Hadron spectroscopy at BESIII

Recent results and future perspectives

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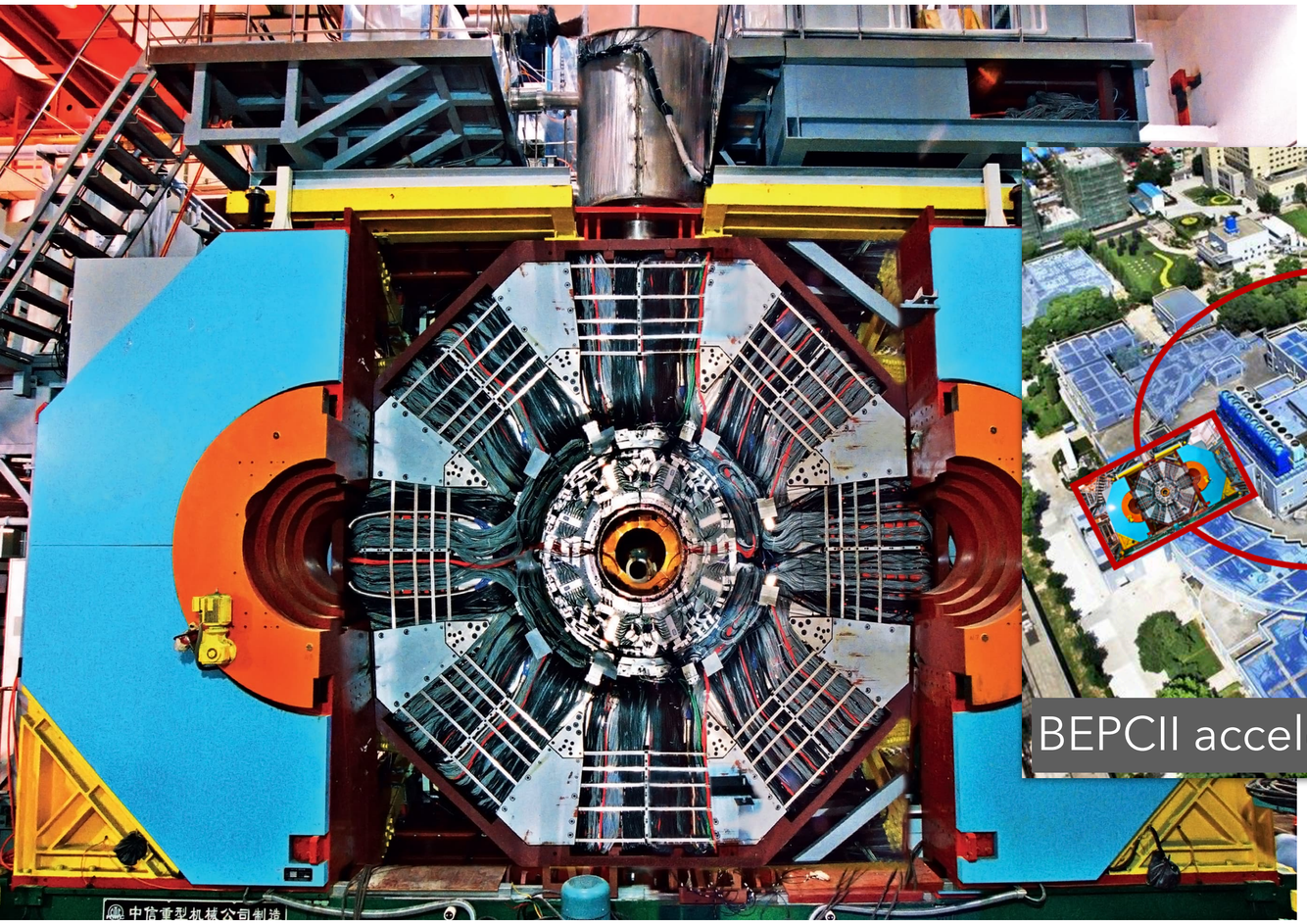
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

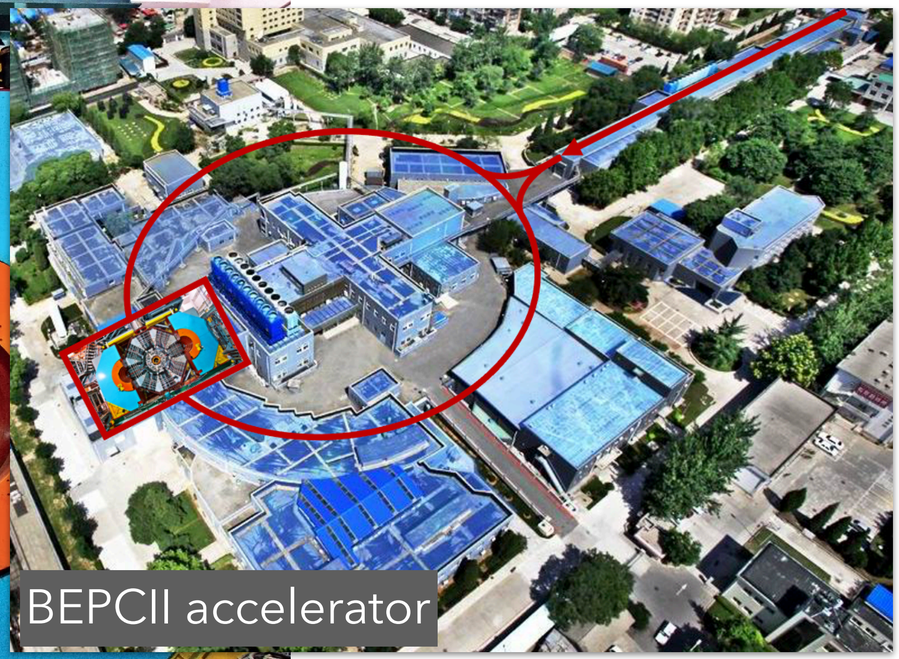
JG|U

HIM
Helmholtz-Institut Mainz

April 15th, 2025

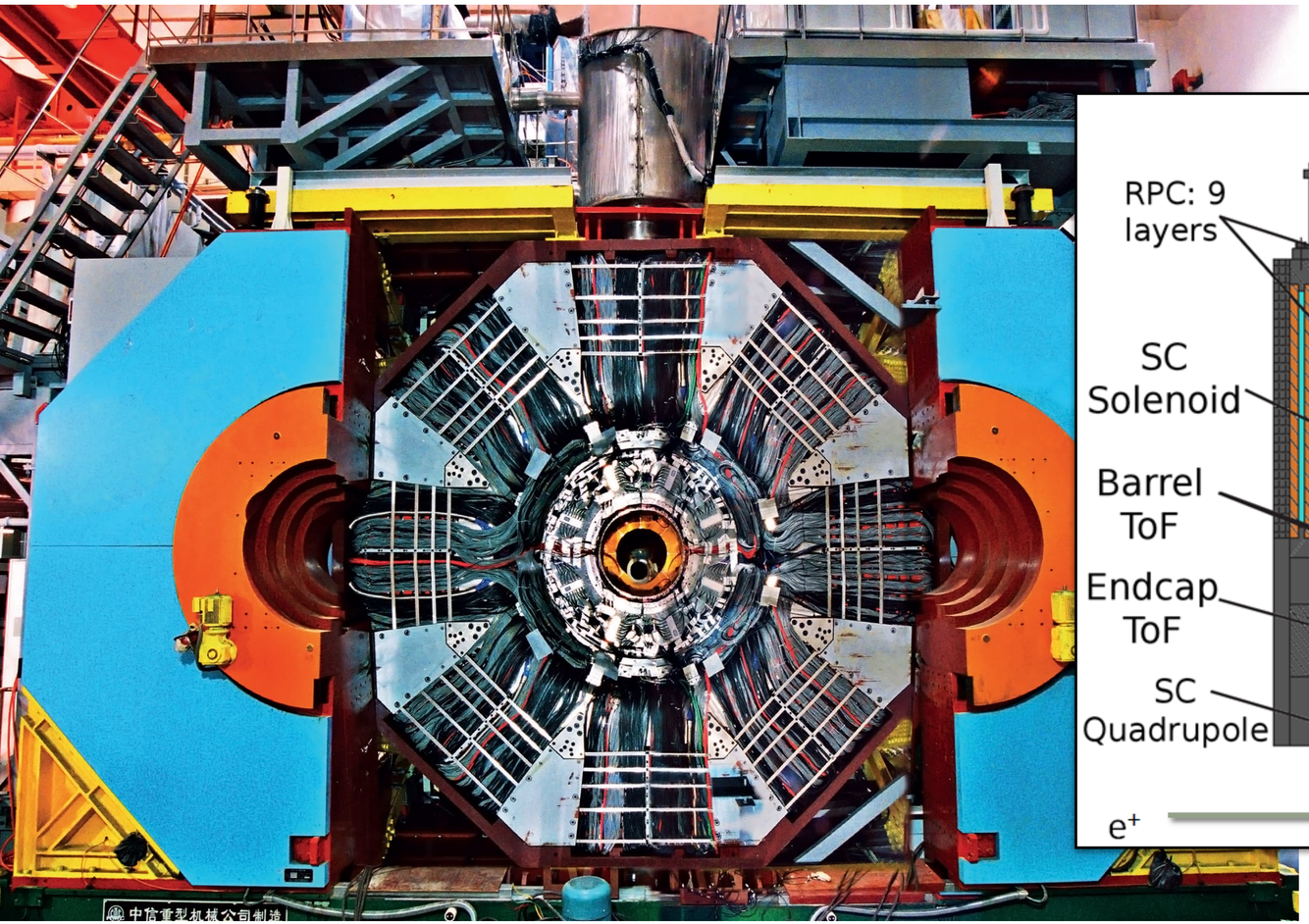
BESIII

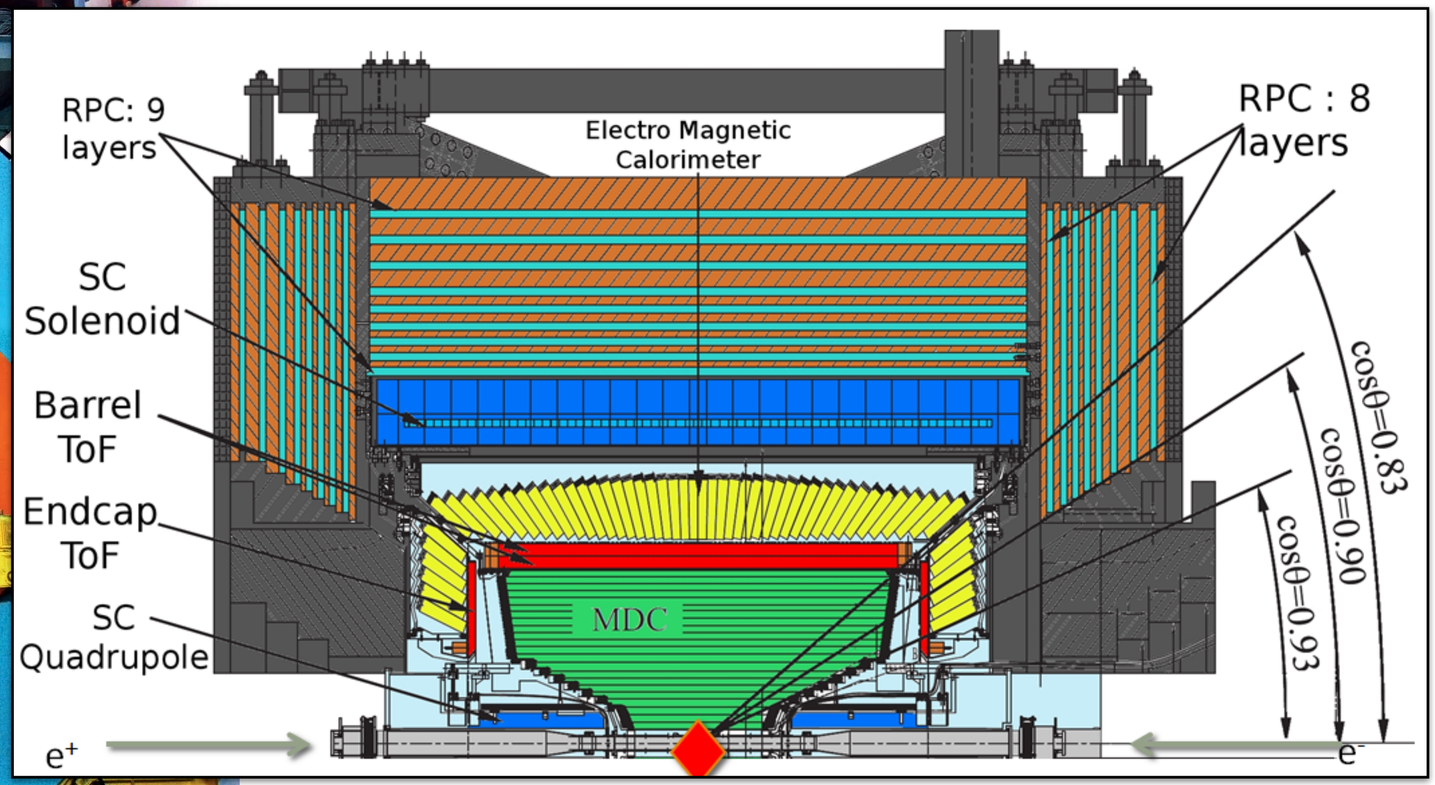




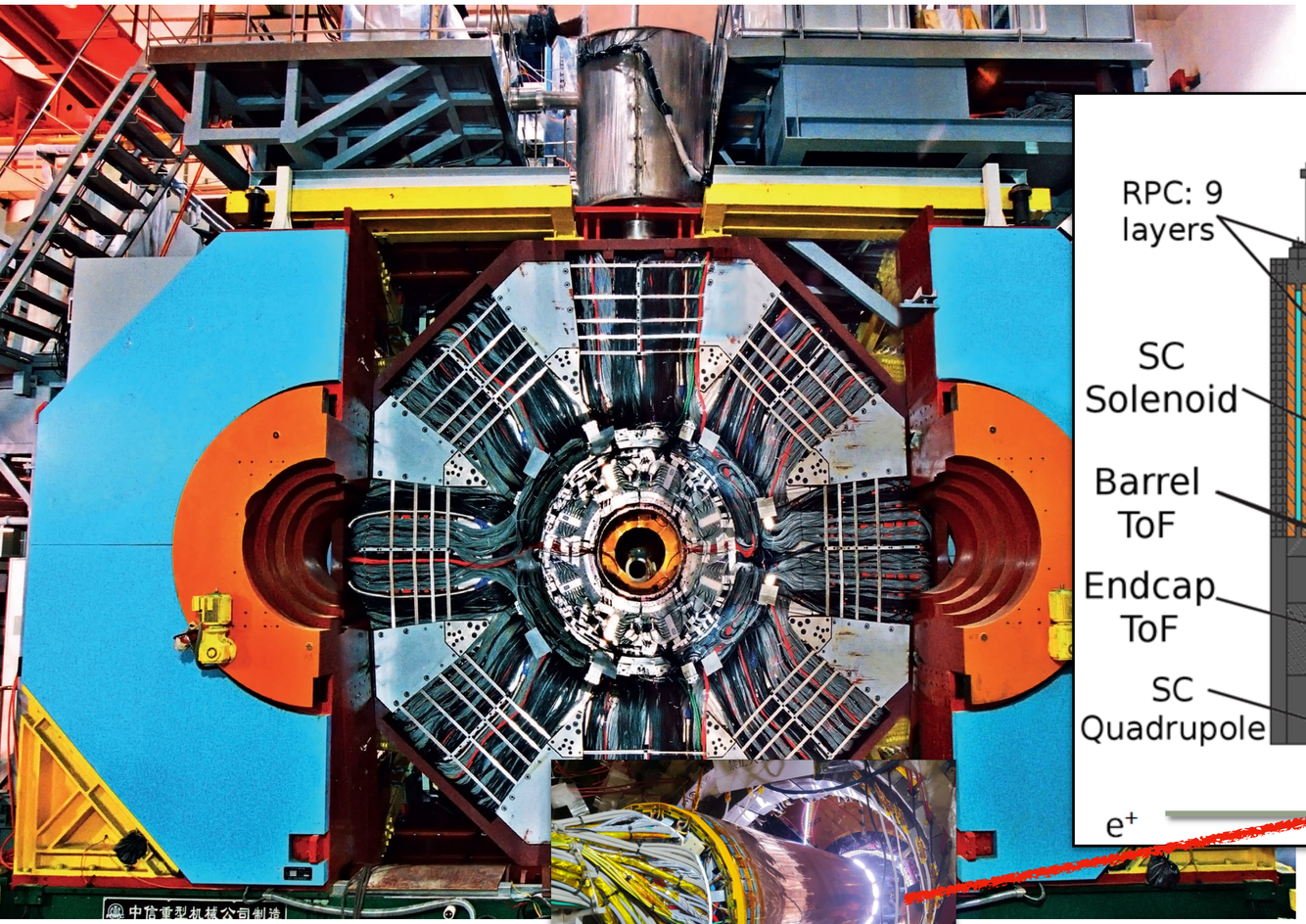
- located at IHEP, Beijing
- operating in τ-charm region: 2 GeV $-$ 5 GeV
- luminosity of 10^{33} $\mathrm{cm}^{-2}s^{-1}$
- over 600 members from 85 institutes in 17 countries

BESIII

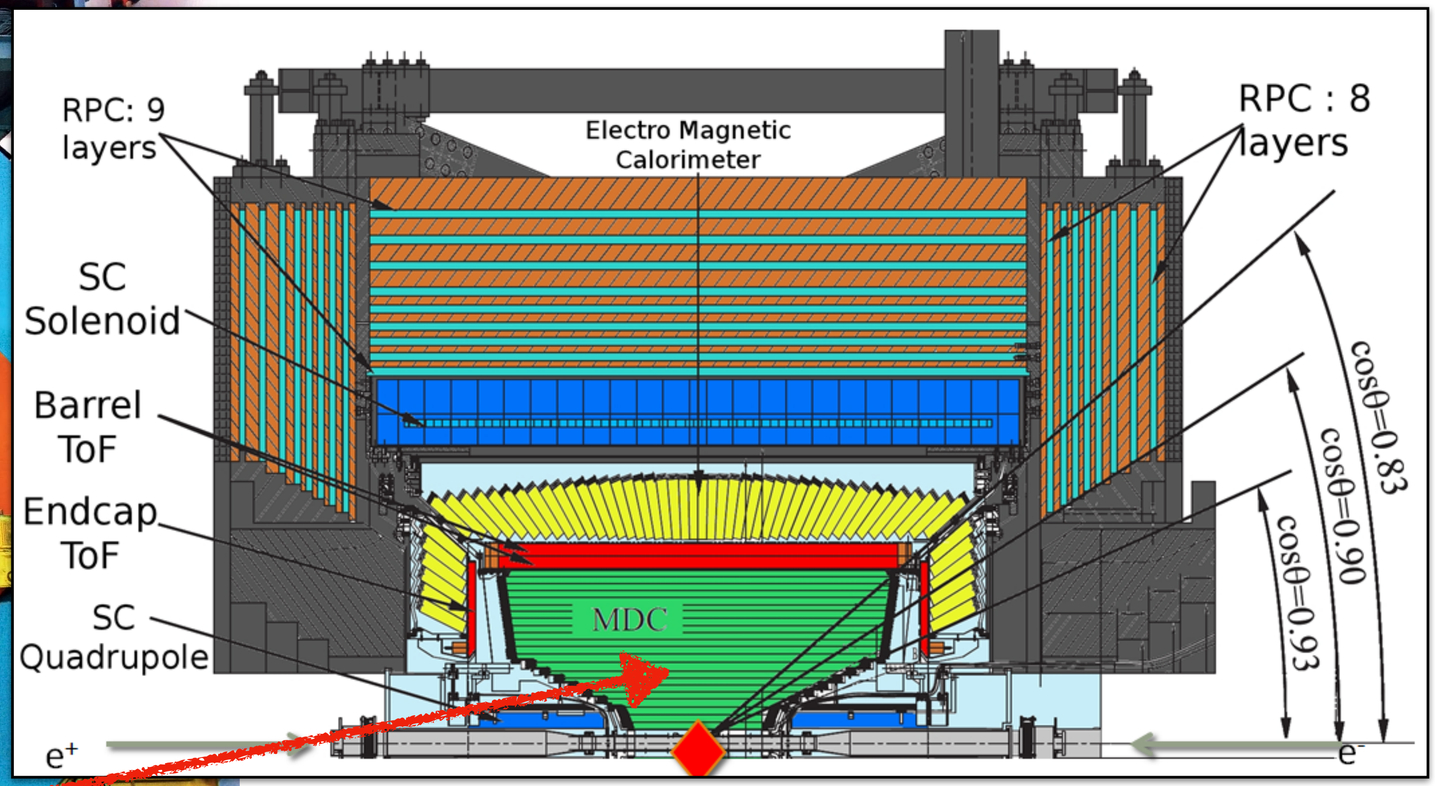



RPC: 9
layers
SC
Solenoid
Barrel
ToF
Endcap
ToF
SC
Quadrupole
Electro Magnetic
Calorimeter
RPC : 8
layers
MDC
cosθ=0.83
cosθ=0.90
cosθ=0.93
e+
e-

BESIII



new inner tracker!


