Experimental Status of Conventional Charmonium Spectroscopy

Xiongfei Wang(王雄飞)
IHEP, CAS

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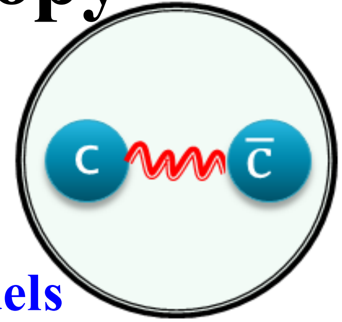
Outline

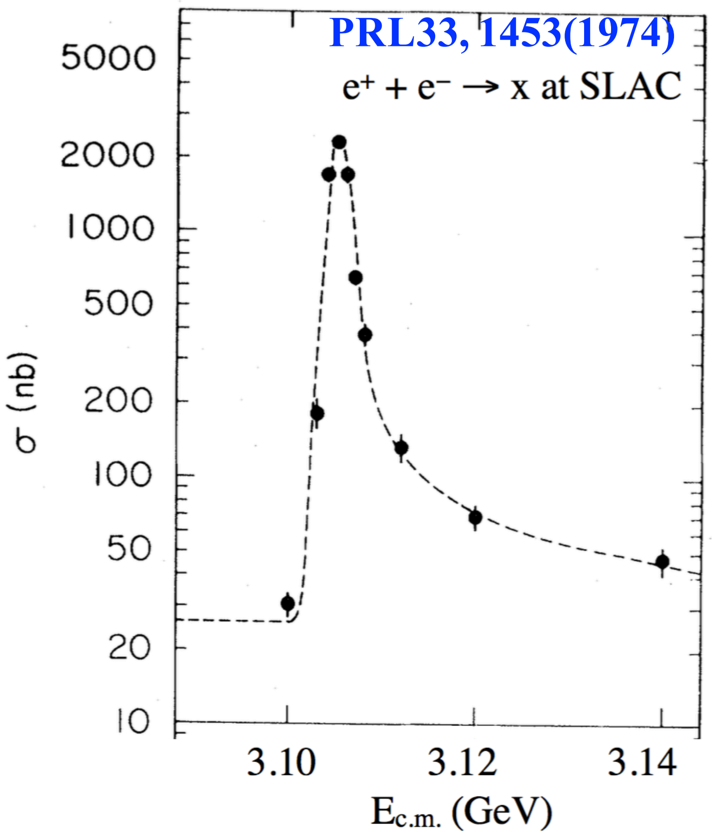
- **Introduction**
  - **Conventional charmonium spectroscopy (CCS)**
  - **Experimental apparatus**
- **Recent CCS results**
  - **J/ψ and $\psi(2S)$ resonance parameters**
  - **$\chi_{cJ}(1P)$ resonance parameters**
  - **$\eta_c(1S)$ resonance parameters**
  - **Observations of $X(3823)$ and $X^*(3860)$**
- **Summary**

Conventional Charmonium Spectroscopy

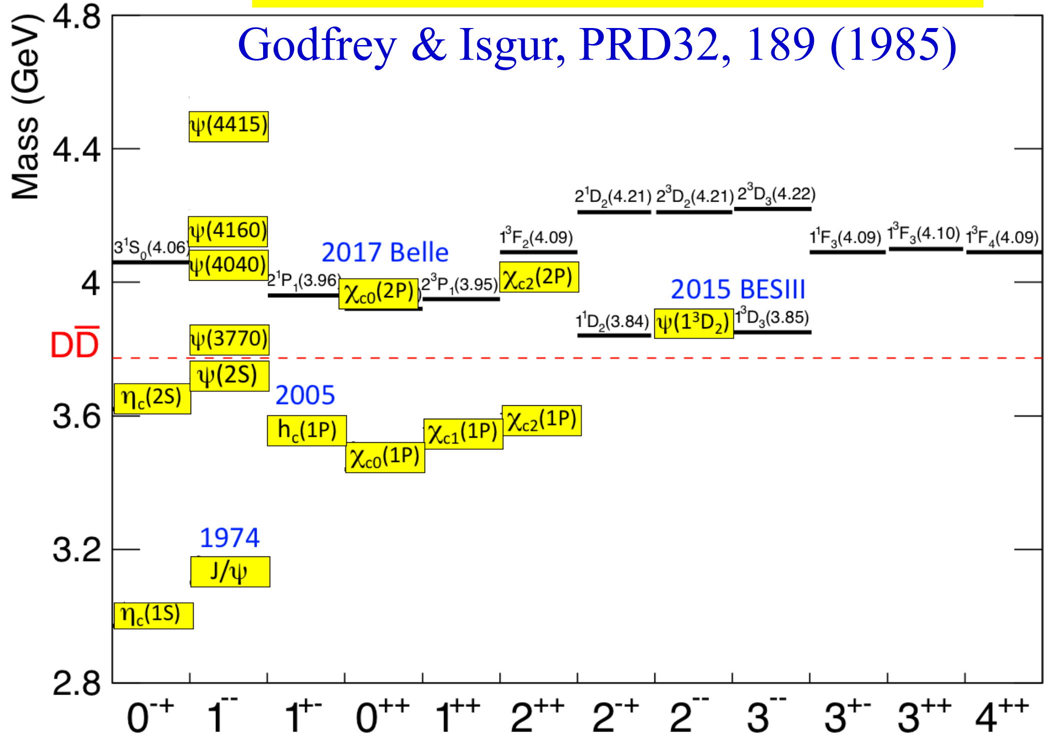


- **Nonrelativistic $c\bar{c}$ bound states**
- **$J/\psi\ (1^3S_1)$ is the first member with $J^{PC} = 1^{--}$, other shown in right plots like $\psi(2S), \psi(1D), etc.$.**
- **Observations are consistent with predictions from potential models and L-QCD in describing spectra & onium properties!**

November (1974) Revolution

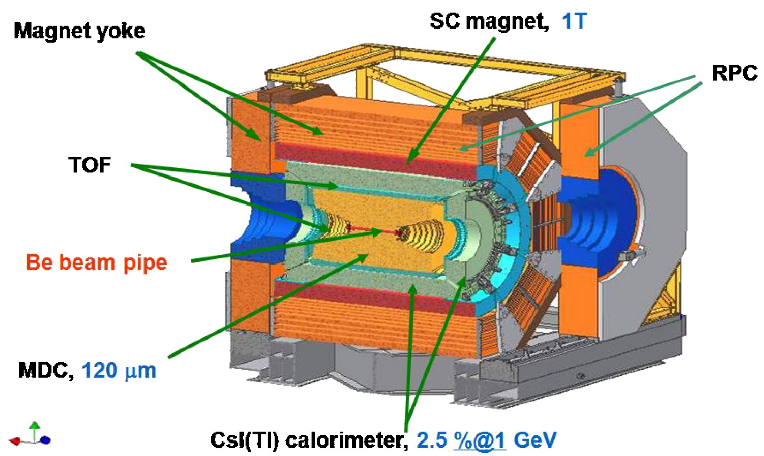


Discovered, predicted

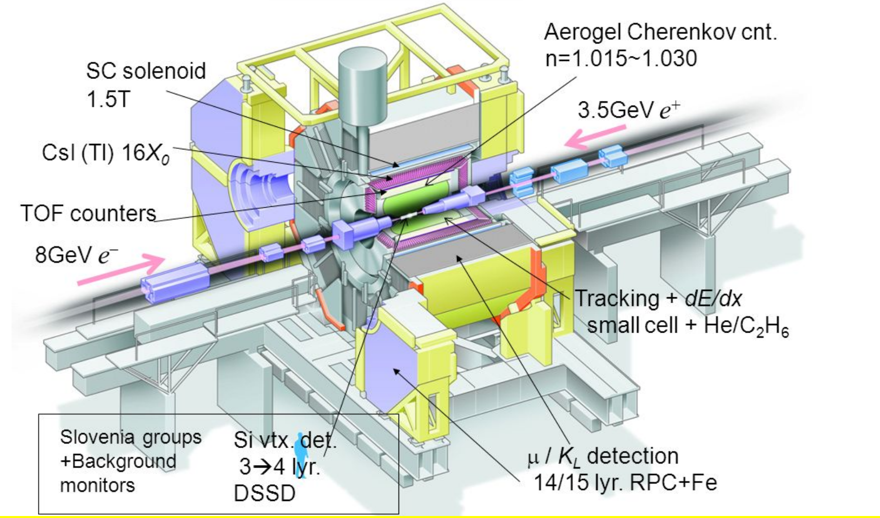


Experimental apparatus

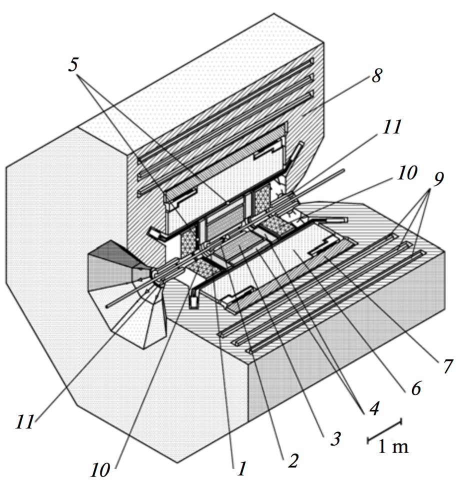
BESIII experiment designed for studying in tau-c physics region (NIMA614 (2010) 345-399)



Belle experiment designed for studying rare B-meson decay at ϒ(4S) resonance (NIMA 479(2002) 117-232)

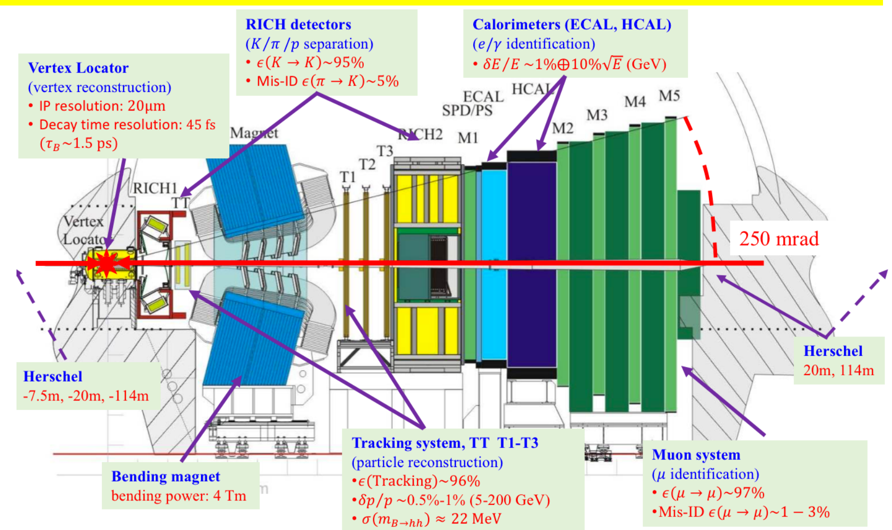


KEDR experiment designed for studying the *c*, *b* quarks and two photon physics (PPN, 2013, Vol. 44, No. 4, pp. 657–702)



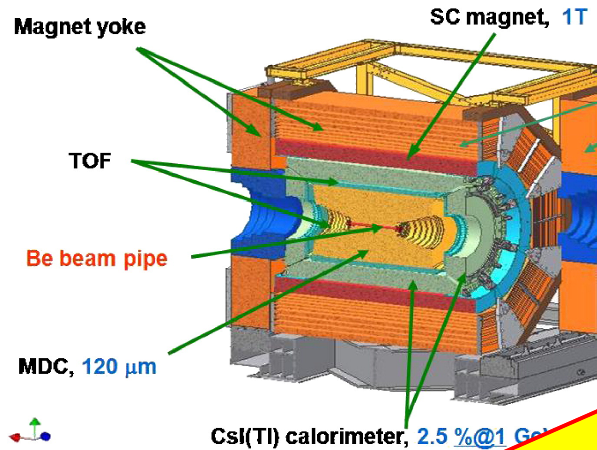
The central part of the KEDR detector: vacuum chamber of the collider (*1*); vertex detector (*2*); drift chamber (*3*); aerogel threshold Cherenkov counters (*4*); time of flight counters (*5*); liquid krypton barrel calorim eter (*6*); superconductive solenoid (*7*), magnet yoke (*8*); muon chambers (*9*); endcap CsI calorimeter (*10*); com pensating coil (*11*).

