Review of charmonium(-like) results at Belle and Belle II

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On behalf of the Belle and Belle II Collaborations

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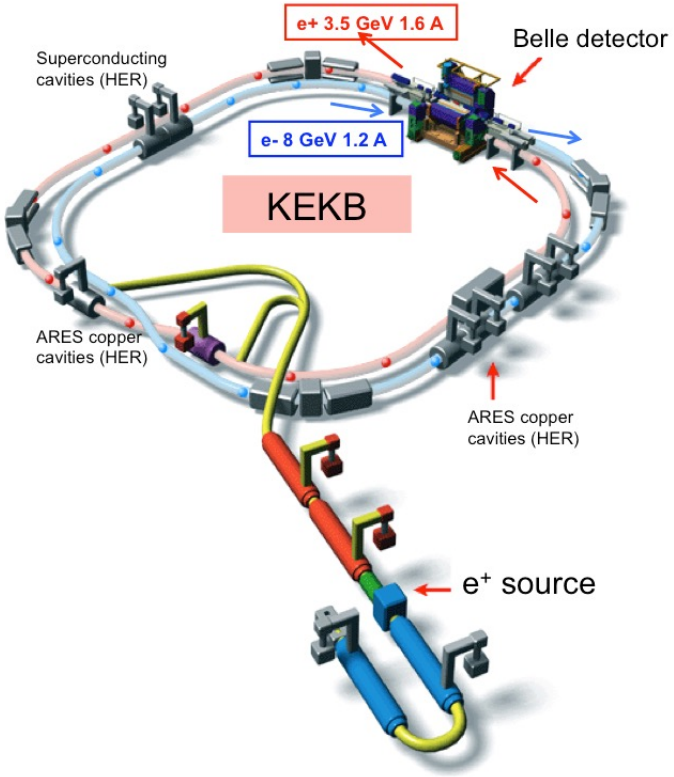
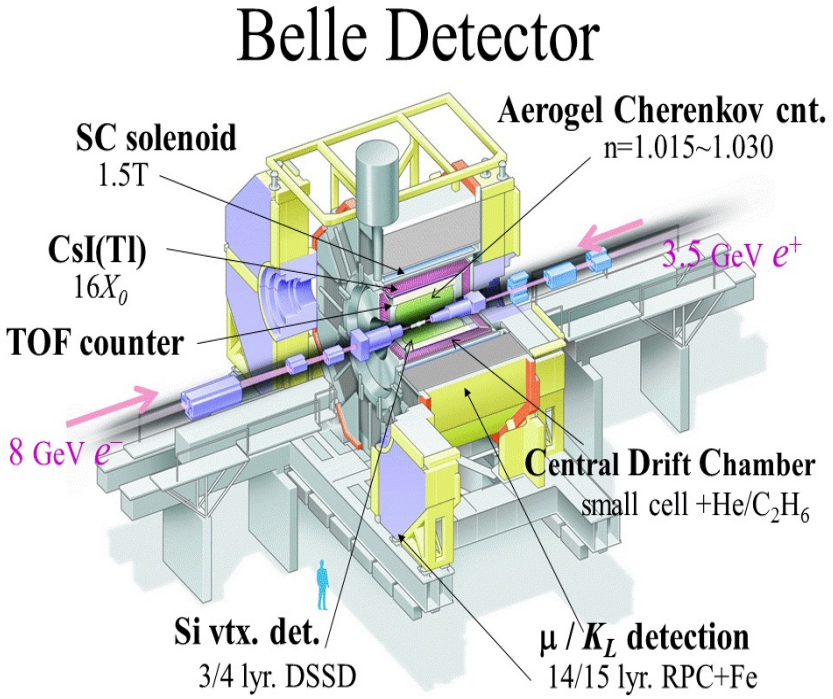
KEKB and Belle

$\sqrt{s} \sim 10.6$ GeV

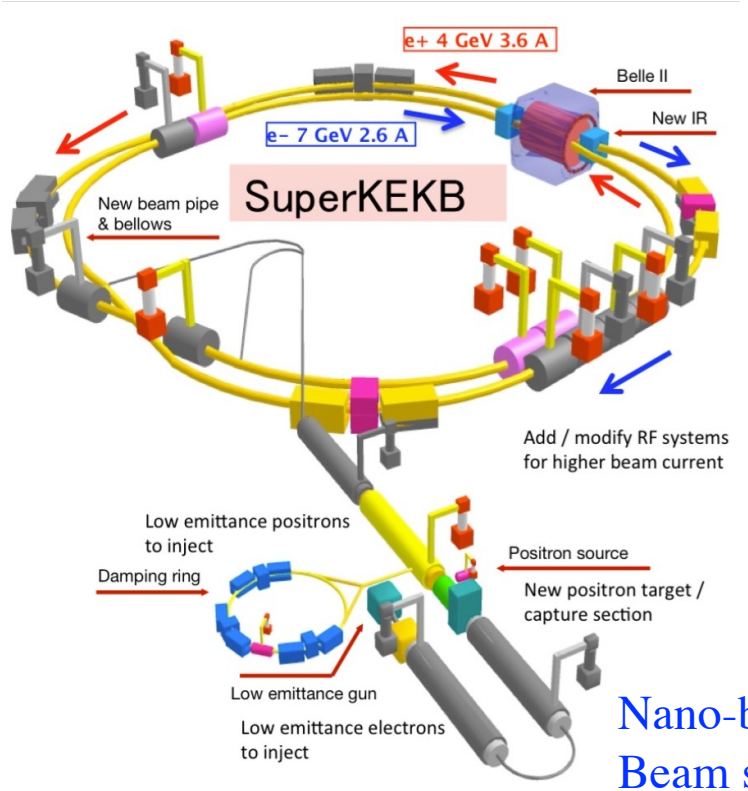
- ✓ Peak luminosity: $2.11\times10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- ✓ Integrated luminosity (~980 fb^{-1} in total):

  $\Upsilon(5S)$: 121 fb^{-1}, $\Upsilon(4S)$: 711 fb^{-1}, $\Upsilon(3S)$: 3 fb^{-1},
  $\Upsilon(2S)$: 25 fb^{-1}, $\Upsilon(1S)$: 6 fb^{-1}, continuum: 90 fb^{-1}





