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Studies of quarkonium at Belle and Belle II

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Pacific Northwest National Laboratory
APS DPF – Aug 01 2017

U.S. DEPARTMENT OF ENERGY

Outline

- Introduction
- Recent Belle results
  - Searches for exotic particles in Upsilon decays
  - $\Upsilon(4S) \to \eta, \pi\pi\ \Upsilon(pS)$ transitions
- The Belle II Experiment
  - Plans and status
  - Physics potential

Introduction

Quarkonium Introduction

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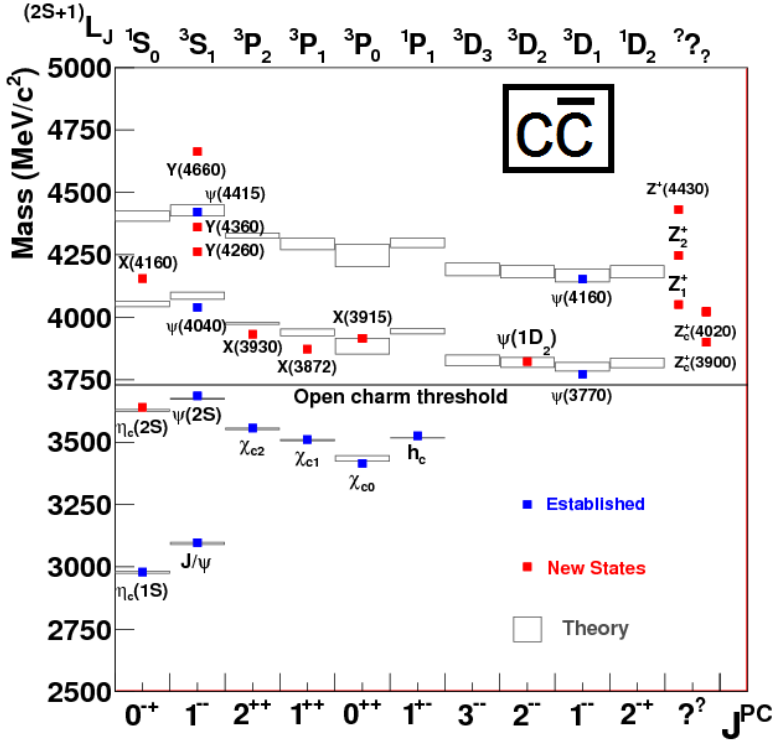
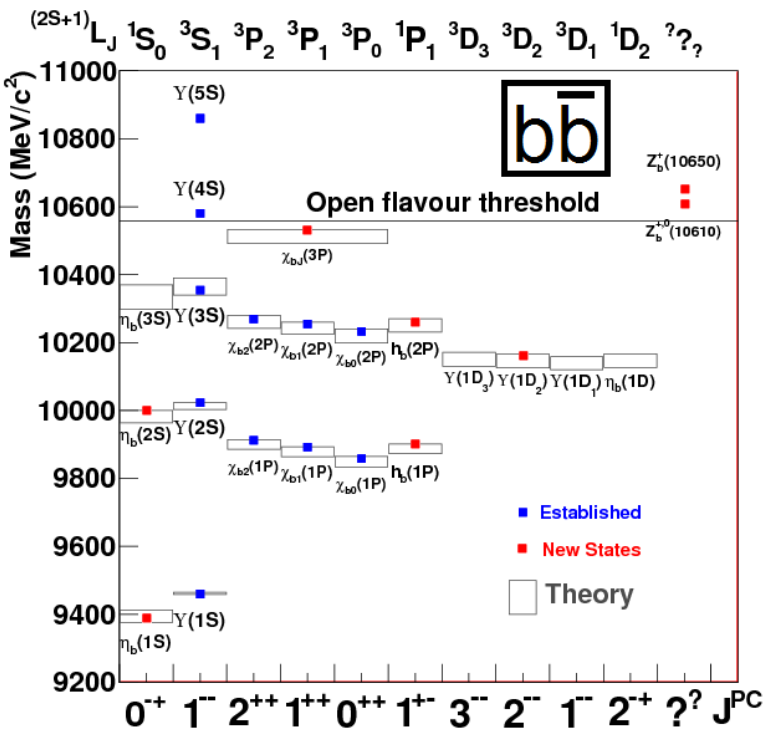
- **Bound state of heavy quark/anti-quark pair ($c\bar{c}$, $b\bar{b}$)**
- Large spectrum of particles, many recent discoveries





Quarkonium Introduction

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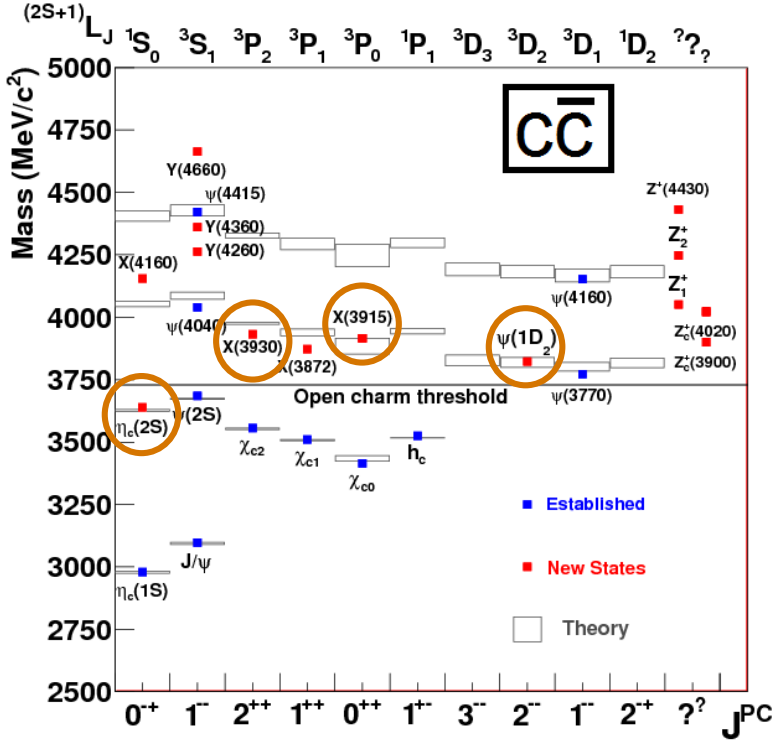
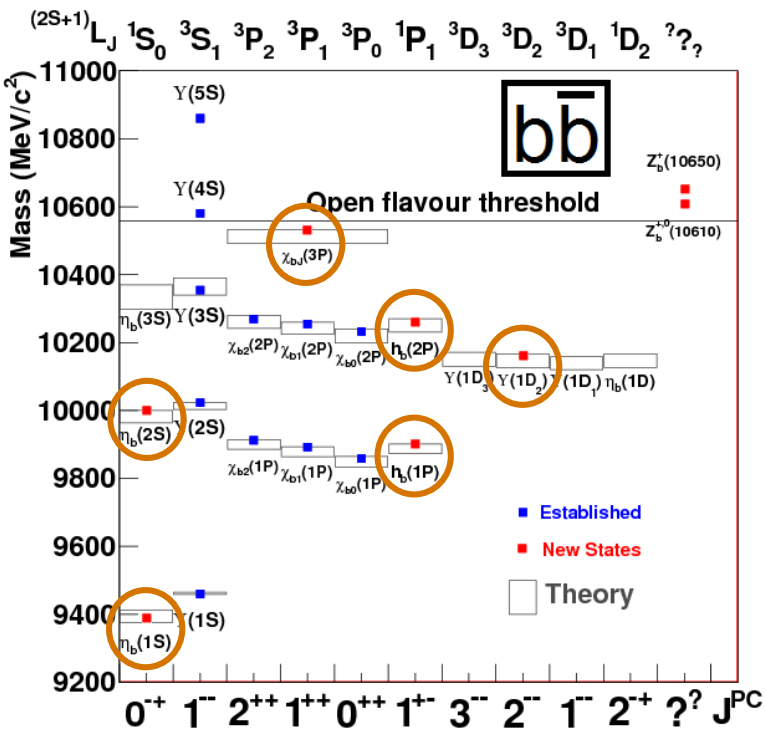
- **Bound state of heavy quark/anti-quark pair ($c\bar{c}$, $b\bar{b}$)**
- Large spectrum of particles, many recent discoveries
- First discoveries of long-predicted quarkonia





Quarkonium Introduction

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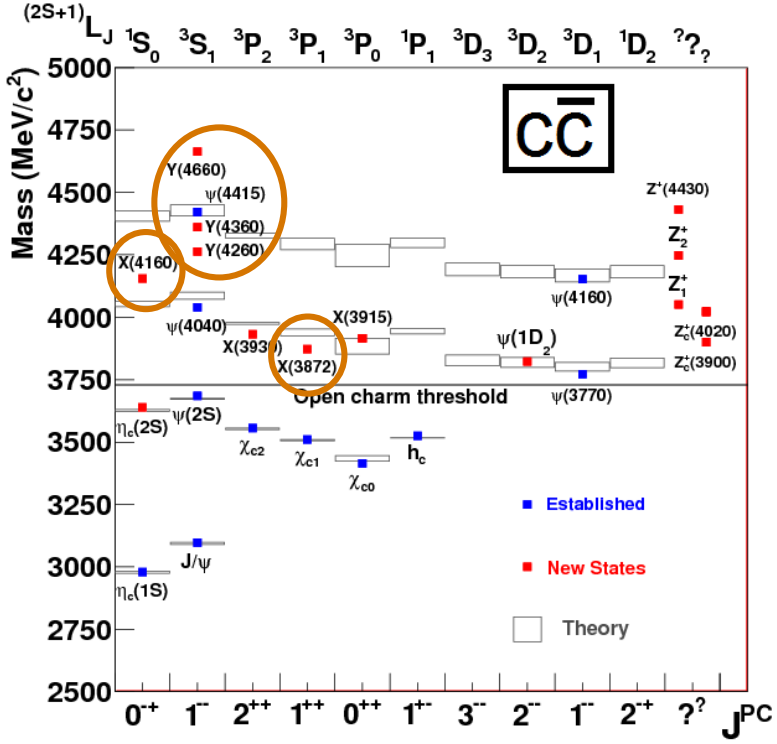
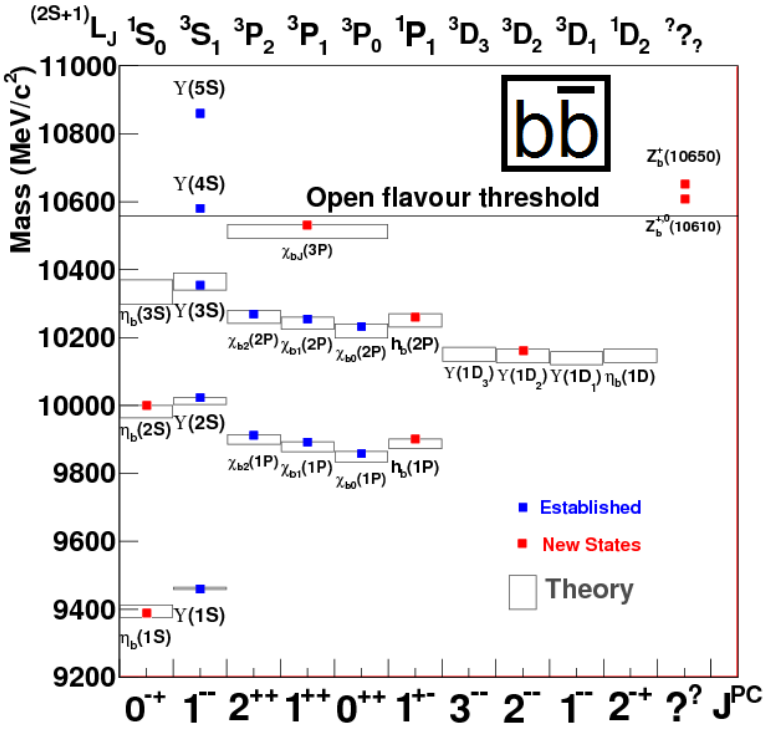
- **Bound state of heavy quark/anti-quark pair ($c\bar{c}$, $b\bar{b}$)**
- Large spectrum of particles, many recent discoveries
- Many difficult to explain within the quarkonium model