LHCb experiment aiming for precision measurements in *b*, *c* sectors. (JINT3(2008)S08005)



Experimental apparatus

BESIII experiment designed for studying in tau-c physics region (NIMA614 (2010) 345-399)



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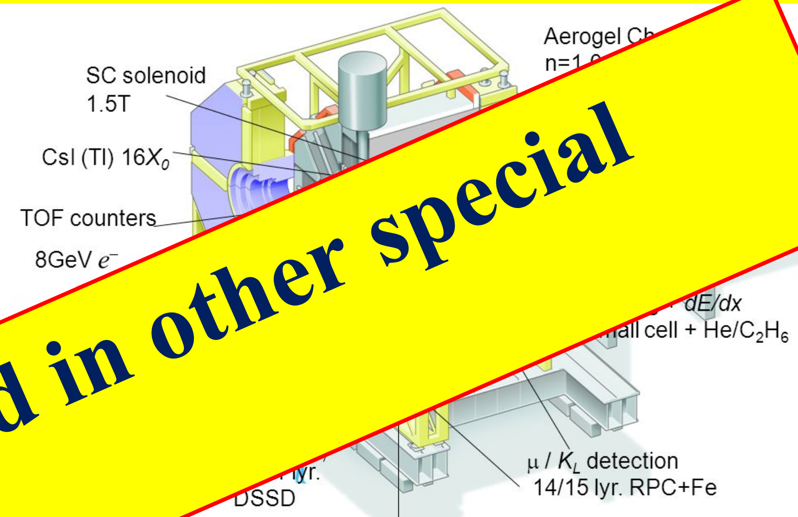
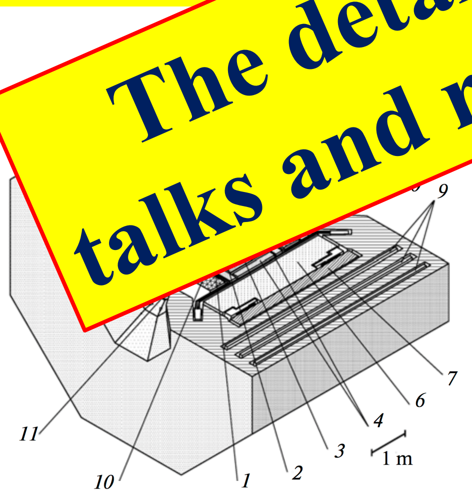
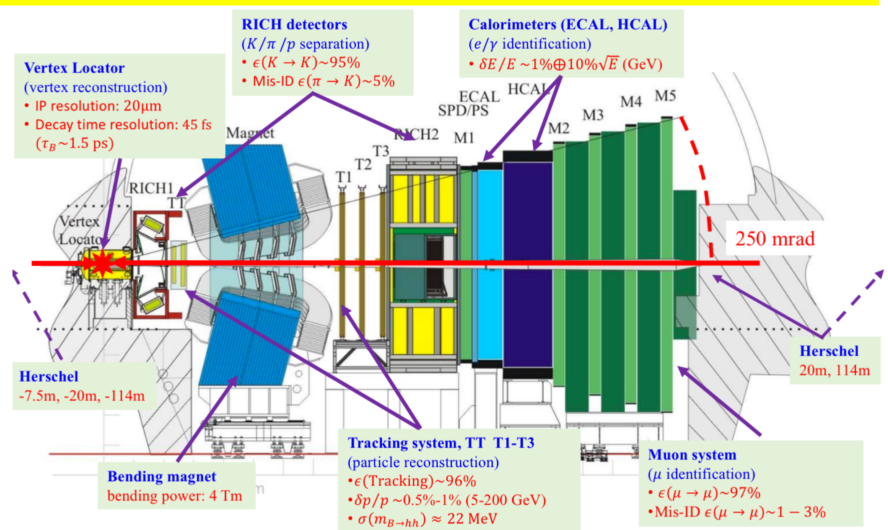


KEDR experiment desig… quarks and two photon… 657–702)



…the KEDR …uum chamber of the …er (*1*); vertex detector (*2*); drift chamber (*3*); aerogel threshold Cherenkov counters (*4*); time of flight counters (*5*); liquid krypton barrel calorim eter (*6*); superconductive solenoid (*7*), magnet yoke (*8*); muon chambers (*9*); endcap CsI calorimeter (*10*); com pensating coil (*11*).

…Cb experiment aiming for precision measurements in b, c sectors. (JINT3(2008)S08005)



The details can be found in other special talks and references!

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- **Recent CCS results**
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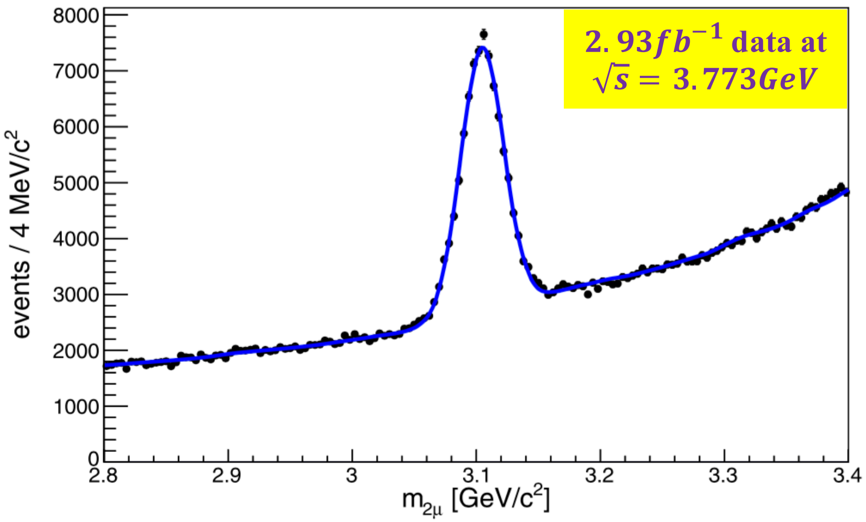
- Summary

J/ψ and $\psi(2S)$ resonance parameters

BESIII KEDR

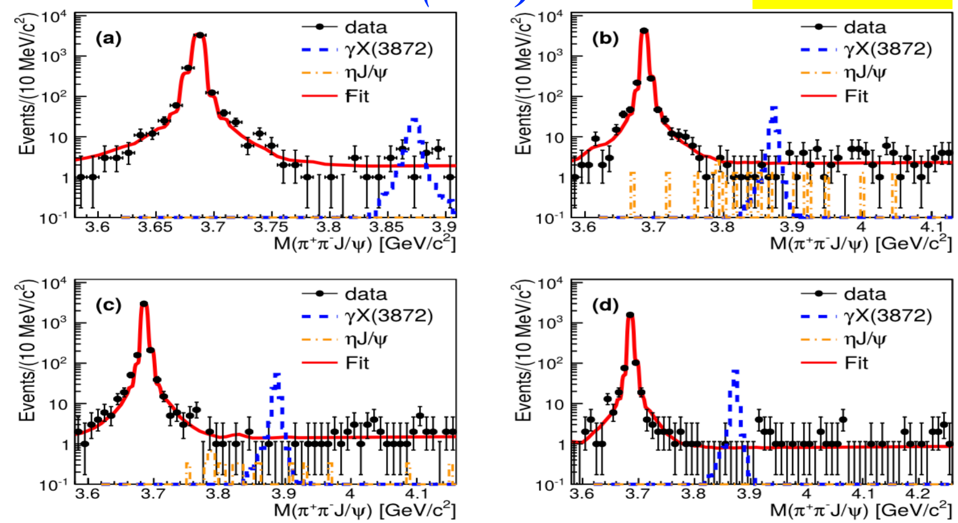
Measurement of $J/\psi, \psi(3686)$ electronic width

PLB 761(2016) 98-103



PLB 749(2015) 414-420

Data above 4.0GeV



- **The process $e^+e^- \to J/\psi\gamma \to \mu^+\mu^-\gamma$ applied for J/ψ electronic width**

Measurement	$\Gamma_{ee} \cdot \mathcal{B}_{\mu\mu}$ [eV]	Used $\mathcal{B}_{\mu\mu}$ value [%]	Γ_{ee} [keV]
BaBar	$330.1 \pm 7.7_{stat} \pm 7.3_{sys}$	5.88 ± 0.10 [PDG2002]	5.61 ± 0.20
CLEO-c	$338.4 \pm 5.8_{stat} \pm 7.1_{sys}$	$5.953 \pm 0.056_{stat} \pm 0.042_{sys}$ [CLEO]	$5.68 \pm 0.11_{stat} \pm 0.13_{sys}$
KEDR	$331.8 \pm 5.2_{stat} \pm 6.3_{sys}$	5.94 ± 0.06 [PDG2008]	5.59 ± 0.12
This work	$333.4 \pm 2.5_{stat} \pm 4.4_{sys}$	$5.973 \pm 0.007_{stat} \pm 0.037_{sys}$ [BESIII]	$5.58 \pm 0.05_{stat} \pm 0.08_{sys}$

- **The process $e^+e^- \to \gamma_{ISR}\pi^+\pi^-J/\psi$ for $\psi(3686)$ electronic width with ISR method**

$$\Gamma_{ee}^{\psi(3686)} = (2213 \pm 18_{stat} \pm 99_{sys})\ \text{eV}$$

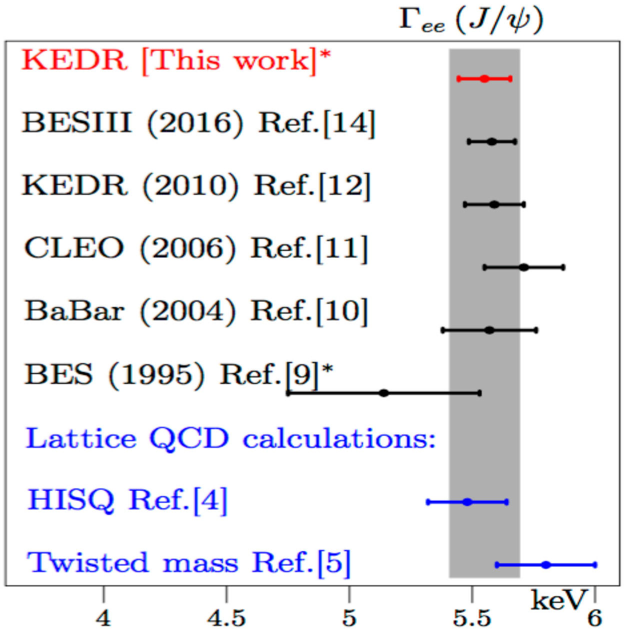
$$\Gamma_{ee}^{X(3872)}\mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi) < 0.13\ \text{eV} \quad @\ 90\%\ C.L.$$

