Experimetal review of vector charmonium(-like) and couple channel analysis

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山东大学
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HIM
HELMHOLTZ
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JG|U
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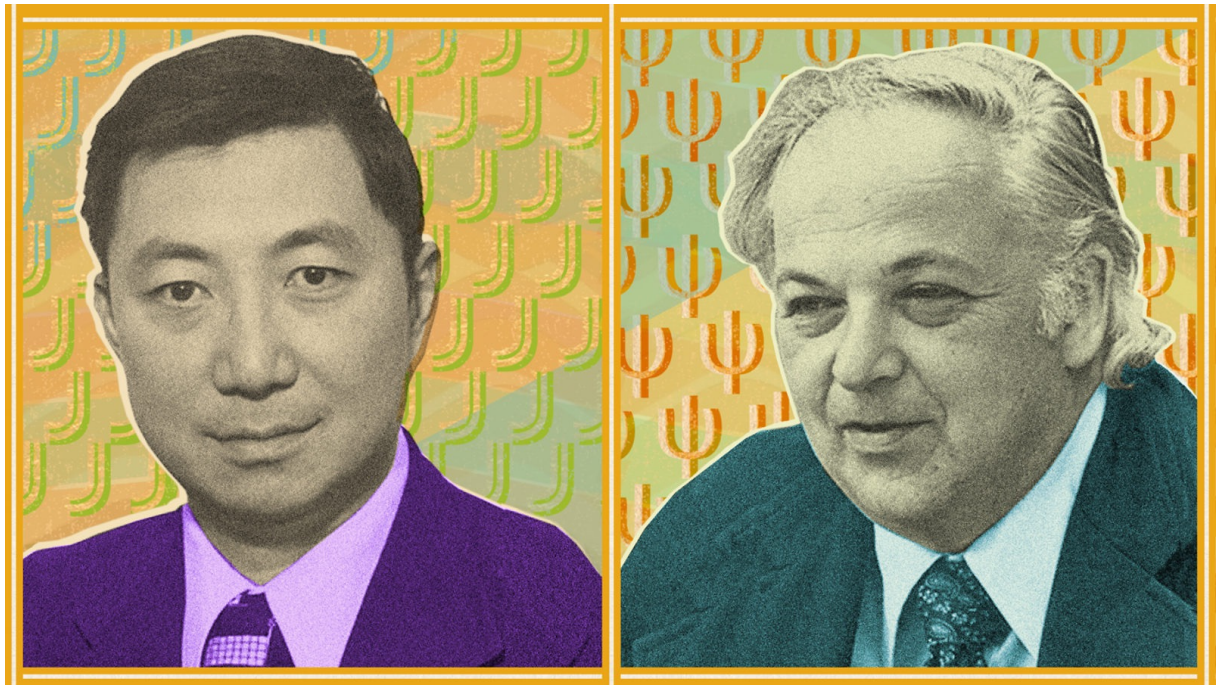
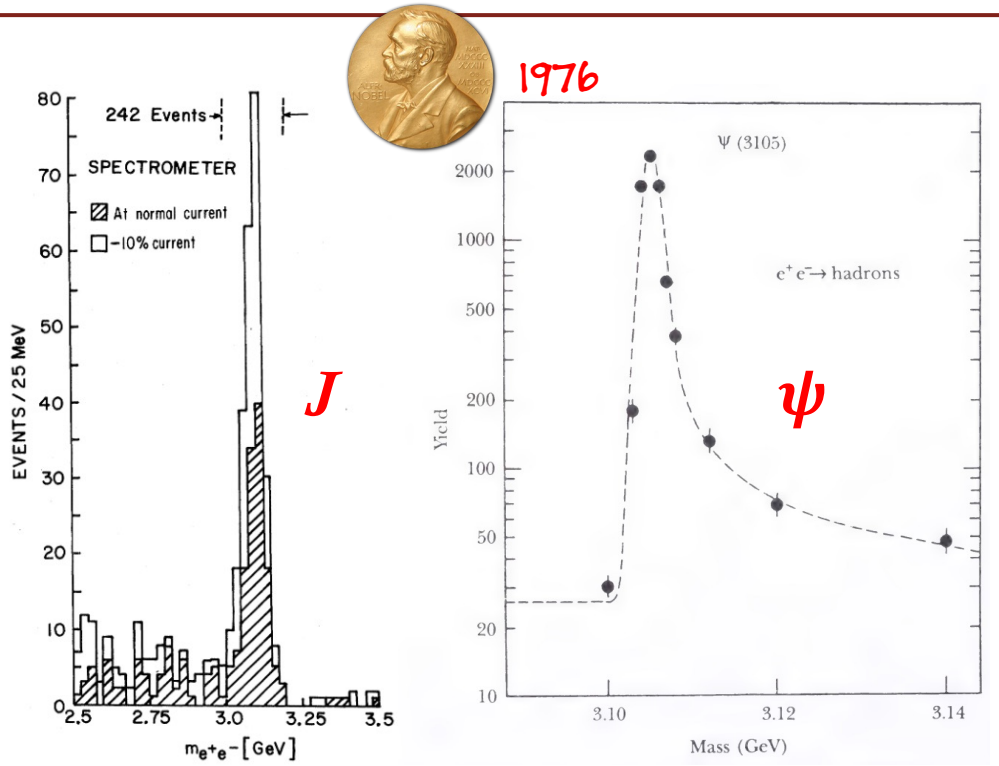
J/ψ

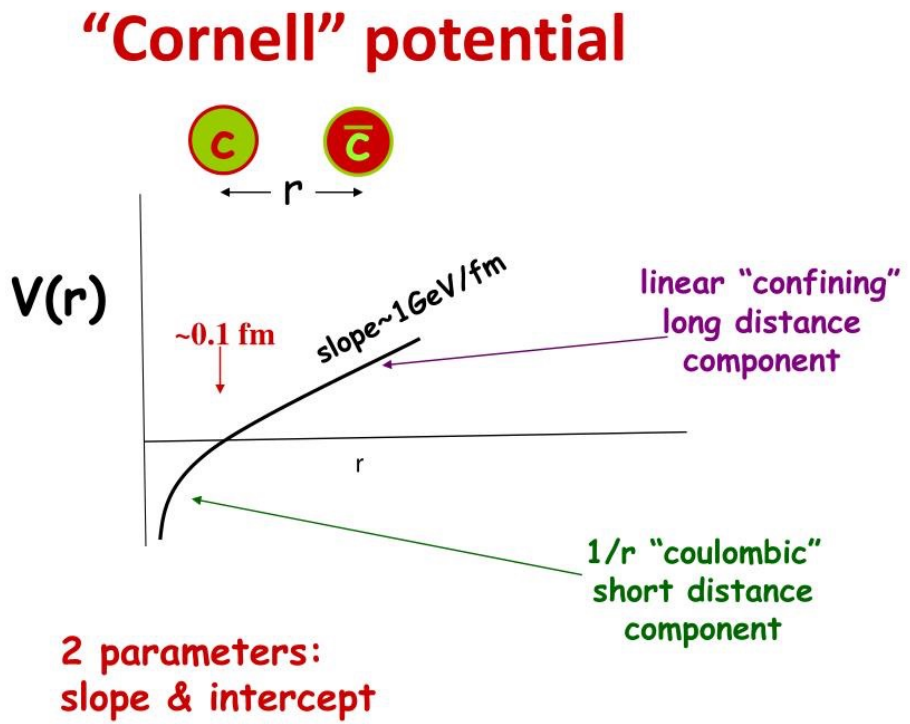
Phys. Rev. Lett. 33, 1404 (1974) E598
Phys. Rev. Lett. 33, 1406 (1974) SLAC



