Istituto Nazionale di Fisica Nucleare
SEZIONE DI TORINO

Bottomonium at Belle II

Excited QCD 2024

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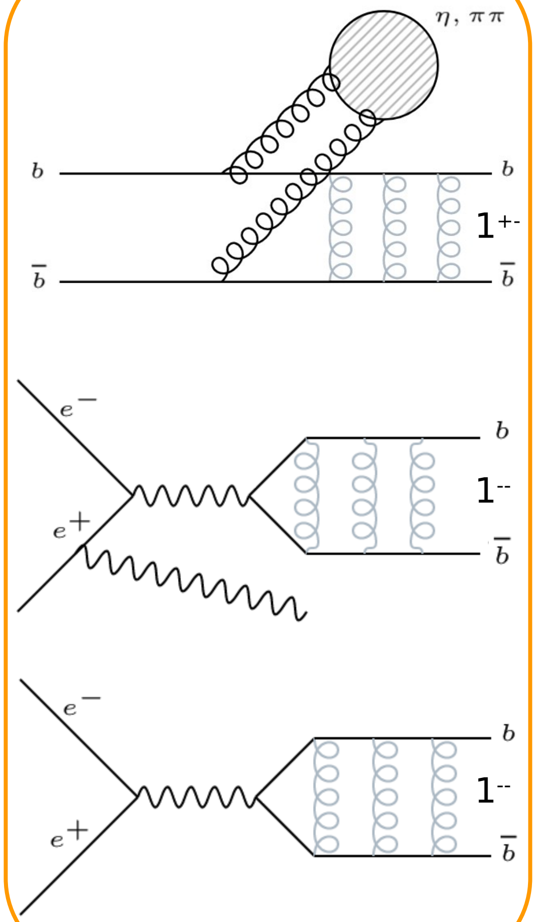
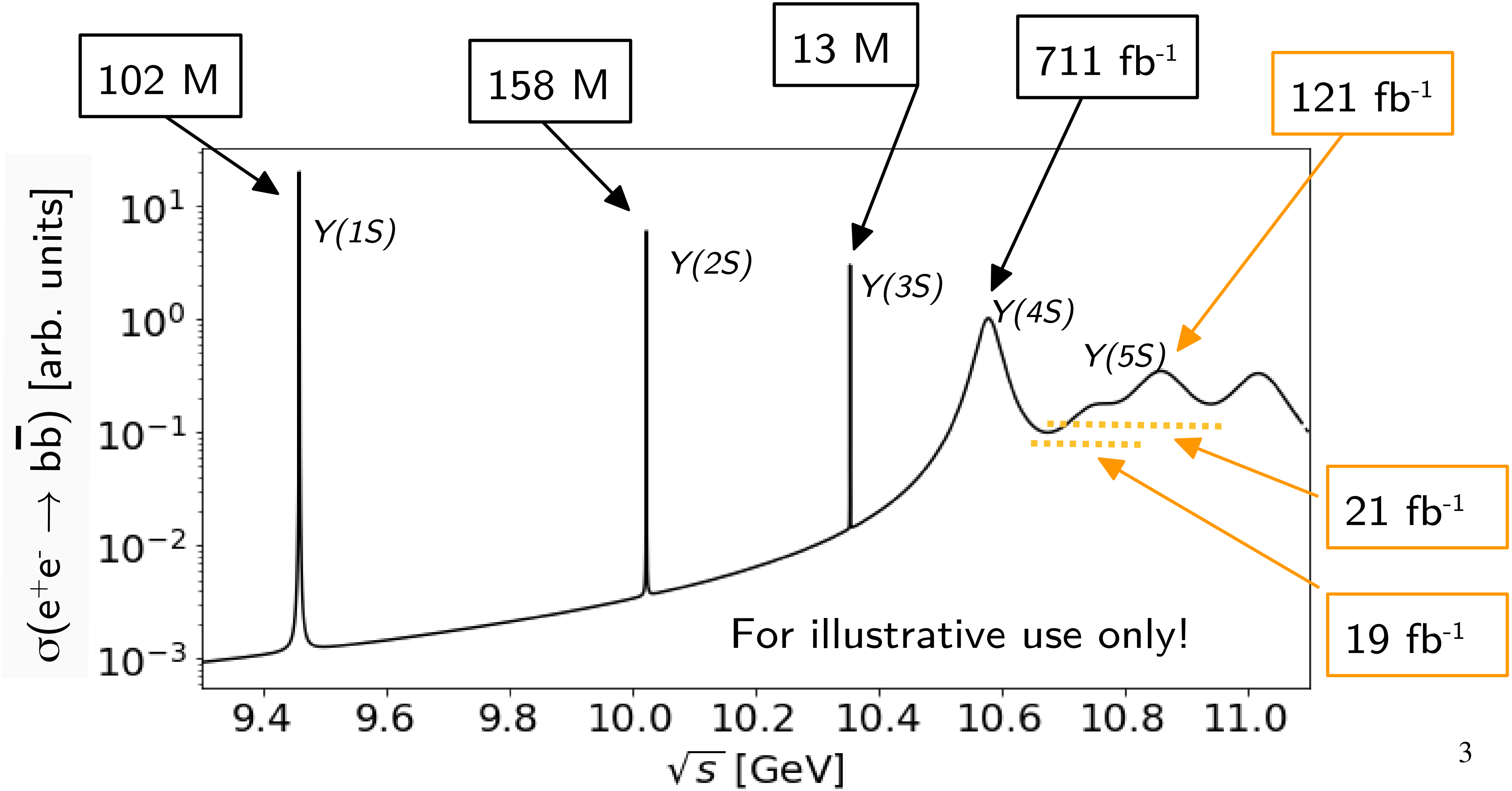
Quarkonia at Belle II: how?

Bottomonium

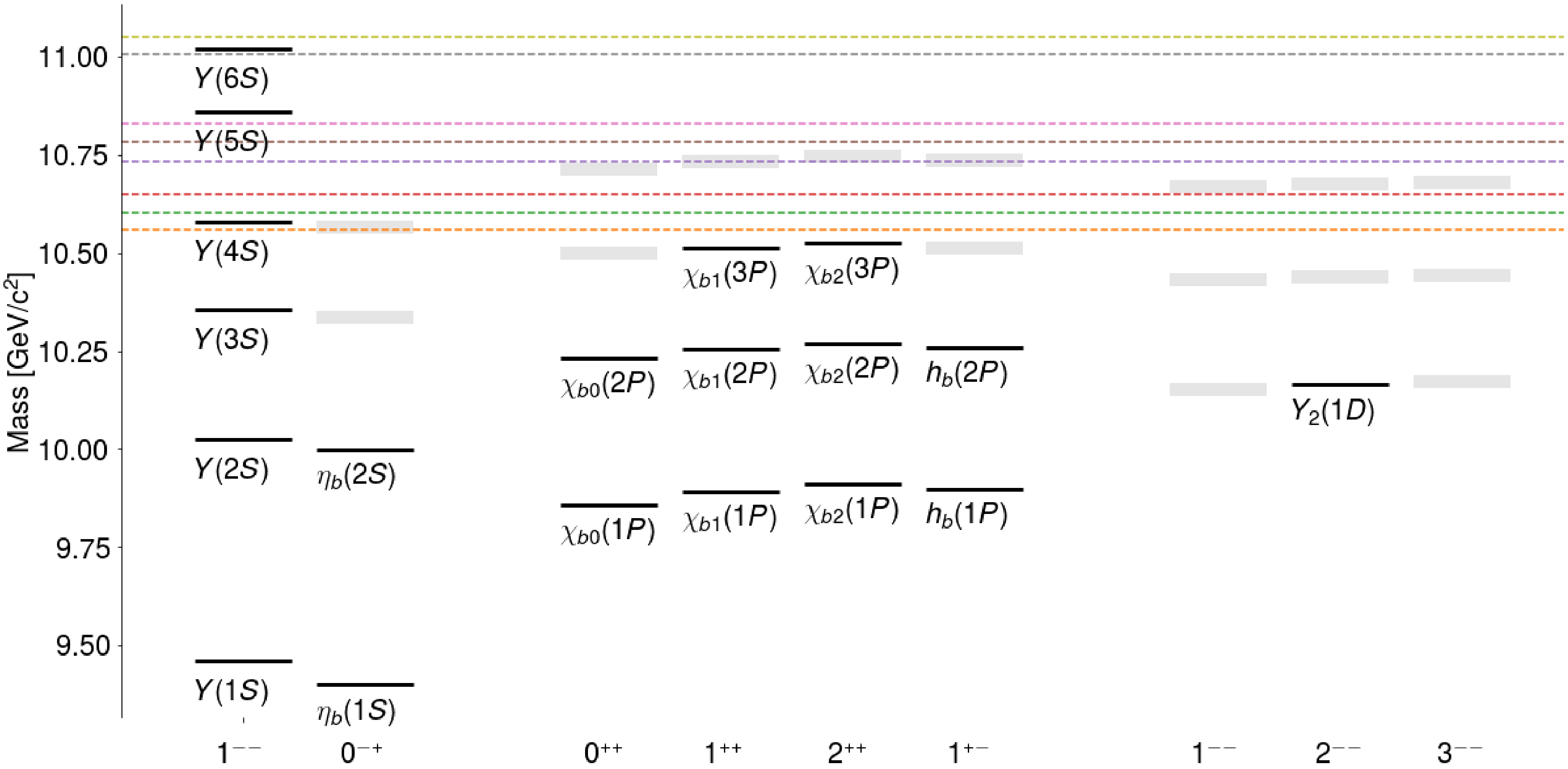
- Hadronic transitions from Υ(4S)
  - Best gateway to $h_b(1P)$ and $\eta_b(1S)$!
- ISR production
- Direct production



