Amplitude analysis of heavy meson systems at BESIII

XYZ states – recent progress and future perspectives

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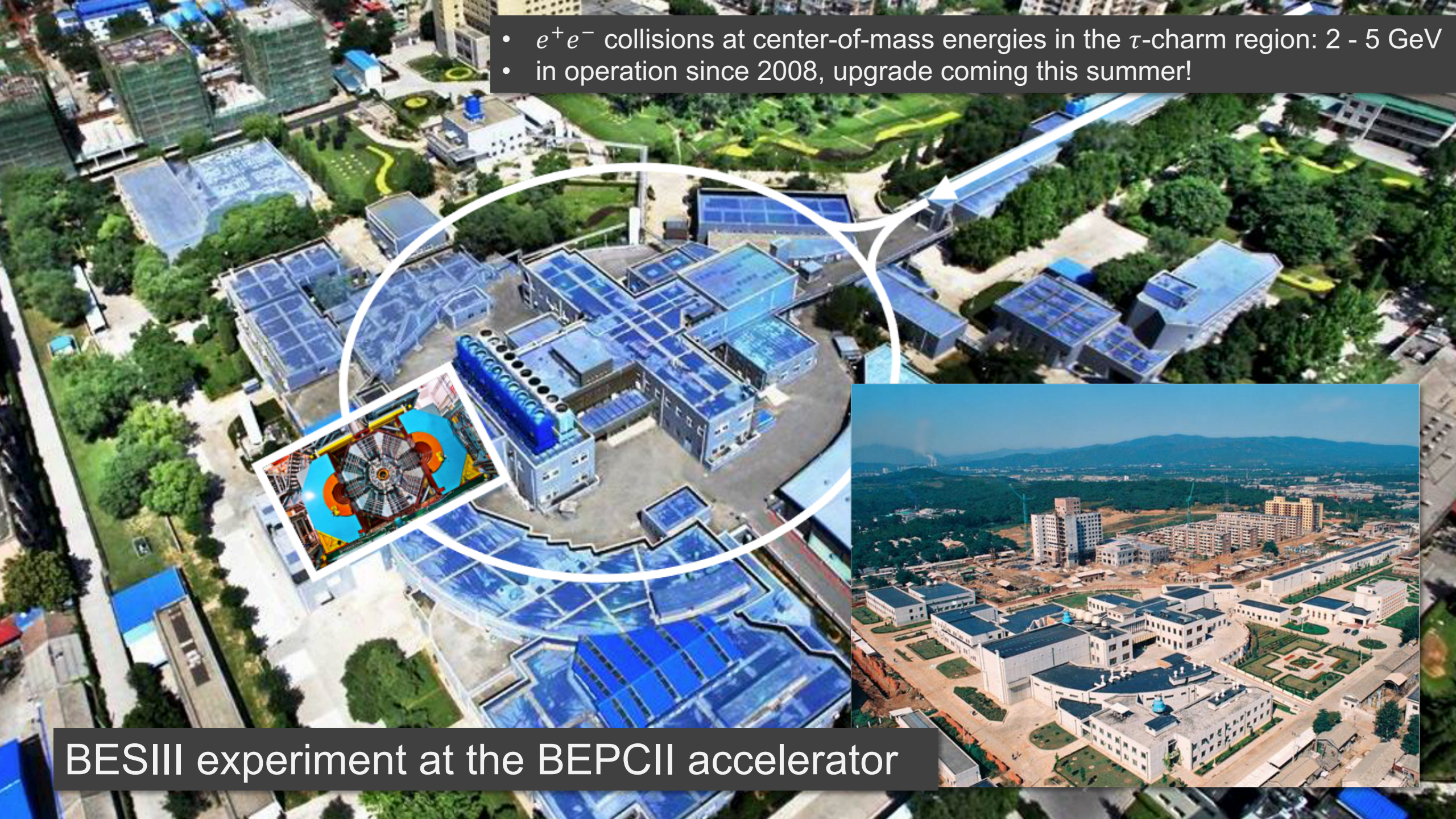
PWA13/ATHOS8
May 31st, 2024

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

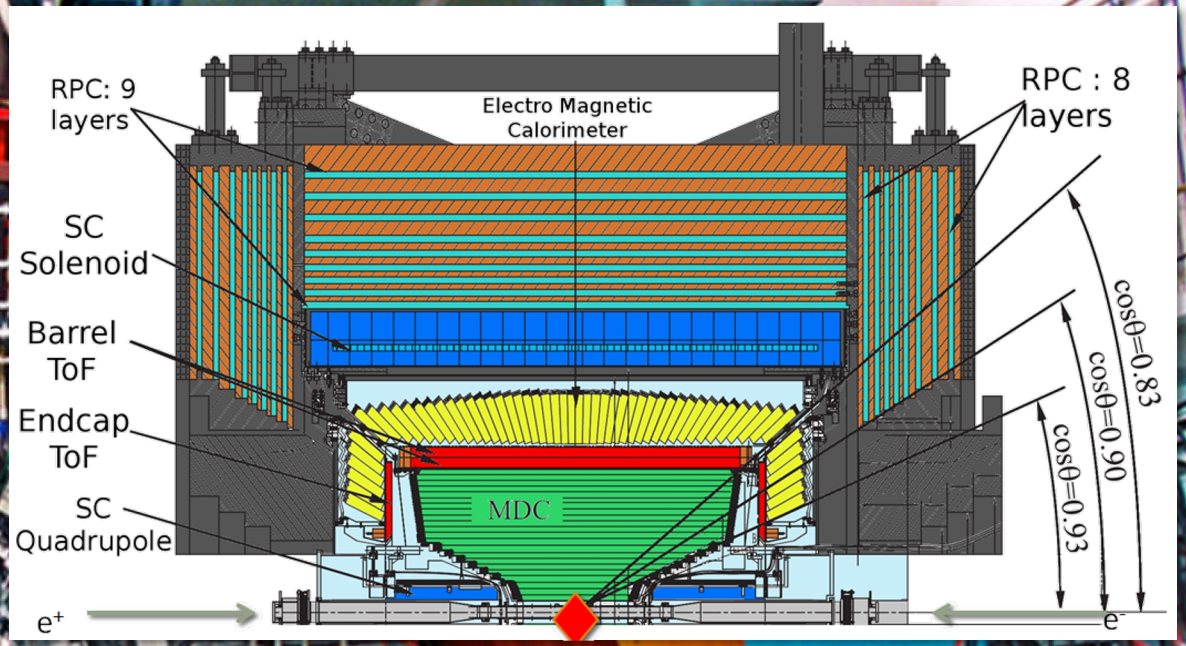
JG|U

- e^+e^- collisions at center-of-mass energies in the τ-charm region: 2 - 5 GeV
- in operation since 2008, upgrade coming this summer!



BESIII experiment at the BEPCII accelerator

The BESIII experiment

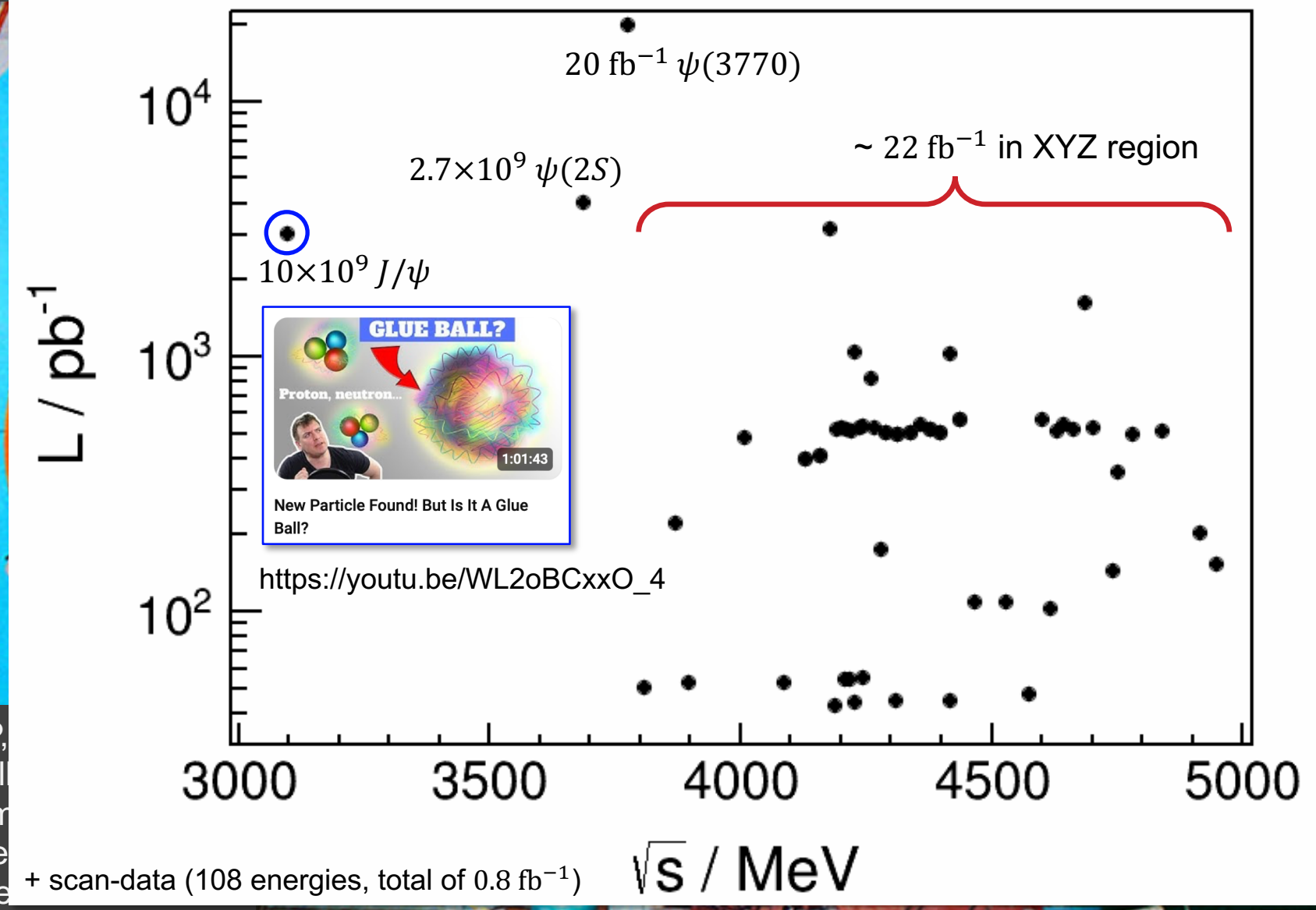


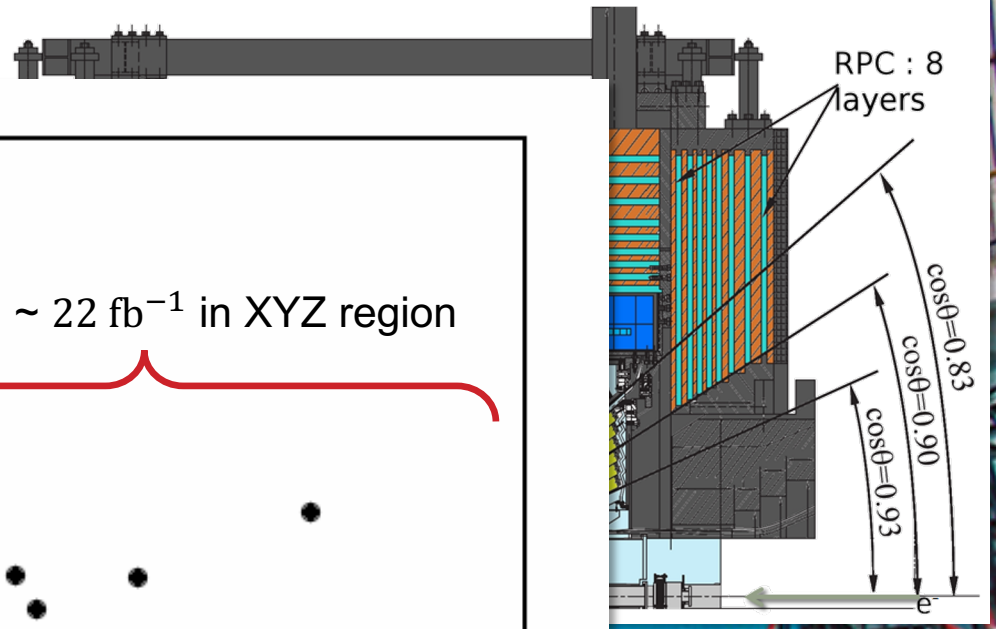
Beijing Spectrometer BESIII:

- drift chamber in 1 T magnetic field
- time-of-flight detector
- electromagnetic calorimeter
- muon counter

- located at IHEP, Beijing
- international collaboration:
  - > 600 members
  - 85 institutes
  - 17 countries

The BESIII experiment





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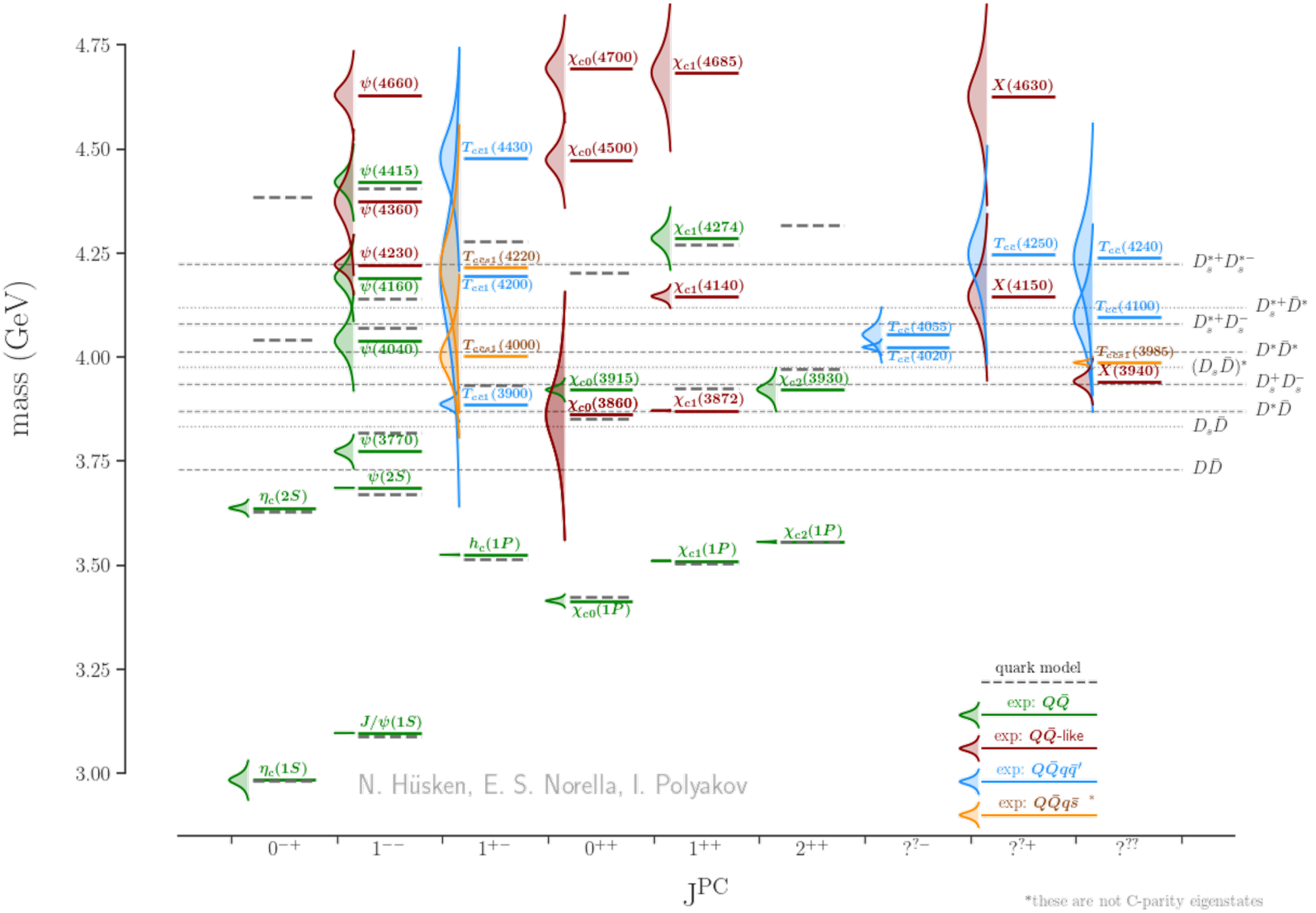
XYZ physics



