# Physics prospects of exotic and conventional bottomonia at Belle II


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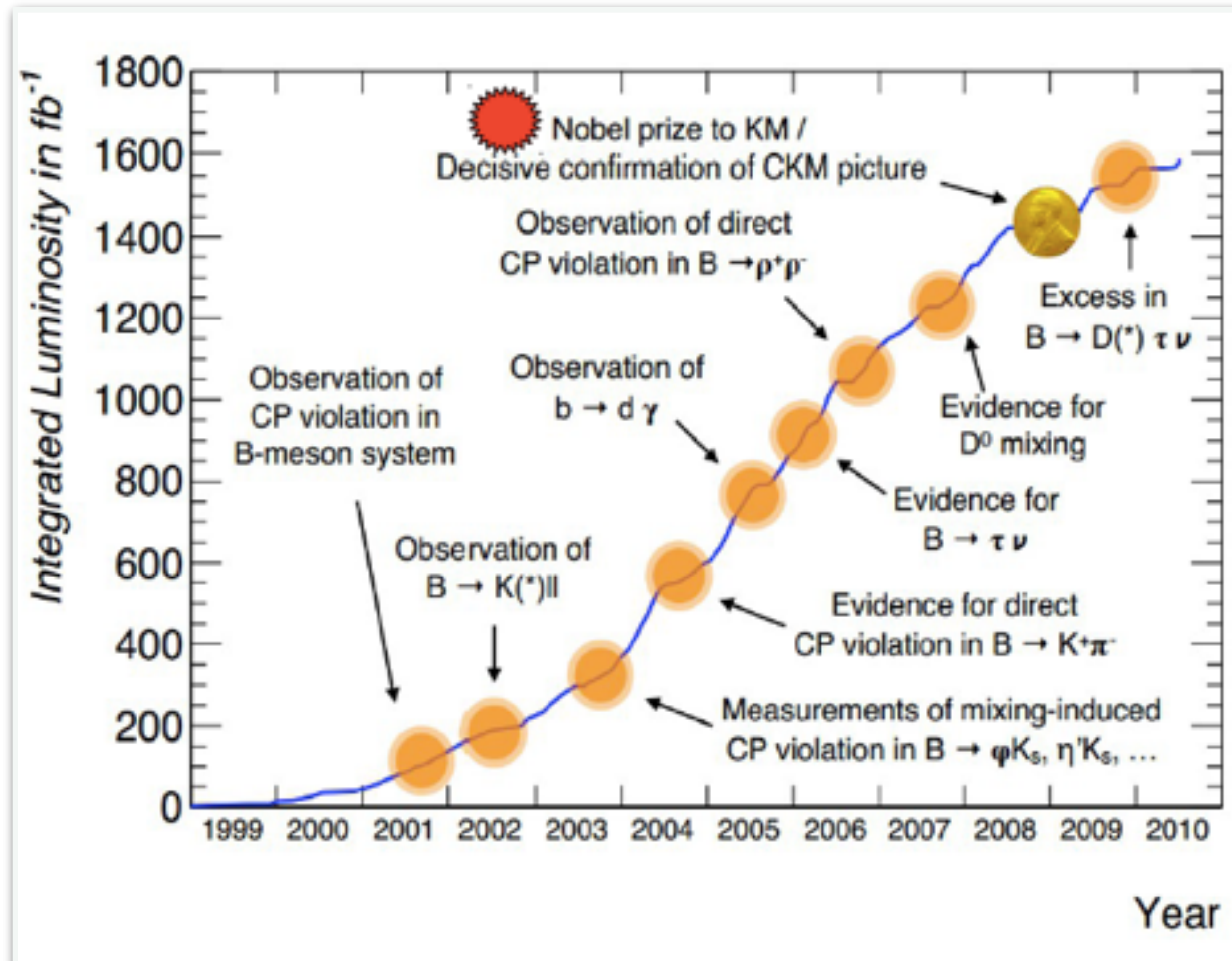
# B-factories laurels

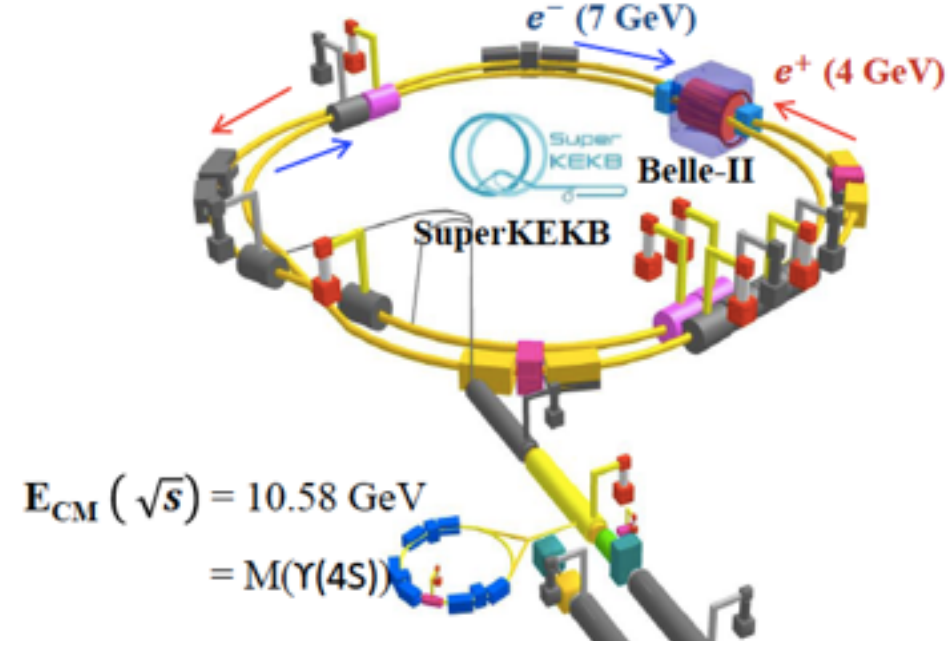
- B-factories (Belle, BaBar) reaped rich physics harvest in just one decade, namely CKM matrix elements, unitary triangle parameters, charm mixing, first observation of exotic X(3872) [most cited Belle paper]. …
- Belle has made rich contribution to quarkonium spectroscopy
- However, still few unsolved mysteries remain such as hierarchy in SM, large matter anti-matter asymmetry in nature
- Hunt on in the intensity/precision frontier at SuperKEKB



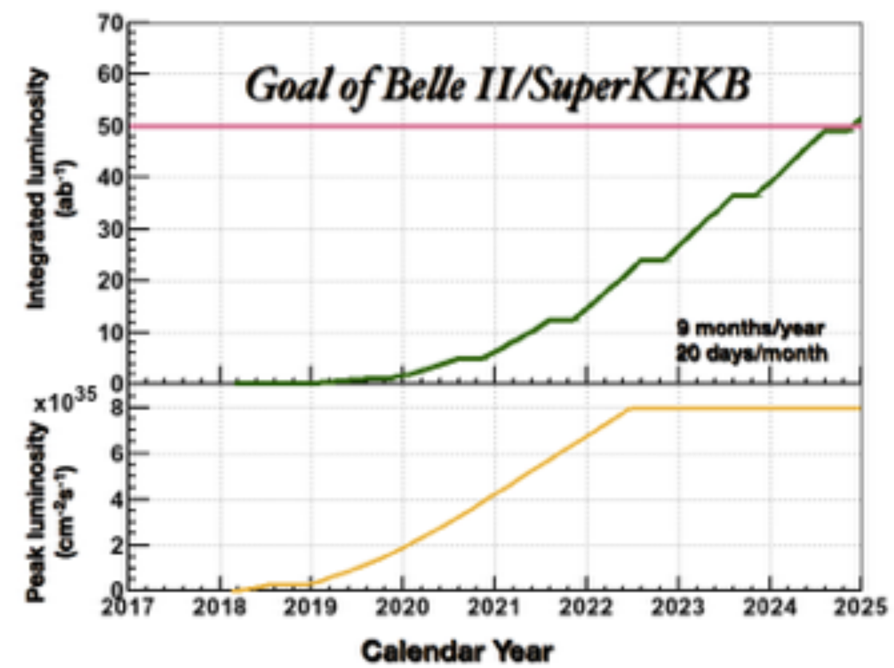

**Belle at KEKB, Japan**
**BaBar at SLAC, U.S.A**
**Belle upgrade : Belle II at SuperKEKB, Japan**

# Belle II at SuperKEKB

- Boost (βγ) = 0.28 [0.67 x KEKB]
- $E_{CM}$ = 10.58 GeV [Similar as KEKB]
- Peak luminosity = 8.0 x $10^{35}$ $cm^{-2}$ $s^{-1}$[40 x KEKB]
- Integrated luminosity = 50 $ab^{-1}$ (by 2025) [50 x Belle]



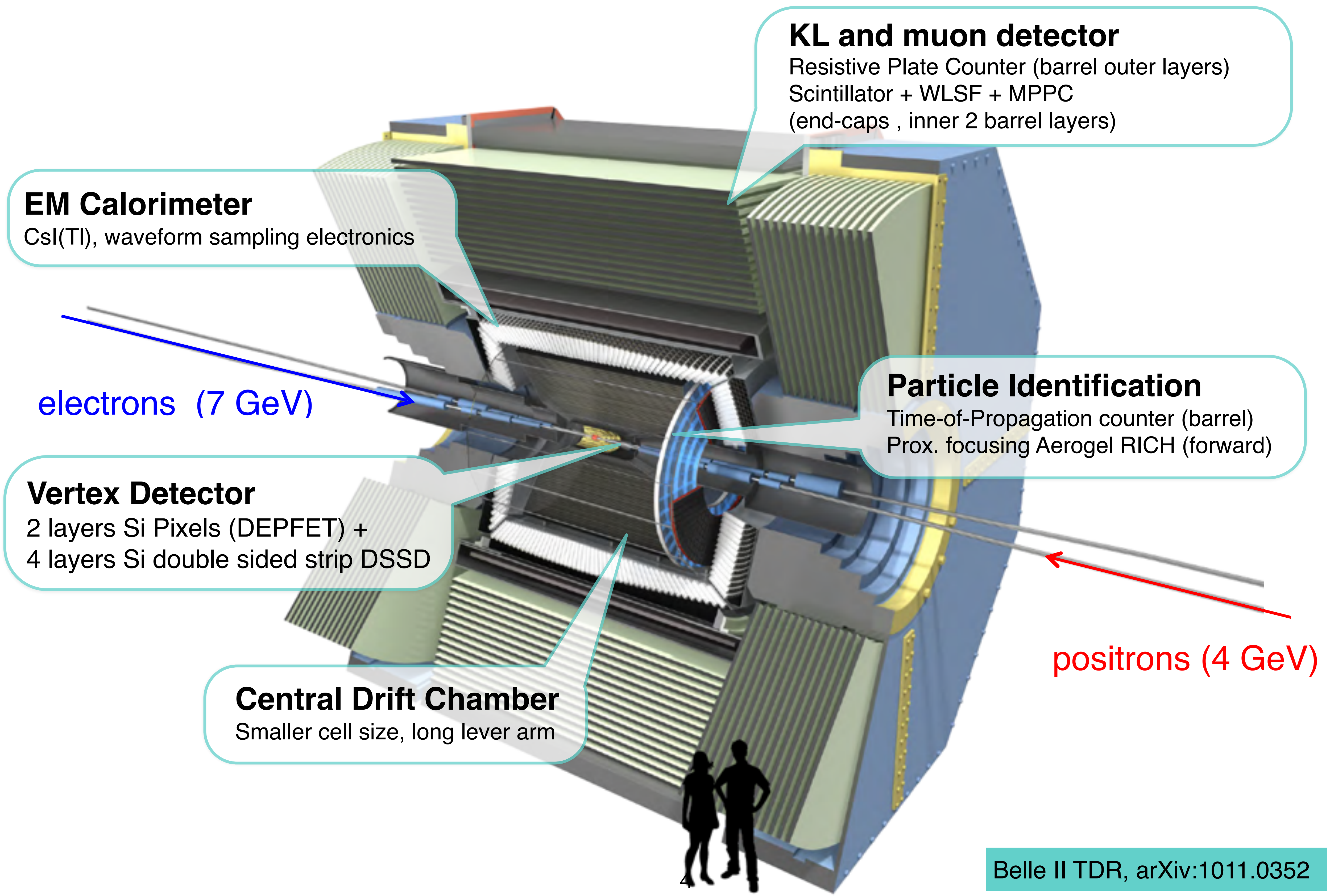

SuperKEKB luminosity projection




- KEKB: 3 μm (vertical) x 100 μm (horizontal)
  SuperKEKB: 60 nm (vertical) x 10 μm (horizontal)
  - Increased current (×2 KEKB)
  - Several other upgrades: RF magnet, vacuum

| | Energy (GeV) LER/HER | $\beta_y^*$ (mm) LER/HER | $\varepsilon_x$ (nm) LER/HER | $\xi_y$ LER/HER | φ (mrad) | $I_{beam}$ (A) LER/HER | Luminosity ($cm^{-2}s^{-1}$) x $10^{34}$ |
|---|---|---|---|---|---|---|---|
| KEKB Achieved | 3.5/8.0 | 5.9/5.9 | 18/24 | 0.129/0.090 | 11 | 1.64/1.19 | 2.11 |
| SuperKEKB | **4.0/7.0** | **0.27/0.41** | **3.2/2.4** | **0.09/0.09** | **41.5** | **3.6/2.62** | **80** |

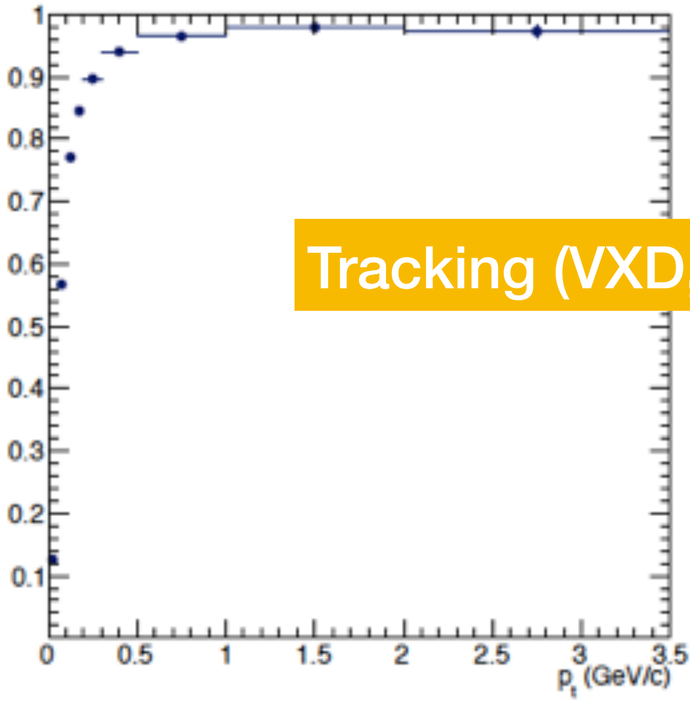
# Belle II Detector

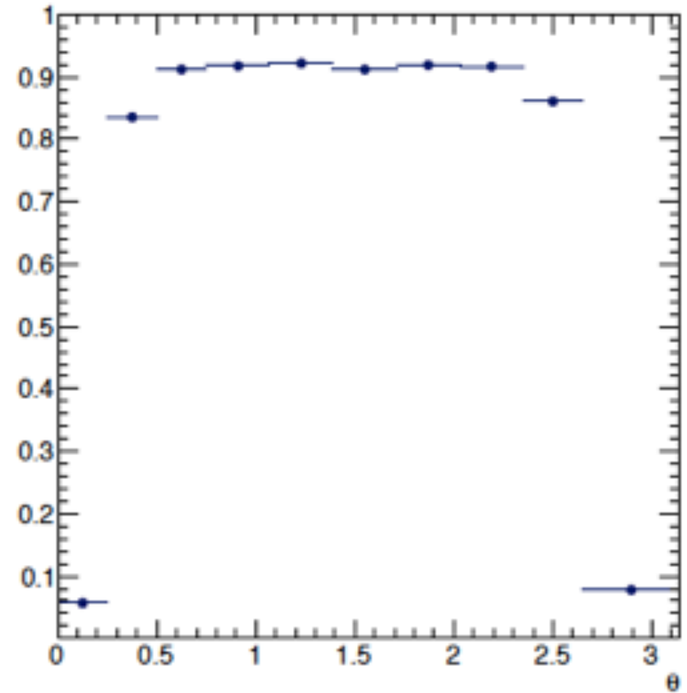



Belle II TDR, arXiv:1011.0352

# Belle II Performance Plots

Tracking (VXD, CDC)

