First analysis of Belle II energy scan data

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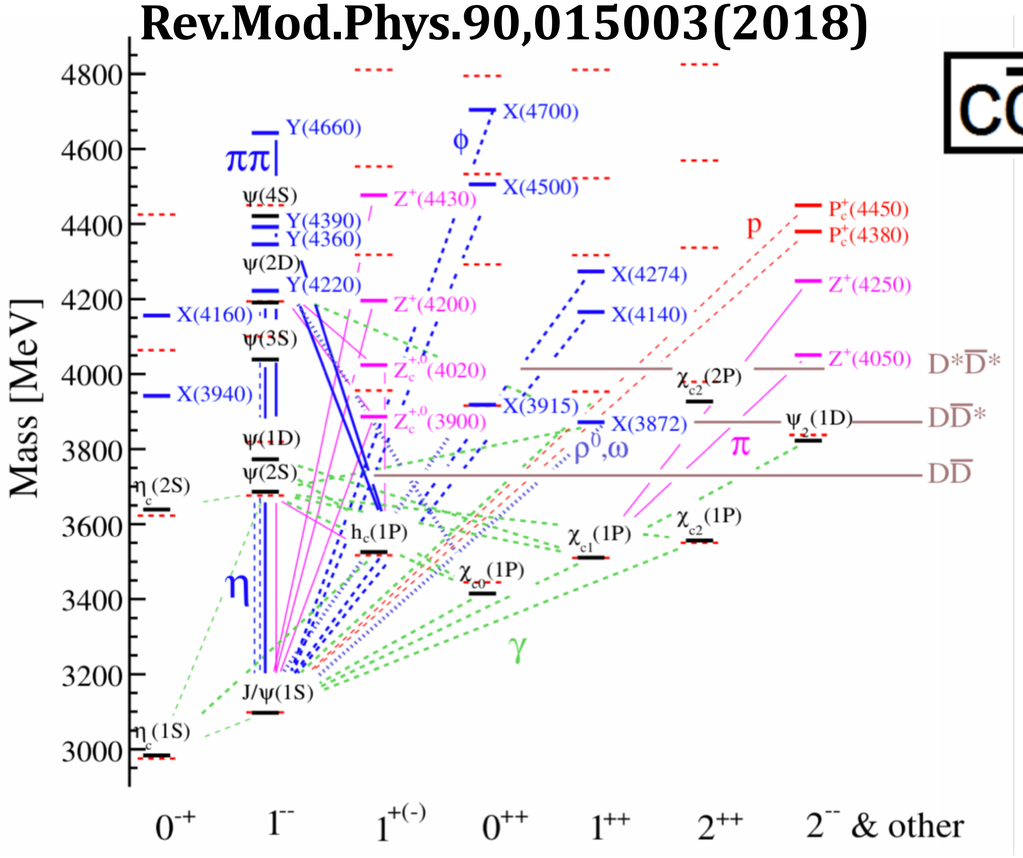
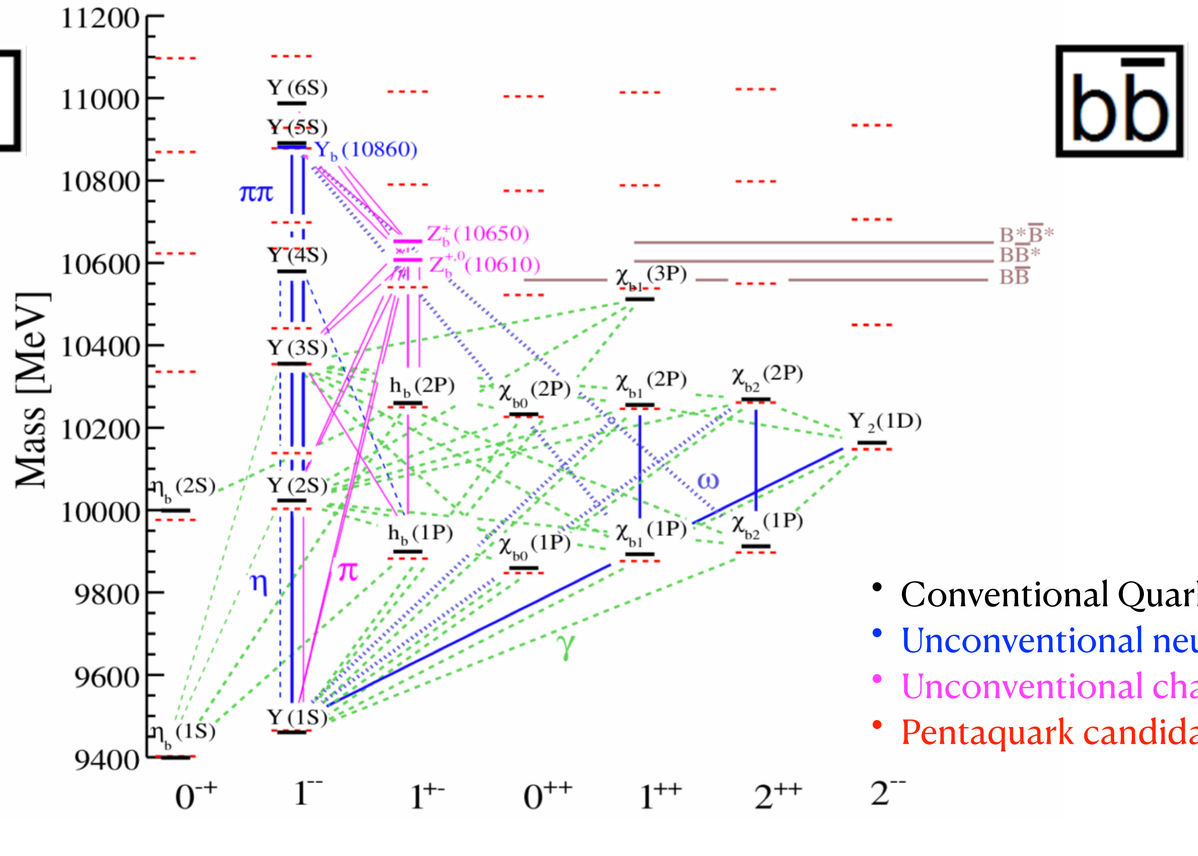
(On behalf of the Belle II Collaboration)

Quarkonium

Rev.Mod.Phys.90,015003(2018)