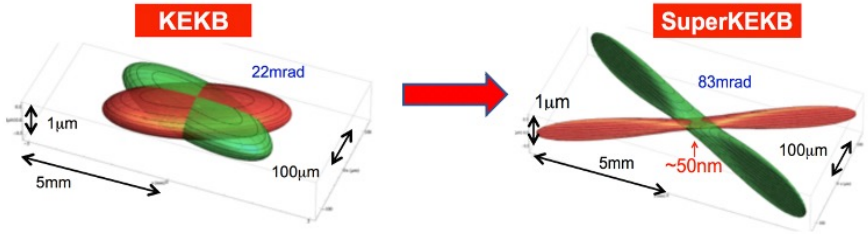
SuperKEKB and Belle II

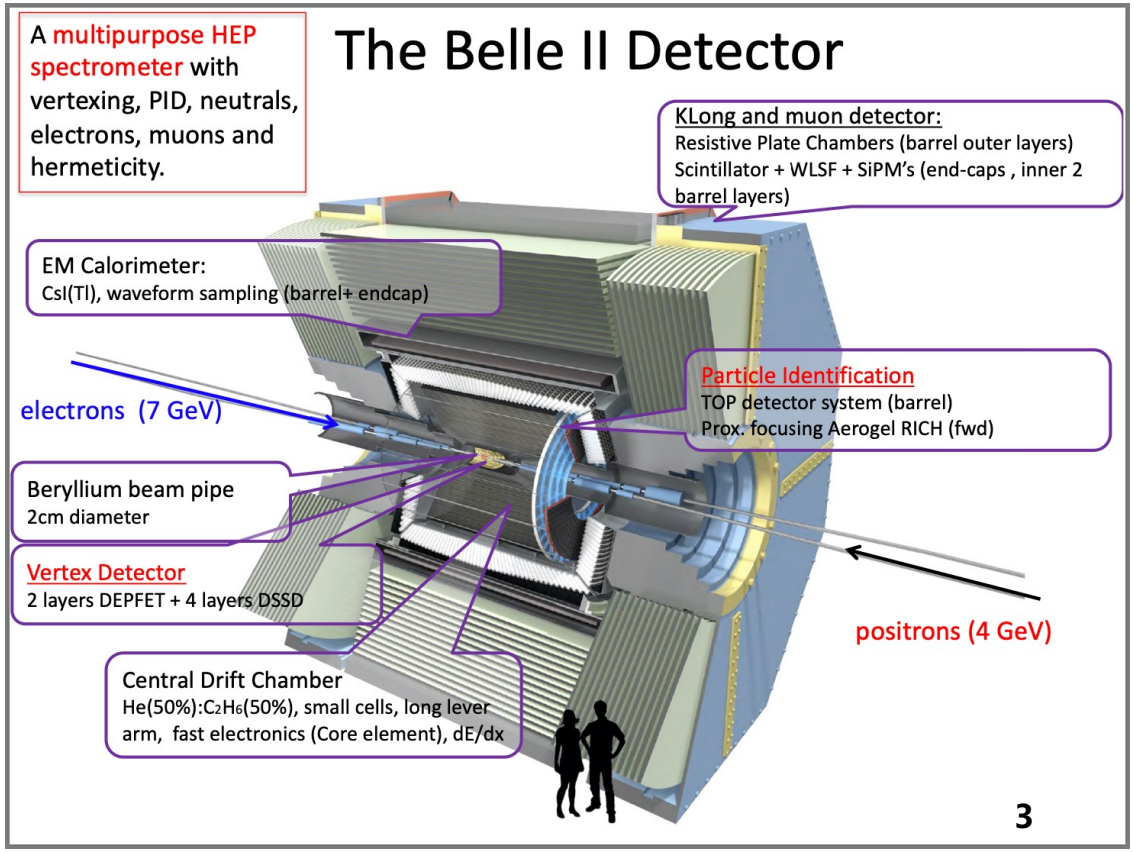


- ✓ Achieved peak luminosity: 0.5×10^{35} $cm^{-2}s^{-1}$
- ✓ Integrated luminosity: 577/fb
- ✓ 42 fb^{-1} off-resonance, 60 MeV below $\Upsilon(4S)$
- ✓ 19 fb^{-1} energy scan between 10.6 to 10.8 GeV for exotic hadron studies

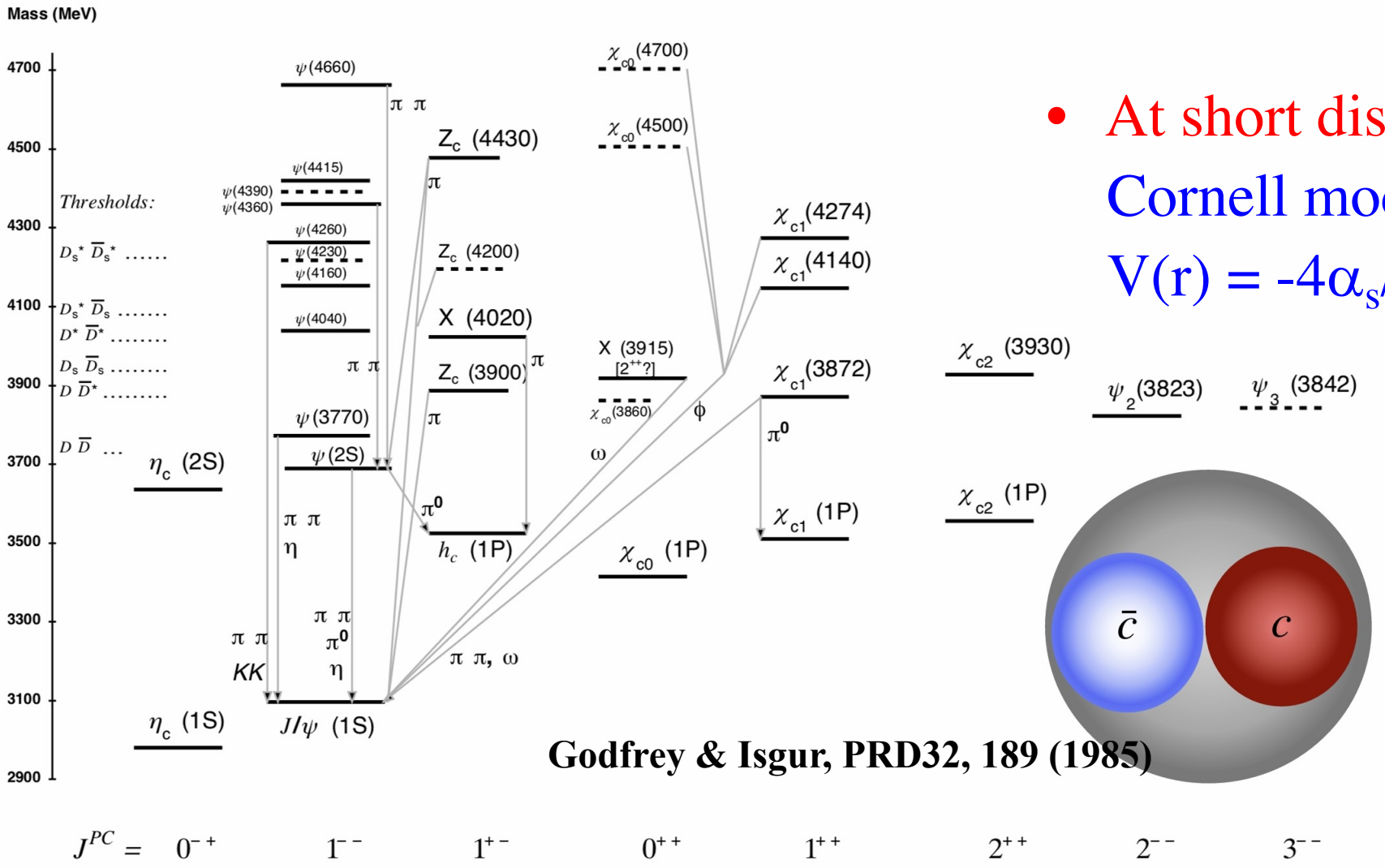
$\sqrt{s} \sim 10.58$ GeV

Nano-beam design:
Beam squeezing: ×20 smaller
Target luminosity: KEKB×40





Charmonium(-like) Spectrum



Godfrey & Isgur, PRD32, 189 (1985)

- At short distance
  Cornell model works pretty well
  $V(r) = -4\alpha_s/3r + kr$

$n^{(2S+1)}L_J$

n radial quantum number

S total spin of c & cbar

L orbital angular momentum

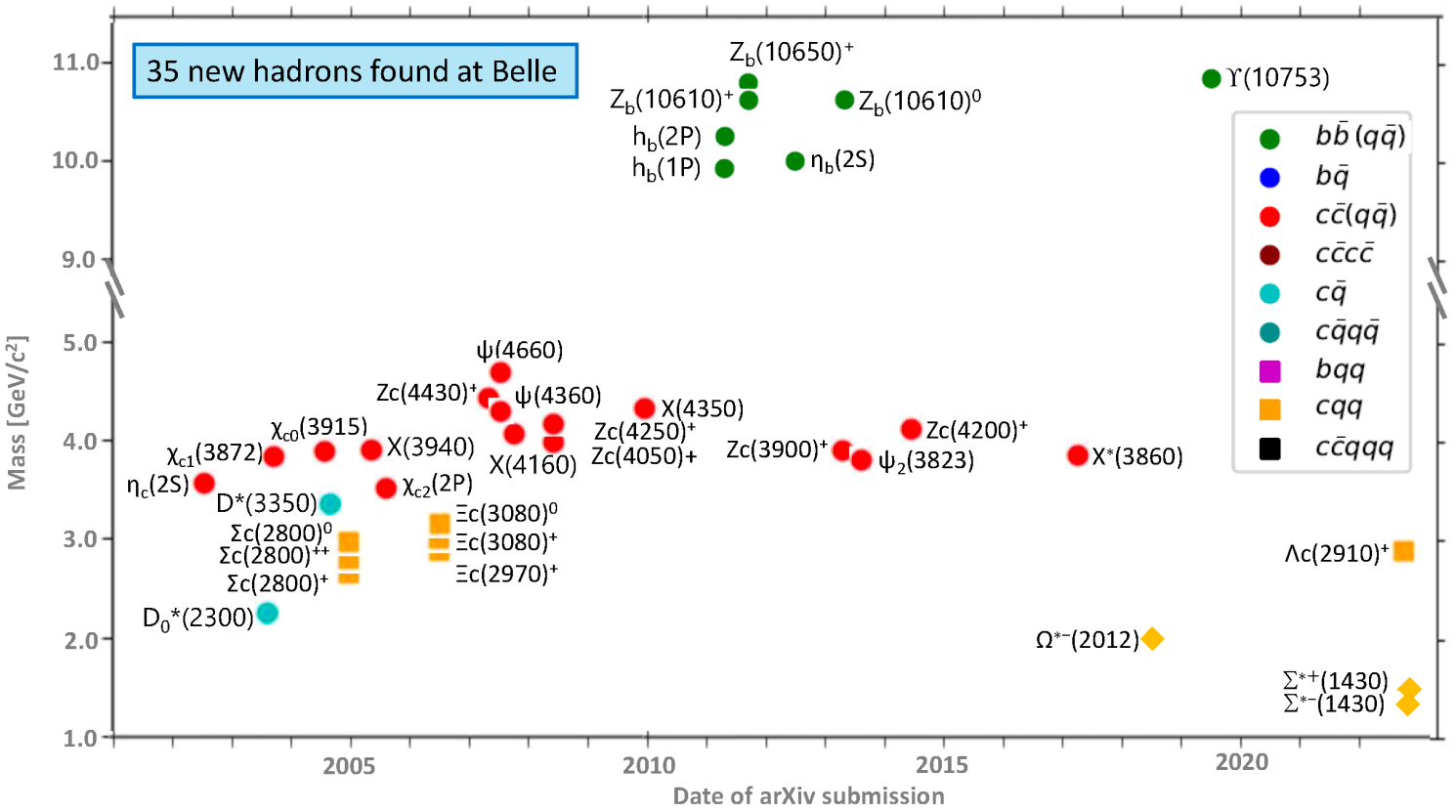
L = 0, 1, 2 ... correspond to S, P, D, …

$J = S + L$

$P = (-1)^{L+1}$ parity

$C = (-1)^{L+S}$ charge conj.

