Spectroscopy and exotic hadrons in Belle/BelleII

Exotic heavy meson spectroscopy and structure at the EIC,

CFNS, Stony Brook,

April 14-17, 2025

Ralf Seidl (RIKEN), for the BelleII collaboration

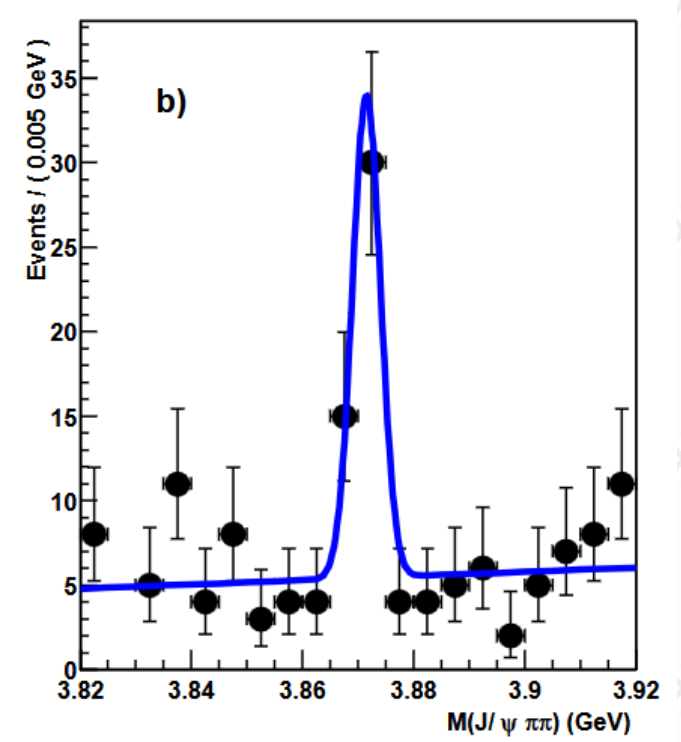
RIKEN

Outline

- Introduction to XYZ states in e^+e^- annihilation
- KEKB and the Belle/BelleII experiments
- Existing and future measurements on XYZ states
- Heavy baryon spectroscopy
- Light and other spectroscopy opportunities

X(3872)→J/ψππ

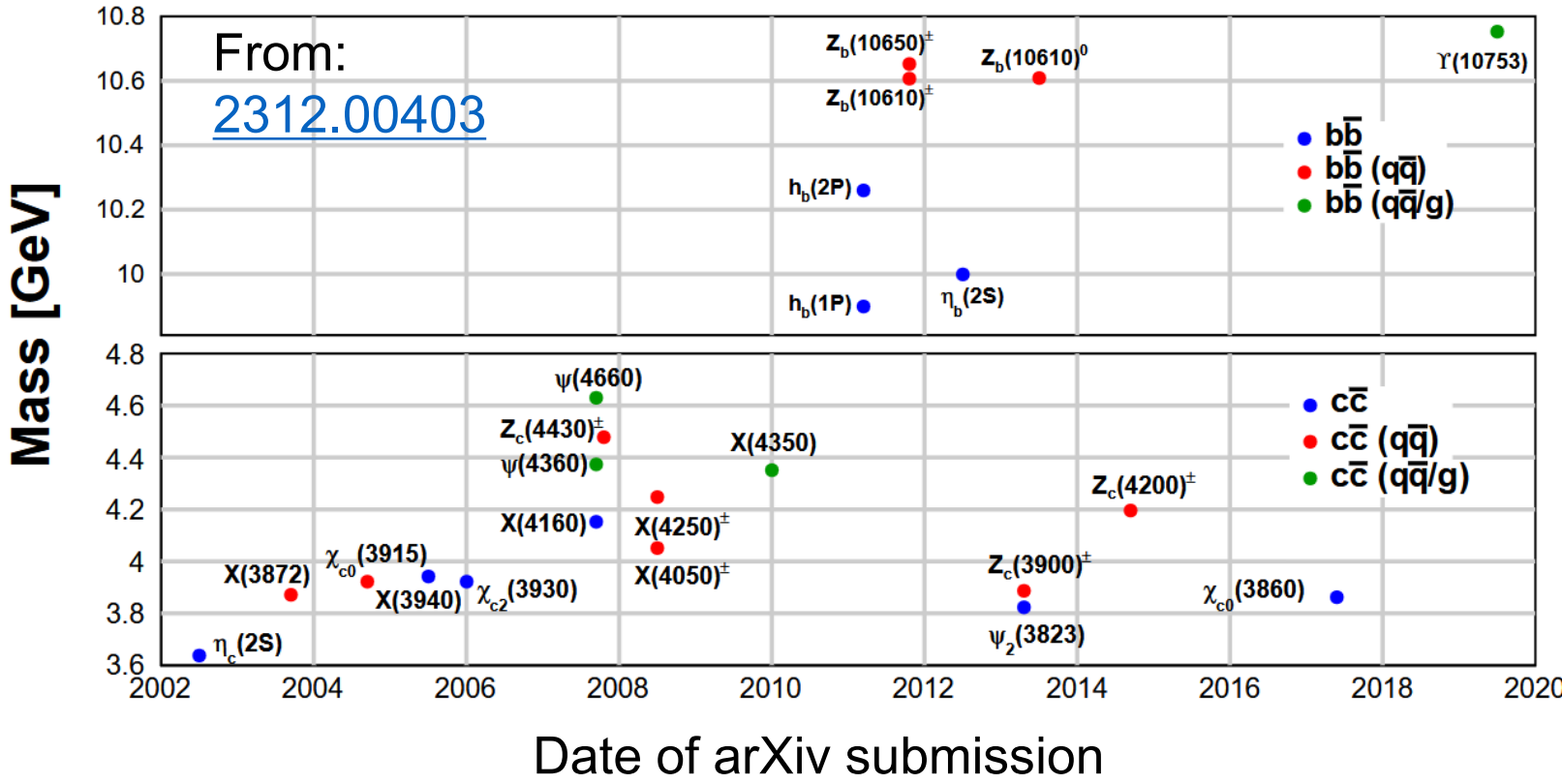
- First observed by Belle in $B^+ \rightarrow X(3872)K^+$ decays
- Since then, confirmed by many other experiments, various decay channels
- The start of discovering many XYZ states at various facilities



PRL 91 (2003) 262001

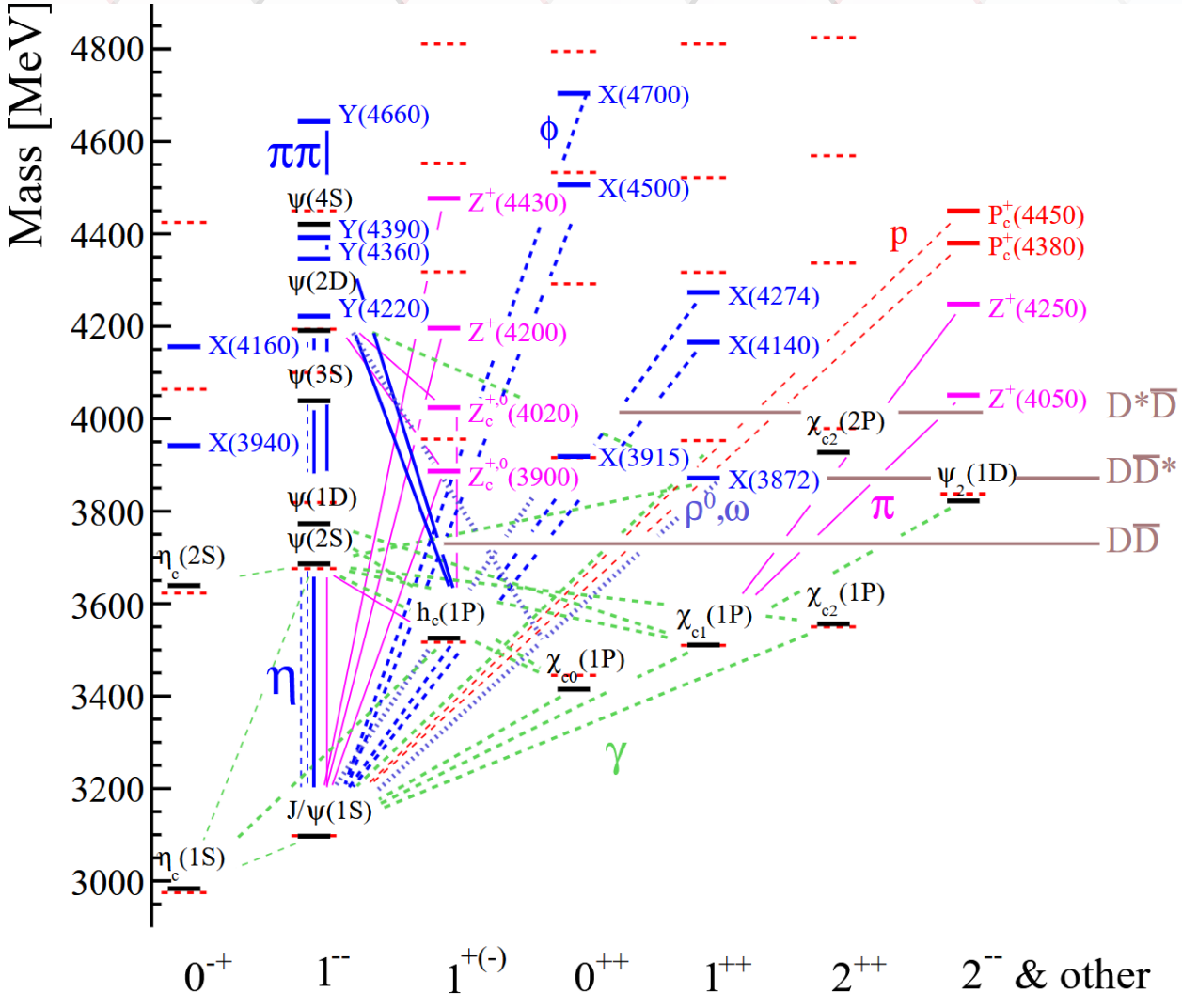
Introduction: quarkonia-like measurements at Belle

