Exclusive open-charm near-threshold cross sections in a coupled-channel approach

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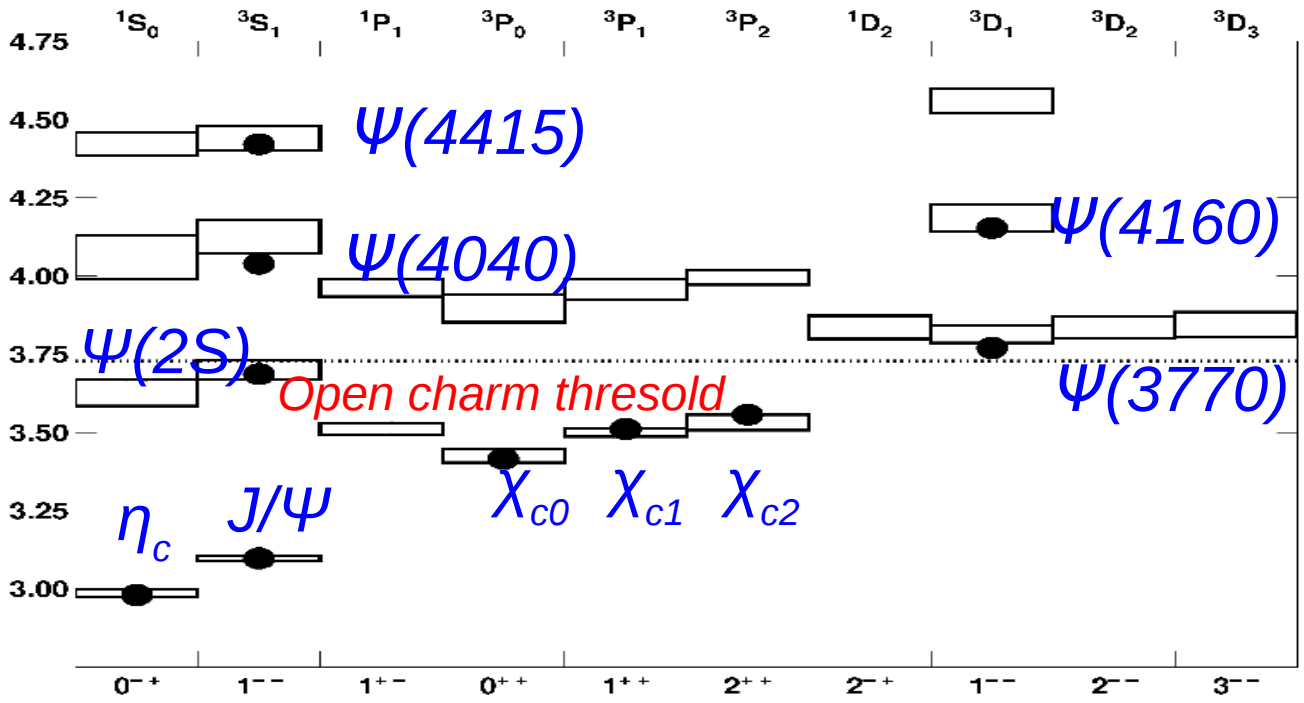
Based on
T. Uglov, Yu. Kalashnikova, A. Nefediev, G. Pakhlova, P. Pakhlov **JTEP Lett. 105, 1, 1-7 (2017)**

Charmonium: first data

The first ($c\bar{c}$) state was first discovered in 1974



During next 6 years another 9 states was found:

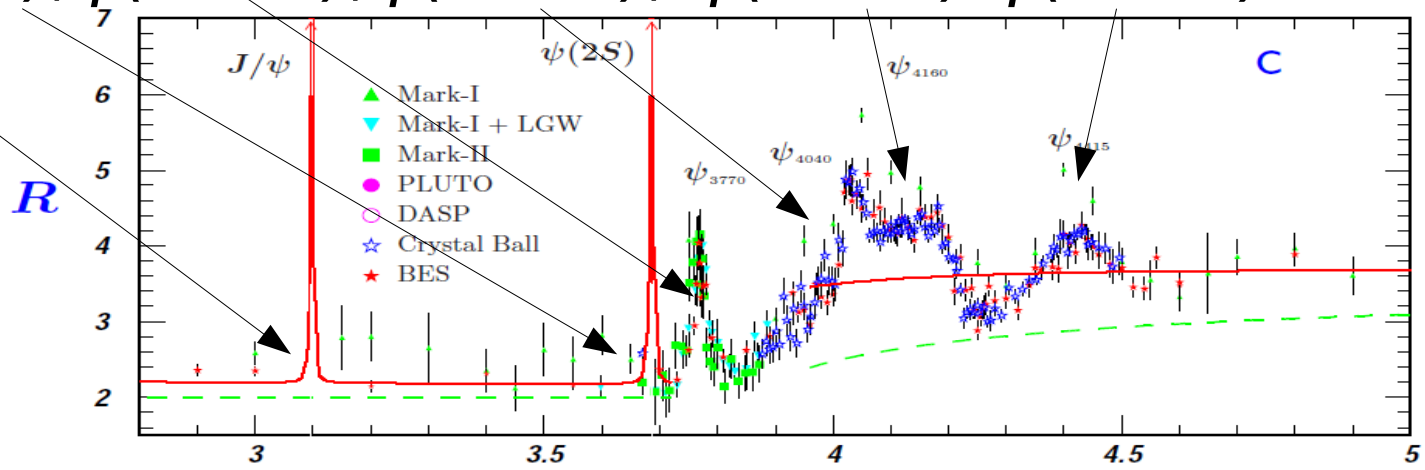
$J^P=1^{--}$: *J/ψ, ψ(2S),ψ(3770),ψ(4040), ψ(4160) ψ(4415)*

