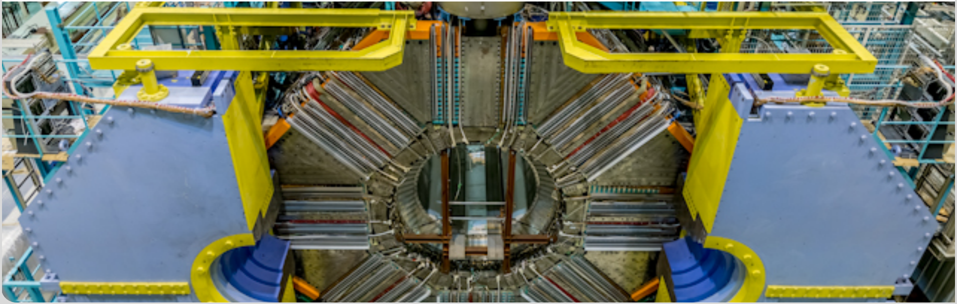
Hadron Spectroscopy Studies at Belle II

XLVII International Symposium on Multiparticle Dynamics, Tlaxcala, Mexico

Nils Braun for the Belle II Collaboration | 12.09.2017

ETP - KARLSRUHE INSTITUTE OF TECHNOLOGY



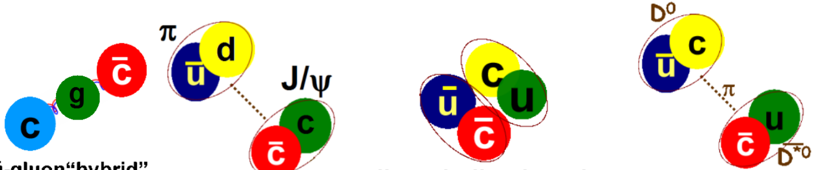
Quarkonium and Quarkonium-like states

Quarkonium

conventional quarkonium

positronium

Theory models for Quarkonium-like/Exotic States



$q\bar{q}$-gluon“hybrid”

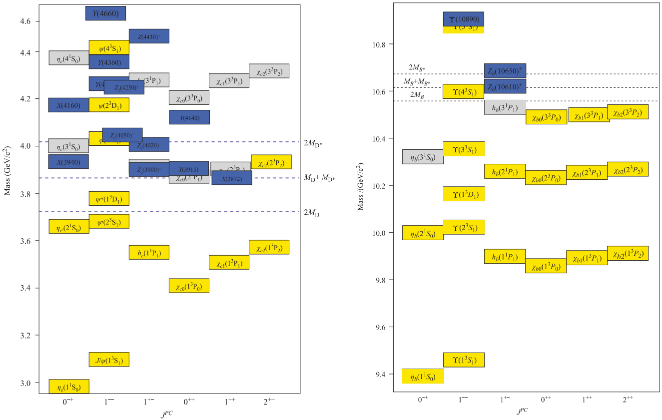
hadroquarkonium

diquark-diantiquark

$D^0 - \bar{D}^{*0}$ “molecule”

Quarkonium and Quarkonium-like states

charmonium(like) bottomonium(like)



Established states | Predicted, undiscovered | Charged *XYZ* mesons

Starting from the discovery of X(3872) in 2003, more than 20 exotic states have been reported!

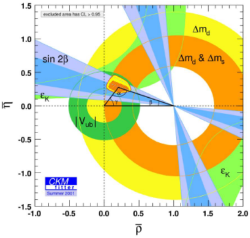
Introduction to Belle II

Belle - A success story

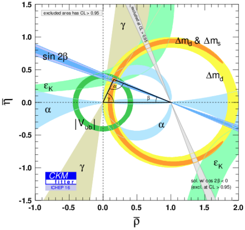
Karlsruher Institut für Technologie

- KEKB was an electron-positron collider at KEK in Tsukuba/Japan which studied the decay of B mesons at the $\Upsilon(4S)$ resonance
- It had a large physics program, including:
  - Measurements of CKM matrix elements and angles of the unitarity triangle
  - Observation of direct CP violation in B decays
  - Measurements of rare decay modes
  - Searches for rare τ decays
  - *Discovery of exotic hadrons including charged charmonium- and bottomonium-like states*