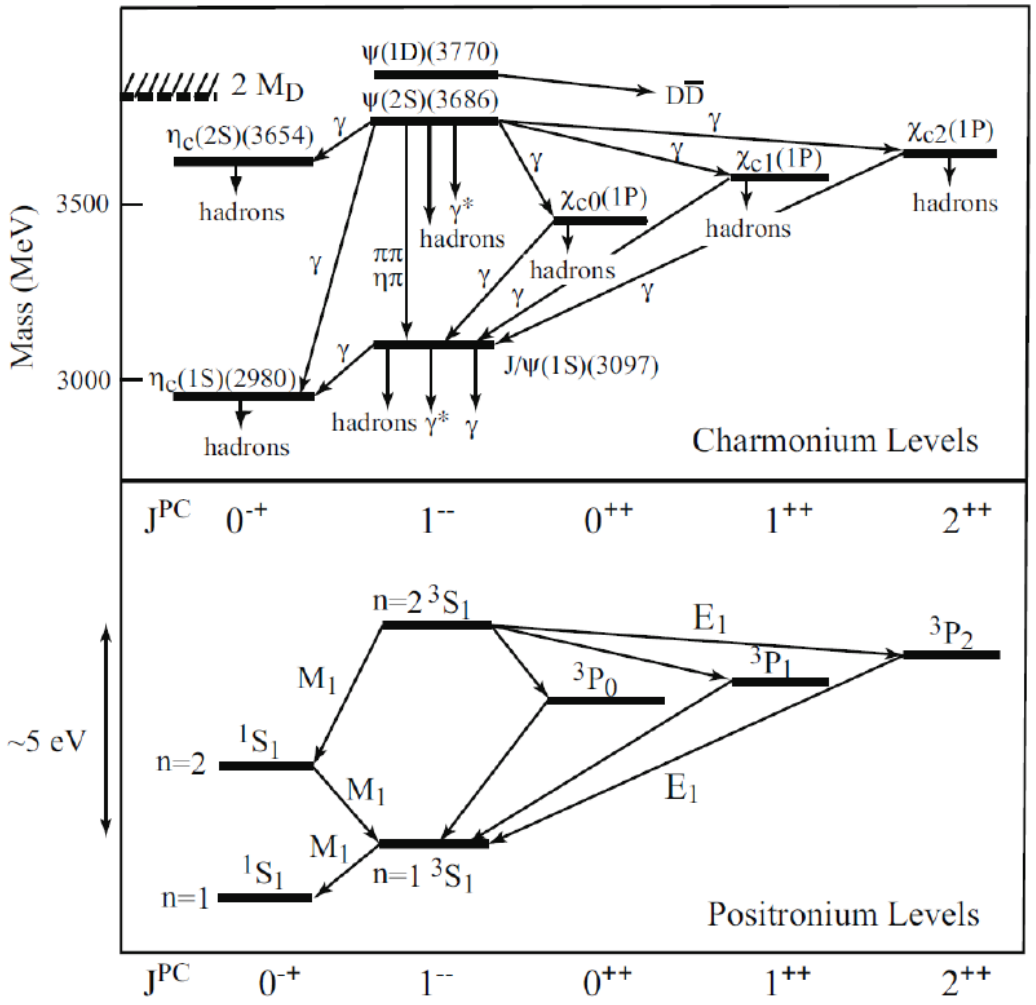


50 years ago, the discovery of J/ψ particle begins our study in charm sector

$c\bar{c}$ spectrum

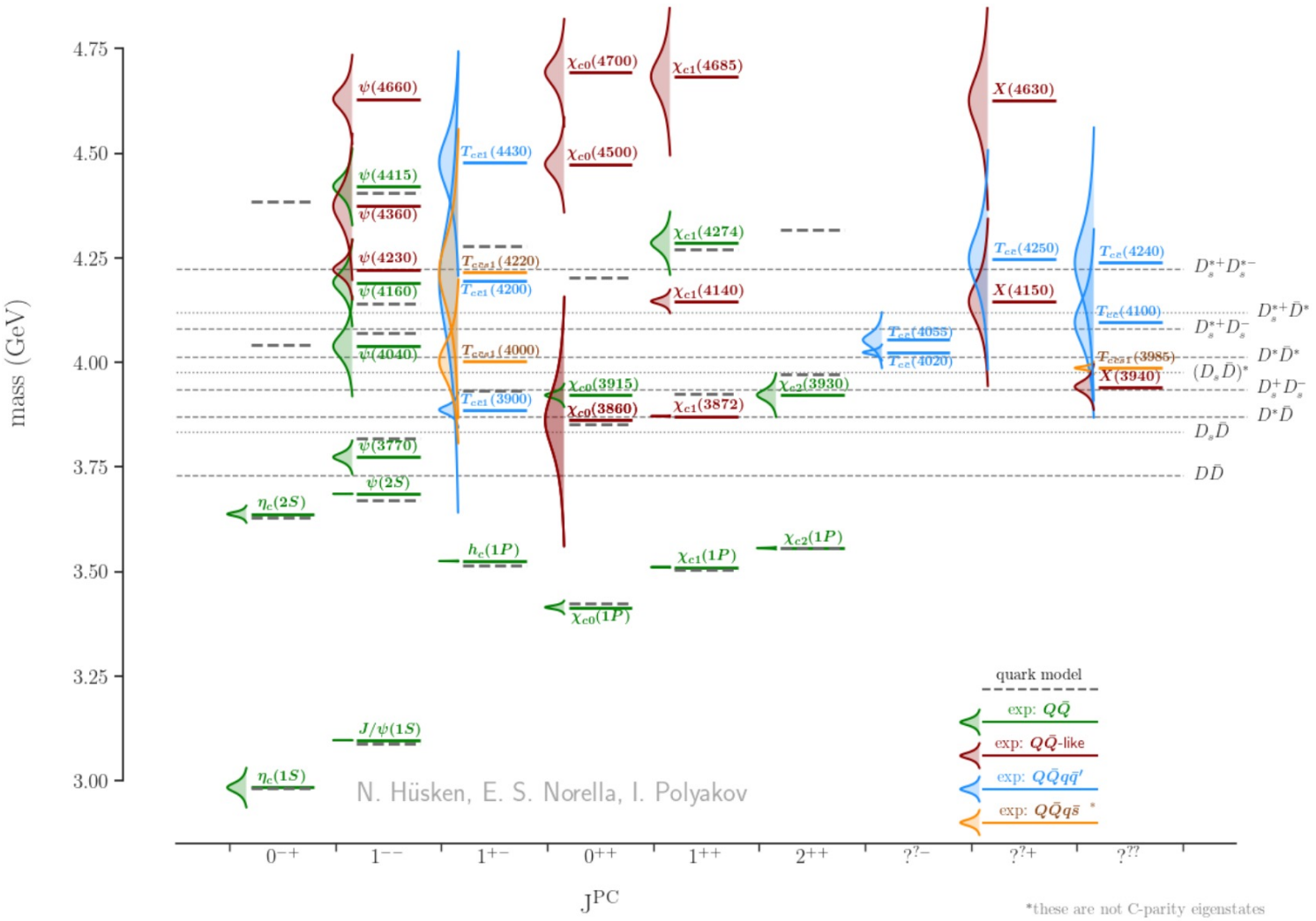


$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + kr$$



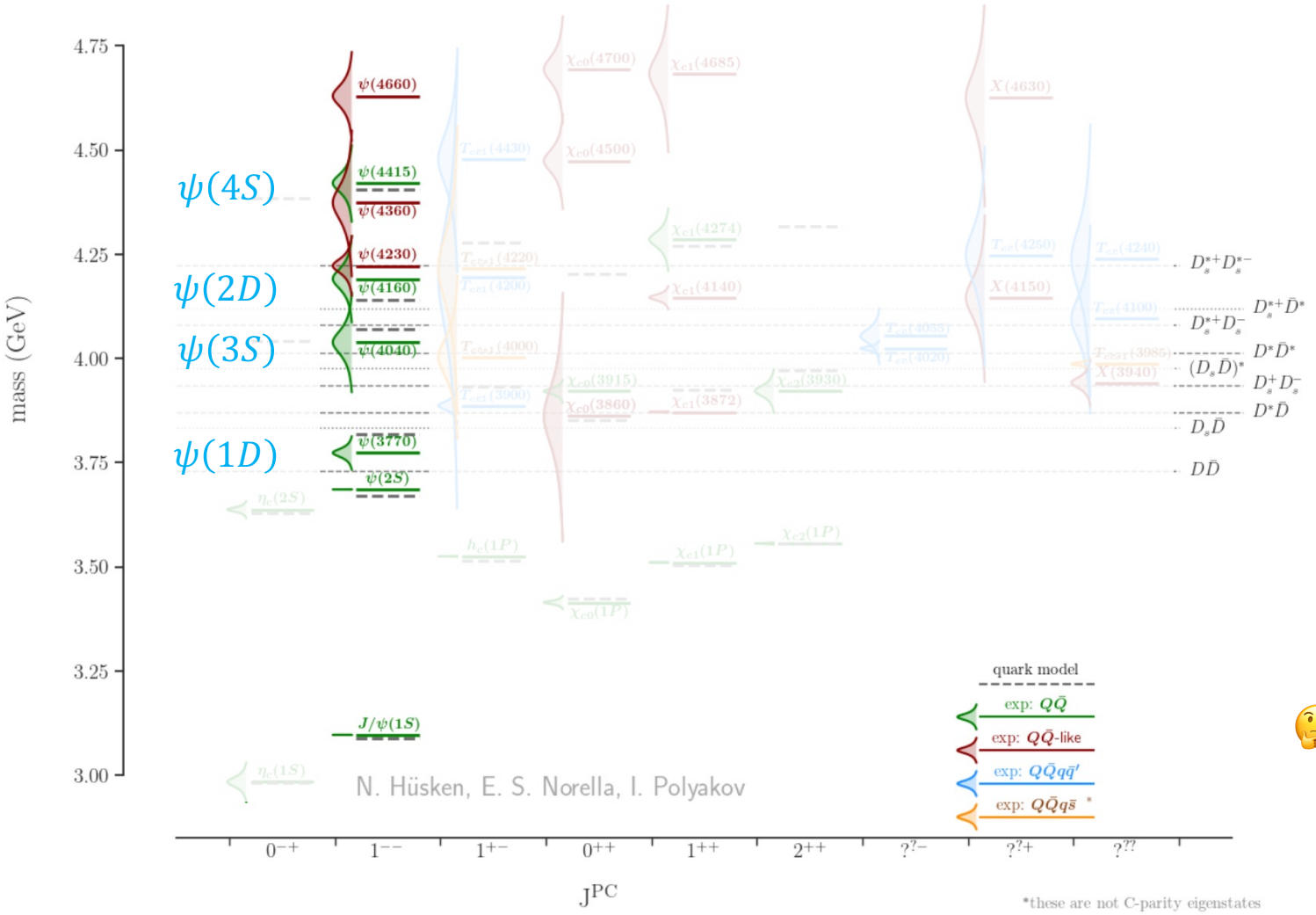
Good agreement with experiments

$c\bar{c}$ spectrum



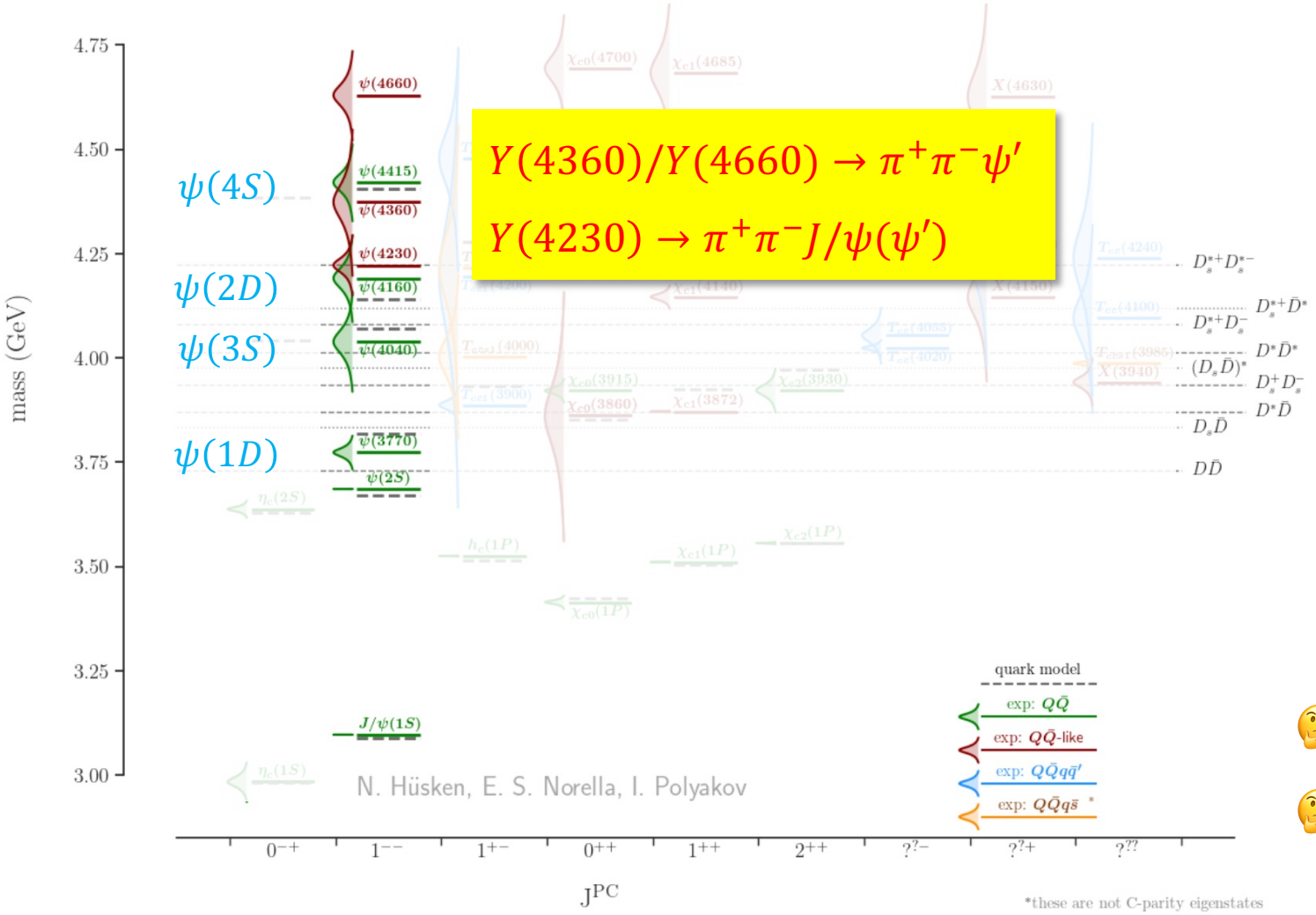
- Unexpected states
- Near threshold
- Couple with hidden charm
- Non-zero charge

$c\bar{c}$ spectrum



🤔 **Overnumerous vector states?**

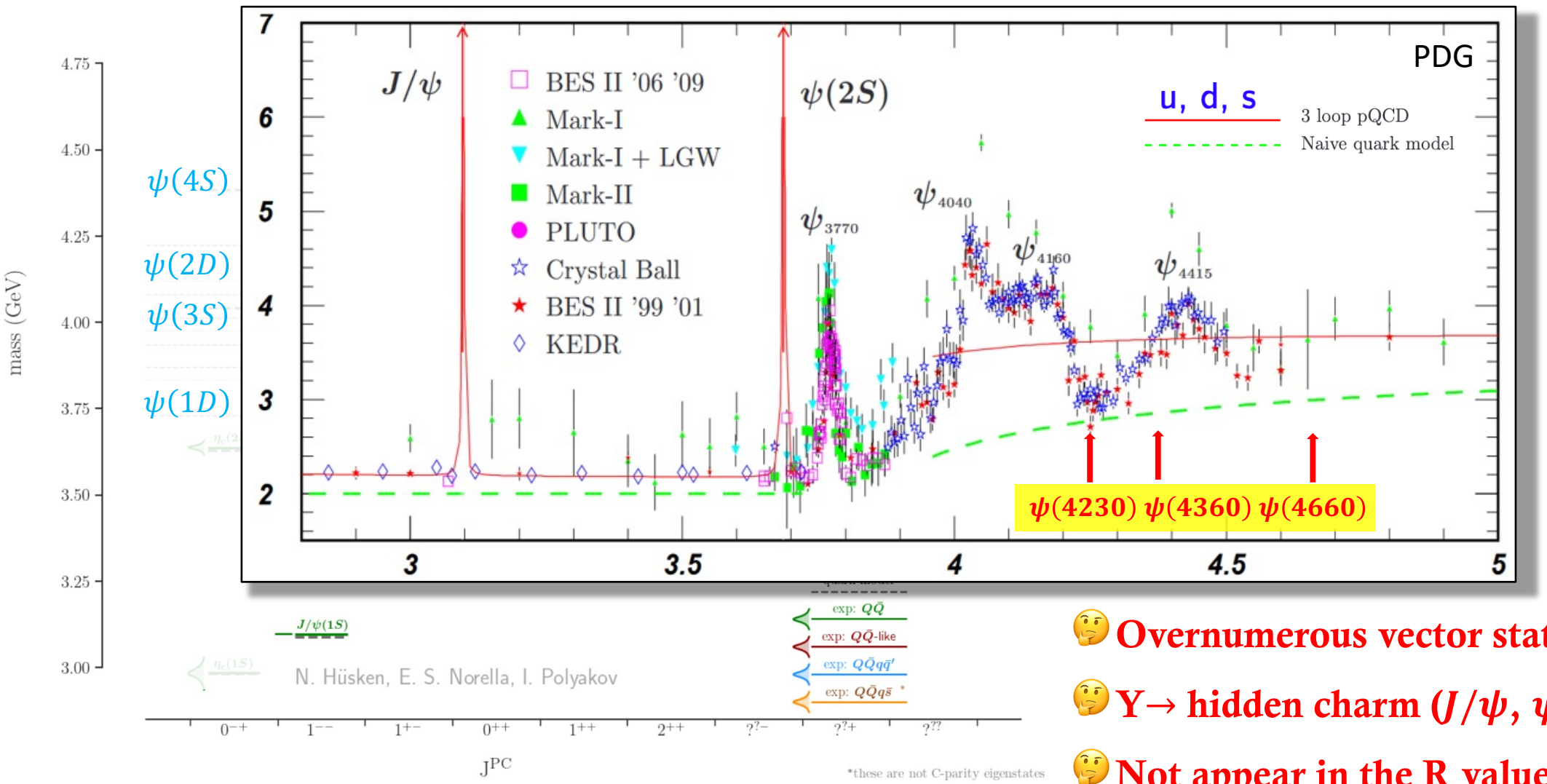
$c\bar{c}$ spectrum



🤔 **Overnumerous vector states?**

🤔 **Y→ hidden charm (J/ψ, ψ'), OZI?**

$c\bar{c}$ spectrum



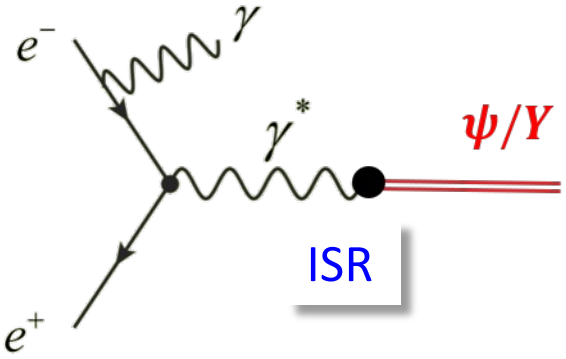
🤔 Overnumerous vector states?

