XYZ Physis prospects at the Belle II experiment

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DESY and IHEP

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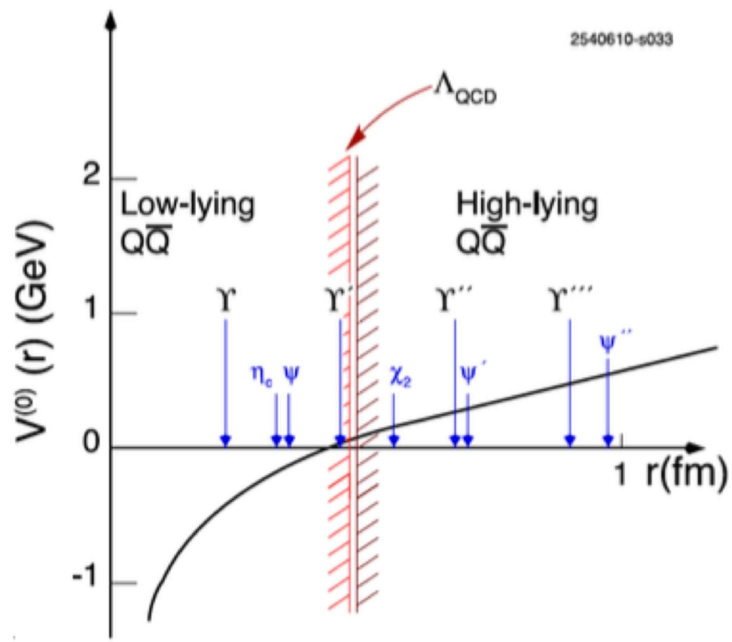
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Quarkonium spectroscopy

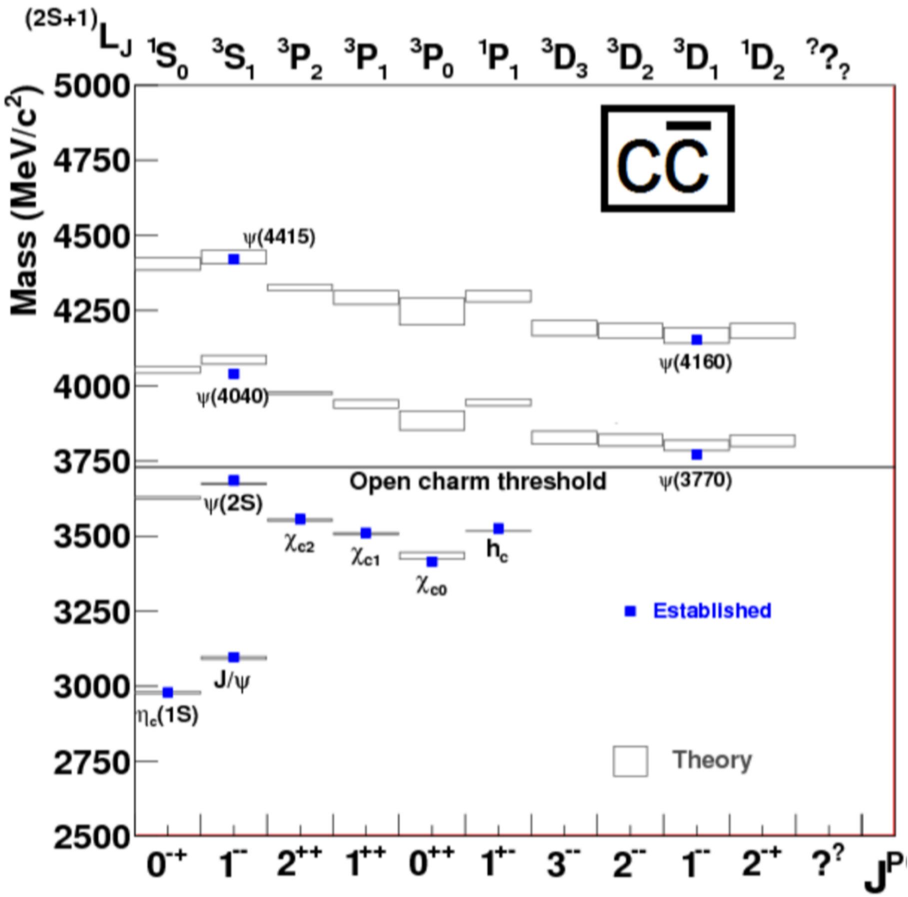
- Heavy quarkonium - bound state of a heavy quark and a heavy anti-quark
- Test the interplay between perturbative and non-pertubative QCD
- Potential models achieved tremendous success in the early years in accurately predicting the excitation spectrum
- Effective Field Theories (NRQCD, potential NRQCD) and Lattice QCD put the studies of quarkonium on more rigorous grounds.