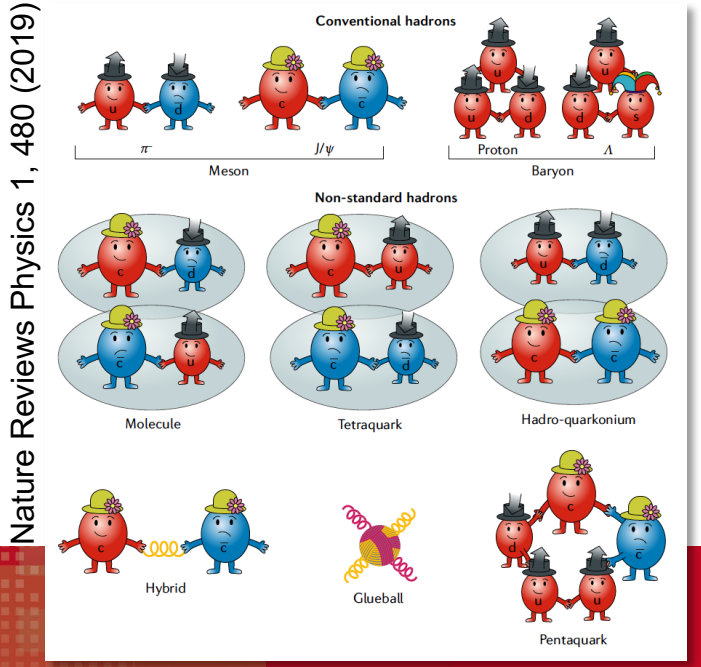
- $c\bar{c}$ spectrum from potential models:

$$V_{q\bar{q}} = -\frac{4}{3}\cdot\frac{\alpha_s(r)}{r} + k\cdot r$$

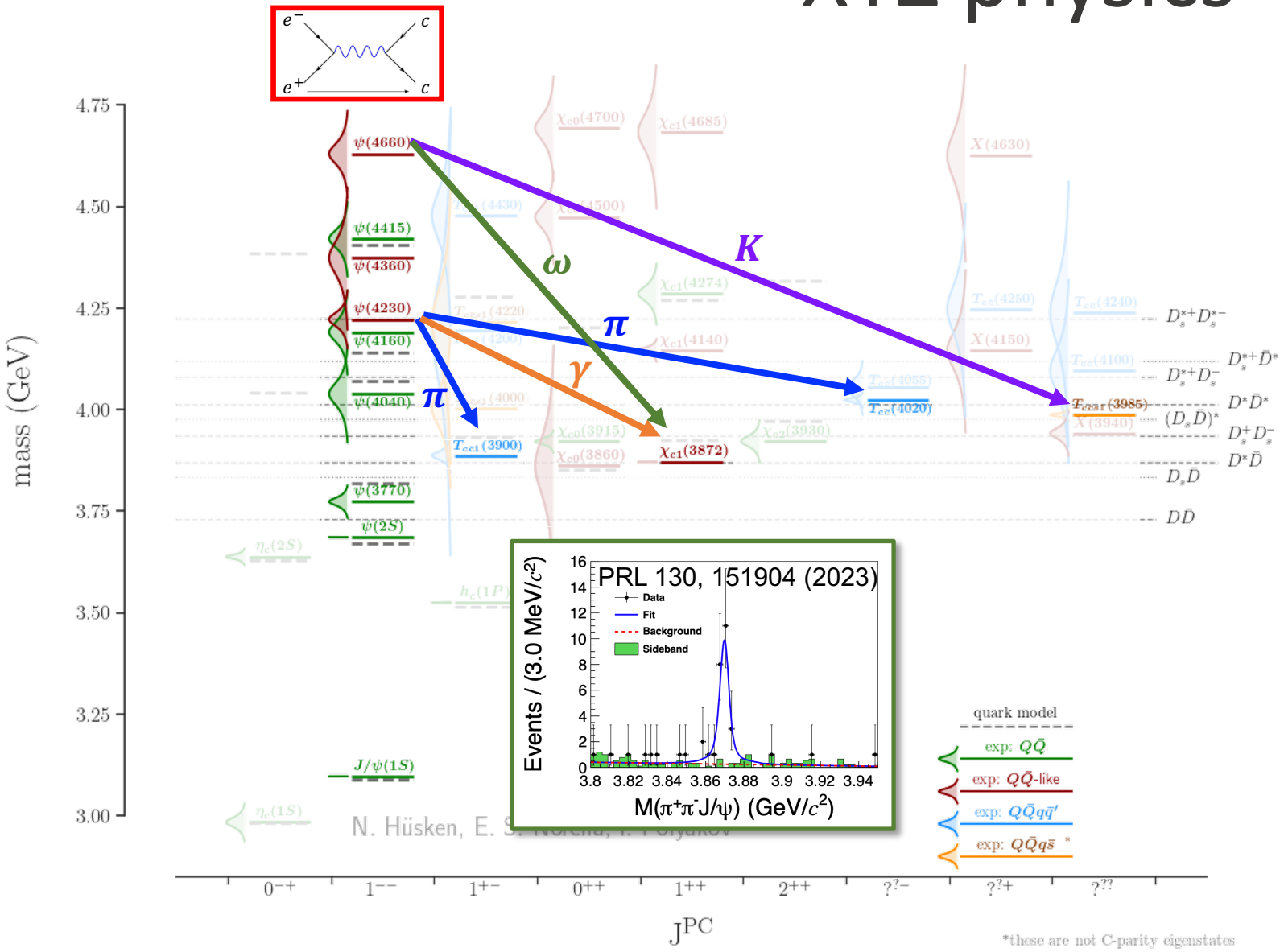
+ spin-dependent terms

see e.g.: Godfrey & Isgur, PRD 32 (1985) 189-231
Barnes, Godfrey, Swanson, PRD 72 (2005) 054026
Godfrey & Moates, PRD 92 (2015) 054034

- good agreement with experiments
- many additional states seen in experiments like BaBar, Belle, BESIII, LHCb, …



XYZ physics



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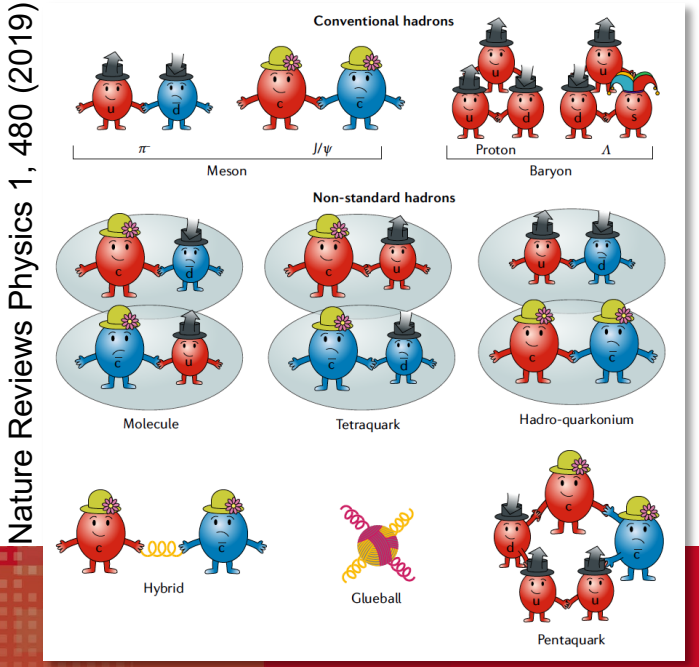
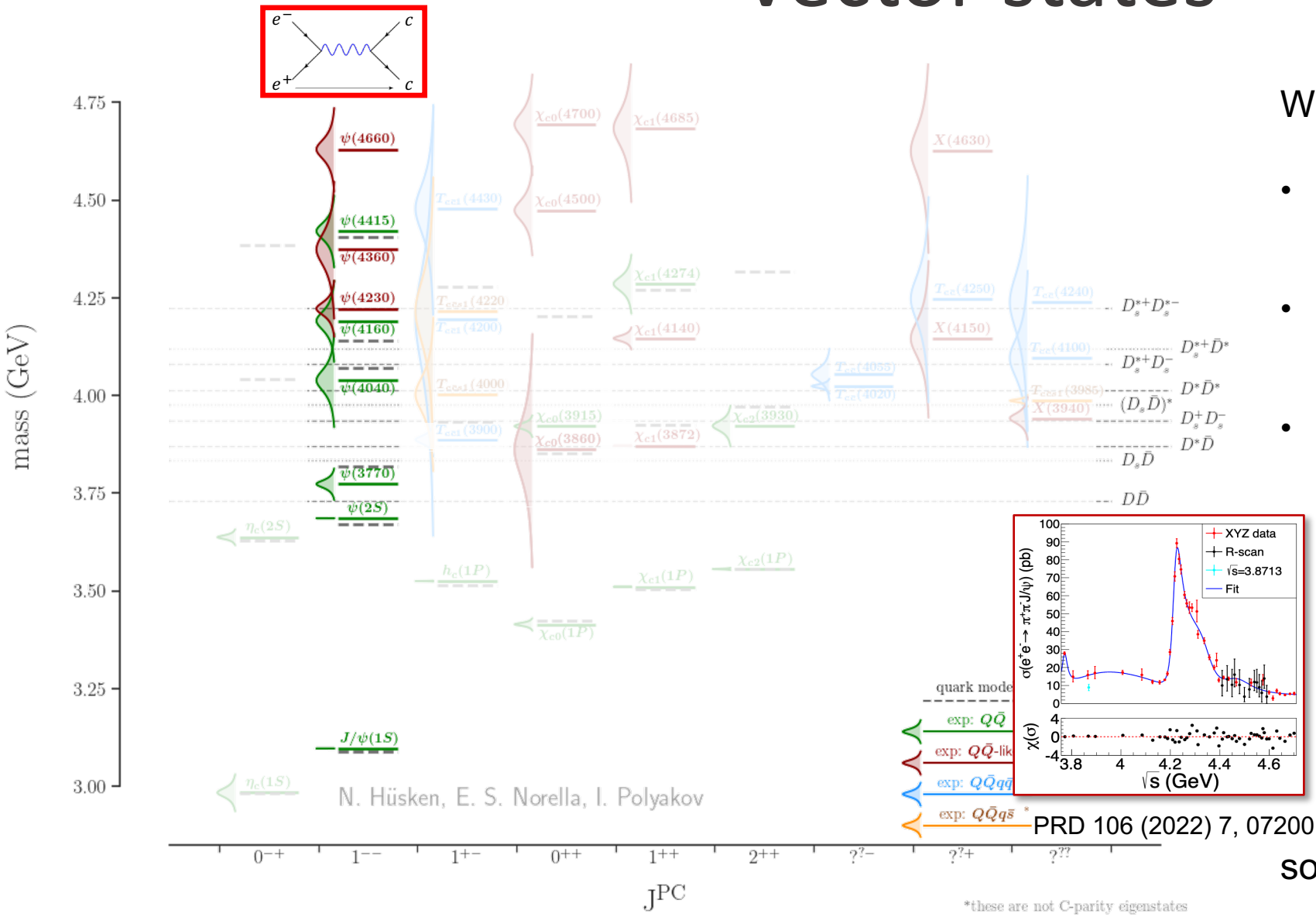


Vector states

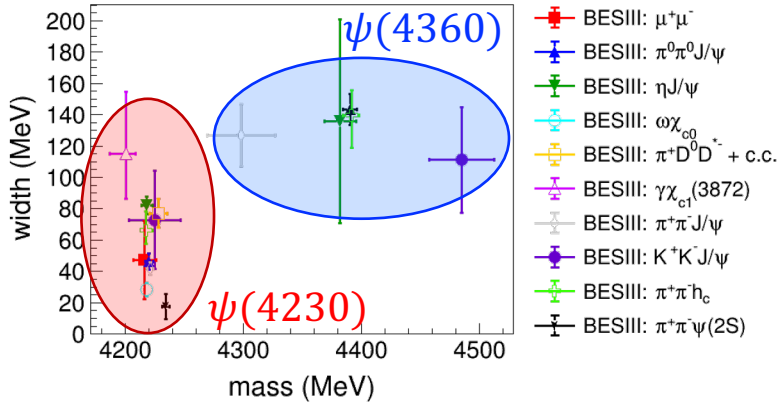
Vector states



PRD 106 (2022) 7, 072001

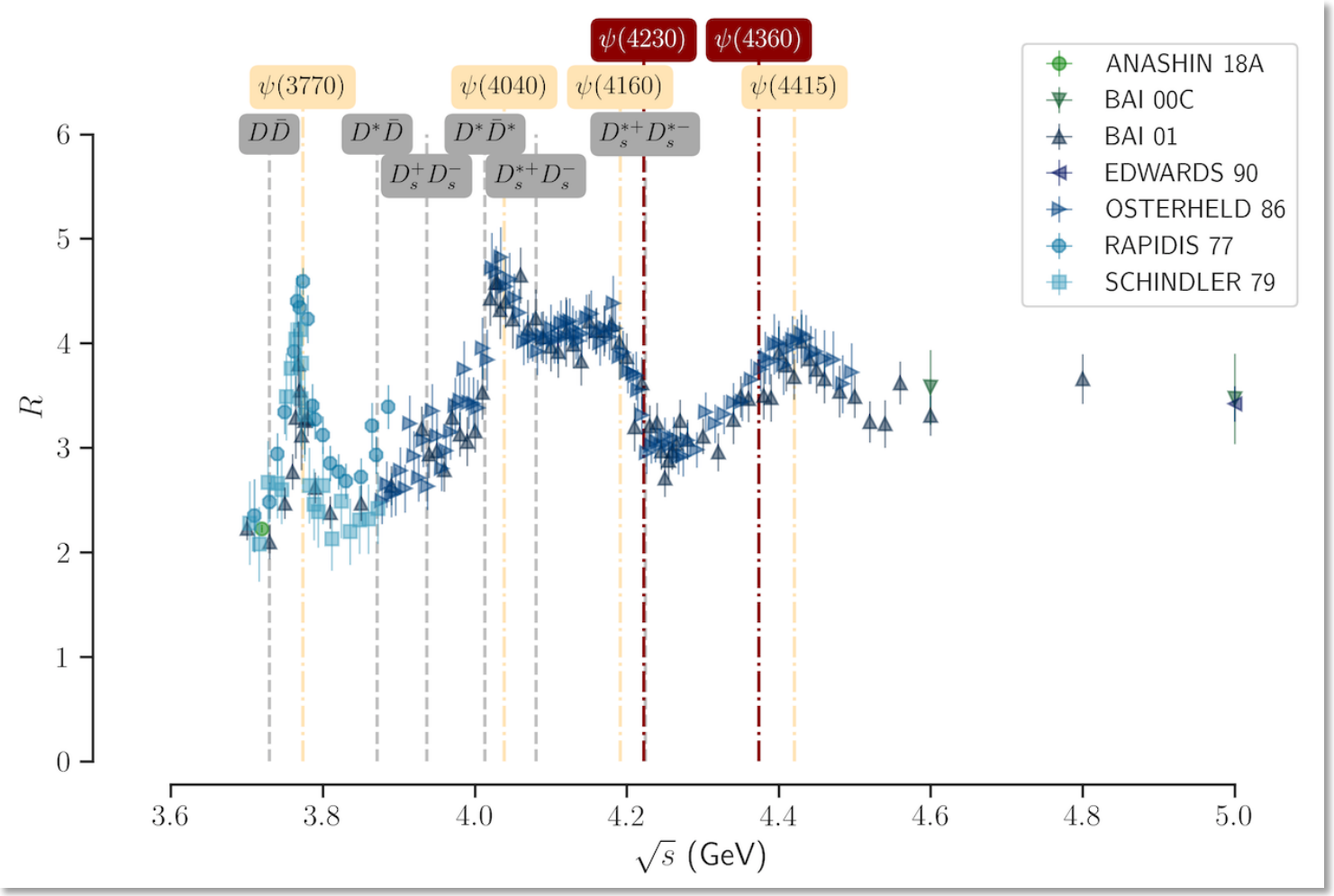
What is the situation?

- predicted states between 3.7 and 4.6 GeV: $\psi(1D)$, $\psi(3S)$, $\psi(2D)$ and $\psi(4S)$
- commonly identified as $\psi(3770)$, $\psi(4040)$, $\psi(4160)$ and $\psi(4415)$
- at least three additional peaks observed: $\psi(4230)$, $\psi(4360)$ and $\psi(4660)$



so, what is going on?

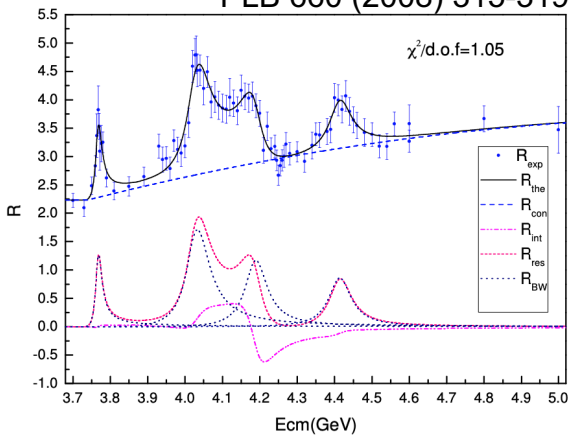
Vector states



Conventional vector charmonia (?)

