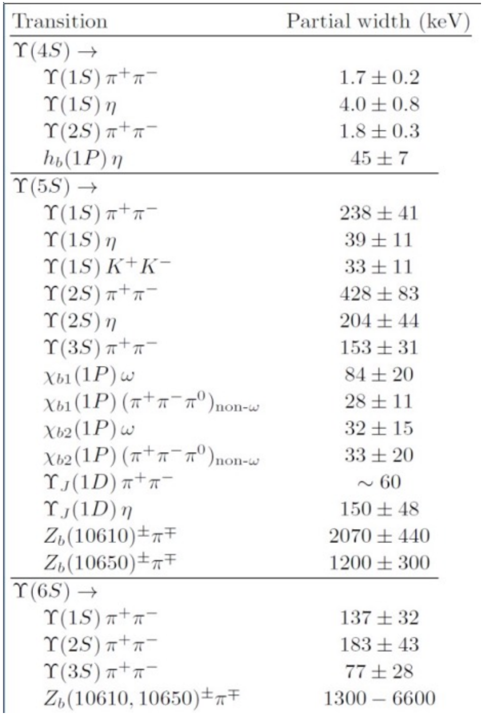
Review of bottomonium decay results at Belle

Baoshang Gao
Nankai University, China
(on behalf of the Belle & Belle II Collaborations)

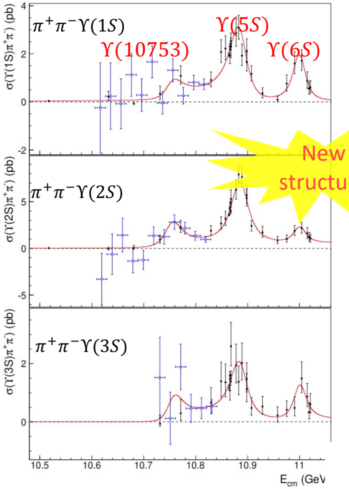
16th International Workshop on Heavy Quarkonium – QWG 2024
February 26, 2024-March 1, 2024
IISER, Mohali, India

Bottomonium at Belle

Alternative explanation is that the transitions $\Upsilon(nS) \rightarrow \Upsilon(ms)$ proceed via exotic admixture



Transition	Partial width (keV)
$\Upsilon(4S) \rightarrow$	
$\Upsilon(1S)\,\pi^+\pi^-$	1.7 ± 0.2
$\Upsilon(1S)\,\eta$	4.0 ± 0.8
$\Upsilon(2S)\,\pi^+\pi^-$	1.8 ± 0.3
$h_b(1P)\,\eta$	45 ± 7
$\Upsilon(5S) \rightarrow$	
$\Upsilon(1S)\,\pi^+\pi^-$	238 ± 41
$\Upsilon(1S)\,\eta$	39 ± 11
$\Upsilon(1S)\,K^+K^-$	33 ± 11
$\Upsilon(2S)\,\pi^+\pi^-$	428 ± 83
$\Upsilon(2S)\,\eta$	204 ± 44
$\Upsilon(3S)\,\pi^+\pi^-$	153 ± 31
$\chi_{b1}(1P)\,\omega$	84 ± 20
$\chi_{b1}(1P)\,(\pi^+\pi^-\pi^0)_{\text{non-}\omega}$	28 ± 11
$\chi_{b2}(1P)\,\omega$	32 ± 15
$\chi_{b2}(1P)\,(\pi^+\pi^-\pi^0)_{\text{non-}\omega}$	33 ± 20
$\Upsilon_J(1D)\,\pi^+\pi^-$	~ 60
$\Upsilon_J(1D)\,\eta$	150 ± 48
$Z_b(10610)^\pm\pi^\mp$	2070 ± 440
$Z_b(10650)^\pm\pi^\mp$	1200 ± 300
$\Upsilon(6S) \rightarrow$	
$\Upsilon(1S)\,\pi^+\pi^-$	137 ± 32
$\Upsilon(2S)\,\pi^+\pi^-$	183 ± 43
$\Upsilon(3S)\,\pi^+\pi^-$	77 ± 28
$Z_b(10610, 10650)^\pm\pi^\mp$	$1300 - 6600$

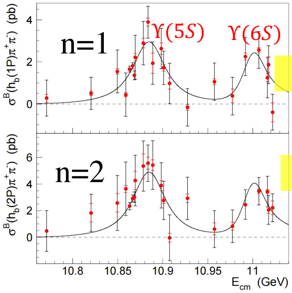


New structure

PRL 117(2006) 142001

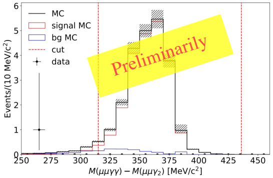
JHEP 10 (2019) 220

$Z_b^+\pi^- \rightarrow h_b(nP)\pi^+\pi^-$

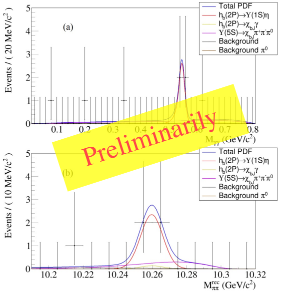


EVIDENCE

FIRST OBS.