35 new hadrons found at Belle

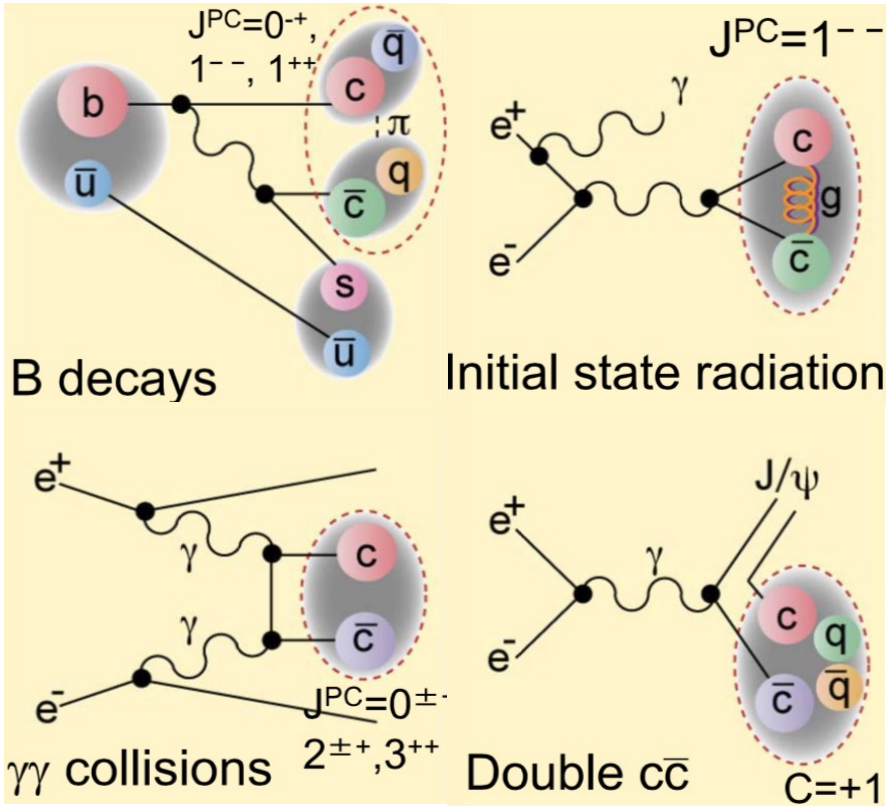


https://qwg.ph.nat.tum.de/exoticshub/

35 new hadrons were found at Belle. **10 of these are "exotic"** and cannot be explained in the conventional quark model while the nature of 8 of them are still under investigation. The remaining 17 states are consistent with the quark model. Measurements of all these states will provide critical insights for QCD.

Production of Charmonium(-like) states at B-factory

- **B decay ($B \to KX_{c\bar{c}}$)**
  - ✓ CKM favored process, large branching fractions 10^{-3}~10^{-4}
  - ✓ $J^{PC} = 0^{-+}, 1^{--}, 1^{++}, \ldots$
- **Initial-state radiation (ISR)**
  - ✓ $J^{PC} = 1^{--}$
- **Two-photon process**
  - ✓ $J^{PC} = 0^{-+}, 0^{++}, 2^{++}, 2^{-+}, \ldots$
- **Double charmonium**
  - ✓ e.g. $e^+e^- \to J/\psi X(3940)$ [PRL 98,082001(2007)]

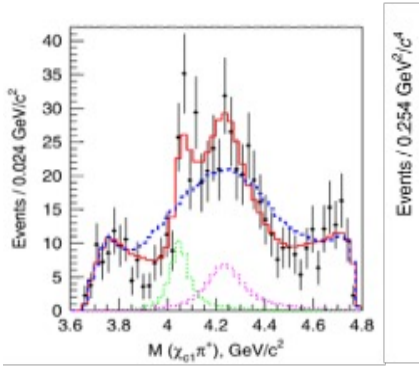


Expected statistics @50 ab^{-1} of XYZ

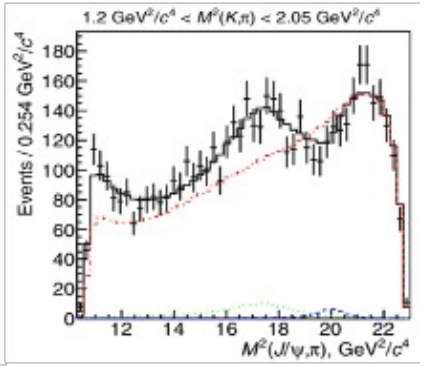
State	Production and Decay	N
X(3872)	$B \to K$X(3872), X(3872)$\to J/\psi\pi^+\pi^-$	$\simeq$14400
Y(4260)	ISR, Y(4260)$\to J/\psi\pi^+\pi^-$	$\simeq$29600
Z(4430)	$B \to K^{\mp}$Z(4430), Z(4430)$\to J/\psi\pi^{\pm}$	$\simeq$10200

Charmonium(-like) states via B decays

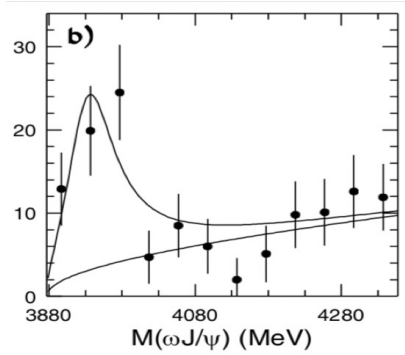
- Confirm Z_c states $Z(4050)^+$, $Z(4200)^+$, $Z(4250)^+$ and search for neutral partners
- Full amplitude analysis to $B \to K\omega J/\psi$ and $B \to K\omega\chi_{c1}$ to determine the spin-parties of $X(3915)$, $Z(4050)^+$ and $Z(4250)^+$.
- Confirmation of $X(3872)$ width measurement with $D^0\bar{D}^0\pi^0$ mode, search for more open-flavor decay modes, e.g., $B \to K(D\bar{D})$, $B \to K(D\bar{D}^*)$, $B \to K(D^*\bar{D}^*)$, $B \to K(D\bar{D}^{**})$… with more B mesons
- Absolute branching fractions are unique for Belle II
- Systematic investigations of charmonium plus light hadron final states: $\boldsymbol{B \to K(c\bar{c}+h)}$



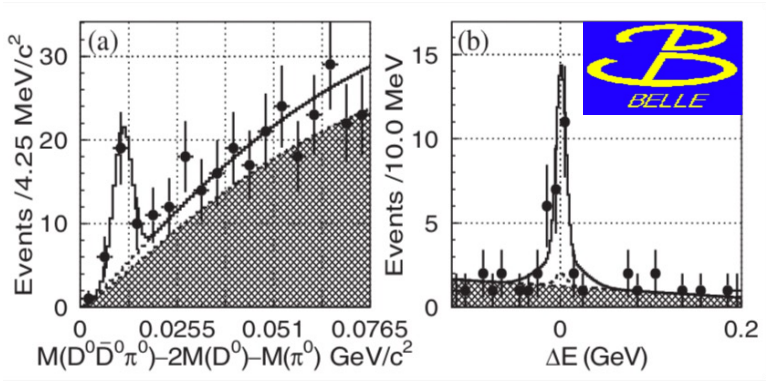
$Z(4050/4250) \to \pi^+\chi_{c1}$
PRD 78,072004



