The charmoniumlike Y states @ BESIII

Changzheng Yuan (苑长征)
IHEP, Beijing
(for the BESIII collaboration)

Experimental and theoretical status of and perspectives for XYZ states
(virtual) Darmstadt, Apr. 12 – 15, 2021

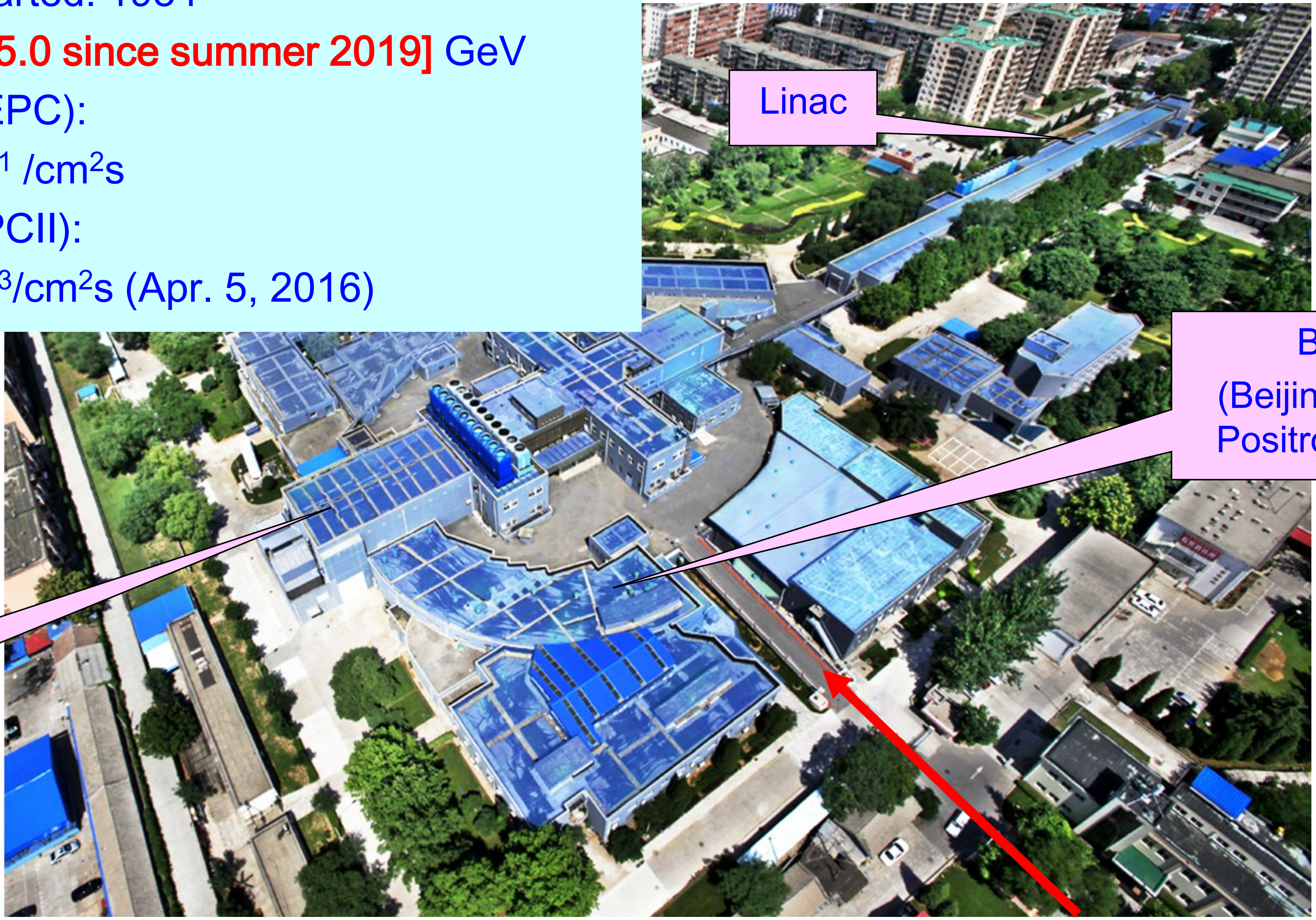
Beijing Electron Positron Collider (BEPC)

- Construction started: 1984

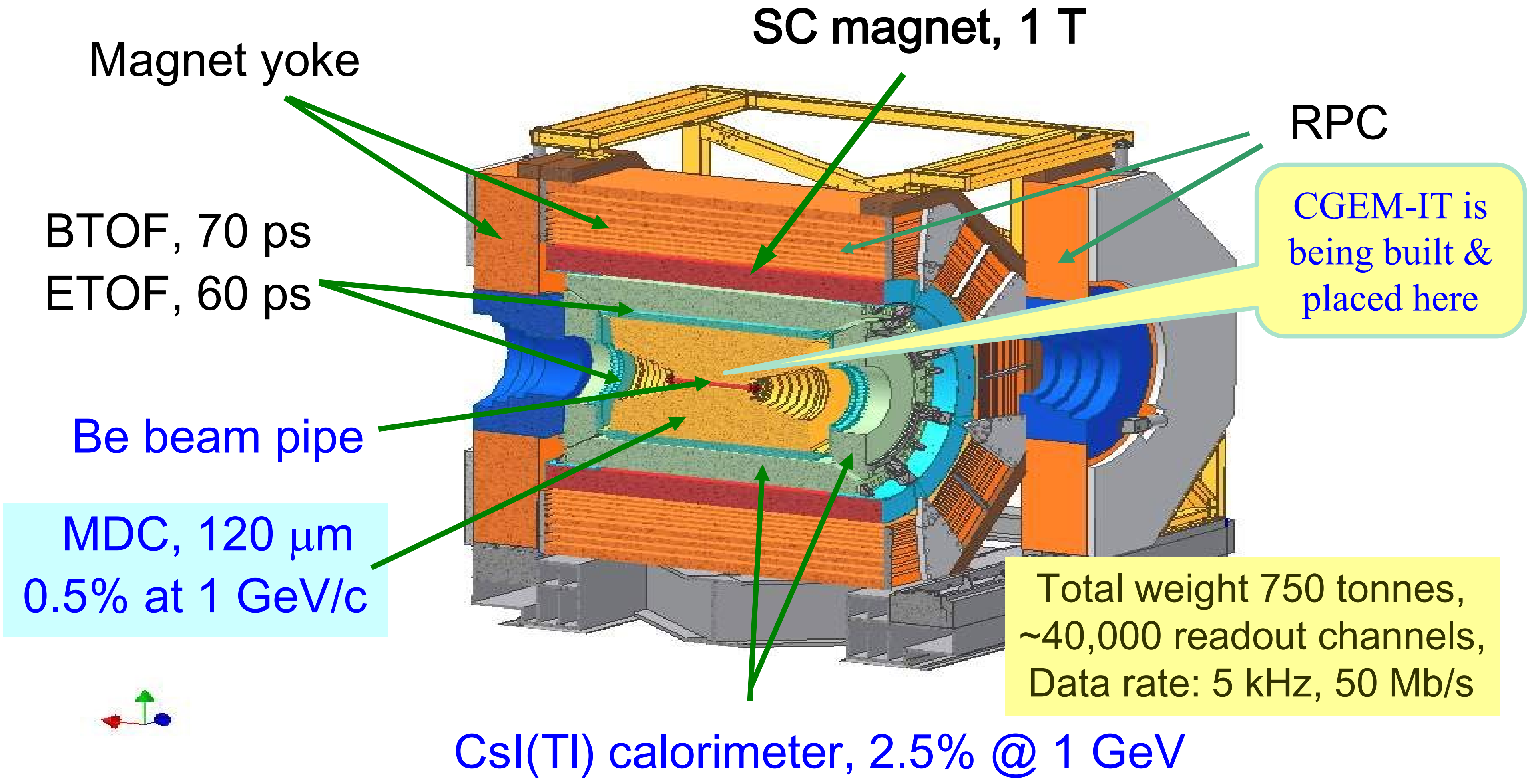
  E_{cm}: 2 — 4.6 [5.0 since summer 2019] GeV
- 1989-2005 (BEPC):

  L_{peak}=1.0x10^{31} /cm^2s
- 2008-now (BEPCII):

  L_{peak}=1.0x10^{33}/cm^2s (Apr. 5, 2016)



BESIII detector



Has been in full operation since 2008, all subdetectors are in very good status!

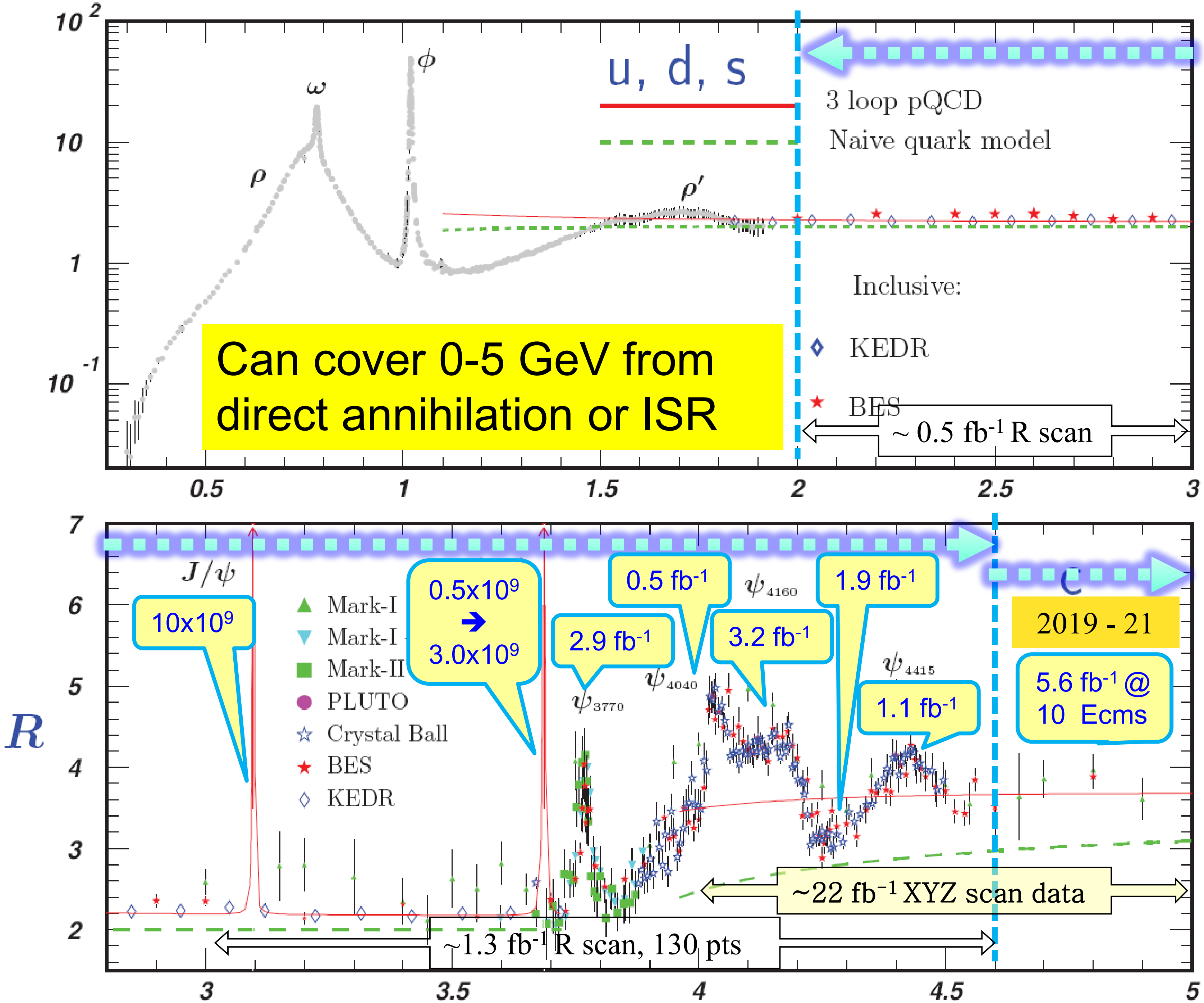
BESIII Collaboration

15 countries, 75 institutions

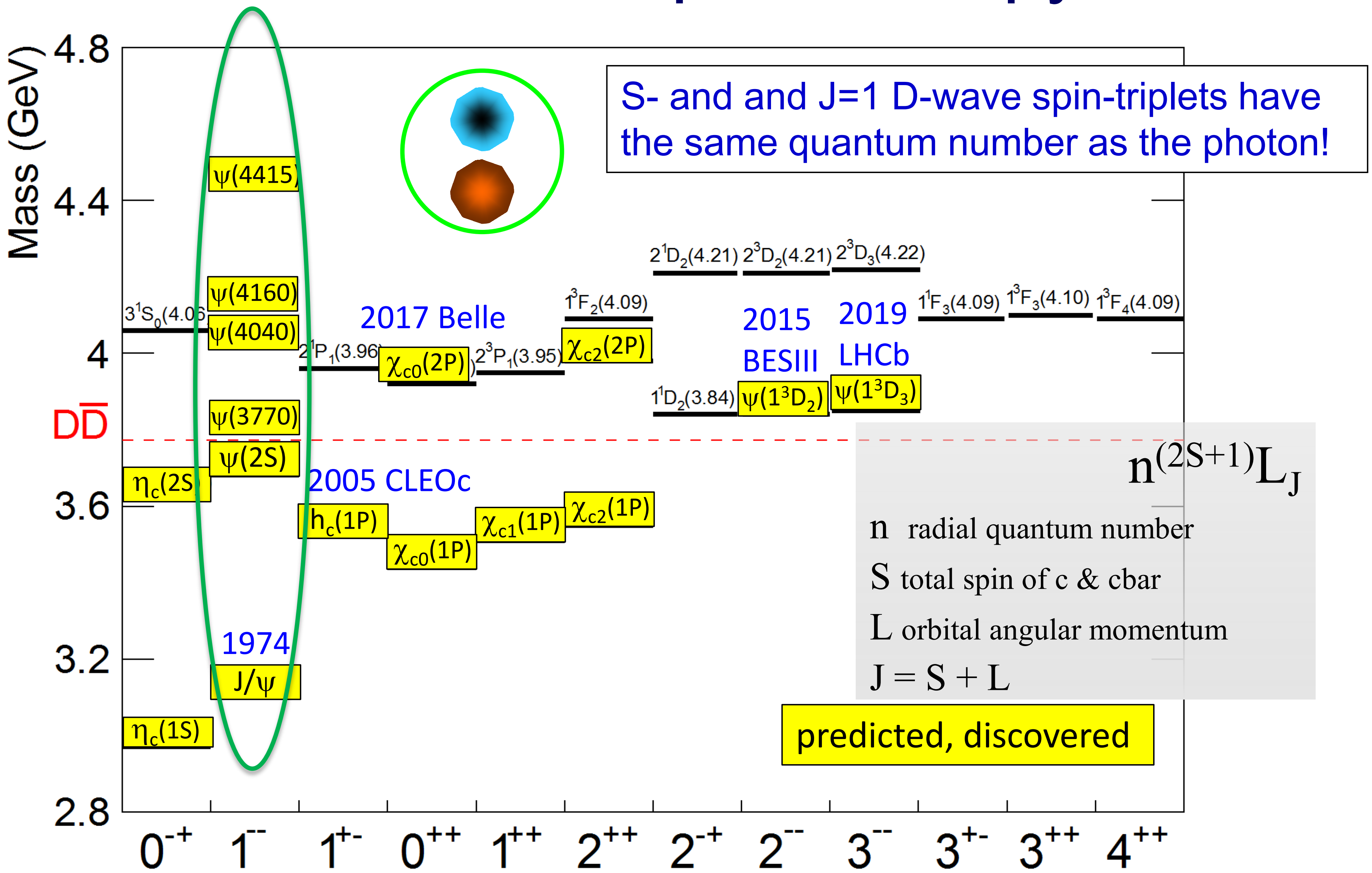
~450 members

photo: summer 2019, Shanghai

BESIII


u, d, s
3 loop pQCD
Naive quark model
Inclusive:
KEDR
BES
~ 0.5 fb-1 R scan
Can cover 0-5 GeV from direct annihilation or ISR
R
J/ψ
Mark-I
Mark-I
Mark-II
PLUTO
Crystal Ball
BES
KEDR
10x10^9
0.5x10^9 ➔ 3.0x10^9
2.9 fb-1
0.5 fb-1
3.2 fb-1
1.9 fb-1
1.1 fb-1
2019 - 21
5.6 fb-1 @ 10 Ecms
~22 fb-1 XYZ scan data
~1.3 fb-1 R scan, 130 pts

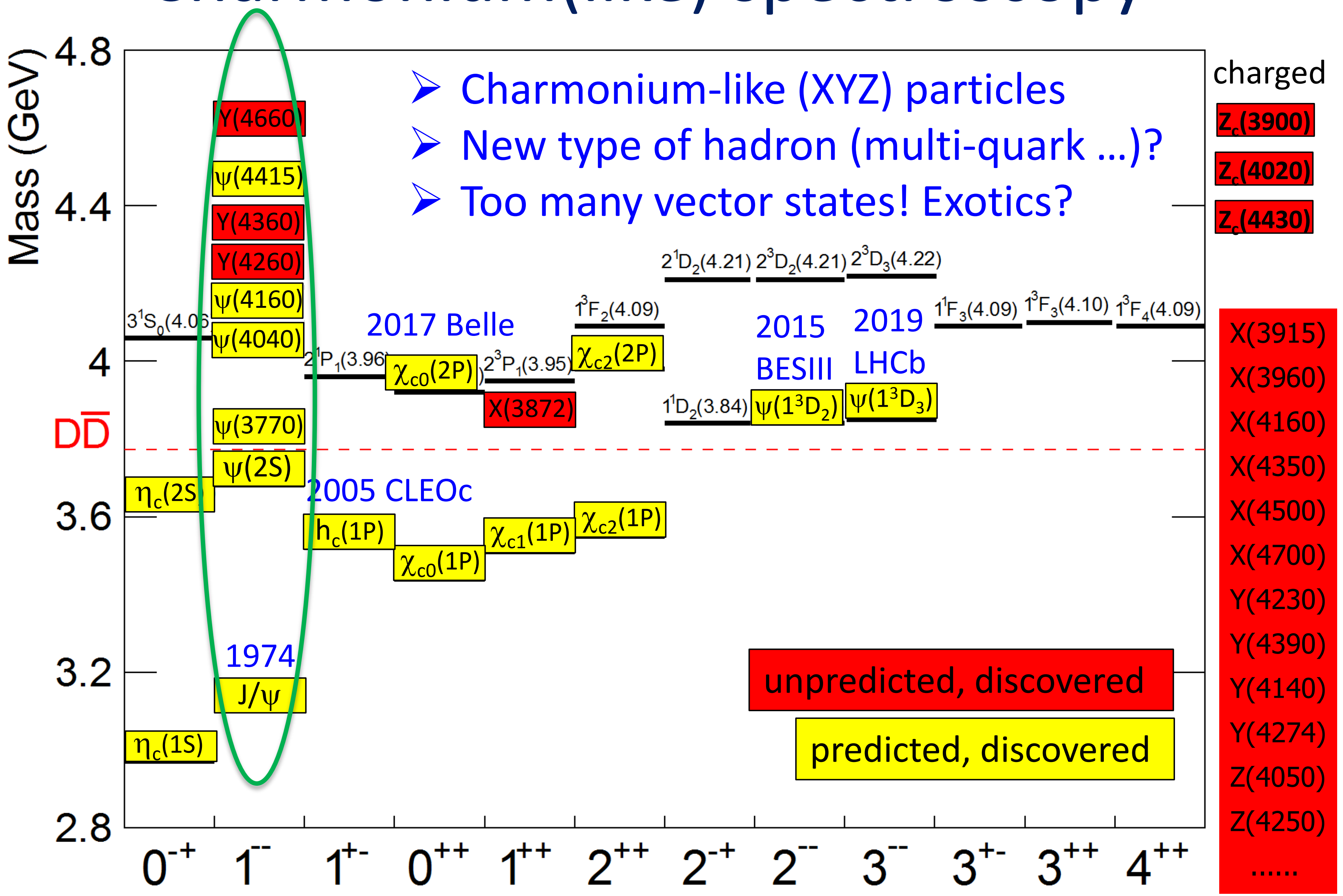
Charmonium spectroscopy



Godfrey & Isgur, PRD32, 189 (1985)

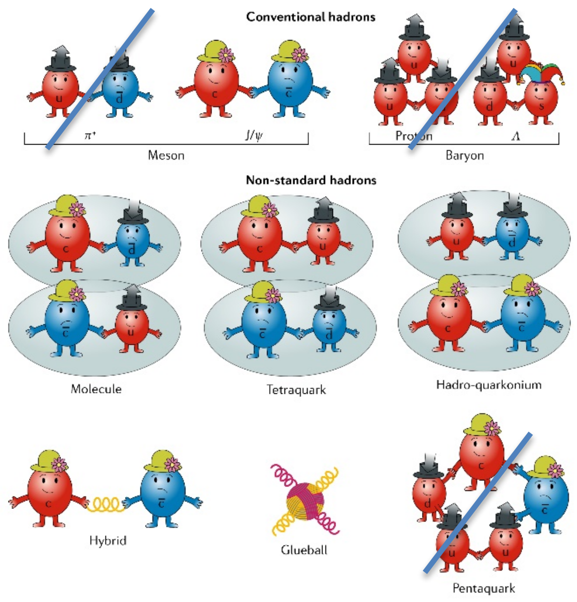
Charmonium(like) spectroscopy

Y(xxxx)
=
ψ(xxxx)
in PDG



Godfrey & Isgur, PRD32, 189 (1985)

What are these ψ's & Y's? [mass>$2m_D$]



arXiv: 2001.01164

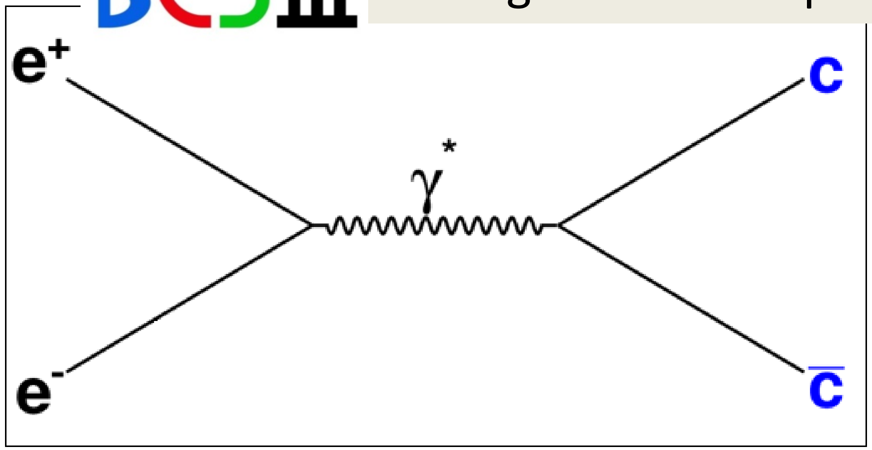
- Vector charmonia
  - 1^3D_1, 3^3S_1, 2^3D_1, 4^3S_1, 3^3D_1, 5^3S_1, 4^3D_1, 6^3S_1, …
- Vector charmonium hybrids
- Vector tetraquark states
- Vector hadro-charmonia
- Vector hadronic molecules ($\omega\chi_{cJ}$, $\bar{D}D_1$, $\bar{\Lambda}_c\Lambda_c$, ……)
- Kinematic effects (thresholds, coupled channels, interference, …)
- ……

➔ What experimental information is available?

