Study of Charmonium-(like) states via ISR at Belle

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(for the Belle collaboration)

IHEP, Beijing

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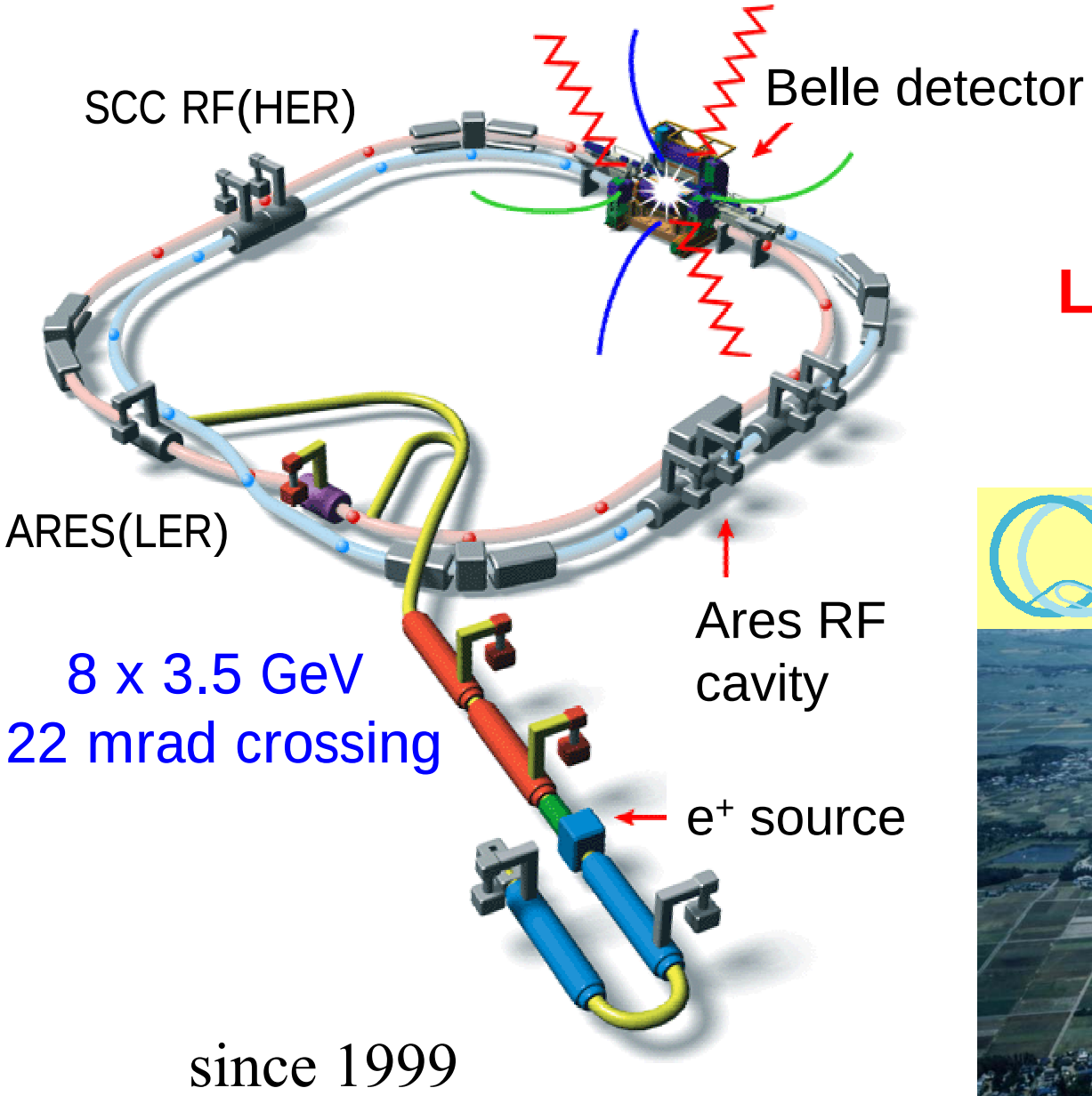
Outline

- Introduction
- Part I: the Y states via $e^+e^- \rightarrow h^+h^-$ + charmonium
  - $e^+e^- \rightarrow \pi^+\pi^- J/\psi$
  - $e^+e^- \rightarrow \pi^+\pi^- \psi(2S)$
  - $e^+e^- \rightarrow K^+K^- J/\psi$
- Part II: the ψ states via $e^+e^- \rightarrow$ charmed meson pair
  - $e^+e^- \rightarrow DD$
  - $e^+e^- \rightarrow DD^*$
  - $e^+e^- \rightarrow D^*D^*$
  - $e^+e^- \rightarrow DD_2(2460)$
- Summary

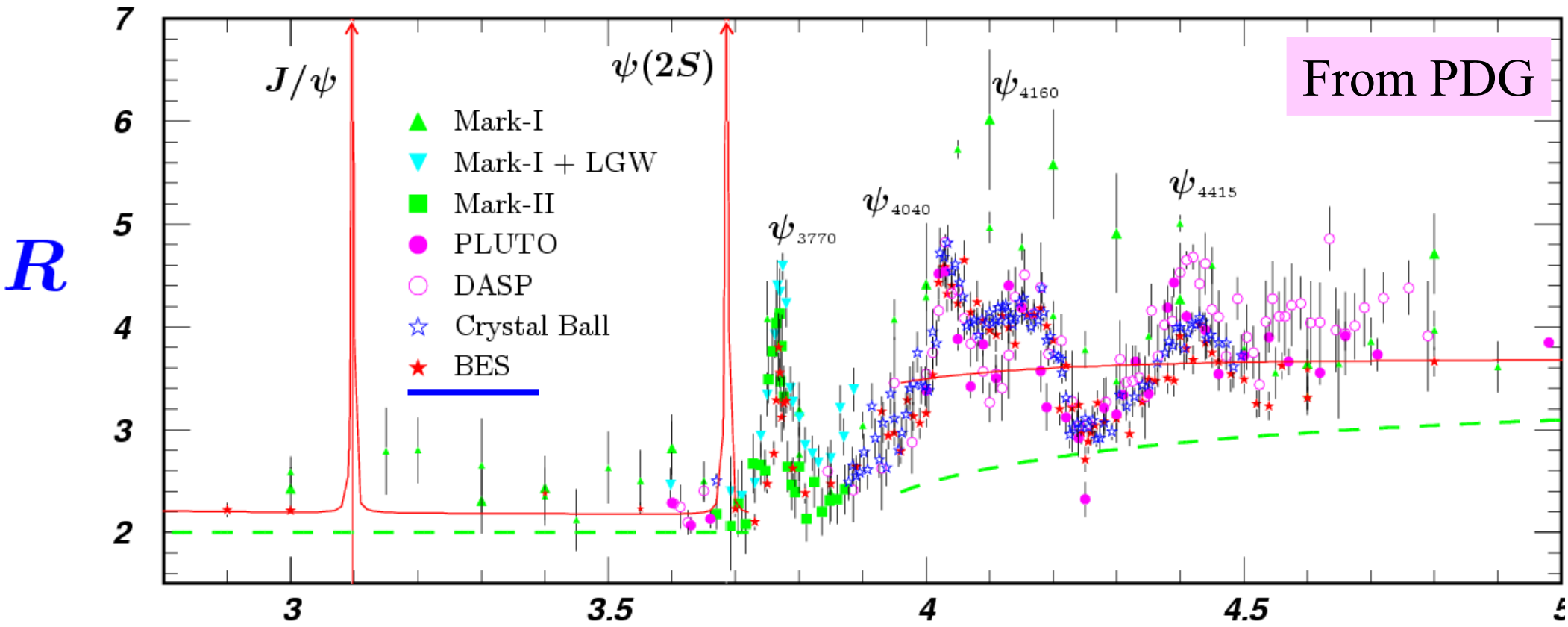
The KEKB Collider

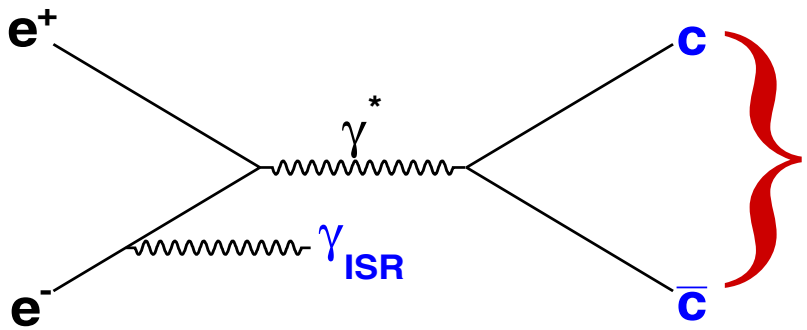


World record:

L = 1.7 x 10^{34}/cm^2/sec

R values/ψ states/Y states





$J^{PC} = 1^{--}$

ψ', ψ'', Y…

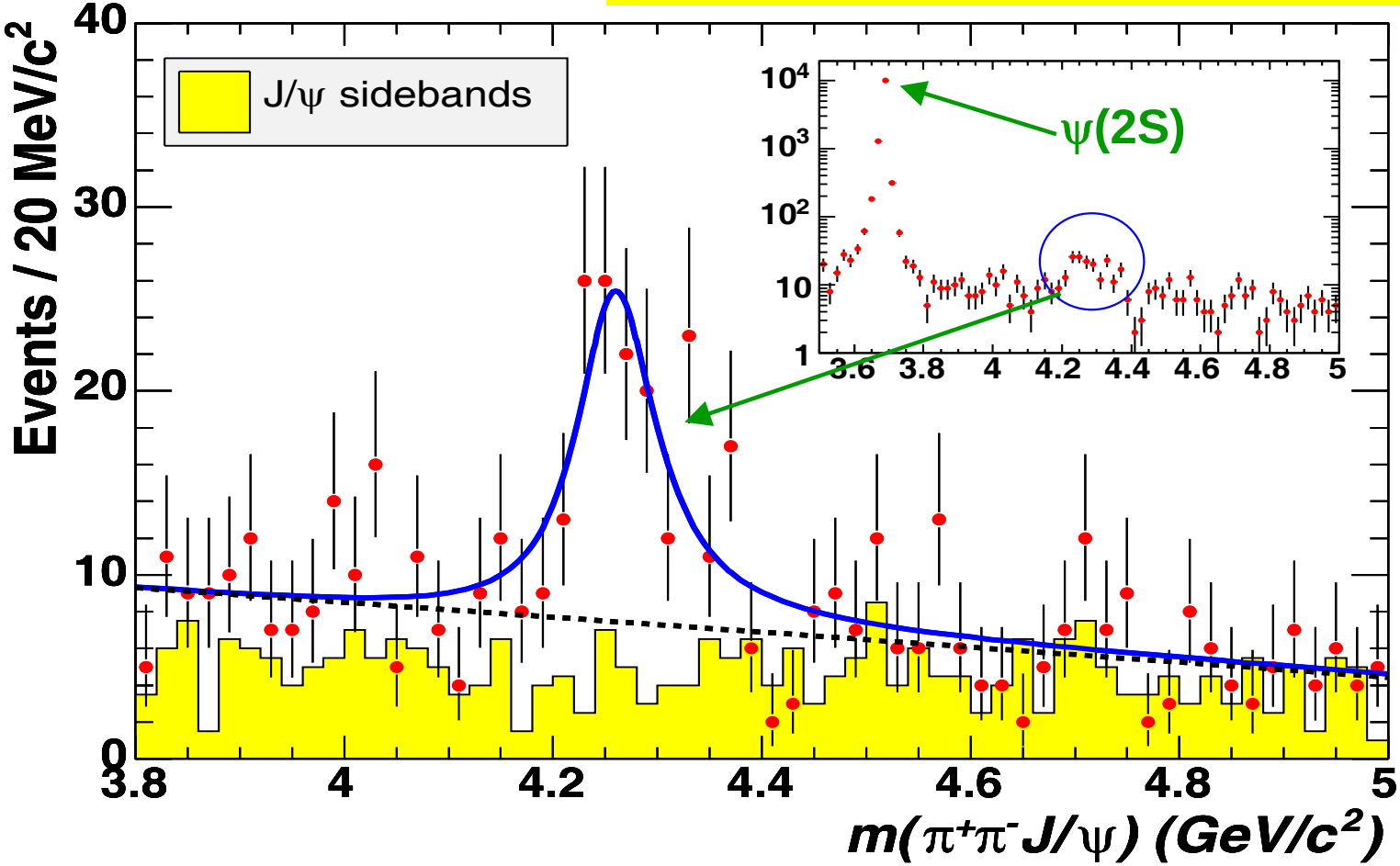
The Y states should also appear in this plot (between 4.0 and 4.7 GeV!)

Part I

Y states via $e^+e^- \rightarrow h^+h^- +$ charmonium

PRL95, 142001 (2005)

$\pi^+\pi^- J/\psi$ Mass



BaBar: 232 fb^{-1}

>8σ significance structure called Y(4260)

M(J/ψππ) of ψ(2S) with J/ψ constraint is well described by Cauchy shape funct.

- fit with Rel-BW × PhaseSpace ⊗ Reso + 2nd polynomial (BKGD)
- fit-probability (χ^2) is about 2.6%, N_{events} = 125±23

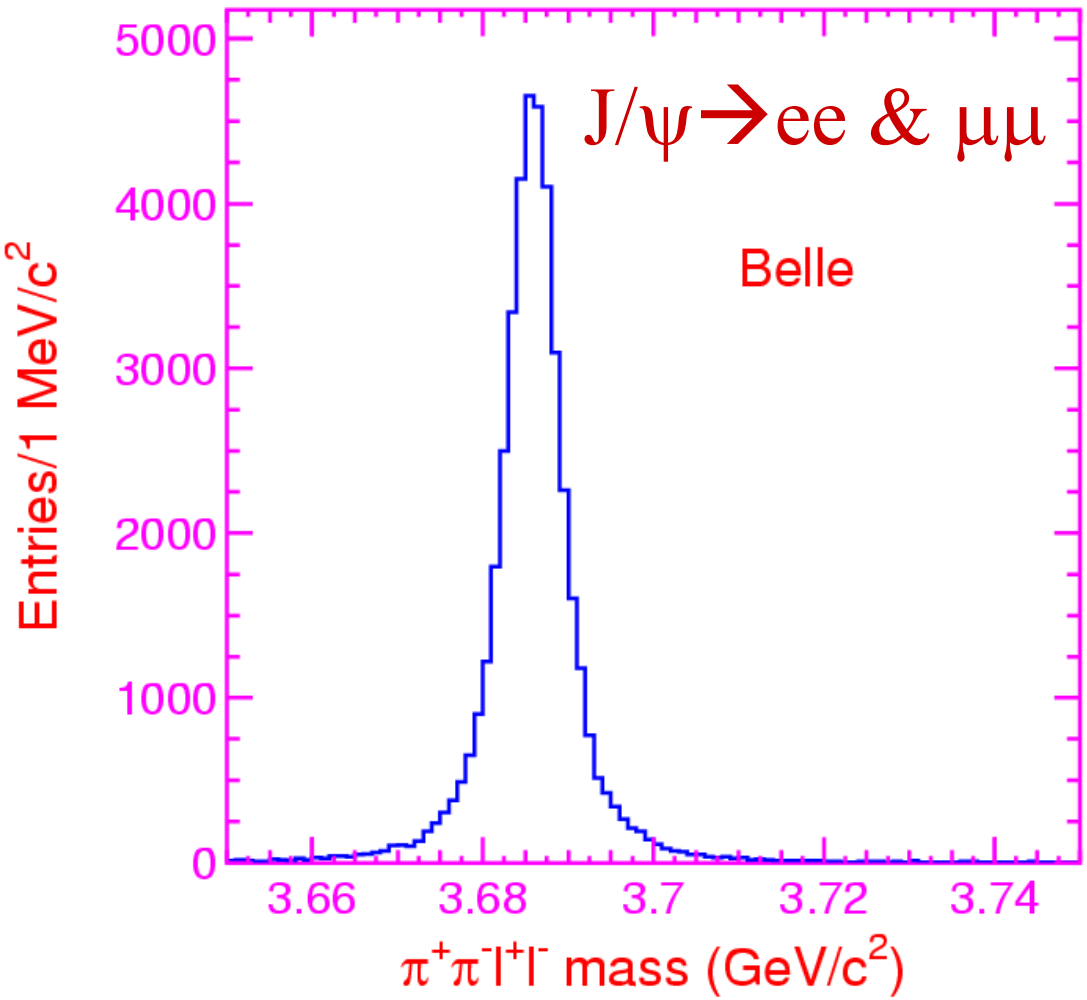
$$m = 4259 \pm 8^{+2}_{-6}\ \text{MeV}$$

$$\Gamma = 88 \pm 23^{+6}_{-4}\ \text{MeV}$$

$$\Gamma(Y \to e^+e^-) \cdot B(Y \to \pi^+\pi^- J/\psi) = 5.5 \pm 1.0^{+0.8}_{-0.7}\ \text{eV}$$