$Z(4200/4430) \to \pi^+J/\psi$
PRD 90,112009



$X(3915) \to \omega J/\psi$
PRL 94,182002

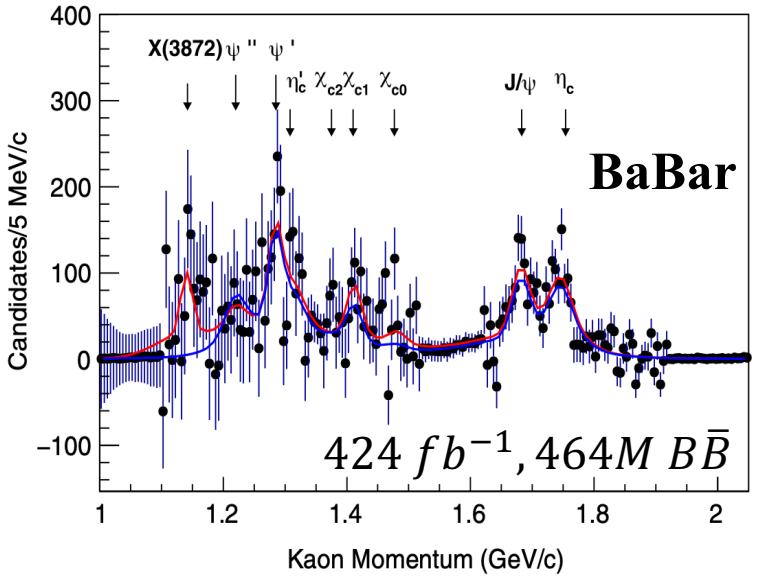


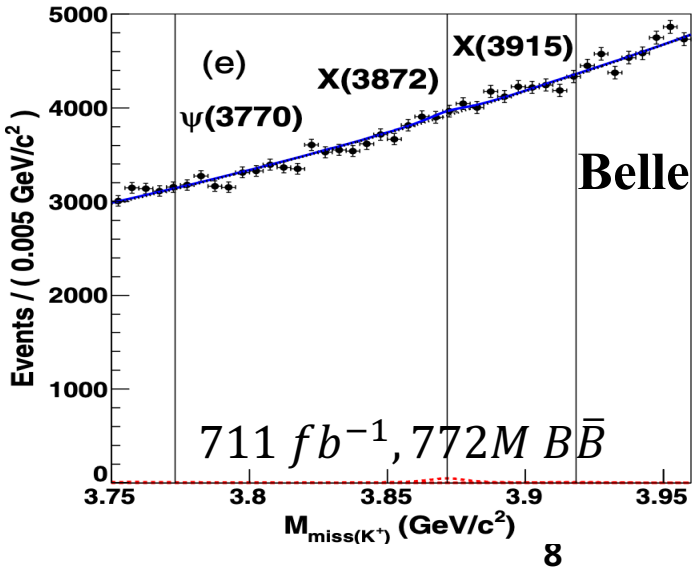
$B \to KX(3872)(\to D^0\bar{D}^0\pi^0)$
PRL 97,162002

☞ Inclusive measurement of $Br(B^{\pm} \to K^{\pm}X(3872))$

- Determination of the $\mathrm{Br}(\mathrm{B}^{\pm} \to X(3872)K^{\pm})$ leads to $\mathrm{Br}(X(3872) \to \pi^{+}\pi^{-}J/\psi)$, bringing useful information regarding complex nature of the $X(3872)$
- Experimental measurements:
  - ✓ Belle: $Br(B^{+} \to K^{+}X) < 2.6\times10^{-4}$ [PRD 97,012005 (2018)]
  - ✓ BABAR: $Br(B^{+} \to K^{+}X) = (2.1 \pm 0.6 \pm 0.3)\times10^{-4}$ [PRL 124, 152001 (2020)]
- Theoretical calculations: $Br(B^{+} \to K^{+}X)$
  - ✓ $Br(B^{+} \to K^{+}X_{c\bar{c}}) = \left(7.88^{+4.87}_{-3.76} \text{ or } 3.8^{+0.9+0.6+0.3}_{-0.8-0.5-0.2}\right)\times10^{-4}$, [CPC 41.1(2017):03101]
  - ✓ $Br\left(B^{+} \to K^{+}X_{tetraq}\right) = (2.1 \pm 1.0)\times10^{-4}$ [arXiv:2208.07990 (2022)]
  - ✓ $Br(B^{+} \to K^{+}X_{mol}) = (0.07\sim1)\times10^{-4}$

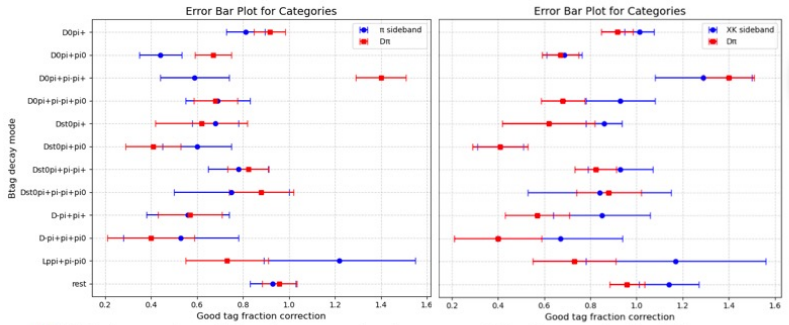
Branching fraction	Structure
$\mathcal{B}(\mathrm{X}(3872) \to \mathrm{J}/\psi\pi^{+}\pi^{-})$ $\sim 50\%$	Tetraquark State [PRD 71, 014028 (2005)]
$\mathcal{B}(\mathrm{X}(3872) \to \mathrm{J}/\psi\pi^{+}\pi^{-})$ $< 10\%$	Molecular state [PRD 72, 054022 (2005), PRD 69, 054008 (2004)]



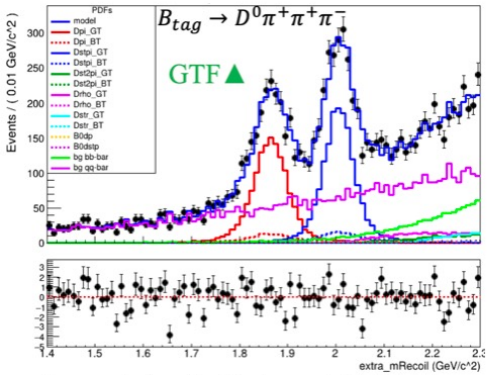


☞ Inclusive measurement of $Br(B^{\pm} \to K^{\pm}X(3872))$

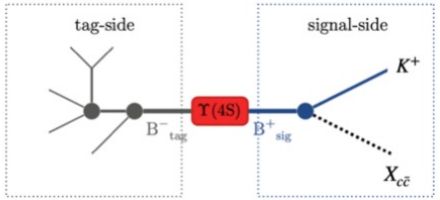
STRATEGY:



✓ Validation confirmed that the assumption is correct within the magnitude of the errors.



An example for a fit of the tag mode $D^0\pi^+\pi^-\pi^+$ for π-sample.



FEI - Tagging reconstruction. Fig taken from BelleII documentation.

Reduce number of parameters

Path

3 Validation (fit Mbc)

Beam constraint mass:

$$M_{bc} = \sqrt{(\frac{E_{beam}}{2})^2 - p_{tag}^2}$$

2 π - Fit range | π - SB | K - SB

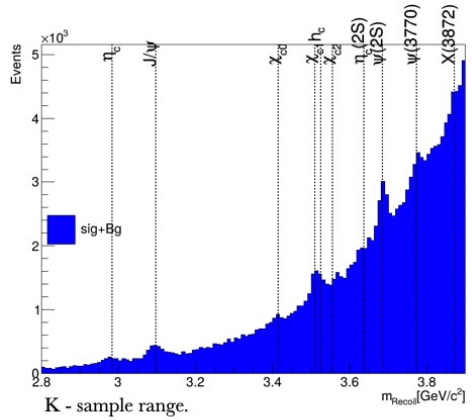
More robust determination of the FEI good-tag fraction using $B \to D^{(*)}\pi$

Simultaneous Fit among the tag modes | Extract $GTFC_t$ | Extract $\frac{Br(B^{\pm} \to \pi^{\pm}D^{*0})}{Br(B^{\pm} \to \pi^{\pm}D^0)}$ Global parameter

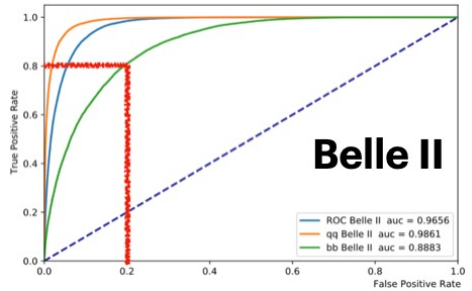
1 We aim to significantly improve the measurement precision using M_{rec}

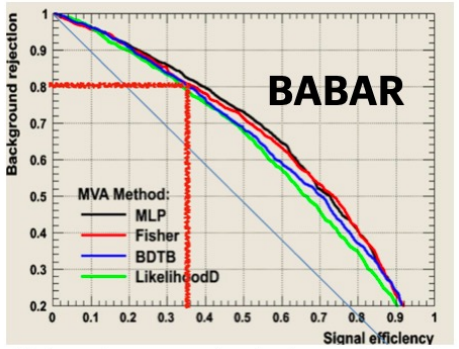
More data Bellel (711 fb^{-1}) Bellell (365 fb^{-1}) | A more efficient tagging reconstruction algorithm (FEI) | Better performing deep NN To suppress combinatorial Bg.