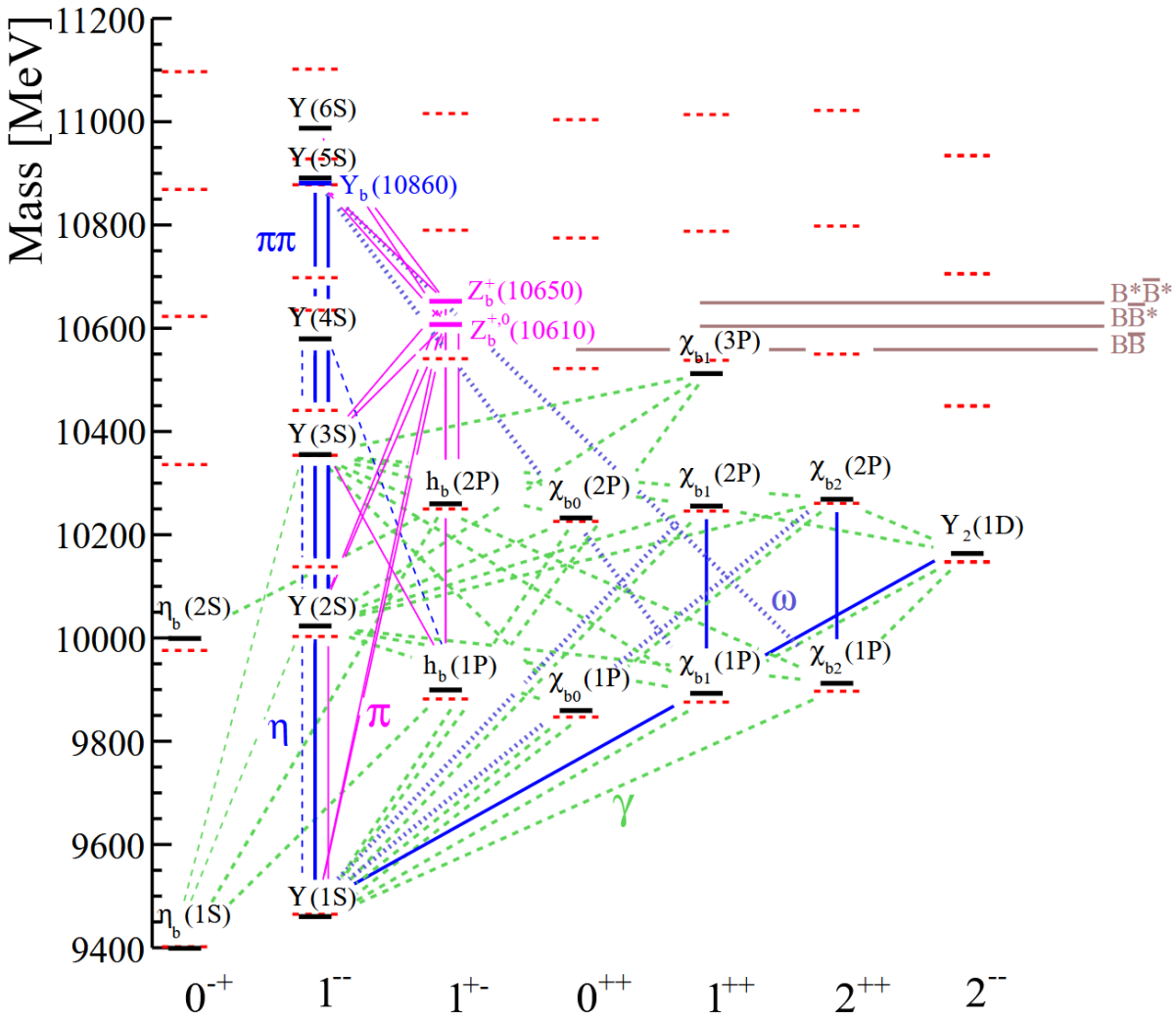
- Various charm and b pair states have been identified at Belle experiment
- Wealth of data (~1 ab^{-1}) still provides new results
- BelleII starting to confirm states with increasing luminosity



Main questions: observed spectra vs. theory;
quarkonium vs. molecule vs. tetraquark vs. hybrids

Status of onium-like states

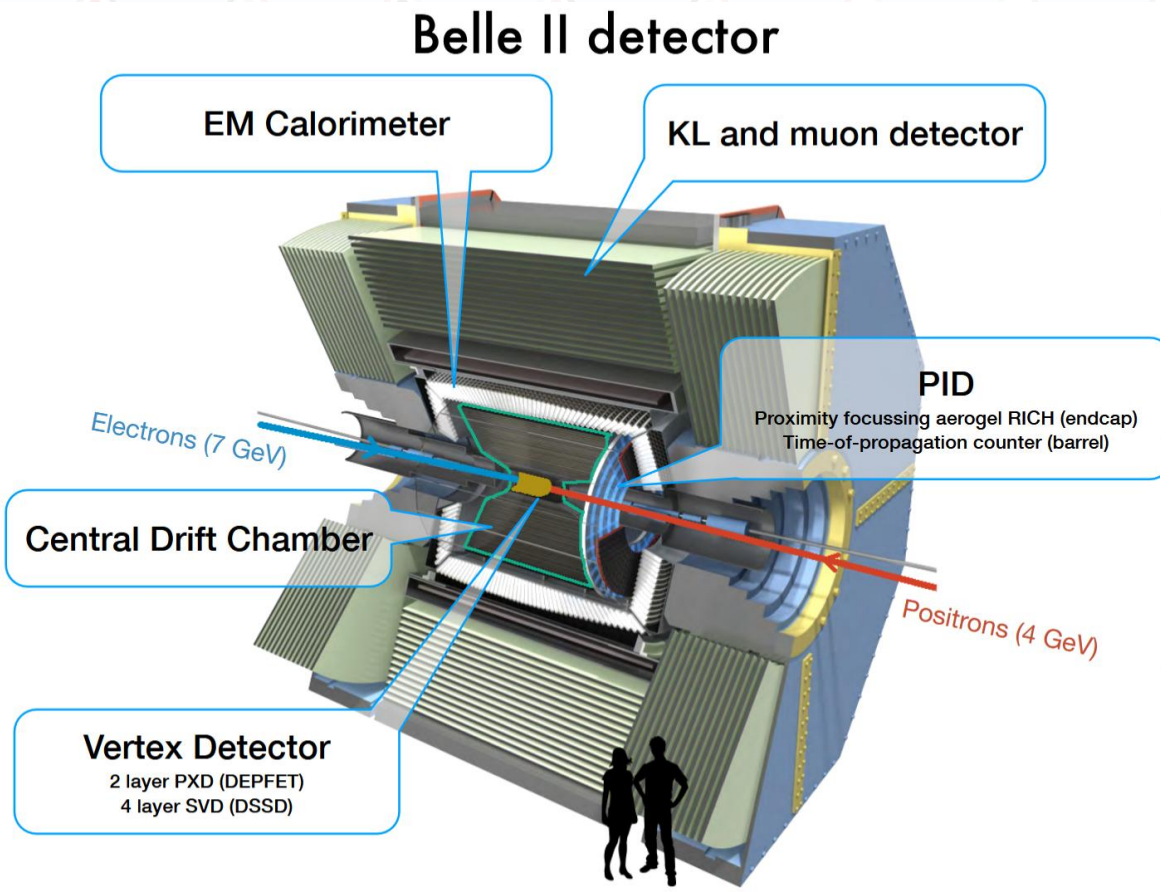




Olsen et. al: [*RMP* 90 (2018) 015003]

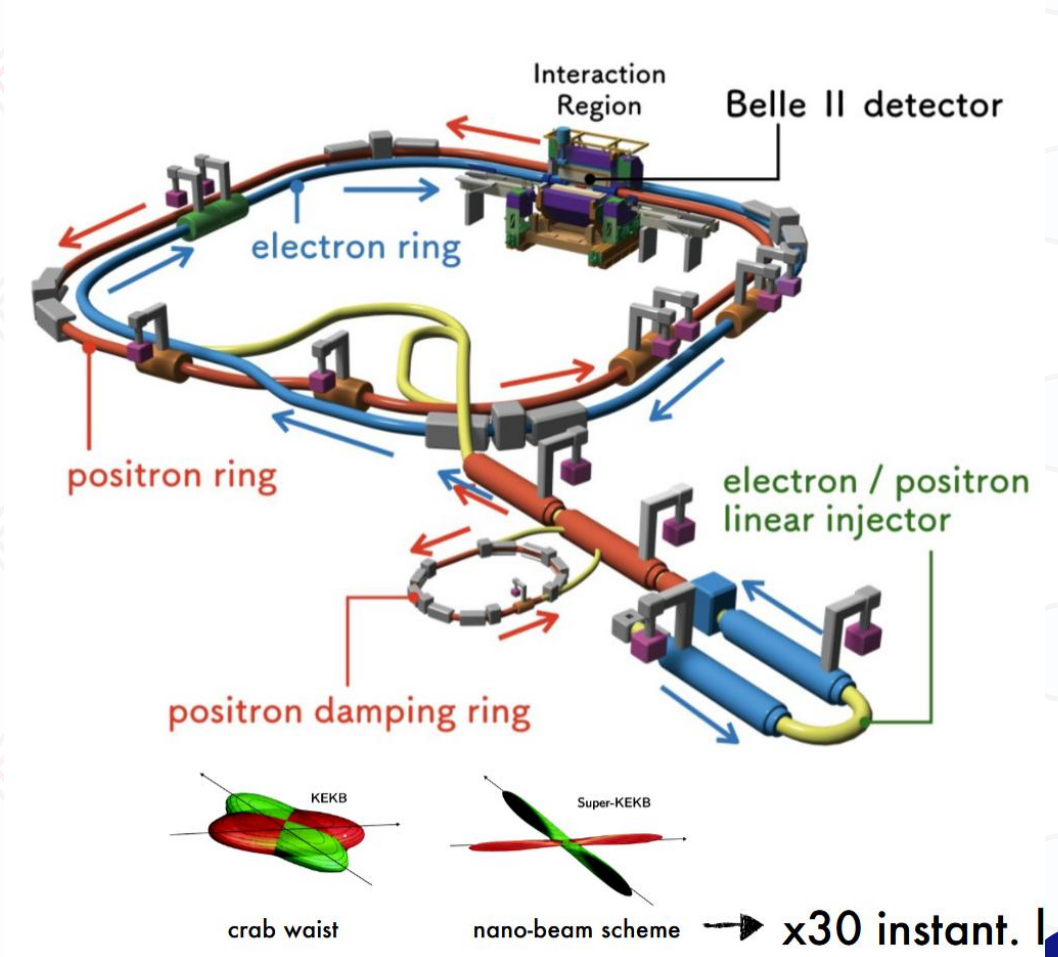
Belle/Belle II physics goals

- Main goal of Belle/BelleII:
  - CP violation in the quark sector via $B^0 - \bar{B}^0$ mixing
  - CKM matrix
  - Rare B decays
- Center of mass energy typically at Y(4S) resonance (10.58 GeV) → creates $B\bar{B}$ pairs to study mixing
- Asymmetric beam energies →boosted cms for longer-lived B mesons in the lab frame
- Additional runs below Y(4S) resonance ($e^+e^- \rightarrow q\bar{q}$) and scans above for Y(5S), Y(10753), etc