Preliminarily



Preliminarily

Υ(1S) hadronic decays

And many others

……

Selected Topics

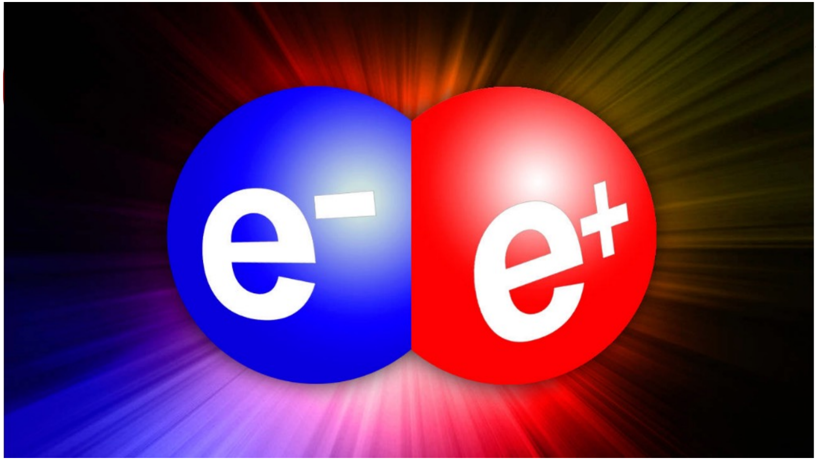
$*$ Search for $h_b(2P) \rightarrow \gamma \chi_{bJ}(1P)$ [NEW];

$*$ Evidence for $h_b(2P) \rightarrow \Upsilon(1S)\eta$ and search for $h_b(1P, 2P) \rightarrow \Upsilon(1S)\pi^0$ [NEW];

$*$The study of $\Upsilon(2S) \rightarrow \mathrm{D}_{\mathrm{s}}^{(*)+} + \mathrm{D}_{\mathrm{sJ}}^{-} + \mathrm{c.c.}$ [PRD 108, 112015 (2023)].

TOPIC ONE

Search for $h_b(2P) \to \gamma \chi_{bJ}(1P)$



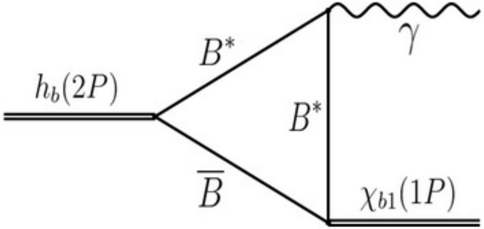
Motivation

☞ The production of $b\bar{b}$ spin singlets is generally rare in e^+e^- collisions because it requires the spin flip of a heavy quark in a hadronic or radiative transition.

☞ The $h_b(2P)$ is produced via the $\Upsilon(10860) \rightarrow h_b(2P)\pi^+\pi^-$ transition with a surprisingly large rate[1].

☞ $h_b(2P) \rightarrow \chi_{b1}\gamma$ decay is suppressed due to heavy quark spin symmetry. Relativized Quark Model (RQM) predicts $\mathcal{B}[h_b(2P) \rightarrow \gamma\chi_{bJ}(1P)]= 10^{-6} - 10^{-5}$[2] .

☞ There could be enhancement due to hadron admixture in $h_b(2P)$ .The coupled-channel model predicts $\mathcal{B}[h_b(2P) \rightarrow \gamma\chi_{bJ}(1P)]= 10^{-2} - 10^{-1}$[3][4].



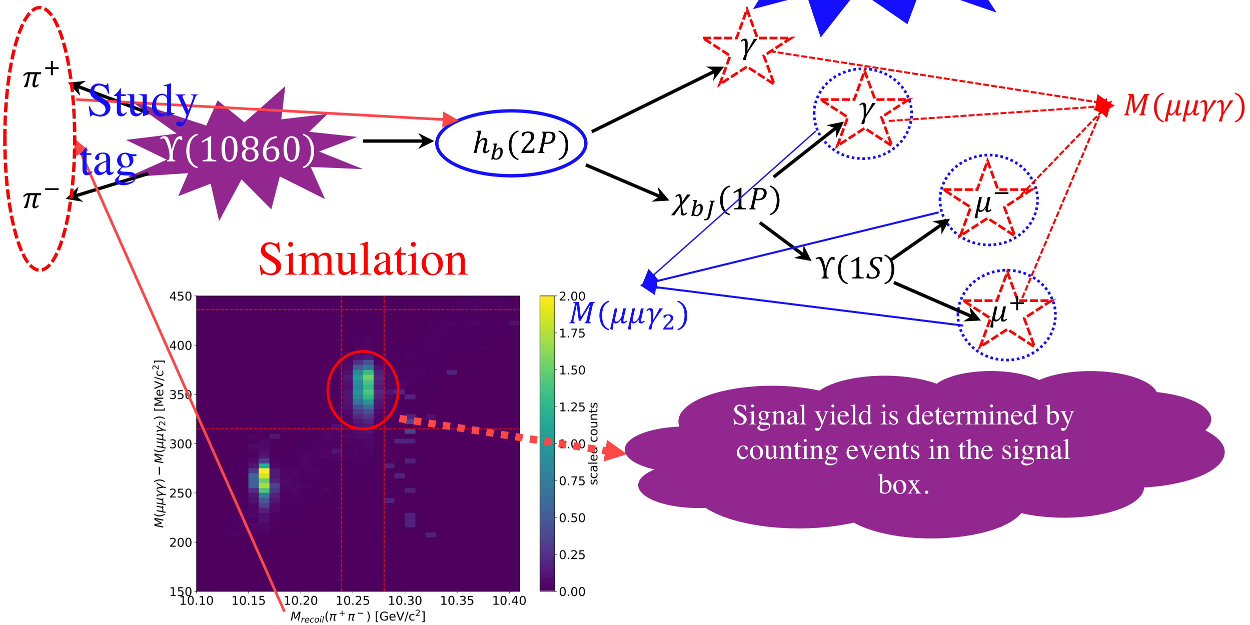
https://arxiv.org/abs/physics/9711021

[1] PRL **108**, 032001 (2012), Belle collaboration.
[2] PRD **32**, 189 (1985), Stephen Godfrey et al.
[3] PLB **760**, 417 (2016), Feng-Kun Guo et al.
[4] https://arxiv.org/abs/physics/9711021

Search for $h_b(2P) \rightarrow \gamma\chi_{bJ}(1P)$

☞ **Data samples:**

$\Upsilon(10860)$: 121.4 fb^{-1}

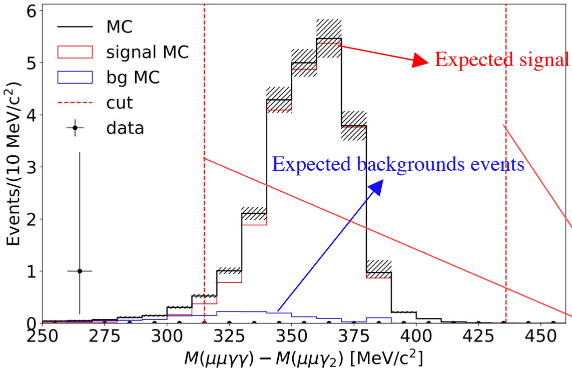


Decay chains

Simulation

Signal yield is determined by counting events in the signal box.