🤔 Y→ hidden charm (J/ψ, ψ'), OZI?

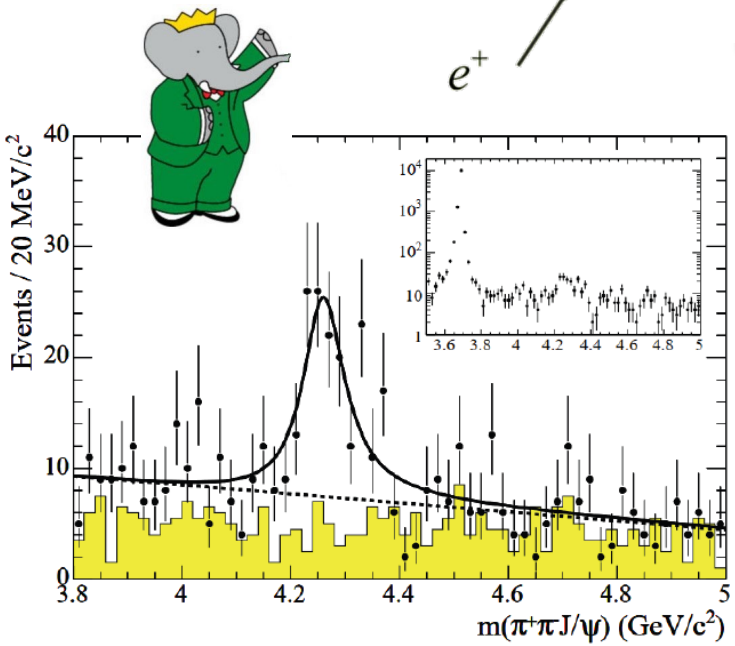
🤔 Not appear in the R value!

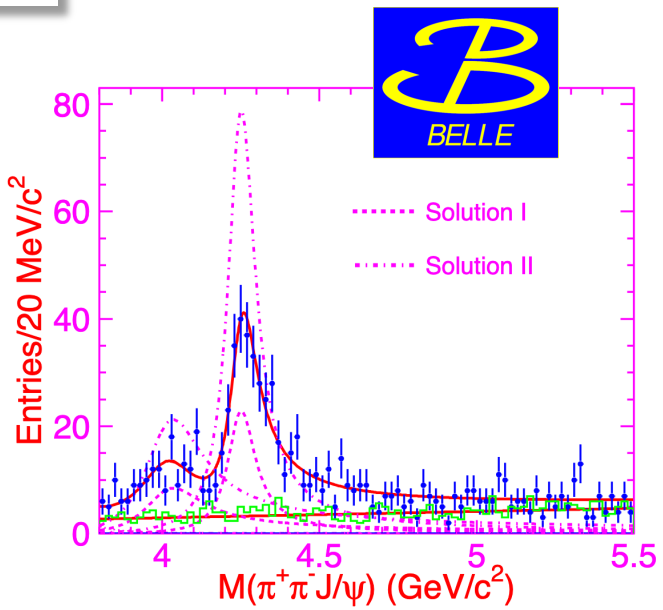
Production

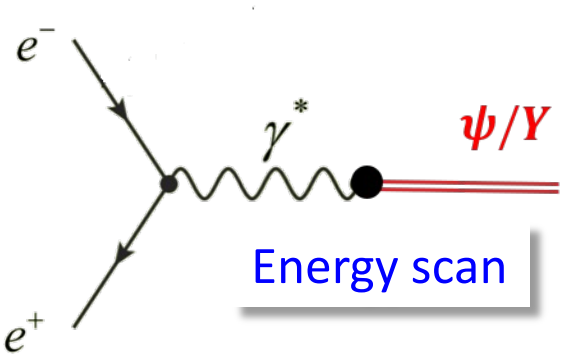
PRL 95, 142001 (2005), BaBar
PRL 99, 182004 (2007), Belle
PRL 118, 092001 (2017), BESIII



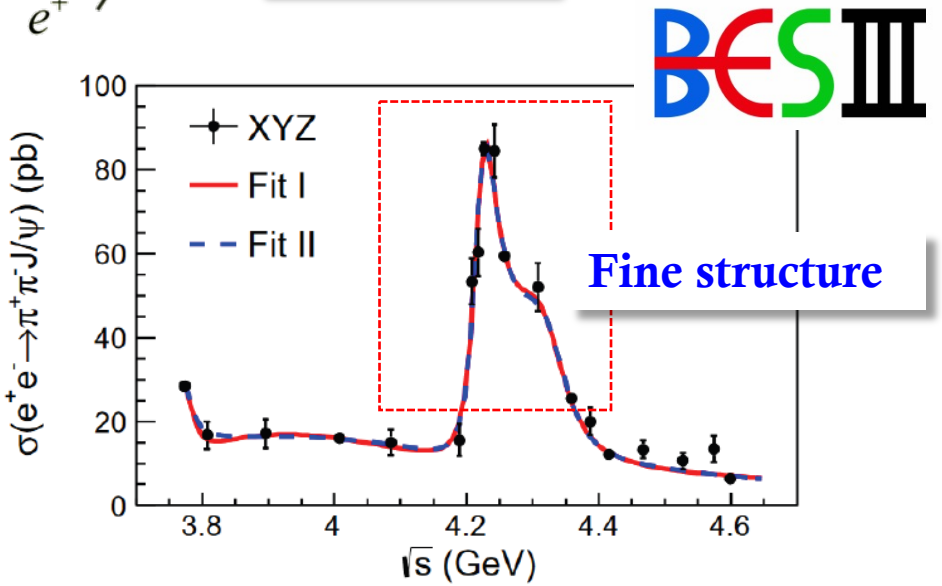
ISR







Energy scan

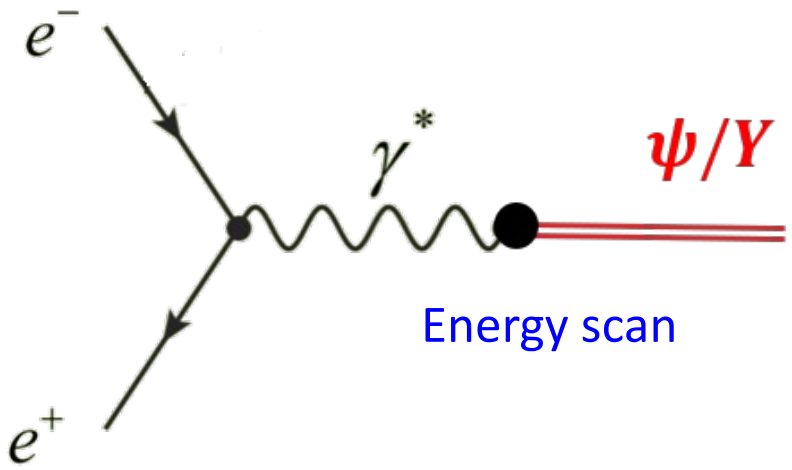


Fine structure

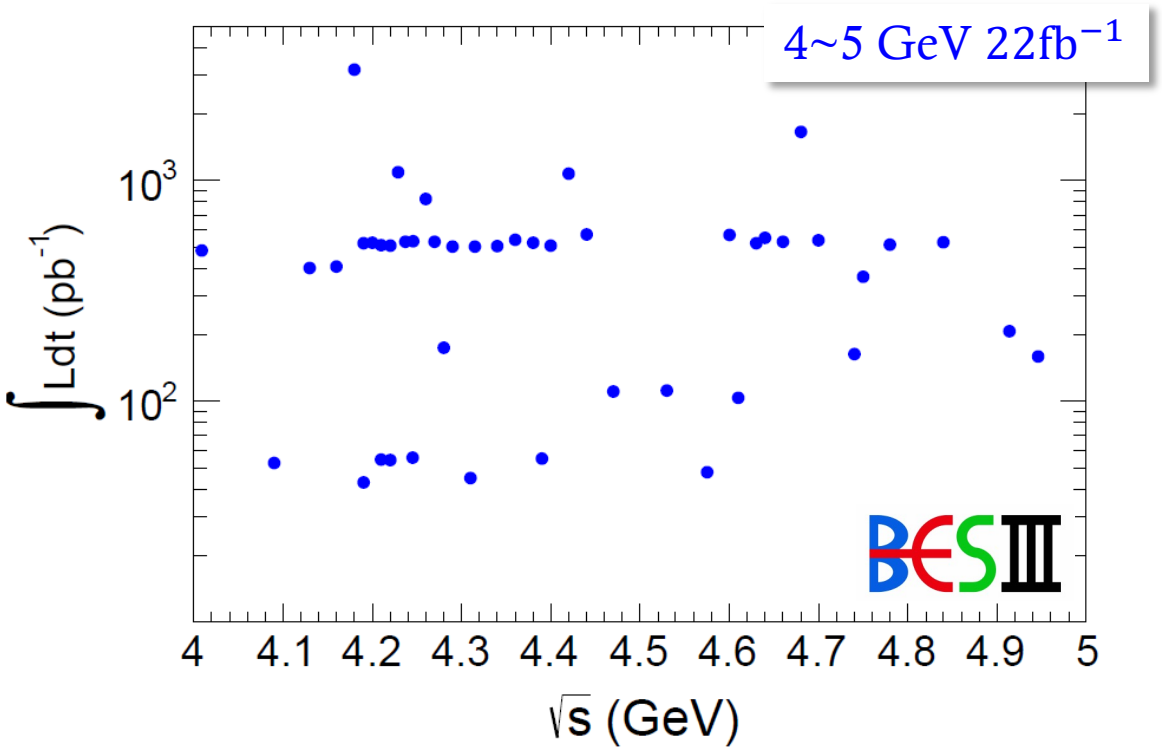
$Y(4260)$ ➡ $Y(4220) + Y(4320)$

tau-charm facility (ψ/Y factory) is really a "good stuff", tells us more!

Production



Energy scan



- After BESIII collecting e^+e^- collision data above 4.0 GeV
- dedicate efforts into vector charmonium(-like) study
- higher precisions, expose more channels, …

Production

$\psi(4230)$ MASS — 4222.7 ± 2.6 MeV (S = 1.7)

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
4222.7 ± 2.6	**OUR AVERAGE**	Error includes scale factor of 1.7. See the ideogram below.			
$4234.4 \pm 3.2 \pm 0.2$		[1] ABLIKIM	2021AJ	BES3	$e^+ e^- \to \pi^+\pi^-\psi(2S)$
$4216.7 \pm 8.9 \pm 4.1$		[2] ABLIKIM	2020AG	BES3	$e^+ e^- \to \mu^+\mu^-$
$4220.4 \pm 2.4 \pm 2.3$		[3] ABLIKIM	2020N	BES3	$e^+ e^- \to \pi^0\pi^0 J/\psi$
$4218.6 \pm 3.8 \pm 2.5$		[3] ABLIKIM	2020O	BES3	$e^+ e^- \to \eta J/\psi$
$4218.5 \pm 1.6 \pm 4.0$		[4] ABLIKIM	2019AI	BES3	$e^+ e^- \to \omega\chi_{c0}$
$4228.6 \pm 4.1 \pm 6.3$		ABLIKIM	2019R	BES3	$e^+ e^- \to \pi^+ D^0 D^{*-}$ + c.c.
$4200.6\ ^{+7.9}_{-13.3} \pm 3.0$		[5] ABLIKIM	2019V	BES3	$e^+ e^- \to \gamma\chi_{c1}(3872)$
$4222.0 \pm 3.1 \pm 1.4$		[6] ABLIKIM	2017B	BES3	$e^+ e^- \to \pi^+\pi^- J/\psi$
$4218\ ^{+5.5}_{-4.5} \pm 0.9$		ABLIKIM	2017G	BES3	$e^+ e^- \to \pi^+\pi^- h_c$

$\psi(4360)$ MASS — 4372 ± 9 MeV (S = 2.9)

