Q^2 distribution of $X(3915)$ single-tag two-photon production

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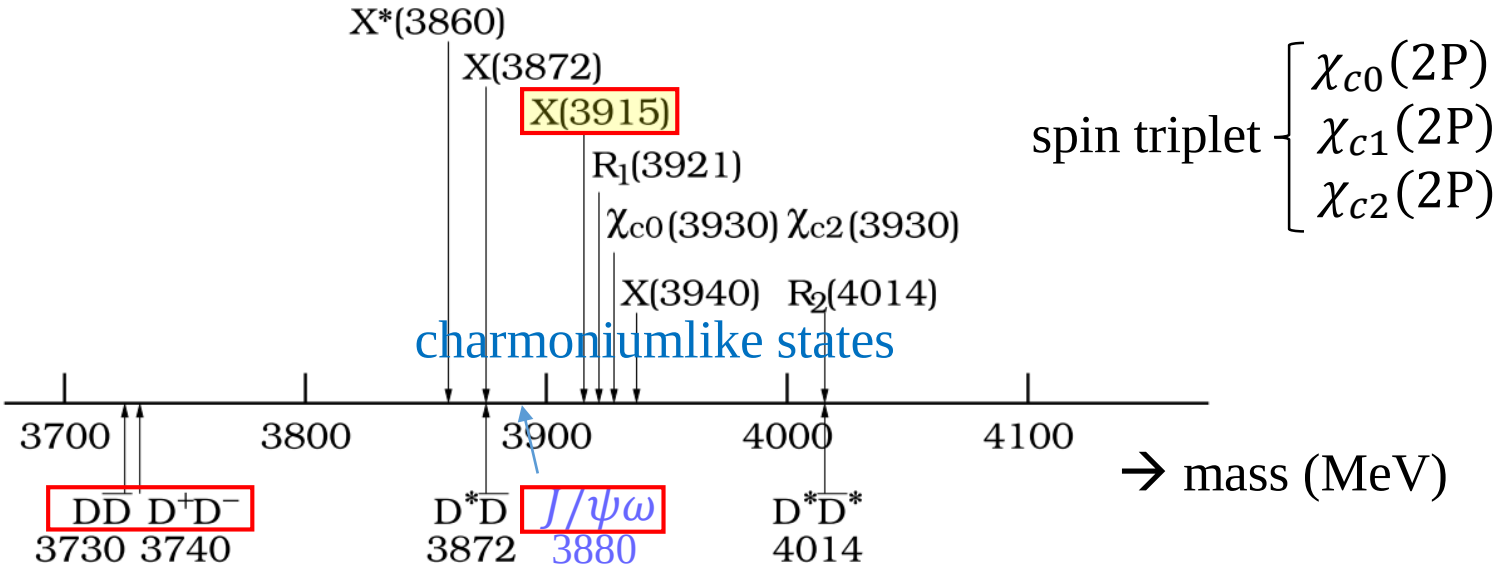
(On behalf of the Belle(II) collaboration)

$\gamma\gamma^* \to X(3915) \to J/\psi\omega$ $X(3915)$ (= PDG: $\chi_{c0}(3915)$)

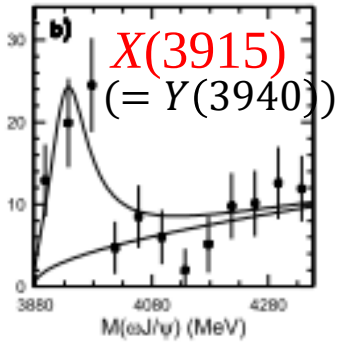
Y. Teramoto and S. Uehara *et al.* (Belle), PRD 108, 012004 (2023)



Brief history

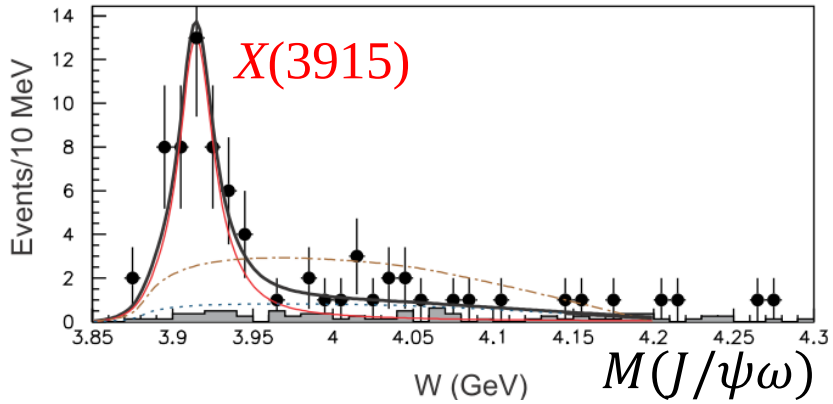
(1) $B^- \to J/\psi\omega K^-$ (Belle)

S.-K. Choi and S. L. Olsen *et al.*, PRL 94, 182002 (2005)



(2) $\gamma\gamma \to J/\psi\omega$ (Belle)

S. Uehara *et al.*, PRL 104, 092001 (2010)



M: 3915±3 ± 2 MeV

Γ : 17±10 ± 3 MeV

N: 49±14 ± 4 events

signf. 7.7σ

refer → no-tag 2γ measurement

(3) $\gamma\gamma \to J/\psi\omega$ (BABAR)

J. P. Lees *et al.*, PRD 86, 072002 (2012)

M: 3919.4±2.2 ± 1.6 MeV

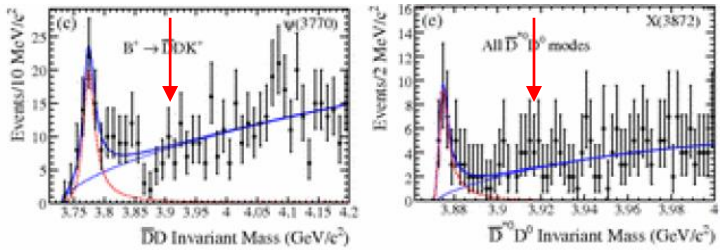
$\to J^P = 0^+$

$X(3915)$ exotic?

