Early Y(nS) running at Belle 2

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Outline

1. Belle II & SuperKEKB in phase II
2. Recent results on Bottomonium-like states
3. Phase II considerations
4. Quarkonium(like) in Phase II
5. Dark sector and exotics
6. Quarkonium(like) beyond Phase II

*** I consider early running to primarily focus on the 2018 partial detector run, phase II.**
I will briefly mention phase III topics.

Belle II & SuperKEKB

So when do we start Belle II ?

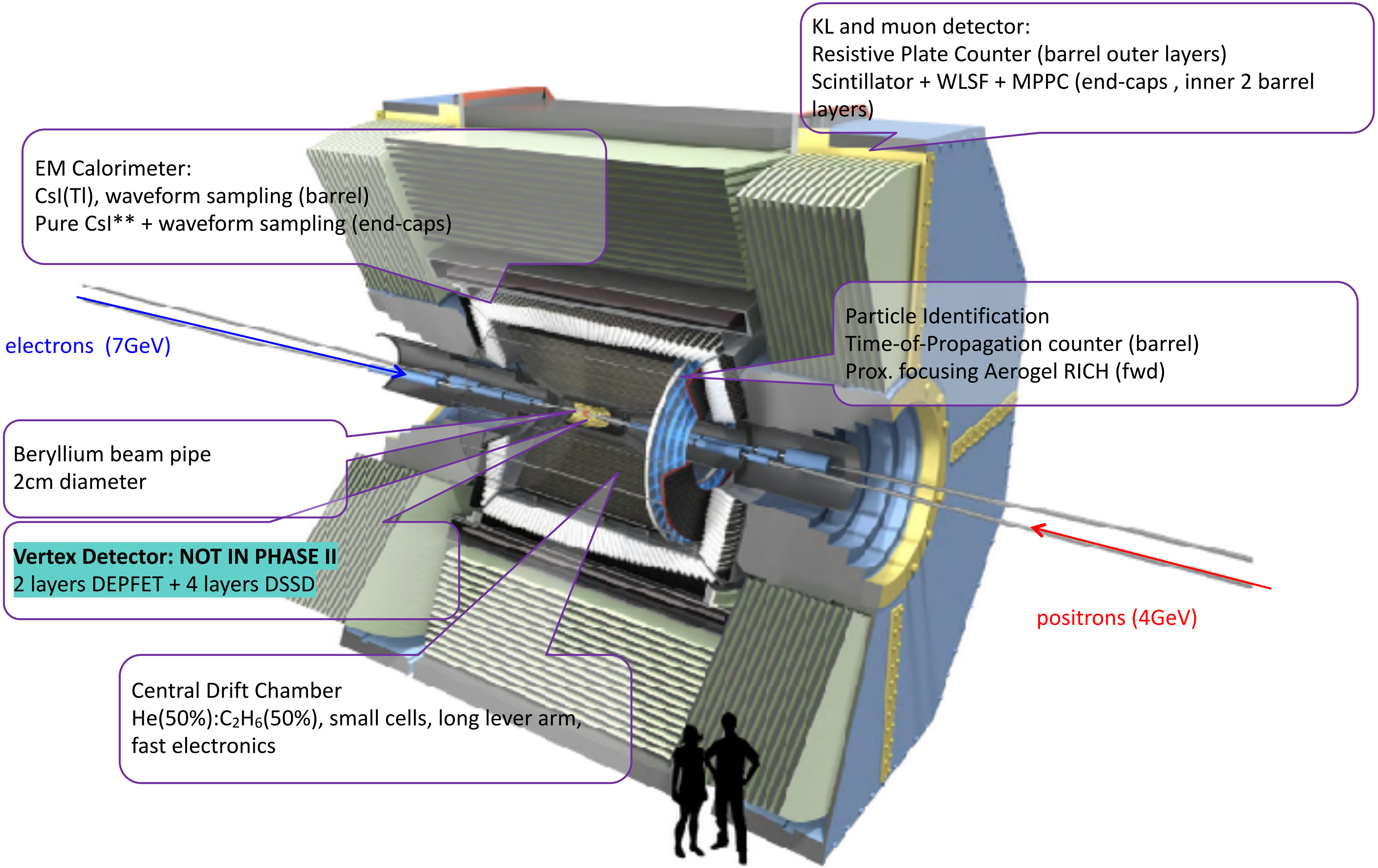
BEAST PHASE I:
Feb-June 2016
(Belle II roll-in in March 2017).

PHASE II Operation: Starts in ~Jan 2018
[Begin with damping ring commissioning; First collisions; *limited physics without vertex detectors*]

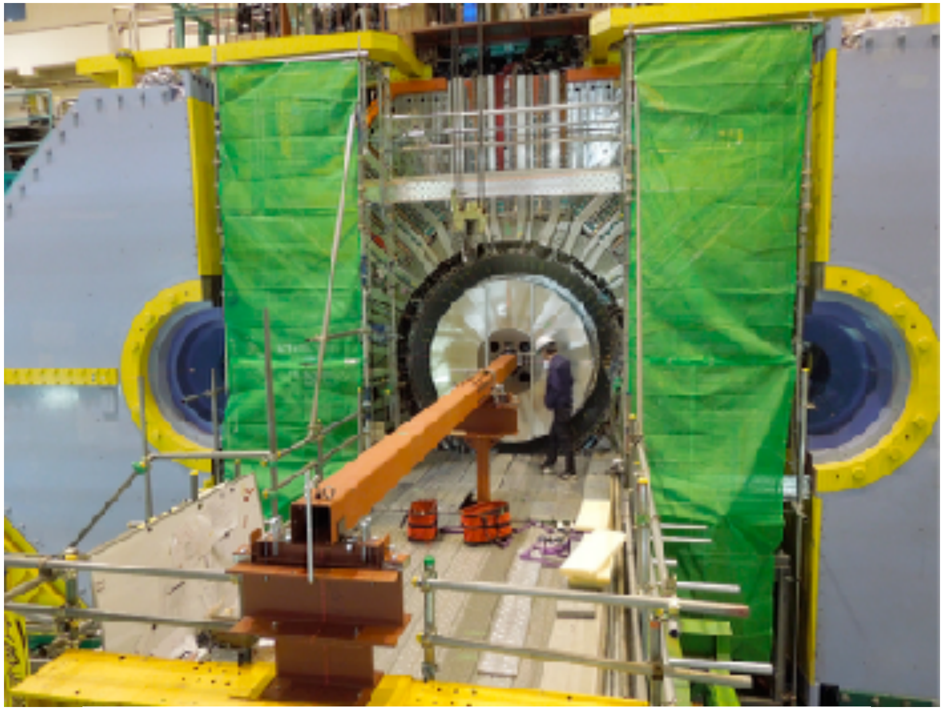
Phase III: Belle II Physics Running:
late 2018 [vertex detectors in]

QCSL at the IP, Aug 2016
QCSR will be at KEK, Dec 2016

Belle II Detector

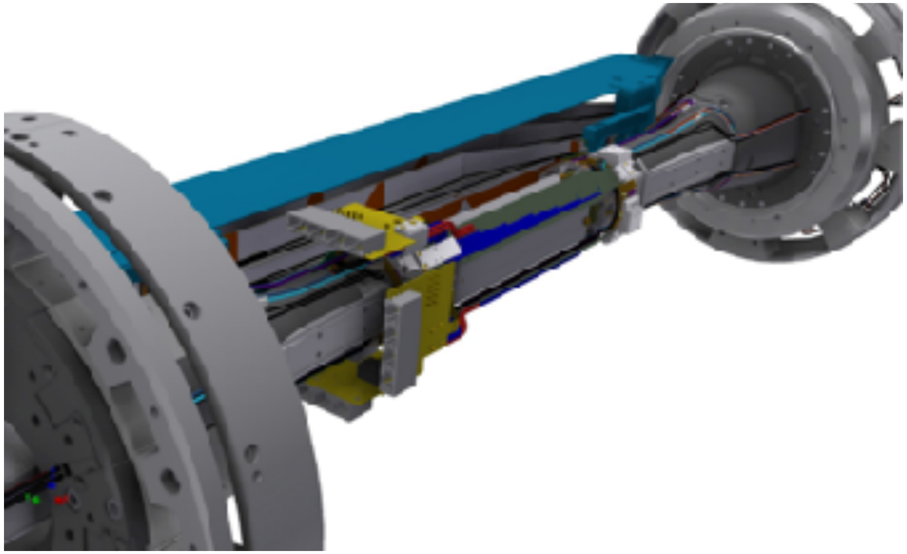


Belle II in Phase II

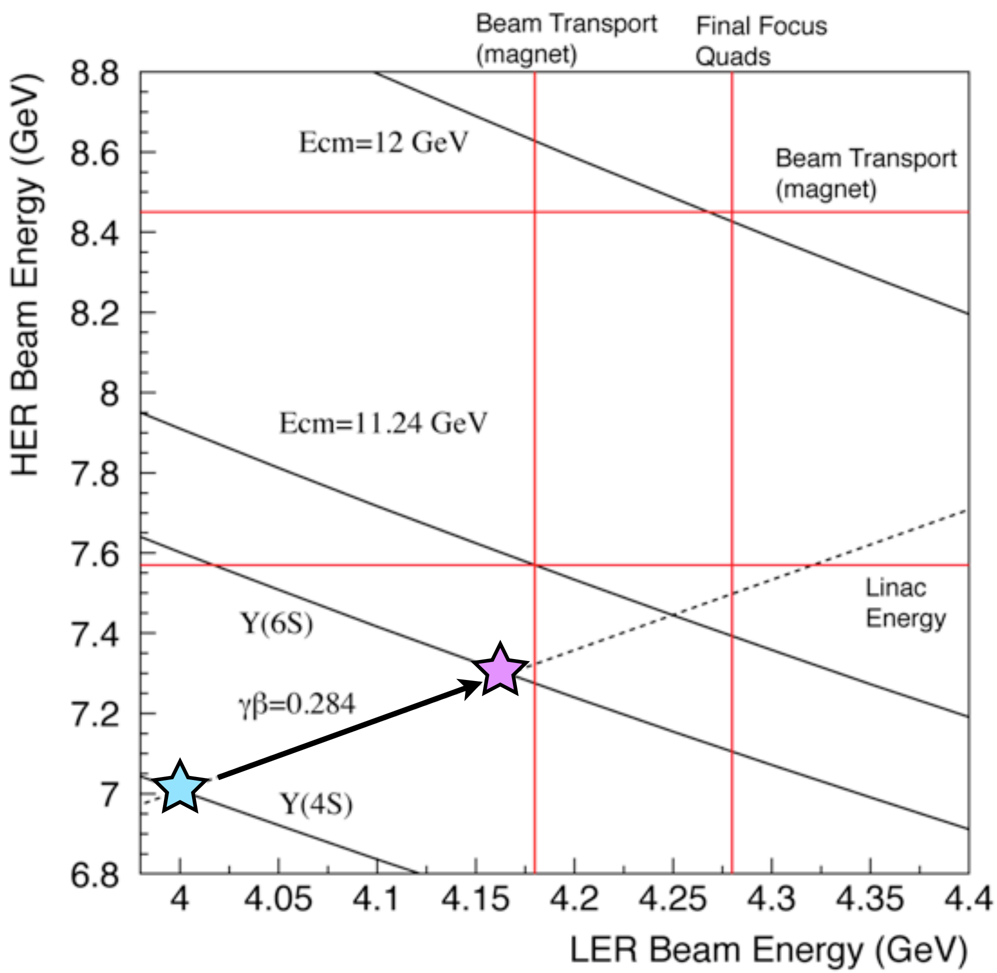


Oct 2016: CDC (Central Drift Chamber)

BEAST silicon detector setup
(used for beam background study)



Accelerator ECM reach



Start from Υ(4S) operation at Phase-2

10 fb^{-1} at Υ(6S) is requested by Belle II.

~20 days

(80 % efficiency with $8x10^{33}$)

↕

5 months operation at Phase-2

E_{CM} max with constant γβ=0.284 is ~ 11.1 GeV

Thresholds of narrow S & P wave states

Particles	Threshold, GeV/c^2
$B^{(*)}\bar{B}^{**}$	11.00 – 11.07
$B_s^{(*)}\bar{B}_s^{**}$	11.13 – 11.26
$\Lambda_b\,\bar{\Lambda}_b$	11.24
$B^{**}\bar{B}^{**}$	11.44 – 11.49
$B_s^{**}\bar{B}_s^{**}$	11.48 – 11.68
$\Lambda_b\,\bar{\Lambda}_b^{**}$	11.53 – 11.54
$\Sigma_b^{(*)}\,\bar{\Sigma}_b^{(*)}$	11.62 – 11.67
$\Lambda_b^{**}\,\bar{\Lambda}_b^{**}$	11.82 – 11.84

Accelerator Conditions

fundamental tuning
QCS, collision device check — 1 month

↓

beta squeezing: 2.2 mm

↓

increasing beam current
with keeping L_{sp} — 3 months

↓ tentative goal

$L = 10^{34}$ $cm^{-2}s^{-1}$ at Υ(4S)
L tuning with physics run

Plan A

Further beta squeezing
with physics run — 1 month

Plan B

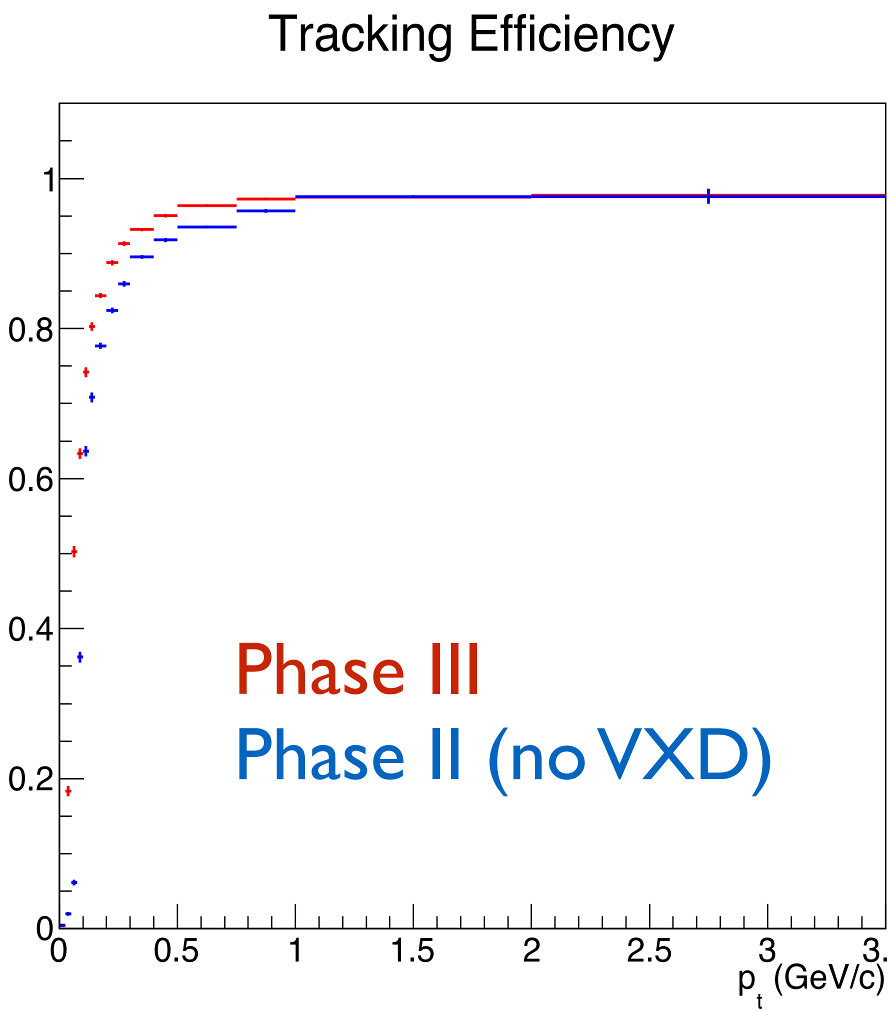
Υ(6S) for 10 fb^{-1} *
with physics run — 1 month

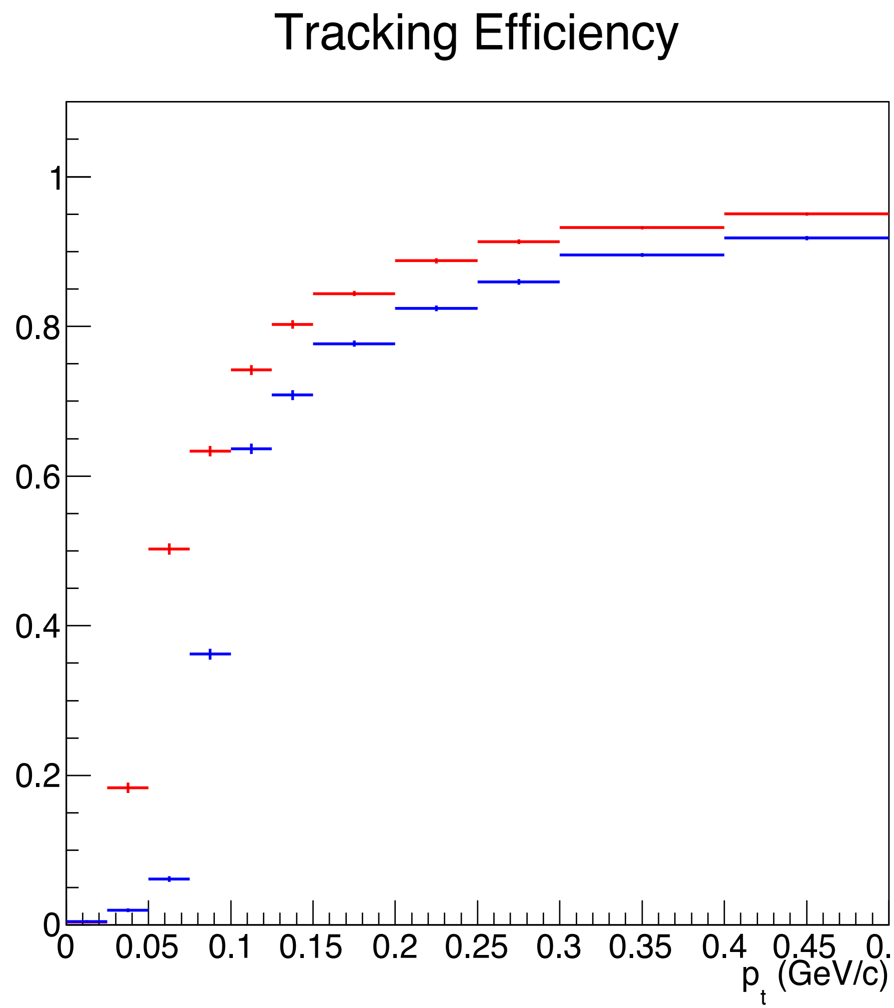
*We hope for 20-30 fb^{-1}

Risks:
(1) lack of QCS corrector margin
(2) degradation of optics; quit different from Υ(4S)
(3) lack of linac energy due to trouble