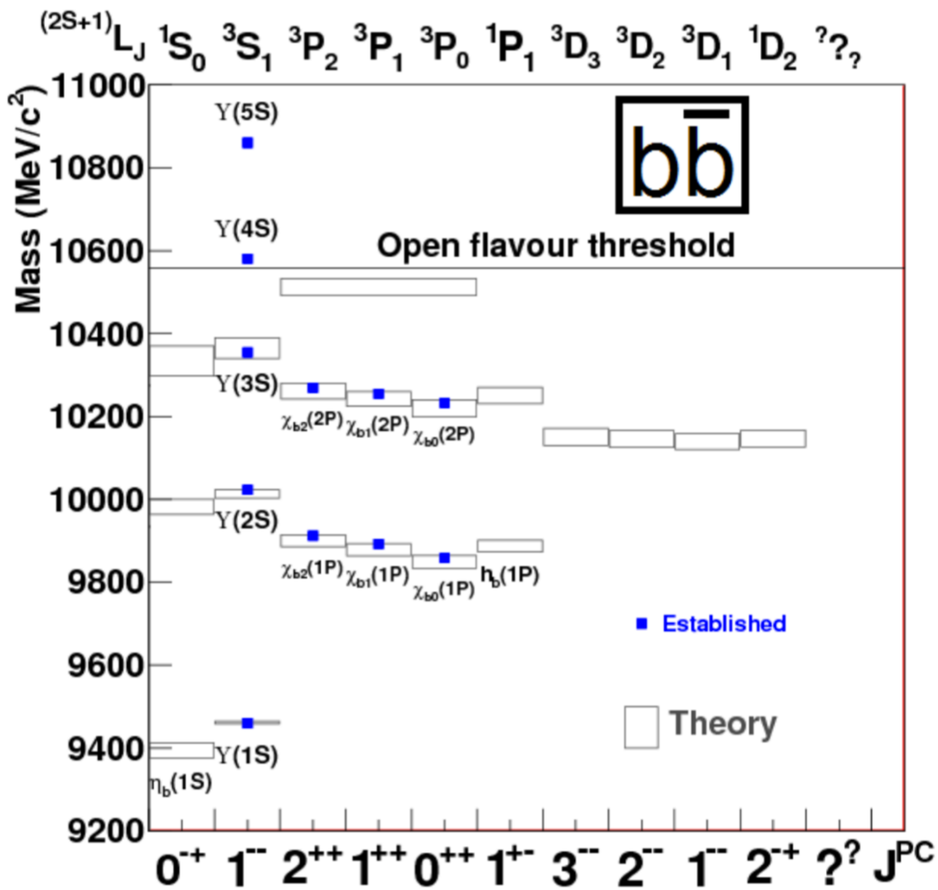


Cornell potential

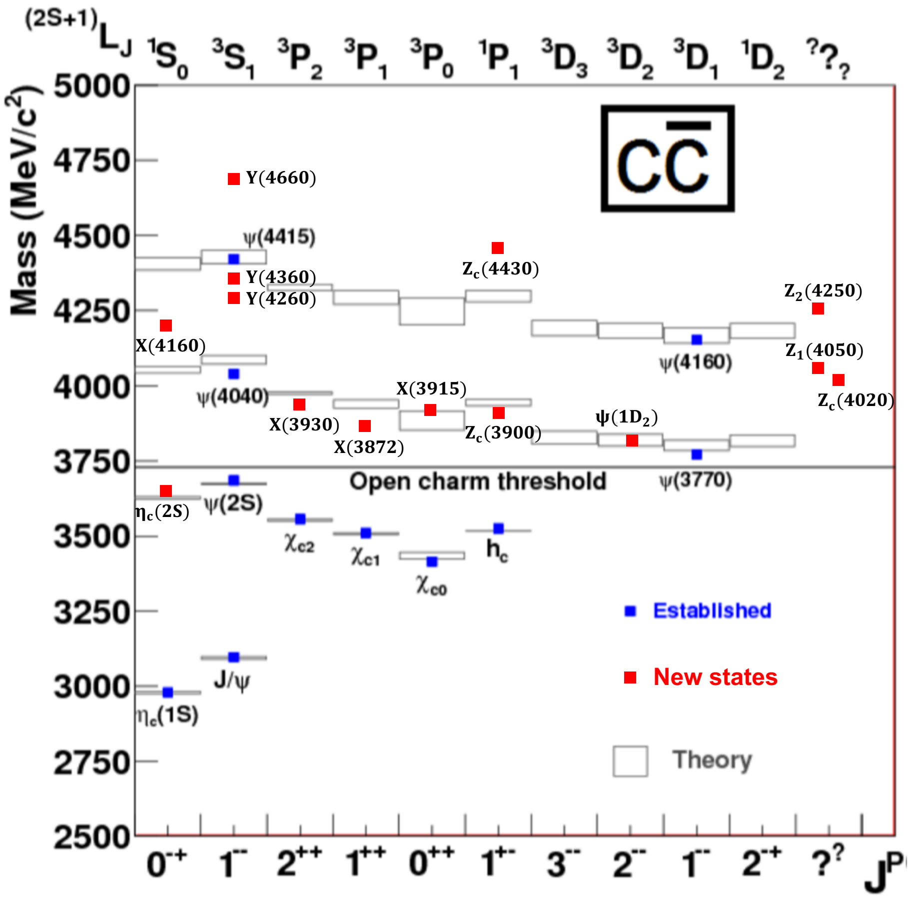
$$V(r) = -\frac{K}{r} + br$$

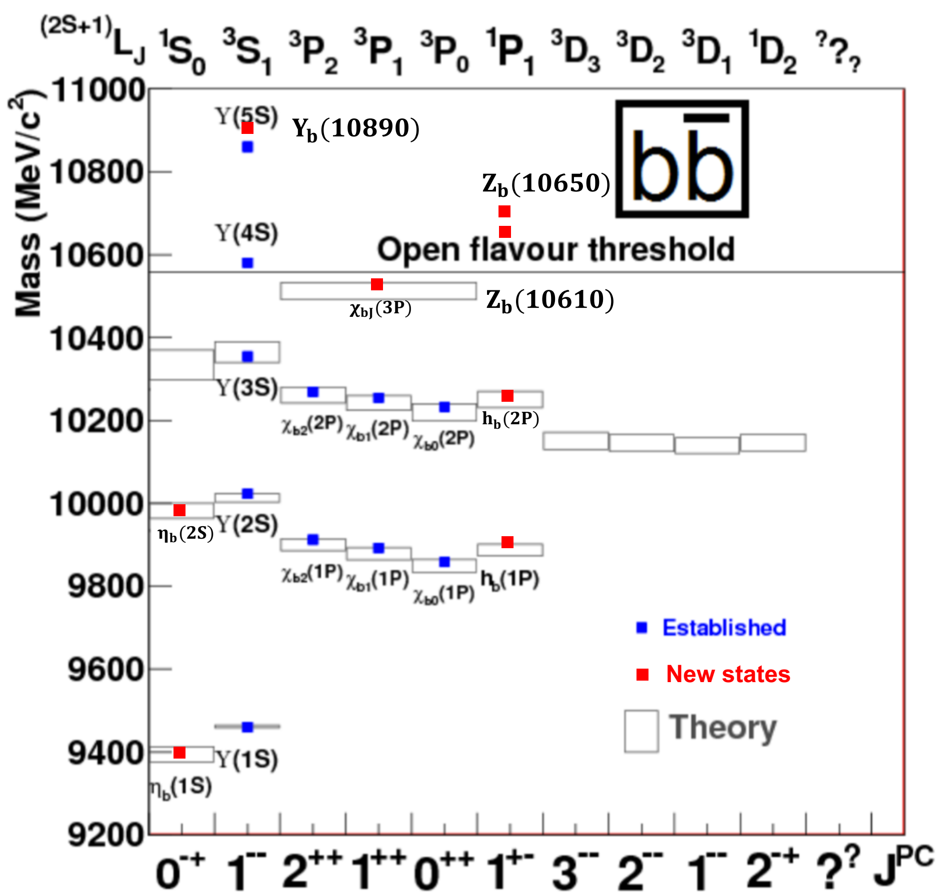
Quarkonium spectra ~1999



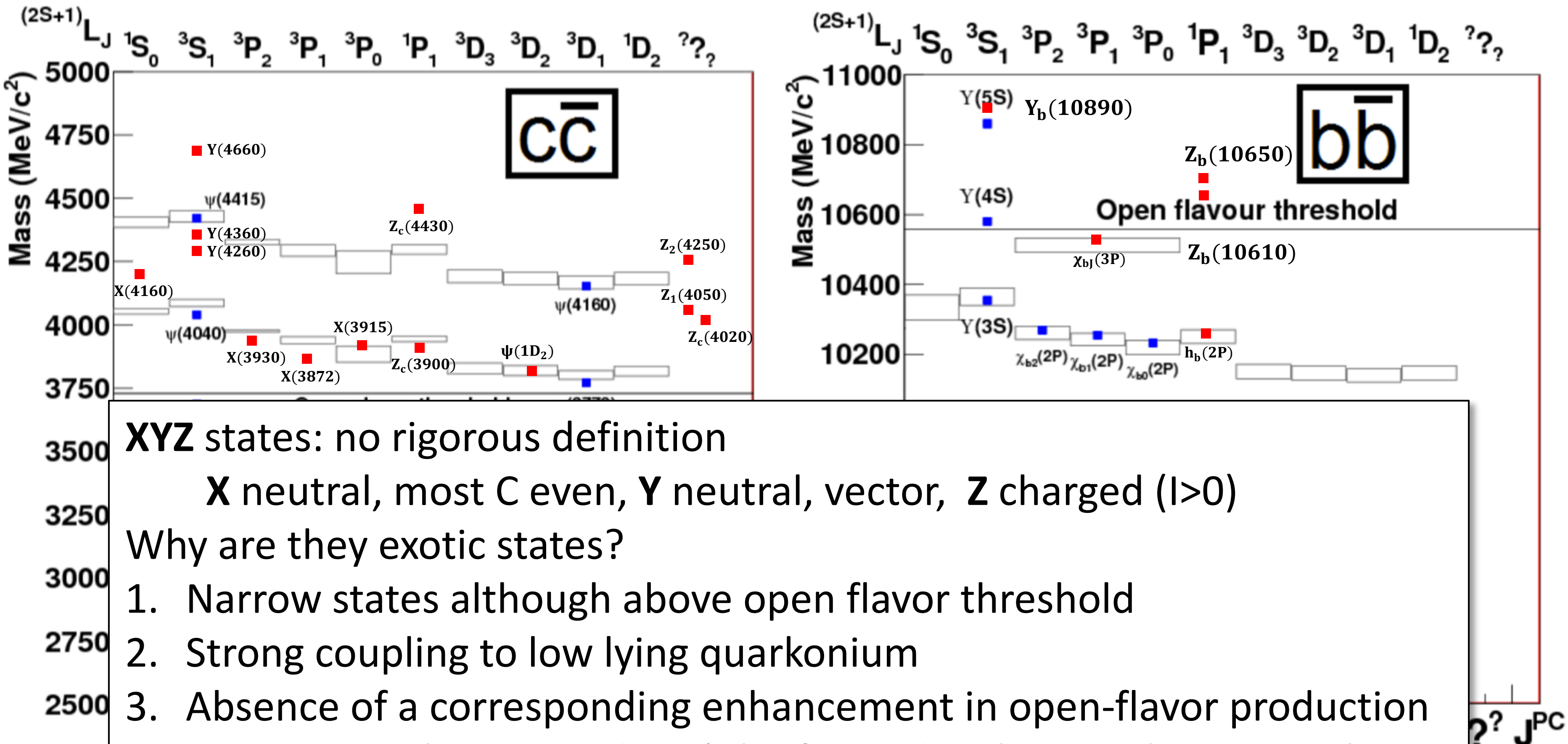


Quarkonium spectra at post B-factories era





The XYZ states



XYZ states: no rigorous definition

X neutral, most C even, **Y** neutral, vector, **Z** charged (I>0)

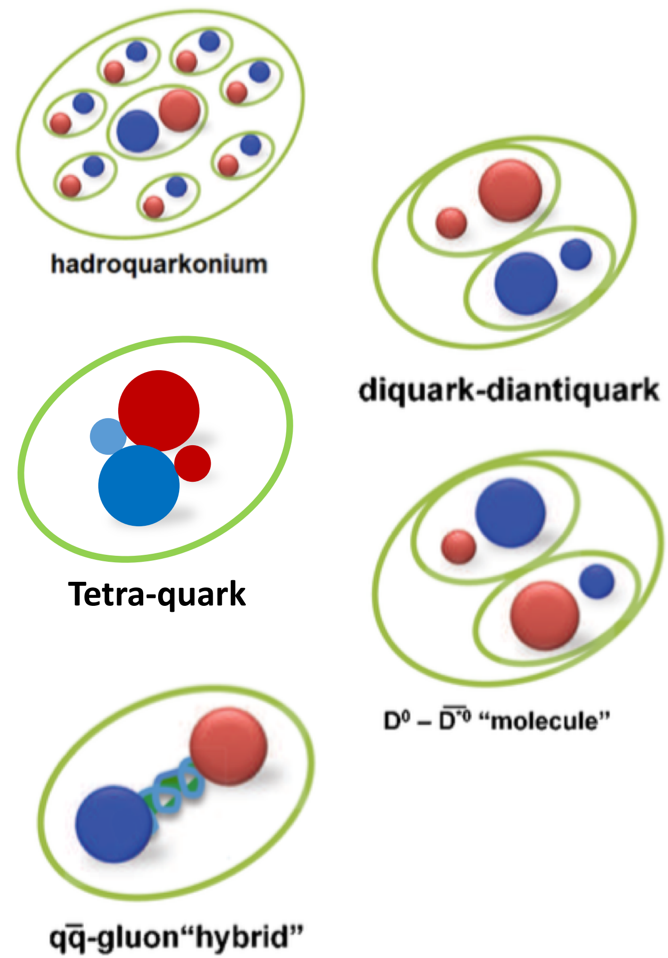
Why are they exotic states?

1. Narrow states although above open flavor threshold
2. Strong coupling to low lying quarkonium
3. Absence of a corresponding enhancement in open-flavor production
4. Z states are charged and can't be formed with a quark anti-quark pair

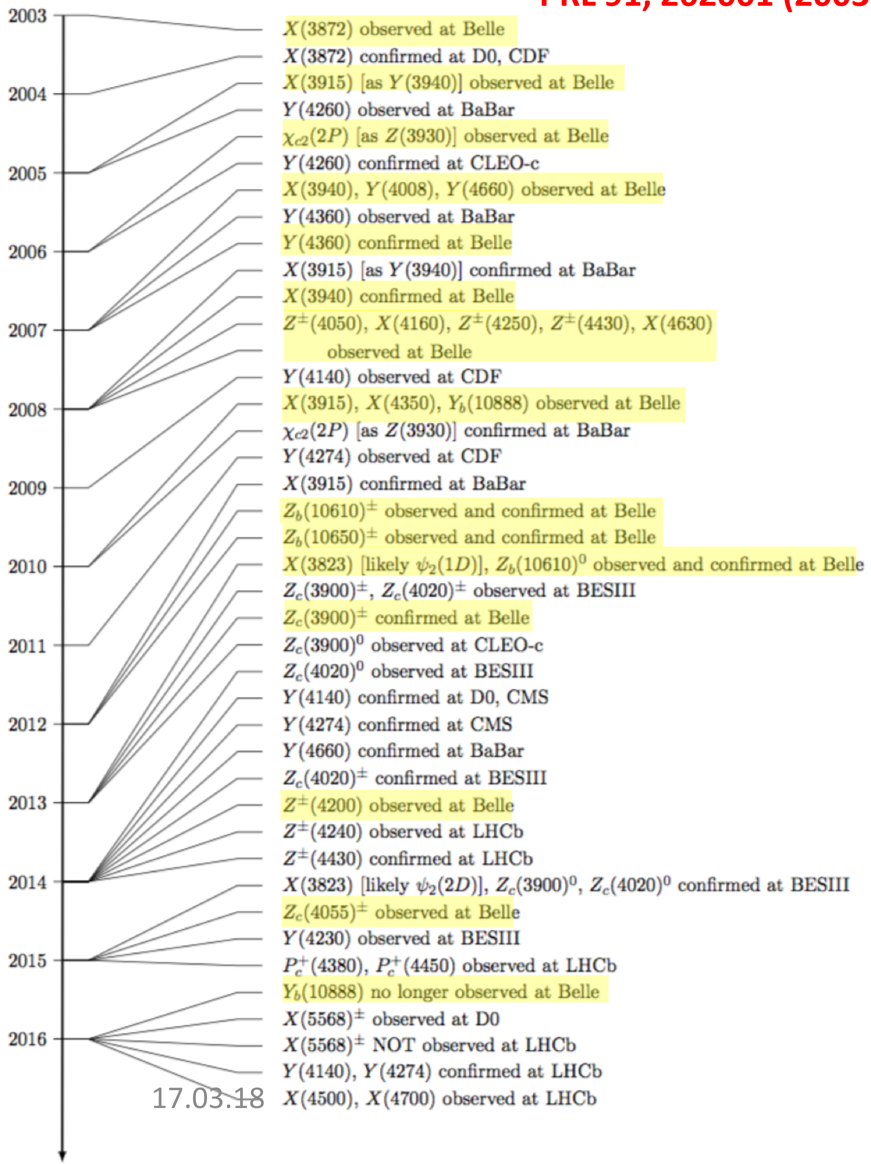
challenged the simple picture that has been so successful for decades!

