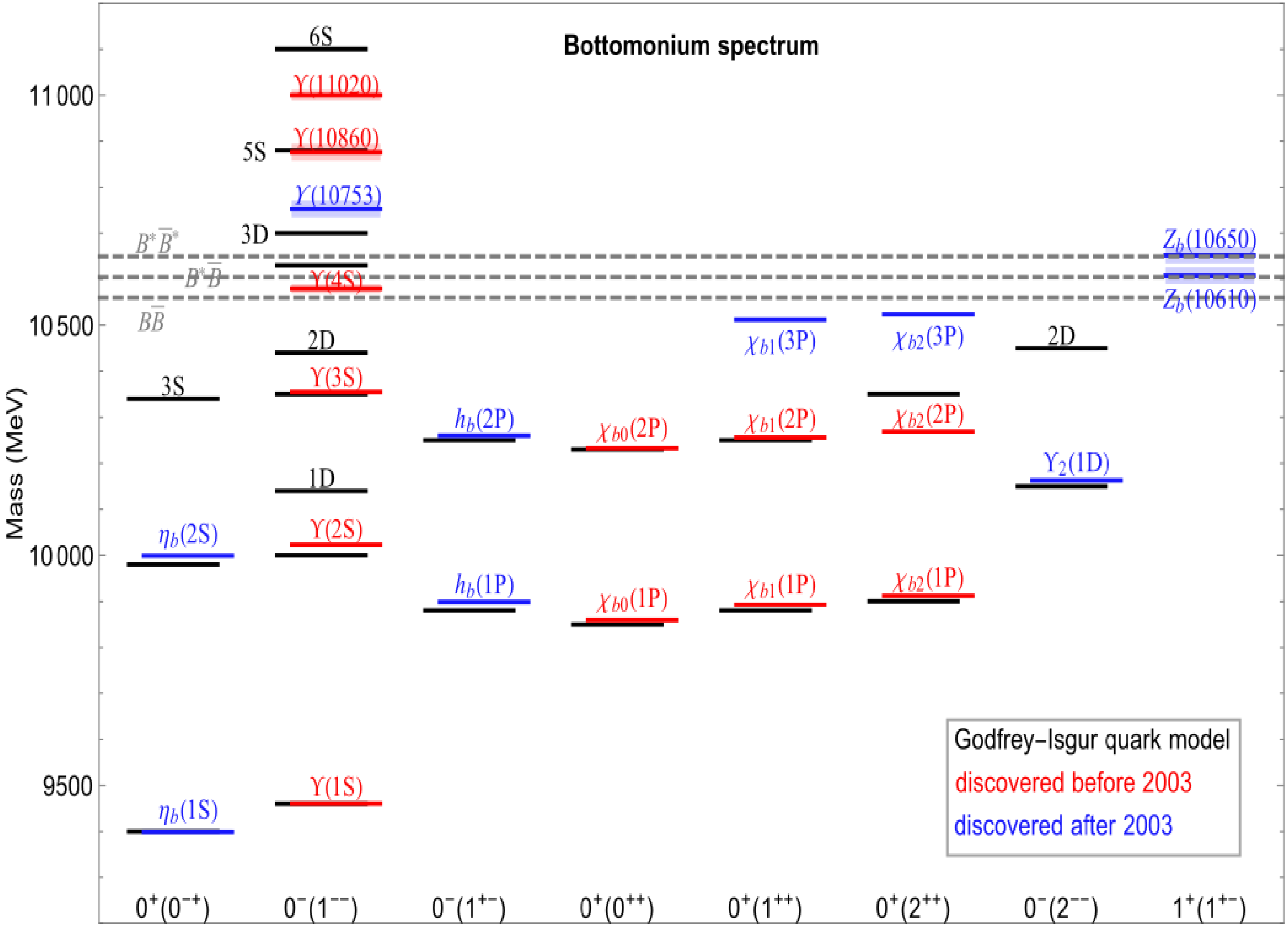
3.类粲（底）夸克偶素

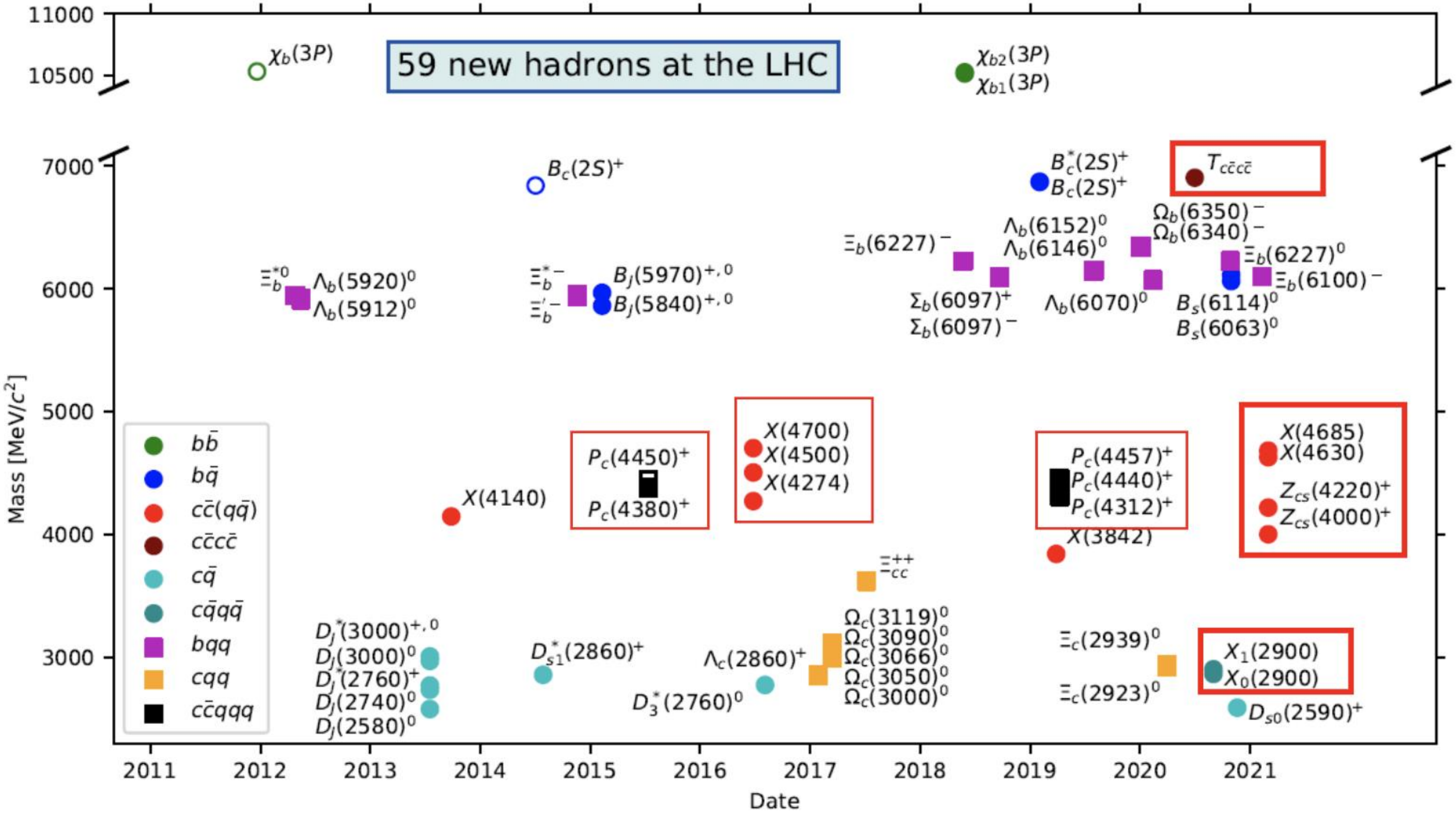
overpopulated
charmonium(-like)
states



	I^G	J^{PC}
$X(3915)$	0^+	0^{++} or 2^{++}
$X(3940, 4160)$	$?^?$	$?^{??}$
$X(4350)$	0^+	$?^{?+}$
$Z_c^{\pm}$	1^+	1^{+-}
R_{c0}	1^+	0^{--}
$X(4020, 4055)^{\pm}$	1^+	$?^{?-}$
$X(4050, 4250)^{\pm}$	1^-	$?^{?+}$

3.类粲（底）夸克偶素


Bottomonium spectrum
Mass (MeV)
11 000
10 500
10 000
9500
6S
Υ(11020)
5S
Υ(10860)
Υ(10753)
3D
$B^*\bar{B}^*$
$B^*\bar{B}$
Υ(4S)
$B\bar{B}$
2D
3S
Υ(3S)
h_b(2P)
χ_{b0}(2P)
χ_{b1}(2P)
χ_{b2}(2P)
χ_{b1}(3P)
χ_{b2}(3P)
2D
Z_b(10650)
Z_b(10610)
1D
Υ_2(1D)
η_b(2S)
Υ(2S)
h_b(1P)
χ_{b0}(1P)
χ_{b1}(1P)
χ_{b2}(1P)
Υ(1S)
η_b(1S)
Godfrey–Isgur quark model
discovered before 2003
discovered after 2003
$0^+(0^{-+})$
$0^-(1^{--})$
$0^-(1^{+-})$
$0^+(0^{++})$
$0^+(1^{++})$
$0^+(2^{++})$
$0^-(2^{--})$
$1^+(1^{+-})$



59 new hadron states (conventional & exotic) observed at LHC, most of them discovered at LHCb

3.1 X(3872)的发现

2003 年 Belle 实验利用在 $\Upsilon(4S)$ 共振能区采集到的 153 兆 $B\bar{B}$ 事例，在 $B^\pm \to K^\pm\pi^+\pi^-J/\psi$ 过程中观测到了 $X(3872) \to \pi^+\pi^-J/\psi$ 的共振峰结构，统计显著性超 10σ。实验定义，

$$\Delta E \equiv E_B^{CM} - E_{beam}^{CM}, \qquad M_{bc} \equiv \sqrt{(E_{beam}^{CM})^2 - (p_B^{CM})^2}, \qquad (7.114)$$

其中 E_{beam}^{CM} 是质心系中的束流能量，E_B^{CM} 和 p_B^{CM} 是质心系中 B 介子候选者的能量和动量。在 M_{bc}、$M_{\pi^+\pi^-J/\psi}$ 和 ΔE 的谱上均看到了 $X(3872)$ 的信号峰，如图 7.9所示。当时给出的 $X(3872)$ 质量和宽度为，

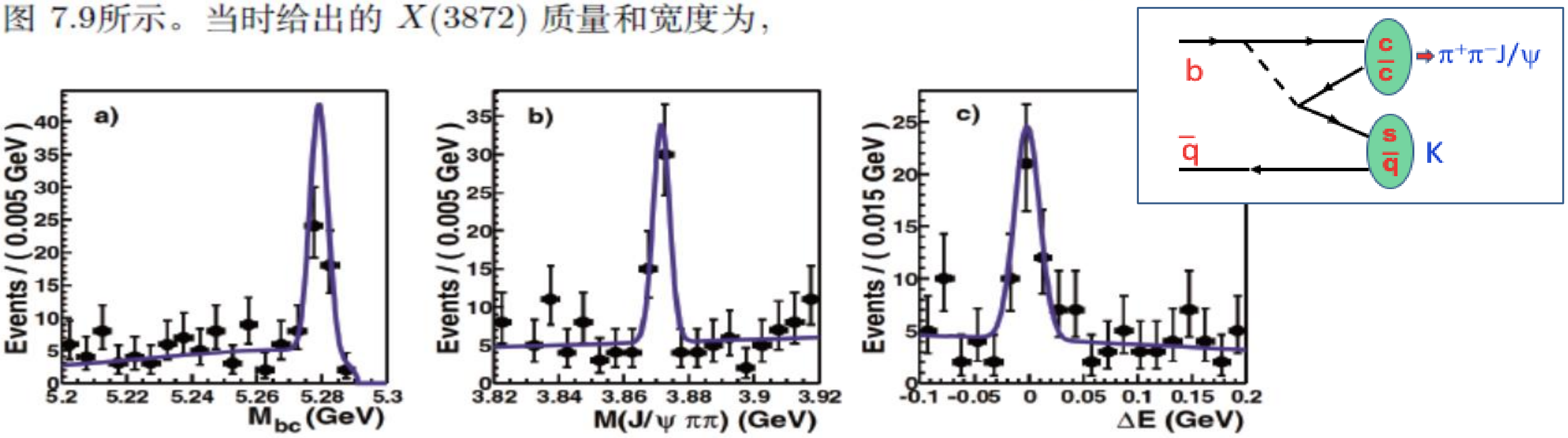
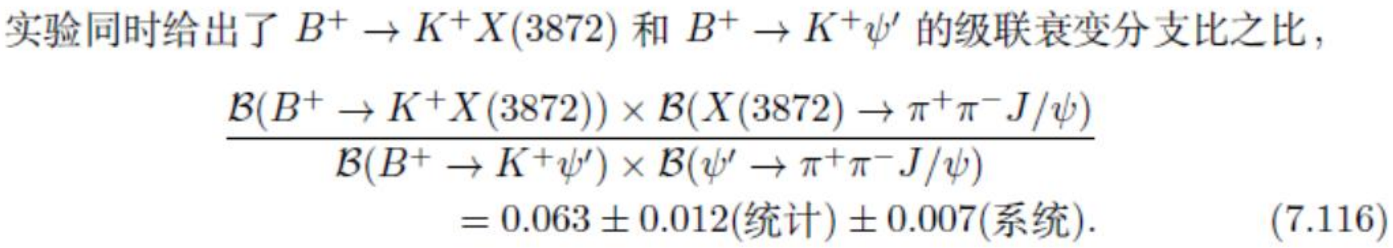


图 7.9: $X(3872) \to \pi^+\pi^-J/\psi$ 信号区的拟合结果在（a）M_{bc}、（b）$M_{\pi^+\pi^-J/\psi}$ 和（c）ΔE 谱上的投影 [34]。

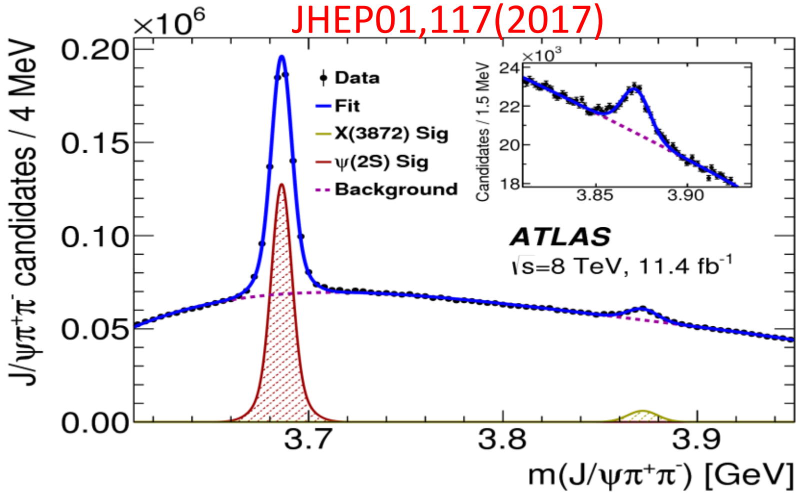
$$M = [3872.0 \pm 0.6(\text{统计}) \pm 0.5(\text{系统})]MeV, \quad \Gamma < 2.3MeV\ (90\%\ \text{置信度}).(7.115)$$

3.1 X(3872)的产生

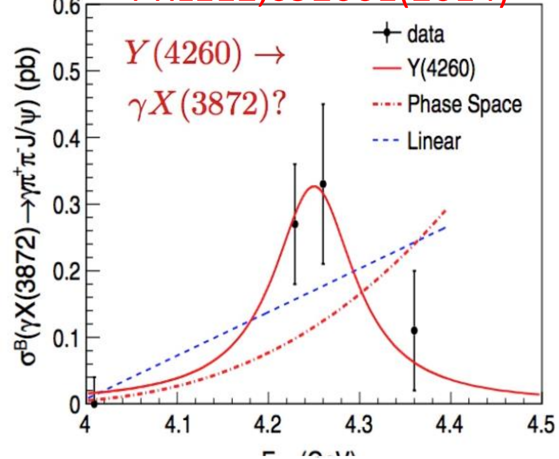


实验同时给出了 $B^+ \to K^+X(3872)$ 和 $B^+ \to K^+\psi'$ 的级联衰变分支比之比，

$$\frac{\mathcal{B}(B^+ \to K^+X(3872)) \times \mathcal{B}(X(3872) \to \pi^+\pi^-J/\psi)}{\mathcal{B}(B^+ \to K^+\psi') \times \mathcal{B}(\psi' \to \pi^+\pi^-J/\psi)} = 0.063 \pm 0.012(\text{统计}) \pm 0.007(\text{系统}). \qquad (7.116)$$

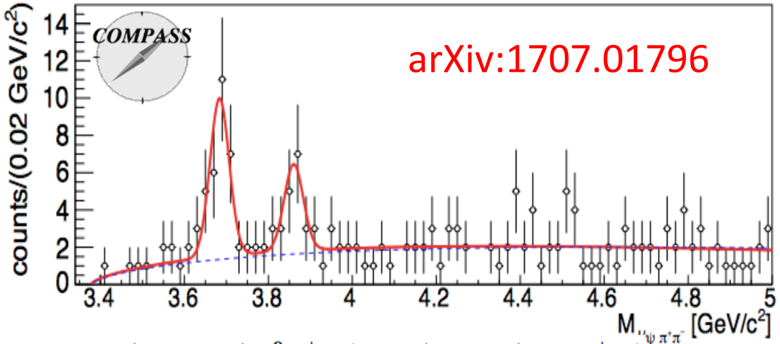


JHEP01,117(2017)



PRL112,092001(2014)

Suggestive of $Y(4260) \to \gamma X(3872)$

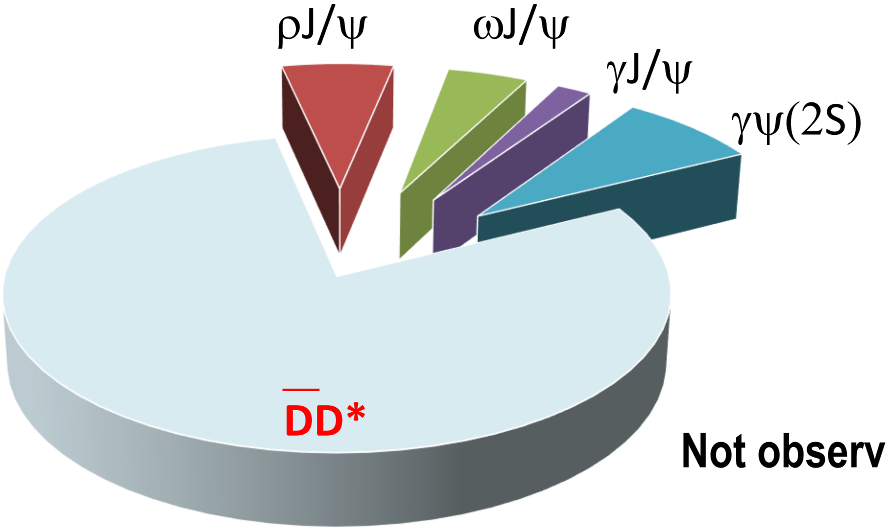


arXiv:1707.01796

$\mu^+ N \to \mu^+ X^0 \pi^\pm N' \to \mu^+(J/\psi\pi^+\pi^-)\pi^\pm N'$

- In B decays – KX similar to charmonia,
  - – K*X smaller than charmonia
  - – KπX
- In pp/pp collision – rate similar to charmonia
- Radiative transition of the excited vector charmonium(like)? – $J^{pc}=1^{++}$

3.1 X(3872)的衰变



Not observed in $\eta_c h$ decay

- Strongly coupling to **DD***
- **Not observed in $\eta_c h$ decay**

3.1 X(3872)的性质

- Properties

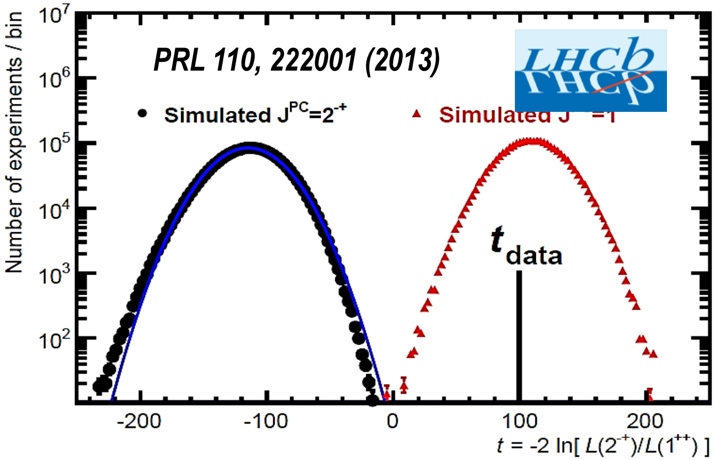
  M-M($D^0 \bar{D}^{*0}$)=0.01±0.18 MeV

  Γ<1.2 MeV

- I=0， $J^{PC}=1^{++}$
- Production

  B decays， hadron collisions,

Y(4260) decays?, muonproduction?



$$\frac{\mathcal{B}(X(3872) \to \psi(2S)\gamma)}{\mathcal{B}(X(3872) \to J/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29$$

Theoretical predictions :
- **DD* molecule : (3-4)×10^{-3}**
- **Charmonium : 1.2–15**
- **Mixture : 0.5–5**

Not a pure DD* molecule

	Relative BF
$J/\psi\rho$	1
$J/\psi\omega$	0.8 ± 0.3
$J/\psi\gamma$	0.21 ± 0.06
D^0D^{*0}	~10

Isospin violation

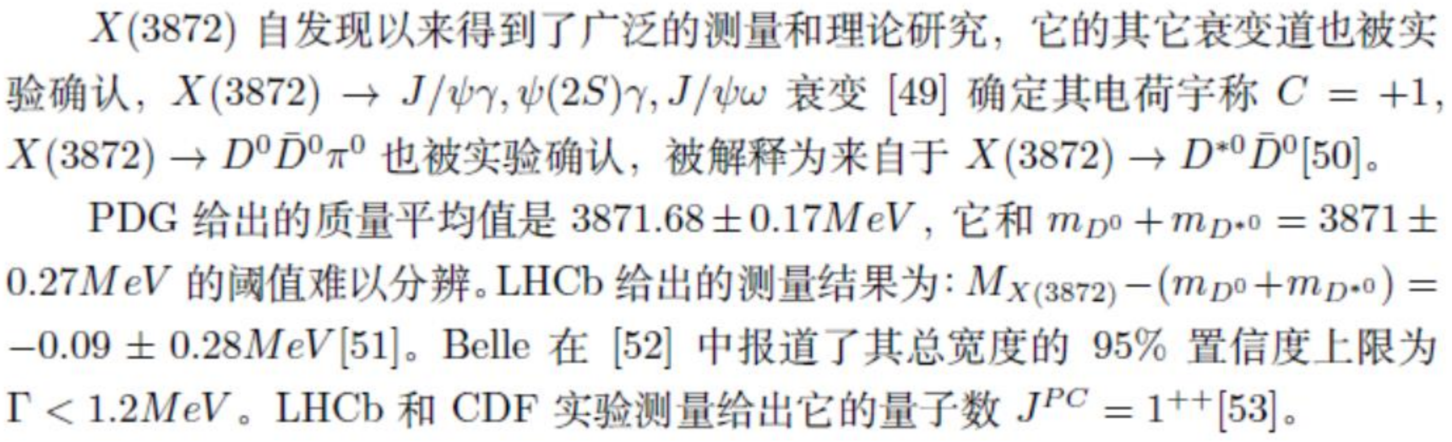
↓

a DD* molecule

A mixture of a DD* molecule and a χ_{c1}' charmonium

Named χ_{c1}(3872) in PDG2

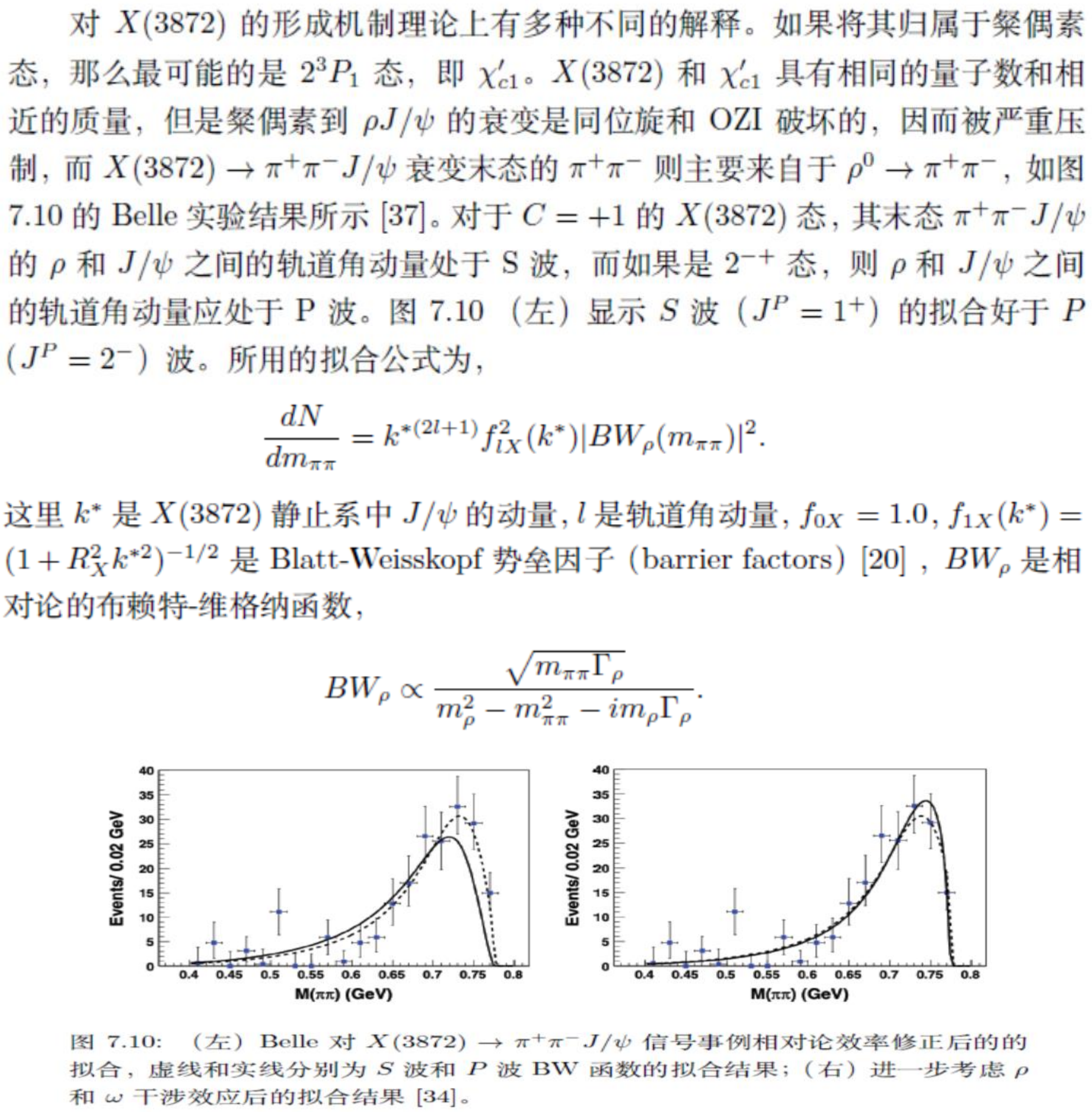
3.1 X(3872)的性质



$X(3872)$ 自发现以来得到了广泛的测量和理论研究，它的其它衰变道也被实验确认，$X(3872) \to J/\psi\gamma, \psi(2S)\gamma, J/\psi\omega$ 衰变 [49] 确定其电荷宇称 $C = +1$，$X(3872) \to D^0\bar{D}^0\pi^0$ 也被实验确认，被解释为来自于 $X(3872) \to D^{*0}\bar{D}^0$[50]。