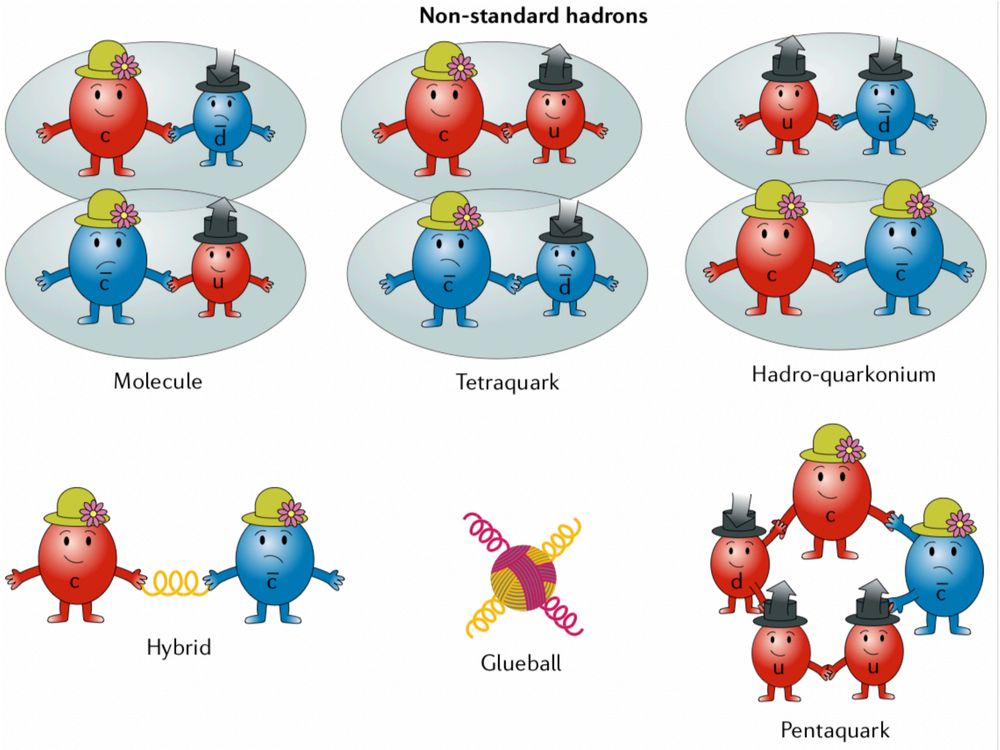
- Conventional Quarkonium
- Unconventional neutral states
- Unconventional charged states
- Pentaquark candidates

- Below $D\bar{D}/B\bar{B}$ thresholds-both charmonium and bottomonium are successful stories of QCD.
- There are certain parallels in the properties of hadrons containing $c\bar{c}$ and $b\bar{b}$.

Exotic interpretations

Quark model [Physics Letters 8, 214(1964)]:

- Conventional hadrons: mesons (2 quarks) and baryons (3 quarks)
- QCD does not forbid hadrons with > **3** quarks !!



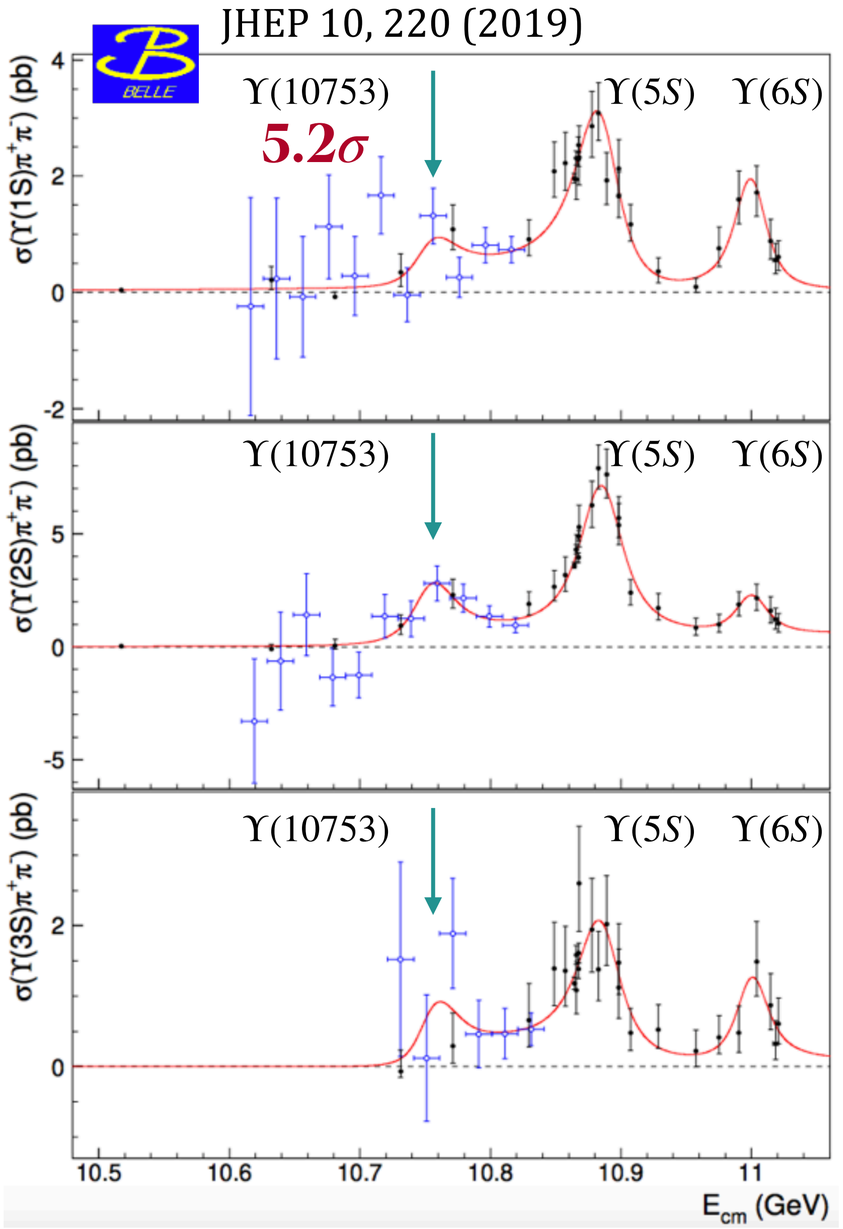
Nature Rev. Phys. 1(2019)8, 480-494 (2019)

Physics Reports 873,1 (2020)

In addition, screened potential, cusps effect, final state interaction ...

High priority: seek unified picture describing all XYZ states, not state-by-state

New structure: $\Upsilon(10753)$



- Belle: several ~1fb^{-1} scan points below $\Upsilon(5S)$
- New structure $\Upsilon(10753)$ observed in the $\pi^+\pi^-\Upsilon(nS)$ transition[1]

	$\Upsilon(10860)$	$\Upsilon(11020)$	New structure
M (MeV/c^2)	$10885.3 \pm 1.5\,^{+2.2}_{-0.9}$	$11000.0^{+4.0\,+1.0}_{-4.5\,-1.3}$	$10752.7 \pm 5.9\,^{+0.7}_{-1.1}$
Γ (MeV)	$36.6^{+4.5\,+0.5}_{-3.9\,-1.1}$	$23.8^{+8.0\,+0.7}_{-6.8\,-1.8}$	$35.5^{+17.6\,+3.9}_{-11.3\,-3.3}$

- Interpreted as conventional bottomonium[2] or exotics state[3] .
- Predicted to decay into $\omega\chi_{bJ}$ with a BF of 10^{-3} based on the mixing of conventional states 4S and 3D[4].

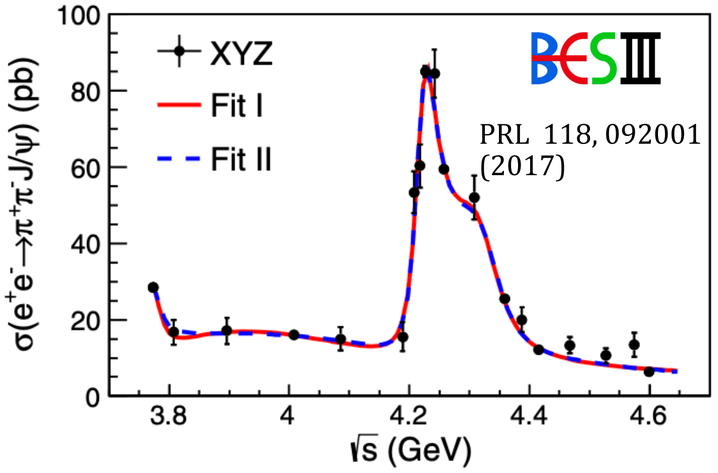
[1]. JHEP 10, 220 (2019); [2]. PRD 105, 074007(2022); PRD 104,034036 (2021); EPJC 80,59 (2020)

[3]. PRD 104,034019(2021); PRD 103,074507(2021); Chin. Phys. C 43, 123102 (2019); [4]. PRD 104,034036)2021.

