Quarkonium studies at Belle II

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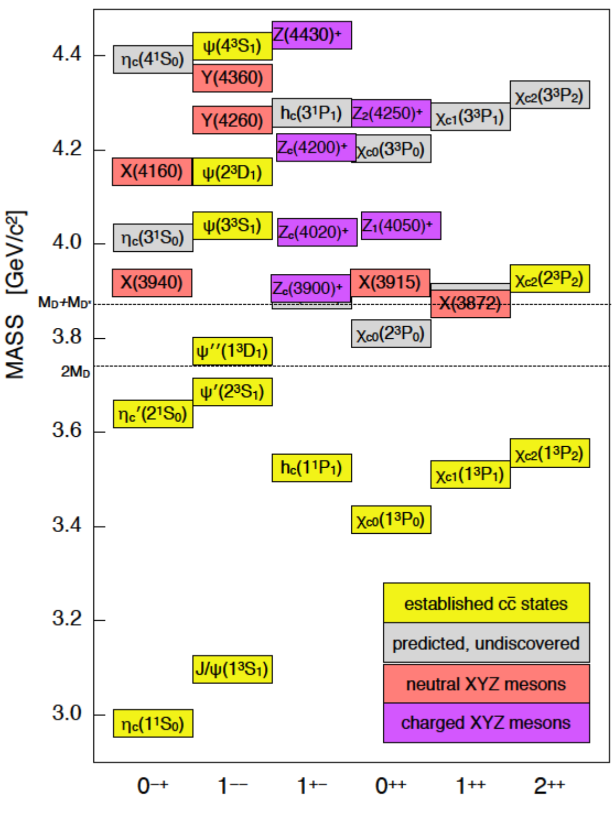
Paradigm shift in the hadron spectroscopy



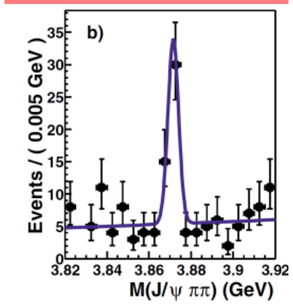
arXiv:1511.01589

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

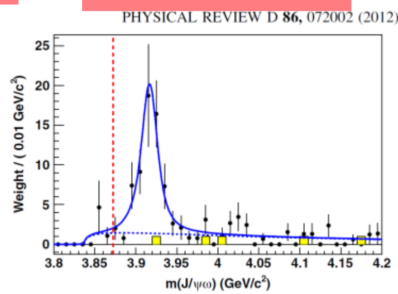
Some states have charge, which can not be achieved by $c\bar{c}$

$X(3872) \to J/\psi \pi^+\pi^-$

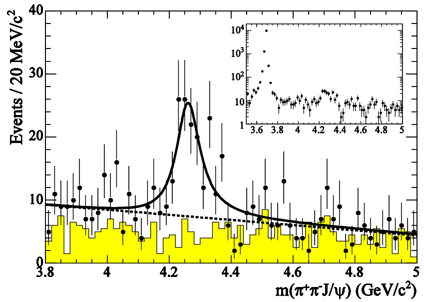


Phys. Rev. Lett. 91.262001

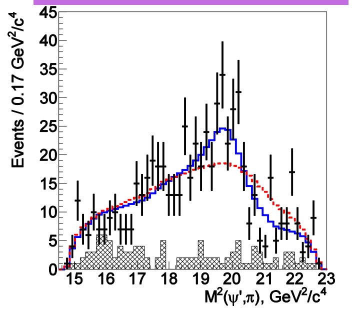
$X(3915) \to J/\psi\omega$



$Y(4260) \to J/\psi \pi^+\pi^-$



$Z(4430)^+ \to \psi(2S)\pi^+$

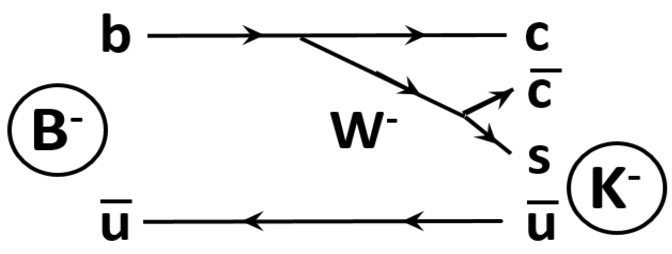


Phys. Rev. D **88**, 074026 (2013)

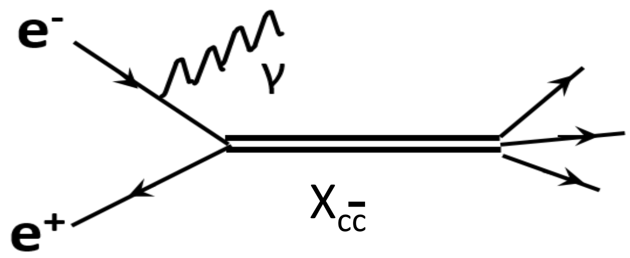
Homeworks from B-factory experiments (= Belle, BaBar):

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

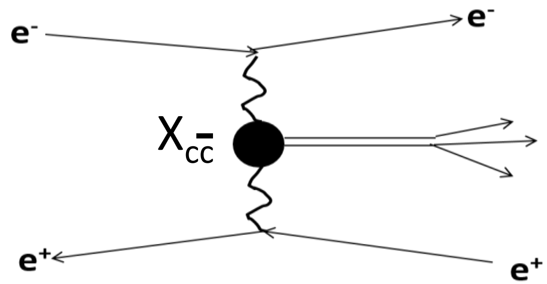
B-factory = hadron factory!



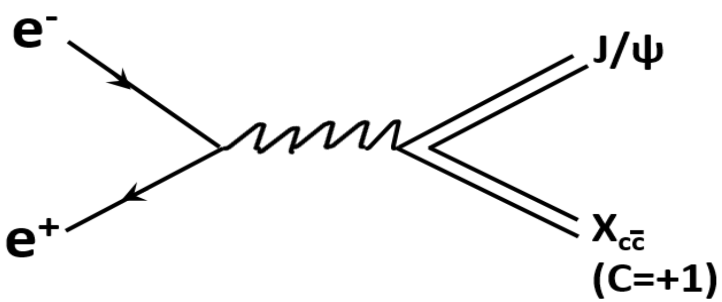
B meson decay
- X(3872), Z(4430)….
- Open charm hadrons



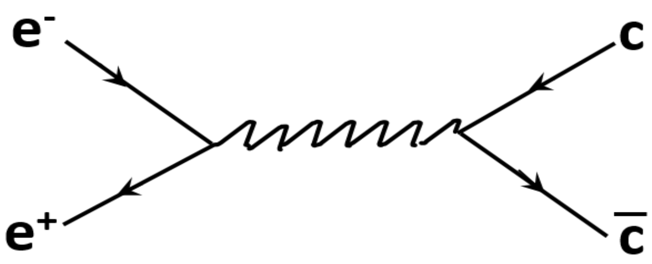
Initial state radiation
- $J^{PC}=1^{--}$
- Y(4260)



Two photon collision
- $J^{PC}=0^{++}$, 2^{++}….
- Extract two photon width

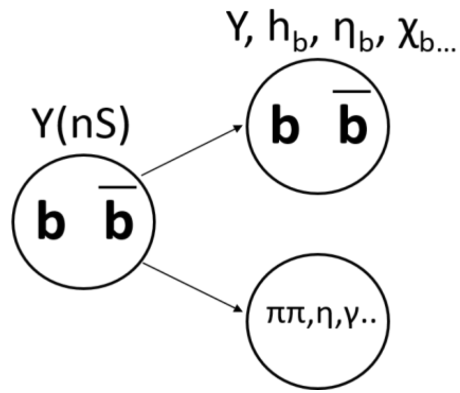


Double charmonium
- C-even charmonium



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

Charm mesons/baryons



Bottomonium transition

Z_b states

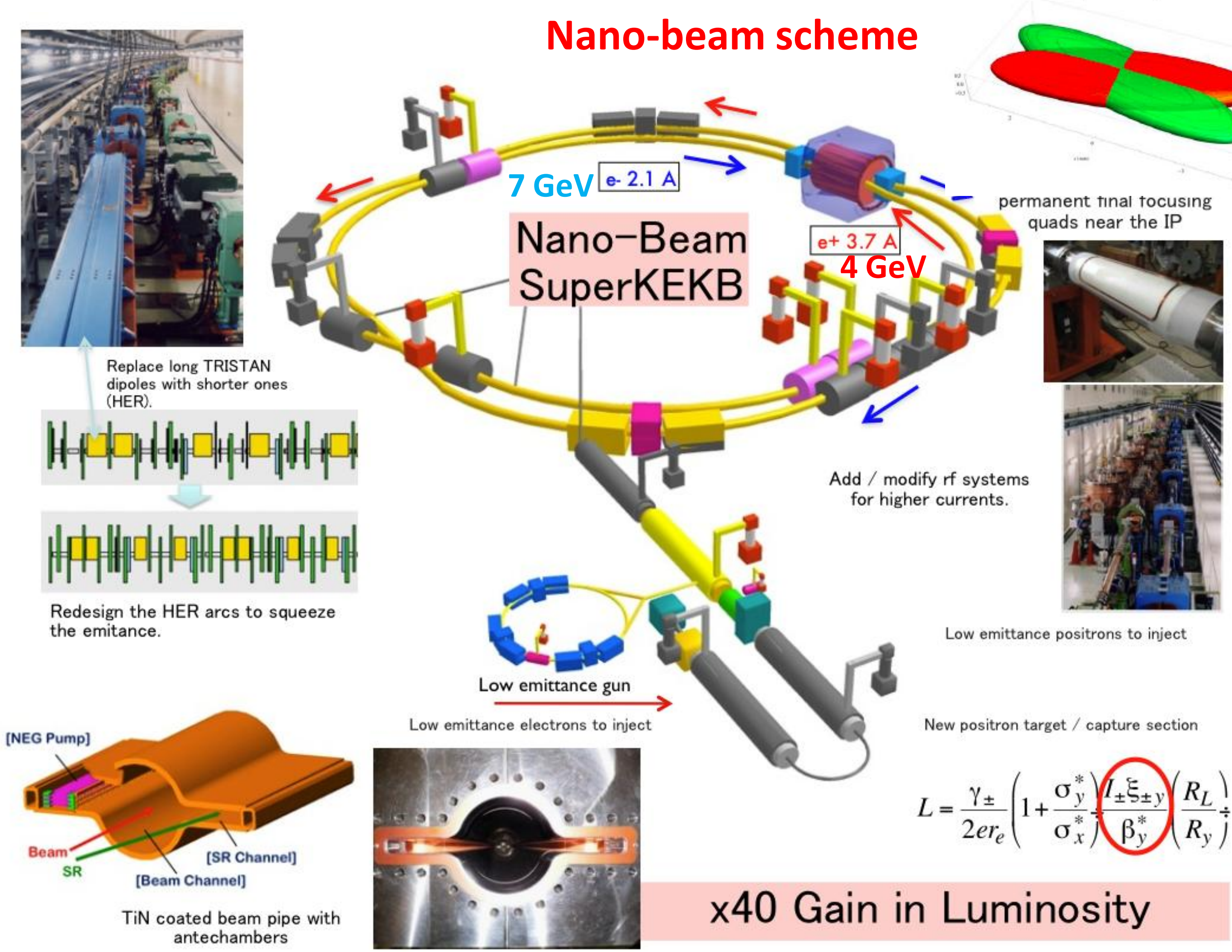
“New hadrons” from B-factories

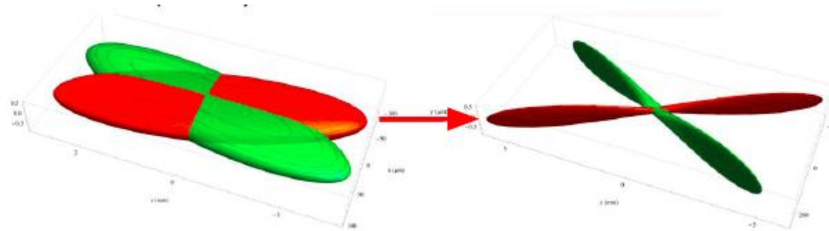
Hadron Type

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) ≒ $\chi_{c0}(2P)$ X(3940) X(4160)				
Two-photon	$\chi_{c2}(2P)$				
$e^+e^- \rightarrow cc^{bar}$			$D^*_{s0}(2317)$ $D_0(2550)$ $D_J^*(2600)$ $D_J(2740)$ $D_3^*(2750)$ $D^*_{s1}(2700)$ $D^*_{s1}(2860)$ $D_{sJ}(3040)$	$\Sigma_c(2800)$ $\Lambda_c(2940)$ $\Xi_c(2980)$ $\Xi_c(3080)$ $\Omega_c(2770)$ $\Xi_c(3055)$	
Υ(nS) decay		$Z_b(10610)$ $Z_b(10650)$ $\eta_b(2S)$ $h_b(1P)$ $h_b(2P)$			Ω(2012)
Charm baryon decay					Ξ(1620)

~40 new hadrons discovered!

