Study of charmonium-like states in two-photon collisions at Belle

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Two recent results from Belle two-photon processes

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

$R_1(3921)$ (and $R_2(4014)$)

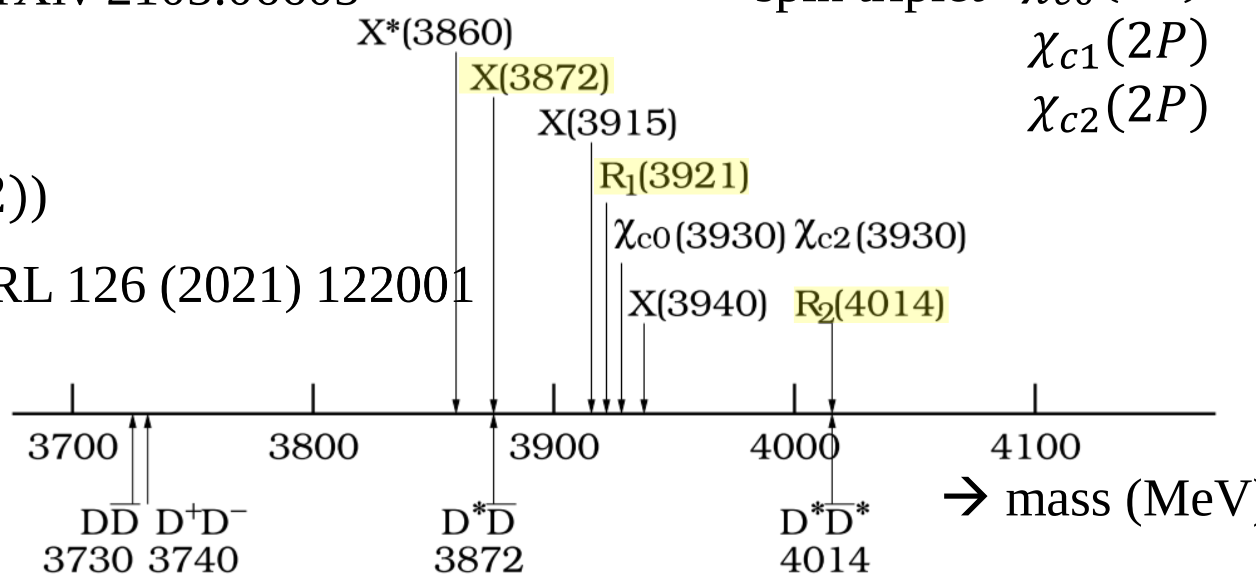
X.L.Wang *et al.* (Belle), arXiv 2105.06605

spin triplet $\chi_{c0}(2P)$
$\chi_{c1}(2P)$
$\chi_{c2}(2P)$

(2) $\gamma\gamma^* \to J/\psi\pi^+\pi^-$

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

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



Two-photon interaction

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

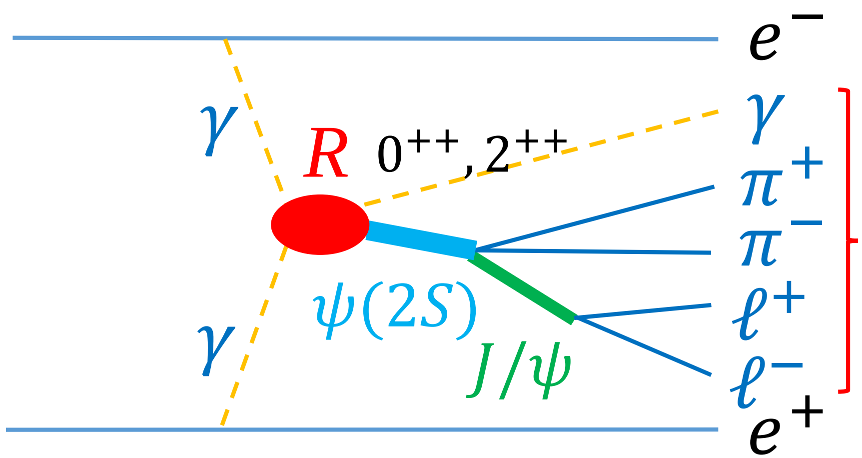
Used data: 980 fb^{-1} $\Upsilon(nS)(n = 1,2,3,4,5)$ Belle

→ Evidence for new $\chi_{c0}(2P), \chi_{c2}(2P)$-like state

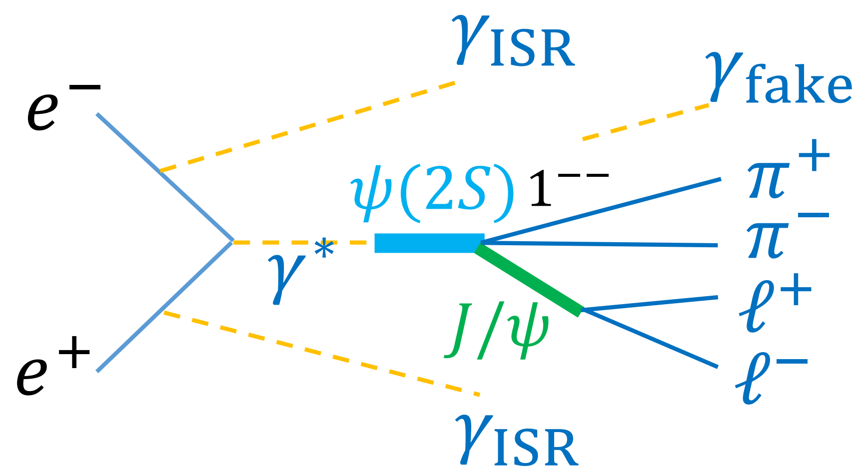
X.L.Wang *et al.* (Belle), arXiv 2105.06605; submiting to JHEP

$$\gamma\gamma \to \gamma\psi(2S)$$
$$\psi(2S) \to J/\psi\pi^+\pi^-$$

signal: $\gamma\gamma$



background:
Initial State Radiation (ISR)

