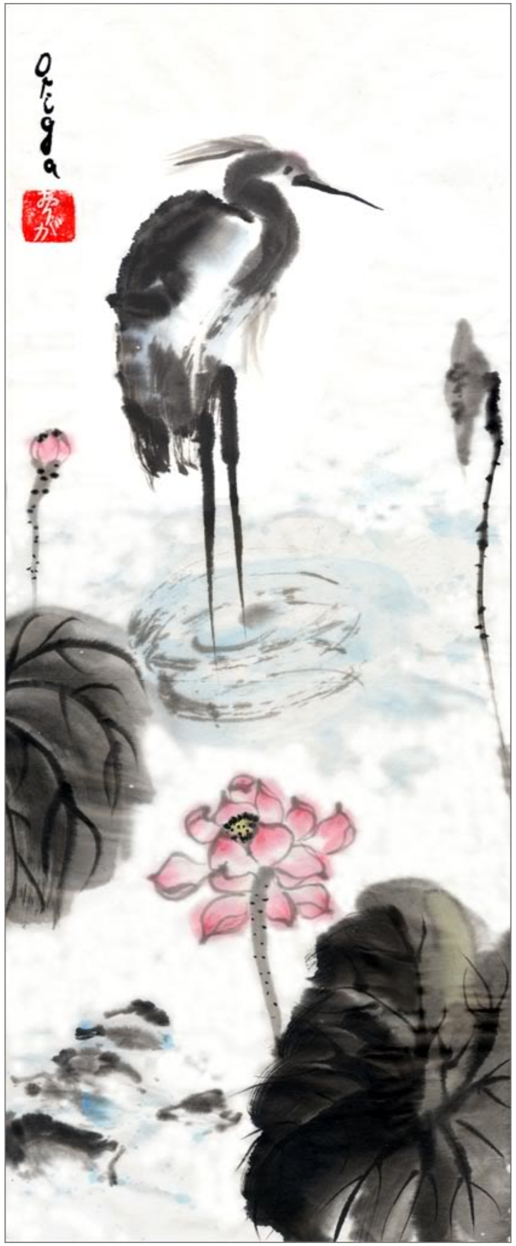
International Workshop on e^+e^- from Phi to Psi , 13-16 October, Beijing, China

e^+e^- to charm cross sections via ISR

Galina Pakhlova

ITEP, Belle collaboration



Motivation to study cross sections $e^+e^- \to$ *open charm*

Parameters of the $J^{PC} = 1^{--}$ conventional charmonia

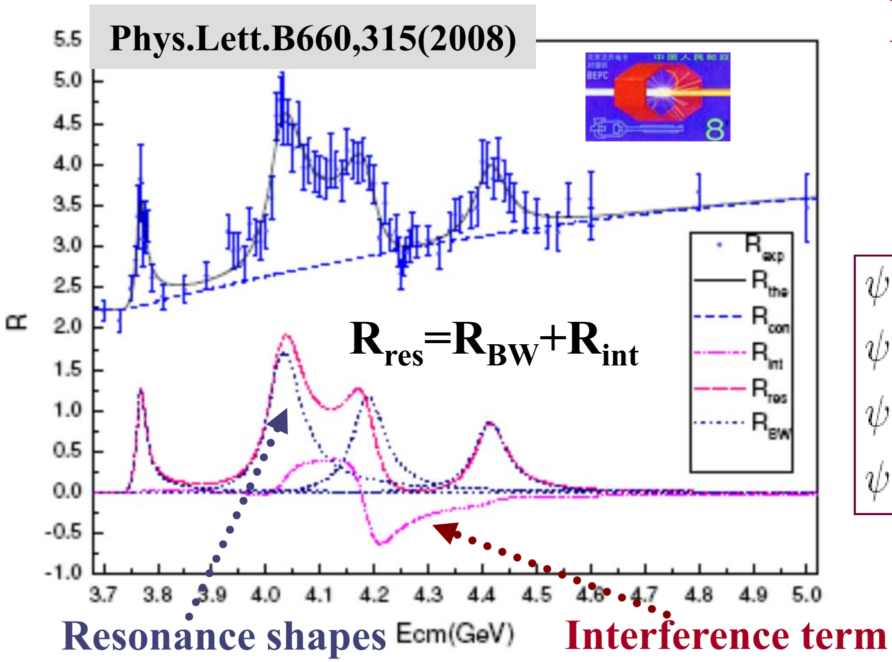
ψ(3770), ψ(4040), ψ(4160), ψ(4415)

$M, \Gamma_{tot}, \Gamma_{ee}$ remain quite uncertain and model dependent

To fix the resonance parameters we need to know their decay channels to take into account their interference:

- **non-resonant contribution**
- **many open charm thresholds**

BES fit to the inclusive R spectrum



All possible two-body decays of ψ(3770), ψ(4040), ψ(4160), ψ(4415) are included

$$\begin{aligned}
\psi(3770) &\Rightarrow D\bar{D};\\
\psi(4040) &\Rightarrow D\bar{D}, D^*\bar{D}^*, D\bar{D}^*, \bar{D}D^*, D_s\bar{D}_s;\\
\psi(4160) &\Rightarrow D\bar{D}, D^*\bar{D}^*, D\bar{D}^*, \bar{D}D^*, D_s\bar{D}_s, D_s\bar{D}_s^*;\\
\psi(4415) &\Rightarrow D\bar{D}, D^*\bar{D}^*, D\bar{D}^*, \bar{D}D^*, D_s\bar{D}_s, D_s\bar{D}_s^*, D_s^*\bar{D}_s^*.
\end{aligned}$$

Significant effect of interference : model dependent!

	M, MeV	Γ_{tot} , MeV	Γ_{ee} , keV	δ, deg	
ψ(3770)	3772.92 ± 0.35	27.3 ± 1.0	0.265 ± 0.018		PDG09
	3772.0 ± 1.9	30.4 ± 8.5	0.22 ± 0.05	0	BES08
ψ(4040)	4039 ± 1	80 ± 10	0.86 ± 0.07		PDG09
	4039.6 ± 4.3	84.5 ± 12.3	0.83 ± 0.20	130 ± 46	BES08
ψ(4160)	4153 ± 3	103 ± 8	0.83 ± 0.07		PDG09
	4191.7 ± 6.5	71.8 ± 12.3	0.48 ± 0.22	293 ± 57	BES08
ψ(4415)	4421 ± 4	62 ± 20	0.58 ± 0.07		PDG09
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

To reduce model dependence we need to measure exclusive cross sections to open charm final states

Potential models & ψ states

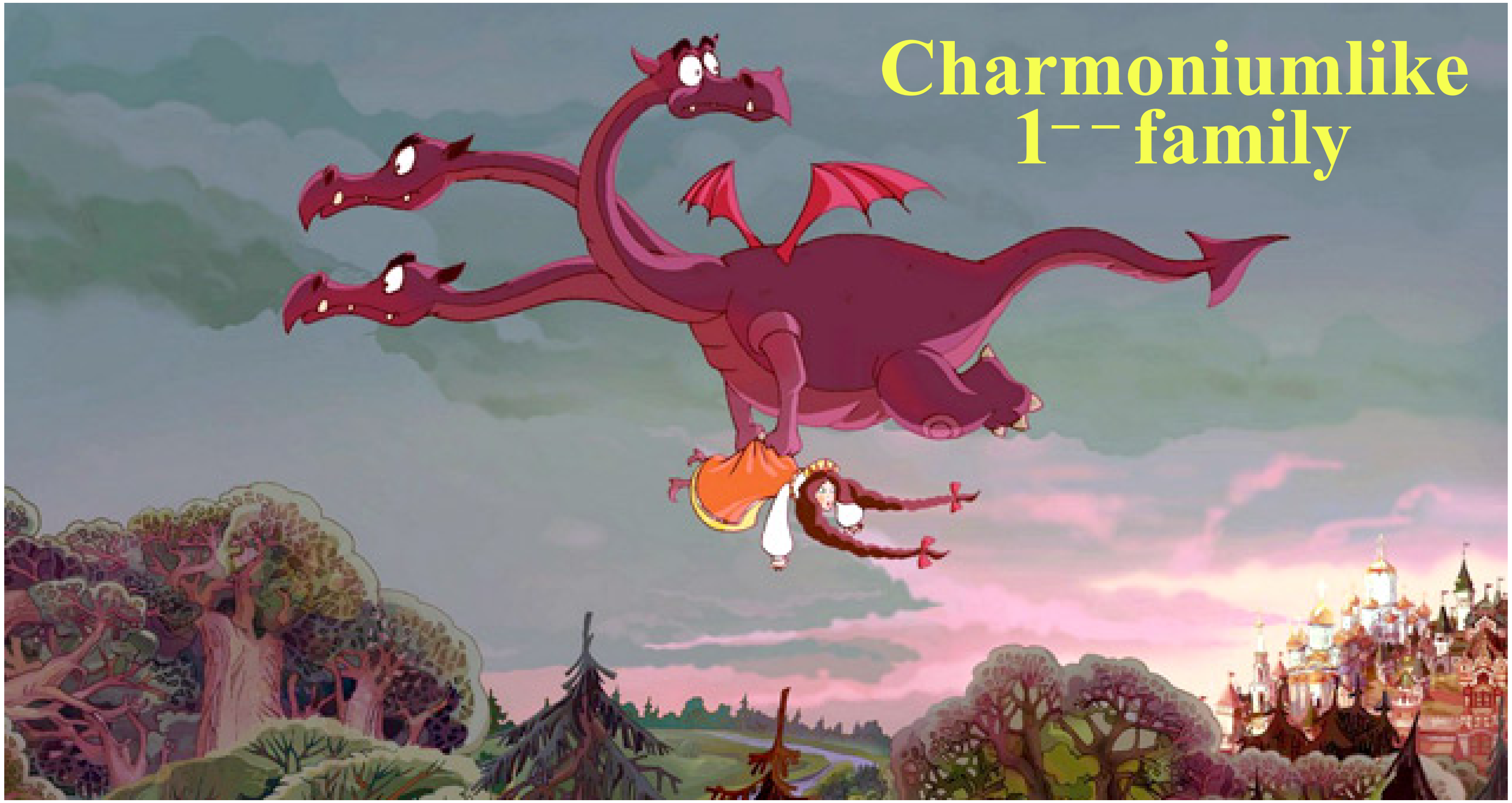
- **Mass spectrum**
  - In general agreement with data
- **Open charm decays**
  - via nonperturbative gluodynamics
    - difficult to compute
    - good probes of strong QCD
- **Only inclusive measurements**

State	Mode	Width, GeV PDG09	$^3P_0$	$\rho K \rho$
$\psi(3770)$	$D\overline{D}$	27.3 ± 1.0	33	11
$\psi(4040)$	$D\overline{D}$	?	0.1	2.3
	$D\overline{D}^*$		25	17
	$D^*\overline{D}^*$		25	5
	$D_s\overline{D}_s$		6	1.6
	Total	80 ± 10	57	26
$\psi(4160)$	$D\overline{D}$	?	12	
	$D\overline{D}^*$		0.3	
	$D^*\overline{D}^*$		27	2.6
	$D_s\overline{D}_s$		6	
	$D_s^*\overline{D}_s^*$		11	
	Total	103 ± 8	57	
$\psi(4415)$	$D^*\overline{D}^*$	?	12	
	$D\overline{D}_1$		24	
	$D\overline{D}_2$		18	
	$D_s\overline{D}_s^*$		2	
	Total	62 ± 20	60	

E.Swanson, Phys.Reports 429(2006)

More theoretical and experimental efforts are required

State		PDG09	GI85	F91	EQ94	ZVR95	EFG03	BGS05
1^3S_1	J/ψ	3096.919 ± 0.011	3098	3104	3097	3100	3096	3090
2^3S_1	$\psi(2S)$	3686.09 ± 0.04	3676	3670	3686	3730	3686	3672
1^3D_1	$\psi(3770)$	3772.92 ± 0.35	3819	3840		3800	3798	3785
3^3S_1	$\psi(4040)$	4039 ± 1	4100			4180	4088	4072
2^3D_1	$\psi(4160)$	4153 ± 3	4194					4142
4^3S_1	$\psi(4415)$	4421 ± 4	4450					4406

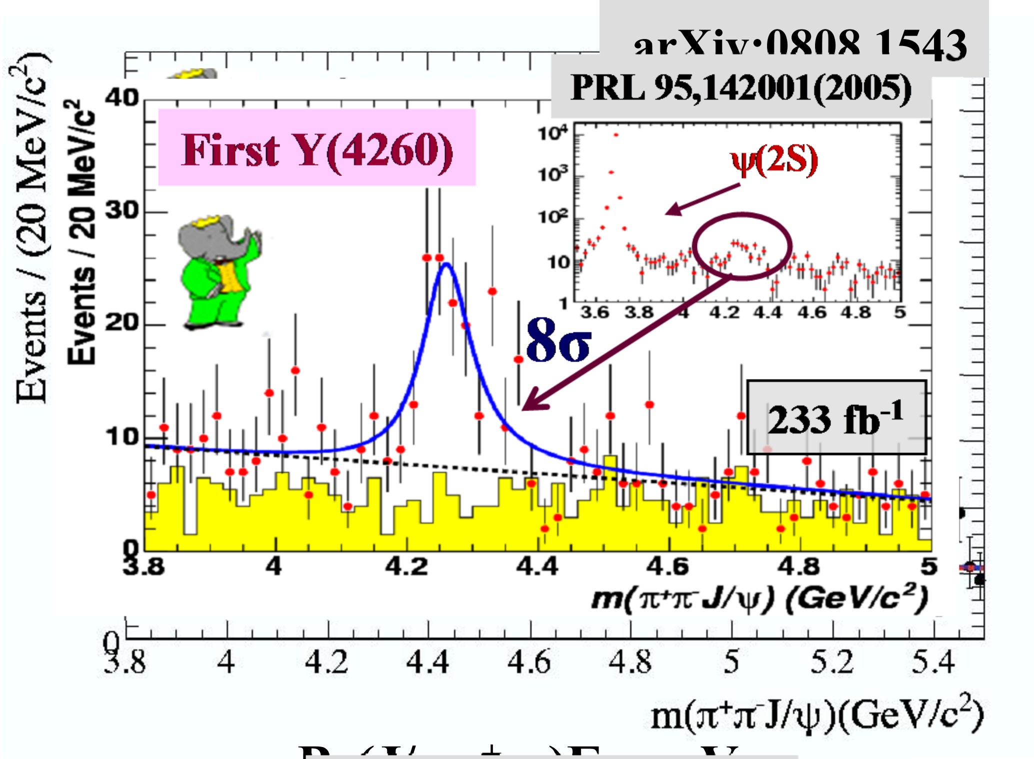


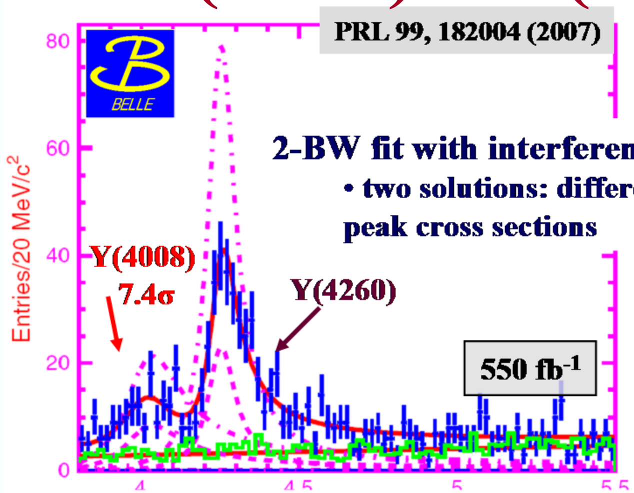
One more reason to study e^+e^- to charm cross sections