$J^P=0^{-+}$: η_c

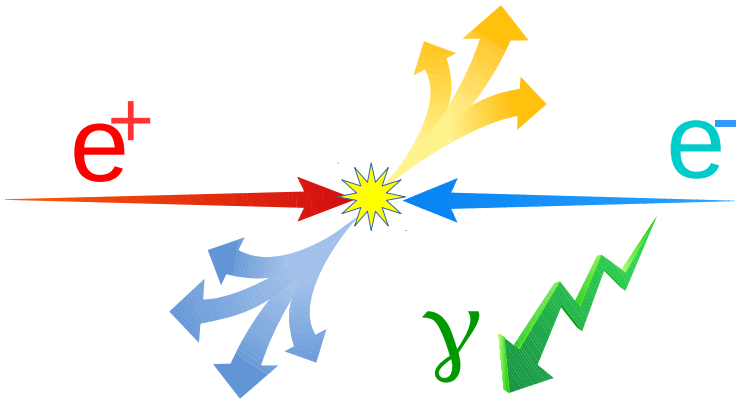
$J^P=0^{++}$: χ_{c0}

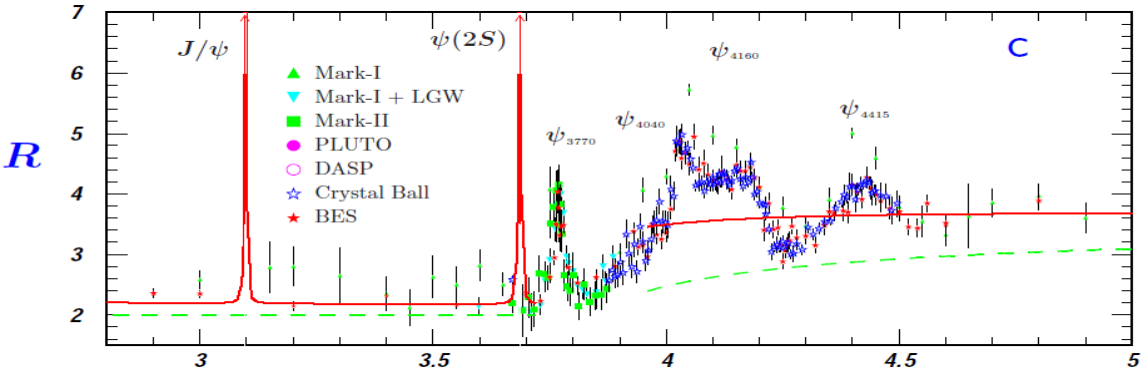
$J^P=1^{++}$: χ_{c1}

$J^P=2^{++}$: χ_{c2}

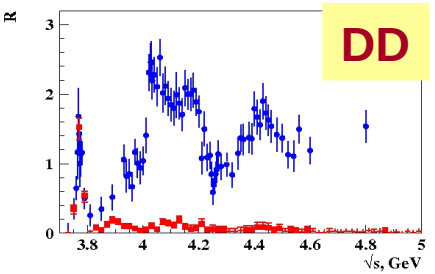


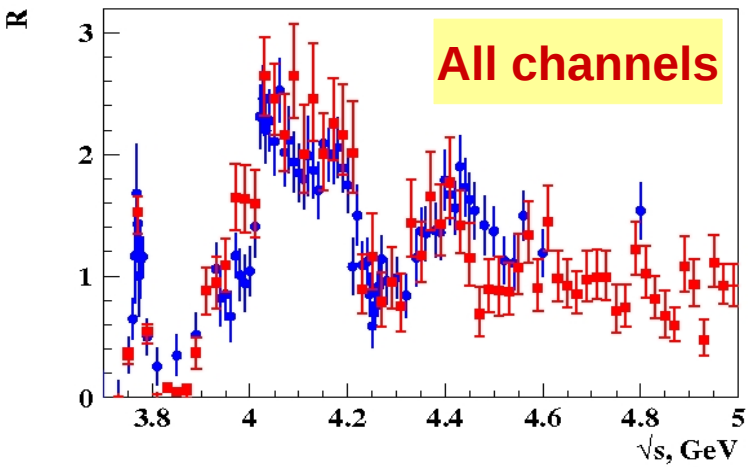
1^{--} states in e^+e^- annihilation

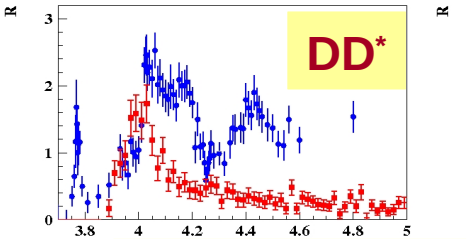


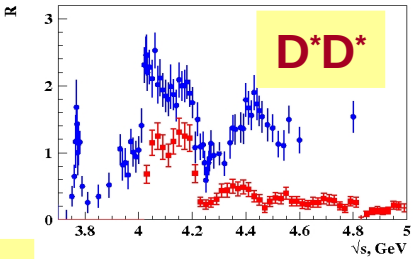


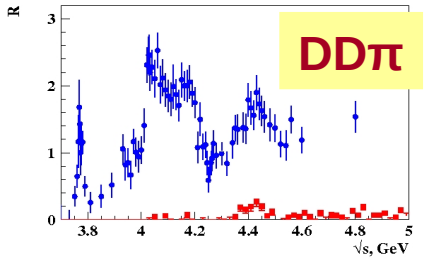
Full cross-section is almost saturated by the sum of the exclusive charmed meson production cross-sections