Theoretical models

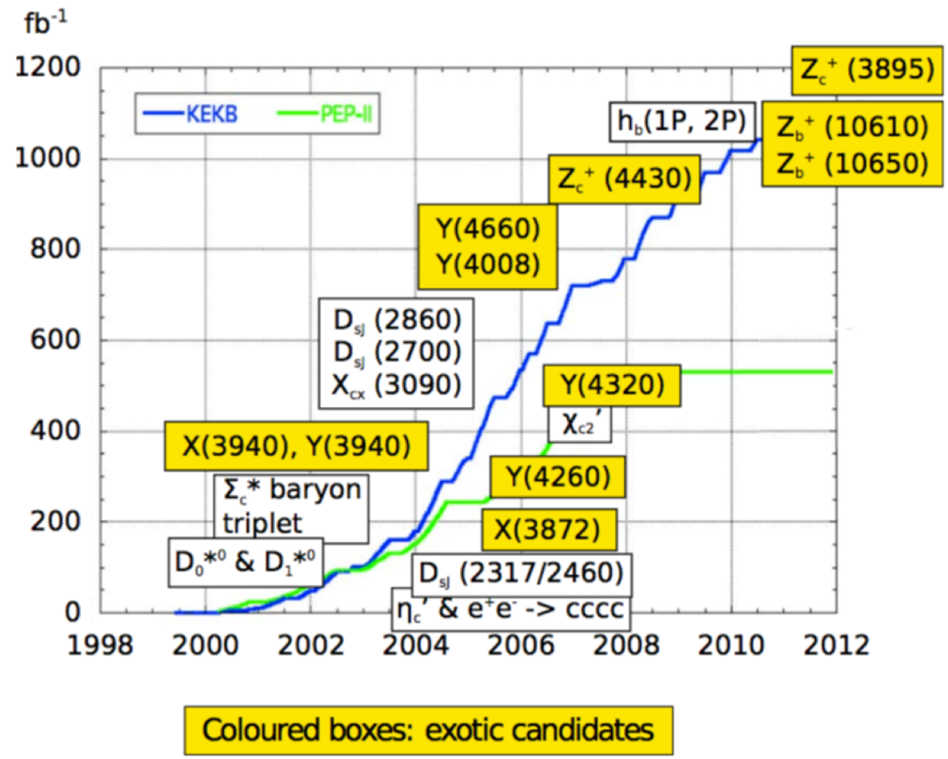
- **Hadro-quarkonium**: compact quarkonium-like core surrounded by light quarks
- **Diquark-onium**: compact diquark and anti-diquark substructures
- **Compact tetra-quark:** Compact four quarks states
- **Hadronic molecules**: heavy and light quarks and anti-quarks combined to form a hadron pair
- **Hybrids**: both gluons and quarks act as active degrees of freedom (contribute to quantum numbers)
- **Kinematical effects:** threshold re-scattering



Belle's contribution to XYZ physics

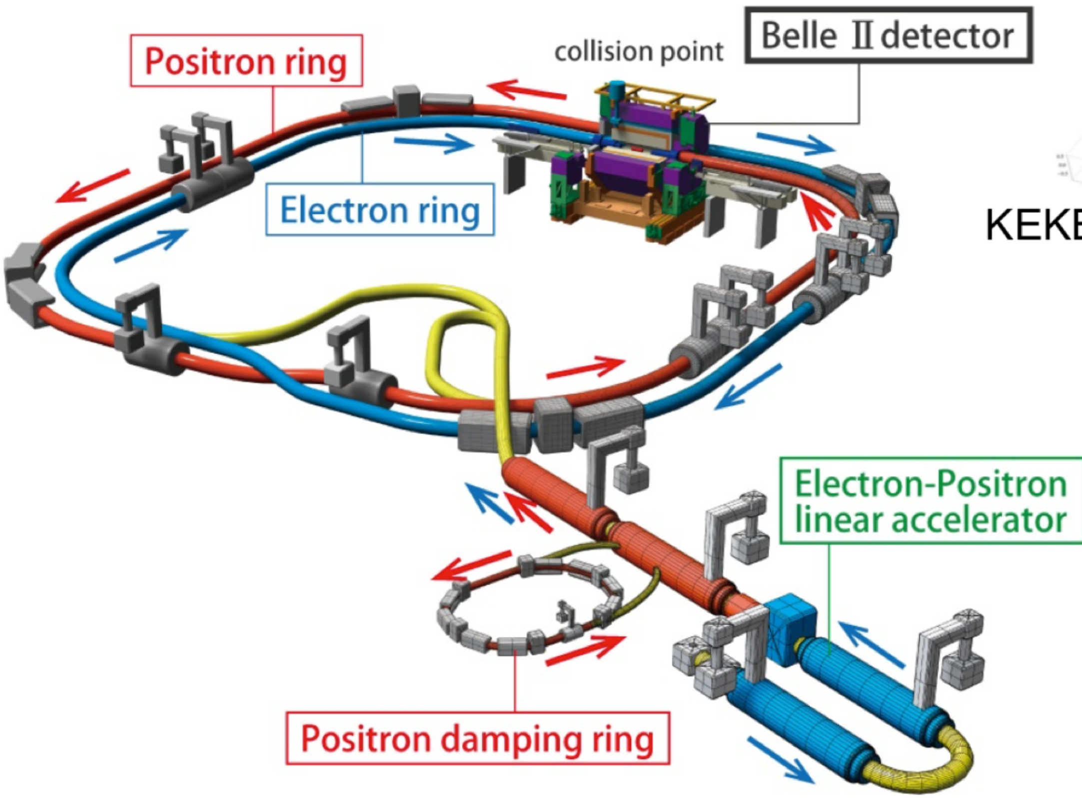


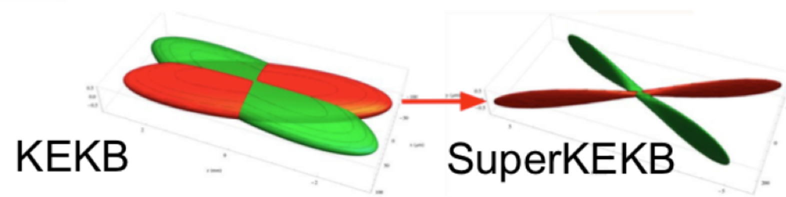
PRL 91, 262001 (2003), *cited by ~1400 records, most quoted paper at Belle!*



Belle observed the first exotic state X(3872), and contributes to almost half of the observations (confirmations) for the following XYZ states !

KEKB to SuperKEKB





Reduce beam size to a few 100 atomic layers! (goal is 60nm)

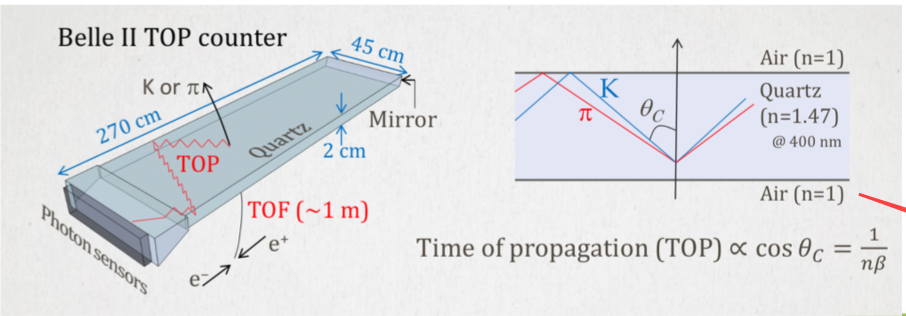
Doubled beam currents

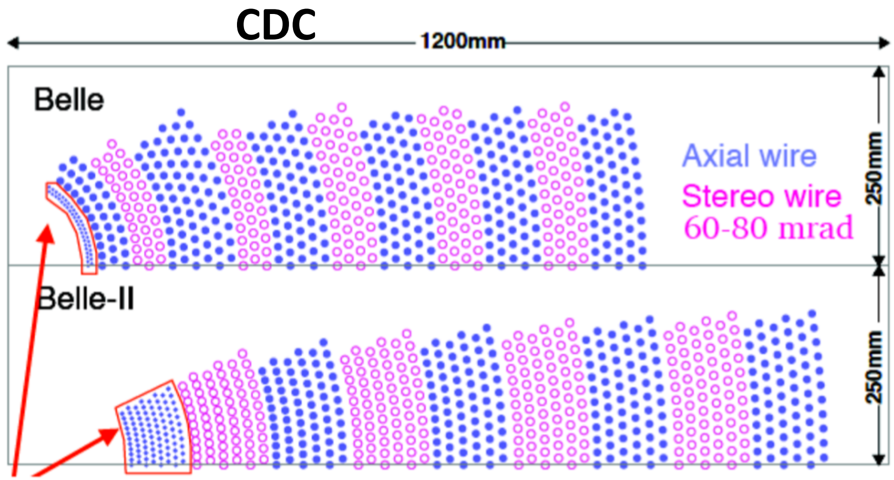
This yields a x40 higher peak luminosity (8x10^{35} cm^{-2}s^{-1})

BelleII will collect a dataset 50 times larger than Belle by 2025 (50 ab^{-1})

