Charmonium-like studies at Belle II

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(On behalf of the Belle II Collaboration)

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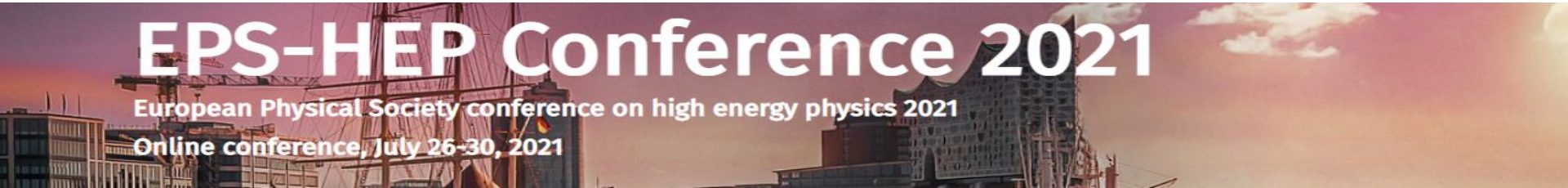
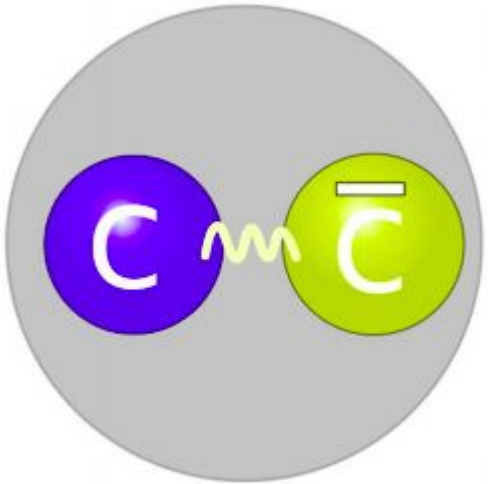


Outline of the talk:

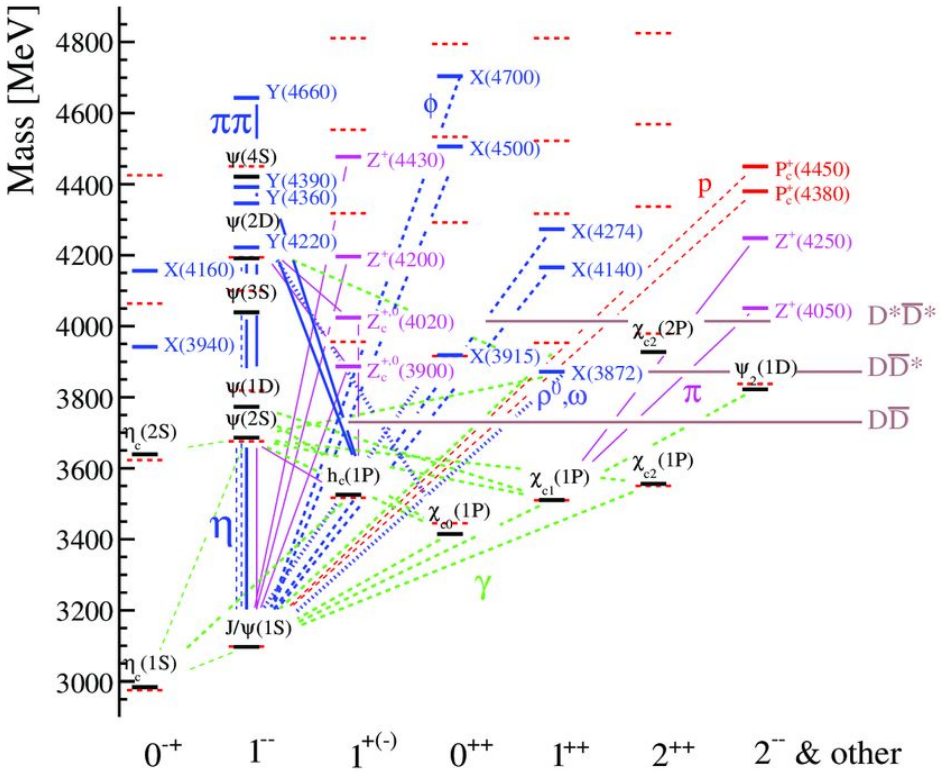
- Introduction to quarkonium and the exotics
- Overview of the Belle II experiment
- X(3872) rediscovery at Belle II
- ISR preliminary results at Belle II
- Summary

Introduction:

- Quarkonium: $q\bar{q}$ meson with a heavy quark (i.e. q = c or b).
- Is a best playground for constituent quark model.
  - Simple two body system.
  - Large mass
    - Non-relativistic, perturbative.
- Also a good playground for exotics
  - Quark model predictions are robust.
- Exotics?
  - Tetraquarks, molecular states, hybrids, glueballs..