Track Reconstruction

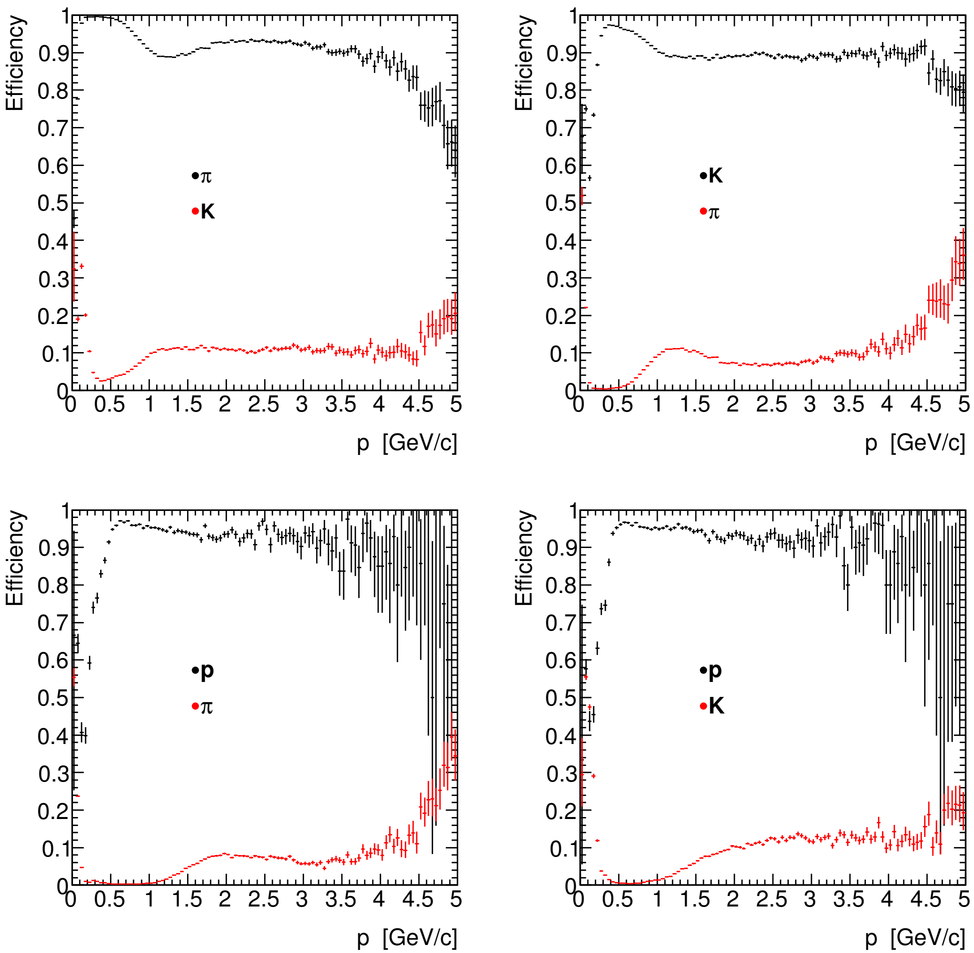
- CDC inner radius = , B-field = 1.5 T



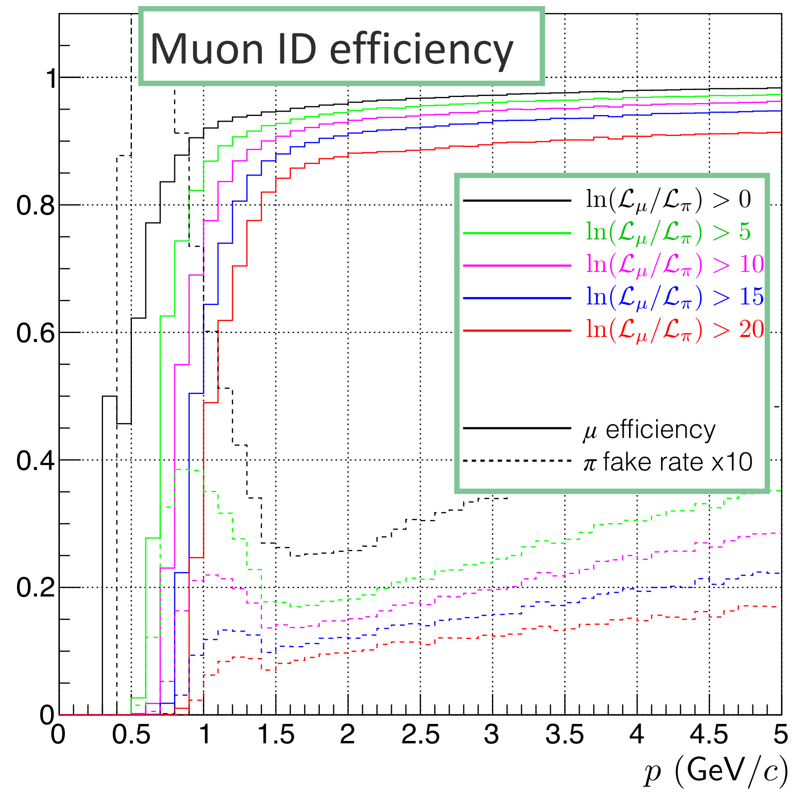


Particle Identification

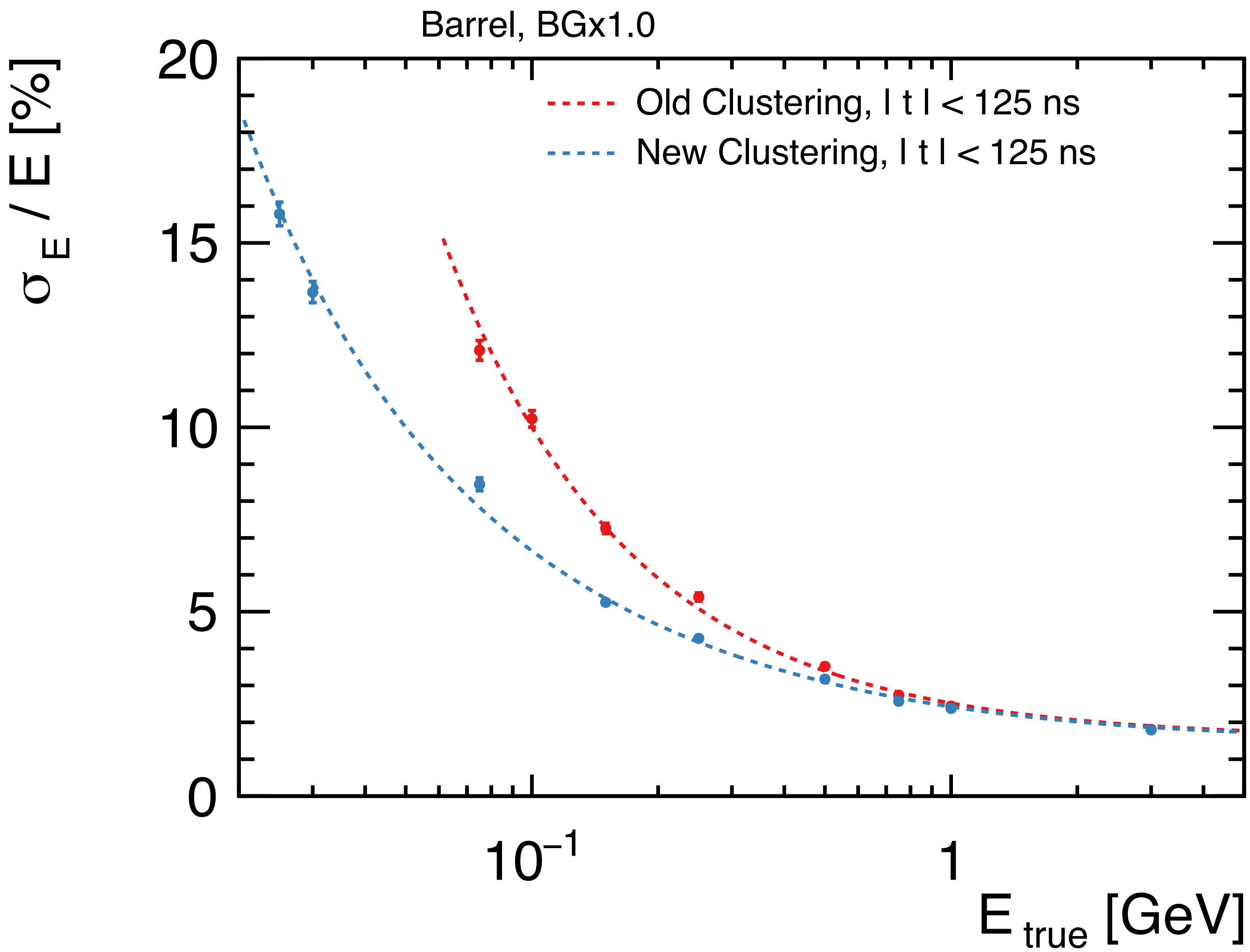
(TOP, ARICH, dE/dx[CDC])



(TOP, ARICH, dE/dx[CDC], KLM)



Neutral reconstruction



Production & Cross Sections

- New L1 menu under evaluation. HLT output estimated to be ~10 nb (expected from Belle)
- 5.5 nb hadronic + τ pairs, 4.5 nb leptonic (triggered and prescaled)

Physics process	Cross section [nb]	Cuts	Reference	HLT eff., Output
$\Upsilon(4S)$	1.05 ± 0.10	-	[10]	99.7%, 1.05 nb
$u\bar{u}(\gamma)$	1.61	-	KKMC	
$d\bar{d}(\gamma)$	0.40	-	KKMC	
$s\bar{s}(\gamma)$	0.38	-	KKMC	
$c\bar{c}(\gamma)$	1.30	-	KKMC	99%, 3.7 nb (total $q\bar{q}$)
$e^+e^-(\gamma)$	300 ± 3 (MC stat.)	$10° < \theta^*_{e's} < 170°$, $E^*_{e's} > 0.15$ GeV	BABAYAGA.NLO	
$e^+e^-(\gamma)$	74.4	e's (p >0.5GeV) in ECL	-	2.1 (total)
$\gamma\gamma(\gamma)$	4.99 ± 0.05 (MC stat.)	$10° < \theta^*_{\gamma's} < 170°$, $E^*_{\gamma's} > 0.15$ GeV	BABAYAGA.NLO	0.1 nb (total)
$\gamma\gamma(\gamma)$	3.30	γ's (p >0.5GeV) in ECL	-	
$\mu^+\mu^-(\gamma)$	1.148	-	KKMC	
$\mu^+\mu^-(\gamma)$	0.831	μ's (p >0.5GeV) in CDC	-	
$\mu^+\mu^-\gamma(\gamma)$	0.242	μ's (p >0.5GeV) in CDC, ≥ 1 γ (E_γ >0.5GeV) in ECL	-	0.6 nb (total)
$\tau^+\tau^-(\gamma)$	0.919	-	KKMC	85.2 %, 0.8 nb
$\nu\bar{\nu}(\gamma)$	0.25×10^{-3}	-	-	
$e^+e^-e^+e^-$	39.7 ± 0.1 (MC stat.)	$W_{\ell\ell} > 0.5$GeV	AAFH	
$e^+e^-e^+e^-$	1.1	≥ 2 tracks (p >0.5 GeV) in CDC	-	1.5 nb (total)
$e^+e^-\mu^+\mu^-$	18.9 ± 0.1 (MC stat.)	$W_{\ell\ell} > 0.5$GeV	AAFH	
$e^+e^-\mu^+\mu^-$	1.0	≥ 2 tracks (p >0.5 GeV) in CDC	-	1.6 nb (total)

TABLE I: Total production cross section from various physics processes from collisions at $\sqrt{s} = 10.573$ GeV to be used for MC normalization.

Trigger: More flexible, improved access to low multiplicity channels

- Challenge
  - Total physics event rate ~10kHz @$8x10^{35}$ $cm^{-2}s^{-1}$
  - High beam-induced backgrounds
    - Touschek scattering proportional to the inverse of beam size
    - One order higher than Belle
- Physics
  - >99.9% efficient for B and D physics
  - Low multiplicity processes challenge the trigger due to substantial QED background
    - Precision electroweak tests of ee and μμ
    - LFV and leptonic τ decay
    - Precision ISR for g-2: ππ/KK/pp/... and one photon
    - Searches for Dark Photons and Light Higgs
- Scheme: Hardware trigger + Software trigger
  - Level 1 (L1): hardware based
  - High Level Trigger (HLT): software based

L1 improvements

- Data flow : parallel → high-speed serial links
- Data rate : 16 Mbps → 190 Mbps (CDC wire case)
- Logic : hard-coded →FPGA

Phases 2 &3: Full physics preparation

Phase 2 will provide sufficient data to begin calibration and physics preparation. These will be repeated in phase 3.
Non exhaustive list.

1. Performance measurements in data using control modes
- Tracking: CDC only in phase 2
- Particle ID: K/π, lepton, proton ID.
- Neutral reconstruction efficiency and resolution: π0, γ, KL

2. Normalisation measurements and trigger stability checks, e.g.
- Luminosity (precision)
- B-counting

3. Trigger Menu & Performance
- Trigger efficiency measurements, L1 and HLT
- Trigger menu tuning

4. Algorithm tests
- Full event interpretation (B-tag)

5. Background measurements
- Beam background characterisation and impact on reconstruction.
- Collection of beam background for overlay in MC.

6. Simulation tuning
- Unbiased measurements of qq for Pythia tuning.

Recent results in Bottomonium-like states

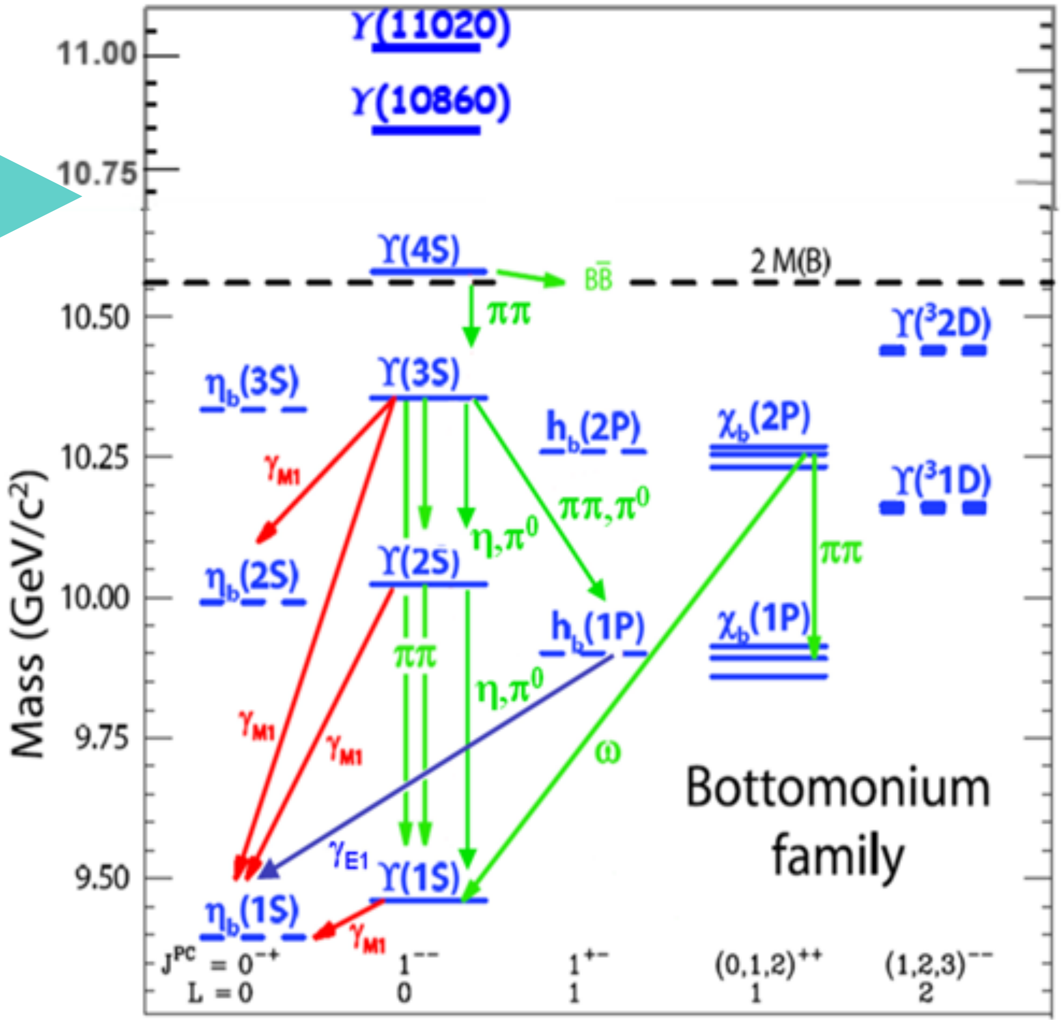
Bottomonia

Bottomonium

- atomic-like bound bb states

Bottomonium-like

- additional quark pair

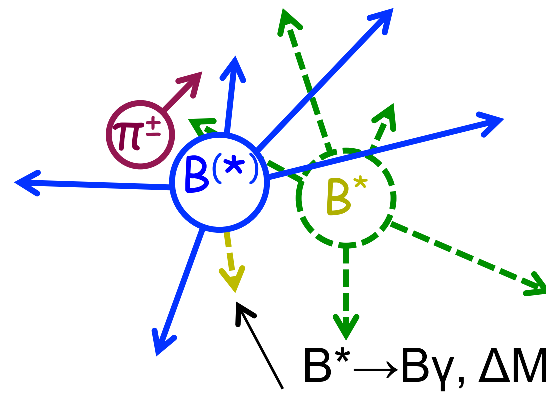


History of Bottomonium-like states @ e^+e^-

- **Belle collected 120 fb^{-1} near Υ(5S) and 5.6 fb^{-1} near Υ(6S)**
  - Υ(5S)= Υ(10860), Υ(6S)= Υ(11020)
- Unexpectedly high rate to $\Upsilon(nS)\pi^+\pi^-$ (n=1,2,3), $x10^2$, at Υ(5S)
  - PRL 100, 112001 (2008)
- $\sigma(\Upsilon(nS)\pi\pi)$, σ(bb) vs CMS energy: "Υ(5S)" peaks offset by 9±4 MeV
  - PRD 82, 091106 (2010)
- Bottomonium-like $Z_b^\pm(10610)$, $Z_b^\pm$ (10650) in 5 channels at Υ(5S): $\Upsilon(nS)\pi^\pm$, $h_b(mP)\pi^\pm$ (m=1,2)
  - PRL 108, 122001 (2012)
- Neutral Bottomonium-like $Z_b^0(10610)$ to $\Upsilon(nS)\pi^0$ at Υ(5S)
  - PRD 88, 052016 (2013)
- $Z_b^\pm(10610)$, $Z_b^\pm$ $(10650)\rightarrow\Upsilon(nS)\pi^\pm$ amplitude analysis yields $J^P=1^+$
  - PRD 91, 072003 (2015)

