



Radiative Transitions in e^+e^- collisions above 4 GeV at BESIII

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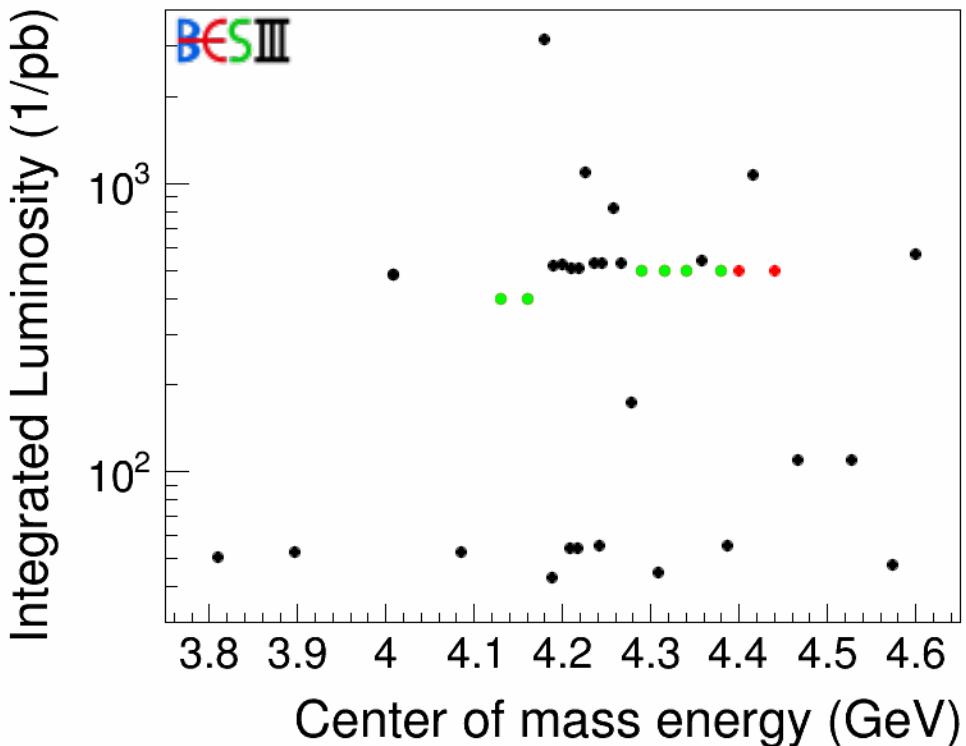
Outline

- Motivation
- Data samples at BESIII
- Radiative transitions above 4 GeV
 - $e^+e^- \rightarrow \gamma\eta_c$
 - $e^+e^- \rightarrow \gamma\chi_{cJ}$
 - $e^+e^- \rightarrow \gamma X(3872)$
 - $e^+e^- \rightarrow \gamma X(4140)$
- Summary

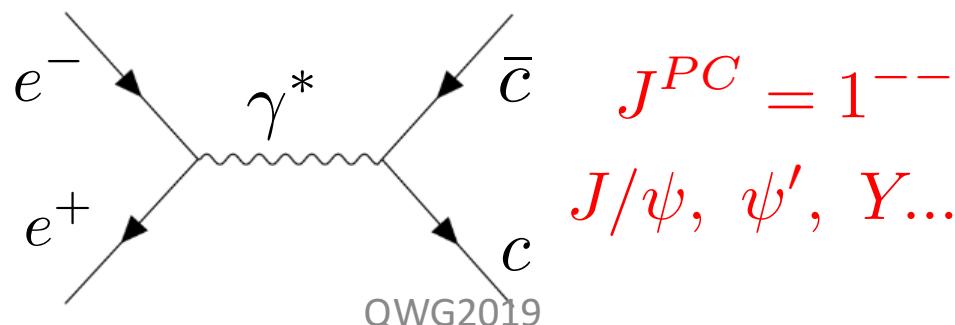
Radiative Transition

- Interesting feature of charmonium physics
- Straightforward to evaluate in $c\bar{c}$ potential models
- Well understand charmonium states under open charm threshold
- A series of charmonium-like states, $X(3872)$, $Y(4260)$, Z_c etc, with unclear interpretation above threshold
 - Search for radiative transition above 4 GeV
 - Understand the charmonium-like states and their correlations
 - Search for new C-even charmonium-like states (e.g. $X(3915)$, $Y(4140)$)

Data samples @ BESIII



- $\sim 13 \text{ fb}^{-1}$ e^+e^- collision data in open charm region:
4.0~4.60 GeV
- More data samples are being taken this year ($\sim 3.8 \text{ fb}^{-1}$)
- A scan experiment for vector charmonium-(like) states



Evidence for $e^+e^- \rightarrow \gamma\eta_c$

- $\Upsilon(4260)$ discovered firstly in the initial state radiation (ISR) process $e^+e^- \rightarrow \gamma_{\text{ISR}} \Upsilon(4260) \rightarrow \gamma_{\text{ISR}} \pi^+\pi^- J/\psi$
- $J^{PC} [\Upsilon(4260)] = 1^{--}$, not a traditional charmonium states
- Possible interpretation \rightarrow hybrid meson: extra gluonic degree of freedom allows an M1 transition without spin-flip (flux-tube model)

PRD 79, 094504 (2009)

The rate of decay to $\gamma\eta_c$ will be enhanced relative to $\gamma\chi_{c0}$

partial widths	branching fraction
$\Gamma(Y_{hyb} \rightarrow \gamma\eta_c) = 42 \pm 18 \text{ keV}$	$B(Y(4260) \rightarrow \gamma\eta_c) = 0.035 \pm 0.154 \%$
$\Gamma(Y_{hyb} \rightarrow \gamma\chi_{c0}) \lesssim 20 \text{ keV}$	$B(Y(4260) \rightarrow \gamma\chi_{c0}) \lesssim 0.017 \%$

- Finding evidence for $e^+e^- \rightarrow \Upsilon(4260) \rightarrow \gamma\eta_c$
 \Rightarrow additional support to the hybrid interpretation

Evidence for $e^+e^- \rightarrow \gamma\eta_c$

- $e^+e^- \rightarrow \gamma\eta_c, \eta_c \rightarrow X_i$ (14 η_c decay channels) at six c.m. energies in $4.01 \sim 4.60$ GeV (4.6 fb^{-1})

η_c Mode	Branching Fraction (%)
$\pi^+\pi^-\pi^+\pi^-\pi^0\pi^0$	17.23
$\pi^+\pi^-\pi^0\pi^0$	4.660
$\eta\pi^+\pi^-\pi^+\pi^-$	4.400
$K^+K^-\pi^+\pi^-\pi^0$	3.500
$\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$	2.020
$\pi^+\pi^-\pi^+\pi^-$	1.720
$\eta\pi^+\pi^-$	1.660
$K^-K_S\pi^+\pi^+\pi^-$	1.375
$K^+K_S\pi^-\pi^+\pi^-$	1.375
$K^-K_S\pi^+$	1.300
$K^+K_S\pi^-$	1.300
$K^+K^-\pi^0$	1.040
$K^+K^-\pi^+\pi^-$	0.9500
$K^+K^-\pi^+\pi^-\pi^+\pi^-$	0.8300

PRD 86, 092009 (2012)

