Bottomonium spectroscopy at Belle/Belle II

GDR-InF Annual Workshop 2022

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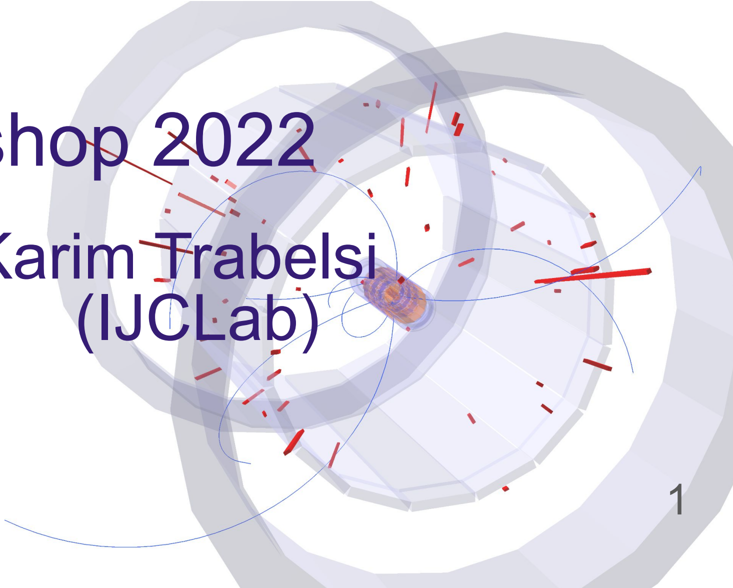
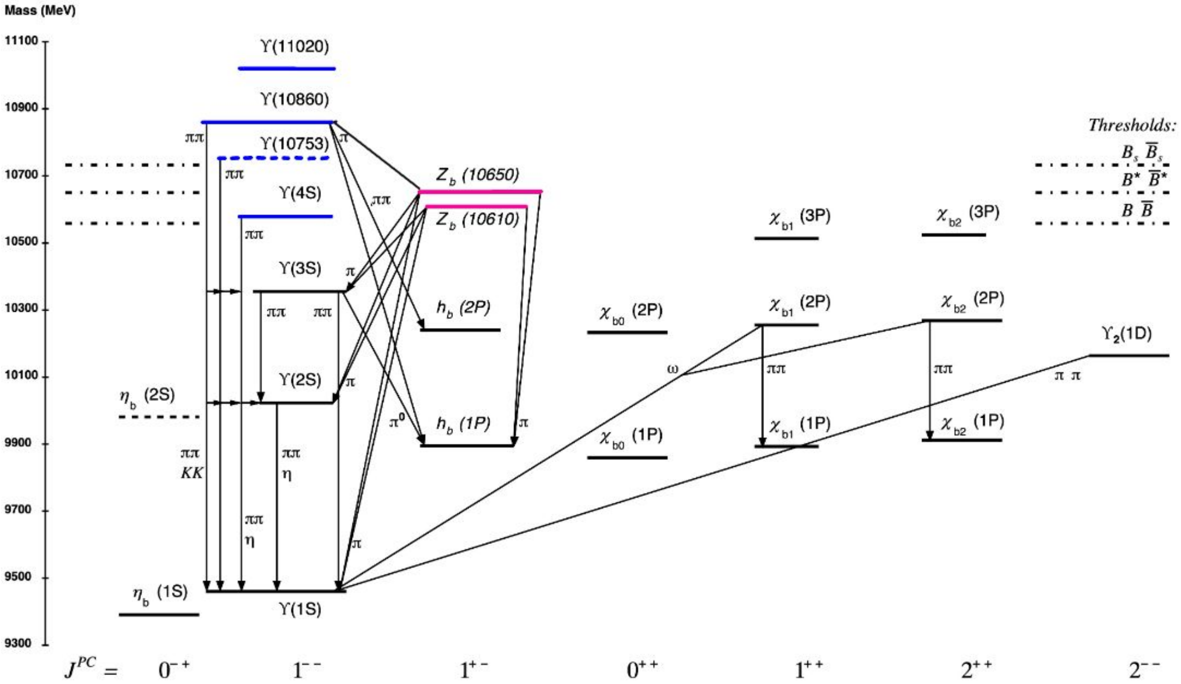
(IJCLab) (HSE) (IJCLab)



Bottomonium



Conventional bottomonium (pure bb states)

Bottomonium-like states (mixture of bb and BB)

Purely exotic states

non-relativistic system (v/c~0.06)

The spectroscopy is similar to a hydrogen atom and we use the same notation.

We have two type of states:

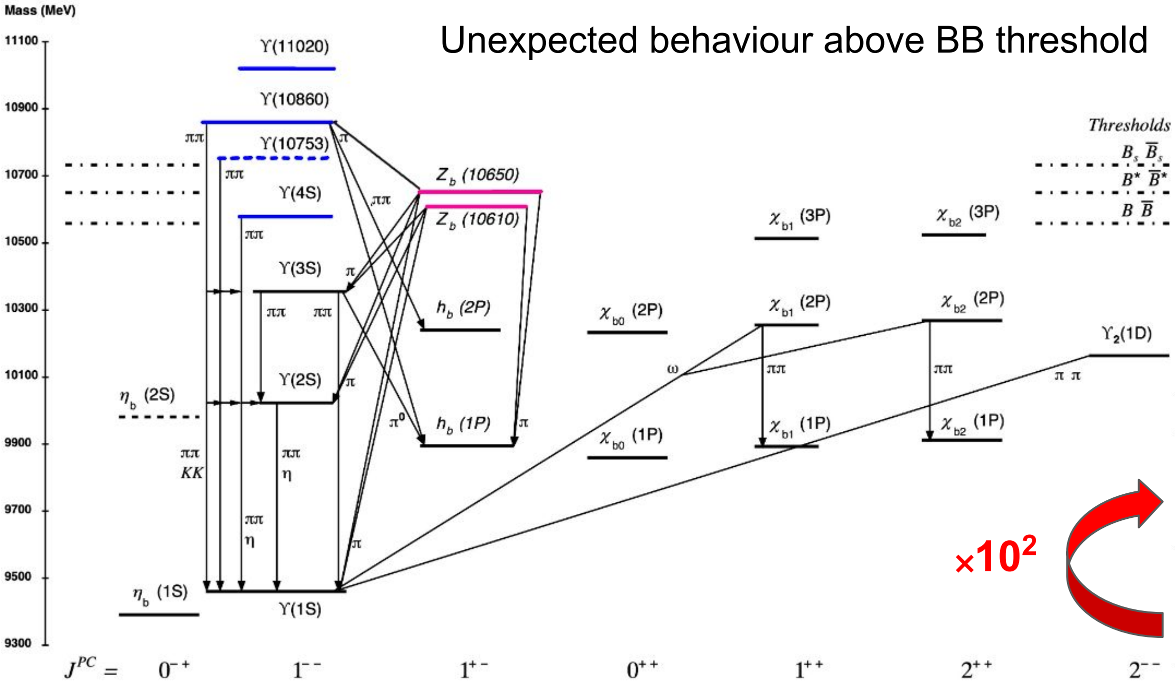
- Below BB threshold
- Above BB threshold

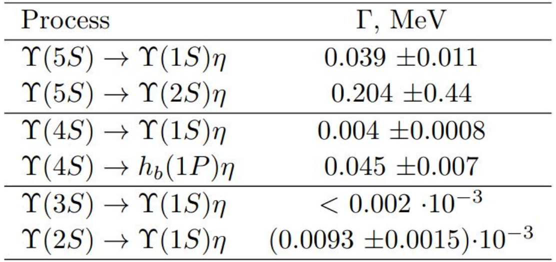
The states below BB mesons threshold are well described by the potential models.