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
4372 ± 9	**OUR AVERAGE**	Error includes scale factor of 2.9. See the ideogram below.			
$4390.3 \pm 6.0 \pm 0.7$		[1] ABLIKIM	2021AJ	BES3	$e^+ e^- \to \pi^+\pi^-\psi(2S)$
$4371.7 \pm 7.5 \pm 1.8$		[2] ABLIKIM	2021AK	BES3	$e^+ e^- \to \gamma\chi_{c2} \to \gamma\gamma J/\psi$
$4382.0 \pm 13.3 \pm 1.7$		[3] ABLIKIM	2020O	BES3	$e^+ e^- \to \eta J/\psi$
$4320.0 \pm 10.4 \pm 7.0$		[4] ABLIKIM	2017B	BES3	$e^+ e^- \to \pi^+\pi^- J/\psi$
$4391.5\ ^{+6.3}_{-6.8} \pm 1.0$		ABLIKIM	2017G	BES3	$e^+ e^- \to \pi^+\pi^- h_c$
$4347 \pm 6 \pm 3$	279	[5] WANG	2015A	BELL	10.58 $e^+ e^- \to \gamma\pi^+\pi^-\psi(2S)$
$4340 \pm 16 \pm 9$	37	[6] LEES	2014F	BABR	10.58 $e^+ e^- \to \gamma\pi^+\pi^-\psi(2S)$

$\psi(4660)$ MASS — 4630 ± 6 MeV (S = 1.4)

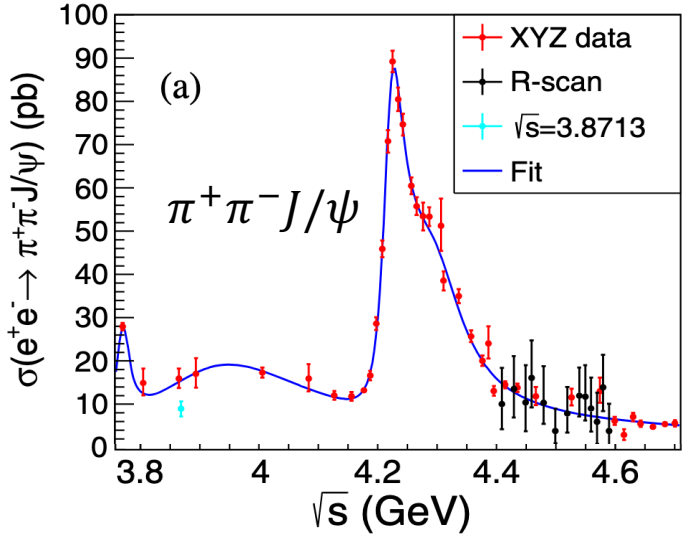
VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
4630 ± 6	**OUR AVERAGE**	Error includes scale factor of 1.4. See the ideogram below.			
$4651.0 \pm 37.8 \pm 2.1$		[1] ABLIKIM	2021AJ	BES3	$e^+ e^- \to \pi^+\pi^-\psi(2S)$
$4619.8\ ^{+8.9}_{-8.0} \pm 2.3$	66	[2] JIA	2020	BELL	$e^+ e^- \to \gamma D_s^+ D_{s2}^*(2573)^-$
$4625.9\ ^{+6.2}_{-6.0} \pm 0.4$	89	[3] JIA	2019A	BELL	$e^+ e^- \to \gamma D_s^+ D_{s1}(2536)^-$
$4652 \pm 10 \pm 11$	279	[4] WANG	2015A	BELL	10.58 $e^+ e^- \to \gamma\pi^+\pi^-\psi(2S)$
$4669 \pm 21 \pm 3$	37	[5] LEES	2014F	BABR	10.58 $e^+ e^- \to \gamma\pi^+\pi^-\psi(2S)$
$4634\ ^{+8}_{-7}\ ^{+5}_{-8}$	142	[6] PAKHLOVA	2008B	BELL	$e^+ e^- \to \Lambda_c^+\Lambda_c^-$

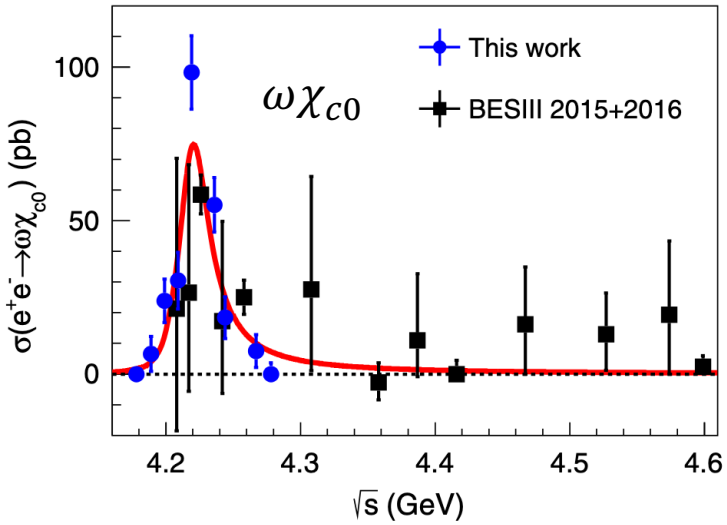
$Z_c(3900)$ MASS — 3887.1 ± 2.6 MeV (S = 1.7)

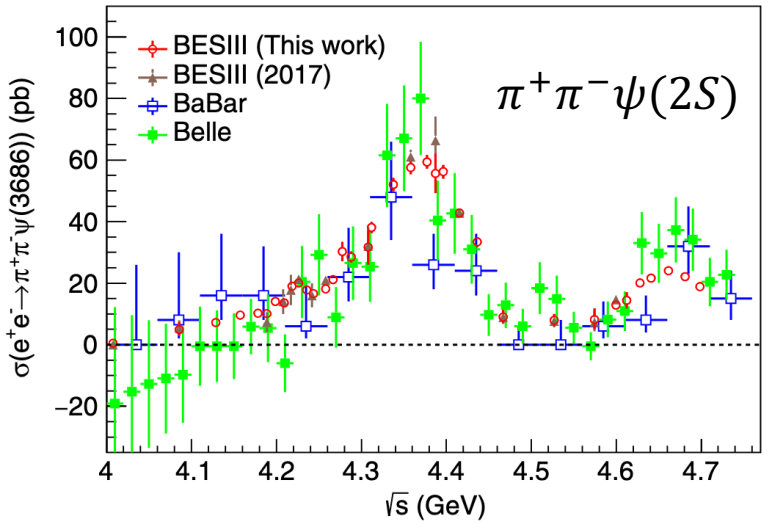
VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
3887.1 ± 2.6	**OUR AVERAGE**	Error includes scale factor of 1.7. See the ideogram below.				
$3893.1 \pm 2.2 \pm 3.0$		[1] ABLIKIM	2020N	BES3	0	$e^+ e^- \to \pi^0\pi^0 J/\psi$
$3902.6\ ^{+5.2}_{-5.0}\ ^{+3.3}_{-1.4}$		[2,3] ABAZOV	2019	D0	$\pm$	1.96 TeV $p\bar{p} \to J/\psi\pi^+\pi^- X$
$3881.2 \pm 4.2 \pm 52.7$	6k	[4] ABLIKIM	2017J	BES3	$\pm$	$e^+ e^- \to \pi^+\pi^- J/\psi$
$3885.7\ ^{+4.3}_{-5.7} \pm 8.4$		[2,4] ABLIKIM	2015AB	BES3	0	$e^+ e^- \to \pi^0 (D\overline{D}^*)^0$
$3881.7 \pm 1.6 \pm 1.6$	1.2k	[2,4] ABLIKIM	2015AC	BES3	$\pm$	$e^+ e^- \to \pi^\pm (D\overline{D}^*)^{-+}$
$3883.9 \pm 1.5 \pm 4.2$	1.2k	[2,4] ABLIKIM	2014A	BES3	$\pm$	$e^+ e^- \to \pi^\pm (D\overline{D}^*)^{-+}$
$3894.5 \pm 6.6 \pm 4.5$	159	[2] LIU	2013B	BELL	$\pm$	$e^+ e^- \to \gamma\pi^+\pi^- J/\psi$
$3886 \pm 4 \pm 2$	81	[2,5] XIAO	2013A		$\pm$	4.17 $e^+ e^- \to \pi^+\pi^- J/\psi$
$3904 \pm 9 \pm 5$	25	[2,5] XIAO	2013A		0	4.17 $e^+ e^- \to \pi^0\pi^0 J/\psi$

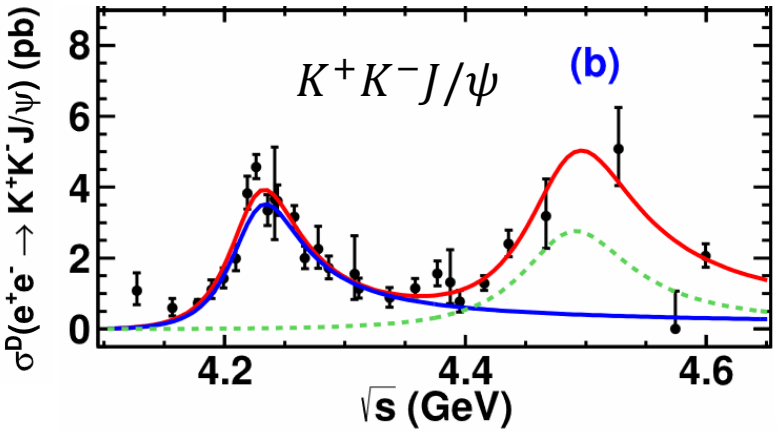
A brief overview

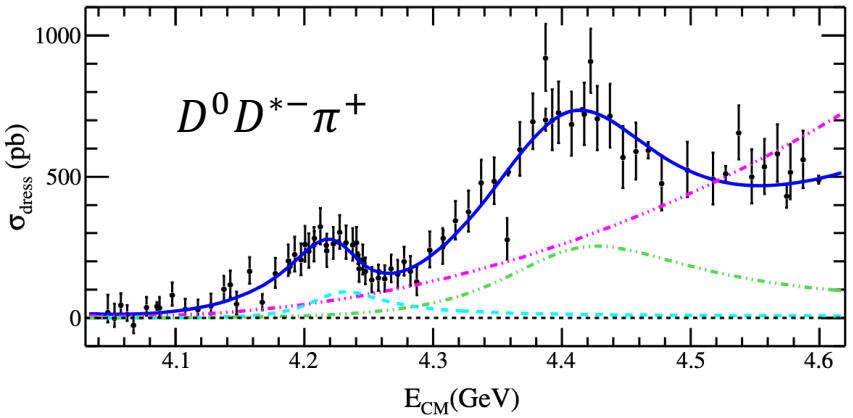
PRD 106, 072001 (2022) CPC 46, 111002 (2022)
PRD 99, 091103 (2019) PRL 122, 102002 (2019)
PRD 104, 052012 (2021) PRL 130, 121901 (2023)

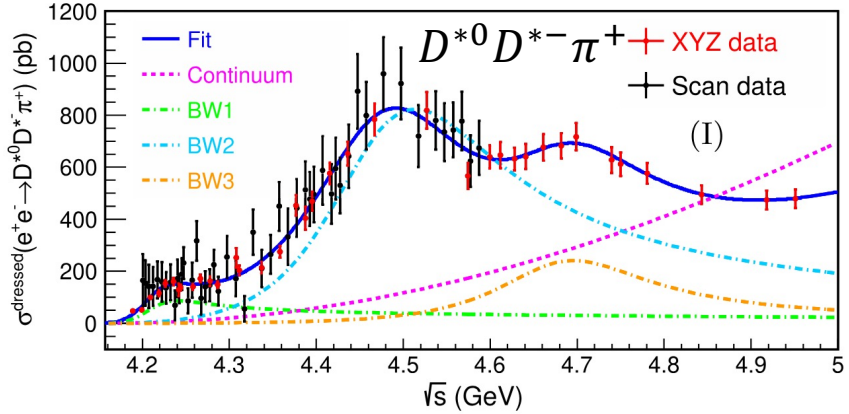










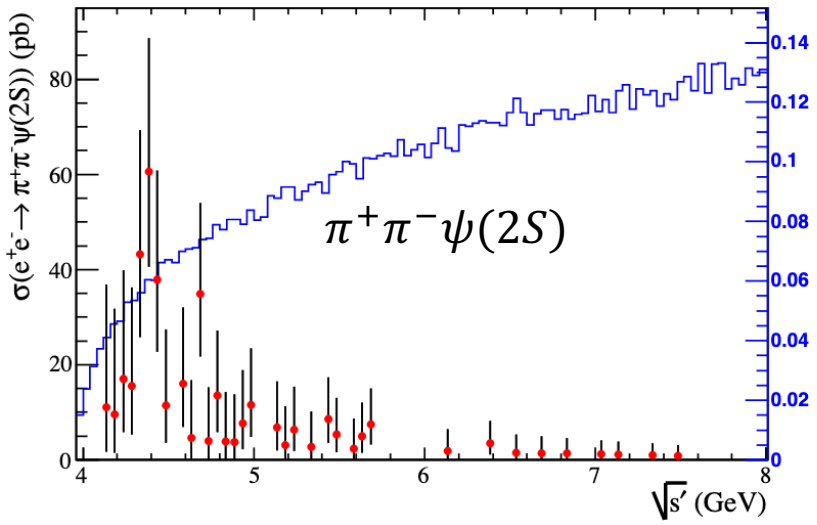


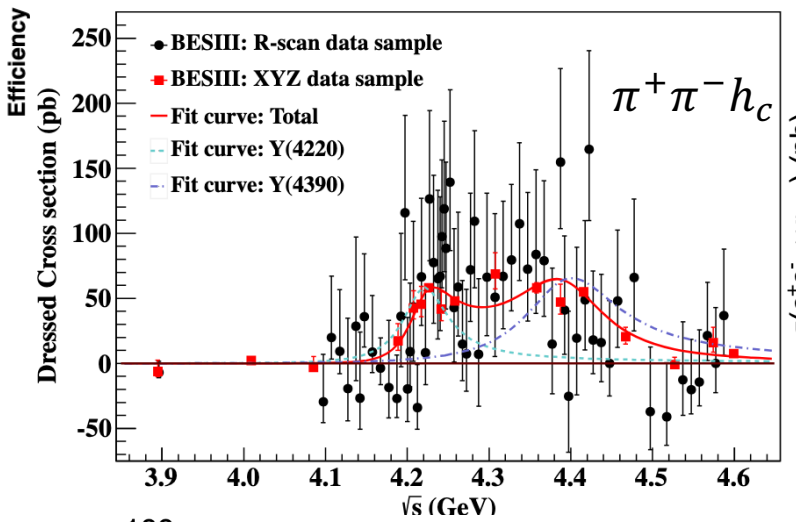
$Y(4230)$ is observed in $\pi^+\pi^- J/\psi, \pi^+\pi^-\psi(2S), \pi^+\pi^- h_c, \pi^+\pi^-\pi^0\eta_c\ \omega\chi_{c0}, K^+K^- J/\psi, \eta J/\psi,$