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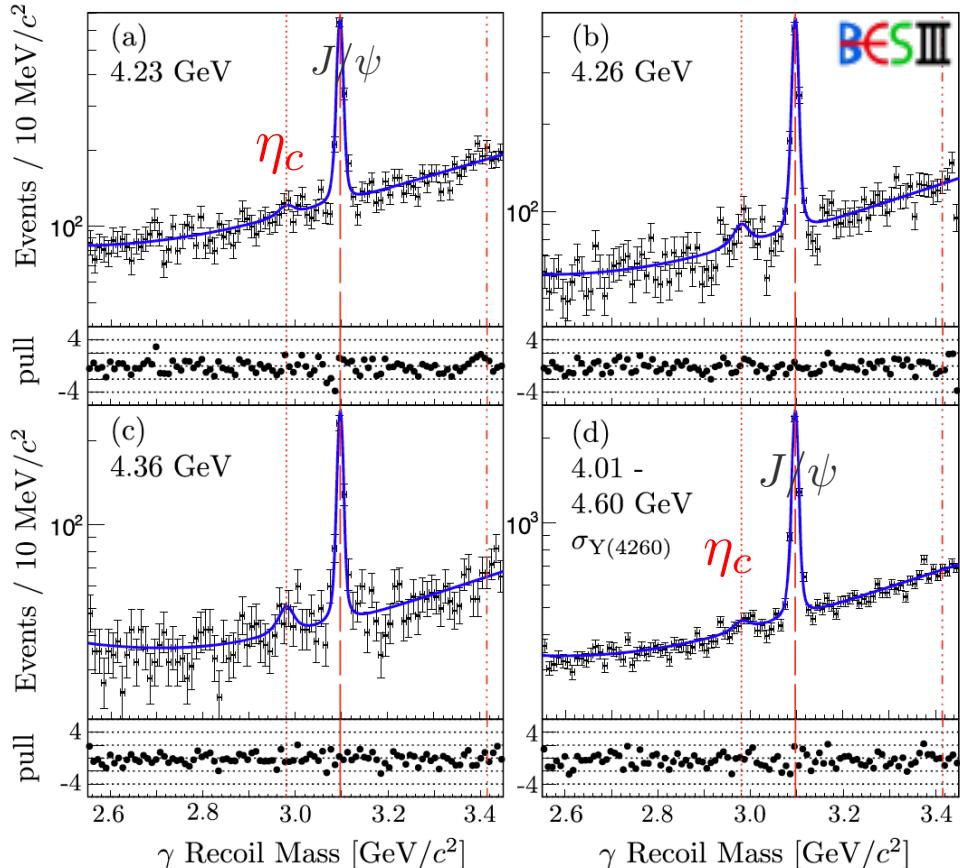
$$\sigma = \frac{N_{measured}}{\mathcal{L}(1 + \delta^{ISR})(1 + \delta^{VP})\epsilon}$$

- $\sigma_{Y(4260)}$: a nonrelativistic Breit-Wigner (BW) for the Y(4260) (mass and width values from the PDG)

PRD 86, 092009 (2012)

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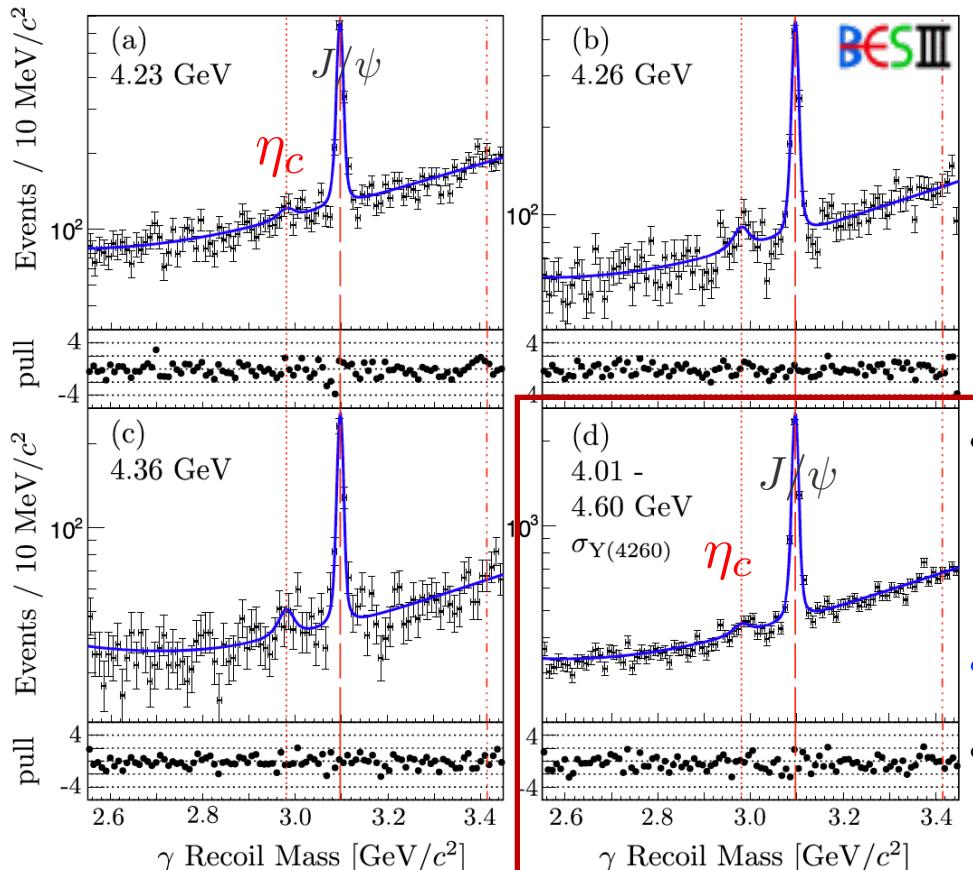
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$\sigma_{Y(4260)}$: a nonrelativistic Breit-Wigner (BW) for the $Y(4260)$ (mass and width values from the PDG)

- Simultaneously fit the recoil-mass distributions of the transition photon associated with the 14 final states X_i
- $\sigma(e^+e^- \rightarrow \gamma\eta_c)$: a shared free parameter
- The η_c signal: nonrelativistic BW function (mass and width fixed to the PDG values)

Evidence for $e^+e^- \rightarrow \gamma\eta_c$

- $e^+e^- \rightarrow \gamma\eta_c, \eta_c \rightarrow X_i$ (14 η_c decay channels) at six c.m. energies in $4.01 \sim 4.60$ GeV



combined

$$\sigma = \frac{N_{measured}}{\mathcal{L}(1 + \delta^{ISR})(1 + \delta^{VP})\epsilon}$$

