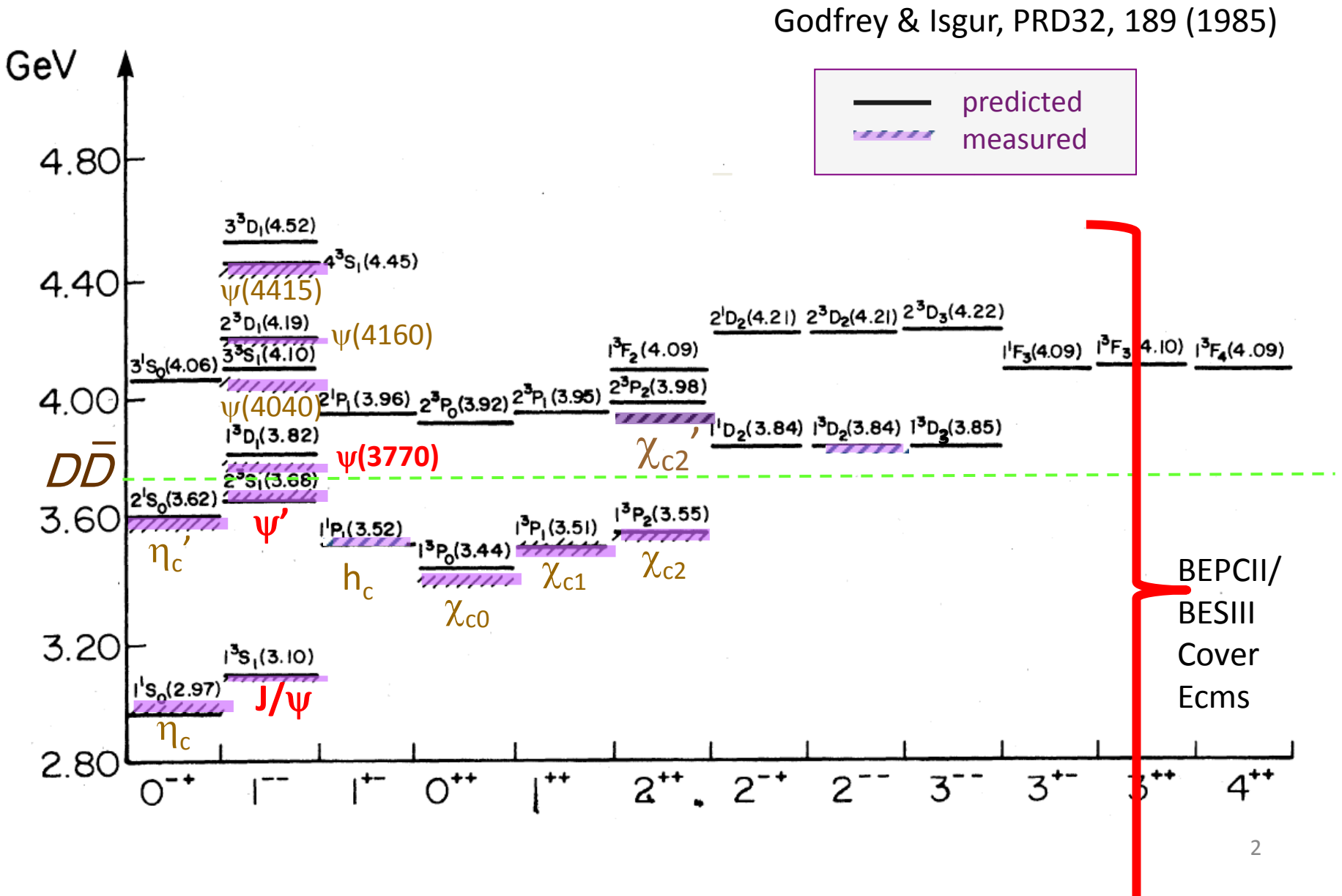
Recent results on exotic states at BESIII

Jingzhi Zhang (IHEP, Beijing), 2016.11.23

Charmonium Spectroscopy



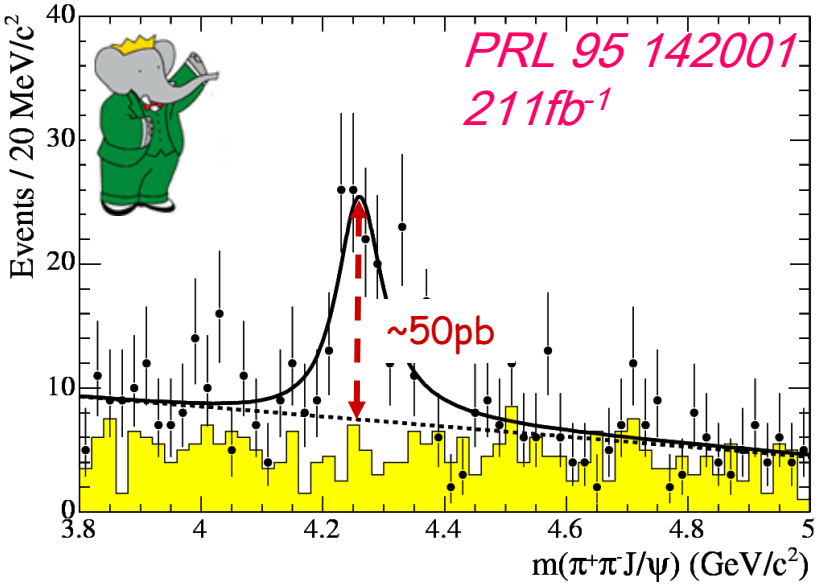
Particles

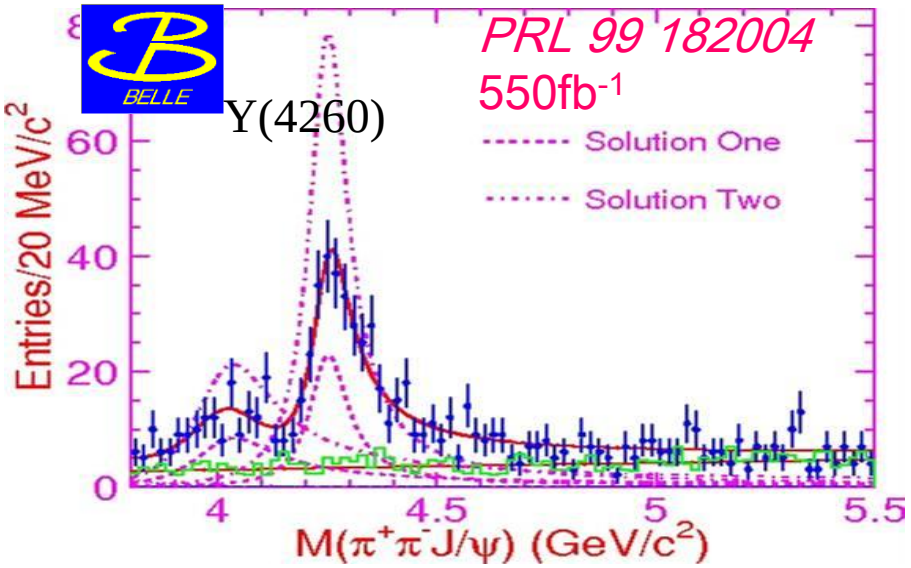
From PDG live

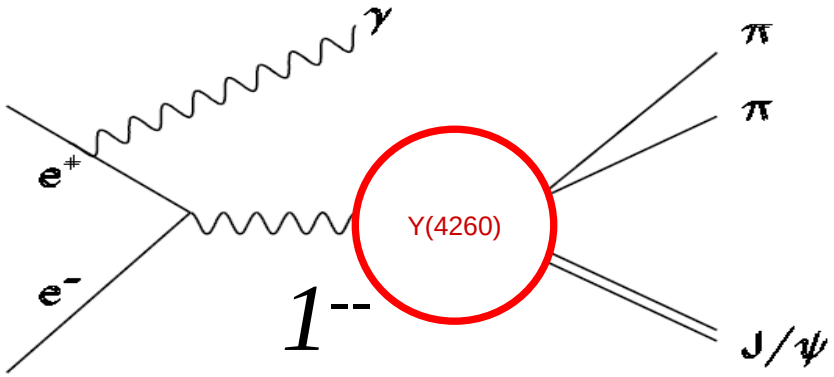
$\eta_c(1S)$
$J/\psi(1S)$
$\chi_{c0}(1P)$
$\chi_{c1}(1P)$
$h_c(1P)$
$\chi_{c2}(1P)$
$\eta_c(2S)$
$\psi(2S)$
$\psi(3770)$
$\psi(3823)$ was $X(3823)$
$X(3872)$
$X(3900)$ ⟶ Z(3900)
$X(3915)$ was $\chi_{c0}(3915)$
$\chi_{c2}(2P)$
$X(3940)$
$X(4020)$ ⟶ Z(4020)
$\psi(4040)$
$X(4050)^{\pm}$ Seen by belle in B→K $\pi\chi_{c1}$

$X(4140)$ Seen by CDF/CMS /D0 in $\phi J/\psi$; not seen by Belle/LHCb
$\psi(4160)$
$X(4160)$
$X(4200)^{\pm}$
$X(4230)$
$X(4240)^{\pm}$
$X(4250)^{\pm}$
$X(4260)$ ⟶ Y(4260)
$X(4350)$
$X(4360)$
$\psi(4415)$
$X(4430)^{\pm}$
$X(4660)$

The Y(4260)

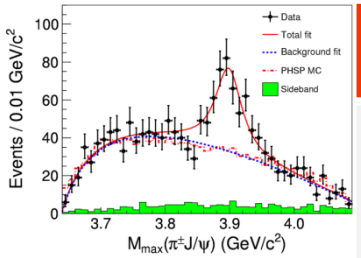






From the data taken around 4.260 GeV, BES found Zs

I=1 ; J^P: favor 1^+ (Ronggang'talk)



