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Spectroscopy of Mesons with Heavy Quarks

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Outline

- QCD, Hadron Physics, & Quark Model
- Charmed Mesons

  D_0*(2308/2407), D_1*(2427)
  D_{s0}*(2317), D_{s1}*(2460), D_{sj}(2632)
  D_{sj}(2690/2715), D_{sj}(2860)
- Charmonium (or charmonium-like states)

  X(3872), X(3940)
  Y(3940), Y(4260)
  Z(3930)
- Summary

QCD & Hadron Physics

- QCD is the underlying theory of strong interaction, which has three fundamental properties: Asymptotic freedom, Confinement, and Chiral symmetry
- Perturbative QCD has been tested to very high accuracy
- The low energy sector of QCD (i.e., hadron physics) remains challenging
- Precision-test of SM and search for new physics require good knowledge of hadrons as inputs (such as parton distribution functions)

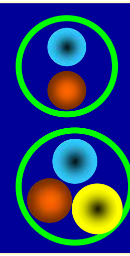
QCD & Hadron Physics

- the motion and interaction of hadrons differ from those of nuclei and quark/gluon/leptons
- Hadron physics is the bridge between nuclear physics and particle physics
- Higgs mechanism contributes around 20 MeV to the nucleon mass through current quark mass
- Nearly all the mass of the visible matter in our universe comes from QCD interaction
- Study of hadron spectroscopy explores the mechanism of confinement and χSB, and the mass origin

Quark Model

Meson（q q）

Baryon（q q q）



- Quark Model is quite successful in the classification of hadrons although it's not derived from QCD
- Any state with quark content other than $q\bar{q}$ or qqq is beyond quark model

Quark Model *vs* QCD

- ***But quark model can't be the whole story***
- QCD may allow much ***richer*** hadron spectrum such as: glueball, hybrid meson/baryon, multiquark states, hadron molecules …
- **Experimental search of these non-conventional states started many years ago**
- **But none** of them has been established without controversy!
- Typical signatures of **these non-conventional states** include:

  -Exotic flavor quantum number like θ^+

  -Exotic J^{PC} quantum number like 1^{-+} exotic meson

  -Overpopulation of the QM spectrum like the scalar isoscalar spectrum below 1.9 GeV: σ, $f_0(980)$, $f_0(1370)$, $f_0(1500)$, $f_0(1710)$, $f_0(1790)$, $f_0(1810)$

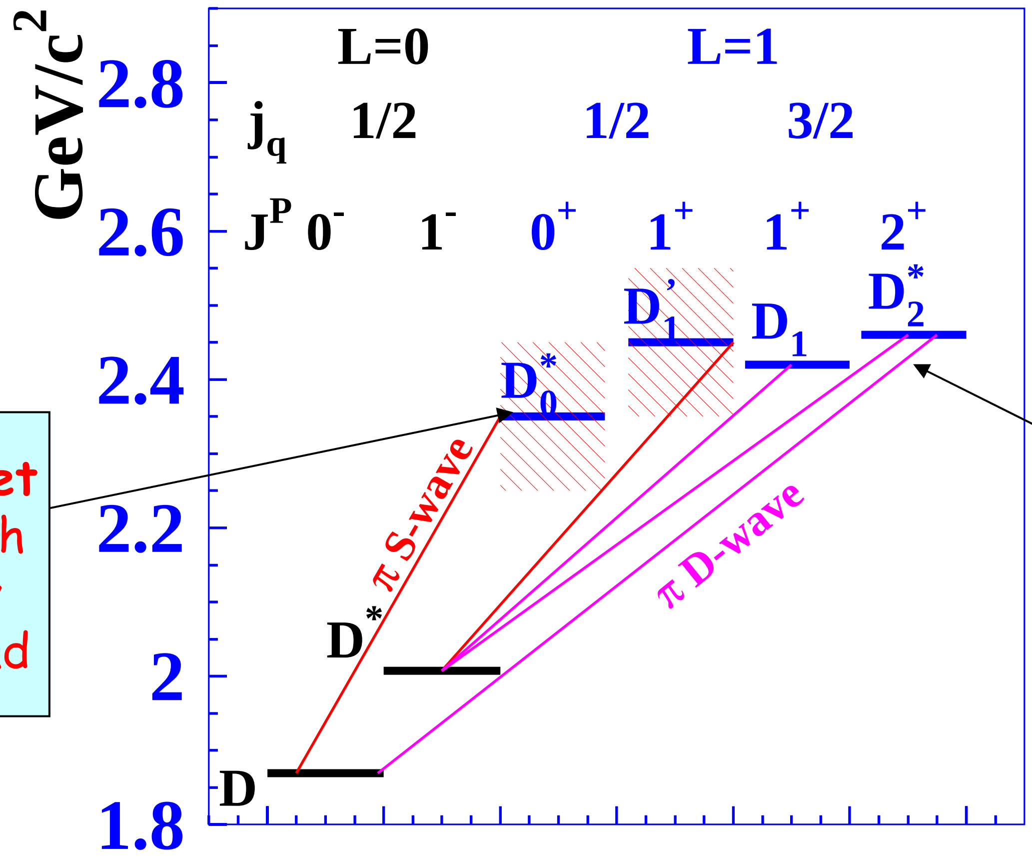
Charmed mesons

- The angular momentum j_l of the light quark in the $Q\bar{q}$ system is a good quantum number in the heavy quark limit
- Heavy mesons form doublets with j_l^P

  L=0: $(0^-, 1^-)$

  L=1: $(0^+,1^+)$, $(1^+, 2^+)$
- $(0^-, 1^-)$ and $(1^+, 2^+)$ doublets agree with theoretical expectation
- There are two puzzles with the $(0^+,1^+)$ doublet
- The heavy-light system is the QCD "hydrogen"!

Energy level of non-strange charmed mesons

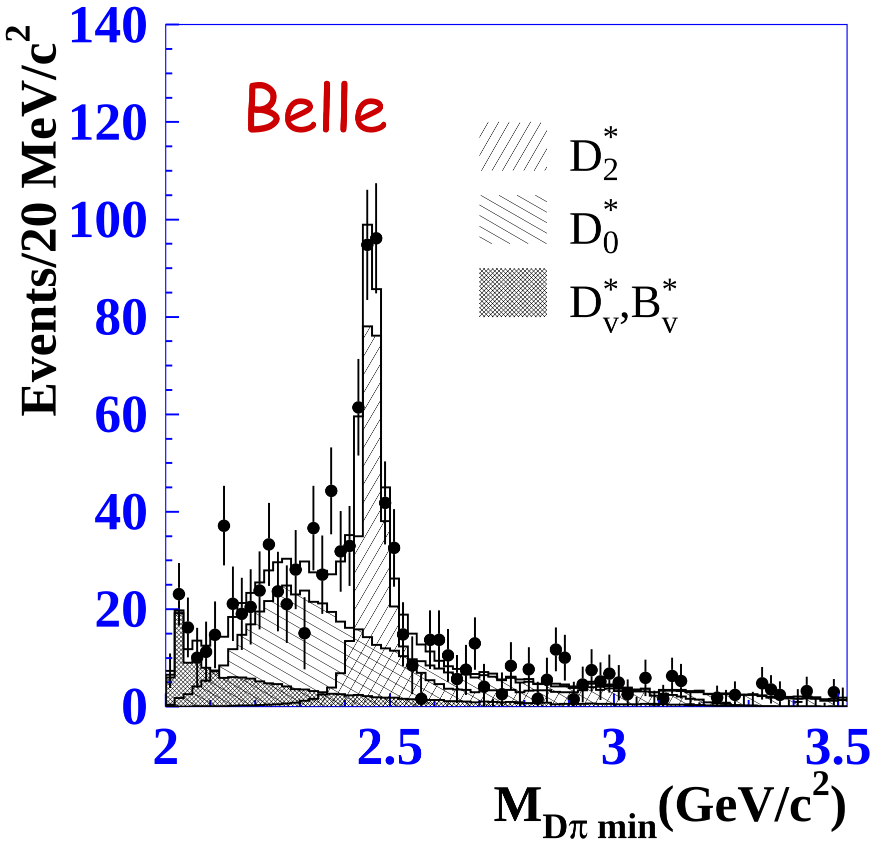


(0⁺,1⁺) doublet decay through s-wave. They are very broad

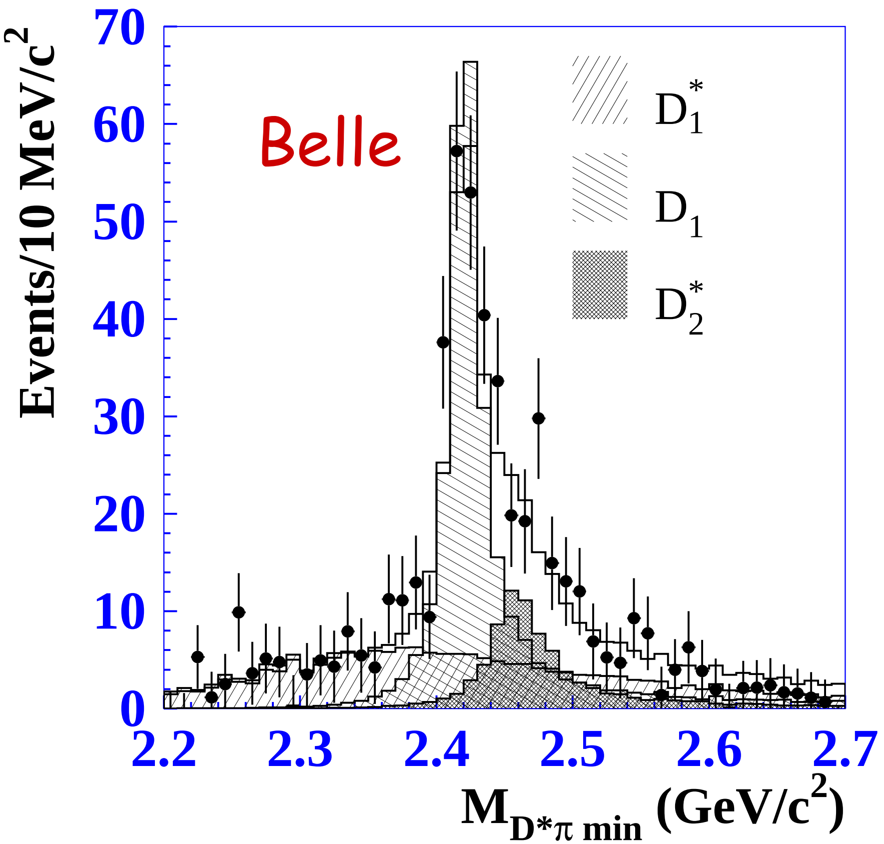
(1⁺,2⁺) doublet decay through d-wave. They are narrow.