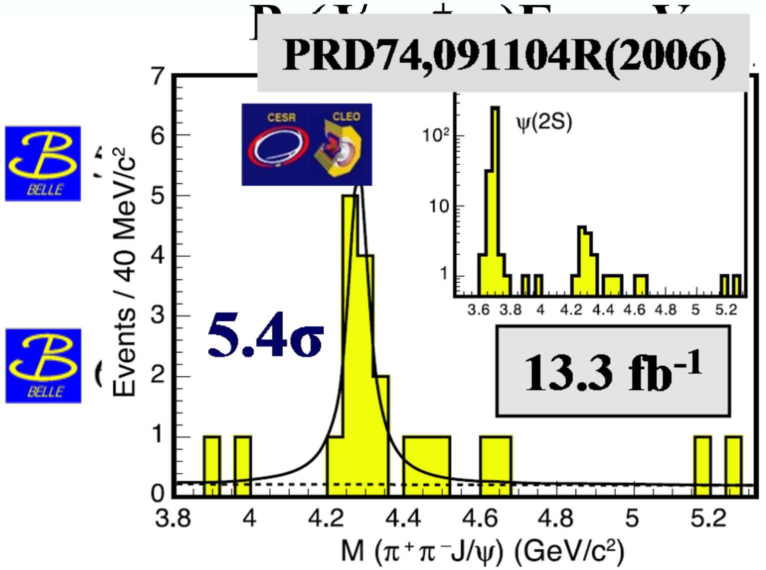
The nature of the charmoniumlike 1⁻⁻ family with masses above open charm threshold remains unclear

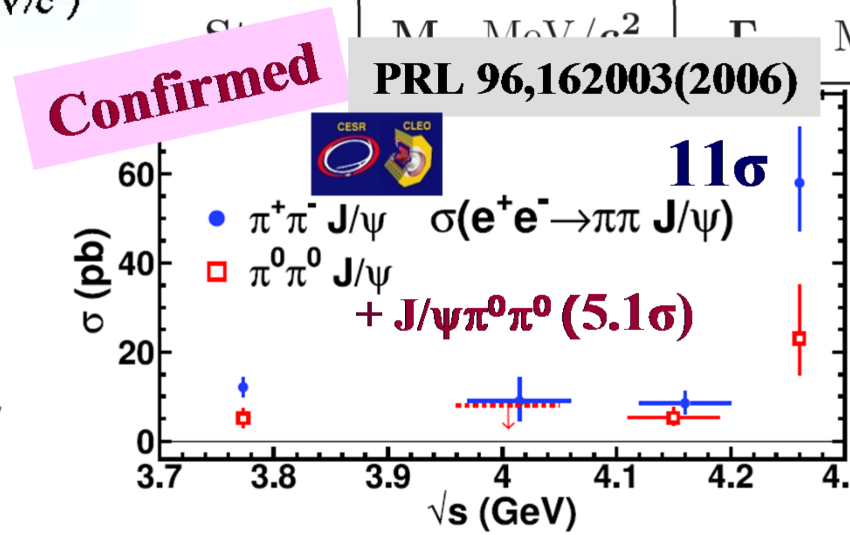
- **Their properties are inconsistent with conventional charmonium**

$e^+e^- \to J/\psi\pi^+\pi^- \gamma_{ISR}$
Y(4260)... Y(4008)?









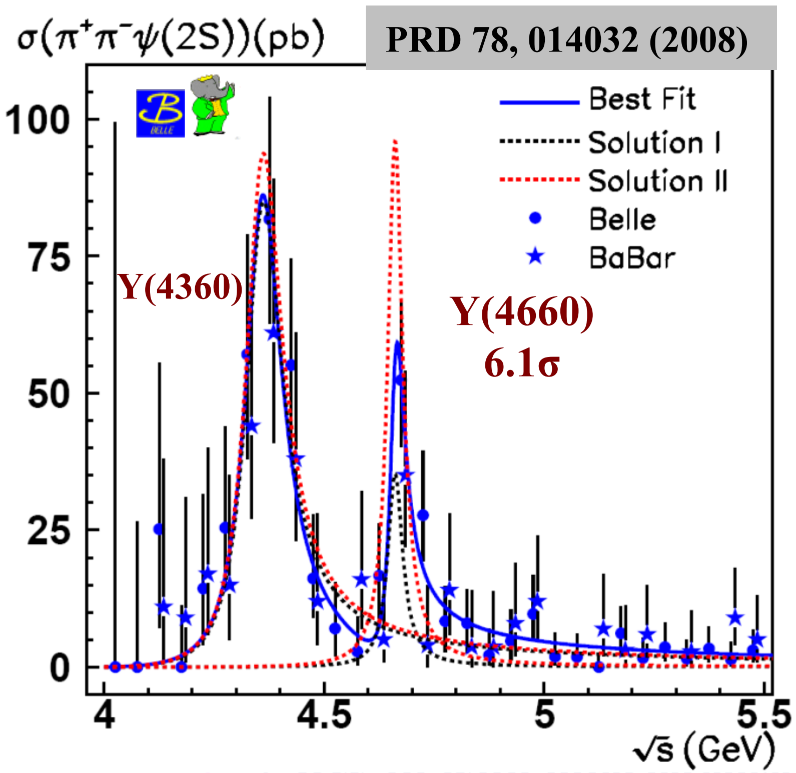
Y(4260)	$4247 \pm 12^{+17}_{-32}$	$108 \pm 19 \pm 10$

...ion is inconsistent with conventional charmonium

Combined fit to BaBar & Belle data on $e^+e^- \to \psi(2S)\,\pi^+\pi^-\,\gamma_{ISR}$

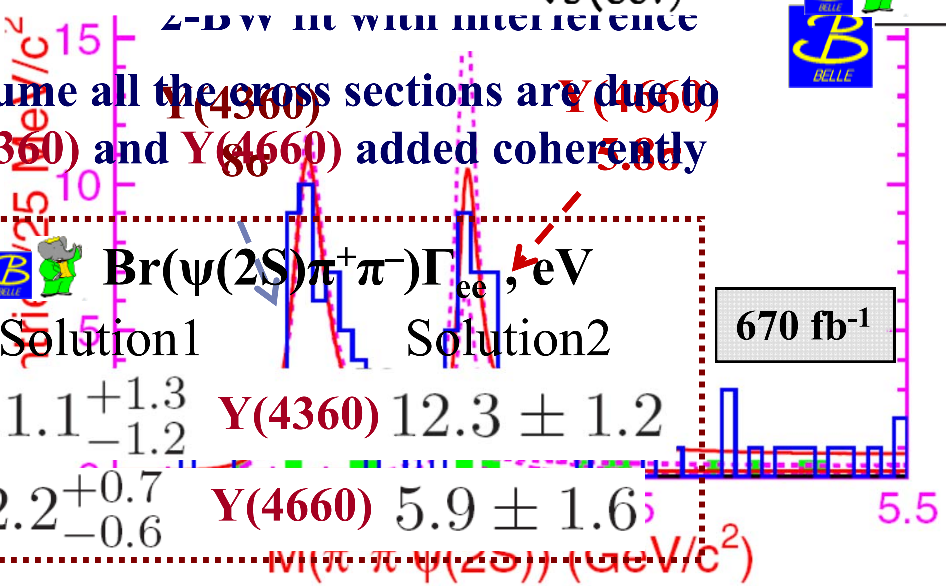
$e^+e^- \to \psi(2S)\,\pi^+\pi^-\,\gamma_{ISR}$ Y(4360), Y(4660) ...

PRD 78, 014032 (2008)



Best measurements of Y(4360) and Y(4660)

State	M, [MeV/c²]	Γ_{tot}, [MeV]
Y(4360)	4324 ± 24	172 ± 33
Y(4360)	$4361 \pm 9 \pm 9$	$74 \pm 15 \pm 10$
Y(4360)	$4355^{+9}_{-10} \pm 9$	$103^{+17}_{-15} \pm 11$
Y(4660)	$4664 \pm 11 \pm 5$	$48 \pm 15 \pm 3$
Y(4660)	$4661^{+9}_{-8} \pm 6$	$42^{+17}_{-12} \pm 6$



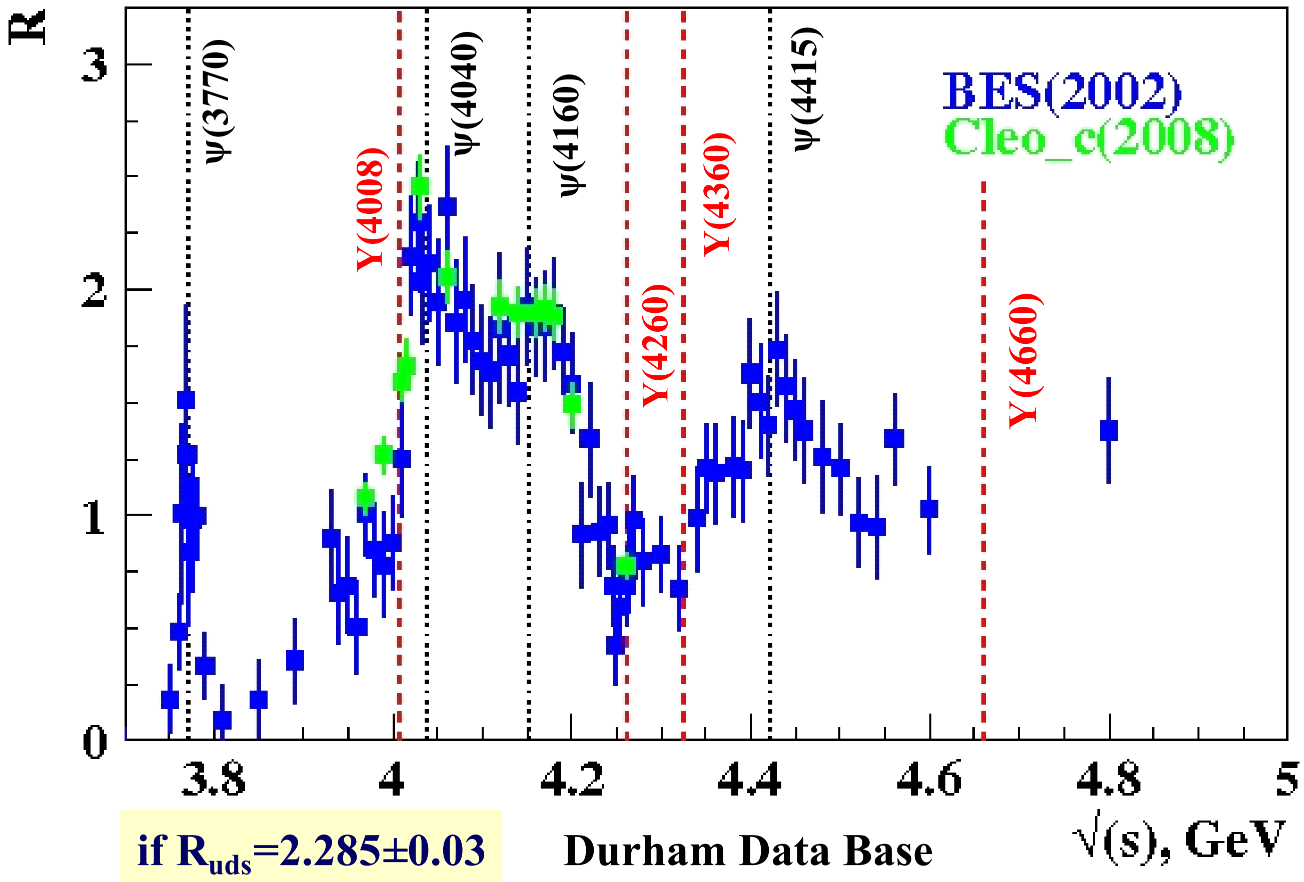
Assume all the cross sections are due to Y(4360) and Y(4660) added coherently

	Solution1		Solution2
$Br(\psi(2S)\pi^+\pi^-)\Gamma_{ee}$, eV			
	$11.1^{+1.3}_{-1.2}$	Y(4360)	12.3 ± 1.2
	$2.2^{+0.7}_{-0.6}$	Y(4660)	5.9 ± 1.6

Absence of open charm production is inconsistent with conventional charmonium

Y states vs inclusive cross section $e^+e^- \to hadrons$

$$R(s) = \sigma(e^+e^- \to hadrons)/\sigma(e^+e^- \to \mu^+\mu^-) - R_{uds}$$



- **Peak positions for M(J/ψππ) & M(ψ(2S)ππ) significantly different**
- **Y(4260) mass corresponds to dip in inclusive cross section**

Potential models & Y states

No room for Y states among conventional 1^{--} charmonium

S.Godfrey and N.Isgur PRD32,189 (1985)

3^3S_1 = ψ(4040)

2^3D_1 = ψ(4160)

4^3S^1 = ψ(4415)