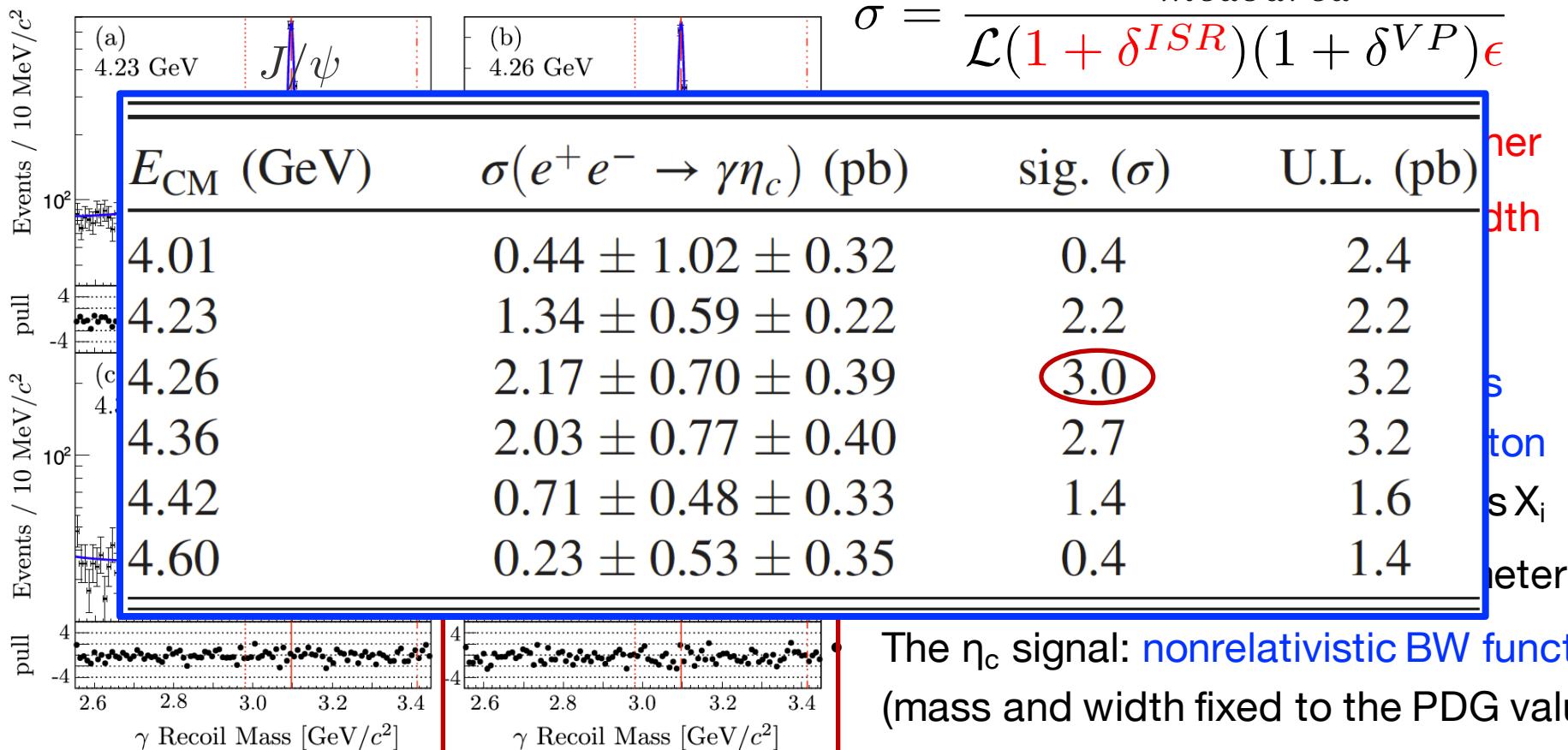
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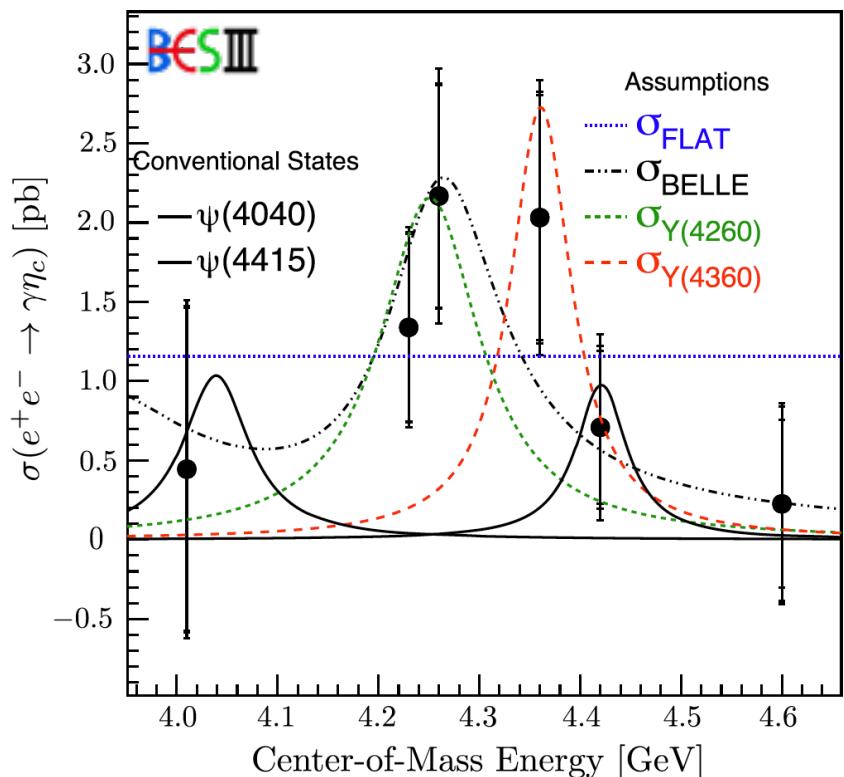
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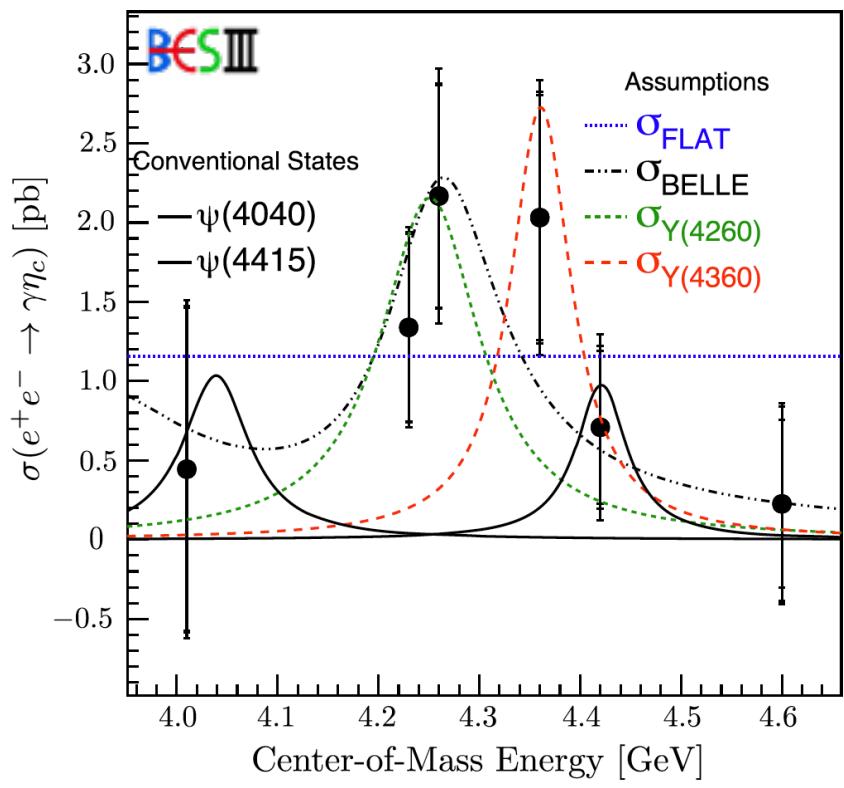
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Evidence for $e^+e^- \rightarrow \gamma\eta_c$