B factories: Belle and BABAR

→ No peak: $B^- \to D\bar{D}K^-, D^*\bar{D}K^-$ ← non-$c\bar{c}$?

$$X(3915) \not\to D\bar{D}$$
$$X(3915) \not\to D^*\bar{D}$$



$M(D\bar{D})$ BABAR $M(D^*\bar{D})$

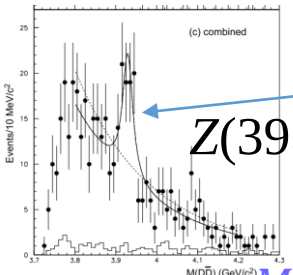
LHCb ← R. Aaij *et al.* (LHCb), PRD 102, 112003 (2020)

$B^- \to D^+D^-K^-$ amplitude analysis

→ found 0^{++}, 2^{++} states: $M \approx 3930$ MeV

$\chi_{c0}(3930)$, $\chi_{c2}(3930)$

$X(3915)$?? $\chi_{c2}(2P)$



$Z(3930)$

$M(D\bar{D})$

$\gamma\gamma \to \chi_{c2}(3930) \to D\bar{D}$

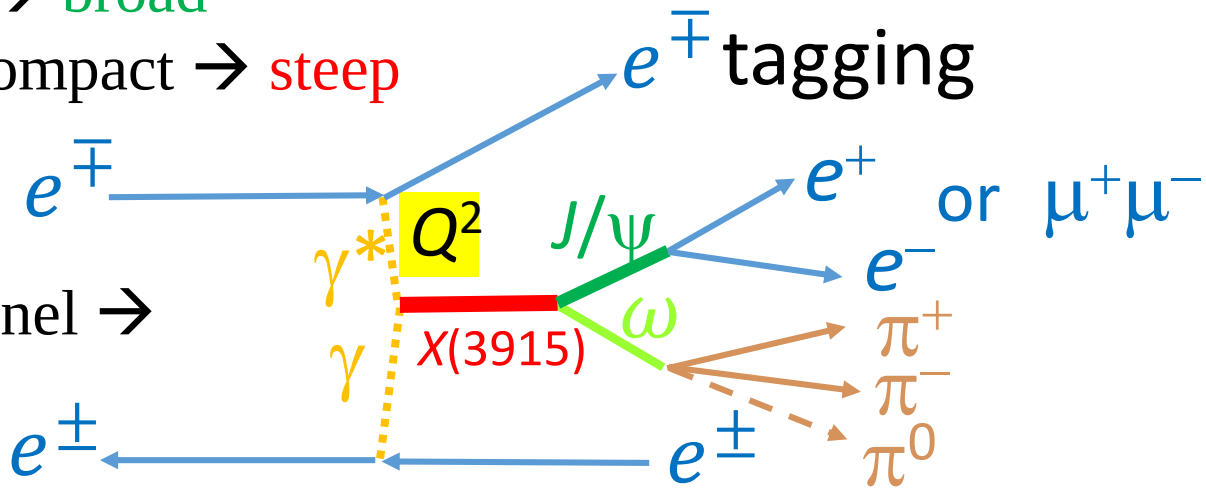
S. Uehara *et al.* (Belle) PRL 96, 082003 (2006)