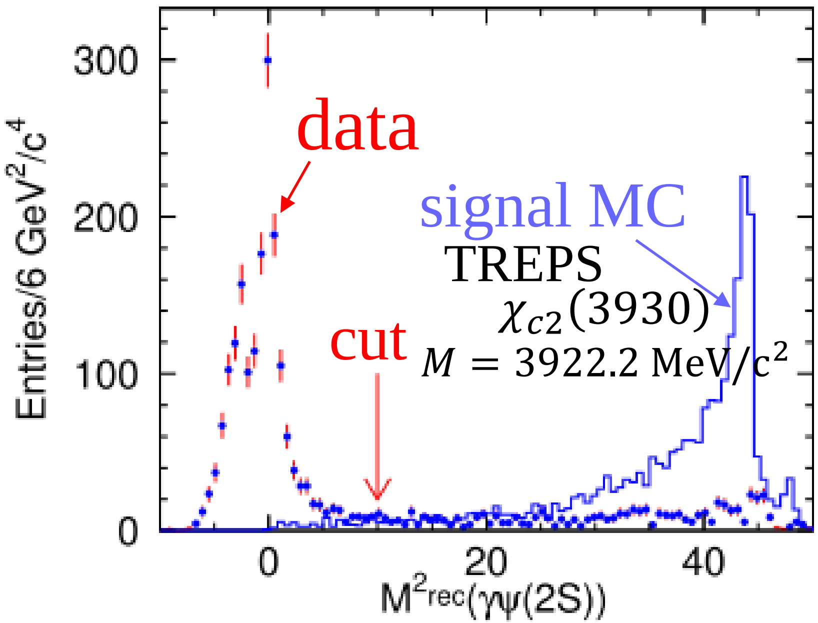


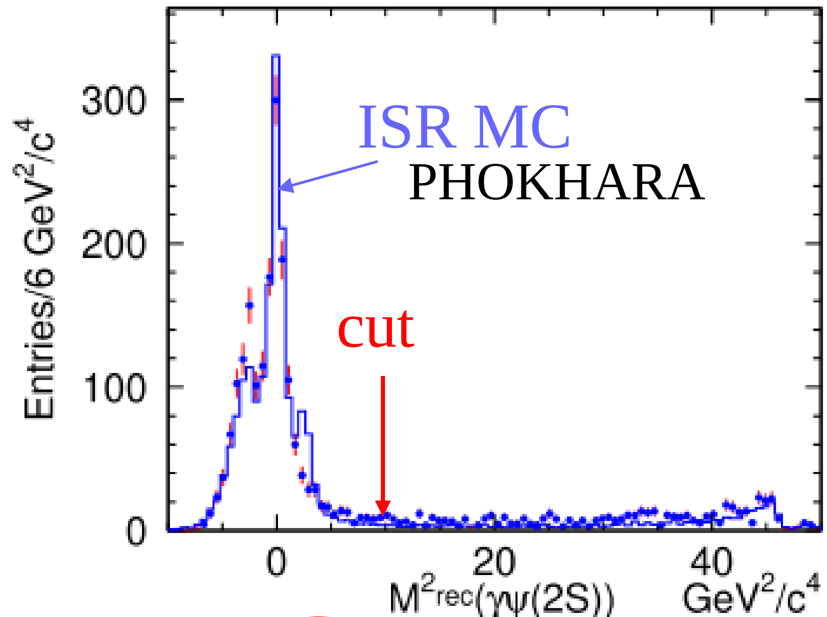
no-tag: e^+e^- missing in beam-pipe

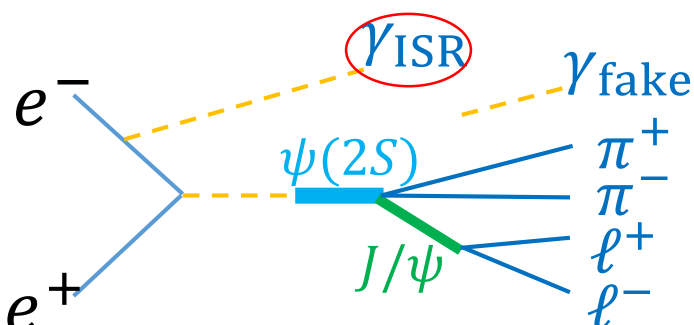
→ high recoil mass

γ_{ISR} $(+\gamma_{ISR})$ missing in beam-pipe

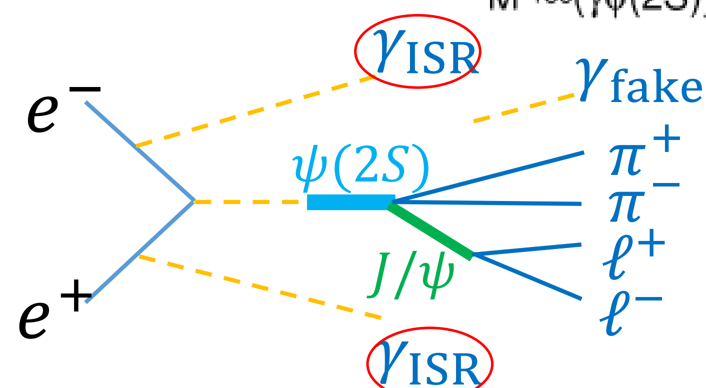
Recoil mass







single γ → $M^2_{\rm rec} = 0$

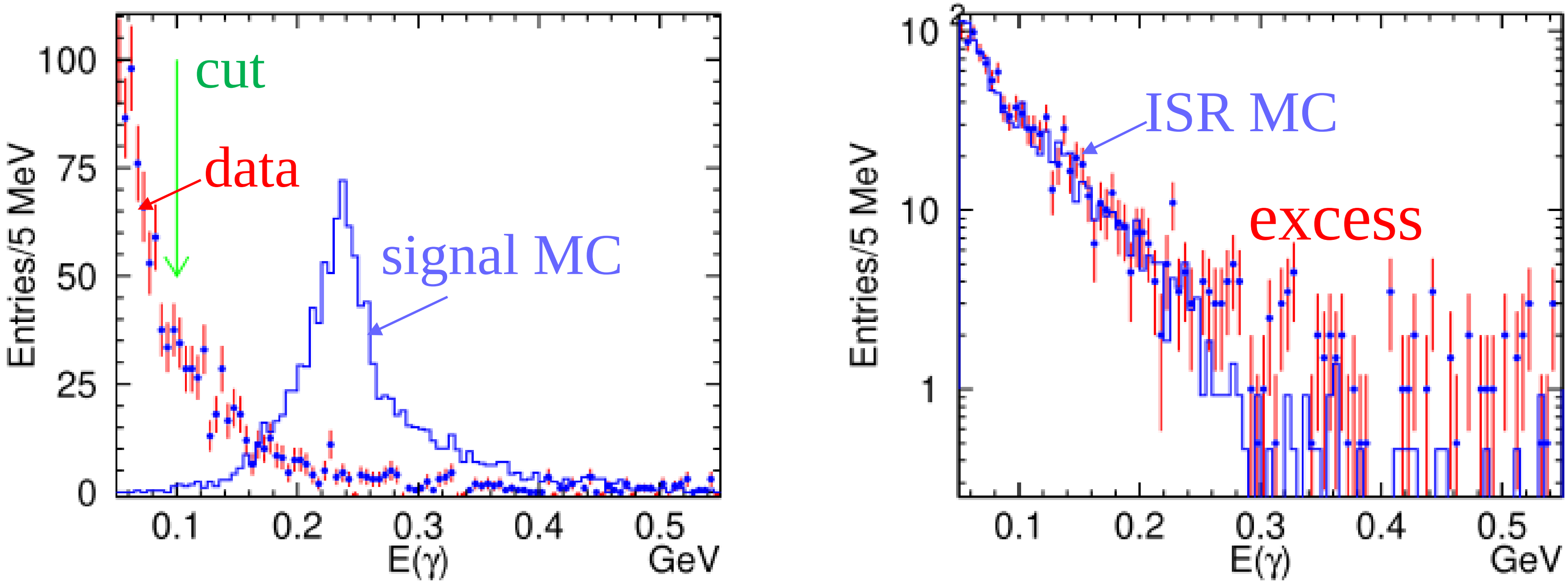


double γ → $M^2_{\rm rec}$ high mass tail

Photon energy: E_γ

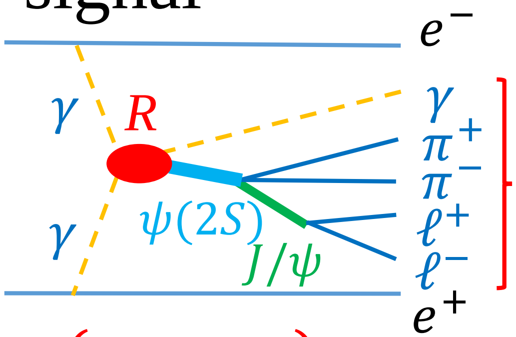
$\gamma\psi(2S)$

- signal γ → high E
- ISR γ → low E
- fake γ → low E



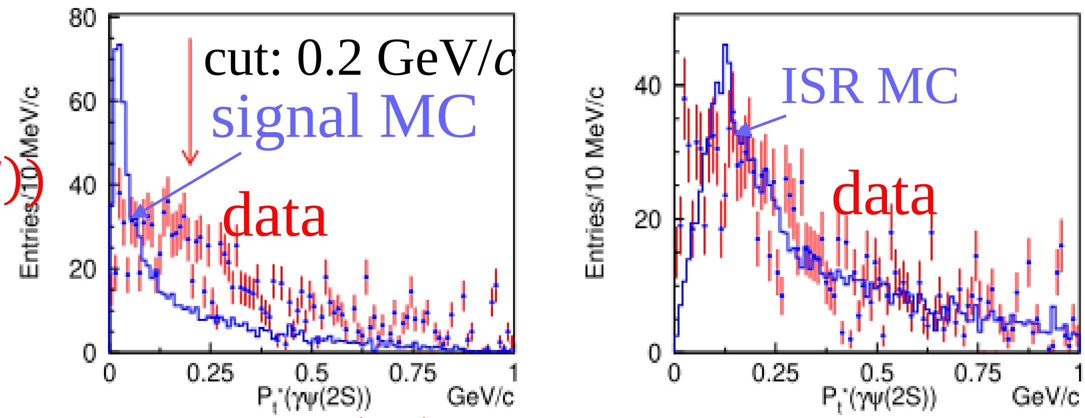
p_T^* balance

signal



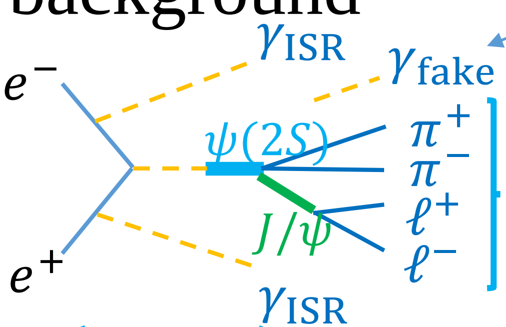
$p_T^*(\gamma\psi(2S))$

$p_T^*(\gamma\psi(2S))$ should balance



→ $p_T^*(\gamma\psi(2S))$