$e^+e^- \rightarrow \psi'$ as reference signal

N^{obs}	Lum (/fb)	Cross section (pb)
15,444	547.8	15.42±0.12±0.89

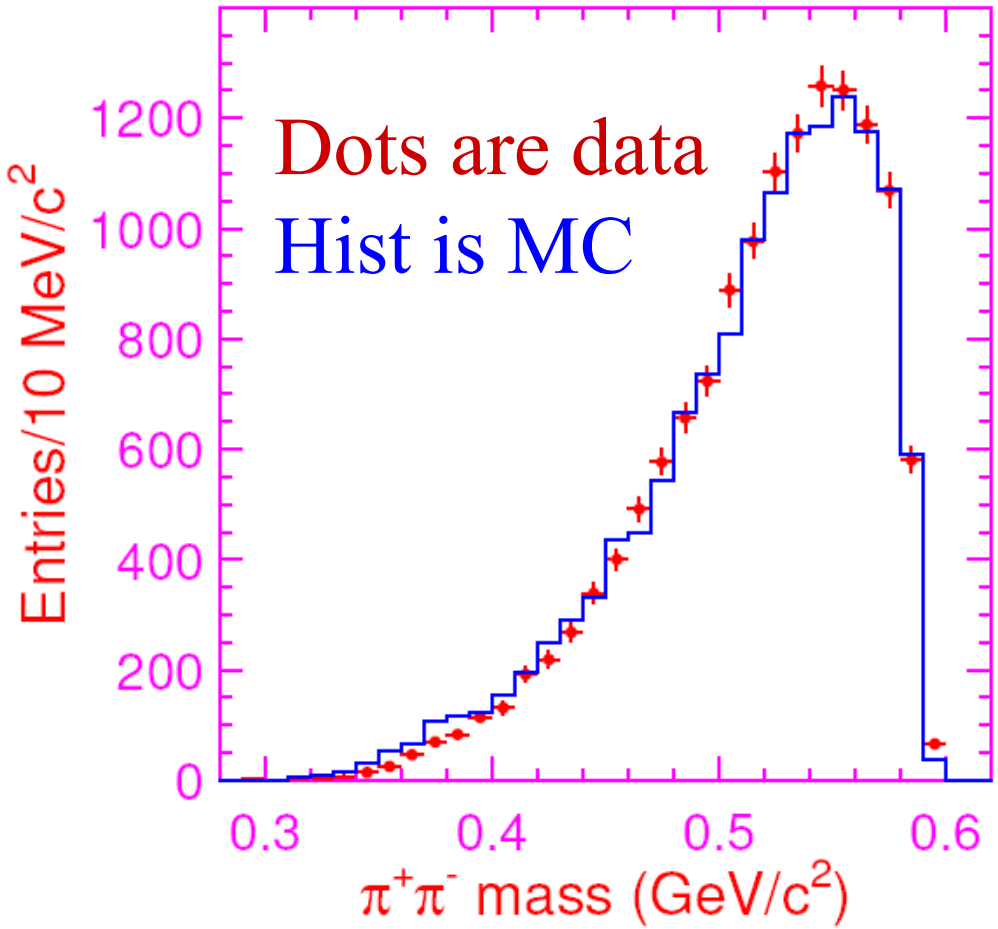


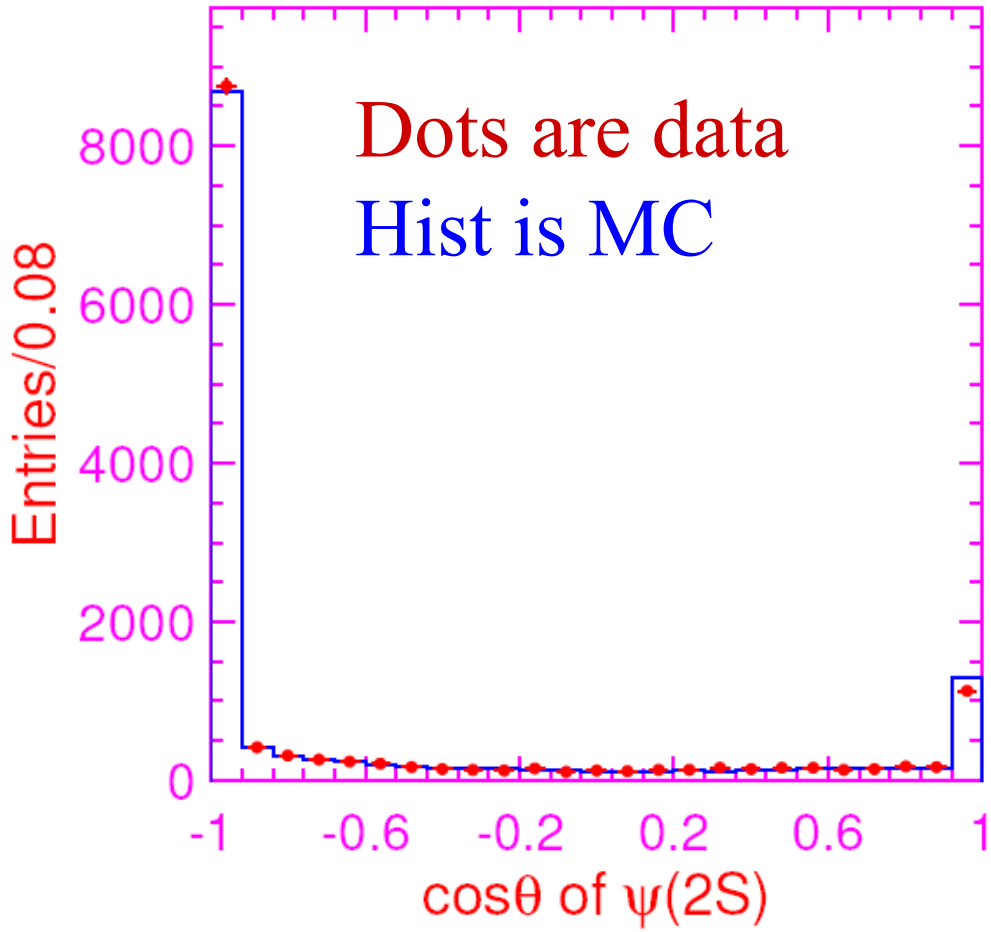
- From cross section, one gets partial width to e^+e^-.
- Γ_{ee}=2.54±0.02±0.15 keV
- PDG'06
  - Γ_{ee}=2.48 ± 0.06 keV
- Belle agrees with other experiments well.

Belle: C.Z.Y & C.P. Shen et al., PRL99, 182004 (2007)

ψ' sample: Data vs MC

We used Phokhara





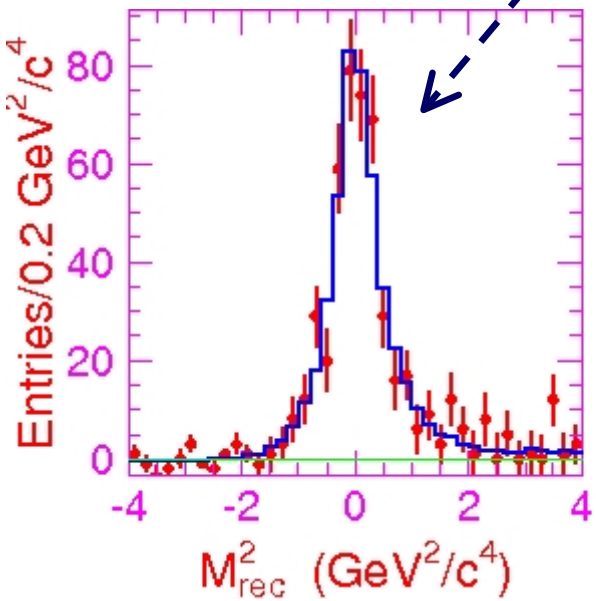
Good agreement between data and MC simulation.

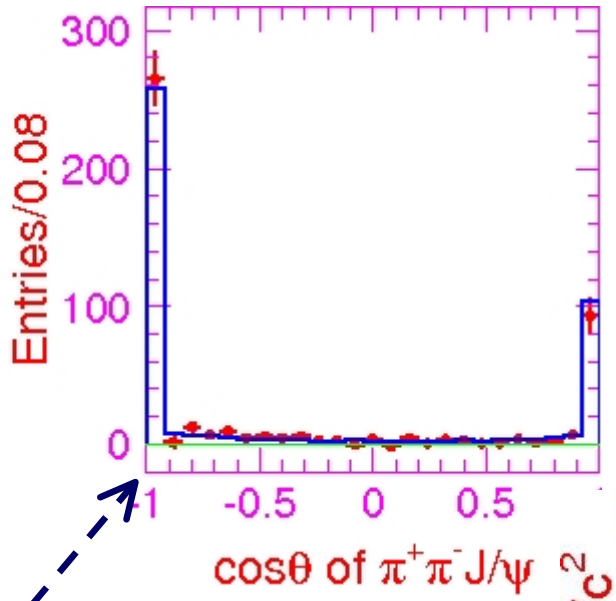
➔(ISR events & background low & MC reliable)

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

Clear signal of missed massless particle (γ_{ISR})

Lum=548 fb^{-1}

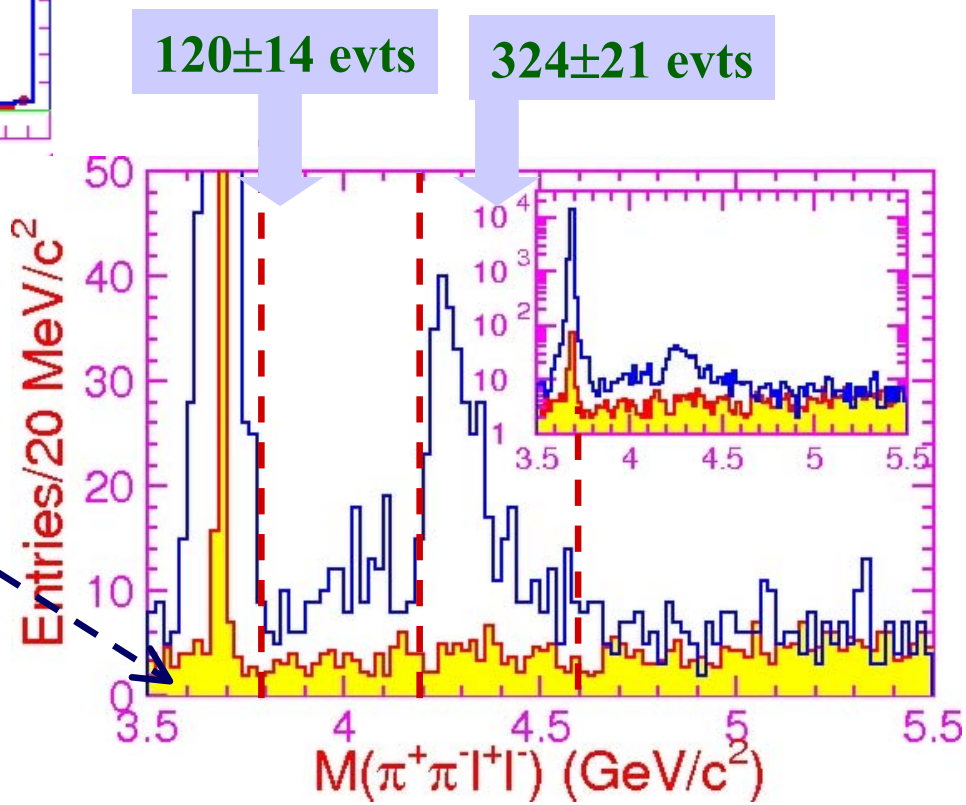




$J/\psi(\to l^+l^-)+\pi\pi$ + no extra tracks

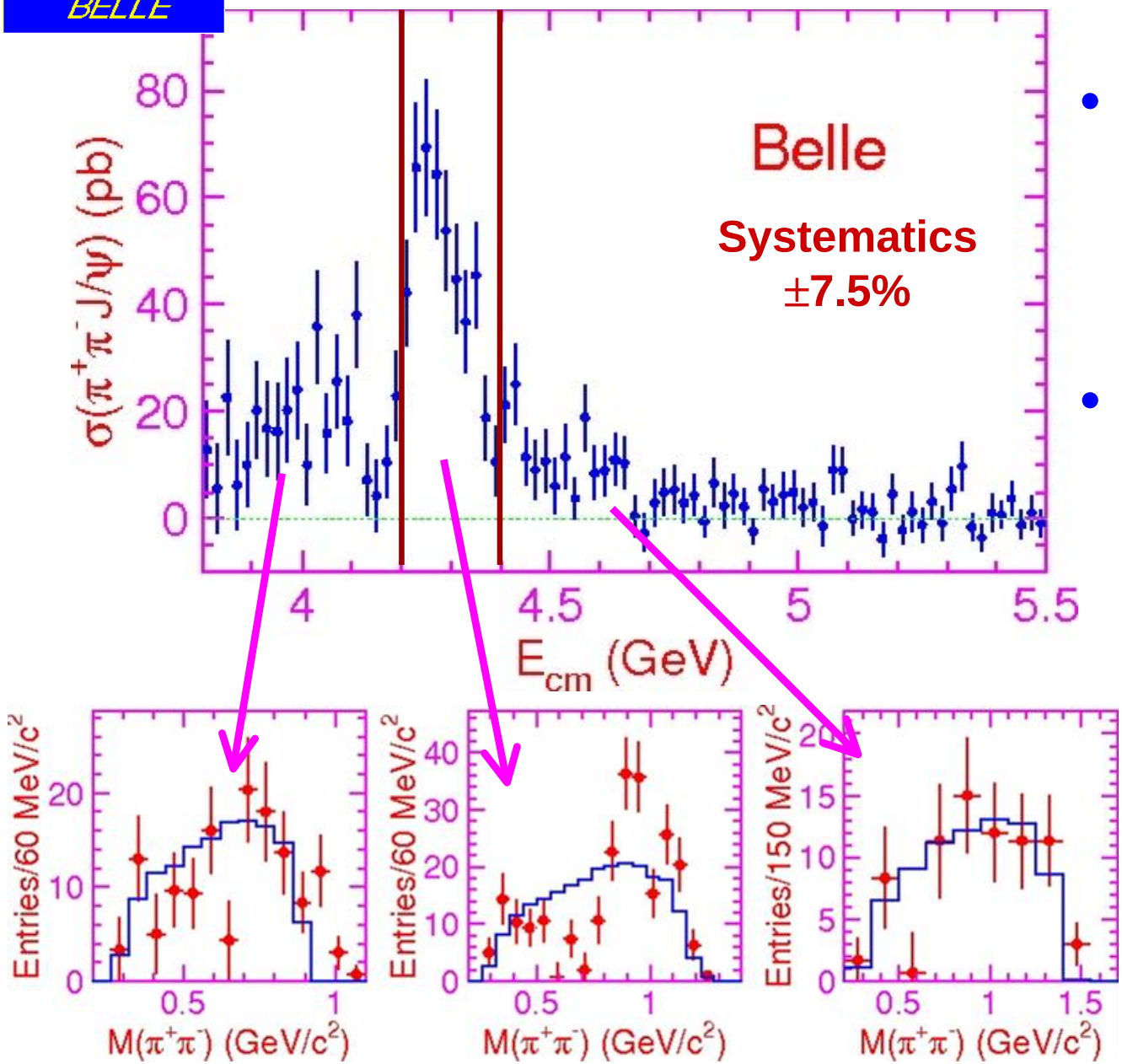
detection of γ_{ISR} is not required

- **Polar angle distribution agrees well with ISR expectation**
- **Combinatorial background estimated by J/ψ sidebands**
- **Backgrounds from real $(J/\psi\ \pi\pi)_{non\ ISR}$ or $J/\psi\ X_{non\ \pi\pi}$ are negligibly small**



Belle: C.Z.Y & C.P. Shen et al., PRL99, 182004 (2007)

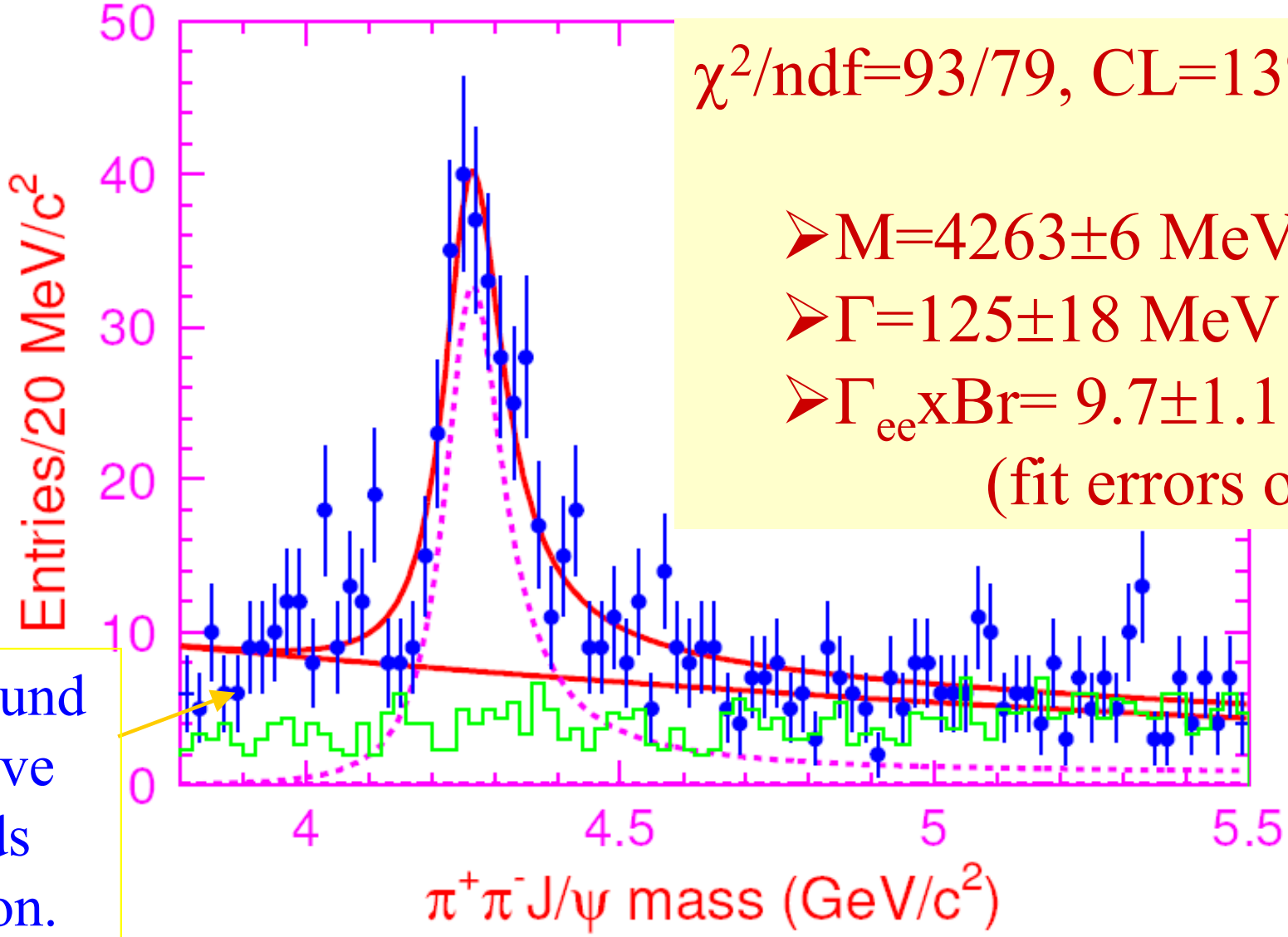
$e^+e^- \to \pi^+\pi^- J/\psi$ via ISR



- **Background subtracted $M(J/\psi\pi\pi)$ corrected for efficiency and differential luminosity**
- **$M_{\pi\pi}$ spectra in different $\sqrt{s}$ regions:**
  - **$\sqrt{s}$ = 3.8 -4.2 & 4.4-4.6 GeV in agreement with 3-body phase space**
  - **Y(4260) region**
    $\sqrt{s}$ = 3.8 -4.15 GeV: two clusters at low and high masses (scalars?)

Belle: C.Z.Y & C.P. Shen et al., PRL99, 182004 (2007)

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



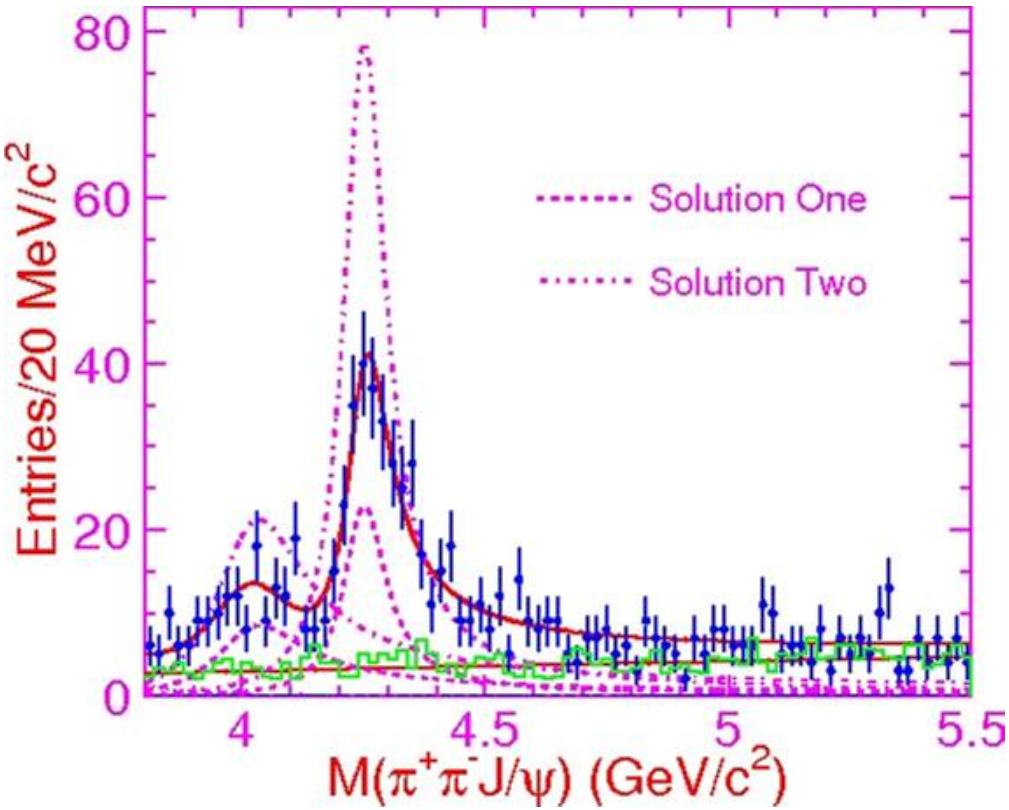
χ^2/ndf=93/79, CL=13%

- M=4263±6 MeV
- Γ=125±18 MeV
- Γ_{ee}xBr= 9.7±1.1 eV (fit errors only)

Background well above sidebands estimation.

Fit with function Babar used. Similar results are got.

