XVI MWPF
mexican workshop
on particles and fields

Hadron spectroscopy studies at Belle II

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XVI Mexican Workshop on Particles and Fields, October 2017

SuperKEKB

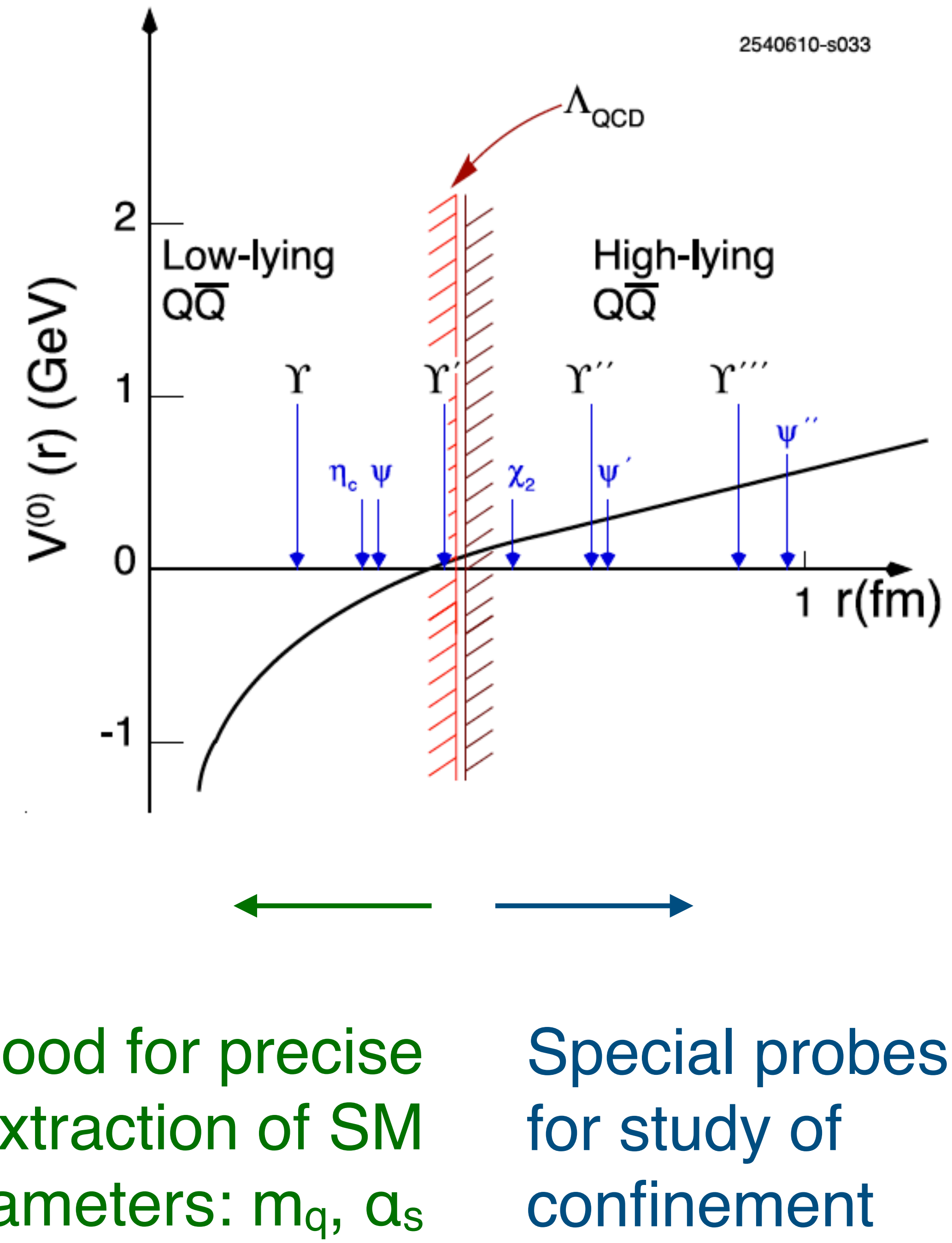
Belle II

Carnegie Mellon

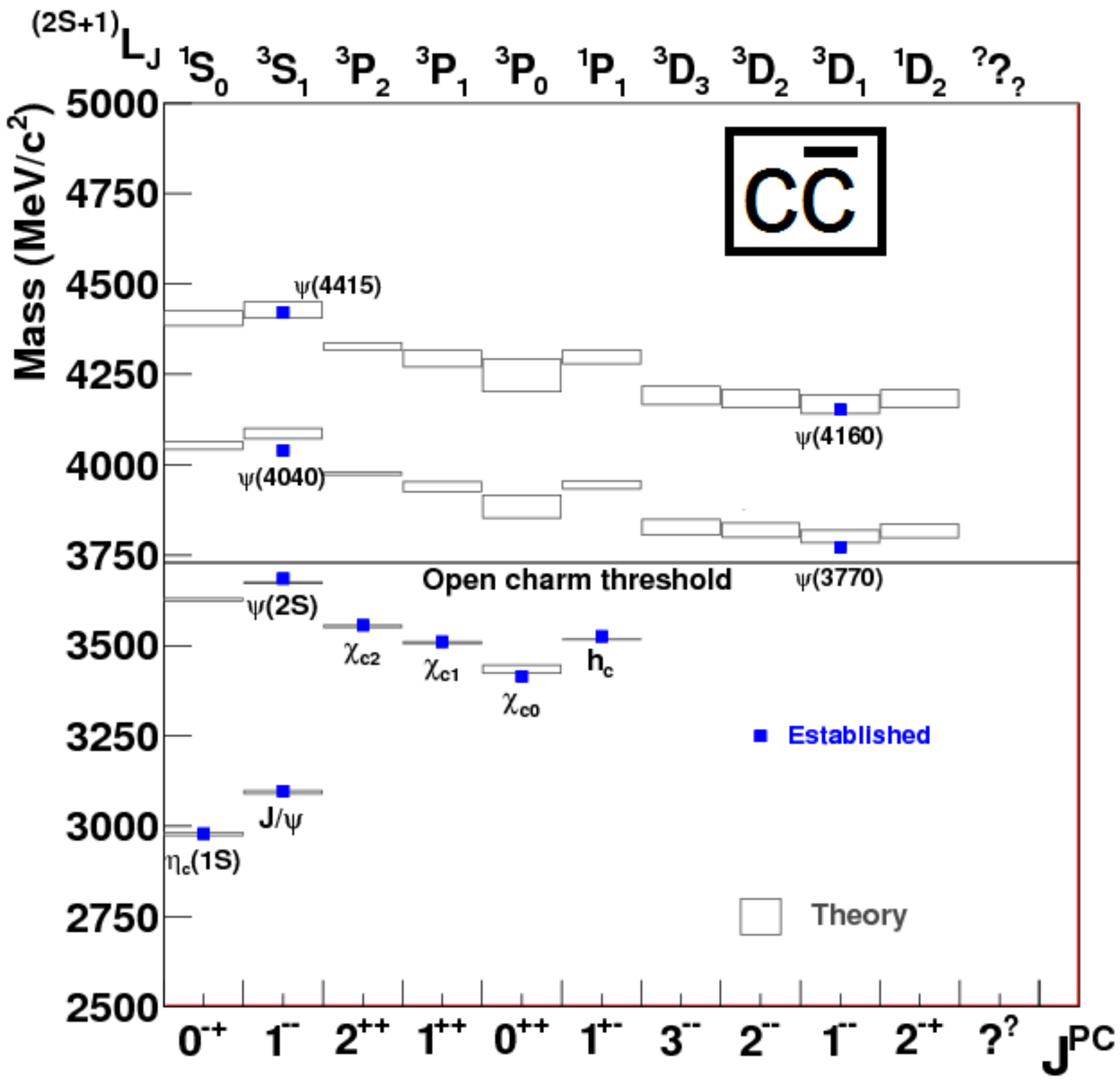
U.S. DEPARTMENT OF ENERGY | Office of Science

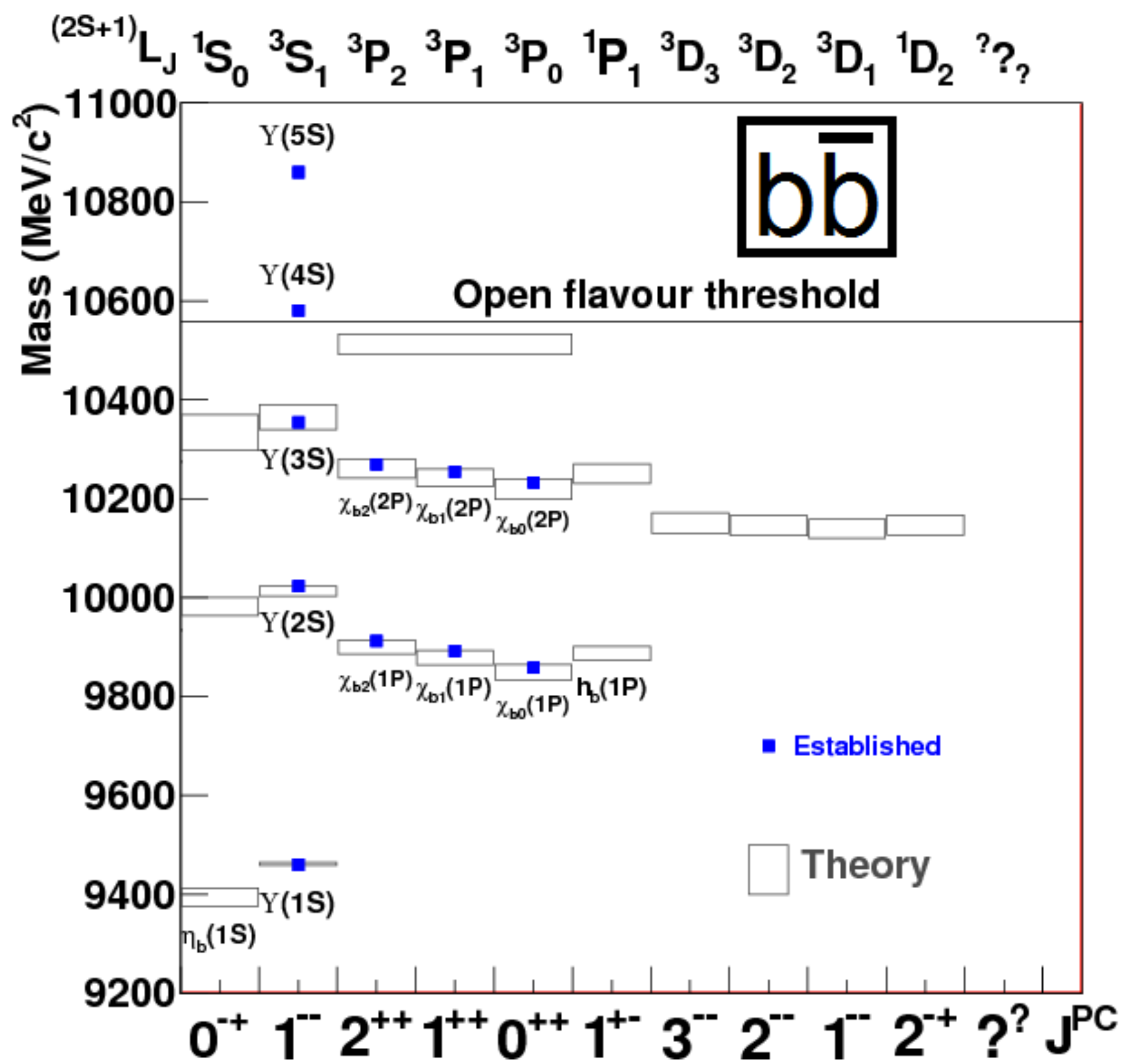
Hadron spectroscopy

- Range of physical scales heavy quark spectroscopy interesting for tests of QCD
  - Makes calculations difficult, but allows to test the interplay between perturbative and nonpertubative QCD
- Heavy quarkonium - bound state of a heavy quark and a heavy anti-quark
  - Mass larger than QCD scale Λ_{QCD} (scale at which nonpertubative effects become dominant)
  - Mass m, relative momentum p ~mv, binding energy E ~ mv² all at different scales
- Large mass of quarkonium makes it suitable for probing BSM models in decays



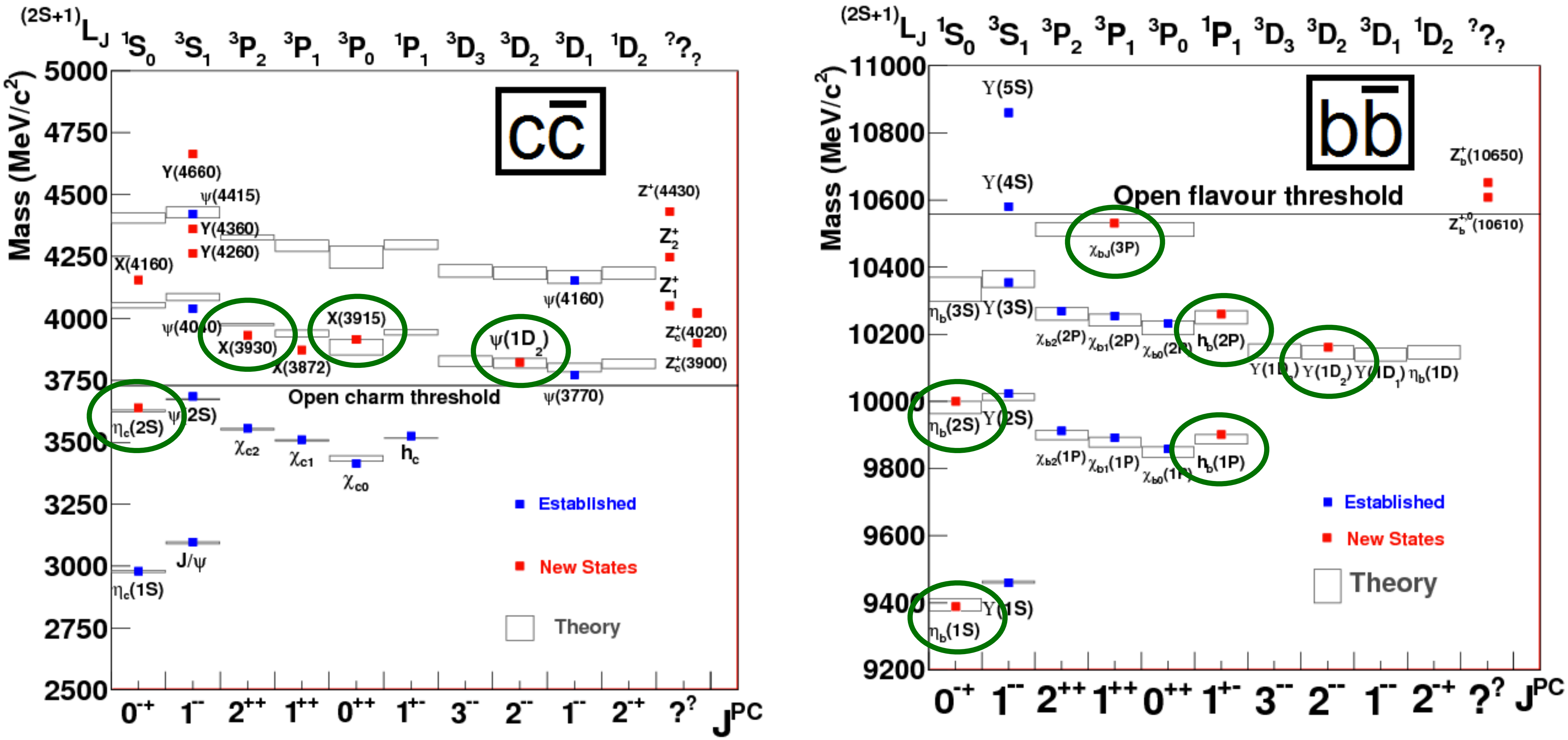
Quarkonium spectra before B-factory era (~1999)





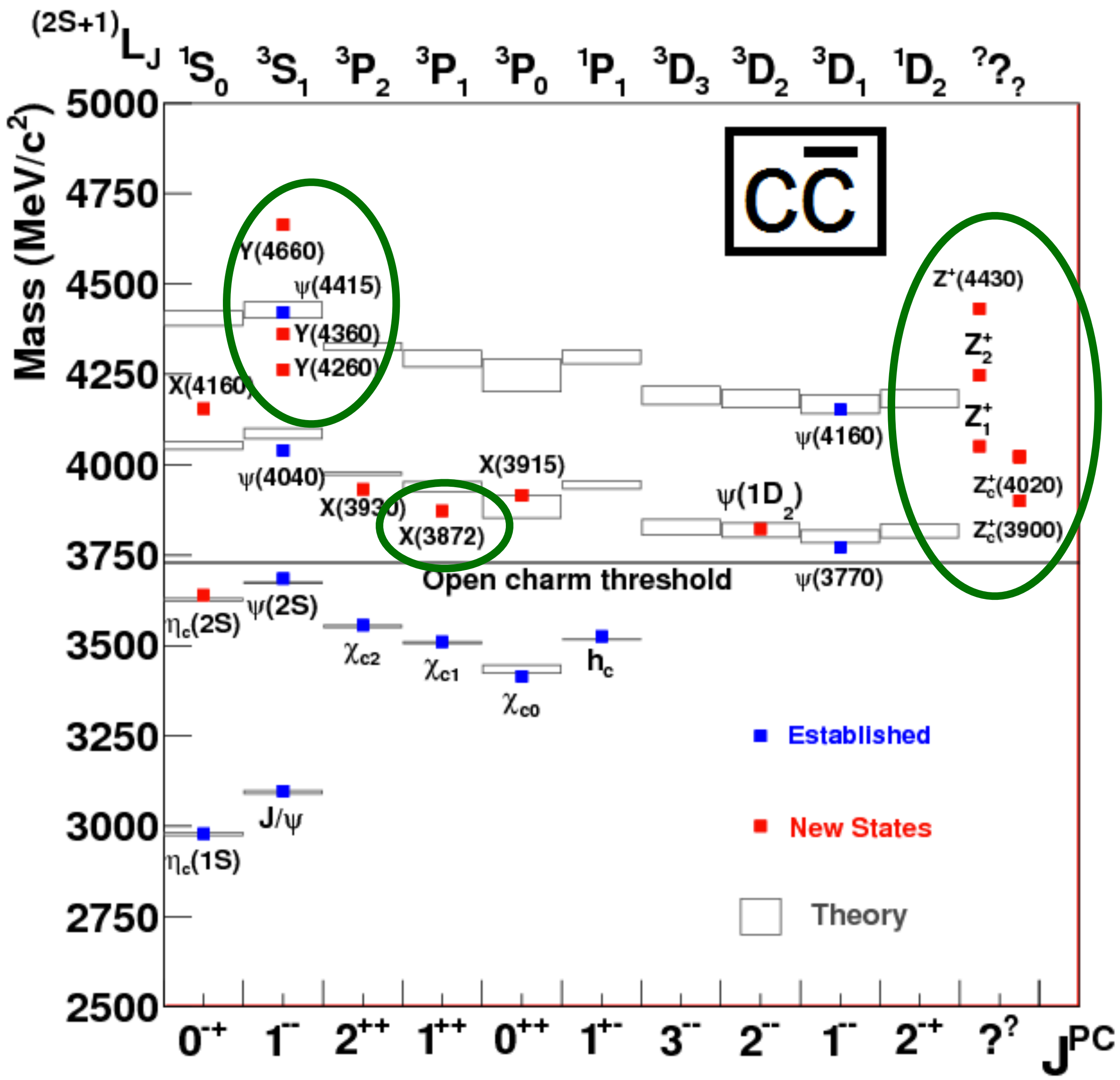
- Significant number of expected, but missing states

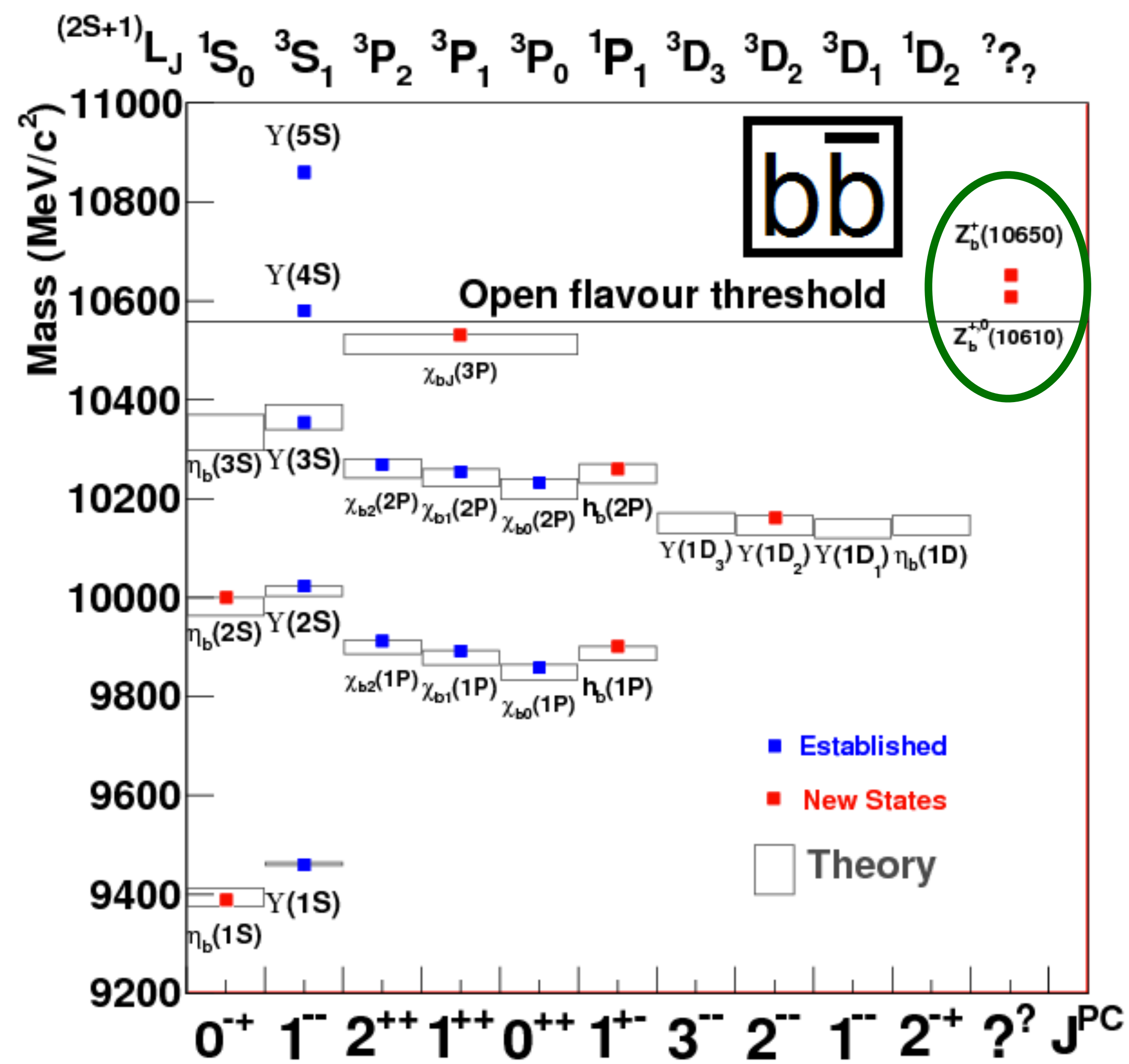
Quarkonium spectra post B-factories



- Discoveries of long-predicted conventional quarkonia

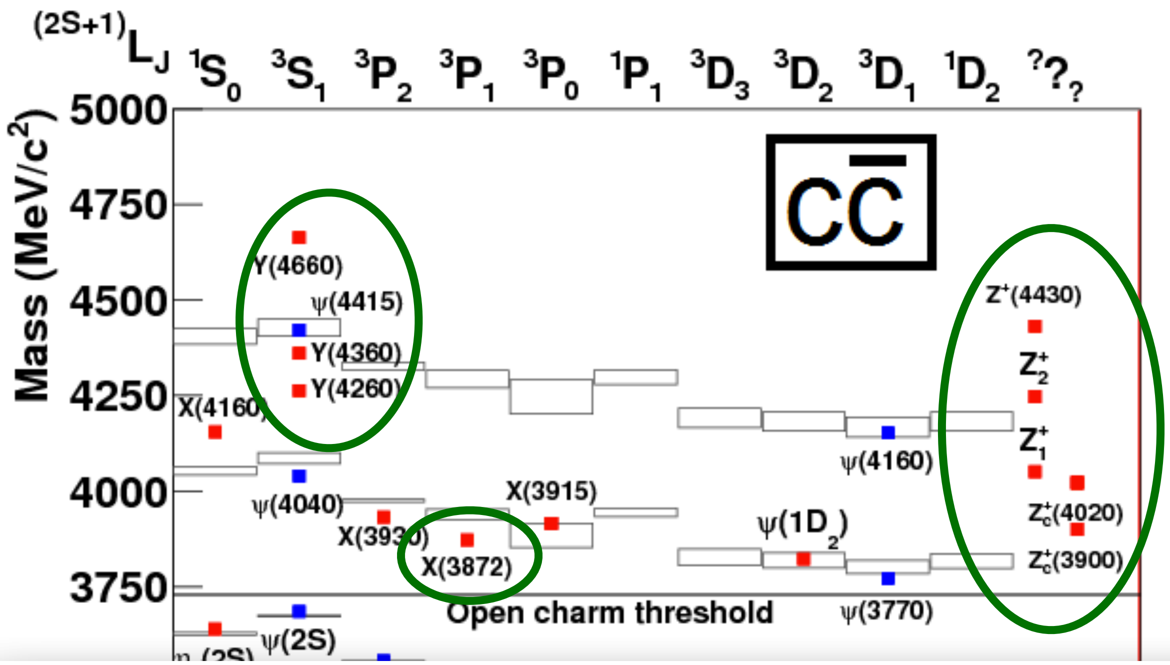
Quarkonium spectra post B-factories

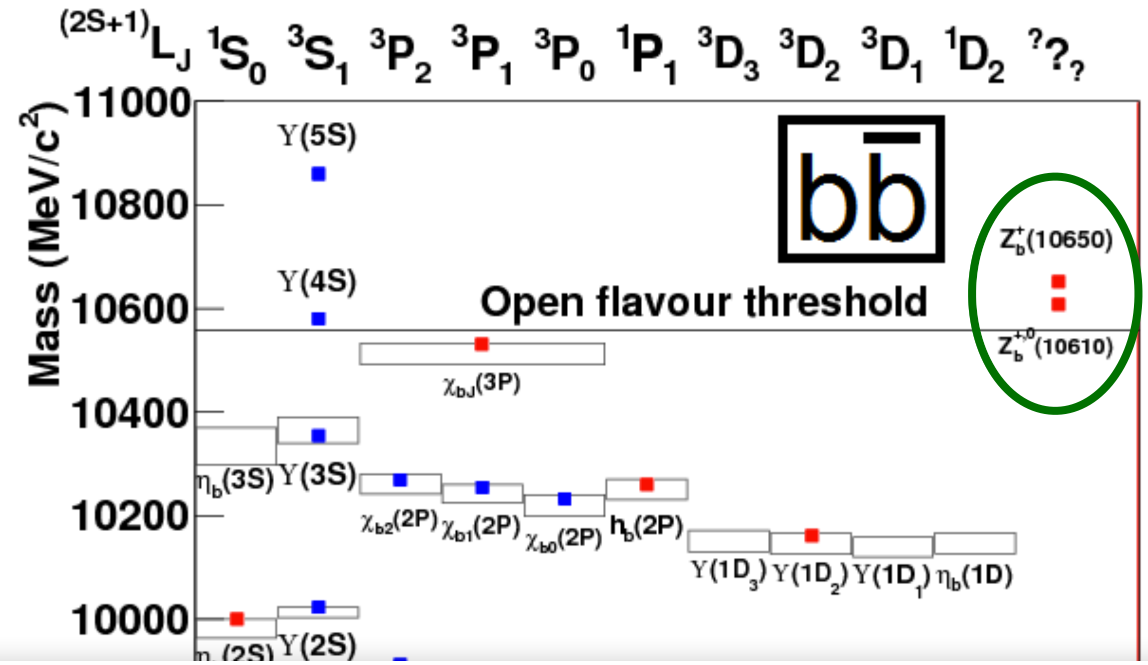




- Discoveries of long-predicted conventional quarkonia
- A few surprises - difficult to explain by quarkonium model
- Charged states - cannot be $c\bar{c}/b\bar{b}$ pair!

Quarkonium spectra post B-factories





X states

Isospin I = 0

$J^P \neq 1^{--}$

Narrow resonance

Y states

Isospin I = 0

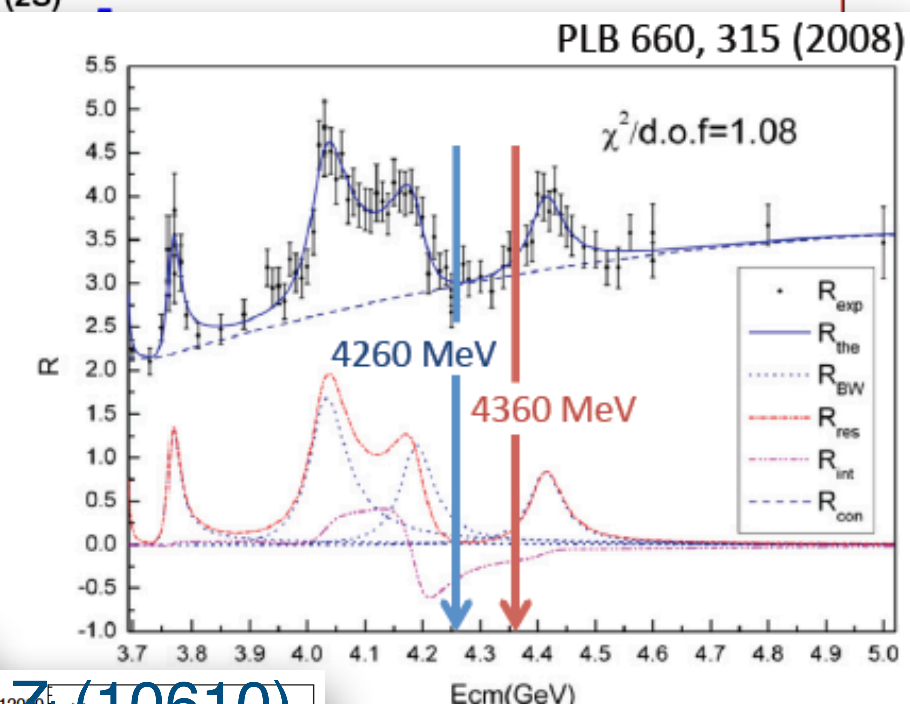
$J^P = 1^{--}$

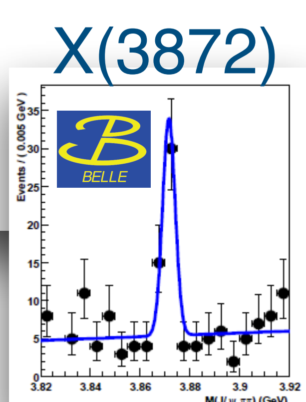
No corresponding enhancement of open-charm production

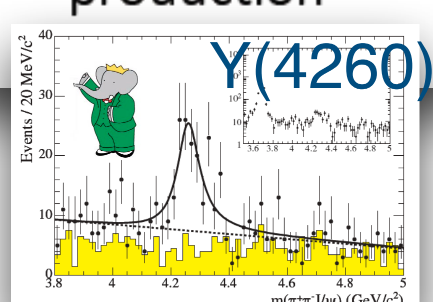
Z states

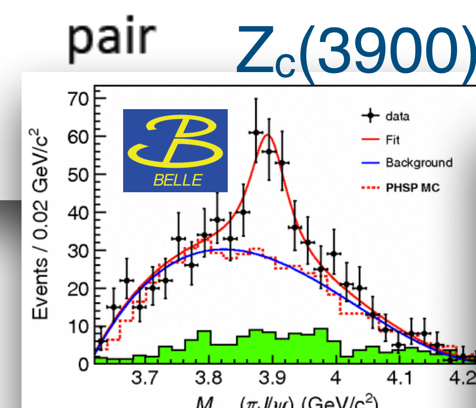
Isospin I ≠ 0

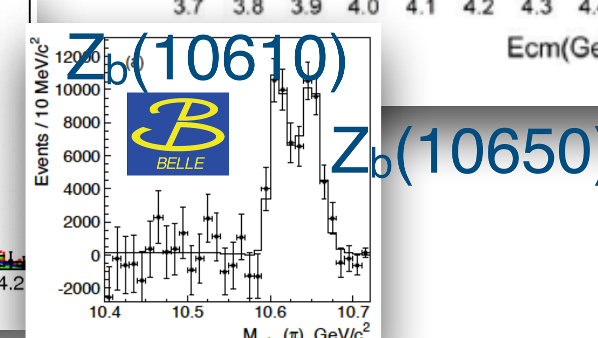
Cannot consist of a quark-antiquark pair





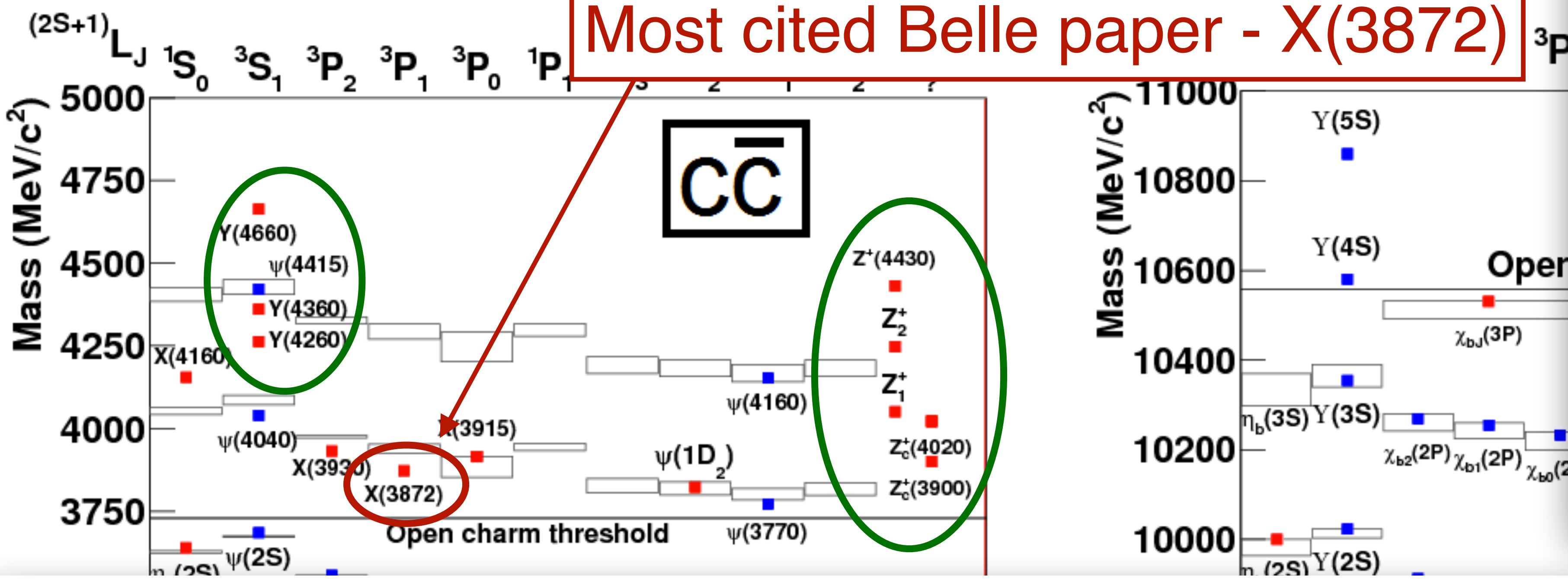




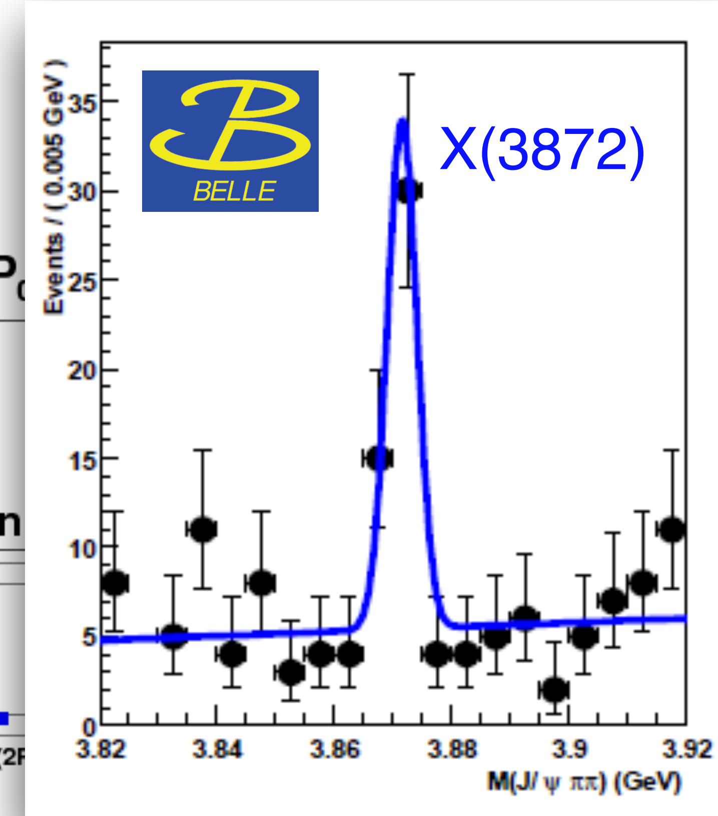


Quarkonium spectra post B-factories

Most cited Belle paper - X(3872)

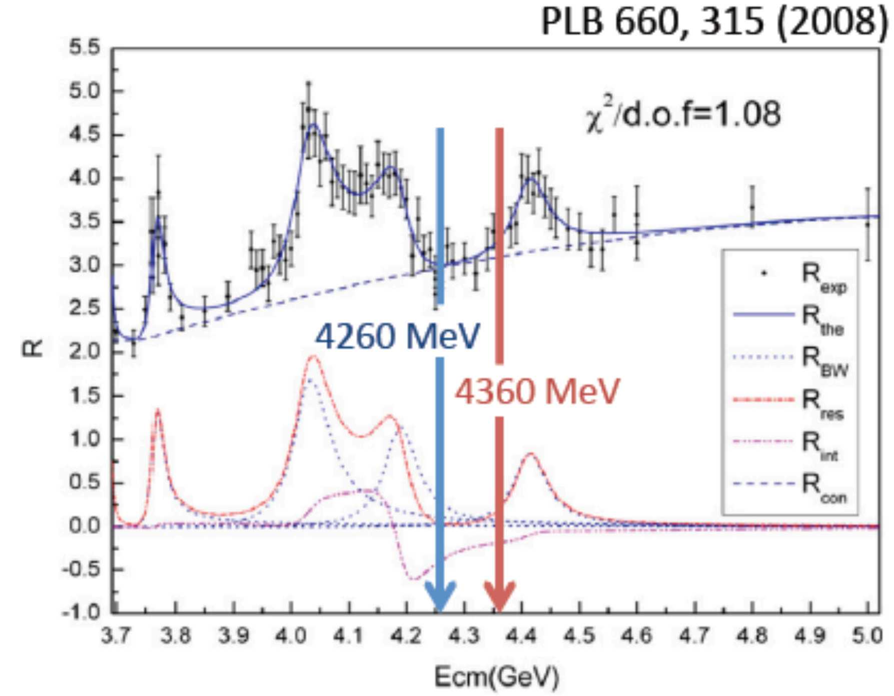


PRL 91, 262001 (2003)



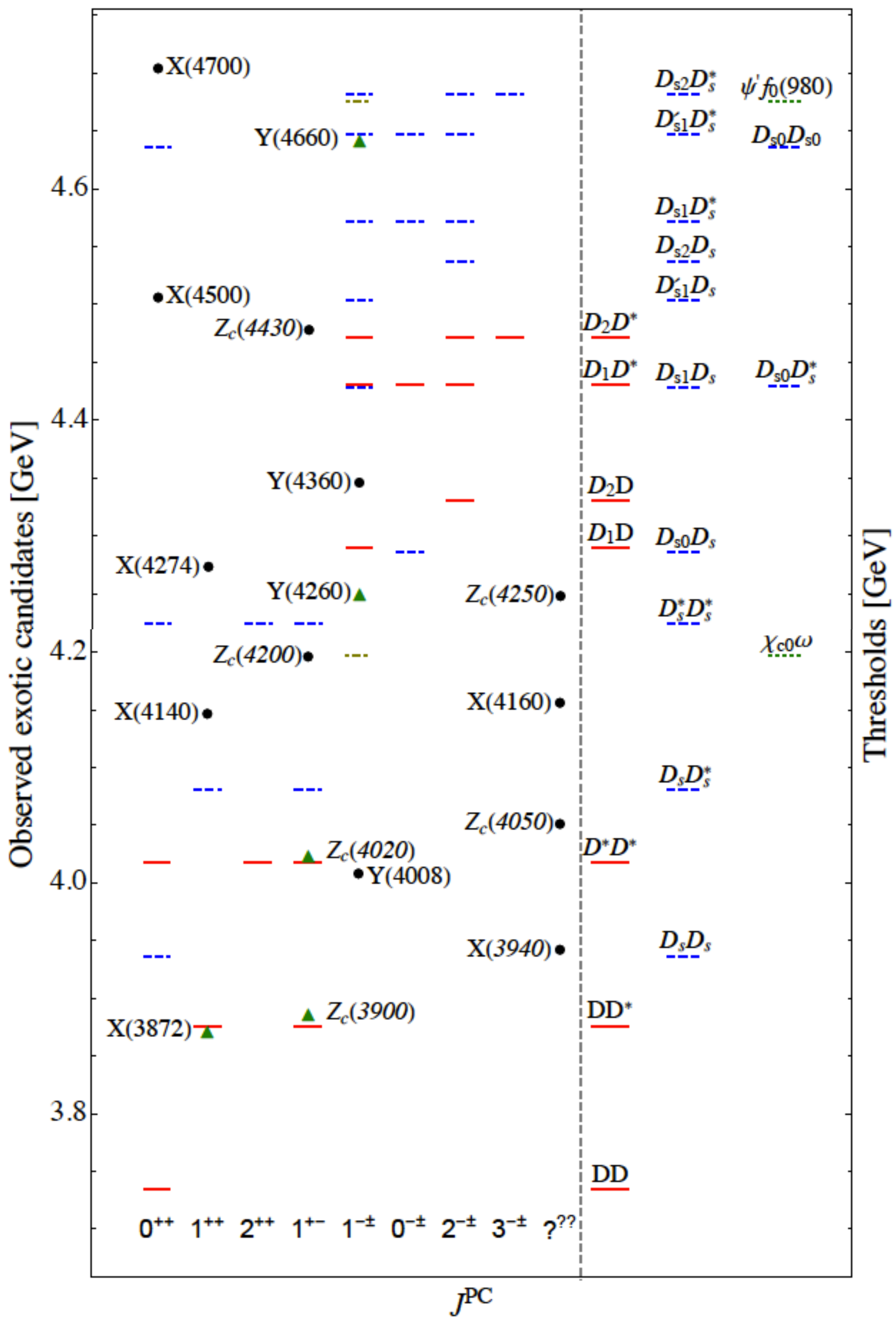
X states	Y states	Z states
Isospin I = 0	Isospin I = 0	Isospin I ≠ 0
$J^P \neq 1^{--}$	$J^P = 1^{--}$	
Narrow resonance	No corresponding enhancement of open-charm production	Cannot consist of a quark-antiquark pair

PLB 660, 315 (2008)



- Charged states - cannot be $c\bar{c}/b\bar{b}$ pair!