- information almost exclusively from $e^+e^- \to \text{hadrons}$

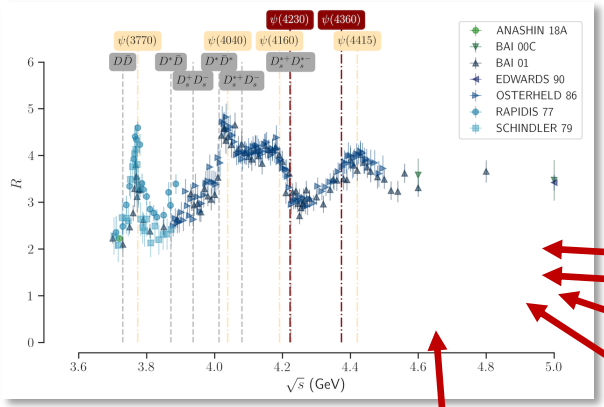
PLB 660 (2008) 315-319

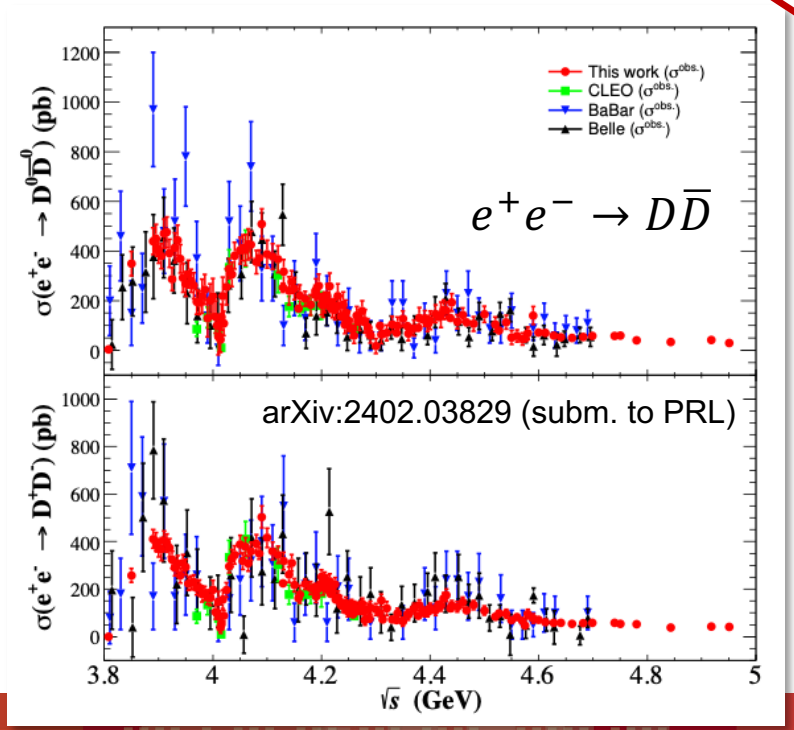


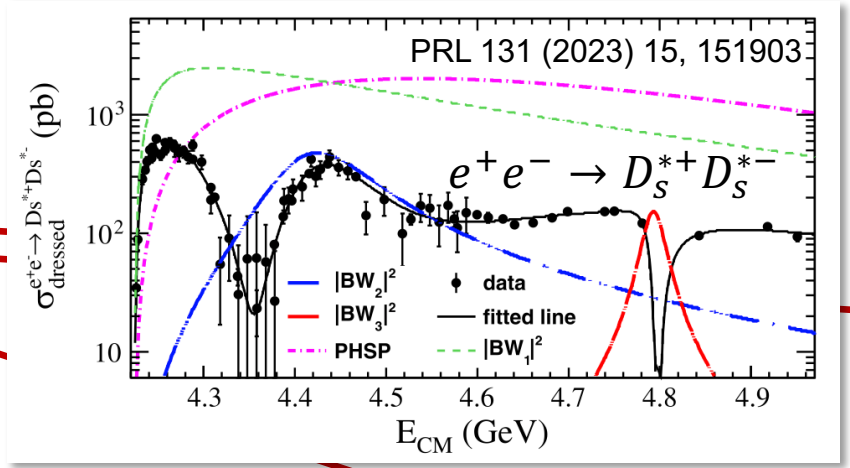
- but: this is a sum of highly non-trivial exclusive processes

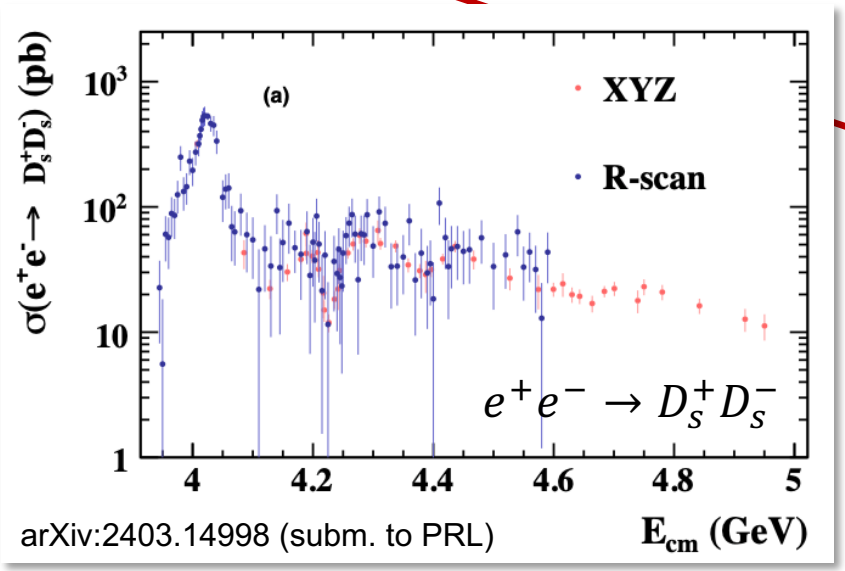
- should we really interpret the inclusive cross section like this?

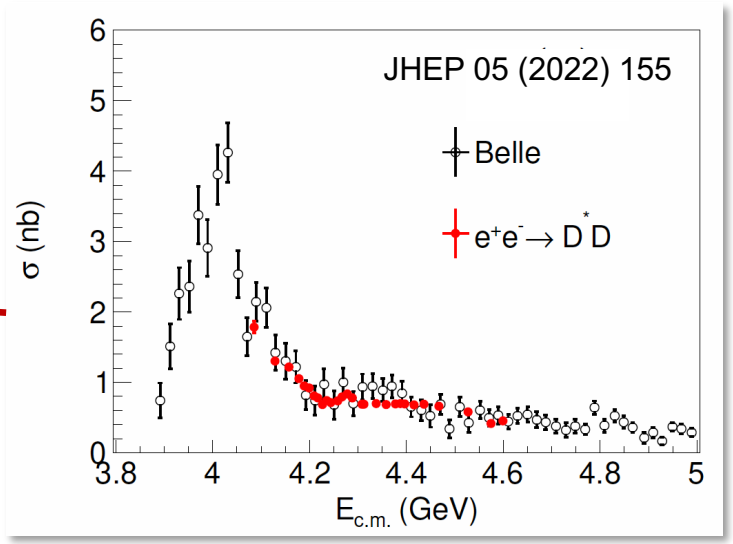
Vector states

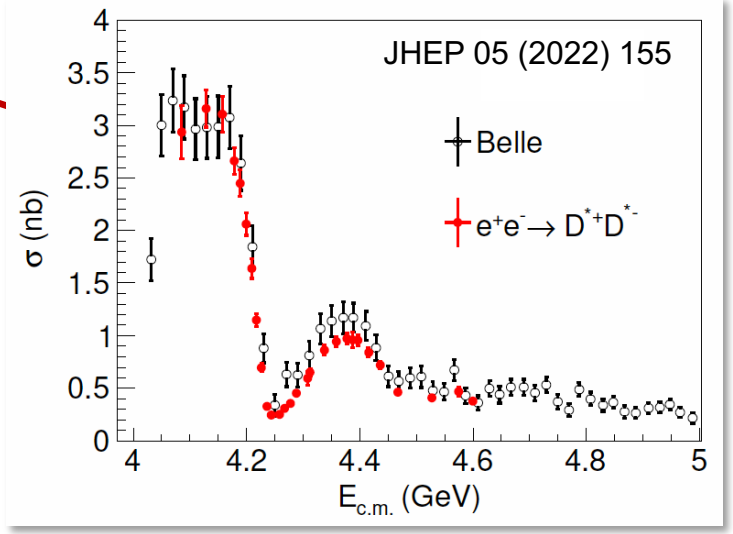




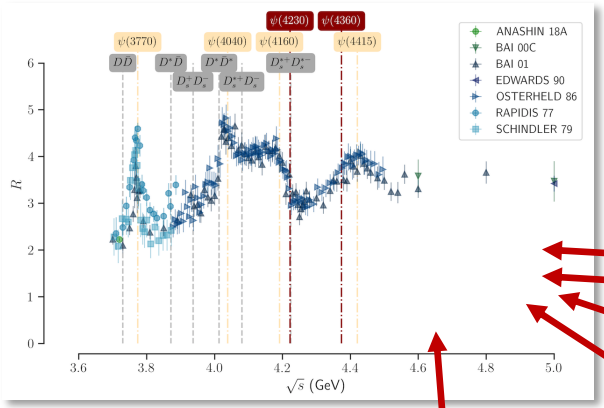


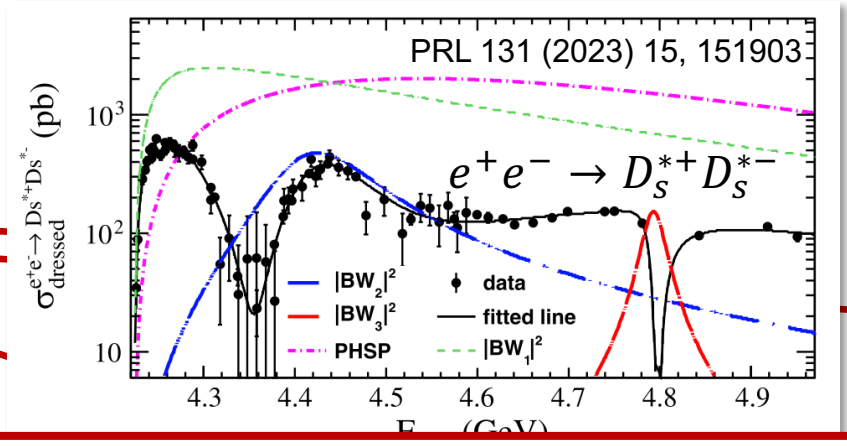


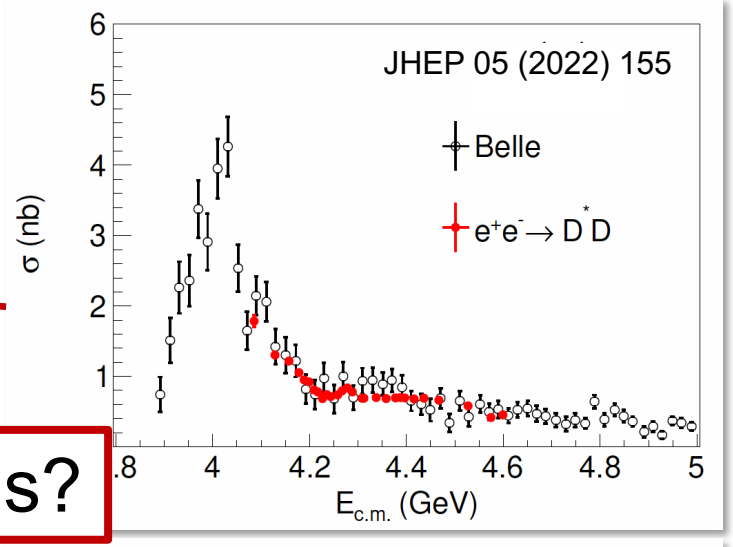




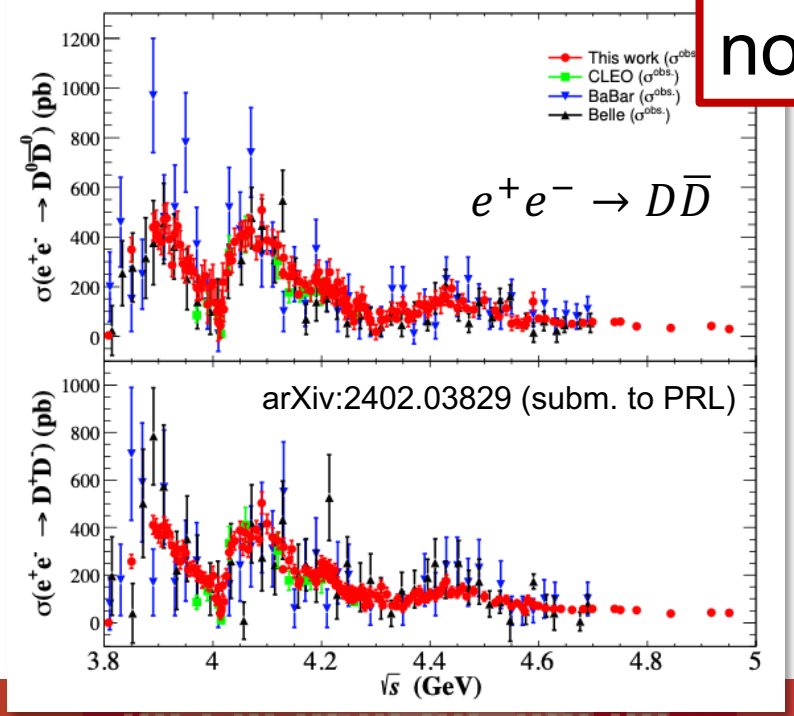
Vector states

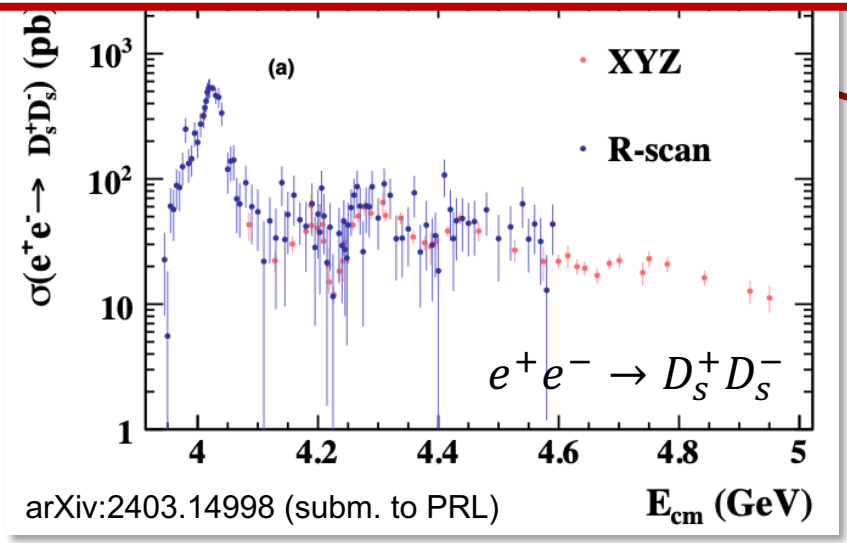


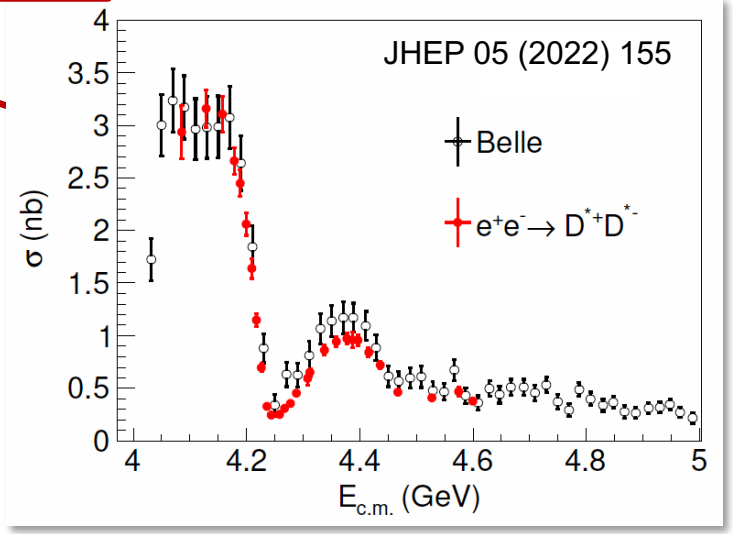




now, how do we interpret all this?

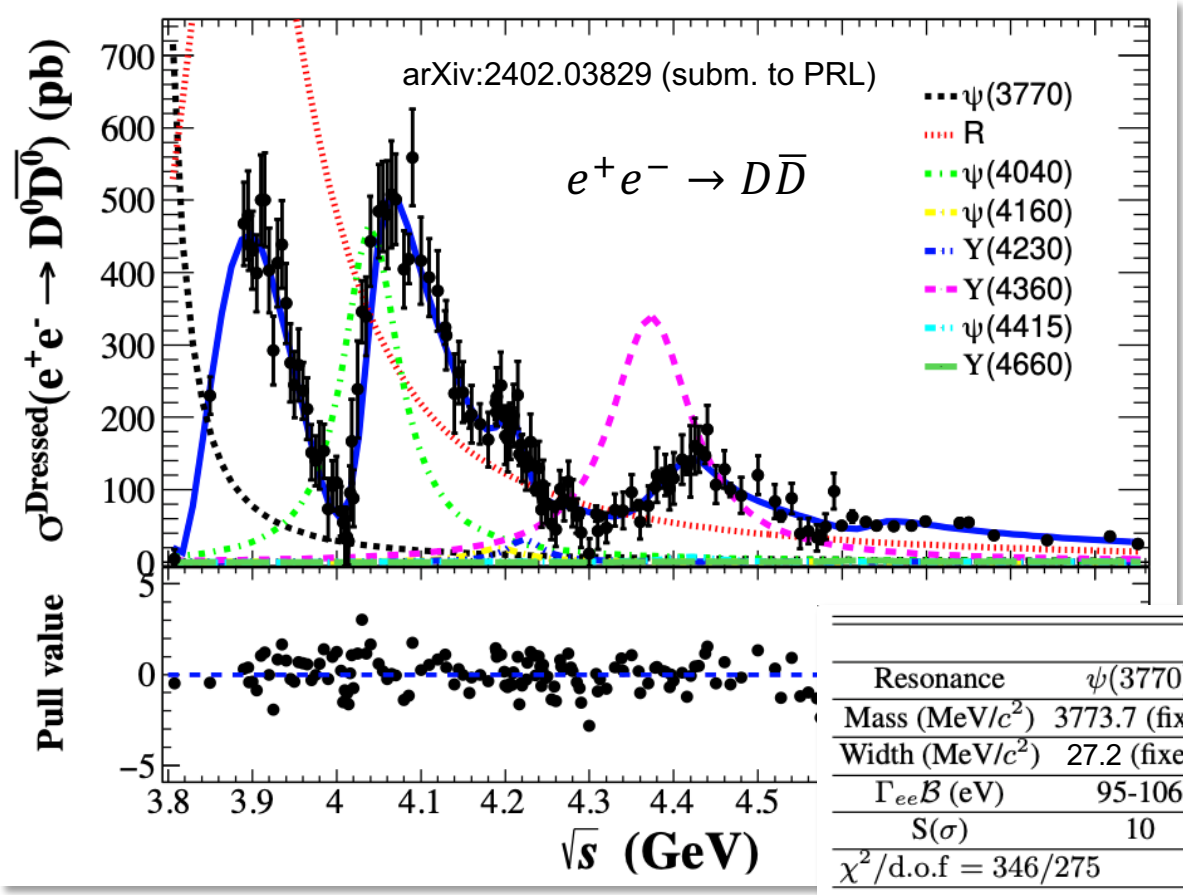






Vector states

(a) using Breit-Wigner amplitudes fitted to single channels



hard to interpret:

- large interference terms
- multi-solution problem: 128 ambiguous solutions

but what is this?

- a new $D^*\bar{D}$ P-wave resonance?
  Z.-Y. Lin et al., arXiv:2403.01727
- something else?