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



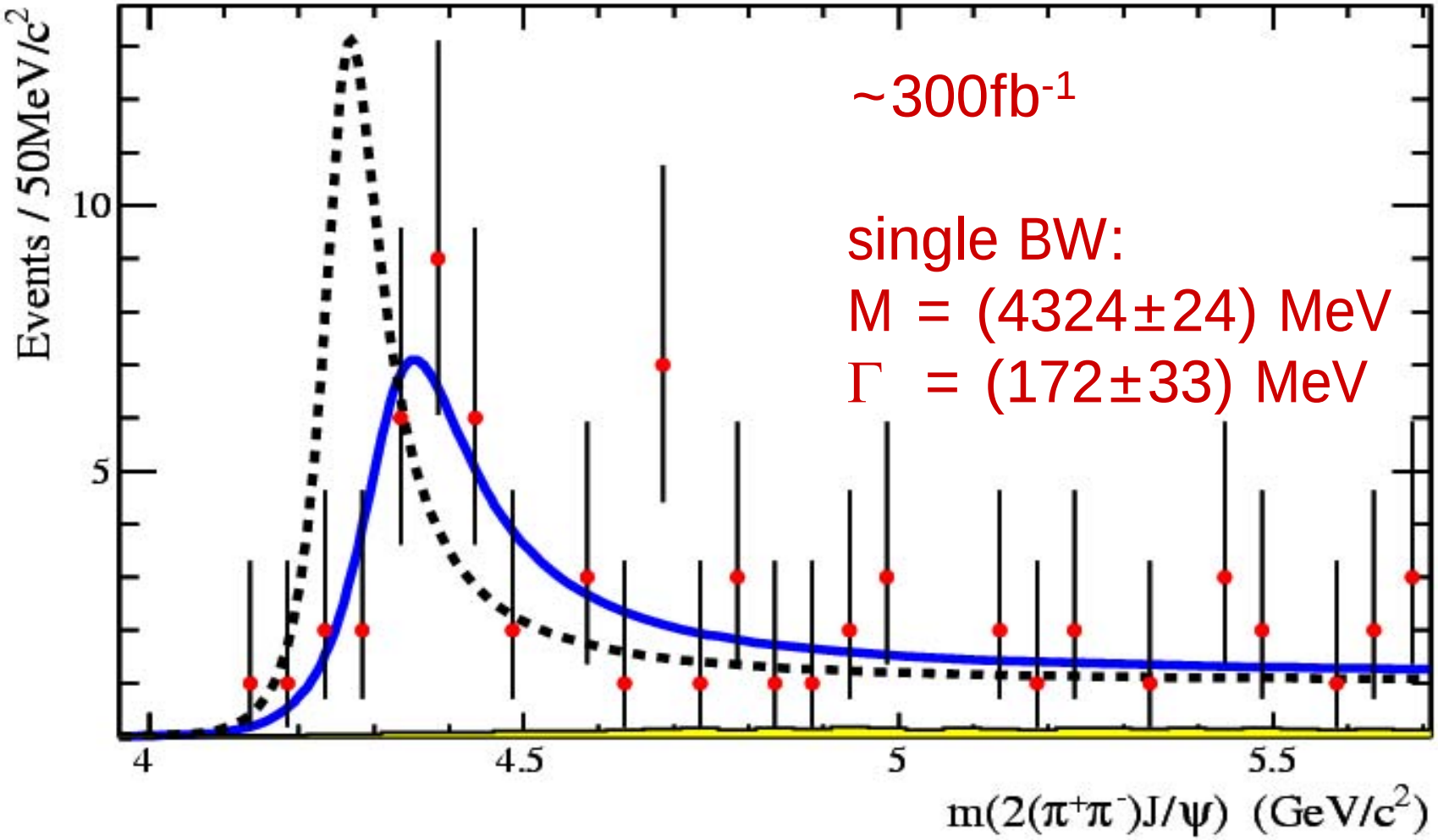
- **Non resonant $J/\psi\pi\pi$?**
- **Re-scattering $ee \to D^{(*)}D^{(*)} \to J/\psi\pi\pi$?**
- **Another broad state ?**
  - **Check the latter hypothesis and influence of interference of Y(4260) with non-Y contribution:**
  - **Fit with 2 coherent BWs**
  - **Two-fold ambiguity in amplitude (constructive-destructive interference) + model uncertainty due to ψ' tail**

Parameters	Solution I	Solution II
$M(R1)$	$4008 \pm 40^{+114}_{-28}$	
$\Gamma_{\rm tot}(R1)$	$226 \pm 44 \pm 87$	
$\mathcal{B}\cdot\Gamma_{e^+e^-}(R1)$	$5.0 \pm 1.4^{+6.1}_{-0.9}$	$12.4 \pm 2.4^{+14.8}_{-1.1}$
$M(R2)$	$4247 \pm 12^{+17}_{-32}$	
$\Gamma_{\rm tot}(R2)$	$108 \pm 19 \pm 10$	
$\mathcal{B}\cdot\Gamma_{e^+e^-}(R2)$	$6.0 \pm 1.2^{+4.7}_{-0.5}$	$20.6 \pm 2.3^{+9.1}_{-1.7}$
ϕ	$12 \pm 29^{+7}_{-98}$	$-111 \pm 7^{+28}_{-31}$

2-BW fit with interference better describes the data: Y(4260) parameters are different (especially peak cross section – large uncertainty)

Belle: C.Z.Y & C.P. Shen et al., PRL99, 182004 (2007)

$e^+e^- \to \pi^+\pi^-\psi(2S)$ via ISR at BaBar



BaBar: B. Aubert et al., PRL98, 212001 (2007)

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

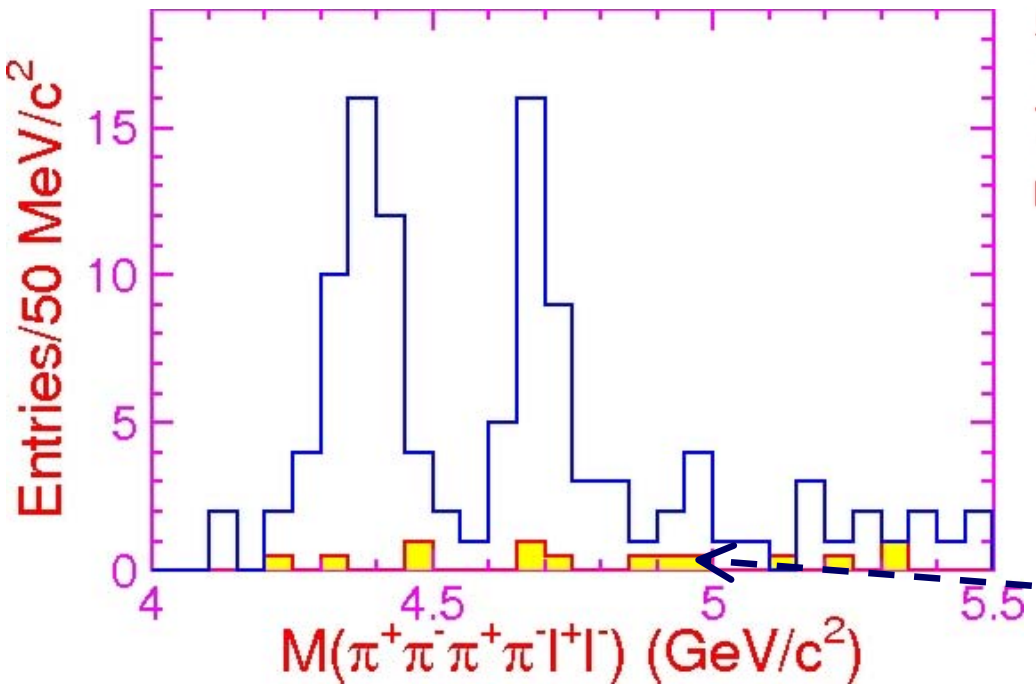
673 fb^{-1}

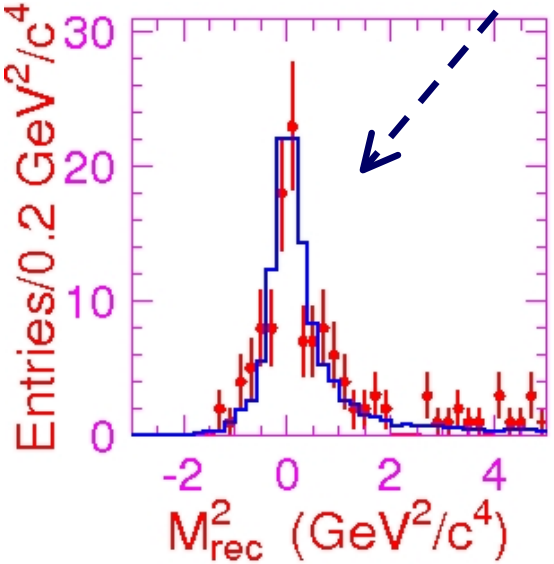
- Clear signal of missed massless particle ($M_{rec}^2(\psi'\pi\pi)\sim 0$)

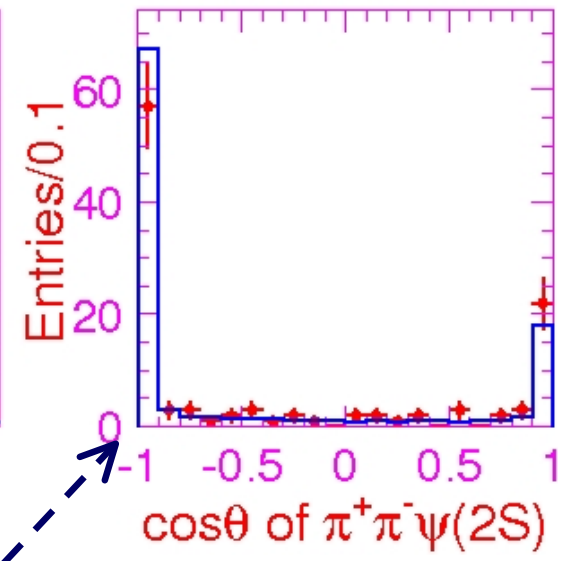
$\psi(\to J/\psi\ \pi\pi)$ + $\pi\pi$ + no extra tracks

detection of γ_{ISR} is not required

Similar analysis: efficiency is smaller; bgs are almost negligible





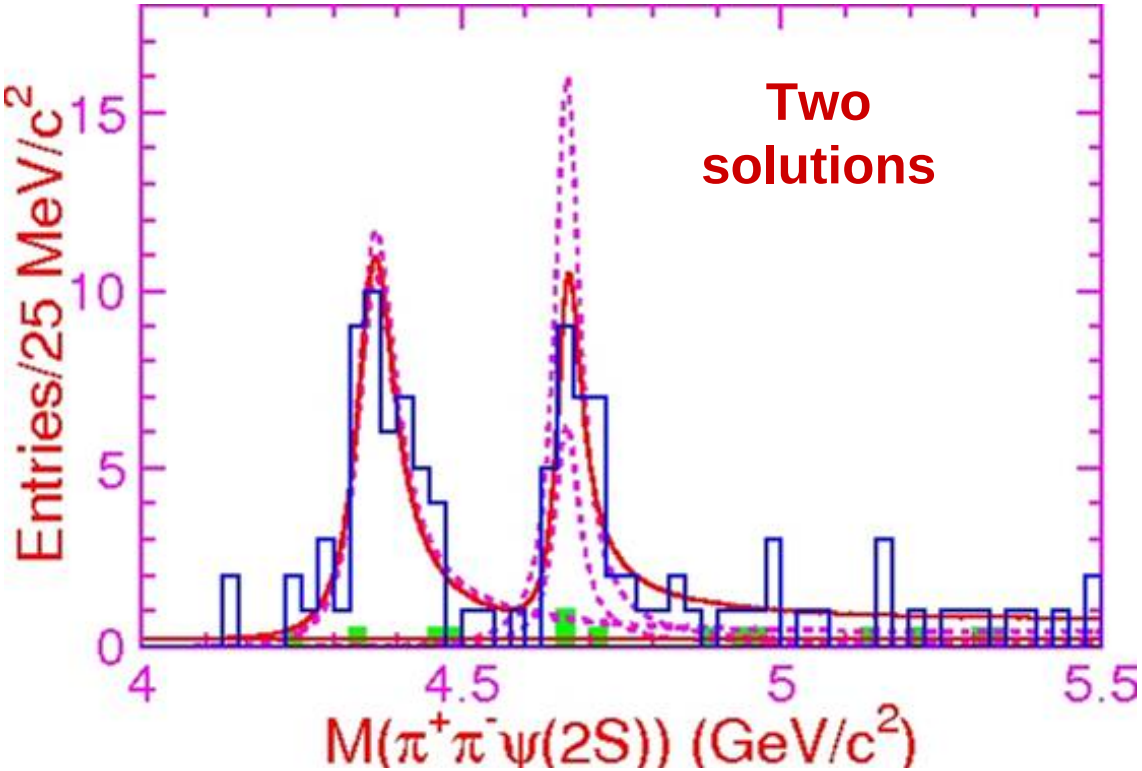


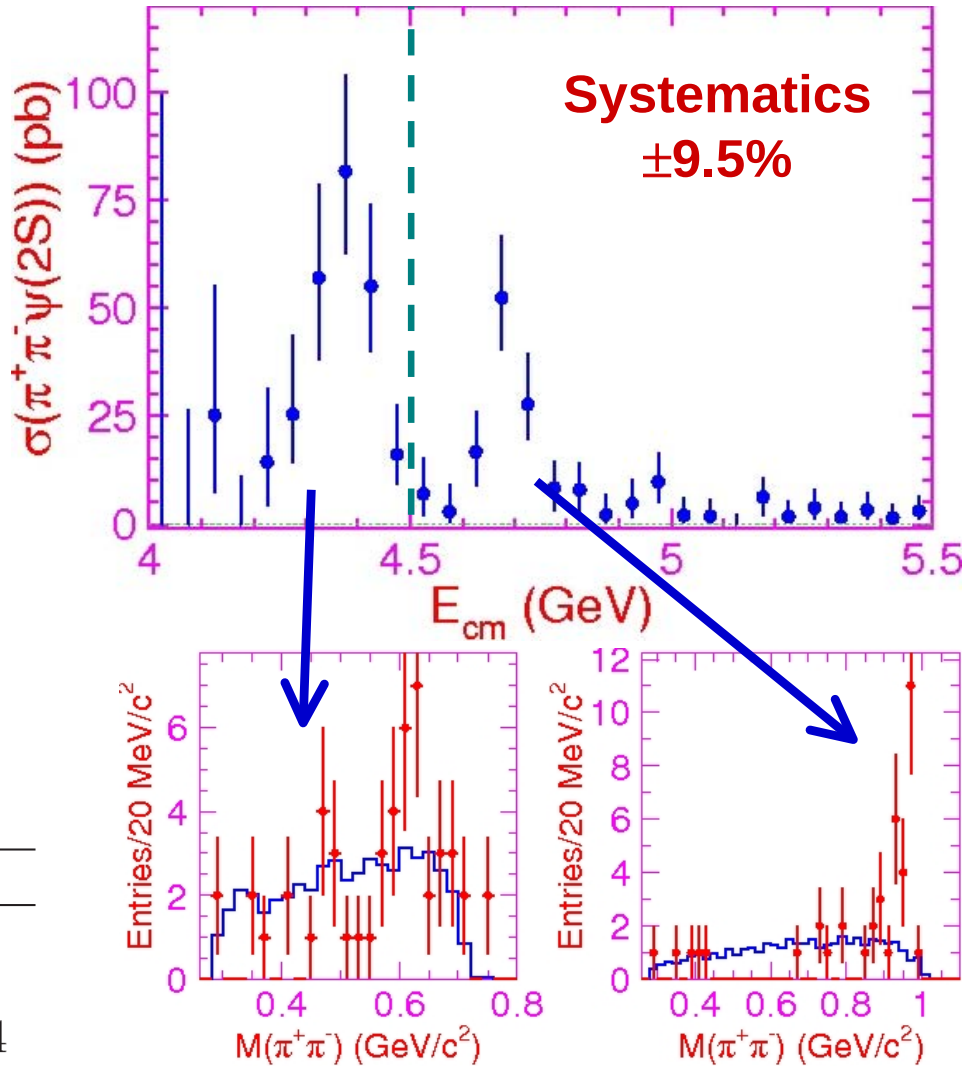
- Polar angle distribution agrees well with ISR expectation
- Combinatorial background estimated by ψ' sidebands
- Backgrounds from real $(\psi'\pi\pi)_{non\ ISR}$ or $\psi' X_{non\ \pi\pi}$ are negligibly small

Two significant clusters: One is near BaBar reported enhancement PRL98, 212001 (2007) + NEW at M~ 4.7 GeV

Belle: X.L. Wang & C.Z.Y et al., PRL99, 142002 (2007)

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





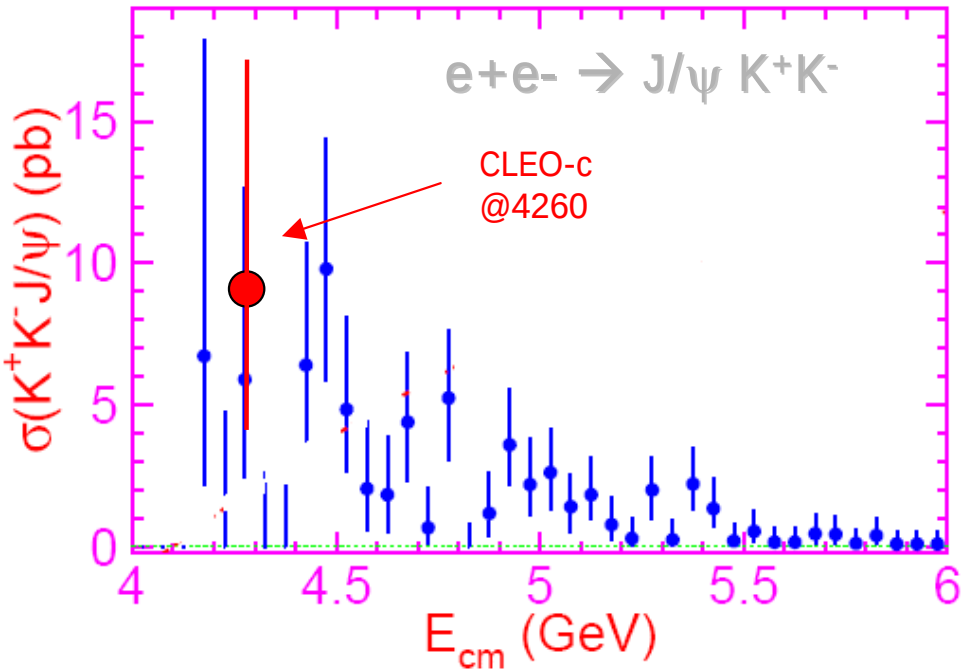
Parameters	Solution one	Solution two
$M(Y(4360))$	$4361 \pm 9 \pm 9$	
$\Gamma_{\rm tot}(Y(4360))$	$74 \pm 15 \pm 10$	
$\mathcal{B} \cdot \Gamma_{e^+e^-}(Y(4360))$	$10.4 \pm 1.7 \pm 1.5$	$11.8 \pm 1.8 \pm 1.4$
$M(Y(4660))$	$4664 \pm 11 \pm 5$	
$\Gamma_{\rm tot}(Y(4660))$	$48 \pm 15 \pm 3$	
$\mathcal{B} \cdot \Gamma_{e^+e^-}(Y(4660))$	$3.0 \pm 0.9 \pm 0.3$	$7.6 \pm 1.8 \pm 0.8$
ϕ	$39 \pm 30 \pm 22$	$-79 \pm 17 \pm 20$