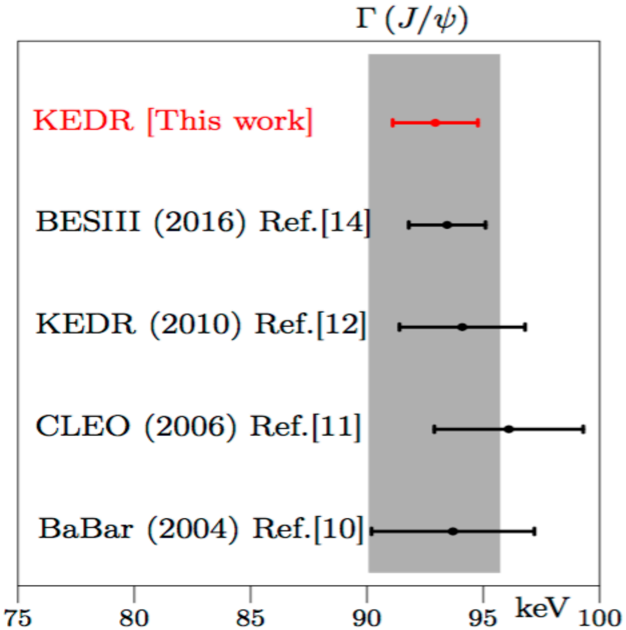
- **Measurements are consistent with the PDG values**

Precise measurement of $\Gamma_{ee}(J/\psi)$

- Understanding the quarkonium decay dynamics
- Scan observed cross section $e^+e^- \to e^+e^-$ and $e^+e^- \to hadron$ in the vicinity of the J/ψ resonance. JHEP05(2018)119

$$\Gamma_{ee}(J\psi) = (5.550 \pm 0.056 \pm 0.089)keV$$
$$\Gamma = (92.94 \pm 1.83)keV$$





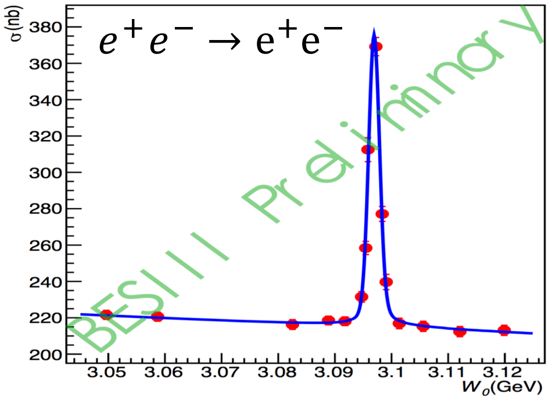
*Direct measurement.

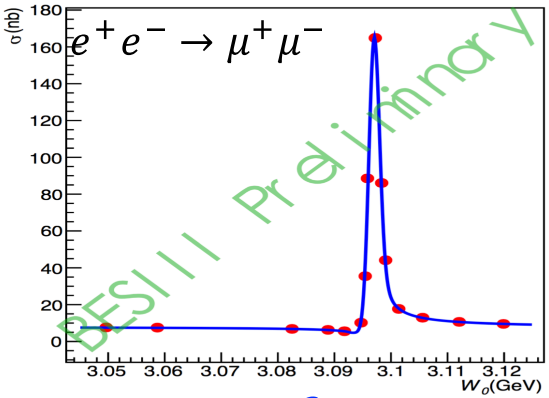
- **Consistent with those from other measurements, PDG value, some of predictions**

BESIII Precise measurement of J/ψ decay width

- Precise measurements of J/ψ decay widths provide a better understanding of the underlying physics.
- Updated with processes $e^+e^- \to e^+e^-$ and $e^+e^- \to \mu^+\mu^-$ at 15 c.m. energy points in the vicinity of the J/ψ resonance.

Simultaneous fit





Numerical Results

Parameters and their covariance matrix from fitting

Symbol	Value (keV)	V_{i1} (keV^2)	V_{i2} (keV^2)
$\Gamma_{ee}\Gamma_{ee}/\Gamma_{tot}$	0.348	0.0000684	0.0000373
$\Gamma_{ee}\Gamma_{\mu\mu}/\Gamma_{tot}$	0.339	0.0000373	0.0000300

$\Downarrow$ **PRD88 (2013) 032007**

Combined with $B(J/\psi \to l^+l^-) = \Gamma_{ll}/\Gamma_{tot} = (5.978 \pm 0.040)\%$

$\Downarrow$

Symbol	Result
$\Gamma_{ee}/\Gamma_{\mu\mu}$	1.025 ± 0.014
Γ_{tot}	(94.3 ± 1.9) keV
Γ_{ll}	(5.64 ± 0.09) keV

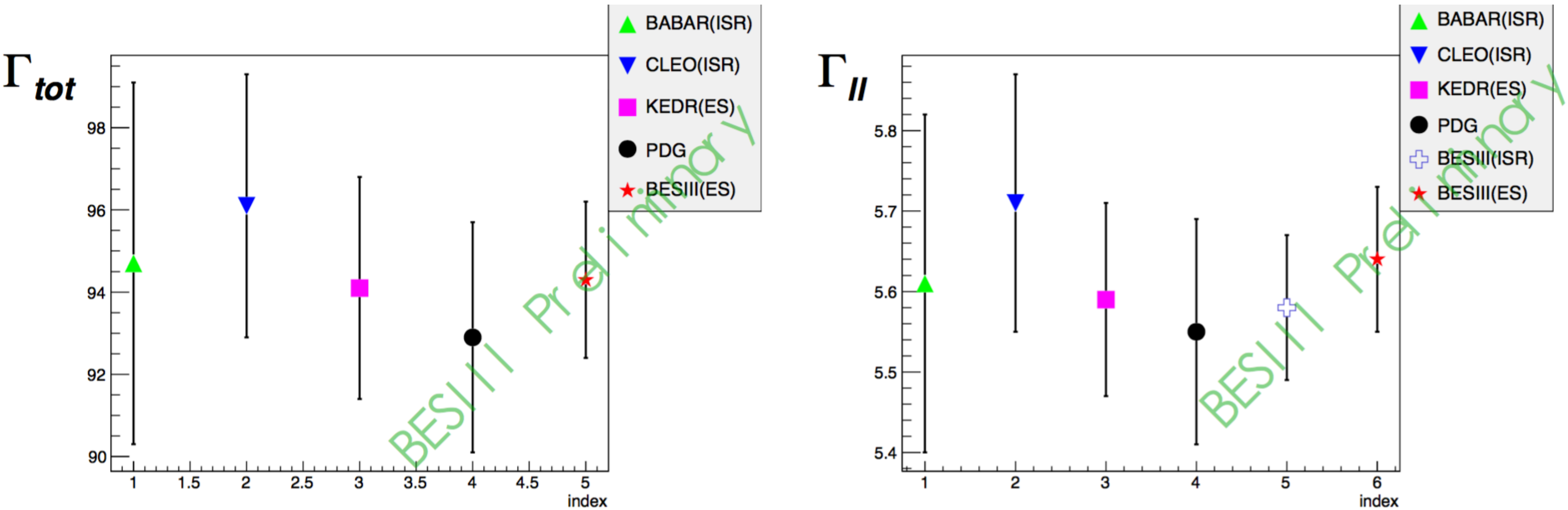
BESIII Preliminary

- **A global χ^2 function for decay width extraction: $\chi^2 = \Delta\sigma^T \cdot V^{-1} \cdot \Delta\sigma$**

(See the details for backup page)

Precise measurement of J/ψ decay width

Comparison with results from others



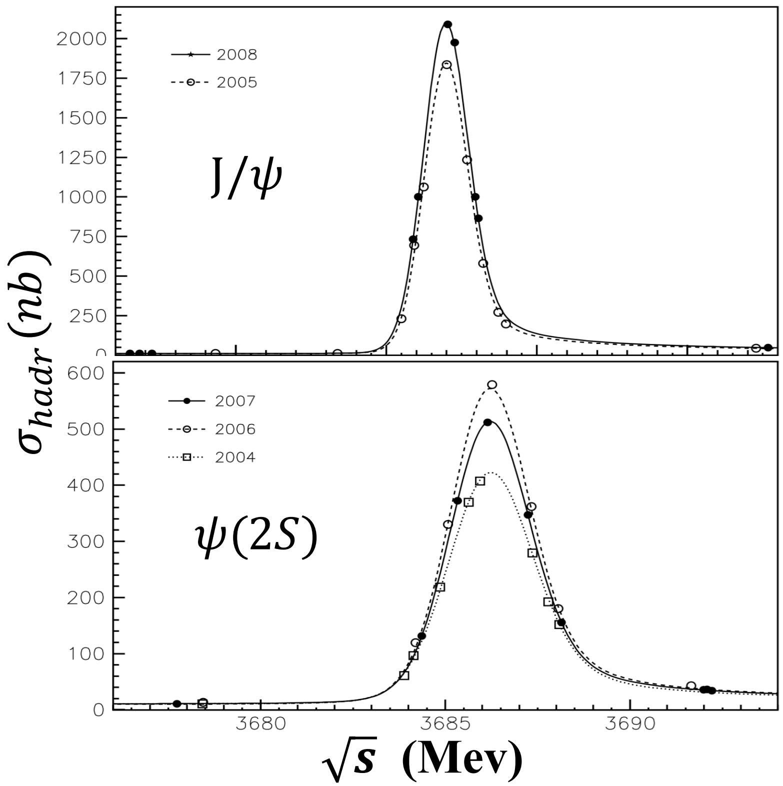
- BESIII result is consistent with those from others.
- Together with BESIII result using ISR, this result achieves the best accuracy in the world by far.