Bottomonium

Mod. Phys. Lett. A 32, №04, 1750025

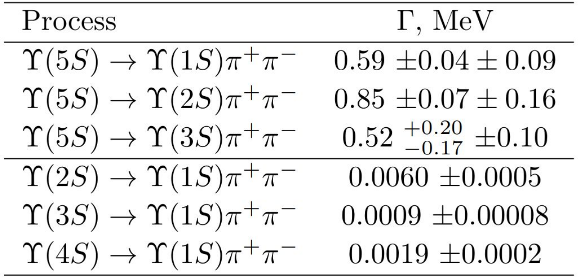
Unexpected behaviour above BB threshold





Process	Γ, MeV
$\Upsilon(5S) \to \Upsilon(1S)\eta$	0.039 ± 0.011
$\Upsilon(5S) \to \Upsilon(2S)\eta$	0.204 ± 0.44
$\Upsilon(4S) \to \Upsilon(1S)\eta$	0.004 ± 0.0008
$\Upsilon(4S) \to h_b(1P)\eta$	0.045 ± 0.007
$\Upsilon(3S) \to \Upsilon(1S)\eta$	$< 0.002 \cdot 10^{-3}$
$\Upsilon(2S) \to \Upsilon(1S)\eta$	$(0.0093 \pm 0.0015) \cdot 10^{-3}$

×10^2



Process	Γ, MeV
$\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-$	$0.59 \pm 0.04 \pm 0.09$
$\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$	$0.85 \pm 0.07 \pm 0.16$
$\Upsilon(5S) \to \Upsilon(3S)\pi^+\pi^-$	$0.52\ ^{+0.20}_{-0.17} \pm 0.10$
$\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$	0.0060 ± 0.0005
$\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$	0.0009 ± 0.00008
$\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$	0.0019 ± 0.0002

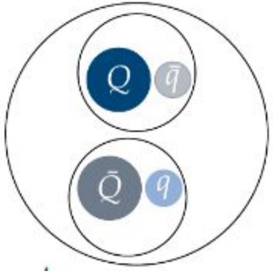
PRL 100, 112001 (2008)

Conventional bottomonium (pure bb states)
Bottomonium-like states (mixture of bb and BB)
Purely exotic states

Theoretical models

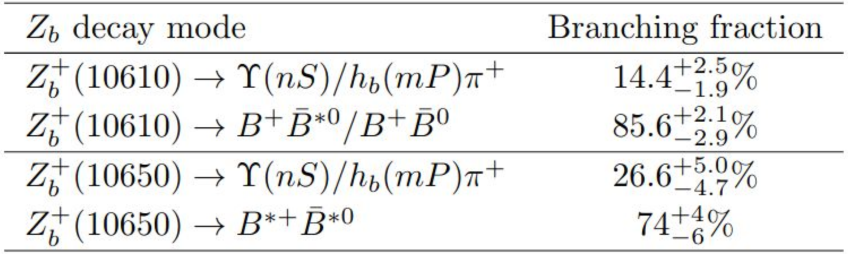
PhysRep, 873, 1-154

Hadronic molecule



Compound state of two hadrons. The most promising model.
The bottomonium-like states can be described as a mixture of pure bottomonium and a molecular component:

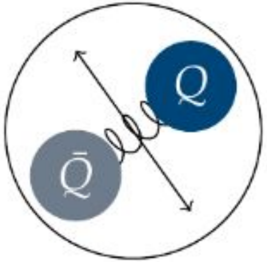
$$Y(4S, 5S) = C_1 \cdot |bb > + C_2 \cdot |B_{(s)}^{((*)*)} B_{(s)}^{((*)*)}>$$



Z_b decay mode	Branching fraction
$Z_b^+(10610) \rightarrow \Upsilon(nS)/h_b(mP)\pi^+$	$14.4^{+2.5}_{-1.9}\%$
$Z_b^+(10610) \rightarrow B^+\bar{B}^{*0}/B^+\bar{B}^0$	$85.6^{+2.1}_{-2.9}\%$
$Z_b^+(10650) \rightarrow \Upsilon(nS)/h_b(mP)\pi^+$	$26.6^{+5.0}_{-4.7}\%$
$Z_b^+(10650) \rightarrow B^{*+}\bar{B}^{*0}$	$74^{+4}_{-6}\%$

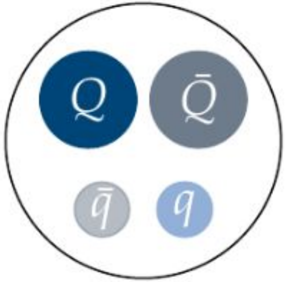
PRL, 108, 122001 (2012)

Hybrid



Conventional quark-antiquark mesons with excited gluon degrees of freedom.

Compact tetraquark

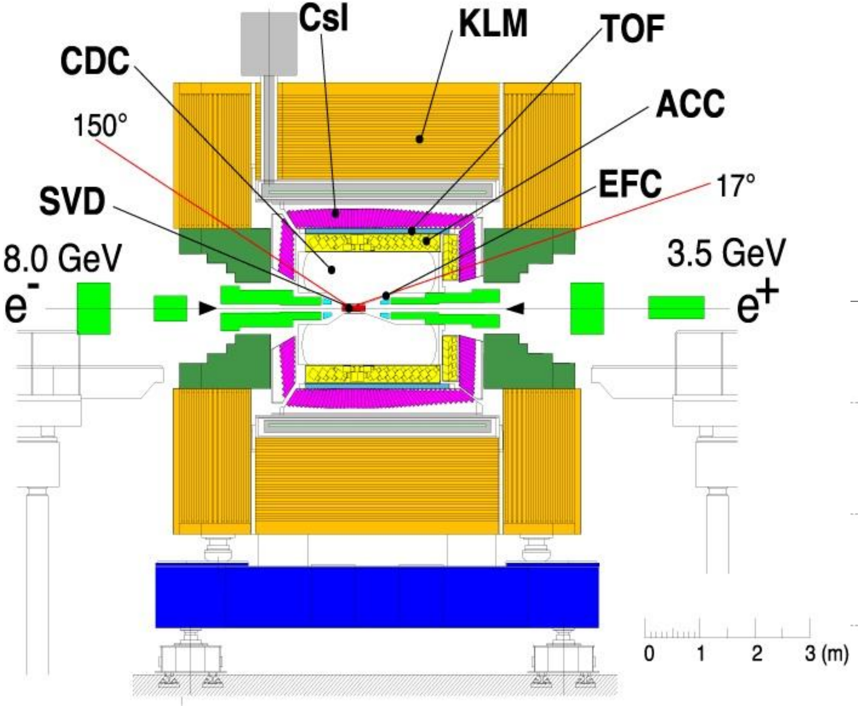


States containing four constituent quarks irrespective of their clustering.

Hadroquarkonium

Compact quarkonium core surrounded by an excited light-quark cloud.