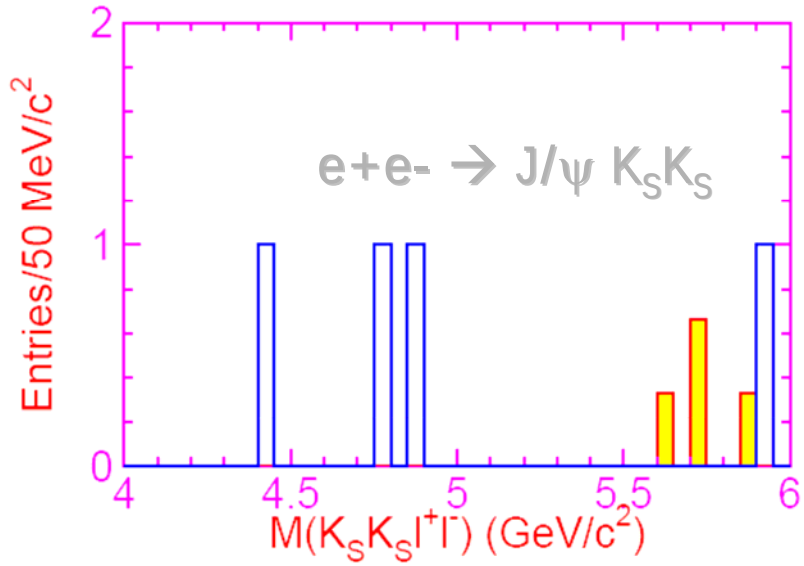
Y(4360) – consistent with BaBar
Y(4660) – NEW (5.8σ)

Belle: X.L. Wang & C.Z.Y et al., PRL99, 142002 (2007)

$e^+e^- \rightarrow K^+K^-J/\psi$ via ISR

- CLEO-c observed 3 K^+K^-J/ψ at Ecm=4.26 GeV and assumed from Y(4260)
- Belle : first observation of $e^+e^- \rightarrow J/\psi\ K^+K^-$ and evidence for $e^+e^- \rightarrow J/\psi\ K_SK_S$



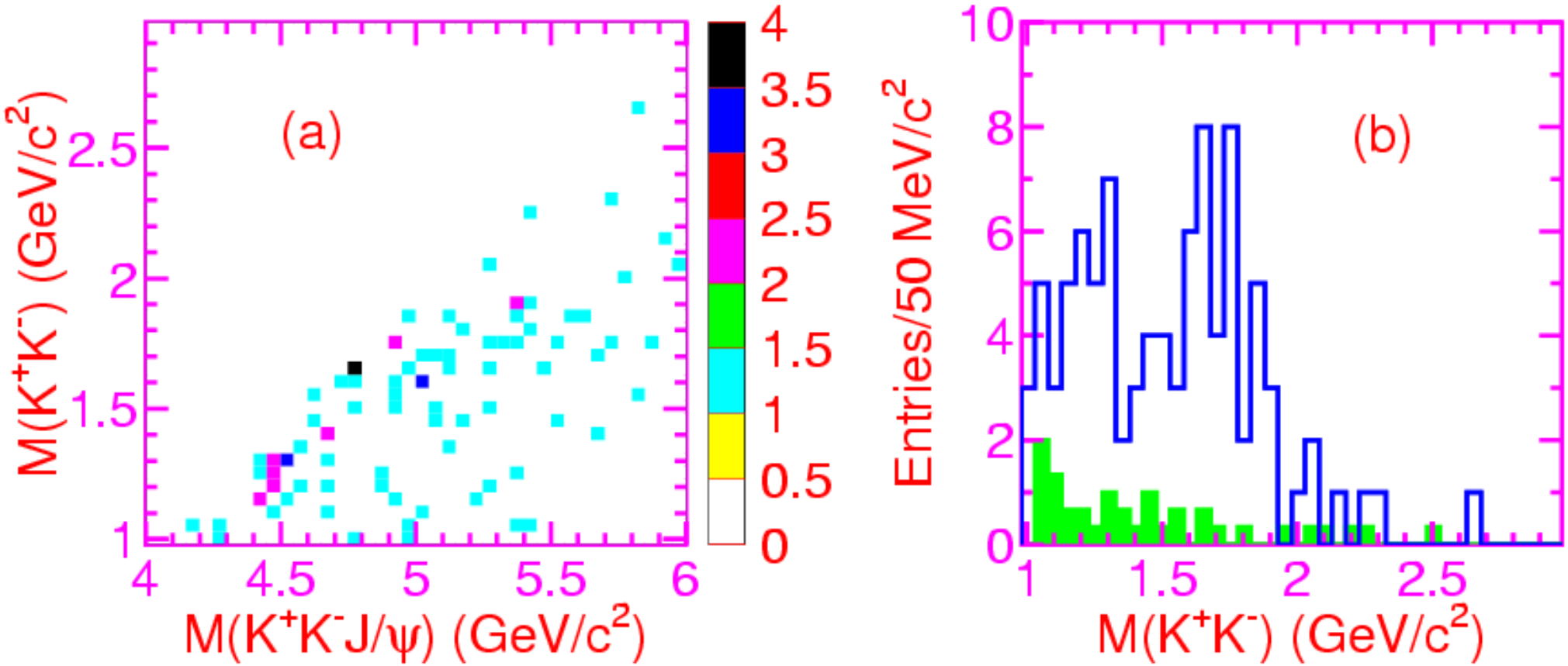


$\sigma(e^+e^- \rightarrow J/\psi K_SK_S)/\ \sigma(e^+e^- \rightarrow J/\psi K^+K-) = 0.6^{+0.5}_{-0.4}$

Consistent with isospin (0.5)

Belle: C.Z.Y & C.P. Shen et al., arXive:0709.2565

$e^+e^- \to K^+K^-J/\psi$ via ISR



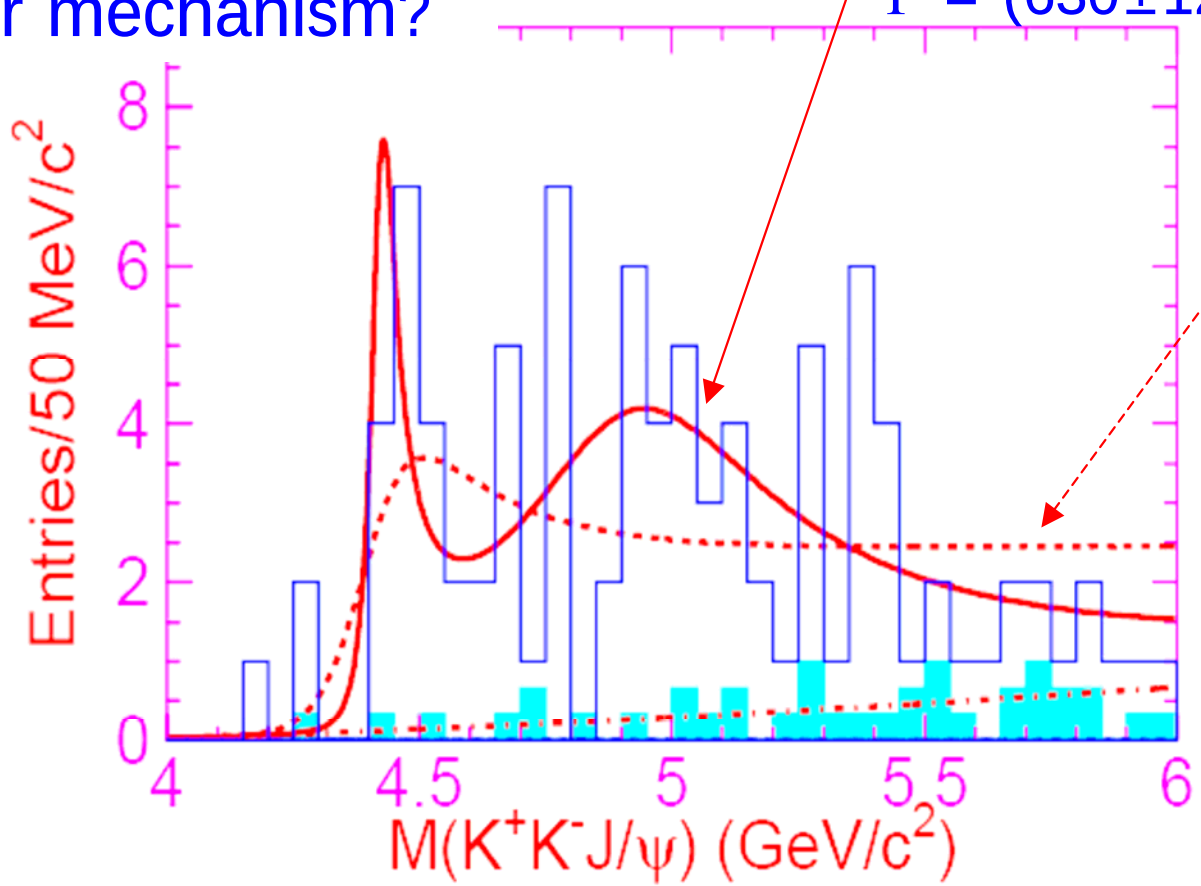
KK invariant mass tends to be large!

Belle: C.Z.Y & C.P. Shen et al., arXive:0709.2565

$e^+e^- \to K^+K^-J/\psi$ via ISR

New resonance or just continuum production, or other mechanism?

PDG $\psi(4415)$ + 1 BW:
M = (4875±132) MeV
Γ = (630±126) MeV

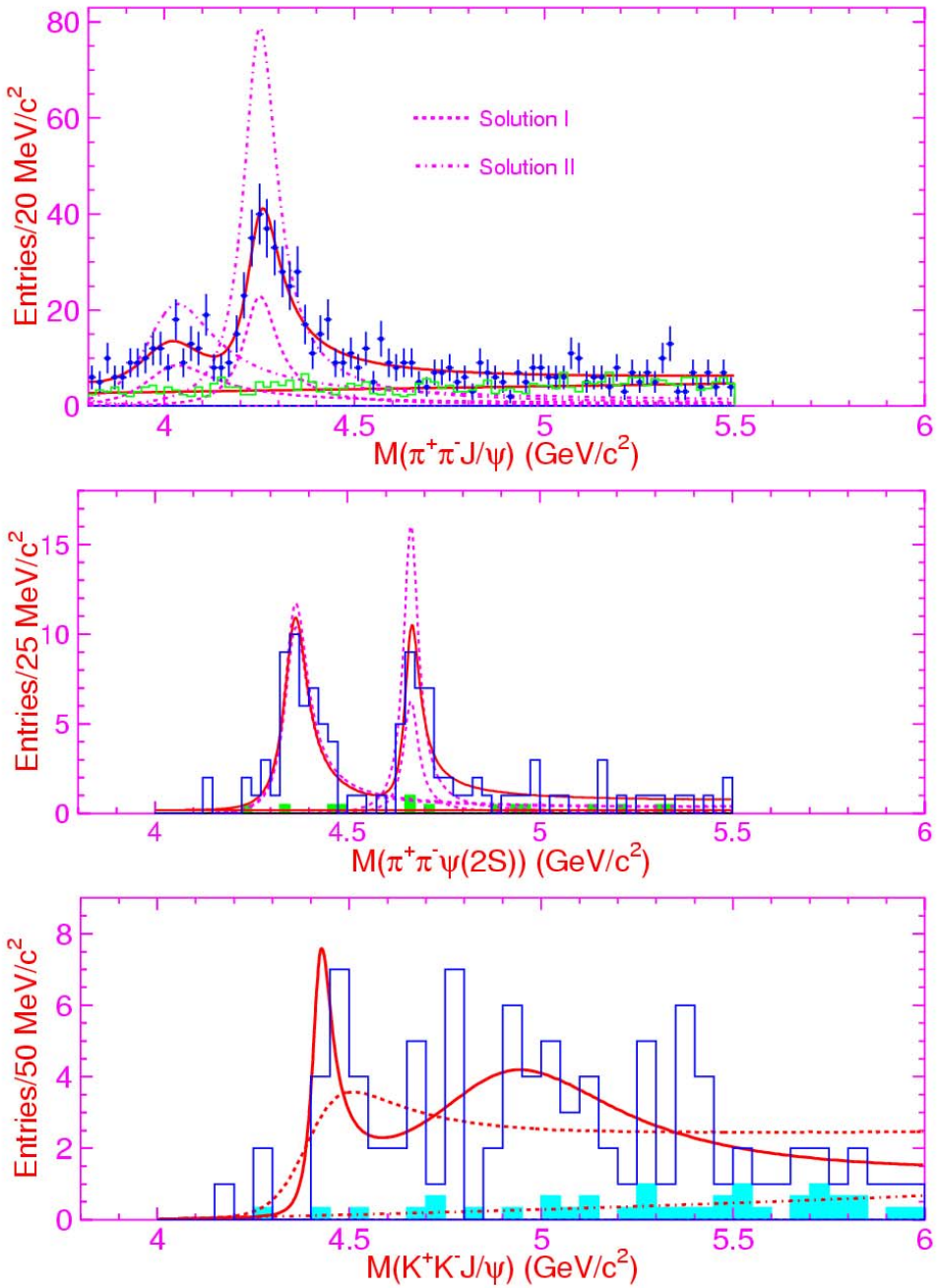


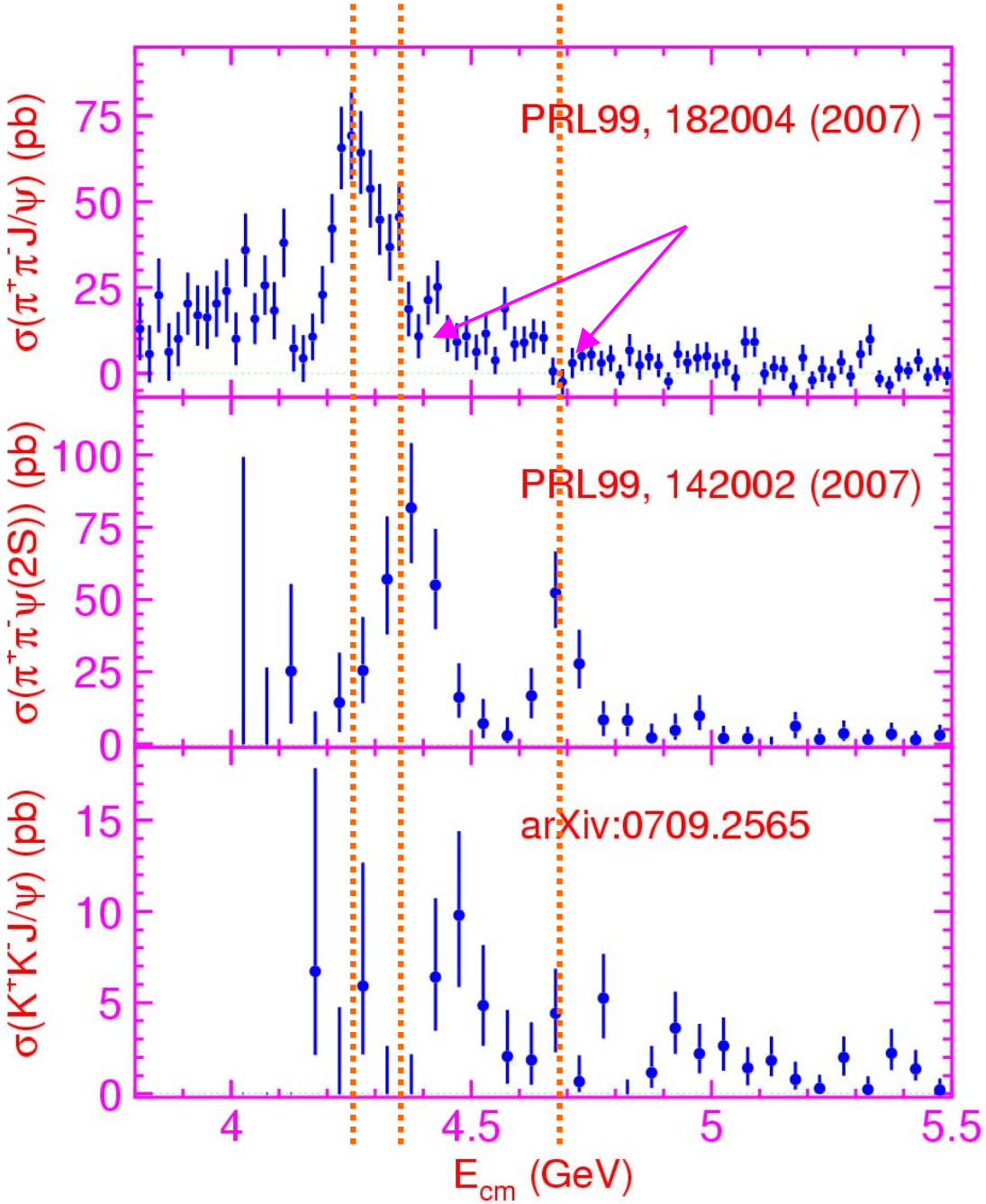
single BW:
M = (4430±38) MeV
Γ = (254±49) MeV

$$\Gamma\left(Y(4260) \to e^+e^-\right) \cdot B\left(Y \to K^+K^-J/\psi\right) < 1.2 \text{ eV @ } 90\% \text{ C.L.}$$

Belle: C.Z.Y & C.P. Shen et al., arXive:0709.2565

$\pi^+\pi^-J/\psi$, $\pi^+\pi^-\psi(2S)$, and K^+K^-J/ψ

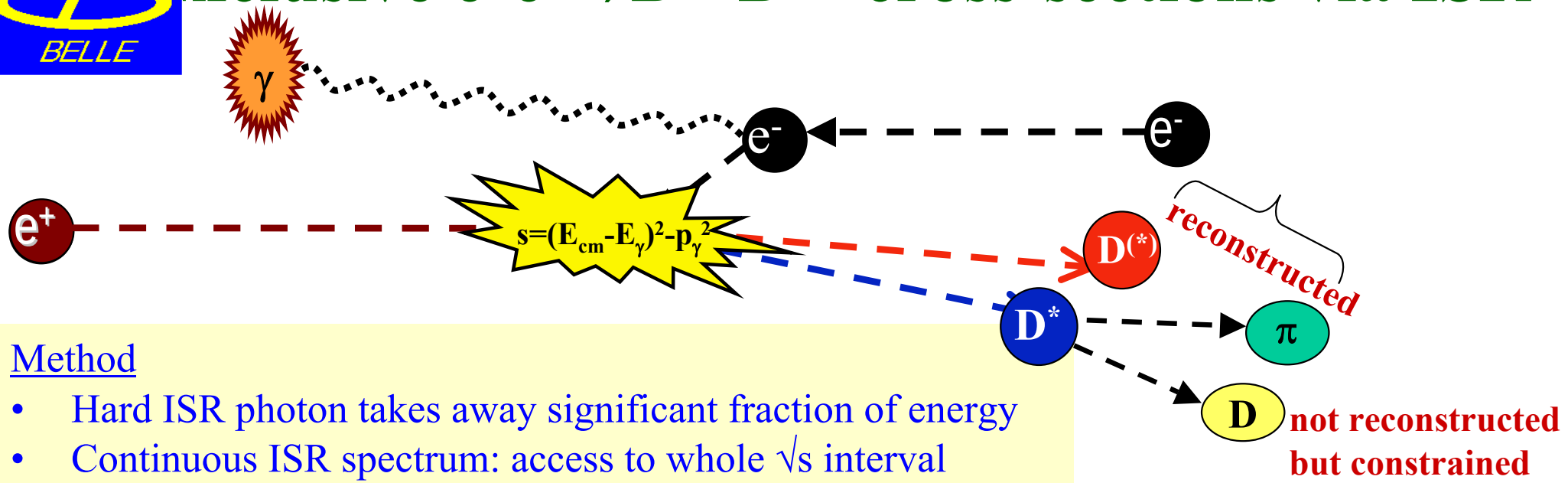




Part II

$e^+e^- \rightarrow$ charmed meson pair

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



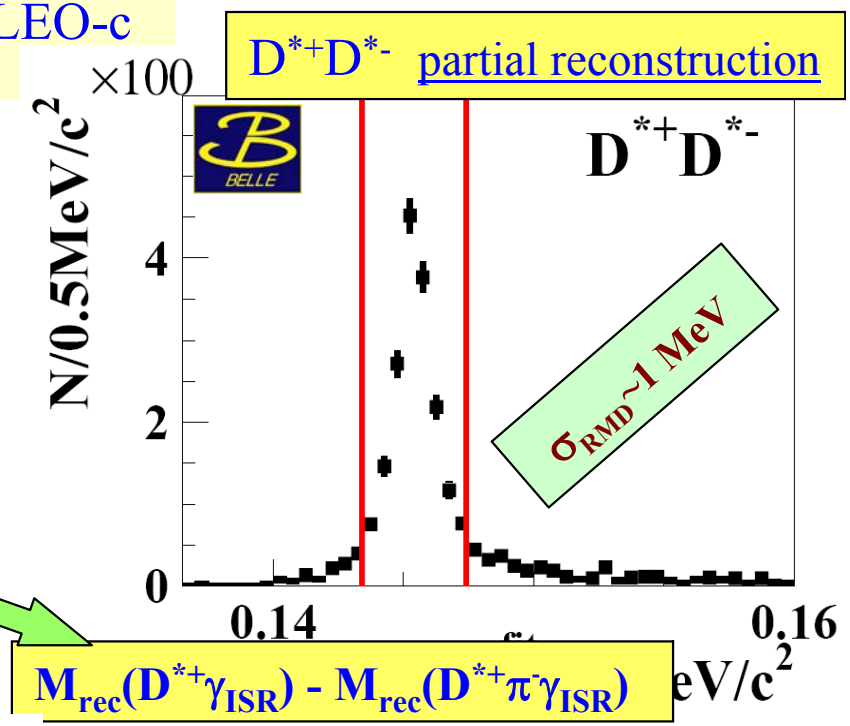
Method

- Hard ISR photon takes away significant fraction of energy
- Continuous ISR spectrum: access to whole √s interval
- α_{em} suppression, but ~ 700/fb at Belle vs ~ 60/pb CLEO-c