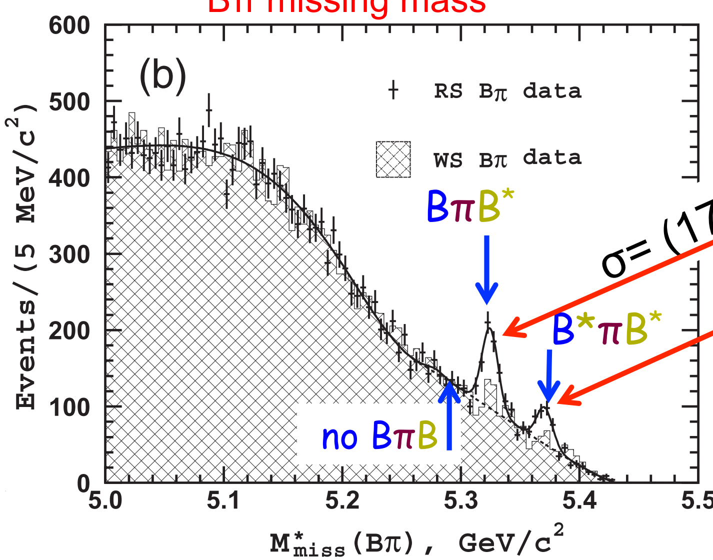
Z_b states

- $Z_b^{\pm}(10610) \rightarrow B^*B$, $Z_b^{\pm}(10650) \rightarrow B^*B^*$ observed
  - PRL 116, 212001 (2016)
- Exclusive events $B^*B(^*)\pi^{\pm}$
  - Fully reconstructed $B^{0/\pm} + \pi$
  - Sign of $\pi^{\pm}$ correlates w/ B flavour
  - "wrong sign" – background + mixed B^0
  - $B\pi$ missing mass: peaks at M_{B^*}, $M_{B^*}+\Delta M$



$B^* \rightarrow B\gamma$, $\Delta M \sim 45$ MeV
Photon not reconstructed

Bπ missing mass



Select $B\pi B^*$, $B^*\pi B^*$ events

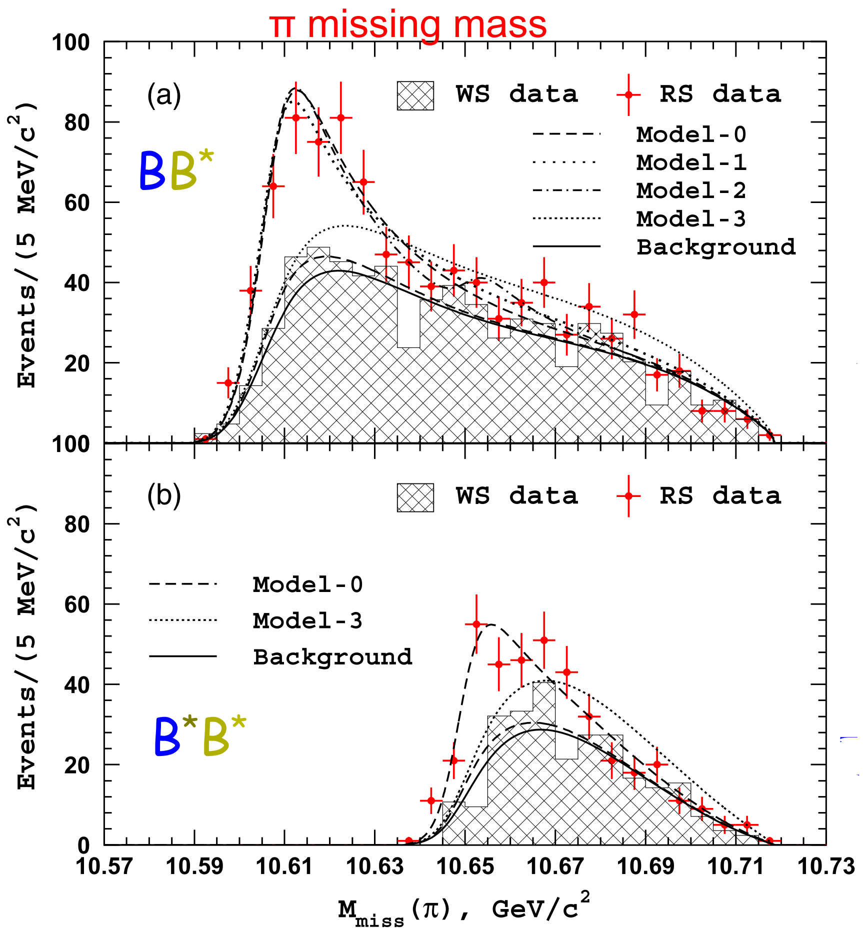
σ= (17.4±1.6±1.9) pb

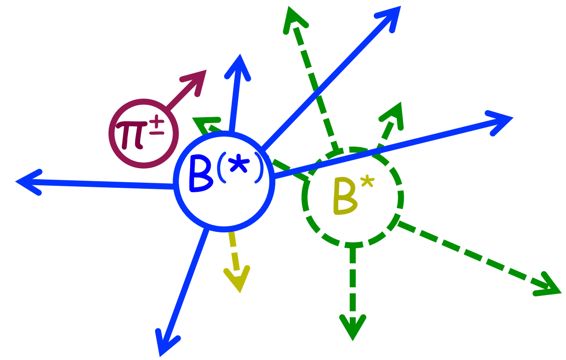
σ= (8.75±1.15±1.04) pb

➢ Probe B^*B^*, BB^* mass through π missing mass

Zb states

- $Z_b^{\pm}(10610) \rightarrow B^*B$, $Zb\pm\ (10650) \rightarrow B^*B^*$ observed
  - PRL 116, 212001 (2016)





$Z_b(10610)$ dominates $B^*B\pi$

$Z_b(10650)$ dominates $B^*B^*\pi$

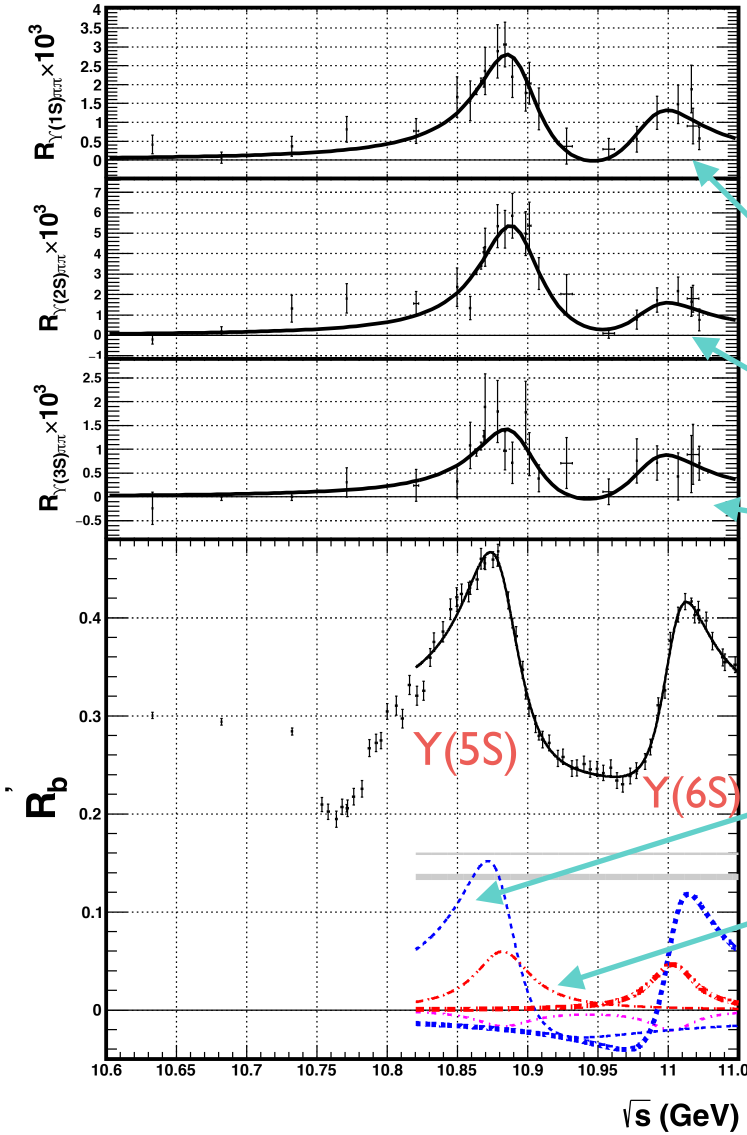
Zb states

$B^*B^{(*)}$ dominate Z_b channels observed so far

Channel	Fraction, %	
	$Z_b(10610)$	$Z_b(10650)$
$\Upsilon(1S)\pi^+$	$0.54^{+0.16+0.11}_{-0.13-0.08}$	$0.17^{+0.07+0.03}_{-0.06-0.02}$
$\Upsilon(2S)\pi^+$	$3.62^{+0.76+0.79}_{-0.59-0.53}$	$1.39^{+0.48+0.34}_{-0.38-0.23}$
$\Upsilon(3S)\pi^+$	$2.15^{+0.55+0.60}_{-0.42-0.43}$	$1.63^{+0.53+0.39}_{-0.42-0.28}$
$h_b(1P)\pi^+$	$3.45^{+0.87+0.86}_{-0.71-0.63}$	$8.41^{+2.43+1.49}_{-2.12-1.06}$
$h_b(2P)\pi^+$	$4.67^{+1.24+1.18}_{-1.00-0.89}$	$14.7^{+3.2+2.8}_{-2.8-2.3}$
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	$85.6^{+1.5+1.5}_{-2.0-2.1}$	$\cdots$
$B^{*+}\bar{B}^{*0}$	$\cdots$	$73.7^{+3.4+2.7}_{-4.4-3.5}$

Favors "meson molecule" configuration model
[Voloshin PRD 87, 091501 (2013)]

Υ(10860) and Υ(11020) via σ(e⁺e⁻ → Υ(nS)π⁺π⁻) @ Belle



- σ(Υ(nS)ππ), σ(bb) vs CMS energy redux, additional data (tot 22 points)
  - PRD 93, 011101 (2016)

No continuum: expect same for other Z_b-dominated events– $h_b(mP)\pi\pi$, $B^*B^{(*)}\pi$

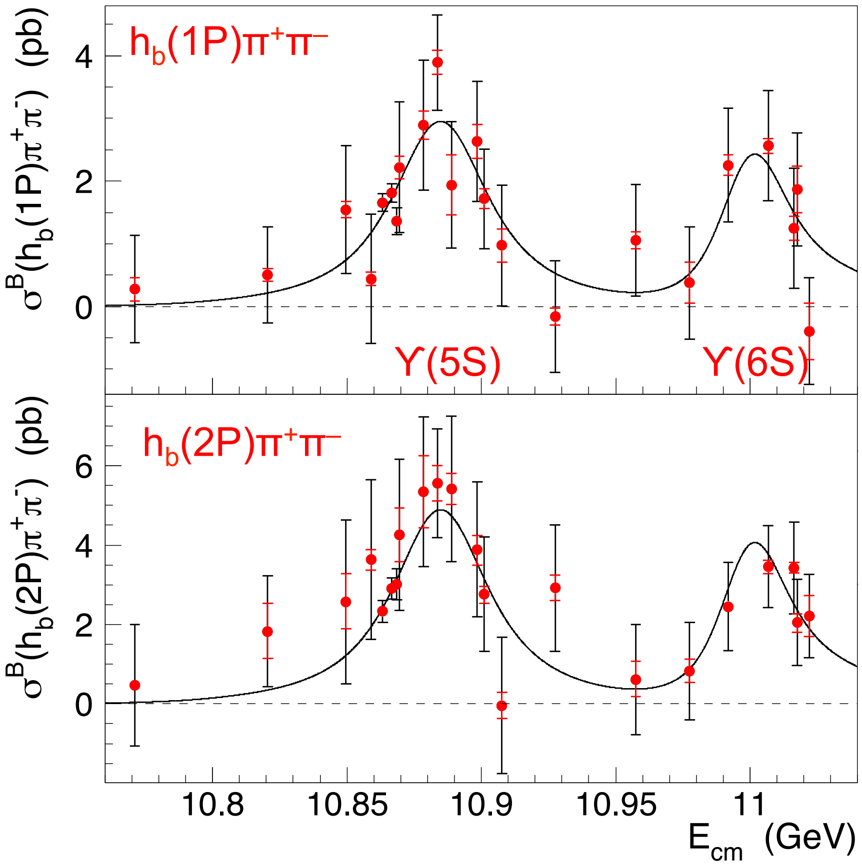
Large continuum-Υ(5S) interference

$\Upsilon(nS)\pi\pi+h_b(mP)\pi\pi+BB^*\pi+B^*B^*\pi$ Saturate "Υ(5S)"

Mutually incompatible⇒simple fit model for R_b should not be used for Υ(5S) mass, width

Z_b via h_b

- hb(mP)ππ vs CMS energy, evidence for Zb at Y(6S)
  - arXiv:1508.06562



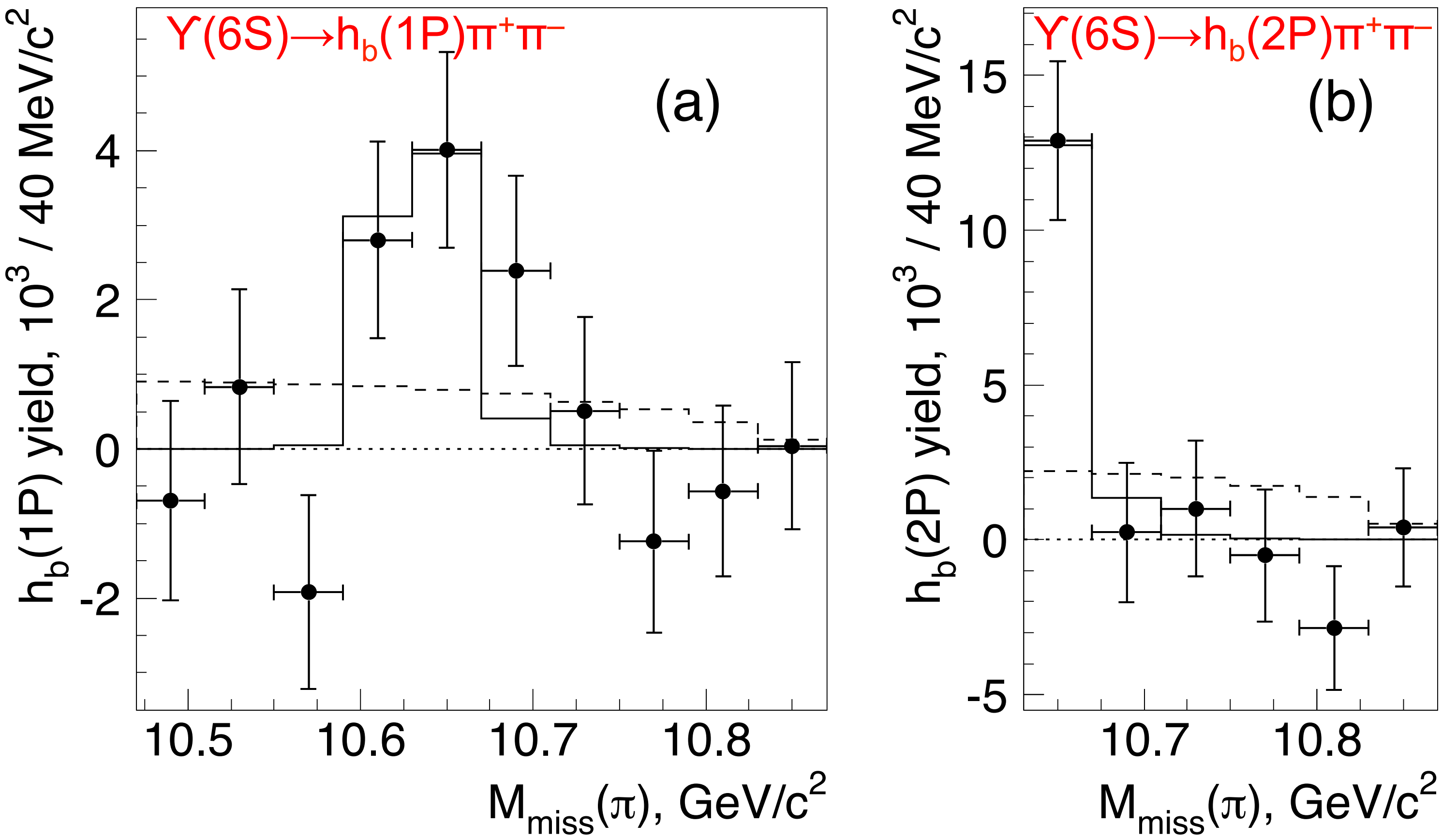
- Select $h_b(mP)$ via $\pi^+\pi^-$ missing mass