The Results for $h_b(2P) \to \gamma\chi_{bJ}(1P)$



We count the number of events in the signal region. No events are found in the signal box and the background count is $1.06^{+0.29}_{-0.20}$ on the simulated data.

Signal region

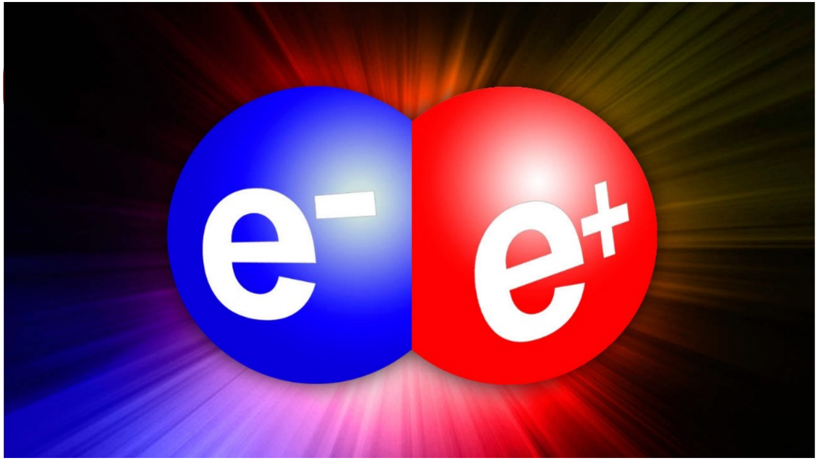
We set upper limits below :

Channel	$\mathcal{B}$
$h_b(2P) \to \gamma\chi_{b2}(1P)$	$< 1.2 \times 10^{-2}$
$h_b(2P) \to \gamma\chi_{b1}(1P)$	$< 5.4 \times 10^{-3}$
$h_b(2P) \to \gamma\chi_{b0}(1P)$	$< 2.7 \times 10^{-1}$

The results is consistent with the RQM expectations and excludes the results from the coupled-channel model.

TOPIC TWO

Evidence for $h_b(2P) \rightarrow \Upsilon(1S)\eta$ and search for $h_b(1P, 2P) \rightarrow \Upsilon(1S)\pi^0$



Motivation

☞ $h_b(2P) \to \Upsilon(1S)\eta$ decay is suppressed due to heavy quark spin symmetry.

☞ Hadronic transitions between heavy quarkonium states can be mostly described with the QCD multiple expansion model (*QCDME*) [1], including $h_b(1P, 2P)$ are expected to have decay properties similar to $\chi_b(1P, 2P)$[2].

☞ Theoretical prediction: the $R_{h_b}(R_{\chi_{b1}})$ is the ratio of the annihilation rates for the $h_b(1P, 2P)(\chi_b(1P, 2P))$, the predicted value of $R_{h_b}/R_{\chi_{b1}}$=1 [3] .

☞ Based on recent results, the $R_{h_b}/R_{\chi_{b1}}$ is 0.24 with 1.5σ discrepancy from unity and the discrepancy would further increase if the rate of $h_b(2P) \to \Upsilon(1S)\eta$ is as large as 10%.

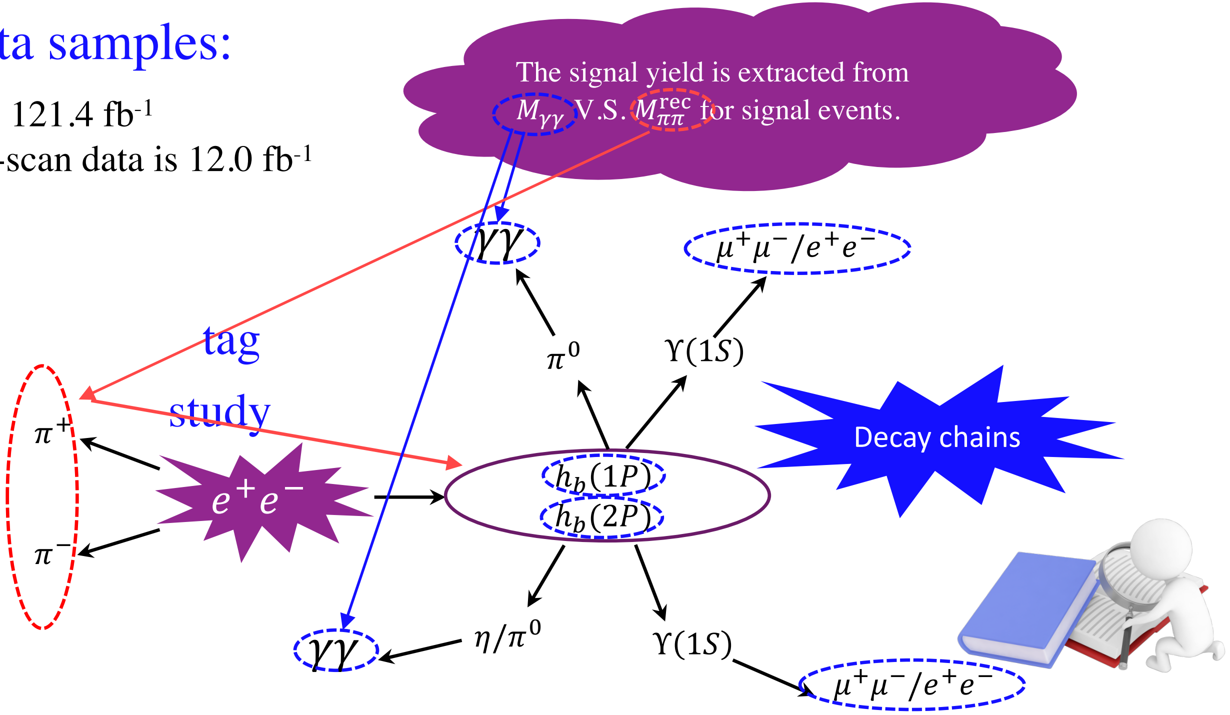
[1] NPB **154**, 365 (1979) M. B. Voloshin.
[2] PRD **66**, 014012 (2002) Stephen Godfrey.
[3] PRD **86**, 094013 (2012) Xin Li et al.