Charmonium-like above threshold:



[Rev. Mod. Phys. 90 (2018) 15003]

Observed States:
Conventional Charmonium
Unconventional neutral states
Unconventional charged states
Pentaquark candidates

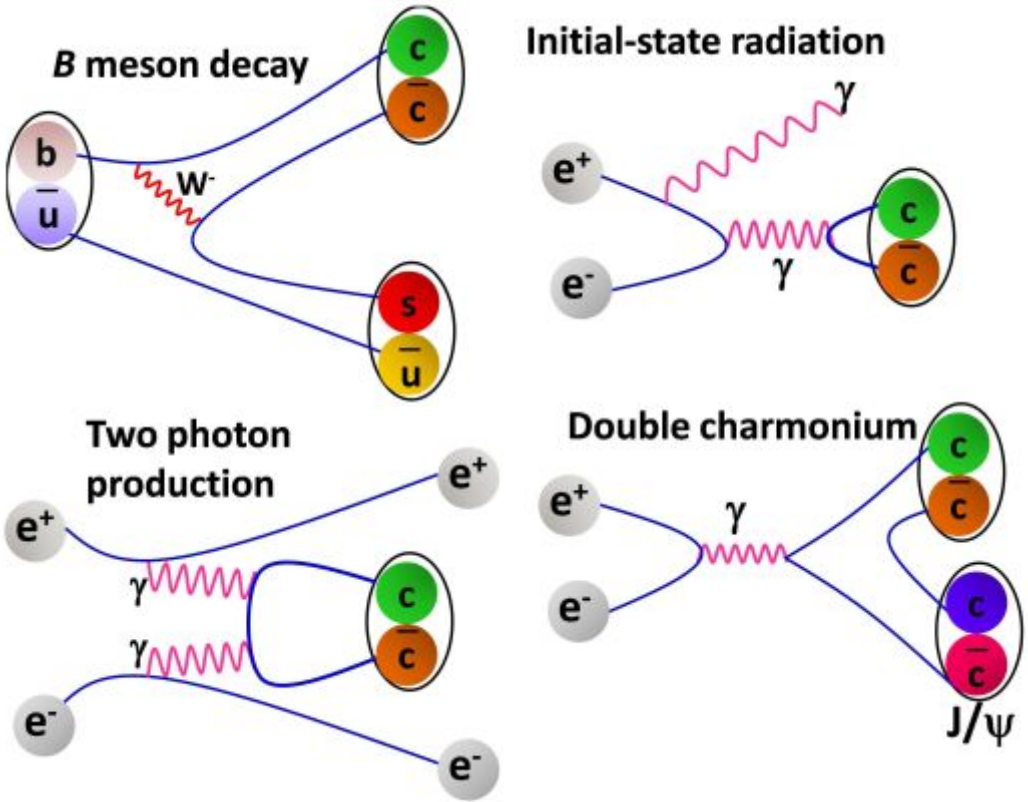
Expected States

Kinematic threshold

- Below threshold: Mostly mesons/baryons bound states.
- Above threshold: Zoo of more complex states so called XYZ states which have not yet been understood.

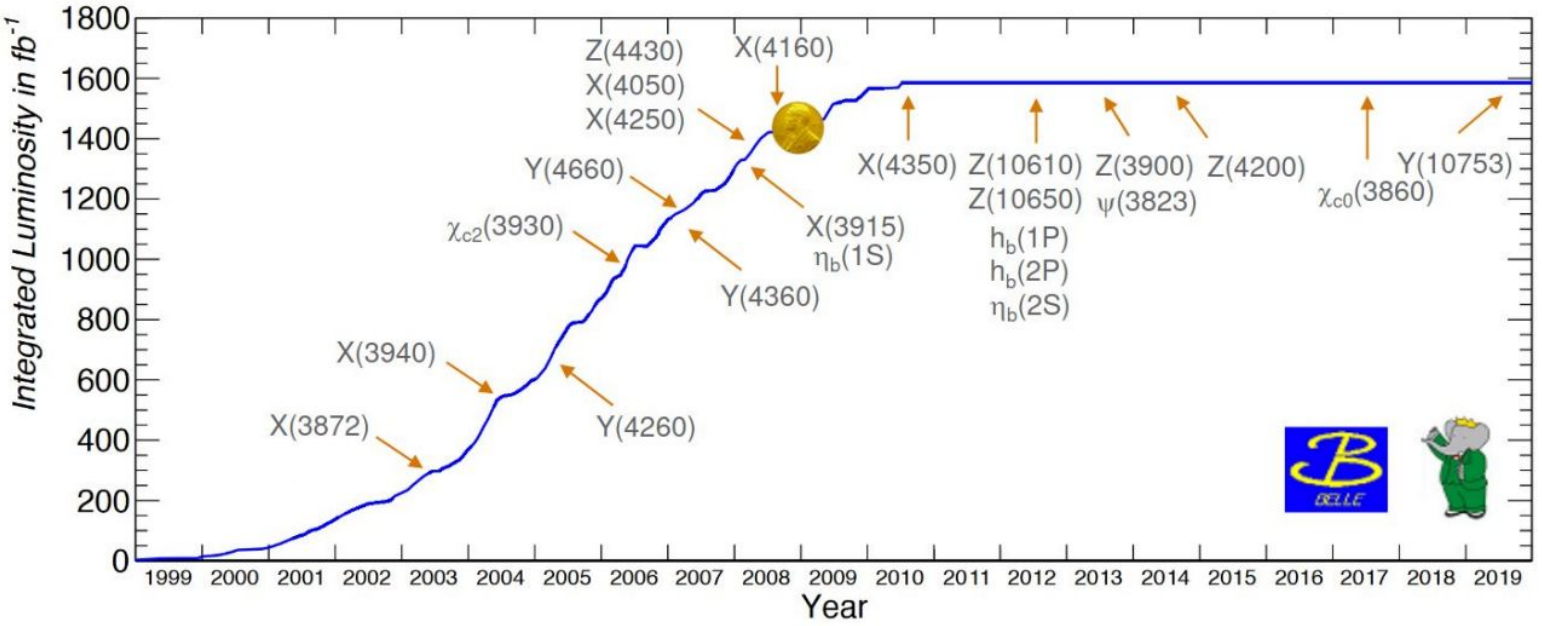
Charmonium Production at B-factories:

- B decay ($B \rightarrow K X_{c\bar{c}}$)
  - $J^{PC} = 0^{-+}, 1^{--}, 1^{++}$
- Initial-state Radiation (ISR)
  - $J^{PC} = 1^{--}$
- Two-photon Process
  - $J^{PC} = = 0^{-+}, 0^{++}, 2^{++}, 2^{-+}$
- Double charmonium
  - e.g. $e^+e^- \rightarrow J/\psi X$ [PRL 98, 082001 (2007)]

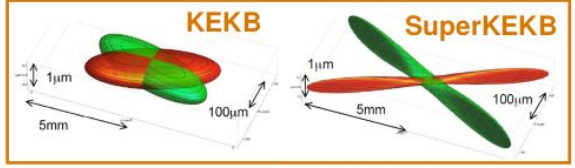


The B-factories Legacy:

- B-factories already provided excited results such as CKM matrix elements, CPV in B Decays and so on.
- It has also made rich contribution to quarkonium spectroscopy.
- First exotic state - X(3872) observed at Belle in 2003.



SuperKEKB & Belle II:



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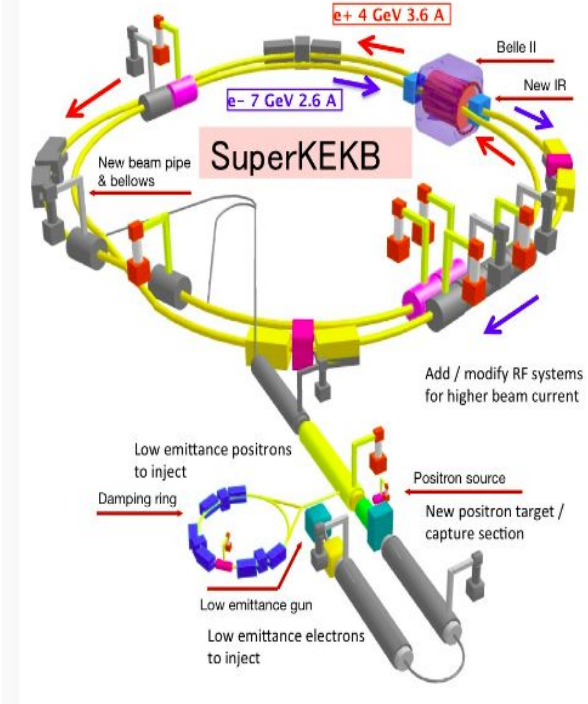
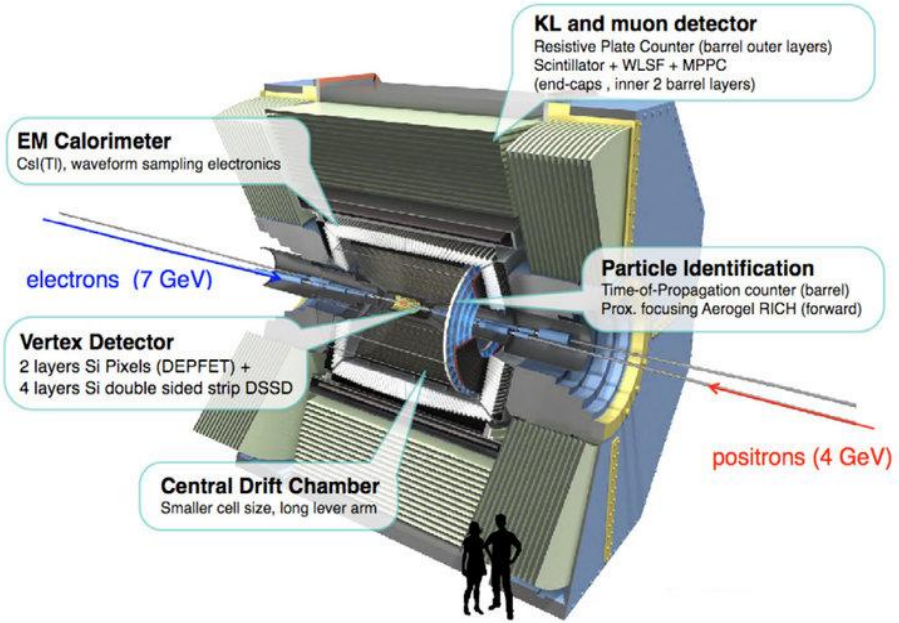
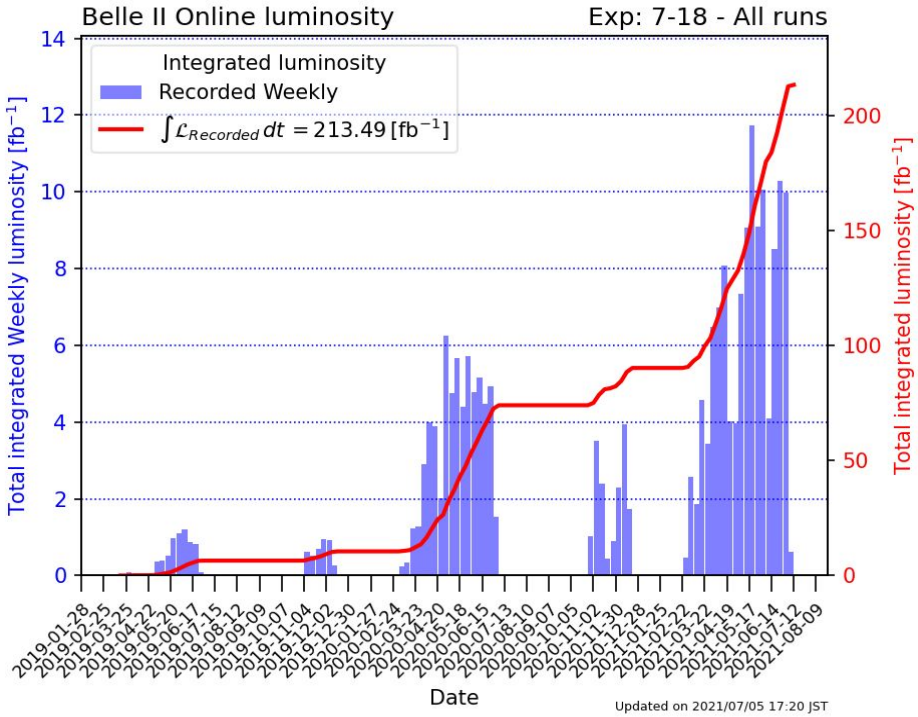
Belle II

