Istituto Nazionale di Fisica Nucleare
SEZIONE DI TORINO

Bottomonium at Belle (II)

Excited QCD 2024
Benasque, January 19th 2024

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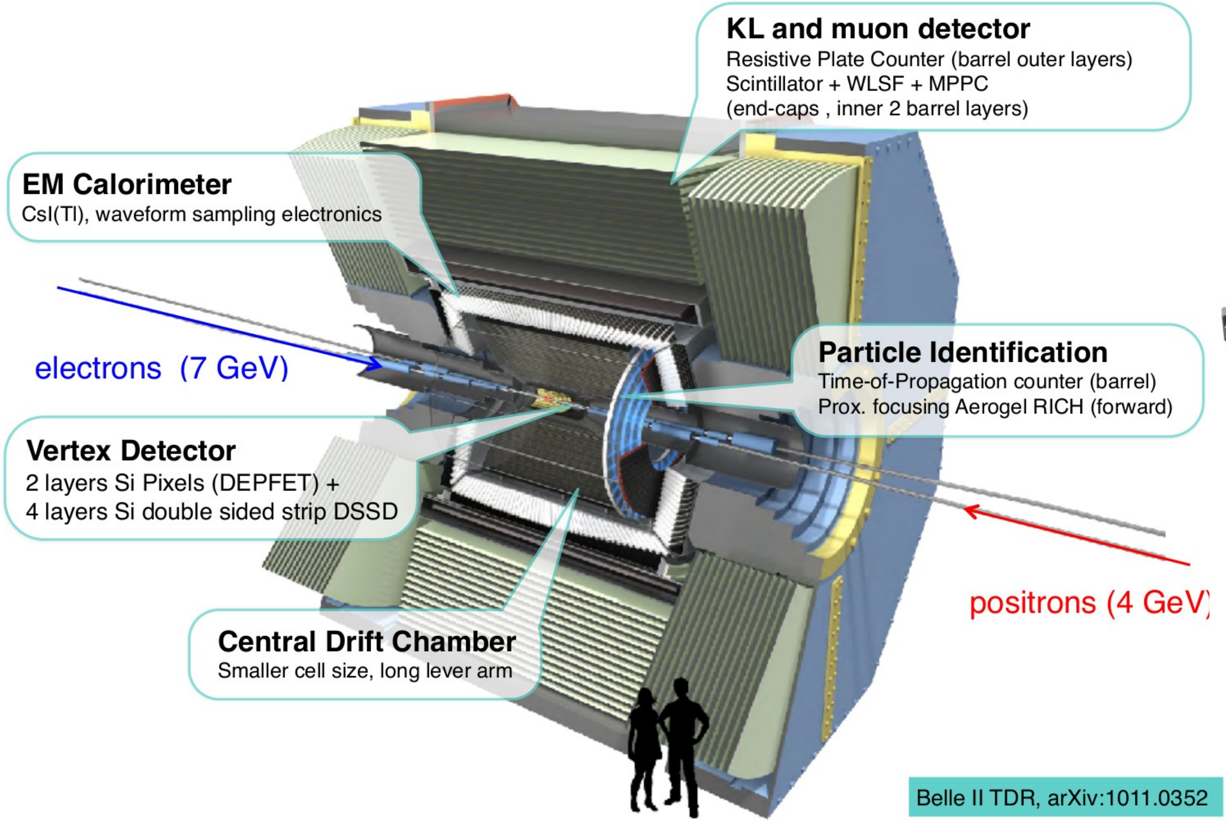
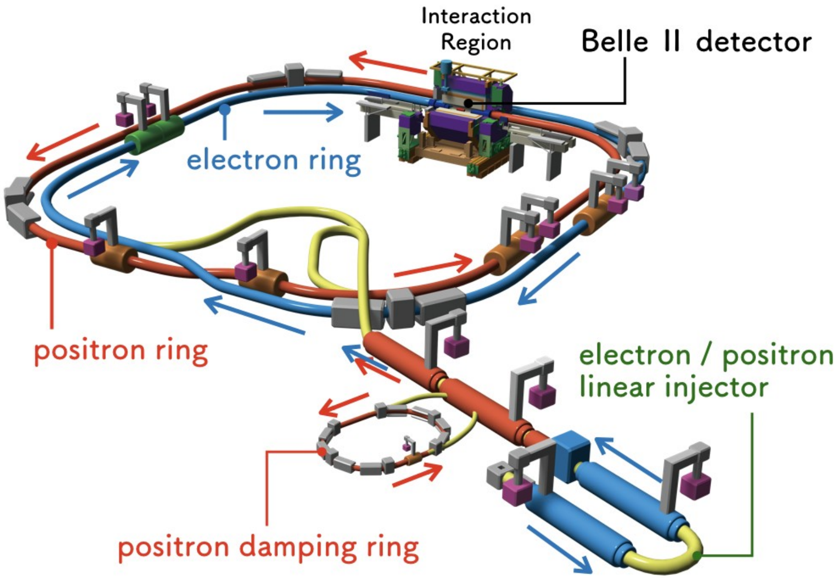
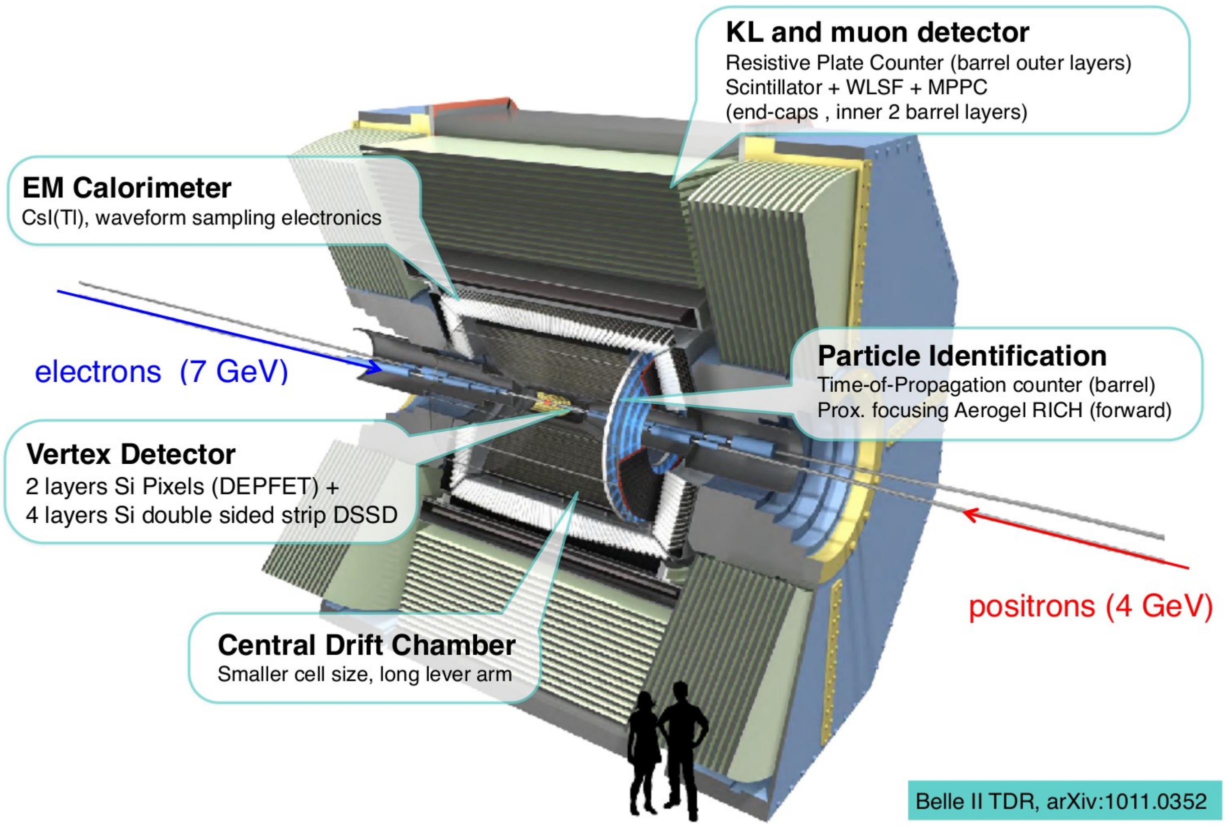
The Belle II detector