PRL,110,252001

$Z_c^{\pm}(3900)$

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

M=3899.0±3.6±4.9MeV

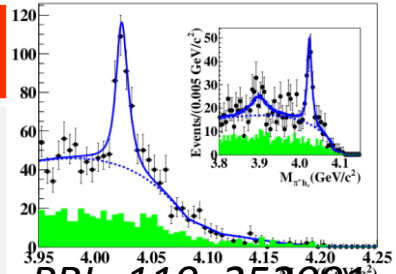
Γ = 46±10±20 MeV

$Z_c^{\pm}(4020)$

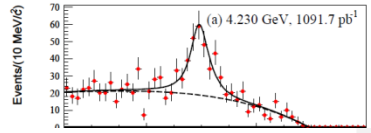
$e^+e^- \to \pi^+\pi^- h_c$

M= 4022.9±0.8±2.7MeV

Γ = 7.9±2.7±2.6 MeV



PRL, 110, 252001



PRL.115.112003

$Z_c^0(3900)$

$e^+e^- \to \pi^0\pi^0 J/\psi$

M=3894.8±2.3 MeV

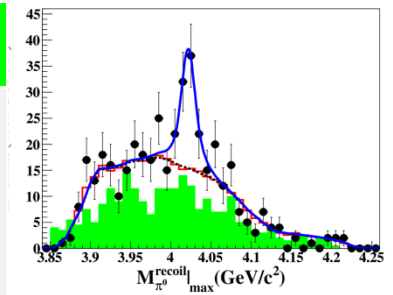
Γ =29.6±8.2 MeV

$Z_c^0(4020)$

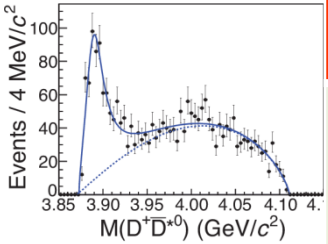
$e^+e^- \to \pi^0\pi^0 h_c$

M=4023.9±2.2±3.8 MeV

Γ Fixed at $Z_c^{\pm}(4020)$



PRL, 113, 212002



PRL,112, 022001

$Z_c^{\pm}(3885)$

$e^+e^- \to \pi(D^*D)^{\pm}$

M=3883.9±1.5±4.2 MeV

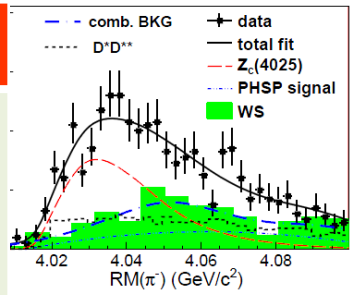
Γ =24.8±3.3±11 MeV

$Z_c^{\pm}(4025)$

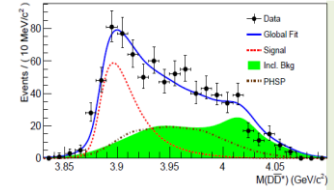
$e^+e^- \to \pi(D^*D^*)^{\pm}$

M= 4026.3±2.6±3.7 MeV

Γ = 24.8±5.6±7.7 MeV



PRL, 113, 212002



PRL, 115, 222002

$Z_c^0(3885)$

$(D^*D)^0$

M=3885.7±4.3±8.4 MeV

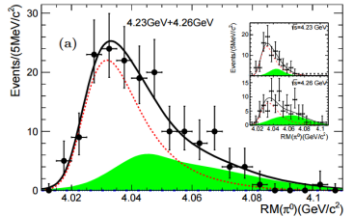
Γ = 35±12±15 MeV

$Z_c^0(4025)$

$(D^*D^*)^0$

M= 4025.5±2.0±3.1 MeV

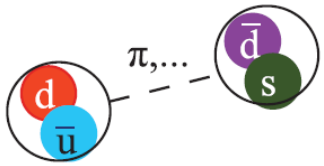
Γ = 23.0±6.0 ±1.0MeV



PRL,115.182002

Many proposals

- Conventional state
- Hybrid → if Y(4260) is a hybrid, BF(Y→$\gamma\chi_c$) <<BF(Y→ $\gamma\eta_c$)
- Hadronic molecules, → predict small Z→$\rho\eta_c$



arXiv:1303.6608, 1304.2882, 1304.1850

- Tetraquark states → predict large Z→$\rho\eta_c$

arXiv:1110.1333, 1303.6857
arXiv:1304.0345, 1304.1301

- Meson loop (arXiv:1303.6355)
- ISPE model (arXiv:1303.6842)

Initial single pion emission

Searches for more Z_c states

- $Z_c(3900)$ J^{pc}
- $Z_c(3900) \rightarrow \rho\eta_c$
- $Z_c(3900) \rightarrow \gamma\eta_c(2S)$ or $\gamma\chi_{c0}$
- $Z_c(4040) \rightarrow \pi^0\psi'$
- $Zc(4040) \rightarrow \pi^+\psi'$
- $e^+e^- \rightarrow \gamma\eta_{c2}(^1D_2)$
- $e^+e^- \rightarrow \pi^+\pi^-$ X(3823)
- $Zc(3900) \rightarrow J/\psi\eta$ in $J/\psi\eta\eta$
- $e+e- \rightarrow \eta_c\eta\ \pi\pi$ for Z(xxxx)
- $e+e- \rightarrow \chi_{c1/2}\pi\ \pi$ for Z(4050)
- .....

Open charm cross section

- $e^+e^- \rightarrow D+X$
- $e^+e^- \rightarrow DD$
- $e^+e^- \rightarrow D_s^+D_s^-$
- $e^+e^- \rightarrow D_s D_s^*$
- $e^+e^- \rightarrow D_s^*D_s^*$
- $e^+e^- \rightarrow D_2(2460)D \rightarrow DD\pi$
- $e^+e^- \rightarrow DD^*\pi$
- $e^+e^- \rightarrow \pi^+\pi^-DD$
- .....

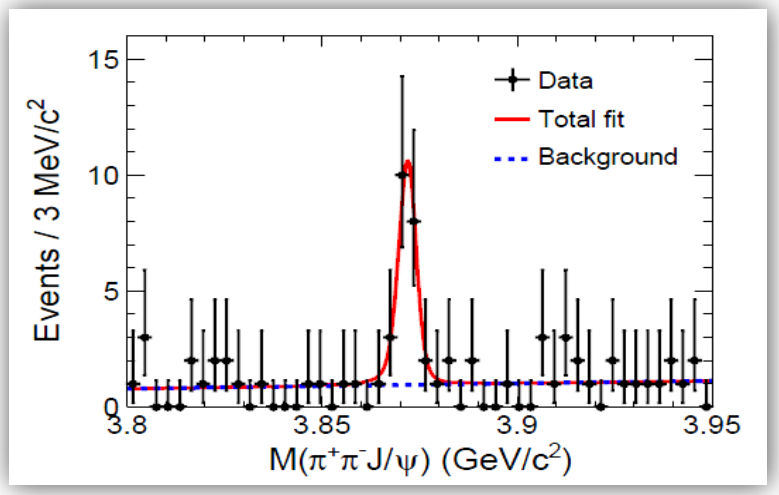
Cross-section of non-DDbar

- $e^+e^- \rightarrow \gamma X(3872)$ (finish)
- $e^+e^- \rightarrow \gamma\chi_{cJ}$ (finished)
- $e^+e^- \rightarrow \gamma X(4140)$ (finish
- $e^+e^- \rightarrow \gamma\eta_c$
- $e^+e^- \rightarrow \pi^+\pi^- h_c$
- $e^+e^- \rightarrow \pi^+\pi^- J/\psi$
- $e^+e^- \rightarrow \omega J/\psi$
- $e^+e^- \rightarrow KKJ/\psi$
- $e^+e^- \rightarrow \eta\ h_c$
- $e^+e^- \rightarrow \pi^+\pi^-\pi^0\eta_c$, $\pi\rho\eta_c$
- $e^+e^- \rightarrow \mu^+\mu^-$
- $e^+e^- \rightarrow \eta Y(2175)$
- $e^+e^- \rightarrow \phi\ \chi_{cJ}$
- $e^+e^- \rightarrow \eta'\ J/\psi$
- $e^+e^- \rightarrow \eta\ \psi'$

"Topics" will be presented

Found $e^+e^- \rightarrow \gamma X(3872)$

- Search for $\gamma X(3872)$ with $X(3872) \rightarrow \pi\pi J/\psi$ at E_{cm}=4.23, 4.26 and 4.36 GeV

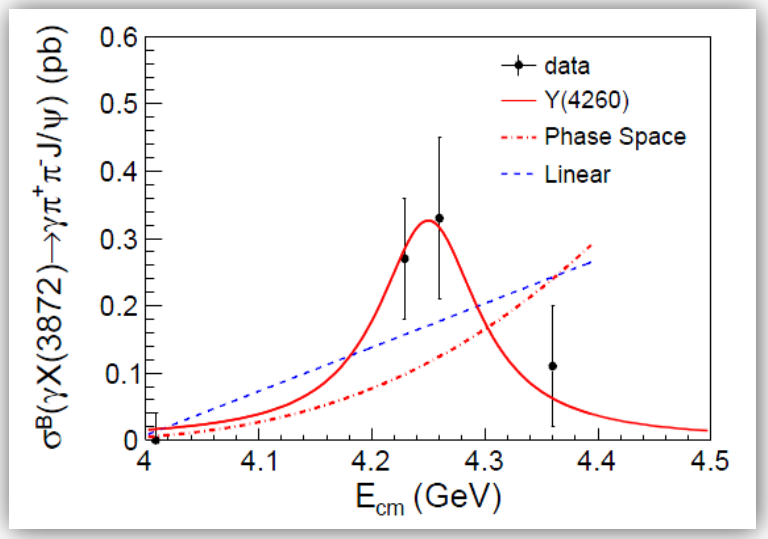


- top: summed over all data X(3872) significance = $6.3\ \sigma$

- Production in Y(4260) decay suggestive, but not conclusive

- If from Y(4260)

$$\frac{B(Y(4260) \rightarrow \gamma X(3872))}{B(Y(4260) \rightarrow \pi^+\pi^- J/\psi)} \approx 0.1$$

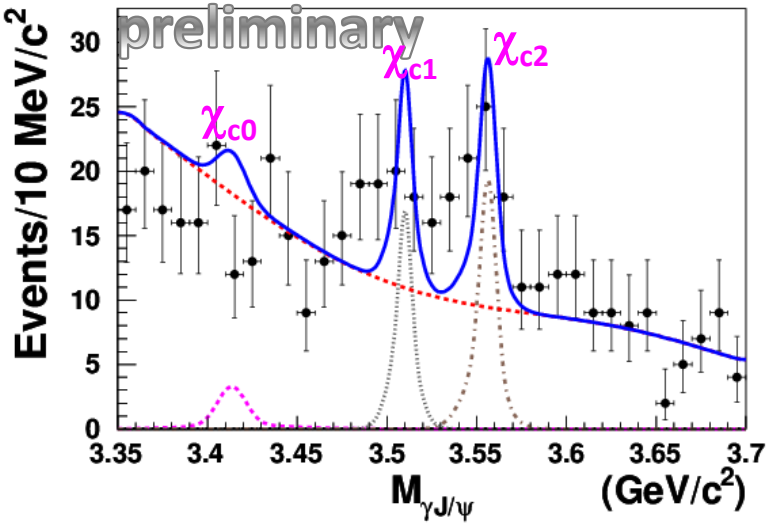


[BESIII RPL112,092001]

Study of $e^+e^- \rightarrow \gamma\chi_{cJ}$

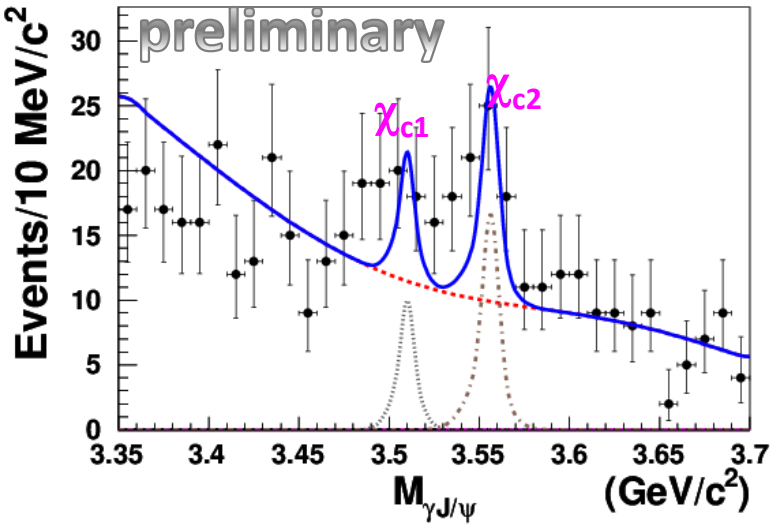
-- Help to understand the nature of Y(4260)

Fit to M(γJ/ψ) for *summing the events in the 4 CME points*



the statistical significance is **1.2σ, 3.0σ, 3.4σ** *for* χ_{c0}, χ_{c1}, χ_{c2} respectively.