Belle (II) relevant datasets



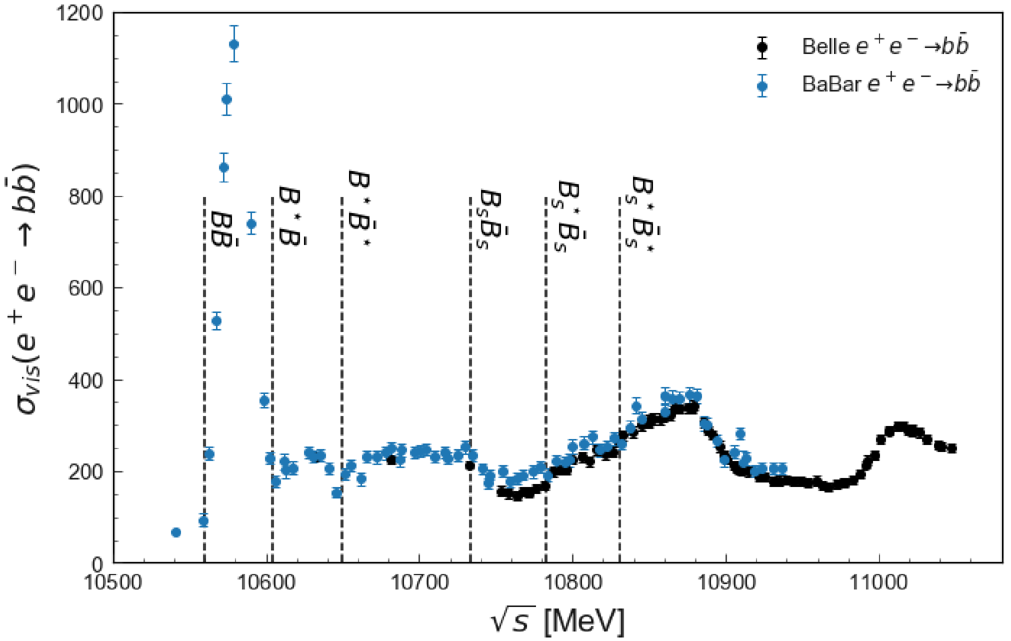
The threshold region

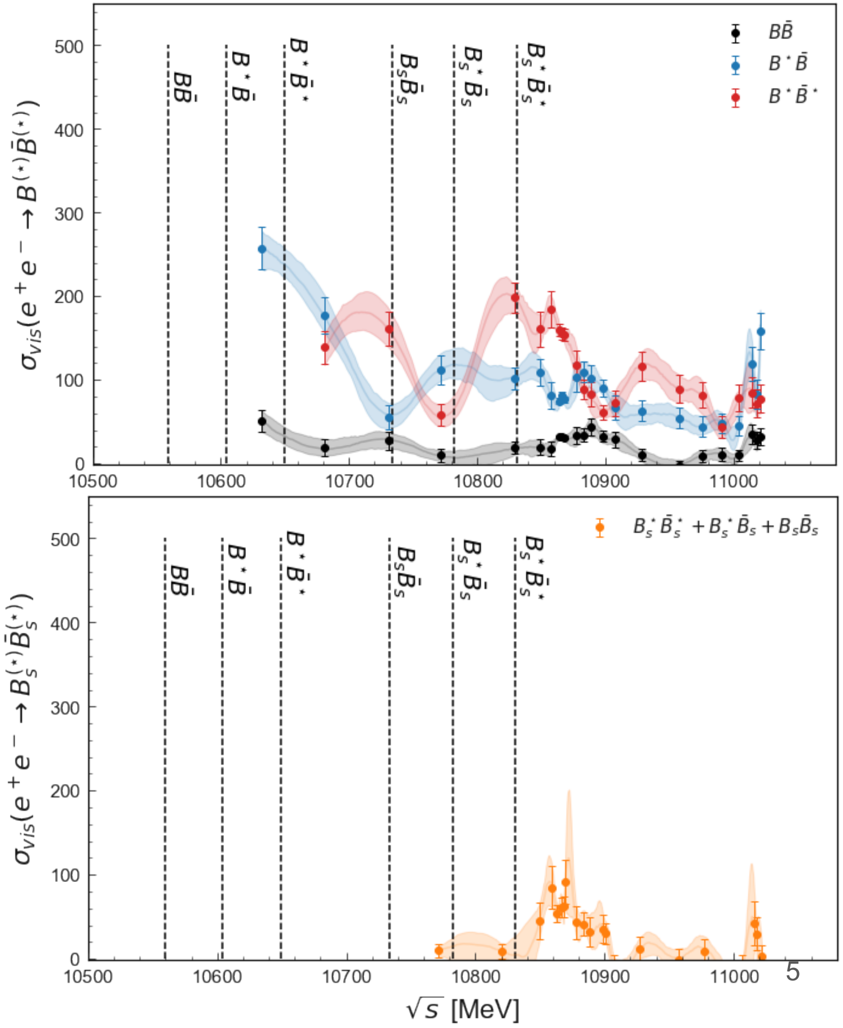


The threshold region: open flavour

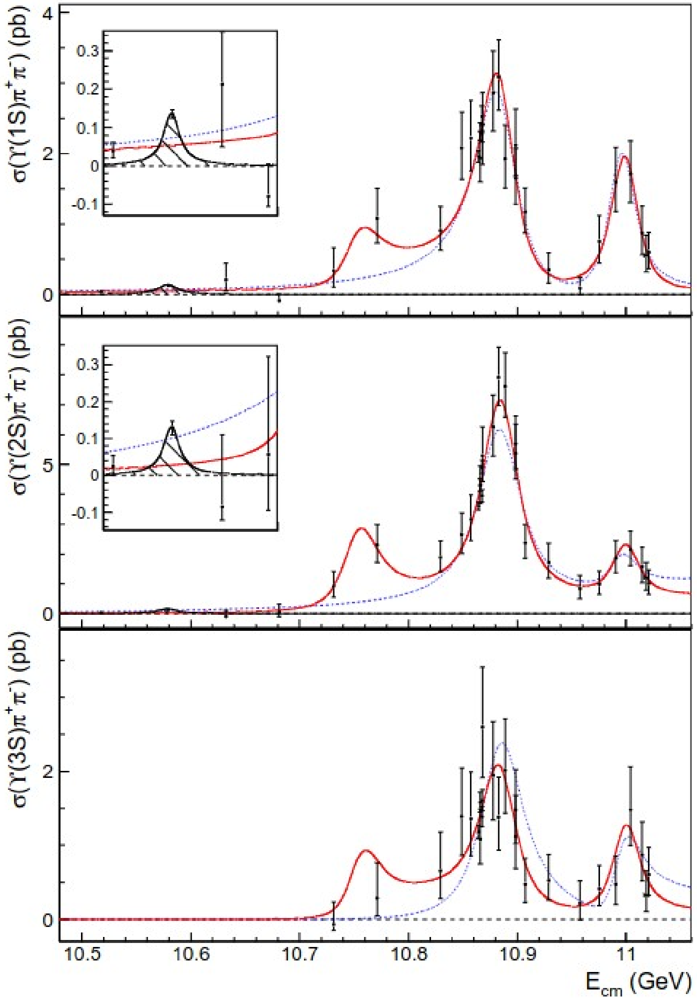
JHEP10(2019)220 (*Belle*):

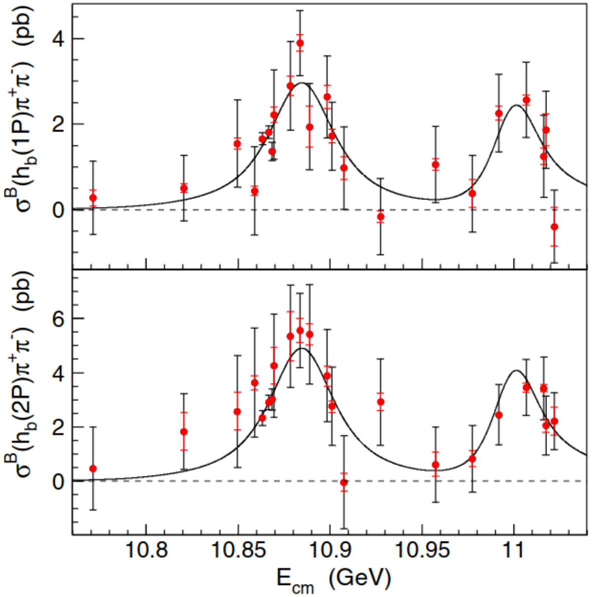
- "High-stat" scan points: 1 fb^{-1} each
- Some resonance appears in the ppY(nS) cross section

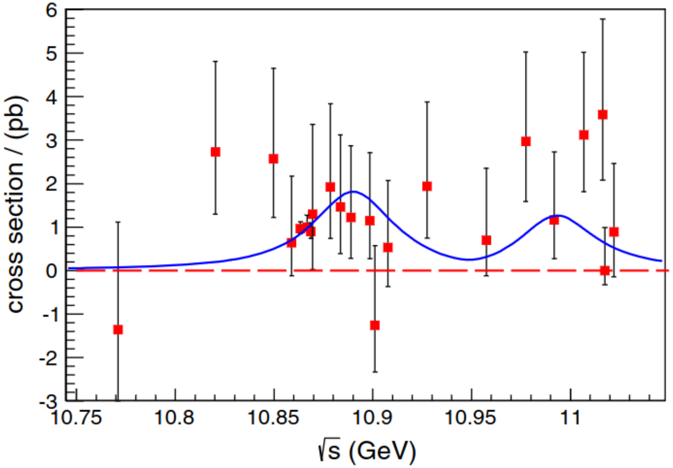




The threshold region: hidden flavour





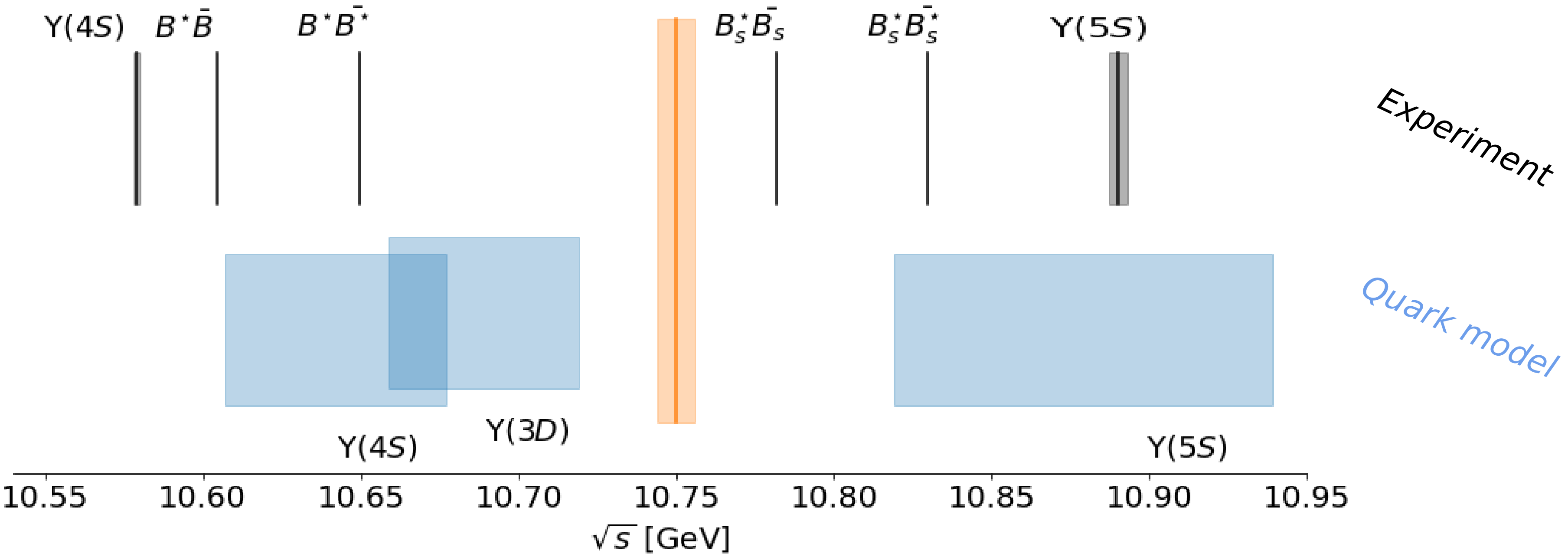


New structure in $\pi\pi$Y(nS), the Y(10750)

	$\Upsilon(10860)$	$\Upsilon(11020)$	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)	$36.6^{+4.5}_{-3.9}\,^{+0.5}_{-1.1}$	$23.8^{+8.0}_{-6.8}\,^{+0.7}_{-1.8}$	$35.5^{+17.6}_{-11.3}\,^{+3.9}_{-3.3}$

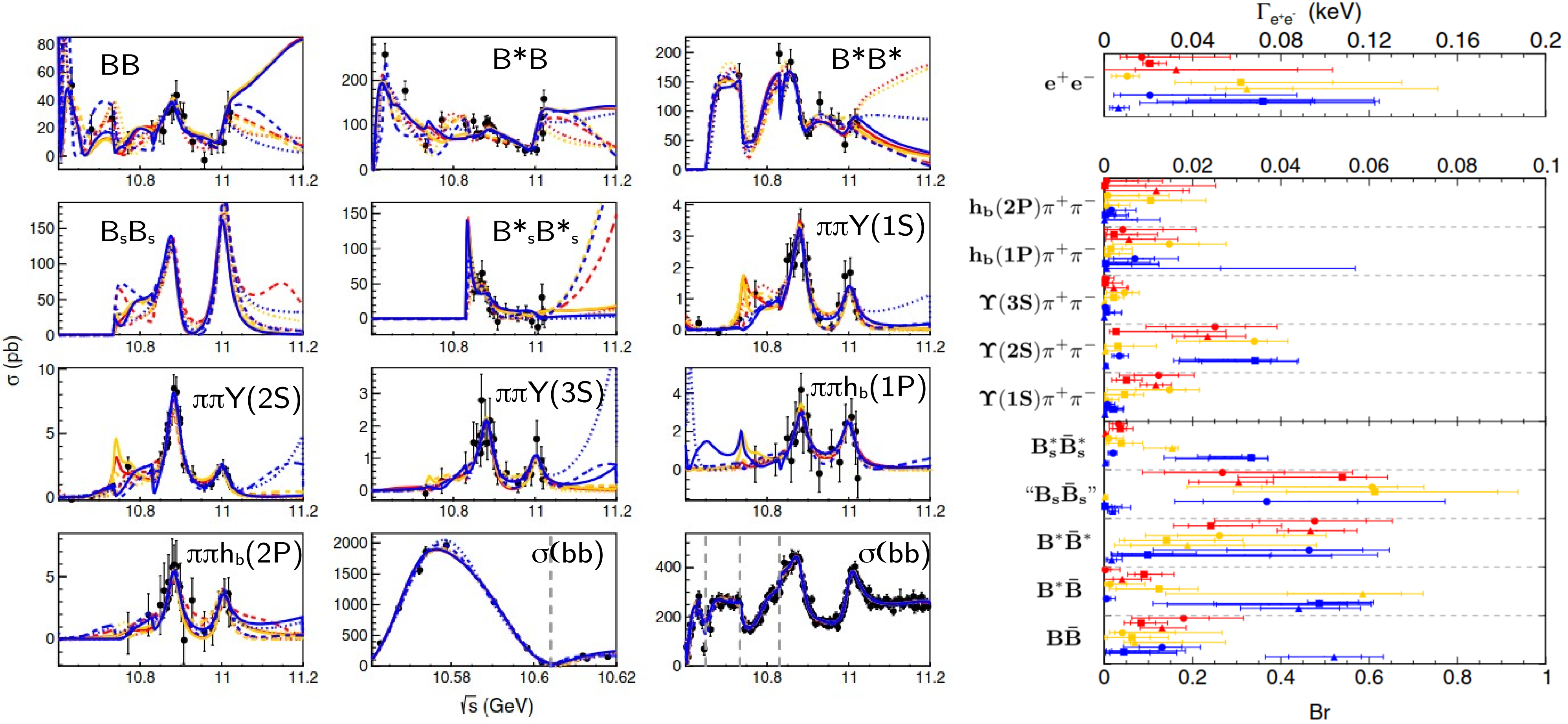
Mass and quantum numbers

- J^{PC} must be 1^{--}
- No direct matching to conventional states (but may be an S-D mixing?)
- **Can it be an exotic?**



Global fits

Husken Mitchell Swanson PRD 106 094013 (2022)



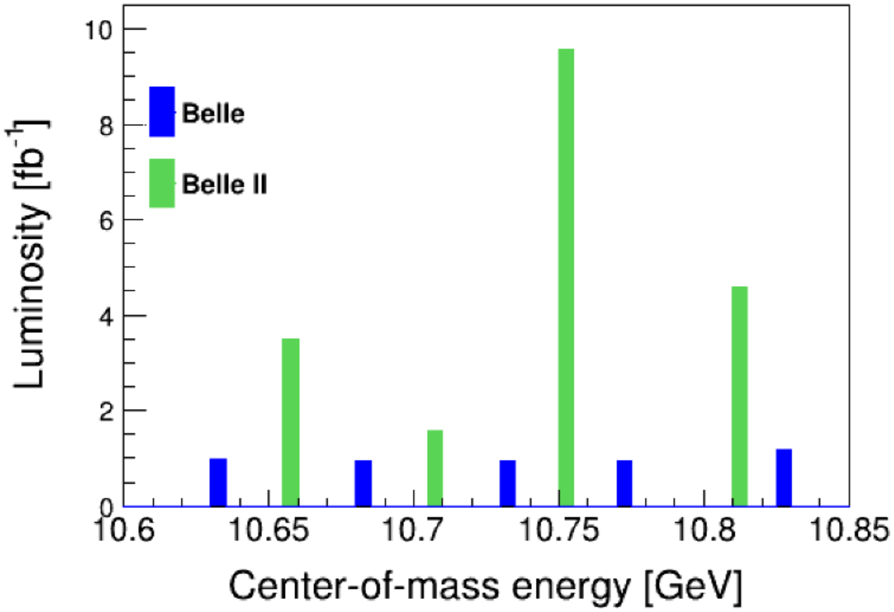
The new Belle II dataset

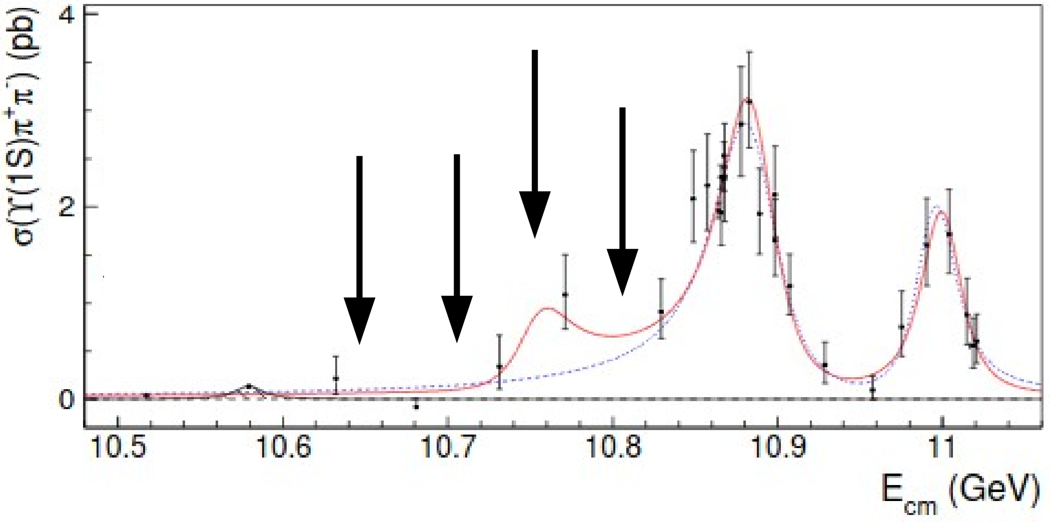
In fall 2021 Belle II took data above the Υ(4S)