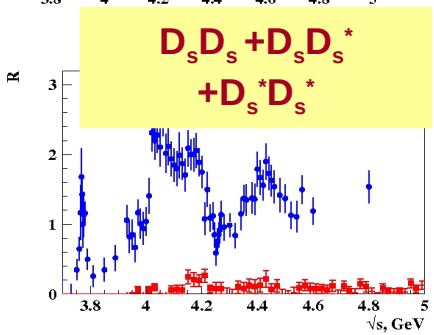


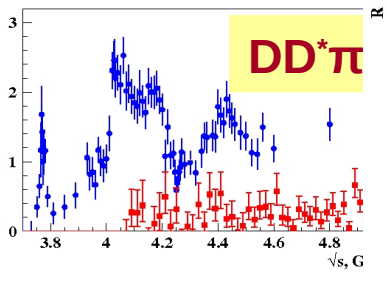


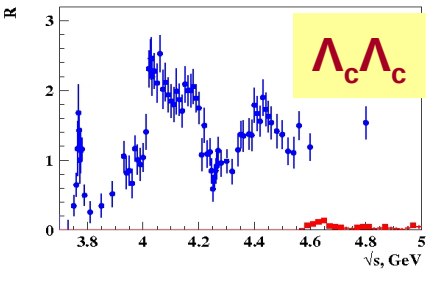








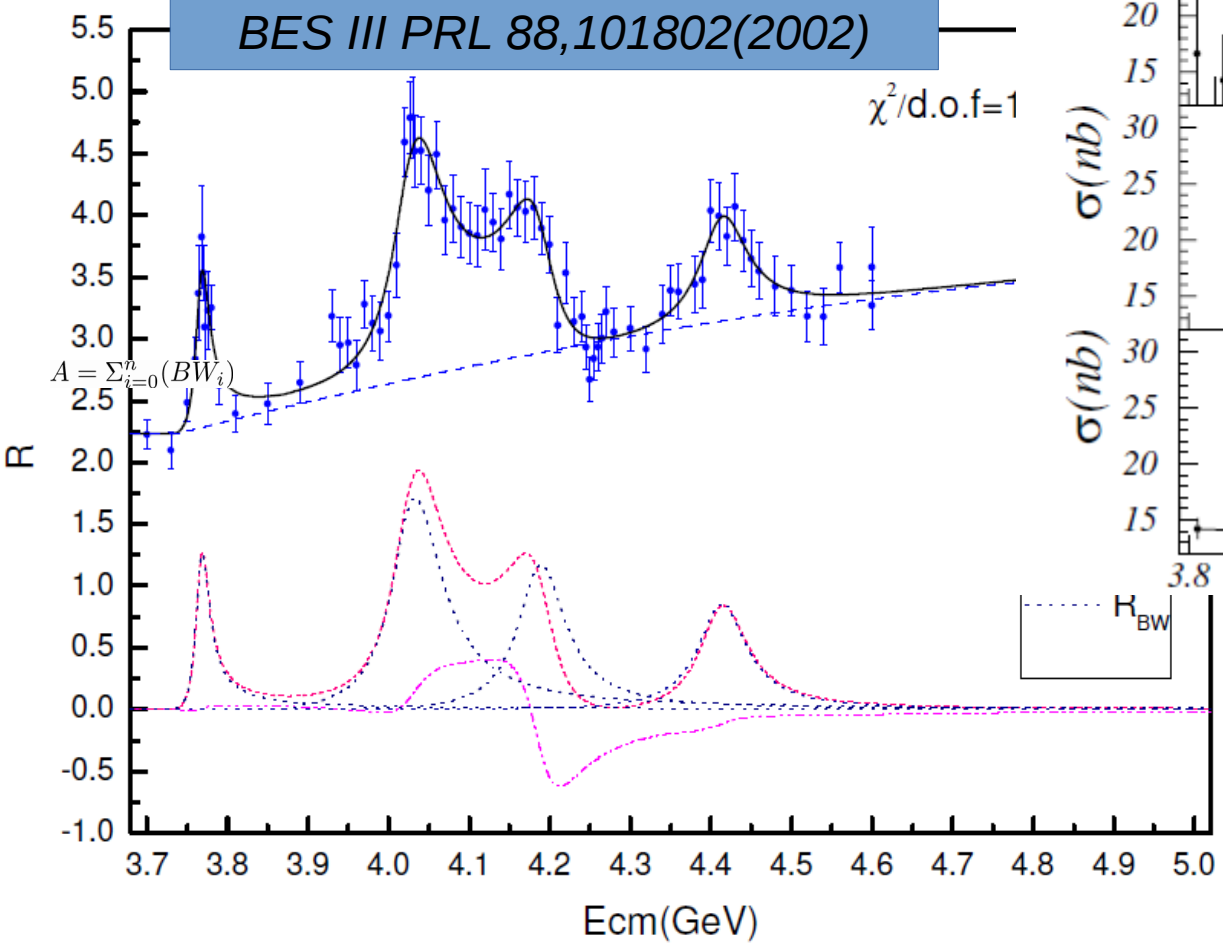




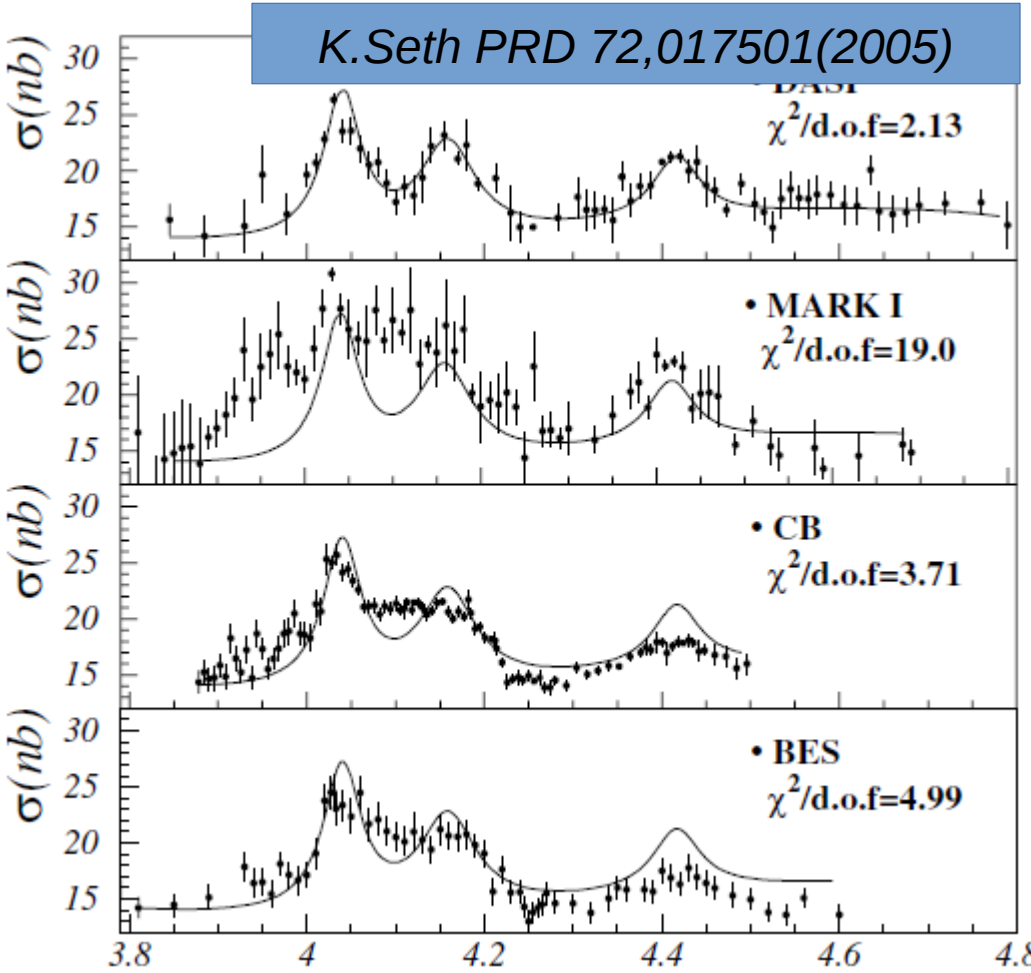
Inclusive fits

$$A = \Sigma_{i=0}^{n} BW(\psi_i)$$

BES III PRL 88,101802(2002)



K.Seth PRD 72,017501(2005)



Inclusive fit problems

- Looks ugly.

- Use ***inclusive*** cross-section only. No information on exclusive channels cross-section is used.

- Various thresholds of the open charm modes are not regarded (no ψ↔DD transitions/rescattering)

K-matrix and amplitude

$$S = 1 + 2iA,$$

$$A = K(1 - iK)^{-1},$$

$$AA^\dagger = \frac{1}{2i}(A - A^\dagger).$$

Ensures unitarity

i runs over $D^{(*)}\bar{D}^{(*)}$ channels,
α runs over ψ's

$$(P^{-1}(s))_{\alpha\beta} = (M_\alpha^2 - s)\delta_{\alpha\beta} - i\sum_m G_{m\alpha}G_{m\beta}$$

$$K_{ij} = \sum_\alpha G_{i\alpha}(s)\frac{1}{M_\alpha^2 - s}G_{j\alpha}(s),$$

$$\Gamma_{e\alpha} \equiv \Gamma(\psi_\alpha \to e^+e^-) = \frac{\alpha g_{e\alpha}^2}{3M_\alpha^3}.$$

Electron width

$$G_{i\alpha}^2(s) = g_{i\alpha}^2\frac{k_i^{2l_i+1}}{\sqrt{s}}\theta(s - s_i)$$

Coupling constant