PDG 给出的质量平均值是 $3871.68 \pm 0.17 MeV$，它和 $m_{D^0} + m_{D^{*0}} = 3871 \pm 0.27 MeV$ 的阈值难以分辨。LHCb 给出的测量结果为：$M_{X(3872)} - (m_{D^0} + m_{D^{*0}}) = -0.09 \pm 0.28 MeV$[51]。Belle 在 [52] 中报道了其总宽度的 95% 置信度上限为 $\Gamma < 1.2 MeV$。LHCb 和 CDF 实验测量给出它的量子数 $J^{PC} = 1^{++}$[53]。

3.1 X(3872)的性质



对 $X(3872)$ 的形成机制理论上有多种不同的解释。如果将其归属于粲偶素态，那么最可能的是 2^3P_1 态，即 χ'_{c1}。$X(3872)$ 和 χ'_{c1} 具有相同的量子数和相近的质量，但是粲偶素到 $\rho J/\psi$ 的衰变是同位旋和 OZI 破坏的，因而被严重压制，而 $X(3872)\to\pi^+\pi^-J/\psi$ 衰变末态的 $\pi^+\pi^-$ 则主要来自于 $\rho^0\to\pi^+\pi^-$，如图 7.10 的 Belle 实验结果所示 [37]。对于 $C=+1$ 的 $X(3872)$ 态，其末态 $\pi^+\pi^-J/\psi$ 的 ρ 和 J/ψ 之间的轨道角动量处于 S 波，而如果是 2^{-+} 态，则 ρ 和 J/ψ 之间的轨道角动量应处于 P 波。图 7.10（左）显示 S 波（$J^P=1^+$）的拟合好于 P（$J^P=2^-$）波。所用的拟合公式为，

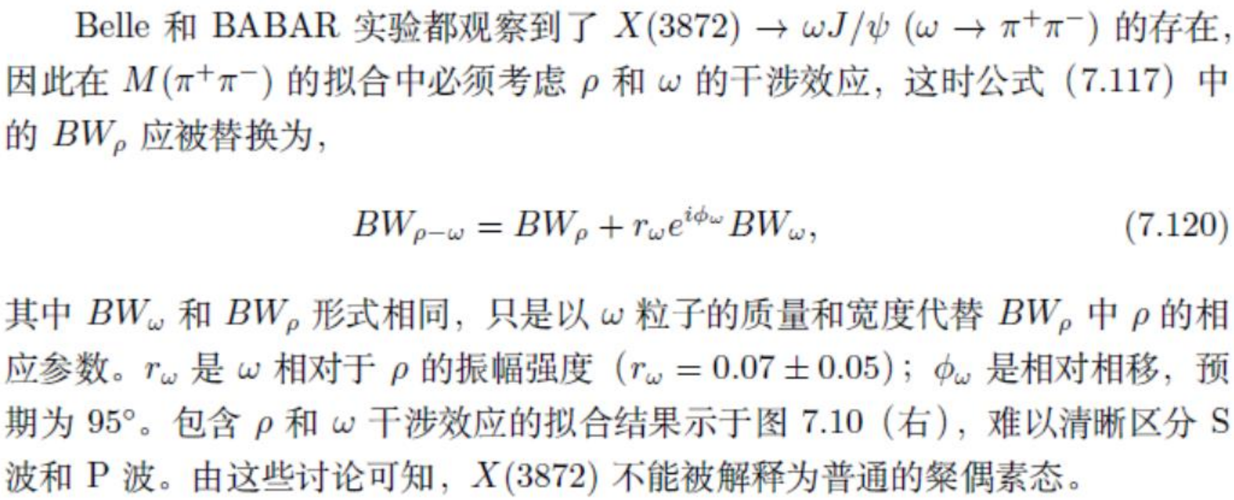
$$\frac{dN}{dm_{\pi\pi}} = k^{*(2l+1)} f_{lX}^2(k^*)|BW_\rho(m_{\pi\pi})|^2.$$

这里 k^* 是 $X(3872)$ 静止系中 J/ψ 的动量，l 是轨道角动量，$f_{0X}=1.0$，$f_{1X}(k^*)=(1+R_X^2k^{*2})^{-1/2}$ 是 Blatt-Weisskopf 势垒因子（barrier factors）[20]，BW_ρ 是相对论的布赖特-维格纳函数，

$$BW_\rho \propto \frac{\sqrt{m_{\pi\pi}\Gamma_\rho}}{m_\rho^2 - m_{\pi\pi}^2 - i m_\rho\Gamma_\rho}.$$

图 7.10：（左）Belle 对 $X(3872)\to\pi^+\pi^-J/\psi$ 信号事例相对论效率修正后的的拟合，虚线和实线分别为 S 波和 P 波 BW 函数的拟合结果；（右）进一步考虑 ρ 和 ω 干涉效应后的拟合结果 [34]。

3.1 X(3872)的性质

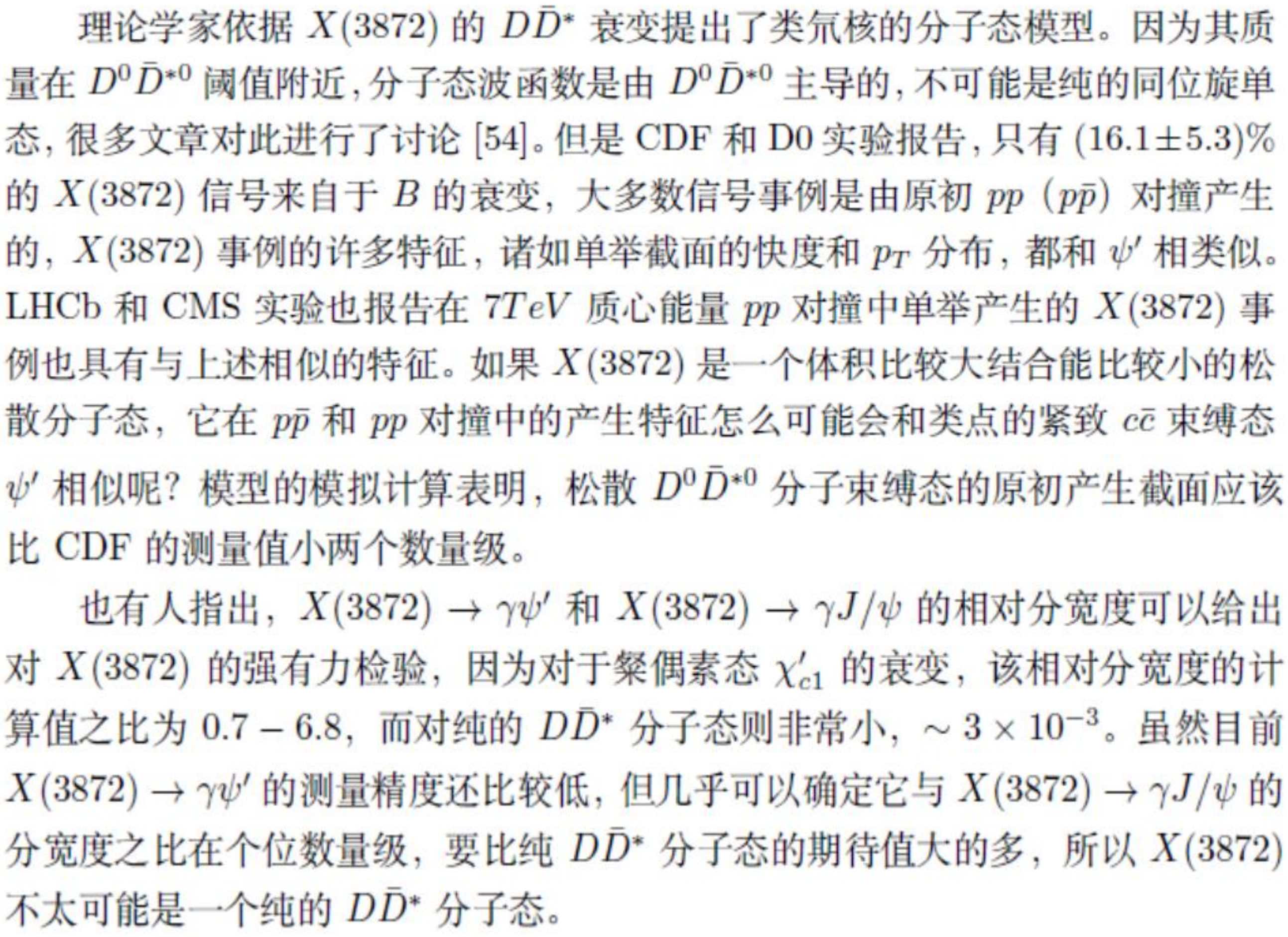


Belle 和 BABAR 实验都观察到了 $X(3872) \to \omega J/\psi$ ($\omega \to \pi^+\pi^-$) 的存在，因此在 $M(\pi^+\pi^-)$ 的拟合中必须考虑 ρ 和 ω 的干涉效应，这时公式（7.117）中的 BW_ρ 应被替换为，

$$BW_{\rho-\omega} = BW_\rho + r_\omega e^{i\phi_\omega} BW_\omega, \tag{7.120}$$

其中 BW_ω 和 BW_ρ 形式相同，只是以 ω 粒子的质量和宽度代替 BW_ρ 中 ρ 的相应参数。r_ω 是 ω 相对于 ρ 的振幅强度（$r_\omega = 0.07 \pm 0.05$）；ϕ_ω 是相对相移，预期为 95°。包含 ρ 和 ω 干涉效应的拟合结果示于图 7.10（右），难以清晰区分 S 波和 P 波。由这些讨论可知，$X(3872)$ 不能被解释为普通的粲偶素态。

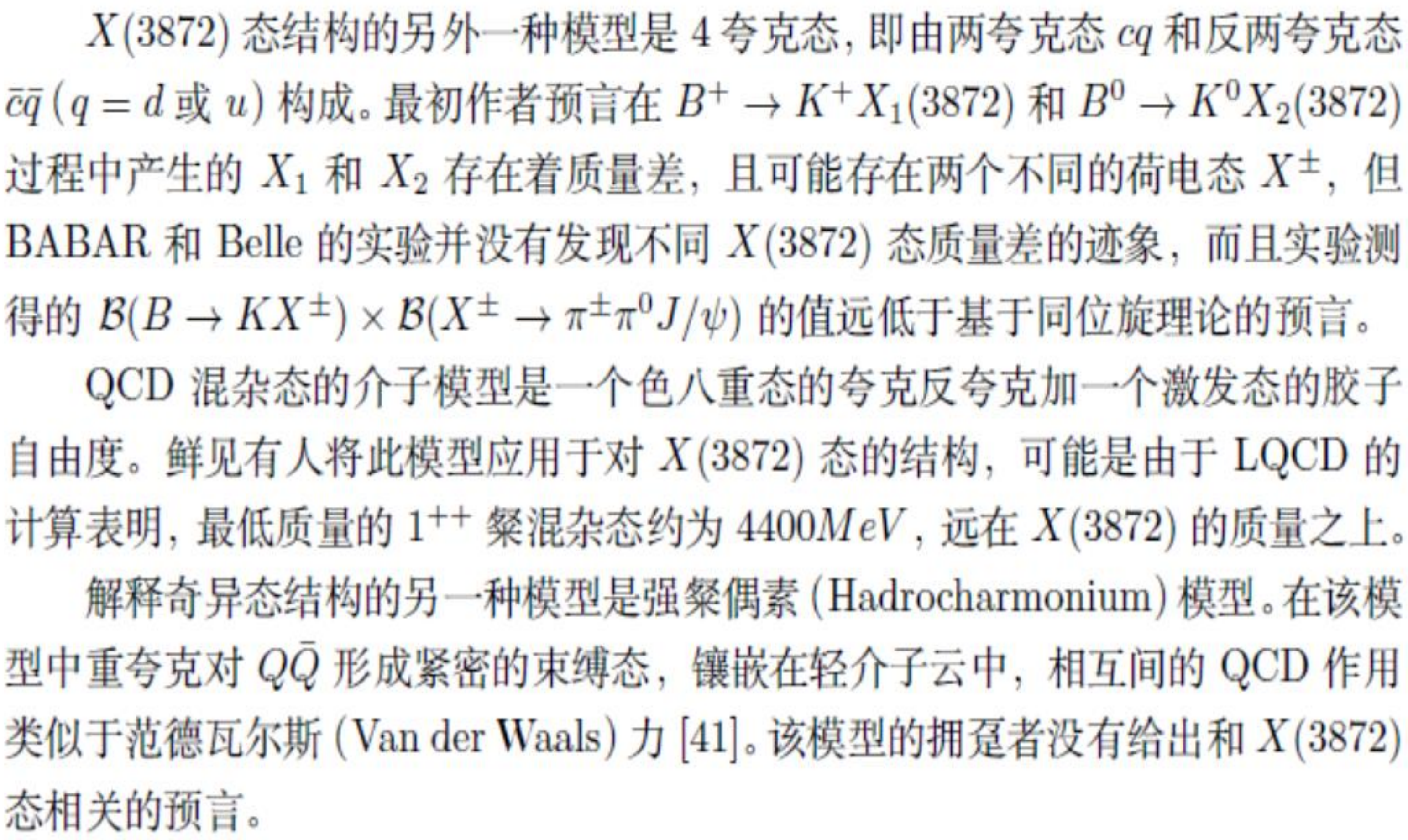
3.1 X(3872)的性质



理论学家依据 $X(3872)$ 的 $D\bar{D}^*$ 衰变提出了类氘核的分子态模型。因为其质量在 $D^0\bar{D}^{*0}$ 阈值附近，分子态波函数是由 $D^0\bar{D}^{*0}$ 主导的，不可能是纯的同位旋单态，很多文章对此进行了讨论 [54]。但是 CDF 和 D0 实验报告，只有 (16.1±5.3)% 的 $X(3872)$ 信号来自于 B 的衰变，大多数信号事例是由原初 pp（$p\bar{p}$）对撞产生的，$X(3872)$ 事例的许多特征，诸如单举截面的快度和 p_T 分布，都和 ψ' 相类似。LHCb 和 CMS 实验也报告在 $7TeV$ 质心能量 pp 对撞中单举产生的 $X(3872)$ 事例也具有与上述相似的特征。如果 $X(3872)$ 是一个体积比较大结合能比较小的松散分子态，它在 $p\bar{p}$ 和 pp 对撞中的产生特征怎么可能会和类点的紧致 $c\bar{c}$ 束缚态 ψ' 相似呢？模型的模拟计算表明，松散 $D^0\bar{D}^{*0}$ 分子束缚态的原初产生截面应该比 CDF 的测量值小两个数量级。

也有人指出，$X(3872)\rightarrow\gamma\psi'$ 和 $X(3872)\rightarrow\gamma J/\psi$ 的相对分宽度可以给出对 $X(3872)$ 的强有力检验，因为对于粲偶素态 χ'_{c1} 的衰变，该相对分宽度的计算值之比为 0.7 – 6.8，而对纯的 $D\bar{D}^*$ 分子态则非常小，$\sim 3\times10^{-3}$。虽然目前 $X(3872)\rightarrow\gamma\psi'$ 的测量精度还比较低，但几乎可以确定它与 $X(3872)\rightarrow\gamma J/\psi$ 的分宽度之比在个位数量级，要比纯 $D\bar{D}^*$ 分子态的期待值大的多，所以 $X(3872)$ 不太可能是一个纯的 $D\bar{D}^*$ 分子态。

3.1 X(3872)的性质

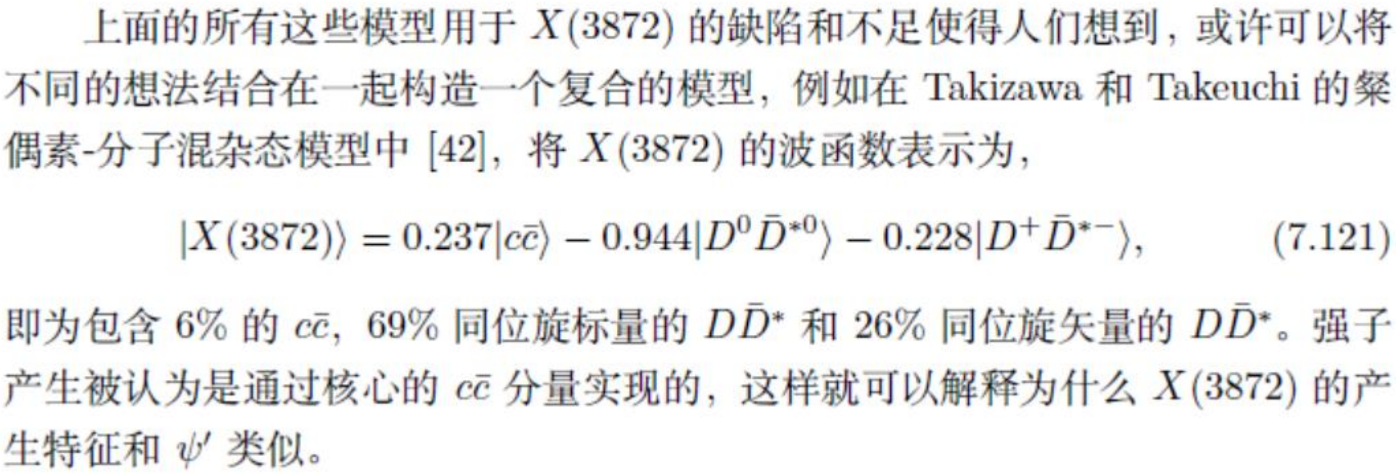


$X(3872)$ 态结构的另外一种模型是 4 夸克态，即由两夸克态 cq 和反两夸克态 $\bar{c}\bar{q}$ ($q = d$ 或 u) 构成。最初作者预言在 $B^+ \to K^+X_1(3872)$ 和 $B^0 \to K^0X_2(3872)$ 过程中产生的 X_1 和 X_2 存在着质量差，且可能存在两个不同的荷电态 $X^\pm$，但 BABAR 和 Belle 的实验并没有发现不同 $X(3872)$ 态质量差的迹象，而且实验测得的 $\mathcal{B}(B \to KX^\pm) \times \mathcal{B}(X^\pm \to \pi^\pm\pi^0 J/\psi)$ 的值远低于基于同位旋理论的预言。

QCD 混杂态的介子模型是一个色八重态的夸克反夸克加一个激发态的胶子自由度。鲜见有人将此模型应用于对 $X(3872)$ 态的结构，可能是由于 LQCD 的计算表明，最低质量的 1^{++} 粲混杂态约为 $4400MeV$，远在 $X(3872)$ 的质量之上。

解释奇异态结构的另一种模型是强粲偶素 (Hadrocharmonium) 模型。在该模型中重夸克对 $Q\bar{Q}$ 形成紧密的束缚态，镶嵌在轻介子云中，相互间的 QCD 作用类似于范德瓦尔斯 (Van der Waals) 力 [41]。该模型的拥趸者没有给出和 $X(3872)$ 态相关的预言。

3.1 X(3872)的性质

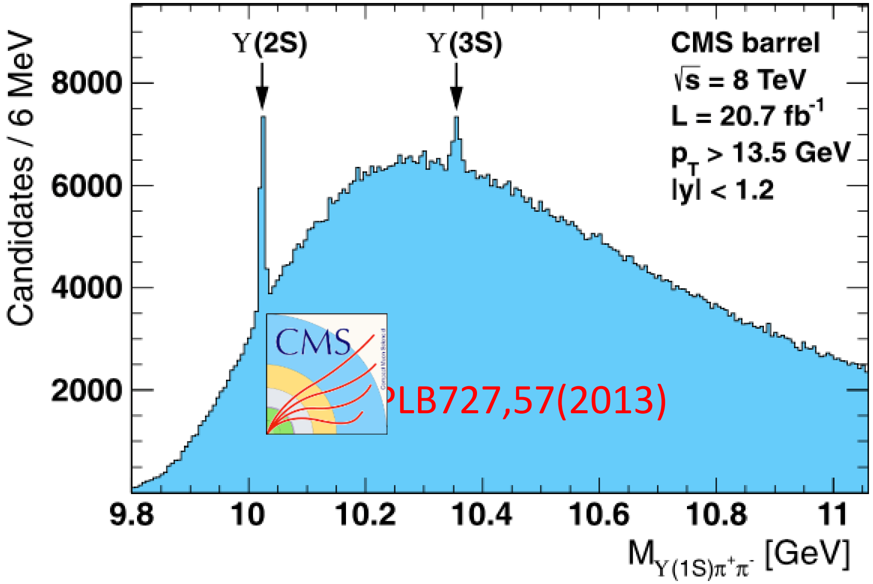


上面的所有这些模型用于 $X(3872)$ 的缺陷和不足使得人们想到，或许可以将不同的想法结合在一起构造一个复合的模型，例如在 Takizawa 和 Takeuchi 的粲偶素-分子混杂态模型中 [42]，将 $X(3872)$ 的波函数表示为，

$$|X(3872)\rangle = 0.237|c\bar{c}\rangle - 0.944|D^0\bar{D}^{*0}\rangle - 0.228|D^+\bar{D}^{*-}\rangle, \tag{7.121}$$