Quarkonium Introduction

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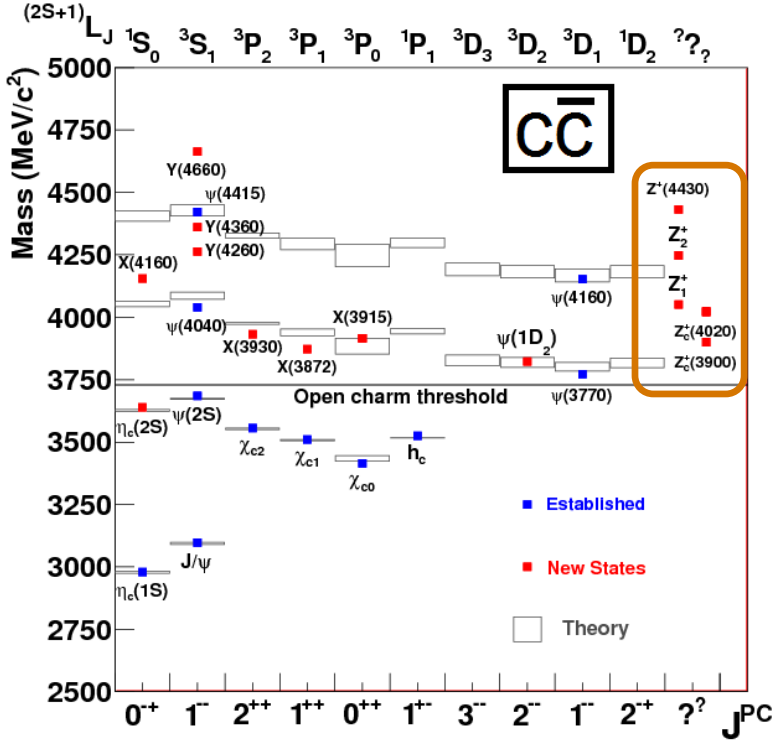
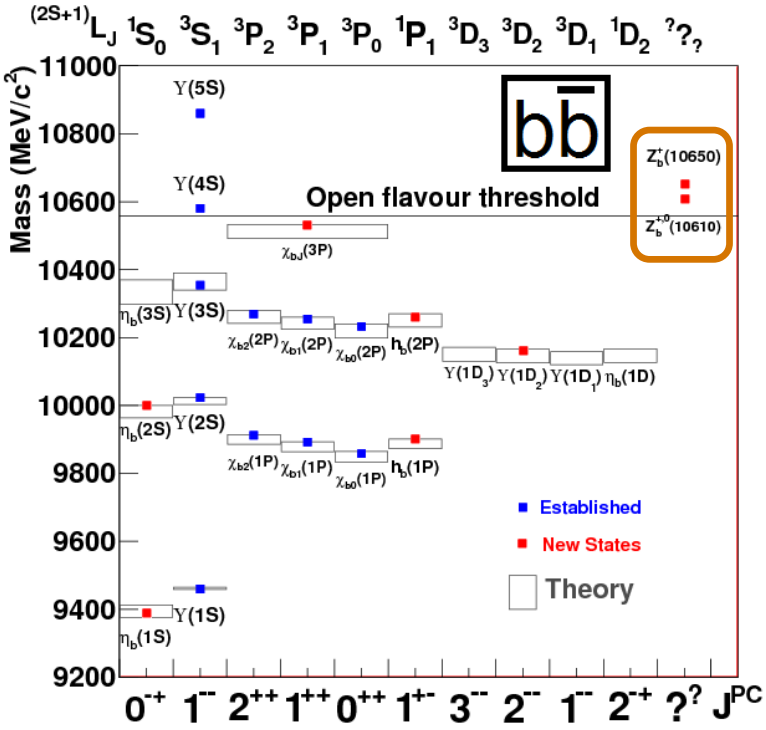
- **Bound state of heavy quark/anti-quark pair ($c\bar{c}$, $b\bar{b}$)**
- Large spectrum of particles, many recent discoveries
- Several states have non-zero charge: cannot be $q\bar{q}$ pair!





A new form of matter?

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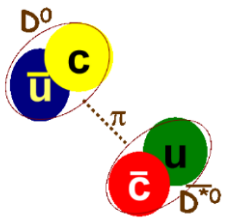
- Meson Molecules
  - Weakly bound state of two mesons

    e.g.: Tornqvist, PLB 590, 209 (2004)



$D^0 - \bar{D}^{*0}$ "molecule"

- "Tetraquarks"
  - Color-singlet diquarks bound directly by strong force

    Polosa et al., PRD 89, 114010 (2014)

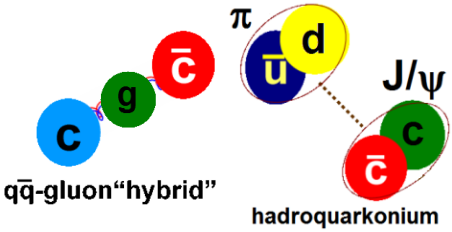
diquark-diantiquark

- Other exotica
  - Hybrids: quarkonium with bound excited gluon

    Barnes et al., PRD 52, 5242 (1995)

  - Hadroquarkonium: qq-light hadron interaction

    Dubinskiy et al., PLB 671, 82 (2009)



$q\bar{q}$-gluon"hybrid"

hadroquarkonium

- Nothing special
  - Kinematic effects / standard quarkonium

    e.g.: Swanson, PRD 91, 034009 (2015)

conventional quarkonium

A new form of matter?

- Meson Molecules
  - Weakly bound state of two mesons
  - e.g.: Tornqvist, [illegible] 0, 209 [illegible] 4)
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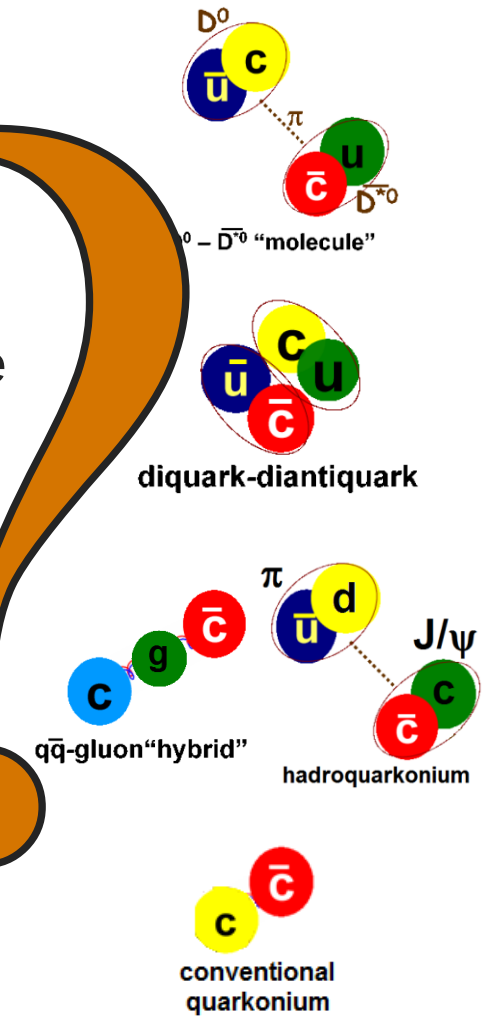
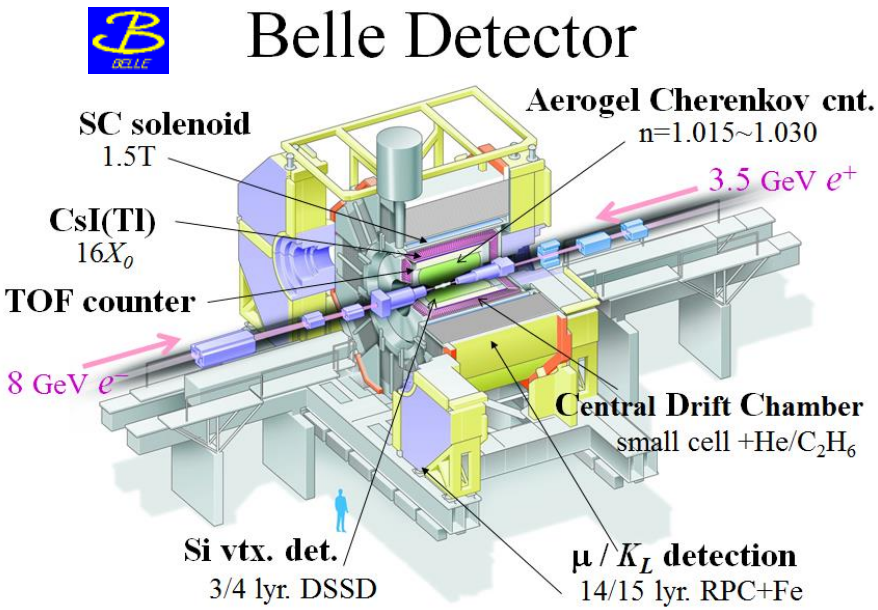
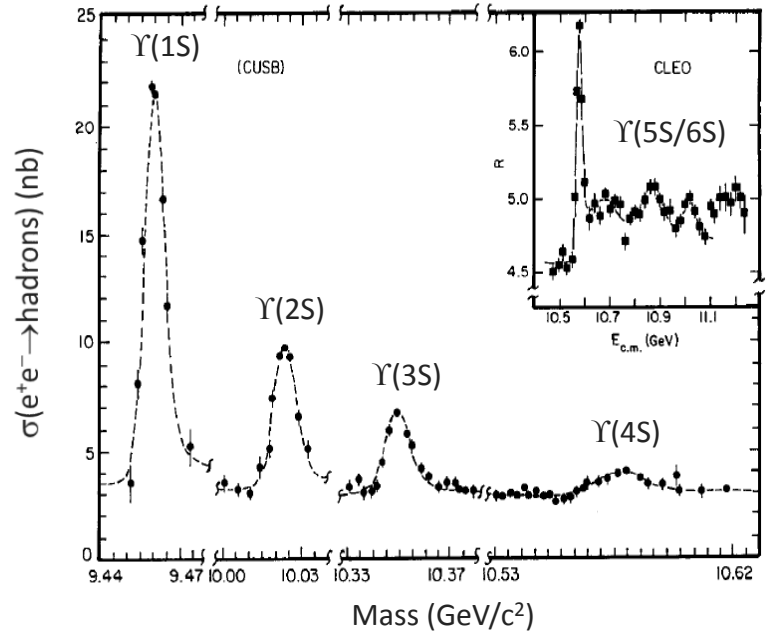