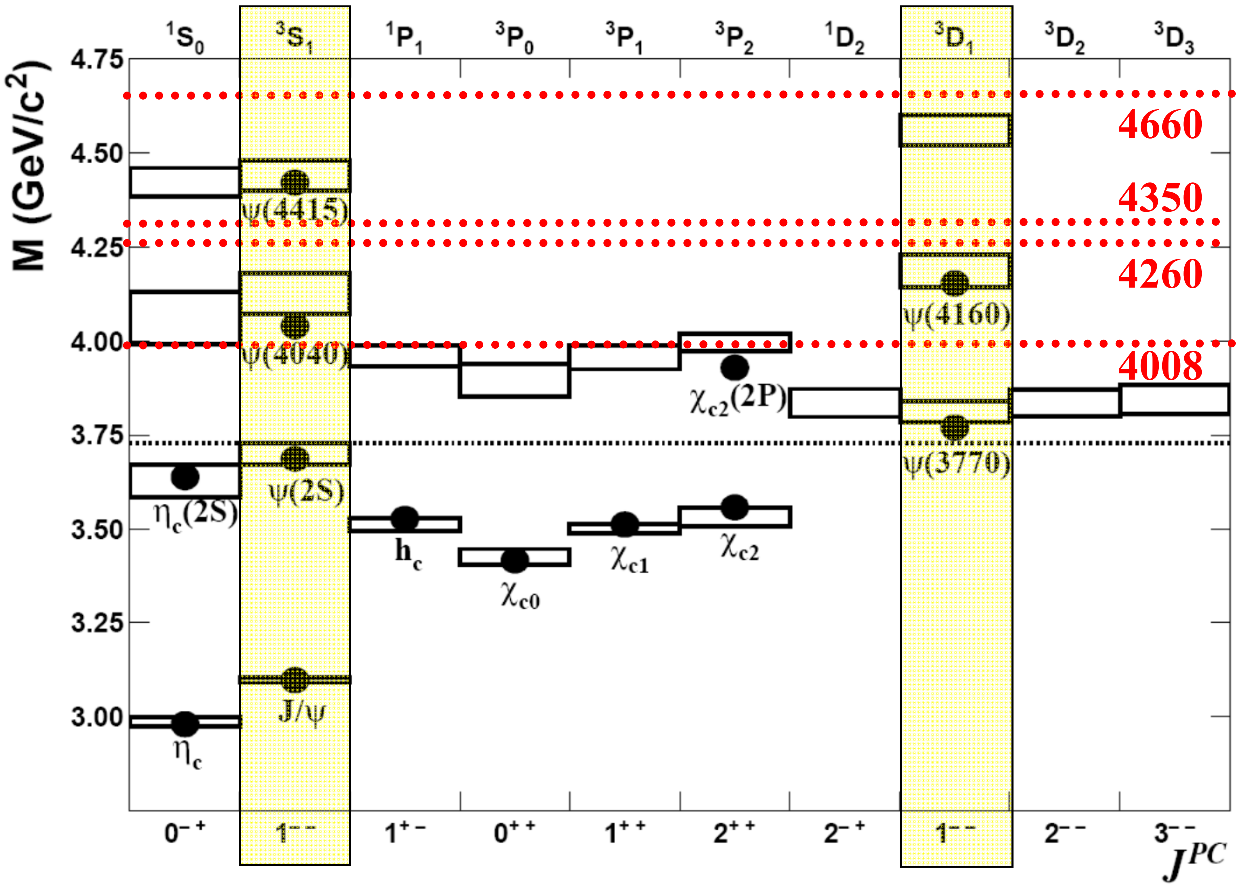
masses of predicted

3^3D_1 (4520)

5^3S_1 (4760)

4^3D_1(4810)

are higher (lower)



Interpretations of Y states

- Y(4360) &Y(4660) are conventional charmonia with shifted masses
  - Y(4360) = 3^3D_1 , Y(4660) = 5^3S_1

G.J Ding, J.J.Zhu, M.L.Yan, Phys.Rev.D77:014033 (2008)
A.M.Badalyan, B.L.G.Bakker, I.V.Danilkin, Phys.Atom.Nucl.72:638-646,(2009)

  - $4^3S^1 \neq \psi(4415) = 4^3D_1(4661)$; Y(4360)=$4^3S_1(4389)$, Y(4660)=5^3S_1 (4614) or $4^3D_1(4661)$

J.Segovia, A.M.Yasser, D.R.Entem, F.Fernandez Phys.Rev.D78:114033,(2008).

- Charmonium hybrids

Zhu S.L.; Close F.E.; Kou E. and Pene O.

  - The lightest hybrid is expected by LQCD around 4.2 GeV
  - The dominant decays $Y(4260) \rightarrow D^{(*)}D^{(*)}\pi$, via virtual D^{**}

- Hadro-charmonium
  - Specific charmonium state "coated" by excited light-hadron matter

S.Dubinskiy, M.B.Voloshin, A.Gorsky

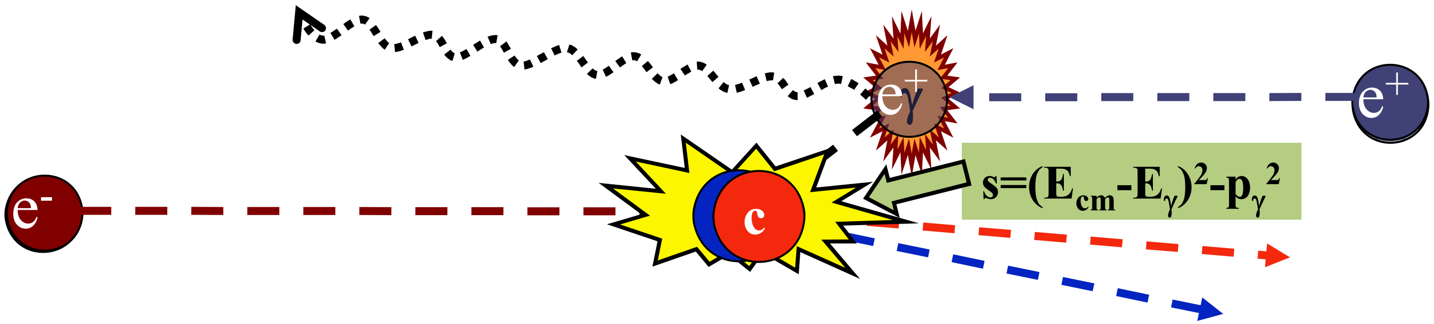
- Multiquark states
  - [cq][cq] tetraquark — *Maiani L., Riquer V., Piccinini F., Polosa A.D.*
  - DD_1 or D^*D^0 molecules — *Swanson E.; Rosner J.L., Close F.E.*

- Heavy meson hadronic molecules
  - Y(4660) is $\psi(2S)f_0(980)$ bound state

F.K.Gou,C.Hanhart, S.Krewald,U.G.Meissner

- S-wave charm meson thresholds — *Lui X.*

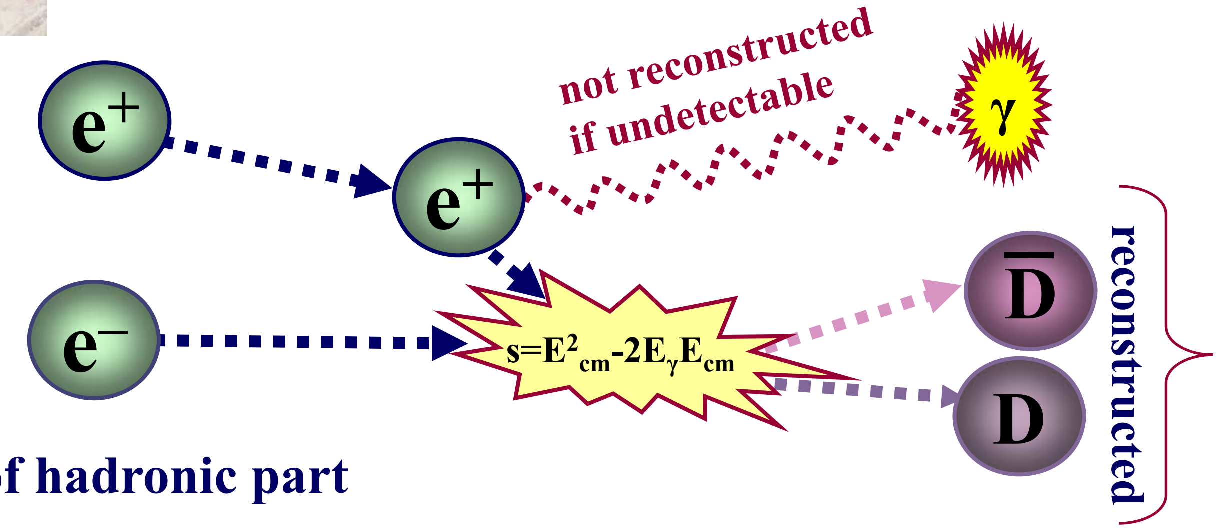
Use ISR to measure open charm exclusive final states



ISR at B factories

- Quantum numbers of final states are fixed $J^{PC} = 1^{--}$
- Continuous ISR spectrum:
  - access to the whole $\sqrt{s}$ interval
- α_{em} suppression compensated by huge luminosity
  - comparable sensitivity to energy scan (CLEOc, BES)

$e^+e^- \rightarrow DD$ via ISR with full reconstruction

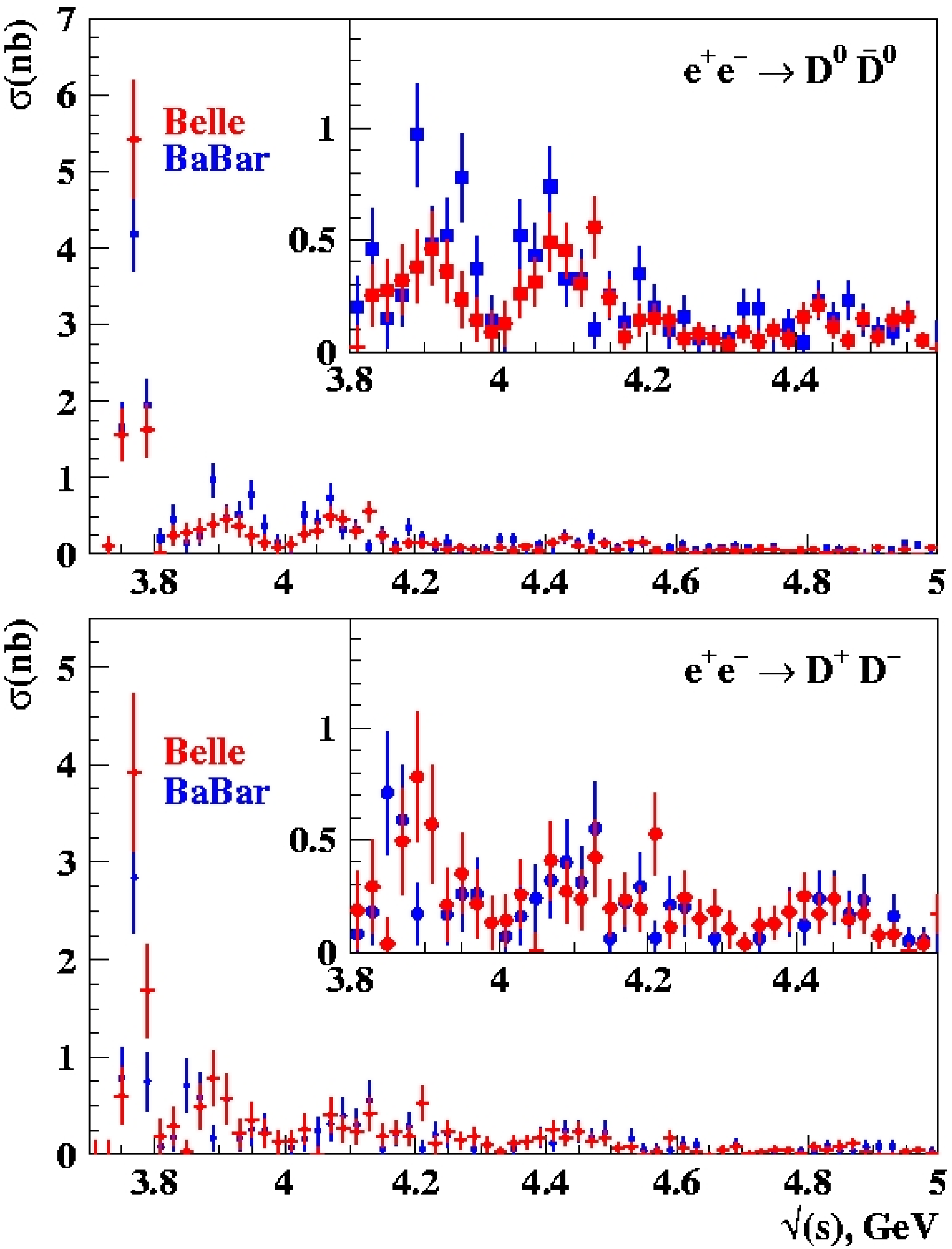


- *__Full reconstruction__* **of hadronic part**
- **ISR photon detection is not required**
  - **but used if it is in the detector acceptance**
- **__Translate measured DD mass spectrum to cross section__**

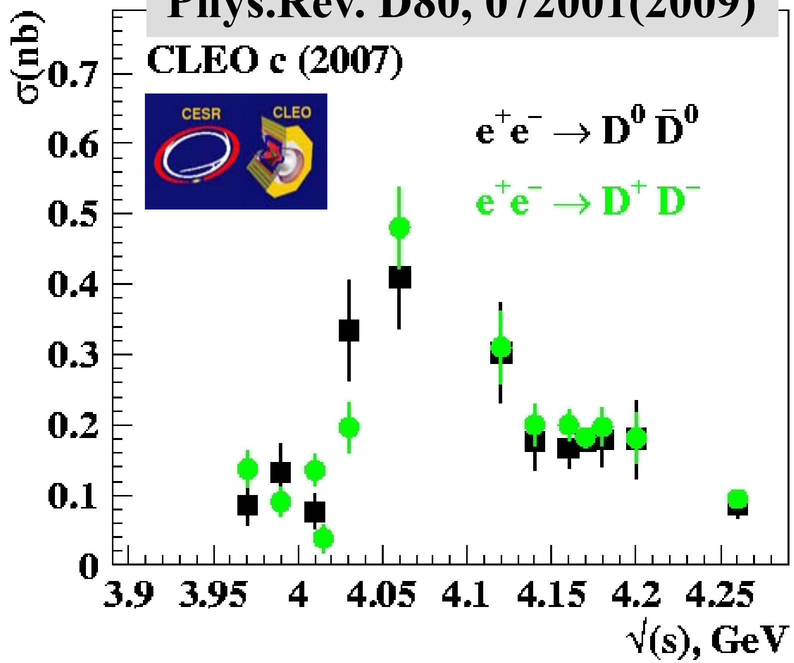
$\sigma(e^+e^- \to DD)$

Phys.Rev.D77,011103(2008)

Phys.Rev. D76, 111105(2007)