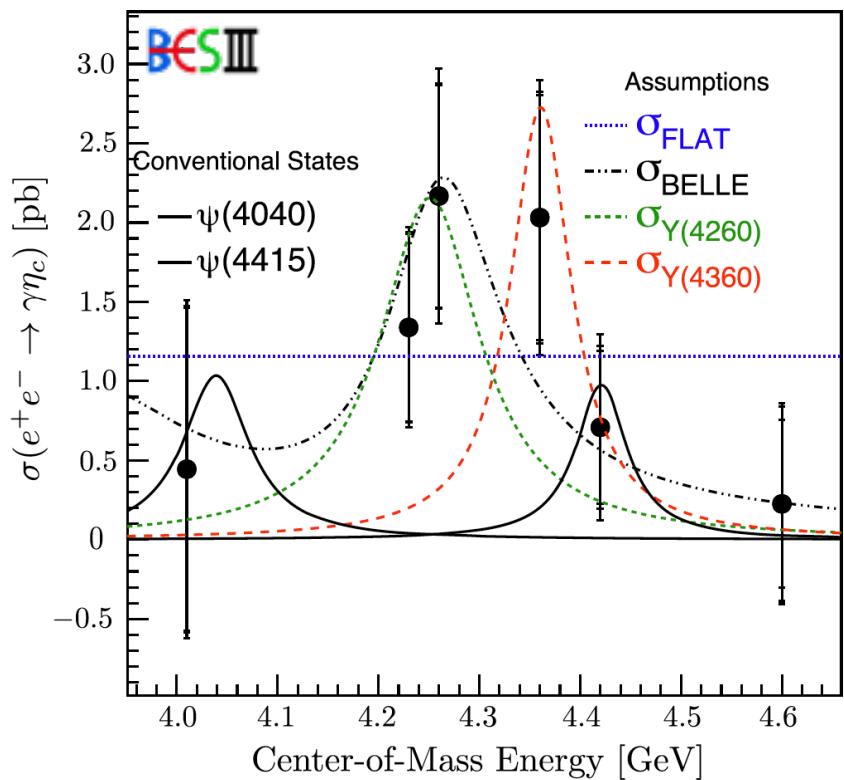


Evidence for $e^+e^- \rightarrow \gamma\eta_c$



- Four different assumptions to combine the data from six c.m. energies
 => larger sample for $e^+e^- \rightarrow \gamma\eta_c$
- => Compare the $Y(4260)$ hypothesis ($\sigma_{Y(4260)}$) to others
- $\sigma_{Y(4260)}$: a nonrelativistic BW for $Y(4260)$
- σ_{FLAT} : constant JHEP 10, 71 (2014)
- σ_{BELLE} : Belle parameterization of $\sigma(e^+e^- \rightarrow \pi^+\pi^-J/\psi)$, modeled with a $Y(4008)$ and $Y(4260)$ PRL 110, 252002 (2013)
- $\sigma_{Y(4360)}$: a nonrelativistic BW for $Y(4360)$

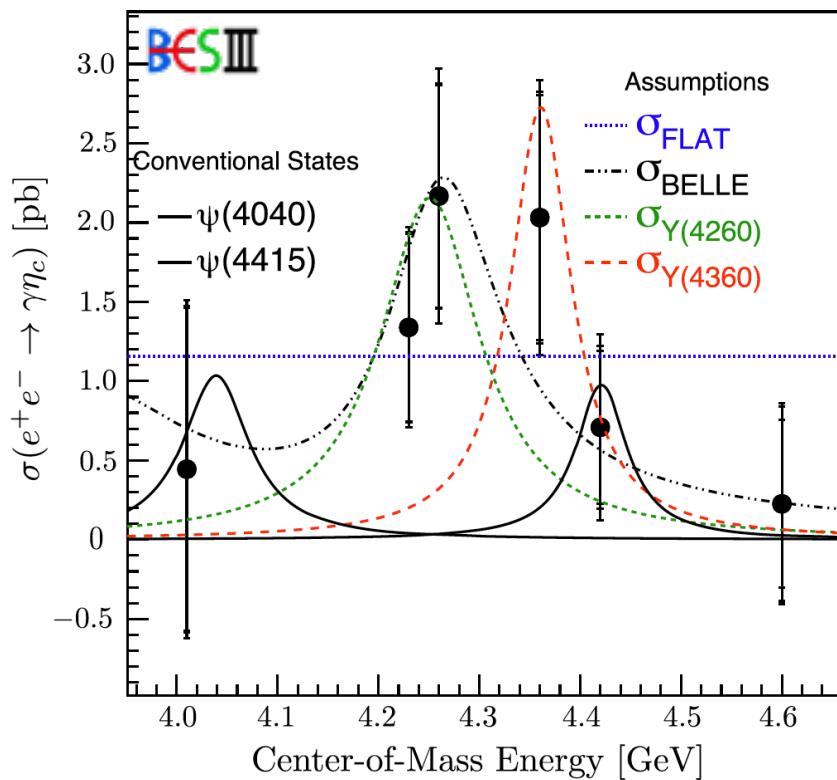
Evidence for $e^+e^- \rightarrow \gamma\eta_c$



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- $\sigma_{Y(4360)}$: a nonrelativistic BW for $Y(4360)$

- Simultaneous fit to the 6×14 recoil mass distributions of transition photon
- Each energy share the same $\sigma(e^+e^- \rightarrow \gamma\eta_c)$
- Between different energies, $\sigma(e^+e^- \rightarrow \gamma\eta_c)$ is constrained to follow the $\sigma_{Y(4260)}$, σ_{FLAT} , σ_{BELL} , $\sigma_{Y(4360)}$

Evidence for $e^+e^- \rightarrow \gamma\eta_c$



Assumption	$\sigma_{\text{peak}}(e^+e^- \rightarrow \gamma\eta_c)$ (pb)	sig. (σ)	U.L. (pb)
σ_{FLAT}	$1.16 \pm 0.27 \pm 0.20$	4.1	1.6
σ_{BELL}	$2.27 \pm 0.49 \pm 0.39$	4.5	3.1
$\sigma_{Y(4260)}$	$2.11 \pm 0.49 \pm 0.36$	4.2	2.9
$\sigma_{Y(4360)}$	$2.72 \pm 0.71 \pm 0.46$	3.6	3.9

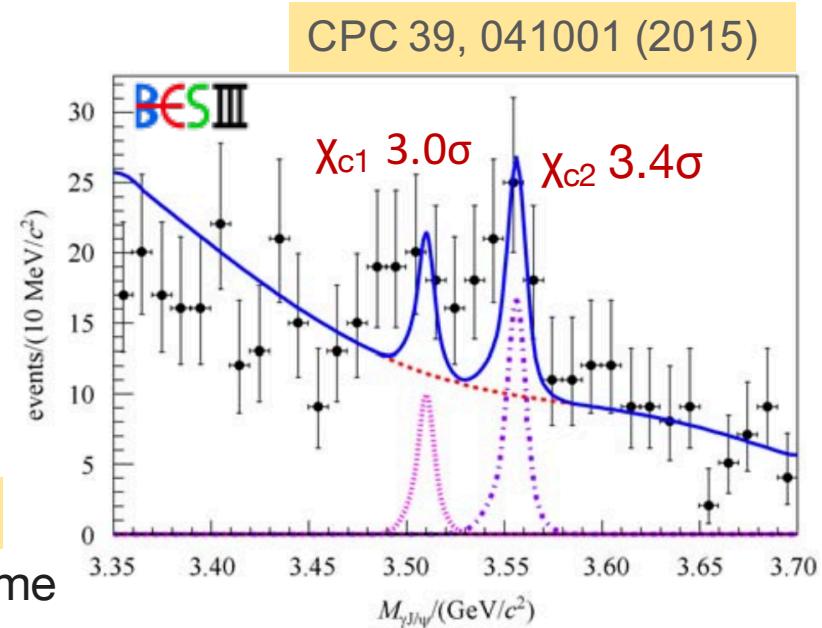
- The statistic significance of the $\gamma\eta_c$: 3.6σ
- The cross section is **better explained by $\sigma_{Y(4260)}$** than by conventional charmonium states:
 $\psi(4040)$ (1.9σ), $\psi(4160)$ (3.5σ), $\psi(4415)$ (1.9σ)