KEDR

Measurement of J/ψ and $\psi(2S)$ masses

- **Based on six high precision scans of the J/ψ region and seven high precision scans of $\psi(2S)$.**
- **Fit to the inclusive hadronic cross sections.**
- **Beam energy was determined using the resonance depolarization method.**

PLB 749(2015) 50-56



- **Weighting of results on masses**

$$\langle M\rangle = \sum w_i \cdot M_i,$$
$$\sigma^2_{\text{stat}} = \sum w_i^2 \cdot \sigma^2_{\text{stat},i},$$
$$\sigma^2_{\text{syst}} = \sum w_i^2 \cdot (\sigma^2_{\text{syst,i}} - \sigma^2_{\text{syst,0}}) + \sigma^2_{\text{syst,0}},$$
$$w_i = 1/(\sigma^2_{\text{stat},i} + \sigma^2_{\text{syst},i} - \sigma^2_{\text{syst,0}}),$$

Here $\sigma^2_{syst,0}$ denotes a common part of systematic uncertainty

Resonance parameters on masses

$$\mathbf{M_{J/\psi} = 3096.900 \pm 0.002 \pm 0.006\ MeV}$$
$$\mathbf{M_{\psi(2S)} = 3686.099 \pm 0.004 \pm 0.009\ MeV}$$

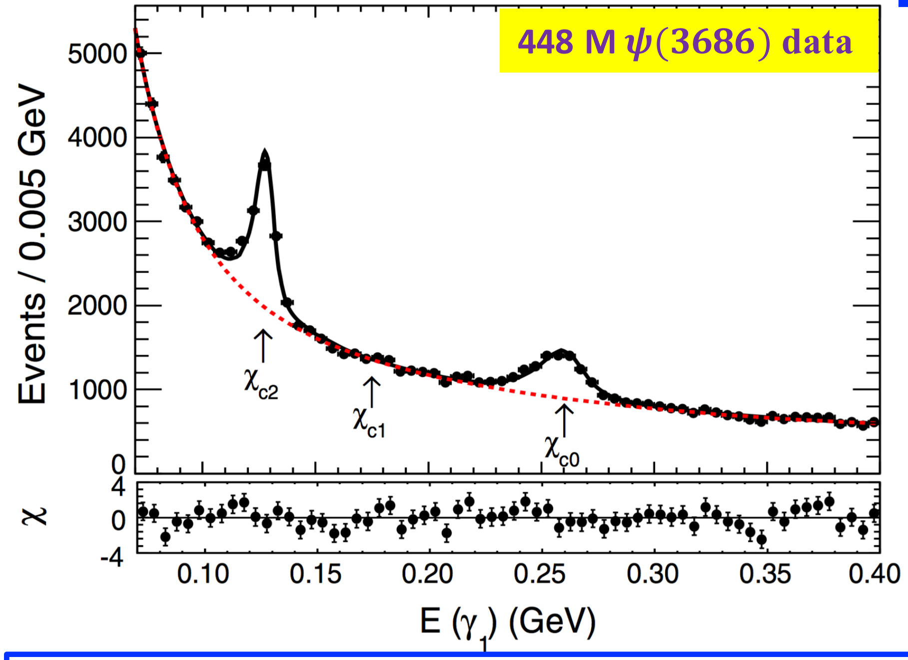
- **Consistent with PDG value within the error!**

$\chi_{cJ}(1P)$ resonance parameters

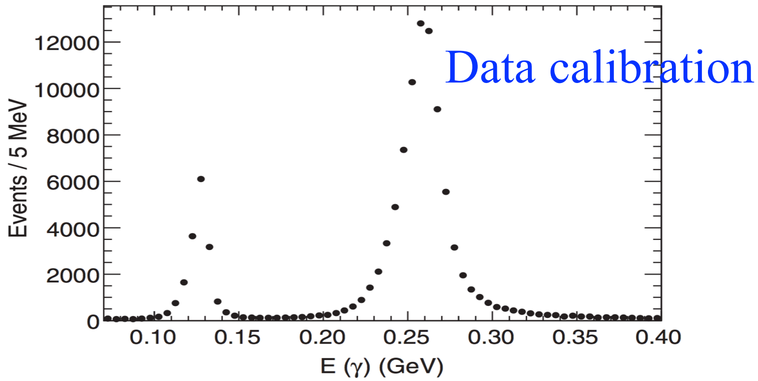
Improvement measurement of $\Gamma_{\gamma\gamma}(\chi_{c0,2})$

- **Updated with the process $\chi_{c0,2} \to \gamma\gamma$ based on $\psi(2S)$ radiative decay.**

PRD96, 092007(2017)



- The $\chi_{c0,2}$ shape modeled and fixed in the fit by the control sample $\psi(3686) \to \gamma\chi_{c0,2}, \chi_{c0,2} \to K^+K^-$



$\mathcal{B}_1 = \mathcal{B}(\psi(3686) \to \gamma\chi_{c0,2}) \cdot \mathcal{B}_2 = \mathcal{B}(\chi_{c0,2} \to \gamma\gamma)$

$\Gamma_{\gamma\gamma}(\chi_{c0,2} \to \gamma\gamma) = \mathcal{B}(\chi_{c0,2} \to \gamma\gamma) \times \Gamma(\chi_{c0,2})$,

$$\mathcal{R} = \frac{\Gamma_{\gamma\gamma}(\chi_{c2} \to \gamma\gamma)}{\Gamma_{\gamma\gamma}(\chi_{c0} \to \gamma\gamma)}$$

Quantity	PDG average values[a]	CLEO-c[b]	BESIII[b]	This measurement[b]
$\mathcal{B}_1 \times \mathcal{B}_2 (10^{-5})(\chi_{c0})$[c]	2.23 ± 0.14	$2.17 \pm 0.32 \pm 0.10$	$2.17 \pm 0.17 \pm 0.12$	$1.93 \pm 0.08 \pm 0.05$
$\mathcal{B}_1 \times \mathcal{B}_2 (10^{-5})(\chi_{c2})$[c]	2.50 ± 0.15	$2.68 \pm 0.28 \pm 0.15$	$2.81 \pm 0.17 \pm 0.15$	$2.83 \pm 0.08 \pm 0.06$
$\mathcal{B}_2 (10^{-4})(\chi_{c0})$[c]	2.23 ± 0.13	$2.31 \pm 0.34 \pm 0.15$	$2.24 \pm 0.19 \pm 0.15$	$1.93 \pm 0.08 \pm 0.07$
$\mathcal{B}_2 (10^{-4})(\chi_{c2})$[c]	2.74 ± 0.14	$3.23 \pm 0.34 \pm 0.24$	$3.21 \pm 0.18 \pm 0.22$	$3.10 \pm 0.09 \pm 0.13$
$\Gamma_{\gamma\gamma}(\chi_{c0})$ keV	2.24 ± 0.19	$2.36 \pm 0.35 \pm 0.22$	$2.33 \pm 0.20 \pm 0.22$	$2.03 \pm 0.08 \pm 0.14$
$\Gamma_{\gamma\gamma}(\chi_{c2})$ keV	0.53 ± 0.03	$0.66 \pm 0.07 \pm 0.06$	$0.63 \pm 0.04 \pm 0.06$	$0.60 \pm 0.02 \pm 0.04$
$\mathcal{R}$	0.236 ± 0.024	$0.278 \pm 0.050 \pm 0.036$	$0.271 \pm 0.029 \pm 0.030$	$0.295 \pm 0.014 \pm 0.028$

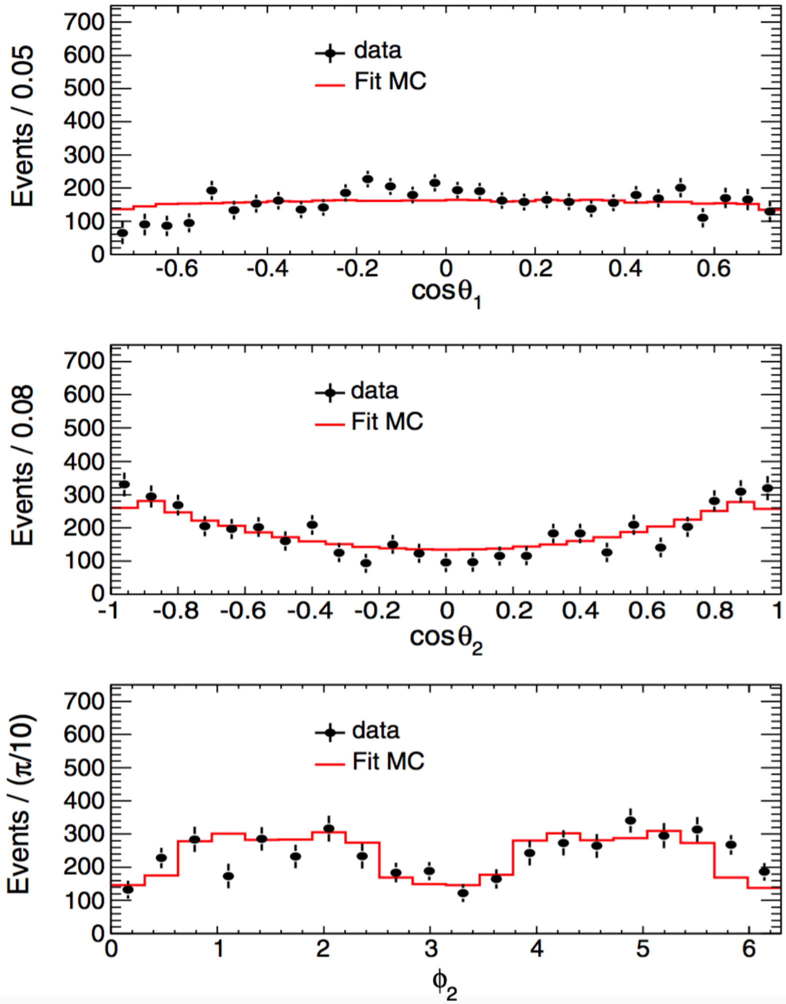
Upper limits for χ_{c1}:
$\Gamma_{\gamma\gamma}(\chi_{c1}) < 5.3$ eV@90%C.L.
$\mathcal{B}(\chi_{c1} \to \gamma\gamma) < 6.3 \times 10^{-6}$

- **More precise measurement, consistent with the previous experimental results!**
- **Precisely measured $\mathcal{R}$ calibrates the different theoretical potential models.**

Improvement measurement of $\Gamma_{\gamma\gamma}(\chi_{c0,2})$

- **A helicity amplitude analysis is performed for superposition of helicity-zero ($\lambda = 0$) and helicity-two ($\lambda = 2$) components for $\chi_{c2} \to \gamma\gamma$ decay.**

PRD96, 092007(2017)



- **Variables definition:**
  - ✓ θ_1: polar angle of radiative photon, with respect to the direction of positron beam;
  - ✓ θ_2/ϕ_2: polar/azimuthal angle of one of photons in $\chi_{c2} \to \gamma\gamma$ process at χ_{c2} rest frame, with respect to the direction of radiative photon direction;

Two photon width ratio for $\chi_{c2} \to \gamma\gamma$

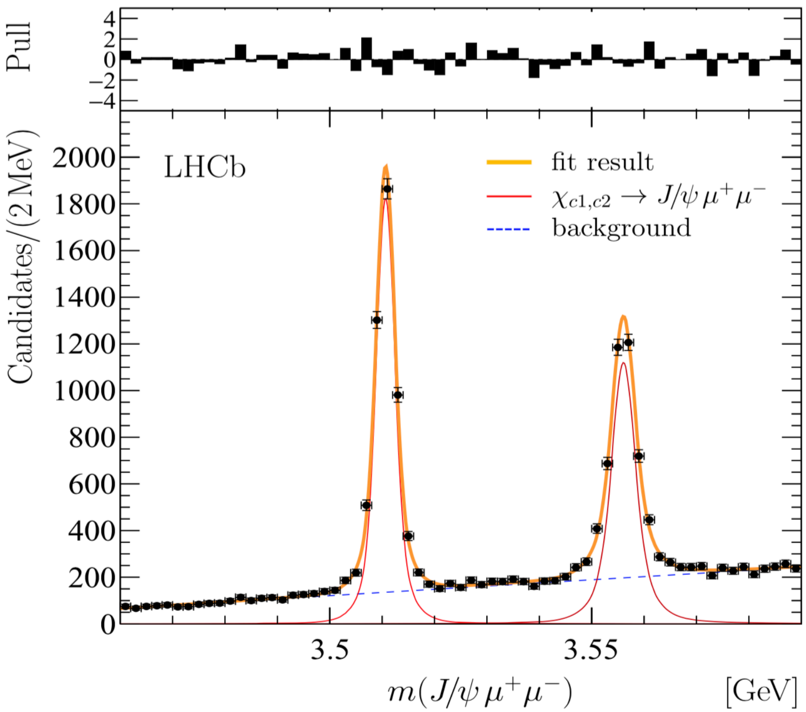
$$f_{0/2} = \frac{\Gamma_{\gamma\gamma}^{\lambda=0}(\chi_{c2})}{\Gamma_{\gamma\gamma}^{\lambda=2}(\chi_{c2})} = (0.0 \pm 0.6 \pm 1.2)\times 10^{-2}$$

