Quarkonium at Belle II

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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
  – QM predictions are robust
    → Exotics (Tetraquarks, hybrids, molecular states, glueballs, ...) are distinguishable
Production mechanisms in $e^+e^-$

- B decays – charmonia
- Direct production/Initial State Radiation (ISR)
  - $J^{PC}=1^{--}$
- Two photon collision
  - $J^{PC}=0^{++}, 2^{++}, ...$
- Quarkonium transitions
  - Feed-down from higher states
Quarkonia summary

- Good agreement below open flavor threshold
- Exotic candidates, so called XYZ states, discovered
Remaining questions

• Many XYZ states were found, but
  – Which ones are exotic?
  – If exotic, what kind?
    Molecule? Tetraquark? Hybrid? Something else?
  – Goal: classification of these states

• \( J^P \) is not determined yet for some XZ states
  – Most important measurement in the coming days

• More states?
  – Several more should be discovered especially in b sector
  – Interesting to compare \( XYZ_c \) and \( XYZ_b \)
  – Discovery of unexpected?
SuperKEKB and Belle II

Upgrade for SuperKEKB and Belle II to achieve 30x peak $\mathcal{L}$

- Reduction in the beam size by $1/20$ at the IP.
- Doubling the beam currents.

$$L = \frac{\gamma_{e^\pm}}{2e r_e} \left( 1 + \frac{\sigma_y^*}{\sigma_x^*} \right) \left( \frac{l_{e^\pm}}{\xi_{e^\pm}} \right) \left( \frac{R_L}{R_{\xi_y}} \right)$$

- First turns achieved Feb. 2016
- Beam-background studies ongoing

Goal: x50 more statistics than Belle
Belle II detector

Superconducting solenoid (1.5 T)

K_L and \( \mu \) detector
- Resistive plate chamber (outer barrel)
- Scintillator + MPPC (inner 2 barrel layers, end-caps)

Electromagnetic calorimeter
CsI(Tl), waveform sampling

Particle ID detectors
- TOP (Time-of-Propagation) counter (barrel)
- Aerogel RICH (forward end-cap)

Tracking detector
Drift chamber (He + C_2H_6) of small cell, longer lever arm with fast readout electronics

Silicon vertex detector
- 1\( \rightarrow \)2 layers DEPFET (pixel)
- 4 outer layers DSSD

Trigger and DAQ
Max L1 rate: 0.5\( \rightarrow \)30 kHz
Pipeline readout

GRID computing

Better performance even at the higher trigger rate and beam background
Belle II integrated luminosity

Achieved

- Instantaneous luminosity already exceeded Belle
- Integrated luminosity will exceed Belle within a few years
- Goal: 50 ab\(^{-1}\) around 2031.

Prospect

Total: 213 fb\(^{-1}\)
Charmonia
Charmonia by B-decay

- Rich source for charmonium-like mesons
  - Not only discovery, but to identify nature of the states
- In decay modes $B \rightarrow KX$
  - $J^{PC}$-determination: B and K are spinless, so $J_Z(X)=0$
  - Determination of absolute branching fraction:
    X can be identified in recoil (missing) mass
- Good signals in Belle II with the present luminosity
  - Clear $J/\psi$ signals both in ee and $\mu\mu$ modes
  - $B \rightarrow \psi(2S)K$, $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$
J/ψ in B decay

• PDF: CrystalBall+Gaussian for ee, double gaussian for μμ
X(3872)

- Rediscovery of X(3872) in B → X(3872)K → J/ψππK with 63 fb$^{-1}$ (4.6σ significance) — ~20% higher efficiency than Belle

- Near future: Measurement of absolute BR with 1-5 ab$^{-1}$ using missing mass in B → XK.
Pole position search

• Flatte fitting with $X(3872) \rightarrow J/\psi \pi \pi$ alone cannot pin-down parameters [LHCb, PRD102.092005(2020)]
  – Scaling behavior of Flatte distribution.

• Simultaneous fit with $X(3872) \rightarrow D^0 \bar{D}^{*0}$
Charmonia by ISR

• Can use data from all higher energies.
  – Line shape study possible with single datasets
  – Decomposition of many nearby states

• Channels of interest
  – $\pi^+\pi^- J/\psi(\psi(2S), h_c, ...)$: Y(4260), Z(3900), ...
  – $K^+K^- J/\psi(\psi(2S))$: Strange partners of Z?
  – $\omega \chi_{c0}$: Y(4220)?

• Competition with BESIII energy scan
  – Similar effective luminosity
  – Wider mass range accessible
Belle II progress: $J/\psi \rightarrow \mu\mu$ via ISR
Bottomonia
Bottomonia

• **New things @Belle II**
  - Measurement at $Y(6S)$ becomes possible
    $\Rightarrow$ Expect more $Z_b$ states
  - Radiative transitions between bottomonia

• **Most missing conventional bottomonia below the open bottom threshold should be found; e.g.,**
  - $\chi_b(3P)$ triplet
  - $Y(2D_3)$ triplet
  - $\eta_b(3S), \eta_b(1D), Y(1D_{1,3})$
  - F-wave states
  - Several others
New states?

• Some $X_{Y\bar{Z}_c}$ states should have analogs in $b$ sector
  – $Y_b$ states will be searched for in energy scan. (see next slide for $Y(10753)$)
  – Help to identify the nature of these states

• Expected new states?
  – Yes, there are some: especially for partner states of $Z_b$

• Possibility for unexpected?
  – Yes, it’s always there. Who knows?
Energy scan \( \sim 10.751 \) GeV

- \( Y(10753) \)?
  - Hints in \( Y(nS)\pi\pi \) & inclusive \( b\bar{b} \) data
  - Significance 5.2\( \sigma \)
  - Exotic? Conventional?

[Chin. Phys. C 44 8, 083001 (2020)]

[Belle, JHEP10(2019)220]
Belle II plan

• Near the end of 2021, we will take data at 4 points
  – 10.751 GeV (9.5 fb\(^{-1}\)), 10.657 GeV (1.5 fb\(^{-1}\)),
    10.706 GeV (3.5 fb\(^{-1}\)), and 10.810 GeV (2 fb\(^{-1}\))
  – To establish the existence
Belle II progress: $Y(nS) \rightarrow Y(1,2S)\pi\pi$

- ISR production
- Better than previous Belle result
  [PRD96 (2017)052005]
  - $3S \rightarrow 2S$ transition seen thanks to improved low momentum tracking
- Dalitz analysis of $Y(4S) \rightarrow Y(nS)\pi\pi$ is ongoing
Summary

• Belle II will acquire x50 more statistics than Belle
  – Instantaneous luminosity already surpassed
  – Identify the nature of known candidates
  – Expecting a lot of further discoveries

• Charmonia -- Rediscovery of X(3872)
  – With better efficiency than Belle
  – Other XYZ states will be rediscovered soon

• Bottomonia
  – Good performance demonstrated in $Y(nS) \rightarrow Y(1,2S)\pi\pi$
  – Plan to take data around 10.75 GeV for $Y(10753)$ in 2021
  – Higher energy run in future for $Y(6S)$