Next generation: SuperKEKB





$$\begin{cases} \sigma_y = 62\text{nm (HER)} \\ \sigma_y = 48\text{nm (LER)} \end{cases}$$

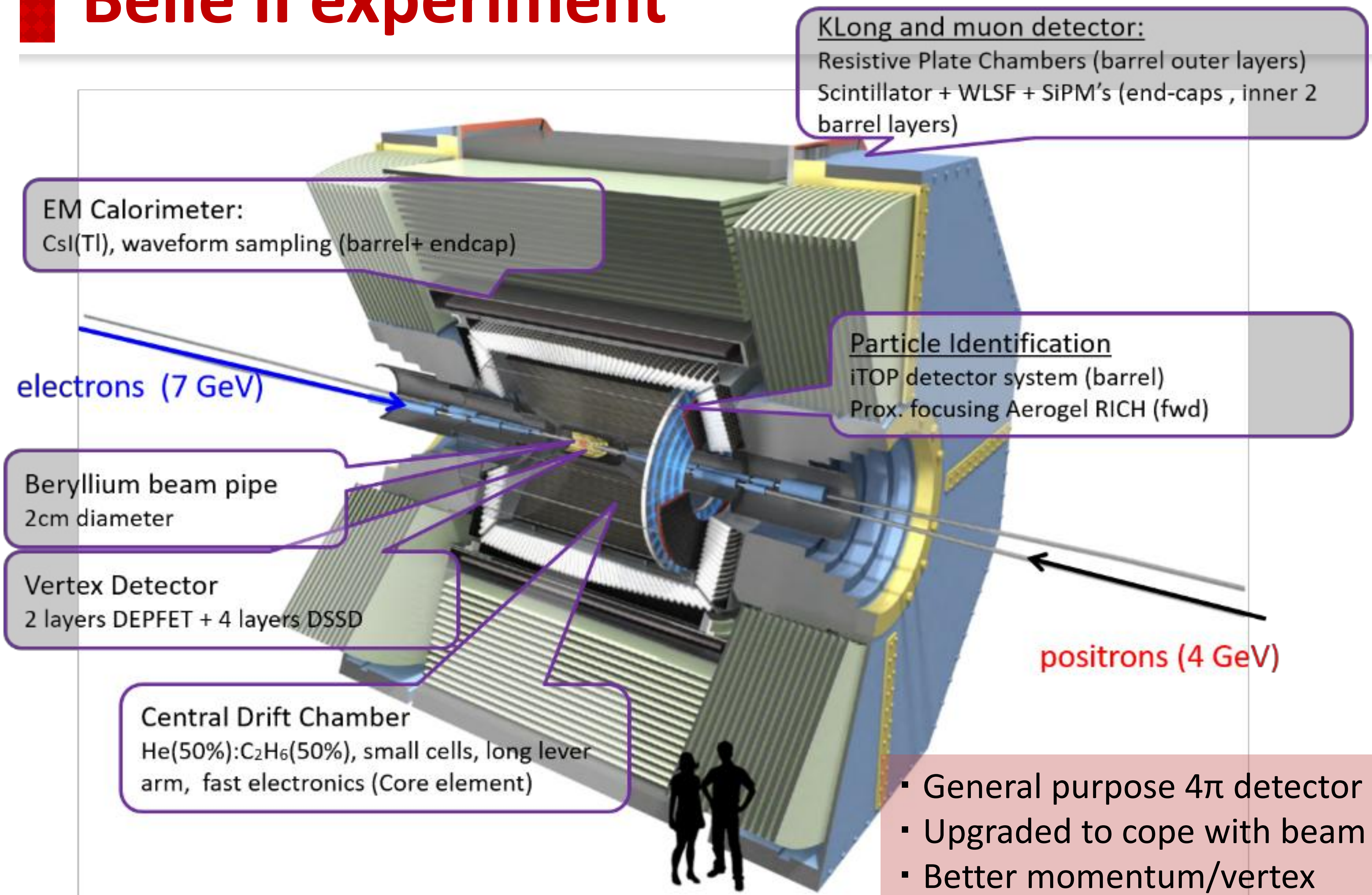
Crossing angle: ~40mrad

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm\xi_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right)$$

x40 Gain in Luminosity

(x2 beam current, 1/20 beam size)

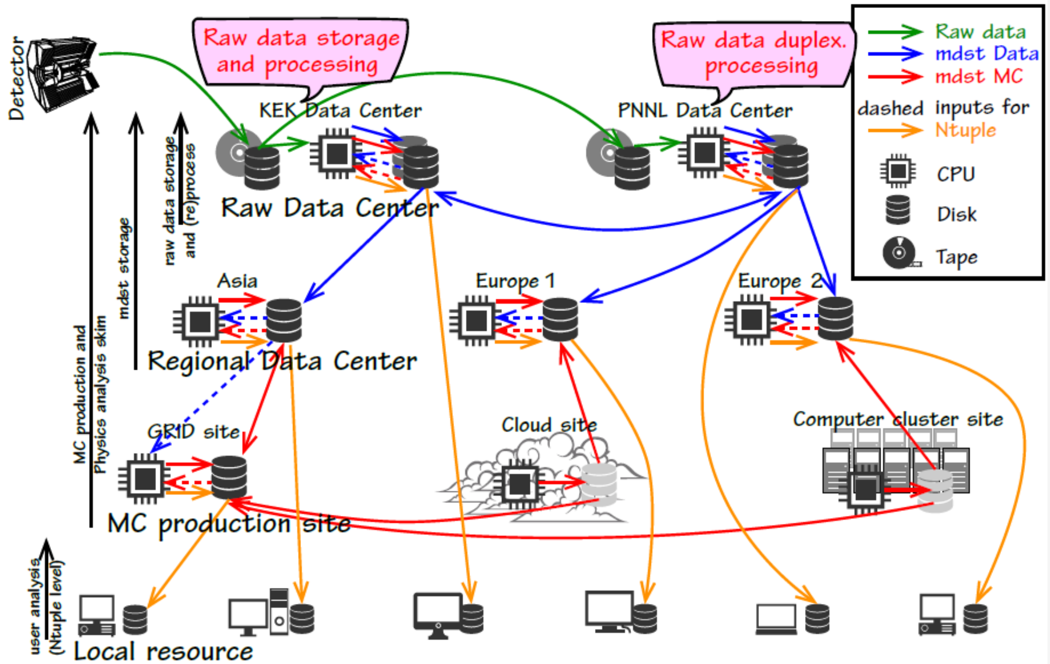
Belle II experiment

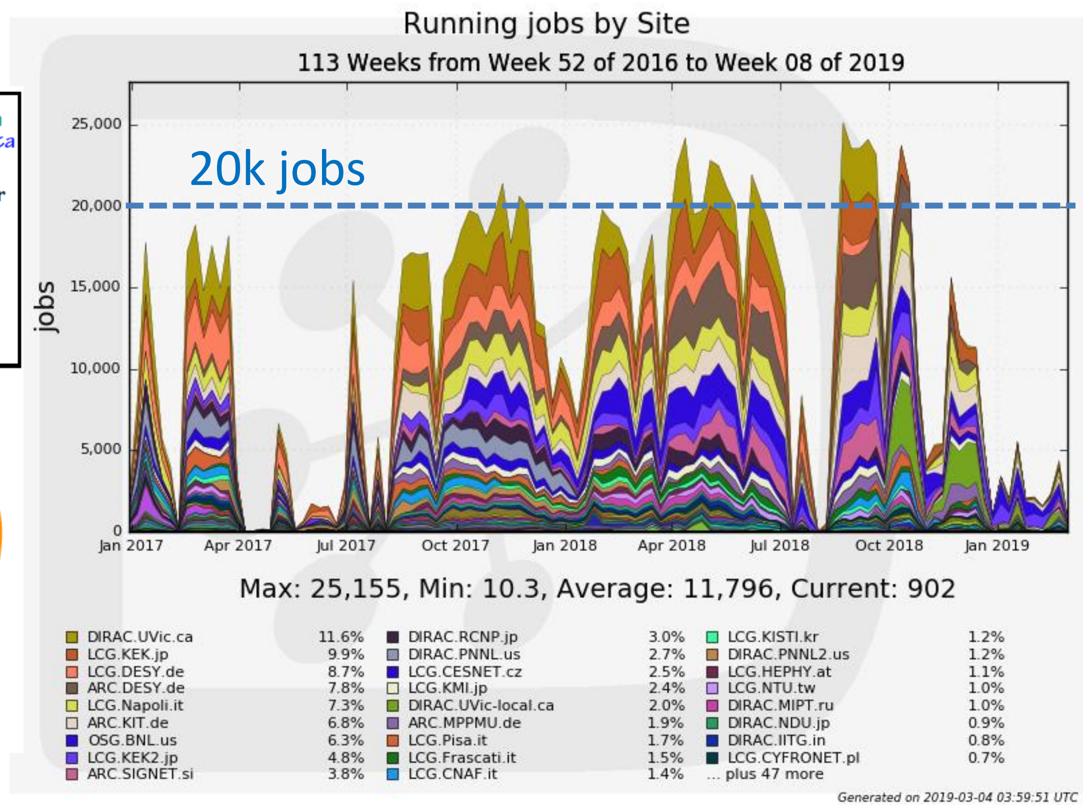


- General purpose 4π detector
- Upgraded to cope with beam BG
- Better momentum/vertex
- Improved PID with RICH technique

More than 900 Physicists from ~ 100 institutes in 26 countries/region

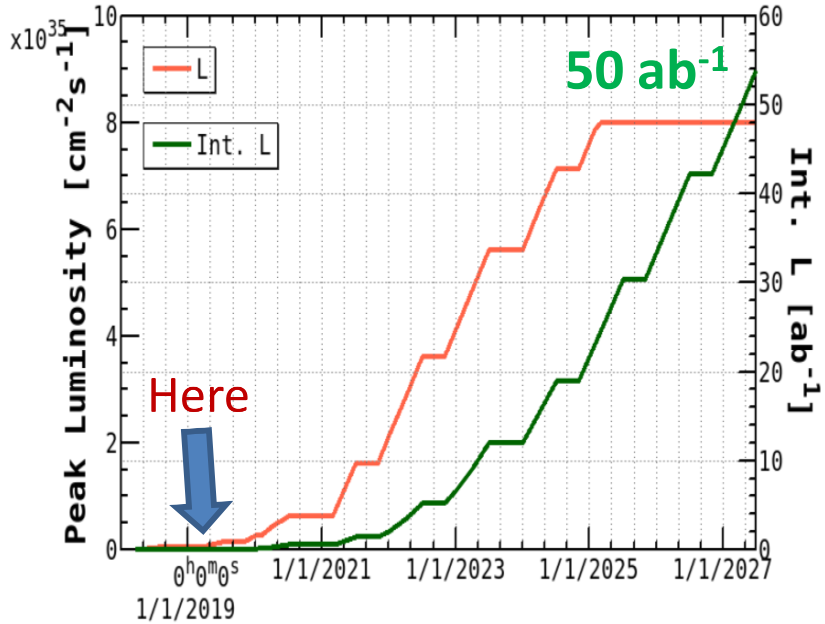
Belle II computing

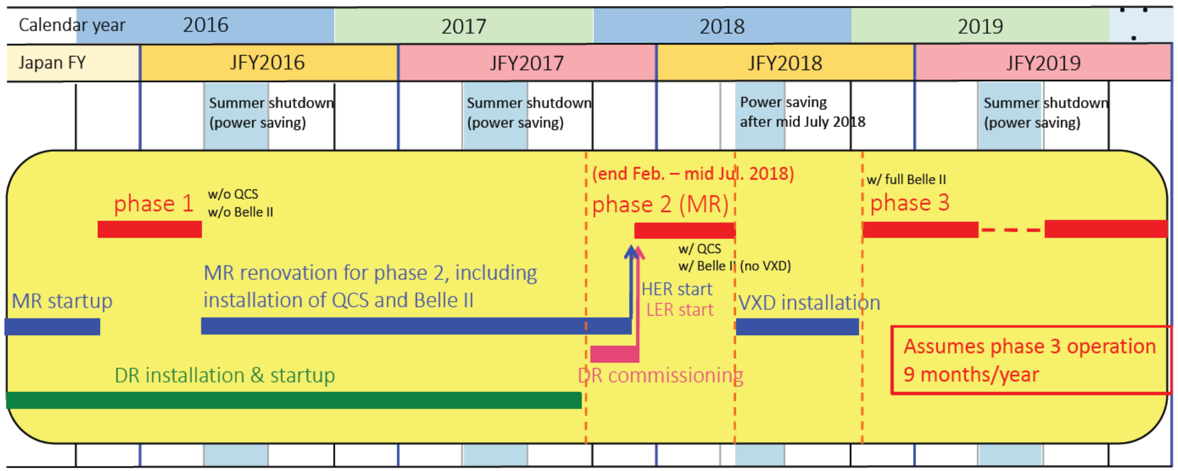




- Big data → huge computing resource needed!
  - $O(10^5)$ CPU cores, O(100 PB) storage
- Belle II adapted distributed computing model
- MC production on-going with ~50 sites by automated system.