The study of $h_b(2P) \to \Upsilon(1S)\eta$ and $h_b(1P, 2P) \to \Upsilon(1S)\pi^0$

Data samples:

☞ $\Upsilon(5S)$: 121.4 fb^{-1}

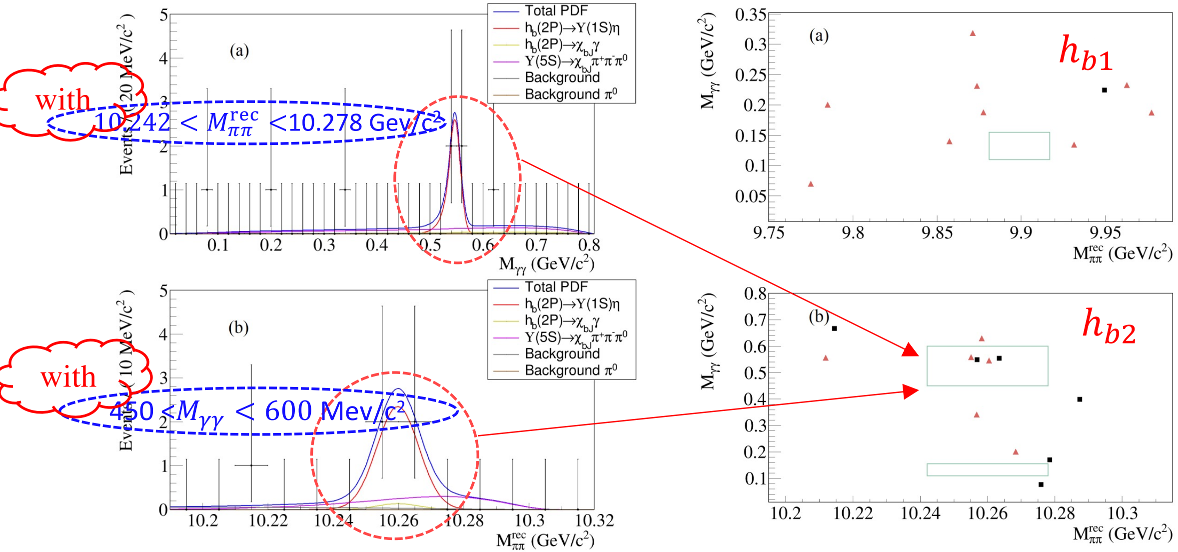
☞ Energy-scan data is 12.0 fb^{-1}



The signal yield is extracted from $M_{\gamma\gamma}$ V.S. $M_{\pi\pi}^{\rm rec}$ for signal events.

The Results of $h_b(2P) \to \Upsilon(1S)\eta$ and $h_b(1P,2P) \to \Upsilon(1S)\pi^0$

- ☞ $\mathcal{B}[h_b(2P) \to \Upsilon(1S)\eta] = (7.1^{+3.7}_{-3.2} \pm 0.8)\times 10^{-3}$ 3.5σ
- ☞ $\mathcal{B}[h_b(2P) \to \Upsilon(1S)\pi^0] < 1.8\times 10^{-3}$ at 90% confidence level.
- ☞ $\mathcal{B}[h_b(1P) \to \Upsilon(1S)\pi^0] < 1.8\times 10^{-3}$ at 90% confidence level.



with $10.242 < M_{\pi\pi}^{\rm rec} < 10.278$ GeV/c²

with $450 < M_{\gamma\gamma} < 600$ Mev/c²

h_{b1}

h_{b2}

The hindered M1 decays between P-wave bottomonium state $h_b(2P) \to \chi_{bJ}(1P)\gamma$ with $J = 0,1,2$.

Results discussion

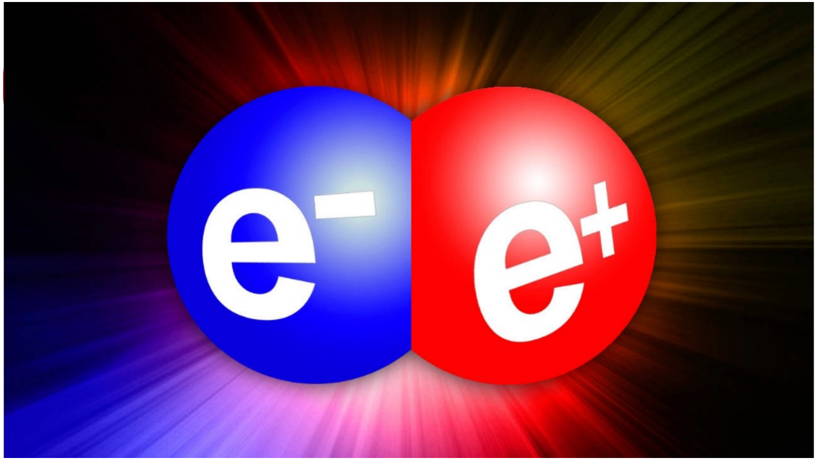
We see evidence of the $h_b(2P) \to \Upsilon(1S)\eta$ transition with significance of the signal is 3.5σ.