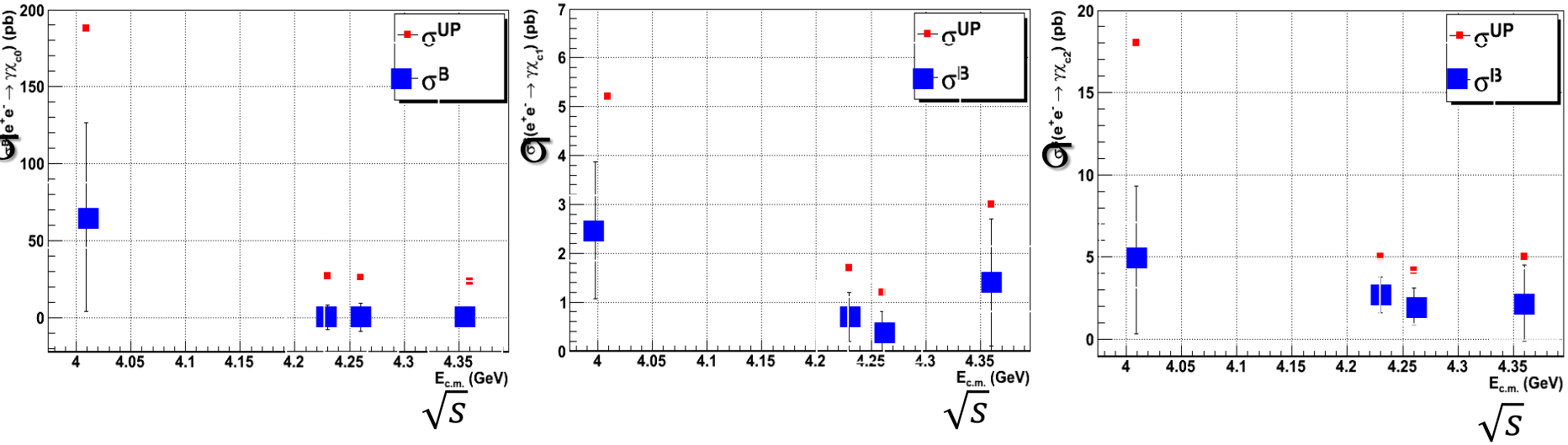
A simultaneous fit to M(γJ/ψ) at 4 CME points *with assuming the production* $\sigma(e^+e^- \rightarrow \gamma\chi_{cJ})$ *at different* $\sqrt{s}$ *follows the lineshape of Y(4260)*



the stat. significance is **0, 2.4, 4.0 σ** for χ_{c0}, χ_{c1}, χ_{c2} , respectively

The measured Born corss-section $\sigma(e^+e^- \rightarrow \gamma\chi_{cJ})$

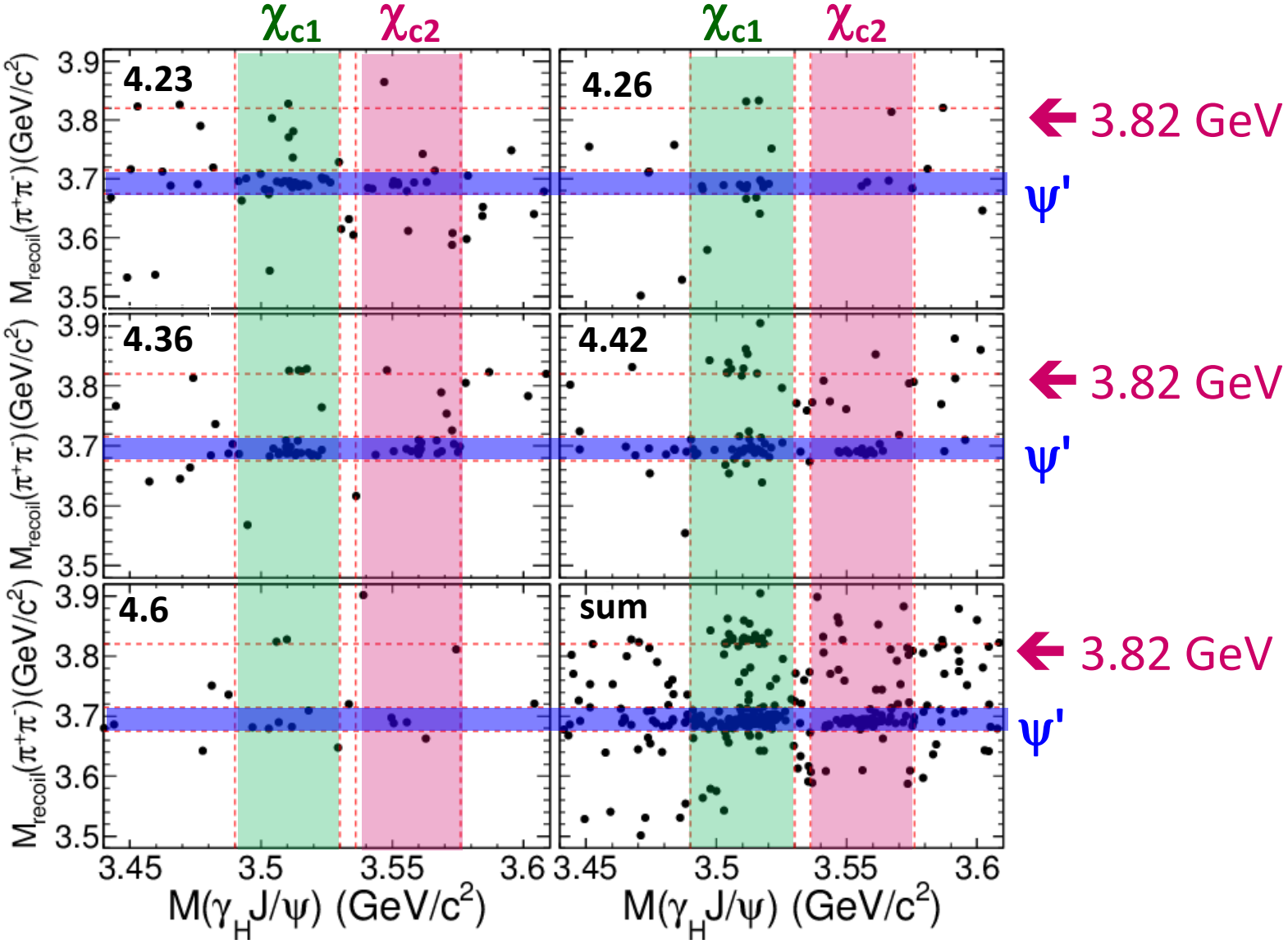
$e^+e^- \rightarrow \gamma\chi_{c0}$ $e^+e^- \rightarrow \gamma\chi_{c1}$ $e^+e^- \rightarrow \gamma\chi_{c2}$



The upper limits on the cross section of e+e- → $\gamma\chi_{cJ}$ are compatible with the theoretical predication. Ref: arXiv:1310.8597

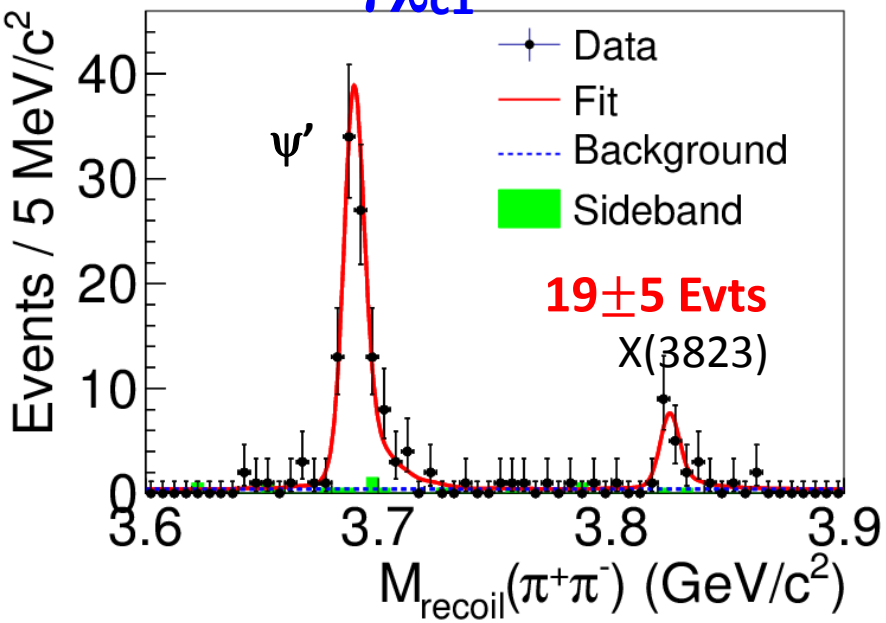
$e^+e^- \to \pi^+\pi^- X(3823)[\psi_2(1^3D_2)]$, $X \to \gamma\chi_{c1}$

M_{reoil} ($\pi\pi$) vs. M(γJ/ψ) for Selected Events

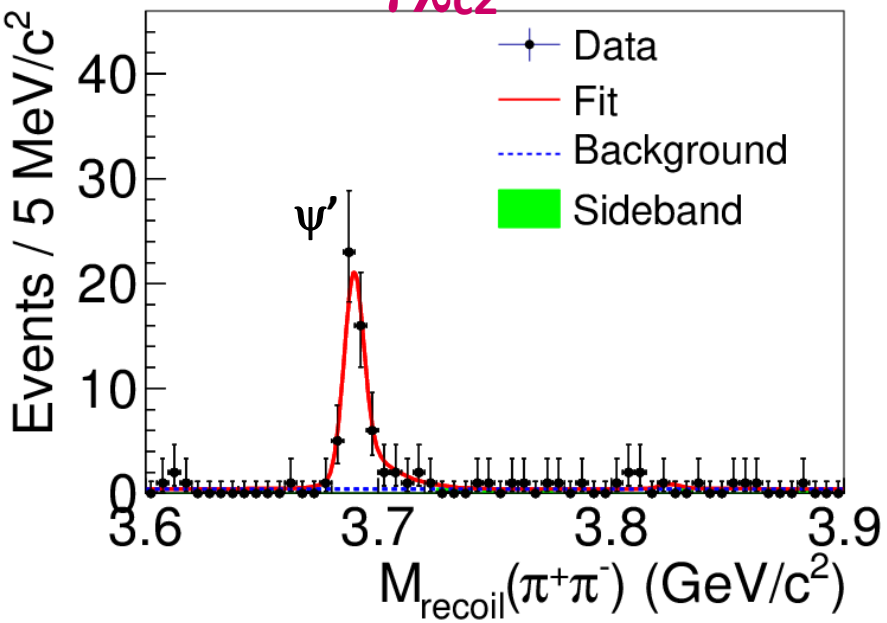


Simultaneous Fit to the $M_{recoil}(\pi^+\pi^-)$

For $\gamma\chi_{c1}$ events



For $\gamma\chi_{c2}$ events



- ψ' is used to calibrate the absolute mass scale.
- Simultaneous fit with common X(3823) mass for diff. energies and for $\gamma\chi_{c1}$, $\gamma\chi_{c2}$ mode.
- Signal: MC shape ⊗ Gauss; bkg: linear function.