The non-strange $(0^+, 1^+)$ doublet (D_0^*, D_1^*) are very broad

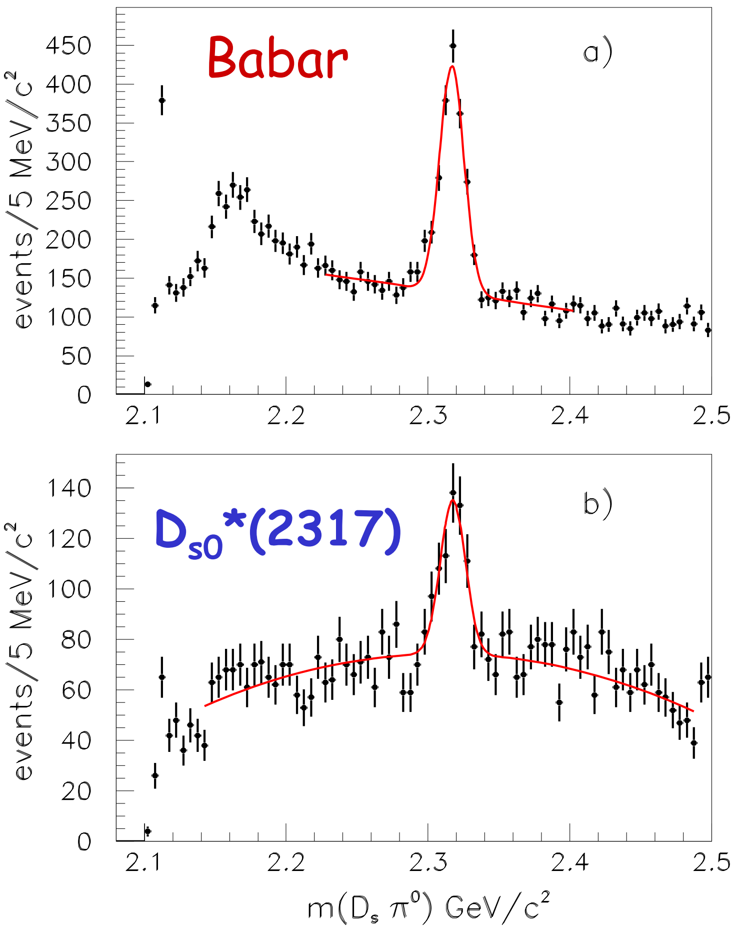
Belle: (2407, 240) MeV
Focus: (2308, 276) MeV

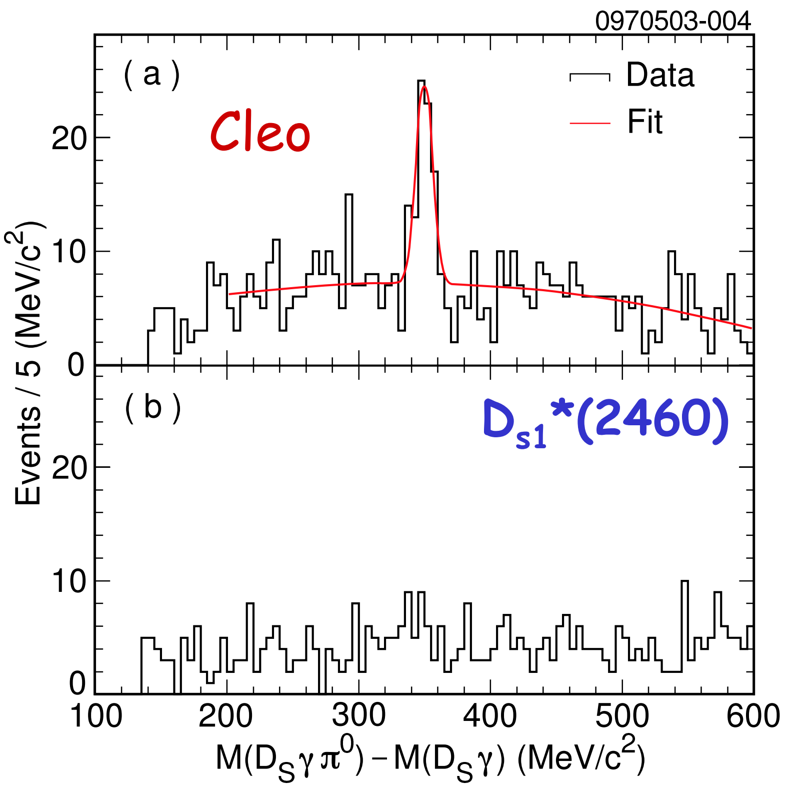


Belle: (2427, 387) MeV



The strange $(0^+, 1^+)$ doublet [$D_{s0}^*(2317)$, $D_{s1}^*(2460)$] are very very narrow





Low Mass Puzzle of D_{s0}^*, D_{s1}^*

- D_{s0}^* (D_{s1}^*) lies below DK (D*K) threshold
- ~160 MeV below quark model prediction
- They are very narrow
- Strong decays violate isospin symmetry and occur with help of a virtual η meson: $D_{s0}^* \rightarrow D_s\eta \rightarrow D_s\pi^0$
- The mass of D_{s0}^* from three lattice QCD simulations is still larger than experimental value
- Naively one would expect $D_{s0}^*(2317)$ lies 100 MeV above $D_0^*(2308/2407)$ because of mass difference between strange and up quarks
- → why is the mass of D_{s0}^* (D_{s1}^*) so low?
- → why are D_{s0}^* and D_0^* nearly degenerate?

Tetraquarks?

- Low mass of D_{s0}* (D_{s1}*) inspired the tetraquark scheme
- If D_0* and D_{s0}* were in the anti-symmetric 3* multiplet, they would have the same mass (Dmitrasinovic, PRL05)

$$|D_0^*\rangle = \frac{1}{2}|c(s(\bar{u}\bar{s} - \bar{s}\bar{u}) - d(\bar{d}\bar{u} - \bar{u}\bar{d}))\rangle$$

$$|D_{s0}^*\rangle = \frac{1}{2}|c(u(\bar{u}\bar{s} - \bar{s}\bar{u}) - d(\bar{d}\bar{s} - \bar{s}\bar{d}))\rangle$$

- But tetraquarks always contain color-singlet*singlet component→ fall apart easily→ very broad
- Two difficult issues: (1) where are the (0^+,1^+) in QM? (2) where are those partner states in same multiplet?
- Babar scanned around 2.31 GeV, 2.46 GeV and below 2.7 GeV and found NO additional (0^+,1^+) states and NO spin-flavor partner states!

Belle and Babar measured the ratio of radiative and strong decay widths

	Belle	Babar	CLEO	LCQSR
$\frac{\Gamma\left(D^*_{sJ}(2317)\to D^*_s\gamma\right)}{\Gamma\left(D^*_{sJ}(2317)\to D_s\pi^0\right)}$	< 0.18 [88]		< 0.059	0.13
$\frac{\Gamma(D_{sJ}(2460)\to D_s\gamma)}{\Gamma\left(D_{sJ}(2460)\to D^*_s\pi^0\right)}$	$0.55 \pm 0.13 \pm 0.08$ [88]	$0.375 \pm 0.054 \pm 0.057$ [95]	< 0.49	0.56
$\frac{\Gamma\left(D_{sJ}(2460)\to D^*_s\gamma\right)}{\Gamma\left(D_{sJ}(2460)\to D^*_s\pi^0\right)}$	< 0.31 [88]		< 0.16	0.02
$\frac{\Gamma\left(D_{sJ}(2460)\to D^*_{sJ}(2317)\gamma\right)}{\Gamma\left(D_{sJ}(2460)\to D^*_s\pi^0\right)}$		< 0.23 [94]	< 0.58	0.015

- Assuming D_{s0}^*/D_{s1}^* are conventional $c\bar{s}$ mesons, theoretical ratio from light-cone QCD sum rules/$^3P_0$ model is consistent with Belle/Babar's recent data (Wei, Zhu, PRD06; Lu, Zhu, PRD06; Colangelo PRD05)

Coupled channel effects

- **Coupled channel effects may be origin of the low mass puzzle of** D_{s0}^* (D_{s1}^*) since they have
  - **-Same quantum number as S-wave DK (D*K) continuum**
  - **-Very close to DK (D*K) threshold (46 MeV)**
  - **-D_{s0}^*DK coupling is very large**
- **Within quark model, the configuration mixing effects between "bare" (0^+, 1^+) and DK (D*K) may lower the mass of** D_{s0}^* (D_{s1}^*)
- Within QCD sum rule framework, the **DK continuum contributes ~30% to the spectral density and lowers** D_{s0}^* **mass significantly** (Dai, Zhu 06)
- **This mechanism also provides a possible explanation why quenched lattice QCD simulations get a higher mass since quenched approx. ignores the meson loop**

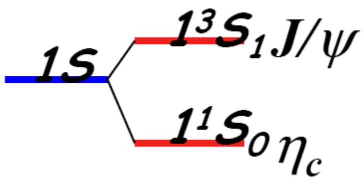
Charmonium: playground of new models

Central potential:

$$V(r) = -\frac{4}{3}\frac{\alpha_s(r)}{r} + br$$

Spin-spin interactions:

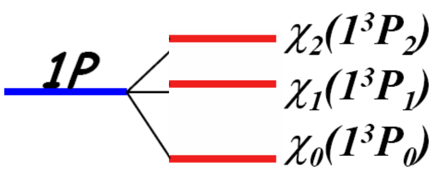
$$\frac{4\alpha_s(r)}{3m_im_j}\left\{\frac{8\pi}{3}\vec{S}_i\cdot\vec{S}_j\,\delta^3(\vec{r}_{ij}) + \frac{1}{r_{ij}^3}\left[\frac{3\vec{S}_i\cdot\vec{r}_{ij}\vec{S}_j\cdot\vec{r}_{ij}}{r_{ij}^2} - \vec{S}_i\cdot\vec{S}_j\right]\right\}$$