RPC: 9 layers
SC Solenoid
Barrel ToF
Endcap ToF
SC Quadrupole
Electro Magnetic Calorimeter
RPC : 8 layers
MDC
cosθ=0.83
cosθ=0.90
cosθ=0.93
e+
e-

BESIII

broad physics program:

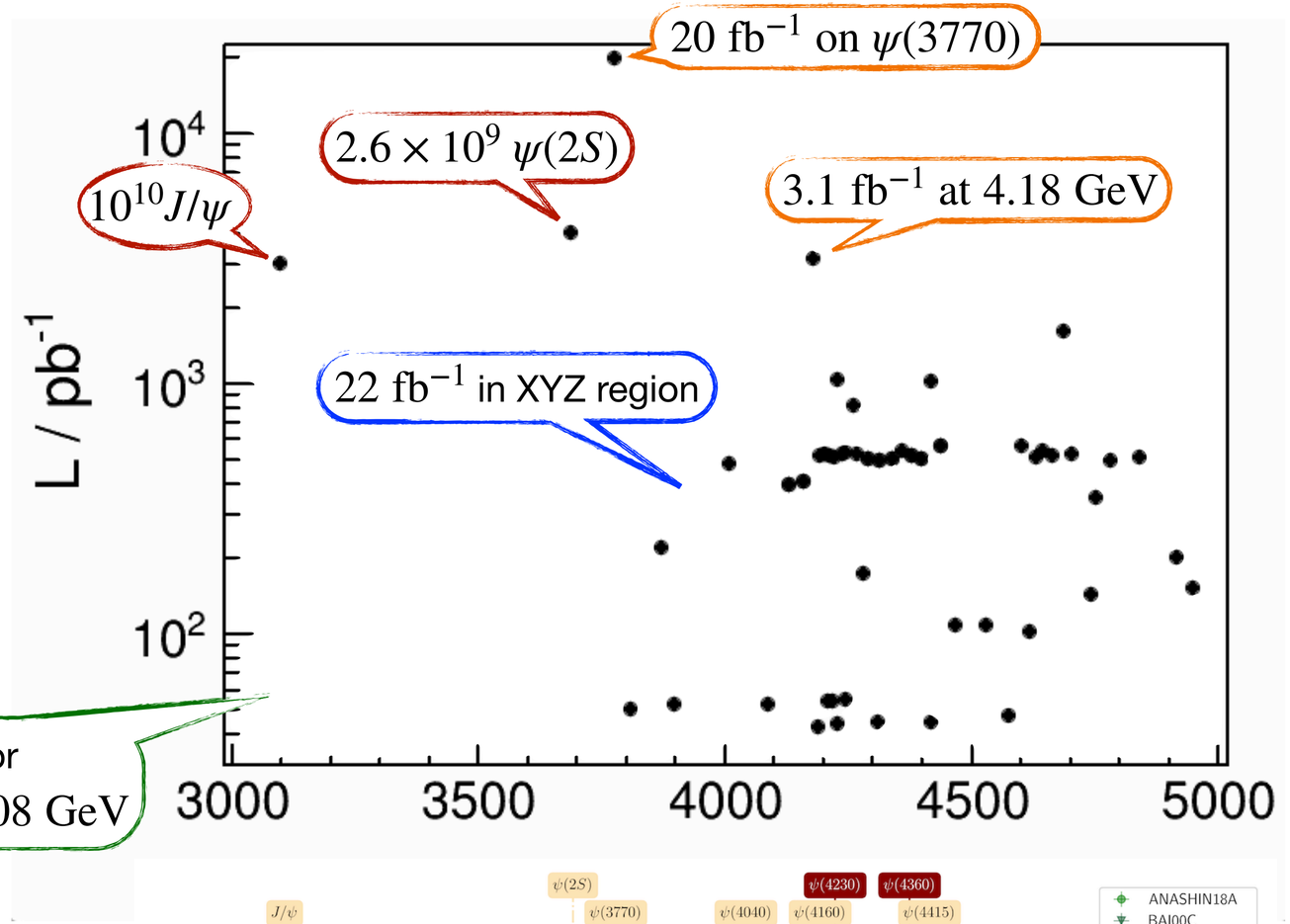
- light hadron spectroscopy including searches for glueballs and hybrid mesons
- η and η' decays
- charmonium transitions
- hyperon physics

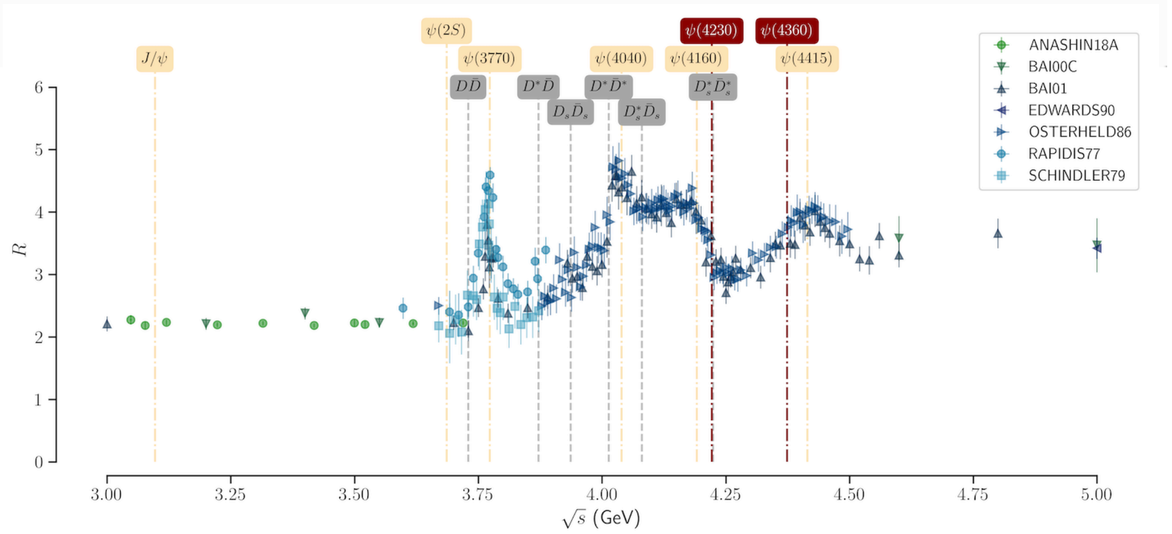
- excited ρ, ω, ϕ

- D, D_s decays
- $D^0\bar{D}^0$ pairs
- initial-state-radiation physics
- two-photon fusion

- spectroscopy of charmonium(-like) states
- decays of $X(3872)$, $Z_c(3900)$, …
- open-charm production
- charmed baryons

- …



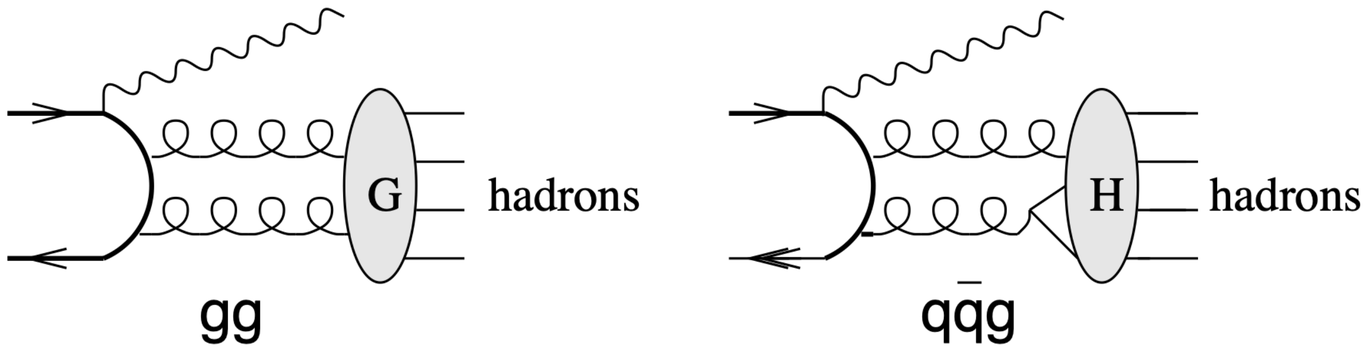


Light hadron spectroscopy

Radiative J/ψ decays

a unique laboratory for light hadron spectroscopy:

- clean, high statistics sample of J/ψ decays
- well-defined initial state with $J^{PC} = 1^{--}$
- radiative decays provide gluon-rich environment



eConf C020620 (2002) THAT07

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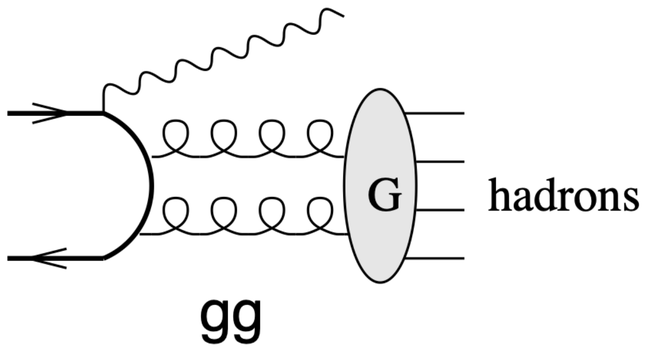

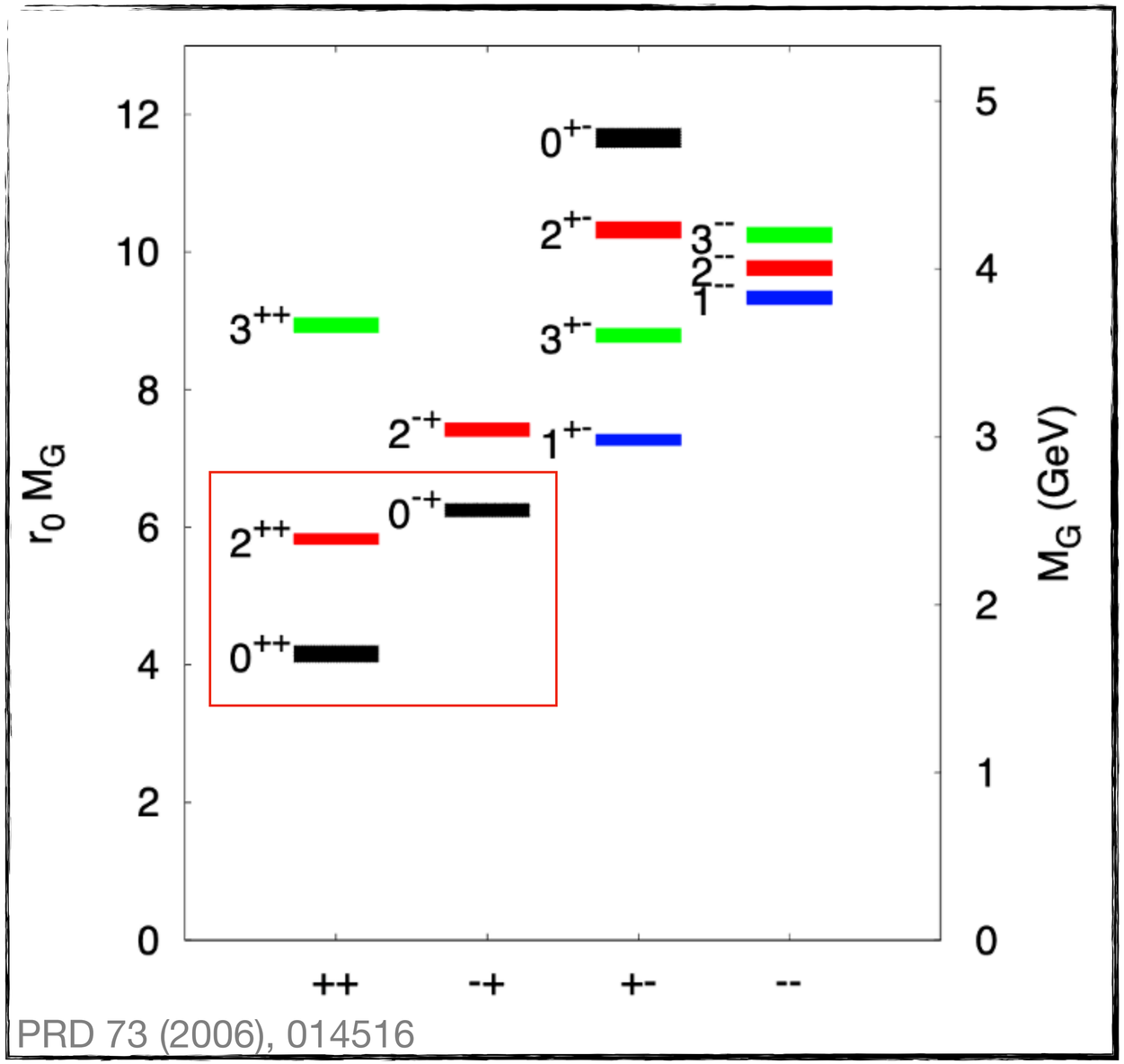

Radiative J/ψ decays

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- clean,
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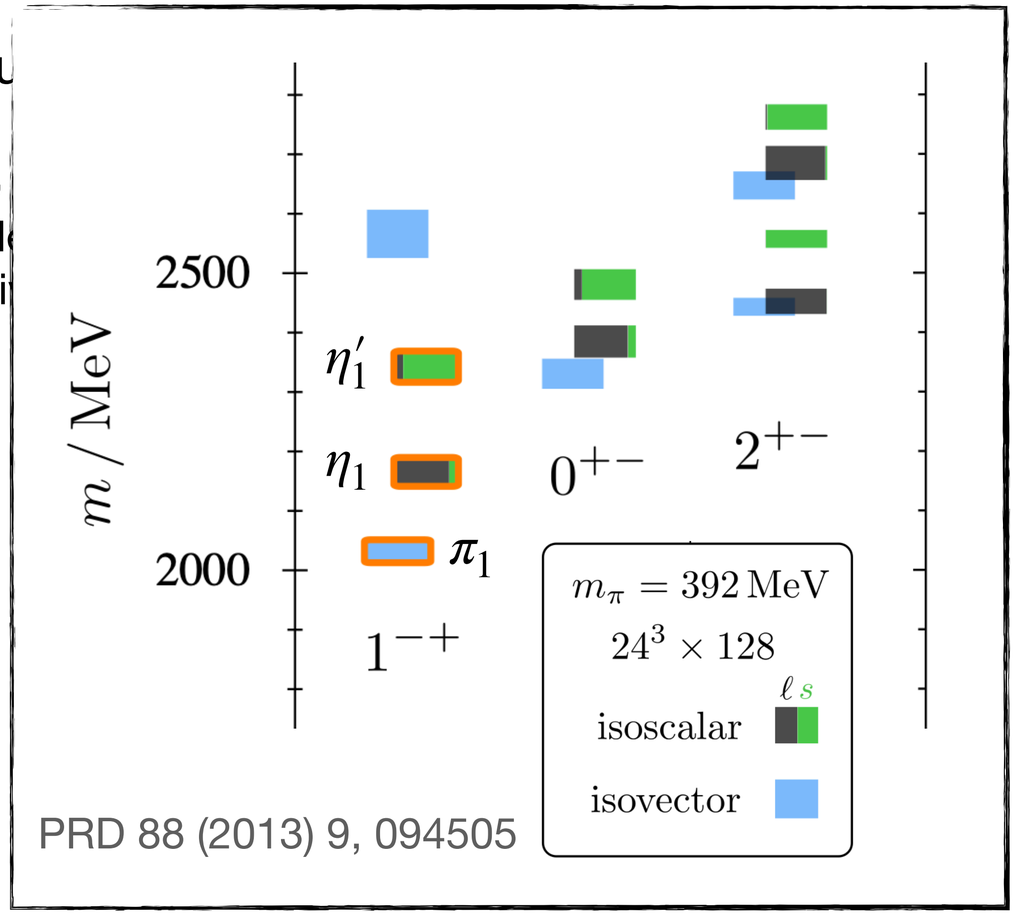
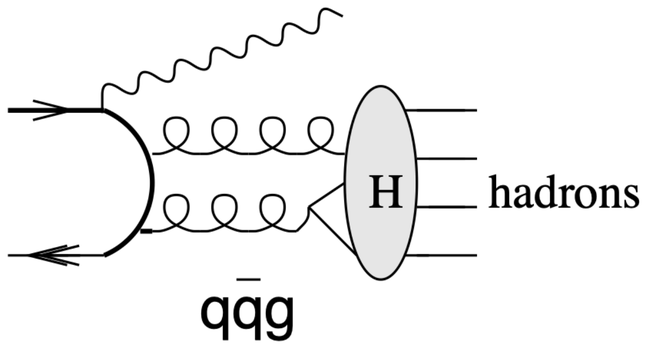