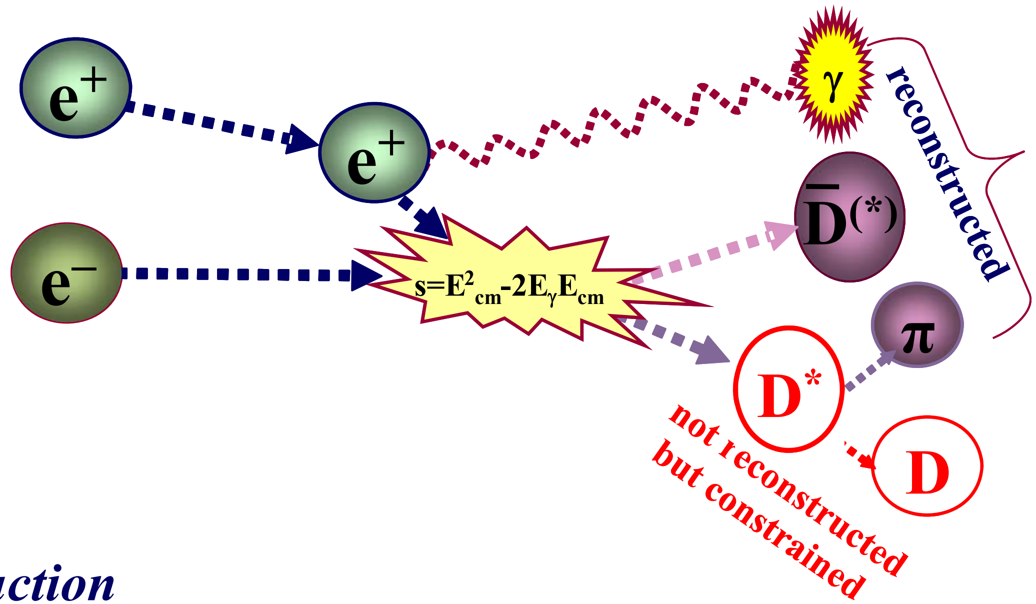


Phys.Rev. D80, 072001(2009)



- Broad structure around 3.9 GeV
    - in *qualitative agreement* with coupled-channel model?
- Some structure at 4.0-4.2 GeV
    - Statistics are small …ψ(4040)? ψ(4160)?
- Hint of ψ(4415)

$e^+e^- \to D^{(*)}D^*$ via ISR with partial reconstruction

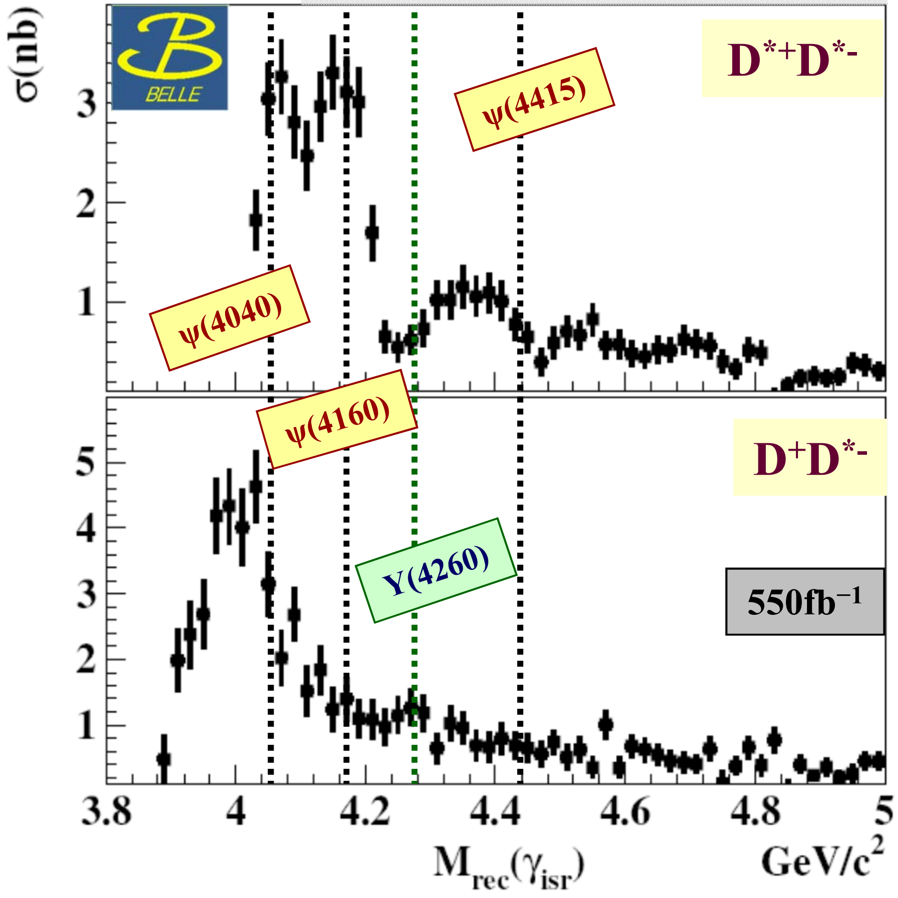


DD^* & D^*D^*

- D^* *partial reconstruction*
  - increase eff ~ 10-20 times
- Detection of ISR photon
- Translate measured mass recoil against $\gamma_{ISR} \equiv D^{(*)}D^*$ mass spectrum to cross section

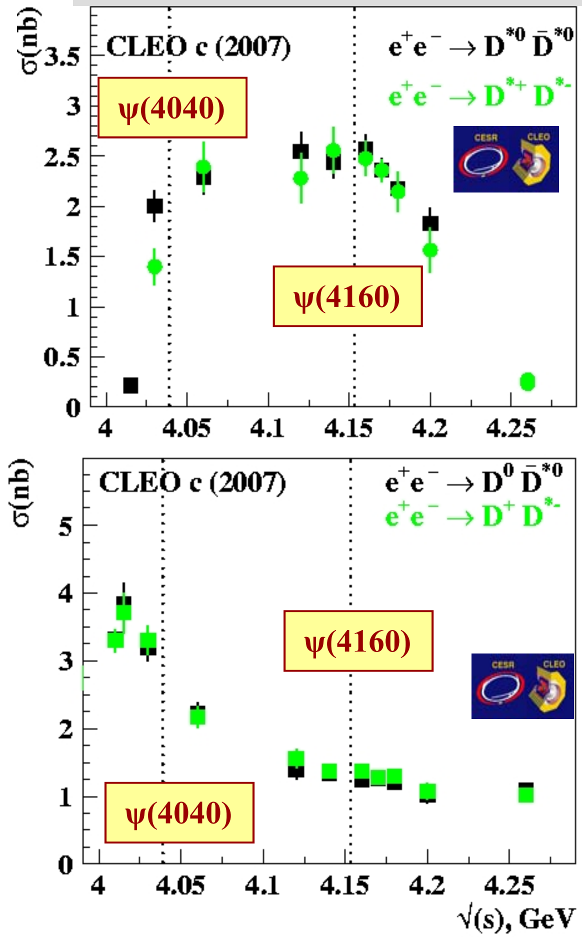
Exclusive $e^+e^- \to D^{(*)}D^*$ cross-sections

Phys. Rev. Lett. 98, 092001 (2007)

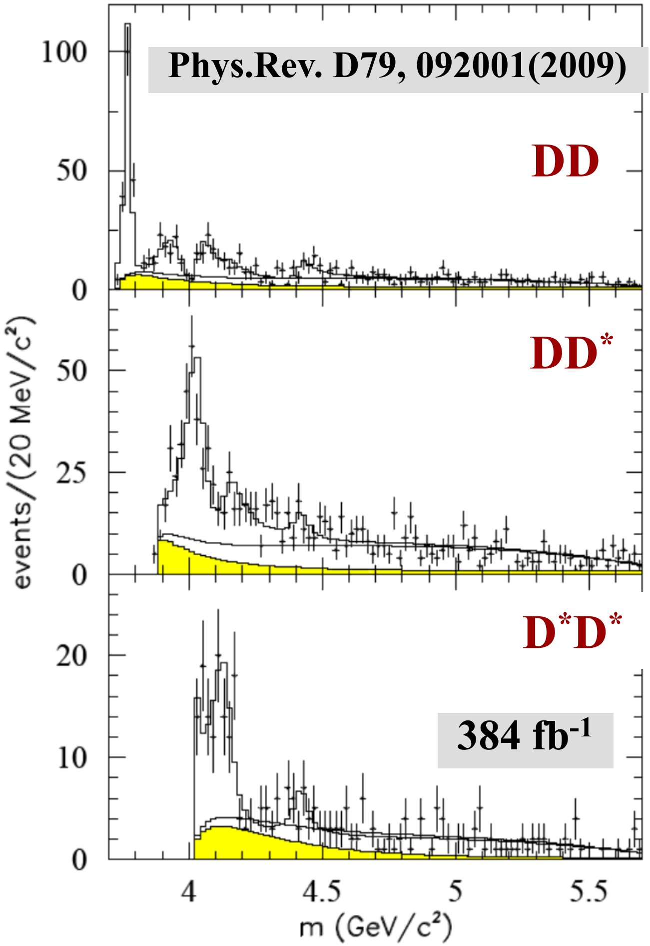


Systematic errors ≈ statistical errors

Phys.Rev. D80, 072001(2009)



- D^*D^*
  - complicated shape of cross section
  - clear dip at $M(D^*D^*) \sim 4260$ GeV (similar to inclusive R)
- DD^*
  - broad peak at threshold (shifted relative to 4040 GeV)



New BaBar: $e^+e^- \to D^{(*)}D^*$

- **Full reconstruction of hadronic part**
- **Both charged and neutral final states**
- **Fit by sum of ψ states with** ***fixed masses&widths from PDG*** *(due to limited statistics)*

No evidence is found for Y(4260)→ DD, DD*,D*D*

$$\frac{\mathcal{B}(Y(4260)\to D^*\overline{D})}{\mathcal{B}(Y(4260)\to J/\psi\pi^+\pi^-)} < 34$$

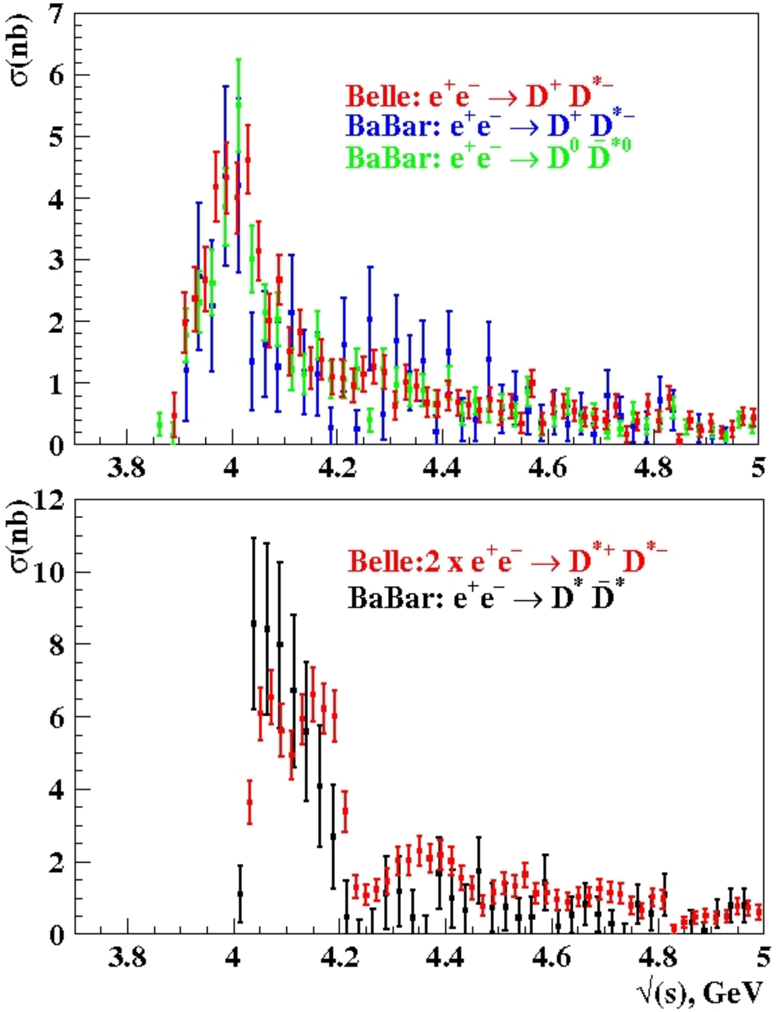
$$\frac{\mathcal{B}(Y(4260)\to D^*\overline{D}^*)}{\mathcal{B}(Y(4260)\to J/\psi\pi^+\pi^-)} < 40$$

Br ratios seem to disagree with potential models …

… uncertainties are too large

Ratio	measurement	$^3P_0$	C^3 and $\rho K\rho$
1) $\mathcal{B}(\psi(4040)\to D\overline{D})/\mathcal{B}(\psi(4040)\to D^*\overline{D})$	$0.24 \pm 0.05 \pm 0.12$	0.003	0.14 [14]
2) $\mathcal{B}(\psi(4040)\to D^*\overline{D}^*)/\mathcal{B}(\psi(4040)\to D^*\overline{D})$	$0.18 \pm 0.14 \pm 0.03$	1.0	0.29 [14]
3) $\mathcal{B}(\psi(4160)\to D\overline{D})/\mathcal{B}(\psi(4160)\to D^*\overline{D}^*)$	$0.02 \pm 0.03 \pm 0.02$	0.46	0.08 [6]
4) $\mathcal{B}(\psi(4160)\to D^*\overline{D})/\mathcal{B}(\psi(4160)\to D^*\overline{D}^*)$	$0.34 \pm 0.14 \pm 0.05$	0.011	0.16 [6]
5) $\mathcal{B}(\psi(4400)\to D\overline{D})/\mathcal{B}(\psi(4400)\to D^*\overline{D}^*)$	$0.14 \pm 0.12 \pm 0.03$	0.025	
6) $\mathcal{B}(\psi(4400)\to D^*\overline{D})/\mathcal{B}(\psi(4400)\to D^*\overline{D}^*)$	$0.17 \pm 0.25 \pm 0.03$	0.14	