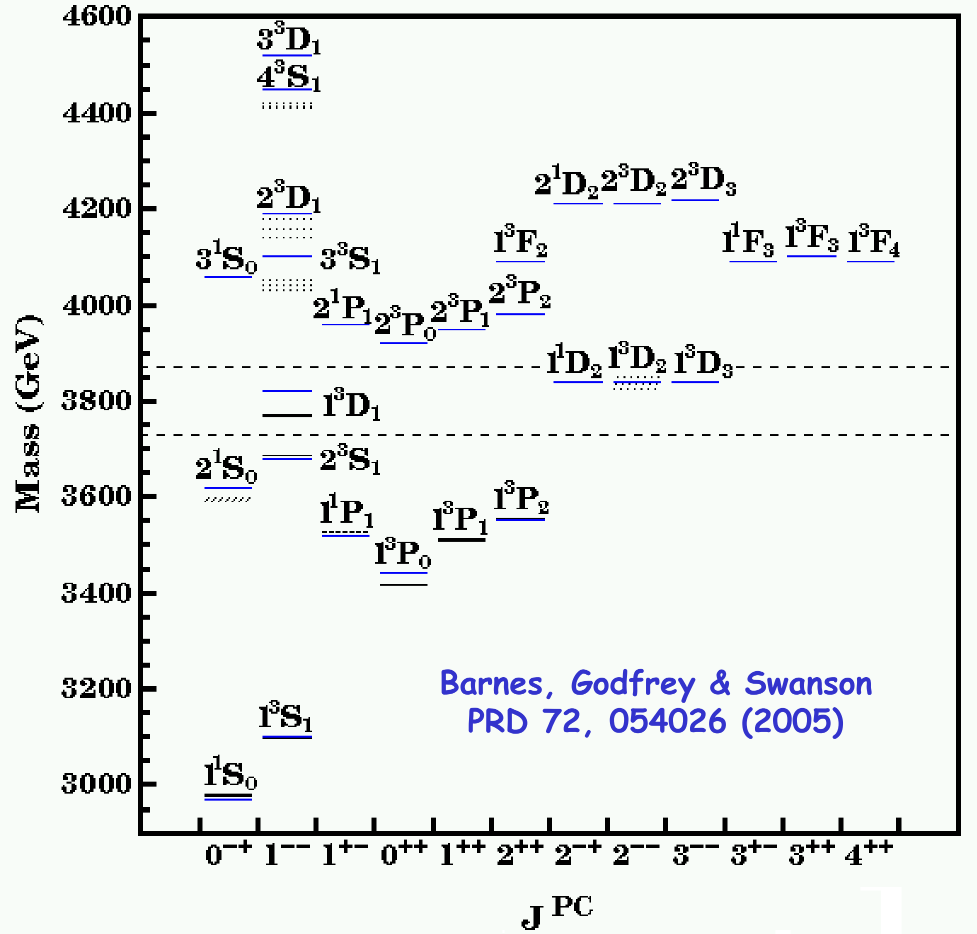


Spin-orbit interactions:

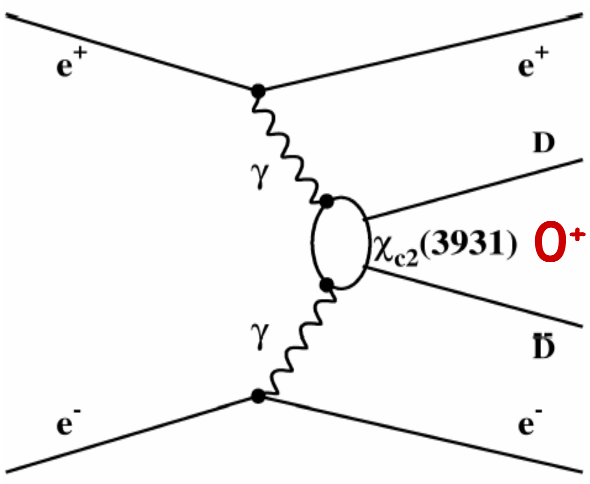
$$H_{ij}^{s.o.(cm)} = \frac{4\alpha_s(r)}{3r_{ij}^3}\left(\frac{1}{m_i}+\frac{1}{m_j}\right)\left(\frac{\vec{S}_i}{m_i}+\frac{\vec{S}_j}{m_j}\right)\cdot\vec{L}$$

$$H_{ij}^{s.o.(tp)} = \frac{-1}{2r_{ij}}\frac{\partial V(r)}{\partial r_{ij}}\left(\frac{\vec{S}_i}{m_i^2}+\frac{\vec{S}_j}{m_j^2}\right)\cdot\vec{L}$$





$\gamma\gamma \rightarrow Z(3930) \rightarrow D\bar{D}$ at Belle

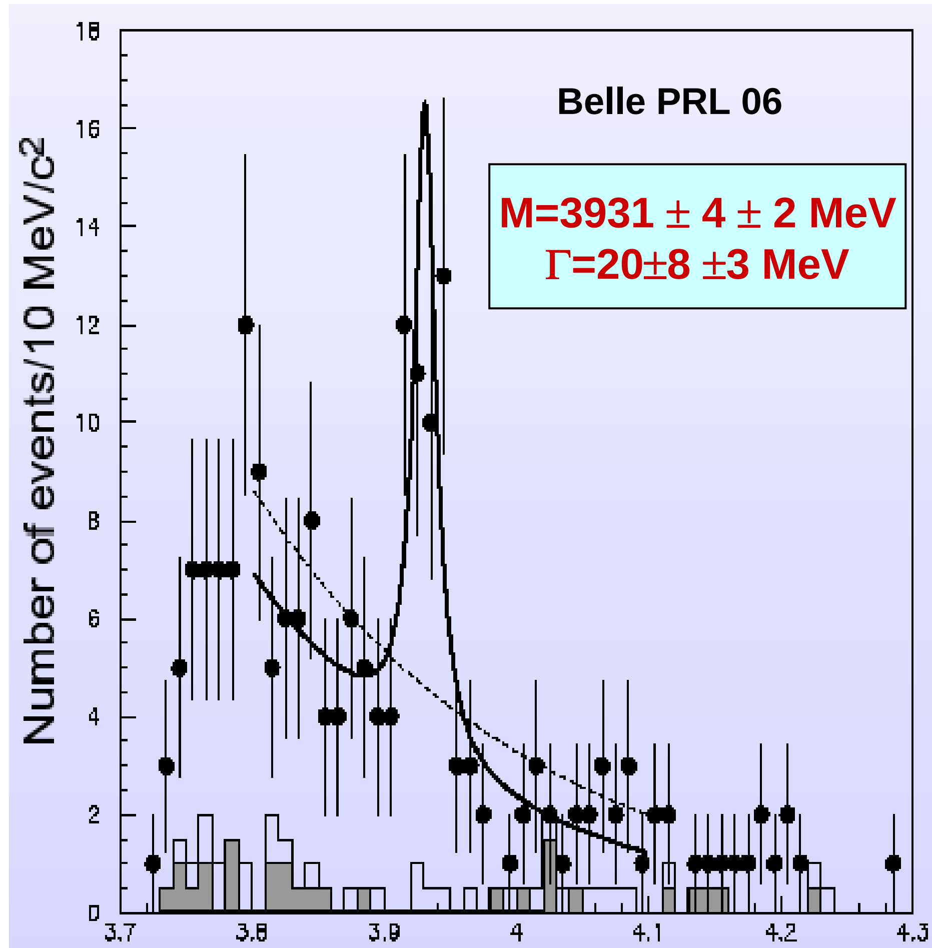


0^{++}, 2^{++}

Angular distribution
→ J=2

Matches well to χ_{c2}' expectations

$D^*\bar{D}$ mode to be discovered



M(DD) GeV

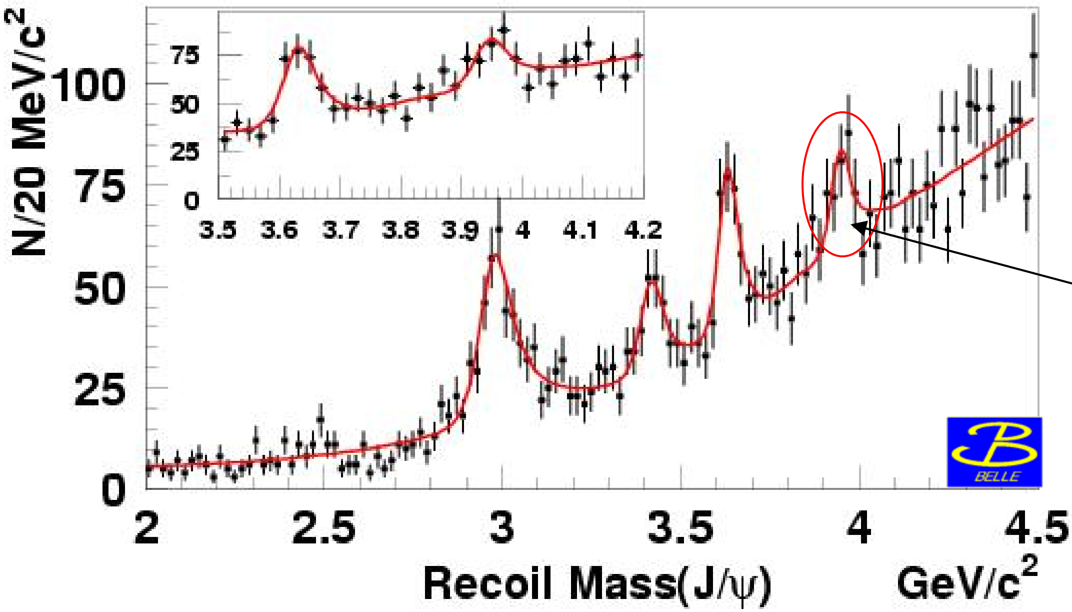
Z(3930) vs Quark Model

- **Charmonium states around 3940 MeV from Quark Model**

State	PDG[17]	BGS[13]	GI[13]	EFG[14]	Cornell[3]	CP-PACS[15]	Chen[16]
$\chi_2(2^3P_2)$	3931 ± 5^a	3972	3979	3972	–	4030 ± 180	–
$\chi_1(2^3P_1)$		3925	3953	3929	–	4067 ± 105	4010 ± 70
$\chi_0(2^3P_0)$		3852	3916	3854	–	4008 ± 122	4080 ± 75
$h_c(2^1P_1)$		3934	3956	3945	–	4053 ± 95	3886 ± 92
$\psi(3^3S_1)$	4040 ± 10	4072	4100	4088	4110 [4225]	–	–
$\eta_c(3^1S_0)$		4043	4064	3991	4110	–	–
$\psi_3(1^3D_3)$		3806	3849	3815	3810	–	3822 ± 25
$\psi_2(1^3D_2)$		3800	3838	3811	3810	–	3704 ± 33
$\psi(1^3D_1)$	3769.9 ± 2.5	3785	3819	3798	3810 [3755]	–	–
$\eta_{c2}(1^1D_2)$		3799	3837	3811	3810	–	3763 ± 22