EPS 2001



EPS 2016



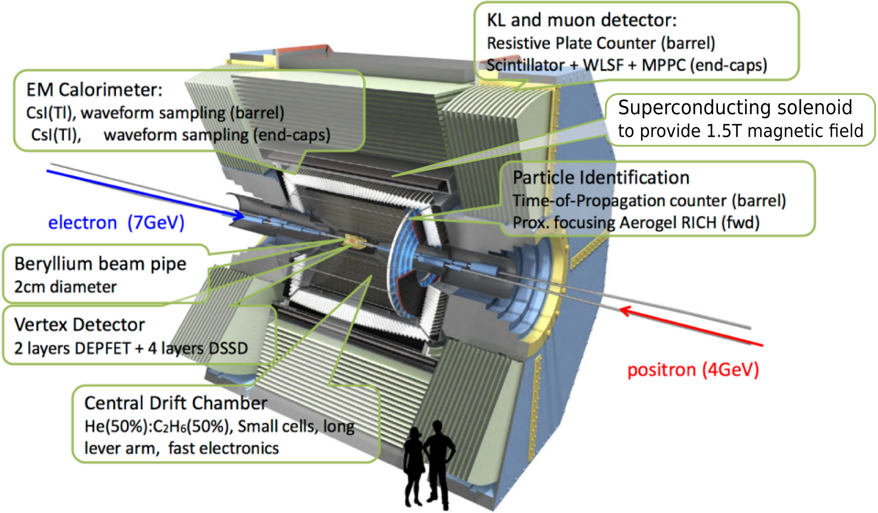
From Belle to Belle II

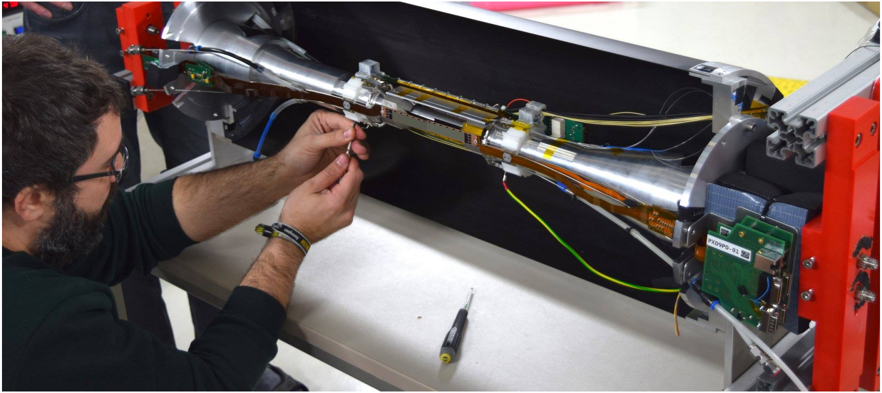
	KEKB	Super KEKB
Instantaneous Luminosity in $10 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	2	80
Integrated Luminosity in ab^{-1}	1	50
Runtime	1998 to 2010	start in 2018
Detector	Belle	Belle II
Raw Data	1 PB	100 PB (projected)

Higher precision – wider range of topologies – better spectroscopy

- Higher luminosity also leads to a higher background $\Rightarrow$ need for better detector, better trigger, better software reconstruction
- World-wide collaboration is working on the upgrade (681 scientists from 100 institutes in more than 20 countries)

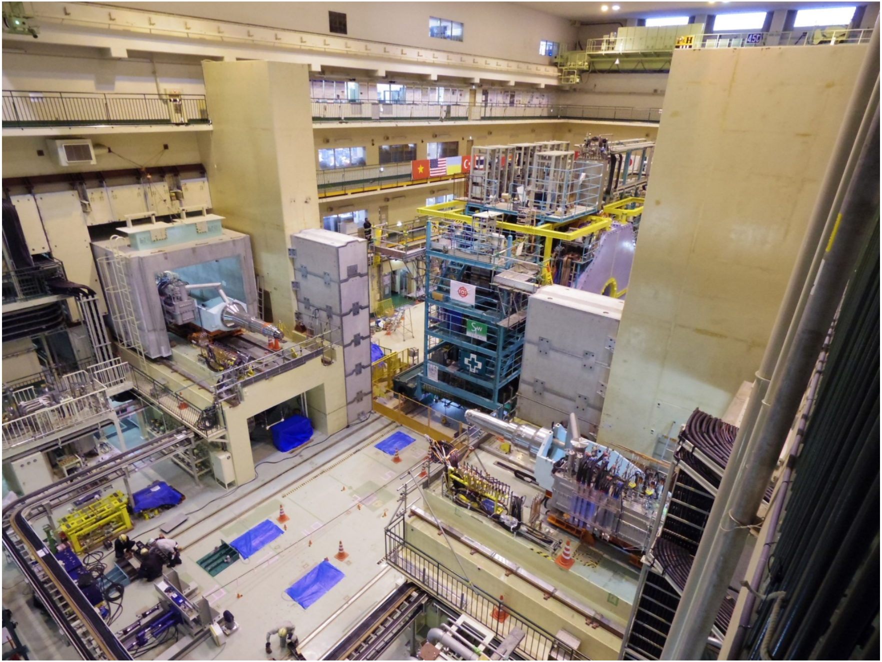
Belle II Detector

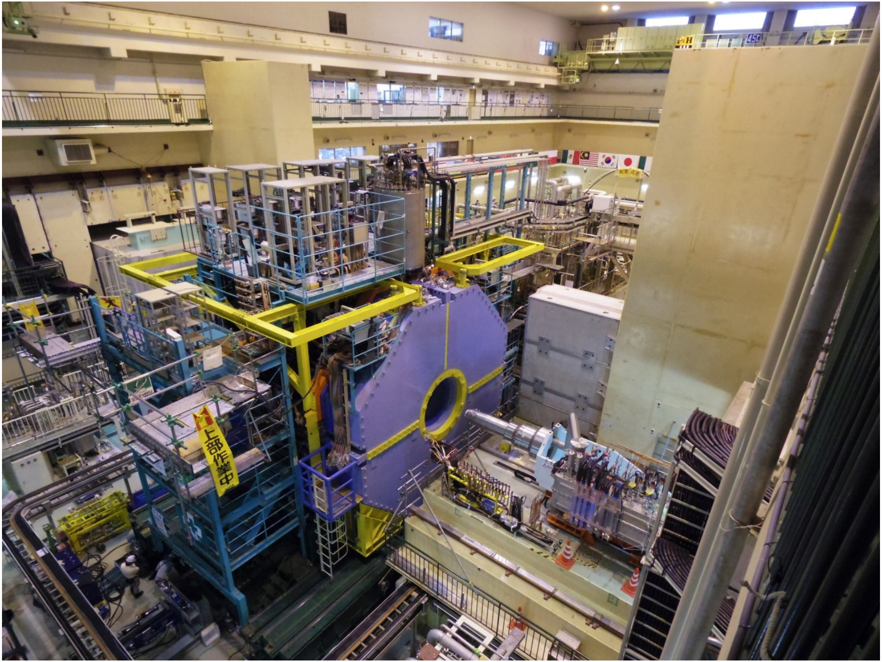




First beam test for the innermost tracking detectors at DESY, Germany.