Global schedule





- Plan to accumulate 50 ab^{-1} (x50 times of Belle)

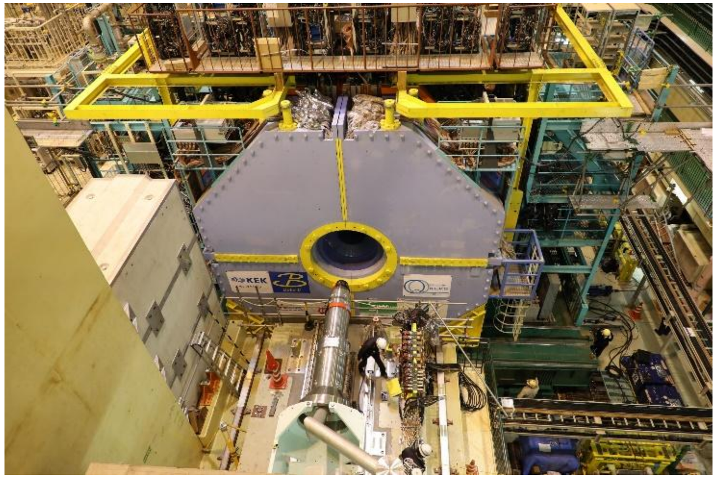
- Phase1: SuperKEKB commissioning w/o final focusing and w/o Belle II detector but beam background detectors (=BEAST) installed

- Phase2: Collision data taking w/ final focusing. No VXD (2018 Apr-Jul, Achieved peak luminosity: $5 \times 10^{33}/cm^2/s$. Collected **0.0005 ab^{-1}**)

- Phase3: Collision data taking w/ full Belle II detector (2019 Mar): **Just started!**

Highlights in these 2 years

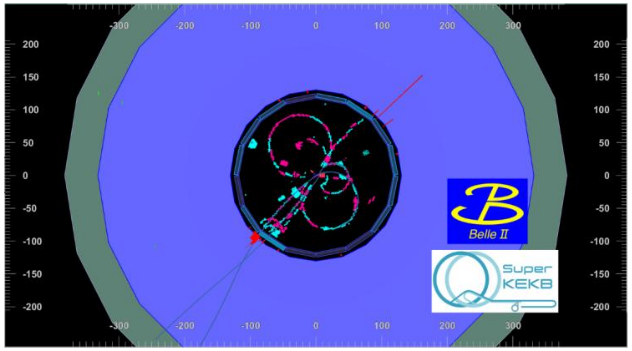
Belle II roll-in



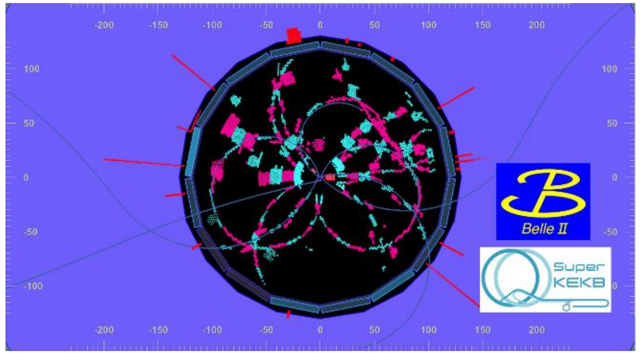
Apr 11, 2017

First collisions at phase2!