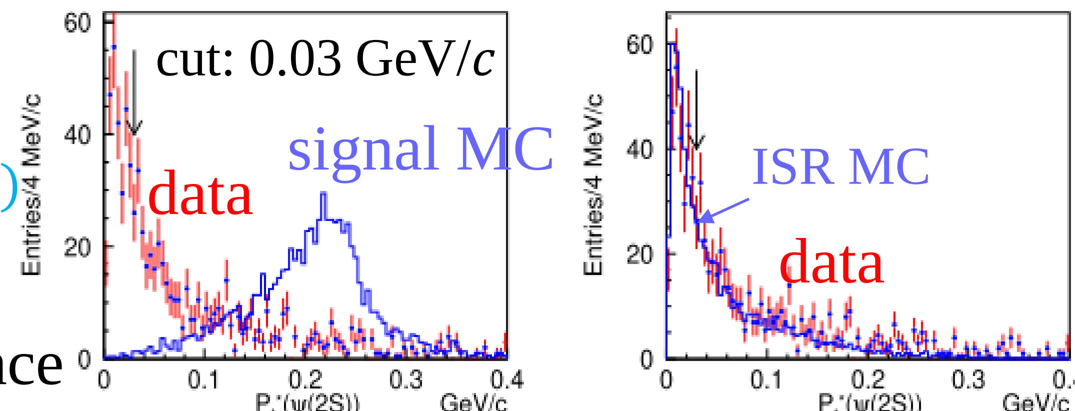
background



noise

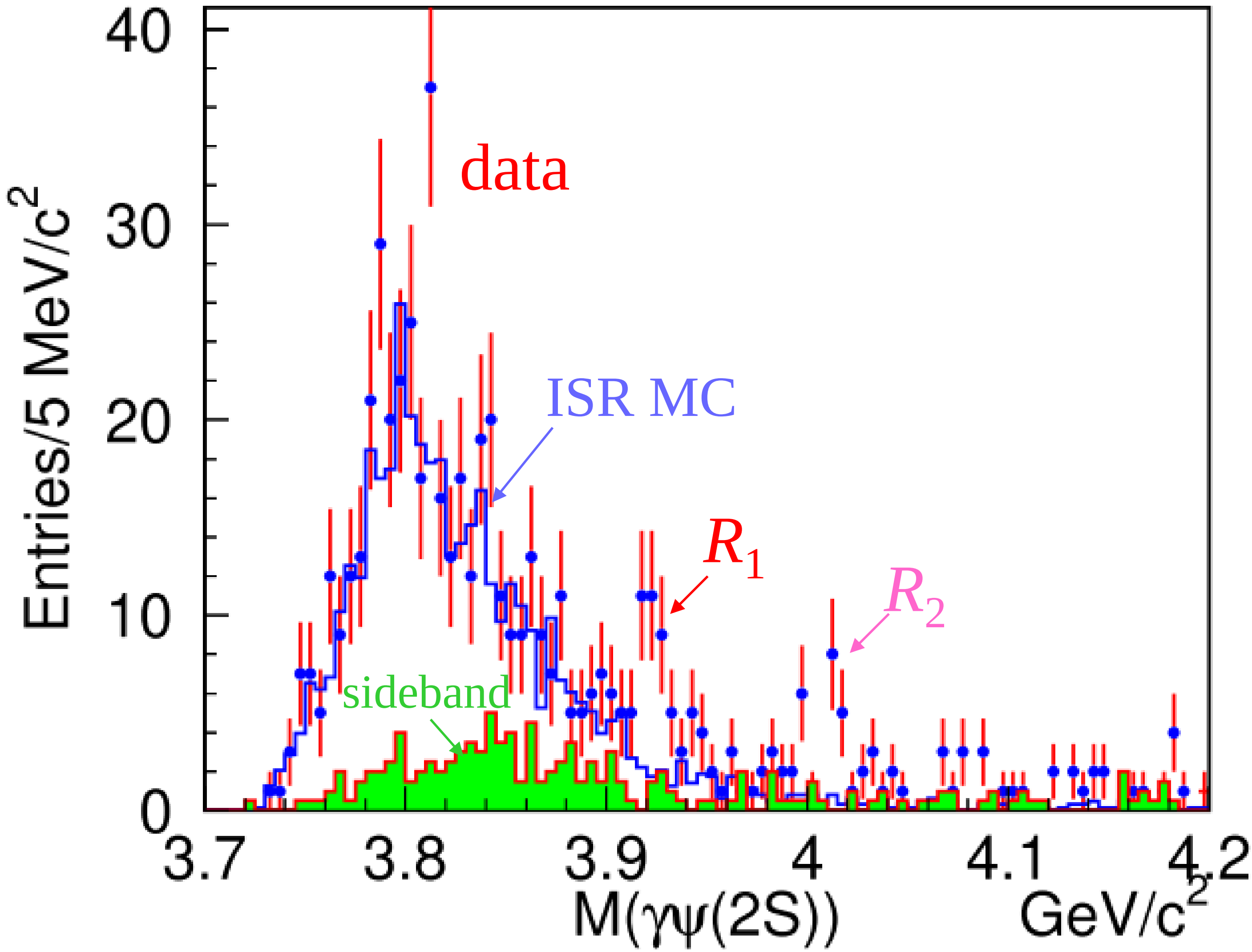
$p_T^*(\psi(2S))$

$p_T^*(\psi(2S))$ should NOT balance



→ $p_T^*(\psi(2S))$

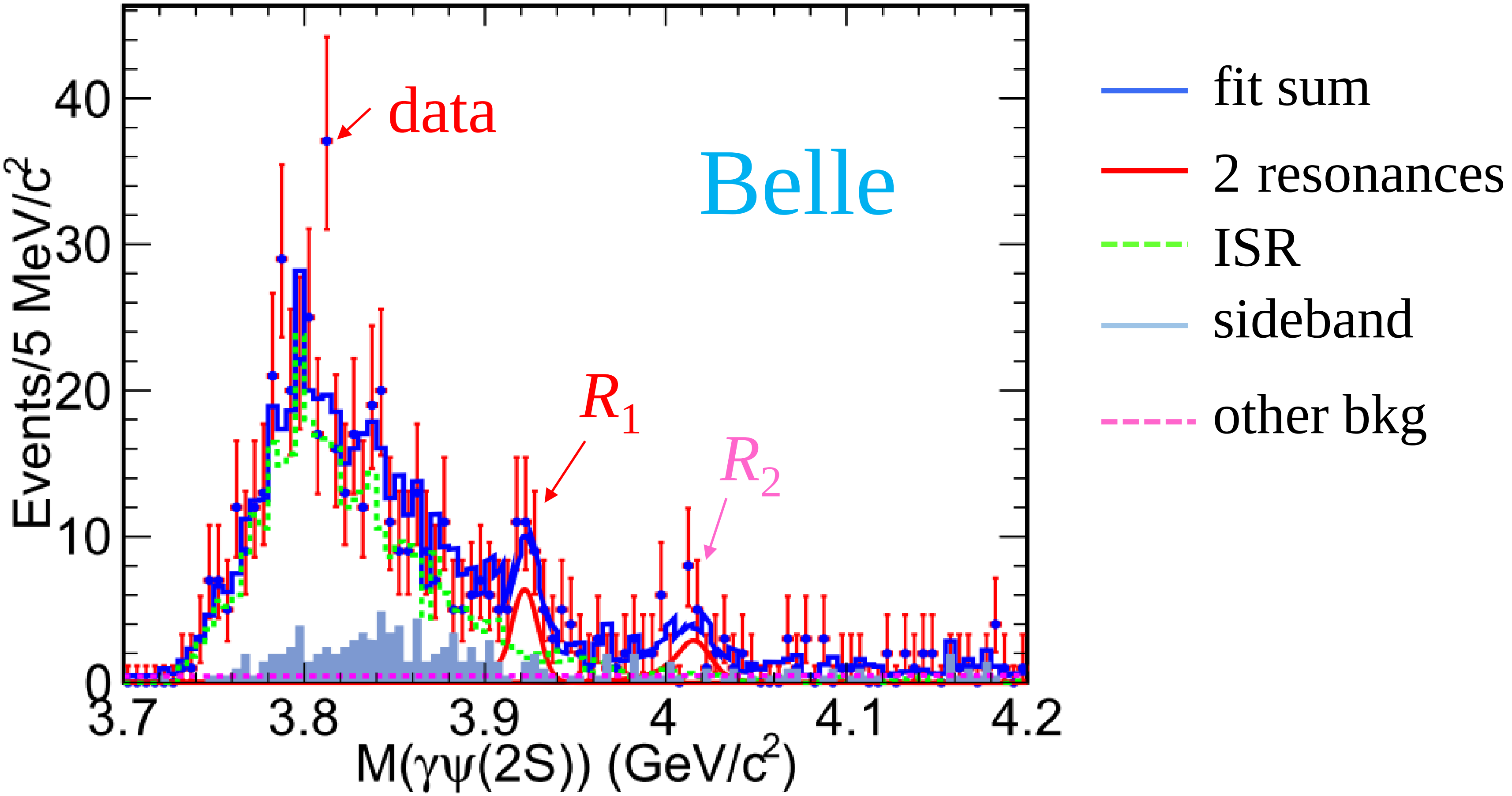
$M(\gamma\psi(2S))$



$M(\gamma\psi(2S))$: fit

binned extended maximum likelihood fit

$$f_{\rm PDF} = f_{\rm R1} + f_{\rm R2} + f_{\rm ISR} + f_{\rm bkg} + f_{\rm sideband}$$



Results

Resonant parameters		$J=0$	$J=2$
R_1	M_1	$3921.3 \pm 2.4 \pm 1.6$ MeV$/c^2$	
	Γ_1	$0.0 \pm 5.3 \pm 2.0$ MeV	
	Γ_1^{UL}	11.5 MeV	
	$\Gamma_{\gamma\gamma}\mathcal{B}(R_1 \to \gamma\psi(2S))$	$8.2 \pm 2.3 \pm 0.9$ eV	$1.6 \pm 0.5 \pm 0.2$ eV
R_2	M_2	$4014.4 \pm 4.1 \pm 0.5$ MeV$/c^2$	
	Γ_2	$6 \pm 16 \pm 12$ MeV	
	Γ_2^{UL}	39.3 MeV	