No continuum
– consistent with expectation from $\Upsilon\pi\pi$ scan, $h_b\pi\pi$ at $\Upsilon(5S)$

- Significance at $\Upsilon(6S)$
  - $h_b(1P)\pi^+\pi^-$ 3.5σ
  - $h_b(2P)\pi^+\pi^-$ 5.3σ

- Search for $Z_b^\pm$: Plot $\pi^\pm$ missing mass in $h_b(mP)\pi^+\pi^-$ events→

Z_b via h_b



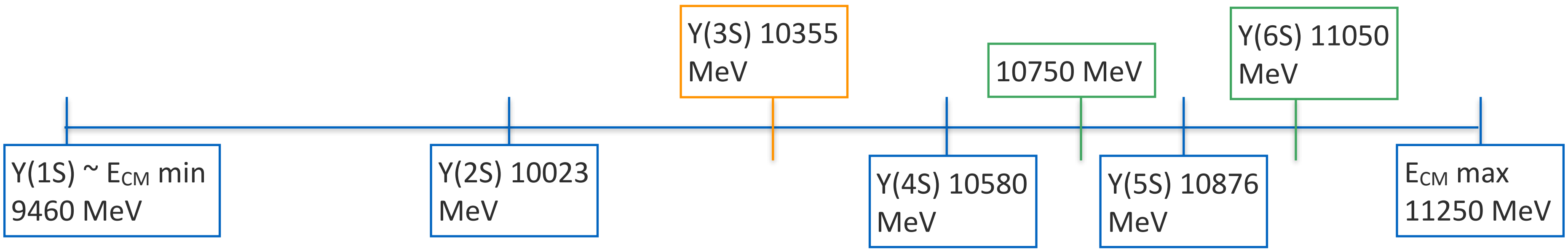
- Events saturated by $Z_b^{\pm}$ states, no nonresonant contribution
- Relative rates to $Z_b(10610)$, Z_b (10650) loosely constrained;
- Hypothesis of only Z_b (10610) excluded at 3.3σ

Phase II

Existing data sets at varying E_{CM}

- Significant data sets already taken at other resonances.
- Limitations for quarkonia studies with small mass differences, no VXD for slow tracks.
- Scans may be challenging for accelerator.
- Belle was not optimised for low multiplicity triggering - new opportunities at Belle II if we redesign the trigger logic.

Options in Phase 2 : Quarkonium



2 highlight options for ~20 fb^{-1}

10750 MeV: Take O(10 fb^{-1}) at 10.75, near R_{Υ} bump. Analogous transitions in charm revealed new structures.

Υ(6S): Study $\pi^{\pm} Z_b^{\pm}$(10610/50)[→$\pi^{\pm} h_b$(1P)] modes Analogous transitions to **Υ(5S) → ππ Υ(nS)**

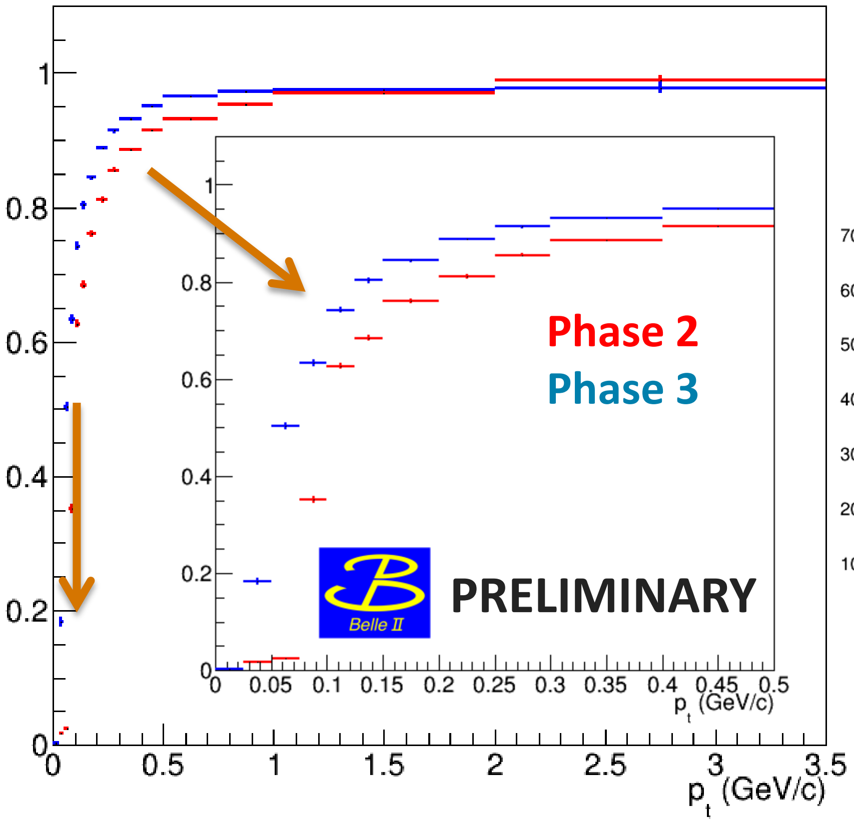
at either E_{CM}, new triggers for dark photons can be employed.

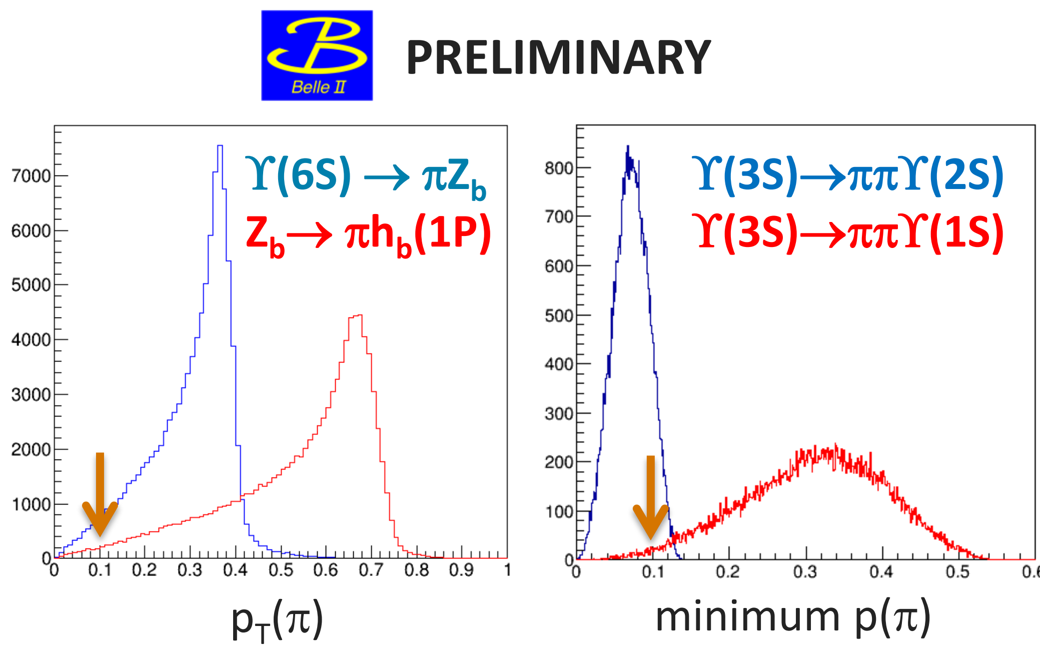
Quarkonia options

Energy	Outcome	fb^{-1}	Comments
Υ(1S) On	N/A	60+	Limited interest. Low end for machine
Υ(2S) On	New physics	20+	Special triggers
Υ(1D) Scan	Particle discovery	10-20	
Υ(3S) On	Many -onia topics	200+	Known resonance. Needs lumi.
Υ(3S) Scan	Precision QED	~10	Need to understand beam conditions for scans.
Υ(2D) Scan	Particle discovery	10-20	Unknown masses
>Υ(4S) Scan	Particle discovery	10+	Energy to be determined
Υ(6S) On	**Particle discovery**	**30+**	**Upper limit of machine E**
Single γ	**New physics**	**20+**	**Special triggers required**

Y(3S) Vs Y(6S) Physics

- Lack of vertex detector diminishes low p_T track reconstruction
- Y(3S) → $\pi^+\pi^-$Y(2S) unfeasible, but Y(6S)→ π Z_b(π h_b(nP)) unaffected





Other options with a Small data set (mostly Phase III)

Phase 3 Full physics ~Dec 2018-

B2TiP Nov 2015, G. Inguglia

$\Upsilon(nS) \to \pi^+\pi^-\Upsilon(1S), (n = 2, 3)$

Υ(nD) Scan : unseen $\Upsilon(1^3D_J)$ and $\Upsilon(2^3D_J)$

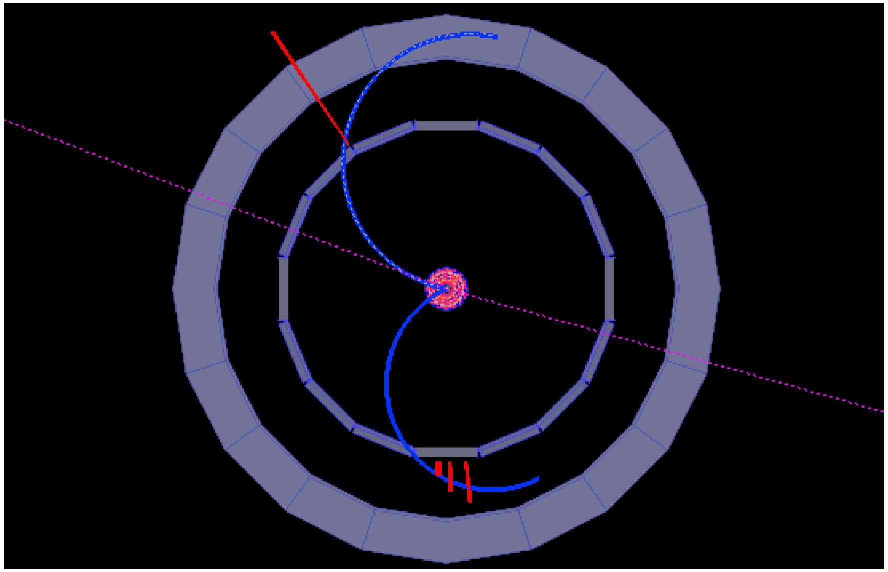
$\Upsilon(3S) \to \gamma\, \chi_{bJ}(1P)$ w/ converted photons

Dark Higgs: $\Upsilon(2S)$ & $\Upsilon(3S) \to \Upsilon(nS)\, \pi\pi$, $\Upsilon(nS) \to \chi\, \chi$

Exotic: Dark photons, $e^+e^- \to A'\, \gamma$

μ pair cross section

light quark & charm fragmentation



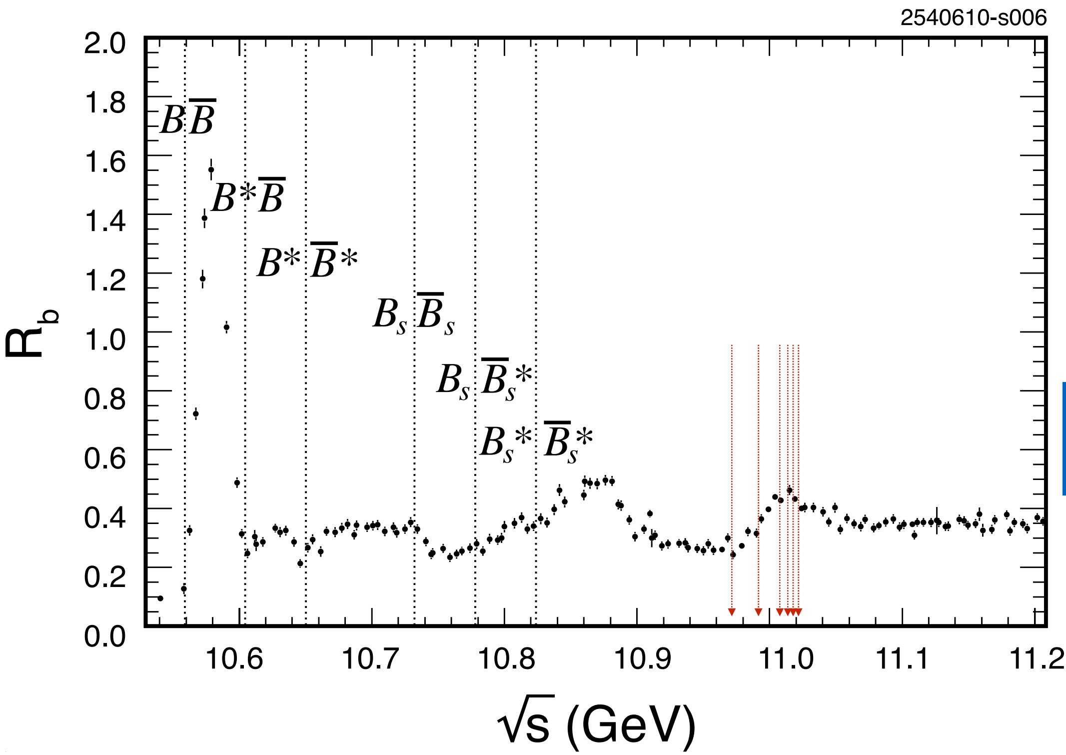
Υ(6S) case in Phase II

Plans (wishlist)

- Search for higher mass Z_b-like particles.
- Observation of separate Z_b peaks from Υ(6S).
- Hadronic transitions from Υ(6S) (ππ,η,ω,KK).
  - virtual meson loops and connection with tetraquarks.
- R_b decomposition at Υ(6S).
- Trigger validation for Υ(1S) → invisible and hb → γγ
- Trigger validation for bottomonium physics.

Υ(6S) = Υ(11020)

- $\sigma(e^+e^- \to \Upsilon(6S)) = 0.15$ nb. ~1 Million Υ(6S) in 10 fb^{-1}.
- Above thresholds for production of new- & poorly measured states **$B_J^{(**)}$, QCD Hybrids, W_{bJ} & X_b (ππ transition), $h_b(3P)$ and Υ(2D)**.