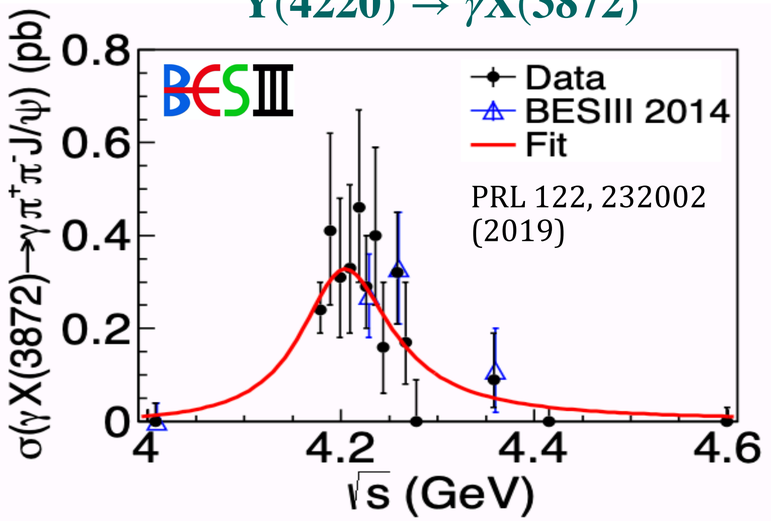
X_b: Bottomonium counterpart of $X(3872)$?

- Two close peaks observed in the cross sections for $e^+e^- \to \pi^+\pi^- J/\psi$ by BESIII[1] and $e^+e^- \to \pi^+\pi^-\Upsilon(nS)$ by Belle[2], respectively. These peaks may indicate similar nature.
- $Y(4220) \to \gamma X(3872)$[3] and $\omega\chi_{c0}$[4] , observed by BESIII.
- Evidence of $\Upsilon(5S) \to \omega\chi_{b1,2}$ observed by Belle[5], BESIII observed higher charmonium decays to $\omega\chi_{c1,2}$[6].
- So expect the $\Upsilon(10753)$ state to decay into γX_b with $X_b \to \omega\Upsilon(1S)$, as well as a potential resonance in the line shape of $\sigma(e^+e^- \to \omega\chi_{b1,2})$.

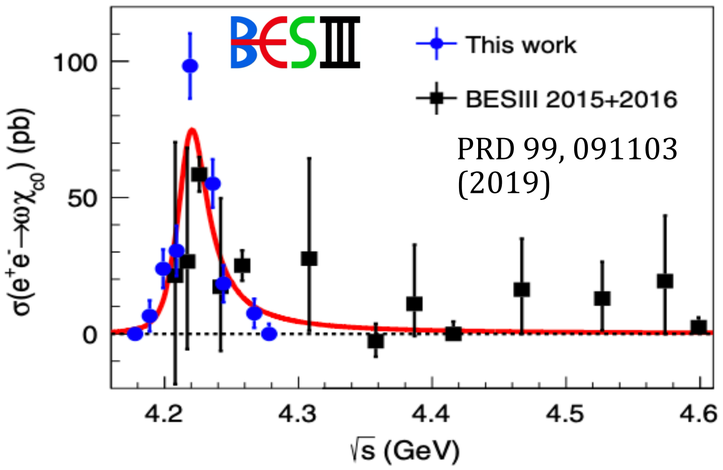
Y(4220)/Y(4230) → $\pi^+\pi^-$J/ψ



Y(4220) → γX(3872)

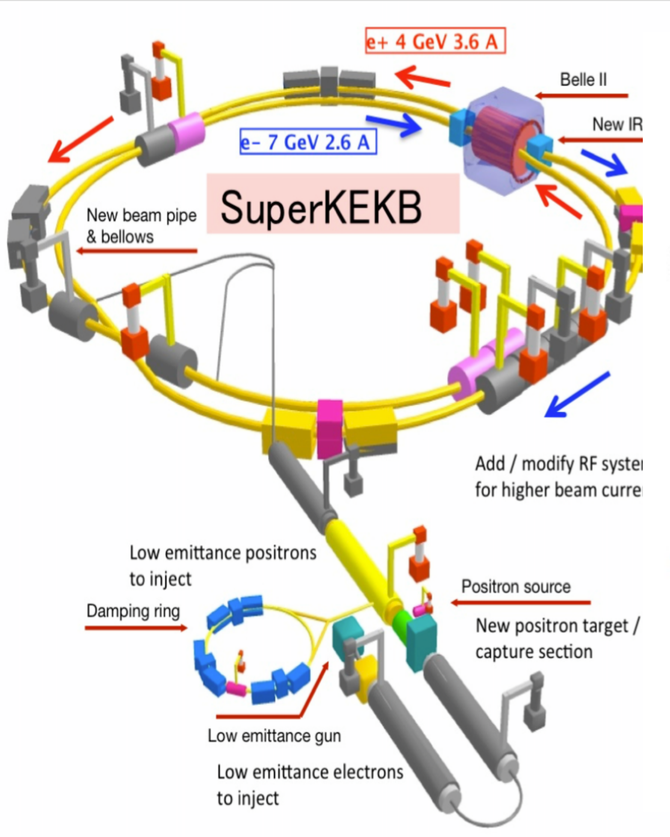


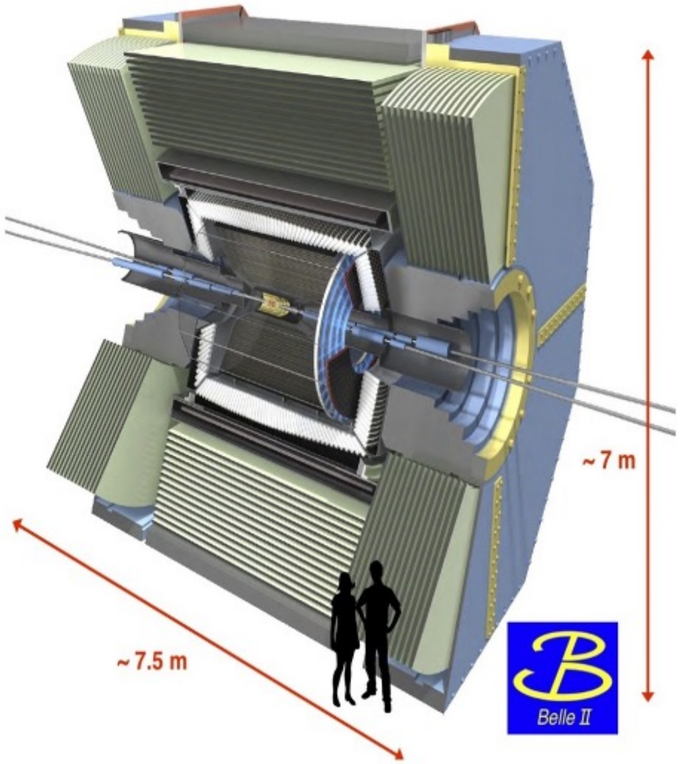
Y(4220) → $\omega\chi_{c0}$



[1]. PRL 91, 262001(2003); [2]. JHEP 10, 220 (2019); [3]. PRL 122, 232002 (2019); [4]. PRD 99, 091103 (2019); [5]. PRD 98, 091102 (2018); [6]. PRD 93,011102(R) (2016)

