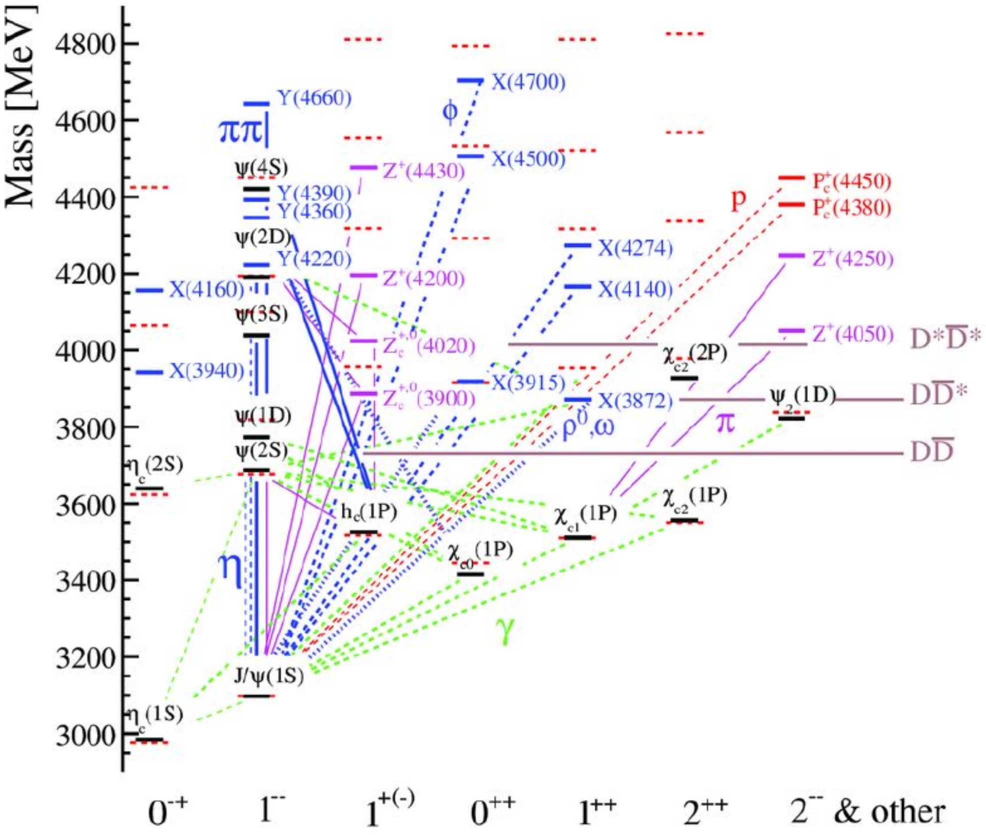
Recent results on charmonium and bottomonium states at Belle

Pavel Krokovny
Budker INP

- Charmonia results
- Bottomonia results
- Belle II prospects
- Summary

Charmonia



[Rev. Mod. Phys. 90 (2018) 15003]

Observed States:

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

Below kinematic threshold:

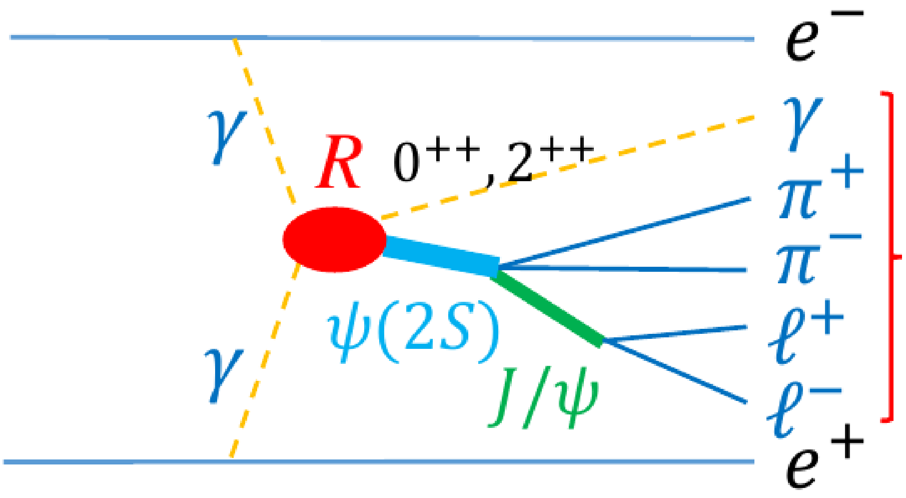
mostly bound states of mesons/baryons.

Above threshold:

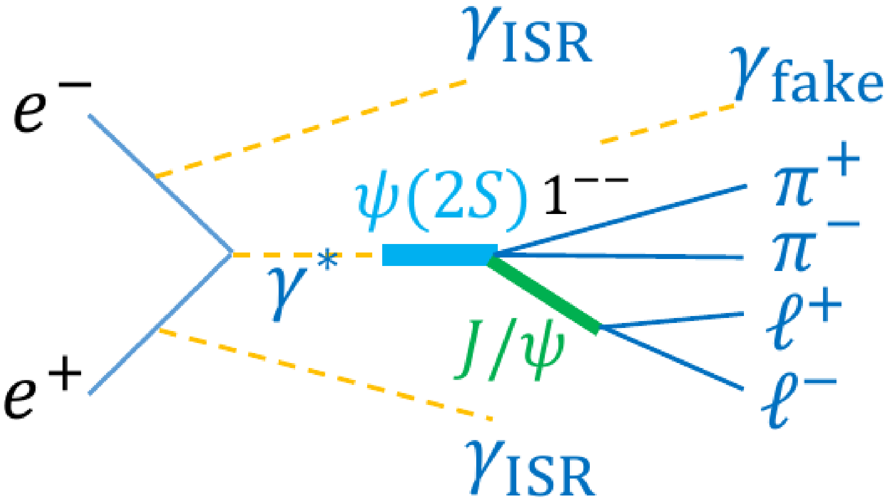
zoo of complex XYZ states.

$\gamma\gamma \to \gamma\ \psi(2S) \to \gamma J/\psi\pi^+\pi^-$

Signal:
$\gamma\gamma$



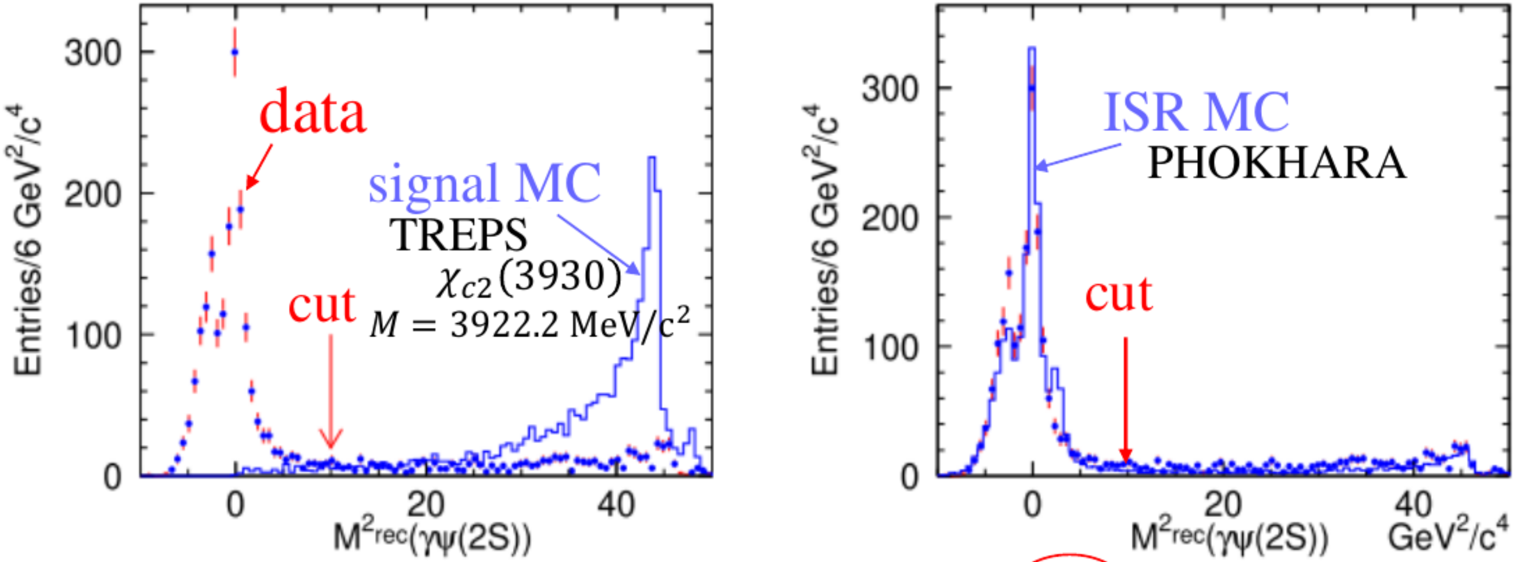
Background:
Initial State Radiation (ISR)