Quarkonium-like states

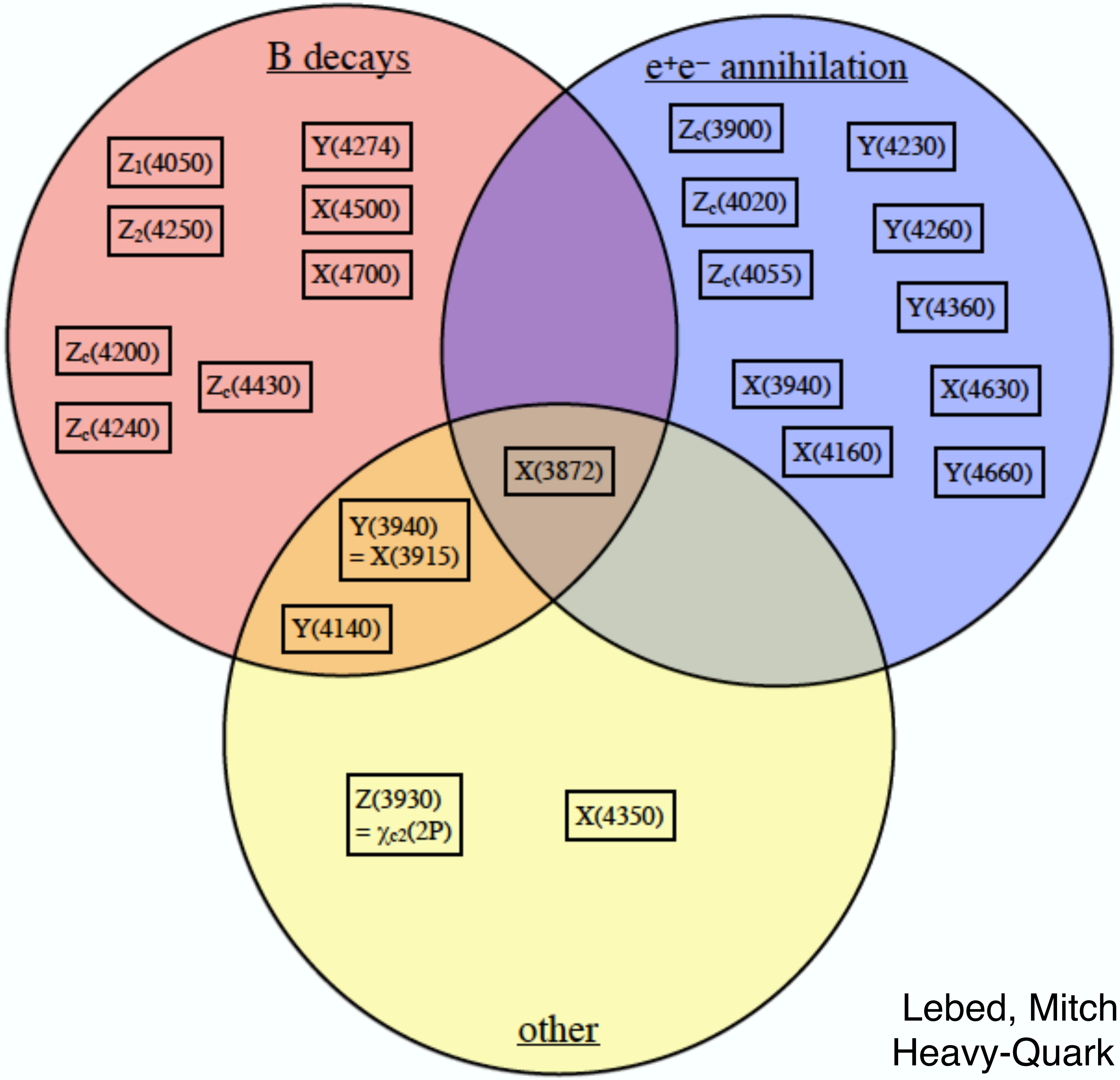


F.-K. Guo et al. arXiv:1705.00141

- Potentially exotic X, Y, Z states
  - Very likely more deg. of freedom than just heavy quark and anti-quark
  - Charged states explicitly “exotic” (non-$q\bar{q}$)
  - Many states close to and above open flavor strong decay threshold
- First possibility to explore nonstandard configurations long conjectured
  - Hybrids, multiquark states
  - Important to characterize these states

Image credit: R. Mitchell

Quarkonium-like states

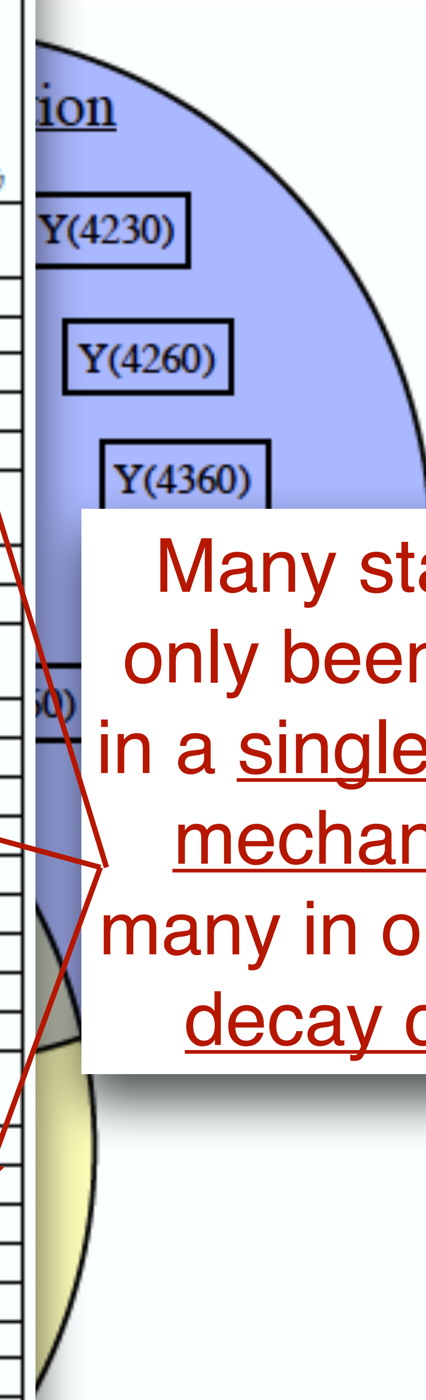


Lebed, Mitchell, Swanson, Heavy-Quark QCD Exotica, PPNP 93, 143 (2017)

Image credit: R. Mitchell

Qu

Particle	$I^G J^{PC}$	Mass [MeV]	Width [MeV]	Production and Decay
$X(3823)$ $(\psi_2(1D))$	(0^-2^{--})	3822.2 ± 1.2 [176]	< 16	$B \to KX;\ X \to \gamma\chi_{c1}$ $e^+e^- \to \pi^+\pi^- X;\ X \to \gamma\chi_{c1}$
$X(3872)$	0^+1^{++}	3871.69 ± 0.17 [176]	< 1.2	$B \to KX;\ X \to \pi^+\pi^- J/\psi$ $B \to KX;\ X \to D^{*0}\bar{D}^0$ $B \to KX;\ X \to \gamma J/\psi, \gamma\psi(2S)$ $B \to KX;\ X \to \omega J/\psi$ $B \to K\pi X;\ X \to \pi^+\pi^- J/\psi$ $e^+e^- \to \gamma X;\ X \to \pi^+\pi^- J/\psi$ pp or $p\bar{p} \to X$ + any.; $X \to \pi^+\pi^- J/\psi$
$Z_c(3900)$	1^+1^{+-}	3886.6 ± 2.4 [176]	28.1 ± 2.6	$e^+e^- \to \pi Z;\ Z \to \pi J/\psi$ $e^+e^- \to \pi Z;\ Z \to D^*\bar{D}$
$X(3915)$	0^+0^{++}	3918.4 ± 1.9 [176]	20 ± 5	$\gamma\gamma \to X;\ X \to \omega J/\psi$
$Y(3940)$				$B \to KX;\ X \to \omega J/\psi$
$Z(3930)$ $(\chi_{c2}(2P))$	0^+2^{++}	3927.2 ± 2.6 [176]	24 ± 6	$\gamma\gamma \to Z;\ Z \to D\bar{D}$
$X(3940)$		$3942^{+7}_{-6} \pm 6$ [41]	$37^{+26}_{-15} \pm 8$	$e^+e^- \to J/\psi + X;\ X \to D\bar{D}^*$
$Y(4008)$	1^{--}	$3891 \pm 41 \pm 12$ [23]	$255 \pm 40 \pm 14$	$e^+e^- \to Y;\ Y \to \pi^+\pi^- J/\psi$
$Z_c(4020)$	$1^+?^{?-}$	4024.1 ± 1.9 [176]	13 ± 5	$e^+e^- \to \pi Z;\ Z \to \pi h_c$ $e^+e^- \to \pi Z;\ Z \to D^*\bar{D}^*$
$Z_1(4050)$	$1^-?^{?+}$	$4051 \pm 14^{+20}_{-41}$ [133]	82^{+21+47}_{-17-22}	$B \to KZ;\ Z \to \pi^\pm\chi_{c1}$
$Z_c(4055)$	$1^+?^{?-}$	$4054 \pm 3 \pm 1$ [148]	$45 \pm 11 \pm 6$	$e^+e^- \to \pi^\mp Z;\ Z \to \pi^\pm\psi(2S)$
$Y(4140)$	0^+1^{++}	$4146.5 \pm 4.5^{+4.6}_{-2.8}$ [125]	$83 \pm 21^{+21}_{-14}$	$B \to KY;\ Y \to \phi J/\psi$ pp or $p\bar{p} \to Y$ + any.; $Y \to \phi J/\psi$
$X(4160)$		$4156^{+25}_{-20} \pm 15$ [41]	$139^{+111}_{-61} \pm 21$	$e^+e^- \to J/\psi + X;\ X \to D^*\bar{D}^*$
$Z_c(4200)$	1^+1^{+-}	4196^{+31+17}_{-29-13} [46]	$370^{+70+70}_{-70-132}$	$B \to KZ;\ Z \to \pi^\pm J/\psi$
$Y(4230)$	0^-1^{--}	$4230 \pm 8 \pm 6$ [149]	$38 \pm 12 \pm 2$	$e^+e^- \to Y;\ Y \to \omega\chi_{c0}$
$Z_c(4240)$	1^+0^{--}	$4239 \pm 18^{+45}_{-10}$ [138]	$220 \pm 47^{+108}_{-74}$	$B \to KZ;\ Z \to \pi^\pm\psi(2S)$
$Z_2(4250)$	$1^-?^{?+}$	$4248^{+44+180}_{-29-35}$ [133]	$177^{+54+316}_{-39-61}$	$B \to KZ;\ Z \to \pi^\pm\chi_{c1}$
$Y(4260)$	0^-1^{--}	4251 ± 9 [176]	120 ± 12	$e^+e^- \to Y;\ Y \to \pi\pi J/\psi$
$Y(4274)$	0^+1^{++}	$4273.3 \pm 8.3^{+17.2}_{-3.6}$ [125]	$52 \pm 11^{+8}_{-11}$	$B \to KY;\ Y \to \phi J/\psi$
$X(4350)$	$0^+?^{?+}$	$4350.6^{+4.6}_{-5.1} \pm 0.7$ [170]	$13^{+18}_{-9} \pm 4$	$\gamma\gamma \to X;\ X \to \phi J/\psi$
$Y(4360)$	1^{--}	4346 ± 6 [176]	102 ± 10	$e^+e^- \to Y;\ Y \to \pi^+\pi^-\psi(2S)$
$Z_c(4430)$	1^+1^{+-}	4478^{+15}_{-18} [176]	181 ± 31	$B \to KZ;\ Z \to \pi^\pm J/\psi$ $B \to KZ;\ Z \to \pi^\pm\psi(2S)$
$X(4500)$	0^+0^{++}	$4506 \pm 11^{+12}_{-15}$ [125]	$92 \pm 21^{+21}_{-20}$	$B \to KX;\ X \to \phi J/\psi$
$X(4630)$	1^{--}	4634^{+8+5}_{-7-8} [150]	92^{+40+10}_{-24-21}	$e^+e^- \to X;\ X \to \Lambda_c\bar{\Lambda}_c$
$Y(4660)$	1^{--}	4643 ± 9 [176]	72 ± 11	$e^+e^- \to Y;\ Y \to \pi^+\pi^-\psi(2S)$
$X(4700)$	0^+0^{++}	$4704 \pm 10^{+14}_{-24}$ [125]	$120 \pm 31^{+42}_{-33}$	$B \to KX;\ X \to \phi J/\psi$
$P_c(4380)$		$4380 \pm 8 \pm 29$ [35]	$205 \pm 18 \pm 86$	$\Lambda_b \to KP_c;\ P_c \to pJ/\psi$
$P_c(4450)$		$4449.8 \pm 1.7 \pm 2.5$ [35]	$39 \pm 5 \pm 19$	$\Lambda_b \to KP_c;\ P_c \to pJ/\psi$
$X(5568)$		$5567.8 \pm 2.9^{+0.9}_{-1.9}$ [175]	$21.9 \pm 6.4^{+5.0}_{-2.5}$	$p\bar{p} \to X$ + anything; $X \to B_s\pi^\pm$
$Z_b(10610)$	1^+1^{+-}	10607.2 ± 2.0 [176]	18.4 ± 2.4	$e^+e^- \to \pi Z;\ Z \to \pi\Upsilon(1S,2S,3S)$ $e^+e^- \to \pi Z;\ Z \to \pi h_b(1P,2P)$ $e^+e^- \to \pi Z;\ Z \to B\bar{B}^*$
$Z_b(10650)$	1^+1^{+-}	10652.2 ± 1.5 [176]	11.5 ± 2.2	$e^+e^- \to \pi Z;\ Z \to \pi\Upsilon(1S,2S,3S)$ $e^+e^- \to \pi Z;\ Z \to \pi h_b(1P,2P)$ $e^+e^- \to \pi Z;\ Z \to B^*\bar{B}^*$
$Y_b(10888)$	0^-1^{--}	10891 ± 4 [176]	54 ± 7	$e^+e^- \to Y;\ Y \to \pi\pi\Upsilon(1S,2S,3S)$ $e^+e^- \to Y;\ Y \to \pi\pi h_b(1P,2P)$

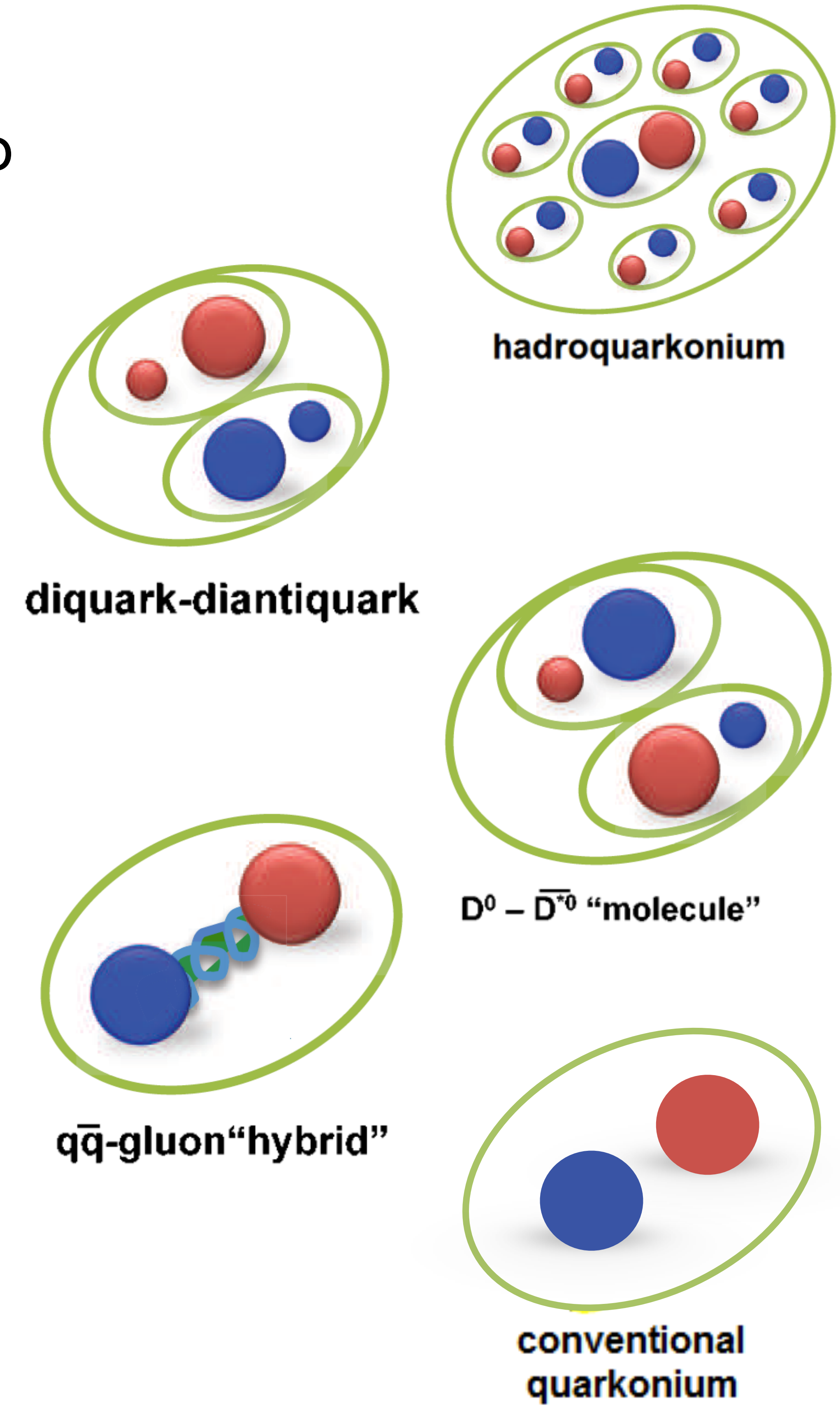


Many states have only been observed in a single production mechanism (and many in only a single decay channel)!

Lebed, Mitchell, Swanson, Heavy-Quark QCD Exotica, PPNP 93, 143 (2017)

Quarkonium-like models

- Most models can be classified according to quark clustering and degrees of freedom
  - **Hadroquarkonium**[1]: compact quarkonium-like core surrounded by light quarks
  - **Tetraquarks**[2]: compact diquark and anti-diquark substructures
  - **Hadronic molecules**[3]: heavy and light quarks and anti-quarks combine to form a hadron pair
  - **Hybrids**[4]: both gluons and quarks act as active degrees of freedom (contribute to quantum numbers)
  - **Kinematical effects**[5]
  - All of the above…



Quarkonium-like models

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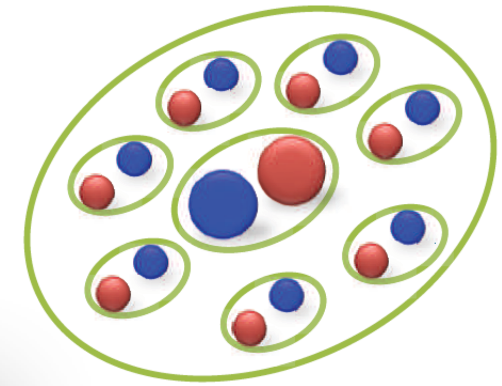
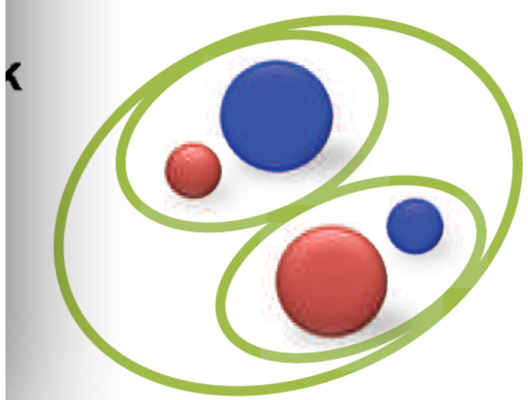
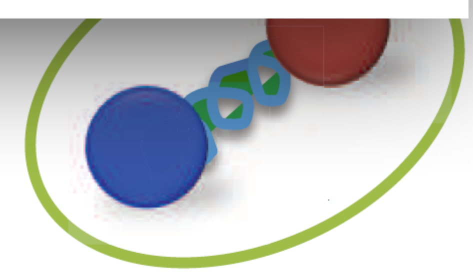
  - **Hadroquarkonium[1]**: compact
    quarkonium-
    light quarks
  - **Tetraquarks**
    anti-diquark
  - **Hadronic m**
    quarks and a
    a hadron pai
  - **Hybrids[4]**: both gluons and quarks act as active degrees of freedom (contribute to quantum numbers)
  - **Kinematical effects[5]**
  - All of the above…

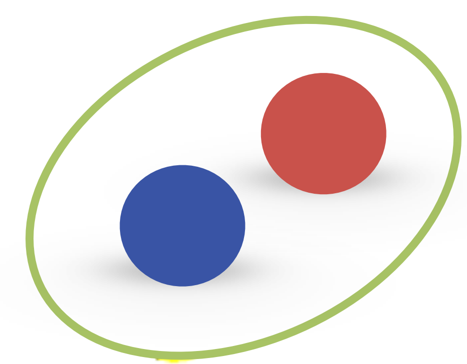
High Priority:

- Identify most prominent component in wave function
- Seek unique picture describing all XYZ states, not state-by-state

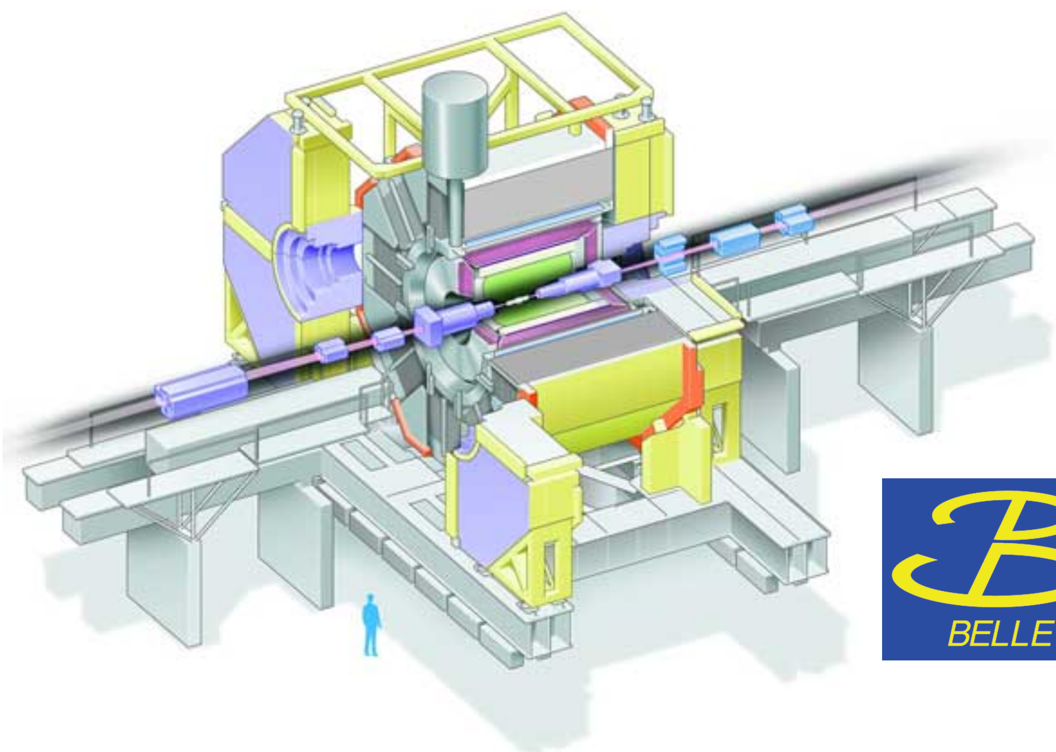






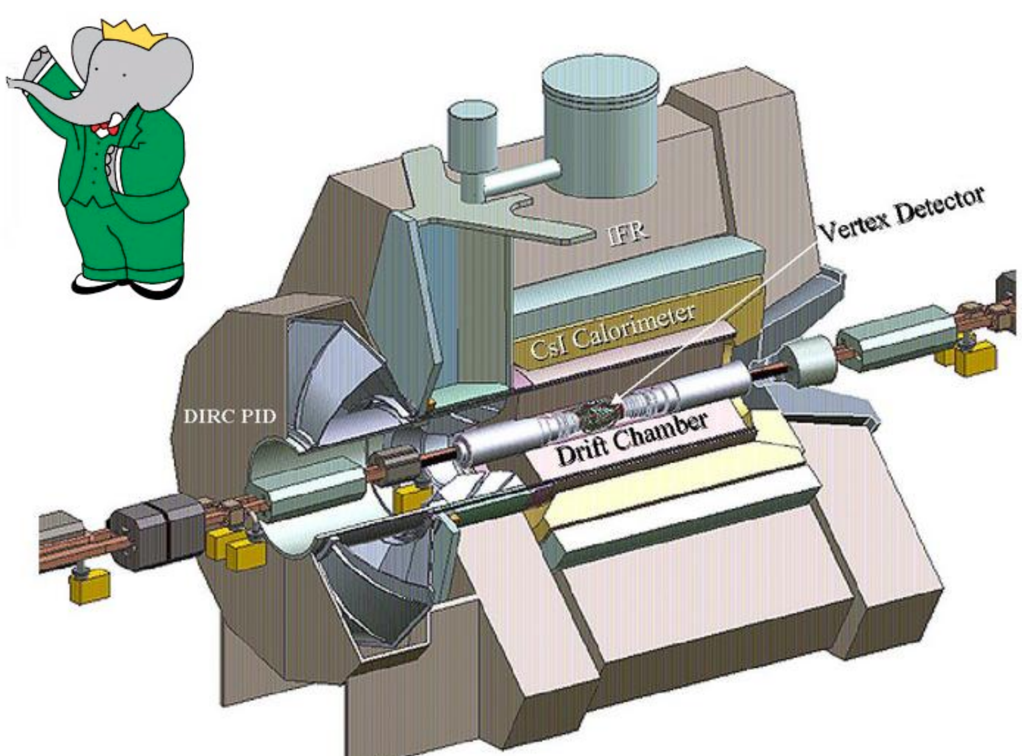


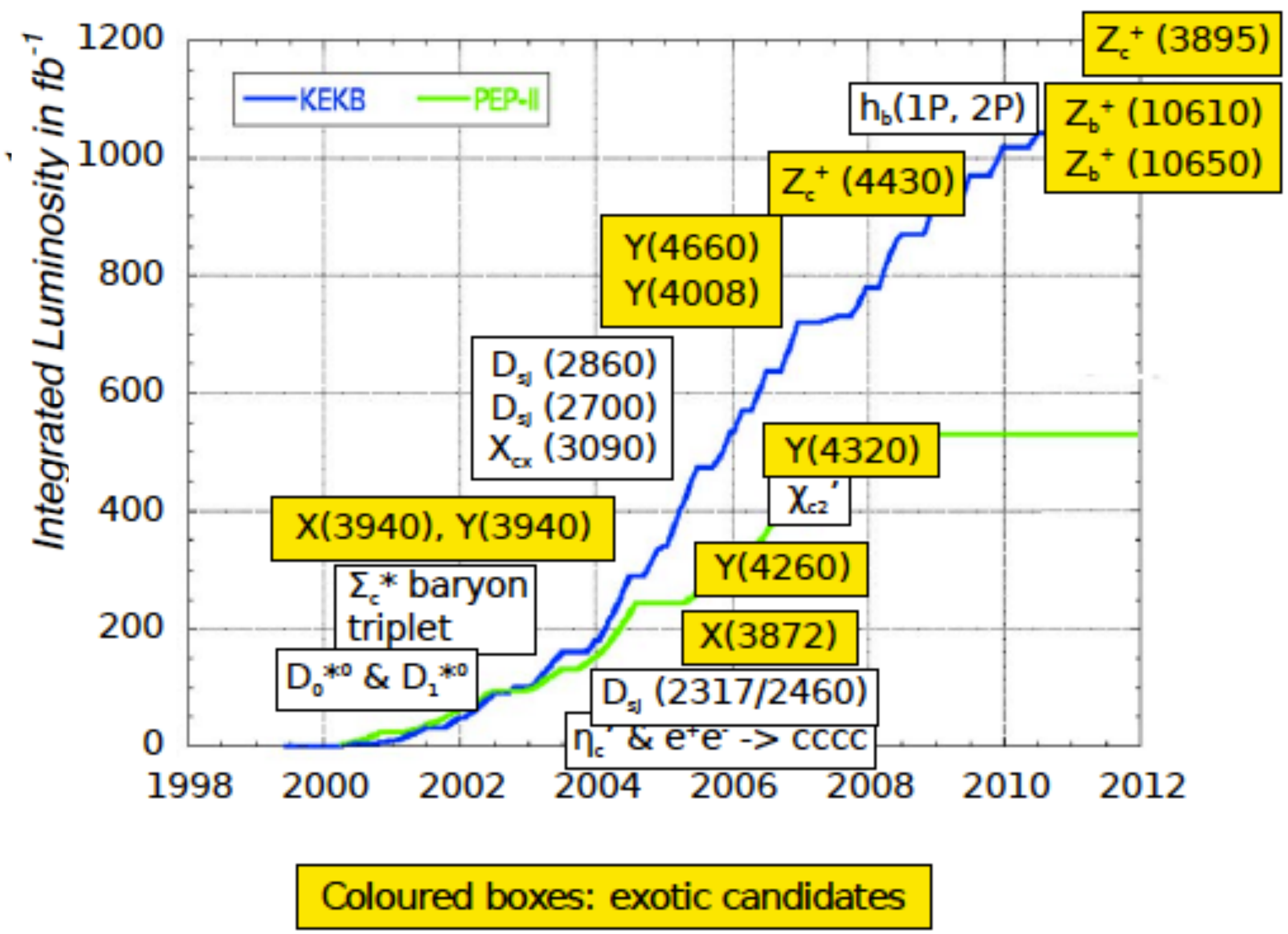
Hadron spectroscopy at the B factories



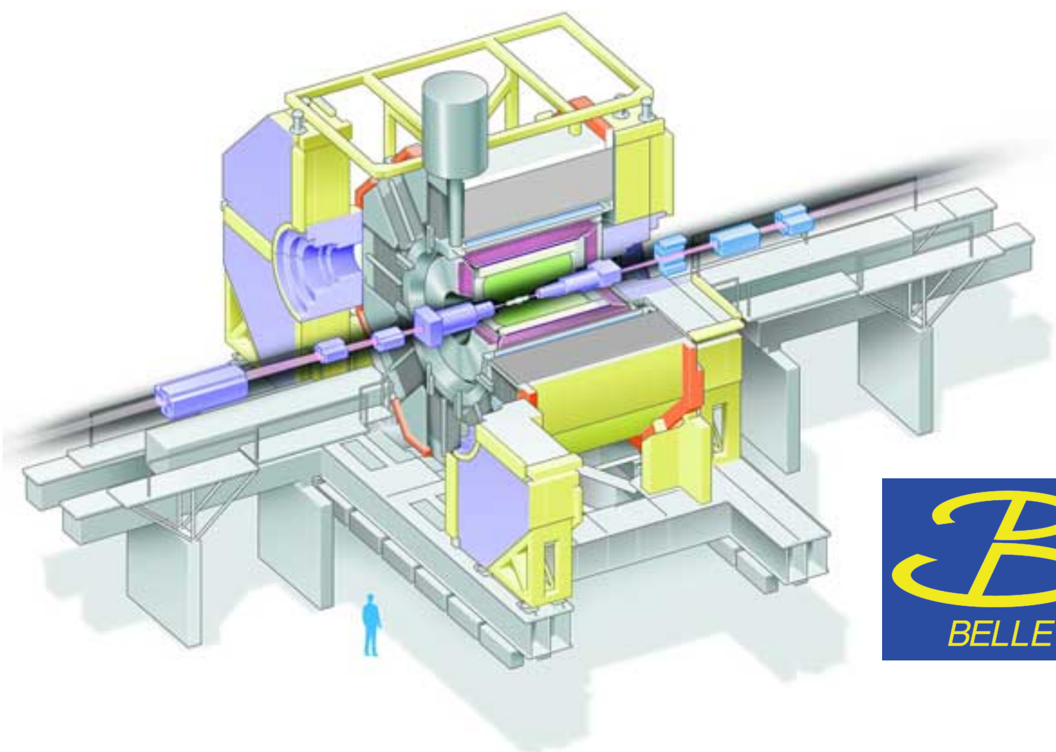
Belle/KEKB (KEK) and BaBar/PEP-II (SLAC)

Very successful physics programs with a combined recorded sample over 1.5 ab^{-1} (1.25 x 10^9 $B\bar{B}$)





