# Belle II Early Physics Program of Bottomonia Spectroscopy and Dark Sector Searches

25th International Workshop on Deep Inelastic Scattering and Related Topics — Birmingham, United Kingdom

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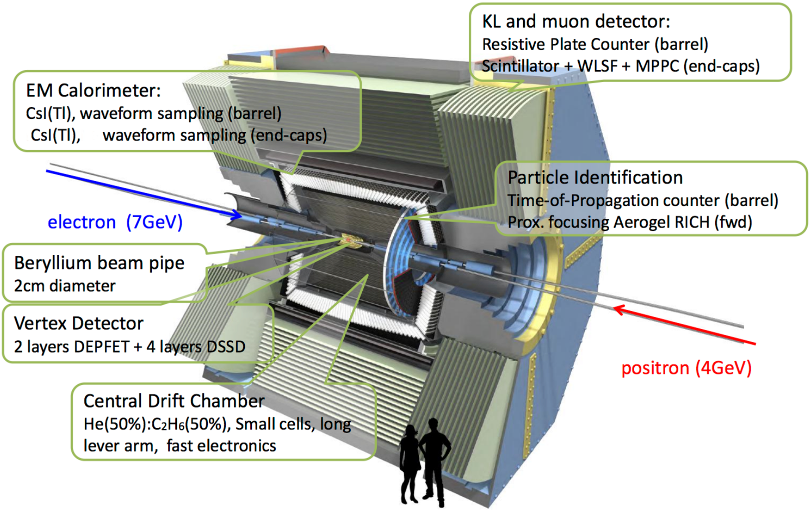
# The Belle II Experiment and its Goals

- KEKB was an electron-positron collider at KEK in Tsukuba/Japan which studied the decay of B mesons at the Υ(4S) resonance
- Nobel Prize in Physics 2008 to Kobayashi and Maskawa
- The SuperKEKB collider and the Belle II detector will build on the previous success:
  - Study the B meson system in far greater precision
  - Probe for new physics in a wide range of interesting topologies
  - Spectroscopy of Quarkonium systems
- The Belle II Collaboration: 681 scientists from 100 institutes in 23 countries

| | KEKB | Super KEKB | Factor |
|---|---|---|---|
| Instantaneous Luminosity | $2 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ | $8 \times 10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ | 40 |
| Integrated Luminosity | $1\,\mathrm{ab}^{-1}$ | $50\,\mathrm{ab}^{-1}$ | 50 |
| Runtime | 1998 to 2010 | start in 2017 | |
| Detector | Belle | Belle II | |
| Raw Data | 1 PB | 100 PB (projected) | 100 |

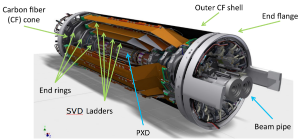
# Belle II Detector

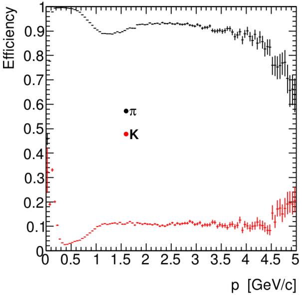


# Highlights of the Belle II Design

Completely new VerteX Detector (VXD):

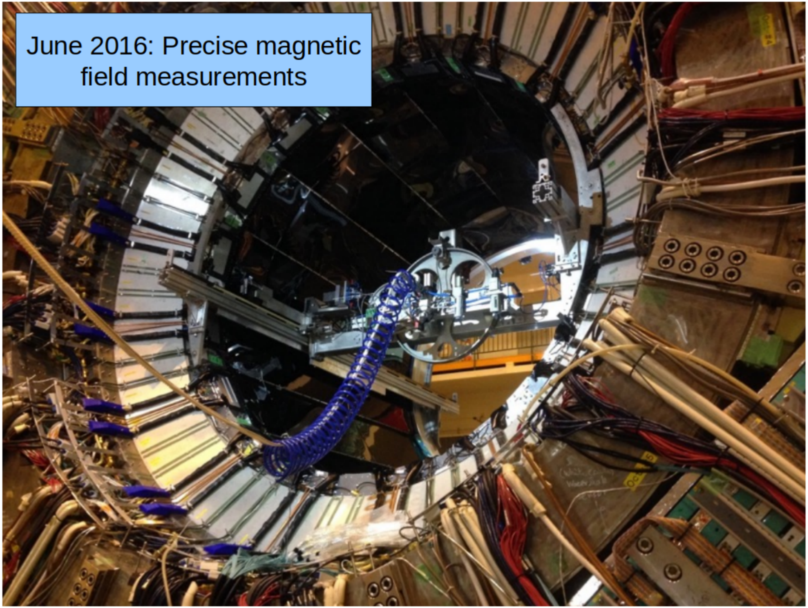
- Two inner DEPFET Pixel Layer (PiXel Detector) : PXD
- Four outer Silicon Strip Layers (Silicon Vertex Detector) : SVD
- Very light mechanical structure: $X/X_0 \approx 0.5\%$ per SVD layer, $X/X_0 \approx 0.19\%$ per PXD layer
- Factor 1.5 improvement of the impact parameter over a wide range with the new inner tracking system (compared to Belle)