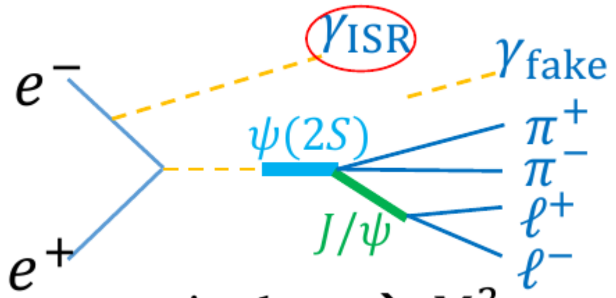


No tag:
e^+e^- are missing in the beam pipe
→ High recoil mass

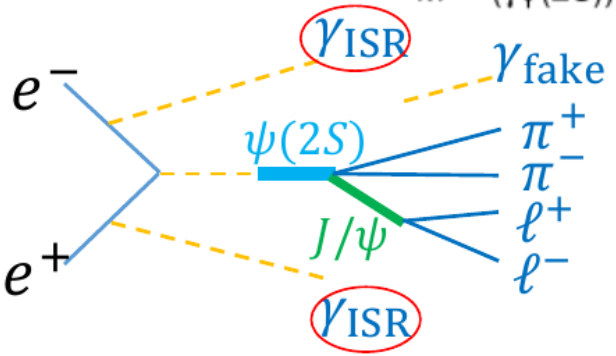
γ_{ISR} are missing in the beam pipe

Recoil mass





single γ → $M^2_{\mathrm{rec}} = 0$

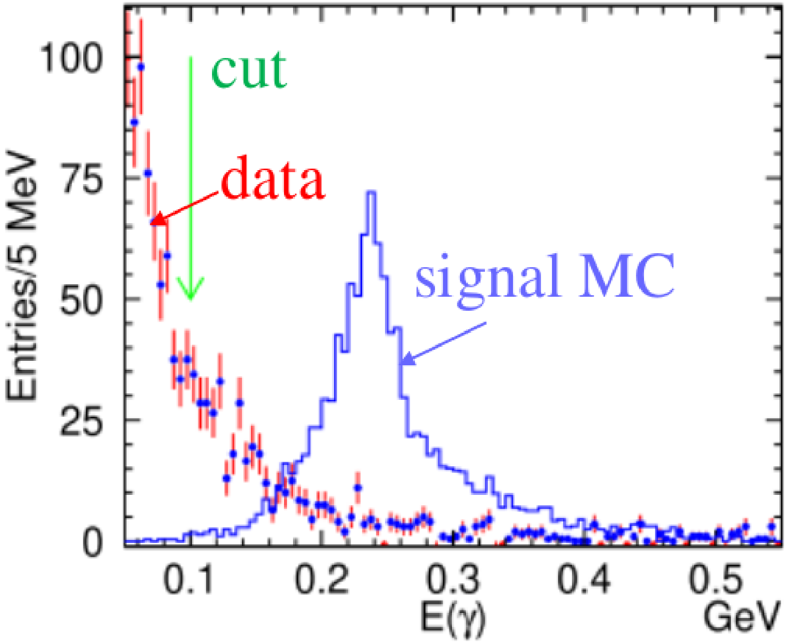


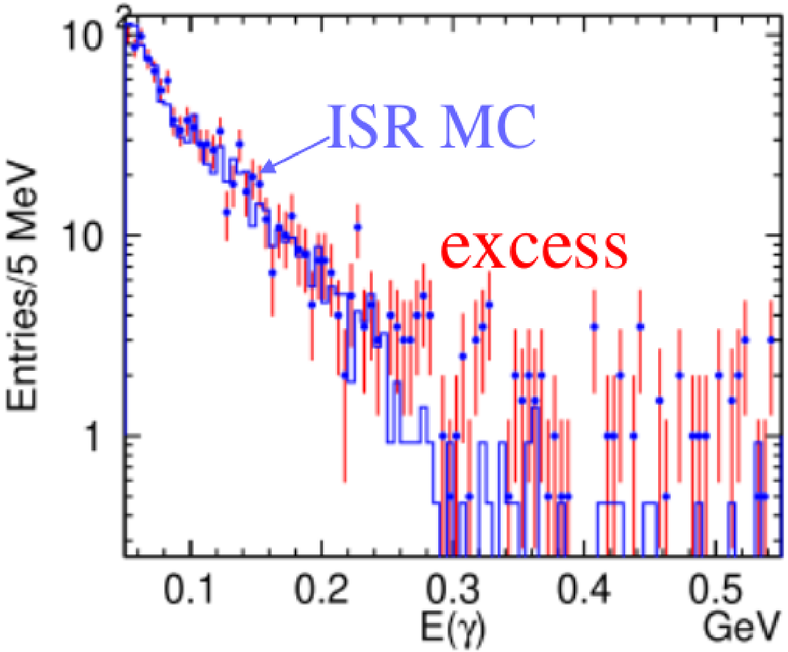
double γ → M^2_{rec} high mass tail

Photon energy

$\gamma\psi(2S)$

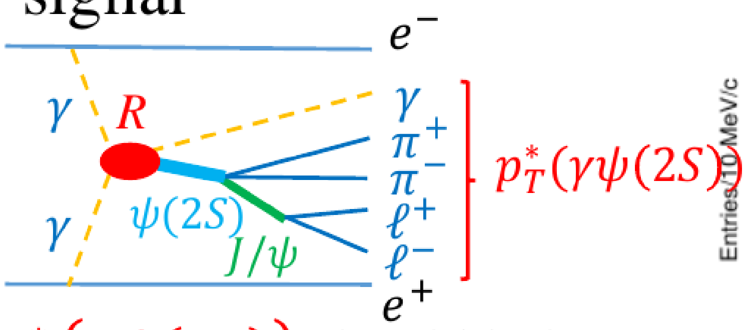
- signal γ → high E
- ISR γ → low E
- fake γ → low E