- $B(Y(4260) \rightarrow \gamma\eta_c)/B(Y(4260) \rightarrow \pi^+\pi^- J/\psi) = 0.034 \pm 0.009$ with $\sigma_{Y(4260)}$ assumption
- $\sigma_{\text{peak}}(e^+e^- \rightarrow \gamma\chi_{c0})/\sigma_{\text{peak}}(e^+e^- \rightarrow \gamma\eta_c) < 2.8$ at 90% C.L.
- The enhancement of $e^+e^- \rightarrow \gamma\eta_c$ may suggest production via a hybrid charmonium state

Evidence for $e^+e^- \rightarrow \gamma X_{cJ}$

- $\psi(4040, 4160, 4415) / Y(4260, 4360, 4660)$
 $\rightarrow \gamma X_{cJ}(2P)$ by the electric dipole (E1)
transitions between charmonia or other exotic mechanisms
 - arXiv:1310.8597
- NRQCD: $\sigma(e^+e^- \rightarrow \gamma X_{cJ}) \sim 0.1\text{-}0.9 \text{ pb}$
- Shed more light on the properties of the $Y(4260)$
 - PRL 96, 162003 (2006)
- Existing investigation by CLEO for the first time

$$e^+e^- \rightarrow \gamma X_{cJ} \rightarrow \gamma\gamma J/\psi$$



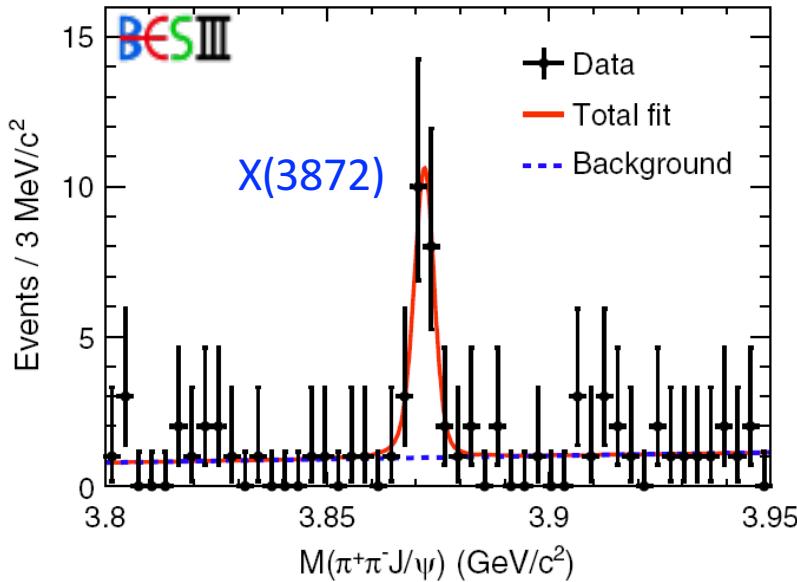
$$\sqrt{s}=4.009, 4.230, 4.260 \text{ & } 4.360 \text{ GeV}$$
$$\sim 2.895 \text{ fb}^{-1}$$

- Find the evidence of $e^+e^- \rightarrow \gamma X_{c1,2}$, no signal for $e^+e^- \rightarrow \gamma X_{c0}$
- ~3 times more data from 4.15-4.42 GeV, more precise measurements and cross section line shapes are expected!

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

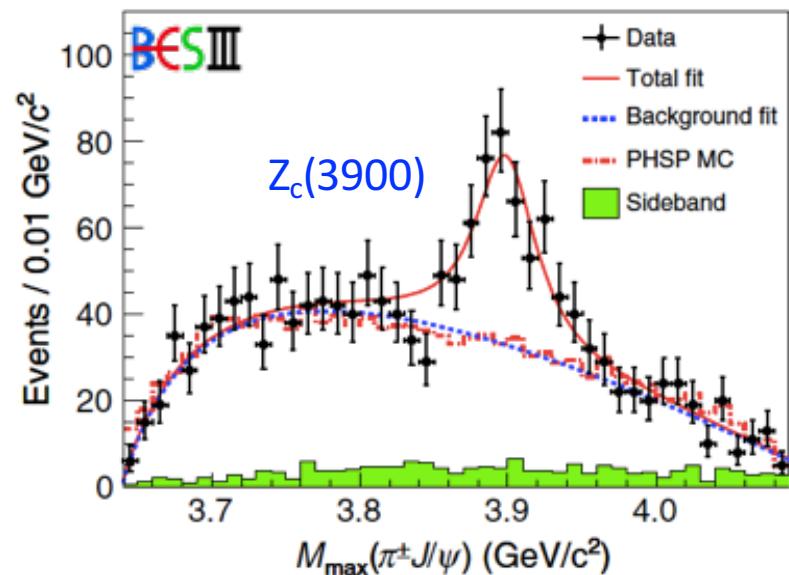
PRL 112, 092001 (2014)

e^+e^- (at 4260 MeV) $\rightarrow \gamma X(3872) \rightarrow \gamma\pi^+\pi^-J/\psi$



PRL 110, 252001 (2013)

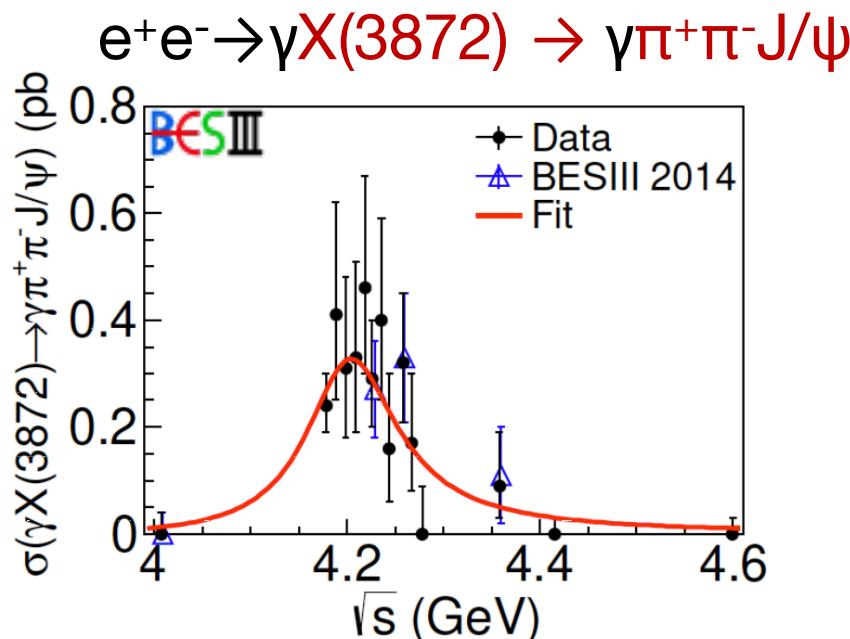
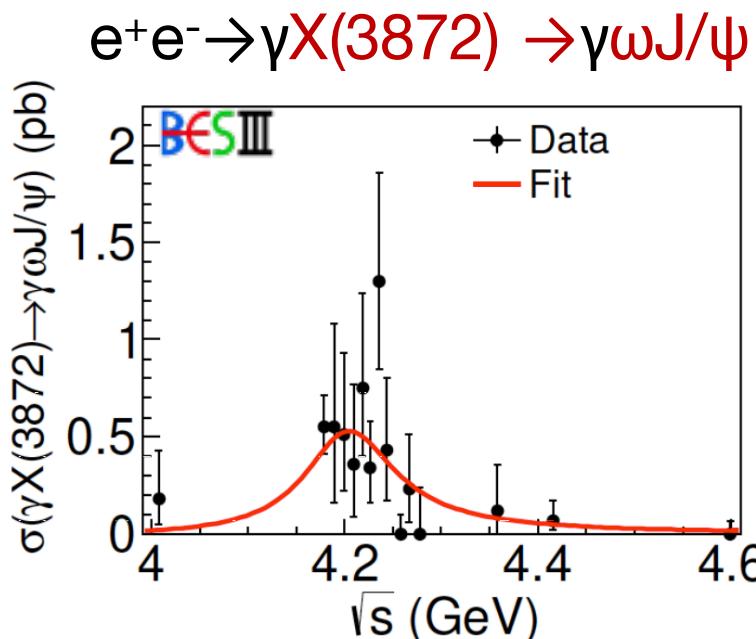
e^+e^- (at 4260 MeV) $\rightarrow \pi^+\pi^-J/\psi$