The obtained $\mathcal{B}[h_b(2P) \to \Upsilon(1S)\eta] = (7.1^{+3.7}_{-3.2} \pm 0.8)\times10^{-3}$ noticeably differs from the expectation of 10% and the updated value of $R_{h_b}/R_{\chi_{b1}}$ is around 0.23.

We do not observe any signal for the isospin violating decays $h_b(1P, 2P) \to \Upsilon(1S)\pi^0$ and the upper limits are found to be $\mathcal{B}[h_b(1P) \to \Upsilon(1S)\pi^0] = 1.8\times10^{-3}$ and $\mathcal{B}[h_b(2P) \to \Upsilon(1S)\pi^0] = 1.8\times10^{-3}$.

TOPIC THREE

The study of $\Upsilon(2S) \to D_s^{(*)+} D_{sJ}^{-} + c.c.$

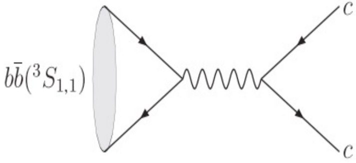


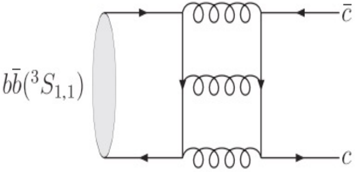
Motivation

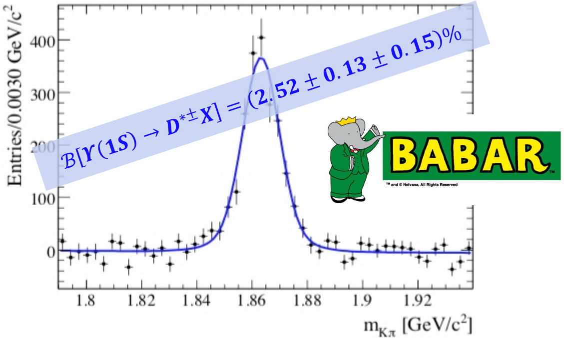
☞ Rare decays involving $\Upsilon(1S, 2S) \rightarrow c\bar{c}$ due to the OZI suppressed.

☞ Bound states of heavy quarks provide a powerful testing ground for QCD, including the $\mathcal{B}(\Upsilon(1S) \rightarrow D^+D^-) \sim 10^{-5} - 10^{-4}$[1], $\mathcal{B}(\Upsilon(1S) \rightarrow c\bar{c}) \approx 2.7\%$ [2].

☞ $\mathcal{B}[\Upsilon(1S) \rightarrow D^{*\pm}X]$ measured by BABAR Collaboration[3].







$\mathcal{B}[\Upsilon(1S) \rightarrow D^{*\pm}X] = (2.52 \pm 0.13 \pm 0.15)\%$

$\Upsilon(1S)$ using the decay chain $\Upsilon(2S) \rightarrow \pi^+\pi^-\Upsilon(1S)$.

[PHYSICAL REVIEW D, 81,011102(R)(2010)]

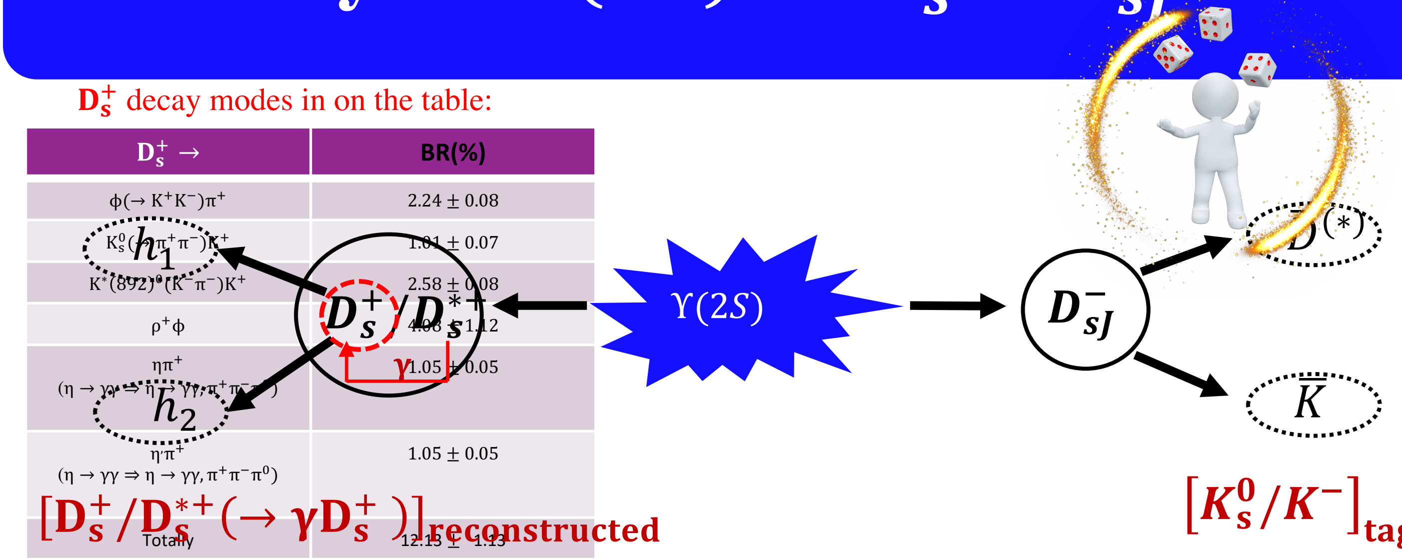
[1] PRD **74**, 094016(2006), Hai-Bo Li et al.

[2] PRD **78**, 094017(2008), Yu-Jie Zhang et al.