- Improved Central Drift Chamber which builds on Belle's established design: Denser inner layer and larger radius for better momentum reconstruction
- New Time-of-Flight (TOP), Aerogel-RICH detectors and drift chamber dE/dX for particle identification
- Upgrade to the hardware Level-1 trigger to support triggers for low-multiplicity events

## June 2016: Precise magnetic field measurements




October 2016: CDC Installation

# Members of the Collaboration in front of the Belle II Detector

Belle II

# 11. April LIVE CAST: Roll-in of Belle 2 Detector


Link to livecast: `https://t.co/7k54fKQMYV`

`https://www.belle2.org`

`https://twitter.com/belle2collab`

`https://www.facebook.com/belle2collab`

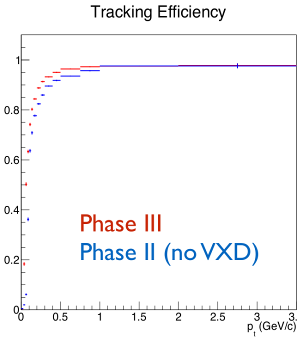
# Belle II Commissioning and Early Physics Opportunities

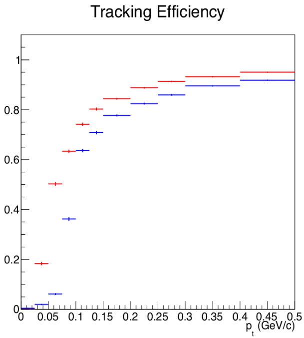
- **BEAST Phase I** completed Feb-June 2016: SuperKEKB commissioning with the BEAST detector to characterize the beam environment
- **Phase II** End of 2017 / early 2018:
  - Roll-in of Belle II detector: 11. April 2017
  - Belle II without the inner silicon-based VXD tracking system
  - Commissioning of damping ring and first $e^+e^-$ collisions
  - Characterize background radiation innermost tracking system is exposed to
  - Estimated duration $\sim$ 5 month and recording of $20 - 40\,\text{fb}^{-1}$ at various energies
  - First months will be commissioning data to test the sub-detectors and to study the machine background
- **Phase III** End of 2018/Beginning 2019:
  - Start of data taking with the complete Belle II detector
  - Primary running at $\Upsilon(4S)$ for B-pair production

# Detector and Reconstruction Performance

## Phase II

- Due to missing VXD system: degraded tracking efficiency and resolution, especially for particles $< 500\,\mathrm{MeV}$
- The CDC tracking system will be fully installed and provide sufficient hits for high-pt tracks
- Particle identification systems and ECL are not affected by the missing VXD system



# Quarkonium Spectroscopy at B-Factories

- The B-Factories Belle and BaBar made important contributions to better understand the spectrum of Charmonium and Bottomonium
- Unexpected findings by the B-factories were the observation of many Quarkonium-like states
- Belle in 2003: discovery of the exotic Charmonium state X(3872)[1]
- Since then, many other experiments have confirmed the discovery
- In 2013, LHCb determined the quantum numbers of X(3872)[2]

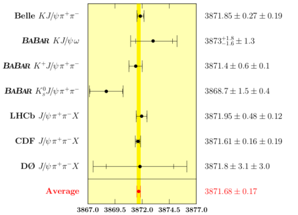
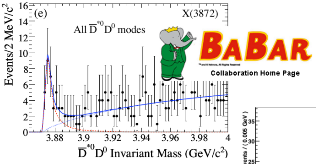
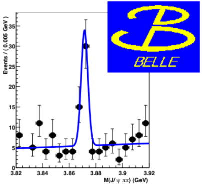



**Figure 18.3.3.** Measured mass of the $X(3872)$. We show the measurements which contribute to the average in Beringer et al. (2012).