The first measurement:

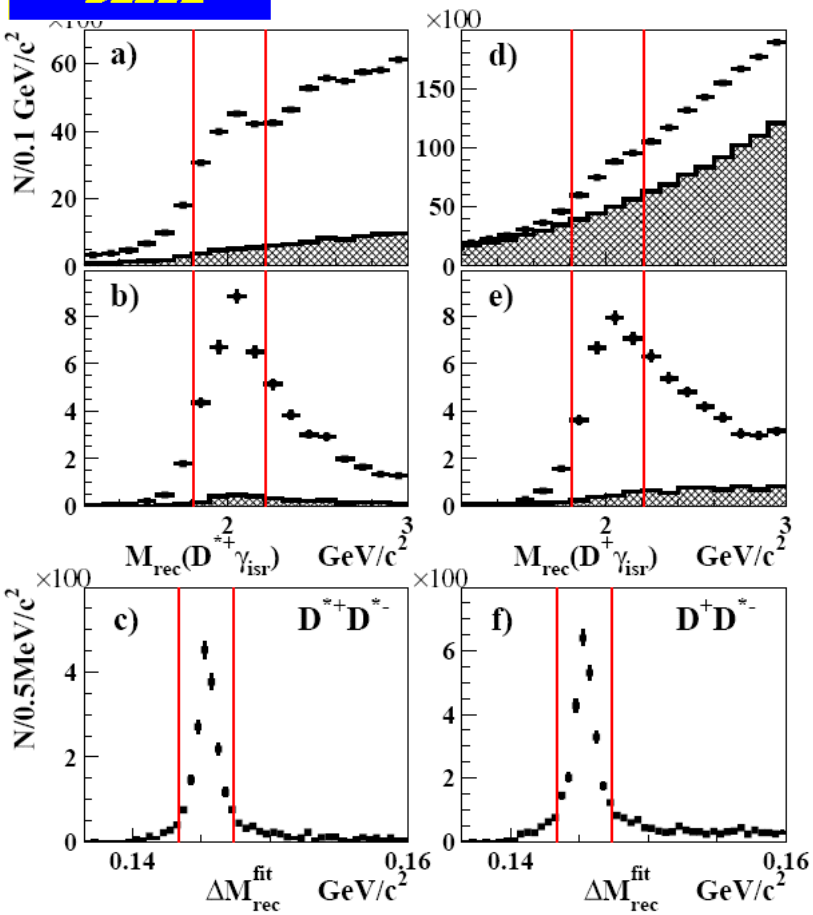
Belle: $D^{*+}D^{*-}$, $D^{+}D^{*-}$ with partial reconstruction

- increase eff ~10--20 times
- narrow peak in recoil mass difference $M_{rec}(D^{*+}\gamma_{ISR}) - M_{rec}(D^{*+}\pi^-\gamma_{ISR})$, because of cancelation of momentum smearing
  - Tight ΔM_{rec} cut ⇒ small background



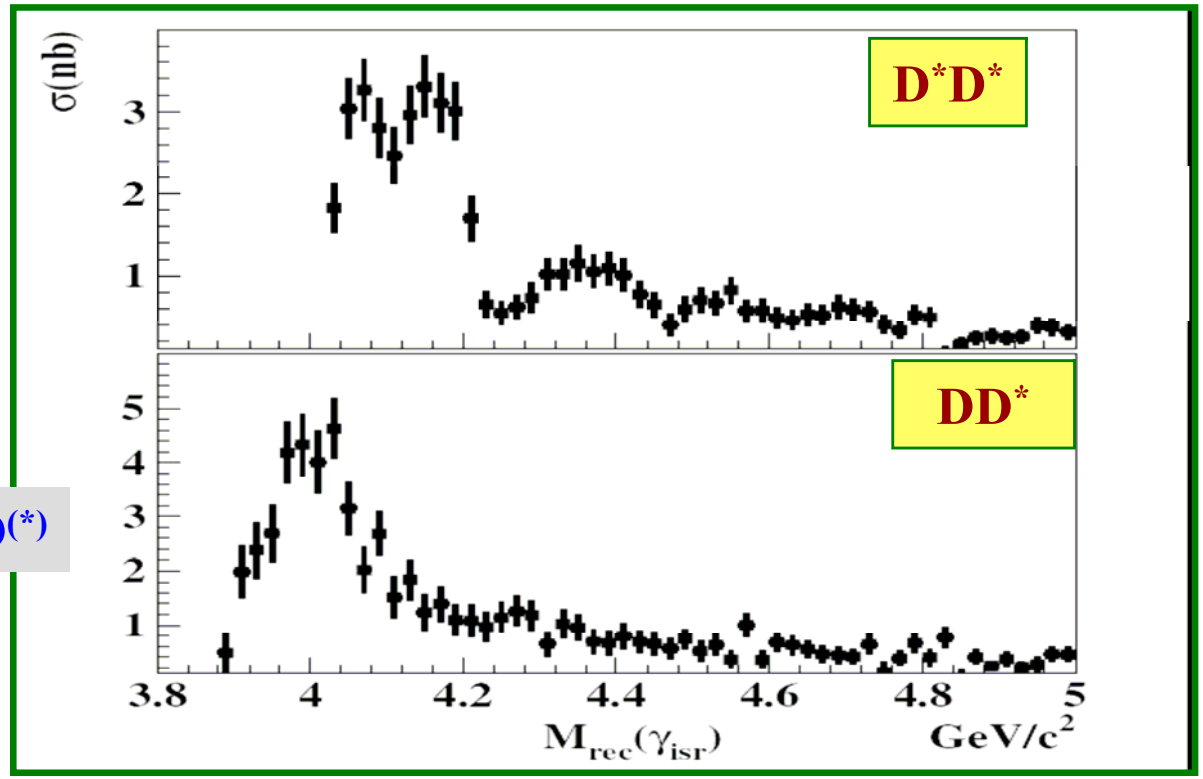
Belle: G. Pakhlova et al., PRL98, 092001 (2007)

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



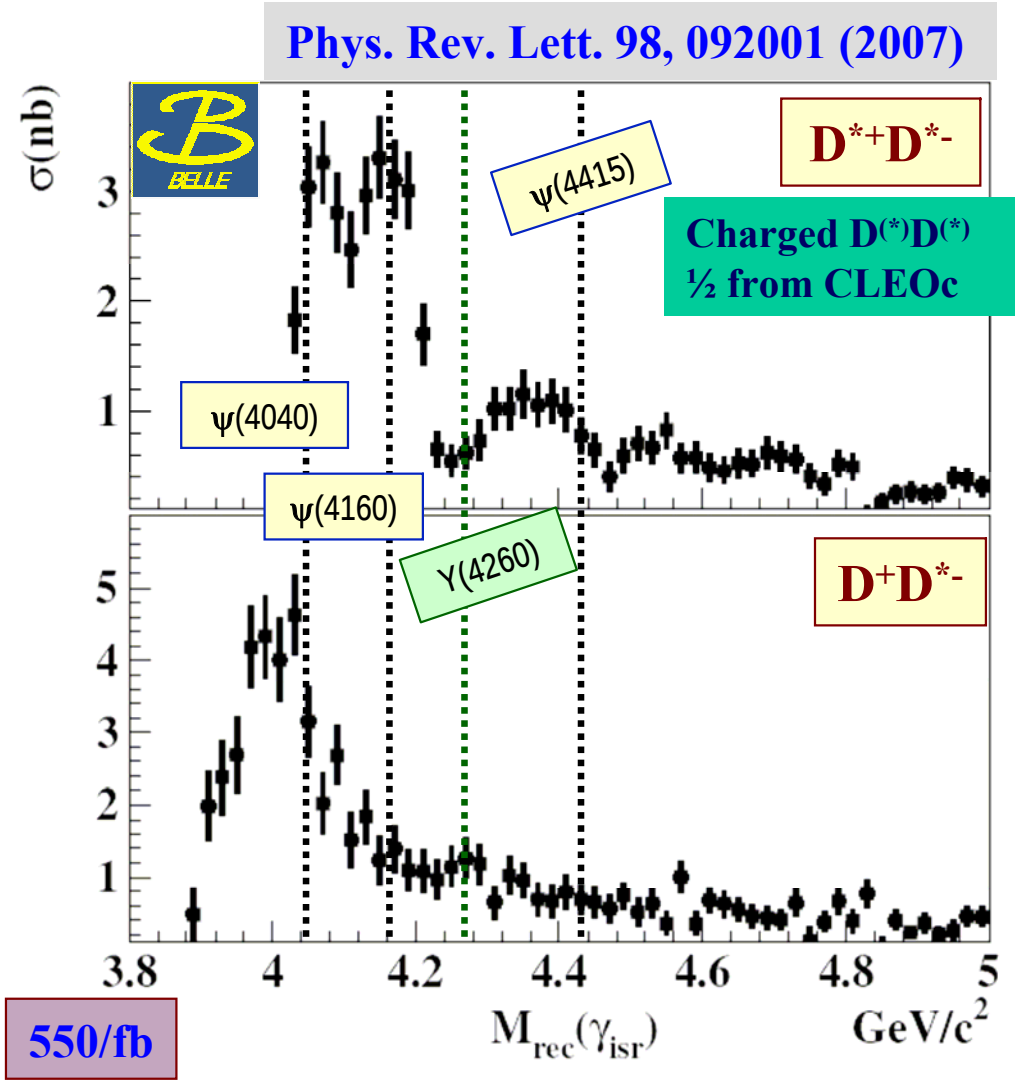
- $ee \to D^*D^{(*)}$ with partial reconstruction: $D^{(*)} + \gamma_{ISR} + \pi_{slow}$ (from unreconstructed D^*)
- Use recoil mass difference to suppress bgs
- Use kinematic constraint $M_{recoil}(D^* \gamma_{ISR}) \to M_D$ to improve resolution

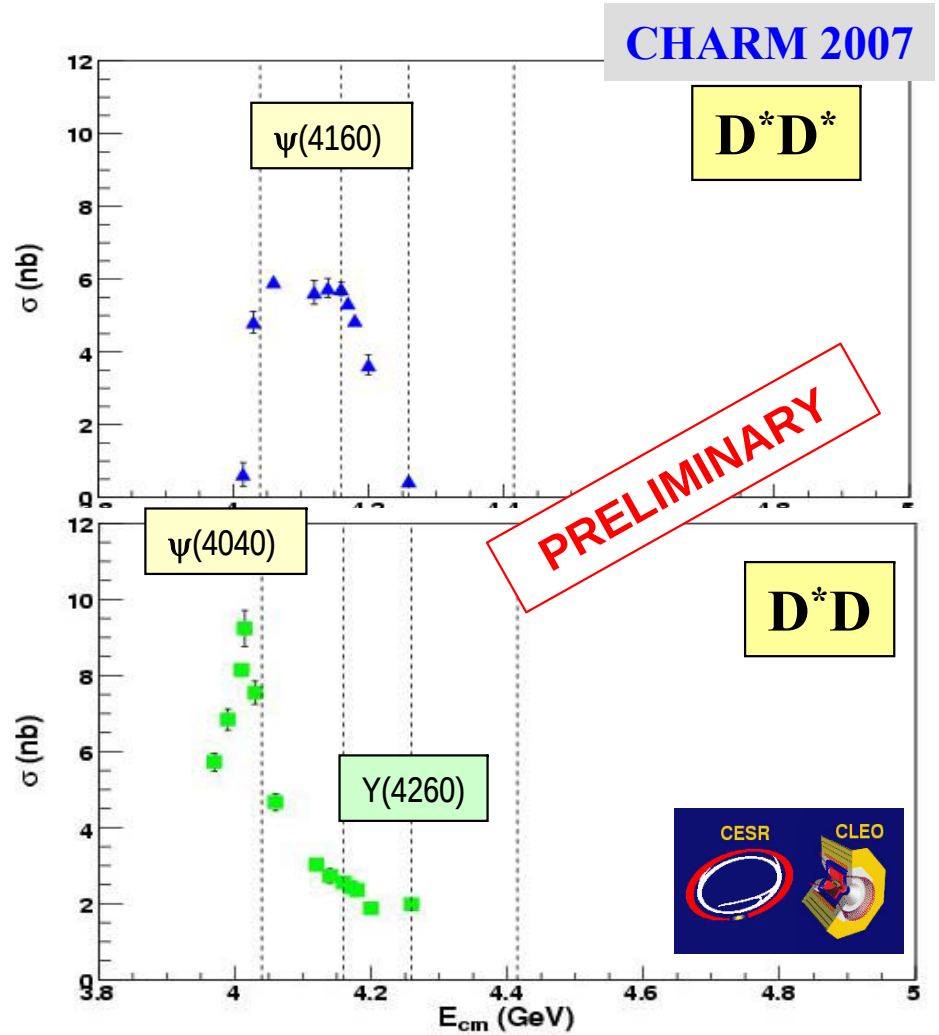
×2 to account for neutral $D^*D^{(*)}$



Belle: G. Pakhlova et al., PRL98, 092001 (2007)

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





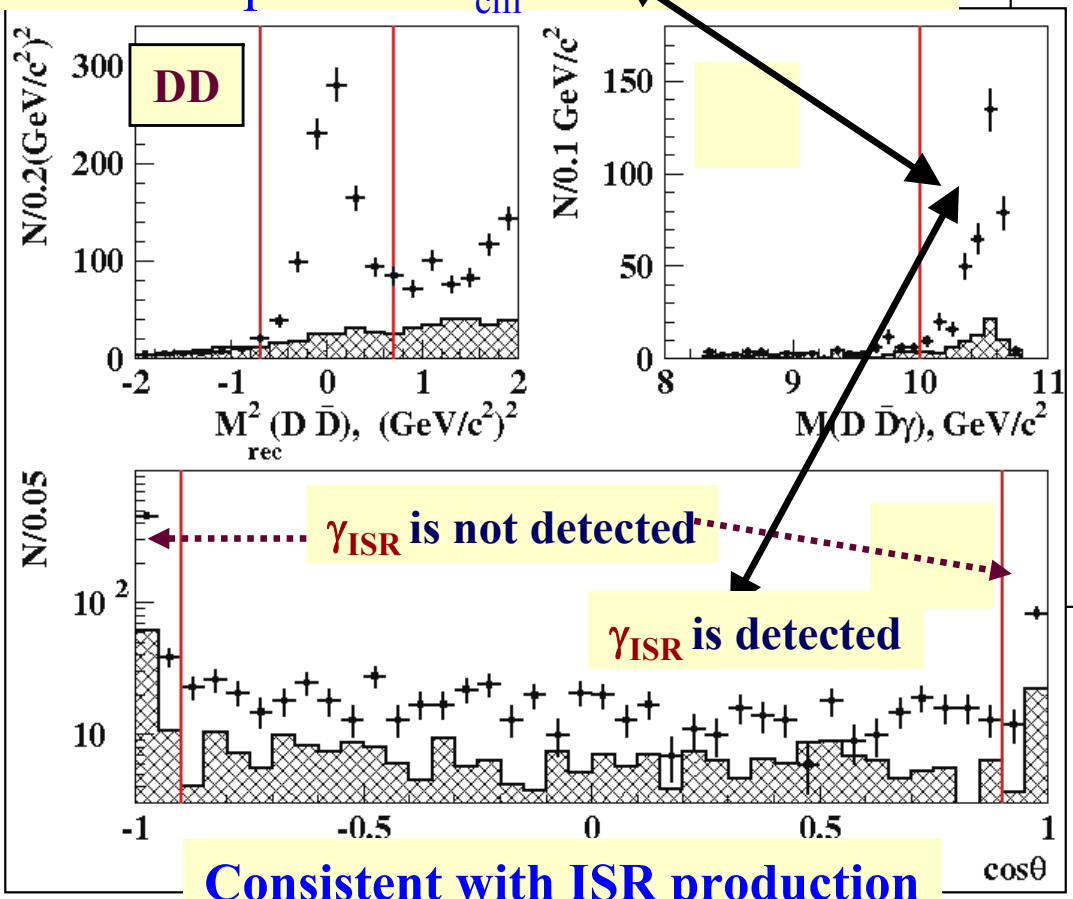
Y(4260) signal

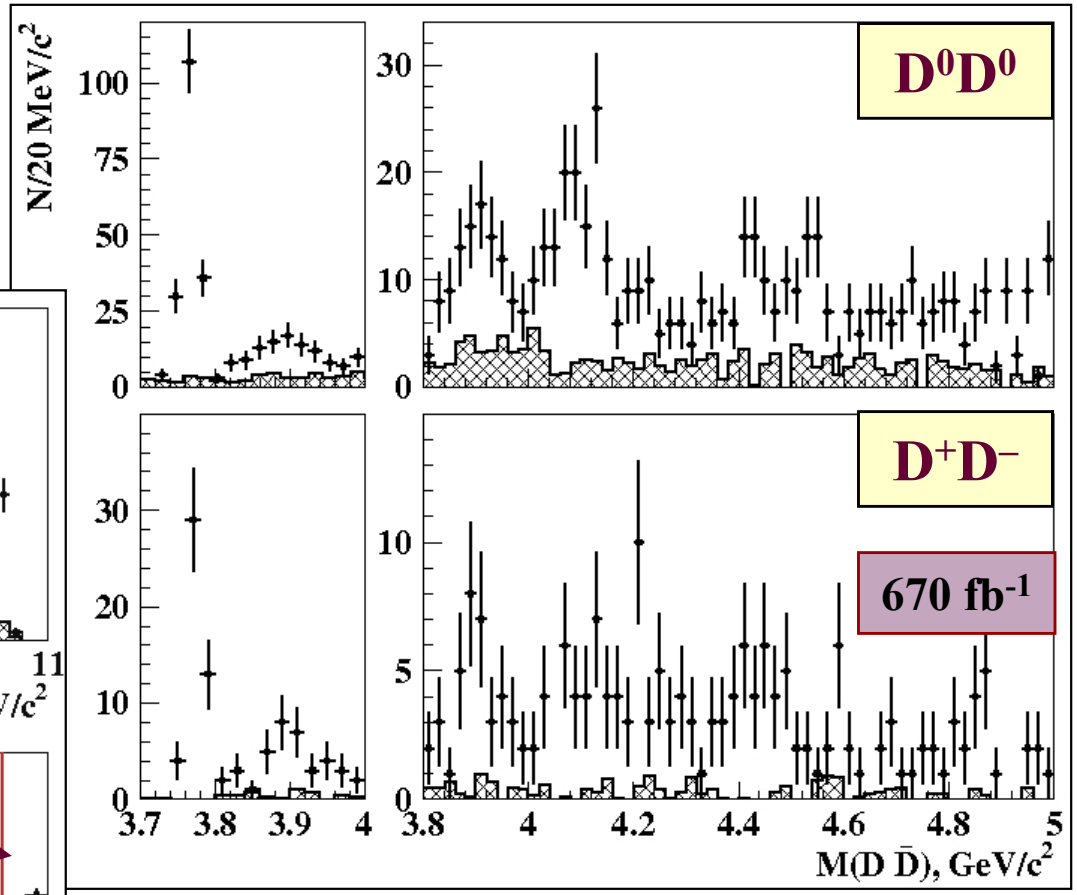
D^*D : hint, but not significant

D^*D^* : clear dip (similar to inclusive R)