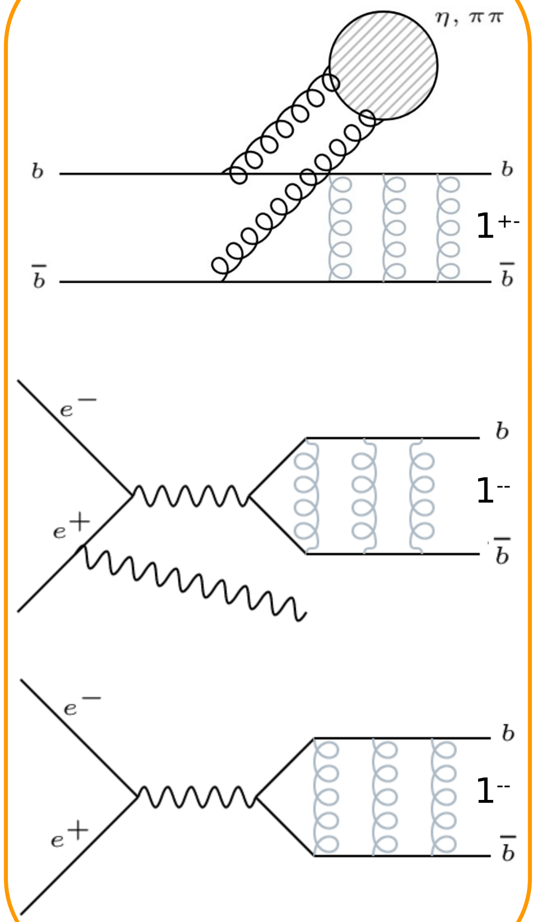
Belle II TDR, arXiv:1011.0352



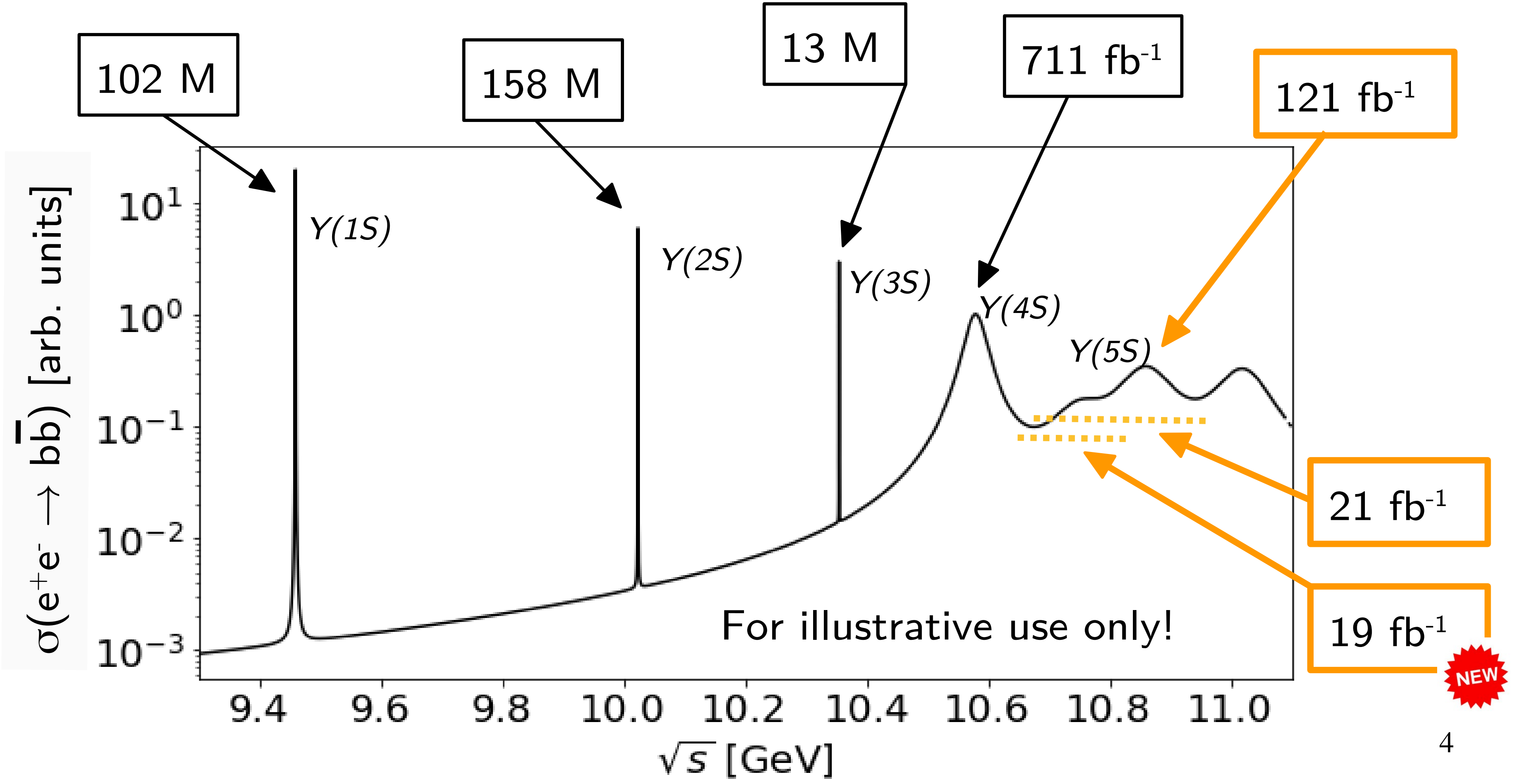
Belle II and Bottomonia



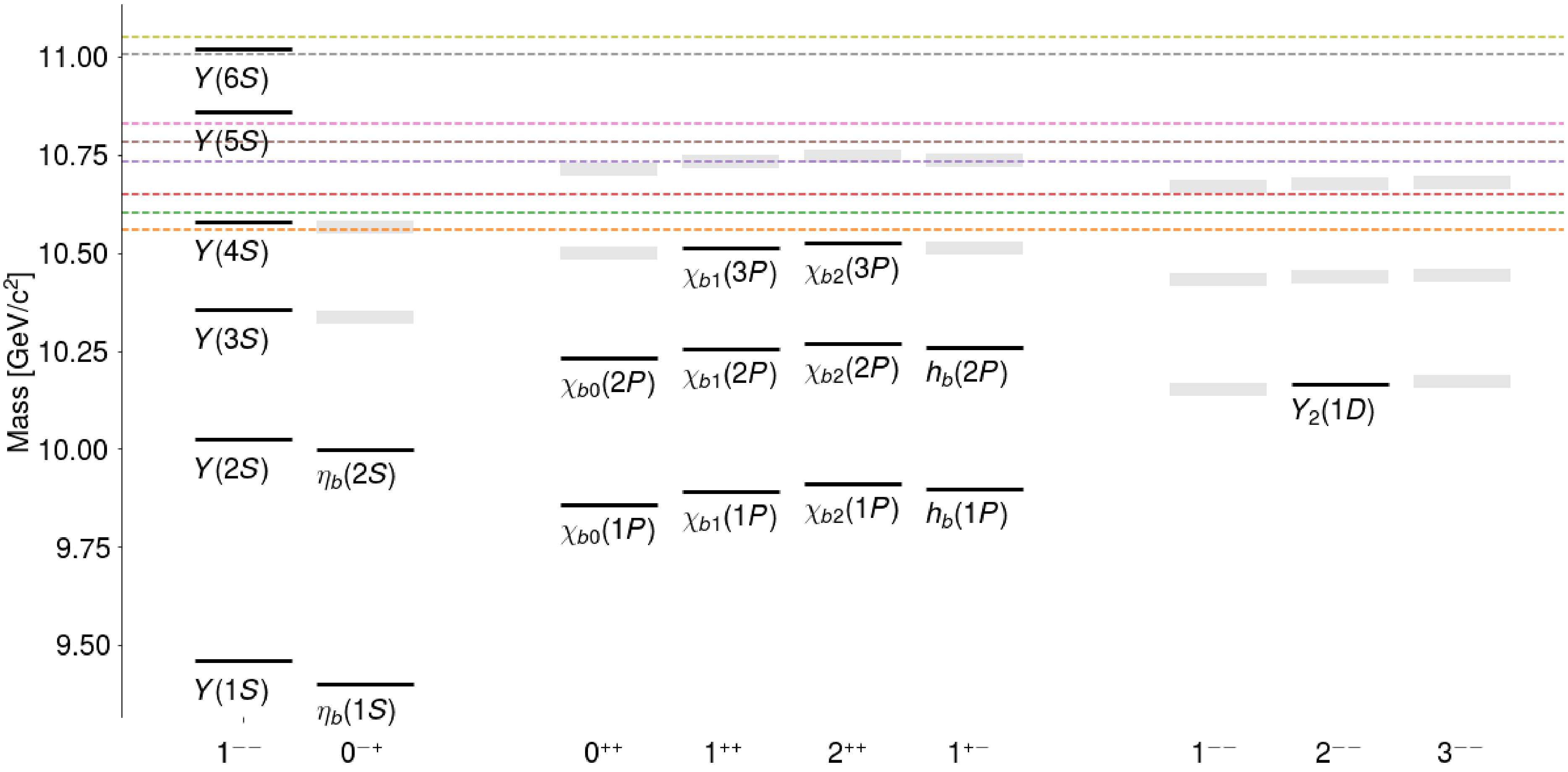
Belle II TDR, arXiv:1011.0352



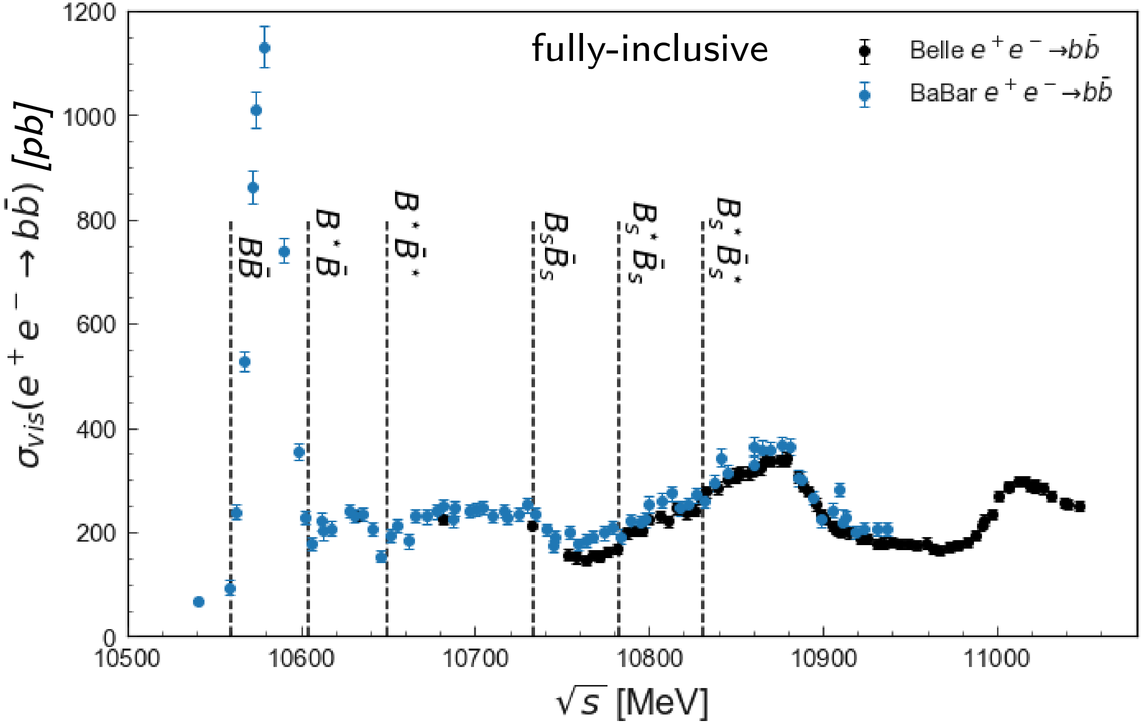
Belle (II) relevant datasets

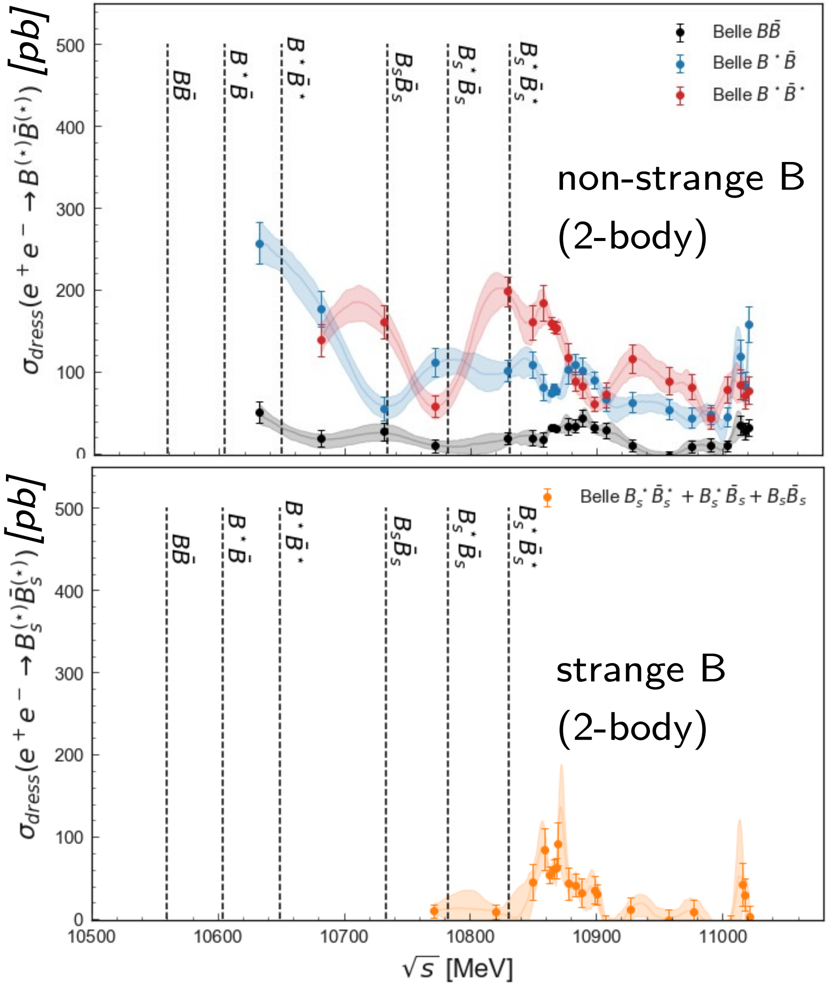


The threshold region

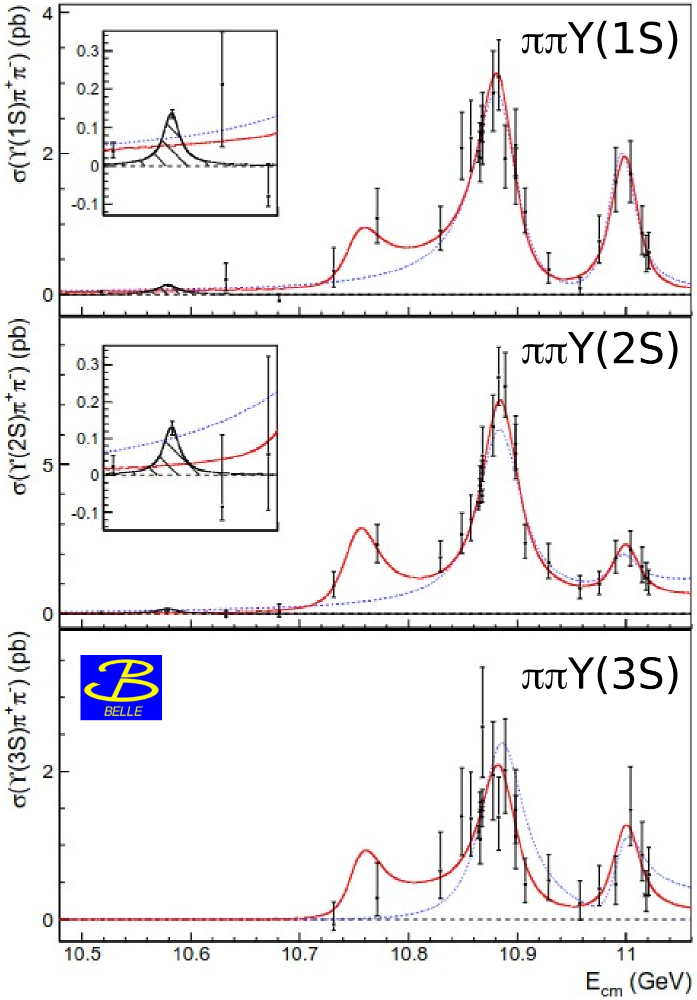


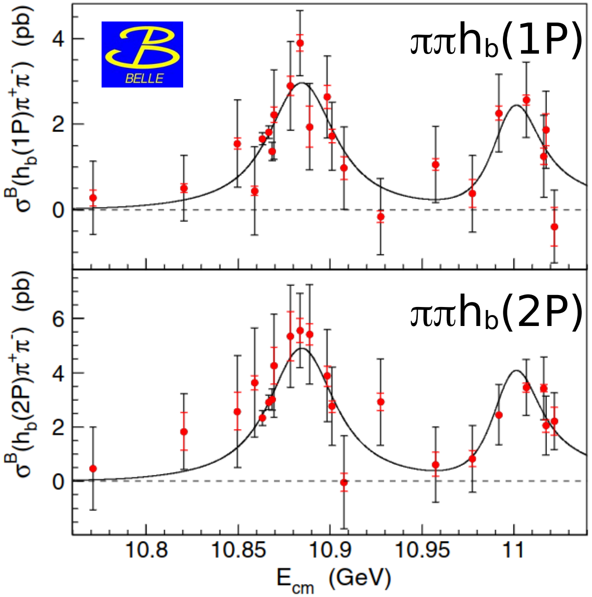
The threshold region: open flavour

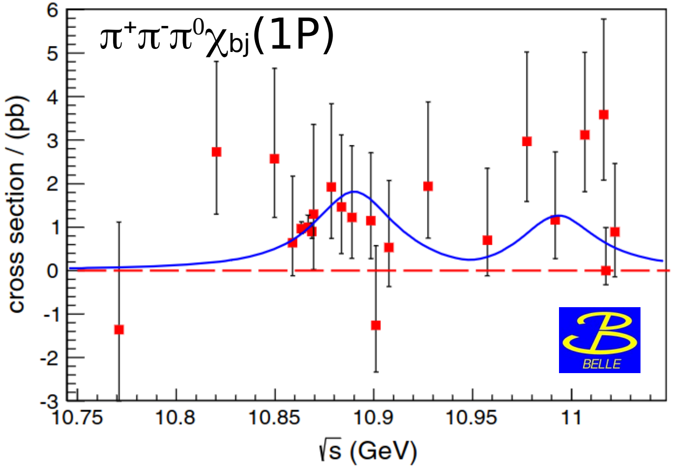




The threshold region: hidden flavour





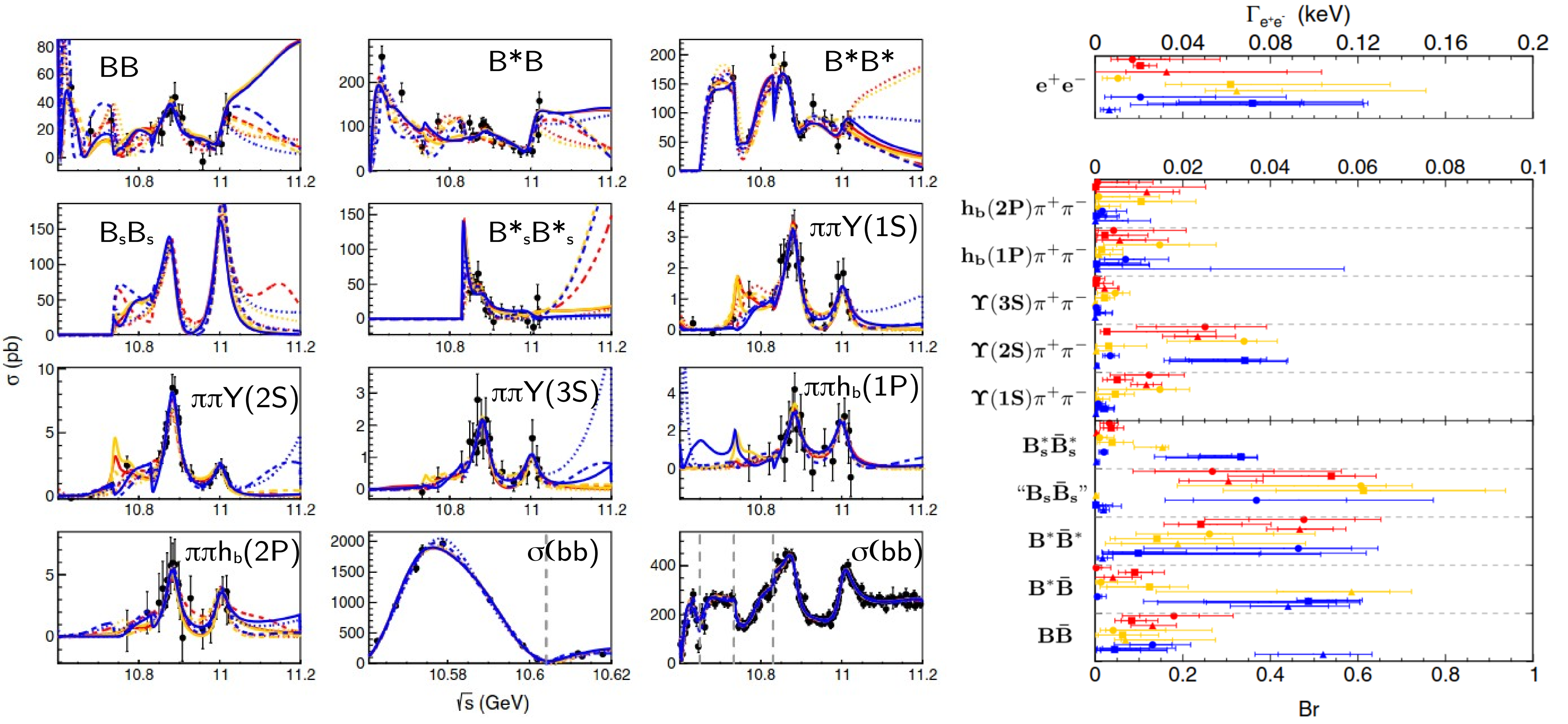


New structure in ππΥ(nS), the Υ(10750)

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

Global fits

[Hüsken et al. PRD 106 094013 (2022)]



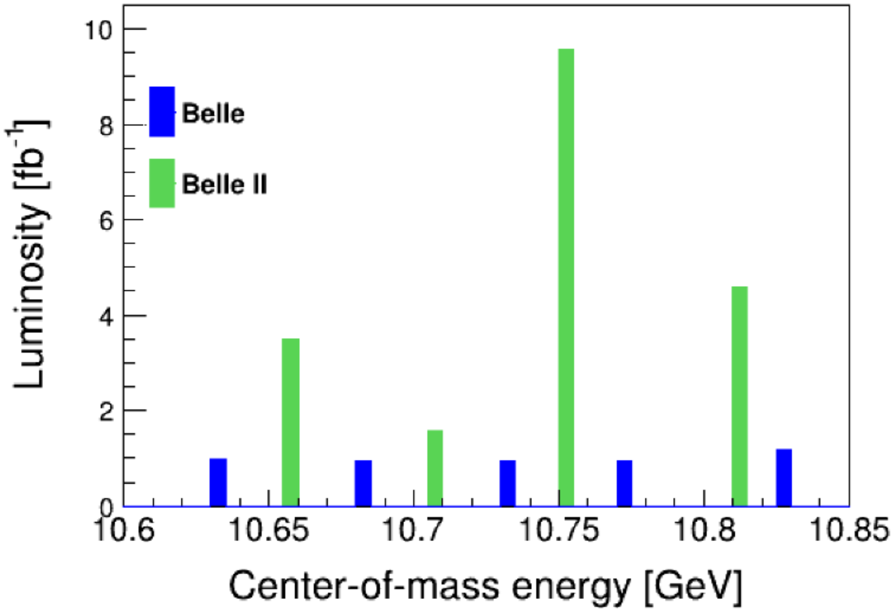
The new Belle II dataset

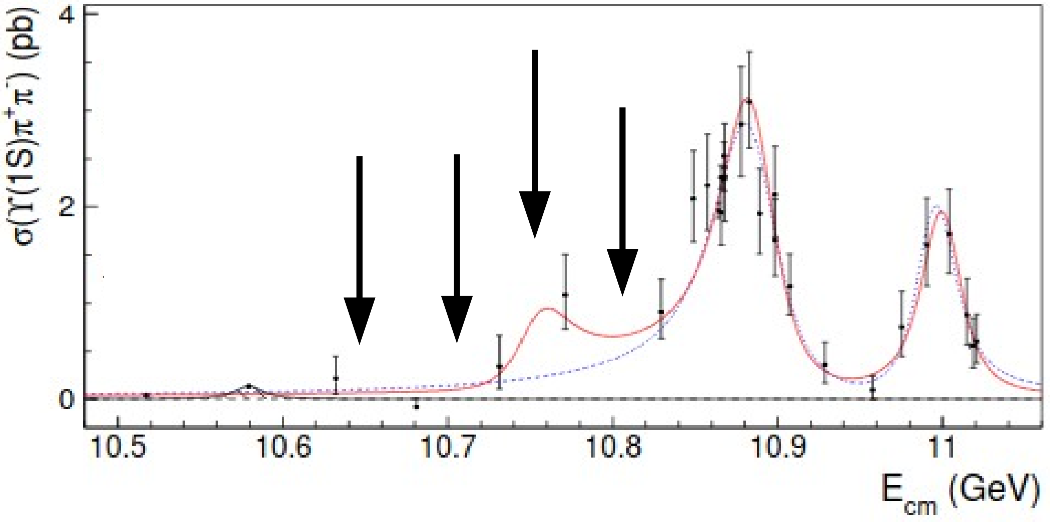
In fall 2021 Belle II took data above the Υ(4S)

→ Goal: study the golden channels to characterize the Υ(10750)

→ Special data taking, lots of discussions and preparation

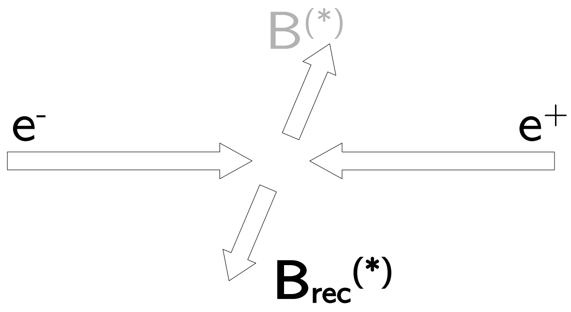
→ If you have an idea and you like it, don't give up ;)