- SuperKEKB: Asymmetric e^- (7 GeV) - e^+ (4GeV) collider at KEKB, Japan. $\sqrt{s}$ = 10.58 GeV = m(**Υ(4S)**).
- SuperKEKB goal: >30 x KEKB luminosity.
- Belle II is placed at an interaction point of SuperKEKB.





Belle II Dataset:



- Increasing by: 1-1.5 fb^{-1} per day.
- Luminosity record: 3.1 x 10^{34} $cm^{-2}s^{-1}$.
- Belle II goal: 50 ab^{-1} (~50x Belle data).

X(3872):

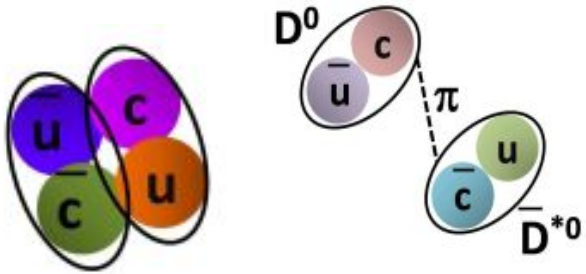
- First discovered at Belle in 2003 in $B \rightarrow K(J/\psi\pi^+\pi^-)$
  - 14.4±4.6 events (4.6σ) PRL 91, 262001 (2003)

- Upper limit from Belle: Γ < 1.2 MeV.
  Measured BW width from LHCb: Γ = 1.19 ± 0.19 MeV.

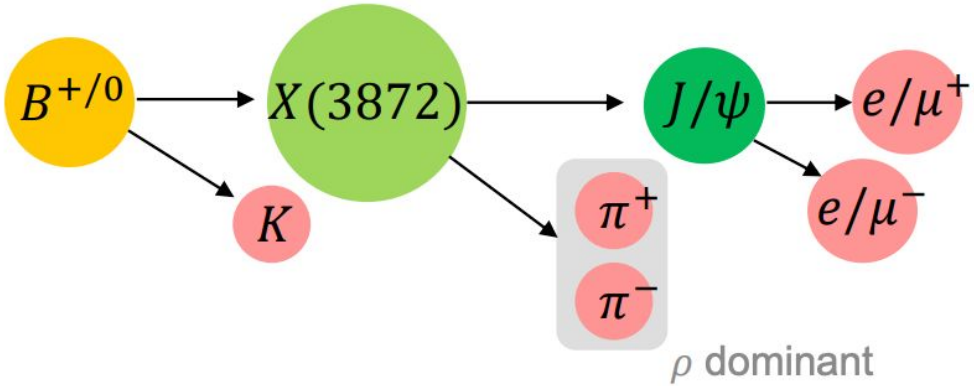
- It has been widely studied in various decay modes.

Productions in	$B \rightarrow KX$, $p\bar{p}$, pp, $e^+e^- \rightarrow \gamma X$
Well established decay modes	$J/\psi\pi^+\pi^-$, $J/\psi\pi^+\pi^-\pi^0$, $J/\psi\gamma$, $\psi(2S)\gamma$, $D\bar{D}\pi$, $D\bar{D}\gamma$, $\pi^0\chi_{c1}$

- Yet the complete nature of this state is unknown.
  - Tetraquark/Molecule..?
  - Needs more experimental results to clarify its nature.



Search for X(3872) at Belle II:

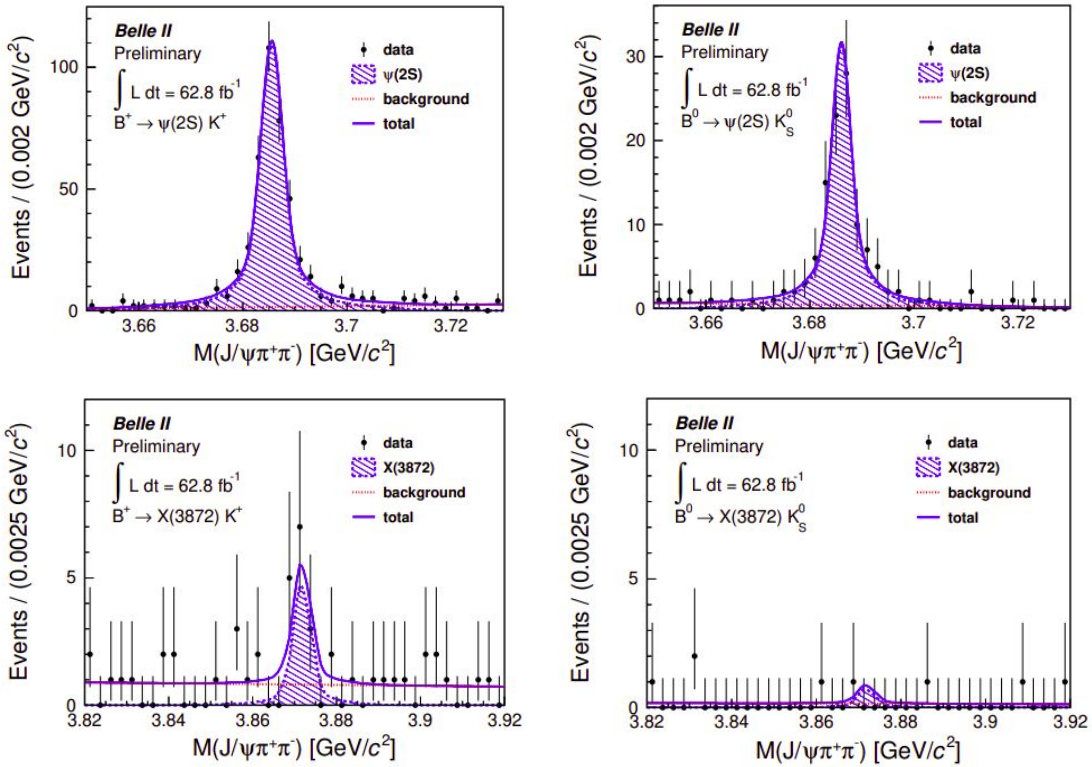


- Data Sample: 62.8 fb^{-1}.
- Reconstruction of final states:
  - $B^{\pm} \rightarrow \pi^+ \pi^- J/\psi(l^+l^-)K^{\pm}$
  - $B^0 \rightarrow \pi^+ \pi^- J/\psi(l^+l^-)K_s$
- Standard Selection criteria:
  - Particle identification.
  - Continuum suppression.
  - Kinematics criteria: $M_{\pi^+\pi^-}$, M_{bc} & $|\Delta E|$.

    $M_{bc} = \sqrt{(E^{*2}_{beam} - \mathbf{p}^{*2}_{B})}$

    $|\Delta E| = E^*_B - E^*_{beam}$

Rediscovery at Belle II:



- Calibration: $B \rightarrow \psi(2S)K$.
- First X(3872) at Belle II:
  - 14.4±4.6 events (4.6σ) Consistent with belle.

[BELLE2-NOTE-PL-2021-002]

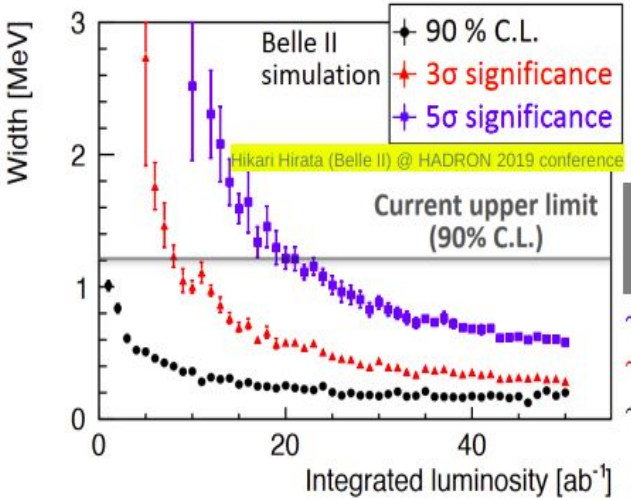
$(B^0 \rightarrow X(3872)K^0)/(B^+ \rightarrow X(3872)K^+) = 0.5$[assumed] Belle, PRD 84, 052004 (2011)

Belle II Potential: XYZ

- Full width measurement at Belle II with $B \to KX(3872)$: $X(3872) \to DD\pi$!
- Due to low Q-value, the mass resolution is extremely good →expected improvement on width with 50 ab^{-1}

mode	Q value [MeV]
$J/\psi\pi^+\pi^-$	495.65±0.17
$D^0\bar{D}^0\pi^0$	7.05±0.18
$D^0\bar{D}^{0*}$	0.01±0.18

- Search for other exotics such as $Z_c(3900)$ at DD* threshold (better slow pion reconstruction efficiency at Belle II > 60%).



Current WORLD AVERAGE from LHCb
$\Gamma = 1.19 \pm 0.19$ MeV
JHEP08(2020)123 / PRD102,092005(2020)

~570 keV
~280 keV
~180 keV

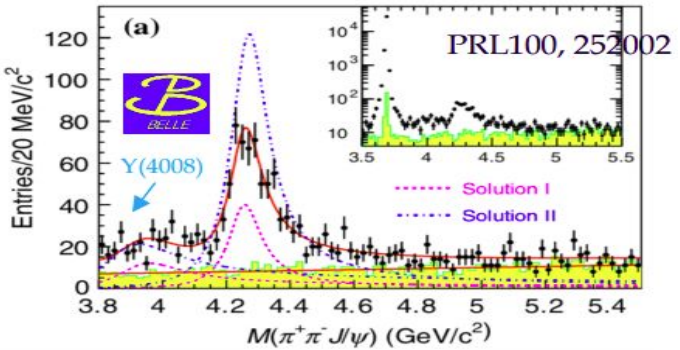
- Projection with 50 ab^{-1} (extrapolated from belle):