Recent Belle Results

The Belle Experiment





- Data collection (1999-2010): ~1.1 ab^{-1}
- Record luminosity: 2.1x10^{34} cm^{-2} s^{-1}
- Collaboration: ~400 members
- 430+ publications

Υ(5S):	121 fb^{-1} =	36 M
Υ(4S):	711 fb^{-1} =	772 M
Υ(3S):	3 fb^{-1} =	12 M
Υ(2S):	25 fb^{-1} =	158 M
Υ(1S):	6 fb^{-1} =	102 M
Off/scan:	100 fb^{-1}	

Search for XYZ states in $\Upsilon(1S)$ decays

PRD 93, 112013 (2016)

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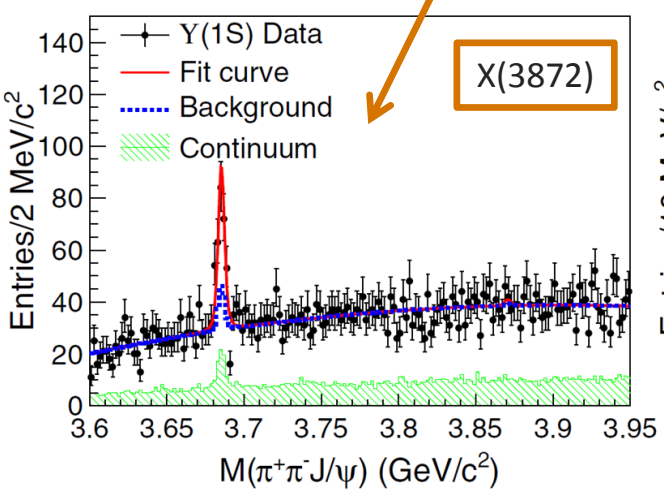
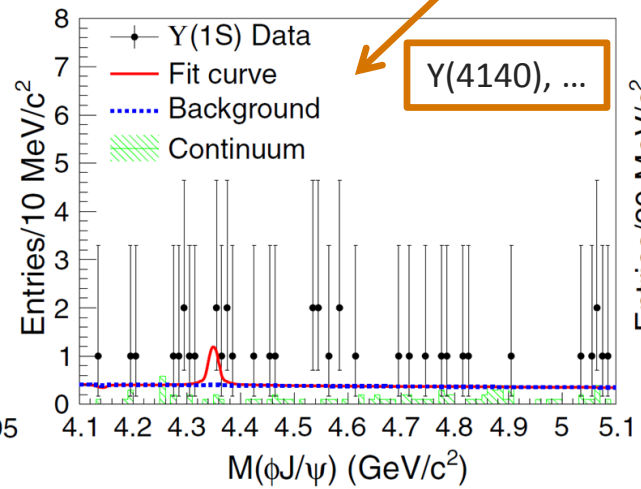
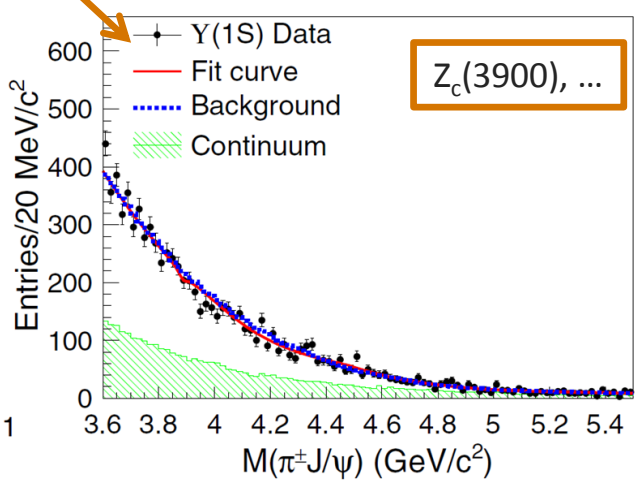
- XYZ states decay preferentially to π and $q\bar{q}$
- Non-negligible inclusive $\Upsilon(1S) \to J/\psi$ and $\psi(2S)$ branching fraction

- Search for: $\pi^+\pi^- J/\psi$, $\pi^+\pi^-\psi(2S)$, $K^+K^- J/\psi$, $\phi J/\psi$, $\pi^\pm J/\psi$, $\pi^\pm\psi(2S)$, $K^\pm J/\psi$

102M $\Upsilon(1S)$







- Inclusive BF measurement, limits on 14 XYZ modes

Search for 0^{--} glueball in $\Upsilon(1S)$ and $\Upsilon(2S)$ decay

PRD 95, 012001 (2017)

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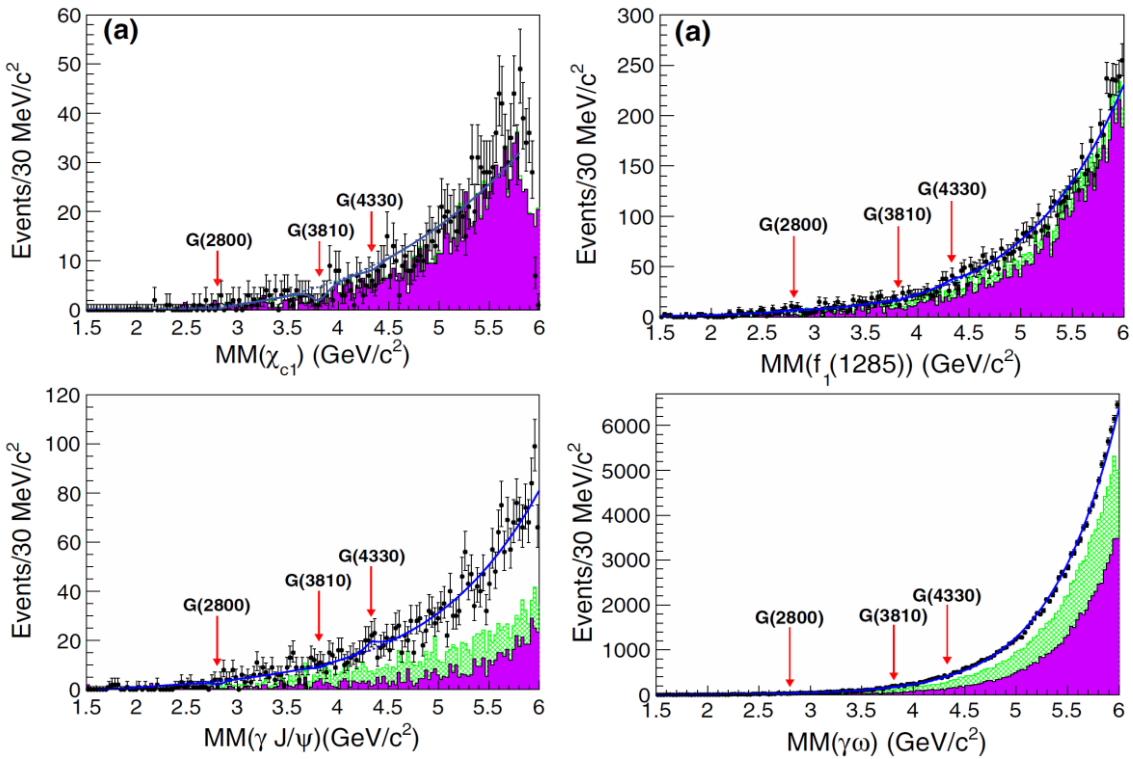
- Search of bound gluon states (G_0) in $b\bar{b}$ decays
- Predicted decay modes: $\Upsilon(1S,2S)\to\chi_{c1}G_0$, $f_0(1285)G_0$, $\chi_{b1}\to J/\psi G_0$, ωG_0



102M $\Upsilon(1S)$
158M $\Upsilon(2S)$

- Inclusive $\Upsilon(1S,2S)\to\chi_{c1}$, limit for m_{G_0}=2.8, 3.81, 4.33 GeV, Γ_{G_0}=0–500 MeV

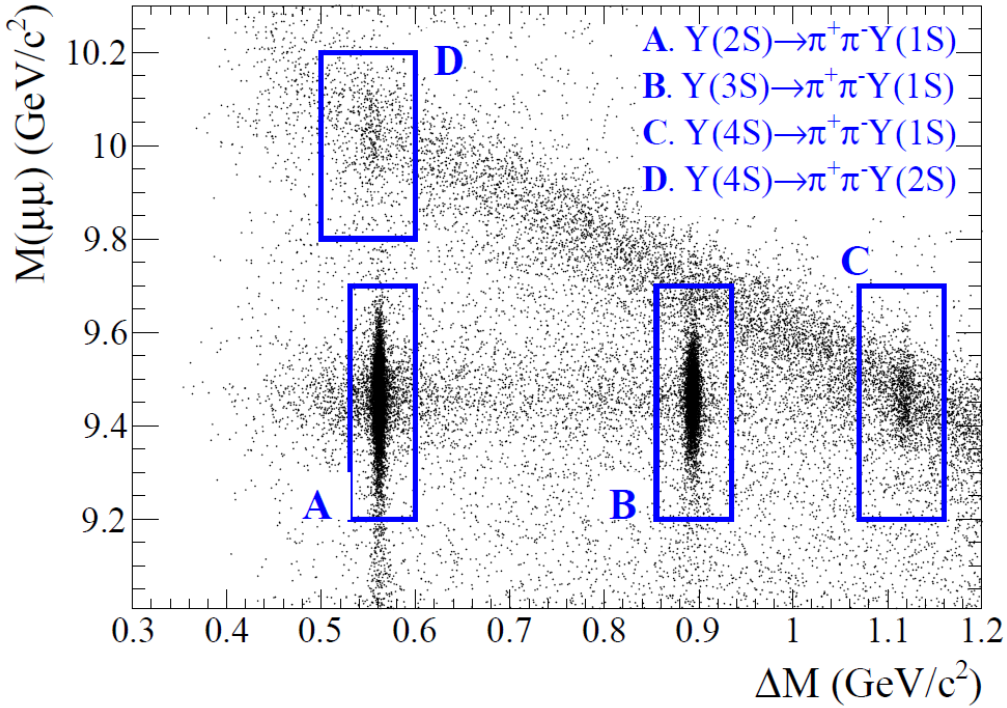
Study of η and ππ transitions in ϒ(4S)

arXiv:1707.04973 (2017)