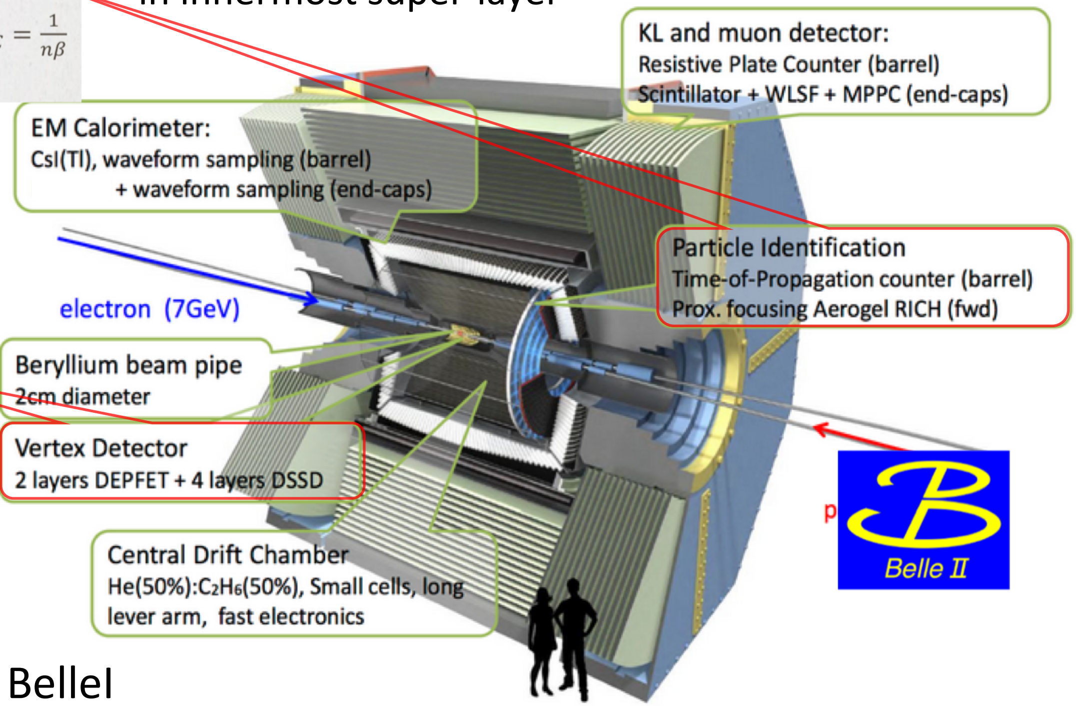
The BelleII detector

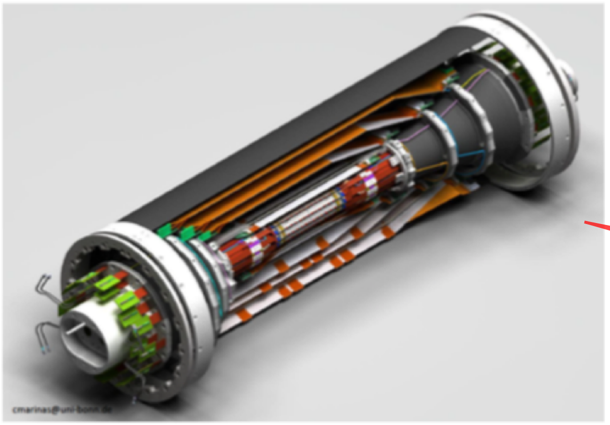
Compact TOP, better $K\ \pi$ separation, allows larger CDC





More layers and smaller cell in innermost super-layer

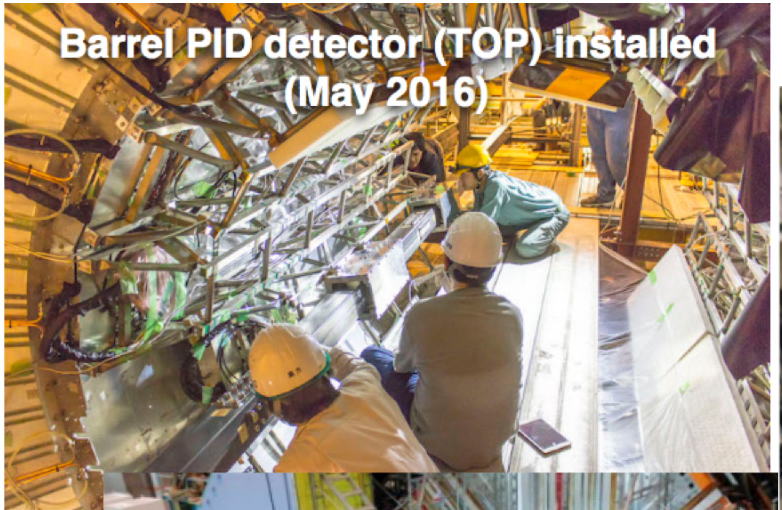


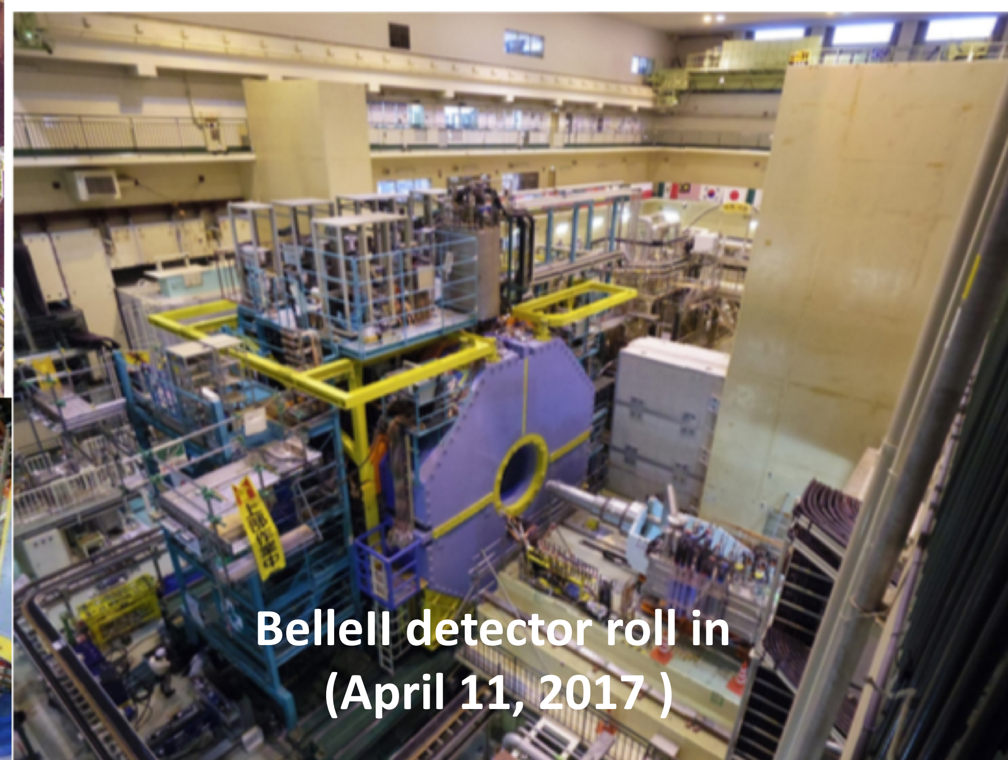


DEPFET PXD: first HEP implementation

Spatial resolution is two time better than BelleI

The milestones of BelleII assembling

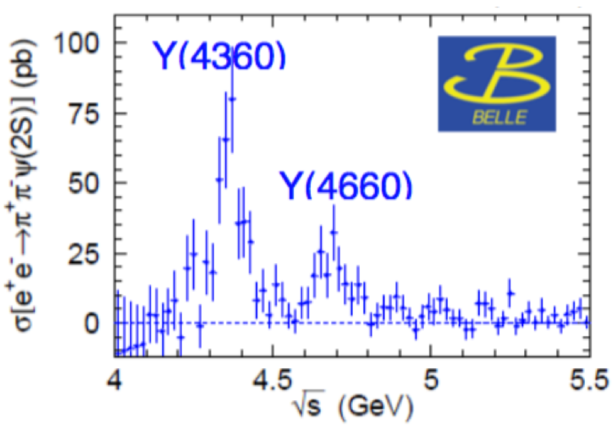


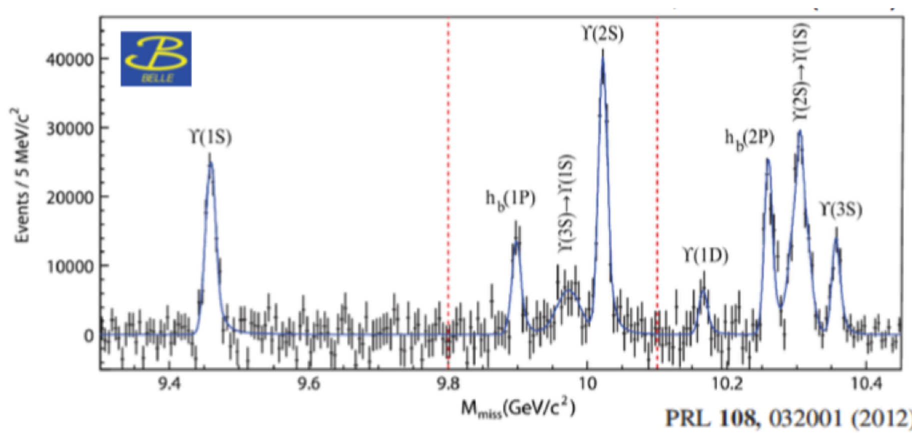


Unique capabilities of B factories

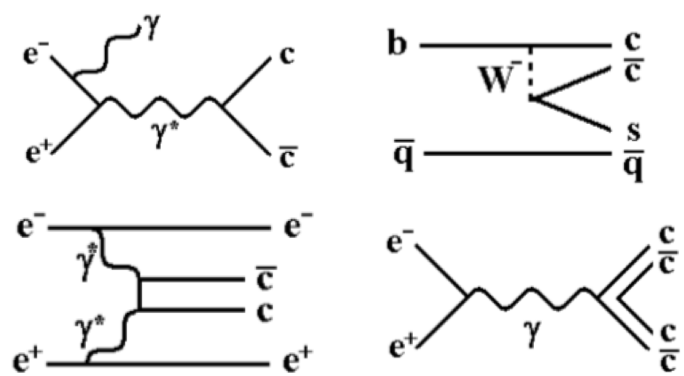
BelleII is an ideal laboratory to study exotic states!

