Heavy Flavor Hadron Physics at Belle and Belle II

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10th anniversary J-PARC Symposium 2019

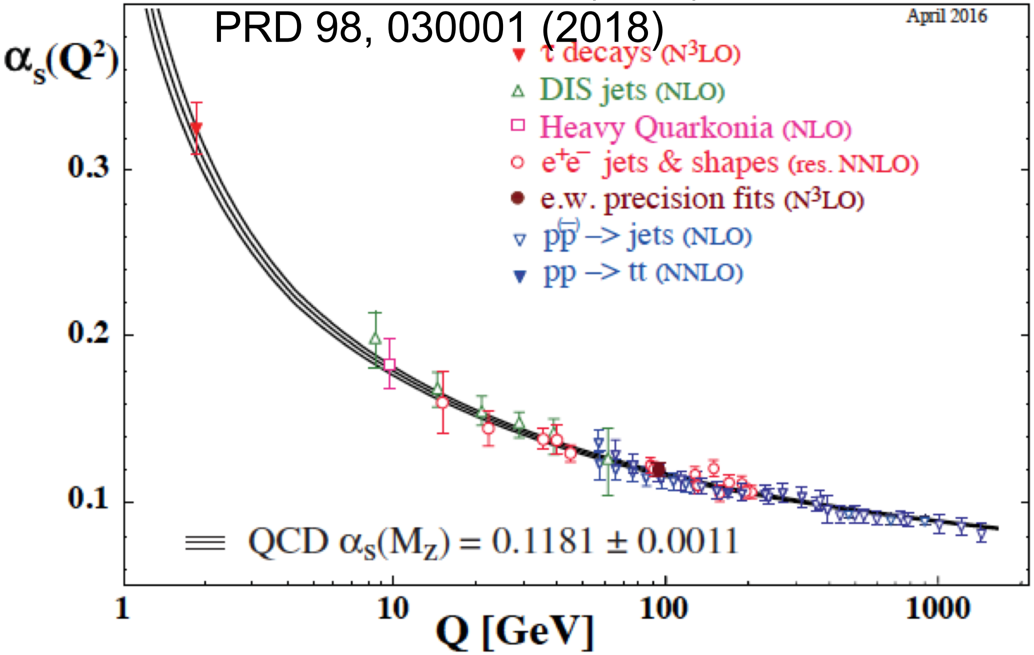
2019 Sep. 25th

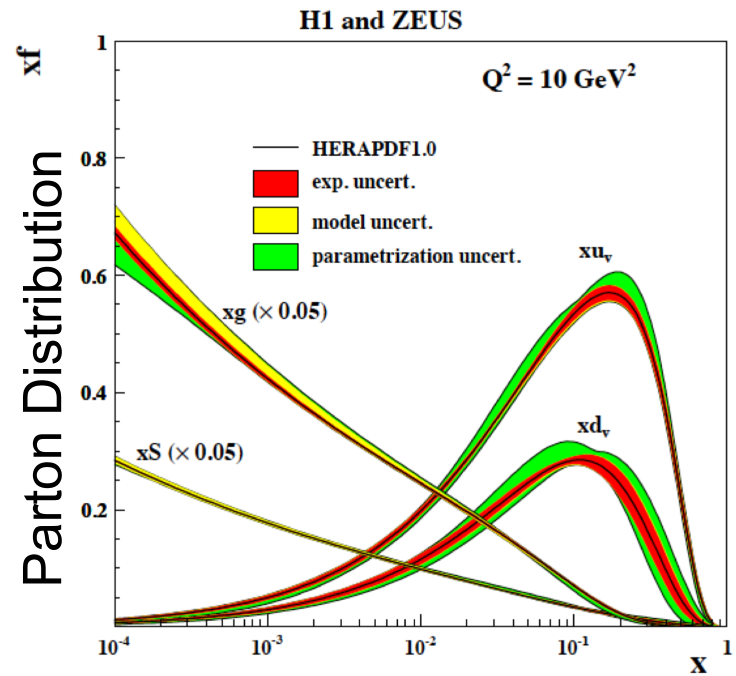
Outline

- A big picture (in my personal point of view)
  - Identify effective degree of freedom → spectroscopy
  - Generalized parton distribution(GPD)
- Intensity frontier e^+e^- experiments : Belle & Belle II
  - Variety of recorded reactions, access various final states.
- Hadron spectroscopy
  - XYZ states and charm baryons
- Importance of low multiplicity events
  - Two photon events and GPD.
- Summary

A big picture (in my personal opinion)

