Recent Bottomonium Results From Belle II

QNP2024

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JGU Mainz

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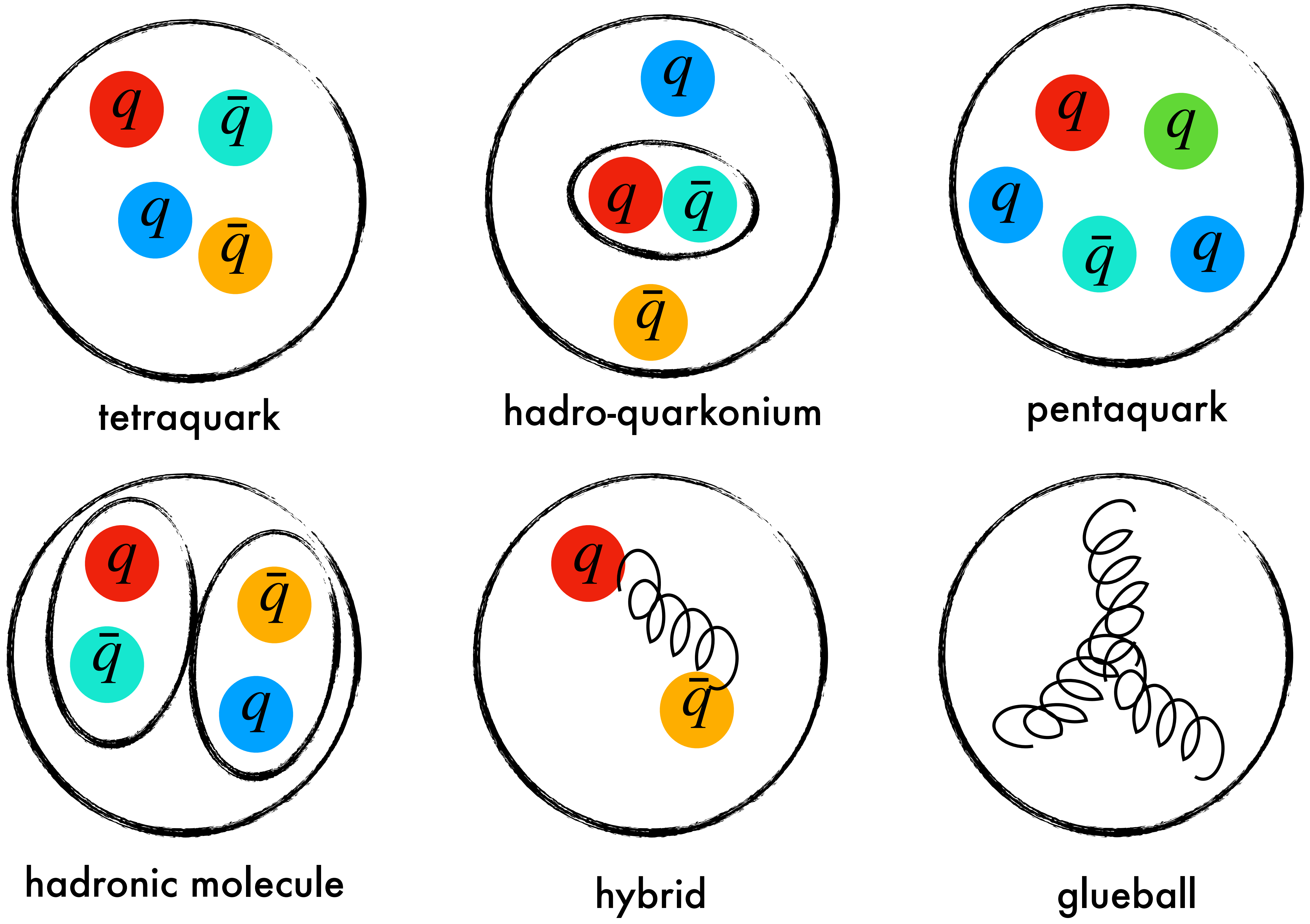
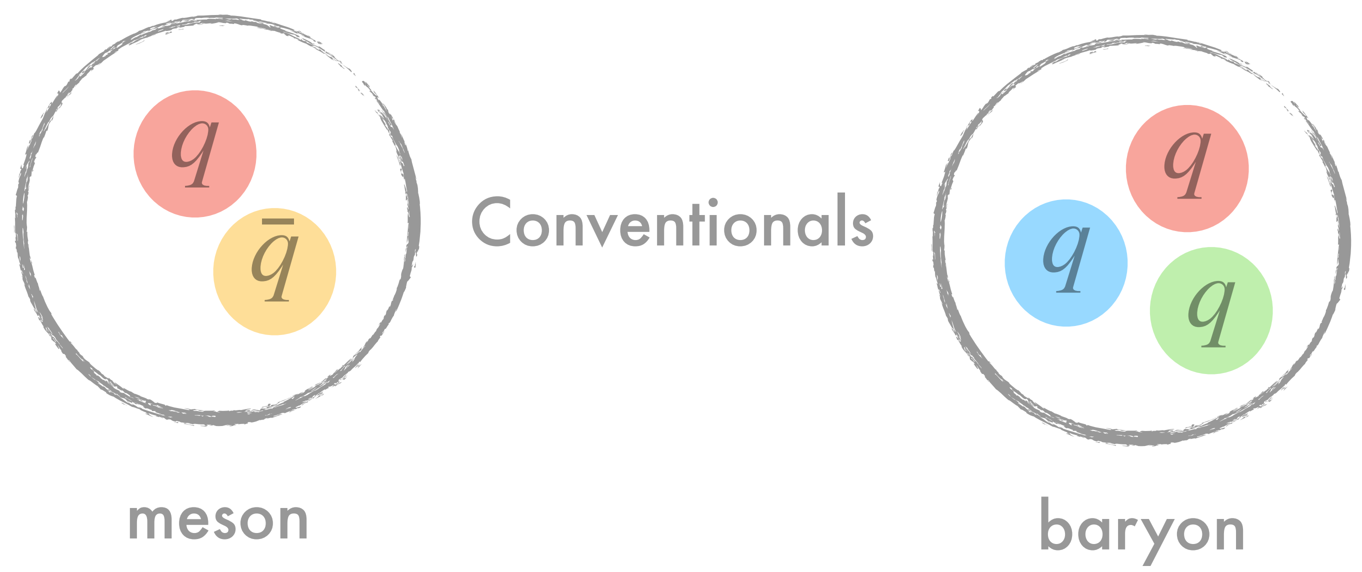
Quarkonium Spectroscopy





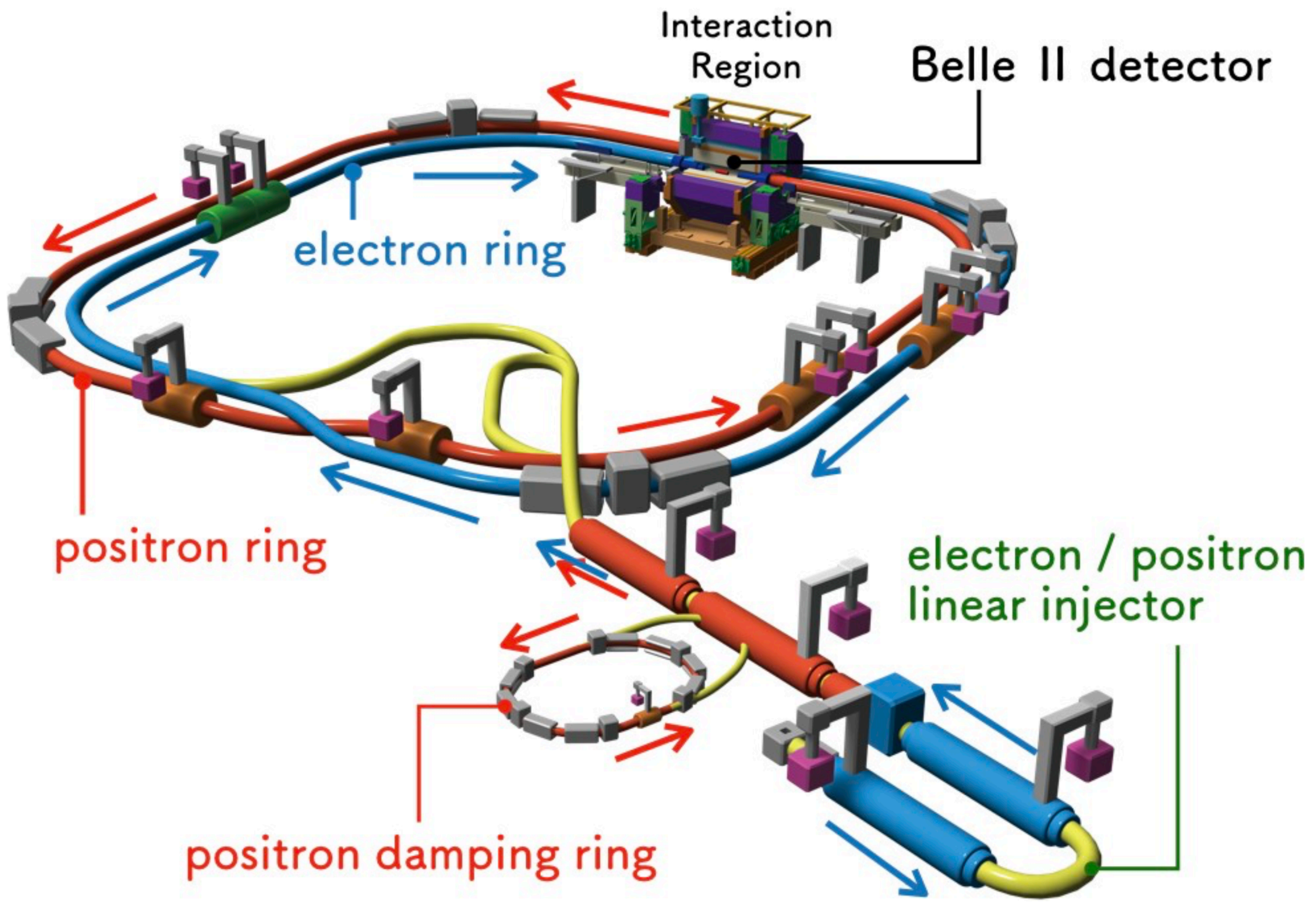
- Investigated by 1st-gen B-Factories
  - New production mechanisms, transitions, many (unexpected) XYZ states observed in charmonium and bottomonium
    - X(3872), Y(4260), Z(10610), …
    - $\boxed{\Upsilon(10753)}$
- Ambiguous interpretations, not definite

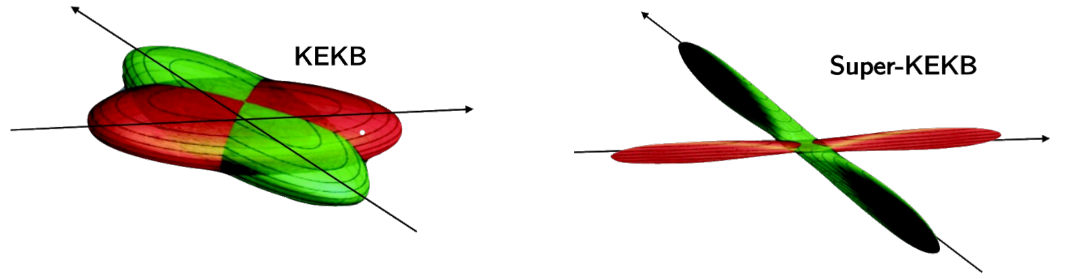
- **Better understanding is needed!**

How To Get Bottomonium

SuperKEKB

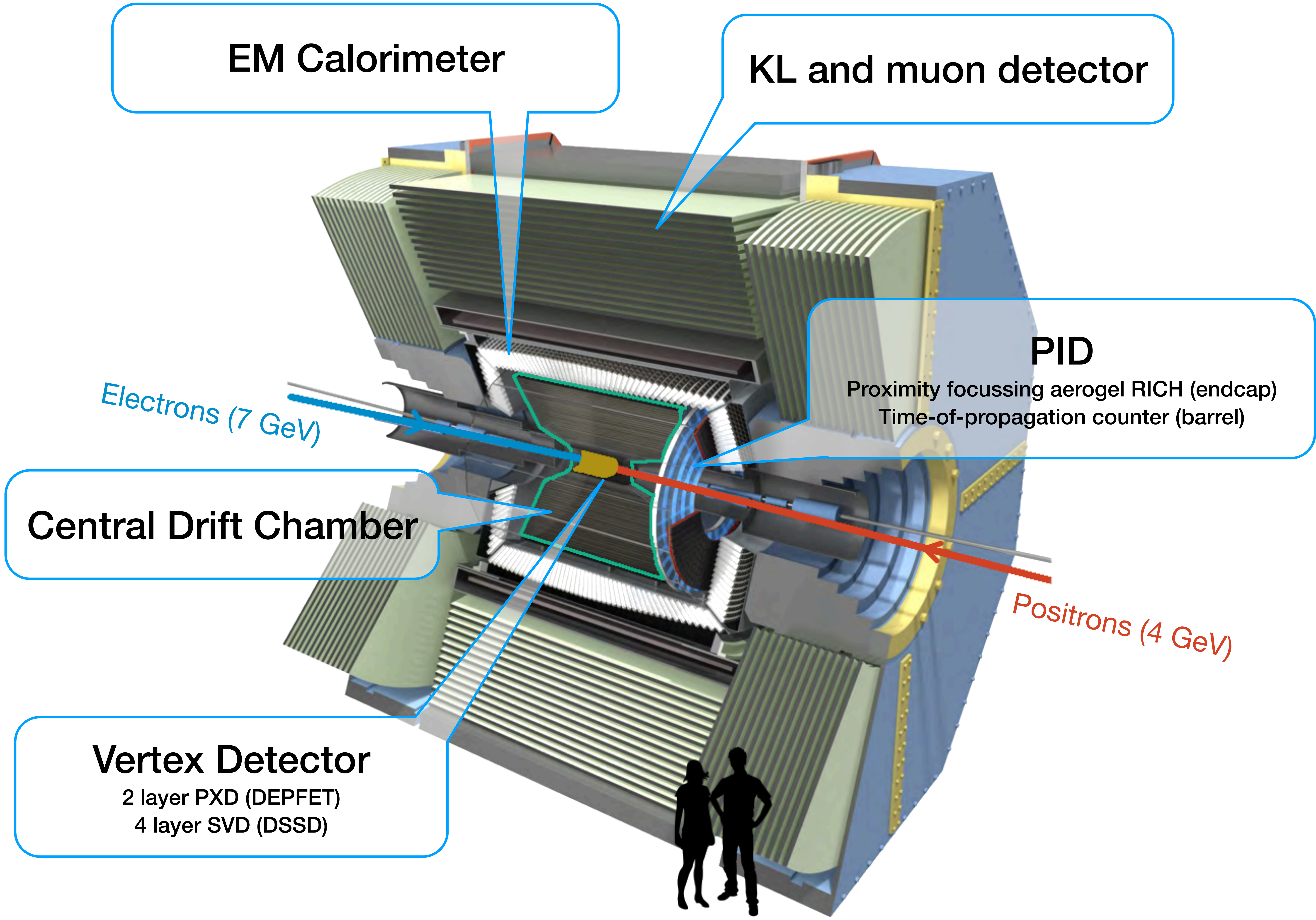
Instant. luminosity: ~$4.7\text{x}10^{34}\text{cm}^{-2}\text{s}^{-1}$





crab waist   nano-beam scheme → x30 instant. luminosity

Belle II detector

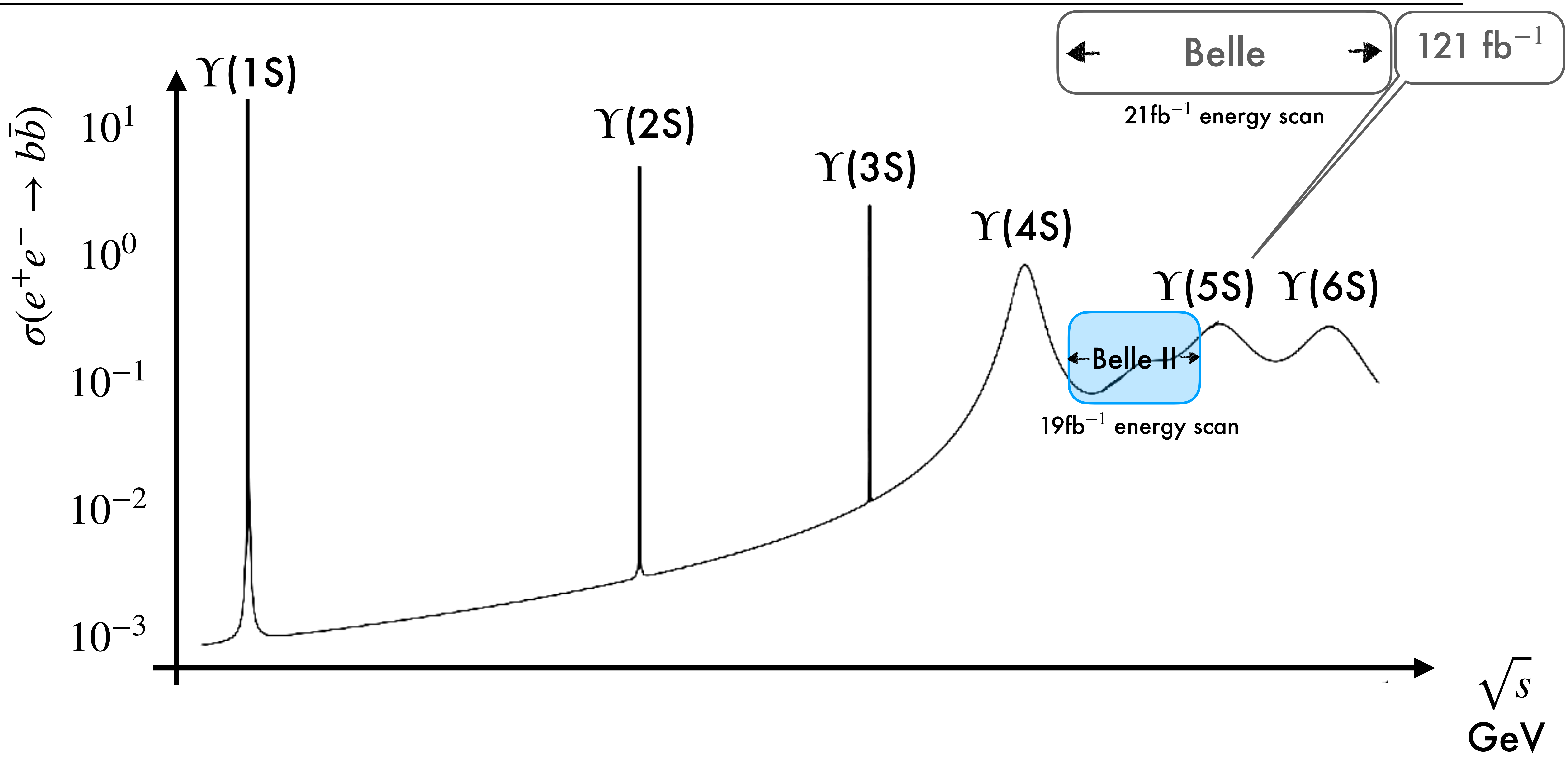


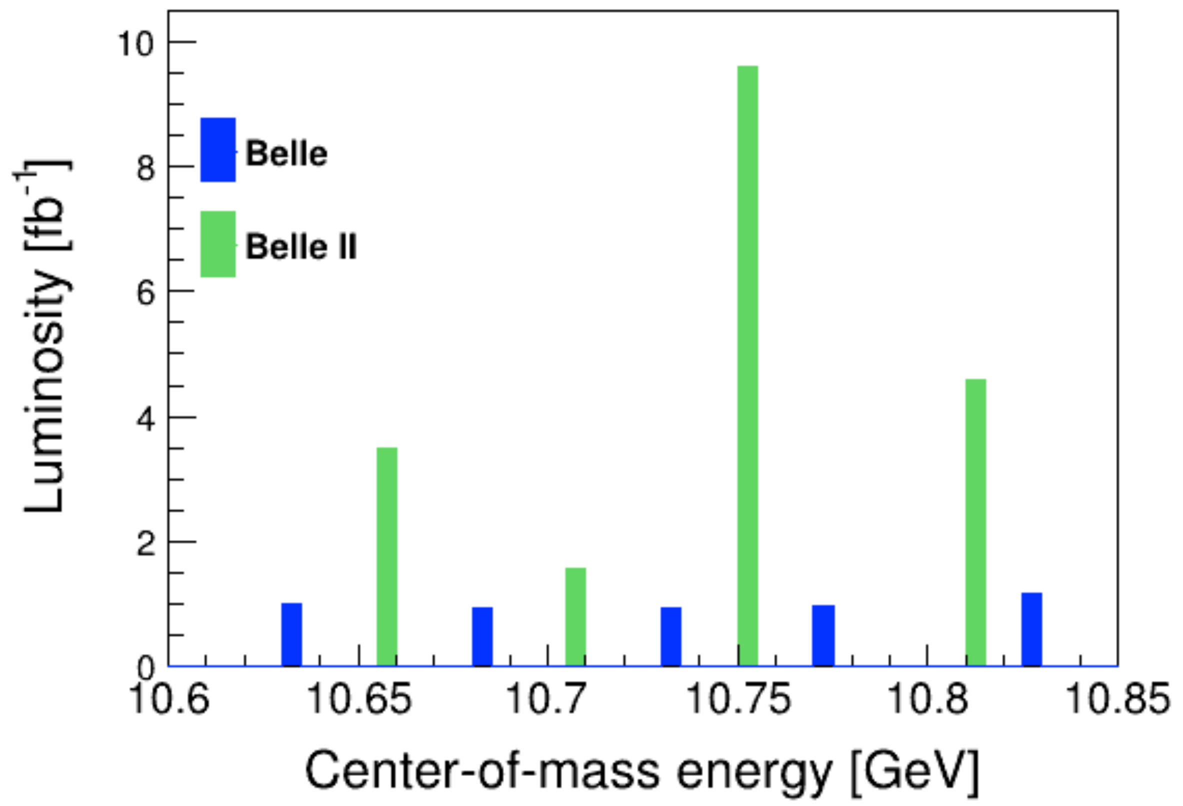
Belle II Technical Design Report

Belle II Energy Scan

- Main Goal of Belle II energy scan:

  <u>Confirm and Study the</u> $\boxed{\Upsilon(10753)}$





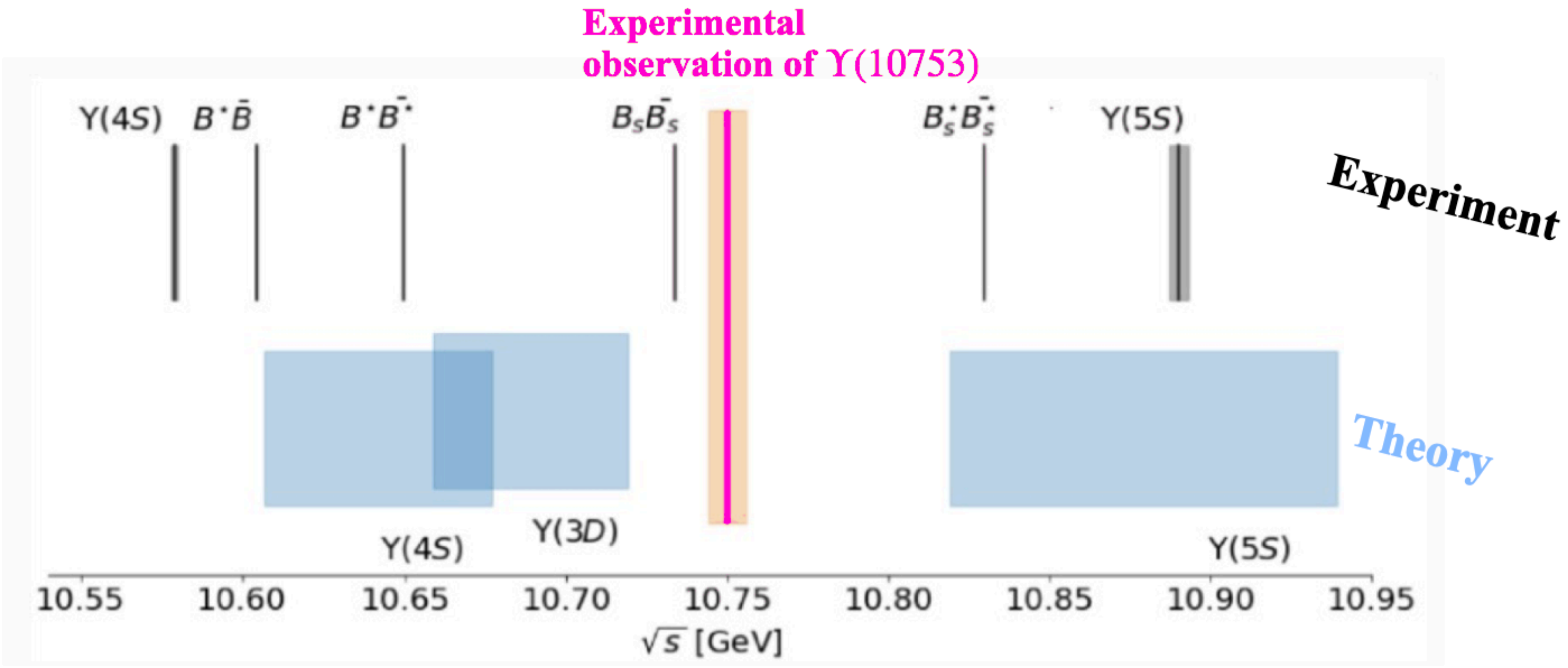
- Belle II energy scan in between Belle points
  (successfully collected $19 fb^{-1}$ of data)

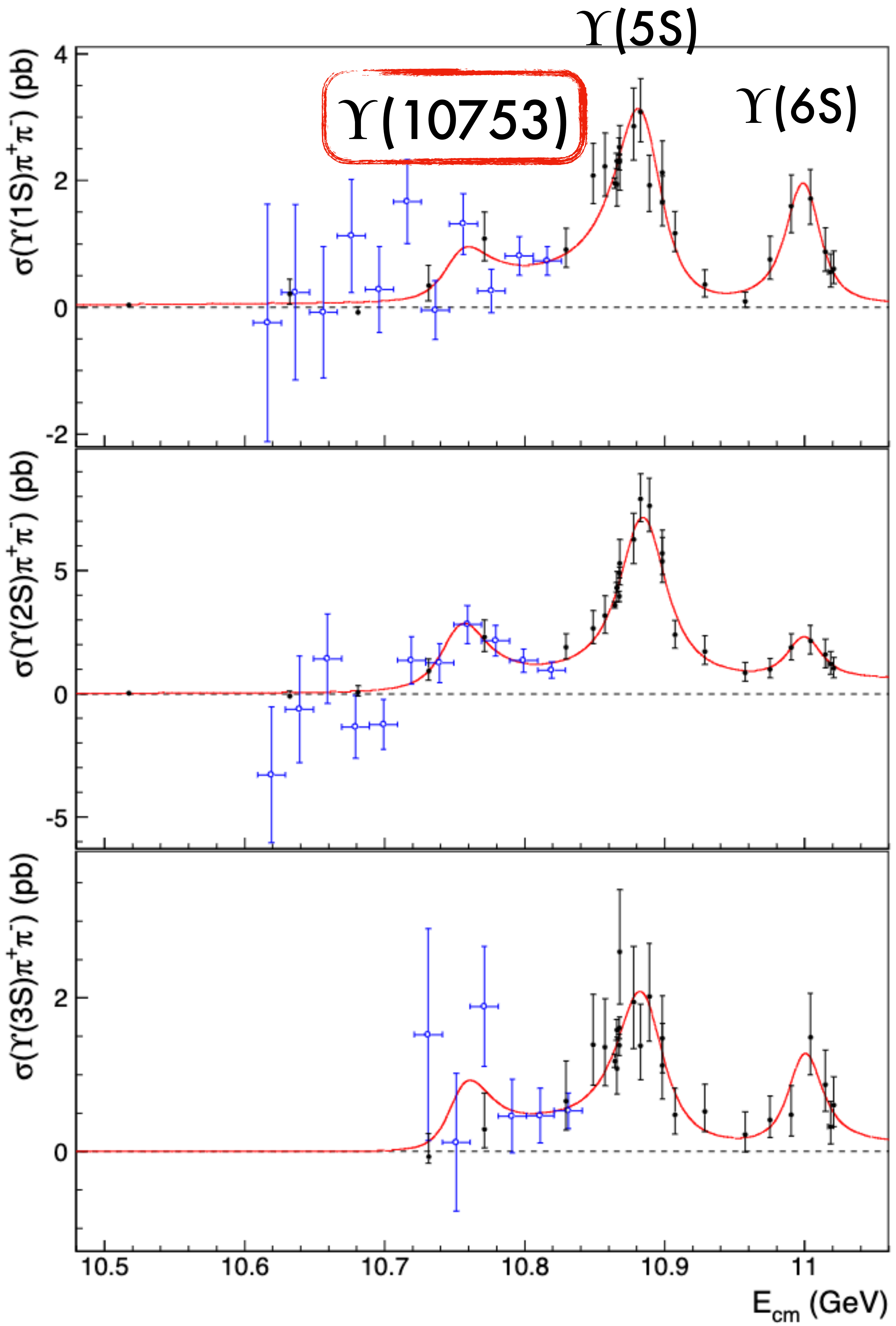
$$\mathbf{e^+e^-} \to \Upsilon\mathbf{(nS)}\ \pi^+\pi^-$$

Enhancement At 10.753 GeV

JHEP 10 (2019) 220

- Structure of $\Upsilon(10753)$ seen in $e^+e^- \to \Upsilon(\mathrm{nS})\ \pi^+\pi^-$ at Belle (5σ)



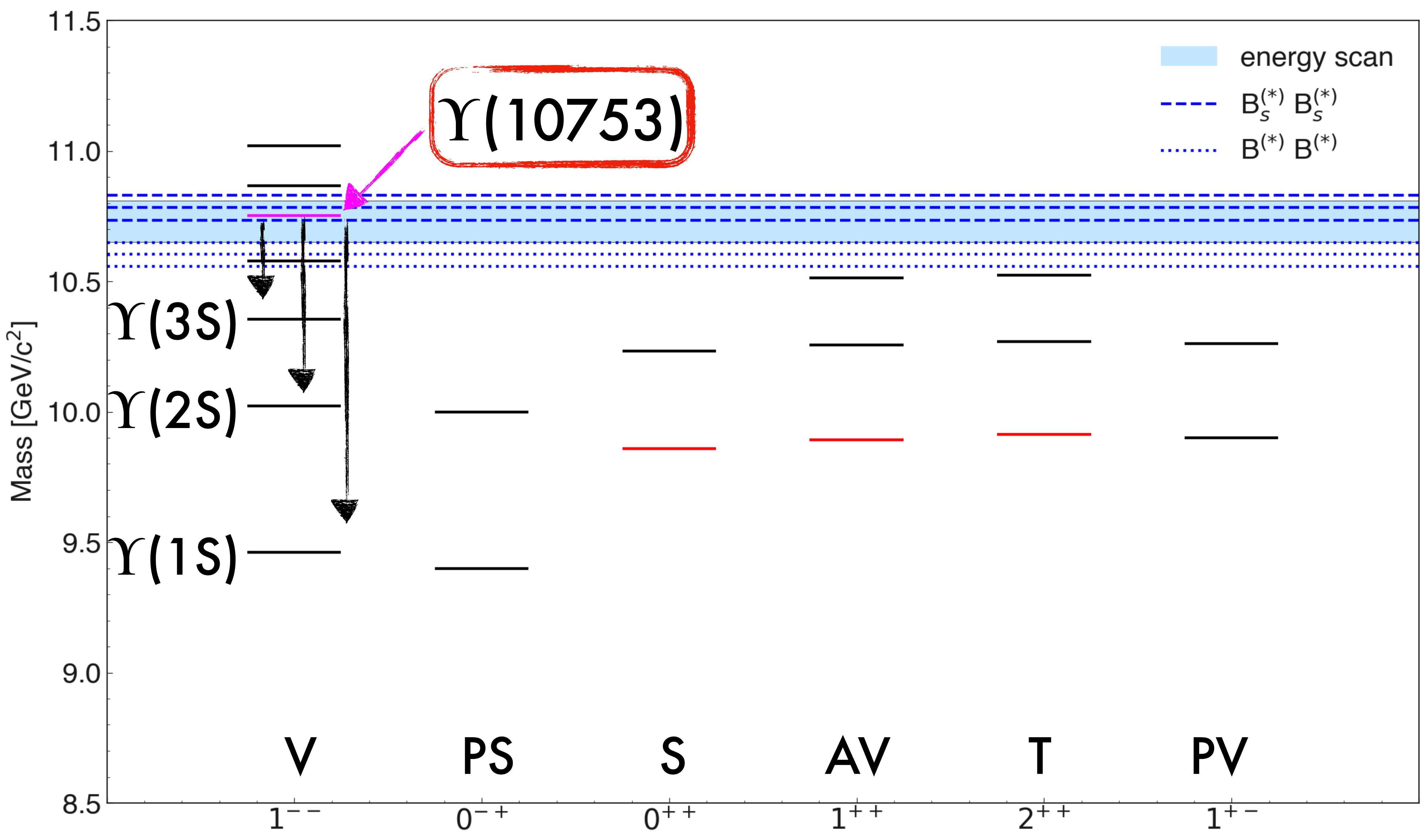


- Tetraquark? Molecule? Hybrid? Conventional $b\bar{b}$?
  - Conventional:
    PRD 101, 014020 (2020)
    EPJC 80, 59 (2020)
    PLB 803, 135340 (2020)
    PPNP 117, 103845 (2021)
    PRD 105, 074007 (2022)
    EPJP 137, 357 (2022)
    ...
  - Exotic:
    CPC 43, 123102 (2019)
    PLB 802, 135217 (2020)
    PRD 103, 074507 (2021)
    PRD 104, 034019 (2021)
    ...

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

arxiv: 2401.12021 (JHEP accepted)

- $\Upsilon(10753)$ discovery?
  - Existence confirmation?
  - Measure the di-pion spectrum
  - Z_b contributions?

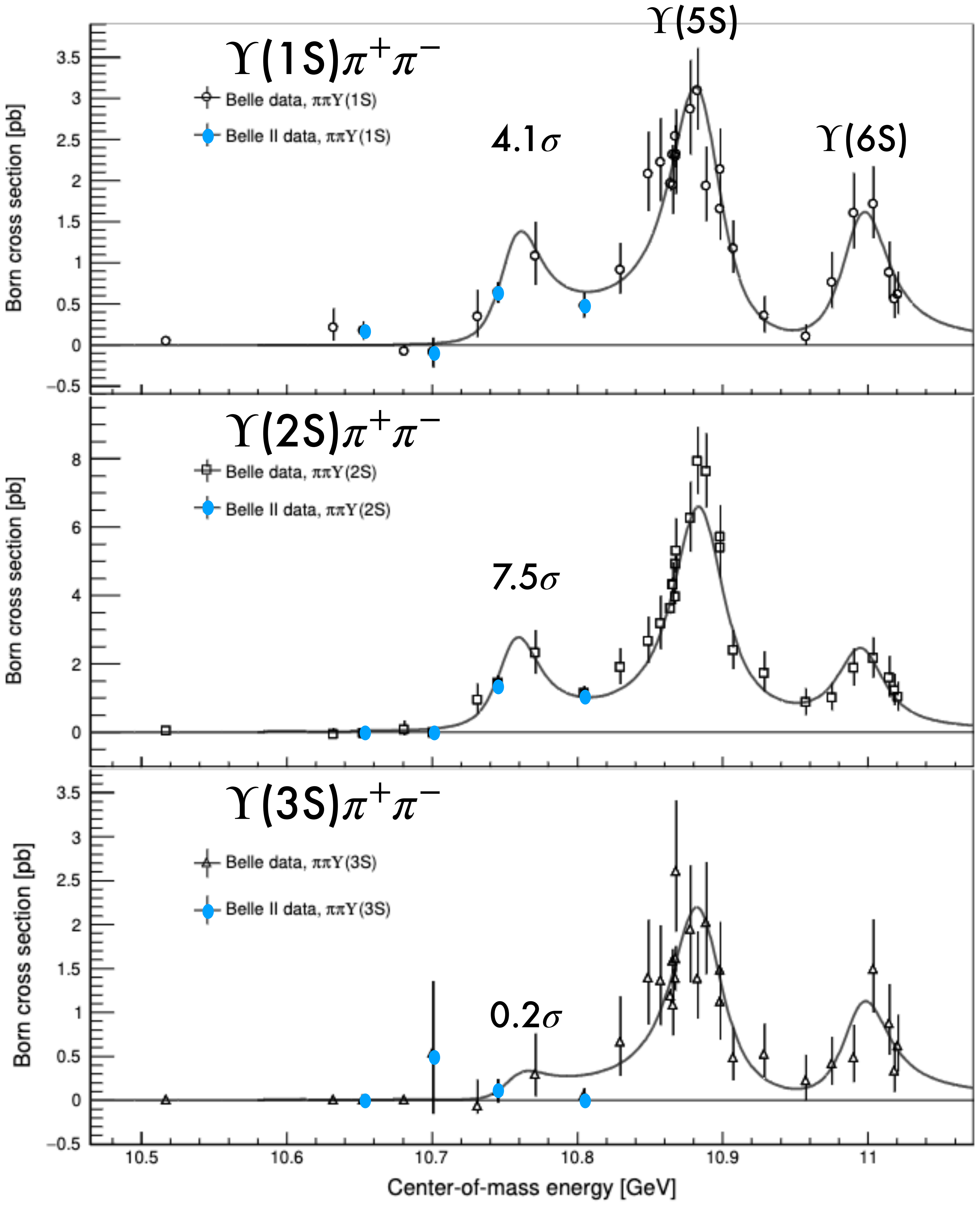


$e^+e^- \to \Upsilon(nS)\,\pi^+\pi^-$

arxiv: 2401.12021 (JHEP accepted)

- $\Upsilon(10753)$ discovery?
    - Existence - Confirmed
        - 8σ combined significance (Belle + Belle II)
        - Mass $10756.6 \pm 2.7 \pm 0.9$ MeV
        - Width $29.0 \pm 8.8 \pm 1.2$ MeV

$\mathcal{R}^{\Upsilon(10753)}_{\sigma(3S/2S)}$	$\mathcal{R}^{\Upsilon(5S)}_{\sigma(3S/2S)}$	$\mathcal{R}^{\Upsilon(6S)}_{\sigma(3S/2S)}$
$0.10^{+0.05}_{-0.04}$	$0.32^{+0.04}_{-0.03}$	$0.41^{+0.16}_{-0.12}$