$\rightarrow$ Goal: study the golden channels to characterize the Υ(10750)

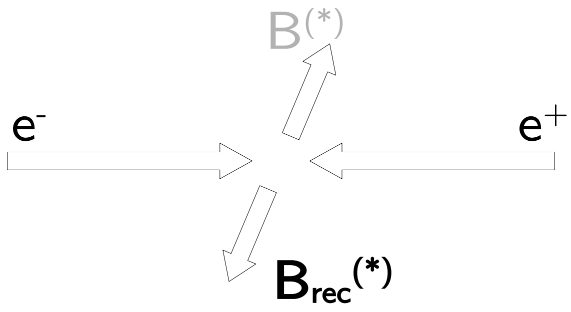
$\rightarrow$ Special data taking, lots of discussions and preparation

$\rightarrow$ If you have an idea and you like it, don' give up ;)





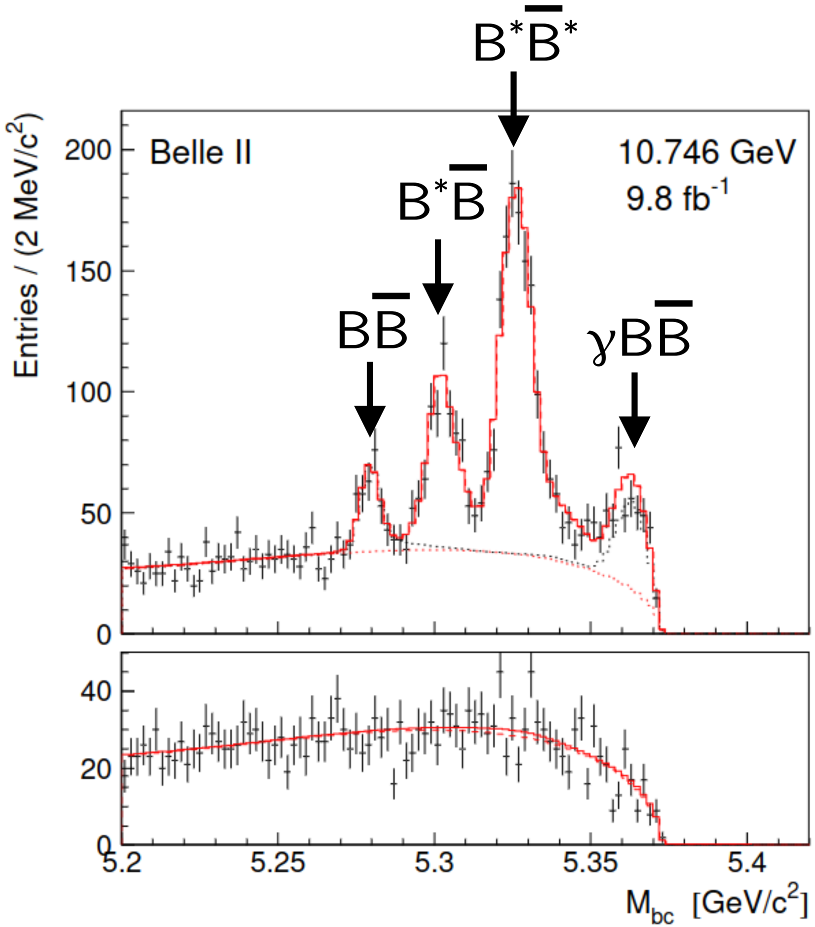
BB decomposition updated



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})

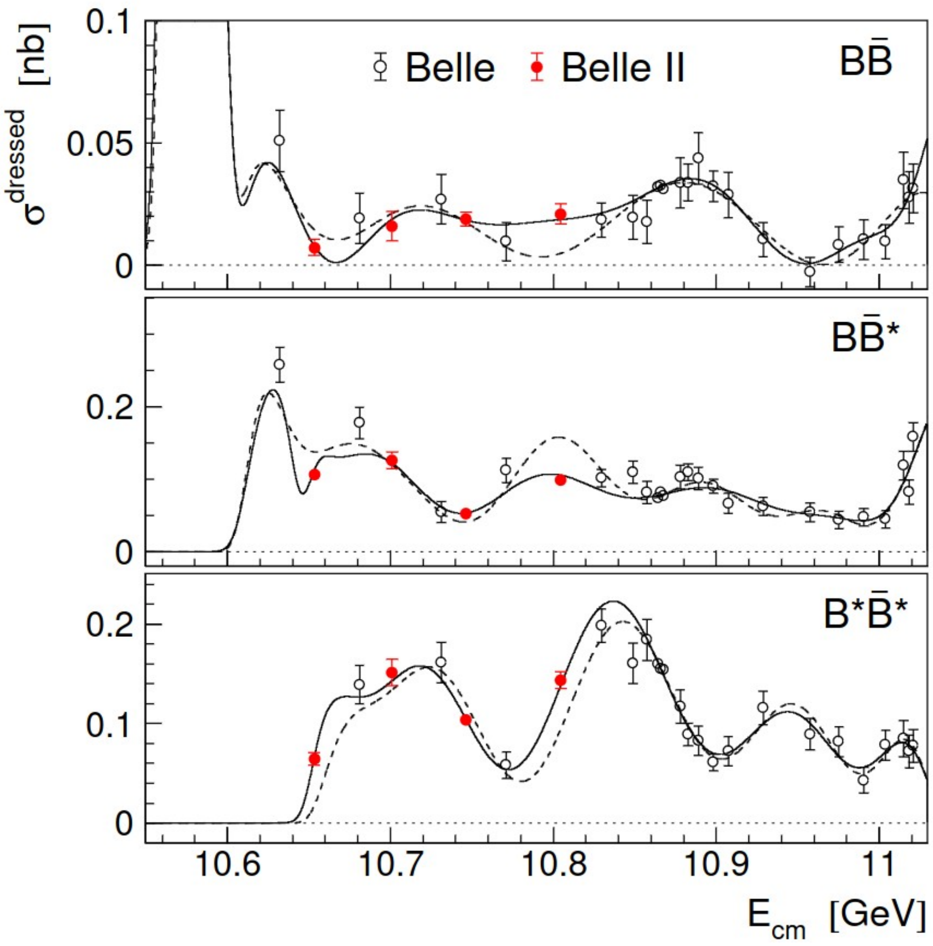
$$M_{\rm bc} = \sqrt{(E_{\rm cm}/2)^2 - p_B^2}$$



BB decomposition updated

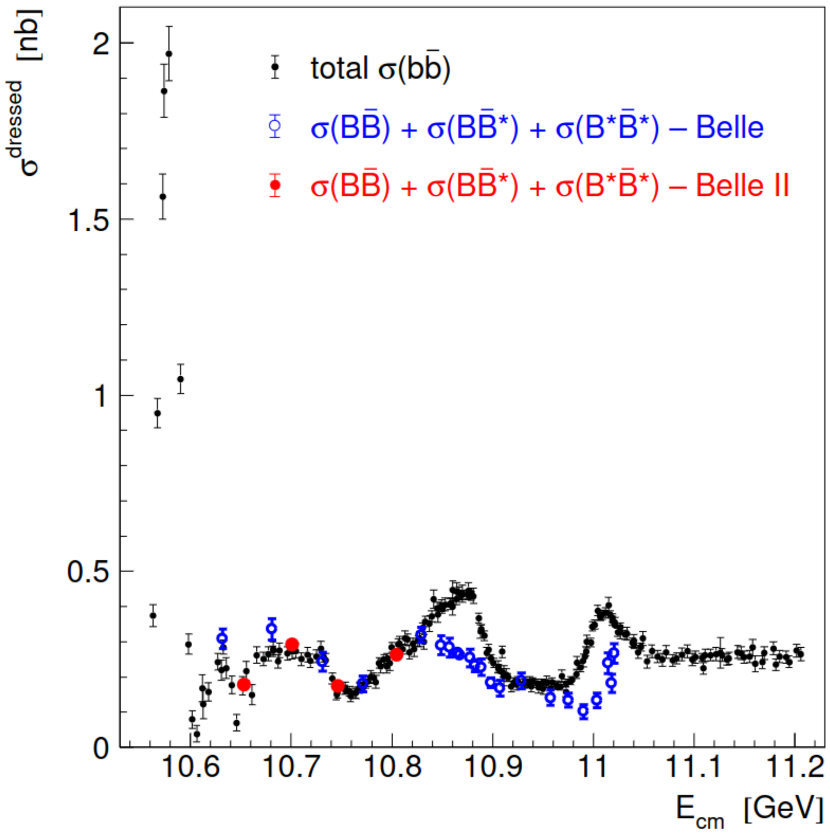
Prominent features:

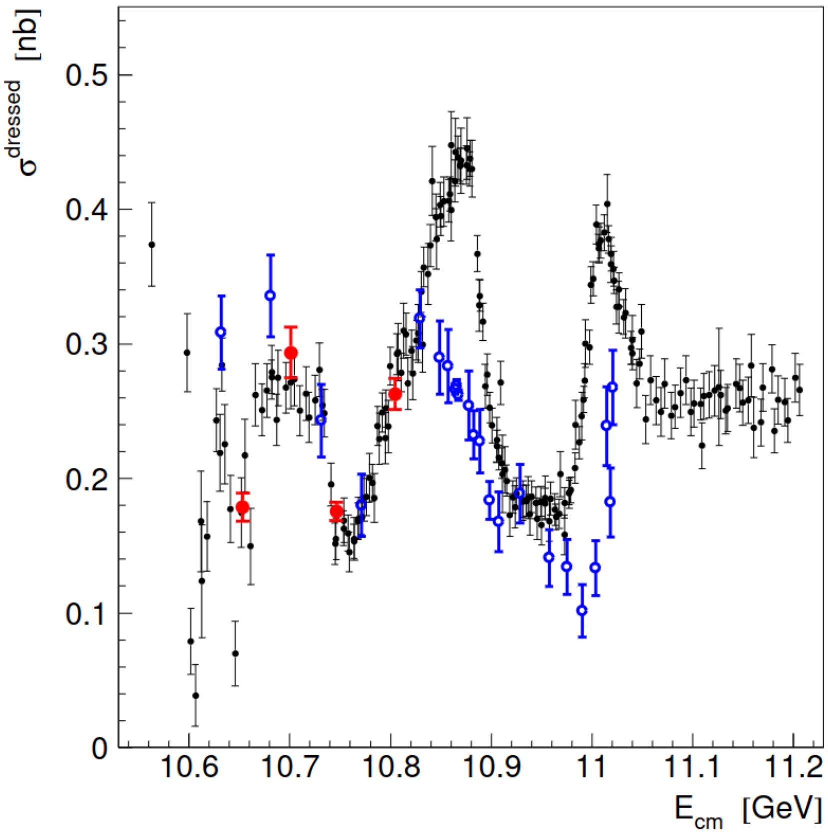
- → Sharp rise in B^*B^*
  - → first point only ∼2 MeV above $B^{0*}B^{0*}$ threshold
- → Deep in B^*B at the B^*B^* threshold



BB decomposition updated

Do we saturate the total cross section?





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

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

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

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

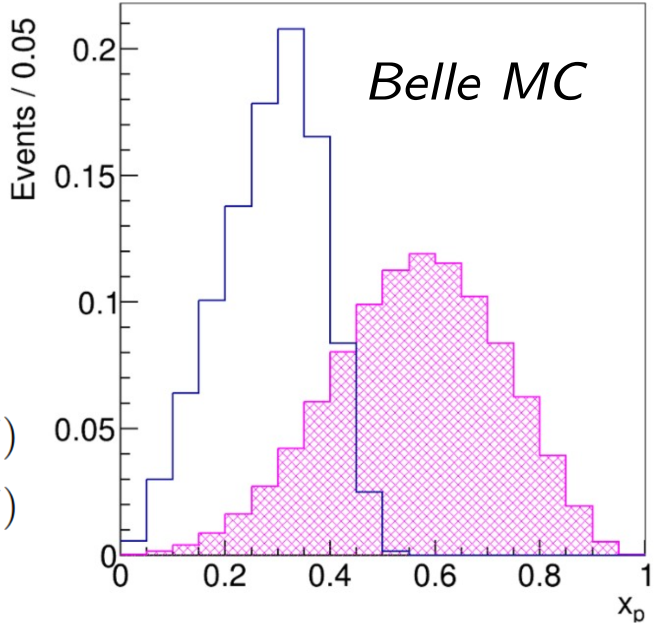
→ Solve the equation system:

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

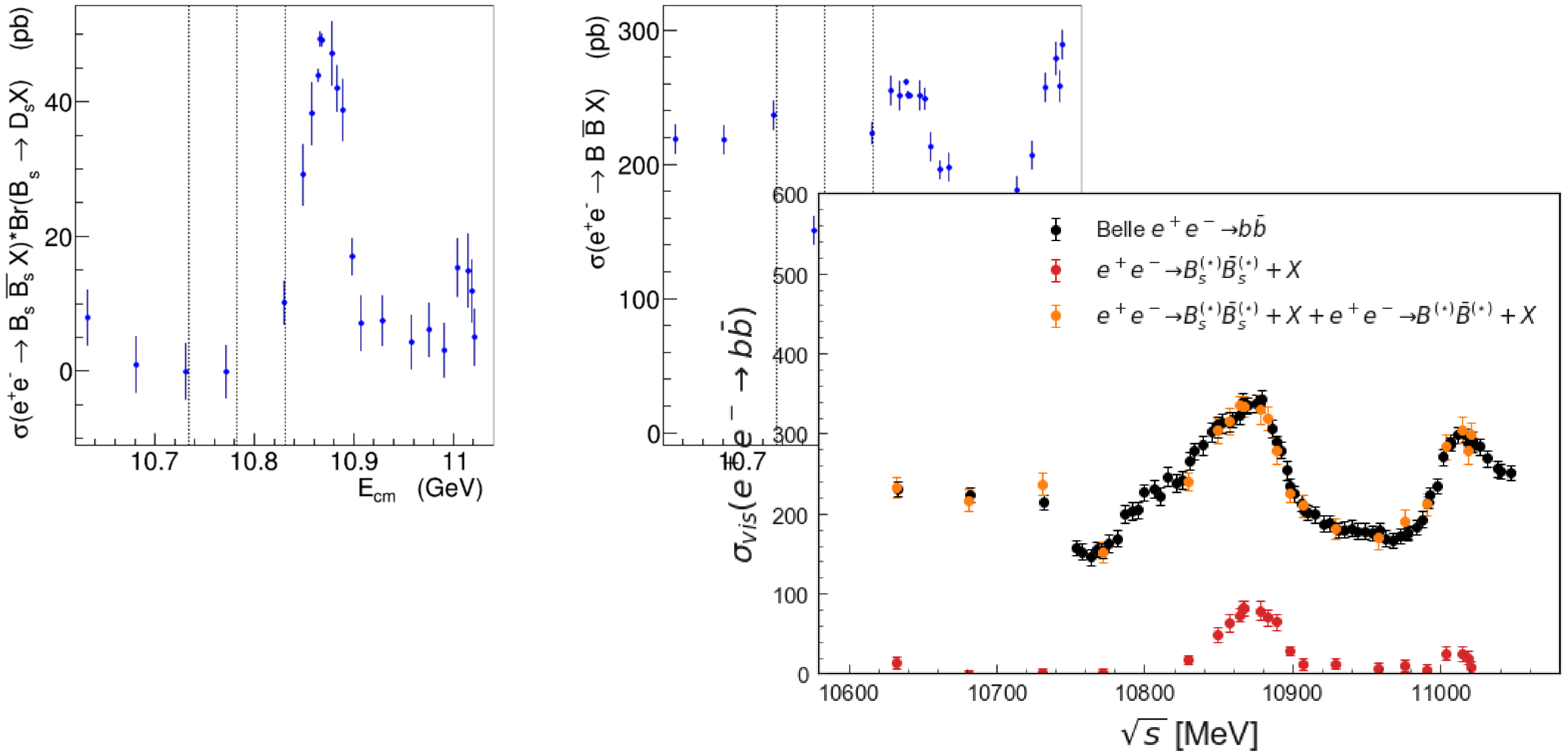
$$\sigma(e^+e^- \to b\bar{b} \to D^0/\bar{D}^0 X) = 2\,C\,\sigma(e^+e^- \to B_s^0\bar{B}_s^0 X)\mathcal{B}(B_s^0 \to D_s^\pm X) + 2\,\sigma(e^+e^- \to B\bar{B} X)\mathcal{B}(B \to D^0/\bar{D}^0 X)$$

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

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



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



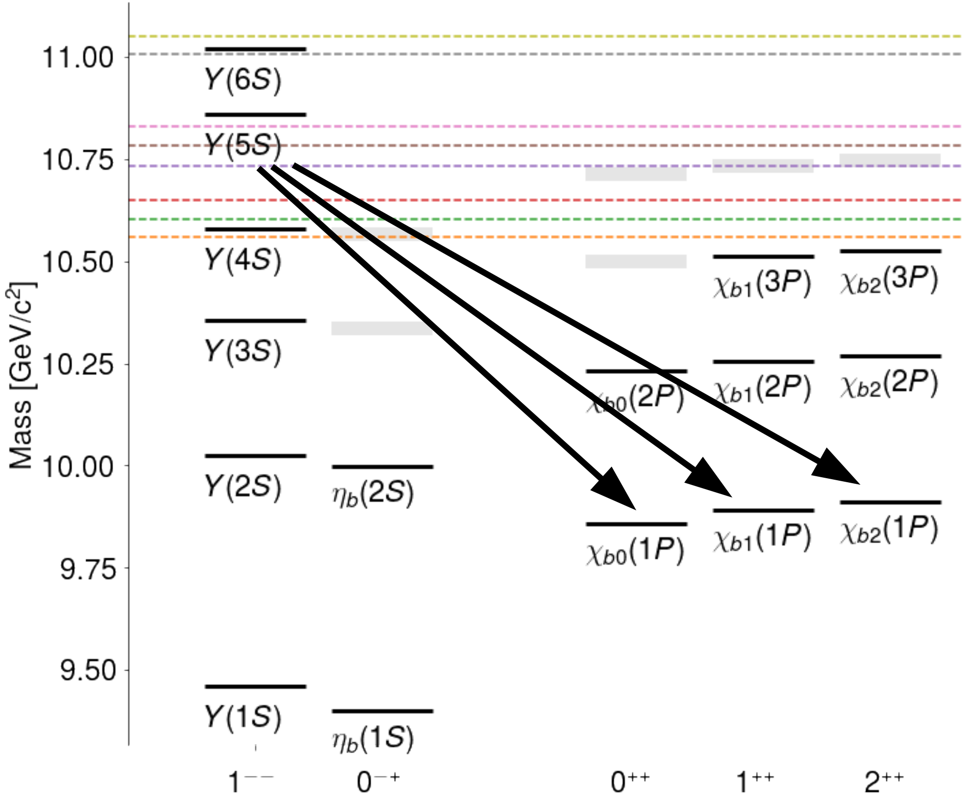
Chib omega

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

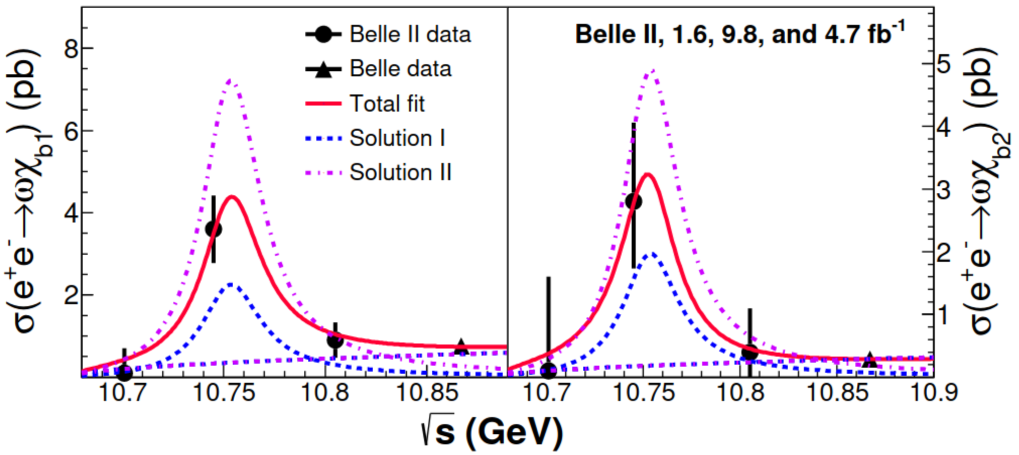
[Y.S. Li, et al., PRD 104, 034036 (2021)]

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

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

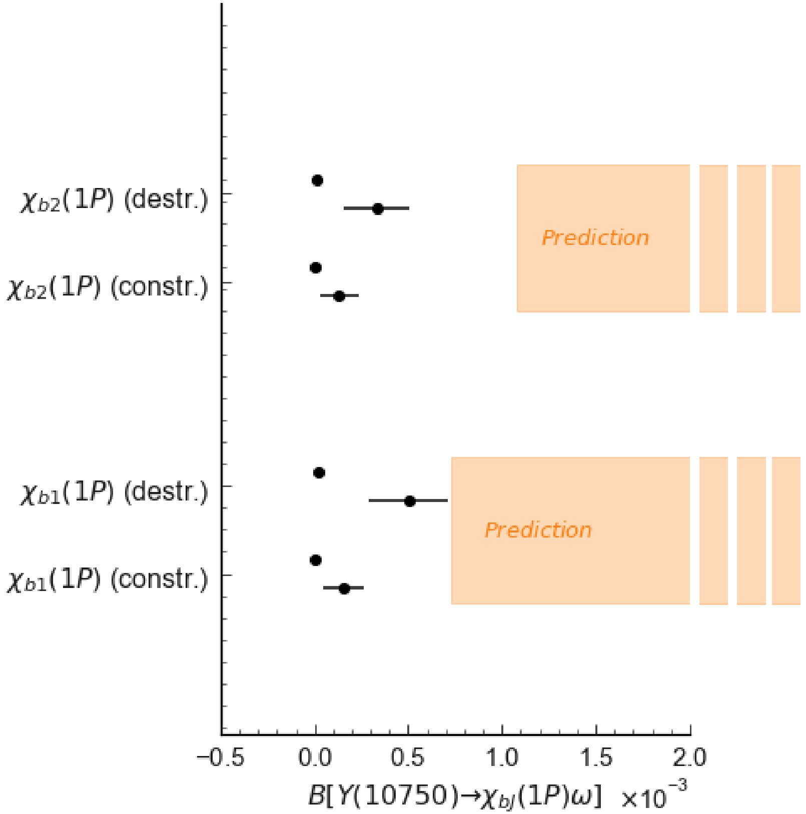


Chib omega



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

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



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

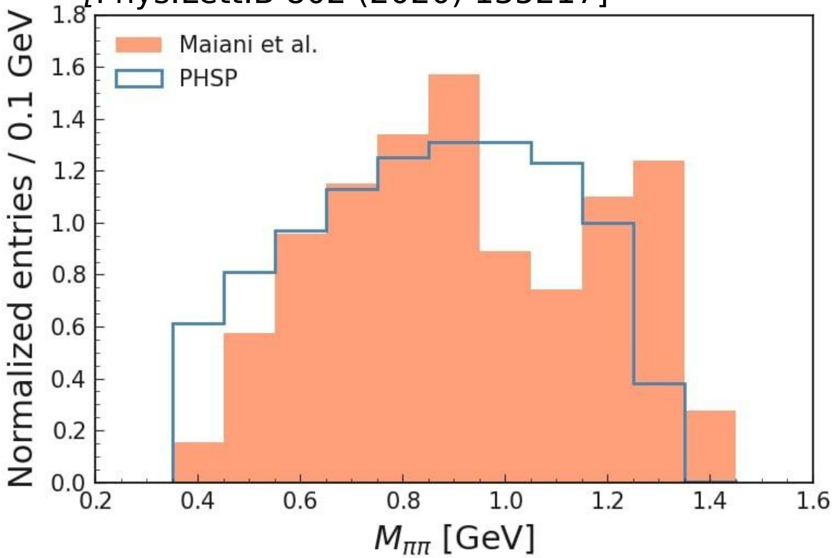
Discovery mode of the Y(10750)

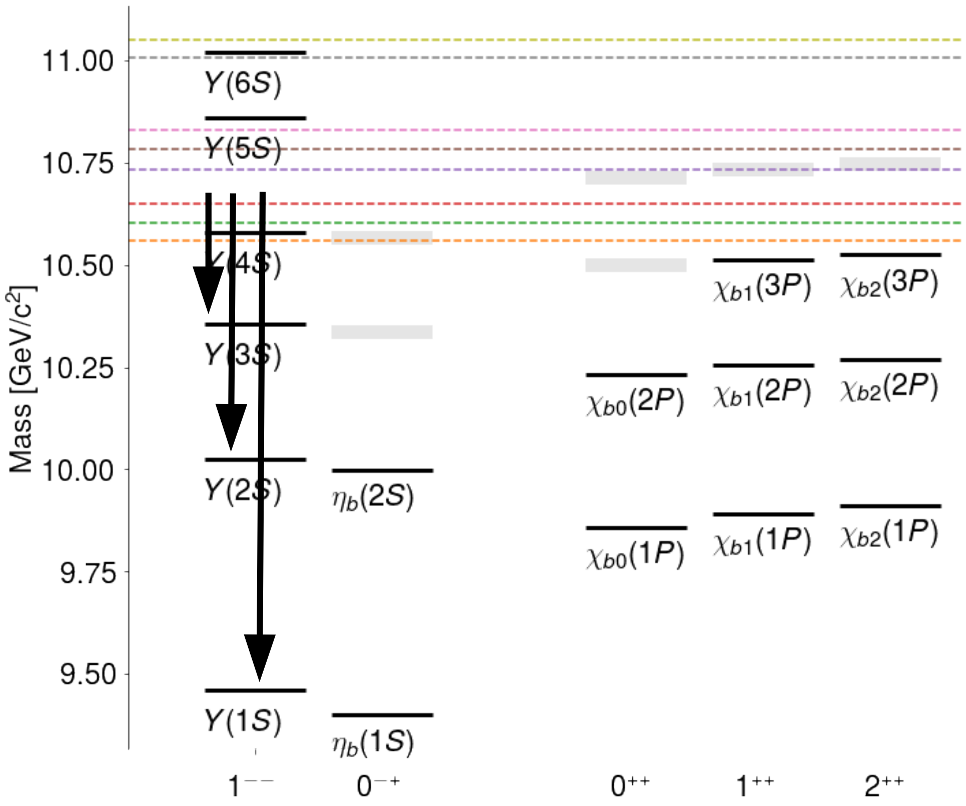
→ Confirm its existence

→ Measure the di-pion spectrum

→ look for Z_b contributions

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





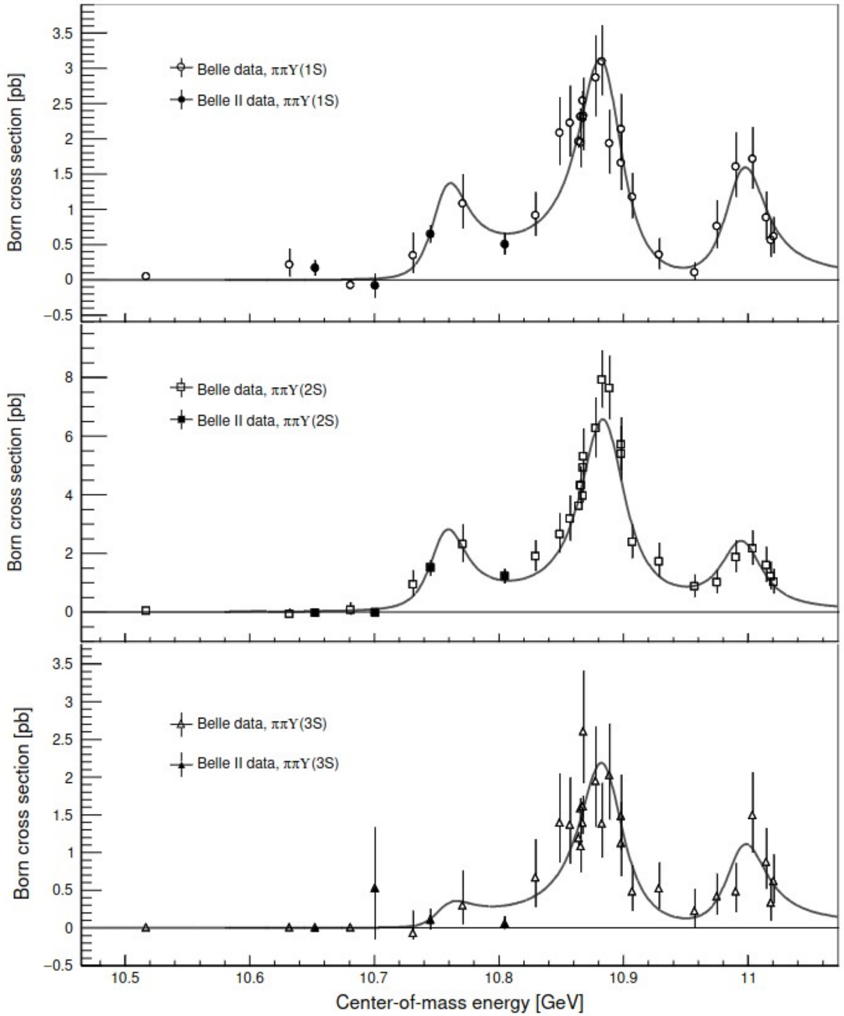
$e^+e^- \rightarrow Y(nS)\ \pi^+\pi^-$

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	$0.46^{+0.15}_{-0.12}$	$0.10^{+0.05}_{-0.04}$	$0.45^{+0.04}_{-0.04}$	$0.32^{+0.04}_{-0.03}$	$0.64^{+0.23}_{-0.13}$	$0.41^{+0.16}_{-0.12}$