B factories



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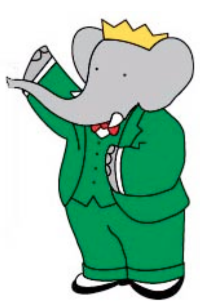
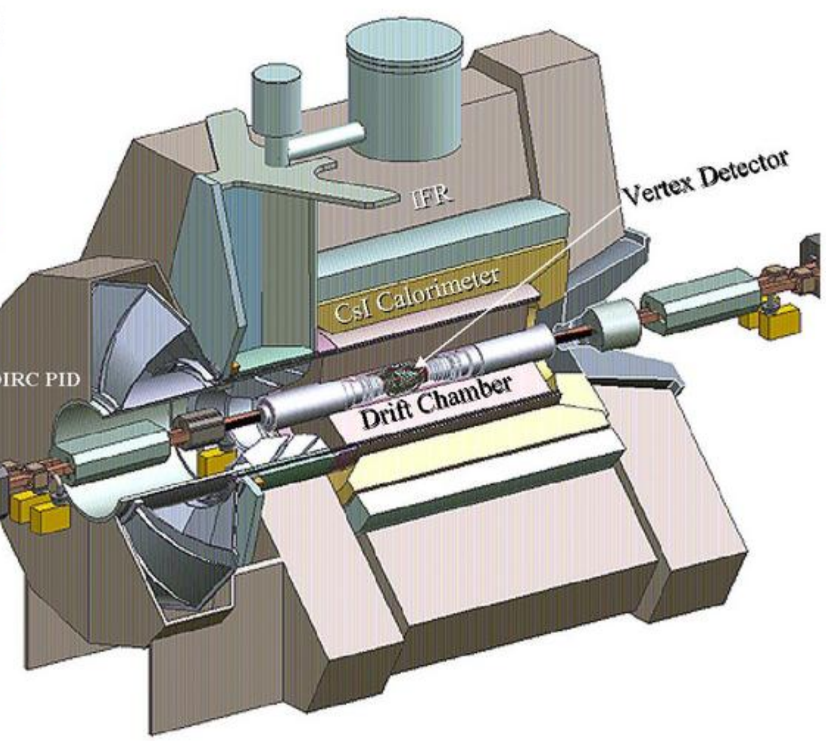
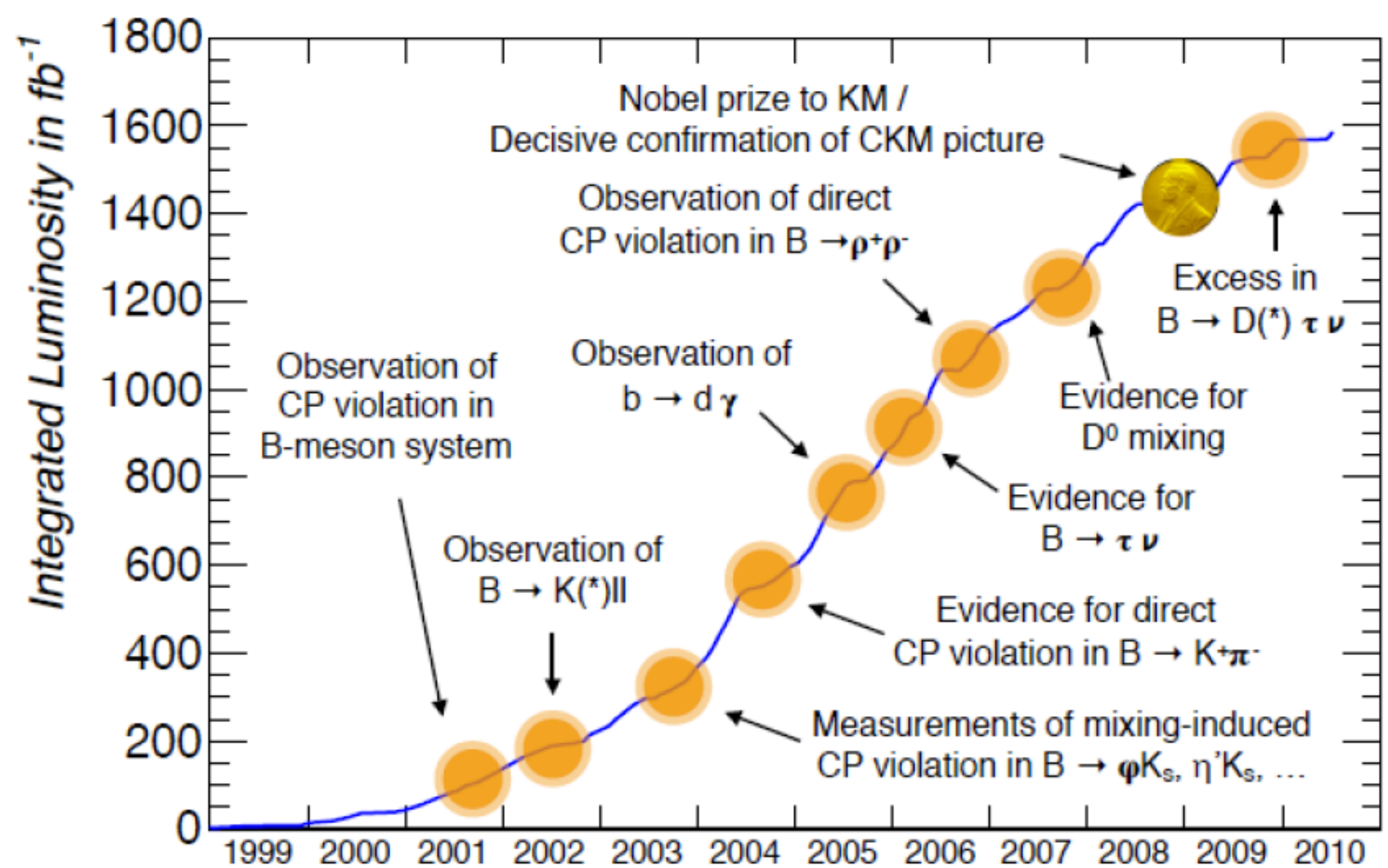
— Experimental confirmation of CKM mechanism as source of CPV in the SM

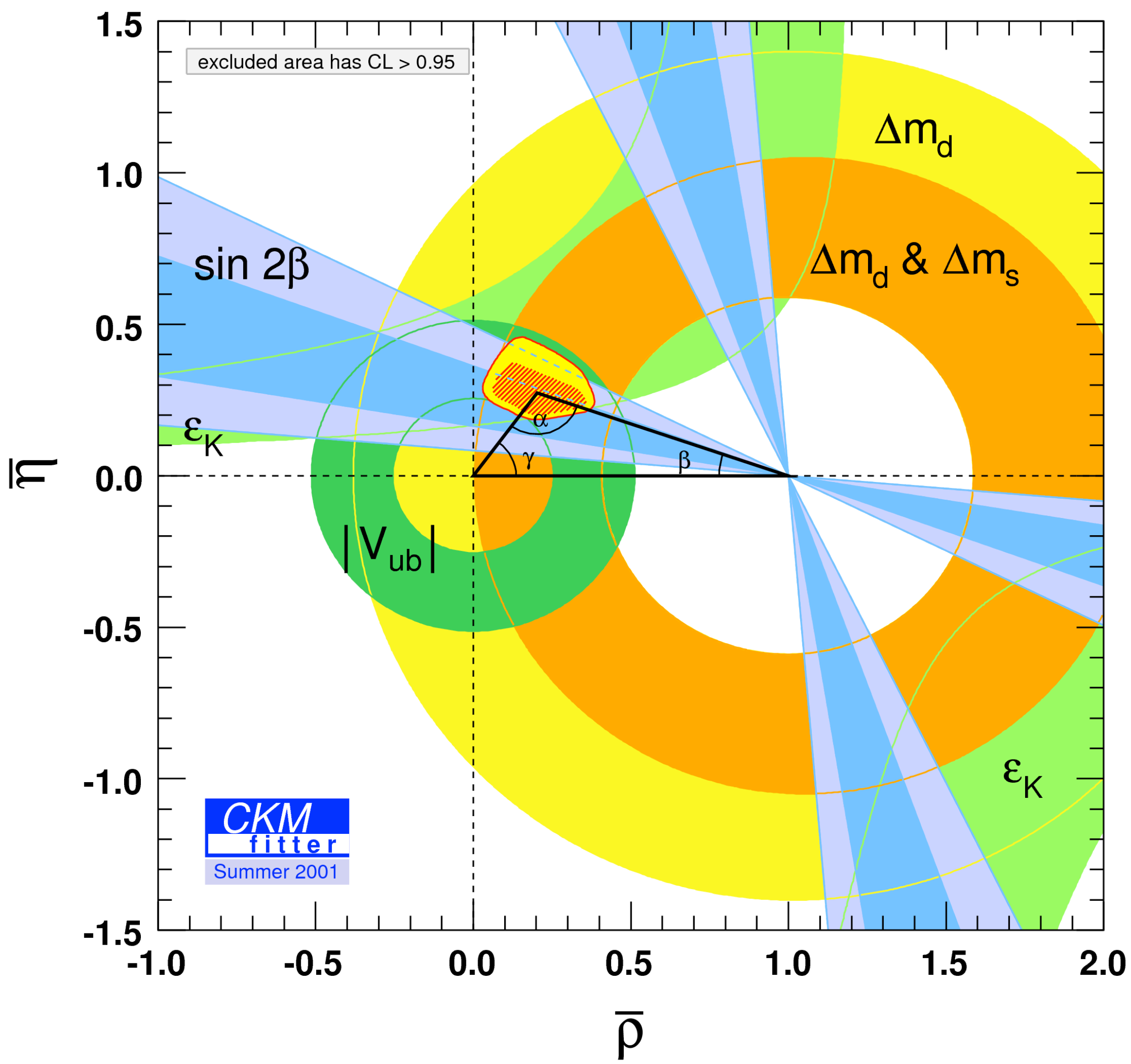




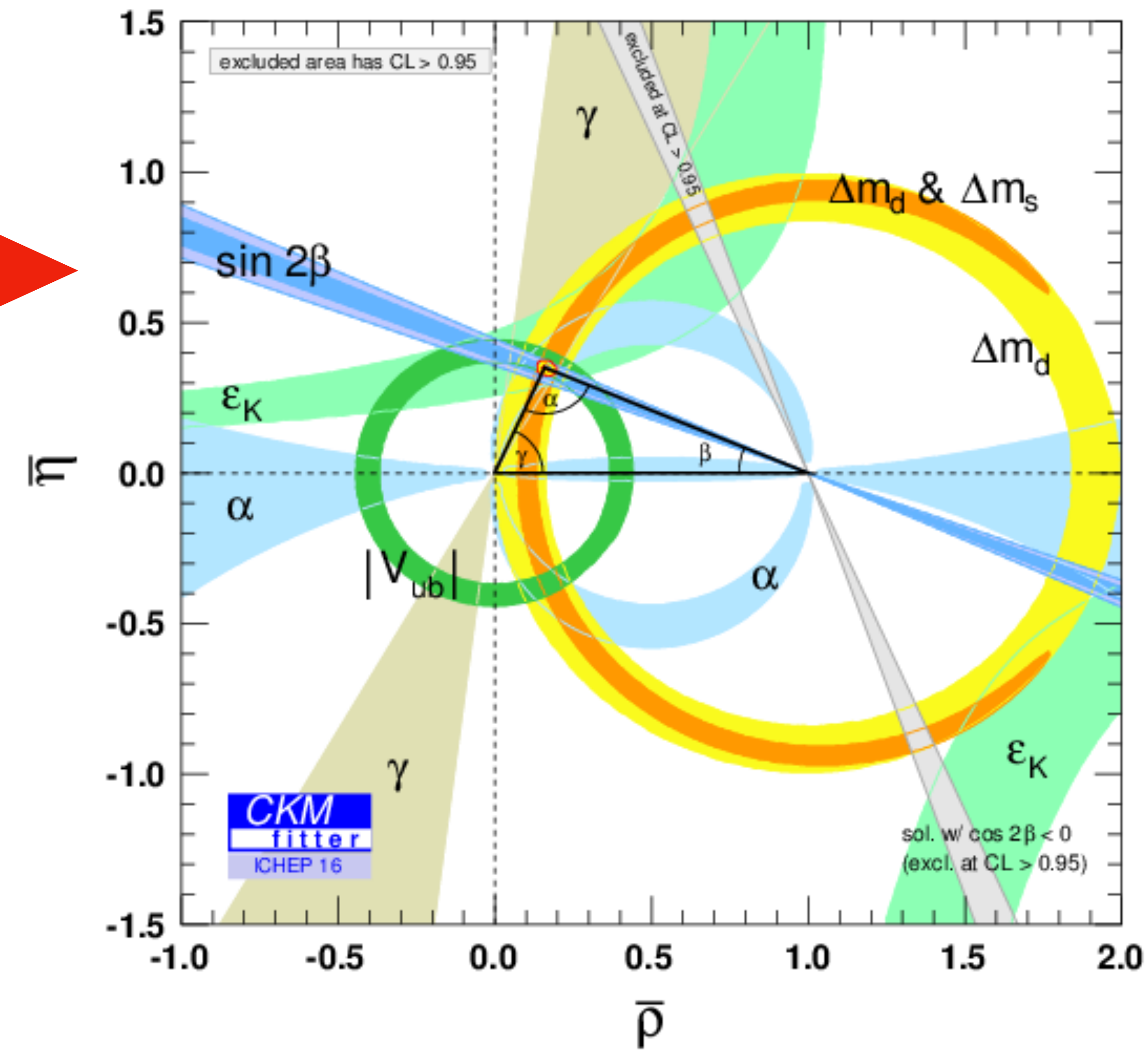


Results from global fits to data

2001: CP violation in the B system is established following the first measurements of the CKM parameter sin2β by BaBar and Belle



State of the art:
ICHEP **2016** conference

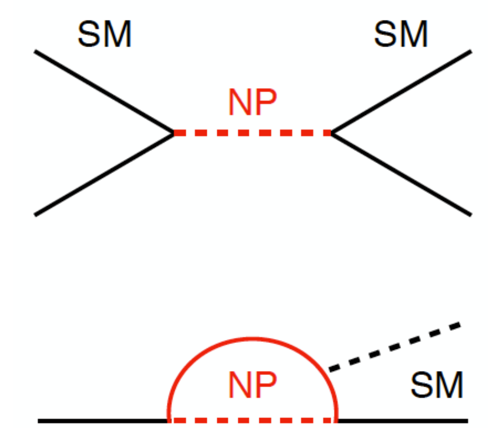


Excellent agreement between SM and results from B-factories and LHCb

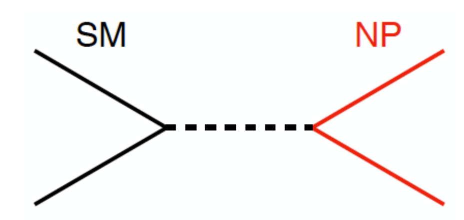
Prospects for New Physics at Belle II

- Search for NP in the flavor sector at the **intensity frontier**
  - Flavor physics as a probe for beyond the TeV scale
- Signatures of new particles or processes observed through measurements of suppressed flavor physics reactions or from deviations from SM predictions
  - An observed discrepancy can be interpreted in terms of NP models
  - Need significantly more data to make this possible
  - Ultimate goal of Belle II: 50 ab^{-1} data sample

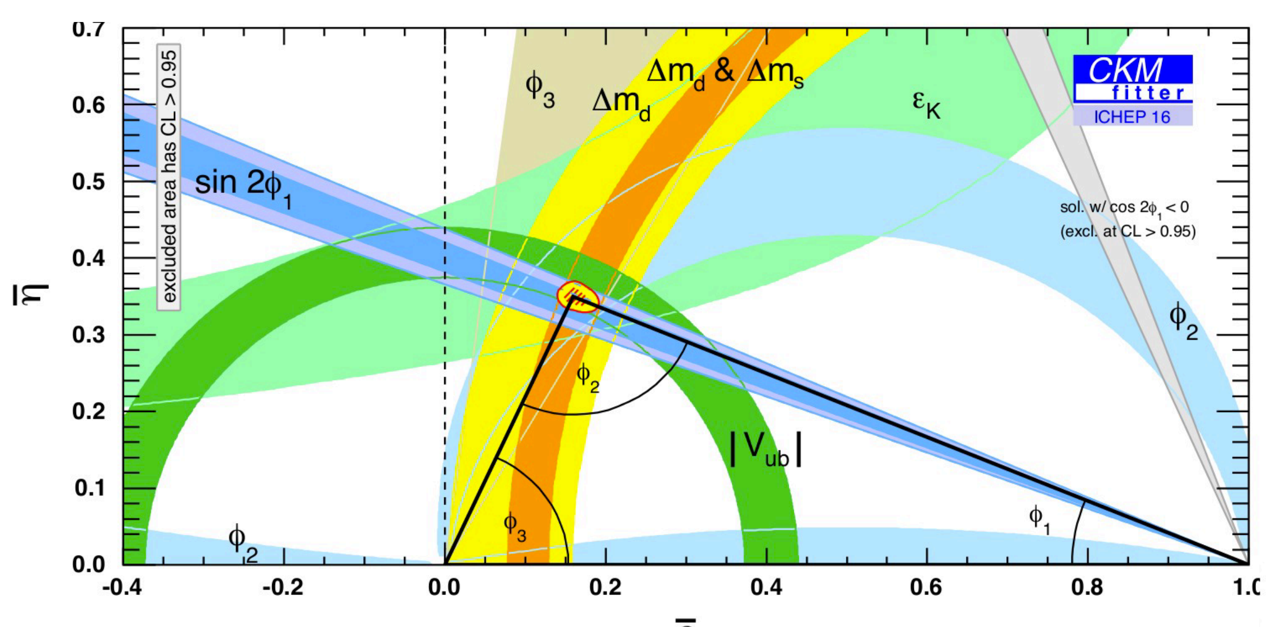
Intensity frontier: indirectly reveal NP virtual particles in loops – probe energy above 10 TeV



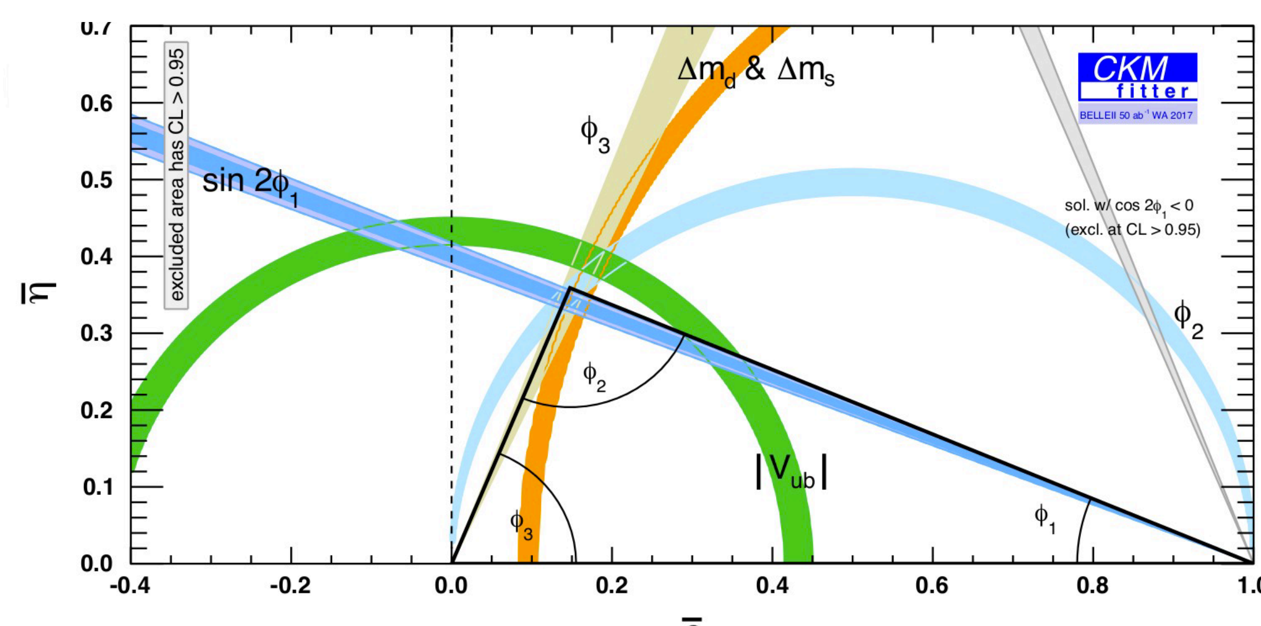
Energy frontier
Direct production of new particles - limited by beam energy



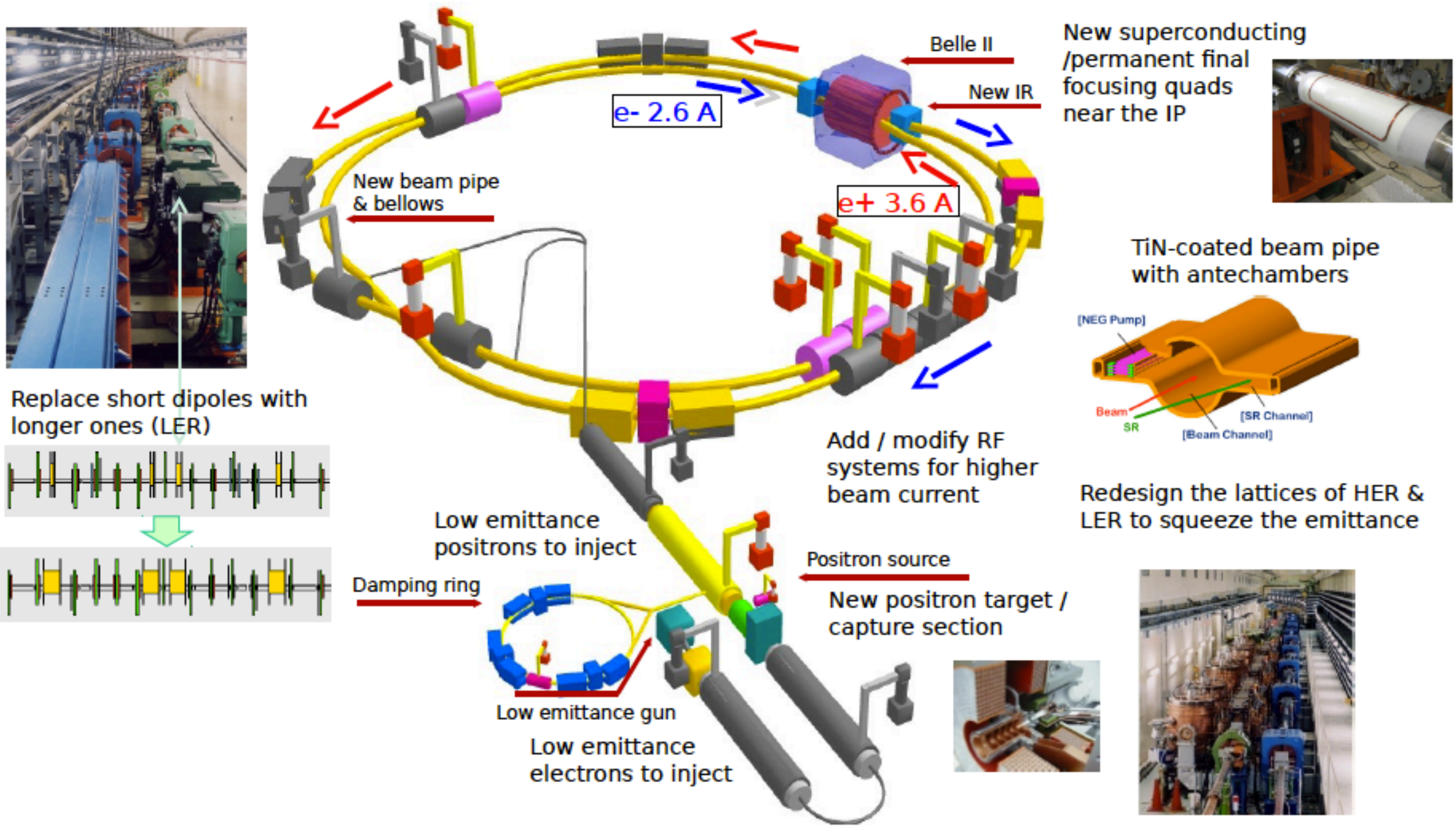
State of the art 2016



Belle II 50 ab^{-1}



SuperKEKB
The next generation B-factory



*gray - recycled, color - new

SuperKEKB
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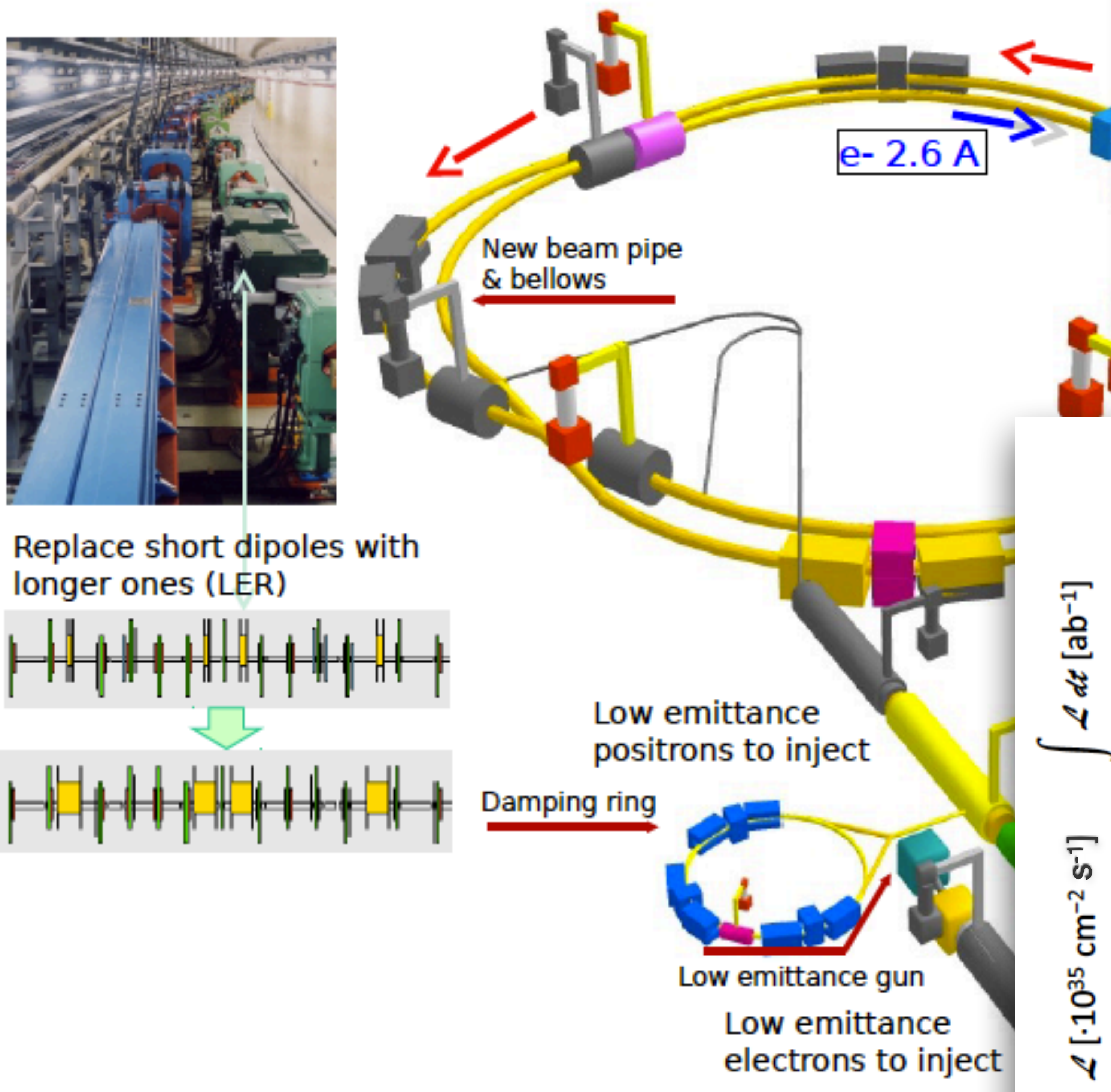
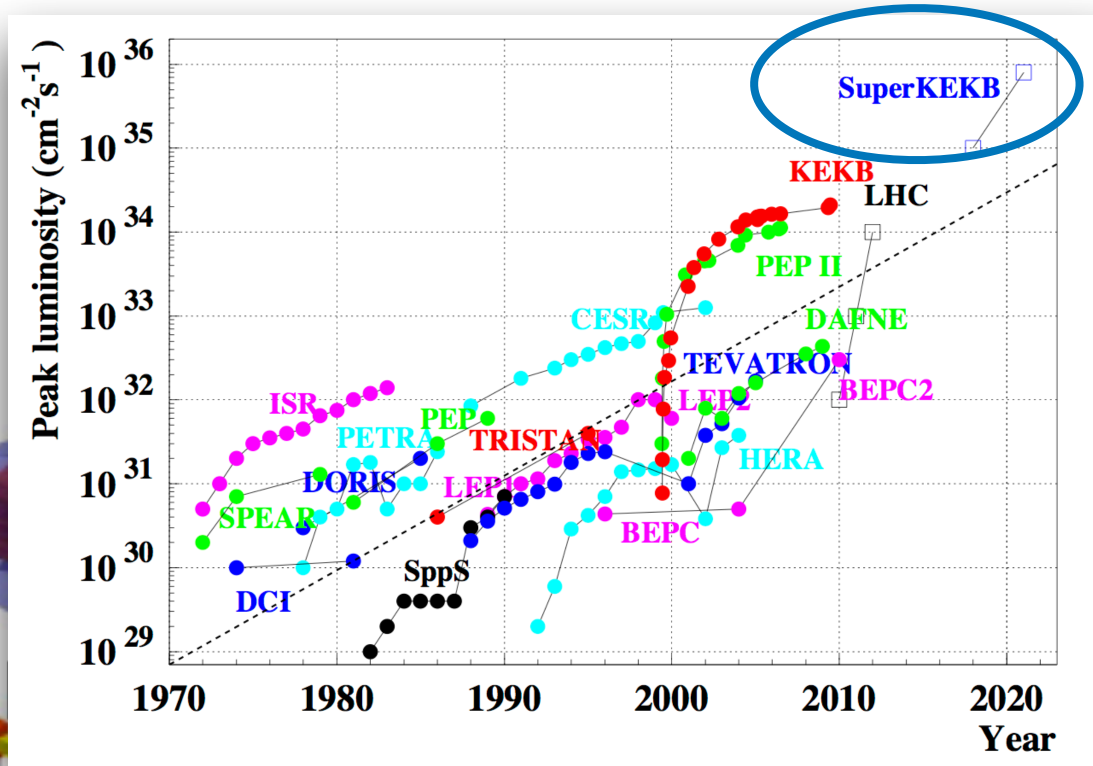
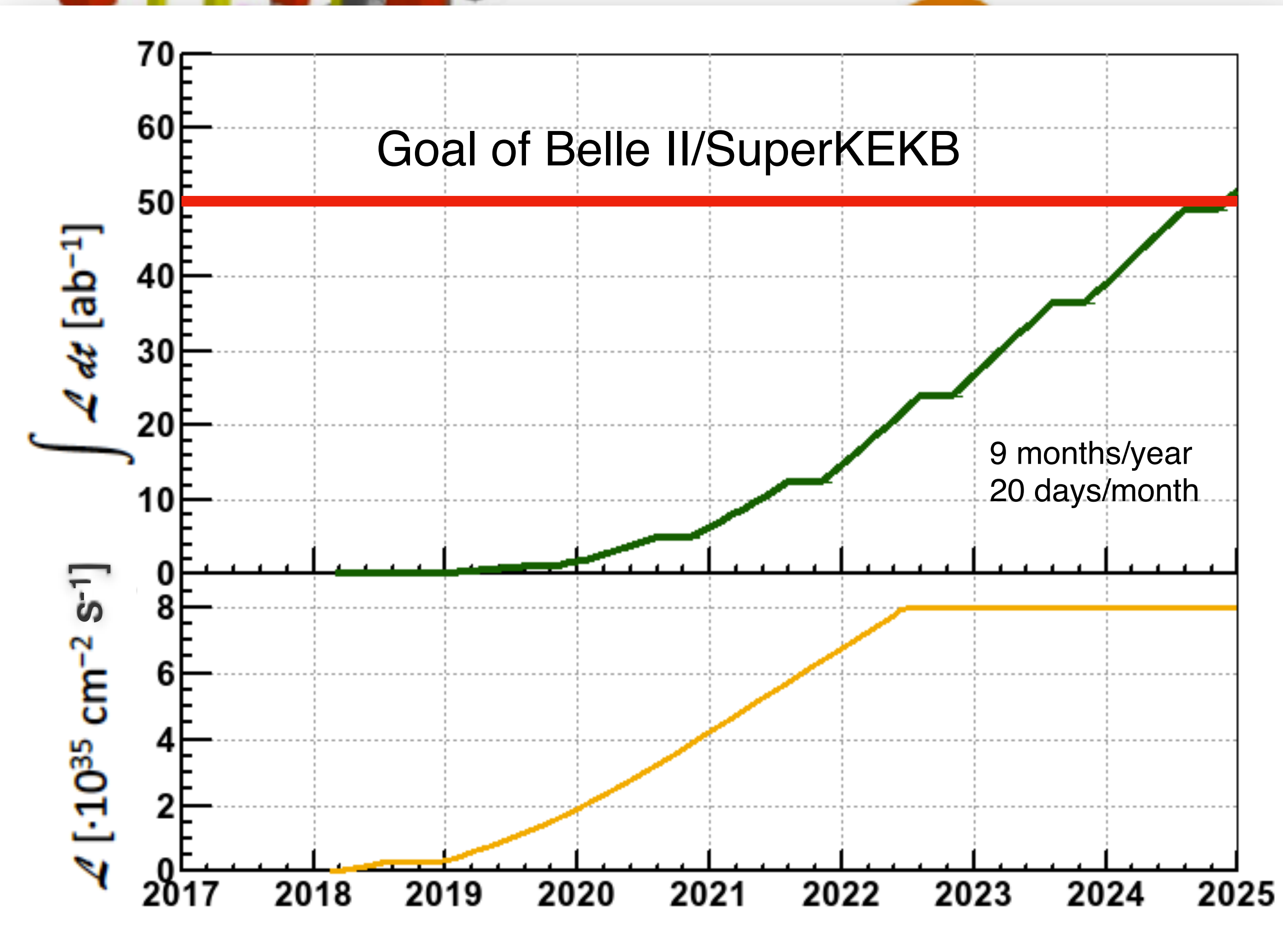






*gray - recycled, color - new

SuperKEKB nanobeams

To get 40x luminosity of KEKB

Reduce beam size to a few 100 atomic layers!

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*}\left(\frac{R_L}{R_{\xi_y}}\right)$$

Lorentz factor

Beam current

Beam-Beam parameter

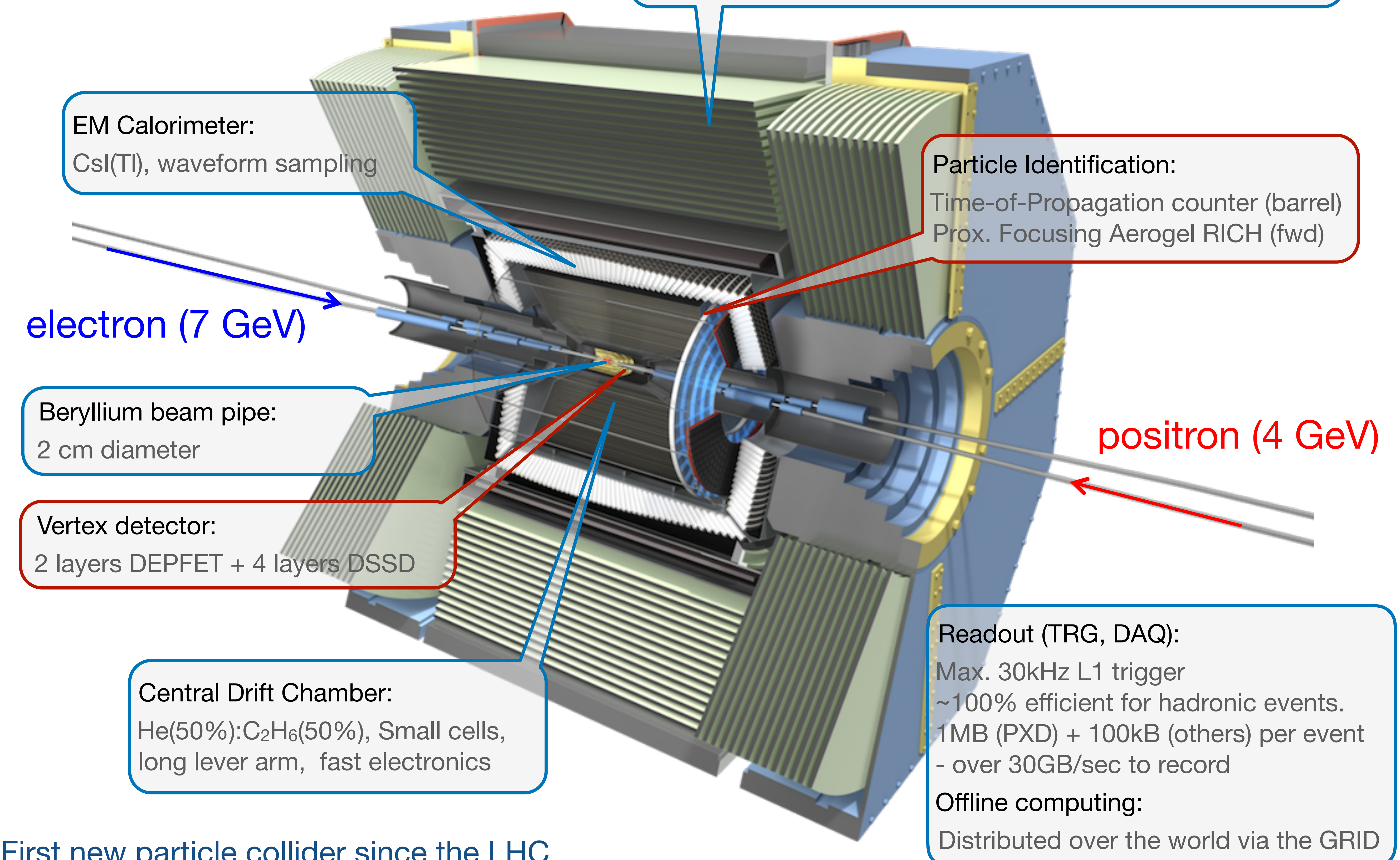
Geometrical reduction factors (crossing angle, hourglass effect)

Beam aspect ratio at IP

Vertical beta function at IP

Parameter		KEKB		SuperKEKB		units
		LER	HER	LER	HER	
beam energy	E_b	3.5	8	4	7	GeV
CM boost	$\beta\gamma$	0.425		0.28		
half crossing angle	ϕ	11		41.5		mrad
horizontal emittance	ε_x	18	24	3.2	4.6	nm
beta-function at IP	β_x^*/β_y^*	1200/5.9		32/0.27	25/0.30	mm
beam currents	I_b	1.64	1.19	3.6	2.6	A
beam-beam parameter	ξ_y	0.129	0.090	0.0881	0.0807	nm
beam size at IP	σ_x^*/σ_y^*	100/2		10/0.059		µm
Luminosity	L	2.1 x 10^{34}		8 x 10^{35}		$cm^{-2}s^{-1}$

The Belle II detector



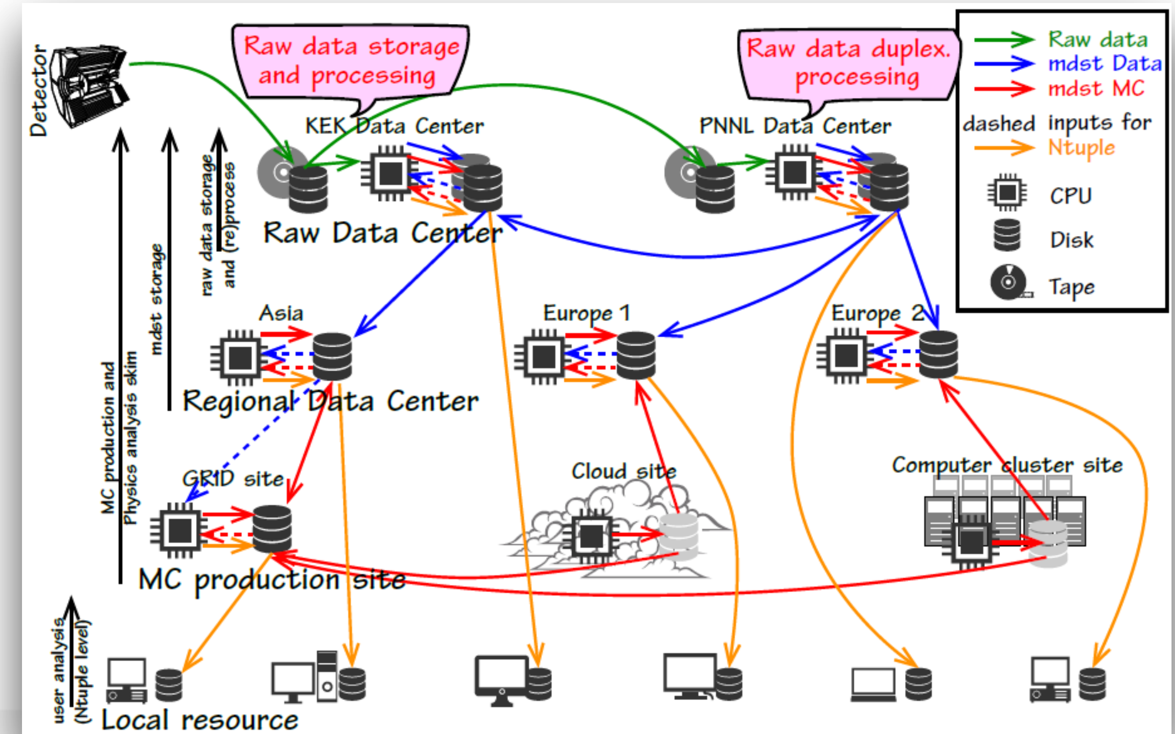
First new particle collider since the LHC
(intensity rather than energy frontier; e^+e^- rather than pp)