[3] PRD **81**,011102(R)(2010), BaBar collaboration.

The study of $\Upsilon(2S) \to D_s^{(*)+} D_{sJ}^- + c.c.$

$\mathbf{D_s^+}$ decay modes in on the table:



$\mathbf{D_s^+} \to$	**BR(%)**
$\phi(\to K^+K^-)\pi^+$	2.24 ± 0.08
$K_S^0(\to \pi^+\pi^-)K^+$	1.01 ± 0.07
$K^*(892)^0(K^-\pi^-)K^+$	2.58 ± 0.08
$\rho^+\phi$	4.08 ± 1.12
$\eta\pi^+$ $(\eta \to \gamma\gamma \Rightarrow \eta \to \gamma\gamma, \pi^+\pi^-\pi^0)$	1.05 ± 0.05
$\eta'\pi^+$ $(\eta \to \gamma\gamma \Rightarrow \eta \to \gamma\gamma, \pi^+\pi^-\pi^0)$	1.05 ± 0.05
Totally	12.13 ± 1.13

$[\mathbf{D_s^+}/\mathbf{D_s^{*+}}(\to \gamma \mathbf{D_s^+})]_{\mathbf{reconstructed}}$

$[K_S^0/K^-]_{\mathbf{tag}}$

$$M_{rec}\left(D_s^{(*)+}\right) = \sqrt{(E_{C.M.} - E_{D_s^{(*)+}})^2 - (\vec{P}_{C.M.} - \vec{P}_{D_s^{(*)+}})^2} \Rightarrow \mathbf{D_{sJ}^-}$$

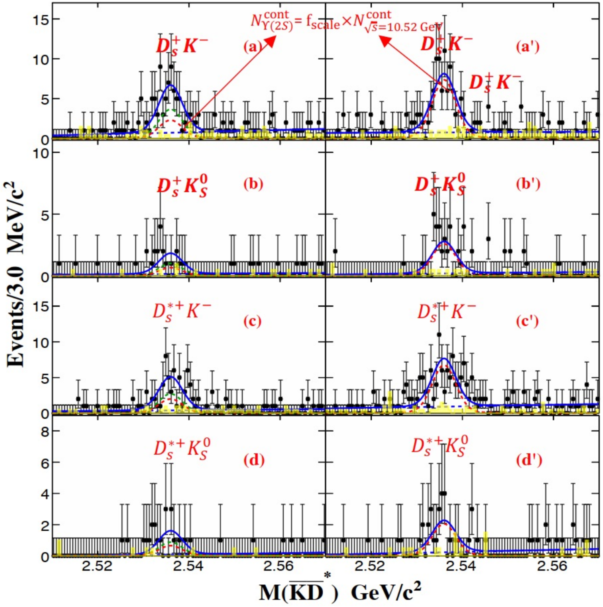
$$M_{rec}\left(D_s^{(*)+}K\right) = \sqrt{(E_{C.M.} - E_{D_s^{(*)+}} - E_K)^2 - (\vec{P}_{C.M.} - \vec{P}_{D_s^{(*)+}} - \vec{P}_K)^2} \Rightarrow D^{(*)0}/D^{(*)-}$$

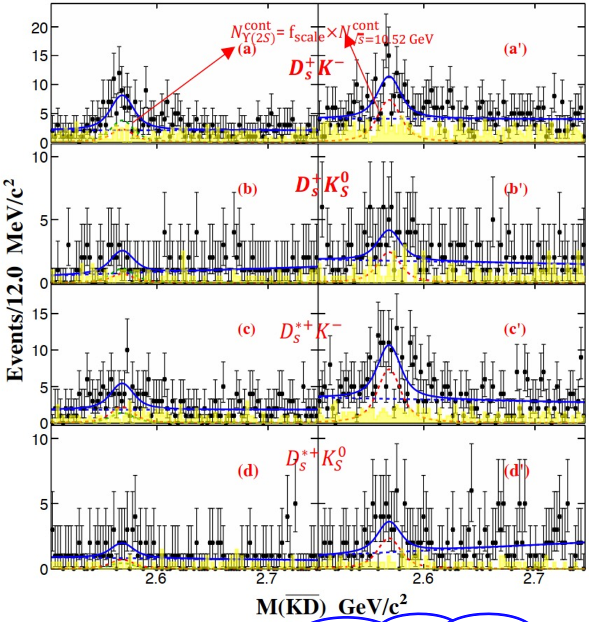
$M_{rec}\left(D_s^{(*)+}\right)$- $M_{rec}\left(D_s^{(*)+}K\right) + m(\bar{D}^{(*)})$ are used to improve the resolutions of $\mathbf{D_{sJ}^-}$.

Distributions of $M(\bar{K}\bar{D}^*)$

$$\mathcal{B}\left(\Upsilon(2S)\to D_s^{(*)+}D_{sJ}^{(*)-}\right)\times\mathcal{B}\left(D_{SJ}^{(*)-}\to D^{(*)}K\right)=\frac{N_{fit}^{\Upsilon(2S)}-(N_{fit}^{\Upsilon(cont)}\times f_{scale})}{\Sigma_i(\epsilon_i\times\mathcal{B}_i)\times N_{tot}}$$

$$\sigma\left(e^+e^-\to D_s^{(*)+}D_{sJ}^{(*)-}\right)\times\mathcal{B}\left(D_{SJ}^{(*)-}\to D^{(*)}K\right)=\frac{N_{fit}^{cont}\times|1-\Pi|^2}{\Sigma_i(\epsilon_i\cdot\mathcal{B}_i)\times\mathcal{L}\times(1+\delta_{ISR})}$$





$$R_{\rm iso,1}=\frac{\mathcal{B}[D_{s1}(2536)^-\to D^*(2010)^-K_S^0]}{\mathcal{B}[D_{s1}(2536)^-\to D^*(2007)^0K^-]}=0.48\pm0.07\pm0.02$$

$$R_{\rm iso,2}=\frac{\mathcal{B}[D_{s2}^*(2573)^-\to D^-K_S^0]}{\mathcal{B}[D_{s2}^*(2573)^-\to D^0K^-]}=0.49\pm0.10\pm0.02$$

There are in good agreement with expected values of 0.498 and 0.497 from isospin symmetry.