PRD 88 (2013) 9, 094505

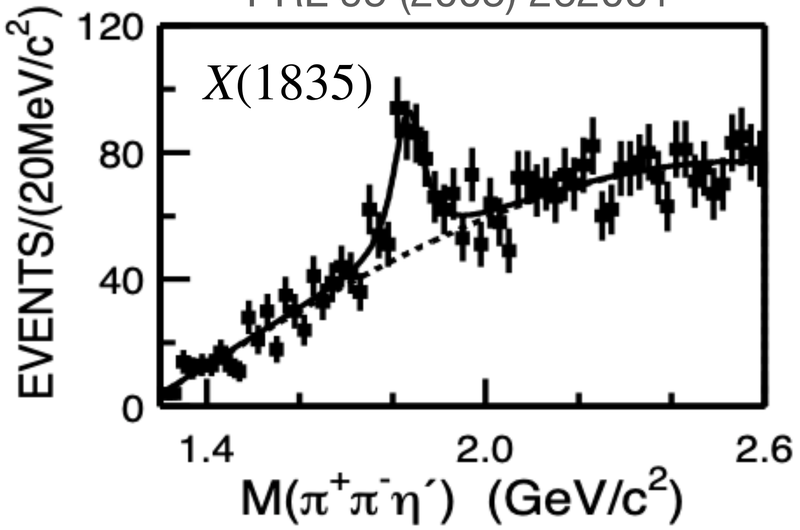


eConf C020620 (2002) THAT07

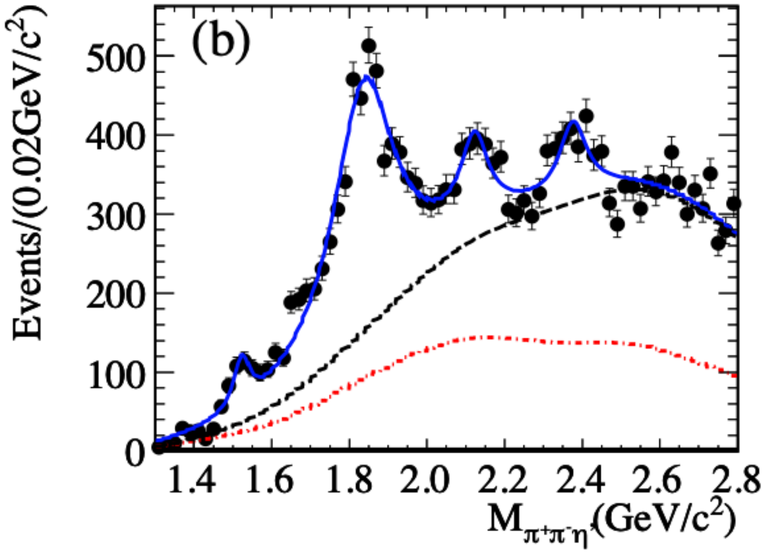
$J/\psi \to \gamma\eta'\pi^+\pi^-$

or why you can never have too many J/ψ

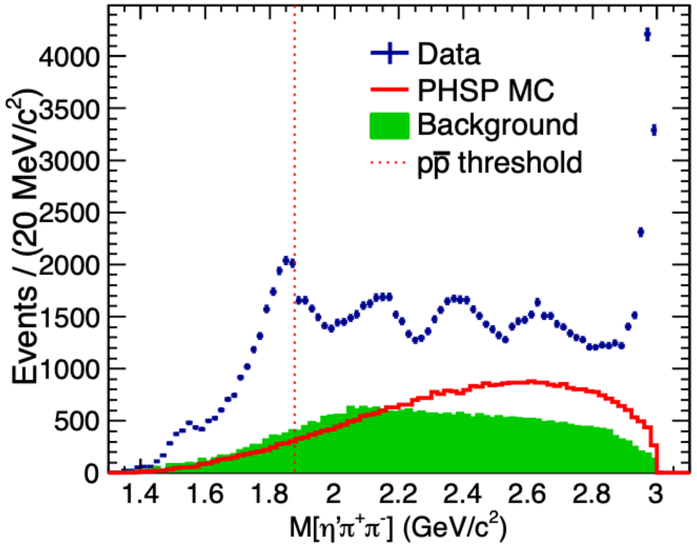
PRL 95 (2005) 262001



PRL 106 (2011) 072002



PRL 117 (2016) 4, 042002

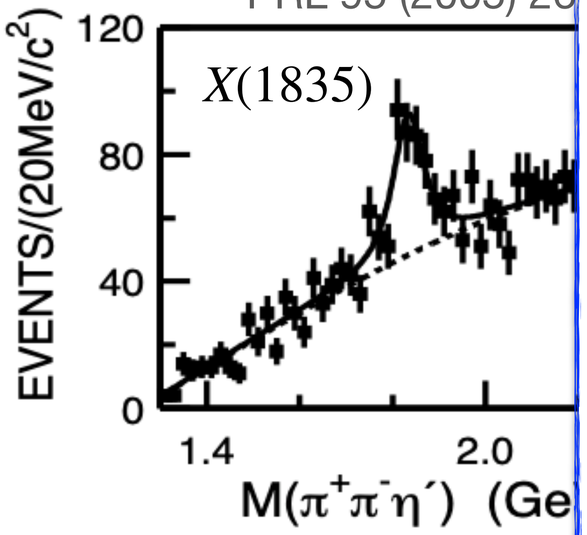


58×10^6 J/ψ → 225×10^6 J/ψ → 1.3×10^9 J/ψ

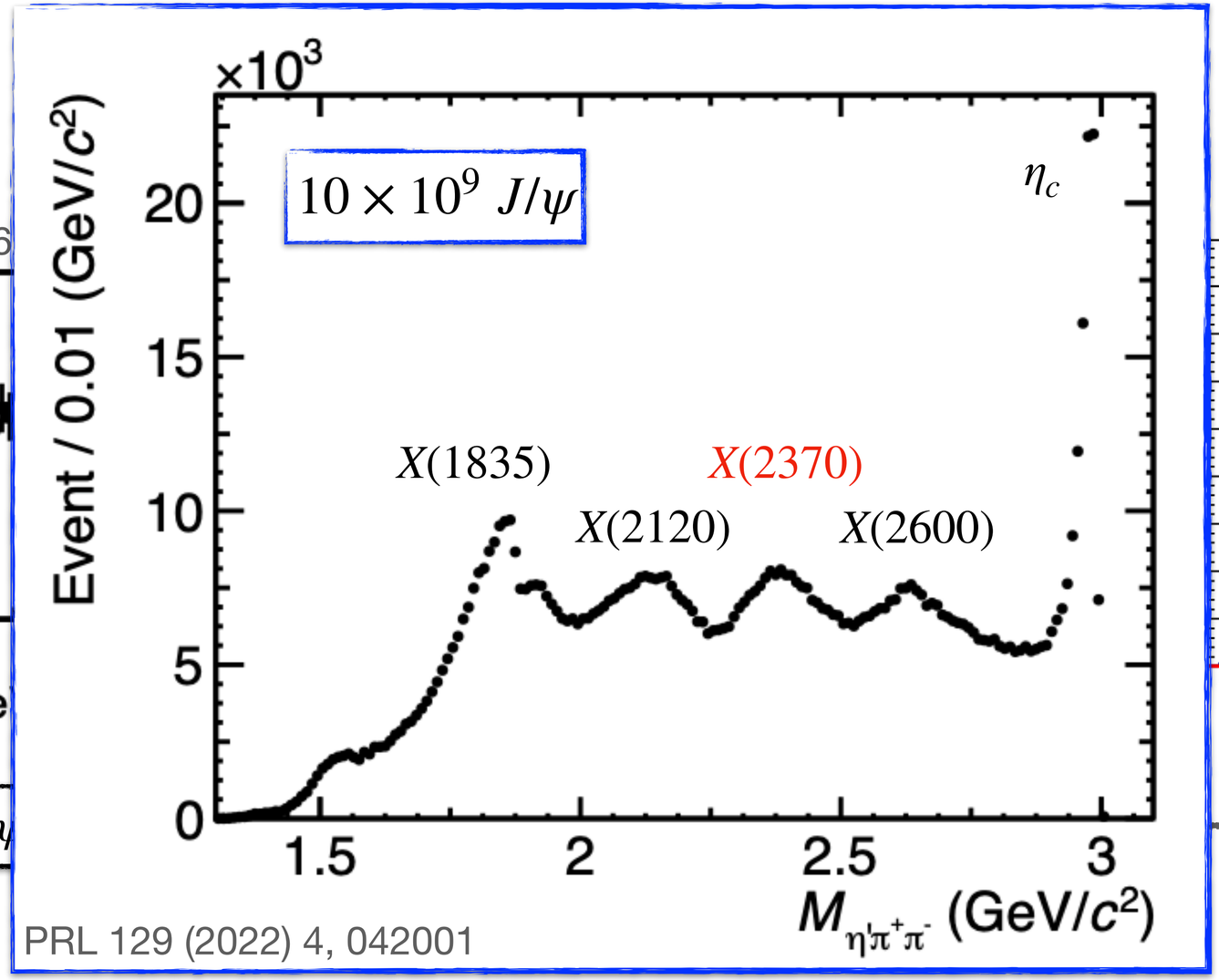
$J/\psi \to \gamma\eta'\pi^+\pi^-$

or why you can never have too many J/ψ

PRL 95 (2005) 26

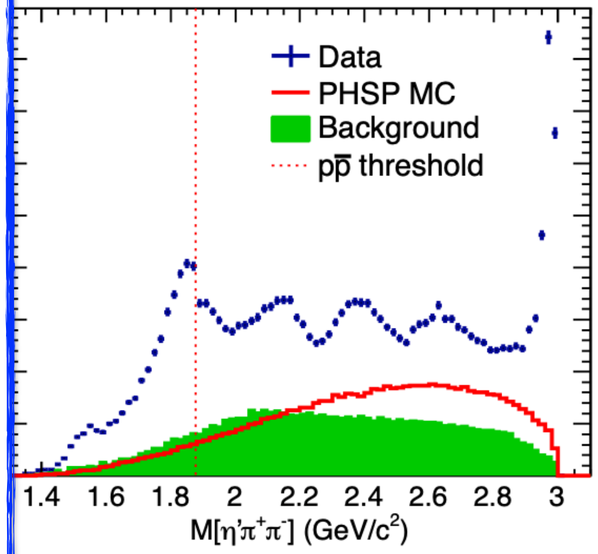


58×10^6 J/ψ



PRL 129 (2022) 4, 042001

PRL 117 (2016) 4, 042002



1.3×10^9 J/ψ

The $X(2370)$

Bericht
10.05.2024
Lesedauer ca. 2 Minuten
Drucken
Teilen

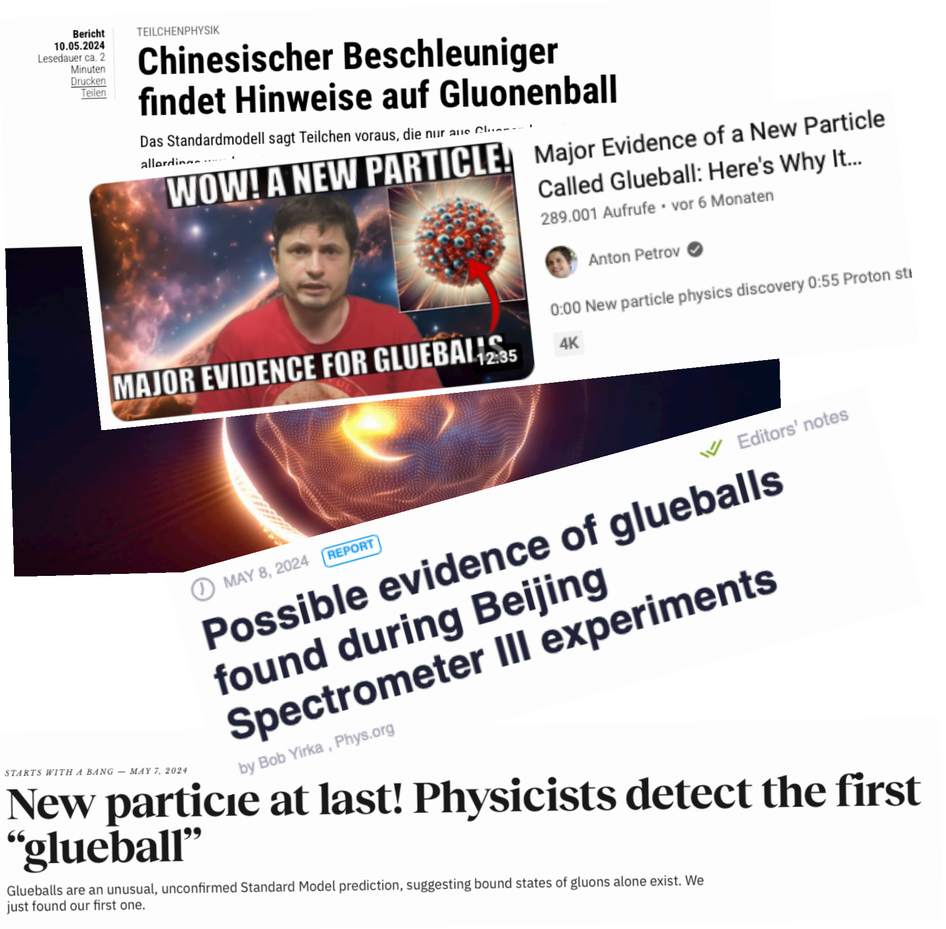
TEILCHENPHYSIK

Chinesischer Beschleuniger findet Hinweise auf Gluonenball

Das Standardmodell sagt Teilchen voraus, die nur aus Gluonen bestehen – allerdings wurden sie noch nie beobachtet. Nun scheint ein chinesischer Beschleuniger solche Gluonenbälle erstmals nachgewiesen zu haben.

von Manon Bischoff

The $X(2370)$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TEILCHENPHYSIK
Chinesischer Beschleuniger findet Hinweise auf Gluonenball
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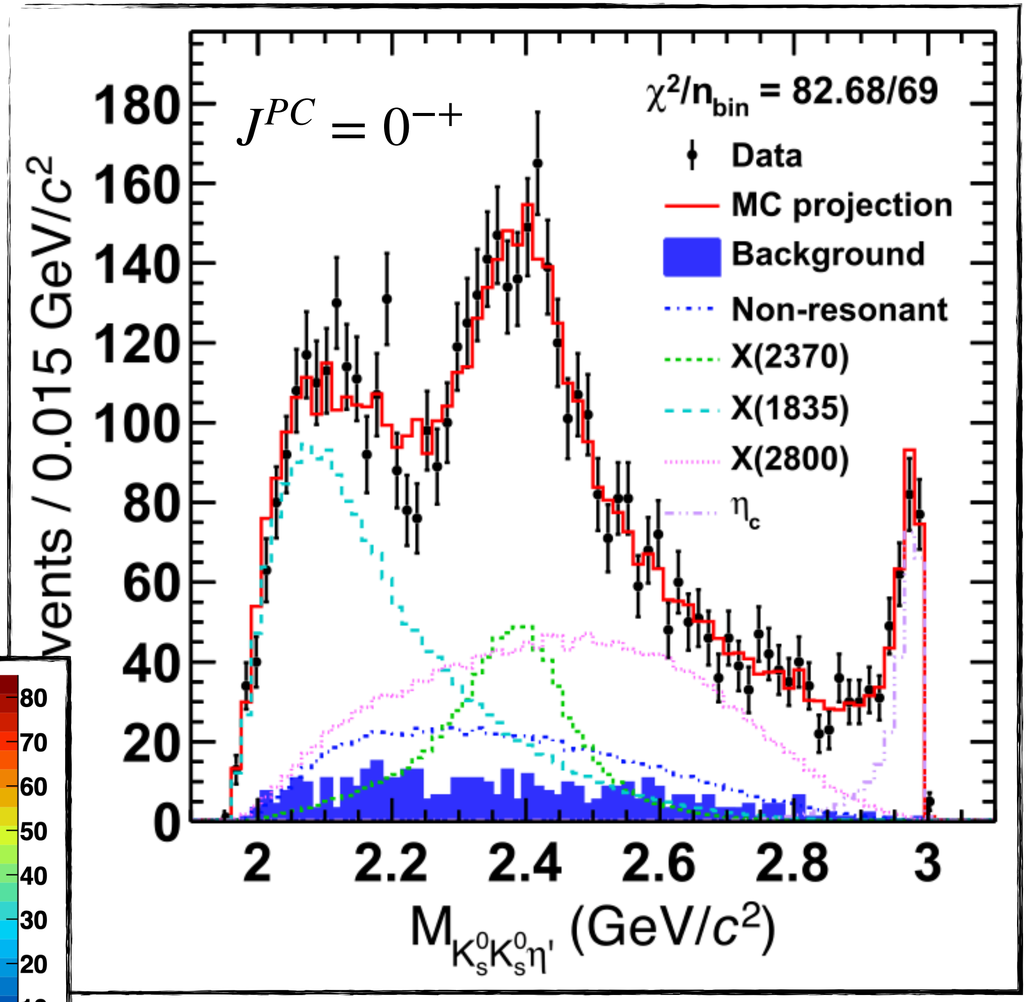
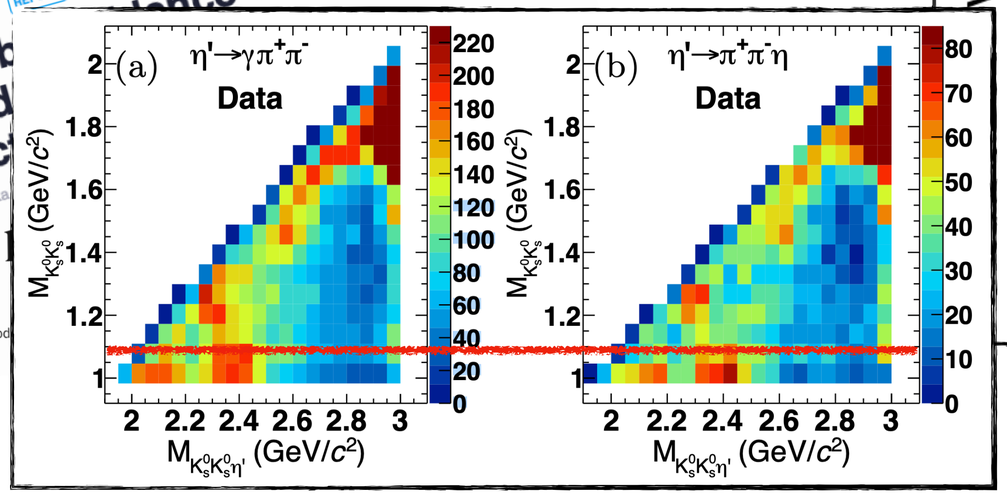
WOW! A NEW PARTICLE!
MAJOR EVIDENCE FOR GLUEBALLS
12:35
Major Evidence of a New Particle Called Glueball: Here's Why It...
289.001 Aufrufe • vor 6 Monaten
Anton Petrov
0:00 New particle physics discovery 0:55 Proton st
4K
Editors' notes
MAY 8, 2024
REPORT
Possible evidence of glueballs found during Beijing Spectrometer III experiments
by Bob Yirka , Phys.org
STARTS WITH A BANG — MAY 7, 2024
New particle at last! Physicists detect the first "glueball"
Glueballs are an unusual, unconfirmed Standard Model prediction, suggesting bound states of gluons alone exist. We just found our first one.

The $X(2370)$

Spin-parity of $X(2370)$ in $J/\psi \to \gamma K_S^0 K_S^0 \eta'$



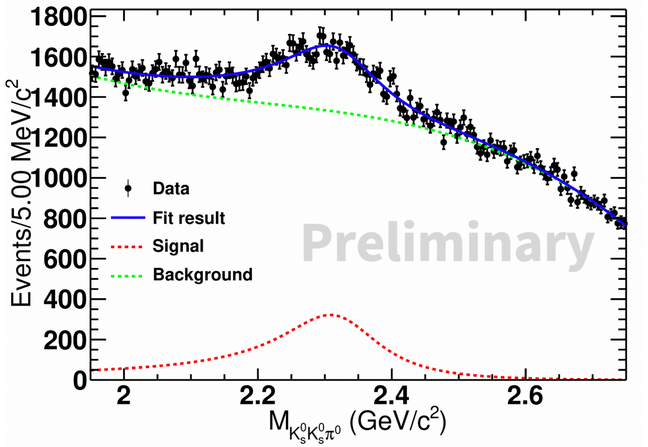
PRL 132, 181901 (2024)



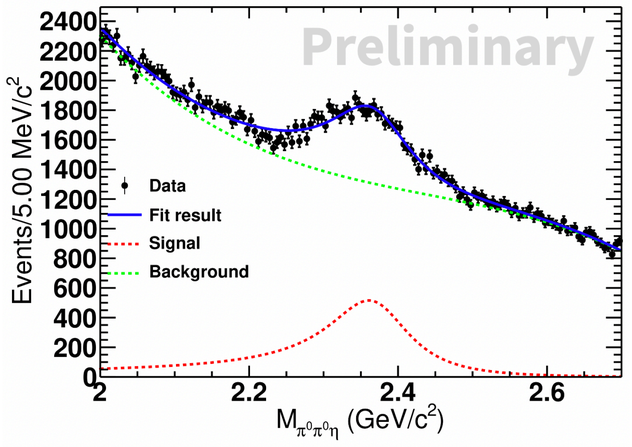
The $X(2370)$

- solid evidence for a new pseudoscalar in multiple final states

$J/\psi \to \gamma K_S^0 K_S^0 \pi^0$



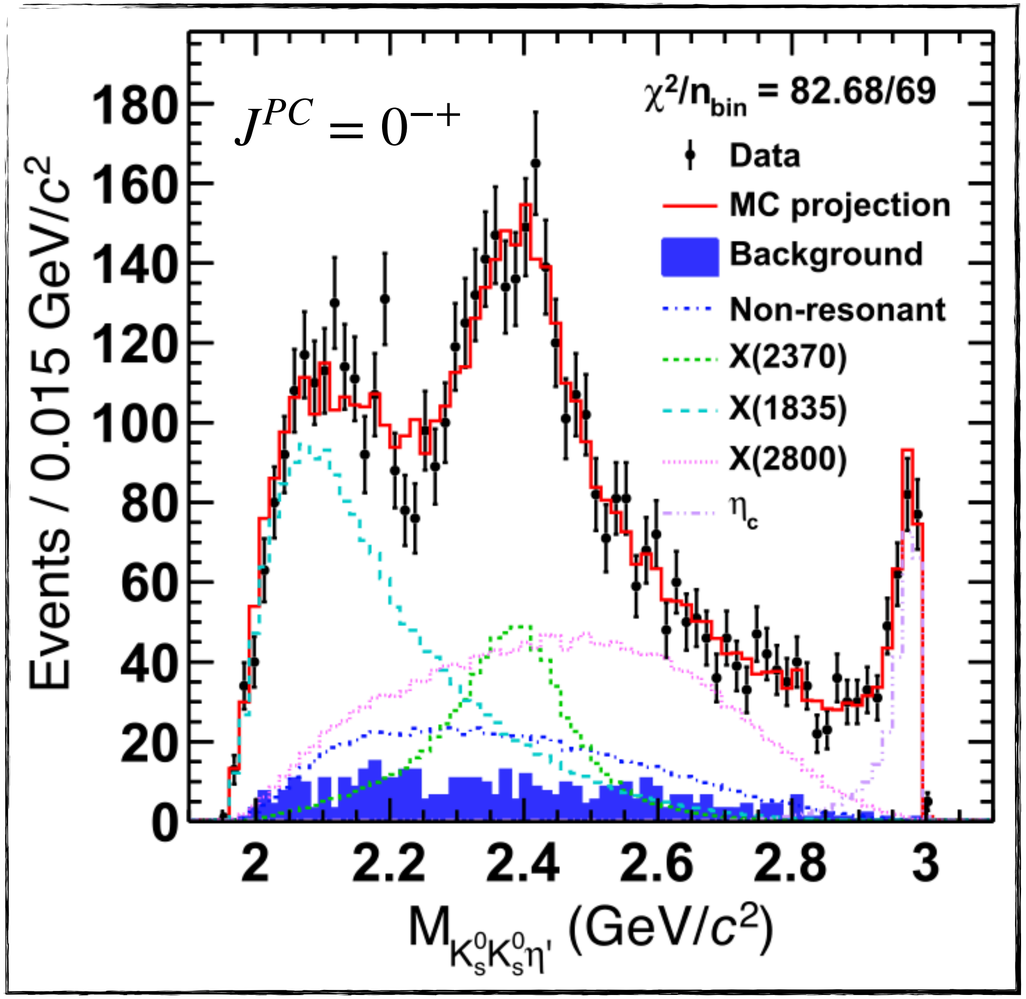
$J/\psi \to \gamma \eta \pi^0 \pi^0$



- possibly through $f_0(980)\eta'$ and $a_0(980)\pi$ intermediate states

→ we need to know much more!