	$\Gamma_{\gamma\gamma}\mathcal{B}(R_2 \to \gamma\psi(2S))$	$5.3 \pm 2.7 \pm 2.5$ eV	$1.1 \pm 0.5 \pm 0.5$ eV
	$\Gamma_{\gamma\gamma}^{\mathrm{UL}}\mathcal{B}(R_2 \to \gamma\psi(2S))$	12.8 eV	2.6 eV
R_1	$M_{X(3915)}$	3918.4 MeV$/c^2$ (fixed)	
	$\Gamma_{X(3915)}$	20 MeV (fixed)	
	$\Gamma_{\gamma\gamma}\mathcal{B}(X(3915) \to \gamma\psi(2S))$	$10.9 \pm 3.1 \pm 1.2$ eV	$2.2 \pm 0.6 \pm 0.2$ eV
R_1	$M_{\chi_{c2}(3930)}$	—	3922.2 MeV$/c^2$ (fixed)
	$\Gamma_{\chi_{c2}(3930)}$	—	35 MeV (fixed)
	$\Gamma_{\gamma\gamma}\mathcal{B}(\chi_{c2}(3930) \to \gamma\psi(2S))$	—	$2.4 \pm 0.7 \pm 0.4$ eV

⬅ 4.0σ

⬅ 2.8σ

$R_1 \equiv X(3915)$

$R_1 \equiv \chi_{c2}(3930)$

→ Evidence for $R_1(3921)$ which can be $X(3915)$ or $\chi_{c2}(3930)$

$\chi_{cJ}(2P)$, exotics?