SuperKEKB accelerator

- Asymmetric 4 GeV e^+ on 7 GeV e^- (was 3.5 GeV on 8 GeV in KEKB)
- Nano-beams + higher beam currents to reach 30 x KEKB instantaneous luminosity
- World highest instantaneous luminosity 5.1 * 10^{34} cm^{-2} s^{-1} reached (12/2024)
- aiming to collect 50 x Belle luminosity
- Eventually add polarization



Belle and BelleII detector comparison

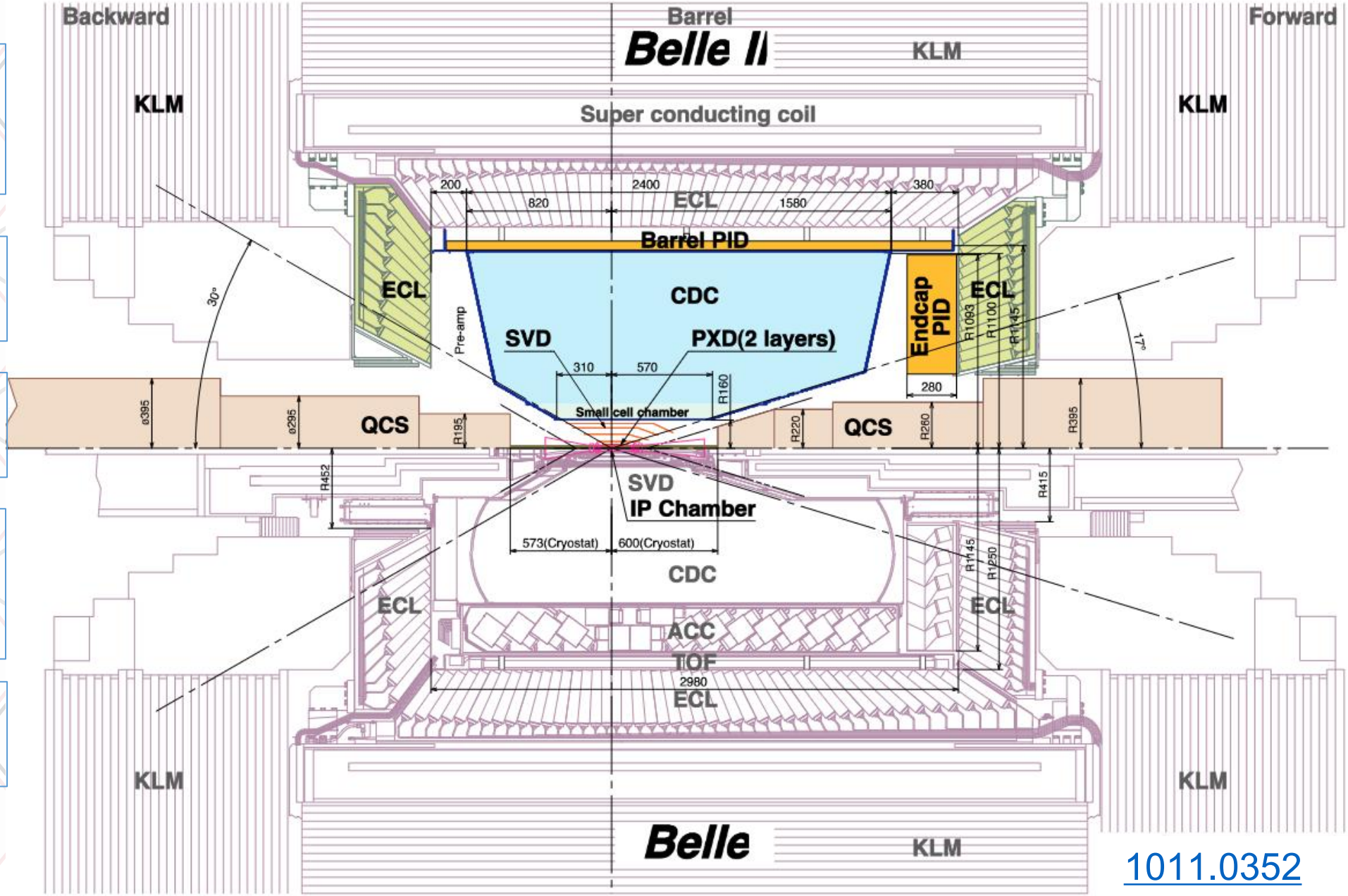
From 4 SVD layers → 2 Pixel + 4 Double-sided Strip layers

Larger drift chamber, faster readout

Improved PID with TOP and ARICH

KLM system with RPCs and scintillating fibers

Waveform sampling readout for calorimeter

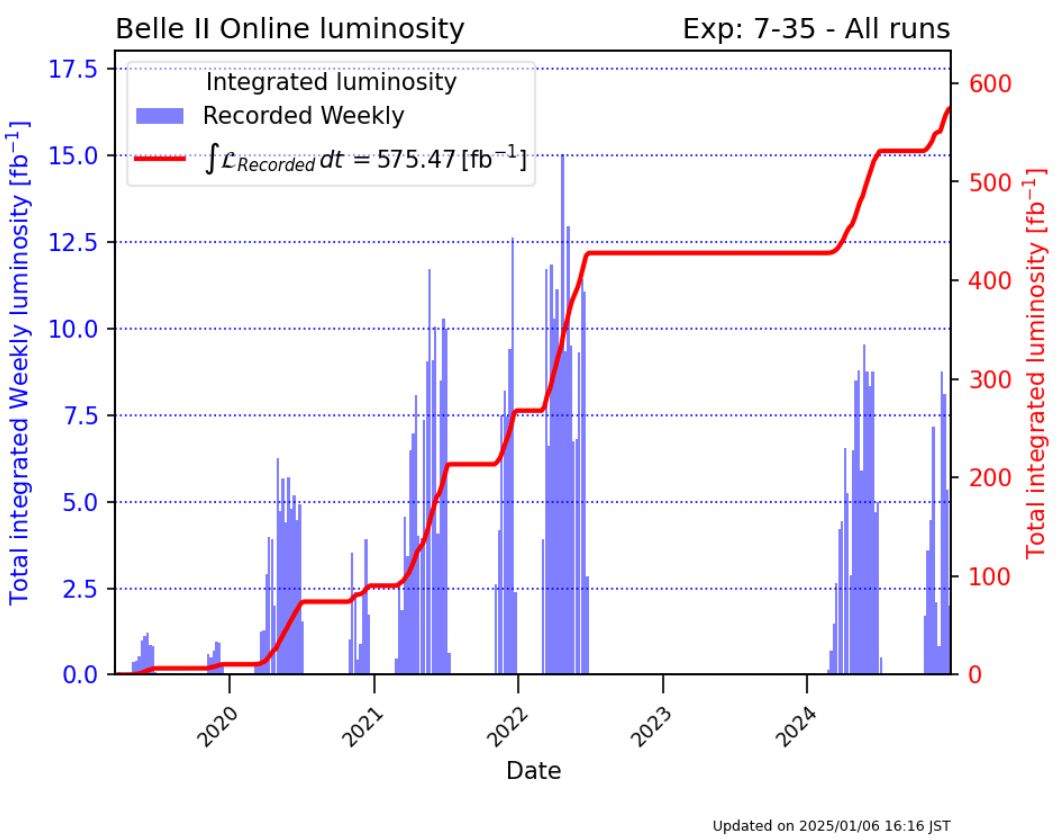


1011.0352

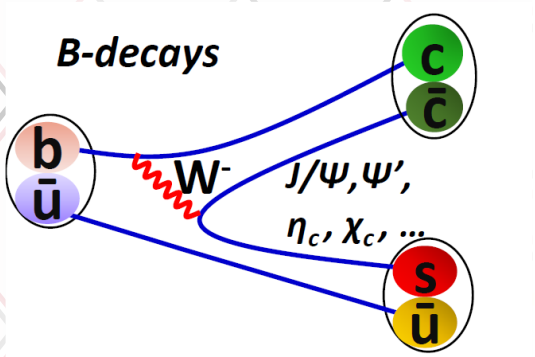
Accumulated luminosity

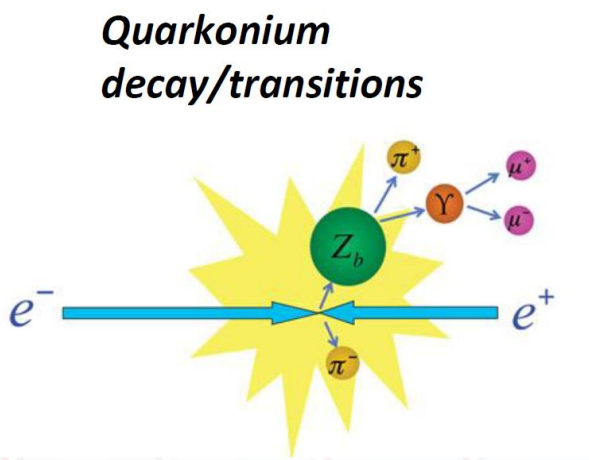
- Already recorded a reasonable fraction of the Belle luminosity:

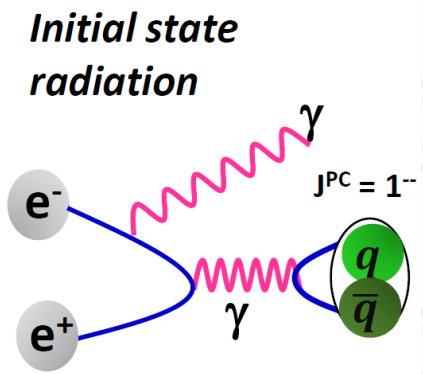
  Belle 1.04 ab^{-1}; Belle II 575 fb^{-1}
- Pixel detector is still not operated while accelerator improves stability
- Other detectors taking data as planned
- About half of Belle luminosity reached at various energies