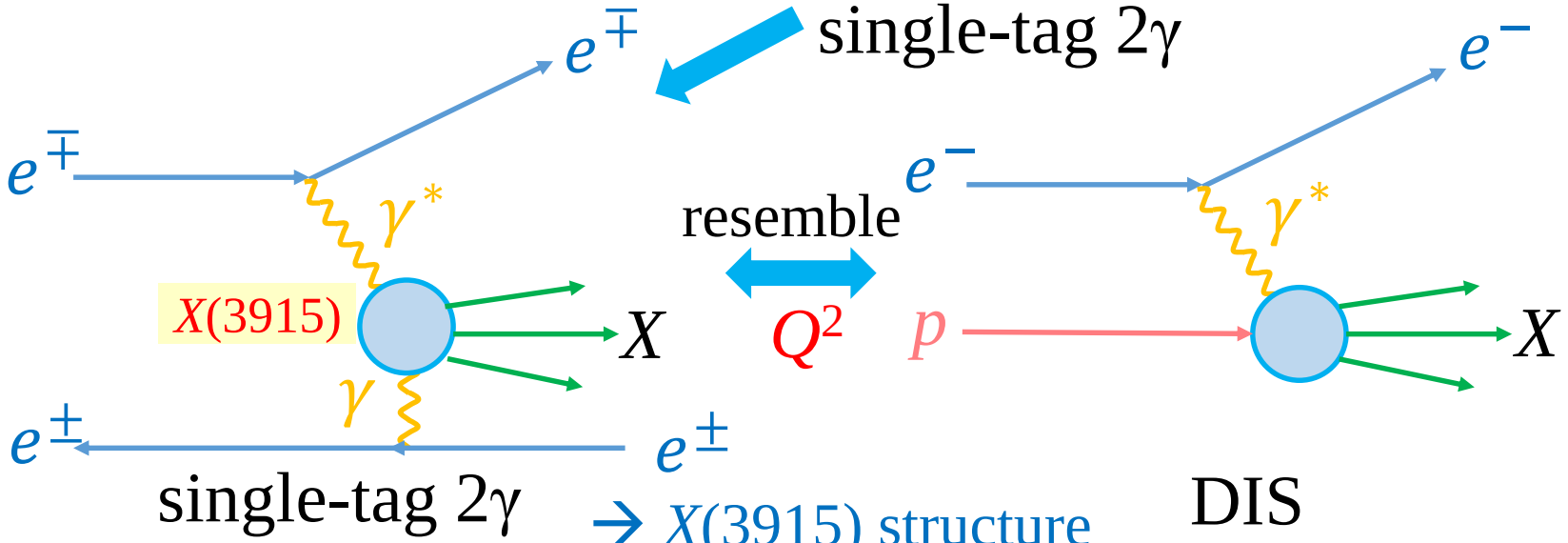
+ BABAR

Single-tag 2γ → $X(3915)$: Q^2

Q^2 { $c\bar{c}$ → compact → broad
exotics → not compact → steep

$Q^2 = -q^2$





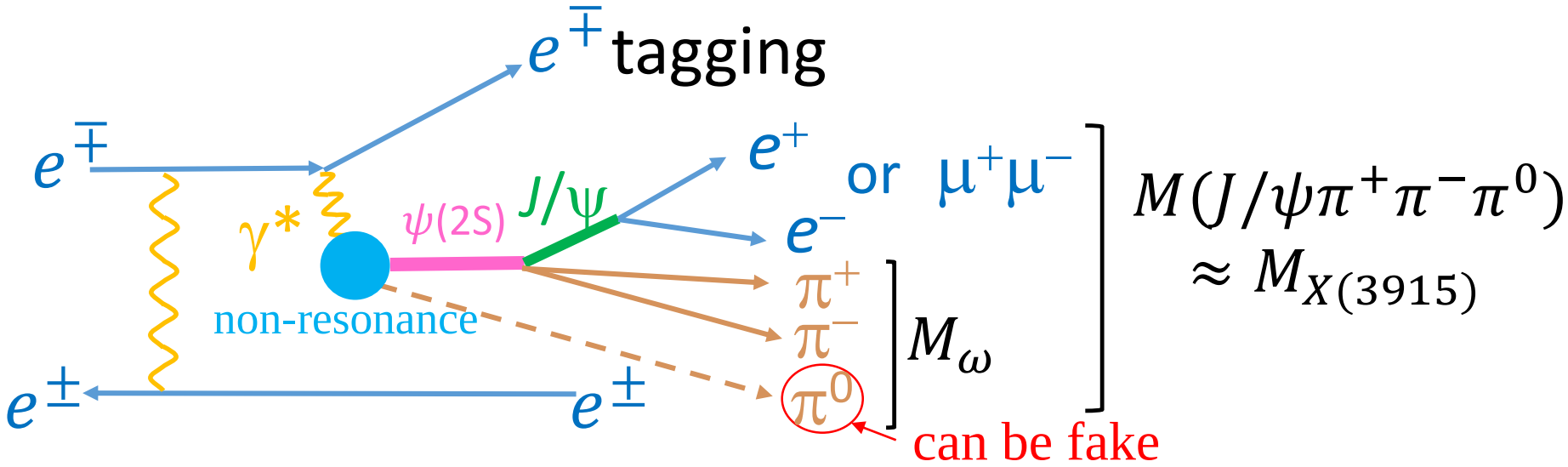
→ $X(3915)$ structure

Data analysis

Used data: 825 fb^{-1} Belle detector

Blind analysis: $M(J/\psi\omega)$ = 3918±30 MeV

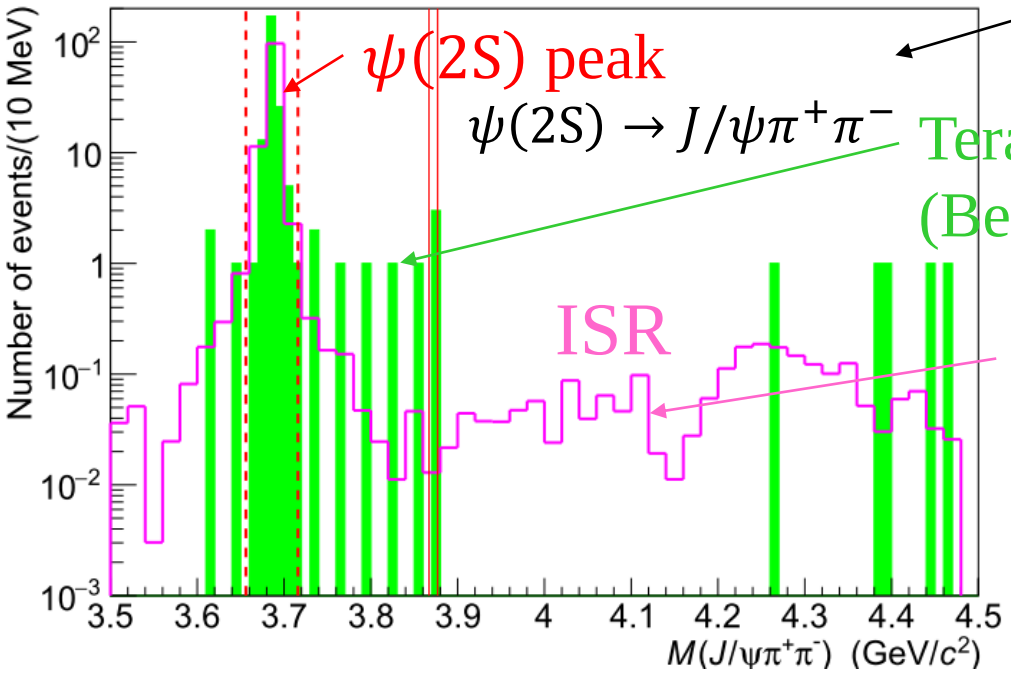
Major background: internal bremsstrahlung



γ noises → fake π^0

$\psi(2S)$ veto

$\gamma^* \rightarrow \psi(2S)$ production → huge



$M(J/\psi\pi^+\pi^-)$

cited: single-tag 2γ $X(3872)$ analysis

Teramoto, Uehara, Masuda *et al.* (Belle), PRL 126, 122001 (2021)