- Cover both beauty and charm sectors





- Variety of production mechanisms (for charmonium-like)
  - ee annihilation
  - B decay
  - Two photon production
  - Double charmonium production
- High luminosity



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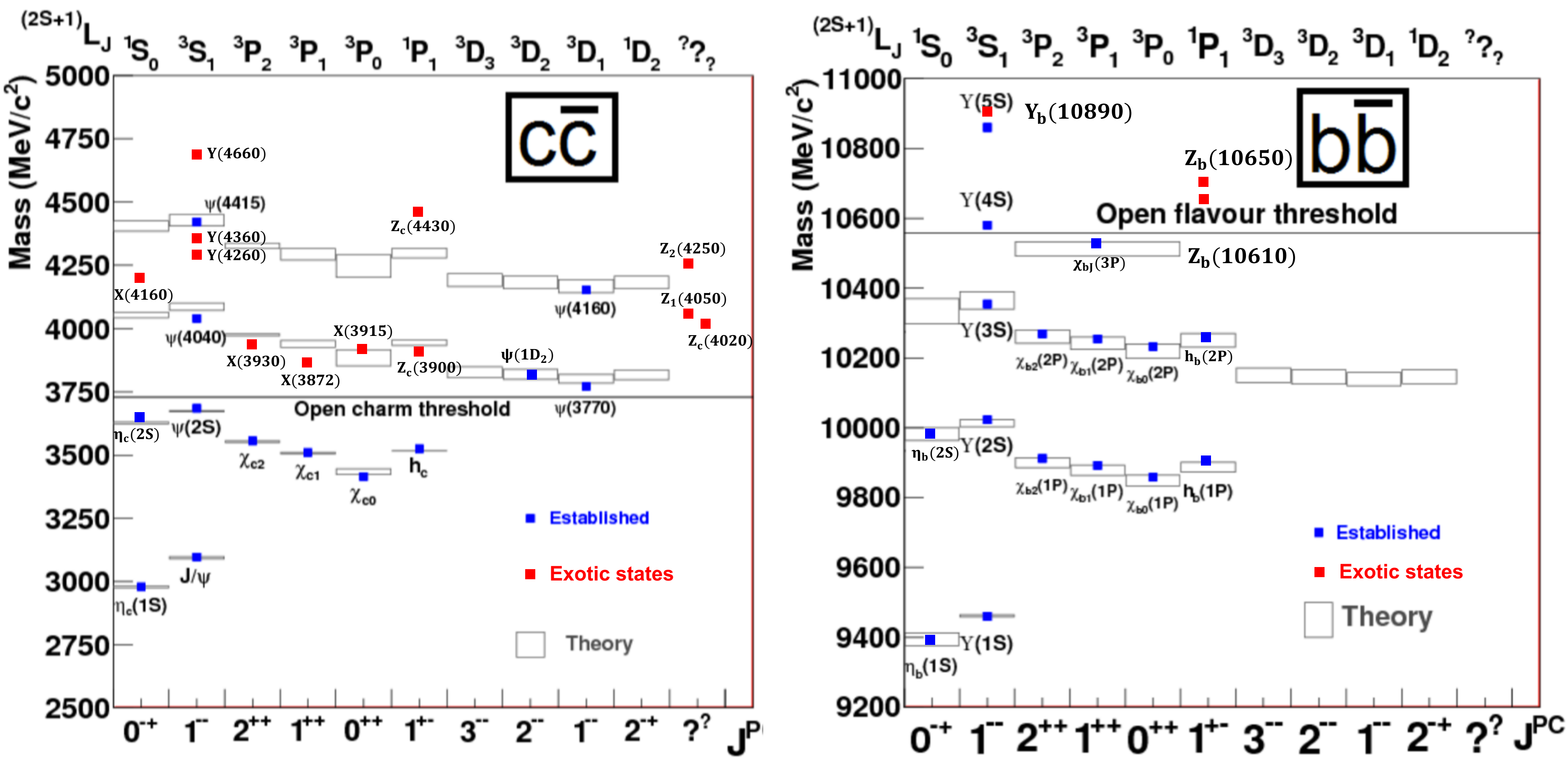

- **Dozens vs 3 !! why are there fewer bottomonium-like states than charmonium-like states?**

Search for flavor analogy exotic states

- Flavor- independence of gluon exchange implies that flavor analog states should exist.
- The $Z_b(10610)$ and $Z_b(10650)$ can be considered as bottom partners to the $Z_c(3900)$ and $Z_c(4020)$.
- There should be lots of Y_b and X_b found in the beauty sector.
- The existence and property of the bottom partners will reveal the nature of the corresponding states
- E.g. if $X(3872)$ is a weakly bound $D\overline{D}^*$, then the corresponding X_b would be expected at mass 10640 MeV, however, in some models, X_b will not exist or have other expected mass.
- **BelleII can give access to a larger landscape for XYZ states**

Production of charmonium-like states

$X(3872)$	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	$e^+e^- \to \pi Z;\ Z \to \pi J/\psi$ $e^+e^- \to \pi Z;\ Z \to D^*\bar{D}$
$X(3915)$ $Y(3940)$	0^+0^{++}	3918.4 ± 1.9 [176]	20 ± 5	$\gamma\gamma \to X;\ X \to \omega J/\psi$ $B \to KX;\ X \to \omega J/\psi$
$Z(3930)$ $(\chi_{c2}(2P))$	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]	$139^{+111}_{-61} \pm 21$	$e^+e^- \to J/\psi + X;\ X \to D^*\bar{D}^*$
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$Y(4274)$	0^+1^{++}	$4273.3 \pm 8.3^{+17.2}_{-3.6}$ [125]	$52 \pm 11^{+8}_{-11}$	$B \to KY;\ Y \to \phi J/\psi$
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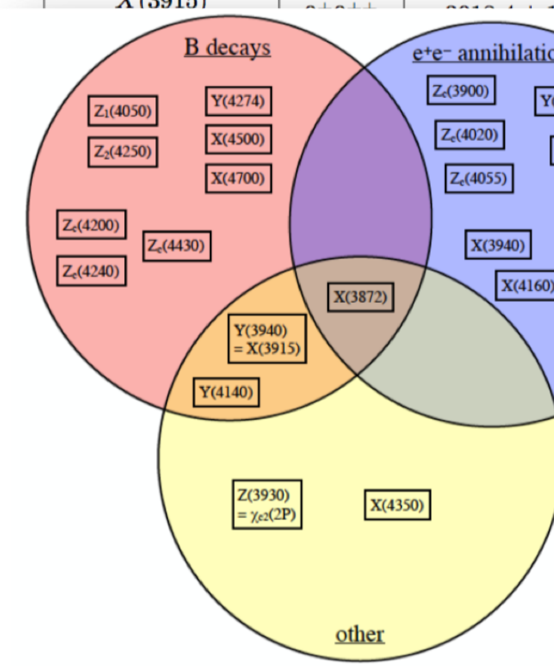

Lebed, Mitchell, Swanson, Heavy-Quark QCD Exotica, PPNP 93, 143 (2017)

Many states have only been observed in a single production mechanism or only a single decay channel

BelleII can produce these states in:
B decay,
ee annihilation,
$\gamma\gamma$ fusion,
double charmnium

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J^{pc} of Some states are still unclear due to insufficient dataset

BelleII will collect a huge data sample that we never had before

X(3872) -- still puzzling

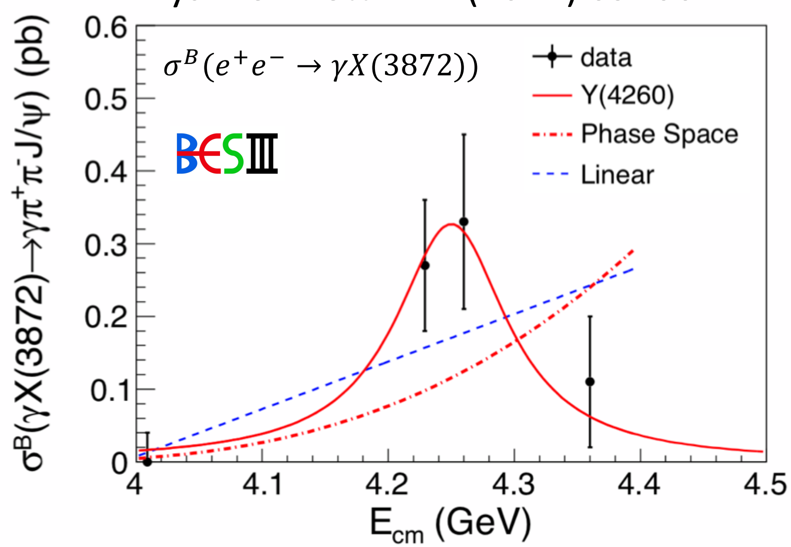
Properties:

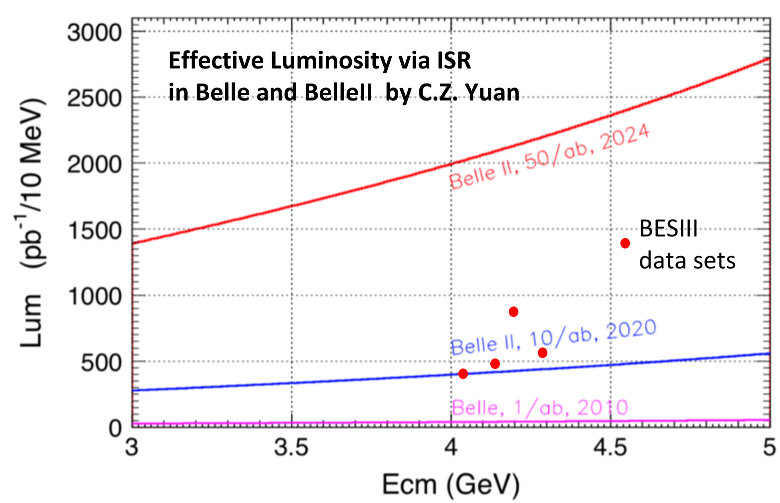
- Narrow state near to $D^{*0}\overline{D}^0$. $J^{PC} = 1^{++}$
- Good candidate for molecule.
- Produced in B decay, ee annihilation, pp collision
- Decay to $\rho^0 J/\psi$, $\omega J/\psi$, $D^{*0}\overline{D}^0$. Probably can be produced in radiative decay of Y(4260)

Opportunity at BelleII:

- Confirm the Y(4260) production, it may indicate both Y(4260) and X(3872) are a combination of molecular and $c\bar{c}$.
- BelleII will get 4 times more data in this region from ISR by 2024.
- Search for flavor analogy exotic states X_b

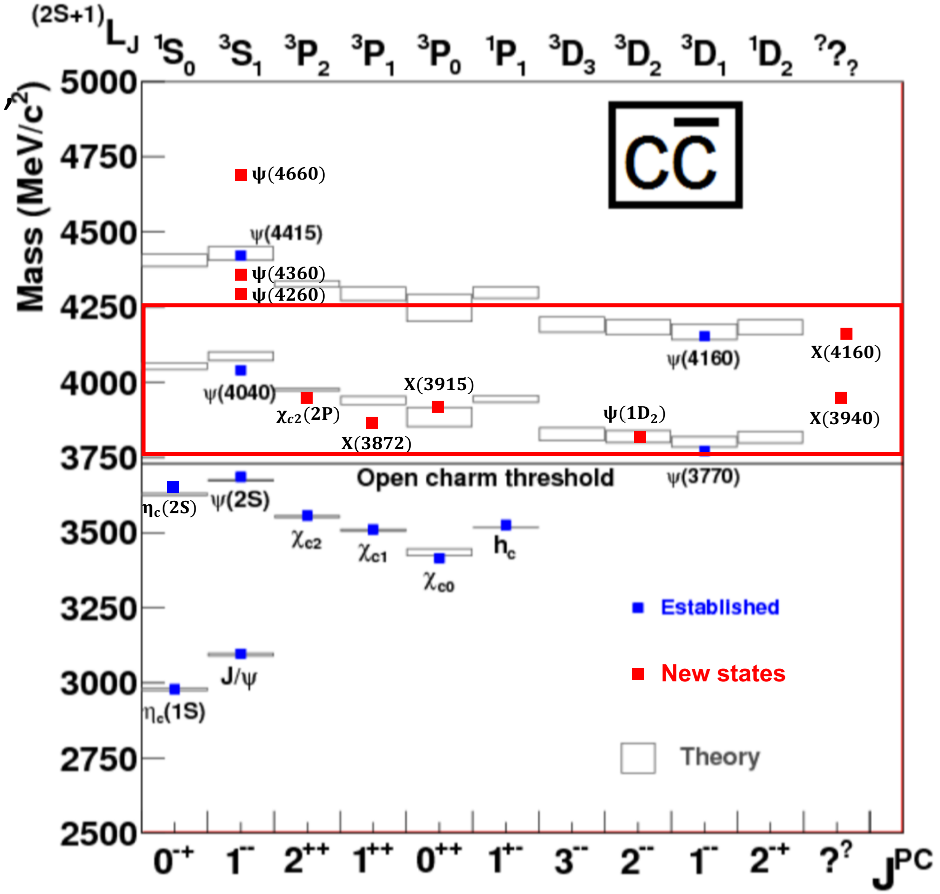
Phys. Rev. Lett. 112 (2014) 092001





The region between 3.9 ~4.2 GeV

- Spectrum of states were observed:
  X(3823), X(3915)/Y(3940),Z(3930) X(3940),
  X(4160)
- Challenge here is to separate exotic candidates from quark-model states.
  1. Some assignments are settled:
     X(3823)→$\psi(1D_2)$
     Z(3930)→$\chi_{c2}(2P)$