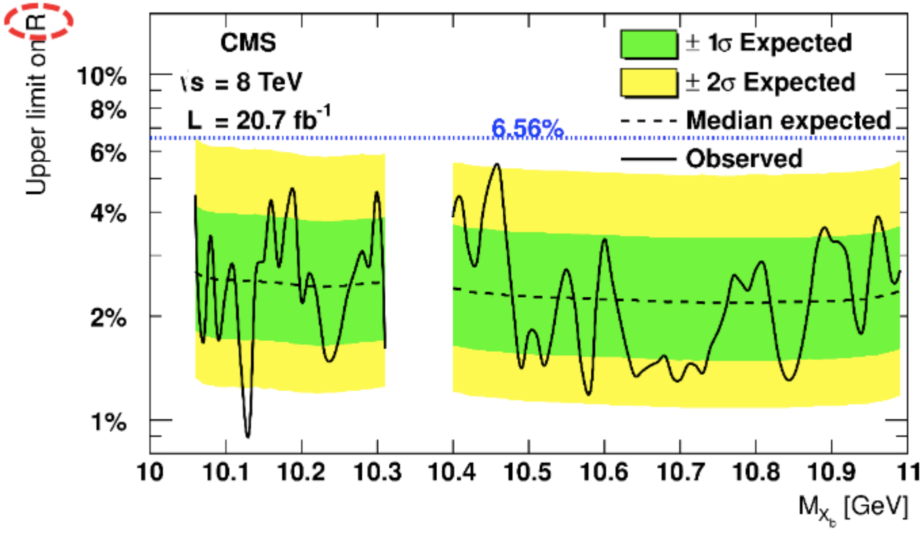
即为包含 6% 的 $c\bar{c}$，69% 同位旋标量的 $D\bar{D}^*$ 和 26% 同位旋矢量的 $D\bar{D}^*$。强子产生被认为是通过核心的 $c\bar{c}$ 分量实现的，这样就可以解释为什么 $X(3872)$ 的产生特征和 ψ' 类似。

3.1 含底夸克 X 粒子



PLB727,57(2013)

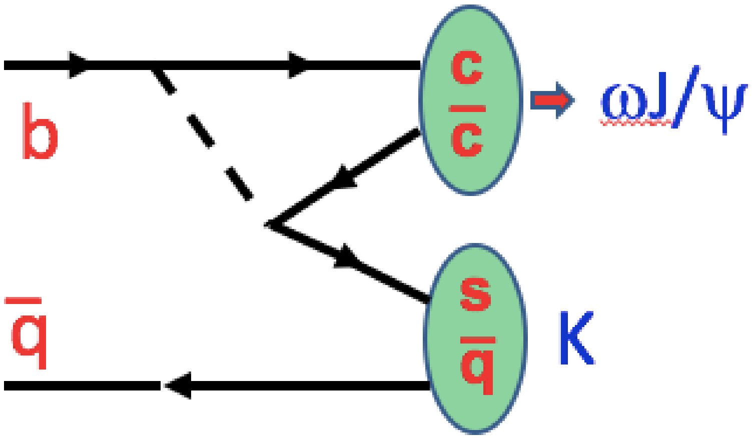
$$pp \rightarrow X_b \rightarrow \Upsilon(1S)\pi^+\pi^-$$



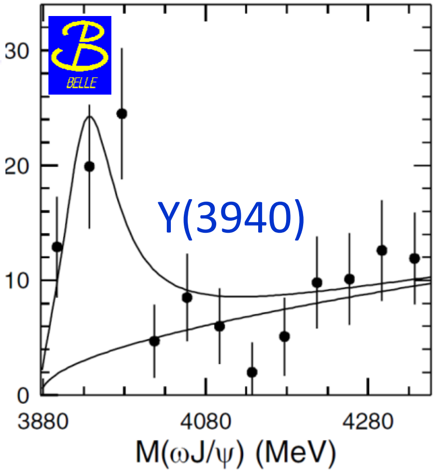
$$R \equiv \frac{\sigma\left(pp \to X_b \to \Upsilon(1S)\pi^+\pi^-\right)}{\sigma\left(pp \to \Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-\right)}$$

- Structure close to BB* threshold ~ 10605 MeV？
- **No clear peak besides Y(2S) and Y(3S) !**

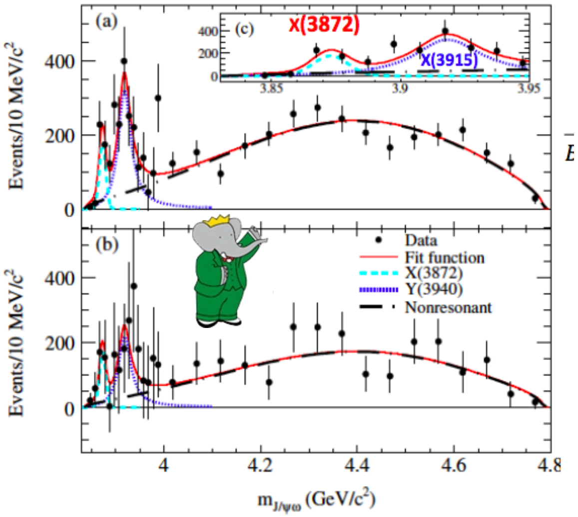
3.1 其他X粒子态



PRL94, 182002 (2005)



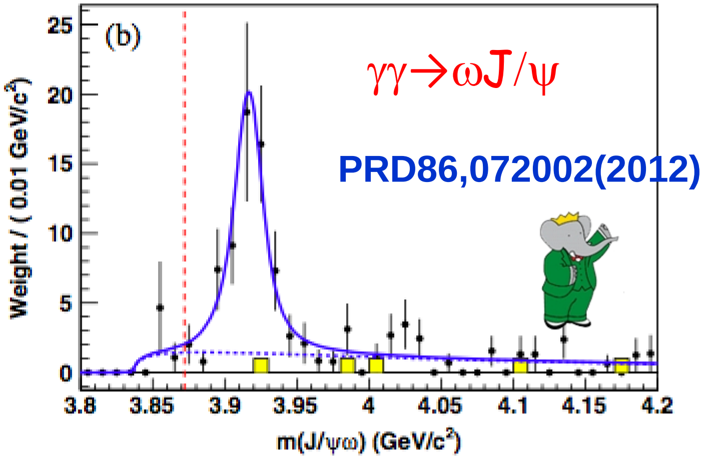
PRD82, 011101 (2010)



- Unexpected peak around 3.94 GeV
- Observed in two photon process by both Babar and Belle

M = 3918.4±1.9 MeV
Γ = 20±5 MeV

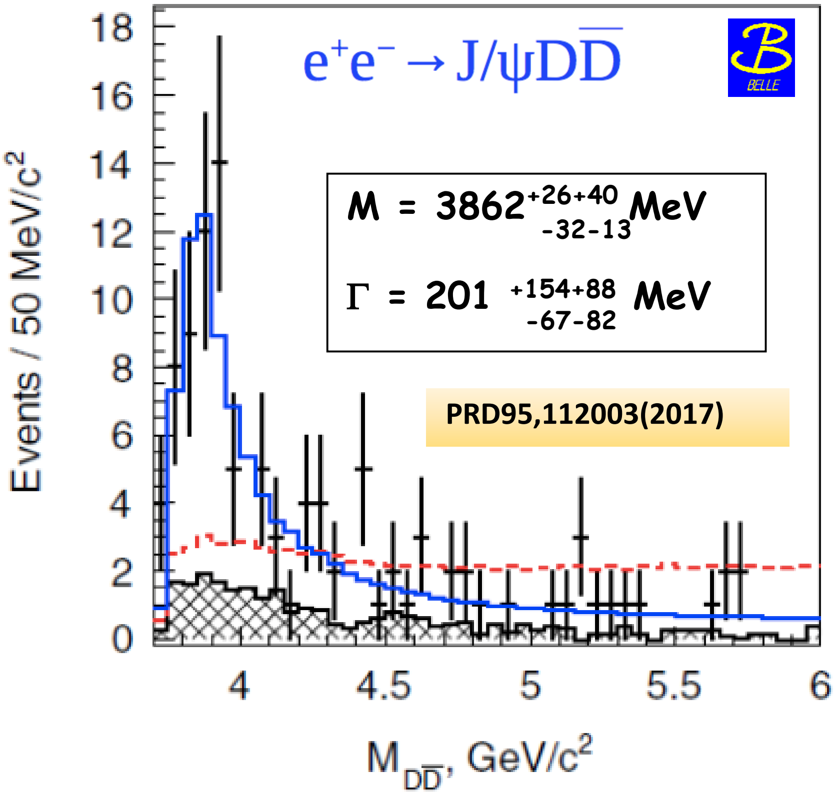
- Babar's preferred $J^{PC} = 0^{++}$
- X(3915) = χ_{c0} **(2P)?** Belle found a better χ_{c0} **(2P) candidate ！**



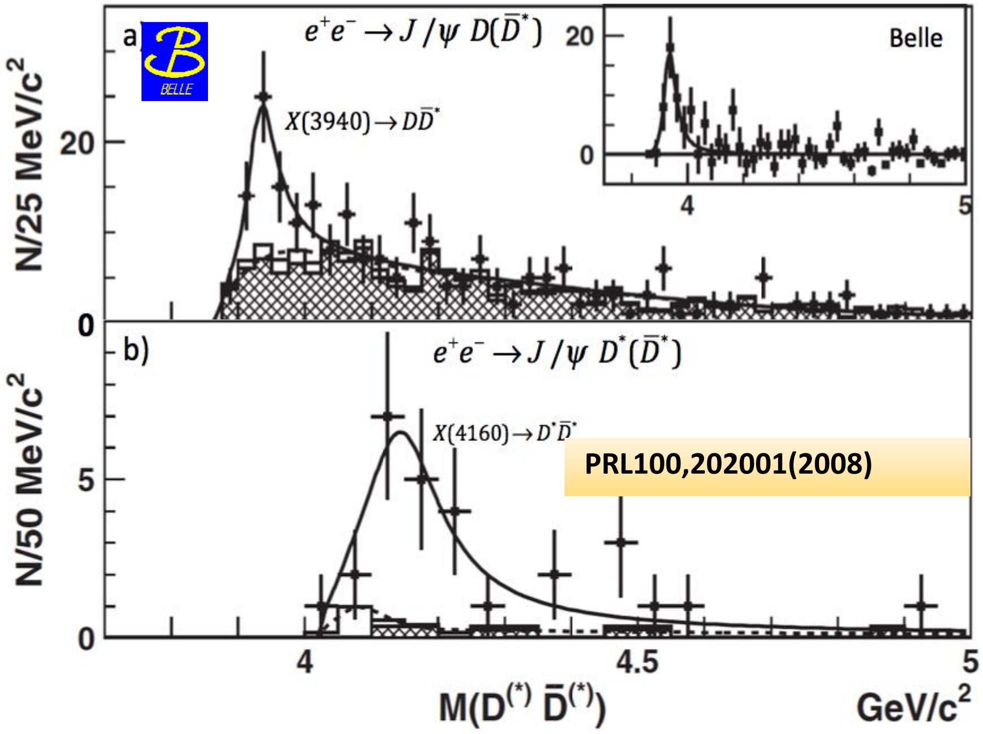
γγ→ωJ/ψ

PRD86,072002(2012)

3.1 其他X粒子态



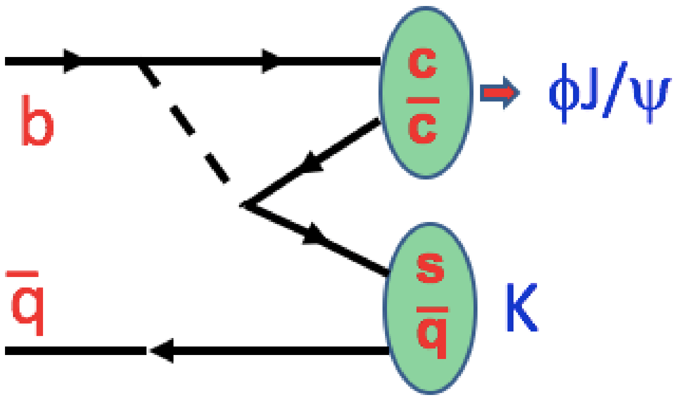
PRD95,112003(2017)

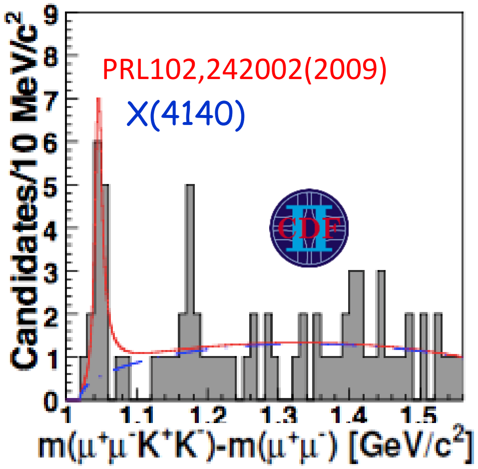


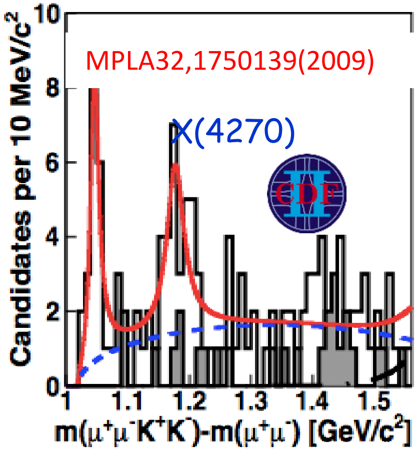
PRL100,202001(2008)

- X(3860): J^{PC} favors 0^{++} ;Consistent with $\chi_{c0}(2P)$ hypothesis
- X(3940) [X(4160)]: close to DD*(D*D*) threshold; did not show up in M(DD)

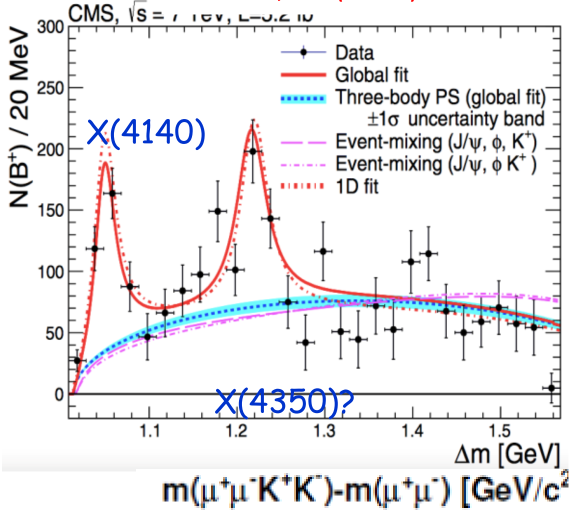
3.1 其他X粒子态

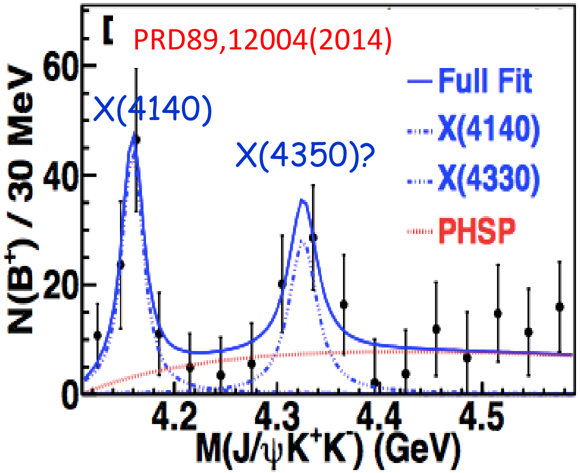


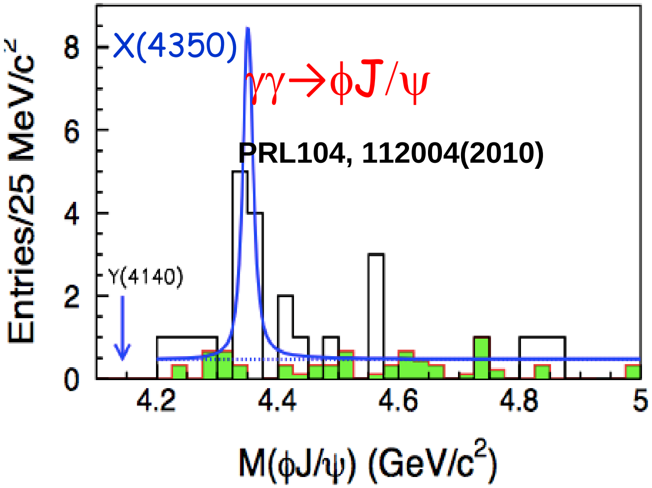

PRL102,242002(2009)


MPLA32,1750139(2009)

PLB734,261(2014)



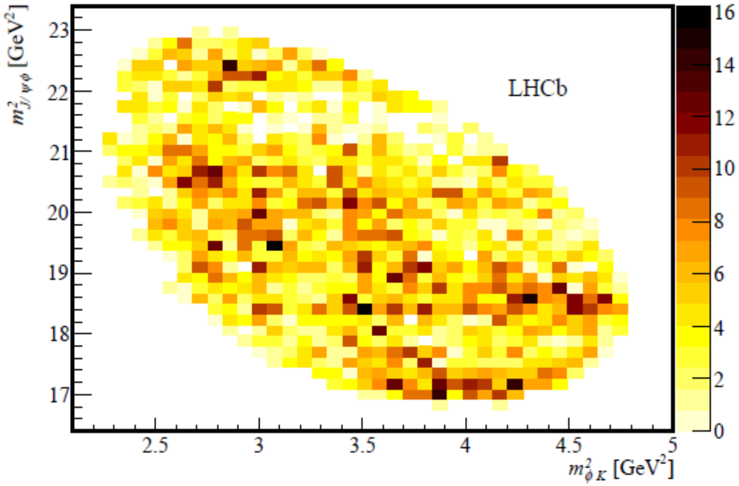

PRD89,12004(2014)

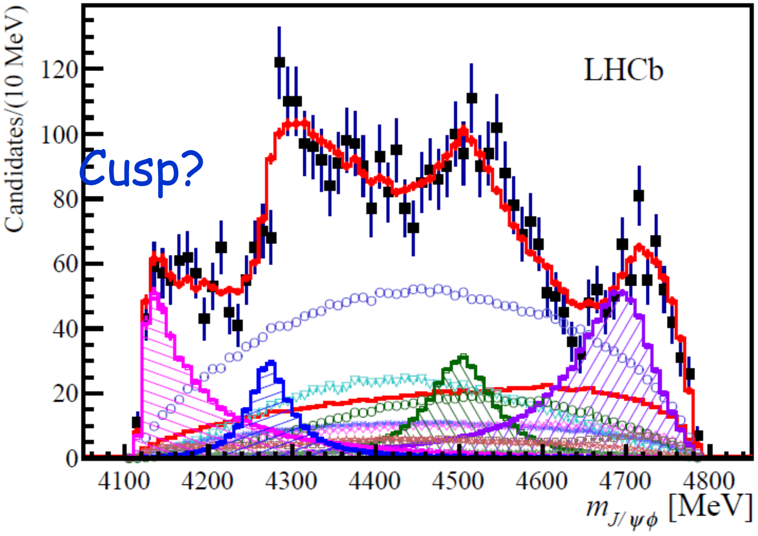

PRL104, 112004(2010)

3.1 其他X粒子态

Latest results from LHCb

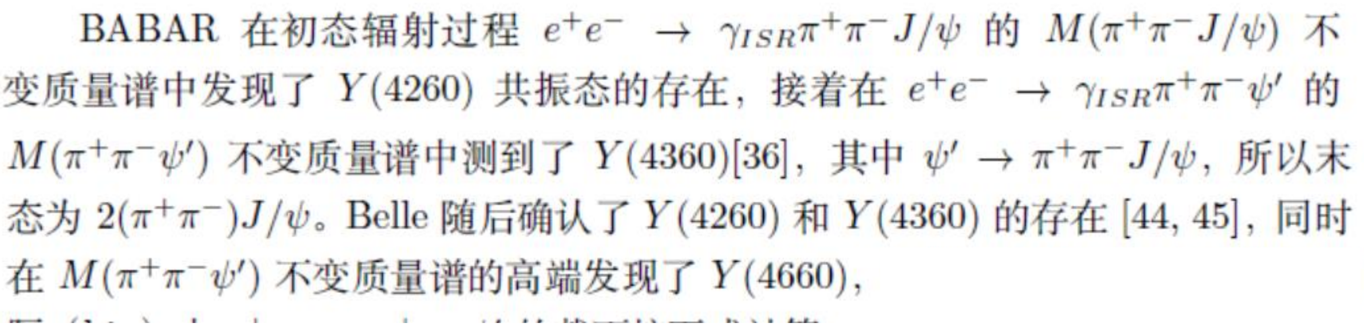
[PRL 118 (2017) 022003], [PRD 95 (2017) 012002]





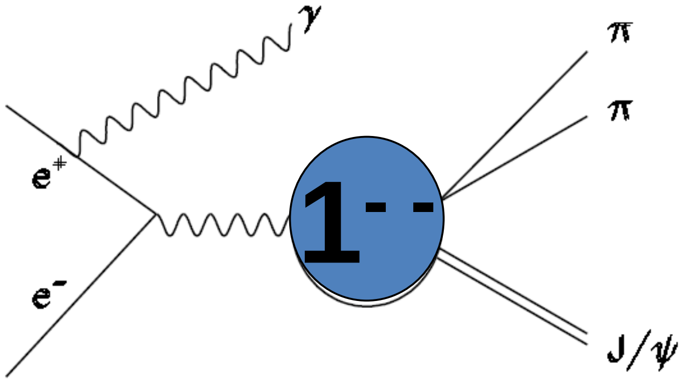
Contribution	J^{PC}	Significance	M_0 [MeV]	Γ_0 [MeV]
$X(4140)$	1^{++}	8.4σ	$4146.5\pm4.5\,^{+4.6}_{-2.8}$	$83\pm21\,^{+21}_{-14}$
$X(4274)$	1^{++}	6.0σ	$4273.3\pm8.3\,^{+17.2}_{-\ \ 3.6}$	$56\pm11\,^{+\ 8}_{-11}$
$X(4500)$	0^{++}	6.1σ	$4506\pm11\,^{+12}_{-15}$	$92\pm21\,^{+21}_{-20}$
$X(4700)$	0^{++}	5.6σ	$4704\pm10\,^{+14}_{-24}$	$120\pm31\,^{+42}_{-33}$

3.2 Y 粒子态

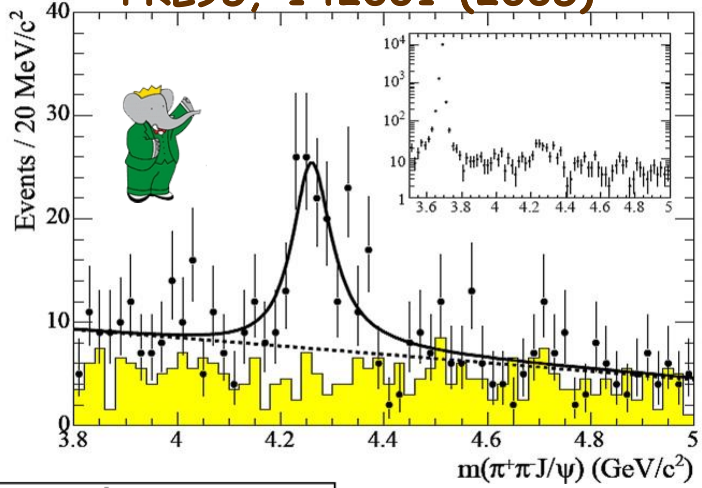


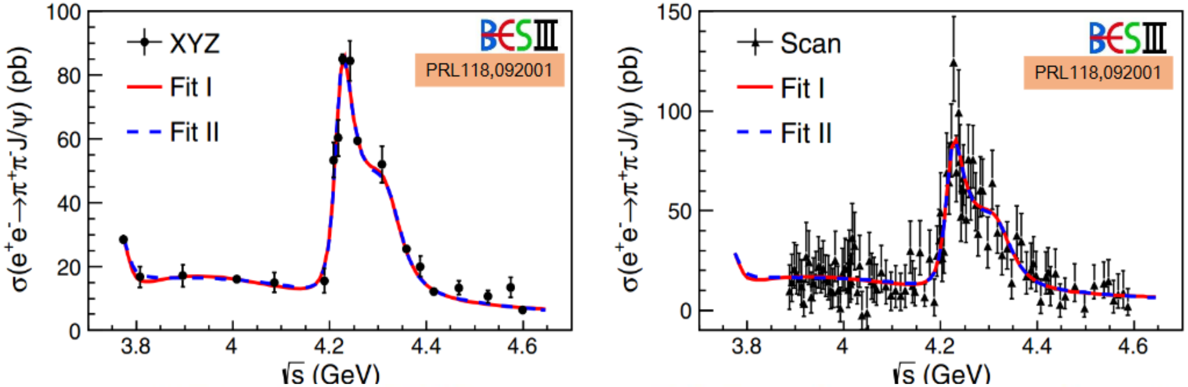
BABAR 在初态辐射过程 $e^+e^- \to \gamma_{ISR}\pi^+\pi^-J/\psi$ 的 $M(\pi^+\pi^-J/\psi)$ 不变质量谱中发现了 $Y(4260)$ 共振态的存在，接着在 $e^+e^- \to \gamma_{ISR}\pi^+\pi^-\psi'$ 的 $M(\pi^+\pi^-\psi')$ 不变质量谱中测到了 $Y(4360)$[36]，其中 $\psi' \to \pi^+\pi^-J/\psi$，所以末态为 $2(\pi^+\pi^-)J/\psi$。Belle 随后确认了 $Y(4260)$ 和 $Y(4360)$ 的存在 [44, 45]，同时在 $M(\pi^+\pi^-\psi')$ 不变质量谱的高端发现了 $Y(4660)$，