M=3821.7±1.3MeV

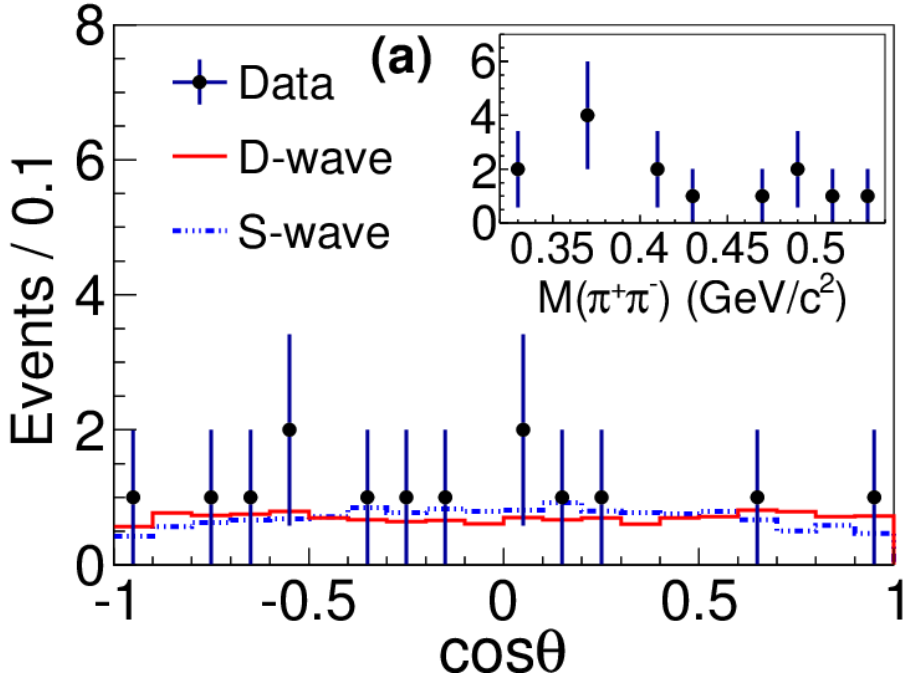
Γ(x)<16 MeV at 90% C.L.

Significance: 6.2 σ in $\gamma\chi_{c1}$

No X(3823) events in $\gamma\chi_{c2}$

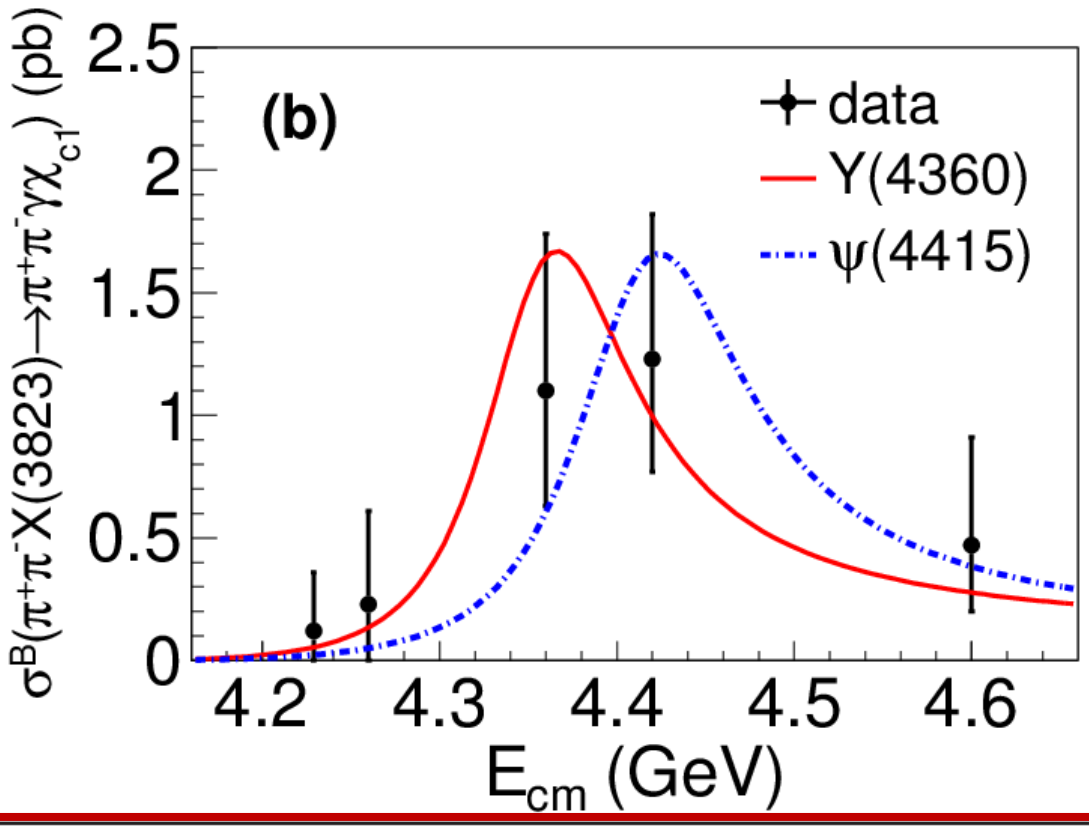
$\mathcal{B}(X\rightarrow\gamma\chi_{c2})/\mathcal{B}(X\rightarrow\gamma\chi_{c1})<0.42$

Angular Distribution of $e^+e^- \rightarrow \pi^+\pi^- X(3823)$



Assume the $\pi\pi$ dominated by **S-wave**, **D-wave** between the $\pi\pi$ system and X(3823);
Due to limited statistics, both S-wave and D-wave hypotheses can be accepted.

The Cross-section



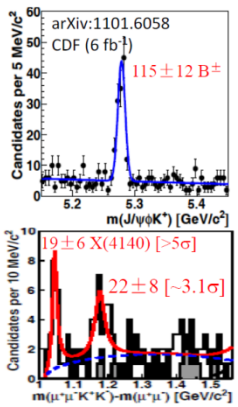
$\sqrt{s}$ (GeV)	$\mathcal{L}$ (pb^{-1})	$N^{\rm obs}$	ϵ	$1+\delta$	$1/\lvert 1-\Pi\rvert^2$	$\sigma_X^B\cdot\mathcal{B}_1$ (pb)	$\sigma_X^B\cdot\mathcal{B}_2$ (pb)
4.230	1092	$0.7^{+1.4}_{-0.7}$ (<3.8)	0.168	0.755	1.056	$0.12^{+0.24}_{-0.12}\pm 0.02$ (<0.64)	···
4.260	826	$1.1^{+1.8}_{-1.2}$ (<4.6)	0.178	0.751	1.054	$0.23^{+0.38}_{-0.24}\pm 0.04$ (<0.98)	···
4.360	540	$3.9^{+2.3}_{-1.7}$ (<8.2)	0.196	0.795	1.051	$1.10^{+0.64}_{-0.47}\pm 0.15$ (<2.27)	(<1.92)
4.420	1074	$7.5^{+3.6}_{-2.8}$ (<13.4)	0.145	0.967	1.053	$1.23^{+0.59}_{-0.46}\pm 0.17$ (<2.19)	(<0.54)
4.600	567	$1.9^{+1.8}_{-1.1}$ (<5.4)	0.157	1.075	1.055	$0.47^{+0.44}_{-0.27}\pm 0.07$ (<1.32)	···

X(4140) -- a good candidate for D_s^* ($\bar{D}_s^*$) molecular

From Liming Zhang

X(4140) and X(4274)

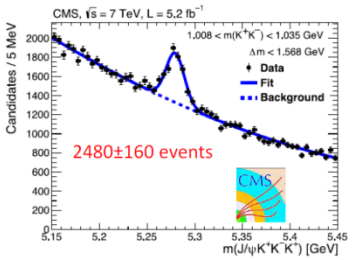
- CDF observed a narrow $(J/\psi\phi)$ structure in $B^+ \to J/\psi\phi K^+$ decays [Initial publication on 2.7 fb^{-1} PRL102, 242002 (2009)]
  - $M = 4143.4 \pm 3.0 \pm 0.6$ MeV
  - $\Gamma = 15.3^{+10.4}_{-6.1} \pm 2.5$ MeV
  - Necessarily exotic since it is narrow and above the $D_s^+ D_s^-$ threshold
  - $[cs\bar{c}\bar{s}]$ tetraquark ?
  - Hint of a second structure: $X(4274)$
- Not confirmed by B-factories and LHCb with 0.37fb^{-1} data



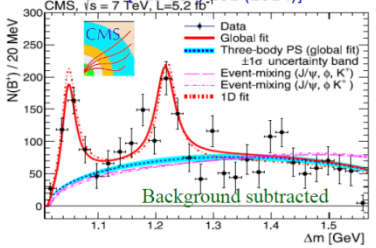
L. Zhang 26

X(4140) and X(4274) from CMS

- Crucial to check by different experiments with larger statistics.



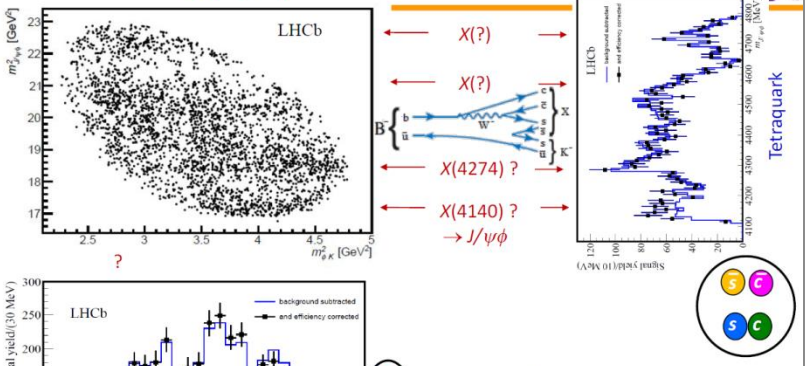
[PLB 734, 261 (2014)]



X(4274-4351)?	CDF [arXiv:1101.6058]	CMS [PLB 734, 261 (2014)]	DØ [PRD 89, 012004 (2014)]
Significance	3.1σ	>3σ	
M_0 (MeV)	$4274.4^{+8.4}_{-6.7} \pm 1.9$	$4313.8 \pm 5.3 \pm 7.3$	4328.5 ± 12.0
Γ_0 (MeV)	$32.3^{+21.9}_{-15.3} \pm 7.6$	$28^{+15}_{-11} \pm 19$	

L. Zhang 28

$B^+ \to J/\psi\phi K^+$

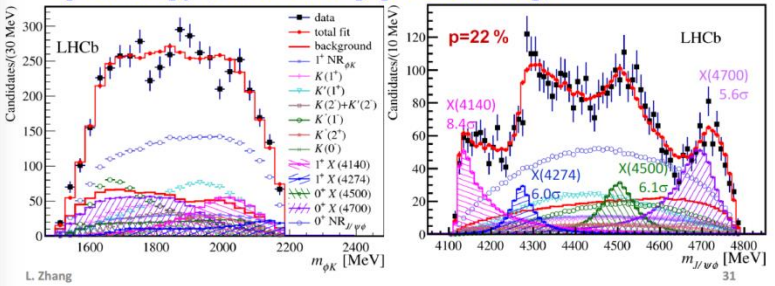


L. Zhang Kaon excitations 30

$X(4140)$ & $X(4274)$: identified as $J^{PC} = 1^{++}$ at $> 5\sigma$

LHCb-PAPER-2016-019 arXiv: 1606.07898

- Four X states + NR $J/\psi\phi$ give very significant improvements over the models with K*s alone
- Default model also includes NR ϕK + 7 K^* (float M_0 and Γ_0) that are significant
- These results add significantly to the knowledge of K spectroscopy (results in the paper and backup)



L. Zhang 31

Search for Y(4140)→ϕ J/ψ at BESIII

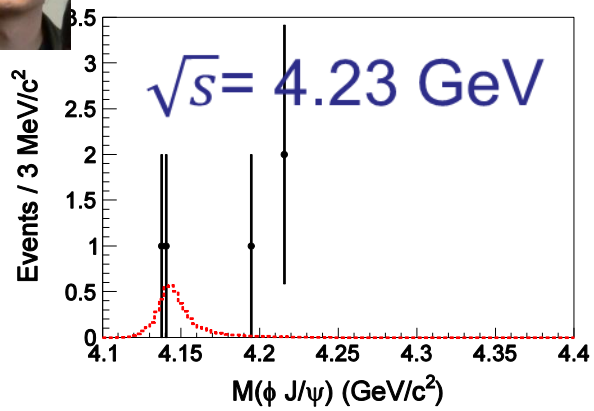
e+e- → γ ϕ J/ψ; J/ψ→ $e^+e^-/\mu^+\mu^-$