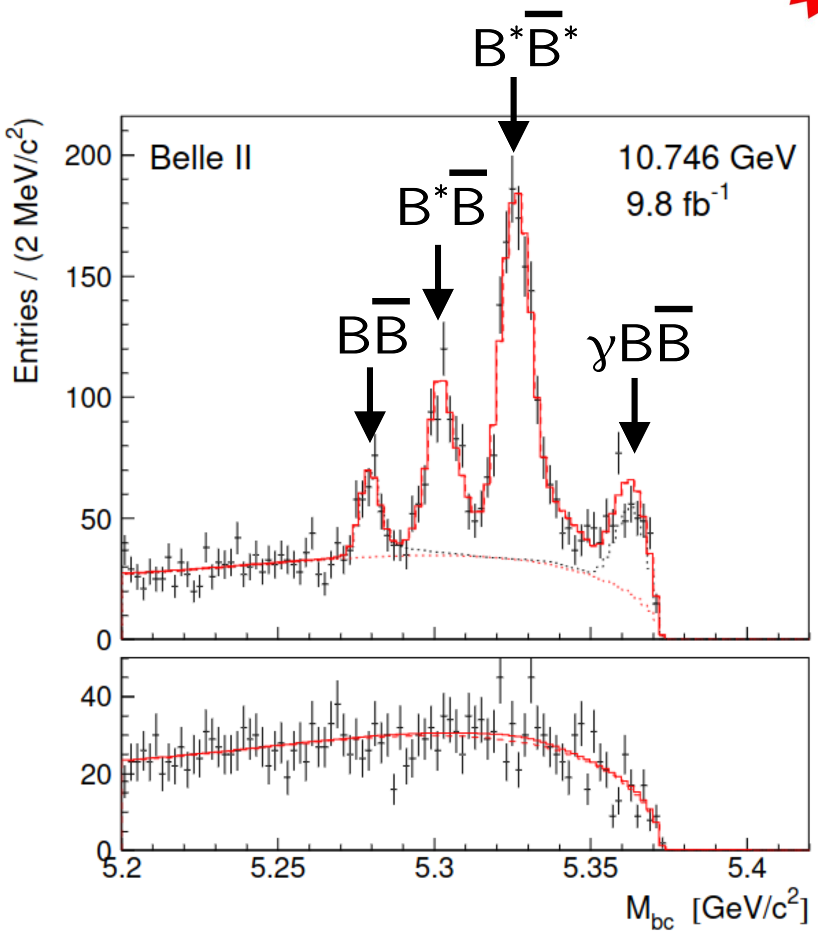
News: open flavour cross sections

BB decomposition updated



[Belle II Preliminary]

NEW



Semi-inclusive reconstruction:

- → Reconstruct one $B^{(*)}$ in 16 modes with $D_{(s)}^{(*)}$ or J/ψ
- → Ignore γ from B^* to B
- → Separate processes by momentum (M_{bc})

$$M_{\rm bc} = \sqrt{(E_{\rm cm}/2)^2 - p_B^2}$$

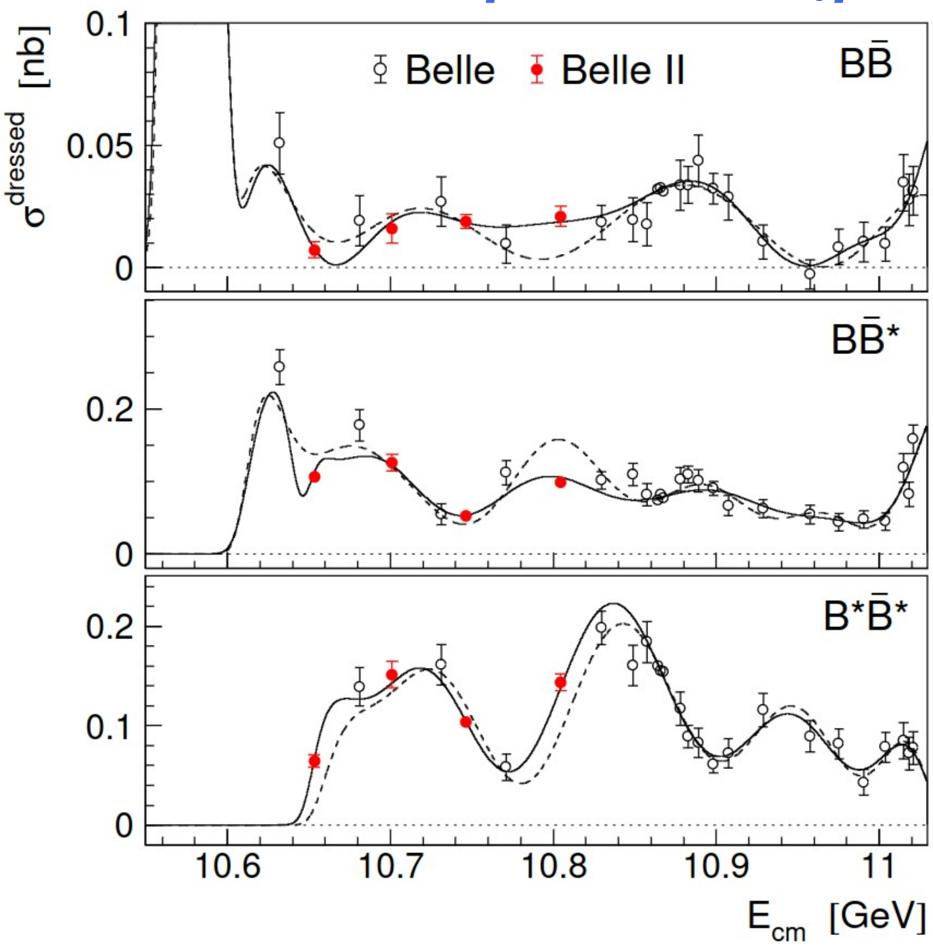
BB decomposition updated

Prominent features:

→ Sharp rise in B^*B^*
  → first point only ~2 MeV above $B^{0*}B^{0*}$ threshold
  → Indication of bound state?

→ Dip in B^*B at the B^*B^* threshold

[Belle II Preliminary]



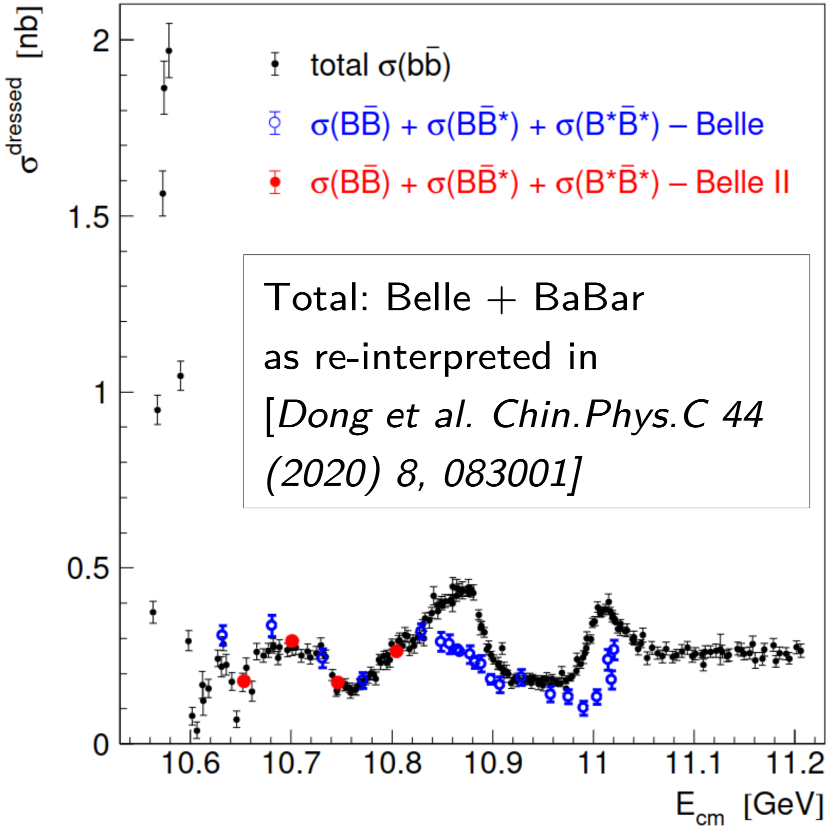
BB decomposition updated

[Belle II Preliminary]

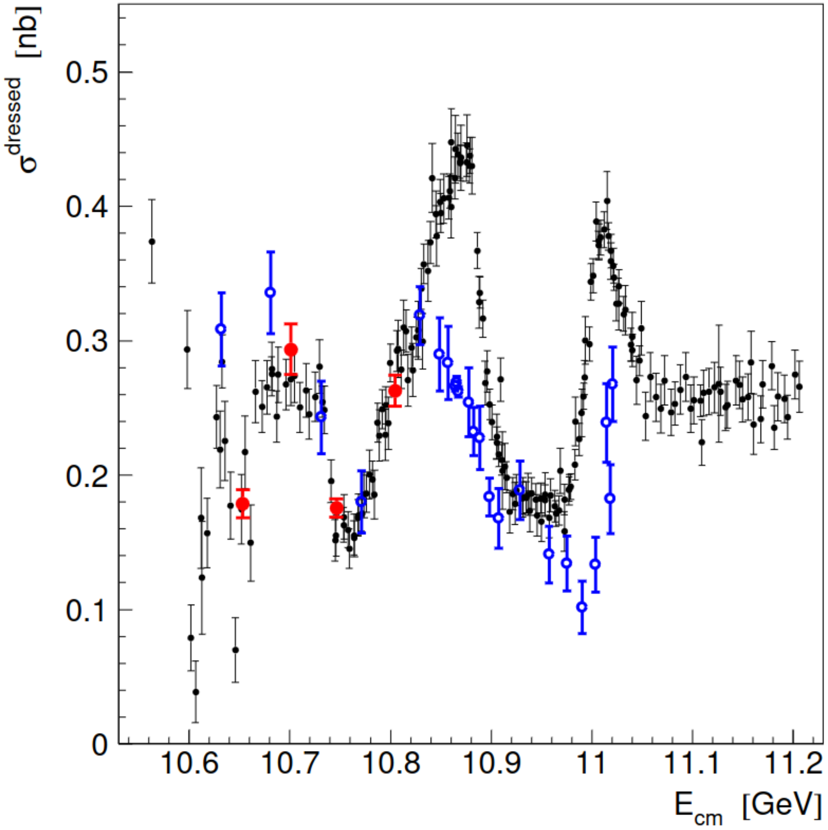
NEW

Do we saturate the total cross section?

→ not yet!



Total: Belle + BaBar as re-interpreted in [*Dong et al. Chin.Phys.C 44 (2020) 8, 083001*]



$e^+e^- \rightarrow B^{(*)}B^{(*)}+X$ and $B_s^{(*)}B_s^{(*)}+X$

[JHEP 08 2023, 131 (2023)]

NEW

Measure the fully-inclusive $e^+e^- \rightarrow B_{(s)}^{(*)}B_{(s)}^{(*)}+X$

→ Use D^0 as proxy for a B^0

→ Use D_s^- as proxy for B_s^0

→ Use D momentum to identify the quark-level process

$e^+e^- \rightarrow b\bar{b} \rightarrow D_{(s)} + X$

$e^+e^- \rightarrow u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c} \rightarrow D_{(s)} + X$

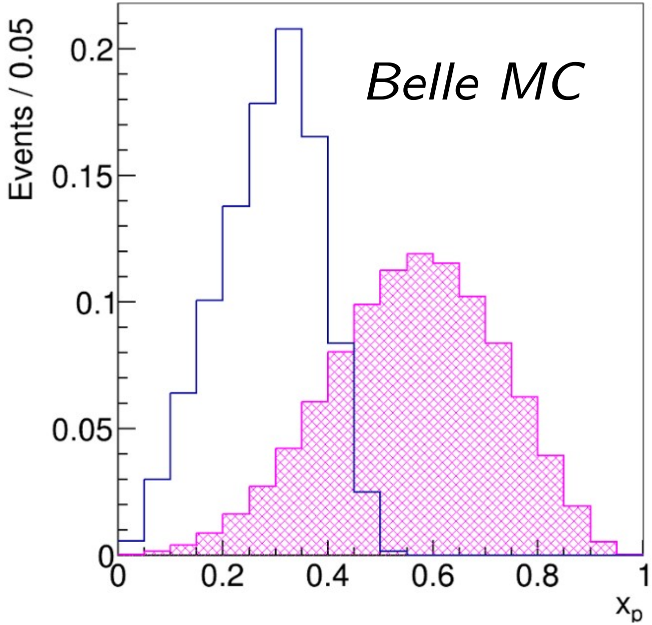
→ Solve the equation system:

$$\sigma(e^+e^- \to b\bar{b} \to D_s^\pm X) = 2\,\sigma(e^+e^- \to B_s^0\bar{B}_s^0\,X)\mathcal{B}(B_s^0 \to D_s^\pm X) + 2\,\sigma(e^+e^- \to B\bar{B}\,X)\mathcal{B}(B \to D_s^\pm X),$$

$$\sigma(e^+e^- \to b\bar{b} \to D^0/\bar{D}^0 X) = 2\,\sigma(e^+e^- \to B_s^0\bar{B}_s^0\,X)\mathcal{B}(B_s^0 \to D^0/\bar{D}^0 X) + 2\,\sigma(e^+e^- \to B\bar{B}\,X)\mathcal{B}(B \to D^0/\bar{D}^0 X).$$

$BF[B^0 \rightarrow D^0 + X] \sim 67\%$

$BF[B_s^0 \rightarrow D_s^- + X] \sim 60\%$



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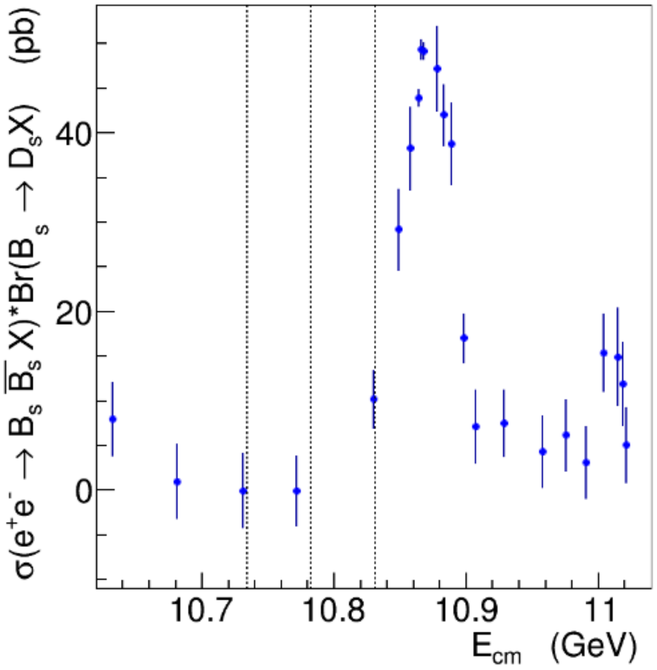

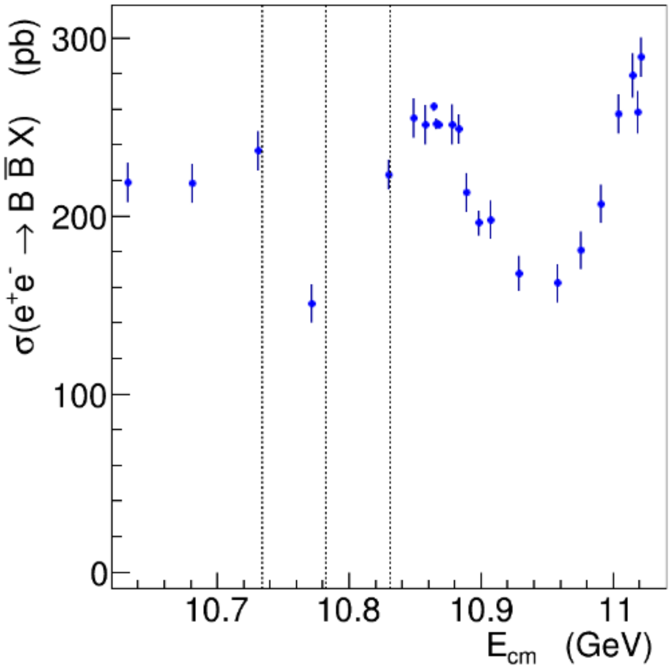

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[JHEP 08 2023, 131 (2023)]