$q\bar{q}$

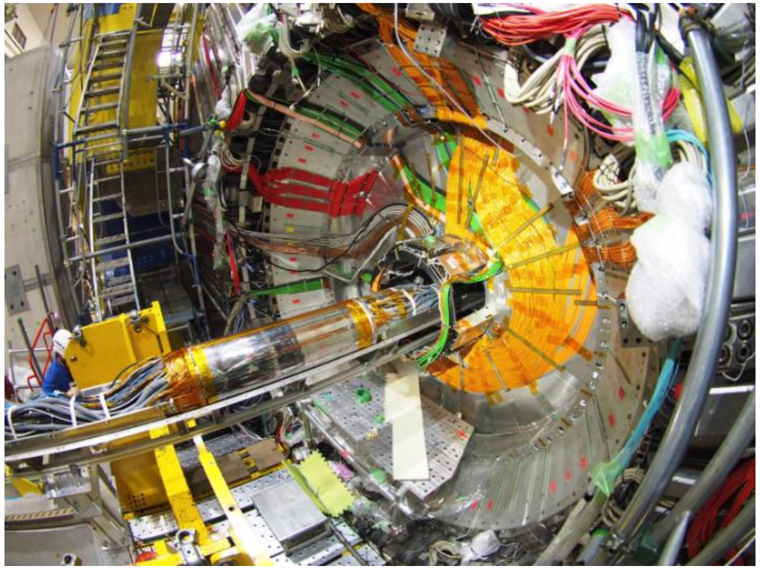


$e^+e^- \to \gamma^* \to BB$



Apr 26, 2018

VXD installation



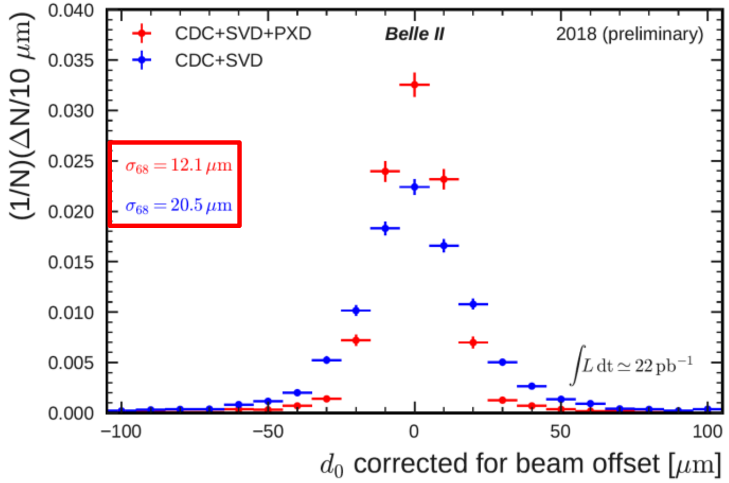
Nov 26, 2018

Phase 3 started

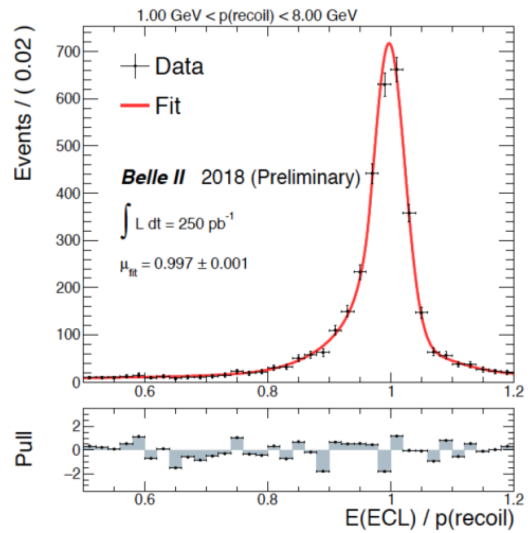
Mar 25th, 2019

Physics performance

Track impact parameter

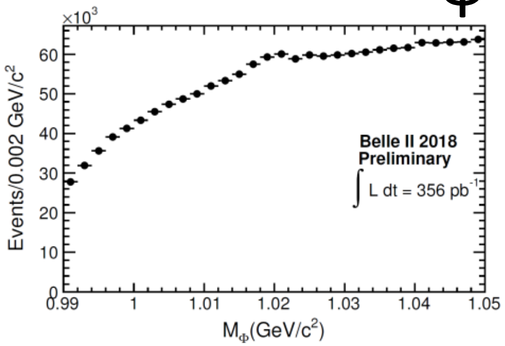


E_{ECL}/p(recoil) in $e^+e^- \rightarrow e^+e^-\gamma$

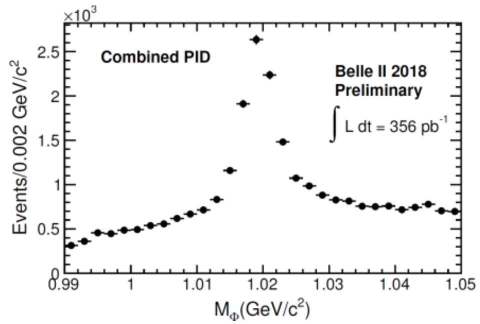


Kaon ID

$\phi \rightarrow K^+K^-$



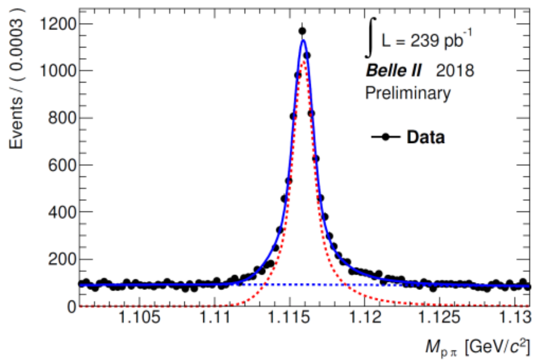
w/o PID

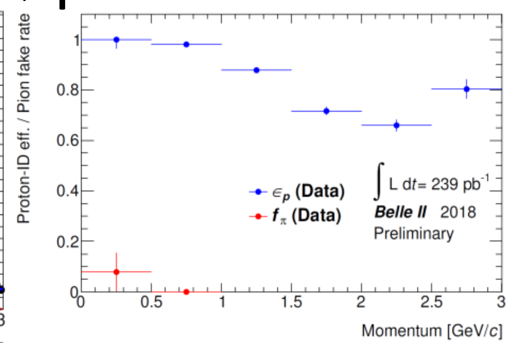


w/ PID

Proton ID

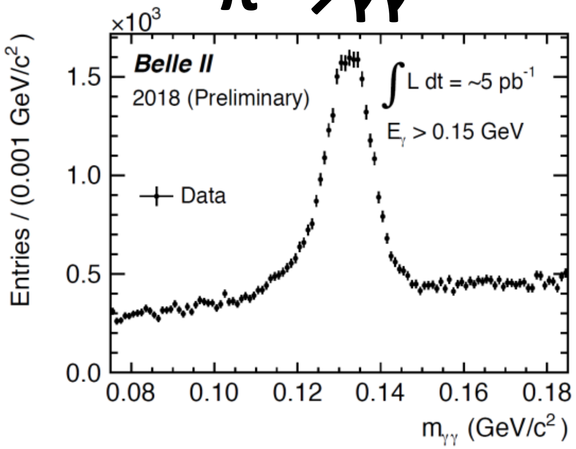
$\Lambda \rightarrow p\pi^-$



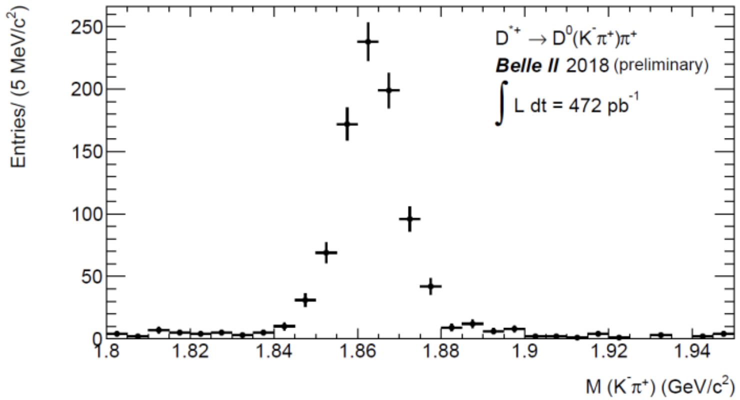


Re-discoveries in Phase 2 data

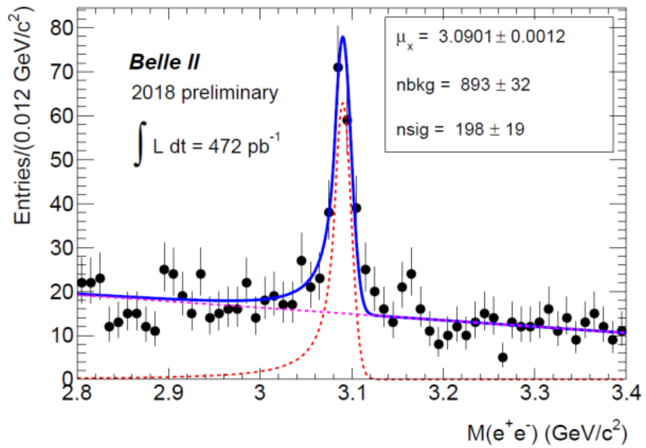
$\pi^0 \rightarrow \gamma\gamma$



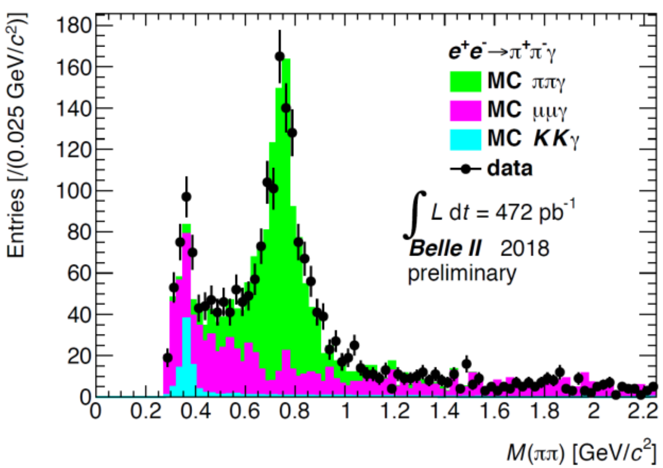
$D^{*+} \rightarrow D^0\pi^+$



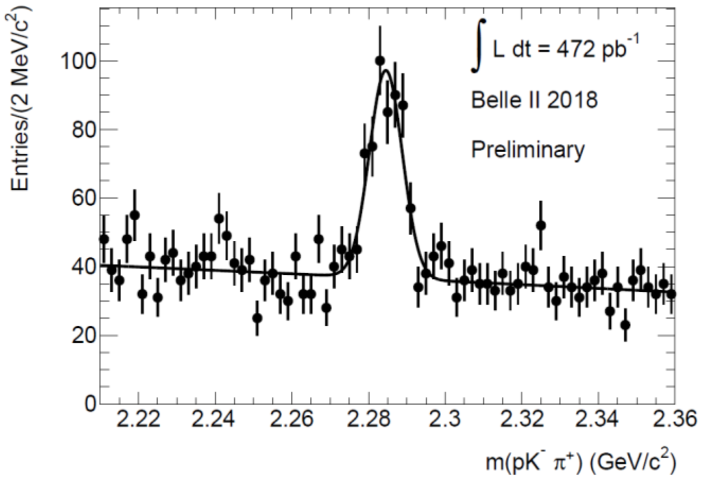
$J/\psi \rightarrow e^+e^-$



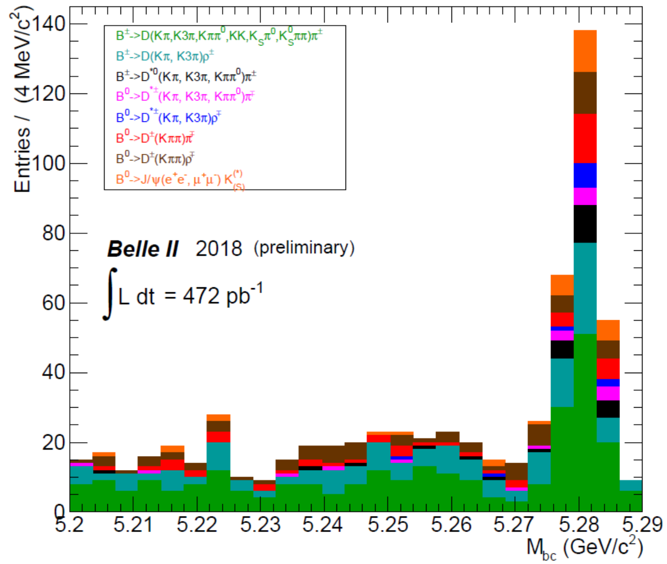
$e^+e^- \rightarrow \pi^+\pi^-\gamma$



$\Lambda_c^+ \rightarrow pK^-\pi^+$

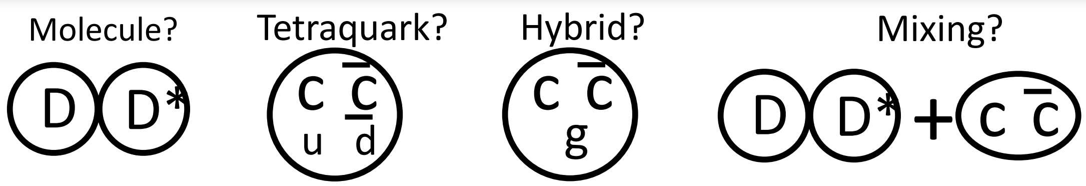


$B \rightarrow$ hadronic

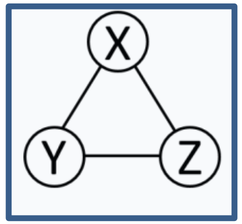


Role of Belle II for quarkonium physics

- Nature of **each XYZ?**

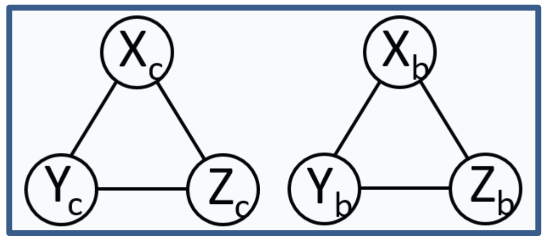


- Understand (part of) XYZ in a **unified way?**



New multiplet?

- Understand **charm and bottom in a unified way?**



Further new multiplet?

- What Belle II can do is ..
  - Measure properties of already observed states (J^{PC}, decay, production…)
  - Establish the states whose evidence was not very strong.
  - Discover new states.

- Many topics covered by [Belle II Physics book]

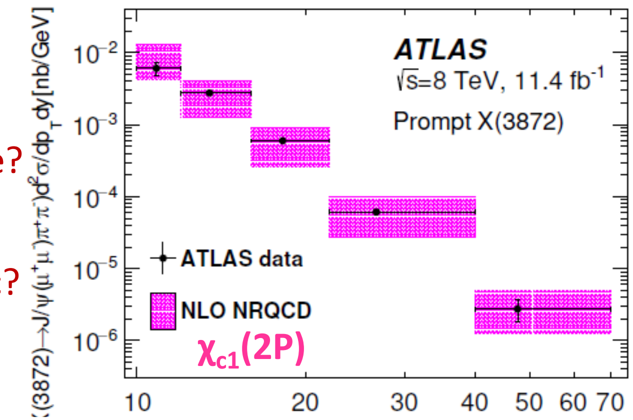
B-decays: X(3872)

- Firstly observed by Belle in $B^+ \to K^+ (J/\psi \pi^+ \pi^-)$. The poster boy
  - $J^{PC} = 1^{++}$
  - 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 $\chi_{c1}(2P)$ } $c\bar{c}$?

JHEP01(2017)117



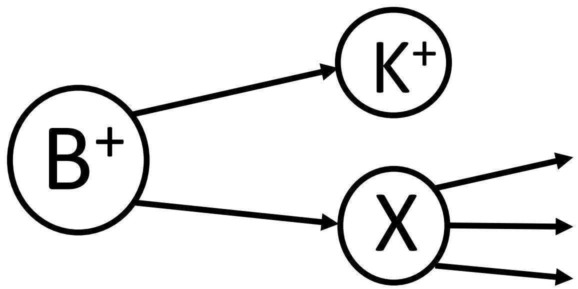
⇓

Decays and production play essential role

Many things missing in the decay property

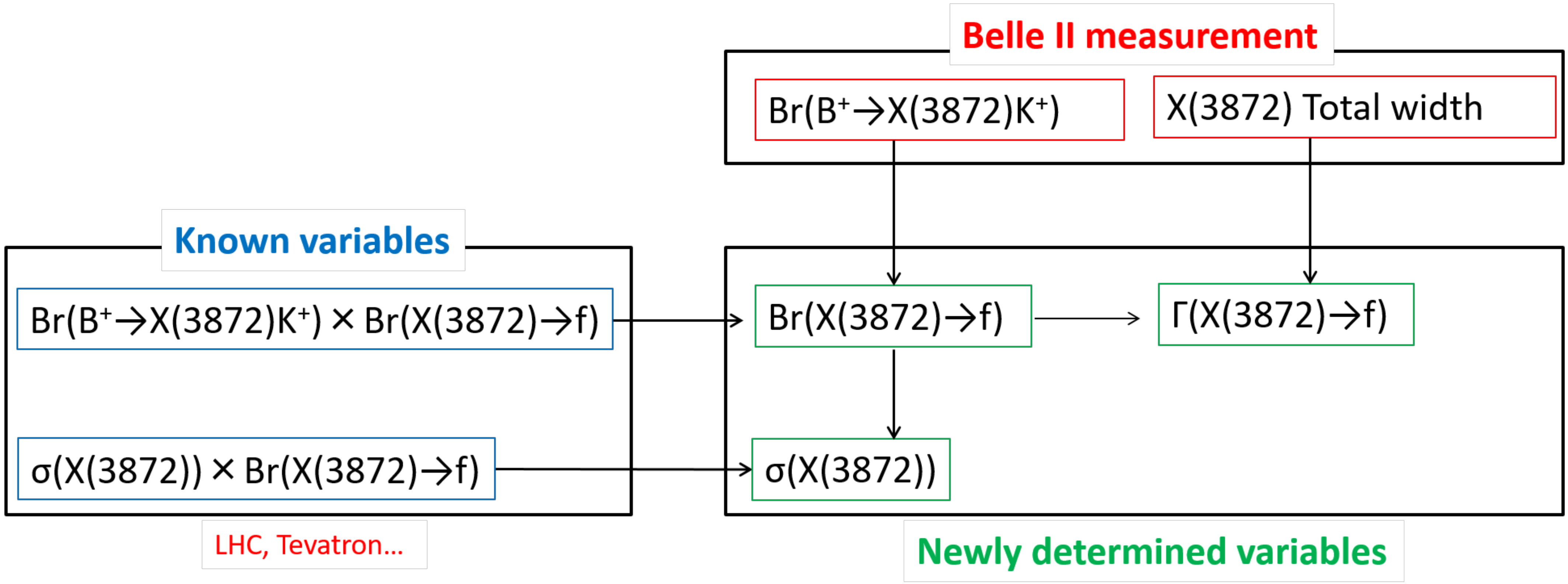
- Total width:
  only the upper limit of 1.2 MeV is determined.

- Branching fraction:
  Only the product of two branching fractions are measured.