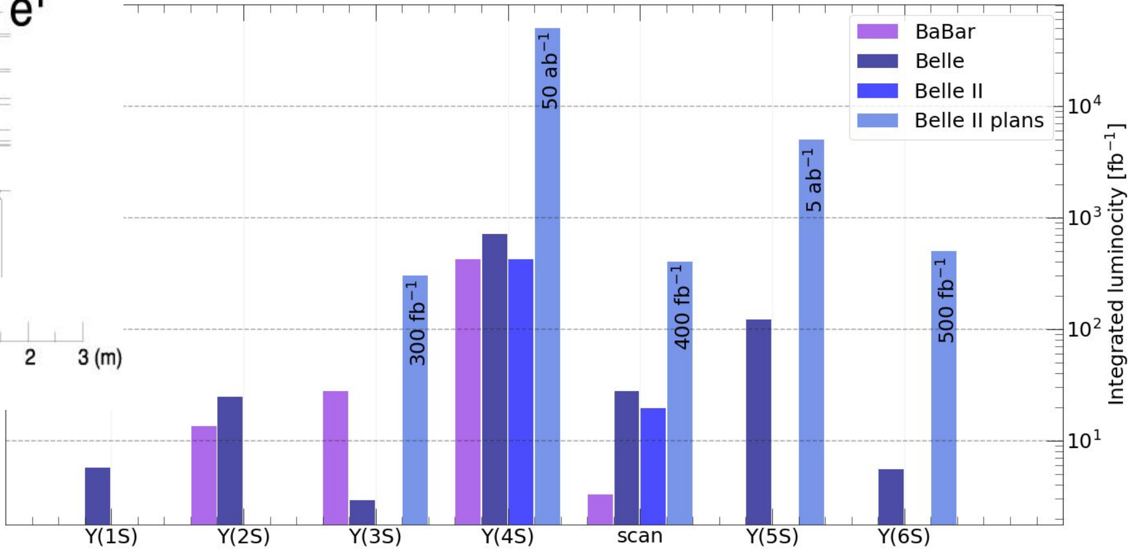
KEKB and Belle



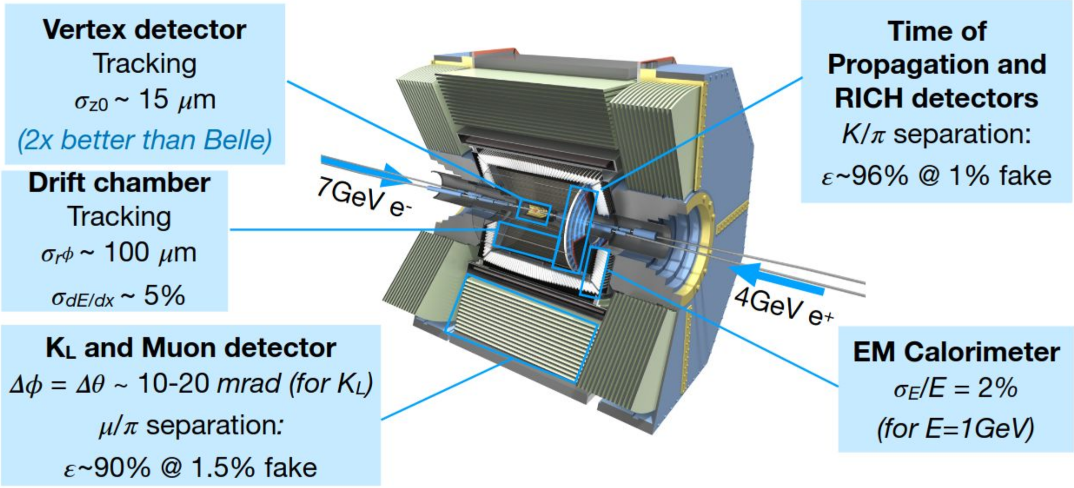
EPJ C 74, 3026 (2014)

Collected data:

- 121 fb^{-1} at ϒ(5S) ~7.11 × 10^6 B_sB_s
- 711 fb^{-1} at ϒ(4S) ~771 × 10^6 BB
- 3 fb^{-1} at ϒ(3S)
- 24 fb^{-1} at ϒ(2S)
- 6 fb^{-1} at ϒ(1S)
- 26 fb^{-1} scan above ϒ(4S)



SuperKEKB and Belle II



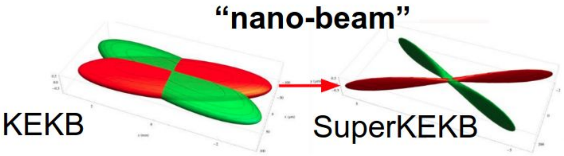
Vertex detector
Tracking
$\sigma_{z0} \sim 15\ \mu m$
(2x better than Belle)

Drift chamber
Tracking
$\sigma_{r\phi} \sim 100\ \mu m$
$\sigma_{dE/dx} \sim 5\%$

K_L and Muon detector
$\Delta\phi = \Delta\theta \sim 10\text{-}20$ *mrad (for K_L)*
μ/π separation:
ε~90% @ 1.5% fake

Time of Propagation and RICH detectors
K/π separation:
ε~96% @ 1% fake

EM Calorimeter
$\sigma_E/E = 2\%$
(for E=1GeV)

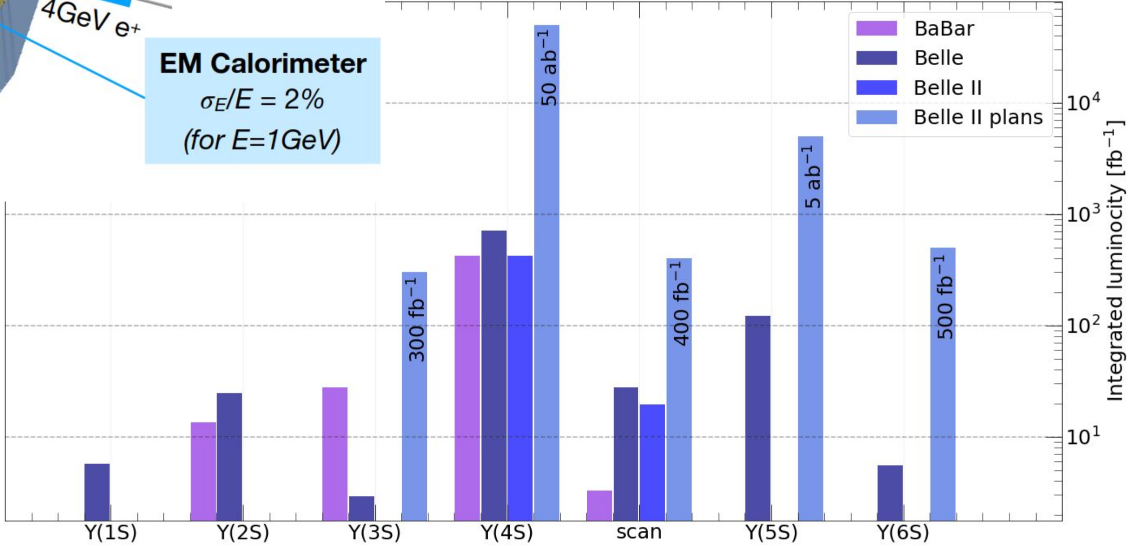


”Nano-beams” × current increase (x2)
↓
x40 instant luminosity increase.

Collected data:

- 424 fb^{-1} at ϒ(4S)
- 19 fb^{-1} scan above ϒ(4S)

Improved detector and software performance.
The main goal is to increase statistics!



