Rc measurements & vector charmonia

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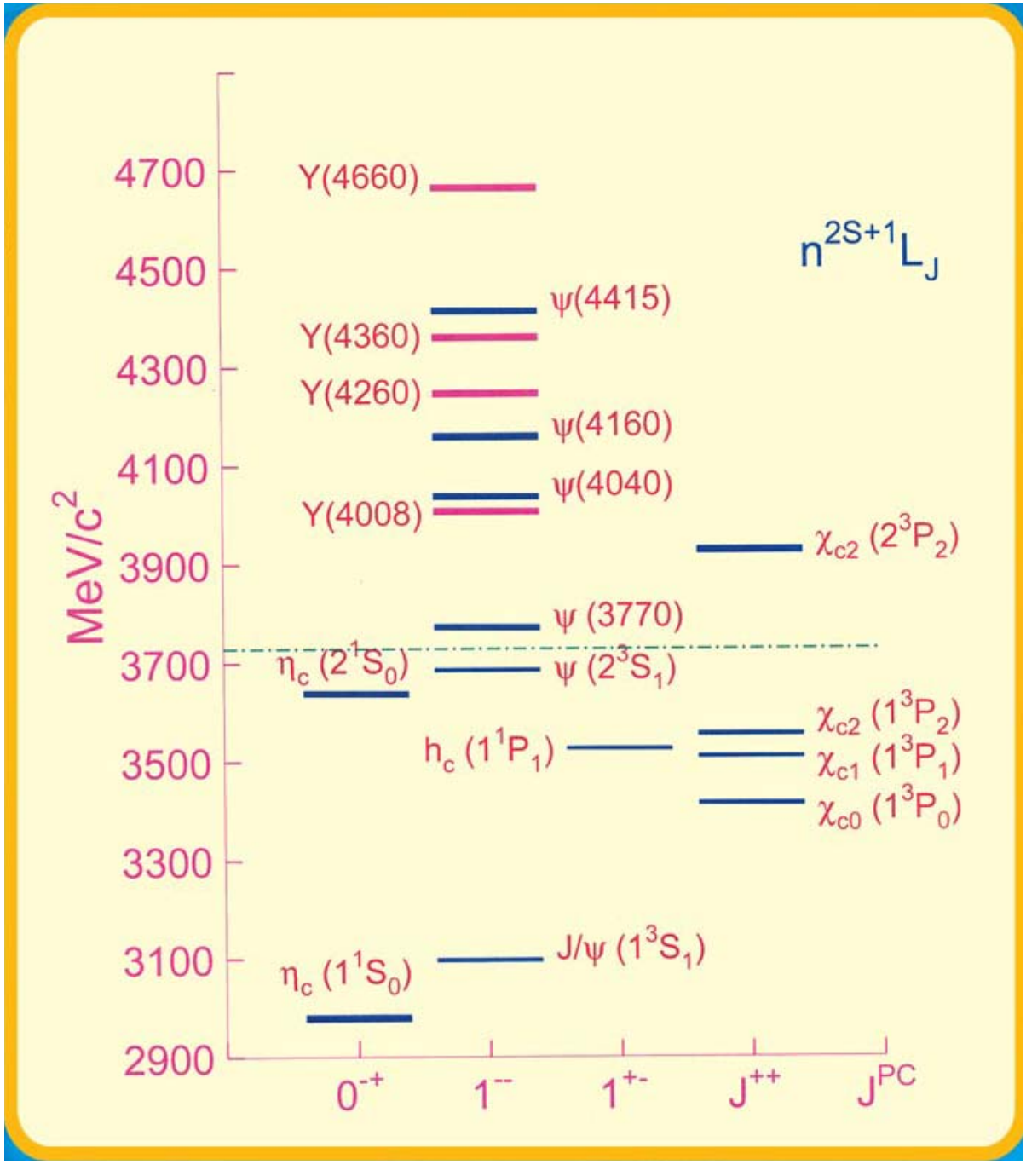
(BES & Belle collaborations)

Fermilab, May 18, 2010

Outline

- Introduction
- Rc measurements
  - R scan: BESII & CLEOc + prior BES
  - ISR: Belle & BaBar
- Vector charmonium spectroscopy
- Summary

High mass vector charmonia



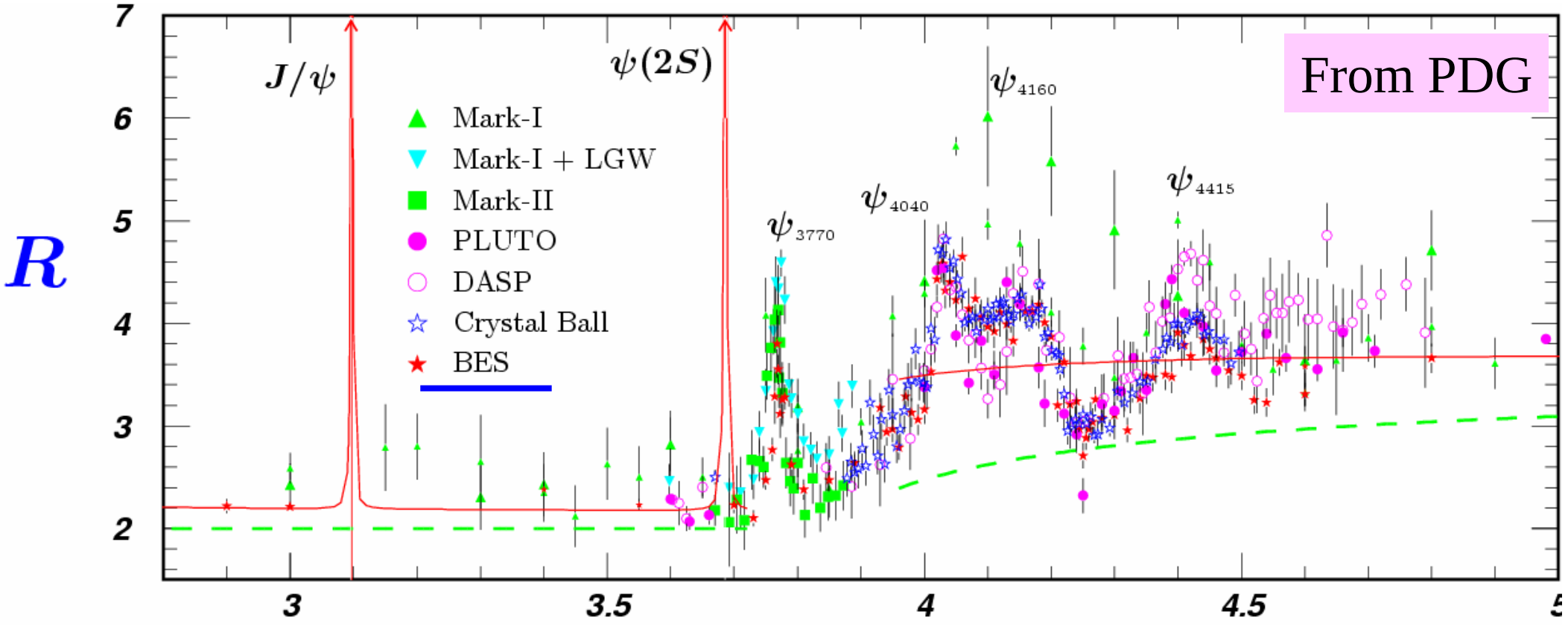
Too many vectors!

What is the nature of the newly observed states?

Charmonium?
Hybrid?
Hadro-charmonium?
Tetraquark?
Molecular?
…

Can we answer?

R & Rc



All the vector charmonium states appear in this plot (between 3.0 and 4.7 GeV!). We extract resonant parameters from these (and more) Rc data!

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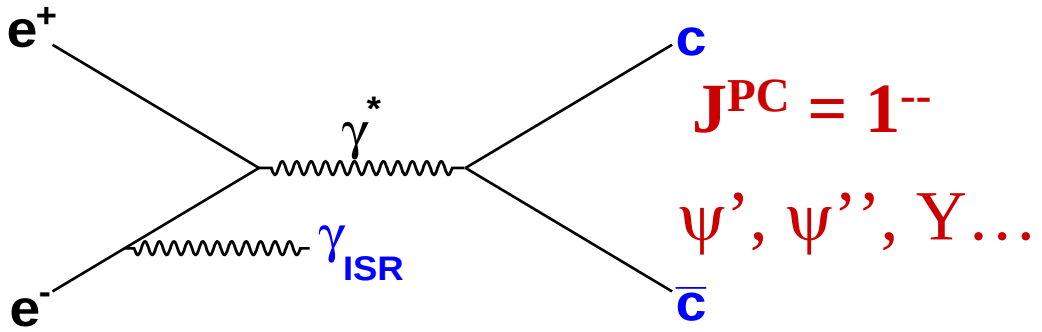
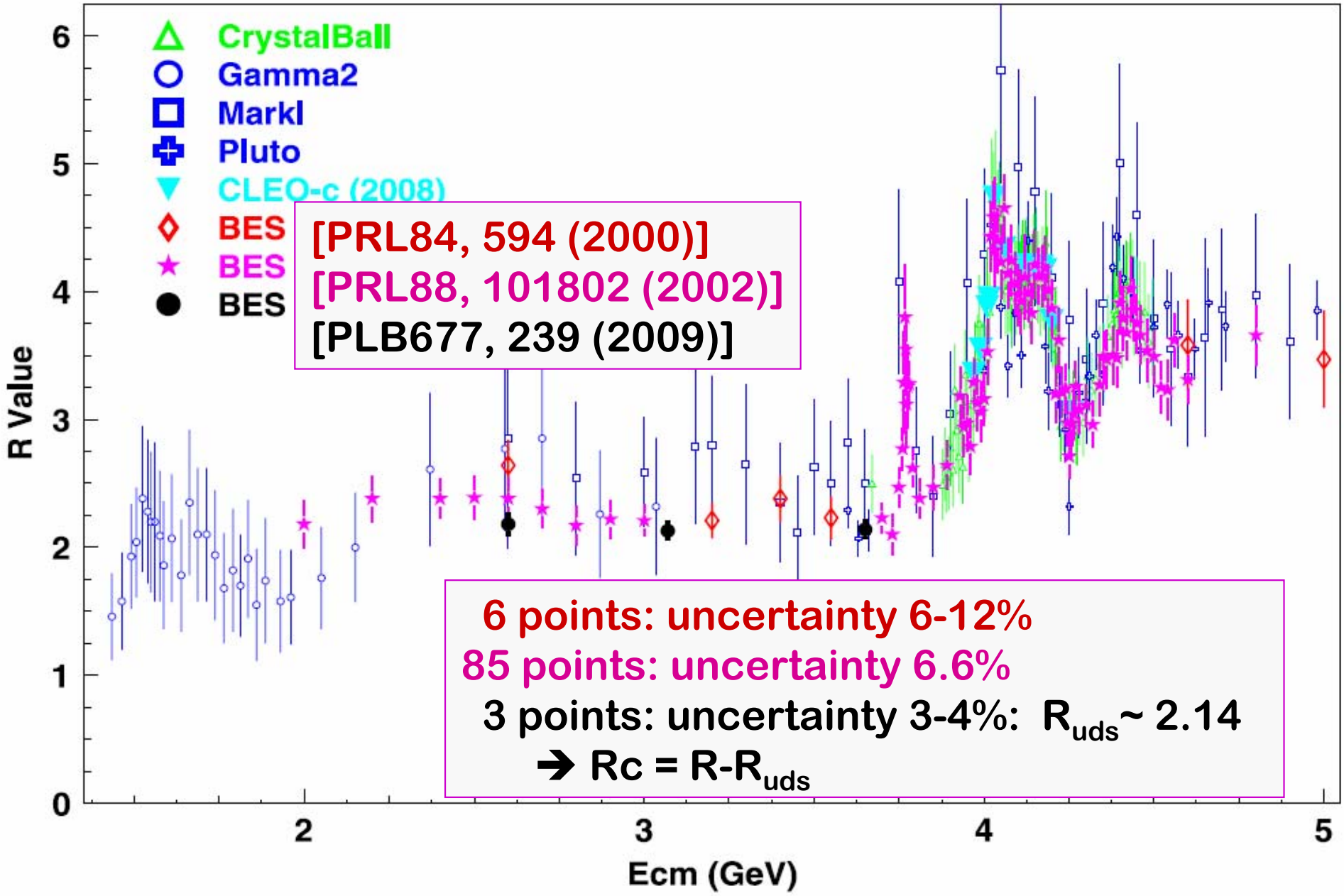
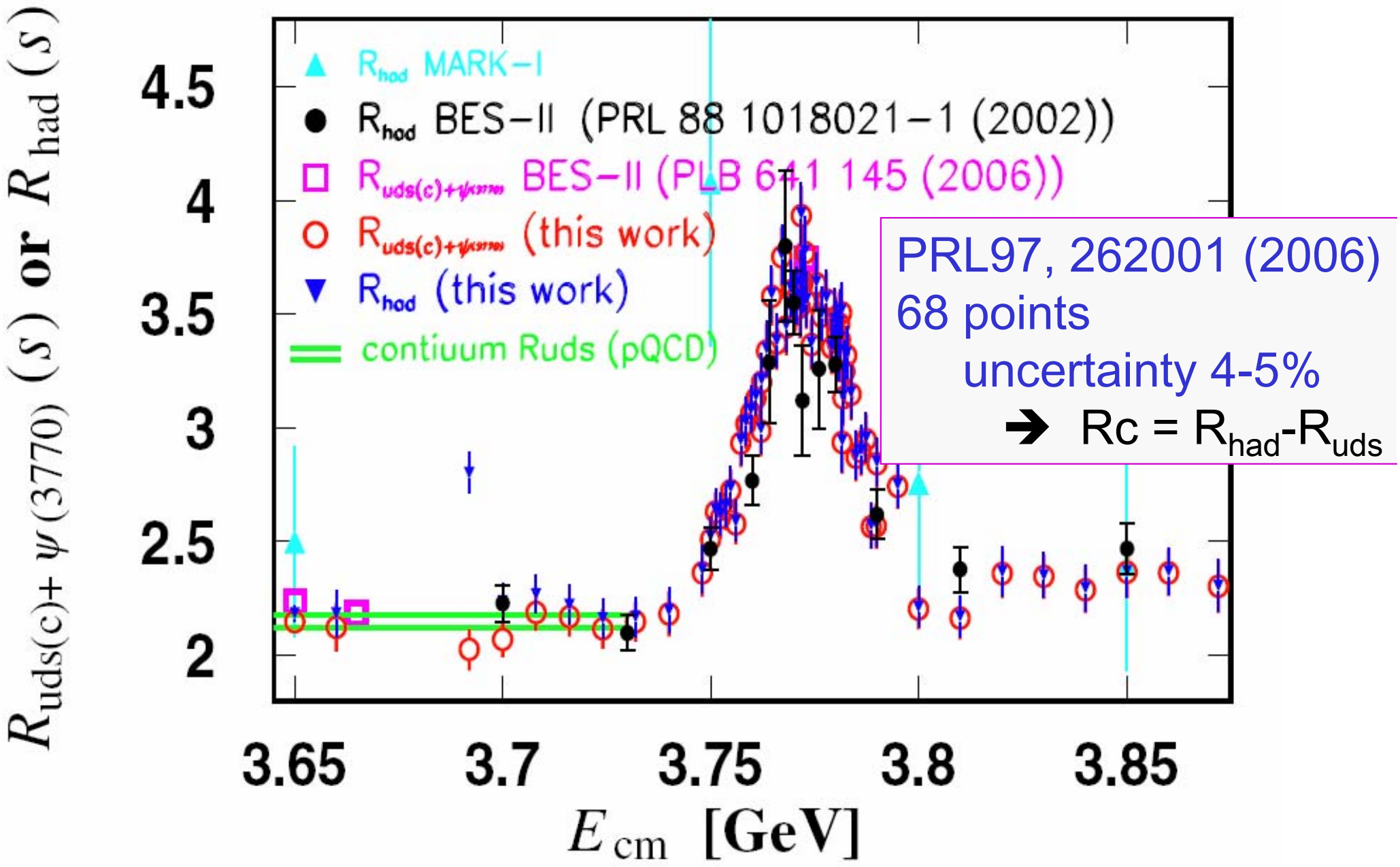