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

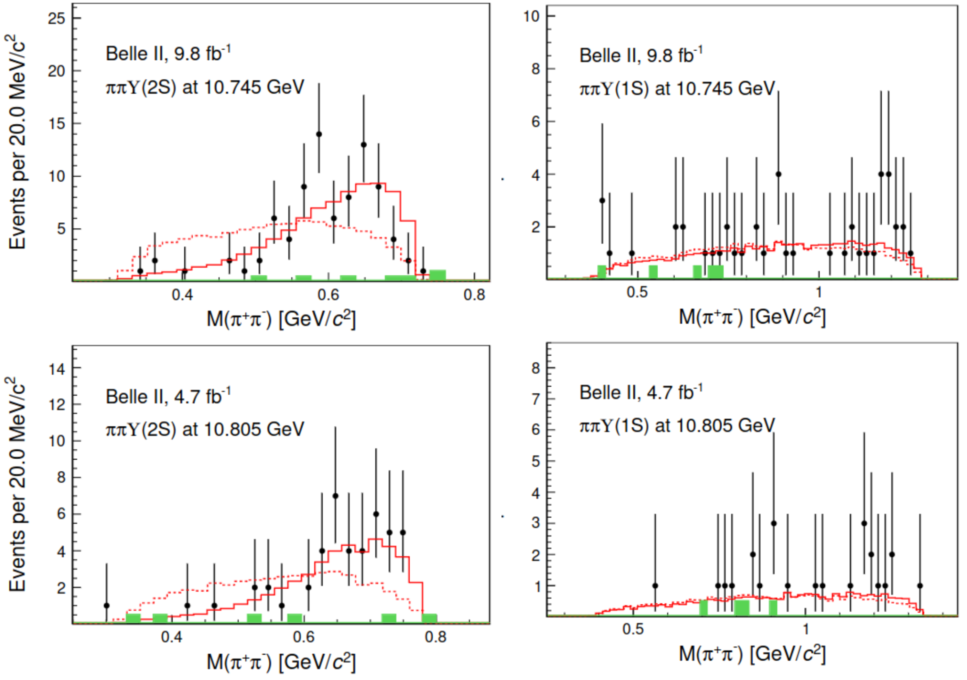
Discovery mode of the Y(10750)

→ Confirm its existence

  → >8 σ combined significance (B+BII)

→ Measure the di-pion spectrum

  → Compatible with what observed in Y(2S) → ππ Y(1S) or PHSP



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

Discovery mode of the Y(10750)

→ Confirm its existence

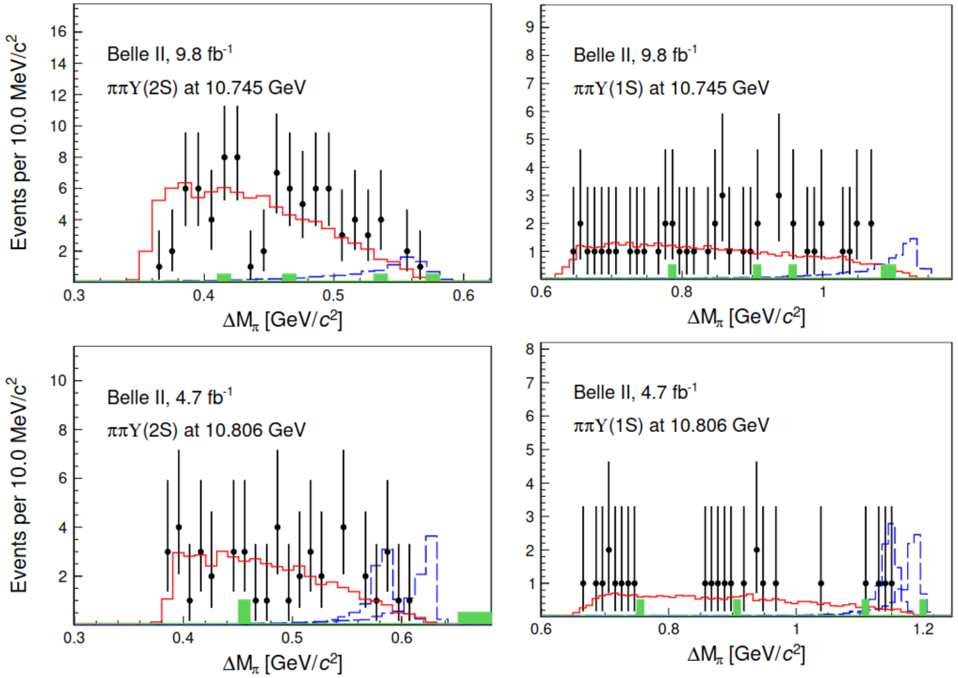
→ >8 σ combined significance (B+BII)

→ Measure the di-pion spectrum

→ Compatible with what observed in Y(2S) → ππ Y(1S) or PHSP

→ Check for Z_b contributions

→ None



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

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

Predicted by some models to be very large

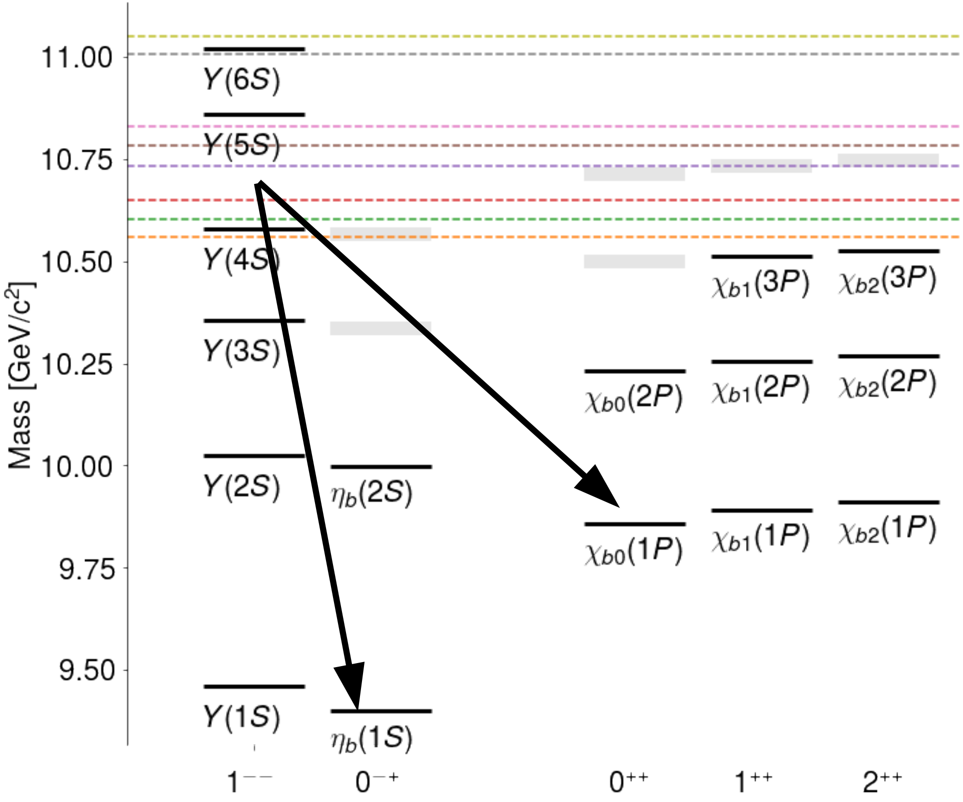
Mode	$\mathcal{B}(4q)$ (%)	$\mathcal{B}(b\bar{b})$ (%)
$B\overline{B}$	$39.3^{+38.7}_{-22.9}$	21.3
$B\overline{B}^*$	~ 0.2	14.3
$B^*\overline{B}^*$	$52.3^{+54.9}_{-31.7}$	64.1
$B_s\overline{B}_s$	-	0.3
$\omega\eta_b$	$7.9^{+14.0}_{-5.0}$	-
$f_0(1370)\Upsilon$	$0.2^{+0.6}_{-0.2}$	-
$\omega\Upsilon$	~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

Strategy:

→ reconstruct ω

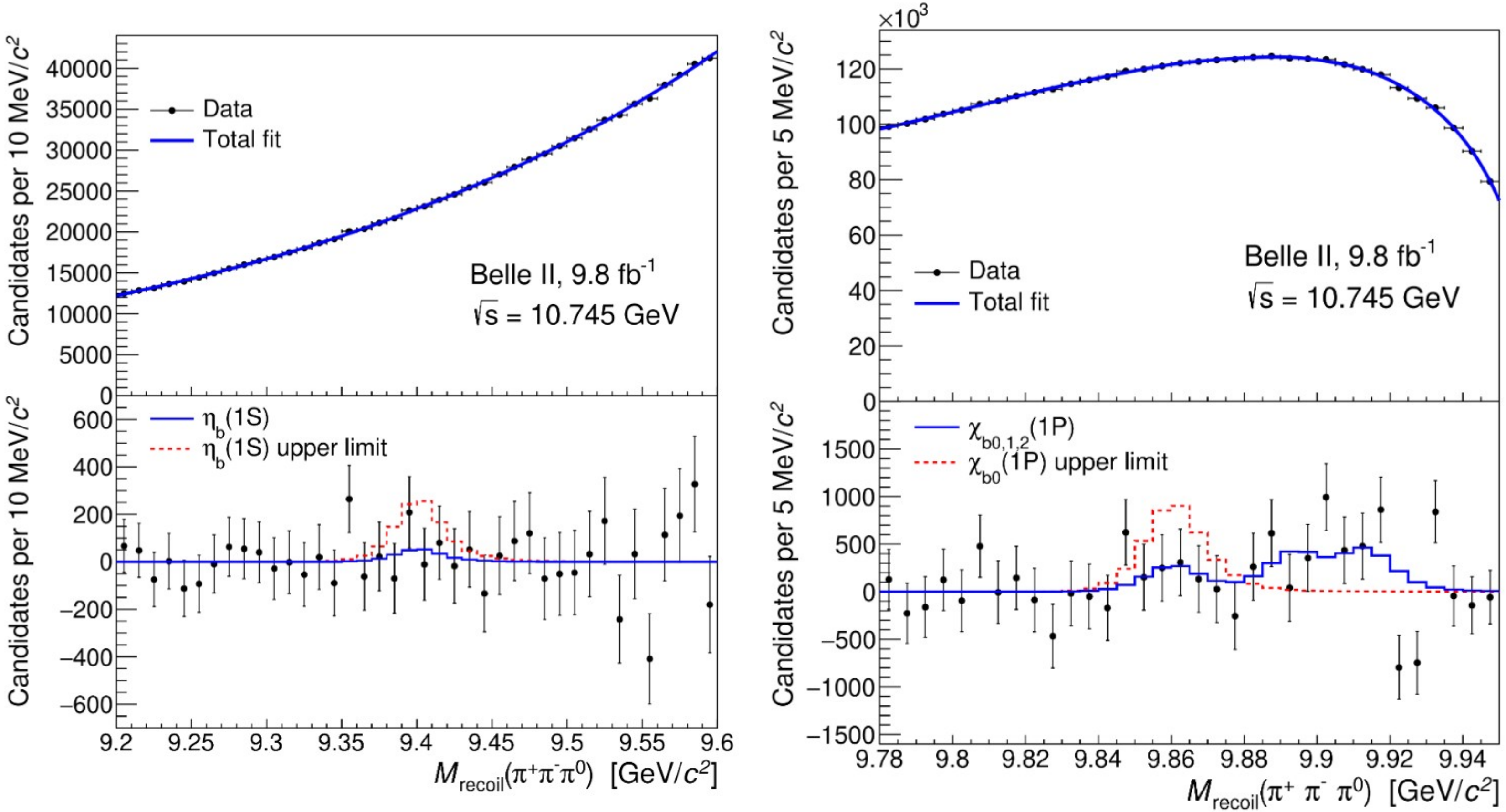
→ measure its recoil mass

→ Look at $\omega\ \chi_{b0}(1P)$ too



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

arXiv:2312.13043

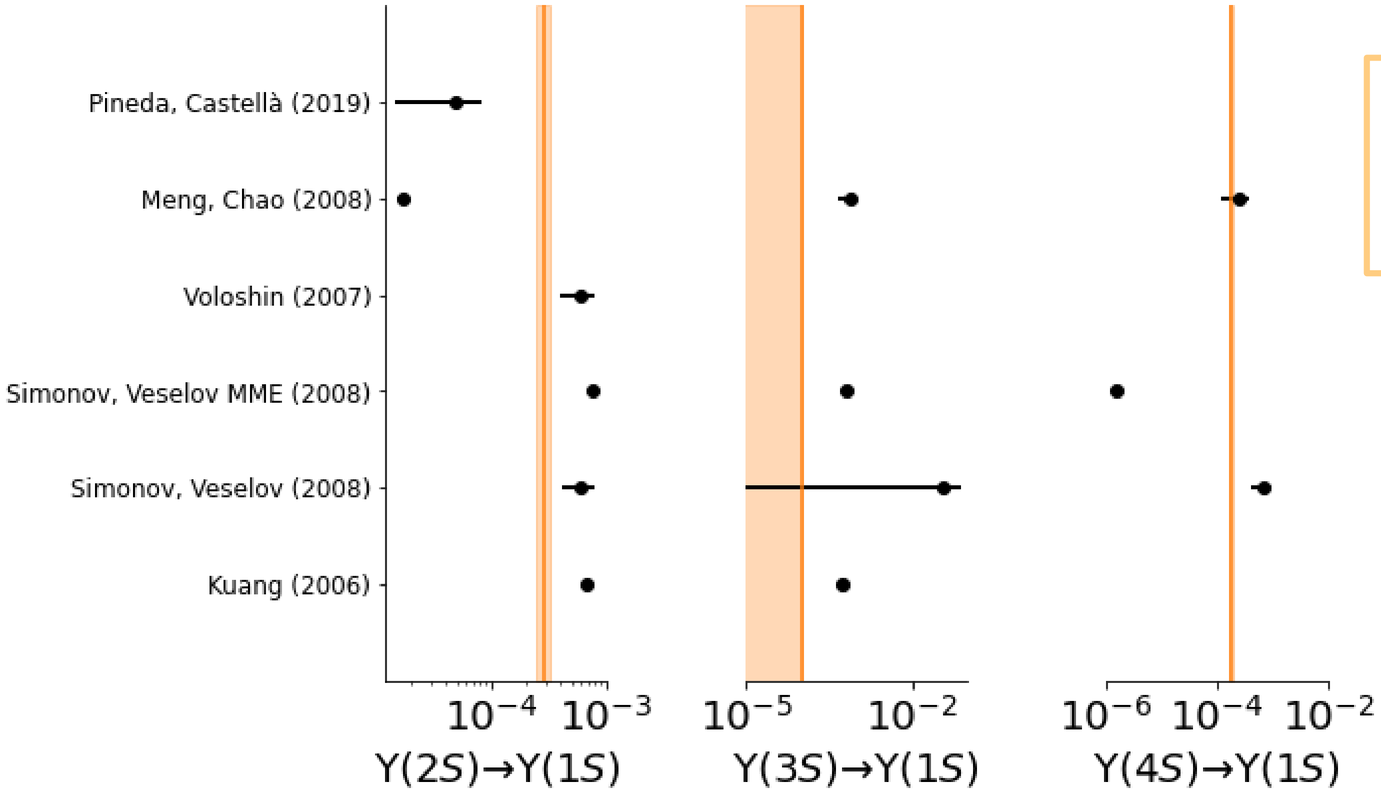


No evidence of ω transitions!

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

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

The rate of η transitions seems quite challenging to predict



BF $\Upsilon(nS) \to \eta\, \Upsilon(mS)$

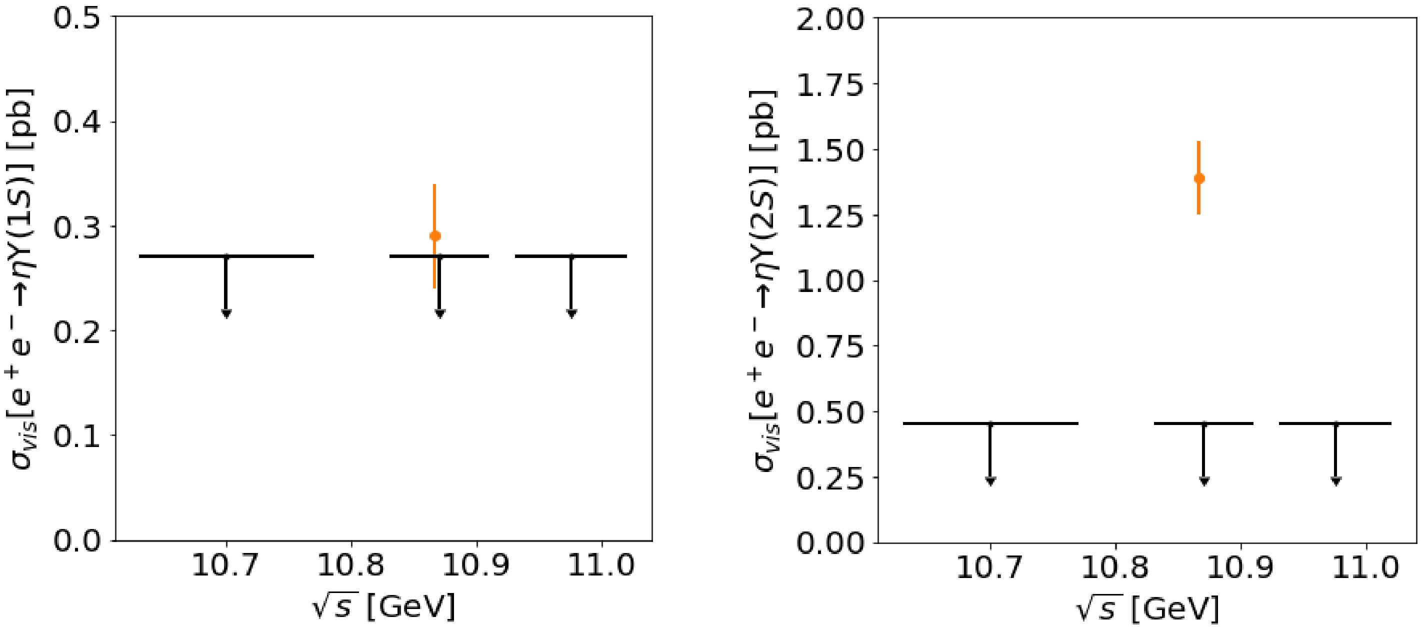
$\Upsilon(5S) \to \eta\, \Upsilon(1S, 2S)$

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

Results of the combined decays modes:

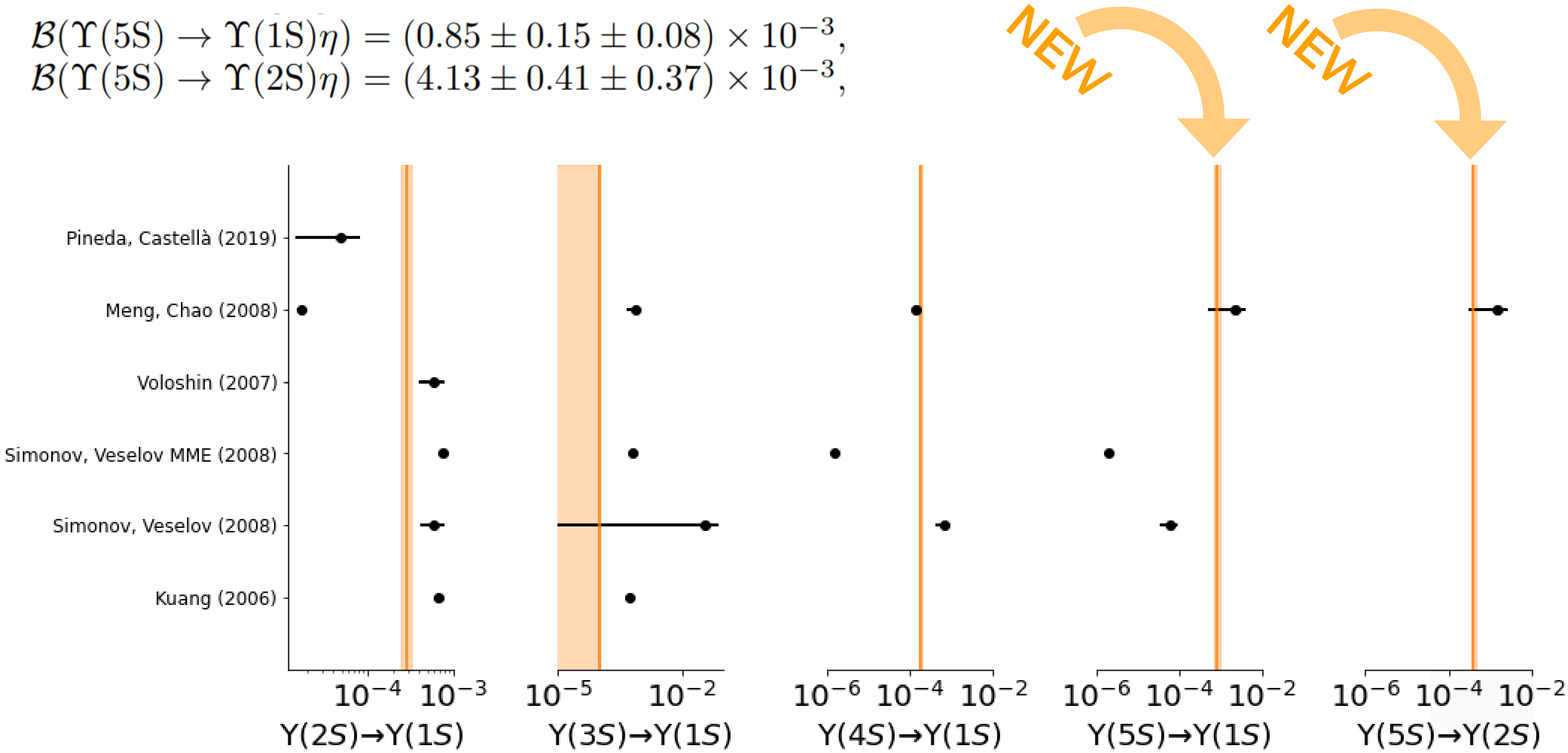
$$\sigma_{\rm B}(e^+e^- \to \Upsilon(2{\rm S})\eta) = 2.07 \pm 0.21 \pm 0.19 \text{ pb},$$
$$\sigma_{\rm B}(e^+e^- \to \Upsilon(1{\rm S})\eta) = 0.42 \pm 0.08 \pm 0.04 \text{ pb},$$

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



η transitions updated

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

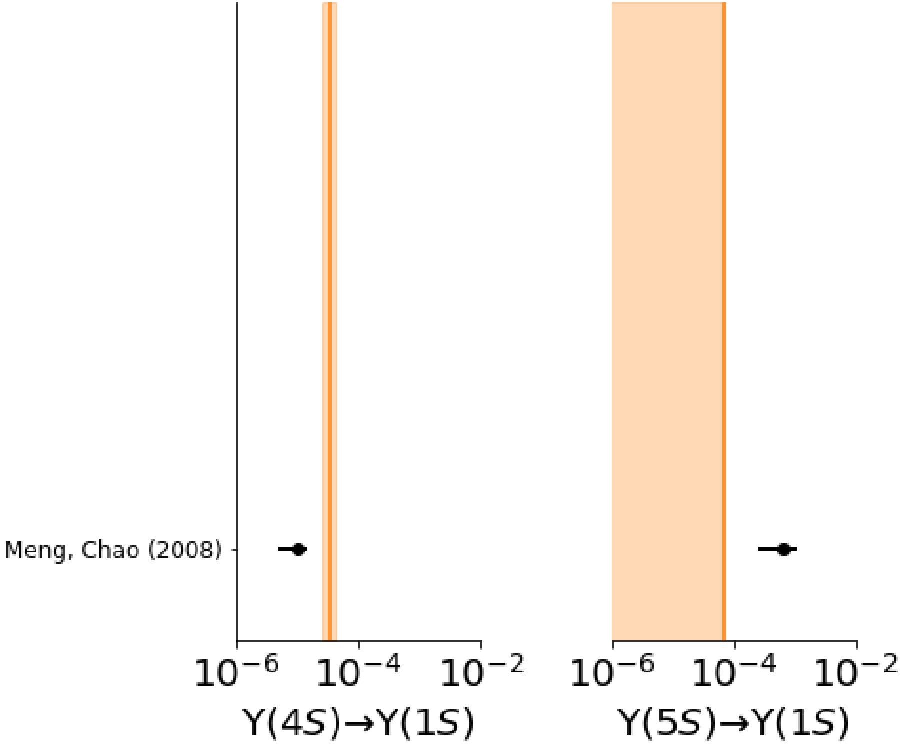


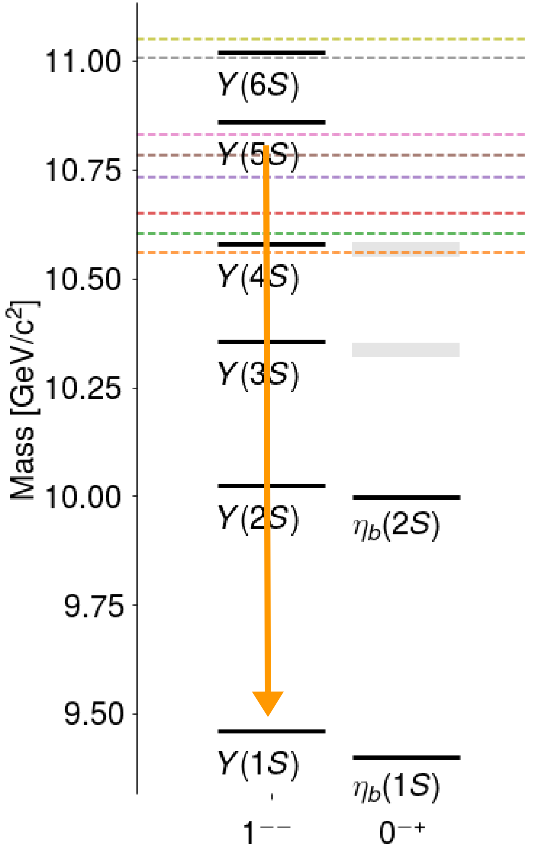
$\Upsilon(5S) \to \eta' \ \Upsilon(1S)$

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

Combining the two decay modes:

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



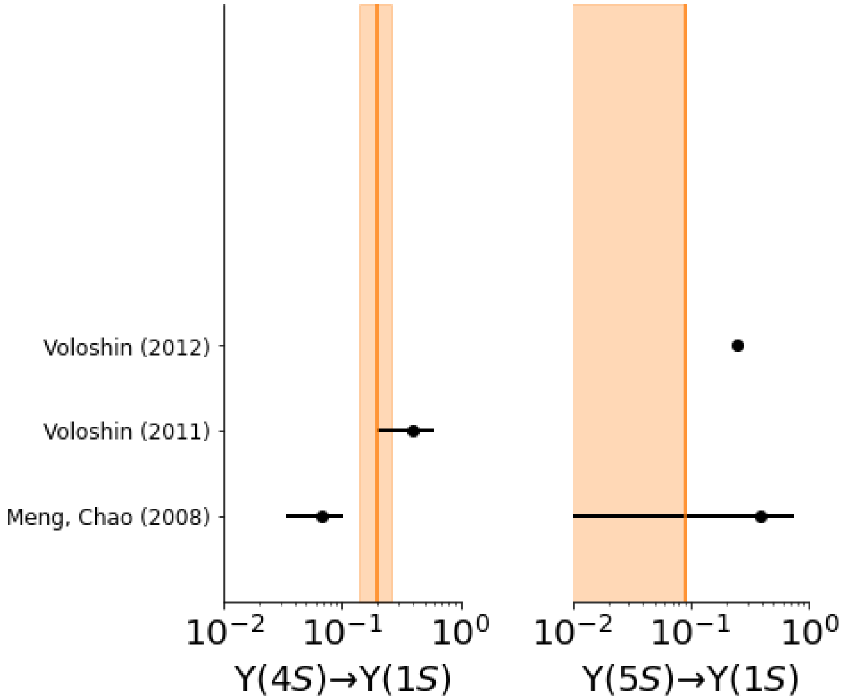


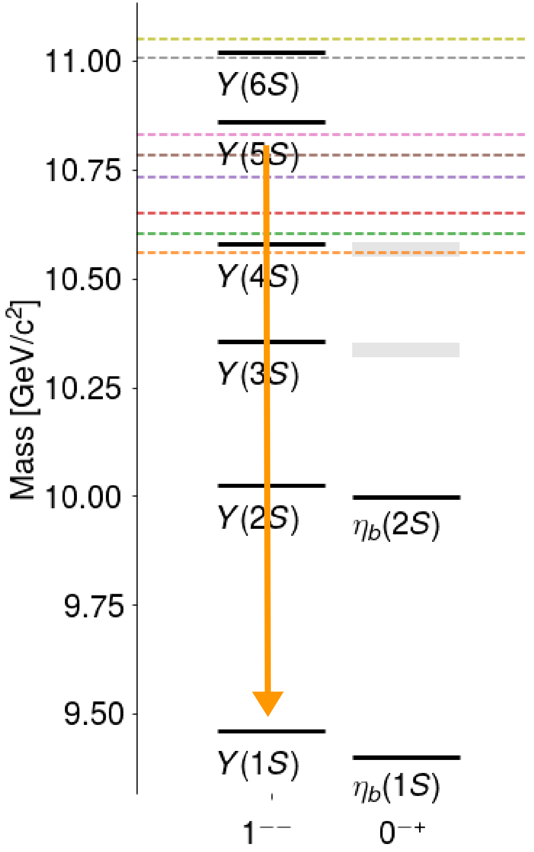
$\Upsilon(5S) \to \eta' \Upsilon(1S)$

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

Combining the two decay modes:

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





Conclusions

Belle measured two new hadronic transitions:

→ **First evidence of $\chi_{b0}(2P) \rightarrow \omega\, \Upsilon(1S)$**

  → Can this teach us something about the X(3872)?

→ **(almost) Last missing η transition, the $\Upsilon(5S) \rightarrow \Upsilon(1S)$.**

  → Pattern for breakdown of QCDME above threshold confirmed

  → No evidence of η' transition, upper limit below the observed rate at the $\Upsilon(4S)$

→ **What next? h_b decays, hindered radiative transtions...**

Backup

In this talk

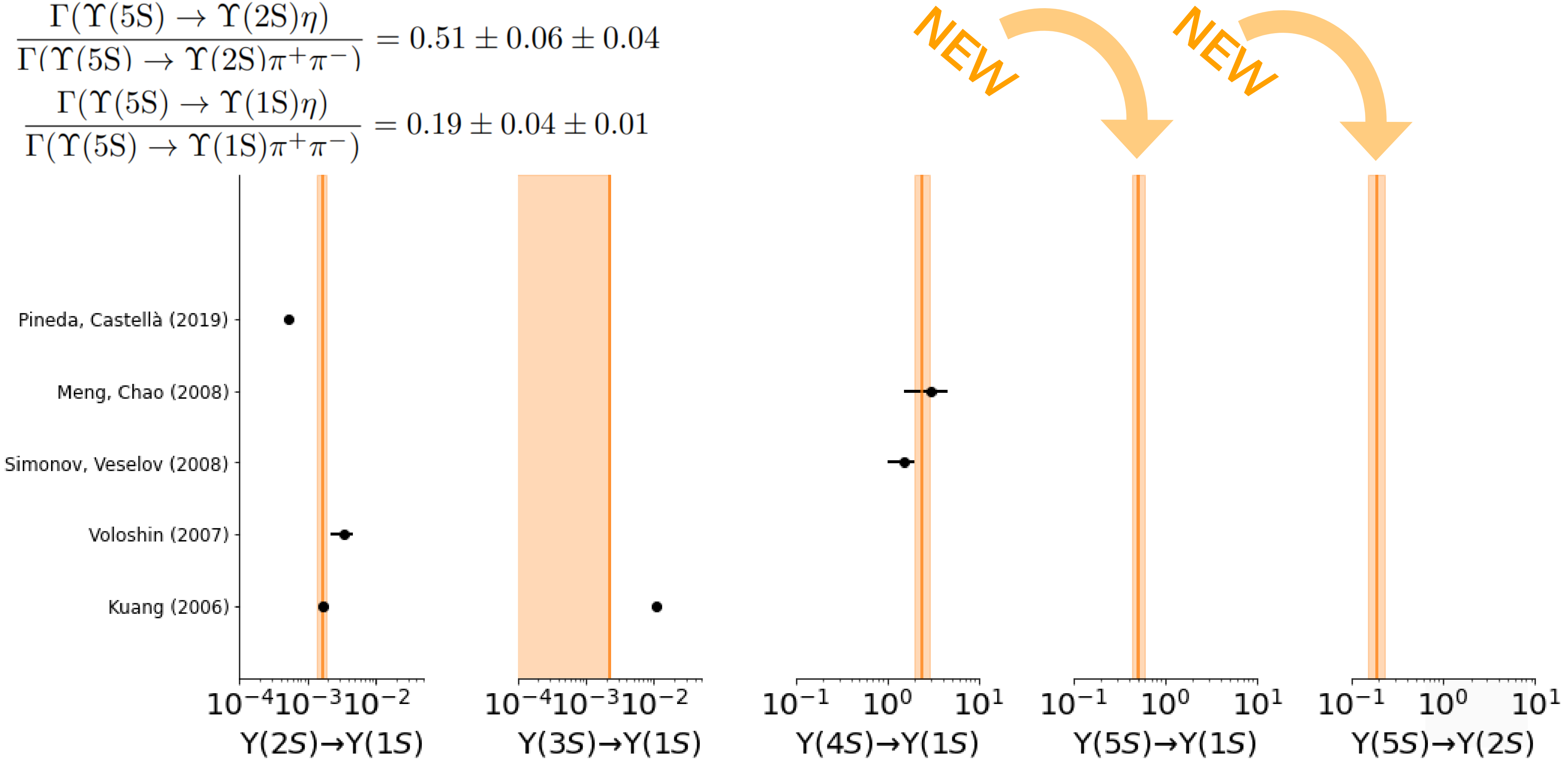
Belle dataset:

1) BsBsX https://inspirehep.net/literature/2660525
2) B*B* https://inspirehep.net/literature/1859137
3) Bs*Bs* https://inspirehep.net/literature/1488374
4) pipipi0chib https://journals.aps.org/prd/abstract/10.1103/PhysRevD.98.091102
5) pipi hb https://inspirehep.net/literature/1389855
6) pipi Y https://inspirehep.net/literature/1735193

$\eta/\pi\pi$ Ratio updated

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

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

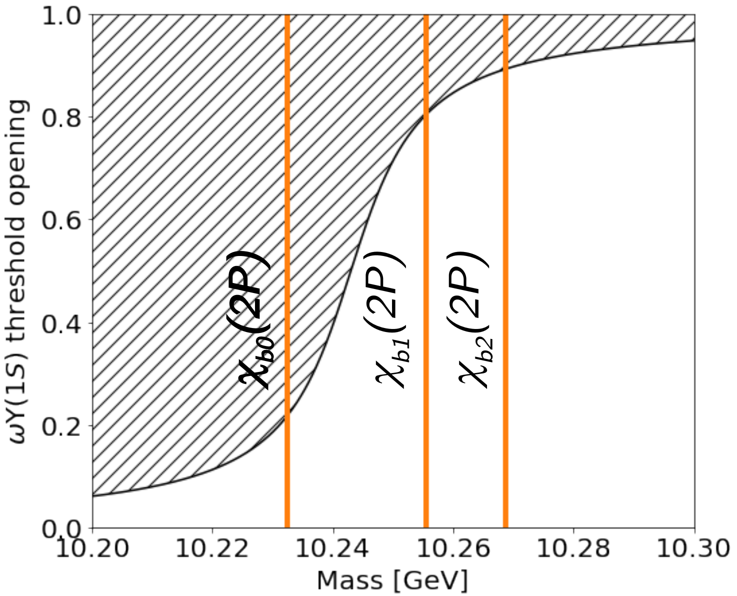


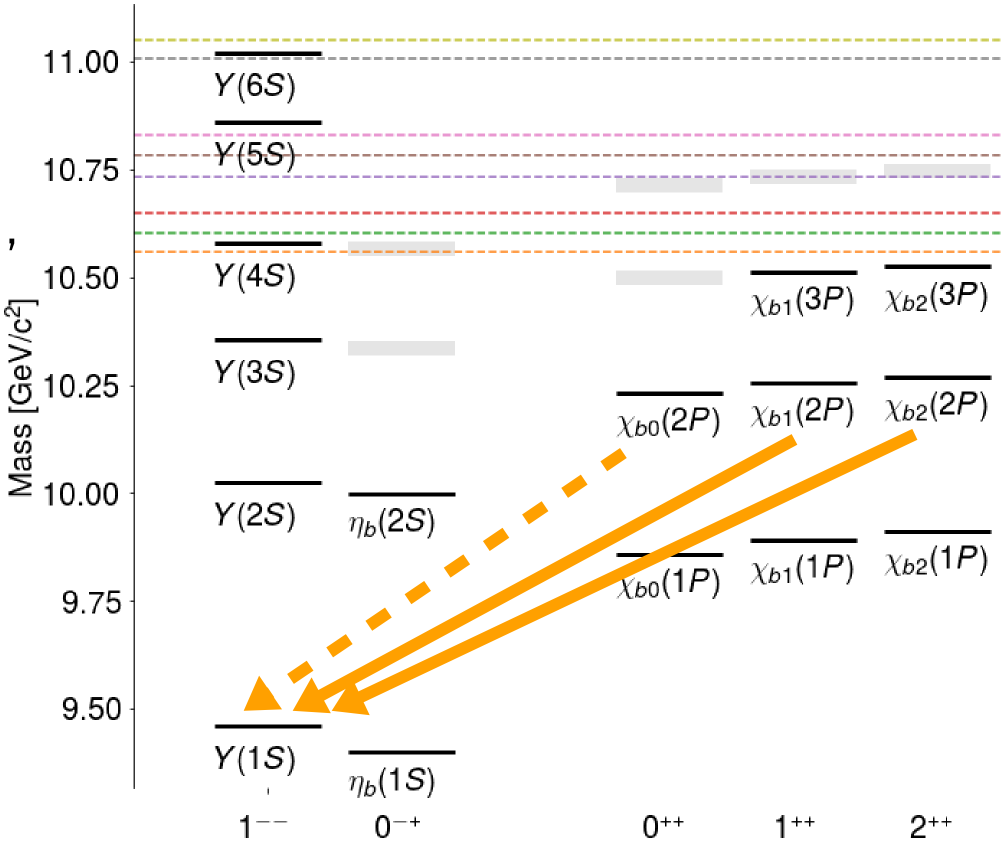
$\chi_{b0}(2P) \to \omega Y(1S)$

Peculiar features

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

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





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

Peculiar features

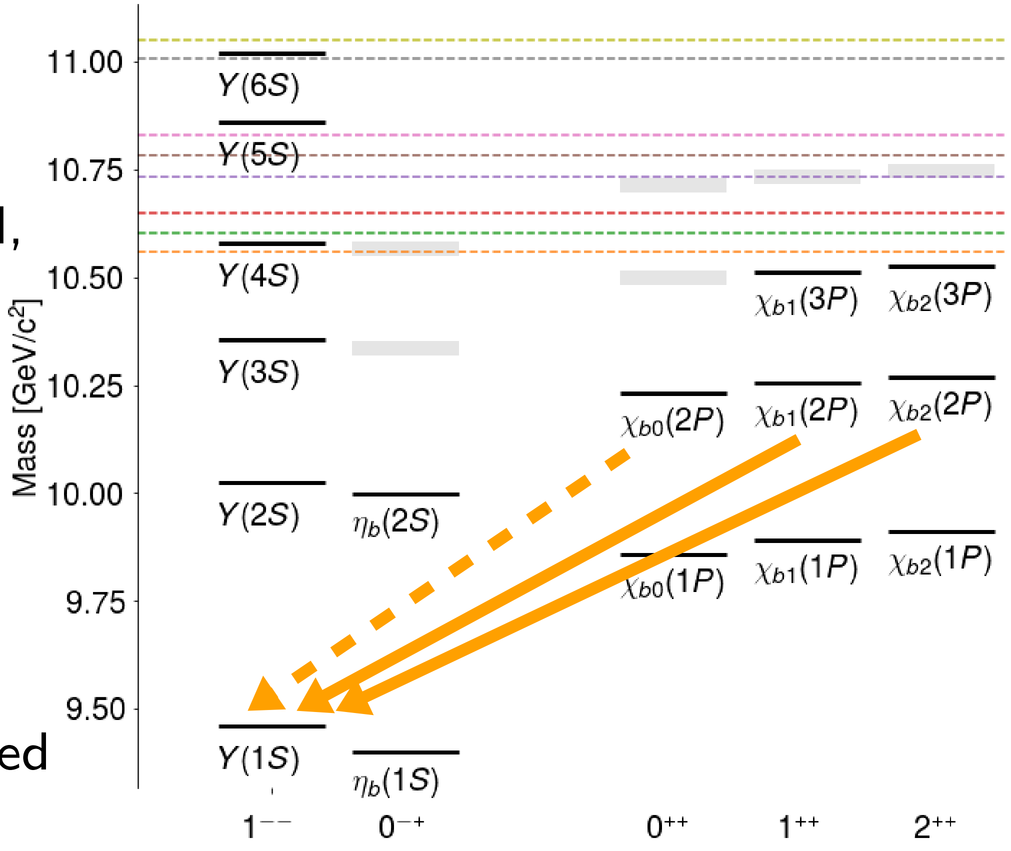
$\to$ ω Y(1S) threshold between χ_{b0} and χ_{b1}