[PTEP 2020 (2020) 2, 029201](#)

Bottomonium production

Prompt production

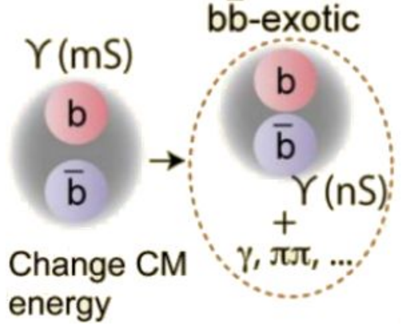
LHCb ALICE CMS ATLAS EXPERIMENT

Direct production in e^+e^- collisions

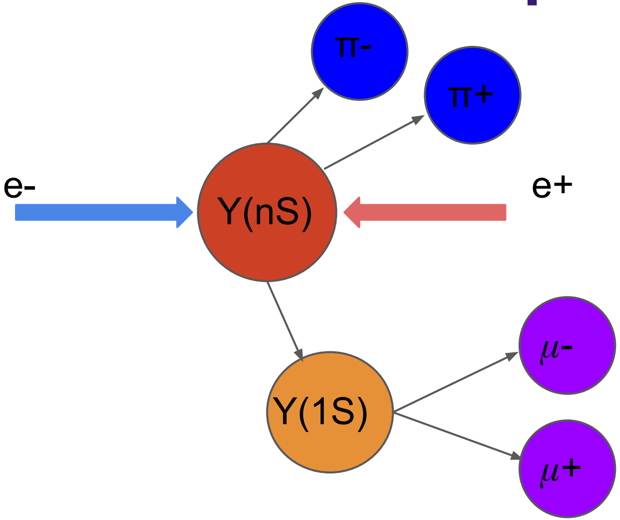
Belle II

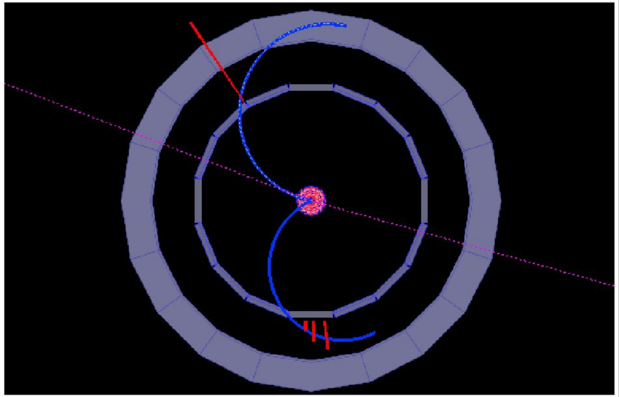
- Provides a unique clean environment (we have only bottomonium in the event);
- Precise measurement of the beam energy gives access to “unreconstructable” particles and decay modes;
- Allows tuning CM energy
- Only Υ(nS) states can be produced with quantum numbers of the photon 1^{--}
- Other quantum numbers can be obtained via hadronic or radiative transitions from 1^{--} states;

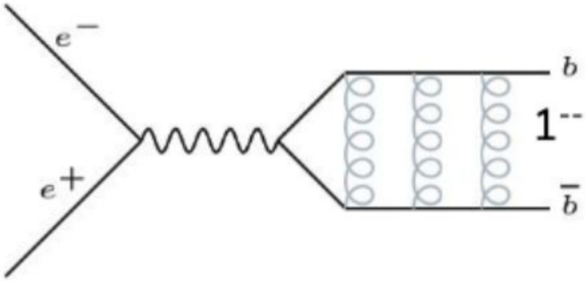
gives access to exotic states above Υ(4S)

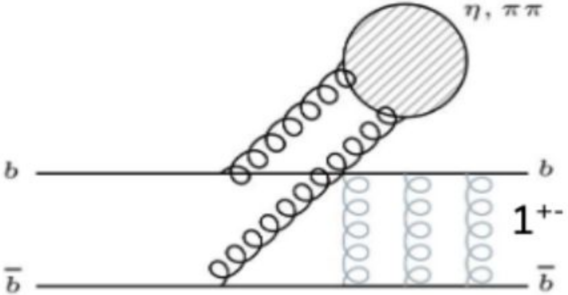


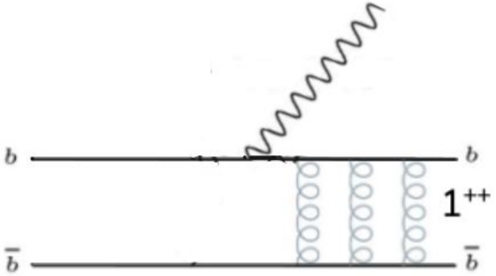
Bottomonium production











- Provides a unique clean environment (we have only bottomonium in the event);
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- Allows tuning CM energy
- Only Υ(nS) states can be produced with quantum numbers of the photon 1^{--}
- Other quantum numbers can be obtained via hadronic or radiative transitions from 1^{--} states;

Discovery of the Y(10753)

Y(10753) state was observed in the e+ e- →Y(nS) π+ π- (n = 1,2,3) cross section energy dependence.

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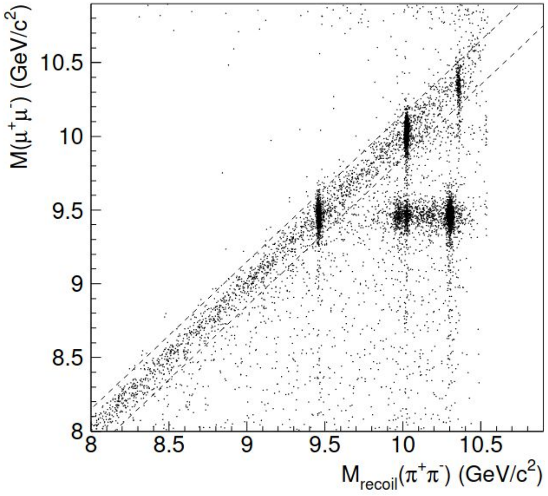
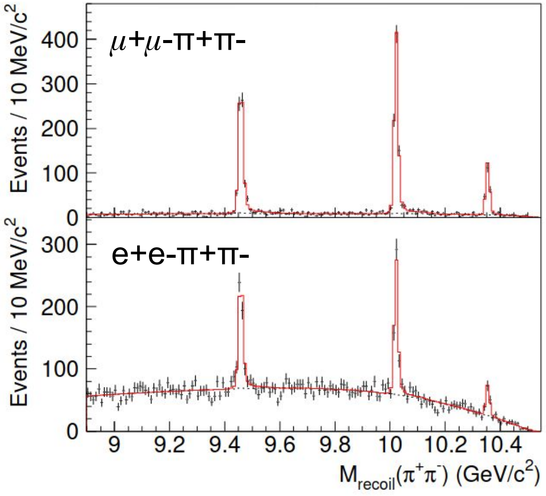
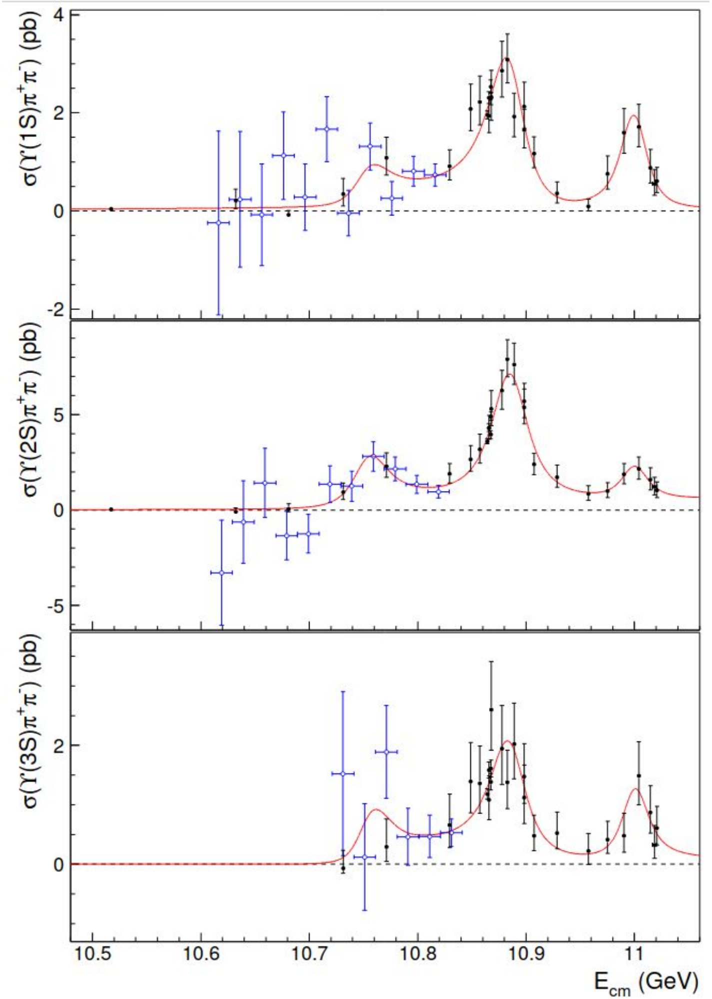
√s = 10.864 GeV   L = 47.647 fb^{-1}