0



K - sample range.





We have a better separation : for the same Bg rejection of 80% in the X(3872) region:
We get : 80% sig-efficiency
Babar : 36% sig-efficiency

☞ Inclusive measurement of $Br(B^{\pm} \to K^{\pm}X(3872))$

① INCLUSIVE MEASUREMENT OF $Br(B^{\pm} \to K^{\pm}X(3872))$

Fit M_{rec} distribution for K-sample: $M_{rec} = \sqrt{(p^{\mu}_{ee} - p^{\mu}_{B_{tag}} - p^{\mu}_{K})^2}$

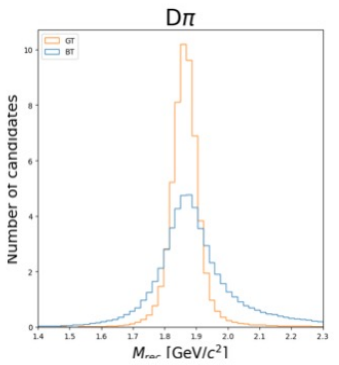
$$e^+e^- \to \Upsilon(4S) \to B^+_{sig}\, B^-_{tag} \to FEI$$
$$K^+ \quad X_{c\bar{c}} \hookleftarrow$$

FIT STRATEGY:

- Use MC template (hist. shapes)
- Divide the signal into events coming from correct (GoodTag) or wrong (BadTag) B_{tag} reconstruction:

  Good Tag Fraction (GTF): $R_{s,t} = \frac{N^{GT}_{s,t}}{(N^{GT}_{s,t} + N^{BT}_{s,t})}$

- Signal fit structure : $P_{s,t} = G_s P^{GT}_{s,t} + (1 - G_s) P^{BT}_{s,t}$
- $G_{s,t} = R_{s,t} C_t$
- GTF Correction: $C_t = \frac{R^{data}_{s,t}}{R^{MC}_{s,t}}$
- Simultaneous fit between the tag modes:



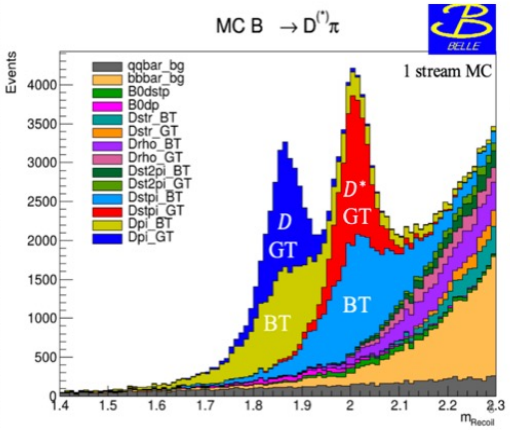
e.g difference between signal reco. with good/bad Btag reco. (M_{rec} distribution).

$D^0\pi^+, D^0\pi^+\pi^0, D^0\pi^+\pi^-\pi^+, D^0\pi^+\pi^-\pi^+\pi^0, D^{*0}\pi^+, D^{*0}\pi^+\pi^0,$
$D^{*0}\pi^+\pi^-\pi^+, D^{*0}\pi^+\pi^-\pi^+\pi^0, D^-\pi^+\pi^+, D^-\pi^+\pi^+\pi^0,$ rest.

- $\frac{Br(B^{\pm} \to K^{\pm}X_{c\bar{c}})}{Br(B^{\pm} \to K^{\pm}J/\psi)}$ as a global floating parameter.

② MORE ROBUST DETERMINATION OF THE FEI GOOD-TAG FRACTION USING $B \to D^{(*)}\pi$

Anzats: GTFC per tag mode doesn't depend on the signal mode.
Use π- sample (fit M_{rec} distribution) to determine $GTFC_t$



π sample - M_{rec} distribution.

π - SAMPLE FIT

- Similar to the K-sample, but $K \to \pi$
- Idea: extract $GTFC_t$ from π-fit and insert in K-fit
- Along the way we also obtain a low-systematics measurement of the BR ratio $\frac{Br(B^{\pm} \to \pi^{\pm}D^{*0})}{Br(B^{\pm} \to \pi^{\pm}D^{0})}$

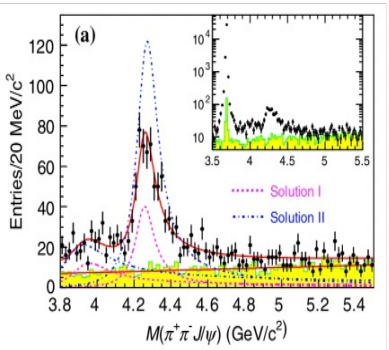
③ VALIDATION

$$e^+e^- \to \Upsilon(4S) \to B^+_{sig}\, B^-_{tag} \qquad M_{bc} = \sqrt{(\frac{E_{beam}}{2})^2 - p^2_{tag}}$$

- For the anzats validation — fit to Mbc distribution.
- Executed in 3 different ways:
  1. Check the use of Mbc at the π-fit range
  2. π-side band (SB)
  3. K-SB

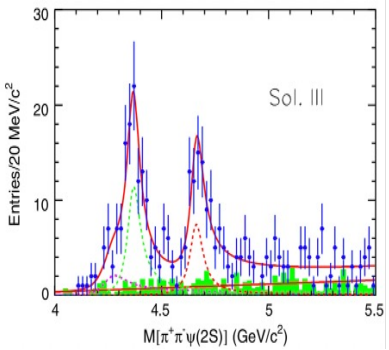
Charmonium(-like) states via ISR processes

- Confirm Z_c states and search for neutral partners
- Measure more precisely the line-shapes of more final state, including open-charm final states .
- Search for more Y states in more process, such as Y →charmed baryon pairs, charmed strange meson pairs.



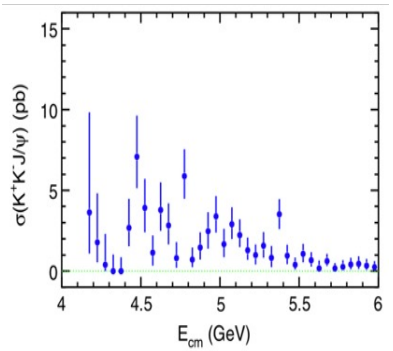
Q1: $Y(4008)$?

PRL 110, 252002



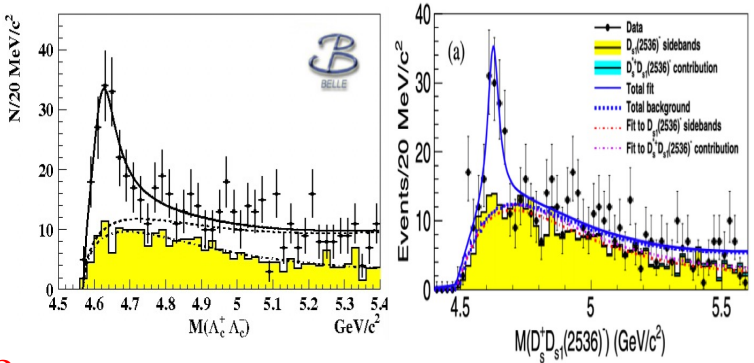
Q2: $Y(4260)$?

PRD 91, 112007



Q3: more structure?

PRD 89, 072015



PRL 101,172001, PRD 100, 111103(R)

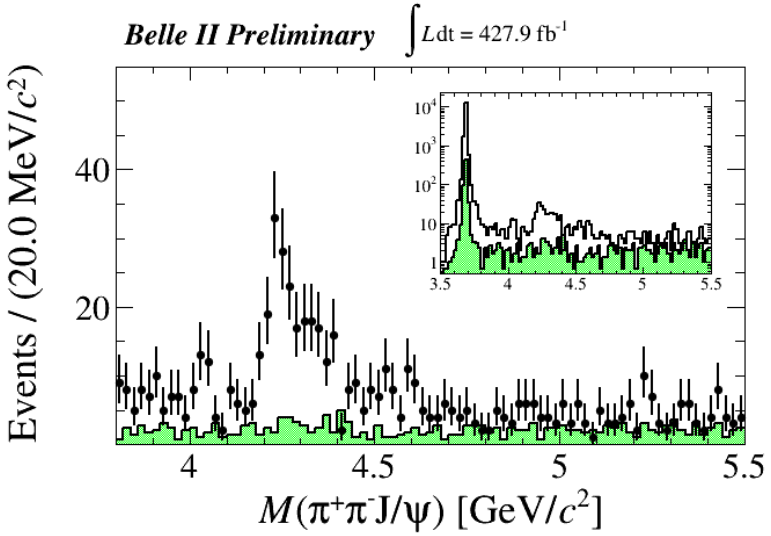
Q4: Same?