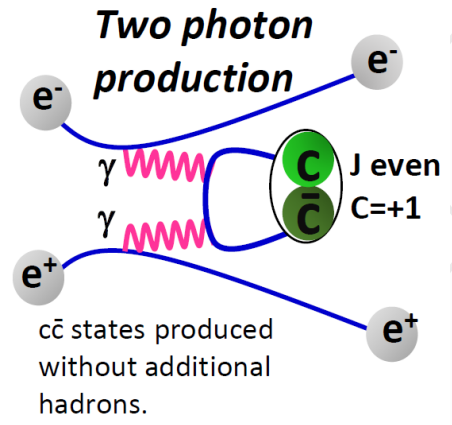


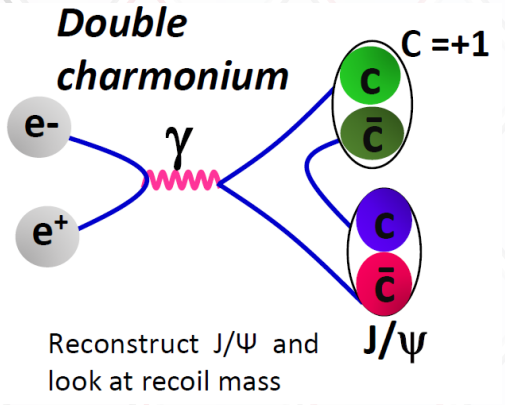
Types of processes at B factories to create exotics











Also, particle production in fragmentation q→hX

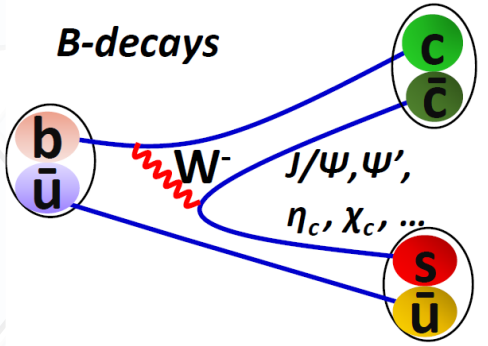
- Different sub processes access different J^{PC} states and mass ranges

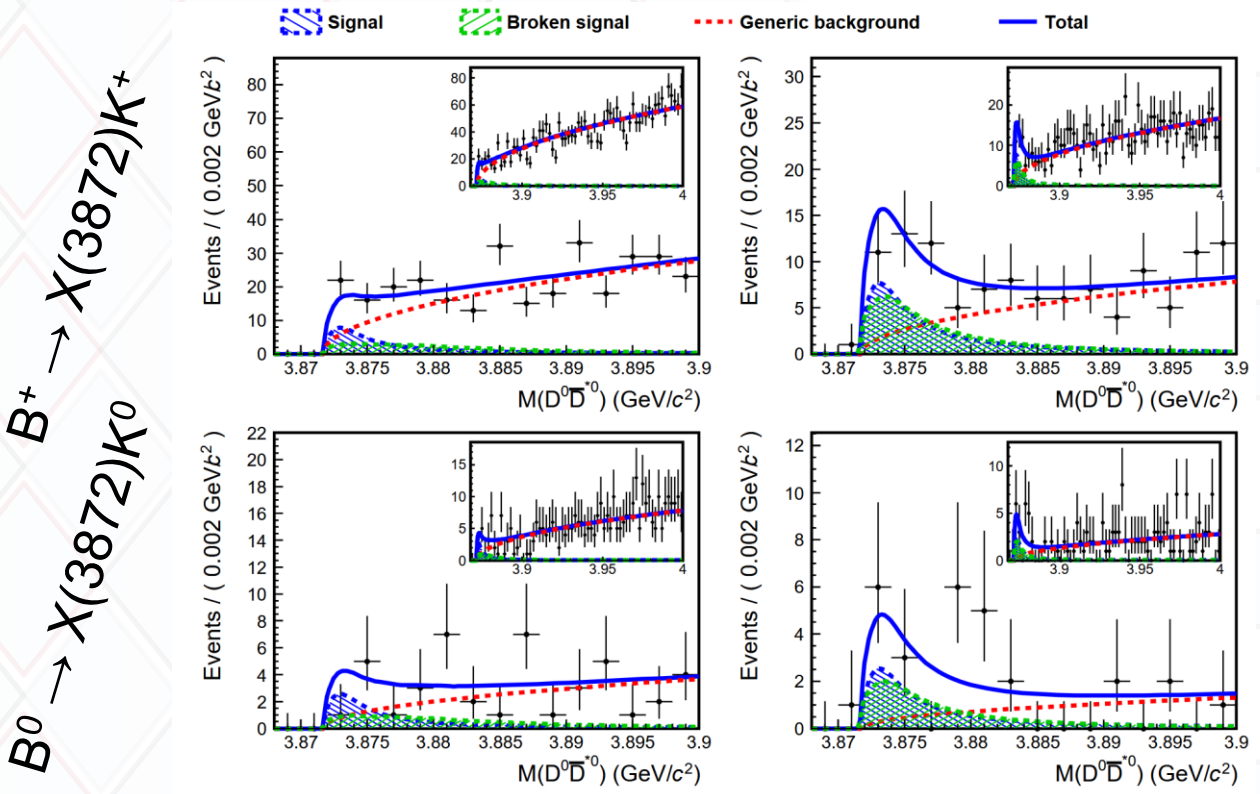
Drawings taken from V. Bhardwaj

B decays

- Look for X(3872) decays into D meson pairs to understand type of lineshape, BR:

- $D^0\overline{D^{*0}}$ coupling lower limit g = 0.075 (at 95% Credibility)
- $BF(B^0 \to X(3872)K^0 / BF(B^+ \to X(3872)K^+ = 1.34^{+0.47}_{-0.40}(stat)\ ^{+0.10}_{-0.12}(syst)$

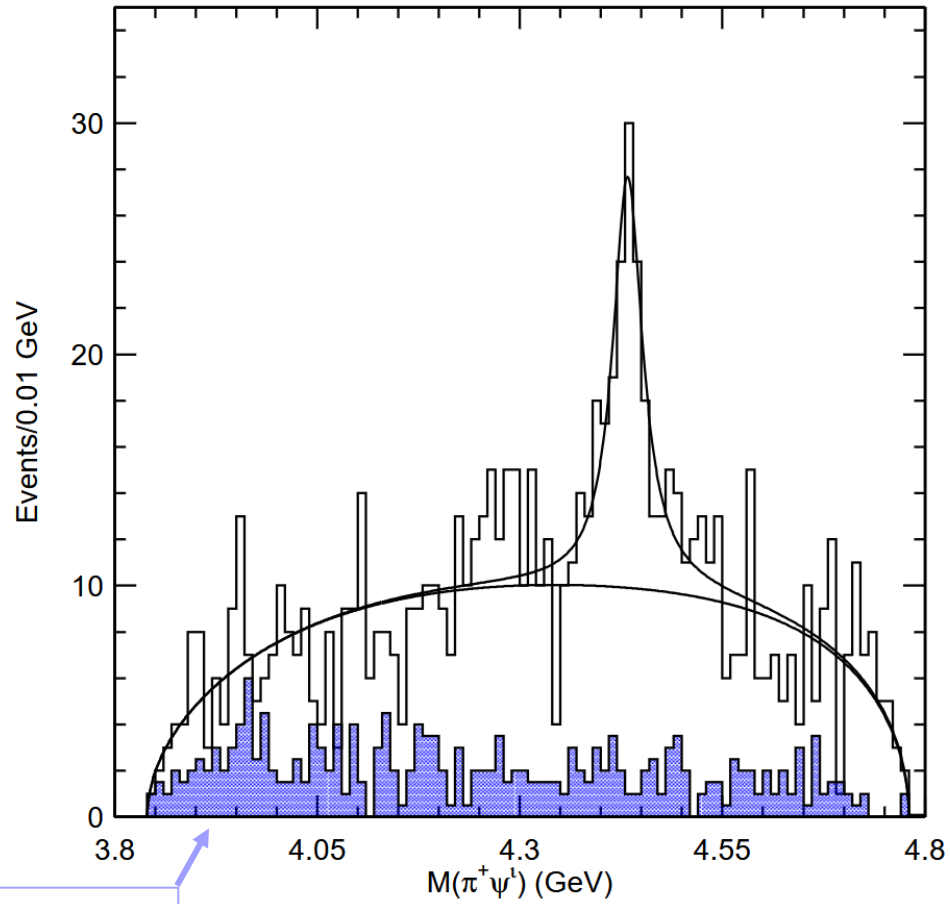




PRD 107 (2023) 112011

Charged resonances in B decays

- $Z^+(4430)$: Smoking gun for exotic resonances as charged particles with c and cbar content
- Studied in $B \to K\pi^{\pm}\psi'$ decays
- Amplitude analysis prefers $J^P = 1^+$
- Situation more complicated for charged resonances, as substantial non-resonant background interference needs to be considered