- Dipion transitions linked to XYZ states in quarkonium decay
- Hadronic $b\bar{b}$ transitions via η predicted to be suppressed
- Recent results indicate enhanced $\Upsilon(4S)\to\eta\Upsilon(1S)$ and $\Upsilon(4S)\to\eta h_b(1P)$

- Consider
  - $\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S,2S)$
    - $\Upsilon(1S,2S) \to \mu^+\mu^-$
  - $\Upsilon(4S,1D) \to \eta\Upsilon(1S)$
    - $\eta \to \pi^+\pi^-\pi^0$

- L_{int} = 496 fb^{-1}
  - 538M ϒ(4S)
  - ~8.5M ϒ(2S) via ISR
  - ~14.2M ϒ(3S) via ISR



Study of η and ππ transitions in ϒ(4S): Dipion results

arXiv:1707.04973 (2017)

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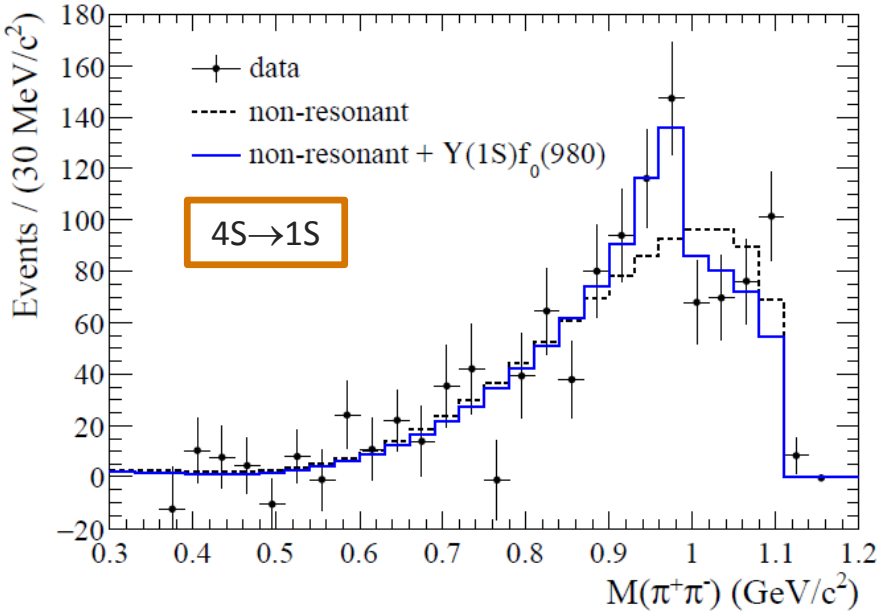
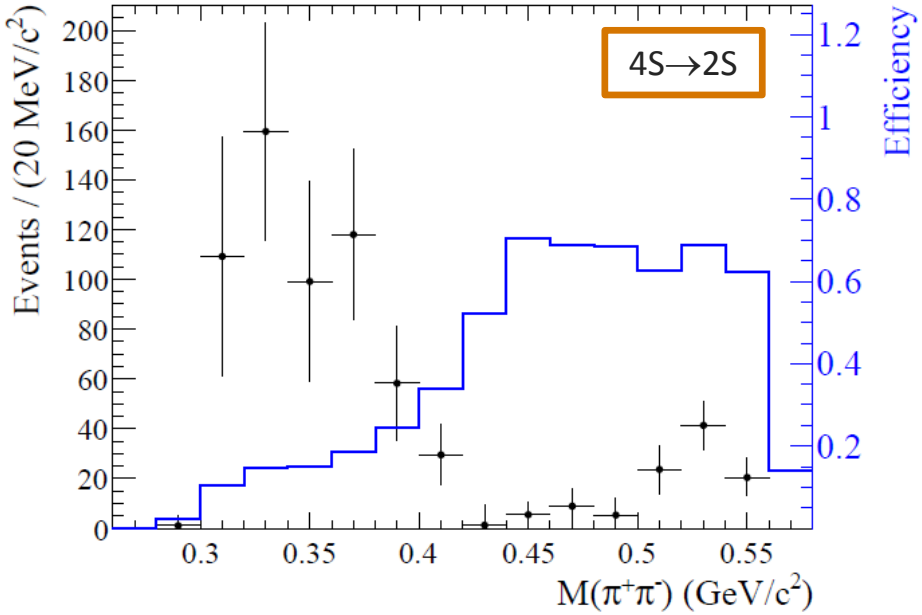
- Measurements consistent with PDG values





$\mathcal{B}(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S)) = (8.2 \pm 0.5 \pm 0.4)\times 10^{-5}$

$\mathcal{B}(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(2S)) = (7.9 \pm 1.0 \pm 0.4)\times 10^{-5}$

- Detailed fit of $_s$Plot projection of m(ππ)
- First indications of $f_0(980)$ contribution (~2.8σ)

Study of η and ππ transitions in ϒ(4S): Eta results

arXiv:1707.04973 (2017)

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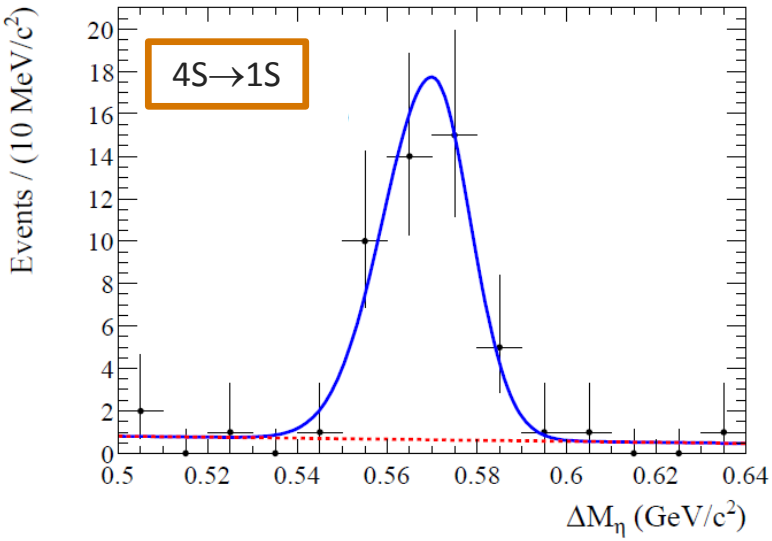
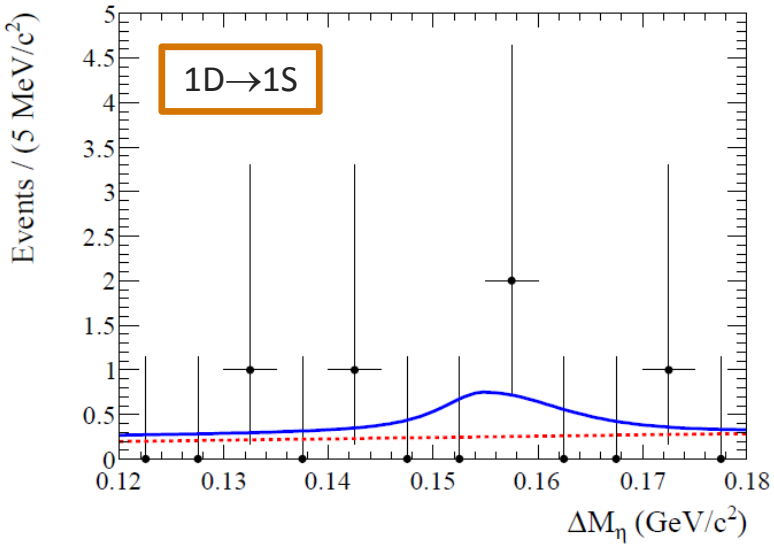
- Confirm enhancement of η transition over ππ, in violation of theory
- No evidence for ϒ(1D)→ηϒ(1S) in ϒ(4S) data





$$\mathcal{B}(\Upsilon(4S) \to \eta\Upsilon(1S)) = (1.70 \pm 0.23 \pm 0.08)\times 10^{-4}$$

$$\mathcal{R} = 2.07 \pm 0.30 \pm 0.11$$

$$\mathcal{B}(\Upsilon(4S) \to \gamma\gamma\Upsilon(1^3D_{1,2}))\times\mathcal{B}(\Upsilon(1^3D_{1,2}) \to \eta\Upsilon(1S)) < 2.3 \times 10^{-5}$$

Belle II

Belle II Collaboration

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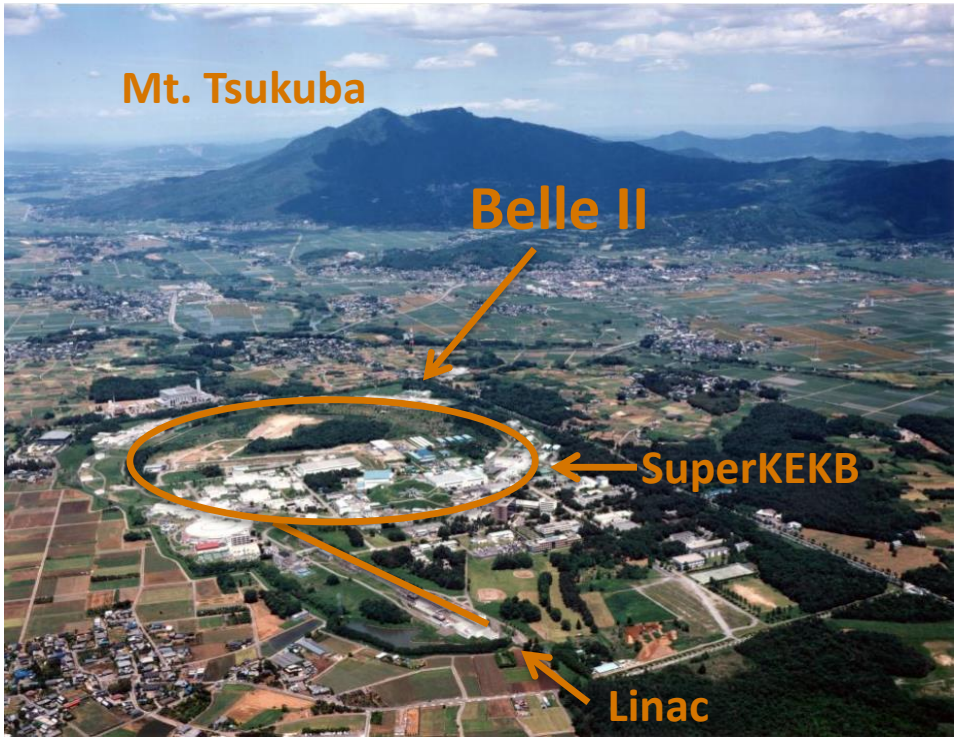
- 750+ members, 101 institutions, 23 countries
- US participation: ~80 members, 14 institutions
- Located at KEK in Tsukuba, Japan