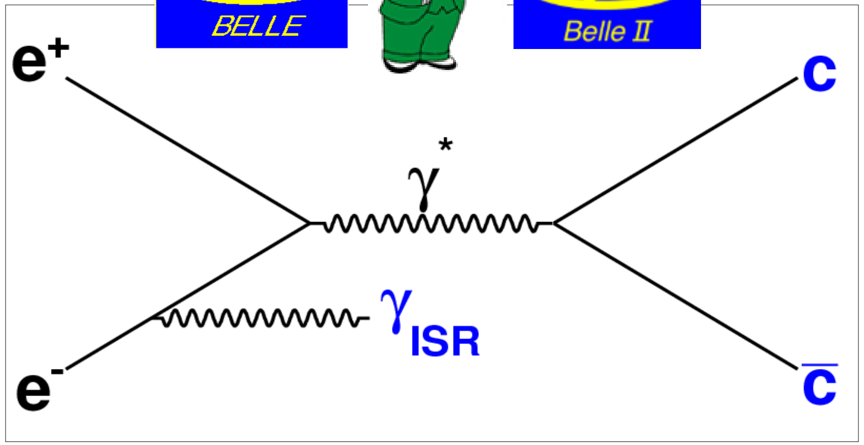
How did we get the experimental measurements?

（ψ’s from inclusive, Y’s from exclusive）

BESIII + old generation Exps.



BELLE Belle II

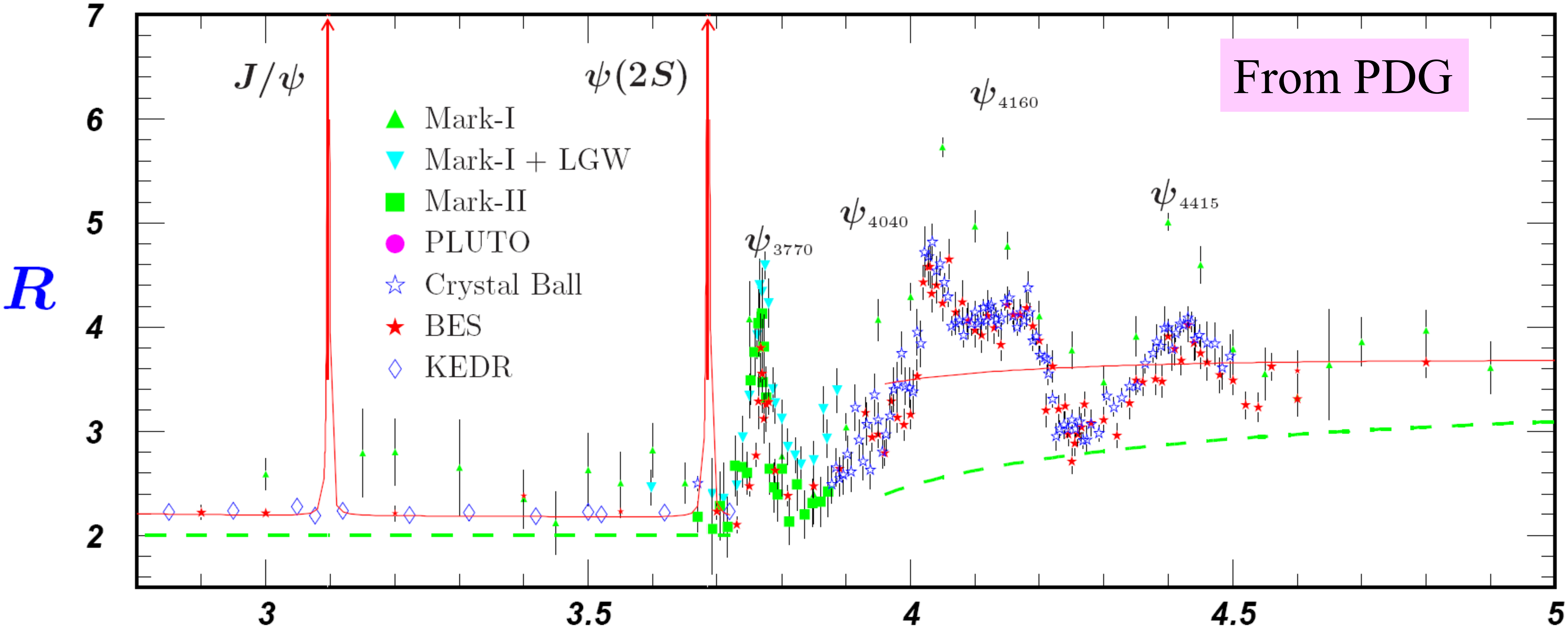


ISR = initial state radiation

Experimental measurements

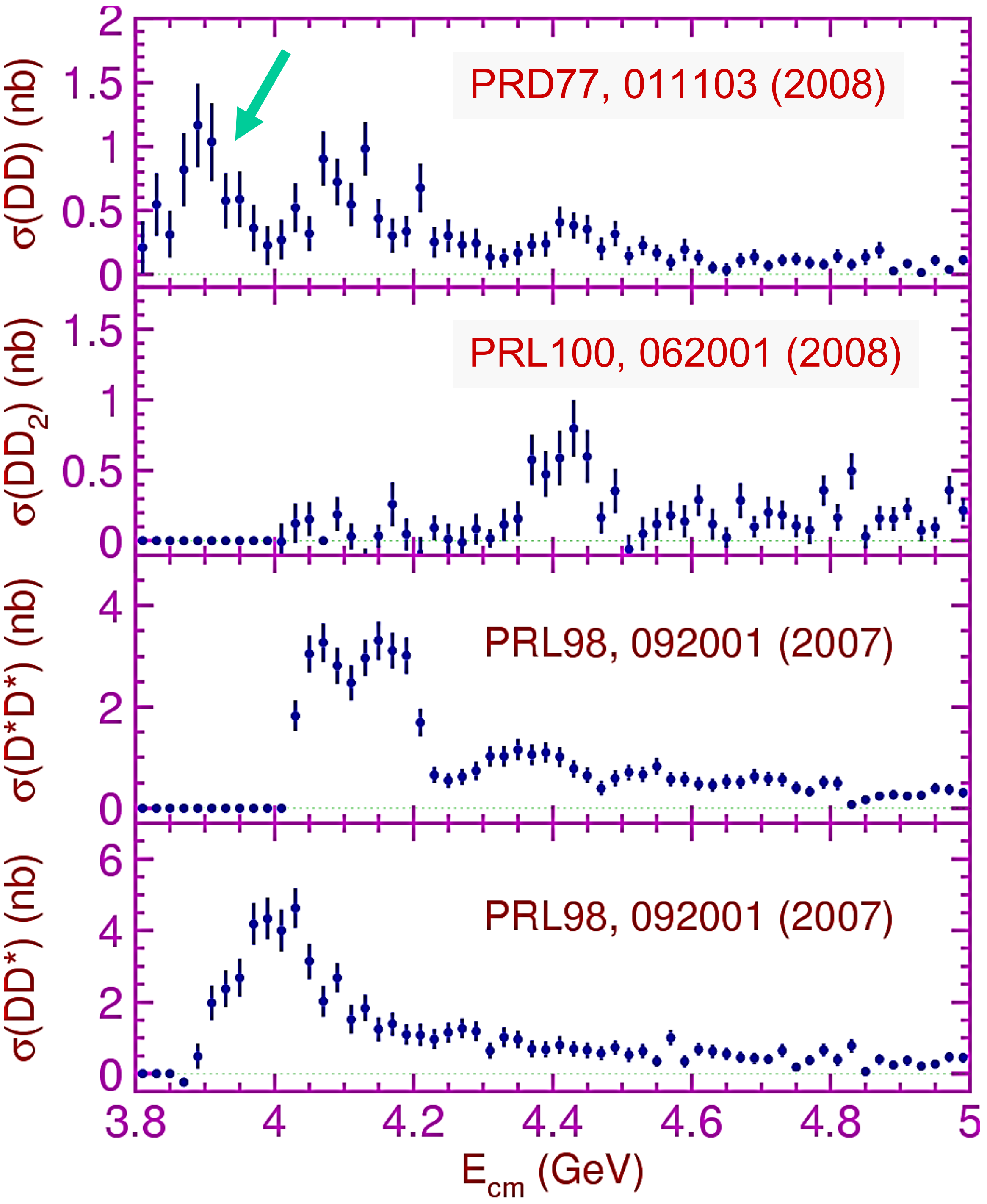
- $e^+e^- \to$ inclusive hadrons = R values
- $e^+e^- \to$ charmed mesons
- $e^+e^- \to$ charmed baryons
- $e^+e^- \to$ charmonium + hadrons, γ, …
- $e^+e^- \to$ light hadrons
- $e^+e^- \to$ lepton pairs

Inclusive cross sections, most precise data from BESII & Crystal Ball



BESIII is going to measure R with <3% uncertainty cover this full energy region

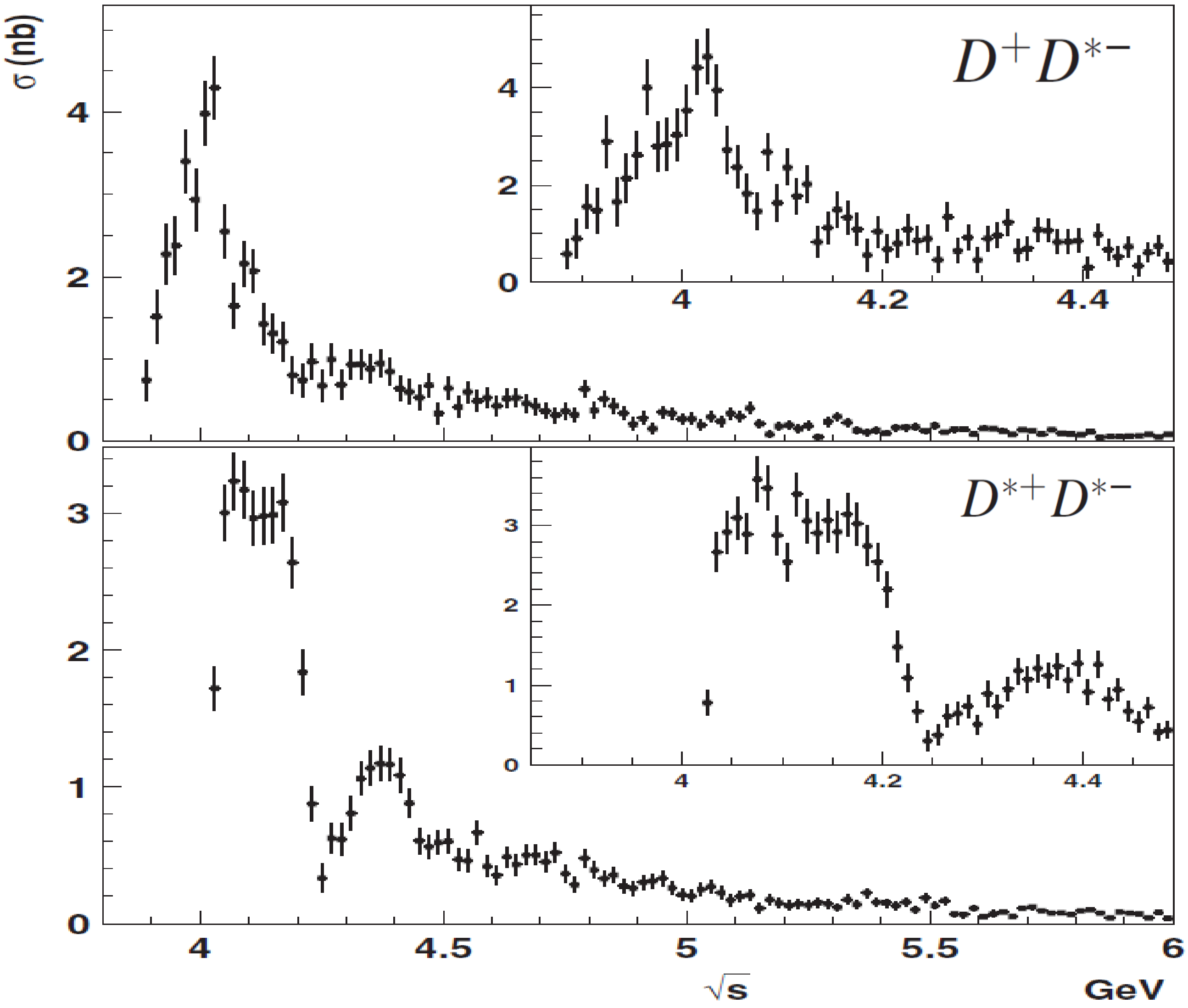
Belle R_D Scan via ISR



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

- Some peaks are not obvious in inclusive cross section;
- Interference could be mode-dependent
- Could be non-resonant amplitude in each different mode

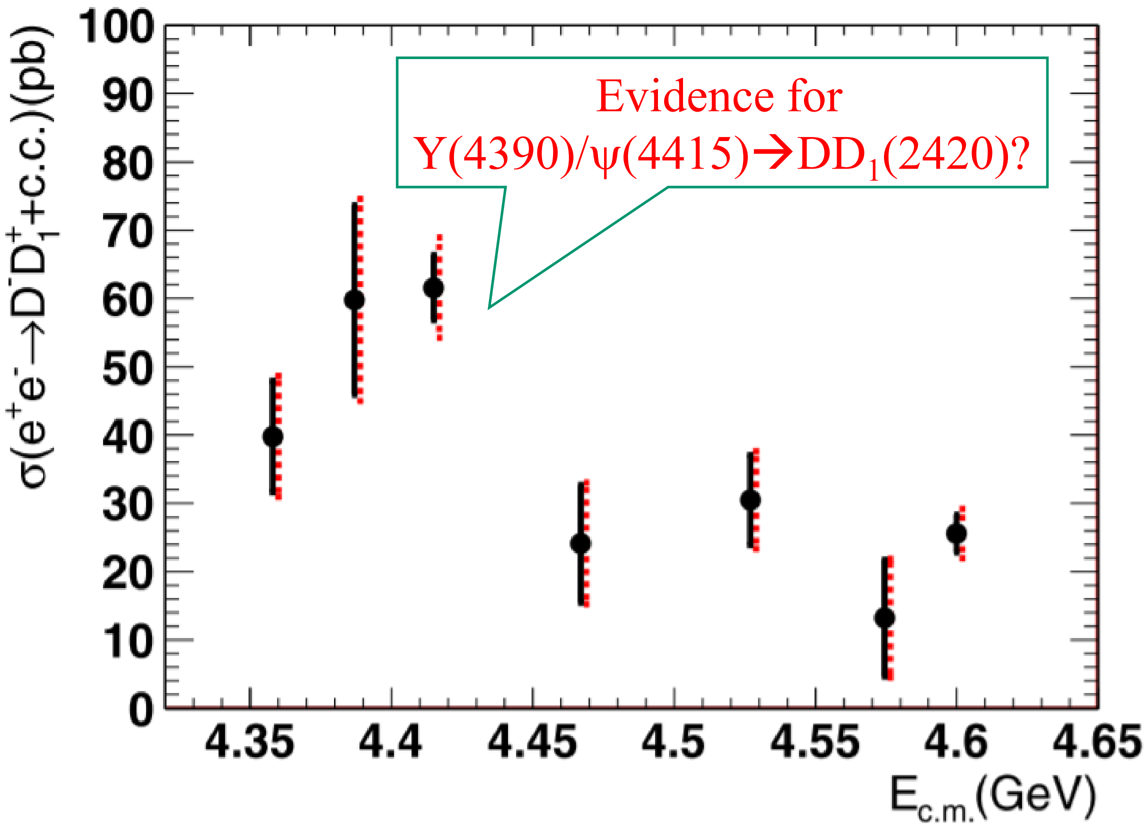
Belle $\bar{D}^*D$, $\bar{D}^*D^*$ updated

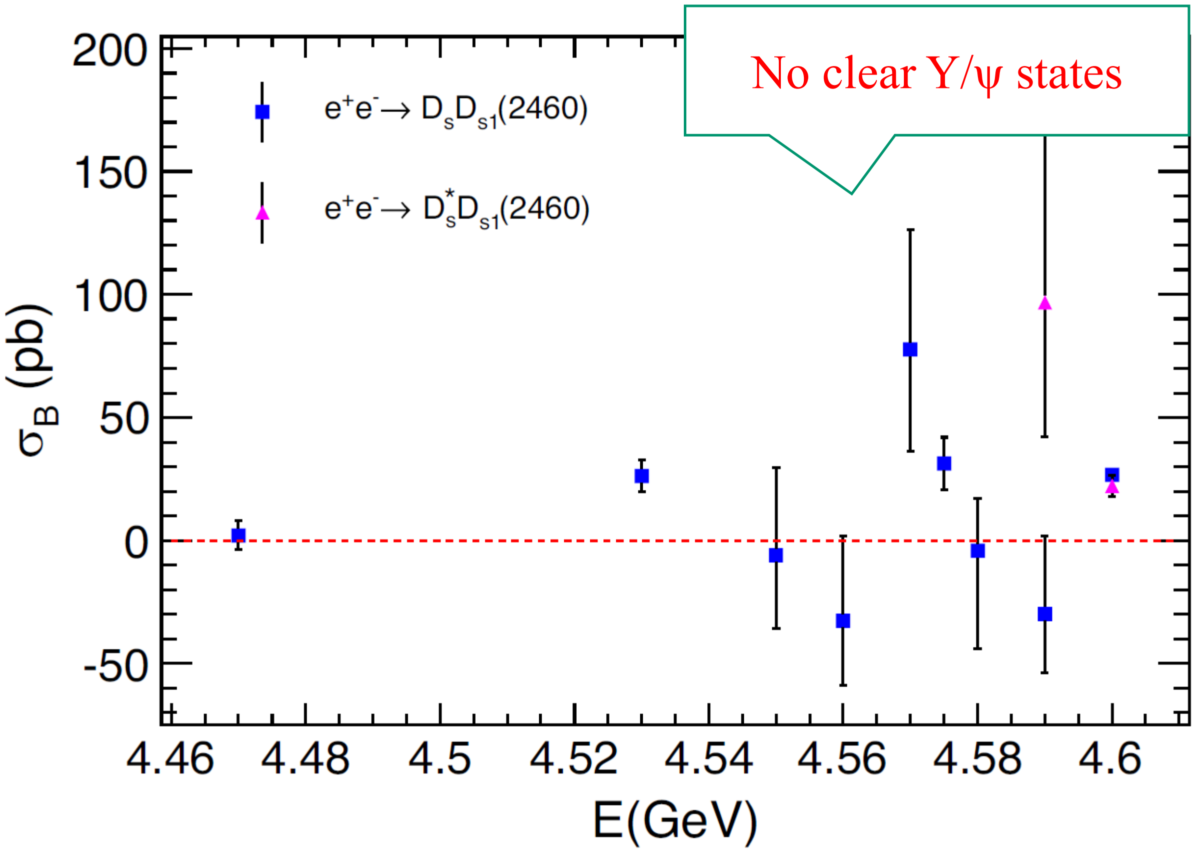


- Full Belle sample, 951/fb
- Improved tracking efficiency
- Extended energy range
- Reduced uncertainties