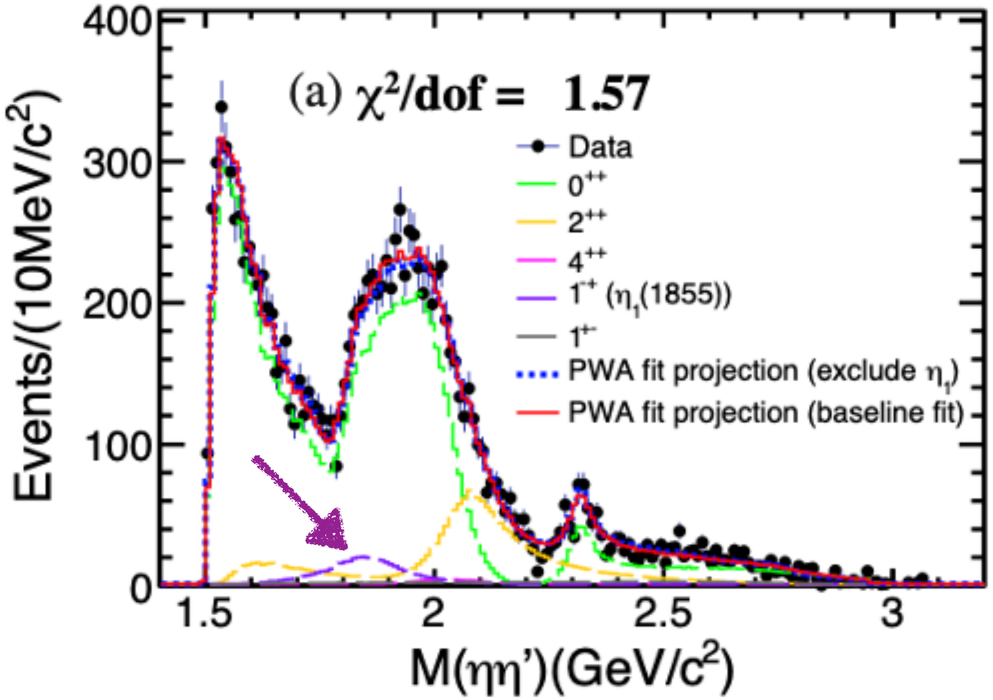
Spin-parity of $X(2370)$ in $J/\psi \to \gamma K_S^0 K_S^0 \eta'$

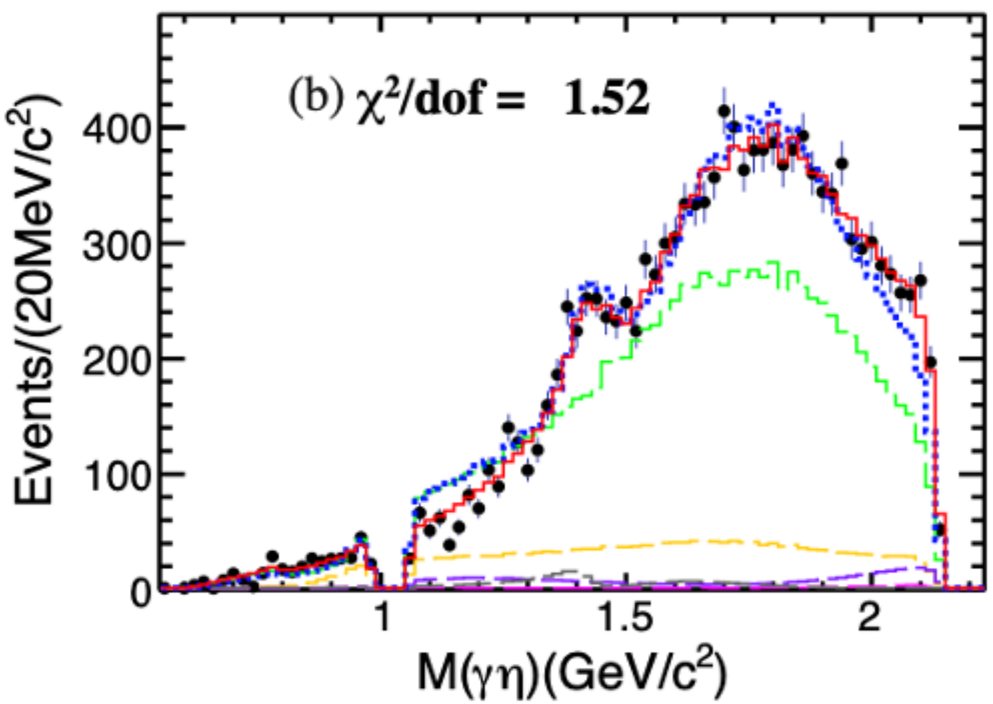


PRL 132, 181901 (2024)

$J/\psi \to \gamma\eta\eta'$

- a new spin-exotic: the $\eta_1(1855)$ with $J^{PC} = 1^{-+}$





PRL 129 (2022) 19, 192002, PRL 130 (2023) 15, 159901 (erratum)
PRD 106 (2022) 7, 072012, PRD 107 (2023) 7, 079901 (erratum)

$J/\psi \to \gamma\eta\eta'$

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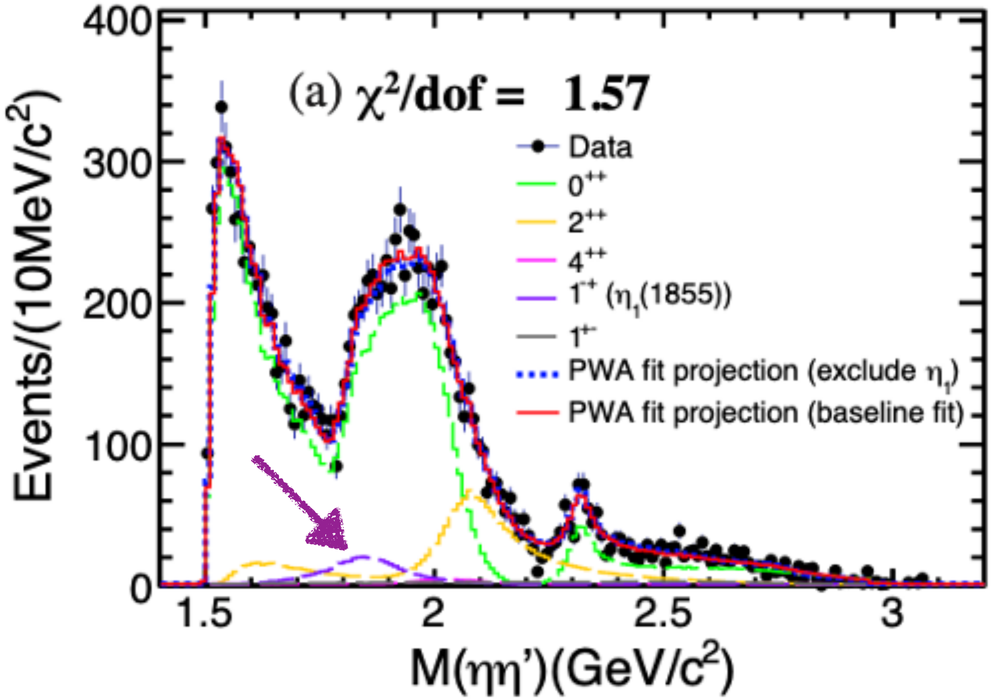
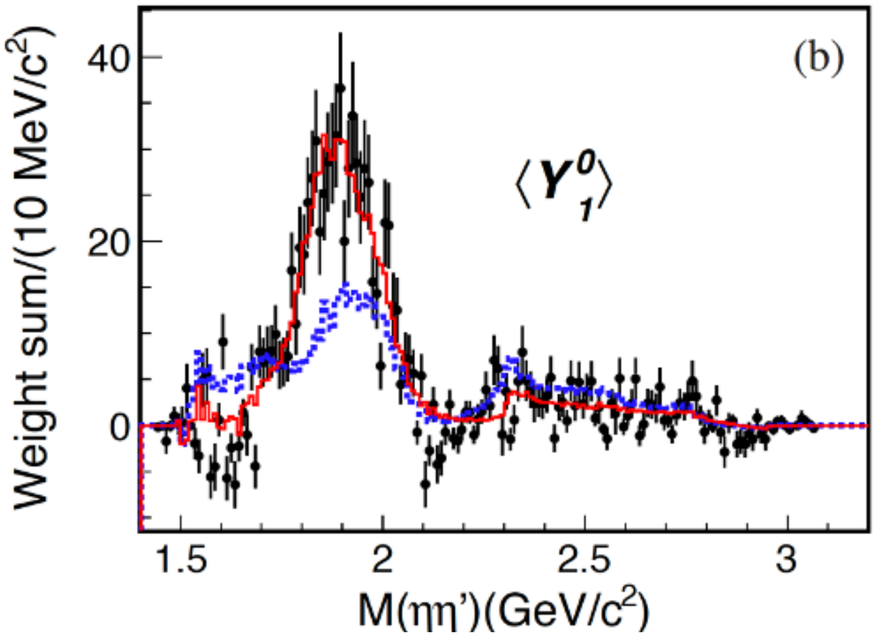
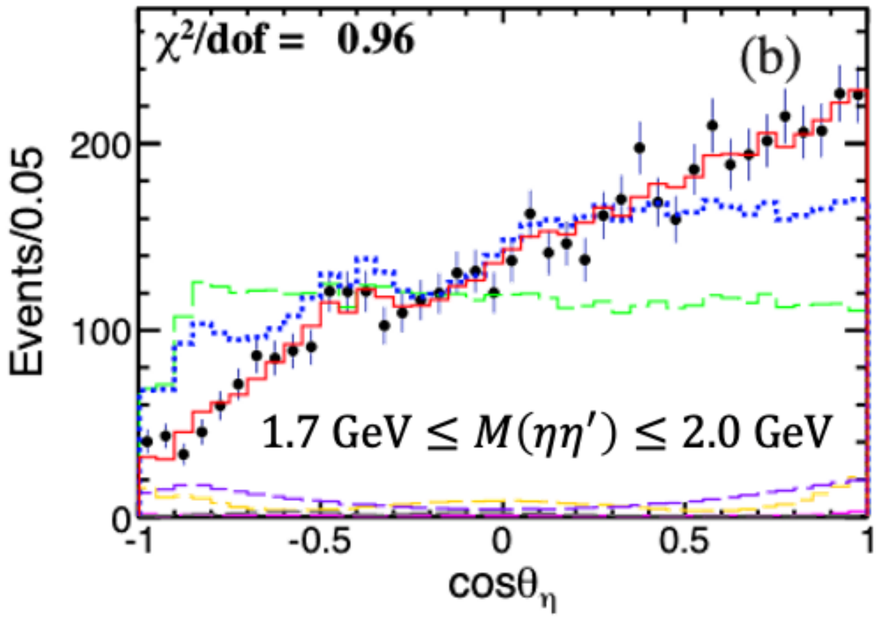






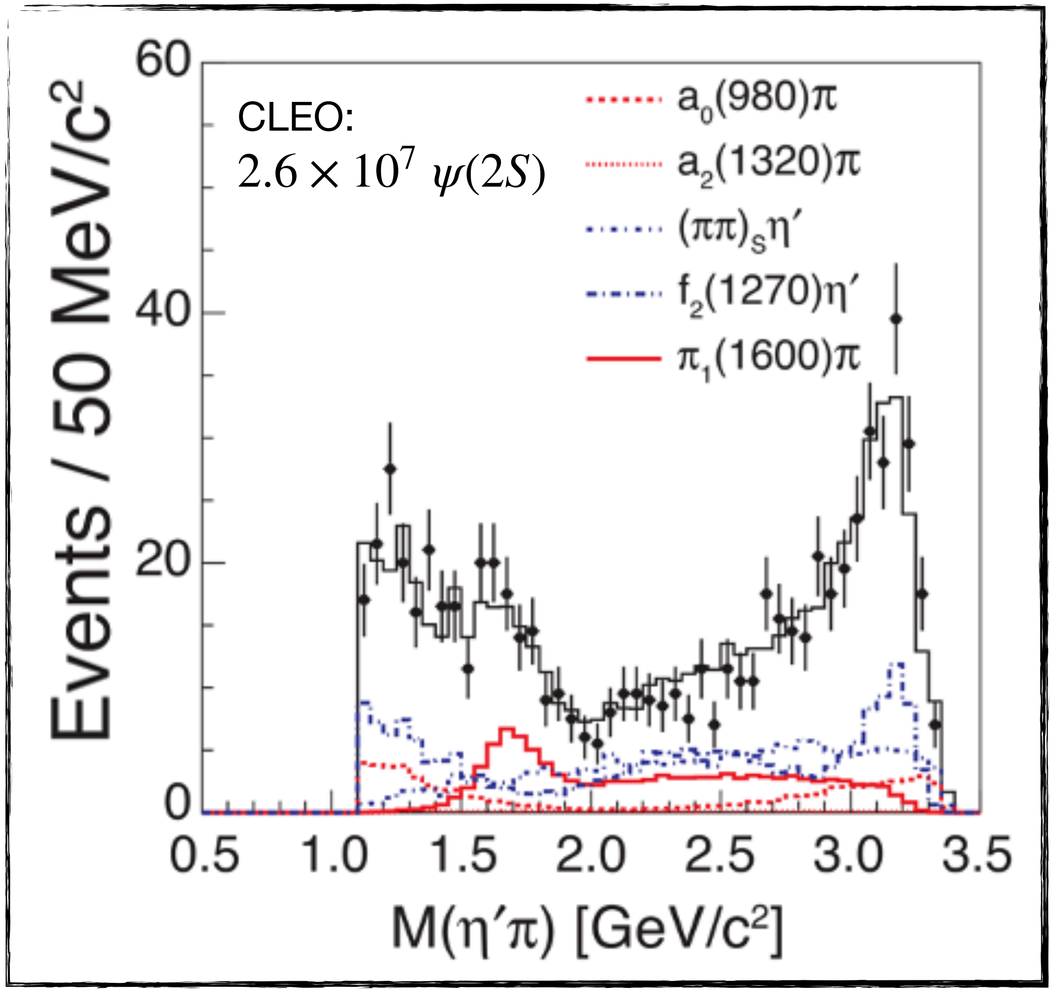
→ need independent confirmation

→ need more info on production & decay for interpretation

PRL 129 (2022) 19, 192002, PRL 130 (2023) 15, 159901 (erratum)
PRD 106 (2022) 7, 072012, PRD 107 (2023) 7, 079901 (erratum)

$\chi_{c1} \to \eta'\pi\pi$

and the case for a large $\psi(2S)$ sample

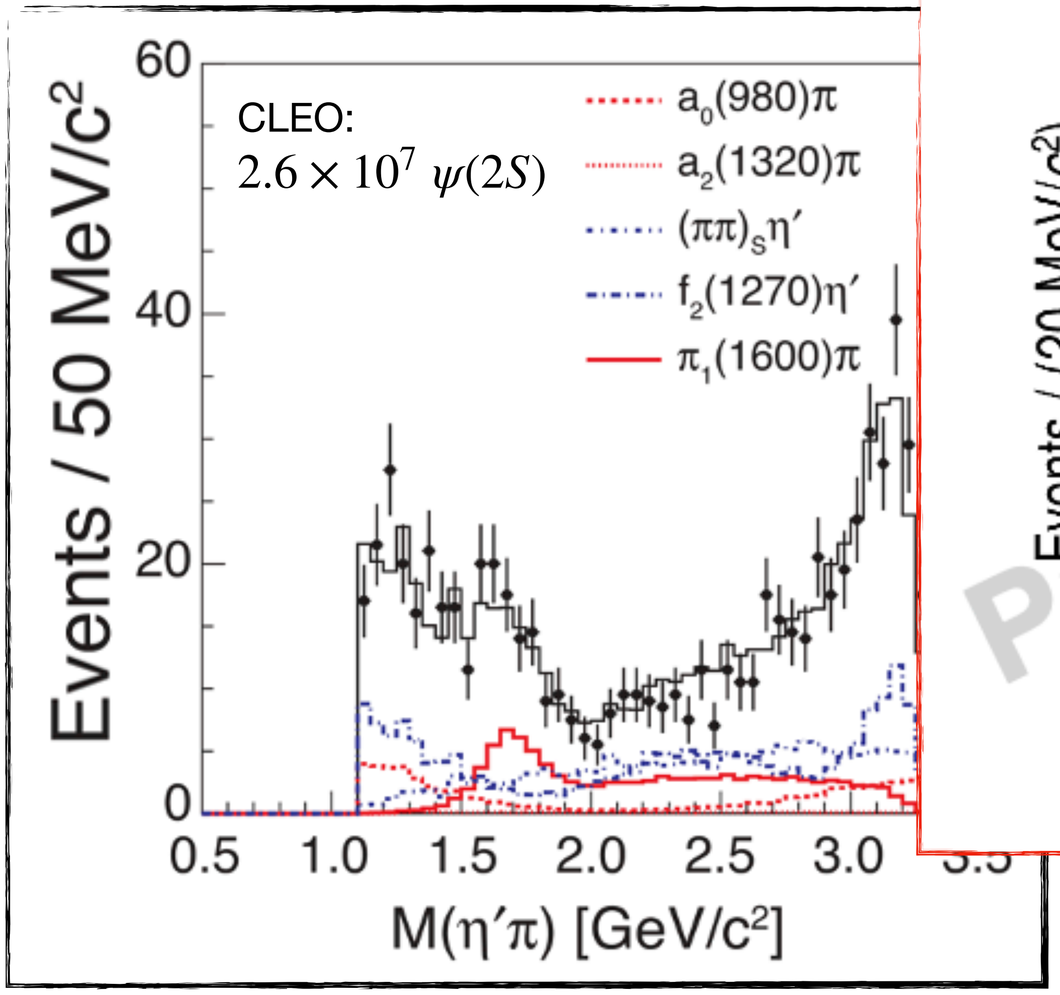


CLEO see a $\pi_1(1600)$, but lack evidence for phase-motion

PRD 84, 112009 (2011)

$\chi_{c1} \to \eta'\pi\pi$

and the case for a large $\psi(2S)$ sample



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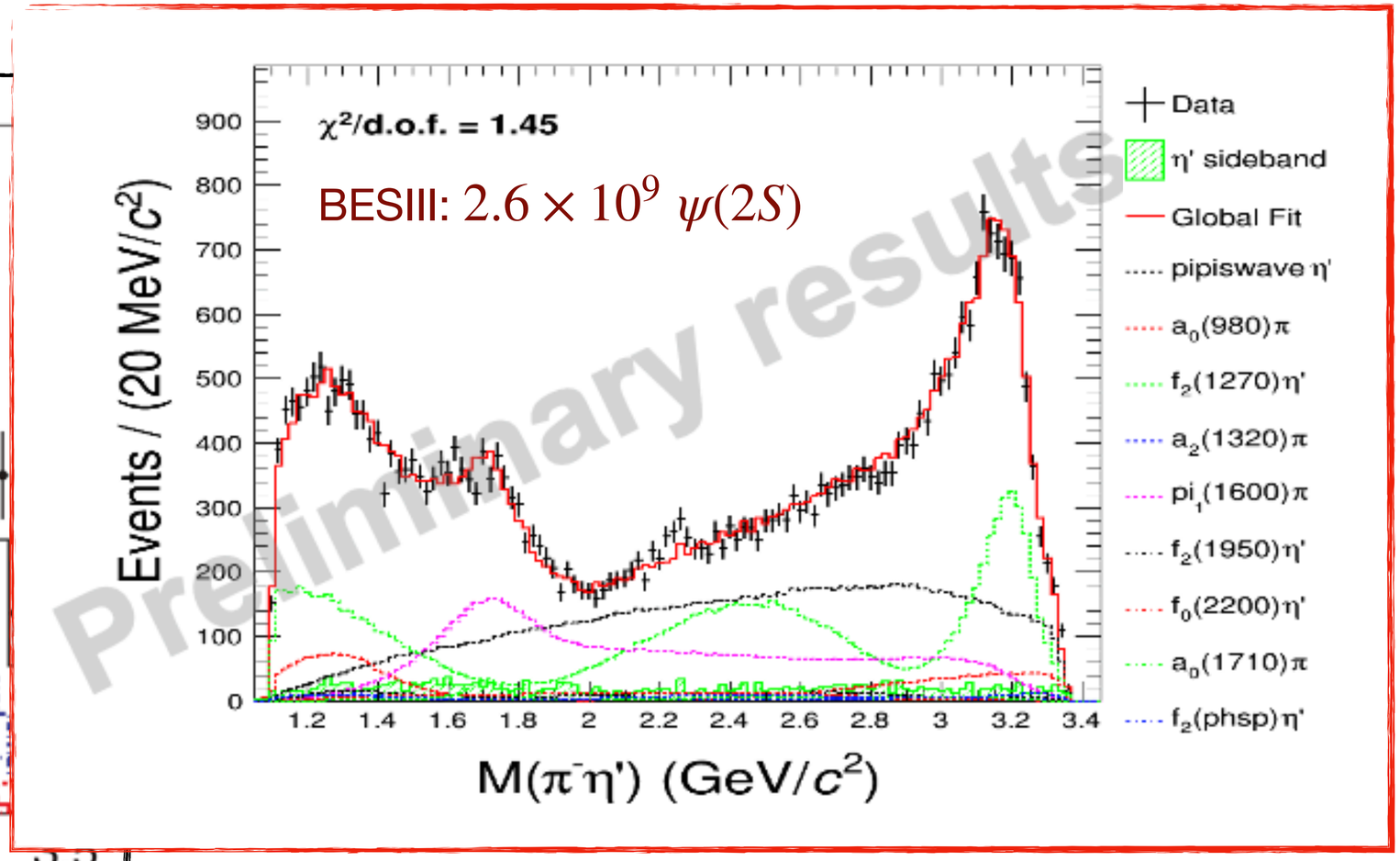
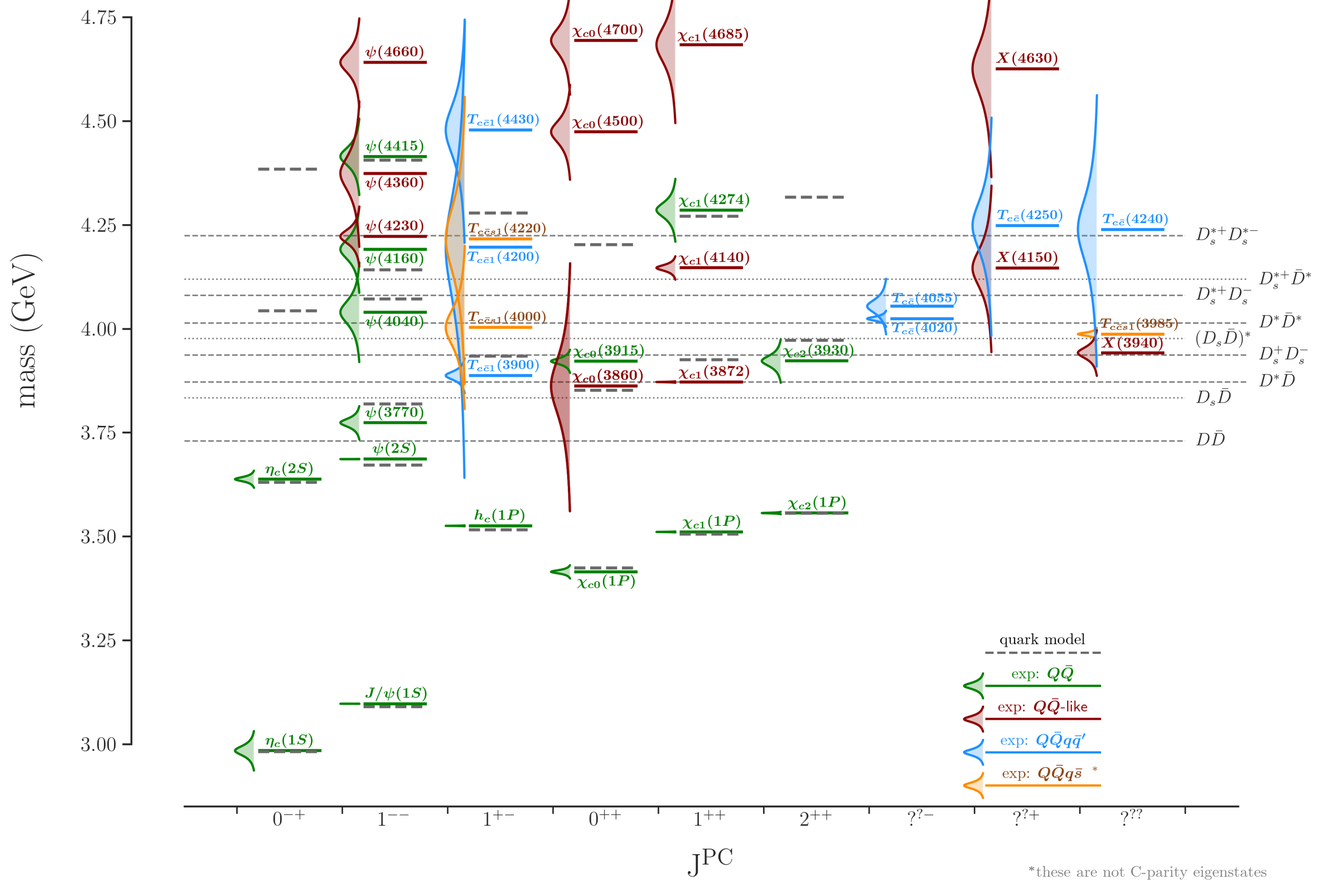