State	Production and Decay	N
X(3872)	B→KX(3872), X(3872)→J/Ψπ+π-	~14400
Y(4230)	ISR, Y(4230)→J/Ψπ+π-	~29600
Z(4430)	B→K±Z(4430),Z(4430)→J/Ψπ±	~10200

Belle II TDR: arXiv1011.0352

Charmonium (-like) ISR studies at B-factories

- At Belle, many exotic states have been observed in ISR processes, including Y(4260), Y(4630/4660), etc.
- The process $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ via ISR at C.M. energies upto 5 GeV was first studied by BaBar, where, an unexpected structure at about 4.26 GeV was observed clearly.
  - Which is referred to as Y(4260) state.
  - Subsequently, confirmed by Belle & BESIII in the same process.
- Besides Y(4260), Belle & BESIII also observed a broad excess near 4 GeV, called Y(4008).
- However, the nature of the events at around 4 GeV/c^2 is still ambiguous.
- Therefore, it is necessary to identify the existences of Y(4008) and Y(4320) in $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ at Belle II with a large number of data samples.



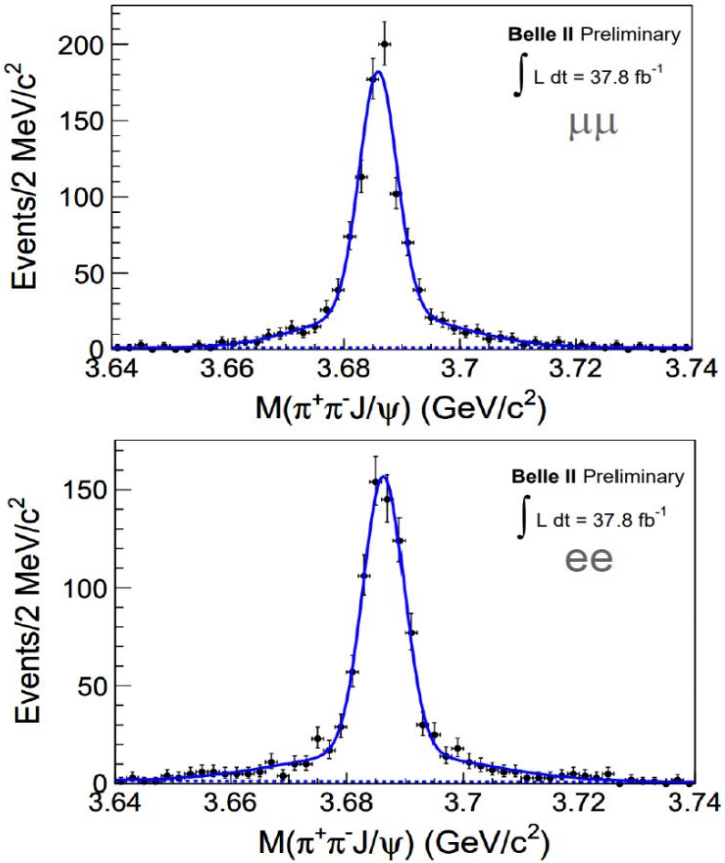
ISR Preliminary results at Belle II

- Reconstruction: $e^+e^- \gamma_{ISR} \rightarrow \pi^+\pi^- J/\psi(l^+l^-)$ final states
  - Nominal PID requirements.
  - $|M(J/\psi) - m_{J/\psi}| < 75$ MeV/c^2.
  - $|M^2_{recoil}(\pi^+\pi^- J/\psi)| < 2$ GeV/c^2.

- Clear observation of ISR $\psi(2S)$ signals.

- Next step: Y(4260) rediscovery.

  Expect ~60 total events per 100 fb^{-1}.



[BELLE2-NOTE-PH-2020-060]

Belle II Potential: ISR

- ISR is a useful tool to study $J^{PC}=1^{--}$ states below the center-of-mass energy.
- Fine structures can be investigated with ISR.
- Line shape of the Y(4260).
- Search for strange partner of $Z_c(3900)^{\pm}$ called the, Z_{cs} in KKJ/ψ.
- Cross-sections of exclusive $c\bar{c}$ + hadrons.

Golden Channels	$E_{c.m.}$ (GeV)	Statistical error (%)	Related XYZ states
$\pi^+\pi^- J/\psi$	4.23	7.5 (3.0)	$Y(4008)$, $Y(4260)$, $Z_c(3900)$
$\pi^+\pi^-\psi(2S)$	4.36	12 (5.0)	$Y(4260)$, $Y(4360)$, $Y(4660)$, $Z_c(4050)$
$K^+K^- J/\psi$	4.53	15 (6.5)	Z_{cs}
$\pi^+\pi^- h_c$	4.23	15 (6.5)	$Y(4220)$, $Y(4390)$, $Z_c(4020)$, $Z_c(4025)$
$\omega\chi_{c0}$	4.23	35 (15)	$Y(4220)$

50 ab^{-1}

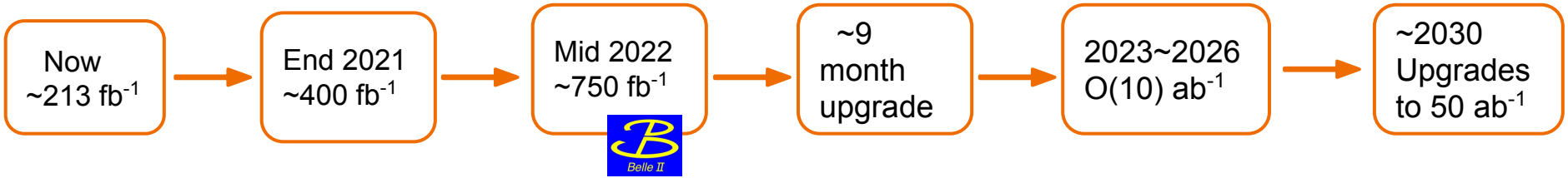
10 ab^{-1}

Belle II TDR: arXiv1011.0352

- ISR analysis process is a unique case at e^+- e^- machines.

