Bundesministerium für Bildung und Forschung

Recent Bottomonium Results From Belle II

QNP2024

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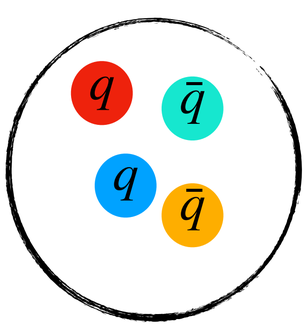
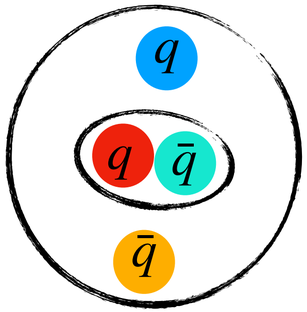
JGU Mainz

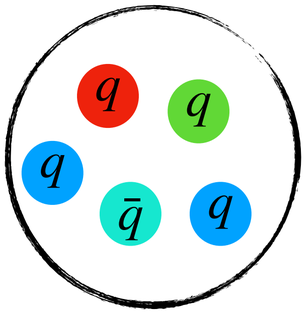
Quarkonium Spectroscopy



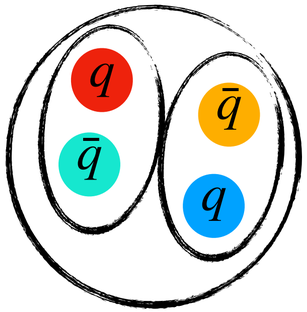
tetraquark



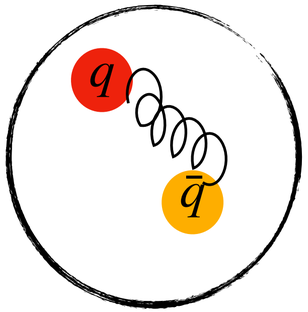
hadro-quarkonium



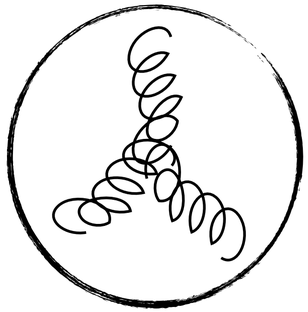
pentaquark

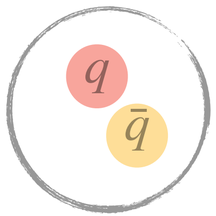


hadronic molecule



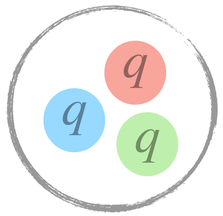
hybrid


glueball



meson

Conventionals



baryon

- Investigated by 1st-gen B-Factories
  - New production mechanisms, transitions, many (unexpected) XYZ states observed in charmonium and bottomonium
    - X(3872), $\psi(4230)$ or $\Upsilon(10753)$ $(=\Upsilon_b)$
- Ambiguous interpretations, not definite

- Better understanding is needed!

How To Get Bottomonium

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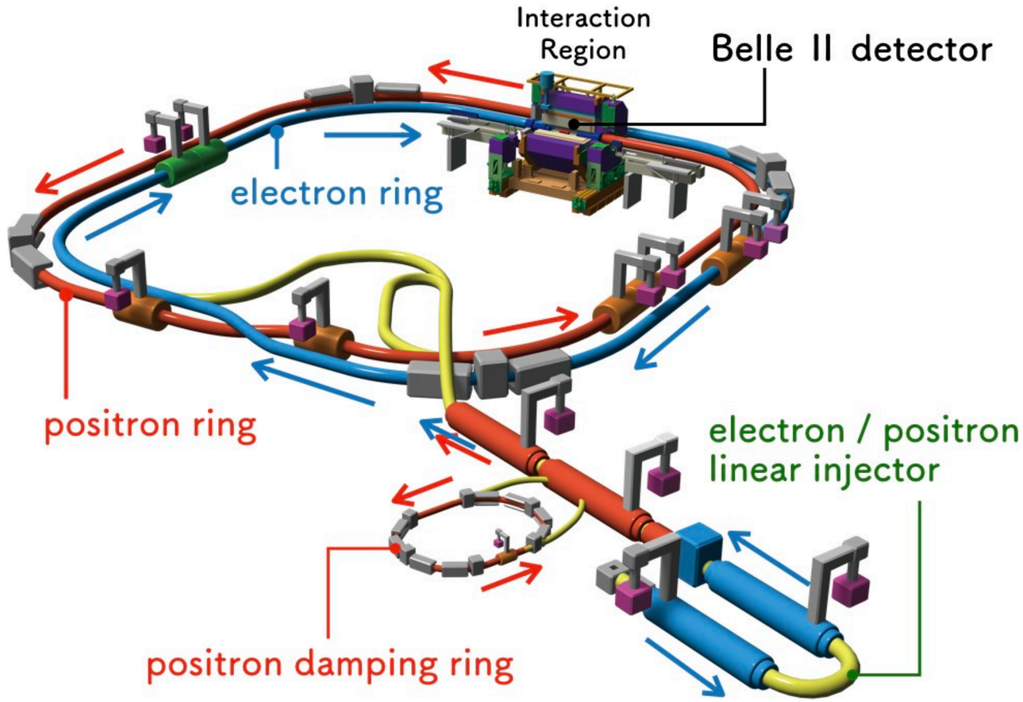
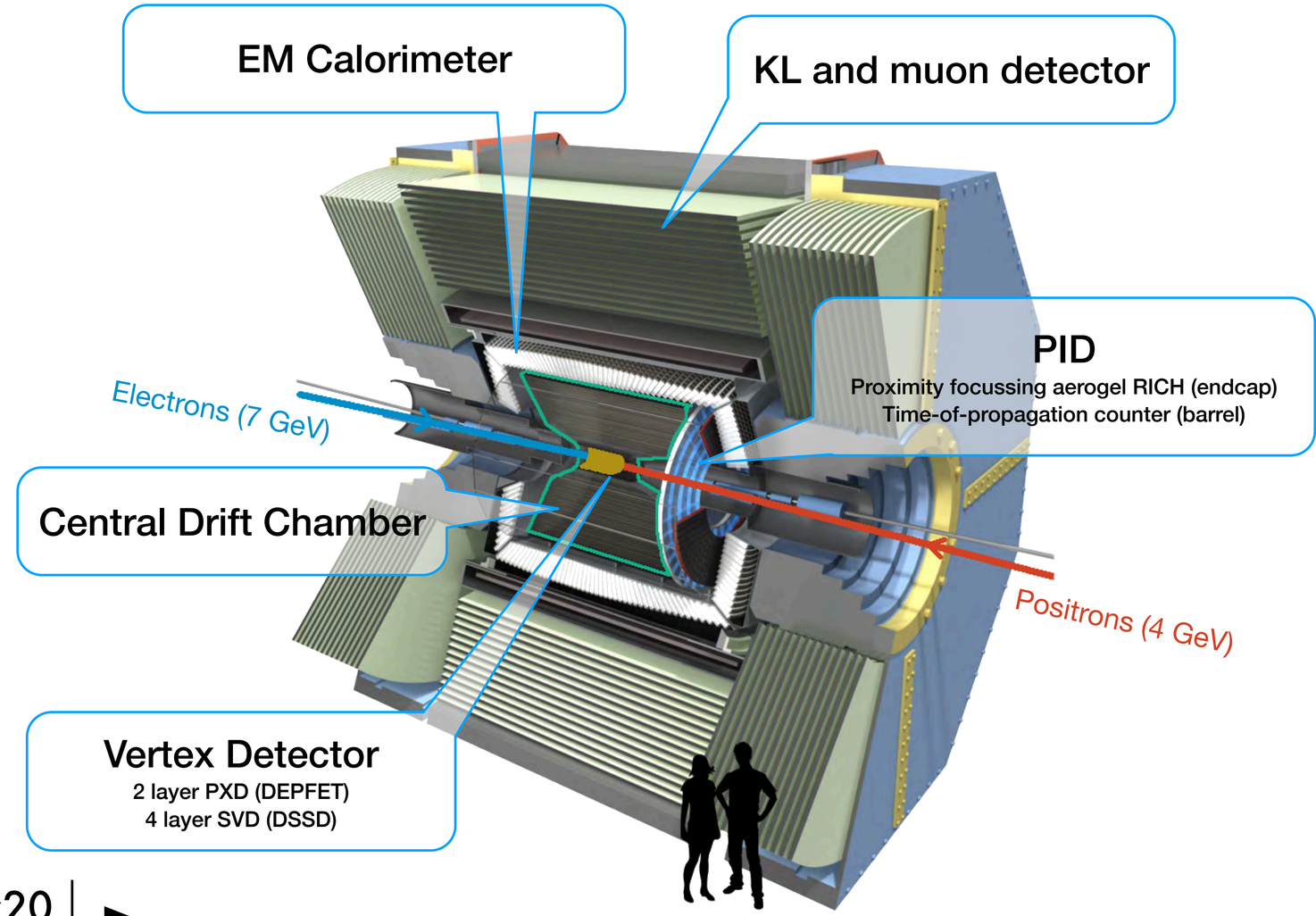
SuperKEKB

Instant. luminosity: ~$4 \times 10^{34} cm^{-2} s^{-1}$



Belle II detector



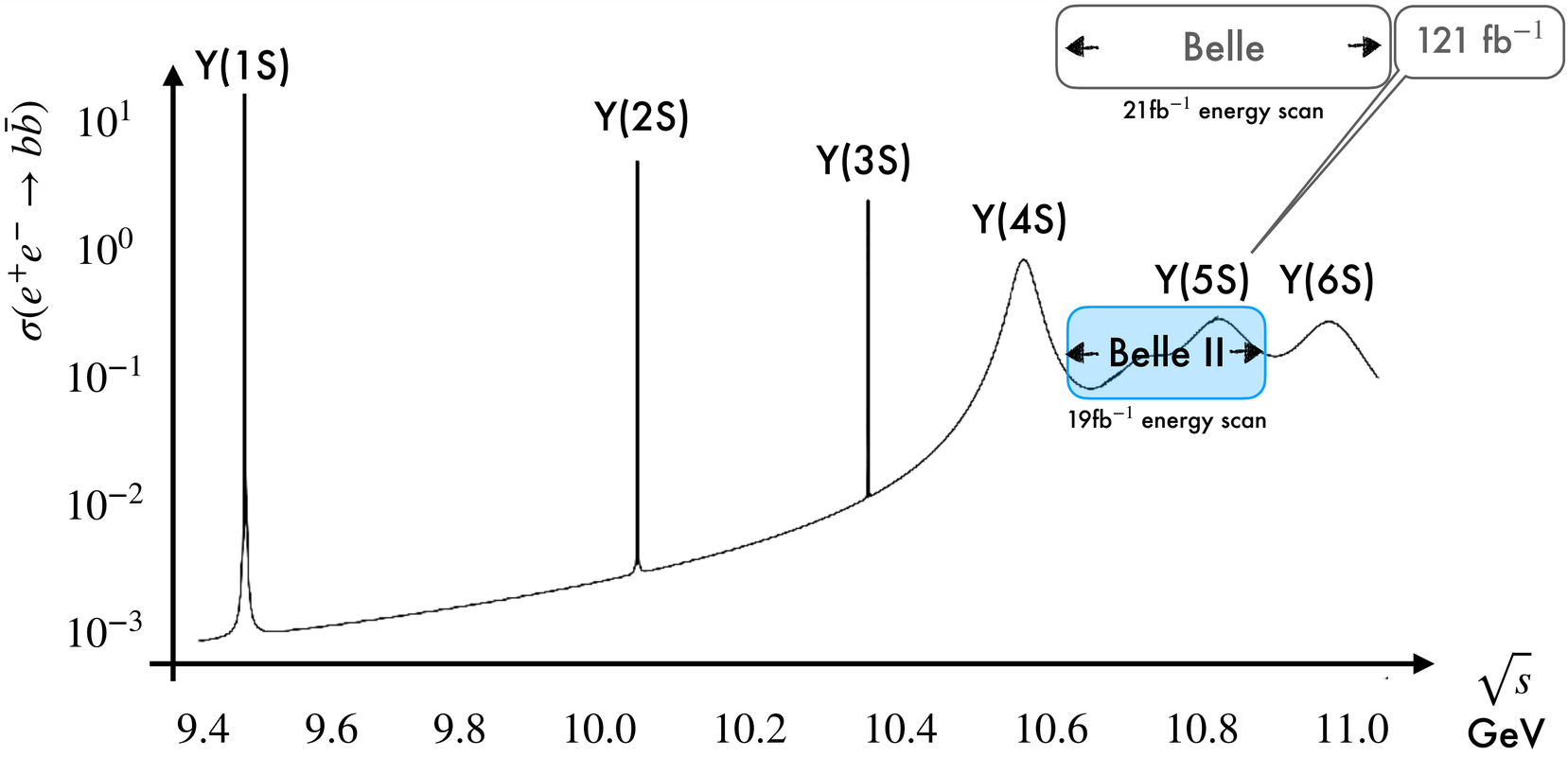
Squeeze the beam (nano-beam): x20
Increase beam current: x2
→ x40 instant. luminosity

Belle II Technical Design Report

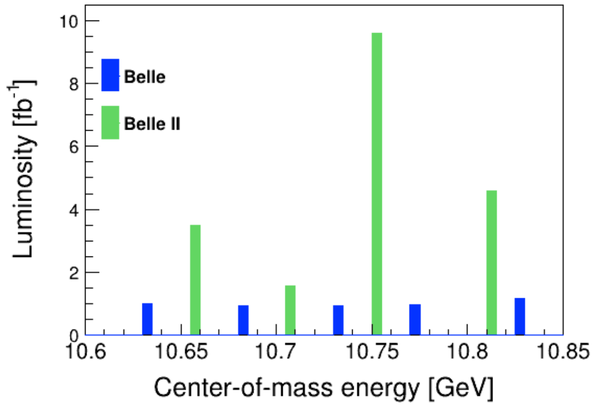
Belle II Energy Scan

- Main Goal of Belle II energy scan:

  Confirm and Study the Υ_b



- Belle II energy scan in between Belle points
  (successfully collected 19fb^{-1} of data)

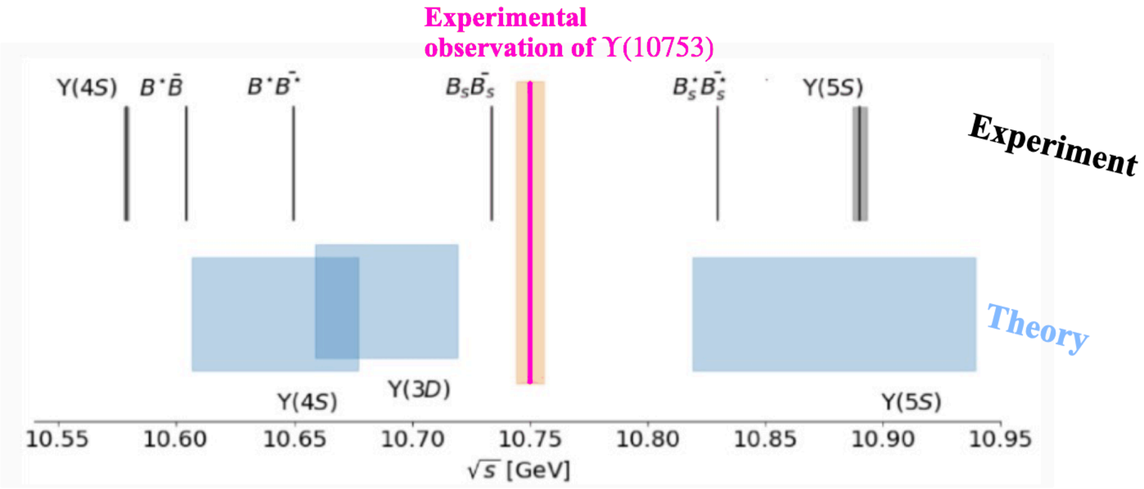


$$e^+e^- \to \Upsilon(nS)\,\pi^+\pi^-$$

Enhancement At 10.753 GeV

JHEP 10 (2019) 220

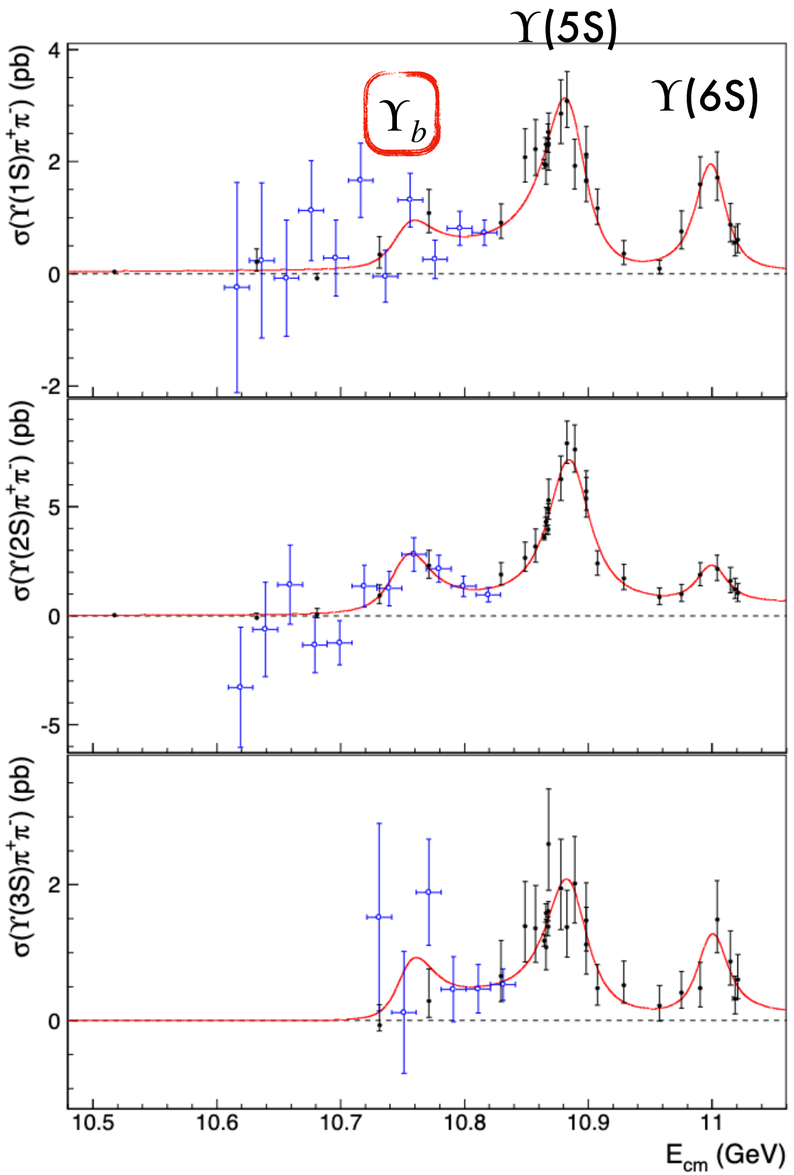
- Structure of Υ_b seen in
  $e^+e^- \to \Upsilon(\mathrm{nS})\,\pi^+\pi^-$ at Belle (5σ)



- Tetraquark? Molecule? Hybrid? Conventional $b\bar{b}$?

- Conventional:
  PRD 101, 014020 (2020)
  EPJC 80, 59 (2020)
  PLB 803, 135340 (2020)
  PPNP 117, 103845 (2021)
  PRD 105, 074007 (2022)
  EPJP 137, 357 (2022)
  …

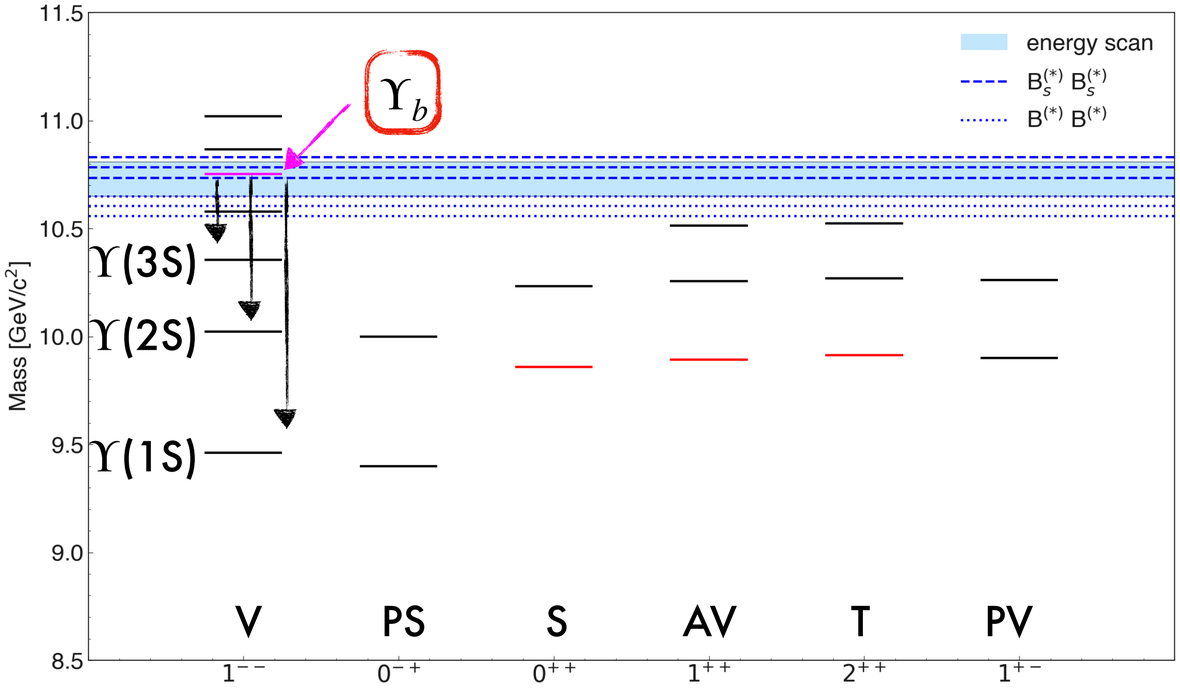
- Exotic:
  CPC 43, 123102 (2019)
  PLB 802, 135217 (2020)
  PRD 103, 074507 (2021)
  PRD 104, 034019 (2021)
  …



$e^+e^- \to \Upsilon(nS)\,\pi^+\pi^-$

arxiv: 2401.12021

- Υ_b discovery?
  - Existence?
  - Measure the di-pion spectrum
  - Z_b contributions?



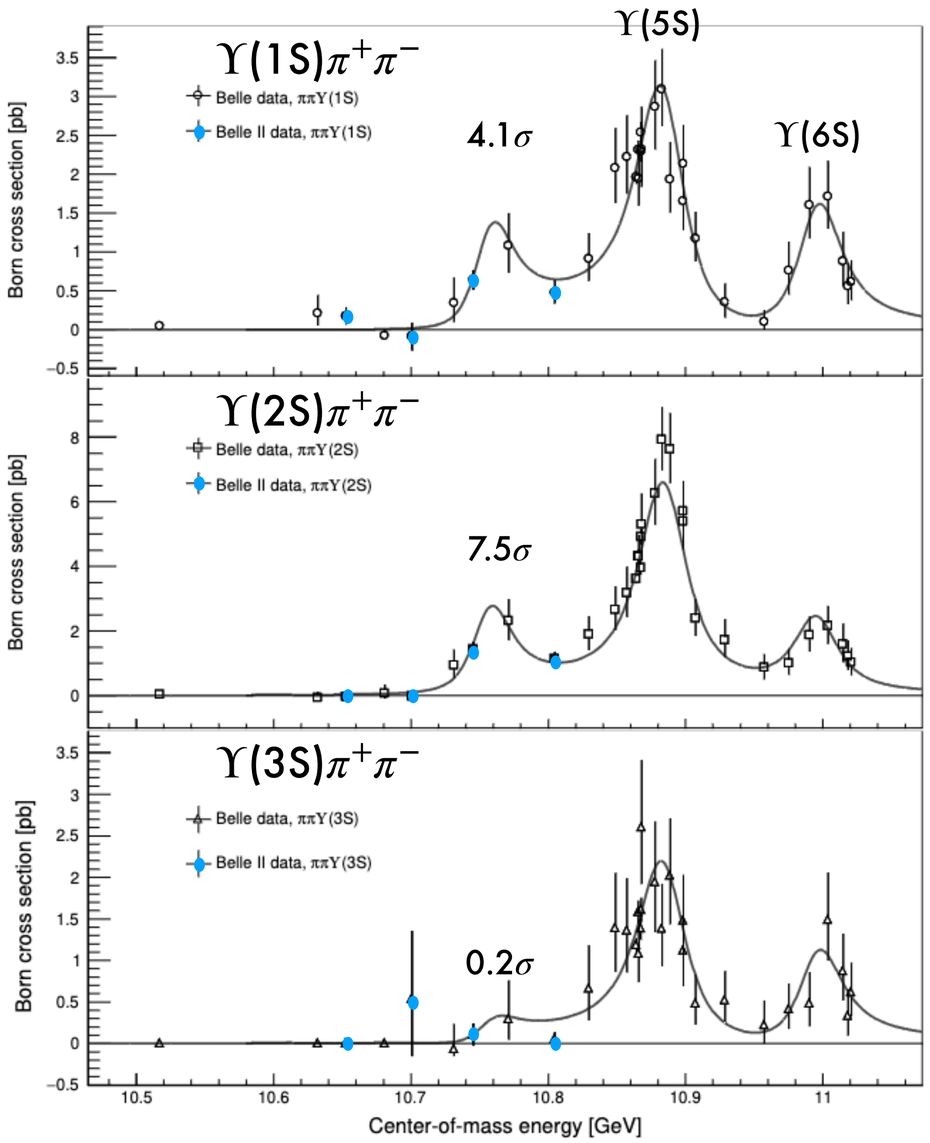
$e^+e^- \to \Upsilon(nS)\,\pi^+\pi^-$

arxiv: 2401.12021

- Υ_b discovery?
  - Existence - Confirmed
    - 8σ combined significance (Belle + Belle II)

	$\mathcal{R}^{\Upsilon(10753)}_{\sigma(1S/2S)}$	$\mathcal{R}^{\Upsilon(10753)}_{\sigma(3S/2S)}$	$\mathcal{R}^{\Upsilon(5S)}_{\sigma(1S/2S)}$	$\mathcal{R}^{\Upsilon(5S)}_{\sigma(3S/2S)}$	$\mathcal{R}^{\Upsilon(6S)}_{\sigma(1S/2S)}$	$\mathcal{R}^{\Upsilon(6S)}_{\sigma(3S/2S)}$
Ratio	$0.46^{+0.15}_{-0.12}$	$0.10^{+0.05}_{-0.04}$	$0.45^{+0.04}_{-0.04}$	$0.32^{+0.04}_{-0.03}$	$0.64^{+0.23}_{-0.13}$	$0.41^{+0.16}_{-0.12}$