- clear signal of $\chi_{c1} \to \pi_1(1600)\pi$
- now looking for other decay modes

Charmonium(-like) states

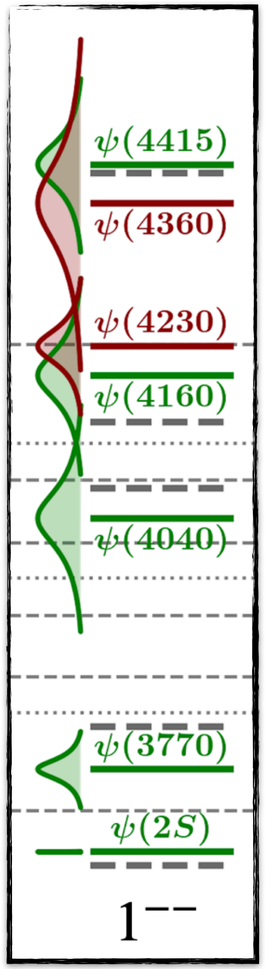
Charmonium(-like) states

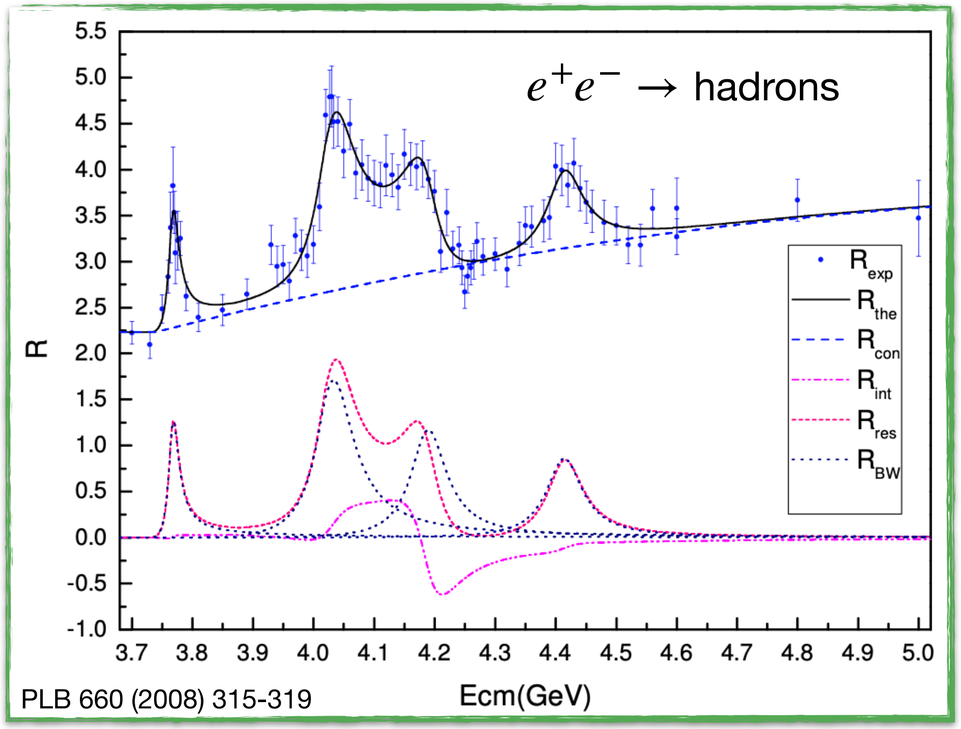


arXiv:2410.06923

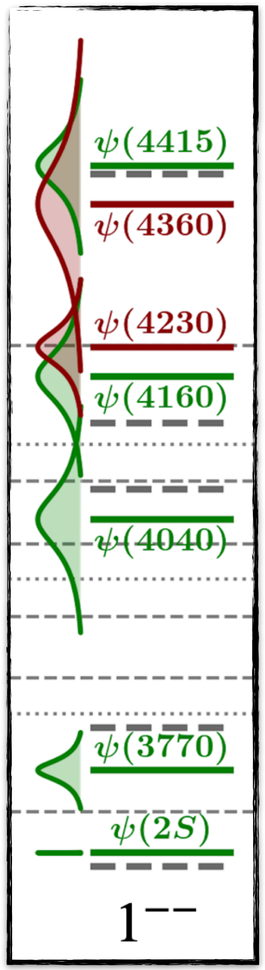
- large number of potentially exotic hadrons discovered above open-charm threshold
- many of them in b-decays at LHCb
- BESIII: directly produce the vector states in e^+e^- annihilation
- transitions to $X(3872)$, Z_c, Z_{cs}

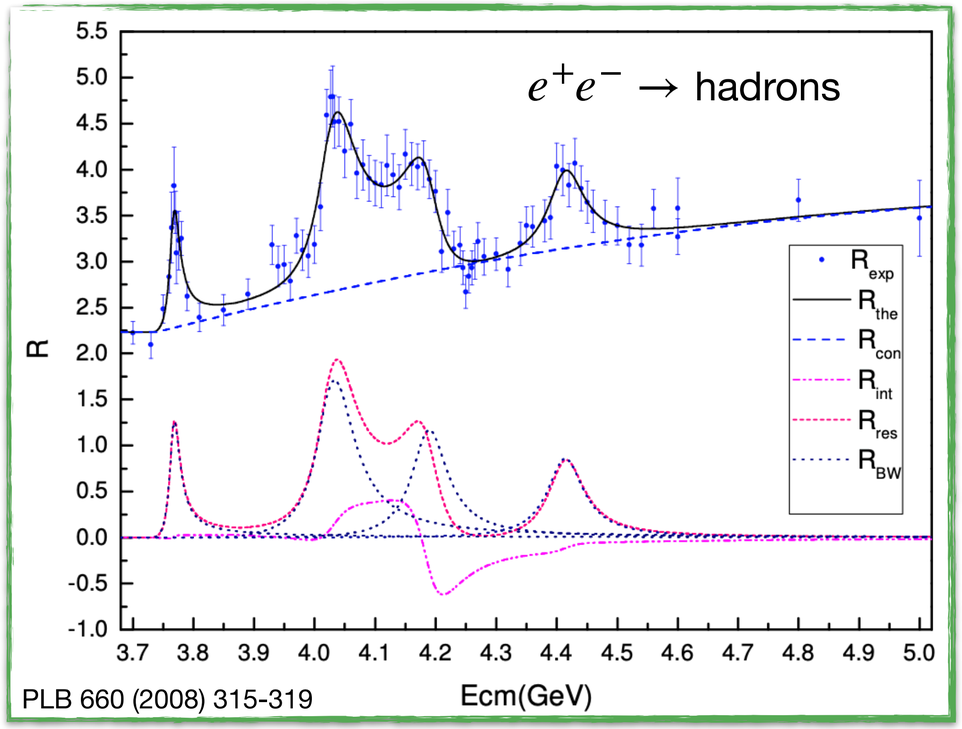
The vector states





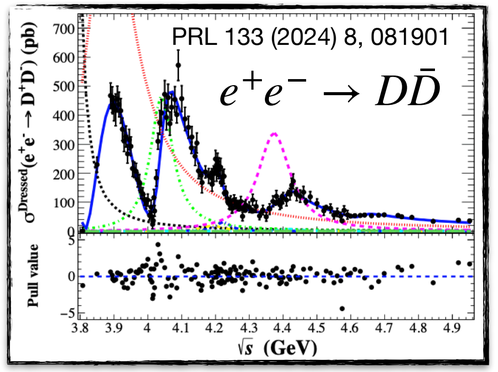
The vector states

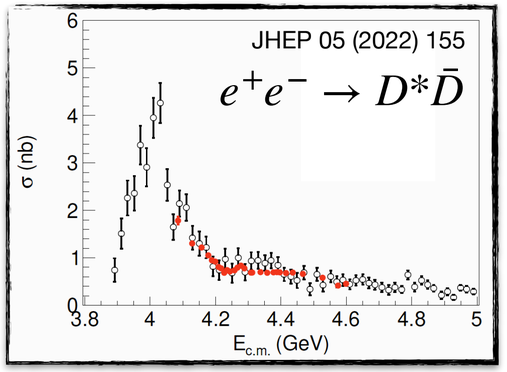


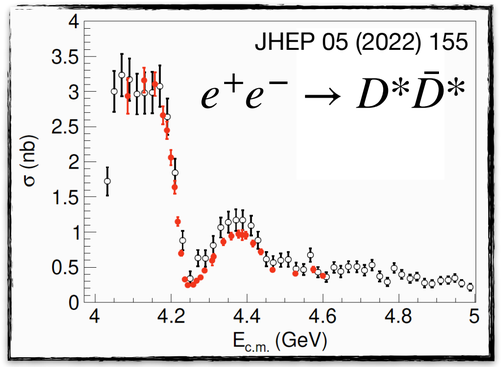


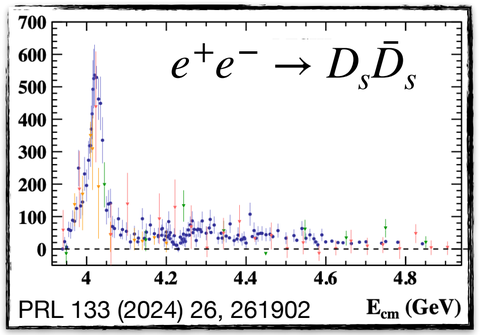
→ working towards exclusive measurements of all the various open-charm production processes

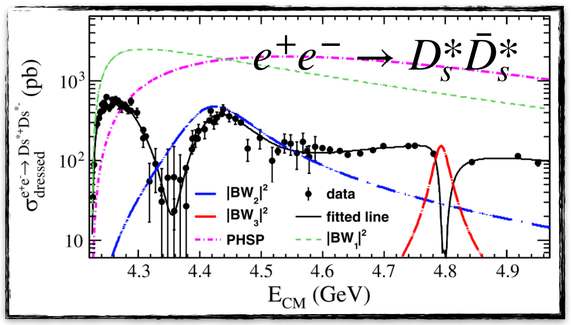
→ cross sections are hard to interpret



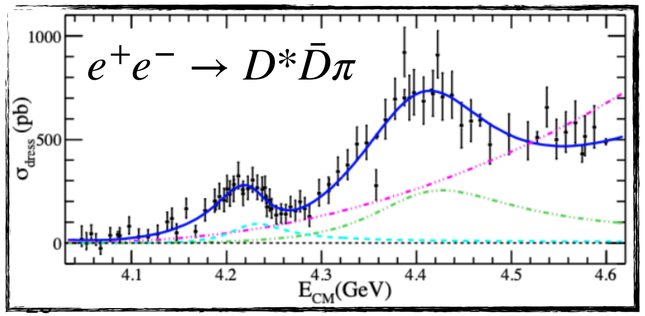




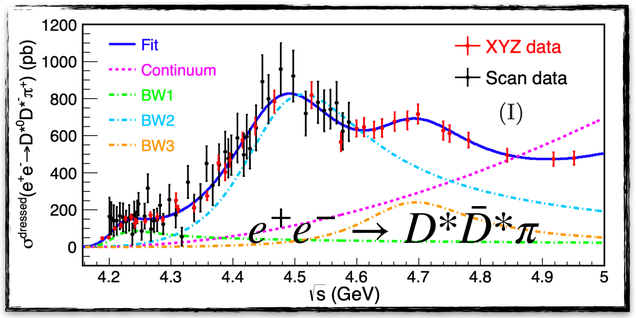




PRL 131 (2023) 15, 151903

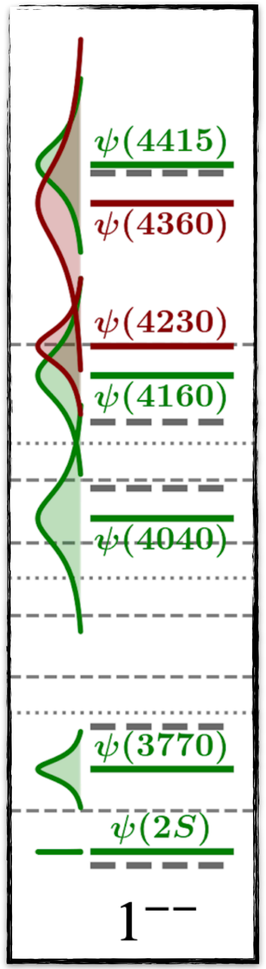


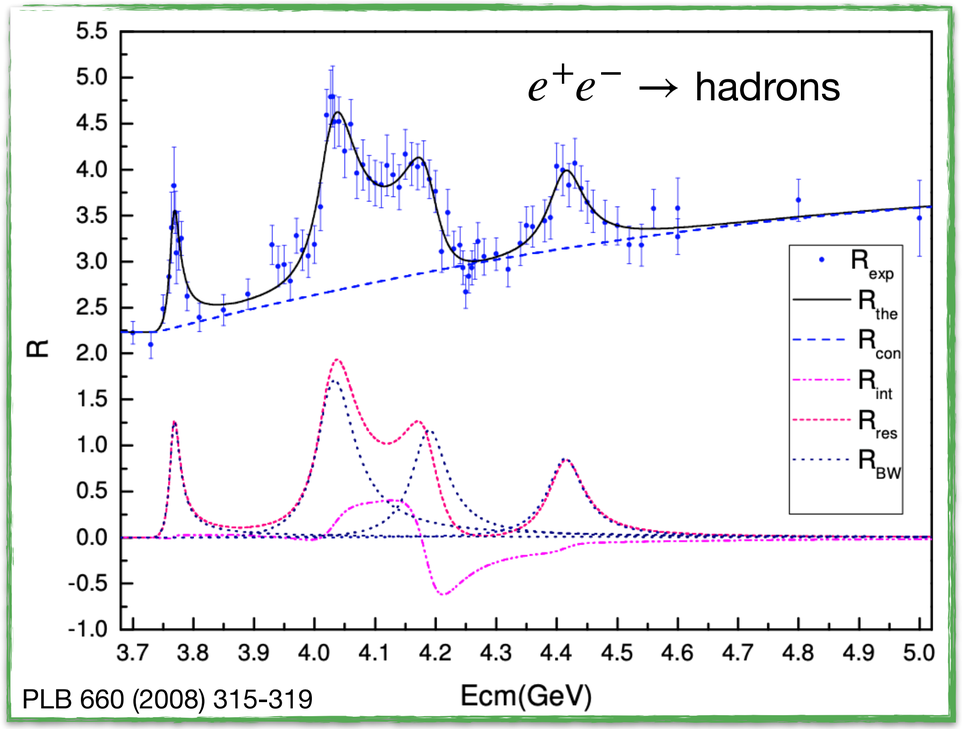
PRL 122 (2019) 10, 102002



PRL 130 (2023) 12, 121901

The vector states





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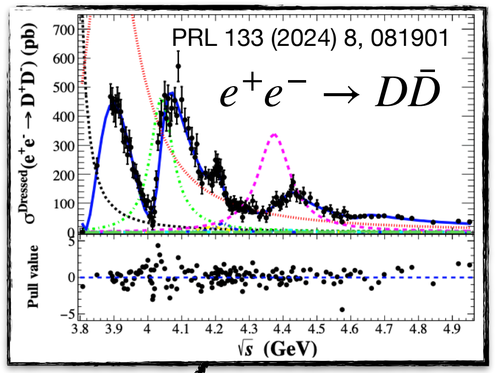
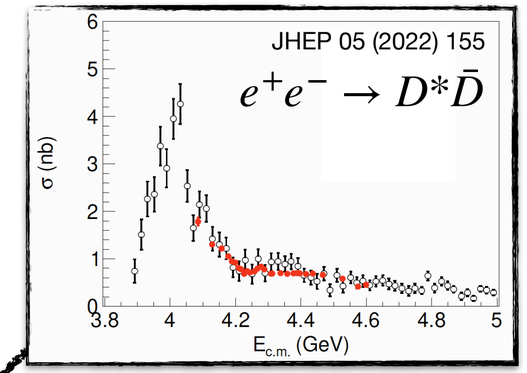
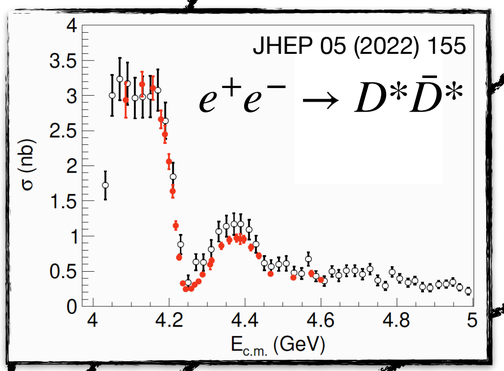
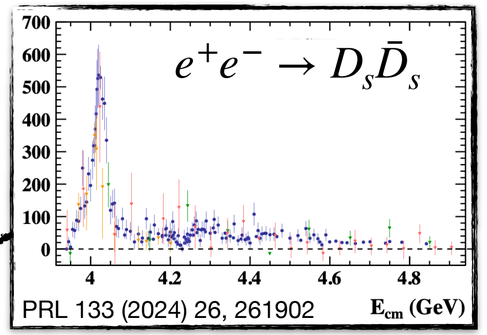
→ cross sections are hard to interpret