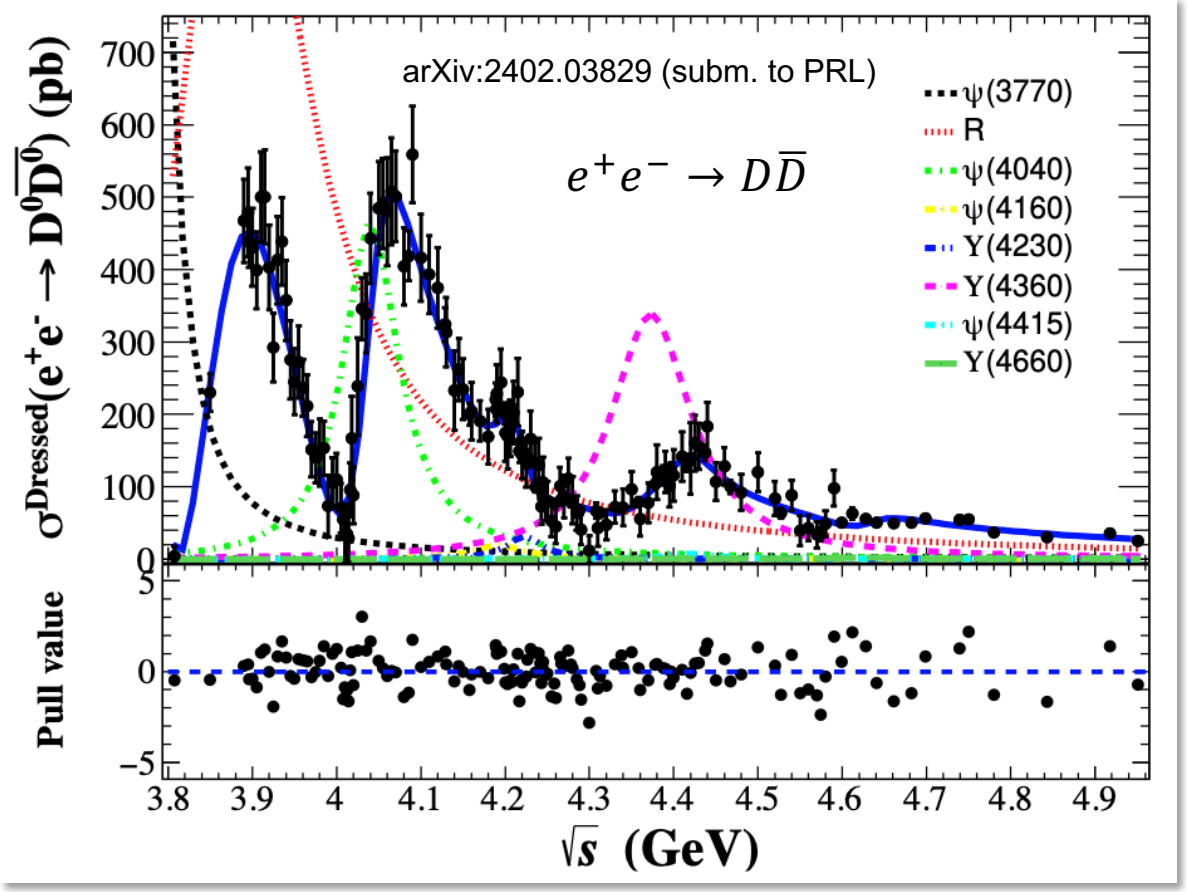
$e^+e^- \to D\bar{D}$								
Resonance	$\psi(3770)$	R	$\psi(4040)$	$\psi(4160)$	$Y(4230)$	$Y(4360)$	$\psi(4415)$	$Y(4660)$
Mass (MeV/c^2)	3773.7 (fixed)	3872.5±14.2±3.0	4039 (fixed)	4191 (fixed)	4222.5 (fixed)	4374 (fixed)	4421 (fixed)	4630 (fixed)
Width (MeV/c^2)	27.2 (fixed)	179.7±14.1±7.0	80 (fixed)	70 (fixed)	48 (fixed)	118 (fixed)	62 (fixed)	72 (fixed)
$\Gamma_{ee}\mathcal{B}$ (eV)	95-106	202-292	41-44	1-2	1-2	50-144	0-2	0-1
S(σ)	10	> 20	13	7	11	11	4	8
χ^2/d.o.f = 346/275				p-value = 0.002				

(should only do this for narrow, isolated resonances)

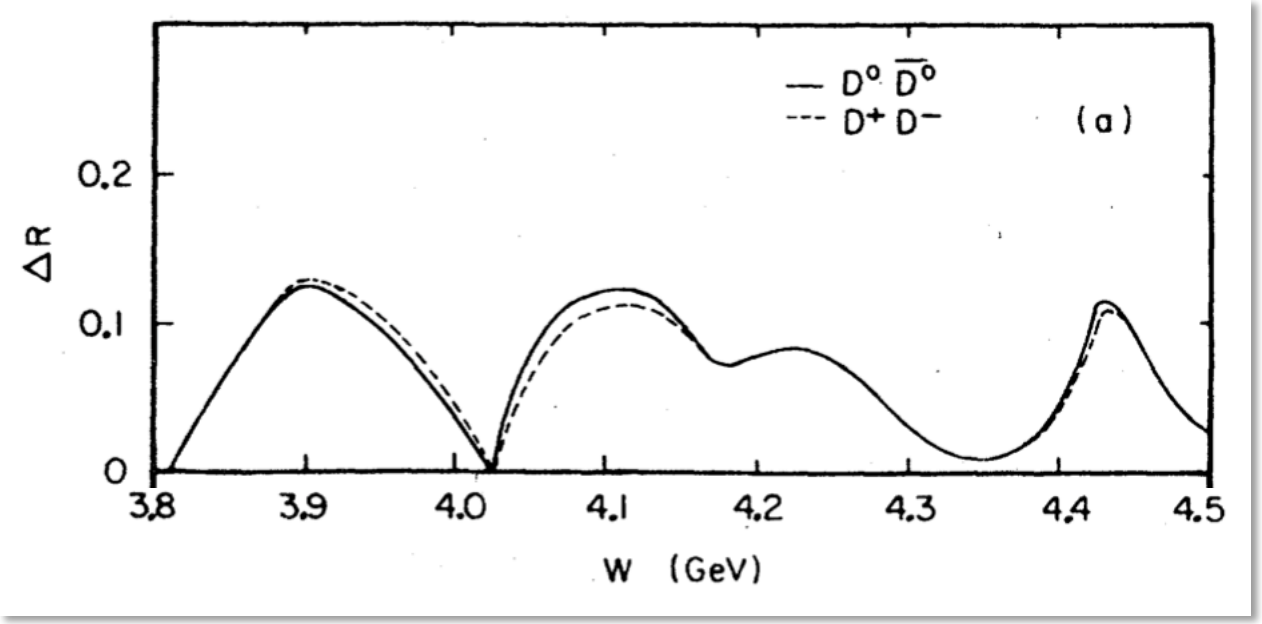
that would be important to know…

Vector states

(b) using coupled channel models



Eichten et al., Phys. Rev. D 21 (1980) 203

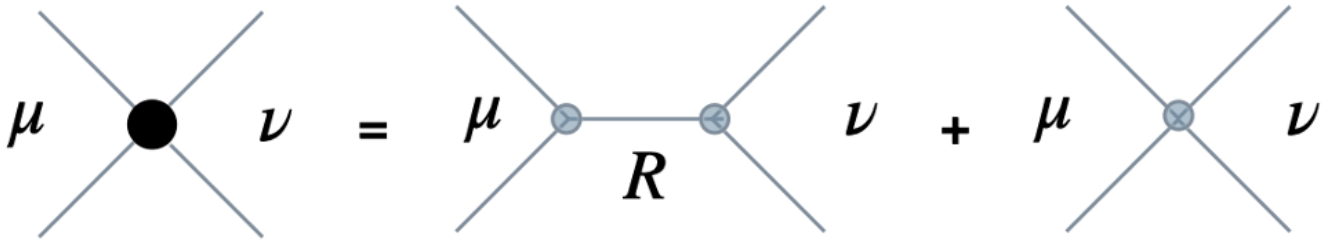


In our calculation there is some weak structure in the 3.9–4.0 GeV region. It does not arise from a $c\bar{c}$ resonance, but from the opening of the $D\bar{D}^* + D^*\bar{D}$ channel and a decrease in the $D\bar{D}$ channel due to a nearby zero in the $3S$ decay amplitude.

Vector states

- if peak near 3.9 GeV is indeed (primarily) from $D^*\overline{D} \leftrightarrow D\overline{D}$ rescattering, a simple K-matrix model should confirm that!

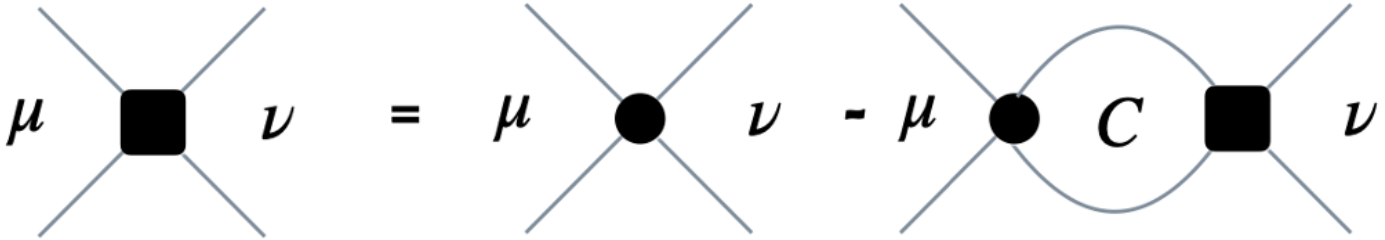
$$K_{\mu\nu} = \sum_R \frac{g_{\mu,R}(s) \cdot g_{\nu,R}(s)}{m_R - s} + b_{\mu\nu}(s)$$



Aitchison's P-vector approach:

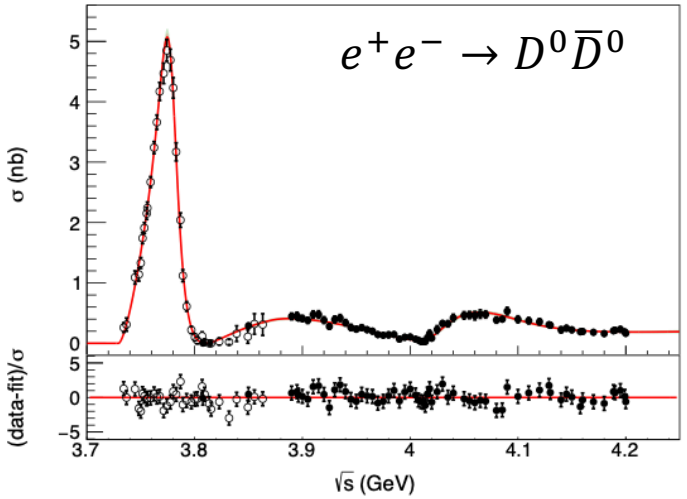
$$M_{\mu,e^+e^-} = \sum_\nu \left(1 + \hat{K}\hat{C}\right)^{-1}_{\mu\nu} P_\nu$$

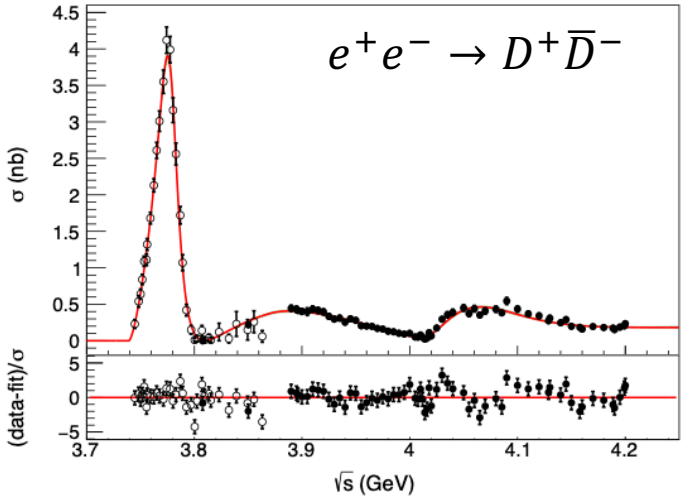
$$P_\nu = K_{\nu,e^+e^-}$$

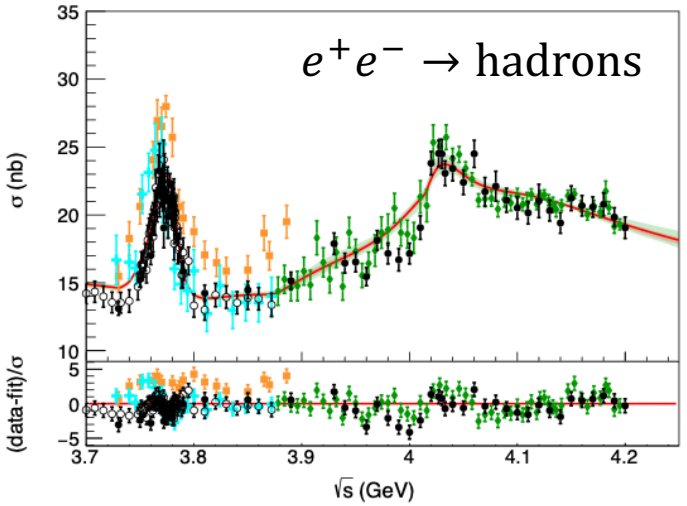


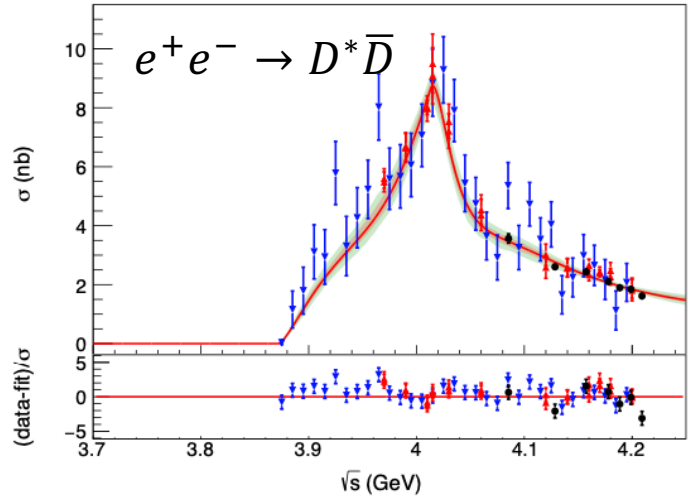
NH, R. Lebed, R. Mitchell, E. Swanson, Y.Q. Wang, C.Z. Yuan, arXiv:2404.03896

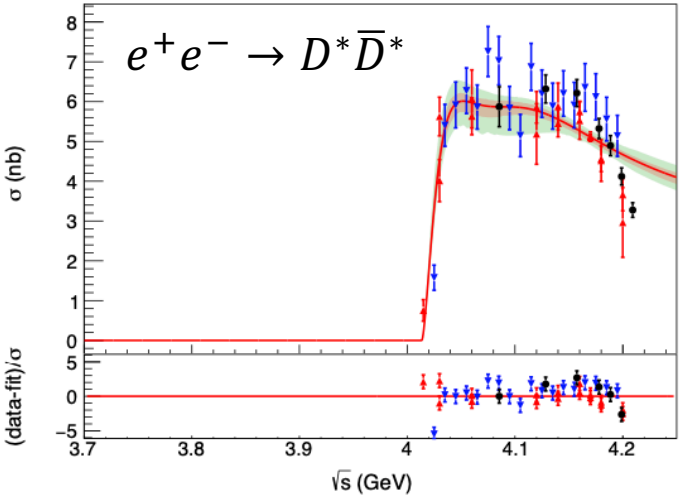
Vector states











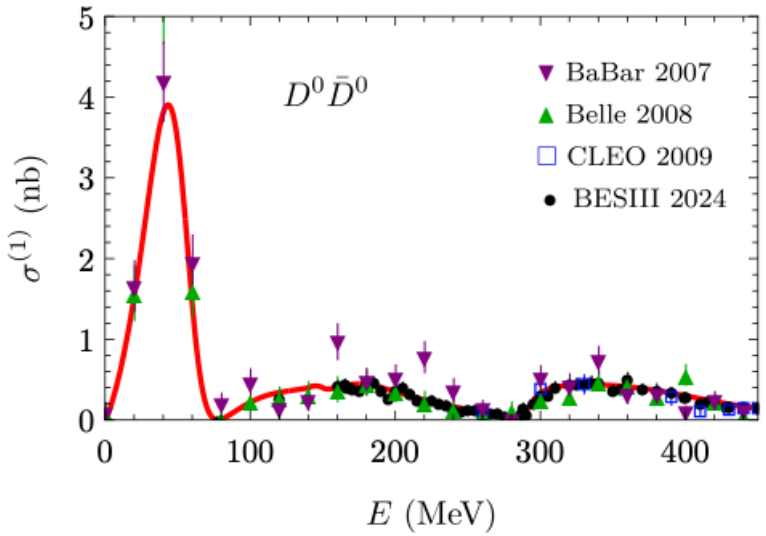
- good fit to $e^+e^- \to D^{(*)}\overline{D}^{(*)}$ data up to 4.2 GeV using two bare poles $\psi(3770)$, $\psi(4040)$
- indeed describe peak near 3.9 GeV without the need for additional pole
- however, no predictive power > 4.2 GeV

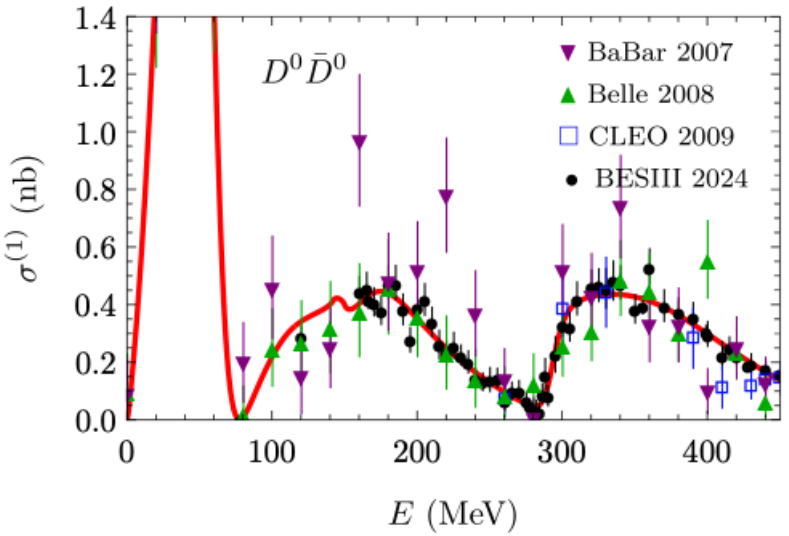
NH, R. Lebed, R. Mitchell, E. Swanson, Y.Q. Wang, C.Z. Yuan, arXiv:2404.03896