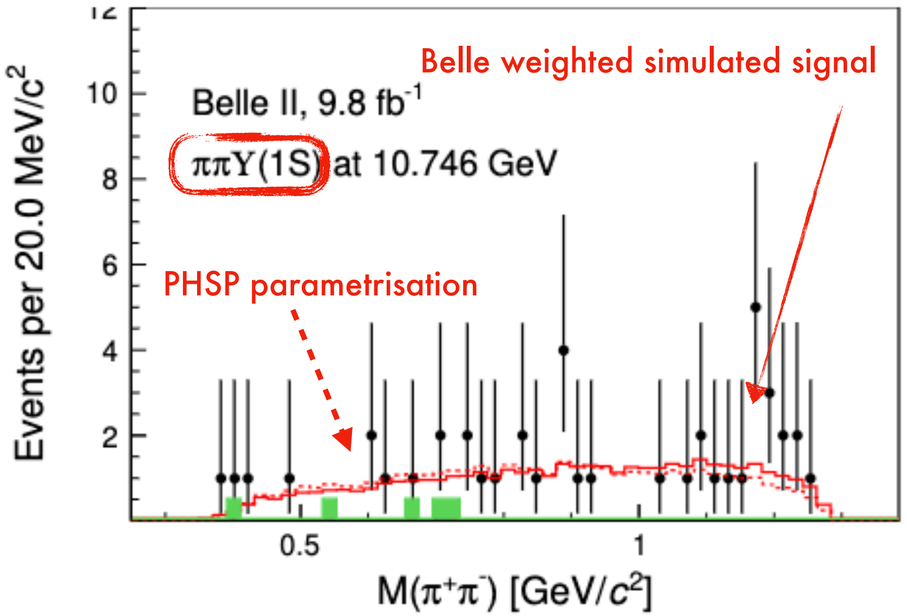
    - Mass $10756.6 \pm 2.7 \pm 0.9$ MeV
    - Width $29.0 \pm 8.8 \pm 1.2$ MeV



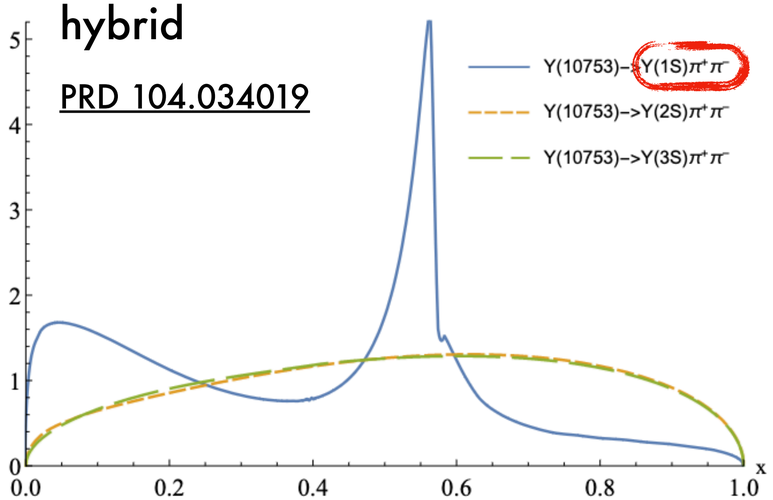
$e^+e^- \to \Upsilon(nS)\,\pi^+\pi^-$

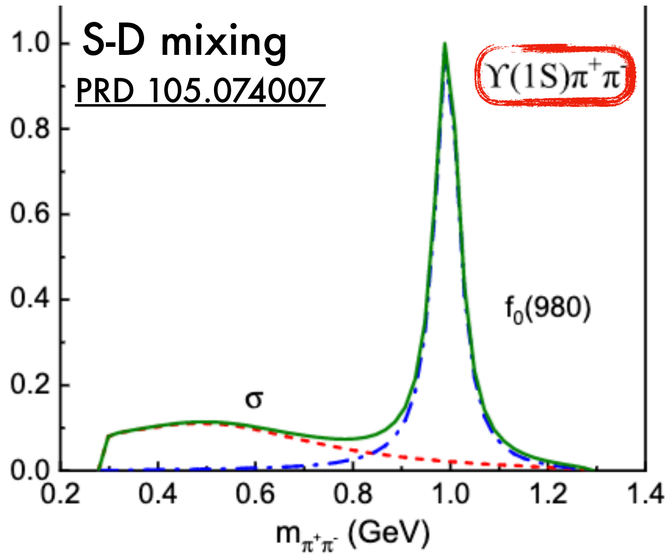
arxiv: 2401.12021

- Υ_b discovery?
  - Existence - Confirmed
  - Measure the di-pion spectrum



- No sign of hybrid
- No sign of S-D mixing

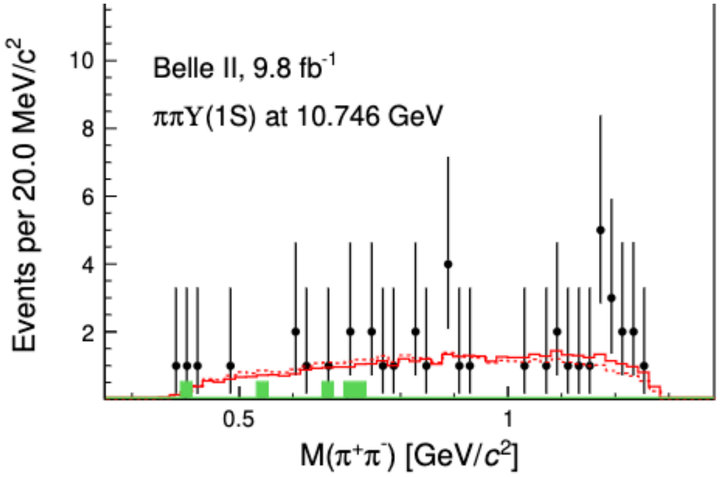




$e^+e^- \to \Upsilon(nS)\,\pi^+\pi^-$

arxiv: 2401.12021

- Υ_b discovery?
  - Existence - Confirmed
  - Measure the di-pion spectrum
    - Tetraquark?



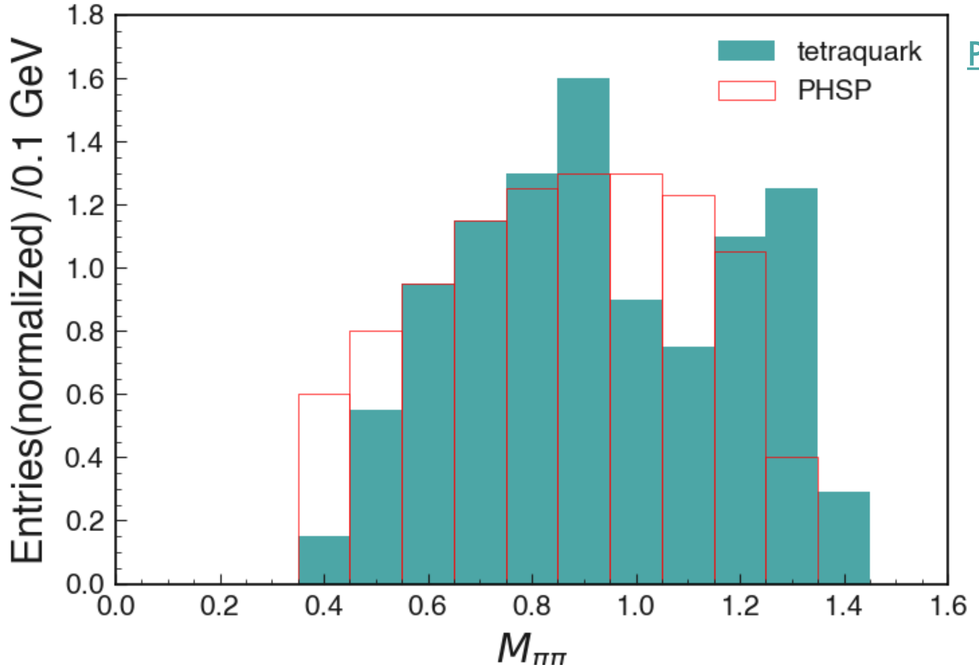
Tetraquark interpretation:

$$\frac{\Gamma(\eta_b\omega)}{\Gamma(Y\pi^-\pi^+)} \approx 30$$

$\sigma(e^+e^- \to \omega\eta_b) < 2.5$ pb

$\sigma(e^+e^- \to \pi^+\pi^-\Upsilon(nS)) \approx 2.0$ pb

CPC 43, 123102

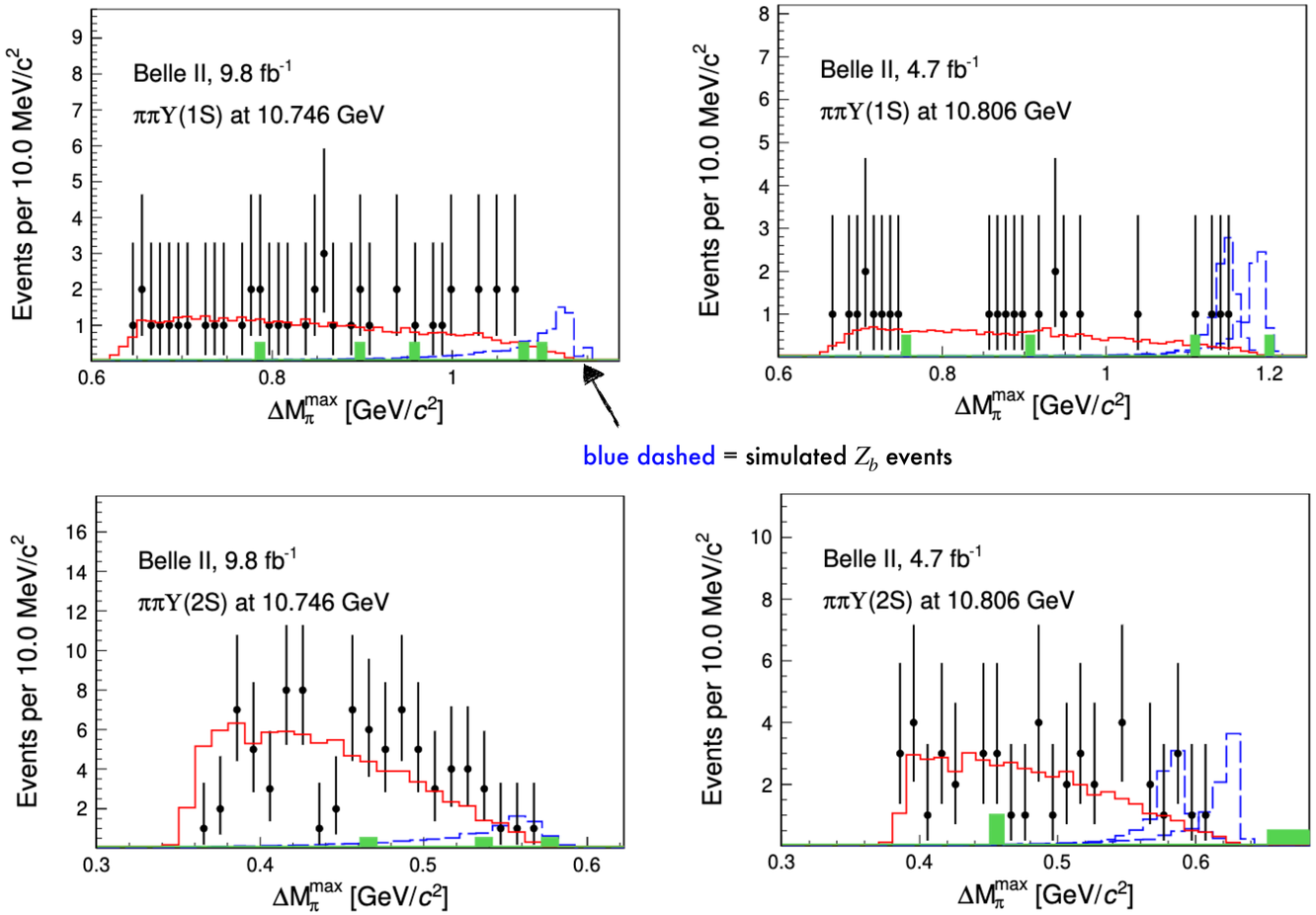


PLB 2020.135217

$e^+e^- \to \Upsilon(nS)\,\pi^+\pi^-$

arxiv: 2401.12021

- Υ_b discovery?
  - Existence - Confirmed
  - Measure the di-pion spectrum
  - $Z_b(10610/10650)$ contributions?
    - No Z_b contributions found



About $e^+e^- \to \Upsilon(nS)\,\pi^+\pi^-$

- Confirmed Belle result with peaking cross section at 10.75 GeV

arxiv: 2401.12021

- No hints of hybrid- or S-D-mixing-structure
- No signal of Z_b resonances observed

- Compatible with tetraquark?

Υ_b = Bottomonium Counterpart Of $\psi(4230)$?

$\psi(4230) \leftrightarrow \Upsilon_b$?