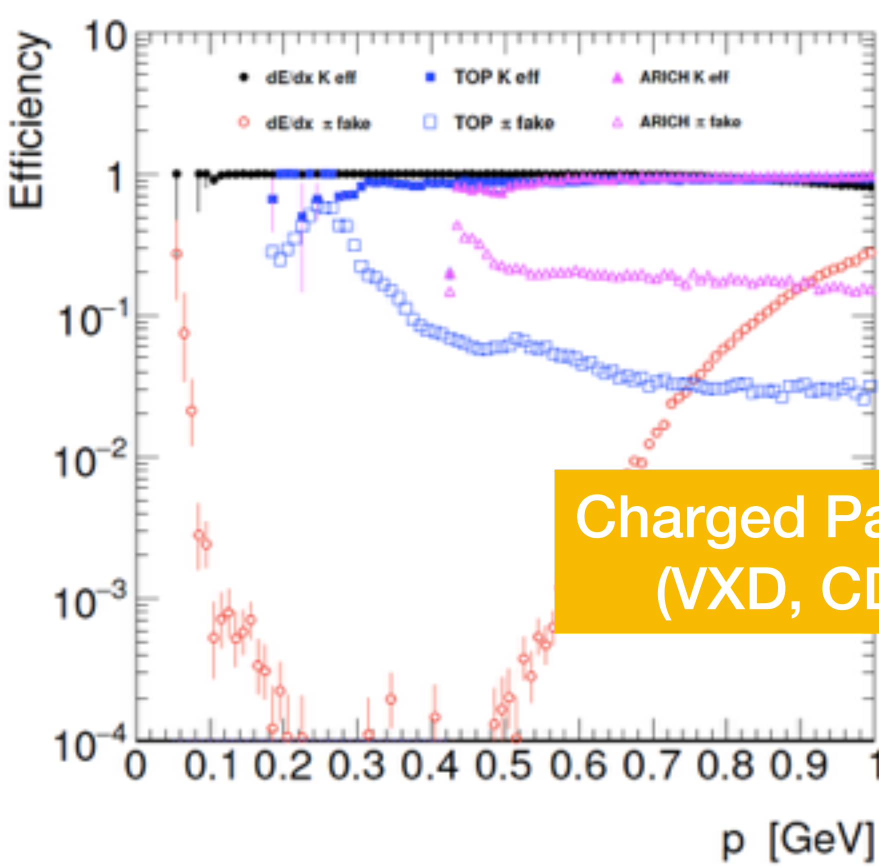


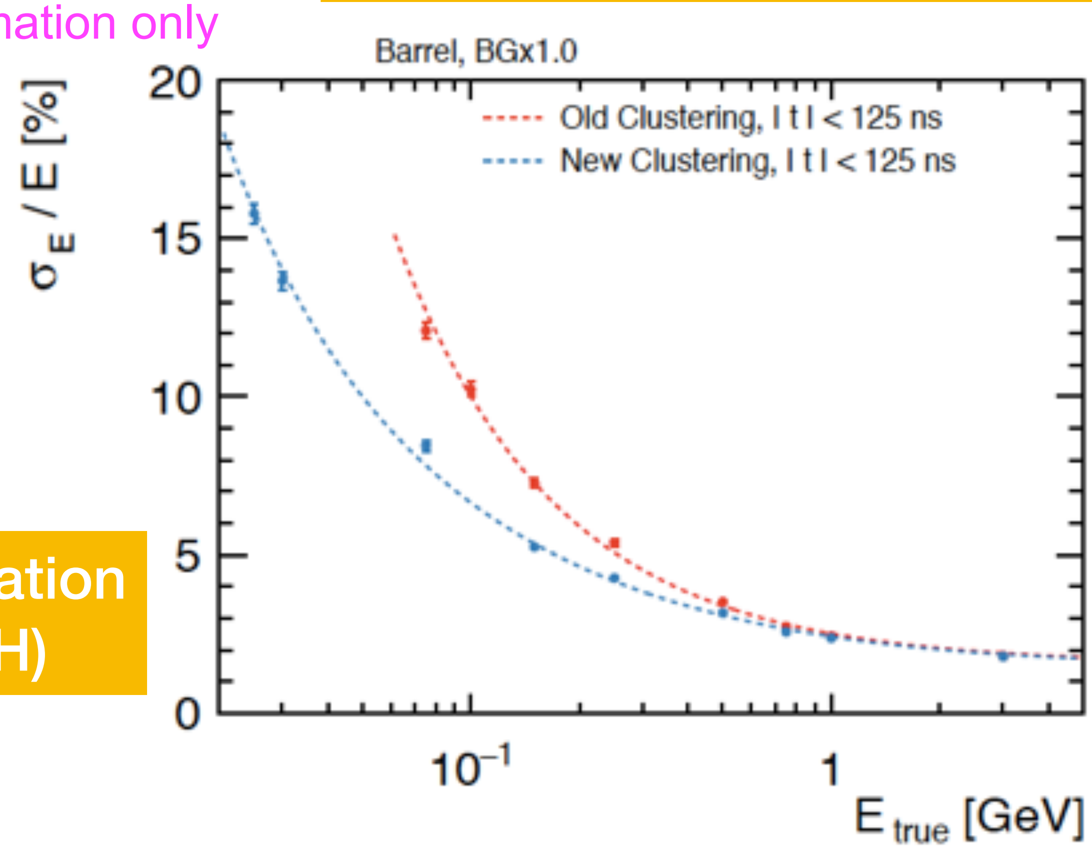

Tracking Efficiency as a function
of transverse momentum (left) and polar angle (right)

Calorimeter Reconstruction (ECL

Kaon detection efficiency and pion fake rate using dE/dx information only

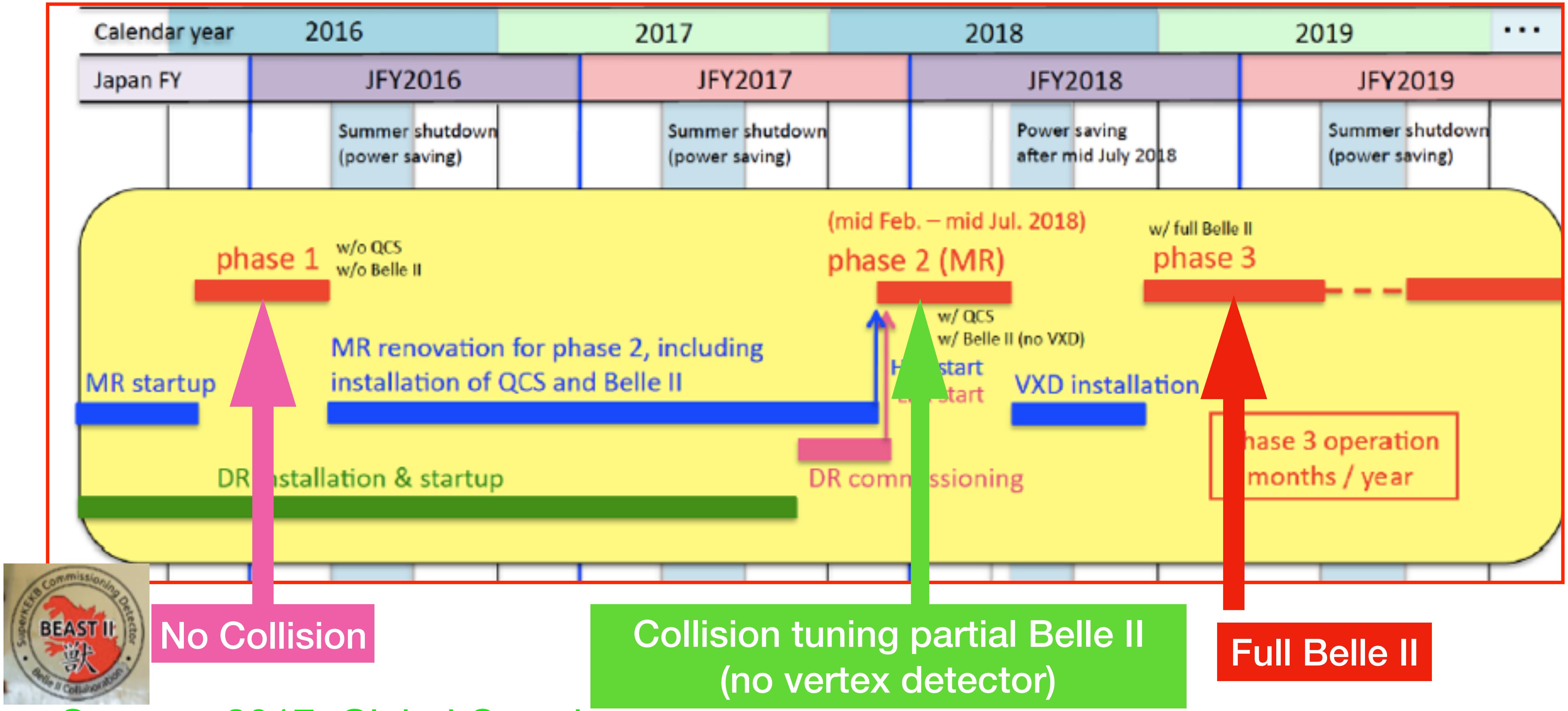



Charged Particle Identification
(VXD, CDC, TOP, ARICH)



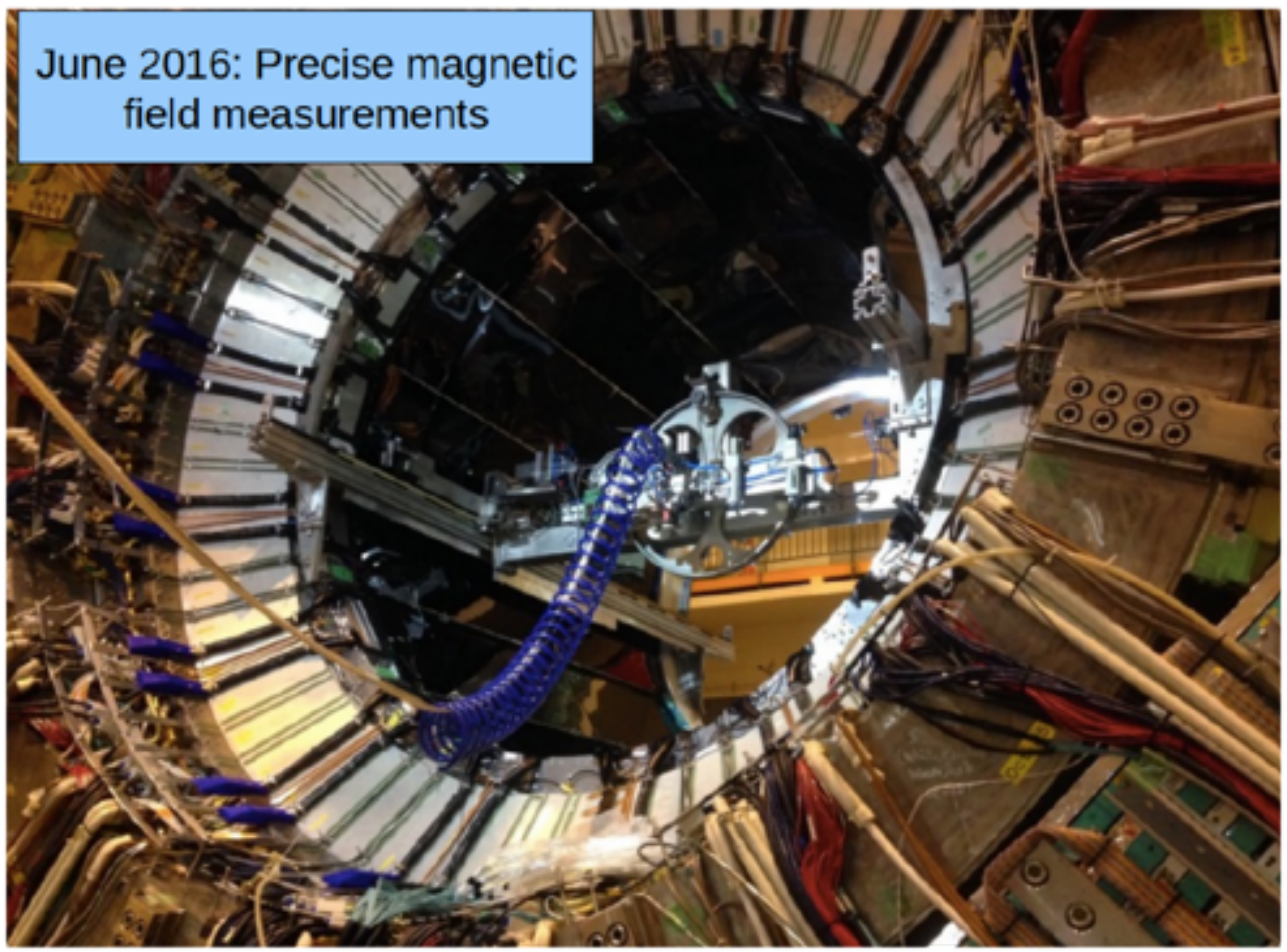

Peak energy resolution in the ECL barrel as function of true
photon energy for full background