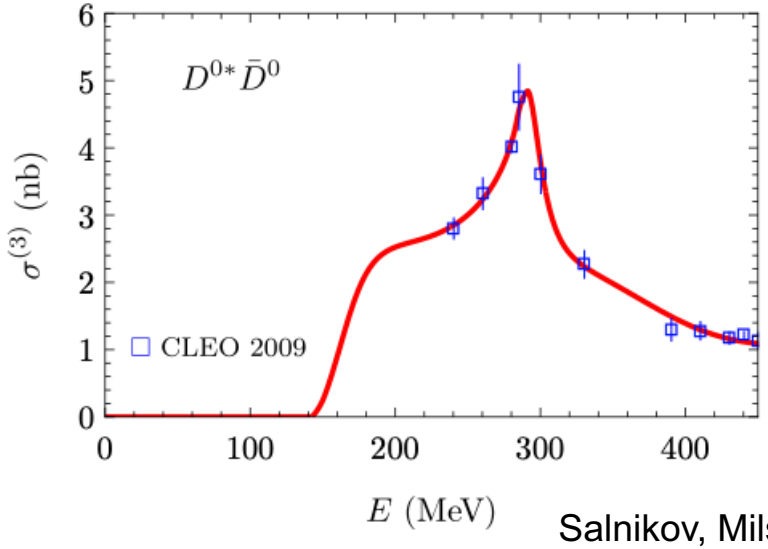
Data from:
BESIII (unoff.) Andy Julin, University of Minnesota
BESIII: arXiv:2402.03829
BESIII: JHEP 05 (2022) 155
Belle: Phys.Rev.D 97 (2018) 1, 012002
CLEO: Phys.Rev.D 80 (2009) 072001
BES: PRL 88, 101802 (2002)
BESII: PRL 97, 262001 (2006)
SPEAR: PRL 39, 526 (1977); A. Osterheld et al. 86; Schindler 79

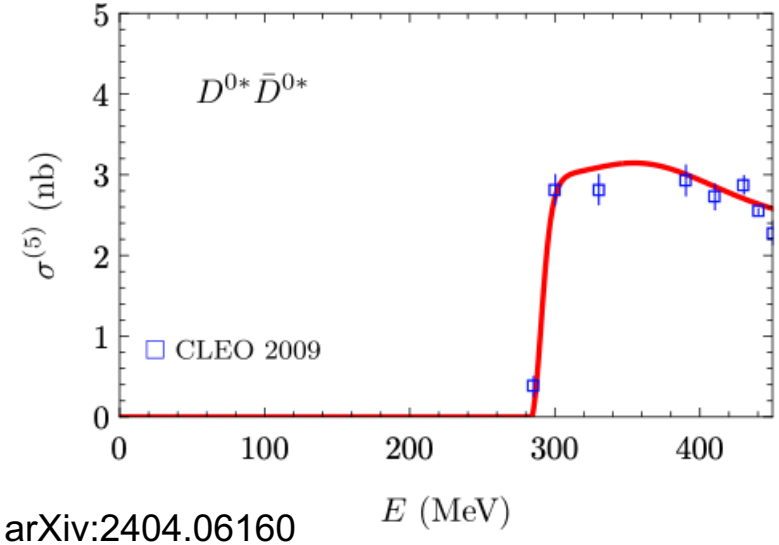
Vector states

different coupled channel model, same result: no pole near 3.9 GeV

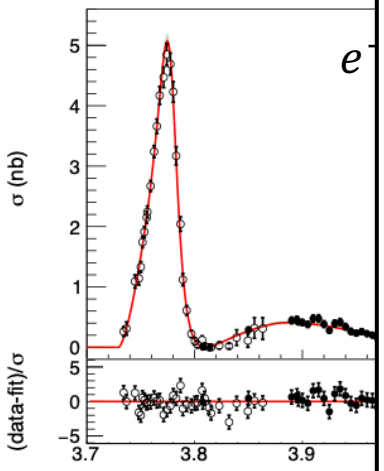


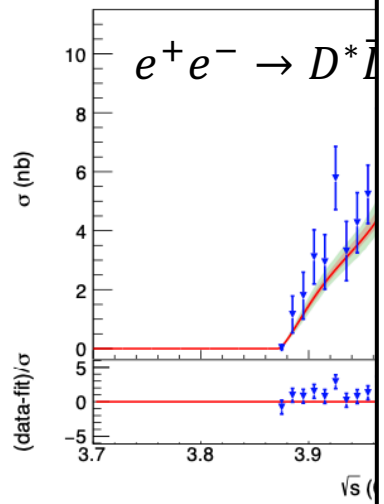






Salnikov, Milstein, arXiv:2404.06160





up to 4.2 GeV
(4040)

eV without the

4.2 GeV

NH, R. Lebed, R. Mitche

Data from:
BESIII (unoff.) Andy
BESIII: arXiv:2402.05829

CLEO: Phys.Rev.D 80 (2009) 072001

SPEAR: PRL 39, 526 (1977); A. Osterheld et al. 86; Schindler 79

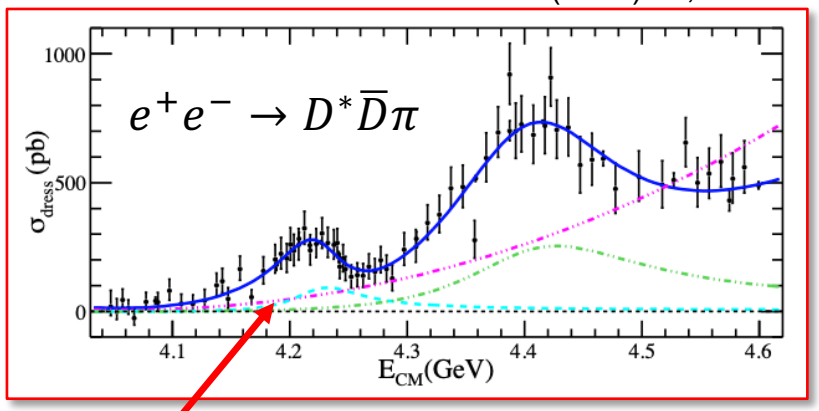
Vector states

Next: extend to higher energies – but challenges await!

- quark model: expect at least two additional bare states
- more open channels:
  - $D\bar{D}$
  - $D^*\bar{D}$, $D\bar{D}\pi$
  - $D_s^+D_s^-$
  - $D^*\bar{D}^*$, $D^*\bar{D}\pi$
  - $D_s^{*+}D_s^-$
  - $D^*\bar{D}^*\pi$
  - $D_s^{*+}D_s^{*-}$
  - $D_1\bar{D}$
  - ...
- more interesting physics:
  - how many states?
  - electronic couplings, hadronic couplings

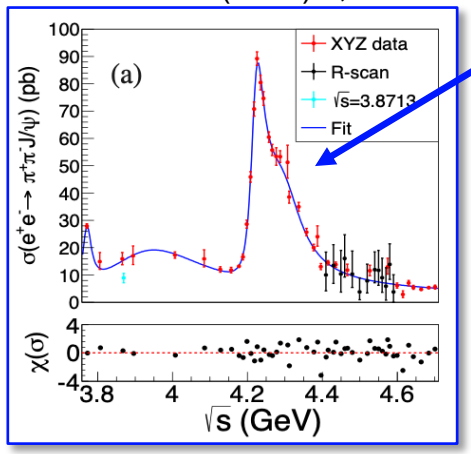
how to incorporate 3-body channels?
→ fairly large cross sections
→ sub-processes contribute to different channels

PRL 122 (2019) 10, 102002

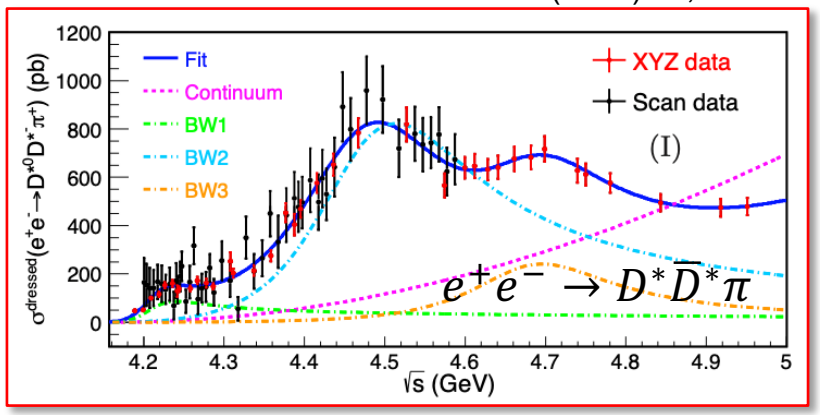


$e^+e^- \to Z_c\pi$

PRD 106 (2022) 7, 072001



PRL 130 (2023) 12, 121901



→ ongoing, direct collaboration: BESIII, E. Swanson, S. Dawid

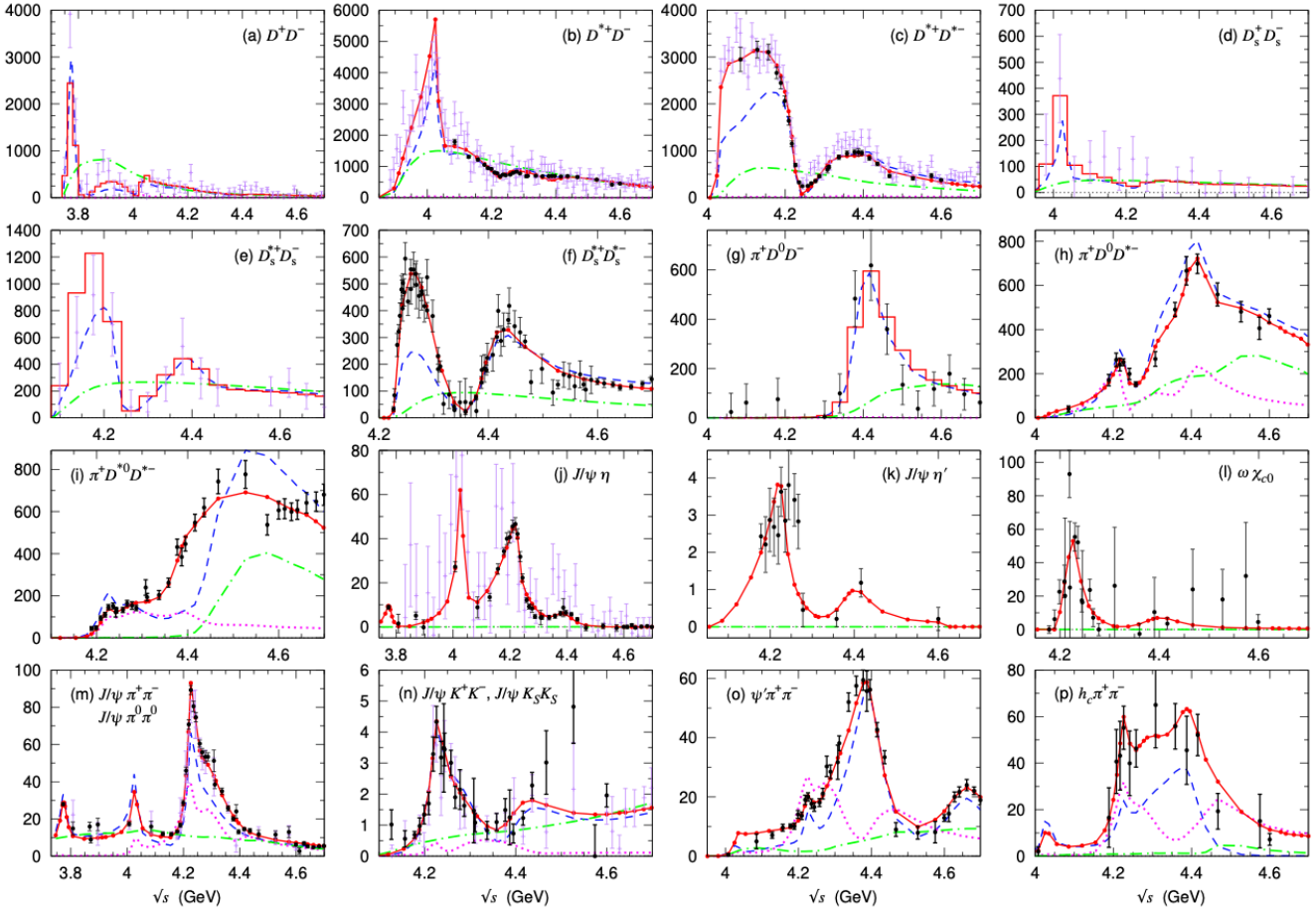
Vector states

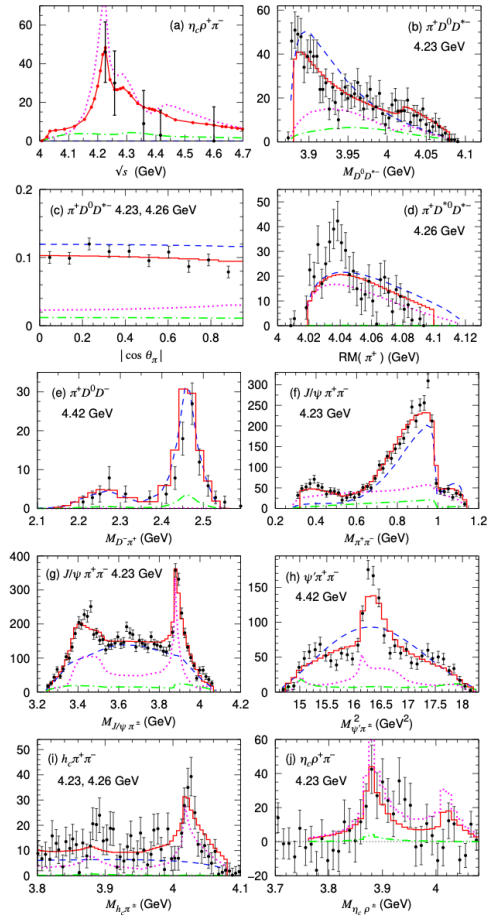
a first attempt was made!

Global coupled-channel analysis of $e^+e^- \to c\bar{c}$ processes in $\sqrt{s} = 3.75 - 4.7$ GeV

S.X. Nakamura,[1,2,3,*] X.-H. Li,[2,3] H.-P. Peng,[2,3] Z.-T. Sun,[1] and X.-R. Zhou[2,3]

arXiv:2312.17658



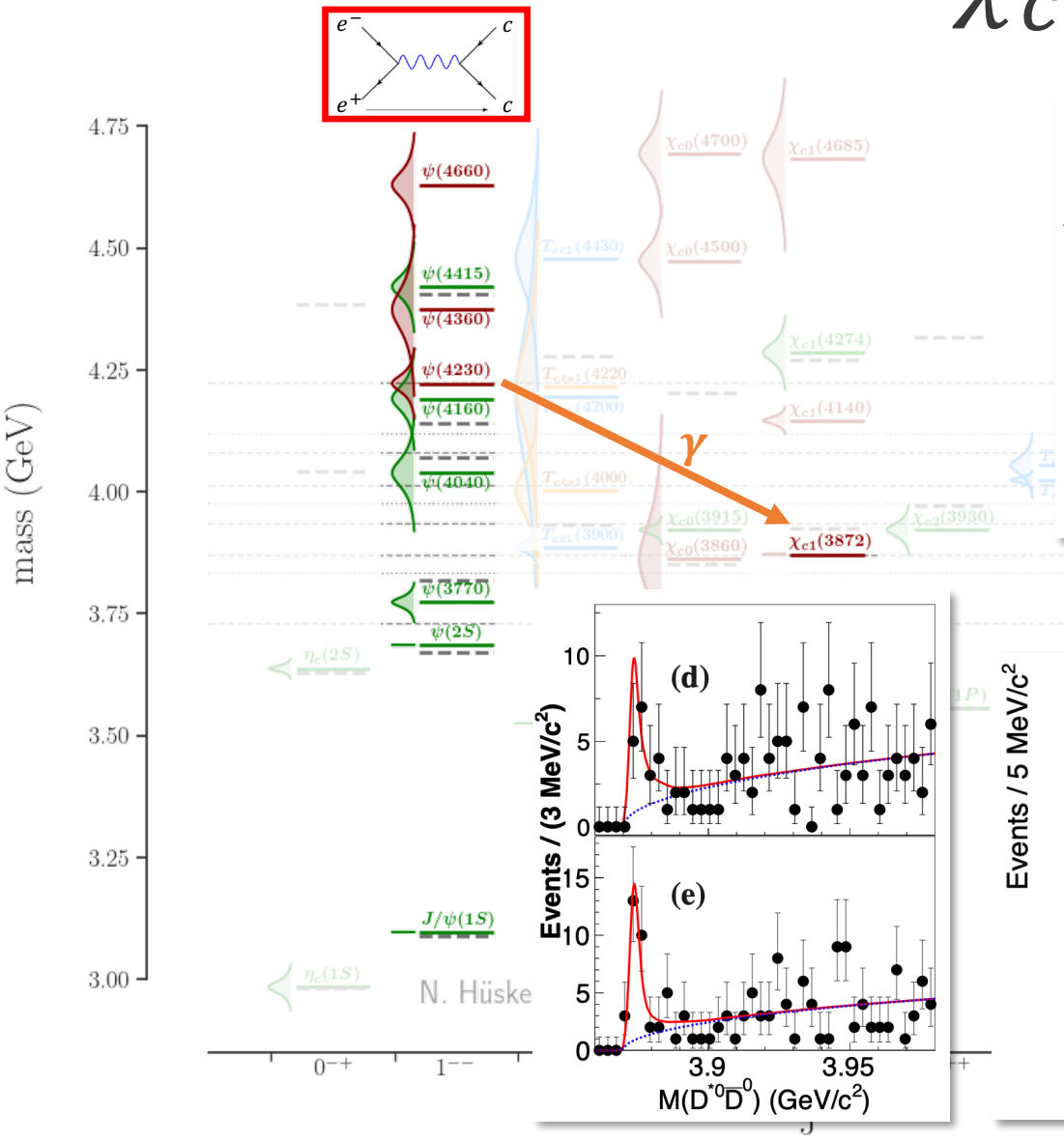


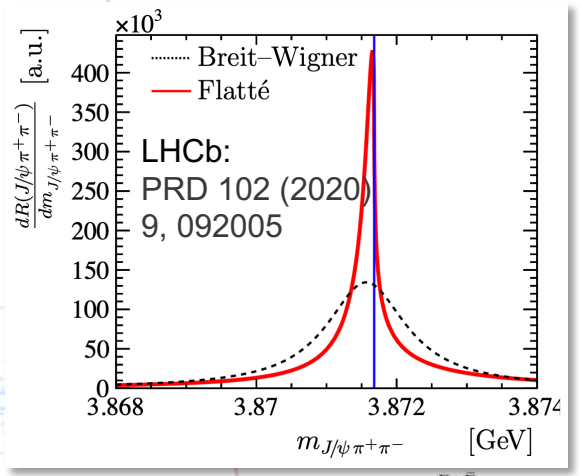
This work		PDG [4]		
M (MeV)	Γ (MeV)	M (MeV)	Γ (MeV)	
3775 ± 2.0	28 ± 1.0	3778.1 ± 0.7	27.5 ± 0.9	$\psi(3770)$
4026 ± 0.1	25 ± 0.3	4039 ± 1	80 ± 10	$\psi(4040)$
4232 ± 1.0	114 ± 1.7	4191 ± 5	70 ± 10	$\psi(4160)$
4226 ± 0.4	36 ± 0.8	4222.5 ± 2.4	48 ± 8	$\psi(4230)$
4309 ± 0.6	328 ± 0.9	–	–	–
4369 ± 0.1	183 ± 0.2	4374 ± 7	118 ± 12	$\psi(4360)$
4394 ± 0.7	93 ± 0.9	4421 ± 4	62 ± 20	$\psi(4415)$
4690 ± 7.3	106 ± 8.8	4630 ± 6	72^{+14}_{-12}	$\psi(4660)$

- they find 7 poles (5 bare poles), but no $\psi(4160)$
- peak at 3.9 GeV is non-resonant!