BESII R Scan (2-5 GeV)

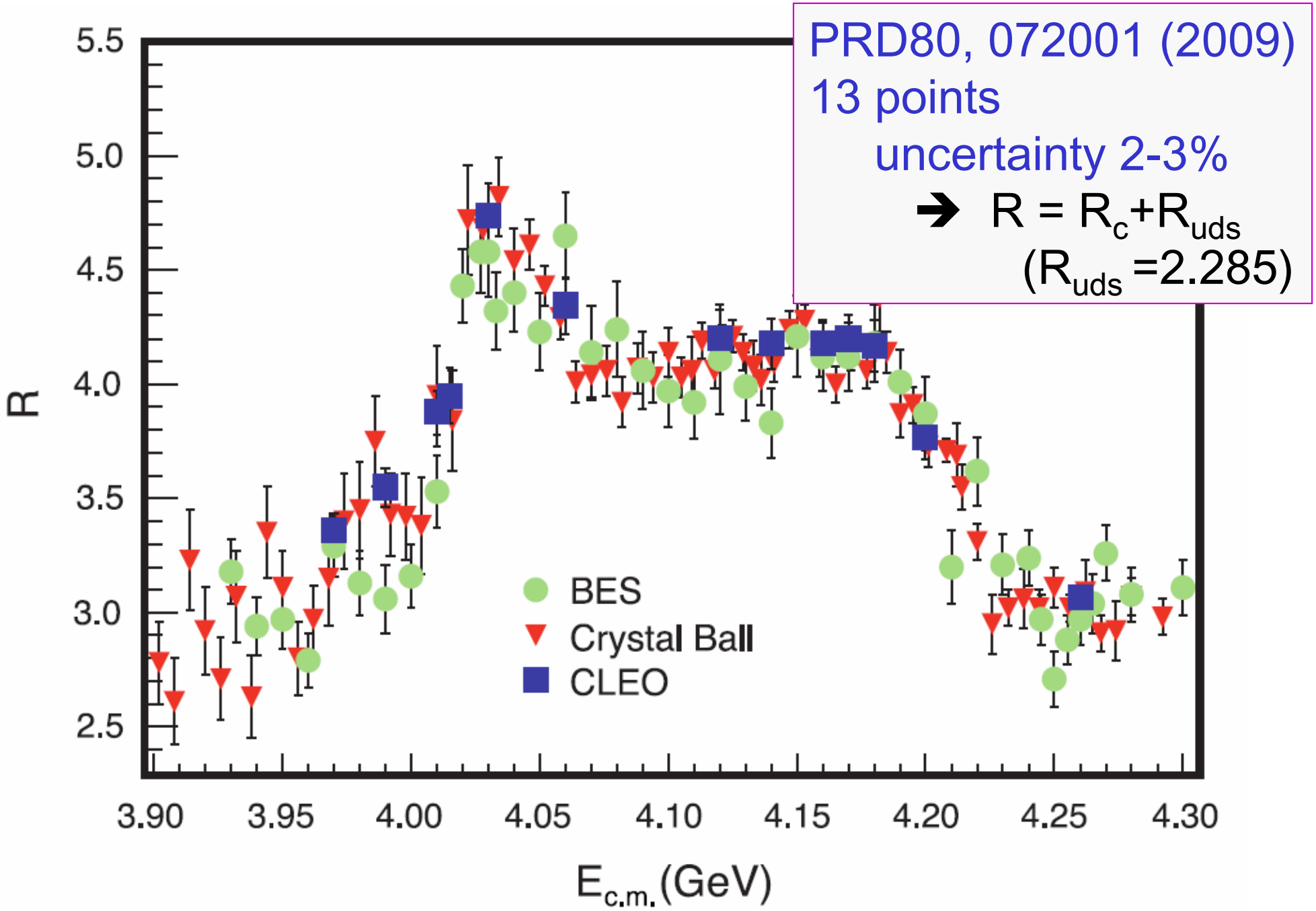


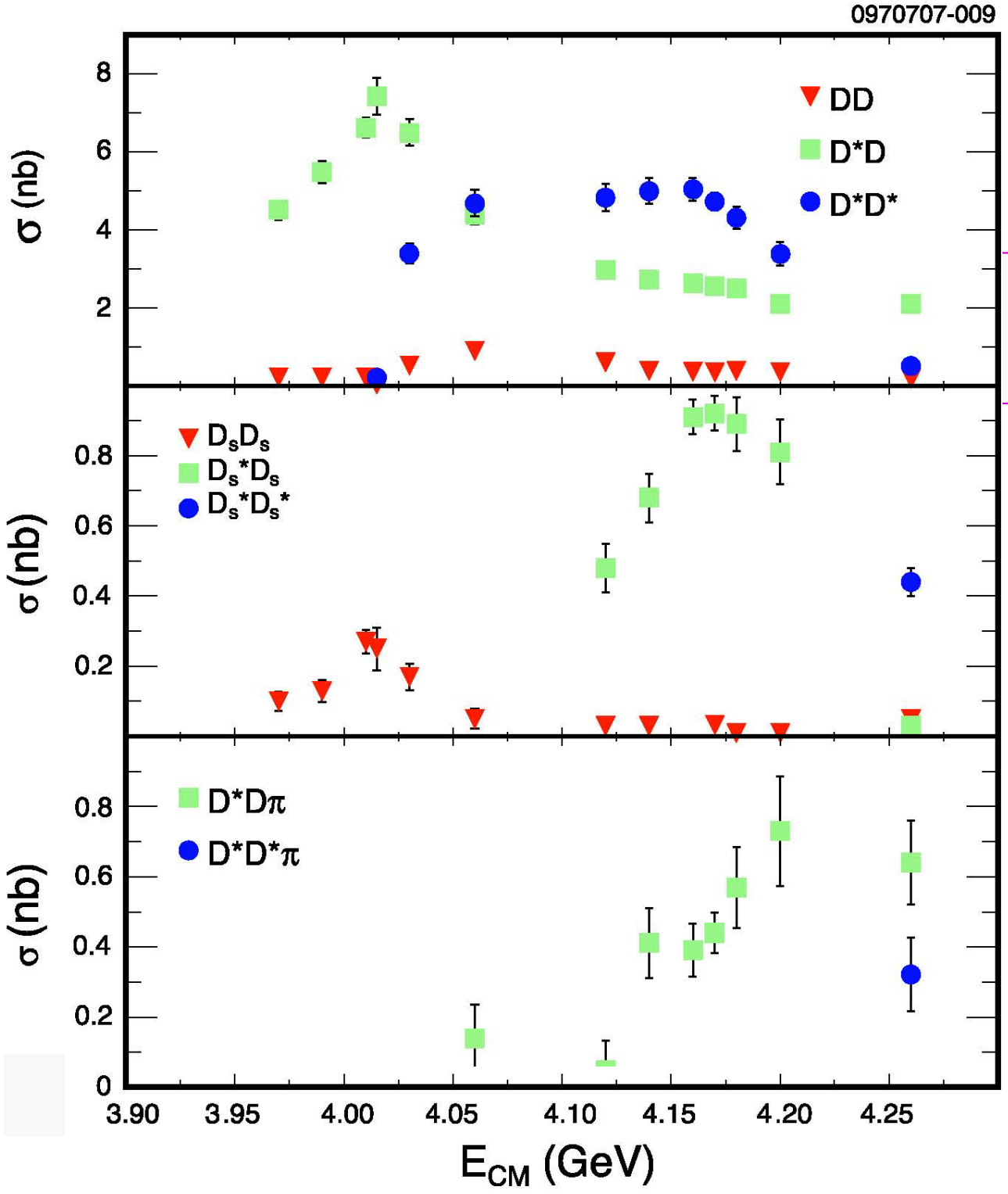
BESII R Scan (around ψ(3773))



PRL97, 262001 (2006)
68 points
uncertainty 4-5%
➔ Rc = R_{had}-R_{uds}

CLEOc R Scan (3.97-4.26 GeV)



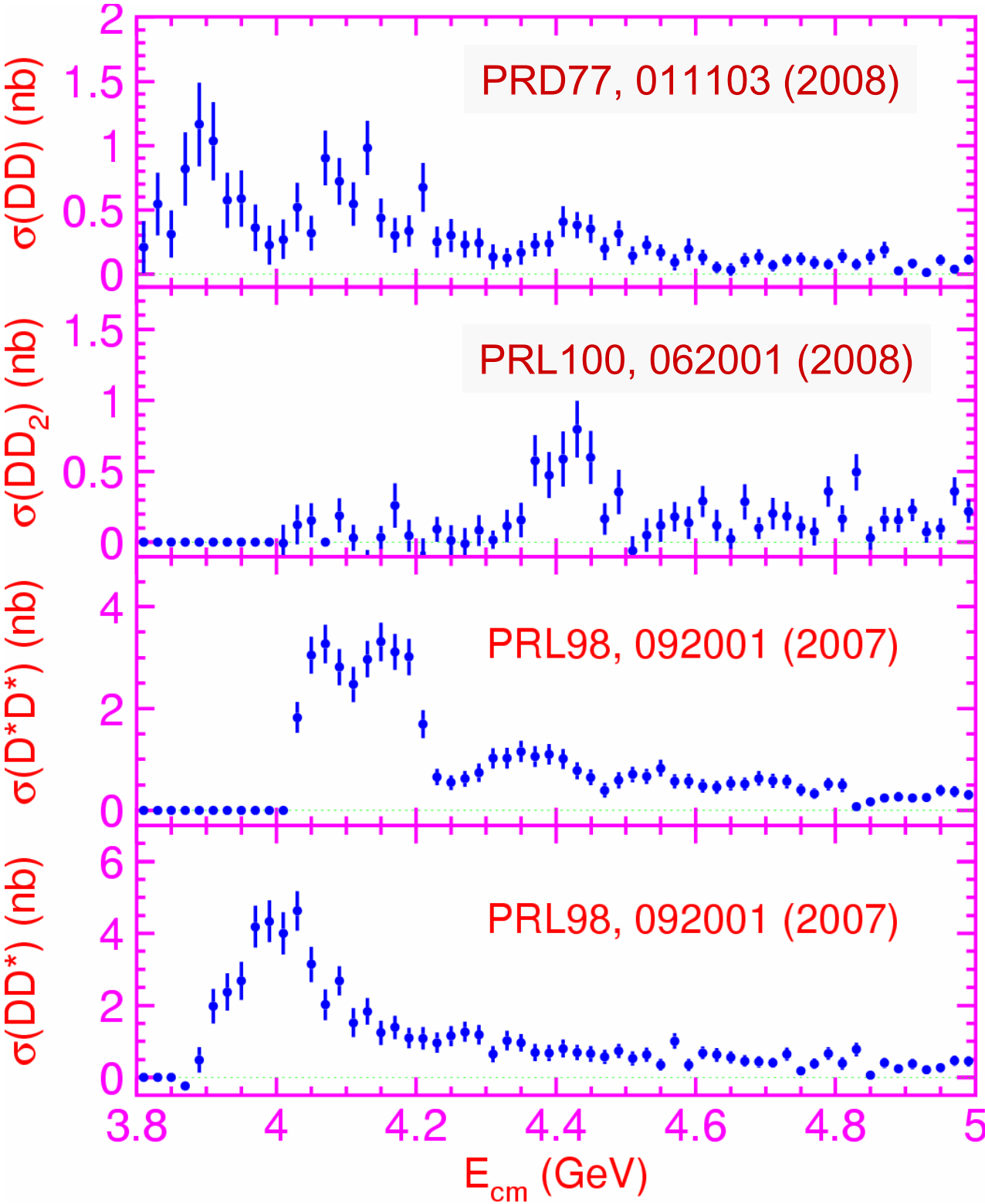


Rc Scan (3.97-4.26 GeV)