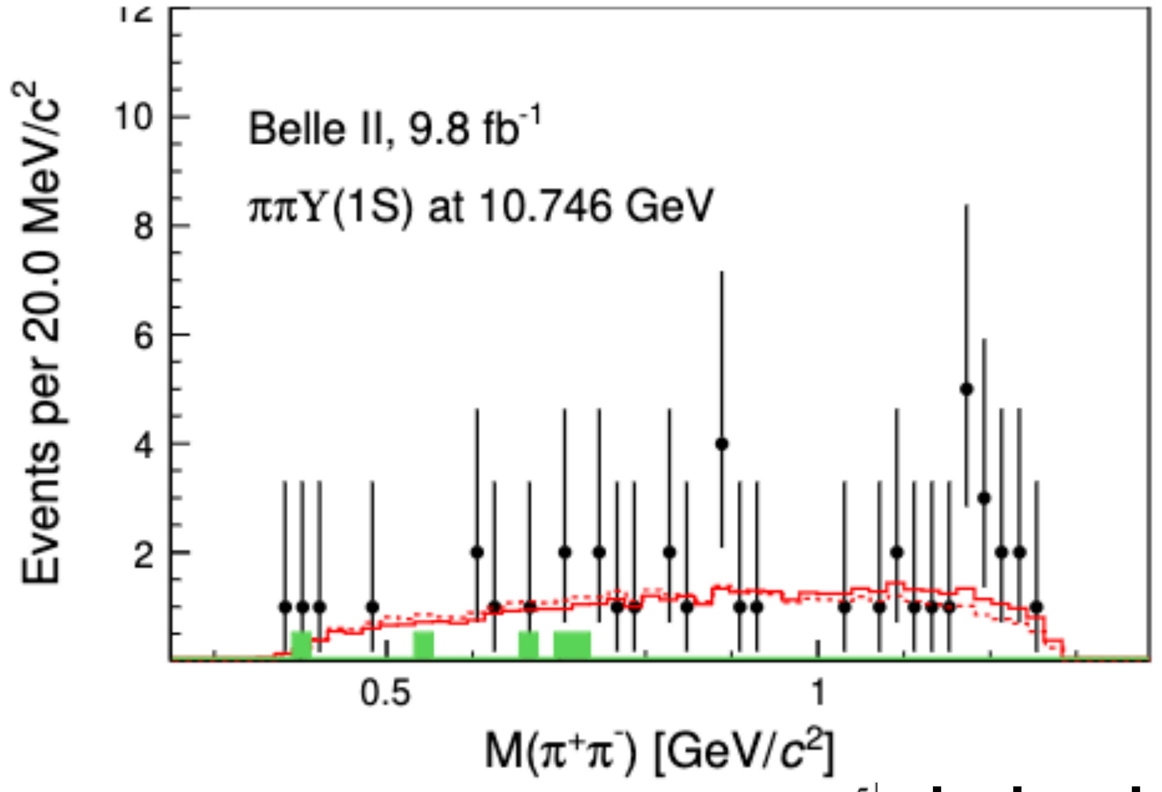
$e^+e^- \to \Upsilon(nS)\,\pi^+\pi^-$

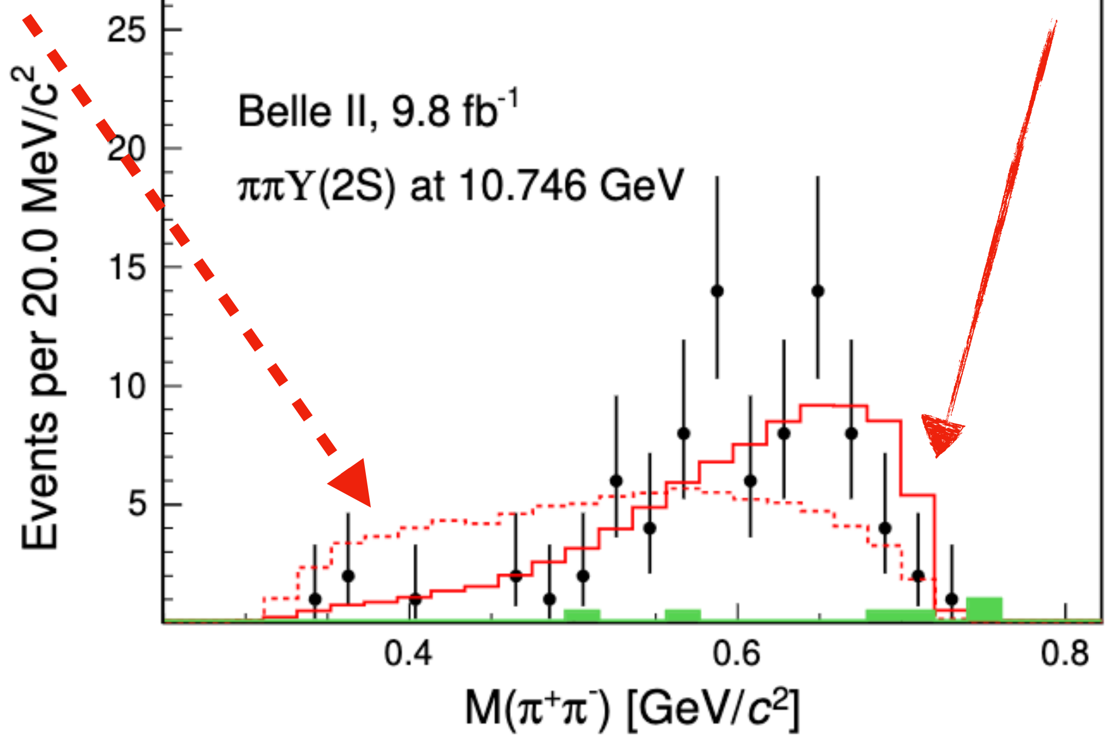
arxiv: 2401.12021 (JHEP accepted)

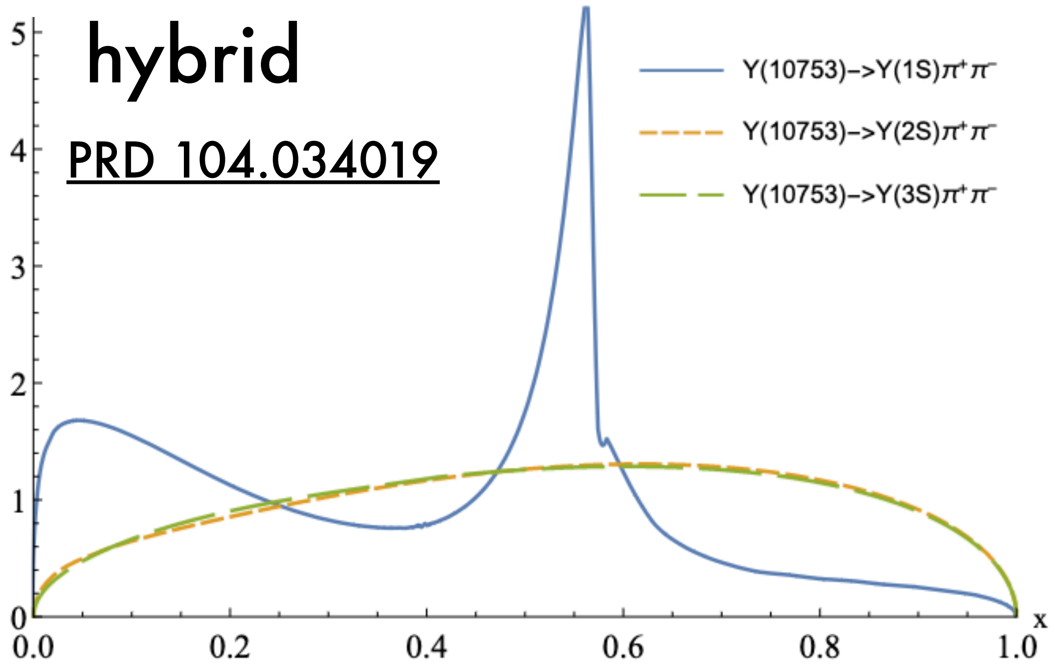
- $\Upsilon(10753)$ discovery?
  - Existence - Confirmed
  - Measure the di-pion spectrum

PHSP parametrisation

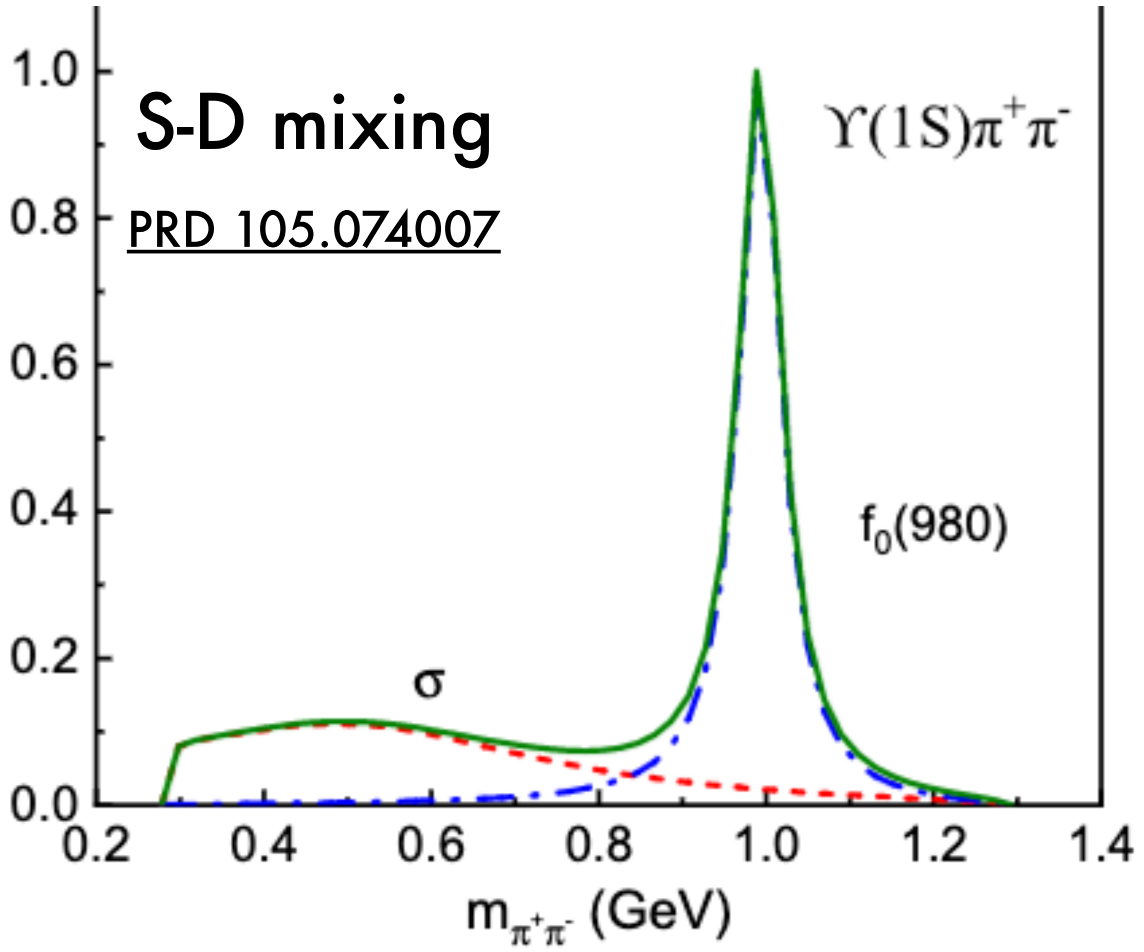
Belle weighted simulated signal

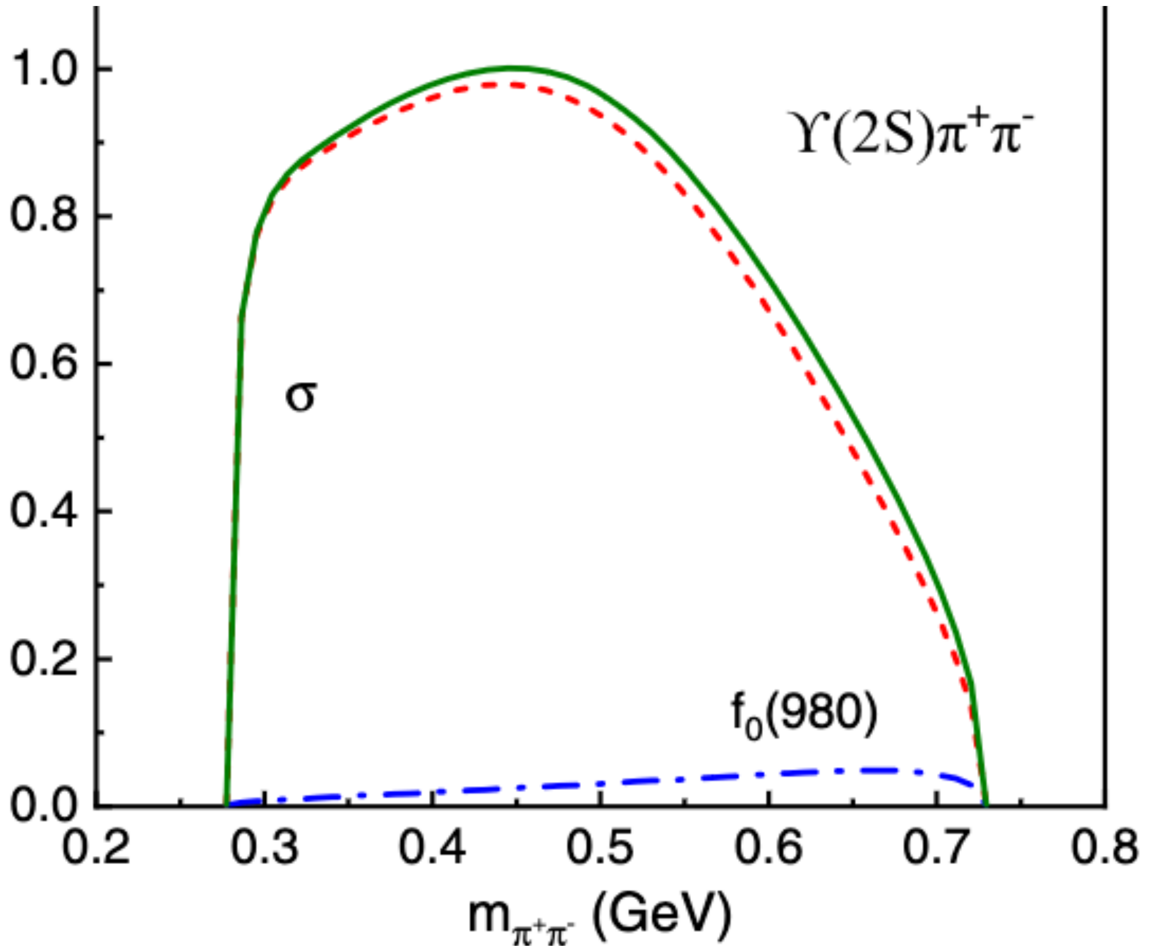






- No sign of hybrid
- No sign of S-D mixing

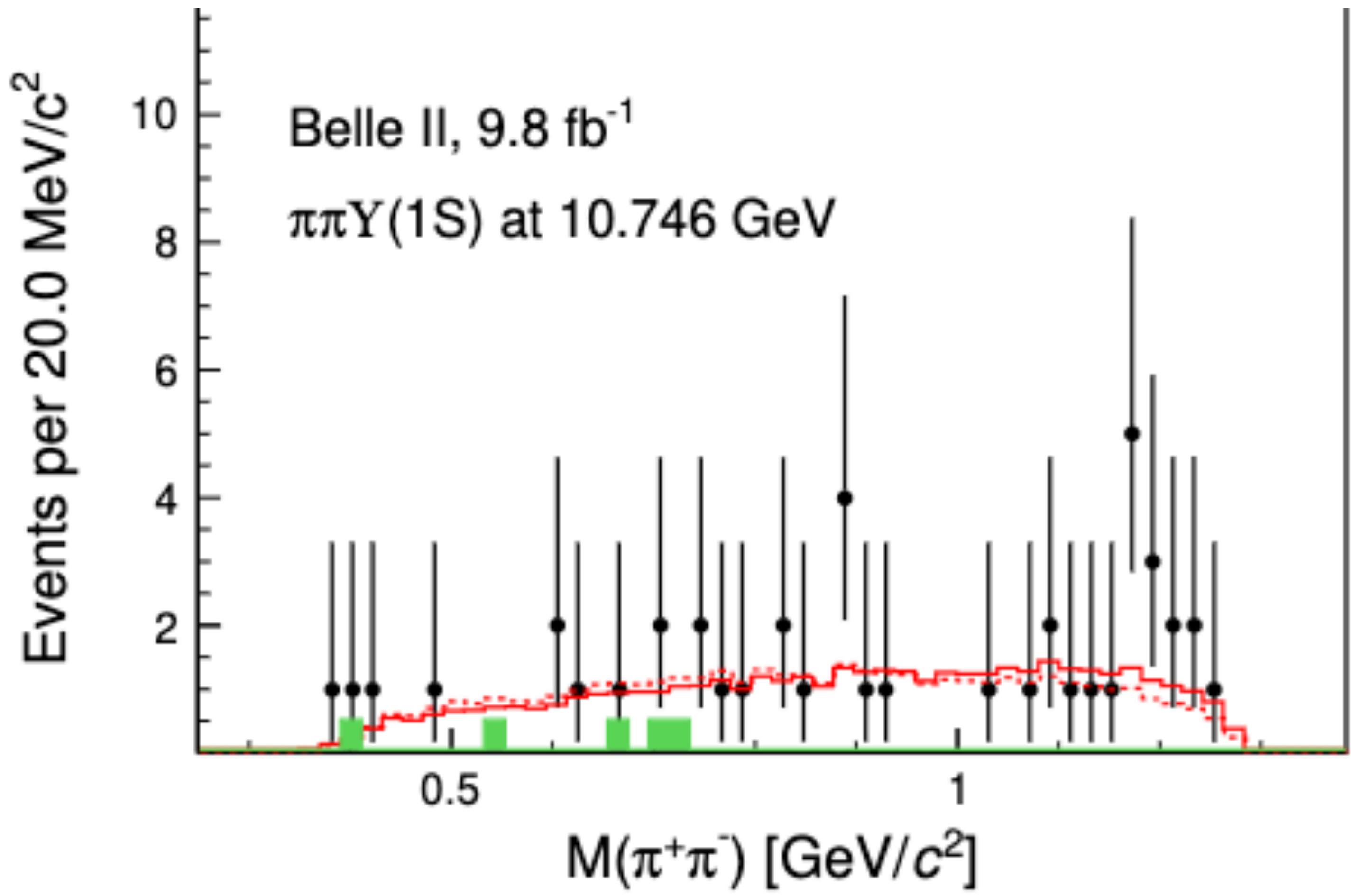




$e^+e^- \to \Upsilon(nS)\,\pi^+\pi^-$

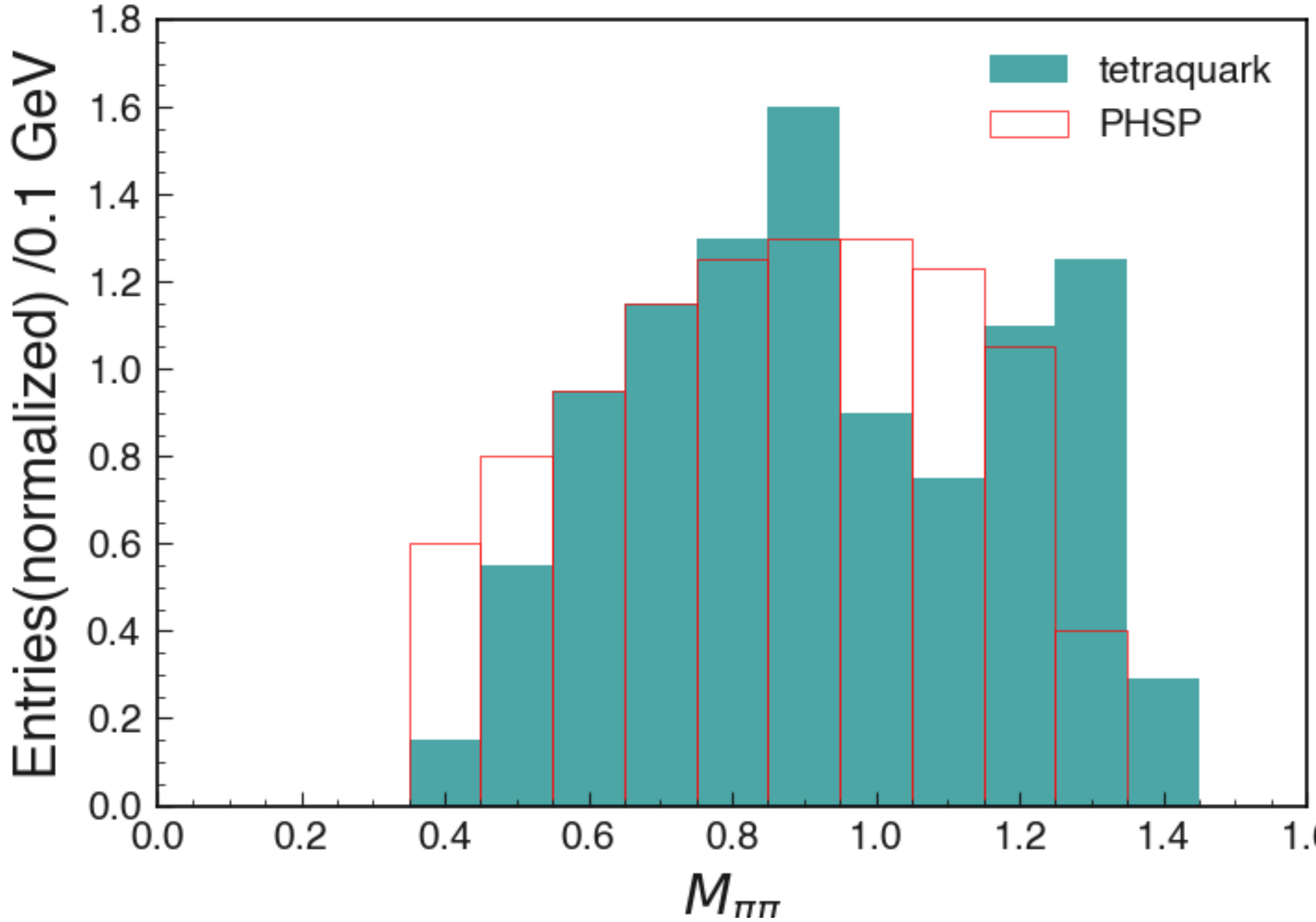
arxiv: 2401.12021 (JHEP accepted)