- Potential connections among the $X(3872)$, $Y(4260)$ and $Z_c(3900)$??
- Strongly hint towards a common underlying nature for them
- More supportive experimental observation for the $Y(4260) \rightarrow \gamma X(3872)$ needed

Based on 11.6 fb^{-1} data at $\sqrt{s}=4.01\sim4.60 \text{ GeV}$ taken by BESIII, study the processes $e^+e^- \rightarrow \gamma X(3872) \rightarrow \gamma\omega J/\psi$ and $e^+e^- \rightarrow \gamma X(3872) \rightarrow \gamma\pi^+\pi^-J/\psi$

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



PRL 118, 092001-092002 (2017)

	$e^+e^- \rightarrow \gamma X(3872)$	$e^+e^- \rightarrow \pi^+ \pi^- J/\psi$	$e^+e^- \rightarrow \pi^+ \pi^- h_c$
Mass (MeV/c^2)	$4200.6^{+7.9}_{-13.3} \pm 2.0$	$4222.0 \pm 3.1 \pm 1.4$	$4218.4^{+5.5}_{-4.5} \pm 0.9$
Γ (MeV)	$115^{+38}_{-26} \pm 12$	$44.1 \pm 4.3 \pm 2.0$	$66.0^{+12.3}_{-8.3} \pm 0.4$

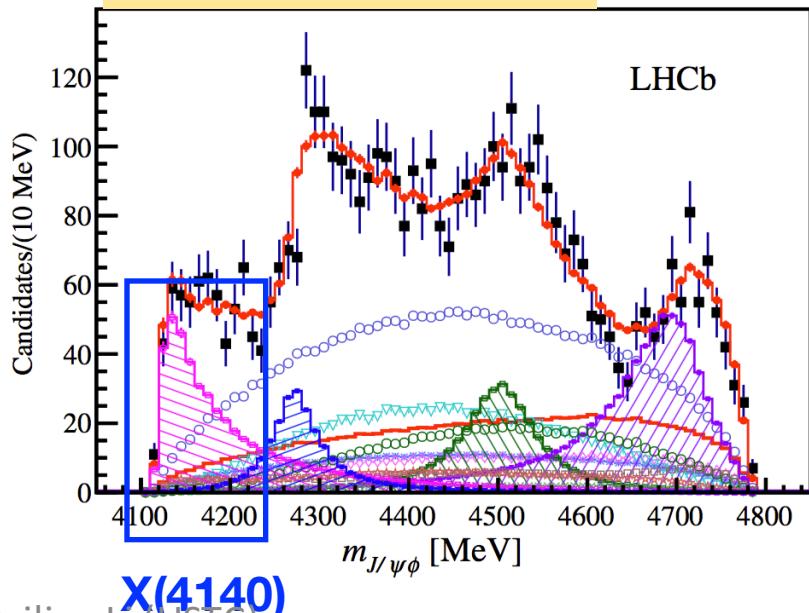
- The mass and width agree with the $\Psi(4160)$ or the $Y(4220)$ within errors

More details about $X(3872)$ can be found in Junhao Yin's report

Search for $e^+e^- \rightarrow \gamma X(4140)$

Year	Experiment luminosity	$B \rightarrow J/\psi\phi K$ yield	Mass (MeV)	$X(4140)$ peak Width (MeV)	Significance	Fraction (%)
2008	CDF 2.7 fb^{-1} [1]	58 ± 10	$4143.0 \pm 2.9 \pm 1.2$	$11.7^{+8.3}_{-5.0} \pm 3.7$	3.8σ	
2009	<i>Belle</i> [22]	325 ± 21	4143.0 fixed	11.7 fixed	1.9σ	
2011	<i>CDF</i> 6.0 fb^{-1} [29]	115 ± 12	$4143.4^{+2.9}_{-3.0} \pm 0.6$	$15.3^{+10.4}_{-6.1} \pm 2.5$	5.0σ	$14.9 \pm 3.9 \pm 2.4$
2011	LHCb 0.37 fb^{-1} [21]	346 ± 20	4143.4 fixed	15.3 fixed	1.4σ	$<7 @ 90\% \text{ CL}$
2013	CMS 5.2 fb^{-1} [25]	2480 ± 160	$4148.0 \pm 2.4 \pm 6.3$	$28^{+15}_{-11} \pm 19$	5.0σ	$10 \pm 3 \text{ (stat.)}$
2013	D0 10.4 fb^{-1} [26]	215 ± 37	$4159.0 \pm 4.3 \pm 6.6$	$19.9 \pm 12.6^{+1.0}_{-8.0}$	3.0σ	$21 \pm 8 \pm 4$
2014	<i>BABAR</i> [24]	189 ± 14	4143.4 fixed	15.3 fixed	1.6σ	$<13.3 @ 90\% \text{ CL}$
2015	D0 10.4 fb^{-1} [27]	$p\bar{p} \rightarrow J/\psi\phi \dots$	$4152.5 \pm 1.7^{+6.2}_{-5.4}$	$16.3 \pm 5.6 \pm 11.4$	4.7σ (5.7σ)	
Average			4147.1 ± 2.4	15.7 ± 6.3		

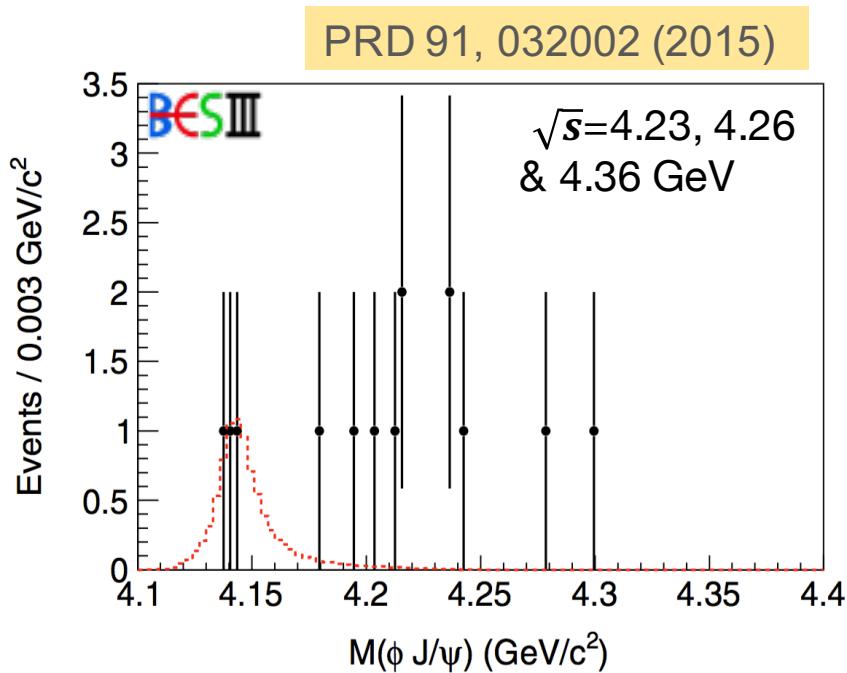
PRD 95, 012002 (2017)



$$\begin{aligned} M &= (4146.5 \pm 4.5^{+4.6}_{-2.8}) \text{ MeV} \\ \Gamma &= (83 \pm 21^{+21}_{-14}) \end{aligned}$$