# TimeLine

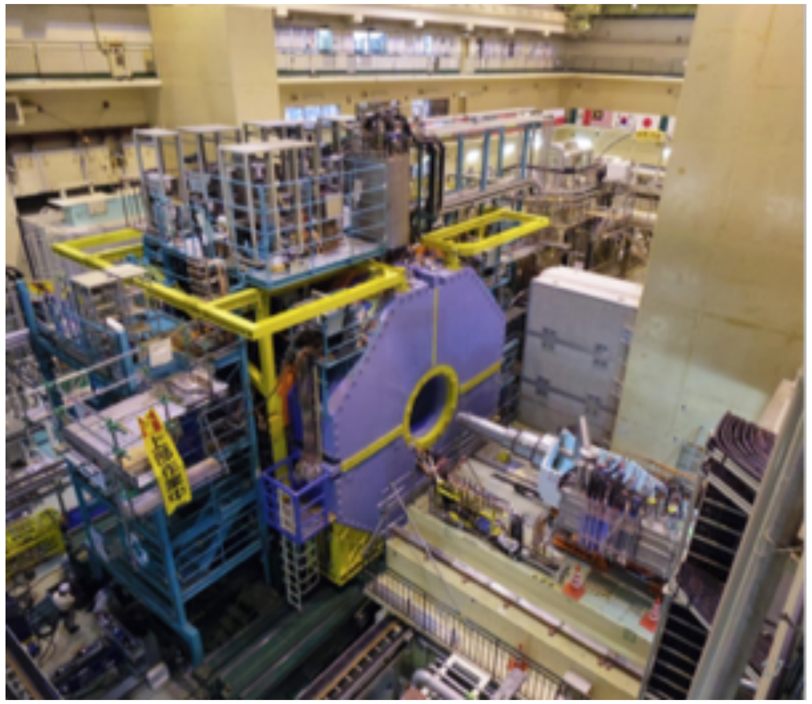


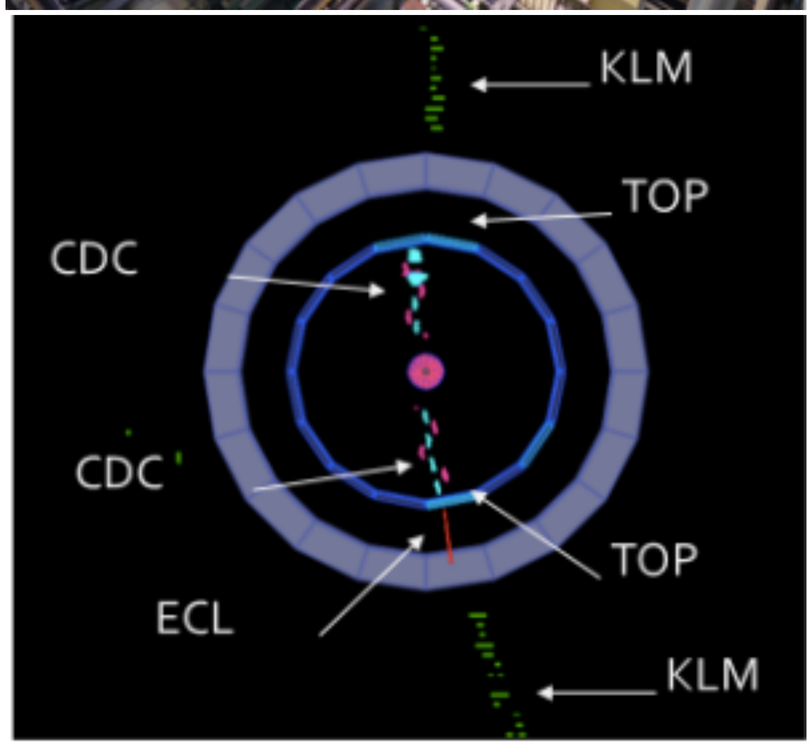

Summer 2017: Global Cosmic ray run
September 2017: ARICH and forward ECL
October 2017: Start Beast Phase II Vertex detector (VXD) commissioning
November 2017 - Summer 2018: Phase 2 commissioning [Tune SUPERKEKB with nano-beams, ensure background levels are compatible with vertex detector operation]
Summer 2018: Install VXD
End 2018: Full detector operation - Start of Physics Run

# Belle II upgrade status




# Belle II Roll in

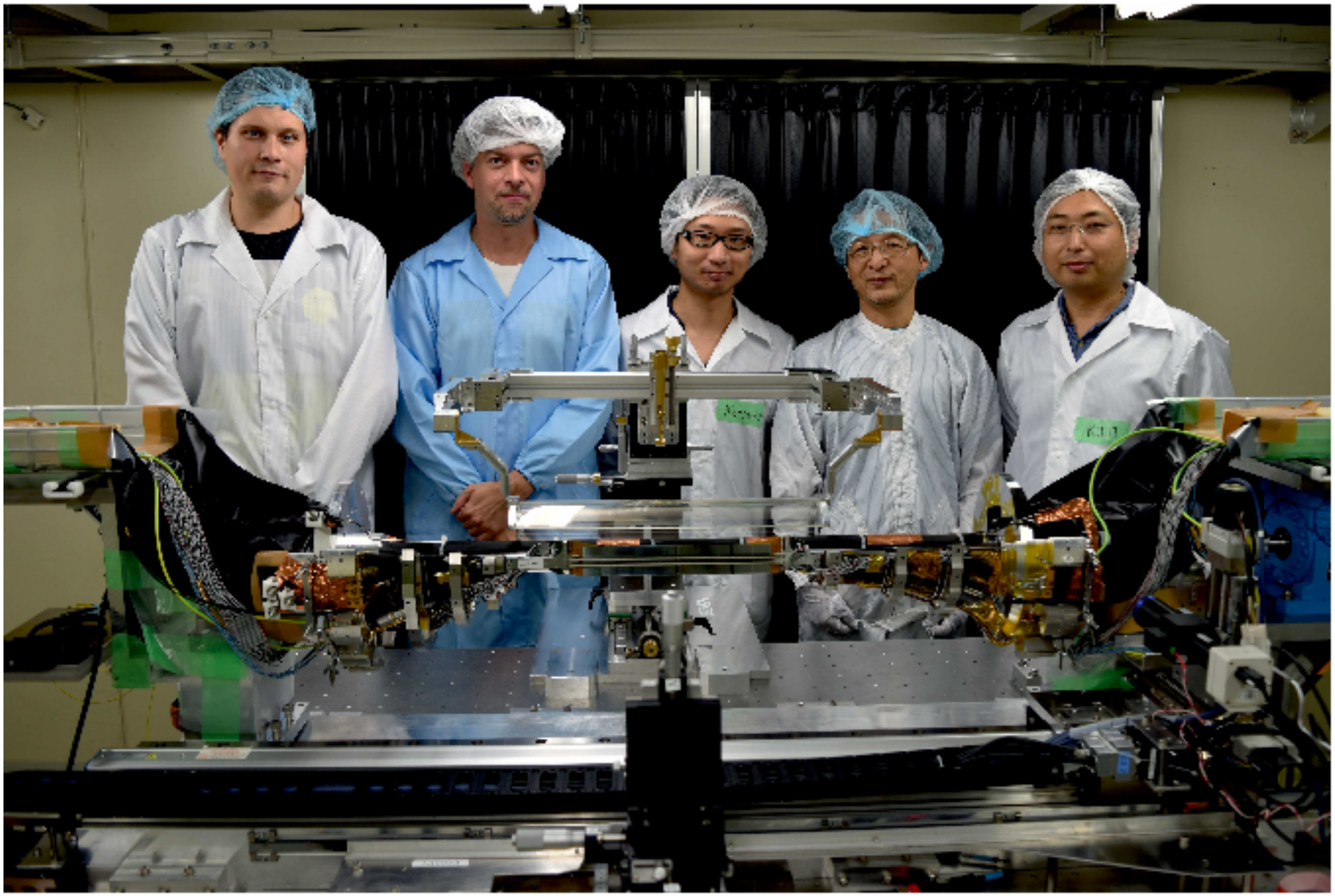





Systems included: CDC, TOP, ECL, KLM
- Magnetic field: 1.5 T


Link to livecast: https://t.co/7k54fKQMYV
https://www.belle2.org
https://twitter.com/belle2collab
https://www.facebook.com/belle2collab

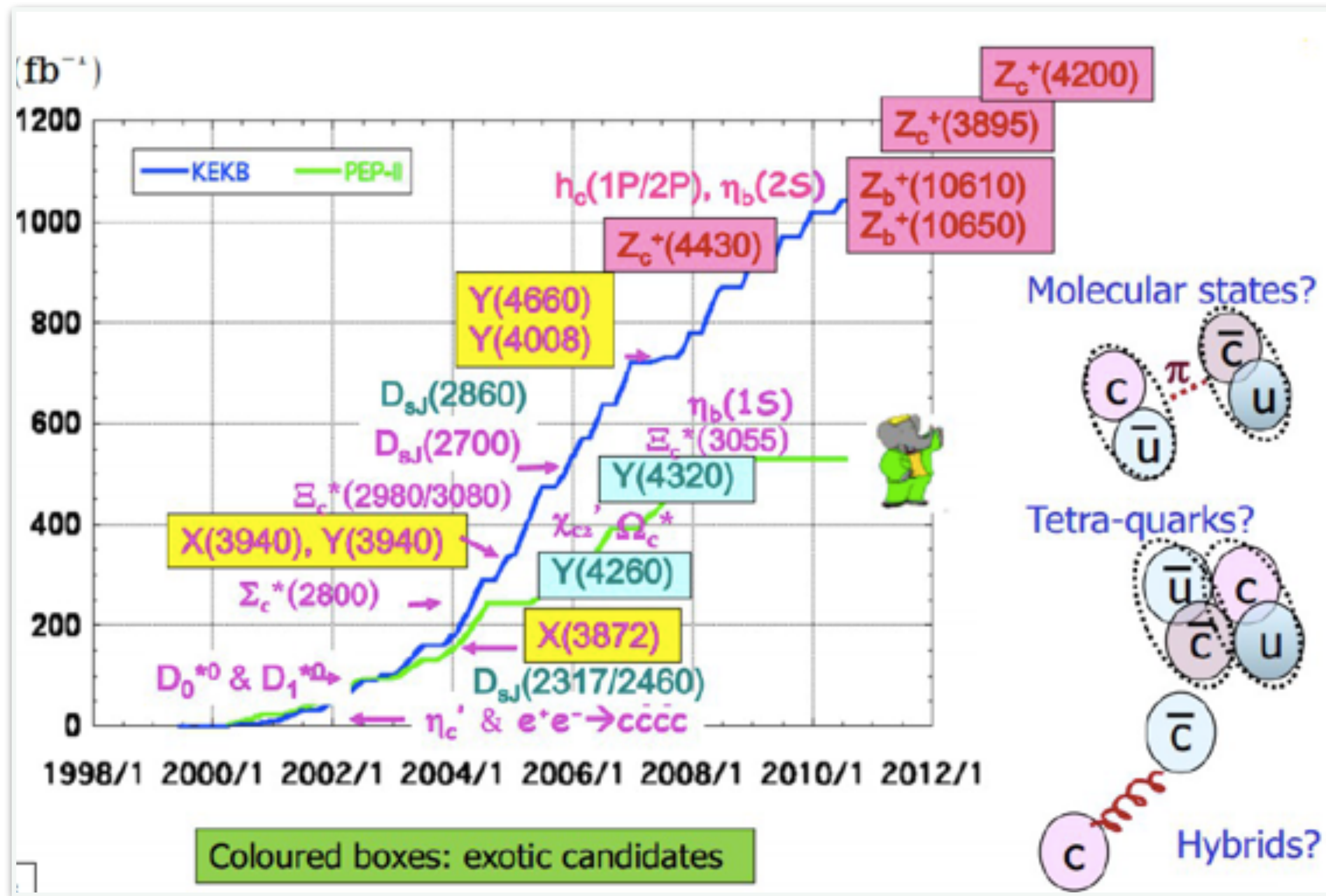
# First SVD ladder mounting

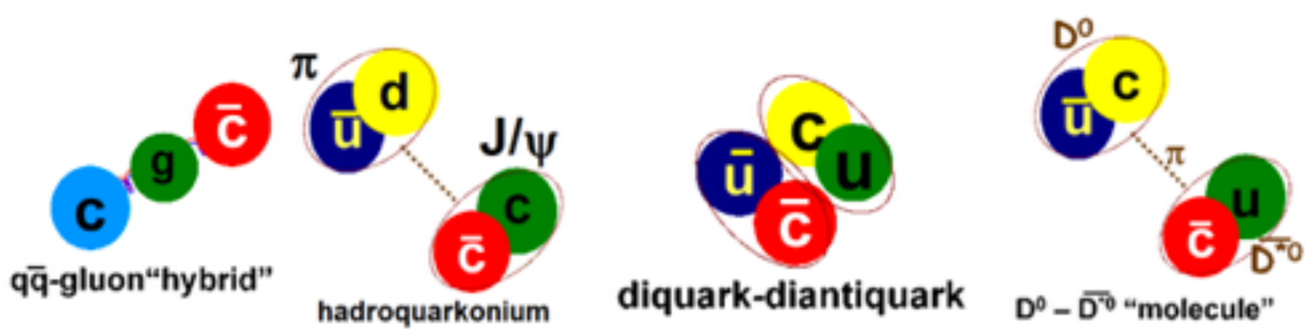


First SVD ladder mounted successfully on September 10, 2017

# Belle II Physics prospects

- Several new states observed that do not fit into conventional quark model
- More states expected, opening up the exotic state studies at Belle II
- Possible models to explain exotic state: Meson Molecules, Tetraquarks, Hybrids, Hadroquarkonium




# Possible Physics searches at Belle II

- Search for hadronic transitions from Y(6S) to study its structure. Possible channels are Y(nS)/$h_b$(mP)ππ with the search for intermediate $Z_b$(10610, 10650)π states, Y(nS)η, Y(1D)(η/ππ), $h_b$(nP)η etc.

- Search for missing bottomonia below BB-bar threshold, e.g. spin-singlet member of the 1D multiplet, all members of the 2D and 1F multiplets

- Search for molecular states - partners of $Z_b$ using radiative and ππ transitions

- Scan near and above Y(6S), to clarify structure of Y(6S) state (decomposition of $R_b$), to search for vector bottomonium-like states and to study the $\lambda_b$ $\lambda_b$-bar threshold region
- **Belle II plans to collect more data at the Y(5S) resonance**

- **Belle II data at the Y(3S), scan above Y(5S) and Y(6S) promises to yield interesting physics results**

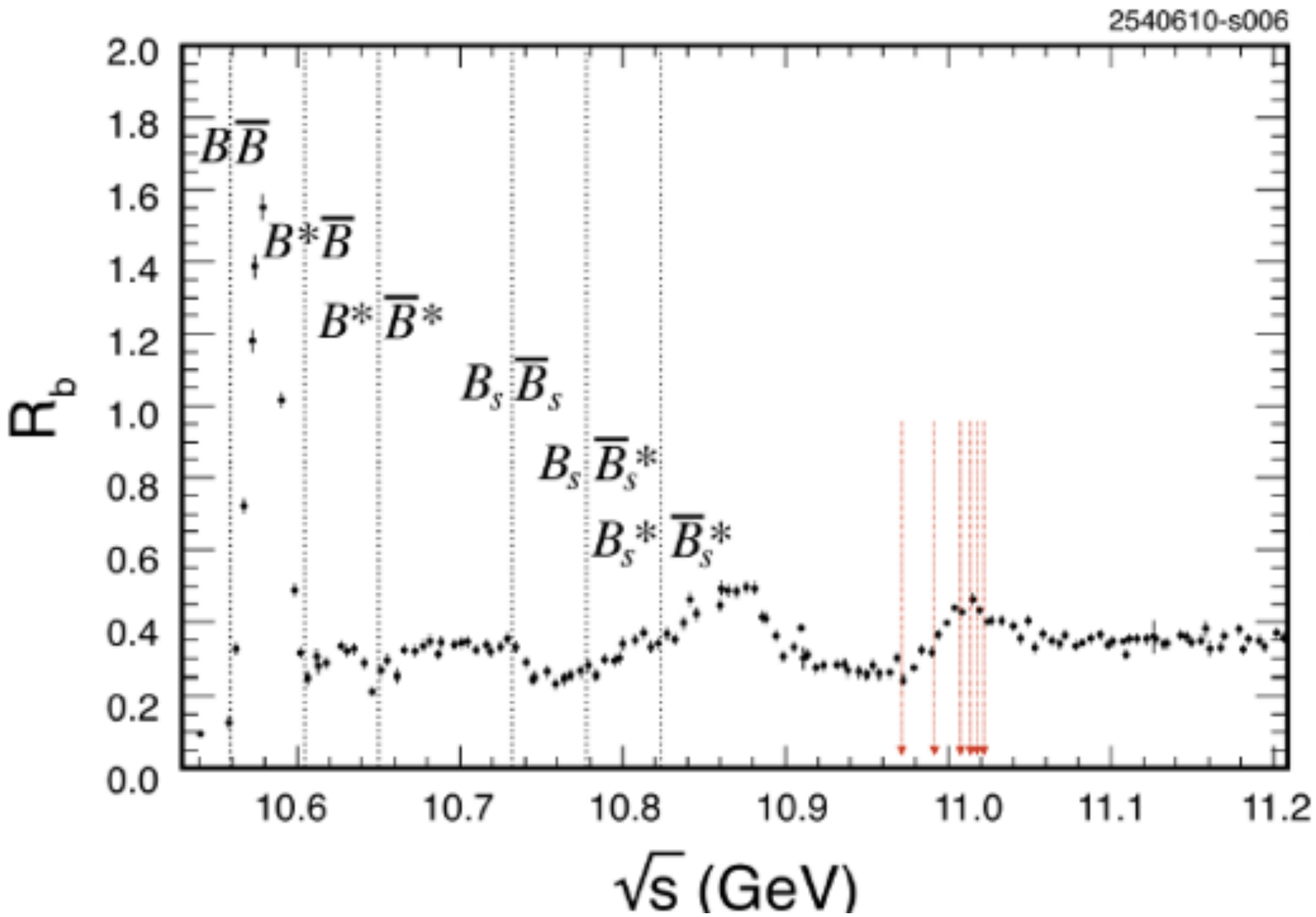
# Datasets available for Y(nS)

| 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 | ~ 5.5 | 36 | 121 | 711 | 772 | 3 | 12 | 25 | 158 | 6 | 102 |