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

Reconstruction strategy:

Mass of ω + $\mu\mu$ pair

$\to$ χ_b(2P) produced by non-reconstructed radiative decay of Y(3S)

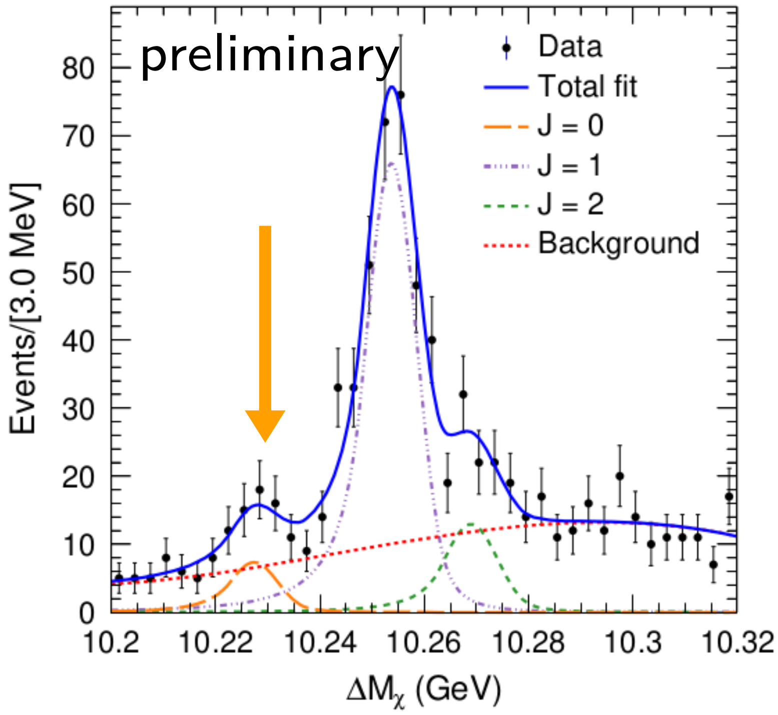


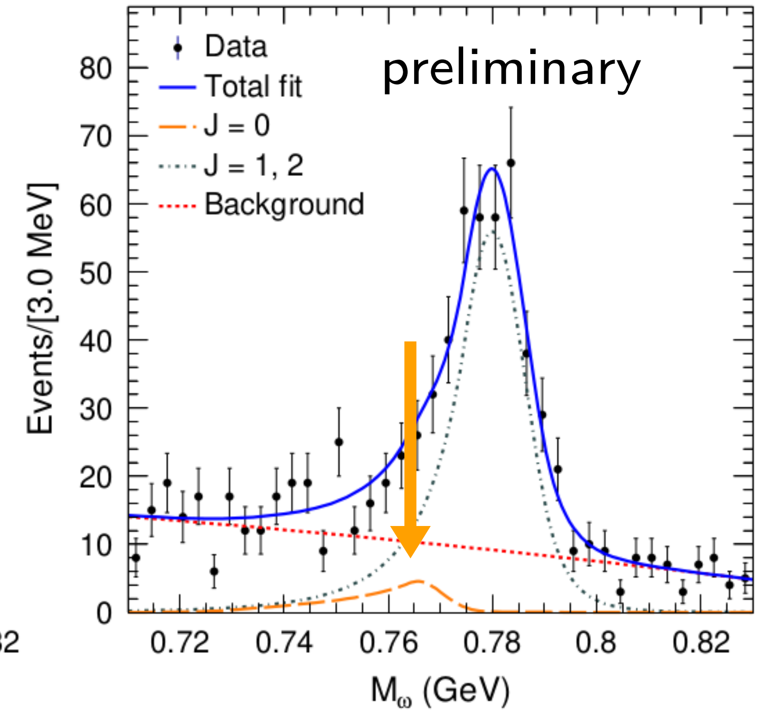
$\chi_{b0}(2P) \to \omega \Upsilon(1S)$

NEW

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

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





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

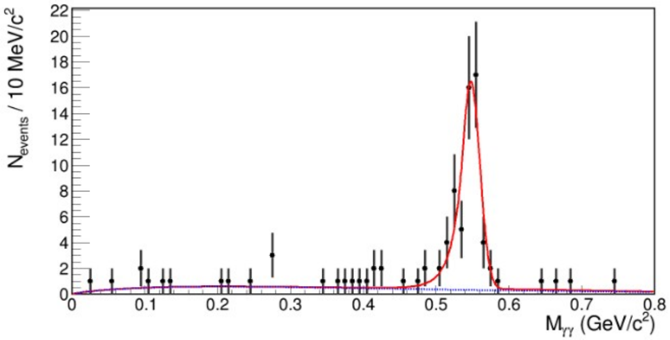
[Phys.Rev.D 104 (2021) 11, 112006]

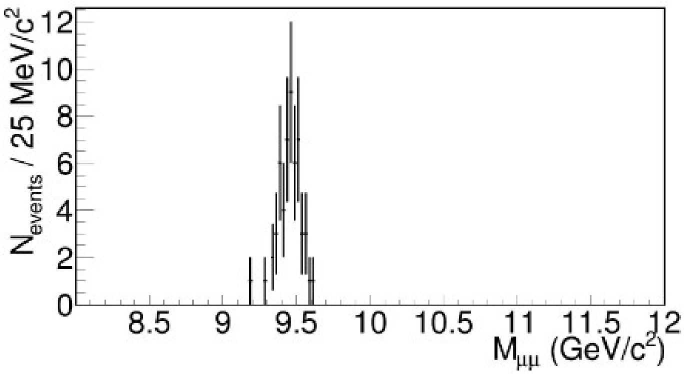
New analysis of η and η' transitions from the Υ(5S) region.

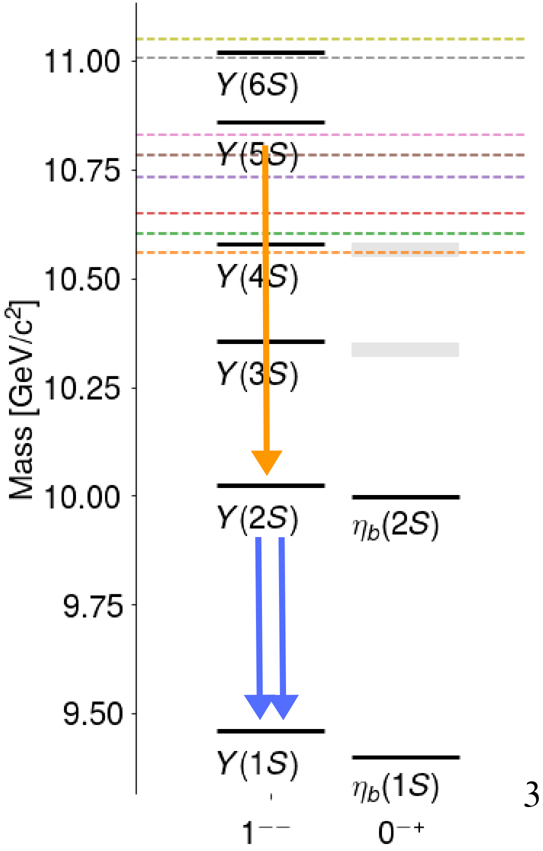
One final state, several decays: **$\mu^+\mu^-$ $\pi^+\pi^-$ $\gamma\gamma$**

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

Υ(1S) 2S→ 1S transition η







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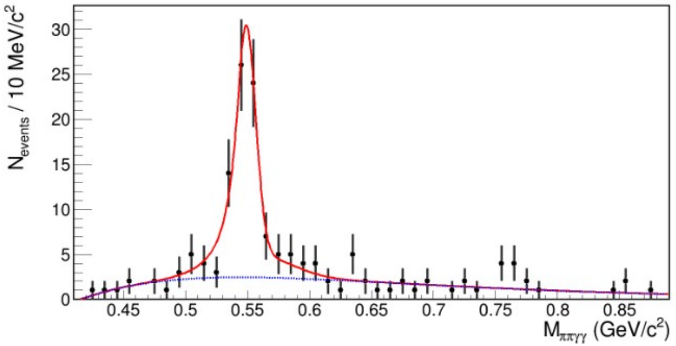
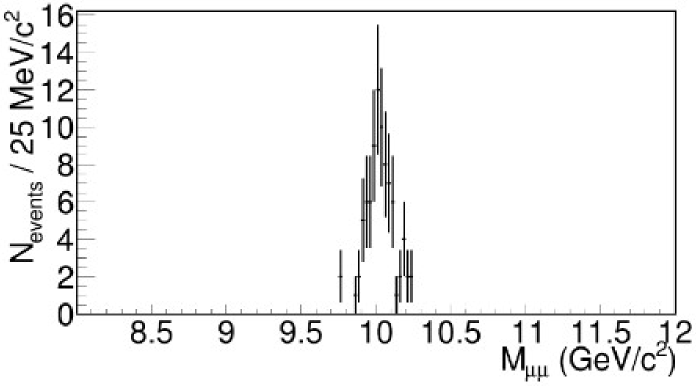
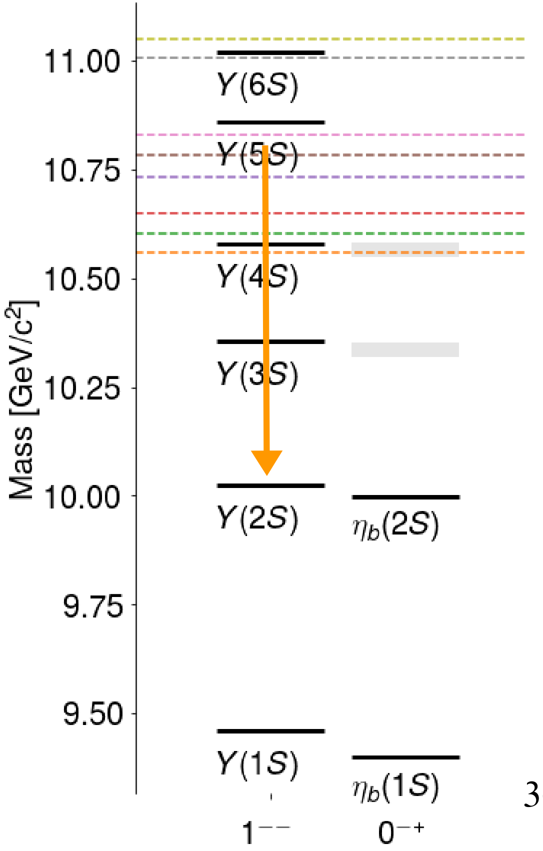
Υ(2S) η







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

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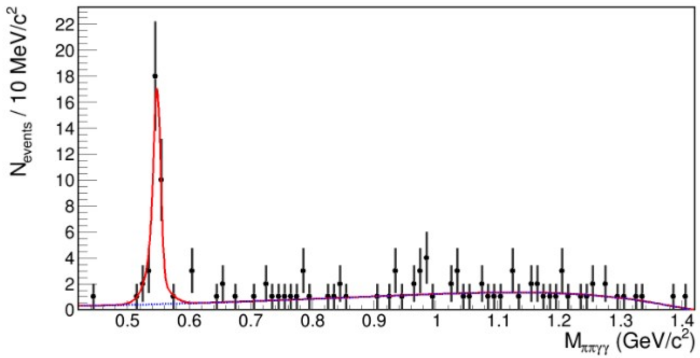
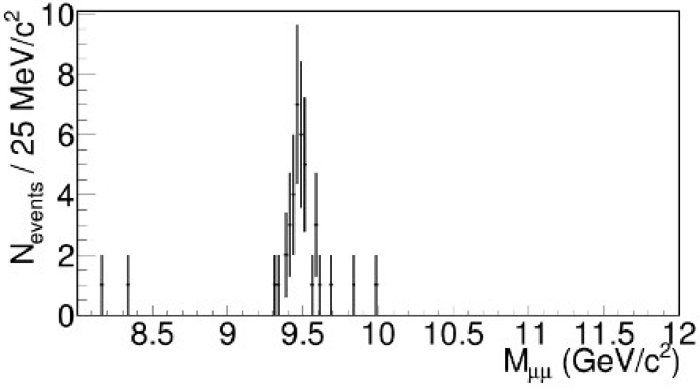
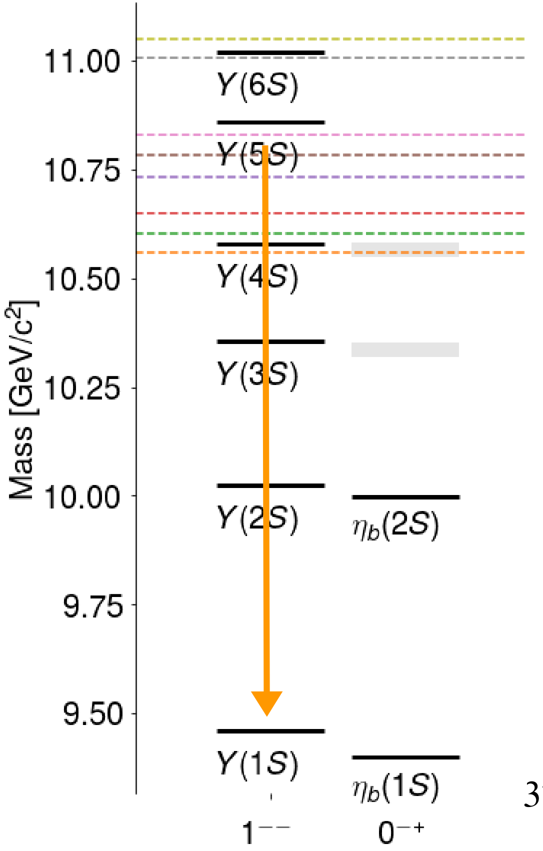
Υ(1S) η







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