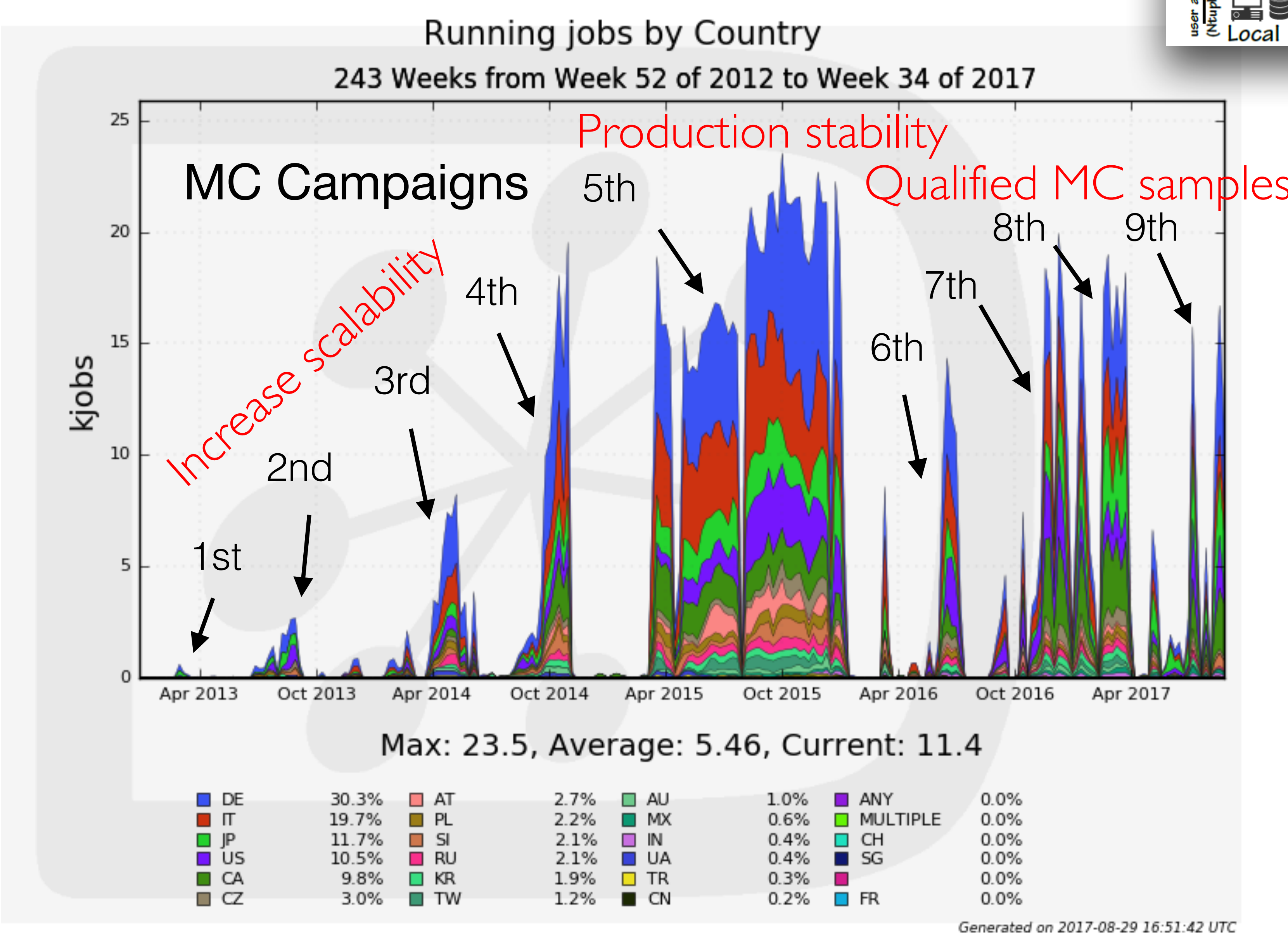
arXiv:1011.0352 [physics.ins-det]

Offline computing

Distributed computing following the LHC model

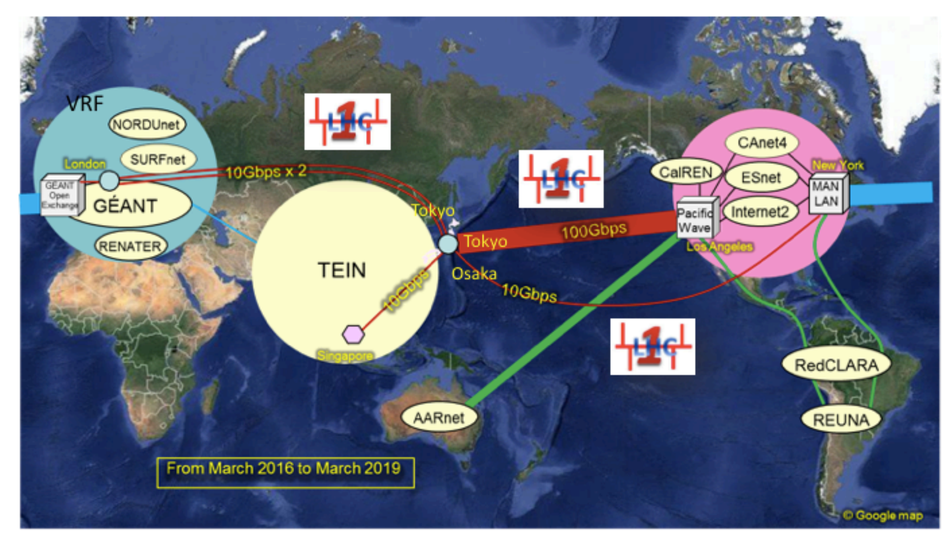
- Manage the processing of massive data sets
- Production of large MC samples
- Many concurrent user analysis jobs





High speed networking data challenge in 2016:

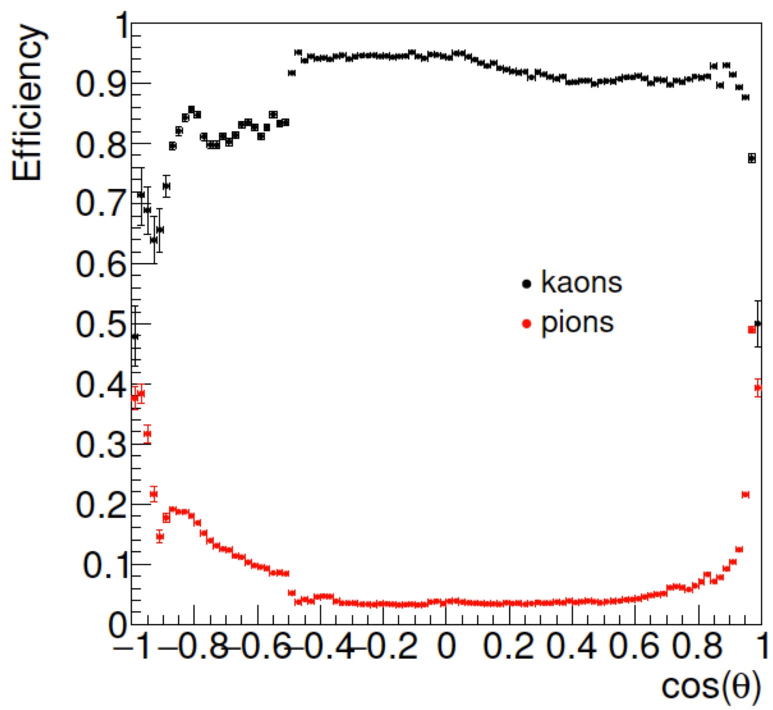
- Belle II networking requirements are satisfied



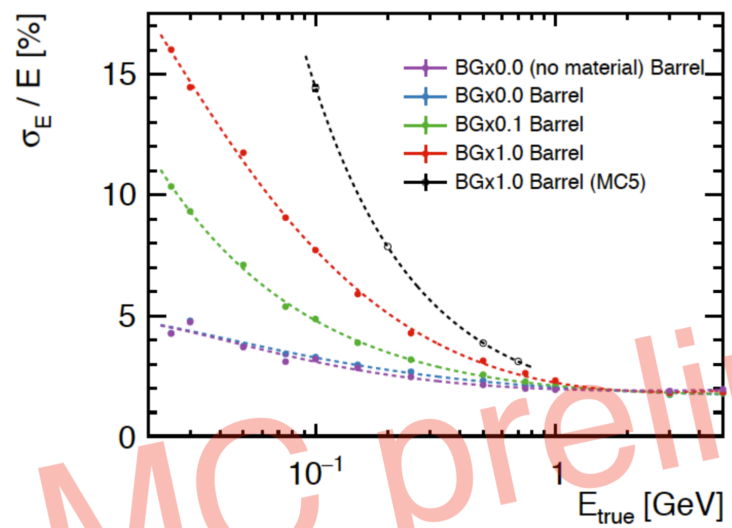
Reconstruction performance (from Belle II MC)

Belle II works similar to or better than Belle despite ~20 times higher beam background!

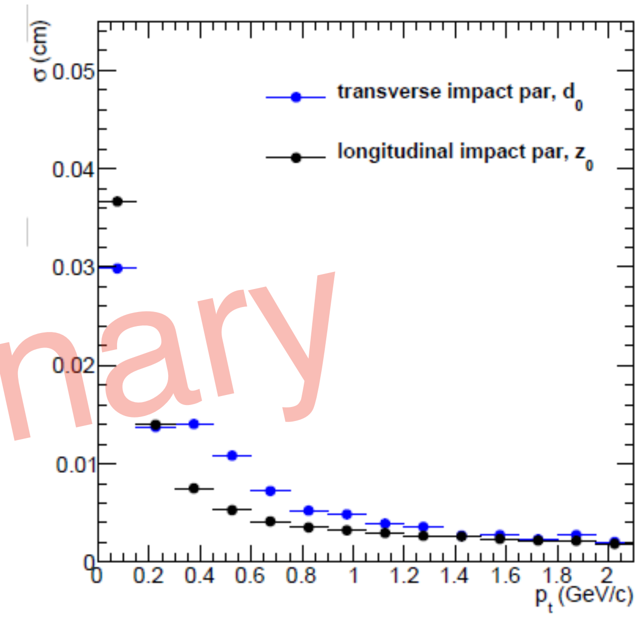
PID performance



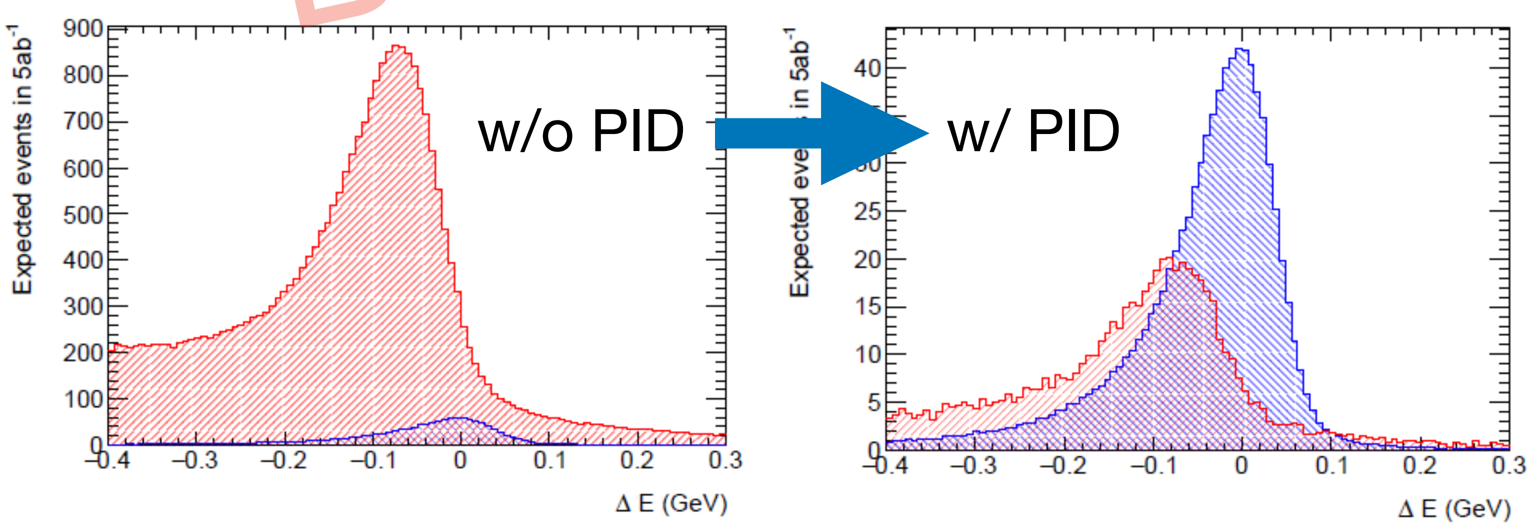
Photon energy resolution



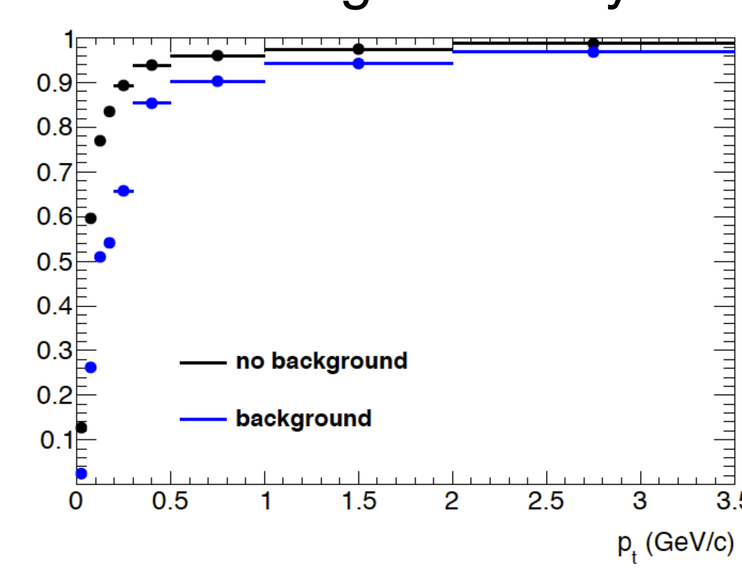
IP resolution



$B^0 \to \rho^0\gamma$ vs. $K^{*0}\gamma$

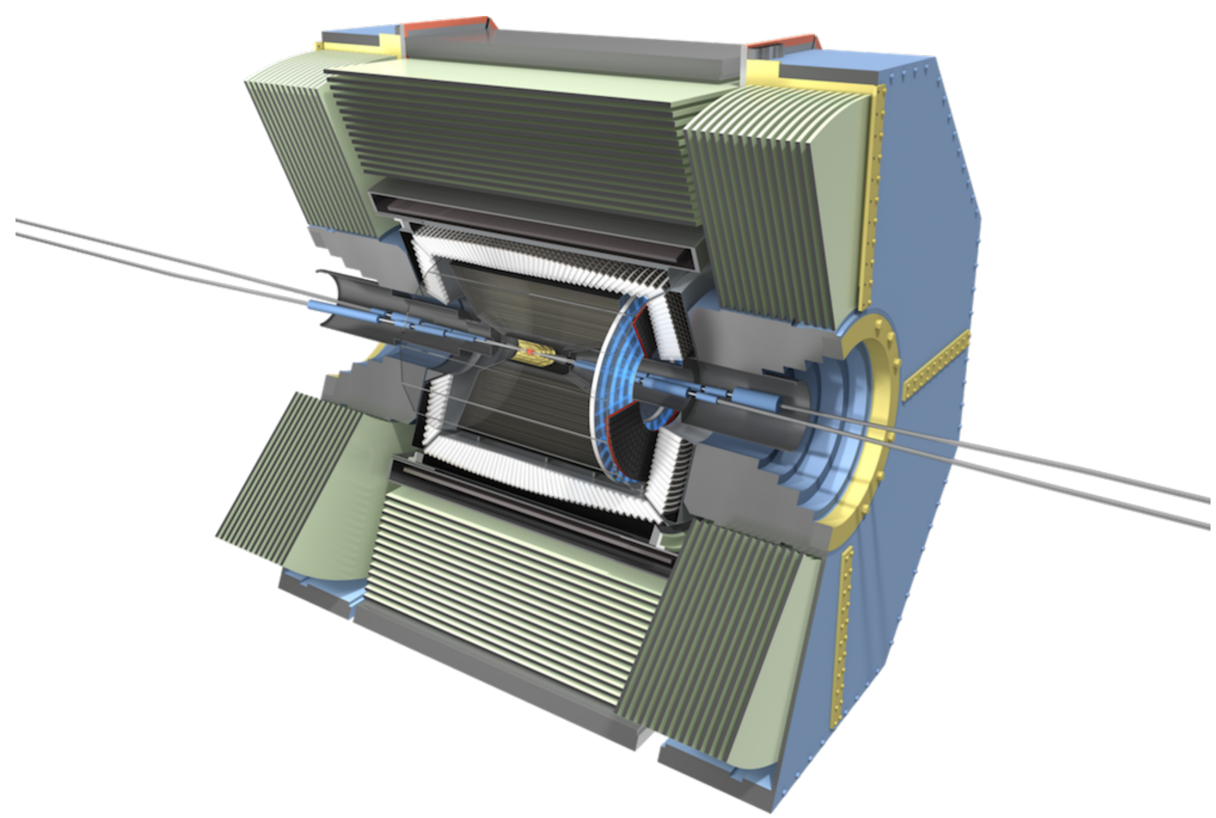


Tracking efficiency



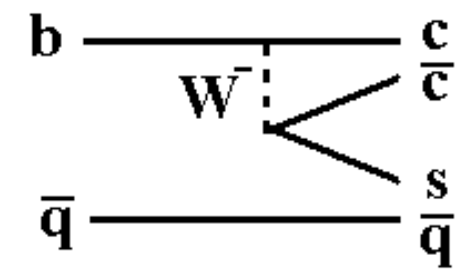
Benefits of hadron spectroscopy at B-factories

- Efficient reconstruction of neutrals (π^0, η, etc.)
- Reconstruct single resonance to explore recoiling system (eg. $e^+e^- \rightarrow J/\psi X$)
- High resolution, hermetic detector with good PID capability
- Using tagged events (i.e., with a fully reconstructed partner B), to measure absolute branching fractions
  - Essential for XYZ studies
  - Considerably lower background than LHCb
- Variety of production mechanisms

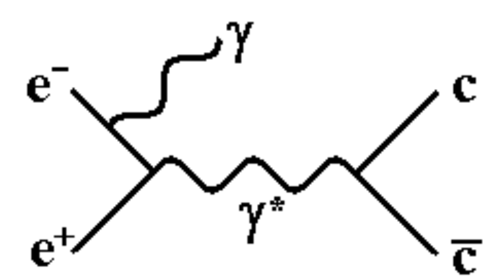


Quarkonium production at B-factories

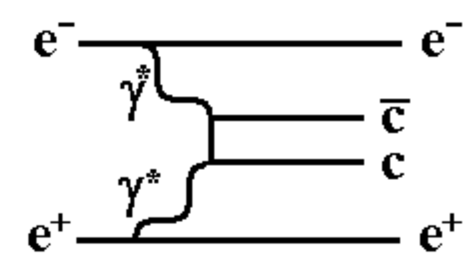
- B decays
    - Charmonium only
    - All quantum numbers accessible



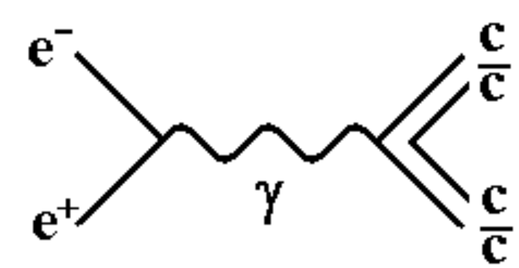
- Direct production / ISR
    - $J^{PC} = 1^{--}$



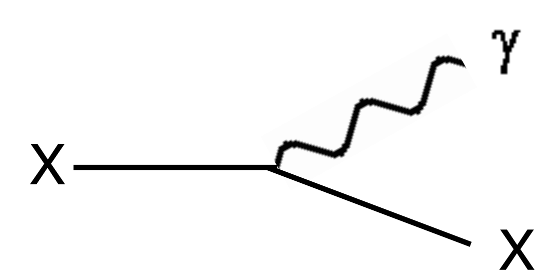
- Two-photon production
    - $J^{PC} = 0^{-+}, 0^{++}, 2^{++}$



- Double charmonium production
    - Seen for J = 0, $J^{PC} = 1^{--}$

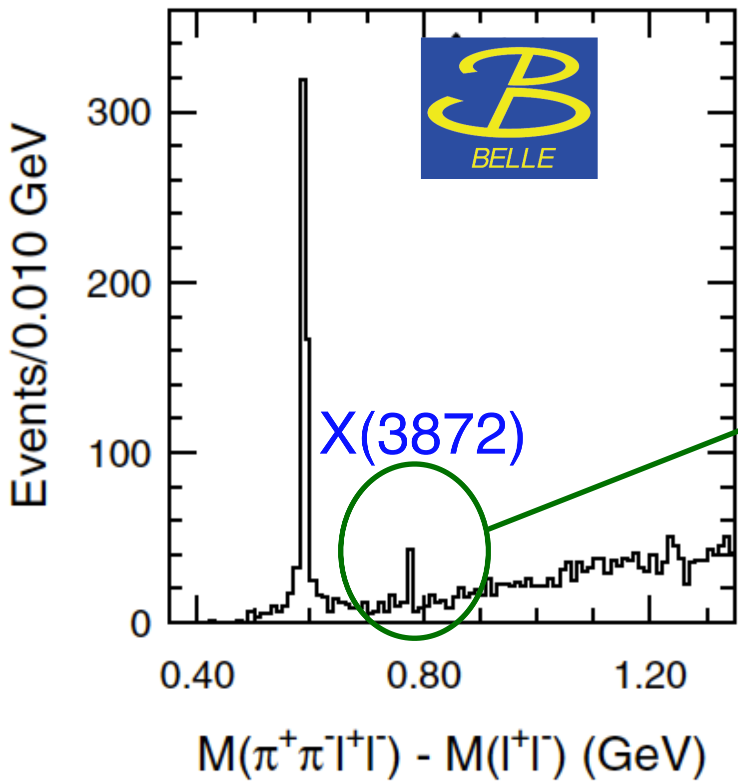


- Quarkonium transitions
    - Hadronic or radiative decays between states

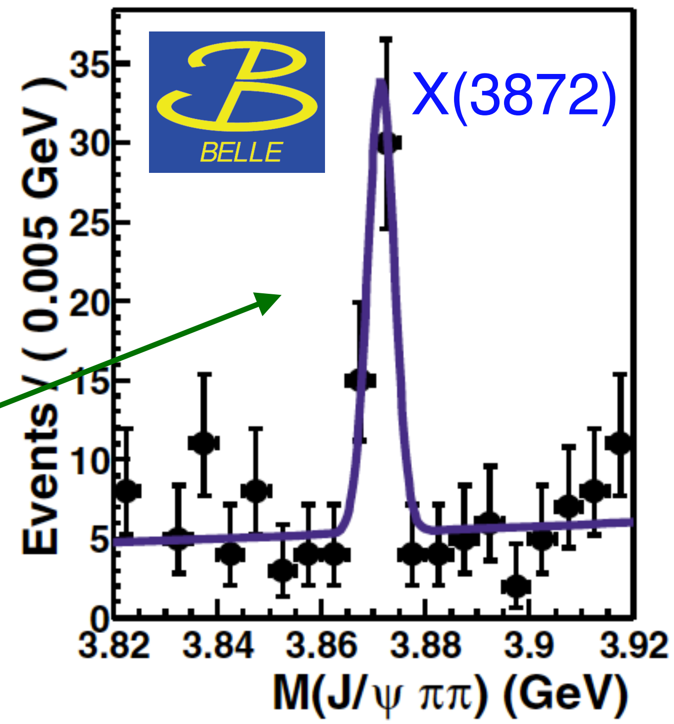


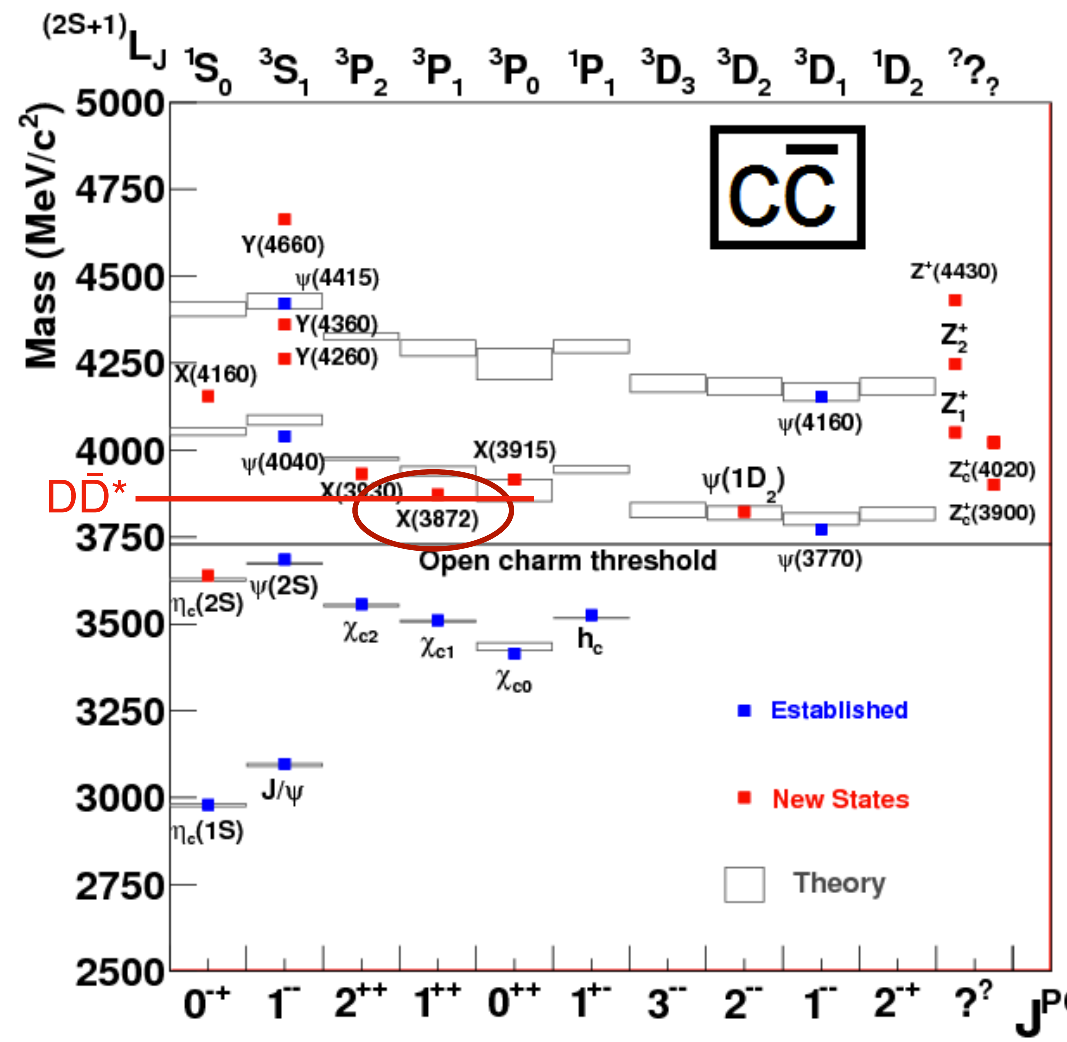
X(3872) discovered by Belle in B→Kπ⁺π⁻J/ψ (2003)

- Seen in all modern HEP experiments
- Decay modes include $\pi^+\pi^- J/\psi$, $\rho^0 J/\psi$, $\omega J/\psi$, $D^0\bar{D}^{0*}$, $\gamma J/\psi$, $\gamma\psi(2S)$



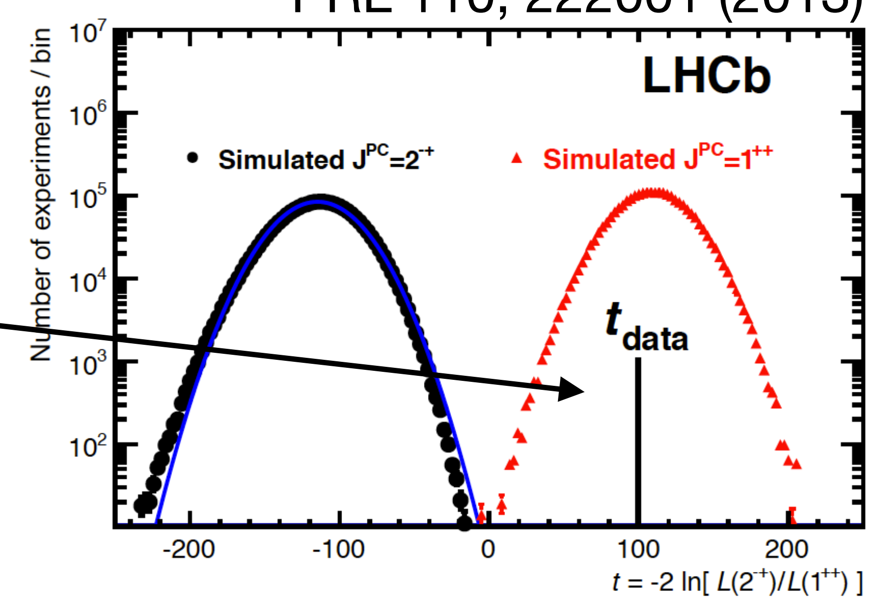
PRL 91, 262001 (2003)





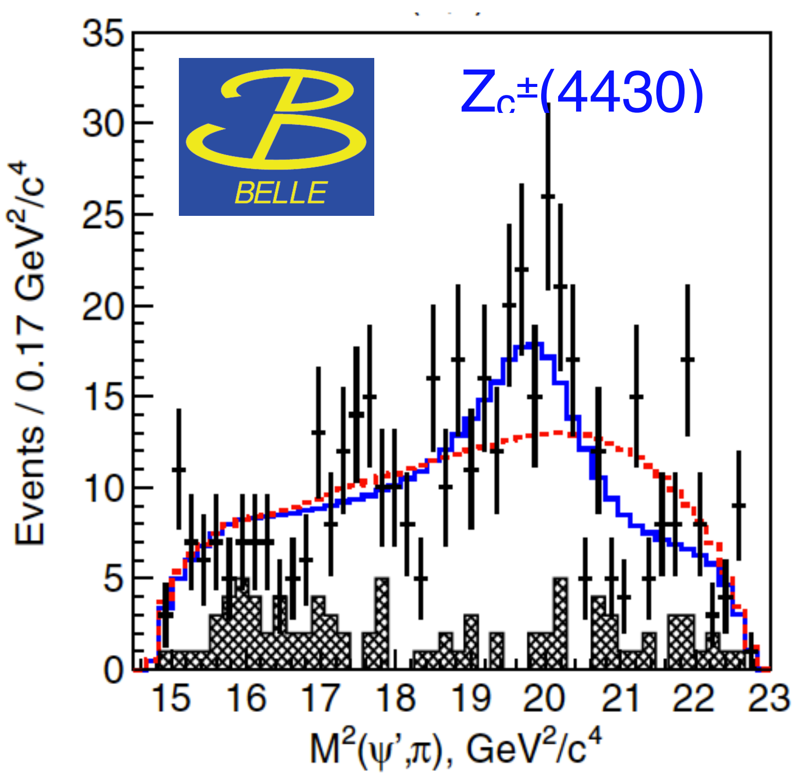
PRL 110, 222001 (2013)

- $J^{PC} = 1^{++}$ settled unequivocally by LHCb

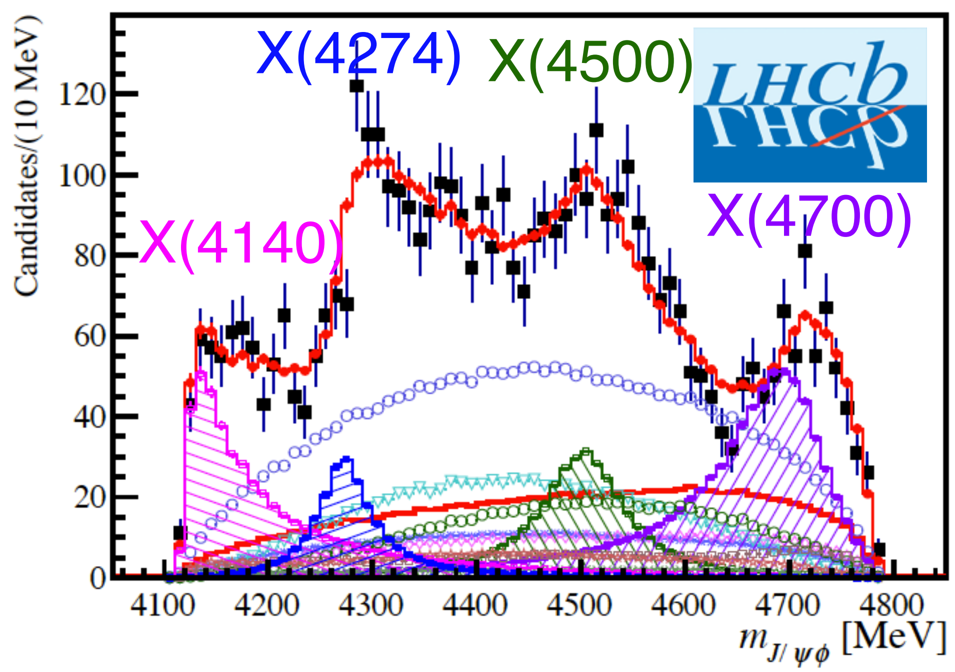


Charmonium-like states from B-decays

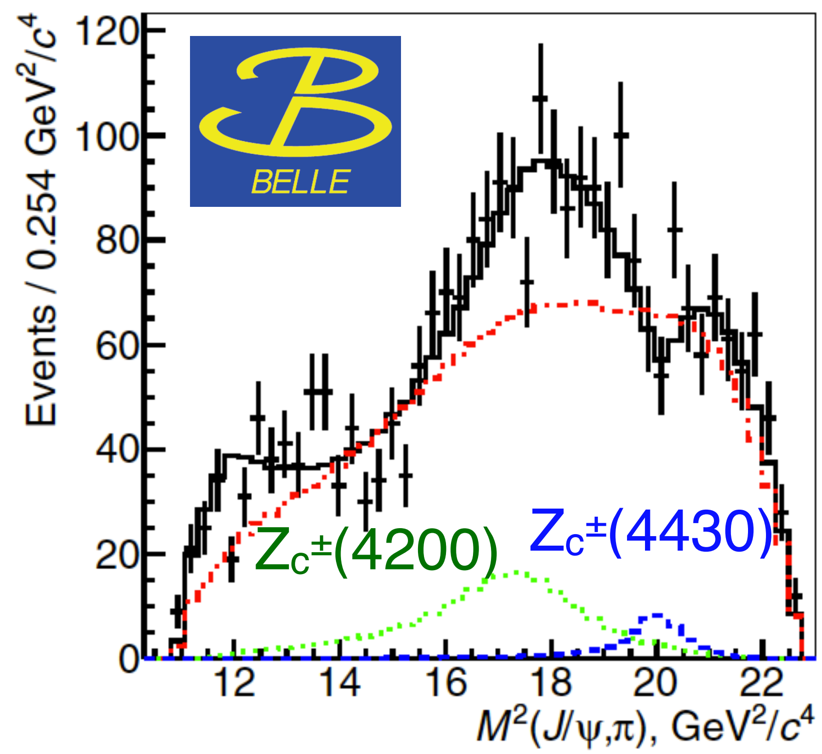
- Enhancements in $\pi^{\pm}\psi(2S)$, $\pi^{\pm}J/\psi$, $\pi^{\pm}\chi_{c1}(1P)$ spectra at various masses
- Belle and LHCb performed amplitude analyses of $B^0 \to K^{\pm}\pi^{\mp}J/\psi$, $K^{\pm}\pi^{\mp}\psi(2S)$, and $K\phi J/\psi$



PRD 88, 074026 (2013)



PRD 95, 012002 (2017)



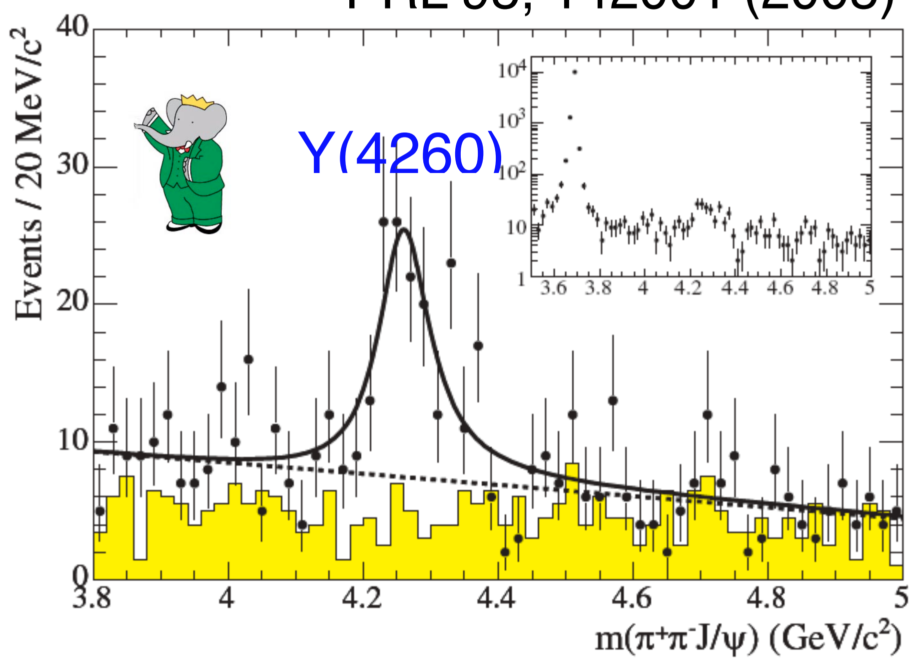
PRD 90, 112009 (2014)

- Important to apply amplitude analysis to $B \to K\omega J/\psi$, $K\pi\chi_{c1}(1P)$ to determine spin-parities of X(3915), $Z_c(4050)$, $Z_c(4250)$
- Comprehensive study of $B \to K(D\bar{D})$, $K(D\bar{D}^*)$, $K(D^*\bar{D}^*)$ needed to search for open-flavor decays of other states