$\chi_{c1}(3872)$

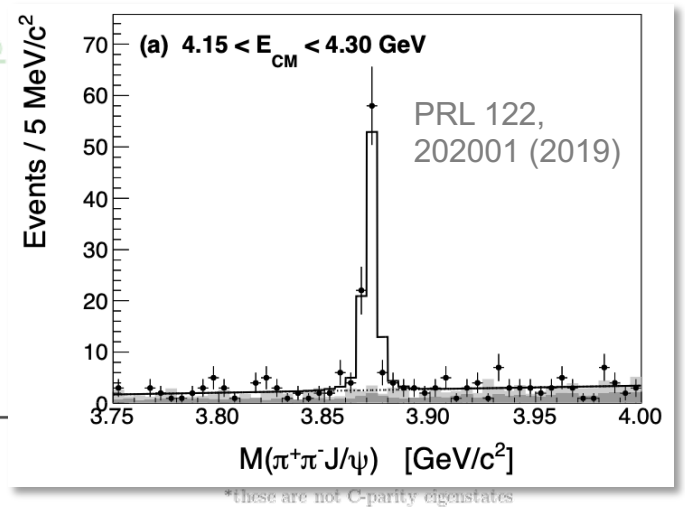
$\chi_{c1}(3872)$

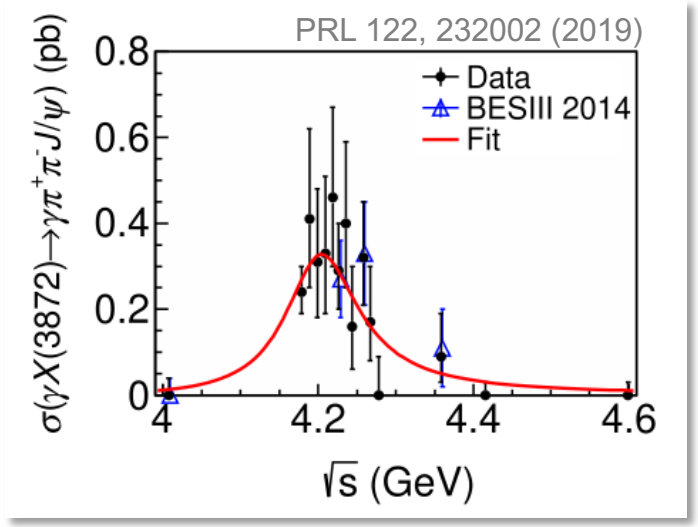




- discovered in 2003
- first width measurement by LHCb
- BESIII: $\psi(4230) \rightarrow \gamma\chi_{c1}(3872)$ production well established

→ contribute to precision studies





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$\chi_{c1}(3872)$

Lineshape studies: based on Hanhart, Kalashnikova, Nefediev, PRD 81, 094028 (2010)

$$\frac{d\mathrm{Br}(D^0\bar{D}^0\pi^0)}{dE} = \mathcal{B}\frac{\mathrm{Br}(D^{*0}\to D^0\pi^0)\times g\times k_{\mathrm{eff}}(E)}{|D(E)|^2}$$

$$\frac{d\mathrm{Br}(\pi^+\pi^- J/\psi)}{dE} = \mathcal{B}\frac{\Gamma_{\pi^+\pi^- J/\psi}}{|D(E)|^2},$$

where

coupling to $D^*\bar{D}$

$$D(E) = E - E_X + \frac{1}{2}g\left[(\kappa_{\mathrm{eff}}(E) + ik_{\mathrm{eff}}(E)) + (\kappa^c_{\mathrm{eff}}(E) + ik^c_{\mathrm{eff}}(E))\right] + \frac{i}{2}\Gamma_0.$$

relative to $D^0\bar{D}^0\pi^0$

(c: charged)

$\Gamma_{\pi^+\pi^- J/\psi} + \Gamma_{\mathrm{known}} + \Gamma_{\mathrm{unknown}}$

- 3 fit parameters: $E_X, g, \Gamma_{\pi^+\pi^- J/\psi}$
- $\Gamma_{\mathrm{known}} = \Gamma_{\gamma J/\psi} + \Gamma_{\gamma\psi(2S)} + \Gamma_{\omega J/\psi} + \Gamma_{\pi^0\chi_{c1}}$ and $\Gamma_{\mathrm{unknown}}$ fixed to global analysis
- resolution (1-2 MeV) taken into account

$$k_{\mathrm{eff}}(E) = \sqrt{\mu_p}\sqrt{\sqrt{(E-E_R)^2 + \Gamma^2_{D^{*0}}/4} + E - E_R},$$

$$\kappa_{\mathrm{eff}}(E) = -\sqrt{\mu_p}\sqrt{\sqrt{(E-E_R)^2 + \Gamma^2_{D^{*0}}/4} - E + E_R} + \sqrt{\mu_p}\sqrt{\sqrt{(E_X-E_R)^2 + \Gamma^2_{D^{*0},\,X}/4} - E_X + E_R}.$$

$\mu_p = \frac{m_{D^*}m_D}{m_{D^*} + m_D}$

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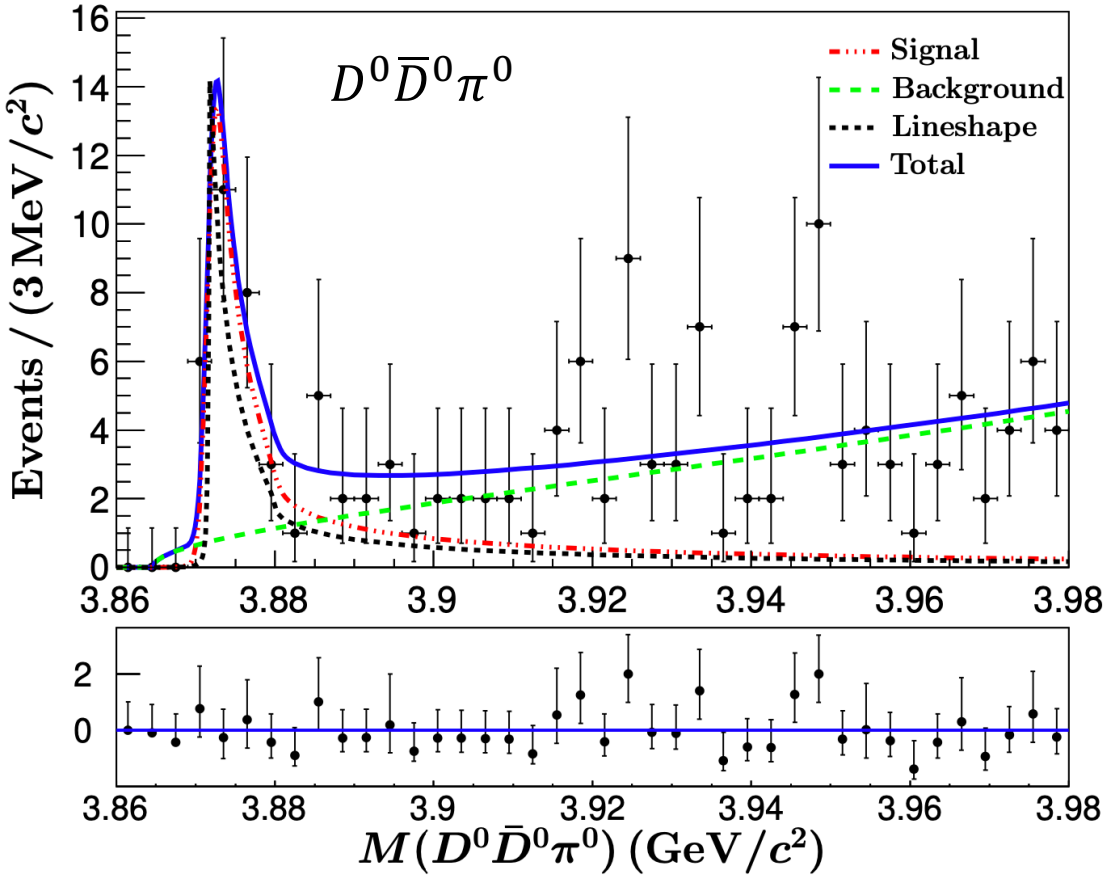
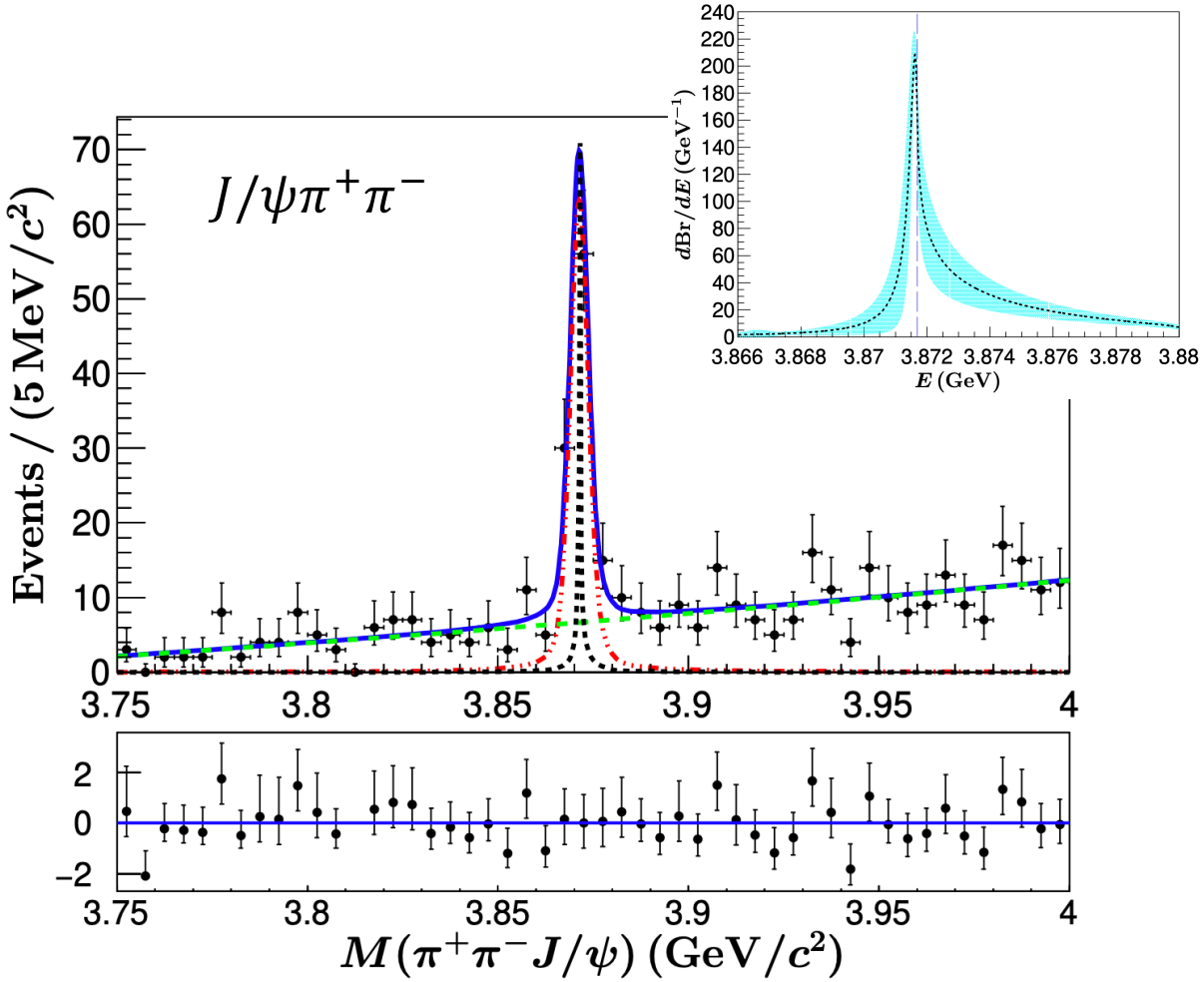
$\chi_{c1}(3872)$