SuperKEKB and Belle II capabilities

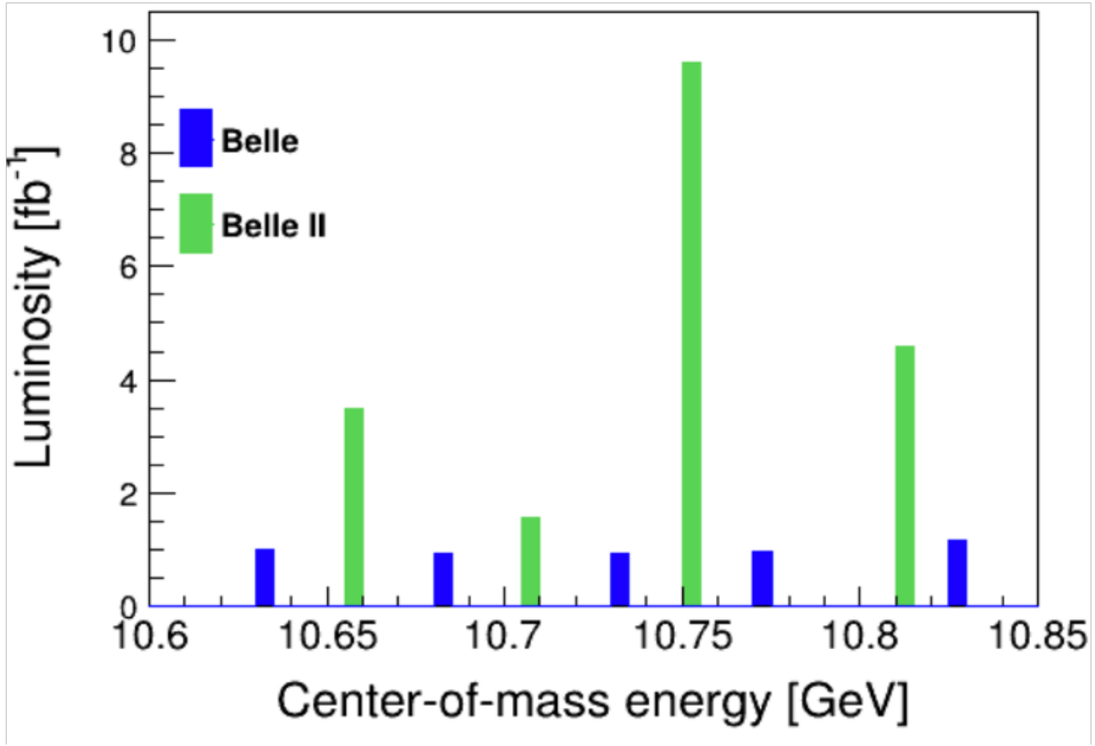




- Asymmetric energy e^+e^- (4 & 7 GeV) collider in Tsukuba, Japan
- Much higher luminosity than predecessor
- Upgraded detectors (better vertex and particle identification performances)
- Achieved peak luminosity: $4.7 \times 10^{34} \mathrm{cm}^{2}\mathrm{s}^{-1}$
- Integrated luminosity: ~424/fb.

Unique scan data near $\sqrt{s} = 10.75$ GeV

- In November 2021, Belle II collected 19fb^{-1} of unique data at energies above the $\Upsilon(4S)$: four energy scan points around 10.75 GeV
- Physics goal: understand the nature of the $\Upsilon(10753)$ energy region.



This is the first showing of these results.

New for ICHEP !

Analysis goals

$e^+e^- \to \omega\chi_{\mathrm{bJ}}$:

- Determine the Born cross section for $e^+e^- \to \omega\chi_{\mathrm{bJ}}$ using unique scan data samples at $\sqrt{s} = 10.701, 10.745$ and 10.805 GeV.
- Study the energy dependence cross section of $e^+e^- \to \omega\chi_{\mathrm{bJ}}$, by combining with Belle data at $\sqrt{s} = 10.867$ GeV[1].

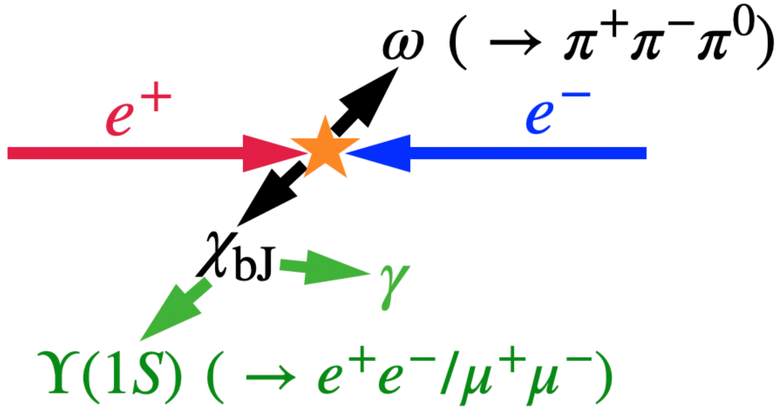
$e^+e^- \to \gamma X_{\mathrm{b}}$:

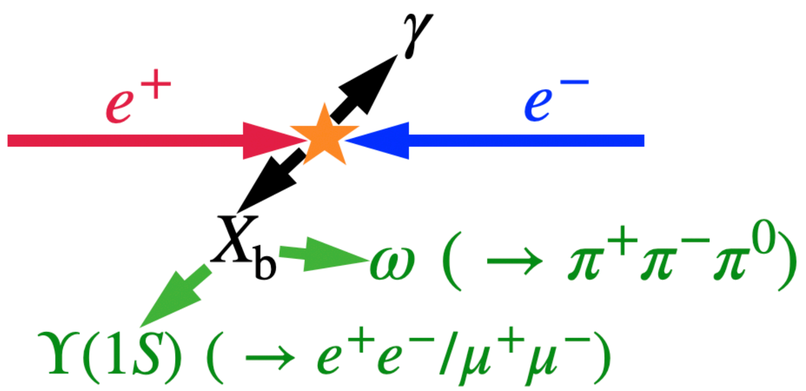
- Search for the X_{b} using the unique scan data samples at $\sqrt{s} = 10.645$, 10.701, 10.745 and 10.805 GeV

[1]PRL 113, 142001(2014);

New for ICHEP !