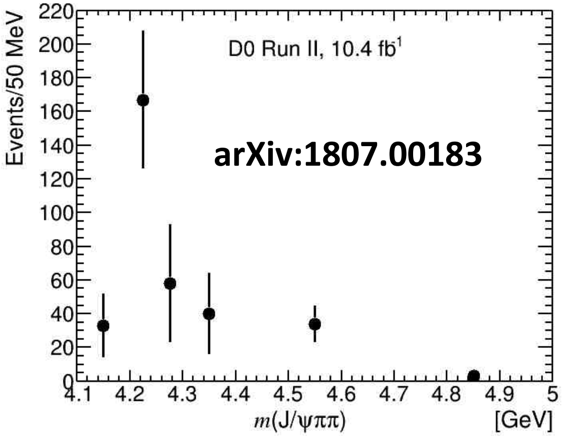
3.2 Y 粒子态Y(4260)



PRL95, 142001 (2005)





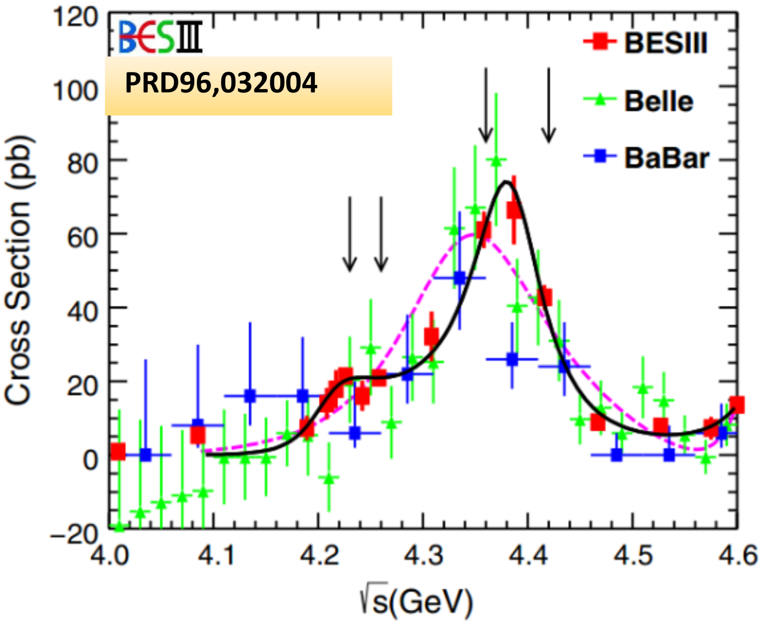


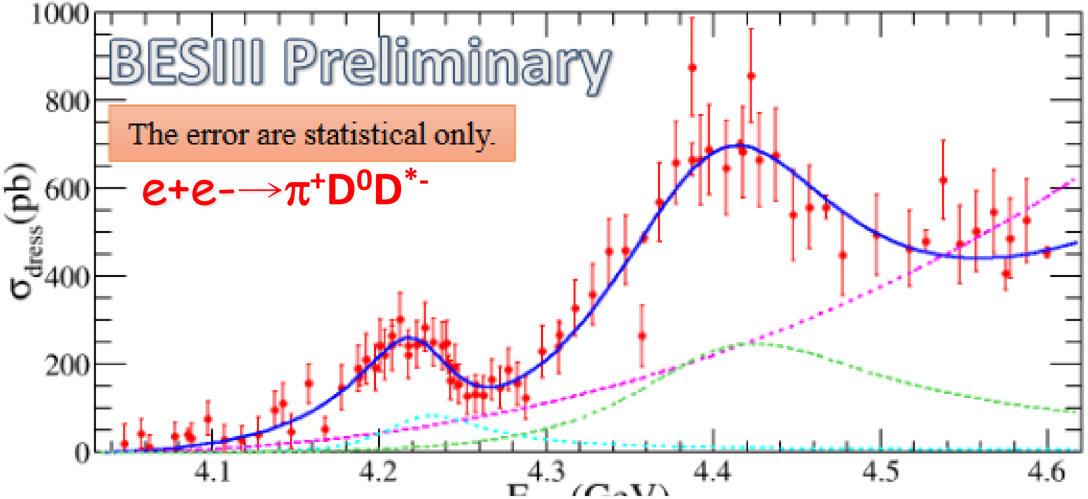
arXiv:1807.00183

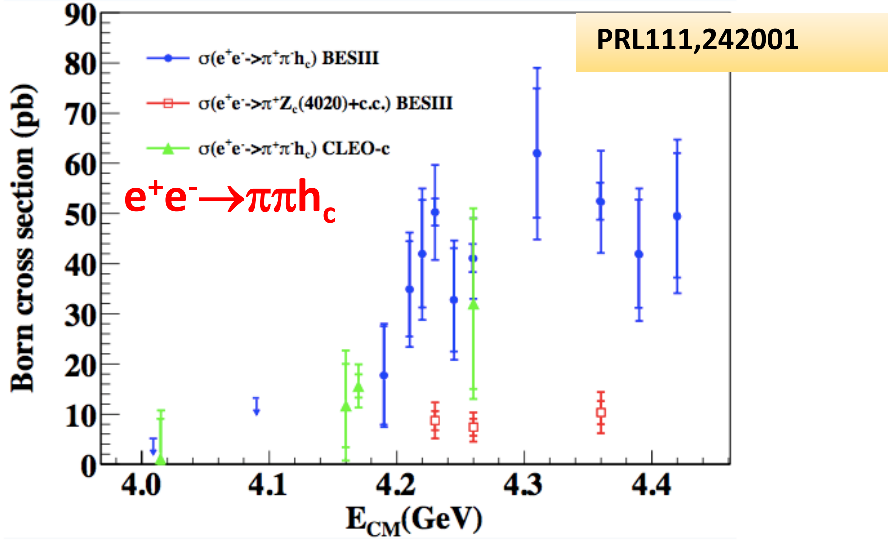
BESIII 实验利用 $9fb^{-1}$ 的 3.77 − 4.60 GeV 数据，在 $e^+e^- \to \pi^+\pi^- J/psi$ 过程中看到了两个共振态结构，如图 7.13所示 [46]。第一个的质量为 $(4222.0\pm3.1\pm1.4)MeV/c^2$，宽度为 $\Gamma=(44.1\pm4.3\pm2.0)MeV$，和 $Y(4260)$ 一致，且给出了共振态参数更为精确的测量。第二个的质量为 $(4320.0\pm10.4\pm7.0)MeV/c^2$，宽度为 $\Gamma=(101.4^{+25.3}_{-19.7}\pm10.2)MeV$，和 $Y(4360)$ 一致。第二个共振态在 $e^+e^-\to\pi^+\pi^-J/\psi$ 道的测量是世界首次，显著性大于 7.6σ。

3.2 Y 粒子态有（4260）

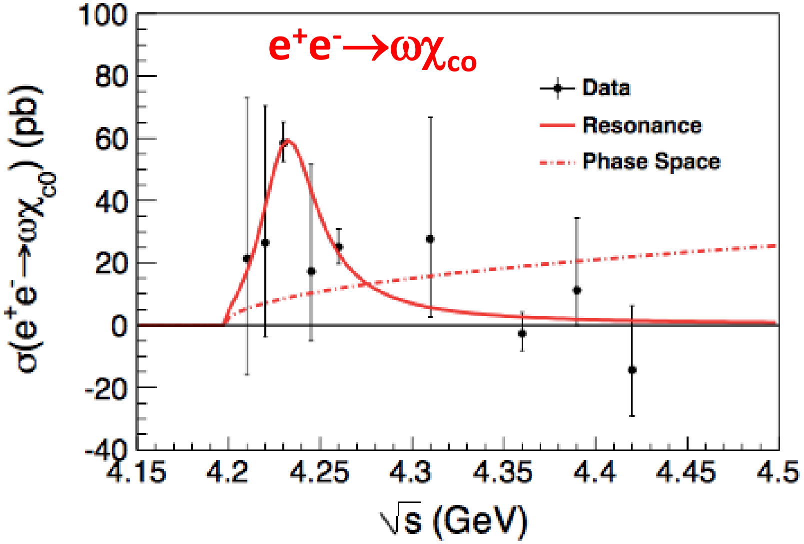
$e^+e^- \to \pi^+\pi^-\psi(2S)$


PRD96,032004


$e^+e^- \to \pi^+D^0D^{*-}$


PRL111,242001

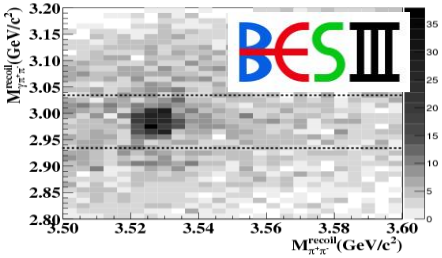
$e^+e^- \to \pi\pi h_c$

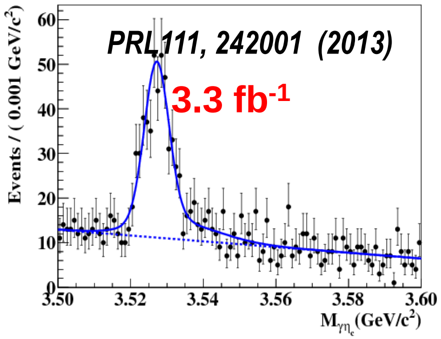

$e^+e^- \to \omega\chi_{c0}$

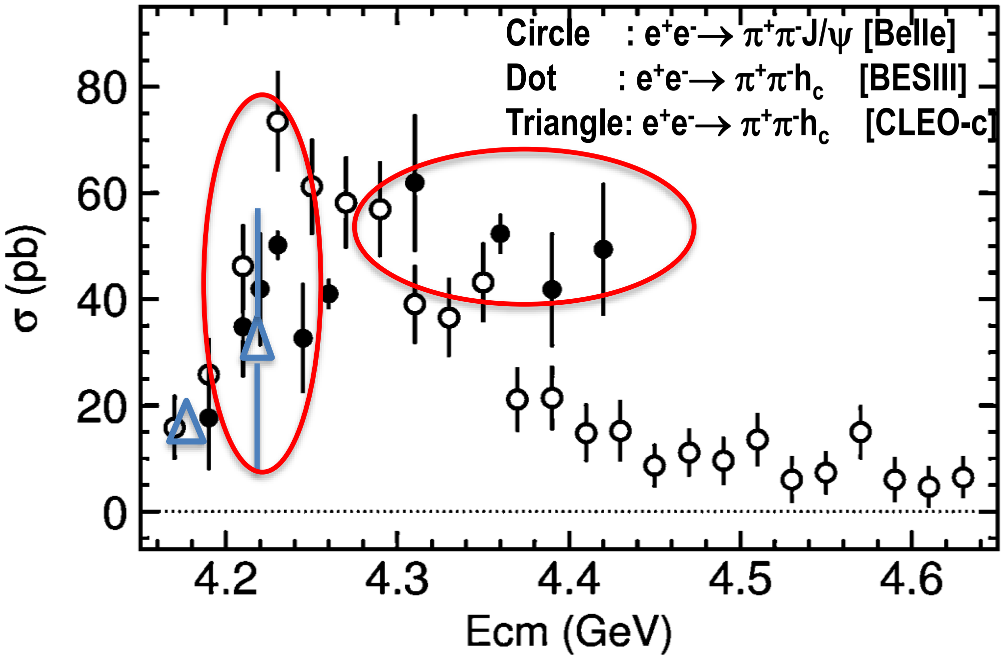
- ✓ Line-shapes are different from that of $\pi^+\pi^-J/\psi$
- ✓ Both Y(4220) and Y(4390) seem significant

3.2 Y 粒子态有（4260）

- Significant $\pi^+\pi^-h_c$ production reported by CLEO @ 4170MeV [PRL 107, 041803 (2011)]
  - Correlated with observed Y(4260) or others charmonium states?
- 3.3fb^{-1} data at 13 energy points from 3900~4420 GeV [$h_c\to\gamma\eta_c$, $\eta_c\to$hadrons, 16 exclusive decay modes]

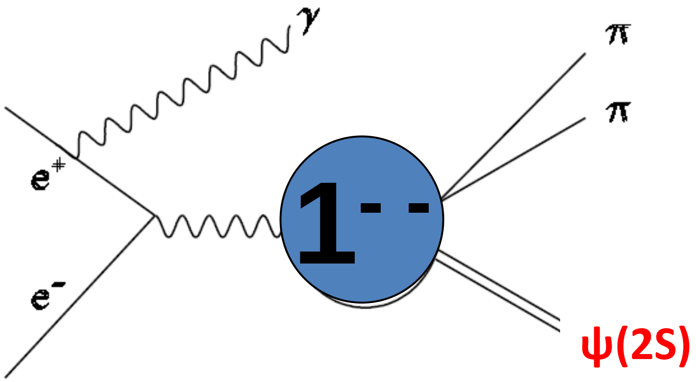


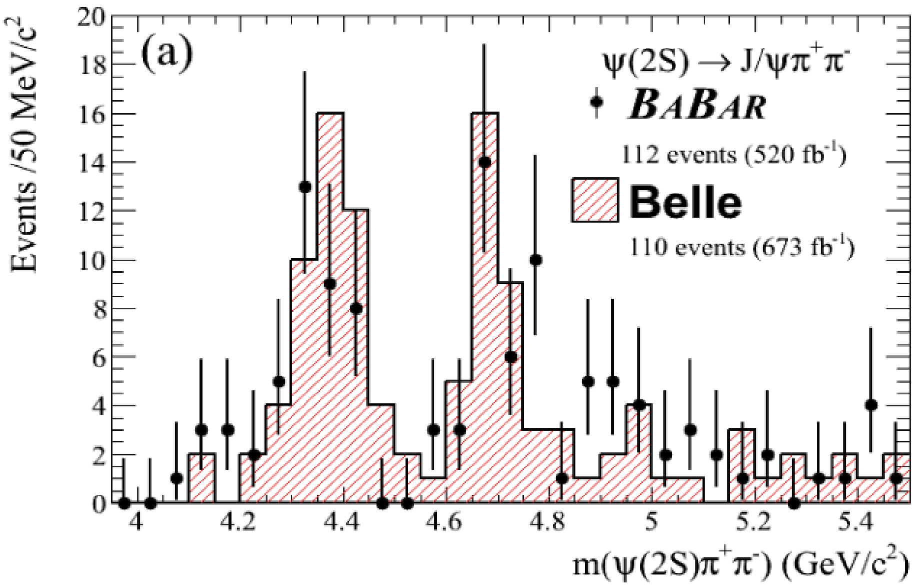




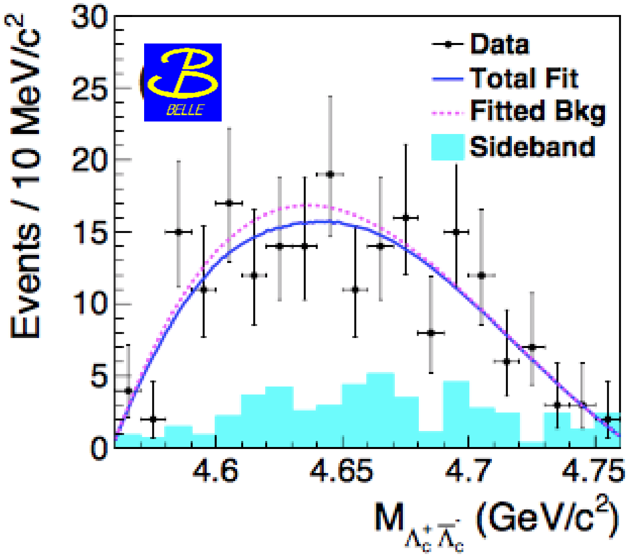
- $\sigma(e^+e^-\to\pi^+\pi^-h_c) \sim \sigma(e^+e^-\to\pi^+\pi^-J/\psi)$, but different line shape.
- Local maximum ~ 4230 MeV, broad structure at ~ 4400 MeV?
- Correlation with Y(4260) or Y(4360) is unclear
- More data around 4230MeV and above 4400MeV is very help.

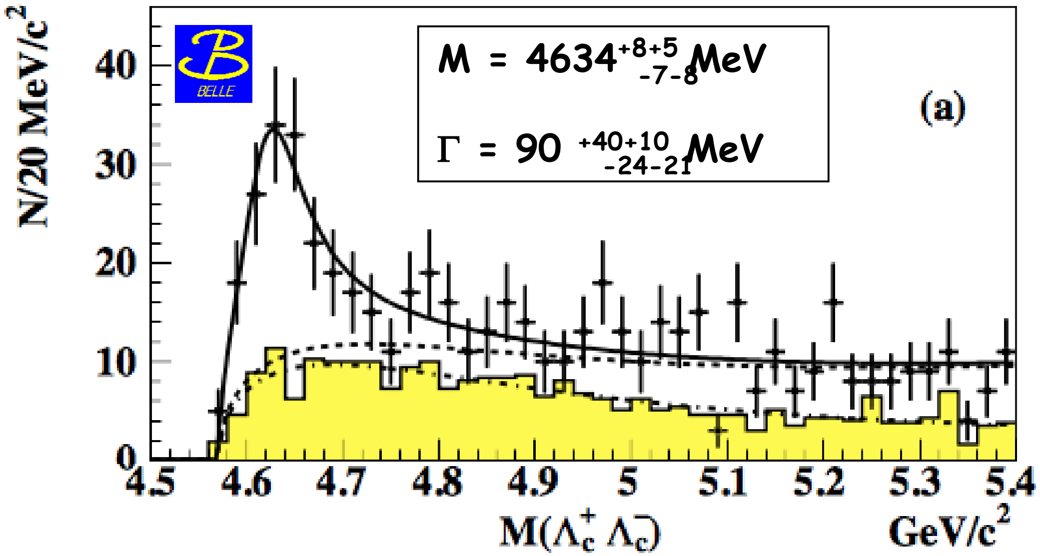
3.2 Y 粒子态Y(4360)/Y(4660)





$B^- \to K^- \Lambda_c^+ \bar{\Lambda}_c^-$



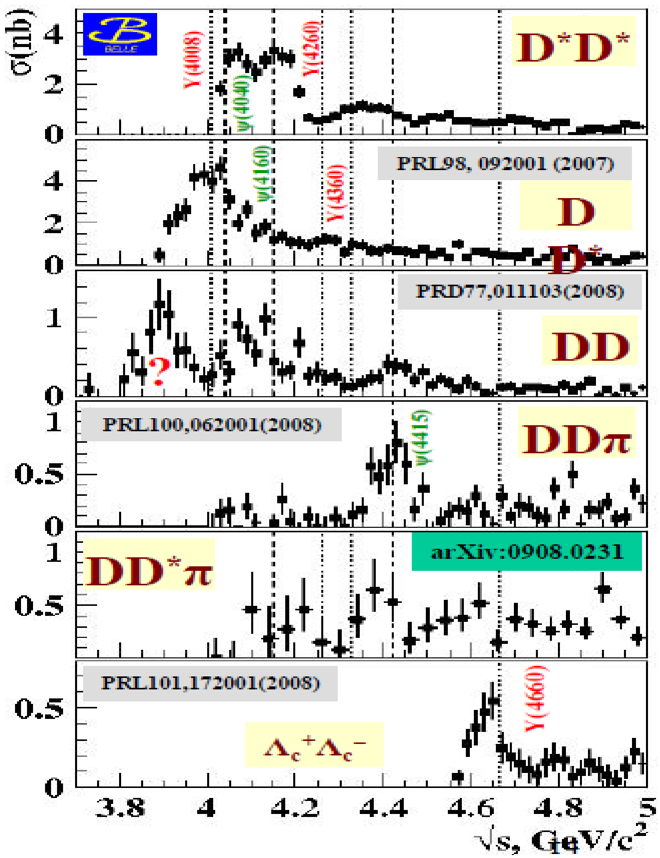


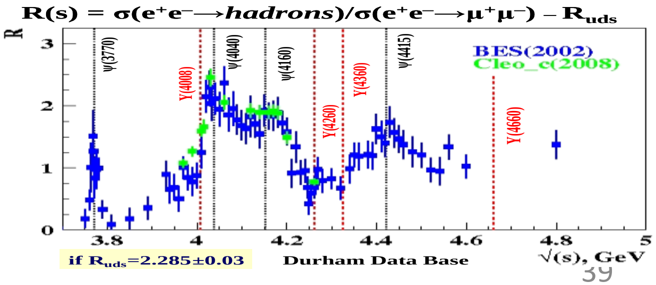
PRL101,172001

3.2 Y 粒子态

- In QM, five states expected between 4 and 4.7GeV
  - 3S/Y(4040), 2D/Y(4160), 4S/Y(4415), 3D, 5S
- But seven states observed:
  - Y(4008), Y(4040), Y(4160), Y(4260), Y(4360), Y(4415), Y(4660)
- Y(4260), Y(4360) and Y(4660) have similar properties
  - All produced in e^+e^- collisions
  - narrow structure above charm threshold
  - Strongly couple to charmonium states
  - No evidence in open-charm process and R-value scan, Large BESIII R value data sample may confirm/improve
- $e^+e^- \to \pi^+\pi^- h_c$ and $\omega\chi_{c0}$ cross section line shape
  - Makes situation more complicate
  - Have fine structures at 4230MeV, strong couple to $\omega\chi_{c0}$?
- What are these Y states
  - Hybrid? Molecule? Threshold effect? …..