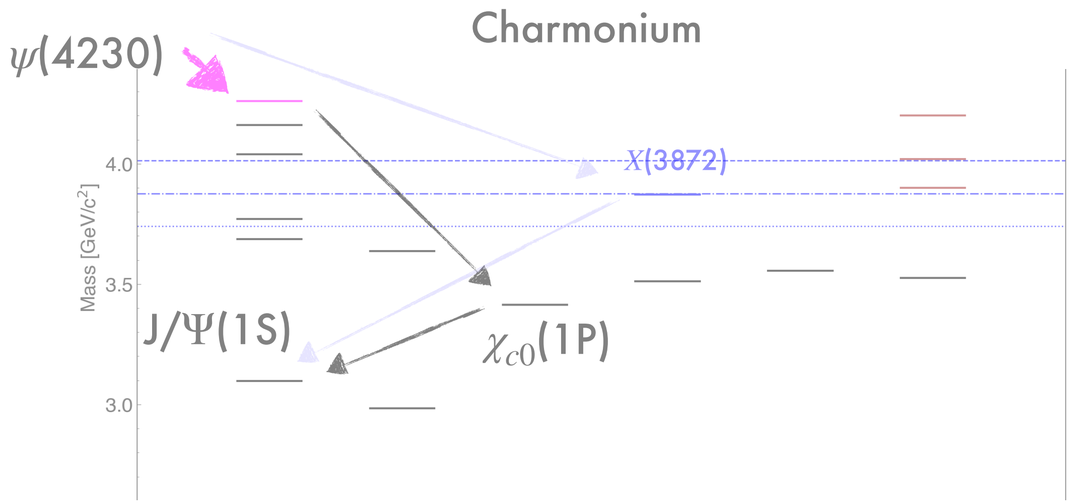
- $\psi(4230)$ was observed in $e^+e^- \to \Psi(nS)\,\pi^+\pi^-$ by BESIII

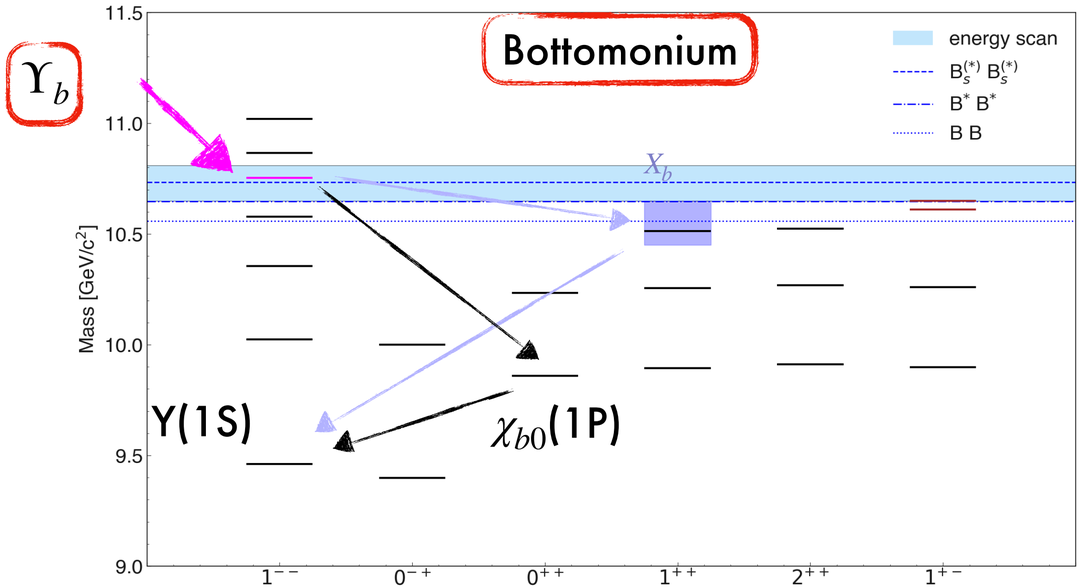
arxiv:1303.5949

- $\psi(4230)$ transitions
  - $\to \omega\chi_{cJ}(1P)$
  - $\to \gamma\, X_c$

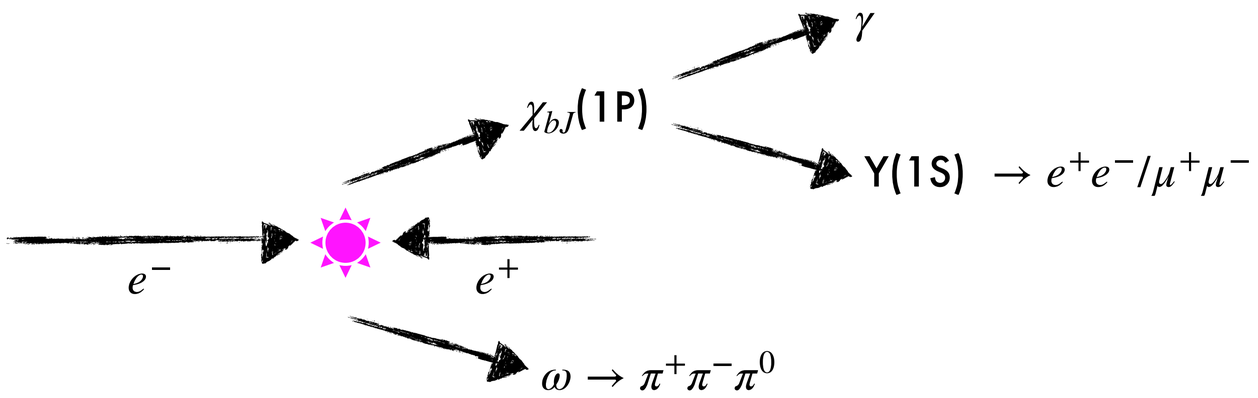
  also seen at BESIII

- Expect similar nature of Υ_b:

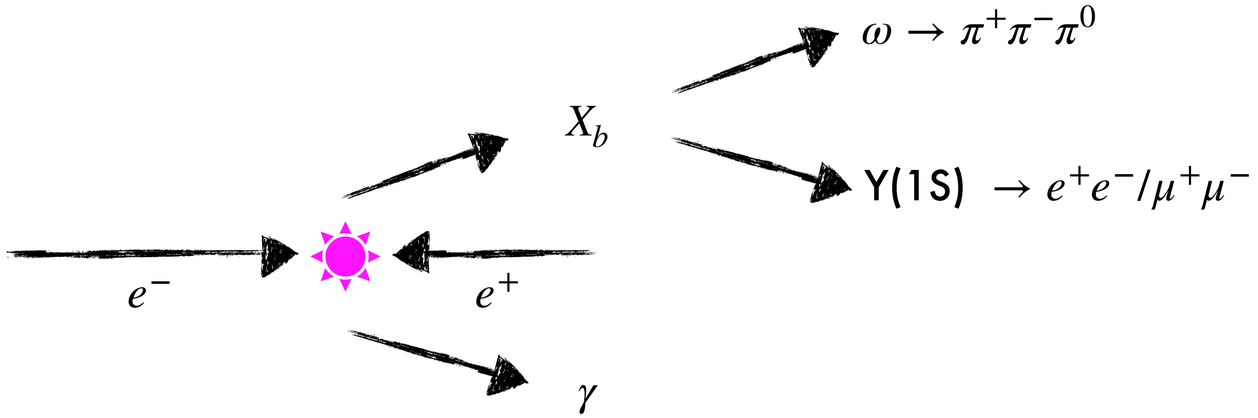




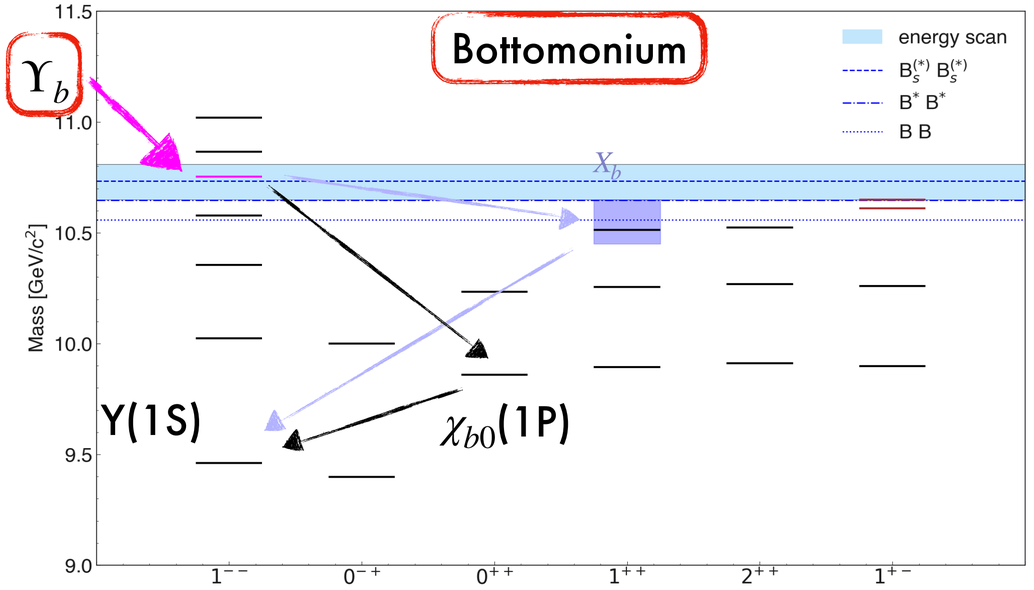
$e^+e^- \to \chi_{bJ}(1P)\,\omega$ PRL 130 091902



Same final states!



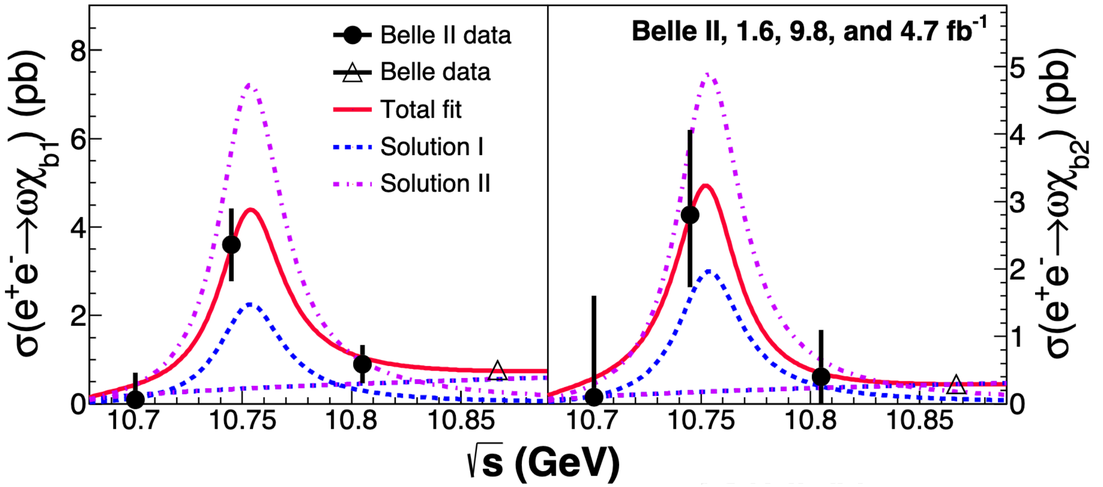
X_b = bottomonium counterpart of X(3872)



$e^+e^- \to \chi_{bJ}(1P)\,\omega$ PRL 130 091902

- **Prediction as a Y(4S) - Y(3D) mixing state:**

$$R_{12} = \frac{\mathcal{B}[\Upsilon_b \to \chi_{b1}\omega]}{\mathcal{B}[\Upsilon_b \to \chi_{b2}\omega]} = (0.18 - 0.22),$$



- **Observation**:

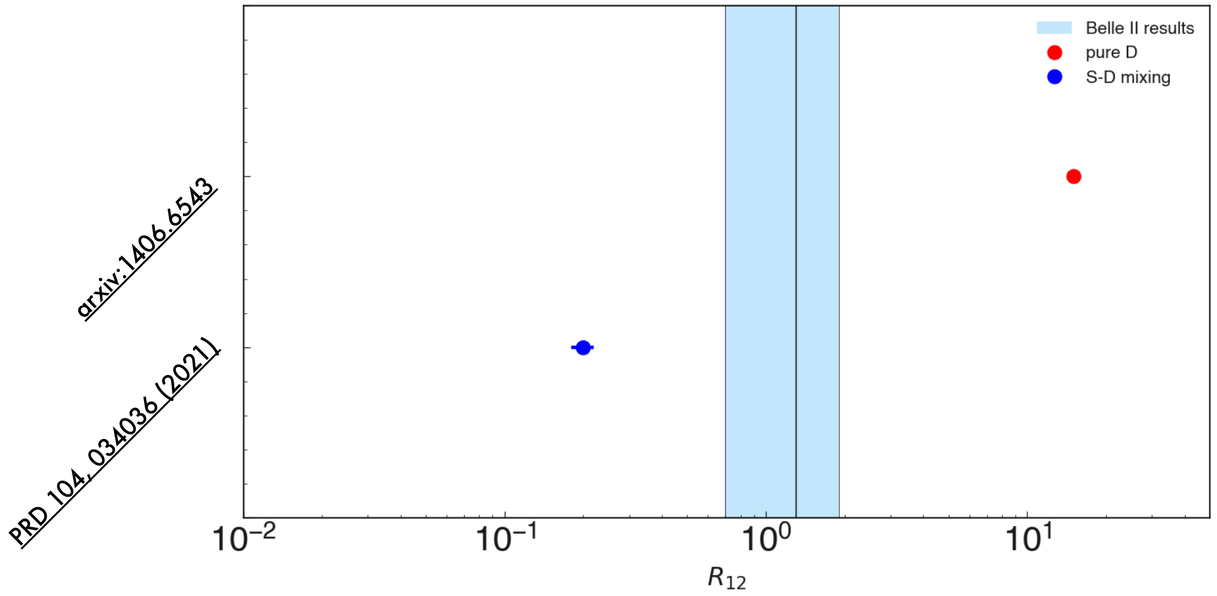
Enhancement at ~10.75 GeV

$$R_{12} = \frac{\Gamma_{ee} \times B[\Upsilon_b \to \omega\chi_{b1}(1P)]}{\Gamma_{ee} \times B[\Upsilon_b \to \omega\chi_{b2}(1P)]} = 1.3 \pm 0.6$$

Disagreement with pure D and S-D mixed state!

$$\frac{\sigma(e^+e^- \to \omega\chi_{bJ})}{\sigma(e^+e^- \to Y(nS)\pi^+\pi^-)} \approx \begin{cases} 1.5 \ @\ Y(10753)\ GeV \\ 0.15 \ @\ Y(5S)\ GeV \end{cases}$$

Different internal structure than Y(5S)?