Summary:

- Current Recorded Luminosity: ~ 213 fb^{-1}.



- Quarkonium/XYZ is the one of the main component of the physics program.
- With the significant increase of statistics compared to Belle, Belle II can measure
  - more precisely the line shapes of the states,
  - determine their spin-parities,
  - search for new decay channels.
- Statistics soon compared to BaBar/Belle.

Stay Tuned!

Thank You!

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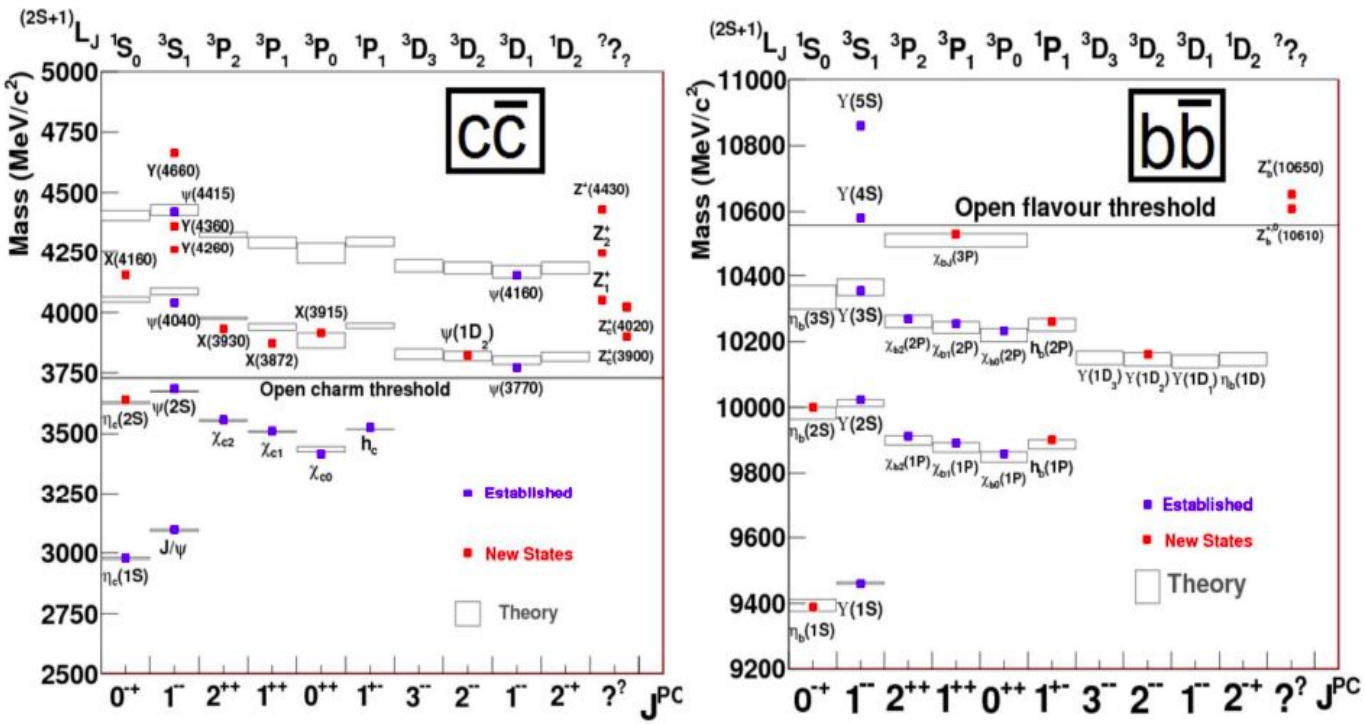
Belle II