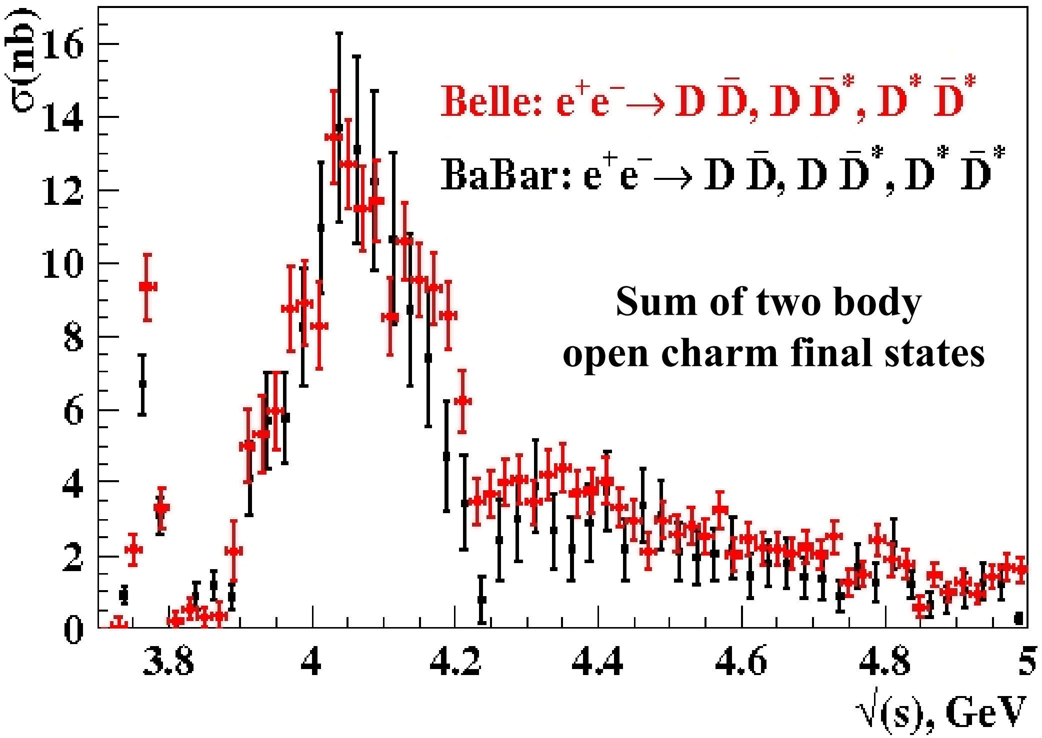
Belle vs BaBar: $\sigma(e^+e^- \to D^{(*)}D^*)$



Phys. Rev. Lett. 98, 092001 (2007)

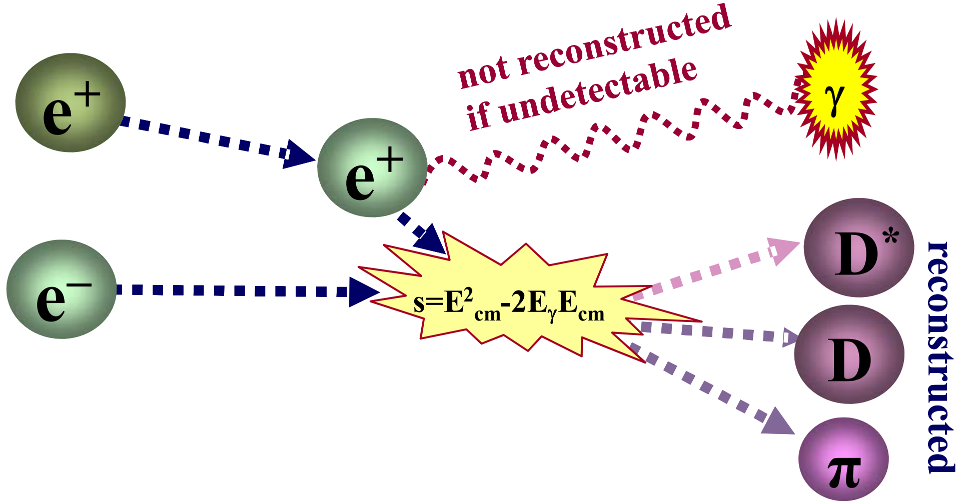
Phys.Rev. D79, 092001(2009)

New



Belle & BaBar results are in very good agreement

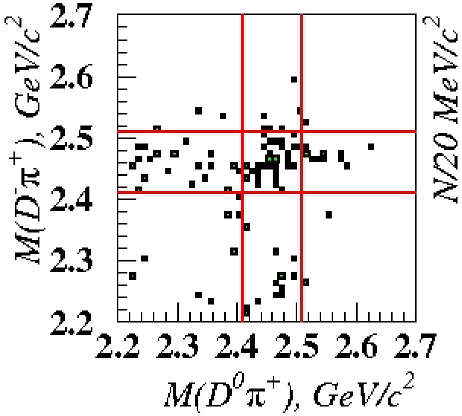
Three-body final states

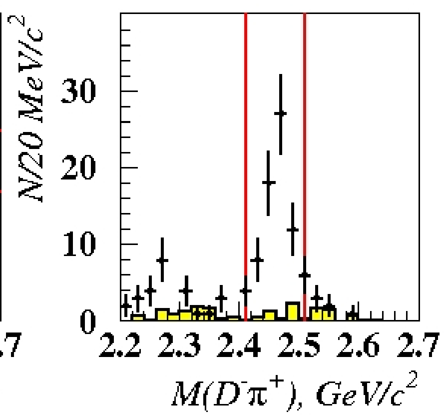


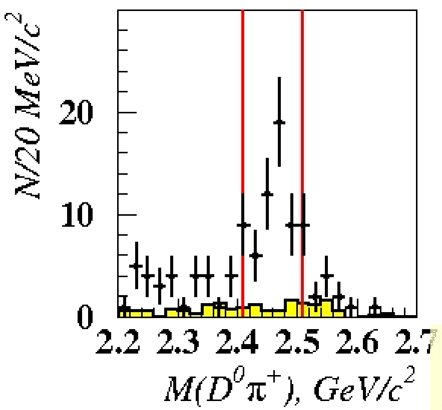
$D^0\, D^{(*)-}\, \pi^+$

- ***Full reconstruction*** **of hadronic part**
- **ISR photon detection is not required**
  - **but used if it is in the detector acceptance**
- **Translate measured $DD^{(*)}\pi$ mass spectrum to cross section**

Resonant structure in $\psi(4415) \to D^0 D^- \pi^+$







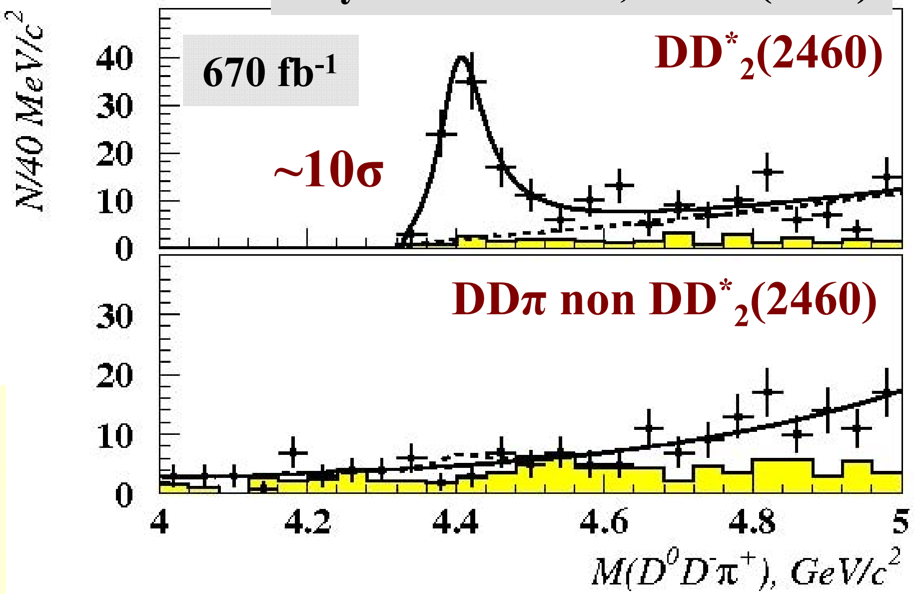
$M(D^0\pi^+)$ vs $M(D^-\pi^+)$ from $\psi(4415)$ region

- **Clear $D^*_2(2460)$ signals**
- **No non-$D^*_2(2460)$ contribution**

$M = 4411 \pm 7$ MeV
$\Gamma_{tot} = 77 \pm 20$ MeV
$N_{ev} = 109 \pm 25$

Consistent with BES,
Phys.Lett.B660,315(2008)
PDG06, Barnes at.al
Phys. Rev. D72, 054026 (2005)

Phys.Rev.Lett.100,062001(2008)

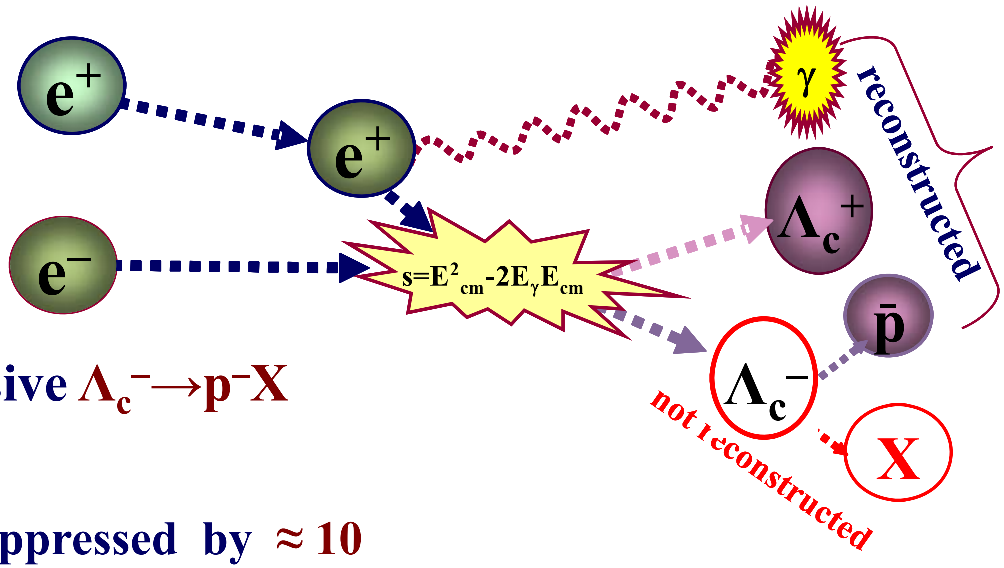


$$\sigma(e^+e^- \to \psi(4415)) \times Br(\psi(4415) \to DD^*_2(2460)) \times Br(D^*_2(2460) \to D\pi) = (0.74 \pm 0.17 \pm 0.07) nb$$

$$Br(\psi(4415) \to D(D\pi)_{non\ D2(2460)}) / Br(\psi(4415) \to DD^*_2(2460)) < 0.22$$

The first charm baryons final state

Partial reconstruction with anti-proton tag

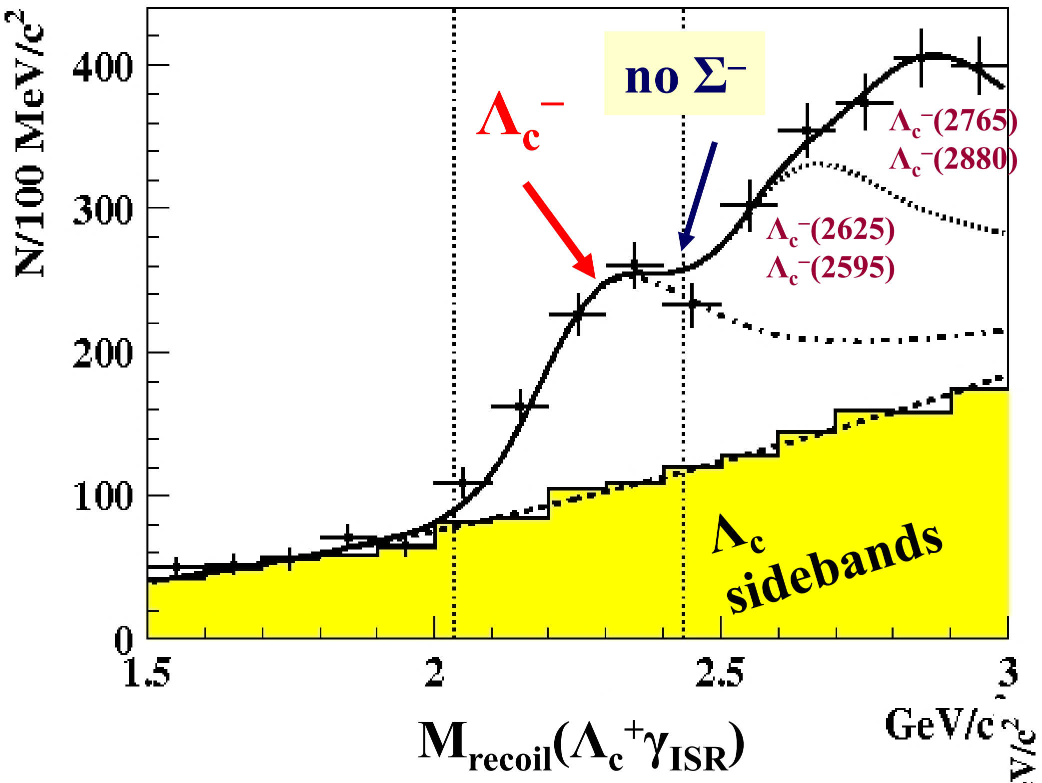


- Reconstruct Λ_c^+
- Use antiproton tag from inclusive $\Lambda_c^- \to p^- X$

  $Br(\Lambda_c^+ \to pX) = (50 \pm 16)\%$

  - combinatorial background suppressed by ≈ 10
- Detect the high energy ISR photon
- Translate measured mass recoil against $\gamma_{ISR} \equiv \Lambda_c^+ \Lambda_c^-$ mass spectrum to cross section

partial reconstruction with $\bar{p}$ tag

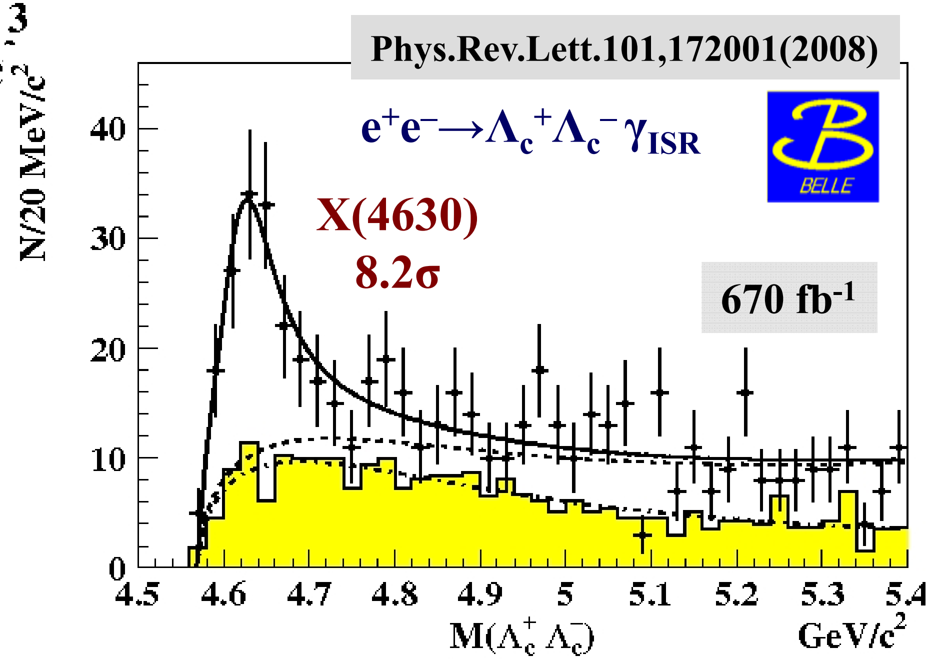


$e^+e^- \to \Lambda_c^+ \Lambda_c^- \gamma_{ISR}$

- Clear peak in $M_{rec}(\Lambda_c^+ \gamma_{ISR})$ distribution at Λ_c mass.

