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Disentangling Charmonia in the Threshold Region

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Motivation

- our understanding of the open-charm threshold region is limited
  - resonances close to thresholds complicate spectroscopic analyses

> Due to the complexity of the $c\bar{c}$ threshold region, in this listing, "seen" ("not seen") means that a cross section for the mode in question has been measured at effective $\sqrt{s}$ near this particle's central mass value, more (less) than 2σ above zero, without regard to any peaking behavior in $\sqrt{s}$ or absence thereof. See mode listing(s) for details and references. [literal PDG quote]

- spectroscopy of $J^{PC} = 1^{--}$ charmonium interesting
  - Search for further exotic states (tetra quark candidates)
  - LHCb study of $B^+ \to K^+\mu^+\mu^-$ shows significant and larger-than-expected contributions from $\psi(4160)$
    [LHCb, PRL 111 112003 (2013); J. Lyon and R. Zwicky, arXiv:1406.0566v1]

- opportunity for BESIII/LHCb synergy!

Experimental Situation

Data on $e^+e^- \to$ open charm

process	BaBar	Belle	BES	CLEO-c[1]
R_c	—	—	✓	✓
$e^+e^- \to D^0\bar{D}^0$	✓	✓	???	✓
$e^+e^- \to D^+D^-$	✓	✓	???	✓
$e^+e^- \to D^0\bar{D}^{*0}$ + c.c.	—	—	???	✓
$e^+e^- \to D^+D^{*-}$ + c.c.	—	✓	???	✓
$e^+e^- \to D^{*0}\bar{D}^{*0}$	—	—	???	✓
$e^+e^- \to D^{*+}D^{*-}$	—	✓	???	✓
$e^+e^- \to D_s^+D_s^-$	✓	(✓)	???	✓
$e^+e^- \to D_s^{*+}D_s^-$ + c.c.	✓	(✓)	???	✓
$e^+e^- \to D_s^{*+}D_s^{*-}$	✓	(✓)	???	✓

Questions

- Can we turn ??? into ✓? ($\to$ BES-II/BES-III?)
- Can we describe all data simultaneously? (**this talk**)

✓ measured and available from HEPData.net

(✓) published, but numerical values not available

— not measured / not published

methods:

ISR BaBar, Belle

energy scan BES-II, CLEO-c

[1] coarse grained and above $\psi(3770)$ only

Status Quo

from the literature [PDG]

resonance	$\psi(3770)$	$\psi(4040)$	$\psi(4160)$	$\psi(4415)$	
$r =$	0	1	2	3	
$I^G(J^{PC})$	$0^-(1^{--})$	$0^-(1^{--})$	$0^-(1^{--})$	$0^-(1^{--})$	
mass [MeV]	3773.13 ± 0.35	4039 ± 1	4191 ± 5	4421 ± 4	
Γ [MeV]	27.2 ± 1.0	80 ± 10	70 ± 10	62 ± 20	
$\Gamma_{e^+e^-}$	$(9.6 \pm 0.7) \times 10^{-6}$	$(1.07 \pm 0.16) \times 10^{-5}$	$(6.9 \pm 3.3) \times 10^{-6}$	$(9.4 \pm 3.2) \times 10^{-6}$	
resonance	$X(3940)$	$X(4230)$	$X(4260)$	$X(4360)$	$X(4660)$
$r =$	4	5	6	7	8
$I^G(J^{PC})$	$?^?(?^{??})$	$?^?(1^{--})$	$?^?(1^{--})$	$?^?(1^{--})$	$?^?(1^{--})$
mass [MeV]	3942 ± 9	4230 ± 10	4230 ± 8	4341 ± 8	4643 ± 9
Γ [MeV]	37^{+27}_{-17}	38 ± 12	55 ± 19	102 ± 9	72 ± 11
$\Gamma_{e^+e^-}$	—	seen	seen	seen	seen

- $X(\dots)$ denotes the states listed as exotic charmonia in the PDG
- we consider only electrically neutral states with (potentially) $J^{PC} = 1^{--}$
- various different analyses techniques used
  - can consistency / statistical compatibility be expected?