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

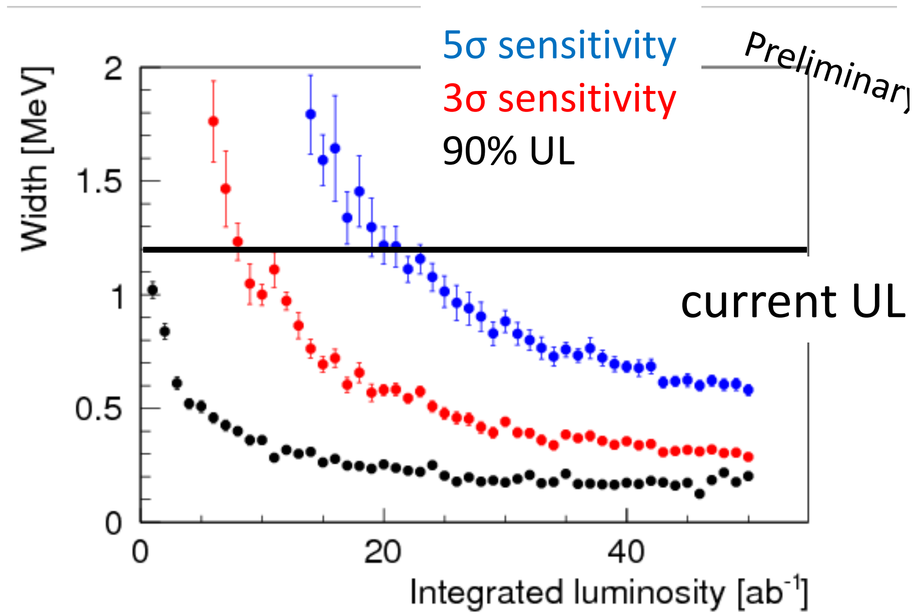
Importance of decay width and branching fraction



Total width with $X(3872) \to D\bar{D}\pi^0$ decay mode

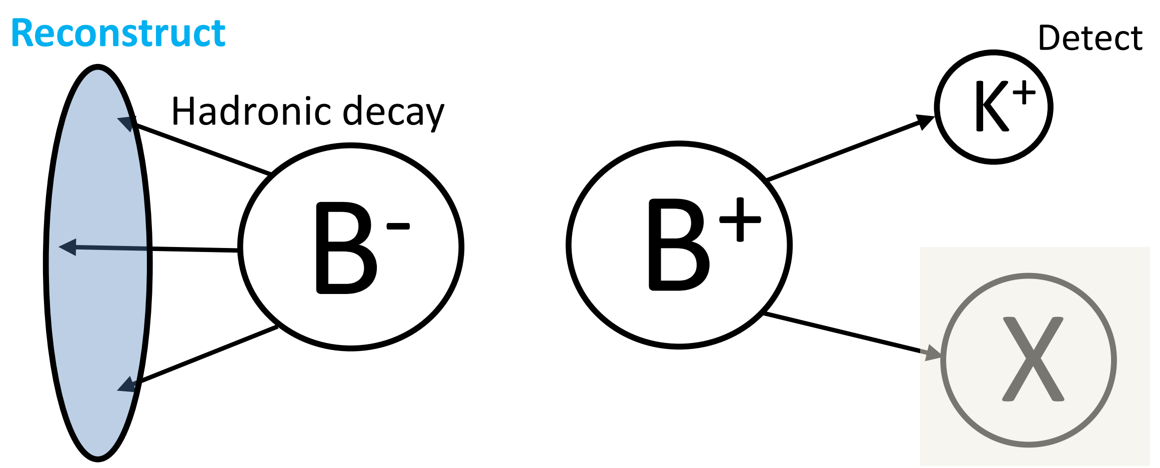
- The mass resolution is important to measure narrow width.
- As the Q-value becomes smaller, the mass resolution becomes better.
- Q-value of $DD\pi^0$ decay has significantly smaller Q-value than $J/\psi\pi\pi$
- The mass resolution is 680 keV: ~3 times better than $J/\psi\pi^+\pi^-$ mode.
  - No width measurement at Belle (1) due to poor statistics
- No bias seen up to O(100 keV) in the simulation.
- Huge improvement is expected.

Decay	Q-value
$J/\psi\pi^+\pi^-$	~500
$D\bar{D}\pi^0$	7

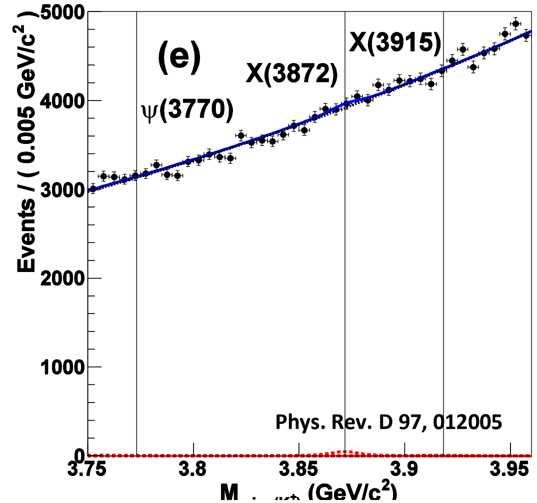


$Br(B^+ \to K^+ X(3872))$

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



Belle1 full statistics result
$< 2.6 \times 10^{-4}$



- Measurement only possible at e^+e^- B-factory.
- There is a lower limit of 1.0×10 -4 from the constraint that all the product of branching fractions to be smaller than 1
- Even in this lower bound 7σ measurement is possible at Belle II (naïve expectation)
- Measurement for X(3915) is also important to determine $Br(X(3915) \to J/\psi\omega)$
- Better B meson reconstruction should improve sensitivity. More realistic simulation on going.

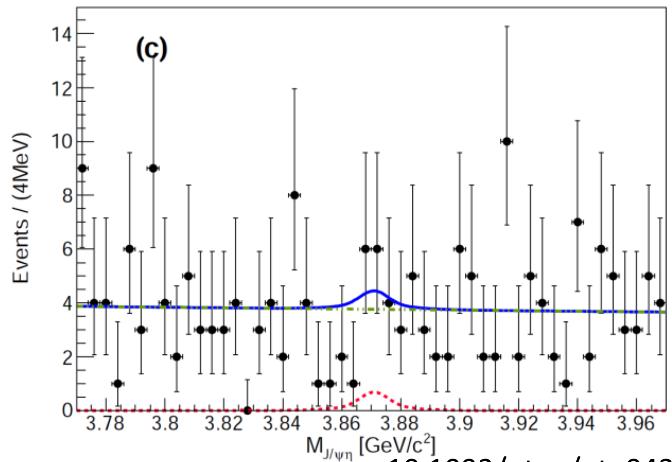
Search for partner states

- **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)→$J/\psi\pi^+\pi^-$

- **Spin partner:**
  - B→K DD and K D*D* not studied in detail yet.

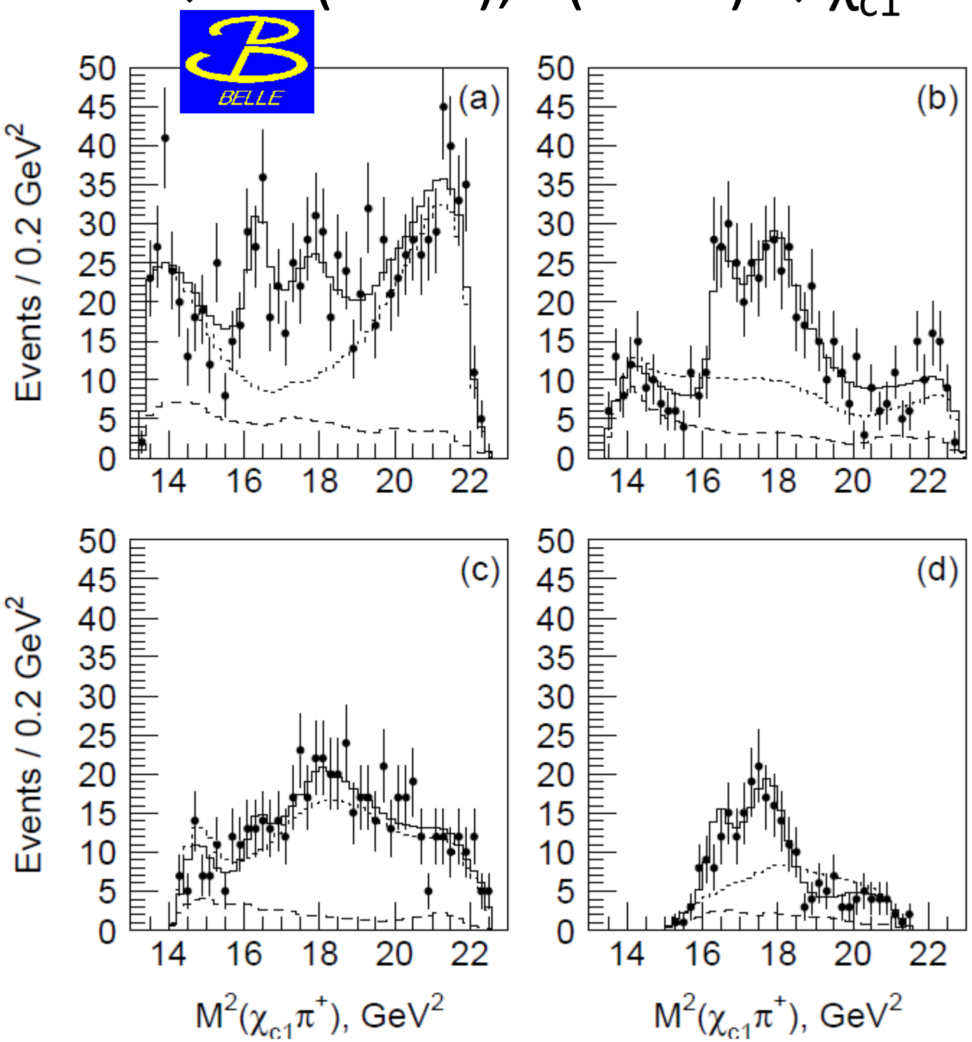
M(J/ψη)



10.1093/ptep/ptu043

B decays: States need confirmation

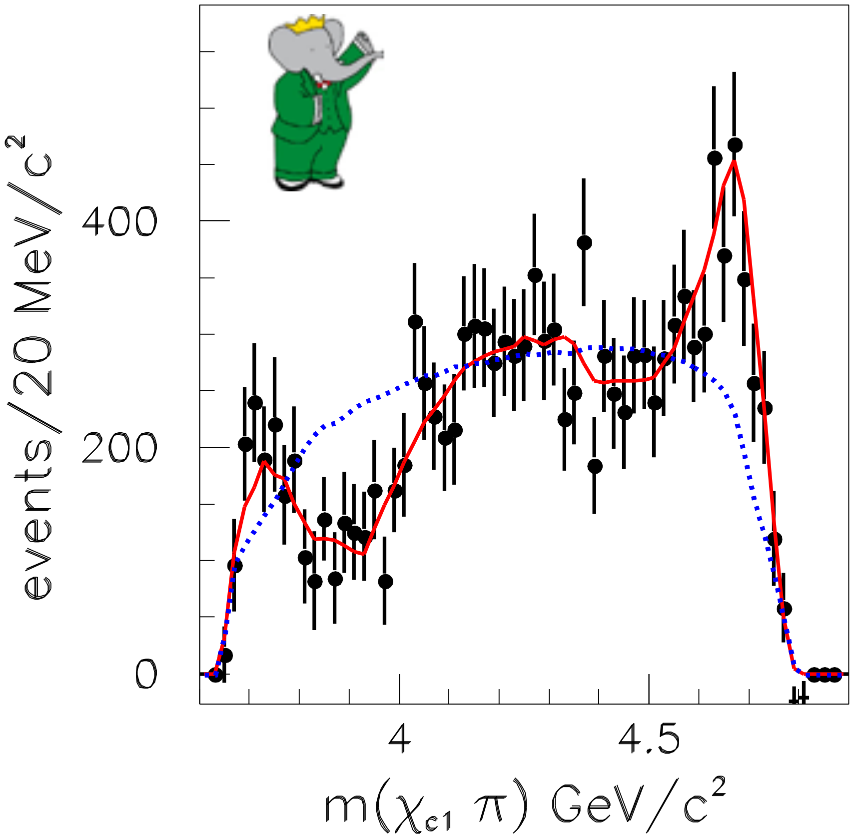
$B^+ \to K^+ Z(4050), Z(4250) \to \chi_{c1}\pi^+$



Phys. Rev. D 78, 072004

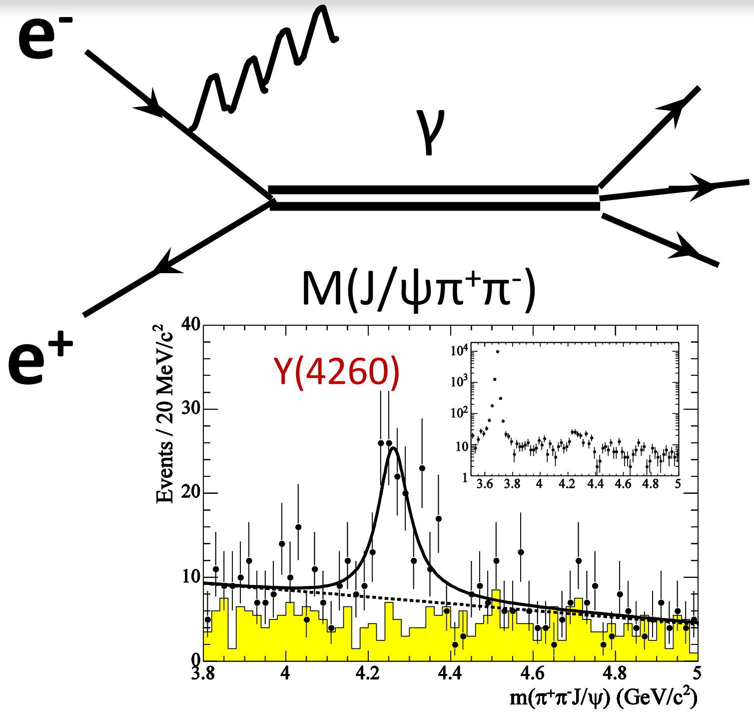
$M(\chi_{c1}\pi^+)$
(in different $M(K\pi)$ bins