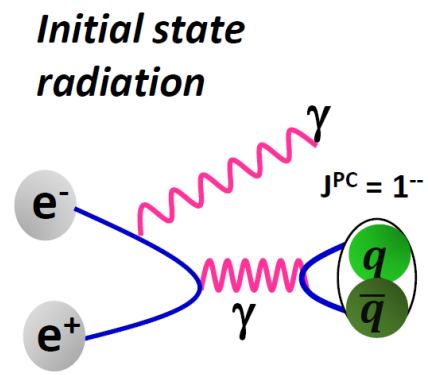


Sideband of ΔE, M_{bc} (B) signal region

PRL 100 (2008) 142001
PRD 88 (2013) 074026

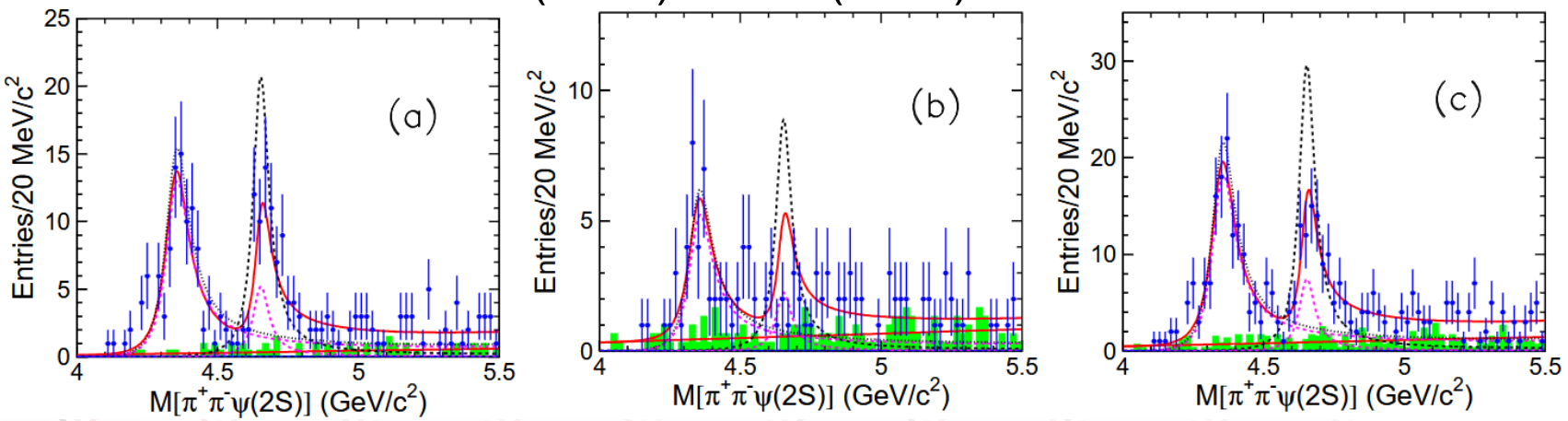
ISR

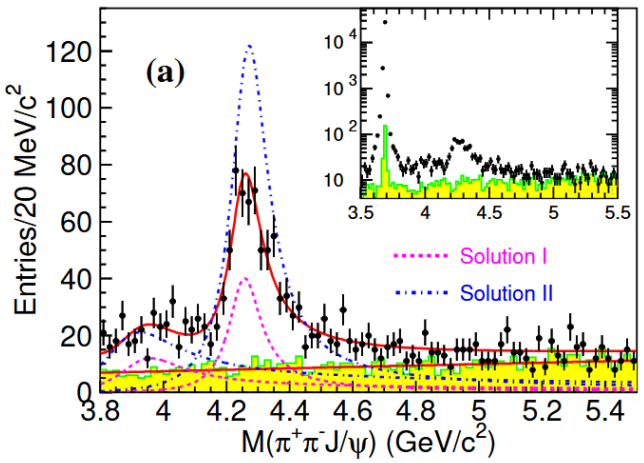
- ISR allows to scan the mass of the final state in a very clean environment
- Photon quantum numbers must be conserved in final states to be created
- Y(4260),Y(4360) and Y(4660) found



PRD 91 (2015) 112007

Y (4360) and Y (4660)



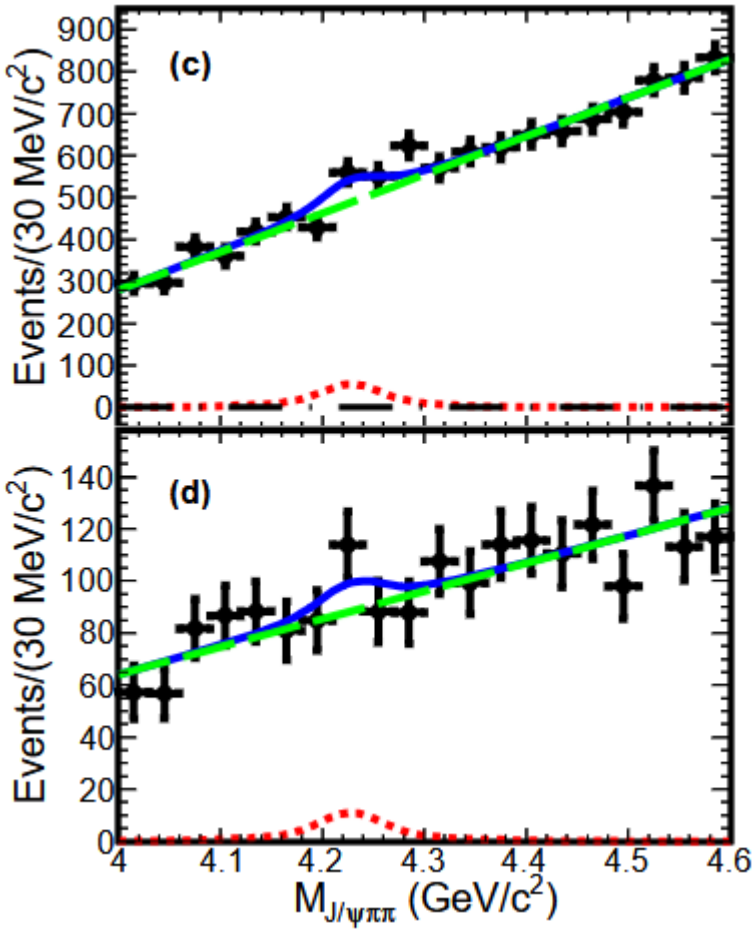


PRL 110 (2013) 252002

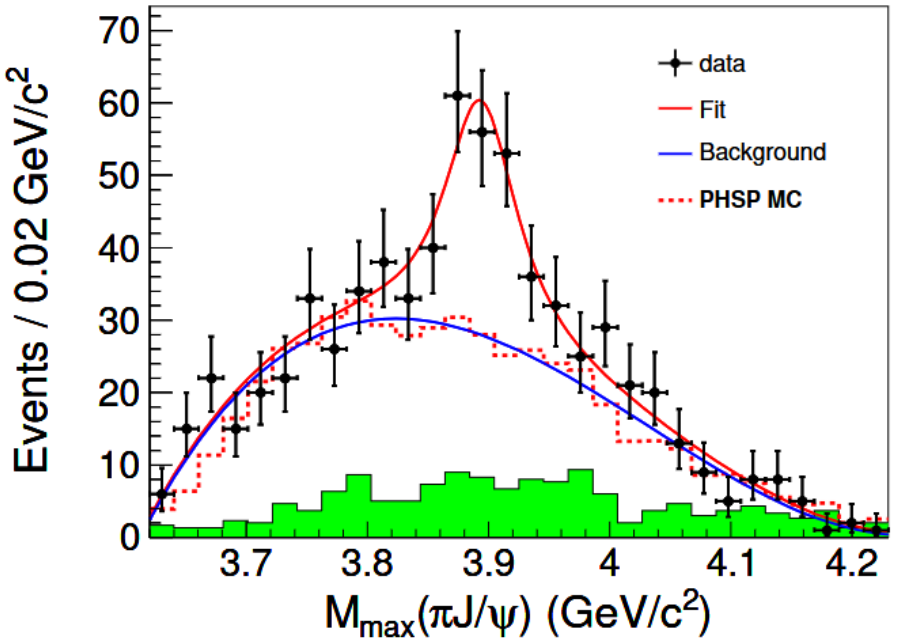
PRL 99 (2007) 182004

$Z_c(3900)$ and Y(4260)

- Y(4260) barely seen in B decays (unlike in ISR events)
- In ISR data, also $Z_c(3900)$ found



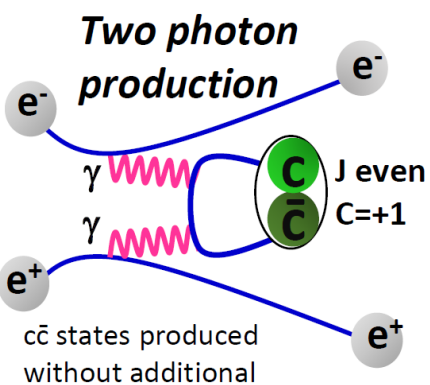
PRD 99 (2019) 7, 071102



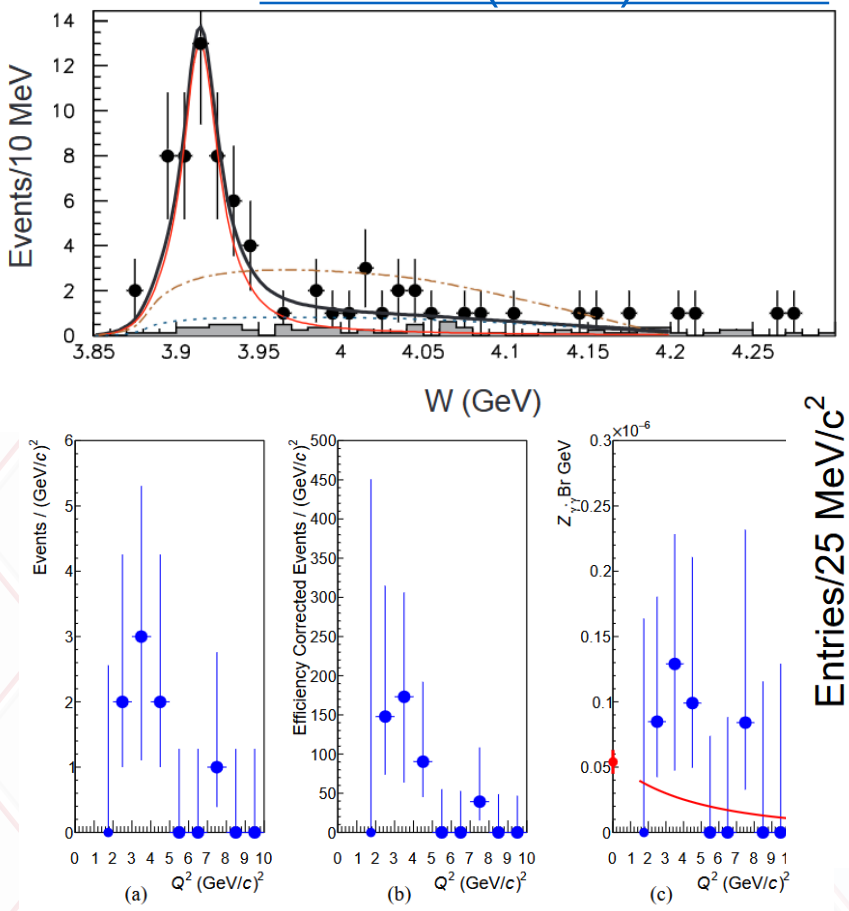
PRL 110 (2013) 252002

Two-photon processes

- X states accessible in two-photon processes:
- $\gamma\gamma \rightarrow \omega J/\psi$ process X(3915)
- $\gamma\gamma \rightarrow \phi J/\psi$ process X(4350)
- Q^2 distribution of X(3915) (relates to FormFactor and possibly type of particle if larger size than $c\bar{c}$)
- Also, X(3872) seen in $J/\psi\pi\pi$ *PRL* 126 (2021) 122001