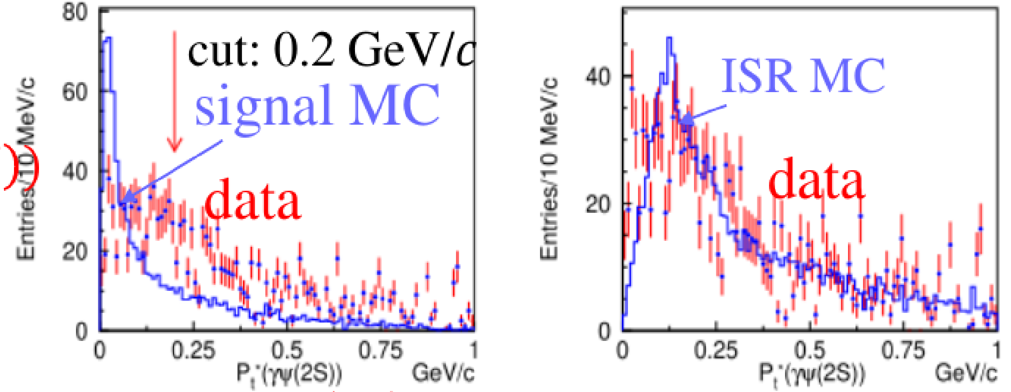


p_T^* balance

signal

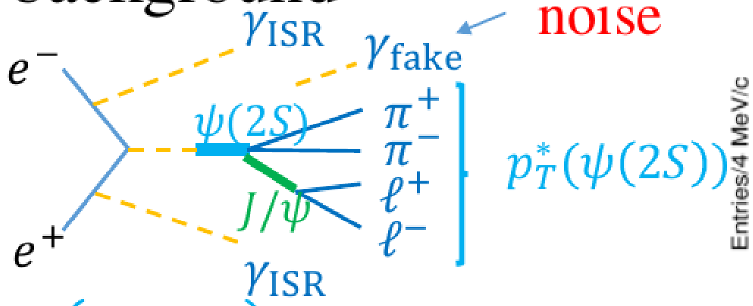


$p_T^*(\gamma\psi(2S))$ should balance

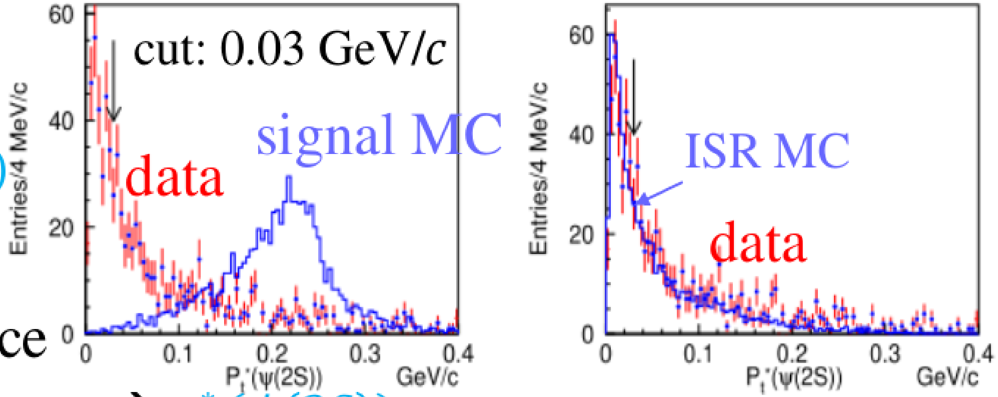


→ $p_T^*(\gamma\psi(2S))$

background



$p_T^*(\psi(2S))$ should NOT balance



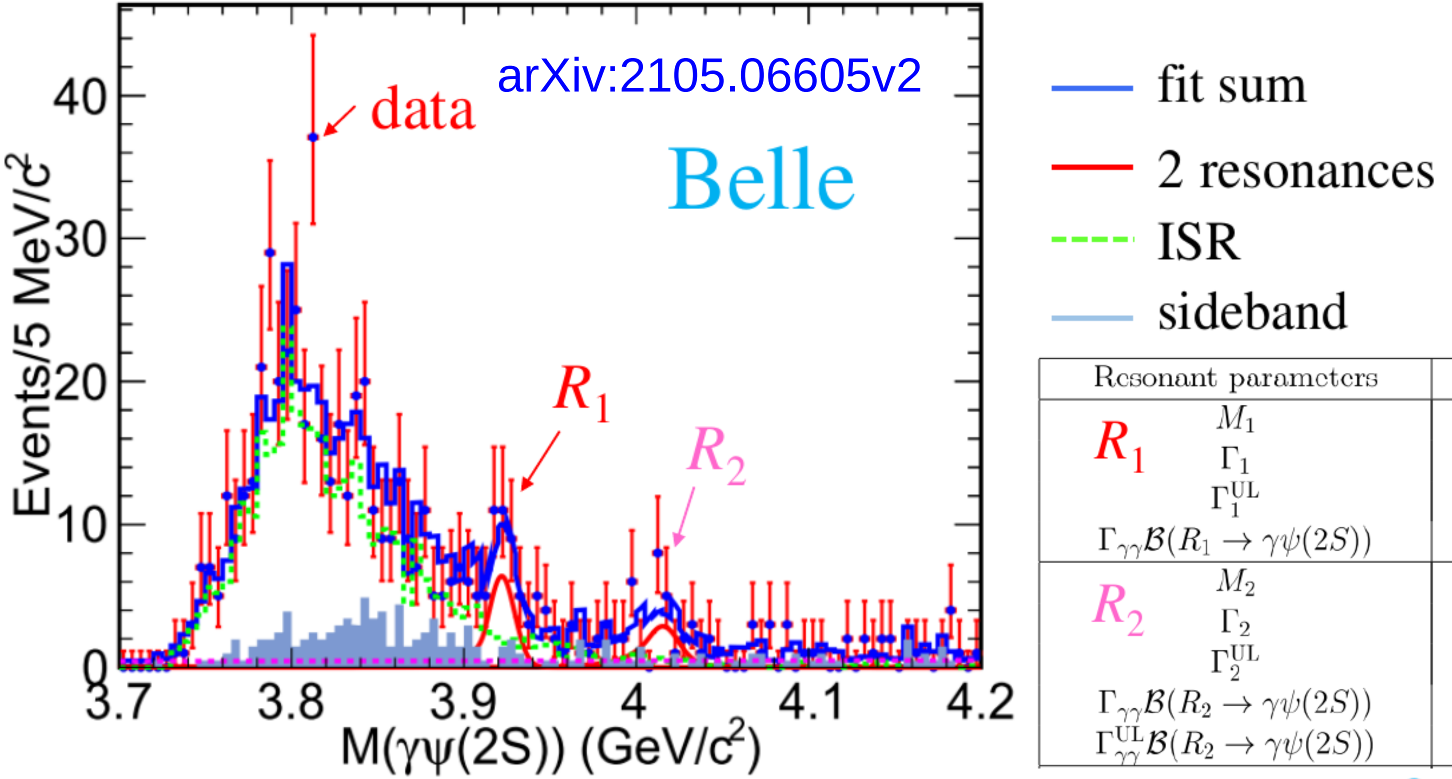
→ $p_T^*(\psi(2S))$

Fit to γψ(2S) invariant mass

binned extended maximum likelihood fit

$$f_{\mathrm{PDF}} = f_{\mathrm{R1}} + f_{\mathrm{R2}} + f_{\mathrm{ISR}} + f_{\mathrm{bkg}} + f_{\mathrm{sideband}}$$

R_1 significance is 4.0 σ
R_2 significance is 3.0 σ (2.8 global)



	Resonant parameters	$J=0$	$J=2$
R_1	M_1	$3921.3 \pm 2.4 \pm 1.6$ MeV/c^2	
	Γ_1	$0.0 \pm 5.3 \pm 2.0$ MeV	
	Γ_1^{UL}	11.5 MeV	
	$\Gamma_{\gamma\gamma}\mathcal{B}(R_1 \to \gamma\psi(2S))$	$8.2 \pm 2.3 \pm 0.9$ eV	$1.6 \pm 0.5 \pm 0.2$ eV
R_2	M_2	$4014.4 \pm 4.1 \pm 0.5$ MeV/c^2	
	Γ_2	$6 \pm 16 \pm 12$ MeV	
	Γ_2^{UL}	39.3 MeV	
	$\Gamma_{\gamma\gamma}\mathcal{B}(R_2 \to \gamma\psi(2S))$	$5.3 \pm 2.7 \pm 2.5$ eV	$1.1 \pm 0.5 \pm 0.5$ eV
	$\Gamma_{\gamma\gamma}^{\mathrm{UL}}\mathcal{B}(R_2 \to \gamma\psi(2S))$	12.8 eV	2.6 eV