- **More precise measurement, consistent with the previous experimental results.**
- **Confirmed helicity-zero component highly suppressed.**

Measurement of $\chi_{c1,2}$ resonance parameters

- **Performed with observation of $\chi_{c1,2} \to J/\psi\mu^+\mu^-$.**

PRL 117,221801(2017)



- **An extended unbinned maximum likelihood fit**
  - ✓ The $\chi_{c1,2}$ signals are modeled by **relativistic Breit-Wigner functions with Blatt-Weisskopf form factors** with a meson radius parameter of 3 GeV^{-1}.
  - ✓ The orbital angular momentum between the J/ψ meson and the $\mu^+\mu^-$ pair is assumed to be 0 (1) for the $\chi_{c1}(\chi_{c2})$cases.

- **Numerical results for resonance parameters:**

Quantity [MeV]	LHCb measurement	Best previous measurement	World average
$m(\chi_{c1})$	3510.71 ± 0.10	3510.72 ± 0.05	3510.66 ± 0.07
$m(\chi_{c2})$	3556.10 ± 0.13	3556.16 ± 0.12	3556.20 ± 0.09
$\Gamma(\chi_{c2})$	2.10 ± 0.20	1.92 ± 0.19	1.93 ± 0.11

$m(\chi_{c2}) - m(\chi_{c0}) = 45.39 \pm 0.07 \pm 0.03$ MeV

- **Observations presented here open up a new avenue for hadron spectroscopy at the LHC.**
  - ✓ **To measure production of $\chi_{c1,2}$ states**
  - ✓ **To extend measurements to low $p_t(\chi_{c1,2})$**
  - ✓ …

$\eta_c(1S)$ resonance parameters

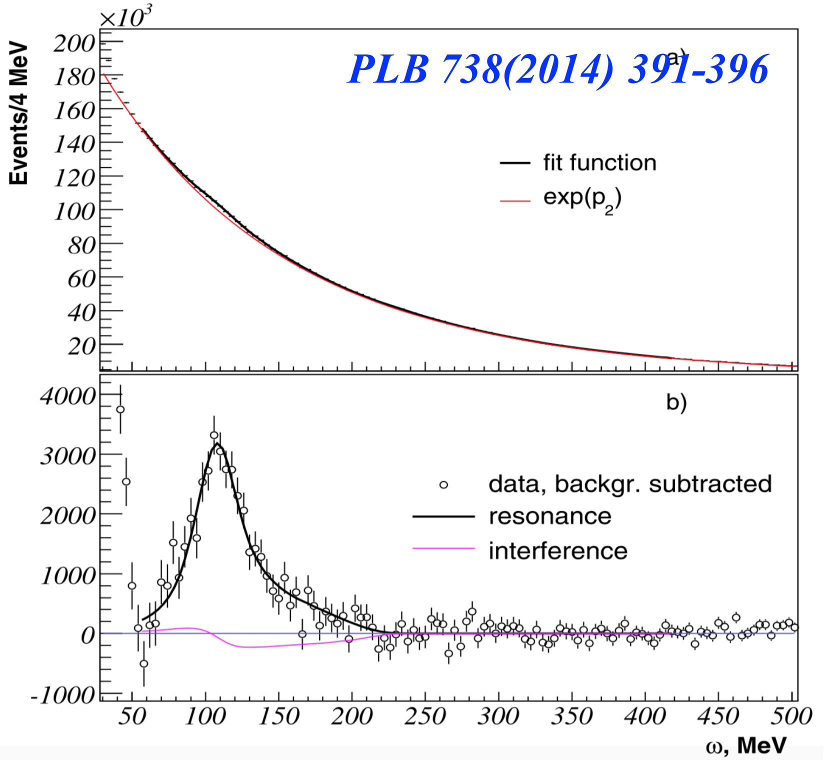
KEDR

LHCb

KEDR

Measurement of $\eta_c(1S)$ resonance parameters

- Using inclusive photon spectrum in process $J/\psi \to \gamma\eta_c$
- Inclusive photon spectrum before/after background subtraction (a/b)
- Taking into account an asymmetric photon lineshape.

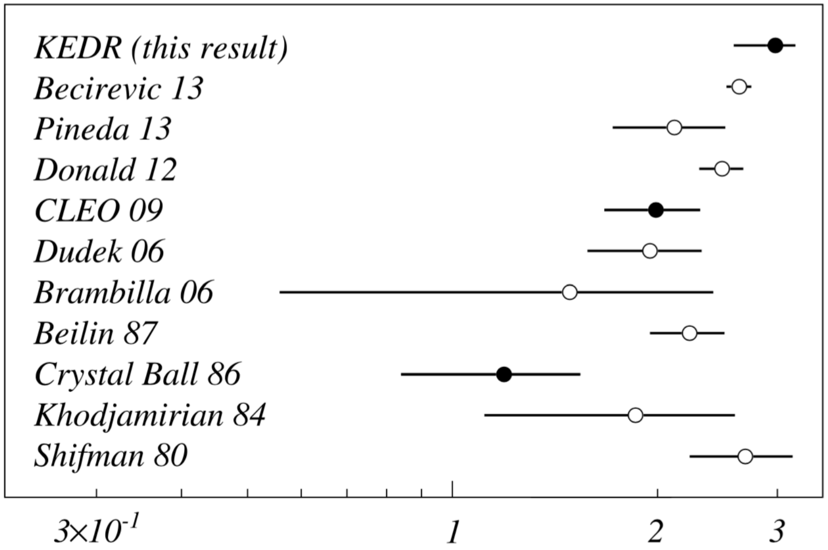


$$M_{\eta_c} = 2983.5 \pm 1.4^{+1.6}_{-3.6}\ \text{MeV}$$
$$\Gamma_{\eta_c} = 27.2 \pm 3.1^{+5.4}_{-2.6}\ \text{MeV}$$

- Consistent with PDG values within 1σ

- Decay rate:

$$\Gamma^0_{\gamma\eta_c} = \frac{1}{BW(\omega_0)}\frac{d\Gamma}{d\omega}(\omega_0) = 2.98 \pm 0.18^{+0.15}_{-0.33}$$

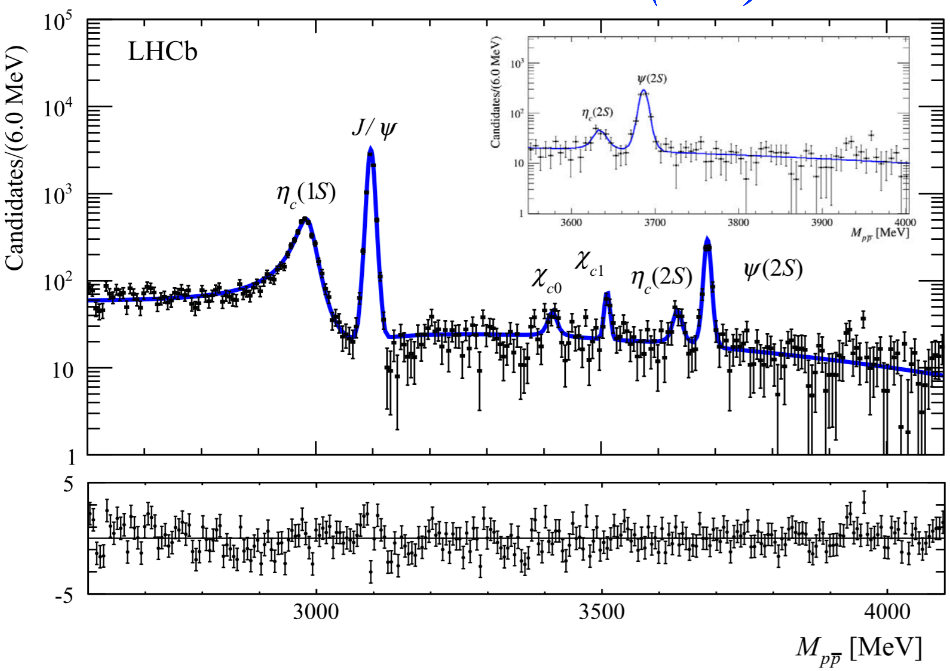


- Consistent with other measurements (close circles) and theoretical predictions (open circles) within the errors.

Measurement of $\eta_c(1S)$ width parameter

- Performed with process $B^+ \to p\bar{p}K^+$ using $3.0\ fb^{-1}$ pp collision data

PLB 769(2017) 305-313



Numerical results on masses

$$M_{J/\psi} - M_{\eta_c(1S)} = 110.2 \pm 0.5 \pm 0.9\ \text{MeV},$$
$$M_{\psi(2S)} - M_{\eta_c(2S)} = 52.5 \pm 1.7 \pm 0.6\ \text{MeV},$$
$$\Gamma_{\eta_c(1S)} = 34.0 \pm 1.9 \pm 1.3\ \text{MeV}.$$

- Consistent with PDG value

$$\Gamma^{PDG}_{\eta_c(1S)} = 31.8 \pm 0.8\ \text{MeV}.$$

- Compared with radiative decays, these mass and width determinations do not depend on the knowledge of the line shapes of the magnetic dipole transition.