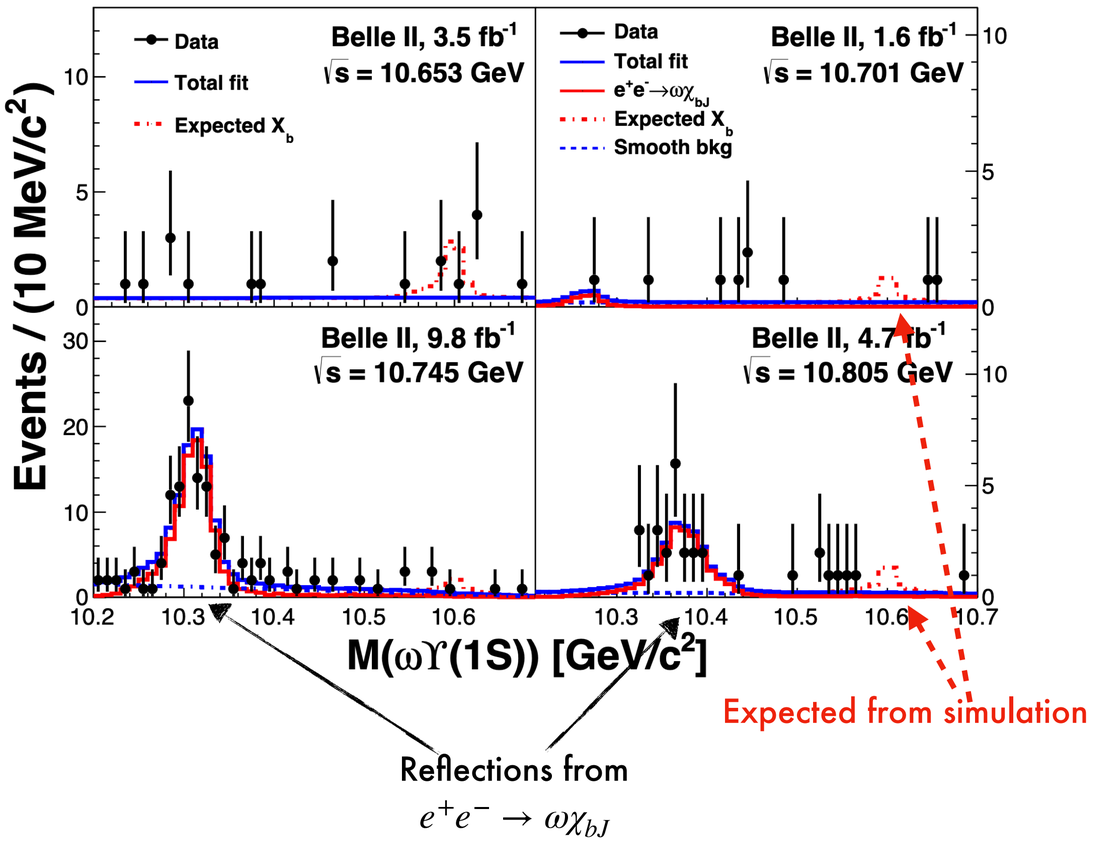
$e^+e^- \to \chi_{bJ}(1P)\,\omega \to \gamma X_b \to \omega Y(1S)$

- Access to X_b

PRL 130 091902

- X_b predicted in molecular and tetra quark models
- No structure from X_b found
- Set upper limites on 10.45 GeV < M(X_b) < 10.65 GeV

$\sqrt{s}$ (GeV)	M_X	$\sigma^{\mathrm{UL}}_{X_b}$ (pb)
10.653		0.55
10.701		0.84
10.745		0.14
10.805		0.37



Summary

- Collected unique dataset at $\sqrt{s}$ ~ 10.75 GeV

- Confirmed Υ_b-state and observed $\Upsilon_b \rightarrow \omega\chi_{bJ}$(1P) transition

- Several indications of the structure of Υ_b, but no clear explanation

- Highly excited bottomonia are good playgrounds for studies and tests of theoretical models

- Beginning of a rich quarkonium physics program where many analyses on 4S and energy scan data are ongoing!

Thanks!

Backup

$e^+e^- \to \eta_b(1S)\omega$ and $\chi_{b0}(1P)\omega$

PRD 109.072013

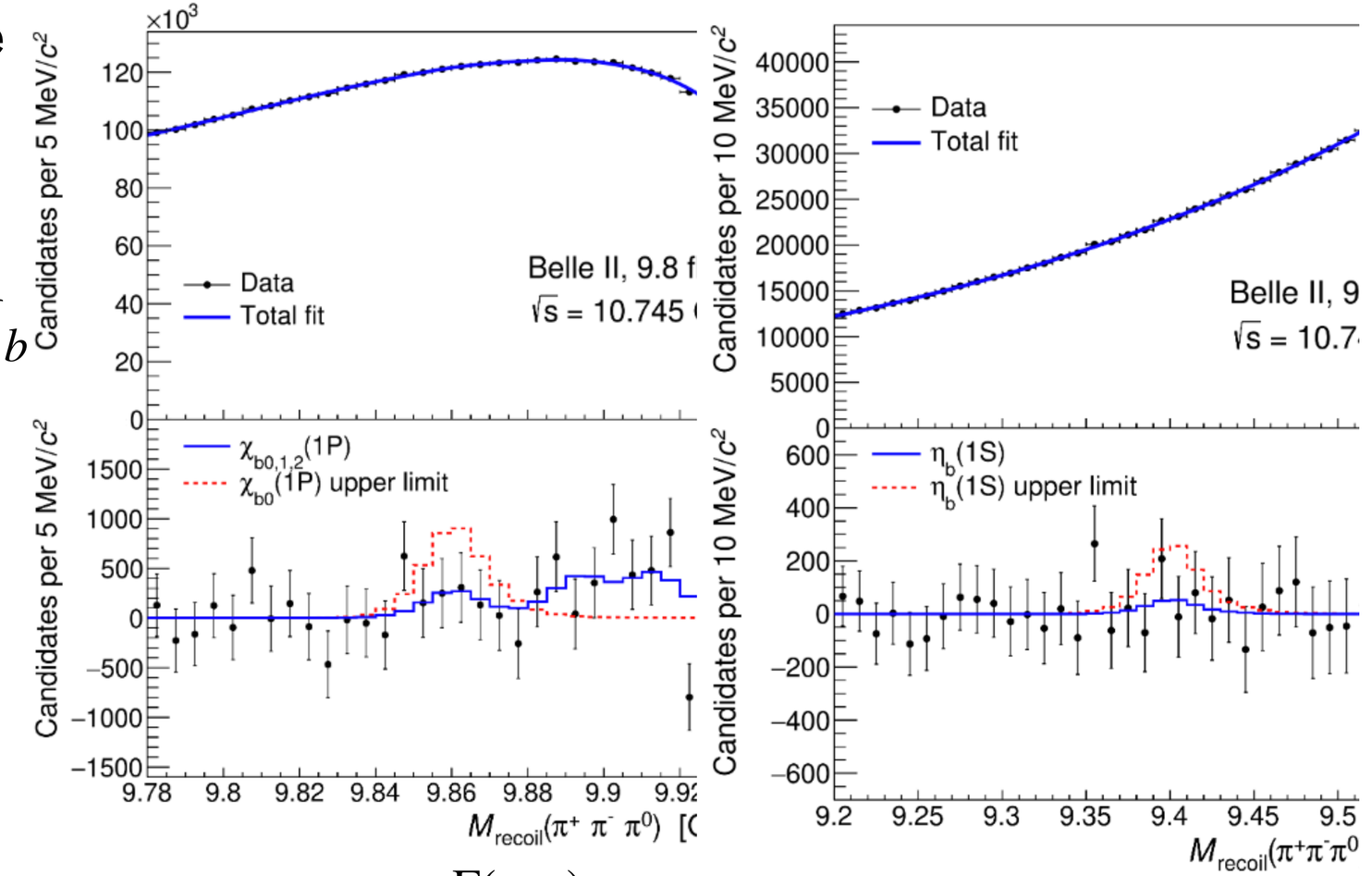
- $\psi(4230) \to \chi_{c0}$ enhanced in the charmonium sector w.r.t. χ_{c1} and χ_{c2}
- No such behaviour found for Υ_b

$$\sigma_B(e^+e^- \to \chi_{b0}(1P)\omega) < 7.8\,\text{pb}.$$

$\sigma_b(e^+e^- \to \chi_{b1}(1P)\omega) = 3.6 \pm 0.9$

$\sigma_b(e^+e^- \to \chi_{b2}(1P)\omega) = 2.8 \pm 1.3$

- $$\frac{\Gamma_{exp}(\eta_b\omega)}{\Gamma_{exp}(Y\pi^-\pi^+)} < 1.25$$



tetraquark $\to \dfrac{\Gamma(\eta_b\omega)}{\Gamma(Y\pi^-\pi^+)} \approx 30$

CPC 43, 123102

4S-3D mixed state: $\dfrac{\Gamma(\eta_b\omega)}{\Gamma(Y\pi^-\pi^+)} \approx (0.2 - 0.4)$

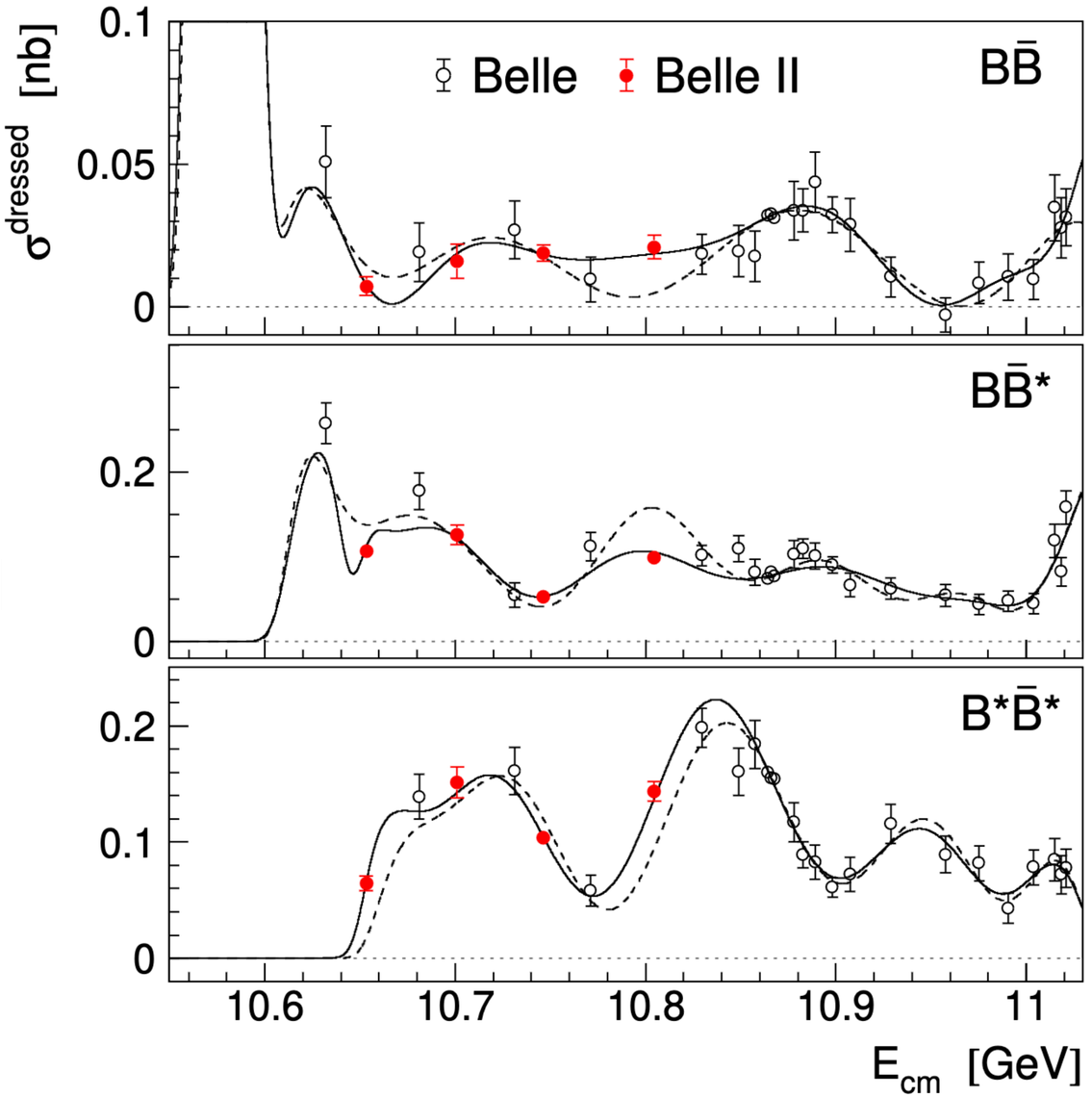
PRD 109.014039

$e^+e^- \to B^*\bar{B}^*, B\bar{B}^*$ and $B\bar{B}$

arxiv:2405.18928

- The open flavor final states make dominant contribution to bb cross-section

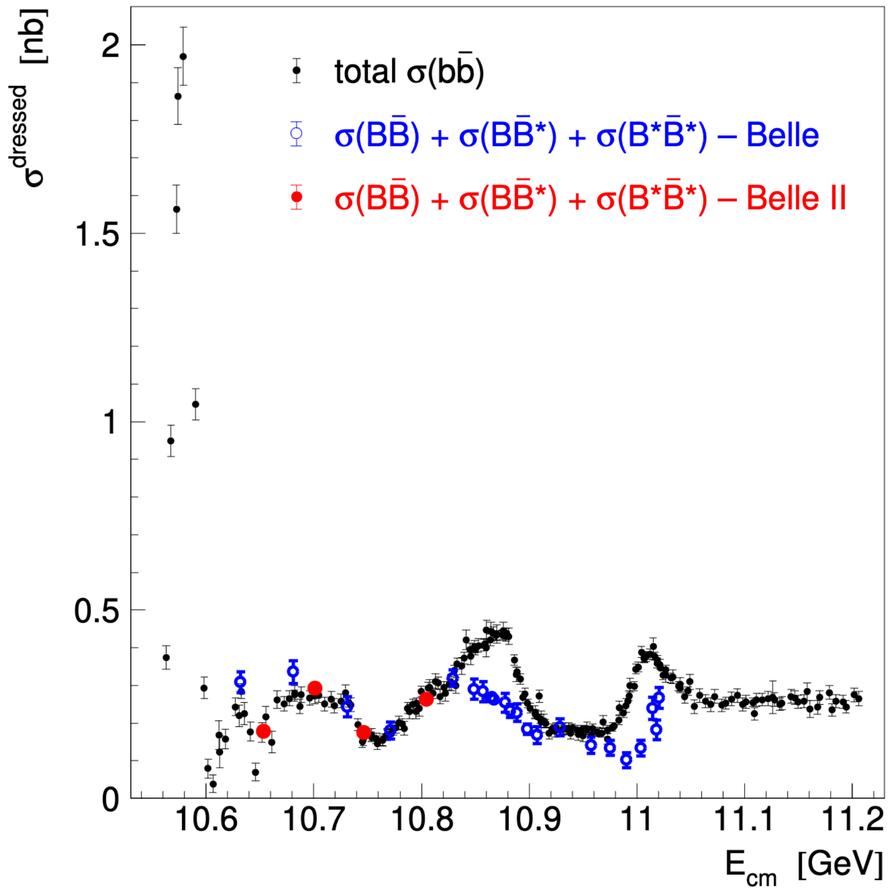
- Sharp rise in $B^*\bar{B}^*$ just above threshold and dip in $B\bar{B}^*$ at $B^*\bar{B}^*$ threshold
  → bound state?

