Belle II prospect for hadron spectroscopy

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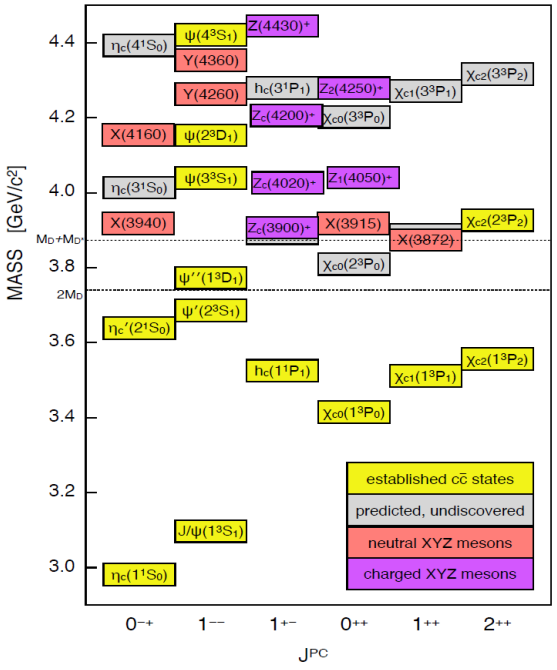
Paradigm shift in the hadron spectroscopy



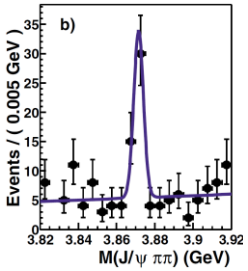
arXiv:1511.01589

Before the B-factory era, charmonium are well understood by the constituent quark model.

B-factories discovered many charmonium-like hadrons deviated from quark model

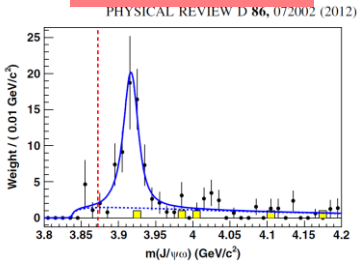
Some states have charge, which can not be achieved by $c\bar{c}$

X(3872)→J/ψπ⁺π⁻

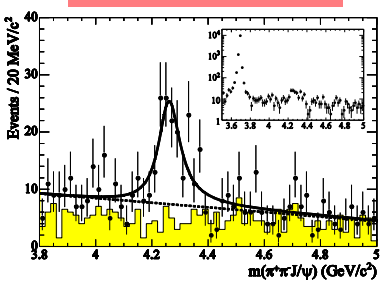


Phys. Rev. Lett. 91.262001

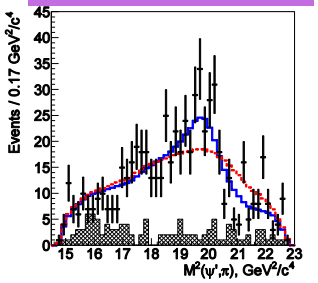
X(3915)→J/ψω



Y(4260)→J/ψπ⁺π⁻



Z(4430)⁺→ψ(2S)π⁺

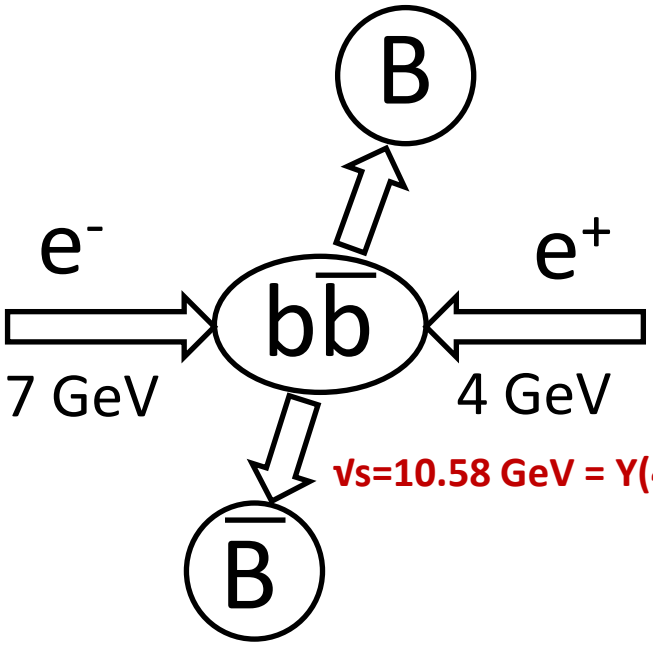


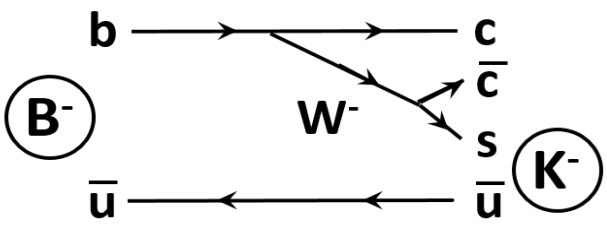
Phys. Rev. D **88**, 074026 (2013)

Homeworks from B-factory experiments (= Belle, BaBar):

- Nature of XYZ particles not understood.
- Missing “conventional” quarkonium. How well quark model works?

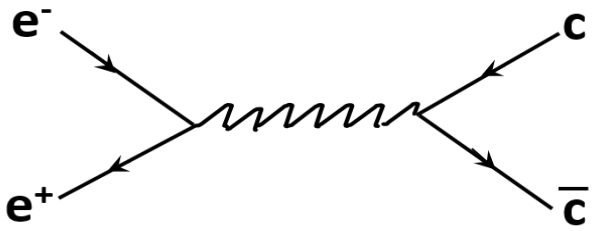
B-factory = hadron factory!





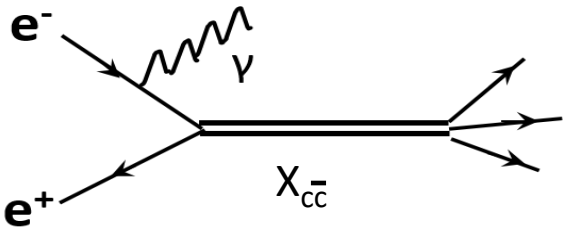
B meson decay

- X(3872), Z(4430)….
- Open charm hadrons



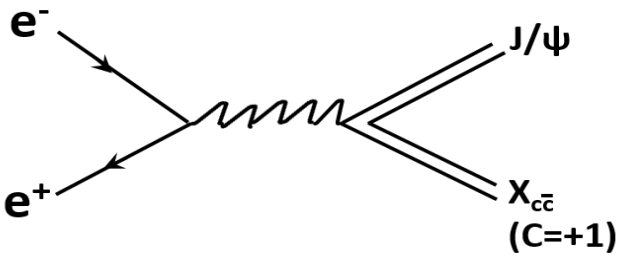
$e^+e^- \to c\bar{c}$

Charm mesons/baryons



Initial state radiation

- $J^{PC}=1^{--}$
- Y(4260)