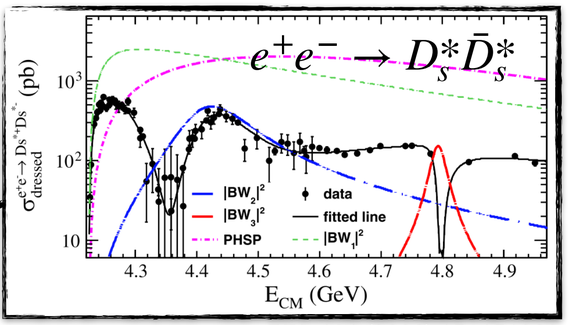
$= \sum_i$



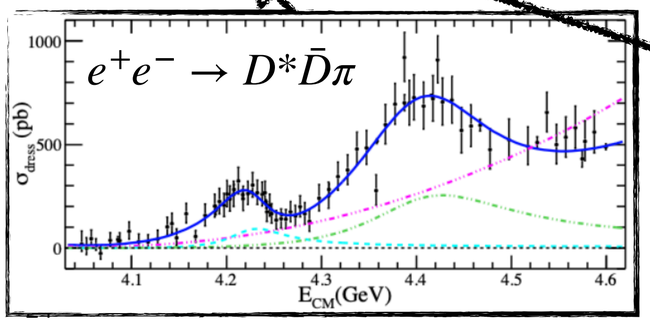




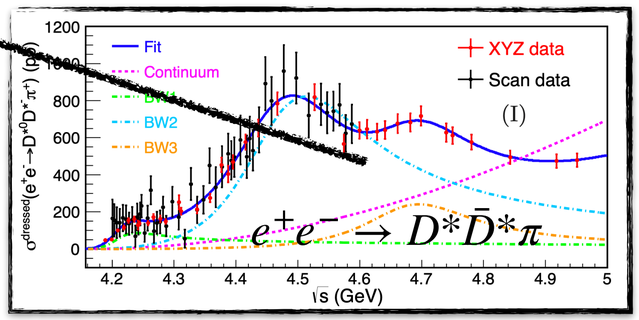




PRL 131 (2023) 15, 151903

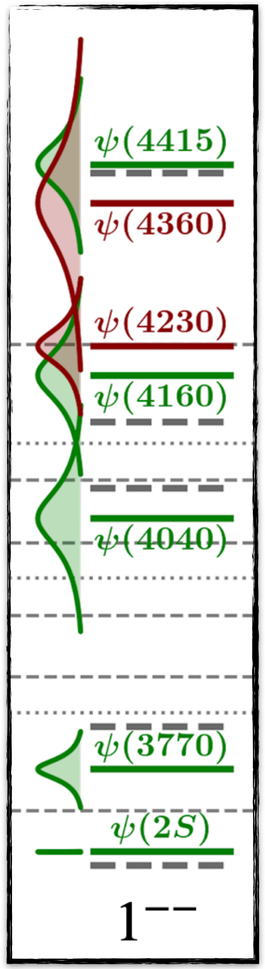


PRL 122 (2019) 10, 102002

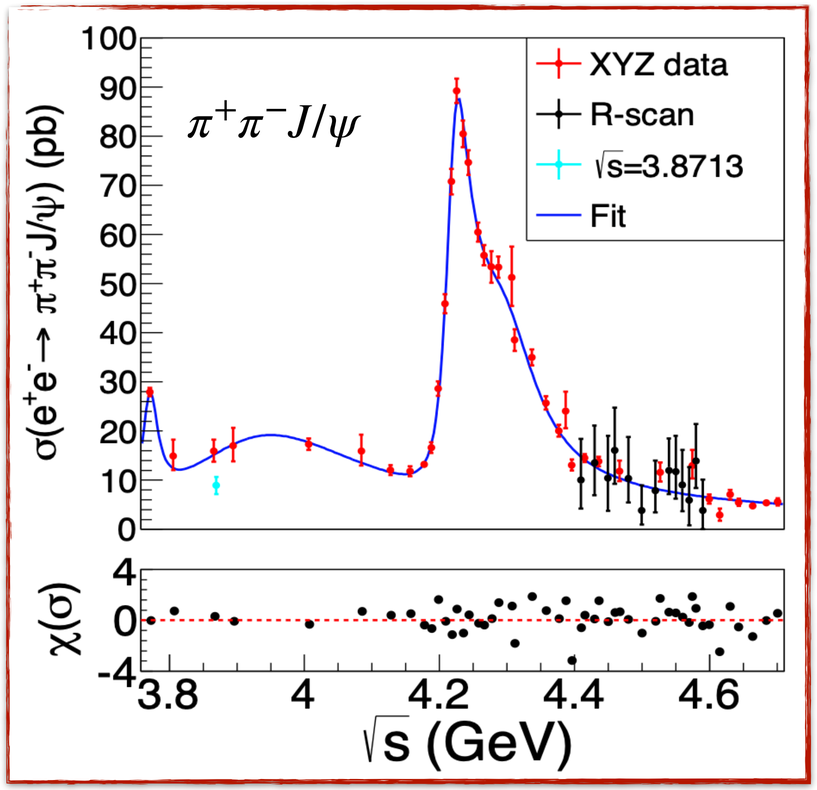


PRL 130 (2023) 12, 121901

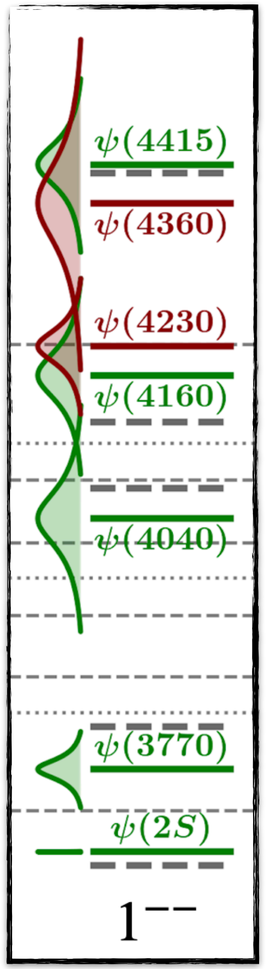
The vector states



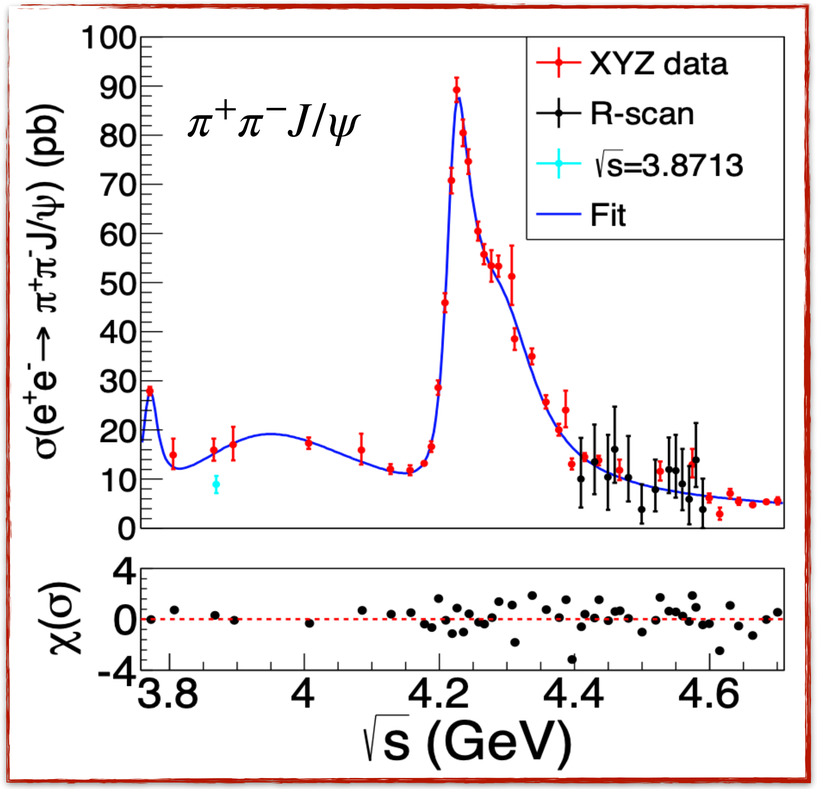
PRD 106 (2022) 7, 072001



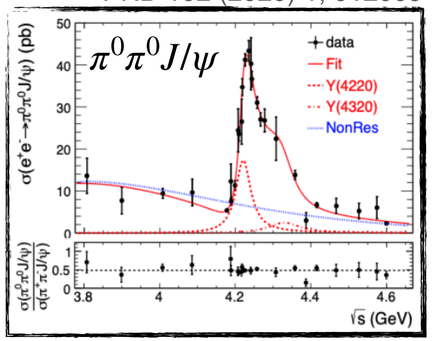
The vector states



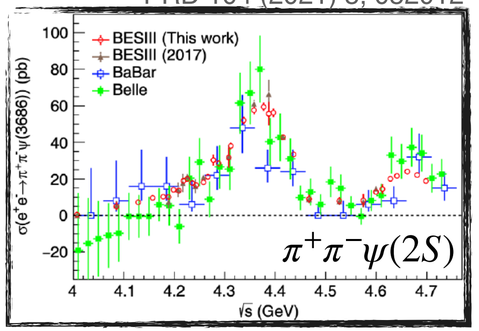
PRD 106 (2022) 7, 072001



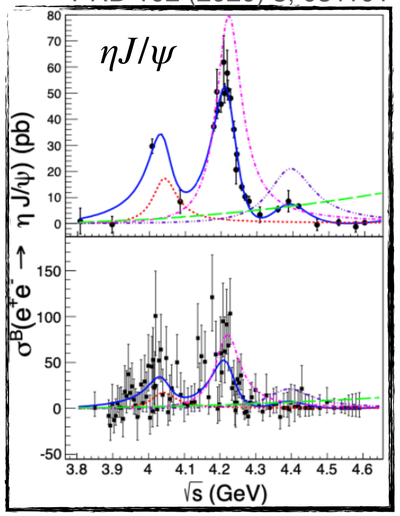
PRD 102 (2020) 1, 012009



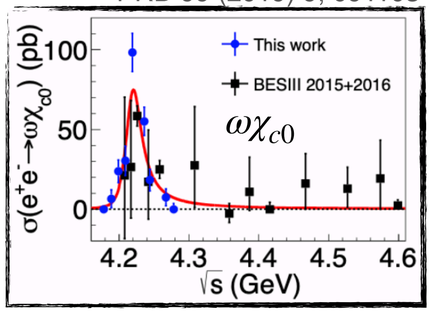
PRD 104 (2021) 5, 052012



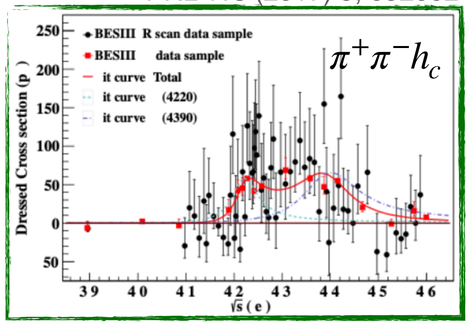
PRD 102 (2020) 3, 031101



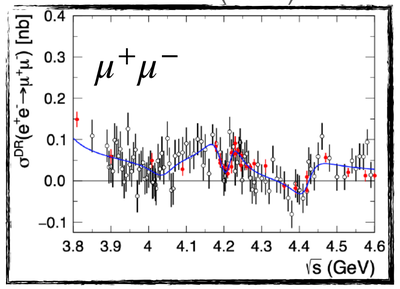
PRD 99 (2019) 9, 091103



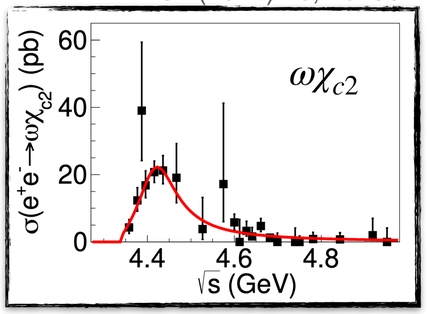
PRL 118 (2017) 9, 092002



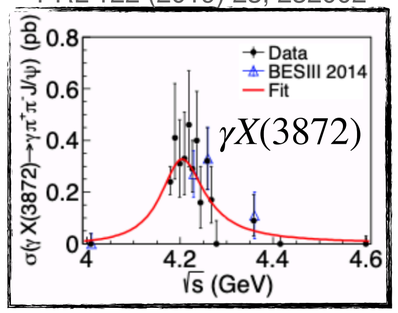
PRD 102 (2020) 112009



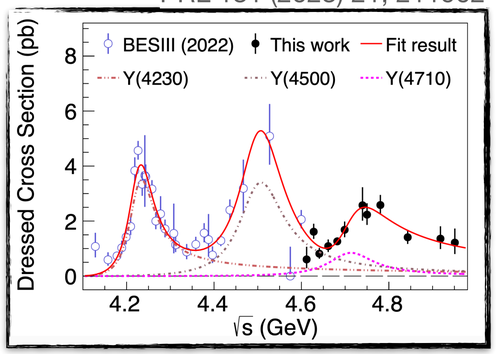
PRL 132 (2024) 16, 161901



PRL 122 (2019) 23, 232002



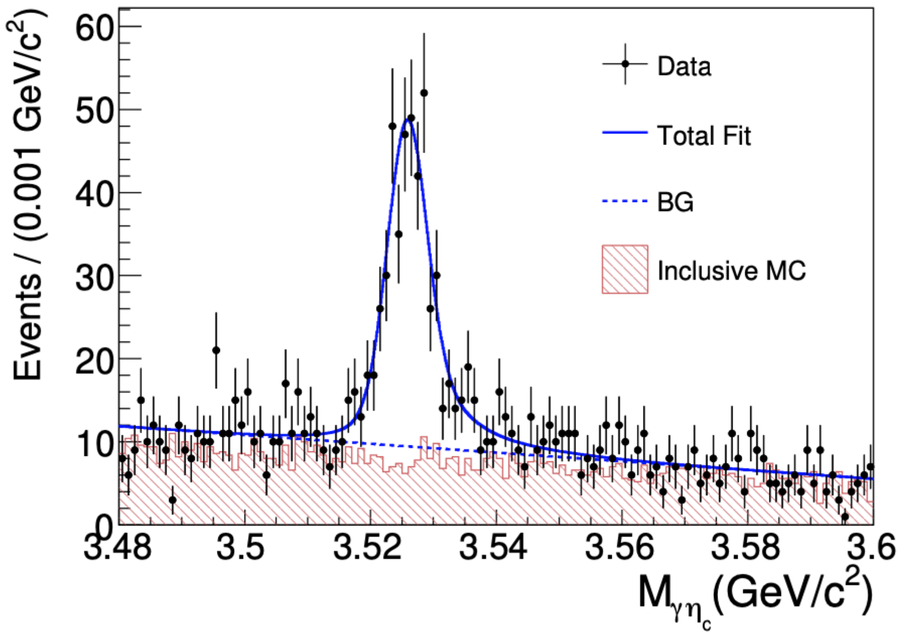
PRL 131 (2023) 21, 211902



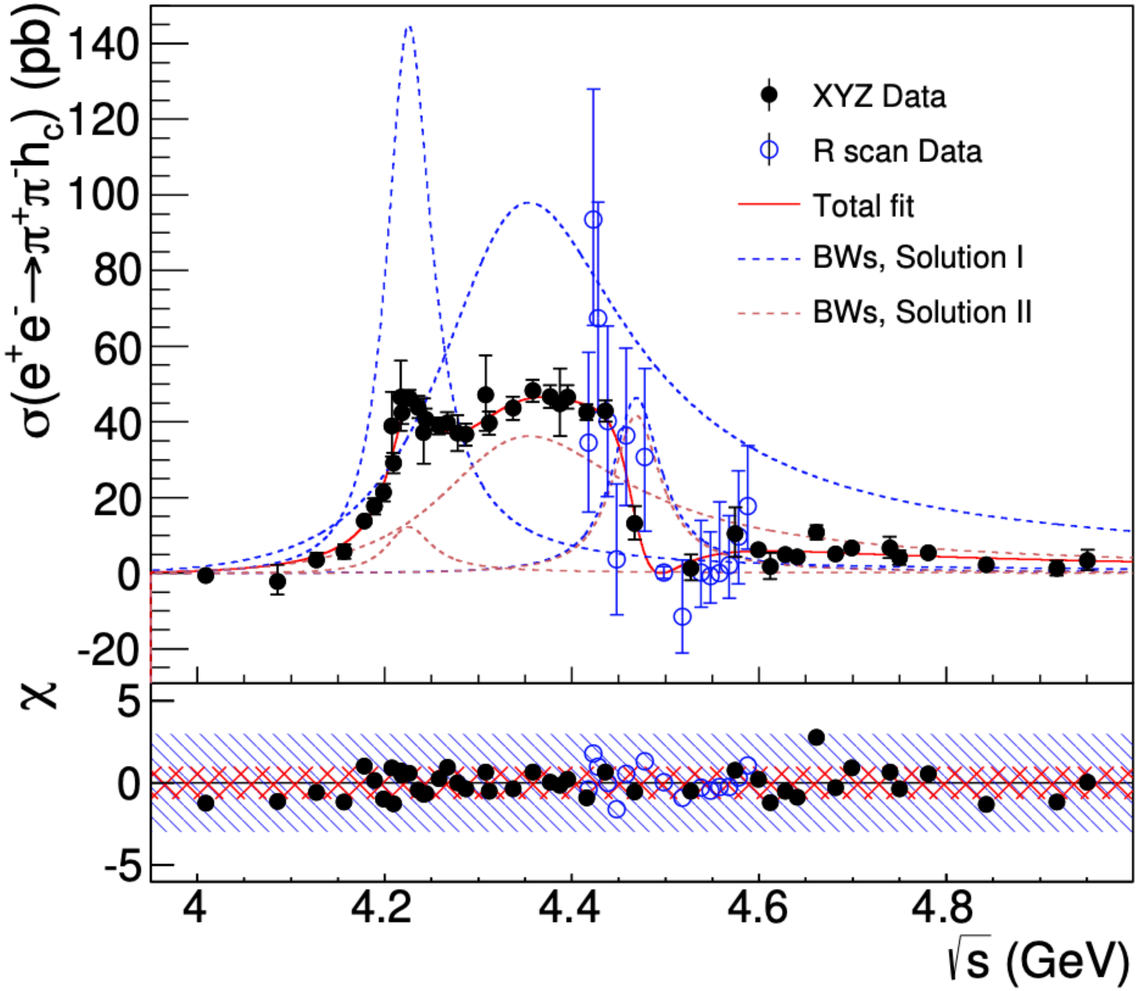
+ many more (including light hadron channels)

Updated $e^+e^- \to h_c\pi^+\pi^-$

$h_c \to \gamma\eta_c$ with η_c reconstructed in 16 different decay modes

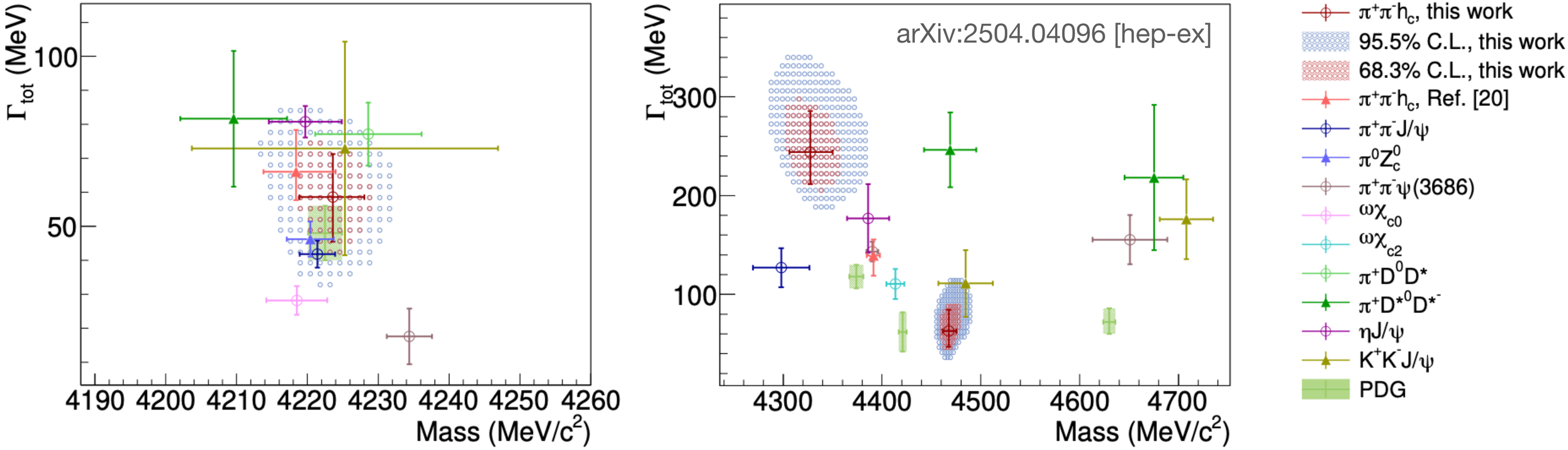


arXiv:2504.04096 [hep-ex]



The vector states - an overview

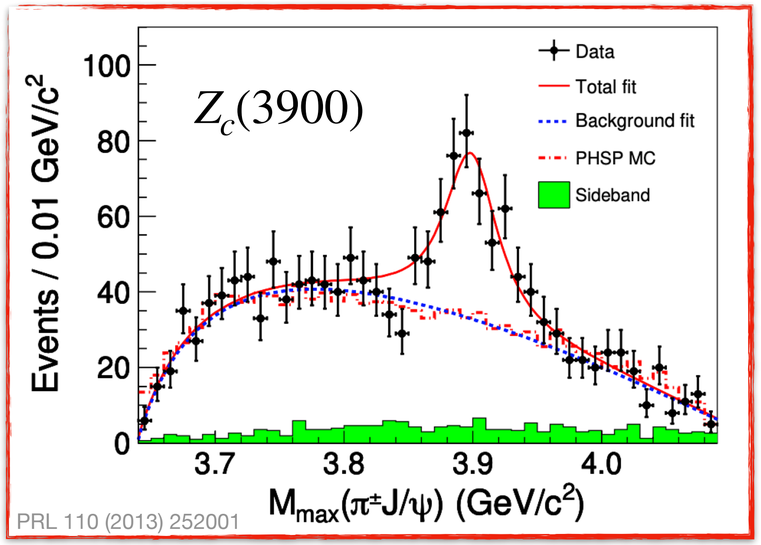
- we know a lot: many, many possible $e^+e^- \to (c\bar{c})(q\bar{q})$, $(c\bar{q})(\bar{c}q)$ processes have been studied



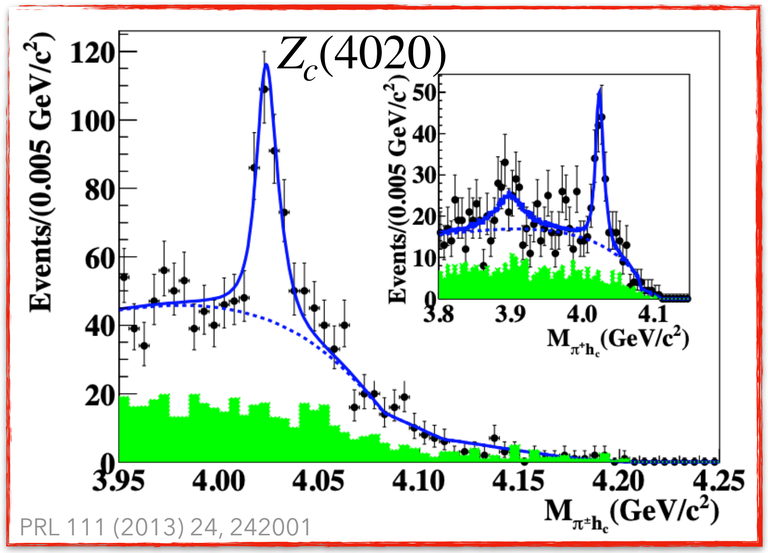
- it still seems we understand too little… no coherent picture of the vector states