$$\Gamma_{i\alpha} \equiv \Gamma(\psi_\alpha \to [D^{(*)}\bar{D}^{(*)}]_i) = \frac{g_{i\alpha}^2}{M_\alpha^2}[p_i(M_\alpha)]^{2l_i+1}$$

Partial decay width

$$A_{ij} = \sum_{\alpha\beta} G_{i\alpha}(s)P_{\alpha\beta}(s)G_{j\beta}(s)$$

$$\sigma_i(s) = \frac{4\pi\alpha}{s^{5/2}}[p_i(s)]^{2l_i+1}\left|\sum_{\alpha,\beta} g_{e\alpha}P_{\alpha\beta}(s)g_{i\beta}\right|^2$$

Cross-section

Considered channels

Isospin-conjugated modes should be treated independently
It doubles number of channels

$$
\begin{aligned}
&D\bar{D}, && 2 \text{ channels},\\
&D\bar{D}^*, && 4 \text{ channels},\\
&D_2\bar{D}, && 4 \text{ channels},\\
&[D^*\bar{D}^*]^P_{S=0}, && 2 \text{ channels},\\
&[D^*\bar{D}^*]^P_{S=2}, && 2 \text{ channels},\\
&[D^*\bar{D}^*]^F_{S=2}, && 2 \text{ channels}.
\end{aligned}
$$

$D^0 D^- \pi^+$ is dominated by $D\bar{D}_2$ corrected to $\mathcal{B}(D_2 \to D\pi)$ $(\mathcal{B}(D_2 \to D\pi) + \mathcal{B}(D_2 \to D^*\pi))$ ratio

$$\psi(2S),\ \psi(3770),\ \psi(4040),\ \psi(4160),\ \psi(4415)$$

16 channels, 5 ψ-states

Fit variables

$$\{M_\alpha,\ \Gamma_{e\alpha},\ g_{i\alpha}\},\quad \alpha=\overline{1,5},\quad i=\overline{1,16},$$ → 40 variables