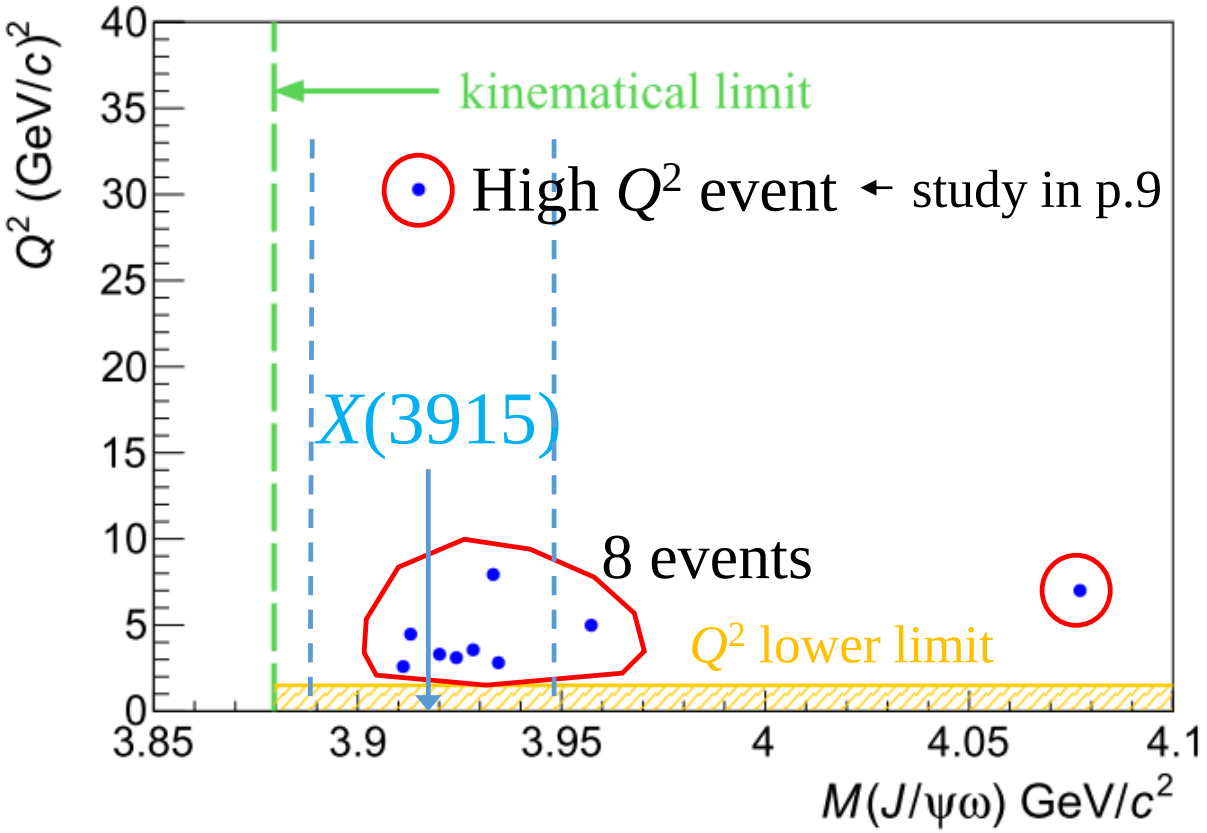
Yuan *et al.* (Belle), PRL 99, 182004 (2007)

$\psi(2S)$ veto: $M(J/\psi\pi^+\pi^-) = 3686 \pm 15$ MeV

→ too narrow

Results: Q^2 vs $M(J/\psi\omega)$

Event selection (conventional) → $J/\psi\omega$ events



Number of events

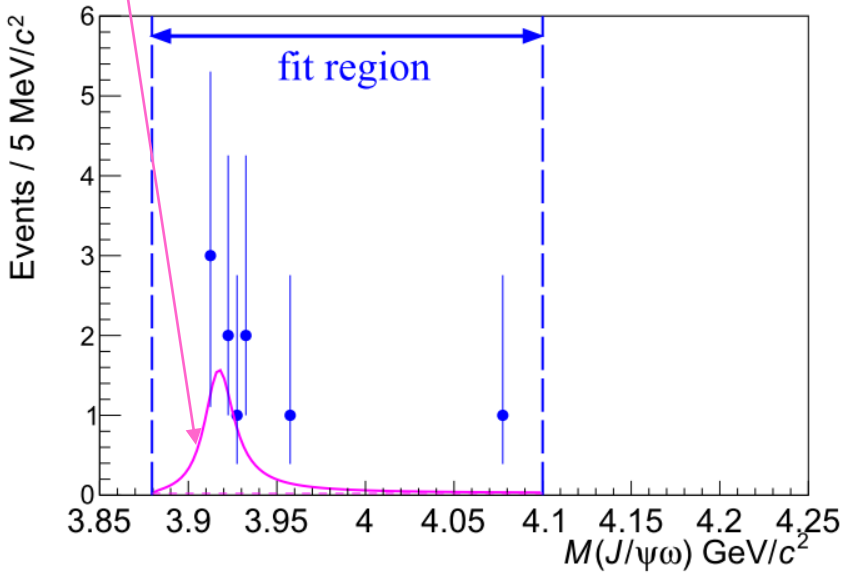
Fit mass distribution

$f_{\mathrm{BW+flat}} = a_{\mathrm{BW}} \cdot f_{\mathrm{BW}} + a_{\mathrm{flat}}$

threshold corrected BW

M = 3918 MeV

Γ = 20 MeV



a_{BW} = 49±18 MeV/(5 MeV)

a_{flat} = 22±35 /(5 MeV)

n_{sig} = 9.0±3.2 events

$n_{\mathrm{bg}}^{\mathrm{fit}}$ = 0.3±0.4 events

Integration a_{flat} over 60 MeV

BG est.: ω sideband n_{bg}^{ω} = 0.4±0.3 → use n_{bg} = 0.4±0.4 events

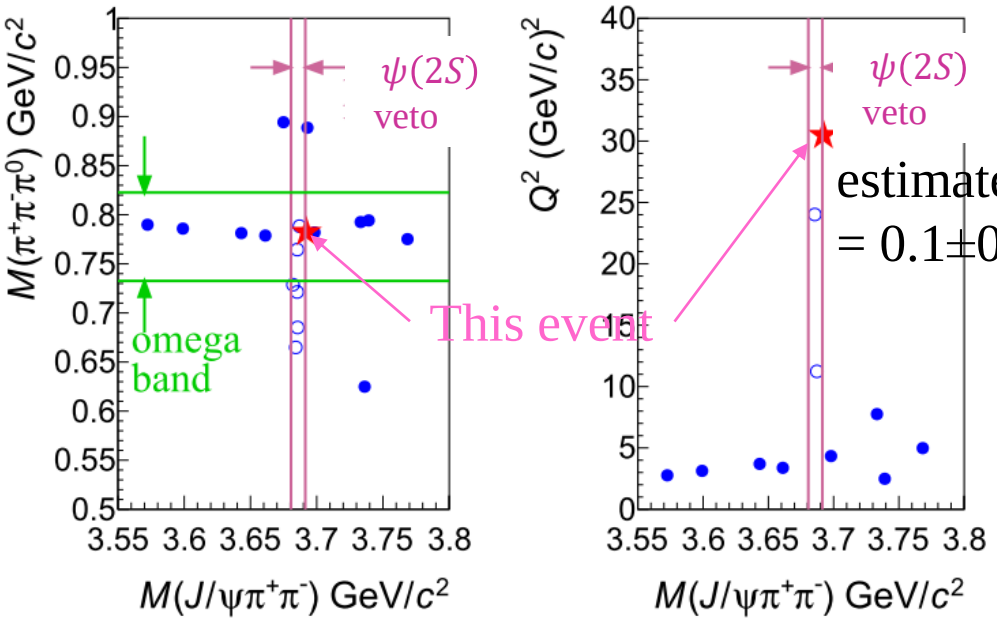
Signal expectation from (no-tag 2γ meas.) + (theory)