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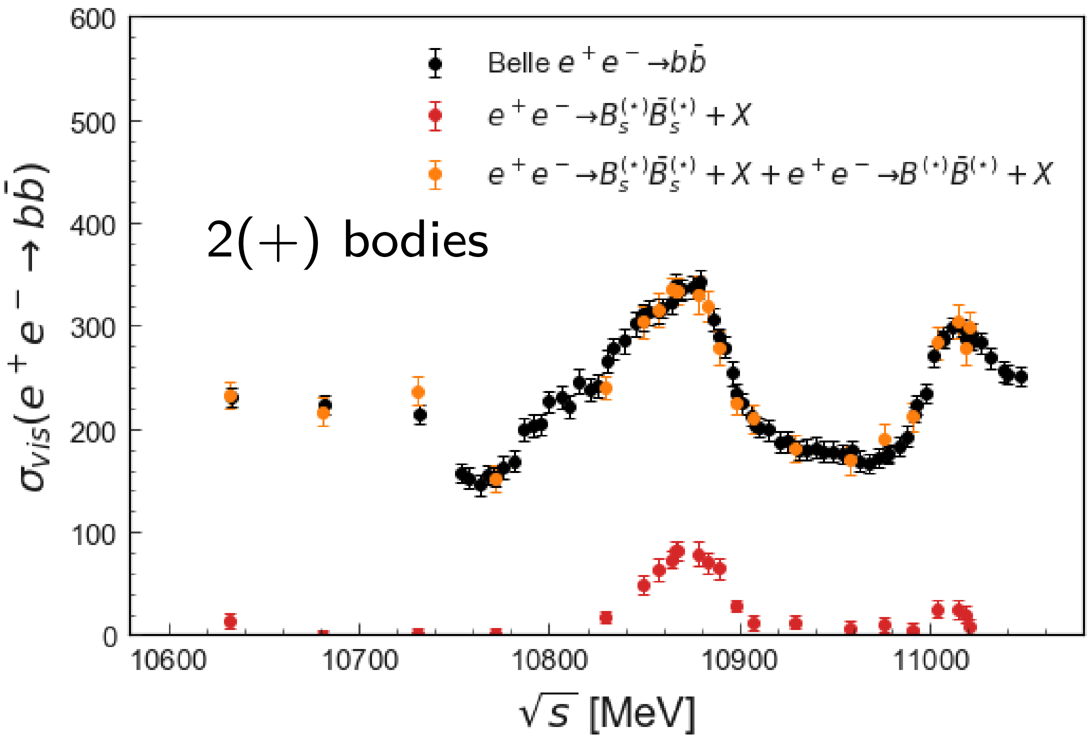
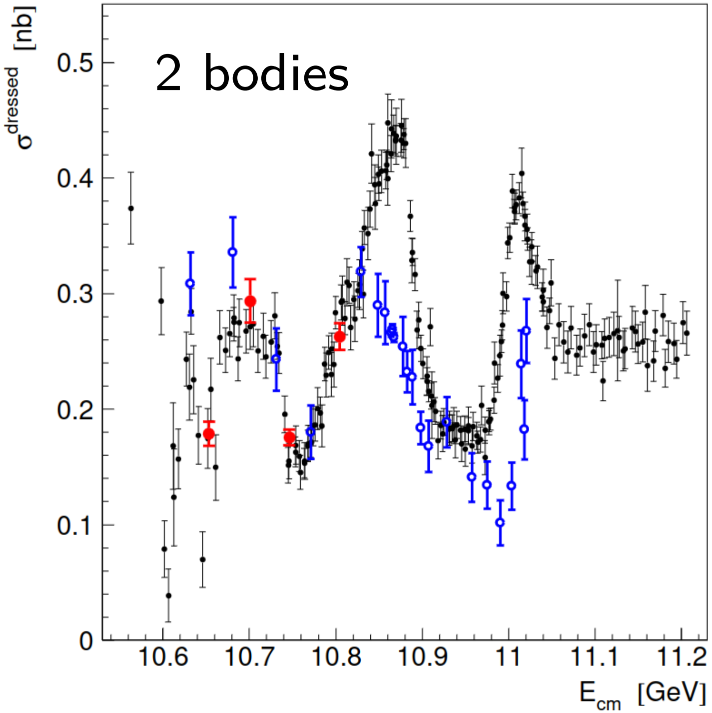




News: hidden flavour cross sections

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

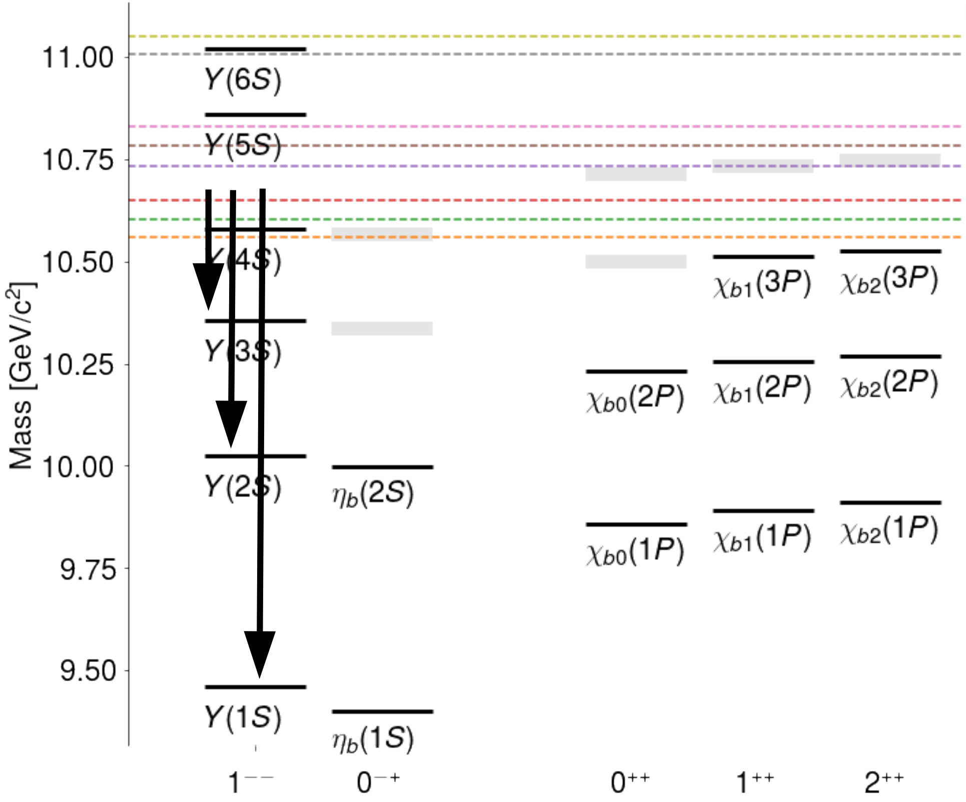
NEW

Discovery mode of the Y(10750)

→ Confirm its existence

→ Measure the di-pion spectrum

→ look for Z_b contributions



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

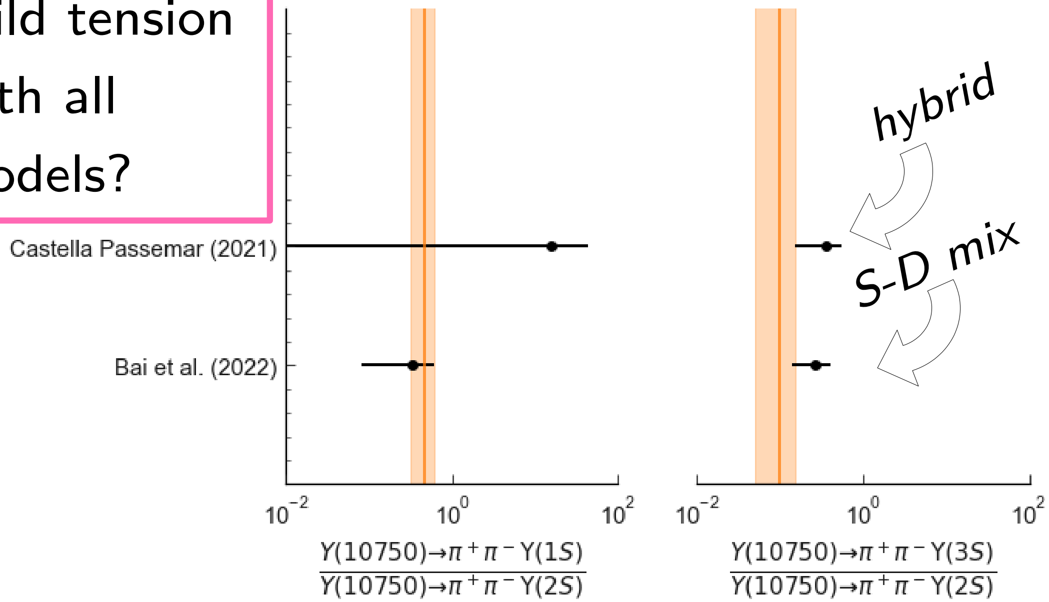
Discovery mode of the Y(10750)

→ Confirm its existence

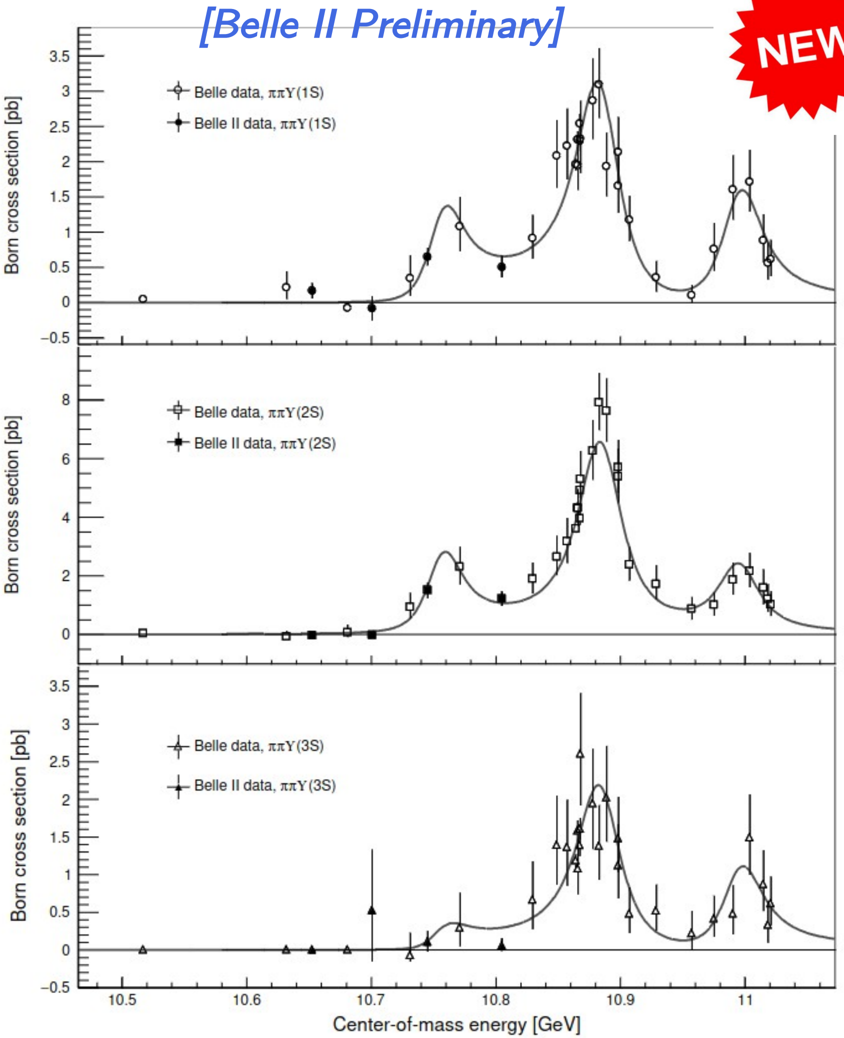
→ >8 σ combined significance (B+BII)

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

Mild tension with all models?



NEW



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

Discovery mode of the Y(10750)

→ Confirm its existence

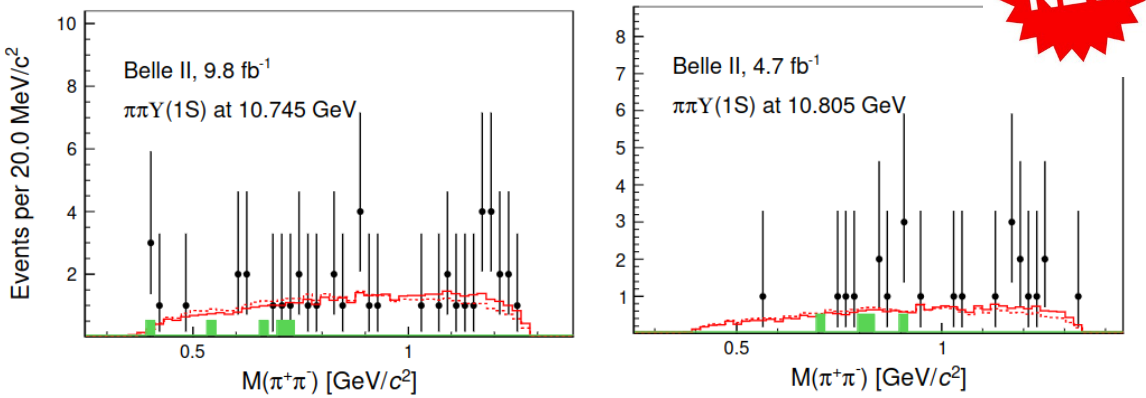
→ Measure the di-pion spectrum

→ **No sign of f_0 in $\pi\pi\Upsilon(1S)$**

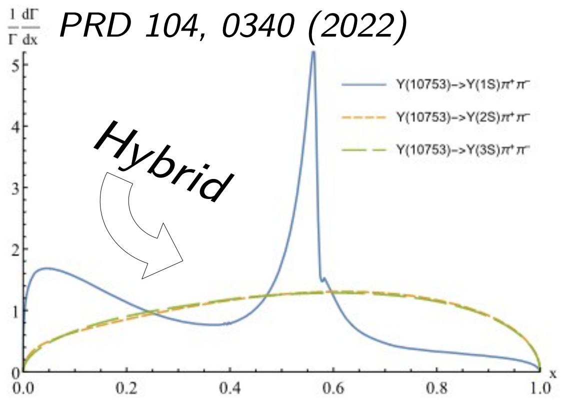
Disagreement with all available predictions

NEW

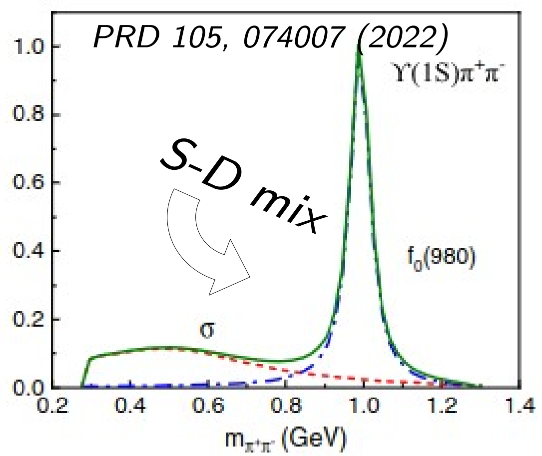
[Belle II Preliminary]



PRD 104, 0340 (2022)



PRD 105, 074007 (2022)



$e^+e^- \rightarrow Y(nS)\ \pi^+\pi^-$

Discovery mode of the Y(10750)

→ Confirm its existence

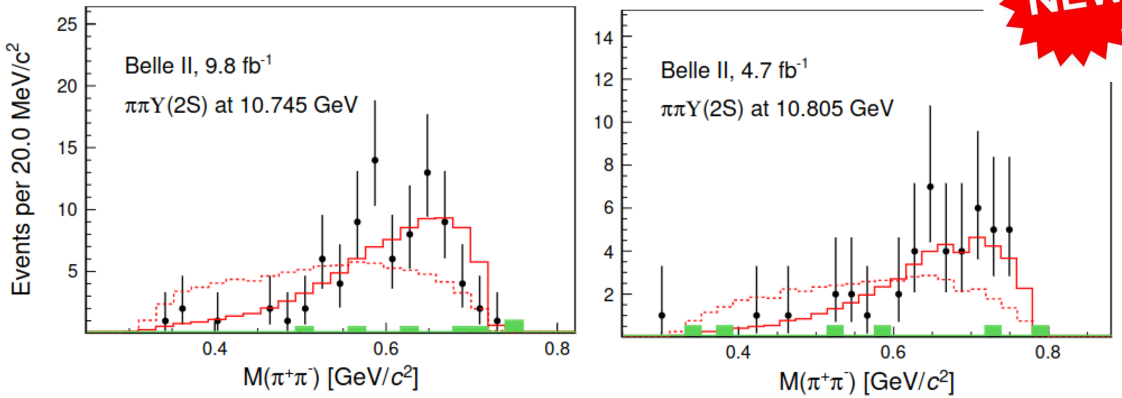
→ Measure the di-pion spectrum

→ No sign of f_0 in ππY(1S)

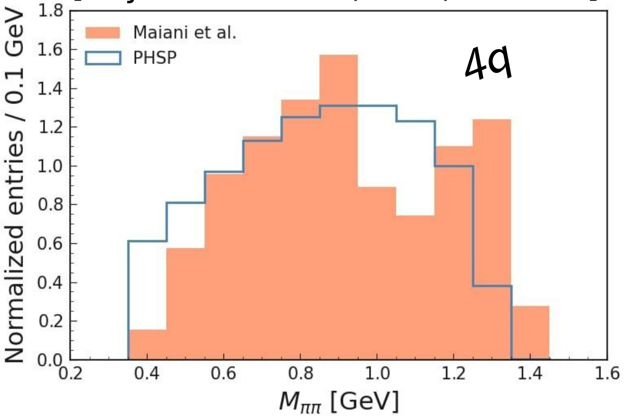
→ M(ππ) similar to what's seen Y(2S) → ππ Y(1S)

Disagreement with S-D model. Compatible with 4q?