CLEOc
PRD80, 072001 (2009)

$E_{c.m.}$ (MeV)	$\int \mathcal{L}dt$ (pb^{-1})
3970	3.85
3990	3.36
4010	5.63
4015	1.47
4030	3.01
4060	3.29
4120	2.76
4140	4.87
4160	10.16
4170	178.89
4180	5.67
4200	2.81
4260	13.11

Belle Rc Scan via ISR

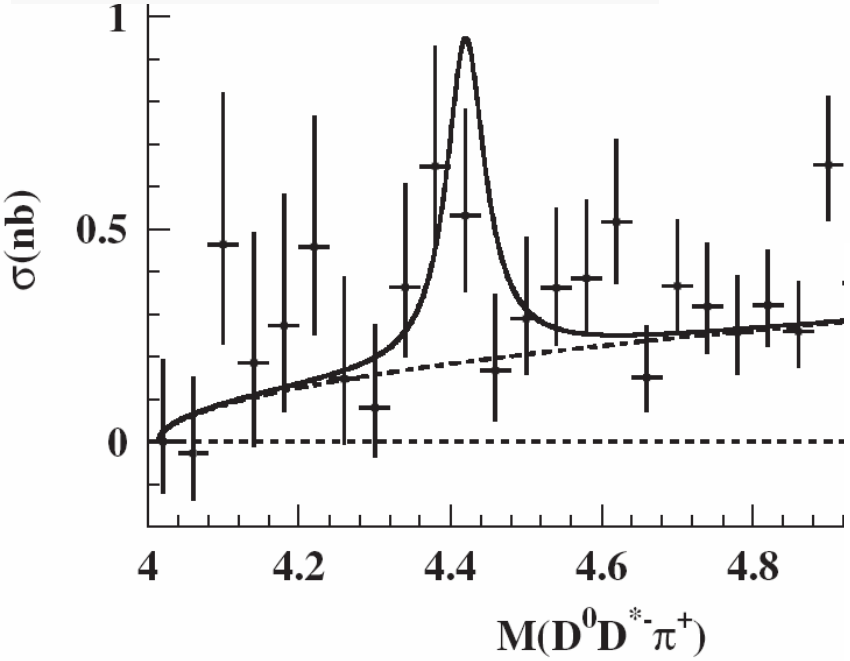


Continuous energy scan. Full mass range in one experiment, errors are large due to low efficiency of ISR & D tag.

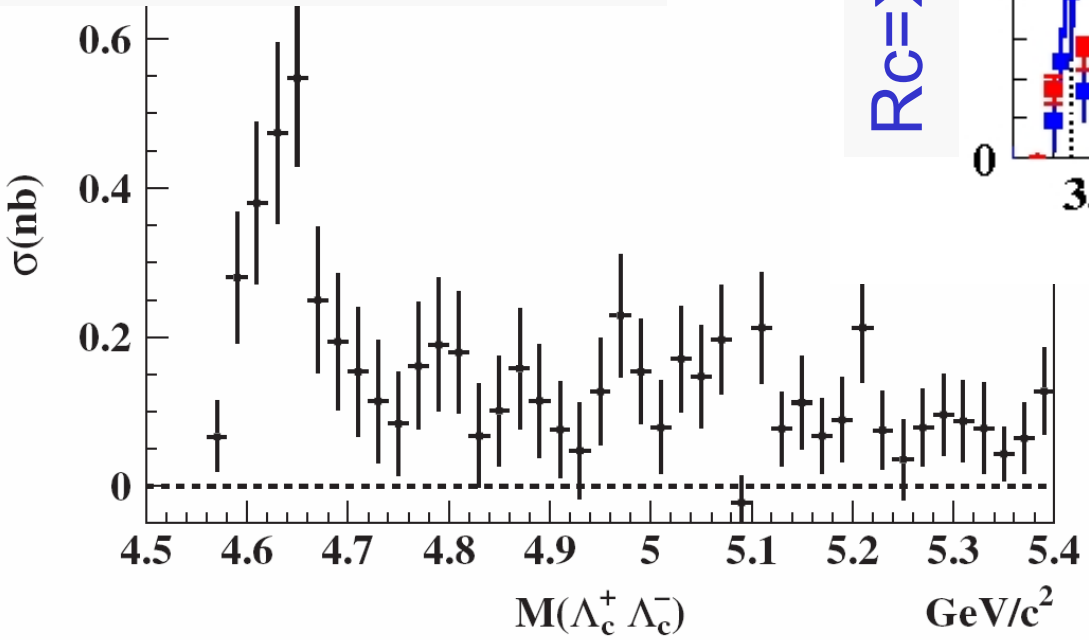
uncertainty 10-50%

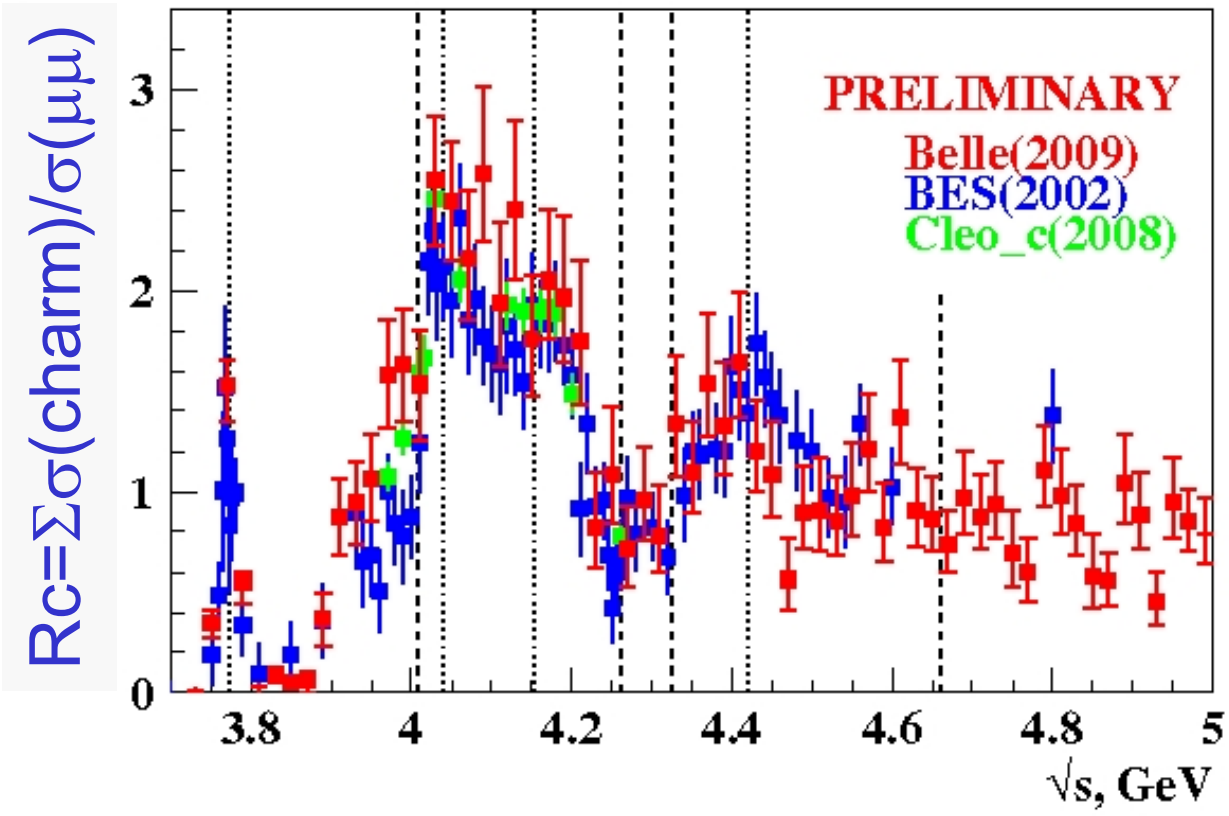
Belle Rc Scan via ISR

PRD80, 091101 (2009)



PRL101, 172001 (2008)

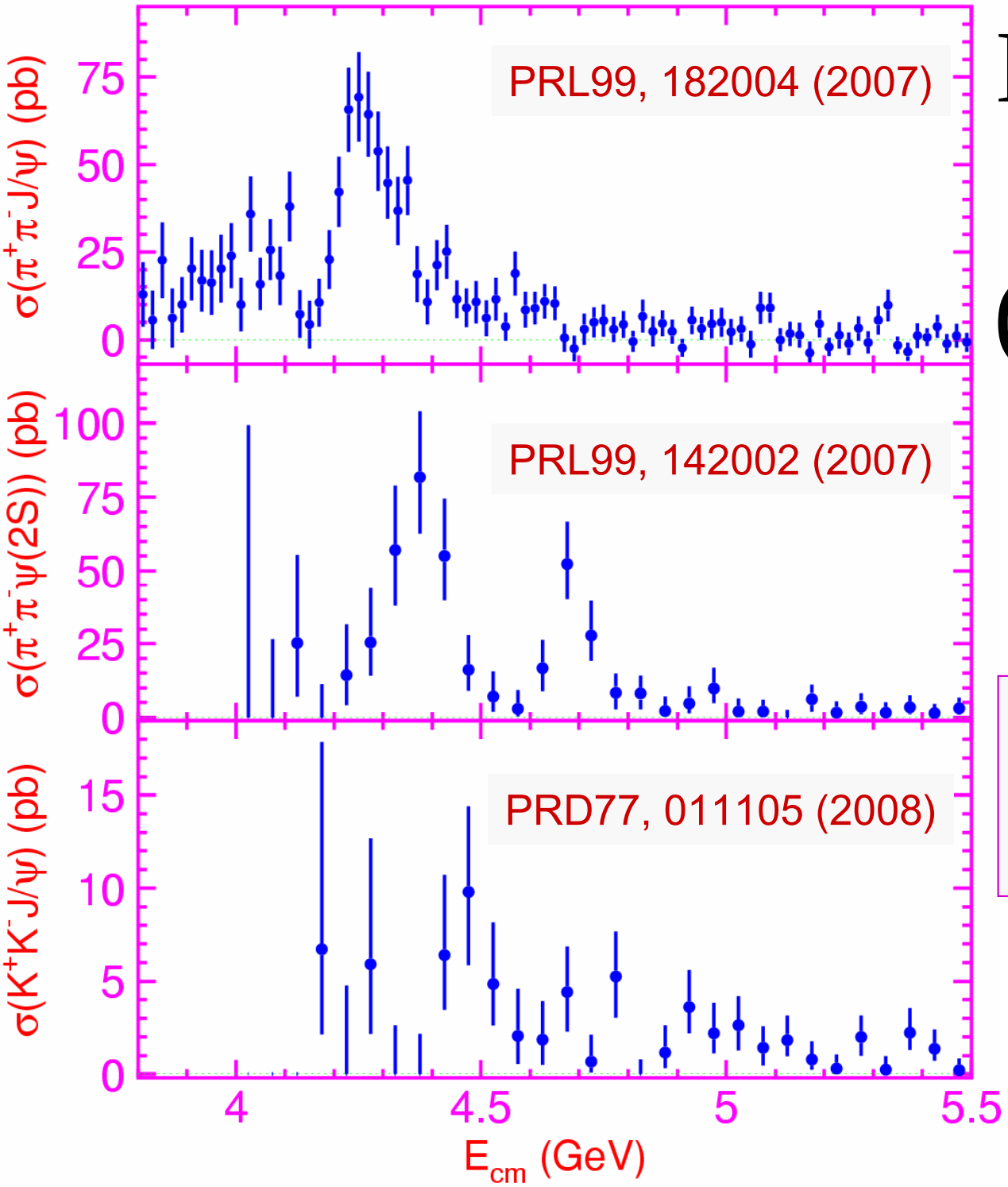




Summed by G. Pakhlova.