PRD 97, 012002 (2018)

BESIII is working on two-body charmed meson pairs, no released results yet for the most important channels ($\bar{D}^{(*)}D^{(*)}$, $\bar{D}_s^{(*)}D_s^{(*)}$).





arXiv:1909.12478, PLB 804, 135395

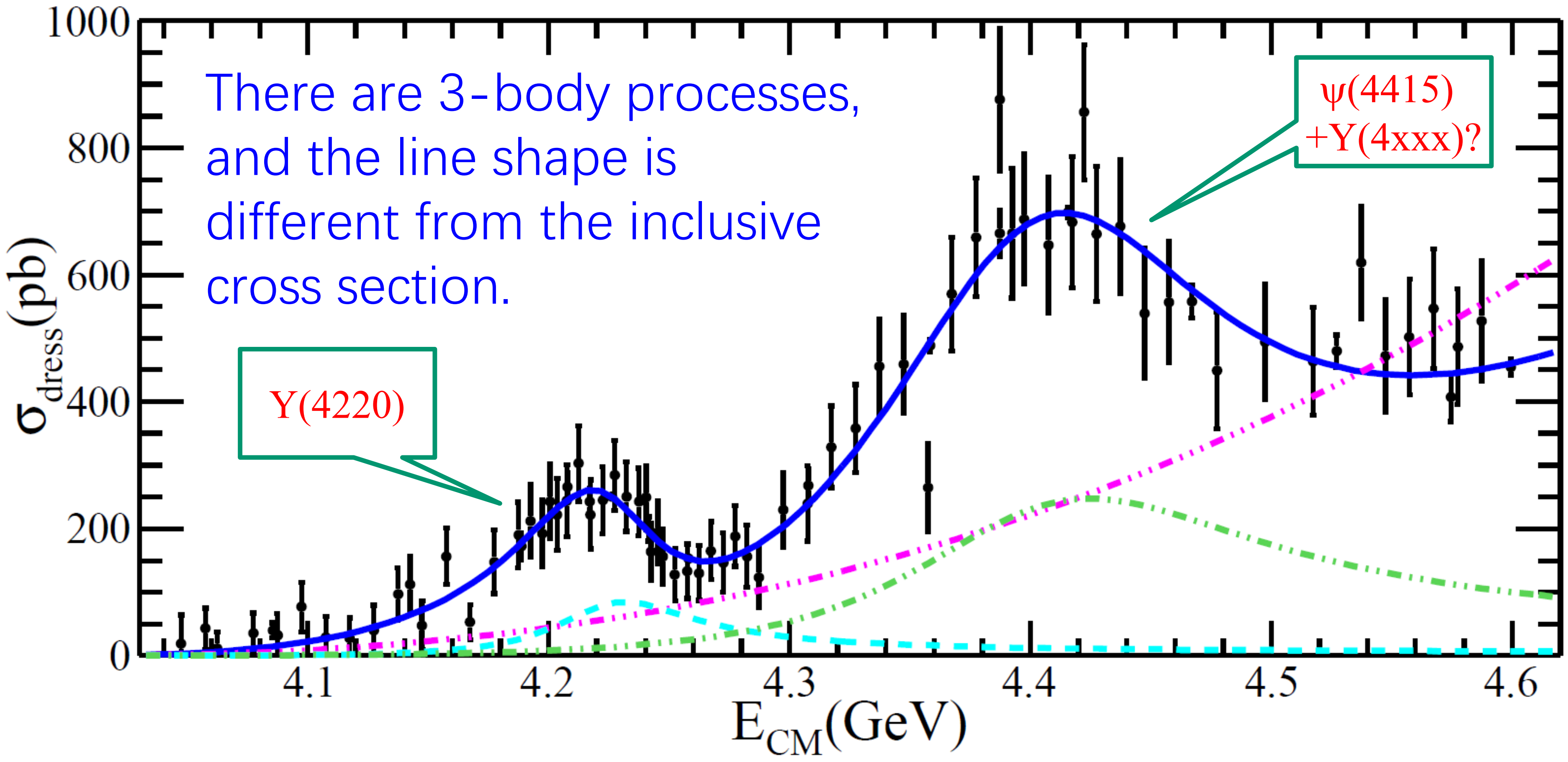
arXiv:2005.05850, PRD 101, 112008

$e^+e^- \to \pi^+ D^0 D^{*-}$+c.c.

PRL122, 102002 (2019)

$$\sigma_{dress} = \frac{N^{obs}}{\mathcal{L}(1+\delta^r)B(D^0 \to K^-\pi^+)\varepsilon}$$

$$\sigma_{\rm dress}(m) = |c \cdot \sqrt{P(m)} + e^{i\phi_1} B_1(m)\sqrt{\frac{P(m)}{P(M_1)}} + e^{i\phi_2} B_2(m)\sqrt{\frac{P(m)}{P(M_2)}}|^2$$

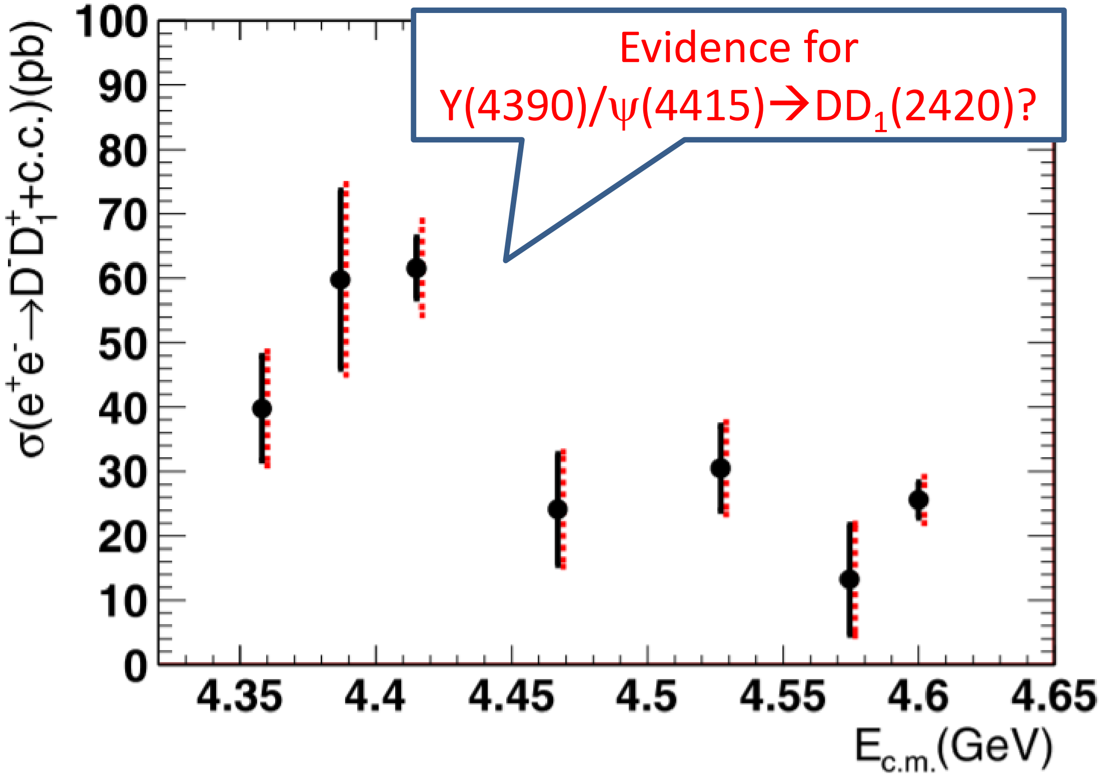


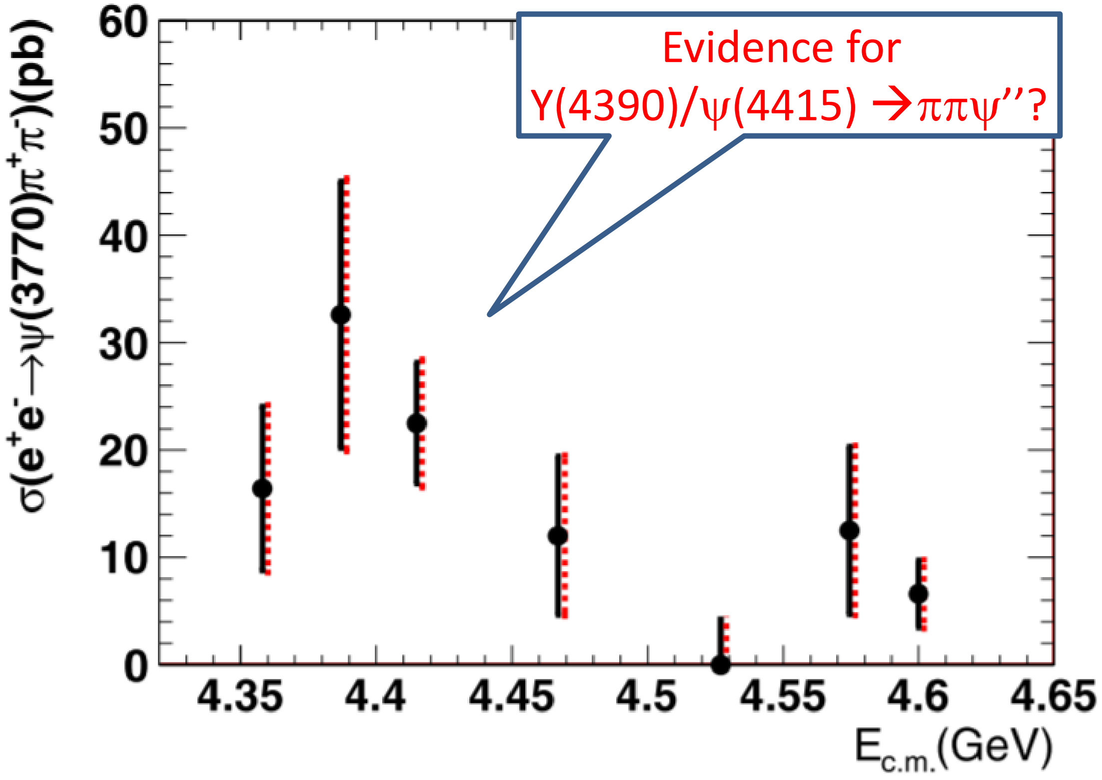
Fit with a phase space term (pink dashed triple-dot line) and two constant width relativistic BW functions (green dashed double-dot line and aqua dashed line).

$\pi^+\pi^-D^+D^-$ – single tag analysis

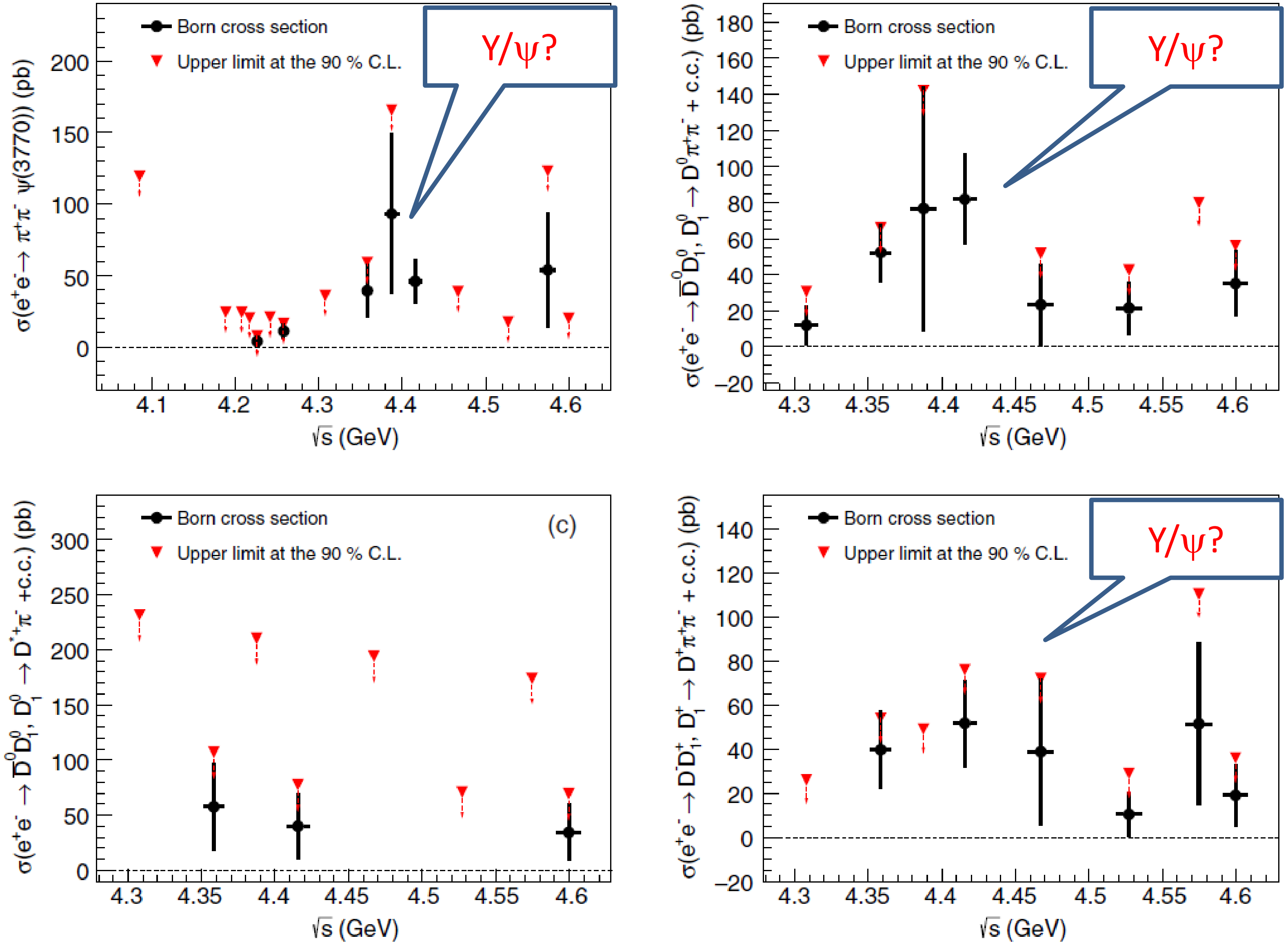
arXiv:1909.12478
PLB 804, 135395

There are 4-body processes in addition to quasi-two-body and quasi-three-body processes, and the line shapes are different from the inclusive cross section.





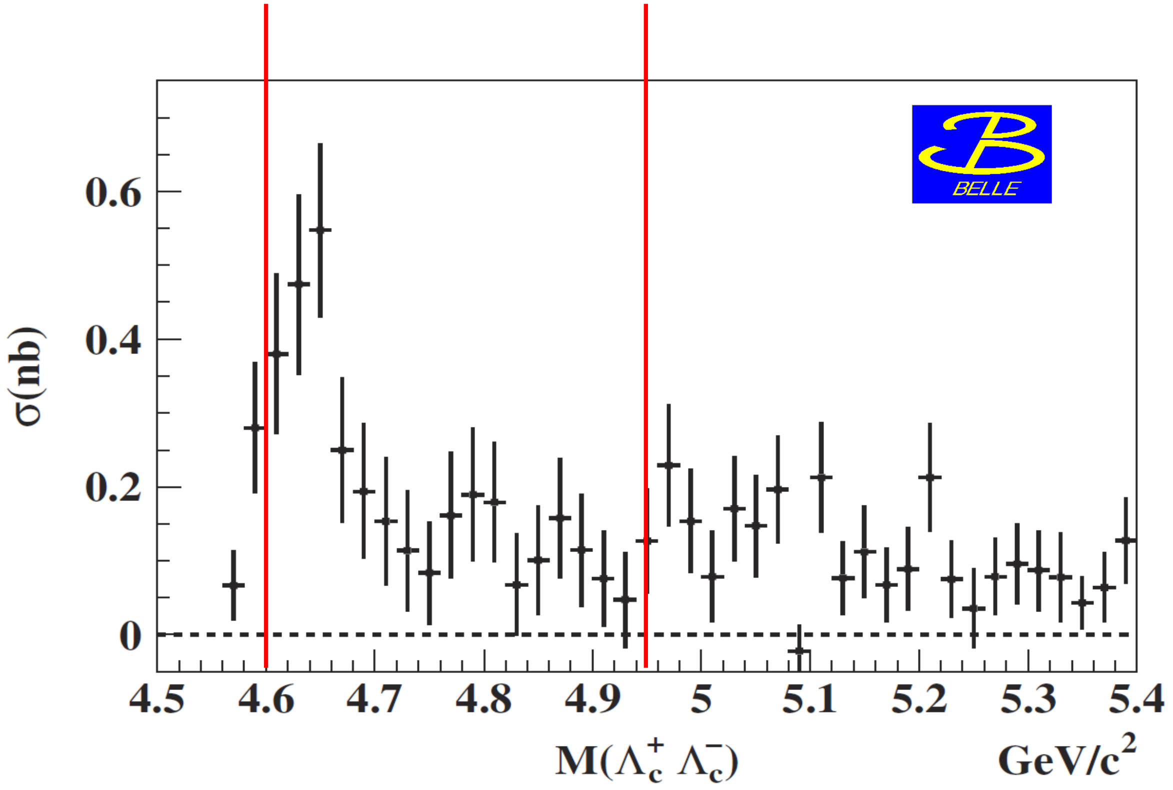
$\pi^+\pi^-D^+D^-$ & $\pi^+\pi^-D^0\bar{D}^0$ – double tag analysis



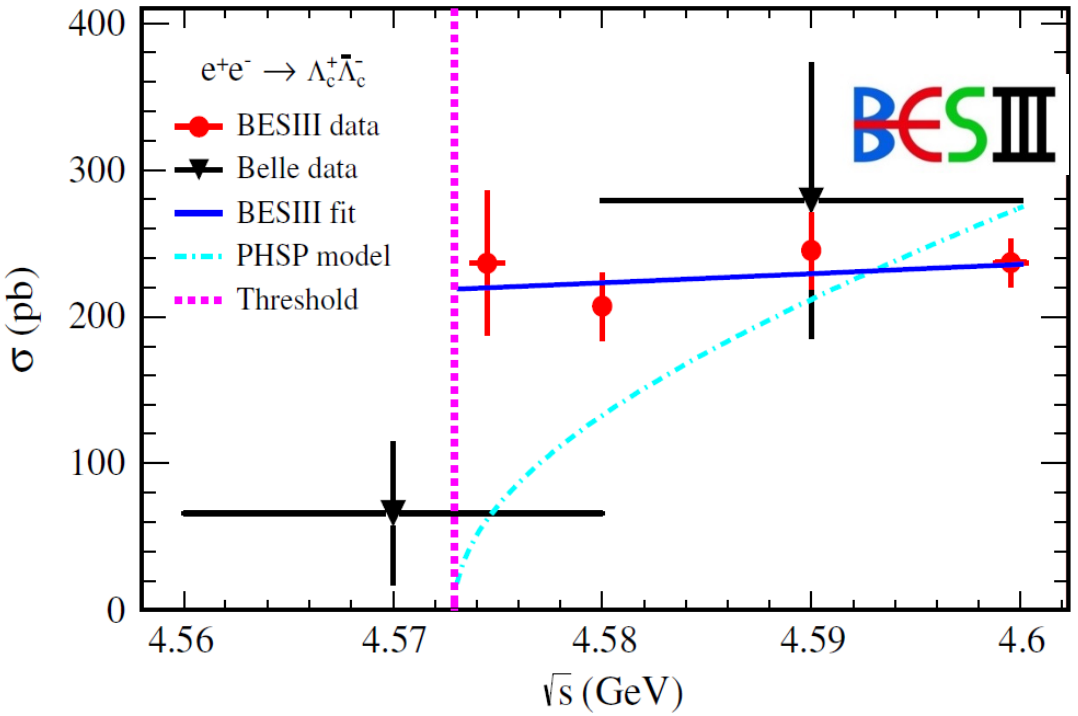
arXiv:1903.08126
PRD 100, 032005

Λ_c baryon pair

Belle: PRL101, 172001 (2008), 695/fb

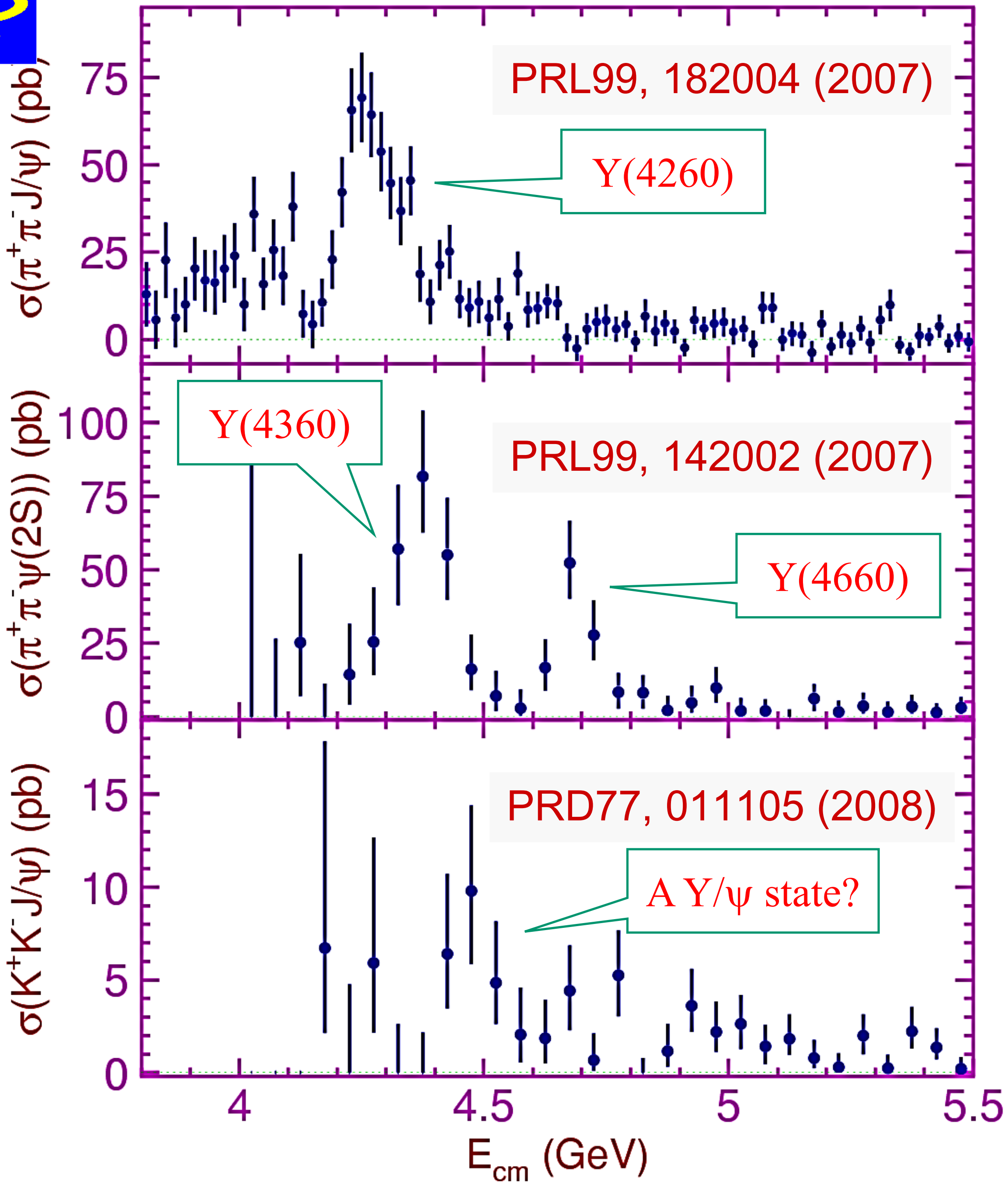


BESIII: PRL120, 132001 (2018)