$e^+e^- \to DD$ at $\sqrt{s}$~3.7–5 GeV via ISR

- $D^0\bar{D}^0$ or D^+D^- + *no extra tracks*
- detection of γ_{ISR} is not required
  - if γ_{ISR} is detected $M(DD\,\gamma_{ISR})$ is required ~ E_{cm}

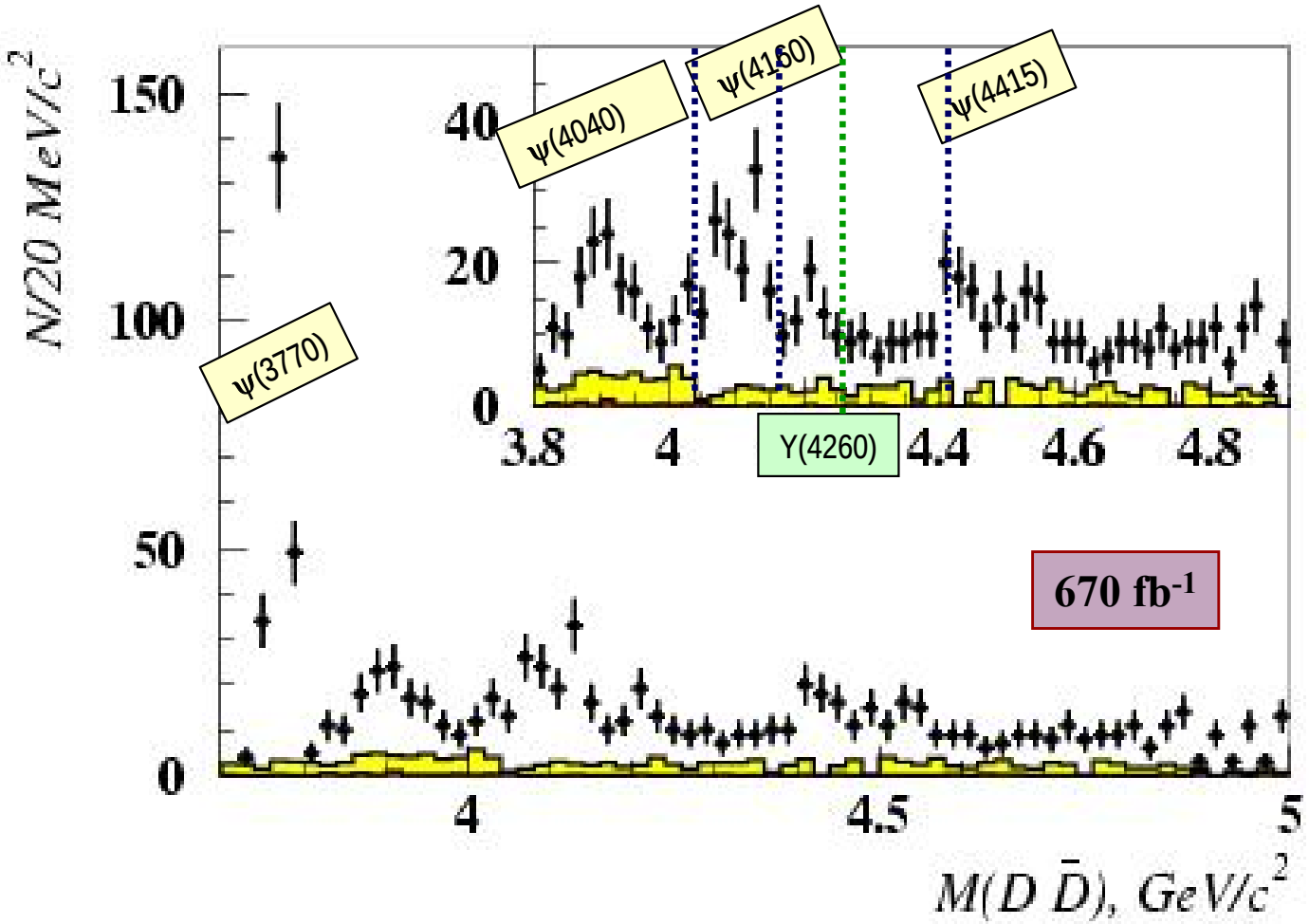


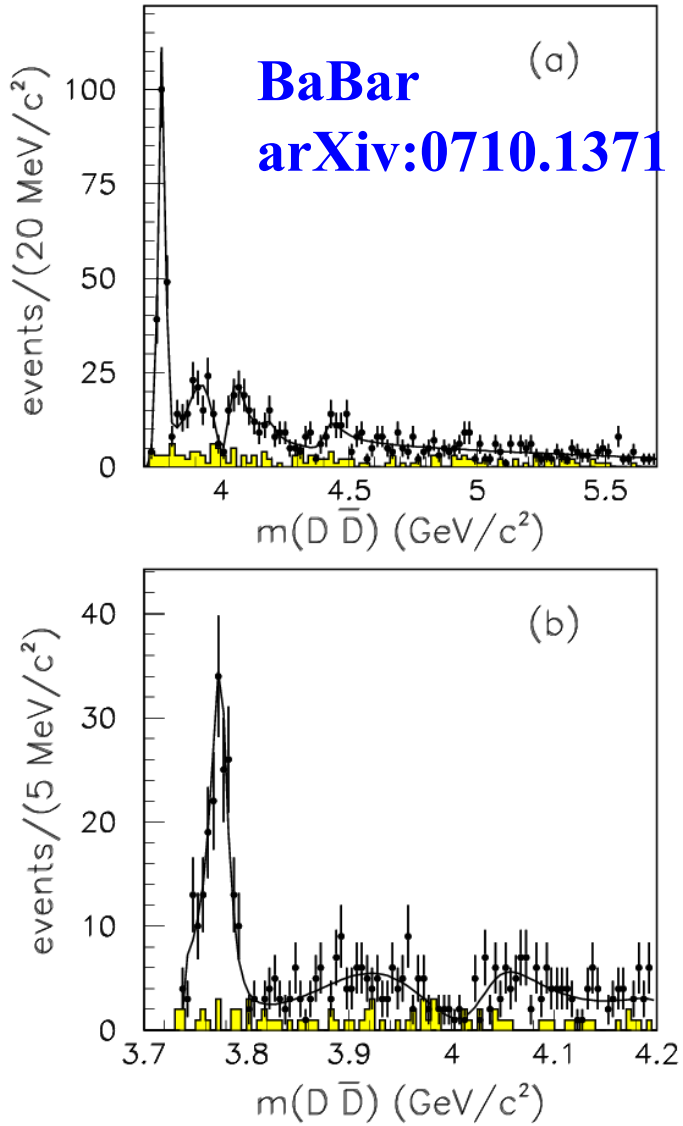


- Combinatorial background are estimated from D sidebands
- Other backgrounds are small and are taken into account

Belle: G. Pakhlova et al., arXiv:0708.0082

$e^+e^- \to DD$ at $\sqrt{s}$~3.7–5 GeV via ISR



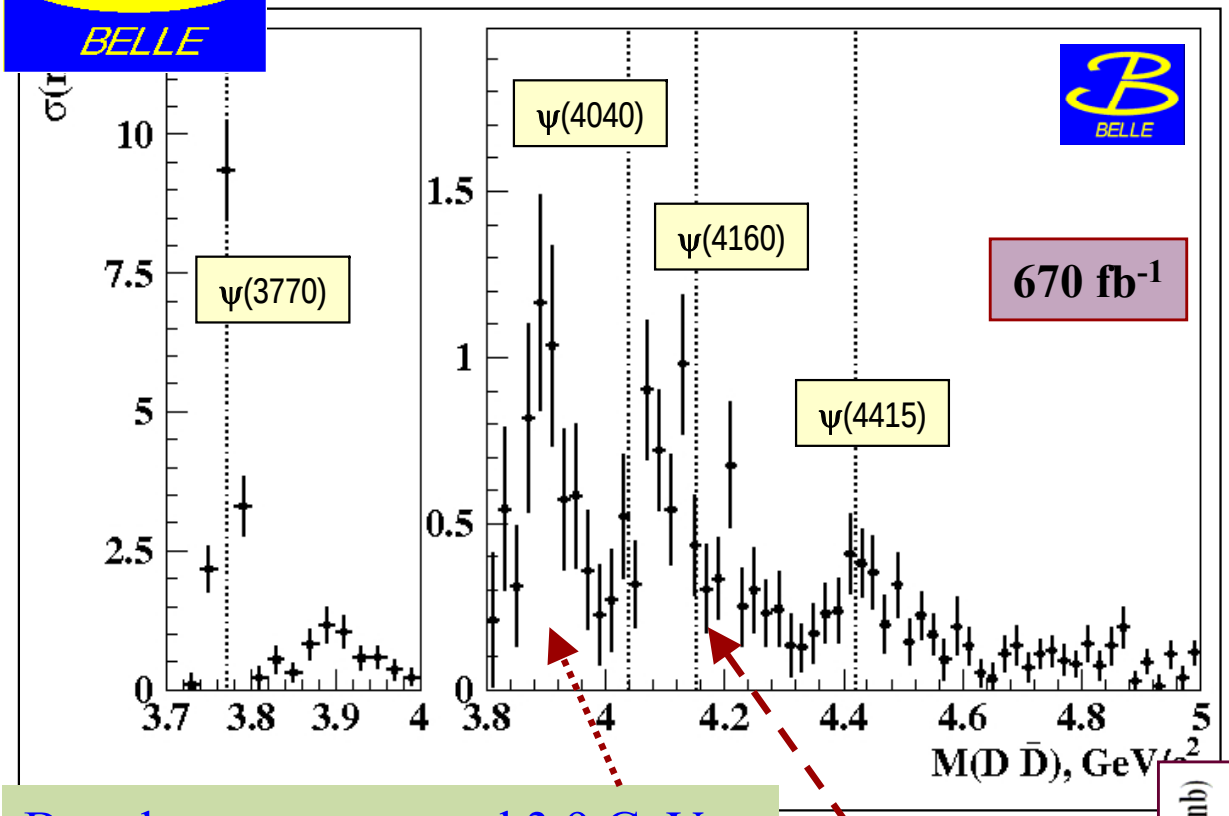


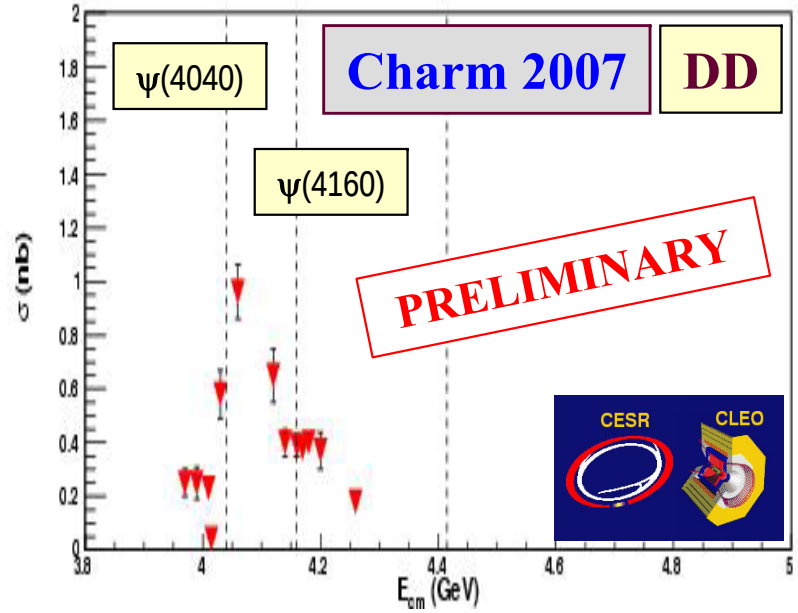
M(DD) is in a qualitative agreement with BaBar

Belle: G. Pakhlova et al., arXiv:0708.0082

Y(4260) signal
DD : no signal

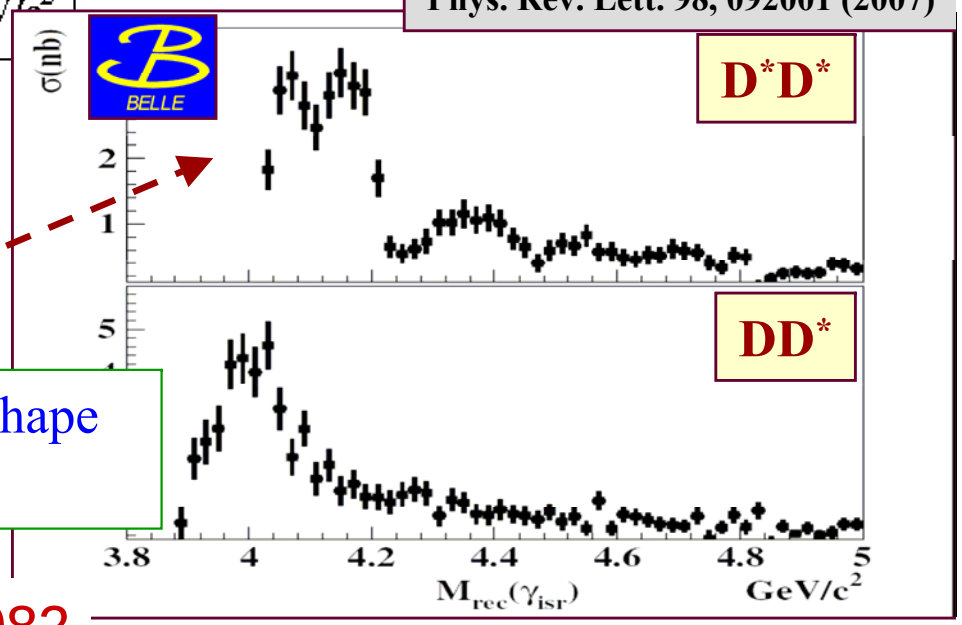
$\sigma(e^+e^- \to DD)$





Broad structure around 3.9 GeV is in qualitative agreement ?? with coupled-channel model Phys. Rev. D21, 203 (1980)

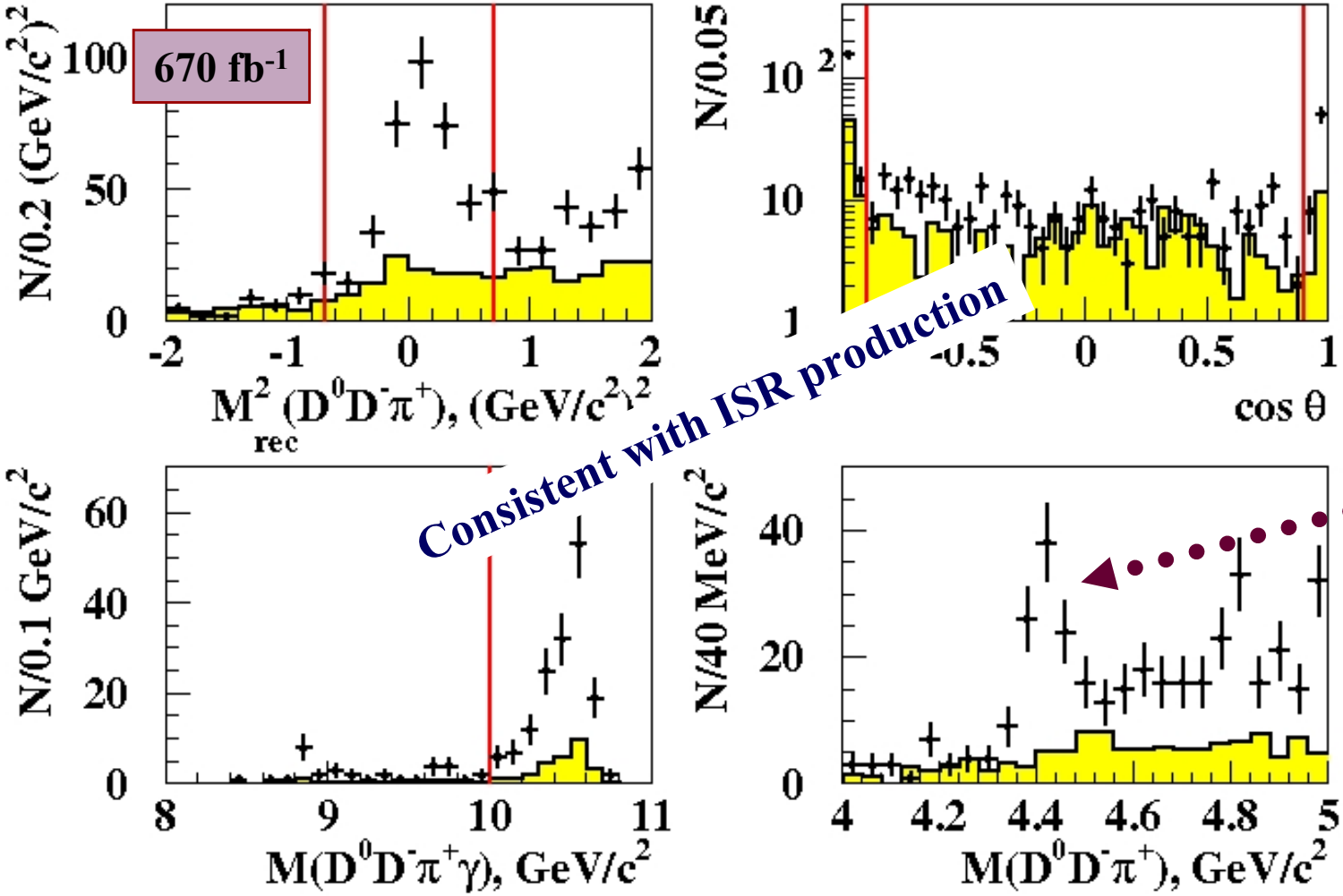
Phys. Rev. Lett. 98, 092001 (2007)



Cross section above 4 GeV has a similar shape to those measured for ee → D*D* ?

Belle: G. Pakhlova et al., arXiv:0708.0082

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



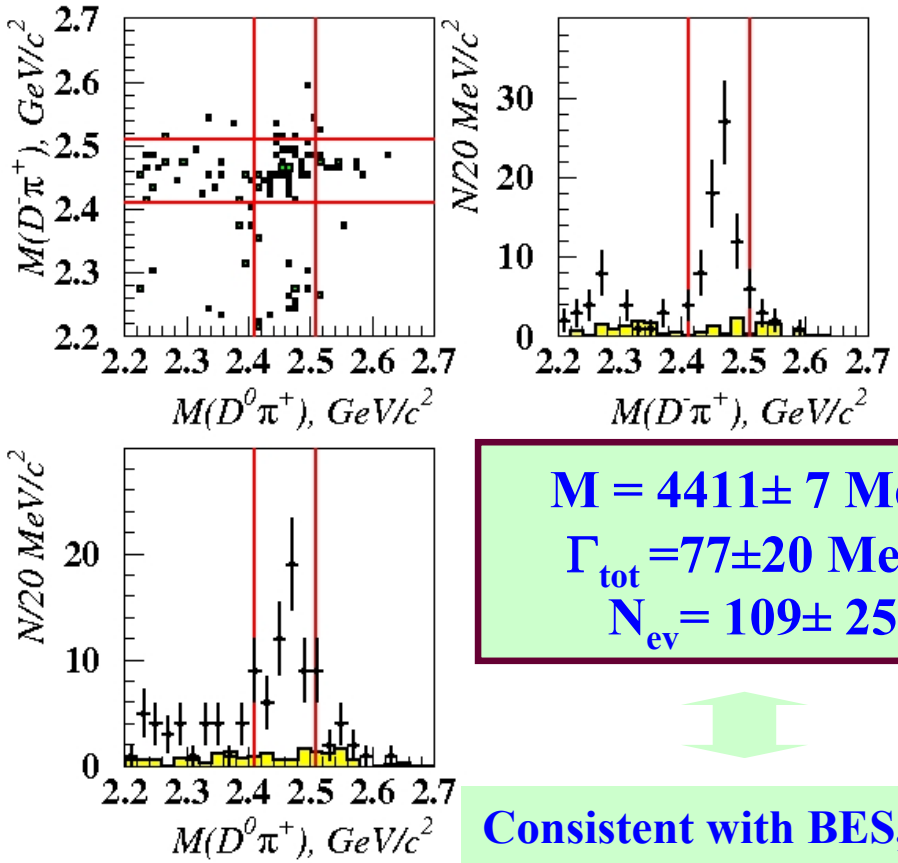
- $D^0\,D^-\,\pi^+$
- *no extra tracks*

Clear signal for $\psi(4415) \to DD\pi$!