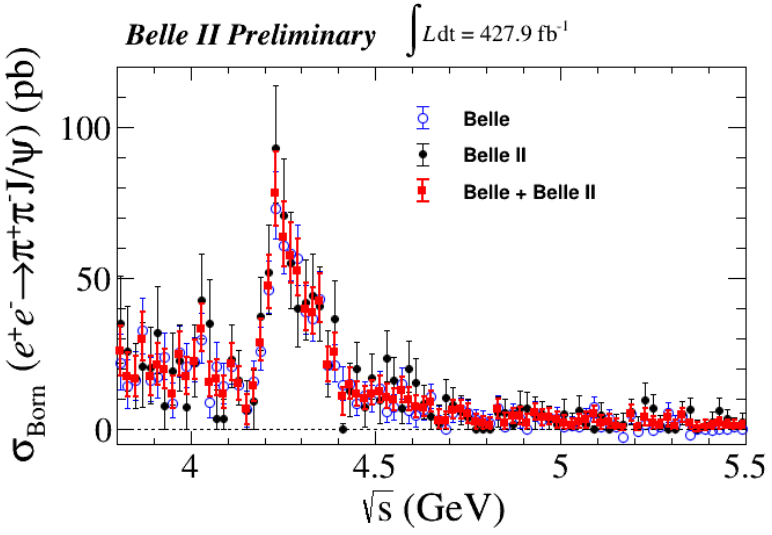
- Perform the analysis of $e^+e^- \to \pi^+\pi^- h_c$, $\omega\chi_{c0}$, and $(D^*\bar{D}^*)^{\pm}\pi^{\mp}$ to confirm the results with BESIII.
- Study the processes $e^+e^- \to \pi^+\pi^-\psi_2(1D)$, $K^+K^-\ \psi(2S)$, $\phi\chi_{cJ}$, $\eta J/\psi$, $\eta' J/\psi$, $\eta\psi(2S)$, $\omega\chi_{cJ}$, etc to search for more charmonium-like states and new decay modes.

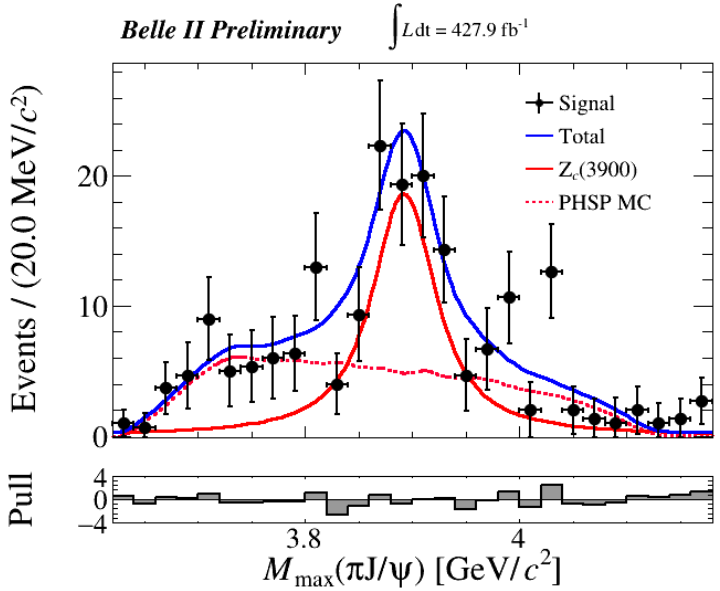
☞ Study of $e^+e^- \to h^+h^-J/\psi$ $(h = \pi/K/p)$ via ISR at Belle II

New!

- Based on the data sample with $L_{int} = 427.9\ \text{fb}^{-1}$ at Belle II， Born cross of $e^+e^- \to \pi^+\pi^-J/\psi$ via ISR is measured.
- The measured results on the cross sections are consistent with Belle and BESIII, within 2σ.
- Clear $Z_c(3900)$ signal with significance of 3.7σ is seen, with fixed mass and width [PRL 110, 252002(2013)]







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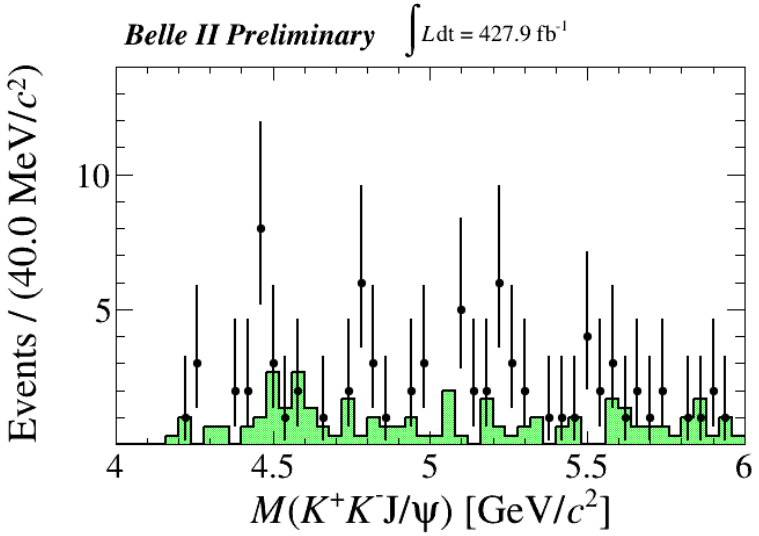
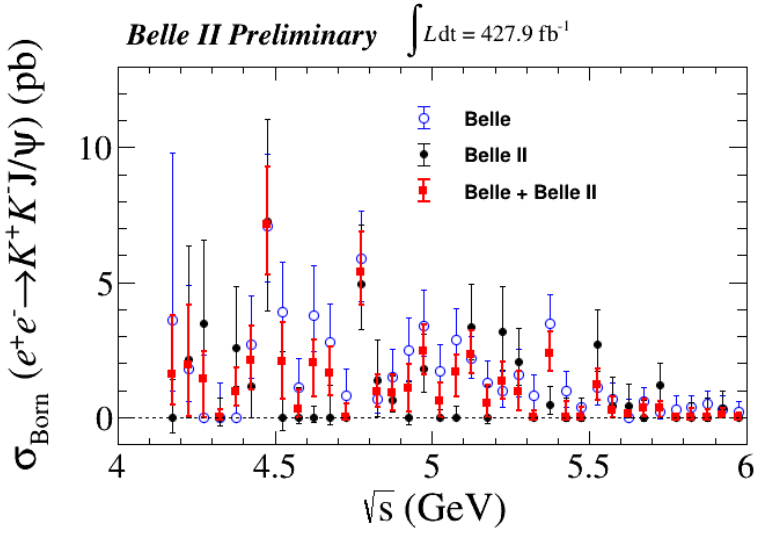
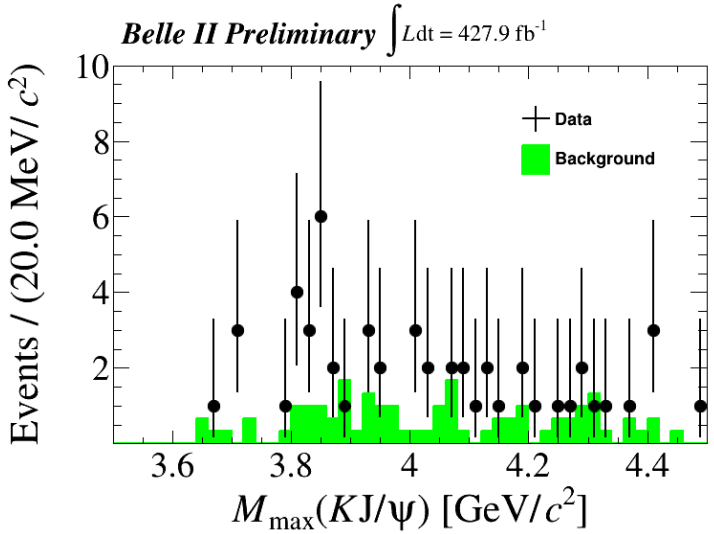
- The measured results on the cross sections are consistent with Belle and BESIII, within 2σ.
- No obvious Z_{cs} signal is observed.