Nature of observed states

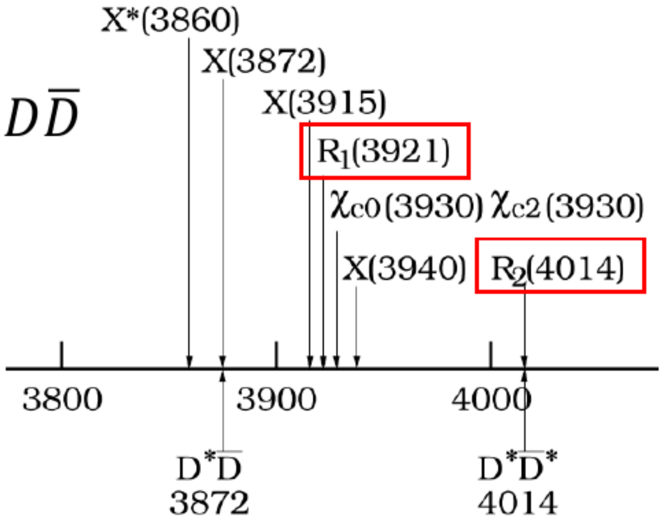
$\chi_{c0}(2P)$

- $X(3915)$ → $\gamma\gamma \to \omega J/\psi$ not seen $D\bar{D}$
- $X^*(3860)$ → $e^+e^- \to J/\psi D\bar{D}$, not seen by LHCb
- $R_1(3921)$ → $= X(3915)$?
- $\chi_{c0}(3930)$(←LHCb) → $B^+ \to D^+D^-K^+$
  $= X(3915)$? $B(D\bar{D}) \leftrightarrow B(\omega J/\psi)$

$\chi_{c2}(2P)$

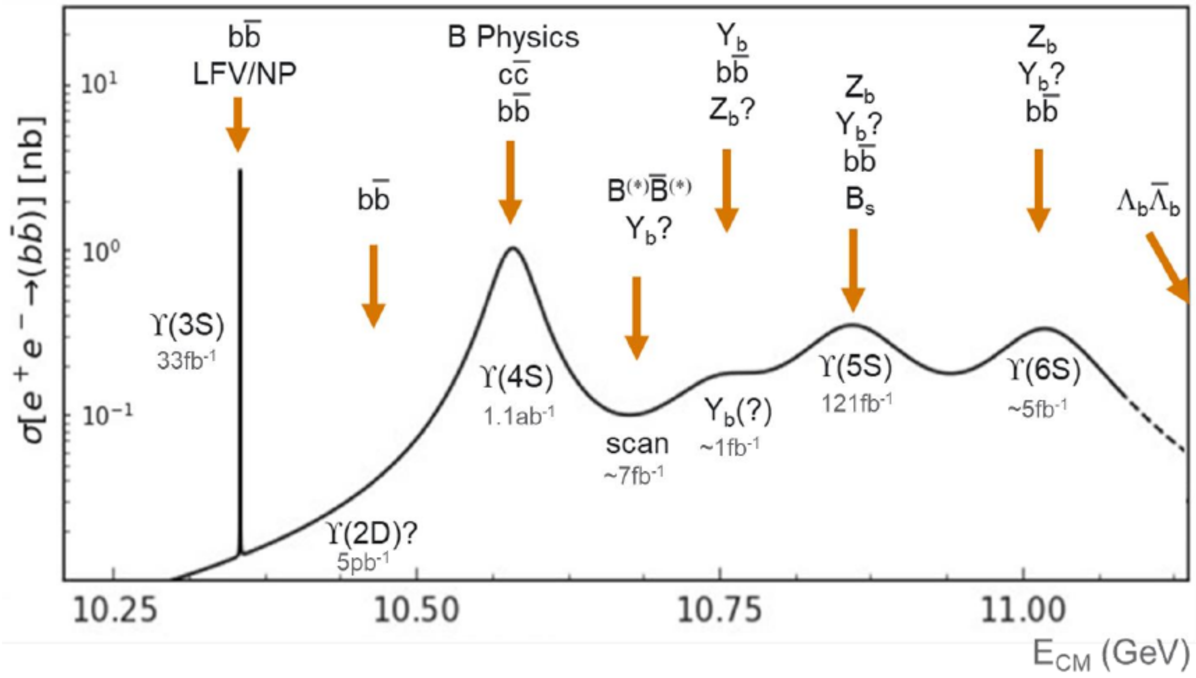
- $Z(3930)$ → $\chi_{c2}(3930)$, $\gamma\gamma \to D\bar{D}$
- $R_1(3921)$ → $= \chi_{c2}(3930)$?
- $R_2(4014)$
- $\chi_{c2}(3930)$ (← LHCb)

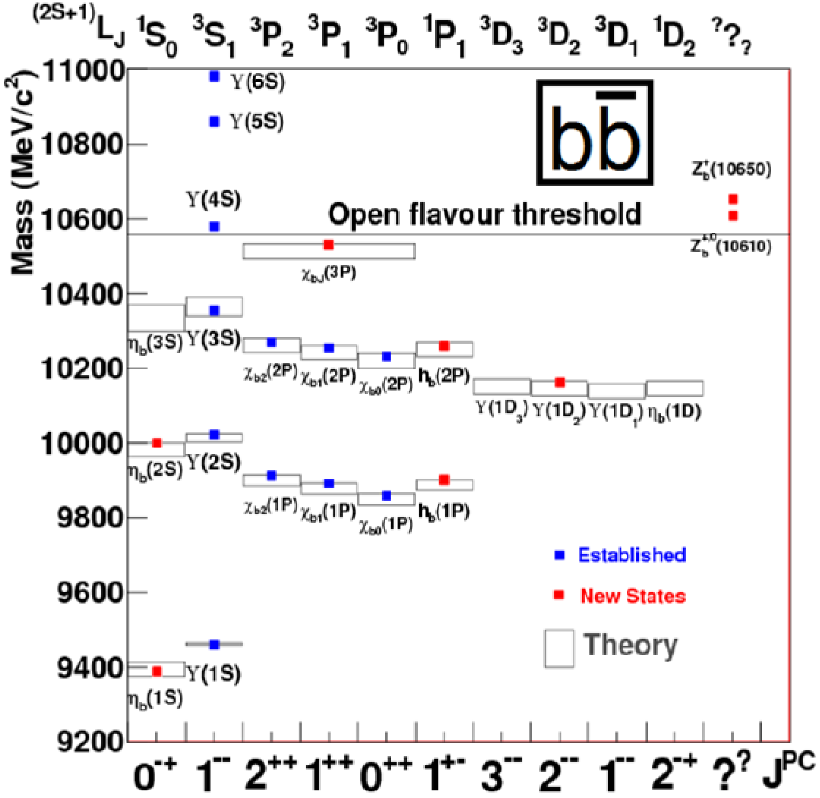
candidates excess → exotics?