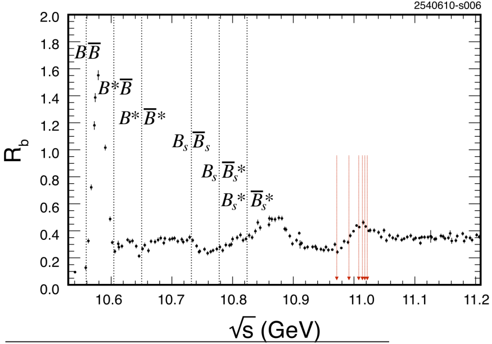




[1] https://arxiv.org/abs/hep-ex/0308029
[2] https://arxiv.org/abs/1302.6269

# Existing $\Upsilon$-related Datasets

| Experiment | Scans Off. Res. | $\Upsilon(6S)$ $fb^{-1}$ | $\Upsilon(5S)$ $fb^{-1}$ | $\Upsilon(5S)$ $10^6$ | $\Upsilon(4S)$ $fb^{-1}$ | $\Upsilon(4S)$ $10^6$ | $\Upsilon(3S)$ $fb^{-1}$ | $\Upsilon(3S)$ $10^6$ | $\Upsilon(2S)$ $fb^{-1}$ | $\Upsilon(2S)$ $10^6$ | $\Upsilon(1S)$ $fb^{-1}$ | $\Upsilon(1S)$ $10^6$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CLEO | 17.1 | - | 0.1 | 0.4 | 16 | 17.1 | 1.2 | 5 | 1.2 | 10 | 1.2 | 21 |
| BaBar | 54 | $R_b$ scan | | | 433 | 471 | 30 | 122 | 14 | 99 | – | |
| Belle | 100 | $\sim 5.5$ | 36 | 121 | 711 | 772 | 3 | 12 | 25 | 158 | 6 | 102 |

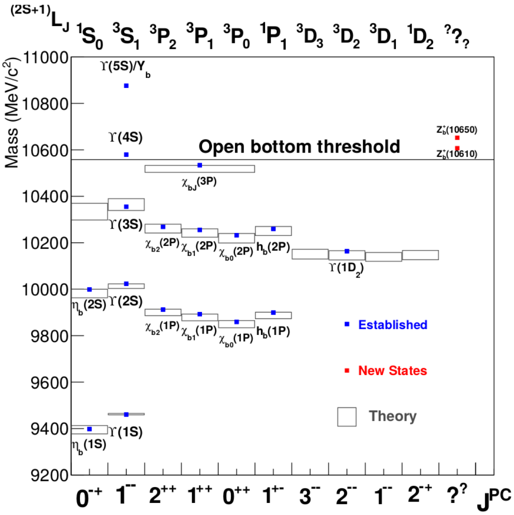
[3]




Belle took 5.5 $fb^{-1}$ data at 6 different energies on and around the $\Upsilon(6S)$ resonance energy.

[3] from B2Tip report, to be published
`https://confluence.desy.de/display/BI/B2TiP+WebHome`

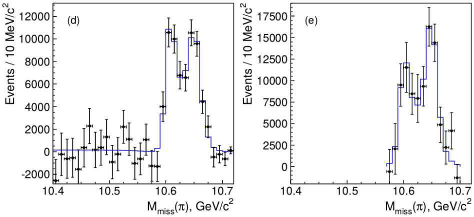
# Bottomonium States



# Belle's $Z_b$ discovery at $Y(5S)$

- Belle observed higher then expected rates[4] for the transition $\Upsilon(5S) \rightarrow h_b(nP)\pi^+\pi^-$
- The rates are unsuppressed relative to $\Upsilon(5S) \rightarrow \Upsilon(nS)\pi^+\pi^-(n = 1, 2, 3)$, even though it should be suppressed due to the spin-flip of one of the $b$
- Analysis of the decay revealed two new charged, and therefore exotic, states $Z_b(10610)$ and $Z_b(10650)$
- The neutral partner $Z_b^0(10610)$ was discovered in the transition $\Upsilon(5S) \rightarrow h_b(nP)\pi^0\pi^0$
- Multiple explanations for the exotic $Z_b$ states exist, for example a molecular nature of the state of at least four quarks