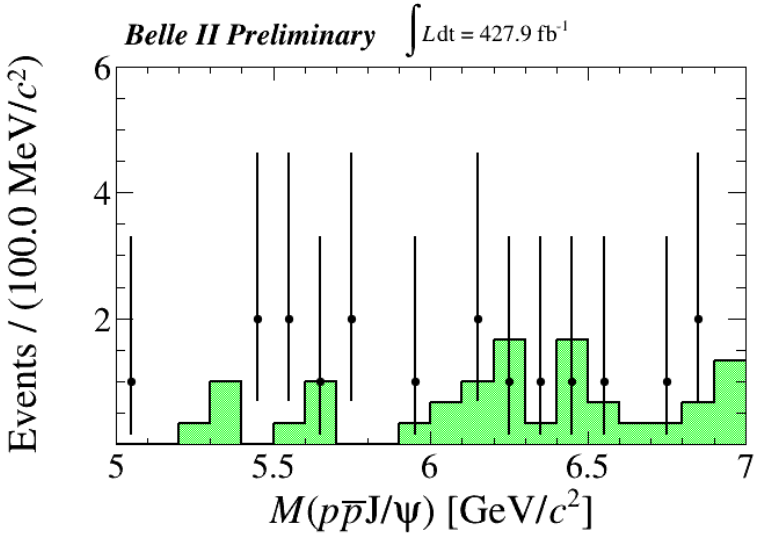


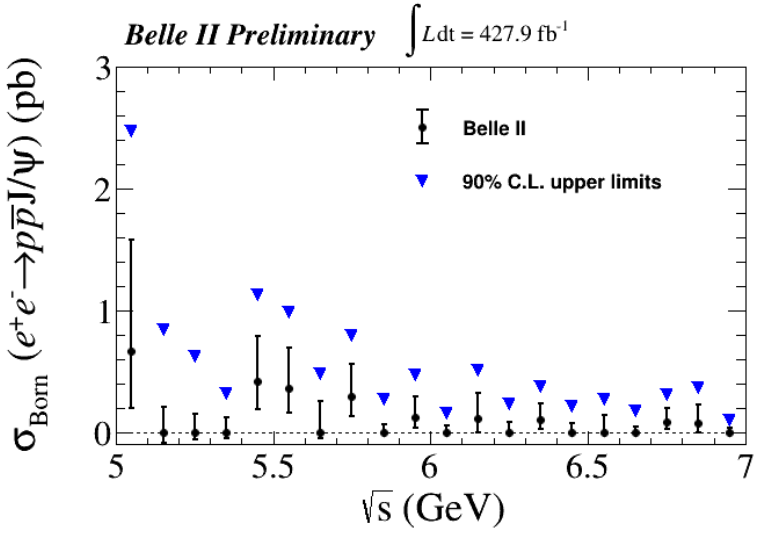


☞ Study of $e^+e^- \to h^+h^-J/\psi$ $(h = \pi/K/p)$ via ISR at Belle II

New!

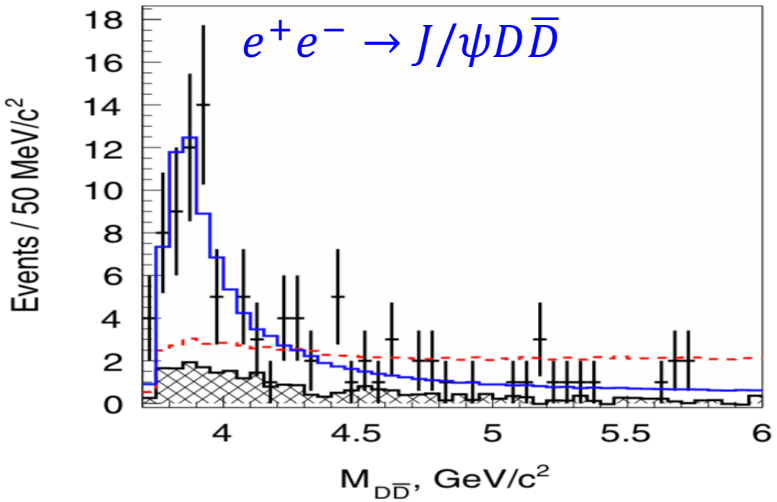
- Based on the data sample with $L_{int} = 427.9$ fb^{-1}at Belle II， Born cross of $e^+e^- \to p\bar{p}J/\psi$ via ISR is measured.
- No obvious signal is observed, and the born cross at 90% C.L. is given.
- The U.L of born cross at 6 GeV (< 0.15 pb) is consistent with the theoretical prediction (~ 4 fb) [arxiv:2508.08694].





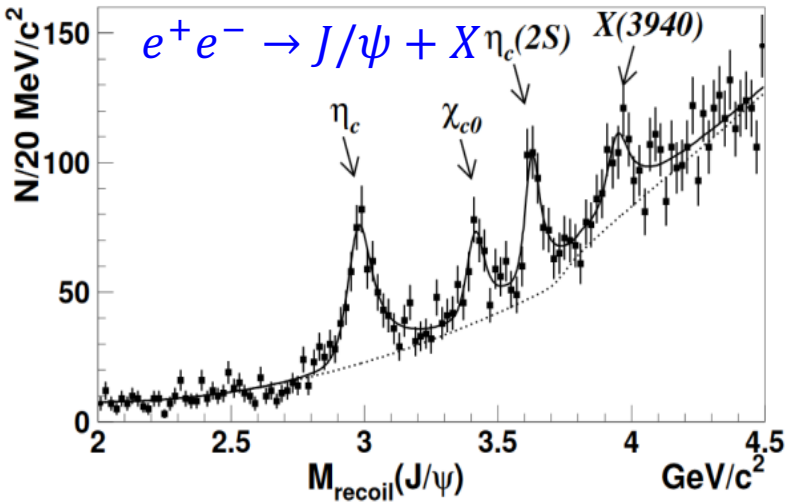
Charmonium(-like) states via Double charmonium processes

- $e^+e^- \to (c\bar{c})_{J=1}(c\bar{c})_{J=0}$ production rule.
- Rediscovery of $X(3940, 4160)$
- Expand to other $c\bar{c}$ $(h_c, \eta_c, \eta_c(2S), \psi(2S), \chi_{cJ}, etc.)$, search for new states



