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

Timofey Uglov (LPI)

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

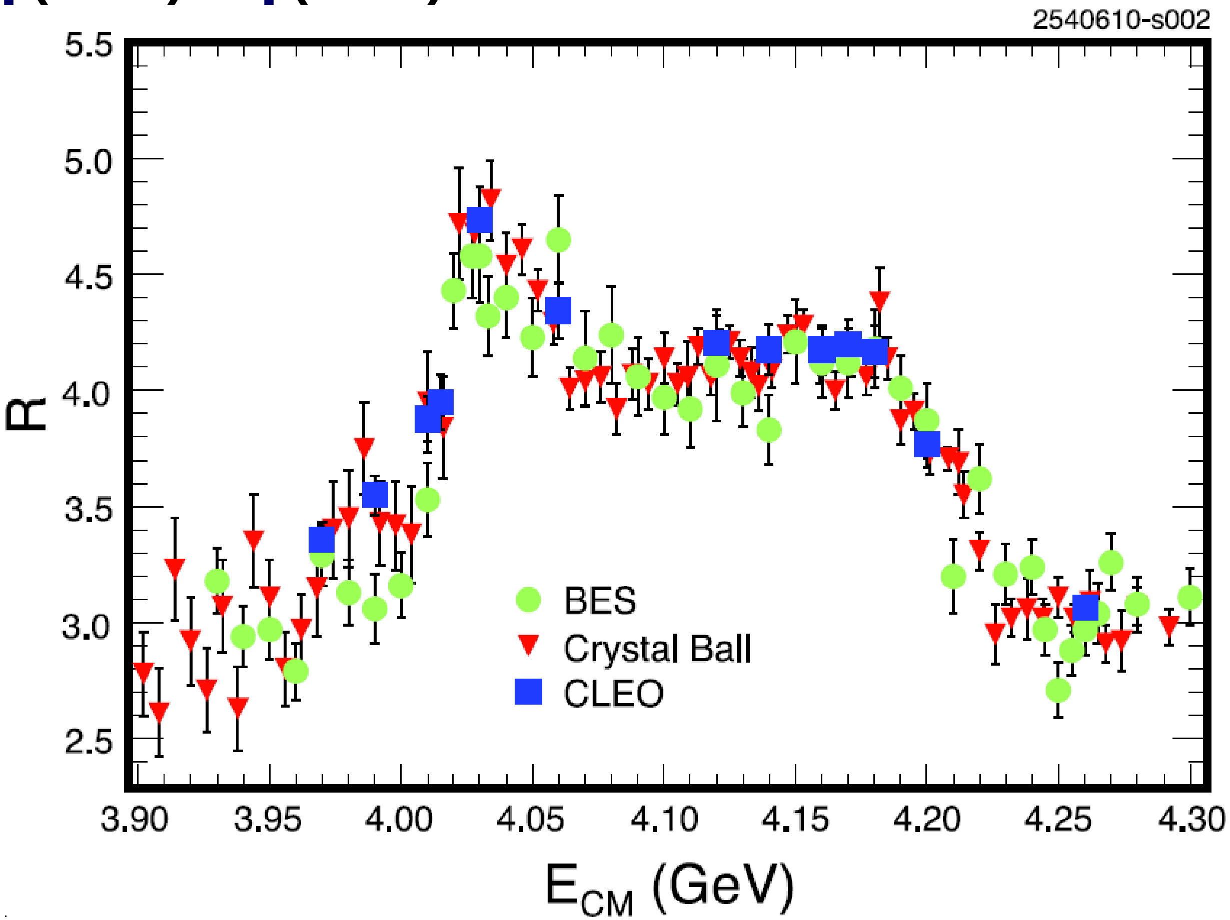
History of the charmonium states

ψ-states were mostly discovered and studied in e^+e^- collider experiments

ψ(4415) MARK-I 1976, DASP 1978

ψ(3770) MARK-I 1977, DELCO 1978, MARK-II 1980, BESII 2005

ψ(4040) и ψ(4160) DASP 1978



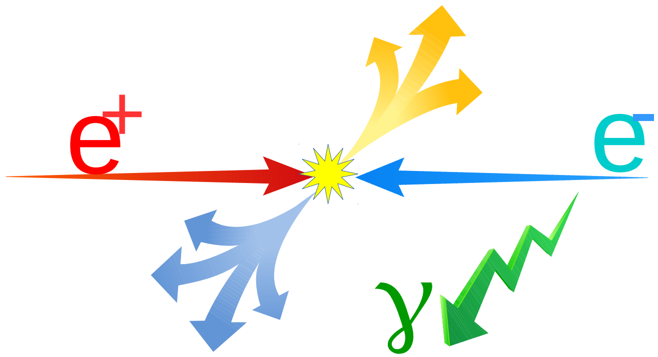
Full cross-section
$e^+e^- \to hadrons$

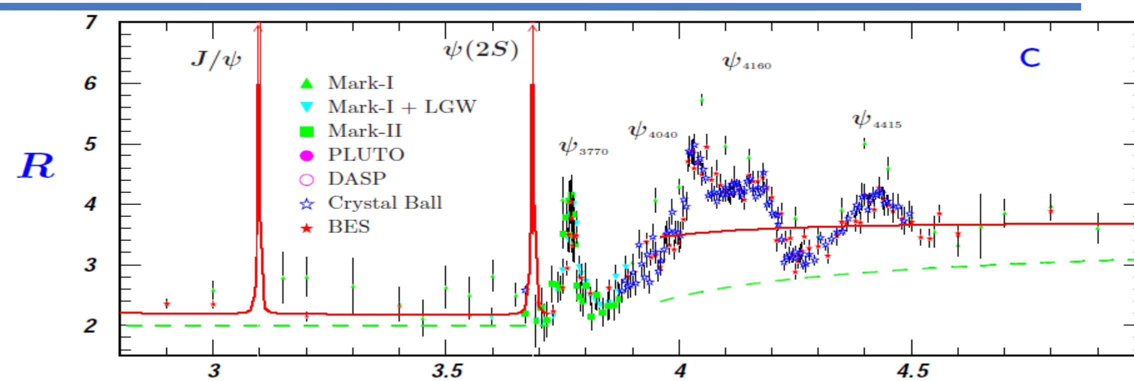