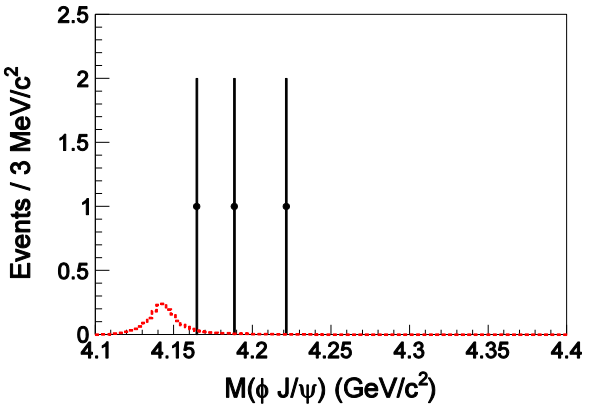
1. ϕ → K^+K^-
   Partial reconstruction, only require one K

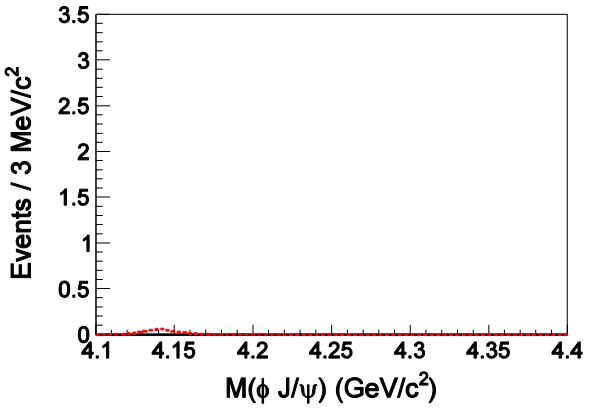
2. ϕ → $K_S K_L$
   Partial reconstruction, only require K_S; the K_L not reconstructed.

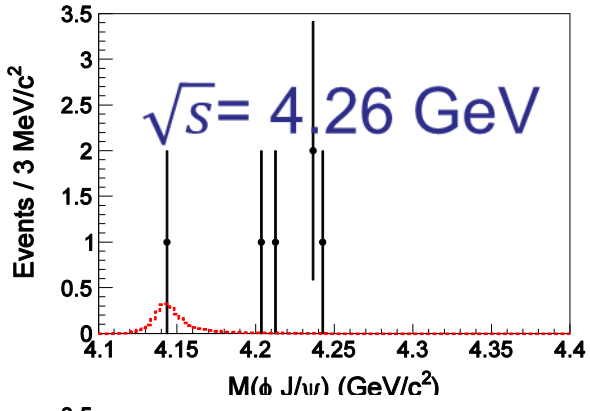
3. ϕ→$\pi^+\pi^-\pi^0$
   Full reconstruction.

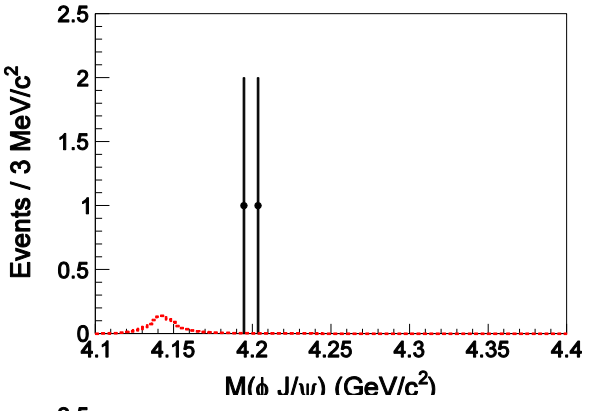
$\phi \to K^+K^-$ $\phi \to K_S^0K_L^0$ $\phi \to \pi^+\pi^-\pi^0$