World's largest data samples at most bottomonium resonances

Y(1D)~10160 MeV

Y(2D)~10450 MeV

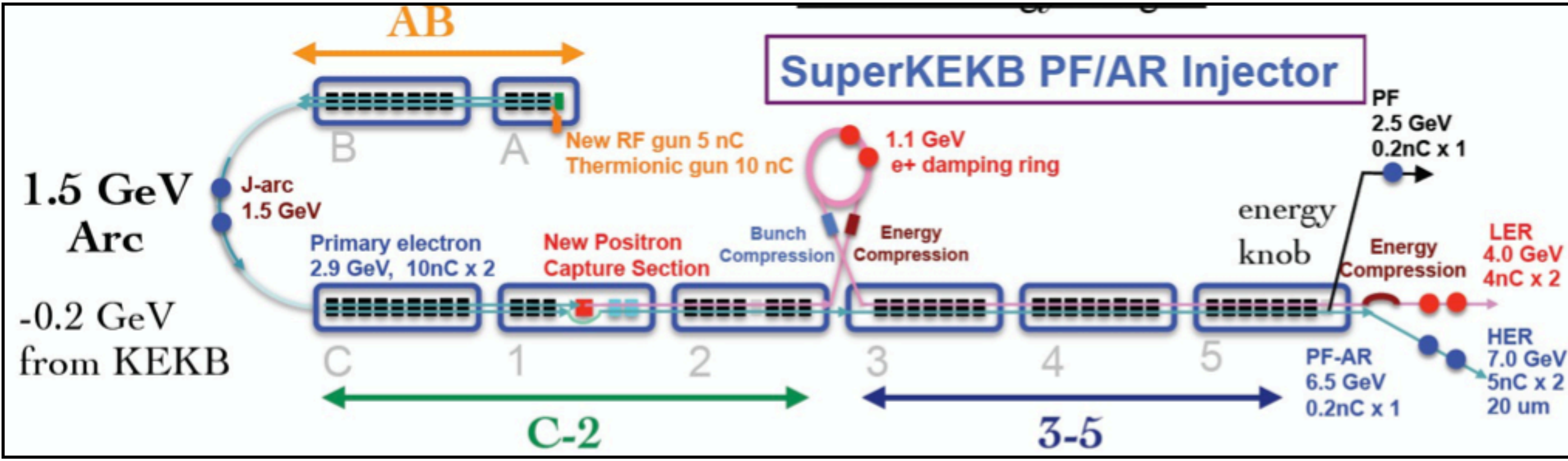


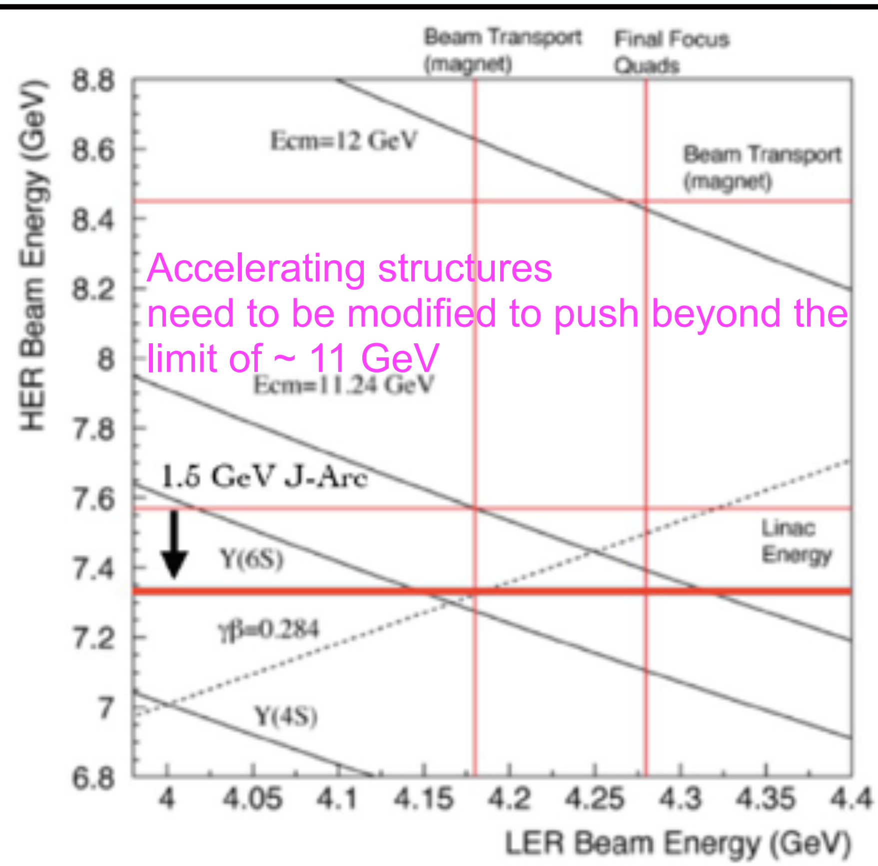

Belle took 5.5 fb$^{-1}$ data at 6 different energies on and around the Y(6S) resonance energy.

https://confluence.desy.de/display/BI/B2TiP+WebHome

# SuperKEKB Limitations

Related to Phase II only



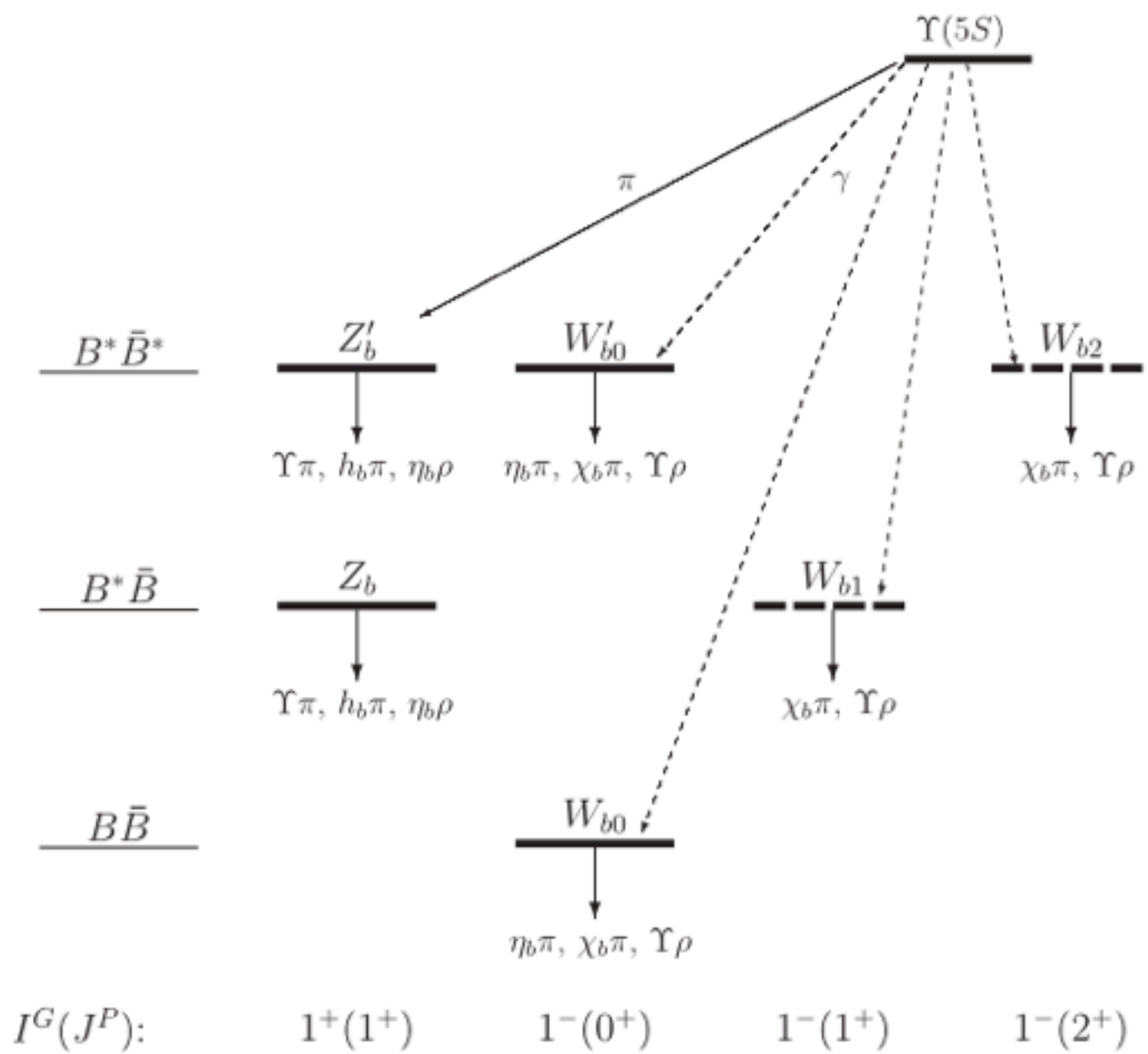

Y(4S): HER- 7 GeV, LER - 4 GeV
A -B, C -2, 3 -5 sectors: 1 backup unit
(1 unit = 160 MeV)
Planned 2 backup units in Phase 3 in C -2

Y(6S): HER- 7.30 GeV, LER - 4.16 GeV
No backup unit in C-5 sector
No backup unit in 3 -5 sector

Difficult to go to Y(6S) in Phase II,
but possible in early Phase III

# $Z_b$ (10610) and $Z_b$ (10650) states

- $Z_b$ states are responsible for large rates of production of $h_b$(1P, 2P) states seen in Y(5S) decays
- Charged $Z_b$ (10610) and $Z_b$(10650) discovered in Y(nS)$\pi^{+/-}$ and $h_b$(mP)$\pi^{+/-}$ at Y(5S) [PRL 108, 122001 (2012), Belle Collaboration]
- Neutral $Z_b$ (10610) discovered in Y(nS)$\pi^0$ at Y(5S) [PRD 88, 052016 (2013), Belle Collaboration]
- Charged $Z_b$ (10610) to $B^*B$ decays and $Z_b$(10650) to $B^*B^*$ decays observed at Y(5S) [PRL 116, 212001 (2016), Belle Collaboration]



# Analysis Technique for Y(nS) to $Z_b$ transitions

- Consider one of the Golden Modes:
Y(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 Y(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 4$^{th}$ order Chebyshev polynomial

# $Z_b$ (10610) and $Z_b$ (10650) states

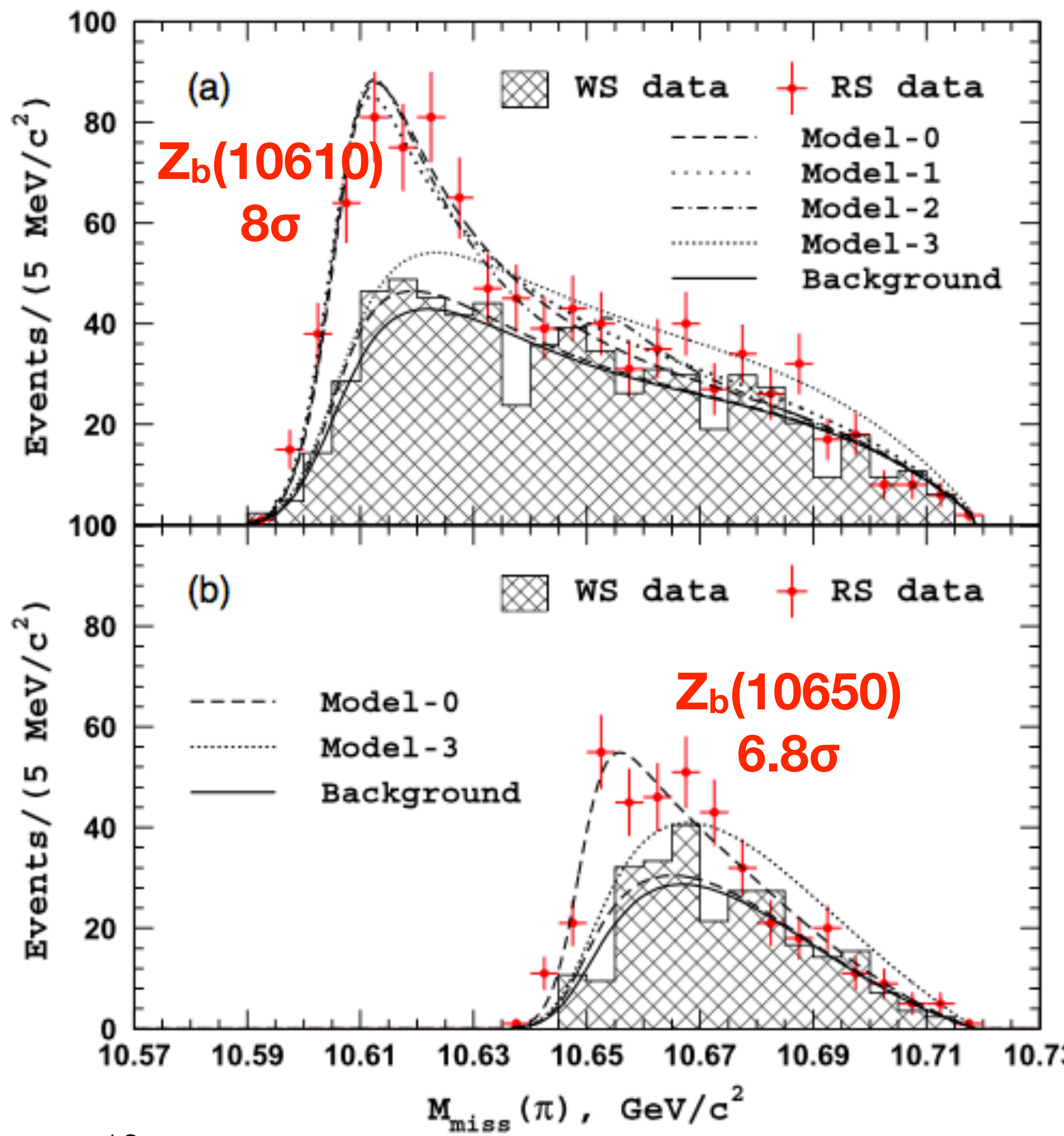
[PRL 116, 212001 (2016)]

Minimum four quark content

Observations are consistent with expectations for molecular state

- Proximity to $BB^*$- bar and $B^*B^*$- bar thresholds and their being dominant decay modes

- $J^P$ measurements, total widths, production rates



# $Z_b$ (10610) and $Z_b$ (10650) states

Are the $Z_b$'s really molecules? [Phs. Rev. D 84, 054010]

$Z_b(10610) = |B^*\bar{B} - B\bar{B}^*\rangle$ and $Z_b(10650) = |B^*\bar{B}^*\rangle$ implies:

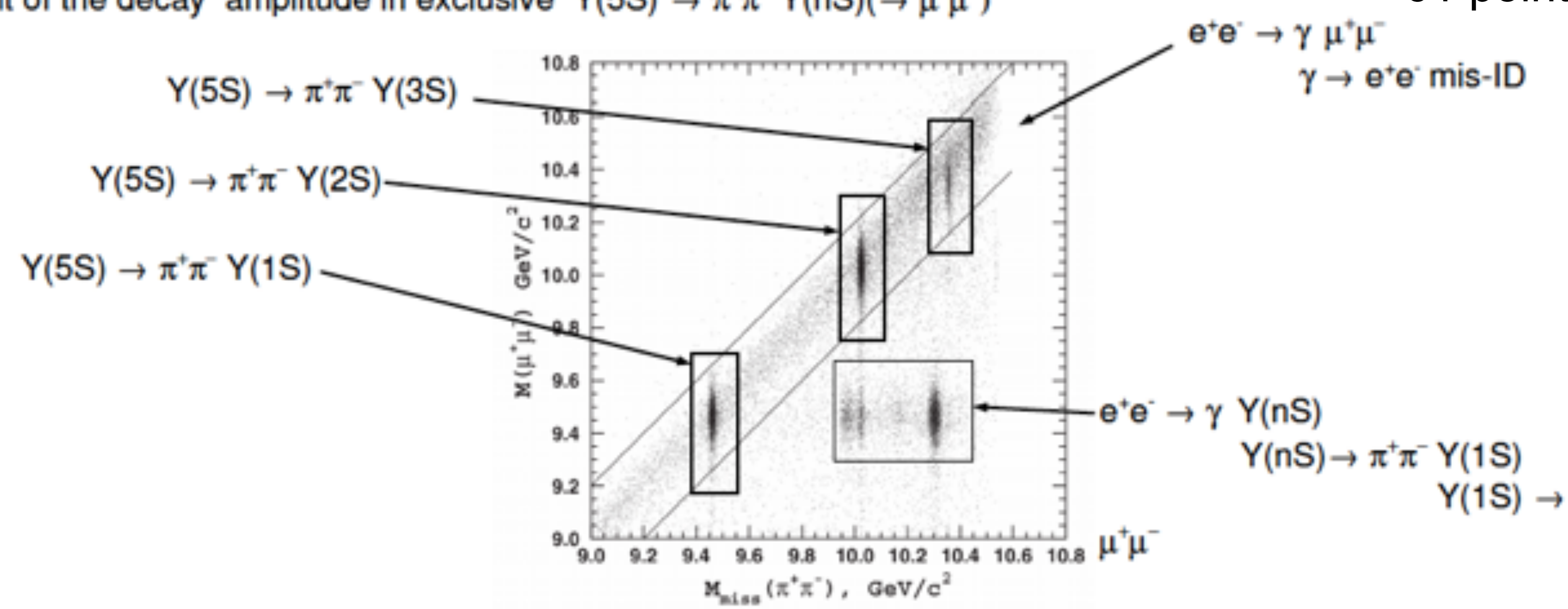
1) M [$Z_b$(10610)] ~ M [$B^*$] + M [B-bar]
2) M [$Z_b$(10650)] ~ 2M [$B^*$]
3) $\Gamma_{Zb} \sim \Gamma_{Zb'}$
4) BF [$Z_b(10650) \rightarrow BB^*$] ~ 0

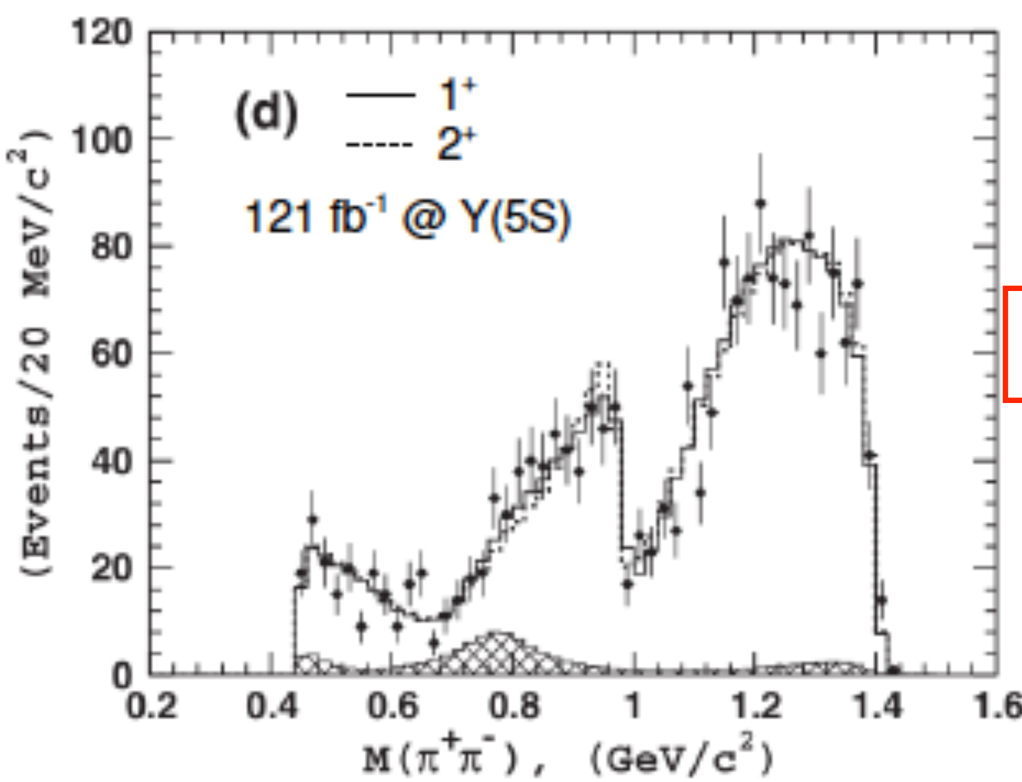
| Channel | Fraction, % | |
|---|---|---|
| | $Z_b(10610)$ | $Z_b(10650)$ |
| $\Upsilon(1S)\pi^+$ | $0.54^{+0.16+0.11}_{-0.13-0.08}$ | $0.17^{+0.07+0.03}_{-0.06-0.02}$ |
| $\Upsilon(2S)\pi^+$ | $3.62^{+0.76+0.79}_{-0.59-0.53}$ | $1.39^{+0.48+0.34}_{-0.38-0.23}$ |
| $\Upsilon(3S)\pi^+$ | $2.15^{+0.55+0.60}_{-0.42-0.43}$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

# $Z_b$ (10610) and $Z_b$ (10650) states

Phys.Rev. D91 (2015) no.7, 072003

Full fit of the decay amplitude in exclusive $\Upsilon(5S) \to \pi^+\pi^- \Upsilon(nS)(\to \mu^+\mu^-)$

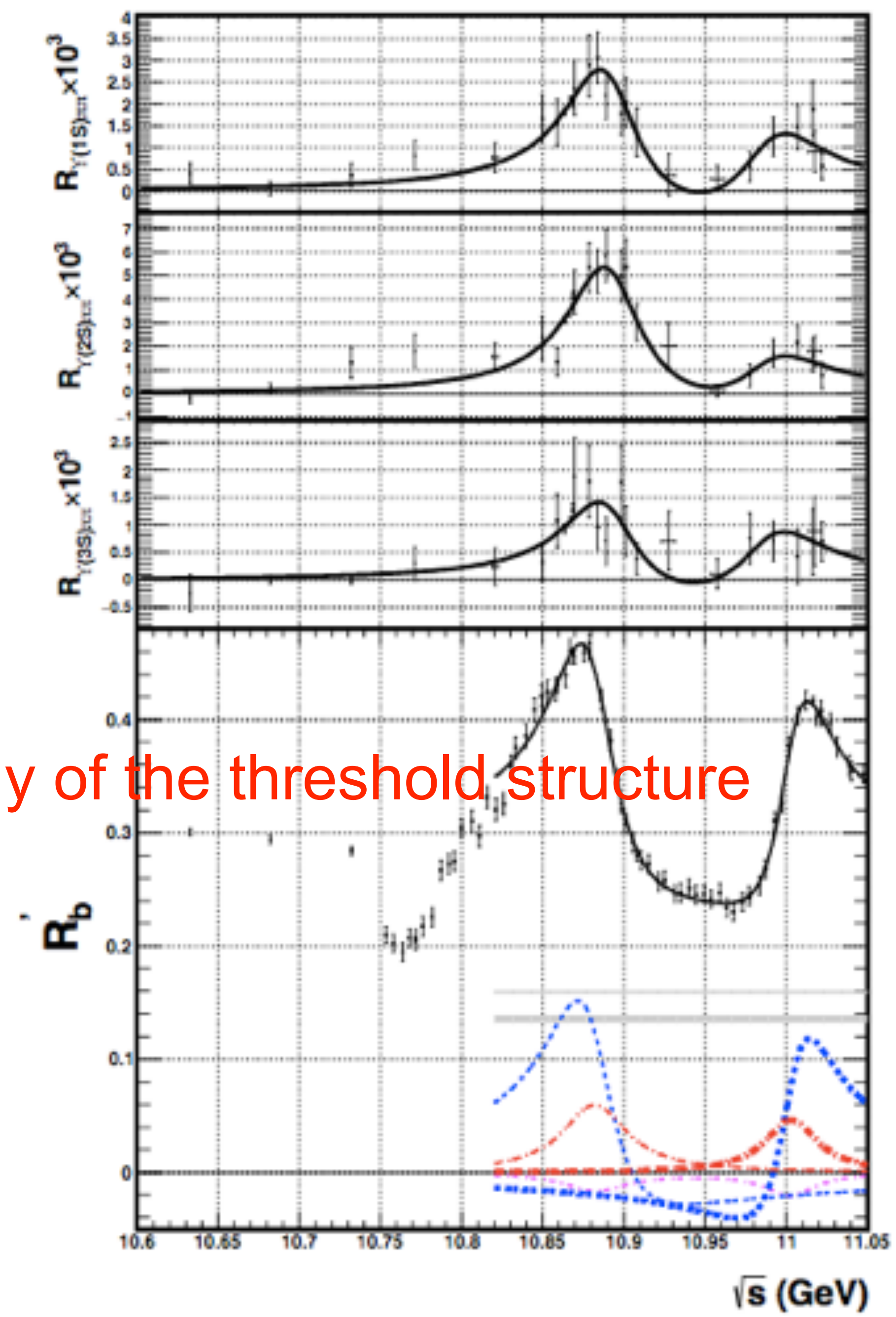



**Best fit: $J^P = 1^+$**

Phys. Rev. D 93, 011101 (2016)

Belle Υ(5S) - Υ(6S) scan:
22 points, 1 fb-1 per point, 5 MeV apart (HILUM)
61 points, 0.5 fb-1 per point, 1 MeV apart (LOWLUM)




$R_b$: study of the threshold structure

First observation of $\Upsilon(6S) \to \pi^+\pi^-\Upsilon(nS)$

# $Z_b$ (10610) and $Z_b$ (10650) states

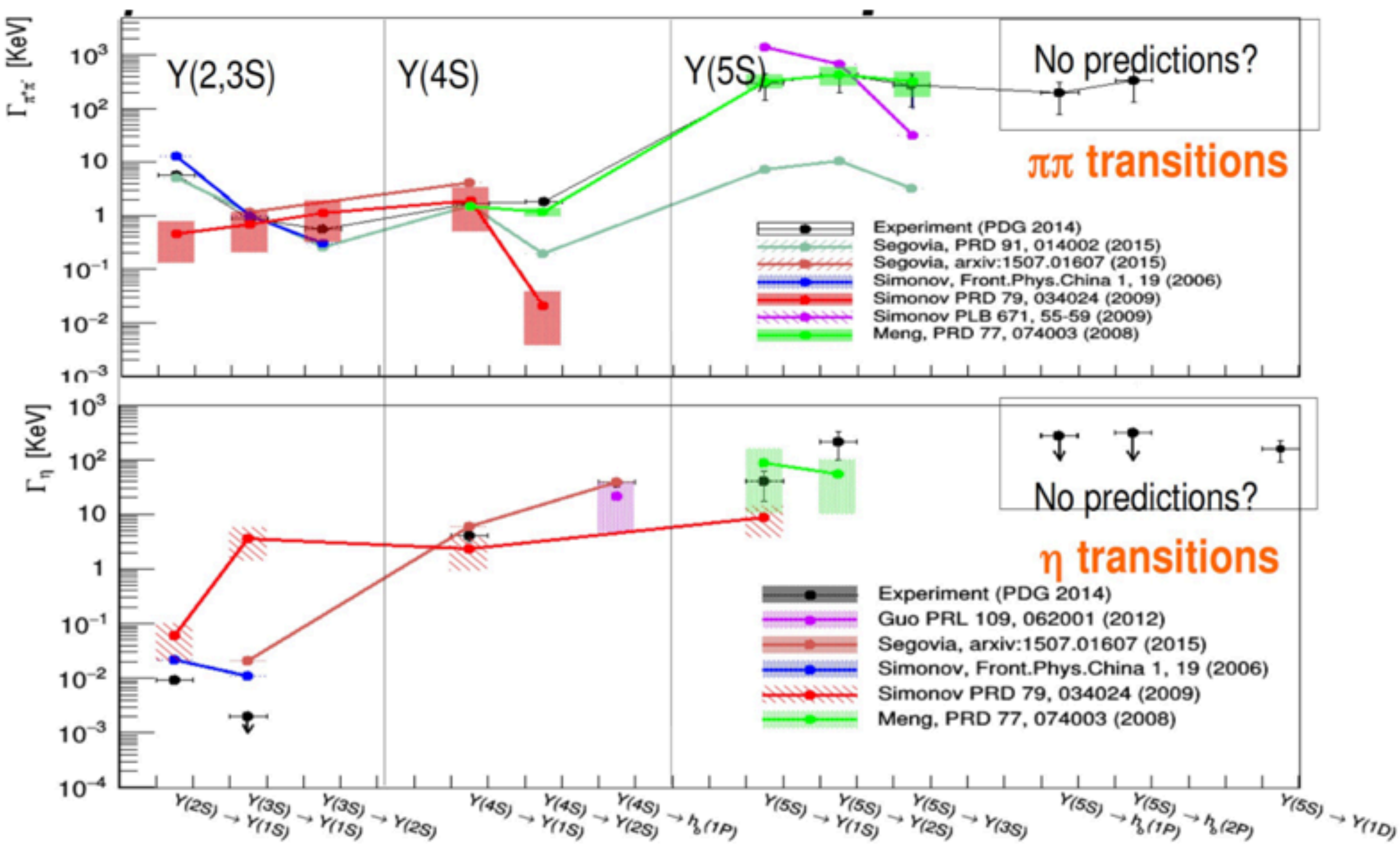
- Produced in both $\Upsilon(5S,6S)$ decays, and it's important that we study production from both resonances in Belle II

    - Expect 20 $fb^{-1}$ of $\Upsilon(6S)$ in Phase 2 or early Phase 3 and much more later
    - Hope to collect at some point a large $\Upsilon(5S)$ sample, increasing its statistics up to ~5 $ab^{-1}$)

- Further analysis is required to understand these states

- At Belle II, aim to improve the understanding of the $Z_b$ (10610) and $Z_b$ (10650) states and the branching fractions