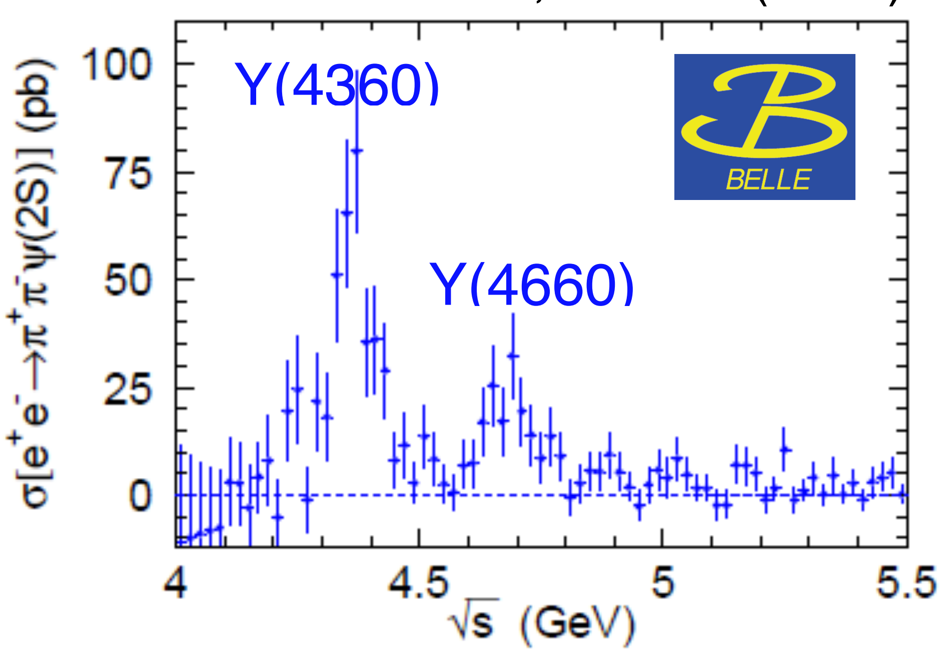
Charmonium-like states from ISR

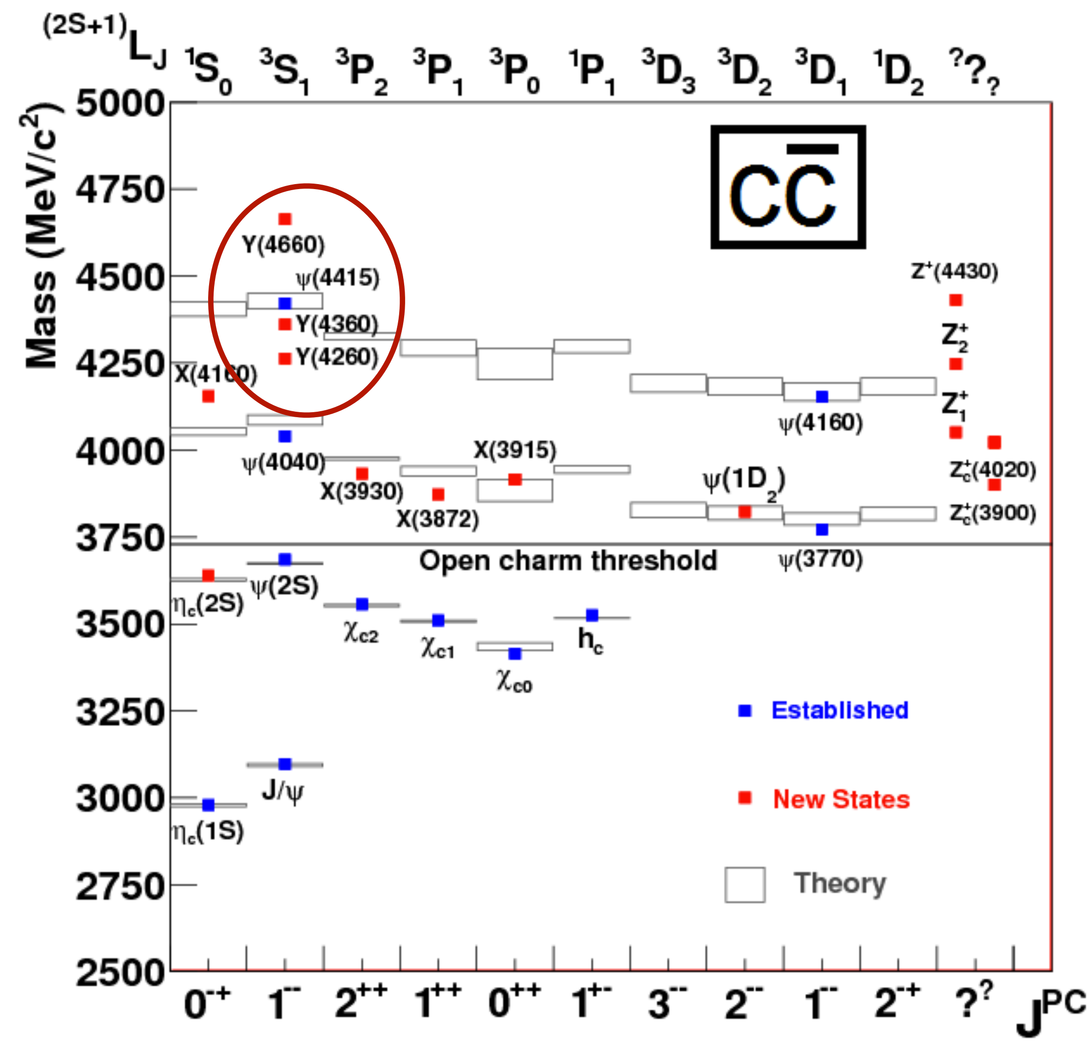
- Y(4260), Y(4360), Y(4660) produced in ISR to ππψ

PRL 95, 142001 (2005)



PRD 91, 112007 (2015)



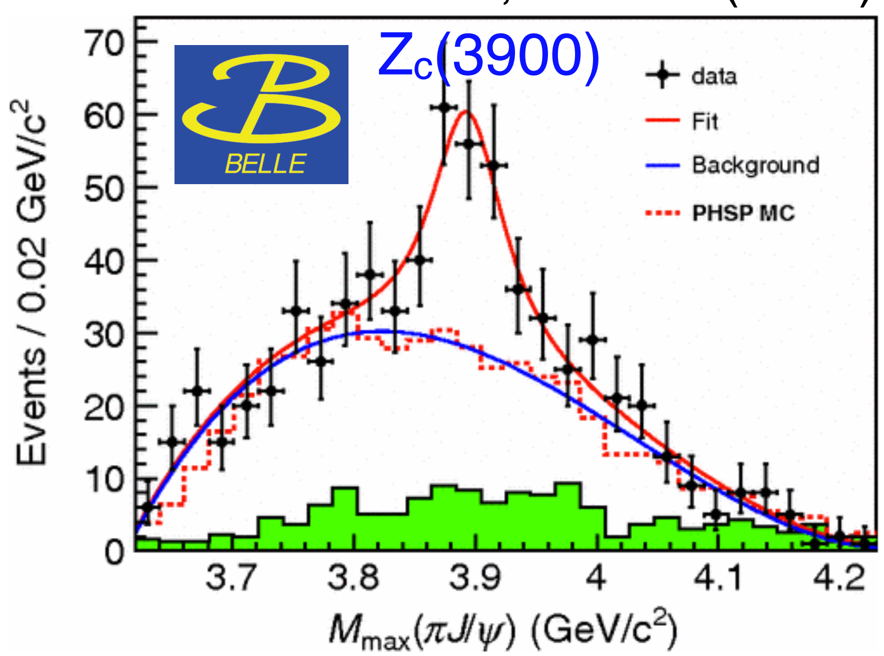


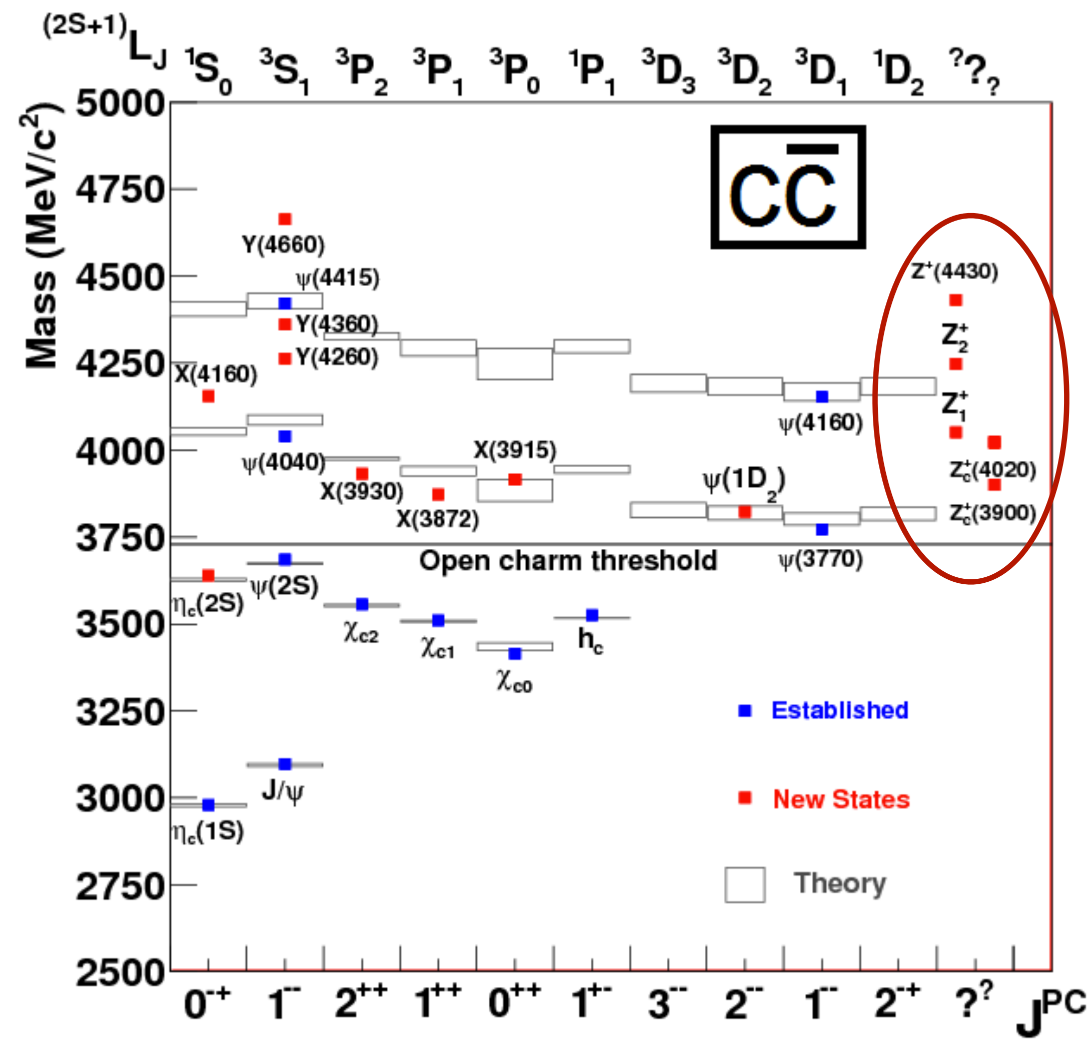
- Overpopulation of charmonium states!
- Molecular ($D_1\bar{D}$), hybrid, tetraquark all offer viable descriptions

Charged, charmonium-like states

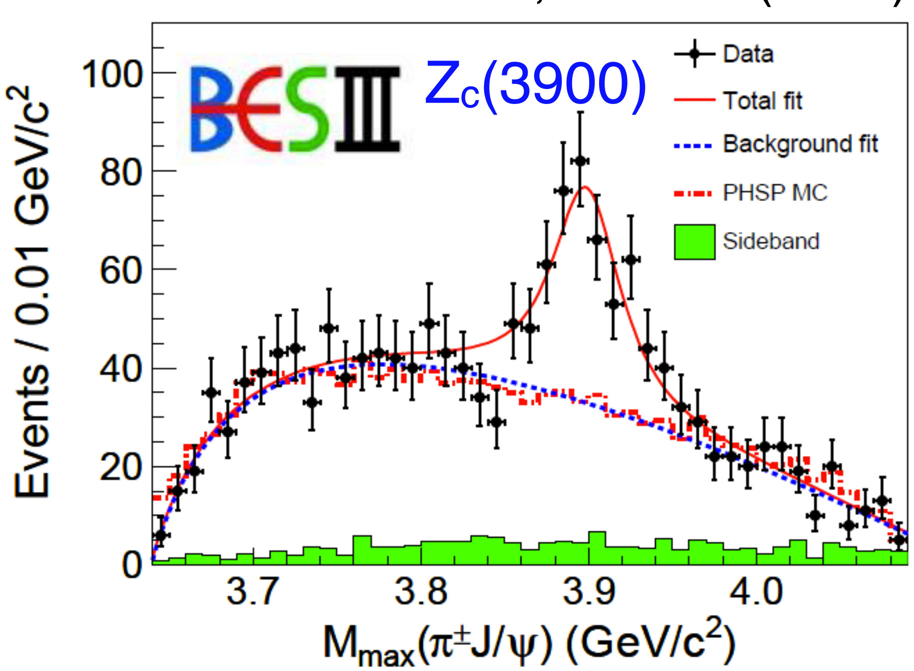
- Y(4260), Y(4360), Y(4660) produced in ISR to ππψ

PRL 110, 252002 (2013)





PRL 110, 252001 (2013)

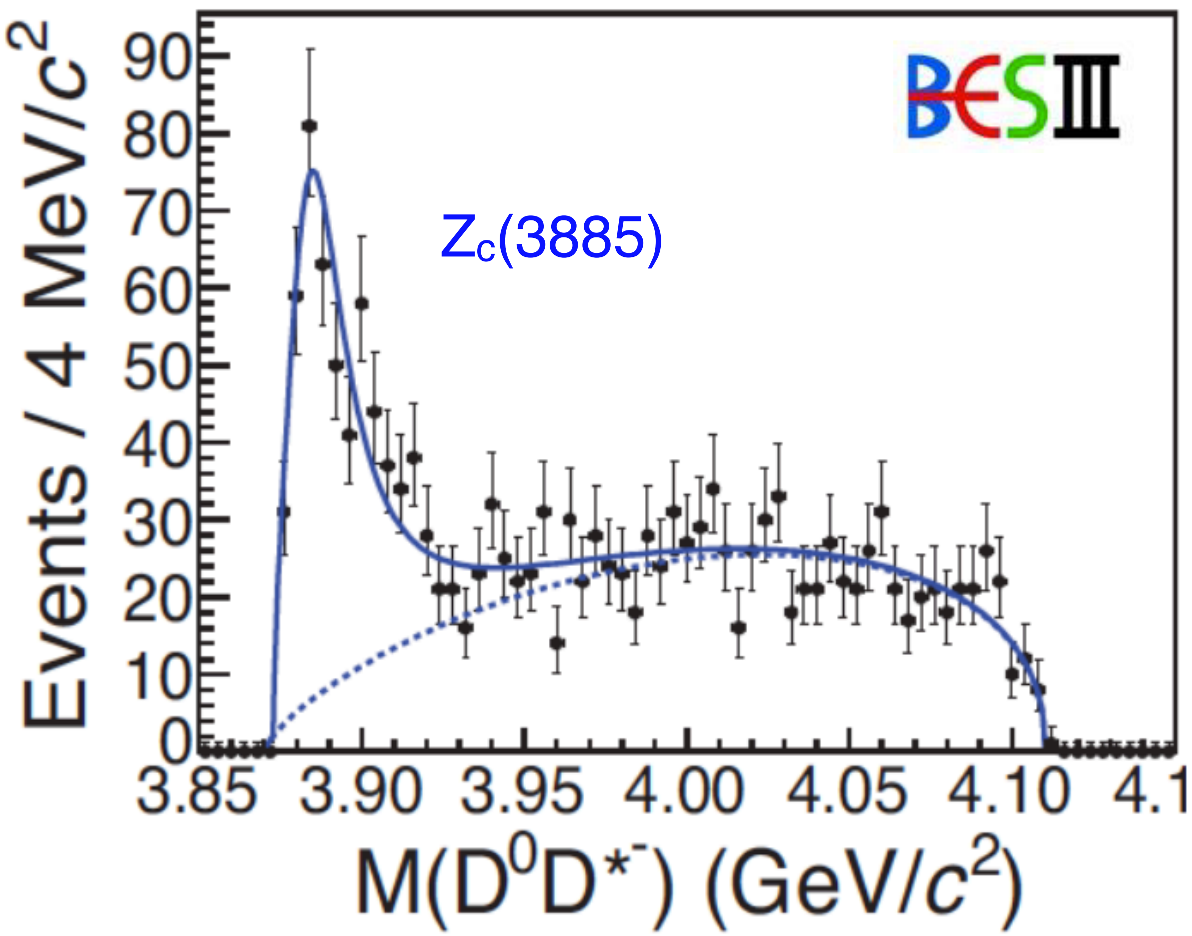


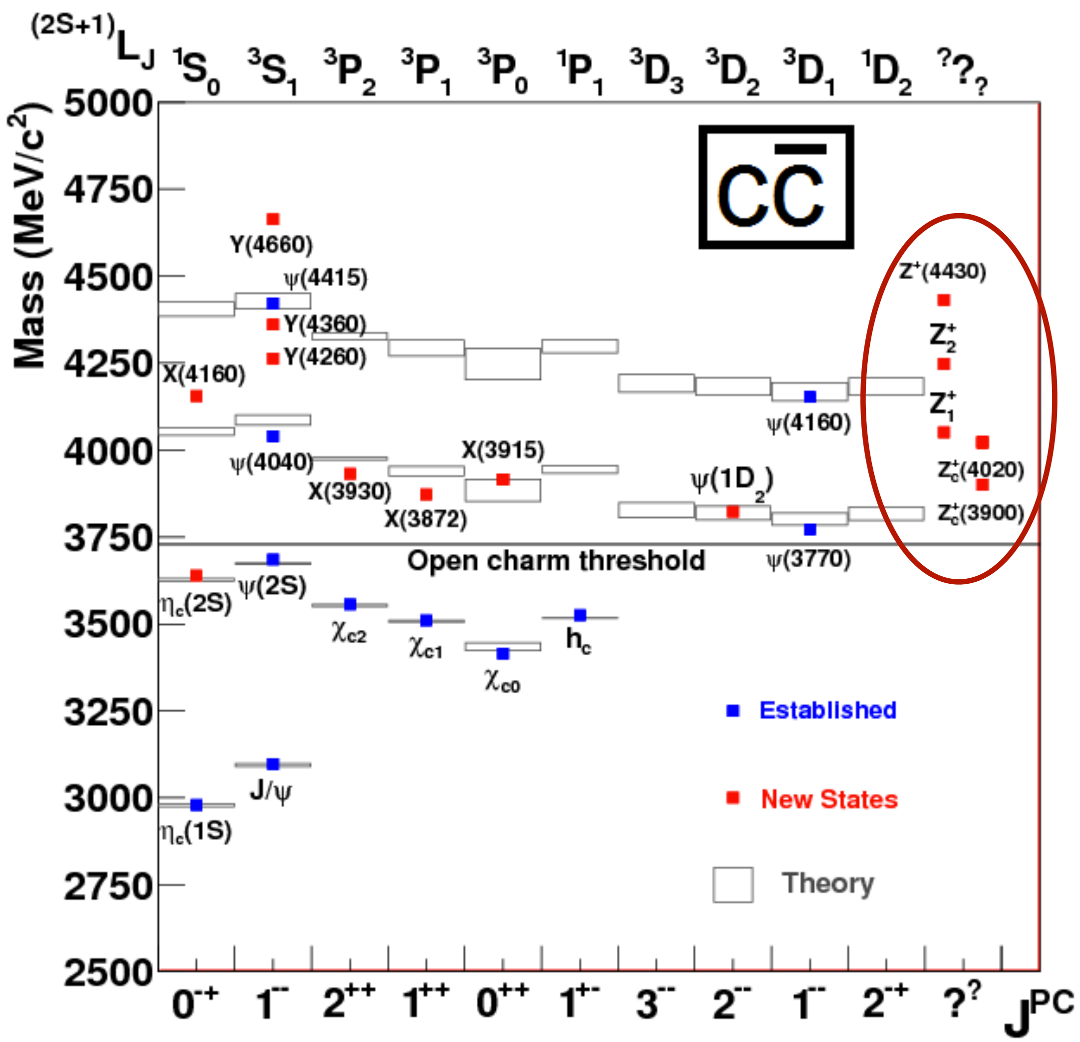
- Evidence for intermediate charged state (manifestly “exotic”)
- Cannot be simple qq̄ pair

Charged, charmonium-like states

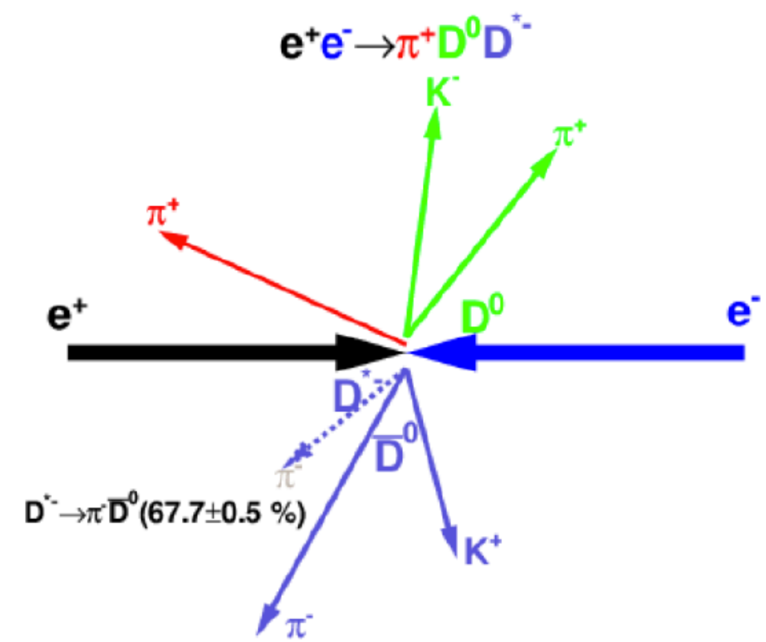
- Y(4260), Y(4360), Y(4660) produced in ISR to ππψ

PRL 112, 022001 (2014)



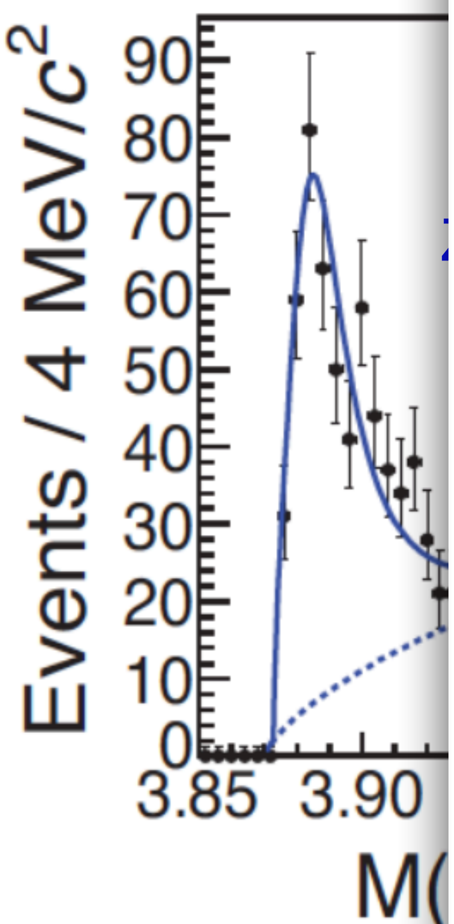


- Partner (same?) state observed decaying to open charm final state

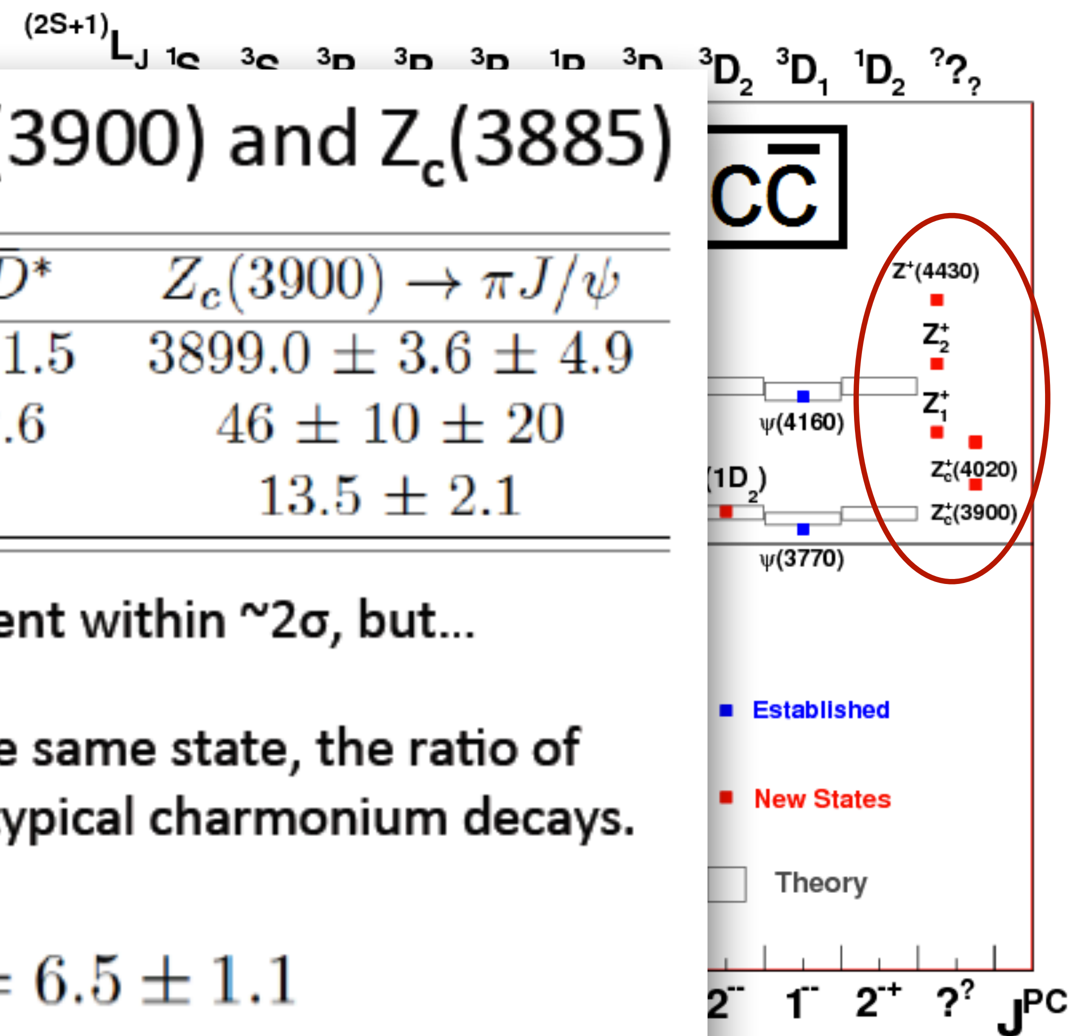


Charged, charmonium-like states

- Y(4260), Y(43
  in ISR to ππψ



- Partner (sa
  to open ch



Comparisons between $Z_c(3900)$ and $Z_c(3885)$

	$Z_c(3885) \to D\bar{D}^*$	$Z_c(3900) \to \pi J/\psi$
Mass / MeV/c^2	$3884.3 \pm 1.2 \pm 1.5$	$3899.0 \pm 3.6 \pm 4.9$
Width / MeV	$23.8 \pm 2.1 \pm 2.6$	$46 \pm 10 \pm 20$
$\sigma \times \mathcal{B}$ / pb	88.0 ± 6.1	13.5 ± 2.1

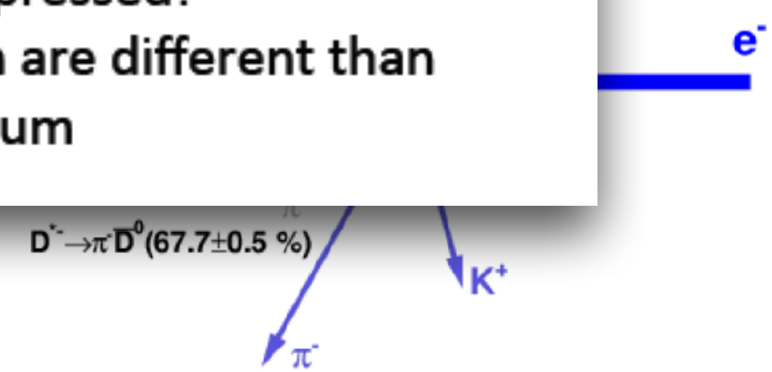
Masses and widths are consistent within ~2σ, but…

If the $Z_c(3900)$ and $Z_c(3885)$ are the same state, the ratio of partial widths is reduced relative to typical charmonium decays.

$$\frac{\Gamma(Z_c(3885) \to D\bar{D}^*)}{\Gamma(Z_c(3900) \to \pi J/\psi)} = 6.5 \pm 1.1$$

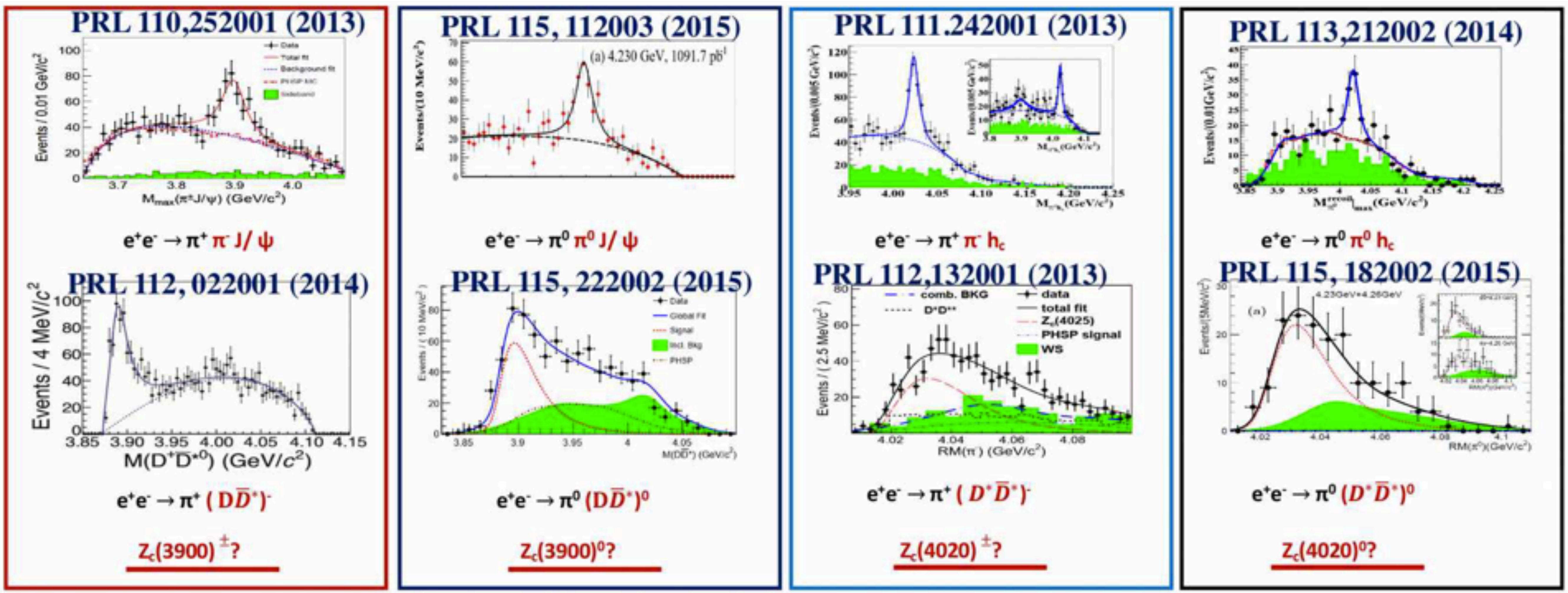
$$\frac{\Gamma(\psi(4040) \to D^*\bar{D}^*)}{\Gamma(\psi(4040) \to \eta J/\psi)} \approx 283$$

Open charm decays are suppressed!
Dynamics of Y(4260) – $Z_c(3900)$ system are different than conventional charmonium



Charged, charmonium-like states

- Several Z states have been measured in $c\bar{c}$ and open charm final states
- Isospin triplet appears to be established for all of them
- Masses and widths are comparable in measurements to $\pi J/\psi$ and $D^{(*)}\bar{D}^*$

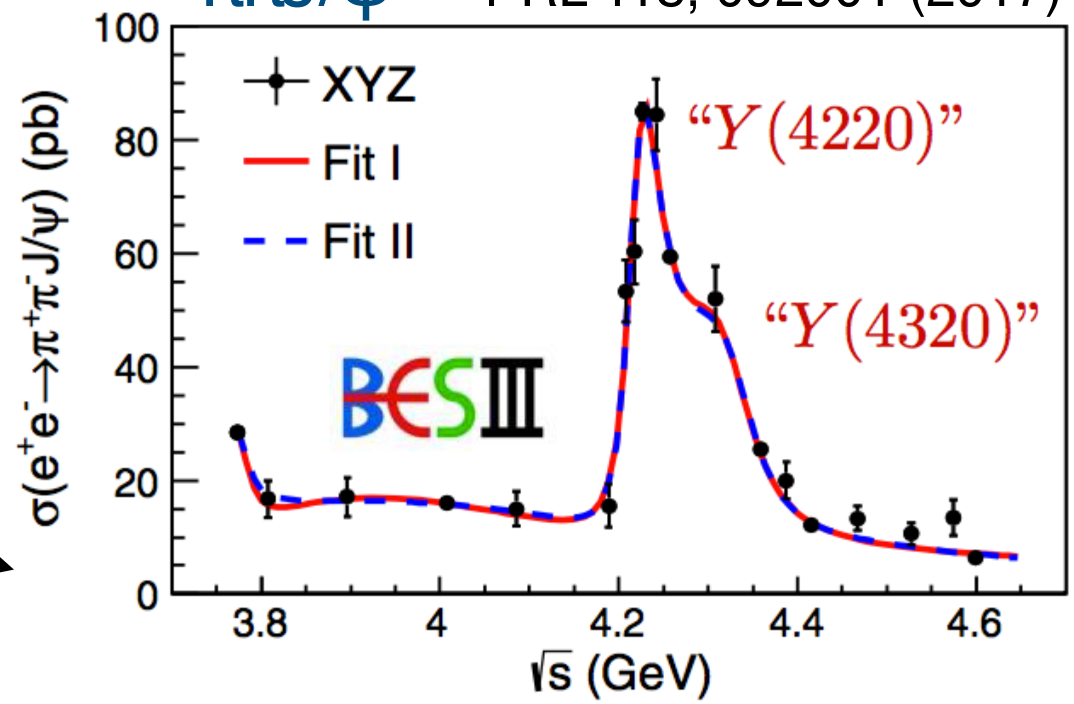


BESIII

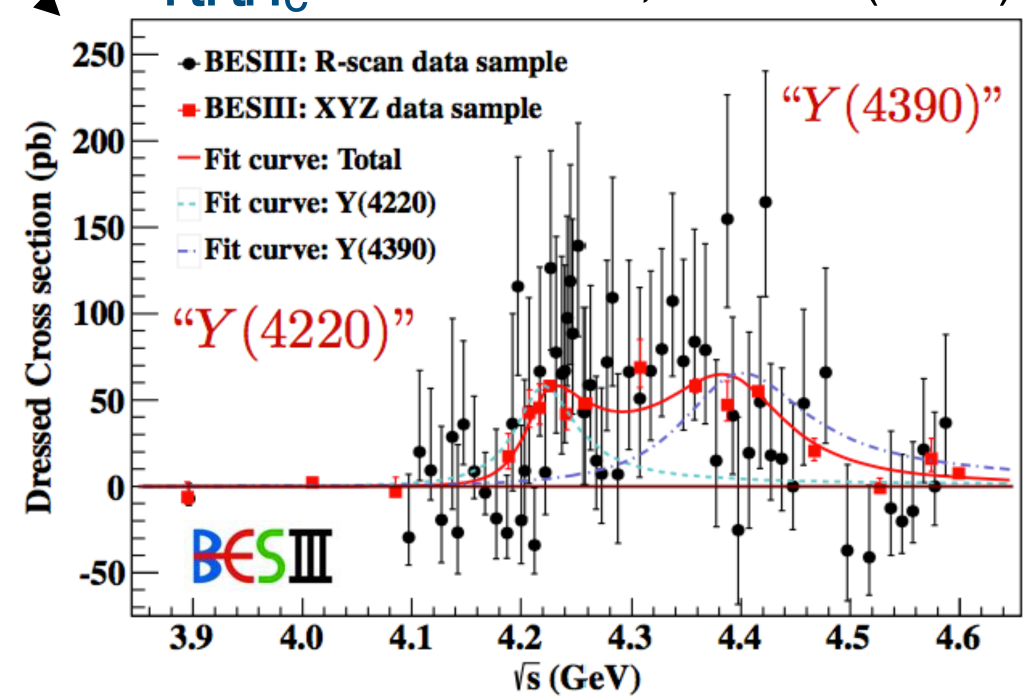
Charmonium-like states from ISR

- More and better data necessary for ISR studies
  - ISR illuminates whole hadron spectrum (line shape, fine structures)
  - Different energies accumulated at once (easier than at 60 points)
  - Energy points > 4.6 GeV (BESIII maximum)
    - Search for pseudoscalar partner of the Y(4660)

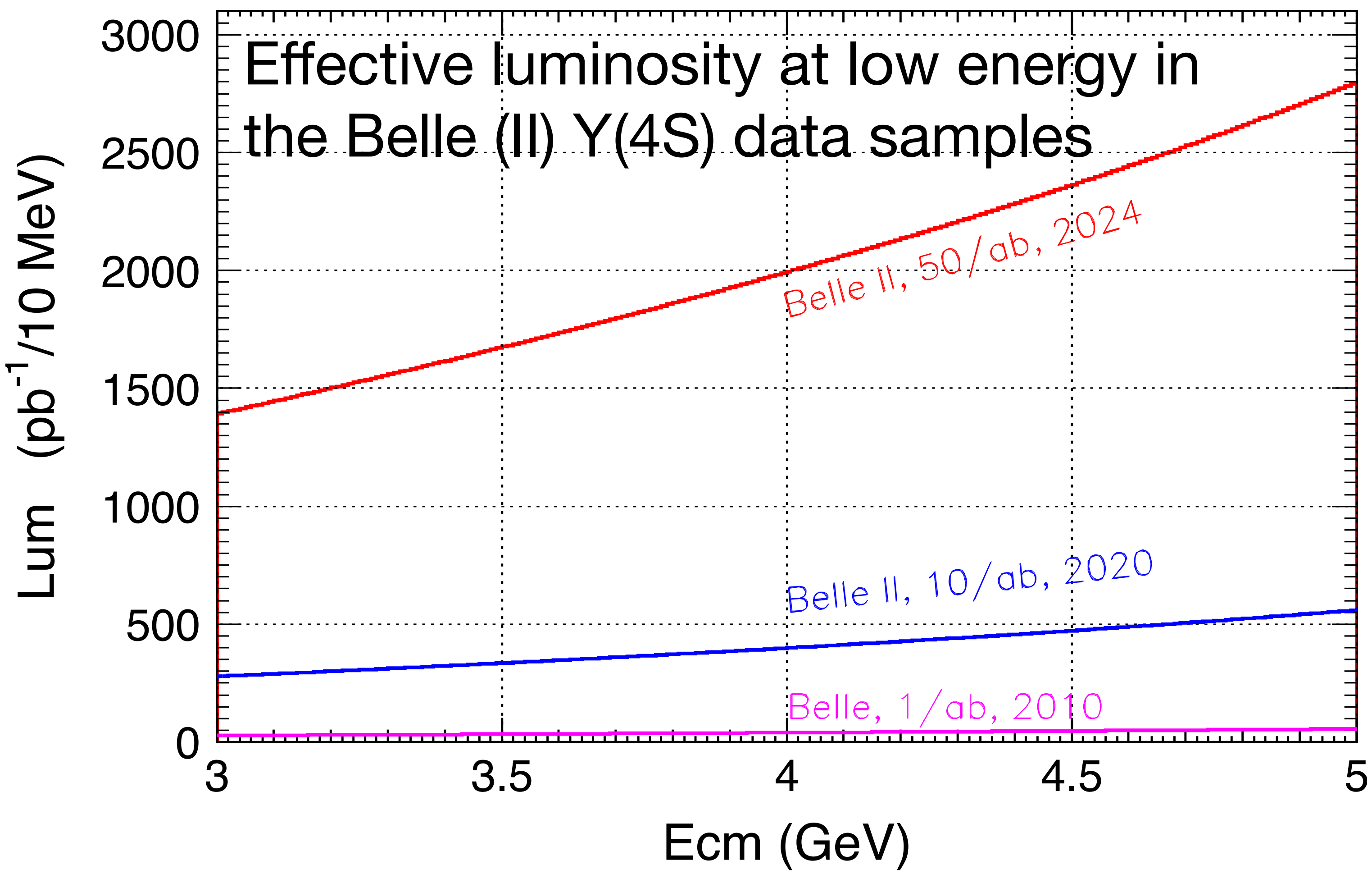
ππJ/ψ PRL 118, 092001 (2017)