Still missing modes (small Xs):

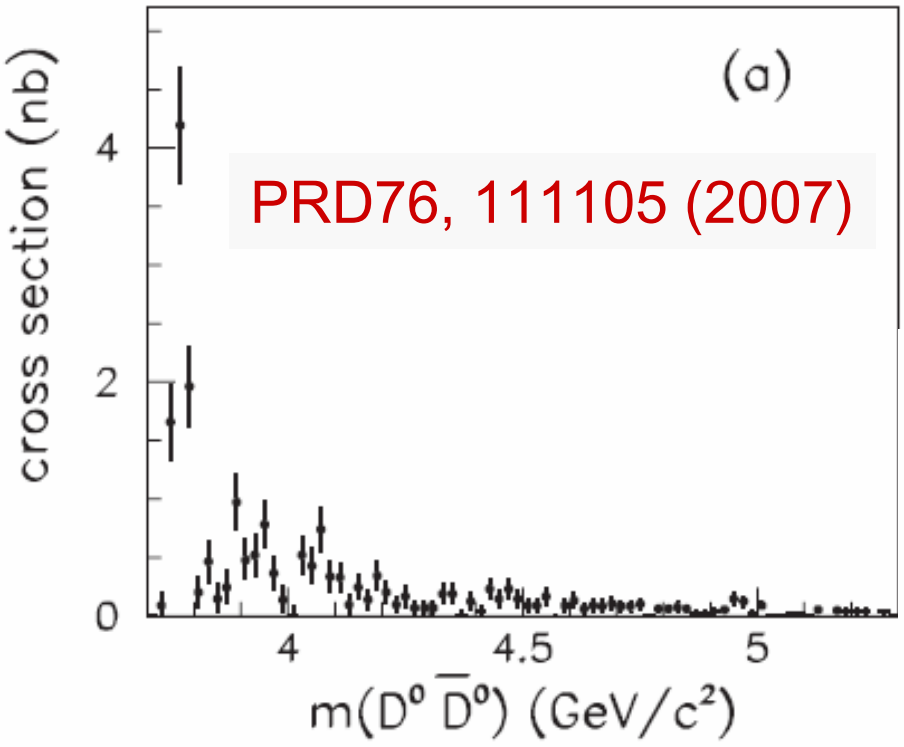
1. Charm strange meson pairs
2. Charmonium+hadron/γ
3. Charm baryons except Λ_c



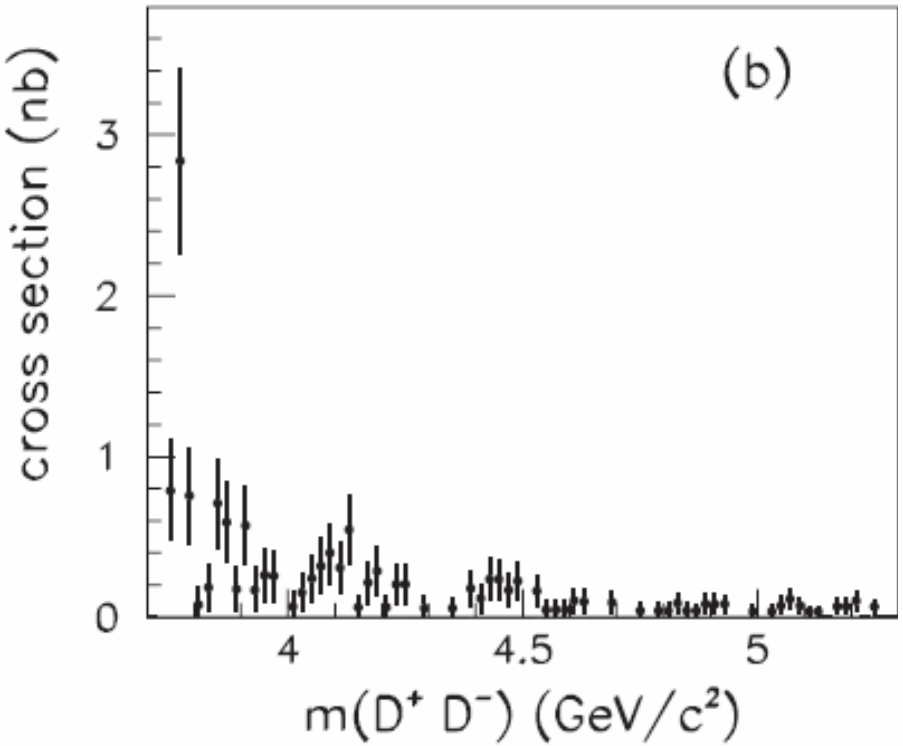
Belle Rc Scan via ISR (charmonium+ hadrons)

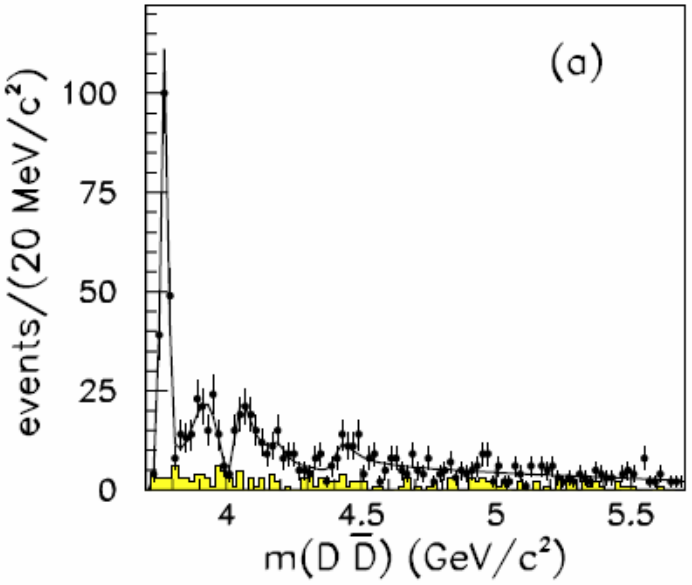
Full reconstruction of the hadronic system, no ISR photon tag

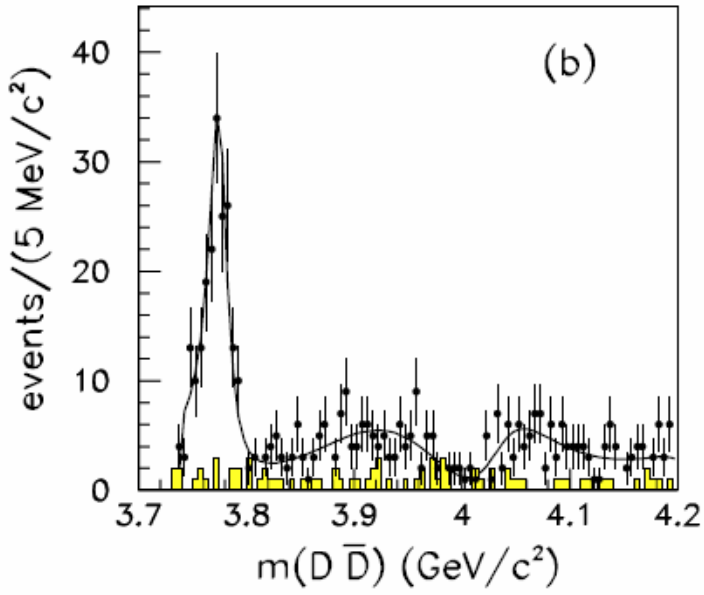
BaBar Rc Scan via ISR



PRD76, 111105 (2007)