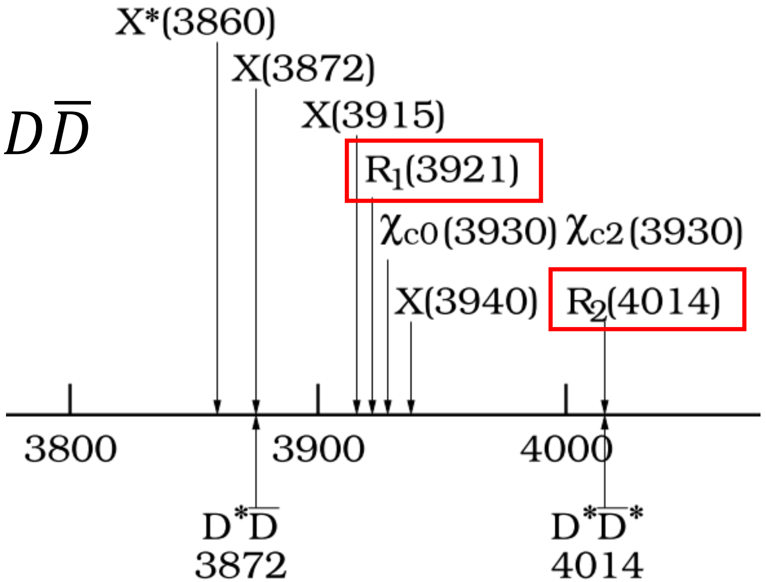
$\chi_{c0}(2P)$

- $X(3915)$ → $\gamma\gamma \to \omega J/\psi$ not seen $D\bar{D}$
- $X^*(3860)$ → $e^+e^- \to J/\psi D\bar{D}$, not seen by LHCb
- $R_1(3921)$ → $= X(3915)$?
- $\chi_{c0}(3930)$(←LHCb) → $B^+ \to D^+D^-K^+$
  $= X(3915)$? $B(D\bar{D}) \leftrightarrow B(\omega J/\psi)$

$\chi_{c2}(2P)$

- $Z(3930)$ → $\chi_{c2}(3930)$, $\gamma\gamma \to D\bar{D}$
- $R_1(3921)$ → $= \chi_{c2}(3930)$?
- $R_2(4014)$
- $\chi_{c2}(3930)$ (← LHCb)

candidates excess → exotics?



Single-tag two-photon interaction

$$\gamma^* \gamma \to J/\psi \pi^+ \pi^-$$

Used data: 825 fb^{-1} $\Upsilon(nS)(n = 1,2,3,4,5)$ Belle

→ First evidence for $X(3872)$ in two-photon interactions

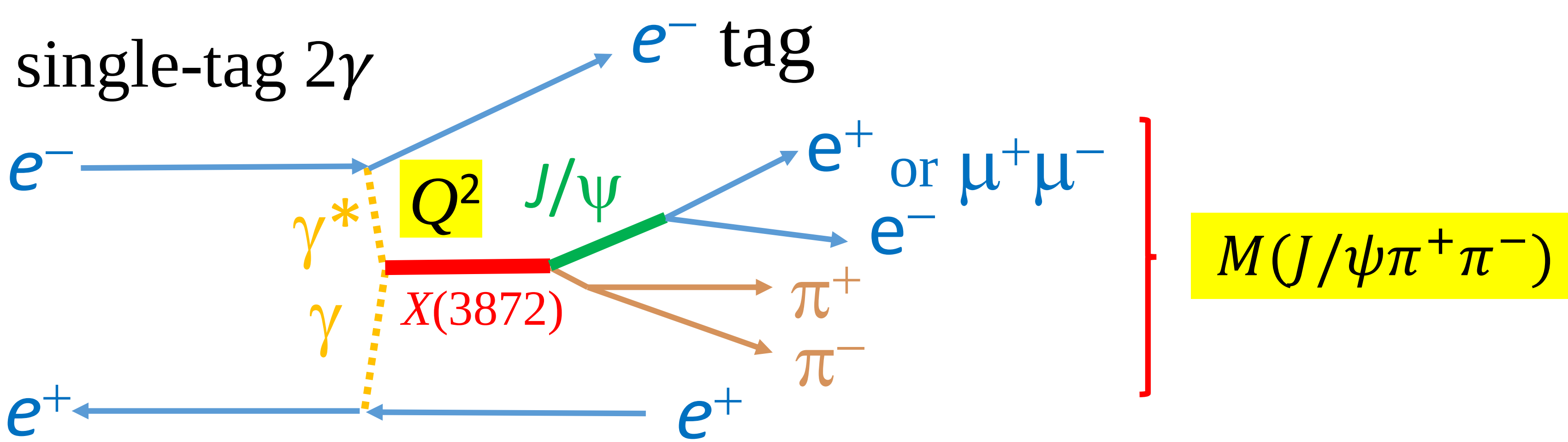
Teramoto *et al.* (Belle), PRL 126 (2021) 122001