Crystal Ball 1986

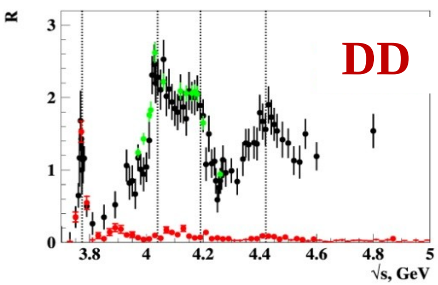
BESII 2005

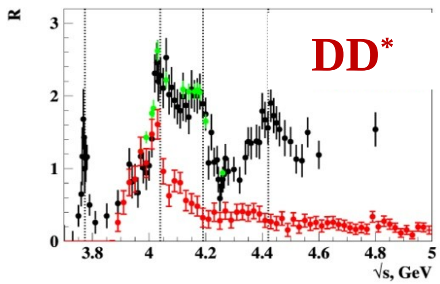
CLEO 2009

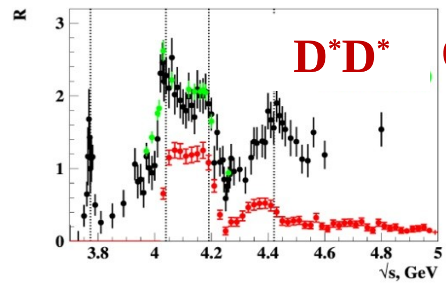
1^{--} states in e^+e^- annihilation



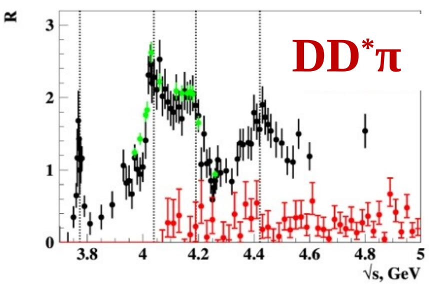


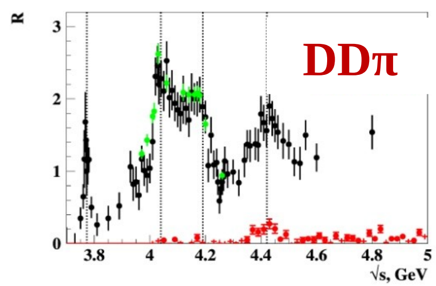


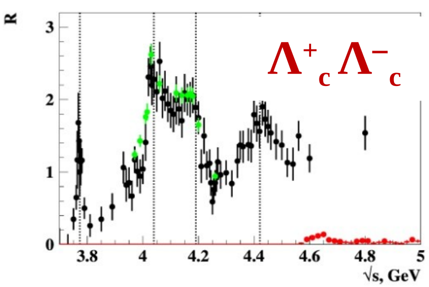


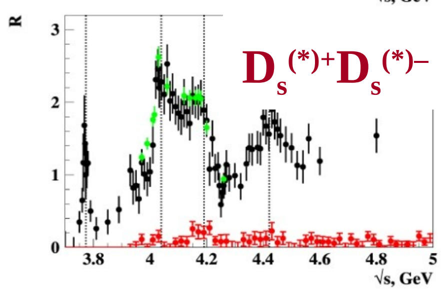


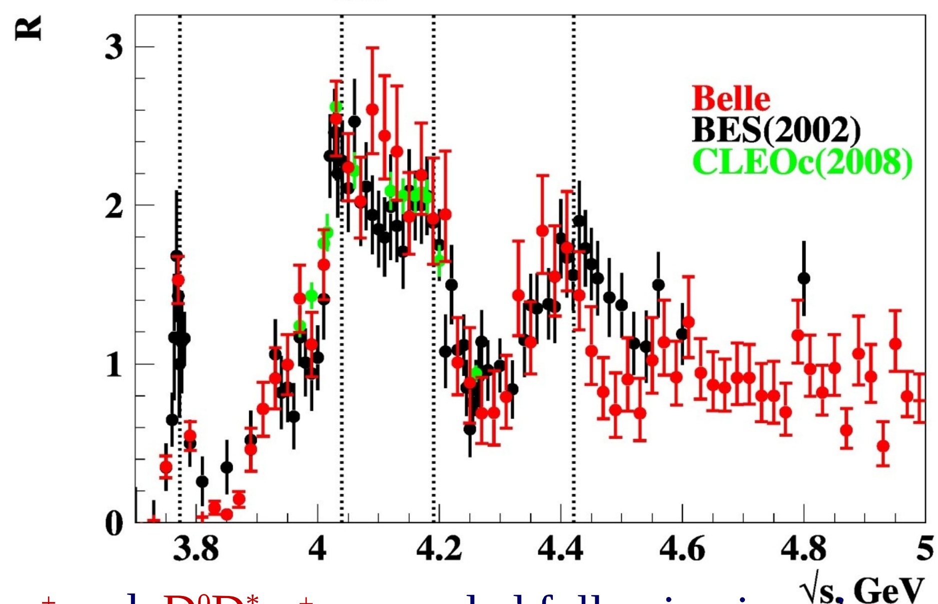
Sum of all measured exclusive cross-sections to open charm saturates the inclusive cross-section