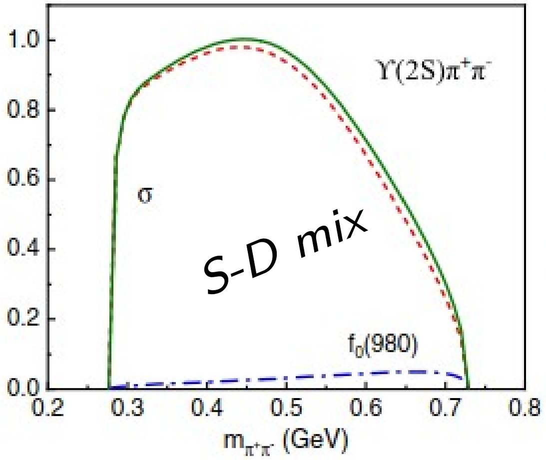
[Belle II Preliminary] NEW



[Phys.Lett.B 802 (2020) 135217]



PRD 105, 074007 (2022)



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

Discovery mode of the Υ(10750)

→ Confirm its existence

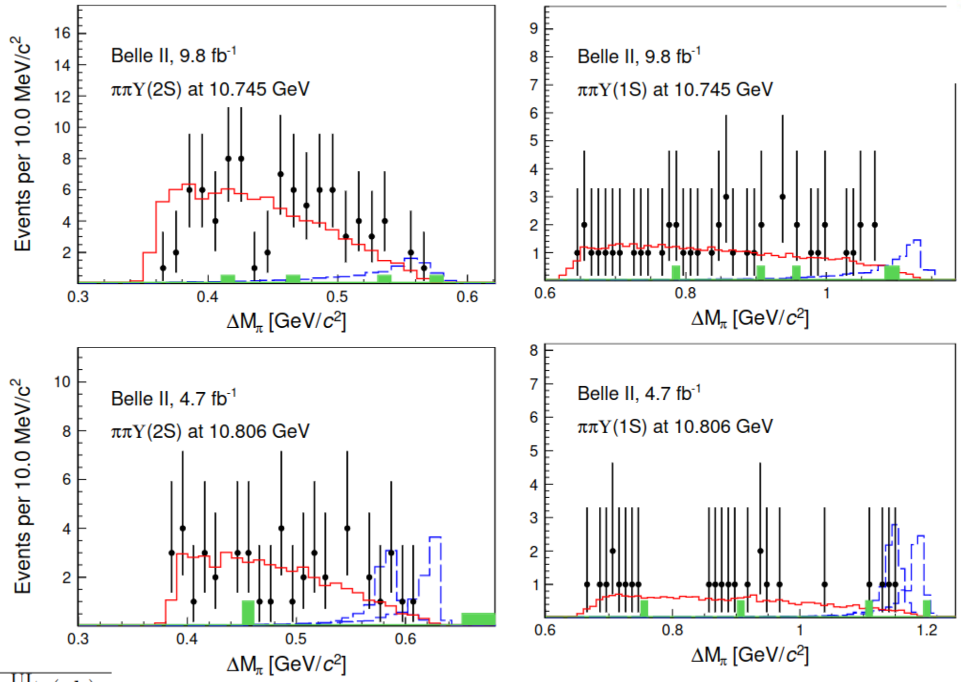
→ Measure the di-pion spectrum

→ look for Z_b contributions

→ **No indication of Z_b**

[Belle II Preliminary]

NEW



Mode	$N_{Z_{b1}}$	$N^{UL}_{Z_{b1}}$	$\sigma_{Z_{b1}}$ (pb)	$\sigma^{UL}_{Z_{b1}}$ (pb)	$N^{UL}_{Z_{b2}}$	$N_{Z_{b2}}$	$\sigma_{Z_{b2}}$ (pb)	$\sigma^{UL}_{Z_{b2}}$ (pb)
10.745 GeV								
$\pi\Upsilon(1S)$	$0.0^{+1.6}_{-0.0}$	< 4.9	$0.00^{+0.04}_{-0.00}$	< 0.13	–	–	–	
$\pi\Upsilon(2S)$	$5.8^{+5.9}_{-4.6}$	< 13.8	$0.06^{+0.06}_{-0.05}$	< 0.14	–	–	–	
10.805 GeV								
$\pi\Upsilon(1S)$	$2.5^{+2.4}_{-1.6}$	< 5.2	$0.21^{+0.20}_{-0.13}$	< 0.43	$0.0^{+0.7}_{-0.0}$	< 5.8	$0.00^{+0.03}_{-0.00}$	< 0.28
$\pi\Upsilon(2S)$	$5.2^{+3.8}_{-3.0}$	< 12.3	$0.15^{+0.11}_{-0.09}$	< 0.35	$0.0^{+0.8}_{-0.0}$	< 6.0	$0.00^{+0.04}_{-0.00}$	< 0.30

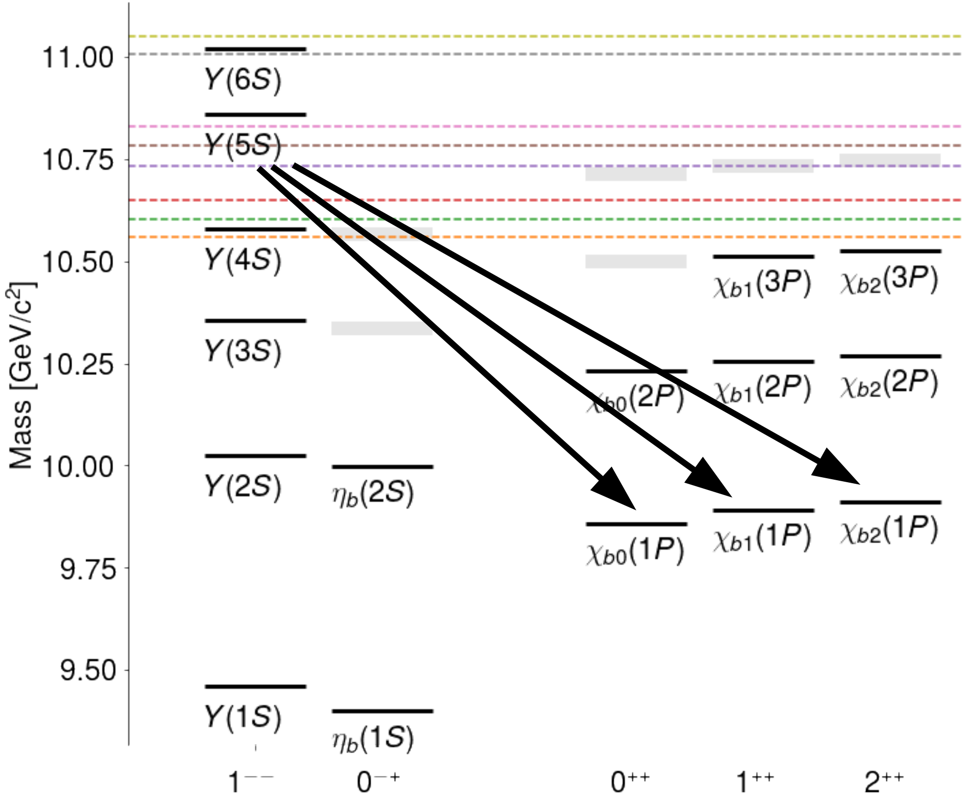
$e^+e^- \to \chi_{b1,2}(1P)\ \omega$

Y(10750) → ω χ_b in the conventional quarkonium model (S-D mixing state)

[Y.S. Li, et al., PRD 104, 034036 (2021)]

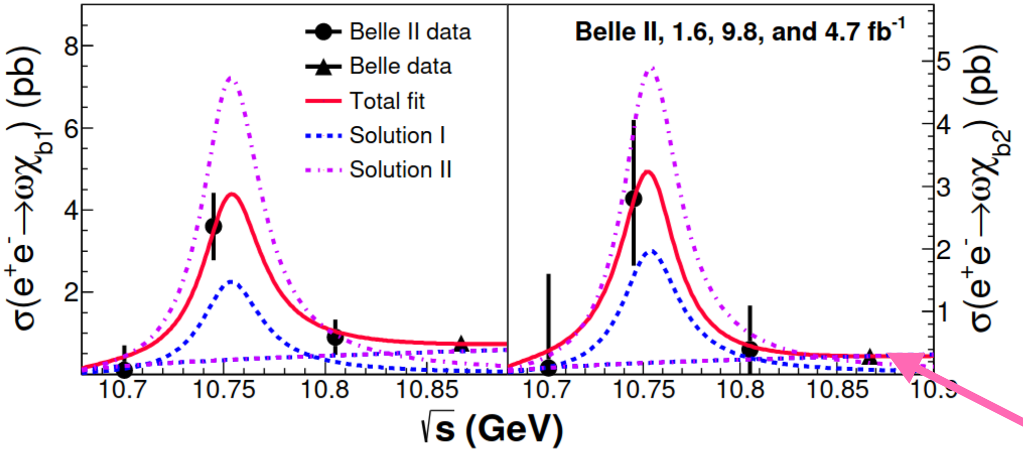
$$\mathcal{B}[\Upsilon(10753) \to \chi_{b0}\omega] = (0.73\text{–}6.94) \times 10^{-3},$$
$$\mathcal{B}[\Upsilon(10753) \to \chi_{b1}\omega] = (0.25\text{–}2.16) \times 10^{-3},$$
$$\mathcal{B}[\Upsilon(10753) \to \chi_{b2}\omega] = (1.08\text{–}11.5) \times 10^{-3}.$$

$$R_{12} = \frac{\mathcal{B}[\Upsilon(10753) \to \chi_{b1}\omega]}{\mathcal{B}[\Upsilon(10753) \to \chi_{b2}\omega]} = (0.18\text{–}0.22)$$
$$R_{02} = \frac{\mathcal{B}[\Upsilon(10753) \to \chi_{b0}\omega]}{\mathcal{B}[\Upsilon(10753) \to \chi_{b2}\omega]} = (0.55\text{–}0.63)$$



$e^+e^- \rightarrow \chi_{b1,2}(1P)\,\omega$

[PRL 130, 091902 (2023)]



$$\sigma[ee \rightarrow \omega\chi_{b0}(1P)] < 11.3\,pb\,@\,10.750\,GeV$$

What we thought was Y(5S) $\rightarrow \omega\chi_{bj}(1P)$ is probably just the tail of the Y(10750)!

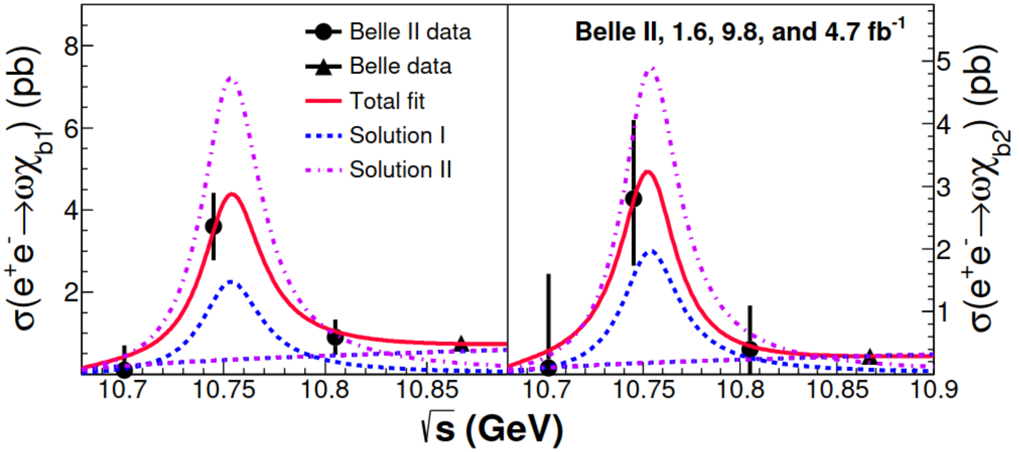
Two solutions (constr. or destr. interference):

$$\Gamma_{ee} \times B[Y(10750) \rightarrow \omega\chi_{b1}(1P)] = \begin{matrix} (0.63 \pm 0.39 \pm 0.20)\,eV \\ (2.01 \pm 0.38 \pm 0.76)\,eV \end{matrix}$$

$$\Gamma_{ee} \times B[Y(10750) \rightarrow \omega\chi_{b2}(1P)] = \begin{matrix} (0.53 \pm 0.40 \pm 0.15)\,eV \\ (1.32 \pm 0.44 \pm 0.53)\,eV \end{matrix}$$

$e^+e^- \rightarrow \chi_{b1,2}(1P)\ \omega$

[PRL 130, 091902 (2023)]



Disagreement with S-D model

$\sigma[ee \rightarrow \omega \chi_{b0}(1P)] < 11.3\ pb\ @\ 10.750\ GeV$

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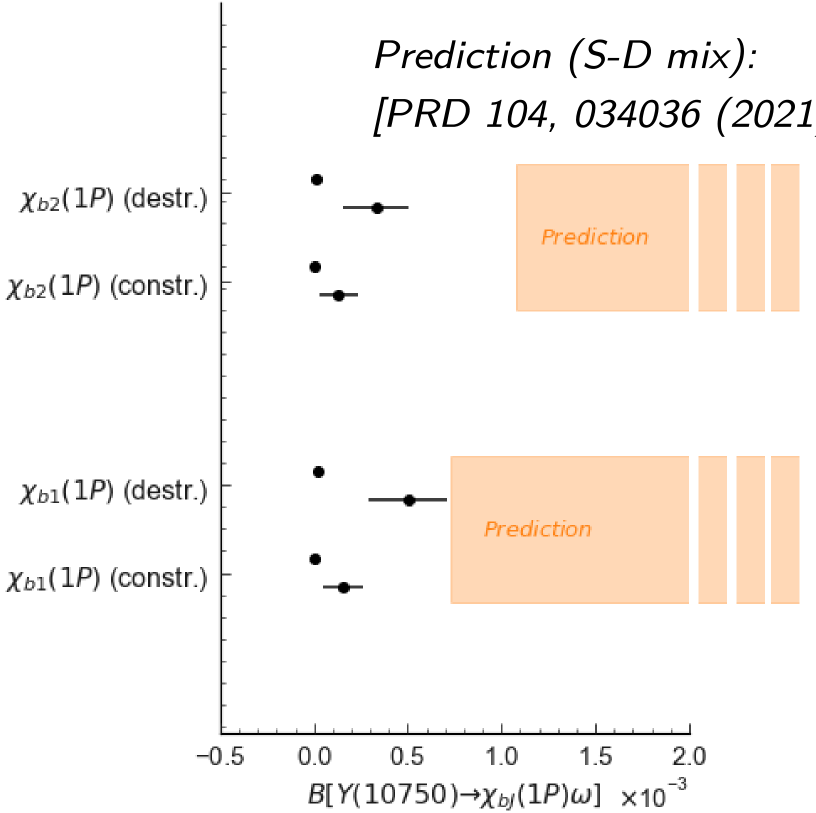
$$\Gamma_{ee} \times B[Y(10750) \rightarrow \omega \chi_{b1}(1P)] = \begin{matrix} (0.63 \pm 0.39 \pm 0.20)\, eV \\ (2.01 \pm 0.38 \pm 0.76)\, eV \end{matrix}$$

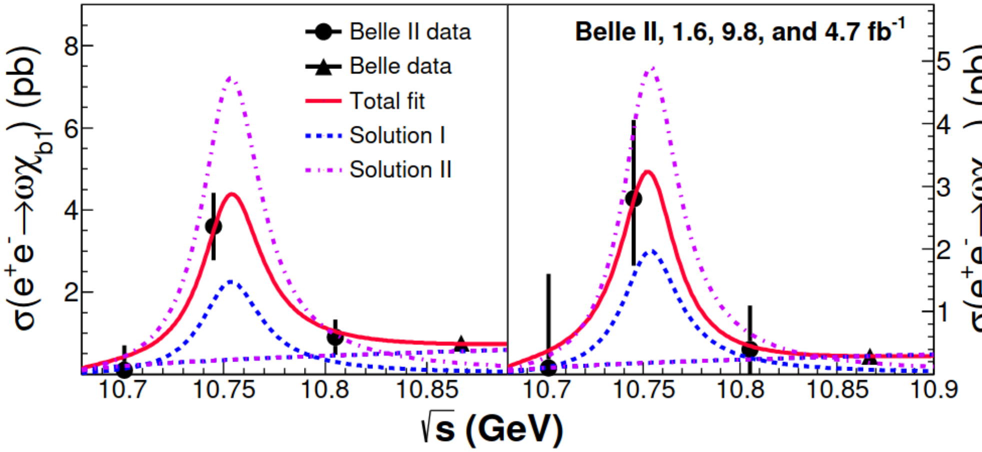
$$\Gamma_{ee} \times B[Y(10750) \rightarrow \omega \chi_{b2}(1P)] = \begin{matrix} (0.53 \pm 0.40 \pm 0.15)\, eV \\ (1.32 \pm 0.44 \pm 0.53)\, eV \end{matrix}$$

Prediction (S-D mix):
[PRD 104, 034036 (2021)]



$e^+e^- \rightarrow \chi_{b1,2}(1P)\ \omega$

[PRL 130, 091902 (2023)]

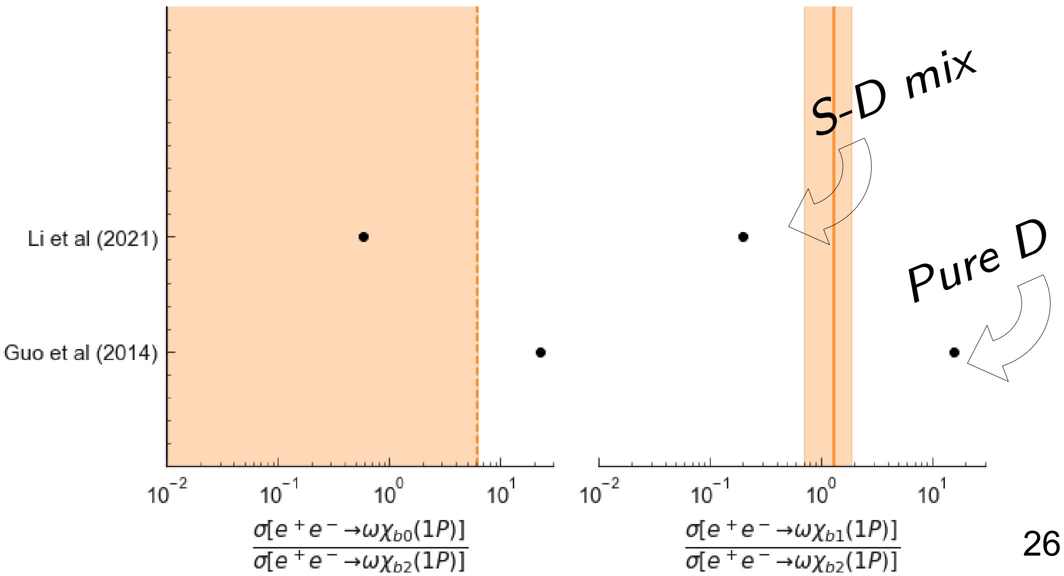


Disagreement with both pure D and S-D mixed predictions

Measured ratios:

$$\frac{B[Y(10750)\rightarrow\omega\chi_{b1}(1P)]}{B[Y(10750)\rightarrow\omega\chi_{b2}(1P)]}=1.3\pm0.6$$