M. Tanabashi et al. (PDG)
PRD 98, 030001 (2018)



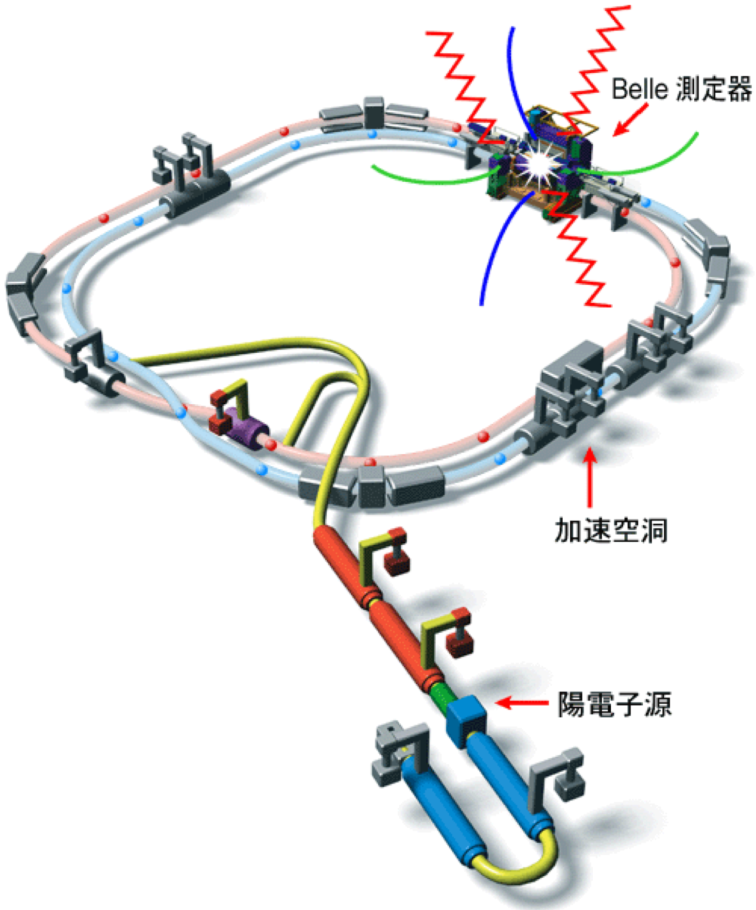


Running of α_S and established.

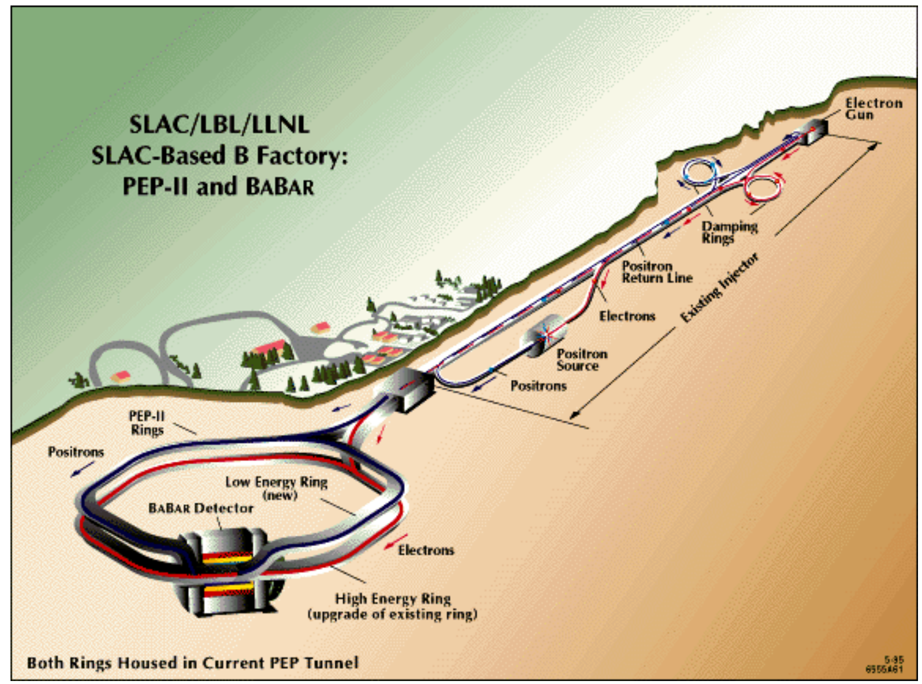
Two issues are identified.