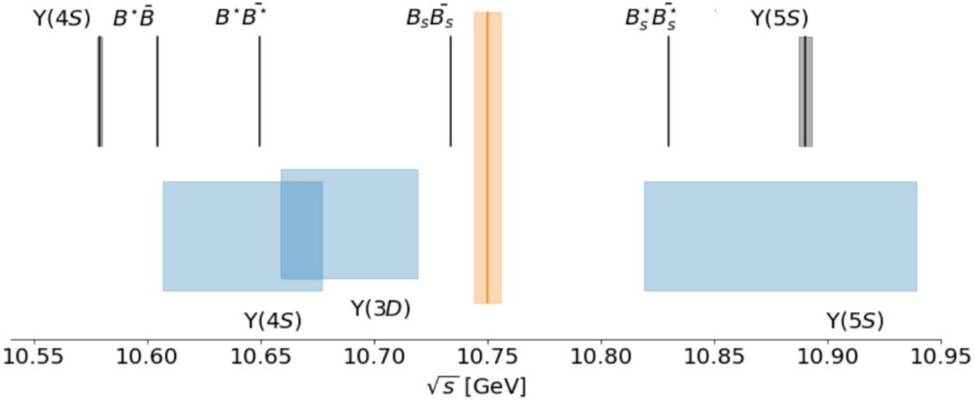




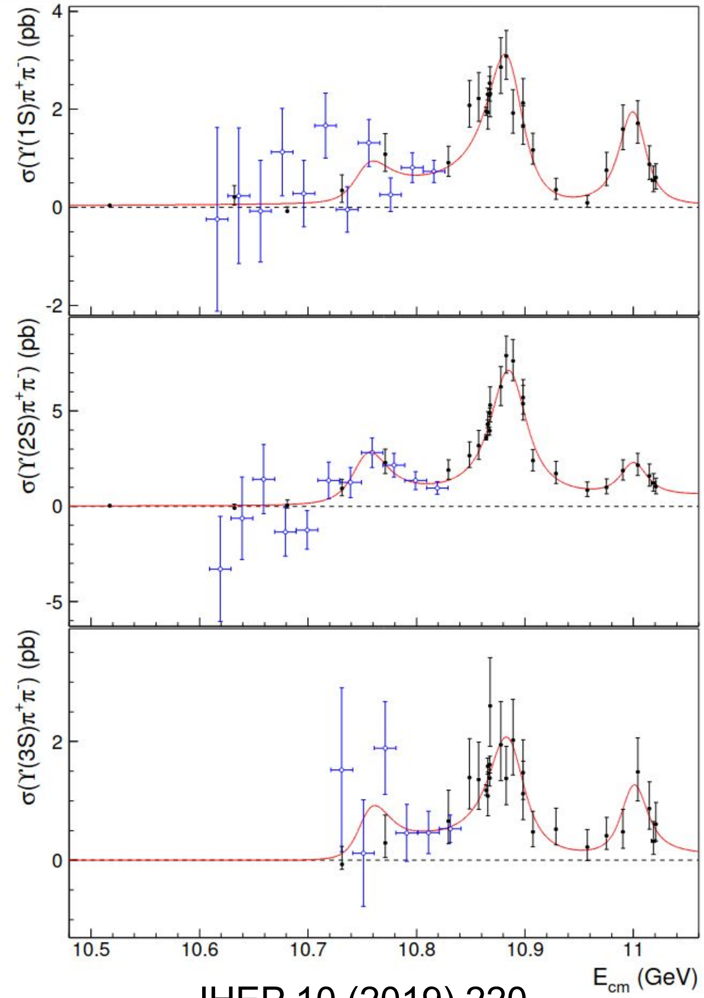
Discovery of the Y(10753)

Y(10753) was observed in the e+ e- →Y(nS) π+ π- (n = 1,2,3) cross section energy dependence.

- Molecular state? Does not coincide with a threshold.
- No obvious conventional bottomonium interpretation.



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



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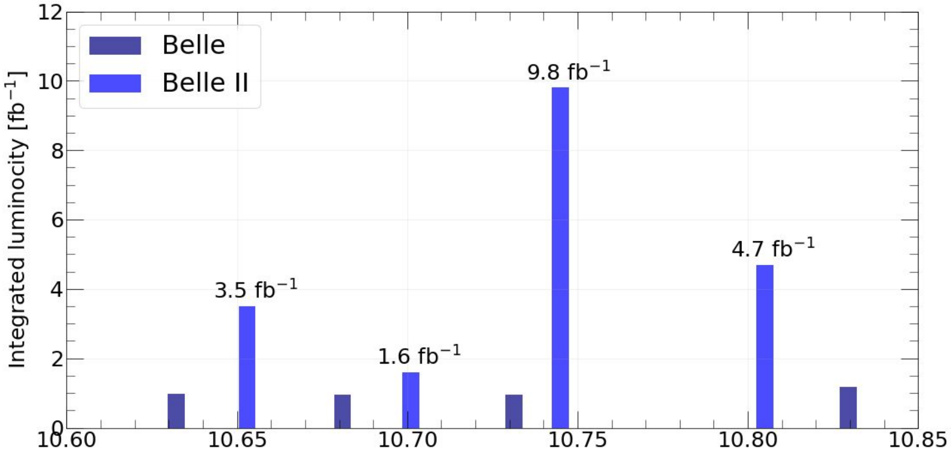
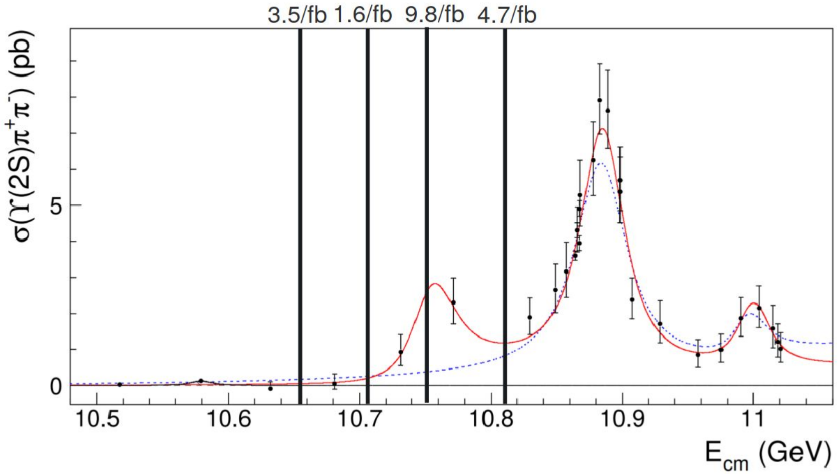
Belle II energy scan above Υ(4S)

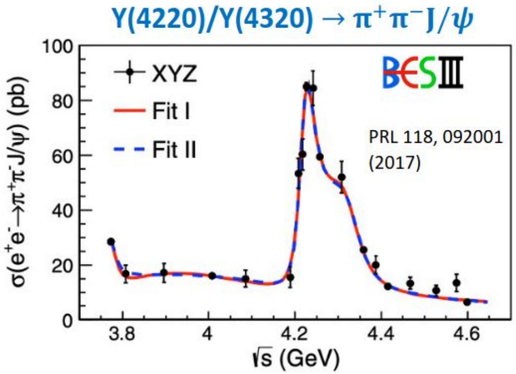
- Unique data provide an opportunity to study Υ(10753) in different final states and understand its nature.
- Scan above Υ(4S) has a good potential for early physics impact by Belle II even with small statistics.