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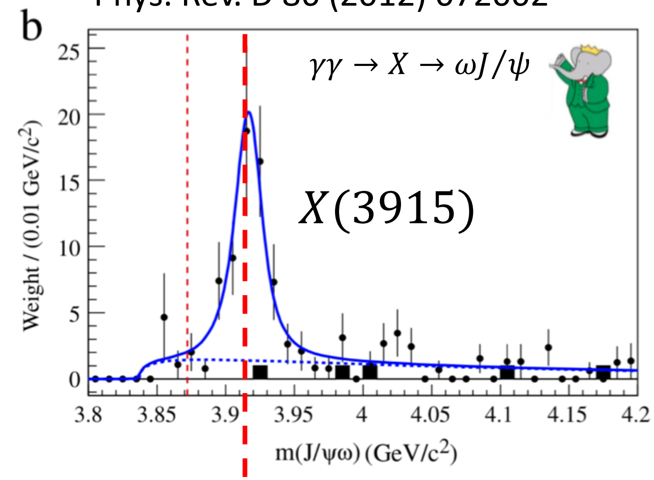
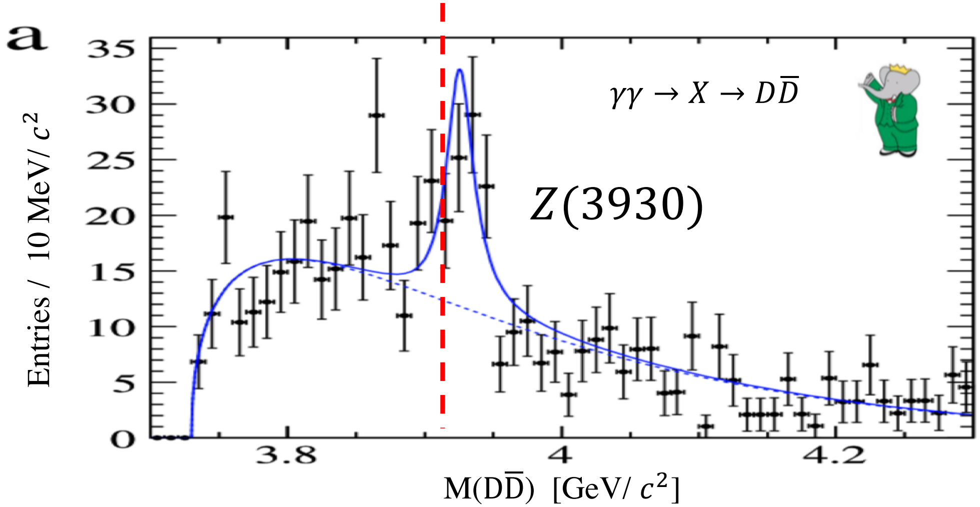
     Search for it in $B \rightarrow KD\bar{D}$ and $\gamma\gamma \rightarrow X \rightarrow D\bar{D}$

Phys. Rev. D 86 (2012) 072002





Phys. Rev. D 81 (2010) 092003

The region between 3.9 ~4.2 GeV

- Spectrum of states were observed :
  X(3823), X(3915)/Y(3940),Z(3930) X(3940), X(4160)
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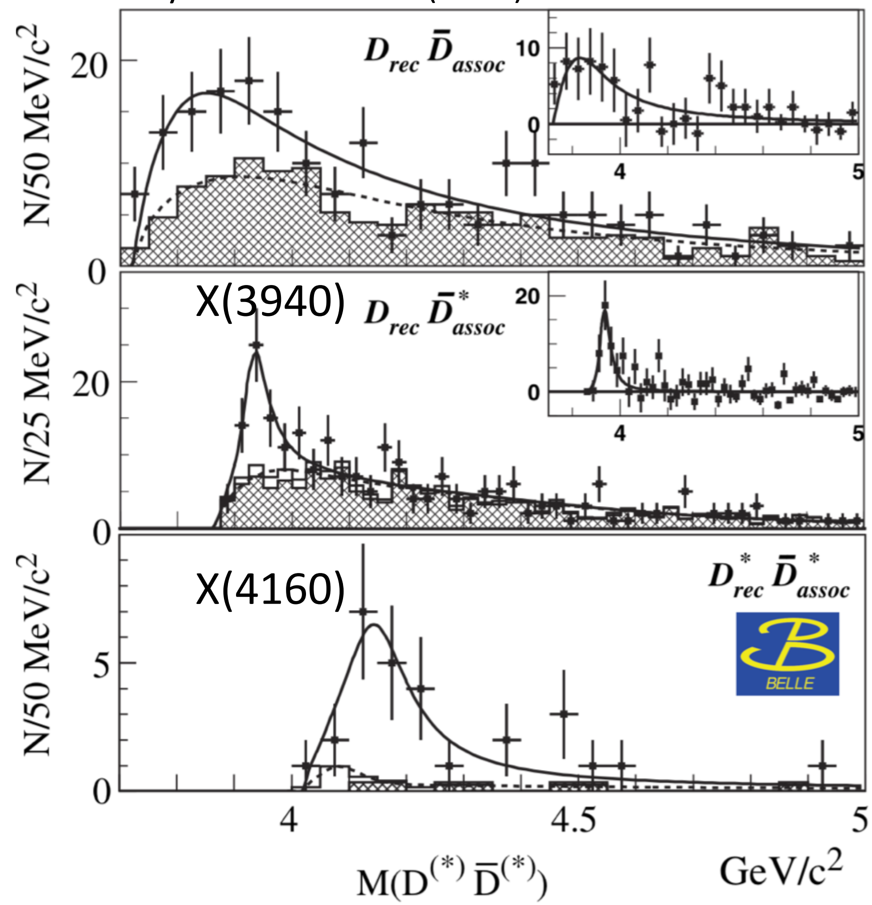
  2. Others are still mysterious:
     X(3915)→ $\chi_{c0}(2P)$?
     Search for it in $B \to KD\bar{D}$ and $\gamma\gamma \to X \to D\bar{D}$
  3. What are the X(3940) and X(4160)?
     Observed in double charmonium
     Determine the J^{PC}
     More production and decay mode: B decay, $\gamma\gamma$ fusion, e^+e^- annihilation…

$e^+e^- \to J/\psi + D\bar{D}, D\bar{D}^*, D^*\bar{D}^*$

Phys. Rev. Lett. 100 (2008) 202001



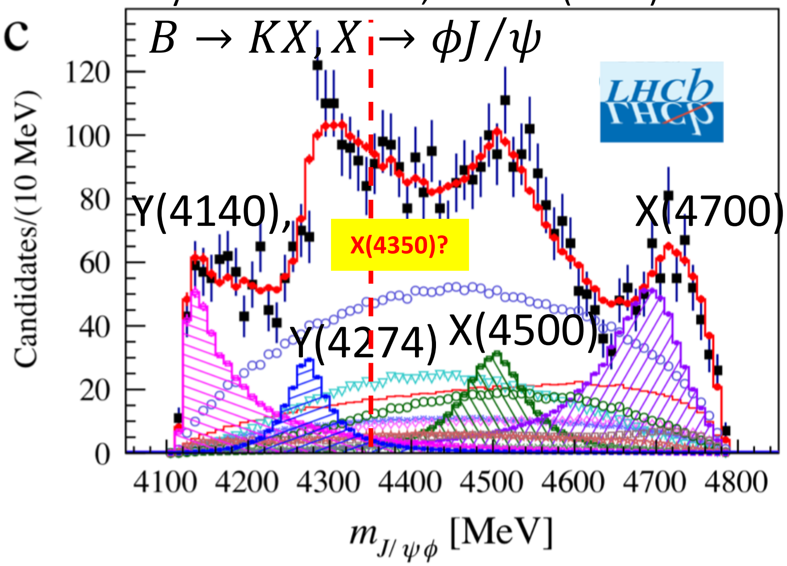
Opportunities at BelleII

Experiment	Scans fb $^{-1}$	$\Upsilon(6S)$ fb $^{-1}$	$\Upsilon(5S)$ fb $^{-1}$ 10^6	$\Upsilon(4S)$ fb $^{-1}$ 10^6	$\Upsilon(3S)$ fb $^{-1}$ 10^6	$\Upsilon(2S)$ fb $^{-1}$ 10^6	$\Upsilon(1S)$ fb $^{-1}$ 10^6
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

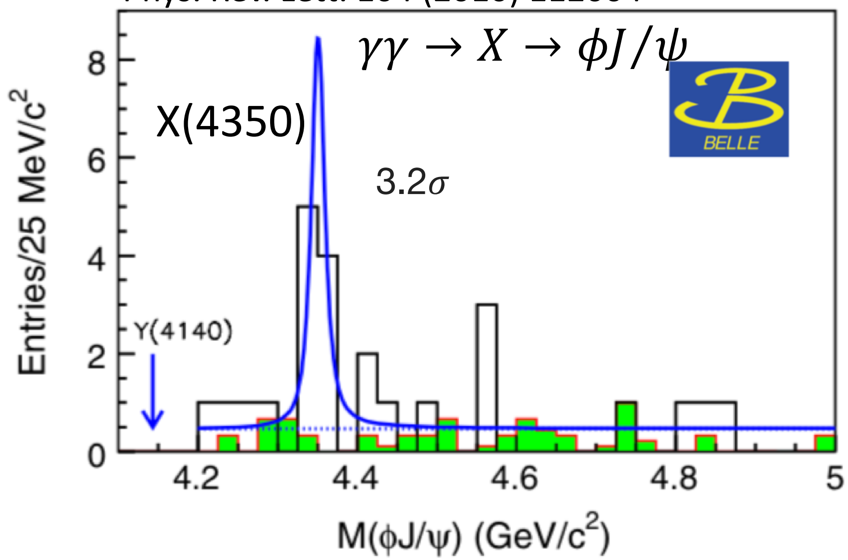
- If we assume BelleII follows the same data taking plan.
- With 100 time larger data set than Babar, BelleII can clarify the existence of X(3915) in $\gamma\gamma \rightarrow X \rightarrow D\overline{D}$
- With 50 time more data at $\Upsilon(4S)$, we can get ~2500 X(3940) and ~1000 X(4160) candidates in $e^+e^- \rightarrow J/\psi + D\overline{D}, D\overline{D}^*, D^*\overline{D}^*$. It will be enough to determine their J^{PC}.
- Searching for these state with large B meson samples also will provide essential information.