Unclear, need to be understood





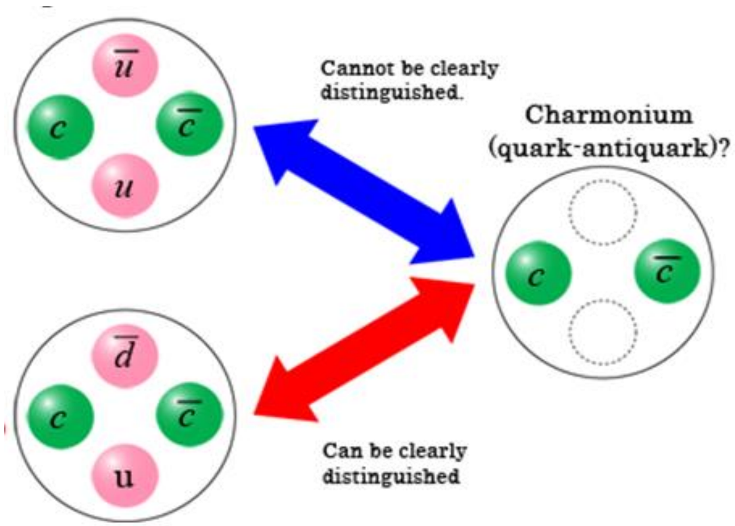
3.3 Z_c粒子态

The most promising way to searching for the exotic hadrons

- Decay into a charmonium or $D^{(*)}\bar{D}^{(*)}$ pair
  - thus contains hidden-$c\bar{c}$ pair
- Have electric charge,
  - thus has two more light quarks

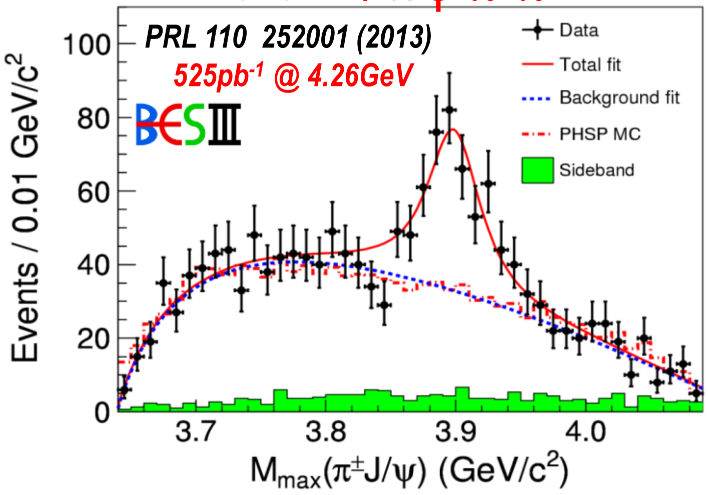
At least 4 quarks, not a conventional meson

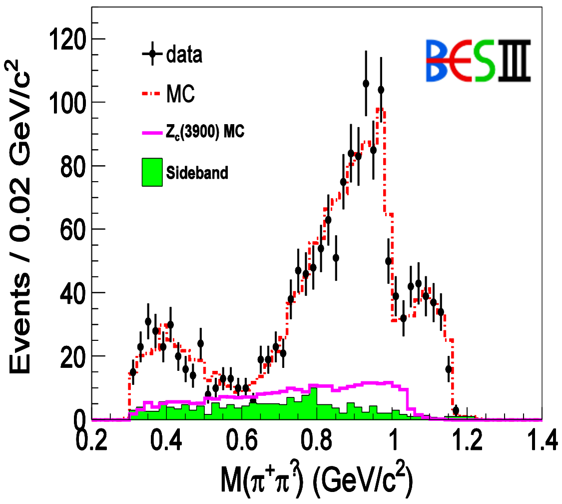
- Observed in final states :
  - $\pi^{\pm}J/\psi$, $\pi^{\pm}\psi(2S)$, $\pi^{\pm}h_c$, $\pi^{\pm}\chi_{cJ}$, $(D^{(*)}\bar{D}^{(*)})^{\pm}$,…
- Experimental search:
  - BESIII/CLEO-c : $e^+e^- \to \pi^{\pm}$ +Exotics, ….
  - Belle/BaBar : $e^+e^- \to (\gamma_{ISR})\pi^{\pm}$+Exotics, ….
  - Belle/BaBar/LHCb: $B \to K^{\pm}$+Exotics, …



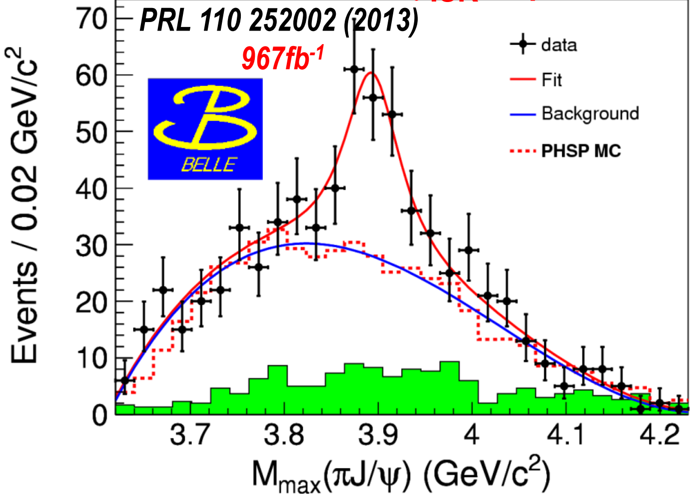
3.3 Z_c粒子态Zc(3900)

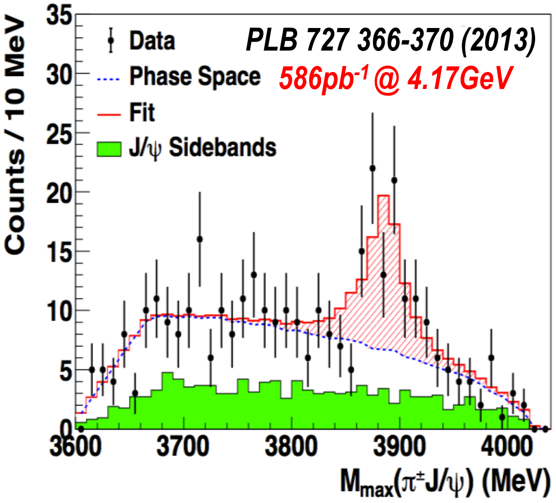
$e^+e^- \to J/\psi\, \pi^+\pi^-$





$e^+e^- \to \gamma_{ISR} J/\psi\, \pi^+\pi^-$





BESIIII

M = 3899.0±3.6±4.9 MeV

Γ = 46±10±20 MeV

307 ± 48 events, >8σ

BELLE

M = 3894.5±6.6±4.5 MeV

Γ = 63±24±26 MeV

159 ± 49 events, >5.2σ

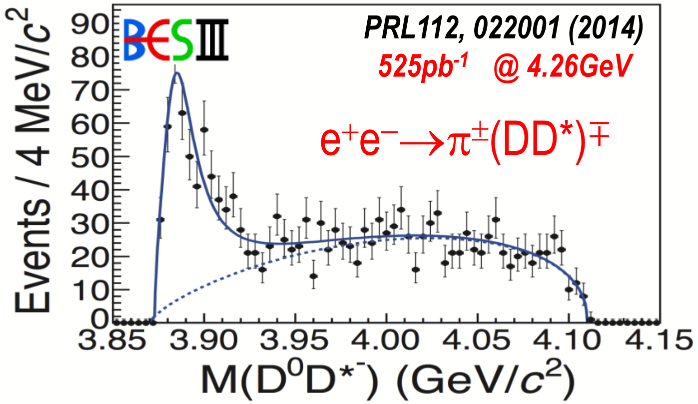
CLEO-c Data

M = 3886±4±2 MeV

Γ = 37±4±8 MeV

81 ± 16 events, >5σ

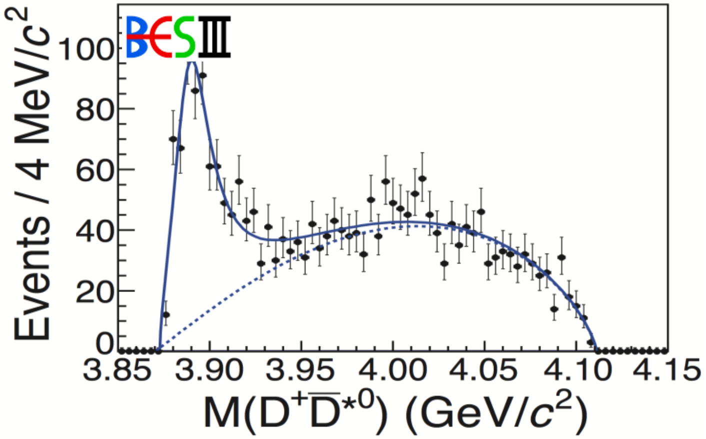
3.3 Z_c粒子态Zc(3900)



PRL112, 022001 (2014)

525pb^{-1} @ 4.26GeV

$e^+e^- \to \pi^\pm (DD^*)^\mp$



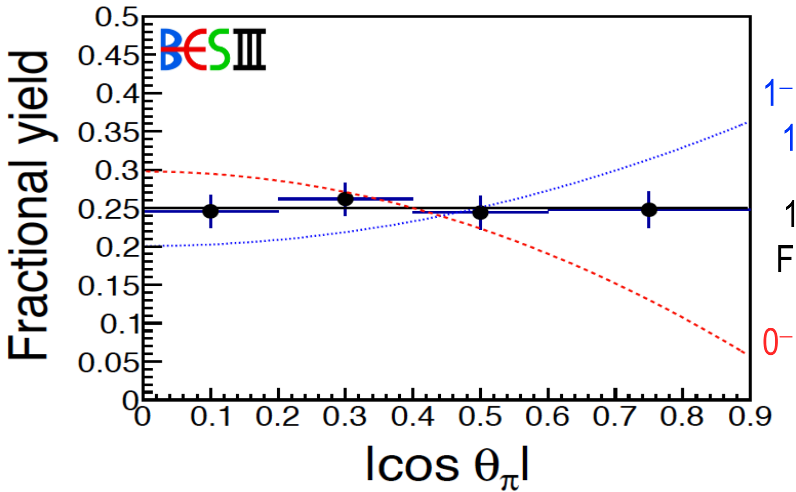
M[Z_c(3885)] = 3883.9±1.5±4.2MeV

Γ[Z_c(3885)] = 24.8±3.3±11.0MeV

2σ/1σ below those of Z_c(3900)

- **Bachelor π angular distribution :**

favors a $J^p=1^+$ assignment



1^- : P wave
$1+\cos^2\theta_\pi$

1^+ : S/D wave
Flat distribution

0^- : P wave
$\sin^2\theta_\pi$

Are Z_c(3900) and Z_c(3885) same states?

- **If Z_c(3885) is Z_c(3900):**

$$\frac{\Gamma(Z_c(3900) \to D\bar{D}^*)}{\Gamma(Z_c(3900) \to \pi J/\psi)} = 6.2 \pm 2.9$$

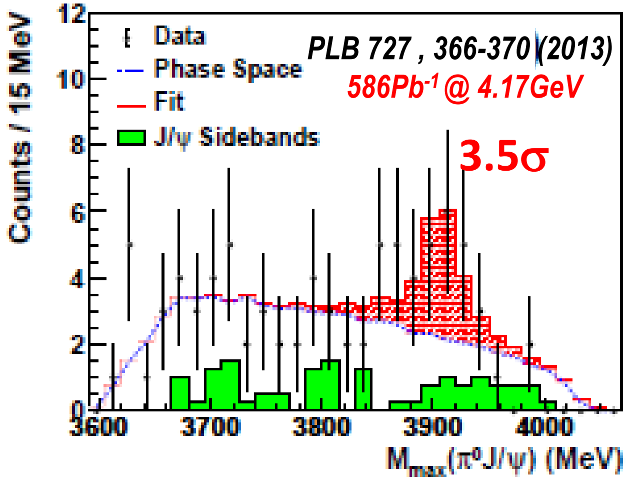
Large non-DDbar coupling

Typical values : ψ(3770)~500, ψ(4040)~200

Very different dynamics in the Y(4260)–Z_c(3900) system?

3.3 Z_c粒子态Zc(3900）

Has an isospin partner, $Z_c(3900)^0$?



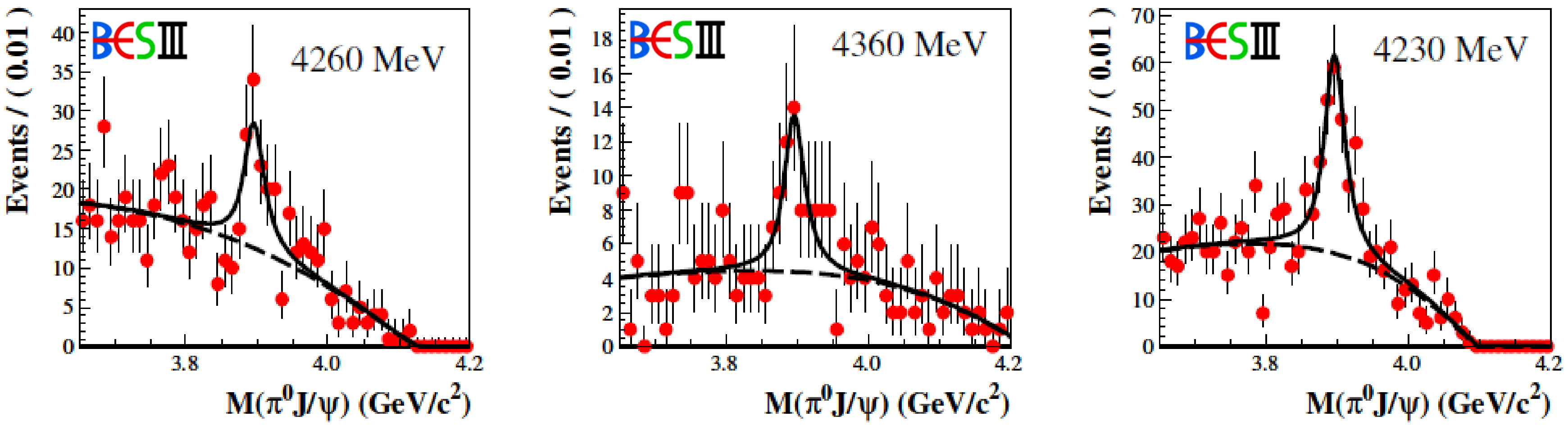
PLB 727 , 366-370 (2013)

586Pb^{-1} @ 4.17GeV

3.5σ

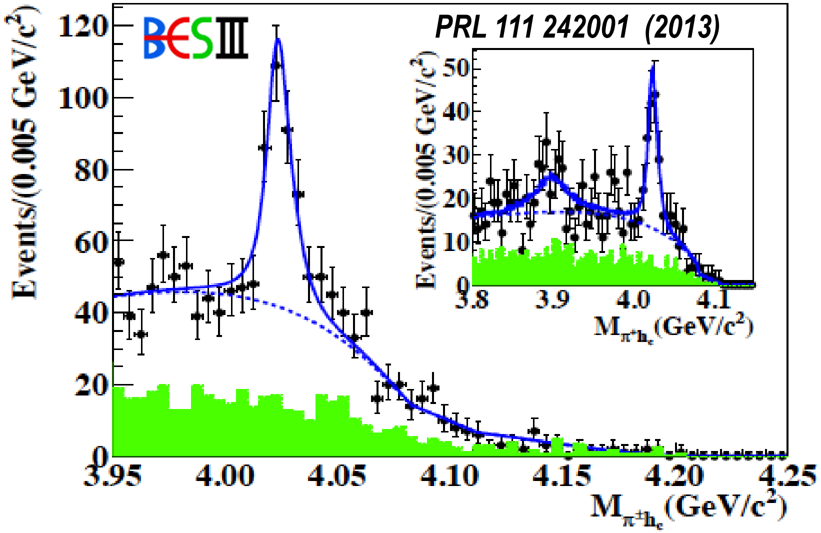
- 2.8fb^{-1} data at 10 energy points from 4230~4420 MeV
- $Z_c(3900)^0$ is observed clearly at E_{cm}=4230, 4260, 4360MeV
- BESIII preliminary results :
  - M= 3894.8±2.3 MeV, Γ = 29.6±8.2 MeV
  - Significance = 10.4 σ

Neutral isospin partner, $Z_c(3900)^0$ observed

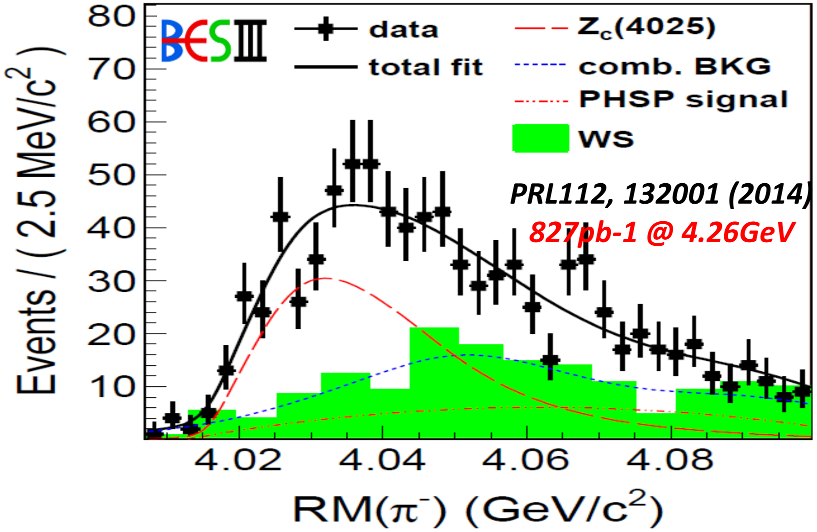


3.3 Z_c粒子态Zc(4020）

$e^+e^- \to \pi^+\pi^- h_c$



$e^+e^- \to \pi^\pm (D^*D^*)^\mp$



- **Narrow $\pi^\pm h_c$ structure observed**
  - **M = 4022.9±0.8±2.7 MeV;**
  - **Γ= 7.9±2.7±2.6 MeV**
  - **Significance ：8.9σ**
- **No significant evidence for $Z_c(3900) \to \pi^\pm h_c$**
  - **Significance 2.1σ**
  - **@ Ecm = 4260 MeV**

$$\sigma(e^+e^- \to \pi^\pm Z_c(3900)^\mp \to \pi^+\pi^- h_c) < 11 \text{ pb}$$

$$\sigma(e^+e^- \to \pi^\pm Z_c(3900)^\mp \to \pi^+\pi^- J/\psi) = 13 \pm 5 \text{ pb}$$

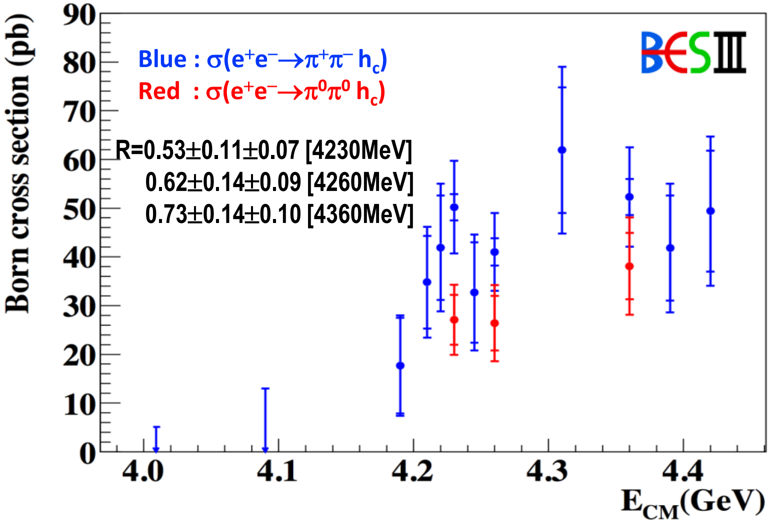
- **Deviation from phase space decay**
  - **M = 4026.3±2.6±3.7 MeV**
  - **Γ = 24.8±5.6±7.7 MeV**
  - **Significance : 10σ**

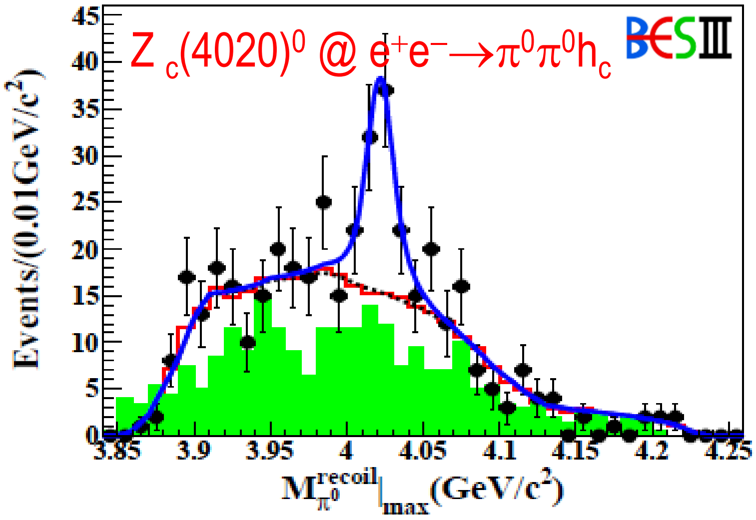
Are $Z_c(4020)$ and $Z_c(4025)$ same particle?

- **If $Z_c(4025)$ is the $Z_c(4020)$**

$$\frac{\Gamma(Z_c(4020) \to D^*\bar{D}^*)}{\Gamma(Z_c(4020) \to \pi h_c)} = 12 \pm 5$$

3.3 Z_c粒子态Zc(4020）





- Study $e^+e^-\rightarrow\pi^0\pi^0h_c$ at E_{cm} = 4230, 4260, 4360 MeV
- X-sec. is about half of that charged process, agree with the expectation of isospin symmetry
- Observe $Z_c(4020)^0$ structure in $\pi_0 h_c$ mass distribution
- BESIII preliminary Result :
  - M[$Z_c(4020)^0$] = 4023.6±2.2±3.9 MeV

    [M[$Z_c(4020)^\pm$] = 4022.9±0.8±2.7 MeV]
  - Width fixed to charged Z_c(4020)
  - Significance : >5σ

Neutral partner of charge Z_c(4020) observed!

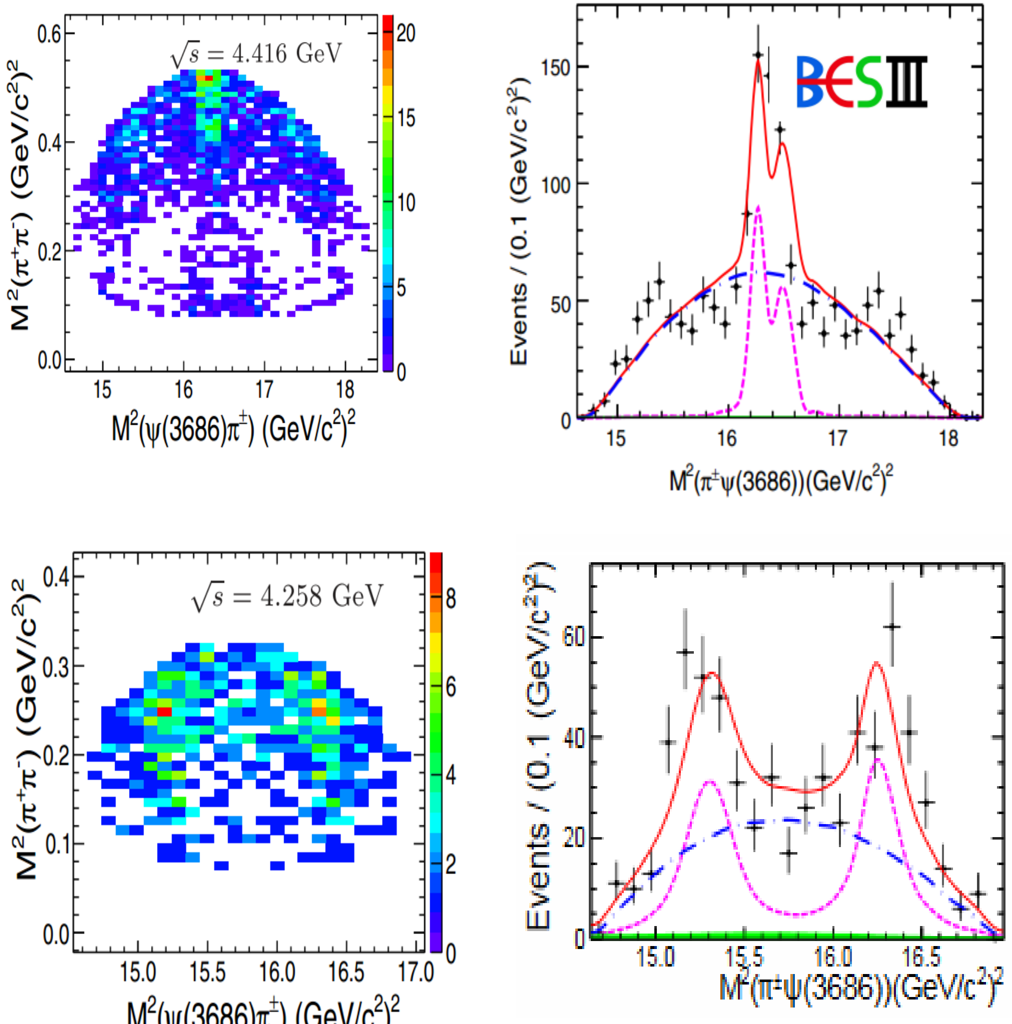
Observation of neutral Z_c(3900) and Z_c(4020)

→

Isovector nature of Z_c states established

3.3 Z_c粒子态Zc(4020)

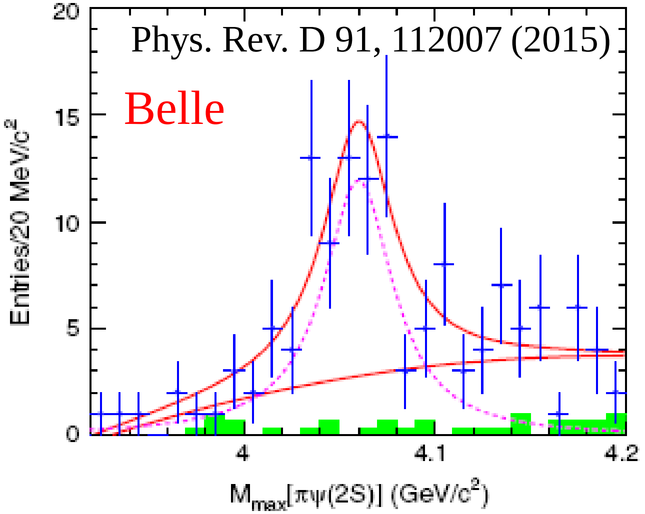
PRD96,032004(2017)



Charge structure in $M(\pi^\pm\psi(3686))$

Mass = (4032.1 ± 2.4) MeV/c²

Width = (26.1±5.3) MeV



Mass = $(4054 \pm 3 \pm 1)$ MeV/c²

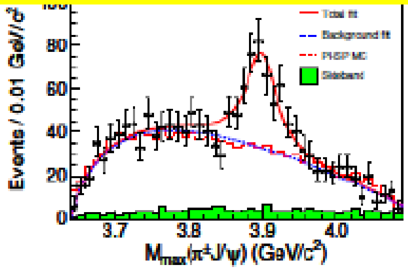
Width = (45±11±6) MeV

Zc(4030) in $e^+e^- \to \pi^+\pi^-\psi(3686)$

3.3 Z_c粒子态@BESIII

Zc(3900)$^+$

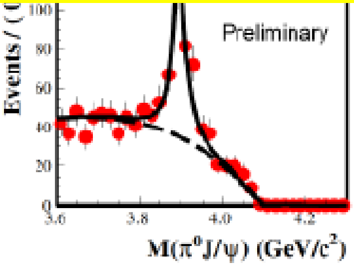
PRL 110, 252001 (2013)



$e^+e^- \to \pi^-\pi^+J/\psi$

Zc(3900)^0

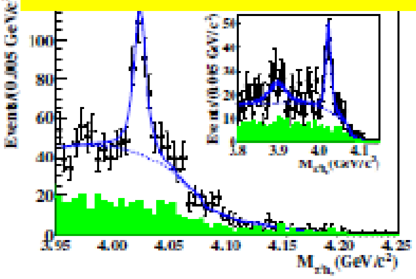
PRL 115, 112003 (2015)



$e^+e^- \to \pi^0\pi^0J/\psi$

Zc(4020)$^+$

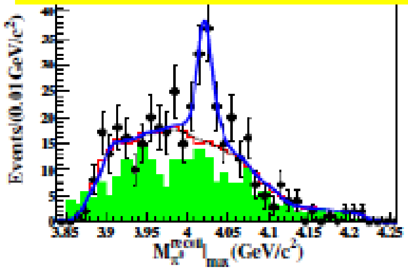
PRL 111, 242001(2013)



$e^+e^- \to \pi^-\pi^+h_c$

Zc(4020)^0

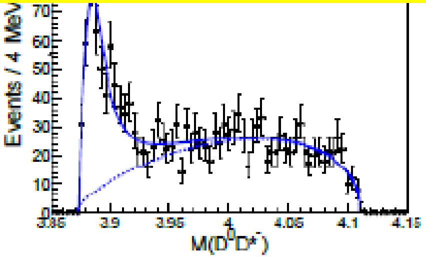
PRL113,212002 (2014)



$e^+e^- \to \pi^0\pi^0h_c$

Zc(3885)$^+$

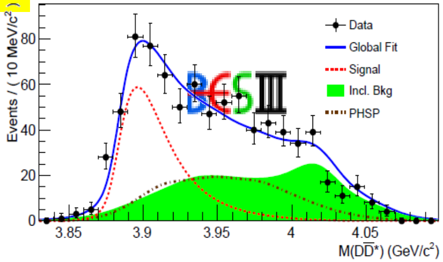
ST: PRL 112, 022001(2014)
DT: PRD92, 092006 (2015)



$e^+e^- \to \pi^-(D\bar{D}^*)^+$

Zc(3885)^0

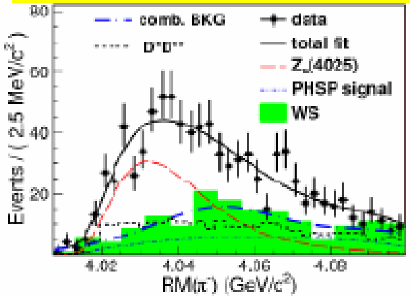
PRL 115, 222002 (2015)



$e^+e^- \to \pi^0(D^*\bar{D}\ )^0$

Zc(4025)$^+$

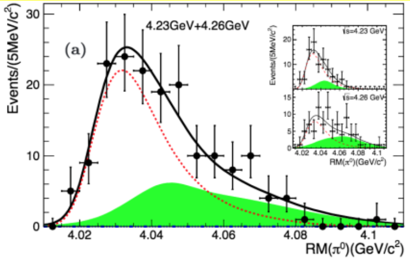
PRL 112, 132001 (2014)



$e^+e^- \to \pi^-(D^*\bar{D}^*)^+$

Zc(4025)^0

PRL115, 182002 (2015)



$e^+e^- \to \pi^0(D^*\bar{D}^*)^0$

Which is the nature of these states?
Different decay channels of the same observed states?
Other decay modes?