Bottomonia

Search exotics by ππ, γ, η transitions



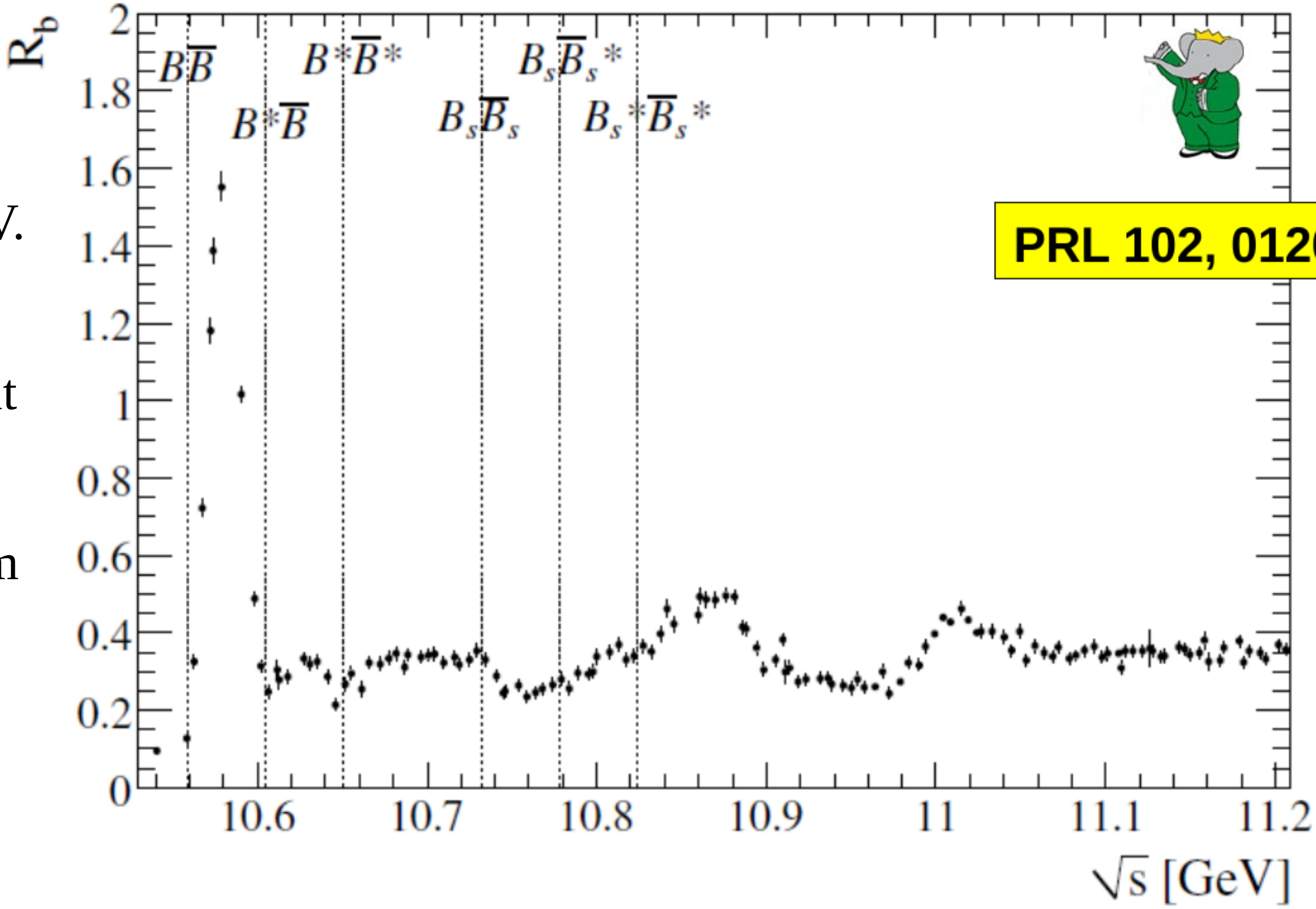


Measurement of $e^+e^- \to b\bar{b}$ cross section

BABAR measured the inclusive $b\bar{b}$ cross section in the region [10.54 : 11.2] GeV.

Observable include the Y(4S), Y(5S), and Y(6S), but not much else.

An exclusive study of bottom meson pair cross sections, however, may have more features and help elucidate the nature of the resonances.



PRL 102, 012001

Events reconstruction

Data samples include:

- 571 fb-1 on the Υ(4S) resonance
- 121 fb-1 on the Υ(5S) resonance
- 16 fb-1 distributed evenly in 16 points between 10.63 and 11.02 GeV

Full reconstruction of one B in event.
Using MVA for signal selection and continuum suppression.

$B^+ \to$	$B^0 \to$
$\bar{D}^0\pi^+$	$D^-\pi^+$
$\bar{D}^0\pi^+\pi^+\pi^-$	$D^-\pi^+\pi^+\pi^-$
$\bar{D}^{*0}\pi^+$	$D^{*-}\pi^+$
$\bar{D}^{*0}\pi^+\pi^+\pi^-$	$D^{*-}\pi^+\pi^+\pi^-$
$D_s^+\bar{D}^0$	$D_s^+D^-$
$D_s^{*+}\bar{D}^0$	$D_s^{*+}D^-$
$D_s^+\bar{D}^{*0}$	$D_s^+D^{*-}$
$D_s^{*+}\bar{D}^{*0}$	$D_s^{*+}D^{*-}$
$J/\psi\,K^+$	$J/\psi\,K_S^0$
$J/\psi\,K_S^0\pi^+$	$J/\psi\,K^+\pi^-$
$J/\psi\,K^+\pi^+\pi^-$	
$D^-\pi^+\pi^+$	$D^{*-}K^+K^-\pi^+$
$D^{*-}\pi^+\pi^+$	

$D^0 \to$	$D^+ \to$	$D_s^+ \to$
$K^-\pi^+$	$K^-\pi^+\pi^+$	$K^+K^-\pi^+$
$K^-\pi^+\pi^0$	$K^-\pi^+\pi^+\pi^0$	$K^+K_S^0$
$K^-\pi^+\pi^+\pi^-$	$K_S^0\pi^+$	$K^+K^-\pi^+\pi^0$
$K_S^0\pi^+\pi^-$	$K_S^0\pi^+\pi^0$	$K^+K_S^0\pi^+\pi^-$
$K_S^0\pi^+\pi^-\pi^0$	$K_S^0\pi^+\pi^+\pi^-$	$K^-K_S^0\pi^+\pi^+$
K^+K^-	$K^+K^-\pi^+$	$K^+K^-\pi^+\pi^+\pi^-$
$K^+K^-K_S^0$		$K^+\pi^+\pi^-$
		$\pi^+\pi^+\pi^-$