October 2016: CDC Installation

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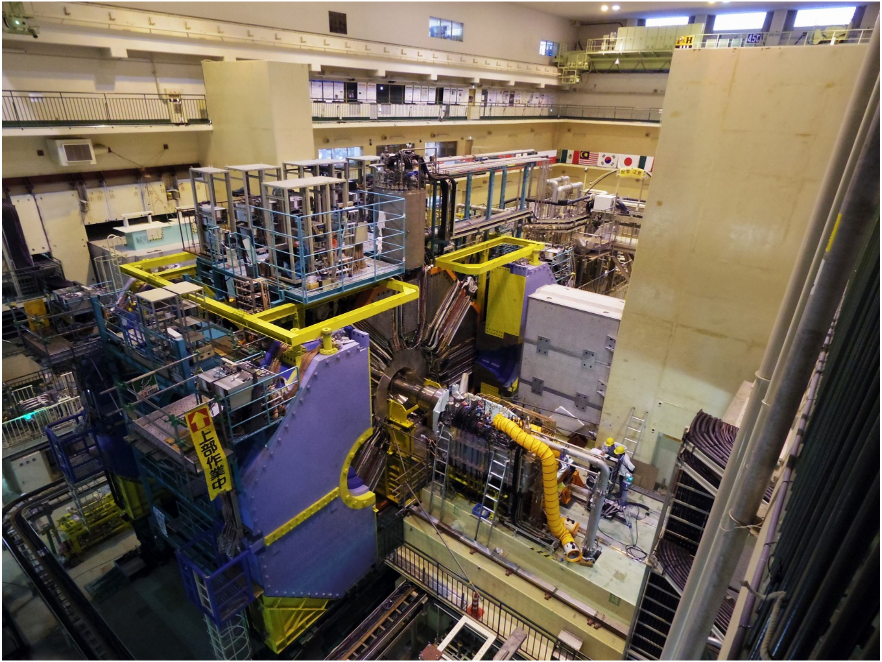
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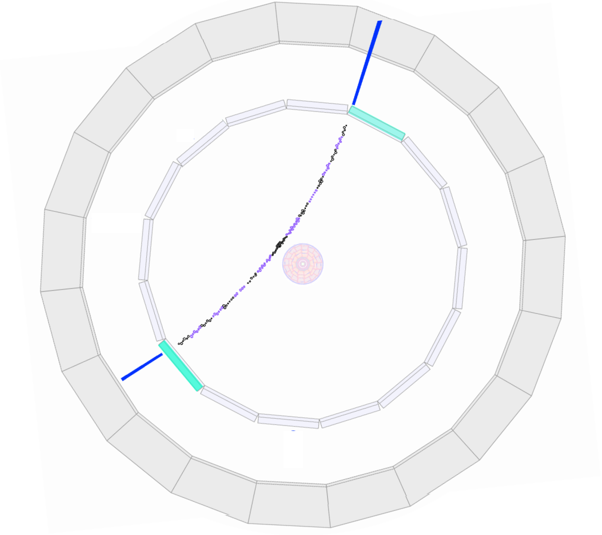
First cosmic events reconstructed with CDC



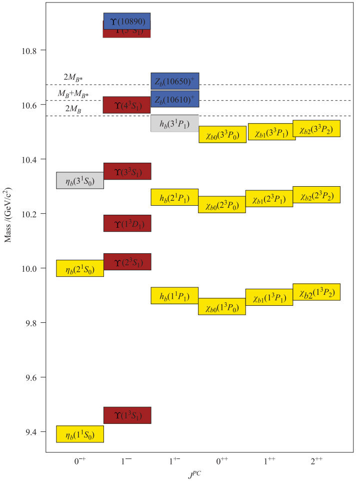
Belle II Commissioning and Early Physics Opportunities

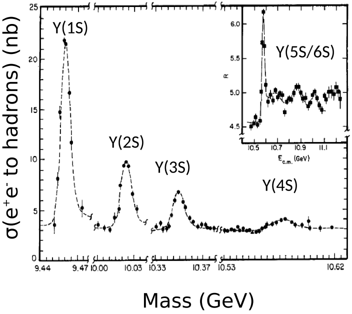
- **BEAST Phase I** completed Feb-June 2016: SuperKEKB commissioning to characterize the beam environment
- **Phase II** Early 2018:
  - Belle II without the inner silicon-based VXD tracking system
  - Characterize background radiation the innermost tracking system is exposed to
  - Estimated duration ~ 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** Beginning 2019:
  - Start of data taking with the complete Belle II detector
  - Primary running at $\Upsilon(4S)$ for B-pair production