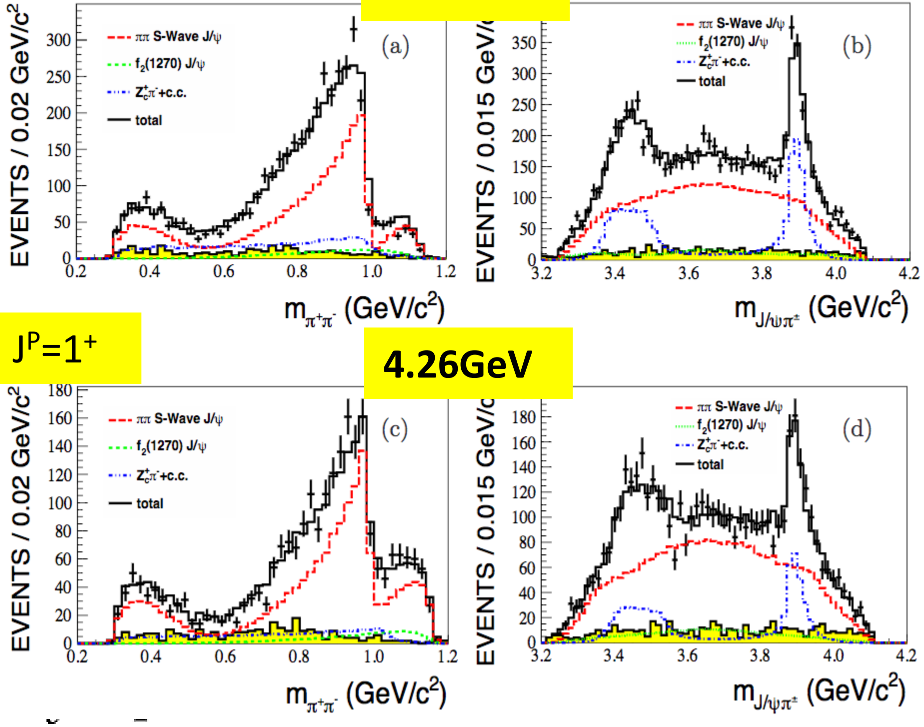
3.3 Z_c粒子态@BESIII

State	Mass (MeV/c²)	Width (MeV)	Decay	Process
$Z_c(3900)^\pm$	$3899.0 \pm 3.6 \pm 4.9$	$46 \pm 10 \pm 20$	$\pi^\pm J/\psi$	$e^+e^- \to \pi^+\pi^- J/\psi$
$Z_c(3900)^0$	$3894.8 \pm 2.3 \pm 2.7$	$29.6 \pm 8.2 \pm 8.2$	$\pi^0 J/\psi$	$e^+e^- \to \pi^0\pi^0 J/\psi$
$Z_c(3885)^\pm$	$3883.9 \pm 1.5 \pm 4.2$ Single D tag	$24.8 \pm 3.3 \pm 11.0$ Single D tag	$(D\bar{D}^*)^\pm$	$e^+e^- \to (D\bar{D}^*)^\pm \pi^\mp$
	$3881.7 \pm 1.6 \pm 2.1$ Double D tag	$26.6 \pm 2.0 \pm 2.3$ Double D tag	$(D\bar{D}^*)^\pm$	$e^+e^- \to (D\bar{D}^*)^\pm \pi^\mp$
$Z_c(3885)^0$	$3885.7^{+4.3}_{-5.7} \pm 8.4$	$35^{+11}_{-12} \pm 15$	$(D\bar{D}^*)^0$	$e^+e^- \to (D\bar{D}^*)^0 \pi^0$
$Z_c(4020)^\pm$	$4022.9 \pm 0.8 \pm 2.7$	$7.9 \pm 2.7 \pm 2.6$	$\pi^\pm h_c$	$e^+e^- \to \pi^+\pi^- h_c$
$Z_c(4020)^0$	$4023.9 \pm 2.2 \pm 3.8$	fixed	$\pi^0 h_c$	$e^+e^- \to \pi^0\pi^0 h_c$
$Z_c(4025)^\pm$	$4026.3 \pm 2.6 \pm 3.7$	$24.8 \pm 5.6 \pm 7.7$	$D^*\bar{D}^*$	$e^+e^- \to (D^*\bar{D}^*)^\pm \pi^\mp$
$Z_c(4025)^0$	$4025.5^{+2,0}_{-4.7} \pm 3.1$	$23.0 \pm 6.0 \pm 1.0$	$D^*\bar{D}^*$	$e^+e^- \to (D^*\bar{D}^*)^0 \pi^0$

3.3 Zc(3900)自旋

Amplitude analysis of $e^+e^- \rightarrow \pi^+\pi^- J/\psi$

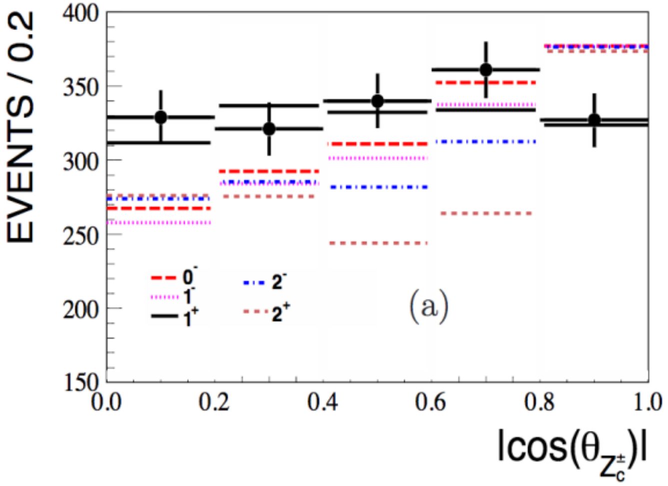
PRL 119.072001 (2017)



4.23GeV

$J^P=1^+$

4.26GeV



J^P is measured to be 1^+ with significance larger than 7.6σ

$$M_{\text{pole}} = 3881.2 \pm 4.2 \pm 52.7 \text{ MeV}, \ \Gamma_{\text{pole}} = 51.8 \pm 4.6 \pm 36.0 \text{ MeV}$$

- Born cross section for $e^+e^- \rightarrow Z_c^+\pi^- + c.c. \rightarrow \pi^+\pi^- J/\psi$

  $21.8 \pm 1.0 \pm 4.4$ pb at 4.23 GeV

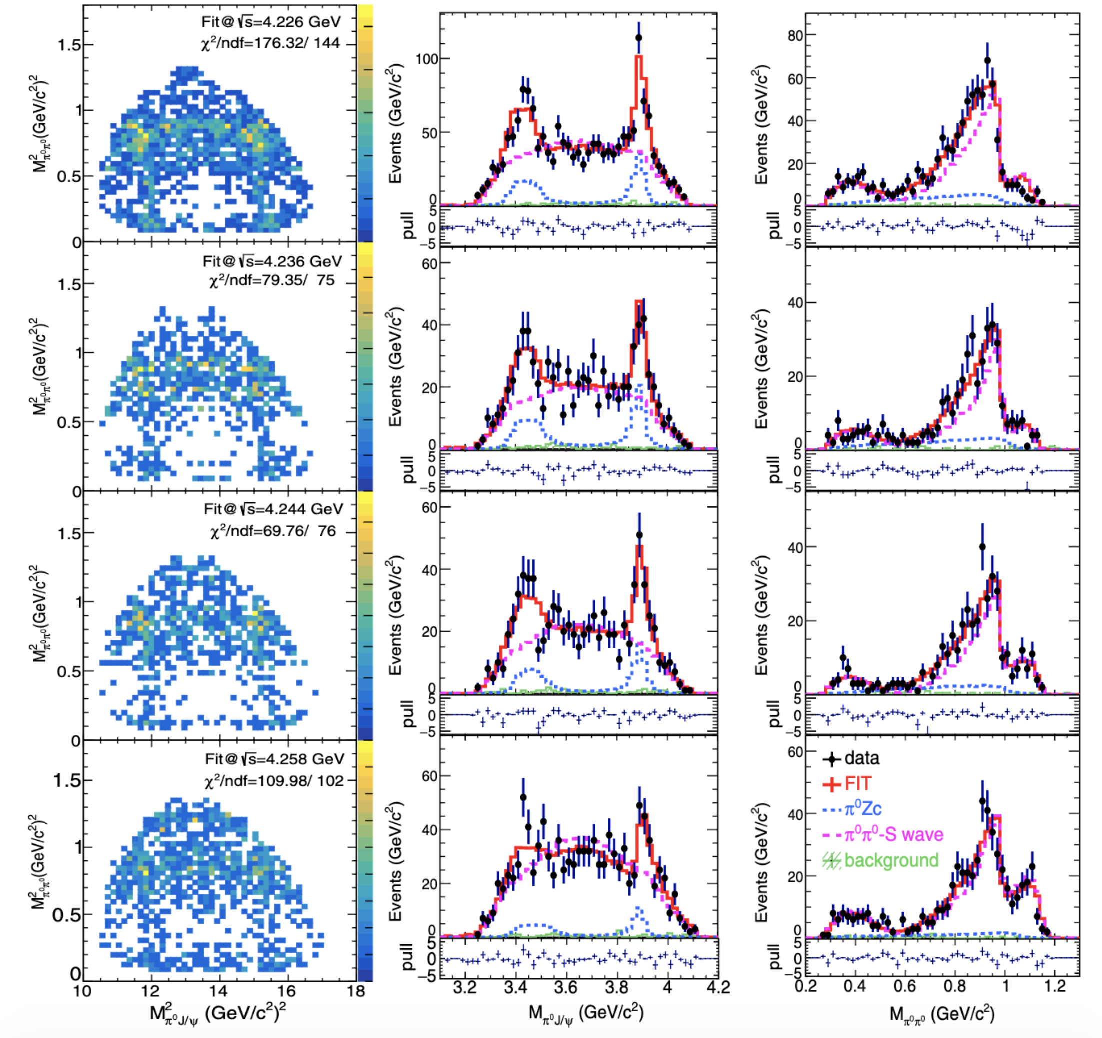
  $11.0 \pm 1.2 \pm 5.4$ pb at 4.26 GeV

$$\frac{\sigma(e^+e^- \rightarrow Z_c^+(4020)\ \pi^- + c.c \rightarrow \pi^+\pi^- J/\psi)}{\sigma(e^+e^- \rightarrow Z_c^+(3900)\ \pi^- + c.c \rightarrow \pi^+\pi^- J/\psi)} < 4\% \quad \text{at 4.23 GeV}$$

$<13\%$ at 4.26 GeV

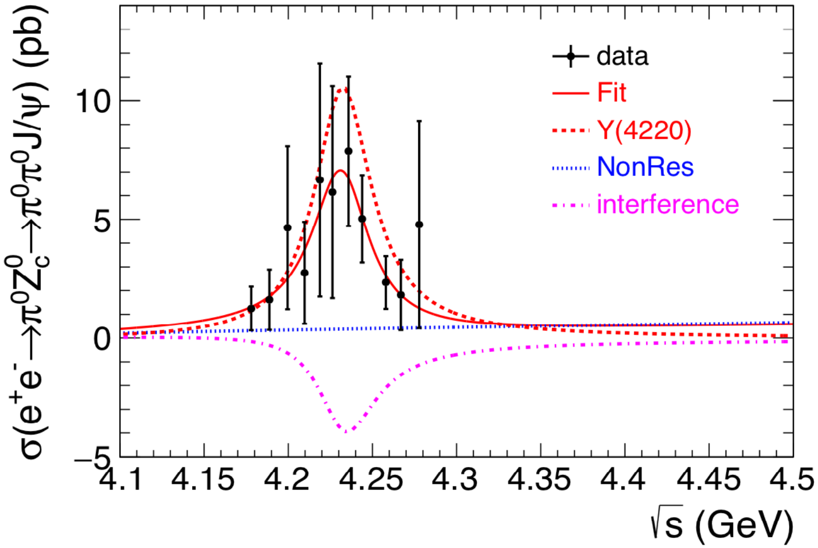
3.3 Zc(3900)自旋

PRD 102, 012009 (2020)

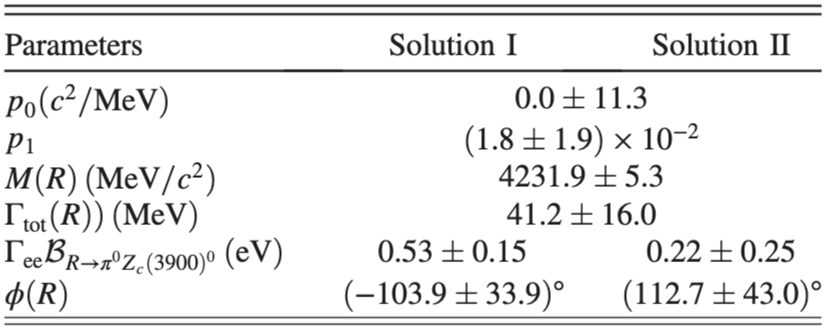


- Simultaneous PWA fit of $e^+e^-\to\pi^0\pi^0 J/\psi$ to the four energy points
- The spin-parity of $\mathrm{Z_c(3900)^0}$ is determined to be 1^+
- The nominal fit includes the intermediate process $\sigma J/\psi$, $f(980)J/\psi$, $f(1370)J/\psi$ and $\pi^0\,\mathrm{Z_c(3900)^0}$.
- Mass and width of $\mathrm{Z_c(3900)^0}$ is measured:
  - $M(\mathrm{Z_c(3900)^0})$ = (3893.0±2.3±19.9) MeV/c^2,
  - $\Gamma(\mathrm{Z_c(3900)^0})$ = (44.2±5.4±9.1) MeV.

3.3 Zc(3900)产生截面



PRD 102, 012009 (2020)



Parameters	Solution I	Solution II
$p_0(c^2/\mathrm{MeV})$	0.0 ± 11.3	
p_1	$(1.8\pm1.9)\times10^{-2}$	
$M(R)$ (MeV/c^2)	4231.9 ± 5.3	
$\Gamma_{\mathrm{tot}}(R))$ (MeV)	41.2 ± 16.0	
$\Gamma_{\mathrm{ee}}\mathcal{B}_{R\to\pi^0 Z_c(3900)^0}$ (eV)	0.53 ± 0.15	0.22 ± 0.25
$\phi(R)$	$(-103.9\pm33.9)^\circ$	$(112.7\pm43.0)^\circ$

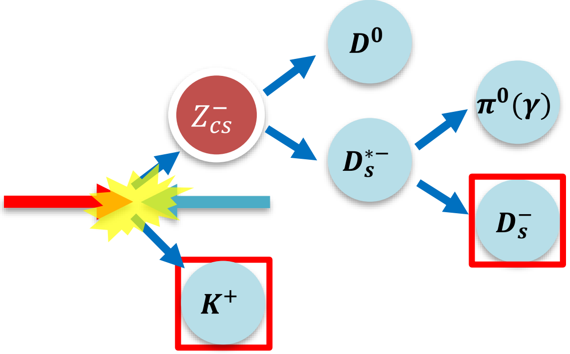
- Zc(3900)^0 resonance parameters are fixed to the results of the previous four-energy-point fit
- The Born cross section of $e^+e^-\to\pi^0 \mathrm{Z_c}(3900)^0\to\pi^0\ \pi^0 J/\psi$ is extracted.
- Clear structure around 4.2 GeV is observed
  - – $M=(4231.9\pm5.3\pm4.9)\ \mathrm{MeV/c^2}$,
  - – $\Gamma=(41.2\pm16.0\pm16.4)$ MeV.
- Compatible with the Y(4220) line shape
- Indication of correlation between the production of the Y(4220) and $\mathrm{Z_c}(3900)$.

3.3 Z_{cs}粒子态

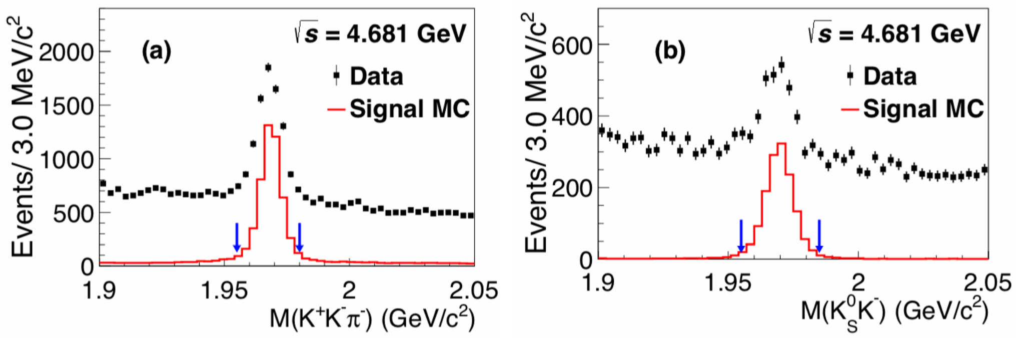
$e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$

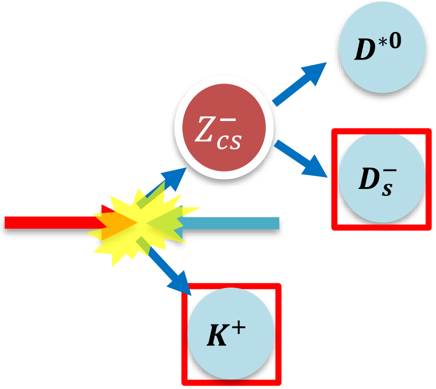
PRL 126, 102001 (2021)

- We analyze 3.7fb^{-1} data accumulated at 4.628, 4.641, 4.661, 4.681 and 4.698GeV in 2020.
- **Partial reconstruction of K^+ and D_s^-**
- Signature in the **recoil mass spectrum of $K^+D_s^-$** to identify the process of $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$

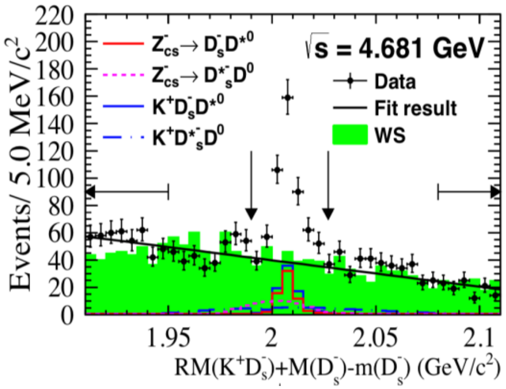


$e^+e^- \to K^+D_s^{*-}D^0$





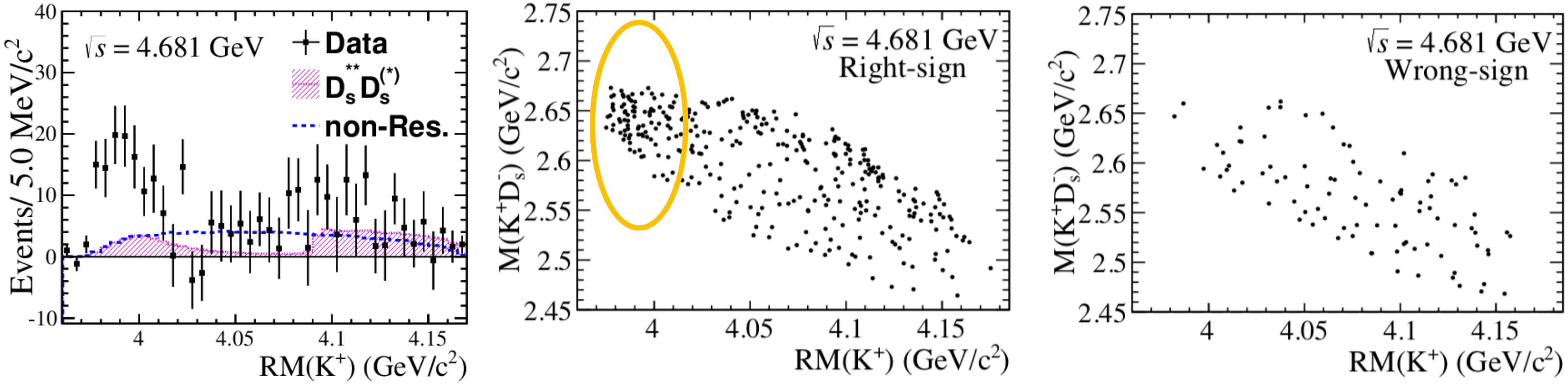
$e^+e^- \to K^+D_s^-D^{*0}$

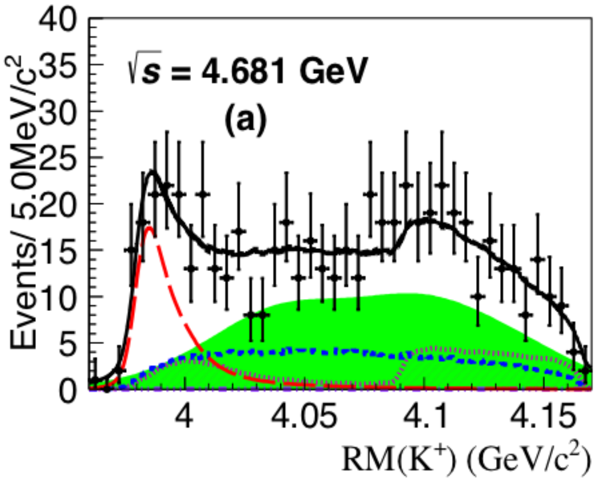


3.4 Z_{cs}粒子态

PRL 126, 102001 (2021)

- Data driven background description: wrong Sign (WS) combination of D_s^- and K^-
- Conventional charmed mesons can not describe the enhancement below 4.0 GeV/c^2 at 4.681 GeV