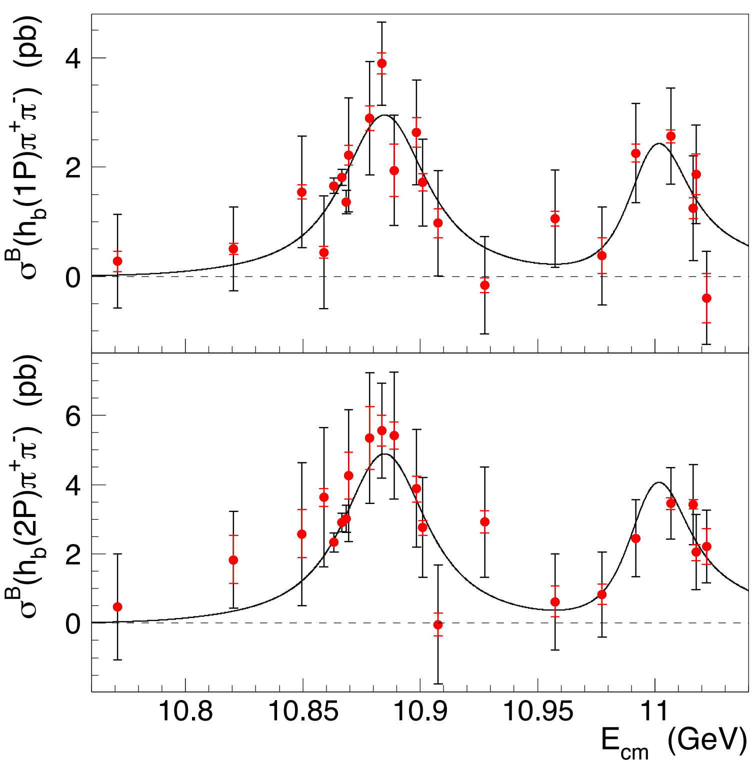
- Belle collected 6 "Υ(6S)" points = ~5.6 fb^{-1} (not all "on-peak")

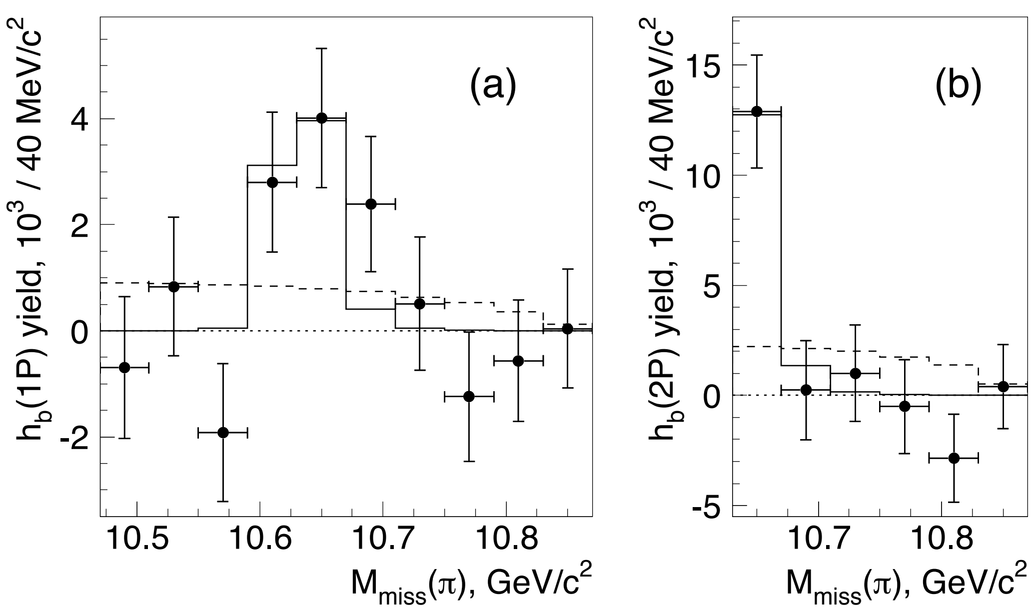
Energy [GeV]	10.977	10.992	11.007	11.016	11.018	11.022
Lumi [fb-1]	0.999	0.985	0.967	0.771	0.859	0.982

Z_b Υ(6S) Scan analysis

Belle arXiv:1508.06562

- Anomalous Υ(5S)→ ππΥ(pS) transitions led to discovery of Z $^{\pm}$(106XX)
- Preliminary evidence for Υ(6S)→ ππh(nP), via πZ$^{\pm}$(106XX)
- Resonance structure of Υ(6S) channel not fully studied



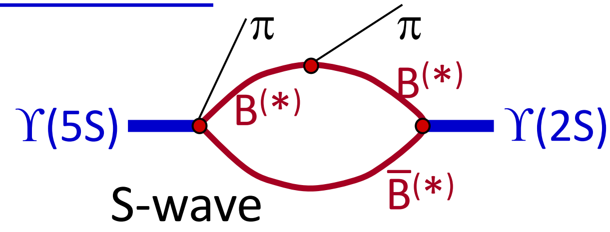


Expected molecular states

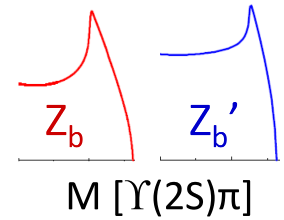
$I^G(J^P)$	Name	Composition	Co-produced particles [Threshold, GeV/c^2]	Decay channels
$1^+(1^+)$	Z_b	$B\bar{B}^*$	π [10.75]	$\Upsilon(nS)\pi$, $h_b(nP)\pi$, $\eta_b(nS)\rho$
$1^+(1^+)$	Z_b'	$B^*\bar{B}^*$	π [10.79]	$\Upsilon(nS)\pi$, $h_b(nP)\pi$, $\eta_b(nS)\rho$
$1^-(0^+)$	W_{b0}	$B\bar{B}$	ρ [11.34], γ [10.56]	$\Upsilon(nS)\rho$, $\eta_b(nS)\pi$
$1^-(0^+)$	W_{b0}'	$B^*\bar{B}^*$	ρ [11.43], γ [10.65]	$\Upsilon(nS)\rho$, $\eta_b(nS)\pi$
$1^-(1^+)$	W_{b1}	$B\bar{B}^*$	ρ [11.38], γ [10.61]	$\Upsilon(nS)\rho$
$1^-(2^+)$	W_{b2}	$B^*\bar{B}^*$	ρ [11.43], γ [10.65]	$\Upsilon(nS)\rho$
$0^-(1^+)$	X_{b1}	$B\bar{B}^*$	η [11.15]	$\Upsilon(nS)\eta$, $\eta_b(nS)\omega$
$0^-(1^+)$	X_{b1}'	$B^*\bar{B}^*$	η [11.20]	$\Upsilon(nS)\eta$, $\eta_b(nS)\omega$
$0^+(0^+)$	X_{b0}	$B\bar{B}$	ω [11.34], γ [10.56]	$\Upsilon(nS)\omega$, $\eta_b(nS)\eta$
$0^+(0^+)$	X_{b0}'	$B^*\bar{B}^*$	ω [11.43], γ [10.65]	$\Upsilon(nS)\omega$, $\eta_b(nS)\eta$
$0^+(1^+)$	X_b	$B\bar{B}^*$	ω [11.39], γ [10.61]	$\Upsilon(nS)\omega$
$0^+(2^+)$	X_{b2}	$B^*\bar{B}^*$	ω [11.43], γ [10.65]	$\Upsilon(nS)\omega$

Z_b Interpretation

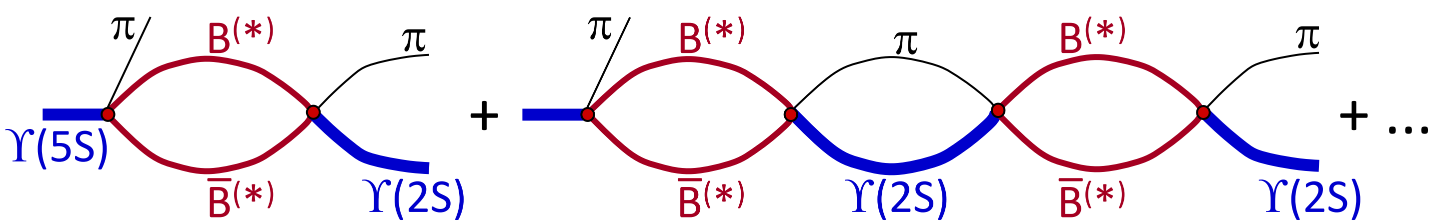
1. Threshold effect



Chen Liu PRD84,094003(2011)

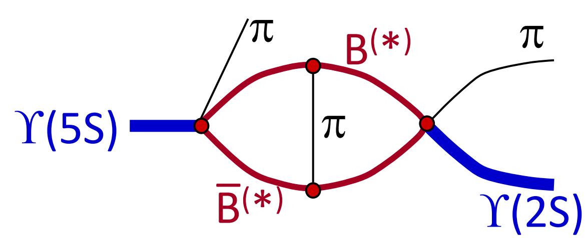


2. Coupled-channel resonance multiple re-scatterings ⇒ pole



3. Deuteron-like molecule

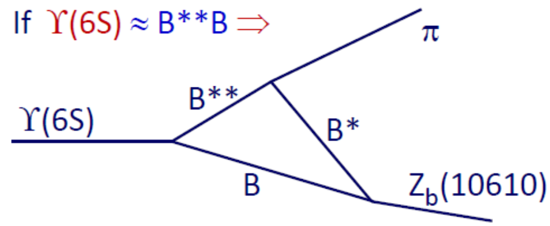
π,ρ,ω,σ exchange



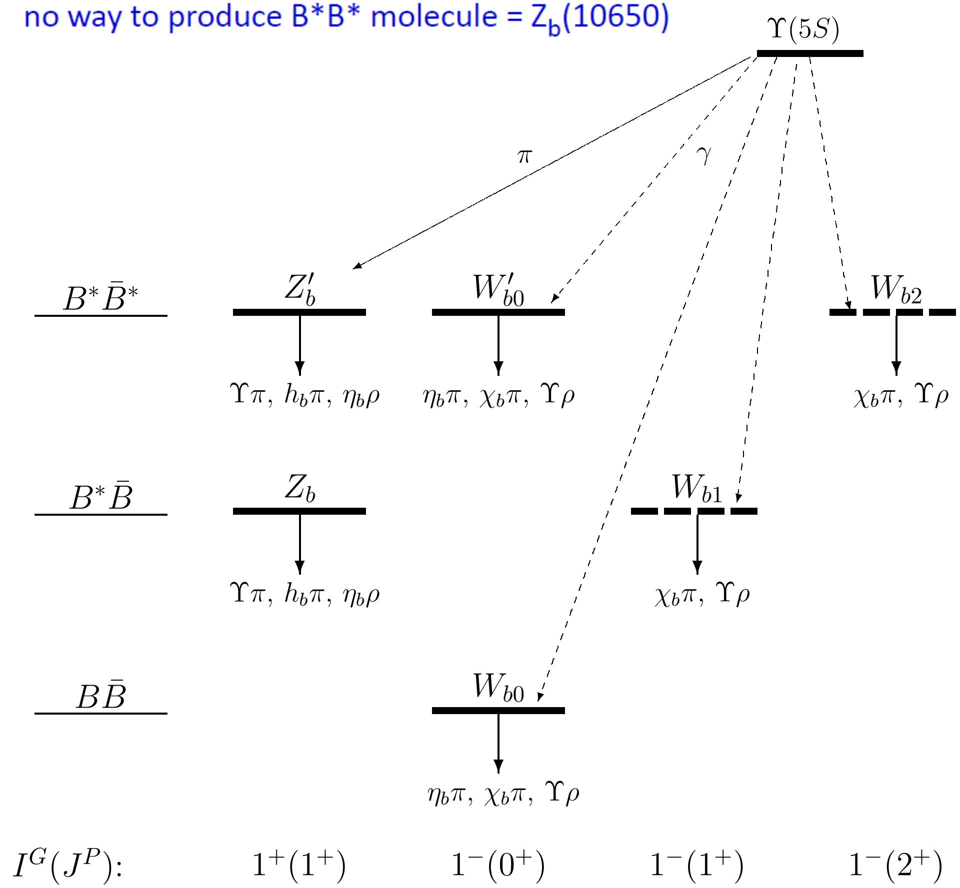
Z_b & W_b

- Closed-flavour decays with the largest branching fractions are 2π transitions into other bottomonium states.
  - Without b-quark spin flip
    Y(5S) →Y(nS)ππ, n < 5
  - With spin flip
    Y(5S)→ h_b(nP)ππ, n = 1,2.
  - Observations didn't follow spin symmetry → led to discovery.
- If Z_b(') are molecules, they have W_b siblings.
  - Not yet seen, the best portal to W_b may be ππ transitions - ρ tail. Possible at 6S, not 5S.
  - Radiative mode analogous to Y(4260)→γ X(3872) - more phase space at 6S for this.

If $\Upsilon(6S) \approx B^{**}B \Rightarrow$

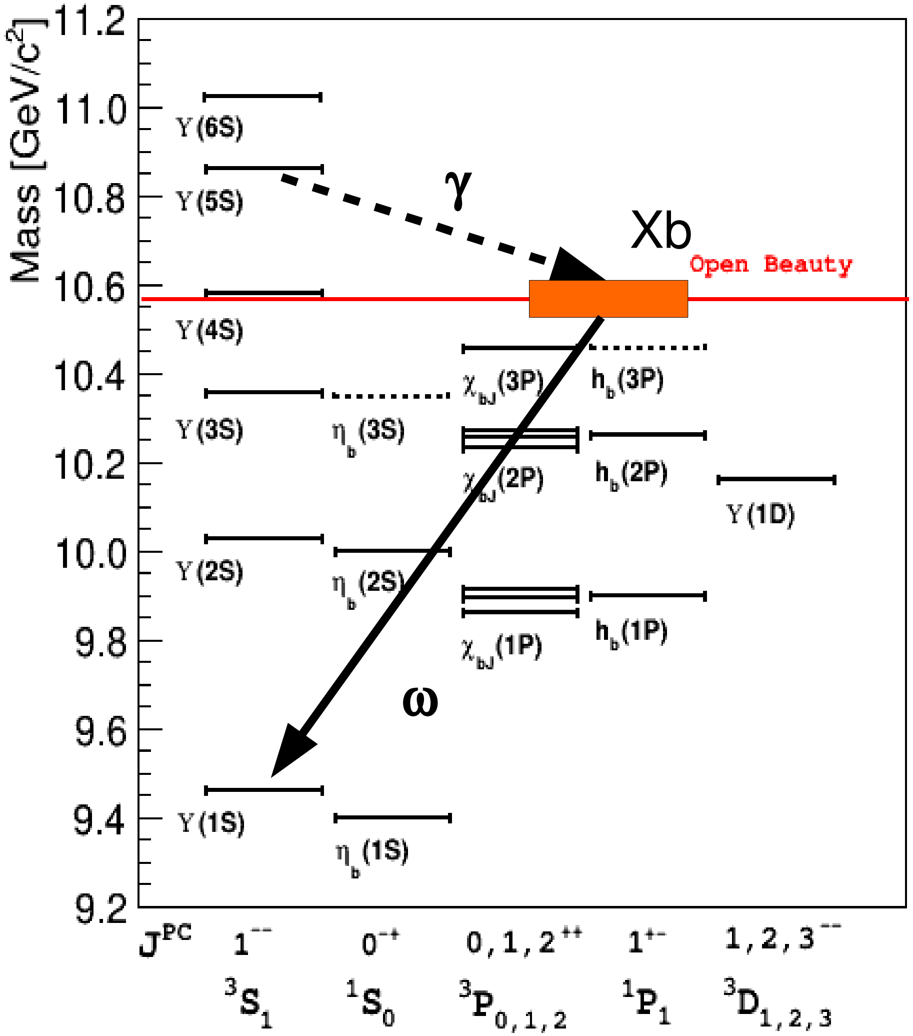


no way to produce B*B* molecule = $Z_b(10650)$



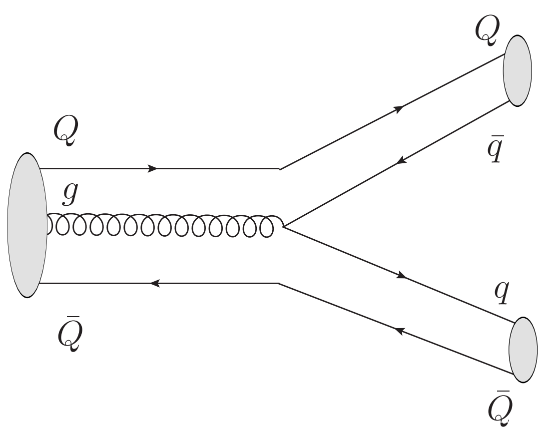
X_b

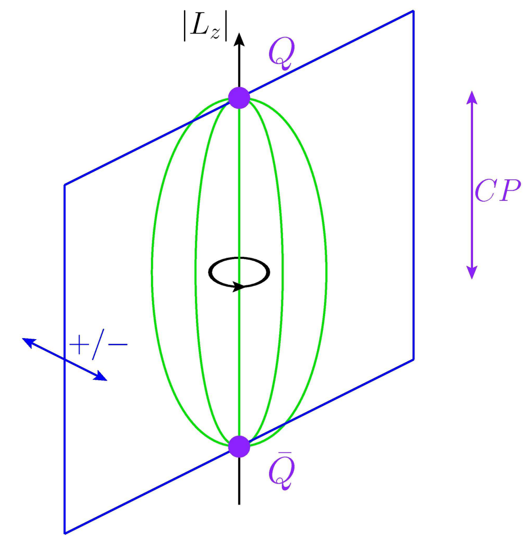
- Isovector Z_b and W_{bJ} states may possess isoscalar C-odd and C-even partners, also residing at the $B^{(*)}\underline{B}^{(*)}$ thresholds.
- Analogous to C-even X (3872)
- Y(6S) is expected to have an enhanced rate to X_b due to phase space.

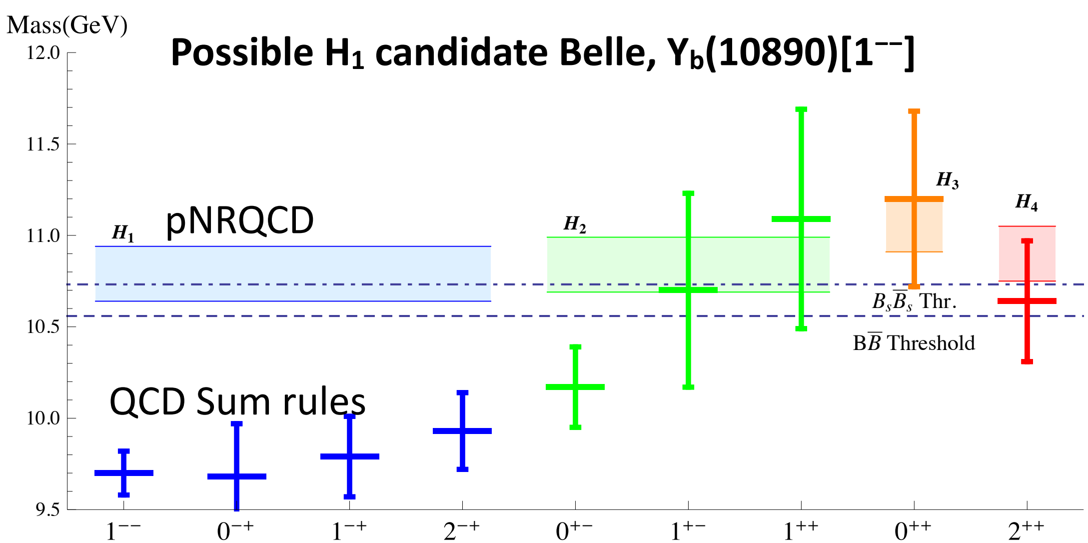


Search for QCD Hybrids?