C even exotic states in $\phi J/\psi$ final states

Phys. Rev. Lett. 118, 022003 (2017)



Phys. Rev. Lett. 104 (2010) 112004

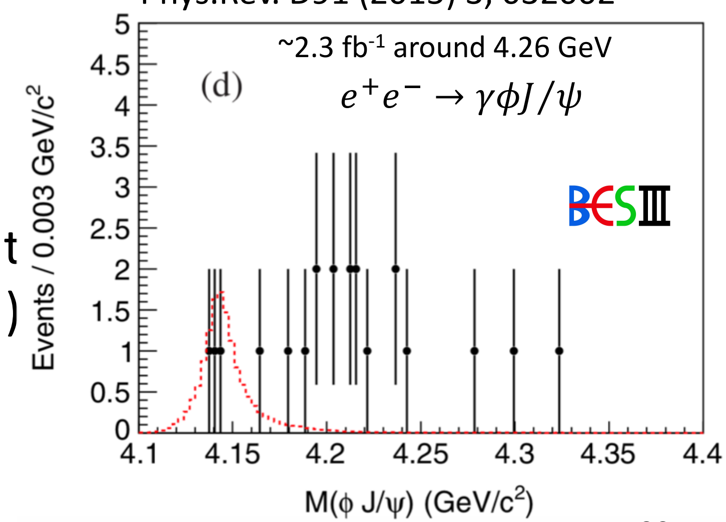


- Why were they only observed in one production process ?
- Not appeared in e^+e^- annihilation

Prospect at BelleII

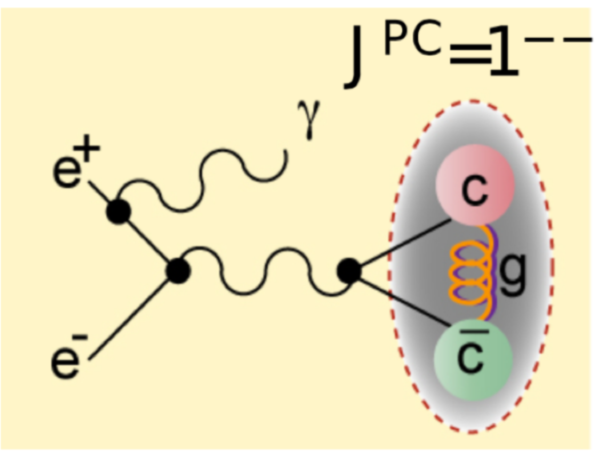
- 4 ab^{-1} data is sufficient to confirm X(4350) at BelleII (estimated by eye, assume same bg.)
- Will have 4~8 time larger data set here at BelleII via $e^+e^- \to \gamma_{isr}\gamma\phi J/\psi$

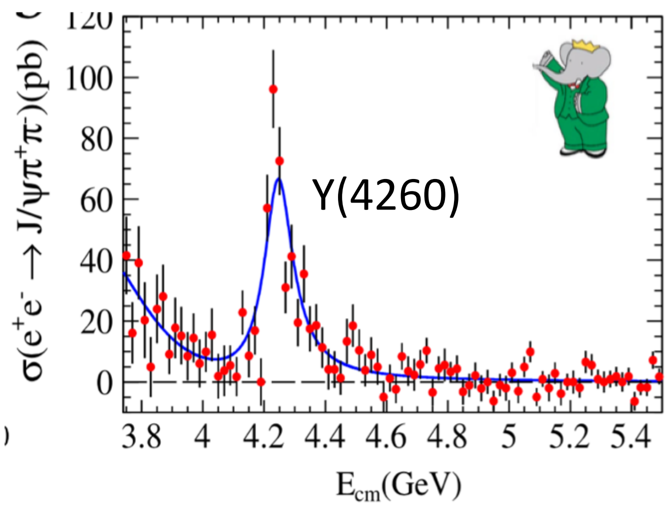
Phys.Rev. D91 (2015) 3, 032002



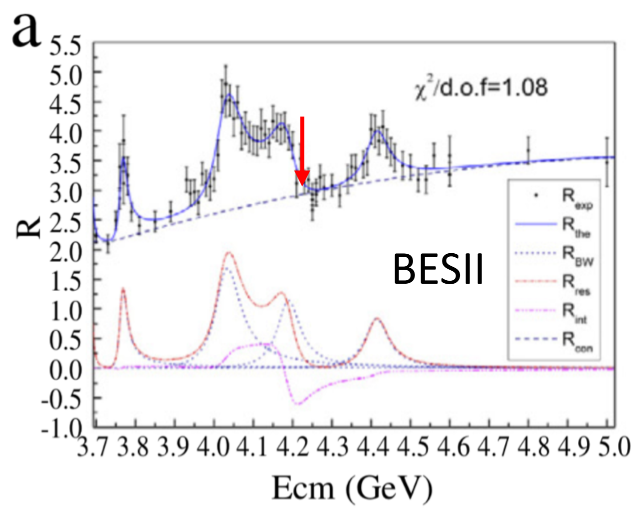
Vector exotic states in e^+e^- annihilation: Y

- e^+e^- annihilation is the most straightforward way to study vector quarkonium-like states.
- Y(4260), Y(4360) and Y(4660) were observed in $e^+e^- \to \pi^+\pi^-\psi(nS)$
- They couple to $\psi(nS)$ strongly but are absent in the open charm production.
- Y(4260) is the candidate for a Hybrid state





Phys. Rev. D 86 (2012) 051102

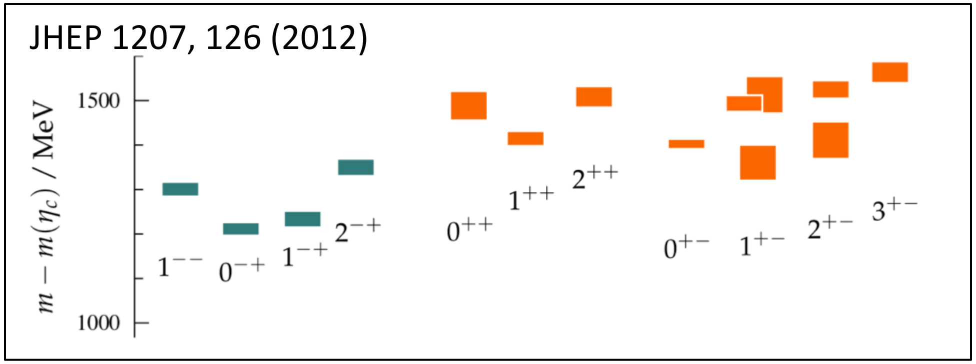


Phys.Lett.B660:315-319,2008

Vector exotic states in e^+e^- annihilation: Y

Is Y(4260) hybrid?

- 1^{-} hybrid charmonium does not couple to the virtual photon very strongly. A dip near 4260 MeV was seen in R scan.
- According to lattice QCD simulation, both the 1^{--} and 1^{-+} hybrid charmonium lie around 4.26 GeV



Phys. Rev. D 79, 094504 (2009)

J^{PC}	mass (MeV)
2^{-+}	~ 4320
1^{--}	4260
1^{-+}	~ 4200
0^{-+}	~ 4190

The lightest charmonium hybrid multiplets based on lattice QCD

Opportunities:

- Search for quantum number partners of Y(4260)
- Search for spin-singlet hidden-charm decay mode, because the $c\bar{c}$ pair is a spin-singlet at initial state .

Vector exotic states in e^+e^- annihilation: Y

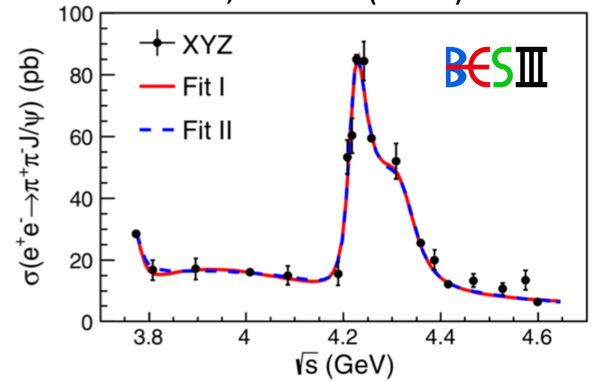
Is Y(4260) one state?

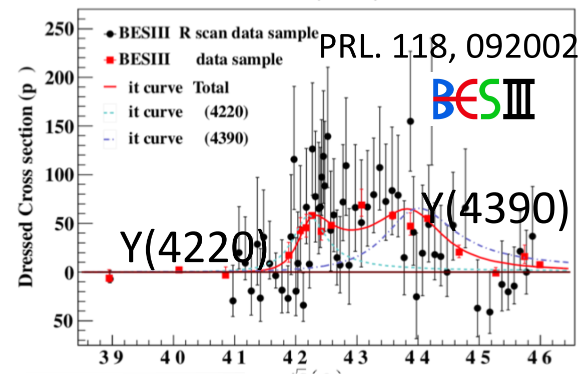
- Recent study of exclusive process $e^+e^- \to \pi^+\pi^- J/\psi, \pi^+\pi^- h_c$ shows a fine structure near 4.2 GeV: Y(4220) and Y(4390)
- To solve the puzzle:
  - More data to pin down the existence of the resonances in this region
  - Explore more exclusive final states with hidden & open charm
  - These searches are also likely to lead to the discovery of new particles

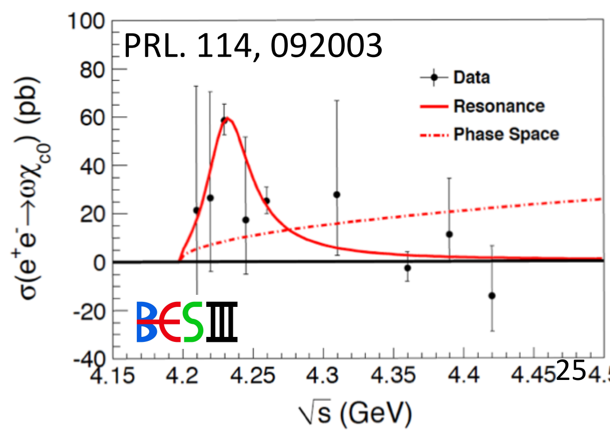
Prospect at BelleII

- With 50 ab^{-1} data at BelleII, we can reduce the error by factor of ~2 (assume same bg.) and have much much higher density of data points in this region!