Fitting Results

QED+QCD: $\mathrm{R}_1 = \mathcal{B}\ (\Upsilon(2S) \to D_s^{(*)+} D_{sJ}^- + c.c.)/\mathcal{B}\ (\Upsilon(2S) \to \mu^+\mu^-)$

The fitting results of $\mathcal{B}(\Upsilon(2S) \to D_s^{(*)+} D_{sJ}^-)\mathcal{B}(D_{sJ}^- \to KD^{(*)})$ (K^- mode)

Final states	$N^{\mathrm{sig}}_{\Upsilon(2S)}$	significance(σ)	$\mathcal{B}(\Upsilon(2S) \to D_s^{(*)} D_{sJ}^-)\mathcal{B}(D_{sJ}^- \to KD^{(*)})(10^{-5})$
$D_s^+ D_{s1}(2536)^-$	$43 \pm 9 \pm 2$	5.3	$1.6 \pm 0.3 \pm 0.2$
$D_s^{*+} D_{s1}(2536)^-$	$43 \pm 9 \pm 2$	4.3	$1.4 \pm 0.4 \pm 0.2$
$D_s^+ D_{s2}^*(2573)^-$	$43 \pm 9 \pm 5$	3.8	$1.4 \pm 0.4 \pm 0.2$
$D_s^{*+} D_{s2}^*(2573)^-$	$43 \pm 9 \pm 2$	1.6	$0.9 \pm 0.5 \pm 0.2$

QED: $\mathrm{R}_2 = \sigma^{\mathrm{Born}}\left(e^+e^- \to D_s^{(*)+} D_{sJ}^- + c.c.\right)/\sigma^{\mathrm{Born}}(\mathrm{e}^+\mathrm{e}^- \to \mu^+\mu^-)$

The fitting results of $\sigma^{\mathrm{B}}(e^+e^- \to D_s^{(*)+} D_{sJ}^-)\mathcal{B}(D_{sJ}^- \to KD^{(*)})$ (K^- mode)

Final states	$N^{\mathrm{sig}}_{\mathrm{cont}}$	significance(σ)	$\sigma^{\mathrm{B}}(e^+e^- \to D_s^{(*)} D_{sJ}^-)\mathcal{B}(D_{sJ}^- \to KD^{(*)})(\mathrm{fb})$
$D_s^+ D_{s1}(2536)^-$	$86 \pm 10 \pm 2$	13.9	$67 \pm 8 \pm 6$
$D_s^{*+} D_{s1}(2536)^-$	$79 \pm 10 \pm 2$	11.8	$84 \pm 11 \pm 11$
$D_s^+ D_{s2}^*(2573)^-$	$102 \pm 17 \pm 21$	7.1	$56 \pm 9 \pm 13$
$D_s^{*+} D_{s2}^*(2573)^-$	$102 \pm 16 \pm 6$	7.6	$106 \pm 17 \pm 12$

$R_1/R_2 = 9.8 \pm 2.5$, 8.0 ± 2.4, $9.7 \pm 3.0$and 4.4 ± 2.8 for the $D_s^+ D_{s1}(2536)^-$, $D_s^{*+} D_{s1}(2536)^-$, $D_s^+ D_{s2}^*(2573)^-$ and $D_s^{*+} D_{s2}^*(2573)^-$ final states in the $D_{sJ}^- \to K^- \overline{D}^{(*)0}$ modes, respectively.

The measured R_1/R_2 values indicate that the strong decay dominates in the $\Upsilon(2S) \to D_s^{(*)+} D_{sJ}^-$ processes.

Summary

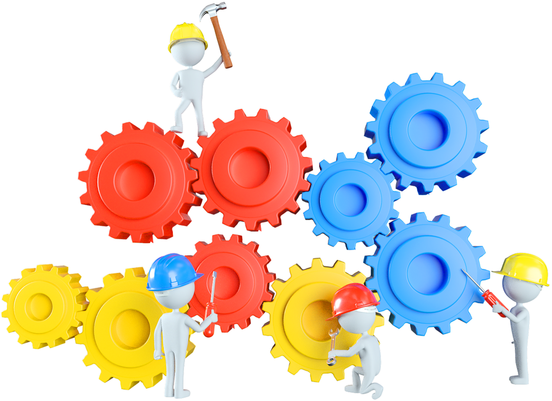
✓ We study the hindered M1 decays between P-wave bottomonium state $h_b(2P) \to \chi_{bJ}(1P)\gamma$ with $J =$ 0,1,2 and set limits on $h_b(2P) \to \chi_{bJ}(1P)\gamma$ processes.

✓ We found the first evidence of the $h_b(2P) \to \Upsilon(1S)\eta$ transition with significance of 3.5σ and set limits on $h_b(1P, 2P) \to \Upsilon(1S)\pi^0$ processes.

✓We observe the charmed strange meson pair $D_s^{(*)+} D_{sJ}^-$ production in $\Upsilon(2S)$ decays and e^+e^- annihilation at $\sqrt{s} = 10.52$ GeV for the first time, where D_{sJ}^- is $D_{s1}(2536)^-$ or $D_{s2}^*(2573)^-$.

✓ There results are in good agreement with expected isospin symmetry and indicates that the strong decay dominates in the $\Upsilon(2S) \to D_s^{(*)+} D_{sJ}^-$ processes.

Thank for your attention!