- Υ(10753) discovery?
  - Existence - Confirmed
  - Measure the di-pion spectrum
    - Tetraquark?



another tetraquark interpretation:

$$\frac{\Gamma(\eta_b\omega)}{\Gamma(Y\pi^-\pi^+)} \approx 30$$ CPC 43, 123102



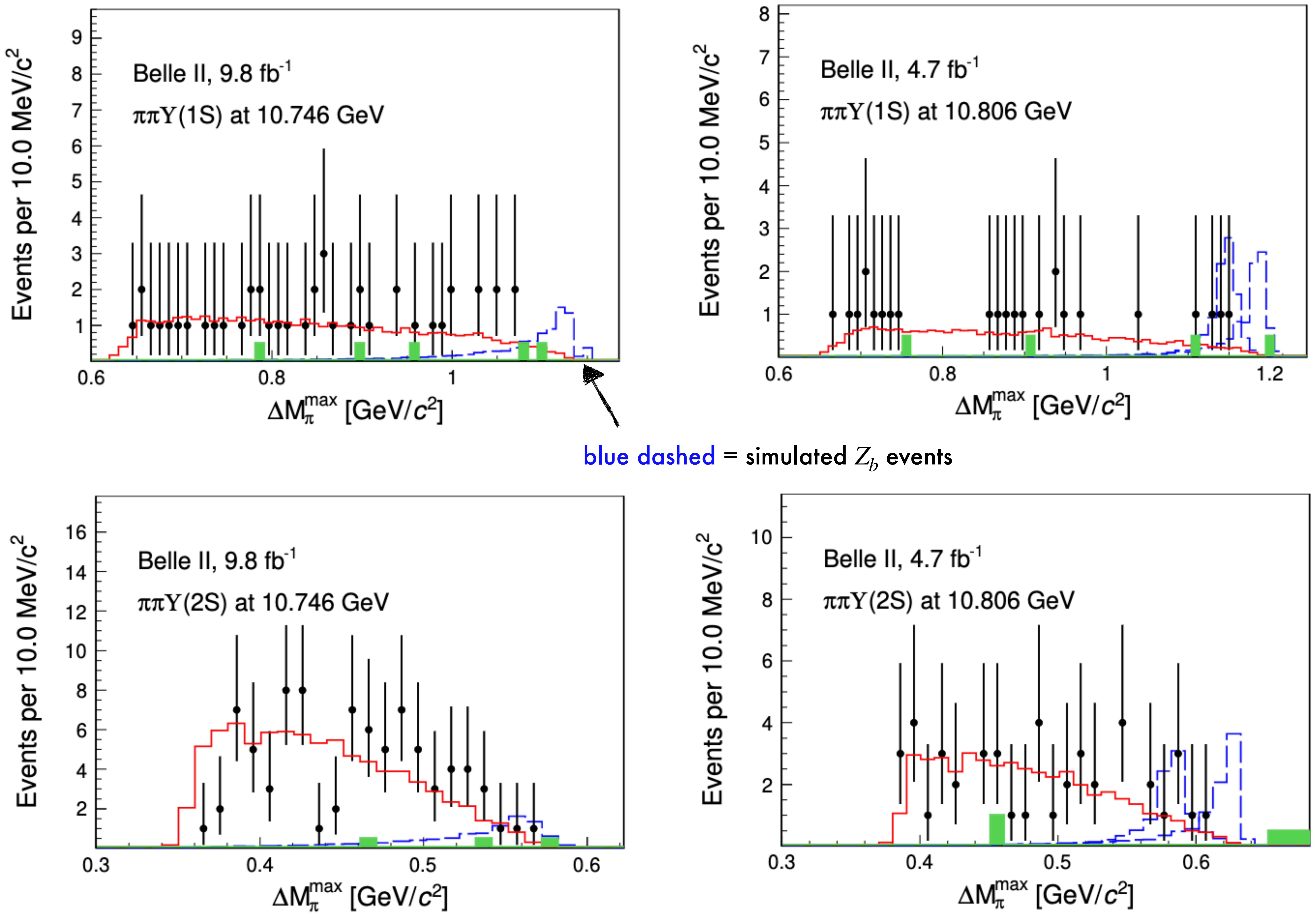
PLB 2020.135217

$$\sigma(e^+e^- \to \omega\eta_b) < 2.5 \text{ pb}$$
$$\sigma(e^+e^- \to \pi^+\pi^-\Upsilon(nS)) \approx 2.0 \text{ pb}$$
$$\to \frac{\Gamma_{exp}(\eta_b\omega)}{\Gamma_{exp}(Y\pi^-\pi^+)} < 1.25$$

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

arxiv: 2401.12021 (JHEP accepted)

- $\Upsilon(10753)$ discovery?
  - Existence - Confirmed
  - Measure the di-pion spectrum
  - $Z_b(10610/10650)$ contributions?
    - No Z_b contributions found in $\Delta M_\pi = M(\pi\mu\mu) - M(\mu\mu)$



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

arxiv: 2401.12021 (JHEP accepted)

- Confirmed Belle result with peaking cross section at 10.75 GeV
- No hints of hybrid- or S-D-mixing-structure
- No signal of Z_b resonances in ΔM_π observed
- Compatible with tetraquark?

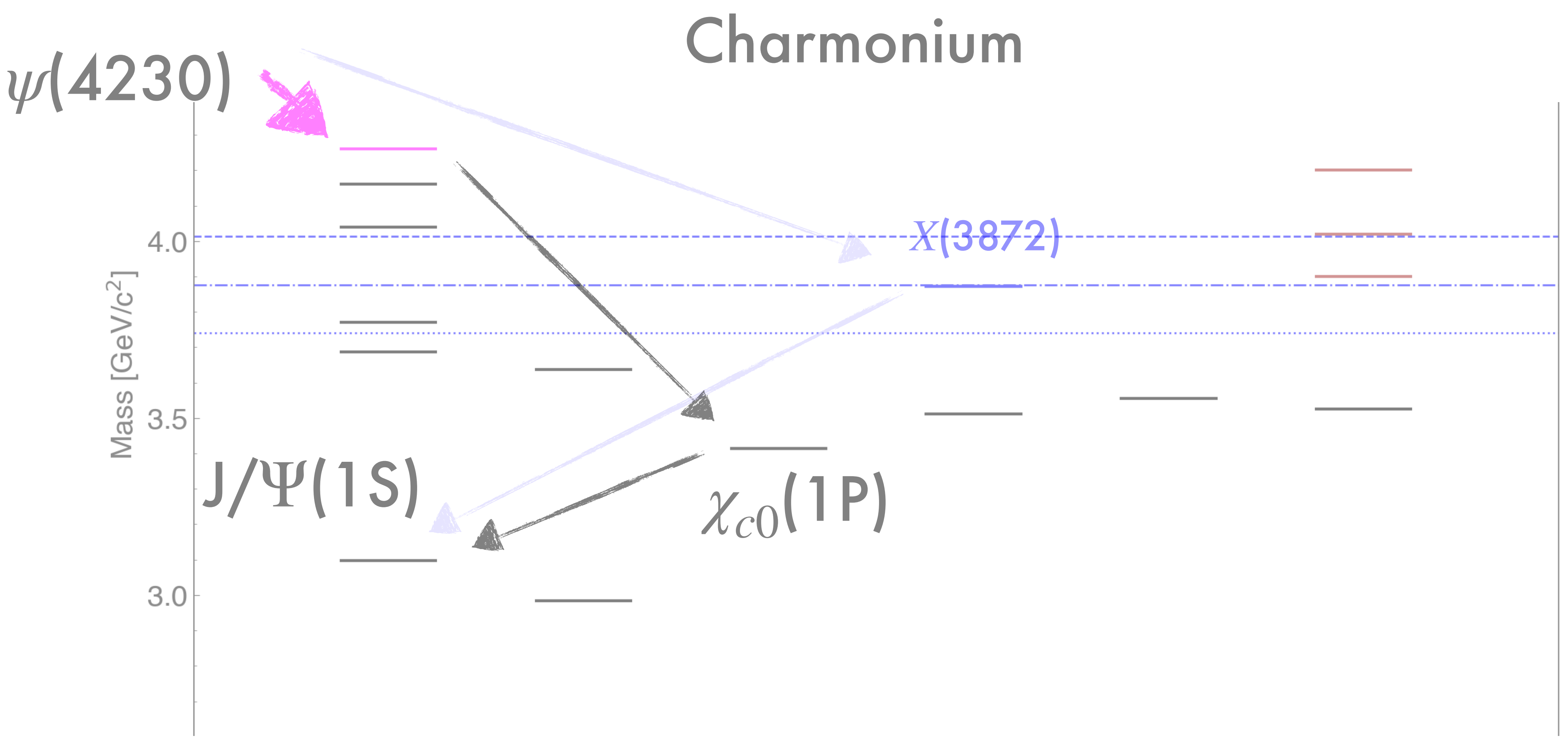
Υ(10753) = Bottomonium Counterpart Of ψ(4230)?

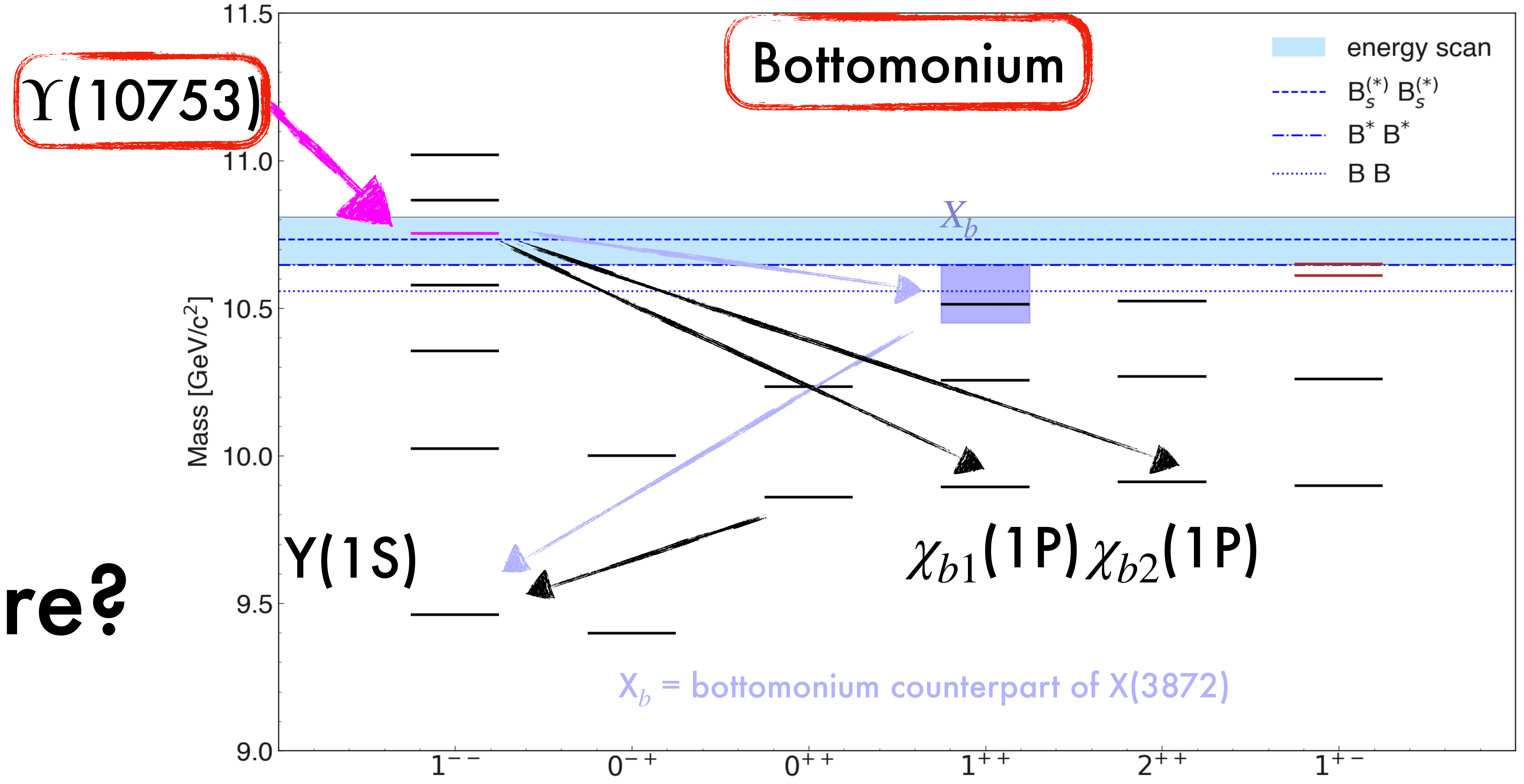
$\psi(4230) \leftrightarrow \Upsilon(10753)$?

- $\psi(4230)$ was observed in $e^+e^- \to J/\Psi(1S)\,\pi^+\pi^-$ by BaBar, BESIII, Belle arxiv:1303.5949

- $\psi(4230)$ transitions
  $\to \omega\chi_{cJ}(1P)$
  $\to \gamma\, X(3872)$
  also seen

- Hypothesis: $\Upsilon(10753)$ similar in nature?

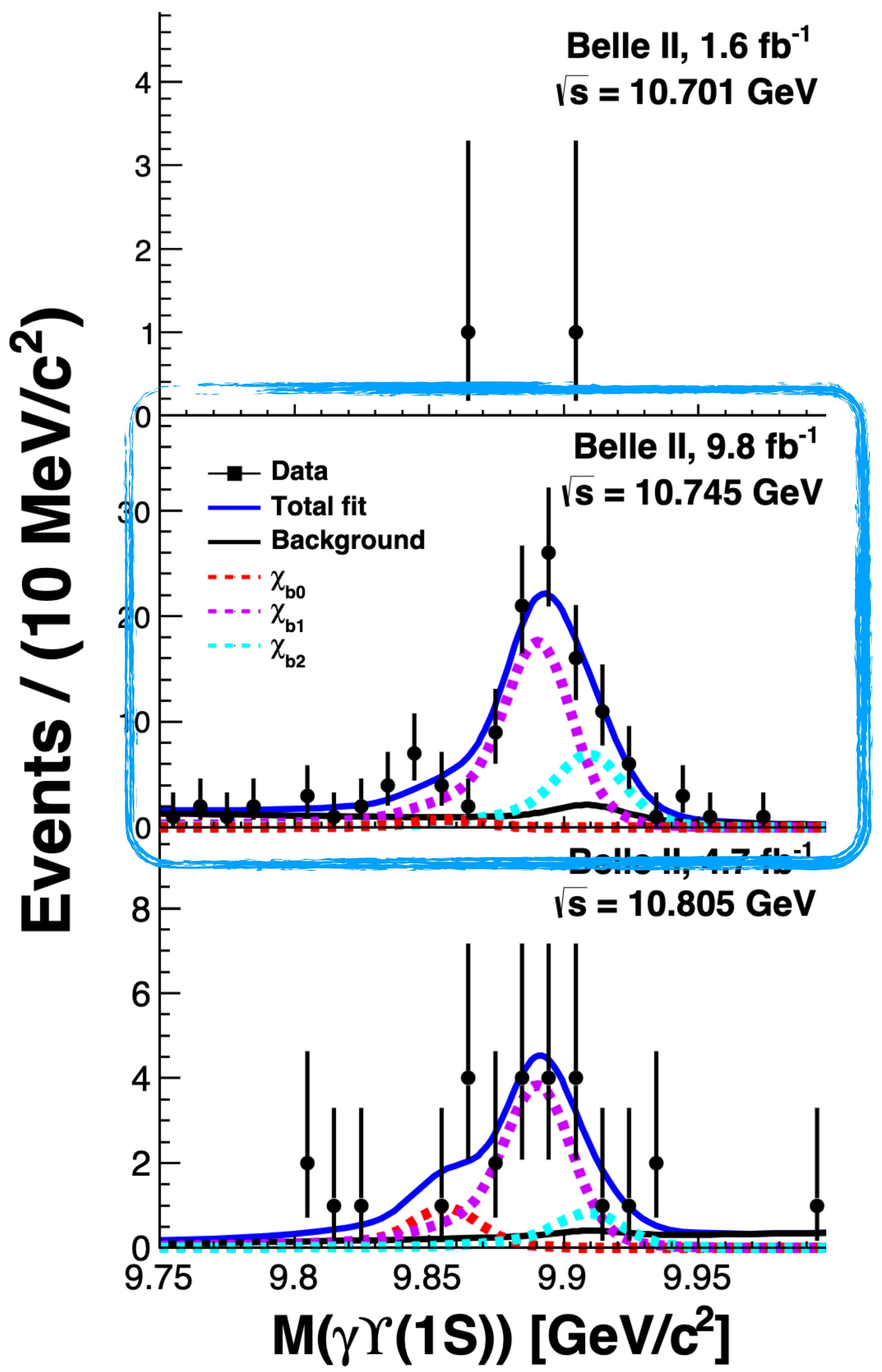


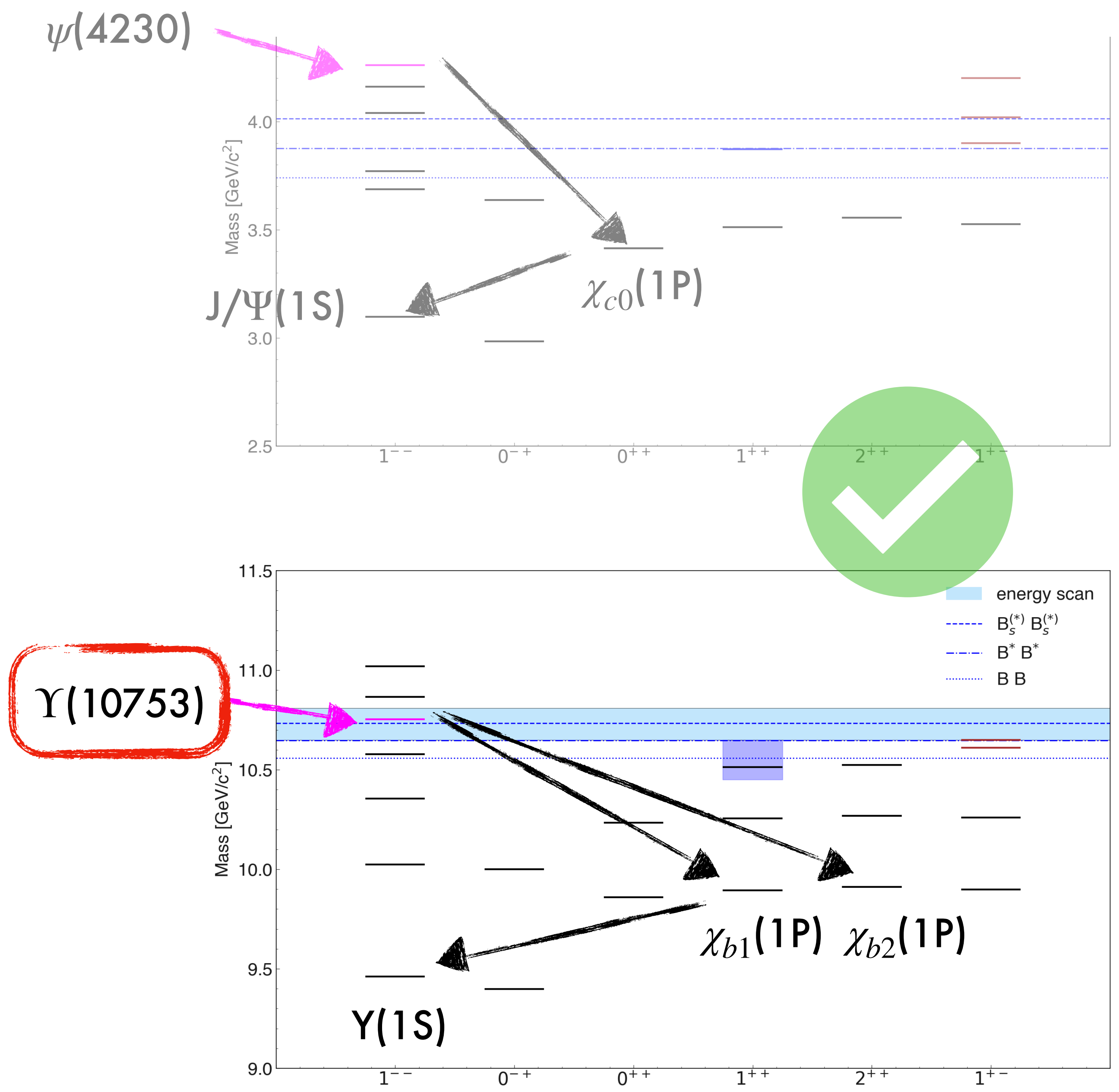


$\psi(4230) \leftrightarrow \Upsilon(10753)$?