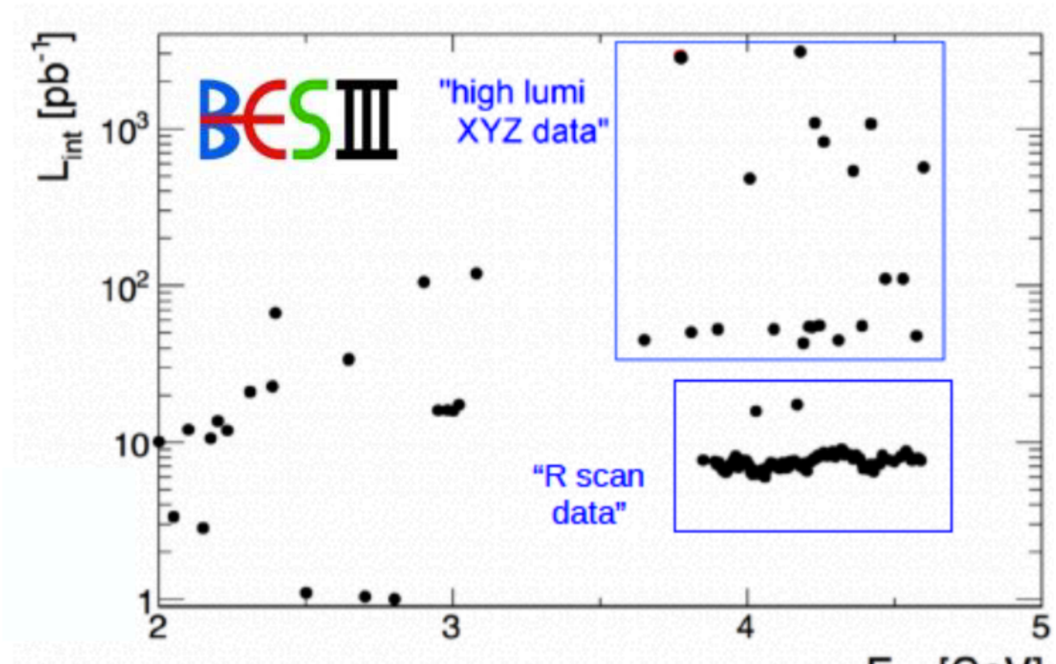


ππh$_c$ PRL 118, 092002 (2017)



Charmonium-like states from ISR



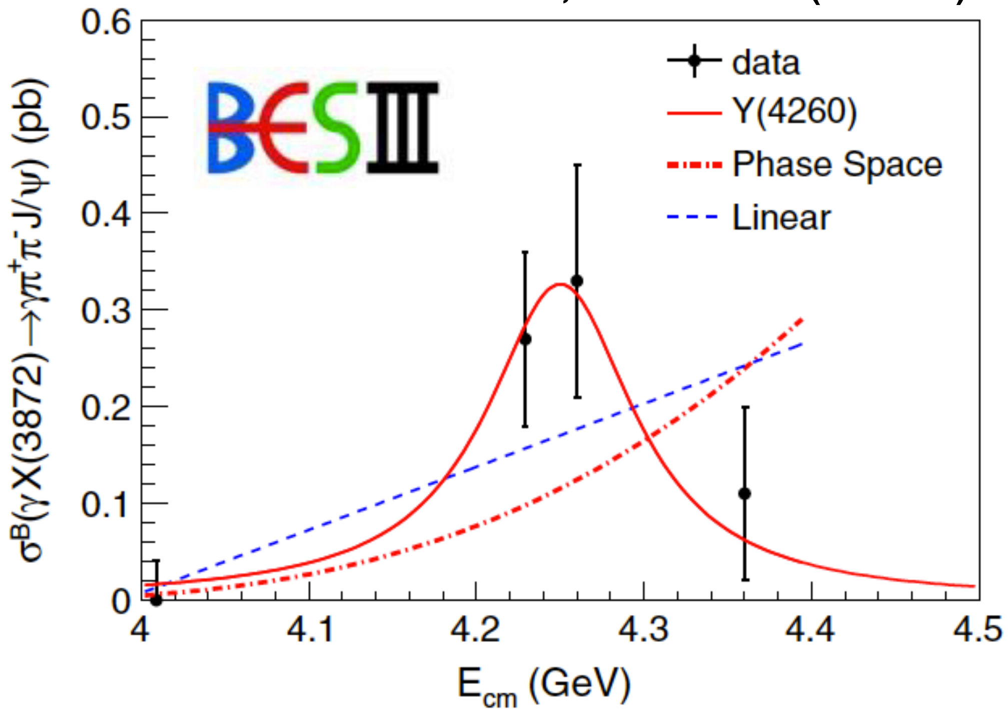


*May be a little stale - data taking ongoing

- Full Belle II data comparable statistics as BESIII for modes like $e^+e^- \to \pi\pi J/\psi$

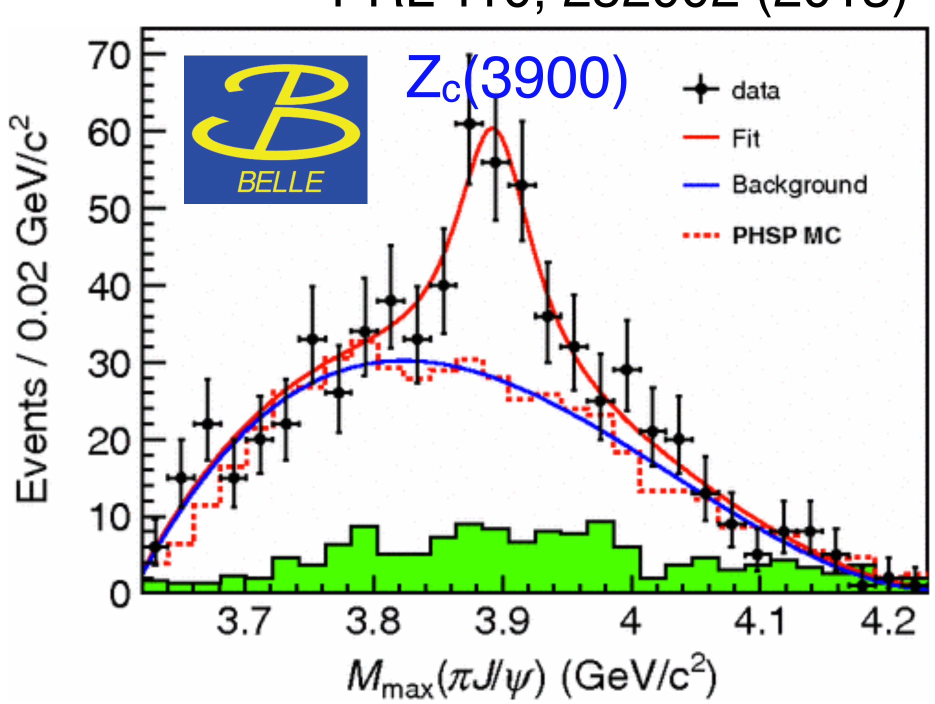
Charmonium-like states from ISR

PRL 112, 092001 (2014)



Y(4260)→γX(3872)?

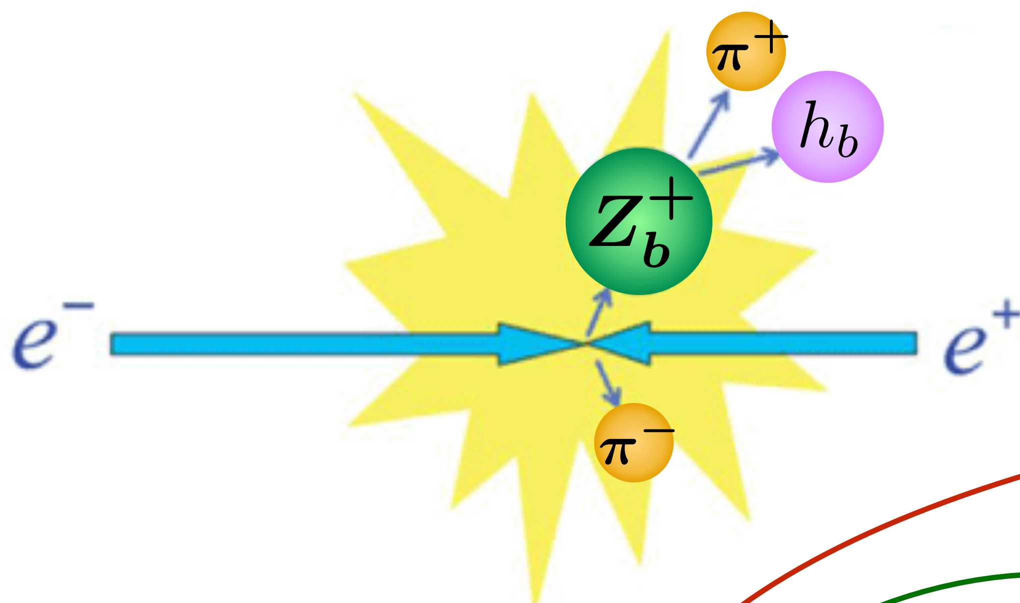
PRL 110, 252002 (2013)



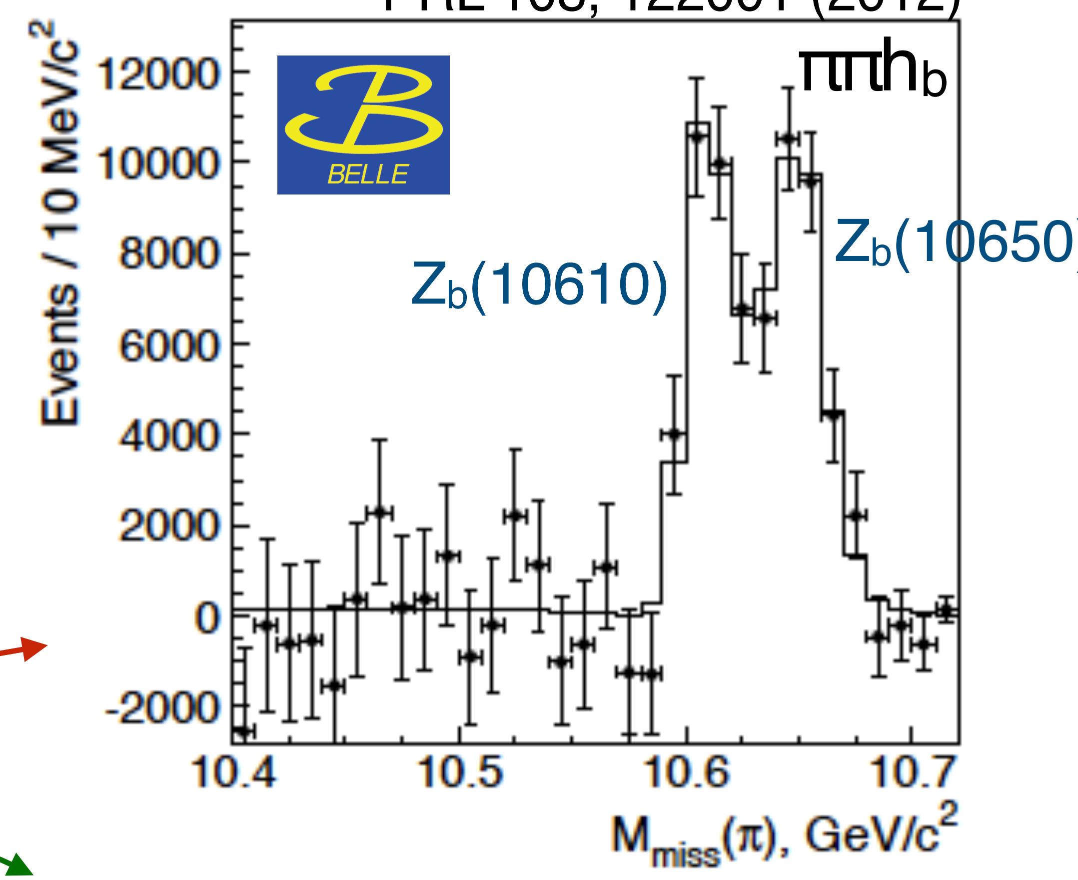
- Questions for Belle II to answer:
  - Are X(3872) and $\psi_2(1D)$ in $e^+e^-\to\gamma\pi\pi J/\psi$ coming from resonance decays or continuum production?
  - Are there other similar X states in similar processes such as $\chi_{c2}(2P)$, X(3915), X(4140), and X(4350)?
  - Can the Z_c states decay into light hadrons?

Charged and neutral $Z_b(10610)$ and $Z_b(10650)$ states

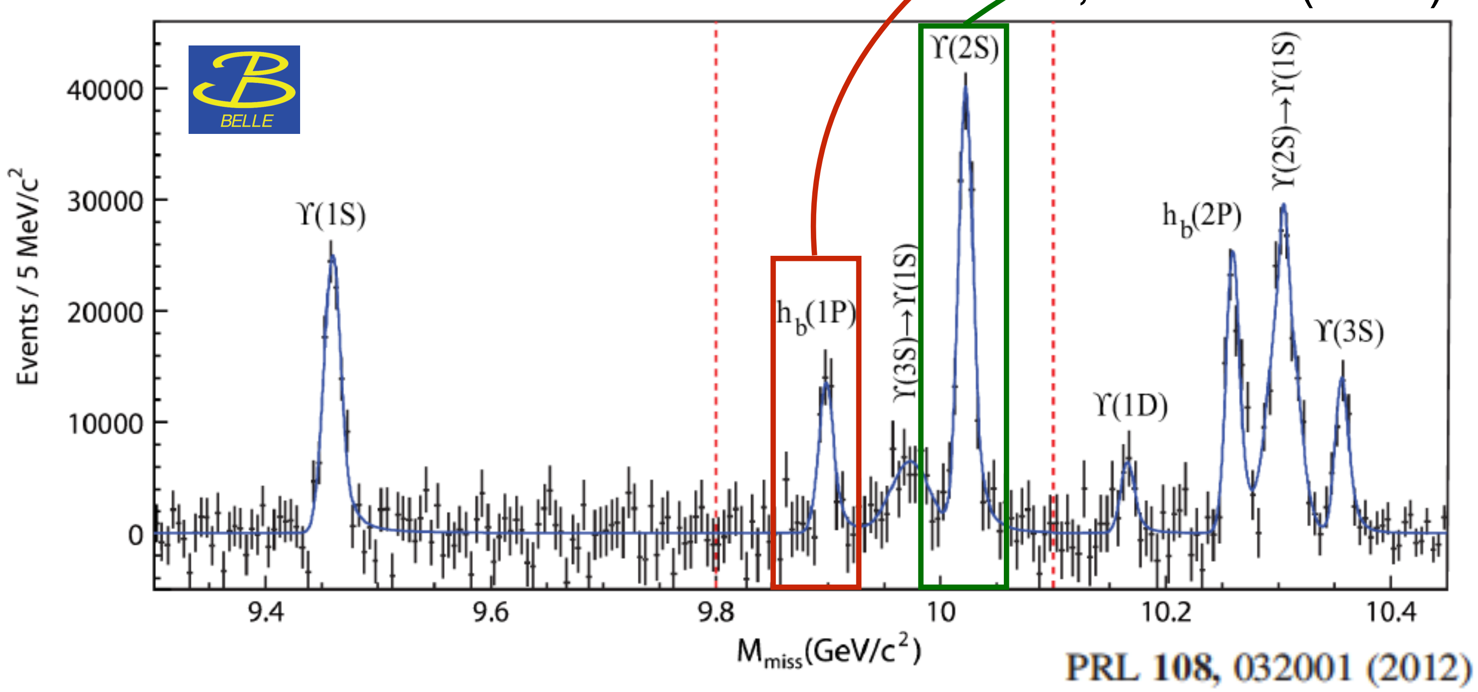
- Z_b^+ in $\Upsilon(nS)\pi^+$ and $h_b(mP)\pi^+$ at $\Upsilon(5S)$

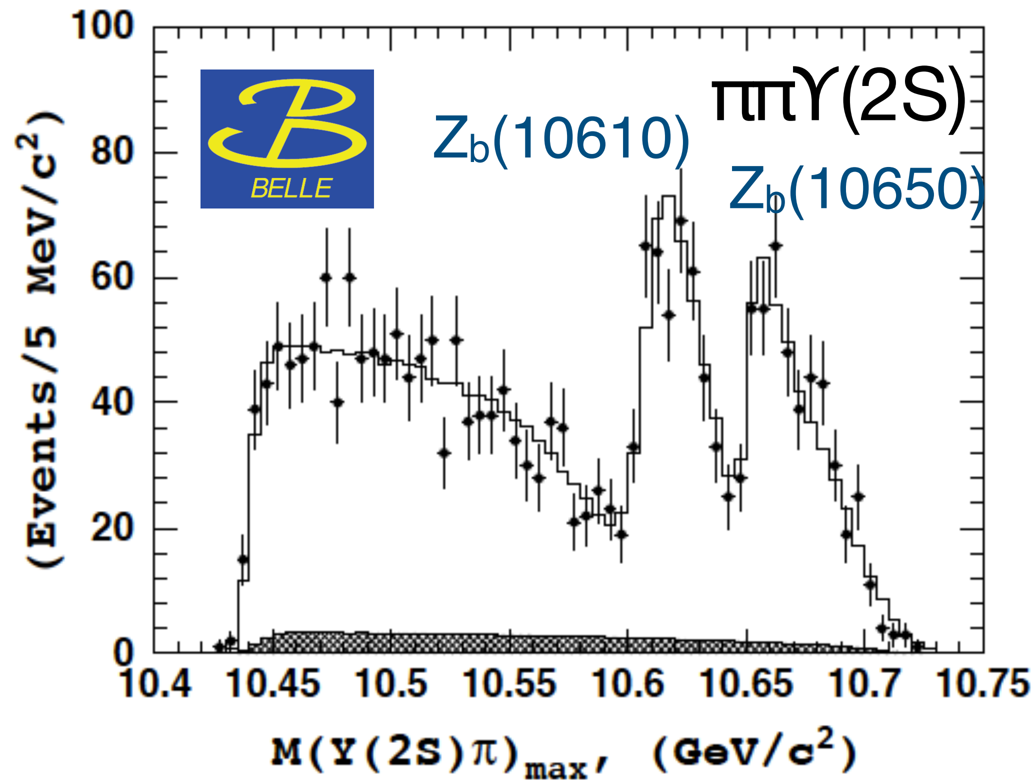


PRL 108, 122001 (2012)



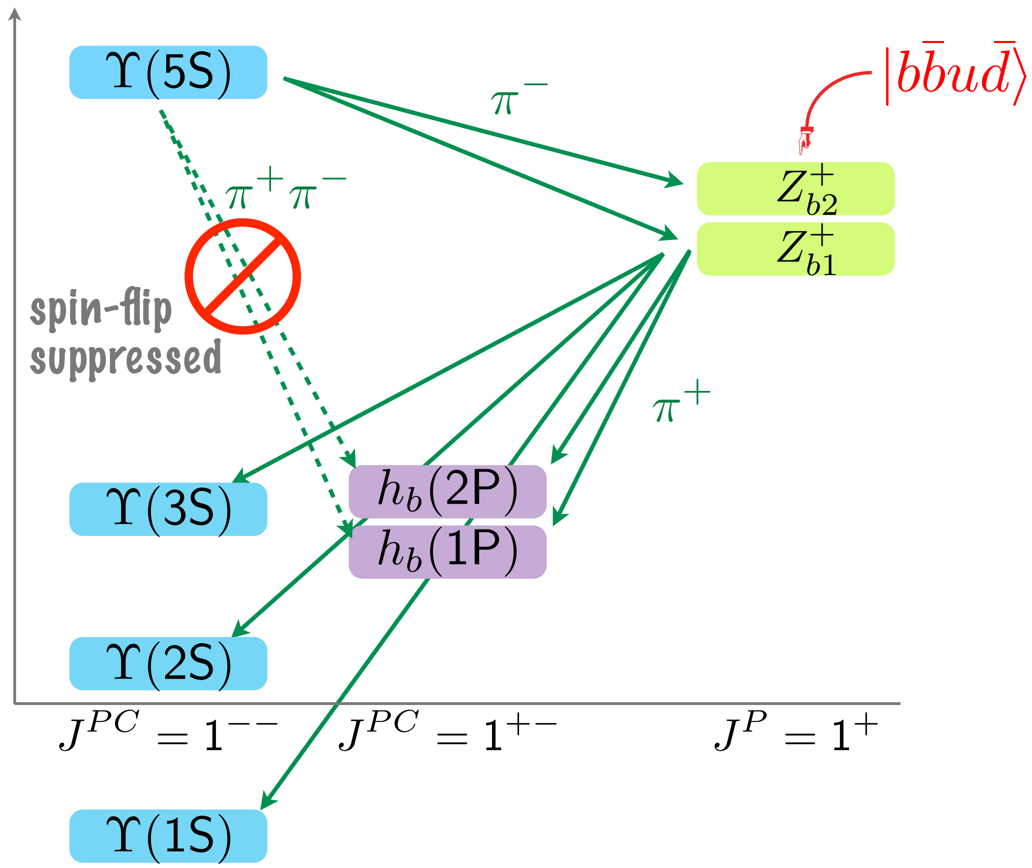
PRL 108, 032001 (2012)



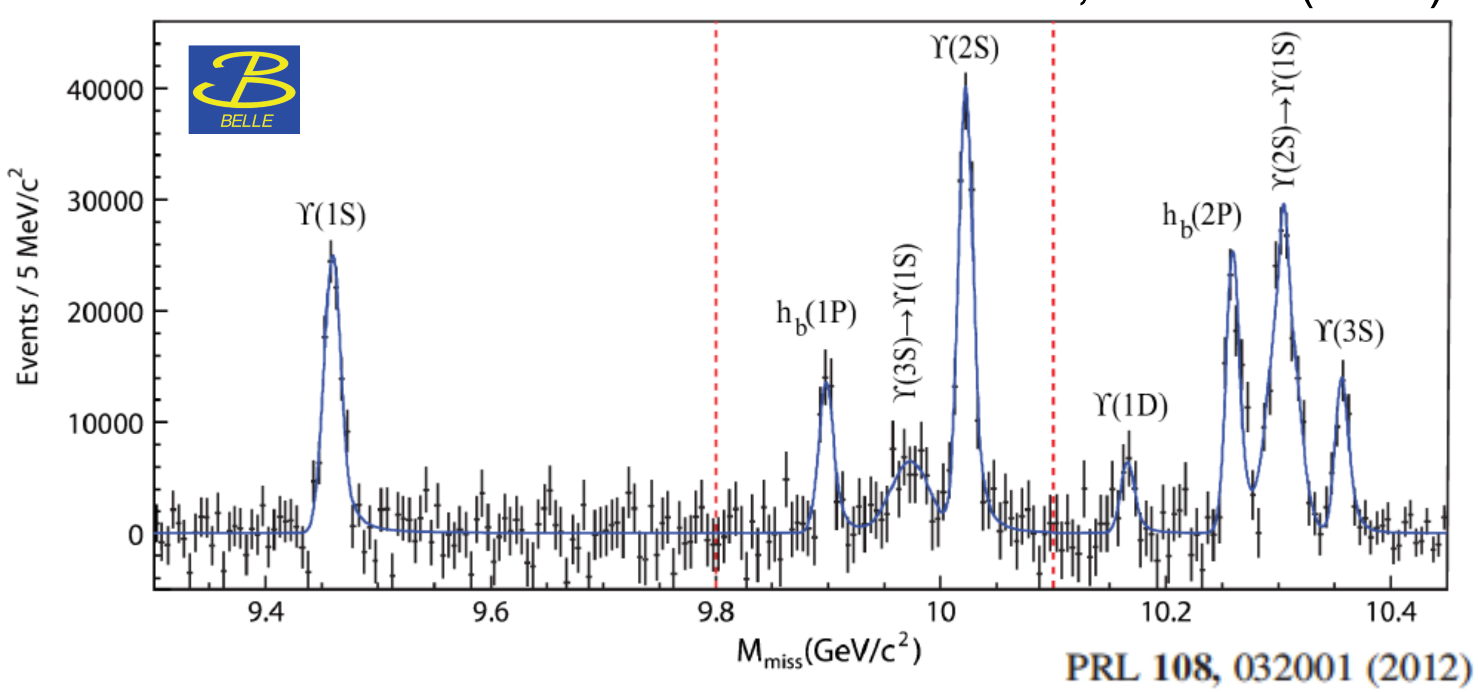


Charged and neutral $Z_b(10610)$ and $Z_b(10650)$ states

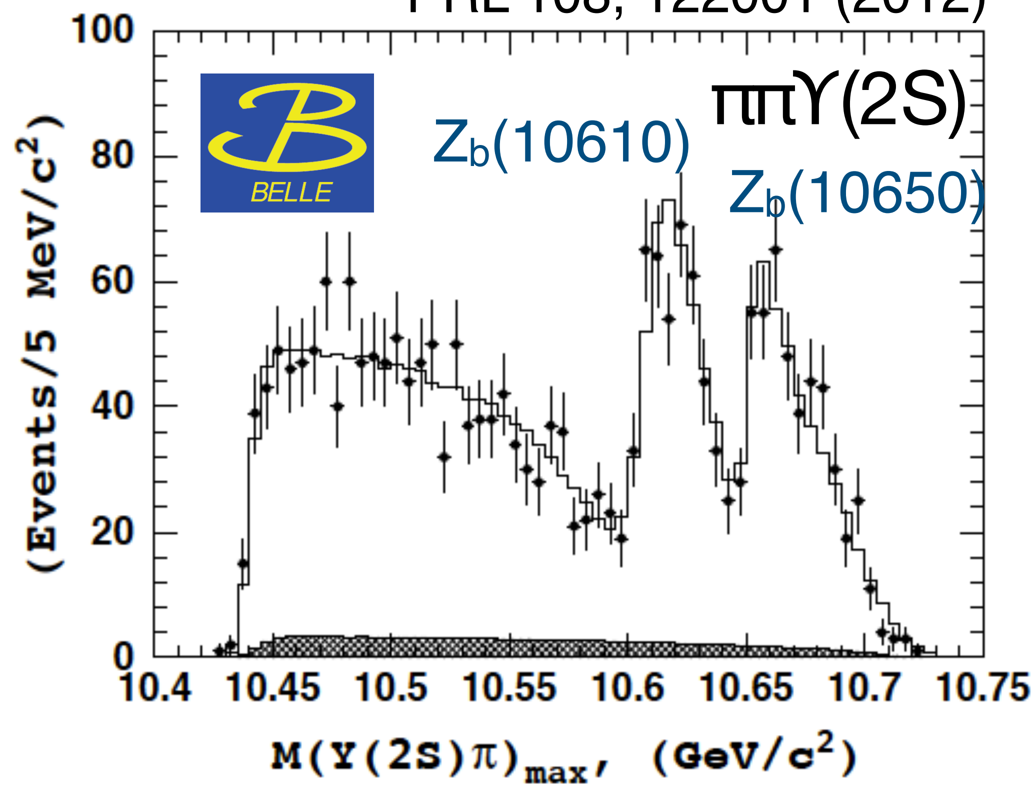
- Z_b^+ in $\Upsilon(nS)\pi^+$ and $h_b(mP)\pi^+$ at $\Upsilon(5S)$
- Responsible for the large rates of production of $h_b(1P, 2P)$ states in $\Upsilon(5S)$ decays
- Proximity to $B\bar{B}^*$ and $B^*\bar{B}^*$ thresholds suggests molecular nature



PRL 108, 032001 (2012)



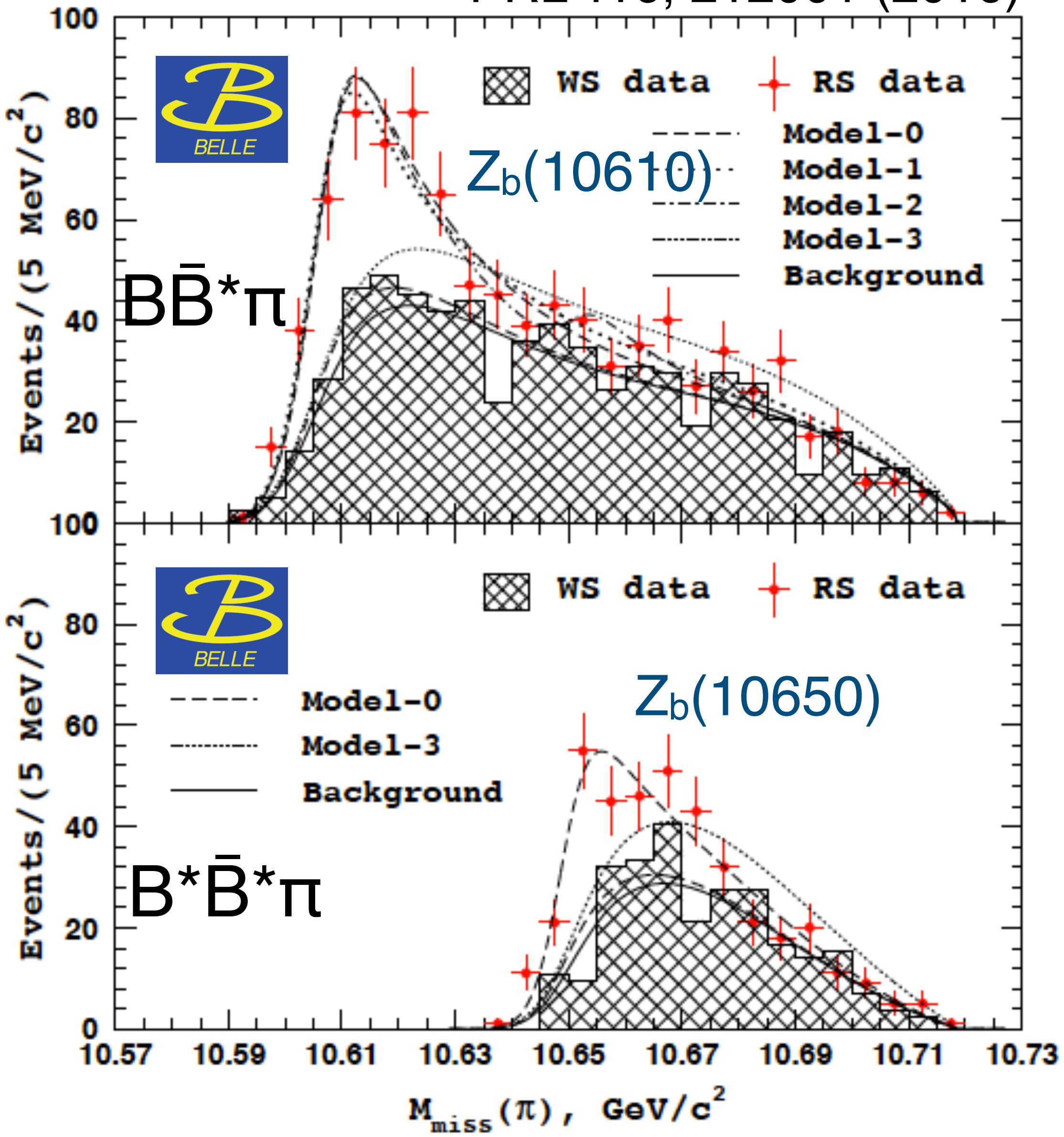
PRL 108, 122001 (2012)



Charged and neutral $Z_b(10610)$ and $Z_b(10650)$ states

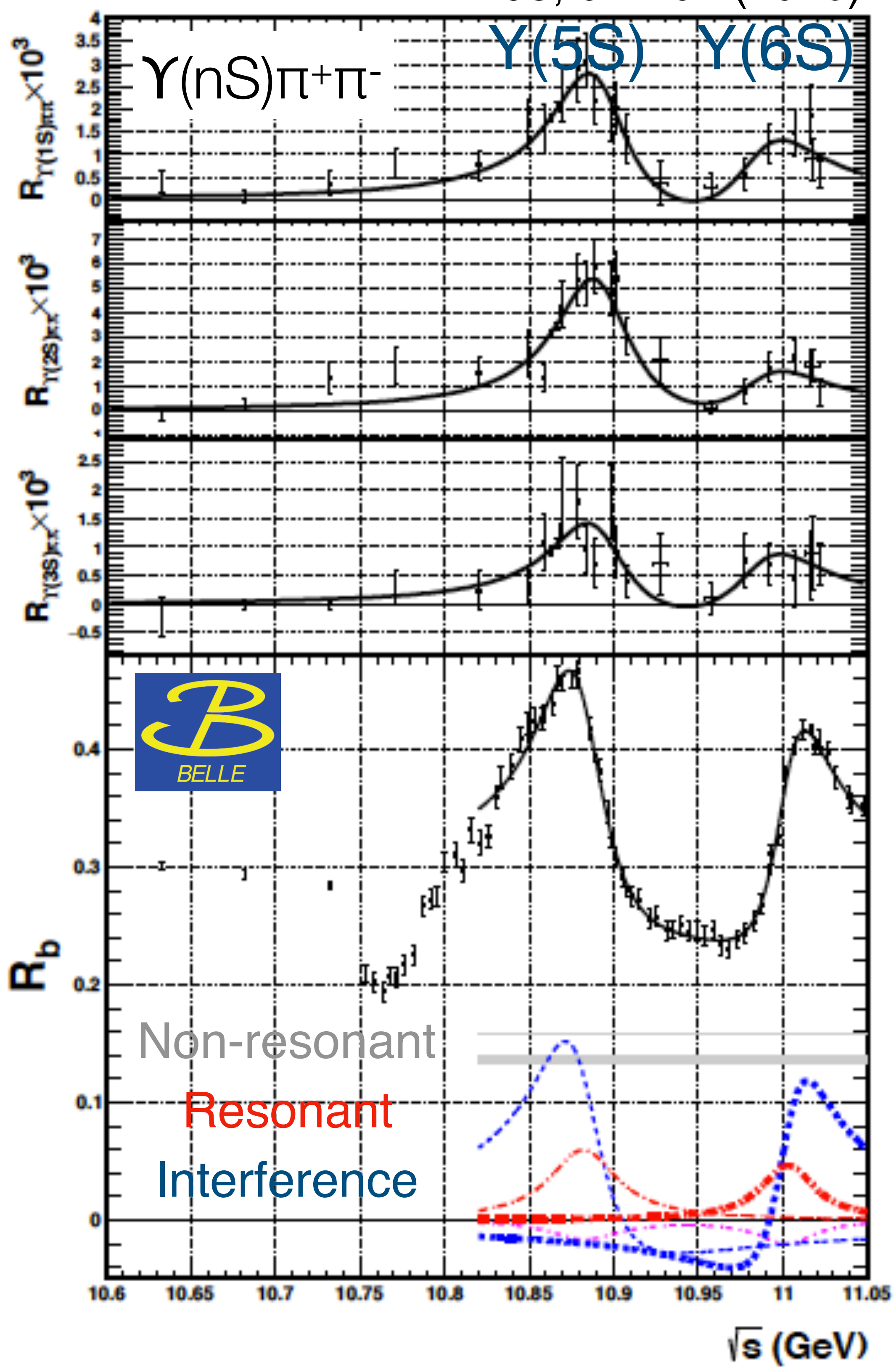
- Z_b^+ in $\Upsilon(nS)\pi^+$ and $h_b(mP)\pi^+$ at $\Upsilon(5S)$
- Responsible for the large rates of production of $h_b(1P, 2P)$ states in $\Upsilon(5S)$ decays
- Proximity to $B\bar{B}^*$ and $B^*\bar{B}^*$ thresholds suggests molecular nature
- $Z_b(10650)$ does not decay to $B\bar{B}^*$
  - Stronger evidence of molecular nature
  - Spin-parity measurements, total widths, production rates also consistent with expectations for molecular states

PRL 116, 212001 (2016)



Charged and neutral $Z_b(10610)$ and $Z_b(10650)$ states

PRD 93, 011101 (2016)

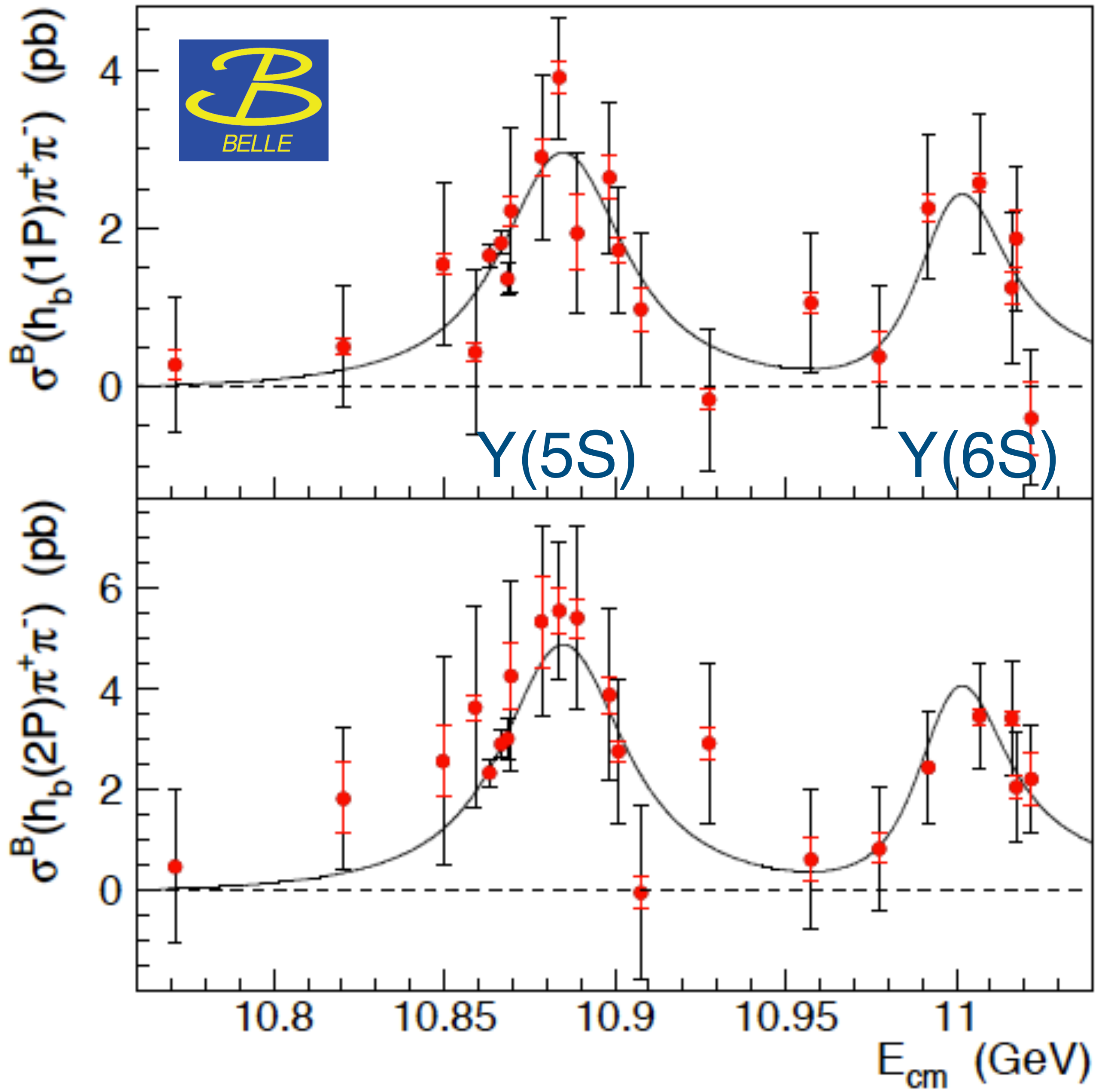


- Υ(5S) transitions to bottomonium(-like) states saturates cross section
- Copious B_s production at Υ(5S) energy
  - If not due to Υ(5S) decays, must come directly from continuum
- But there is sizable interference between continuum and Υ(5S, 6S)
  - Complex threshold structure!