Signal selection

Key variables for analysis are

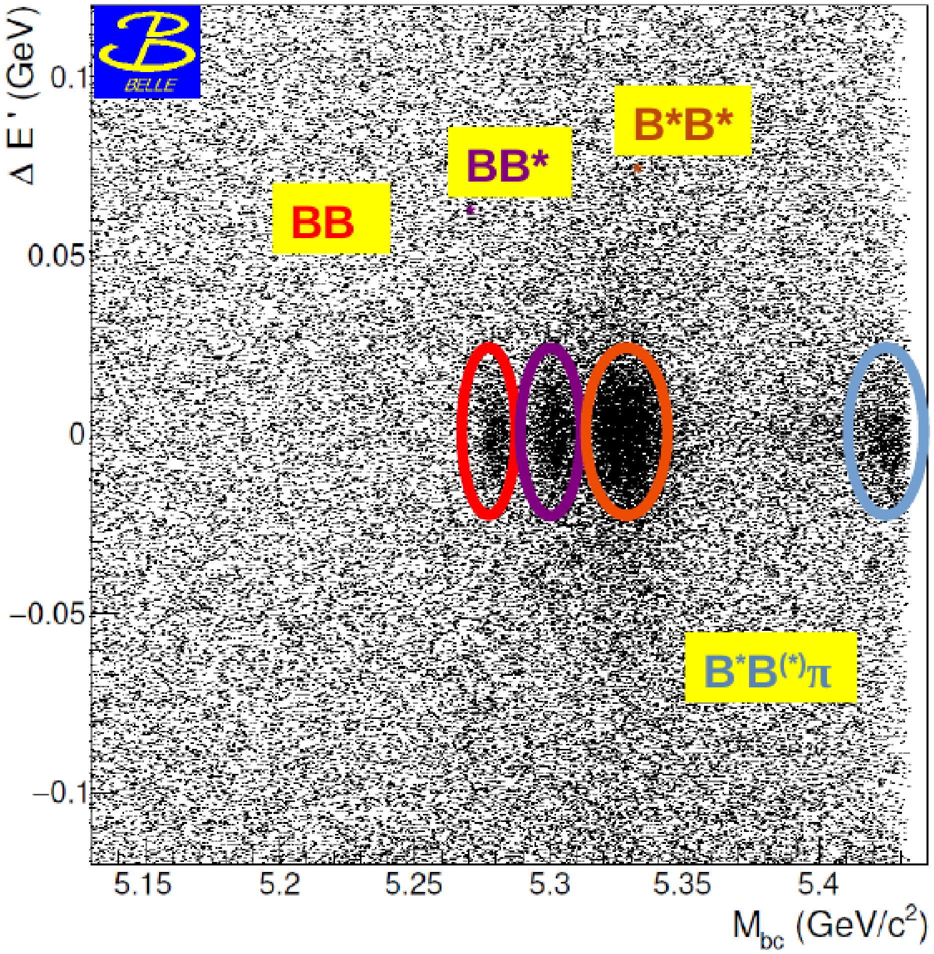
$$M_{bc} \equiv \sqrt{(E_{beam,CM})^2 - (p_{B,CM})^2}$$

$$\Delta E' \equiv \Delta E - M_{bc} + M_B$$

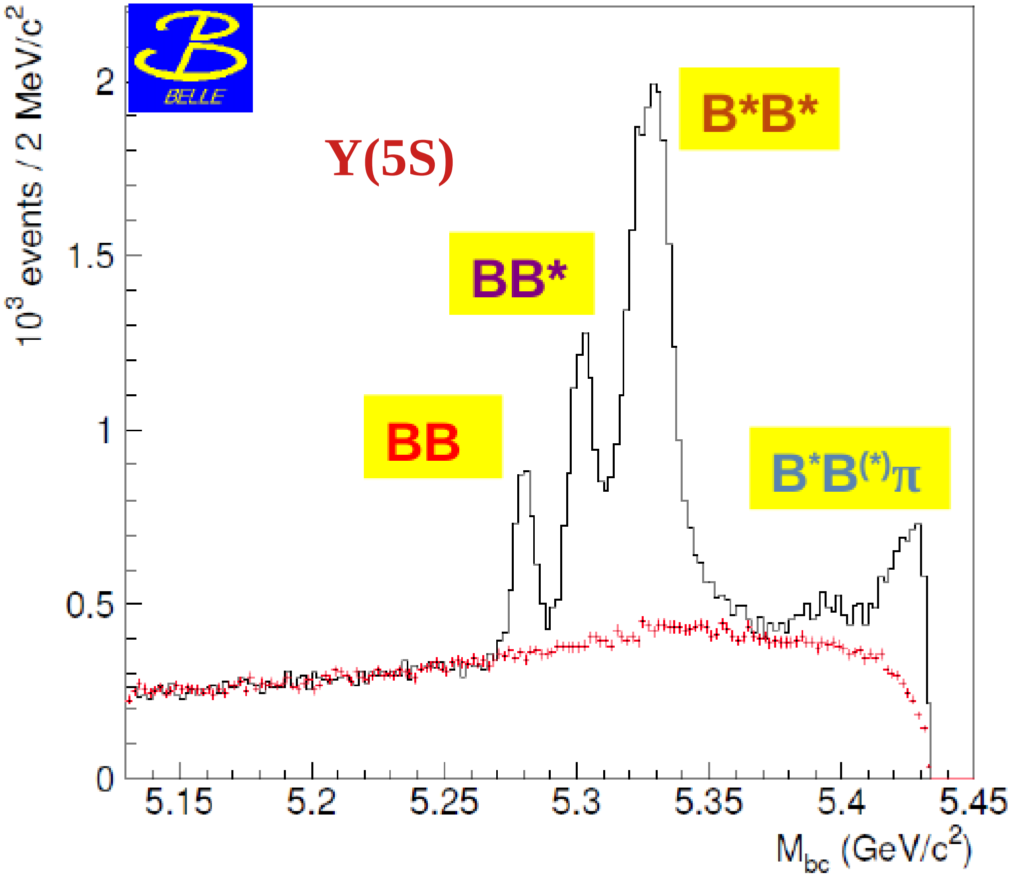
where

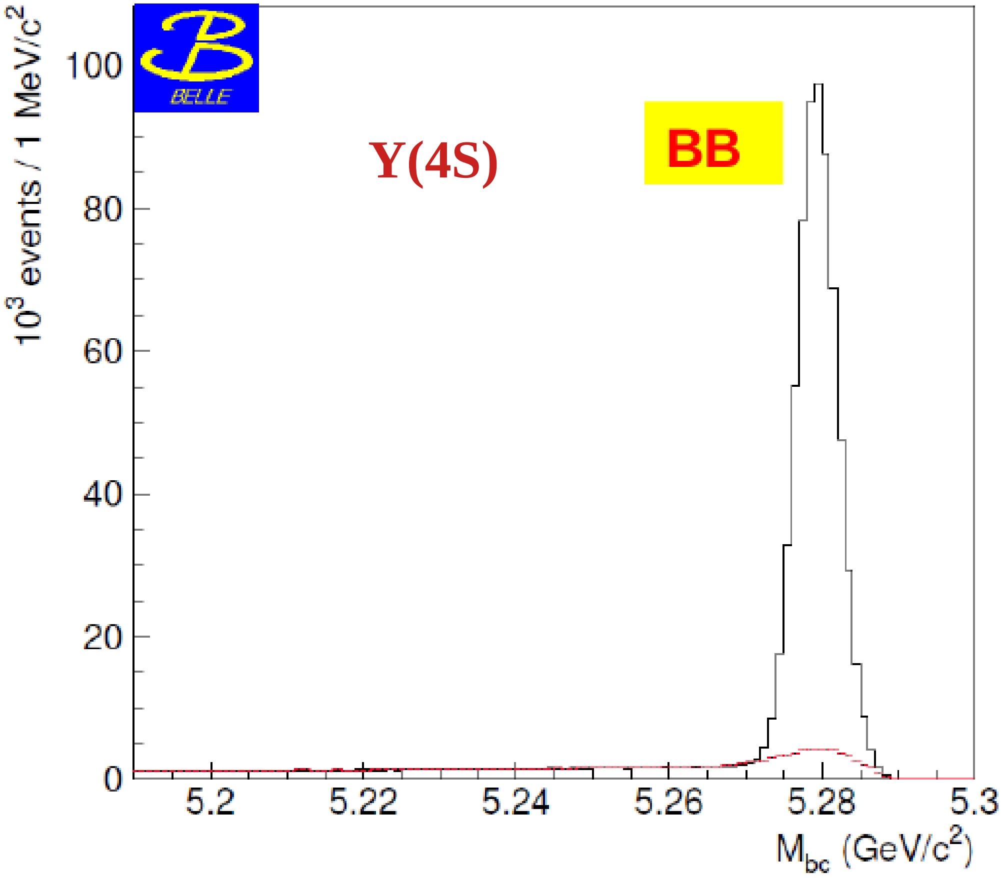
$$\Delta E \equiv E_{B,CM} - E_{beam,CM}$$

$\Delta E'$ has improved resolution and allows all decays (BB, BB*, B*B*) to be selected with a common cut on energy difference