$$\gamma^*\gamma \to X(3872) \to J/\psi\pi^+\pi^-$$

$X(3872)$: $J^{PC} = 1^{++}$

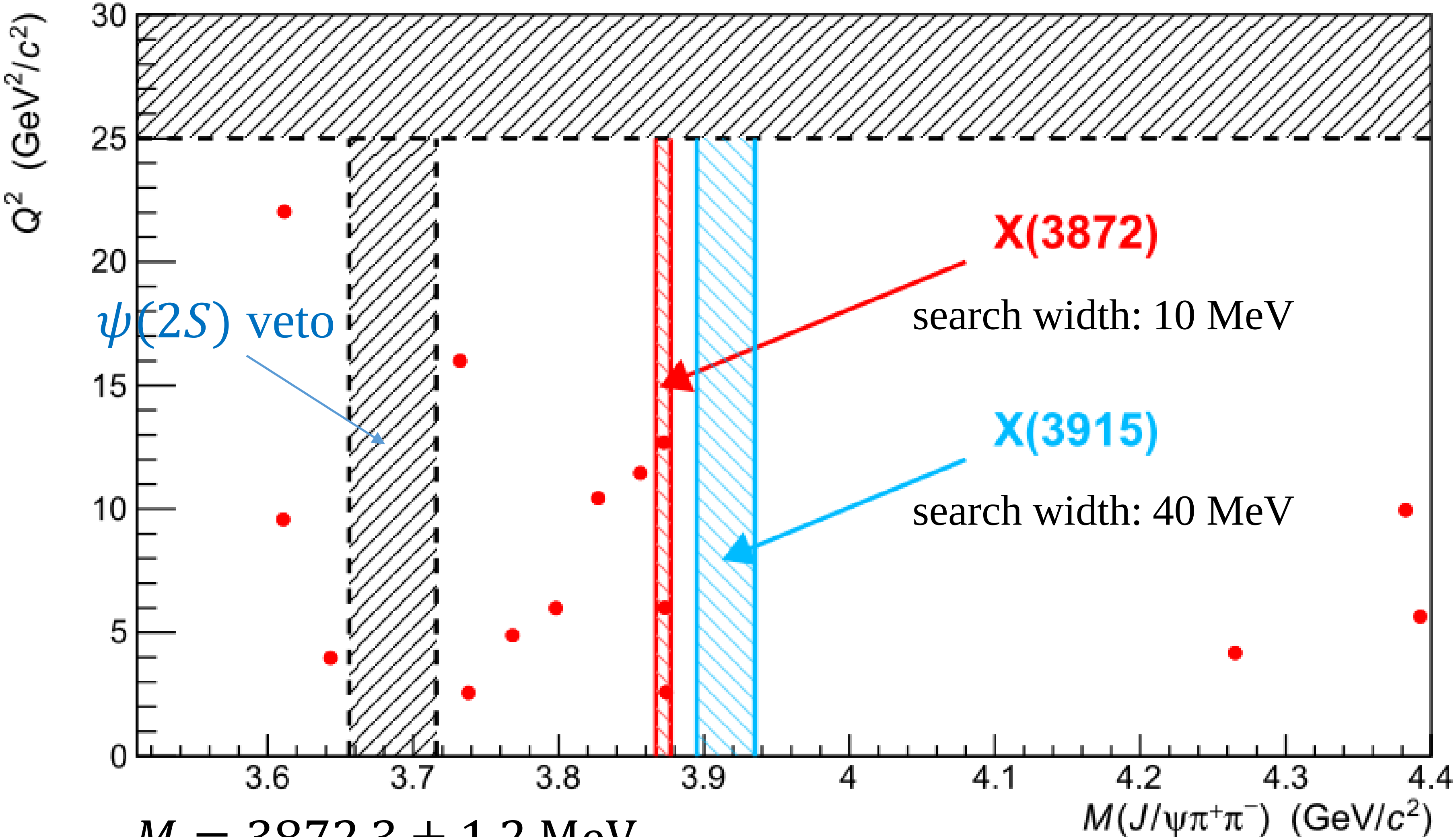
$\gamma\gamma \to X(3872)$ ➡ Not allowed

But, $\gamma^*\gamma \to X(3872)$ ➡ Allowed



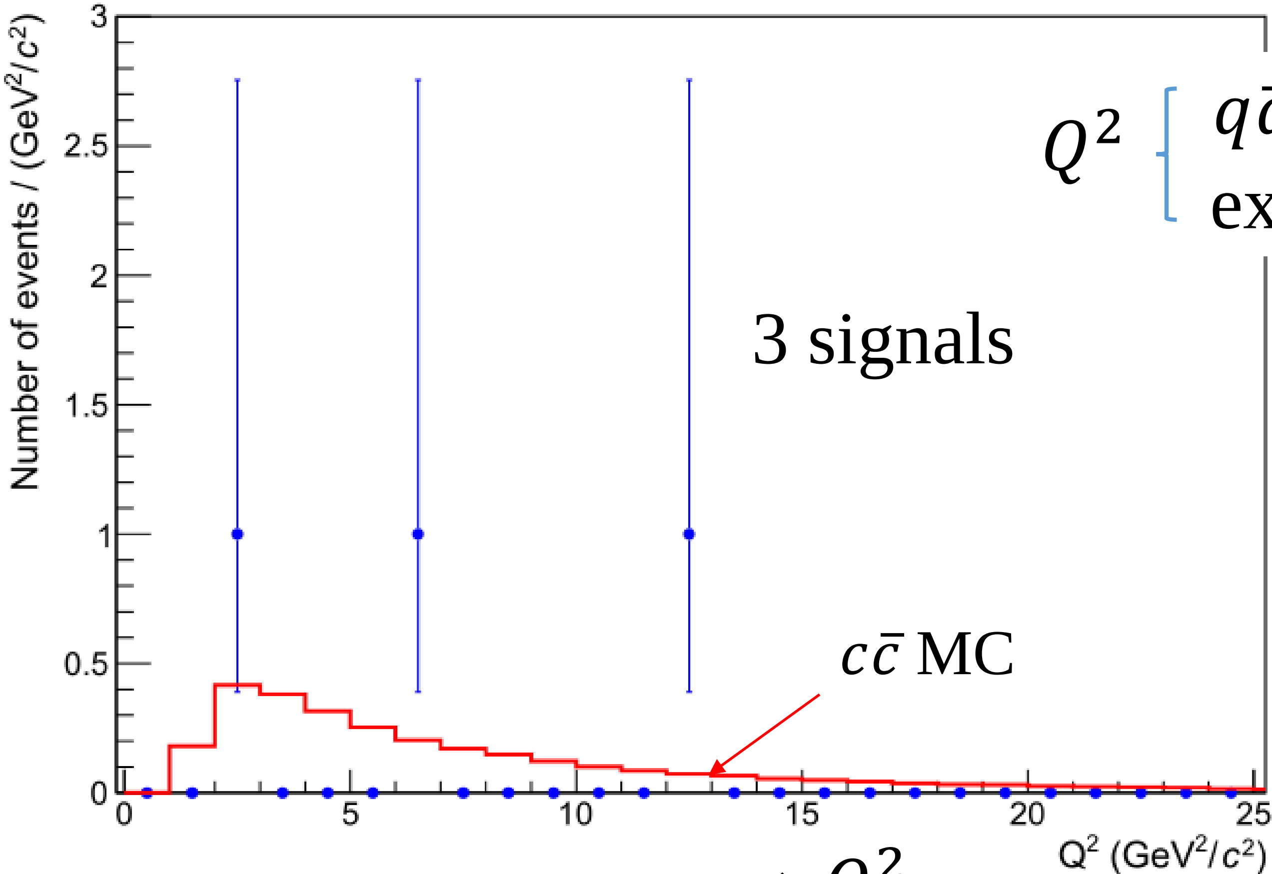
Q^2 { $q\bar{q}$ → broad
exotics → steep