Isosin-conjuated channels have the same parameters, except for D-meson mass

$$|^3S_1\rangle = -\frac{1}{2\sqrt{3}}|D\bar{D}\rangle + \frac{1}{\sqrt{3}}|D\bar{D}^*\rangle_-$$

heavy-quark spin symmetry

$$-\frac{1}{6}|D^*\bar{D}^*\rangle_{P0} + \frac{\sqrt{5}}{3}|D^*\bar{D}^*\rangle_{P2},$$

$$|^3D_1\rangle = \frac{\sqrt{5}}{2\sqrt{3}}|D\bar{D}\rangle + \frac{\sqrt{5}}{2\sqrt{3}}|D\bar{D}^*\rangle_- + \frac{\sqrt{5}}{6}|D^*\bar{D}^*\rangle_{P0}$$

$$-\frac{1}{6}|D^*\bar{D}^*\rangle_{P2},$$

→ 35 variables

$$g_{[D^*\bar{D}^*]_{P2},\alpha} = -\sqrt{20}\, g_{[D^*\bar{D}^*]_{P0},\alpha},\quad \alpha=1,3,5,$$

$$g_{[D^*\bar{D}^*]_{P0},\alpha} = -\sqrt{5}\, g_{[D^*\bar{D}^*]_{P2},\alpha},\quad \alpha=2,4,$$

(∑BW ⇒ 75 variables)

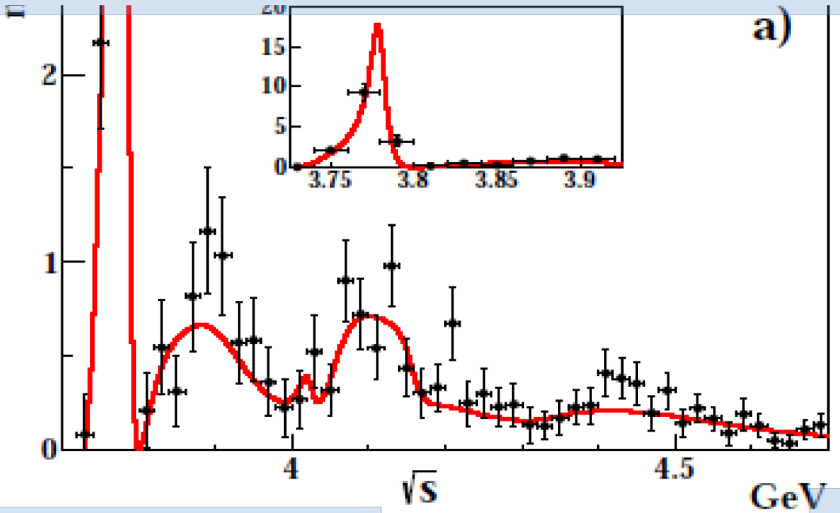
Artificial fit parameters bounds

$$\chi^2_{\rm tot} = \chi^2_{\rm exp} + \sum_{\alpha=1}^{5} \left\{ \left(\frac{M_\alpha - M_\alpha^{\rm PDG}}{50\ {\rm MeV}} \right)^2 + \left(\frac{\Gamma_{e\alpha} - \Gamma_{e\alpha}^{\rm PDG}}{0.5\ {\rm MeV}} \right)^2 + \left(\frac{\sum_{i=1}^{16} \Gamma_{i\alpha}}{200\ {\rm MeV}} \right)^2 \right\}$$