At mass > 2.5 GeV/c²

- contributions from $\Lambda_c^+ \Lambda_c^- \pi^0$
  - *could proceed via $\Lambda_c^+ \Sigma^-$; violates isospin and should be strongly suppressed*
- and $\Lambda_c^+ \Lambda_c^- \pi\ \pi$
  - *could proceed via $\Lambda_c^+ \Lambda_c(2595)^-$, $\Lambda_c^+ \Lambda_c(2625)^-$, $\Lambda_c^+ \Lambda_c(2765)^-$, $\Lambda_c^+ \Lambda_c(2880)^-$*

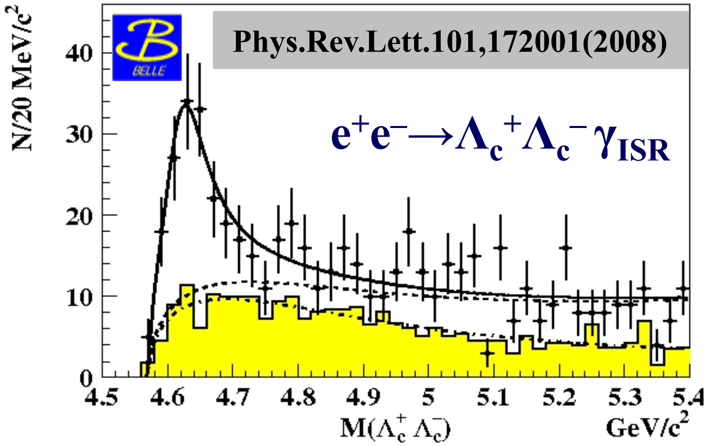


- Total refection contributions < 5% (included in systematics)

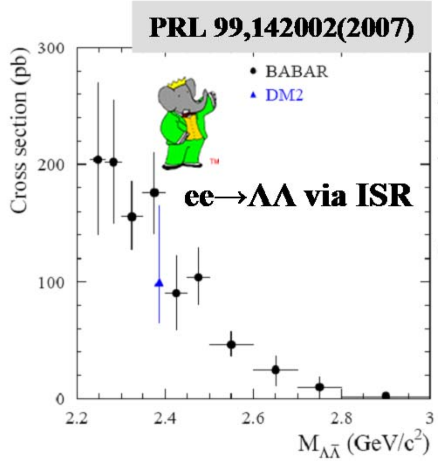
- Look at

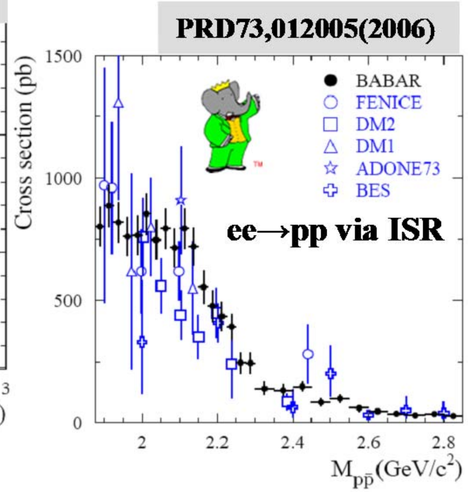
  $M_{recoil}(\gamma_{ISR})$ ≡ Mass spectra of $\Lambda_c^+ \Lambda_c^-$

Interpretations for X(4630)



- no peak-like structure

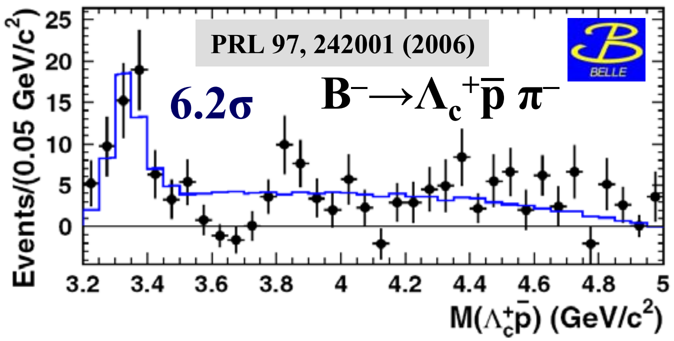




- X(4630) ≡ Y(4660)? $J^{PC}=1^{--}$

State	M, MeV/c^2	Γ_{tot}, MeV
X(4630)	4634^{+8+5}_{-7-8}	92^{+40+10}_{-24-21}
Y(4660)	$4664 \pm 11 \pm 5$	$48 \pm 15 \pm 3$

- dibaryon threshold effect?
  - like in $B\to p\Lambda\pi$, $J/\psi\to\gamma pp$



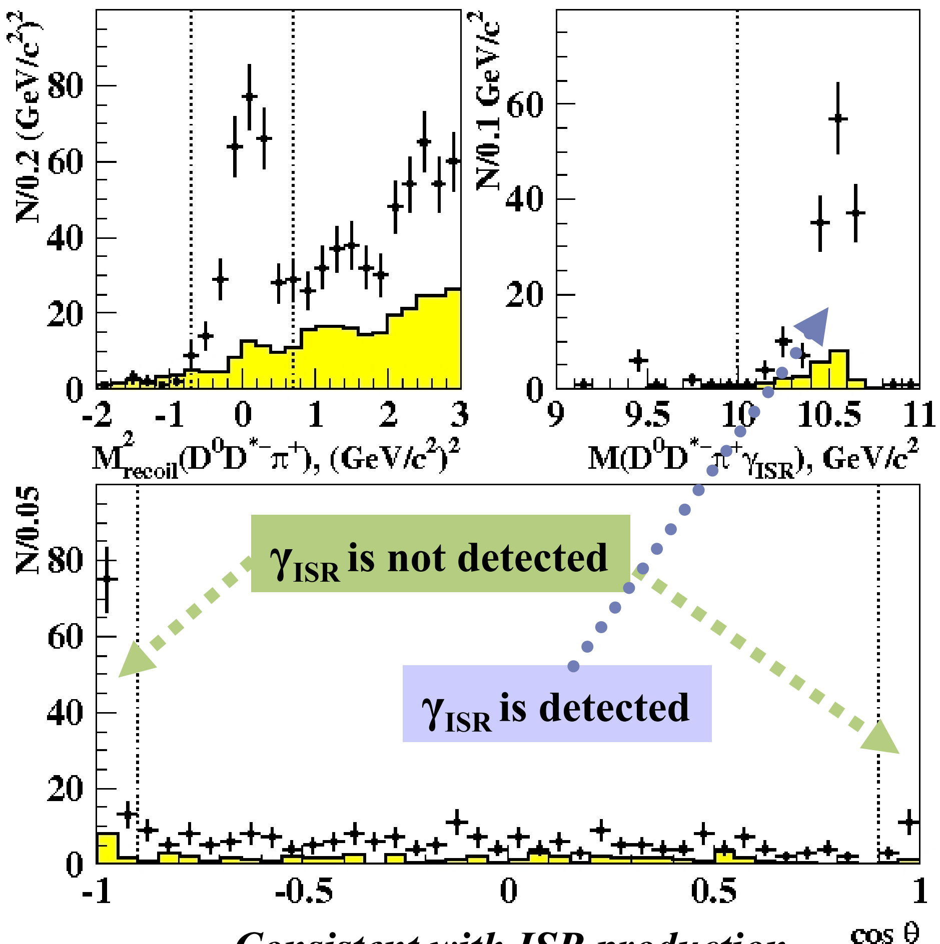
- X(4630) = Y(4660) = charmonium state 5^3S_1 or 4^3D_1 *J.Segovia, A.M.Yasser, D.R.Entem, F.Fernandez*
- Charmonium state 6^3S_1 *B.Q.Li and K.T.Chao*
- Threshold effect *E.Beveren, G.Rupp*
- Y(4660) = $\psi(2S)f_0(980)$ bound state *F.K.Gou, C.Hanhart, S.Krewald, U.G.Meissner*
- Point-like baryons *R.B.Baldini, S.Pacetti, A.Zallo*
- X(4630) = Y(4660) *D.V.Bugg*
- X(4630) = Y(4660) = tetraquark *D.Ebert, R.N.Fausov, V.O. Galkin*

Searching for hybrids via their favorite decay modes

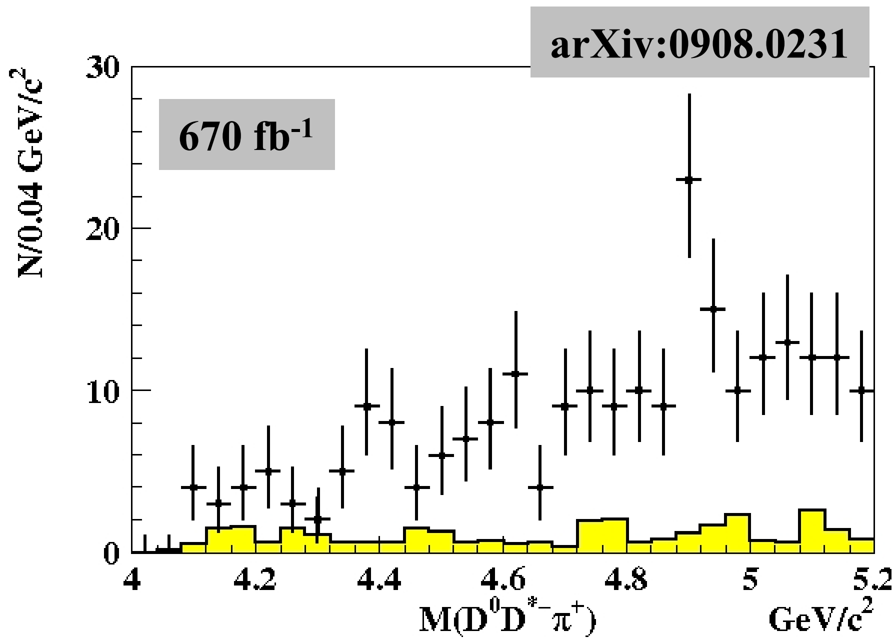
New

$e^+e^- \to D^0D^{*-}\pi^+$ at $\sqrt{s} \sim$ 4–5 GeV via ISR

- Full reconstruction
- No extra tracks
- Detection of γ_{ISR} is not required
  - if γ_{ISR} is detected
  - $M(D^0D^{*-}\pi^+\gamma_{ISR})$ is required ~ E_{cm}



Consistent with ISR production



- Combinatorial bgs are estimated from sidebands D and D^*
- Other bgs are small and taken into account
- *Small efficiency at threshould*

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

$D_1(2420)^0 \to D^{*-}\pi^+ \leftarrow D_2(2460)^0$

$D^0 D^{*-}\pi^+ \leftrightarrow D^0 D_1(2420)^0$ & $D^0 D_2(2460)^0$

$DD^*\pi$ & DD_1 & D^*D_2

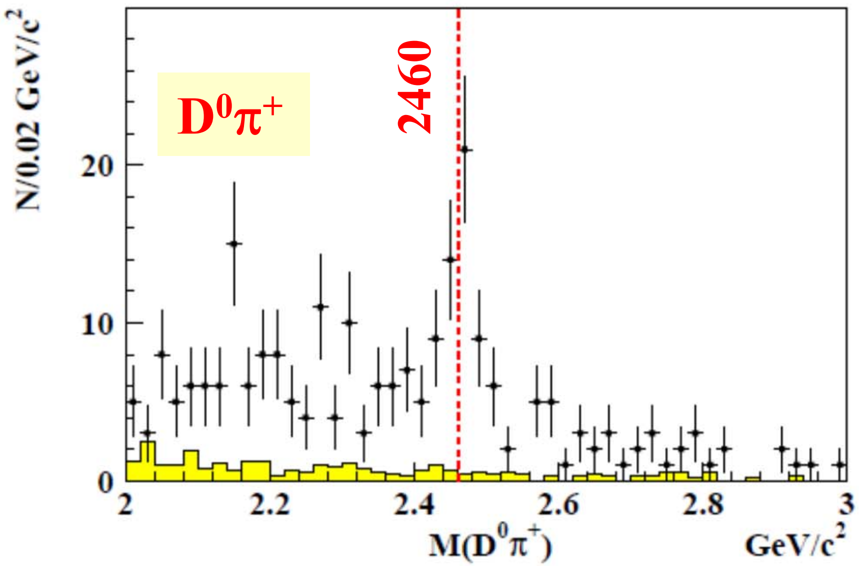
$e^+e^- \to \psi(4415) \to D^0 D_2(2460)^0 \to D^0 D^-\pi^+$ is measured

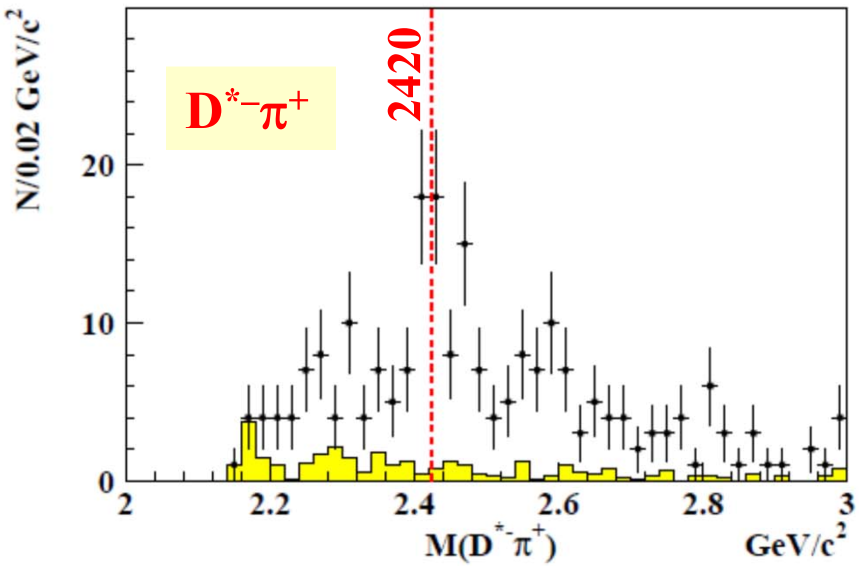
Main problem is to separate $D^0D_1(2420)^0$ from $D^0D_2(2460)^0$