BESIII has data now covering from threshold to 4.95 GeV, comparable precision as at 4.6 GeV is expected!

Belle ISR on charmonium+hadrons



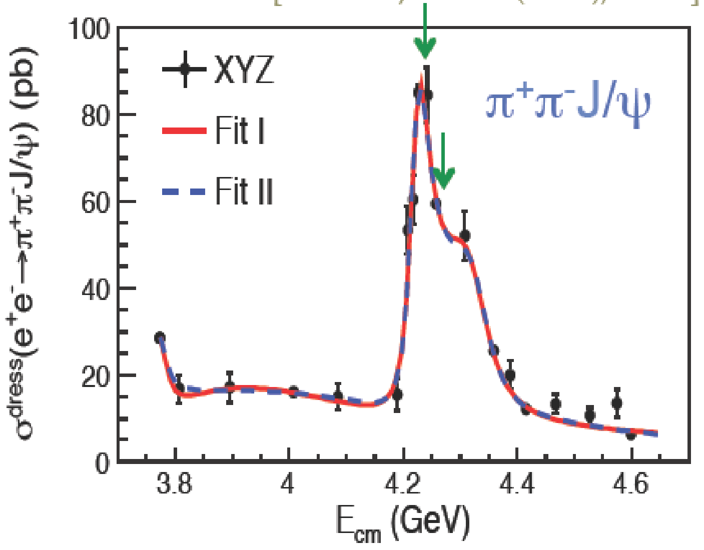
Full reconstruction of the hadronic system, no ISR photon tag

There are hidden-charm processes, and the line shapes are different from the inclusive cross section and the open charm cross sections.

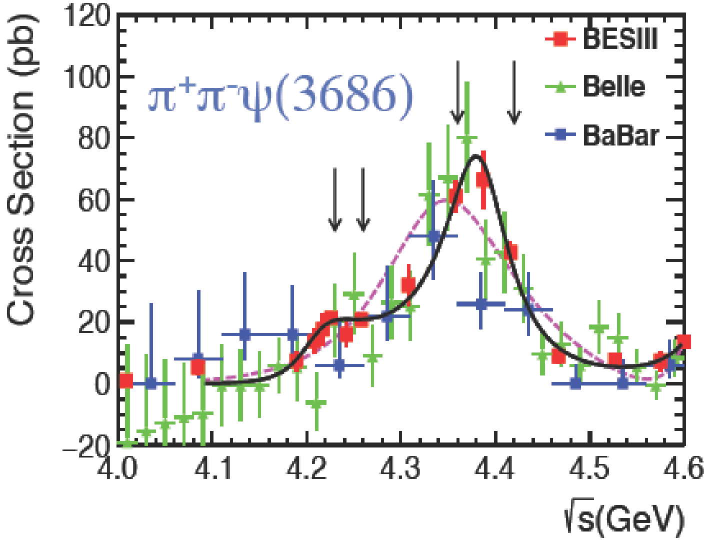
There are Y(4260), Y(4360), and Y(4660) states that are different from excited ψ's.

Charmonium + light hadrons

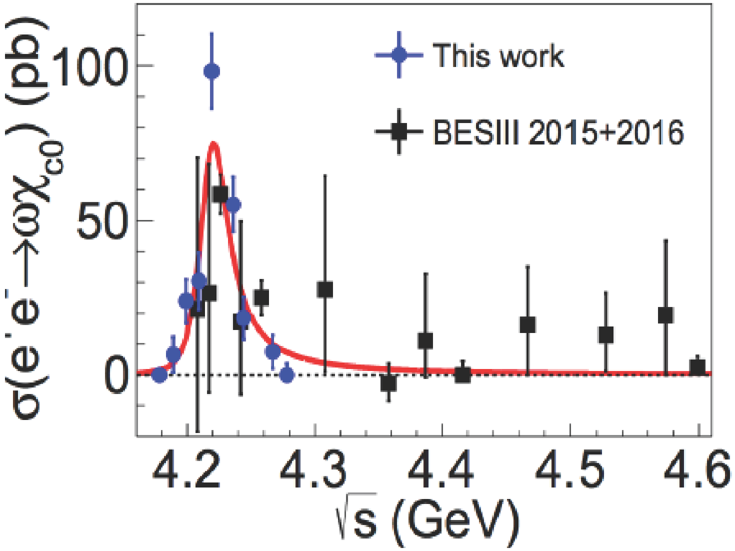
[PRL 118,092001 (2017), 9 fb^{-1}]

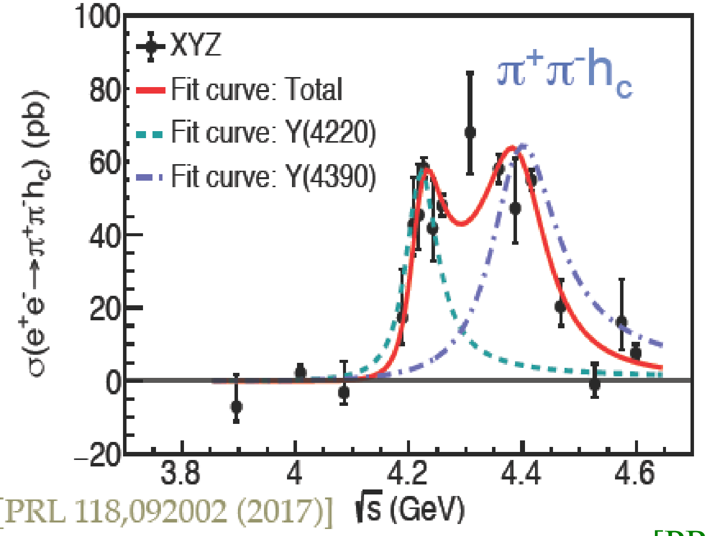


[PRD96, 032004 (2017)]

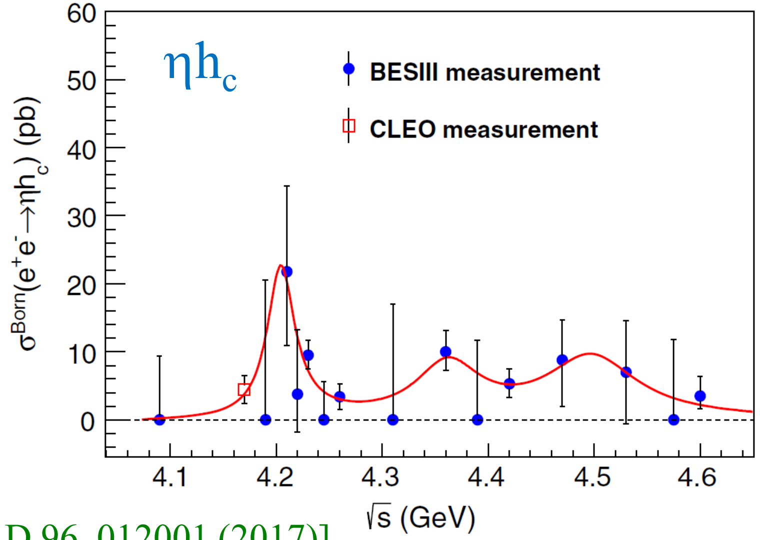


[PRD 99, 091103(R) (2019)]

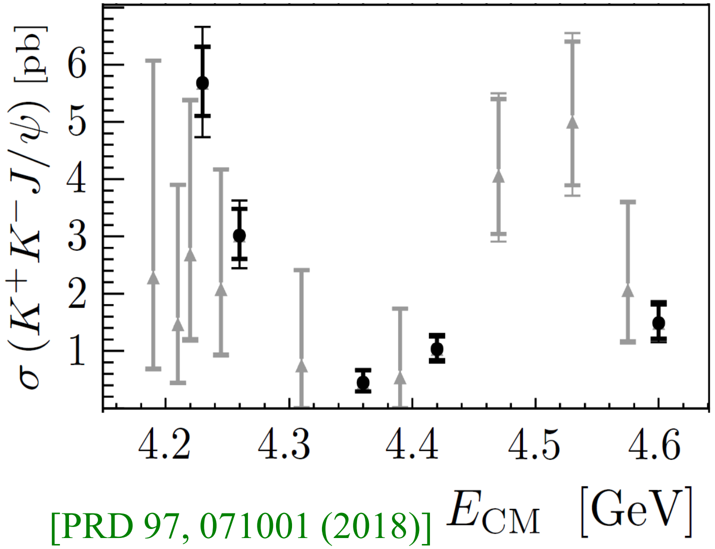




[PRL 118,092002 (2017)]

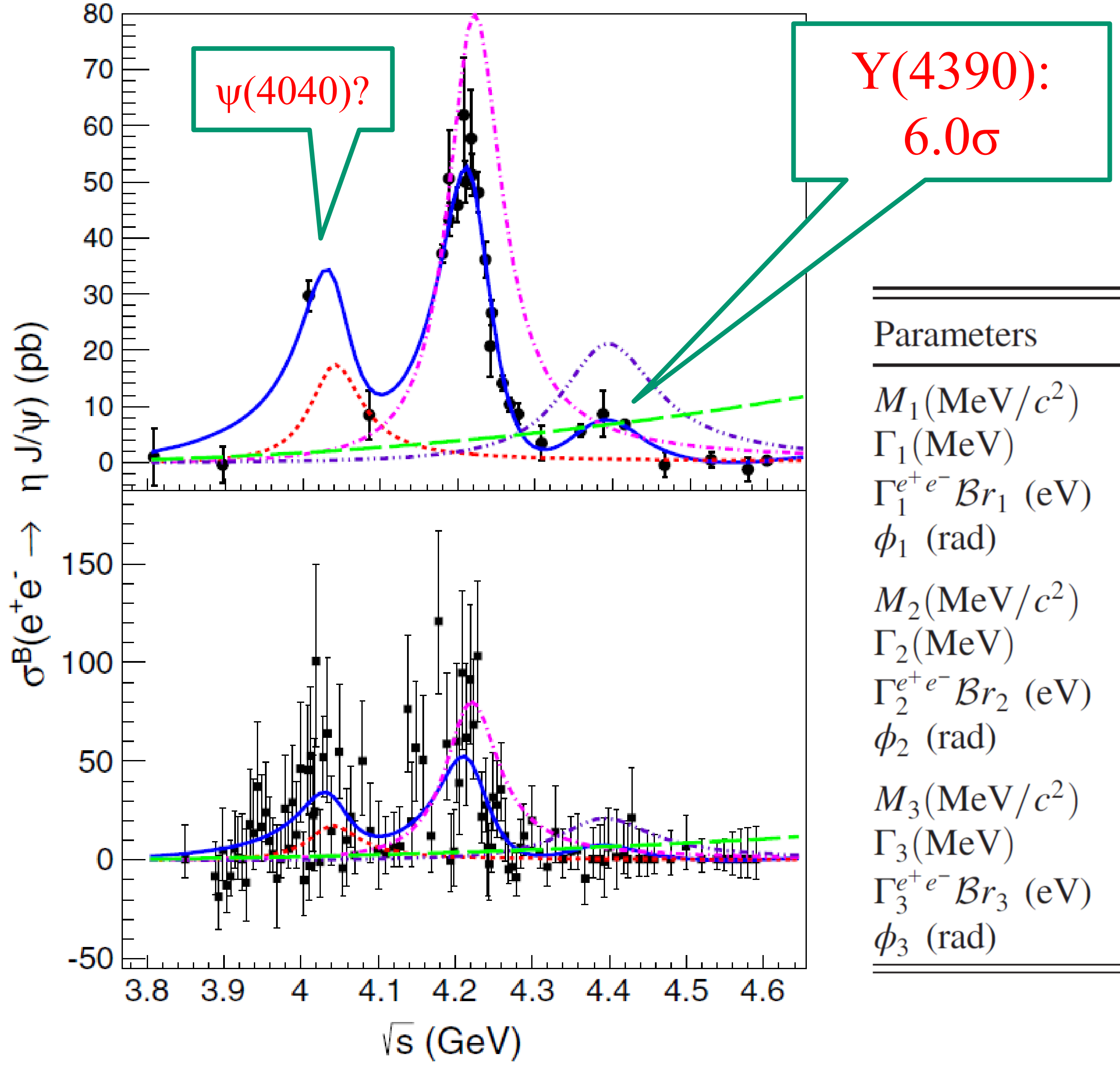


[PRD 96, 012001 (2017)]



[PRD 97, 071001 (2018)]

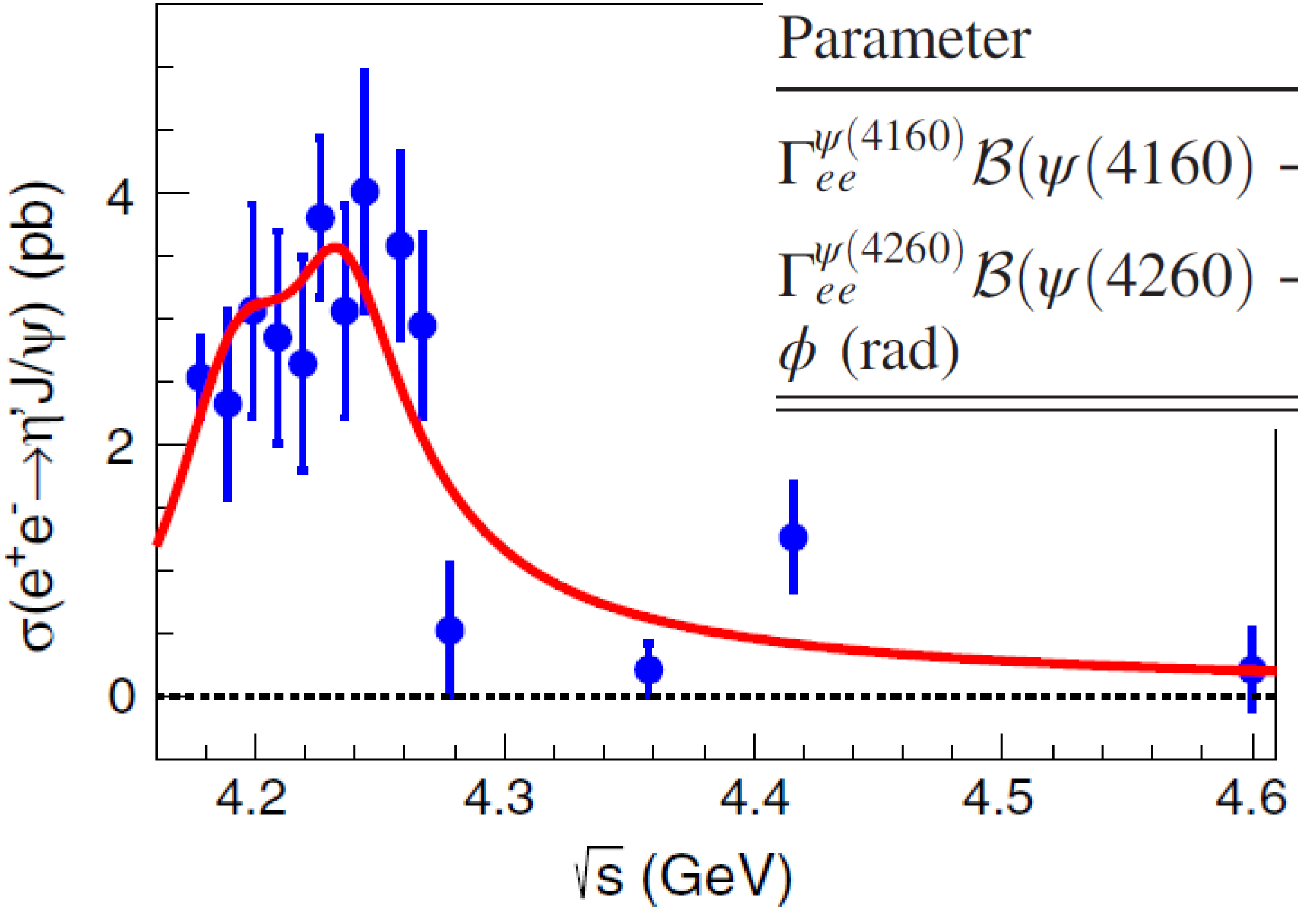
Charmonium + light hadrons: ηJ/ψ



PRD 102, 031101 (2020)

Parameters	Solution 1	Solution 2	Solution 3
$M_1(\mathrm{MeV}/c^2)$		4039(fixed)	
Γ_1(MeV)		80(fixed)	
$\Gamma_1^{e^+e^-}\mathcal{B}r_1$ (eV)	1.5 ± 0.3	1.4 ± 0.3	7.0 ± 0.6
ϕ_1 (rad)	3.3 ± 0.3	3.1 ± 0.3	4.5 ± 0.2
$M_2(\mathrm{MeV}/c^2)$		4218.6 ± 3.8	
Γ_2(MeV)		82.0 ± 5.7	
$\Gamma_2^{e^+e^-}\mathcal{B}r_2$ (eV)	8.0 ± 1.7	4.8 ± 1.0	7.0 ± 1.5
ϕ_2 (rad)	4.2 ± 0.4	3.6 ± 0.3	2.9 ± 0.3
$M_3(\mathrm{MeV}/c^2)$		4382.0 ± 13.3	
Γ_3(MeV)		135.8 ± 60.8	
$\Gamma_3^{e^+e^-}\mathcal{B}r_3$ (eV)	3.4 ± 2.2	1.5 ± 1.0	1.7 ± 1.1
ϕ_3 (rad)	2.8 ± 0.4	3.3 ± 0.4	3.0 ± 0.4

Charmonium + light hadrons: η'J/ψ



Parameter	Solution I	Solution II
$\Gamma_{ee}^{\psi(4160)}\mathcal{B}(\psi(4160)\to\eta' J/\psi)$ (eV)	0.17 ± 0.04	1.07 ± 0.09
$\Gamma_{ee}^{\psi(4260)}\mathcal{B}(\psi(4260)\to\eta' J/\psi)$ (eV)	0.06 ± 0.03	1.38 ± 0.11
ϕ (rad)	-0.03 ± 0.44	2.54 ± 0.04

Mass/width of the resonances are fixed

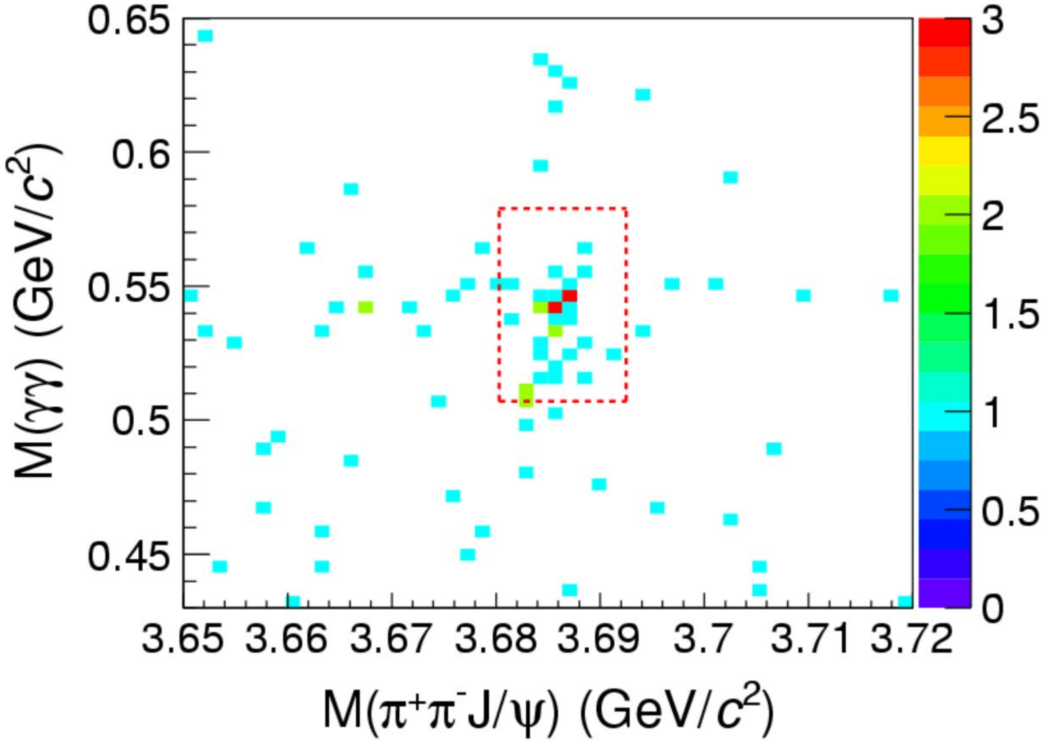
Some data between 4.28 and 4.44 GeV not analyzed. Lack of data between 4.44 and 4.60 GeV.