$n_{\mathrm{sig}}^{\mathrm{th}}$ = 4.1±0.7 events ← $J^P = 0^+$

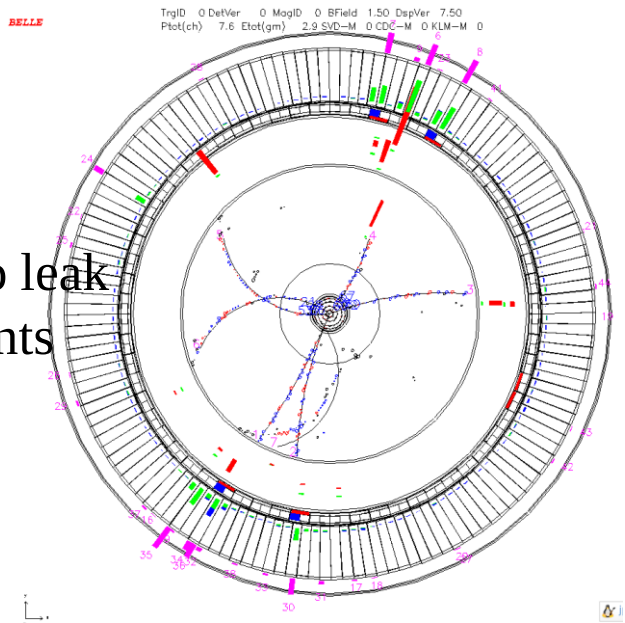
High Q^2 event

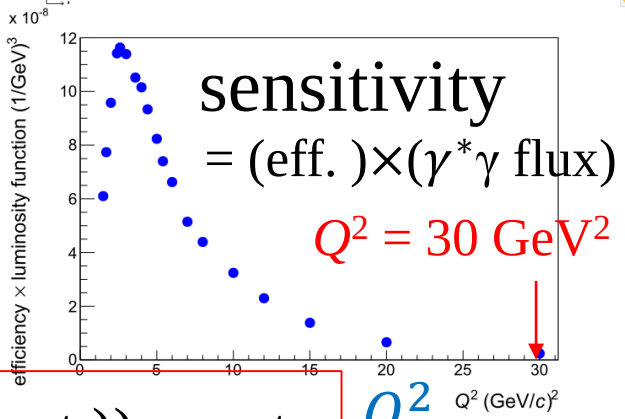
What is high Q^2 event?

ω selected



estimated veto leak
= 0.1±0.1 events





sensitivity
= (eff.)×($\gamma^*\gamma$ flux)

Q^2 = 30 GeV^2

high Q^2 event → $\psi(2S)\pi^0$ → exclude

fit excluding this event

a_{BW} = 43±17 MeV/(5 MeV)

a_{flat} = 25±36 /(5 MeV)

$n_{\mathrm{sig}} = 7.9^{+3.1}_{-3.0}$ (±1.5(syst.)) events

Q^2 distribution: formula

Q^2 distribution formula

$$Z_{\gamma^*\gamma}(Q^2, M^2, \epsilon)\mathcal{B}(X \to J/\psi\omega) = C(Q^2, M^2)\frac{dN_{ee}(X)}{dQ^2}$$

Q^2-dependent $\gamma\gamma$ decay function

expr. dependent corr.

Theory: Schuler, Berends, and Gulik (SBG model) → $c\bar{c}$

$$Z_{\gamma^*\gamma}(Q^2/M^2) = \frac{1}{(1+Q^2/M^2)^4}\left(1+\frac{Q^2}{3M^2}\right)^2\Gamma_{\gamma\gamma}(0)$$

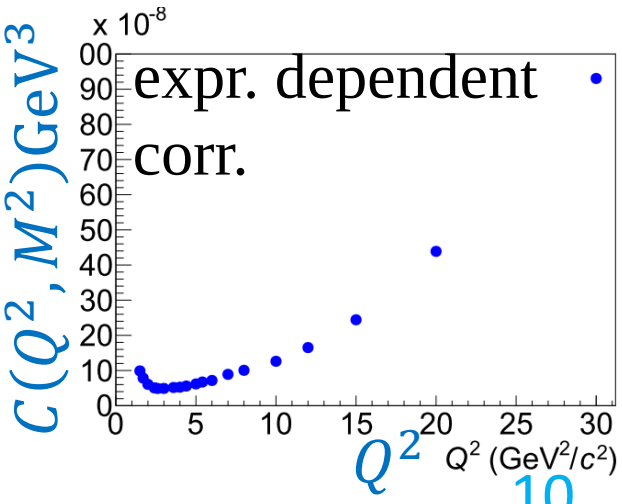
$J^P = 0^+$

2γ decay width

G. A. Schuler *et al.*, NP B523, 423 (1998)

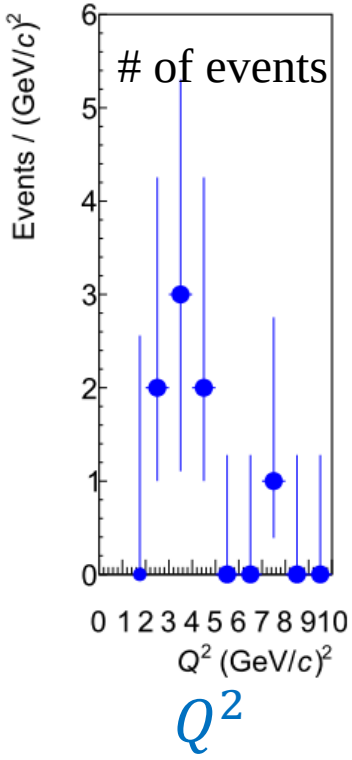
$$1/C(Q^2, M^2) = 8\pi^2\frac{(2J+1)(1+Q^2/M^2)}{M^2}\left.\frac{d^2L_{\gamma^*\gamma}}{dW\,dQ^2}\right|_{W=M} \times \varepsilon_{\text{eff}}(Q^2)\,L_{\text{int}}\,\mathcal{B}(J/\psi \to \ell^+\ell^-)\,\mathcal{B}(\omega \to \pi^+\pi^-\pi^0)$$