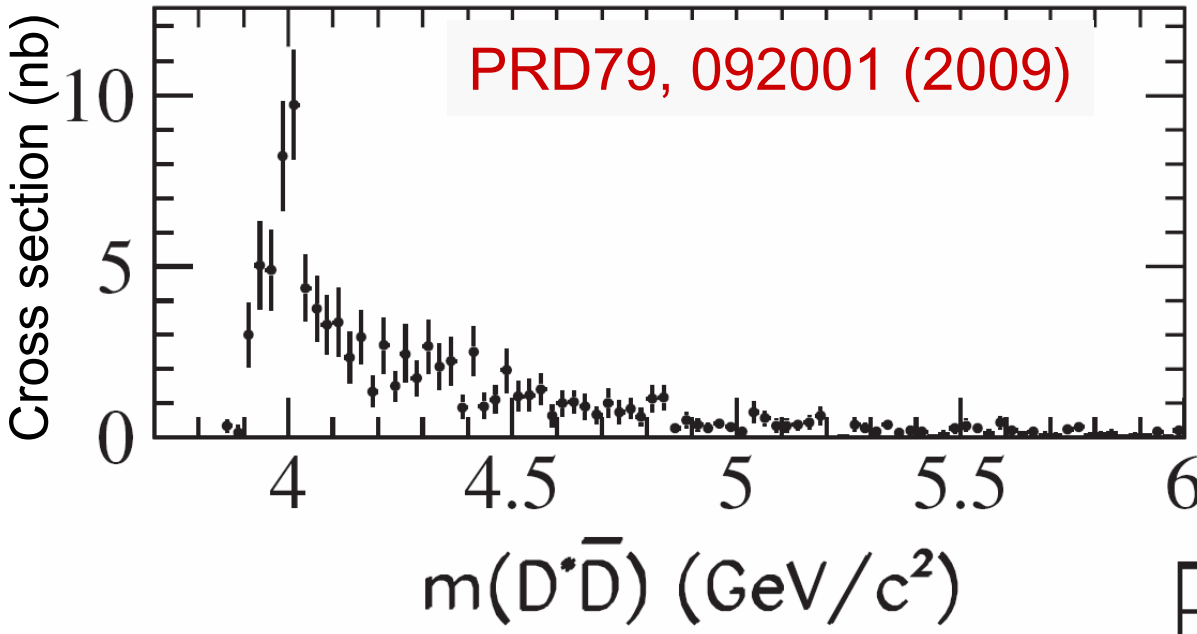


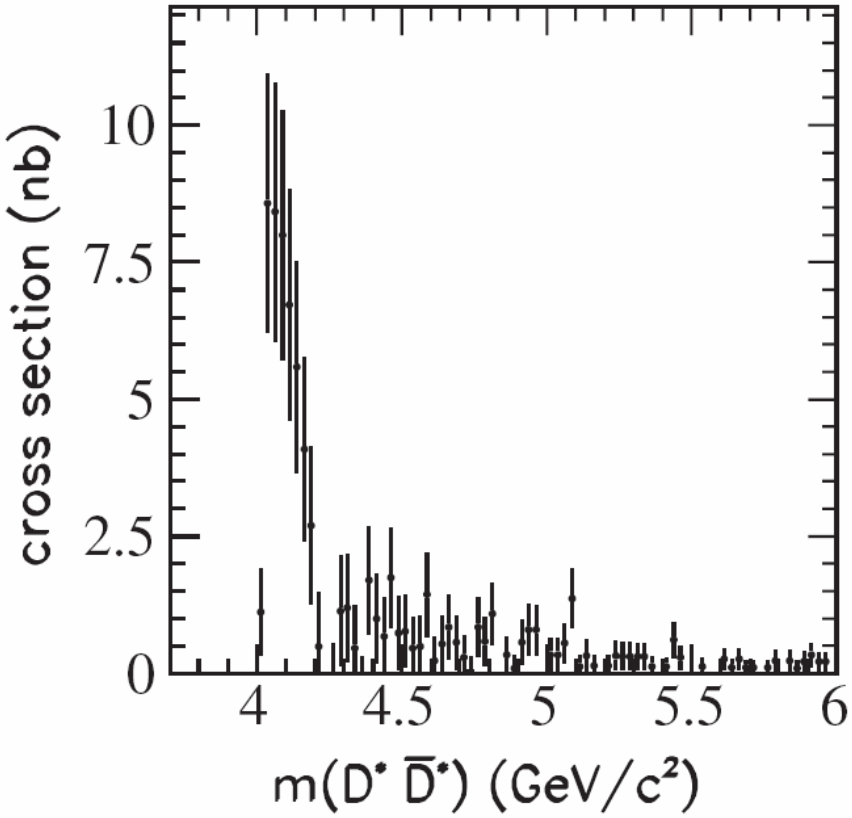


Babar fully reconstruct D- & Dbar decays

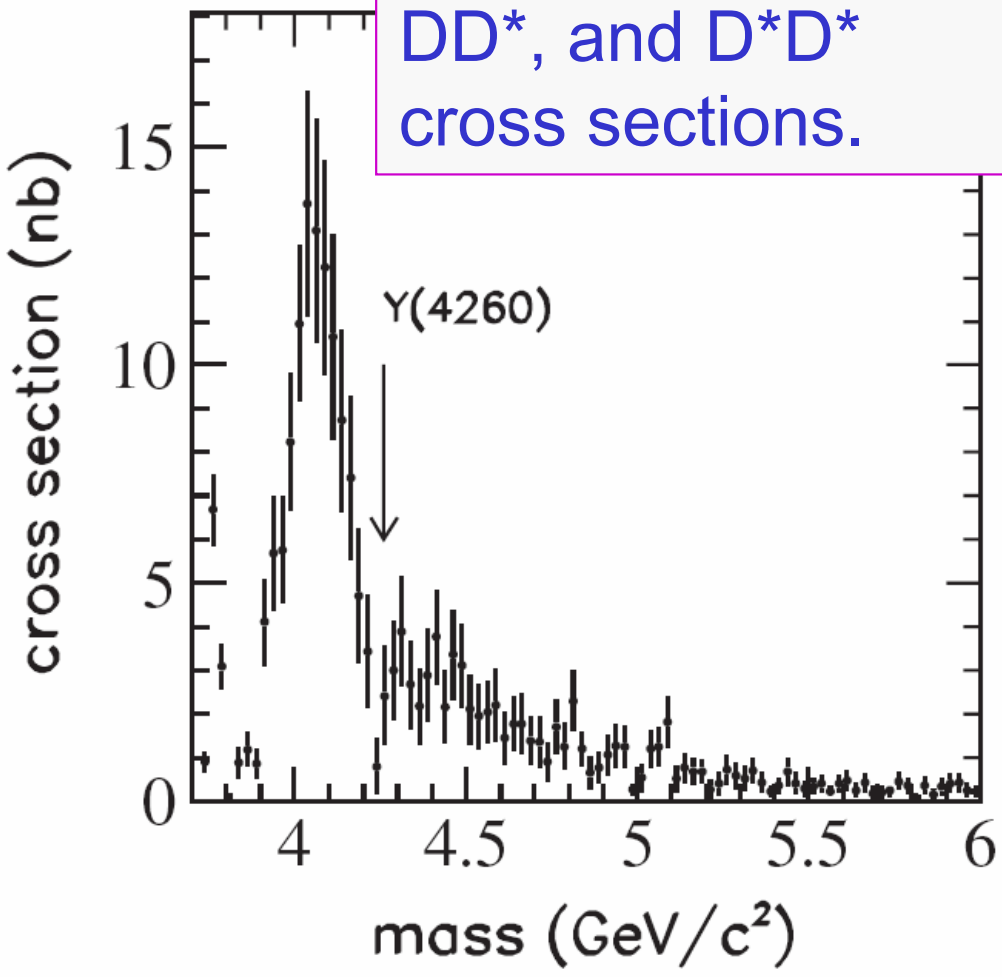
ISR photon detection not required

BaBar Rc Scan via ISR

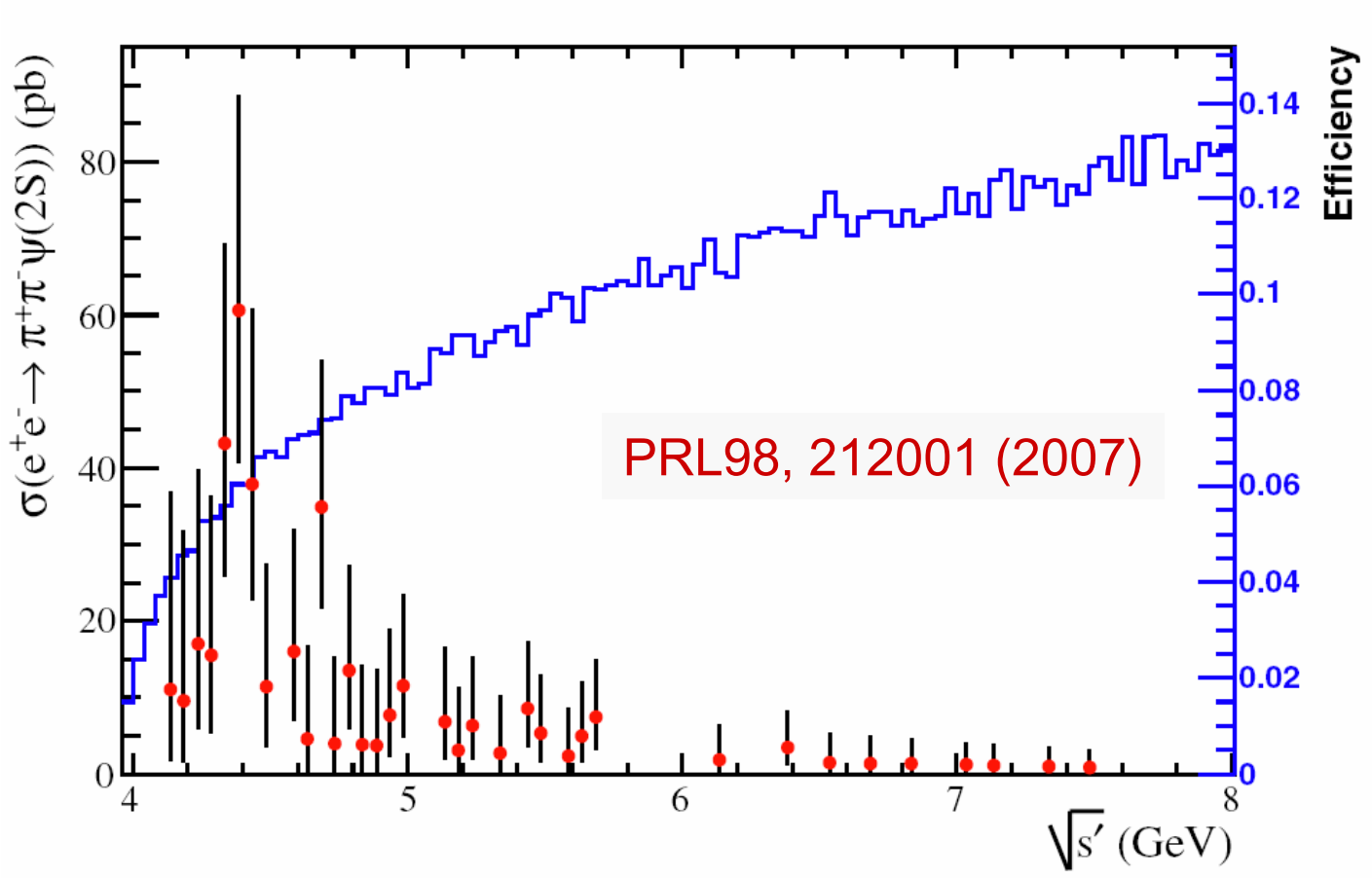




Summed of DDbar, DD*, and D*D* cross sections.



BaBar Rc Scan via ISR (charmonium+hadrons)



Only reported mode from BaBar, $\pi\pi J/\psi$ results not published

A few comments on Rc measurements

- Already lots of data (BES, Belle, BaBar, CLEOc)
- Precisions are not very high, especially for exclusive charm final states
- Charmed strange final states in full range still missing (CLEOc at E<4.3 GeV)
- More charmonium final states from Belle/BaBar full data sample?
- BESIII scan with high statistics
  - 1 fb^{-1}/year now, expect 5 fb^{-1}/year in ~3 years
  - Can measure all final states with cross section > 10 pb
  - May start R scan (E=3-4.6 GeV) in 3-4 years
- Do you have any new idea? Join us or tell us!

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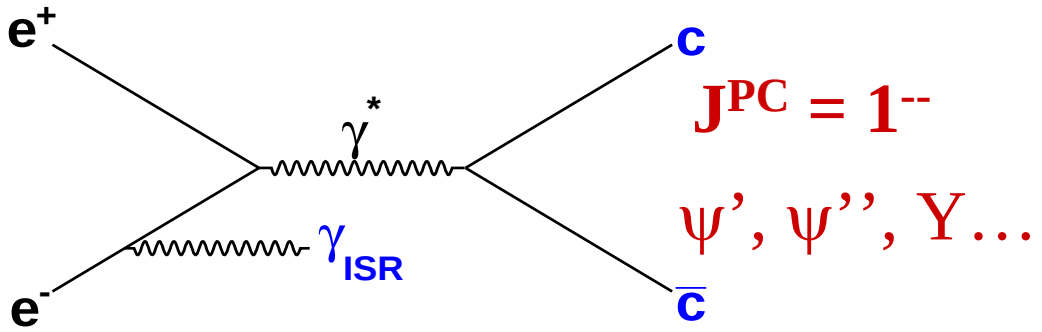
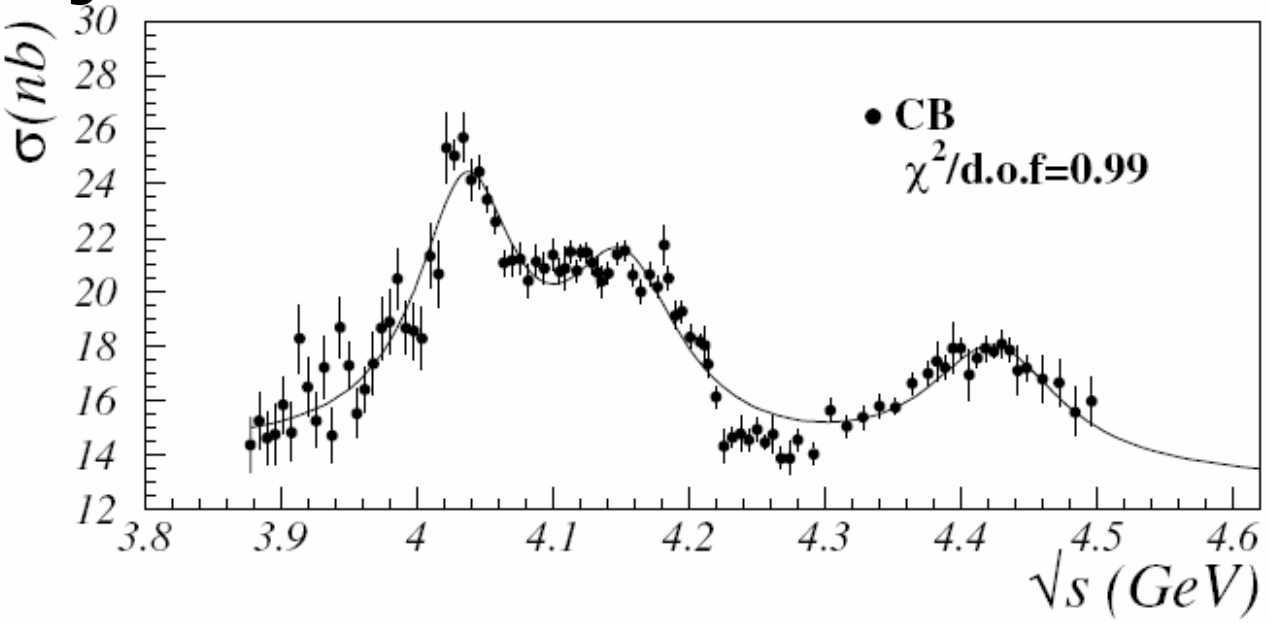
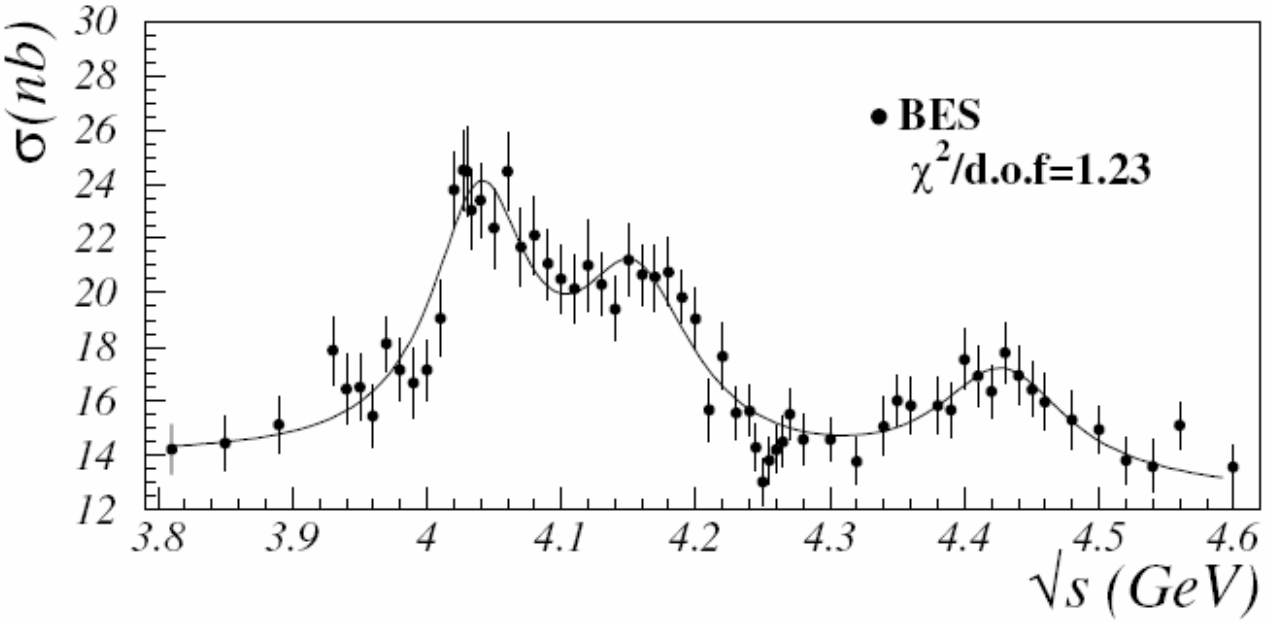


Fit by K.K.Seth

Incoherent sum of 3 BWs

- BES data (M, Γ, Γ_{ee})
  - ψ(4040)
    - 4040 ± 1 MeV
    - 89 ± 6 MeV
    - 0.91 ± 0.13 keV
  - ψ(4160)
    - 4155 ± 5 MeV
    - 107 ± 16 MeV
    - 0.84 ± 0.13 keV
  - ψ(4415)
    - 4429 ± 9 MeV
    - 118 ± 35 MeV
    - 0.64 ±0.23 keV