- Observation of $\eta_c(2S) \to p\bar{p}$ ($6.0\ \sigma$) and search for $\psi(3770), X(3872) \to p\bar{p}$

Relative branching fractions:

$$R_{\eta_c(2S)} = (1.58 \pm 0.33 \pm 0.09)\times 10^{-2},$$
$$R_{\psi(3770)} < 9(10)\times 10^{-2}\ @\ 90(95)\%\ \text{C.L.},$$
$$R_{X(3872)} < 0.20(0.25)\times 10^{-2}\ @\ 90(95)\%\ \text{C.L.}.$$

Observations of X(3823) and $X^*(3860)$

Observation of X(3823) or $\psi_2(3823)$

BELLE BESIII

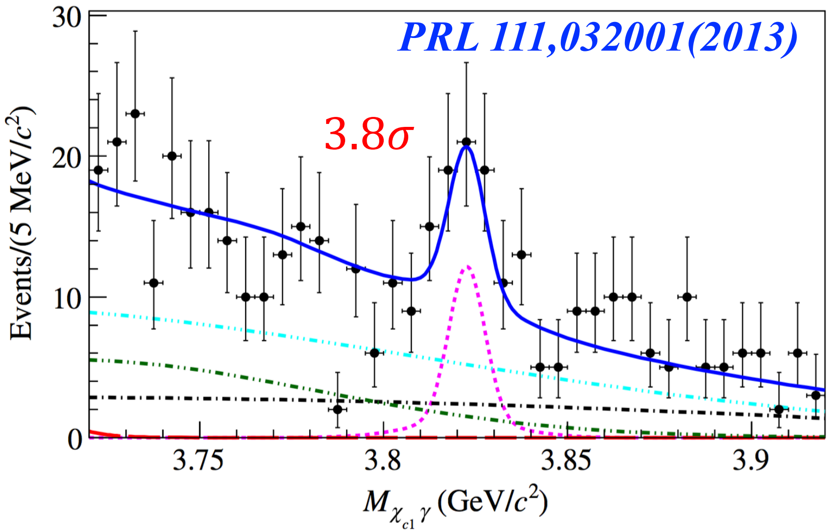
- Status:

$c\bar{c}$ MESONS (including possibly non-$q\bar{q}$ states)

$\psi_2(3823)$ was $X(3823)$ $I^G(J^{PC}) = 0^-(2^{--})$

$\psi(3823)$ MASS	3822.2 ± 1.2 MeV
$\psi(3823)$ WIDTH	< 16 MeV CL=90.0%

- **An evidence by Belle for the first time in process $B \to \gamma\chi_{c1}K$, but not observed in $\gamma\chi_{c2}$ final state.**



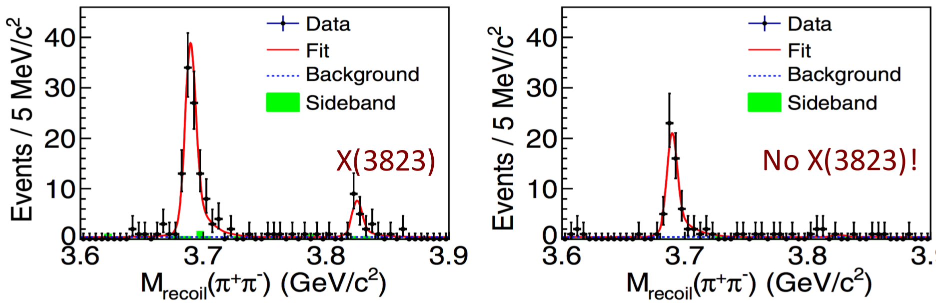
$M^{Belle}_{X(3823)} = 3823.1 \pm 1.8 \pm 0.7$ MeV

$\Gamma^{Belle}_{X(3823)} < 24$ MeV @ 90% C.L.

- Good candidate for $\psi(1^3D_2 c\bar{c})$ charmonium state suggested.
- Production of X(3823)'s ***C-odd*** partner.

- **Observed by BESIII in process $e^+e^- \to \pi^+\pi^-\gamma\chi_{c1}$ with 6.2σ statistical significance.**

PRL 115,011803(2015)



- ✓ Simultaneous fit to data at 4.23, 4.26, 4.36, 4.42, 4.60 GeV
- ✓ $\psi(2S)$ signal for calibration

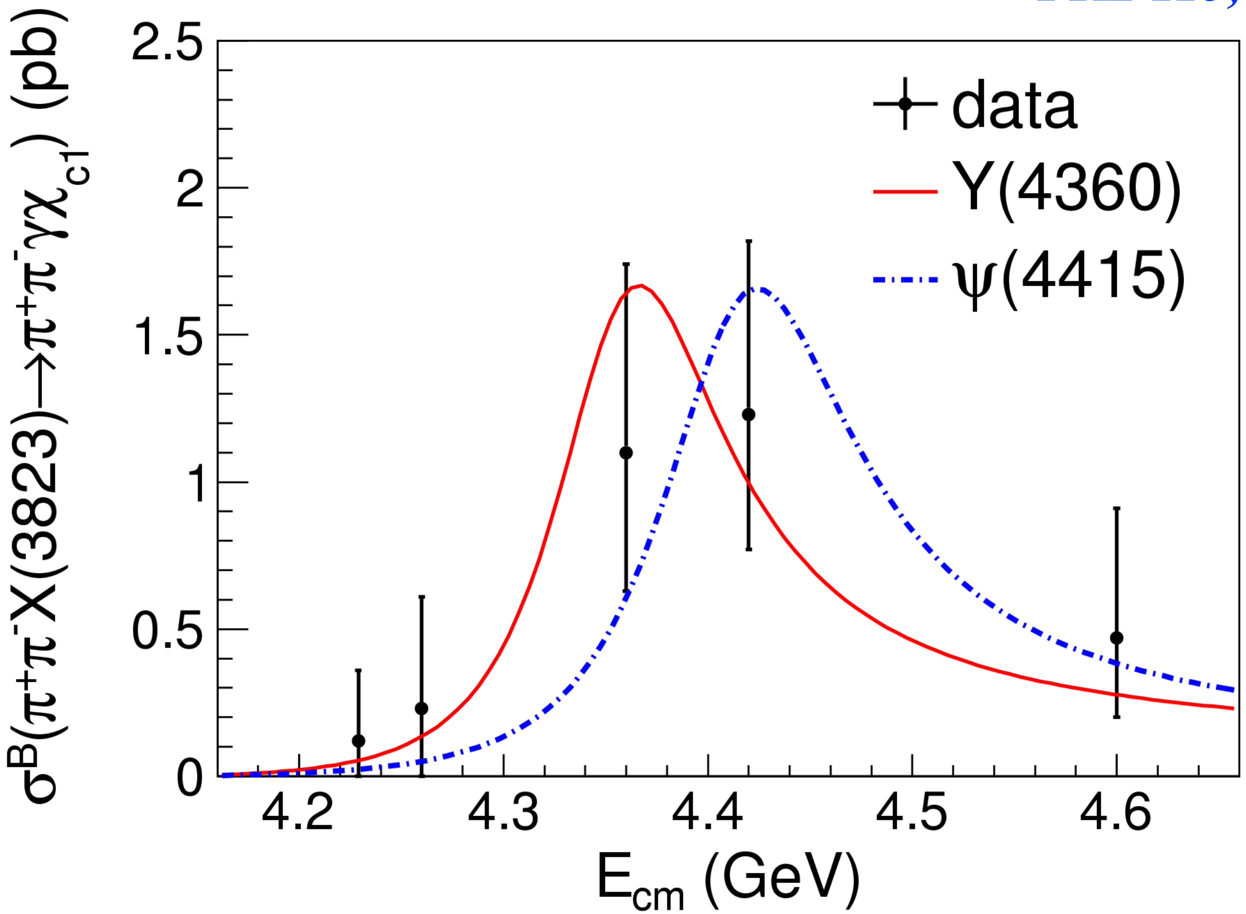
$M^{BESIII}_{X(3823)} = 3821.7 \pm 1.3 \pm 0.7$ MeV

$\Gamma^{BESIII}_{X(3823)} < 16$ MeV @ 90% C.L.

- These measurements are in good agreement with the assignment of the $X(3823)$ state as the $\psi(1^3D_2)$ charmonium state.

Production cross section

PRL 115,011803(2015)



1. Energy dependent cross section of $e^+e^- \to \pi^+\pi^- X(3823)$.
2. Both Y(4360) and Y(4415) line shape give reasonable description.

Observation of $X^*(3860)$ or $\chi_{c0}(2P)$

$c\bar{c}$ MESONS

$X(3915)$ **was** $\chi_{c0}(3915)$ $I^G(J^{PC}) = 0^+(0 or 2^{++})$

No $\chi_{c0}(2P)$ candidate now!

The experimental analysis prefers $J^{PC} = 0^{++}$. However, a reanalysis presented in ZHOU 2015C shows that if helicity-2 dominance assumption is abandoned and a sizable helicity-0 component is allowed, a $J^{PC} = 2^{++}$ assignment is possible.

$X(3915)$ MASS	3918.4 ± 1.9 MeV
$X(3915)$ WIDTH	20 ± 5 MeV (S = 1.1)

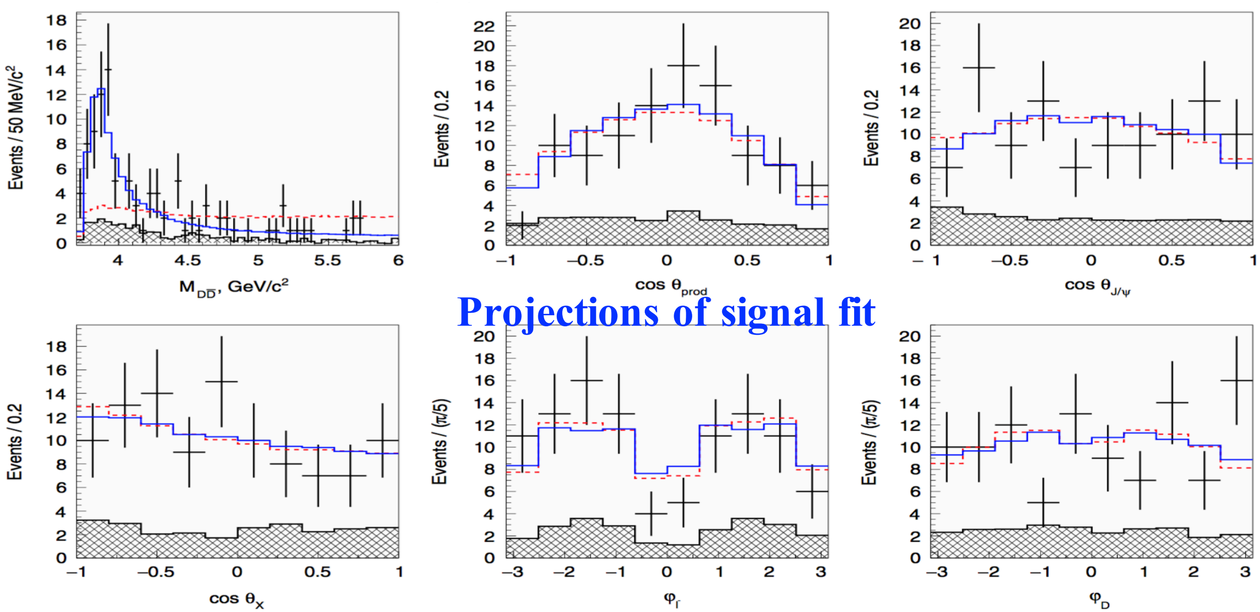
- **A full amplitude analysis performed to the $e^+e^- \to J/\psi D\bar{D}$ process (D∈ D^0, D^+) in a six-dimensional parameters space:**

$$\Phi = (M_{D\bar{D}}, \theta_{prod}, \theta_{J\psi}, \theta_{X*}, \varphi_{l^-}, \varphi_D)$$

where, θ_{prod} production angle; $\theta_{J\psi}, \theta_{X*}$ helicity angles; φ_{l^-}, φ_D azimuthal angles.