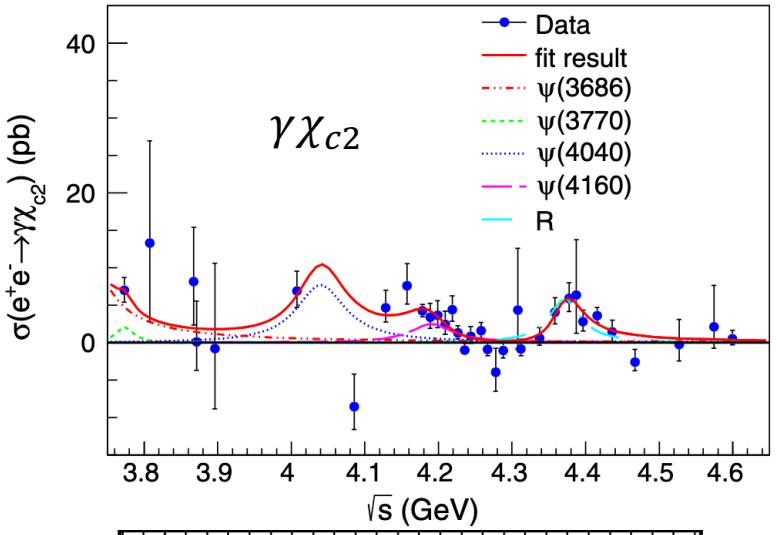
$D_s^*\bar{D}_s^*$ threshold $D^0D^{*-}\pi^+, D^{*0}D^{*-}\pi^+$

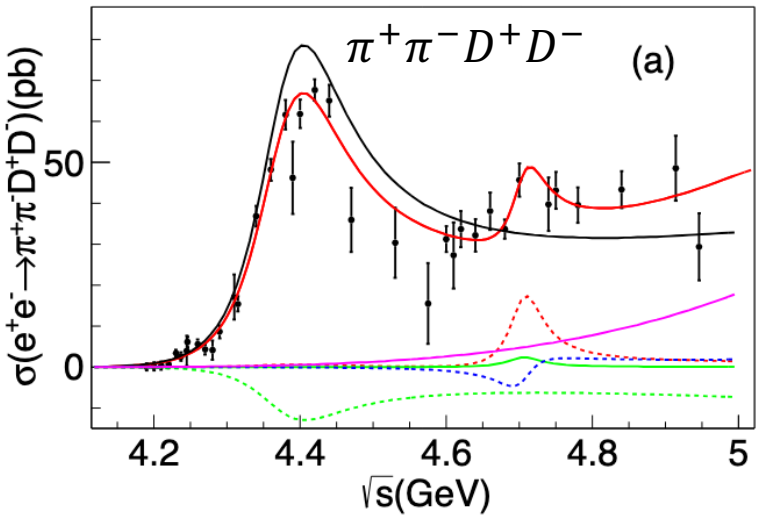
A brief overview

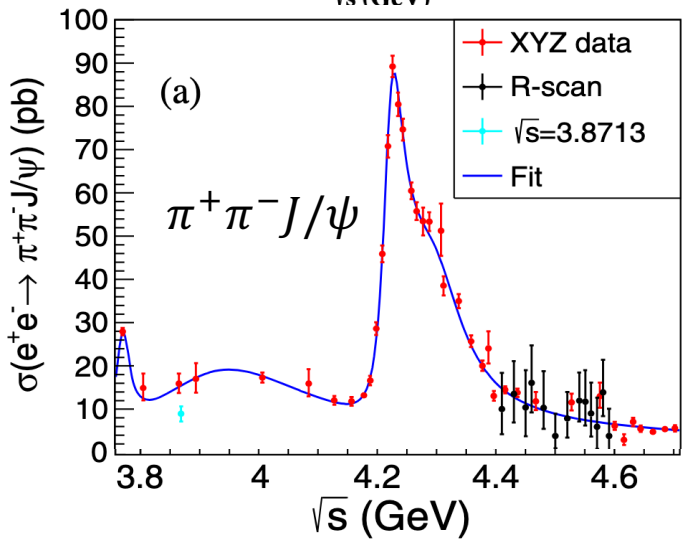
PRL 98, 212001 (2007)
PRL 118, 092002 (2017)
PRD 104, 092001 (2021)
PRD 106, 052012 (2022)
PRD 106, 072001 (2022)
PRD 109, 092012 (2024)

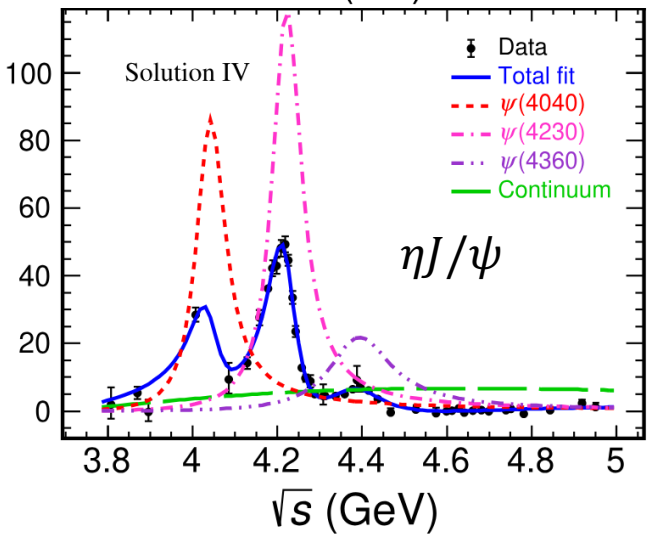








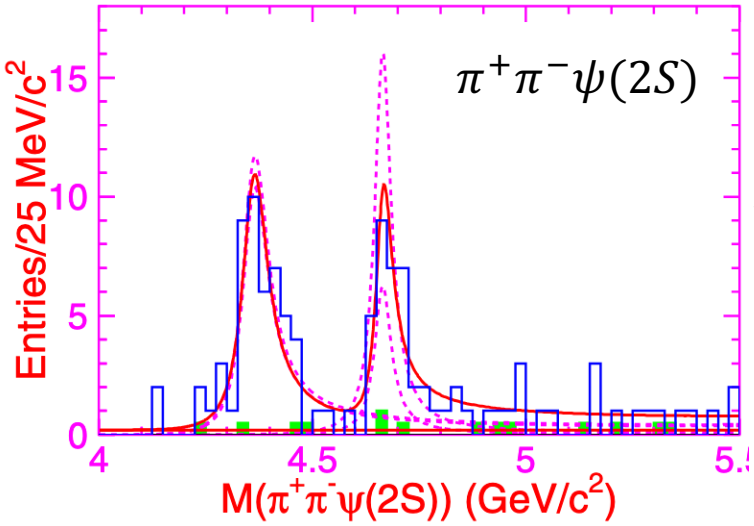


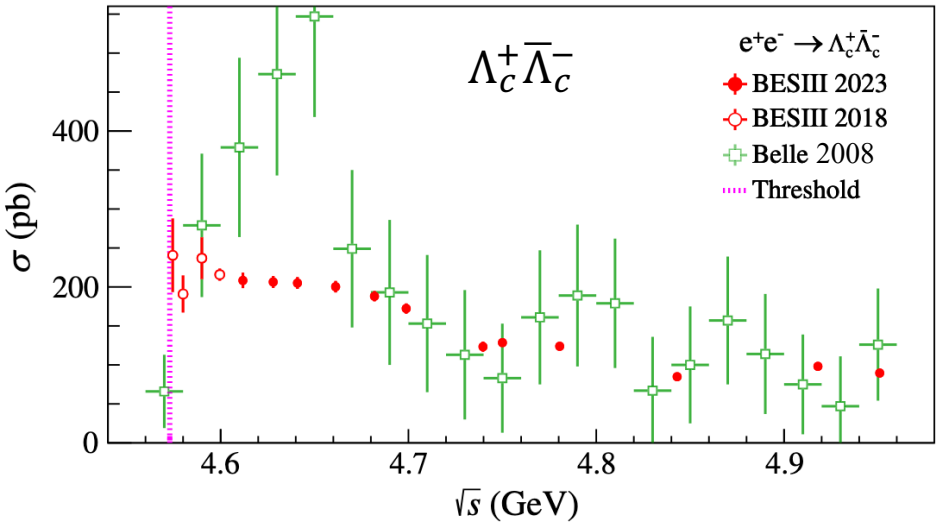


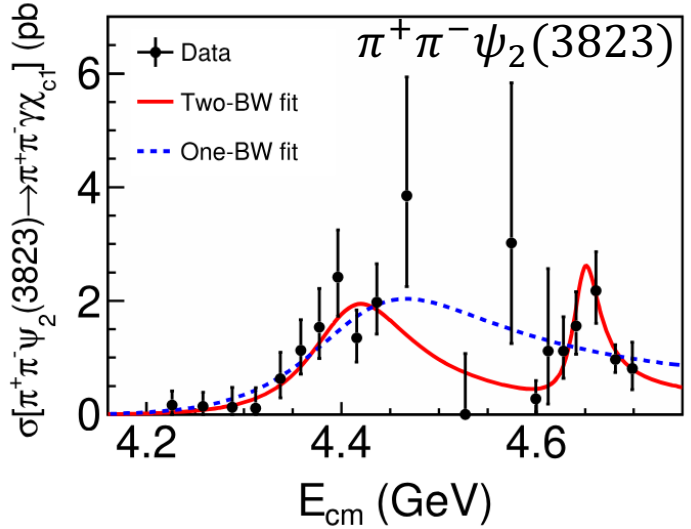
$Y(4360)/Y(4390)/Y(4320)$?

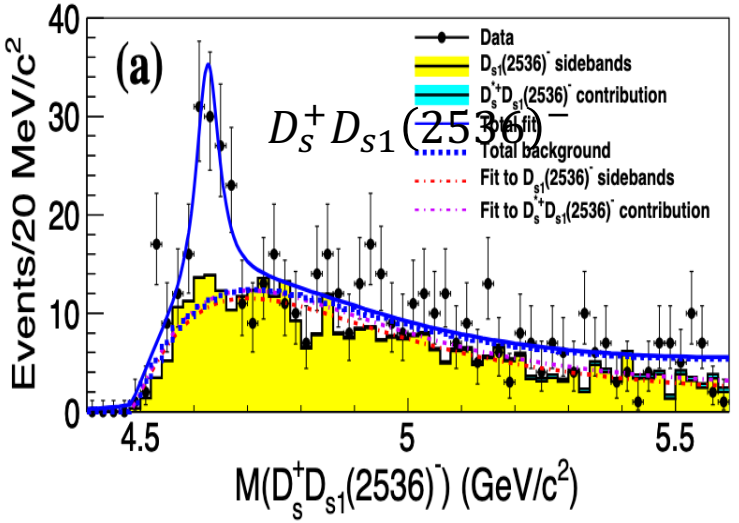
A brief overview

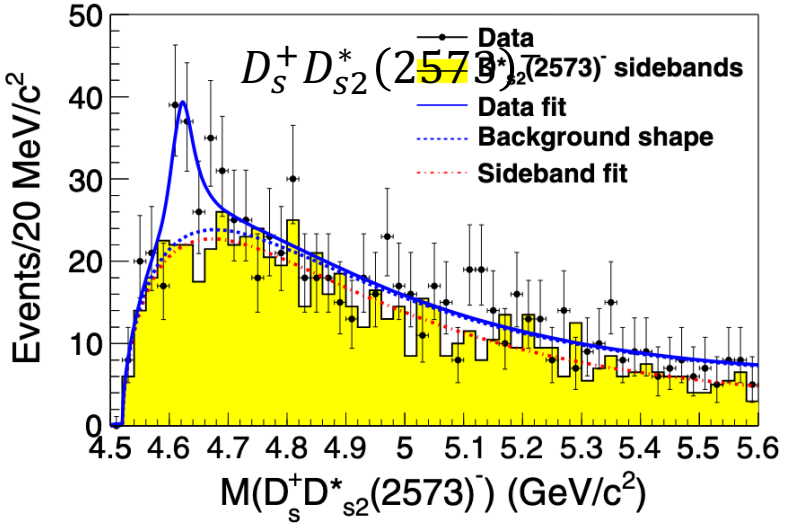
PRL 99, 142002 (2007)
PRL 131, 191901 (2023)
PRL 129, 102003 (2022)
PRD 100, 111103 (2019)
PRD 101, 091101 (2020)
JHEP 01, 132 (2023)