Accelerator Upgrade

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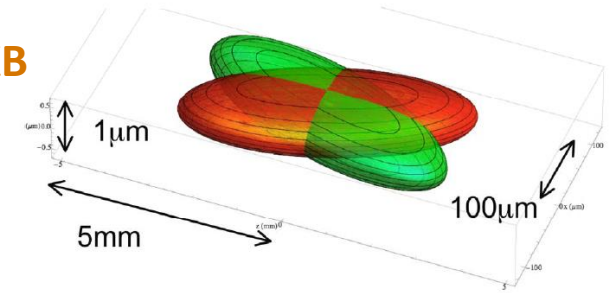
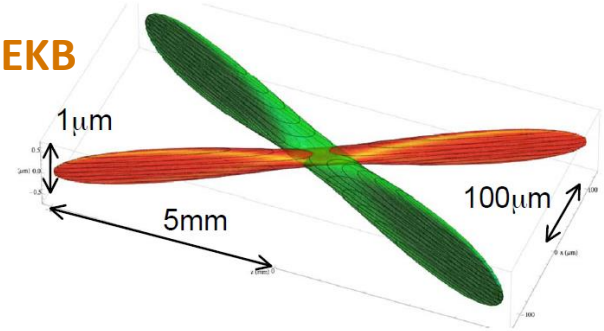
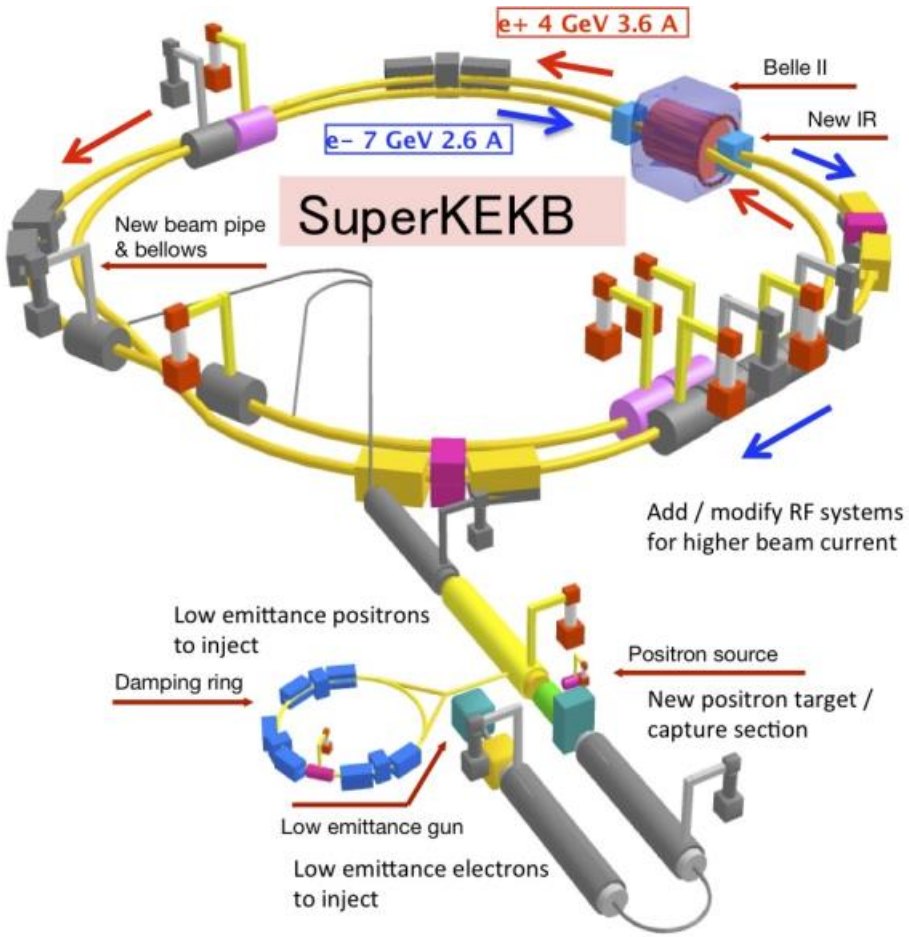
- Factor of 40x increase in luminosity
- "Nano-beam" interaction point
- Increase in current
- Energy: e^- (7 GeV) e^+ (4 GeV)

KEKB



SuperKEKB





Detector Upgrade

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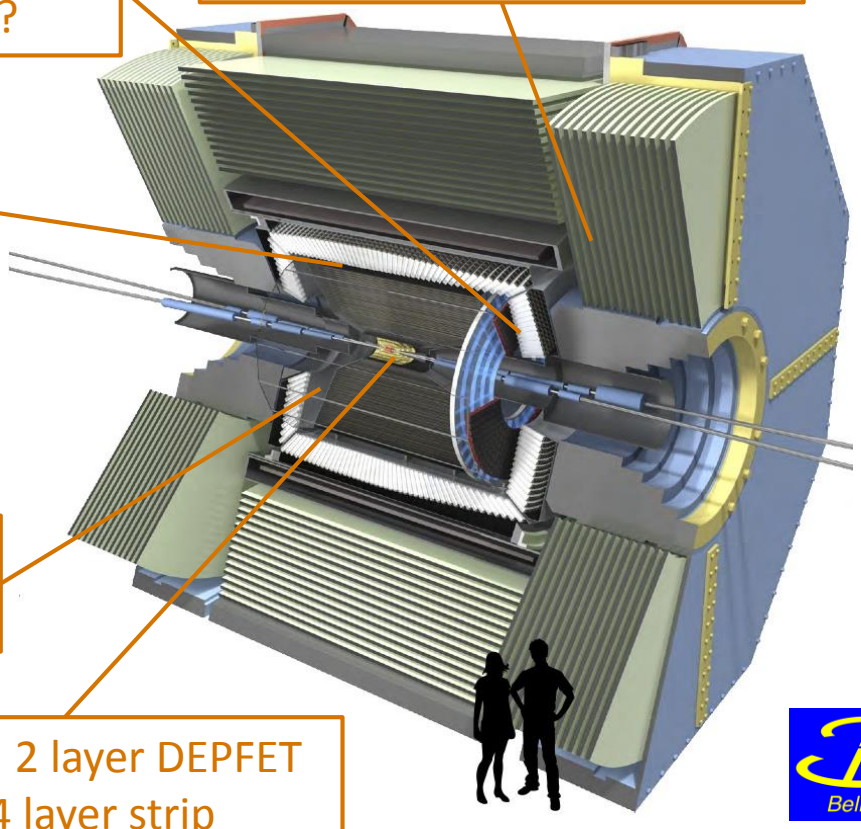
ECAL: readout, pure CsI upgrade?

Muons: plastic scintillator, electronics upgrade

PID: iTOP barrel, aerogel endcap



Tracking: small-cell drift chamber

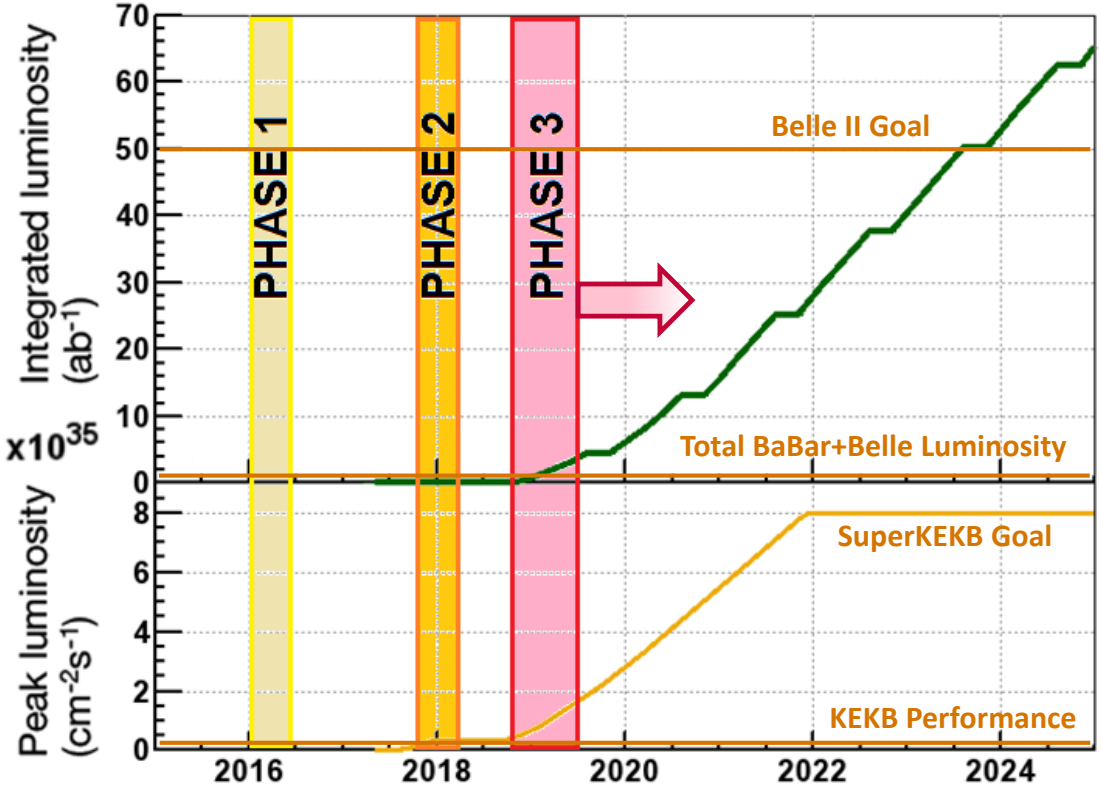
Vertexing: 2 layer DEPFET Si pixel + 4 layer strip

Belle II

arXiv:1011.0352 (2011)

Belle II Schedule and Plans

- Phase 1 (completed 2016)
  - Accelerator commissioning
- Detector roll-in: April 2017
- Phase 2 (2017/18)
  - Partial detector
  - Background study
  - First collisions (10±10 fb^{-1})
- Phase 3 (2018/19)
  - Nominal Belle II start
- **Ultimate goal: 50 ab^{-1}**