- **QM prediction of χ'_{c2} mass is 40-100 MeV higher**
- **This is the typical accuracy of QM for higher charmonium above open charm decay threshold**

$e^+e^- \rightarrow J/\psi\ X(3940)$



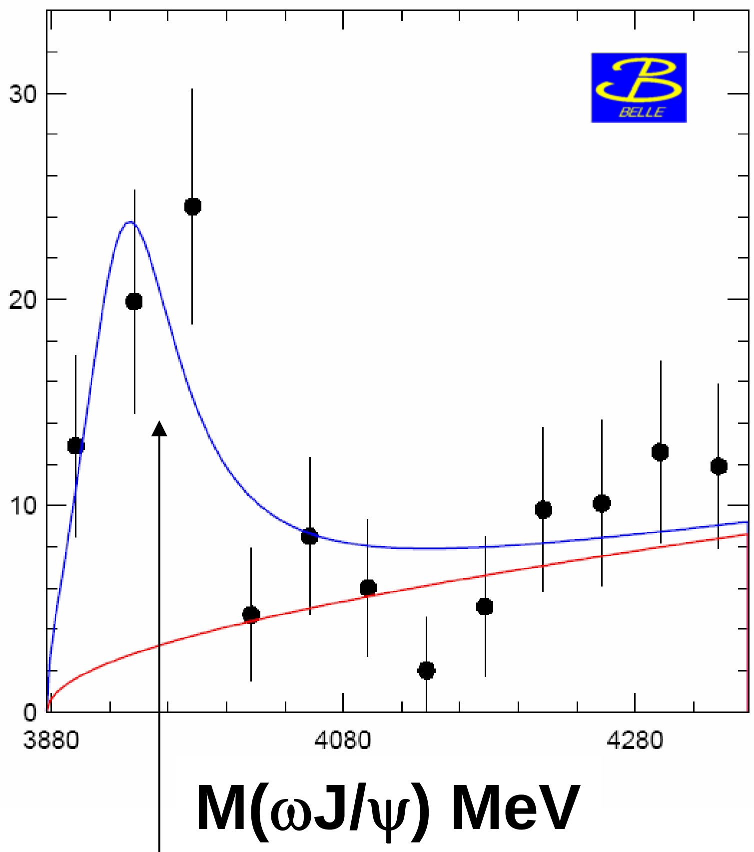
M = (3943 ± 6 ± 6)M eV
Γ < 52 MeV; C = +

Belle observed X(3940) in $\overline{D}D^*$ channel but not in $\overline{D}D$ & $\omega J/\psi$ modes; such a decay pattern is typical of χ'_{c1}

But the ground state χ_{c1} is not seen in the same expt → X(3940) does not look like χ'_{c1}

X(3940) may be η_c" except that it's 100 MeV below QM prediction

Y(3940) in B→K ωJ/ψ



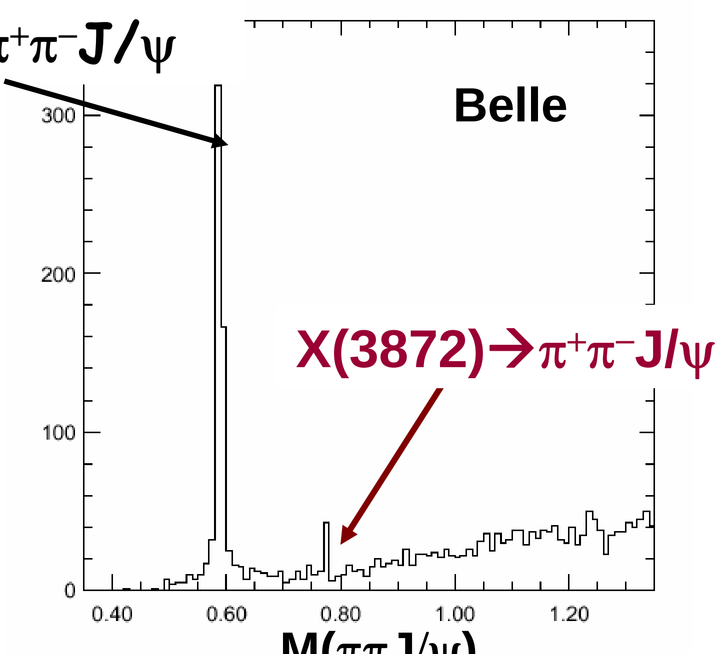
$M \approx 3940 \pm 11$ MeV
$\Gamma \approx 92 \pm 24$ MeV

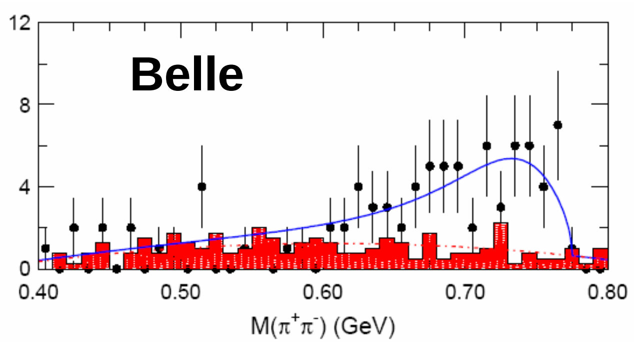
Belle observed a broad threshold enhancement in ωJ/ψ channel in B decays

The hidden charm decay Y(3940) → ωJ/ψ violates $SU_F(3)$ flavor symmetry.
Γ(Y(3940) → ωJ/ψ) > 7 MeV
Very puzzling!

Not confirmed by other expts yet

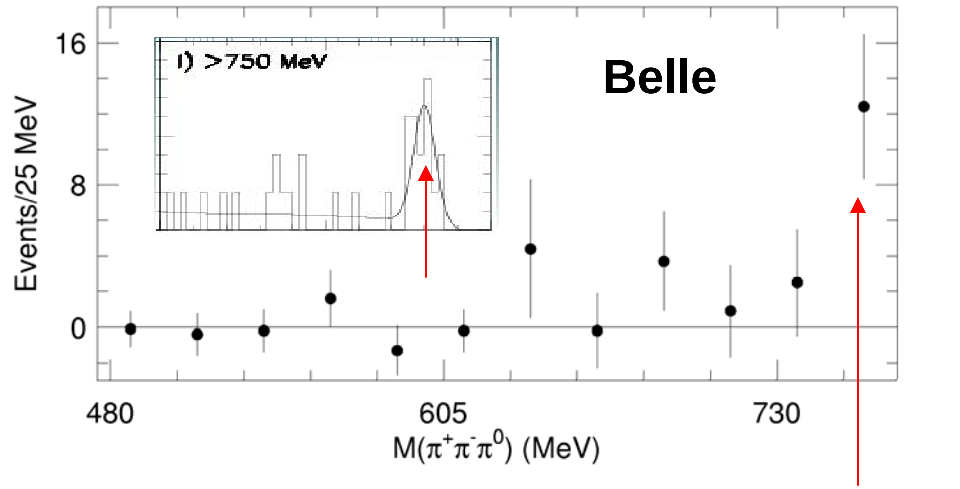
X(3872) in B→K $\pi^+\pi^-$ J/ψ





M(ππ) looks like a ρ

X(3872) in B→K $\pi^+\pi^-\pi^0$ J/ψ

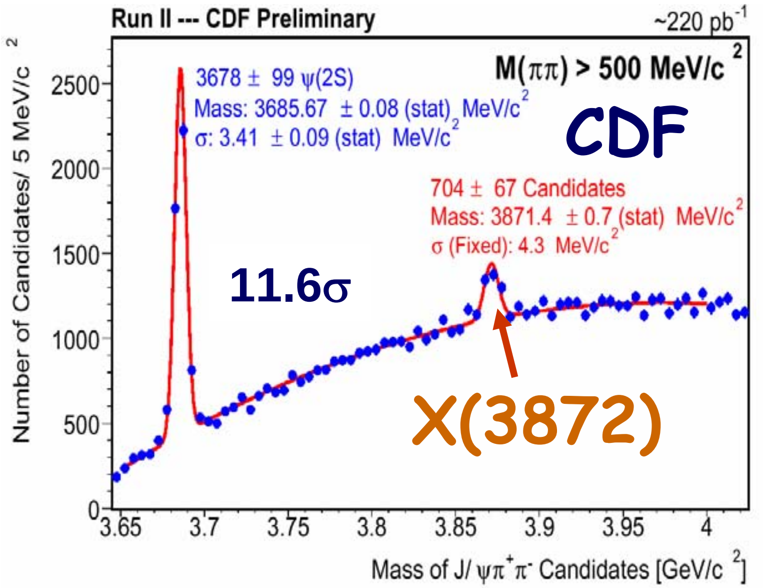


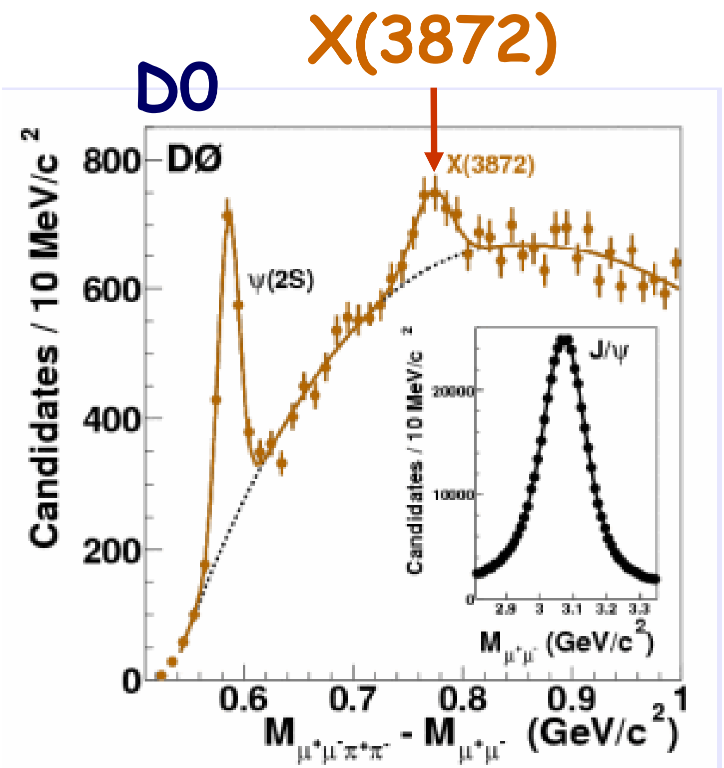
Belle first observed X(3872) in ρJ/ψ and ωJ/ψ modes in B decays