luminosity function

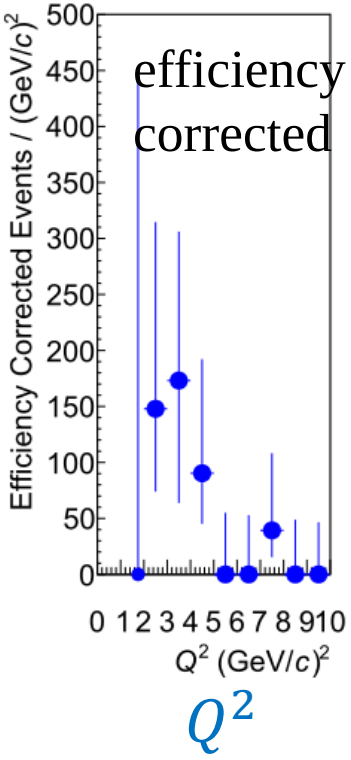


Q^2 distribution: measurement

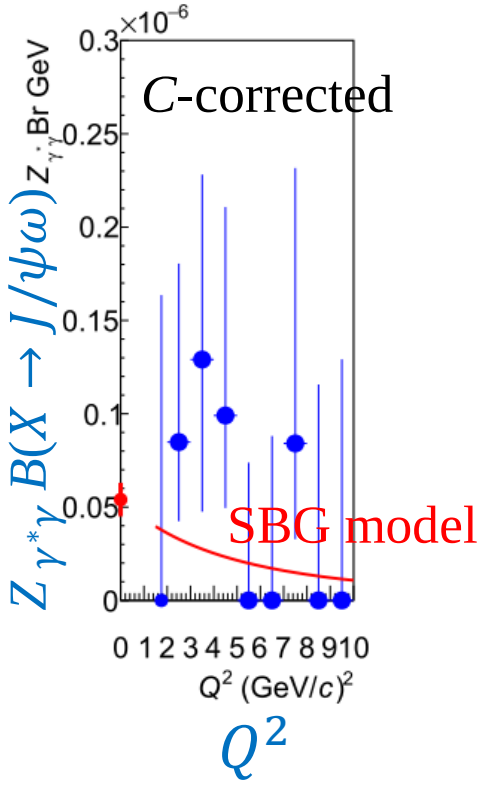
Measured Q^2 distribution: exclude high Q^2 event



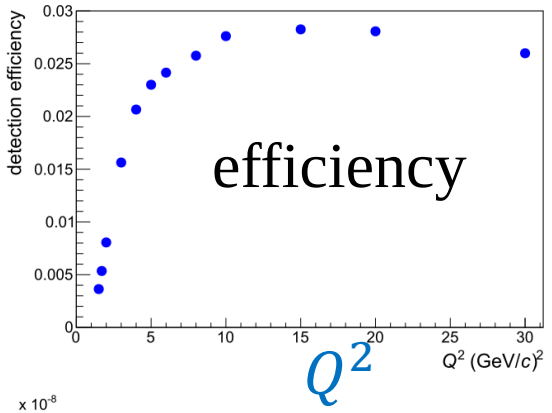
Q^2



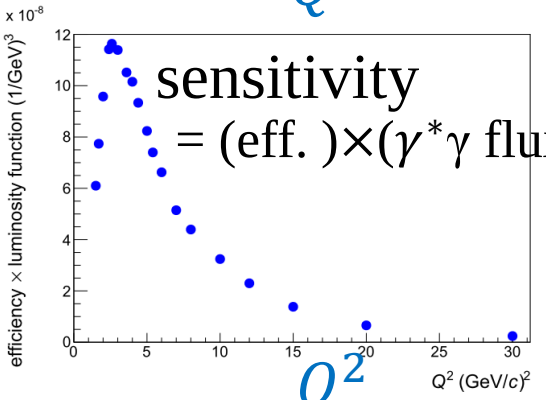
Q^2



Q^2



Q^2



Q^2

Item	Measurement		SBG model
Relative yield	1.9 ± 0.9		1.0
mean → $\langle Q^2 \rangle$ $(\mathrm{GeV}/c)^2$	4.5 ± 0.7	↔	4.8
width → $\sqrt{\langle (Q^2 - \langle Q^2 \rangle)^2 \rangle}$ $(\mathrm{GeV}/c)^2$	1.9 ± 0.8	↔	2.4

$c\bar{c}$ theory

← agrees

Conclusion & Summary

- We measure Q^2 distribution of $X(3915)$ by single-tag 2γ
- Q^2 distribution → agrees with SBG model: $c\bar{c}$
- Comparison with exotic model → not done yet.
- Number of signals = 7.9±3.1(stat.)±1.5(syst.)
  expected = 4.1±0.7 ← no-tag 2γ meas. + SBG model
- Future study by Belle II → reduce uncertainties

Thank you.

Backups: $c\bar{c}$-like mini-review

- $X(3915)$
- $X^*(3860)$
- $\chi_{c0}(3930)$
- $X(3940)$
- $X(3872) \rightarrow \chi_{c1}(3872)$
- $Z(3930) \rightarrow \chi_{c2}(3930)$
- $\chi_{c2}(3930)$
- $R_1(3921)$, $R_2(4014)$

Mass (1)