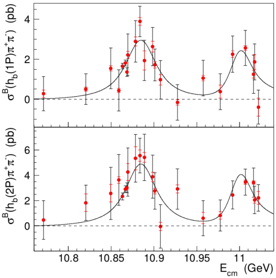
| State | Mass (MeV/$c^2$) | Width (MeV/$c^2$) | Reference |
|---|---|---|---|
| $Z_b^{\pm}(10610)$ | $10607.2 \pm 2.0$ | $18.4 \pm 2.4$ | [67] |
| $Z_b^{\pm}(10650)$ | $10652.2 \pm 1.5$ | $11.5 \pm 2.2$ | [67] |
| $Z_b^{0}(10610)$ | $10609 \pm 4 \pm 4$ | – | [69] |

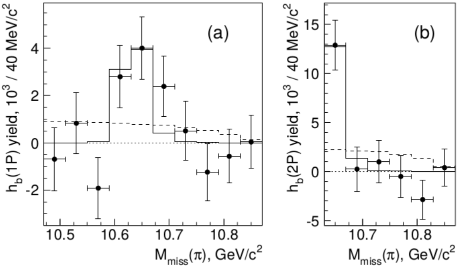



[4] https://arxiv.org/abs/1110.2251

# Belle's Indications for $\Upsilon(6S) \to Z_b$

Preliminary evidence at Belle, but not sufficient statistics to clearly separate $Z_b$ contributions[5]



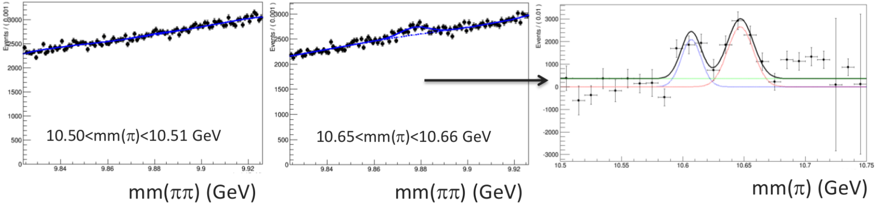

[5] https://arxiv.org/abs/1508.06562

# Analysis Technique for $\Upsilon(pS) \to Z_b$ transitions

- Consider one of the Golden Modes:
  $\Upsilon(6S) \to \pi Z_b(\pi h_b(nP))$
- The missing mass can be computed for the two pion system
  $M_{miss}(\pi\pi) = \sqrt{(E_{c.m.} - E_{\pi\pi})^2 - p_{\pi\pi}^2}$
  and for each pion individually
  $M_{miss}(\pi) = \sqrt{(E_{c.m.} - E_{\pi})^2 - p_{\pi}^2}$
- One of the pion's missing mass must be within
  $10.55\,\text{GeV} < M_{miss}(\pi) < 10.70\,\text{GeV}$ to select the pion created in the $\Upsilon(6S) \to \pi Z_b$ transition
  - The missing mass of this pion can be used to deduce the $Z_b$ properties
- Additional requirements to suppress background:
  - High Particle ID confidence for pion hypothesis
  - Pions originated at the interaction point of Belle II
- Fitting the $M_{miss}(\pi)$ distribution with Gaussian plus 4th order Chebyshev polynomial

# Belle II's $\Upsilon(6S)$ measurements in Phase II

- May take $\sim 20 - 40\,\mathrm{fb}^{-1}$ during the Phase II data taking and $\sim 10\,\mathrm{fb}^{-1}$ at $\Upsilon(6S)$ resonance energy
- Using the Golden Modes:
  - $\Upsilon(6S) \to \pi Z_b(\pi h_b(nP))$
  - $\Upsilon(6S) \to \pi Z_b(\pi \Upsilon(pS)(l^+ l^-))$
- Monte-Carlo studies show that a good separation is possible with $10\,\mathrm{fb}^{-1}$ of data