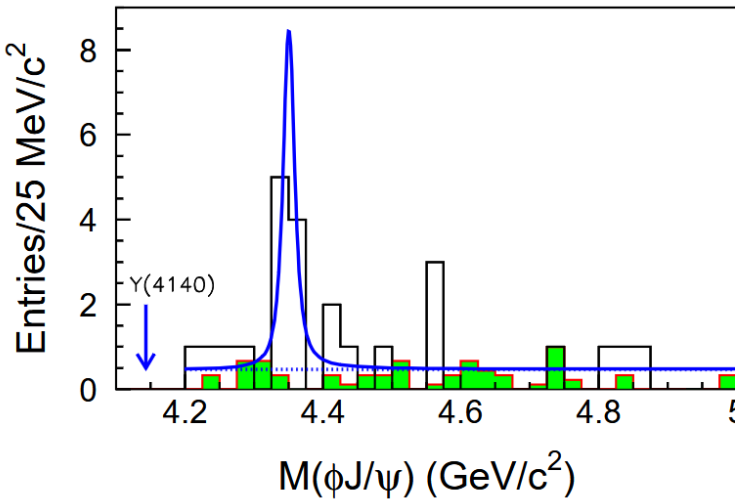


PRL 104 (2010) 092001



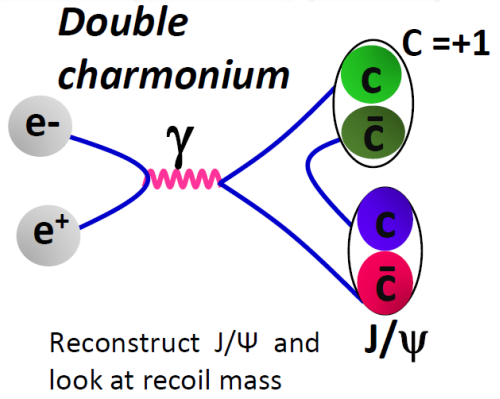
PRD 108 (2023) 012004

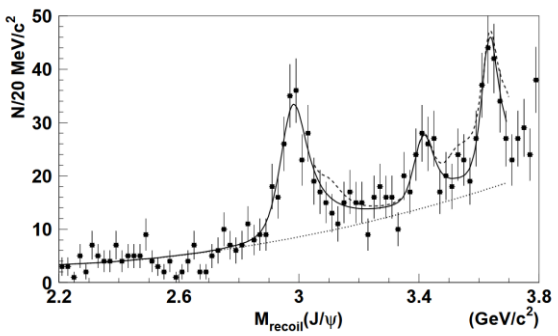
*PRL*104 (2010) 112004



Double-charm

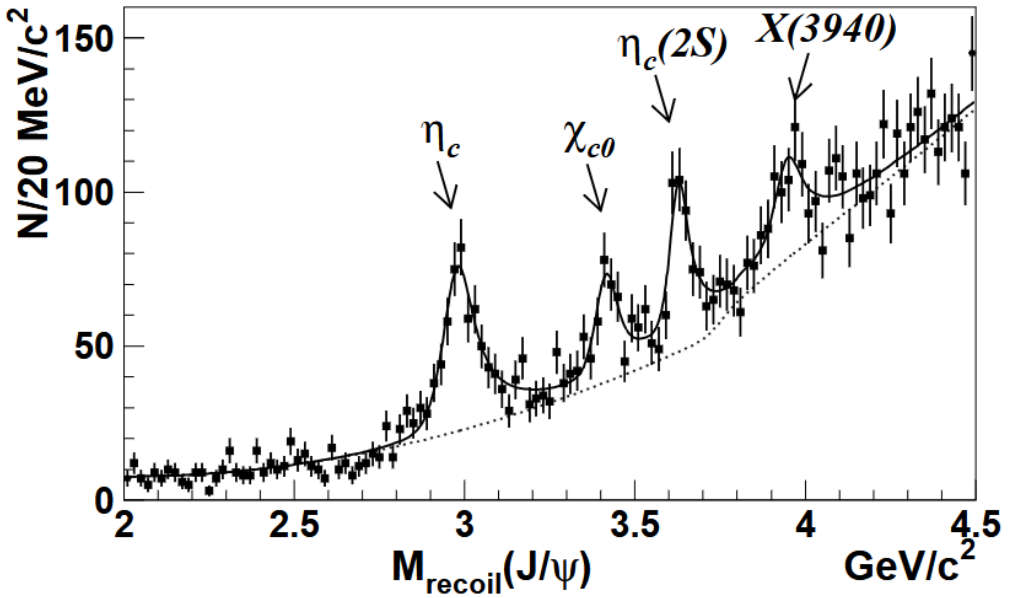
- Very rare process of creating double charmonium pairs, but dominant prompt J/ψ production process
- Use recoiling mass of J/ψ to search for states
- Discovery of the X(3940)(J=0?)





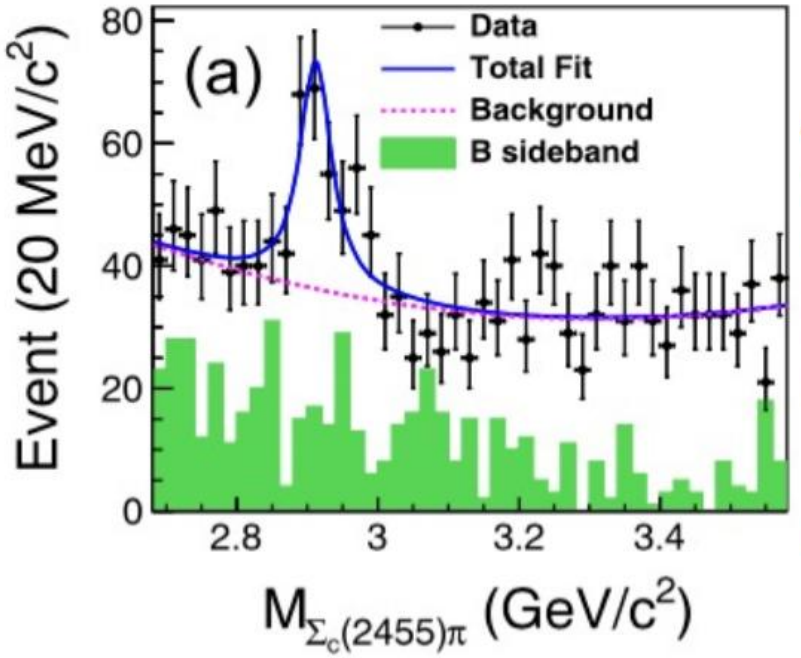
PRD 70 (2004) 071102, PRL 89 (2002) 142001

PRL 98 (2007) 082001

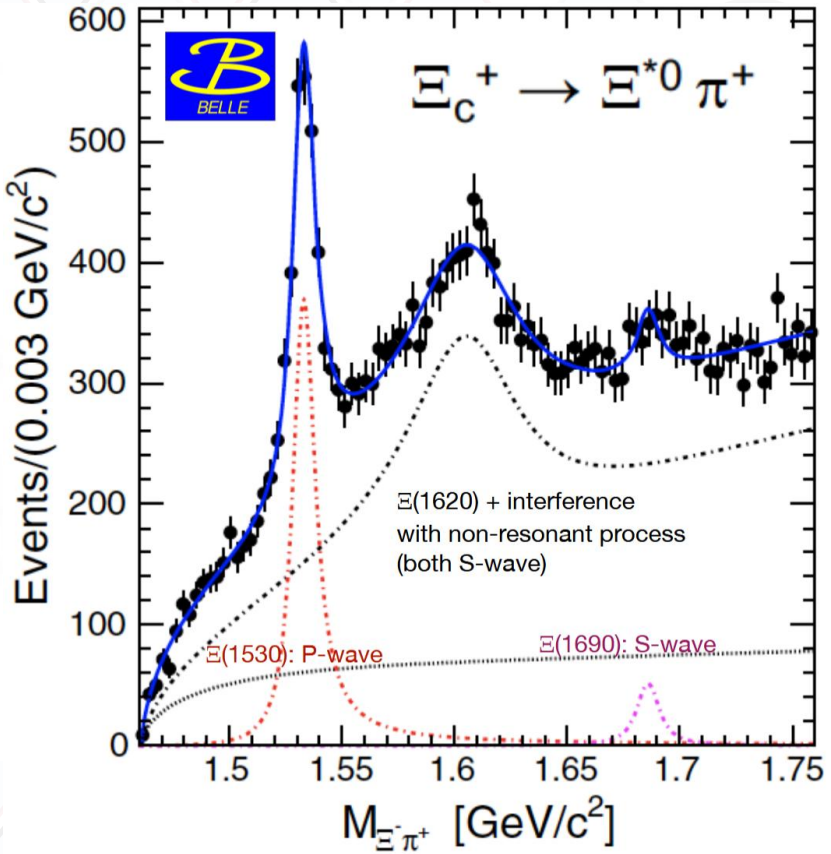


Heavy Baryon production

- Not just mesons, plenty of light and heavy baryons are being produced in B factories
- Various states found, e.g excited $\Lambda_c(2910)^+$, $\Xi(1620)^0$ and $\Xi(1690)^0$
- Mass, width and BF for $\Lambda_c(2625)^+$ (*PRD* 107 (2023) 032008)



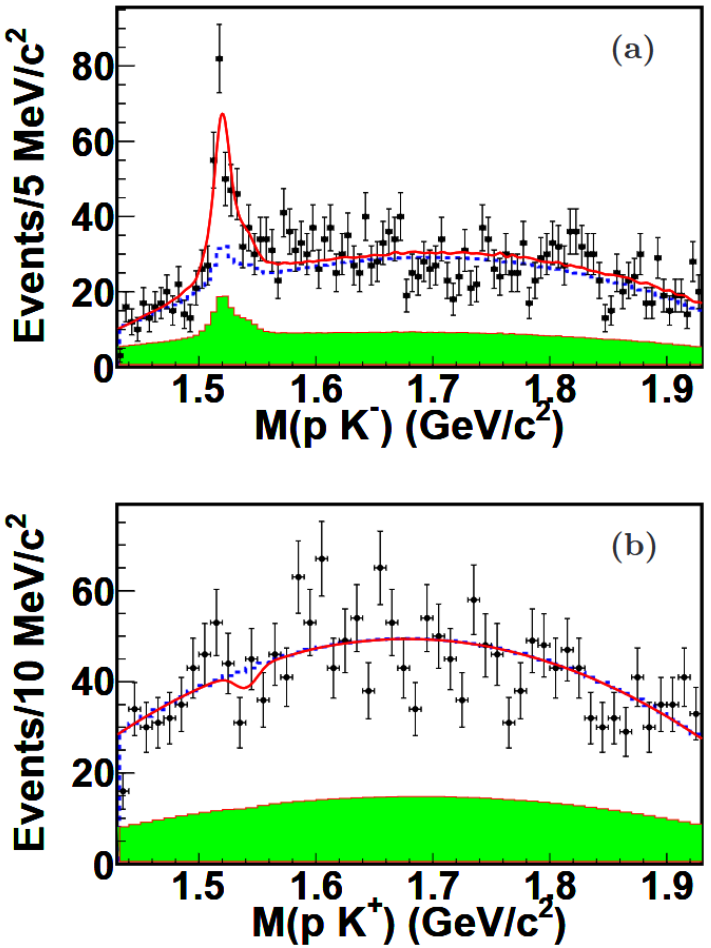
PRL 130 (2023) 031901



PRL 122 (2019) 072501

Baryon production in two-photon processes

- LEPS initially reported a pentaquark candidate in the nK final state at around 1540 MeV
- Two-photon production of $pK - \overline{pK}$ final state can look for neutral and doubly charged versions of it
- $\Lambda(1520)$ clearly visible, but $\theta(1540)$ not