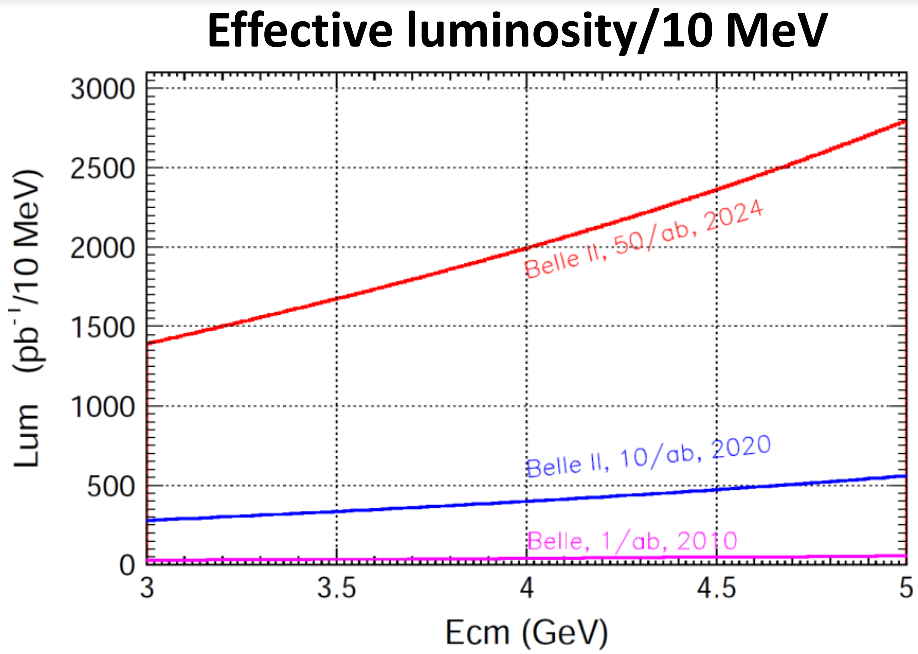
BaBar reported $m(\chi_{c1}\pi^+)$ can be described by resonances in $K\pi$ channel only



Confirmation by Belle II is needed

Initial State Radiation



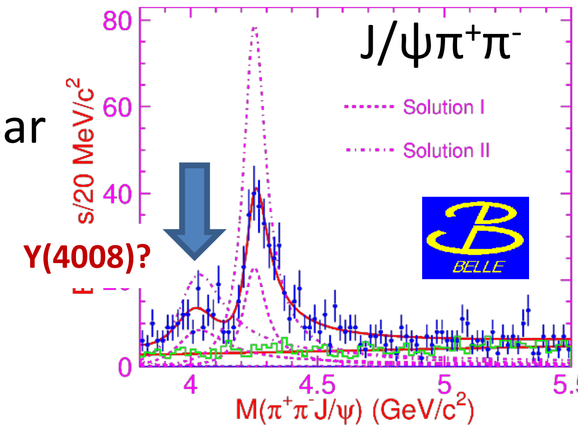


- One of the best probes to study 1^{--} quarkonium states.
- Many "Y" states are reported from B-factories and BES III.
- Also many "Z" states from "Y" decay.
- 50 ab^{-1} data corresponds to 2000-2300 pb^{-1}/10 MeV at 4-5 GeV.
  → Compatible with BES III
- Belle II has advantage to access energy higher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

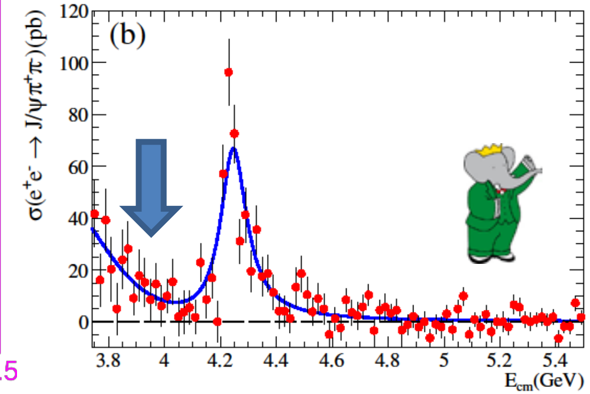
Initial State Radiation golden modes

- **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..**

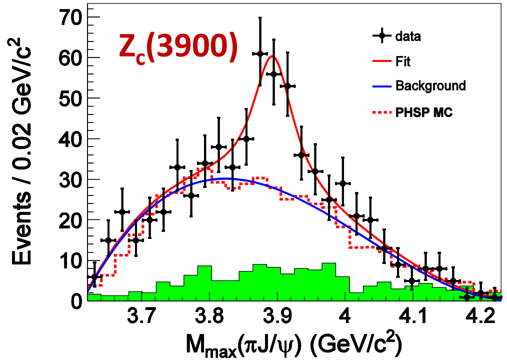
Golden Channels	$E_{c.m.}$ (GeV)	Statistical error (%)	Related XYZ states
$\pi^+\pi^- J/\psi$	4.23	7.5 (3.0)	$Y(4008)$, $Y(4260)$, $Z_c(3900)$
$\pi^+\pi^-\psi(2S)$	4.36	12 (5.0)	$Y(4260)$, $Y(4360)$, $Y(4660)$, $Z_c(4050)$
$K^+K^- J/\psi$	4.53	15 (6.5)	Z_{cs}
$\pi^+\pi^- h_c$	4.23	15 (6.5)	$Y(4220)$,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

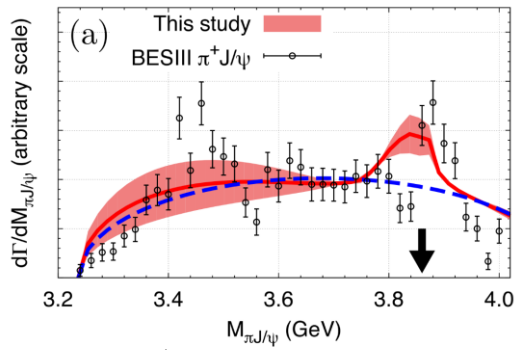


Phys. Rev. Lett. 99, 182004



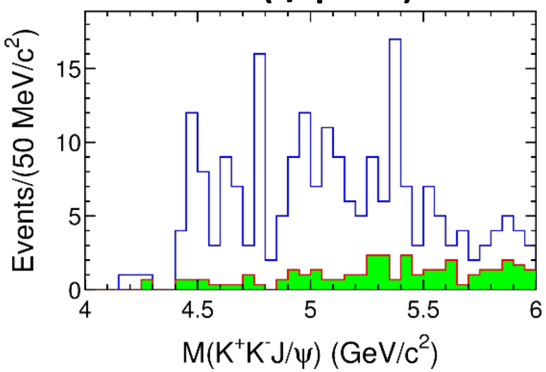
DD*Cusp reproduce the peak?



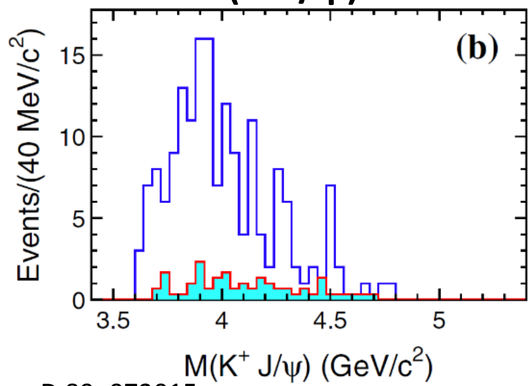


Phys. Rev. Lett. 117, 242001

M(J/ψK+K-)

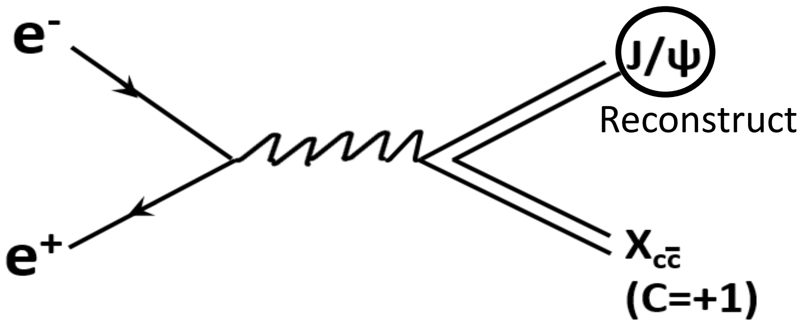


M(K+ J/ψ)



Phys. Rev. D 89, 072015

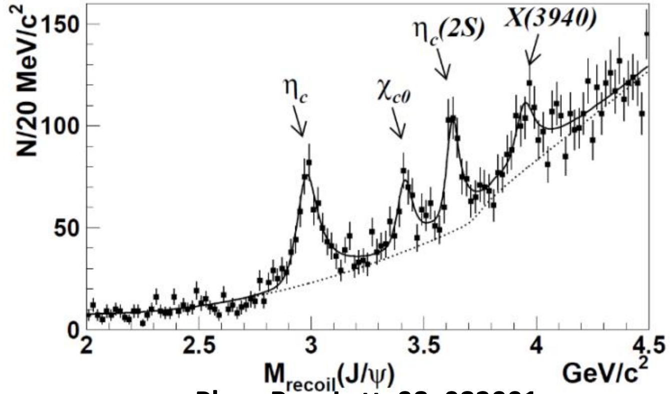
Double charmonium production



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

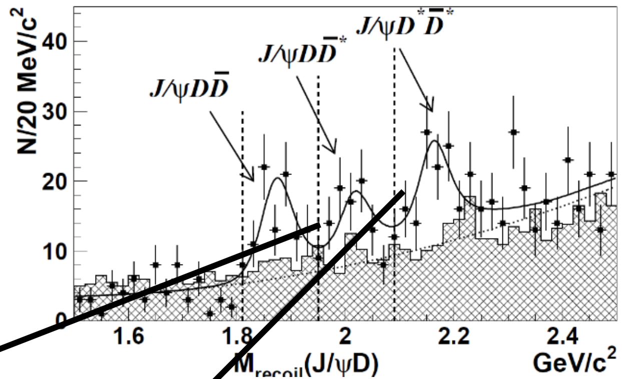
- Observation of two new states
  - X(3940): observed both inclusive and exclusive $D\bar{D}$
  - X(4160): Observed in exclusive $D\bar{D}^*$

J/ψ missing mass

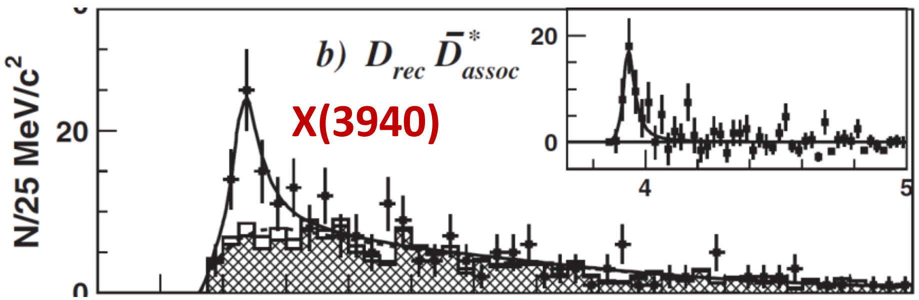


Phys. Rev. Lett. 98, 082001

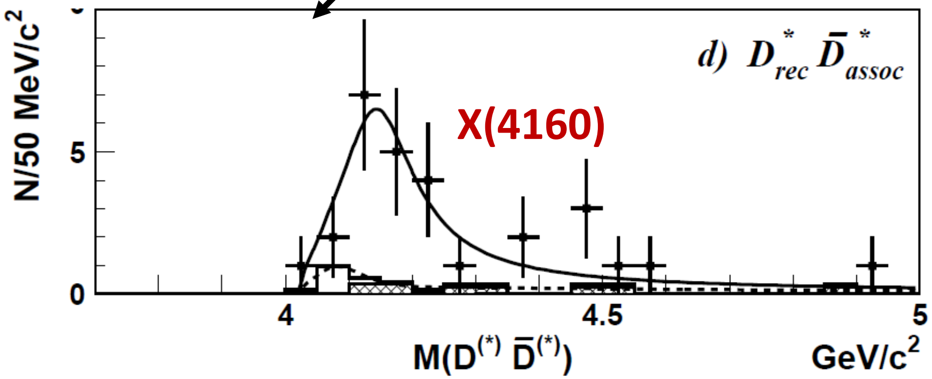
J/ψ D missing mass



DD* mass



D*D* mass

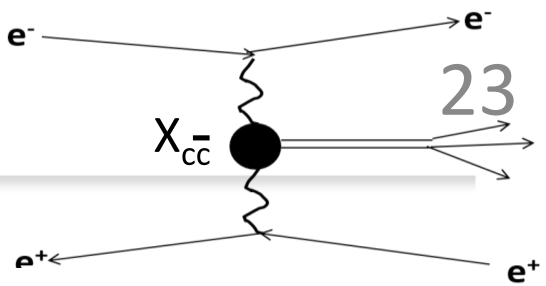


Phys. Rev. Lett. 100, 2020C

Interpretation of X(3940/4160) and beyond

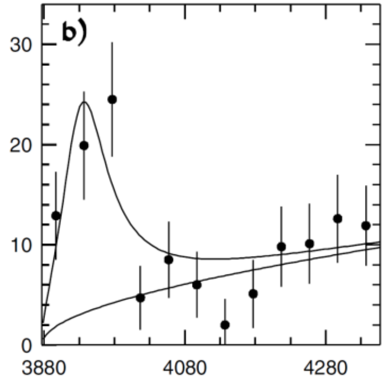
- All the known states observed in missing mass are J=0.
  X(3940/4160) should be J=0?
- If J=0, C-parity = +1 and decay into DD* indicate they are η_c family.
- However, the mass of X(3940) is ~100 MeV lower than quark model prediction.
- Also, the predicted mass of $\eta_c(4S)$ is 4400 MeV/c^2.
- Could 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.