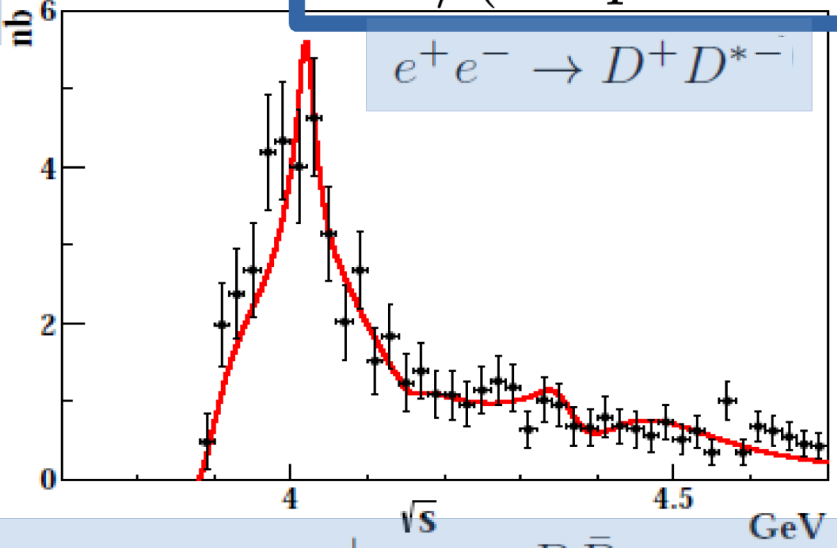
Fit results

$$\chi^2/n.d.f. = 158/(191 point - 33 par)$$

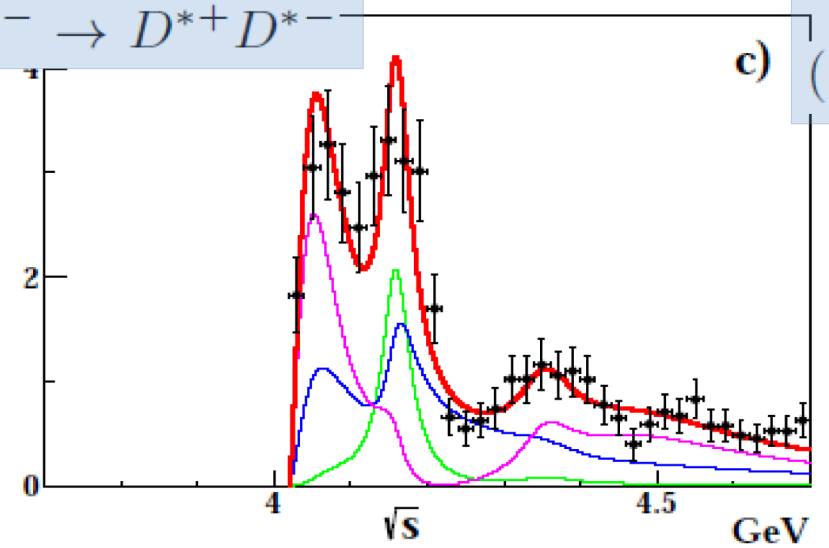
$e^+e^- \to D\bar{D}$
$([e^+e^- \to D^+D^-]+[e^+e^- \to D^0\bar{D}^0])$



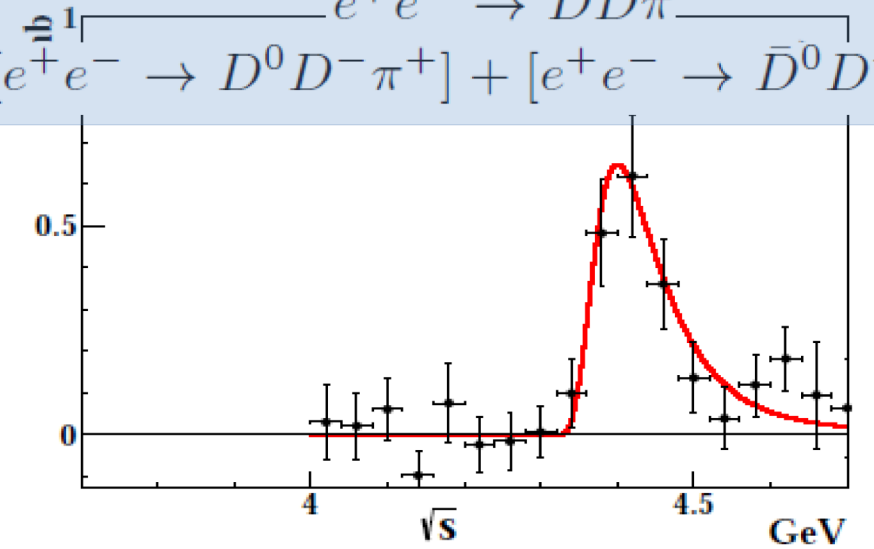
$e^+e^- \to D^+D^{*-}$



$e^+e^- \to D^{*+}D^{*-}$



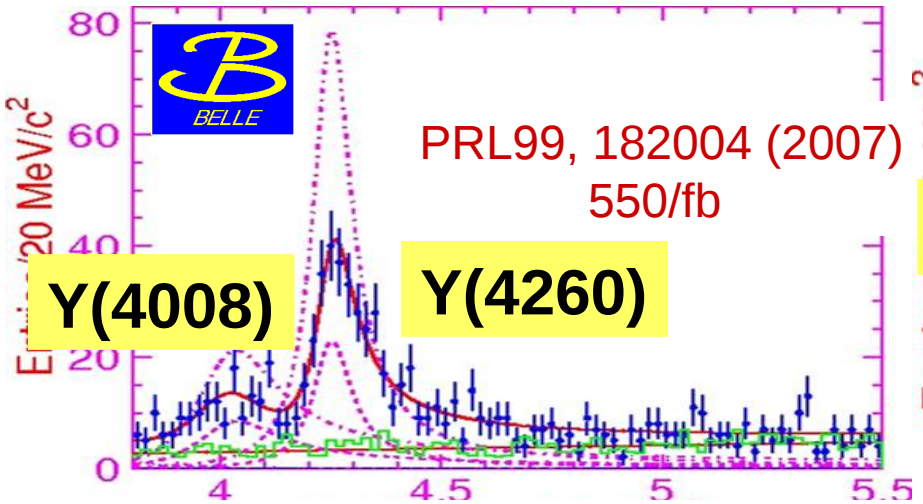
$e^+e^- \to D\bar{D}\pi$
$([e^+e^- \to D^0D^-\pi^+] + [e^+e^- \to \bar{D}^0D^+\pi^-])$