Theoretical Model

Based on K-matrix formalism

our assumptions:

- resonance widths are saturated by two-body channels
- virtual two-body contributions can shift resonance poles sizeable

We use K-matrix approach w/ analytic continuation of phase space factors below thresholds

cross-sections $\boxed{\sigma_{f\to i}(s) \propto \left|\hat{T}_{fi}(s)\right|^2 \Big/ s}$

- $\hat{T} = \hat{K}\,(I - i\rho\hat{K})^{-1}$ ... scattering matrix
- ρ ... density matrix of states (kinematics)
- invariant K-matrix:

$$\hat{K}_{ij} = \sum_r \frac{g^0_{ri}\, g^0_{rj}\; B^\ell_{ri}(s)\, B^\ell_{rj}(s)}{m_r^2 - s}$$

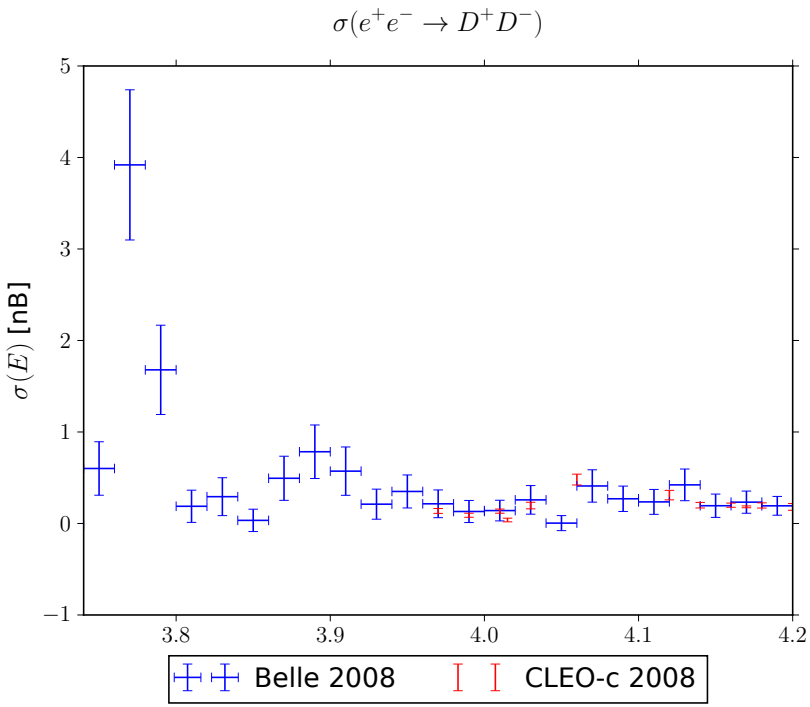
$B^\ell(s)$ ... ratios of centrifugal barrier factors (for example Blatt-Weisskopf barrier factors)

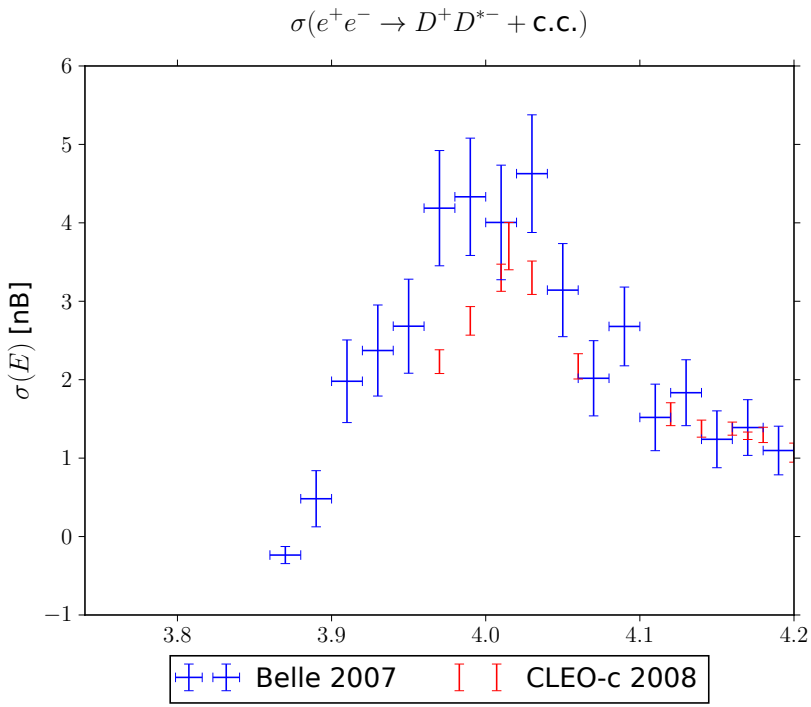
Fit parameters:

- coefficients g^0_{ri} of residue function, real (can be negative)
- resonance masses m_r, real and positive