Analysis overview

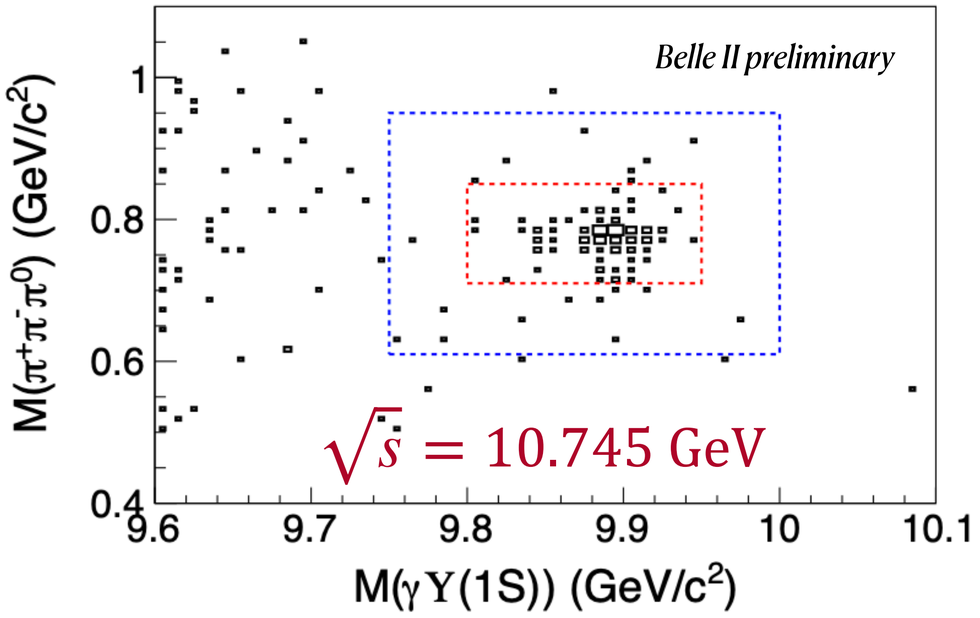


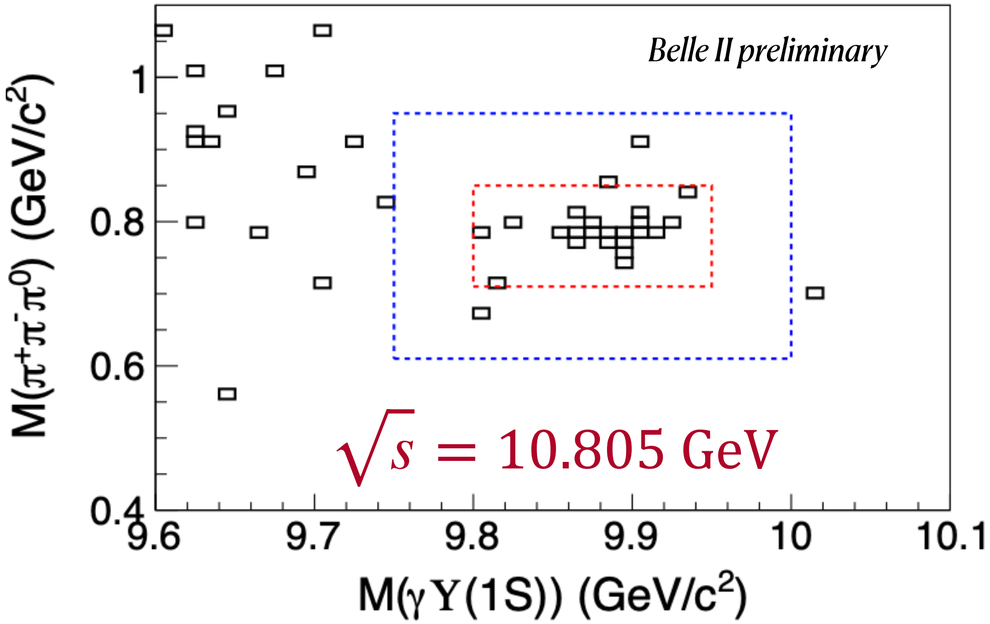


- Event selection
  - 4 or 5 charged tracks.
  - standard Belle II PID: 90%-95% efficiency with 1–5% misID.
  - photons from χ_{bJ} decays: $E_\gamma > 50$ MeV
  - π^0 candidates: $M(\gamma\gamma) \in (0.105, 0.150)$ GeV/c^2 with 90% efficiency.
  - Constrained kinematic fit to $\pi^+\pi^-\pi^0\gamma e^+e^-/\mu^+\mu^-$final.
  - Best candidate based on best fit quality.
- Data driven corrections and systematics from control samples

New for ICHEP !

Mass distributions

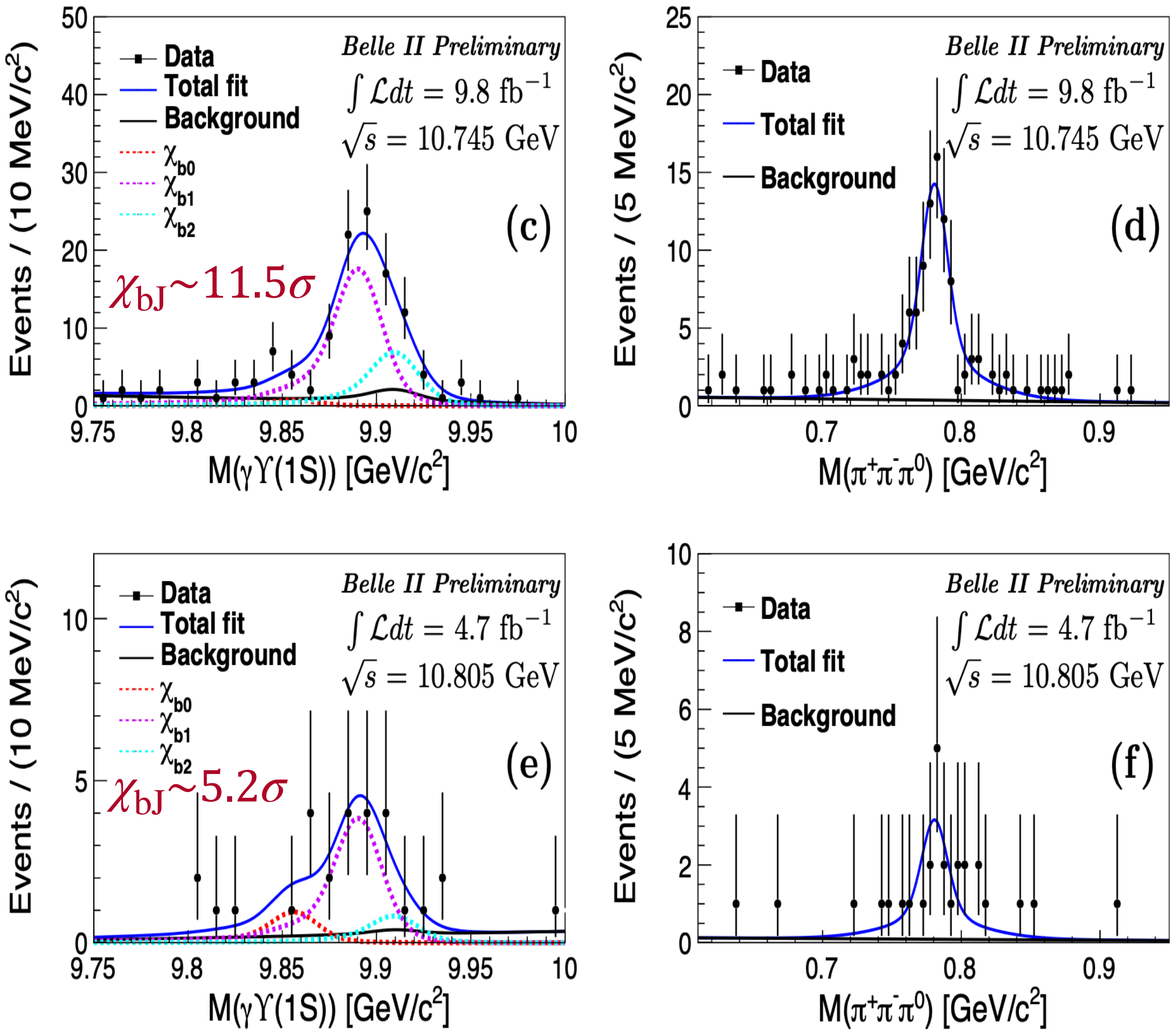




- Red box contains 95% of signals
- Blue box defines one-dimensional projection ranges

New for ICHEP !