Belle II Early Physics Prospects

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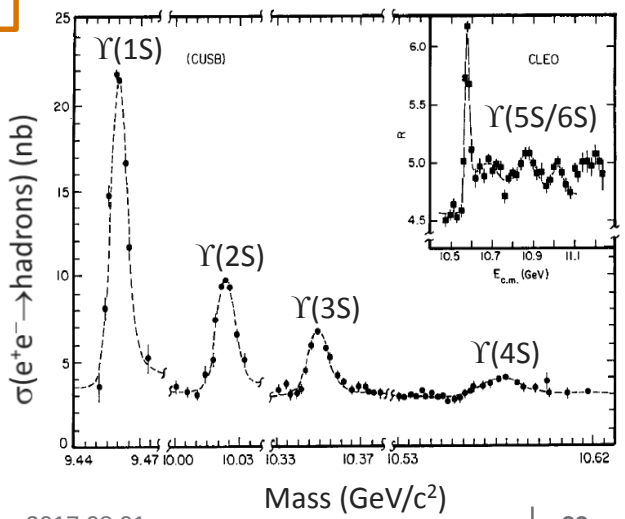
- Existing B-Factories ~1.5 ab^{-1}: **opportunity for other results in Phase 2/3?**

Experiment	Scans / Off. Res. fb^{-1}	$\Upsilon(5S)$ 10876 MeV fb^{-1}	10^6	$\Upsilon(4S)$ 10580 MeV fb^{-1}	10^6	$\Upsilon(3S)$ 10355 MeV fb^{-1}	10^6	$\Upsilon(2S)$ 10023 MeV fb^{-1}	10^6	$\Upsilon(1S)$ 9460 MeV fb^{-1}	10^6
CLEO	17.1	0.4	0.1	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	121	36	711	772	3	12	25	158	6	102

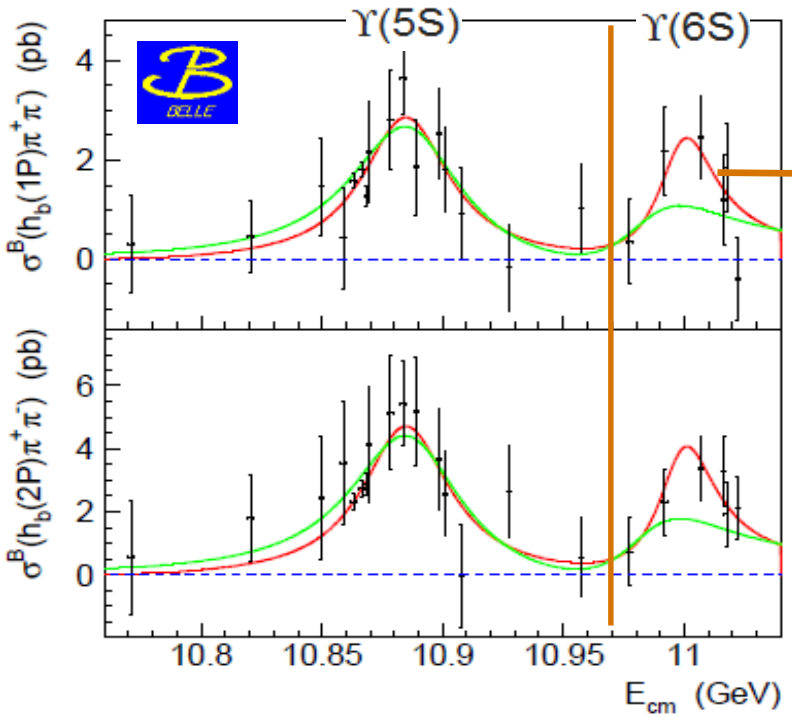
Potential impact with O(10-100) fb^{-1}

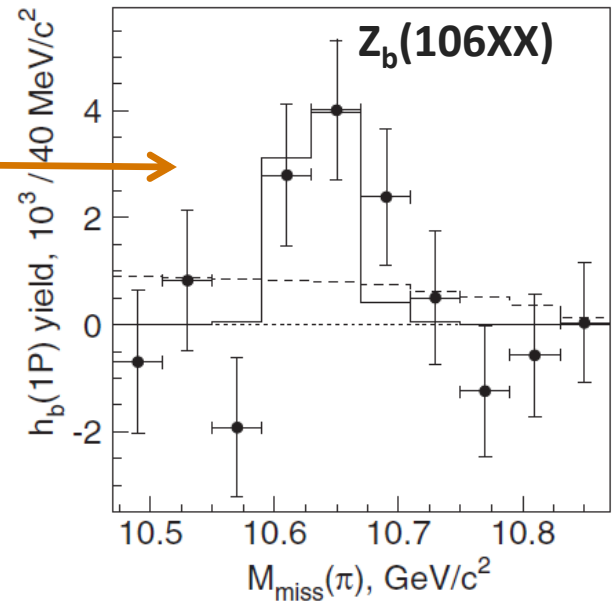
- Below Υ(4S)
  - Bottomonium search/study, NP in decays
  - Scan for direct production of $\Upsilon(n^3D_1)$
- Above Υ(4S)
  - Study of exotic four-quark states
  - <6fb^{-1} accumulated by Belle at $E_{CM}=\Upsilon(6S)$



Physics Potential at $\Upsilon(6S)$

- Discovery of $Z_b^{\pm}(10610,10650)$ via $\Upsilon(5S)\to\pi\pi b\bar{b}$ transitions at Belle
- Evidence for $\Upsilon(6S)\to\pi\pi h_b(nP)$, via $\pi Z_b^{\pm}(106XX)$ decay





PRL 117, 142001 (2016)

- **Study nature of $\Upsilon(6S)$, exotic quarkonia, bottomonium discovery**

Υ(6S): What could we do?

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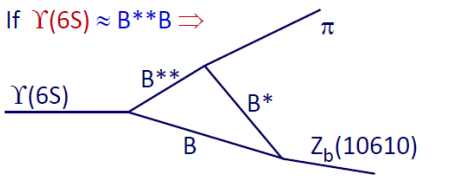
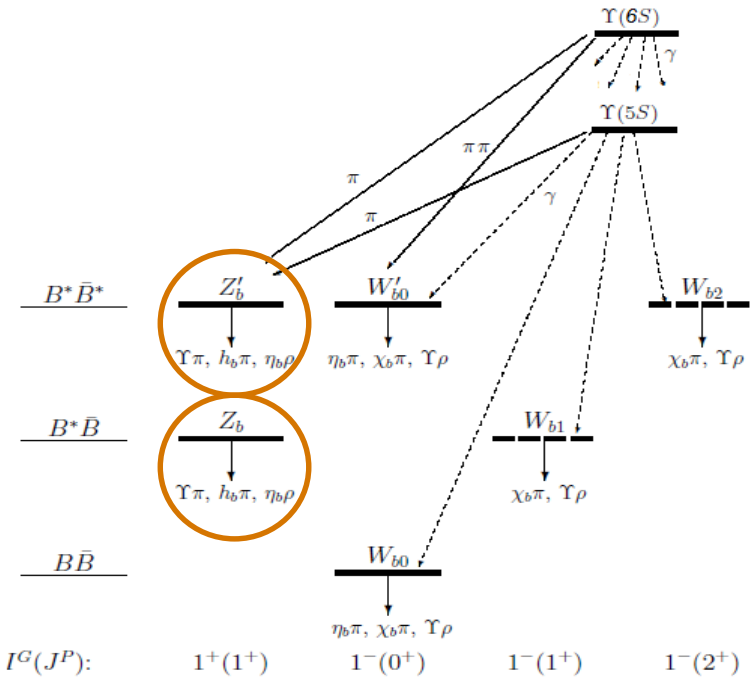
"New States"

- Understand $\Upsilon(6S) \to Z_b$ decay
  - $\Upsilon(6S) \to \pi^+\pi^- h_b(1P,2P)$
  - $\Upsilon(6S) \to \pi^+\pi^- \Upsilon(1S,2S,3S)$ (+ $\ell^+\ell^-$ exclusive)
  - Also with $\pi^o\pi^o$?



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

- Evidence Z_b is a molecular state
- Should have partners ("W_b")
- Potential searches
  - $\Upsilon(6S) \to \gamma\, W_{b0}$
  - $\Upsilon(6S) \to \pi^+\pi^-(\rho)\, W_{b0}$ possible?
  - $W_{b0} \to \eta_b\pi,\ \chi_b\pi,\ \Upsilon\rho$



Voloshin, PRD 84, 031502 (2011)

Υ(6S): What could we do?

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Quarkonia Transitions

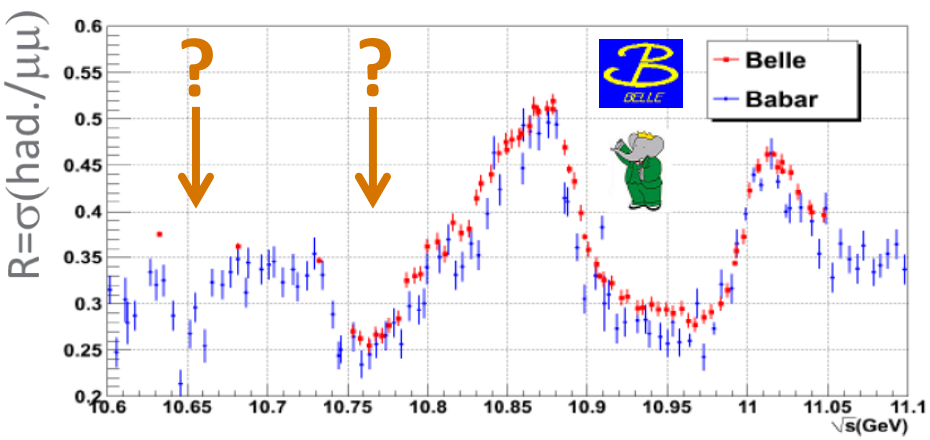
- Analogies to Υ(5S) evidence/observations at Belle
  - $\Upsilon(6S) \to \pi^+\pi^- \Upsilon(n^3D_J)$
  - $\Upsilon(6S) \to \eta\, \Upsilon(pS)$ and $\eta\, \Upsilon(n^3D_J)$
  - $\Upsilon(6S) \to \omega\, \chi_b(1P)$
  - $\Upsilon(6S) \to K^+K^- \Upsilon(1S)$
  - Inclusive and exclusive searches for all of the above
- Understand the nature of above-threshold Υ(mS) states

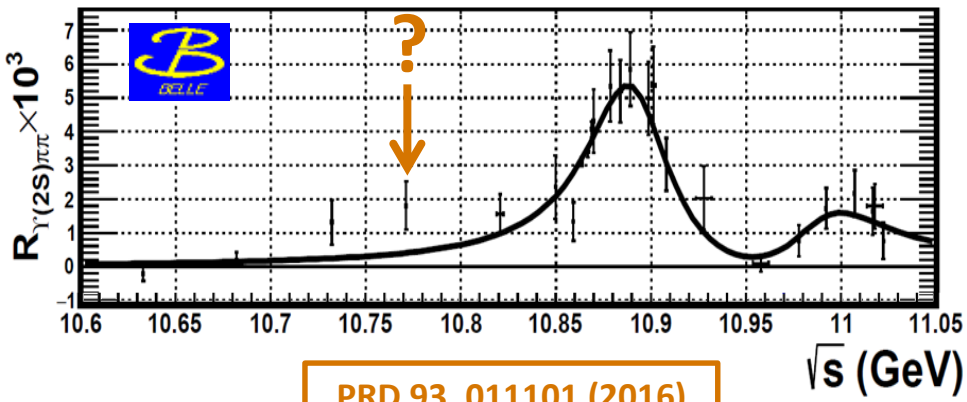
Bottomonium Discovery

- Υ(6S) phase space opens possibility for first discovery:
  - $h_b(3P)$: $\Upsilon(6S) \to \pi^+\pi^- h_b(3P)$
  - Y(2D): $\Upsilon(6S) \to \pi^+\pi^- \Upsilon(2D)$ or $\to \eta\, \Upsilon(2D)$
  - 1F bottomonium multiplet via dipion transition?