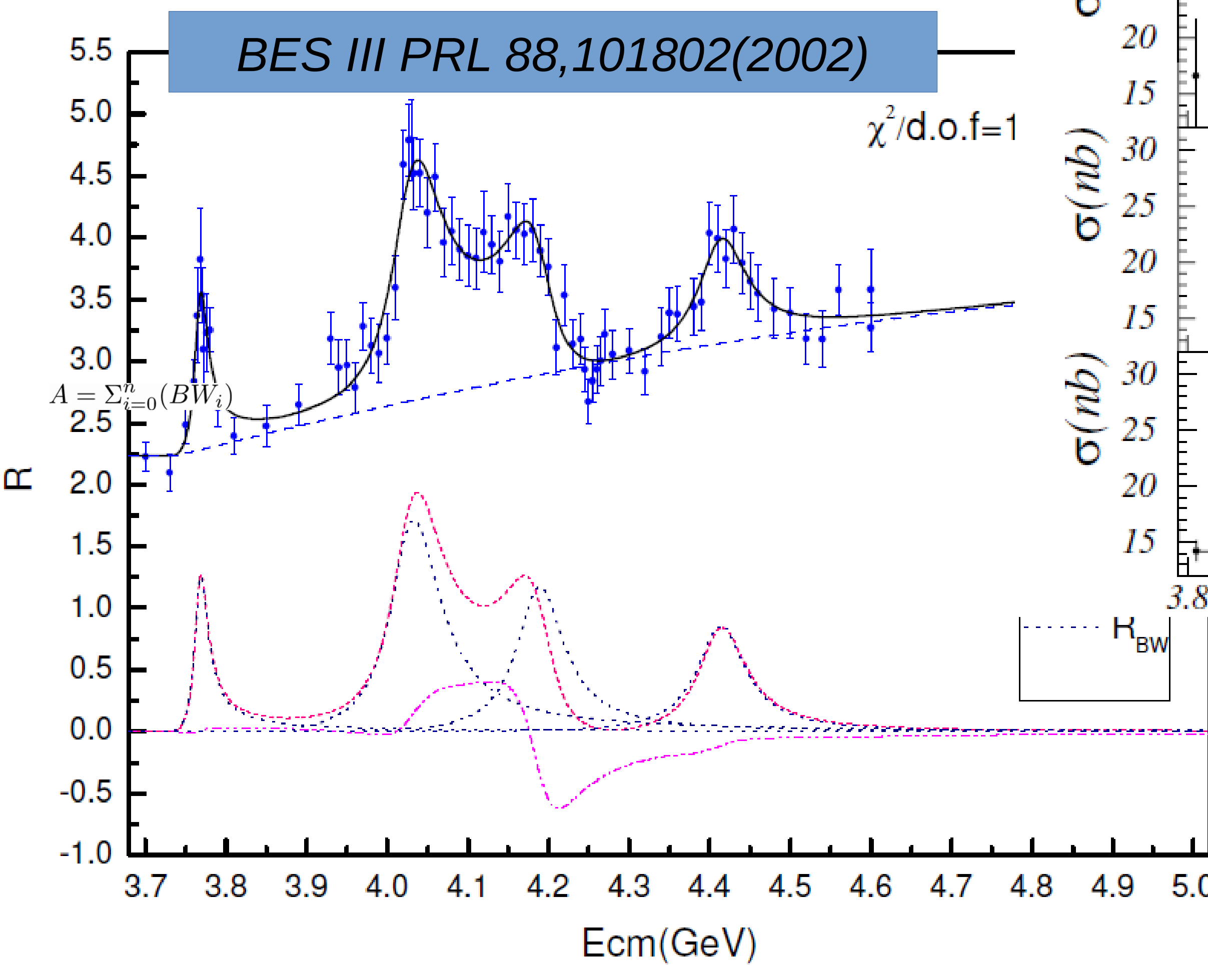


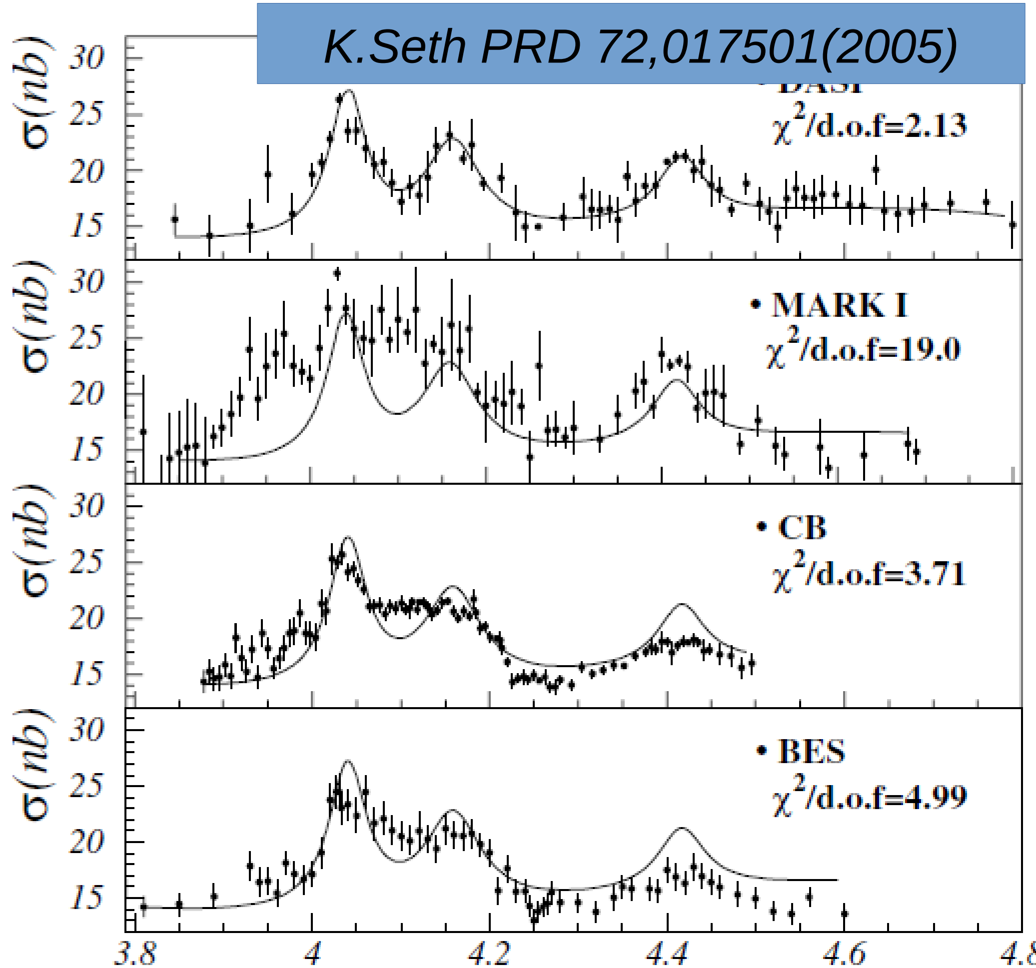


Contributions of D^+D^{*-}, $D^{*+}D^{*-}$, $D^0D^-\pi^+$ and $D^0D^{*-}\pi^+$ are scaled following isospin symmetry

Inclusive fits

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





Inclusive fit: coupled channels

EICHTEN, GOTTFRIED, KINOSHITA, LANE, AND YAN
PRD 21 203 (1980)

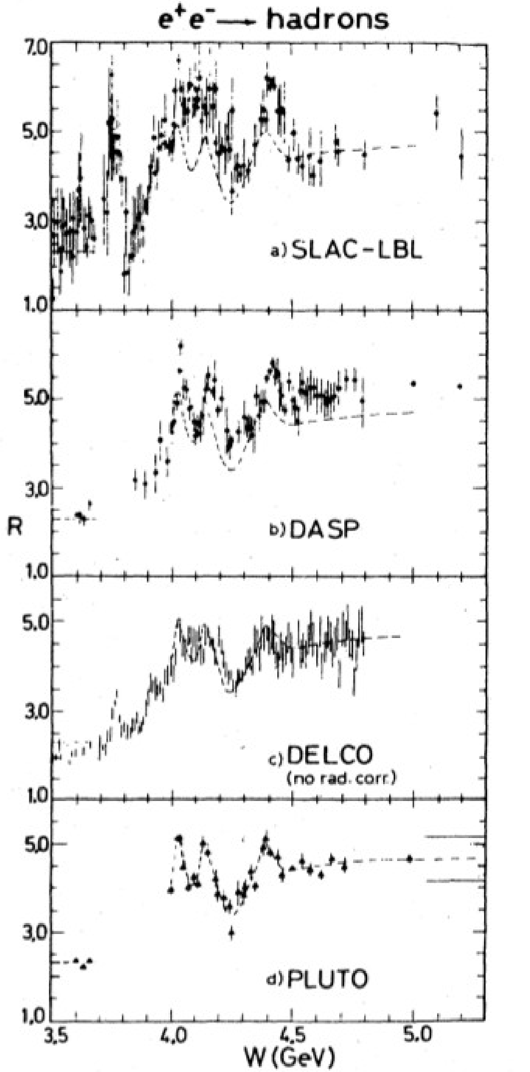


FIG. 15. Results of R (including $e^+e^- \to \tau^+\tau^-$) from four experiments: (a) SLAC-LBL (Ref. 44), (b) DASP (Ref. 46), (c) DELCO (Ref. 45), (d) PLUTO (Ref. 47). The curves represent a hand-drawn line through the PLUTO data. The band in Fig. 15(d) indicates the systematic errors of the PLUTO measurement. The plots shown were compiled by G. Feldman.

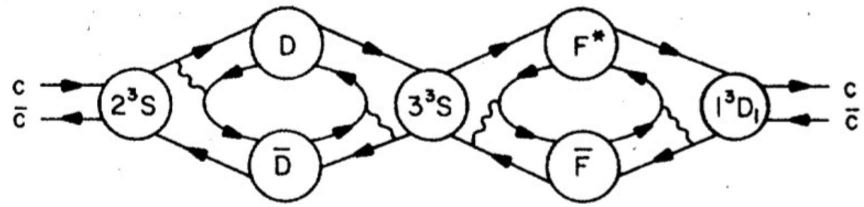


FIG. 8. The propagation of a $c\bar{c}$ pair in the presence of open and closed decay channels as described in the Green's function $\mathcal{G}$.