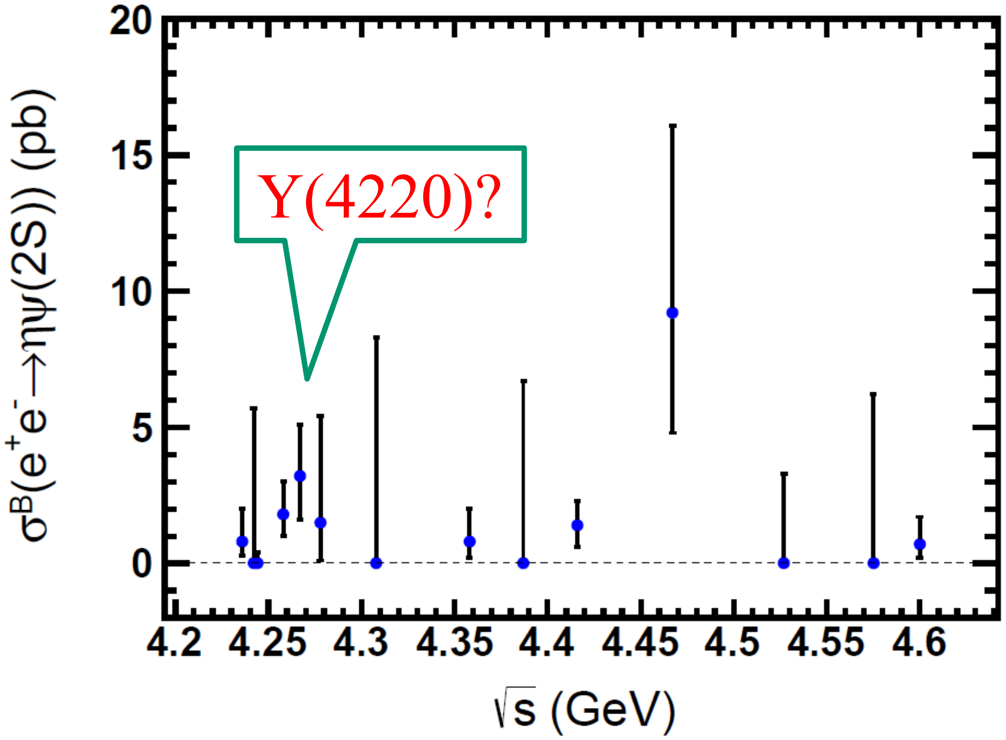
PRD 101, 012008 (2020)

Charmonium + light hadrons: ηψ'

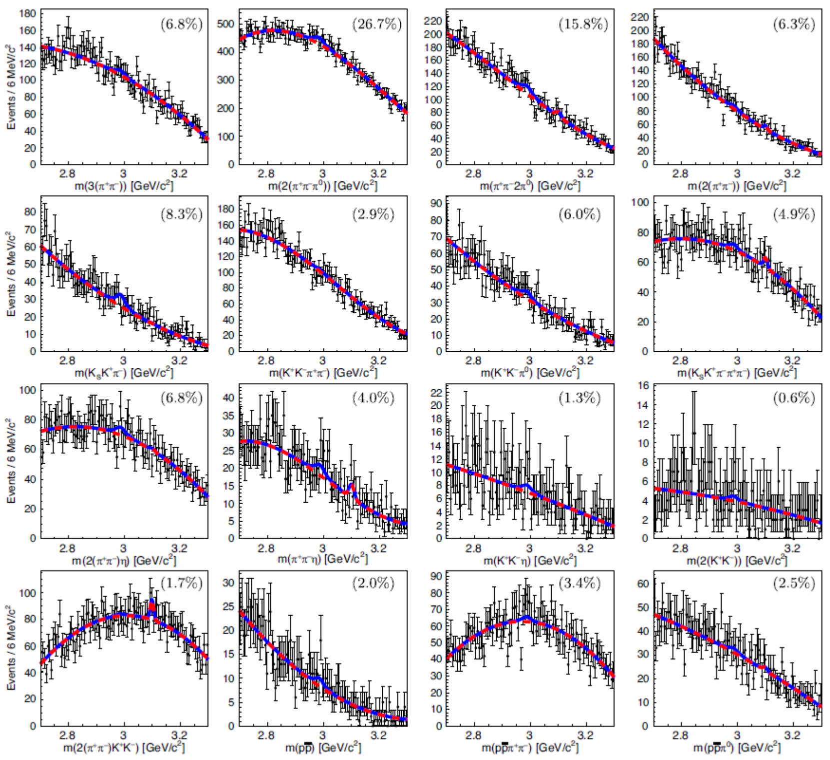
arXiv:2103.01480

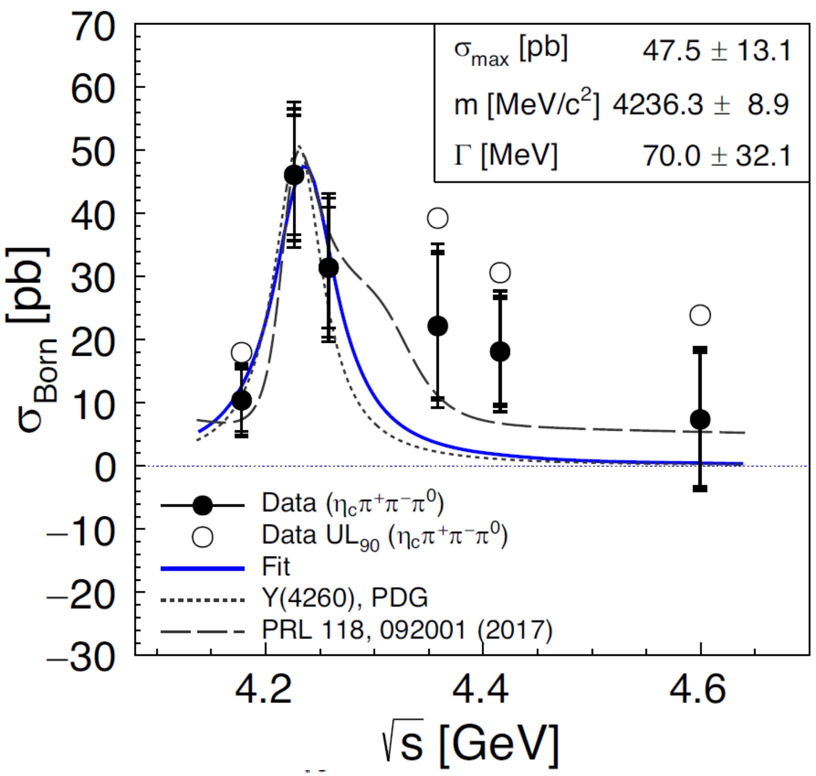
34 observed events with 11 expected background





Charmonium + light hadrons: $\eta_c\pi^+\pi^-\pi^0$





PRD 103, 032006 (2021)

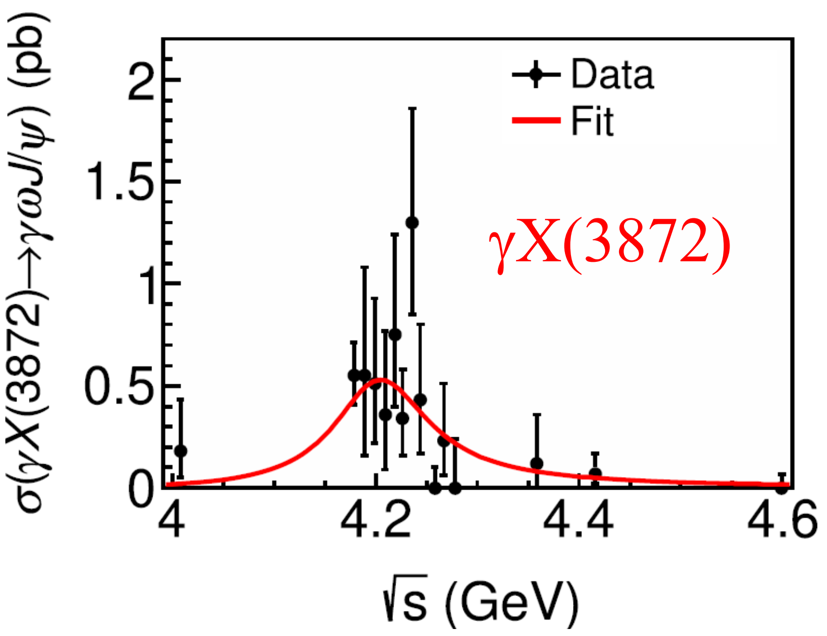
PRD 100, 111102(R) (2019)

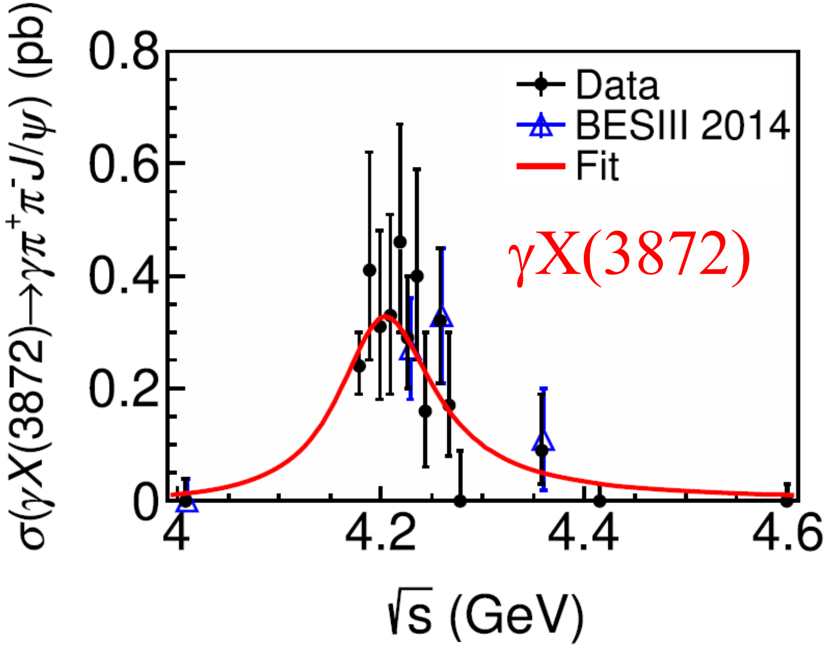
Clear evidence for $Y(4220)\rightarrow\eta_c\pi^+\pi^-\pi^0$

$\sqrt{s}$ [GeV]	$\mathcal{L}$ [pb^{-1}]	N_{obs}	κ	f_{VP}	$\sum \epsilon_i \mathcal{B}_i$ [%]	σ_{Born} [pb]	UL_{90} [pb]	$\mathcal{S}_{stat}/\mathcal{S}_{tot}$ [σ]
4.1780	3189.0	530 ± 246	[0.720, 0.734]	1.056	2.0	$10.4^{+5.0}_{-4.9} \pm 2.9$	17.9	2.2/1.9
4.2263	1091.7	786 ± 159	[0.716, 0.731]	1.056	2.0	$46.1^{+9.5}_{-9.4} \pm 6.6$	61.0	5.1/4.6
4.2580	825.7	465 ± 134	[0.786, 0.824]	1.054	2.0	$31.4^{+9.6}_{-9.6} \pm 6.7$	46.6	3.5/3.2
4.3583	539.8	242 ± 115	[0.802, 0.880]	1.051	2.1	$22.2^{+11.4}_{-11.3} \pm 6.2$	39.2	2.2/1.9
4.4156	1073.6	379 ± 165	[0.780, 0.850]	1.053	2.2	$18.1^{+8.4}_{-8.4} \pm 4.5$	30.6	2.3/2.1
4.5995	566.9	79 ± 102	[0.763, 0.807]	1.055	2.0	$7.4^{+10.6}_{-10.5} \pm 3.9$	23.9	0.8/0.7

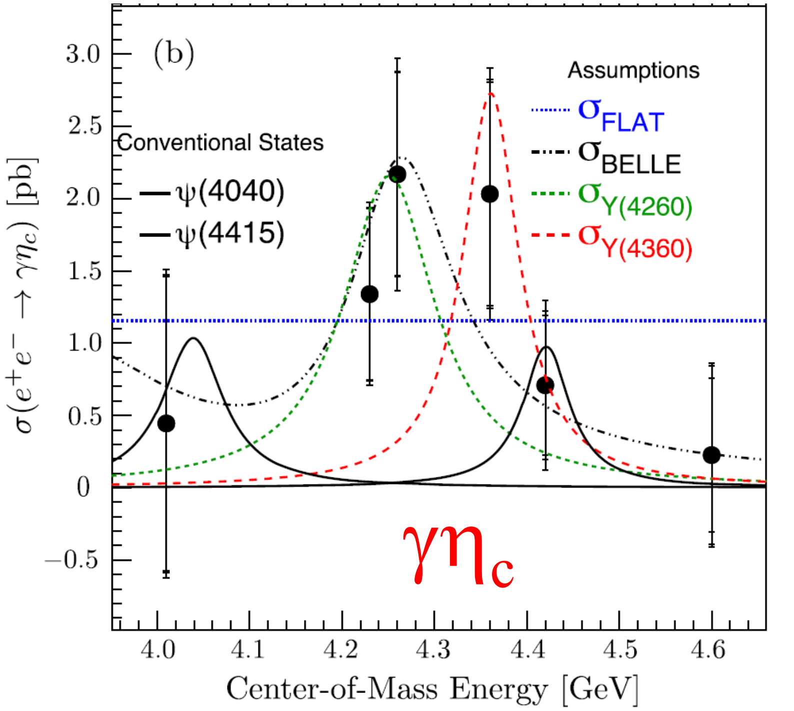
Charmonium + γ

PRL 122, 232002 (2019)





PRD 96, 051101(R) (2017)



$$M[Y(4200)] = 4200.6^{+7.9}_{-13.3} \pm 3.0 \text{ MeV}/c^2$$

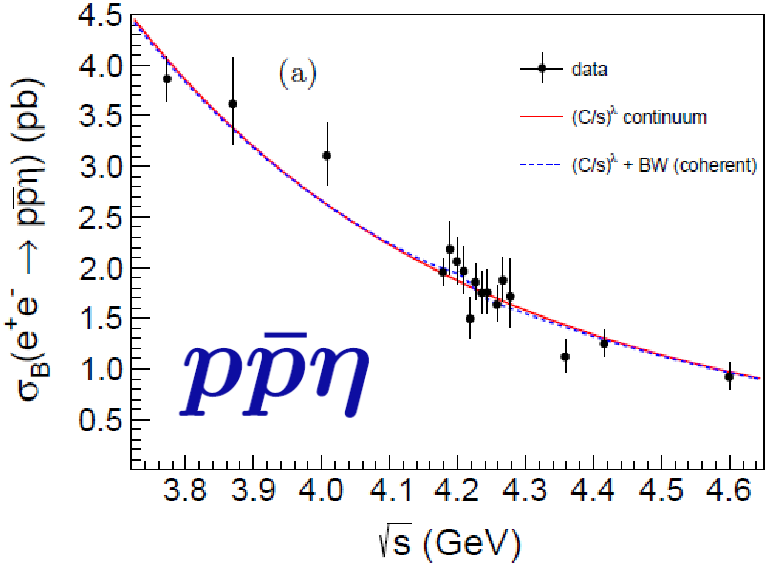
$$\Gamma[Y(4200)] = 115^{+38}_{-26} \pm 12 \text{ MeV}$$

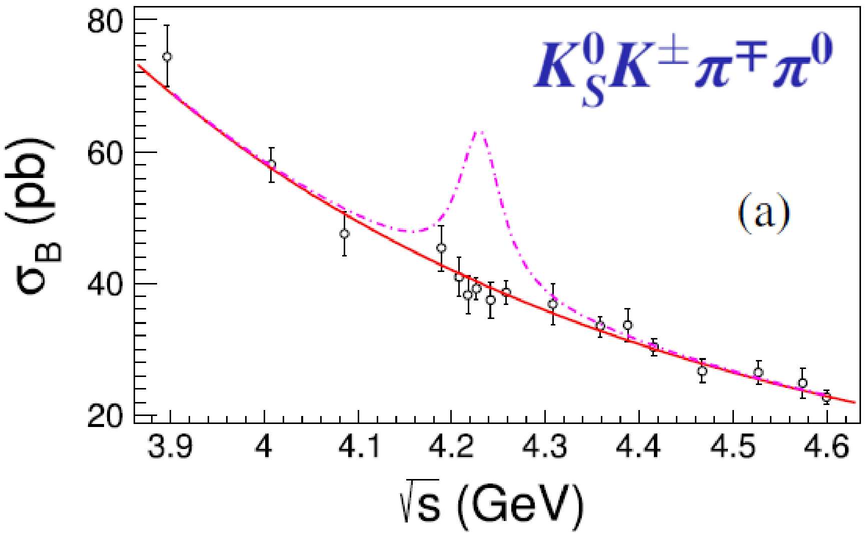
$\gamma\chi_{cJ}$ results will be available very soon.

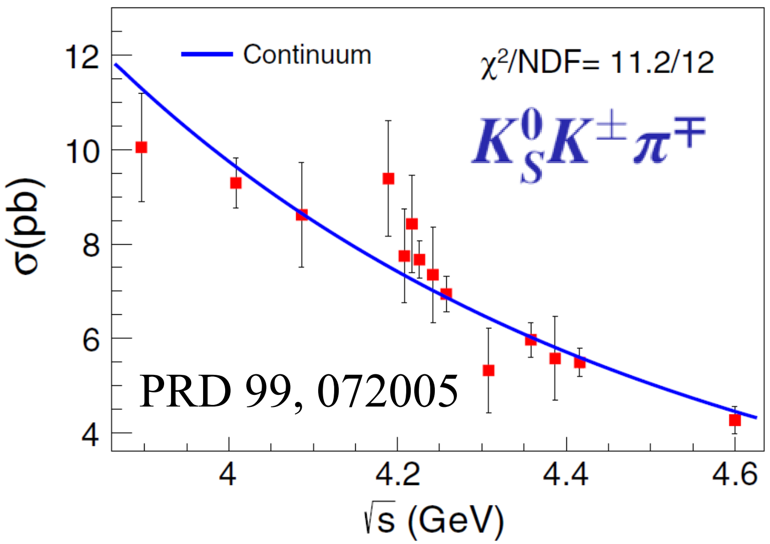
Need data between 4 and 4.16 GeV to check if there is contribution from ψ(4040).