- **Observation of a new charmonium-like state $X^*(3860)$ with 6.5σ statistical significance.**

PRD 95,112003(2017)



Projections of signal fit

Resonance parameters

$$M_{X^*(3860)} = 3862^{+26+40}_{-32-23}\,\text{MeV}$$

$$\Gamma_{X^*(3860)} = 201^{+154+88}_{-67-82}\,\text{MeV}$$

- **The $J^{PC} = 0^{++}$ hypothesis is favored over the $J^{PC} = 2^{++}$ hypothesis at the level of 2.5σ.**

Observation of $X^*(3860)$ or $\chi_{c0}(2P)$

PRD 95,112003(2017)

- **Comparison of the $X^*(3860)$ and known charmonium-like states**

State	J^{PC}	Nonresonant amplitude: Constant	NRQCD	$M_{D\bar{D}}^{-4}$
$X(3915)$	0^{++}	5.2σ	4.3σ	3.3σ
$X(3915)$	2^{++}	6.1σ	6.1σ	4.9σ
$\chi_{c2}(2P)$	2^{++}	6.8σ	7.0σ	6.2σ
$X(3940)$	2^{++}	6.0σ	5.6σ	5.2σ
$X(4160)$	0^{++}	6.8σ	6.3σ	5.8σ
$X(4160)$	2^{++}	10.7σ	11.0σ	13.5σ
$\chi_{c0}(2P)$ (lattice)	0^{++}	4.3σ	3.6σ	2.7σ

- **2.7σ difference from predicted $\chi_{c0}(2P)$**

- **The $X^*(3860)$ global significance for alternative models**

Model	Significance
Default (constant nonresonant)	8.5σ
NRQCD nonresonant	7.6σ
$M_{D\bar{D}}^{-4}$ nonresonant	6.5σ
Background mass calculation	8.4σ
Optimization ($a = 4$)	8.1σ
Optimization ($a = 6$)	8.1σ

- **Disagree with the NRQCD prediction**

A new conventional charmonium candidate?

- ✓ A better candidate for $\chi_{c0}(2P)$ charmonium state than $X(3915)$, well matched to expectation of $\chi_{c0}(2P)$ from potential model.
- ✓ Agree with $\chi_{c0}(2P)$ parameters determined from an alternative fit to Belle and BABAR:

$$M = 3837.6 \pm 11.5 \text{ MeV}$$
$$\Gamma = 221 \pm 19 \text{ MeV}$$

- ✓ A conventional charmonium state above $D\bar{D}$ threshold, coincide with $\chi_{c0}(2P)$.

Summary of recent experimental status for CCS

CCS	Collab.	M(MeV)	Γ_{tot}(keV)	Γ_{ll}(keV)	Γ_{ee}(keV)	COMMENT
J/ψ	BESIII	---	94.3 ± 1.9	5.64 ± 0.09	5.58 ± 0.09	$e^+e^-\to e^+e^-, \mu^+\mu^-$ $e^+e^-\to J/\psi\gamma\to\mu^+\mu^-\gamma$ $e^+e^-\to e^+e^-$(hadron)
	KEDR	3096.900 ± 0.006	92.94 ± 1.83	---	5.550 ± 0.105	Inclusive hadronic mode
	PDG	3096.900 ± 0.006	92.9 ± 2.8	---	---	PDG AVERAGE
$\psi(2S)$	BESIII	---	---	----	2.213 ± 0.100	$e^+e^-\to\gamma_{ISR}\pi^+\pi^-J/\psi$
	KEDR	3686.009 ± 0.098	---	---	---	Inclusive hadronic mode
	PDG	3686.009 ± 0.098	296 ± 8	---	---	PDG AVERAGE

CCS	Collab.	M(MeV)	Γ(MeV)	$\Gamma_{\gamma\gamma}$(keV)	COMMENT
χ_{c0}	BESIII	---	---	2.03 ± 0.16	$\psi(3686)\to\gamma\chi_{c0}, \chi_{c0}\to\gamma\gamma$
	LHCb	---	---	---	---
	PDG	3414.75 ± 0.31	10.5 ± 0.6	---	PDG AVERAGE
χ_{c1}	BESIII	---	---	$<5.3\times10^{-3}$	$\psi(3686)\to\gamma\chi_{c0}, \chi_{c0}\to\gamma\gamma$
	LHCb	3510.71 ± 0.14	---		$\chi_{c1,2}\to J/\psi\mu^+\mu^-$
	PDG	3510.66 ± 0.07	0.84 ± 0.04	---	PDG AVERAGE
χ_{c2}	BESIII	---	---	2.03 ± 0.16	$\psi(3686)\to\gamma\chi_{c0}, \chi_{c0}\to\gamma\gamma$
	LHCb	3556.10 ± 0.13	2.10 ± 0.20	---	$\chi_{c1,2}\to J/\psi\mu^+\mu^-$
	PDG	3556.20 ± 0.09	1.93 ± 0.11	---	PDG AVERAGE

- Tables summarize more precise measurement, consistent with PDG average!

Summary of recent experimental status for CCS

CCS	Collab.	M(MeV)	Γ_{tot}(keV)	Γ_{ll}(keV)	Γ_{ee}(keV)	COMMENT
J/ψ	BESIII	---	94.3 ± 1.9	5.64 ± 0.09	5.58 ± 0.09	$e^+e^-\to e^+e^-,\mu^+\mu^-$ $e^+e^-\to J/\psi\gamma\to\mu^+\mu^-\gamma$ $e^+e^-\to e^+e^-$(hadron)
	KEDR	3096.900 ± 0.006	92.94 ± 1.83	---	5.550 ± 0.105	Inclusive hadronic mode
	PDG	3096.900 ± 0.006	92.9 ± 2.8	---	---	PDG AVERAGE
$\psi(2S)$	BESIII	---	---	----	2.213 ± 0.100	$e^+e^-\to\gamma_{ISR}\pi^+\pi^-J/\psi$
	KEDR	3686.009 ± 0.098	---	---	---	Inclusive hadronic mode
	PDG	3686.009 ± 0.098	296 ± 8	---	---	PDG AVERAGE

CCS	Collab.	M(MeV)	Γ(MeV)	$\Gamma^0_{\gamma\eta_c}$(keV)	COMMENT
$\eta_c(1S)$	KEDR	$2983.5\pm1.4^{+1.6}_{-3.6}$	$27.2\pm3.1^{+5.4}_{-2.6}$	$2.98\pm0.18^{+0.15}_{-0.33}$	$J/\psi\to\gamma\eta_c$
	LHCb	---	$34.0.\pm1.9\pm1.3$	---	$B^+\to p\bar{p}K^+$
	PDG	2983.4 ± 0.5	$31.8.\pm0.8$	---	PDG AVERAGE
$X(3823)$ Or $\psi_2(3823)$	Belle	$3823.1\pm1.8\pm0.7$	<24	---	$B\to\gamma\chi_{c1}K$
	BESIII	$3821.7\pm1.3\pm0.7$	<16	---	$e^+e^-\to\pi^+\pi^-\gamma\chi_{c1}$
	PDG	3822.2 ± 1.2	<16	---	PDG AVERAGE
$X^*(3860)$ Or $\chi_{c0}(2P)$	Belle	3862^{+26+40}_{-32-23}	$201^{+154+88}_{-67-82}$	---	$e^+e^-\to J/\psi D\bar{D}$
	PDG	---	---	---	PDG AVERAGE

- **Tables summarize more precise measurement, consistent with PDG average!**

Summary

- **Lots of progress in the study of conventional charmonium states at BESIII, Belle, KEDR and LHCb, recently.**
  - **Precise/improved measurements:**
    - ✓ J/ψ **and** $\psi(2S)$ **resonance parameters**
    - ✓ $\chi_{cJ}(1P)$ **resonance parameters**
    - ✓ $\eta_c(1S)$ **resonance parameters**
  - **Observations of** $\psi(1^3D_2)=X(3823)$ **and** $\chi_{c2}(2P)=X^*(3860)$
- **BESIII/Belle/KEDR/LHCb will continue the study, Belle II at KEK will start data taking very soon.**

Thanks for your attention!

Backup

Decay width extraction — Global χ^2

To consider:

- Correlations between measured cross sections of the same channel at different energy points;
- Correlations between measured cross sections of different channels at the same energy point,

a global χ^2 function is constructed:

$$\chi^2 = \Delta\sigma^T \cdot V^{-1} \cdot \Delta\sigma$$

where

$$\Delta\sigma(i) = \begin{cases} \sigma_{ee}^{exp}(i) - \sigma_{ee}^{the}(i) & i = 1-15 \\ \sigma_{\mu\mu}^{exp}(i-15) - \sigma_{\mu\mu}^{the}(i-15) & i = 16-30 \end{cases}$$

and

$$V(i,j) = \begin{cases} V_{ee}(i,j) + \delta(i-j)(\frac{d\sigma_{ee}^{the}}{dW_0}(i)\Delta W_0(i))^2 & i = 1-15, j = 1-15 \\ \frac{\sigma_{ee}^{exp}(i)\sigma_{\mu\mu}^{exp}(j-15)}{L(i)L(j-15)} V_L(i, j-15) + \delta(i+15-j)\frac{d\sigma_{ee}^{the}}{dW_0}(i)\frac{d\sigma_{\mu\mu}^{the}}{dW_0}(i)(\Delta W_0(i))^2 & i = 1-15, j = 16-30 \\ \frac{\sigma_{ee}^{exp}(j)\sigma_{\mu\mu}^{exp}(i-15)}{L(i-15)L(j)} V_L(i-15, j) + \delta(i-j-15)\frac{d\sigma_{ee}^{the}}{dW_0}(j)\frac{d\sigma_{\mu\mu}^{the}}{dW_0}(j)(\Delta W_0(j))^2 & i = 16-30, j = 1-15 \\ V_{\mu\mu}(i-15, j-15) + \delta(i-j)(\frac{d\sigma_{\mu\mu}^{the}}{dW_0}(i-15)\Delta W_0(i-15))^2 & i = 16-30, j = 16-30 \end{cases}$$

Decay width extraction — Formulas and parameters

- Analytical formulas for resonance terms and interference terms of cross sections of $e^+e^- \to e^+e^-$ and $e^+e^- \to \mu^+\mu^-$ with ISR considered are carefully derived [1] with structure function method [2]

$$\sigma(s, \cos\theta) = \int \bar{\sigma}(s(1-x), \cos\theta) F(s,x) dx$$

- The energy spread effect is described by gauss distribution

$$\sigma'(W_0) = \int \sigma(W) \left(\frac{1}{\sqrt{2\pi}\sigma_W} \exp^{-\frac{(W-W_0)^2}{2\sigma_W^2}} \right) dW$$

- The FSR factor $R^{FSR}(W_0)$ are obtained via numerical method with the Babayaga generator as the ratio of the calculated cross sections with the FSR switch therein turned on and off. With it

$$\sigma^{the}(W_0) = \sigma'(W_0) \cdot R^{FSR}(W_0)$$

- The final function form of the theoretical cross section formula:

$$\sigma_{ll}^{the} = \sigma_{ll}^{the}(W_0, M, \Gamma_{tot}, \Gamma_{ee}\Gamma_{ll}/\Gamma_{tot}, \sqrt{\Gamma_{ee}\Gamma_{ll}}, \sigma_W) \text{ with } ll = ee \text{ or } \mu\mu$$

- $\Gamma_{ee}\Gamma_{ee}/\Gamma_{tot}$ and $\Gamma_{ee}\Gamma_{\mu\mu}/\Gamma_{tot}$ can be obtained by measuring these cross sections and then fitting them.
- Combined $B(J/\psi \to l^+l^-) = \Gamma_{ll}/\Gamma_{tot}$ measured by our BESIII collaboration in 2013 [3], Γ_{tot} and Γ_{ll} can be obtained from $\Gamma_{ee}\Gamma_{ee}/\Gamma_{tot}$ and $\Gamma_{ee}\Gamma_{\mu\mu}/\Gamma_{tot}$ by parameter transformation.