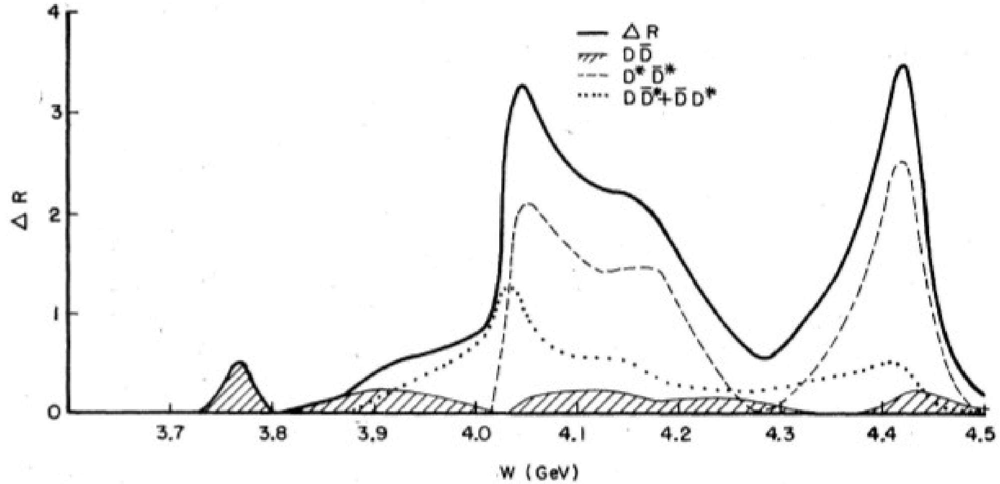
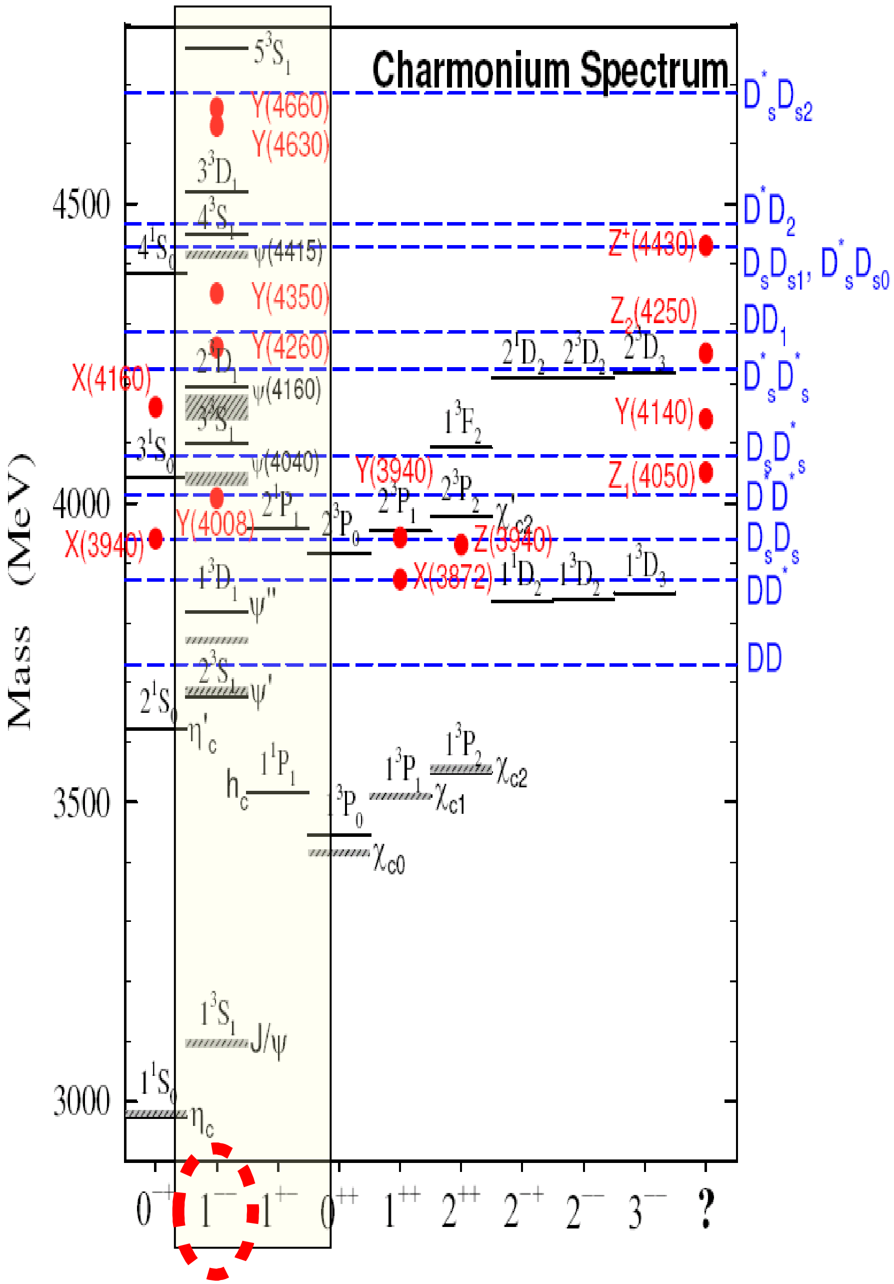


FIG. 13. The charm contribution to R in the region $3.7 < W < 4.5$ GeV as computed in the coupled-channel model. Contributions from $F_1\bar{F}_2$ channels are included but not indicated separately since they are too small; they are shown in Fig. 12.

Main problems of the inclusive fits

- Bad data description
- Use only part of the information available: either inclusive or one of exclusive spectra
- Open-charm thresholds are disregarded
- No correct accounting for $\psi \leftrightarrow DD$ transitions/rescattering
- Interference btw. two and more BW leads to the multiple solutions

Measured x-sections description



Four (five?) ψ states
five (three?) Y-states
at least 10 open-charm thresholds

Correct procedure:

Simultainious fit to all exclusive spectra, which accounts for all possible final states interfierence and for all opening thresholds

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

Exclusive channels

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

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

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

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

16 channels, 5 ψ-states

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

$$|^3S_1\rangle = -\frac{1}{2\sqrt{3}}|D\bar{D}\rangle + \frac{1}{\sqrt{3}}|D\bar{D}^*\rangle_- - \frac{1}{6}|D^*\bar{D}^*\rangle_{P0} + \frac{\sqrt{5}}{3}|D^*\bar{D}^*\rangle_{P2},$$

heavy-quark spin symmetry

$$|^3D_1\rangle = \frac{\sqrt{5}}{2\sqrt{3}}|D\bar{D}\rangle + \frac{\sqrt{5}}{2\sqrt{3}}|D\bar{D}^*\rangle_- + \frac{\sqrt{5}}{6}|D^*\bar{D}^*\rangle_{P0} - \frac{1}{6}|D^*\bar{D}^*\rangle_{P2},$$