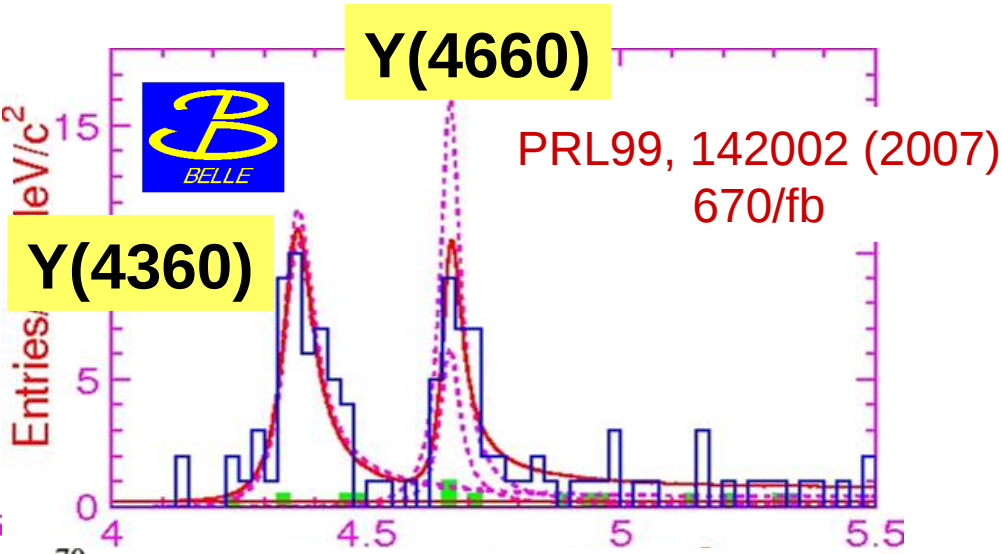


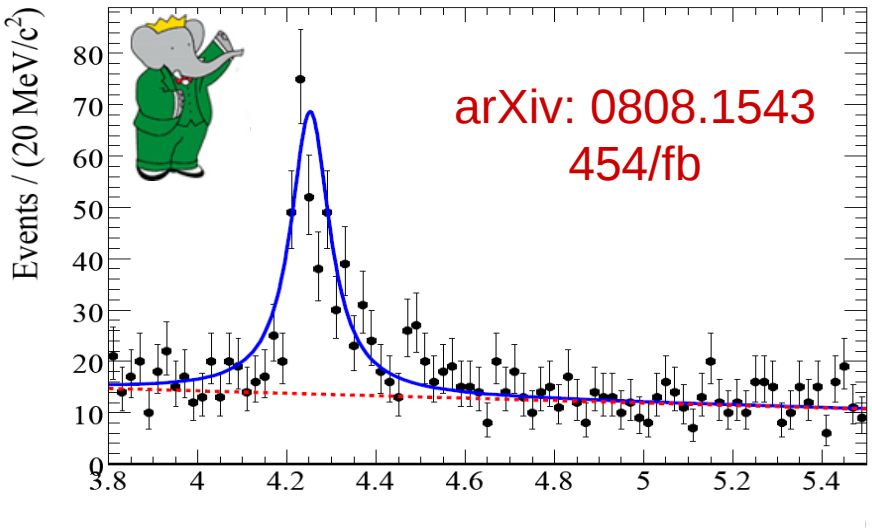
Fit results (II)

	ψ_1	ψ_2	ψ_3	ψ_4	ψ_5
PDG name	$\psi(2S)$	$\psi(3770)$	$\psi(4040)$	$\psi(4160)$	$\psi(4415)$
M, MeV	3686* (fixed)	3782 ± 1	4115 ± 14	4170 ± 7	4515 ± 18
Coupling constants $g_{i\alpha}$ $\alpha = 1 \ldots 5$, $i = D\bar{D}$, $D\bar{D}^*$, *etc*					
$D\bar{D}$	3.0 ± 0.3	-1.8 ± 0.3	-0.1 ± 0.1	0.3 ± 0.1	-0.1 ± 0.1
$D\bar{D}^*$	-4.7 ± 0.5	-3.1 ± 0.3	2.4 ± 0.2	-0.0 ± 0.7	-0.7 ± 0.2
$[D^*\bar{D}^*]^P_{S=0}$	4.8 ± 0.5	6.9 ± 0.9	-0.1 ± 0.2	0.6 ± 0.5	-0.3 ± 0.1
$[D^*\bar{D}^*]^P_{S=2}$	-21.7 ± -2.3	-3.1 ± -0.4	0.5 ± 0.9	-0.3 ± -0.2	1.5 ± -0.3
$[D^*\bar{D}^*]^F_{S=0}$, MeV^{-2}	62.2 ± 15.1	-1.6 ± 5.4	-1.0 ± 2.8	8.0 ± 1.4	0.2 ± 0.6
$D_2\bar{D}$, MeV^{-1}	-8.2 ± 29.3	25.2 ± 7.7	-23.5 ± 3.3	-1.0 ± 7.4	-1.5 ± 1.4
Partial decay widths $\Gamma_{i\alpha}$, MeV					
e^+e^-	2.354* (fixed)	0.2 ± 0.0	1.6 ± 0.3	0.7 ± 0.4	1.4 ± 0.3
D^+D^-	-	5.6 ± 1.7	0.4 ± 0.8	4.3 ± 2.6	0.5 ± 1.0
$D^0\bar{D}^0$	-	7.5 ± 2.2	0.4 ± 0.8	4.5 ± 2.7	0.5 ± 1.0
D^+D^{*-}	-	-	110.7 ± 23.5	0.0 ± 0.5	32.8 ± 17.4
$[D^*\bar{D}^*]^P_{S=0}$	-	-	0.1 ± 0.2	3.6 ± 6.5	5.9 ± 2.6
$[D^*\bar{D}^*]^P_{S=2}$	-	-	1.2 ± 6.8	0.7 ± 0.3	118.0 ± 729.4
$[D^*\bar{D}^*]^F_{S=0}$	-	-	0.2 ± 1.0	58.6 ± 22.9	2.3 ± 14.2
$D_2^+D^-$	-	-	-	-	11.7 ± 21.1