Double charmonium

- C-even charmonium

“New hadrons” from B-factories

Hadron Type

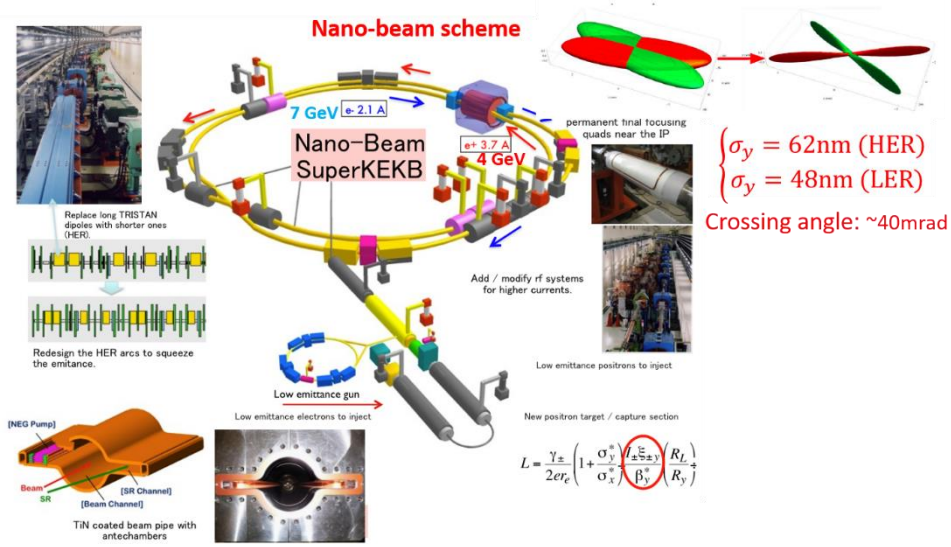
Reaction	Charmonium (-like)	Bottomonium (-like)	D, $D_{(s)}$	Charmed baryon	Hyperon
B-decay	$\eta_c(2S)$ $\psi_2(3823)$ $X(3872)$ $X(3915)$ $Z_c(4050)$ $Z_c(4250)$ $Z_c(4430)$ $Z_c(4200)$		$D^*_0(2400)$ $D_1(2430)$	$\Xi_c(2930)$	Belle BaBar
Initial State Radiation	$Y(4260)$ $Z(3900)$ $Y(4008)$ $Y(4360)$ $Y(4660)$				
Double charmonium	$X(3860) \doteqdot \chi_{c0}(2P)$ $X(3940)$ $X(4160)$				
Two-photon	$\chi_{c2}(2P)$				
$e^+e^- \to c\bar{c}$			$D^*_{s0}(2317)$ $D_0(2550)$ $D_J^*(2600)$ $D_J(2740)$ $D_3^*(2750)$ $D^*_{s1}(2700)$ $D^*_{s1}(2860)$ $D_{sJ}(3040)$	$\Sigma_c(2800)$ $\Lambda_c(2940)$ $\Xi_c(2980)$ $\Xi_c(3080)$ $\Omega_c(2770)$ $\Xi_c(3055)$	
Y(nS) decay		$Z_b(10610)$ $Z_b(10650)$ $\eta_b(2S)$ $h_b(1P)$ $h_b(2P)$			$\Omega(2012)$
Charm baryon decay					$\Xi(1620)$

~40 new hadrons discovered!

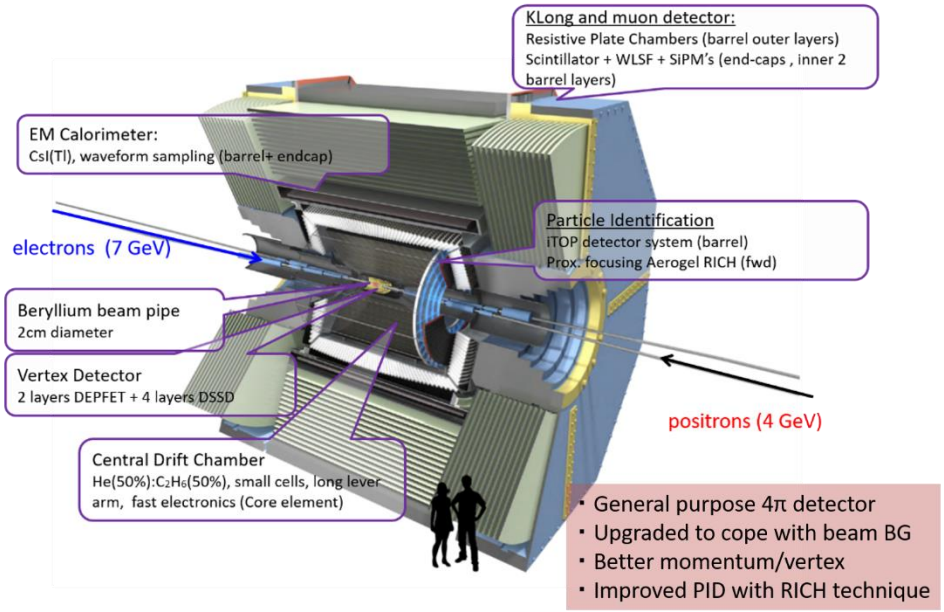
Today: Prospect for Charmonium (-like) and charmed baryons

SuperKEKB/Belle II experiment

SuperKEKB

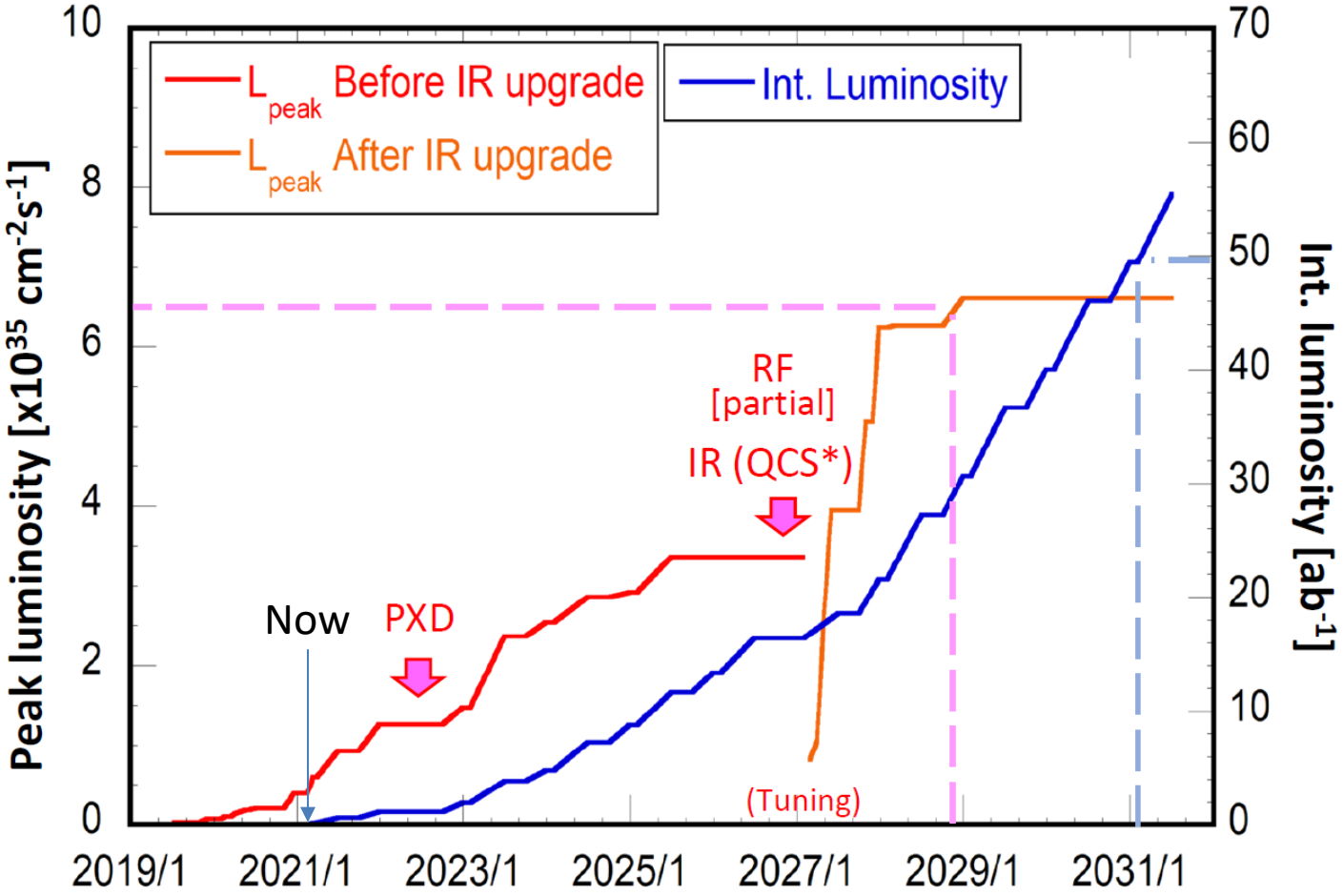


Belle II detector



- Upgrade of KEKB/Belle experiment
- Target Luminosity:
  - 30 times higher peak luminosity compared to KEKB (= 6×10^{35} /cm^2/s)
  - 50 times higher integrated luminosity (= 50 ab^{-1})
- Detector upgrade for better performance and to cope with higher beam BG
- Grid computing to handle O(100 PB) data.
- Many physics programs: The Belle II Physics Book