- A quarkonium hybrid consists of Q, anti-Q in a color octet configuration and a gluonic excitation g. Similar system to diatomic molecule.







- Spin symmetry multiplets

H_1	$\{1^{--}, (0,1,2)^{-+}\}$	Σ_u^-, Π_u
H_2	$\{1^{++}, (0,1,2)^{+-}\}$	Π_u
H_3	$\{0^{++}, 1^{+-}\}$	Σ_u^-
H_4	$\{2^{++}, (1,2,3)^{+-}\}$	Σ_u^-, Π_u
H_5	$\{2^{--}, (1,2,3)^{-+}\}$	Π_u

QCD Hybrid Production & Decay

- Υ(11020) is above threshold for b b g hybrid production.
- Hypothesised, not found/confirmed.

TABLE VI. 10.7 GeV $b\bar{b}$ hybrid decay modes (MeV).

			alt	10.9 GeV hybrid	standard	IKP	reduced
2^{-+}	B^*B	P	.1	0	.5	3	44
1^{-+}	B^*B	P	.1	0	.5	3	44
0^{-+}	B^*B	P	.5	0	2	13	177
1^{--}	B^*B	P	.2	0	1.2	7	88
2^{+-}	B^*B	D	.08	.05	.25	1	22
1^{+-}	B^*B	S	.02	.1	.2	5	13
	B^*B	D	.02	.02	.15	.6	12
1^{++}	B^*B	S	.01	.05	.25	2	7
	B^*B	D	.1	.05	.5	1	24

Swanson et al.

- Scan would be best way to probe various masses.
- With Υ(6S) we can start looking.

Y(6S) Measurements, W, X and Z States & Hybrids

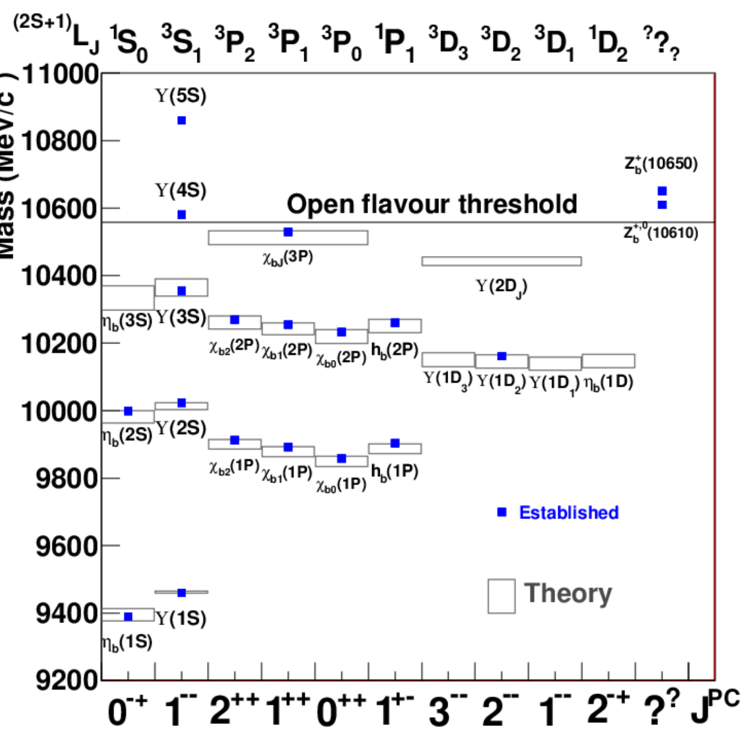
- Program based on decay modes that have been seen with the Y(5S) sample at some level.
- Assume similar rates as from Y(5S) where relevant.

#	Mode	Feasibility x Interest
1	$\Upsilon(6S) \to Z_b^+ \pi^- \to h_b(1P, 2P) \pi^+ \pi^-$	***
2	$\Upsilon(6S) \to Z_b^+ \pi^- \to \Upsilon(1S, 2S, 3S) \pi^+ \pi^-$	***
3	$\Upsilon(6S) \to Z_b^+ \pi^- \to \eta_b \rho$	*
4	$\Upsilon(6S) \to W_b^0 \gamma$, $W_b \to \eta_b \pi, \chi_b \pi, \Upsilon\rho$	*
5	$\Upsilon(6S) \to W_b^0 \pi^+ \pi^-$, $W_b \to \eta_b \pi, \chi_b \pi, \Upsilon\rho$	**
6	$\Upsilon(6S) \to \gamma X_b (\to \omega \Upsilon(1S))$	**
7	$\Upsilon(6S) \to \pi \pi X_b (\to \omega \Upsilon(1S))$	*
8	QCD hybrids in BB*	*

- Searches also for neutral modes to $\pi^0 \pi^0$

Υ(6S) Measurements, Conventional quarkonia

- High mass opens up access to most $\Upsilon(n^3D_J)$ states, & unseen bottomonium states. Marginal discovery potential.
- Not clear if ~10-30 fb^{-1} is sufficient.



Quarkonia transitions | **1* due to stat limitation**

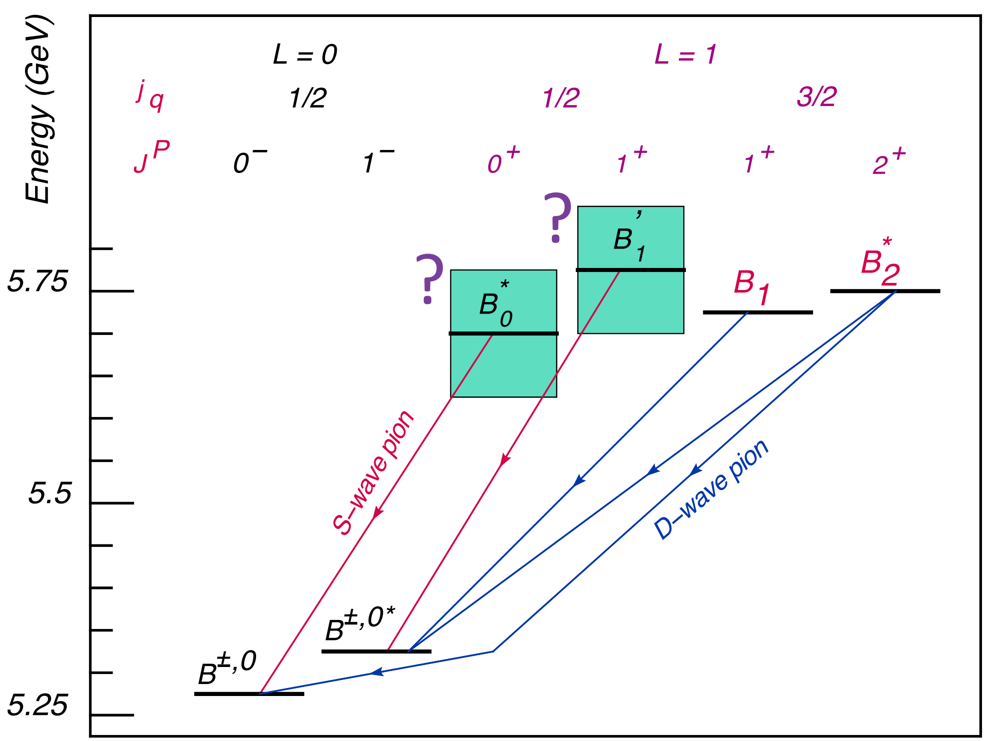
1	$\Upsilon(6S) \to \pi\,\pi\,\Upsilon(n^3D_J)$	*
2	$\Upsilon(6S) \to \eta\,\Upsilon(pS)$ and $\eta\,\Upsilon(n^3D_J)$	*
3	$\Upsilon(6S) \to K^+ K^- \Upsilon(pS)$, strangeness unexplored	*
4	$\Upsilon(6S) \to \omega\,\chi_b(1P)$	*

Bottomonium discovery

5	$\Upsilon(6S) \to \pi^+ \pi^- h_b(3P)$	*
6	$\Upsilon(6S) \to \pi^+ \pi^- \Upsilon(2D)$ or $\eta\,\Upsilon(2D)$	*
7	$\Upsilon(6S) \to$ 1F bottomonium multiplet via dipion transition	?

Excited B_J/B^{**} states

- B anti-B_J production near threshold in Y(6S) - may be useful for resolving states.
- e.g. m(Y(6S)) - m(B_1)-m(B) ~ 20 MeV
- Reconstructed in S- and D-wave pion transitions.
- Is the D_J puzzle replicated in the B_J system?



In **c$\bar{s}$** system, $J^P = 0^+$ and $J^P = 1^+$ states (both L = 1) have predicted masses **~100 MeV higher** than measured masses of the $\mathbf{D_{sJ}}$ mesons.

→ Might not be simple quark-antiquark configurations

PDG 2014 (masses and widths in MeV)

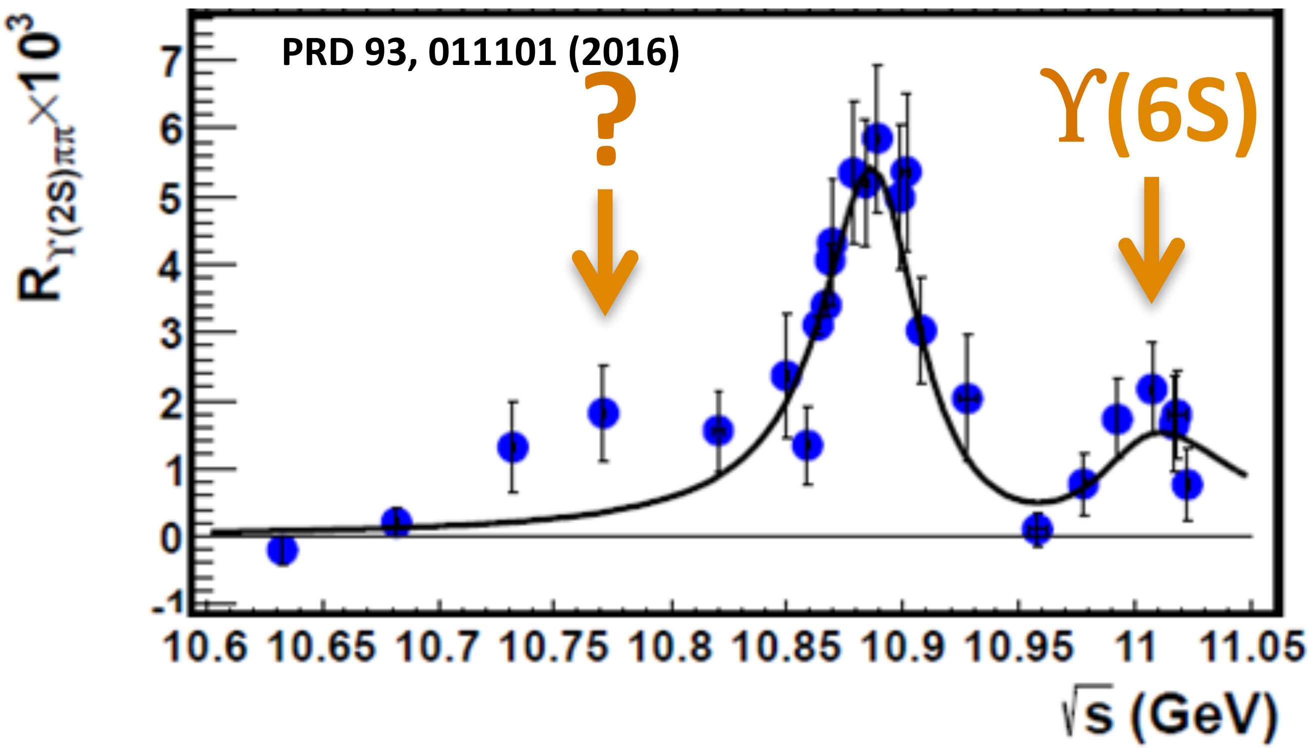
Resonance	mass	width
B^*	5325.2 ± 0.4	–
$B_1(5721)^0$	5723.5 ± 2.0	–
$B_2^*(5747)^0$	5743 ± 5	23^{+5}_{-11}
B_s^*	$5415.4^{+2.4}_{-2.1}$	–
$B_{s1}(5830)^0$	5828.7 ± 0.4	–
$B_{s2}(5840)^0$	5839.96 ± 0.20	1.6 ± 0.5

6S measurements, Spectroscopy & Production

1	B_J mesons spectroscopy, Y(11020) → $B^{(*)}$ anti-$B_J^{(*)}$	**
2	$\sigma(B^{(*)}B^{(*)})$, $\sigma(B_s^{(*)}B_s^{(*)})$, possible structure study	*
3	f_{Bs}, f_{Bd} @ Y(6S), Characterisation of Y(6S) decay for open flavour.	*
4	R_b - may be of partial interest	?
5	q anti-q production - Pythia tuning. Doesn't have to at 6S.	?

Physics study preparation

- Currently working on large MC samples to test analyses and build physics case.
  - Incremental step from 5.6fb^{-1} (6S) @ Belle (but not all at σ(peak))
- **Great opportunity/exercise for analysis and paper production.**
- Keeping in mind alternative operating points as Plan B.

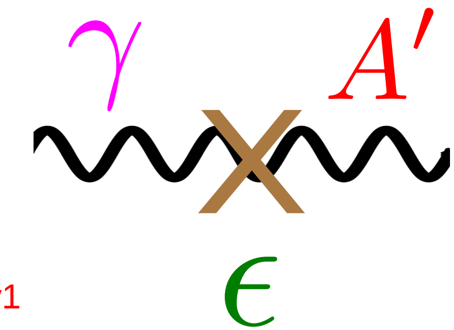


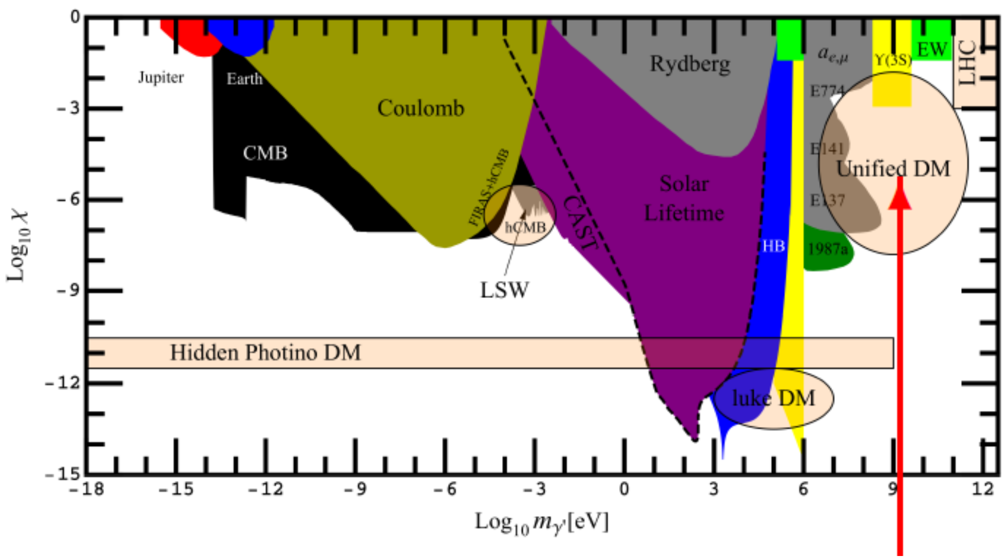
Phase II

Dark Sector & Other exotics

Dark Sector

- If dark matter is non-WIMP what hope do we have?
  - Dark gauge bosons, or dark photons, A' = g' = A = U postulated:
    - Very small couplings to SM, may be ow mass: of order MeV to GeV
  - Recent interest in dark sector models that:
    - Explain observed anomalies
    - Often introduce, in addition, a dark Higgs boson, h'





arXiv:1002.0329v1

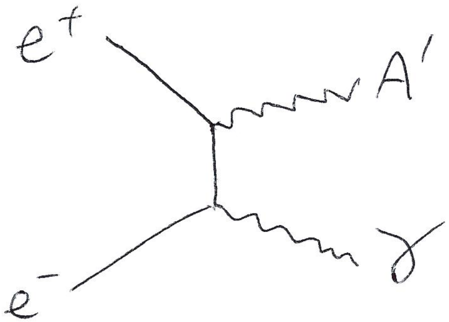
astrophysical and cosmological constraints and experimental limits

kinetic mixing ($\chi = \varepsilon$) vs. A' boson mass

BaBar, Belle, and Belle II can cover region between a few MeV/c^2 and 10 GeV/c^2

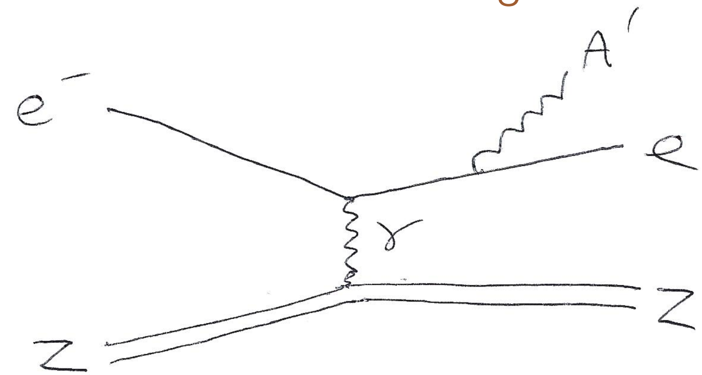
Dark Photon Mechanisms

e⁺e⁻ annihilation



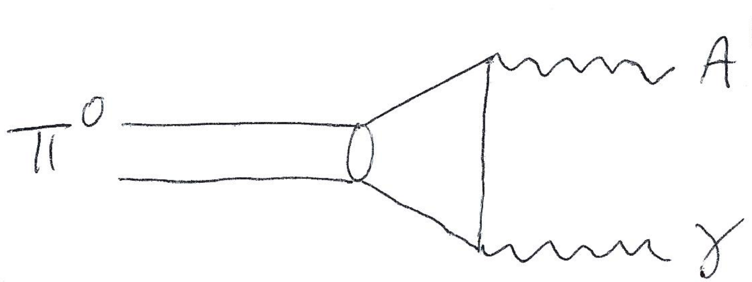
$$\sigma \propto \varepsilon^2 \alpha^2 \left(1 - m_{A'}^2 / E_{CM}^2\right) / E_{CM}^2$$