M_{bc} for signal ΔE` region & side-bands

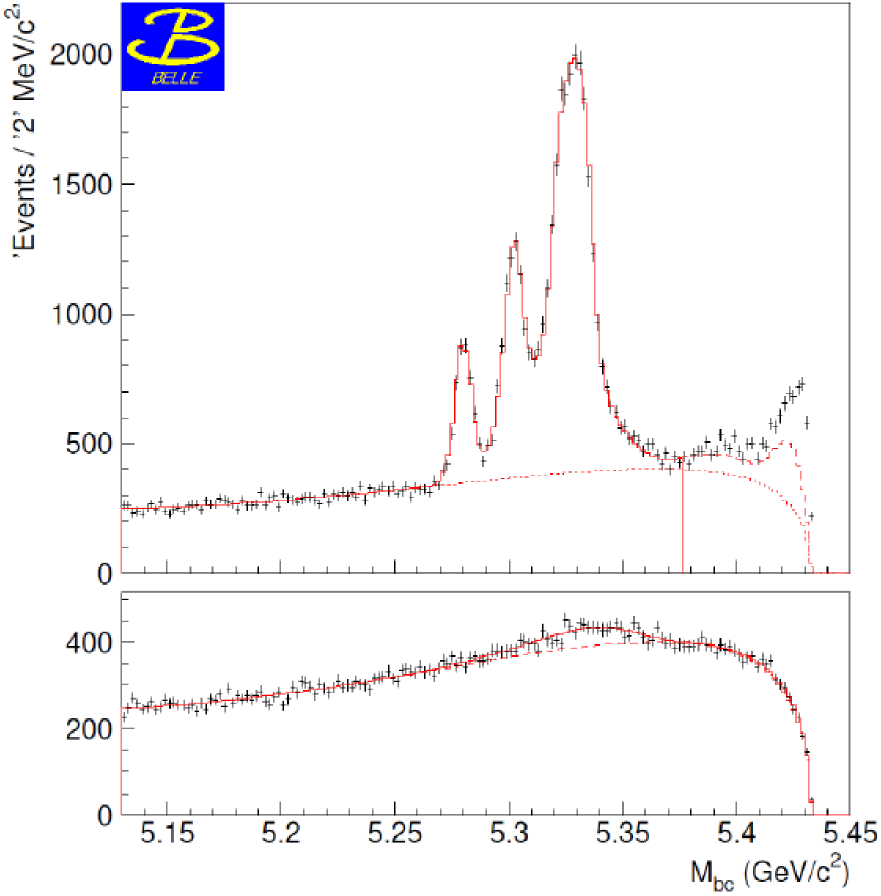




M_{bc} fit

- Fit M_{bc} distributions, selected in ΔE\` signal region and ΔE\` side-bands, for data taken at Υ(5S)

- A similar fit is done for all 16 data points in the scan, to study the energy dependence of the cross sections

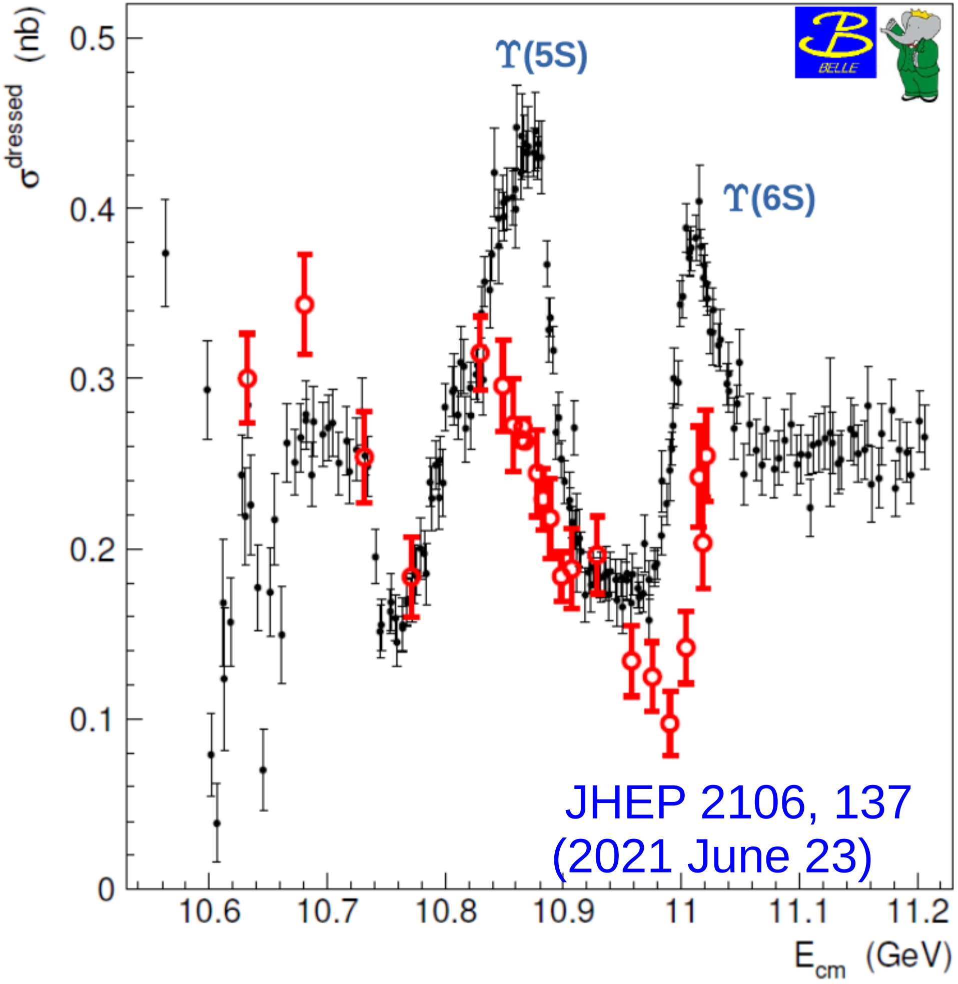


Cross section

- Note the discrepancy in the cross section of R_b and the sum of these two body modes near the Y(5S) – the excess is $B_S^{(*)}\overline{B}_S^{(*)}$, $B^{(*)}\overline{B}^{(*)}n\pi$,bottomonia + light hadrons.

- The two-body sum of $B\overline{B}$, $B\overline{B}^*$ and $B^*\overline{B}^*$ does **not** peak at the Y(5S) mass, despite theoretical expectations

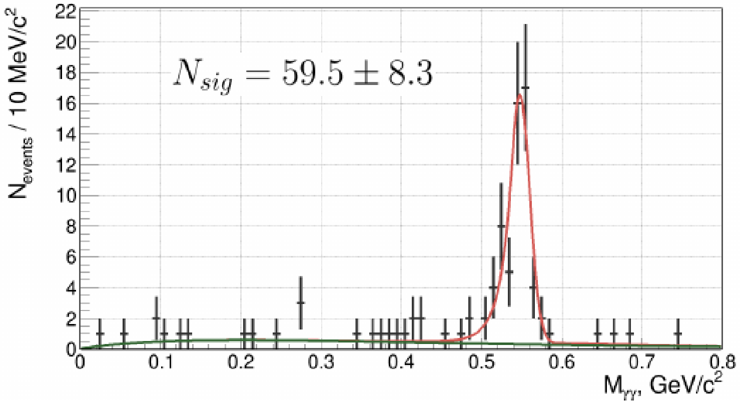
- Results are published in JHEP 2106, 137 (2021 June 23).