Simultaneous fit

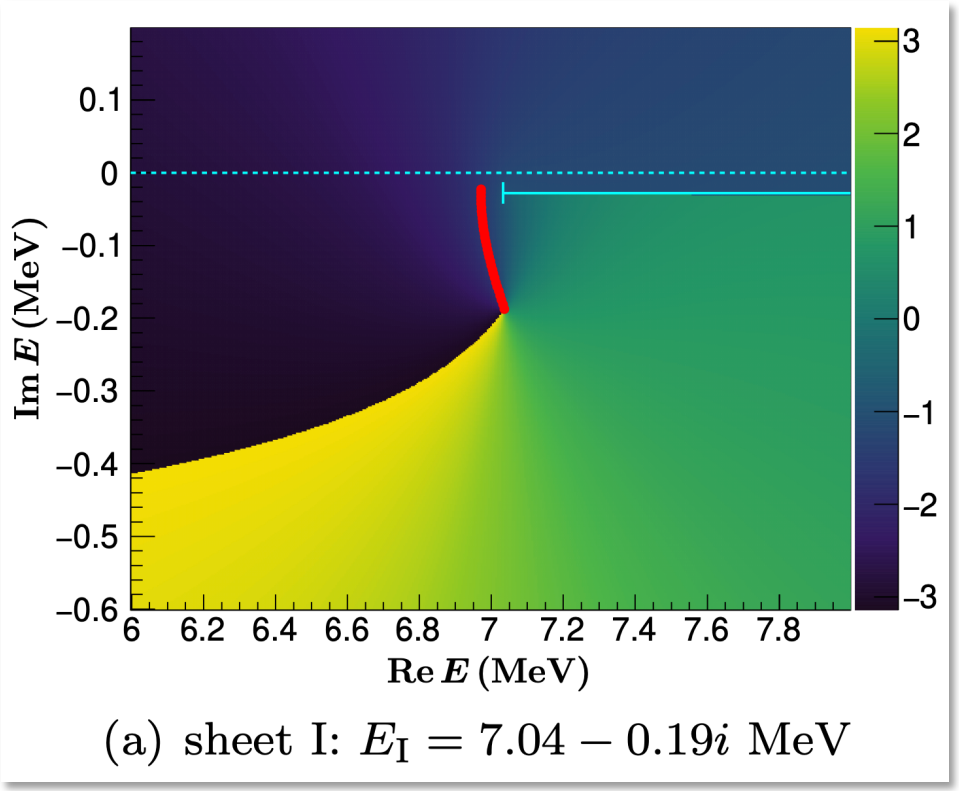




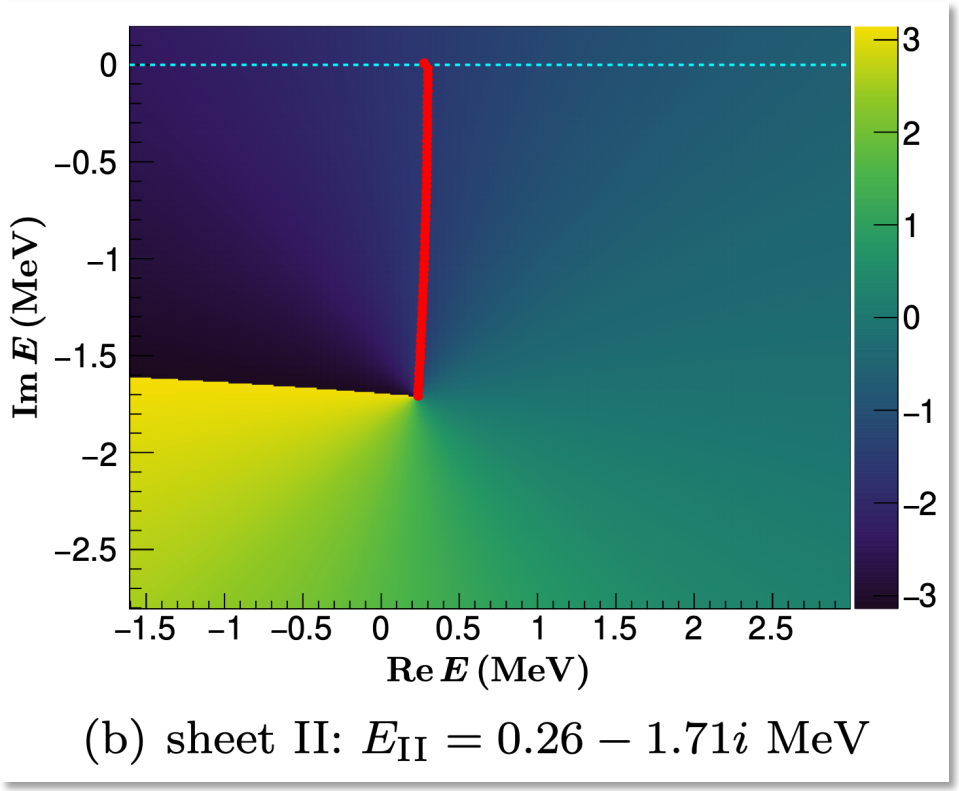
PRL 132 (2024) 15, 151903

$\chi_{c1}(3872)$

PRL 132 (2024) 15, 151903



(a) sheet I: $E_{\mathrm{I}} = 7.04 - 0.19i$ MeV



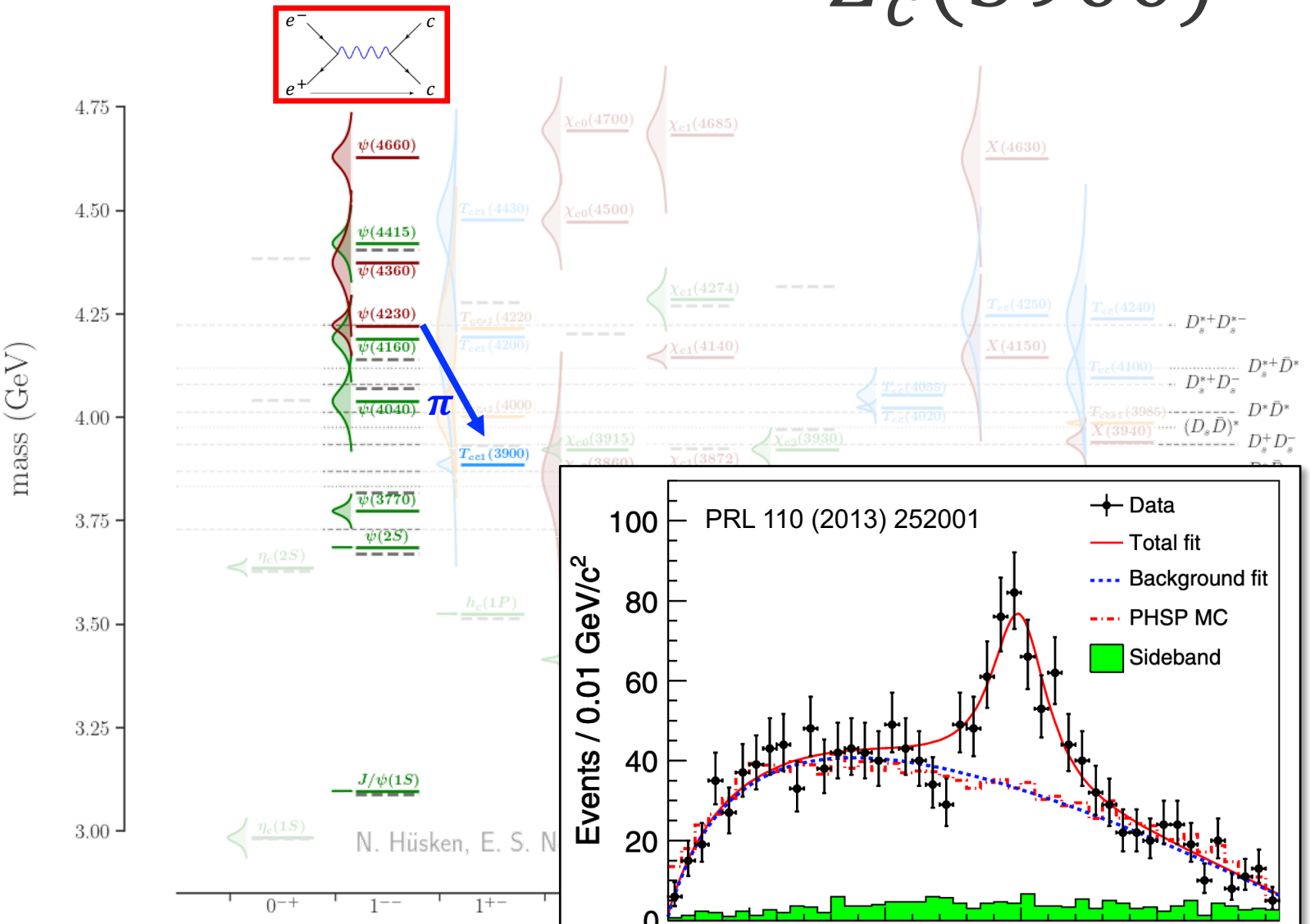
(b) sheet II: $E_{\mathrm{II}} = 0.26 - 1.71i$ MeV

	BESIII	LHCb
g	$0.16 \pm 0.10^{+1.12}_{-0.11}$	$0.108 \pm 0.003^{+0.005}_{-0.006}$
pole (sheet I)	$(7.04 \pm 0.15^{+0.07}_{-0.08})$ $- i(0.19 \pm 0.08^{+0.14}_{-0.19})$	$7.10 - i0.13$
$\Gamma(\pi^+\pi^- J/\psi)/\Gamma(D^0\bar{D}^{*0})$	$0.05 \pm 0.01^{+0.01}_{-0.02}$	0.11 ± 0.03
Z	0.18	0.15

→ $D^0\bar{D}^{*0}$ channel more sensitive to lineshape
→ results consistent with LHCb
→ room to improve with more data!

$Z_c(3900)$

$Z_c(3900)$



- charged charmonium-like discovered in 2013 in $J/\psi\pi^{\pm}$
- spin-parity from PWA based on ~2 fb^{-1} at 4.23 and 4.26 GeV

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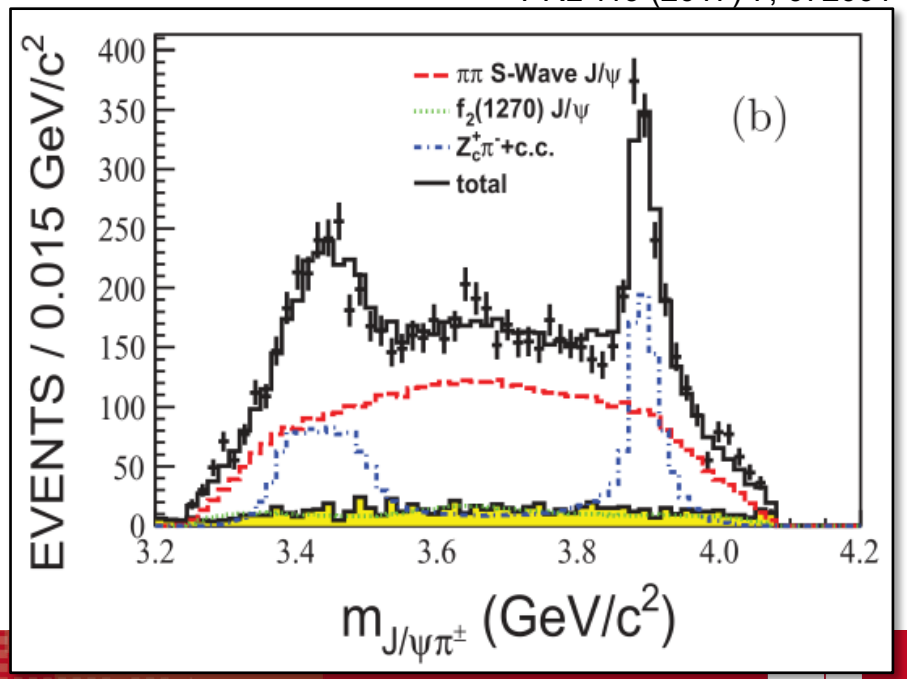
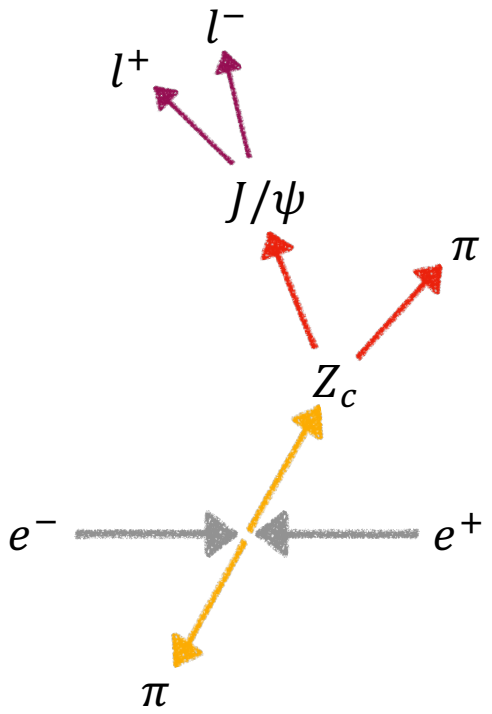


$Z_c(3900)$



- new (preliminary) results based on ~12 fb^{-1} at 17 energies between 4.13 and 4.36 GeV
- PWA in helicity formalism
- 2 models:

  (I) $f_0(980)$ as Flatté, $\sigma(500), f_0(1370), f_2(1270)$ and $Z_c(3900)$ as Breit-Wigner
  PLB 607, 243 (2005)

  (II) $\sigma(500), f_0(980), f_0(1370)$ with K-matrix, $f_2(1270)$ and $Z_c(3900)$ as Breit-Wigner
  EPJA 16, 229 (2003)

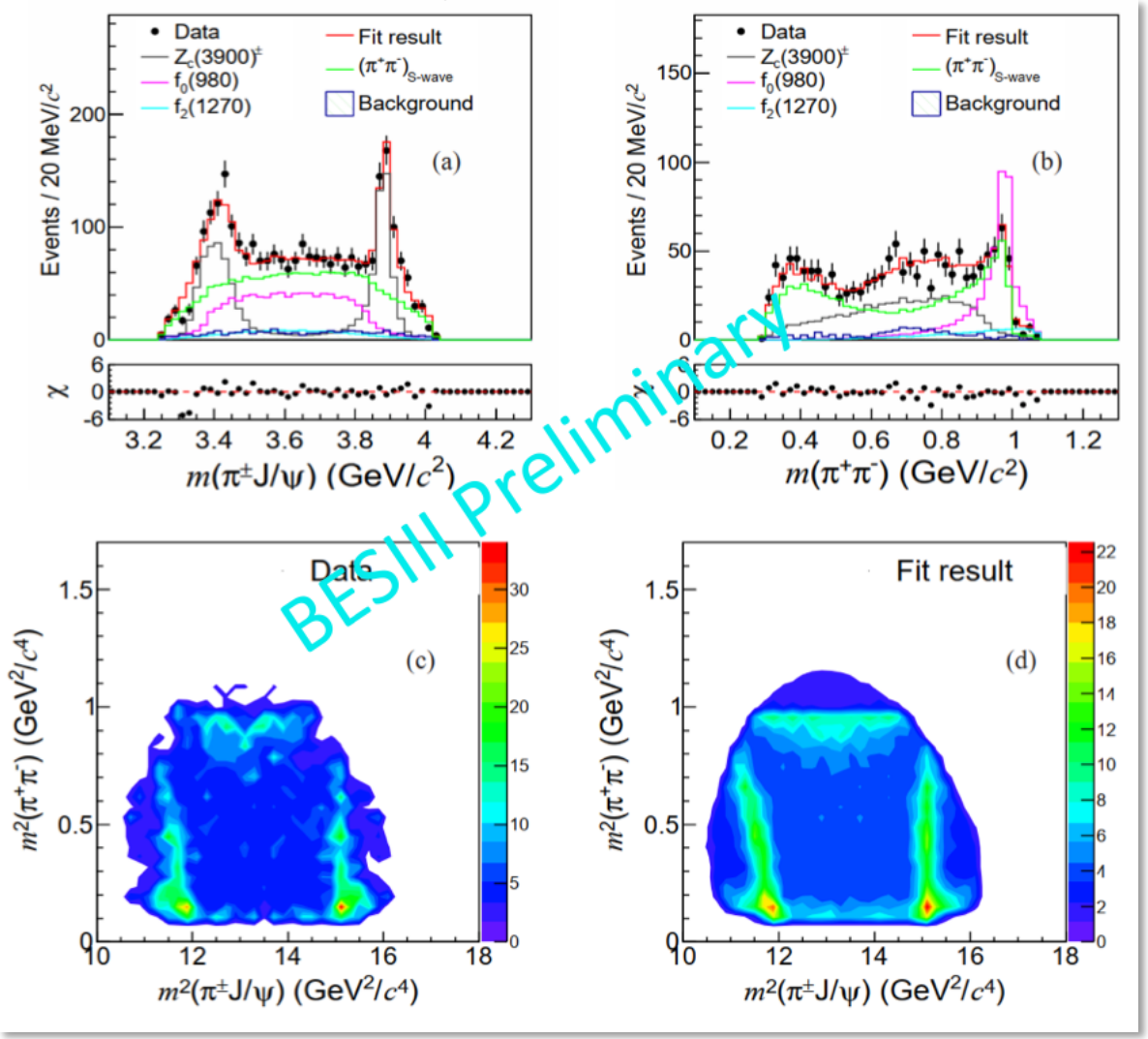
- mass and width of $Z_c(3900)$ determined from simultaneous fit to groups of center-of-mass energies
- fit fractions then determined from fits to single energies, with all masses and widths fixed

$\sqrt{s}$ (GeV)	M (MeV/c^2)	Γ (MeV)
$4.1567 - 4.1989$	3883.5 ± 1.6	38.6 ± 3.6
$4.2091 - 4.2357$	3884.0 ± 1.0	37.8 ± 1.6
$4.2438 - 4.2776$	3884.9 ± 1.8	34.2 ± 3.3
$4.2866 - 4.3583$	3890.0 ± 2.3	36.1 ± 4.2
Average	$3884.6 \pm 0.7 \pm 3.3$	$37.2 \pm 1.3 \pm 6.6$

BESIII Preliminary

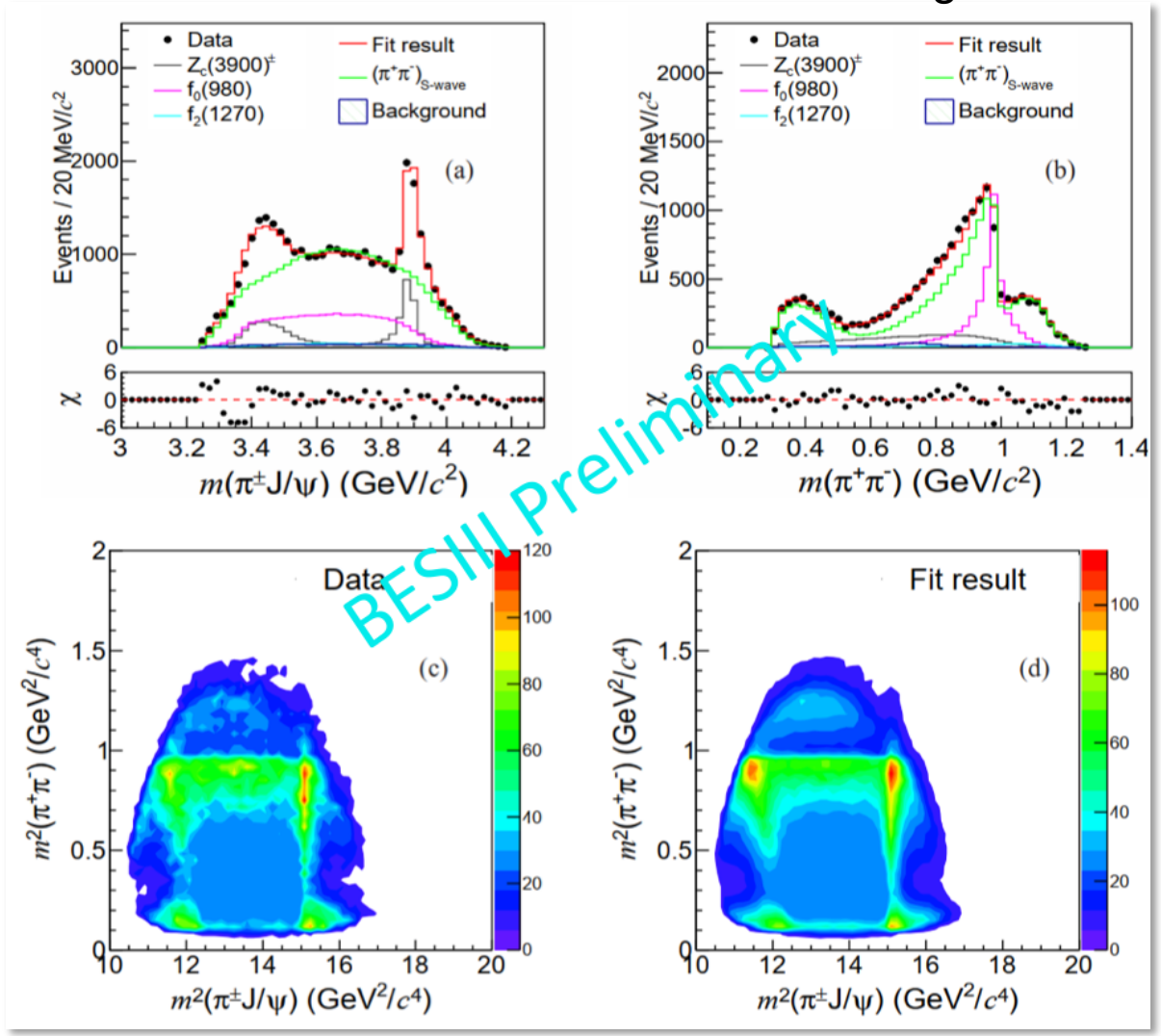
$Z_c(3900)$

$\sqrt{s} = 4.178$ GeV



BESIII Preliminary

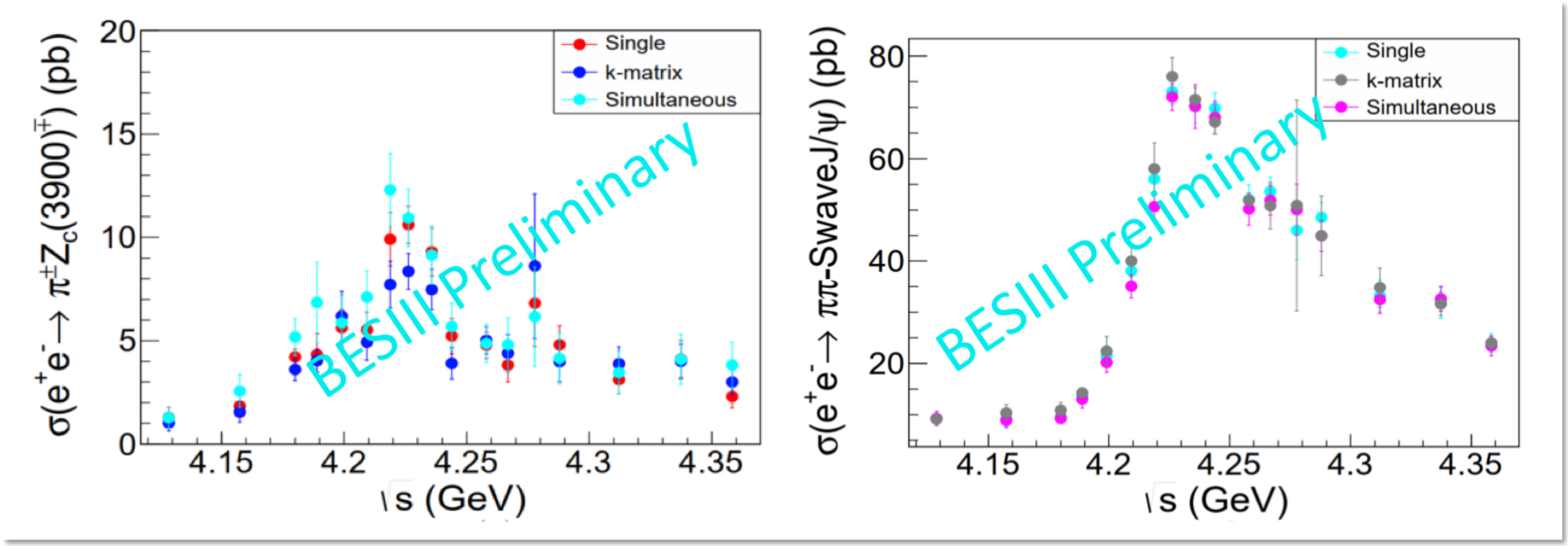
sum over all center-of-mass energies



BESIII Preliminary

$Z_c(3900)$

- cross sections of sub-processes → clear indication of resonant production of $Z_c\pi$, $(\pi\pi)_{S-\mathrm{wave}}\,J/\psi$