Backup

Selections for studying of $\Upsilon(2S) \to D_s^{(*)+} D_{sJ}^{-} + c.c.$

For charged tracks

1. kaons: $\mathcal{L}(K)/\mathcal{L}(K)+\mathcal{L}(\pi)>0.6$.Pions:$\mathcal{L}(K)/\mathcal{L}(K)+\mathcal{L}(\pi)<0.4$, $P_T>0.1$ GeV/c
2. $|dr|<0.5$ cm and $|dz|<2.0$ cm.
3. K_S^0 is selected by nisKsFinder package select good candidates.

For γ candidates

1.For $\pi^0 \to \gamma\gamma$
$E_\gamma > 25$ MeV in barrel, $E_\gamma > 50$ MeV in endcap.

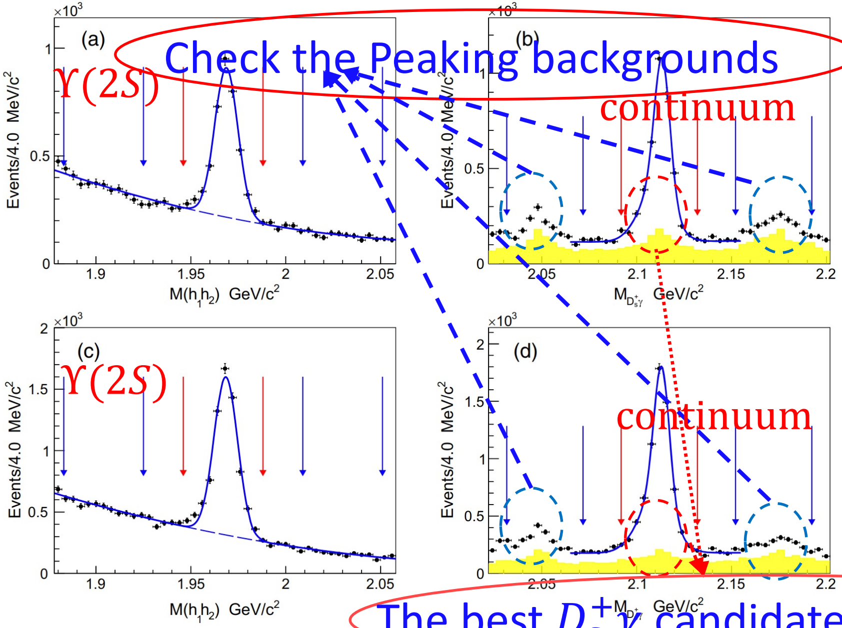
2. For $\eta(\to \gamma\gamma)$
$E_\gamma > 150$ MeV in barrel and endcap.

3.For γ_{targ} (decay from D_s^{*+})candidates
$E_\gamma > 50$ MeV in barrel, $E_\gamma > 100$ MeV in endcap.

For $D_s^{(*)+}$candidates

1.Vertex Fit and Mass Constraint for $D_s^{(*)+}$.
2. The best $D_s^+\gamma$ combination per a event with the best mass fit χ^2 to avoid multiple combinations.

$D_s^{(*)+}$ signal distributions



Check the Peaking backgrounds

$\Upsilon(2S)$

continuum

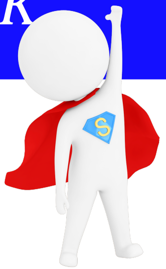
$\Upsilon(2S)$

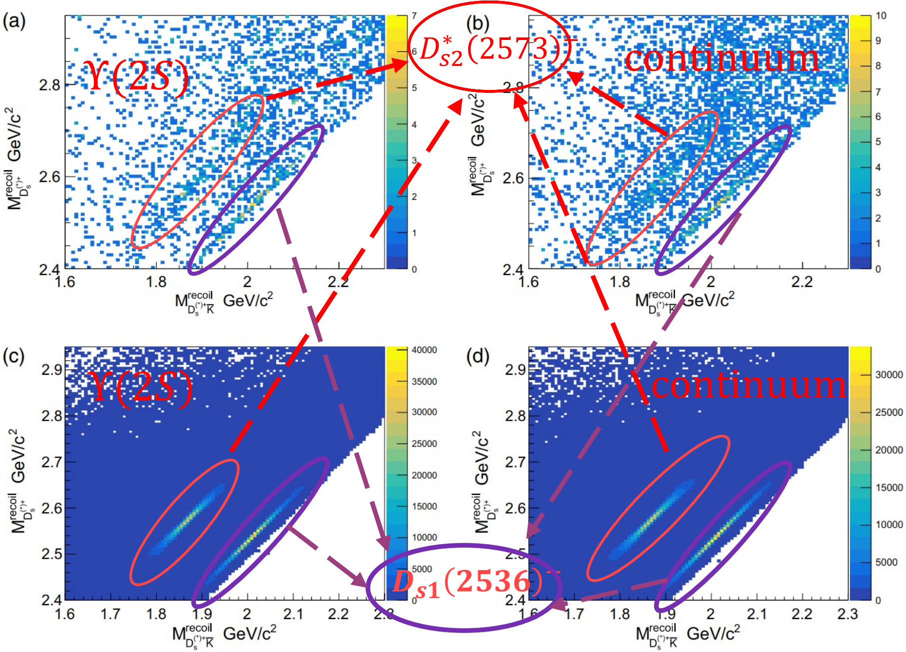
continuum

The best $D_s^+\gamma$ candidates combinations

- D_s^+ signal mass window is defined as $|M(h_1h_2) - m(D_s^+)| < 3\sigma_{D_s^+}$ (≈ 7 MeV/c^2).
- D_s^{*+} signal mass window is defined as $|M(D_s^+\gamma) - m(D_s^{*+})| < 3\sigma_{D_s^{*+}}$ (≈ 7 MeV/c^2).
- The yellow shade histogram is from D_s^+ sidebands

Distributions of $M^{recoil}_{D_s^{(*)+}}$ v.s. $M^{recoil}_{D_s^{(*)+}\overline{K}}$





There are clear bands in the distributions of data corresponding to the productions of the $D_{s1}(2536)^-$ and $D_{s2}^*(2573)^-$.