Observation of $e^+e^- \to \omega\chi_{\mathrm{bJ}}$



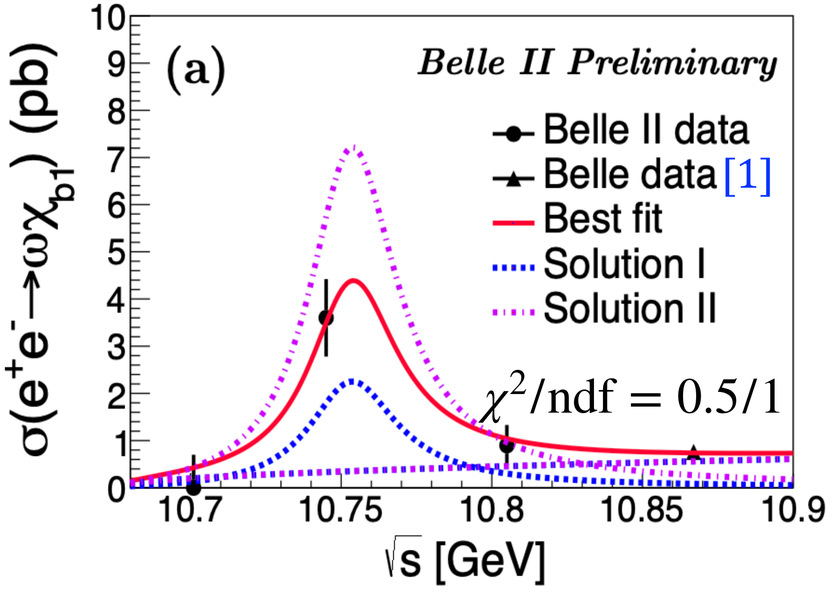
Two dimensional unbinned maximum likelihood fit to $M(\gamma\Upsilon(1S))$ and $M(\pi^+\pi^-\pi^0)$.

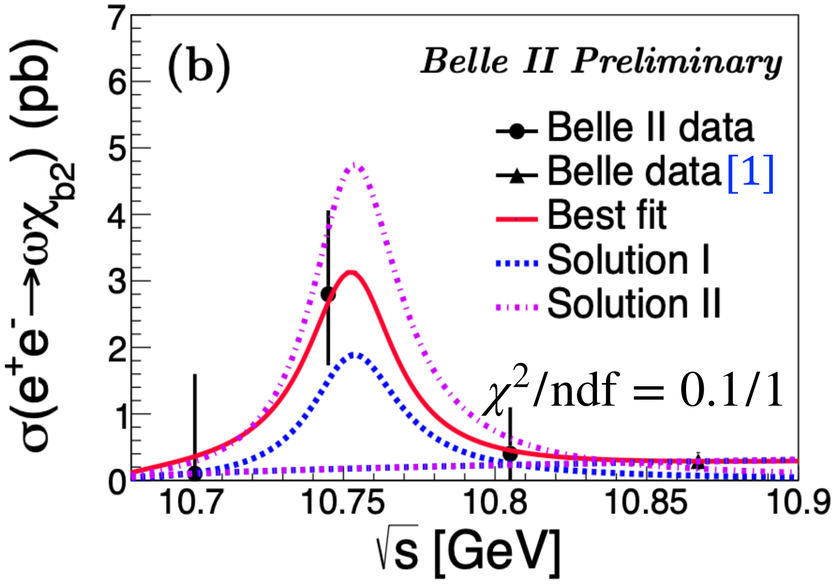
Channel	$\sqrt{s}$ (GeV)	$N^{\mathrm{sig.}}$	$\sigma_{\mathrm{B}}^{(\mathrm{up})}$ (pb)
$e^+e^- \to \omega\chi_{b1}$	10.745	$68.9^{+13.7}_{-13.5}$	$3.6^{+0.7}_{-0.7}$ (stat.) $\pm$ 0.4 (syst.)
$e^+e^- \to \omega\chi_{b2}$		$27.6^{+11.6}_{-10.0}$	$2.8^{+1.2}_{-1.0}$ (stat.) $\pm$ 0.5 (syst.)
$e^+e^- \to \omega\chi_{b1}$	10.805	$15.0^{+6.8}_{-6.2}$	1.6 @ 90% C.L.
$e^+e^- \to \omega\chi_{b2}$		$3.3^{+5.3}_{-3.8}$	1.5 @ 90% C.L.

No evident signal are found at $\sqrt{s} = 10.710$ GeV.

New for ICHEP !

Observation of $\Upsilon(10753) \to \omega\chi_{bJ}$





The $e^+e^- \to \omega\chi_{b1/2}$ cross sections peak at $\Upsilon(10753)$ while no obvious peak at $\Upsilon(10860)$ is found!

Combine with Belle measurement[1] to fit cross section with function:

$$\sigma_{\omega\chi_{b1/2}}(\sqrt{S}) = |\sqrt{PS_2(\sqrt{S})} + BW(\sqrt{S})e^{i\phi}|^2,\ BW(\sqrt{S}) = \frac{\sqrt{12\pi\Gamma_{ee}\mathcal{B}_f\Gamma}}{s - M^2 - iM\Gamma}\sqrt{\frac{PS_2(\sqrt{S})}{PS_2(M)}}$$

M and Γ are fixed referring to Ref. [2]

$\Gamma_{ee}\mathcal{B}_f$	Solution I	Solution II
$\Gamma_{ee}\mathcal{B}(\Upsilon(10753) \to \omega\chi_{b1})$	$(0.63 \pm 0.39 \pm 0.20)$ eV	$(2.01 \pm 0.38 \pm 0.76)$ eV
$\Gamma_{ee}\mathcal{B}(\Upsilon(10753) \to \omega\chi_{b2})$	$(0.53 \pm 0.46 \pm 0.15)$ eV	$(1.32 \pm 0.44 \pm 0.55)$ eV

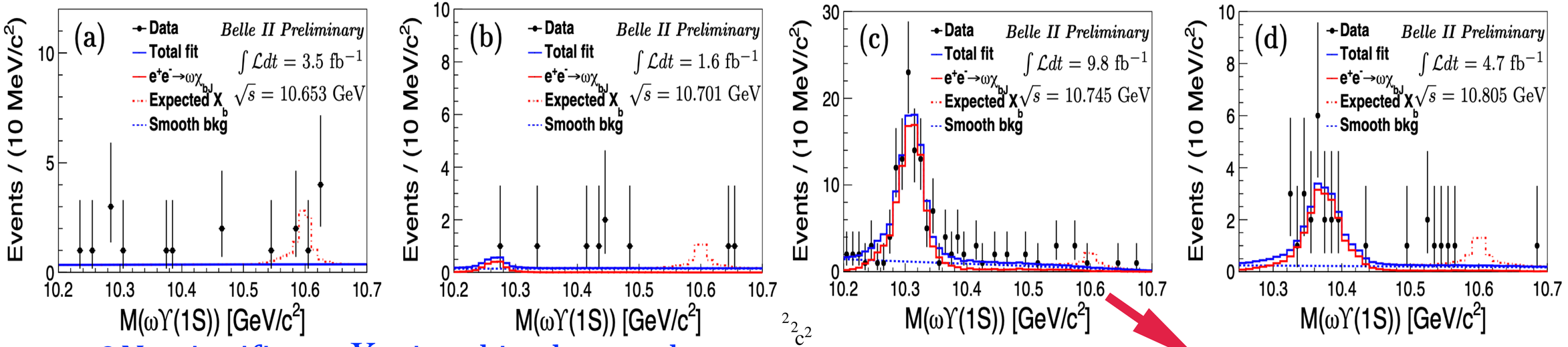
- $\dfrac{\Gamma_{ee}\mathcal{B}(\Upsilon(10753) \to \omega\chi_{b1})}{\Gamma_{ee}\mathcal{B}(\Upsilon(10753) \to \omega\chi_{b2})} \sim 1.0$ agrees with the expectation for NRQCD[3]
- $\dfrac{\Gamma_{ee}\mathcal{B}(\omega\chi_{b1/2})}{\Gamma_{ee}\mathcal{B}(\pi^+\pi^-\Upsilon(2S))}$[2] ~ 1.5 for $\Upsilon(10753)$ and ~ 0.1 for $\Upsilon(10860)$

[1]PRL 113, 142001(2014); [2]. JHEP 10, 220(2019); [3]. arXiv:2112.09092;

New for ICHEP !