PRL 130 091902

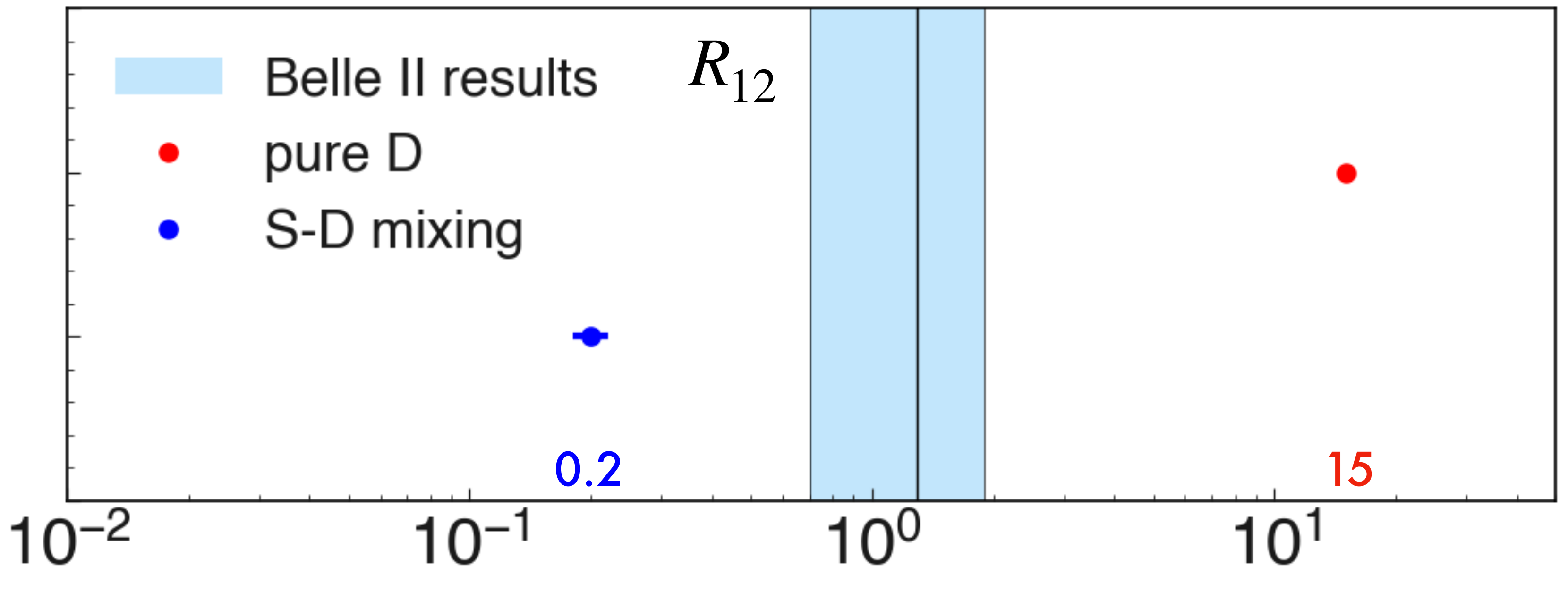
- Hypothesis: similar nature of $\Upsilon(10753)$?
- Observed new transitions: $\Upsilon(10753) \to \omega\chi_{bJ}$!





- Further investigation:

$$R_{12} = \frac{\Gamma_{ee} \times B[\Upsilon(10753) \to \omega\chi_{b1}(1P)]}{\Gamma_{ee} \times B[\Upsilon(10753) \to \omega\chi_{b2}(1P)]} = 1.3 \pm 0.6$$



PRD 104, 034036 (2021)   PLB 2014.09.043

Compare cross-section

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

Different internal structure than Y(5S)?

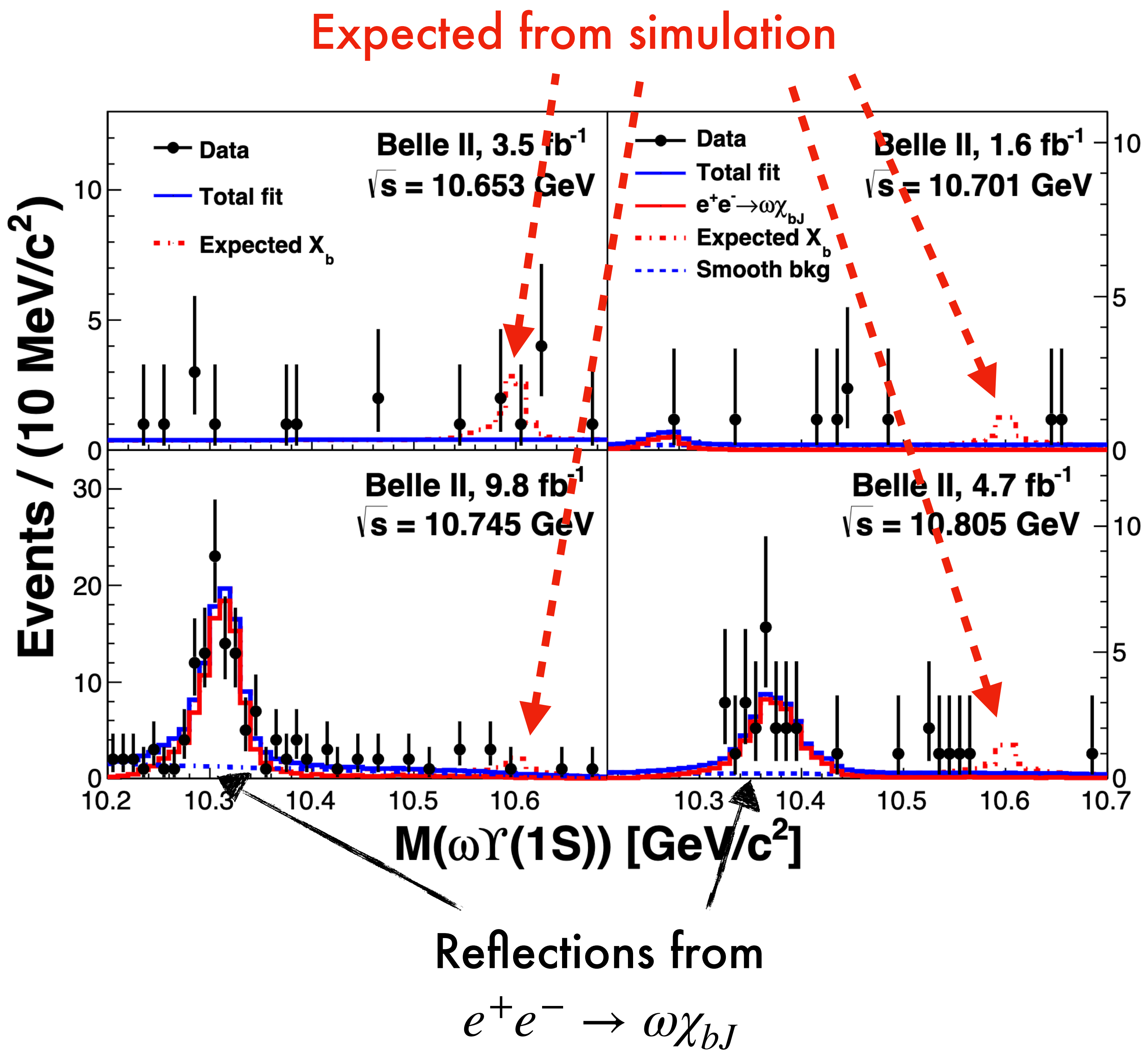
$\psi(4230) \leftrightarrow \Upsilon(10753)$?

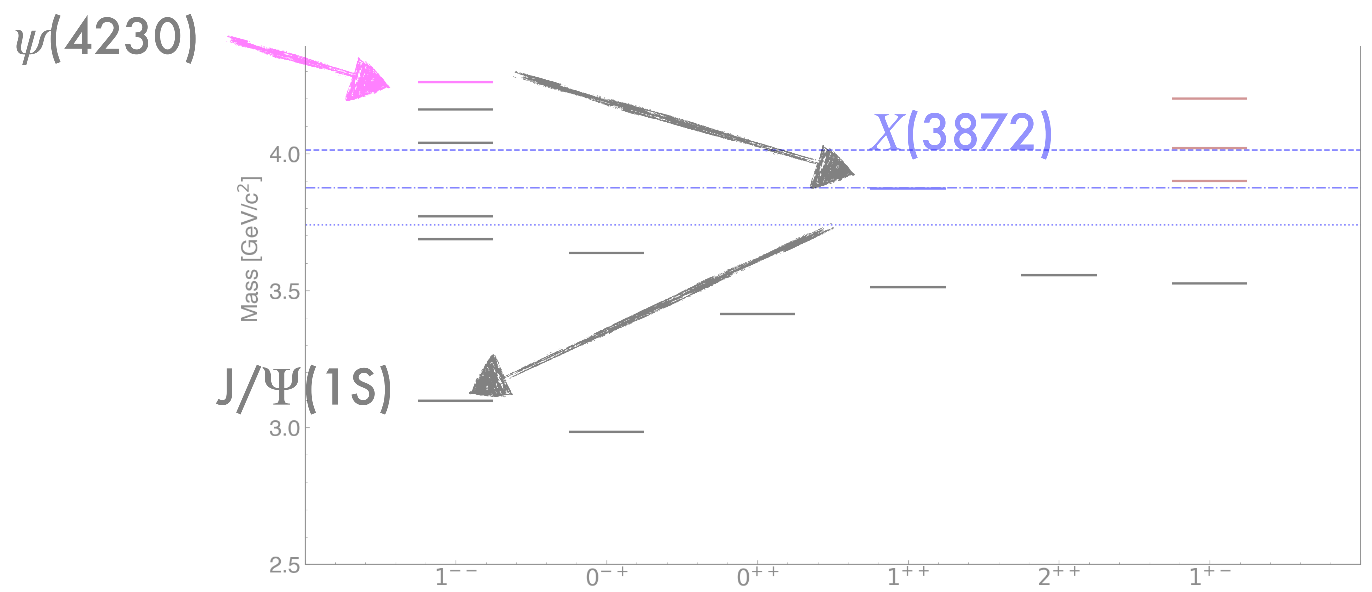
PRL 130 091902

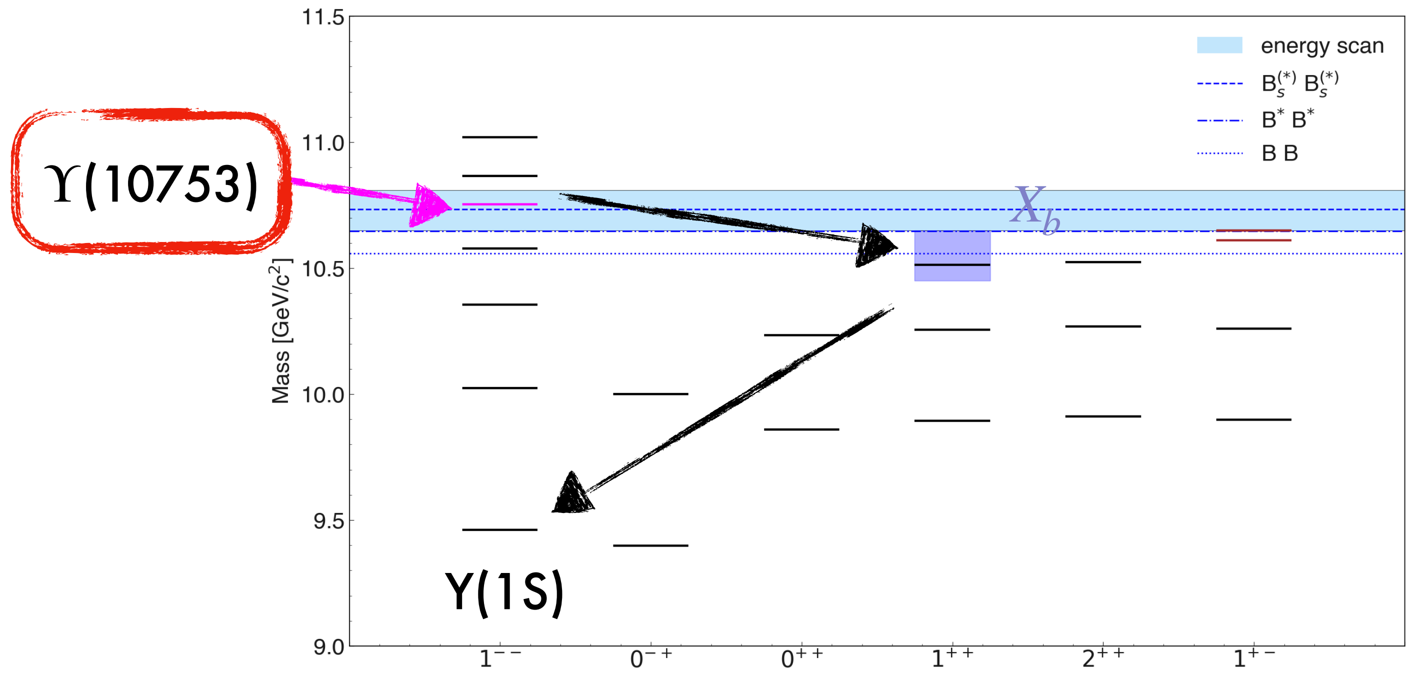
- Hypothesis: similar nature of $\Upsilon(10753)$?
- Access to X_b due to same final states as in $\omega\chi_{bJ}$!
- X_b predicted in molecular and tetraquark models
- No X_b structure found
  $\rightarrow$ set upper limits

10.45 GeV < M(X_b) < 10.65 GeV

$\sqrt{s}$ GeV	$\sigma_B(e^+e^- \to \gamma X_b) \times B(X_b \to \omega\Upsilon(1S))$
10.653	(0.14-0.55) pb
10.701	(0.25–0.84) pb
10.745	(0.06–0.14) pb
10.805	(0.08–0.37) pb







X_b = bottomonium counterpart of X(3872)

Summary

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

- Confirmed Υ(10753)-state and observed Υ(10753) $\rightarrow \omega\chi_{bJ}$(1P)

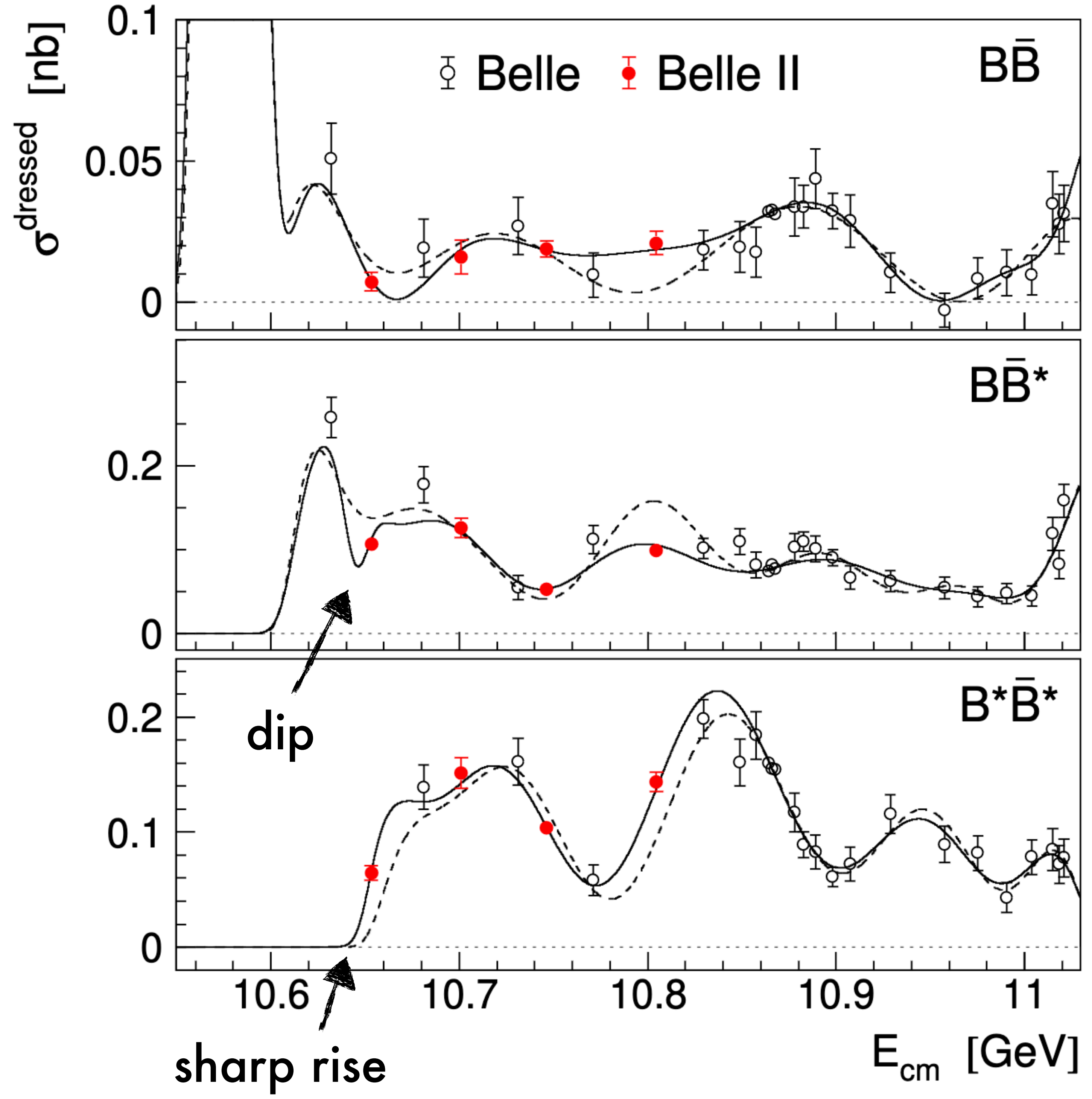
- Several indications of the structure of Υ(10753), but no clear explanation

- No bottomonium analog of X(3872) seen

- Rich quarkonium physics program where many analyses on 4S and energy scan data are ongoing ($\pi\pi h_b(1P)$, $\eta h_b(1P)$, $B\bar{B}$,...)

arxiv:2405.18928

Outlook to open flavour channel



Thanks!