# η vs ππ transition in Υ(nS)

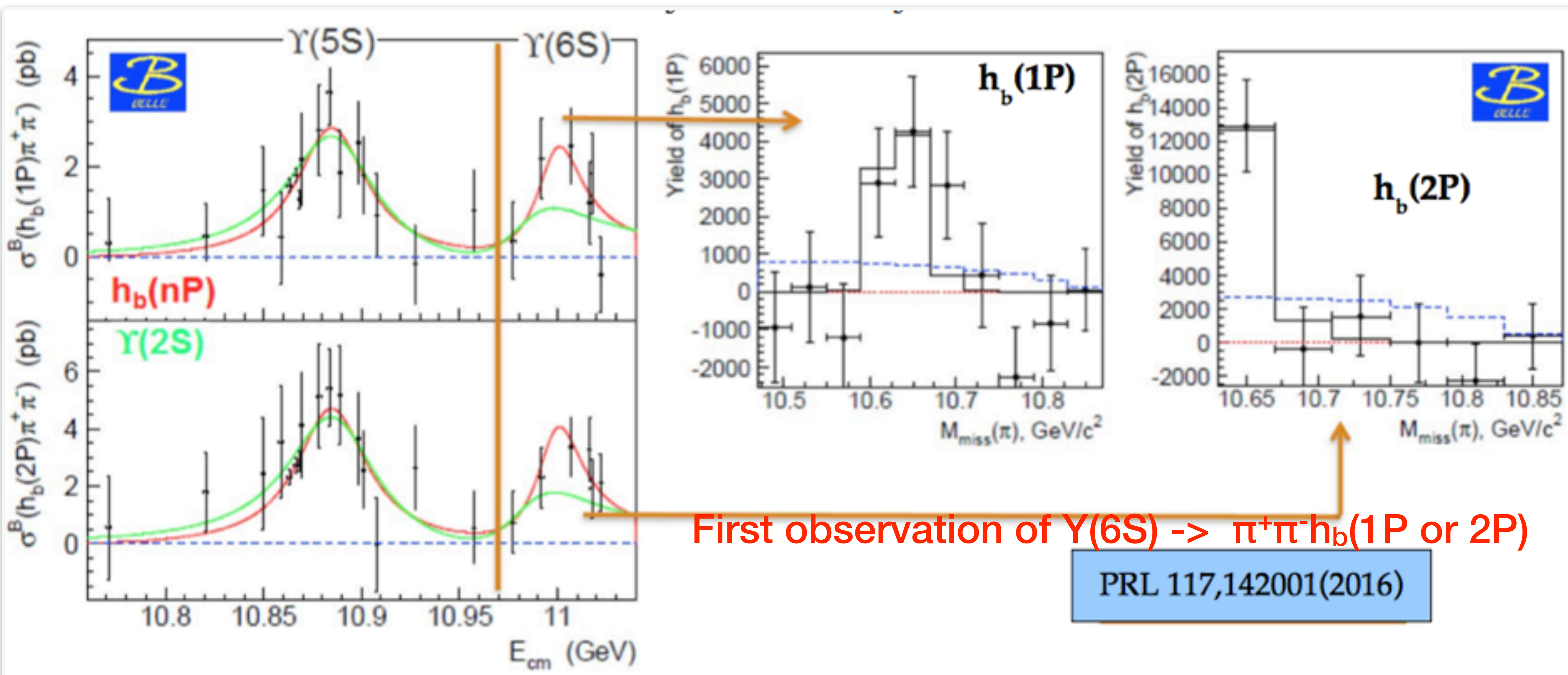



Model not established yet which can describe both transitions below and above the open flavor threshold

# Belle result: $e^+e^-$ to $h_b(1,2P)\pi\pi$

- Clear evidence of dipion transitions to both the $h_b$ states at 6 different energies on and around Υ(6S) (1 $fb^{-1}$ each)
- Difficult to quantify the fractions decaying via $Z_b(10610)$ and $Z_b(10650)$ due to low statistics

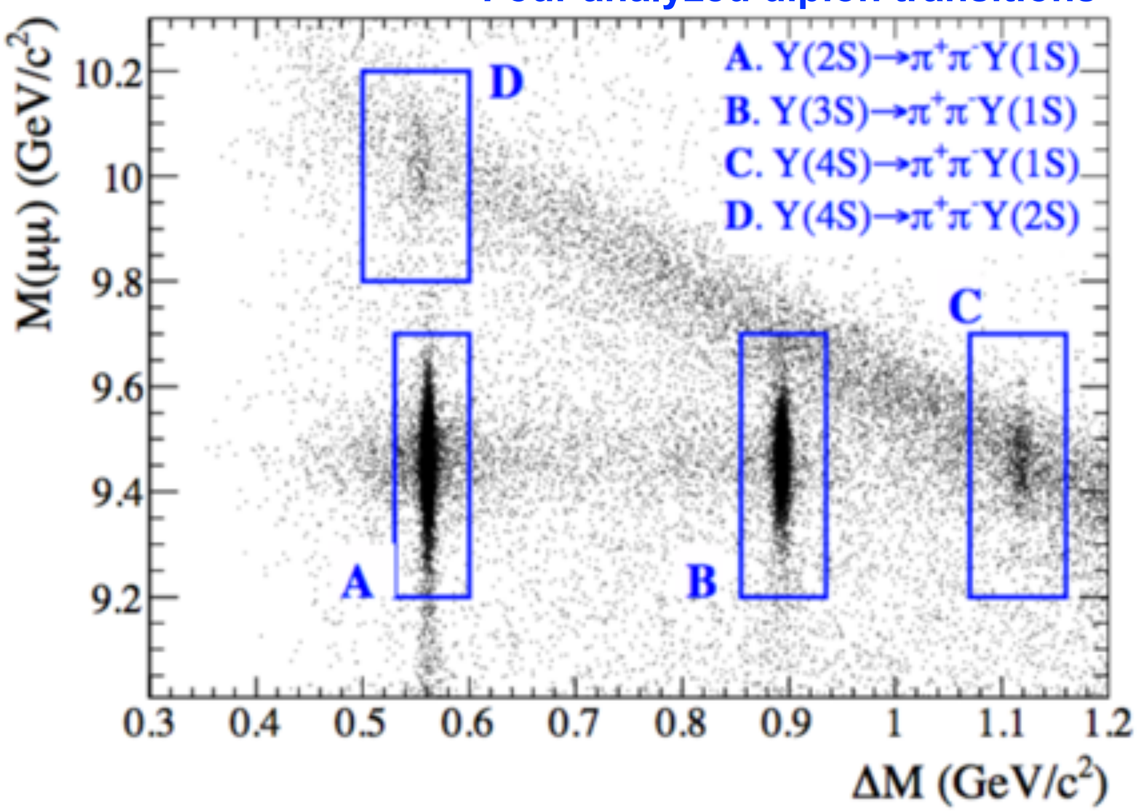
Single pion recoil spectrum shows "$Z_b$-like" structures
Open question: Is this decay completely $Z_b$ mediated?

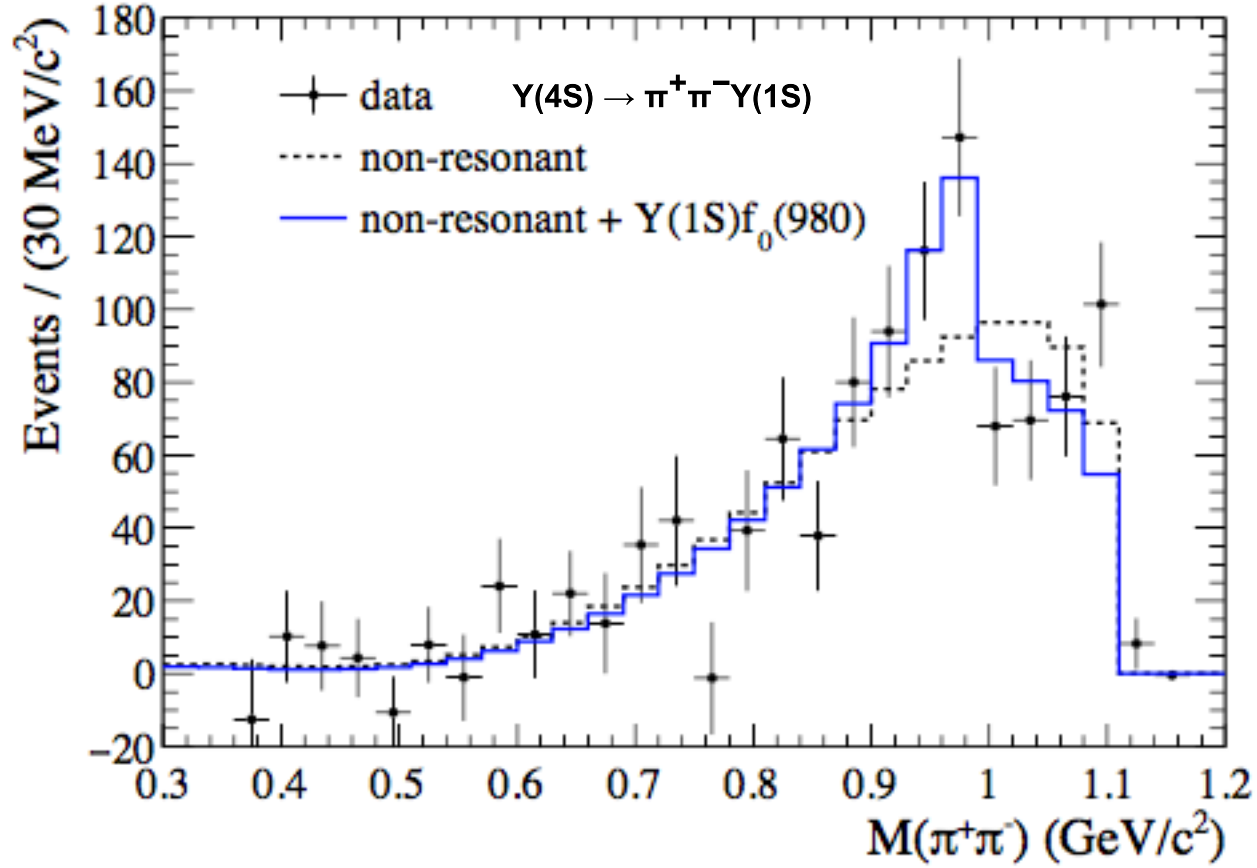



Belle II is planning to take more data at Υ(6S) during the first or second year of data taking

# η and ππ transitions

(ArXiV 1707.04973)




| Measurement | Result | PDG value [17] |
|---|---|---|
| $\mathcal{B}(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S))$ | $(8.2 \pm 0.5 \ \pm 0.4) \ \times 10^{-5}$ | $(8.1 \pm 0.6) \ \times 10^{-5}$ |
| $\mathcal{B}(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(2S))$ | $(7.9 \pm 1.0 \ \pm 0.4) \ \times 10^{-5}$ | $(8.6 \pm 1.3) \ \times 10^{-5}$ |
| $\mathcal{B}(\Upsilon(4S) \to \eta\Upsilon(1S))$ | $(1.70 \pm 0.23 \pm 0.08) \ \times 10^{-4}$ | $(1.96 \pm 0.28) \ \times 10^{-4}$ |
| $\mathcal{R}$ as in Eq. 1 | $2.07 \pm 0.30 \pm 0.11$ | $2.41 \pm 0.42$ |

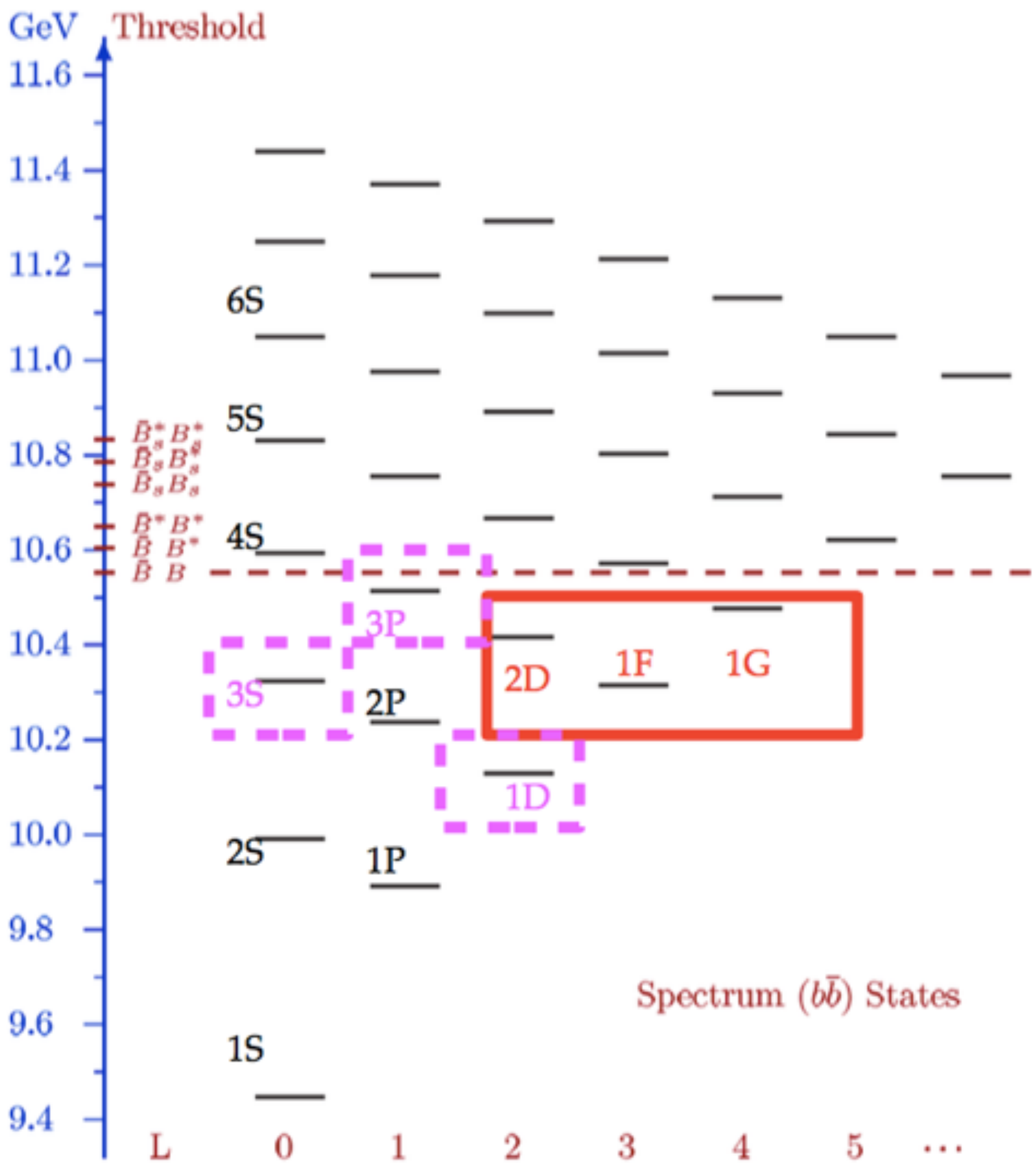
Model that includes the contribution from the $f_0(980)$ meson is preferred by the data, with a statistical significance of 2.8σ

# Tetra quarks between Y(5S) and Y(6S)

| Label | $J^{PC}$ | charmonium-like State | charmonium-like Mass [MeV] | bottomonium-like State | bottomonium-like Mass [MeV] |
|---|---|---|---|---|---|
| $X_0$ | $0^{++}$ | — | 3756 | — | 10562.2 |
| $X_0'$ | $0^{++}$ | — | 4024 | — | 10652.2 |
| $X_1$ | $1^{++}$ | $X(3872)$ | 3890 | — | 10607.2 |
| $Z$ | $1^{+-}$ | $Z_c^+(3900)$ | 3890 | $Z_b^{+,0}(10610)$ | 10607.2 |
| $Z'$ | $1^{+-}$ | $Z_c^+(4020)$ | 4024 | $Z_b^+(10650)$ | 10652.2 |
| $X_2$ | $2^{++}$ | — | 4024 | — | 10652.2 |
| $Y_1$ | $1^{--}$ | $Y(4008)$ | 4024 | $Y_b(10891)$ | 10891.1 |
| $Y_2$ | $1^{--}$ | $Y(4260)$ | 4263 | $Y_b(10987)$ | **10987.5** |
| $Y_3$ | $1^{--}$ | $Y(4290)$ (or $Y(4220)$) | 4292 | — | **10981.1** |
| $Y_4$ | $1^{--}$ | $Y(4630)$ | 4607 | — | 11135.3 |
| $Y_5$ | $1^{--}$ | — | 6472 | — | 13036.8 |