Experiment	Scans	$\Upsilon(6S)$	$\Upsilon(5S)$		$\Upsilon(4S)$		$\Upsilon(3S)$		$\Upsilon(2S)$		$\Upsilon(1S)$	
	Off. Res.	fb^{-1}	fb^{-1}	10^6	fb^{-1}	10^6	fb^{-1}	10^6	fb^{-1}	10^6	fb^{-1}	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	~ 5.5	36	121	711	772	3	12	25	158	6	102

Quarkonium and Quarkonium-like states

bottomonium(like)

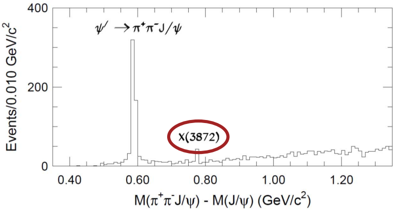


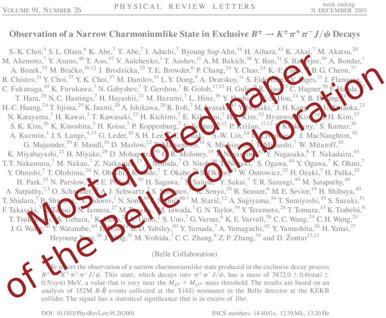


Hadron Spectroscopy at Belle II

Belle - Another success story

- The series of discoveries started with the observation of the η_c' meson in $\mathrm{B} \to \mathrm{K}\eta_c'$ decays.
- The first exotic state was X(3872) – again found in $\mathrm{B} \to \mathrm{K}$X(3872) decays





VOLUME 91, NUMBER 26 PHYSICAL REVIEW LETTERS week ending 31 DECEMBER 2003

Observation of a Narrow Charmoniumlike State in Exclusive $B^\pm \to K^\pm \pi^+ \pi^- J/\psi$ Decays

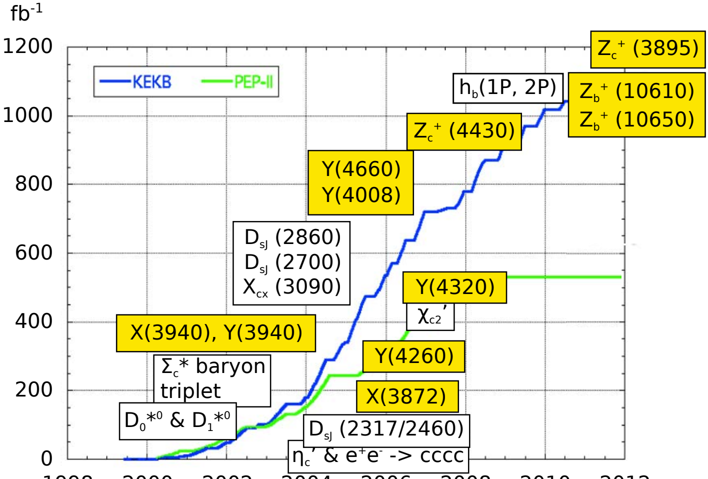
S.-K. Choi,[5] S. L. Olsen,[6] K. Abe,[7] T. Abe,[7] I. Adachi,[7] Byoung Sup Ahn,[14] H. Aihara,[43] K. Akai,[7] M. Akatsu,[20] M. Akemoto,[7] Y. Asano,[48] T. Aso,[47] V. Aulchenko,[1] T. Aushev,[11] A. M. Bakich,[38] Y. Ban,[31] S. Ba[illegible]jee,[39] A. Bondar,[1] A. Bozek,[25] M. Bračko,[18,12] J. Brodzicka,[25] T. E. Browder,[6] P. Chang,[24] Y. Chao,[24] K.-F. [illegible] B. G. Cheon,[37] R. Chistov,[11] Y. Choi,[37] Y. K. Choi,[37] M. Danilov,[11] L. Y. Dong,[9] A. Drutskoy,[11] S. Eid[illegible] [illegible],[11] J. Flanagan, C. Fukunaga,[45] K. Furukawa,[7] N. Gabyshev,[7] T. Gershon,[7] B. Golob,[17,12] H. Gule[illegible] [illegible] C. Hagner,[50] [illegible] T. Hara,[29] N. C. Hastings,[7] H. Hayashii,[21] M. Hazumi,[7] L. Hinz,[16] [illegible] [illegible]-S. Hou,[24] Y. B. H[illegible] H.-C. Huang,[24] T. Iijima,[20] K. Inami,[20] A. Ishikawa,[20] R. Itoh,[7] [illegible] [illegible] J. H. Kang [illegible] [illegible],[21] N. Katayama,[7] H. Kawai,[2] T. Kawasaki,[27] H. Kichimi,[7] E. Kik[illegible],[7] [illegible] Kim,[52] Hyunwo[illegible] [illegible] H. Kim,[37] S. K. Kim,[36] K. Kinoshita,[3] H. Koiso,[7] P. Koppenburg,[7] [illegible] P. Križan,[17,12] [illegible] S. Kumar,[30] A. Kuzmin,[1] J. S. Lange,[4,33] G. Leder,[10] S. H. Lee,[illegible] [illegible] S.-W. Lin,[24] [illegible] J. MacNaughton,[10] G. Majumder,[39] F. Mandl,[10] D. Marlow,[32] [illegible],[45] S. Mi[illegible] [illegible] W. Mitaroff,[10] K. Miyabayashi,[21] H. Miyake,[29] D. Mohapatra,[50] [illegible] R. Moloney,[19] [illegible],[42] Y. Nagasaka,[8] T. Nakadaira,[43] T. T. Nakamura,[7] M. Nakao,[7] Z. Natkanie[illegible] [illegible] Nishida,[7] O. Nitoh,[46] [illegible] S. Ogawa,[40] Y. Ogawa,[7] K. Ohmi,[7] Y. Ohnishi,[7] T. Ohshima,[20] N. Oh[illegible] [illegible] [illegible] T. Okabe,[illegible] [illegible] W. Ostrowicz,[25] H. Ozaki,[7] H. Palka,[25] H. Park,[15] N. Parslow,[illegible] [illegible],[50] H. Sagawa,[7] [illegible] Y. Sakai,[7] T. R. Sarangi,[49] M. Satapathy,[49] A. Satpathy,[7,3] O. Schn[illegible] A. J. Schwartz,[3] S. S[illegible] [illegible] Senyo,[20] R. Seuster,[6] M. E. Sevior,[19] H. Shibuya,[40] T. Shidara,[7] B. Sh[illegible] [illegible] [illegible] N. Son[illegible] [illegible],[48,†] M. Starič,[12] A. Sugiyama,[34] T. Sumiyoshi,[45] S. Suzuki,[51] F. Takasaki,[7] [illegible] N. Tamura,[27] [illegible] M. Tawada,[7] G. N. Taylor,[19] Y. Teramoto,[28] T. Tomura,[43] K. Trabelsi,[6] T. Tsu[illegible] S. Uehara,[7] [illegible] S. Uno,[7] G. Varner,[6] K. E. Varvell,[38] C. C. Wang,[24] C. H. Wang,[23] J. G. Wa[illegible] Y. Watanabe,[44] [illegible] B. D. Yabsley,[50] Y. Yamada,[7] A. Yamaguchi,[42] Y. Yamashita,[26] H. Yanai,[27] Heyoung [illegible],[36] J. [illegible],[31] M. Yoshida,[7] C. C. Zhang,[9] Z. P. Zhang,[35] and D. Žontar[17,12]