Above ϒ(4S): Other points of interest

- Other $B^{(*)}B^{(*)}$ thresholds show potential
  - R_b dip versus $\pi\pi\Upsilon$ rise
  - Similar features as charm thresholds?
  - Sign of "Y_b" states?
- Limited luminosity from previous scans: <1 fb^{-1}

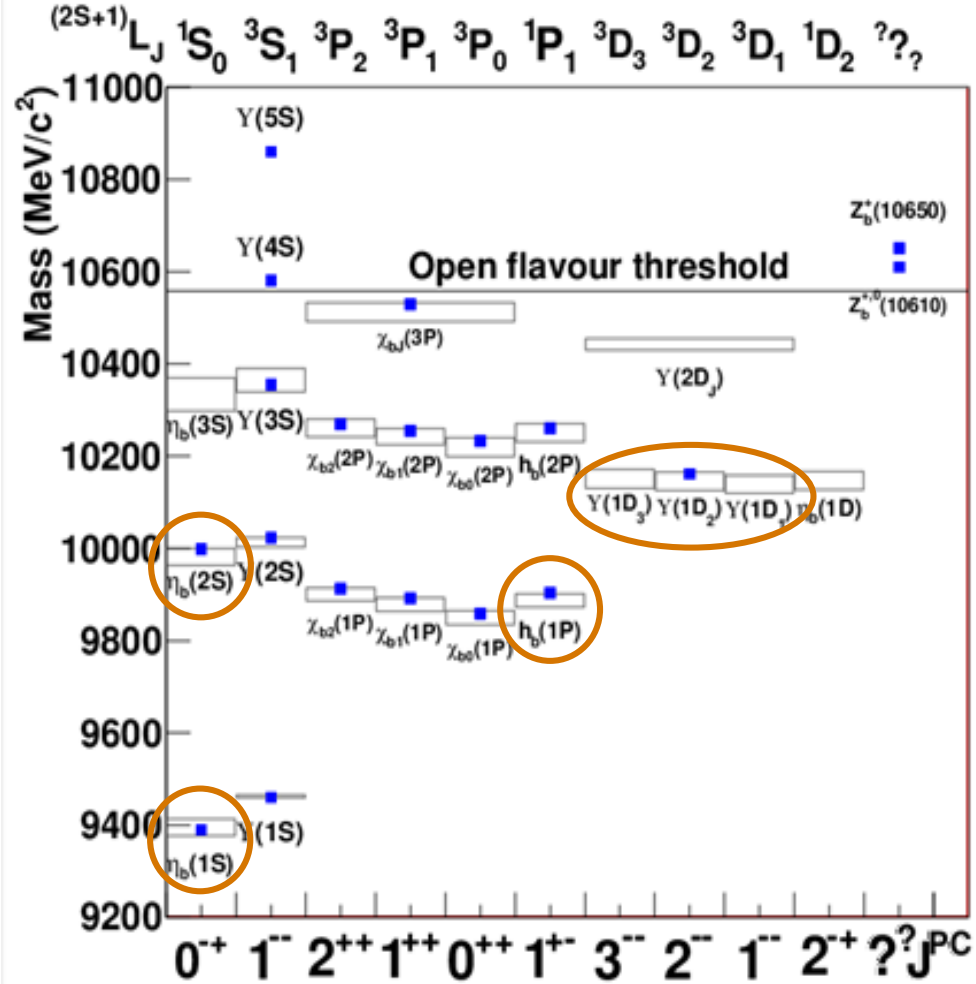




PRD 93, 011101 (2016)

Below $\Upsilon(4S)$: Bottomonium physics

- $200 fb^{-1}$ ~7x BaBar $\Upsilon(3S)$
- Focus on conventional $b\bar{b}$ physics
  - $\Upsilon(1^3D_J)$ triplet
    - J=1,3 yet to be discovered
    - Accessed via $\Upsilon(3S)$ decays or scan
  - $\eta_b(1S,2S)$
    - Confirm $m(\eta_b(1S,2S))$
  - Hadronic/radiative transitions
- New Physics
  - $\Upsilon(1S,2S)\rightarrow\chi\bar{\chi}/\nu\bar{\nu}$ invisible decays
  - $\chi_{b0}\rightarrow\tau^+\tau^-$ light Higgs search
  - Dark sector decays $\Upsilon(nS)\rightarrow\gamma\chi\bar{\chi}$



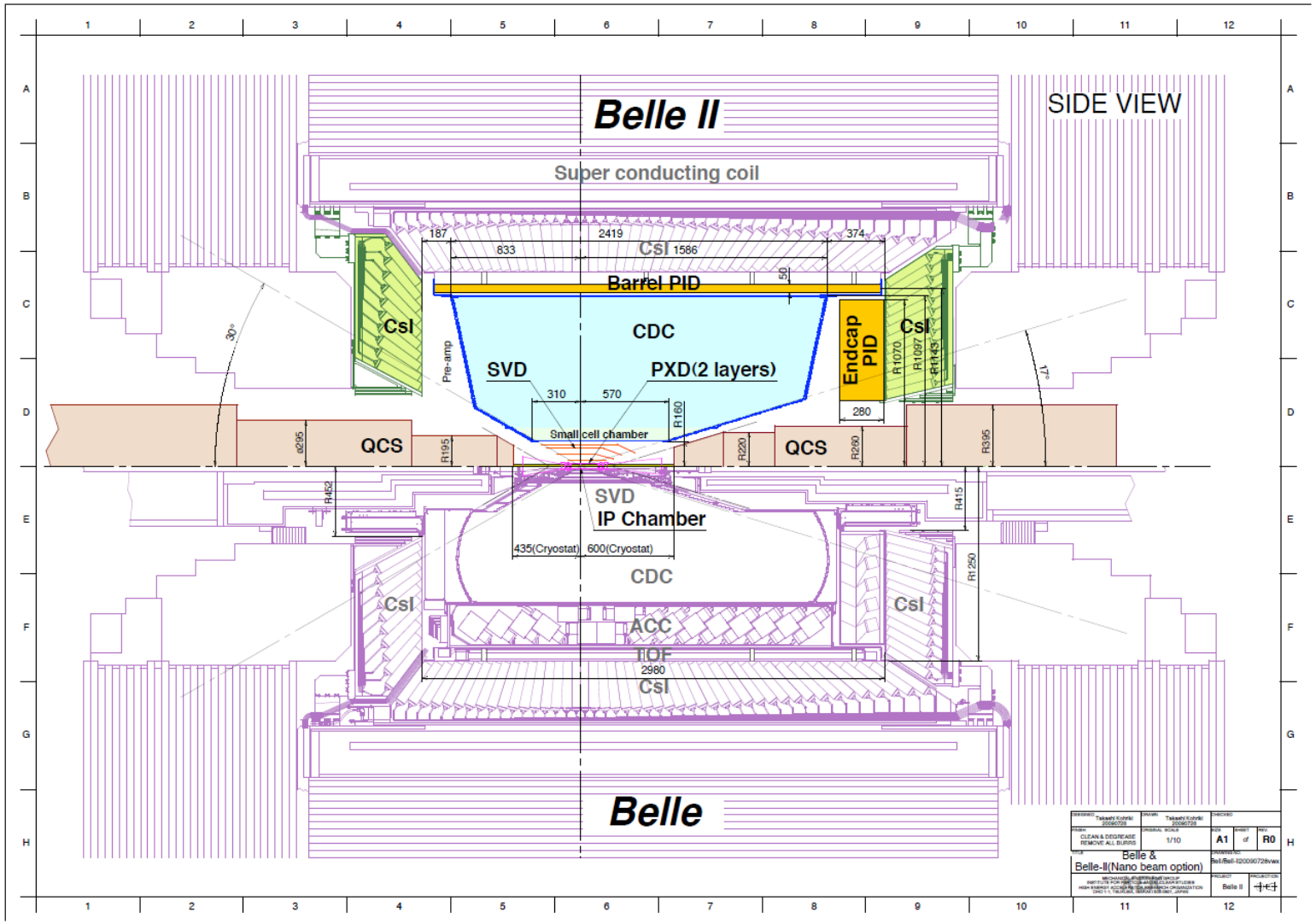
Conclusion

Conclusions

- Quarkonium / “New States”
  - Active field with many recent particle discoveries
  - Puzzles related to nature of exotic tetraquarks and conventional $q\bar{q}$ states
- The Belle Experiment
  - Continues to provide relevant results
  - Measurement of $\Upsilon(4S)\rightarrow\pi^+\pi^-/\eta\ b\bar{b}$ transitions
  - Limits on searches for XYZ production
- SuperKEKB / Belle II Experiment
  - Commissioning this autumn, nominal start 2018
  - Next generation flavor factory: 50x more data and improved detector
  - Unique potential for further understanding of exotic hadrons and quarkonium

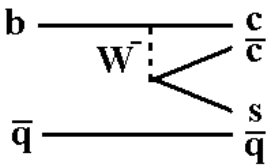
Backup

Detector Upgrade

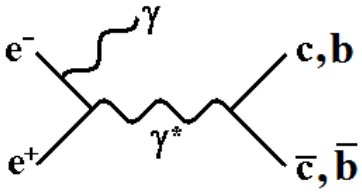


Quarkonium production at e^+e^- colliders

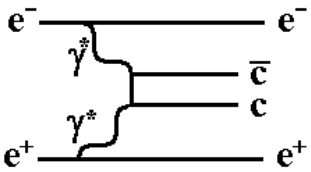
- B decays
  - Charmonium only
  - All quantum numbers available