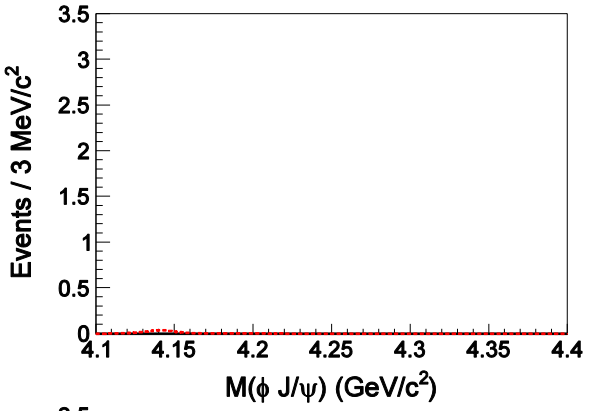


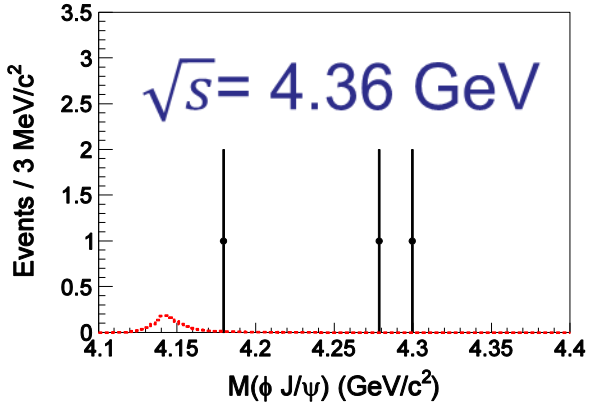


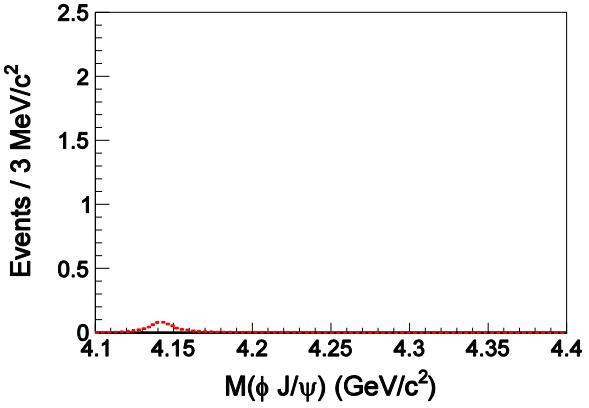


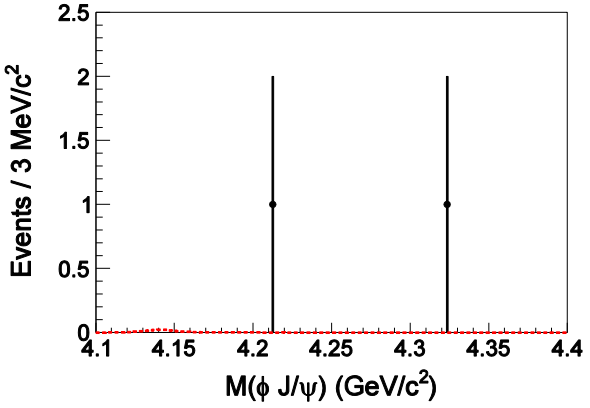




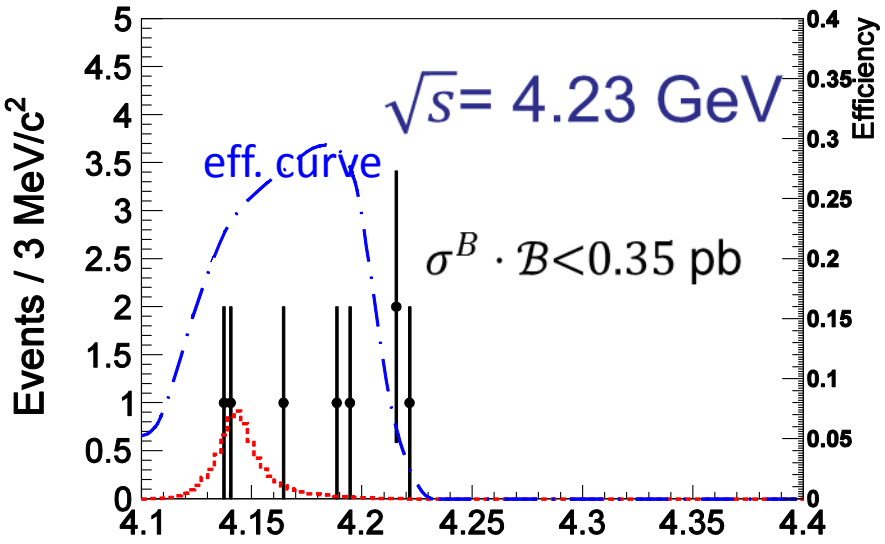


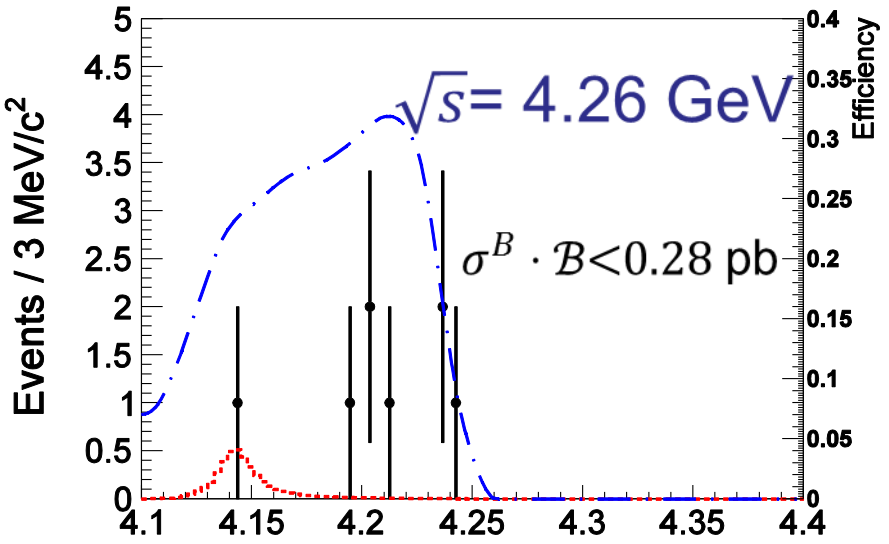


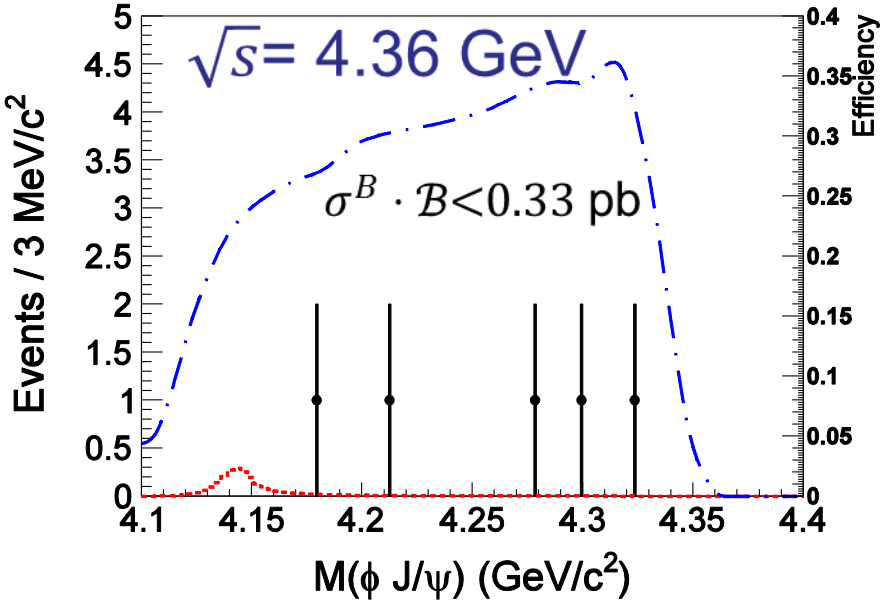


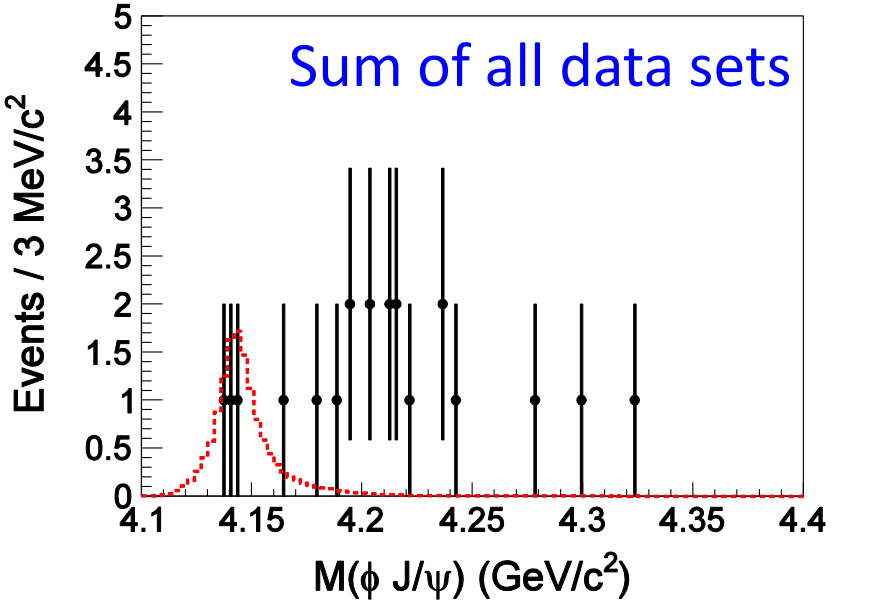


Combine 6 modes (3 ϕ modes $\otimes$ 2 J/ψ modes)









No significant Y(4140) signal found @ BESIII

Set upper limit at the 90% CL. for

$\sigma^B \times \mathcal{B} = \sigma^B(e^+e^- \to \gamma Y(4140)) \times \mathcal{B}(Y(4140) \to \phi J/\psi)$

$\sqrt{s}$ (GeV/c^2)	Luminosity (pb^{-1})	$(1+\delta)$	$\sigma^B \times \mathcal{B}$
4.23	1094	0.840	<0.35
4.26	827	0.847	<0.28
4.36	545	0.944	<0.33

Systematic error included

Compared with the X(3872) product ion

$\sigma^B(e^+e^- \to \gamma X(3872)) \times \mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi)$

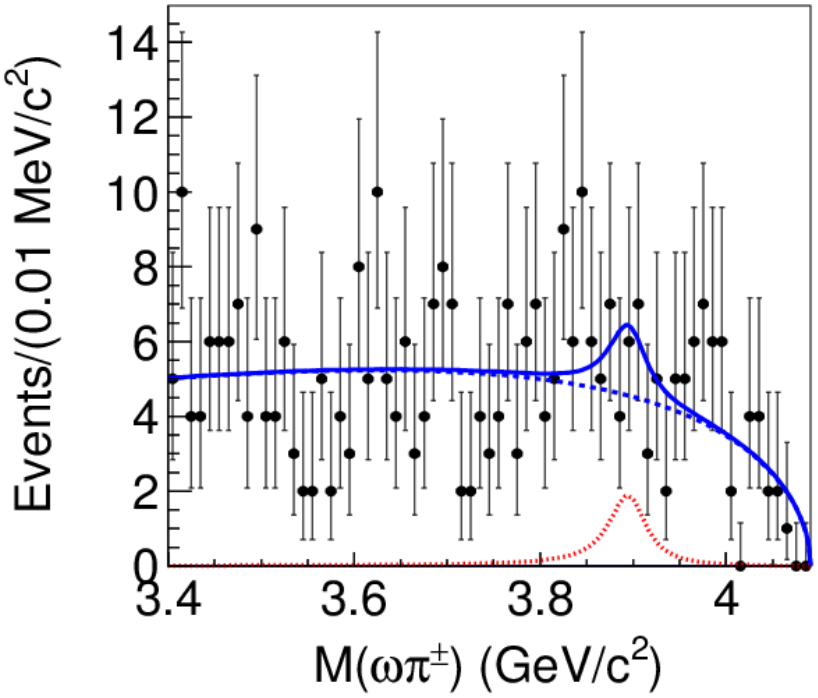
Take $\mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi)$ = 5%. arXiv: 0910.3138

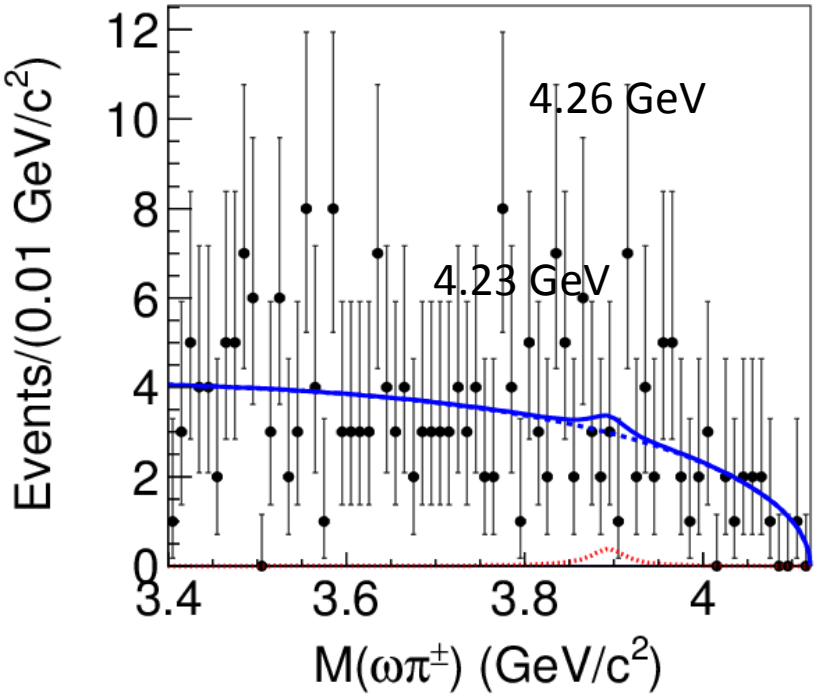
And $\mathcal{B}(Y(4140) \to \phi J/\psi)$ = 30%, molecular calculation, PRD 80, 054019.

$\frac{\sigma^B(e^+e^- \to \gamma Y(4140))}{\sigma(e^+e^- \to \gamma X(3872))} \leq 0.1$ at $\sqrt{s}$=4.23 and 4.26 GeV.

Negative searches also provide useful info about the XYZ

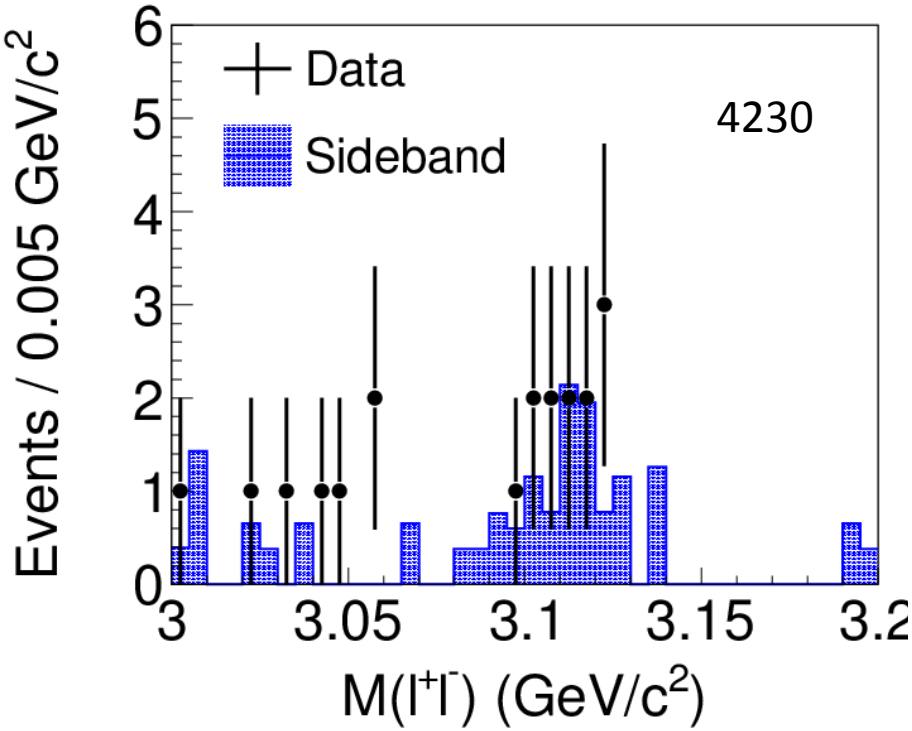
- **No $Z_c(3900)^{\pm} \to \omega\pi^{\pm}$ observed**

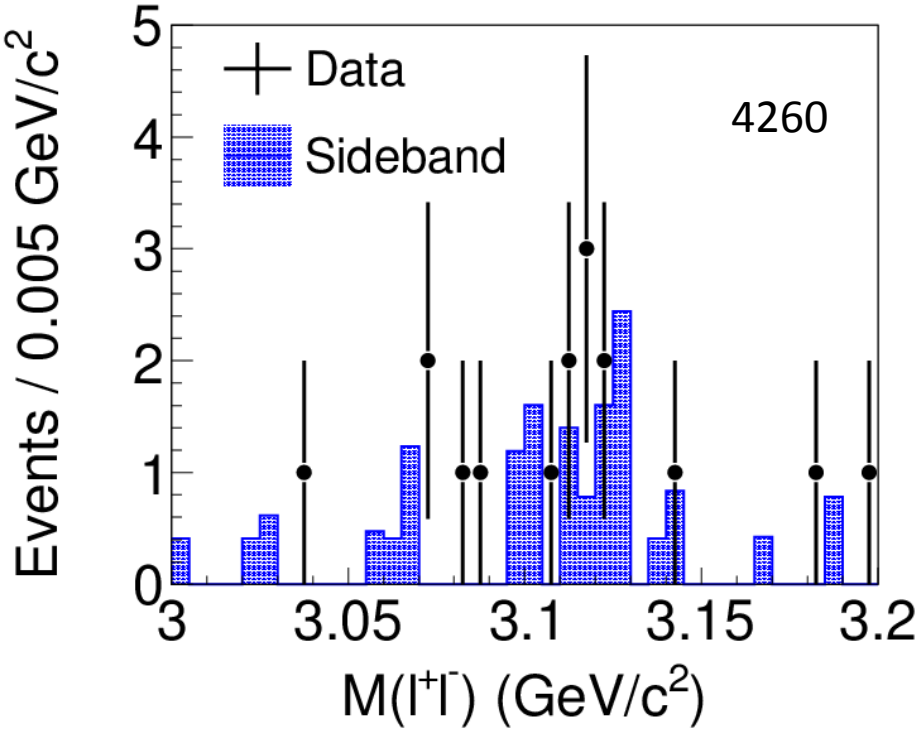




- No resonant structure in $J/\psi\pi$ is observed in $B^0 \to J/\psi\pi^+\pi^-$ by LHCb *[PR,D90,012003],* in $B^0 \to J/\psi K^-\pi^+$ by Belle *[PR,D90,012009]*