(Belle Collaboration)

[illegible] report the observation of a narrow charmoniumlike state produced in the exclusive decay process $B^\pm \to K^\pm \pi^+ \pi^- J/\psi$. This state, which decays into $\pi^+\pi^- J/\psi$, has a mass of $3872.0 \pm 0.6(\mathrm{stat}) \pm 0.5(\mathrm{syst})$ MeV, a value that is very near the $M_{D^0} + M_{D^{*0}}$ mass threshold. The results are based on an analysis of 152M $B\text{-}\bar{B}$ events collected at the $\Upsilon(4S)$ resonance in the Belle detector at the KEKB collider. The signal has a statistical significance that is in excess of 10σ.

DOI: 10.1103/PhysRevLett.91.262001 PACS numbers: 14.40.Gx, 12.39.Mk, 13.20.He

Belle - Another success story continued



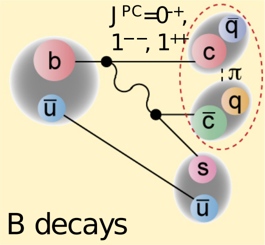
Coloured boxes: exotic candidates

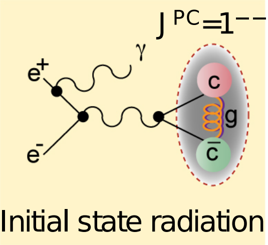
Why Hadron Spectroscopy at Belle II?

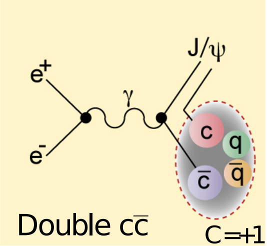
Unique capabilities of B factories:

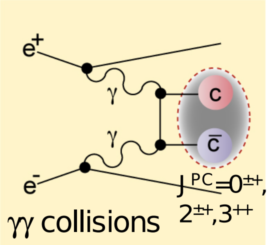
- Exactly two B mesons produced (at $\Upsilon(4S)$)
- Good reconstruction of γ, π^0
- Can reconstruct one resonance, look for the recoiling system (e.g. $\mathrm{e}^+\mathrm{e}^- \to \mathrm{J}/\psi + X$)
- Variety of different production channels
- High resolution, large solid angle spectrometer with particle identification capability makes reconstruction of many decay modes possible.

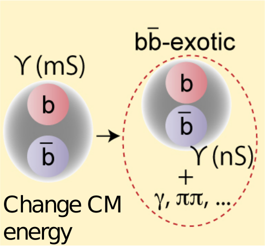
Production of Quarkonium at e^+e^- colliders







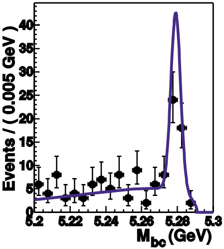


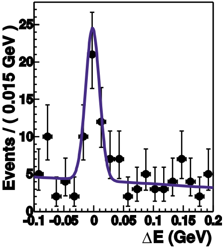


Allowed/favored quantum numbers are different depending on production processes.