Backup

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

PRD 109.072013

- $\psi(4230) \rightarrow \chi_{c0}$ enhanced in the charmonium sector w.r.t. χ_{c1} and χ_{c2}

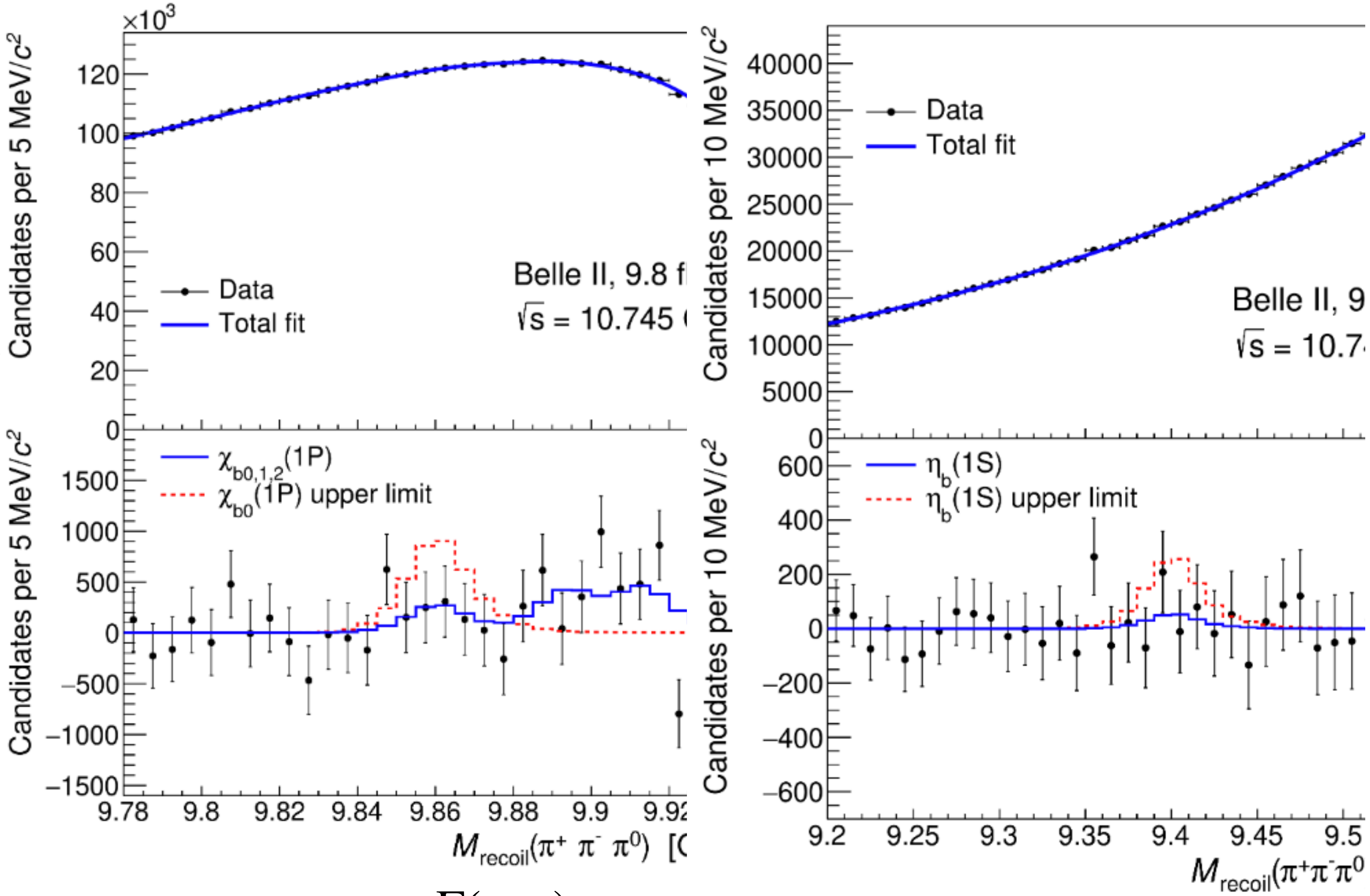
- No such behaviour found for Υ_b

$$\sigma_{\mathrm{B}}(e^+e^- \rightarrow \chi_{b0}(1P)\omega) < 7.8\,\mathrm{pb.}$$

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

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

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



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

CPC 43, 123102

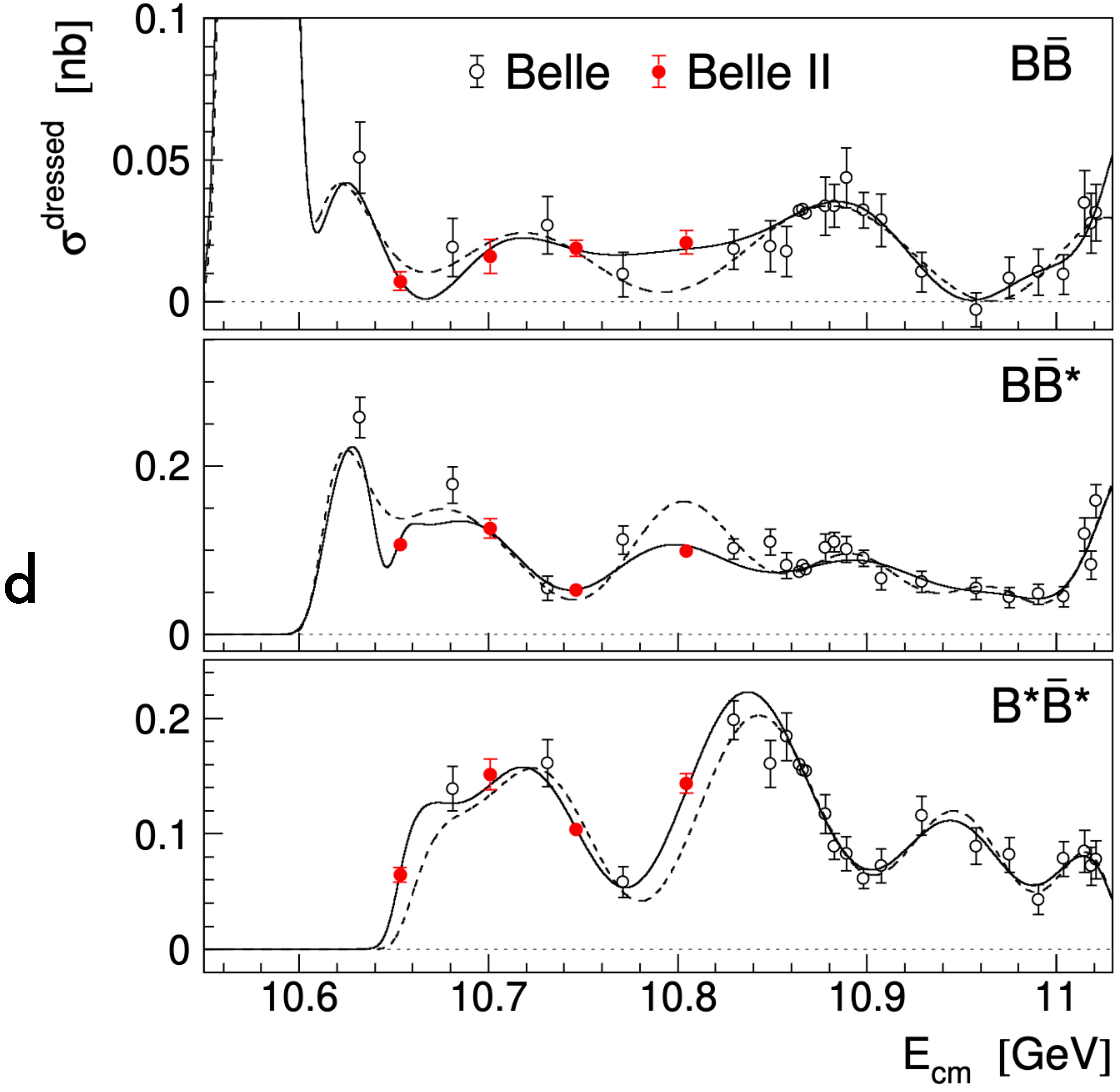
4S-3D mixed state: $\dfrac{\Gamma(\eta_b\omega)}{\Gamma(Y\pi^-\pi^+)} \approx (0.2 - 0.4)$

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

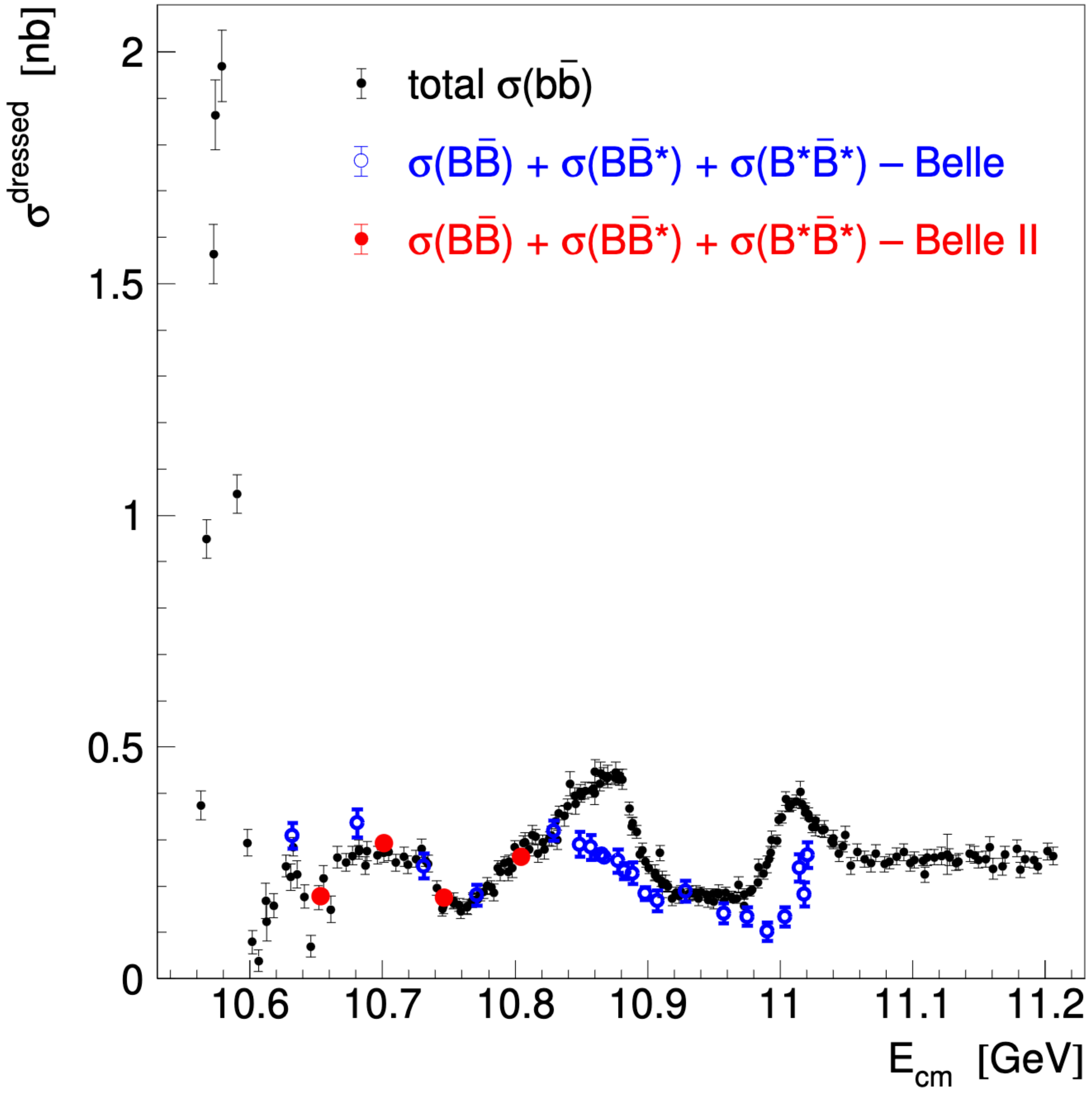


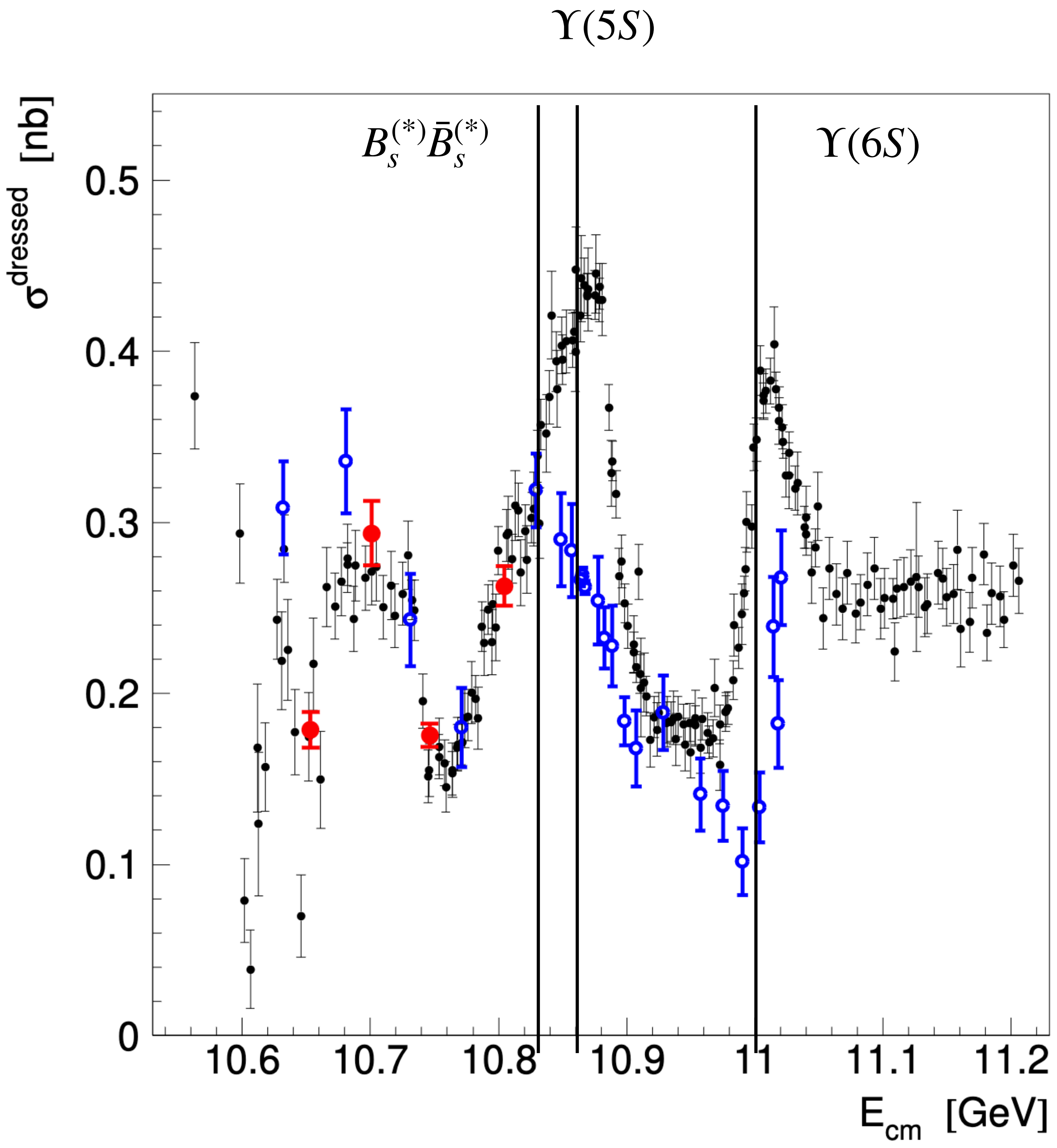
- Sharp rise in $B^*\bar{B}^*$ just above threshold and dip in $B\bar{B}^*$ at $B^*\bar{B}^*$ threshold → bound state?