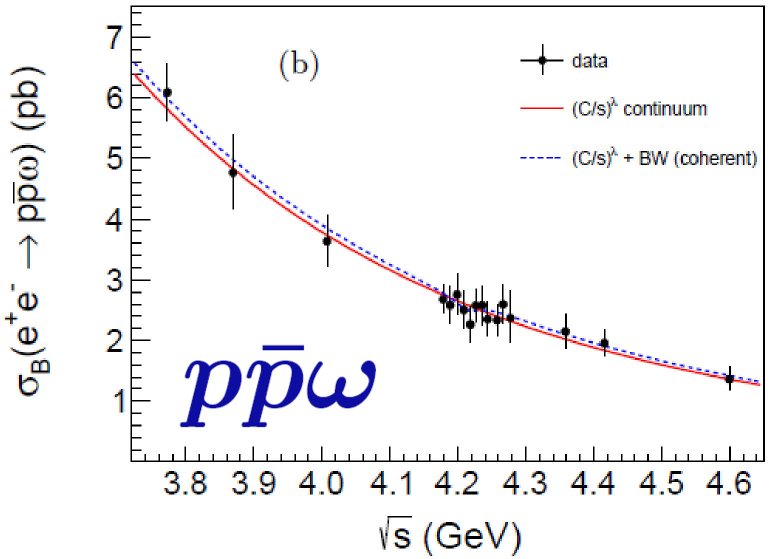
Light hadrons

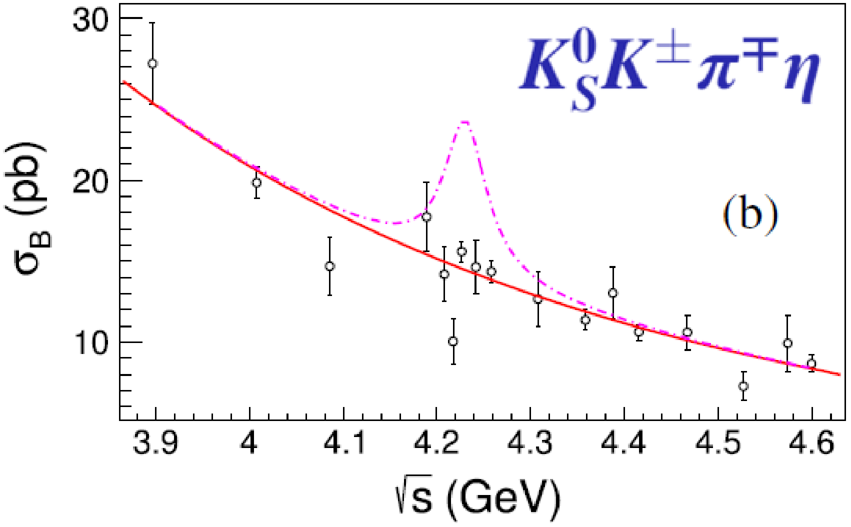
Lots of searches, hints for resonant structures, none is significant!

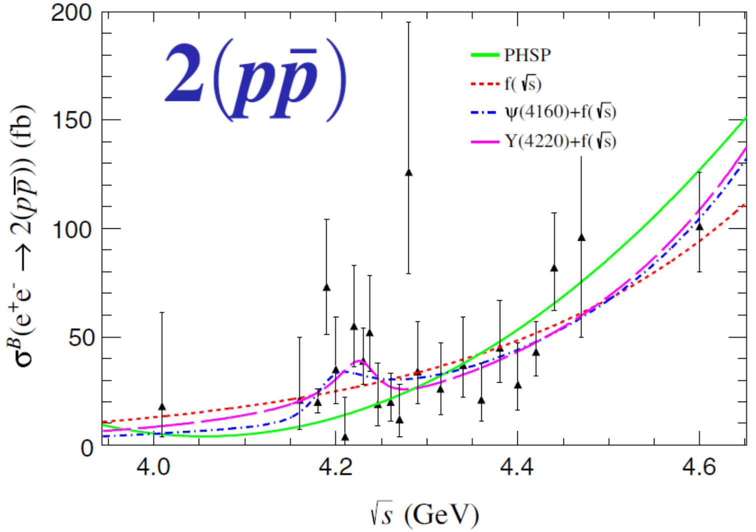










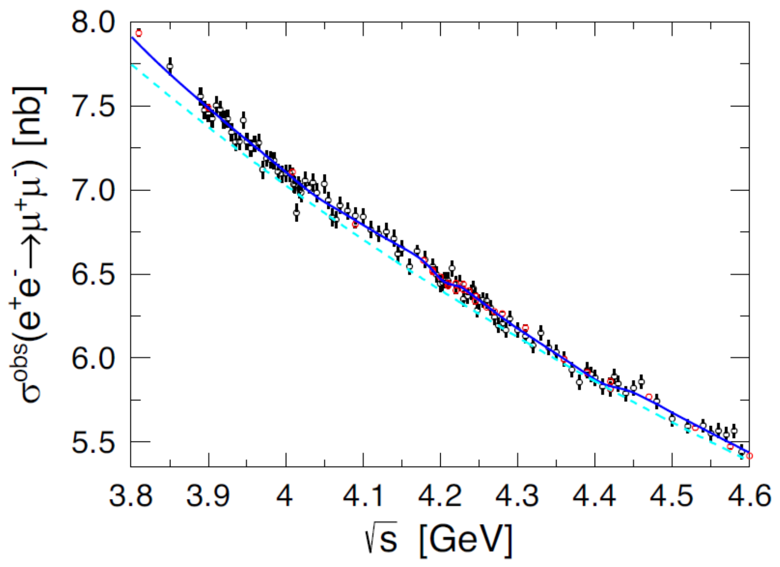


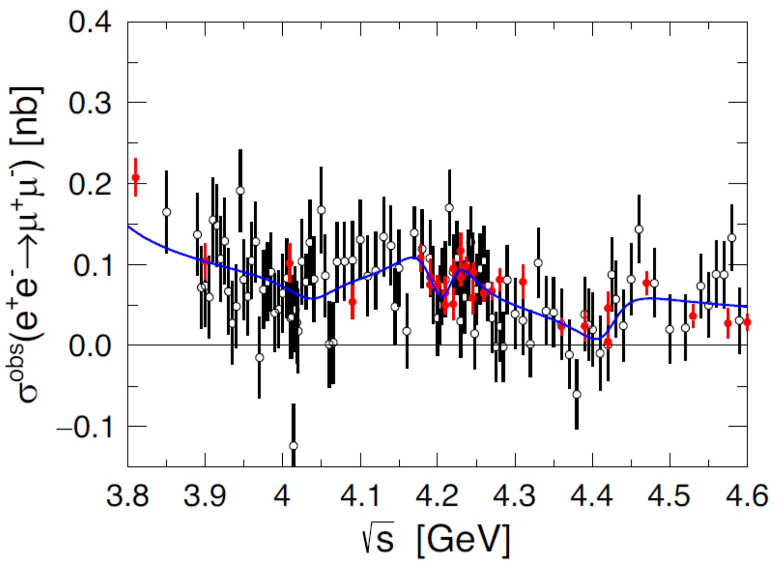
arXiv:2102.04268

arXiv:1810.09395

PRD 103, 052003

Lepton pair vs. vacuum polarization

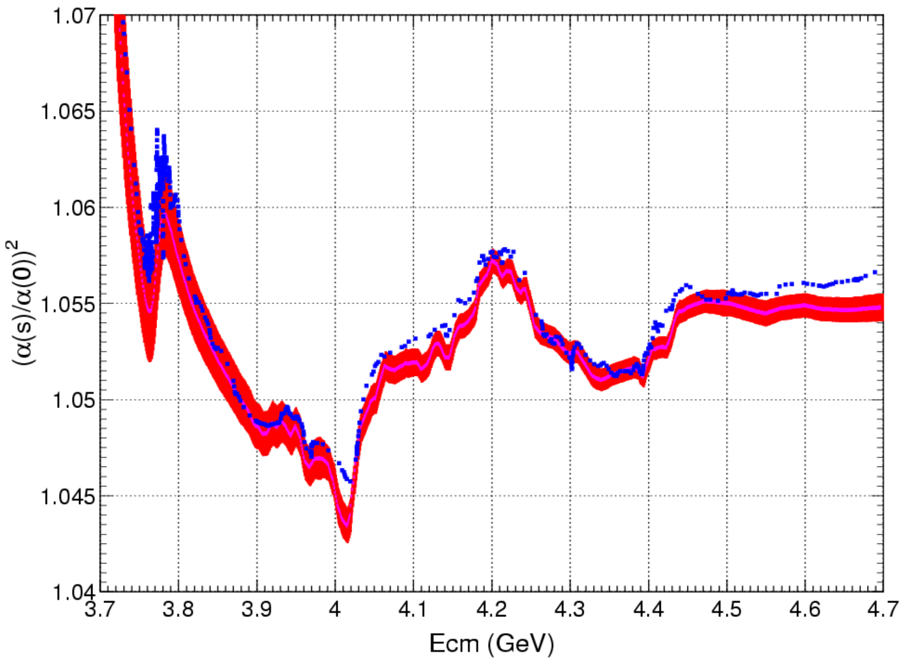




PRD 102, 112009 (2020)

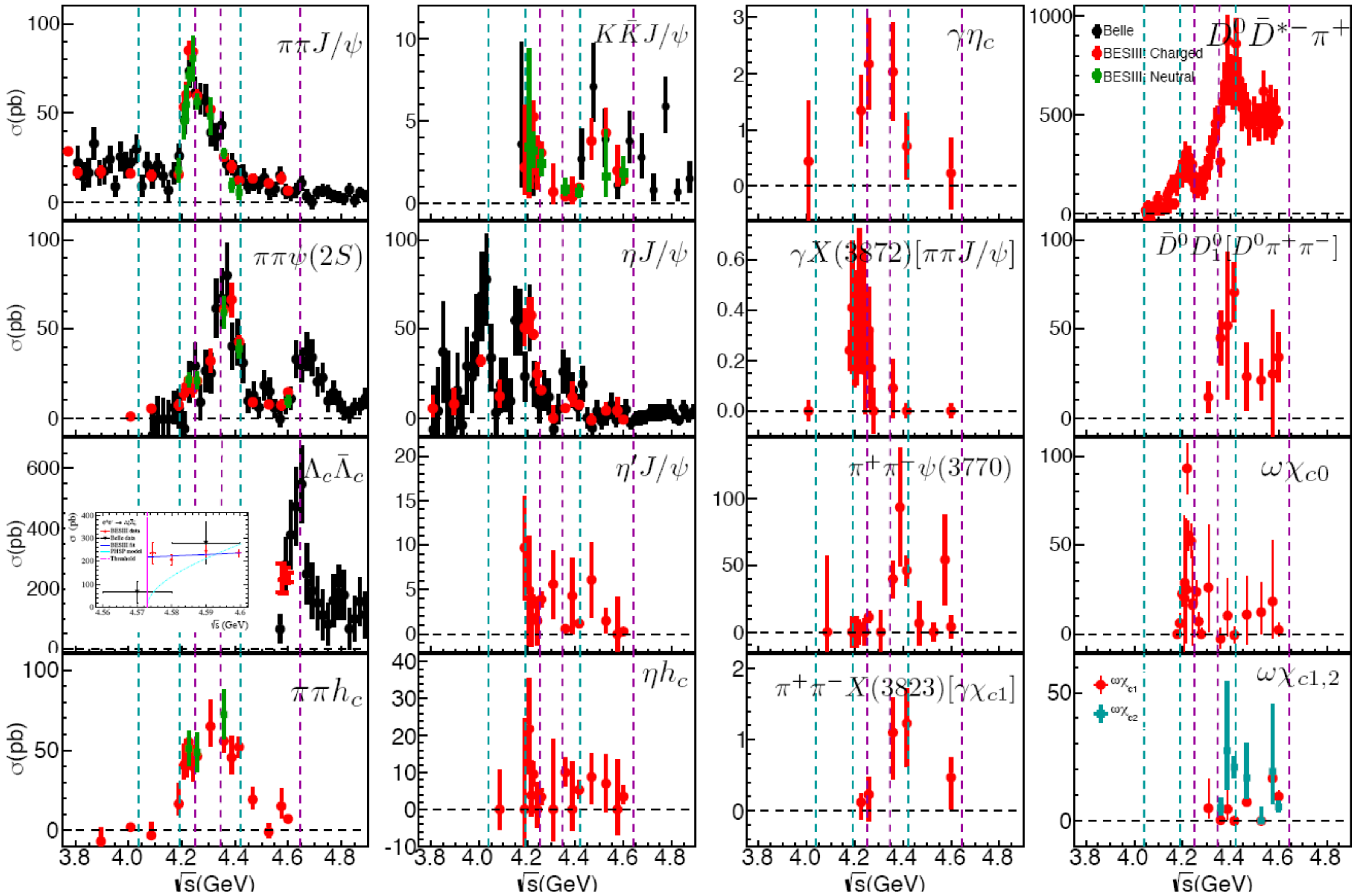
Direct measurement of $e^+e^- \rightarrow \mu^+\mu^-$ cross section with ~3% uncertainty.

Vacuum polarization factors are basically equivalent to the $e^+e^- \rightarrow \mu^+\mu^-$ cross section, but with smaller uncertainty than direct measurement.

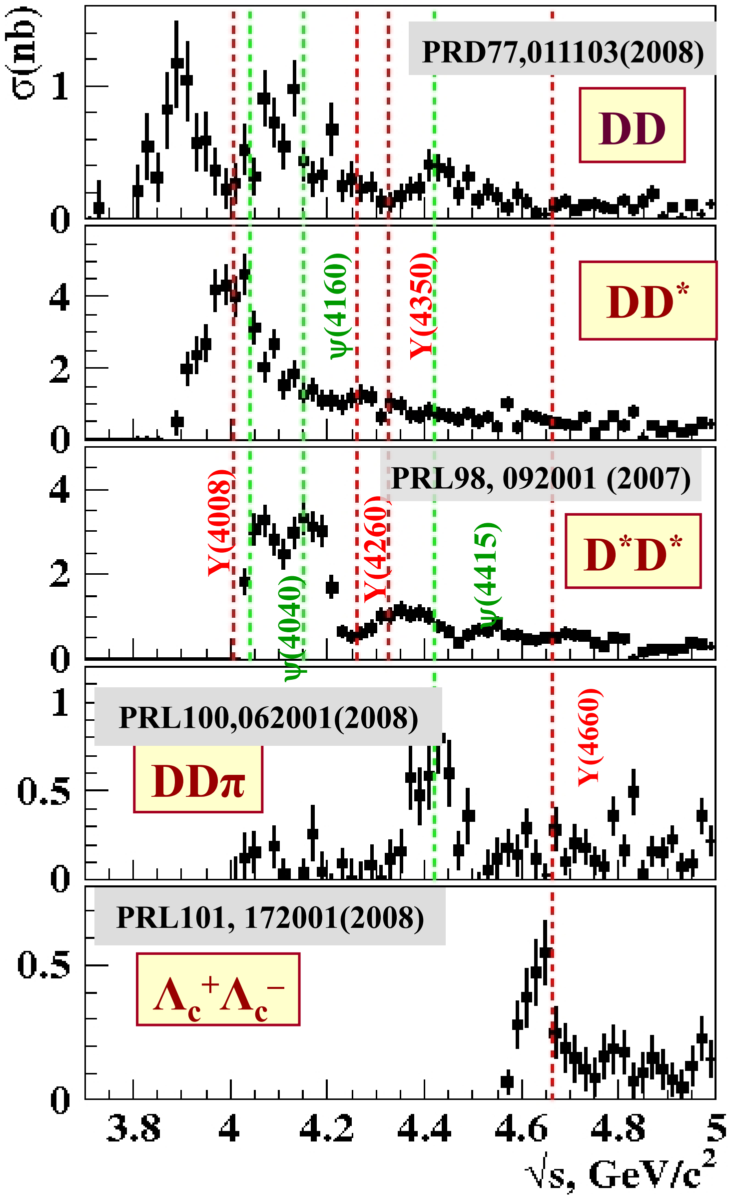


Even with very precise measurement of the cross sections, one needs to apply quite a few non-trivial assumptions to obtain leptonic width of the Y states.

After we have measured all the e^+e^- annihilation cross sections, what do we do to get the resonant parameters of the vector charmonium(-like) states?



From Yuping Guo, talk @ Hadron2019, Guilin



From Galina Pakhlova

Inclusive fit: coupled channels

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

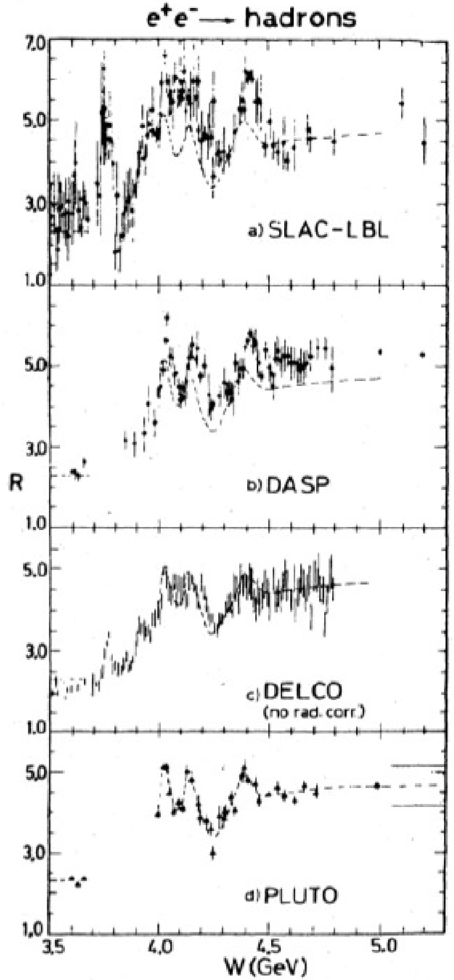


FIG. 15. Results of R (including $e^+e^- \to \tau^+\tau^-$) from four experiments: (a) SLAC-LBL (Ref. 44), (b) DASP (Ref. 46), (c) DELCO (Ref. 45), (d) PLUTO (Ref. 47). The curves represent a hand-drawn line through the PLUTO data. The band in Fig. 15(d) indicates the systematic errors of the PLUTO measurement.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

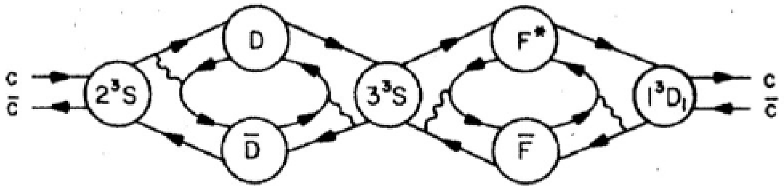


FIG. 8. The propagation of a $c\bar{c}$ pair in the presence of open and closed decay channels as described in the Green's function $\mathcal{G}$.

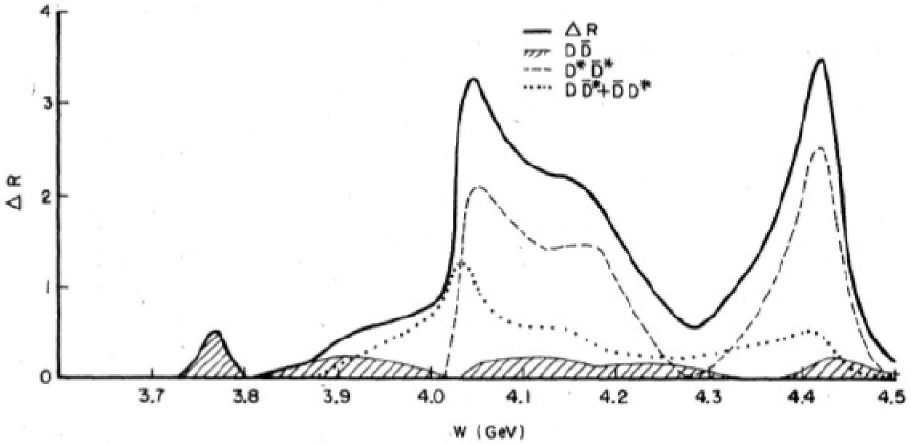


FIG. 13. The charm contribution to R in the region $3.7 < W < 4.5$ GeV as computed in the coupled-channel model. Contributions from $F_1\bar{F}_2$ channels are included but not indicated separately since they are too small; they are shown in Fig. 12.