Schedule



- Physics run started from 2019 Apr.
- Accumulated around 90 fb-1 so far.
- 50 ab^{-1} coms on ~2030

Recent highlights

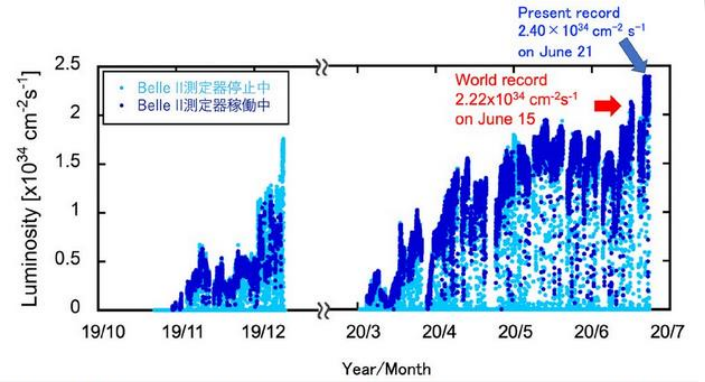


図1. 2019年の秋から2020年6月22日まで、5分間隔で測定したSuperKEKB加速器の瞬間ルミノシティの値 （速報値のため、1%程度の誤差をもつ）

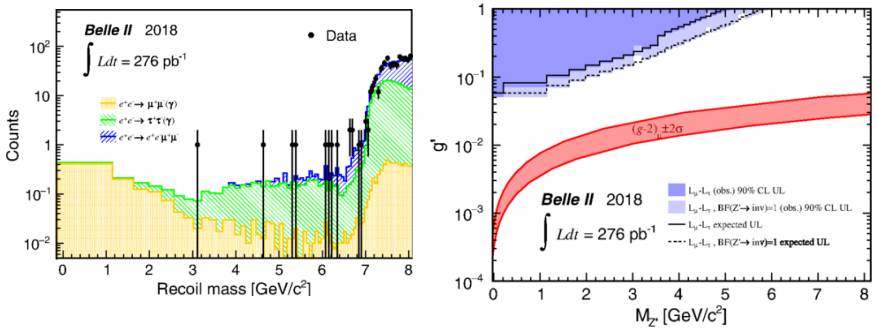
© KEK

Luminosity record by SuperKEKB with a factor 2-3 lower current

https://www.kek.jp/ja/newsroom/2020/06/26/1400/

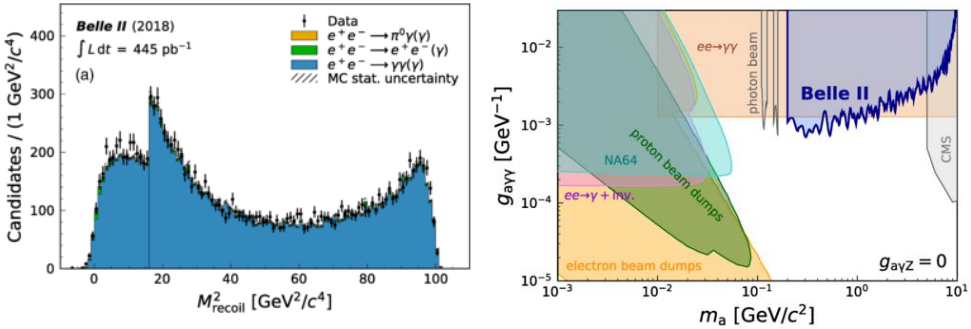
Physics results for dark matter candidate searches

$e^+e^- \rightarrow \mu^+\mu^- Z'$



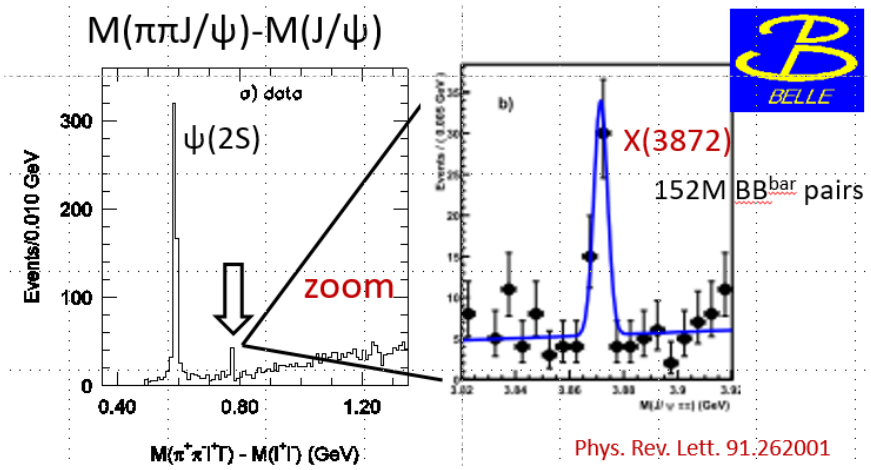
Phys. Rev. Lett. 124, 141801

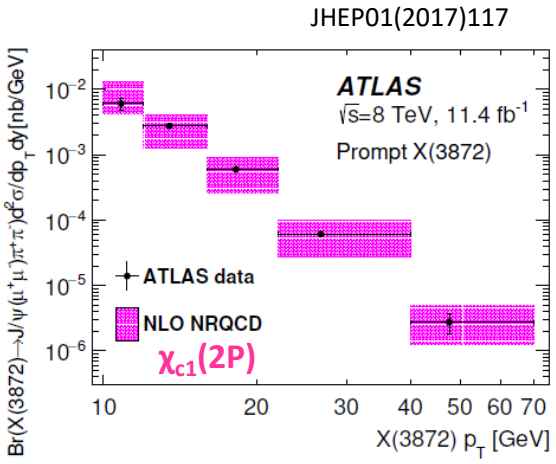
$e^+e^- \rightarrow \gamma a$, a->γγ (Axion Like Particle)



Phys. Rev. Lett. 125, 161806

X(3872): The poster boy





- Firstly observed by Belle in $B^+ \to K^+ (J/\psi\pi^+\pi^-)$.
  - $J^{PC} = 1^{++}$
  - Decay into both of $J/\psi\rho$ (I=1) and $J/\psi\omega$ (I=0): isospin breaking
  - Mass consistent with DD* with O(0.1) MeV presicion.

} $D\bar{D}^*$ molecule?

  - Differential cross section for prompt production cross section at LHC consistent with $\chi_{c1}(2P)$

} $c\bar{c}$?