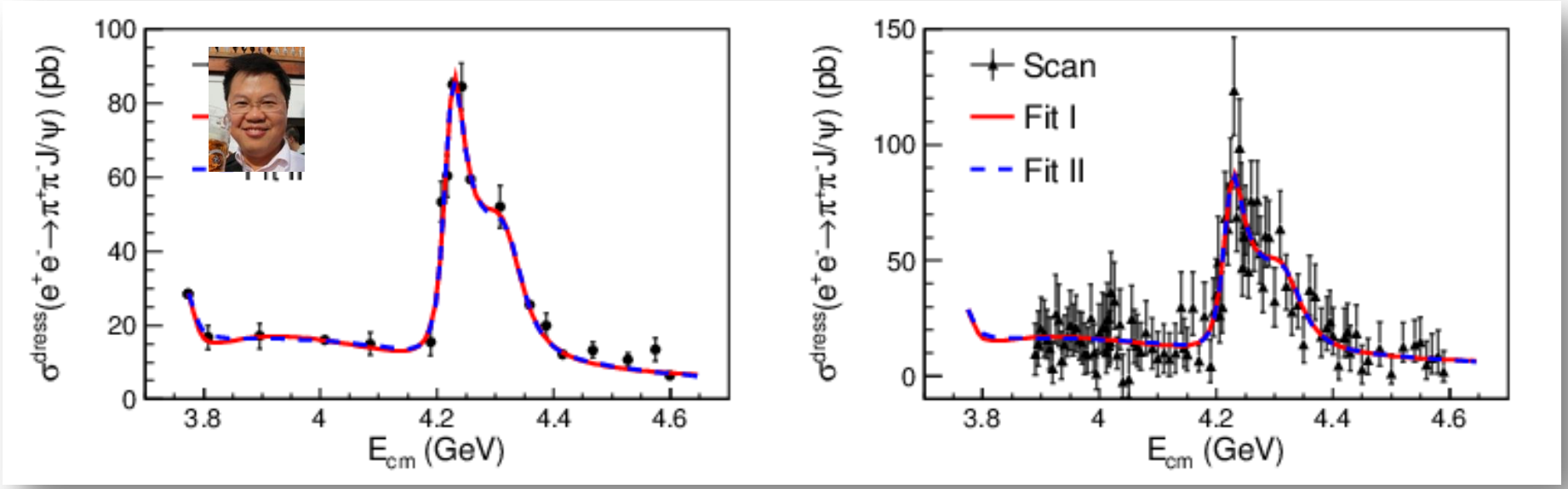
- **No $Y(4260)\to J/\psi\eta\pi^0$ found**
  -- the isospin violating decay

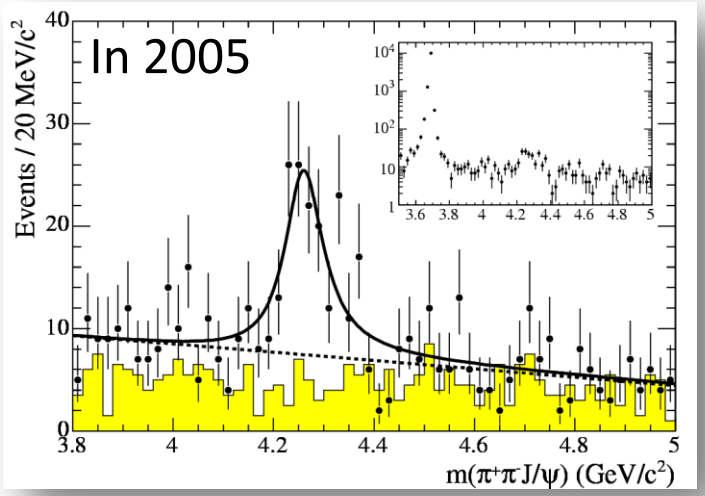




BESIII measured the $\pi^+\pi^-J/\psi$ lineshape ---The Y(4260) is not a simple Breit-Wigner

arXiv:1611.01317 (2016)





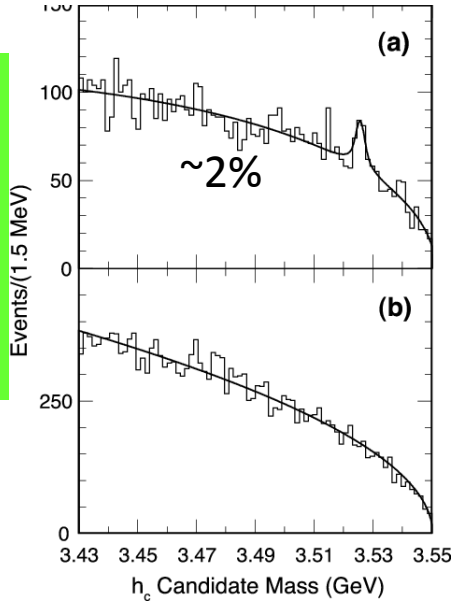
CLEO found h_c in 5π (2009)

BESIII found $h_c \rightarrow \gamma\eta/\eta'$ (2016)

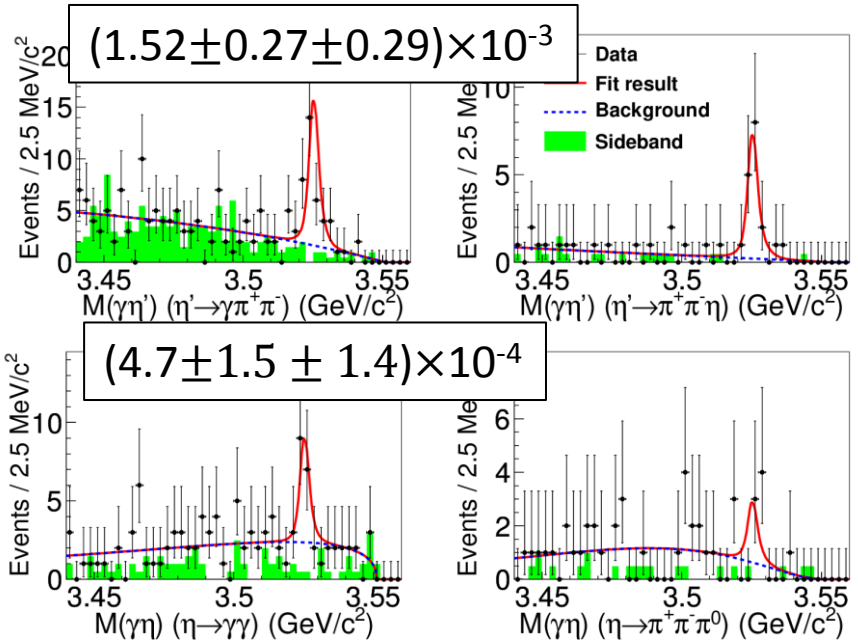
$h_c \rightarrow \gamma\eta_c$

~ 50%

$\eta_c \rightarrow$ hadrons

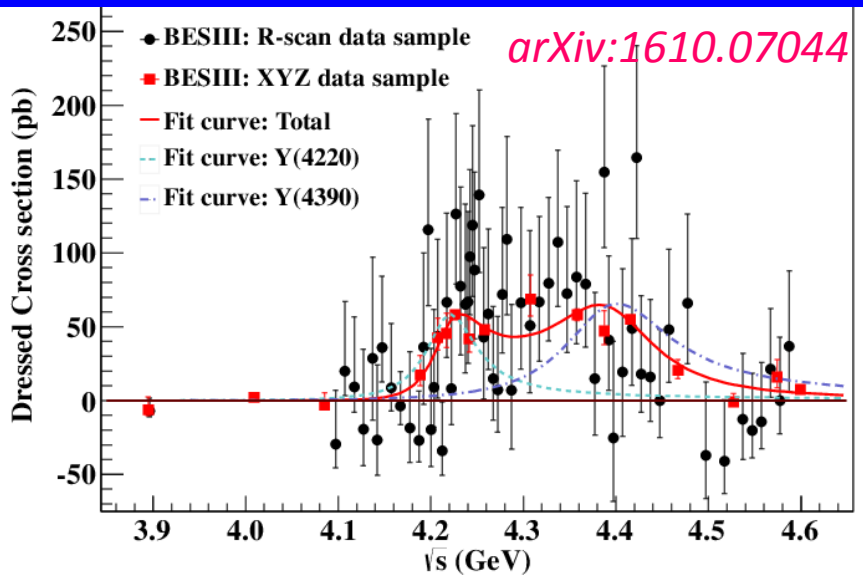


PR,D80,051106



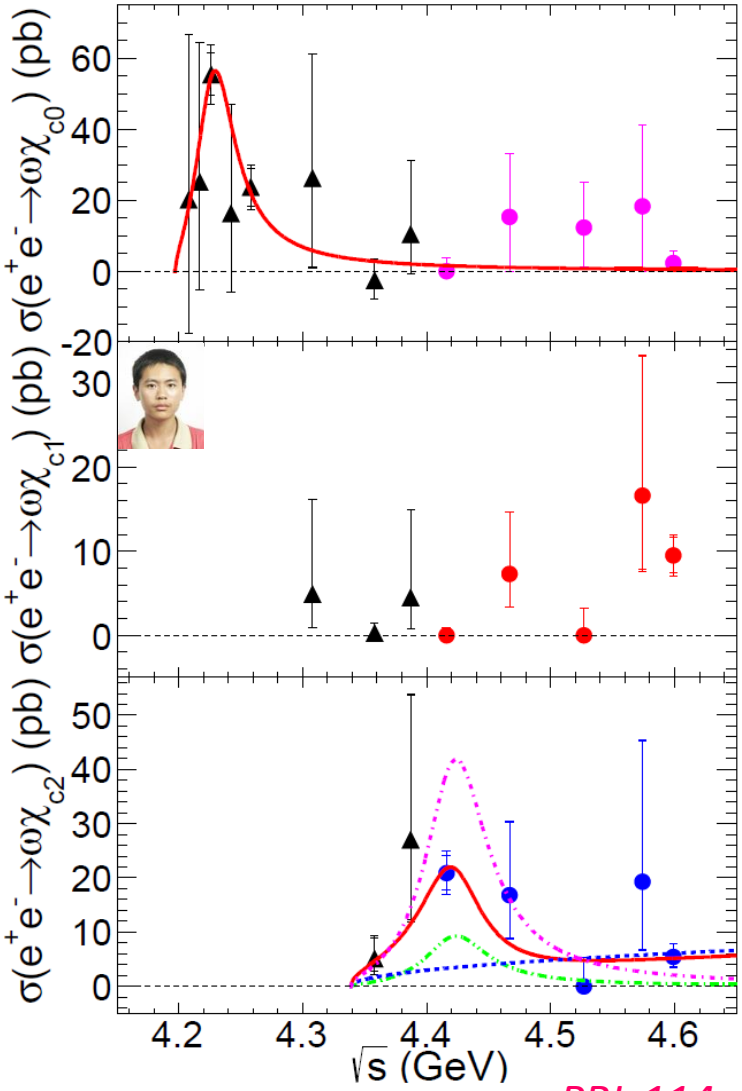
PRL,116, 251802

The ee→ππh_c cross-section



arXiv:1610.07044

$e^+e^- \rightarrow \omega J/\psi$



It seems consistent with the first structure in $\pi+\pi-J/\psi$line shape.