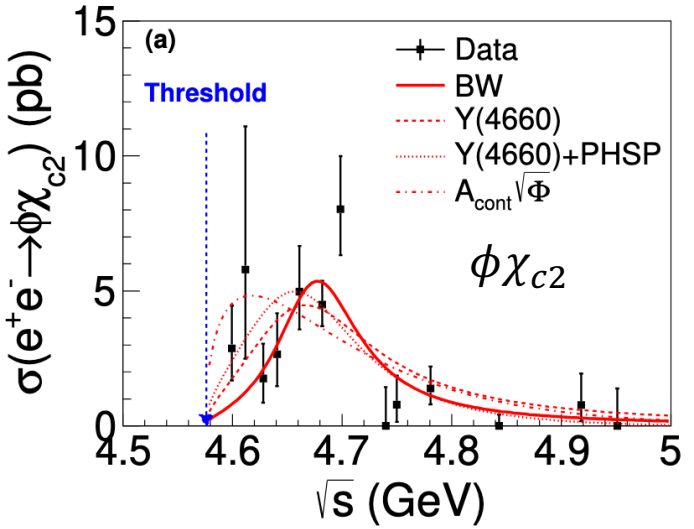








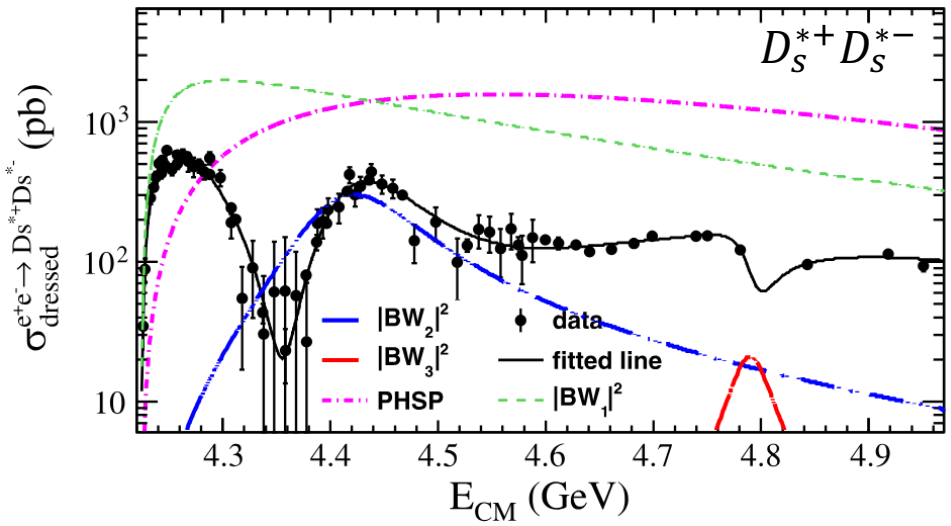


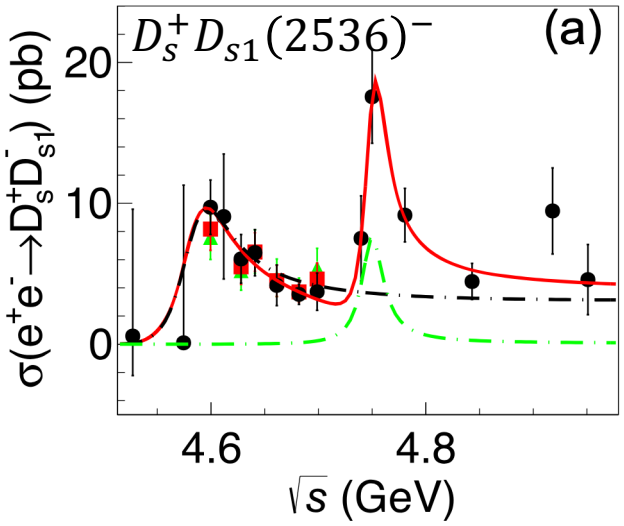


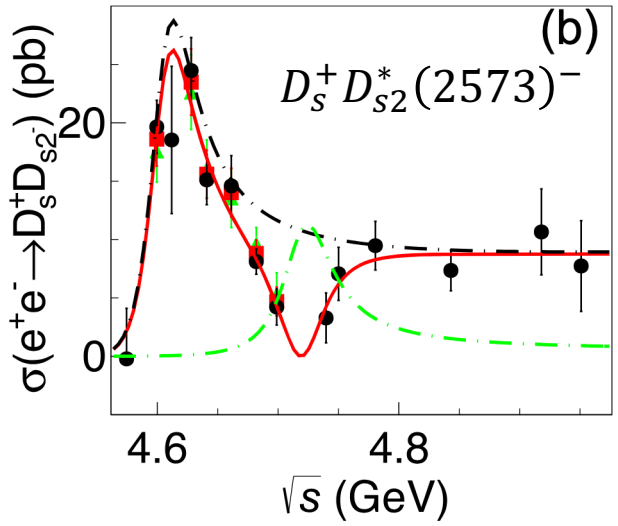
$Y(4660)$ or $Y(4630)$?

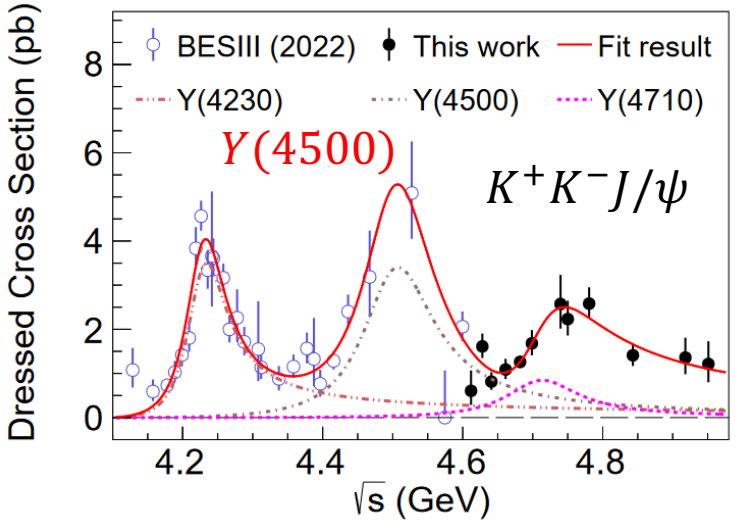
A brief overview

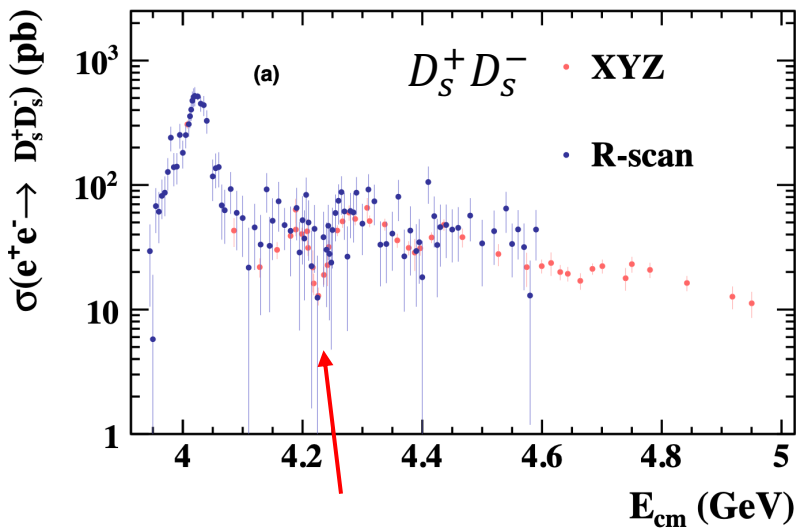
PRL 131, 211902 (2023)
PRL 133, 171903 (2024)
PRL 131, 151903 (2023)
arXiv: 2403.14998











A dip at 4230

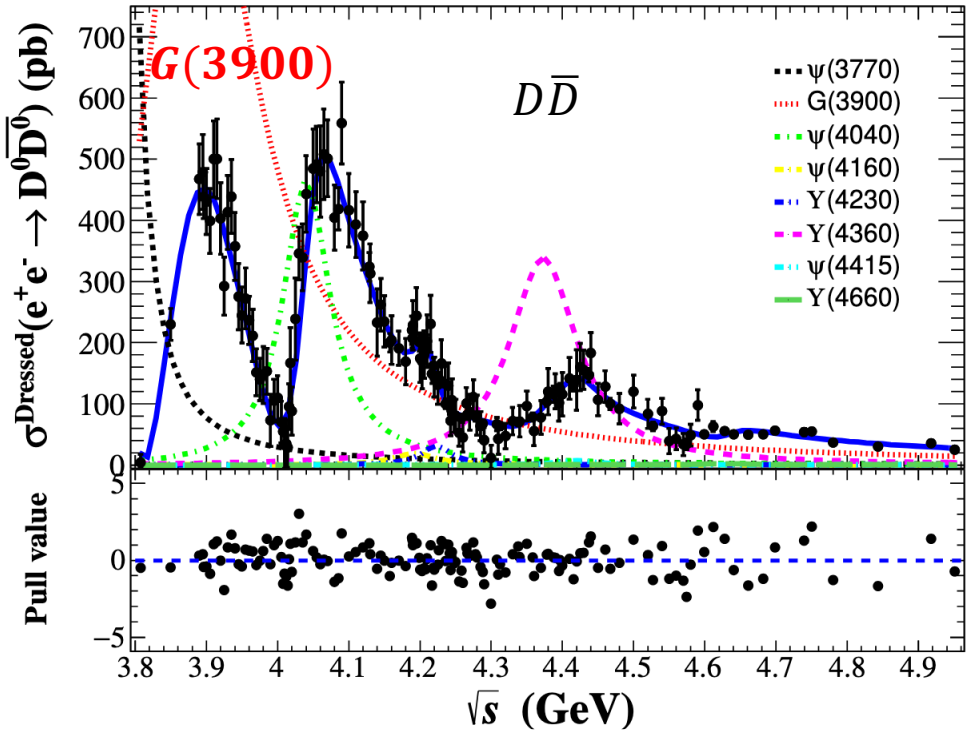
Structrue at 4.75 GeV?

Strange flavour?

What's next

PRL 133, 081901 (2024)

- Nontrivial & overlapping structures in cross sections
- All real $c\bar{c}$?
- Openning thresholds
- Unitarity (sum of BWs is not)
- More precise data available



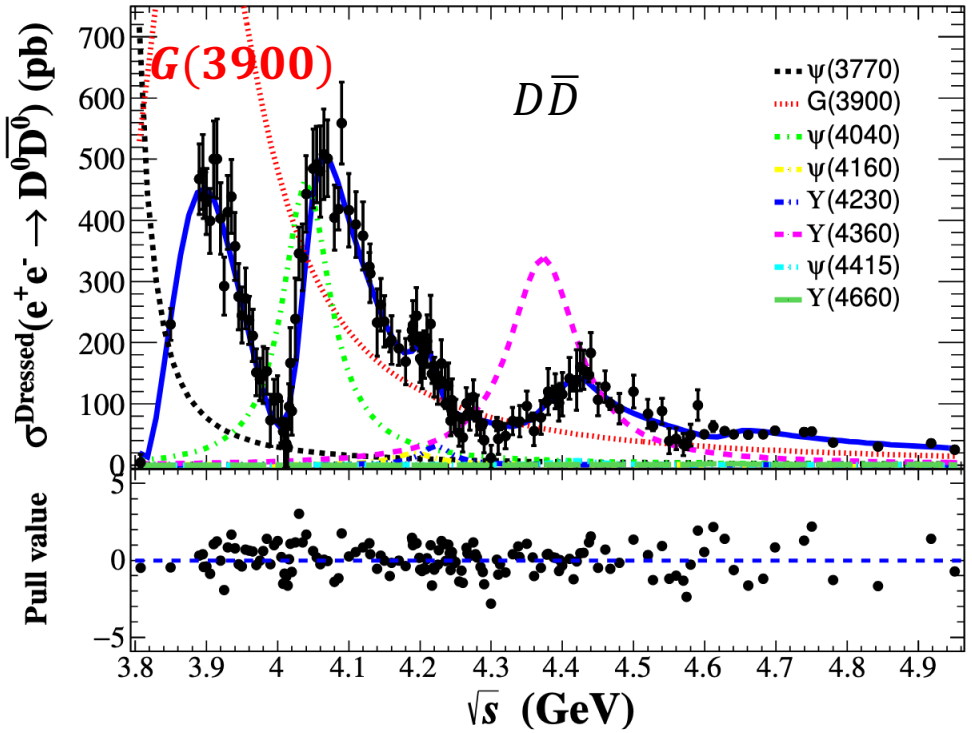
Coherent sum of 8 BWs → $2^{(8-1)} = \mathbf{128}$ **solutions**