→ 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

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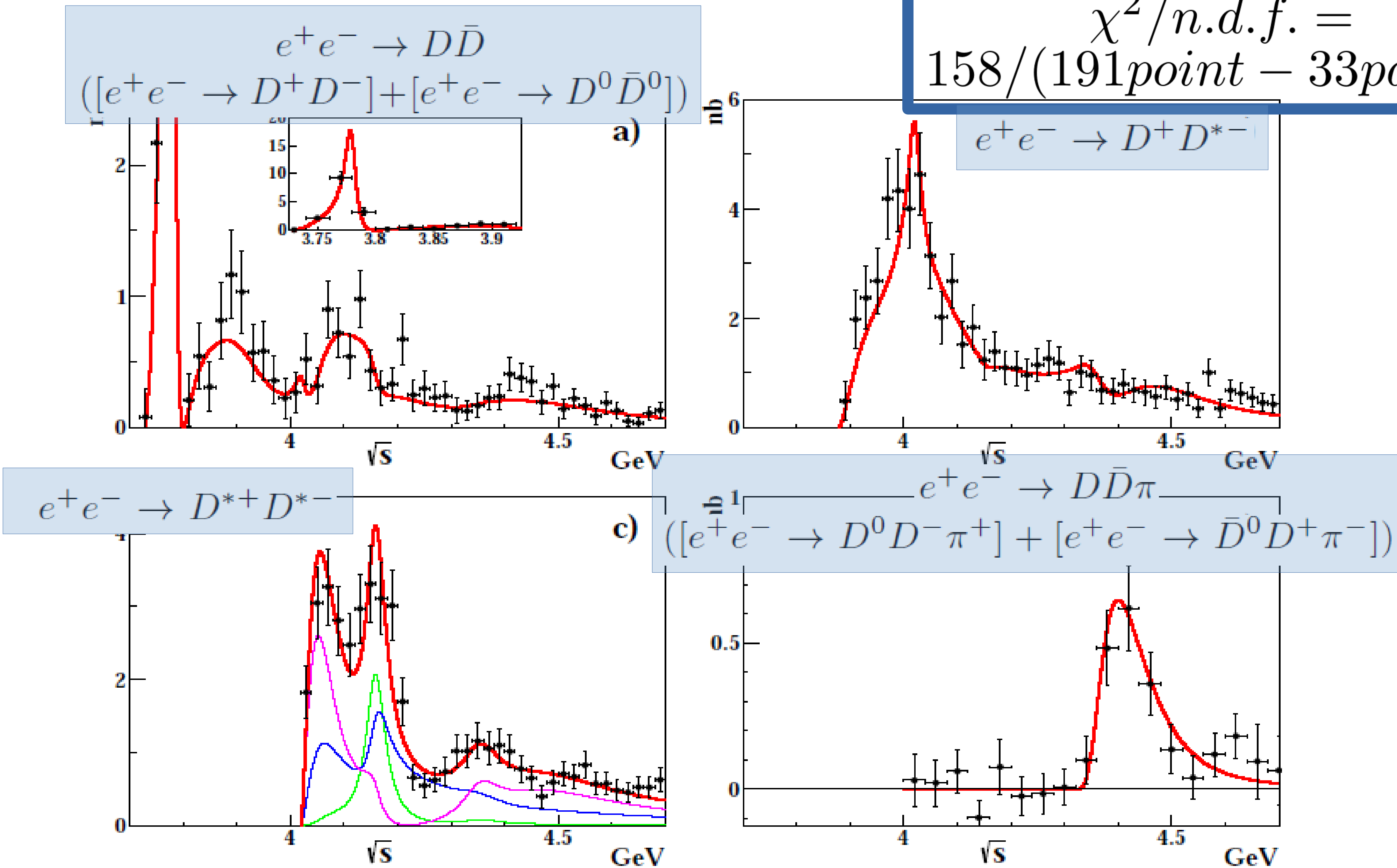
ФИАН