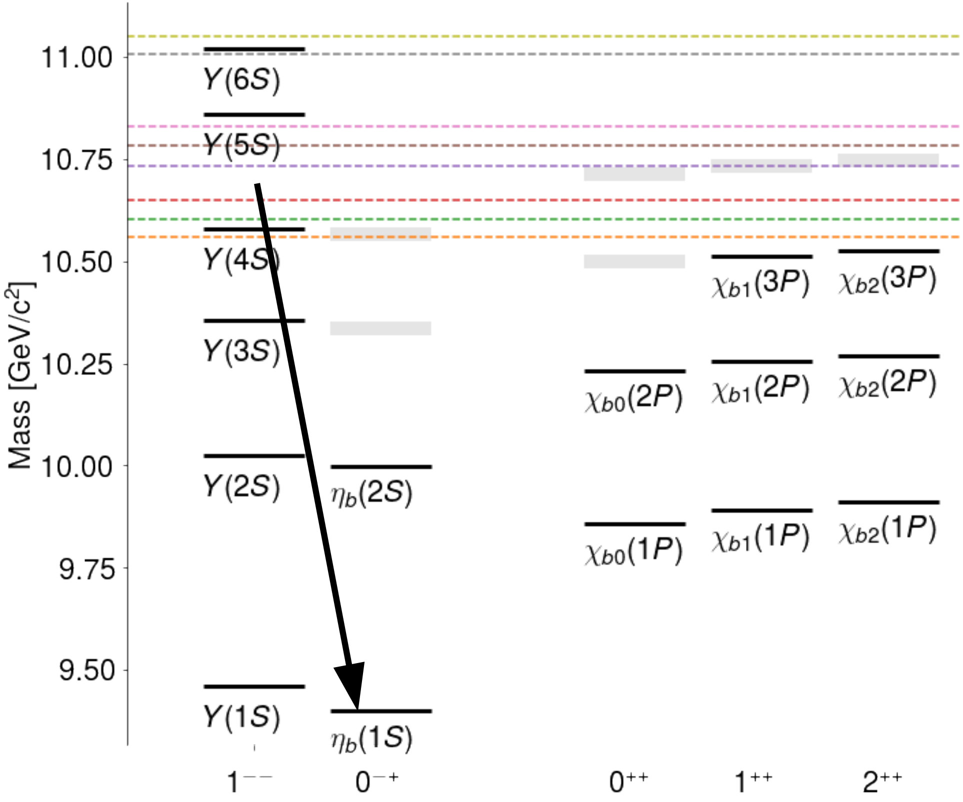
$$\frac{B[Y(10750)\rightarrow\omega\chi_{b0}(1P)]}{B[Y(10750)\rightarrow\omega\chi_{b2}(1P)]}<7$$ *(private extrapolation)*



$e^+e^- \to \eta_b(1S)\ \omega$

[Wang, Chin. Phys. C 43, 123102 (2019)]

Mode	$\mathcal{B}(4q)$ (%)	$\mathcal{B}(b\bar{b})$ (%)
$B\overline{B}$	$39.3^{+38.7}_{-22.9}$	21.3
$B\overline{B}^*$	~ 0.2	14.3
$B^*\overline{B}^*$	$52.3^{+54.9}_{-31.7}$	64.1
$B_s\overline{B}_s$	-	0.3
$\omega\eta_b$	$7.9^{+14.0}_{-5.0}$	-
$f_0(1370)\Upsilon$	$0.2^{+0.6}_{-0.2}$	-
$\omega\Upsilon$	~ 0	-



Strategy:

→ Reconstruct ω

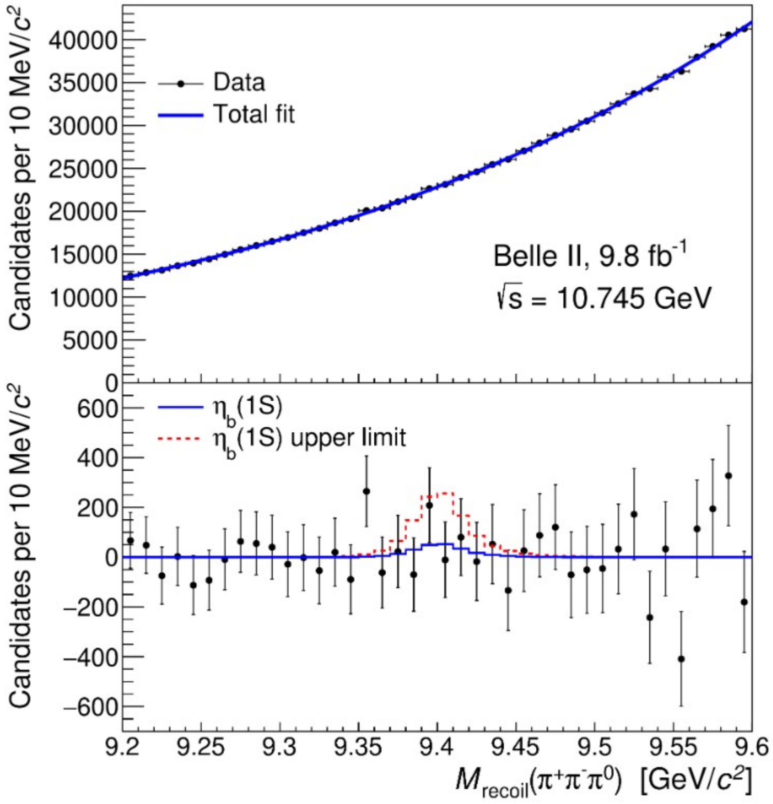
→ Measure its recoil mass

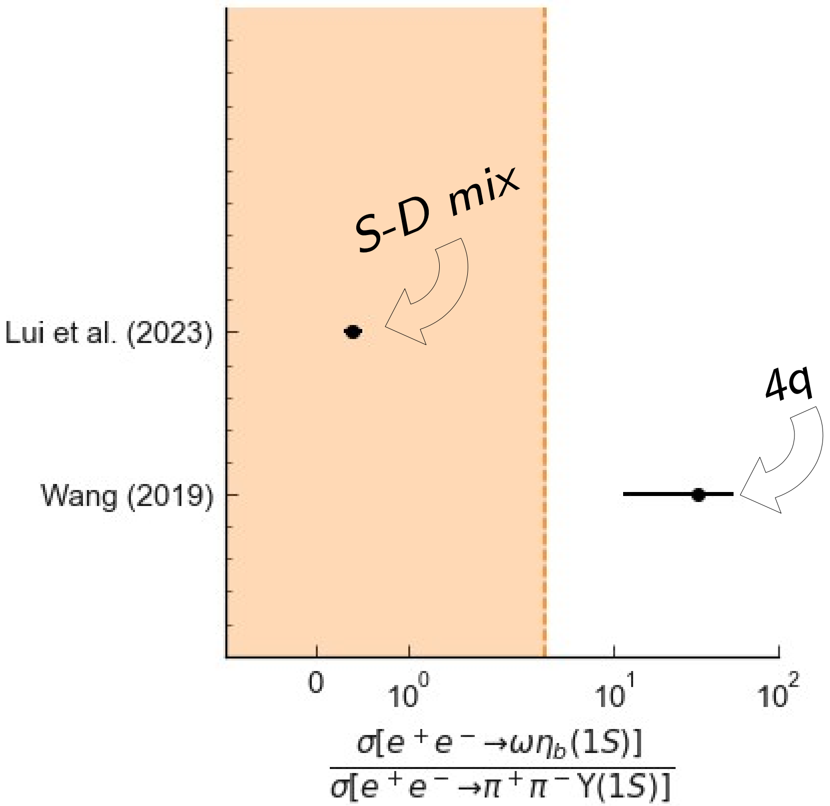
$e^+e^- \to \eta_b(1S)\ \omega$

[arxiv:2312.13043]

NEW

Compatible with S-D mixed





No evidence of ω transition to $\eta_b(1S)$!

$$\sigma_{\rm B}(e^+e^- \to \eta_b(1S)\omega) < 2.5\,{\rm pb}$$

Summary

We don't have yet clear indications on the nature of the $\Upsilon(10750)$

$\rightarrow$ S-D mixed state model compatible with $\omega\eta_b(1S)$, but not with $\omega\chi_{bj}(1P)$

$\rightarrow$ No enhancement of $\omega\eta_b(1S)$ predicted by tetraquark model.

$\rightarrow$ No indication of f_0 in $M(\pi\pi)$ in $\Upsilon(10750) \rightarrow \pi\pi\, \Upsilon(nS)$

$\rightarrow$ New precise data on inclusive and exclusive $e^+e^- \rightarrow B^{(*)}{}_{(s)}\overline{B}^{(*)}{}_{(s)}$ cross sections

  $\rightarrow$ Can be used to get $G[\Upsilon(10750) \rightarrow B^{(*)}\overline{B}^{(*)}]$

  $\rightarrow$ Data are waiting to be fitted ;)

Summary

We don't have yet clear indications on the nature of the $\Upsilon(10750)$

→ S-D mixed state model compatible with $\omega\eta_b(1S)$, but not with $\omega\chi_{bj}(1P)$

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→ New precise data on inclusive and exclusive $e^+e^- \to B^{(*)}_{(s)}\bar{B}^{(*)}_{(s)}$ cross sections

→ Can be used to get $\Gamma[\Upsilon(10750) \to B^{(*)}\bar{B}^{(*)}]$

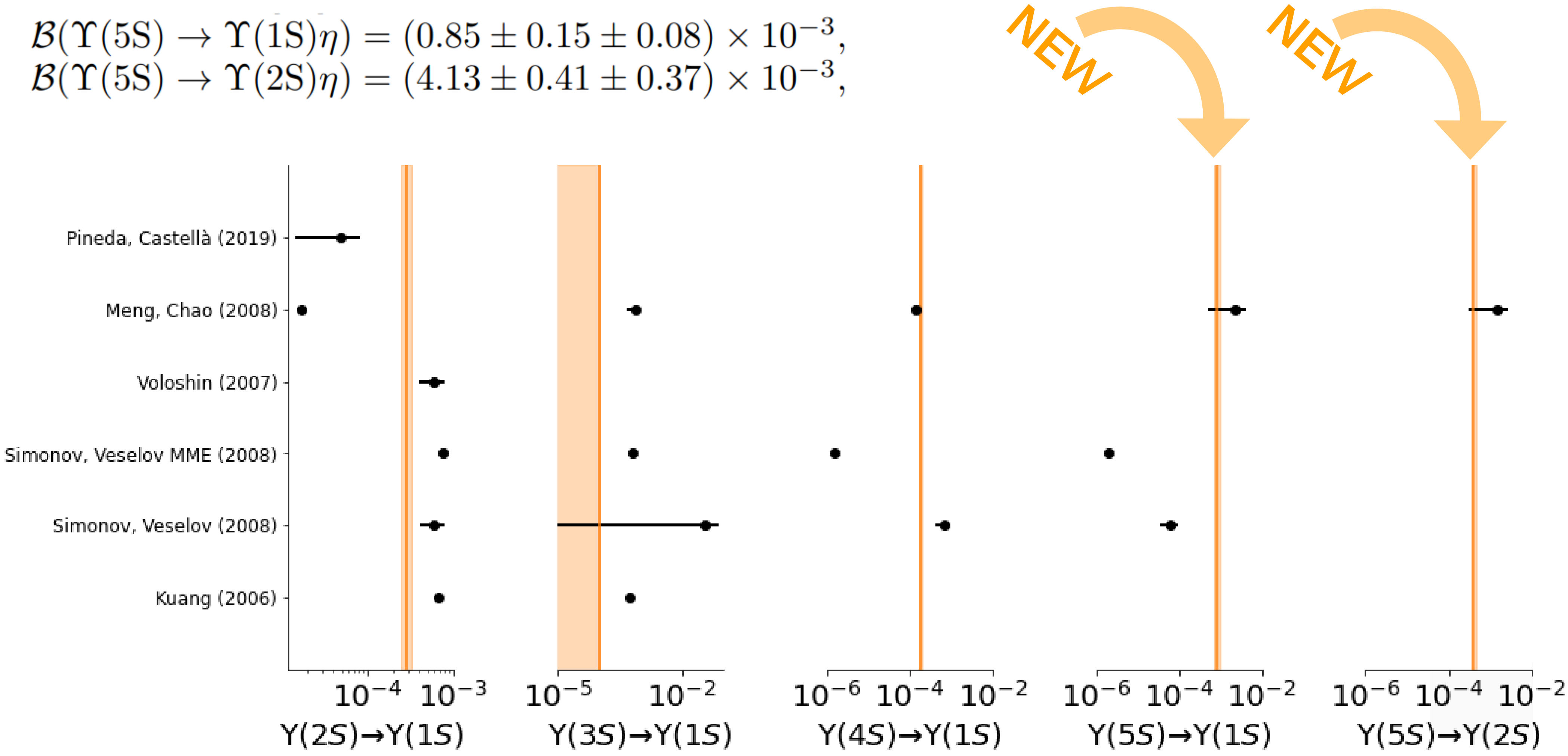
→ Data are waiting to be fitted ;)

What's next: $\pi\pi\ h_b(1P)$, $\eta h_b(1P)$, $\eta\Upsilon(1D)$, $\eta^{(\prime)}\Upsilon(nS)$, $\Upsilon(1S)$ inclusive, radiative transitions...

Backup

η transitions updated

$$\mathcal{B}(\Upsilon(5S) \to \Upsilon(1S)\eta) = (0.85 \pm 0.15 \pm 0.08) \times 10^{-3},$$
$$\mathcal{B}(\Upsilon(5S) \to \Upsilon(2S)\eta) = (4.13 \pm 0.41 \pm 0.37) \times 10^{-3},$$



Belle VS Belle II

arXiv:1808.10567

Tracking and vertexing

$\rightarrow$ More precise

Particle identification

$\rightarrow$ Much more powerful

Calorimetry

$\rightarrow$ ~Unchanged (Better reconstruction, but more backgrounds)

Super-KEKB: the nano-beam scheme

Lorentz factor

Beam current

Beam-beam factor

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{y\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_{y\pm}}}\right)$$

Beam aspect ratio
(flat beam ~ 1-2%)

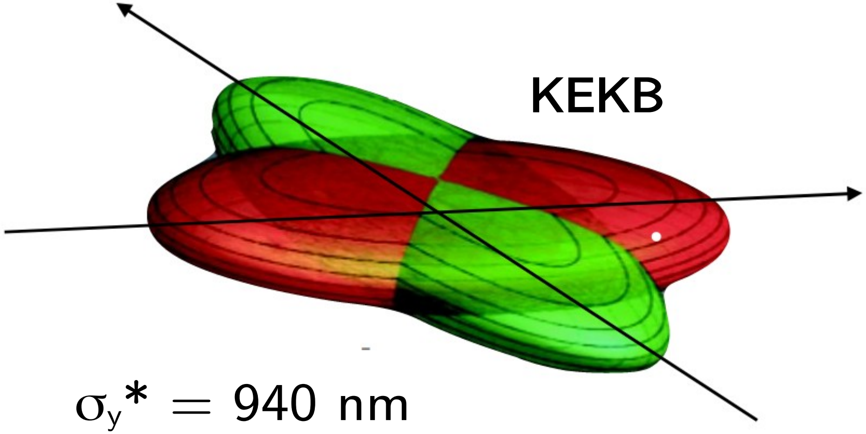
Vertical beta
function at IP

Geometrical corrections
(Hourglass effect...)

Brute force: Increase the current (x2)

Precision: denser beams, smaller β* (x20)