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

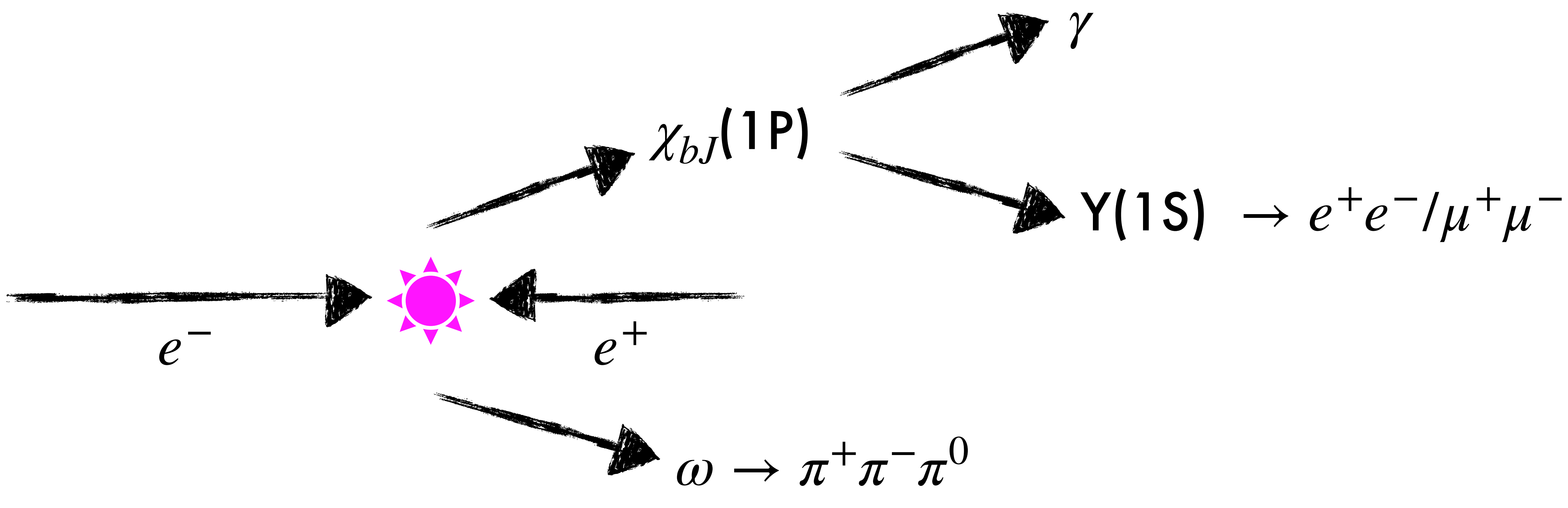
arxiv:2405.18928

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

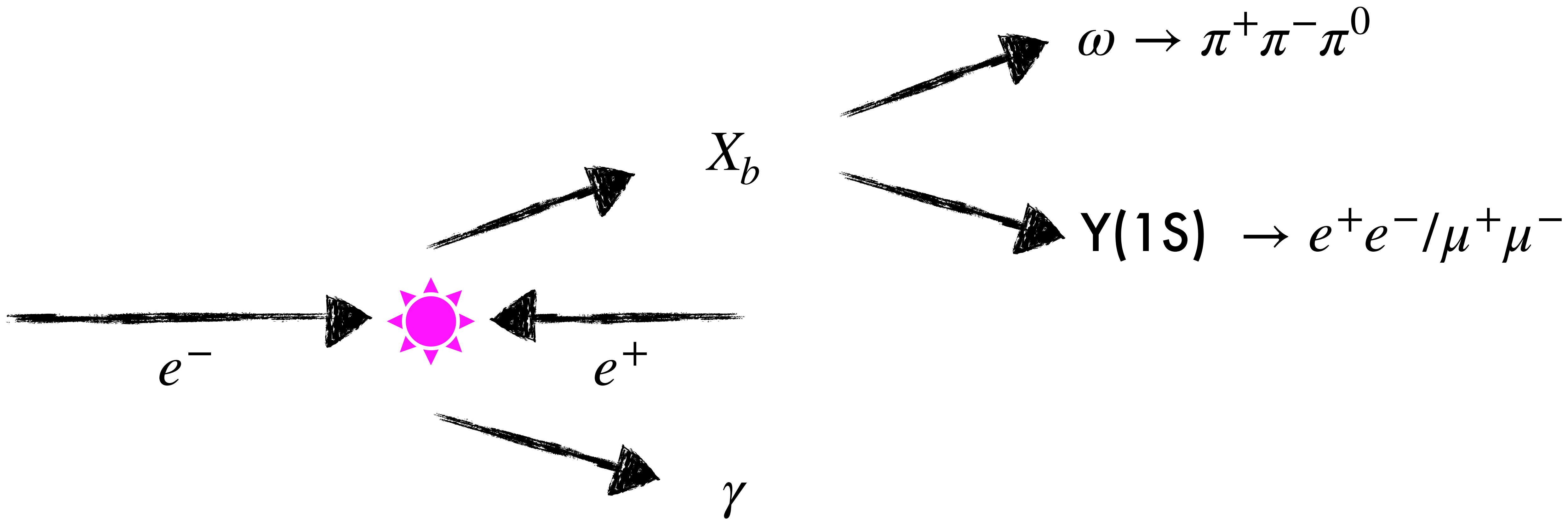


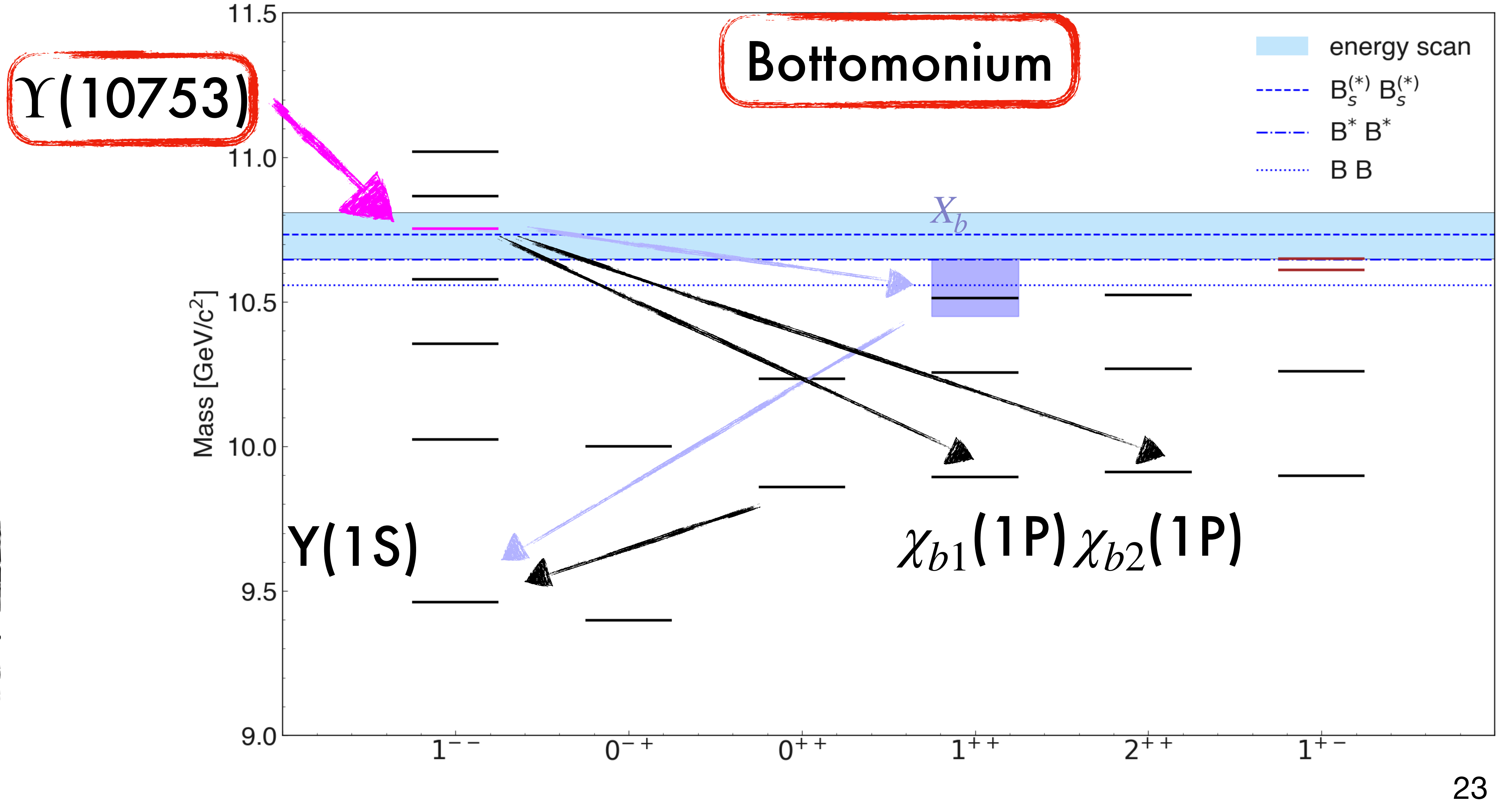


$e^+e^- \to \chi_{bJ}(1P)\,\omega$ PRL 130 091902



Same final states!

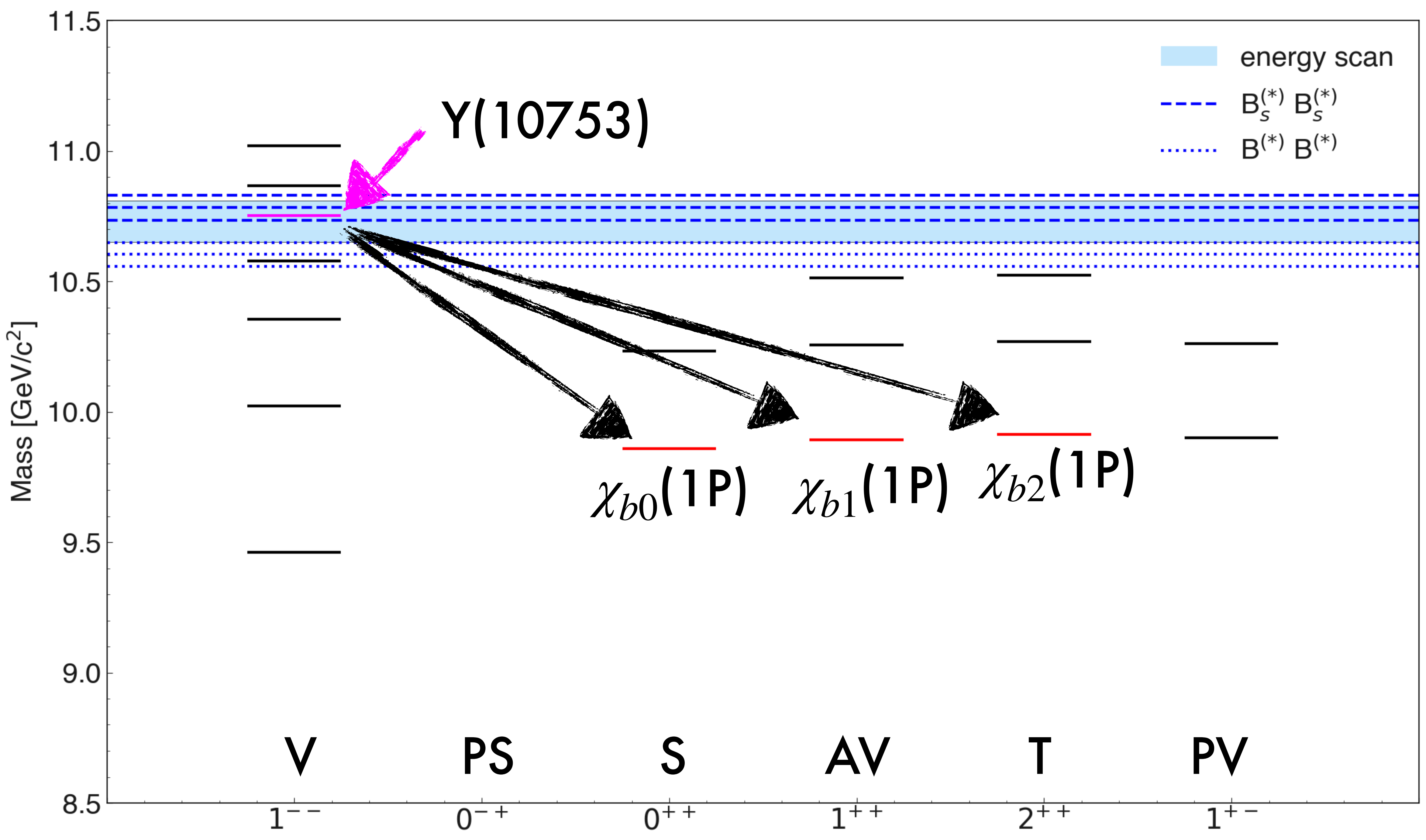




X_b = bottomonium counterpart of X(3872)

$e^+e^- \rightarrow \chi_{bJ}$(1P) ω - event selection

- Υ(10753) $\rightarrow \chi_{bJ}(1P)\ \omega$
- 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



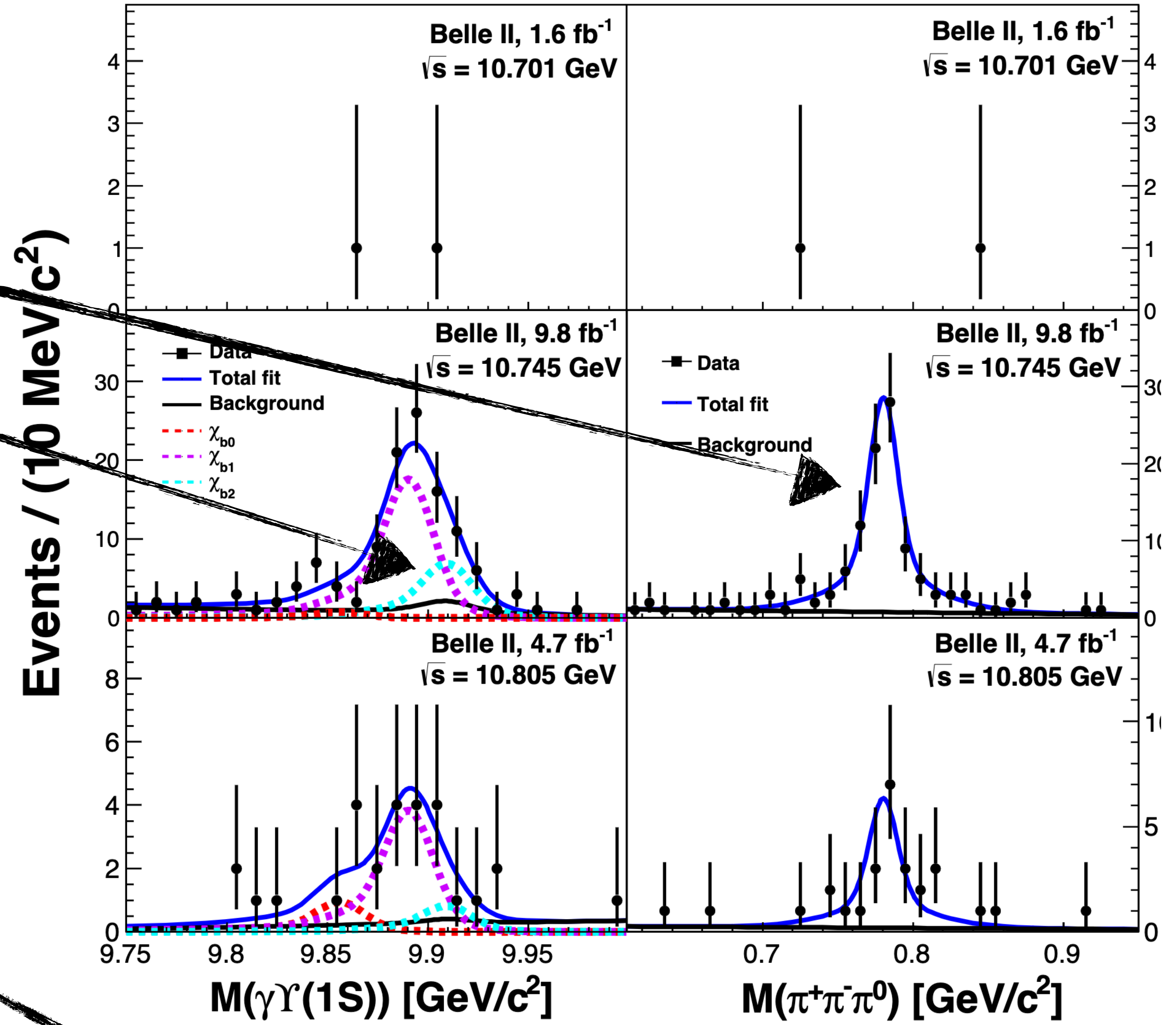
$e^+e^- \rightarrow \chi_{bJ}$(1P) ω - event selection

- 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)

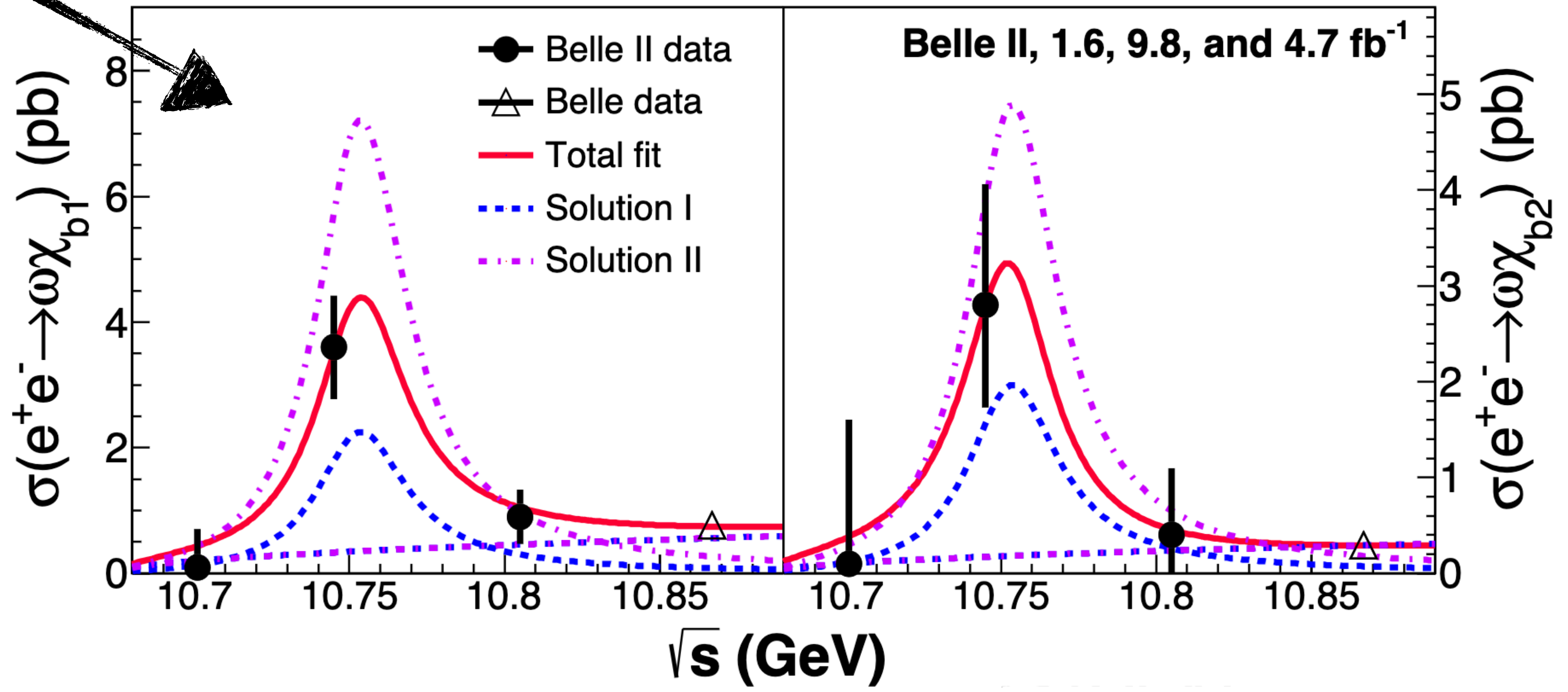


Fixed fit-parameters:
Mass = 10752.7 MeV/c^2
Width = 35.5 MeV

- Constructive (I) and destructive (II) solutions

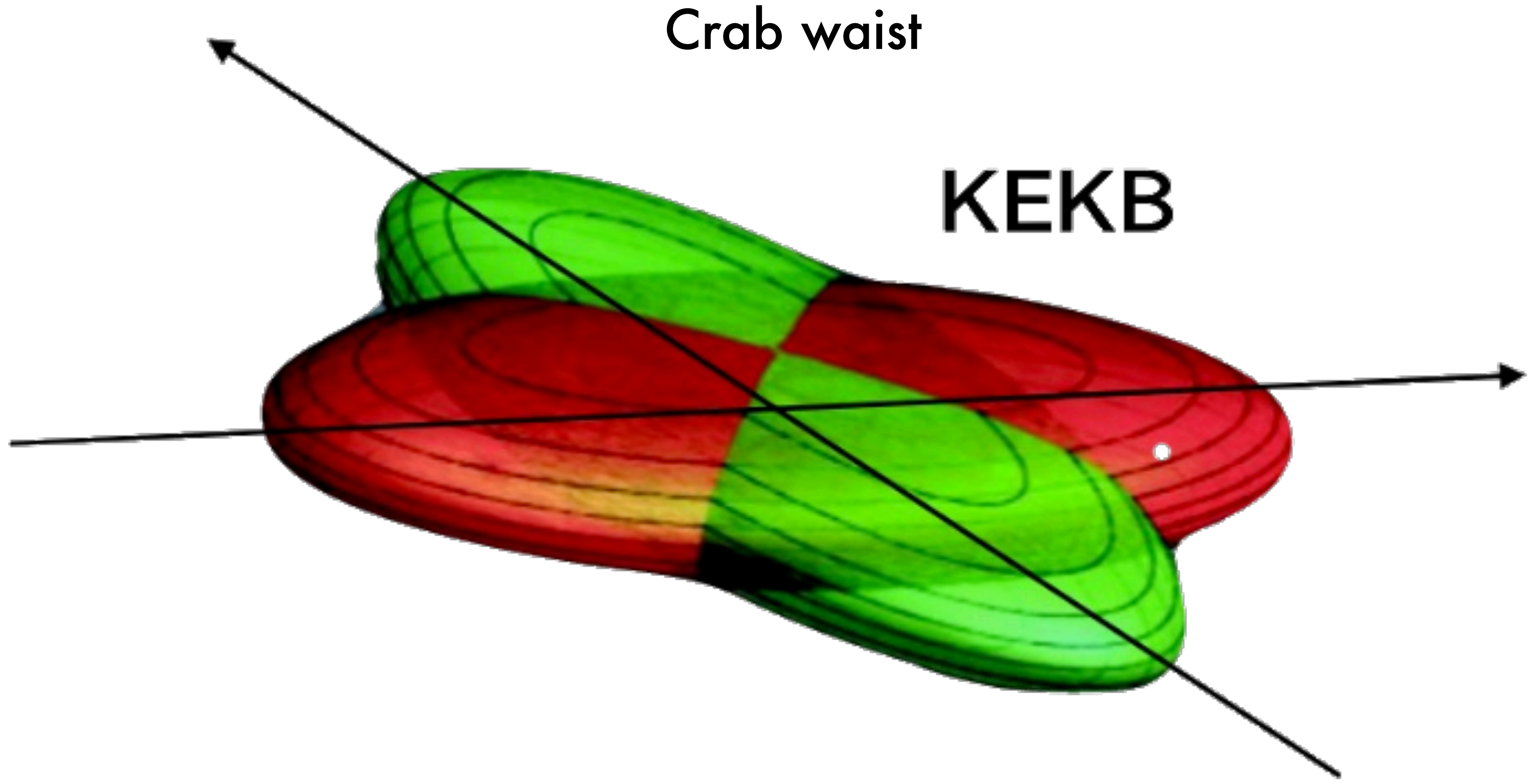
  - $\Gamma_{ee} \times B(e^+e^- \rightarrow \omega\chi_{b1}(1P)) = \begin{matrix} (I)\ 0.63 \pm 0.39 \pm 0.20 \\ (II)\ 2.01 \pm 0.38 \pm 0.76 \end{matrix}$ eV