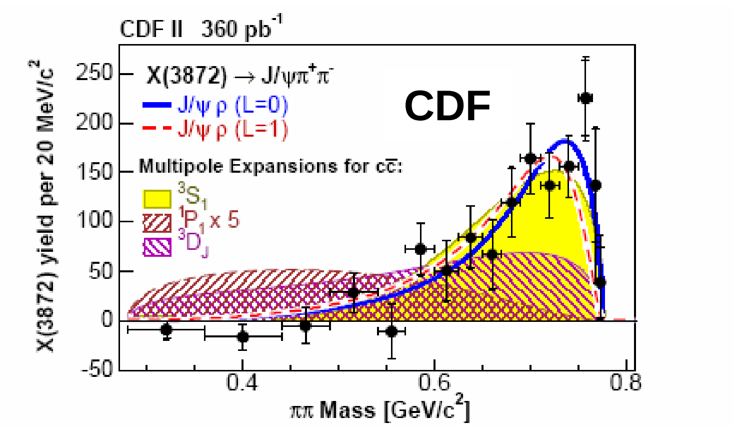
ρ J/ψ mode violates isospin!

PDG: 3871.2 ± 0.5 MeV
width < 2.3 MeV

X(3872) is also seen in $p\bar{p}$





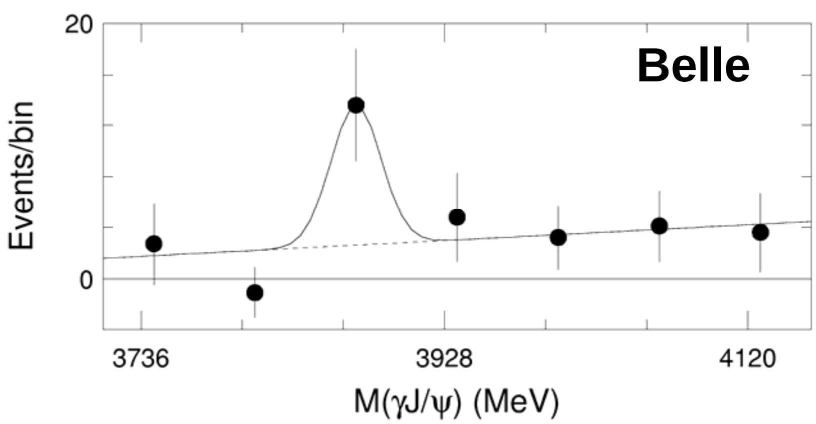


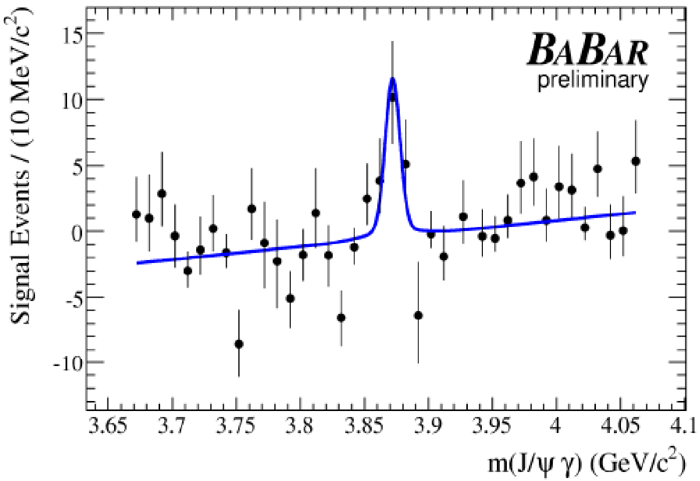
M(ππ) looks like a ρ

Production properties are similar to those of the ψ′

Quantum numbers of X(3872)

X(3872)→$\gamma J/\psi$ seen in:





C = + is established

- From angular correlations of final states→
  -Belle ruled out 0^{++}, 0^{-+}, favors 1^{++}
  -CDF allows only 1^{++} and 2^{-+}
- **Quantum number of X(3872) is probably 1^{++}**
  but 2^{-+} is not ruled out by experiments

More about 2^{-+} charmonium

- Since the 2^{-+} charmonium is the spin-singlet D-wave state and J/ψ is the spin-triplet S-wave state, E1 transition $2^{-+} \rightarrow J/\psi\,\gamma$ is forbidden in the non-relativistic limit
- the D-wave radial WF is orthogonal to the S-wave radial WF, therefore M1 transition $2^{-+} \rightarrow J/\psi\,\gamma$ is also forbidden
- But Belle and BaBar observed the $J/\psi\,\gamma$ mode
- X(3872) is unlikely to be the 2^{-+} charmonium
- Will relativistic corrections change this picture?

Is X(3872) a Molecule?

- X(3872) sits on $\bar{D}^0 D^{0*}$ threshold, very close to $\rho J/\psi$, $\omega J/\psi$, $D^+ D^{-*}$ threshold
- Very narrow, ~100 MeV below QM prediction
- Its hidden charm modes are quite important
- $\rho J/\psi$ decay mode violates isospin symmetry

Based on the above facts, Swanson (& others) proposed:

- X(3872) is mainly $\bar{D}^0 D^{0*}$ molecule bound by quark and pion exchange. Its WF also contains small but important $\rho J/\psi$, $\omega J/\psi$, $D^+ D^{-*}$ components
- The molecule picture explains the proximity to $\bar{D}^0 D^{0*}$ threshold and hidden charm decay modes
- This model has been very popular

Experimental evidence against the molecular assignment

	Molecule	Expts
$\frac{B\left(X(3872) \to \gamma J/\psi\right)}{B\left(X(3872) \to \pi^+\pi^- J/\psi\right)}$	0.007	Belle: 0.14 ± 0.05 Babar 0.25
$\frac{B\left(B^0 \to X(3872) K^0\right)}{B\left(B^+ \to X(3872) K^+\right)}$	0.1	Belle: 1.62
$\frac{B\left(X(3872) \to D^0 \bar{D}^0 \pi^0\right)}{B\left(X(3872) \to \pi^+\pi^- J/\psi\right)}$	0.054	Belle: $9.4^{+3.6}_{-4.3}$
$M_X (D_0 \bar{D}_0 \pi^0)$	$<$ 3.872	Belle: $3875.4 \pm 0.7^{+1.2}_{-2.0}$
$M_X (D_0^* \bar{D}_0)$	$<$ 3.872	Babar: $3875.6 \pm 0.7^{+1.4}_{-1.5}$

Is X(3872) a 1^{++} charmonium?

- Production properties of X(3872) are similar to those of ψ'
- The typical QM accuracy is ~100 MeV. Deviation around 100 MeV may be still acceptable
- Recently CLQCD claimed χ'_{c1} lies around 3853 MeV
- The 1^{++} charmonium assignment deserves further attention!

Obstacles of 1^{++} charmonium assignment

- Low mass

  -Strong S-wave coupled channel effects may lower its mass?

- Large isospin breaking $\rho J/\psi$ decay

  -Hidden charm decay can happen through rescattering mechanism

  $X \rightarrow \overline{D}^0 D^{0*} + D^+ D^{-*} \rightarrow \rho J/\psi\ (\omega J/\psi)$

  -there is isospin symmetry breaking in the mass of $\overline{D}D^*$ pair since $D^+(D^{-*})$ is heavier than $D^0(D^{0*})$

  - $\rho J/\psi$ mode has larger phase space than $\omega J/\psi$ mode since ρ meson is very broad

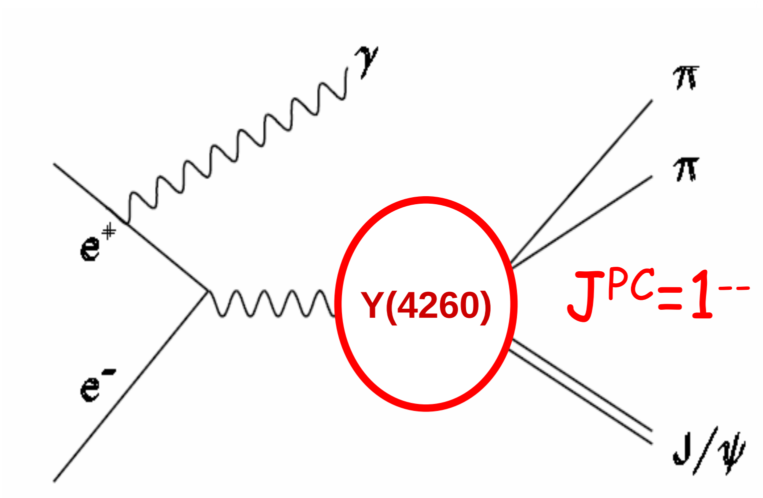
  → The above factors may combine to make large $\rho J/\psi$ decay width?

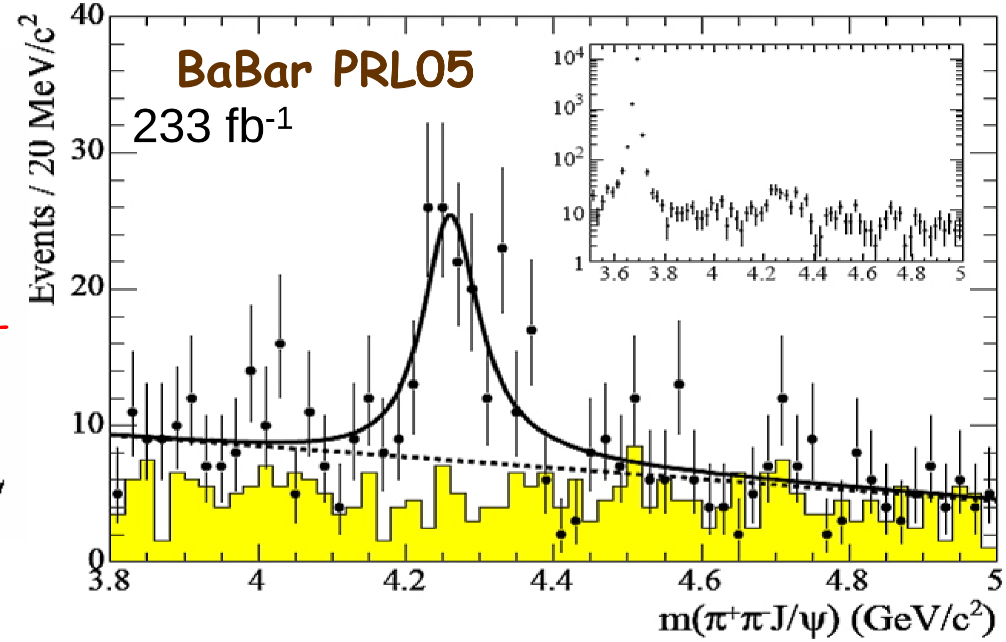
- Narrow width

  -Total width of X(3875) needs exotic scheme such as decreasing quark pair creation strength of $^3P_0$ model near threshold?