Data used in the fit(s)

- use exclusive open charm cross sections by Belle
  - do *not yet* use $D_s^{(*)+} D_s^{(*)-}$
  - *so far* use $\sqrt{s} < 4.2\,\text{GeV}$ only
- several CLEO-c data points are statistically incompatible with the Belle measurements
- use inclusive $\sigma(e^+e^-) \to$ charmed hadrons by BES-II [Using parametrisation by J. Lyon and R. Zwicky, arXiv:1406.0566v1]





Fit models

A: Fit w/ ψ-like charmonia only

- $\psi(3770)$, $\psi(4040)$, $\psi(4160)$ and $\psi(4415)$

B: Fit w/ ψ-like charmonia + $X(3940)$

- $\psi(3770)$, $\psi(4040)$, $\psi(4160)$ and $\psi(4415)$
- $X(3940)$

Common:

- Bayesian fit with uniform priors
- float resonance masses in non-overlapping intervals
- allow couplings of $\psi(3770)$ to above-threshold channels through analytic continuation of the phase space factors

Results

[Preliminary]

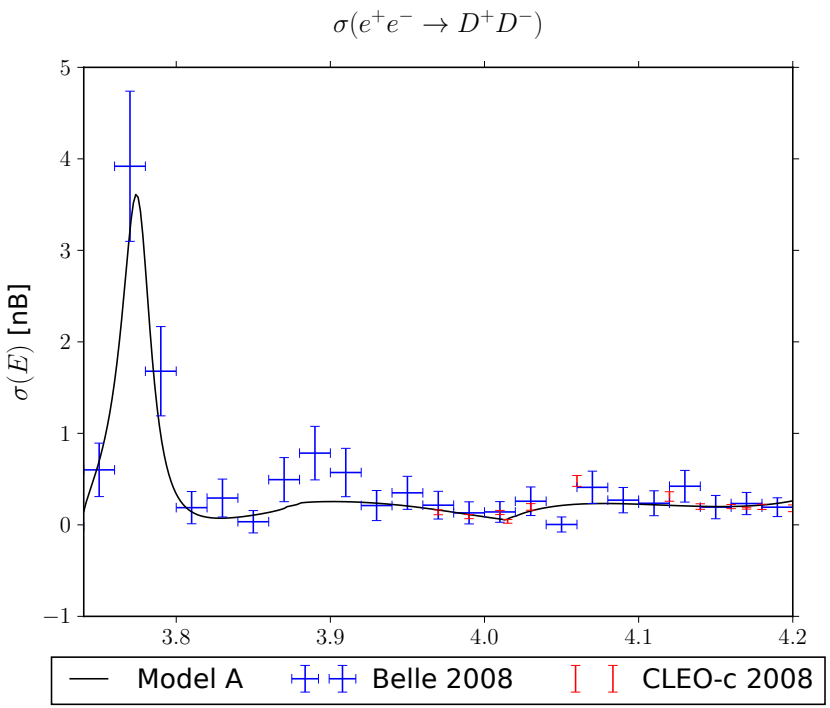
Fit models

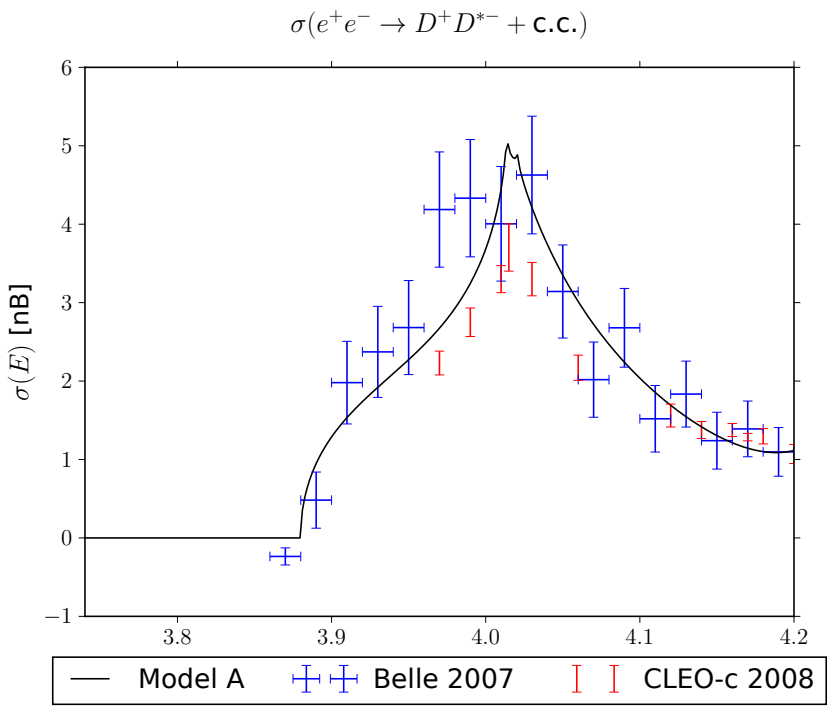
A is able to describe the data well:

$\chi^2/\text{d.o.f.} = 77.7/79$, p value $\sim 52\%$

B yields no significantly better fit, still a fair description of data:

$\chi^2/\text{d.o.f.} = 77.2/71$, p value $\sim 29\%$

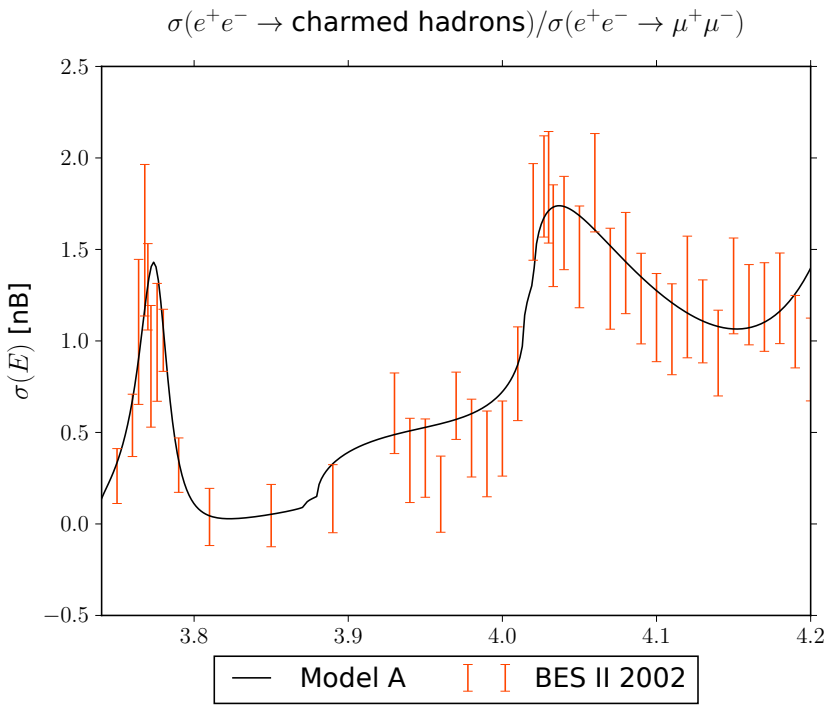


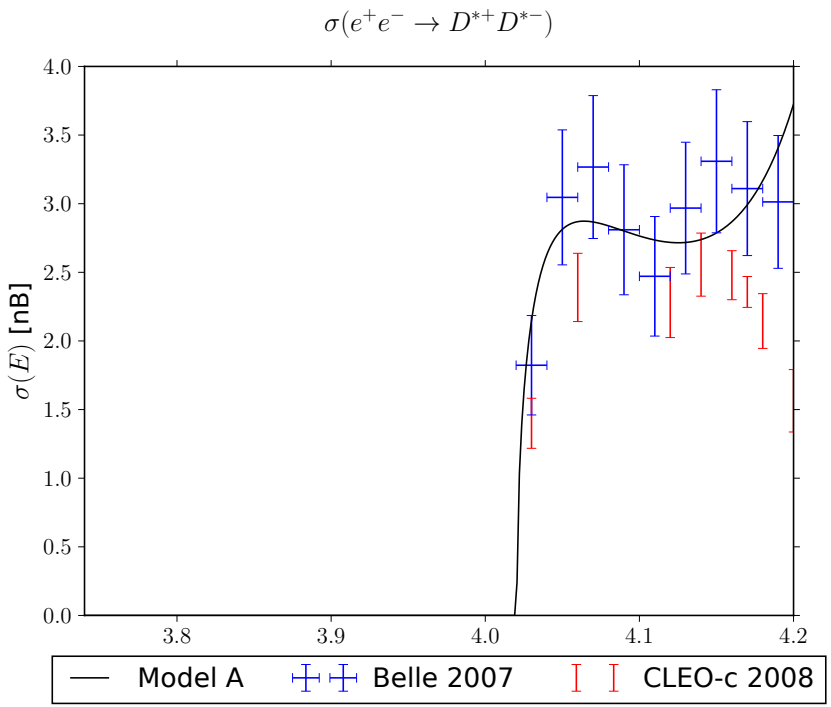


Results

[Preliminary]