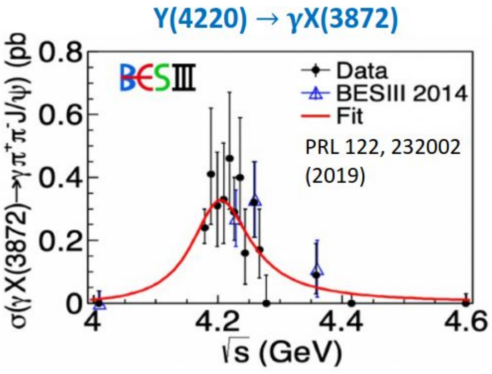


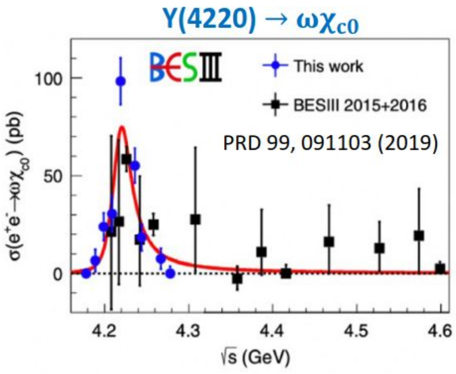


Observation of e+e→ $\omega\chi_{bJ}$(1P) at $\sqrt{s}$ = 10.745 GeV

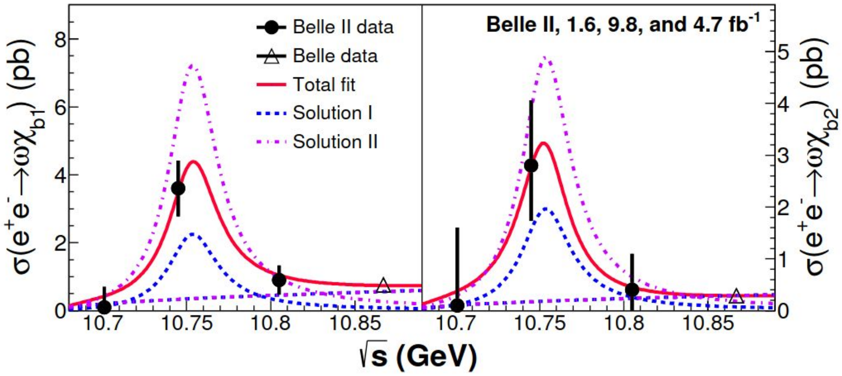
- Similar to Y(10753) structure named Y(4220) was observed in e+e- ⟶ J/Ψ π+π- cross section dependence by BES III (PRL 118, 092001 (2017)).
- BES III also observed the Y(4220) peak in γX(3872) and $\omega\chi_{c0}$ final states (PRL, 122, 232002 (2019), PRD 99, 091103(R) (2019)).
- $\omega\chi_{b1,2}$ production was found to be enhanced near Y(5S) (PRL 113, 142001 (2014)).
- We expect Y(10753) to decay into γ[Xb⟶ωY(1S)] and $\omega\chi_{bJ}$ final states.





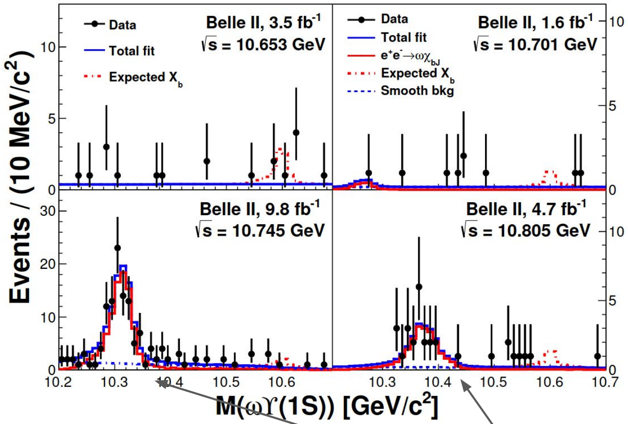


Observation of e+e→ $\omega\chi_{bJ}$(1P) at $\sqrt{s}$ = 10.745 GeV

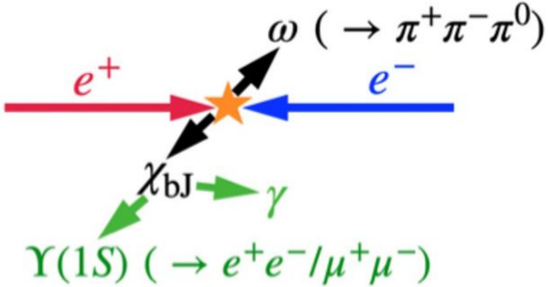


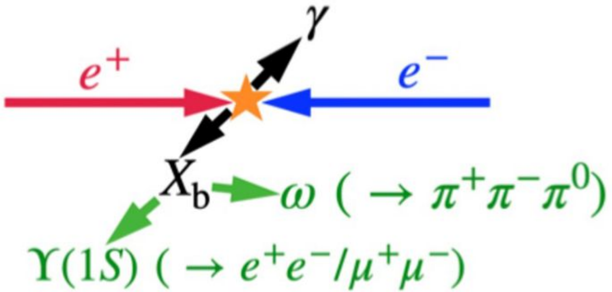
Strongly enhanced at 10.745 GeV.

$$\sigma(e^+e^- \to \omega\chi_{b1}) = 3.6 \pm 0.7 \pm 0.5 \text{ pb}$$
$$\sigma(e^+e^- \to \omega\chi_{b2}) = 2.8^{+1.2}_{-1.0} \pm 0.4 \text{ pb}$$



No evidence of X_b state. These are reflections of $\omega\chi_{bJ}$(1P).





arXiv:2208.13189

Search for e+e- $\rightarrow\eta_b(1S)\omega$ at $\sqrt{s}$ = 10.745 GeV

There is tetraquark interpretation (Chin Phys. C 43 123102 (2019)) of Y(10753) state, which predicts enhancement of the Y(10753) → $\eta_b(1S)\omega$ transition:

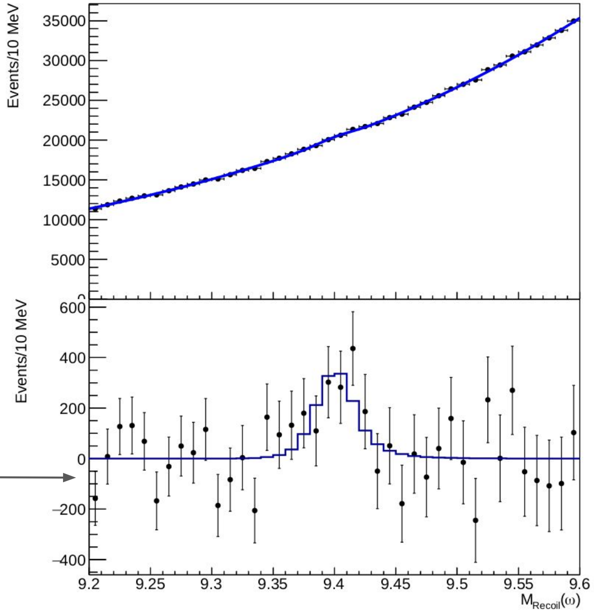
$$\frac{\Gamma(\eta_b\ \omega)}{\Gamma(\Upsilon\ \pi^+\pi^-)} \sim 30$$

We reconstruct only $\omega \rightarrow \pi^+\pi^-\pi^0$ and use the recoil mass to identify signal.

$$M_{\mathrm{recoil}}(\omega) = \sqrt{(\sqrt{s} - E^*_\omega)^2 - (p^*_\omega)^2}$$

Assuming the cross section of this transition is the same as $\omega\chi_{b1}(1P)$, we expect to have enough sensitivity to see the signal.