Strongly model-dependent and limited information

What's next

PRL 133, 081901 (2024)

- Nontrival & overlapping structures in cross sections
- All real $c\bar{c}$?
- Openning thresholds
- Unitarity (sum of BWs is not)
- More precise data available



Coherent sum of 8 BWs → $2^{(8-1)} = \mathbf{128}$ **solutions**

Strongly model-dependent and limited information

💡 A way out: couple-channel analysis & alternative parameterization

P-wave coupled channel effects in electron-positron annihilation, Meng-Lin Du, Ulf-G. Meißner and Qian Wang, Phys.Rev.D 94, 096006 (2016) arXiv: 1608.02537

Exclusive open-charm near-threshold cross sections in a coupled-channel approach, T.V. Uglov, Yu. S. Kalashnikova, A.V. Nefediev, G.V. Pakhlova and P.N. Pakhlov, JETP Lett. 105, 1-7 (2017) arXiv: 1611.07582

Leptonic widths of high ψ-resonances in a unitary coupled-channel model, A.M. Badalian and B.L.G. Bakker, Phys.Rev.D 96, 014030 (2017) arXiv: 1702.06374

Global coupled-channel analysis of $e^+e^- \to c\bar{c}$ processes in $\sqrt{s}$=3.75-4.7 GeV, S.X. Nakamura, X.-H. Li, H.-P. Peng, Z.-T. Sun and X.-R. Zhou, arXiv: 2312.17658

Charmonium states in a coupled-channel model, Zi-Long Man, Cheng-Rui Shu, Yan-Rui Liu and Hong Chen, Eur.Phys.J.C 84, 810 (2024) arXiv: 2402.02765

Production of $D^{(*)}\overline{D}^{(*)}$ near the thresholds in e^+e^- annihilation, S.G. Salnikov and A.I. Milstein, Phys.Rev.D 109, 114015 (2024) arXiv: 2404.06160

How many vector charmoniumlike states lie in the mass range 4.2–4.35 GeV? Leon von Detten, Vadim Baru, Christoph Hanhart, Qian Wang and Daniel Winney, Phys.Rev.D 109, 116002 (2024) arXiv: 2402.03057

Poles and poltergeists in $e^+e^- \to D\overline{D}$ data, Nils Hüsken, Richard F. Lebed, Ryan E. Mitchell, Ya-Qian Wang, and Chang-Zheng Yuan, Phys.Rev.D 109, 114010 (2024) arXiv: 2404.03896

…

Couple channel analysis with K-matrix

- Resonances in K-matrix as sum of poles

$$K_{\mu,\nu} = \sum_R \frac{g_\mu^R g_\nu^R}{m_R^2 - s} + f_{\mu,\nu}$$

$\boldsymbol{g_\mu^R}$ coupling of resonance R to channel μ

$\boldsymbol{f_{\mu,\nu}}$ scattering between channels

Unitarity

- Aitchison's P-vector is used to implement the production

Rescattering

$$\mathcal{M}_{\mu,\, e^+e^-} = \sum_\nu (1 + KC)^{-1}_{\mu,\nu} P_\nu$$

$$P_\nu = K_{ee,\nu} = \sum_R \frac{\alpha^R g_\nu^R}{m_R^2 - s} + B_\nu$$

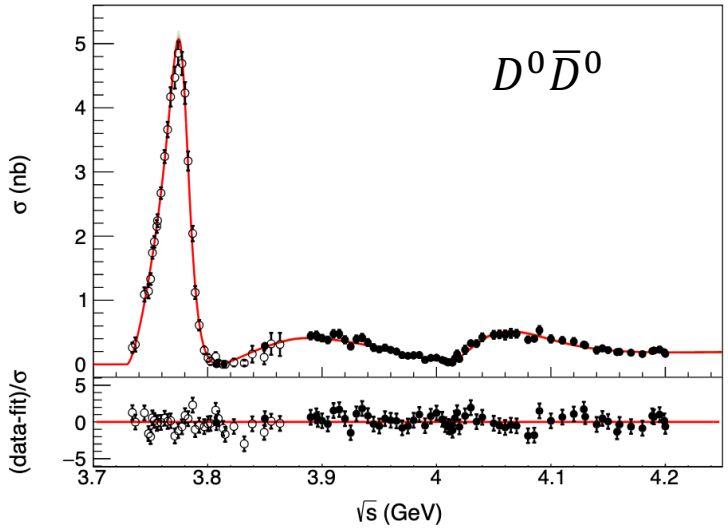
$\boldsymbol{C}$ Chew-Mandelstam function

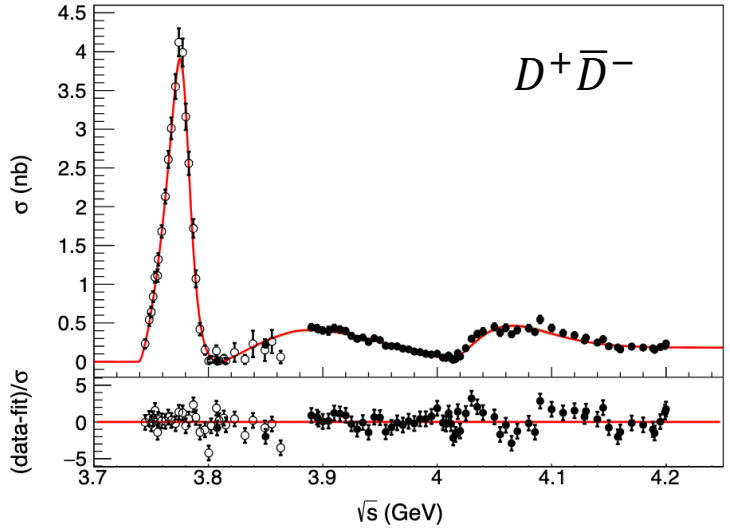
$\boldsymbol{\alpha^R}$ production of resonance R

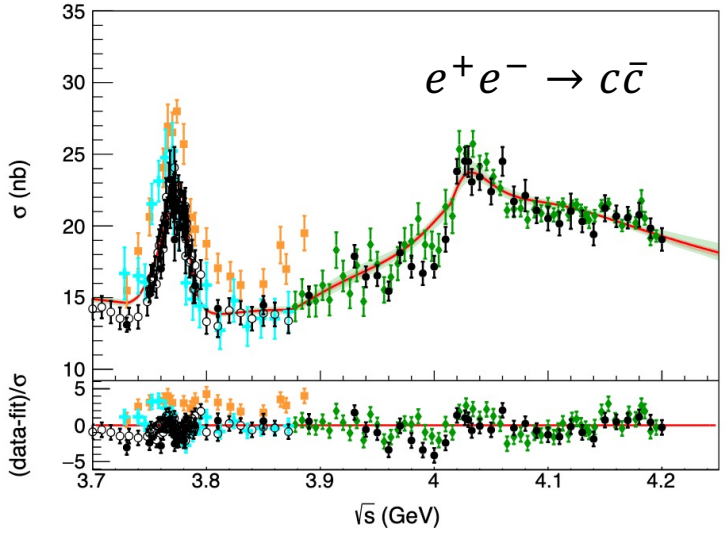
$\boldsymbol{B_\nu}$ direct production of channel ν

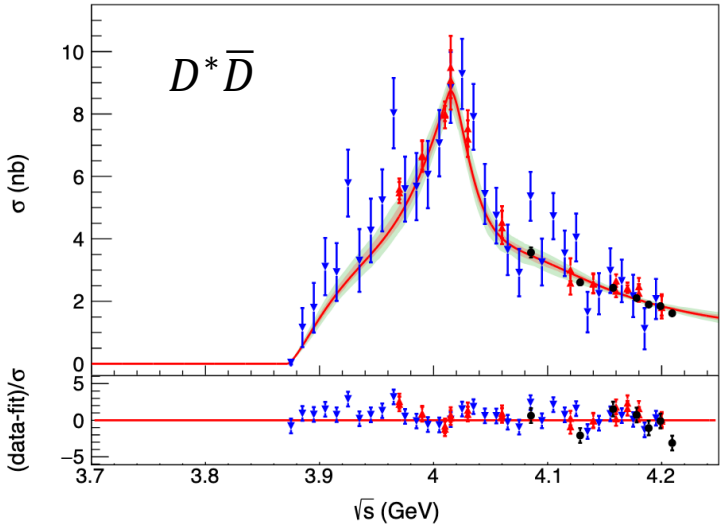
Couple channel analysis with K-matrix

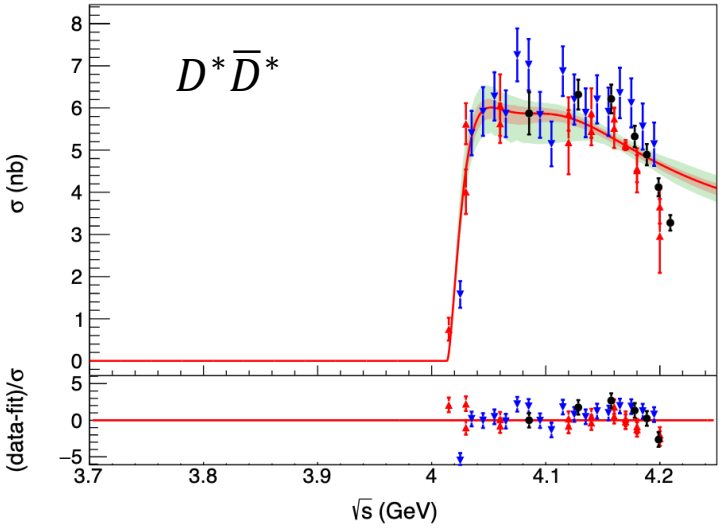
Nils Hüsken et al., PRD 109, 114010 (2024)









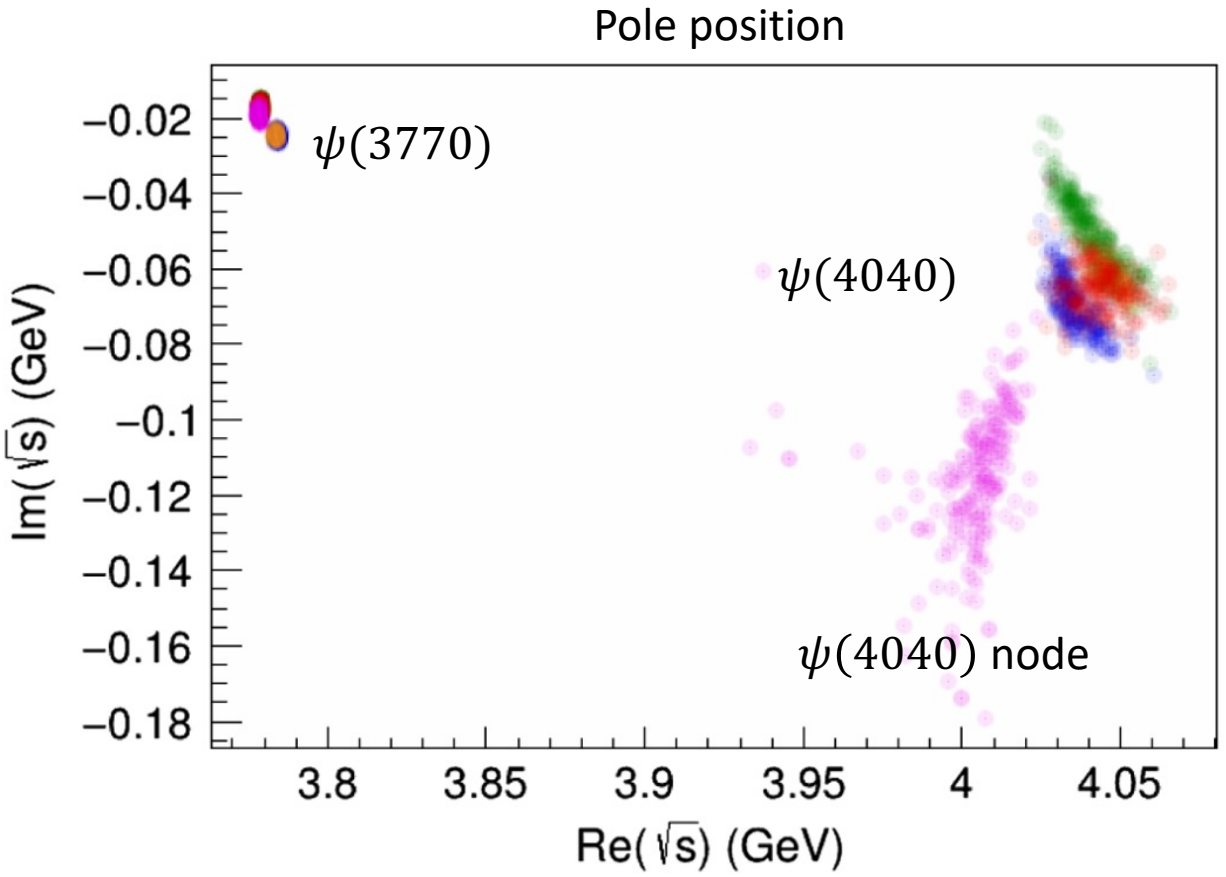


- 2 poles and 5 channels
- Overall good fit quality
- No need extra pole for 3.9 GeV