Two photon collision (1) X(3915)



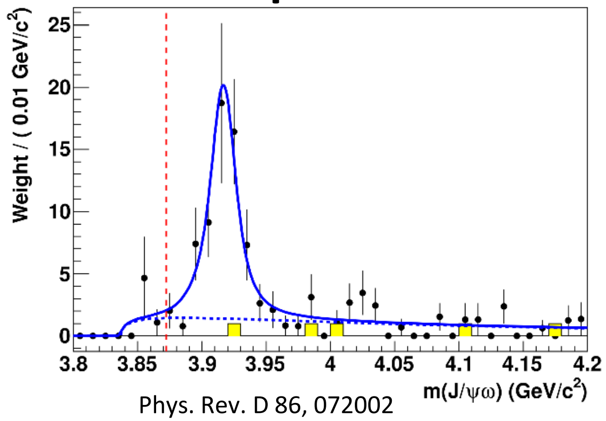
Observed in both B-decay and two-photon

B-decay



Phys. Rev. Lett. 94, 182002

Two photon



Phys. Rev. D 86, 072002

- $J^{PC}=0^{++}$ by BaBar from two photon (good S/N ratio!)

- Difficult to identify as $\chi_{c0}(2P)$
  - The width 20±5 MeV is too narrow for the state above $D\bar{D}$
  - Not observed in $D\bar{D}$, but OZI suppressed J/ψω only: Br(X(3915)→$D\bar{D}$)/Br(X(3915)→J/ψω) < 1.2
  - J/ψω partial width > O(1 MeV): too large as a OZI suppressed decay.
  - $\chi_{c0}(2P)$ candidate recently observed by Belle at mass of ~3860 MeV/c^2

- Molecule is also difficult as pion exchange is not allowed for $D\bar{D}$ or $D_s\bar{D}_s$.

- $cs\bar{c}\bar{s}$ tetraquark ?

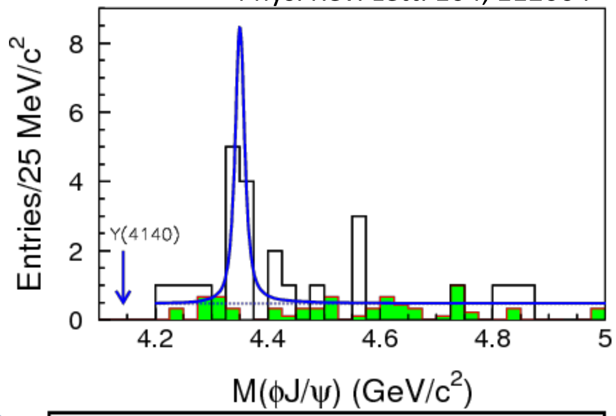
  Look for decay modes including η should be very interesting.

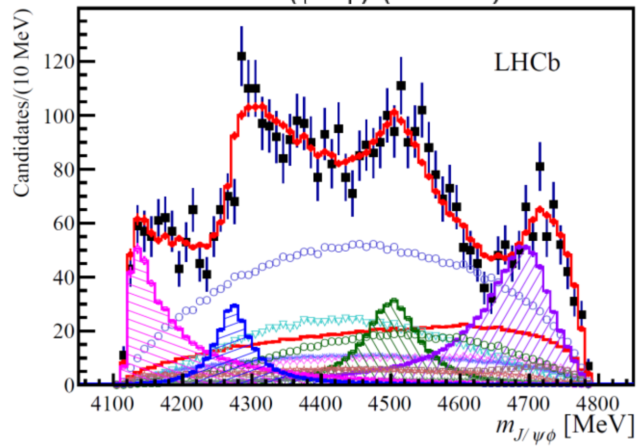
Two photon collision (J/ψ ϕ)

- Belle reported evidence of X(4350) in J/ψϕ (3.2σ).
  This needs to be confirmed together with J^P determination.

- LHCb observed four states:
  X(4140), X(4274), X(4500), X(4700).
  Measurement of two-photon width must be useful.
  Note X(4140) and X(4274) with $J^{PC}=1^{++}$ can not be produced.
  This may make analysis simpler.