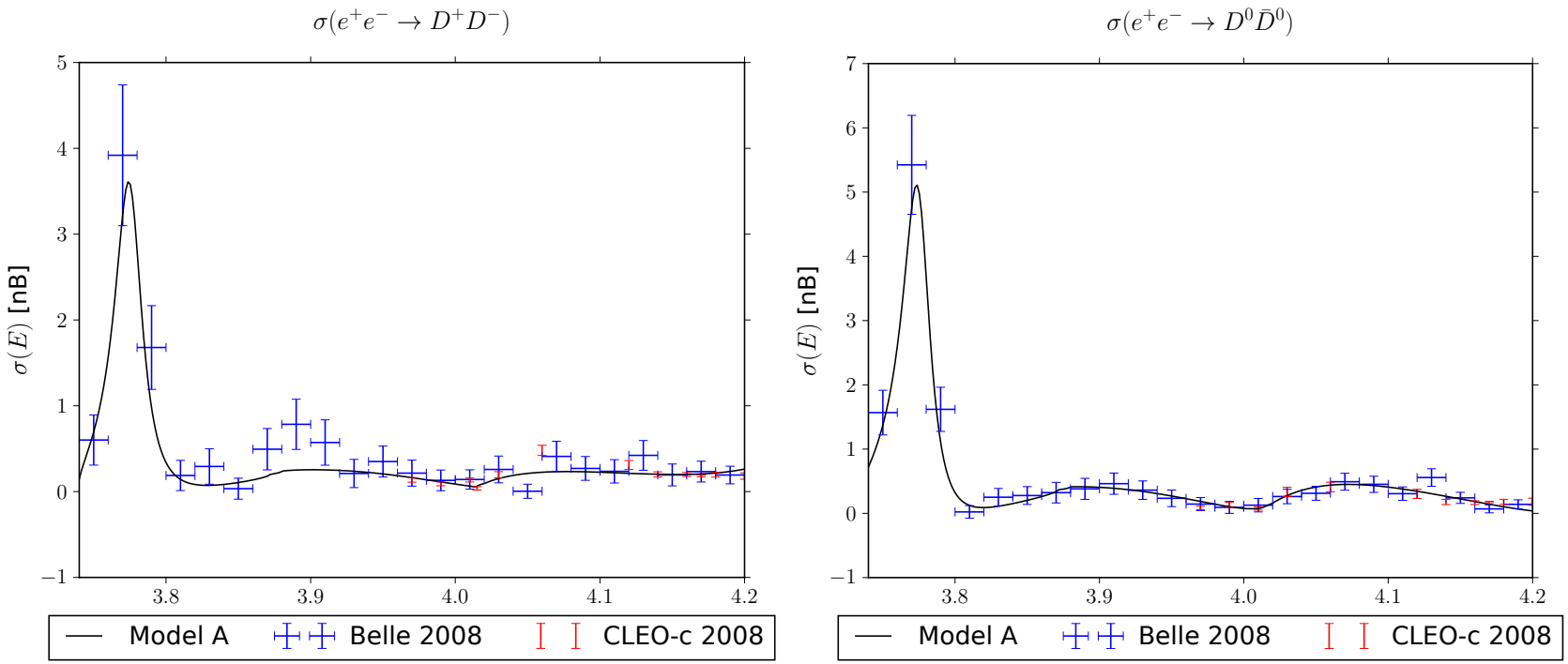
Good description of the background-subtracted BESII data





Resonance at $\sim 3.9\,\mathrm{GeV}$? [Preliminary]

We see an enhancement around $3.9\,\mathrm{GeV}$ in D^+D^-, but not in $D^0\bar{D}^0$



Conclusion & Outlook

not much to conclude

- still in early phases of study, very preliminary
- depending on datasets used, we do find reasonable fits using K-matrix formalism

what still needs to be done

- include further resonances ($X(4230)$, ...)
- include $e^+e^- \to D_s^{(*)+} D_s^{(*)-}$ data (received BaBar data sets earlier this week)
- account for different normalizations
- account for correlations (e.g. CLEO-c exclusive vs inclusive)

what we would like to do

- obtain measurements of exclusive processes from BES, and include them in the fit