Belle II MC study

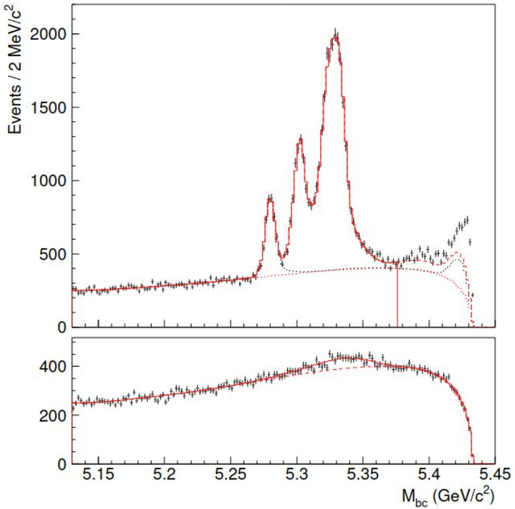


Also we search for e+e− → $\omega\chi_{bJ}(1P)$ (J = 0,1,2) which are found to be enhanced at the scan energies

BB decomposition with B-tagging

Study the energy dependence of the BB pairs production.

B-tagging can be used to measure the $B_{(s)}^{((*)*)}$ $B_{(s)}^{((*)*)}$ cross section energy dependence.
Yet another unique way to study bottomonium at Belle / Belle II.
A good probe for bottomonium models (especially the molecular model)
Improving FEI performance could affect bottomonium studies.



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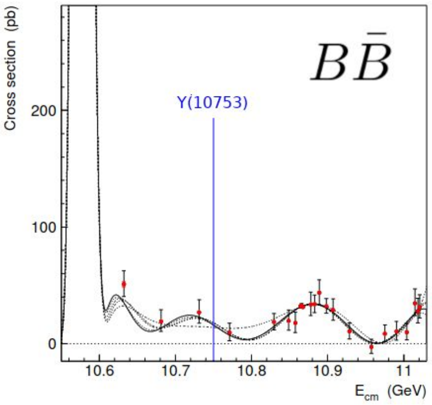
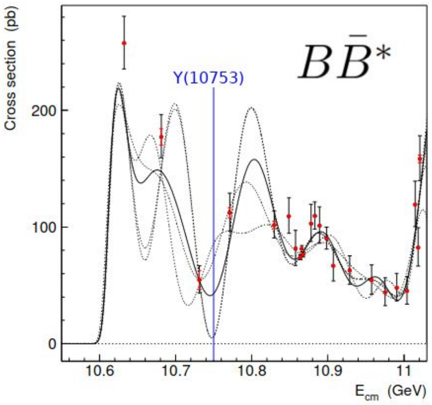
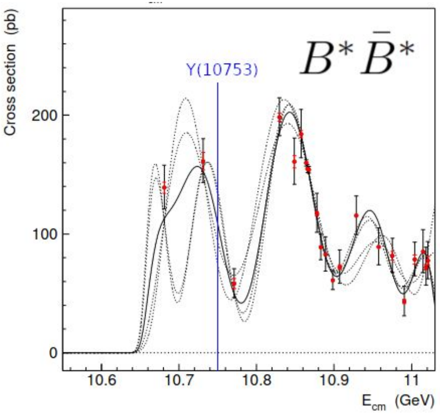
$$M_{\rm bc} = \sqrt{(E_{\rm cm}/2)^2 - p_B^2}$$







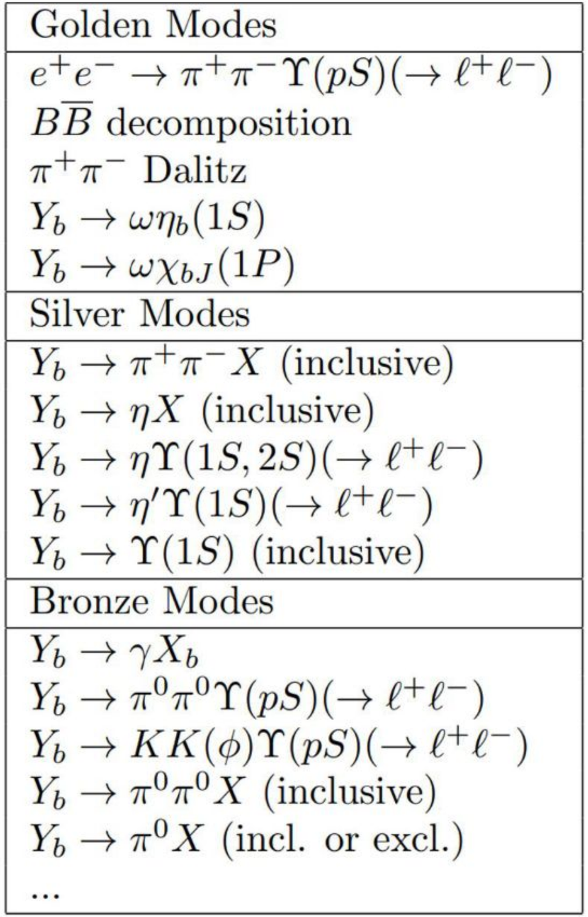
Belle II potential

Scan above Y(4S) gives an opportunity for a lot of unique studies:

- Y(10753) decays to different exclusive and inclusive final states. Study of its properties;
- Energy dependence of the various final state cross sections;
- BB decomposition and its cross section dependence on CM energy;

Wide range of long-term non-Y(4S) possibilities:

- Increase the above-Y(4S) scan statistics;
- Y(6S) region study with high statistics after accelerator upgrade;
- LFV / LFU / spectroscopy with Y(2S,3S) decays;



Golden Modes
$e^+e^- \to \pi^+\pi^-\Upsilon(pS)(\to \ell^+\ell^-)$
$B\overline{B}$ decomposition
$\pi^+\pi^-$ Dalitz
$Y_b \to \omega\eta_b(1S)$
$Y_b \to \omega\chi_{bJ}(1P)$
Silver Modes
$Y_b \to \pi^+\pi^- X$ (inclusive)
$Y_b \to \eta X$ (inclusive)
$Y_b \to \eta\Upsilon(1S, 2S)(\to \ell^+\ell^-)$
$Y_b \to \eta'\Upsilon(1S)(\to \ell^+\ell^-)$
$Y_b \to \Upsilon(1S)$ (inclusive)
Bronze Modes
$Y_b \to \gamma X_b$
$Y_b \to \pi^0\pi^0\Upsilon(pS)(\to \ell^+\ell^-)$
$Y_b \to KK(\phi)\Upsilon(pS)(\to \ell^+\ell^-)$
$Y_b \to \pi^0\pi^0 X$ (inclusive)
$Y_b \to \pi^0 X$ (incl. or excl.)
...