Nils Hüsken et al., PRD 109, 114010 (2024)

Couple channel analysis with K-matrix

Nils Hüsken et al., PRD 109, 114010 (2024)



What we can get:

- Resonance mass
- Resonance width
- Electronic width
- Particle width
- Threshold effect
- Scattering effect
- Different mechanism
- …

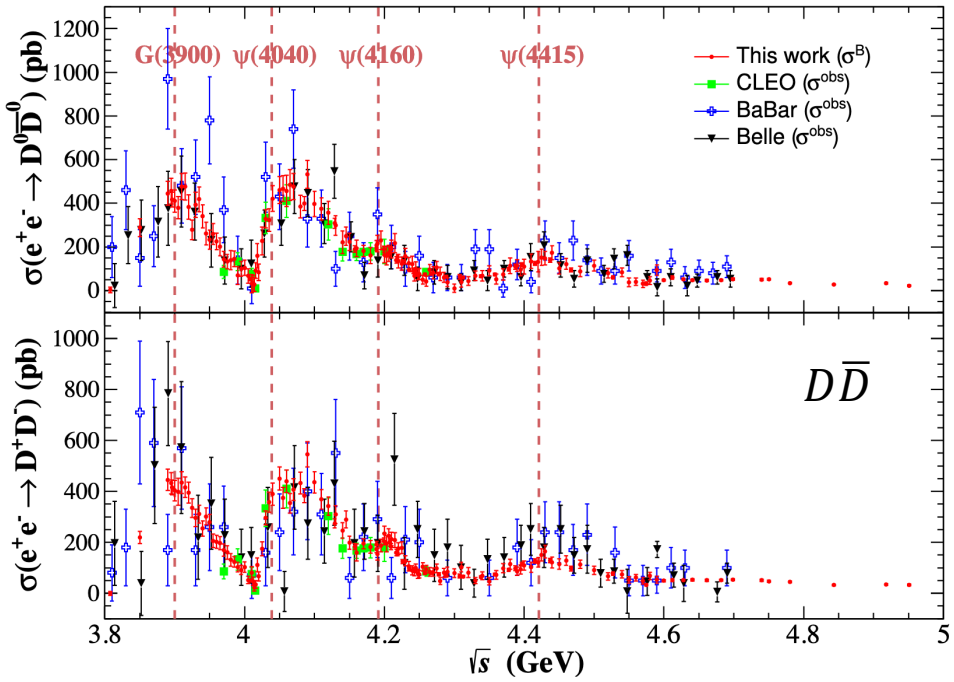
ongoing work of extending to higher energy and including more channels

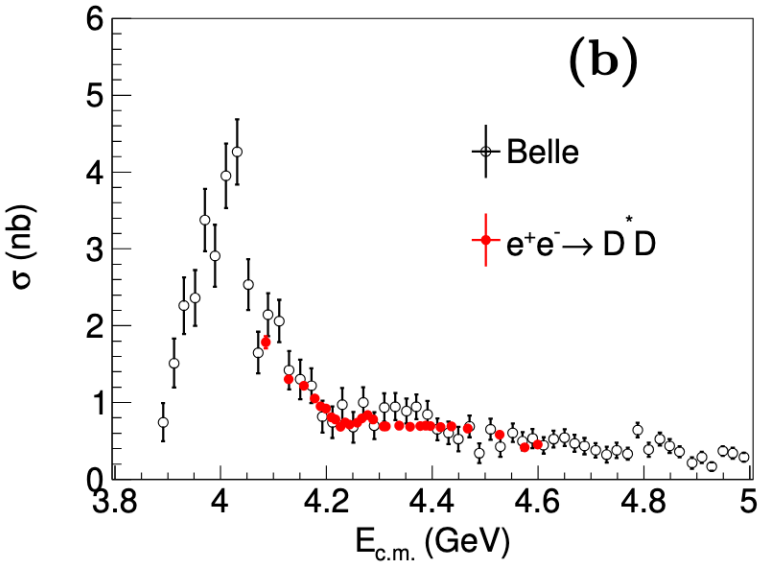
Summary & outlook

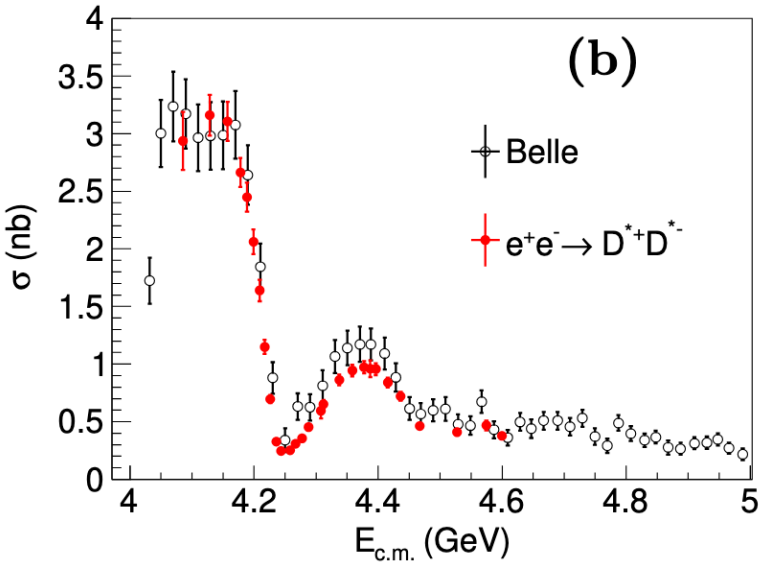
- Nontrivial structrues appear in both open-charm and hidden-charm final states 🧐
- resonance, exotic, rescattering effect …, all of them may have a contribution 😣
- with more precise data (DD, DD^*, D^*D^*, D_sD_s, $D_s^*D_s^*$, $DD^*\pi$, $D^*D^*\pi$, $DD\pi\pi$, …), couple-channel analysis is needed (although problem still remains) 🙂
- which let us extract more information, distinguish one from another 😀
- hopefully, we may soon get the whole picture! 😁

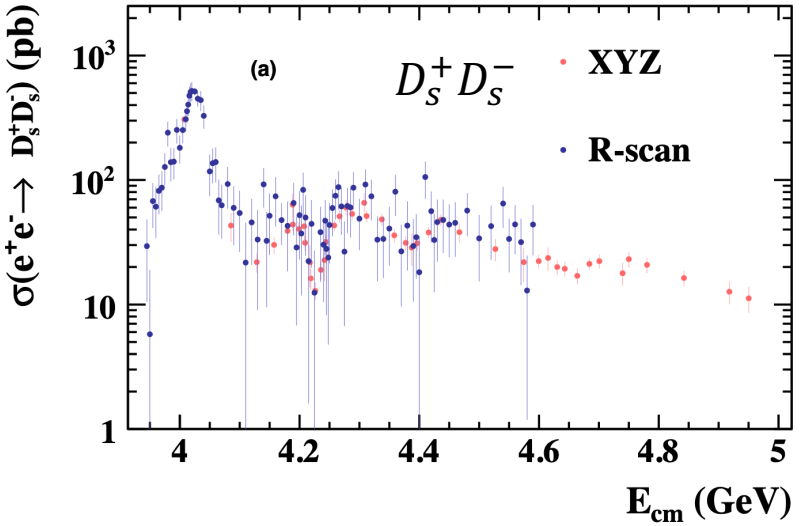
Backup

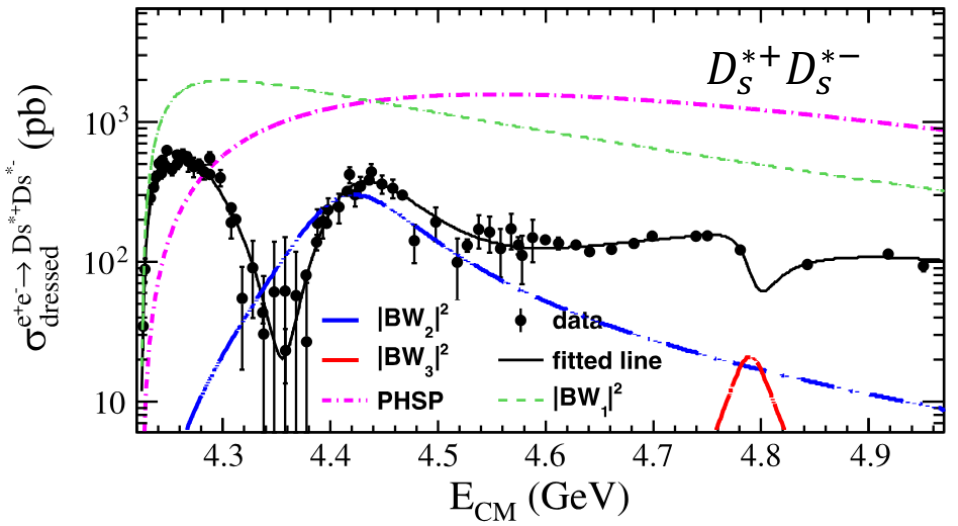
PRL 133, 081901 (2024)
JHEP 05, 155 (2022)
arXiv: 2403.14998
PRL 131, 211902 (2023)



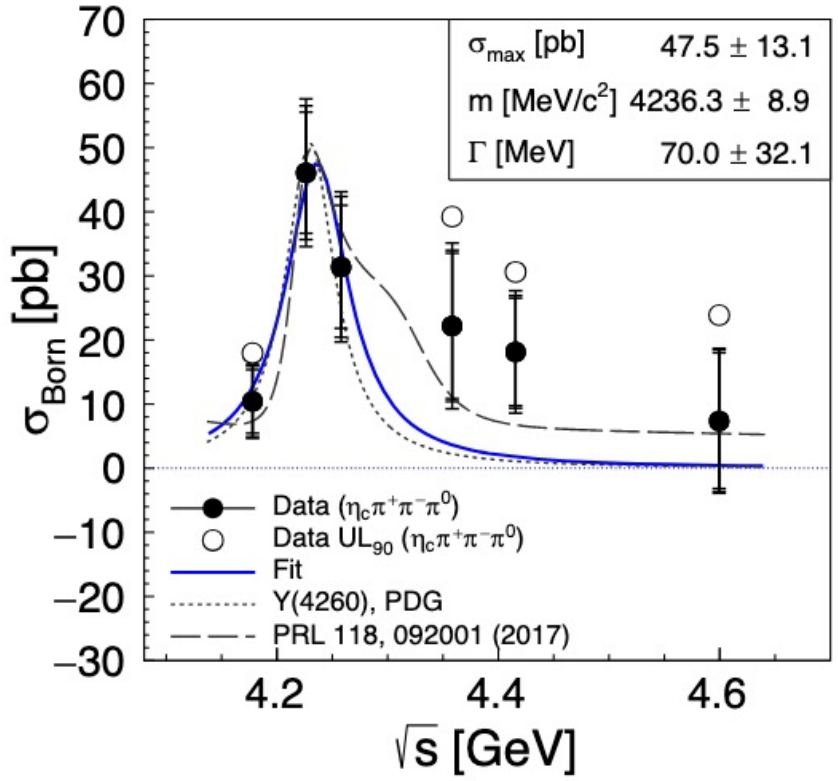




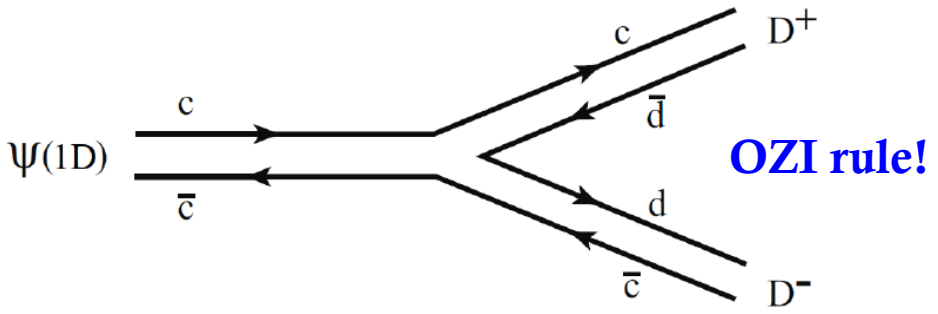




Backup



PRD 103, 032006 (2021)



OZI rule!

$\psi(3770) \rightarrow J/\psi X < 1\%$

Backup

- couplings in general (should) depend on energy

$$g_{\mu,R}(s) = g'_{\mu,R} \cdot k_\mu^L \cdot \exp\left(-k_\mu^2/\beta\right) \cdot (1 - k_\mu^2/q_0^2)$$

E. Eichten et al, PRD 21, 203 (1980)

real-valued fit parameter

ensures $\sigma \to 0$ at threshold

ensures $\sigma \to 0$ for large s

optional node for $\psi(3S)$

- we enforce isospin symmetry in $\psi \to D^0\overline{D}^0$ and D^+D^-, setting $g'_{D^0\overline{D}^0,R} = g'_{D^+D^-,R}$
  $\to$ $\Gamma_{D^0\overline{D}^0}$ and $\Gamma_{D^+D^-}$ will still differ due to $m_{D^+} \neq m_{D^0}$

- for contact- (background-)terms, we test both cases

- all parameters are real, there are no free phases!