Q^2 vs. $M(J/\psi\pi\pi)$: $X(3872)$ signals



$M = 3872.3 \pm 1.2$ MeV

Q^2 distribution

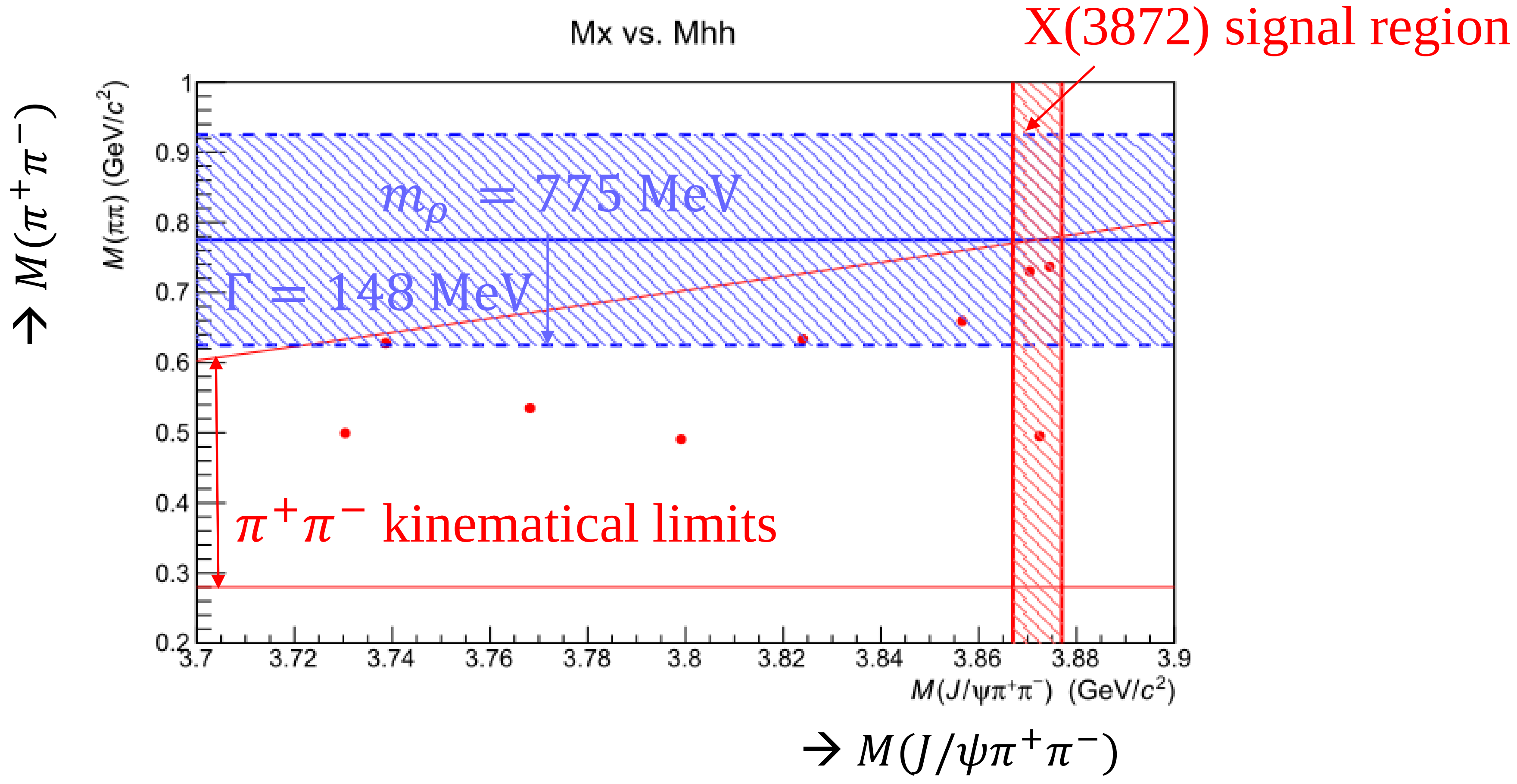


Q^2 { $q\bar{q}$ → broad
exotics → steep

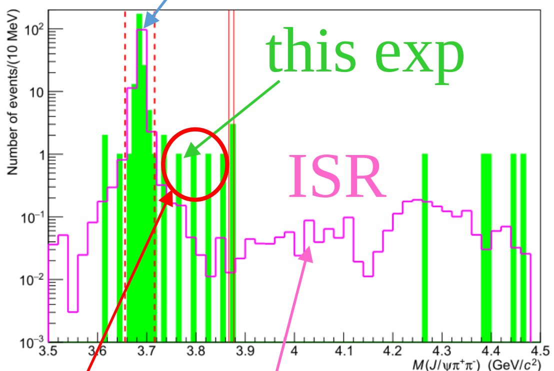
$\rightarrow Q^2$

→ high statics (Belle II)