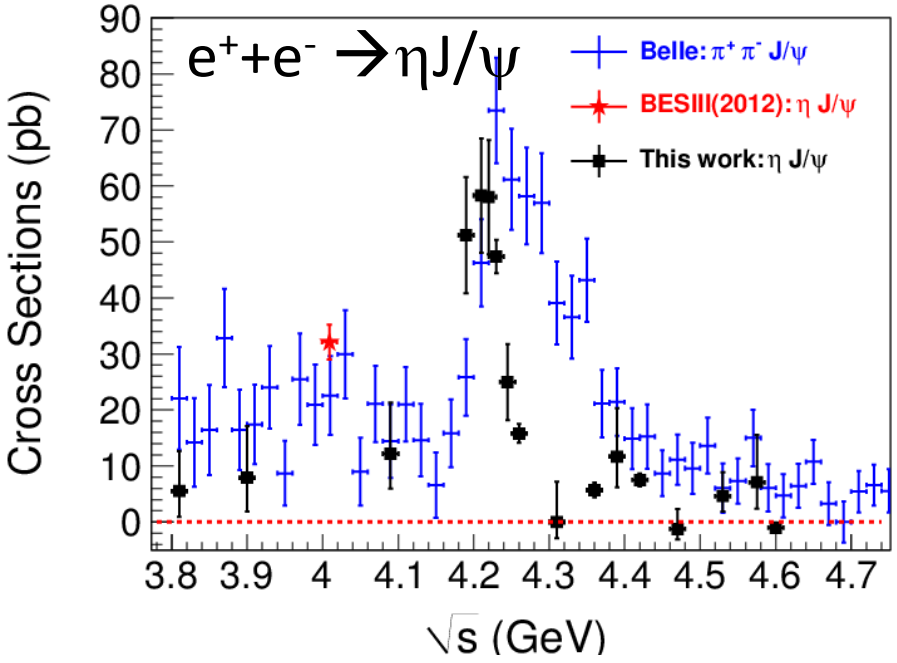
- A tetraquark? Phys.Rev.D91, 117501 (2015)
- ψ(4S)? EPJC 74:3208 (2014)
- Threshold effect?

- No significant $e+e-\rightarrow\omega\chi_{c1}$events

- Can be described by $\psi(4415)$

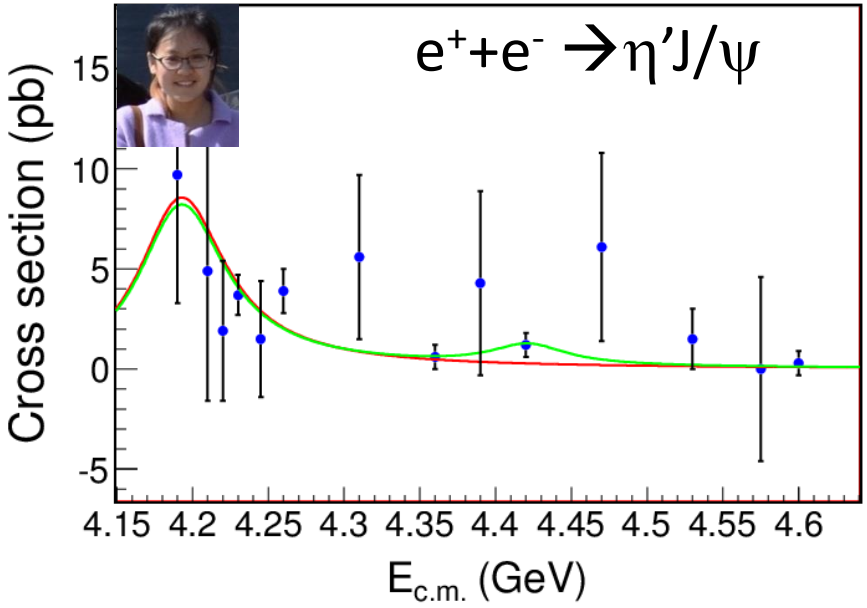
PRL 114, 092003 (2015)
PRD 93, 011102(R) (2016)

$e^+e^- \rightarrow \eta/\eta' J/\psi$



- The cross section peaks around 4.2 GeV
- Different from the e+e- $\rightarrow \pi\pi/\psi$ lineshape.

PRD 91, 112005 (2015)

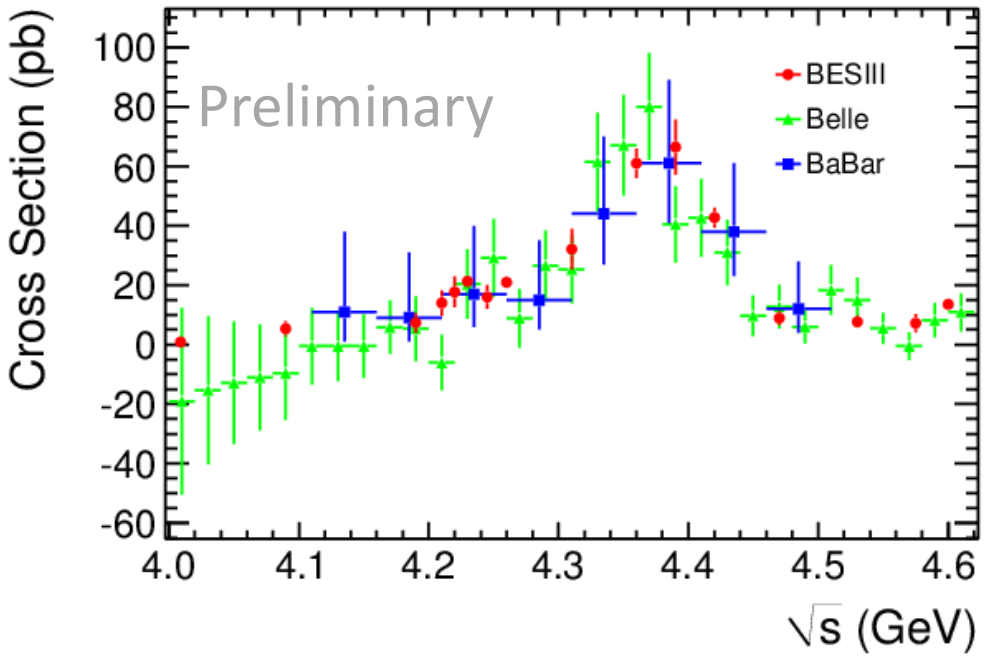


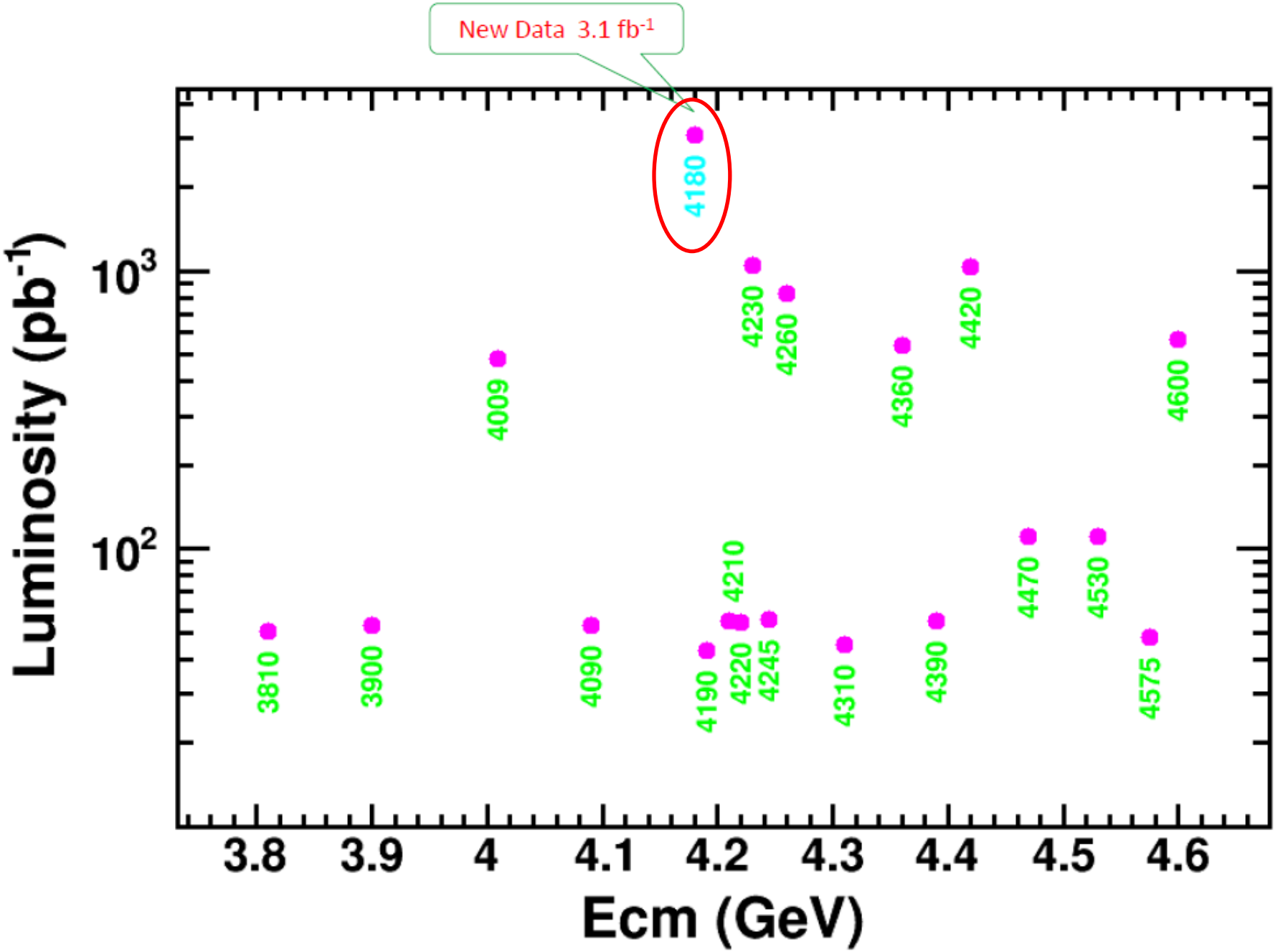
- First observation at $\sqrt{s}$ = 4.23 & 4.26 GeV .
- Fit with ψ (4160) and ψ (4415) resonances (fixed mass and width); looking at data at 4180.
- $\sigma(\eta' J/\psi)$ is much lower than $\sigma(\eta J/\psi)$, in contradiction to the calculation in the framework of NRQCD

PRD 94, 032009 (2016)

$e^+e^- \rightarrow \pi^+\pi^-\psi(3686)$

- Reconstructed modes:
  - Mode I: $\Psi(3686) \rightarrow \pi^+\pi^- J/\psi$, $J/\psi \rightarrow l^+l^-$ ($l=e/\mu$)
  - Mode II: $\Psi(3686) \rightarrow$ neutrals$+J/\psi$, neutrals$=(\pi^0\pi^0, \pi^0, \eta$ and $\gamma\gamma)$ $J/\psi \rightarrow l^+l^-$ ($l=e/\mu$)
- The measured Born cross sections of $e^+e^- \rightarrow \pi^+\pi^-\psi(3686)$




New Data 3.1 fb-1
Luminosity (pb-1)
10^3
10^2
3.8
3.9
4
4.1
4.2
4.3
4.4
4.5
4.6
Ecm (GeV)
4180
4230
4260
4009
4360
4420
4600
4210
4470
4530
3810
3900
4090
4190
4220
4245
4310
4390
4575

Summary

- BESIII is in a unique position to both directly access these states and to search for new states.
- BESIII has been intensively studied the XYZ structures.
- We are for most time limited by statistics. Optimize data taking? Measure more decay modes; build connections between states at this region.
- Very complex structures in the cross sections > 4GeV, which may point to the existence of exotics.
- BESIII plans to take data at 4.19-4.30 GeV. What are you going to do with these data?

人类对微观世界物质组成的探索是无止境的，五彩缤纷的基本粒子带给人们无限的思索和遐想。τ轻子、粲粒子、多夸克态、胶子球，无不引人入胜。感谢北京正负电子对撞机和北京谱仪，为粒子物理学谱写了新的篇章。

—— 赵光达（理论物理学家，中国科学院院士）