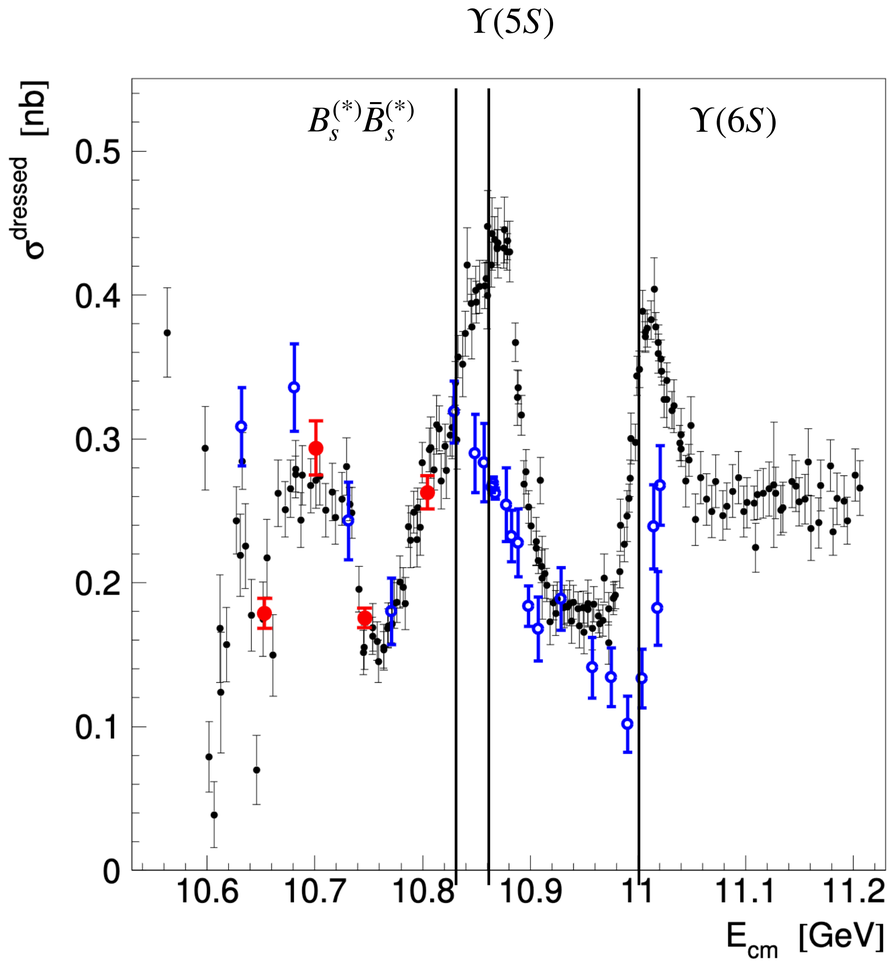


$e^+e^- \to B^*\bar{B}^*, B\bar{B}^*$ and $B\bar{B}$

arxiv:2405.18928

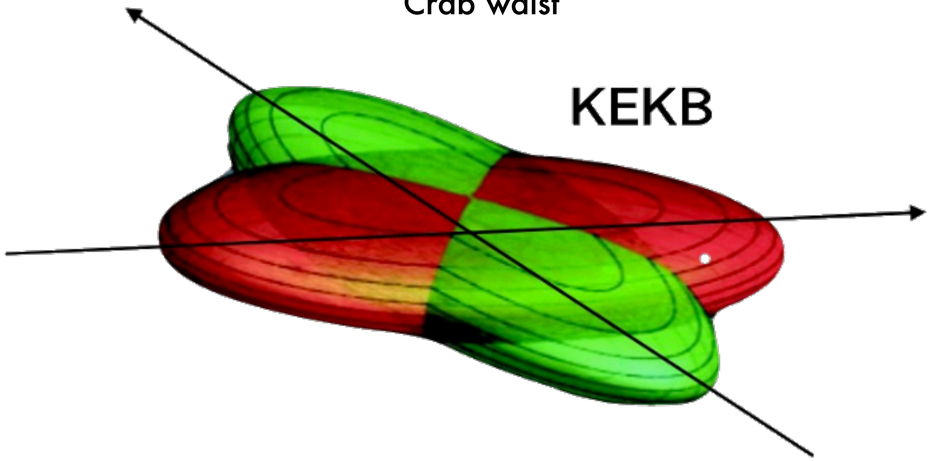
- Saturated $\sigma(b\bar{b})$ below $B_s^{(*)}\bar{B}_s^{(*)}$ threshold
- Energy points consistent with Belle results



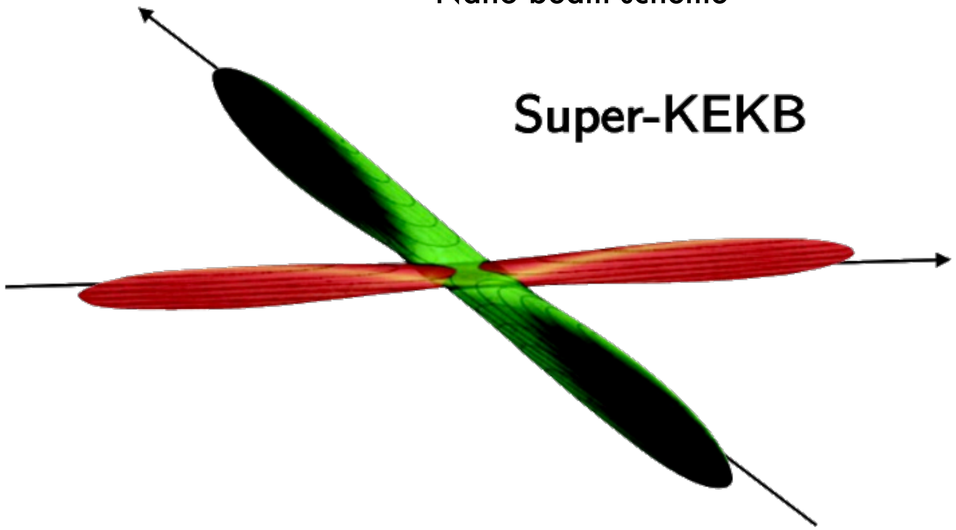


Nano beam scheme

Crab waist



Nano beam scheme



	KEKB Achieved	SuperKEKB
Energy (GeV) (LER/HER)	3.5/8.0	4.0/7.0
ξ_y	0.129/0.090	0.090/0.088
β_y^* (mm)	5.9/5.9	0.27/0.41 → Lumi x20
I (A)	1.64/1.19	3.60/2.62 → Lumi x2
Luminosity ($10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	2.11	80
	$\sigma_y^* = 940$ nm	$\sigma_y^* = 48/62$ nm
	$\sigma_x^* = 147/170\ \mu$m	$\sigma_x^* = 10.1/10.7\ \mu$m

Beam current

Beam-Beam factor

Lorentz factor

$$Lumi = \frac{\gamma_\pm}{2er_e}\left(\frac{I_\pm \xi_\pm}{\beta^*_{y\pm}}\right)\left(\frac{R_L}{R_{\epsilon_y}}\right)$$

Vertical beta function at IP

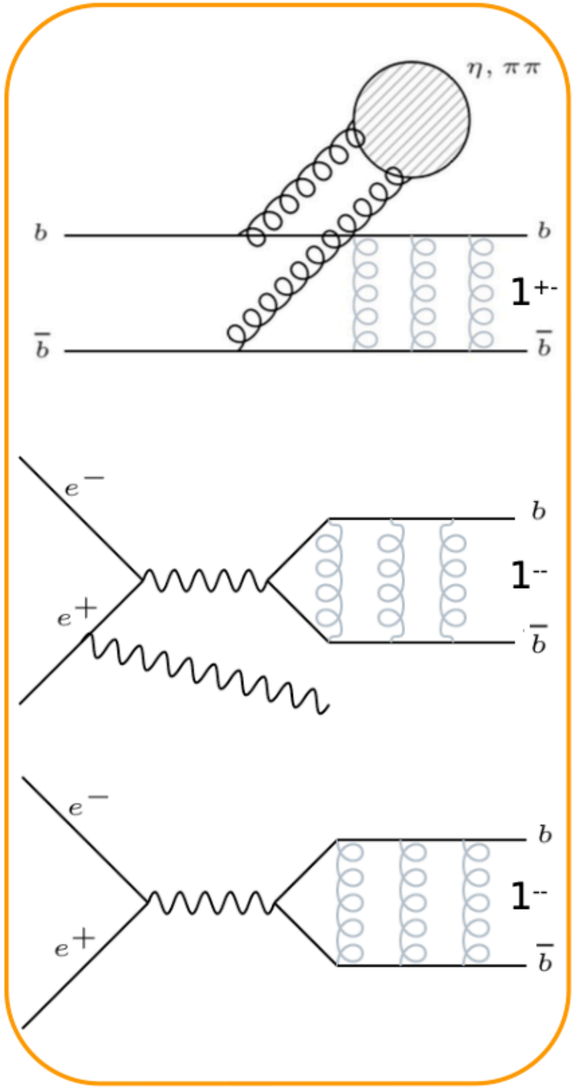
Geometrical corrections (hourglass eff. …)