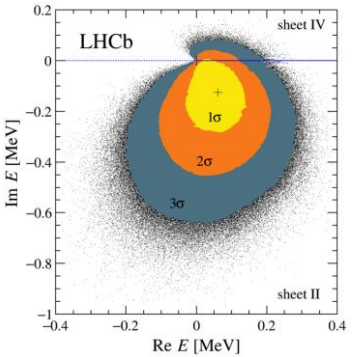
Dynamical information is essential to understand X(3872)

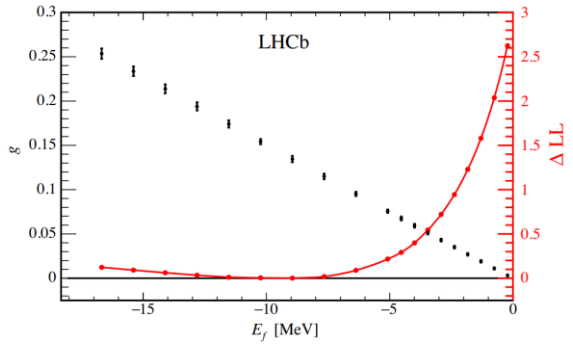
X(3872) coupling to the DD*

- LHCb performed shape analysis of X(3872) → J/ψπ⁺π⁻ with Flatte parameterization
  - Compatible with quasibound DD*, but quasivirtual state is allowed in 2sigma

- Due to the "Scaling law", no sensitivity to determine coupling and mass with J/ψππ mode only

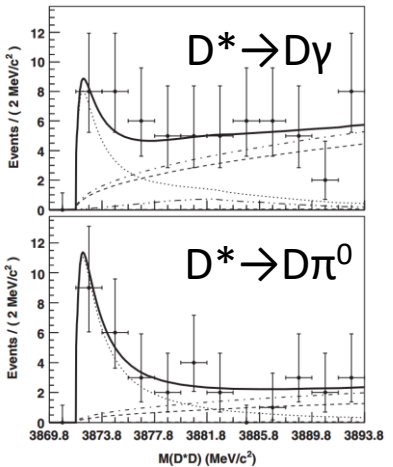
Phys. Rev. D **102**, 092005





$$\frac{dg}{dE_f} = (-15.11 \pm 0.16)\ \text{GeV}^{-1}$$

- In the B-factory, it is possible to study the J/ψππ and DD* simultaneously, to determine the coupling.

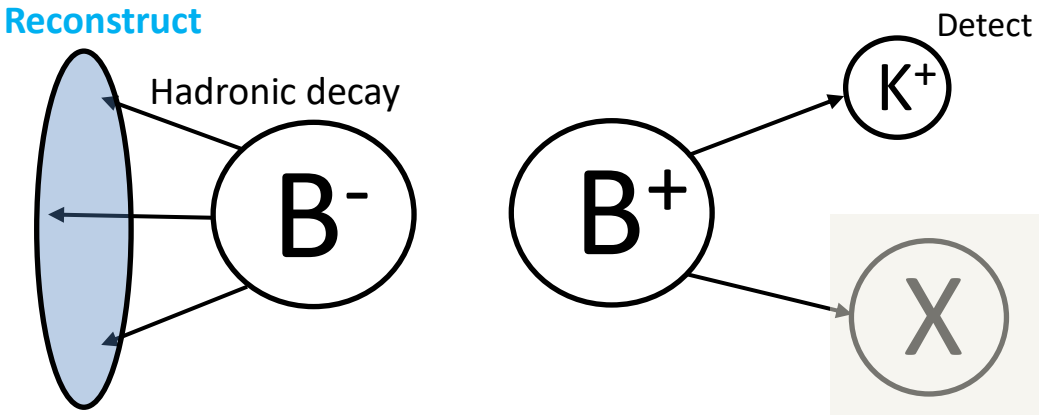


Phys. Rev. D 81, 031103(R)

Br($B^+ \to K^+ X(3872)$)

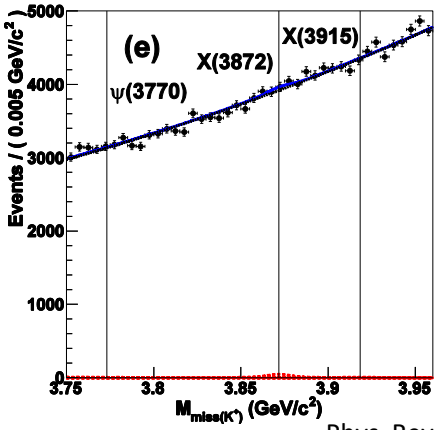
- With invariant mass reconstruction of X(3872), only the product of branching fraction: Br($B^+ \to X(3872)\ K^+$) x Br(X(3872) -> f) can be measured.

- Br ($B^+ \to X(3872)\ K^+$) → Do not look for X(3872) decay
  - Reconstruct X from Missing mass: $M_x^2 = (P_{beam} - P_{BTag} - P_{K+})^2$



Belle full statistics result

$< 2.6 \times 10^{-4}$



Phys. Rev. D 97, 012005

- Measurement only possible at B-factory with only two B meson in final state
- 7σ measurement is possible at Belle II (naïve extrapolation)
- Measurement for X(3915) is also important to determine Br(X(3915)→J/ψω)
- Better B meson reconstruction should improve sensitivity.

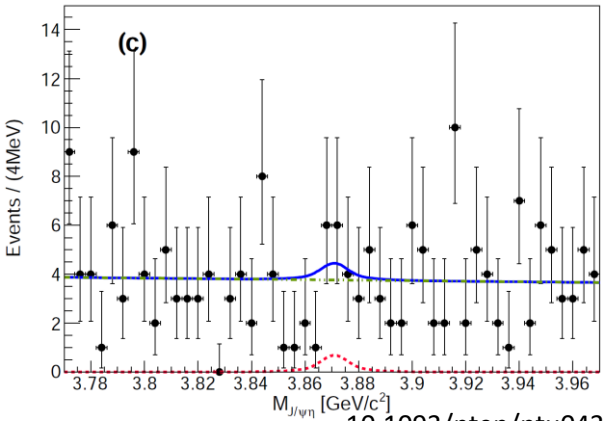
Search for partner states of X(3872)

- **Molecule/tetra-quark scenarios predict existence of X(3872) partner states.**

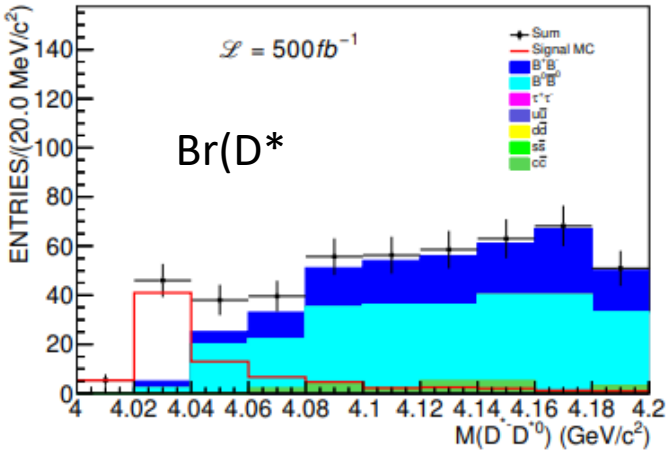
- **C-odd partner:**
  - No structure observed in J/ψη by Belle.
    The upper limit is around half of X(3872)→J/ψπ⁺π⁻
  - X(3872) → η_c γ is another candidate

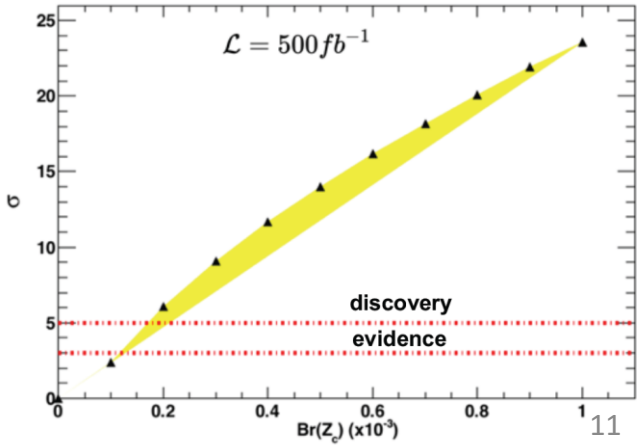
- **Spin partner:**
  - B→K DD and K D*D* not studied in detail yet.
  - Sensitivity of 10(-4) is possible at early stage of Belle II

M(J/ψη)