PRD72, 017501 (2005)

$$\sigma_{BW}(\sqrt{s}) = (3\pi/4p^2)\Gamma_{ee}\Gamma_h/[(\sqrt{s}-M)^2 + (\Gamma_{\rm tot}/2)^2]$$

Fit by BES

$$R_{\rm the} = R_{\rm con} + R_{\rm res}$$

Coherent sum of 4 BWs

$$R_{\rm con} = C_0 + C_1(W - 2M_{D^\pm}) + C_2(W - 2M_{D^\pm})^2$$

$$R_{\rm res} = \frac{\sigma_{\rm res}}{\sigma^0_{\mu\mu}} = \frac{12\pi}{s}\left[|\mathcal{T}_{\psi'}|^2 + |\mathcal{T}_{\rm res}|^2\right]$$

Amplitude of $r \rightarrow f$

$$|\mathcal{T}_{\rm res}|^2 = \sum_f \left| \sum_r \mathcal{T}_r^f(W) \right|^2$$

$$\mathcal{T}_r^f(W) = \frac{M_r\sqrt{\Gamma_r^{ee}\Gamma_r^f}}{W^2 - M_r^2 + iM_r\Gamma_r} e^{i\delta_r}$$

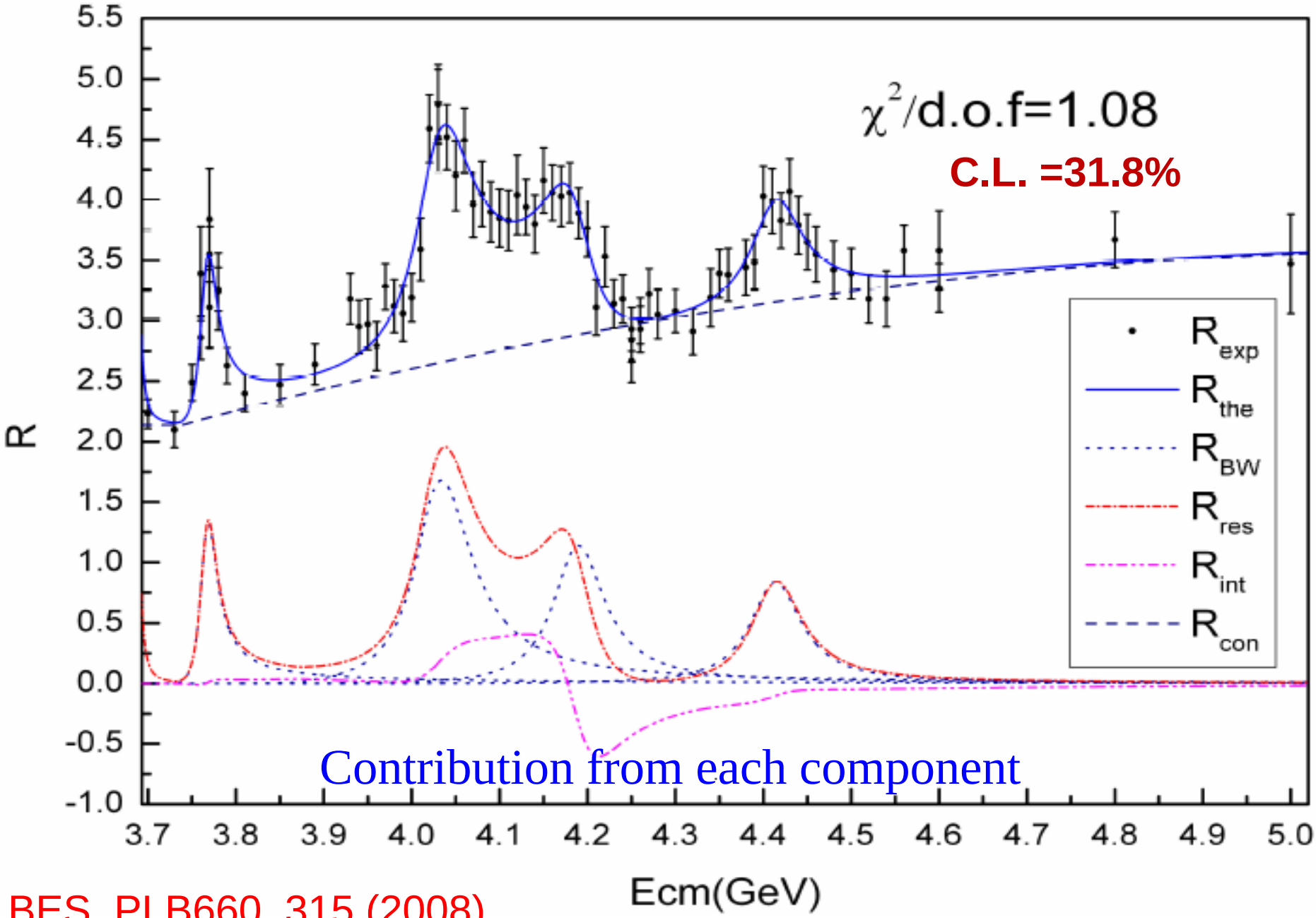
Mass dependent width

$$\Gamma_r^f(W) = \hat{\Gamma}_r \sum_L \frac{Z_f^{2L+1}}{B_L}$$

$$\begin{aligned}
\psi(3770) &\Rightarrow D\bar{D};\\
\psi(4040) &\Rightarrow D\bar{D}, D^*\bar{D}^*, D\bar{D}^*, D_s\bar{D}_s;\\
\psi(4140) &\Rightarrow D\bar{D}, D^*\bar{D}^*, D\bar{D}^*, D_s\bar{D}_s, D_s\bar{D}_s^*;\\
\psi(4415) &\Rightarrow D\bar{D}, D^*\bar{D}^*, D\bar{D}^*, D_s\bar{D}_s, D_s\bar{D}_s^*,\\
&\qquad D_s^*\bar{D}_s^*, D\bar{D}_1, D\bar{D}_2^*.
\end{aligned}$$

BES, PLB660, 315 (2008)

Fit by BES



Contribution from each component

BES, PLB660, 315 (2008)

Final results from BES

The resonance parameters of the high mass charmonia in this work together with the values in PDG2004 [11], PDG2006 [12] and Seth's evaluations [13] based on Crystal Ball and BES data. The total width $\Gamma_{\rm tot} \equiv \Gamma_r(M)$ in Eq. (9)

		$\psi(3770)$	$\psi(4040)$	$\psi(4160)$	$\psi(4415)$
M (MeV/c^2)	PDG2004	3769.9 ± 2.5	4040 ± 10	4159 ± 20	4415 ± 6
	PDG2006	3771.1 ± 2.4	4039 ± 1	4153 ± 3	4421 ± 4
	CB (Seth)	–	4037 ± 2	4151 ± 4	4425 ± 6
	BES (Seth)	–	4040 ± 1	4155 ± 5	4455 ± 6
	BES (this work)	3772.0 ± 1.9	4039.6 ± 4.3	4191.7 ± 6.5	4415.1 ± 7.9
$\Gamma_{\rm tot}$ (MeV)	PDG2004	23.6 ± 2.7	52 ± 10	78 ± 20	43 ± 15
	PDG2006	23.0 ± 2.7	80 ± 10	103 ± 8	62 ± 20
	CB (Seth)	–	85 ± 10	107 ± 10	119 ± 16
	BES (Seth)	–	89 ± 6	107 ± 16	118 ± 35
	BES (this work)	30.4 ± 8.5	84.5 ± 12.3	71.8 ± 12.3	71.5 ± 19.0
Γ_{ee} (keV)	PDG2004	0.26 ± 0.04	0.75 ± 0.15	0.77 ± 0.23	0.47 ± 0.10
	PDG2006	0.24 ± 0.03	0.86 ± 0.08	0.83 ± 0.07	0.58 ± 0.07
	CB (Seth)	–	0.88 ± 0.11	0.83 ± 0.08	0.72 ± 0.11
	BES (Seth)	–	0.91 ± 0.13	0.84 ± 0.13	0.64 ± 0.23
	BES (this work)	0.22 ± 0.05	0.83 ± 0.20	0.48 ± 0.22	0.35 ± 0.12
δ (degree)	BES (this work)	0	130 ± 46	293 ± 57	234 ± 88

BES, PLB660, 315 (2008)

Multiple solutions

Parameter	Solution I	Solution II
σ_0 [nb]	7.88 ± 0.04	7.88 ± 0.08
$\Re(Z)$	0.106 ± 0.004	0.106 ± 0.006
$\Im(Z)$	-0.103 ± 0.003	-1.90 ± 0.006
σ' [nb/MeV]	0.064 ± 0.002	0.064 ± 0.006
$\mathcal{B}(\phi \to \omega\pi^0)$	4.61×10^{-5}	7.62×10^{-3}

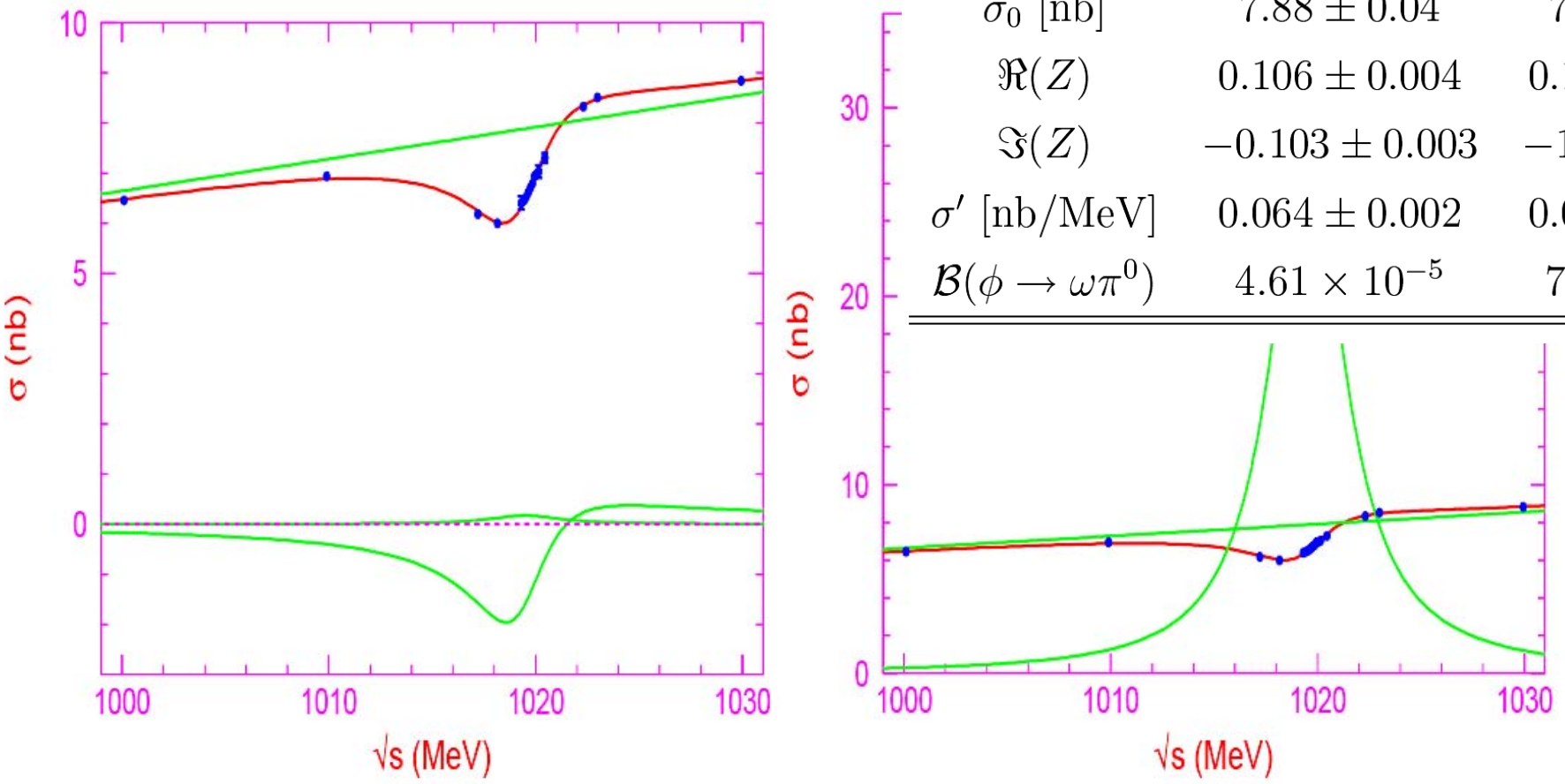


Figure 2: Fit to the $e^+e^- \to \omega\pi^0$ cross sections as a function of center-of-mass energy.