  ...

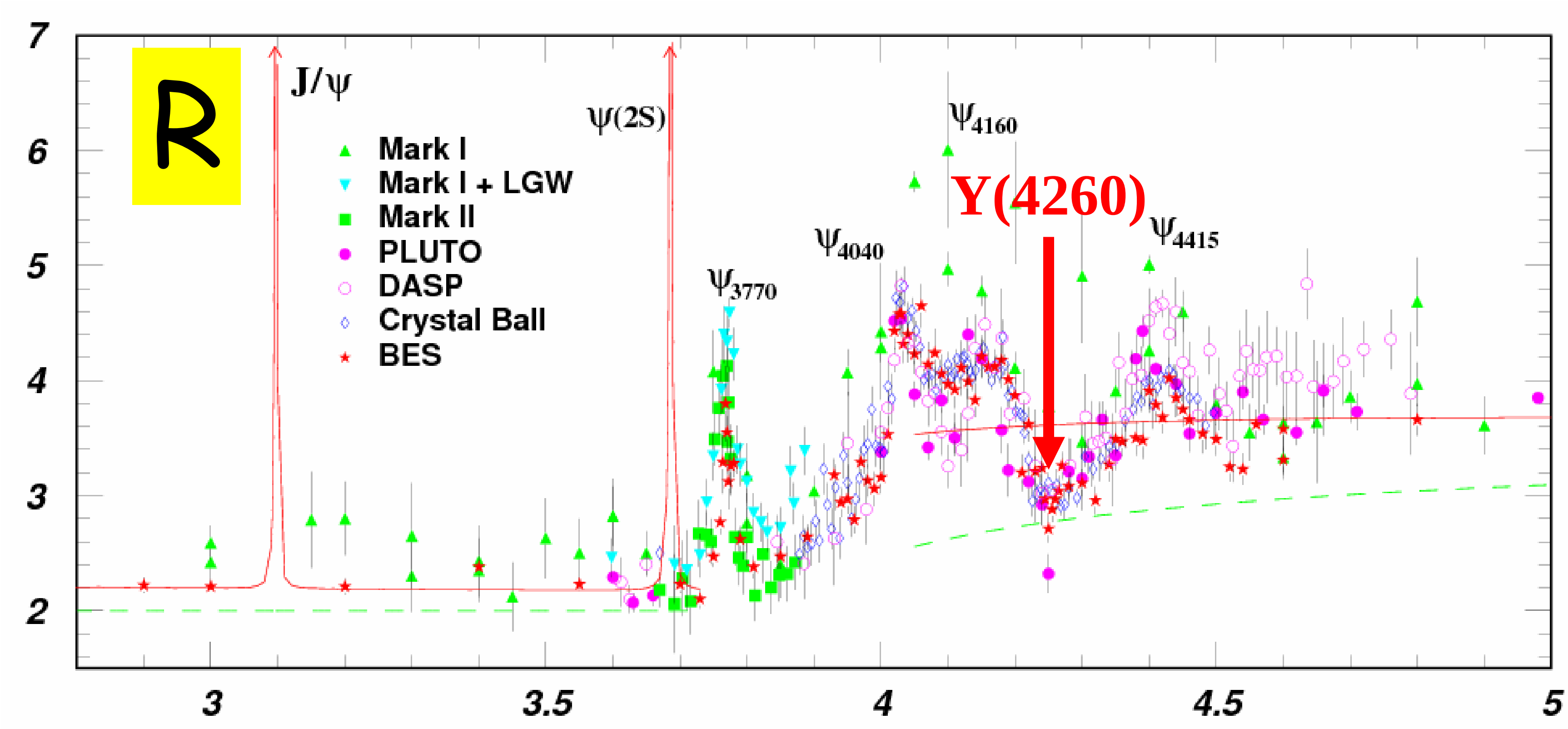
$e^+e^- \rightarrow \gamma_{isr}$ Y(4260) at BaBar





CLEO-c	BaBar	CLEO III	**Belle**
~50 (events)	125 ± 23 (~8σ)	14.1 $^{+5.2}$ (4.9σ)	**165 ± 24(stat) (>7σ)**
4260 (mass)	4259 ± 8 $^{+2}$	4283 $^{+17}$ ± 4	**4295 ± 10 $^{+11}$**
(width)	88 ± 23 $^{+6}$	70 $^{+40}$ ± 5	**133± 26 $^{+13}$**

Y(4260) not seen in $e^+e^- \rightarrow$ hadrons



- R distribution dips around 4.26 GeV
- Its leptonic width is small: $\Gamma(Y\rightarrow e^+e^-)$<240 eV (Mo et al, hep-ex/0603024)
- $\Gamma(Y\rightarrow ee)B(Y\rightarrow J/\psi\pi\pi)\cong$5eV and $\Gamma(Y)$=88MeV implies

Hidden charm decay width is large: $\Gamma(Y\rightarrow J/\psi\pi\pi)$>1.8 MeV!

PDG 1^{--} Charmonium

State	Mass (MeV)	Width (MeV)	e^+e^- Width (keV)
J/ψ	3097	0.091	5.40
$\psi(2\ ^3S_1)$	3686	0.281	2.12
$\psi(3\ ^3S_1)$	4040 ± 10	52 ± 10	0.75 ± 0.15
$\psi(4\ ^3S_1)$	4415 ± 6	43 ± 15	0.47 ± 0.10
$\psi(1\ ^3D_1)$	3770 ± 2.4	23.6 ± 2.7	0.26 ± 0.04
$\psi(2^3D_1)$	4160 ± 20	78 ± 20	0.77 ± 0.23
$\psi(3^3D_1)$	>4400 ?		

All the above states have a sharp peak in R distribution! But Y(4260) has a dip!

What is the Y(4260)?

- If PDG assignment of 1^{--} charmonium is correct
  - No suitable position for Y(4260) in the quark model around this mass region
  - Clear overpopulation of the 1^{--} spectrum

- From BES and CLEOc, the hidden charm decay width of ψ'':

$\Gamma(\psi'' \to J/\psi\pi\pi) \approx 50$keV

  - If Y(4260) is charmonium, one might expect comparable $J/\psi\pi\pi$ width instead of **$\Gamma(Y \to J/\psi\pi\pi) > 1.8$ MeV**
  - Similar dipion transitions from $\psi(4040)$ or $\psi(4160)$ were not observed in the same expts.
  - $\Rightarrow$ is *conventional* charmonium assignment in trouble?

What is the Y(4260)?

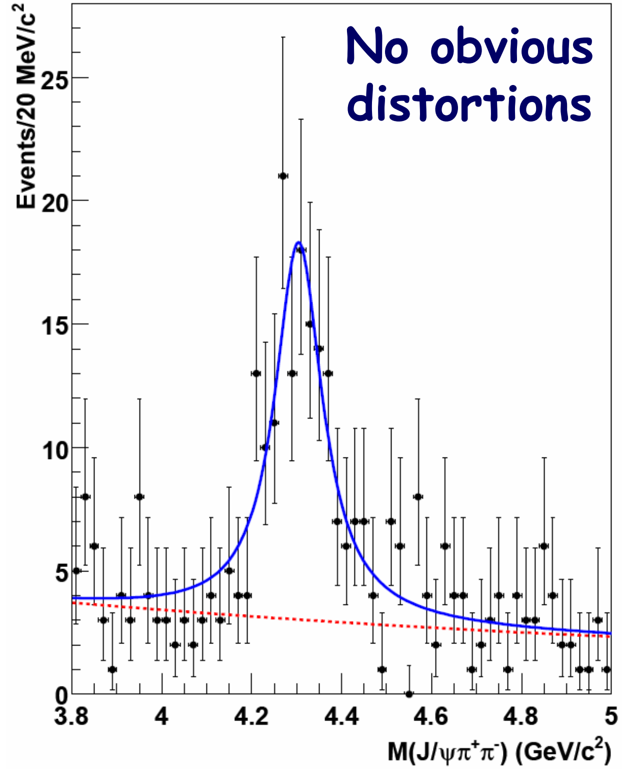
- Glueball? Zhu, PLB05

  Virtual photon does not couple to glues directly.

  Glueballs decay into light hadrons easily.

- Threshold or coupled-channel effects?

  close to $\bar{D}D_1(2420)$, $\bar{D}D_1^*$ or $D_0^*(2310)\,\bar{D}^*$ threshold, possibility not excluded



Is Y(4260) a tetraquark?

- tetraquark falls apart into $D\bar{D}$ very easily. $D\bar{D}$ should be one of the dominant decay modes. Y's width would be much larger than 90 MeV!
- If the isoscalar component of the photon produced Y(4260) ($I^G=0^-$), its isovector componet would also produce Y'(4260) ($I^G=1^+$), which decays into $J/\psi\, \pi^+\pi^-\pi^0$. Ruled out by Babar!

Is Y(4260) a hybrid charmonium?

Zhu, PLB05;
Kou,Pene, PLB05;
Page, Close, PLB05

- Its mass
- leptonic width
- total width
- production cross section
- decay pattern (hidden charm vs open charm)
- flavor blind decays into $J/\psi\pi\pi$, $J/\psi K\bar{K}$
- overpopulation of 1^{--} spectrum
- large hidden charm $J/\psi\, \pi\, \pi$ decay width
- All satisfy the very naïve expectation of a hybrid charmonium

A Surprising Prediction 12 Yrs Ago

- Ding, Chao, Qin, PRD 51 (1995) 5064, "Possible effects of color screening and large string tension in heavy quarkonium spectra"
- Predicted 4S charmonium exactly at 4262 MeV

$$V(r) = -\frac{4\alpha_s}{3r} + Tr\left(\frac{1-e^{-\mu r}}{\mu r}\right)$$

- Is PDG assignment correct? Does PDG miss a 1^{--} state?
- Challenges remain: (1) How to generate the large $J/\psi\ \pi\pi$ decay width? (2) How to explain the dip in the R distribution?