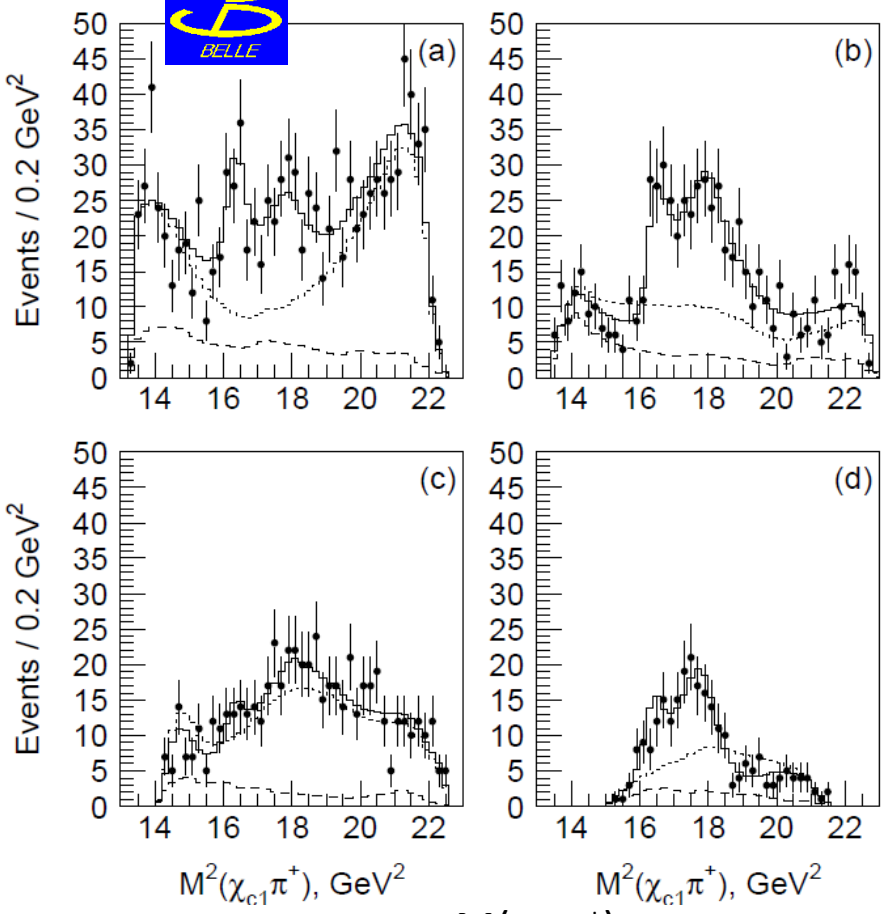
10.1093/ptep/ptu043





B decays: States need confirmation

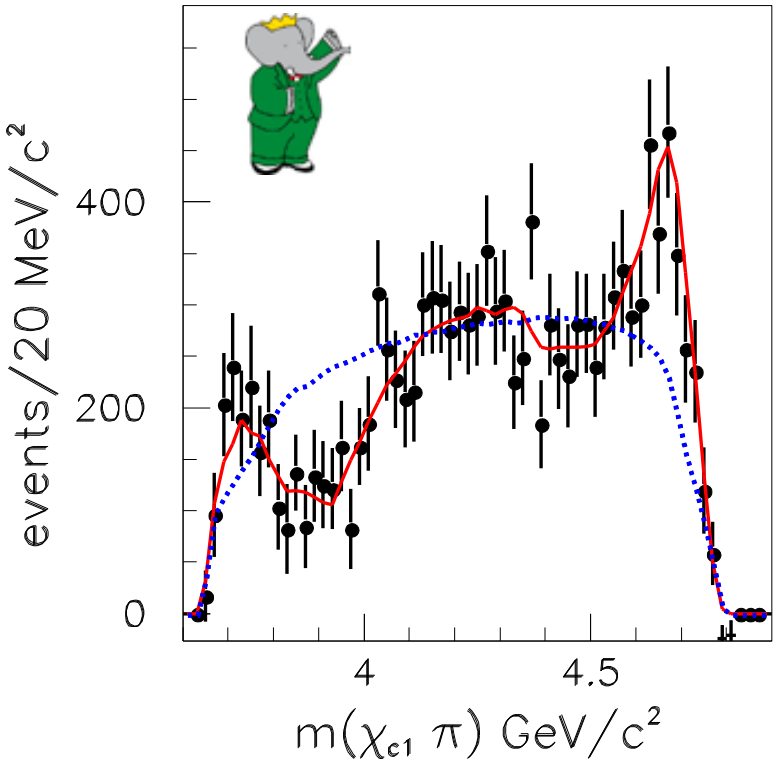
$B^+ \to K^+ Z(4050), Z(4250) \to \chi_{c1}\pi^+$



Phys. Rev. D 78, 072004

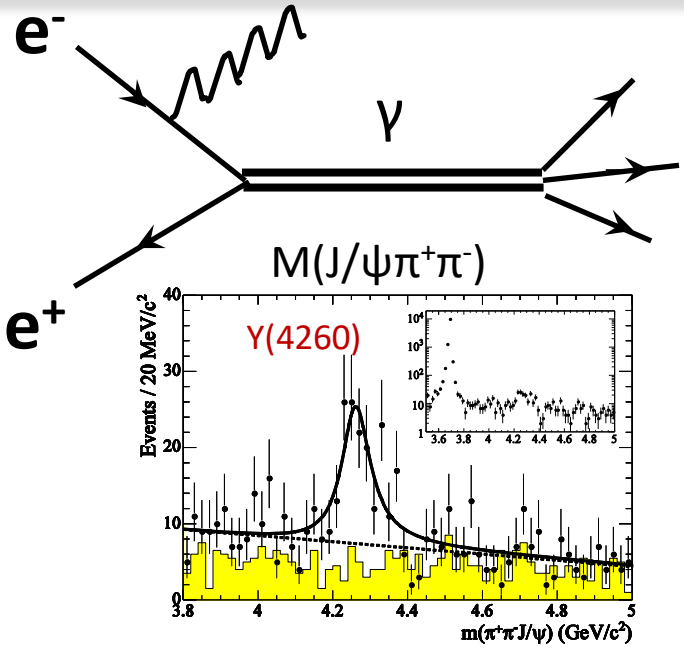
$M(\chi_{c1}\pi^+)$
(in different $M(K\pi)$ bins

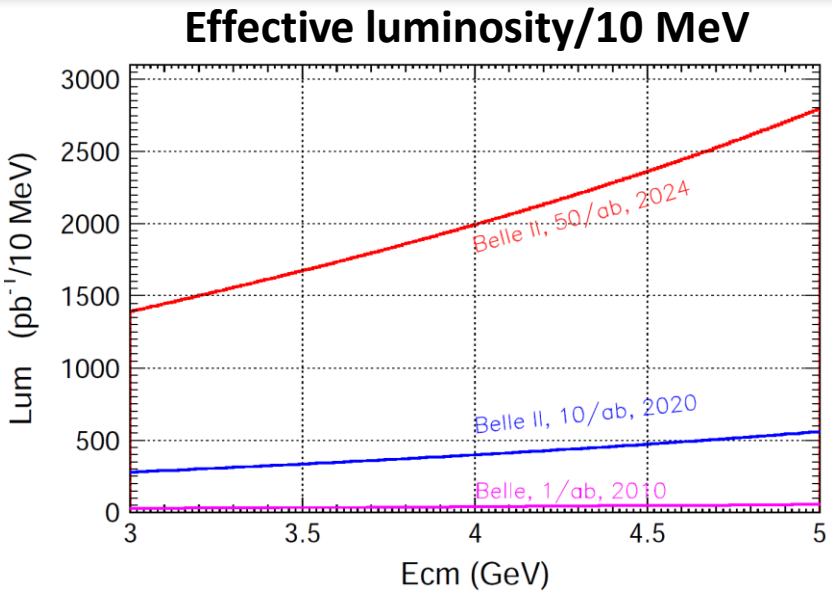
BaBar reported $m(\chi_{c1}\pi^+)$ can be described by resonances in $K\pi$ channel only