Analysis techniques for Quarkonium searches - selection

With X(3872) as an example





Event reconstruction and selection

$$\mathrm{B}^{\pm} \to \mathrm{K}^{\pm}\pi^{+}\pi^{-}\mathrm{J}/\psi$$

- e.g. require two oppositely charged leptons with certain invariant mass

$$3.076 < M_{\ell^+\ell^-} < 3.116\,\mathrm{GeV}$$

- Reconstruct B mesons: Very helpful variables

$$|\Delta E| = |E_{\mathrm{B}}^{\mathrm{cms}} - E_{\mathrm{beam}}^{\mathrm{cms}}|$$

$$M_{\mathrm{bc}} = \sqrt{\left(E_{\mathrm{beam}}^{\mathrm{cms}}\right)^2 - \left(p_{\mathrm{B}}^{\mathrm{cms}}\right)^2}$$

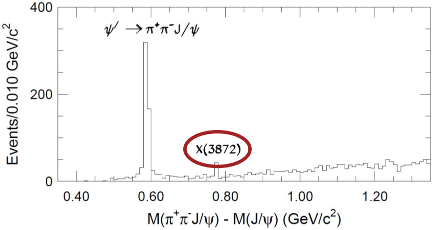
Similar without B mesons.

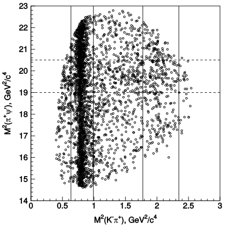
- Background sources: other decays, continuum, combinatorics, beam-induced background

Analysis techniques for Quarkonium studies

Extract information on state, e.g.

- Look at mass distributions $M(\pi^+\pi^-\ell^+\ell^-) - M(\ell^+\ell^-)$ or recoil mass (e.g. of J/ψ)
- Extract mass, width, significance
- Dalitz analysis and fit
- Full angular analysis

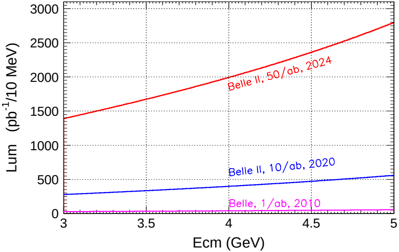




Dalitz analysis of $\mathrm{B} \to \mathrm{K}\pi^+\psi'$ (looking for $Z(4430)^+$) R. Mizuk et al. (Belle collaboration), PRD 80, 03114

Overview of the possible studies - Charmonium(-like)

Large amounts of data is needed ($> 1\,\mathrm{ab}^{-1}$) to be competitive to already performed studies $\Rightarrow$ only for phase III.



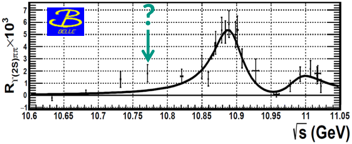
Effective luminosities at low energies by ISR in Belle and Belle II $\Upsilon(4S)$ runs.

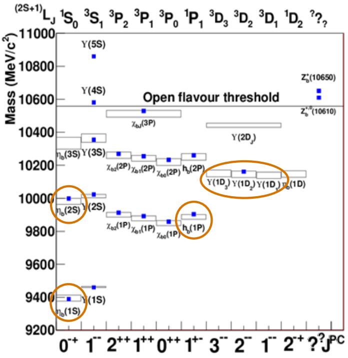
- total amplitude analyses of the three-body decays of charged charmonium-like states (Z^+) in B-decays.
- new exotic vector states (Y), fit for resonance parameters in initial-state radiation.
- Understand ”non-standard” decay properties above the open-charm threshold of standard charmonium ($\psi(4040), \psi(4160)$)
- Y(4140) and Y(4274)

Overview of the possible studies

Interesting and promising examples for bottomonium:

- $\Upsilon(6S)$ beam energy:
  - Understand $\Upsilon(6S) \rightarrow \mathrm{Z}_b$ states (molecular state? partners?)
  - bottomonium discovery ($h_b(3P), \Upsilon(2D)$)
  - sign of a Y_b state?
- $\Upsilon(3S)$ beam energy:
  - conventional bottomonium physics: $\Upsilon(1^3D_J)$ triplet, $\eta_b(1S, 2S)$
  - Hindered radiative transitions
  - dipion transitions
  - invisible decays





Three out of many possible Analyses at Belle II

η transitions

η transitions are always violating the Heavy Quark Spin Symmetry

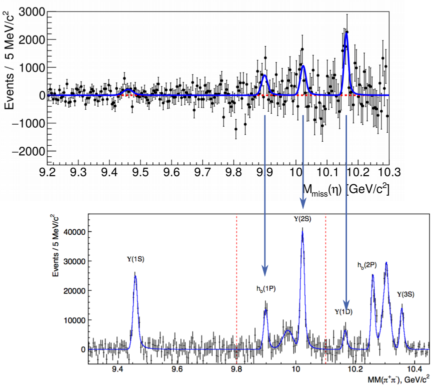
$$\frac{B[\Upsilon(nS) \to \eta\Upsilon(mS)]}{B[\Upsilon(nS) \to \pi\pi\Upsilon(mS)]} \approx \frac{\Lambda^2_{QCD}}{m_b^2} \approx 10^{-3}$$

$\Upsilon(5S) \to \eta\Upsilon(mS)$

(Belle, preliminary)

$\Upsilon(5S) \to \pi\pi\Upsilon(mS)$

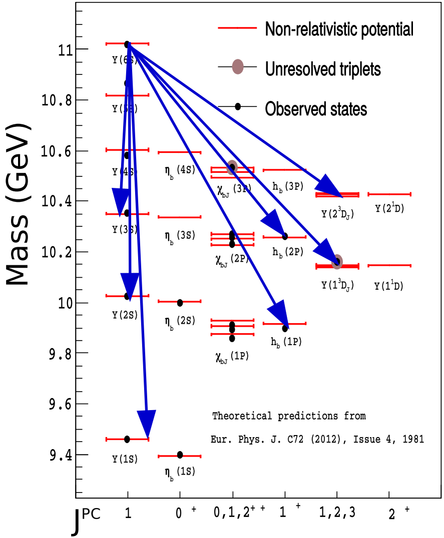
(Belle, Phys. Rev. Lett. 108, 032001)