Phys. Rev. Lett. 104, 112004

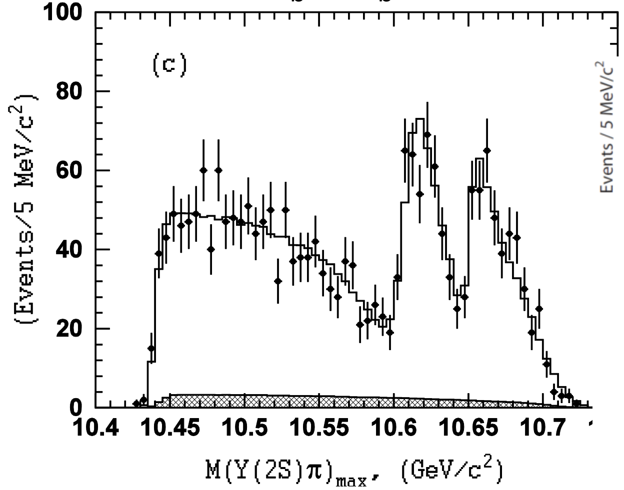




Phys. Rev. Lett. 118, 022003

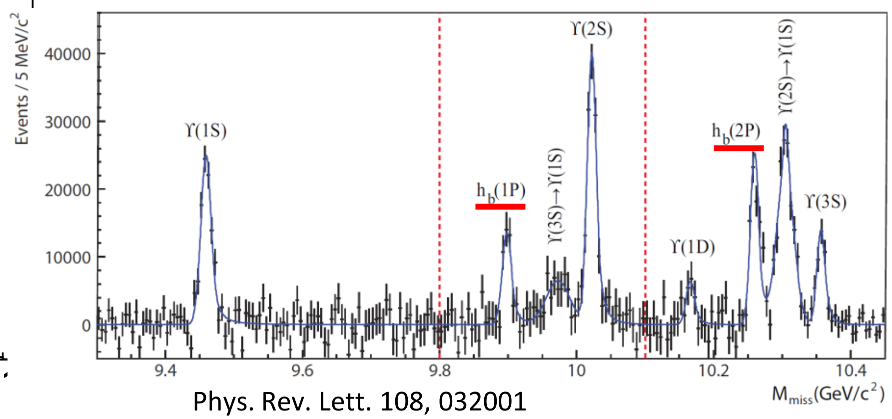
Bottomonium: Digest Belle achievements

$\Upsilon(5S) \to Z_b\pi$, $Z_b \to \Upsilon(nS)\pi$



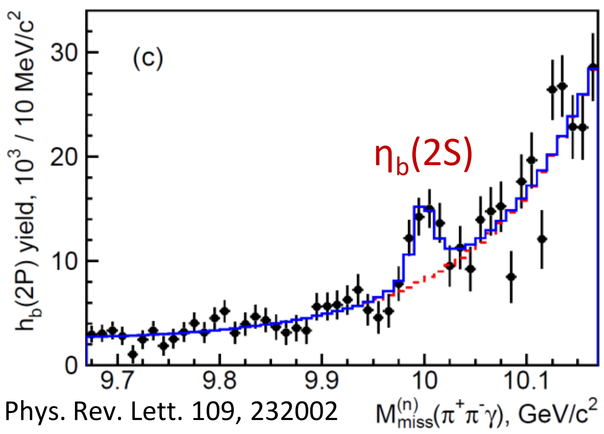
Phys. Rev. Lett. 117, 142001

$\Upsilon(5S) \to \pi\pi X$



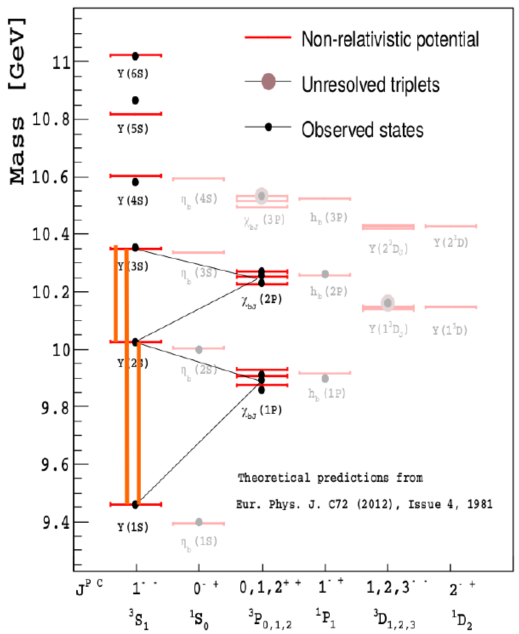
Phys. Rev. Lett. 108, 032001

$\Upsilon(5S) \to \pi\pi\, h_b(2P) \to \eta_b(2P)\gamma$

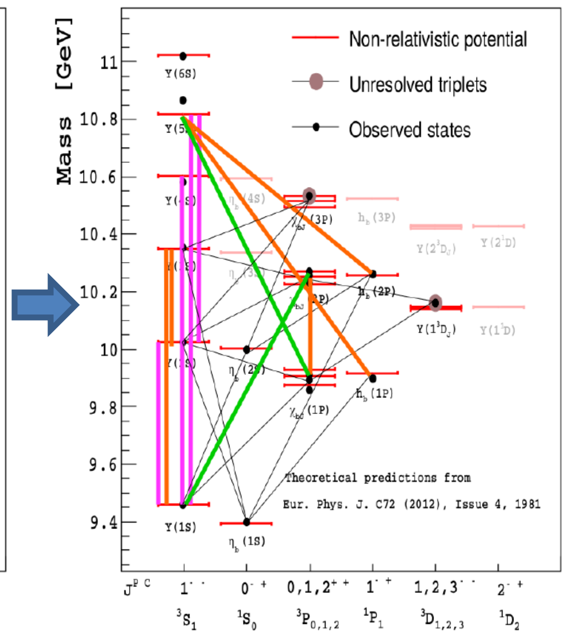


Phys. Rev. Lett. 109, 232002

2000



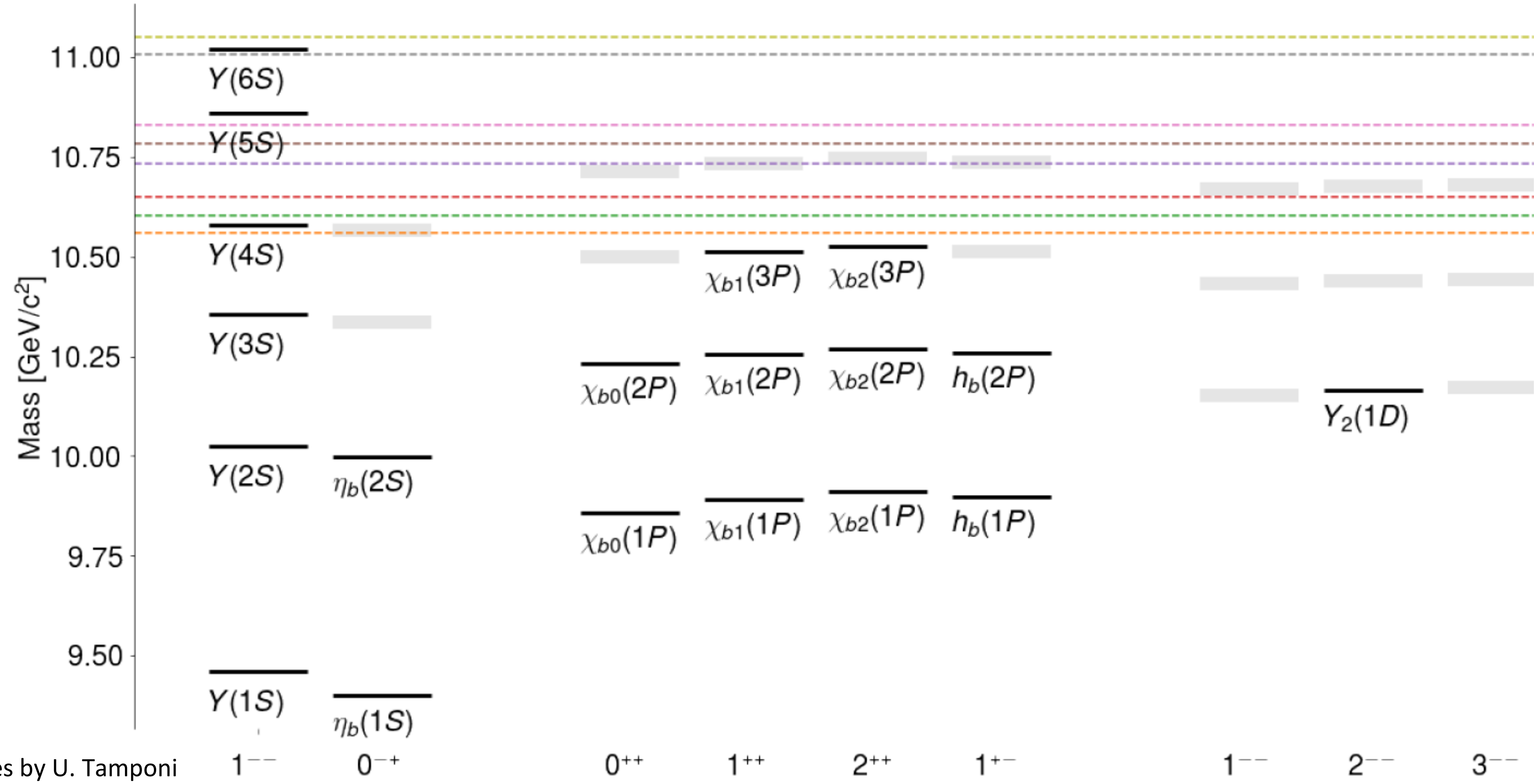
2015



Figures by U. Tamponi

- Fruitful results from 120 fb^{-1} $\Upsilon(5S)$ and energy scan data.
  - Two Z_b states observed:
  - Three conventional bottomonium states
- So many transitions observed.

Conventional bottomonium below threshold

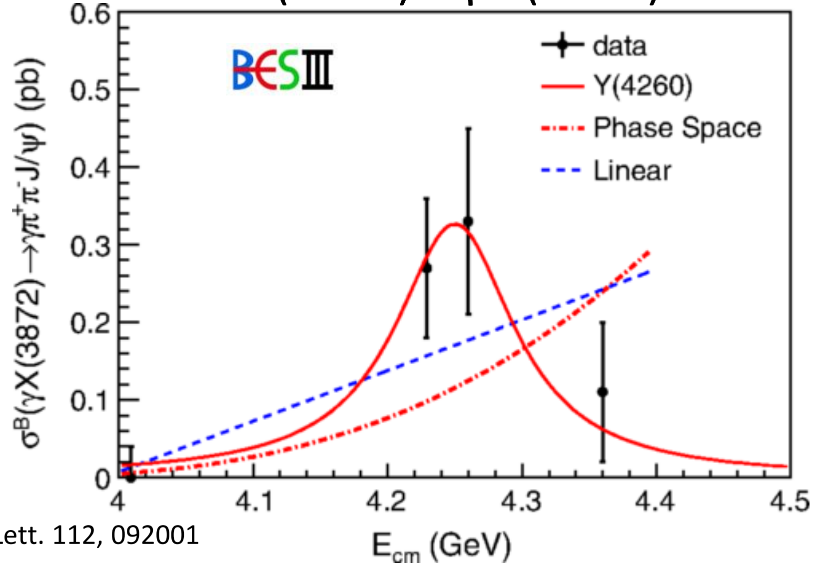


Figures by U. Tamponi

- In contrast to charmonium, up to n=3 states or D, F waves are still below the BB threshold.
- SuperKEKB can reach Υ(6S):
  Many opportunities from transition other than π
- Beam schedule still under discussion.

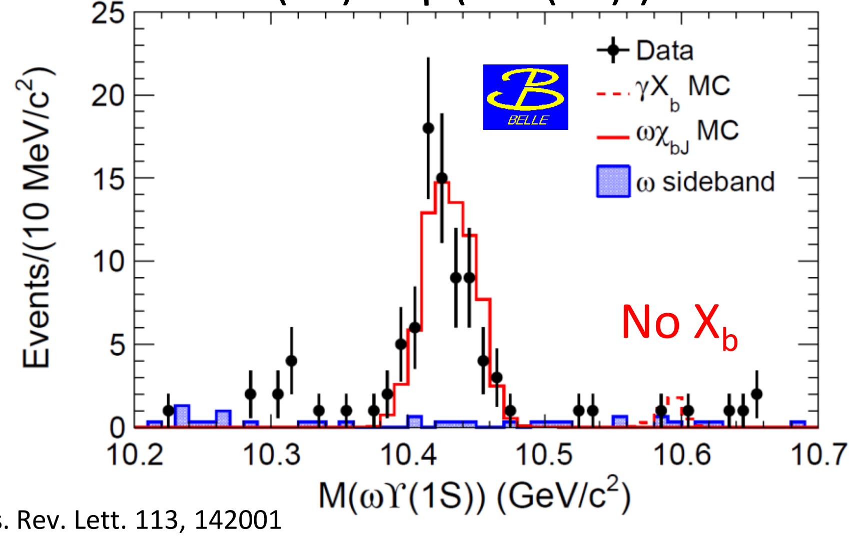
Bottom partner of X(3872)?

Y(4260)→γ X(3872)



Phys. Rev. Lett. 112, 092001

Y(5S) →γ (ωY(1S))



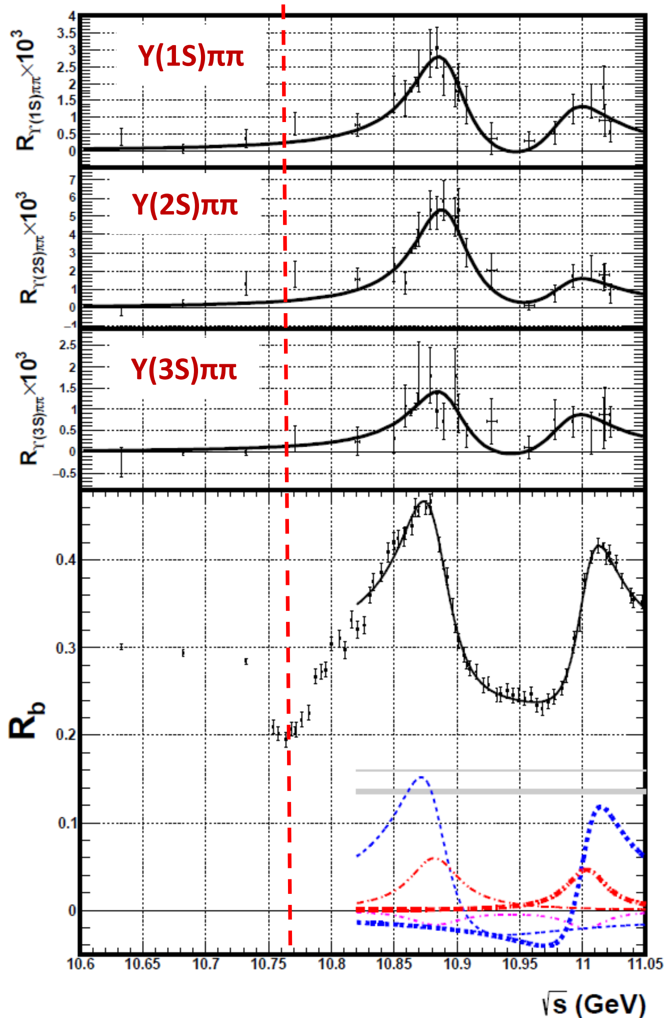
Phys. Rev. Lett. 113, 142001

- BB* molecule with isospin=0 (isospin breaking is expected to be suppressed). Primary decay mode should be ωY(1S).

- Observation of Y(4260)→γ X(3872), but no X_b in Y (5S)→γ (ωY(1S))
  - Not enough statistics ? Br(Y(4260)→γX(3872)/Br(Y(4260)→J/ψ$\pi^+\pi^-$) ~ 0.1
  - Y(4260) and Y(5S) are not the analogue states (next page)?
  - X(3872) comes from accidental coincidence of DD* mass and χ_{c1}(2P)?

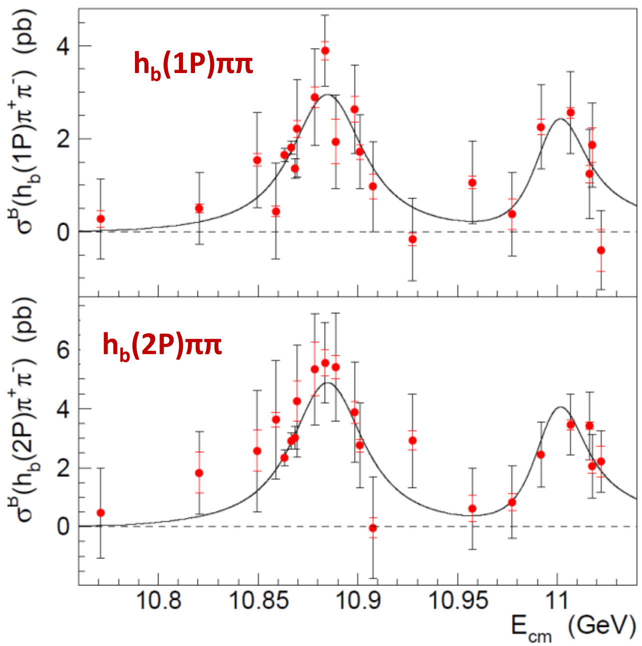
- C-parity Partner of Z_b (= W_b) also predicted in various decay modes such as Y(nS)ρ, $\eta_b\pi$

Energy scan



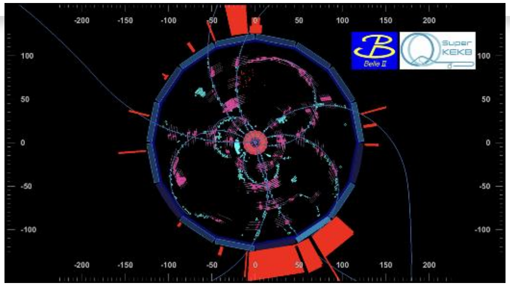
Phys. Rev. D 93, 011101(R)

- Dip in R_b and suggesting structure in Υ(nS)ππ: Another Y_b? Leading another Z_b?
- Final state other than Υ(nS)/h_b ππ.
  - May shed light on the anomalous Υ(5S)→Υ(1-3S)ππ
- Scan with open bottoms: $B^{(*)}B^{(*)}$, $B_s^{(*)}B_s^{(*)}$ indivisually. are expected have many features.
- Belle statistics: < 1 fb^{-1} per point with ~ 10 MeV step. 10 fb^{-1}/10 MeV will be very helpful.



Summary

- Belle II has started!



- Many rediscoveries, good physics performances.
- 50 times statistics opens new door to reveal nature of XYZ exotics:
  - Discover new states
  - Confirmation of
  - J^{PC} determination
  - Production/decay properties

Stay tuned for the coming result for Belle II !

Backup

Name	L	S	J^{PC}	Mass, MeV/c^2	Emitted hadrons [Threshold, GeV/c^2]
$\eta_b(3S)$	0	0	0^{-+}	10336	ω [11.12], ϕ [11.36]
$h_b(3P)$	1	0	1^{+-}	10541	$\pi^+\pi^-$ [10.82], η [11.09], η' [11.50]
$\eta_{b2}(1D)$	2	0	2^{-+}	10148	ω [10.93], ϕ [11.17]
$\eta_{b2}(2D)$	2	0	2^{-+}	10450	ω [11.23], ϕ [11.47]
$\Upsilon_J(2D)$	2	1	$(1,2,3)^{--}$	10441 – 10455	$\pi^+\pi^-$ [10.73], η [11.00], η' [11.41]
$h_{b3}(1F)$	3	0	3^{+-}	10355	$\pi^+\pi^-$ [10.63], η [10.90], η' [11.31]
$\chi_{bJ}(1F)$	3	1	$(2,3,4)^{++}$	10350 – 10358	ω [11.14], ϕ [11.38]
$\eta_{b4}(1G)$	4	0	4^{-+}	10530	ω [11.31], ϕ [11.55]
$\Upsilon_J(1G)$	4	1	$(3,4,5)^{--}$	10529 – 10532	$\pi^+\pi^-$ [10.81], η [11.08], η' [11.49]