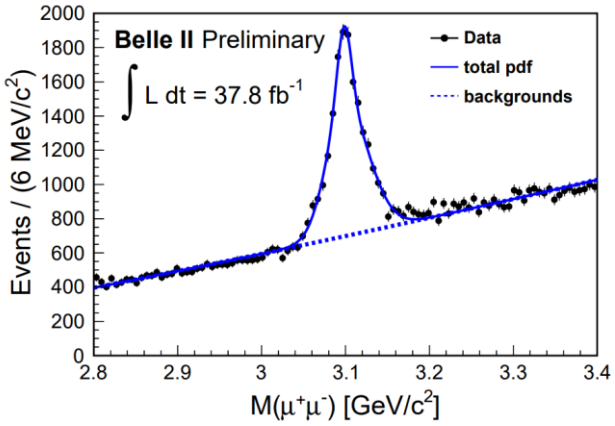


Confirmation by Belle II is necessary

Initial State Radiation







- One of the best probes to study 1^{--} quarkonium states.
- Many "Y" states are reported from B-factories and BES III.
- Also many "Z" states from "Y" decay.
- 50 ab^{-1} data corresponds to 2000-2300 pb^{-1}/10 MeV at 4-5 GeV.
  → Compatible with BES III
- Belle II has advantage to access energy higher than 4.6 GeV, and take data simultaneously.

Initial State Radiation golden modes

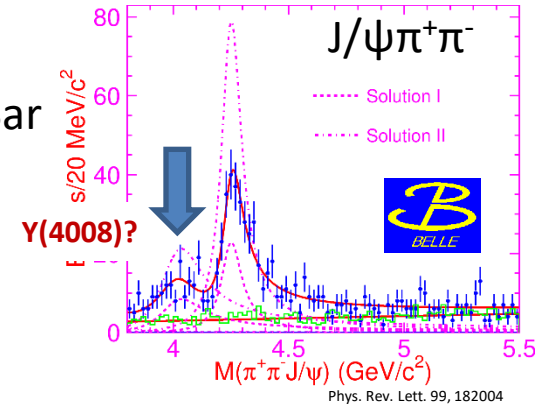
- **States needs confirmation**
  - Y(4008): inconsistent between Belle/BaBar
  - Many states observed by BES III only.

- **State needs further studies**
  - Z(3900): Resonance or cusp?
    Need Argan diagram with amplitude analysis

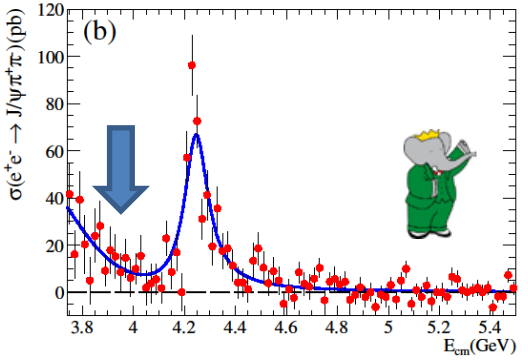
- **New States?**
  - J/ψ K^+K^- for Z_{cs} search.
  - ISR events are observed, but no structure.
  - Need more statistics.

- **And many more..**

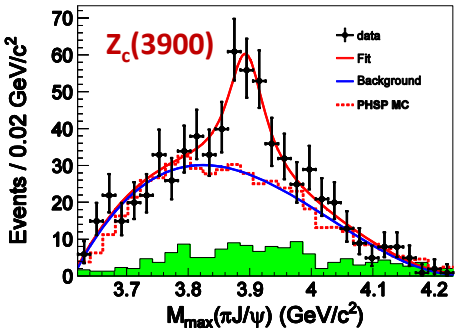
Golden Channels	$E_{c.m.}$ (GeV)	Statistical error (%)	Related XYZ states
$\pi^+\pi^- J/\psi$	4.23	7.5 (3.0)	$Y(4008)$, $Y(4260)$, $Z_c(3900)$
$\pi^+\pi^-\psi(2S)$	4.36	12 (5.0)	$Y(4260)$, $Y(4360)$, $Y(4660)$, $Z_c(4050)$
$K^+K^- J/\psi$	4.53	15 (6.5)	Z_{cs}
$\pi^+\pi^- h_c$	4.23	15 (6.5)	$Y(4220)$,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

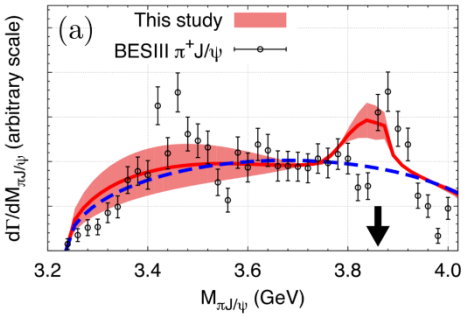


Phys. Rev. Lett. 99, 182004

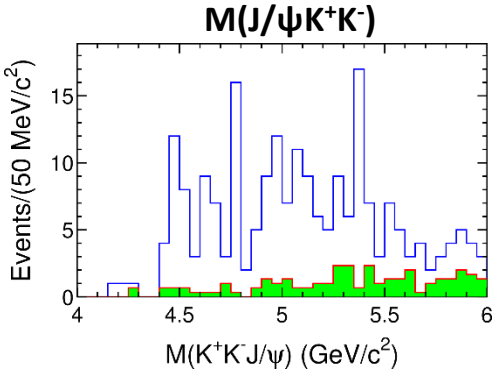


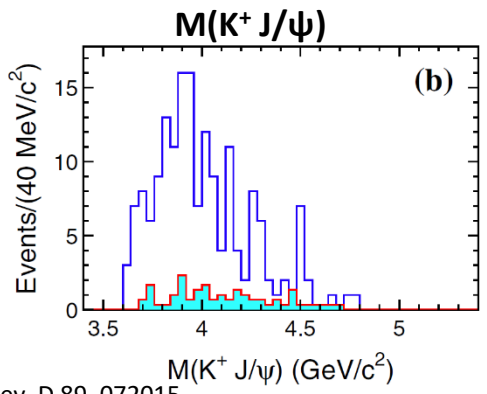
DD*Cusp reproduce the peak?





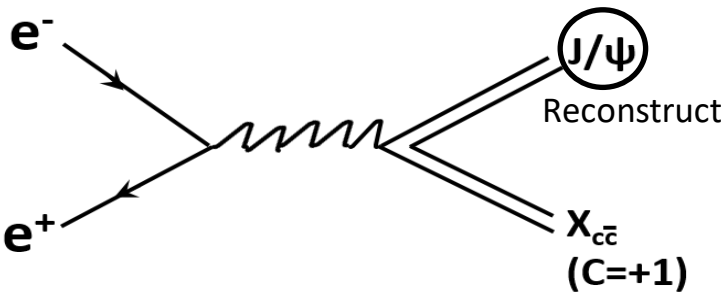
Phys. Rev. Lett. 117, 242001





Phys. Rev. D 89, 072015

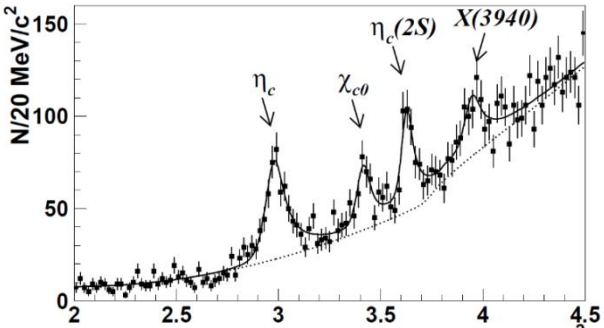
Double charmonium production



- Large cross section revealed importance of next order correction in NRQCD.