Search for X_b

$e^+e^- \to \gamma X_b$:



- No significant X_b signal is observed.
- The peaks are the reflections of $e^+e^- \to \omega\chi_{bJ}$

From simulated events with $M(X_b) = 10.6$ GeV/c^2
The yield is fixed at the upper limit on 90% C.L.

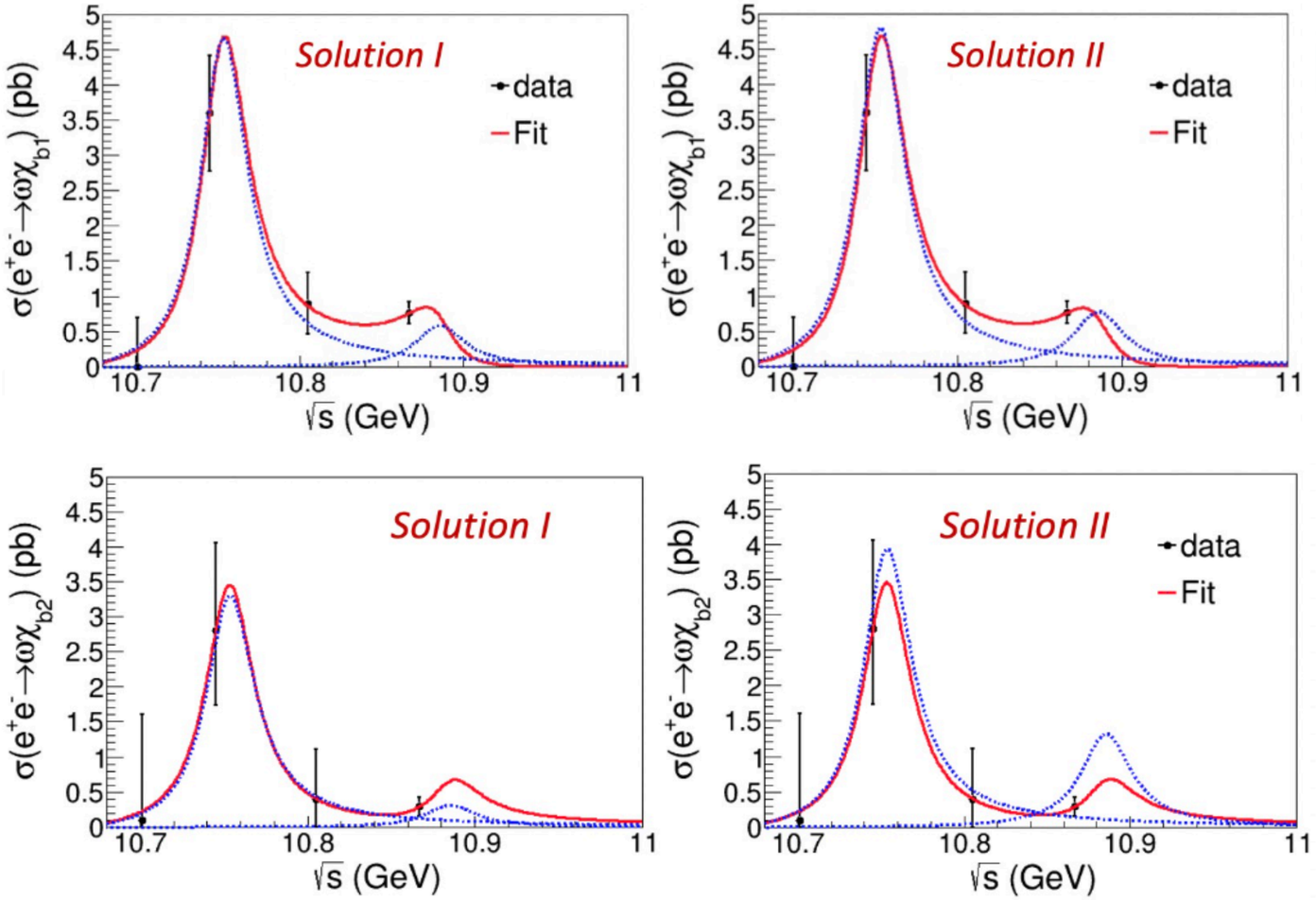
Upper limits of	$\sqrt{s}$ (GeV)	10.653	10.701	10.745	10.805
$\sigma_B(e^+e^- \to \gamma X_b) \cdot \mathcal{B}(X_b \to \omega\Upsilon(1S))$ (pb) at 90% C.L.	$M(X_b) = 10.6$ MeV/c^2	0.45	0.33	0.10	0.14
	$M(X_b) = (10.45, 10.65)$ MeV/c^2	(0.14, 0.54)	(0.25, 0.84)	(0.06, 0.14)	(0.08, 0.36)

Summary

- We are at the beginning of a long program of quarkonium physics.
- The unique scan data near $\sqrt{s} = 10.75$ GeV at Belle II provide an opportunity to understand the nature of the $\Upsilon(10753)$ energy region, as well as the quarkonium spectroscopy.
- New decay modes of $\Upsilon(10753) \to \omega\chi_{\mathrm{bJ}}$ are observed for the first time.
- No significant X_b signal is observed with a mass around 10.6 GeV/c^2, and the upper limits at 90% C.L. are set.
- Other active ongoing analyses based on unique scan data.

Backup

Alternative fit for $\sigma(e^+e^- \to \omega\chi_{bJ})$



$$\sigma_{\omega\chi_{c1/2}}(\sqrt{s}) = |BW_{\Upsilon(10753)} + BW_{\Upsilon(10806)}e^{i\phi}|^2$$

M and Γ are fixed referring to Ref. [1][2]

$$\frac{\Gamma_{ee}B(\Upsilon(10753) \to \omega\chi_{b1})}{\Gamma_{ee}B(\Upsilon(10753) \to \omega\chi_{b2})}$$