- $D_1(2420)^0$: $\Gamma_{tot} = 20.4 \pm 1.7$ MeV
- $D_2(2460)^0$: $\Gamma_{tot} = 43 \pm 4$ MeV (PDG08)

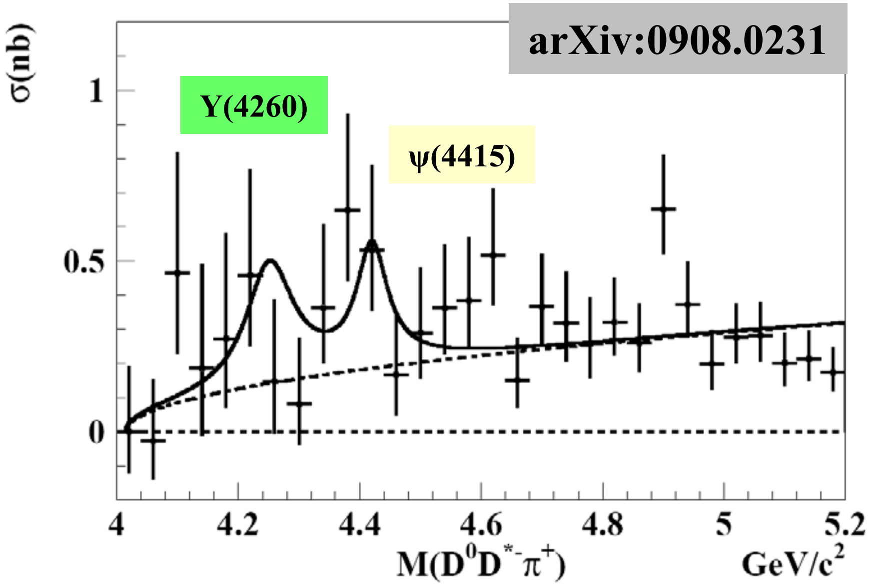
Both DD_1 & D^*D_2 are seen ...

but the statistics is not enough to study their mass spectra!





New Exclusive $e^+e^- \to D^0 D^{*-} \pi^+$ cross-section

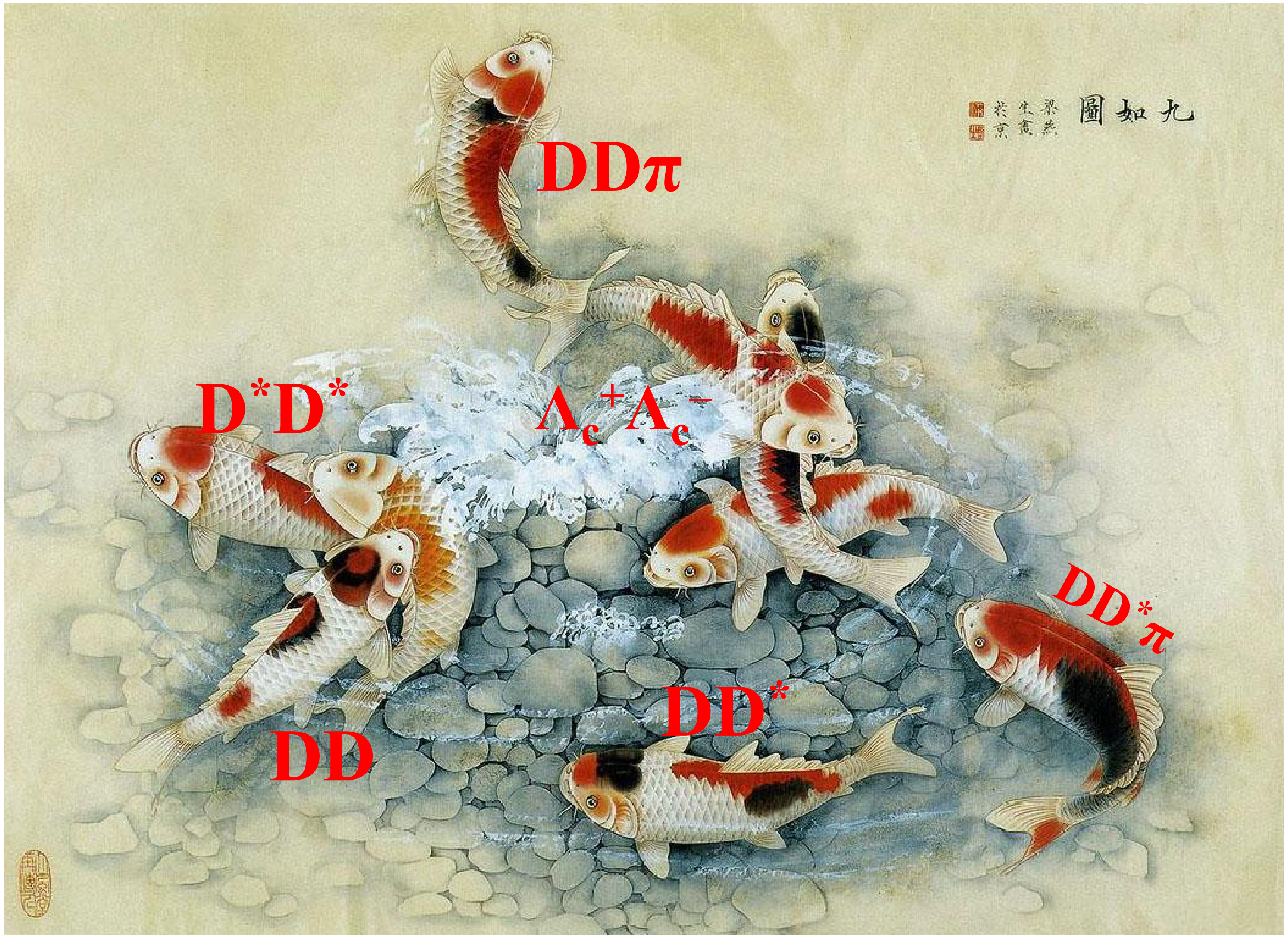


Interference could increase these UL's by factors of 2−4 depending on the final state (for destructive solutions)

- No evident structures: only UL's !
- Baseline fit:
  - RBW for ψ(4415) & threshold function for non-resonant contribution without interference between amplitudes
- To obtain limits on $X \to D^0 D^{*-} \pi^+$, X=Y(4260), Y(4360), Y(4660), X(4630) perform four fits each with one of the X states, ψ(4415) and non-resonant contribution
- Fix masses and total widths from PDG

$\sigma(e^+e^- \to \psi(4415)) \times Br(\psi(4415) \to D^0 D^{*-} \pi^+) < 0.76$ nb at 90% CL
$Br(\psi(4415) \to D^0 D^{*-} \pi^+) < 10.6$ % at 90% CL

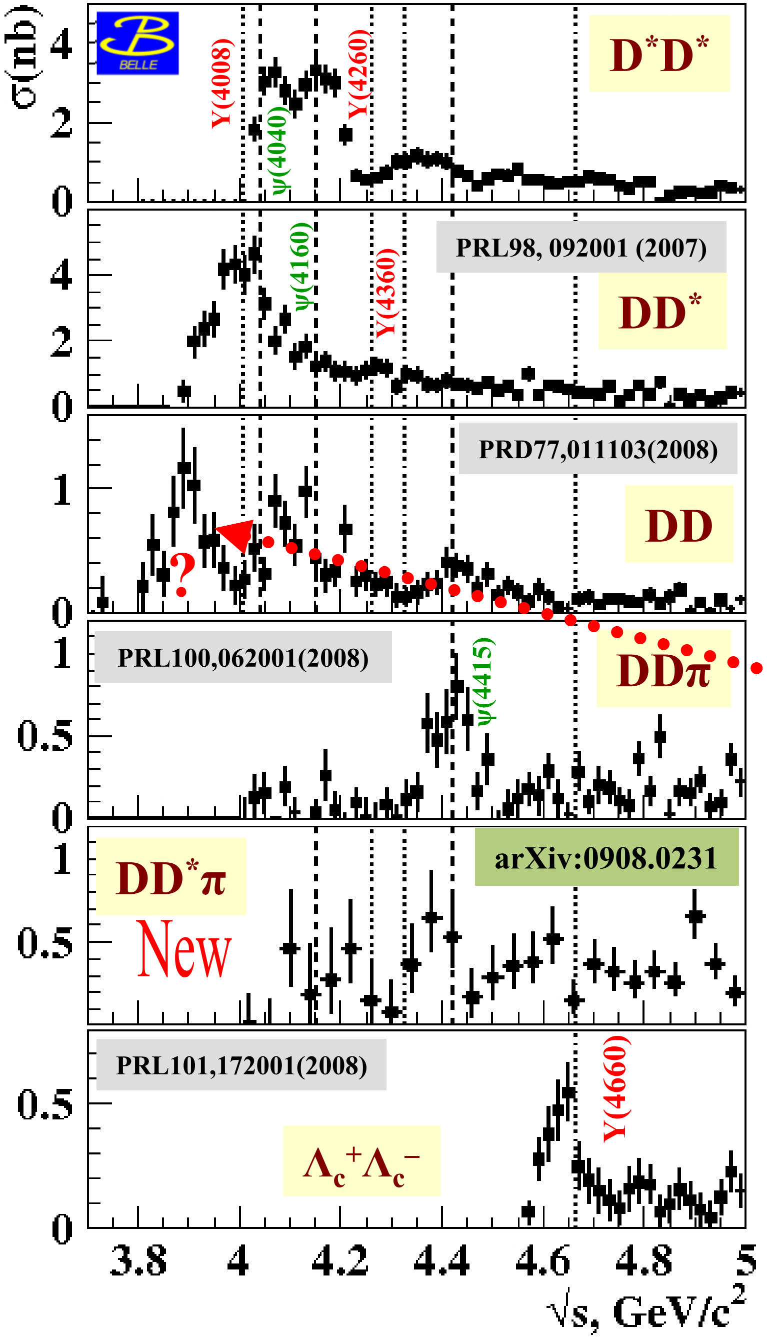
UL at 90% CL	$Y(4260)$	$Y(4350)$	$Y(4660)$	$X(4630)$
$\sigma(e^+e^- \to X) \times \mathcal{B}(X \to D^0 D^{*-} \pi^+)$, [nb]	0.36	0.55	0.25	0.45
$\mathcal{B}_{ee} \times \mathcal{B}(X \to D^0 D^{*-} \pi^+)$, [$\times 10^{-6}$]	0.42	0.72	0.37	0.66
$\mathcal{B}(X \to D^0 D^{*-} \pi^+)/\mathcal{B}(X \to \pi^+\pi^- J/\psi)$	9			
$\mathcal{B}(X \to D^0 D^{*-} \pi^+)/\mathcal{B}(X \to \pi^+\pi^- \psi(2S))$		8	10	



Contribution to the inclusive cross section

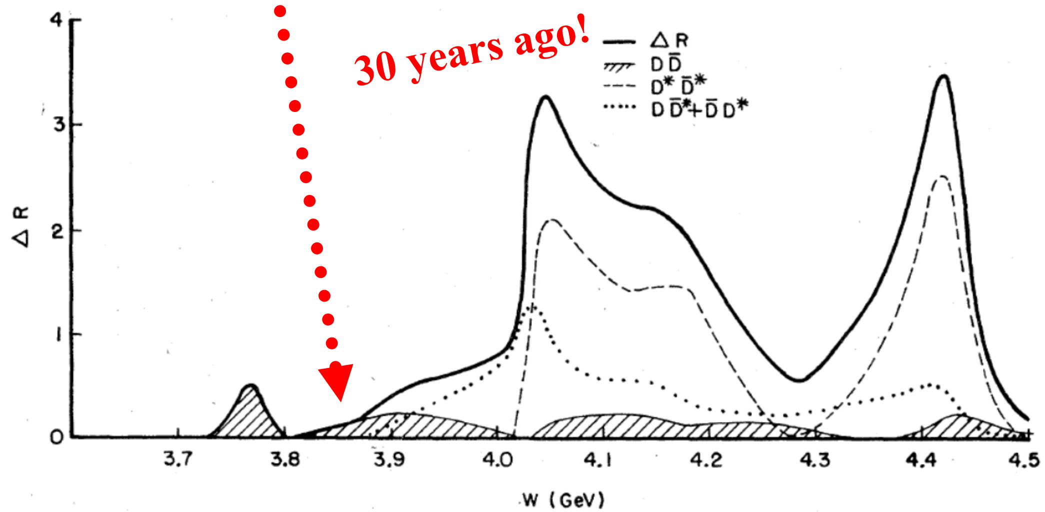
$\sigma(e^+e^- \to$ open charm) via ISR

states vs exclusive cross sections

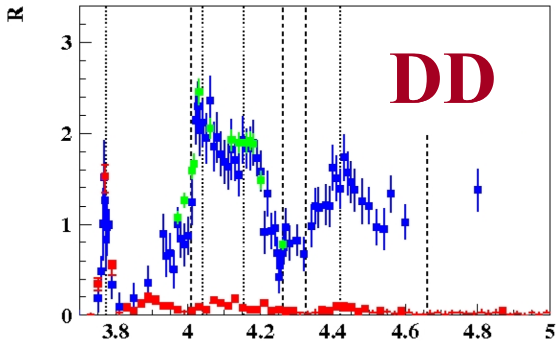


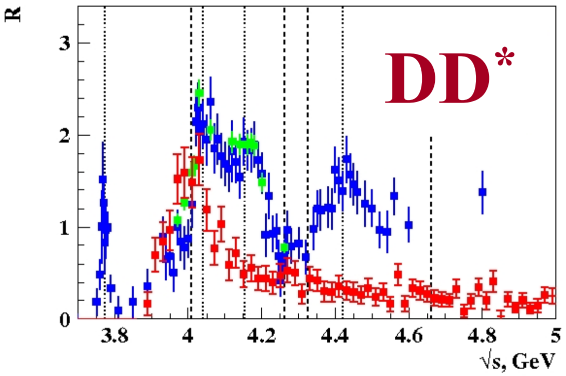
- Y(4008) mass coincides with DD^* peak
- Y(4260) mass corresponds to dip in D^*D^* cross section
- Around Y(4360) mass all measured cross sections are smooth
- Y(4660) mass is close to $\Lambda_c^+\Lambda_c^-$ peak
- Signigicant "peak-like" enhancement near 3.9 GeV in ee→DD

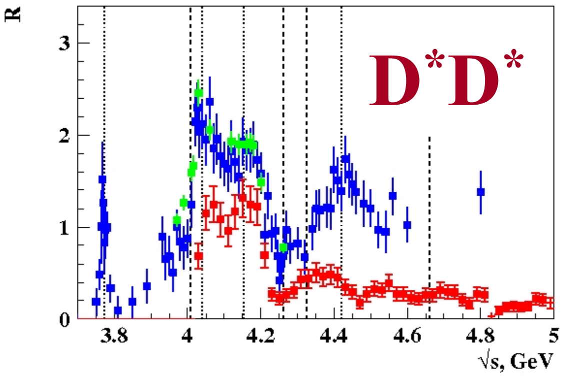
coupled channel effect? or something else?