Tetraquark model (Maiani et al., Ali et al.) predicts a full spectrum of states in both bottomonium and charmonium region - Belle II can explore these states

# Missing pieces of spectrum below threshold




3S: Not yet observed by anyone, maybe reachable from $h_b(3P)$

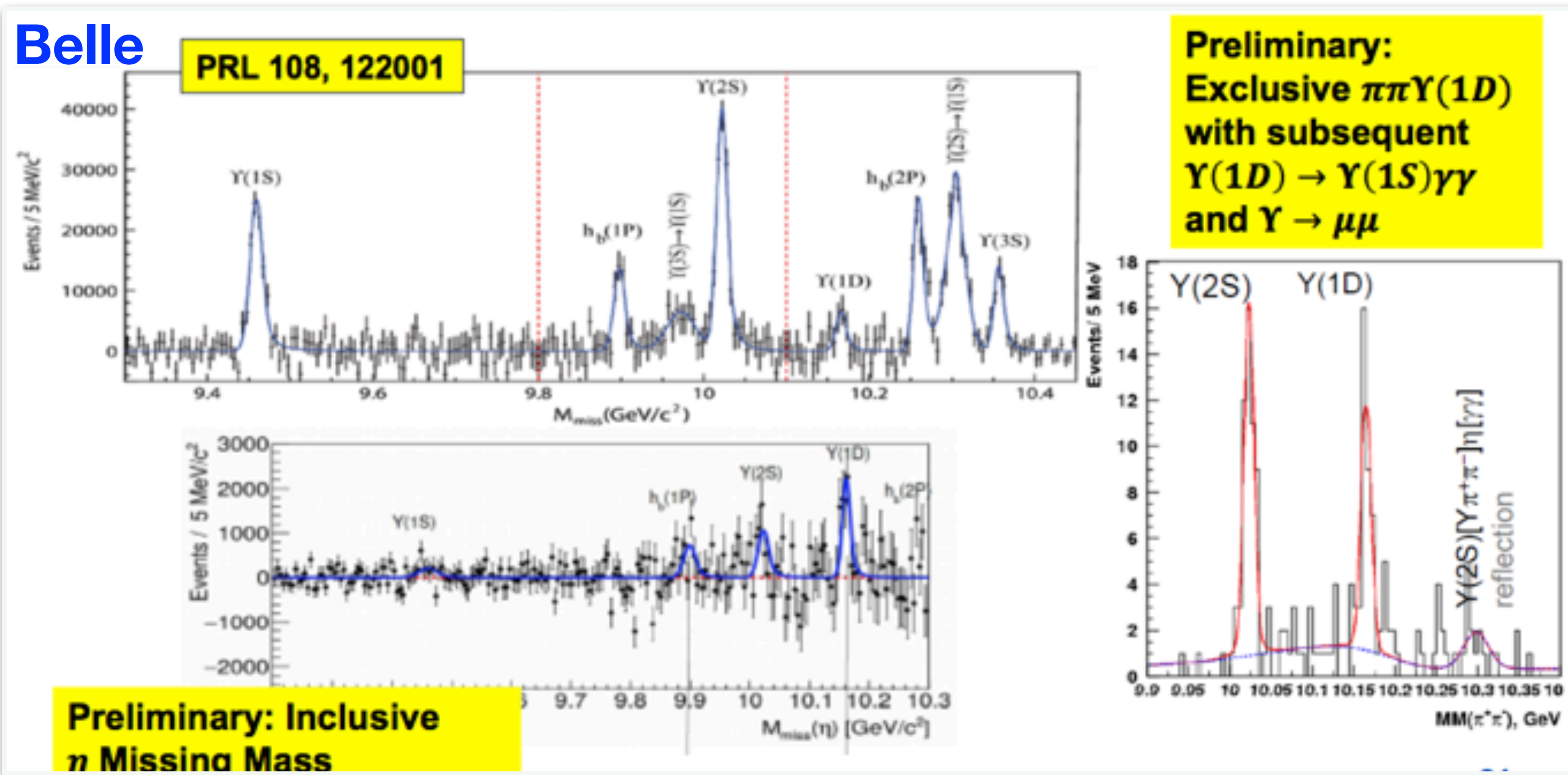
3P: Discovered at LHC, not yet resolved, can we see them from 4S?

Totally unknown: Belle II can search for the lowest member of the 2D triplet with a scan

1D: Triplet states best studied from 3S, singlet ($2^{-+}$) maybe reachable from $h_b(2P)$:

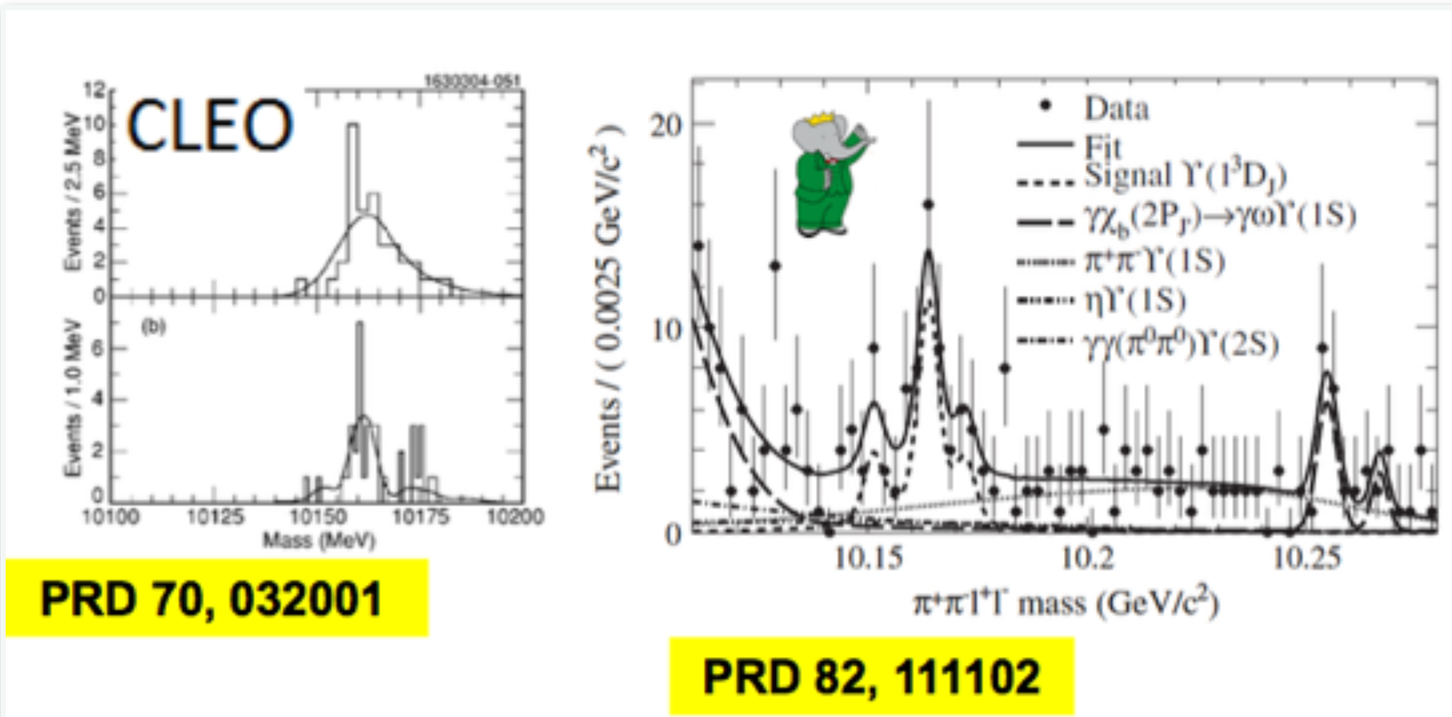
Belle II can scan the $1^{--}$ region

# Unresolved D-wave triplet Υ(1D)




Belle: η and ππ transition in Υ(5S),
but three peaks of Υ(1D) triplet are unresolved

# Belle II prospects for Υ(1D) and Υ(2D)




CLEO (from 3S)
PRD70 (2004) 032001 — $10161.1 \pm 0.6 \pm 1.6$ MeV

BaBar (from 3S)
PRD82 (2010) 111102 — $10164.5 \pm 0.8 \pm 0.5$ MeV

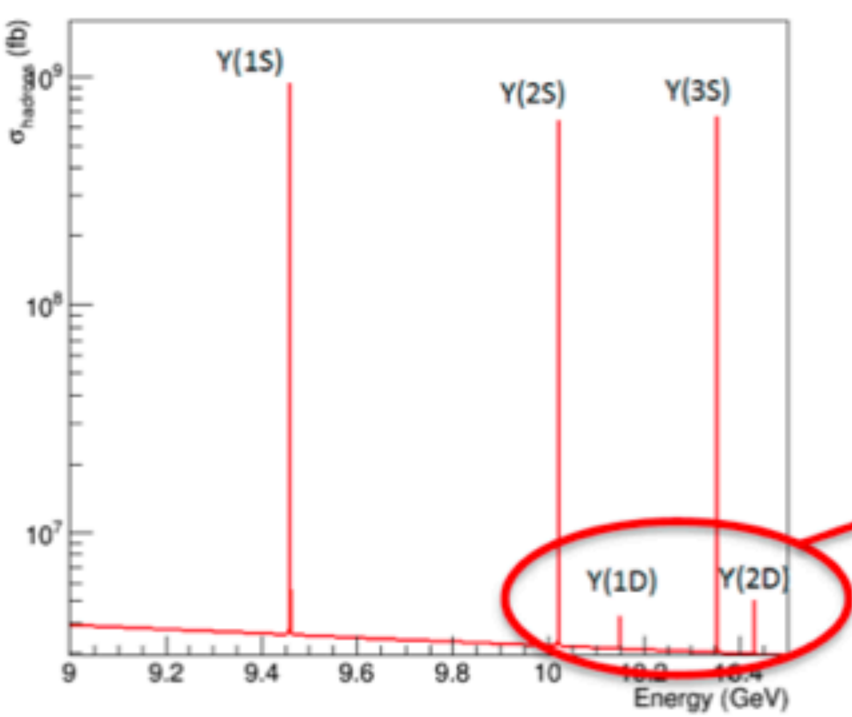
Belle (from 5S)
Proc. EPS-HEP 2013 — $10164.7 \pm 1.4 \pm 1.0$ MeV

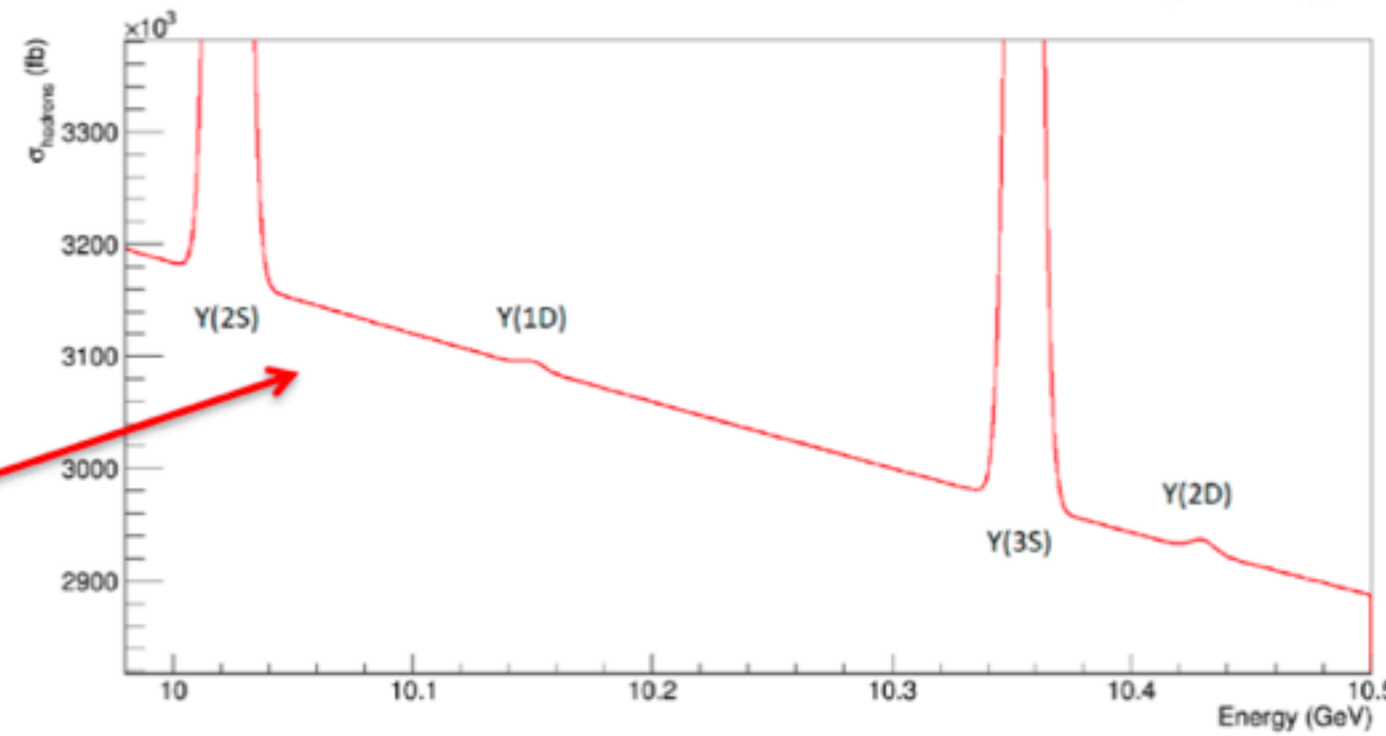
- Υ(2D) is not yet observed
- Sufficient phase space for both η and ππ transition from Υ(6S) to yield Υ(2D)
- Expect ~ 300 $fb^{-1}$ Υ(3S) sample and ~1-2 $ab^{-1}$ Υ(5S) sample - huge statistics to resolve the Υ(1D) peaks

# Scans of Y(1D), Y(2D)

Observable : e+e- to hadrons

Continuum cross section: $\sigma = N_c Q_f^2 \frac{86.8 \text{ nb}}{s\,(\text{GeV}^2)}$




Search for 1D: 7 point scan (5 MeV steps) around 10.15 GeV

Search for 2D: 7 point scan (5 MeV steps?) around 10.43 GeV

IF the 2S scan is successful, we may envisage a longer run on 2D peak and search for 1F states (single photon spectrum, probably large background from ISR Y(3S))