e⁻ bremsstrahlung



$$\sigma \propto \varepsilon^2 \alpha^3 Z^2 / m_{A'}^2$$

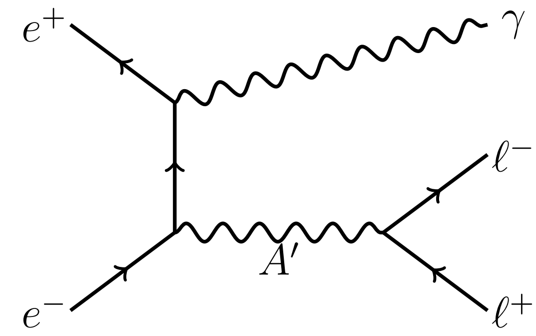
meson decay

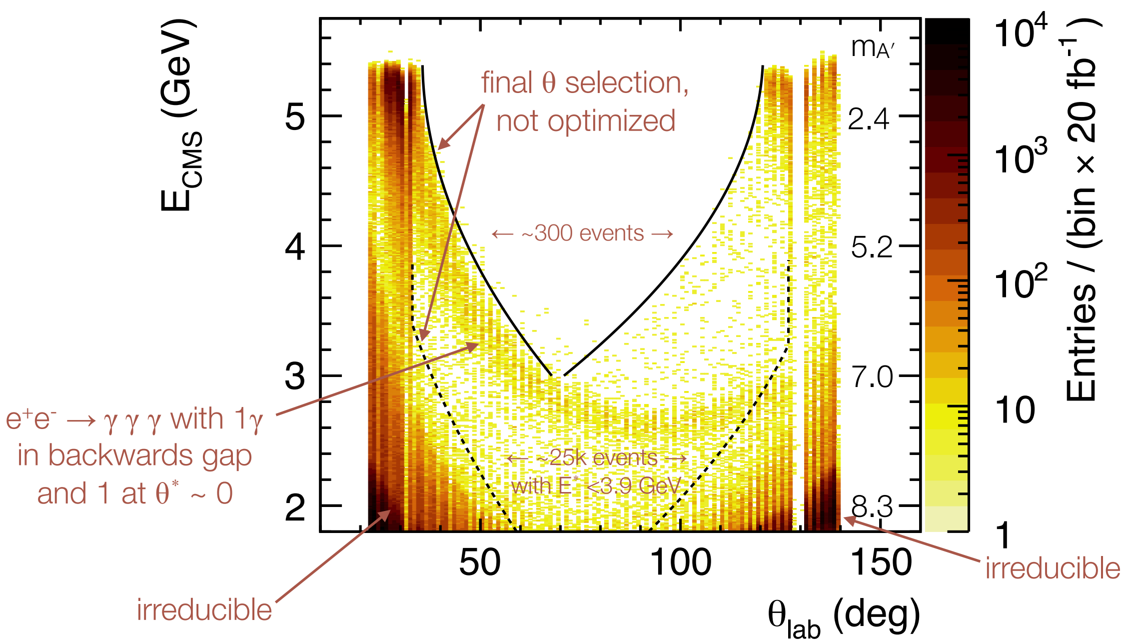


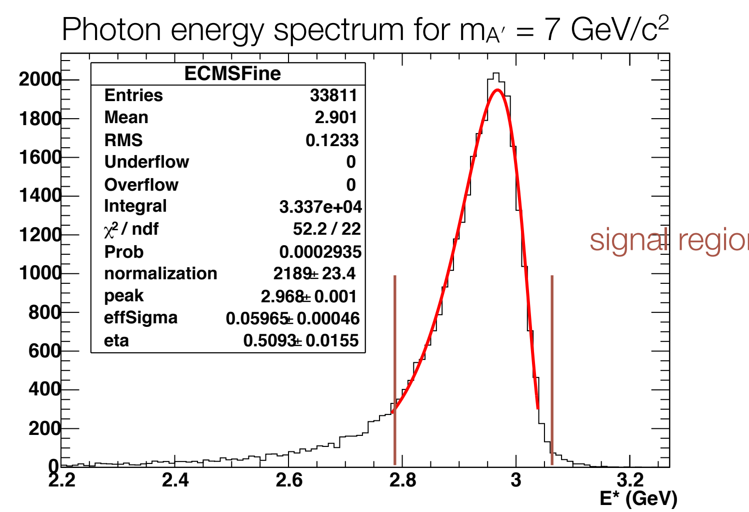
$$\mathcal{B} = 2\varepsilon^2 \left(1 - m_{A'}^2 / m_{\pi^0}^2\right)^3$$

Dark photon to invisible, e+e- → γ A’, A’ → invisible.

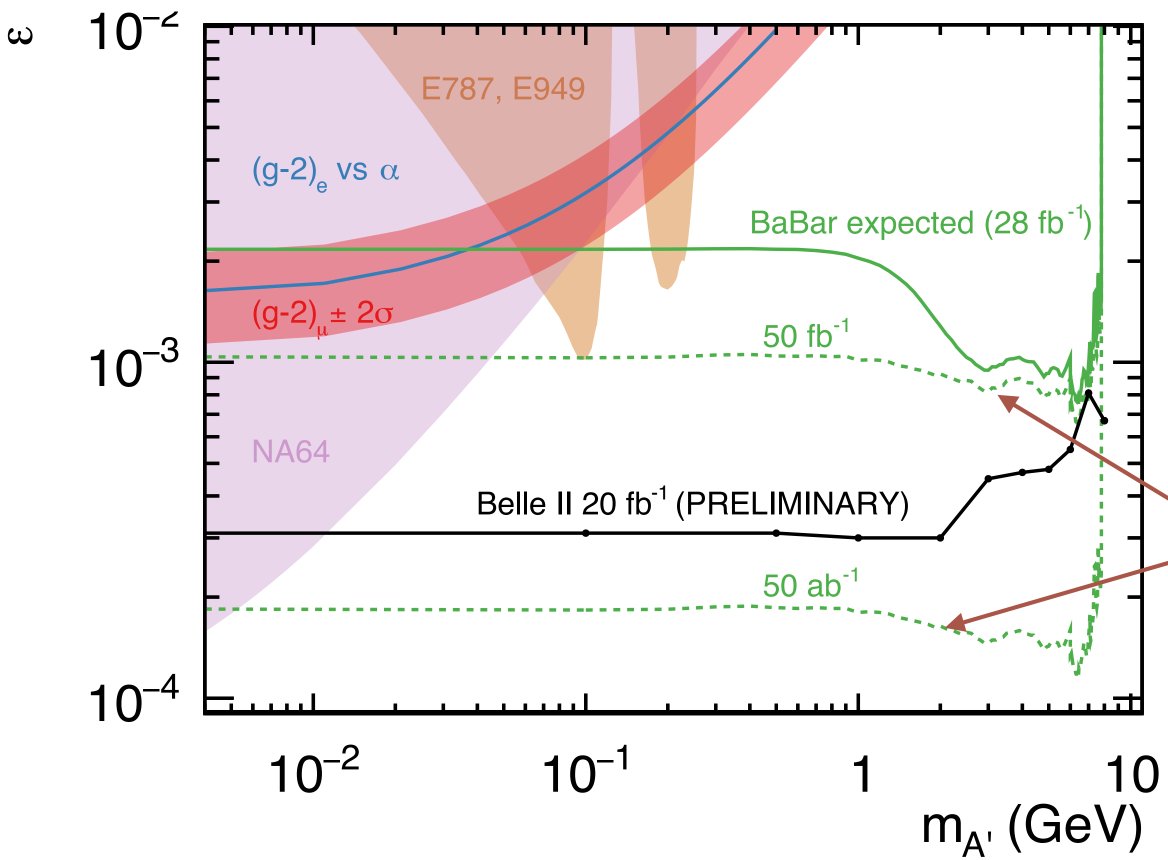
- Requirements: single photon trigger, charged track detection efficiency
- BaBar: 28fb^{-1} single-photon trigger (Υ(2S,3S)) unpublished.







Sensitivity (work in progress)



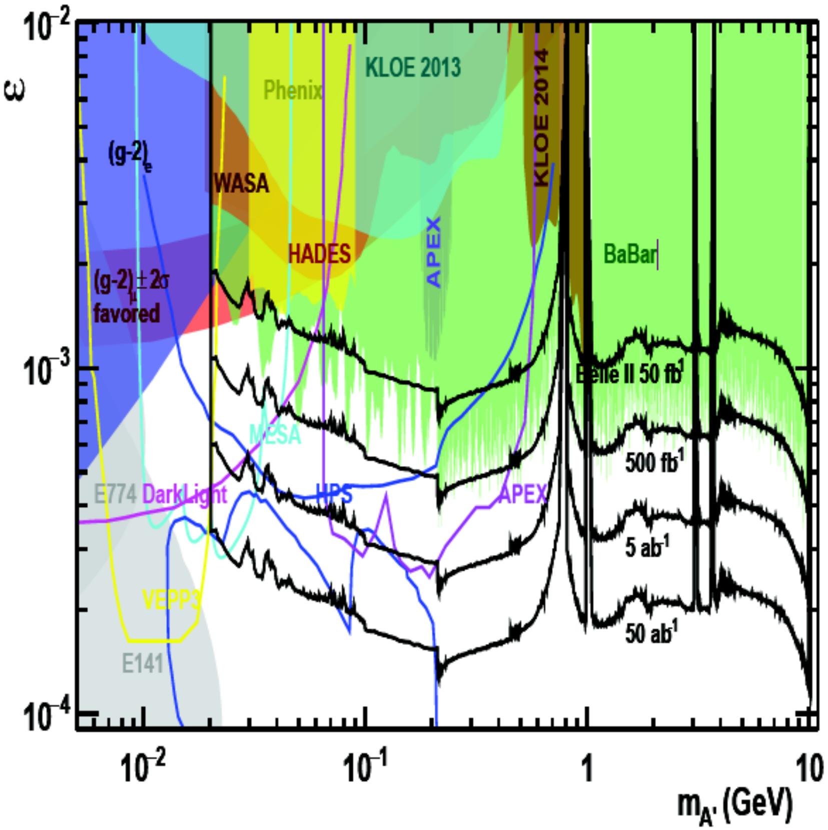
** note MC truth-based background estimation **

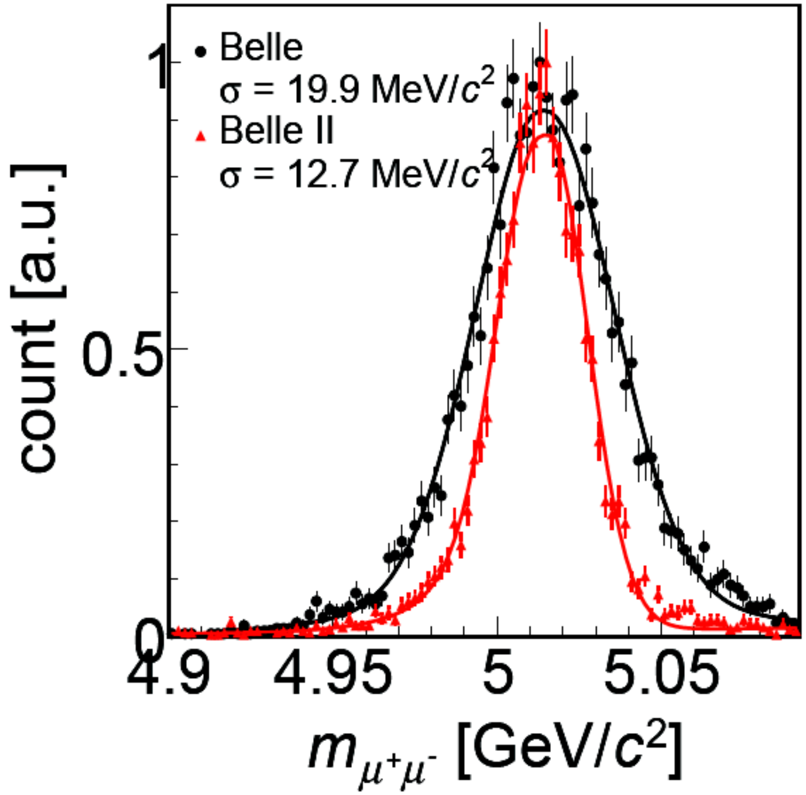
earlier projections

Dark photon to charged final states

Predicted Belle II upper limits extrapolated from BaBar PRL 113, 201801 (2014)

- $e^+e^- \rightarrow \gamma A'$, with $A' \rightarrow l^+l^-$, with $l = e, \mu$
- Extrapolation assuming BaBar trigger efficiency

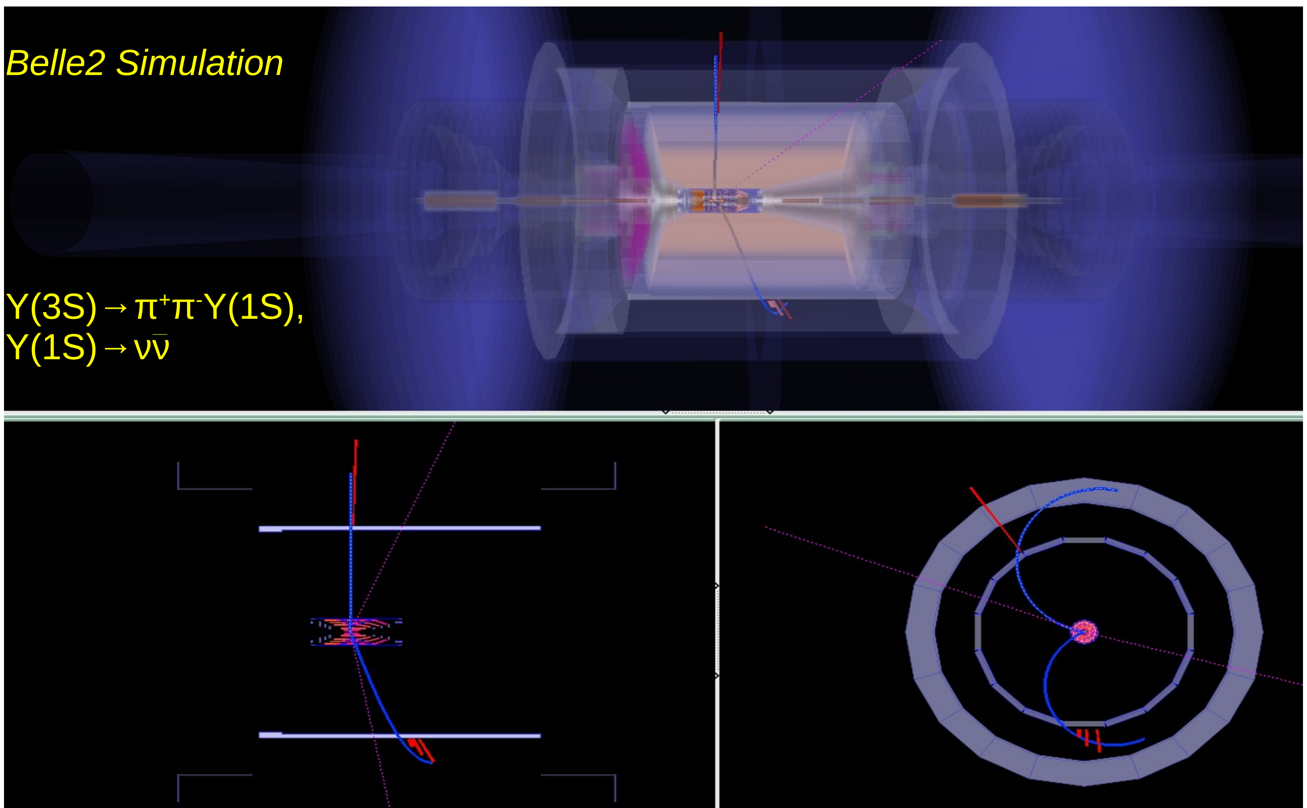




Belle II di–muon invariant mass resolution improved by 35% compared to Belle

Invisible Υ(1S,2S) decays

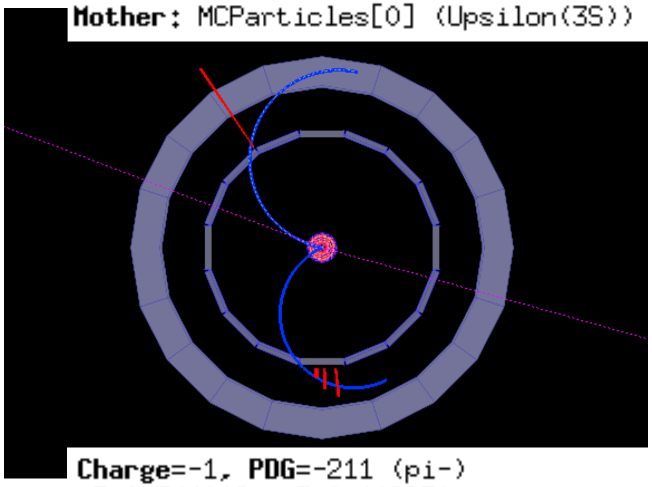
- Low mass dark matter particles however might might play a role in the decays of Υ(1S), having $\Upsilon(1S)\rightarrow\chi\chi$ if kinematic allowed. [Phys. Rev. D **80,** 115019, 2009]
- Also, new mediators (Z', A^0, h^0) or SUSY particles might enhance $\Upsilon(1S)\rightarrow\nu\nu(\gamma)$. [Phys. Rev. D **81**, 054025, 2010]
- In absence of new physics enhancement, Belle2 should be able to strongly constrain the SM $\Upsilon(1S)\rightarrow\nu\nu$



Invisible Y(1S,2S) decays

Y(3S) → π⁺π⁻Y(1S),
Y(1S) → νν

Charge=1, PDG=211 (pi+)
pT=0.420365, pZ=0.000692372
V=(-0.00, -0.00, -0.03)
Mother: MCParticles[0] (Upsilon(3S))



Charge=-1, PDG=-211 (pi-)
pT=0.344016, pZ=0.118851
V=(-0.00, -0.00, -0.03)
Mother: MCParticles[0] (Upsilon(3S))

$$e^+e^- \rightarrow Y(3S)$$
↓(4.4%)
$$Y(3S) \rightarrow \pi^+\pi^- Y(1S)$$
↓
$$Y(1S) \rightarrow invisible$$

$$e^+e^- \rightarrow Y(2S)$$
↓(18.1%)
$$Y(2S) \rightarrow \pi^+\pi^- Y(1S)$$
↓
$$Y(1S) \rightarrow invisible$$

Process	$L_{int}(ab^{-1})$	ϵ	$N(\Upsilon(1S))$	$N_{\Upsilon(1S)\to\nu\bar{\nu}}$	N_{NP} **UL**
$\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$	0.2, $\Upsilon(2S)$	0.1-0.2	2.3×10^8	230-460	6900-13800
$\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$	0.2, $\Upsilon(3S)$	0.1-0.2	3.2×10^7	32-64	945-1890
$\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S)$	50.0, $\Upsilon(4S)$	0.1-0.2	5.5×10^6	5.5-11	165-310
$\Upsilon(5S) \to \pi^+\pi^-\Upsilon(1S)$	5.0, $\Upsilon(5S)$	0.1-0.2	7.6×10^6	7.6-15.2	228-456
$\gamma_{ISR}\Upsilon(2S) \to (\gamma_{ISR})\pi^+\pi^-\Upsilon(1S)$	50.0, $\Upsilon(4S)$	0.1-0.2	1.5×10^8	150-300	4500-9000
$\gamma_{ISR}\Upsilon(3S) \to (\gamma_{ISR})\pi^+\pi^-\Upsilon(1S)$	50.0, $\Upsilon(4S)$	0.1-0.2	3.5×10^7	35-70	1050-2100

Further exotic ideas for phase II data?