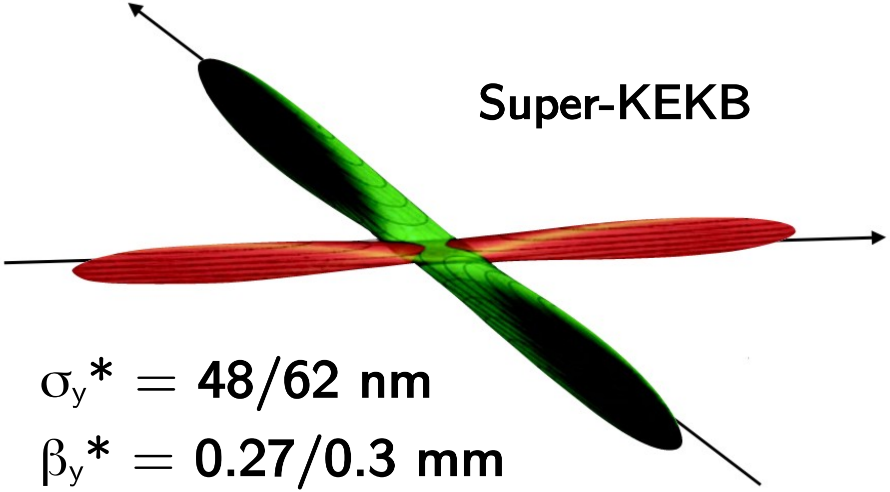
Super-KEKB: the nano-beam scheme



$\sigma_y^* = 940$ nm

$\beta_y^* = 5.9$ mm

$\sigma_x^* = 147/170$ μm



$\sigma_y^* =$ **48/62 nm**

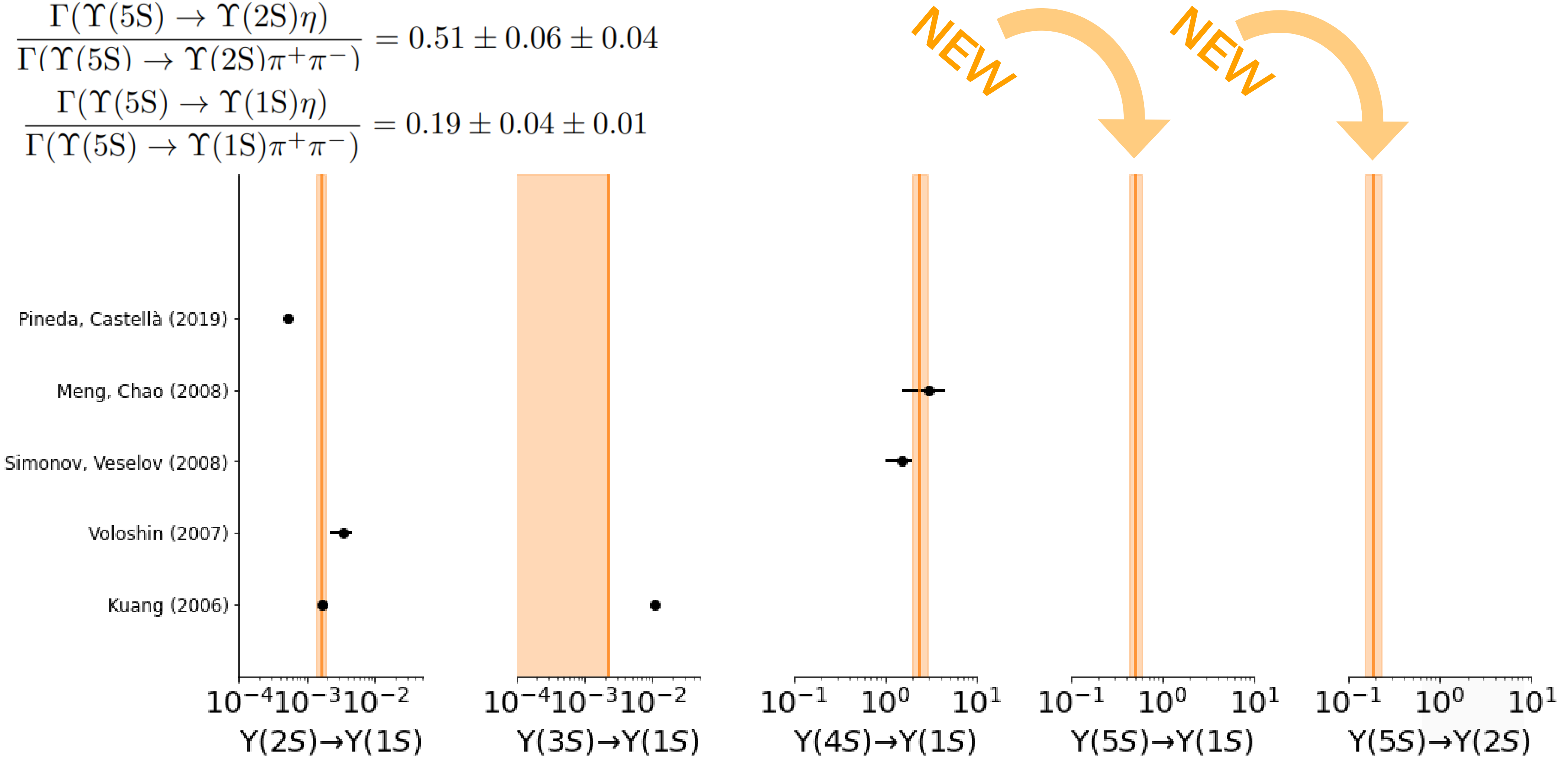
$\beta_y^* =$ **0.27/0.3 mm**

$\sigma_x^* =$ **10.1/10.7 μm**

$\eta/\pi\pi$ Ratio updated

$$\frac{\Gamma(\Upsilon(5S)\to\Upsilon(2S)\eta)}{\Gamma(\Upsilon(5S)\to\Upsilon(2S)\pi^+\pi^-)} = 0.51 \pm 0.06 \pm 0.04$$

$$\frac{\Gamma(\Upsilon(5S)\to\Upsilon(1S)\eta)}{\Gamma(\Upsilon(5S)\to\Upsilon(1S)\pi^+\pi^-)} = 0.19 \pm 0.04 \pm 0.01$$



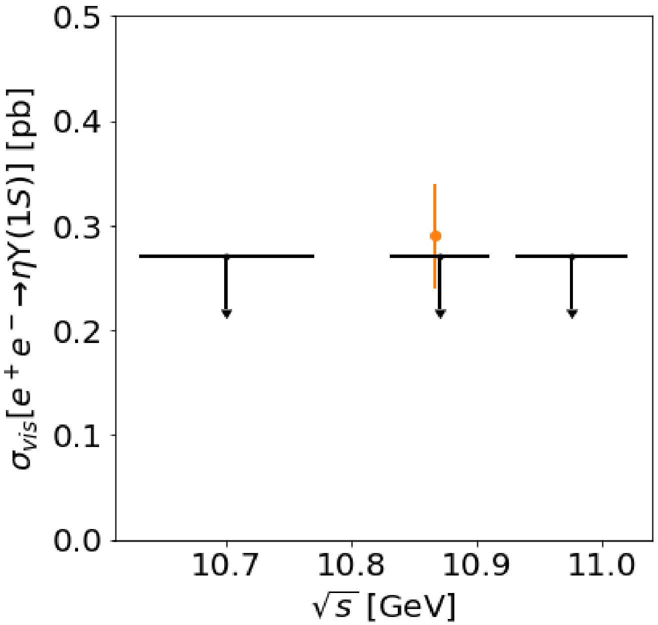
$\Upsilon(5S) \to \eta\, \Upsilon(1S, 2S)$

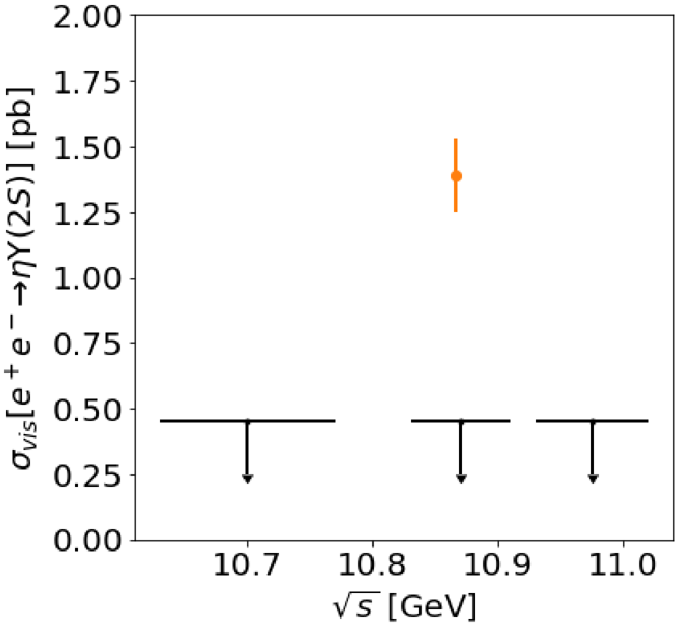
[Phys.Rev.D 104 (2021) 11, 112006]

Results of the combined decays modes:

$$\sigma_{\mathrm{B}}(e^+e^- \to \Upsilon(2\mathrm{S})\eta) = 2.07 \pm 0.21 \pm 0.19 \text{ pb},$$
$$\sigma_{\mathrm{B}}(e^+e^- \to \Upsilon(1\mathrm{S})\eta) = 0.42 \pm 0.08 \pm 0.04 \text{ pb},$$

No Significant yield in the Belle scan data outside the Y(5S)



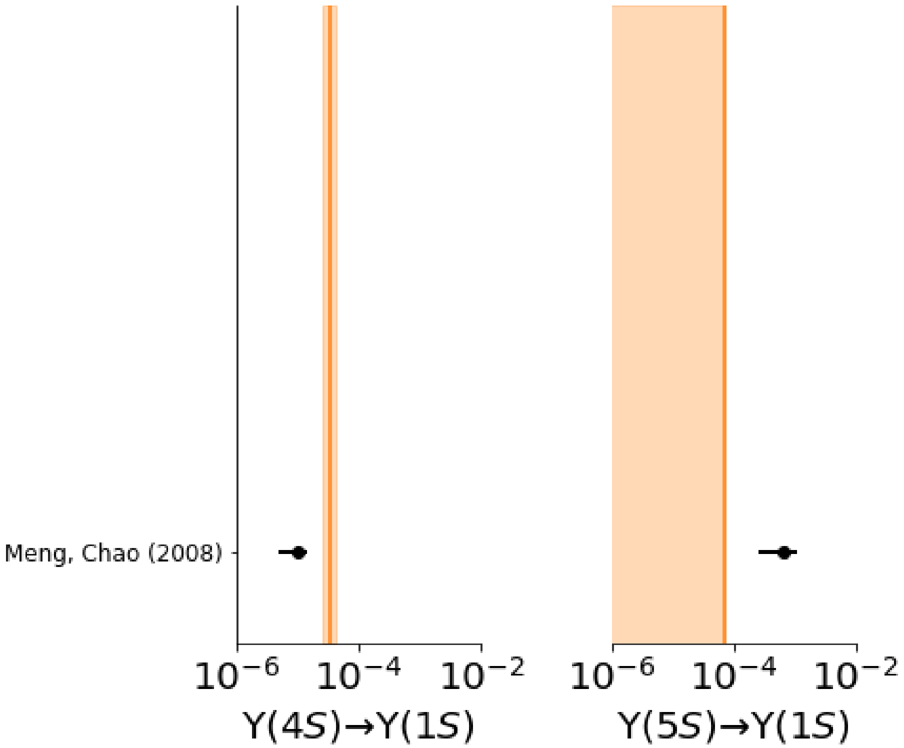


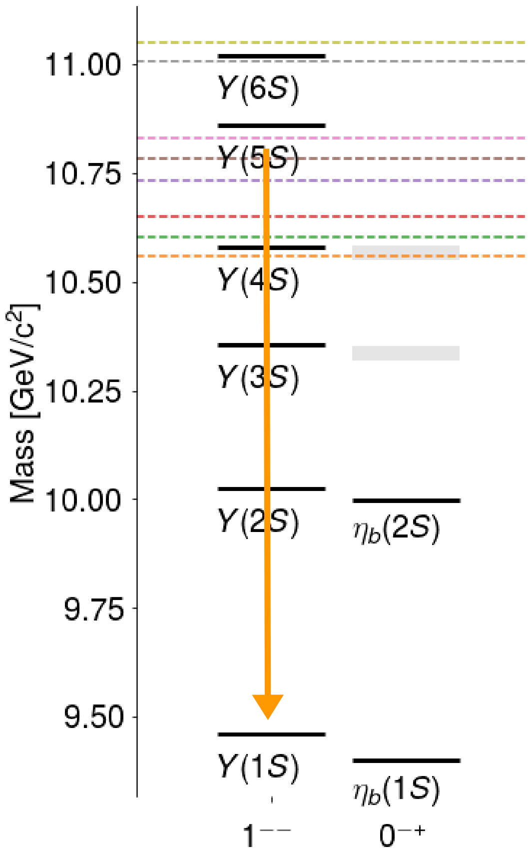
Υ(5S) → η' Υ(1S)

[Phys.Rev.D 104 (2021) 11, 112006]

Combining the two decay modes:

$$\mathcal{B}(\Upsilon(5\mathrm{S}) \to \Upsilon(1\mathrm{S})\eta') < 6.9 \times 10^{-5}, CL = 90\%.$$



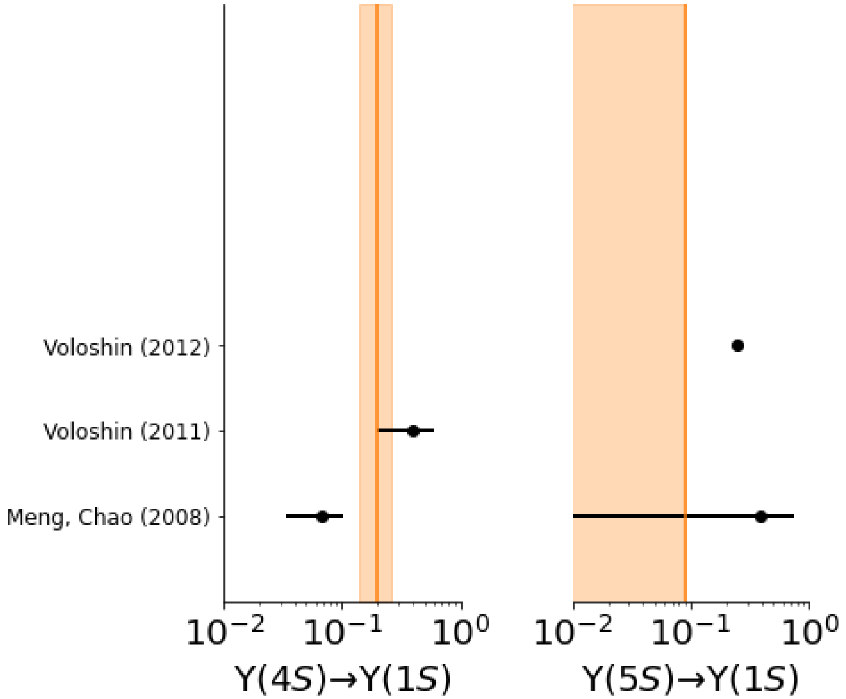


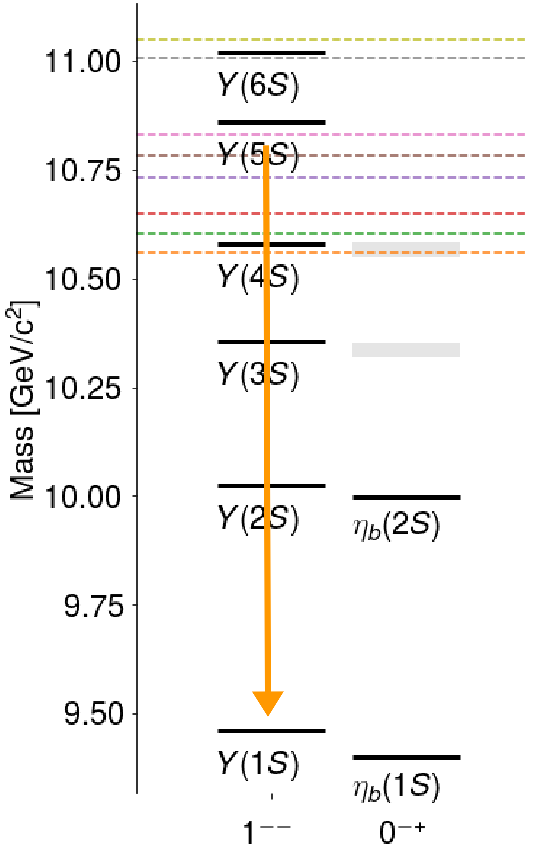
Υ(5S) → η' Υ(1S)

[Phys.Rev.D 104 (2021) 11, 112006]

Combining the two decay modes:

$$\frac{\Gamma(\Upsilon(5S) \to \Upsilon(1S)\eta')}{\Gamma(\Upsilon(5S) \to \Upsilon(1S)\eta)} < 0.09\ (CL = 90\%)$$