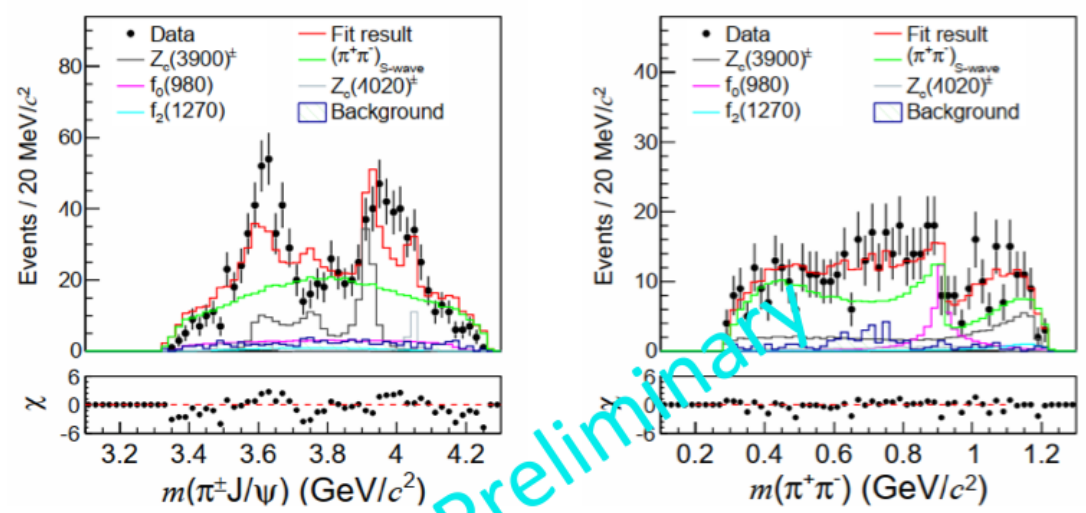


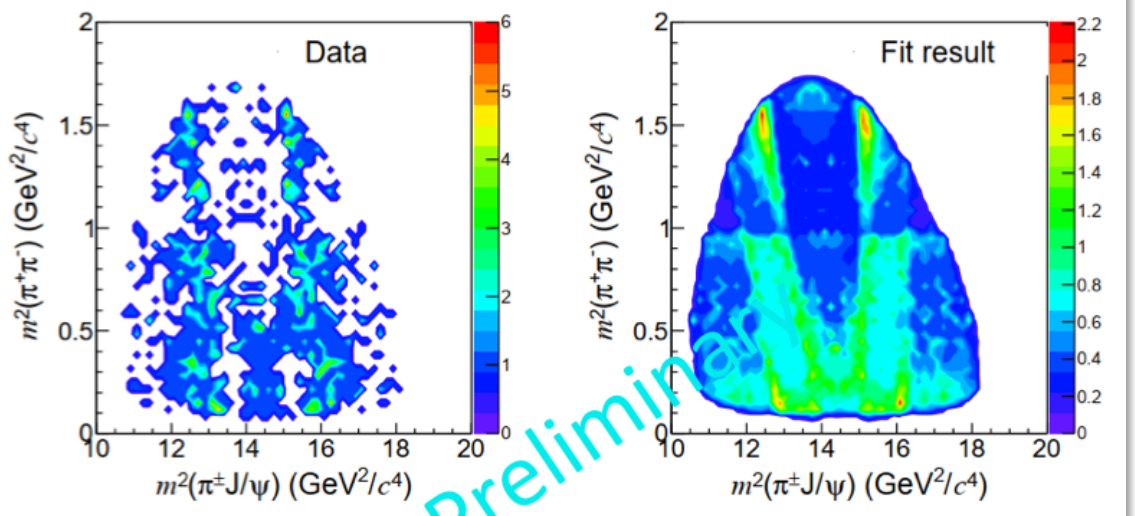
- model-dependence of $(\pi\pi)_{S-\mathrm{wave}}$ seems well under control

$Z_c(3900)$

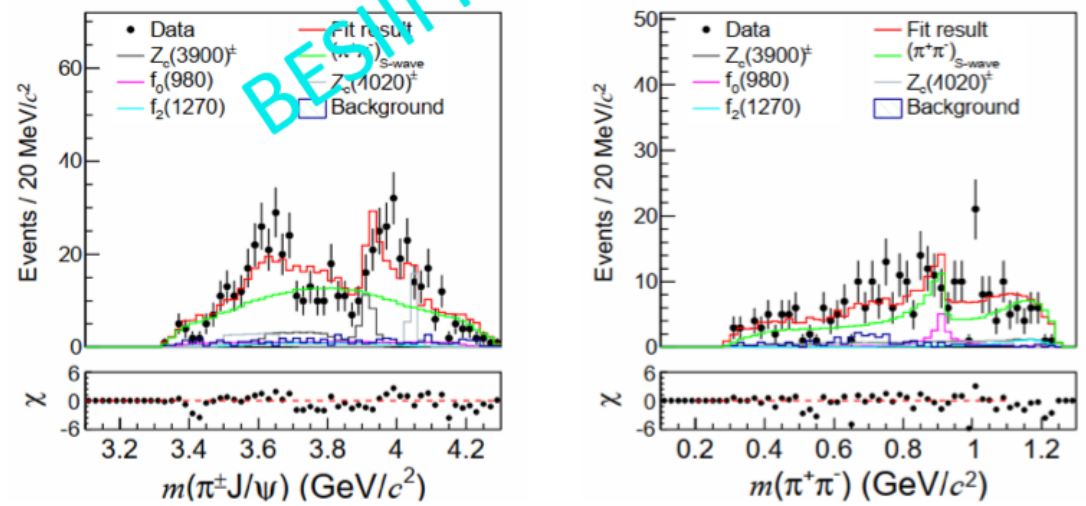
but not all is understood: what happens at larger center-of-mass energies?

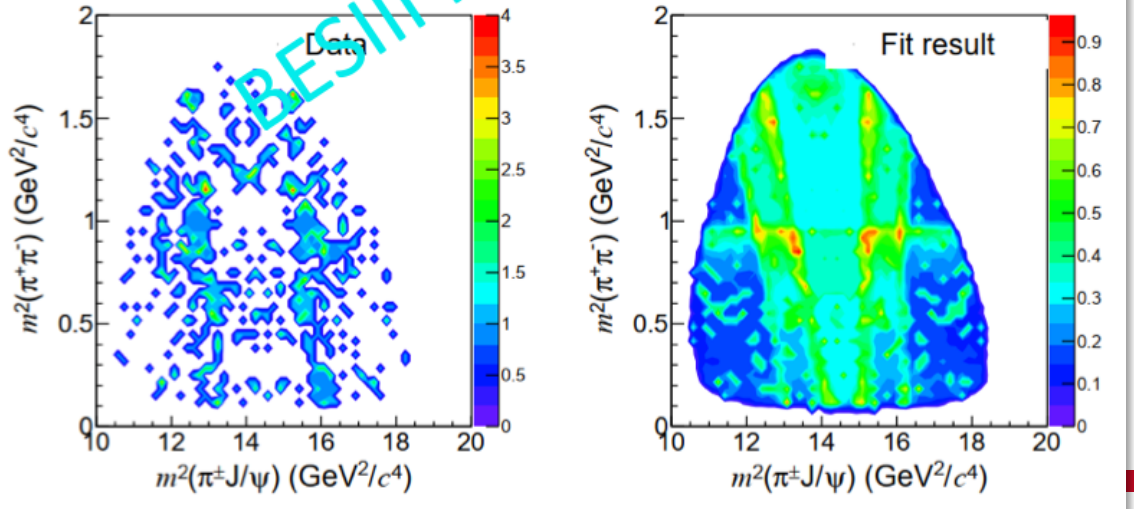
$\sqrt{s} = 4.4156$ GeV





$\sqrt{s} = 4.4359$ GeV





Summary

Summary

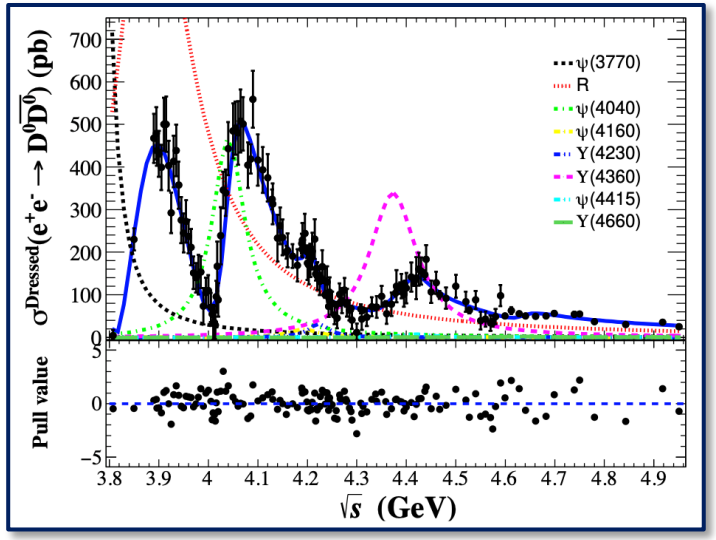
- BESIII remains very active in spectroscopy of charmonium-like states

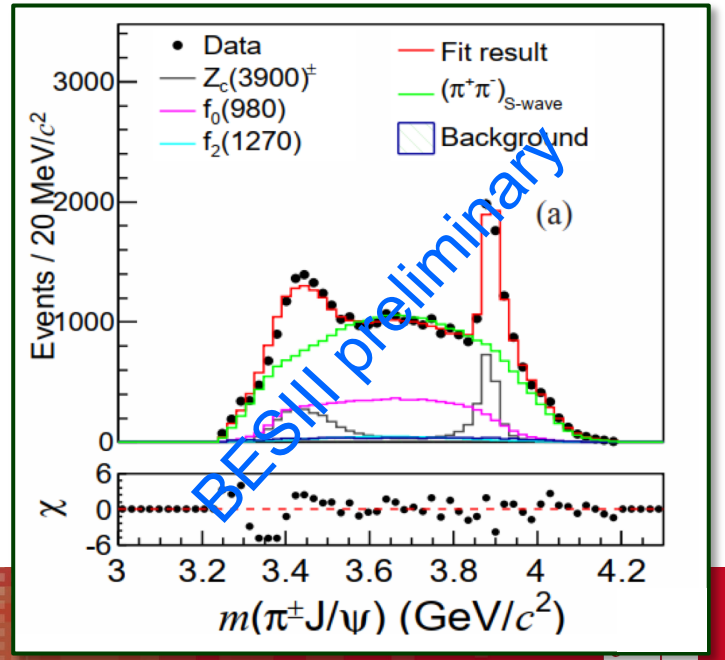
- vector states:
  - clear structures in hidden-charm final states
  - measurements of two- and three-body open-charm cross sections nearly complete
  - interpretation of single channels as well as inclusive cross section is difficult…
  - … coupled channel approaches are needed – and are coming!

- $\chi_{c1}(3872)$:
  - BESIII has established production process: $\psi(4230) \to \gamma\chi_{c1}(3872)$
  - allows to look for new decay modes…
  - … and lineshape studies – can be improved with future data!

- Z_c-states:
  - new data, much more finely spaced in center-of-mass energy
  - study connection between $\psi(4230)$ and $Z_c(3900)$
  - intriguing open question: what happens at larger center-of-mass energies?

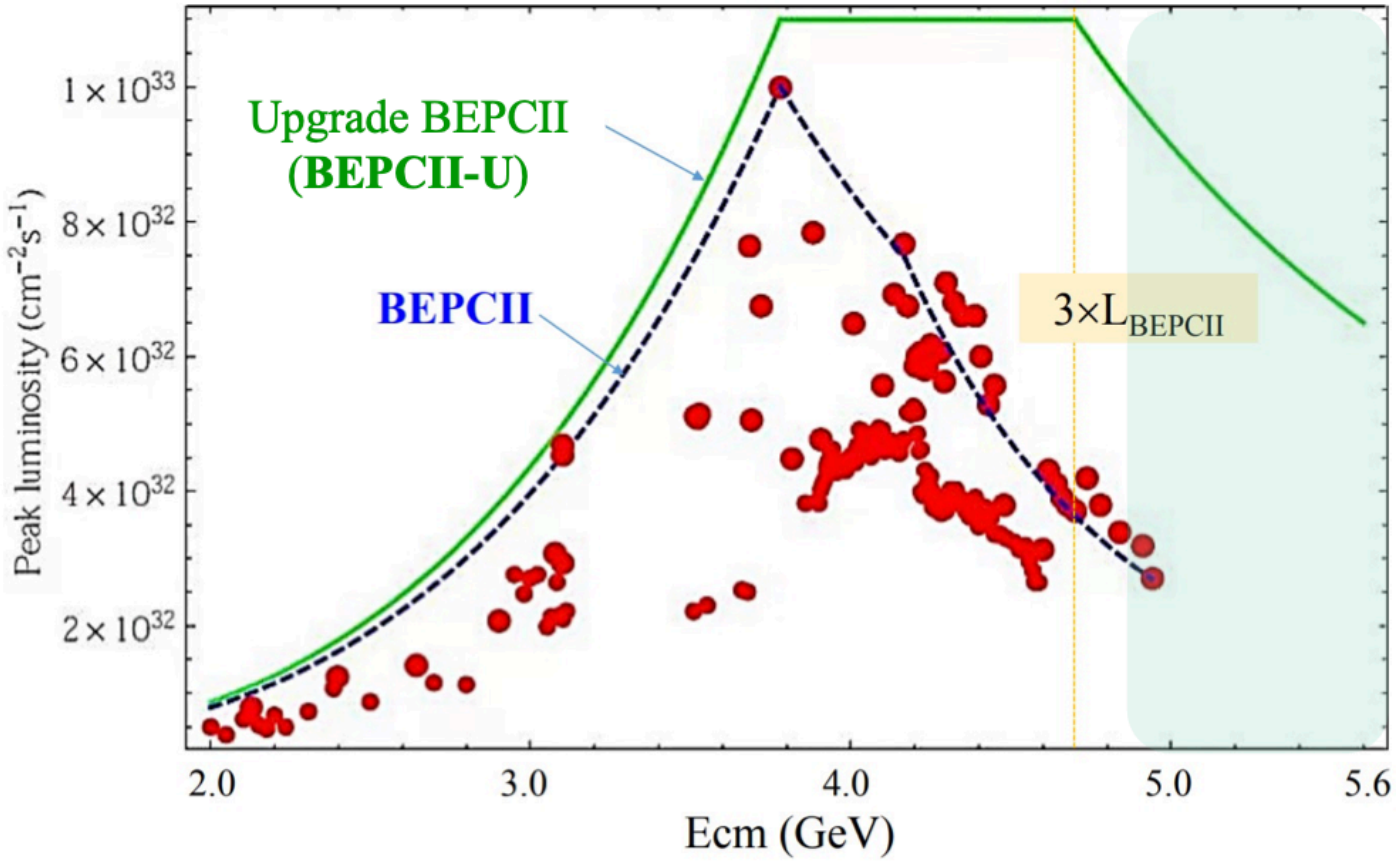
- very much open to experiment-theory collaboration – approach us!





Outlook

Upgrade to BEPCII:



- up to 3x higher luminosities in XYZ region
  - precision XYZ physics at BESIII
  - fine energy scans to study cross sections
  - large datasets at single $\sqrt{s}$ to study X, Z_c lineshapes
  - open to suggestions!
- center-of-mass energies up to $5.6\ \mathrm{GeV}$
  - cross multiple charmed baryon thresholds: $\Sigma_c\bar{\Sigma}_c, \Xi_c\bar{\Xi}_c, \Omega_c\bar{\Omega}_c$
  - above $J/\psi p\bar{p}$ threshold, can we produce pentaquarks?
  - largely unexplored region, new surprises await!

Thank you for your attention!

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