Recent K-matrix fit by T. V. Uglov

g is real, so there will be no multiple solutions!

$$S = 1 + 2iA,$$

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

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

Ensures unitarity

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

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

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

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

Coupling constant

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

Electron width

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

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

T. V. Uglov et al., JETP letters 105, 1 (2017)

Results

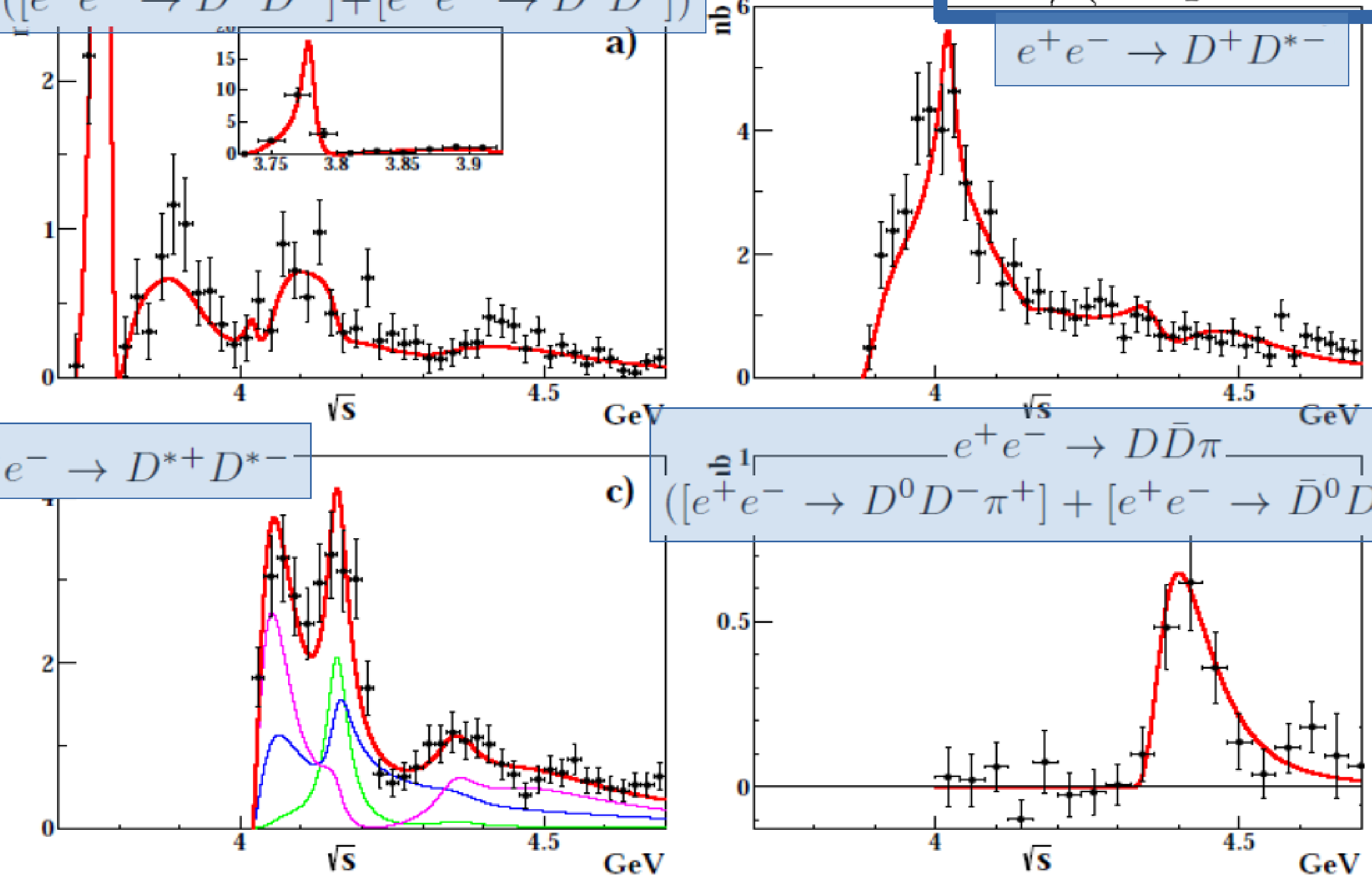
$$\chi^2/n.d.f. = 158/(191point - 33par)$$

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

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

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

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



Still lots of problems in current model

- Model has room to improve (step function, unknown modes, …)
- Only two-body charmed meson final states considered
- Charmed strange meson production not included
- Charmonium final states not included
- No non-resonant amplitude
- Model constraints used; parameters constrained to PDG values
- Y states not included (nor tested if they are needed)
- Fit quality is bad
- …

Seems the right direction for understanding the physics

Summary

- BESIII supplied lots of information on the vectors
  - Y(4220), Y(4260), Y(4320), Y(4360), Y(4390), & Y(4660)
- We do not understand the ψ's and the Y's

Thanks a lot!

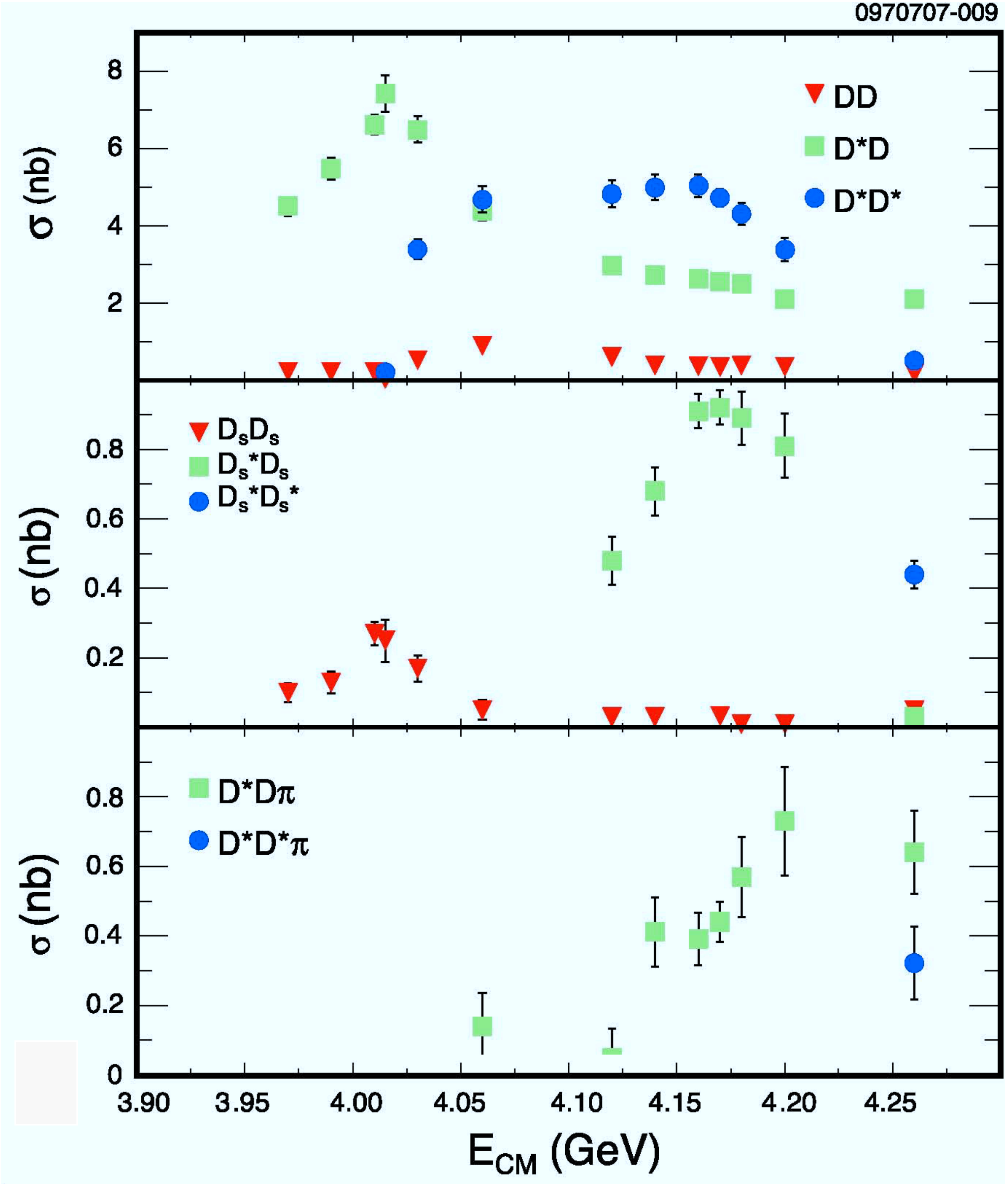
In memory of Mikhail B. Voloshin

From http://scgp.stonybrook.edu/archives/24626

- Met him only once at SCGP workshop: Exotic Hadrons and Flavor Physics: May 28 – June 1, 2018
- Discussion on cross sections of $e^+e^- \rightarrow D_s^{*-}D_{s0}(2317)^+$ and $D_s^-D_{s1}(2460)^+$ which he predicted to be equal (1802.09492); I told him BESIII results would come soon
- BESIII paper (arXiv:2005.05850) was submitted on 12 May 2020!

- A few email exchanges on $Z_c(3900) \rightarrow \rho\eta_c$, $Y(4220) \rightarrow \pi DD^*$, and nature of the $Y(4220)$.
- 斯人已逝，论文永存！

More slides

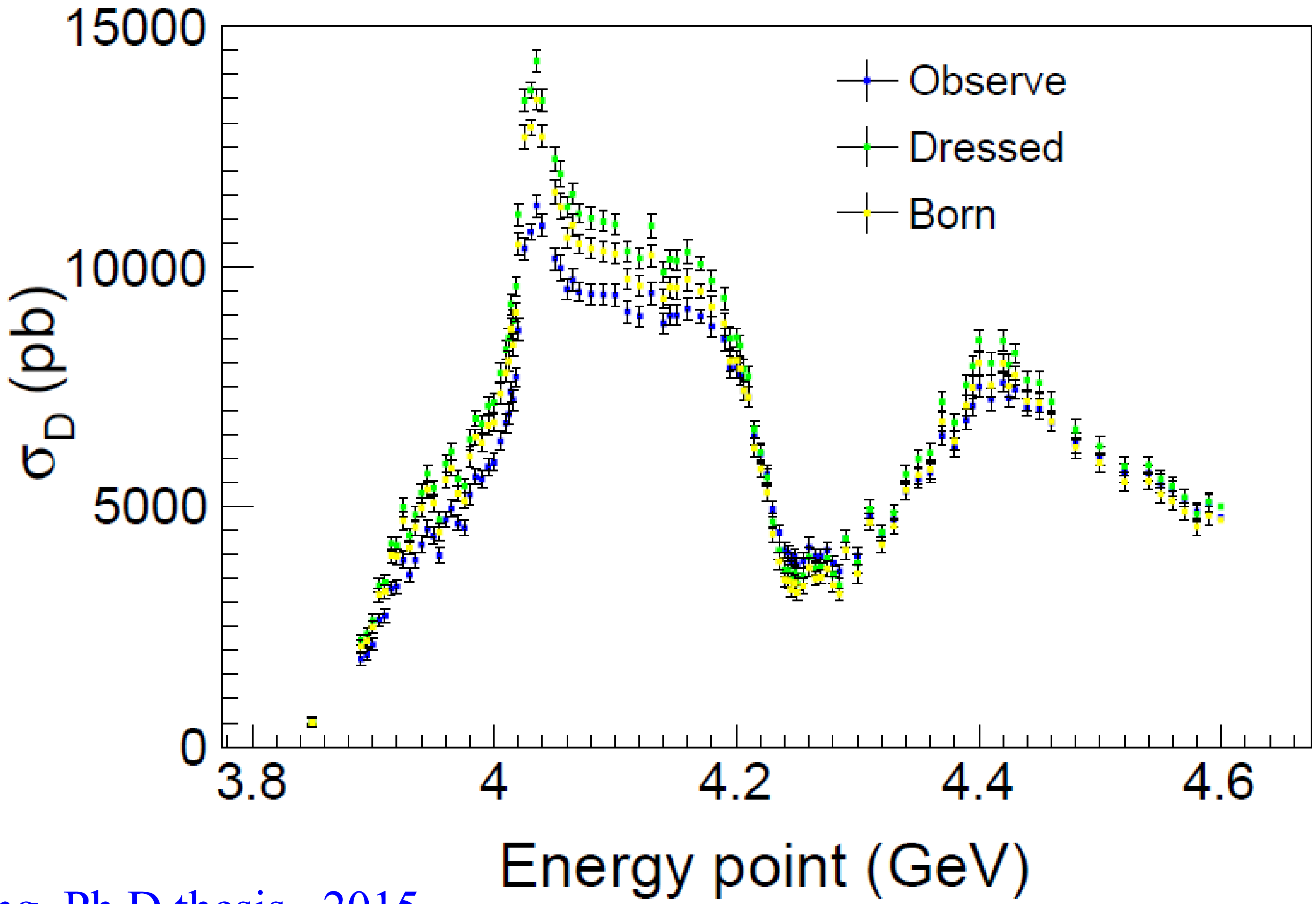


R_D Scan (3.97-4.26 GeV)

CLEOc, PRD80, 072001 (2009)

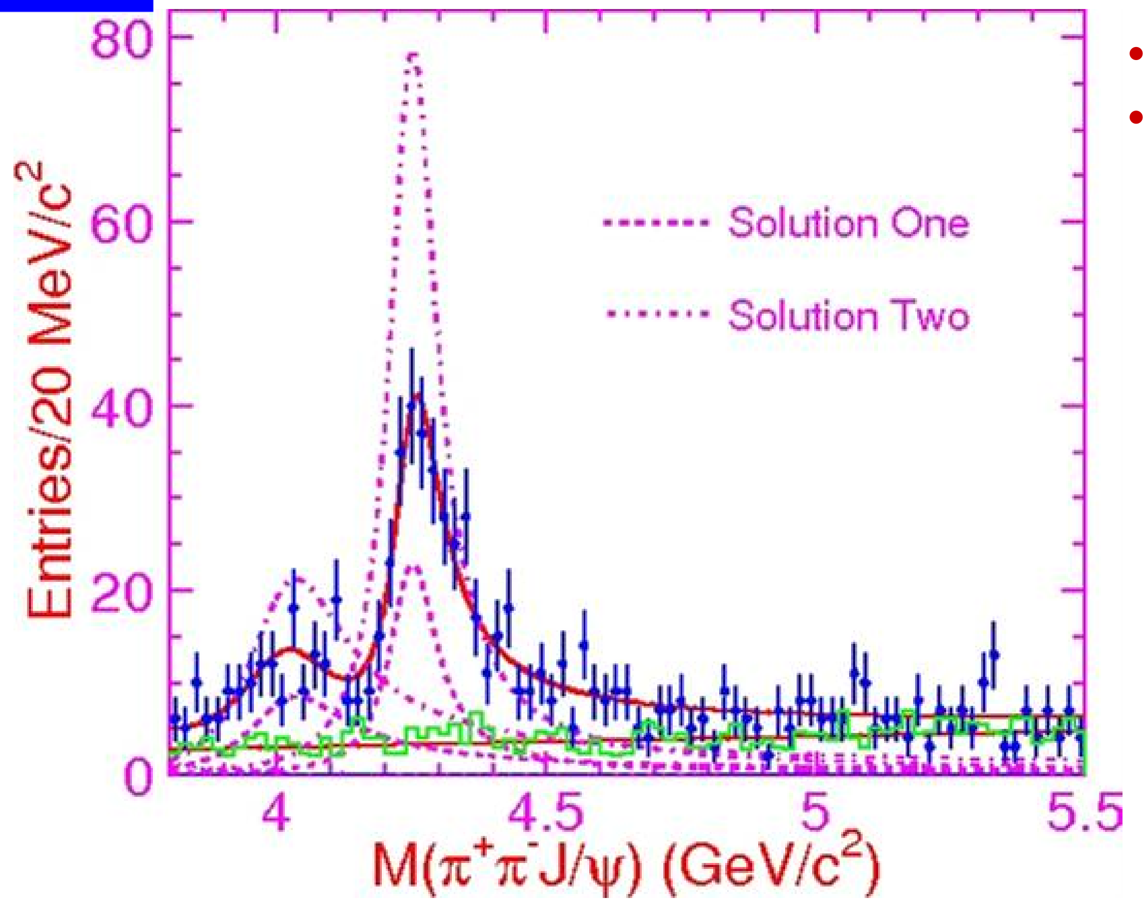
$E_{c.m.}$ (MeV)	$\int \mathcal{L}dt$ (pb^{-1})
3970	3.85
3990	3.36
4010	5.63
4015	1.47
4030	3.01
4060	3.29
4120	2.76
4140	4.87
4160	10.16
4170	178.89
4180	5.67
4200	2.81
4260	13.11

Cross Section for $e^+e^- \to D+X$



Weimin Song, Ph.D thesis, 2015

$e^+e^- \to \pi^+\pi^- J/\psi$ via ISR



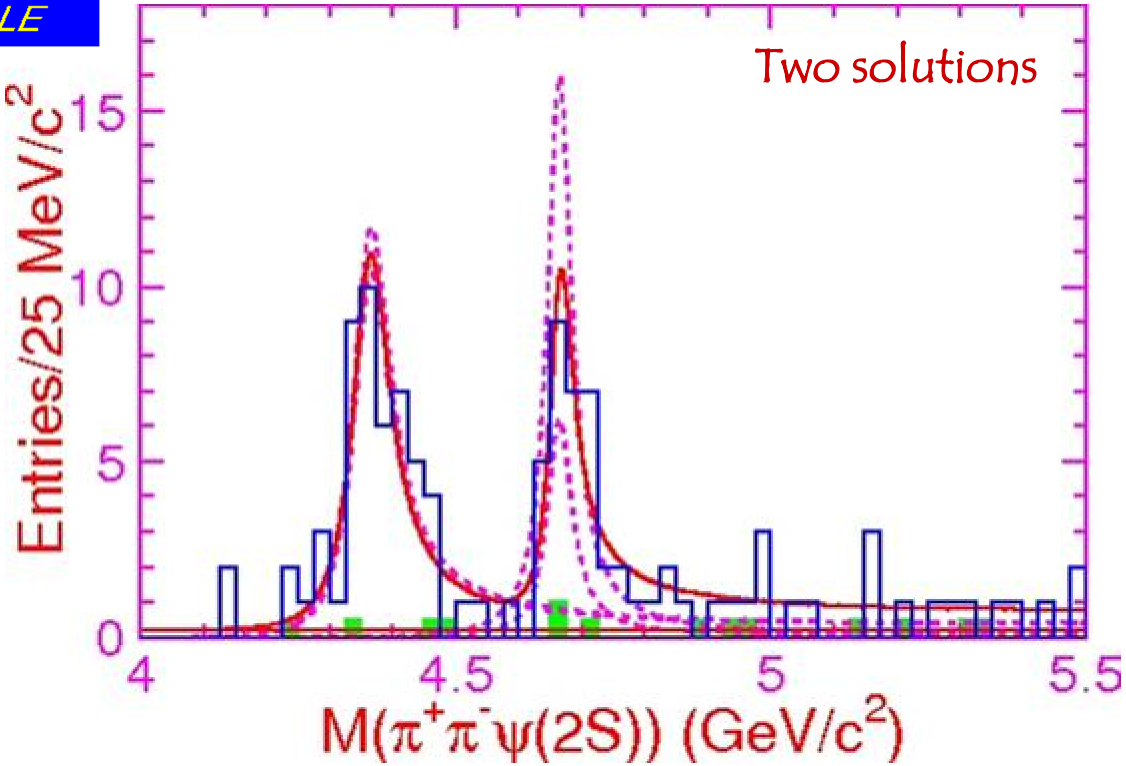
- **Non resonant $J/\psi\pi\pi$?**
- **Re-scattering $ee \to D^{(*)}D^{(*)} \to J/\psi\pi\pi$?**
- **Another broad state ?**
  - **Check the latter hypothesis and influence of interference of Y(4260) with non-Y contribution:**
  - **Fit with 2 coherent BWs**
  - **Two-fold ambiguity in amplitude (constructive-destructive interference) + model uncertainty due to ψ' tail**

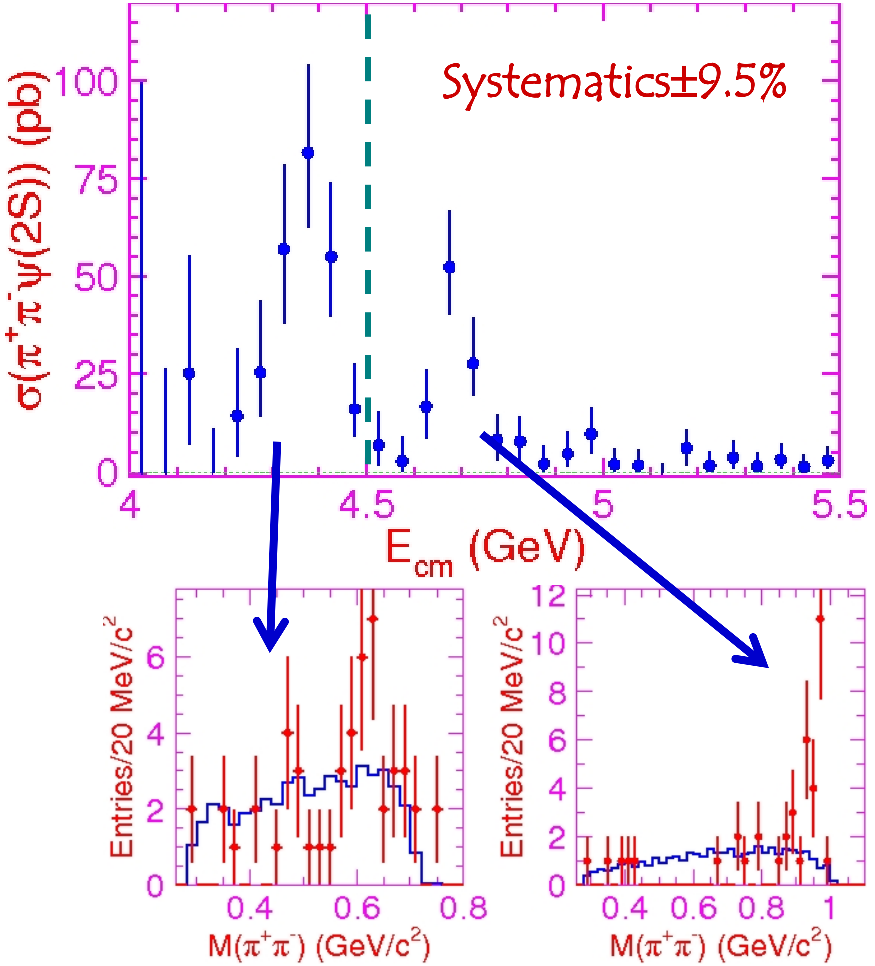
Parameters	Solution I	Solution II
$M(R1)$	$4008 \pm 40^{+114}_{-28}$	
$\Gamma_{tot}(R1)$	$226 \pm 44 \pm 87$	
$\mathcal{B} \cdot \Gamma_{e^+e^-}(R1)$	$5.0 \pm 1.4^{+6.1}_{-0.9}$	$12.4 \pm 2.4^{+14.8}_{-1.1}$
$M(R2)$	$4247 \pm 12^{+17}_{-32}$	
$\Gamma_{tot}(R2)$	$108 \pm 19 \pm 10$	
$\mathcal{B} \cdot \Gamma_{e^+e^-}(R2)$	$6.0 \pm 1.2^{+4.7}_{-0.5}$	$20.6 \pm 2.3^{+9.1}_{-1.7}$
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: CZY & C.P. Shen et al., PRL99, 182004 (2007)