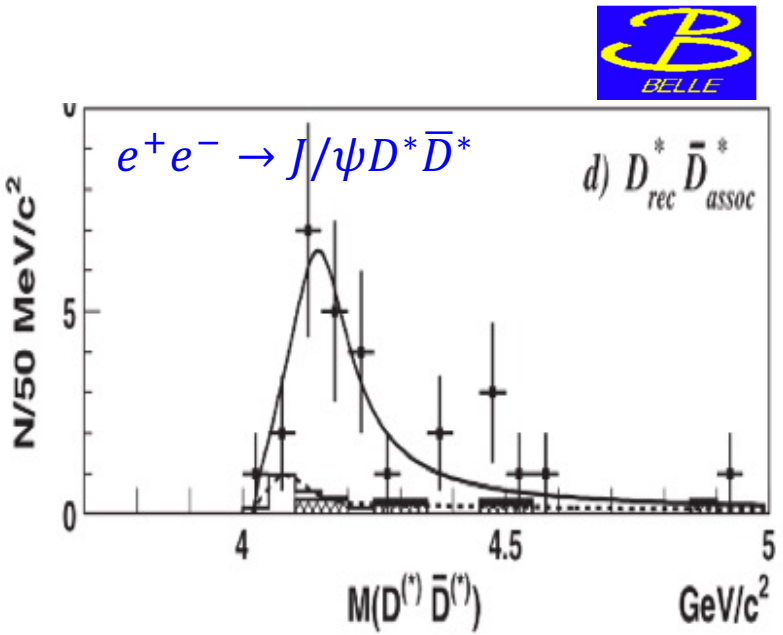
$X(3860) \to D\bar{D}$

PRD95, 112003



$X(3940) \to D\bar{D}^*$

PRL 98, 082001



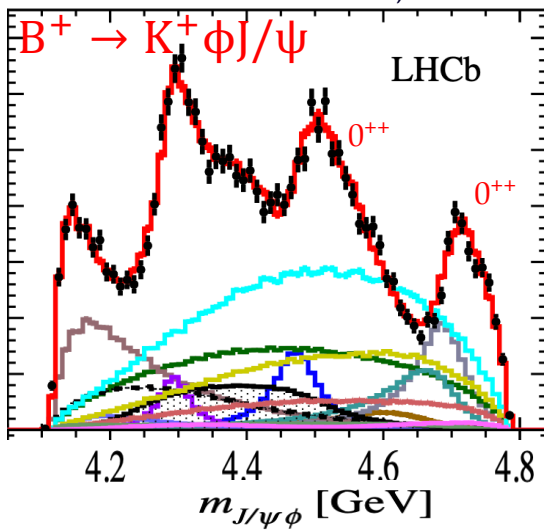
$X(4160) \to D^*\bar{D}^*$

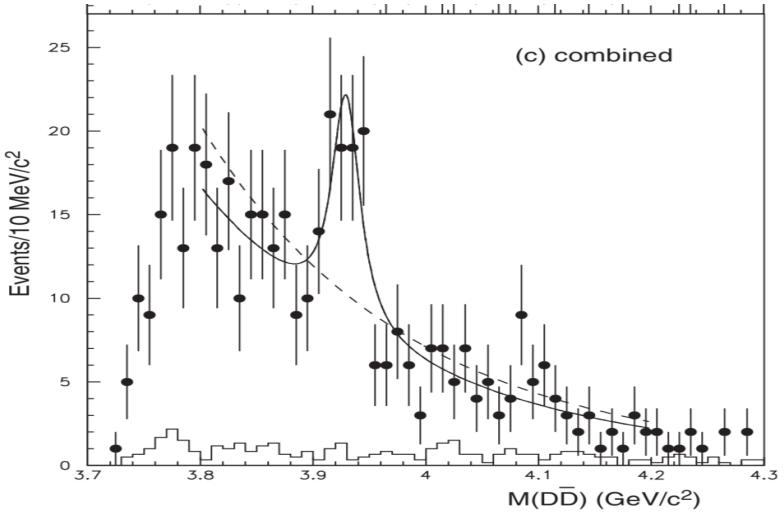
PRL 100, 202001

Charmonium(-like) states via two photons collisions

- Determine J^P values for some confirmed states, like $X(3930)$
- Confirm some states with evidence ? like $X(4350)$
- Search for $X(4500)$ and $X(4700)$ via two photons processes
- With smaller boost at Belle II, the efficiency in two photon process may be a little higher.

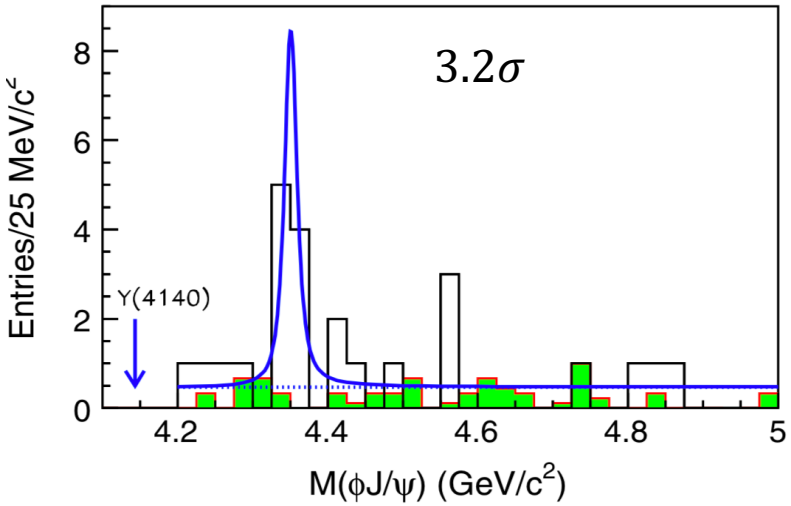
PRL127, 082001





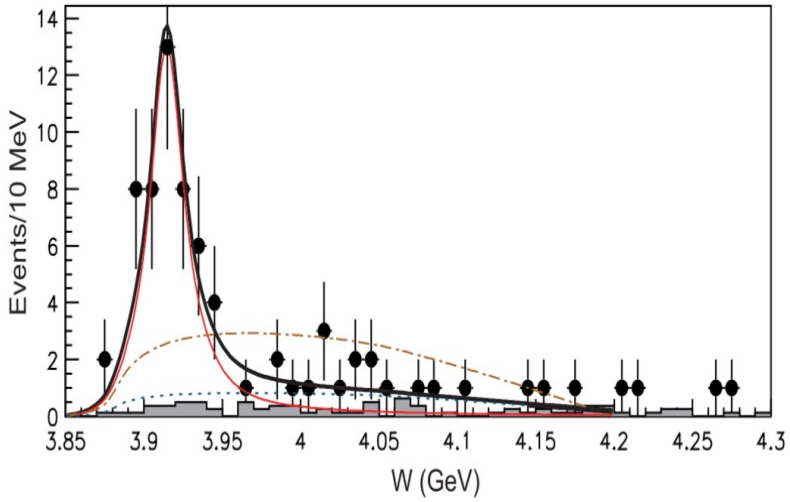
$X(3930) \to D\bar{D}$

PRL 96, 082003



$X(4350) \to \phi J/\psi$

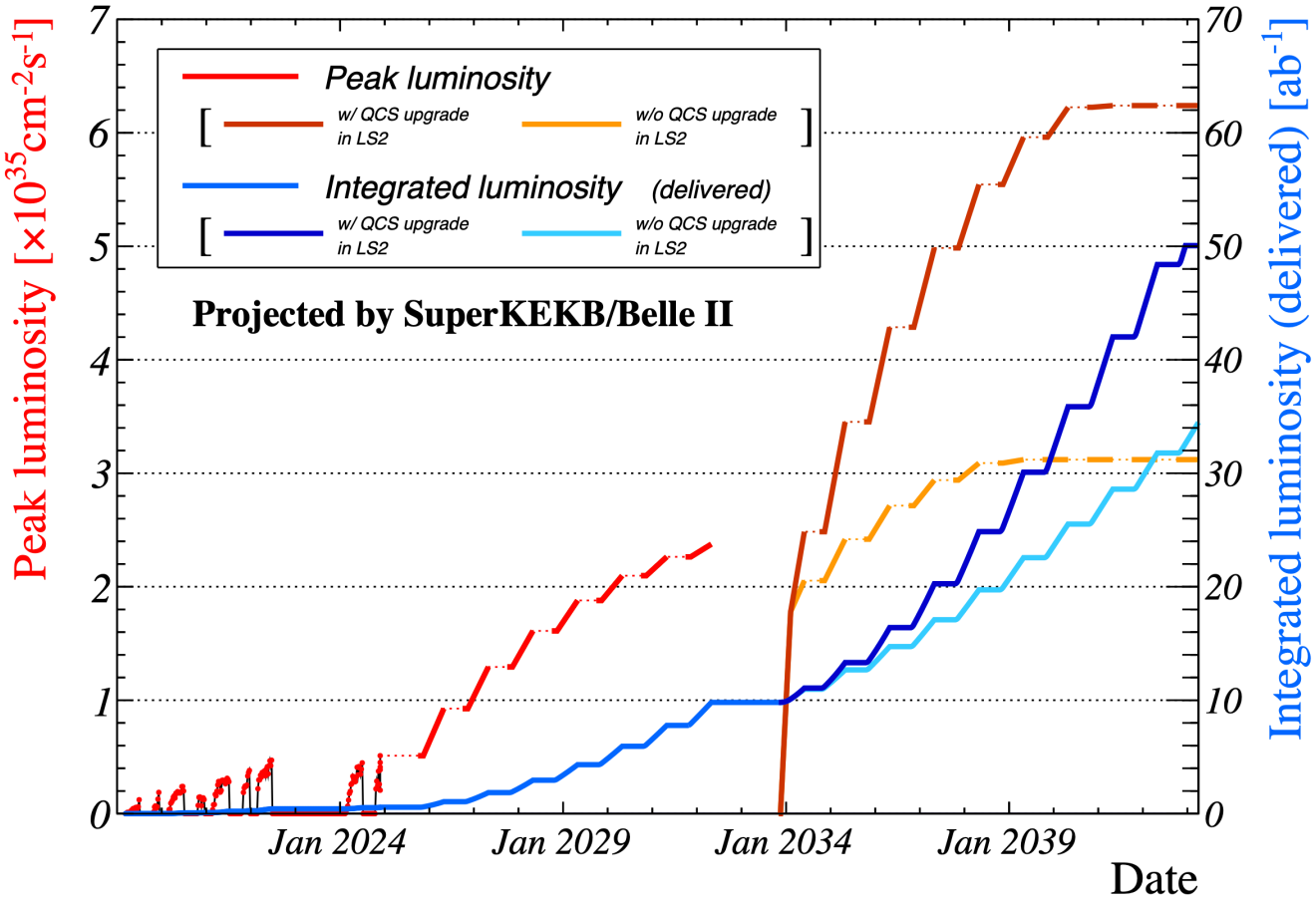
PRL 104, 112004



$X(3915) \to \omega J/\psi$

PRL 104, 092001

Data-taking plan and Prospects



Charmonium-like states:

- B decay ($B \to KX_{c\bar{c}}$)
- Initial-state radiation (ISR)
- Two-photon process
- Double charmonium

- Until 2026, about 1 ab^{-1} data, comparable to Belle
- Until 2029, about 4 ab^{-1} data.

Summary

- Belle II started operation in 2019, and the peak luminosity has achieved $L_{peak} \sim 0.5 \times 10^{35} cm^{-2} s^{-1}$.
- The Belle dataset has not been surpassed by Belle II, and now analyses combine the two data from the two experiments.
- Many charmonium-like states related works are in progress.
- Stay tuned for many results on the charmonium-like states from Belle II in the next few years.

Thanks for your attention!