- similar analysis and backgrounds
- no major bgs except for *combinatorial.*

Belle: G. Pakhlova et al., arXiv:0708.3313

Resonant structure in $\psi(4415)\to DD\pi$



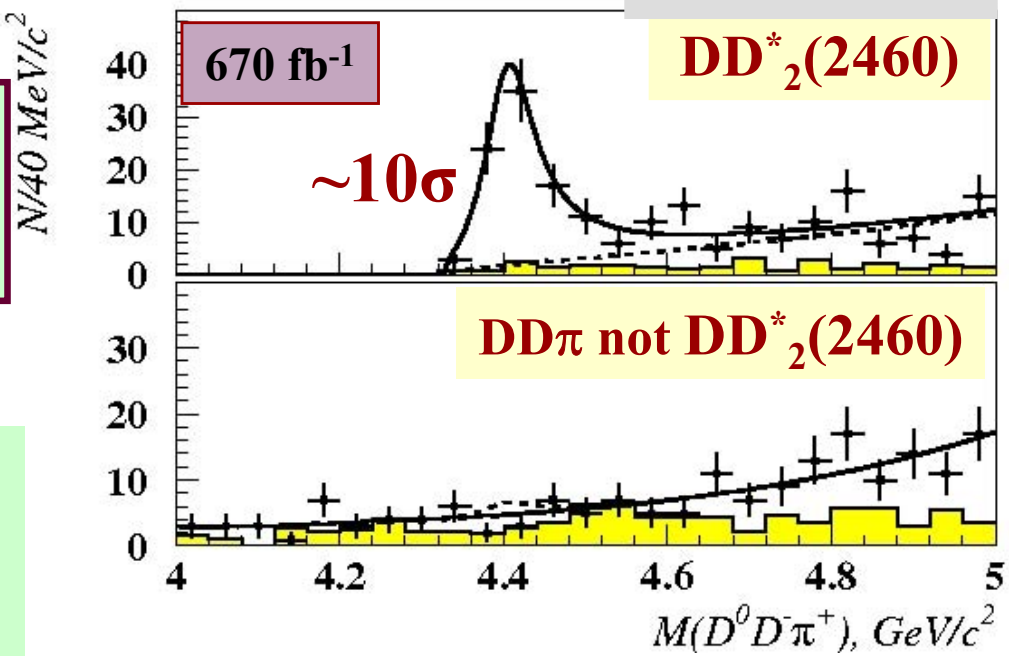
$M(D^0\pi^+)$ vs $M(D^-\pi^+)$ from **$\psi(4415)$** region

- Clear **$D^*_2(2460)$** signals
- Positive interference
- **Non $D^*_2(2460)$** contribution **is not seen**

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

Consistent with BES, hep-ex/0705.4500, PDG06, Barnes at al. PRD72, 054026 (2005)

arXiv:0708.3313



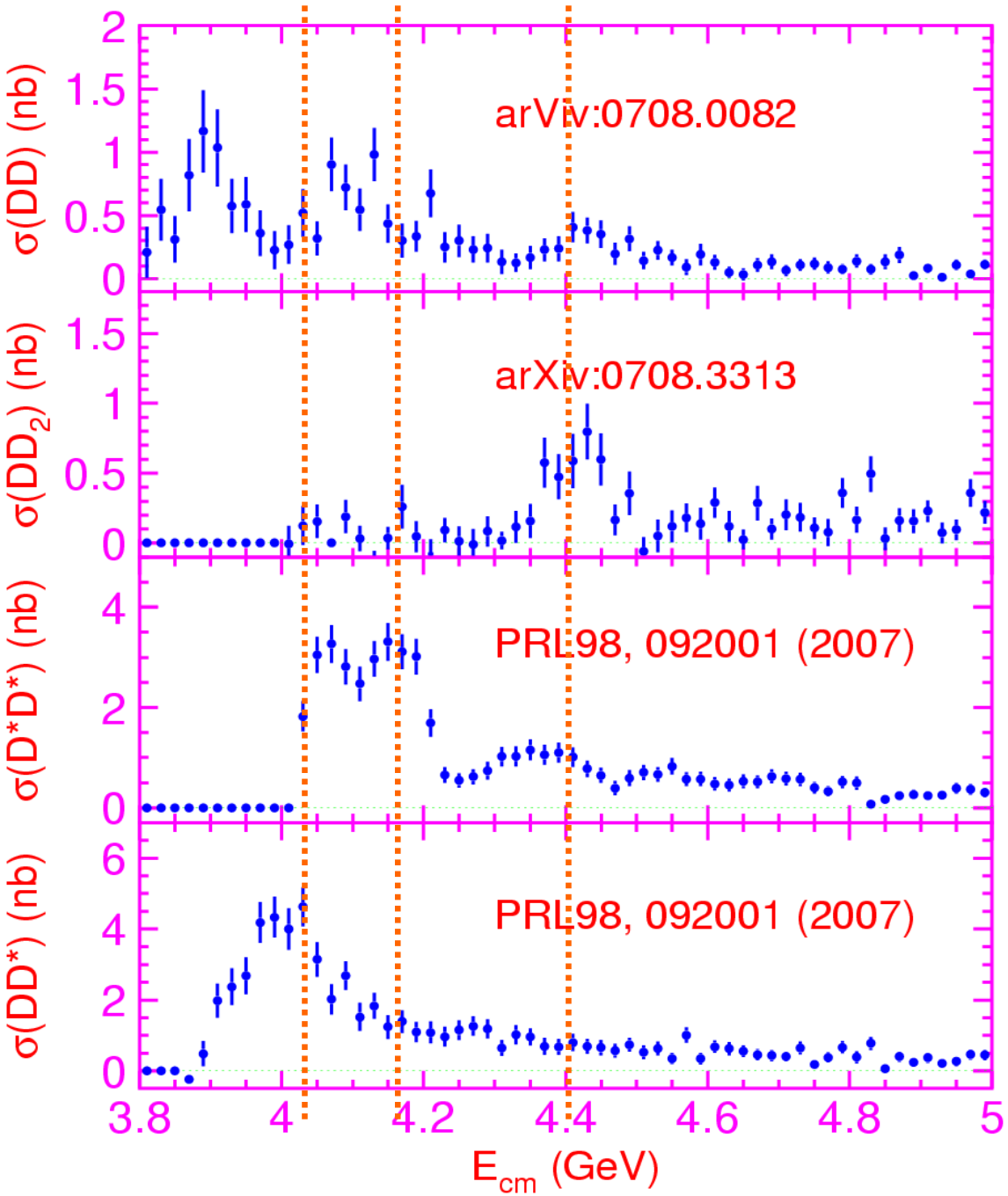
$$\sigma(e^+e^-\to\psi(4415))\times Br(\psi(4415)\to DD^*_2(2460))\times Br(D^*_2(2460)\to D\pi)=(0.74\pm0.17\pm0.07)\text{nb}$$

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

Belle: G. Pakhlova et al., arXiv:0708.3313

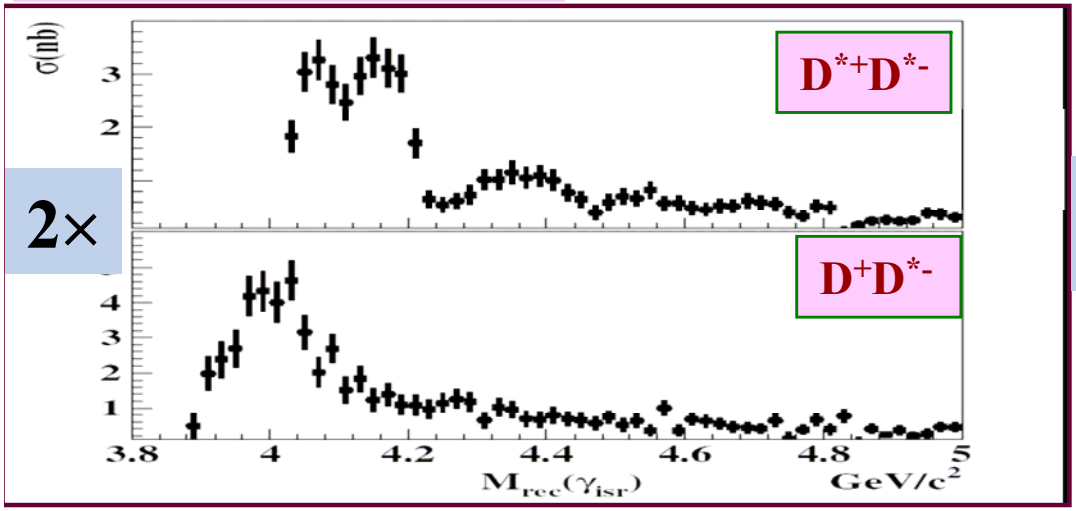
See also P. Pakhlov's talk

DD, DD*, D*D*, DD_2


σ(DD) (nb)
arXiv:0708.0082
σ(DD2) (nb)
arXiv:0708.3313
σ(D*D*) (nb)
PRL98, 092001 (2007)
σ(DD*) (nb)
PRL98, 092001 (2007)
3.8
4
4.2
4.4
4.6
4.8
5
Ecm (GeV)

The decays of the ψ states?

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



2×

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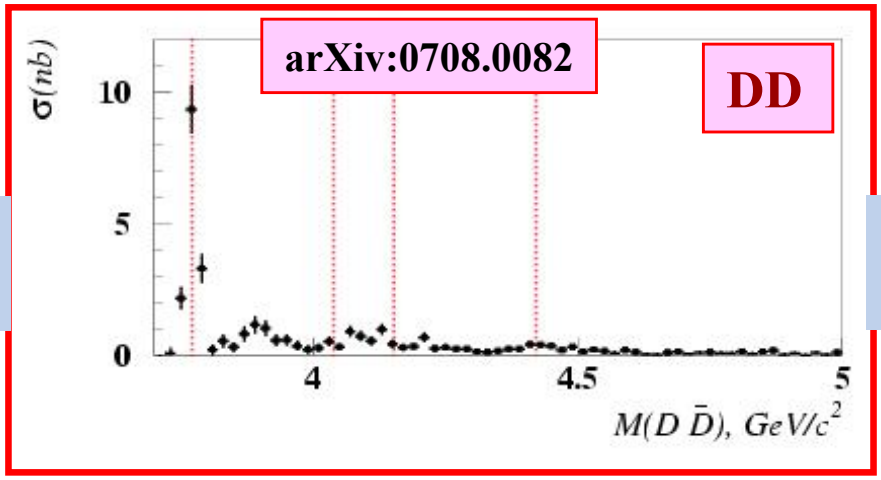

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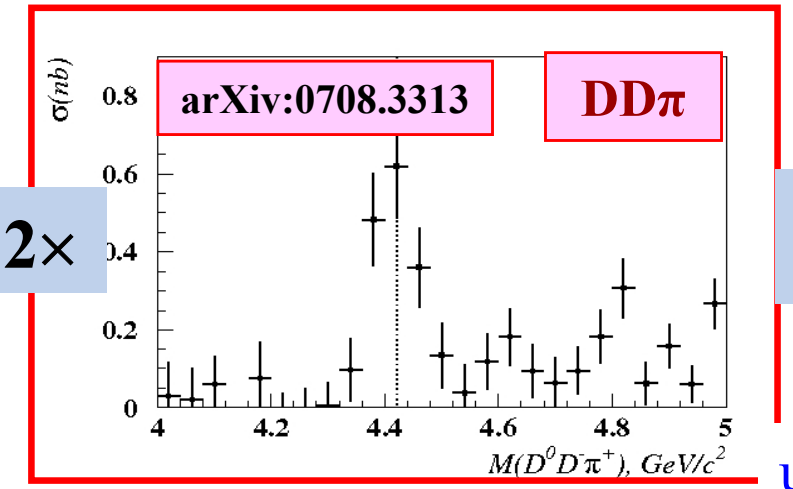

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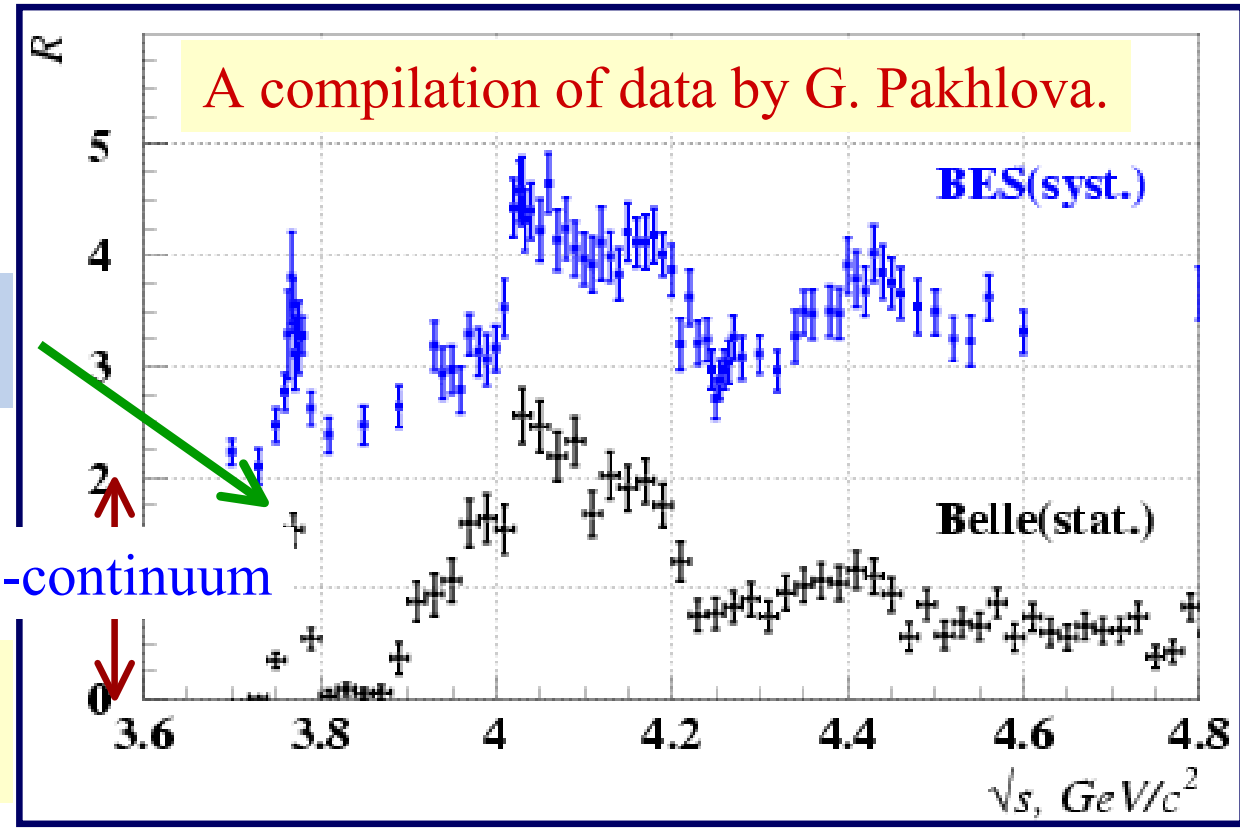

uds-continuum

These 4 final states almost saturate inclusive cross section

Summary

- Y and ψ are studied via ISR at $\sqrt{s}$=10.58 GeV at Belle
- Observation of Y(4008), Y(4260), Y(4360), Y(4660)
- Observation of $e^+e^- \rightarrow J/\psi\, K^+K^-$ & $J/\psi\, K_S K_S$
- Measurement of $e^+e^- \rightarrow DD, DD^*, D^*D^*, DD\pi$

- Nature of the Y states (charmonium, hybrid, …)?
- Resonance parameters of the excited ψ states?
- Y(xxxx)=ψ(xxxx)?

It is time for us to think more about them with all these Belle-BES-CLEOc-BaBar data!

Summary

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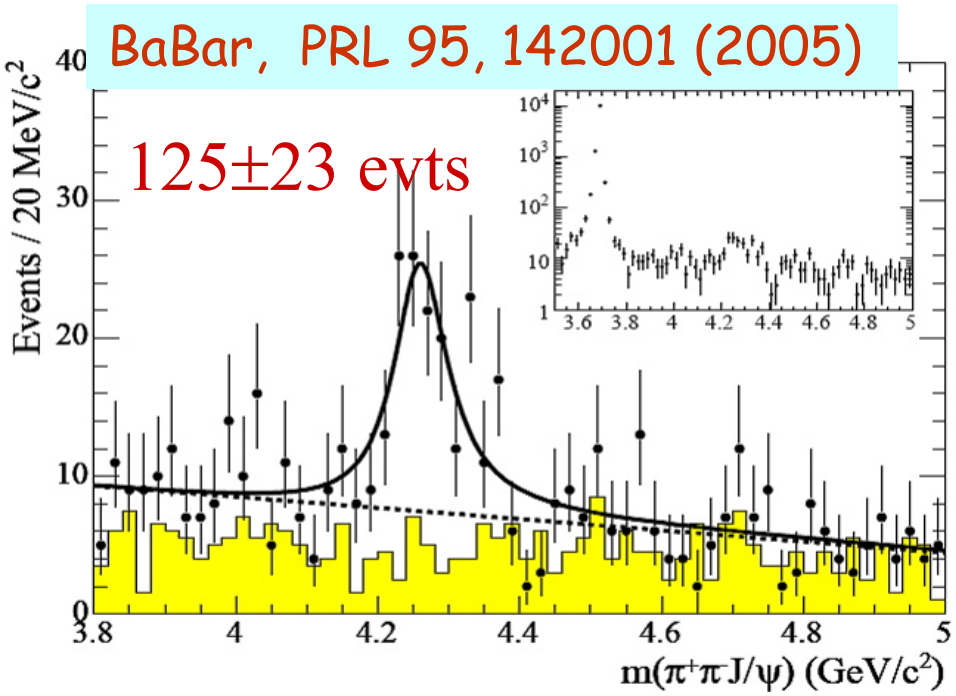
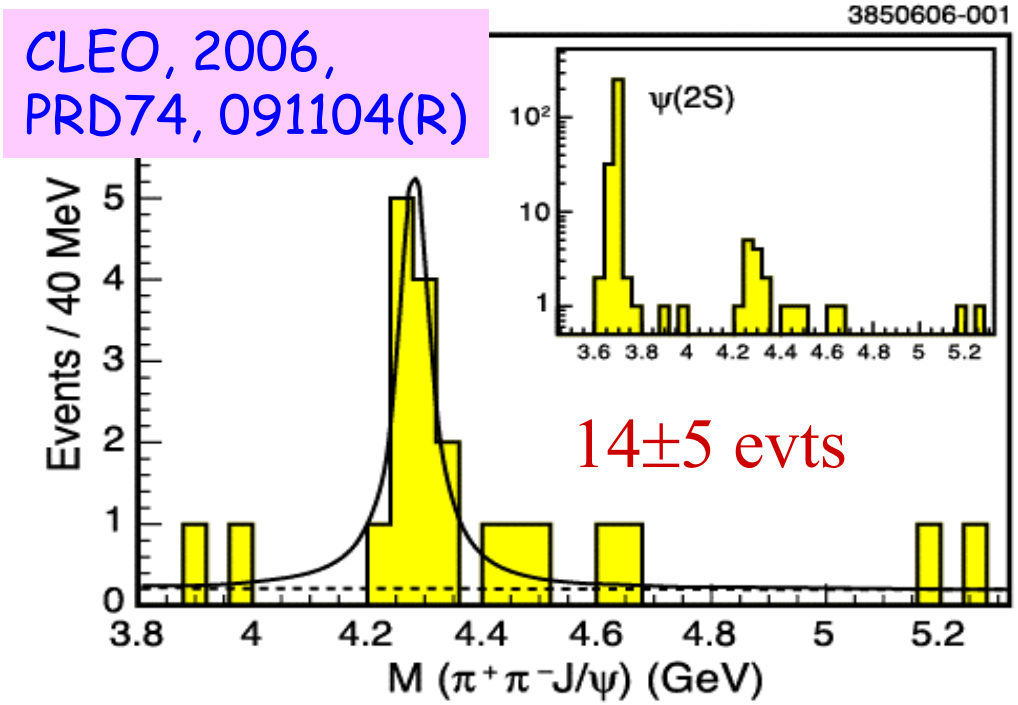
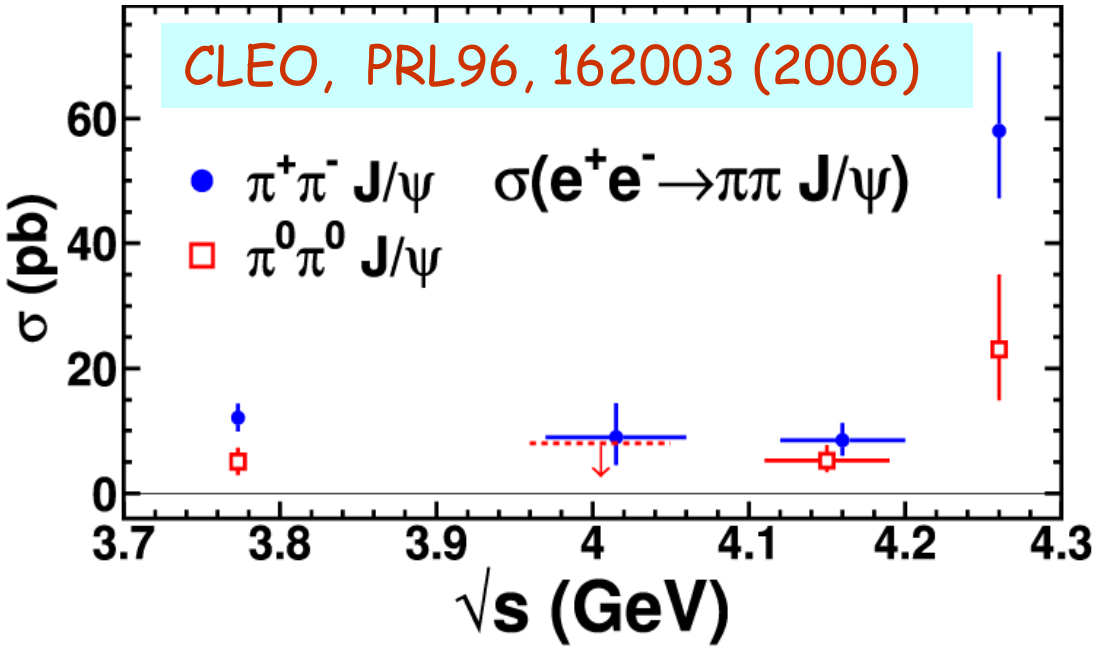
Thanks a lot!