  - $\Gamma_{ee} \times B(e^+e^- \rightarrow \omega\chi_{b2}(1P)) = \begin{matrix} (I)\ 0.53 \pm 0.46 \pm 0.15 \\ (II)\ 1.32 \pm 0.44 \pm 0.55 \end{matrix}$ eV

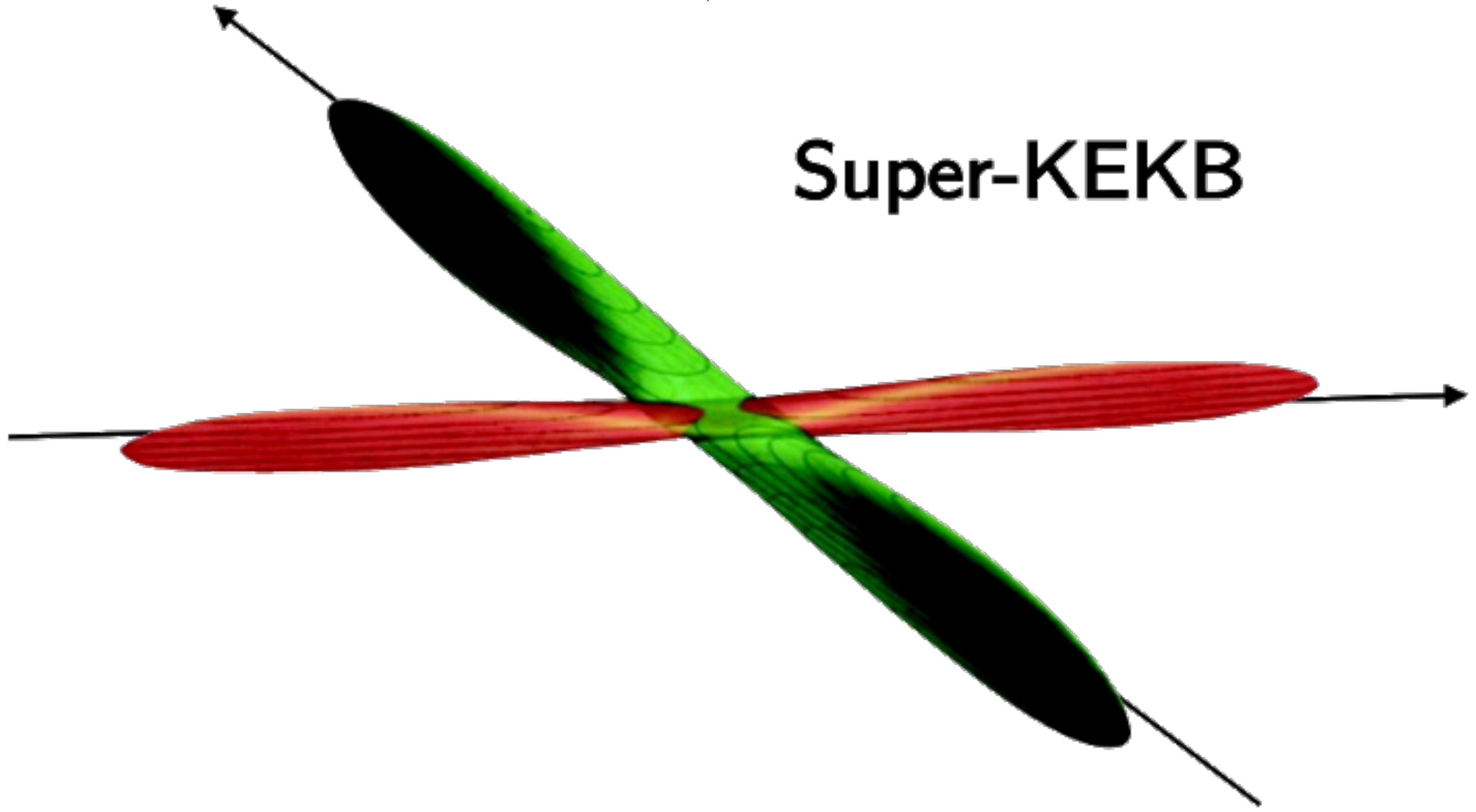


Nano beam scheme

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	

	KEKB Achieved	SuperKEKB
σ_y^*	$= 940$ nm	$= 48/62$ nm
σ_x^*	$= 147/170\ \mu$m	$= 10.1/10.7\ \mu$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

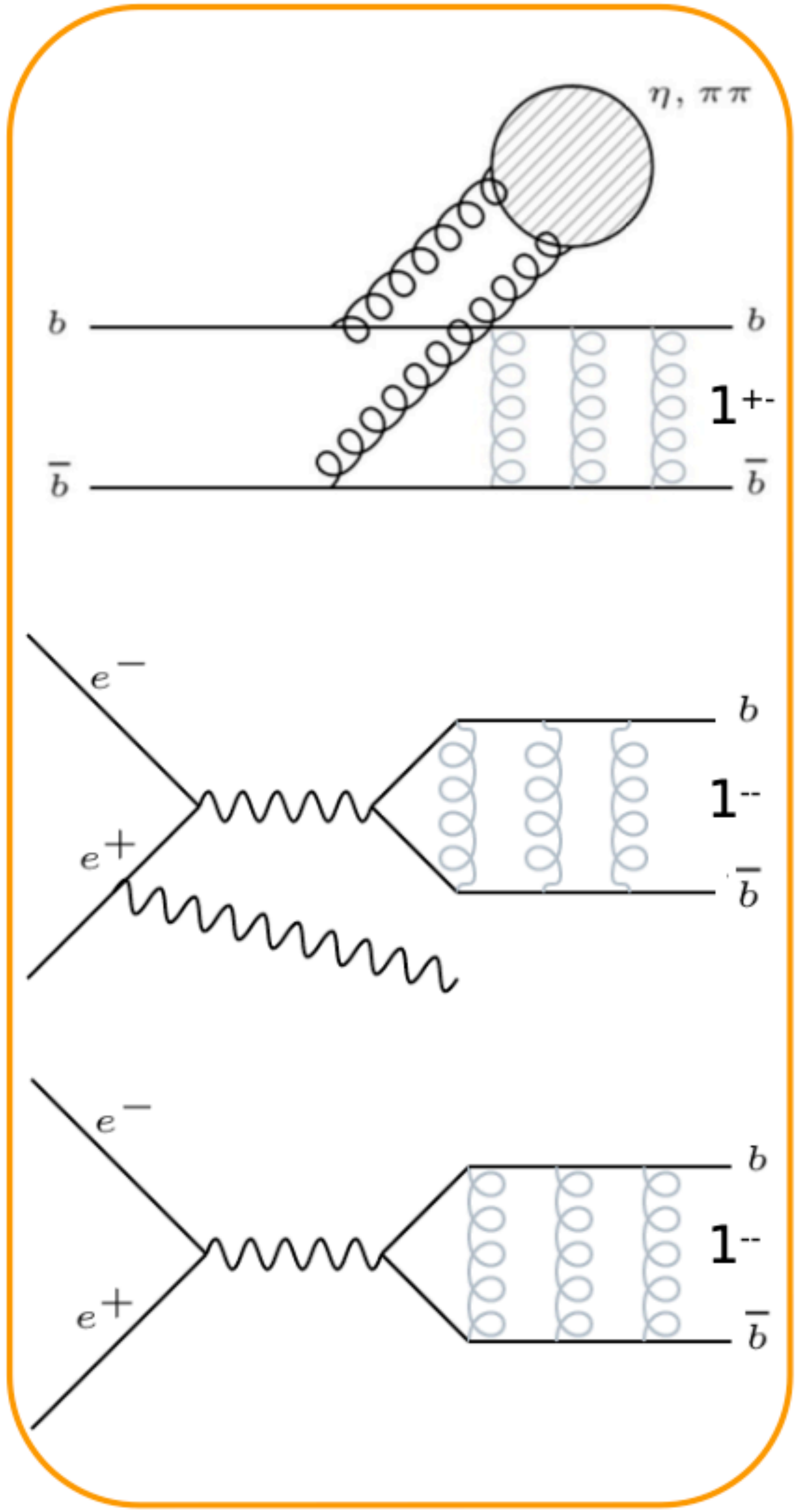
Geometrical corrections (hourglass eff. ...)

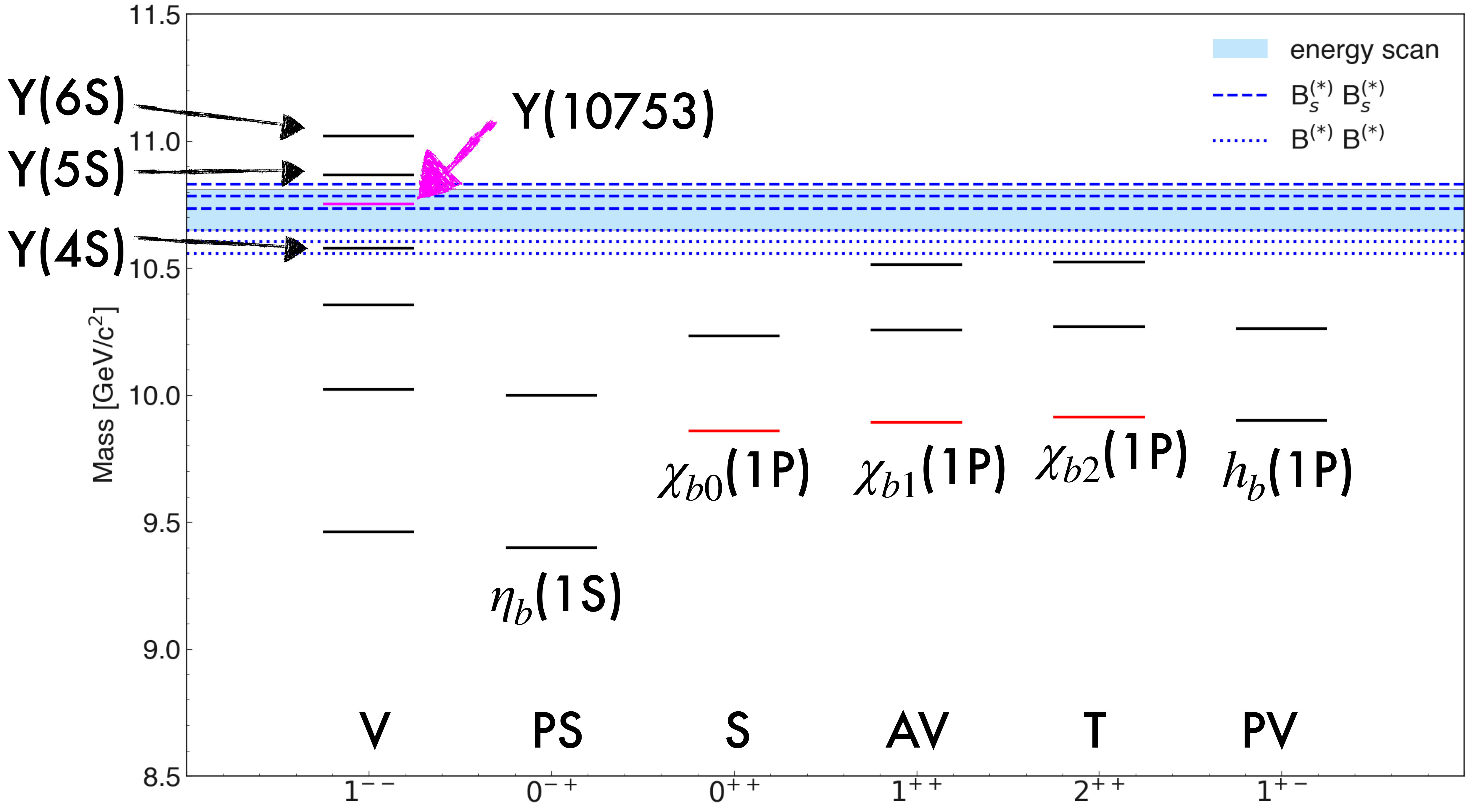
Bottomonium spectrum

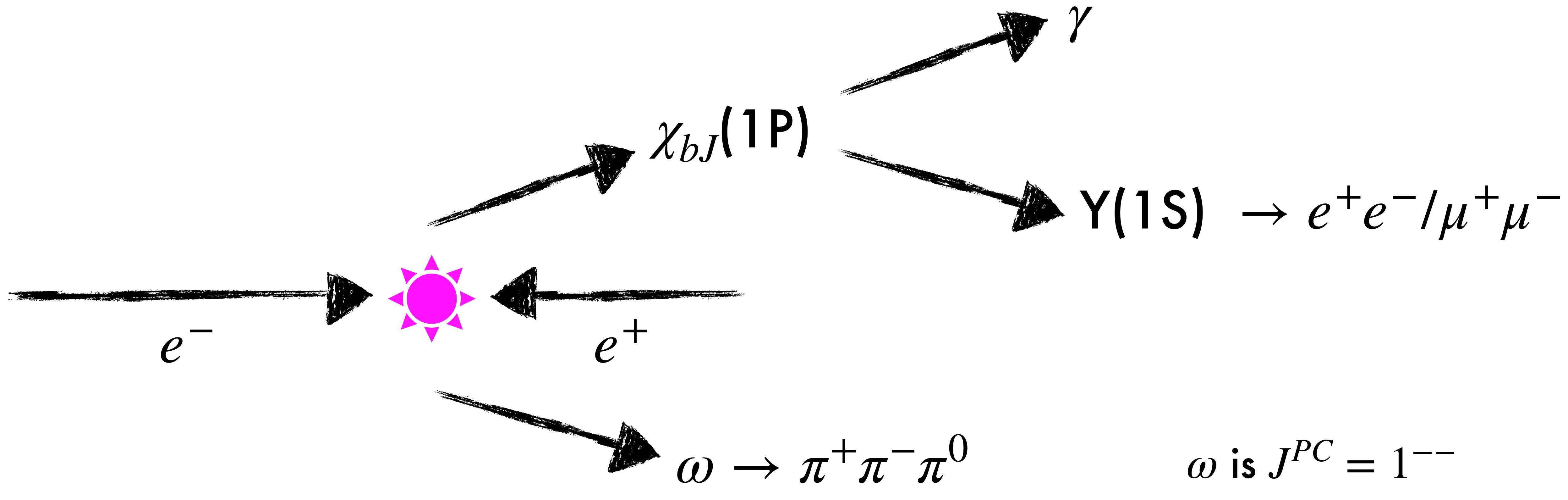
Hadronic transitions

ISR

Direct production





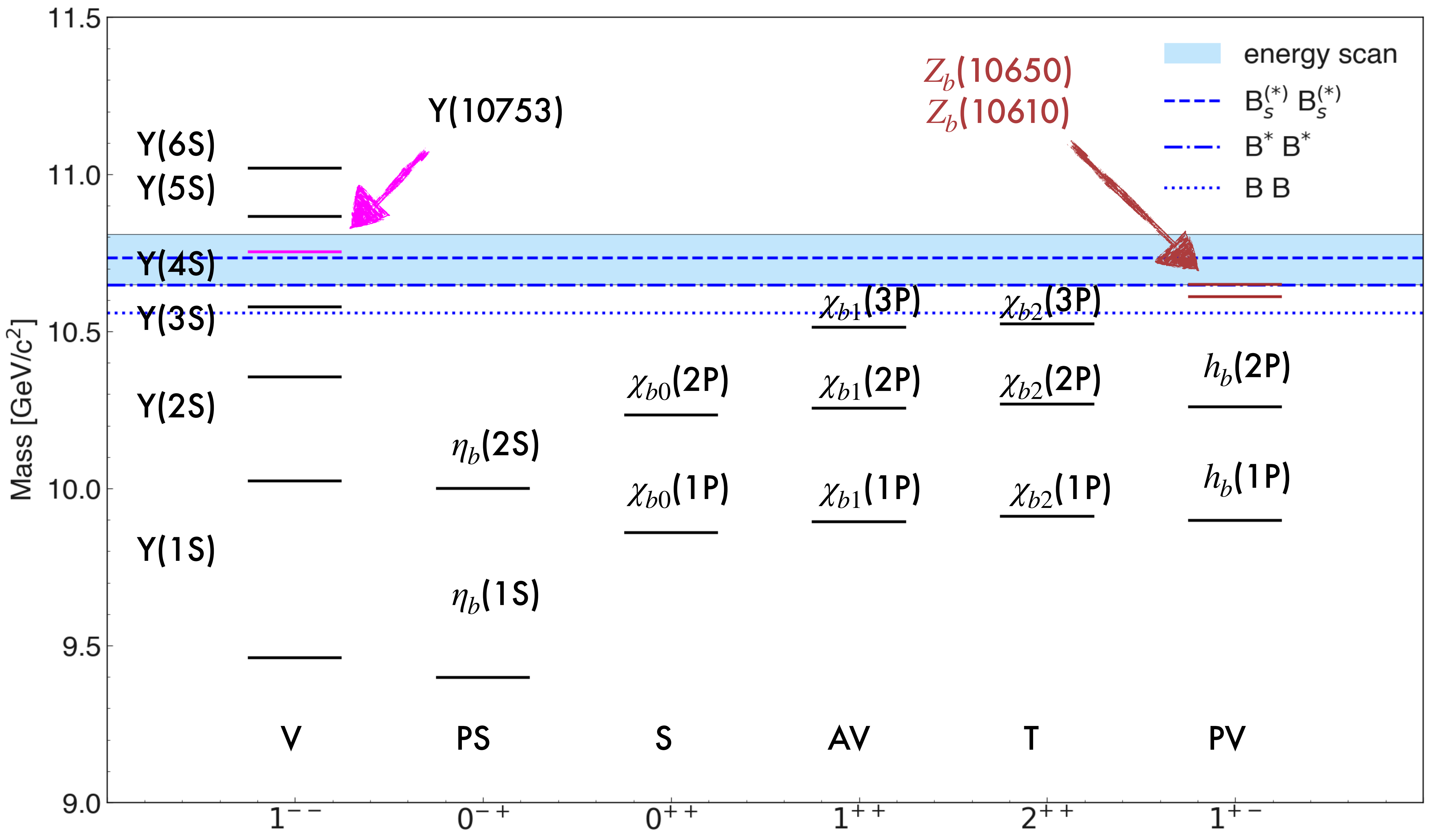


ω is $J^{PC} = 1^{--}$

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 $\pi^+\pi^-$ $\rightarrow$ violation of heavy quark spin symmetry
  - Z_b states observed near $B^{(*)}\bar{B}^*$-threshold consistent with $B^{(*)}\bar{B}^*$-molecule interpretation



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 $b\bar{b}$