CZY, X.H. Mo, P. Wang, arXiv:0911.4791
Same problem exists in fitting Rc data

Multiple solutions in R-fit

Simplified parameterization of the resonance amplitudes

$$\sigma^{the.} = \sigma^{res.} + \sigma^{con.}$$

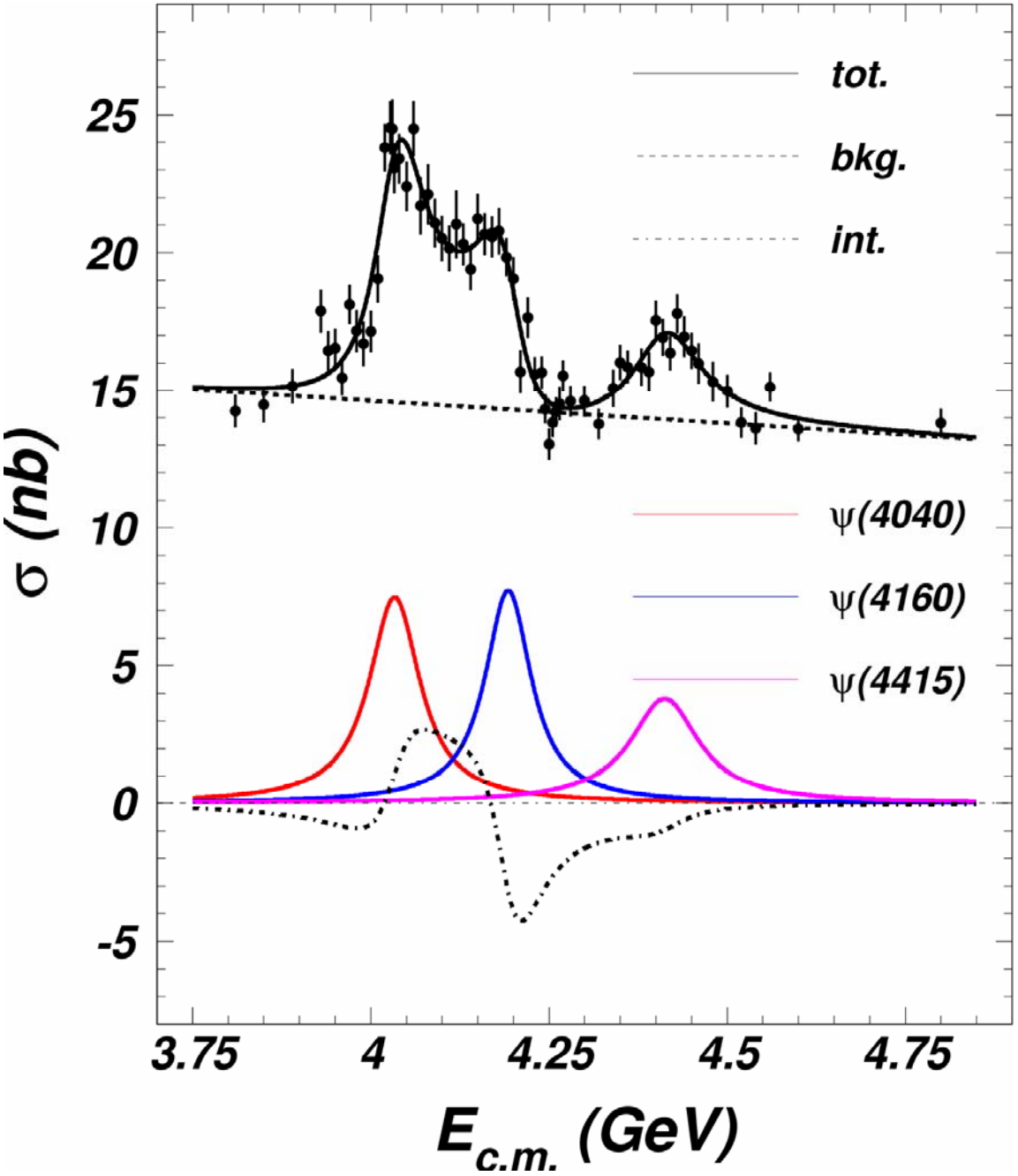
$$\sigma^{con.} = A + B(\sqrt{s} - 2M_{D^\pm})$$

$$\sigma^{res.}(s) = \left| \sum_{j=1}^{3} T_j(s) \right|^2$$

$$T_j(s) = \frac{\sqrt{12\pi\Gamma_j^h\Gamma_j^{ee}}\, e^{i\phi_j}}{s - M_j^2 + iM_j\Gamma_j^t}$$

X.H. Mo, CZY, P. Wang, in preparation

Multiple solutions in BES data



4 solutions with the same fit quality!

BES official fit is only one of the four possible solutions!

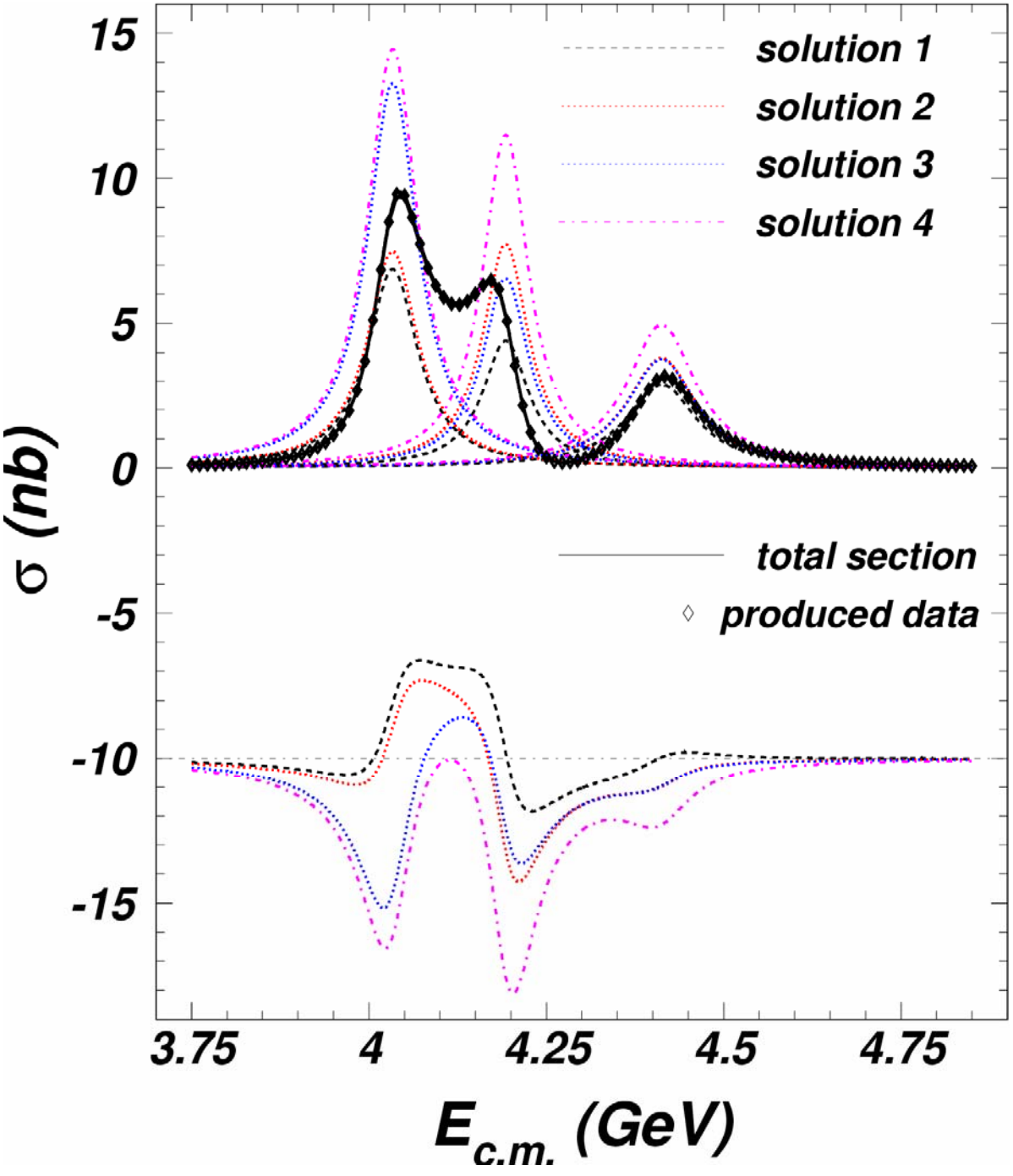
X.H. Mo, CZY, P. Wang, in preparation

Multiple solutions in BES data

	Parameter	$\psi(4040)$	$\psi(4160)$	$\psi(4415)$
Same for all solutions	M (MeV)	4034 ± 6	4193 ± 7	4412 ± 15
	Γ_t (MeV)	87 ± 11	79 ± 14	118 ± 32
Sol. I (same as BES)	$\Gamma_{ee}^{(1)}$ (keV)	0.66 ± 0.22	0.42 ± 0.16	0.45 ± 0.13
	$\phi^{(1)}$ (radian)	0 (fixed)	2.7 ± 0.8	2.0 ± 0.9
Sol. II	$\Gamma_{ee}^{(2)}$ (keV)	0.72 ± 0.24	0.73 ± 0.18	0.60 ± 0.25
	$\phi^{(2)}$ (radian)	0 (fixed)	3.1 ± 0.7	1.4 ± 1.2
Sol.III	$\Gamma_{ee}^{(3)}$ (keV)	1.28 ± 0.45	0.62 ± 0.30	0.59 ± 0.20
	$\phi^{(3)}$ (radian)	0 (fixed)	3.7 ± 0.4	3.8 ± 0.8
Sol. IV	$\Gamma_{ee}^{(4)}$ (keV)	1.41 ± 0.12	1.10 ± 0.15	0.78 ± 0.17
	$\phi^{(4)}$ (radian)	0 (fixed)	4.1 ± 0.1	3.2 ± 0.3

X.H. Mo, CZY, P. Wang, in preparation

Multiple solutions in BES data



Leptonic partial widths are very different in different solutions.

Toy MC (100 points, 1% error) shows that when data are more precise, the difference in Γ_{ee} could be very significant.

Which solution is PHYSICS?

X.H. Mo, CZY, P. Wang, in preparation

Choose one from multiple solutions

Parameter	$\psi(4040)$	$\psi(4160)$	$\psi(4415)$
M (MeV)	4033.5 ± 0.3	4192.8 ± 0.3	4412.4 ± 0.4
Γ_t (MeV)	87.23 ± 0.49	79.00 ± 0.53	118.11 ± 0.56
$\Gamma_{ee}^{(1)}$ (keV)	0.664 ± 0.005	0.417 ± 0.004	0.454 ± 0.003
$\phi^{(1)}$ (radian)	0 (fixed)	2.701 ± 0.012	2.002 ± 0.012
$\Gamma_{ee}^{(2)}$ (keV)	0.723 ± 0.006	0.731 ± 0.005	0.596 ± 0.003
$\phi^{(2)}$ (radian)	0 (fixed)	3.051 ± 0.001	1.432 ± 0.014
$\Gamma_{ee}^{(3)}$ (keV)	1.283 ± 0.005	0.620 ± 0.006	0.590 ± 0.003
$\phi^{(3)}$ (radian)	0 (fixed)	3.732 ± 0.006	3.789 ± 0.013
$\Gamma_{ee}^{(4)}$ (keV)	1.397 ± 0.006	1.087 ± 0.008	0.774 ± 0.003
$\phi^{(4)}$ (radian)	0 (fixed)	4.082 ± 0.005	3.218 ± 0.009

Toy MC with 100 data points with 1% relative error in R measurement.

Which solution should we choose?