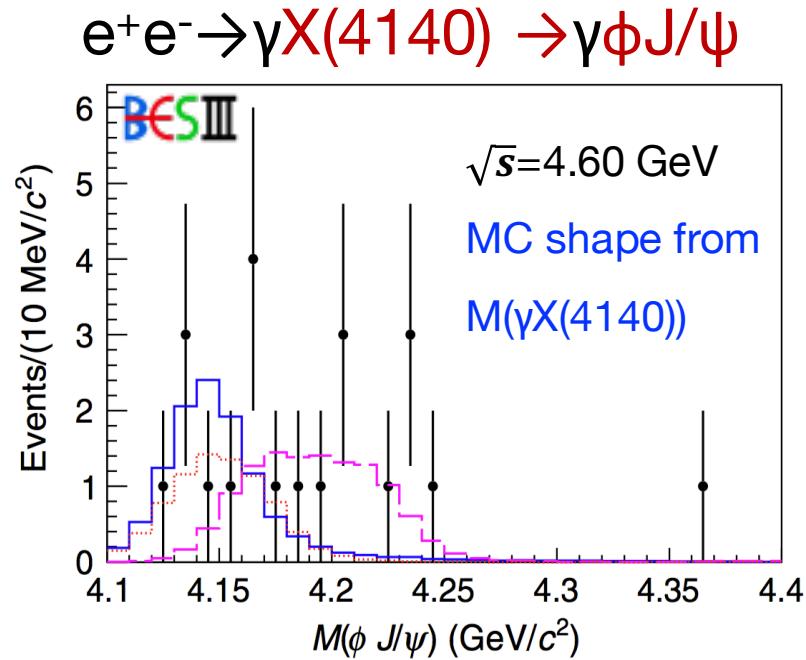
- **X(4140):** First charmonium-like state decaying to two vector mesons consisting of $c\bar{c}$ and $s\bar{s}$ pairs
- Hybrid charmonium state \rightarrow partial width of $Y(4260) \rightarrow \gamma X(4140) \sim \text{tens keV}$

Search for $e^+e^- \rightarrow \gamma X(4140)$



- No obvious $X(4140)$ signal

More data with higher statistics are
need to figure out the character of
 $X(4140)$



\sqrt{s} (GeV)	U.L. at 90% C.L. (pb) $\sigma(e^+e^- \rightarrow \gamma X(4140)) \times B(X(4140) \rightarrow \phi J/\psi)$
4.23	0.35
4.26	0.28
4.36	0.33
4.60	1.20

Summary

- Search for some radiative transition processes with the large data sample above 4 GeV at BESIII
 - First evidence for $e^+e^- \rightarrow \gamma\eta_c$ process
 - Evidence for $e^+e^- \rightarrow \gamma X_{c1,2}$
 - Study of $\sigma(e^+e^- \rightarrow \gamma X(3872))$ with $X(3872) \rightarrow \omega J/\psi$ and $X(3872) \rightarrow \pi^+\pi^- J/\psi$ processes, where mass and width of Y state agree with Y(4220)
 - Search for $e^+e^- \rightarrow \gamma X(4140)$ but no signal observed
 - With more data in charmonium region being taken, more exciting results will come out from BESIII soon

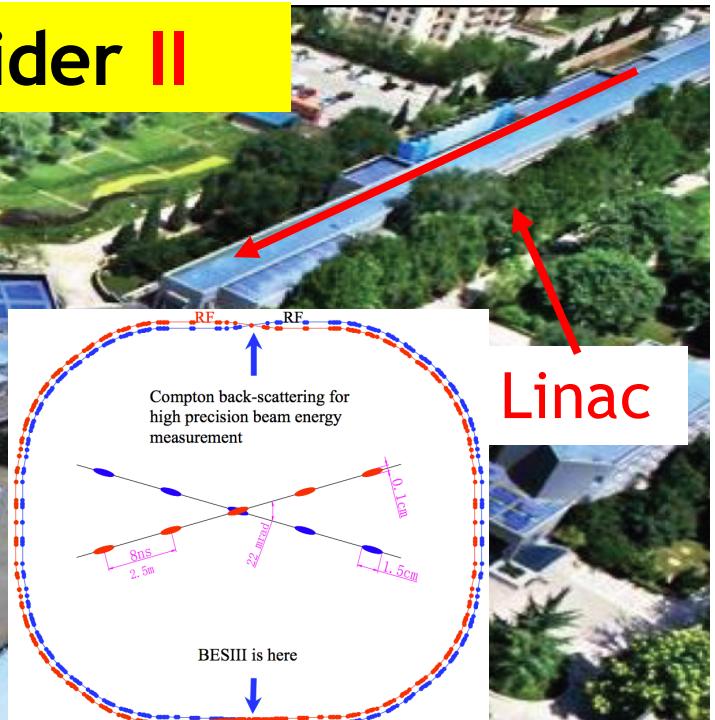
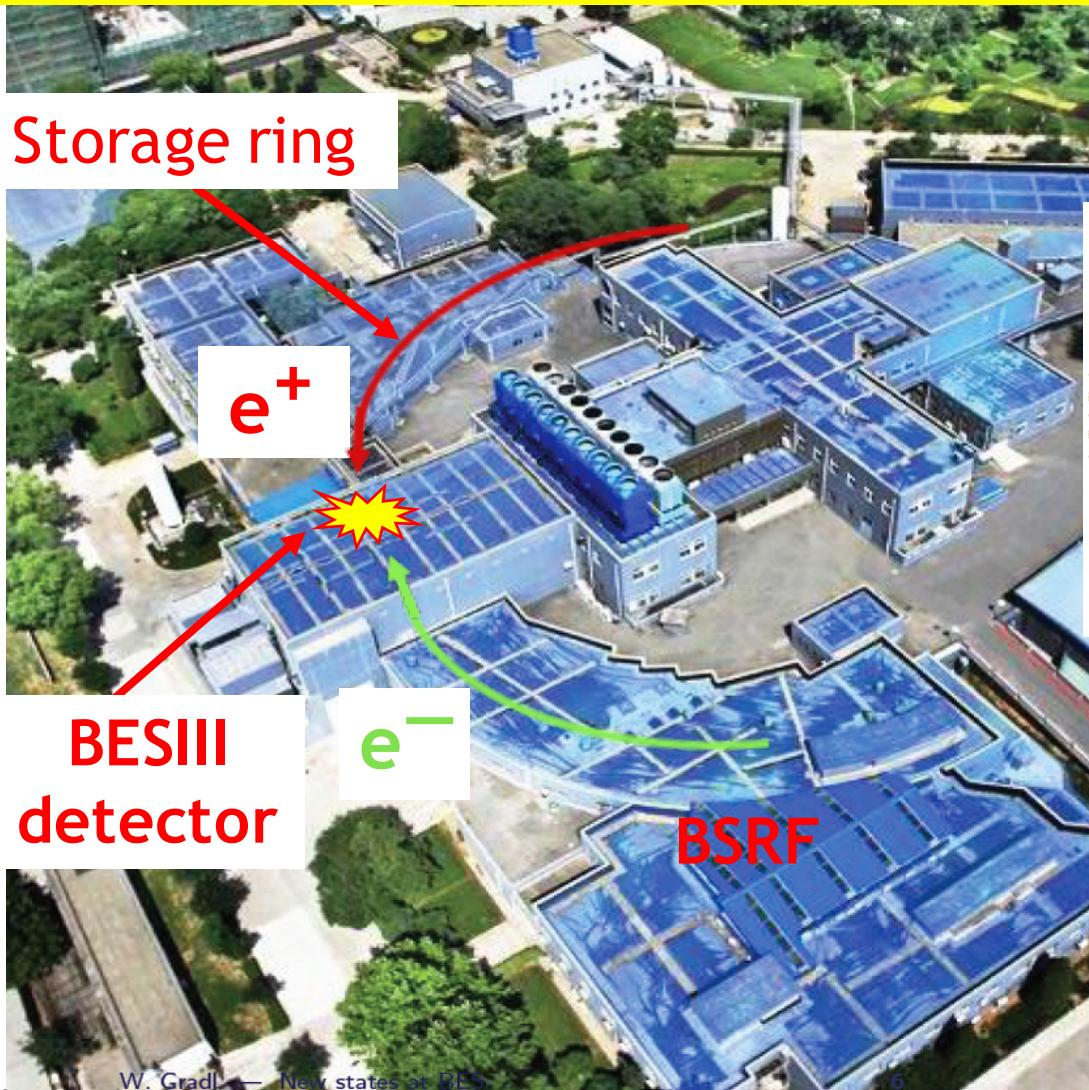
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Thanks!