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

Results

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

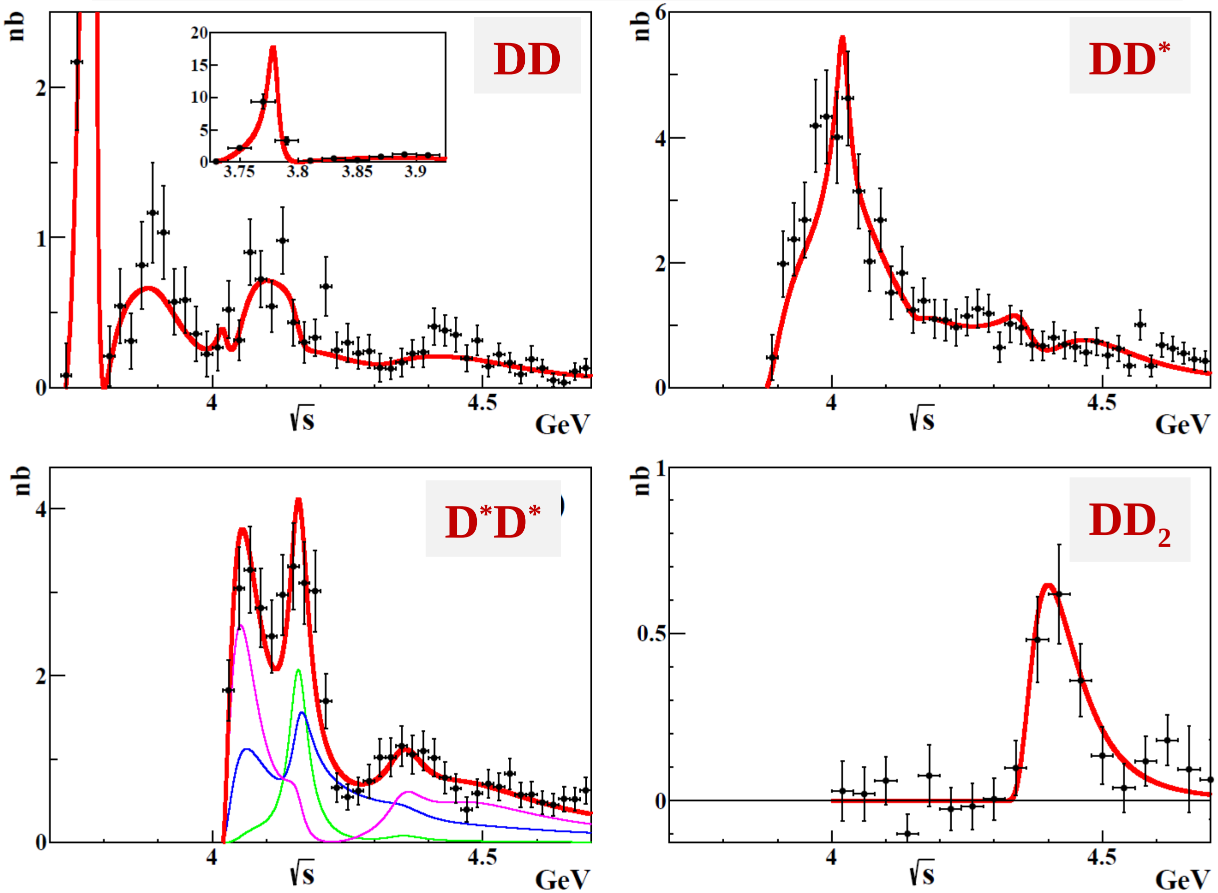


Results (II)

	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

Results (III)

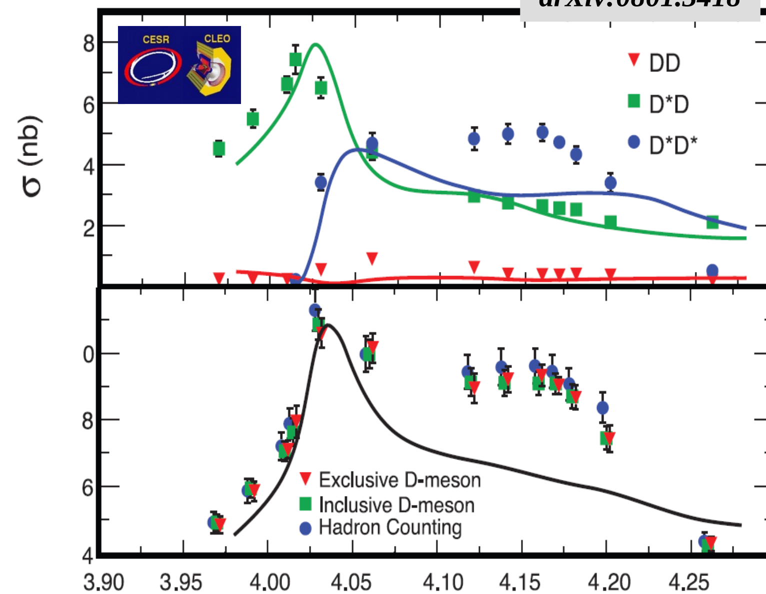
Uglov, Kalashnikova, Nefediev, Pakhlova, Pakhlov JETP Lett 105 (2017) 1



ψ(2S), ψ(3770), ψ(4040), ψ(4160), ψ(4415)

- Complicated thresholds behavior
- Improved model to describe standard and to search for new states

arXiv:0801.3418



Eichten at al

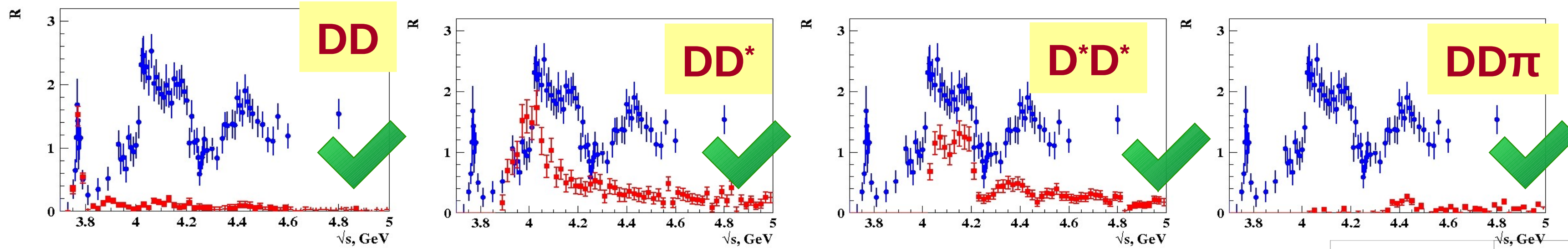
Simultaneous fit to all measured cross sections

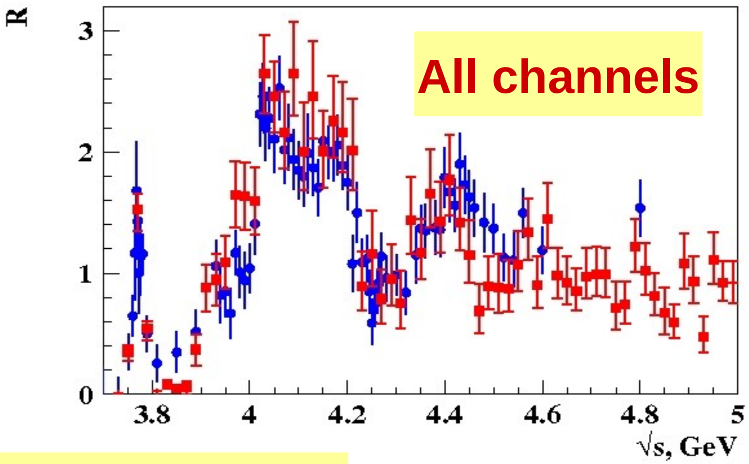
- Parameters: masses, widths, electronic widths, couplings
- Good description of the data