η transitions from $\Upsilon(6S)$

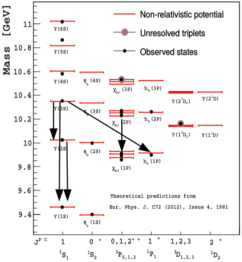
Selection algorithm:

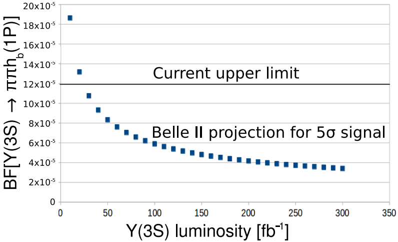
1. Reconstruct event and photons, look for $\eta \to \gamma\gamma$ only $\varepsilon = 58.0\%$
2. Cut on event topology (e.g. number of tracks > 3) $\varepsilon = 52.4\%$
3. Veto on π^0 $\varepsilon = 33.1\%$
4. Kinematic fit on invariant mass



$\Upsilon(3S) \to \pi\pi h_b(1P)$

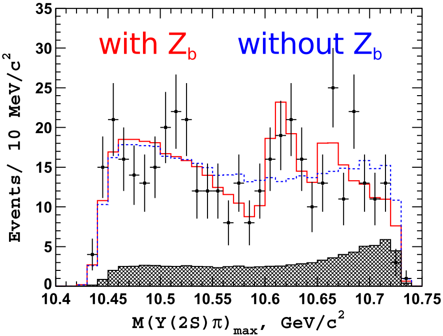
- Current limit on branching fraction of $< 1.2 \times 10^{-4}$ challenges most theoretical models.
- Search using the invariant mass recoiling against the $\pi^+\pi^-$ system (only possible at B-factories!)
- Great improvement possible because of better resolution of Belle II (compared to Belle and BaBar)





Search for partner states of $Z_b(10610)^0$

- $Z_b(10610)^0 \to \Upsilon(2S)\pi^0\pi^0$ was seen with 6.5 σ significance (PhysRev D 88, 052016).
- Theory models may imply partners, which decay into χ_{bJ} (S. Ohkoda et al., PRD 86, 014004 (2012)).
- Higher statistics needed, because signal yield is much lower (γ efficiency and $Br(\chi_{bJ} \to \Upsilon(1S, 2S, 3D)\gamma)$ are multiplied).



Summary

- The large data sample of Belle II will have a large impact on (exotic) quarkonium physics.
- Phase II with a partial detector will start soon.
- Hopefully, a deeper understanding on the origin of exotic states will be possible soon.

Stay tuned!

Thank you for your attention

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- Bottomonium Physics with the first ab^{-1}, *Umberto Tamponi*, 4th B2TiP
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- Dalitz analysis of $B \to K\pi^+\psi'$ decays and the $Z(4430)^+$, arXiv:0905.2869
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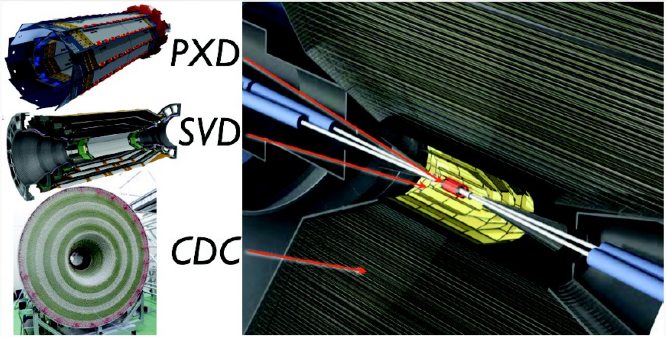
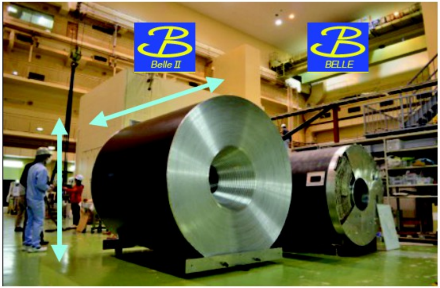
Backup