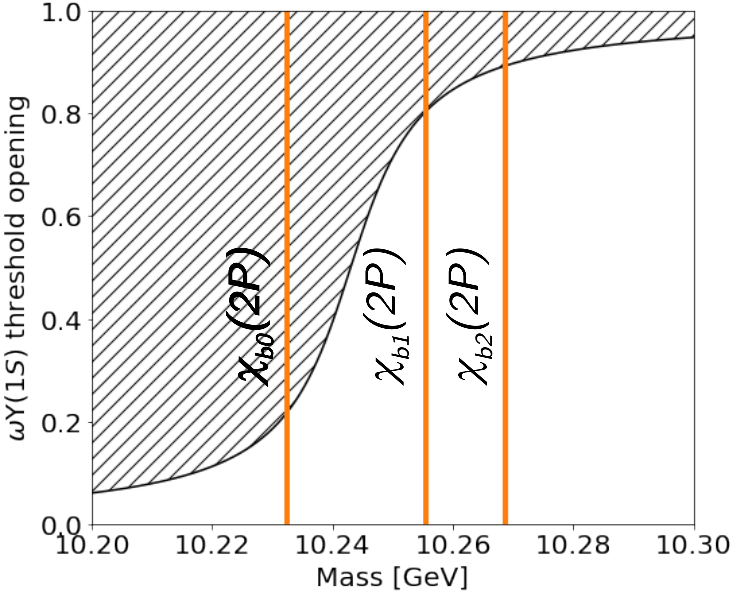


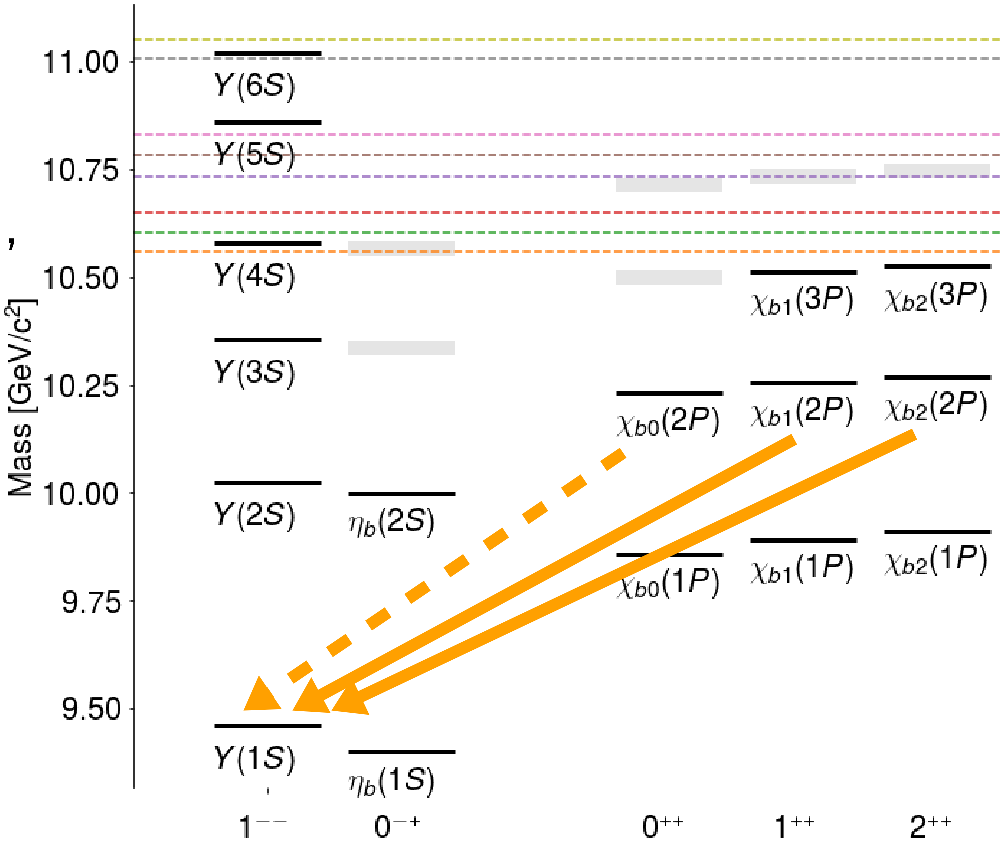
$\chi_{b0}(2P) \to \omega \Upsilon(1S)$

Peculiar features

→ ω Υ(1S) threshold between χ_{b0} and χ_{b1}

→ $\chi_{b0}(2P)$ decay still possible sub-threshold, like in X(3872) → ω J/ψ





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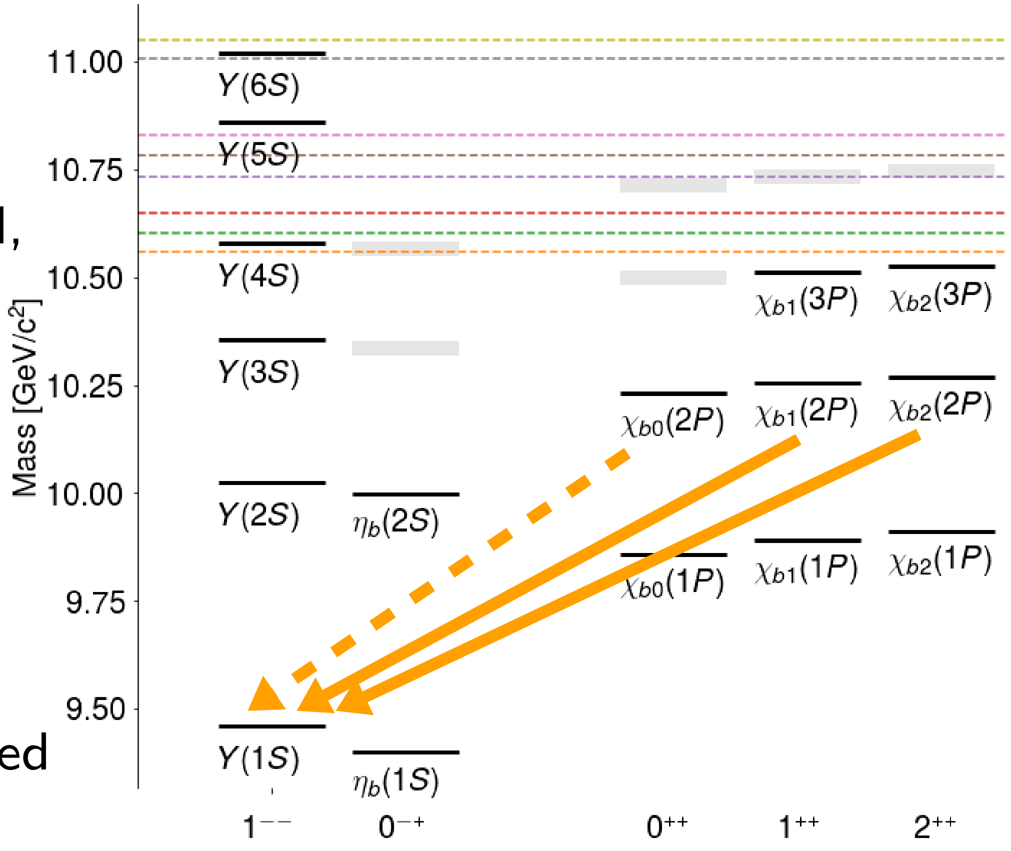
Reconstruction strategy:

Mass of ω + μμ pair

→ $\chi_b(2P)$ produced by non-reconstructed radiative decay of Υ(3S)

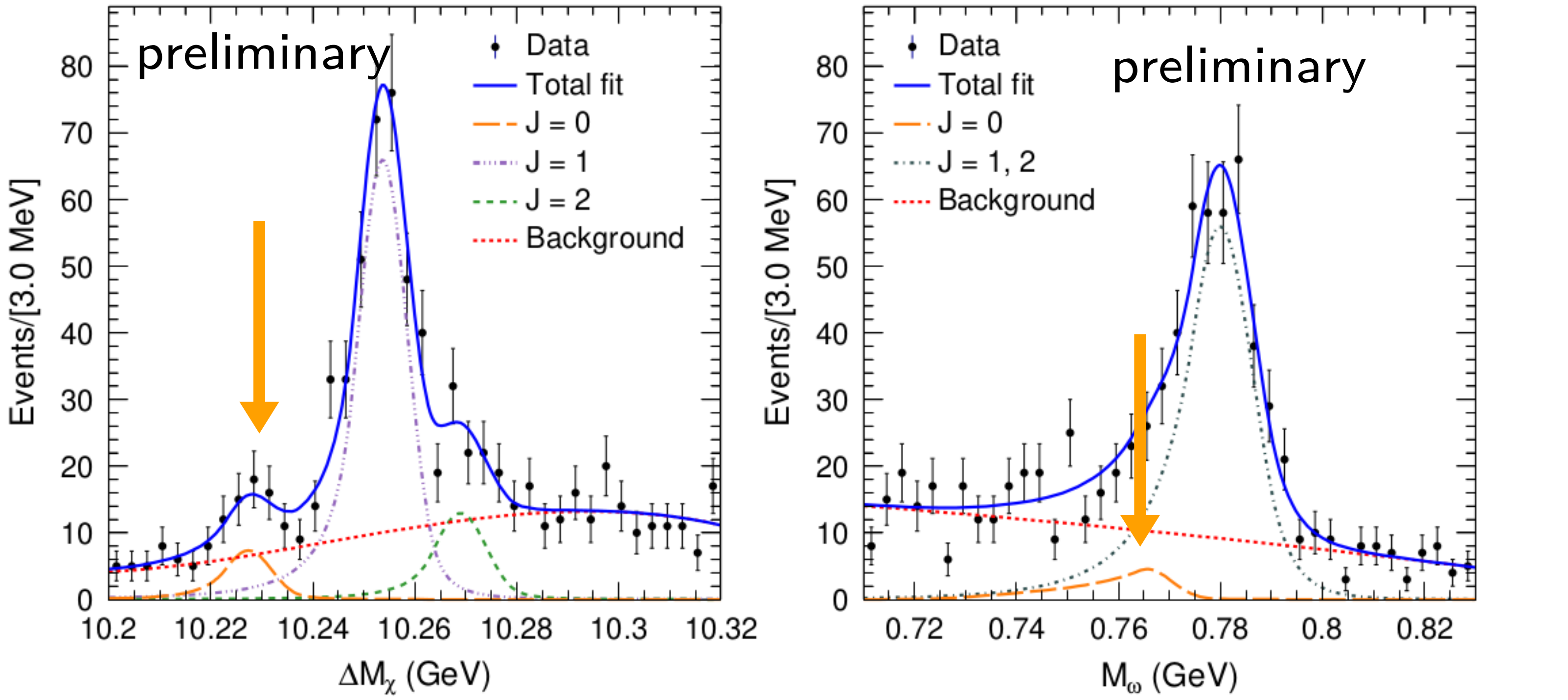


$\chi_{b0}(2P) \to \omega Y(1S)$

NEW

First evidence of $\chi_{b0} \to \omega$ Y(1S) (3.6 σ) preliminary

$$\mathcal{B}(\chi_{b0}(2P) \to \omega\Upsilon(1S)) = (0.54^{+0.19}_{-0.18} \pm 0.07)\%$$



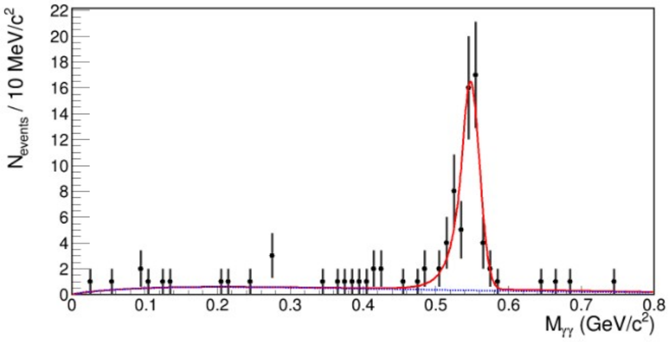
Υ(5S) → η Υ(1S, 2S)

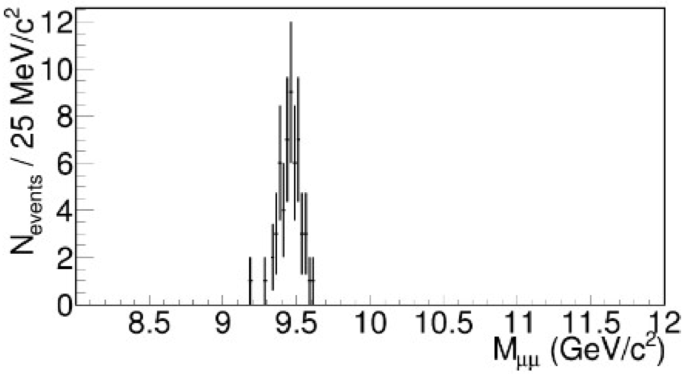
[Phys.Rev.D 104 (2021) 11, 112006]

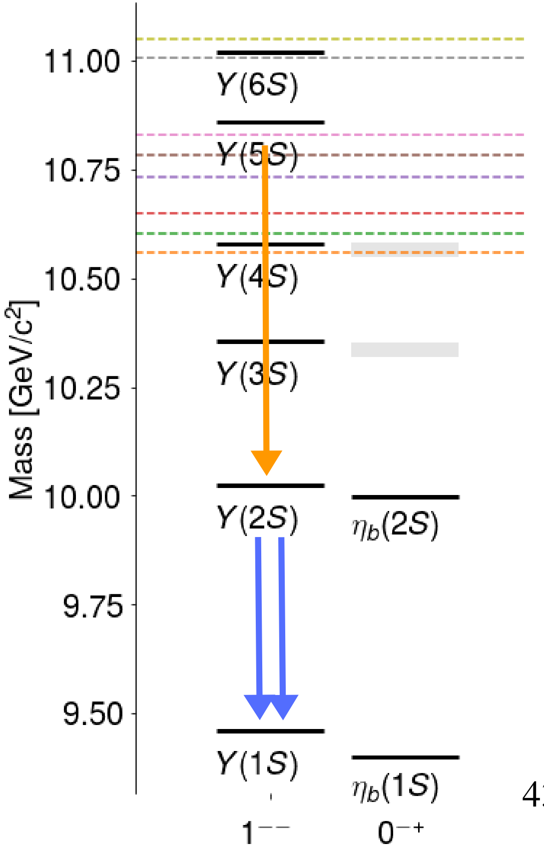
New analysis of η and η' transitions from the Υ(5S) region.

One final state, several decays: **$\mu^+\mu^-$ $\pi^+\pi^-$ γγ**

Υ(2S)[γγ]: $\mu^+\mu^-$ — Υ(1S); $\pi^+\pi^-$ — 2S→ 1S transition; γγ — η







$\Upsilon(5S) \to \eta\, \Upsilon(1S, 2S)$

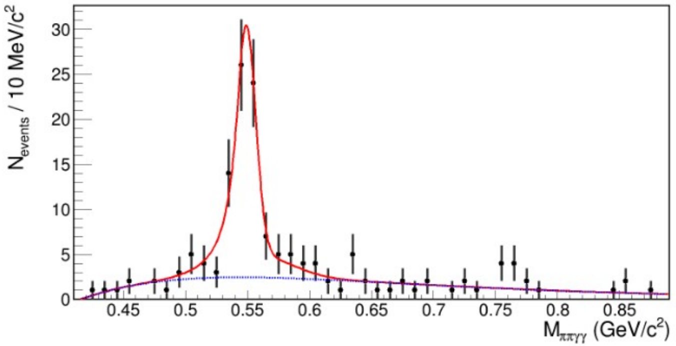
[Phys.Rev.D 104 (2021) 11, 112006]

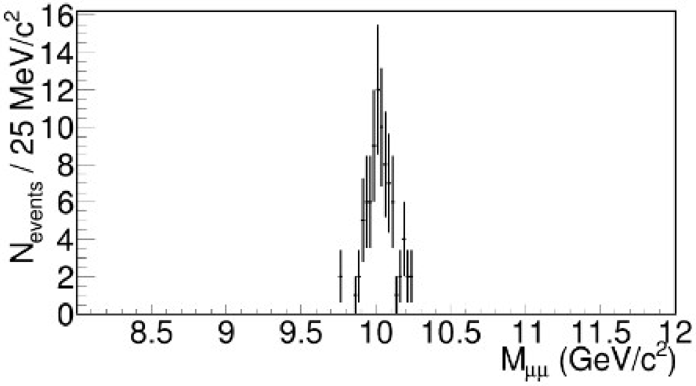
New analysis of η and η' transitions from the Υ(5S) region.

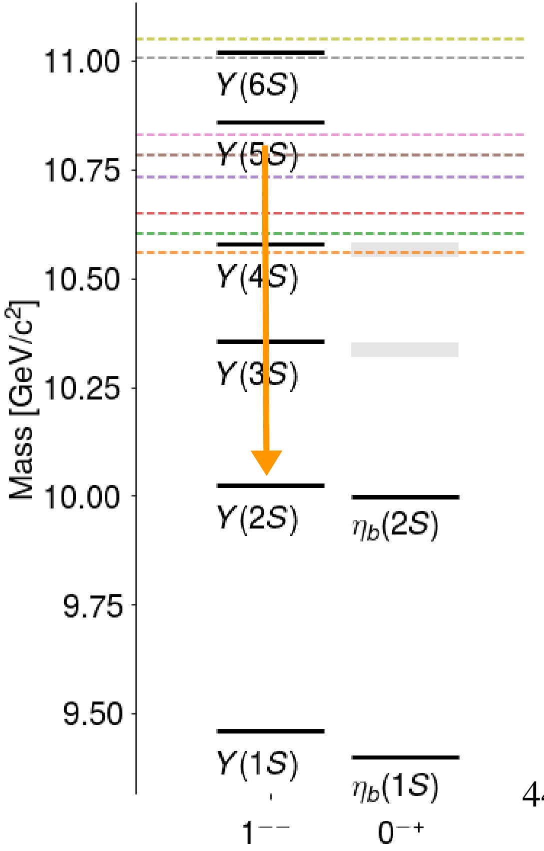
One final state, several decays: **$\mu^+\mu^-$ $\pi^+\pi^-$ $\gamma\gamma$**

Υ(2S)[3π]: $\mu^+\mu^-$ $\pi^+\pi^-$ $\gamma\gamma$

Υ(2S) η







$\Upsilon(5S) \to \eta\, \Upsilon(1S, 2S)$

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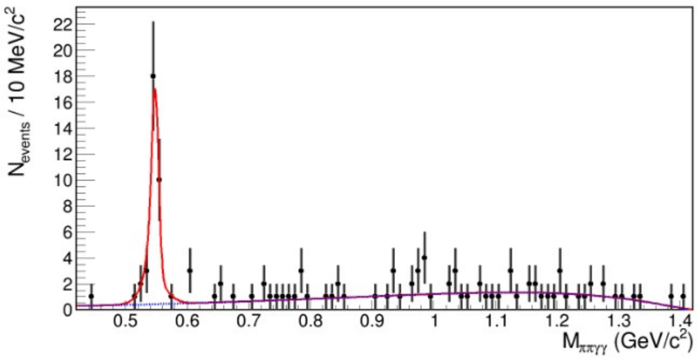
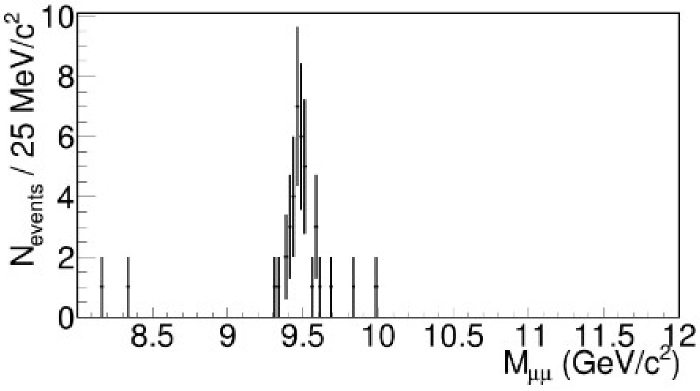
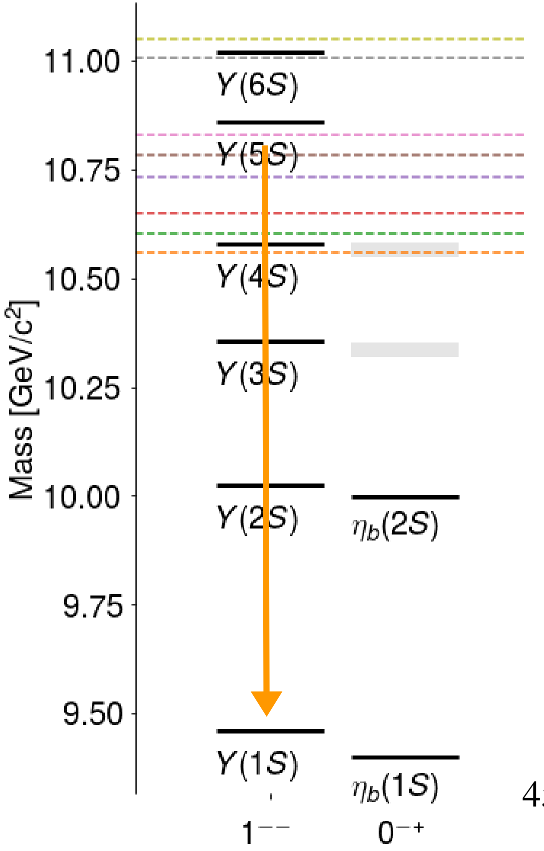
Υ(1S) η







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