Problems

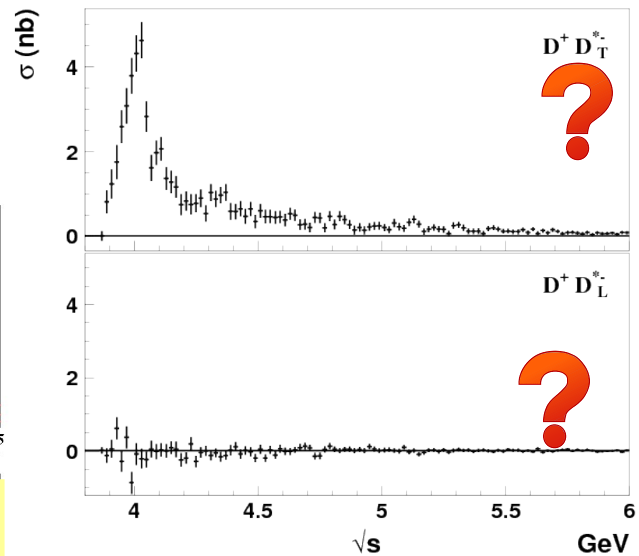
- Only the feasibility of the approach was demonstrated, need some more work to get reliable results
- 'Masses' of the resonances do not coincide to the peaks in the cross-section spectra
- For DD*, D*D* and higher excitation accounting for helicity decomposition is required
- There are no accounting for the real part of the loop in the function
- Use of the artificial bounds

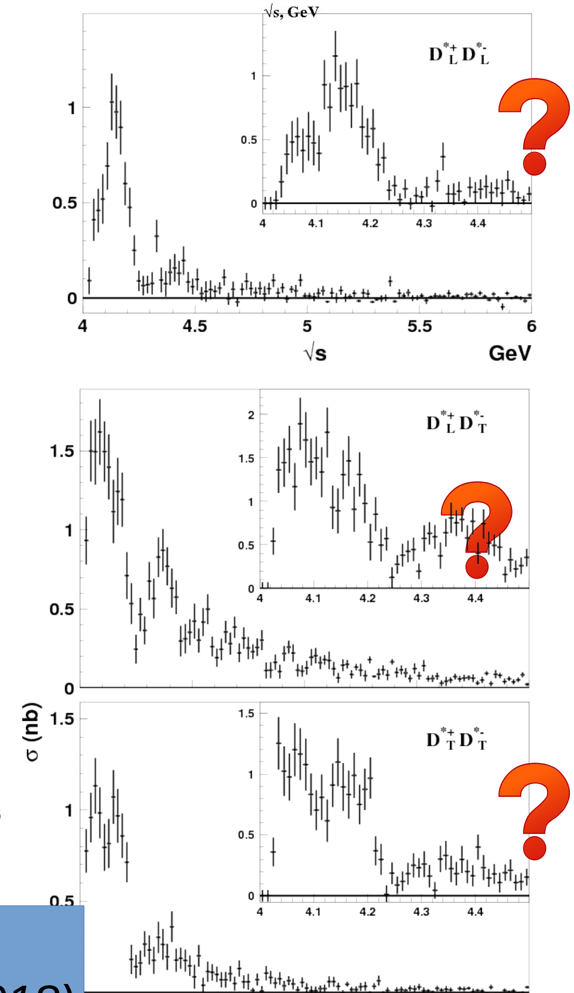
New data

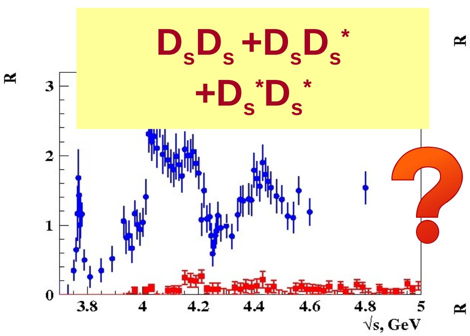


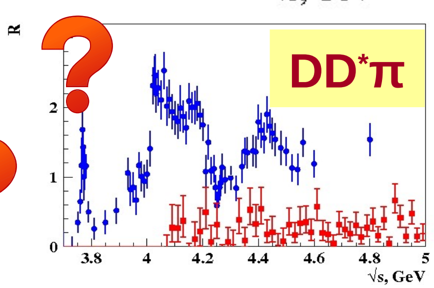


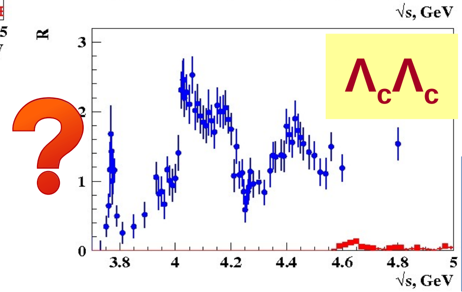
Use ALL avaliable data











BES III data

V. Zhukova et al.
Phys.Rev. D97 1, 012002 (2018)

Ways to improve

- Larger statistics = smaller errors
- Account for the real part of the loop
- Stabilize the fit: no need for artificial bounds
- Check (instead of getting rid of) heavy quark symmetry

Which outcome could be expected?

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ФИАН

- All inclusive and exclusive channels description within one model
- Parameters: coupling constants and masses
- Heavy quark symmetry test
- (?) Determination of the chamonium-like Y-states parameters

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 contributions like $D_s^+ D_s^-$.

- A good χ^2 demonstrates that the suggested approach is able to explain all data simultaneously.

- Waiting for a new data and refined fit functions to solve the ψ and Y puzzles.