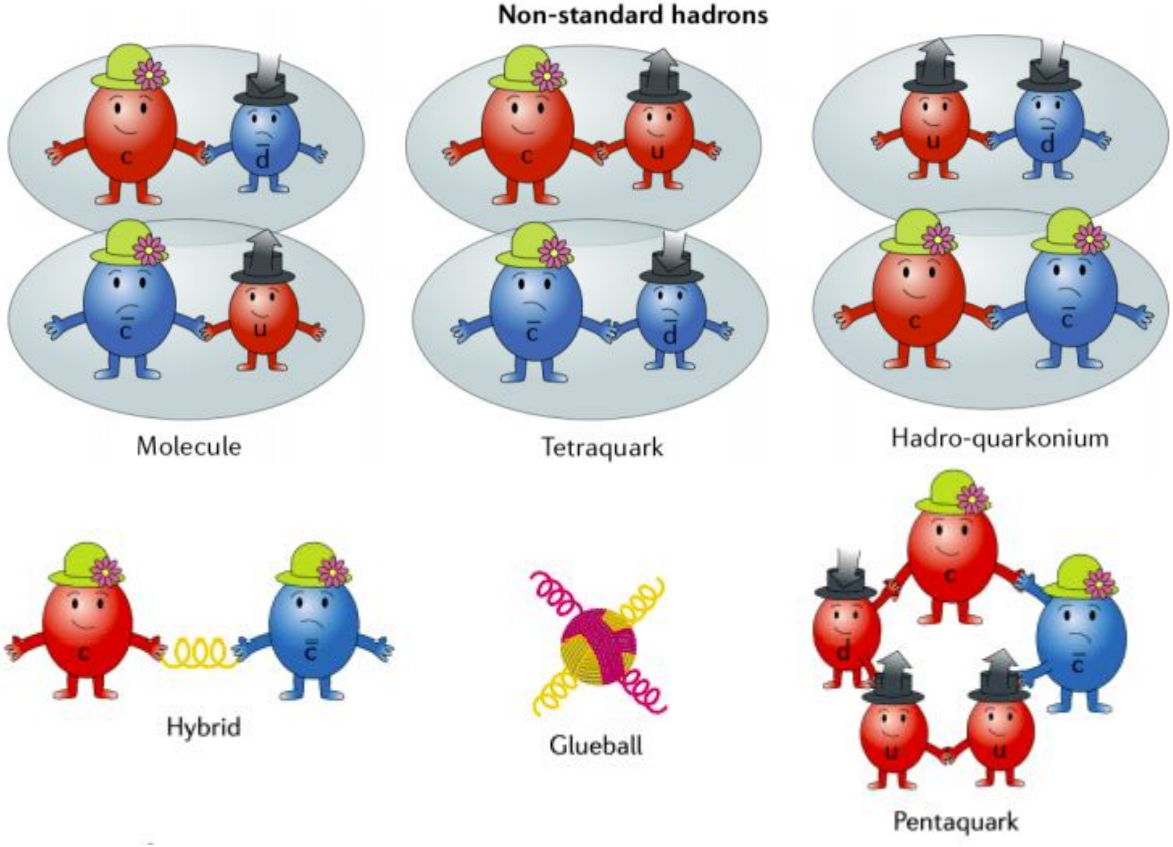
Back Up

Quarkonium Summary:



- Quarkonium: $q\bar{q}$: the simplest system of hadron
- Good agreement below open flavor threshold.
- Exotic candidates, so called XYZ states discovered.

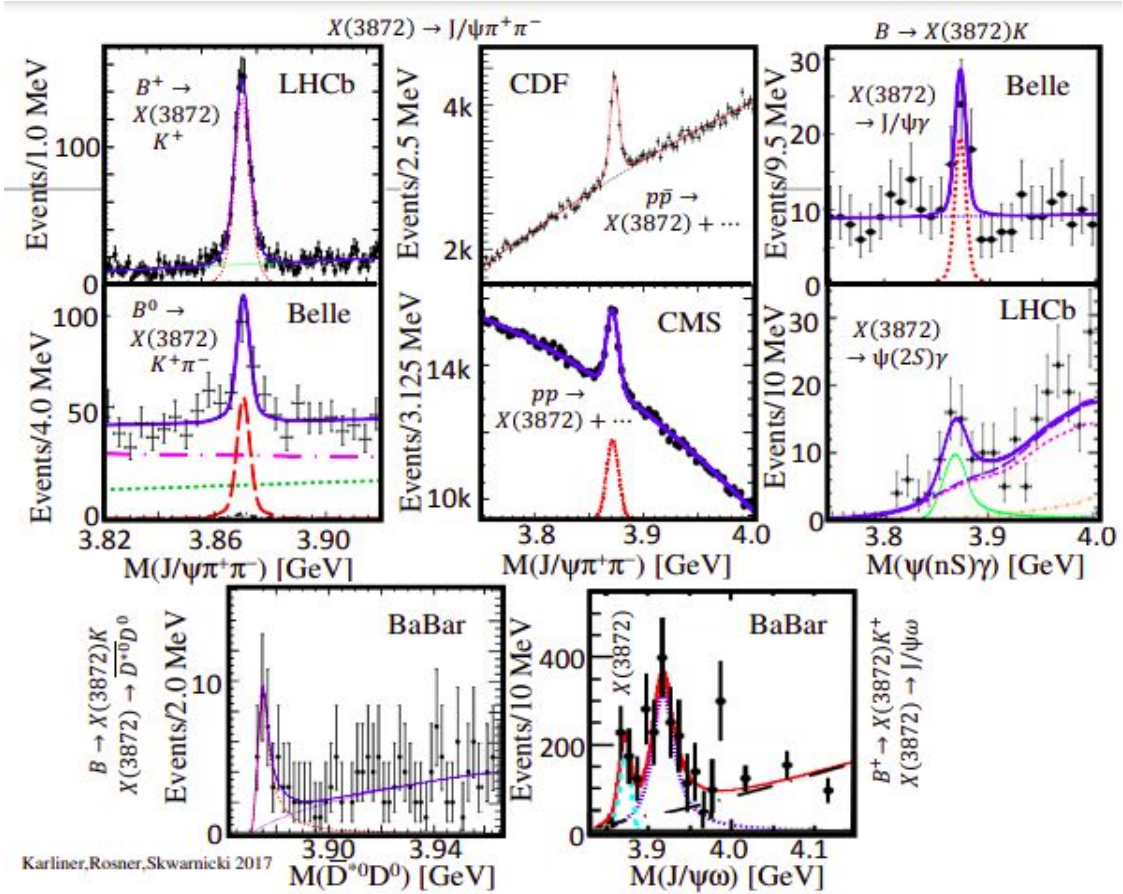
Possible types of Exotic states?



The exotic color-neutral combinations allowed in SM - proposed by Gell-Mann and Zweig, includes tetra-quarks ($qq\bar{q}\bar{q}$), penta-quarks ($qqqq\bar{q}$), glue-balls (gg), and so on.

[Nature Reviews Physics 1, 480 (2019)

X(3872):



[Ann. Rev. Nucl. Part. Sci. 68 (2018) 17]