Back up

Beijing Electron Positron Collider II



E_{beam} : 1.0-2.3 GeV

Double ring: e^+ and e^-

Multi-bunch: 93

Peak luminosity: 1.0×10^{33}
 $\text{cm}^{-2}\text{s}^{-1}$ @3770GeV

Back up

Beijing Spectrum III

NIM A614, 345 (2010)

Drift Chamber (MDC):

$$\sigma_P/P (\%) = 0.5\% \text{ @} 1\text{GeV}$$

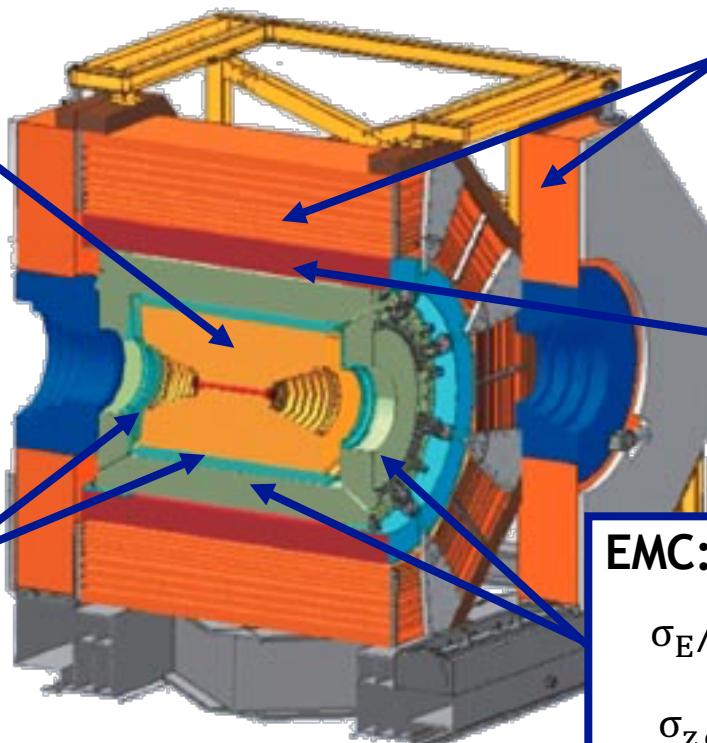
$$\sigma_{dE/dx} (\%) = 6\%$$

Time Of Flight (TOF):

$$\sigma_T: 90 \text{ ps Barrel}$$

$$110 \text{ ps endcap}$$

(60ps after update)



Muon Counter:

8-9 layers RPC

$$\delta_{R,\phi} = 1.4\text{cm} \sim 1.7\text{cm}$$

Super-conducting solenoidal magnet (SC): 1T

EMC: (CsI)

$$\sigma_E/\sqrt{E} (\%) = 2.5\% \text{ @ } 1 \text{ GeV}$$

$$\sigma_{z,\phi} (\text{cm}) = 0.5 - 0.7 \text{ cm}/\sqrt{E}$$

Evidence for $e^+e^- \rightarrow \gamma X_{cJ}$

- $\psi(4040, 4160, 4415) / \Upsilon(4260, 4360, 4660)$
 $\rightarrow \gamma X_{cJ}(2P)$ by the electric dipole (E1)
transitions between charmonia or other

$e^+e^- \rightarrow \gamma X_{cJ} \rightarrow \gamma\gamma J/\psi$

CPC 39, 041001 (2015)

\sqrt{s}/GeV		N^{obs}	significance (σ)	N^{UP}	ϵ (%)	30		$\sigma^{\text{UP}}/\text{pb}$	$\sigma^{\text{B}}/\text{pb}$
						$1+\delta^r$	$1+\delta^v$		
4.009	X_{c0}	7.0 ± 6.6	1.6	18	36.4 ± 0.2			179	$65.0 \pm 61.3 \pm 4.2$
	X_{c1}	4.4 ± 2.6	2.2	9	23.4 ± 0.1	0.738	1.04	5.3	$2.4 \pm 1.4 \pm 0.2$
	X_{c2}	1.8 ± 1.7	1.5	6	8.7 ± 0.1			18	$4.7 \pm 4.4 \pm 0.6$
4.230	X_{c0}	0.2 ± 2.3	0.0	7	37.2 ± 0.2			26	$0.7 \pm 8.0 \pm 0.1$
	X_{c1}	6.7 ± 4.3	1.9	14	44.4 ± 0.2	0.840	1.06	1.7	$0.7 \pm 0.5 \pm 0.1$
	X_{c2}	13.3 ± 5.2	2.9	22	42.0 ± 0.2			5.0	$2.7 \pm 1.1 \pm 0.3$
4.260	X_{c0}	0.1 ± 1.9	0.0	5	36.7 ± 0.2			25	$0.5 \pm 8.8 \pm 0.1$
	X_{c1}	3.0 ± 3.0	1.1	7	42.7 ± 0.2	0.842	1.06	1.1	$0.4 \pm 0.4 \pm 0.1$
	X_{c2}	7.5 ± 3.9	2.3	14	41.7 ± 0.2			4.2	$2.0 \pm 1.1 \pm 0.2$
4.360	X_{c0}	0.1 ± 0.7	0.0	3	32.4 ± 0.2			23	$0.7 \pm 5.0 \pm 0.1$
	X_{c1}	5.2 ± 4.9	2.4	10	31.7 ± 0.2	0.943	1.05	2.9	$1.4 \pm 1.3 \pm 0.1$
	X_{c2}	4.4 ± 4.5	2.0	9	30.3 ± 0.2			5.0	$2.3 \pm 2.3 \pm 0.2$

- Find the evidence of $e^+e^- \rightarrow \gamma X_{c1,2}$, no signal for $e^+e^- \rightarrow \gamma X_{c0}$
- ~3 times more data from 4.15-4.42 GeV, more precise measurements and cross section line shapes are expected!