D^0 1864.83 ± 0.05 MeV

$D^{\pm}$ 1869.58 ± 0.09 MeV

D^{*0} 2006.85 ± 0.05 MeV

$D^{*\pm}$ 2010.26 ± 0.05 MeV

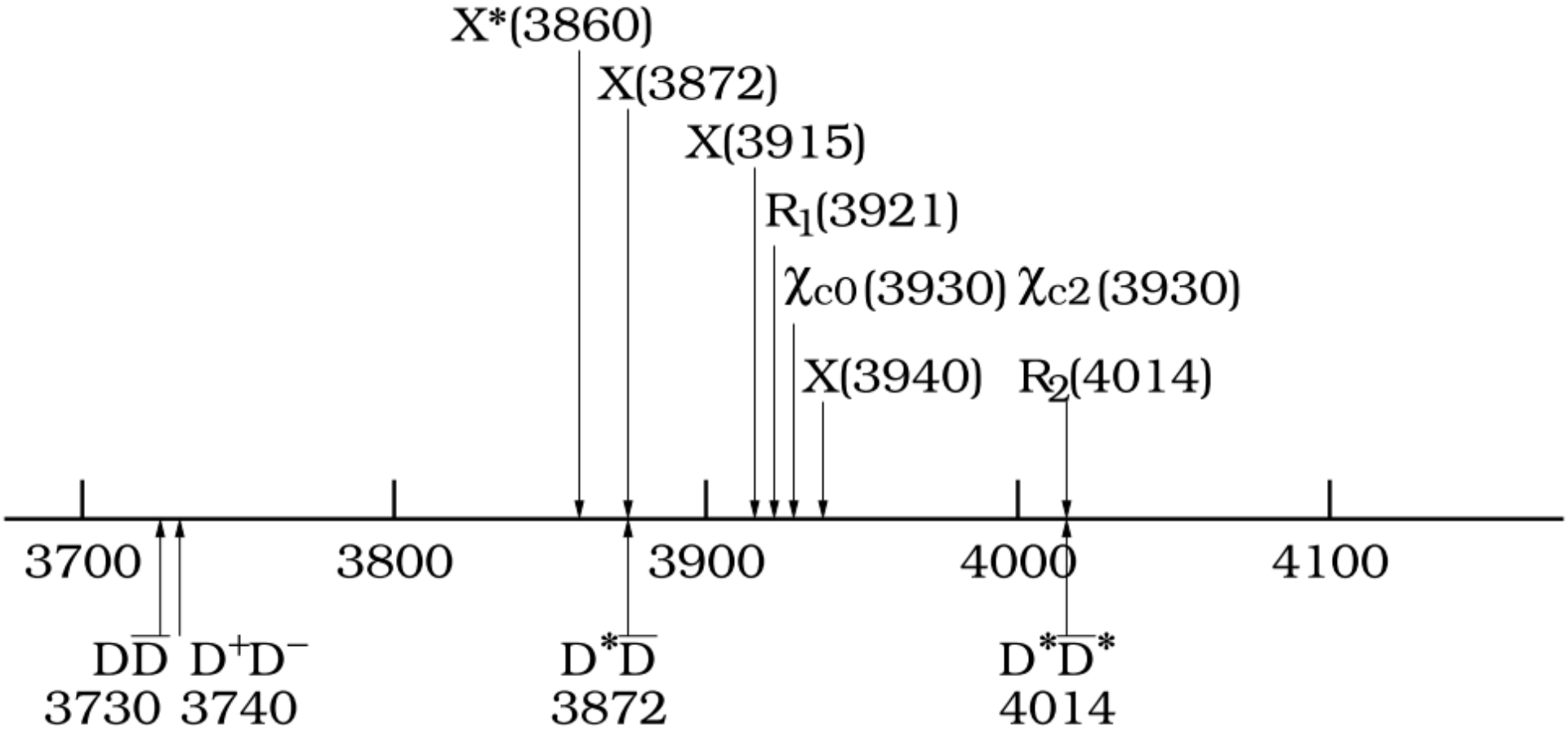
$D\bar{D}$ 3729.66 MeV

D^+D^- 3739.66 MeV

$D^*\bar{D}$ 3871.68 MeV

$D^*\bar{D}^*$ 4013.70 MeV

Mass (2)


X*(3860)
X(3872)
X(3915)
R1(3921)
χc0(3930) χc2(3930)
X(3940) R2(4014)
3700
3800
3900
4000
4100
DD D+D−
3730 3740
D*D
3872
D*D*
4014

χ_{c0}(2P) candidates

OZI suppress

- $X(3915)$ → $\omega J/\psi$ not seen $D\bar{D}$
- $X^*(3860)$ → not seen by LHCb
- $R_1(3921)$ → = $X(3915)$? only seen by Belle
- $\chi_{c0}(3930)$ → = $X(3915)$? only seen by LHCb

χ_{c2}(2P) candidates

$\chi_{c2}(3930)$

Mass 3922.2 ± 1.0 MeV

Γ 35.3 ± 2.8 MeV

- $Z(3930) \rightarrow \chi_{c2}(3930)$ $\gamma\gamma \rightarrow D\bar{D}$
- $R_2(4019)$
- $R_1(3921)$

  not established yet
- $\chi_{c2}(3930)$ $B^- \rightarrow K^- D^+ D^-$

$X(3915)$

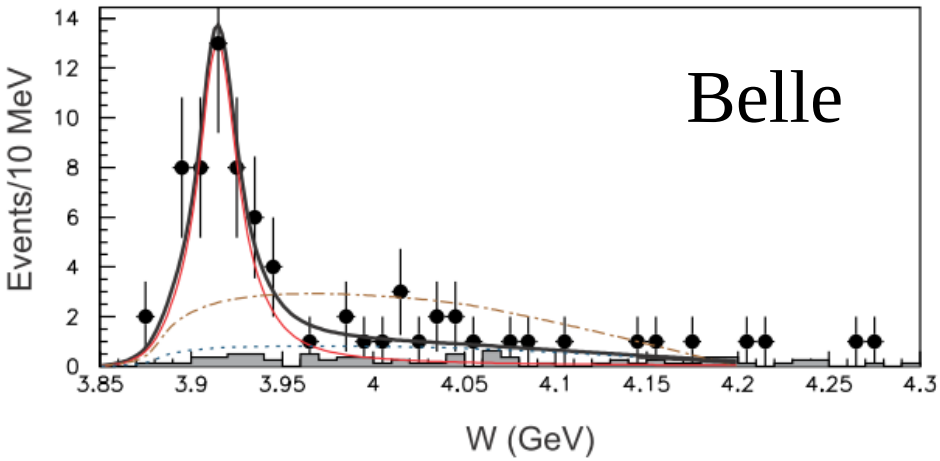
Observation $\gamma\gamma \to \omega J/\psi,\ B^- \to K^-\omega J/\psi$