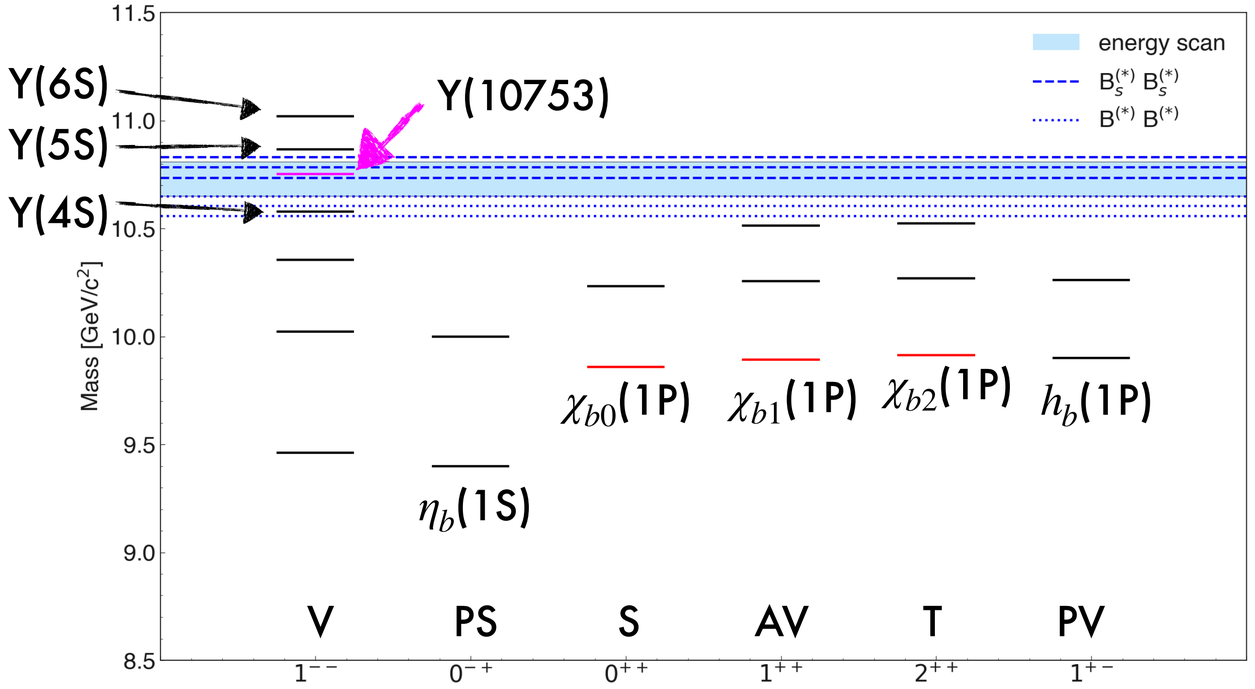
Bottomonium spectrum

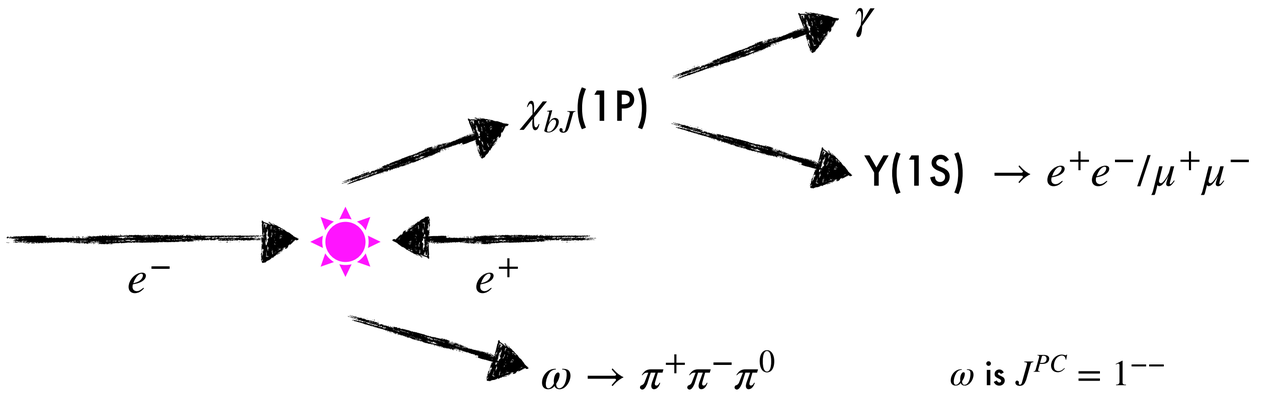
Hadronic transitions

ISR

Direct production

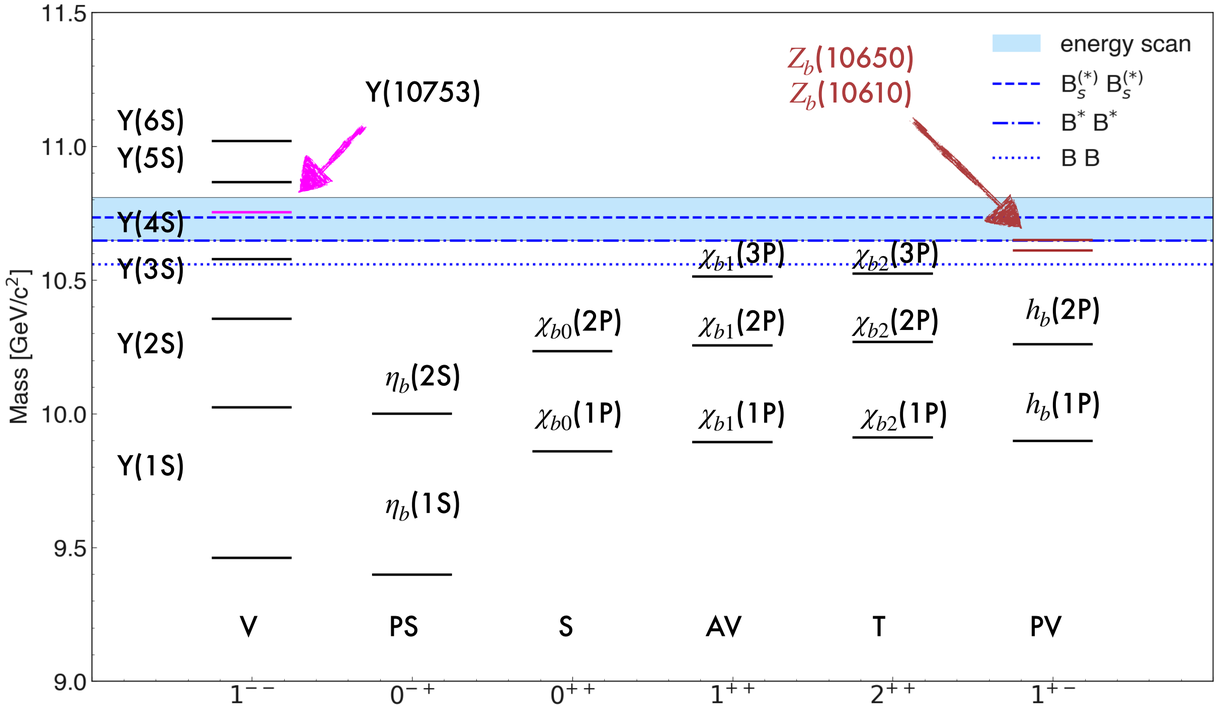






Bottomonium scheme

- Below the $B\bar{B}$-threshold, states are well described by potential models
- Above the $B\bar{B}$-threshold, the states show unexpected behaviour
  - Hadronic transitions to lower bottomonia are strongly enhanced
  - η_b transition not suppressed compared to $\pi^+\pi^-$ → violation of heavy quark spin symmetry
  - Z_b states observed near $B^{(*)}\bar{B}^*$-threshold consistent with $B^{(*)}\bar{B}^*$-molecule interpretation



Why Belle II?

- Optimised for $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$
  - Goal: 50 ab^{-1} of data
    (30 times more than Belle and BaBar together ~1.5 ab^{-1})
  - CKM Metrology
  - New Physics in FCNC ala Penguins
- Total integrated luminosity: ~424 fb^{-1}
  Instant. luminosity: ~4x$10^{34}$$cm^{-2}s^{-1}$
- **<u>Not only B pairs</u>**

More Backup

$e^+e^- \to \chi_{bJ}(1P)\,\omega$ - event selection

- Peaks observed for $\chi_{b1}(1P)$ and $\chi_{b2}(1P)$ and ω

- 2D Fit [M(γ Y(1S)) and M($\pi^+\pi^-\pi^0$)]

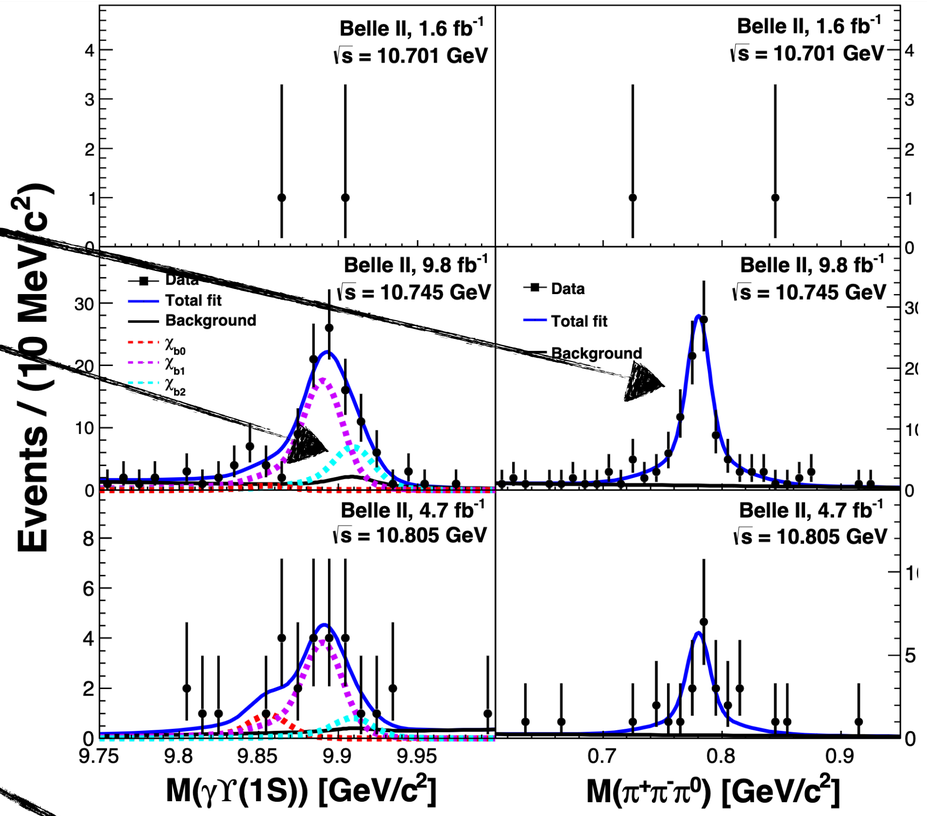
- χ_{bJ}(1P): Crystal Ball (15 MeV width)

- ω: BW + Gaussian (13 MeV width)

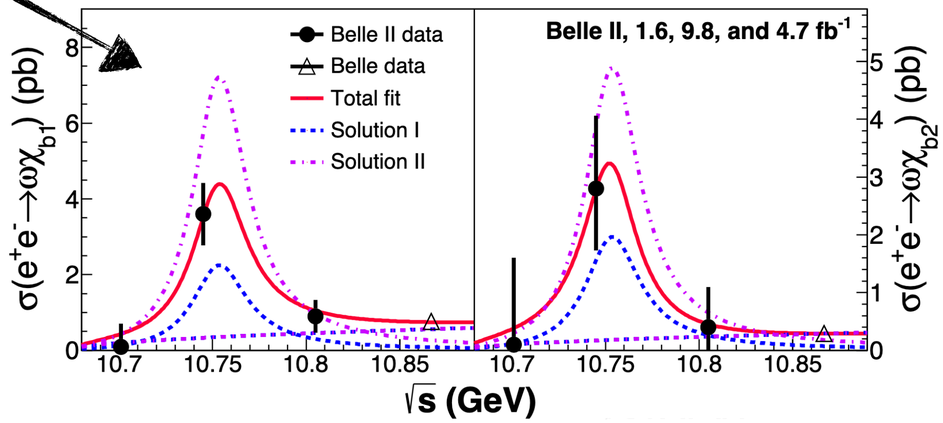
- Constructive (I) and destructive (II) solutions

  - $\Gamma_{ee} \times B(e^+e^- \to \omega\chi_{b1}(1P)) = \begin{matrix}(I)\ 0.63\pm0.39\pm0.20 \\ (II)\ 2.01\pm0.38\pm0.76\end{matrix}$ eV

  - $\Gamma_{ee} \times B(e^+e^- \to \omega\chi_{b2}(1P)) = \begin{matrix}(I)\ 0.53\pm0.46\pm0.15 \\ (II)\ 1.32\pm0.44\pm0.55\end{matrix}$ eV