Belle discovers Y(4360) & Y(4660) in $e^+e^- \to \pi^+\pi^-\psi(2S)$





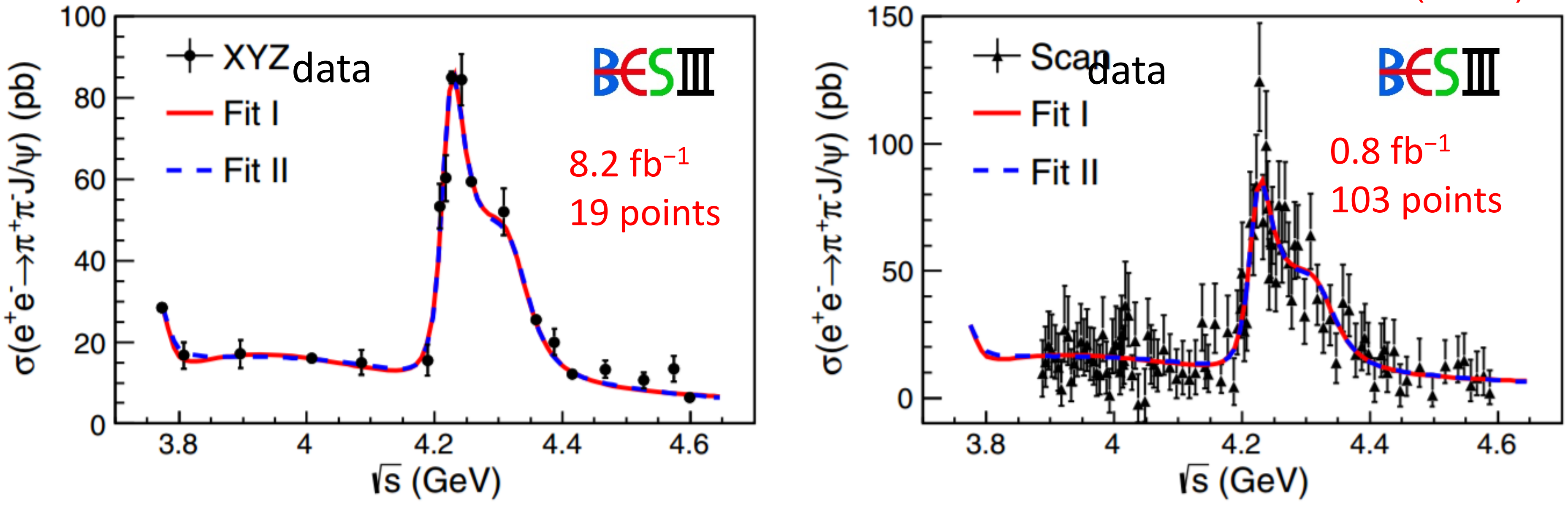
Parameters	Solution one	Solution two
$M(Y(4360))$	$4361 \pm 9 \pm 9$	
$\Gamma_{tot}(Y(4360))$	$74 \pm 15 \pm 10$	
$\mathcal{B} \cdot \Gamma_{e^+e^-}(Y(4360))$	$10.4 \pm 1.7 \pm 1.5$	$11.8 \pm 1.8 \pm 1.4$
$M(Y(4660))$	$4664 \pm 11 \pm 5$	
$\Gamma_{tot}(Y(4660))$	$48 \pm 15 \pm 3$	
$\mathcal{B} \cdot \Gamma_{e^+e^-}(Y(4660))$	$3.0 \pm 0.9 \pm 0.3$	$7.6 \pm 1.8 \pm 0.8$
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 et al., PRL99, 142002 (2007)

$e^+e^- \to \pi^+\pi^- J/\psi$ cross section

PRL118, 092001 (2017)



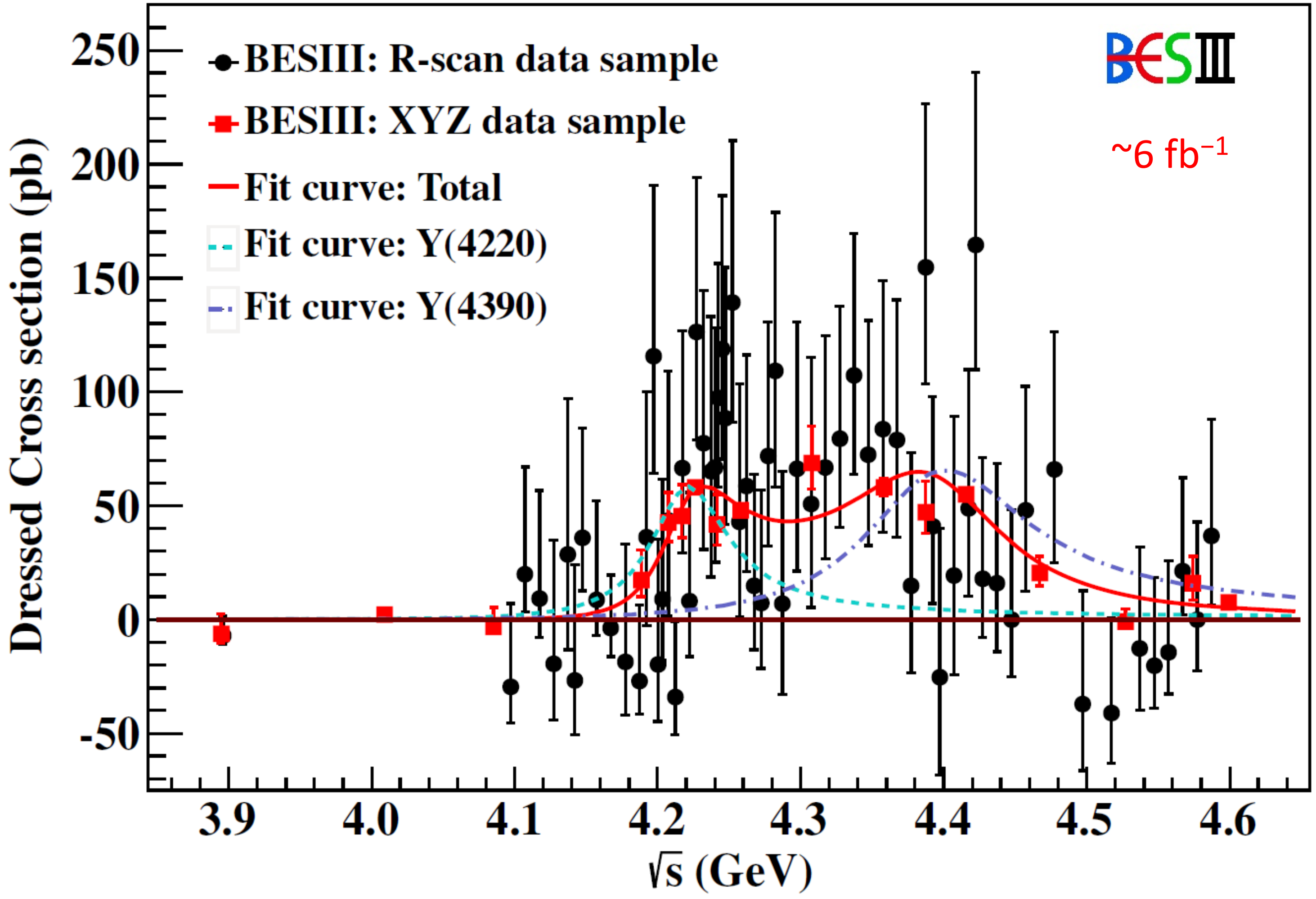
- Most precise cross section measurment to date from BESIII
- Fit I =$|BW_1+BW_2*e^{i\phi 2}+BW_3*e^{i\phi 3}|^2$ or Fit II =$|\exp+BW_2*e^{i\phi 2}+BW_3*e^{i\phi 3}|^2$ (other fits ruled out)
- M = 4222.0 ± 3.1 ± 1.4 MeV (lower)
- Γ = 44.1 ± 4.3 ± 2.0 MeV (narrower)

- A 2nd resonance Y_2 with M=4320.0 ± 10.4 ± 7.0 MeV/c^2

  $\Gamma = 101.4^{+25.3}_{-19.7} \pm 10.2$ MeV
- Observed for the first time, significance > 7.6σ

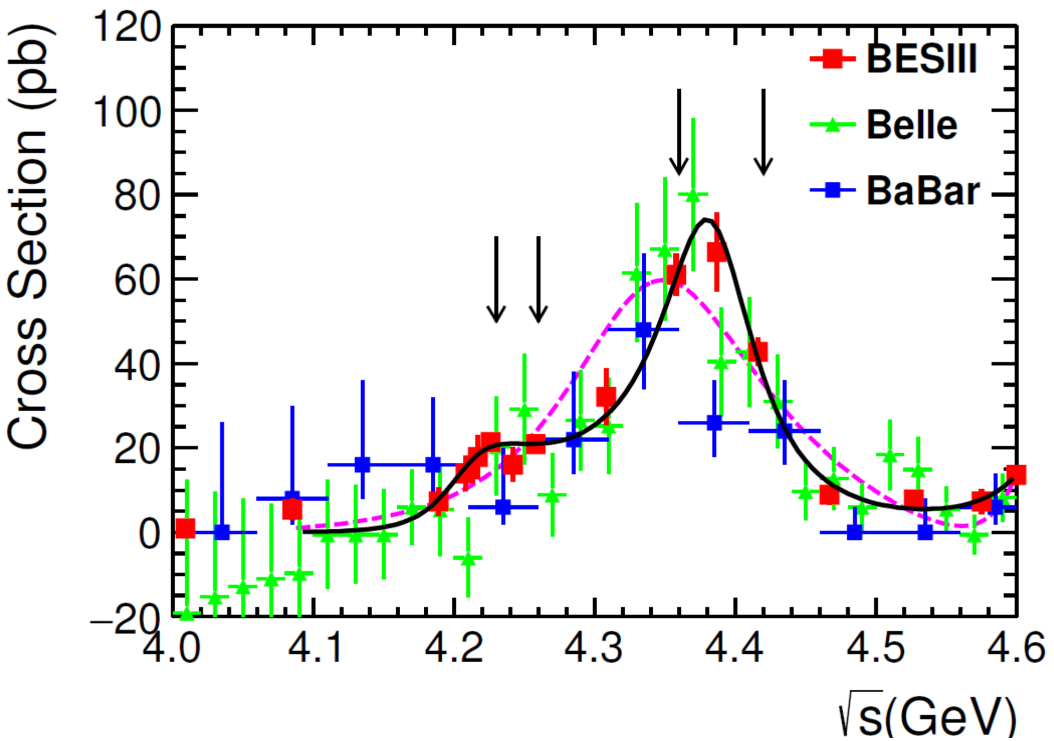
BESIII $e^+e^- \rightarrow \pi^+\pi^- h_c$ cross section

PRL118, 092002 (2017)



- $M_1 = 4218.4^{+5.5}_{-4.5} \pm 0.9$ MeV/c^2, $\Gamma_1 = 66.0^{+12.3}_{-8.3} \pm 0.4$ MeV $\rightarrow$ Y(4220)
- $M_2 = 4391.5^{+6.3}_{-6.8} \pm 1.0$ MeV/c^2, $\Gamma_2 = 139.5^{+16.2}_{-20.6} \pm 0.6$ MeV $\rightarrow$ Y(4390)

The Ys in $e^+e^- \to \pi^+\pi^-\psi'$



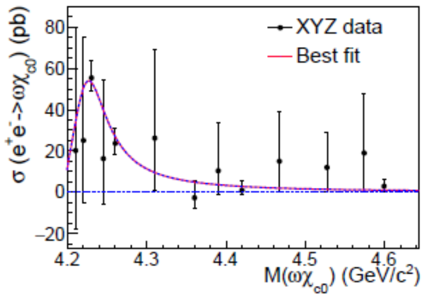
arXiv:1703.08787,
PRD 96, 032004 (2017)

The Y(4220) is necessary

(significance = 5.8σ)

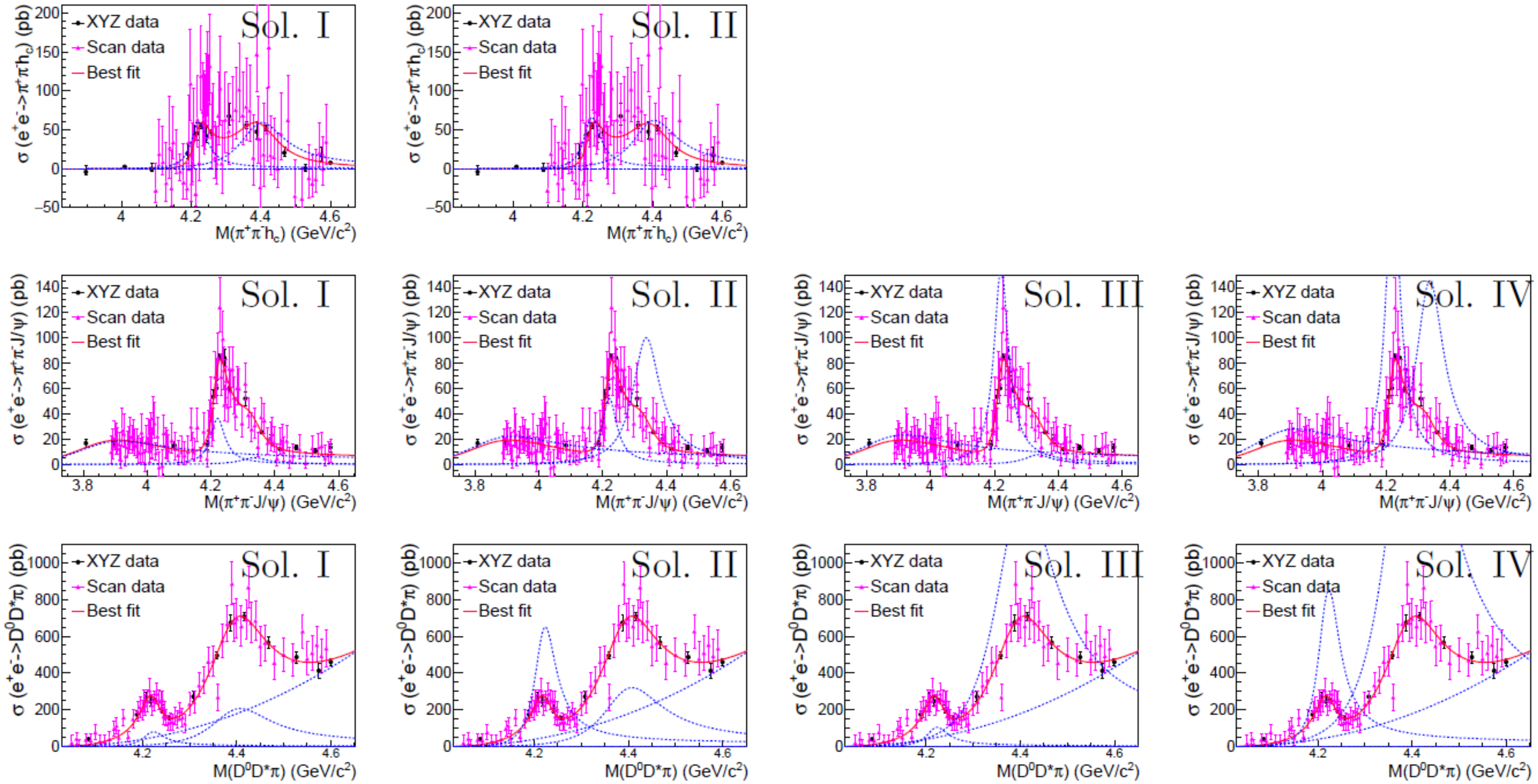
Fix parameters of the Y(4660) to Belle results

Parameters	Solution I	Solution II
$M(Y4220)$ (MeV/c^2)	4209.5 ± 7.4	
$\Gamma(Y(4220))$ (MeV)	80.1 ± 24.6	
$\mathcal{B}\Gamma^{e^+e^-}(Y(4220))$ (eV)	0.8 ± 0.7	0.4 ± 0.3
$M(Y4390)$ (MeV/c^2)	4383.8 ± 4.2	
$\Gamma(Y(4390))$ (MeV)	84.2 ± 12.5	
$\mathcal{B}\Gamma^{e^+e^-}(Y(4390))$ (eV)	3.6 ± 1.5	2.7 ± 1.0
ϕ_1 (rad)	3.3 ± 1.0	2.8 ± 0.4
ϕ_2 (rad)	0.8 ± 0.9	4.7 ± 0.1



Fit results

- $M = 4219.6 \pm 3.3(stat) \pm 5.1(sys)\ \mathrm{MeV}/c^2$
- $\Gamma = 56.0 \pm 3.6(stat) \pm 6.9(sys)\ \mathrm{MeV}$



arXiv: 1703.10351, PRD95, 092007 (2017)

Fit results

	$Y(4008)$	$Y(4220)$	$Y(4320)$	$Y(4390)$
M	3846.3 ± 45.5	4219.6 ± 3.3	4333.2 ± 19.9	4391.5 ± 6.3
Γ	345.6 ± 58.2	56.0 ± 3.6	104.3 ± 44.9	153.2 ± 11.4

	Solution I	Solution II	Solution III	Solution IV
$(\mathcal{B}_{\omega\chi_{c0}} \times \Gamma_{e^+e^-})_{Y(4220)}$	3.4 ± 0.4			
$(\mathcal{B}_{\pi^+\pi^-h_c} \times \Gamma_{e^+e^-})_{Y(4220)}$	4.0 ± 1.1	4.0 ± 1.1		
$(\mathcal{B}_{\pi^+\pi^-h_c} \times \Gamma_{e^+e^-})_{Y(4390)}$	11.7 ± 2.4	11.7 ± 2.5		
ϕ_1	3.1 ± 0.4	-3.2 ± 0.4		
$(\mathcal{B}_{\pi^+\pi^-J/\psi} \times \Gamma_{e^+e^-})_{Y(4008)}$	5.5 ± 0.3	6.6 ± 0.7	6.9 ± 0.7	8.3 ± 0.7
$(\mathcal{B}_{\pi^+\pi^-J/\psi} \times \Gamma_{e^+e^-})_{Y(4220)}$	2.5 ± 0.2	3.5 ± 0.7	10.5 ± 1.1	15.1 ± 1.3
ϕ_2	0.1 ± 0.1	0.8 ± 0.3	-1.8 ± 0.2	-1.0 ± 0.1
$(\mathcal{B}_{\pi^+\pi^-J/\psi} \times \Gamma_{e^+e^-})_{Y(4320)}$	0.7 ± 0.2	13.3 ± 3.8	1.0 ± 0.5	19.4 ± 3.2
ϕ_3	2.2 ± 0.2	-2.0 ± 0.2	1.4 ± 0.6	-2.7 ± 0.1
$(\mathcal{B}_{D^0D^{*-}\pi^+ + c.c.} \times \Gamma_{e^+e^-})_{Y(4220)}$	5.3 ± 0.6	43.3 ± 3.2	6.9 ± 0.8	56.7 ± 4.2
ϕ_4	2.2 ± 0.1	-2.2 ± 0.1	-2.7 ± 0.1	-0.8 ± 0.1
$(\mathcal{B}_{D^0D^{*-}\pi^+ + c.c.} \times \Gamma_{e^+e^-})_{Y(4390)}$	39.7 ± 4.3	61.6 ± 6.6	265.5 ± 16.6	412.0 ± 26.0
ϕ_5	1.9 ± 0.1	1.5 ± 0.2	4.7 ± 0.1	4.2 ± 0.1

arXiv: 1703.10351, PRD95, 092007 (2017)

Exclusive channels

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

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

$D^0D^-\pi^+$
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

Results (II)

Физический институт имени П.Н.Лебедева Российской академии наук ФИАН

	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

Data for XYZ study