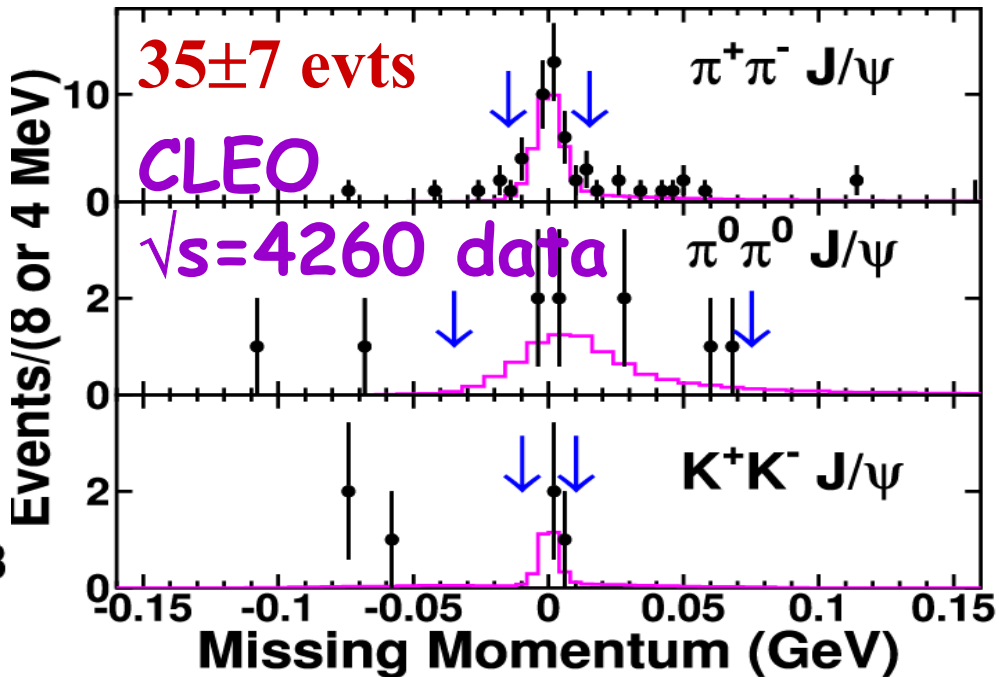
More information

Y(4260) in other experiments









Y(4260) in other experiments

X.H. Mo et al, PLB **640**, 182 (2006)
Using R-values from BES experiment.

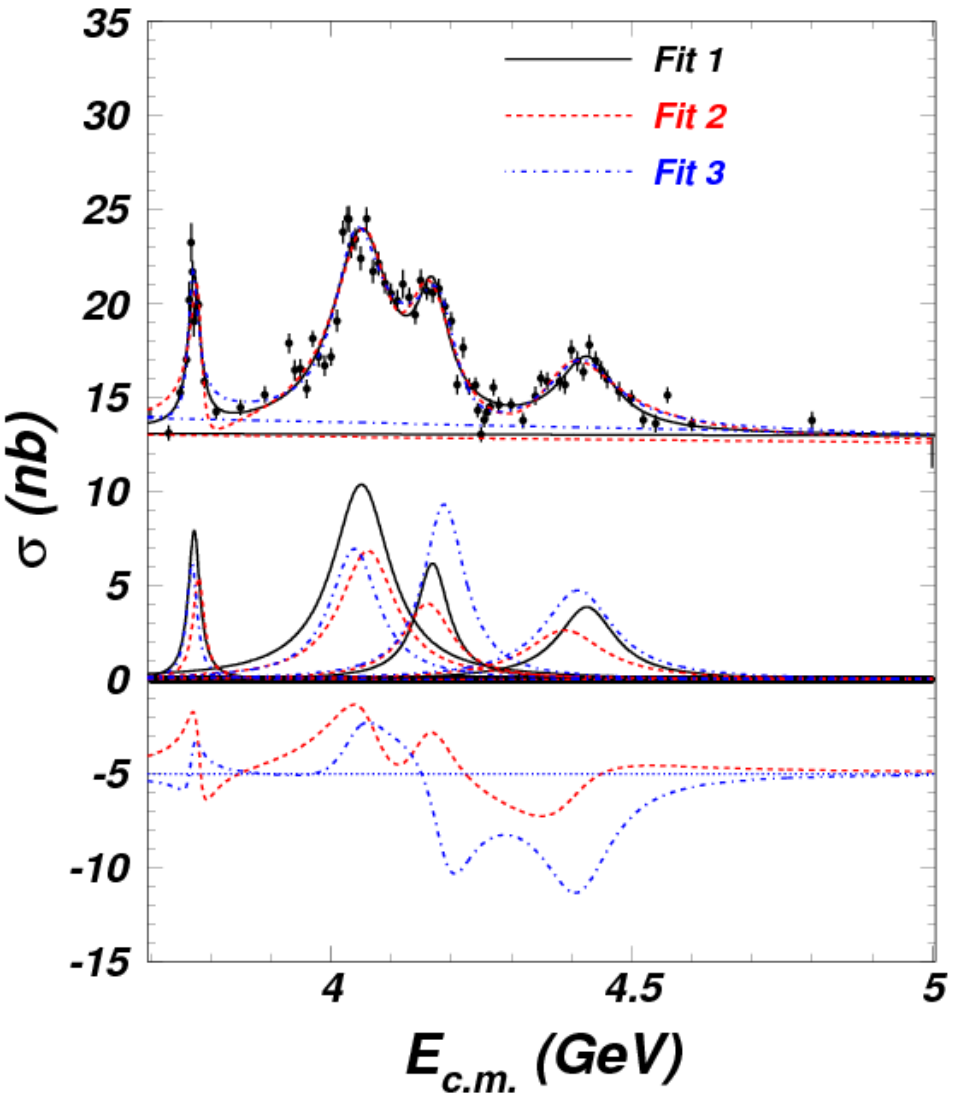
Γ_{ee}<580 eV @90% C.L.

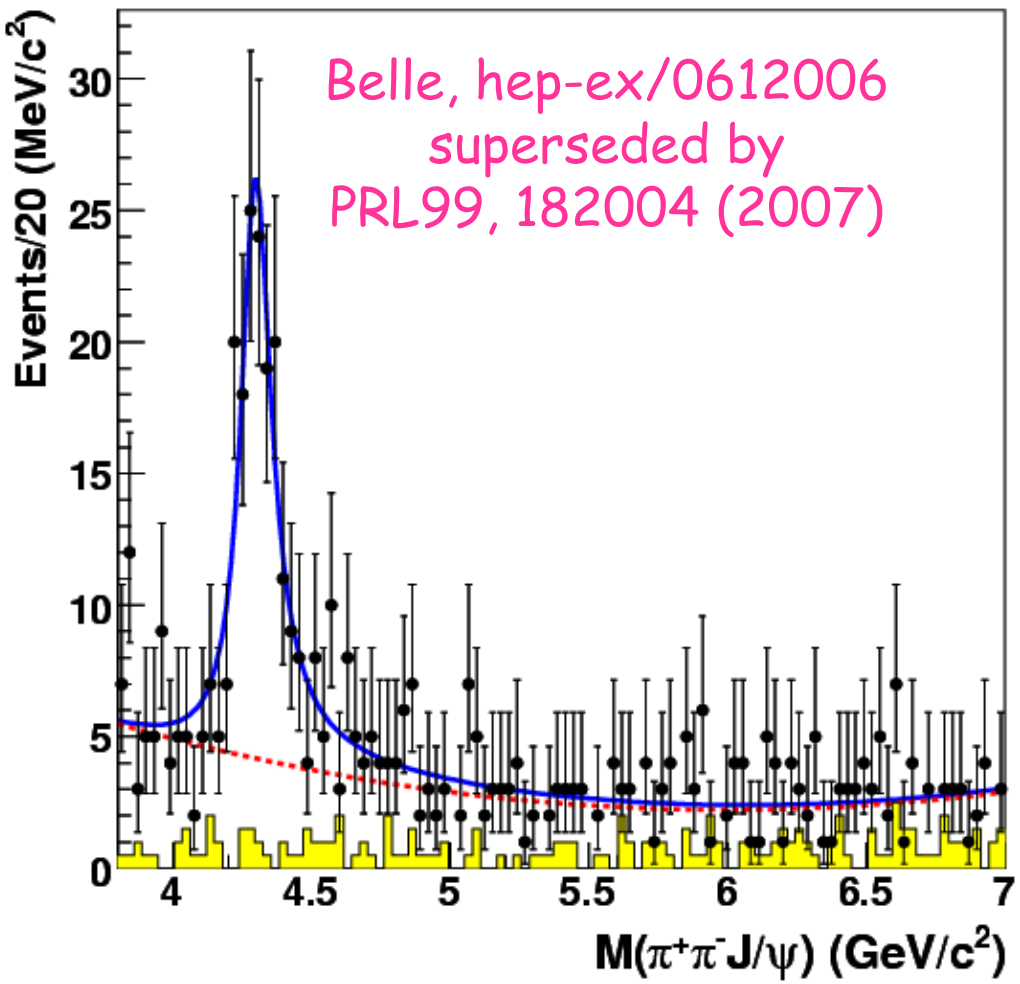
$$N = 165 \pm 24$$

$$M = 4295 \pm 10^{+10}_{-5} \text{ MeV}$$

$$\Gamma = 133 \pm 26^{+13}_{-6} \text{ MeV}$$

$$\Gamma_{ee} \cdot B(Y \to \pi^+\pi^- J/\psi) = 8.7 \pm 1.1^{+0.3}_{-0.9} \text{ eV}$$





Wilks' theorem

If a population is described by the probability density $f(x;\lambda_1,\lambda_2,...,\lambda_p)$ that satisfies reasonable requirements of continuity, and if r of the p parameters of the null hypothesis

$$H_0(\lambda_1=\lambda_{10},\lambda_2=\lambda_{20},...,\lambda_r=\lambda_{r0}),\quad r\le p,$$

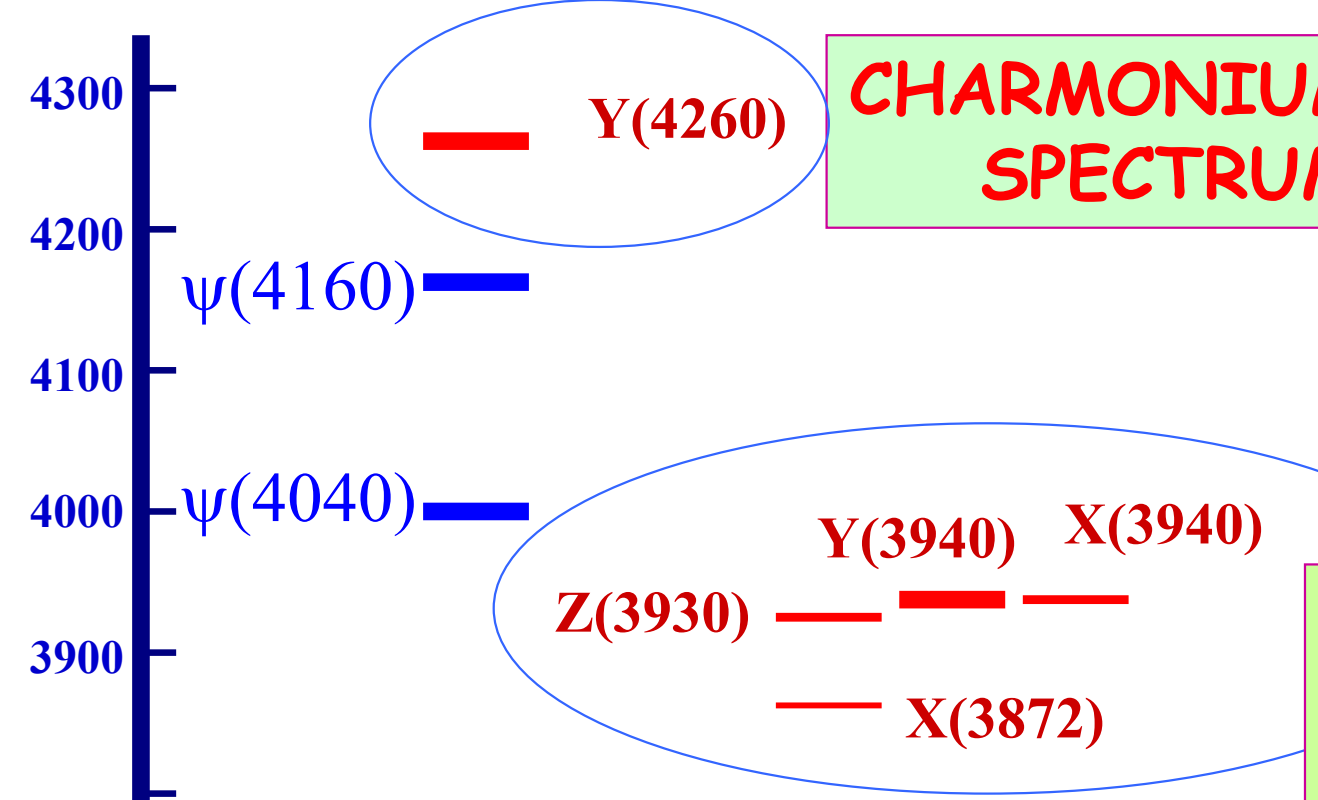
are fixed then the statistic

$$-2\ln T \ (T \text{ is the likelihood ratio})$$

follows a χ^2-distribution with $p-r$ degrees of freedom for very large samples, i.e., for $N\to\infty$. For the case of a simple null hypothesis, i.e., $r=p$, then the number of degrees of freedom is equal to one.

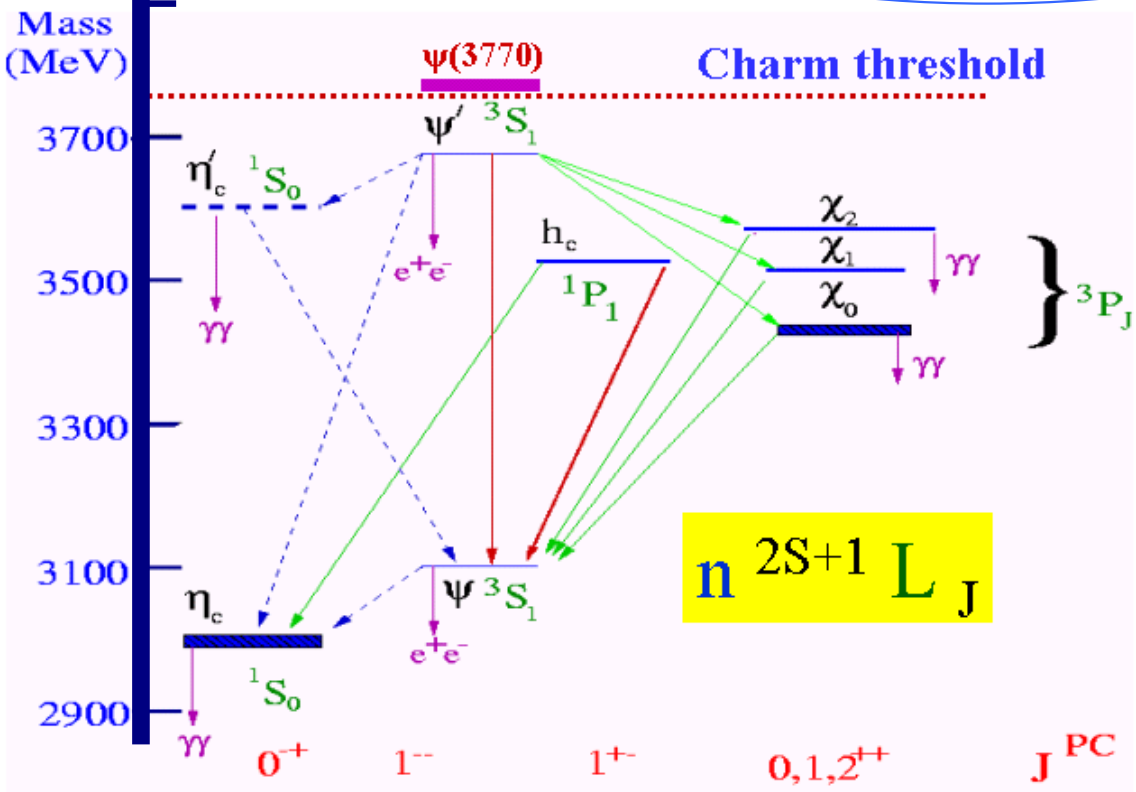
S.S. Wilks, the Annuals of Mathematical Statistics Vol. 9, 60-62 (1938).

CHARMONIUM (?) SPECTRUM



Less known states:

- ψ(4040)
- ψ(4160)
- ψ(4415)



New states from B-factories:

- **X(3872)=DD* (?)**
- **X(3940)=η_c(3S) (?)**
- **Y(3940)=?**
- **Z(3930)=χ_{c2}(2P)**
- **Y(4008)= ψ(3S) (?)**
- **X(4160)=χ_{c0}(3P) (?)**
- **Y(4260)=hybrid (?)**
- **Y(4324)/Y(4360)=?**
- **Z(4430)=tetraquark(?)**
- **Y(4660)= ψ(5S) (?)**

New states every year!

What are they?

Charmonia? Exotic states?