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



Background estimate

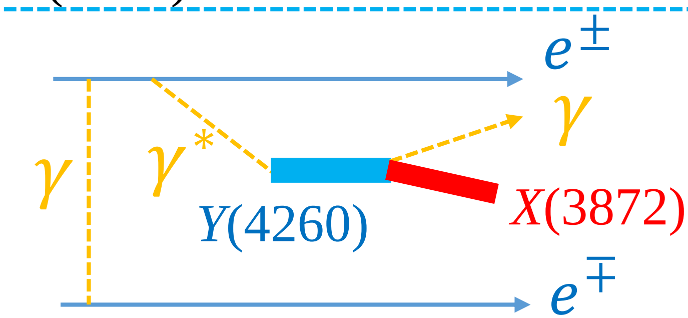


→ $M(J/\psi\pi^+\pi^-)$

$\psi(2S)$ tail
mass reconstruction error/failure

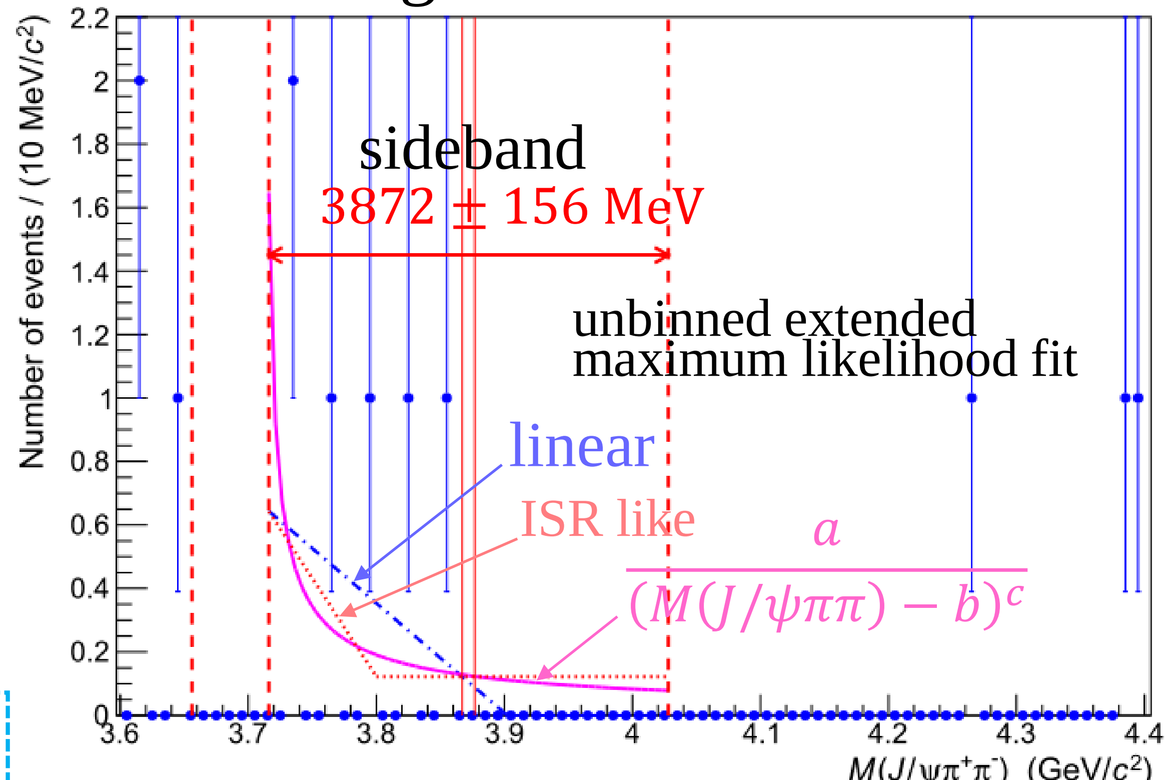
high statistics

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



→ negligible

background fit



$n_b = 0.11 \pm 0.10$ → $M(J/\psi\pi^+\pi^-)$

→ significance 3.2σ

$\gamma\gamma$ decay width

Reduced two-photon decay width: $\tilde{\Gamma}_{\gamma\gamma}$

$$\tilde{\Gamma}_{\gamma\gamma} \equiv \lim_{Q^2\to 0} \frac{M^2}{Q^2} \Gamma^{\mathrm{LT}}_{\gamma^*\gamma}(Q^2)$$

$\gamma^*\gamma$ decay width ← $\gamma_L^*\gamma_T$

Results

$$\tilde{\Gamma}_{\gamma\gamma}\mathcal{B}(X \to J/\psi\pi^+\pi^-) = 5.5^{+4.1}_{-3.8}\ (\mathrm{stat.}) \pm 0.7\ (\mathrm{syst.})\ \mathrm{eV}$$

Assuming Q^2 shape: Schuler-Berends-Gulik model ($1^{++}\ c\bar{c}$)

G. A. Schuler, F. A. Berends and R. van Gulik, NP B523 (1998) 423

$L^{LT} = L^{TT}$ assumed

Summary

(1) $\gamma\gamma \to \gamma\psi(2S)$ → $R_1(3921)$, $R_2(4014)$ → two candidates for $\chi_{cJ}(2P)$

R_1
- $J^{PC} = 0^{++}$ or 2^{++} , 4.0σ
- $M = 3921.3 \pm 2.4 \pm 1.6$ MeV/c^2
- $\Gamma = 0.0 \pm 5.3 \pm 2.0$ MeV $\quad \Gamma < 11.5$ MeV (90%CL)
- $\Gamma_{\gamma\gamma} B\big(R_1 \to \gamma\psi(2S)\big) = 8.2 \pm 2.3 \pm 0.9$ eV $(J^{PC} = 0^{++}, |\lambda| = 0)$
  $= 1.6 \pm 0.5 \pm 0.2$ eV $(J^{PC} = 2^{++}, |\lambda| = 2)$

R_2
- 0^{++} or 2^{++} , 2.8σ
- $M = 4014.4 \pm 4.1 \pm 0.5$ MeV/c^2
- $\Gamma = 6 \pm 16 \pm 12$ MeV $\quad \Gamma < 39.3$ MeV (90%CL)
- $\Gamma_{\gamma\gamma} B\big(R_2 \to \gamma\psi(2S)\big) = 5.2 \pm 2.7 \pm 2.5$ eV $(J^{PC} = 0^{++}, |\lambda| = 0)$
  $= 1.1 \pm 0.5 \pm 0.5$ eV $(J^{PC} = 2^{++}, |\lambda| = 2)$

(2) $\gamma^*\gamma \to J/\psi\pi^+\pi^-$ → $X(3872)$

- 3 events ($n_b = 0.11 \pm 0.10$), 3.2σ → first evidence in 2γ
- $\tilde{\Gamma}_{\gamma\gamma} B(X \to J/\psi\pi\pi) = 5.5^{+4.1}_{-3.8} \pm 0.7$ eV
- Belle II: Q^2 distribution → $X(3872)$ composition

Thank you

Backup Slides

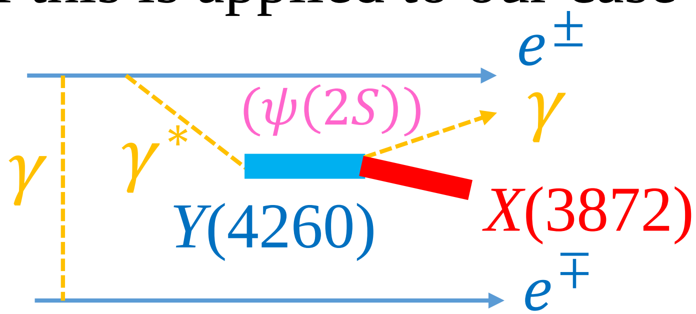
Physics background

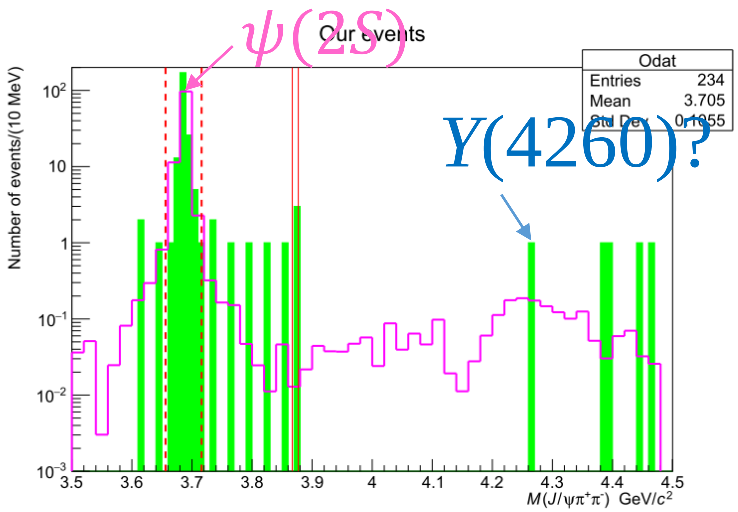
possible background → single virtual γ

Ablikim *et al.* (BESIII) PRL 112 (2014) 092001

$$e^+e^- \to Y(4260) \to \gamma X(3872)$$

→ If this is applied to our case





BESIII

$$\frac{B\big(Y(4260)\to\gamma X(3872)\big)B\big(X(3872)\to J/\psi\pi\pi\big)}{B\big(Y(4260)\to J/\psi\pi\pi\big)} \sim 5\times10^{-3} \qquad +\gamma \text{ veto}$$

→ negligible