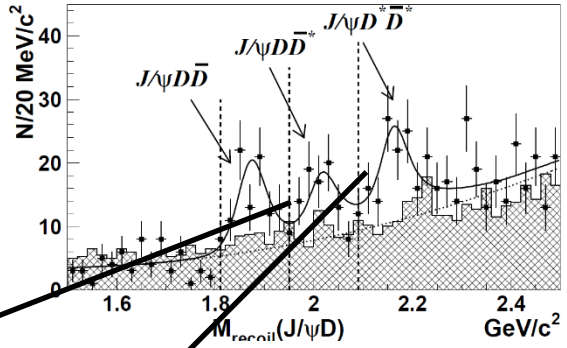
- Observation of two new states
  - X(3940): observed both inclusive and exclusive $D\bar{D}$
  - X(4160): Observed in exclusive $D\bar{D}^*$

J/ψ missing mass

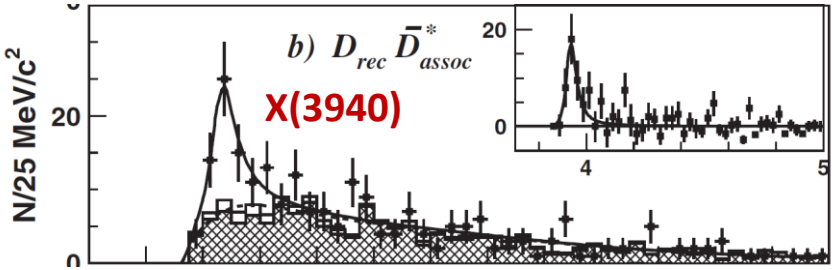


Phys. Rev. Lett. 98, 082001

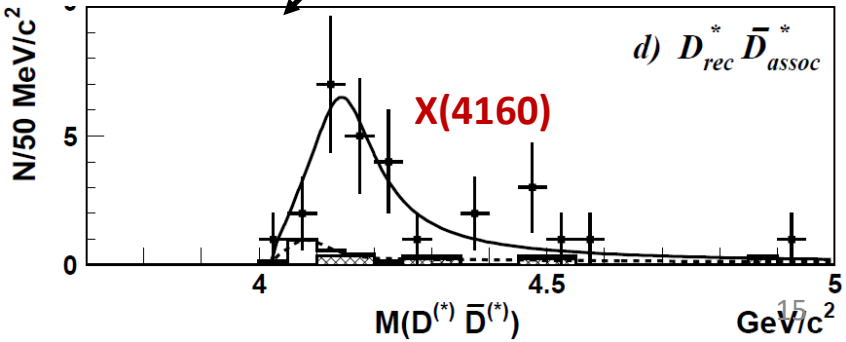
J/ψ D missing mass



DD* mass



D*D* mass



Phys. Rev. Lett. 100, 20200

Interpretation of X(3940/4160) and beyond

- All the known states observed in missing mass are J=0.
  X(3940/4160) should be J=0?
- If J=0, C-parity = +1 and decay into DD* indicate they are η_c family.
- However, the mass of X(3940) is ~100 MeV lower than quark model prediction.
- Also, the predicted mass of $\eta_c(4S)$ is 4400 MeV/c^2.
- Could be a exotic candidate?
- Full amplitude analysis at Belle II is awaited for J^P determination.
- Recoiling against other charmonium (η_c, χ_c …) is also very interesting.

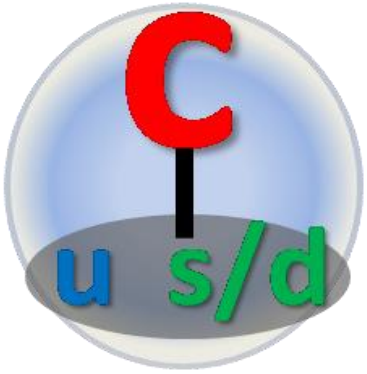
Physics of charmed baryons

- Charm quark is heavy: (1500 MeV/c^2) > u,d,s quarks (300-500 MeV/c^2)
- spin-spin interaction $\propto 1/m_1m_2$
- Di-quark correlation in light quarks
  - New degree of freedom with color (what is the mass?)
  - More simple to understand baryon

Nucleon

Every pair can not be distinguished.

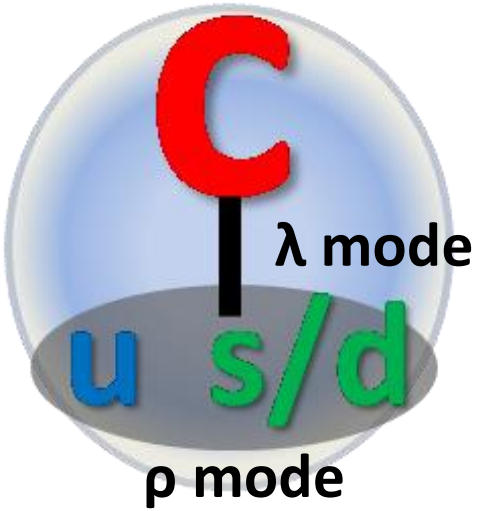
Charmed baryon



Light di-quark and charm quark.

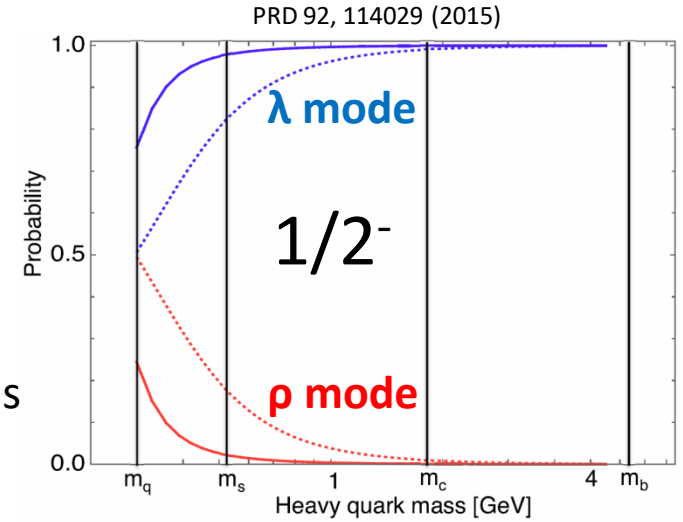
Excitation modes in di-quark picture

- There are two kind of excitation modes.
  - λ mode: excitation between c quark and u-d di-quark.
  - ρ mode: excitation in the di-quarks.