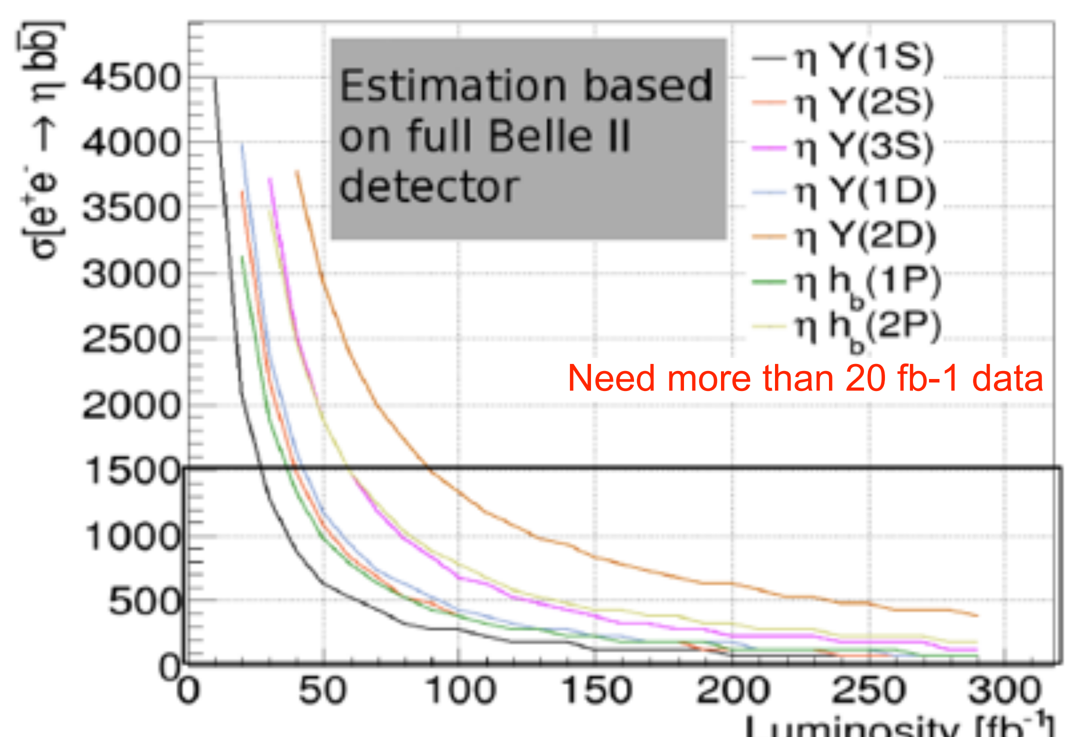
T. Pedlar, 6th International Conference on Exotic Atoms and Related Topics, Vienna, Austria

# Belle II Υ(6S) searches in Phase II

- Υ(6S) transition can be used to access (missing) states below the open beauty threshold
- Interesting to measure, because transitions are always violating the Heavy Quark Spin Symmetry - comparison with QCD multipole expansion computations
- Based on Υ(5S) experience, it is reasonable to expect a cross section < 1500 $fb^{-1}$

Search for missing conventional bottomonia below BB threshold

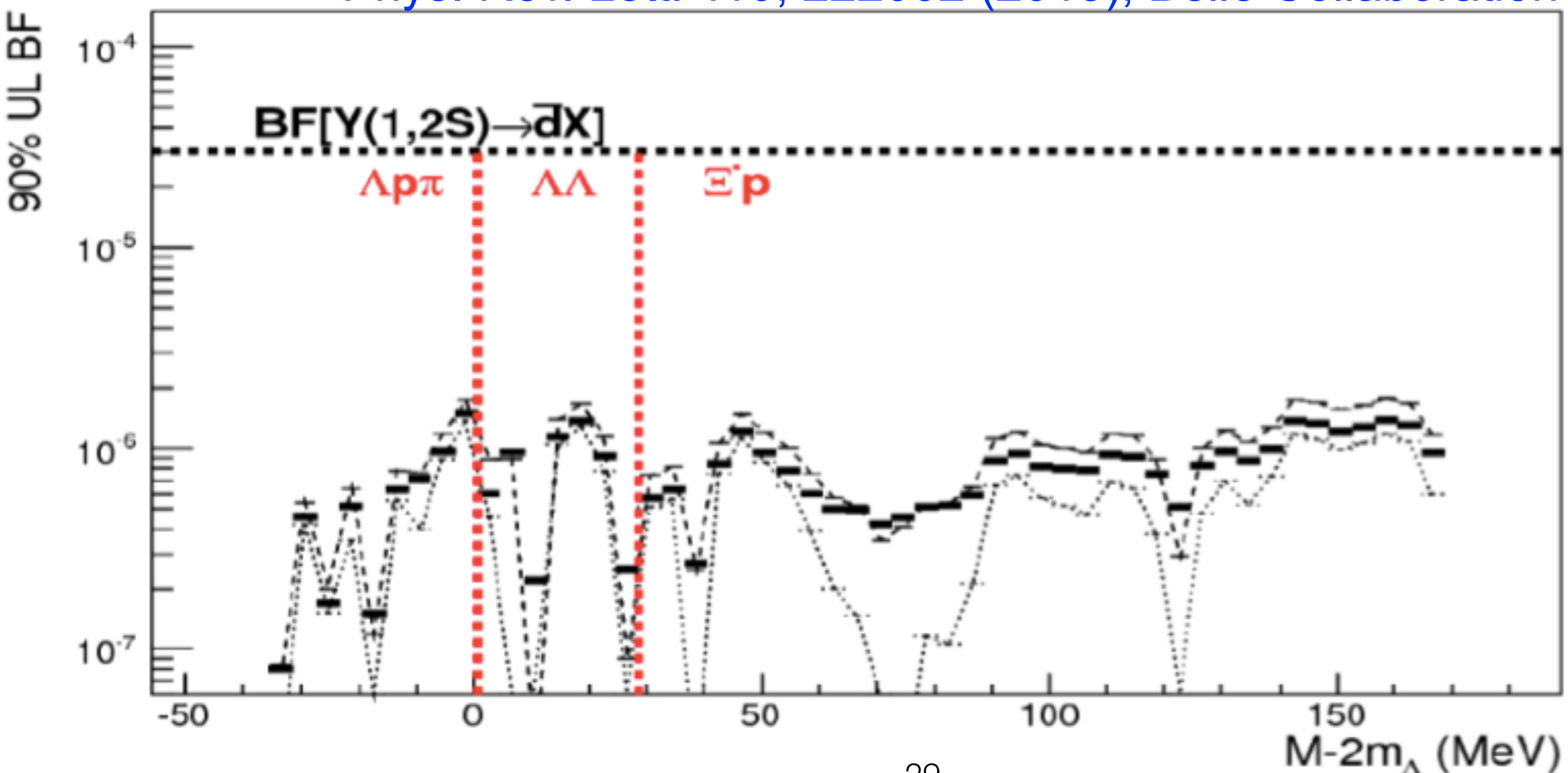
| Name | $L$ | $S$ | $J^{PC}$ | Mass, MeV/$c^2$ | Emitted hadrons [Threshold, GeV/$c^2$] |
|---|---|---|---|---|---|
| $\eta_b(3S)$ | 0 | 0 | $0^{-+}$ | 10336 | $\omega$ [11.12], $\phi$ [11.36] |
| $h_b(3P)$ | 1 | 0 | $1^{+-}$ | 10541 | $\pi^+\pi^-$ [10.82], $\eta$ [11.09], $\eta'$ [11.50] |
| $\eta_{b2}(1D)$ | 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] |



# Search for H-dibaryon

- Belle has performed extensively search for the weakly bound Jaffe's H-dibaryon in Y(1,2S) in a broad mass range, setting limits at O($10^{-1}$) the measured deuteron production
- Belle II will investigate these channels with fully reconstructed final modes and in missing mass

Phys. Rev. Lett. 110, 222002 (2013), Belle Collaboration



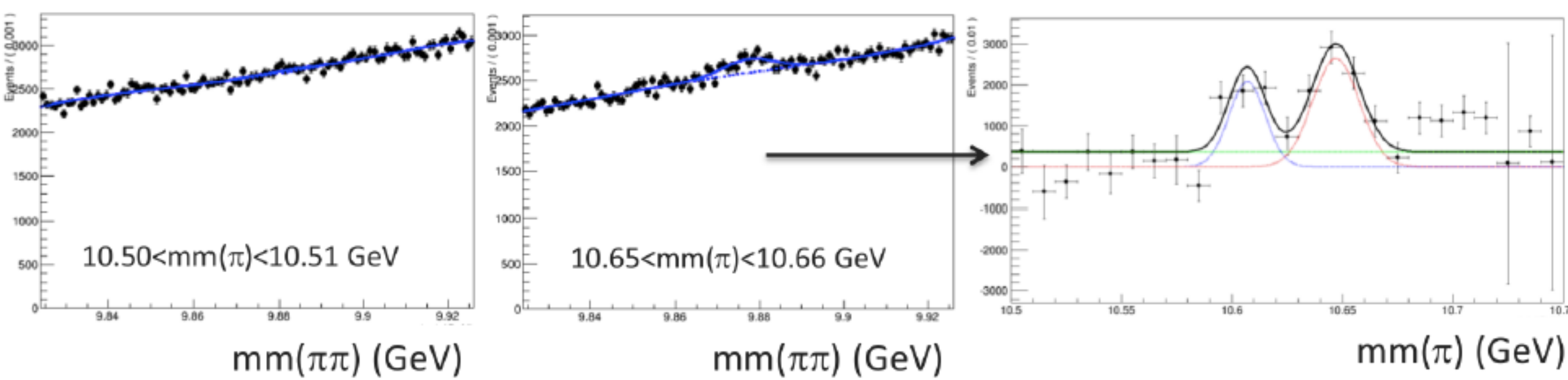
# Belle II Υ(6S) searches in Phase II

Belle II envisions to collect ~ 20 - 40 $fb^{-1}$ data during Phase II and ~ 10 $fb^{-1}$ at Υ(6S) resonance energy

$$\Upsilon(6S) \rightarrow \pi Z_b(\pi h_b(nP))$$
$$\Upsilon(6S) \rightarrow \pi Z_b(\pi \Upsilon(pS)(l^+l^-))$$

Golden modes

Monte Carlo studies show good separation is possible with 10 $fb^{-1}$ of data



# Summary and Outlook

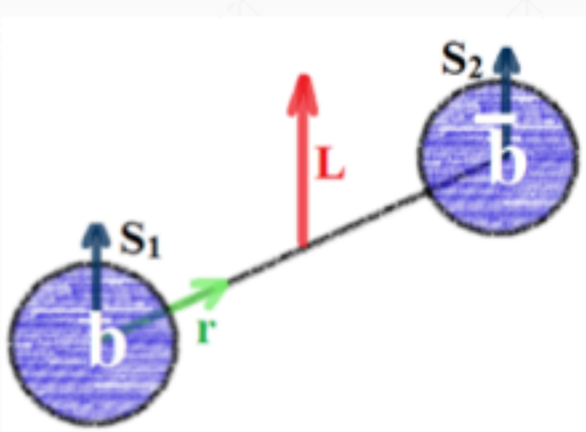
- Belle II has rich physics potential in the exotic and bottomonium sector
- Belle II envisions to understand the nature of bottomonium-like states and complete the standard spectrum
- Υ(6S) running may have a large physics potential, even starting from the first period of data taking (experience from Belle)
- Hints for an exotic state at 10.75 GeV suggest further studies - a fine scan through the whole Υ(4S-6S) region is desired
- Scans of the Υ(1D) and Υ(2D) regions are being planned as well

Expect exciting physics results from Belle II in end 2018 : Stay tuned !!

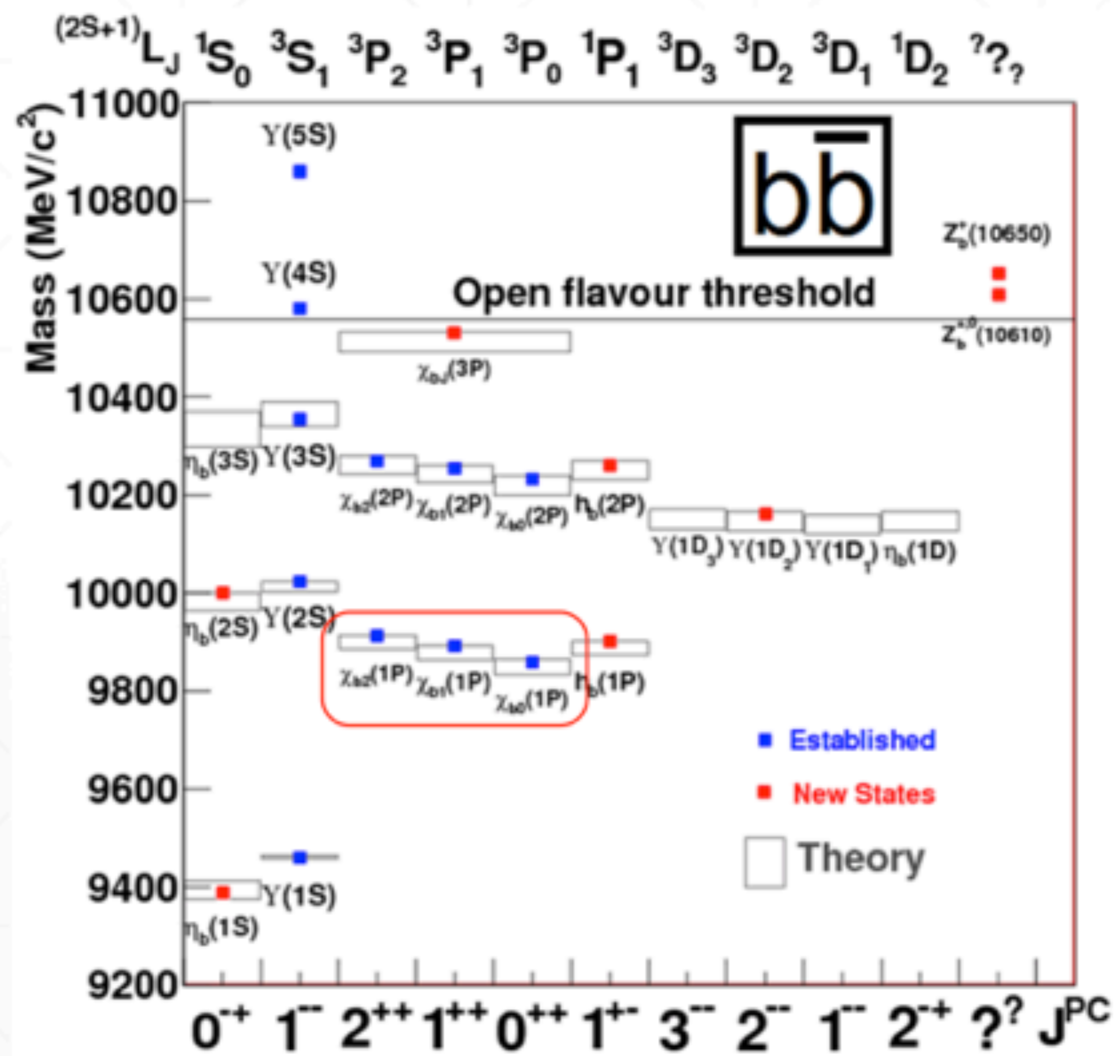
# BACKUP SLIDES

# Bottomonia

- Bottomonium: Bound state of bottom/anti-bottom quark ($b\bar{b}$)
  - QED Analog: Positronium
- Bottomonia are the heaviest known quarkonia ($Q\bar{Q}$) with $m_b \approx 3\, m_c$ → **Nonrelativistic Treatment**
  - Enables Effective Field Theory Treatment
- An Unique Tool for Study of the Meson:
  - Specifically Low Energy QCD




$$S = S_1 + S_2$$
$$J = L + S$$
$$P = (-1)^{L+1}$$
$$C = (-1)^{L+S}$$



# $B^{**}$ spectroscopy

| 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 |

| Resonance | Mass (in MeV) |
|---|---|
| Y(1S) | 9460 |
| Y(2S) | 10023 |
| Y3S) | 10355 |
| Y(4S) | 10579 |
| Y(5S) | 10860 |
| Y(6S) | 11020 |

Y(6S) is very close to $BB^{**}$ threshold

# Physics Program at Y(3S)

Interesting possibility for studying the 3P states via radiative transitions from the Y(4S) utilises hadronic transitions from the Y(3S) and Y(2S) or Y(1S) in the decay chain