Solution I: $\dfrac{1.24 \pm 0.56(\text{stat.})}{0.92 \pm 0.37(\text{stat.})}$

Solution II : $\dfrac{1.28 \pm 0.57(\text{stat.})}{1.09 \pm 0.40(\text{stat.})}$

$\chi^2/\text{ndf} = 0.4$ and 0.1 for $\omega\chi_{b1}$ and $\omega\chi_{b2}$

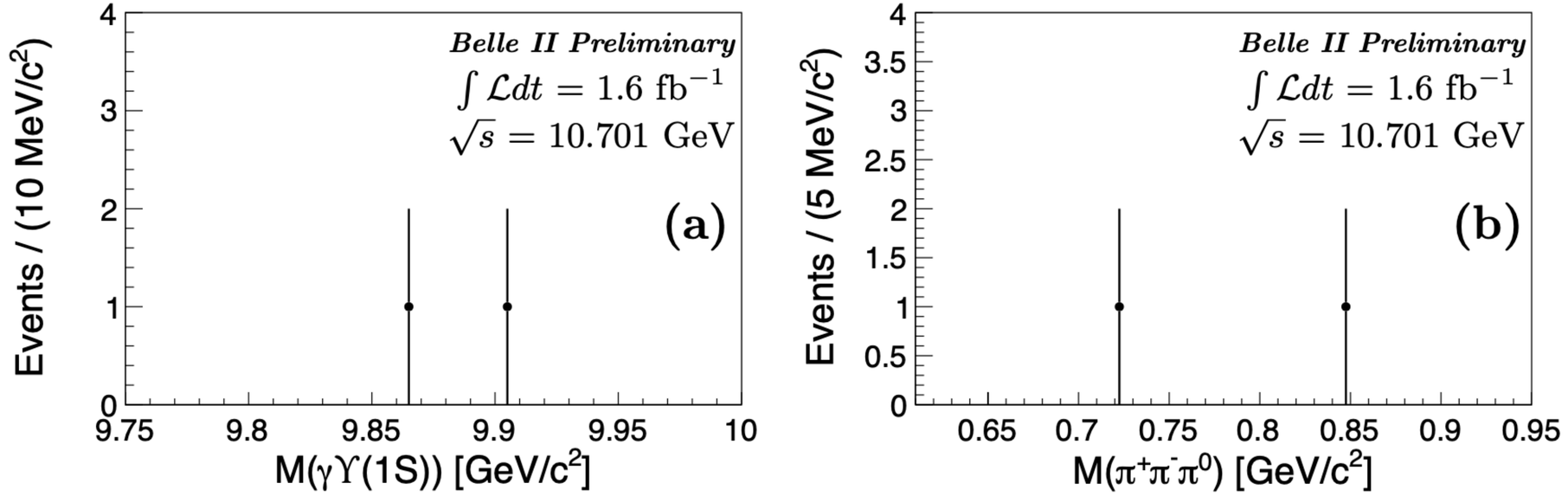
Ref: [1]. JHEP 10, 220(2019);

[2]. PDG 2022

Channel	$\sqrt{s}$ (GeV)	$N^{\rm sig}$	$N^{\rm UL}$	$\Sigma(\sigma)$	ε	$\lvert 1-\Pi\rvert^2$	$1+\delta_{\rm ISR}$	$\sigma_{\rm syst}(\%)$	σ^B (pb)	$\sigma_B^{\rm UL}$ (pb)
$e^+e^- \to \omega\chi_{b0}$	10.701	-	3.0	-	0.184	0.931	0.67	15.7	-	16.5
$e^+e^- \to \omega\chi_{b1}$		$0.0^{+2.1}_{-0.0}$	3.9	-	0.186	0.931	0.64	9.2	$0.0^{+0.7}_{-0.0}$(stat.)	1.2
$e^+e^- \to \omega\chi_{b2}$		$0.1^{+2.2}_{-0.1}$	4.0	-	0.184	0.931	0.62	9.1	$0.1^{+1.4}_{-0.1}$(stat.)	2.5
$e^+e^- \to \omega\chi_{b0}$	10.745	$3.0^{+5.5}_{-4.7}$	11.8	0.5	0.185	0.931	0.65	17.0	$2.8^{+5.1}_{-4.4}$(stat.)	11.1
$e^+e^- \to \omega\chi_{b1}$		$68.9^{+13.7}_{-13.5}$	-	5.9	0.185	0.931	0.65	11.6	$3.6^{+0.7}_{-0.7}$(stat.) $\pm$ 0.4(syst.)	-
$e^+e^- \to \omega\chi_{b2}$		$27.6^{+11.6}_{-10.0}$	-	3.1	0.186	0.931	0.65	13.5	$2.8^{+1.2}_{-1.0}$(stat.) $\pm$ 0.5(syst.)	-
$e^+e^- \to \omega\chi_{b0}$	10.805	$3.6^{+3.8}_{-3.1}$	9.8	1.2	0.184	0.932	1.12	21.1	$4.1^{+4.3}_{-3.5}$(stat.)	11.2
$e^+e^- \to \omega\chi_{b1}$		$15.0^{+6.8}_{-6.2}$	26.0	2.7	0.184	0.932	1.12	16.6	$0.9^{+0.4}_{-0.4}$(stat.)	1.6
$e^+e^- \to \omega\chi_{b2}$		$3.3^{+5.3}_{-3.8}$	12.5	0.8	0.185	0.932	1.11	16.8	$0.4^{+0.7}_{-0.5}$(stat.)	1.5

Systematic uncertainty(%) on $\sigma^{\rm B}(e^+e^- \to \omega\chi_{\rm bJ})$ and $\sigma^{\rm UL}_{\rm B}(e^+e^- \to \gamma X_{\rm b}) \times \mathcal{B}(X_{\rm b} \to \omega\Upsilon(1S))$

Final states	$\omega\chi_{b0}/\omega\chi_{b1}/\omega\chi_{b2}$			γX_b			
$\sqrt{s}$ (GeV)	10.701	10.745	10.805	10.653	10.701	10.745	10.805
Detection efficiency	4.9	4.9	4.9	4.9	4.9	4.9	4.9
Branching fractions	14.7/7.4/7.3	14.7/7.4/7.3	14.7/7.4/7.3	4.7	4.7	4.7	4.7
Radiative correction factor	2.0	5.1	13.7	0.2	0.4	0.5	0.7
Angular distribution	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Fit model	1.0	3.3/4.6/8.2	2.1/1.6/1.0	8.6	3.2	7.0	7.7
Trigger	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Beam-energy	-	3.2/2.5/3.0	3.5/2.3/3.6	-	-	-	-
Luminosity	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Sum	15.7/9.2/9.1	17.0/11.6/13.5	21.1/16.6/16.8	11.1	7.7	9.9	10.4


Belle II Preliminary
$\int \mathcal{L}dt = 1.6$ fb^{-1}
$\sqrt{s} = 10.701$ GeV
(a)
Events / (10 MeV/c^2)
M($\gamma\Upsilon$(1S)) [GeV/c^2]
Belle II Preliminary
$\int \mathcal{L}dt = 1.6$ fb^{-1}
$\sqrt{s} = 10.701$ GeV
(b)
Events / (5 MeV/c^2)
M($\pi^+\pi^-\pi^0$) [GeV/c^2]

Belle II potential — 10.75 GeV

Other active ongoing analyses based on unique scan data:

Channel
$B\bar{B}$ decomposition
$e^+e^- \to \omega\eta_b(1S)$
$e^+e^- \to \phi\eta_b(1S)$
$e^+e^- \to \eta h_b(1P)$
$e^+e^- \to \Upsilon(1S) + X$
$e^+e^- \to \pi^+\pi^- Y_2(1D)$
$e^+e^- \to \pi^+\pi^-\Upsilon(nS)$
$e^+e^- \to \pi^+\pi^- h_b(nP)$

- Precise measurements of the mass and width of $\Upsilon(10753)$
- Search for more decays of $\Upsilon(10753)$
- Search for the the X_b state (the bottomonium counterpart of $X(3872)$)
- Study the $\pi^+\pi^-/\omega/\eta/\phi$ transitions in the e^+e^- annihilations to test NRQCD