TABLE I. Calculated masses and leptonic widths for charmonium states with the screened potential (5) and parameters (8), where $\Gamma_{ee} = \Gamma^0_{ee}[1 - \frac{16}{3\pi}\alpha_s(m_c)]$ with $\alpha_s(m_c) = 0.28$ [16].

States	Mass (MeV)	Γ^0_{ee} (keV)	Γ_{ee} (keV)	$\Gamma^{\rm expt}_{ee}$ (keV)	Candidate
$1S$	3097	10.18	5.34	5.26 ± 0.37	$\psi(3097)$
$2S$	3686	4.13	2.17	2.14 ± 0.21	$\psi(3686)$
$3S$	4053	2.35	1.23	0.75 ± 0.15	$\psi(4040)$
$4S$	4262	1.46	0.77	0.77 ± 0.23	$\psi(4160)$
$5S$	4415	0.91	0.48	0.47 ± 0.10	$\psi(4415)$
$1P$	3526				$\chi(3526)_{\rm c.o.g.}$
$1D$	3805				$\psi(3770)$
$2D$	4105				

Summary (I)

- After four years' extensive theoretical and experimental efforts, the situation of D_{sj} mesons is almost clear
  - $D_{s0}^*(2317)$ and $D_{s1}^*(2460)$ are probably $c\bar{s}$ states
- But the higher charmonium sector is still very controversial
  - Z(3930) is χ_{c2}'
  - X(3940) may be η_c''
  - Y(3940) needs confirmation
  - X(3872) may be a candidate of χ'_{c1} *(or molecule?)*
  - Y(4260) may be a candidate of hybrid charmonium (or charmonium?)

Summary (II)

- BESIII (Beijing) will start taking data this year and will increase its database by 100 times
- Jlab, B factories and other facilities are increasing the database continuously
- J-PARC will start running at the end of next year (?)
- CSR (LanZhou, China) will start running in the near future
- There will be great progress in the search of non-conventional hadrons and more unexpected…

谢谢

ありがとう

Merci

Thank you

Danke

Gracias

Backup slides

B1

Radiative decays of D_{s0}* (D_{s1}*) (keV)

References	[108]	[109]	[112]
$\Gamma(D_{sJ}(2317) \to D_s^* + \gamma)$	1.9	1	4-6
$\Gamma(D_{sJ}(2460) \to D_s\gamma)$	6.2	-	19-29
$\Gamma(D_{sJ}(2460) \to D_s^* + \gamma)$	5.5	-	0.6-1.1
$\Gamma(D_{sJ}(2460) \to D_{sJ}(2317) + \gamma)$	-	-	0.5-1.8

Pionic decays of D_{s0}* (D_{s1}*) (keV)

References	[114]	[113]	[109]	[103]	[108]	[115]	[104]	[116]
$D_{sJ}^*(2317) \to D_s\pi^0$	32	34-44	7 ± 1	21.5	~ 10	16	10-100	150 ± 70
$D_{sJ}(2460) \to D_s^*\pi^0$	35	35-51	7 ± 1	21.5	~ 10	32		150 ± 70

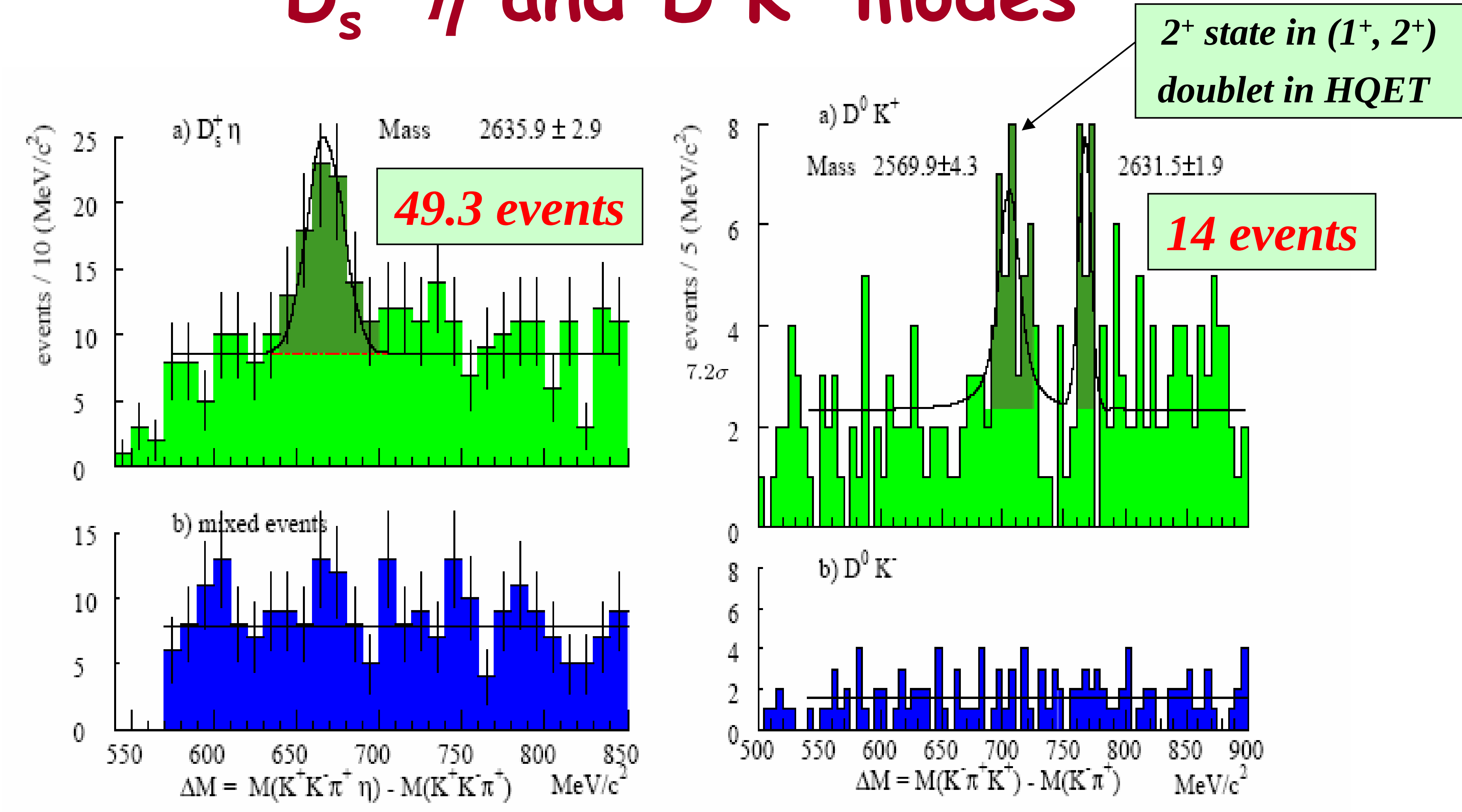
Puzzles of $D_{sJ}(2632)$

- Narrow decay width
  - 274 MeV above D^0K^+
  - 116 MeV above Ds η threshold
  - decay width less than 17 MeV
  - Naive expectation around (100~200) MeV
- Unusual decay pattern

$SU(3)_F$ + $c\bar{s}$ assignment → $$\frac{\Gamma(D^0K^+)}{\Gamma(D_s\eta)} = 2.3 * (1.54)^{2L} \geq 2.3$$

SELEX → $$\frac{\Gamma(D^0K^+)}{\Gamma(D_s\eta)} = 0.16 \pm 0.06$$

SELEX observed $D_{sJ}(2632)$ in $D_s^+\ \eta$ and D^0K^+ modes



B4

- If $D_{sJ}(2632)$ were the 0^+ isoscalar state in tetraquark 15 rep., the ratio of SU(3) C-G coefficients naturally explains its anomalous decay pattern: (Zhu, PRD05)

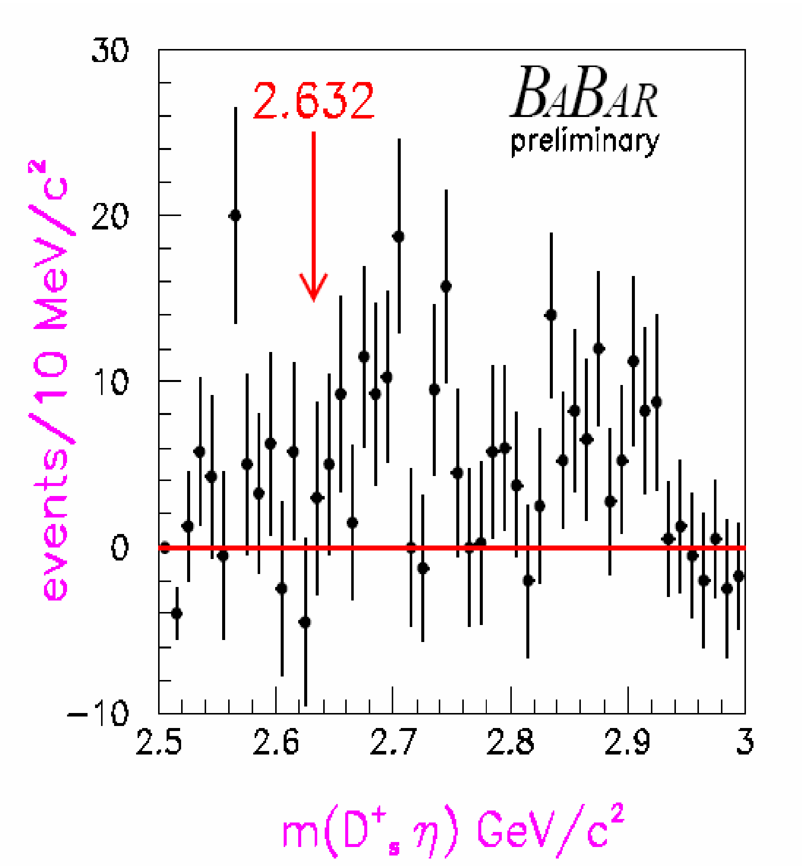
$$\frac{\Gamma(D^{-\prime}_{s,15} \to \bar{D}^0 K^-)}{\Gamma(D^{-\prime}_{s,15} \to D_s^- \eta)} = \left(\frac{1}{\sqrt{6}}\right)^2 * (1.54)^{2L+1} = 0.25$$