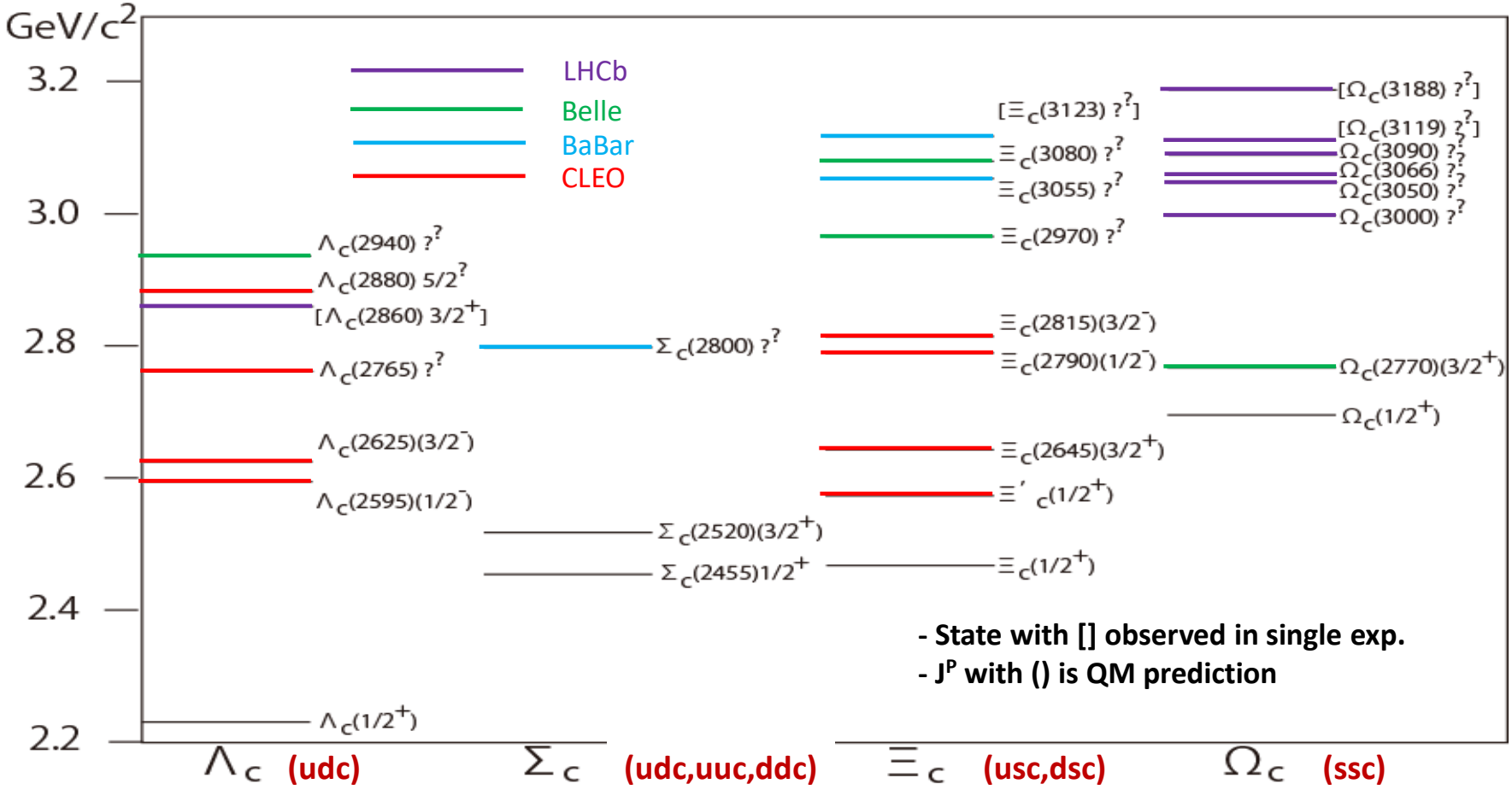
$$\frac{h\omega_\rho}{h\omega_\lambda} = \sqrt{\frac{3m_Q}{2m_q + m_Q}} \sim= \sqrt{3}$$

ρ mode and λ mode is clearly seperated in the charmed baryons



Observed charmed baryons

10.1016/j.ppnp.2019.01.001



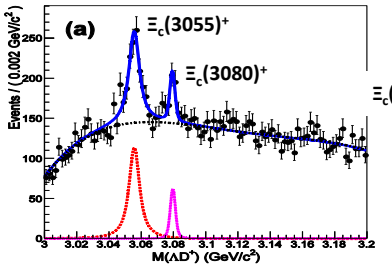
Achievements and missing things

- All the ground states and many excited states observed.
- J^P for a few states determined.
- Many decay modes observed.
  - Important for identification of λ - ρ mode.
- Very precise mass determinations.
  - Isospin splitting depends on baryons.

However…

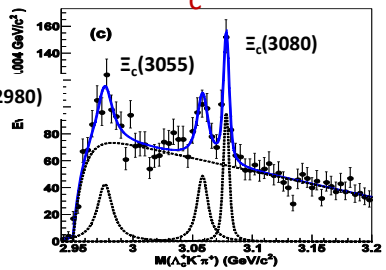
- Nature of
- Still two $1/2^-$ states not observed!
  - Even for λ mode, it is from QM.

ΛD



Phys. Rev. D 94, 032002

$\Sigma_c K$



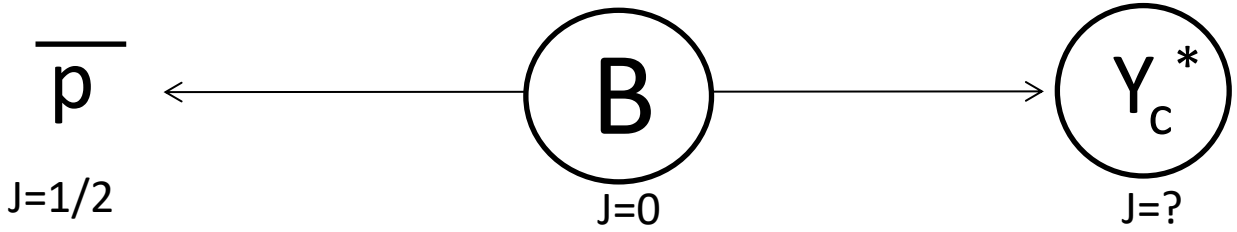
Phys. Rev. D 89, 052003

Particle	$M(\Xi_c^+) - M(\Xi_c^0)$ (MeV/c^2)
$\Xi_c(2645)$	$-0.85 \pm 0.09 \pm 0.08 \pm 0.48$
$\Xi_c(2815))$	$-3.47 \pm 0.12 \pm 0.05 \pm 0.48$
$\Xi_c(2980))$	$-4.8 \pm 0.1 \pm 0.2 \pm 0.5$
$\Xi_c'^+$	$-0.8 \pm 0.1 \pm 0.1 \pm 0.5$
$\Xi_c(2790))$	$-3.3 \pm 0.4 \pm 0.1 \pm 0.5$

Spin determination at Belle II

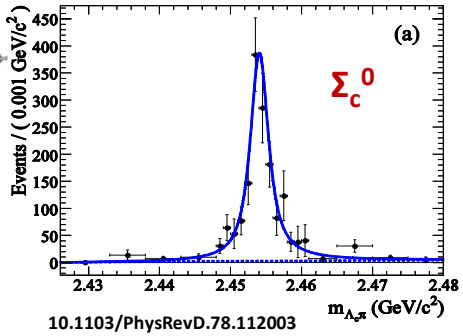
- B-meson two body decay constrains the helicity to be ½
  as B meson has spin zero and proton has spin ½. This largely reduce uncertainty

- Statistics at current B-factory is not good enough for higher excited states.

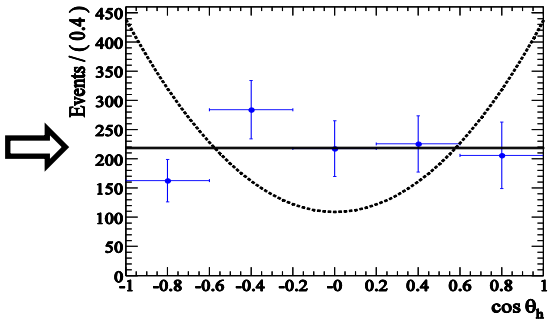


Example

$B \to \Sigma_c^0 \bar{p}$, $\Sigma_c \to \Lambda_c^+ \pi^-$ $\Lambda_c^+ \pi^-$ angular distribution



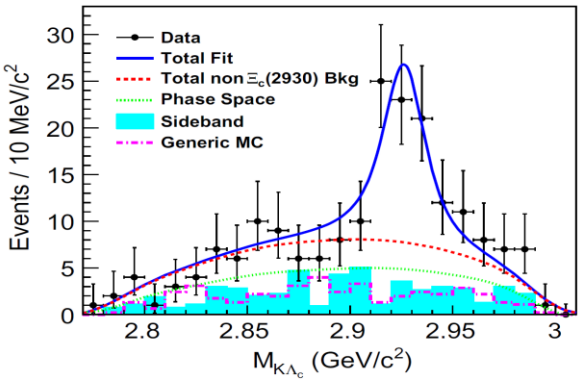
10.1103/PhysRevD.78.112003



S=1/2, exclude 3/2 by ~4σ

Higher excited states observed!

$B \to \Xi_c(2930)\Lambda_c$, $\Xi_c(2930) \to K\Lambda_c$



Eur. Phys. J. C (2018) 78: 252.

Summary

- SuperKEKB/Belle II provides a unique opportunity for the hadron spectroscopy
- Belle II started physics run in 2019 Apr.
- Many results for Charmonium(-like) and charmed baryons are expected.

Stay tuned for coming results from Belle II !

Backup