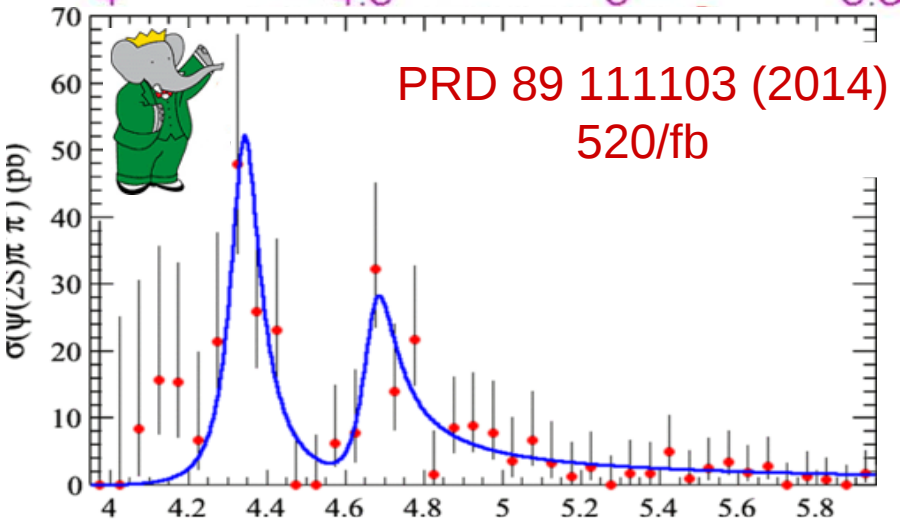
1^{--} Y-family





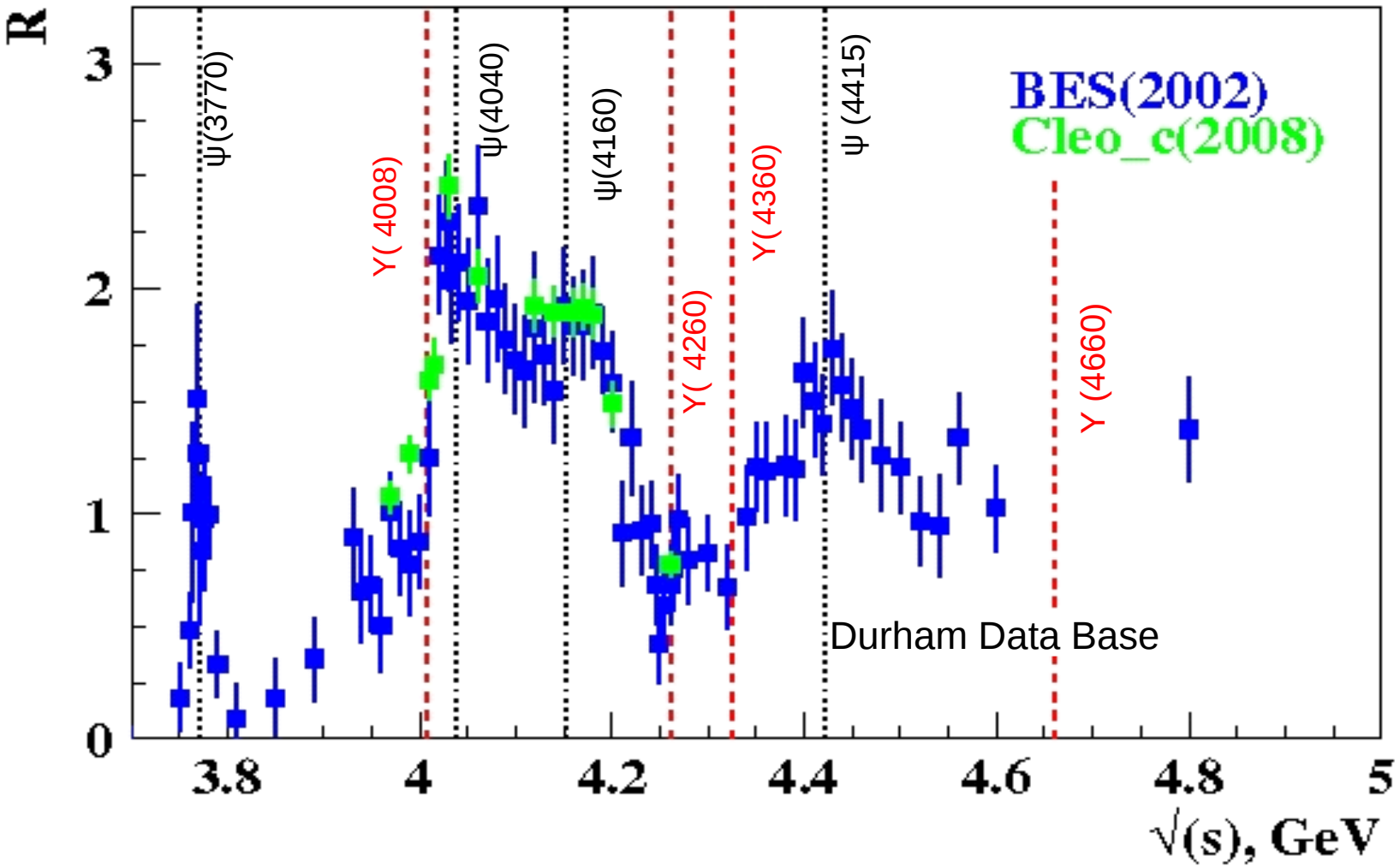


m(J/ψ π+π-)



m(ψ(2S) π+π-)

Queer Y's



- No evidence for Y decays to open-charm hadrons
- No vacant places for Y in $c\bar{c}$ spectroscopy
- No Y in inclusive charm cross-section

New data and future fits

- New higher precision data are needed to fix couplings and masses of ψ-states
- For DD*, D*D* and higher states cross section decomposition to it's helicity components is required
- Fit function, which correctly accounts for the real part of the loop
- Use unitarity to identify the nature of the Y states

Summary

- A fit to the data in the major open-charm channels for sqrt(s) = 3.7 - 4.7 GeV is performed.
- Unitarity is preserved up to the minor contribitions like DsDs.
- A good χ^2 demonstrates that the suggested approach is able to expain all data simultaniously.
- Waiting for a new data and refined fit functions to solve the ψ and Y puzzles.