PRD 93, 112017 (2016)

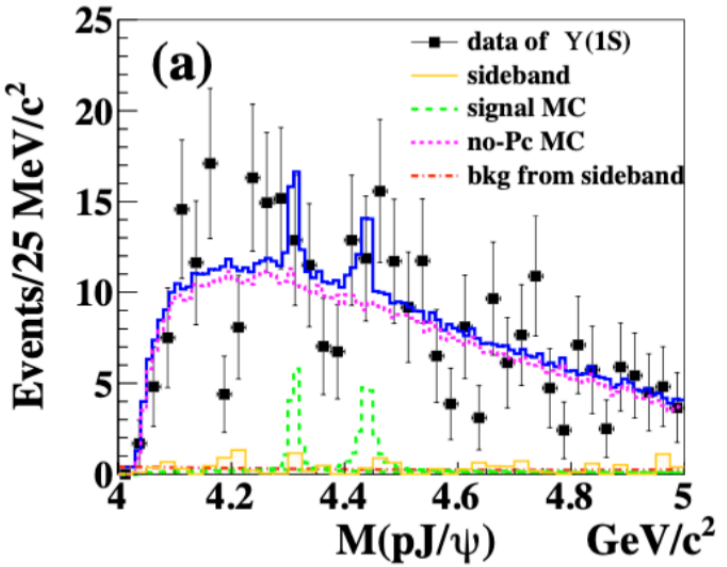
Heavy pentaquark searches

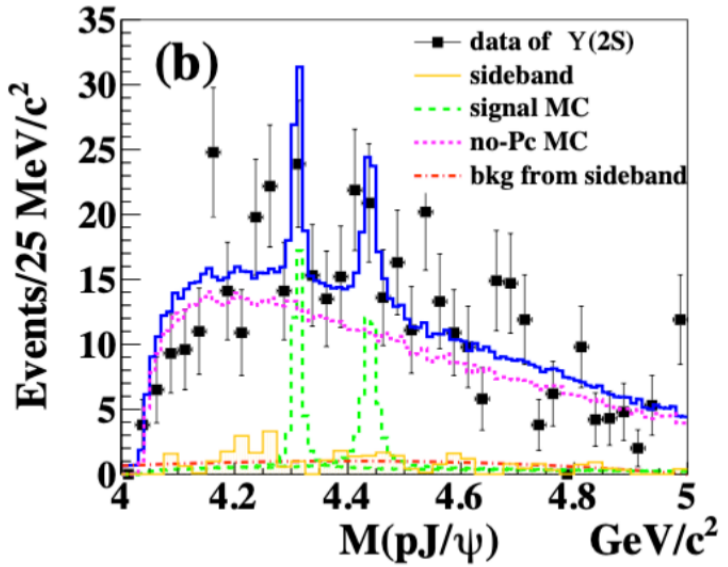
- Use $\Upsilon(1S)$ and $\Upsilon(2S)$ decays and continuum production to look in pJ/ψ decays – upper limits
- Use B decays for Λ_c decay searches of pentaquarks – upper limit:

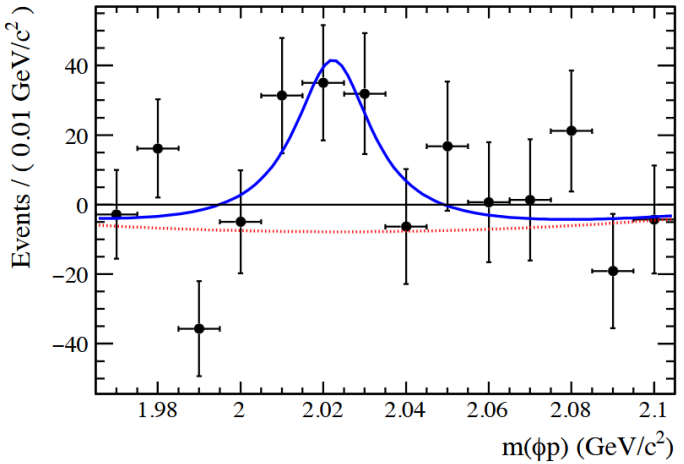
  $B(\Lambda^+_c \to P^+_s \pi^0) \times B(P^+_s \to \phi p)$

  $< 8.3 \times 10^{-5}$ (90%CL)
- Indication of a $P_{\bar{c}cs}(4459)^0$ pentaquark in ΛJ/ψ decays (preliminary)

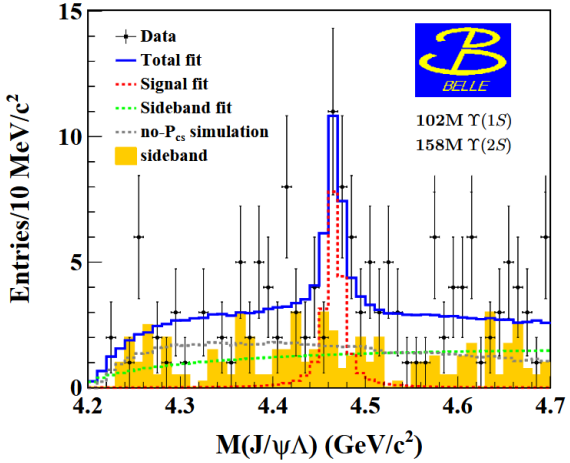
2403.04340







PRD 96 (2017) 05110

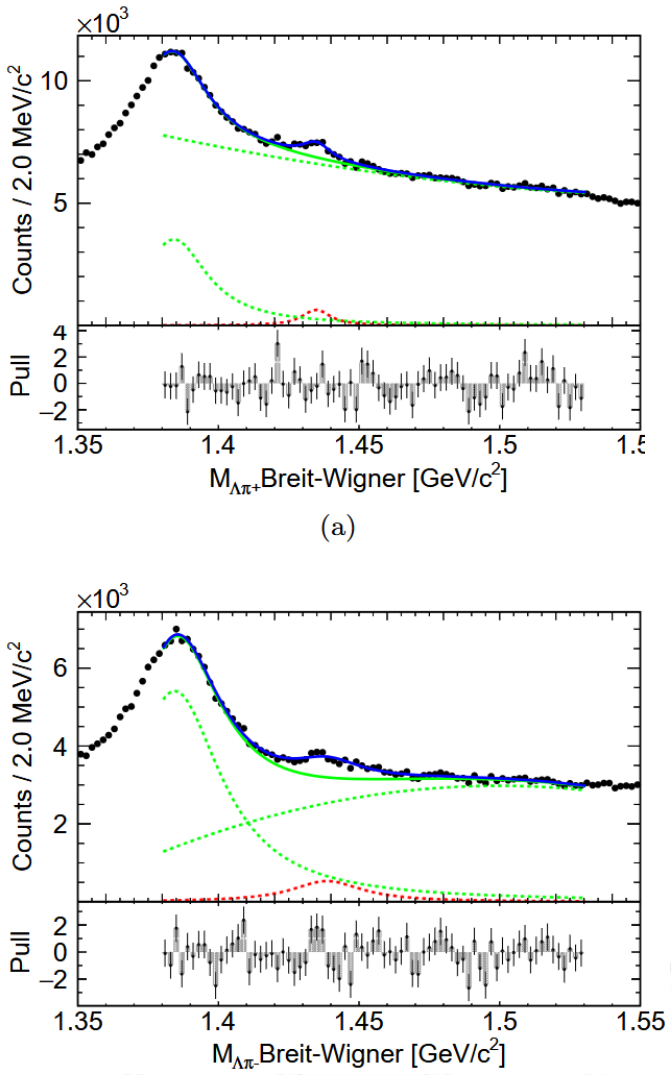


2502.09951

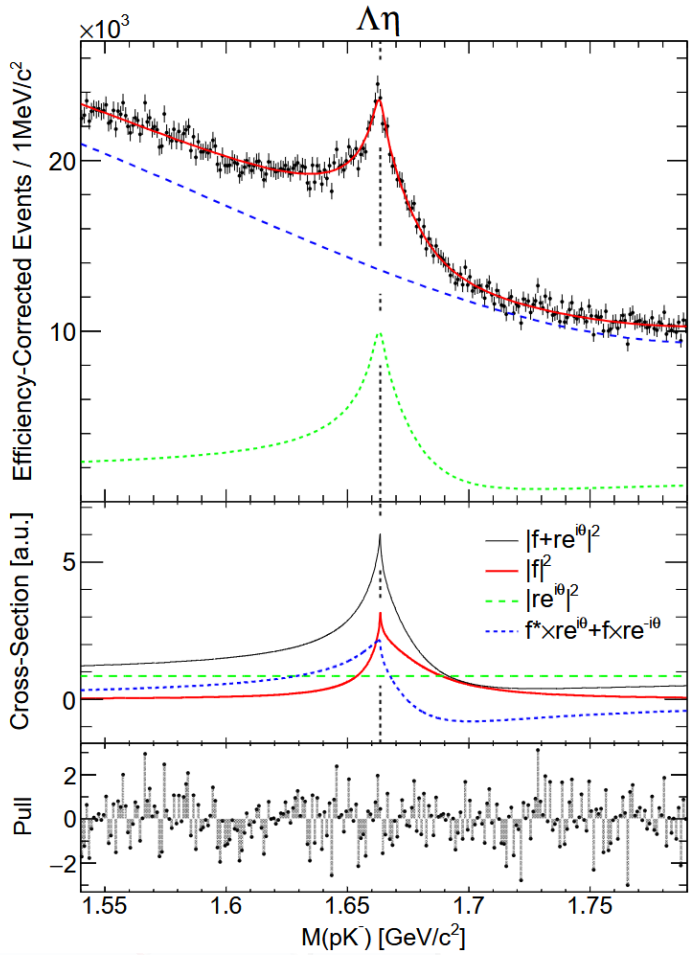
Peaks in Λ_c decays

- Peak seen in $\Lambda\pi$ mass distribution of Λ_c decays:

  M=1434.3 $\pm$ 0.6(stat) $\pm$ 0.9(syst) MeV
- Closeness to $\bar{K}N$ threshold cannot rule out cusp
- Also, cusp seen in Λ_c decays around $\Lambda\eta$ threshold w/o need for new resonance



PRL 130 (2023)151903

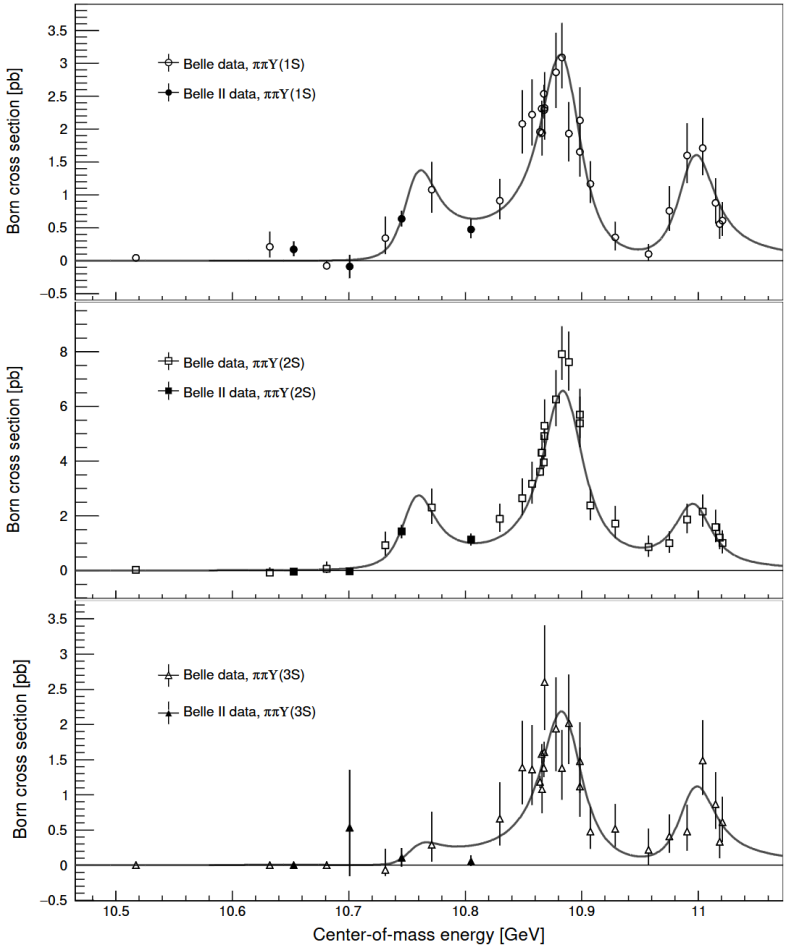


PRD 108 (2023) L031104

Bottomium-like states

JHEP 10 (2019) 220
JHEP 07 (2024) 116

- Various Bottomium-like states found
- Most recently Y(10753) in $e^+e^- \rightarrow Y(nS)\pi\pi$ scans, observed by Belle, confirmed by BelleII
  - hybrid- or S-D-mixing-structure?
  - Compatible with tetraquark? - disfavored by $\omega\eta_b(1S)$ measurement (*PRD* 109 (2024) 072013)
  - Similarity between Y(4260) and Y(10753) in decays
- Also Z_b states 10610 and 10650 found

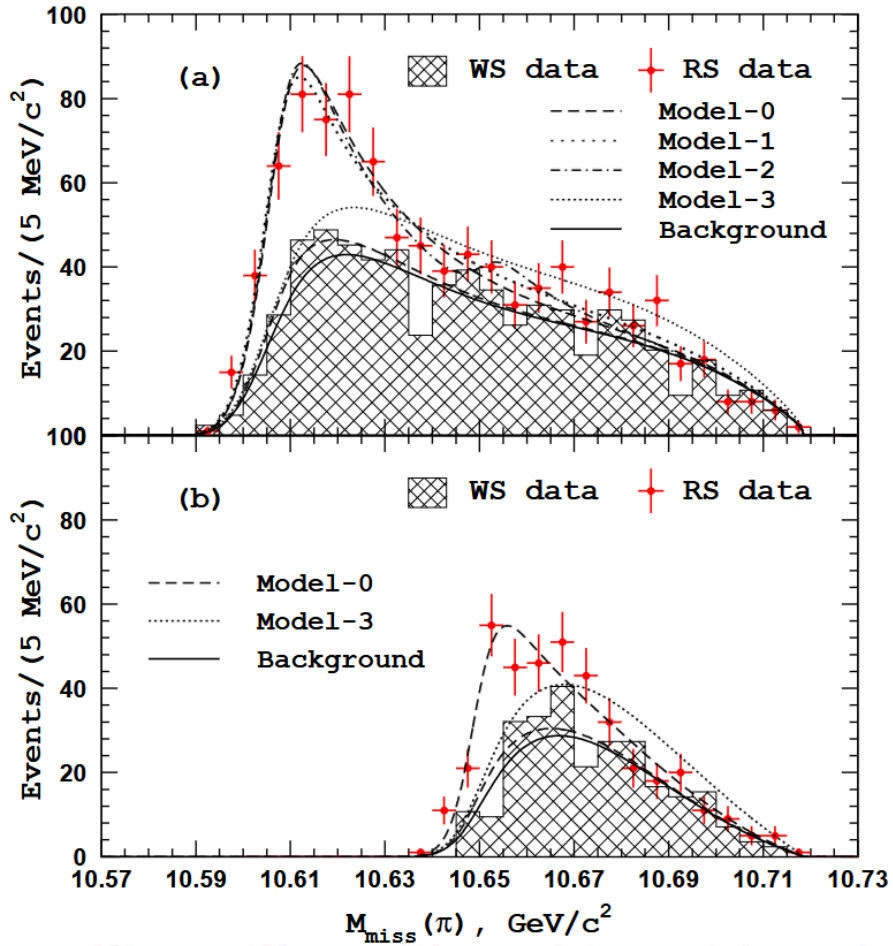


$e^+e^- \rightarrow \Upsilon(nS)\pi^+\pi^-$

$M = 10756.6 \pm 2.7 \pm 0.9\ MeV$

$\Gamma = 29.0 \pm 8.8 \pm 1.2 MeV$

*PRL*116 (2016) 212001



$e^+e^- \rightarrow B^{(*)}B^{(*)}\pi$

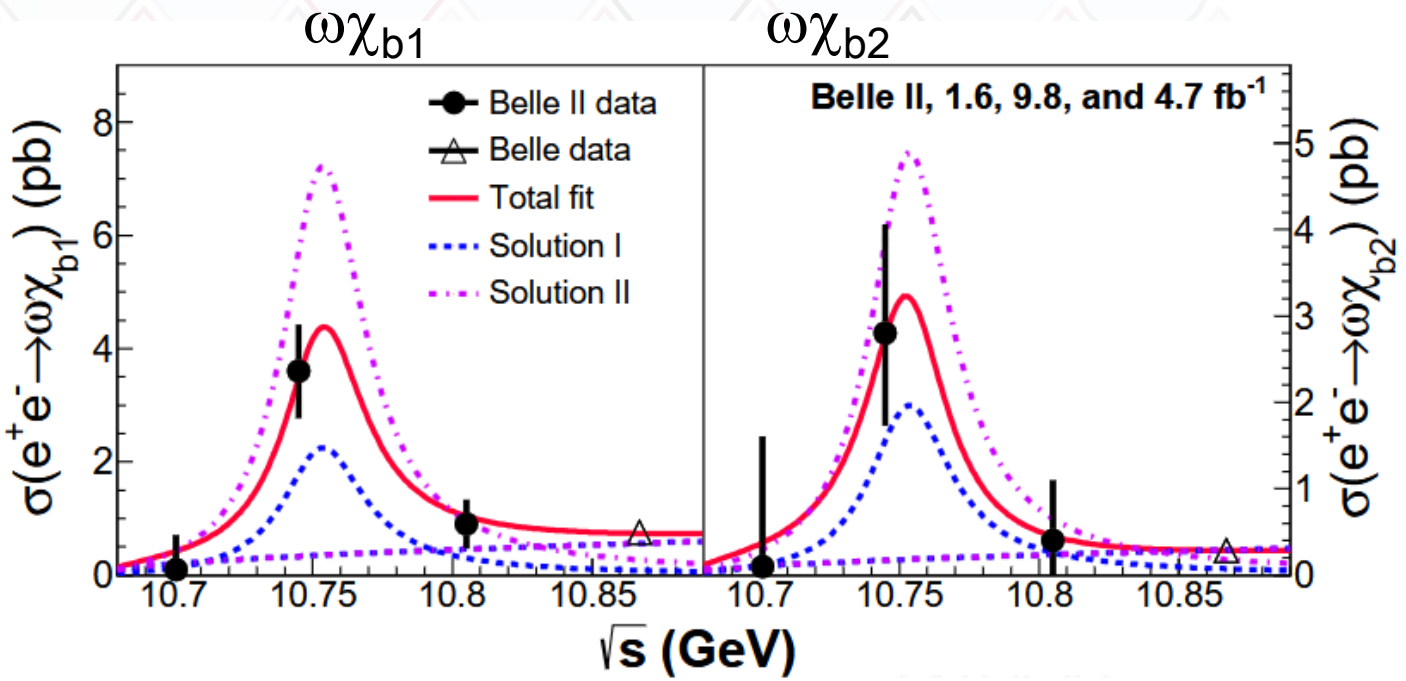
Outlook

- BelleII is running with improved capabilities and higher instantaneous luminosity compared to Belle
- Many XYZ states discovered with Belle, many starting to become available with Belle II
- Concentrate on widths of narrow resonances and BFs to better understand nature of exotic states
- Use ISR to study mass range above BESIII coverage
- Not just XYZ states, also light and heavy baryon measurements and pentaquark searches ongoing

Observation of $\Upsilon(10753) \to \omega\chi_{bJ}$

- Cross section ratio: 1.3 ± 0.6
- Prediction for pure D-wave state: 15
- Prediction for 4S-3D mixed state: 0.2

- Comparison of cross sections to $\Upsilon(nS)$ suggests different structure than $\Upsilon(5S)$



PRL 130 (2023) 091902