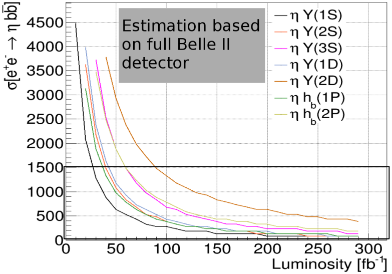


# More with $\Upsilon(6S)$: $\eta$ Transitions

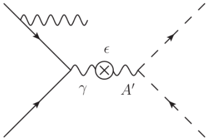
- The $\Upsilon(6S) \to \eta$ transition can be used to access (missing) states below the open beauty threshold
- Interesting to measure, because $\eta$ transitions are always violating the Heavy Quark Spin Symmetry $\to$ comparison with QCD multipole expansion computations
- Based on Y(5S) experience, it is reasonable to expect a cross section $< 1500$ fb

Search for missing conventional bottomonia below BB threshold

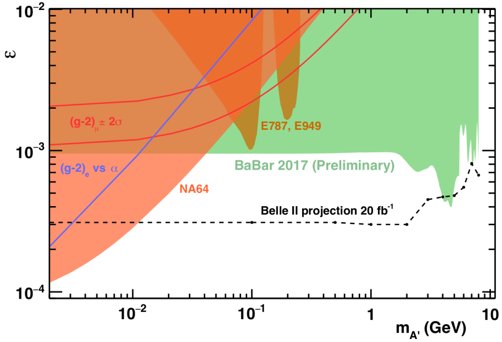
| Name | $L$ | $S$ | $J^{PC}$ | Mass, MeV/$c^2$ | Emitted hadrons [Threshold, GeV/$c^2$] |
|---|---|---|---|---|---|
| $\eta_b(3S)$ | 0 | 0 | $0^{-+}$ | 10336 | $\omega$ [11.12], $\phi$ [11.36] |
| $h_b(3P)$ | 1 | 0 | $1^{+-}$ | 10541 | $\pi^+\pi^-$ [10.82], $\eta$ [11.09], $\eta'$ [11.50] |
| $\eta_{b2}(1D)$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



# Dark Photon Search

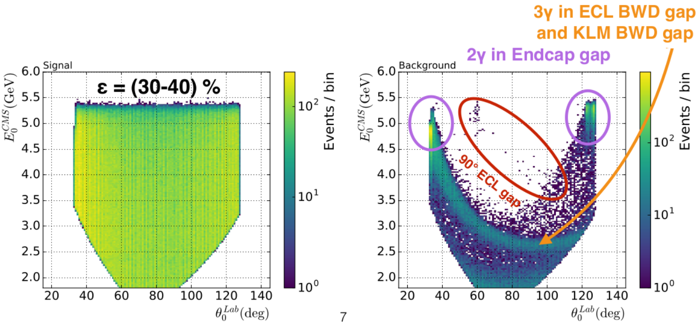



- Hypothetical dark photon (A') production in $e^+e^-$ annihilation
- With 20 $\mathrm{fb}^{-1}$ of recorded events, a preliminary projection shows a big exclusion potential for Belle II's early data taking
- BaBar recently published a dark photon search with 53 $\mathrm{fb}^{-1}$ `https://arxiv.org/abs/1702.03327`



# Belle II's Dark Photon Search in Phase II

- Very challenging experimental signature: A'(invisible) and one $\gamma$
- Special single photon trigger required:
  - Cascaded: different pre-scales for different thresholds
  - Different pre-scales for Barrel and Endcap regions
- Irreducible dominant background $ee \rightarrow ee\gamma$ where both electrons are outside of the detector acceptance
- Good tracking efficiency required to reject events with tracks
- Using KLM cluster information to reject events falling into ECL gaps



## Summary

- Belle II's Phase II commissioning run can already provide important contributions to our understanding of the Bottomonium system and in dark sector searches
- The goal is to record $20 - 40\,\mathrm{fb}^{-1}$ at various energies and at least $10\,\mathrm{fb}^{-1}$ at the $\Upsilon(6S)$ energy
- If accelerator and detector perform as expected:
  Almost double the $\Upsilon(6S)$ data set of Belle and allow to probe the $\Upsilon(6S) \rightarrow Z_b$ transition
- New single photon trigger for dark photon searches can be commissioned and the triggered events used for searches in this area