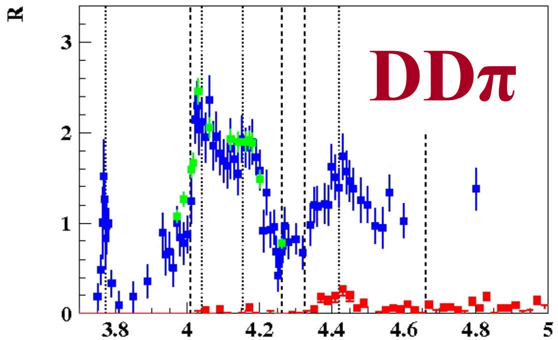


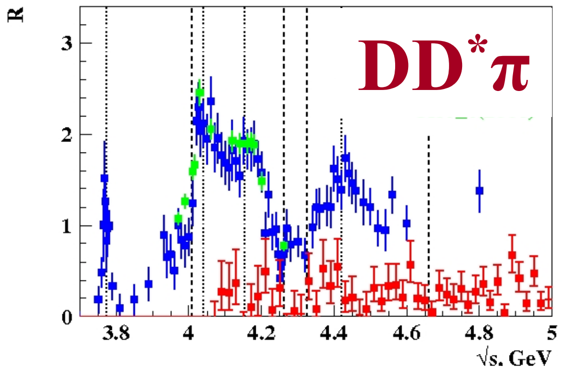
E.Eichten, et al Phys.Rev.D21:203,(1980)

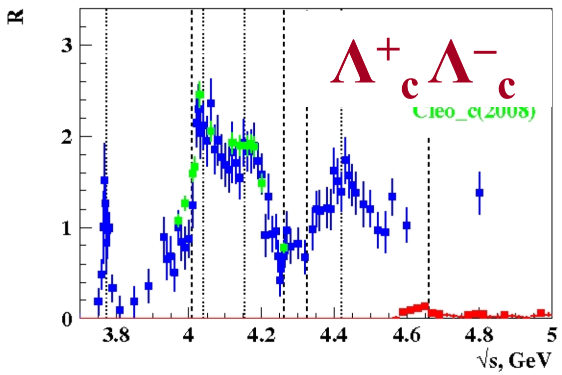




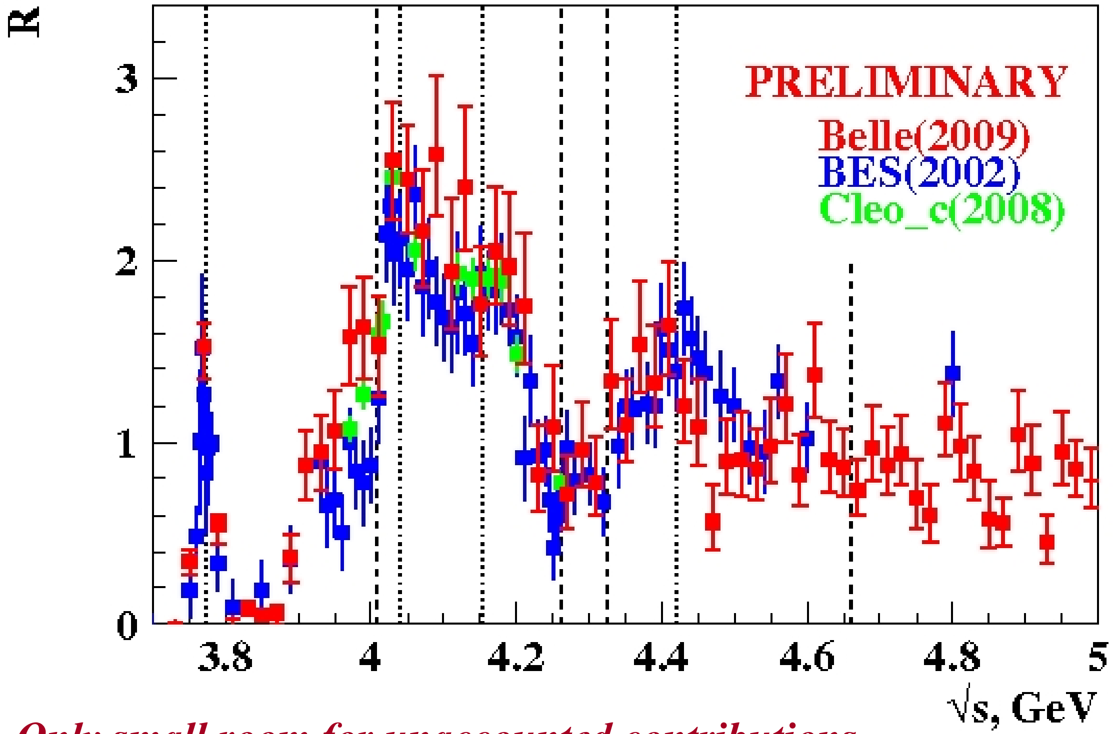








Sum of all exclusive contributions



Only small room for unaccounted contributions

- **Charm strange final states**

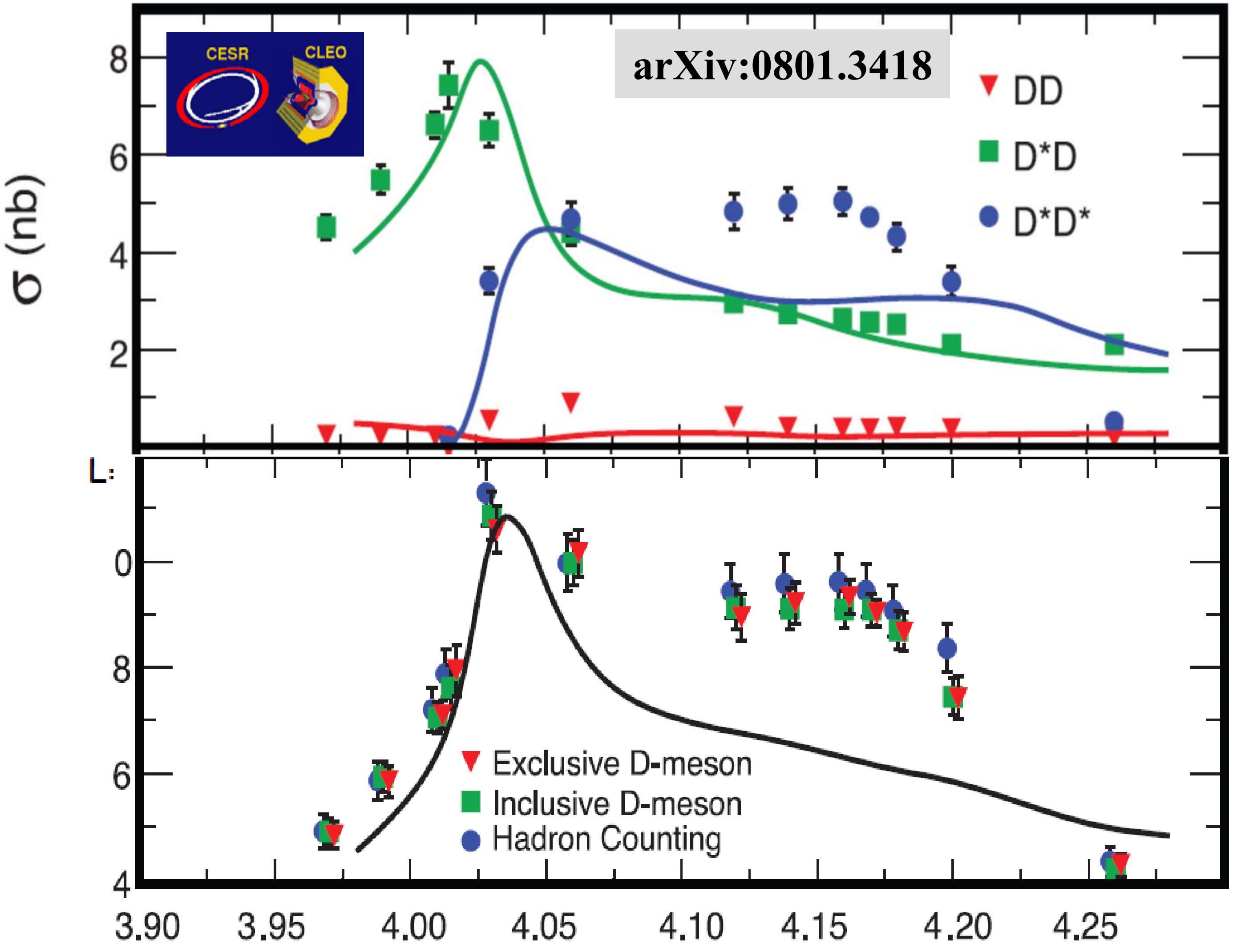
Limited inclusive data above 4.5 GeV

- **Charm baryons final states**

Galina Pakhlova

Cornell Coupled Channel model: R in the threshold region

E.Eichten QWG08



P-wave

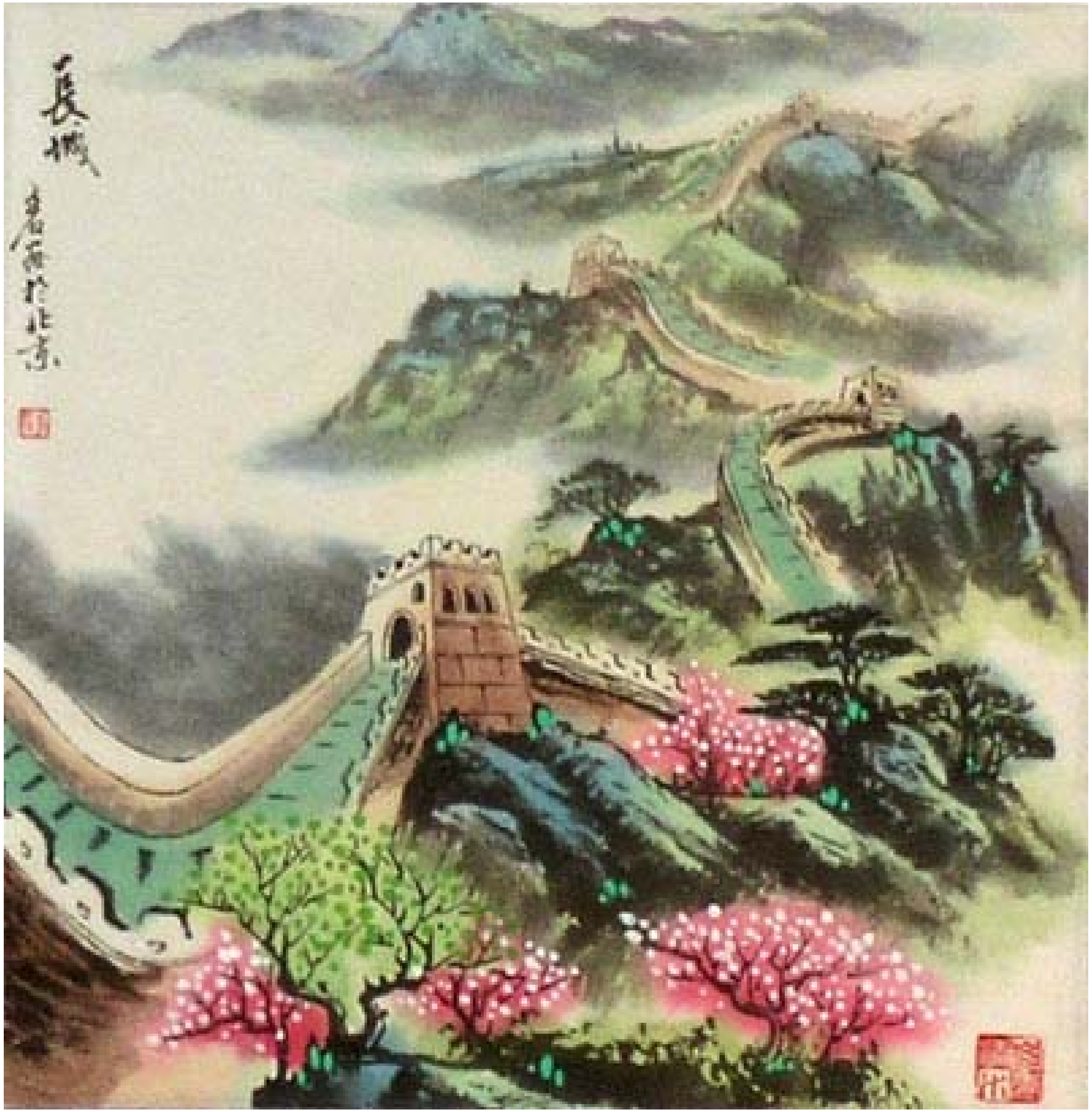
D-wave

S-wave

D-wave

wide D*D(0+),D(*)D′(1+),... S-wave

- Complicated thresholds behaviour
- Need improved model to describe standard and to search for new states



In conclusion

Experiment

For theory

As *Six exclusive open charm final states are measured*
DD, D^*D, D^*D^*, $DD\pi$, $DD^*\pi$, $\Lambda_c\Lambda_c$

and **Their sum is close to $e^+e^- \to$ hadrons**

- **Belle & BaBar & Cleo cross section measurements are nicely consistent with each other**
- ***In charm meson final states no evident peaks corresponding to members of charmonium-like 1^{--} family are found!***
- **$\Lambda_c\Lambda_c$**
  - **enhancement at threshold, quantum numbers, mass and width are consistent with Y(4660)**
    - **Various interpretations**

... it's time to describe these data by realistic common fit and to extract realistic parameters of ψ states ...

Theoretical efforts to describe charm components of inclusive cross section are kindly requested!

All presented cross sections can be found in Durham Data Base

Thank you!