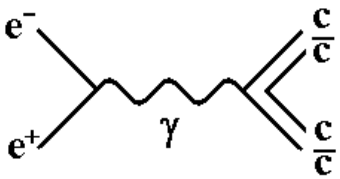
- Direct production / Initial State Radiation (ISR)
  - E_{CM} or below
  - $J^{PC}=1^{--}$



- Two-photon interaction
  - $J^{PC} = 0^{-+}, 0^{++}, 2^{++}$



- Double charmonium production
  - Seen for $J^{PC}=1^{--}$ (J/ψ, $\psi(2S)$) plus J=0 states

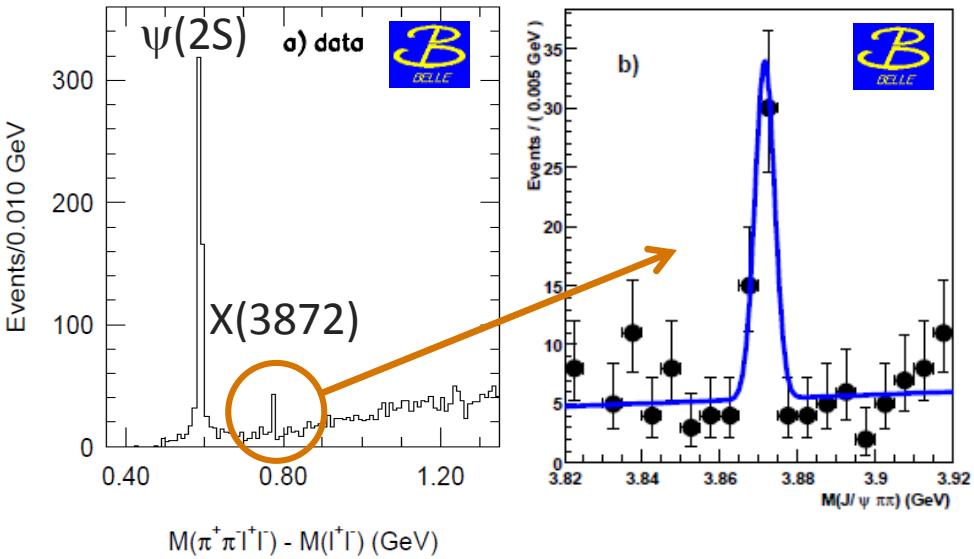


- Quarkonium transitions
  - Hadronic/radiative decays from excited to lower mass states

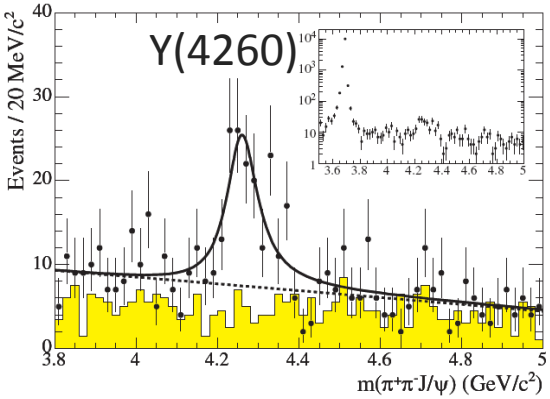
The New Alphabet: X, Y …

- X(3872)
  - Discovered by Belle in 2003
  - $B \to K\ X(3872) \to \pi^+\pi^-\ J/\psi(\ell^+\ell^-)$
  - Seen in all modern hep expts.
  - **Most cited Belle publication**

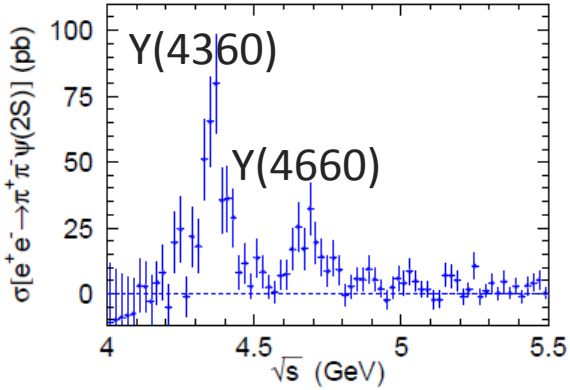
PRL 91, 262001 (2003)



- Y(4260) and friends
  - ISR-produced states decaying to $\pi^+\pi^-\ \psi(1S,2S)$
  - $J^{PC}=1^{--}$: **overpopulated for charmonium model**



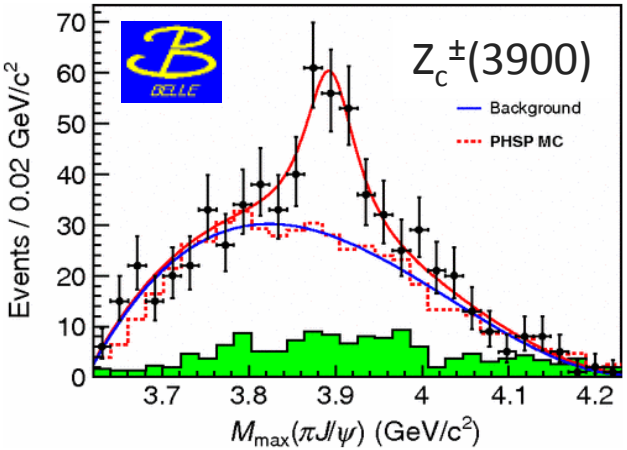
PRL 95, 142001 (2005)



PRD 91, 112007 (2015)

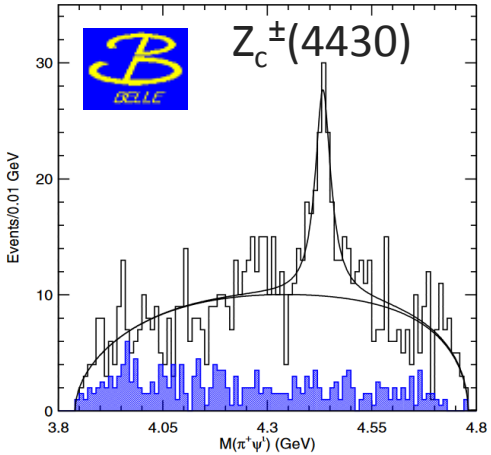
…and Z

- $Z_c^{\pm}(3900)$
  - Intermediate charged state in Y(4260) decay
  - $Y(4260) \to \pi^{\mp} Z_c^{\pm}(3900) \to \pi^{\pm} J/\psi$
  - Simultaneous discovery by Belle and BES-III
  - Several other partners since seen by BES-III



PRL 110, 252002 (2013)

- $Z_c^{\pm}(4430)$
  - Discovered by Belle
  - $B \to K\, Z(4430) \to \pi^{+}\psi(2S)$
  - Confirmed by LHCb
  - Partners seen in $\pi^{+}\chi_{c1}$ and $\pi^{+}J/\psi$



PRL 100, 142001 (2008)

- Non-zero charge cannot be $c\bar{c}$ = four quarks!

$Z_b^{\pm}$ states in the bottomonium system

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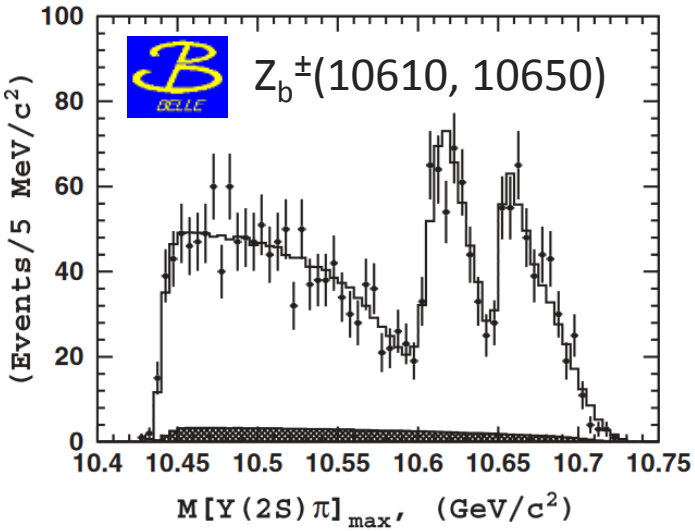
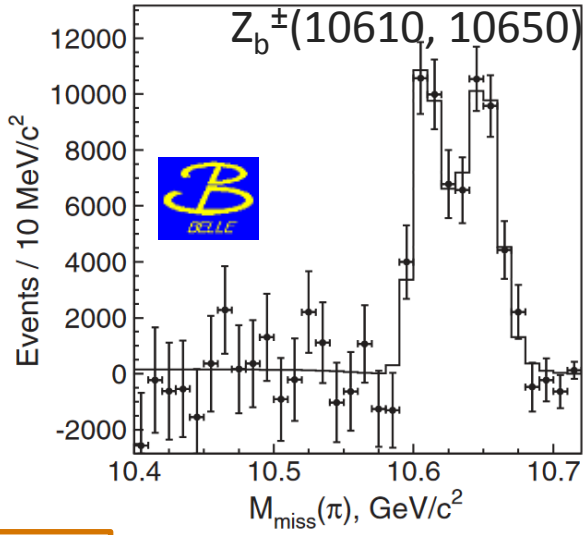
- Anomalous dipion transition rate: $\Upsilon(5S) \to \pi\pi\, b\bar{b}$
- Discovery of $h_b(1P, 2P)$, $\eta_b(2S)$, **indication of charged $Z_b^{\pm}$ states**
- $\Upsilon(5S) \to \pi^{\mp} Z_b^{\pm} \to \pi^{\pm}\Upsilon(1S,2S,3S)$ and $Z_b^{\pm} \to \pi^{\pm} h_b(1P,2P)$
- **Analogous to Y(4260) decays and $Z_c^{\pm}$ in charmonium system!**





PRL 108, 122001 (2012)

Belle II: Other long-term prospects for exotic hadrons

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- ISR-production of Y(4260, etc.)
  - BES-III limited <4.6 GeV, not observed at LHC
  - Belle II is the only way access to Y(4660) and scan in the b-sector
- Study of decay modes involving γ, π^0, η, soft pions
  - B decays with neutral final states, e.g. $X^{\pm}(3872) \to \pi^{\pm}\pi^0 J/\psi$, $Z(4430) \to \pi^0\psi(2S)$
  - Radiative transitions with soft photons
  - Structure in soft dipion decays (e.g. $\Upsilon(mS) \to \pi\pi\, b\bar{b}$)
- Revisit $\Upsilon(5S)$ resonance, increase from $100 fb^{-1}$ to $1\ ab^{-1}$?
- Other surprises?
  - B Factories are exotics factories: the more we looked, the more we found