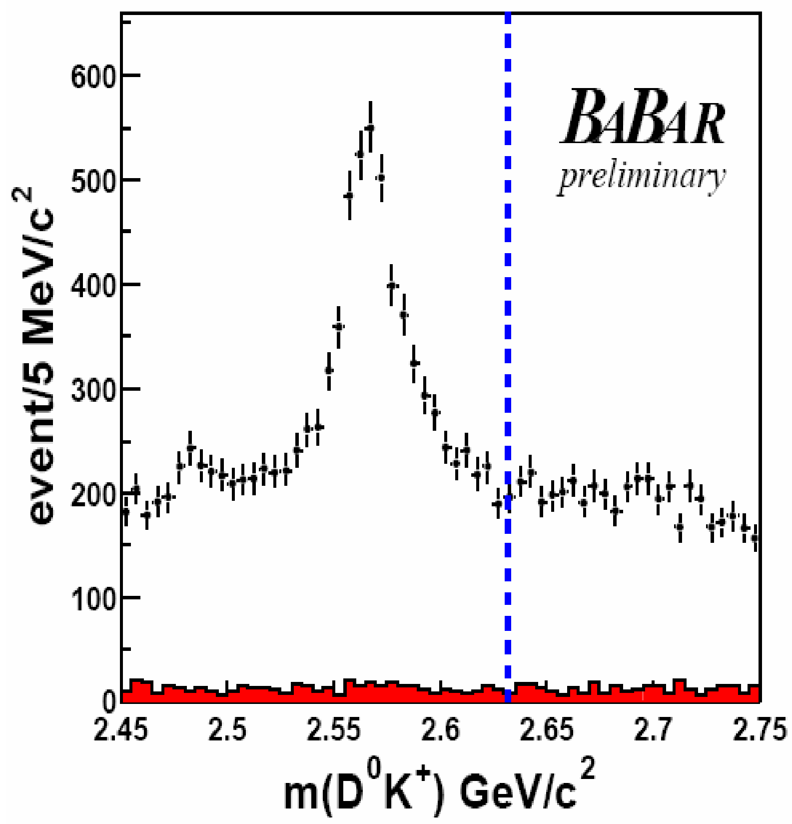
SU(3) C-G

Decay Momentum

- Under tetraquark assumption, it's very difficult to explain its narrow width
- (1) Mixing between D-wave state and the radial excitation of D_s^* and (2) the node in the radial wave function may explain both puzzles (Chang PLB05)

BABAR/CLEO/FOCUS didn't confirm $D_{sJ}(2632)$

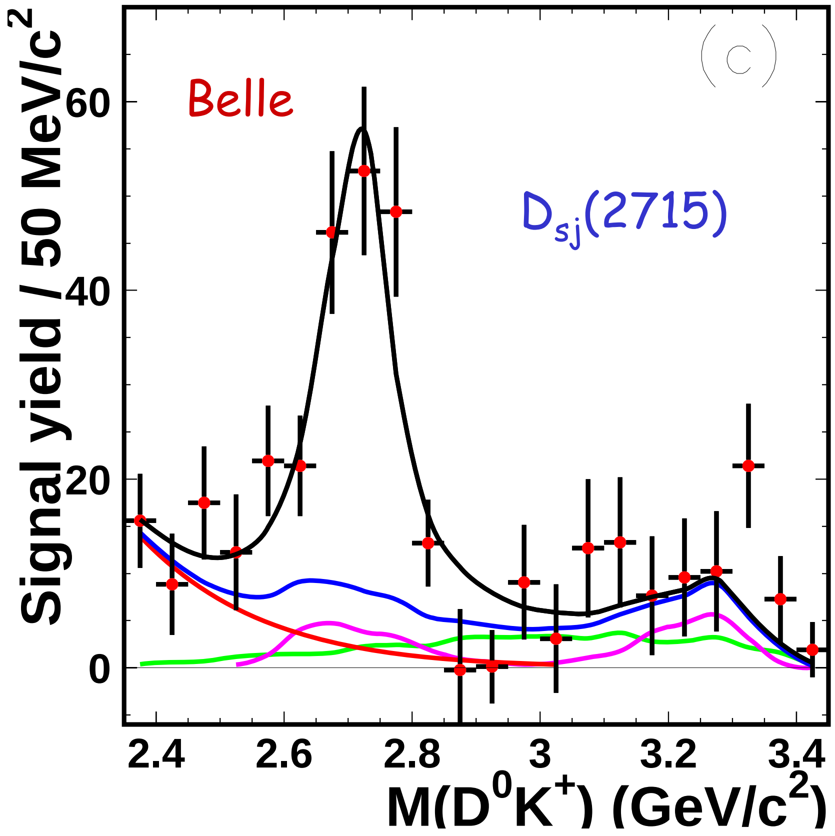




$D_{sj}(2632)$ is probably an experimental artifact

Higher excited charmed mesons

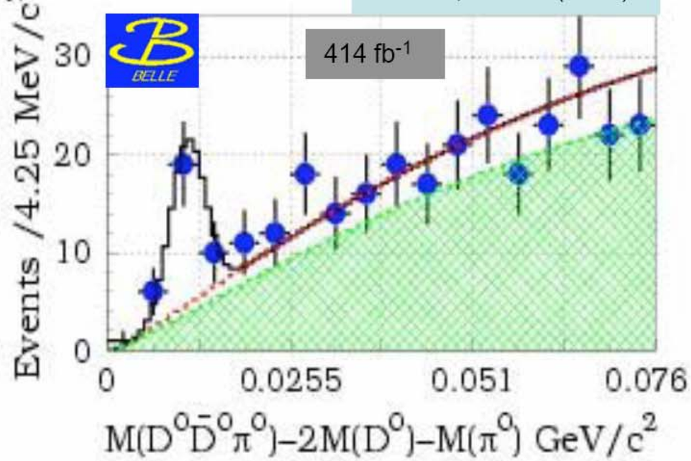
- In DK channel Babar observed two states:
  - $D_{sj}(2860)$ width 48 MeV
  - $D_{sj}(2690)$ width 112 MeV
- Belle reported $J^P=1^-$ state
  - $D_{sj}(2715)$ width 115 MeV
- $D_{sj}(2690/2715)$ may be
  - D-wave 1^- state
  - or radial excitation of D_s^*
- $D_{sj}(2860)$ may be
  - radial excitation of D_{s0}^*
  - or D-wave 3^- state



Study of B → D(*)D(*)K decays: X(3875)?

BELLE: observation of: $B \to X(3872)K^{\pm}$, $X(3872) \to D^0\underline{D}^0\pi^0$

PRL 97, 162002(2006)



$$M = 3875.4 \pm 0.7^{+1.2}_{-2.0}\ MeV/c^2$$

$$B(B^{\pm} \to K^{\pm}X, X \to D^0\overline{D}^0\pi^0) = (1.27 \pm 0.31^{+0.22}_{-0.39})10^{-4}$$

$$\frac{B(X \to D^0\overline{D}^0\pi^0)}{B(X \to J/\psi\pi\pi)} = 9.7 \pm 3.4$$

New Result-Preliminary

BABAR: $B \to \bar{D}^{(*)}D^{(*)}K^+$

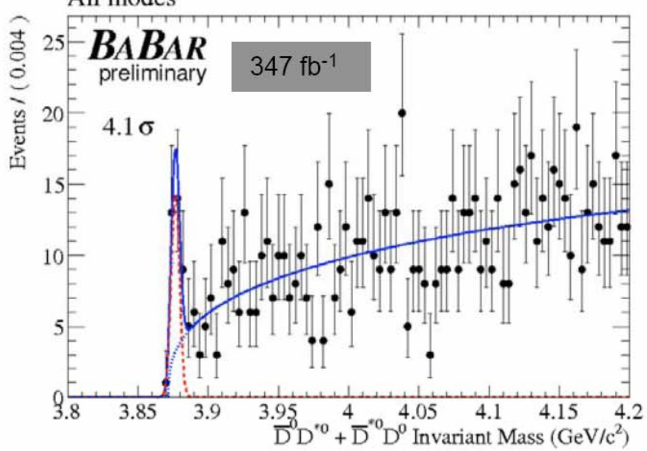
II- search for $\bar{D}^{(*)}D^{(*)}$ resonances

$B^+ \to \bar{D}^0D^{*0}K^+ + \bar{D}^{*0}D^0K^+$

$B^0 \to \bar{D}^0D^{*0}K^0 + \bar{D}^{*0}D^0K^0$

with $D^{*0} \to D^0\pi^0$ and $D^0\gamma$

All modes



$$M = 3875.6 \pm 0.7^{+1.4}_{-1.5}\ MeV/c^2$$

$R(B^0/B^+) = 2.23 \pm 0.93 \pm 0.55$

$\Delta m(B^0/B^+) = 0.2 \pm 1.6$ MeV/c^2

also: $\psi(3770) \to \bar{D}D$: M= 3777.5 ± 3.2 MeV/c^2

Mass:

- ✓ very good agreement btw experiments
- ✓ 2.5σ away from $X \to J/\psi\pi^+\pi$: X(3875)?

Is Y(4260) a hybrid charmonium?

- LQCD → 1^{-+} $c\bar{c}G$ mass around (4.2~4.4) GeV
- Flux tube model predicts 1^{--} state around 4.2 GeV
- Recent LQCD simulation with 1^{--} $c\bar{c}G$ operator claimed signal around 4.26 GeV (Luo PRD06)
- As a hybrid candidate, Y's mass may be reasonable

Is Y(4260) a hybrid charmonium?

- LQCD suggests the hidden bottom decay modes are important for hybrid Upsilon mesons (Bali)
- Flux tube model predicts the L=0 + L=1 selection rule
- In the heavy quark limit, heavy hybrid meson mainly decays into a pair of L=0 and L=1 mesons (Zhu, PRD99)
- Caution: Not tested by experiments since no hybrid mesons have been established yet!
- If true, one expects

Y(4260) → $D\bar{D}$ suppressed

Y(4260) → J/ψ + light hadrons important

→ Consistent with Babar and Cleo's experiments!

Y(4260) → $\bar{D}\, D_1^*$ etc dominant, not discovered yet