Summary

Belle and Belle II are unique devices for bottomonium studies:

- Tunable CM energy;
- Production in e+ e- collisions provides a low background environment;
- Precisely measured CM energy allows the studying of inclusive modes using the missing mass technique.

First results with above-Υ(4S) scan data:

- Successful runs above Υ(4S);
- First observation of Υ(10753) $\rightarrow \chi_{bJ}(1P)\omega$;
- No evidence for X_b (bottomonium analog of X(3872)) at $\sqrt{s}$ = 10.745 GeV;

Thank you for attention!

Backup

Backup

LFV search in bottomonium decays

JHEP 05 2022, 095

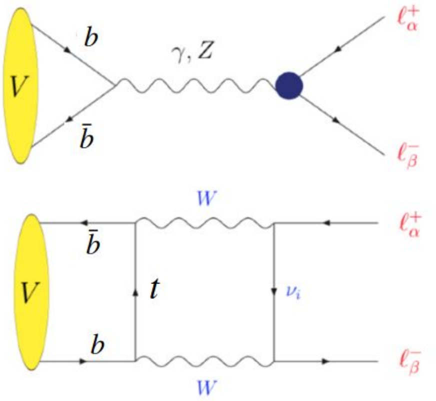
- Y(1S) → $l^{\pm}$ $l^{\pm`}$: Two-body vector meson CLFV process → probing the vector and tensor operators of the effective Lagrangian for NP;

- Y(1S) → $\gamma l^{\pm}$ $l^{\pm`}$ First study of three-body radiative CLFV (complementary access to NP);

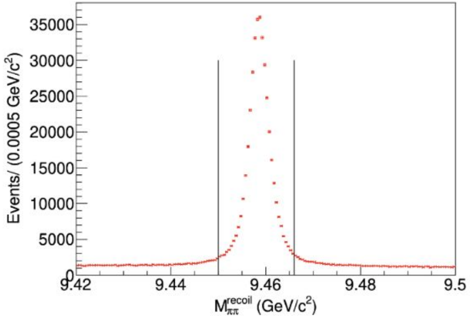
PRD 94, 074023 (2016) PRD 91, 113013 (2015)

- Y(2S) → Y(1S)ππ is prefered over Y(1S)
  PROS
  - higher trigger efficiency (two more tracks in the event);
  - easier QED background suppression;
  - ππ recoil mass has a better resolution;
  CONS
  - Smaller statistics (26M vs 119M) due to BF[Y(1S) → Y(1S)ππ] ~ 18%;

- Background is studied on off-resonance data at 10.52 GeV;



$\pi\pi$ recoil consistent with $\Upsilon(1S)$ mass



$$M_{\pi\pi}^{\mathrm{recoil}} = \sqrt{(E_{e^+e^-} - E_{\pi\pi})^2 - |\vec{p}_{\pi\pi}|^2}$$

$$M_{\pi\pi}^{\mathrm{recoil}} \in (9.45, 9.466)\ \mathrm{GeV}/c^2$$

LFV search in bottomonium decays

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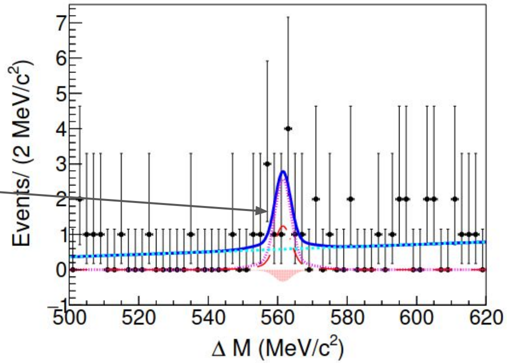
eμ case

LFC decays are used for calibration

The b.r.'s are compared to world average

Expected ~9 events from e/μ mis-ID

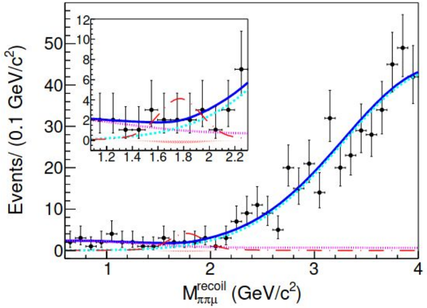
ΔM = M(Y(2S)) - M(Y(1S)) = M(ππ(γ)ll) ~ 560 MeV

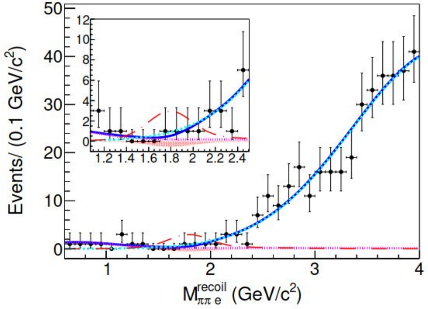


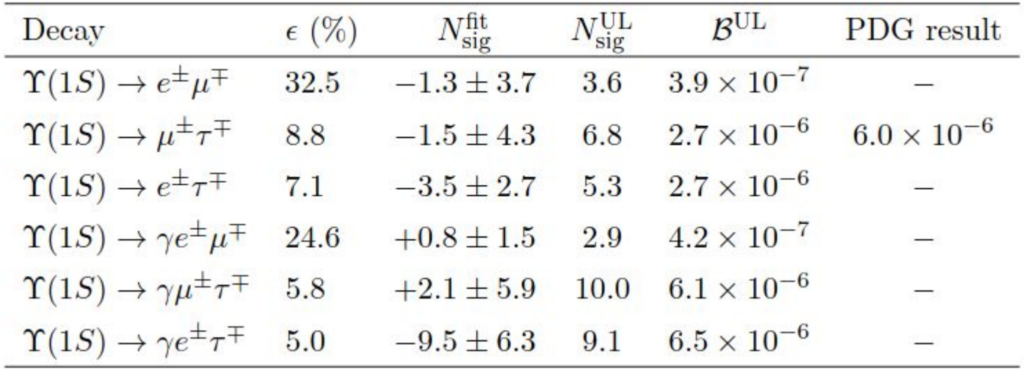
eτ case

Background from $\tau \rightarrow$ e(μ)ν(3πν) decays

Expected peak at τ mass







Decay	ϵ (%)	$N_{\text{sig}}^{\text{fit}}$	$N_{\text{sig}}^{\text{UL}}$	$\mathcal{B}^{\text{UL}}$	PDG result
$\Upsilon(1S) \rightarrow e^{\pm}\mu^{\mp}$	32.5	-1.3 ± 3.7	3.6	3.9×10^{-7}	–
$\Upsilon(1S) \rightarrow \mu^{\pm}\tau^{\mp}$	8.8	-1.5 ± 4.3	6.8	2.7×10^{-6}	6.0×10^{-6}
$\Upsilon(1S) \rightarrow e^{\pm}\tau^{\mp}$	7.1	-3.5 ± 2.7	5.3	2.7×10^{-6}	–
$\Upsilon(1S) \rightarrow \gamma e^{\pm}\mu^{\mp}$	24.6	$+0.8 \pm 1.5$	2.9	4.2×10^{-7}	–
$\Upsilon(1S) \rightarrow \gamma\mu^{\pm}\tau^{\mp}$	5.8	$+2.1 \pm 5.9$	10.0	6.1×10^{-6}	–
$\Upsilon(1S) \rightarrow \gamma e^{\pm}\tau^{\mp}$	5.0	-9.5 ± 6.3	9.1	6.5×10^{-6}	–