[1] X.Y. Zhou, Y.D. Wang, L.G. Xia, Analytical Forms of Cross Sections of Di-lepton Production from e^+e^- Collision around the J/ψ Resonance, arXiv:1701.00218.

[2] E.A. Kuraev, V.S. Fadin, Sov. J. Nucl. Phys., 41 (1985) 466.

[3] M. Ablikim, et al., BESIII Collaboration, Phys. Rev. D 88 (2013) 032007.

Improvement measurement of $\chi_{c0,2}$ two-photon width

Validate reliability of background function.

$$f_{bg} = p_0 + p_1 E + p_2 E^2 + p_3 E^a$$

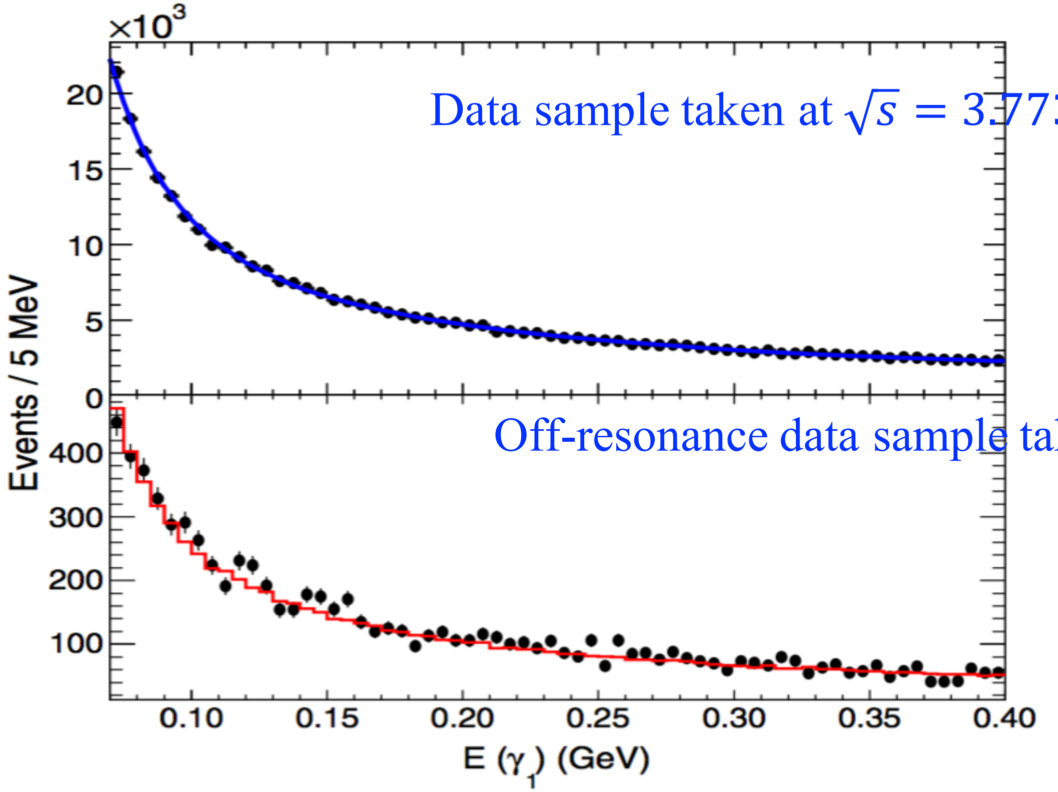


FIG. 2. Background $E(\gamma_1)$ spectrum. Upper plot: The best fit result (blue solid line) to $\psi(3770)$ data (dots with error bar) using Eq. (2). Lower plot: The comparison of $E(\gamma_1)$ spectrum between off-$\psi(3686)$ data (dots with error bar) and $\psi(3770)$ data (red histogram).

Measurement of $\chi_{c1,2}$ resonance parameters at LHCb

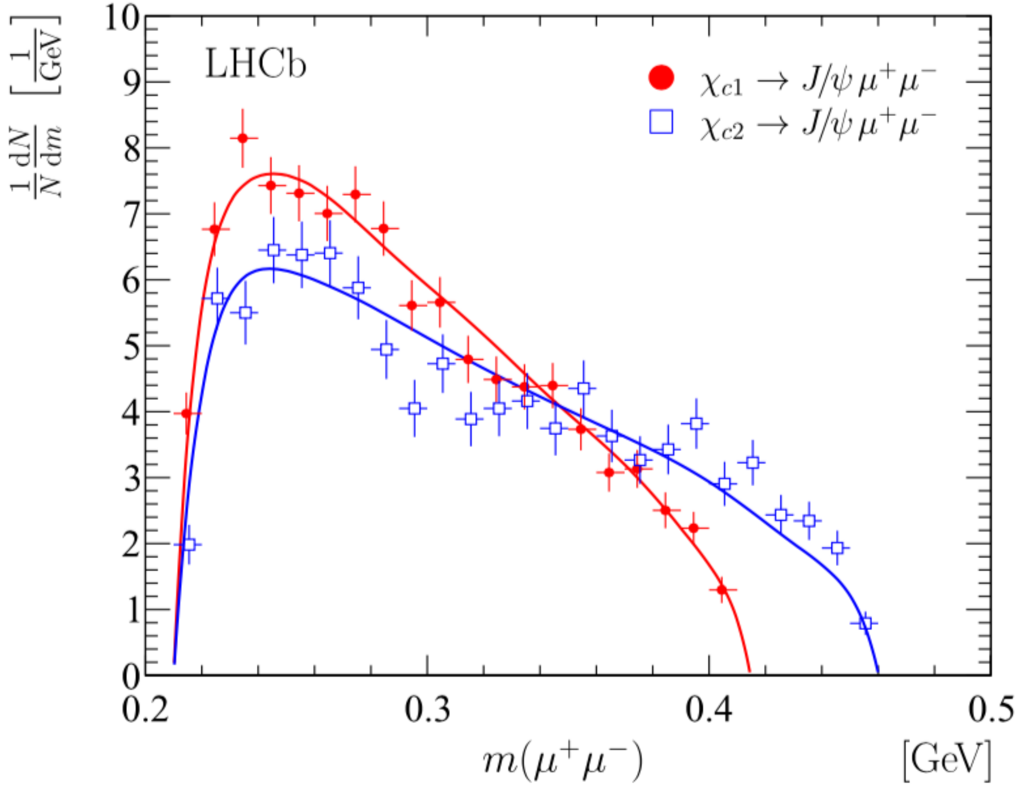


FIG. 2. Background-subtracted $m(\mu^+\mu^-)$ distribution for $\chi_{c1} \to J/\psi\ \mu^+\mu^-$ (solid red circles) and $\chi_{c2} \to J/\psi\ \mu^+\mu^-$ (open blue squares) decays. The distributions are normalized to the unit area. The curves show the expected distribution from the simulation, which uses the model described in Ref. [29].

Observation of $X^*(3860)$ or $\chi_{c0}(2P)$

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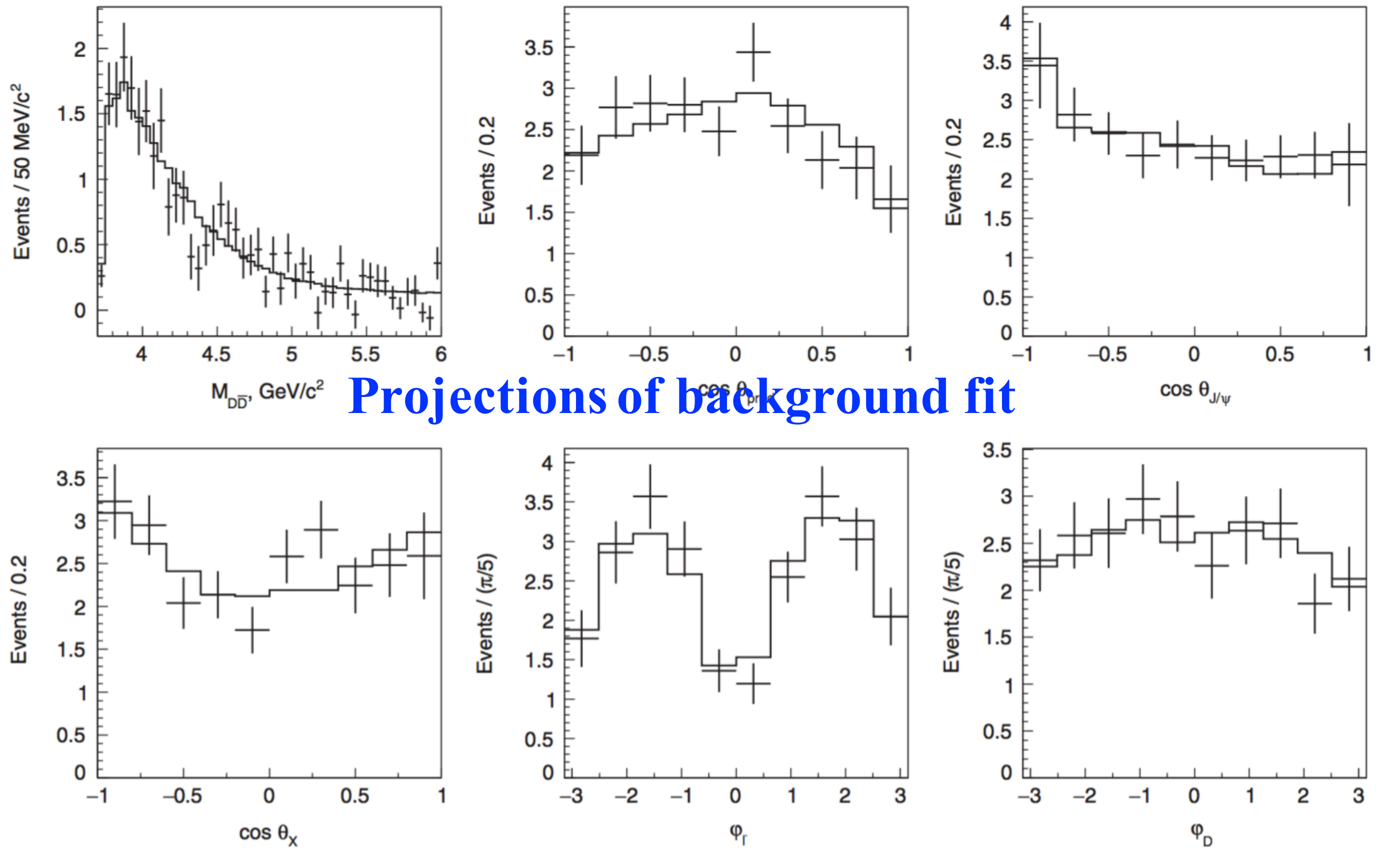

Projections of background fit

FIG. 5. Projections of the background fit results onto $M_{D\bar{D}}$ and angular variables. The points with error bars are data, and the solid line is the fit result.