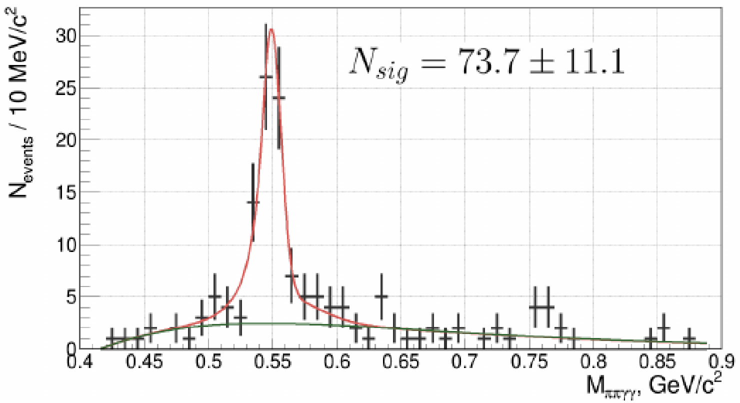
$\Upsilon(5S) \to \Upsilon(nS)\,\eta$

- Belle measured $\Gamma(\Upsilon(5S) \to h_b(mP)\pi^+\pi^-)$ / $\Gamma(\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-) \sim O(1)$ while it was expected to be $O(10^{-2})$ due spin flip, leading to discovery of Zb states.
- $\Gamma(\Upsilon(4,5S) \to \Upsilon(nS)h)$ / $\Gamma(\Upsilon(4,5S) \to \Upsilon(nS)\pi^+\pi^-)$ is also expected to be $O(10^{-2})$, while it was measured to be $2.41 \pm 0.40 \pm 0.12$ for $\Upsilon(4S)$.
- Below $B\bar{B}$ threshold, measured $\Gamma(\Upsilon(2,3S) \to \Upsilon(1S)\eta)$ / $\Gamma(\Upsilon(2,3S) \to \Upsilon(1S)\pi^+\pi^-)$ is consistent with QCDME predictions.
- Analysis of similar processes is crucial for better understanding of the quark structure of bottomonium states above the $B\bar{B}$ threshold.
- Data sample: 118 fb^{-1} at $\Upsilon(5S)$ & 21 fb^{-1} energy scan in 10.63 – 11.02 GeV.
- Decay channels: $\Upsilon(1,2S) \to \mu^+\mu^-$, $\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$, $\eta \to \gamma\gamma$, $\pi^+\pi^-\pi^0$, $\eta' \to \eta\pi^+\pi^-$
- Final state: $\mu^+\mu^-\pi^+\pi^-\gamma\gamma$

Υ(5S) → Υ(nS) η fit

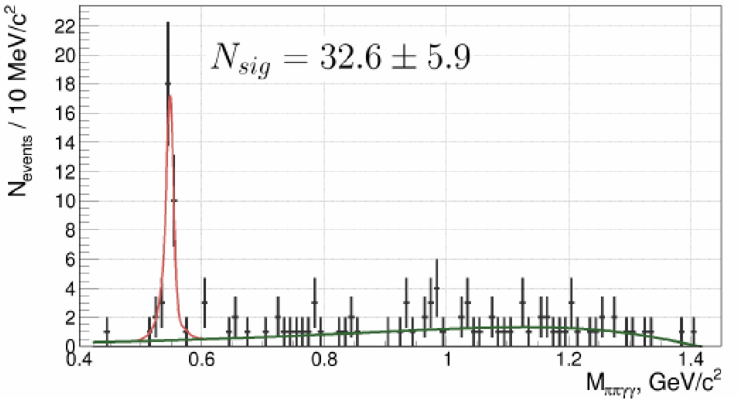


$\Upsilon(2S)\eta[\gamma\gamma]$

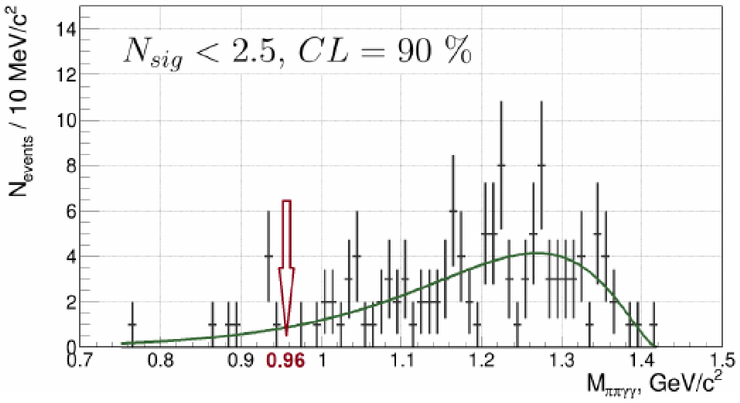


$\Upsilon(2S)\eta[3\pi]$

arXiv:2105.06605v2



$\Upsilon(1S)\eta[3\pi]$



$\Upsilon(1S)\eta'[\pi^+\pi^-\eta]$

$\Upsilon(5S) \to \Upsilon(nS)\,\eta$ results

arXiv:2105.06605v2

Cross section

$$\sigma_{\rm B}(e^+e^- \to \Upsilon(2S)\eta) = 2.07 \pm 0.21 \pm 0.19 \text{ pb},$$
$$\sigma_{\rm B}(e^+e^- \to \Upsilon(1S)\eta) = 0.42 \pm 0.08 \pm 0.04 \text{ pb},$$
$$\sigma_{\rm B}(e^+e^- \to \Upsilon(1S)\eta') < 0.035 \text{ pb}, \ CL = 90\%.$$

Branching fractions

$$\mathcal{B}(\Upsilon(5S) \to \Upsilon(1S)\eta) = (0.85 \pm 0.15 \pm 0.08) \times 10^{-3},$$
$$\mathcal{B}(\Upsilon(5S) \to \Upsilon(2S)\eta) = (4.13 \pm 0.41 \pm 0.37) \times 10^{-3},$$
$$\mathcal{B}(\Upsilon(5S) \to \Upsilon(1S)\eta') < 6.9 \times 10^{-5}, \ CL = 90\%.$$

Decay width ratios

QCDME calculations

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

~0.005

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

~0.03

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

~12

Belle II potential

- Run at Υ(6S) and Υ(5S) and high energy scan:
  - Search for new, predicted, resonances such missing bottomonia, exotic states,
  - Improve precision of already known process and states: e.g. Zb's,
  - Measure the effect of the coupled channel contribution,
  - Study $B^{(*)}\overline{B}^{(**)}$ and $Bs^{(*)}\overline{B}s^{(**)}$ threshold regions (challenging for Super-KEKb).

- Run at Υ(3S) and Υ(2S):
  - Search for missing ππ/η transitions to constrain further theoretical models,
  - Search for new physics: LFV, LFU, new scalars...

Belle II plans

- Main focus to collect Υ(4S) on-peak data.
- Upcoming non-Υ(4S) plans (Nov 2021):
  - 10.751 GeV (10 fb^{-1}): to study Υ_b(10753) on-peak,
  - 10.657, 10.706, 10.810 (1+2+3 fb^{-1}): additional points for $B\bar{B}$ decomposition.
- Expected data: ~400 fb^{-1} by end of 2021, ~750 fb^{-1} by summer 2022.
- 9 month upgrade, then data taking till 2026, expected O(10 ab^{-1}).
- After upgrade: 11 GeV (30 fb^{-1}): to study Υ(6S) on-peak.
- Future proposals: options for larger Υ(6S), Υ(3S), Υ(5S) datasets.

Summary

- Belle experiment data analysis is still ongoing.
- New results are coming for charm and beauty sectors.
- Belle II is collecting data, statistics soon will be comparable to BaBar/Belle.
- Charmonia / bottomonia / XYZ is a significant component of the physics program.
- Advantages with unique production, decay modes related to neutrals.
- Planning for non-Υ(4S) energies.
- Input welcome from community on 10.75 GeV and other $b\bar{b}$ studies.