- Assume the structure as a $D_s^- D^{*0}/D_s^{*-} D^0$ resonance, denoting it as the $Z_{cs}(3985)^-$.
- A fit of $J^P=1^+$ S-wave Breit-Wigner with mass dependent width returns:

$$\boldsymbol{m} = 3985.2^{+2.1}_{-2.0} \pm 1.7 \text{ MeV/c}^2$$

$$\boldsymbol{\Gamma} = 13.8^{+8.1}_{-5.2} \pm 4.9 \text{ MeV}$$

- Global significance: >5.3 $\boldsymbol{\sigma}$

First candidate of the hidden-charm tetraquark with strangeness

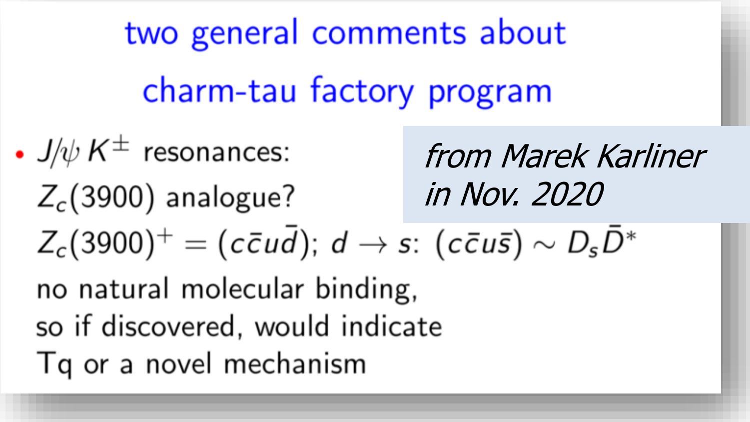
3.4 Z_{cs}粒子态

1643/pb data @4.681 GeV

525/pb data @4.26 GeV

	$Z_{cs}(3985)^{\pm}$	$Z_c(3900)^{\pm}$	$Z_c(3885)^{\pm}$
Mass (MeV/c^2)	$3985.2^{+2.1}_{-2.0} \pm 1.7$	3899.0±3.6±4.9	3883.9±1.5±4.2
Width (MeV)	$13.8^{+8.1}_{-5.2} \pm 4.9$	46±10±26	24.8±3.3±11.0
$\sigma^{Born} \cdot \mathfrak{B}$ (pb)	$4.4^{+0.9}_{-0.8} \pm 1.4$	13.5±2.1±4.8	83.5±6.6±22.0

- close width
- cross section: one-order-of-magnitude less

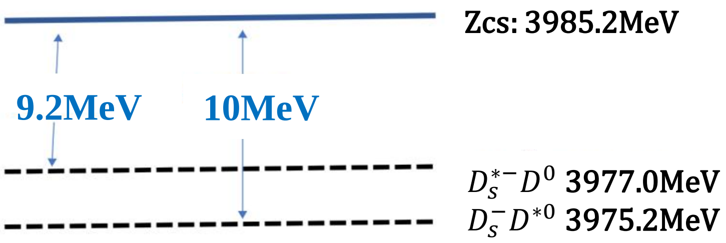


two general comments about

charm-tau factory program

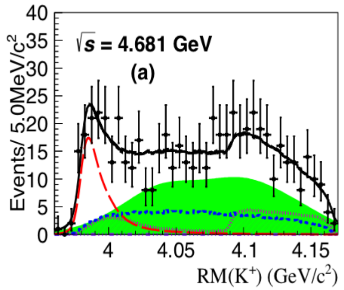
- $J/\psi\, K^{\pm}$ resonances:
  $Z_c(3900)$ analogue?
  $Z_c(3900)^+ = (c\bar{c}u\bar{d})$; $d \to s$: $(c\bar{c}u\bar{s}) \sim D_s\bar{D}^*$
  no natural molecular binding,
  so if discovered, would indicate
  Tq or a novel mechanism

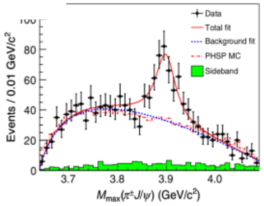
from Marek Karliner in Nov. 2020

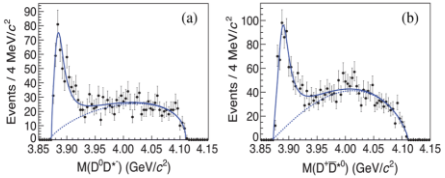


~10 MeV above D_sD^*/D_sD thresholds
similar to $Z_c(3900)$ & $Z_b(10,610)$
(DD*) (BB*)

SU(3) partner of Zc(3900)?







$Z_{cs}(3985)$

$K^-Z_{cs}^+$	$\bar{K}^0Z_{cs}^0$	$K^0\bar{Z}_{cs}^0$	$K^+Z_{cs}^-$
1/4	1/4	1/4	1/4

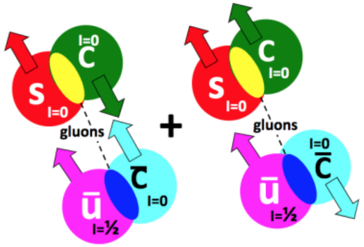
neutral/charged = 1

$Z_c(3900)$

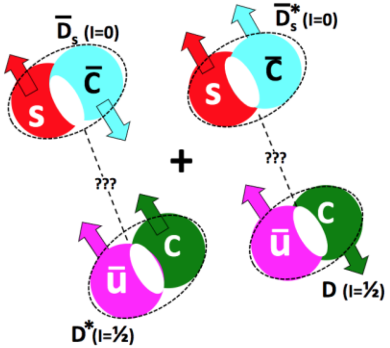
$\pi^-Z_c^+$	$\pi^0Z_c^0$	$\pi^+Z_c^-$
1/3	1/3	1/3

neutral/charged = 1/2

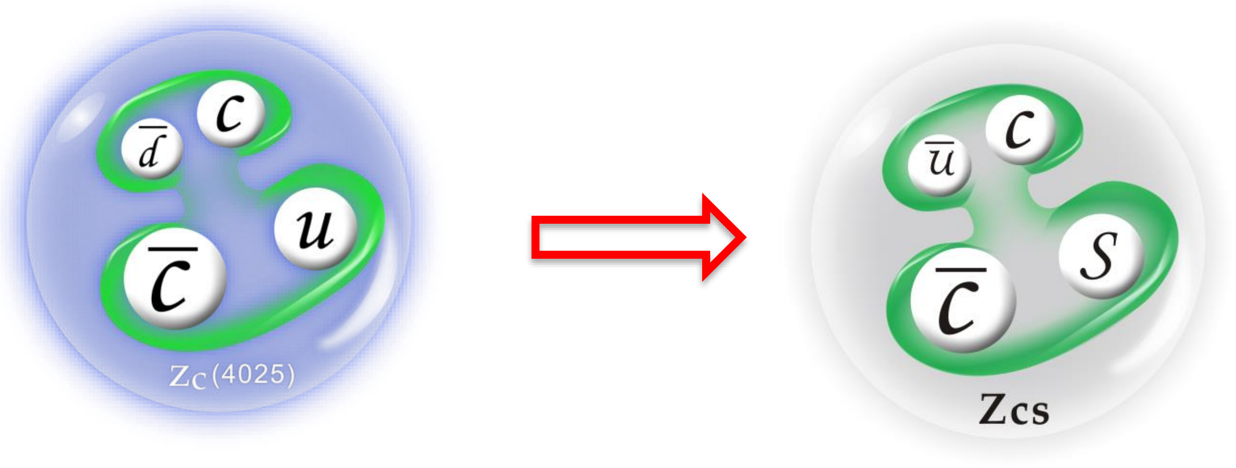
diquark-antidiquark?



D*$\bar{D}_s$ + cc molecule?



3.3 Z_{cs}粒子态



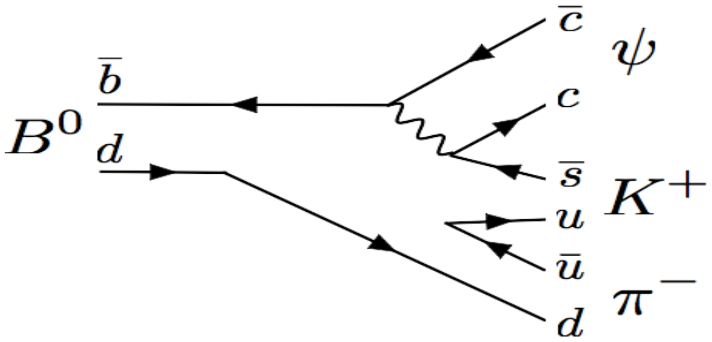
- Several Z_c^- states were observed from in e^+e^- production or B decays, at least have $c\bar{c}d\bar{u}$ four quarks
- Would be nice to look for Z_{cs}, the SU(3) partners of $X(3872)/Z_c(3900)$
- It's useful to distinguish different models
  - Less exchange particles expected the Z_{cs} molecule picture
- Theoretical models have predicted the existence of Z_{cs} state

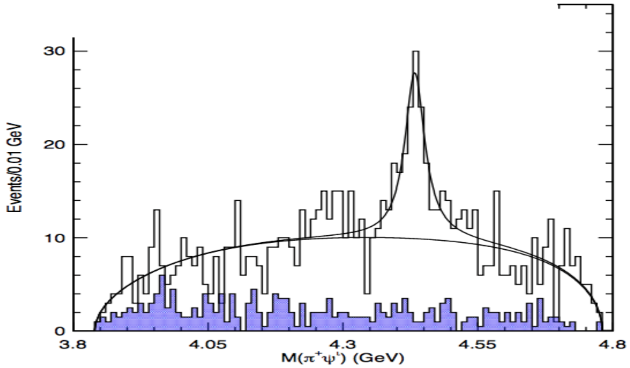
3.3 Z $_c$粒子态Zc(4430）

- originally found by Belle in $B \to (Z(4430)^- \to J/\psi\ \pi^-\ K$ and $B \to (Z(4430)^- \to \psi(2S)\ \pi^-)\ K$

  [PRL 100(2008) 142001, PR D80(2009) 031104, PR D88(2013) 074026]

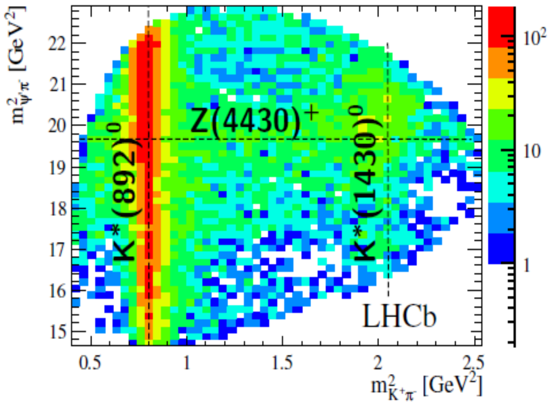
  → *not confirmed by BaBar* [PR D79 (2009) 112001]

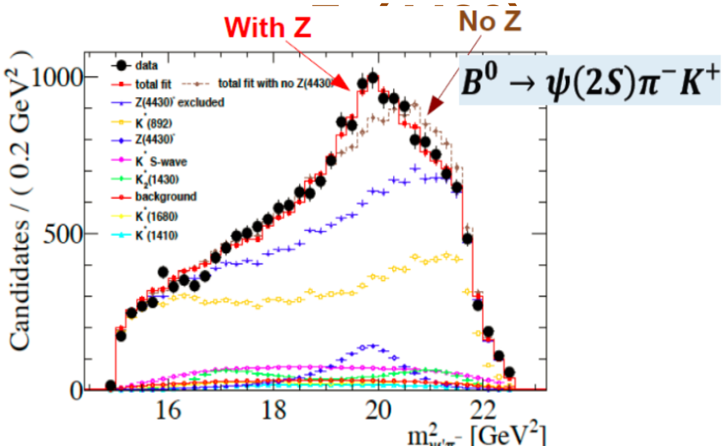




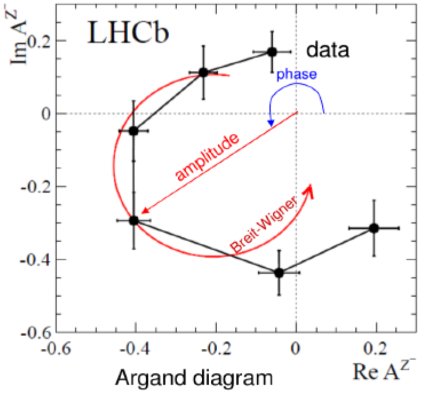
Argand plot indicates a resonance nature of the

PRL112,222002(2014)

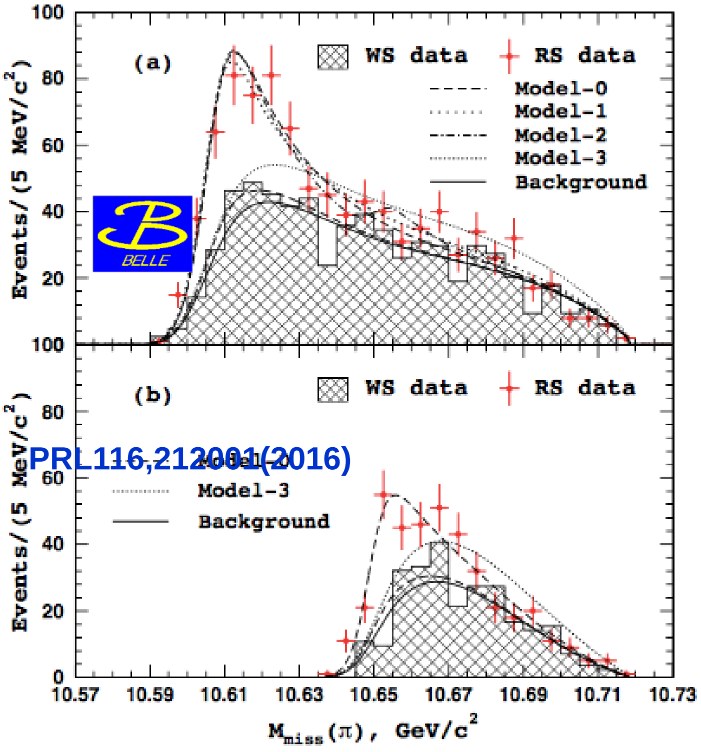




[PRL 112 (2014) 222002]

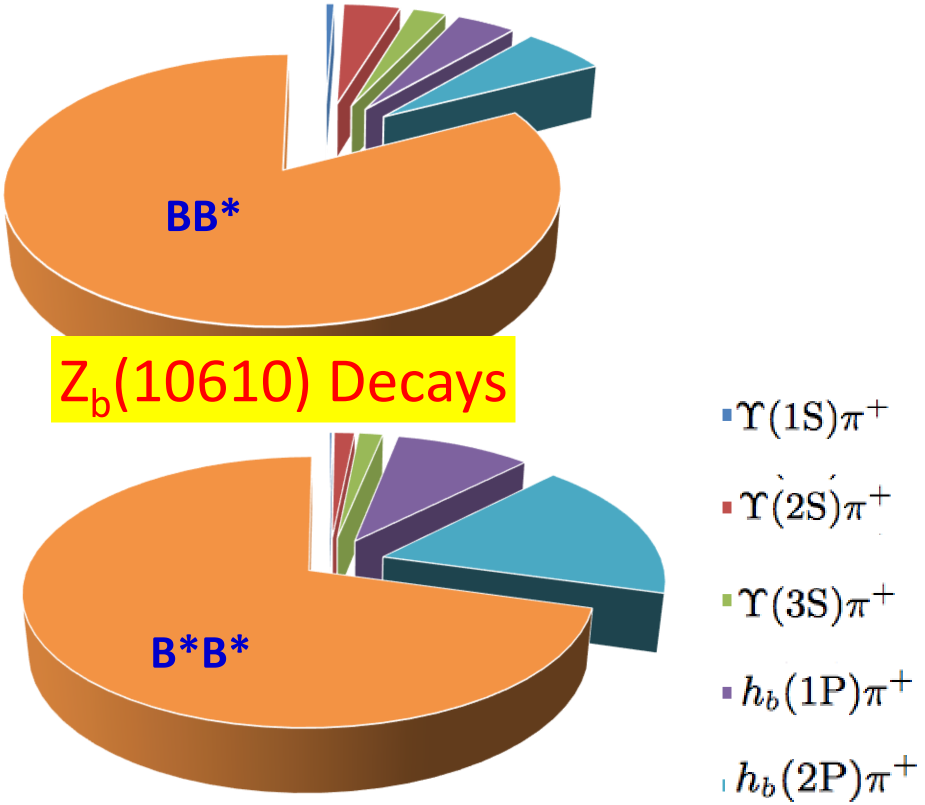


3.4 Z_b粒子态



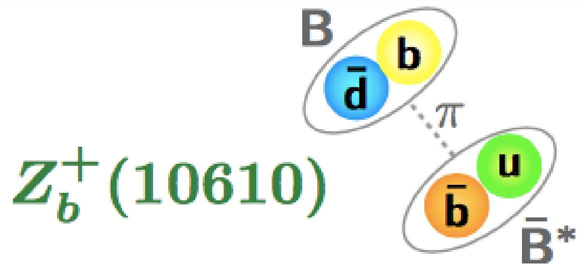
PRL116,212001(2016)

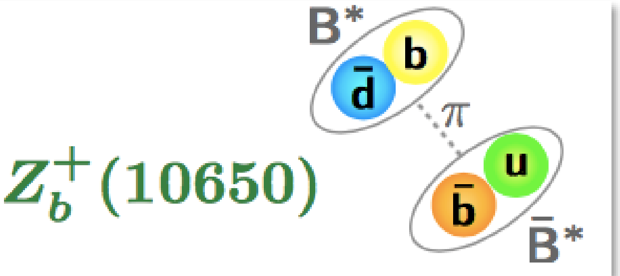
- ✓ Evidence for molecule?



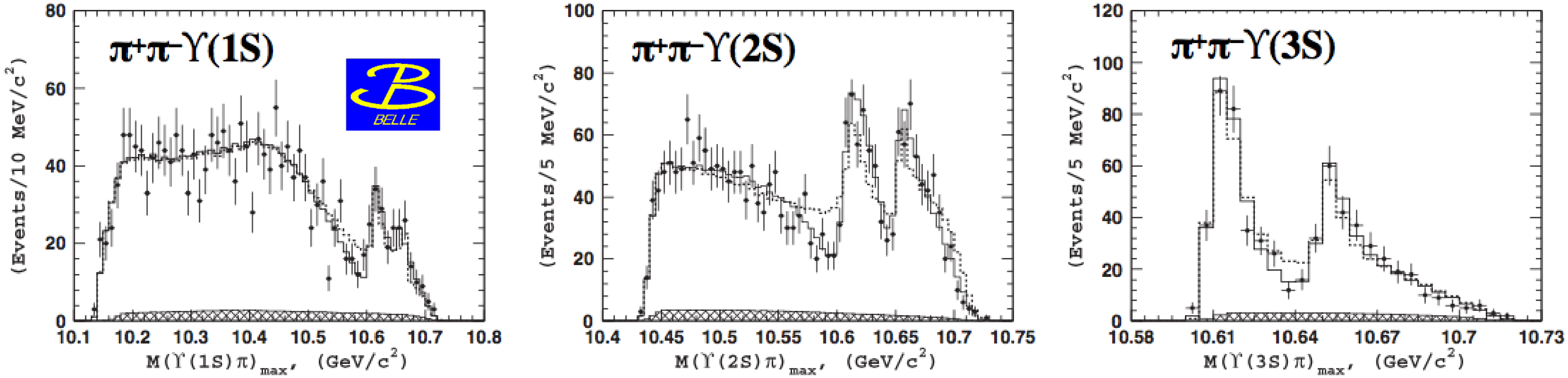
$Z_b(10610)$ Decays

$Z_b(10650)$ Decays



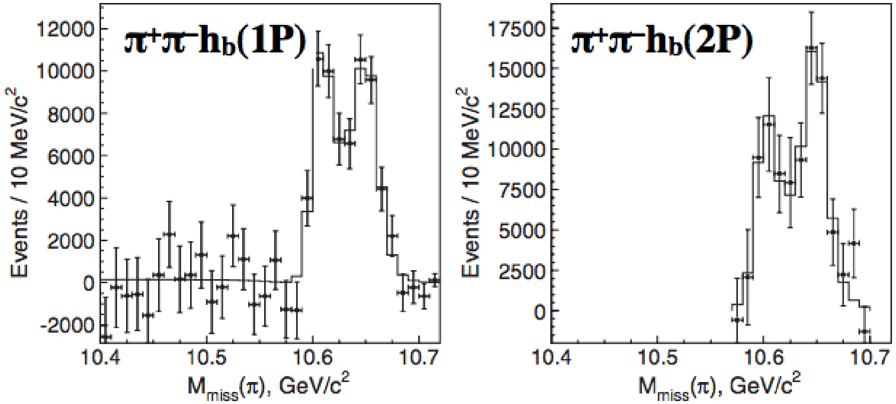


3.4 Z_b粒子态



PRD91,072003(2015), PRL108,122001(2012)

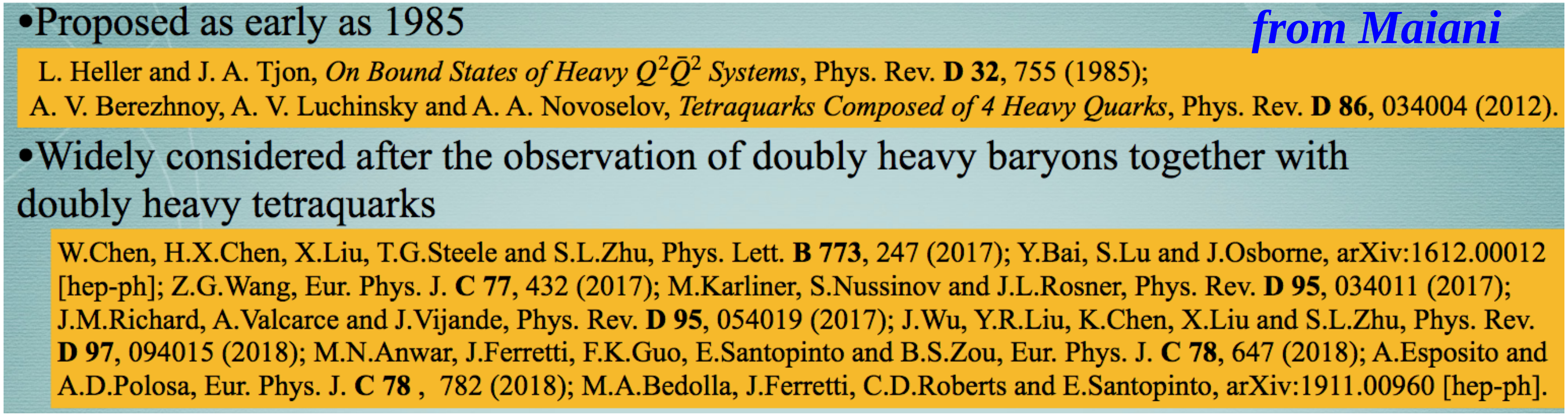
$e^+e^- \to \pi^+\pi^-\Upsilon(ns), \pi^+\pi^-h_b$



- Both $Z_b(10610)$ and $Z_b(10650)$ were observed in different processes
- J^P favors 1^+
- close to BB*, B*B* mass thresholds

4. 全粲四夸克态X(6900)

- Existence of $T_{Q_1Q_2\bar{Q}_3\bar{Q}_4}$ states ($Q_i = c \text{ or } b$) is expected by many QCD models
  - Likely compactly bounded since the interaction between heavy quarks is dominantly mediated by short-range gluon exchange
  - Usually described with the attraction of a diquark (Q_1Q_2) and an anti-diquark ($\overline{Q_3Q_4}$)
  - Never observed before



•Proposed as early as 1985

from Maiani

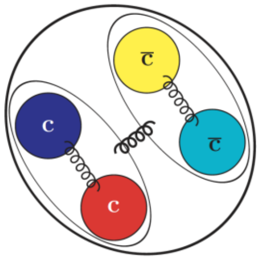
L. Heller and J. A. Tjon, *On Bound States of Heavy $Q^2\bar{Q}^2$ Systems*, Phys. Rev. **D 32**, 755 (1985);
A. V. Berezhnoy, A. V. Luchinsky and A. A. Novoselov, *Tetraquarks Composed of 4 Heavy Quarks*, Phys. Rev. **D 86**, 034004 (2012).

•Widely considered after the observation of doubly heavy baryons together with doubly heavy tetraquarks

W.Chen, H.X.Chen, X.Liu, T.G.Steele and S.L.Zhu, Phys. Lett. **B 773**, 247 (2017); Y.Bai, S.Lu and J.Osborne, arXiv:1612.00012 [hep-ph]; Z.G.Wang, Eur. Phys. J. **C 77**, 432 (2017); M.Karliner, S.Nussinov and J.L.Rosner, Phys. Rev. **D 95**, 034011 (2017); J.M.Richard, A.Valcarce and J.Vijande, Phys. Rev. **D 95**, 054019 (2017); J.Wu, Y.R.Liu, K.Chen, X.Liu and S.L.Zhu, Phys. Rev. **D 97**, 094015 (2018); M.N.Anwar, J.Ferretti, F.K.Guo, E.Santopinto and B.S.Zou, Eur. Phys. J. **C 78**, 647 (2018); A.Esposito and A.D.Polosa, Eur. Phys. J. **C 78** , 782 (2018); M.A.Bedolla, J.Ferretti, C.D.Roberts and E.Santopinto, arXiv:1911.00960 [hep-ph].