- Magnetic monopoles?

Beyond phase II

Conventional bottomonium below Υ(4S)

- Bottomonium offers a unique way to study interactions of QCD. Can use nonrelativistic QM and effective theories. Spin-singlet states permit study of spin-spin interactions.
- Υ(1S) and Υ(2S) are expected to decay mainly via 3 gluons, with a few % probability to two gluons and a γ.
  - 2 and 3-gluon channels probe states made of pure glue (glueballs), light Higgs bosons, and light quark states.
- Υ(1S) and Υ(2S) hadronic decays can be studied to improve understanding of gluon fragmention into hadrons.

Bottomonium plan beyond Phase II

Hadronic transitions

→ Missing η transitions from Y(4S,5S)

→ Missing η transitions from Y(3S)

→ π^0 transitions

→ Y(3S) → $\pi\pi$ h_b(1P)

→ η_b(1S,2S) lineshape

→ Hindered radiative transitions

→ Y(1D,2D) spin singlets (and triplets)

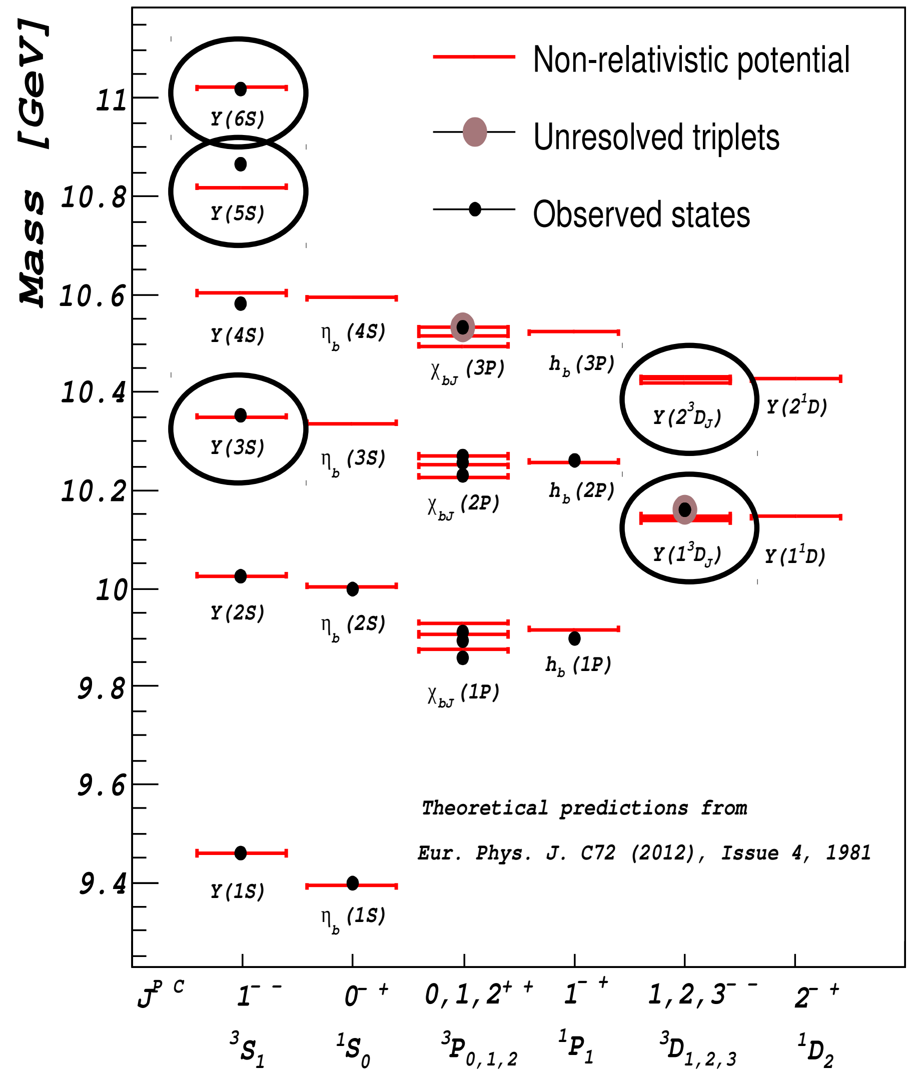
→ Y(1S) → invisible

→ h_b(1P, 2P) → e^+e^-

→ *χ_{b0}(2P) → $\tau^+\tau^-$ (NP)*

→ χ_b(3P) properties

→ *η_b(1S) → $\gamma\gamma$*



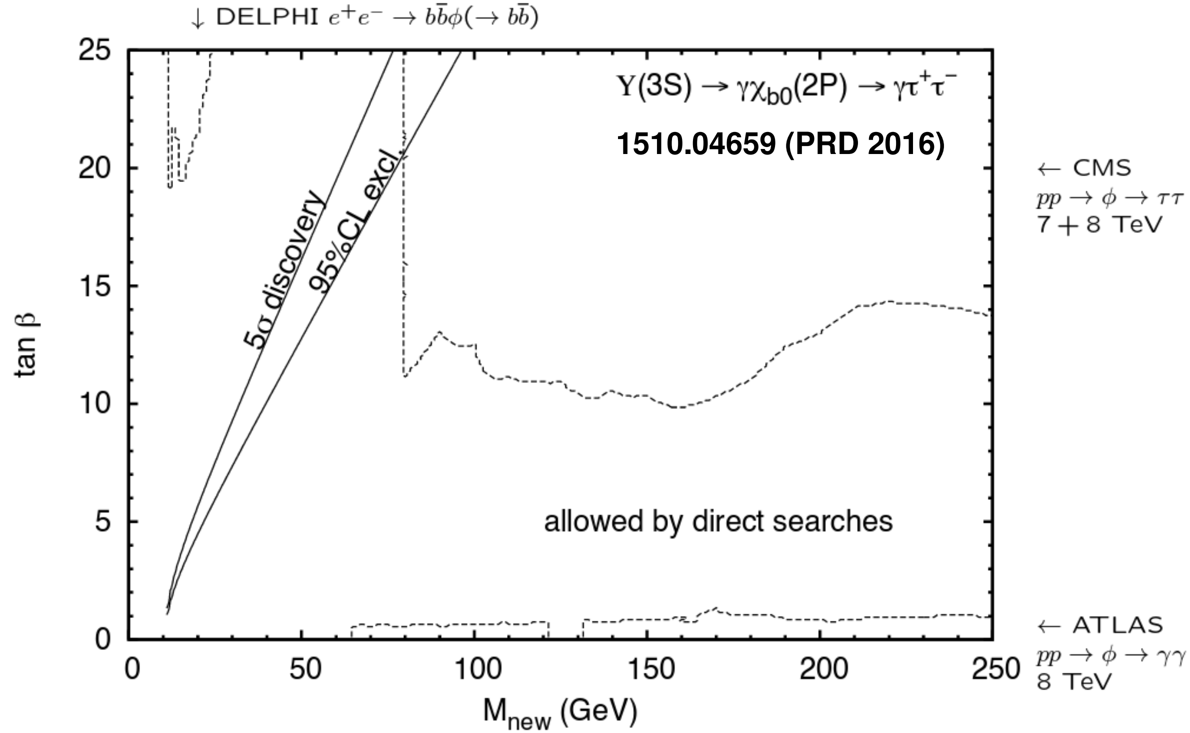
Missing bottomonium levels

Table 1.4: Missing bottomonium levels below the $B\bar{B}$ threshold, their quantum numbers, potential model predictions for masses [35], light hadrons emitted in the transitions from vector bottomonium-like states to the considered bottomonia and thresholds of these transitions.

Name	L	S	J^{PC}	Mass, MeV/c^2	Emitted hadrons [Threshold, GeV/c^2]
$\eta_b(3S)$	0	0	0^{-+}	10336	ω [11.12], ϕ [11.36]
$h_b(3P)$	1	0	1^{+-}	10541	$\pi^+\pi^-$ [10.82], η [11.09], η' [11.50]
$\eta_{b2}(1D)$	2	0	2^{-+}	10148	ω [10.93], ϕ [11.17]
$\eta_{b2}(2D)$	2	0	2^{-+}	10450	ω [11.23], ϕ [11.47]
$\Upsilon_J(2D)$	2	1	$(1,2,3)^{--}$	10441 – 10455	$\pi^+\pi^-$ [10.73], η [11.00], η' [11.41]
$h_{b3}(1F)$	3	0	3^{+-}	10355	$\pi^+\pi^-$ [10.63], η [10.90], η' [11.31]
$\chi_{bJ}(1F)$	3	1	$(2,3,4)^{++}$	10350 – 10358	ω [11.14], ϕ [11.38]
$\eta_{b4}(1G)$	4	0	4^{-+}	10530	ω [11.31], ϕ [11.55]
$\Upsilon_J(1G)$	4	1	$(3,4,5)^{--}$	10529 – 10532	$\pi^+\pi^-$ [10.81], η [11.08], η' [11.49]

BSM Higgs in Υ(3S) decays

Results: $\Upsilon(3S)$ *Heather Logan (Carleton U.)* *New physics in bottomonium decay* *4th B2TIP May 2016*



$$\mathrm{BR}^H(\chi_{b0}(1P) \to \tau\tau) = 3.1 \times 10^{-13}$$
$$\mathrm{BR}^H(\chi_{b0}(2P) \to \tau\tau) = (1.9 \pm 0.5) \times 10^{-12}$$

SM predictions

$$\left.\begin{array}{l}\mathrm{BR}^H(\chi_{b0}(1P) \to \tau\tau) = 3.1 \times 10^{-13} \\ \mathrm{BR}^H(\chi_{b0}(2P) \to \tau\tau) = (1.9 \pm 0.5) \times 10^{-12}\end{array}\right\} \times \left[1 + \frac{M^2_{H_{125}} \tan^2\beta}{M^2_{\text{new}} - M^2_{\chi_{b0}}}\right]^2$$

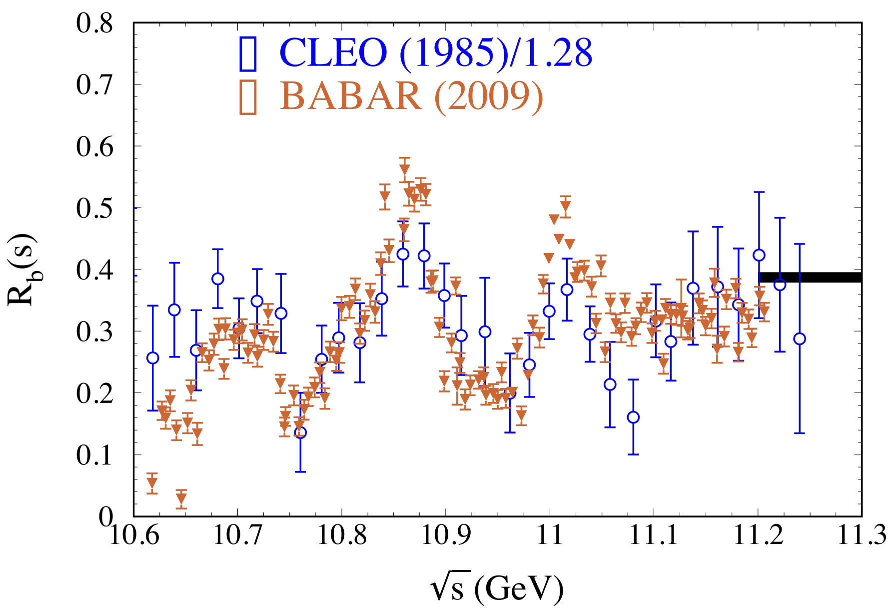
Will only need $(M_{H_{125}}/M_{H_{\text{new}}}) \tan\beta \sim 30$ for $\mathcal{O}(100)$ signal events in $\Upsilon(3S) \to \gamma\chi_{b0}(2P) \to \gamma\tau\tau$

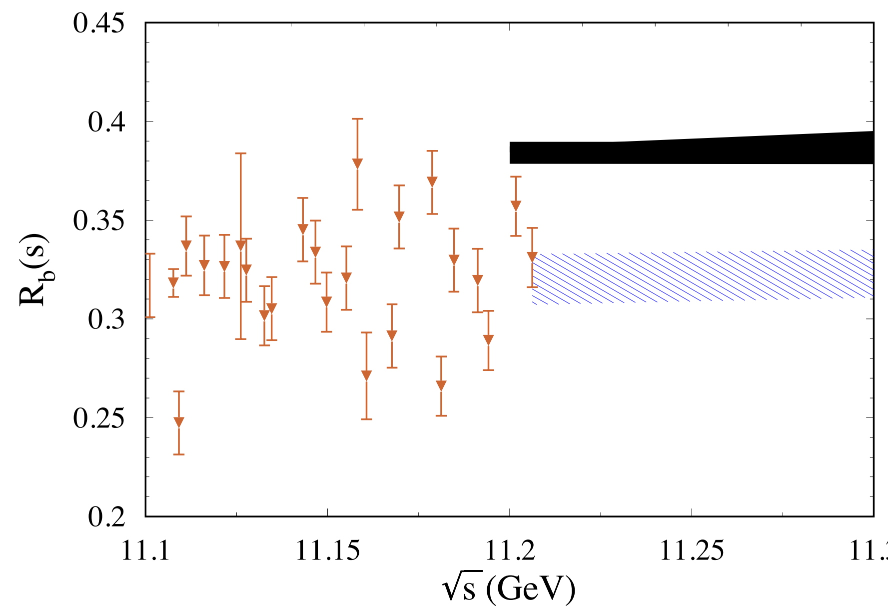
Υ(5S)

- Did not discuss Υ(5S) here. Early running precludes Υ(5S) as we already have 120 fb^{-1}.
  - $\sigma(\Upsilon(5S)) = 0.3$ nb, $f_{Bs} = 0.2$
  - In 1 ab^{-1}, expect 60M B_S pairs.
  - Υ(5S)→ B_S anti-B_S full reconstruction algorithms under development.
    - Challenge due to large excited state production resulting in lack of resolution in extra track and cluster quantities.

b-quark mass

- Data at high ECM may help provide an accurate determination of mb via bottomonium sum-rules.
- Currently there is a discrepancy between pQCD and e+e- near the accelerator threshold region.
- This is important as it is well into the bb continuum region.





Other areas

Light quark Fragmentation	Cross section measurements as a function of z below the B threshold. Improved particle identification and vertex reconstruction in Belle II will help to suppress charm background.
Charm Fragmentation	Cross section measurements as a function of z below the B threshold.
α_s	Determination of the strong coupling constant from fragmentation data.
Pythia tuning	Tuning of Pythia 8 with early Belle II fragmentation data in $\Upsilon(1S)$ and $e^+e^- \to q\bar{q}$ below the B threshold.
Muon-pair asymmetry	Precision electroweak tests and probes of axial-axial operators with measurements of the forward-backward asymmetry.

Summary

- Phase II starts in Jan 2018, for a 5 month run. Machine can reach up to 11.1 GeV E_{CM}.
- Expect about 20 fb^{-1} for Phase II Physics @ Υ(6S).
  - Υ(6S) program looks to further probe bottomonium and bottomonium-like structures through many channels.
- Additional 10-20 fb^{-1} to be taken @ Υ(4S)
  - New triggers open up low multiplicity physics, dark sectors.
- Phase III starts ~Dec 2018, with a full detector.
  - Υ(5S)-Υ(6S) scans, Υ(3S), Υ(nD) scans all on the table.
- MANY more ideas discussed in B2TiP workshops and in B2TiP Quarkonium chapter.