Charged charmonium-like states

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

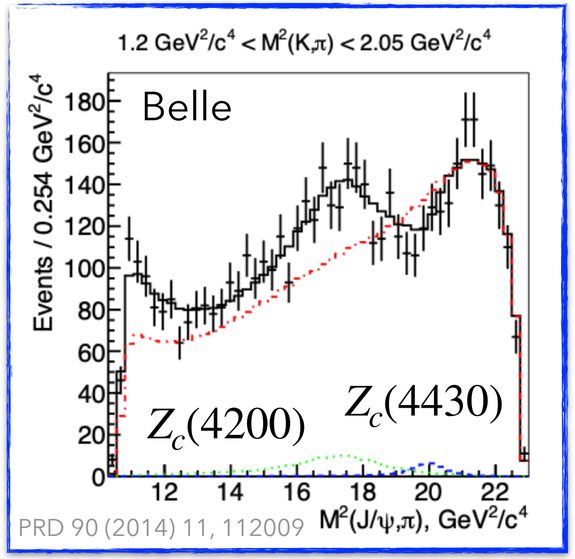


PRL 110 (2013) 252001

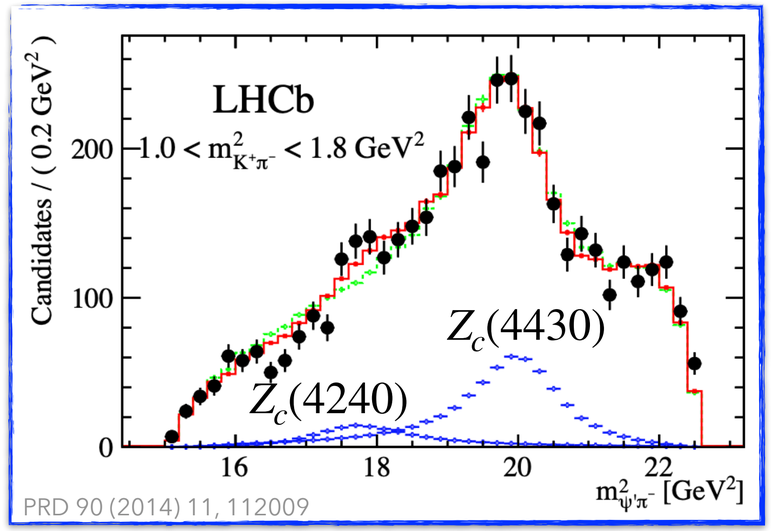


PRL 111 (2013) 24, 242001

$B \to Z_c K$



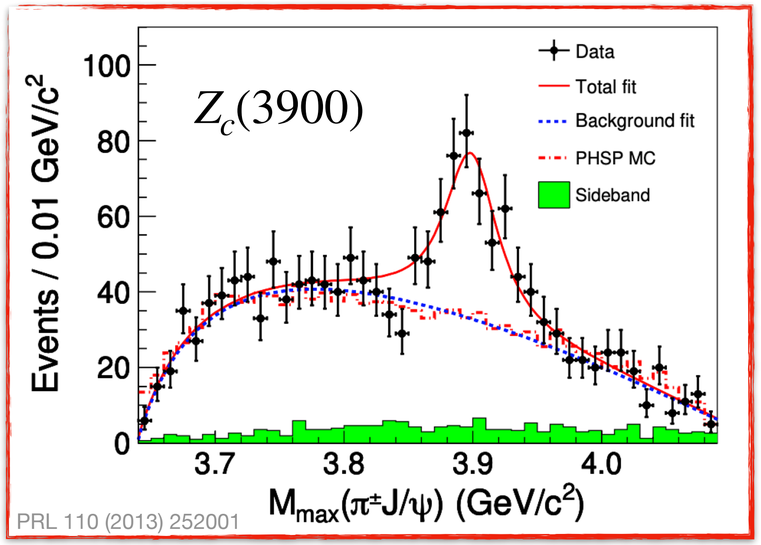
PRD 90 (2014) 11, 112009



PRD 90 (2014) 11, 112009

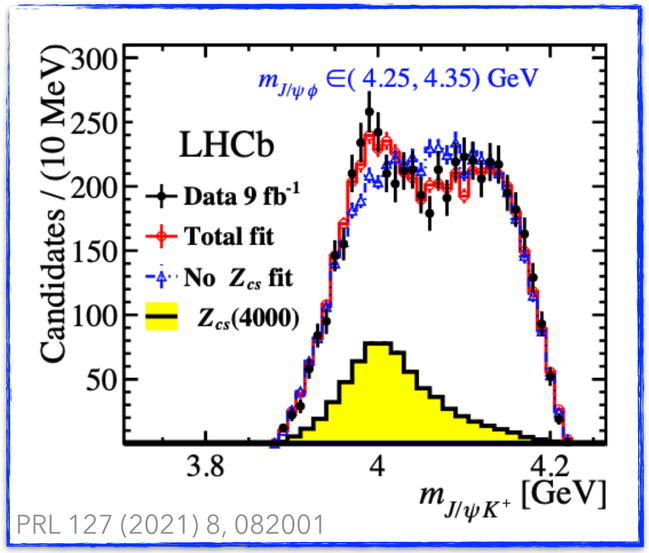
Charged charmonium-like states

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



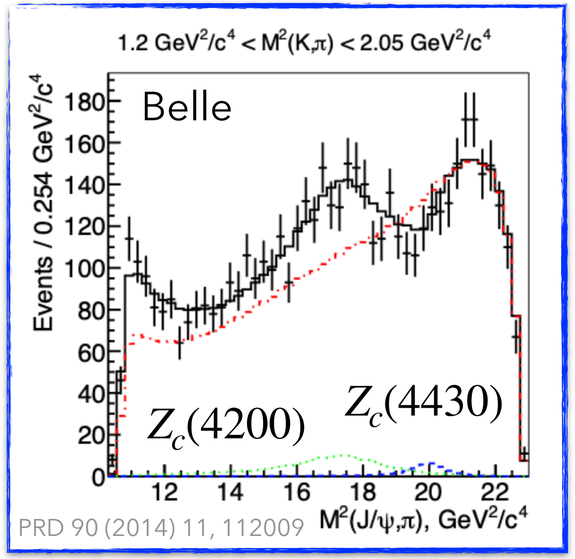
PRL 110 (2013) 252001

$B \to Z_{cs}\phi$



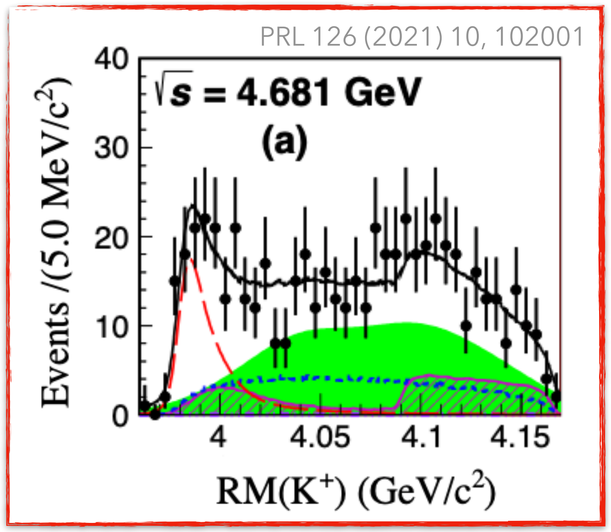
PRL 127 (2021) 8, 082001

$B \to Z_c K$

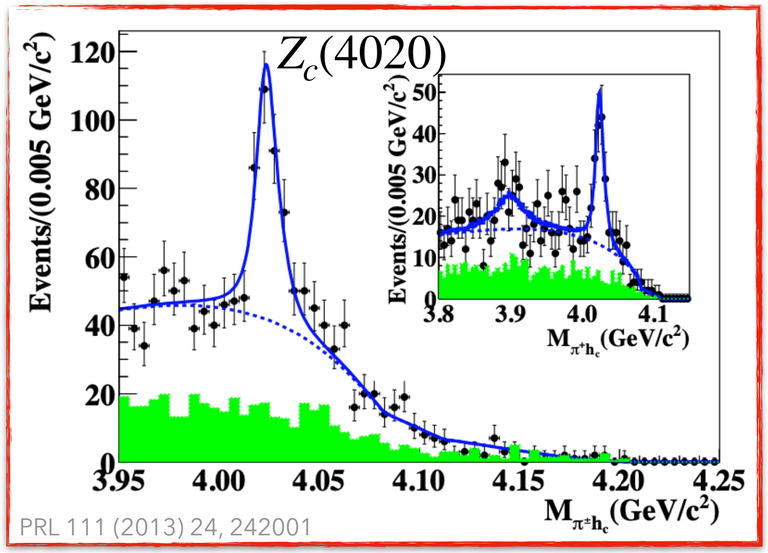


PRD 90 (2014) 11, 112009

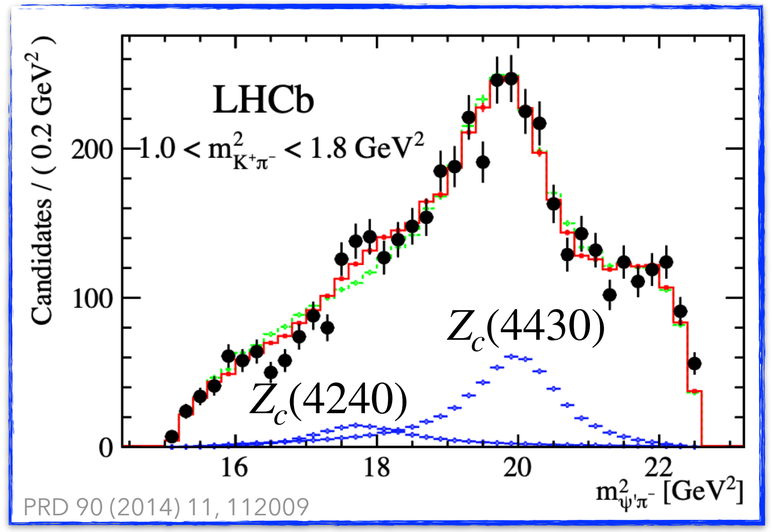
$e^+e^- \to Z_{cs}K$



PRL 126 (2021) 10, 102001



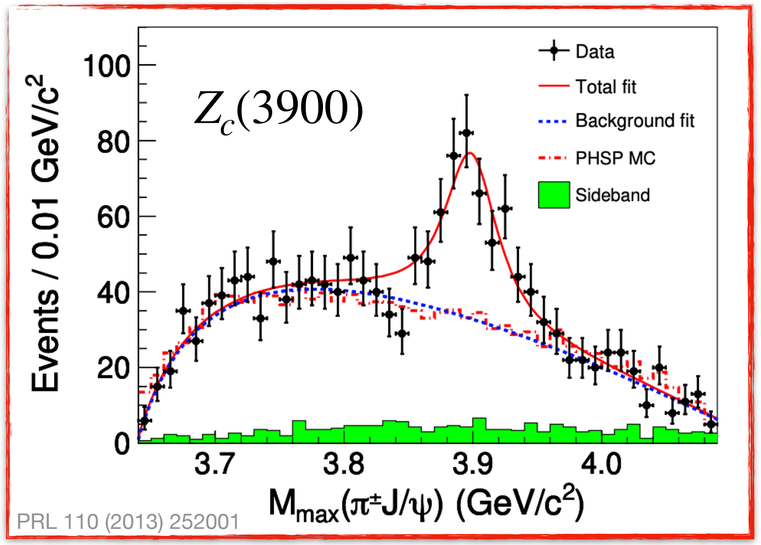
PRL 111 (2013) 24, 242001



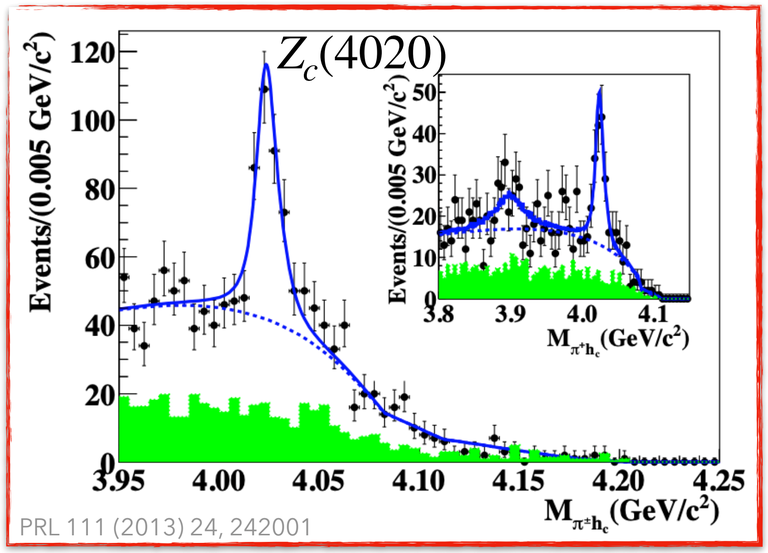
PRD 90 (2014) 11, 112009

Charged charmonium-like states

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

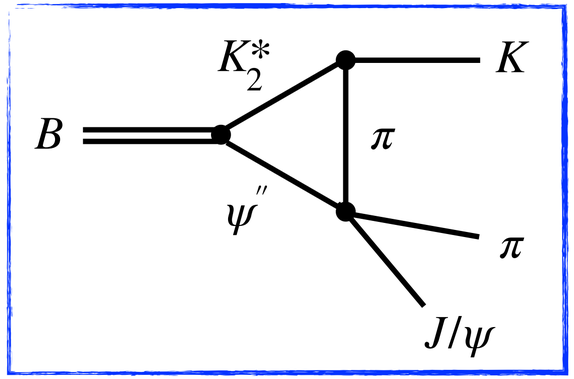


PRL 110 (2013) 252001

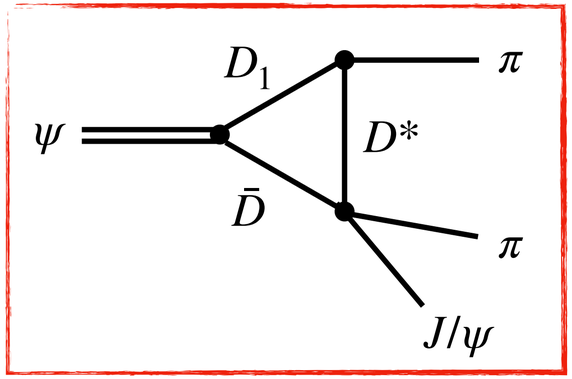


PRL 111 (2013) 24, 242001

are triangle singularities the solution?

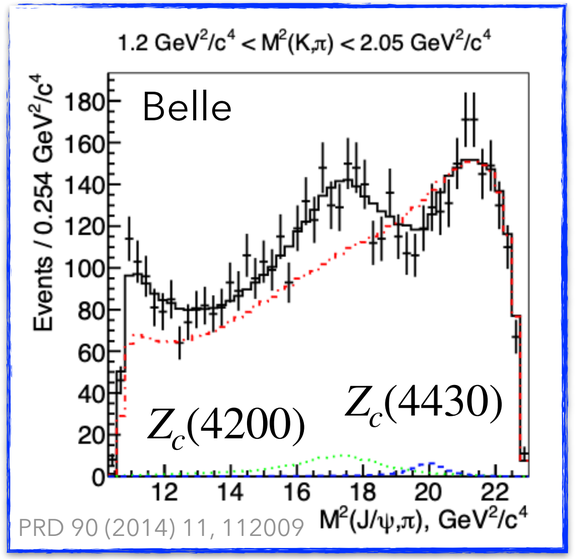


PRD 100 (2019) 1, 011504

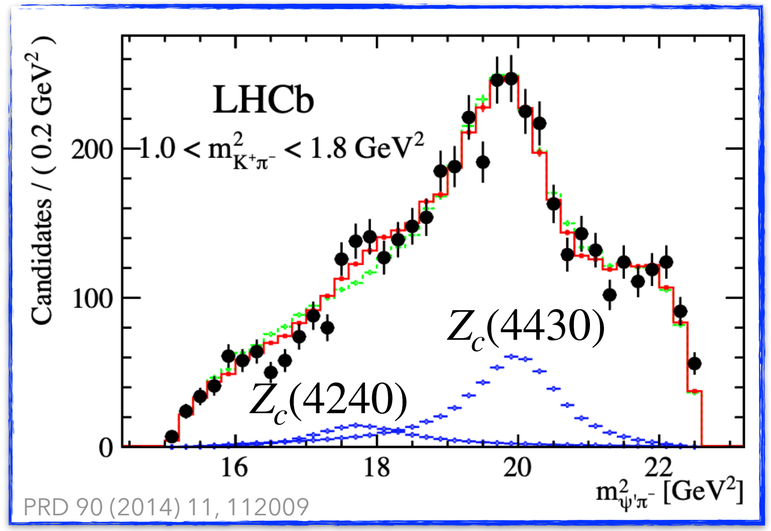


PRL 111 (2013) 13 132003
PLB 747 (2015) 410
PLB 755 (2016) 337
PLB 772 (2017) 200
EPJ C 80 (2020) 12 1179
PRD 109 (2024) 11, 116002