First evidence of $\Upsilon(6S) \to h_b(1P, 2P)\pi^+\pi^-$

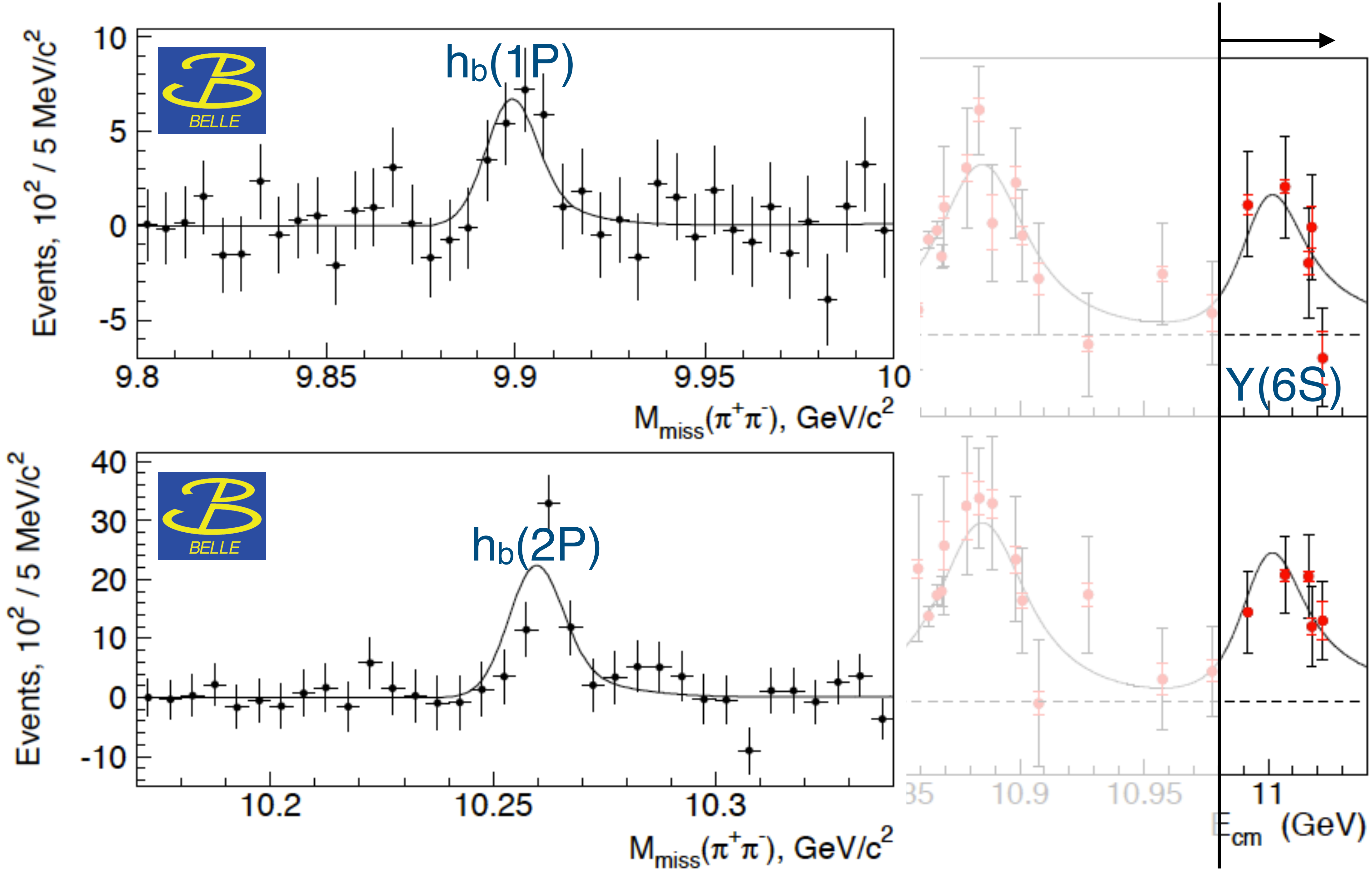
- Measure cross section for $e^+e^- \to h_b(1P, 2P)\pi^+\pi^-$
- In region of $\Upsilon(6S)$, check $M_{miss}(\pi^+\pi^-)$

PRL 117, 142001 (2016)



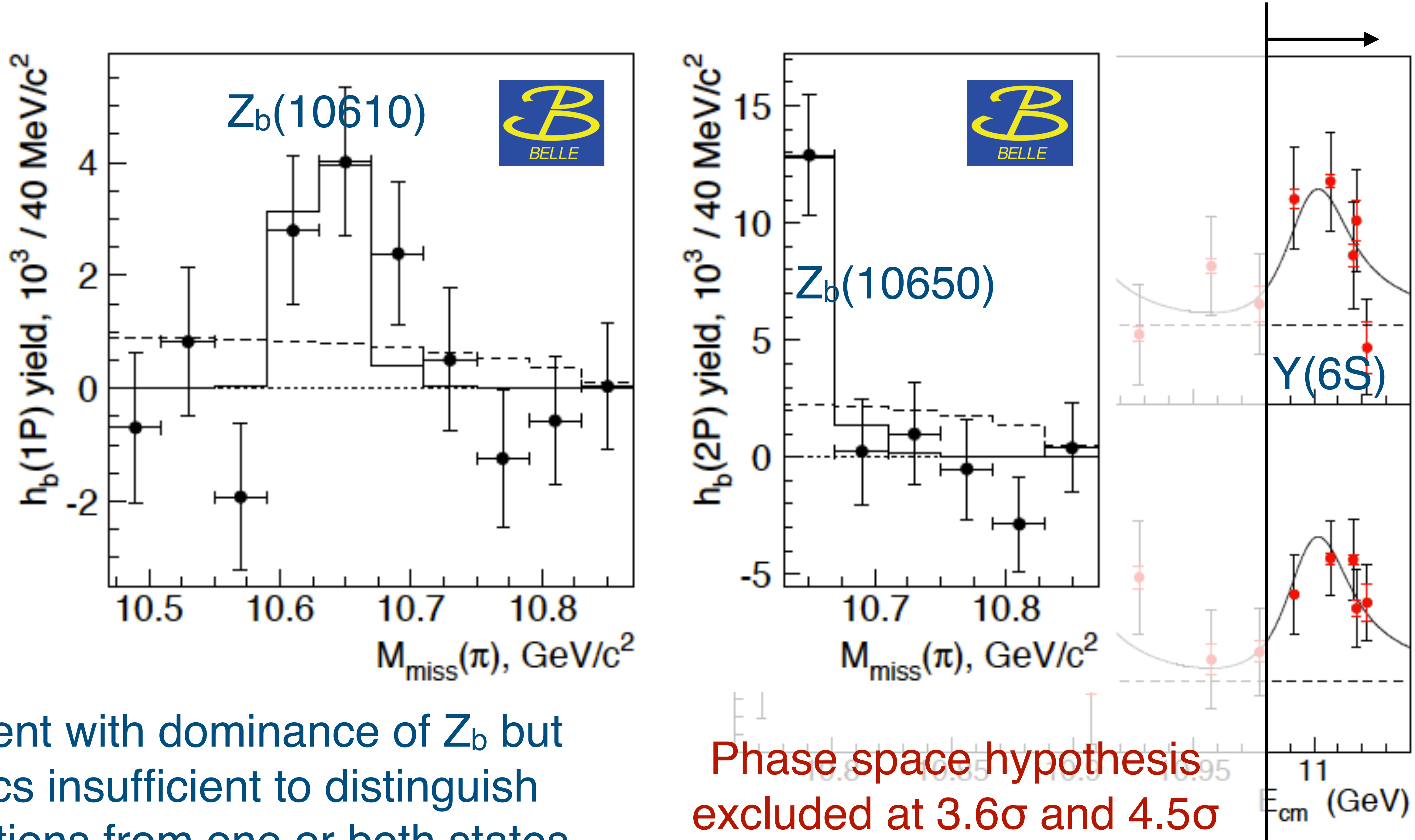
First evidence of $\Upsilon(6S) \to h_b(1P, 2P)\pi^+\pi^-$

- Measure cross section for $e^+e^- \to h_b(1P, 2P)\pi^+\pi^-$
- In region of $\Upsilon(6S)$, check $M_{miss}(\pi^+\pi^-)$



First evidence of $\Upsilon(6S) \to Z_b\pi? \to h_b(1P, 2P)\pi^+\pi^-$

- Measure cross section for $e^+e^- \to h_b(1P, 2P)\pi^+\pi^-$
- In region of $\Upsilon(6S)$, check $M_{miss}(\pi^+\pi^-)$ and $M_{miss}(\pi)$



Consistent with dominance of Z_b but statistics insufficient to distinguish contributions from one or both states

Phase space hypothesis excluded at 3.6σ and 4.5σ

Potential studies of quarkonium-like states at Belle II

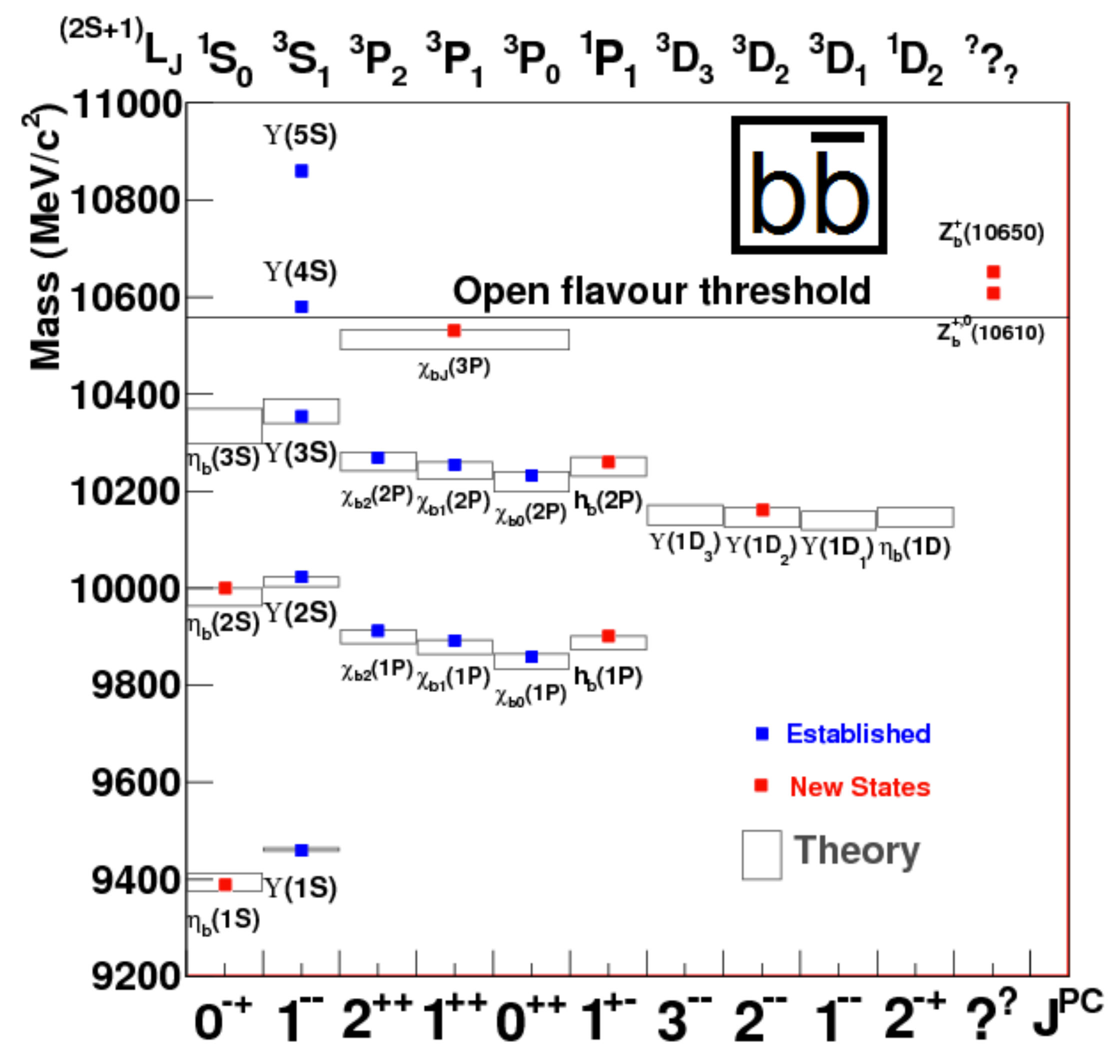
- Existence of Y(4008) and improved precision on $Z_c(3900)$ properties in $\pi\pi J/\psi$, more structures around 4.26 GeV/c^2?
- Presence of the Y(4260) and existence of $Z_c(4050)$ in $\pi\pi\psi(2S)$
- Possible resonance structures, Z_{cs} in KKJ/ψ
- Confirmation of Y(4220), Y(4390), $Z_c(4020)/Z_c(4025)$ in $\pi\pi h_c$
- Existence of Y(4220) in $\omega\chi_{c0}$
- Striking similarities between the isovector Z_c and Z_b states
- Significantly improve the understanding of $Z_b(10610)$ and $Z_b(10650)$ masses and branching fractions

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

- Belle II can provide decisive information!

Missing states below $B\bar{B}$ threshold

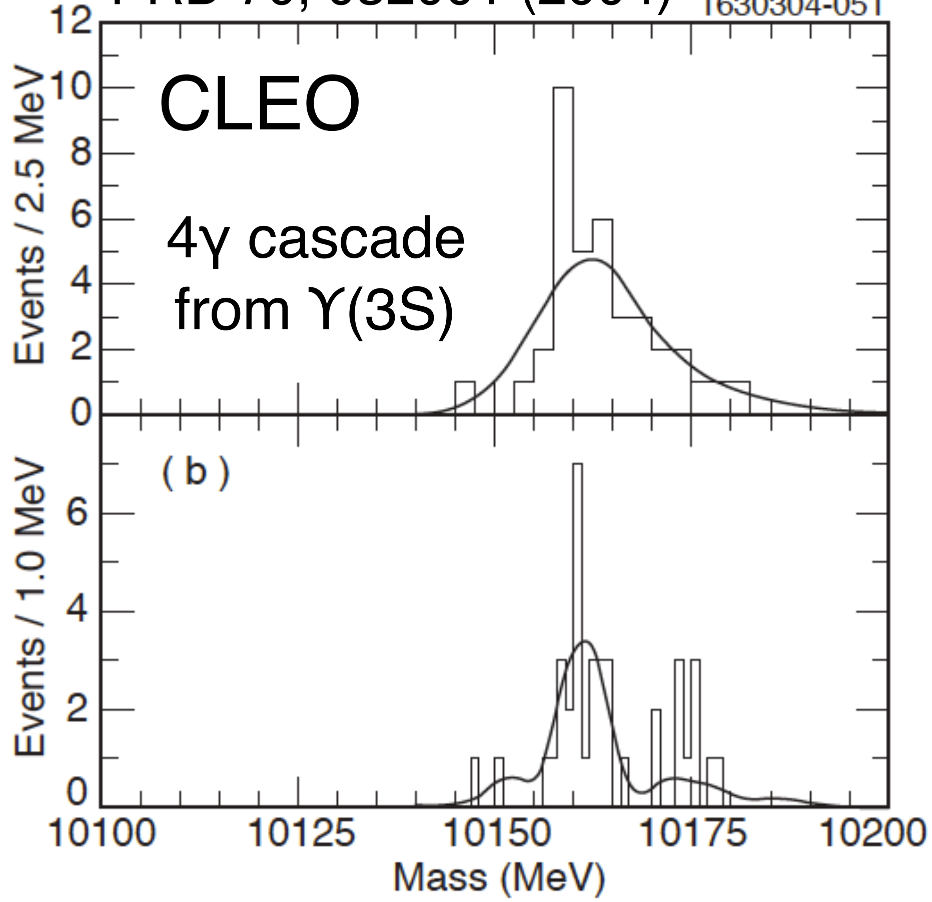
- Below ϒ(4S) threshold, several predicted bottomonium states have yet to be positively identified
    - Separation of $\chi_b(3P)$ triplet $\Upsilon(2D_3)$ triplet, $\eta_b(3S)$, $\Upsilon(^1D_{1,3})$, $\eta_b(1D)$ and F-wave states
    - Evidence for $\eta_b(2S)$ below 5σ
- Of known states, several important parameters need to be measured or have conflicting experimental results
    - Masses and widths of the η_b states
    - χ_{b0} widths
    - Mass splitting of the ϒ(1D) states



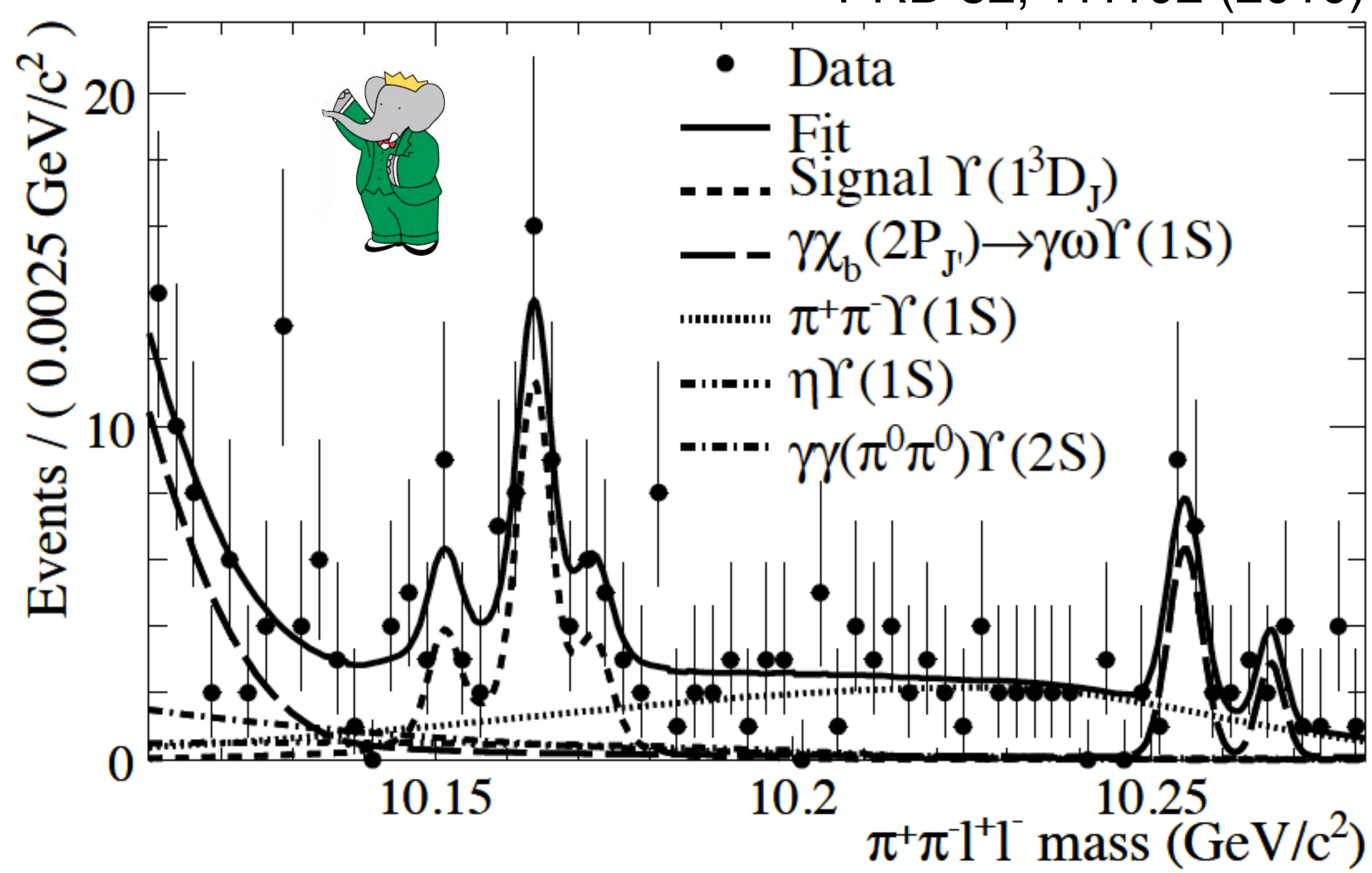
Belle II prospects for Υ(1D) and Υ(2D)

- Υ(1D) was originally observed by CLEO in Υ(3S) decays
- Confirmed in a somewhat different cascade by BaBar
- Neither experiment resolved the 1D triplet into its three states

PRD 70, 032001 (2004)



PRD 82, 111102 (2010)

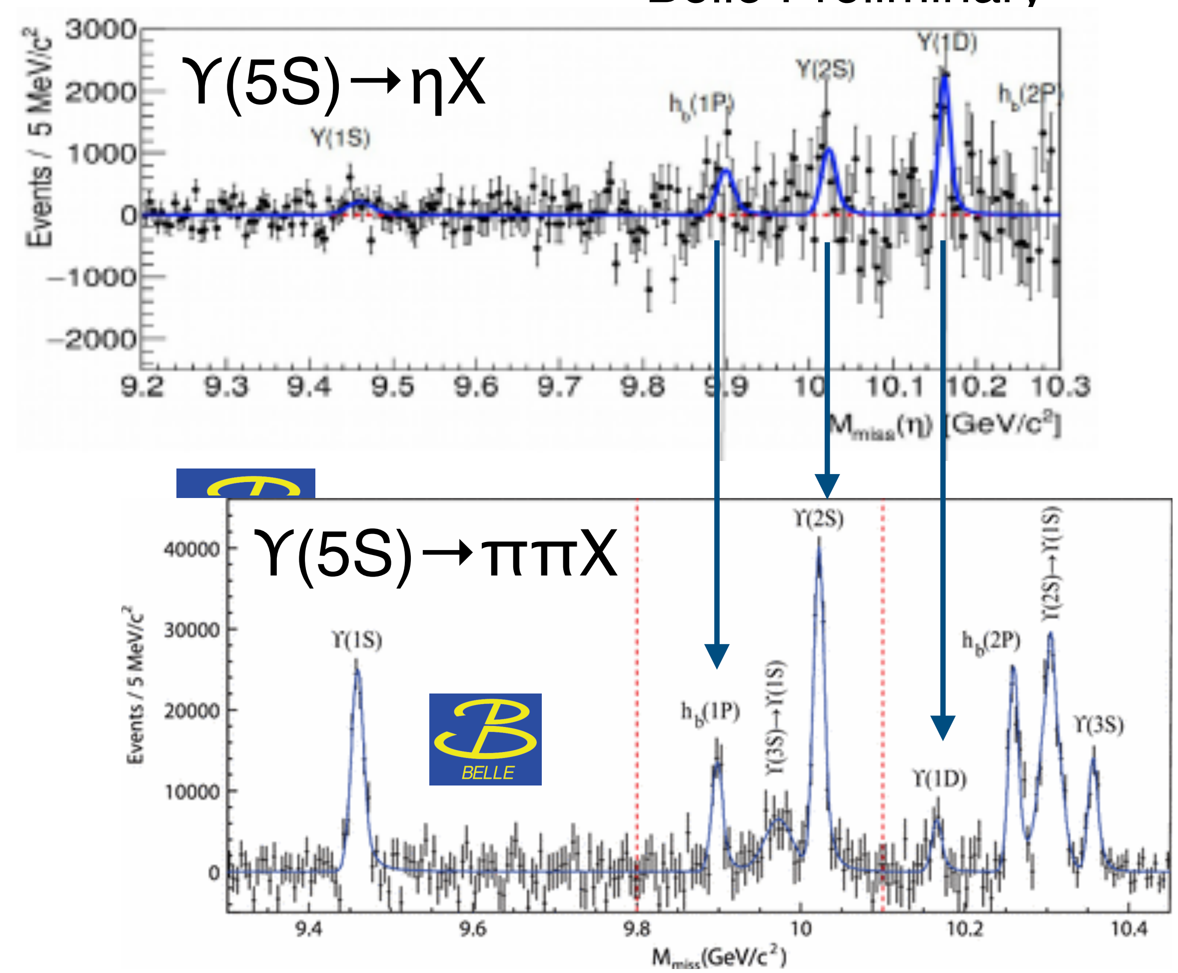


Belle II prospects for Υ(1D) and Υ(2D)

- Belle has observed Υ(1D) in η and ππ transitions from Υ(5S), though no clear differentiation of the three peaks

- Belle II will study Υ(1D) with data taken at Υ(3S) and Υ(5S)
- Also seek Υ(2D) in η transitions from the Υ(6S)
- Scans of Υ(1D, 2D)
  - Study J=1 states in each triplet
  - Discovery of Υ(2D) could lead to a longer run later to search for ππ, η transitions to Υ(1S), or radiative transitions to Υ(1F)

Belle Preliminary



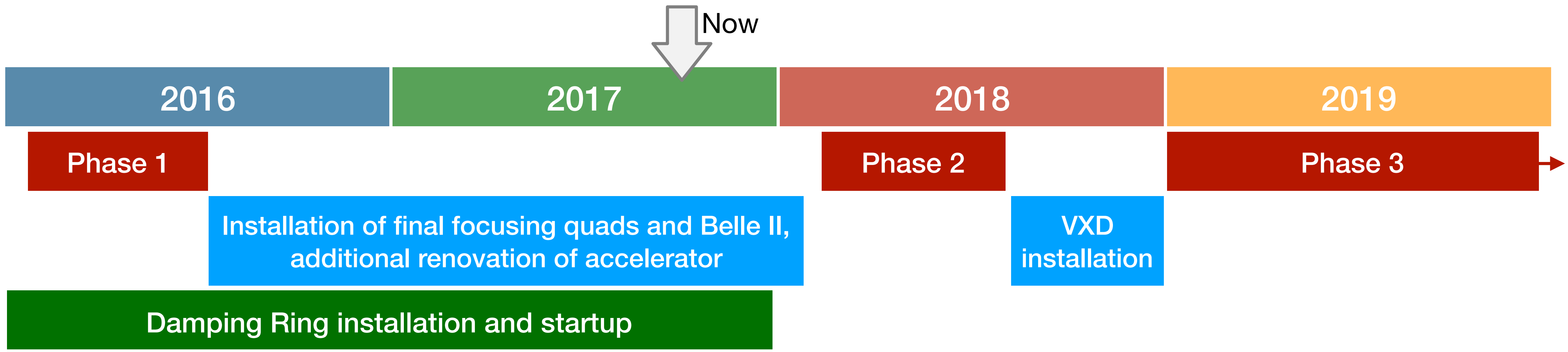
PRL 108, 122001 (2012)

Other potential Belle II spectroscopy studies

- High statistics $\gamma\gamma \to D\bar{D}$ at Belle II needed to more precisely measure $\chi_{c2}(2P)$ parameters, investigate possible $\chi_{c0}(2P)$ signal
- $\gamma\gamma \to \phi J/\psi$ to confirm or deny X(4350) and search for more exotic states
  - $\phi J/\psi$ spectrum rich source of states (see $B^+ \to K^+ \phi J/\psi$ amplitude analysis)
- High statistics at different energies from Υ(1S)-Υ(6S) to measure $\sqrt{s}$ dependence of double charmonium cross sections
- Studies of the known h_b(1P, 2P) and η_b(1S, 2S) states/transitions
- e^+e^- crucial to extract hadronization information
- B meson, D meson, and baryon spectroscopy

- Review of Belle II to be published in the B2TiP report later this year
  - Includes description of detector, software, analysis tools, etc.
  - https://confluence.desy.de/display/BI/B2TiP+ReportStatus

SuperKEKB/Belle II schedule



SuperKEKB/Belle II schedule

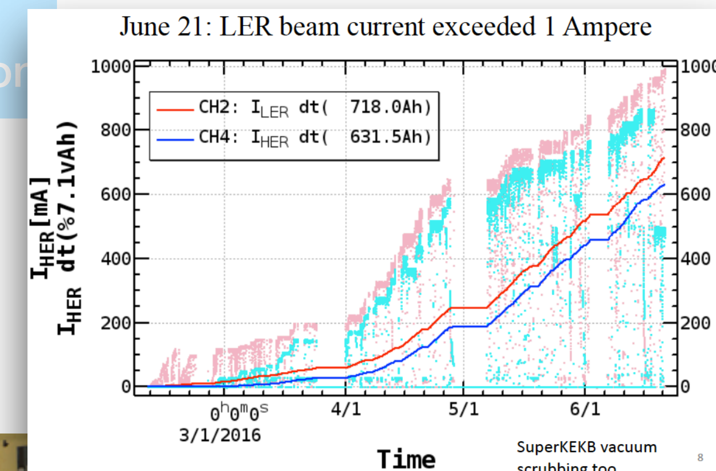
Now

2016	2017	2018	2019
Phase 1		Phase 2	Phase 3 →

Installation of final focusing quads and Belle II, additional renovation of accelerator

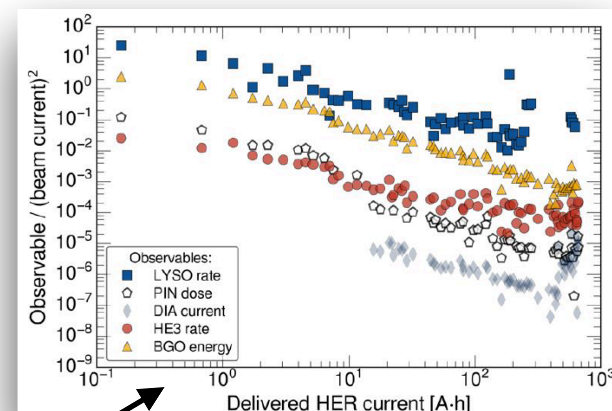
VXD installation

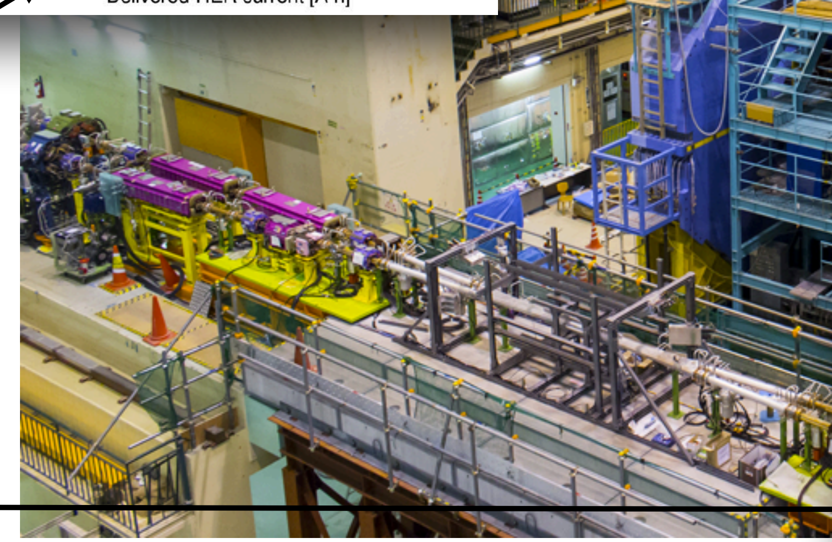
Damping Ring installation and startup

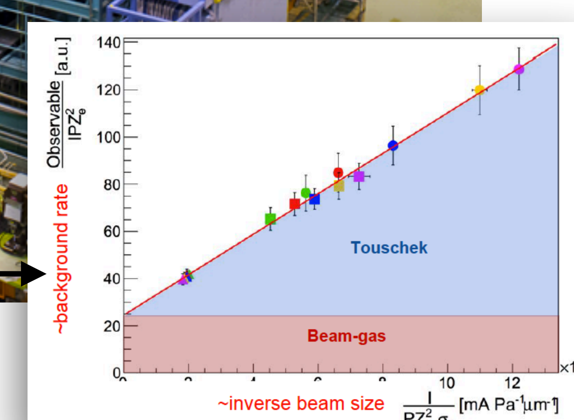


Beam **E**xorcism for **A** **St**able Experiment
Dedicated background monitors

- **"BEAST" Phase 1: Started in Feb 2016**
  - Simple background commissioning detector (diodes, TPCs, crystals). No final focus. Only single beam background studies possible
  - Tune accelerator optics, etc., vacuum scrubbing, beam studies, validation of Belle II beam background simulations







"First measurements of beam backgrounds at SuperKEKB", to be submitted to NIM-A in late 2017

SuperKEKB/Belle II schedule

Now

2016	2017	2018	2019

Phase 1

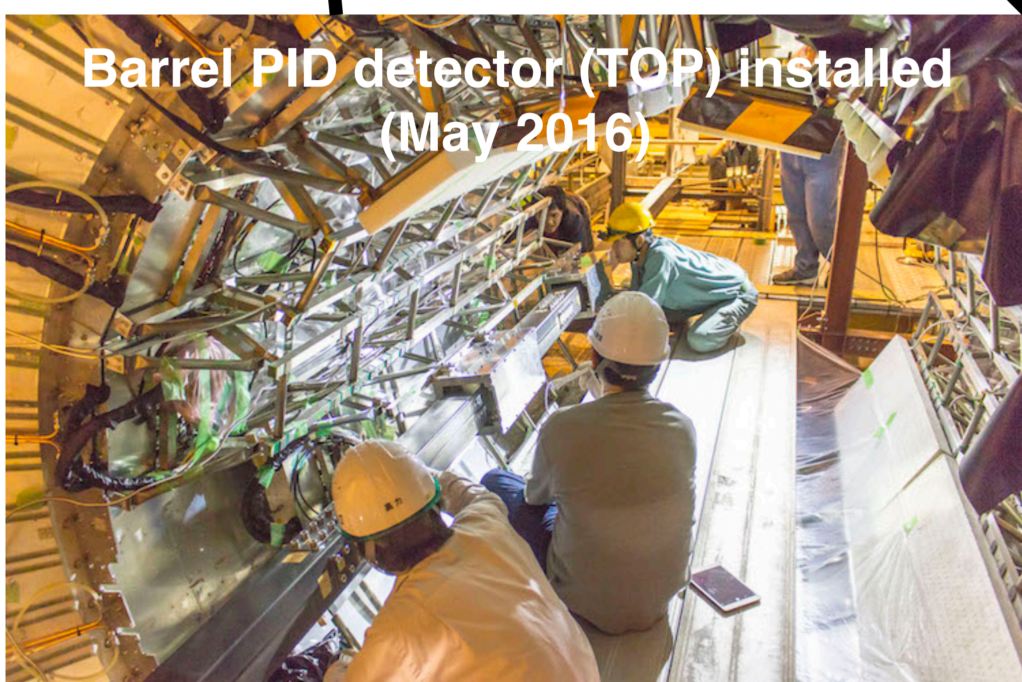
Installation of final focusing quads and Belle II, additional renovation of accelerator

Damping Ring installation and startup

Phase 2

VXD installation

Phase 3



SuperKEKB/Belle II schedule

Now

2016	2017	2018	2019

Phase 1

Phase 2

Phase 3

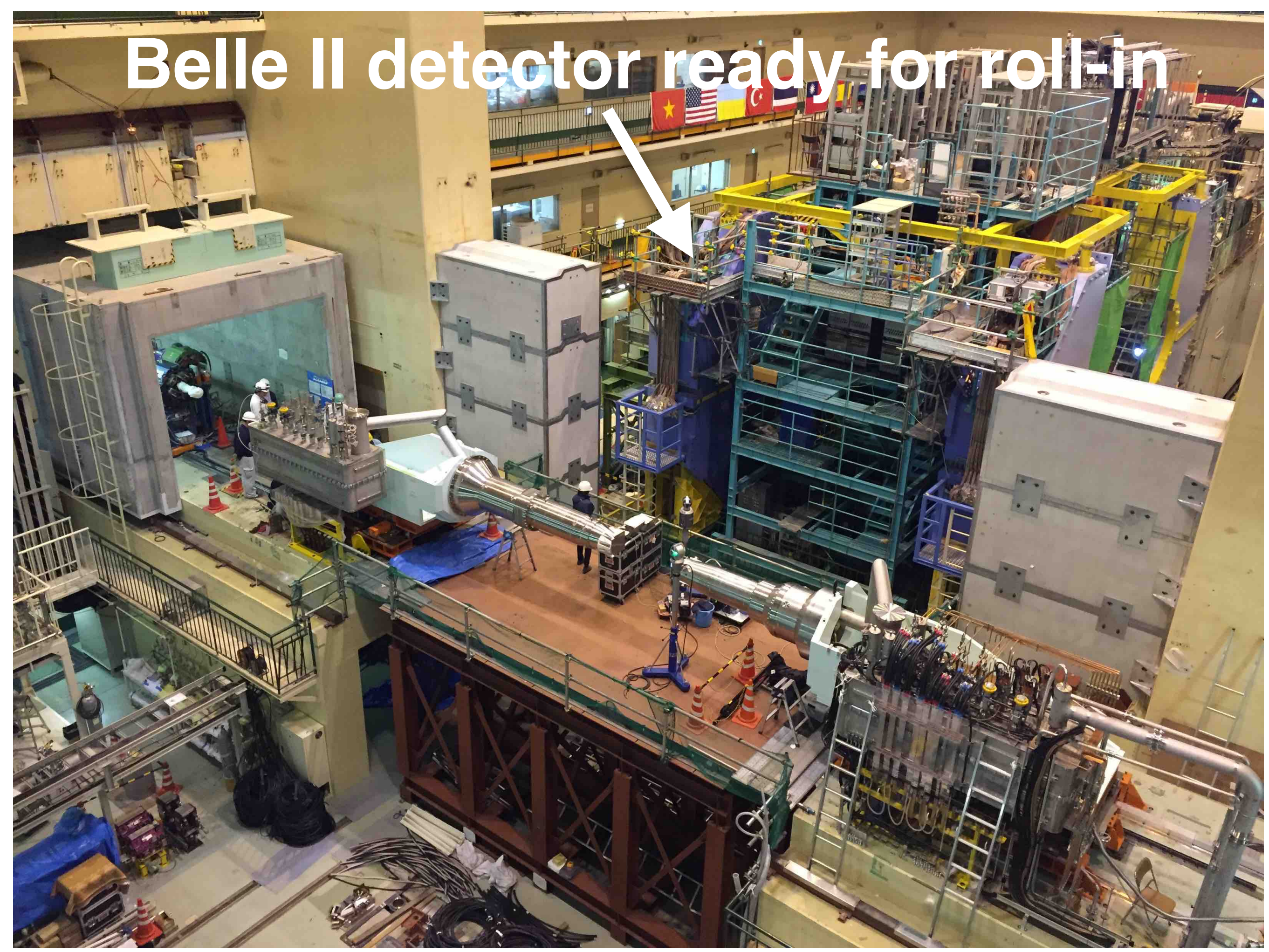
Installation of final focusing quads and Belle II, additional renovation of accelerator