PRL 118, 092001 (2017)

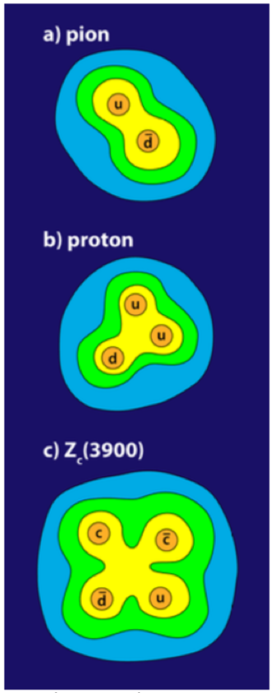




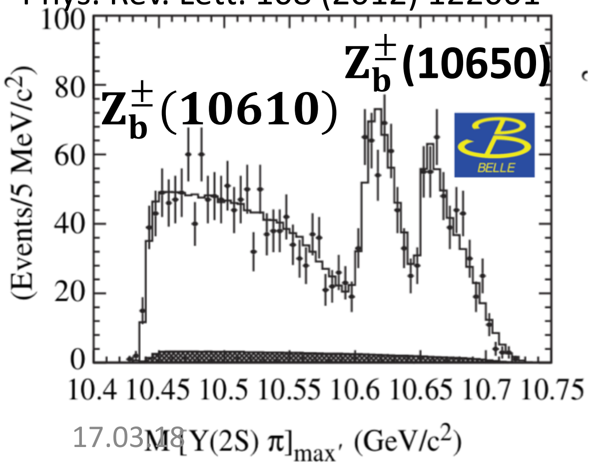


Z_b and Z_c

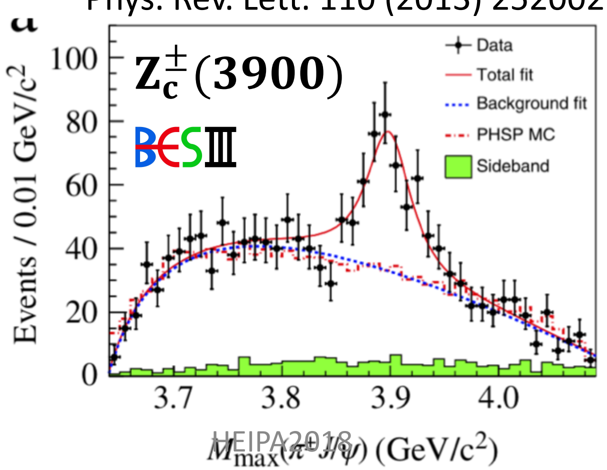
- Although dozens of neutral exotic states were found, despite their unexpected properties, one could not exclude them as conventional quarkonium.
- Their J^{PC} and flavor quantum numbers are compatible with quarkonium.
- Belle discovered $Z_b^{\pm}(10610)/ Z_b^{\pm}(10650)$, whose decay into $\Upsilon\pi^{\pm}$ reveals their constituents to be $b\bar{b}u\bar{d}$.
- BESIII and Belle discovered $Z_c^{\pm}(3900)/Z_c^{\pm}(4020)$, whose decay into $J/\psi\ /h_c\pi^{\pm}$ reveals their constituents to be $c\bar{c}u\bar{d}$.
- Charged quarkonium like states are the smoking gun of exotic states



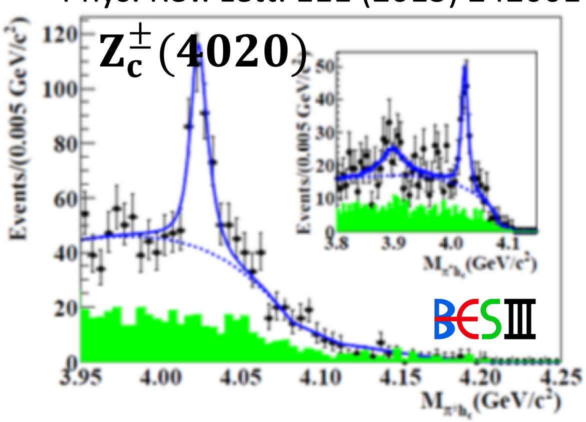
Phys. Rev. Lett. 108 (2012) 122001



Phys. Rev. Lett. 110 (2013) 252002



Phys. Rev. Lett. 111 (2013) 242001



Similarity of $\boldsymbol{Z_b}$ and $\boldsymbol{Z_c}$

They have lot of common features:

- $\boldsymbol{Z_b}$ are close to $\bar{B}B^*$ and $\bar{B}^*B^*$ production threshold
- $I^G J^{PC}$ ($\boldsymbol{Z_b}$)= 1^+1^{+-}
- $\boldsymbol{Z_b}$ Observed both in hidden-bottom modes: $\Upsilon(nS)\pi^\pm$, $h_b(nP)\pi^\pm$ and open-bottom modes: $\bar{B}B^*$ and $\bar{B}^*B^*$
- open-bottom modes: $\bar{B}B^*$ and $\bar{B}^*B^*$ dominate $\boldsymbol{Z_b}$ decay

- $\boldsymbol{Z_c}$ are close to $\bar{D}D^*$ and $\bar{D}^*D^*$ production threshold
- $I^G J^{PC}$ ($\boldsymbol{Z_c}$)= 1^+1^{+-}
- $\boldsymbol{Z_c}$ Observed both in hidden-charmonium modes: J/ψ $/h_c\pi^\pm$ and open-charmonium modes: $\bar{D}D^*$ and $\bar{D}^*D^*$
- open-charmoium modes: $\bar{D}D^*$ and $\bar{D}^*D^*$ dominate $\boldsymbol{Z_c}$ decay

Z_b and Z_c – tetra-quark or molecule?

Are they Tetra-quarks?

- Tetra-quarks will fall apart into a pair of open-flavor mesons or one quarkonium plus light mesons very easily
- Their widths are expected to be large while Z_b / Z_c states are quite narrow
- The higher $Z_b^{\pm}$(10650) state was not observed in the s-wave $\bar{B}B^*$ mode
- The higher $Z_c^{\pm}(4020)$ has not been observed in the s-wave $\bar{D}D^*$ mode

Or Molecule?

- Z_b / Z_c mass are close to $\bar{B}^{(*)}B^*$ and $\bar{D}^{(*)}D^*$
- Narrow widths of the resonances in decay into quarkonium and pion, despite the large phase space, this implies a very small overlap of the wave functions
- X(3872) can be regarded as a I=0 $\bar{D}D^*$ molecule

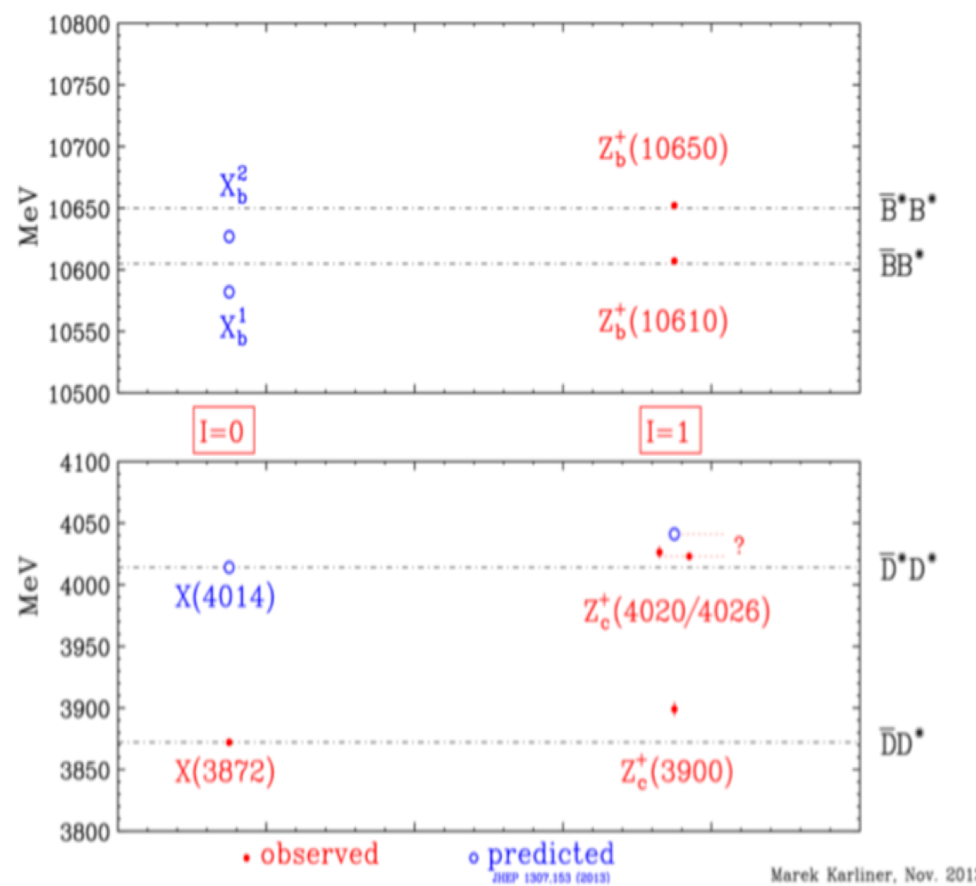
Z_b and Z_c – tetra-quark or molecule?

How to solve the puzzle?

In the molecule framework, there should be serval missing spin partners:

- $X(4014/4013)$ near $\bar{D}^*D^*$ X_b^1 and X_b^2 near $\bar{B}B^*$ and $\bar{B}^*B^*$
- $X(4014/4013)$ can be searched for in ωJ/ψ, $D\bar{D}$, $\bar{D}D^*$. ρJ/ψ would be suppressed
- X_b^1 and X_b^2 can be searched for in $\Upsilon\pi^+\pi^-\pi^0$, $\Upsilon(nS)\gamma$ and $\chi_{bj}\pi^+\pi^-$ $\Upsilon\pi^+\pi^-$ would be suppressed
- Search for Z_b / Z_c decay into $\pi^+\pi^-\pi^0$ η_b/η_c

Marek Karliner DHF14



Summary

- BelleII has the opportunity to solve the puzzles on XYZ states with its unique capabilities.
- Search for flavor-analog exotic states
- Study the discovered XYZ states with various production mechanism and final states
- The first collisions (phaseII) will starts next month.
- The first physics result will come soon!

Thank you for your attention!

Backup