Spin 0^{++} favored, 2^{++} could be

Mass $3915 \pm 3 \pm 2$ MeV

Γ $17 \pm 10 \pm 3$ MeV

significance 7.7σ



$\chi_{c0}(2P)$ candidate, but

Not seen in $J/\psi\ D\bar{D}, K^-D\bar{D}, K^-D^*\bar{D}$

$X^*(3860)$

Observation $e^+e^- \to J/\psi\, X^*(3860)$

$X^*(3860) \to D\bar{D}$

amplitude analysis $J/\psi D\bar{D}$

J/ψ: reconstruct

$D\bar{D}$: recoil mass

Mass 3862^{+26+40}_{-32-13} MeV

Γ 201^{+26+40}_{-67-82} MeV

Spin 0^{++} favored, 2^{++} could be

significance 6.5σ

$\chi_{c0}(2P)$ candidate, but

Not seen in LHCb

$\chi_{c0}(3930), \chi_{c2}(3930)$

Observation $B^+ \to D^+D^-K^+$ (LHCb)

$\chi_{cJ} \to D^+D^-$

Amplitude analysis → both 0^{++} and 2^{++}

$\chi_{c0}(3930)$	Mass	$3923.8 \pm 1.5 \pm 0.4$ MeV
	Γ	$17.4 \pm 5.1 \pm 0.8$ MeV
$\chi_{c2}(3930)$	Mass	$3926.8 \pm 0.24 \pm 0.8$ MeV
	Γ	$34.2 \pm 6.6 \pm 1.1$ MeV

$X(3940)$

Observation $e^+e^- \to J/\psi\, X(3940)$

$X(3940) \to D^*\bar{D}$

recoil mass

Mass 3936 ± 14 MeV

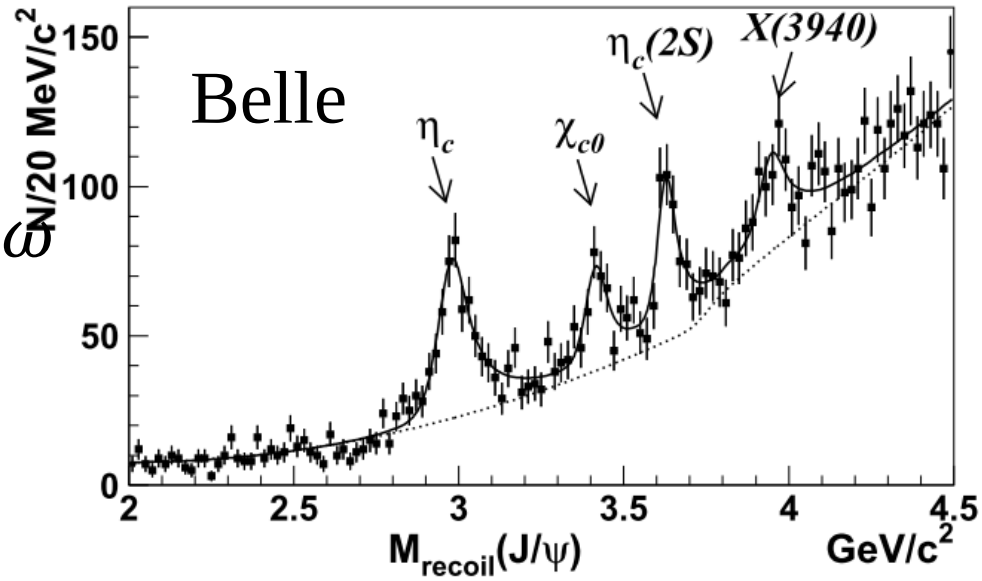
significance 5.0σ

Not seen $X(3940) \not\to D\bar{D}$

$X(3940) \not\to J/\psi\omega$

Spin 0^- or 1^+

$\eta_c(3P)$?



$X(3872) \rightarrow \chi_{c1}(3872)$

$\chi_{c1}(2P)$ 1^{++}

Mass 3871.69 ± 0.17 MeV

Γ < 1.2 MeV

$X(3872) \rightarrow \pi^+\pi^- J/\psi,\ \rho J/\psi, \omega J/\psi$

$Z(3930) \rightarrow \chi_{c2}(3930)$

Observation $\gamma\gamma \rightarrow D\bar{D}$

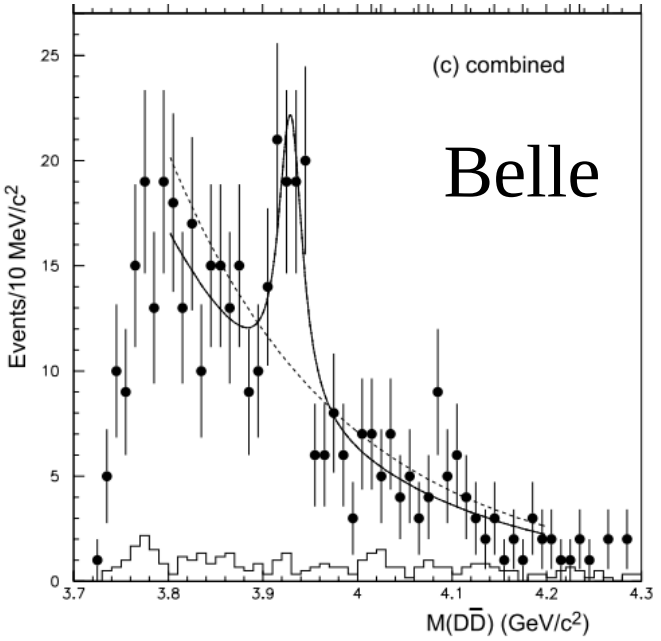
Spin 2^{++}

Mass $3929 \pm 5 \pm 2$ MeV

Γ $29 \pm 10 \pm 2$ MeV

significance 5.3σ

$\chi_{c2}(2P)$ candidate



$R_1(3921), R_2(4014)$

Observation $\gamma\gamma \to \gamma\psi(2S)$

$R_1(3921)$

Mass $3921.3 \pm 2.4 \pm 1.6$ MeV

Γ $0.0 \pm 5.3 \pm 2.0$ MeV

Spin 0^{++} or 2^{++}

significance 4.0σ

candidate $\chi_{c0}(2P), \chi_{c2}(2P)$

$R_2(4014)$

Mass $4014.4 \pm 4.1 \pm 0.5$ MeV

Γ $6 \pm 16 \pm 12$ MeV

significance $3.0\sigma\ (2.8\sigma)$