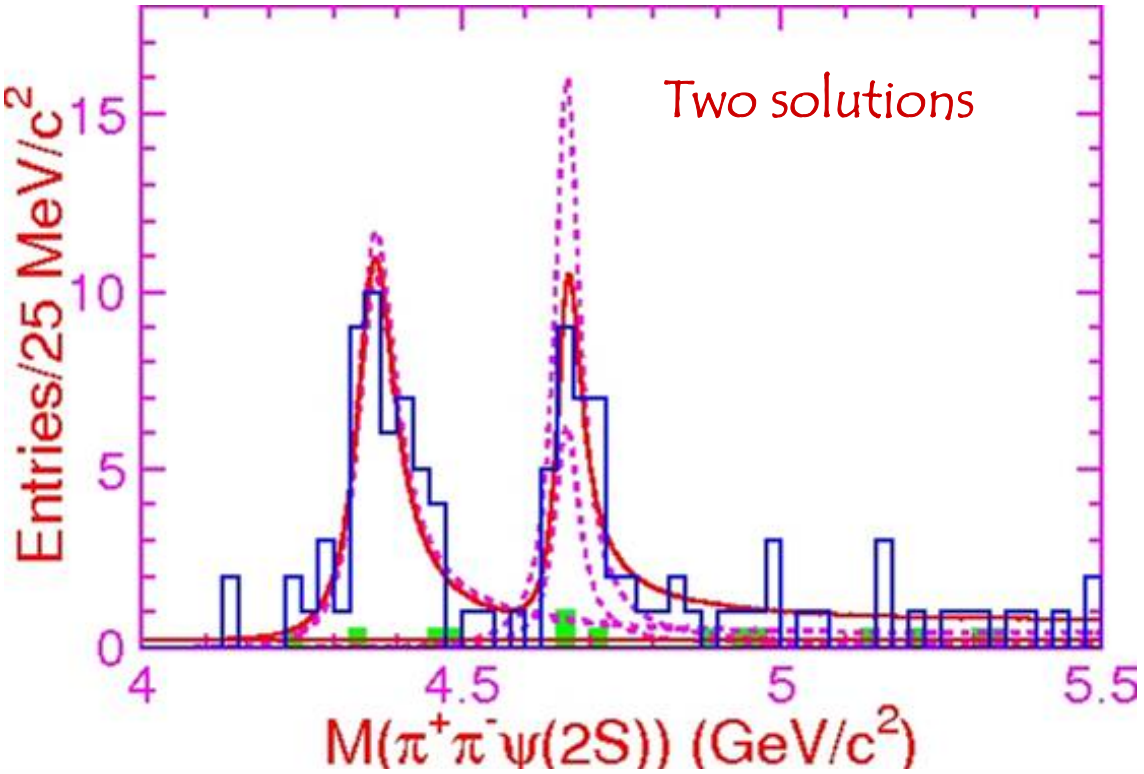
X.H. Mo, CZY, P. Wang, in preparation

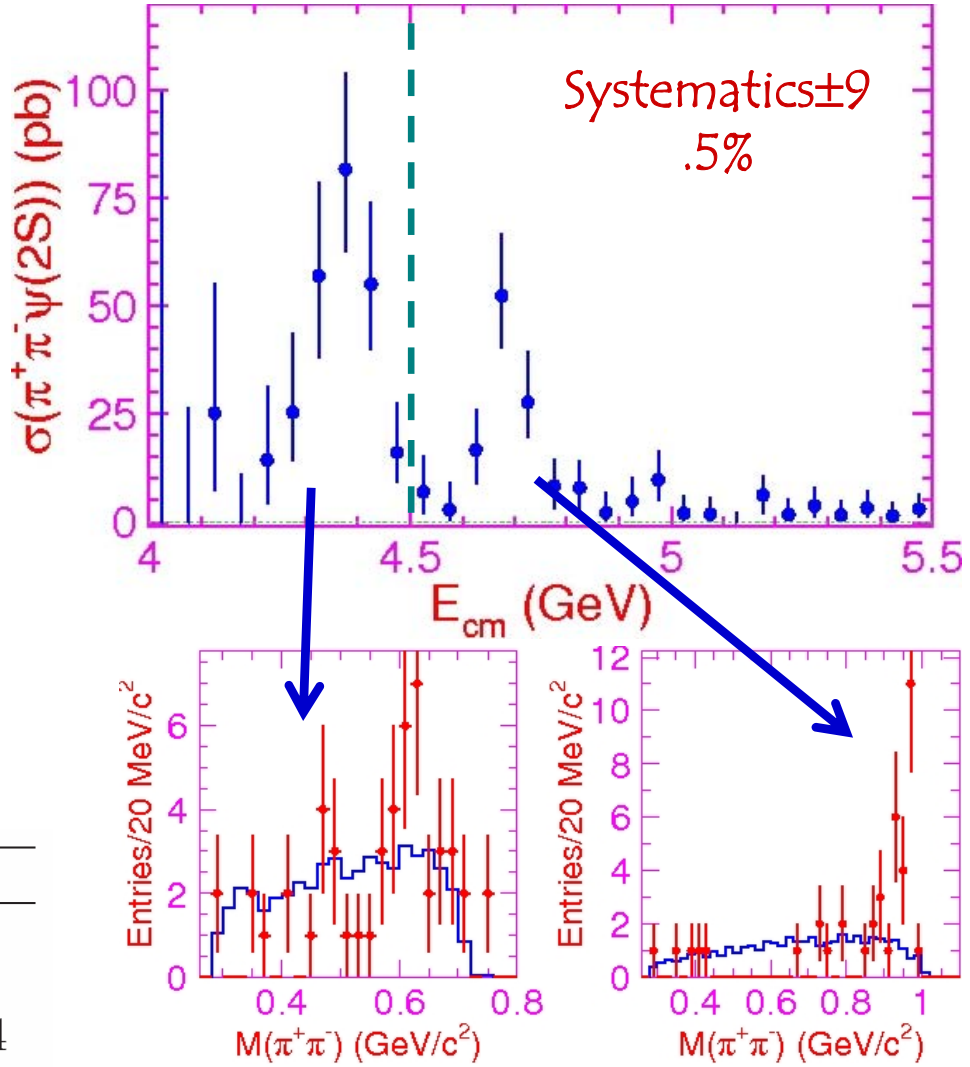
Summary

- Rc measurements
  - R scan: BESII & CLEOc + prior BES
  - ISR: Belle & BaBar
- Vector charmonium spectroscopy
  - How to describe the resonances
  - Use not only inclusive data, but also charm cross sections
  - Multiple solutions
- Future
  - More data from BESIII (<3% error in R)
  - Better models
  - Fit ψ's and Y's simultaneously

Thanks a lot!

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





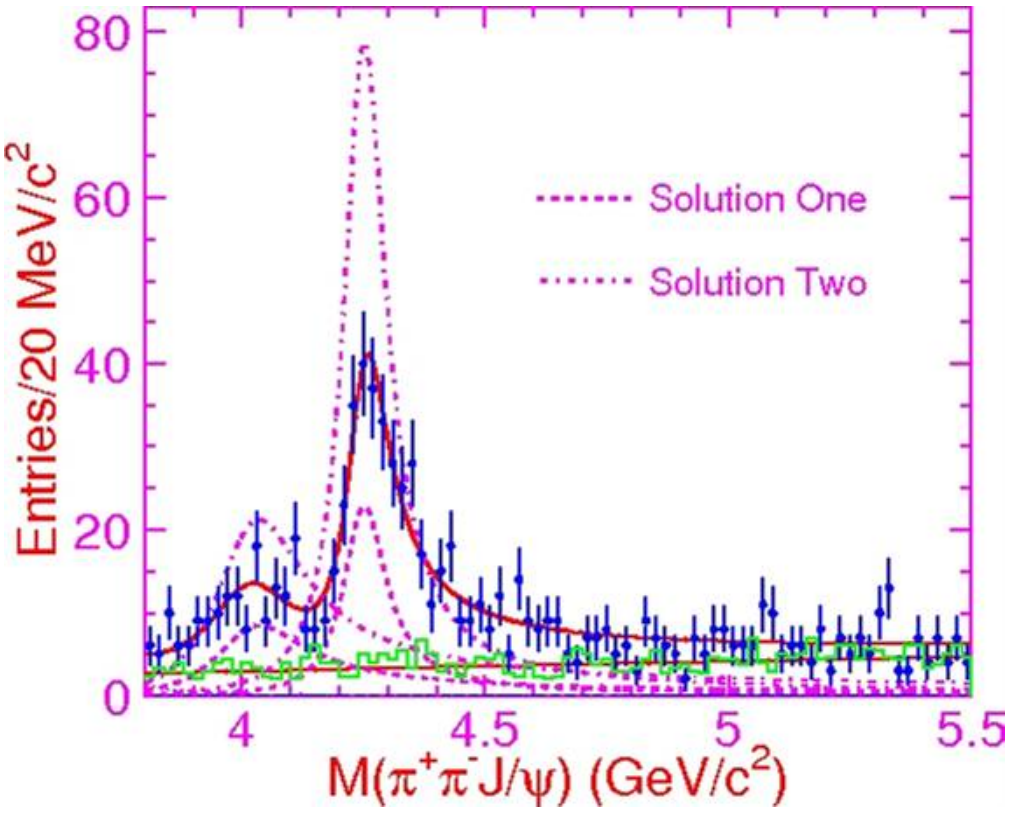
Parameters	Solution one	Solution two
$M(Y(4360))$	$4361 \pm 9 \pm 9$	
$\Gamma_{\rm tot}(Y(4360))$	$74 \pm 15 \pm 10$	
$\mathcal{B} \cdot \Gamma_{e^+e^-}(Y(4360))$	$10.4 \pm 1.7 \pm 1.5$	$11.8 \pm 1.8 \pm 1.4$
$M(Y(4660))$	$4664 \pm 11 \pm 5$	
$\Gamma_{\rm tot}(Y(4660))$	$48 \pm 15 \pm 3$	
$\mathcal{B}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

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

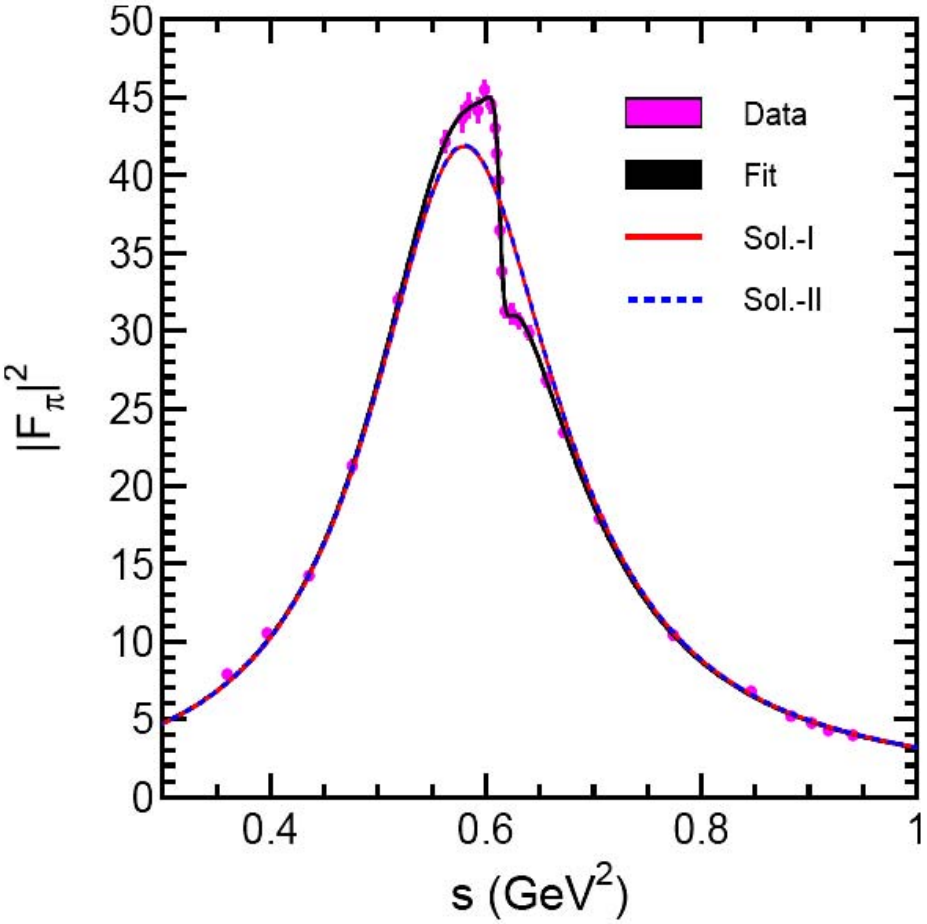


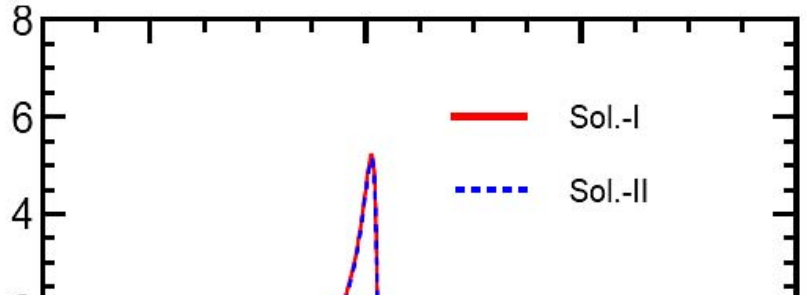
Parameters	Solution I	Solution II
$M(R1)$	$4008 \pm 40^{+114}_{-28}$	
$\Gamma_{\rm tot}(R1)$	$226 \pm 44 \pm 87$	
$\mathcal{B}\cdot\Gamma_{e^+e^-}(R1)$	$5.0 \pm 1.4^{+6.1}_{-0.9}$	$12.4 \pm 2.4^{+14.8}_{-1.1}$
$M(R2)$	$4247 \pm 12^{+17}_{-32}$	
$\Gamma_{\rm tot}(R2)$	$108 \pm 19 \pm 10$	
$\mathcal{B}\cdot\Gamma_{e^+e^-}(R2)$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

Multiple solutions





Parameter	Solution I	Solution II	Davier [8]
m_ρ [MeV]	775.9 ± 0.5		–
Γ_ρ [MeV]	146.0 ± 0.8		–
$\lvert\delta\rvert$ $[\times 10^{-3}]$	1.62 ± 0.06	21.97 ± 0.04	–
ϕ_δ [°]	10.1 ± 1.4	86.56 ± 0.17	–
$\lvert\beta\rvert$	0.086 ± 0.004		–
$\Delta\mathcal{B}^{\text{mixing}}$ [%]	-0.03 ± 0.01	$+0.04 \pm 0.01$	-0.01 ± 0.01
$\Delta a_\mu^{\text{mixing}}$ $[10^{-10}]$	$+2.5 \pm 0.2$	$+1.6 \pm 0.2$	$+2.80 \pm 0.19$

Figure 3: Fit to the $e^+e^- \to \pi^+\pi^-$ form factors below $s = 1$ GeV^2 measured at CMD2

CZY, X.H. Mo, P. Wang, arXiv:0911.4791