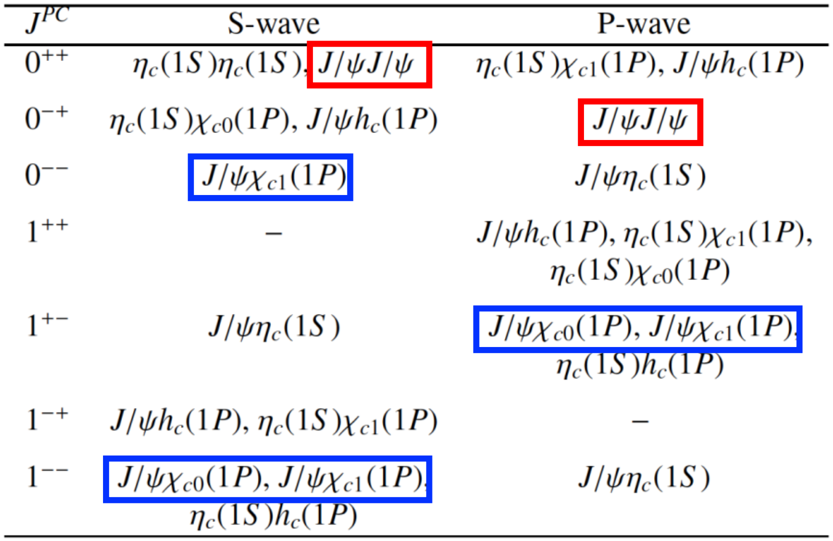
- $T_{bb\bar{b}\bar{b}}$ was not searched for at LHCb and CMS, but not observed
- $T_{cc\bar{c}\bar{c}}$ states predicted to have $M \in [5.8, 7.4]\ \mathrm{GeV}/c$, away from known quarkonia and quarkonium-like exotic states

4. 全粲四夸克态X(6900)



- Using J/ψ pair final states to reconstruct $T_{cc\bar{c}\bar{c}}$
  $J/\psi \to \mu^+\mu^-$ has good trigger efficiency

[arXiv: 1803.02522]

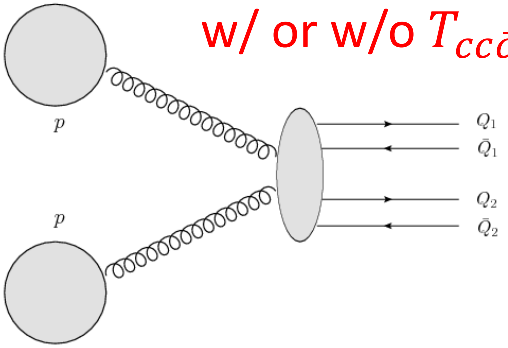


J^{PC}	S-wave	P-wave
0^{++}	$\eta_c(1S)\eta_c(1S)$, $J/\psi J/\psi$	$\eta_c(1S)\chi_{c1}(1P)$, $J/\psi h_c(1P)$
0^{-+}	$\eta_c(1S)\chi_{c0}(1P)$, $J/\psi h_c(1P)$	$J/\psi J/\psi$
0^{--}	$J/\psi\chi_{c1}(1P)$	$J/\psi\eta_c(1S)$
1^{++}	–	$J/\psi h_c(1P)$, $\eta_c(1S)\chi_{c1}(1P)$, $\eta_c(1S)\chi_{c0}(1P)$
1^{+-}	$J/\psi\eta_c(1S)$	$J/\psi\chi_{c0}(1P)$, $J/\psi\chi_{c1}(1P)$, $\eta_c(1S)h_c(1P)$
1^{-+}	$J/\psi h_c(1P)$, $\eta_c(1S)\chi_{c1}(1P)$	–
1^{--}	$J/\psi\chi_{c0}(1P)$, $J/\psi\chi_{c1}(1P)$, $\eta_c(1S)h_c(1P)$	$J/\psi\eta_c(1S)$

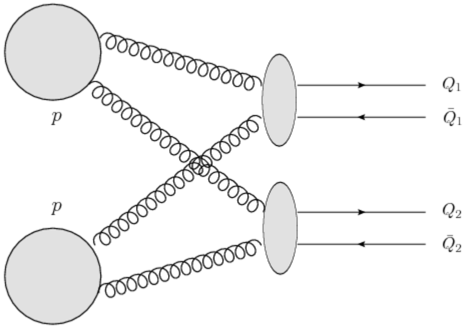
Decays in $2J/\psi$ directly or with feed-down

Single parton scattering (SPS)

w/ or w/o $T_{cc\bar{c}\bar{c}}$



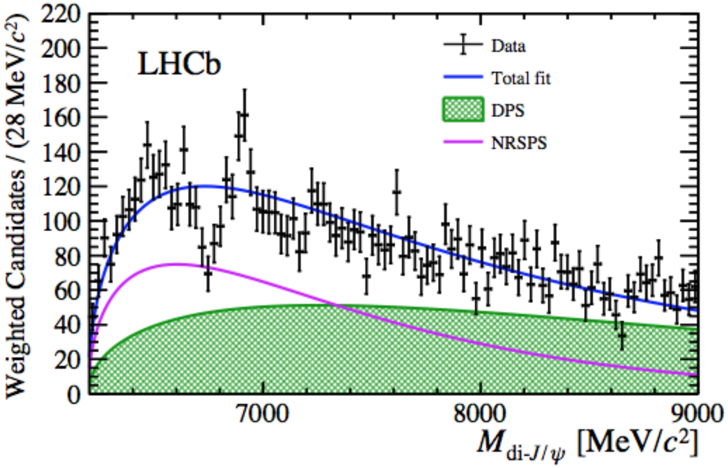
Double parton scatterings (DPS)



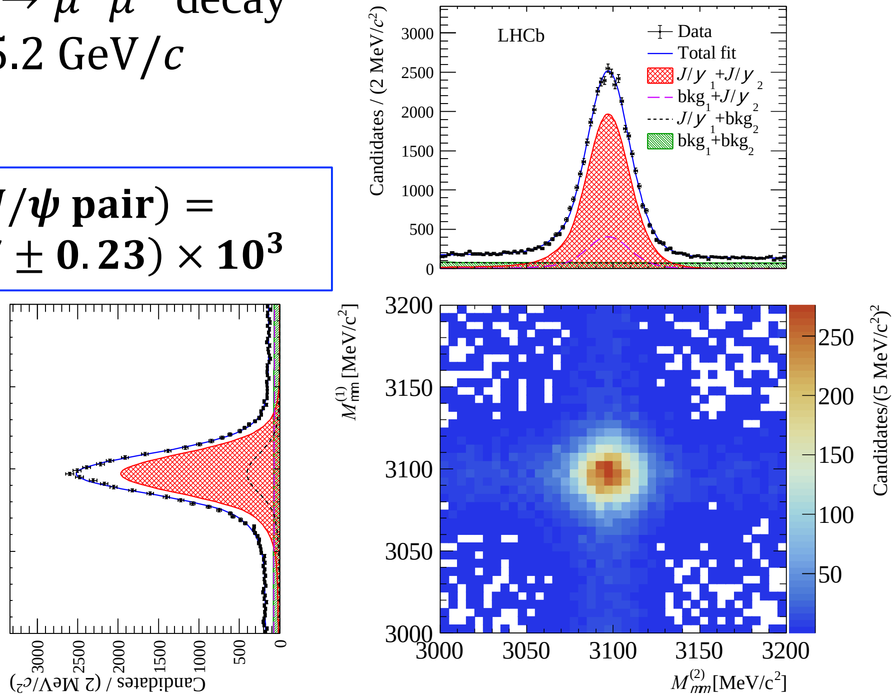
- $T_{cc\bar{c}\bar{c}}$ state production via SPS is dominant over DPS
- DPS: dominates high J/ψ pair mass region

4. 全粲四夸克态X(6900)

- Full Run1+Run2 LHCb data corresponding to 9 fb^{-1}
- J/ψ candidates reconstructed using the $J/\psi \to \mu^+\mu^-$ decay
- SPS enhanced sample with J/ψ-pair $p_\mathrm{T} > 5.2\ \mathrm{GeV}/c$



$$\boldsymbol{N(J/\psi\ \text{pair}) = (33.57 \pm 0.23) \times 10^3}$$



- The J/ψ-pair invariant mass spectrum is inconsistent with non-resonant SPS and DPS only hypothesis by more than 5σ in the [6.2,7.4] GeV/c^2 mass region
  - ✓ A broad structure next to threshold ranging from 6.2 to 6.8 GeV/c^2
  - ✓ A narrower structure at about 6.9 GeV/c^2 ➔ X(6900)
- A narrow peaking structure matching the lineshape of a resonance and a broader structure close to the threshold are fitted in two scenarios

4. 全粲四夸克态X(6900)

- Assuming X(6900) is a resonance with Breit-Wigner lineshape:
  - ✓ Model I: Based on no-interference fit (worse fitting quality)

$$M[\mathrm{X}(6900)] = 6905 \pm 11(\mathrm{stat}) \pm 7(\mathrm{syst})\ \mathrm{MeV}/c^2$$

$$\Gamma[\mathrm{X}(6900)] = 80 \pm 19(\mathrm{stat}) \pm 33(\mathrm{syst})\ \mathrm{MeV}/c^2$$

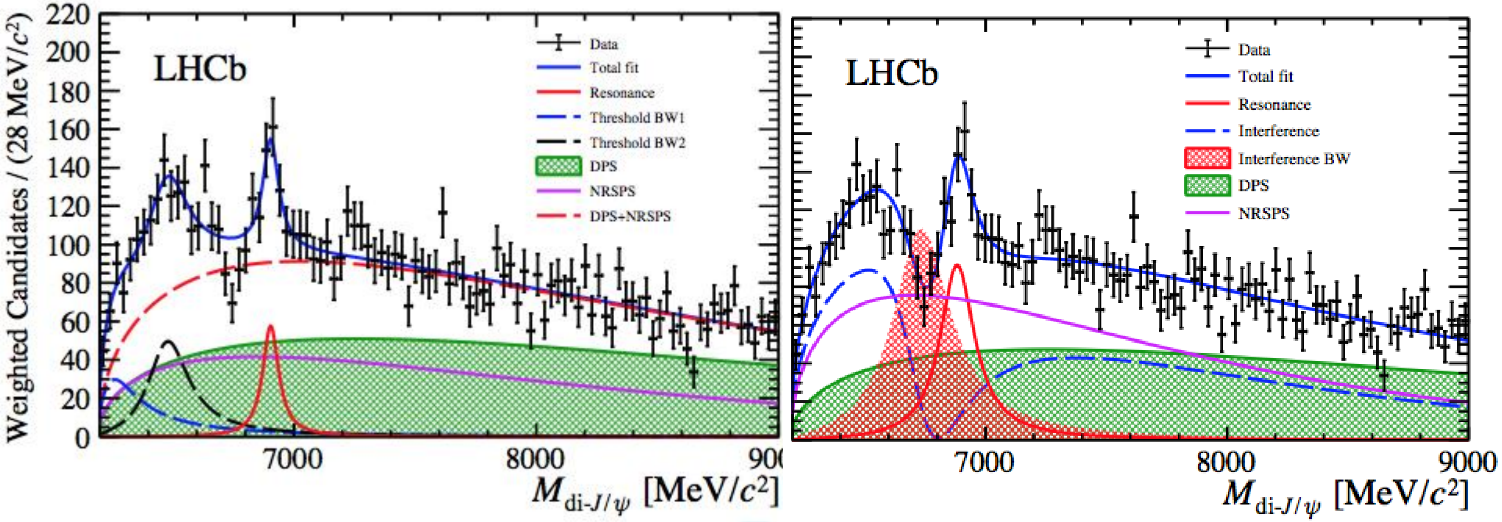
  - ✓ Model II: Based on the simple model with interference (better fitting quality)

$$M[\mathrm{X}(6900)] = 6886 \pm 11(\mathrm{stat}) \pm 11(\mathrm{syst})\ \mathrm{MeV}/c^2$$

$$\Gamma[\mathrm{X}(6900)] = 168 \pm 33(\mathrm{stat}) \pm 69(\mathrm{syst})\ \mathrm{MeV}/c^2$$

consistent with predicted $T_{cc\bar{c}\bar{c}}$ states

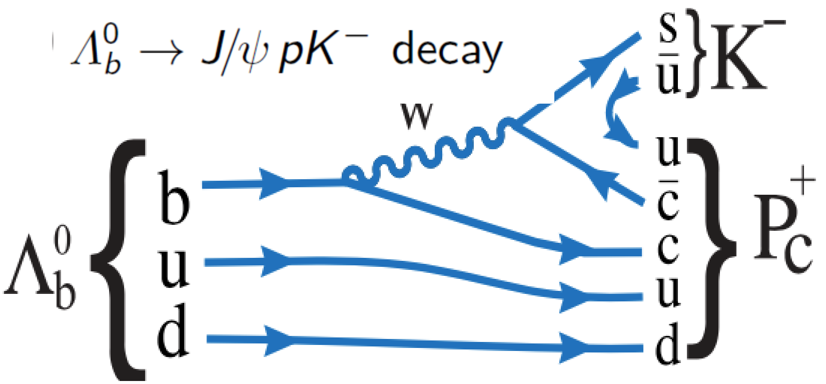
- The lower broader structure is objected to many uncertainties:
  - ✓ feed-down from heavier quarkonia, e.g. $T_{cc\bar{c}\bar{c}} \to \chi_c(\to J/\psi\gamma) + J/\psi$
  - ✓ near-threshold kinematic rescattering effects



5. 五夸克态

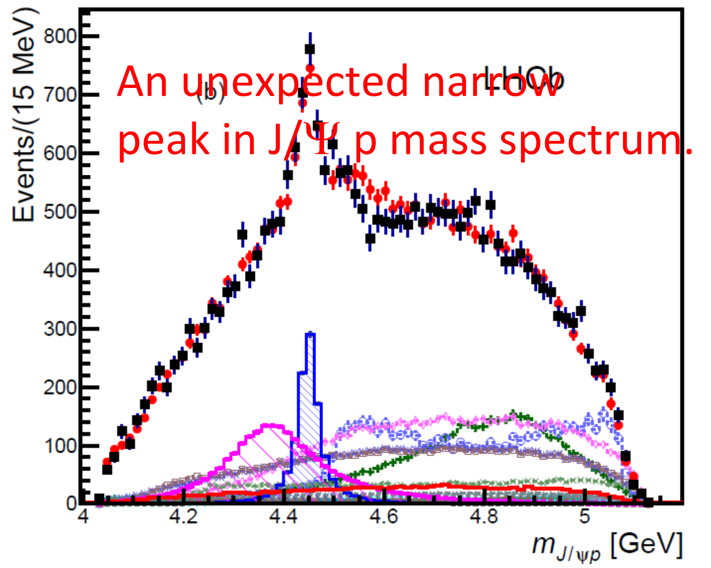
Pc(4380), Pc(4450)

$\Lambda_b^0 \to J/\psi\, pK^-$ decay

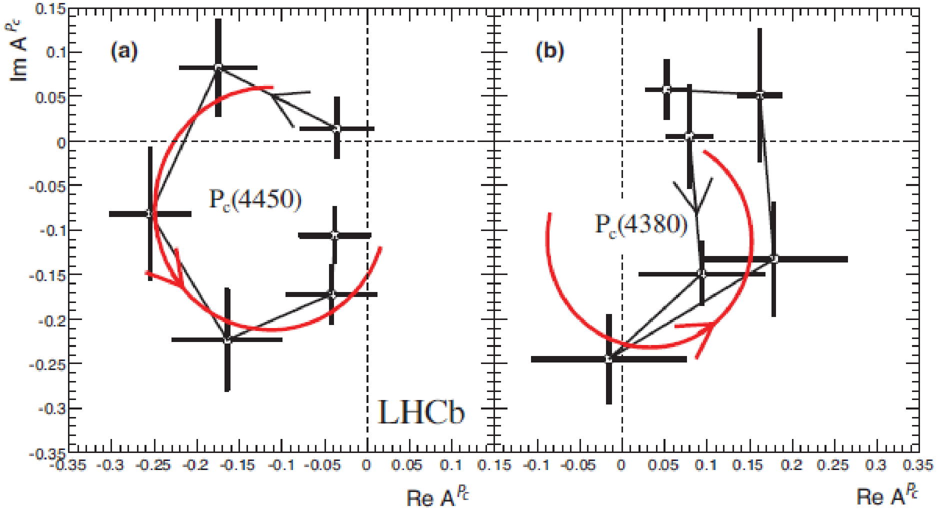


$P_c(4380)$:
$M = 4380 \pm 8 \pm 29\,\mathrm{MeV}$,
$\Gamma = 205 \pm 18 \pm 86\,\mathrm{MeV}$
$P_c(4450)$:
$M = 4449.8 \pm 1.7 \pm 2.5\,\mathrm{MeV}$
$\Gamma = 39 \pm 5 \pm 19\,\mathrm{MeV}$

PRL115, 072001 (2015)
PRL117, 082002 (2016)



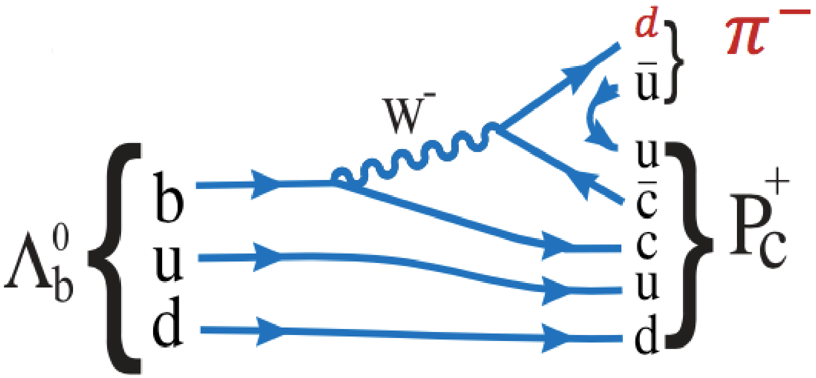
An unexpected narrow peak in J/Ψ p mass spectrum.



Two $J/\psi\, p$ states give the best fit, $J = 3/2$ and $5/2$ with opposite parities

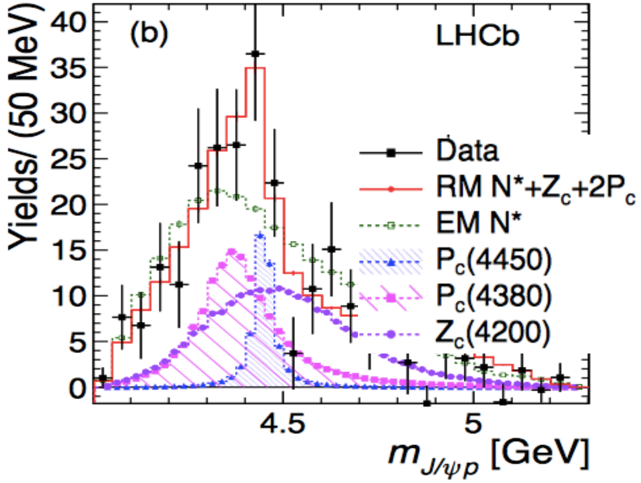
5. 五夸克态

Pc(4380), Pc(4450)



PRL117,082003 (2016)

$\Lambda_b^0 \to J/\psi\, p\pi^-$

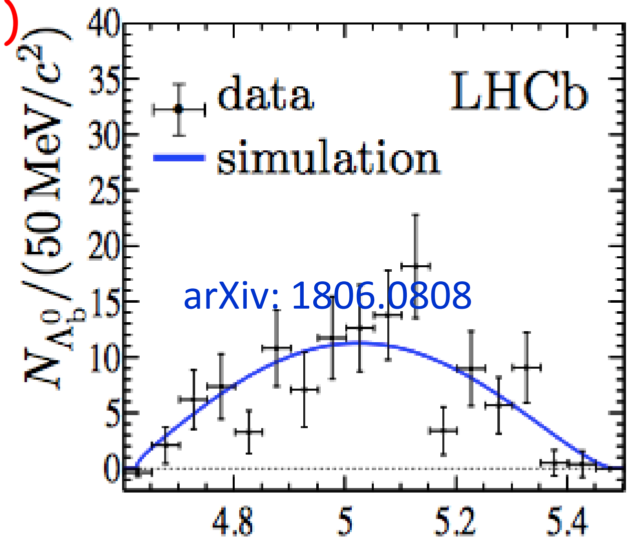


- Cabibbo suppression
- Total significance of Pc(4380) and Pc(4450) is around 3σ
- Contribution from Zc(4220)

Belle, PRD 90, 112009 (2014)

- No clear peak observed in M(ψ(2S)p)

$\Lambda_b^0 \to \psi(2S)p\pi^-$



arXiv: 1806.0808

5. Pc？

Test the nature of **Pc** states ?

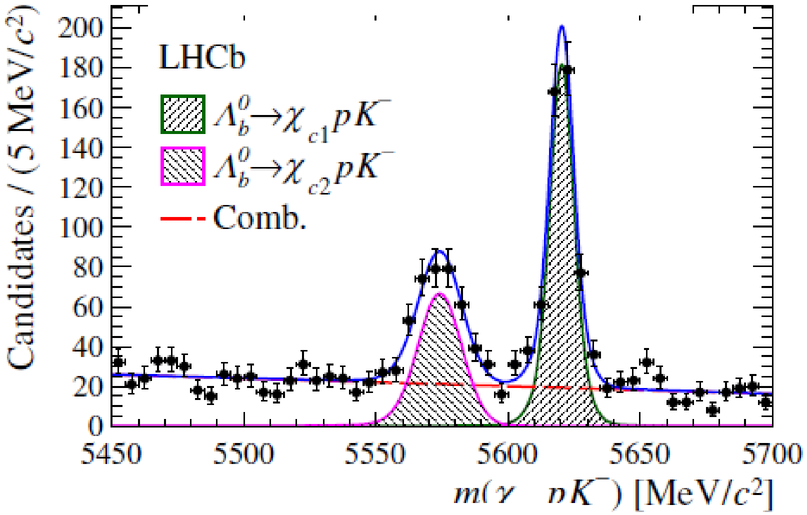
- Structures close to $\chi_{c1}p$ threshold
- Kinematic effect? Absent in

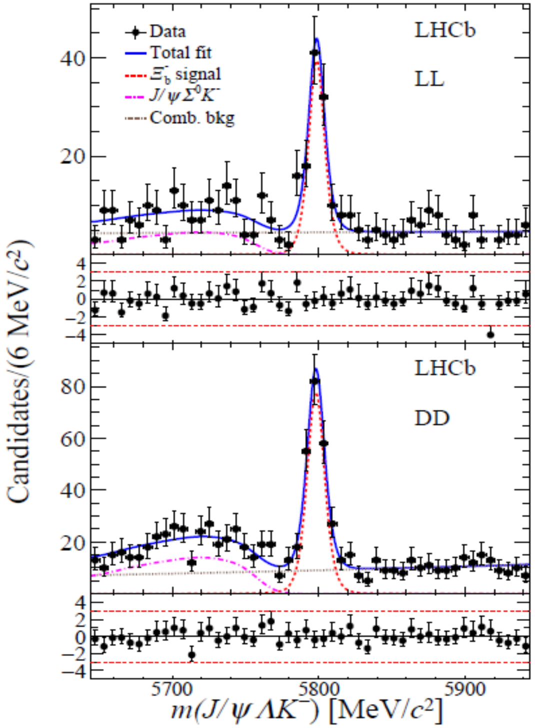
$$\Lambda_b^0 \to \chi_{cJ} p K^-$$

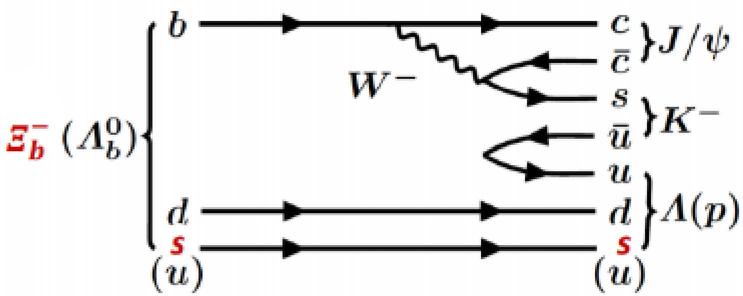
F.K. Guo et al, PRD92,071502 (2015) J

$$\Lambda_b^0 \to \chi_{c2} p K^-$$

[PRL 119 (2017) 062001]







- Any strange hidden-charm pentaquark?
- Observation of $\Xi_b^- \to J/\psi \Lambda K^-$