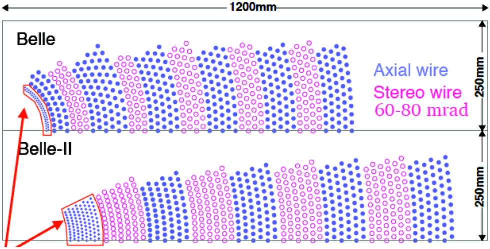
Tracking Detectors



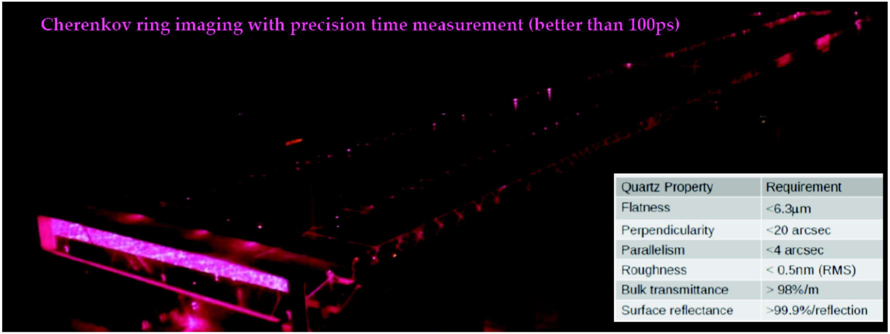
Component	Type	Configuration	Readout	Performance
Beam pipe	Beryllium double-wall	Cylindrical, inner radius 10 mm, 10 μm Au, 0.6 mm Be, 1 mm coolant (paraffin), 0.4 mm Be		
PXD	Silicon pixel (DEPFET)	Sensor size: 15×100 (120) mm^2 pixel size: 50×50 (75) μm^2 2 layers: 8 (12) sensors	10 M	impact parameter resolution $\sigma_{z_0} \sim 20$ μm (PXD and SVD)
SVD	Double sided Silicon strip	Sensors: rectangular and trapezoidal Strip pitch: 50(p)/160(n) - 75(p)/240(n) μm 4 layers: 16/30/56/85 sensors	245 k	
CDC	Small cell drift chamber	56 layers, 32 axial, 24 stereo r = 16 - 112 cm - 83 $\leq z \leq$ 159 cm	14 k	$\sigma_{r\phi} = 100$ μm, $\sigma_z = 2$ mm $\sigma_{p_t}/p_t = \sqrt{(0.2\% p_t)^2 + (0.3\%/\beta)^2}$ $\sigma_{p_t}/p_t = \sqrt{(0.1\% p_t)^2 + (0.3\%/\beta)^2}$ (with SVD)

CDC

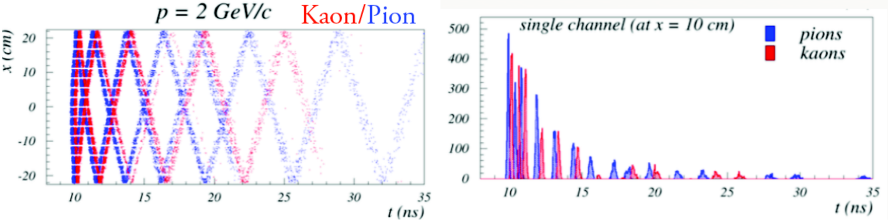

Belle II
BELLE


1200mm
Belle
Axial wire
Stereo wire
60-80 mrad
250mm
Belle-II
250mm

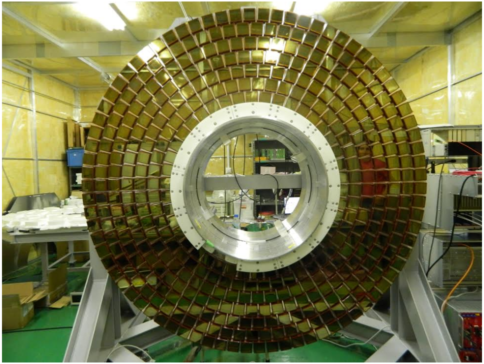
TOP



Quartz Property	Requirement
Flatness	<6.3µm
Perpendicularity	<20 arcsec
Parallelism	<4 arcsec
Roughness	< 0.5nm (RMS)
Bulk transmittance	> 98%/m
Surface reflectance	>99.9%/reflection

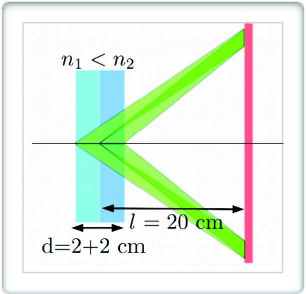


ARICH



- Use two aerogel layers in focusing configuration to increase n. of photons without resolution degradation

$$n_1 = 1.045,\ n_2 = 1.055$$

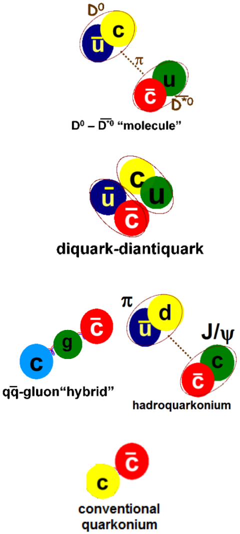


Why Hadron Spectroscopy?

- Large hierarchy of the physical scales makes heavy quarkonium very interesting
  - $m > \Lambda_{\text{QCD}}$
  - heavy-quark bound-state velocity $v \ll 1$
  - mass m, relative momentum $p \sim mv$ and binding energy $E \sim mv^2$ all at different scales
- In pertubative calculations: different scales get entangled. In lattice calculations: requirements on lattice spacing and size are difficult to met
- Ideal test environment for interplay between pertubative and non-pertubative QCD
- Large mass of quarkonium makes it suitable for probing BSM models in decays

Some Theory Explanations

- Meson Molecules:
  Weakly bound state of two mesons
- ”Tetraquarks”:
  Color-singlet diquarks bound directly by strong force
- Other exotica:
  - Hybrids: quarkonium with bound excited gluon
  - Hadroquarkonium: qq-light hadron interaction
- Nothing special:
  Kinematic effects / standard quarkonium



Detector and Reconstruction Performance Phase II

- Due to missing VXD system: lower tracking efficiency and resolution, especially for particles $< 500\,\text{MeV}$
- 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