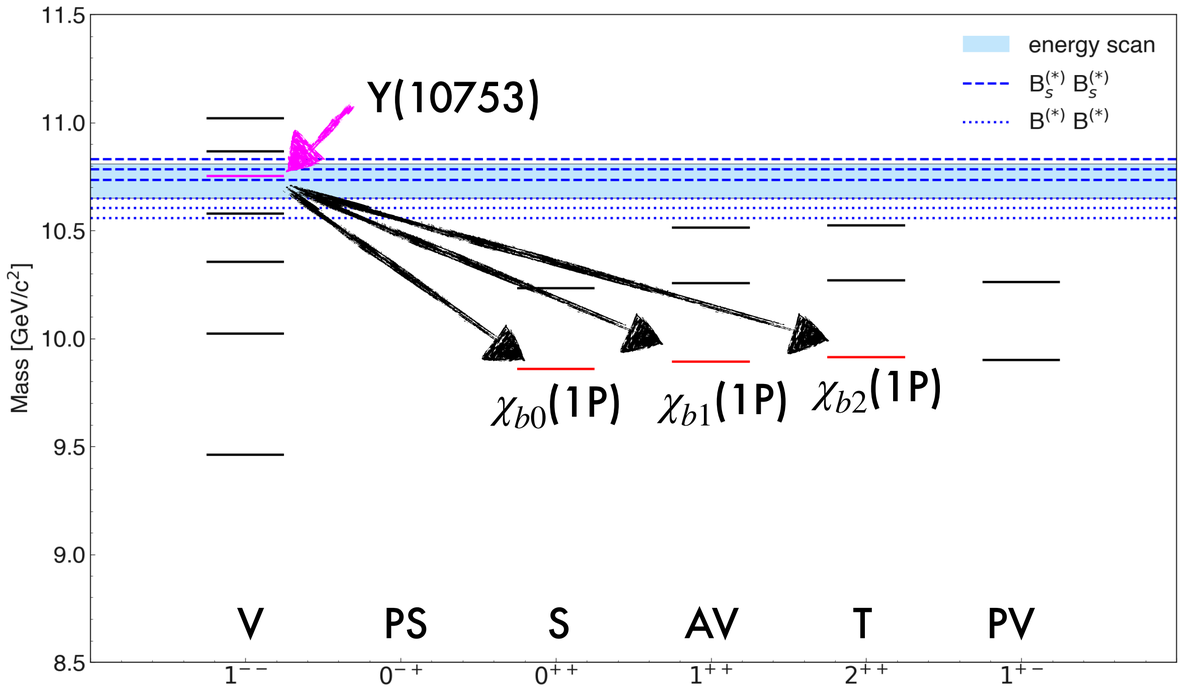


Fixed fit-parameters:
Mass = 10752.7 MeV/c^2
Width = 35.5 MeV

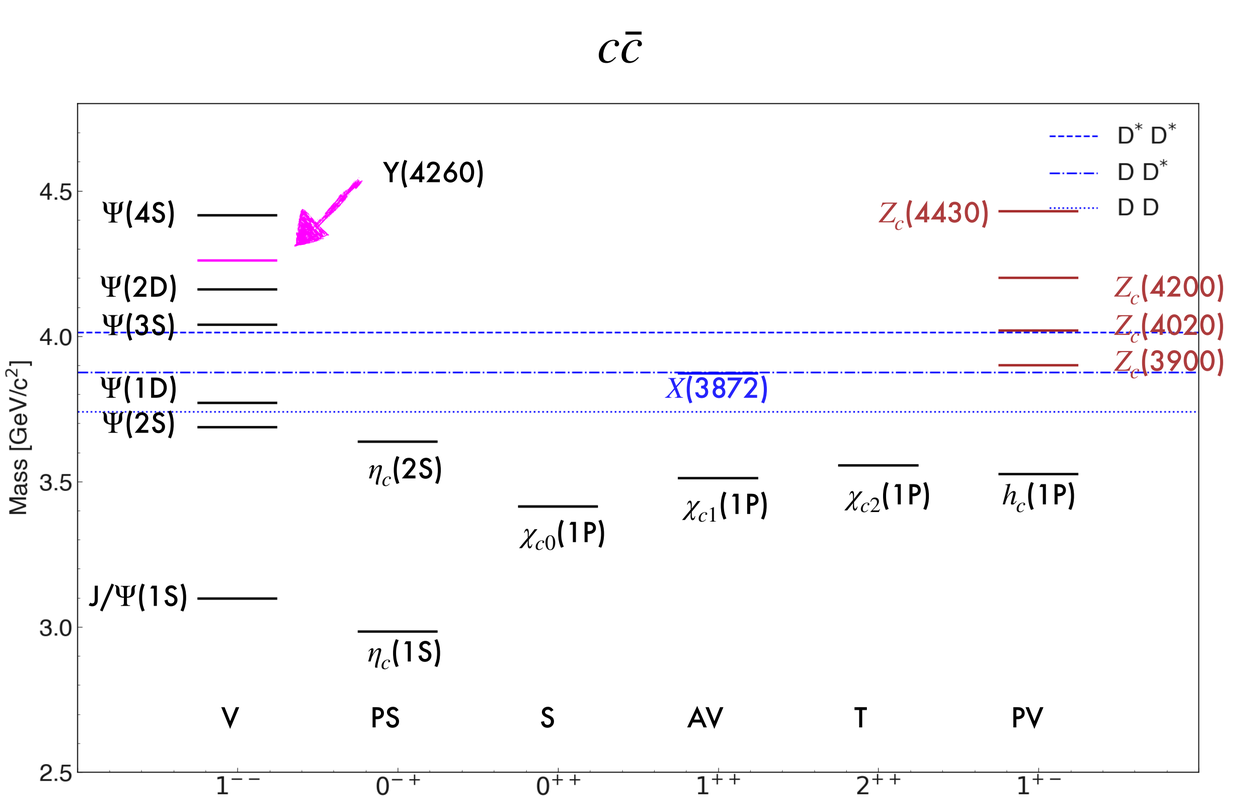


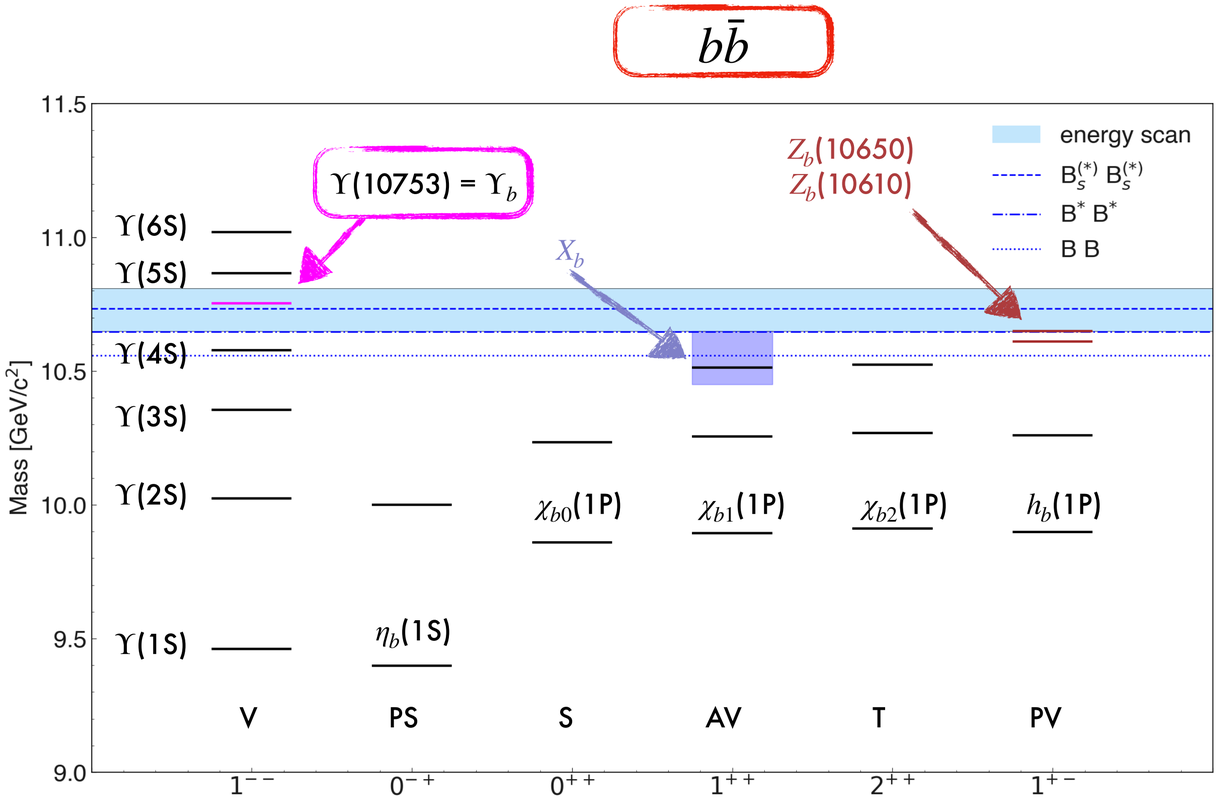
$e^+e^- \to \chi_{bJ}(1P)\,\omega$ - event selection

- $\Upsilon_b \to \chi_{bJ}(1P)\,\omega$
- 4-5 charged tracks
- PID –> 90-95% efficiency
- E(γ) > 50 MeV
- 105 < M($\gamma\gamma$) < 150 MeV/c^2 (90% eff.)
- Kinematic fit
  - Best candidate selection via fit-χ^2



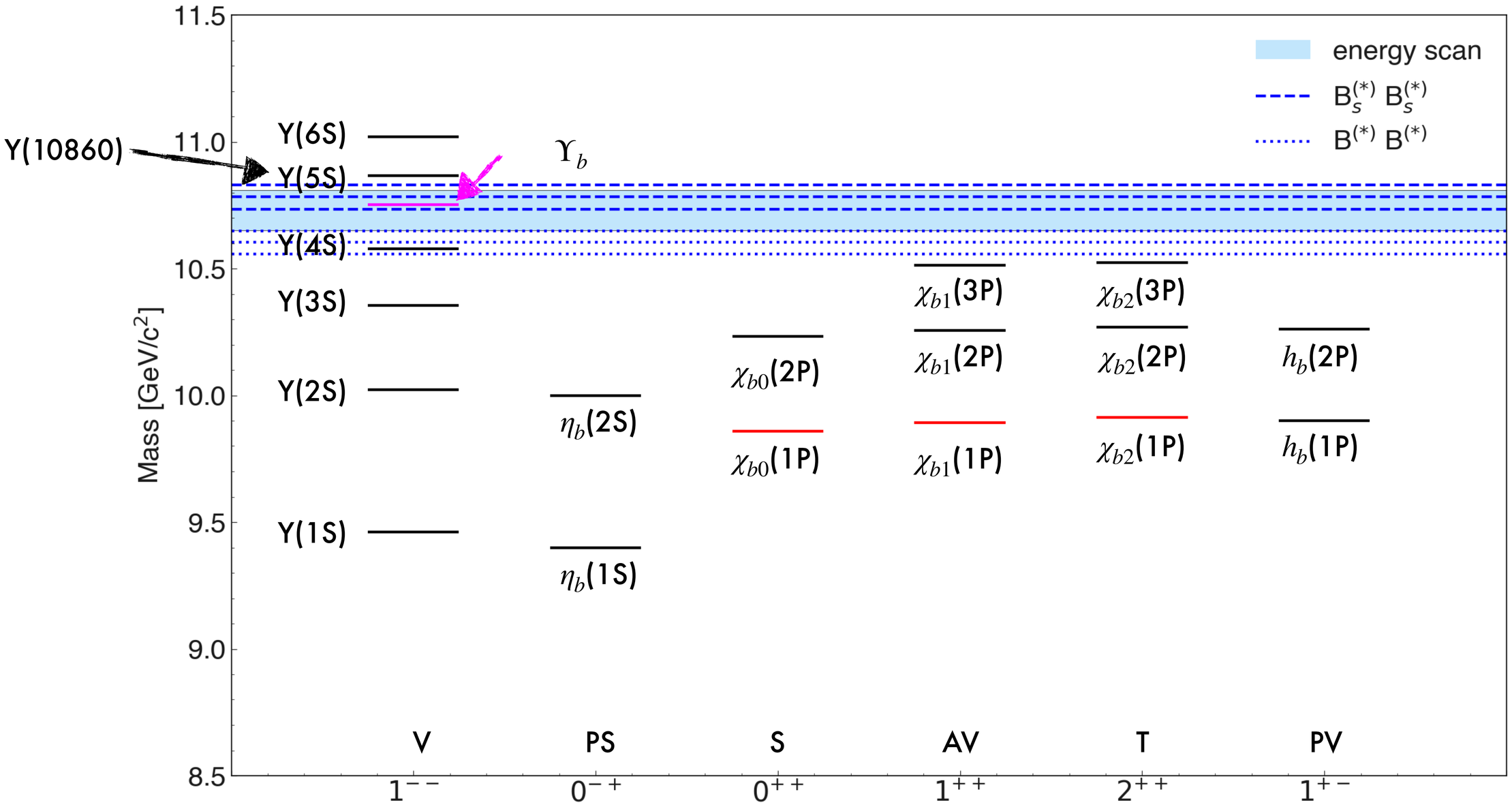
Charmonium / Bottomonium



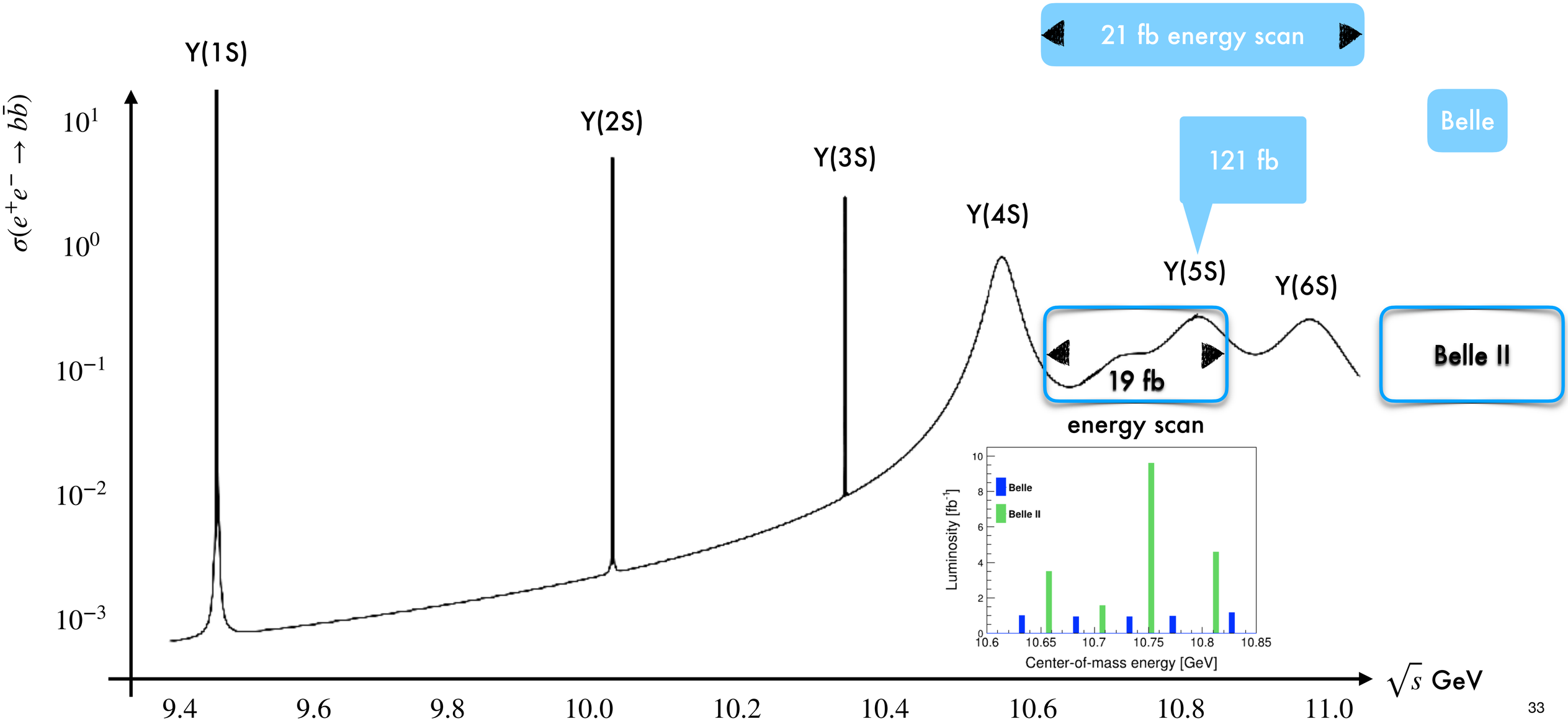


- Heavy quarkonium was investigated in detail by 1st generation B-Factories
  → new production mechanisms, transitions, exotic states,…
- Z_c and Z_b states are close to $D\bar{D}^*$ and $B\bar{B}^*$ threshold and molecular interpretations are favoured for both
- Similar family of particles found in $c\bar{c}$ could also exist in $b\bar{b}$

Bottomonium spectrum



Bottomonium



Summary

- Collected dataset at $\sqrt{s}$ ~ 10.75 GeV

- Several indications of the Y(10753), but no definite explanation
  - No f_0 in Y(10753) $\rightarrow \pi^+\pi^-$ Y(nS)
  - No enhancement of $\omega\eta_b$(1S) as predicted from tetraquark model
  - 4S-3D mixed state OK with $\omega\eta_b$(1S), but not with $\omega\chi_{bJ}$(1P)
  - No X_b in between10.45 - 10.65 GeV
  - No Z_b indications found