VXD installation

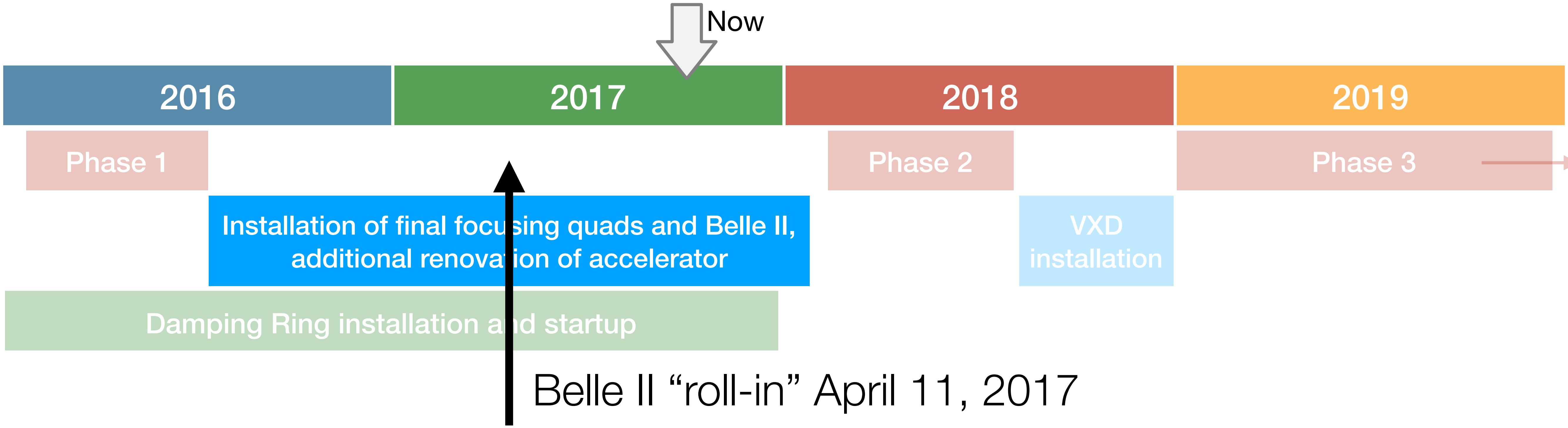
Damping Ring installation and startup

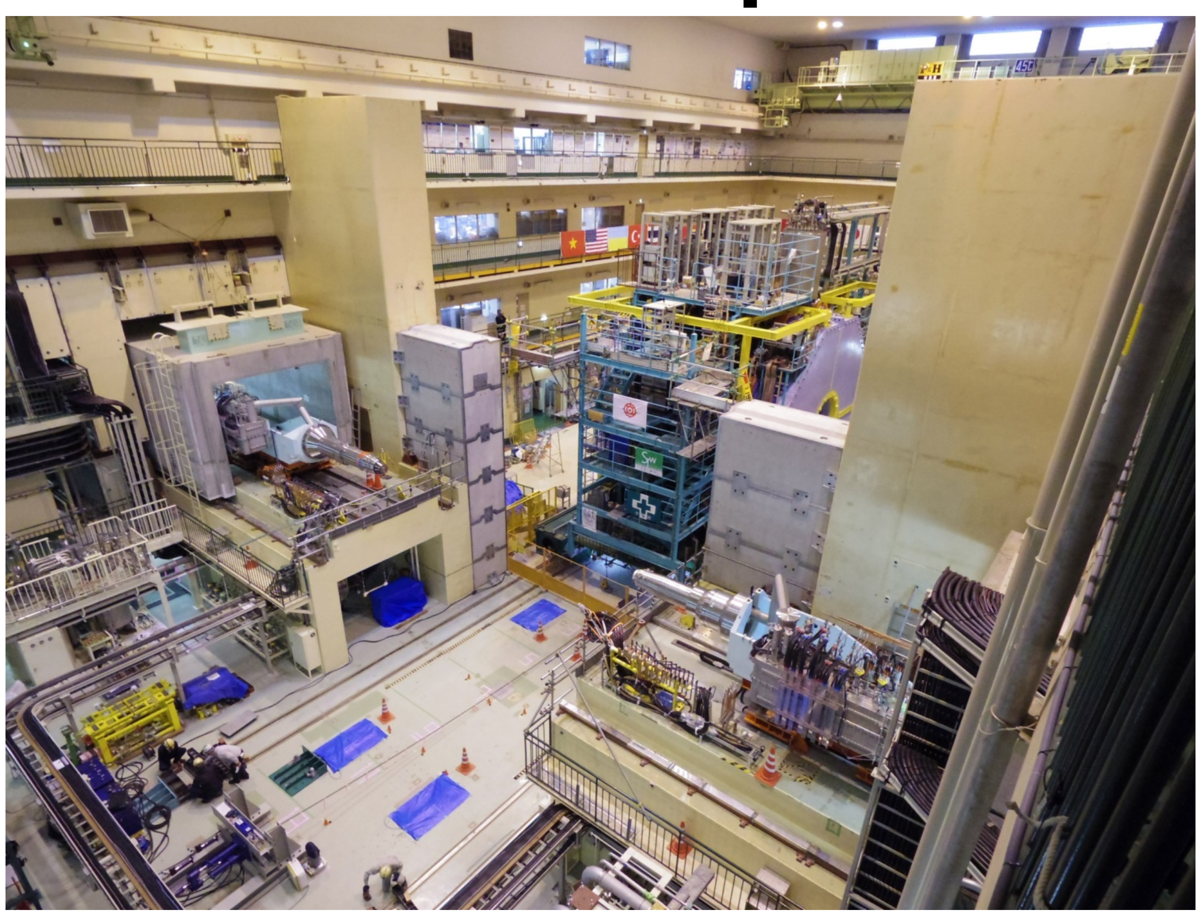
QCSL cooled and excited in Dec. 2016 for the first time

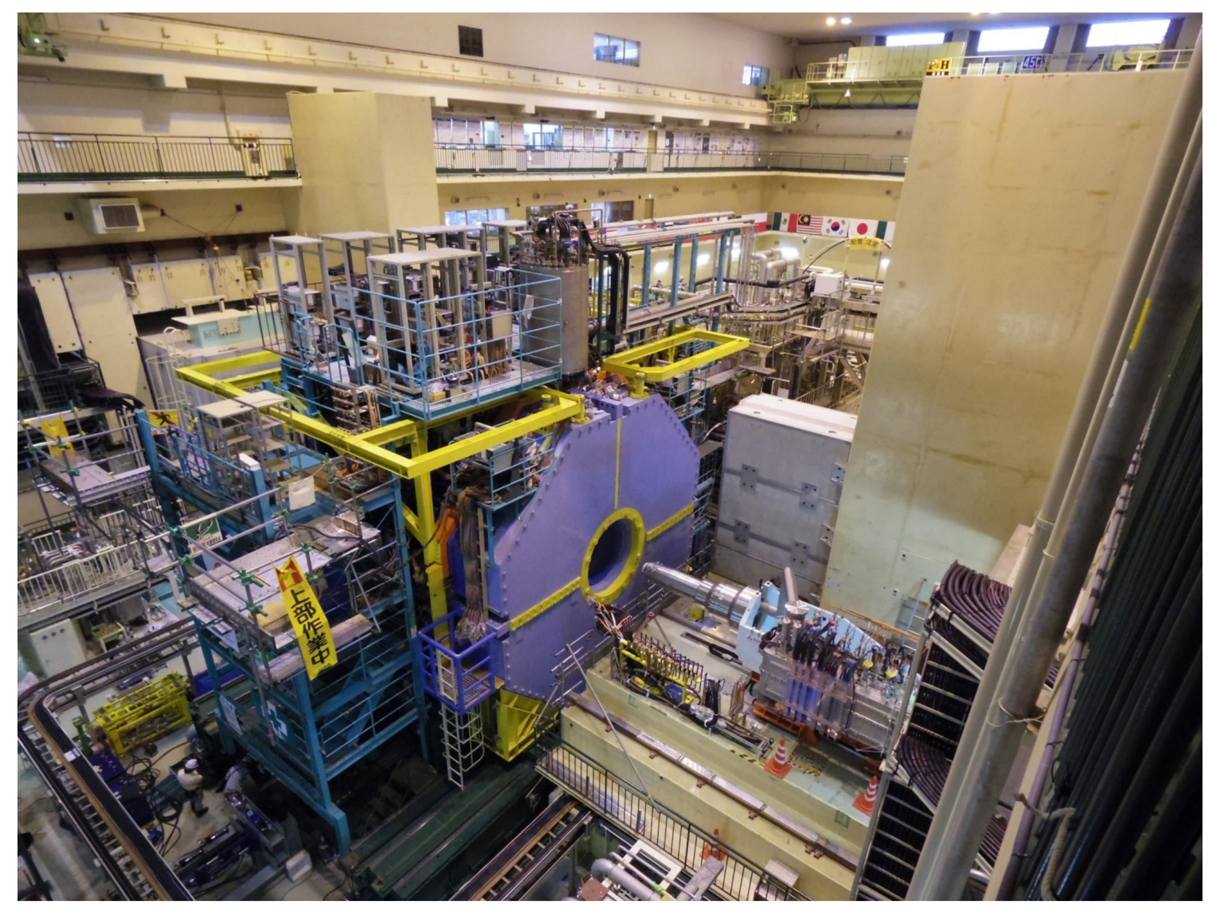
QCSR delivered on Feb. 13, 2017



SuperKEKB/Belle II schedule

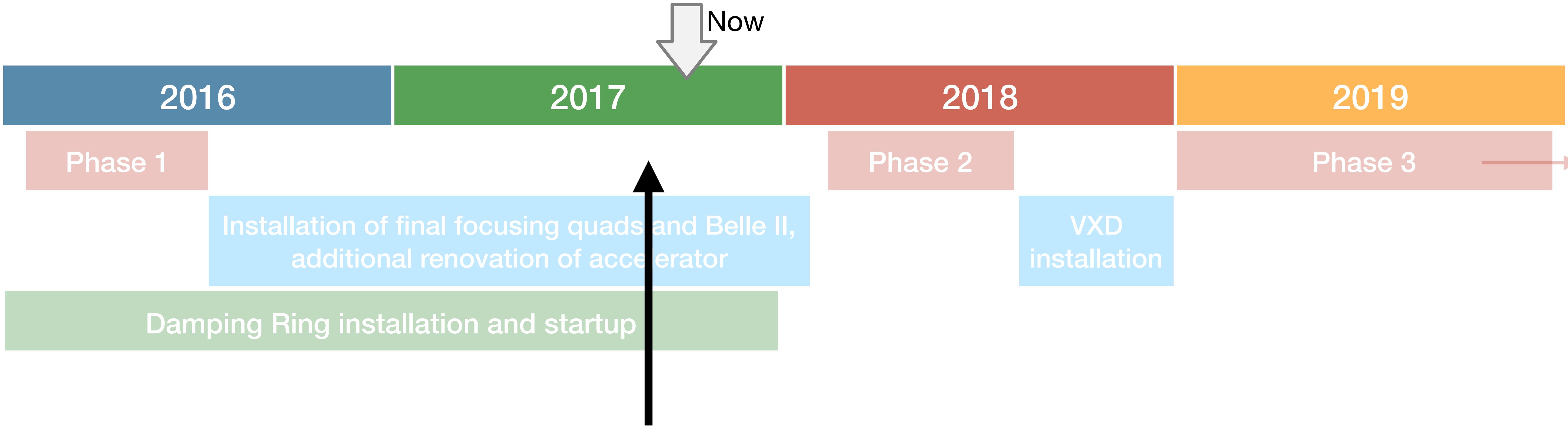




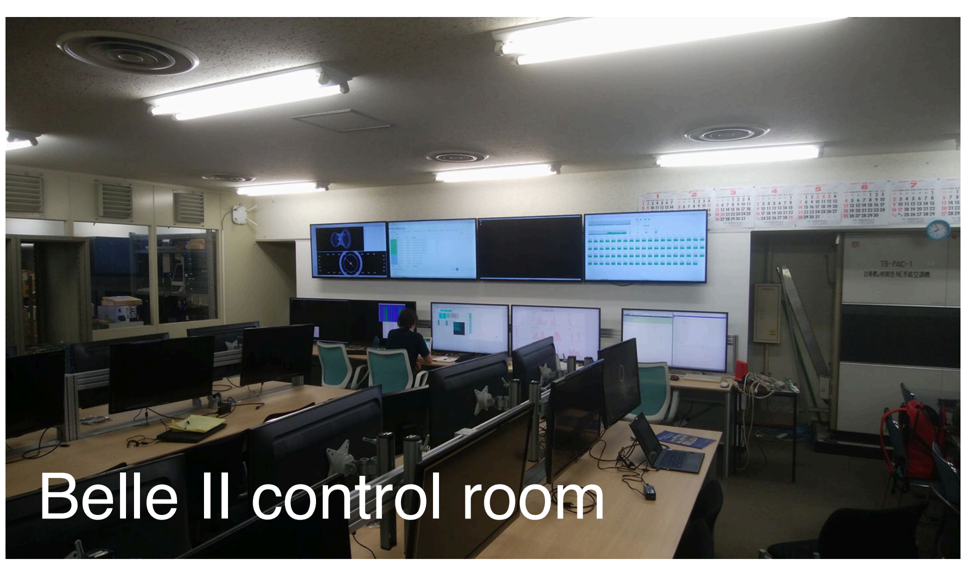


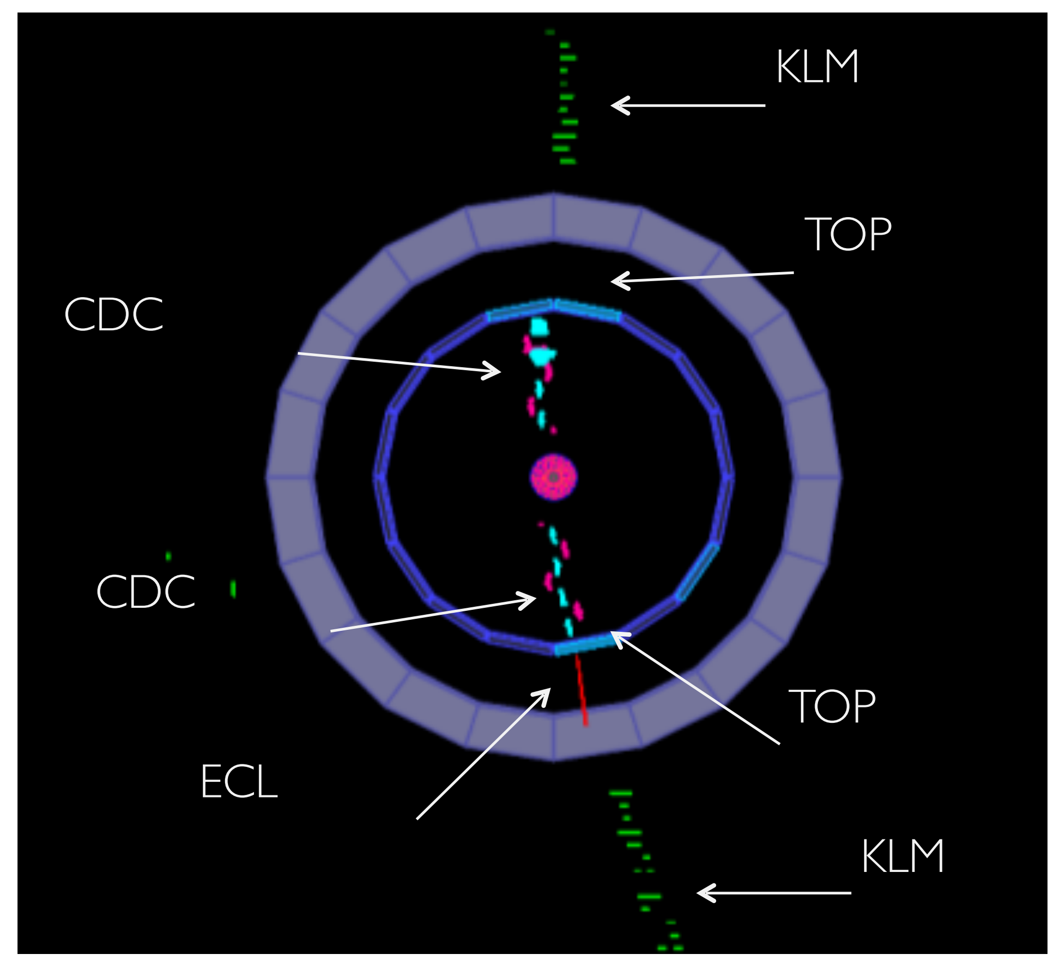
Belle II roll in: 1400 tons, 8m x 8m, moved 13m horizontally

SuperKEKB/Belle II schedule



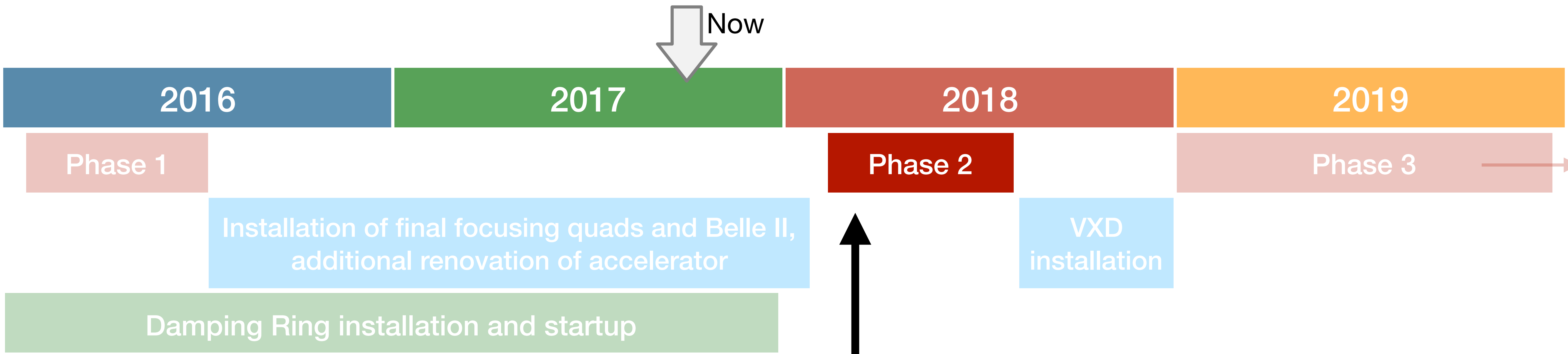
- **Belle II global cosmic run (July - August 2017)**
  - Final 1.5T solenoid field
  - Readout integration of installed sub-detectors and central DAQ

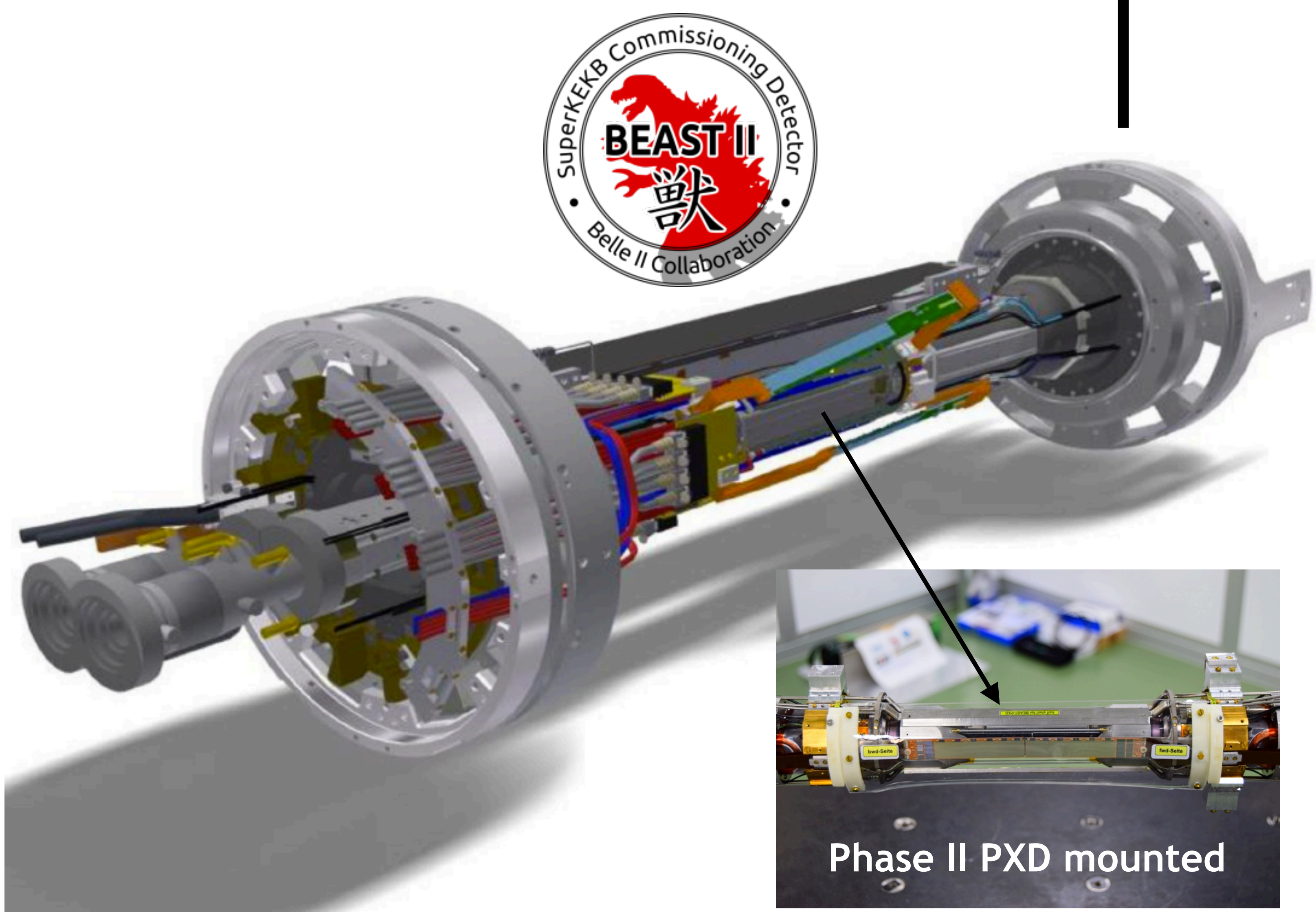




Hits in four outer subdetectors

SuperKEKB/Belle II schedule





SuperKEKB phase 2 commissioning:

- Dec. 2017 - Damping Ring
- Feb. 2018 - Main Ring

Phase 2 goals

- Verification of nanobeams (luminosity > 10^{34} $cm^{-2}s^{-1}$)
- Beam background study, especially in VXD volume
- First physics!

First operation with final focus (collisions!)
Outer Belle II + "BEAST-VXD"

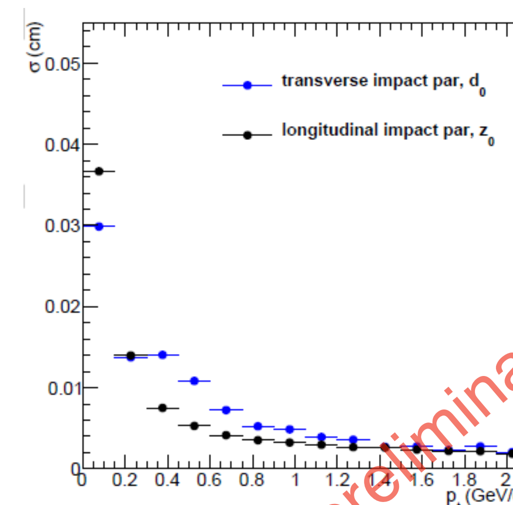
SuperKEKB/Belle II schedule

Now

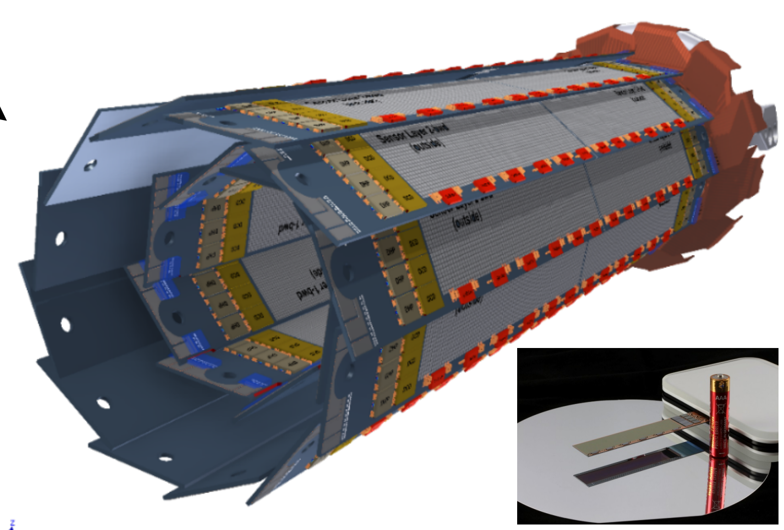
2016	2017	2018	2019

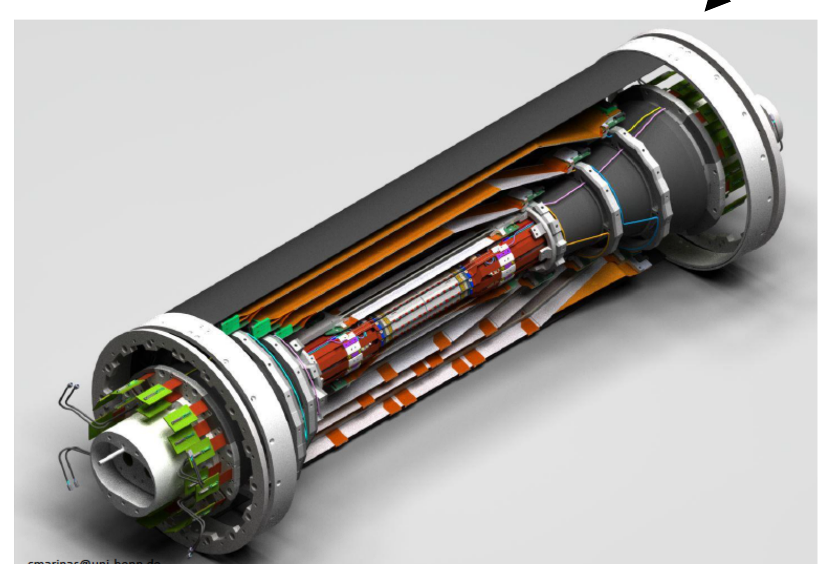
- Phase 1
- Installation of final focusing quads and Belle II, additional renovation of accelerator
- Damping Ring installation and startup
- Phase 2
- VXD installation
- Phase 3

IP resolution



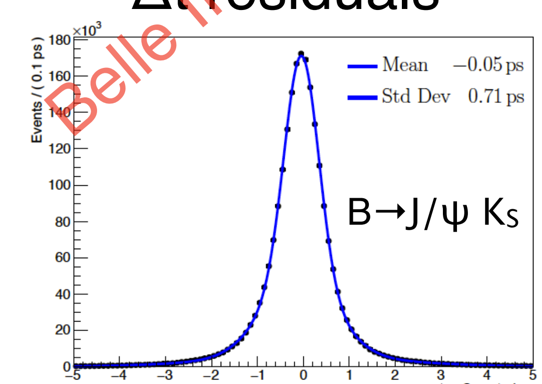
- Vertex detector (VXD)
  - Pixel Detector (PXD): 2 layers of DEPFET pixels
  - Silicon Vertex Detector (SVD): 4 layers of double-sided silicon detectors
- Increased VXD radius: significant improvement expected with respect to Belle in vertex resolution





Belle II MC preliminary

Δt residuals



SuperKEKB/Belle II schedule

Now

2016	2017	2018	2019

Phase 1

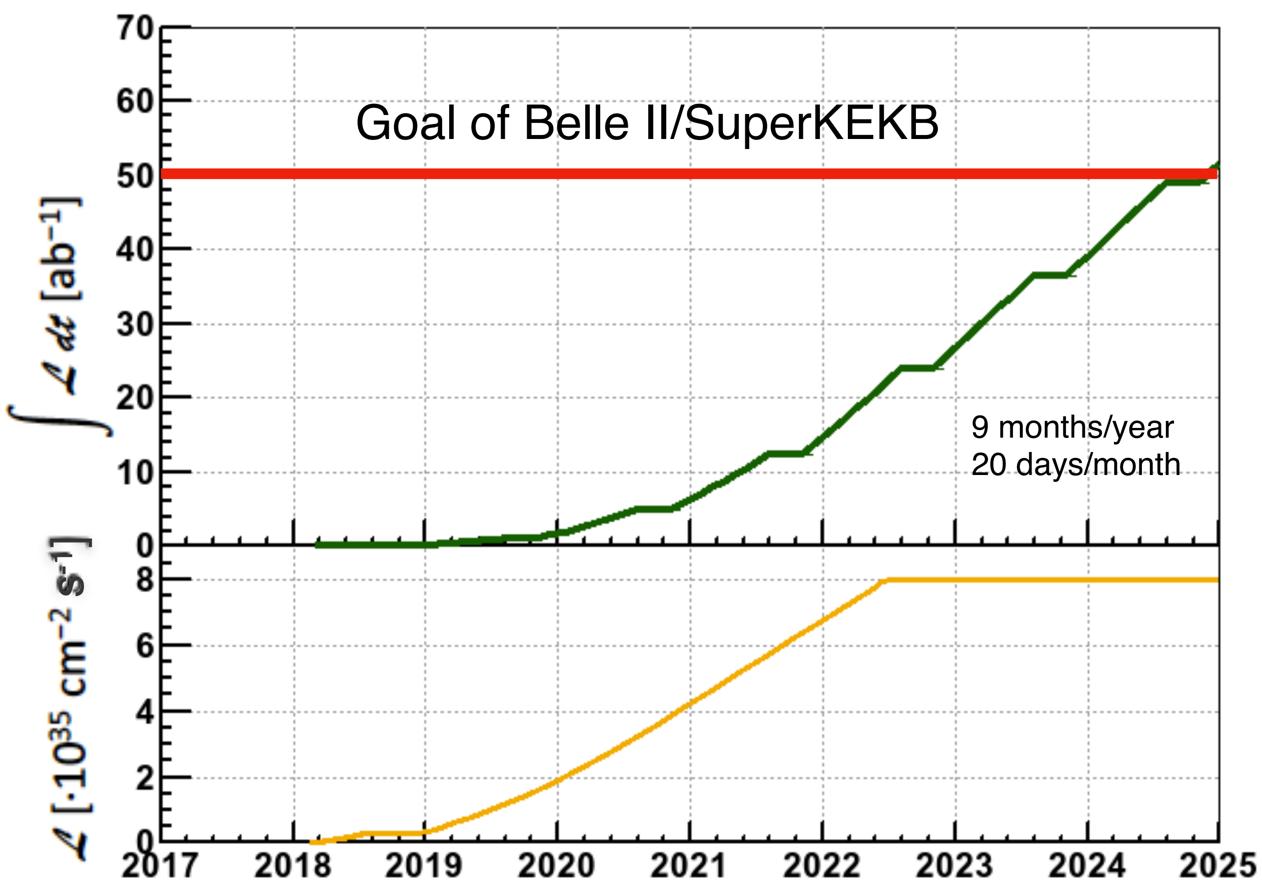
Phase 2

Phase 3

Installation of final focusing quads and Belle II, additional renovation of accelerator

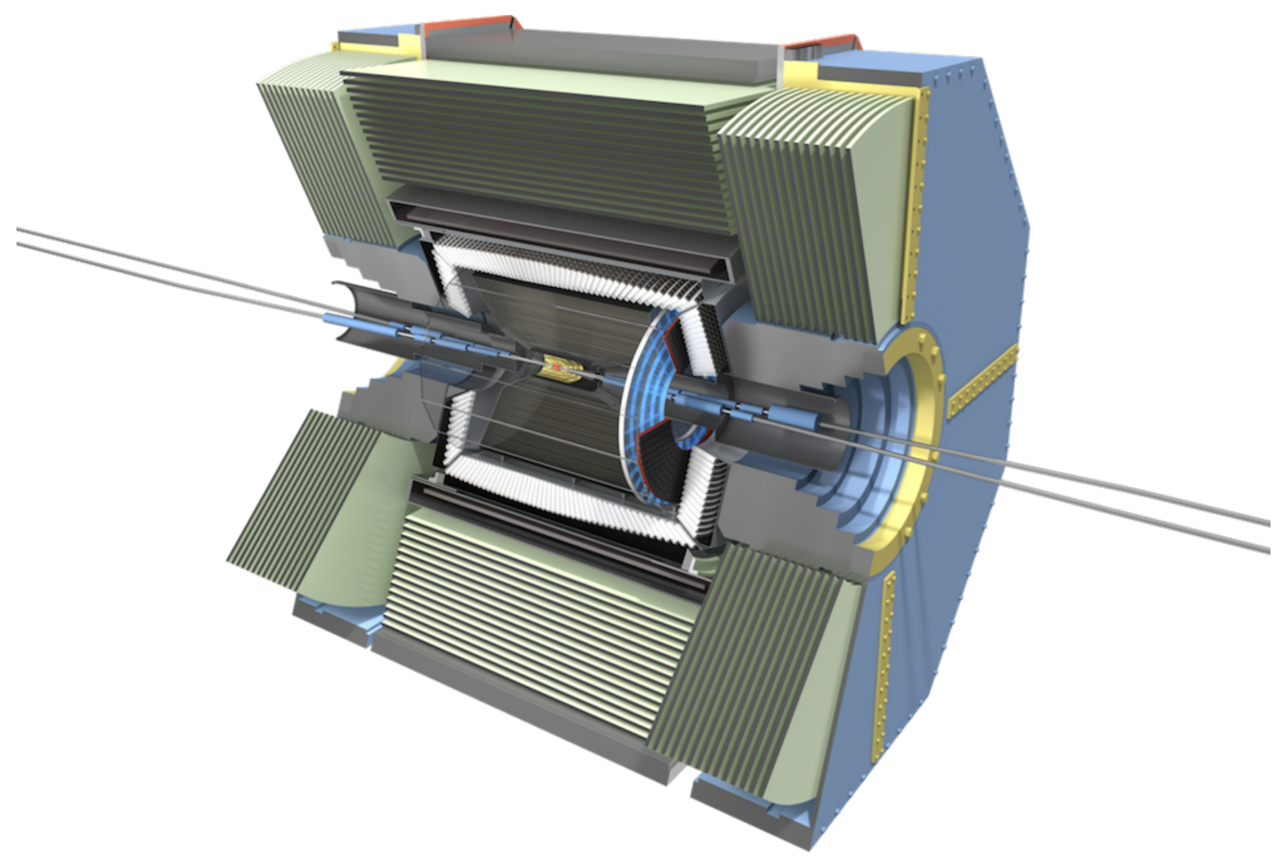
VXD installation

Damping Ring installation and startup



Complete Belle II detector

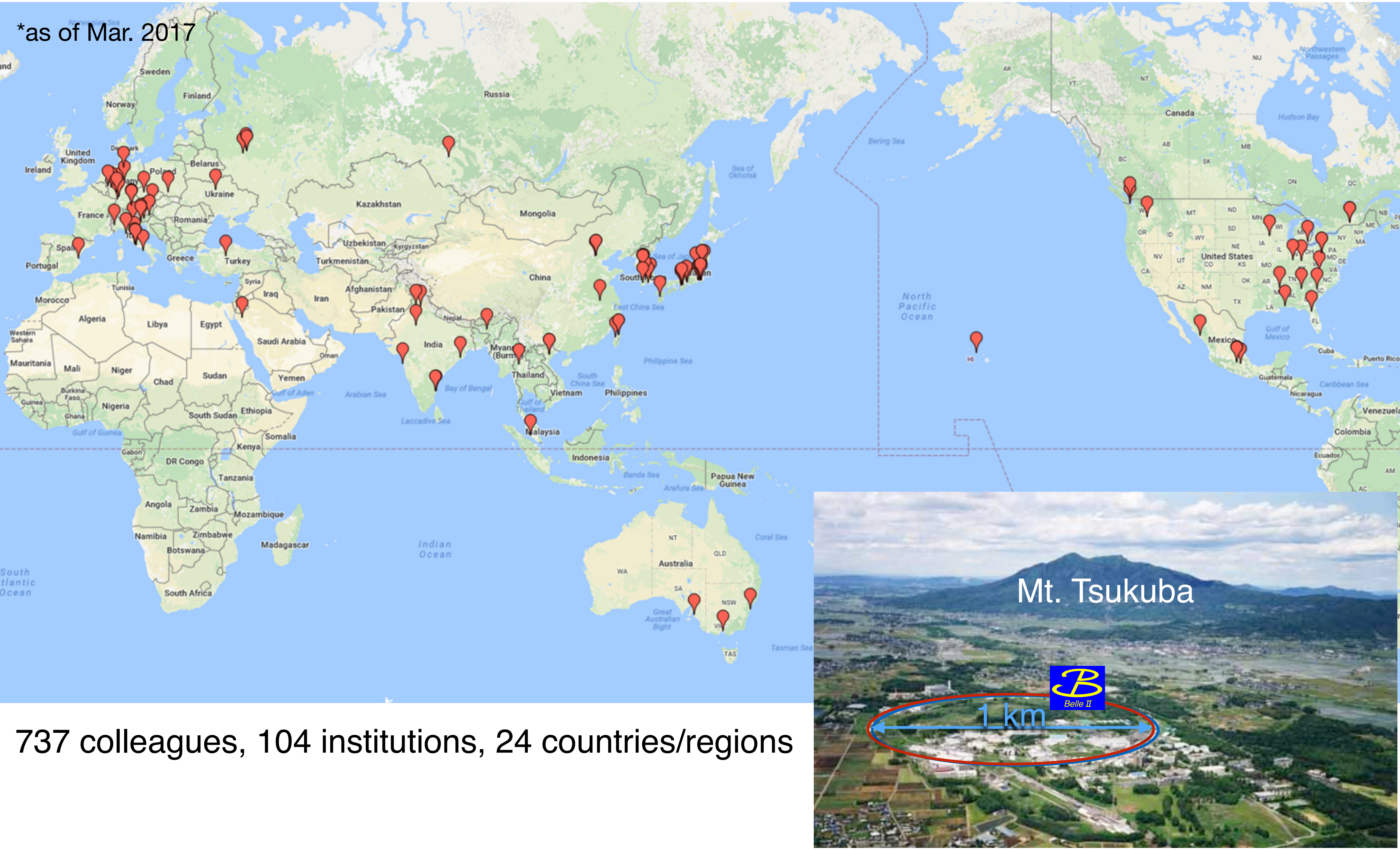
Goal: 50 ab^{-1}



Summary

- Major upgrade at KEK for the next generation B-factory
  - Many detector components and electronics replaced, software and analysis tools also improved!
- Cosmic data taking with central DAQ in 2017
- First physics without vertexing in early 2018
- Full detector operation in late 2018/early 2019
- Belle-II experiment can make significant impacts in hadron spectroscopy
  - Precisely measure line-shapes, map out resonances
  - Determine spin-parities, transitions, and quantum numbers
  - Search for new decay channels (in particular, for the open flavor channels which are not known for most of the states but are very important for their interpretation)
  - Test predictions for unobserved bottomium states
  - And more!

The Belle II Collaboration



737 colleagues, 104 institutions, 24 countries/regions

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1. Dubinskiy et al., PLB 671, 82 (2009)
2. Polosa et al., PRD 89, 114010 (2014)
3. e.g.: Tornqvist, PLB 590, 209 (2004)
4. Barnes et al., PRD 52, 5242 (1995)
5. e.g.: Swanson, PRD 91, 034009 (2015)
6. PRL 100, 142001 (2008)