$B \to Z_c K$



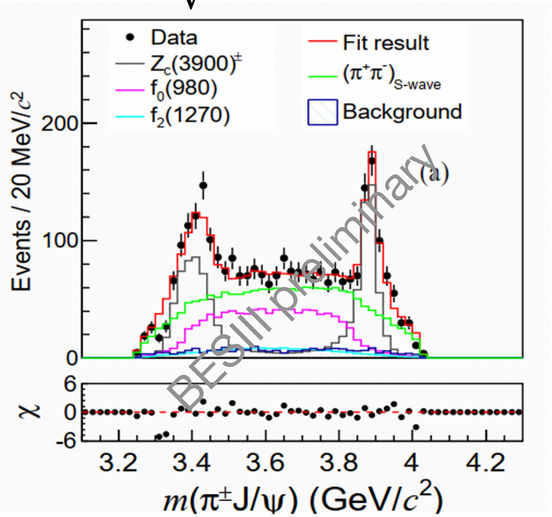
PRD 90 (2014) 11, 112009



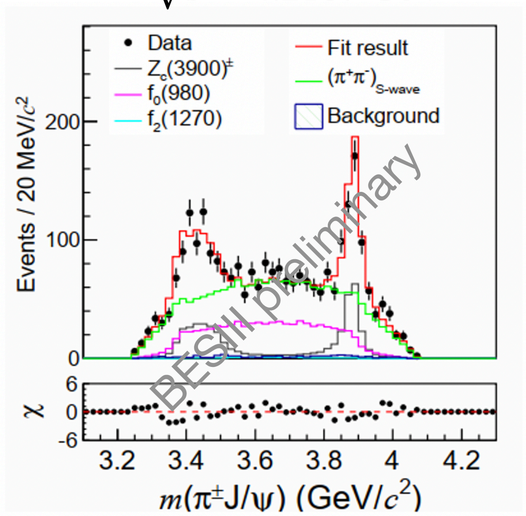
PRD 90 (2014) 11, 112009

Charged charmonium-like states

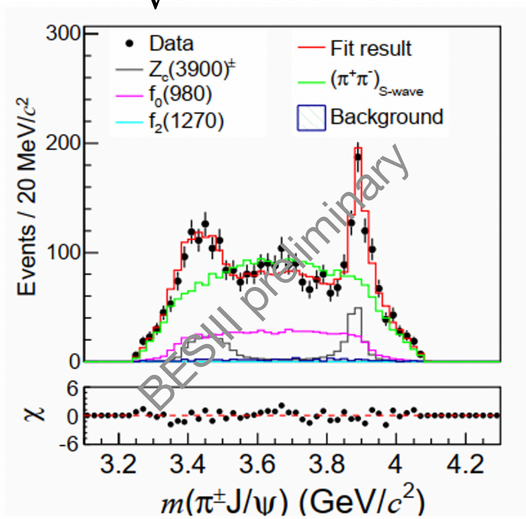
$\sqrt{s} = 4.18$ GeV



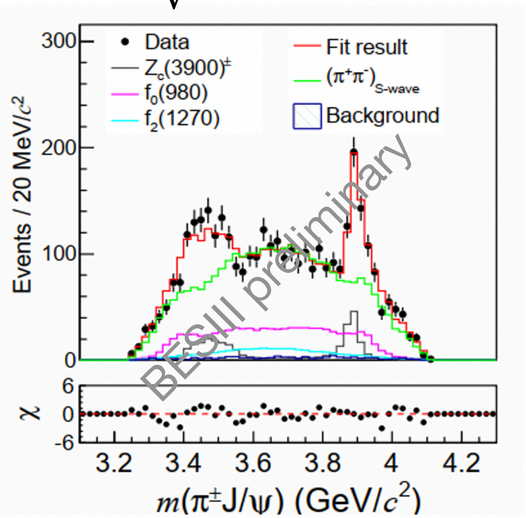
$\sqrt{s} = 4.2187$ GeV



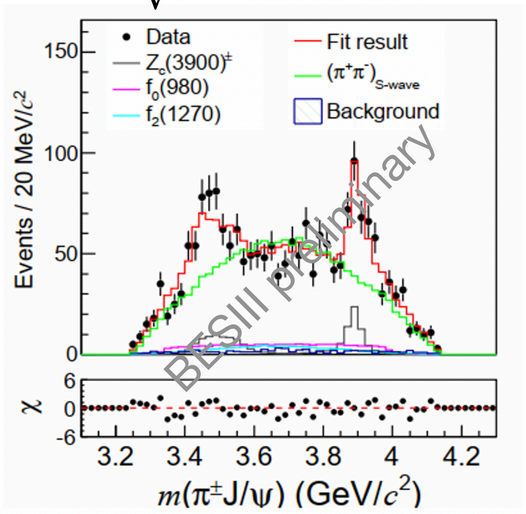
$\sqrt{s} = 4.2357$ GeV



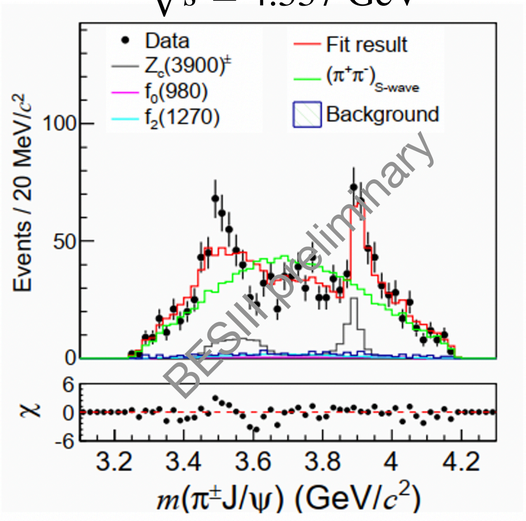
$\sqrt{s} = 4.258$ GeV



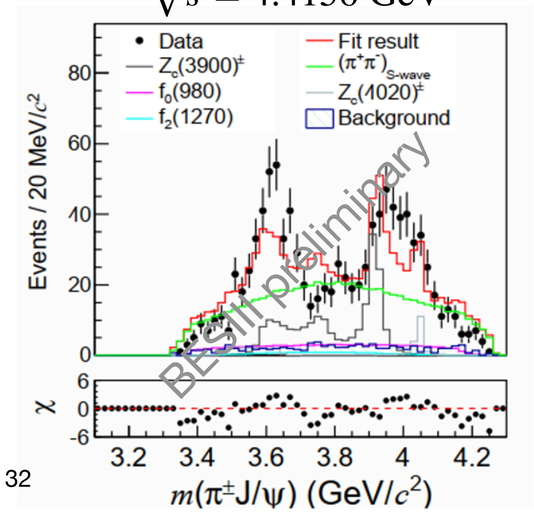
$\sqrt{s} = 4.2866$ GeV



$\sqrt{s} = 4.337$ GeV



$\sqrt{s} = 4.4156$ GeV



→ study how/if the Z_c lineshape varies with c.m. energy

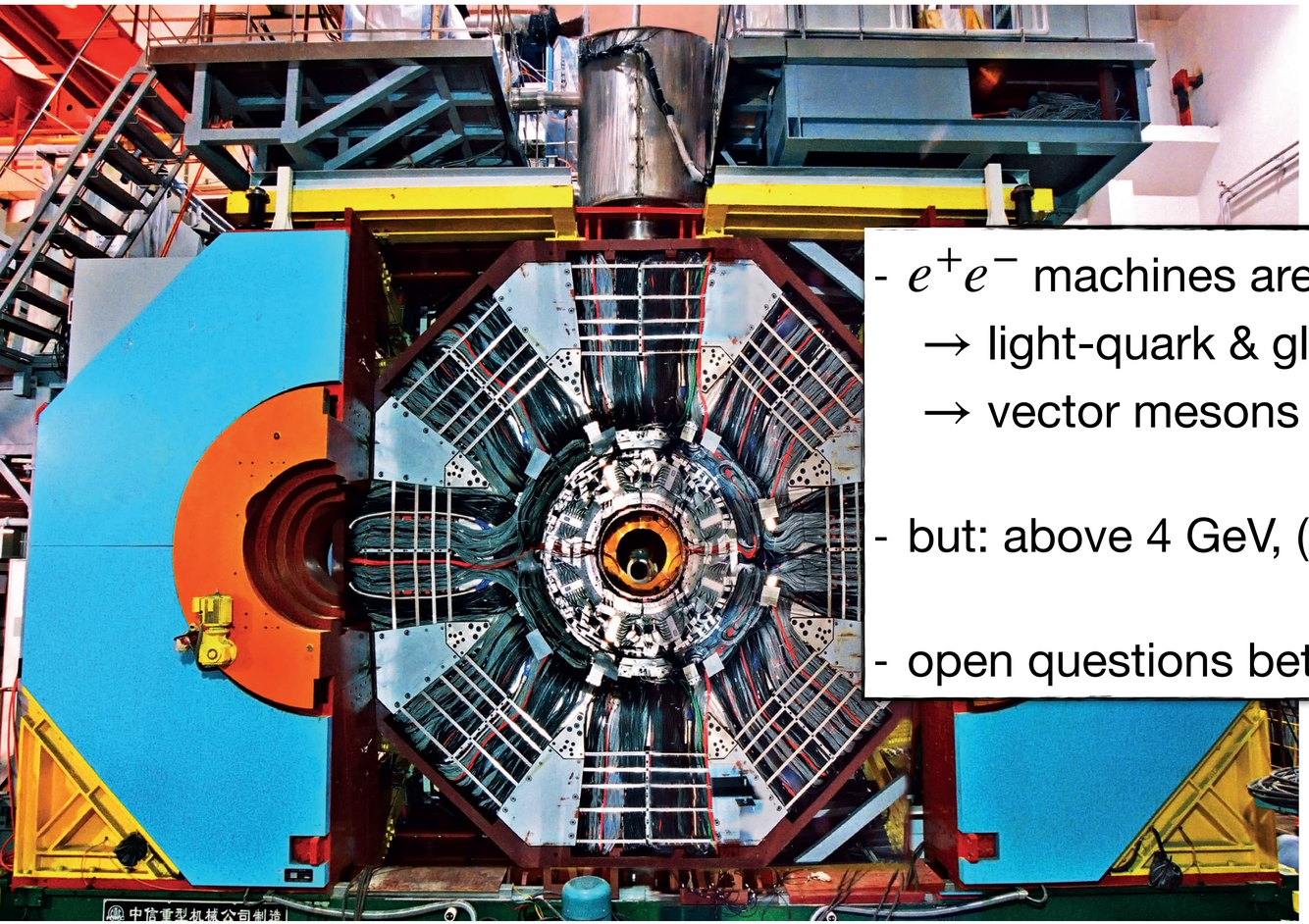
→ we can do this for many energies in small steps

→ more to come in the future

Summary & Outlook

Summary

in the context of photo-/electro-production

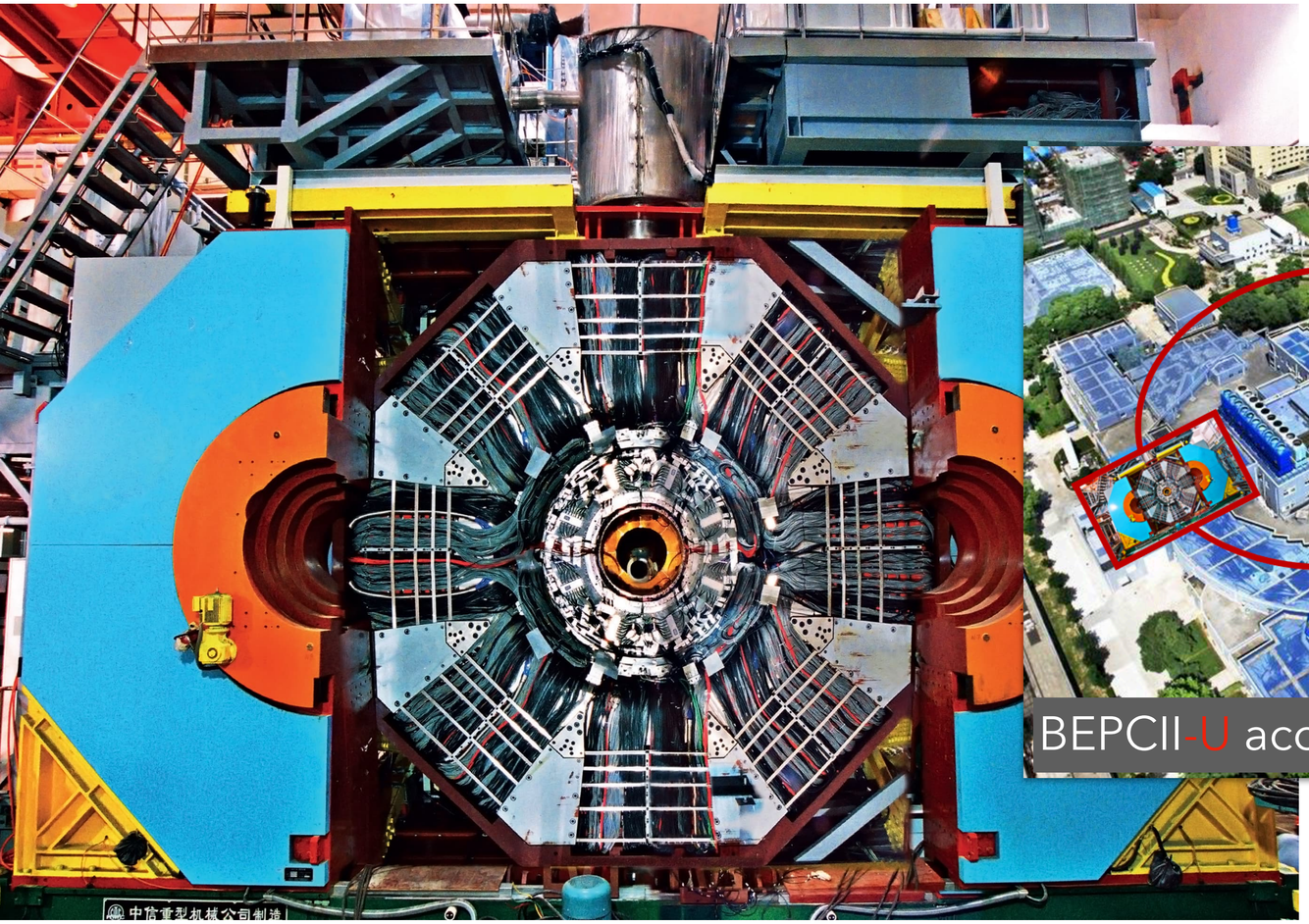


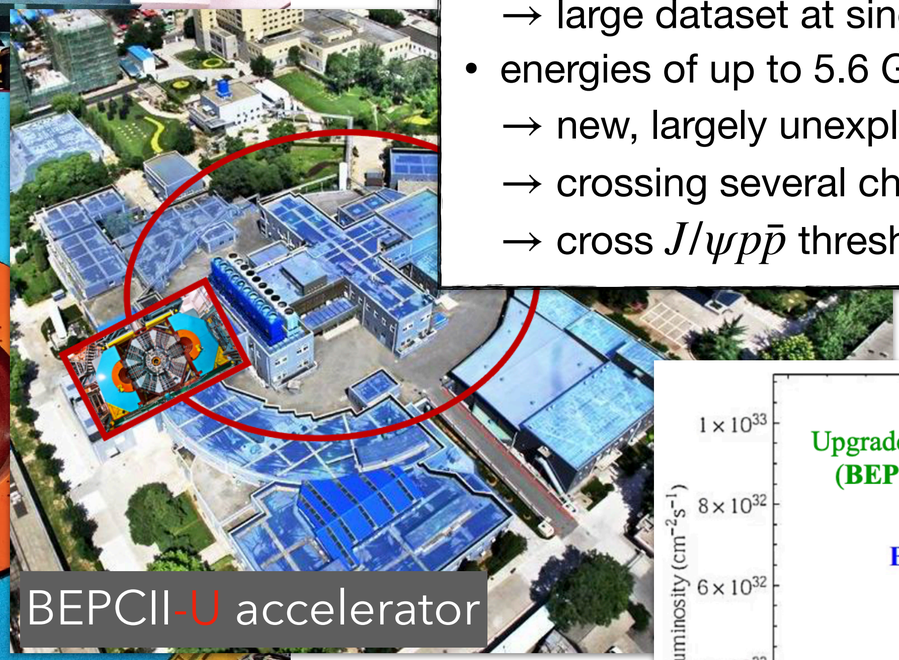
- e^+e^- machines are very powerful at specific tasks in hadron spectroscopy
  → light-quark & gluonic exotics in charmonium decays
  → vector mesons directly in the annihilation

- but: above 4 GeV, (exotic) charmonia with other J^{PC} are a challenge

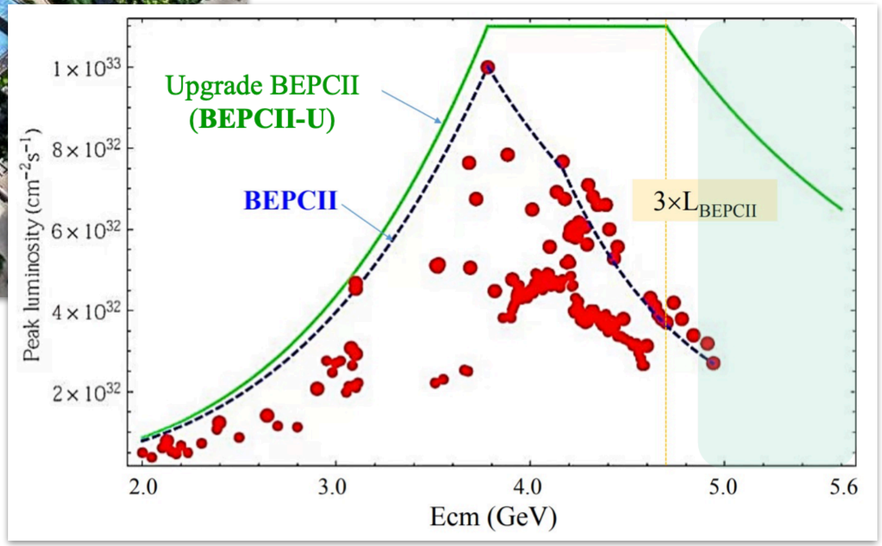
- open questions between e^+e^- and b-decays

Future perspective



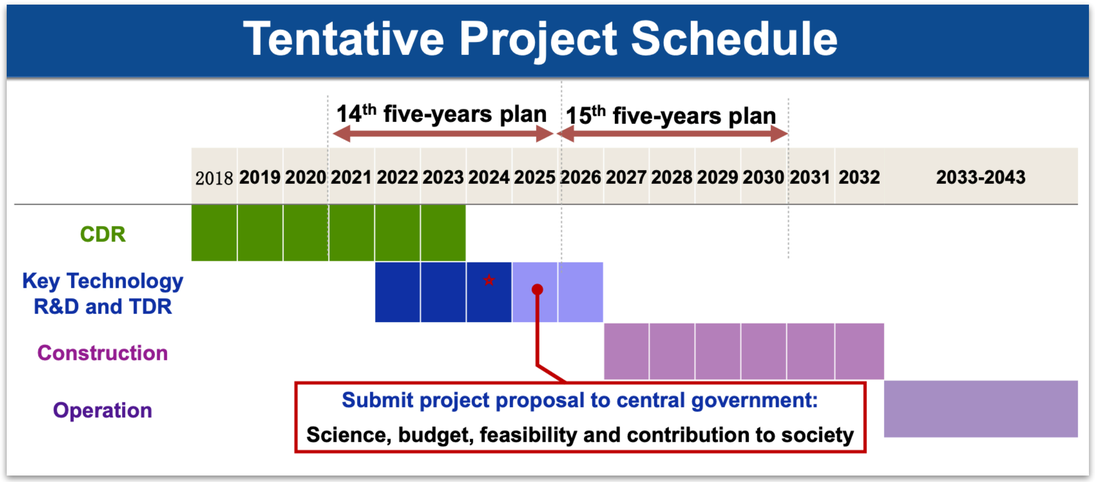


- up to 3x higher luminosities in the XYZ region:
  → enable precision studies of $Z_{c(s)}$-states & $X(3872)$
  → large dataset at single $\sqrt{s}$ versus finer scans?
- energies of up to 5.6 GeV:
  → new, largely unexplored energy region
  → crossing several charmed baryon thresholds
  → cross $J/\psi p\bar{p}$ threshold



More distant future perspective

- energy range: 2 - 7 GeV
- luminosity: $> 0.5 \times 10^{35}$ cm^{-2} s^{-1}
- timeline:



detailed information on technical concepts can be found here:
International Workshop on Future Tau Charm Facilities: https://indico.pnp.ustc.edu.cn/event/1948/overview
CDR: Front. Phys. 19(1), 14701 (2024)

More distant future perspective

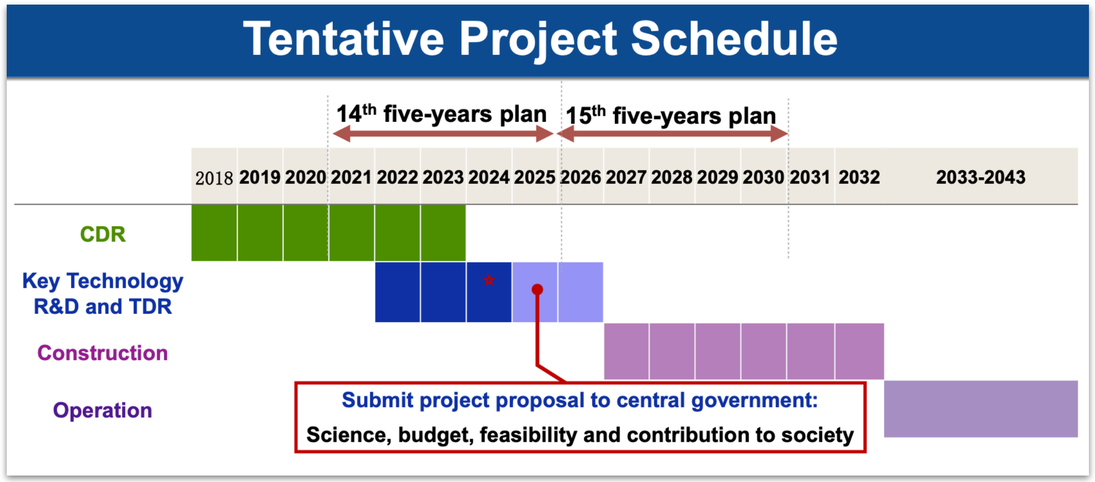
Table 2.1 The expected numbers of events per year at different STCF energy points.

CME (GeV)	Lumi (ab^{-1})	Samples	σ (nb)	No. of events	Remarks
3.097	1	J/ψ	3400	3.4×10^{12}	3 trillion J/ψ
3.670	1	$\tau^+\tau^-$	2.4	2.4×10^{9}	
3.686	1	$\psi(3686)$	640	6.4×10^{11}	600 billion $\psi(2S)$
		$\tau^+\tau^-$	2.5	2.5×10^{9}	
		$\psi(3686) \to \tau^+\tau^-$		2.0×10^{9}	
3.770	1	$D^0\bar{D}^0$	3.6	3.6×10^{9}	a few billion D
		$D^+\bar{D}^-$	2.8	2.8×10^{9}	
		$D^0\bar{D}^0$		7.9×10^{8}	Single tag
		$D^+\bar{D}^-$		5.5×10^{8}	Single tag
		$\tau^+\tau^-$	2.9	2.9×10^{9}	
4.009	1	$D^{*0}\bar{D}^0$ + c.c.	4.0	1.4×10^{9}	$CP_{D^0\bar{D}^0} = +$
		$D^{*0}\bar{D}^0$ + c.c.	4.0	2.6×10^{9}	$CP_{D^0\bar{D}^0} = -$
		$D_s^+D_s^-$	0.20	2.0×10^{8}	
		$\tau^+\tau^-$	3.5	3.5×10^{9}	
4.180	1	$D_s^{+*}D_s^-$+c.c.	0.90	9.0×10^{8}	
		$D_s^{+*}D_s^-$+c.c.		1.3×10^{8}	Single tag
		$\tau^+\tau^-$	3.6	3.6×10^{9}	
4.230	1	$J/\psi\pi^+\pi^-$	0.085	8.5×10^{7}	85 million $\pi\pi J/\psi$
		$\tau^+\tau^-$	3.6	3.6×10^{9}	
		$\gamma X(3872)$			
4.360	1	$\psi(3686)\pi^+\pi^-$	0.058	5.8×10^{7}	
		$\tau^+\tau^-$	3.5	3.5×10^{9}	
4.420	1	$\psi(3686)\pi^+\pi^-$	0.040	4.0×10^{7}	
		$\tau^+\tau^-$	3.5	3.5×10^{9}	
4.630	1	$\psi(3686)\pi^+\pi^-$	0.033	3.3×10^{7}	
		$\Lambda_c\bar{\Lambda}_c$	0.56	5.6×10^{8}	
		$\Lambda_c\bar{\Lambda}_c$		6.4×10^{7}	Single tag
		$\tau^+\tau^-$	3.4	3.4×10^{9}	
4.0–7.0	3	300-point scan with 10 MeV steps, 1 fb^{-1}/point			
> 5	2–7	Several ab^{-1} of high-energy data, details dependent on scan results			

Table 2.2 The expected numbers of produced XYZ-particle events before reconstruction per year at the STCF.

XYZ	$Y(4260)$	$Z_c(3900)$	$Z_c(4020)$	$X(3872)$
No. of events	10^9	10^8	10^8	5×10^6

- energy range: 2 - 7 GeV
- luminosity: $> 0.5 \times 10^{35}$ cm^{-2} s^{-1}
- timeline:



event/1948/overview

Thank you for your attention!