- Effective degree of freedom.
  - ✓ Hadron spectroscopy
- Generalized parton distribution.
  - ✓ Hadron tomography

Legacy of B-factories



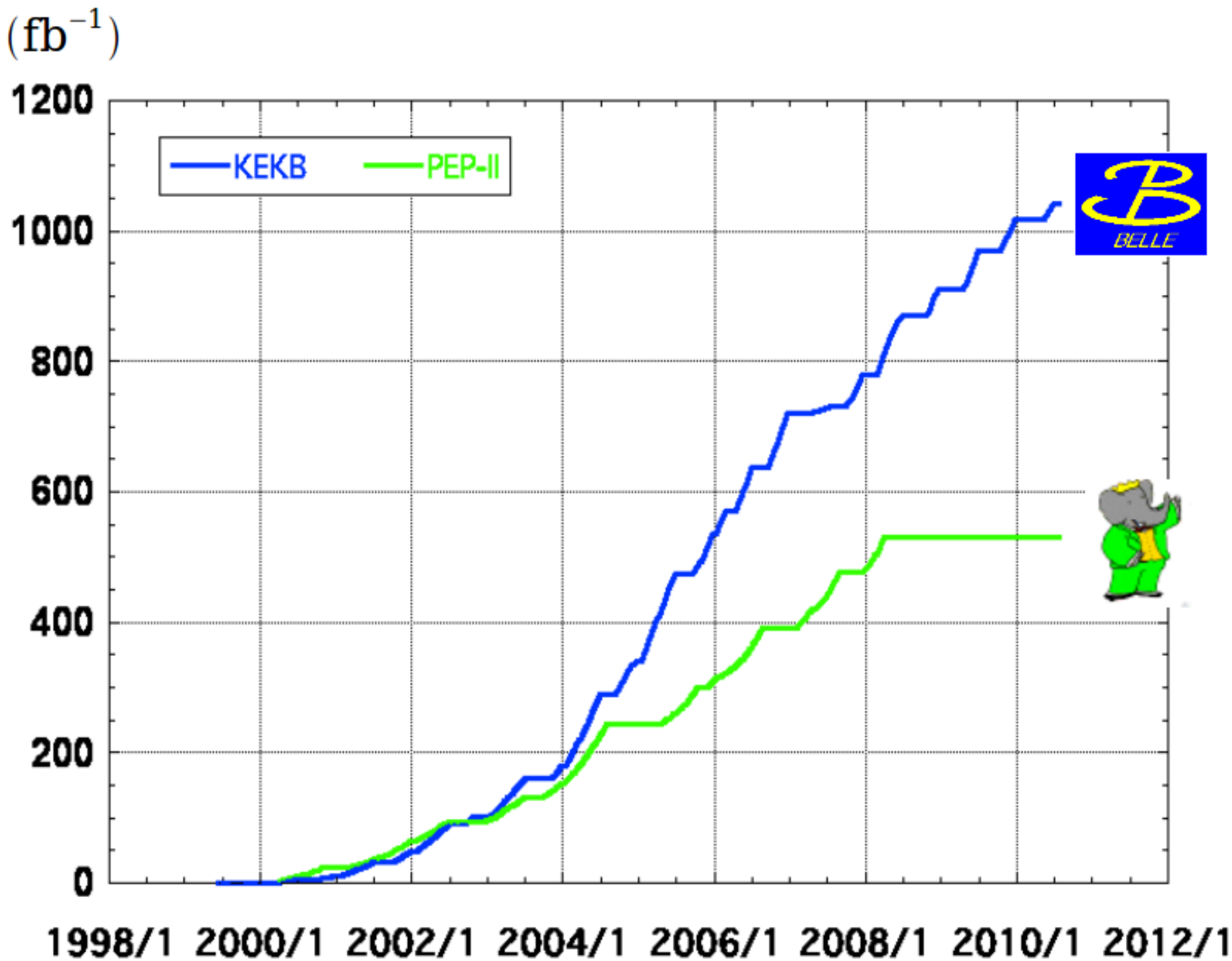
High luminosity, asymmetric-energy e^+e^- colliding beam experiments were desired to study CP violation.



KEKB&Belle 8 GeV × 3.5 GeV (Run 1999-2010)

PEP II&BaBar 9 GeV × 3.1 GeV (Run 1999-2008)

Integrated luminosity of B factories



> 1 ab^{-1}

On resonance:

$\Upsilon(5S)$: 121 fb^{-1}

$\Upsilon(4S)$: 711 fb^{-1} 772M $B\overline{B}$

$\Upsilon(3S)$: 3 fb^{-1}

$\Upsilon(2S)$: 25 fb^{-1}

$\Upsilon(1S)$: 6 fb^{-1}

Off reson./scan:

~ 100 fb^{-1}

~ 550 fb^{-1}

On resonance:

$\Upsilon(4S)$: 433 fb^{-1} 470M $B\overline{B}$

$\Upsilon(3S)$: 30 fb^{-1}

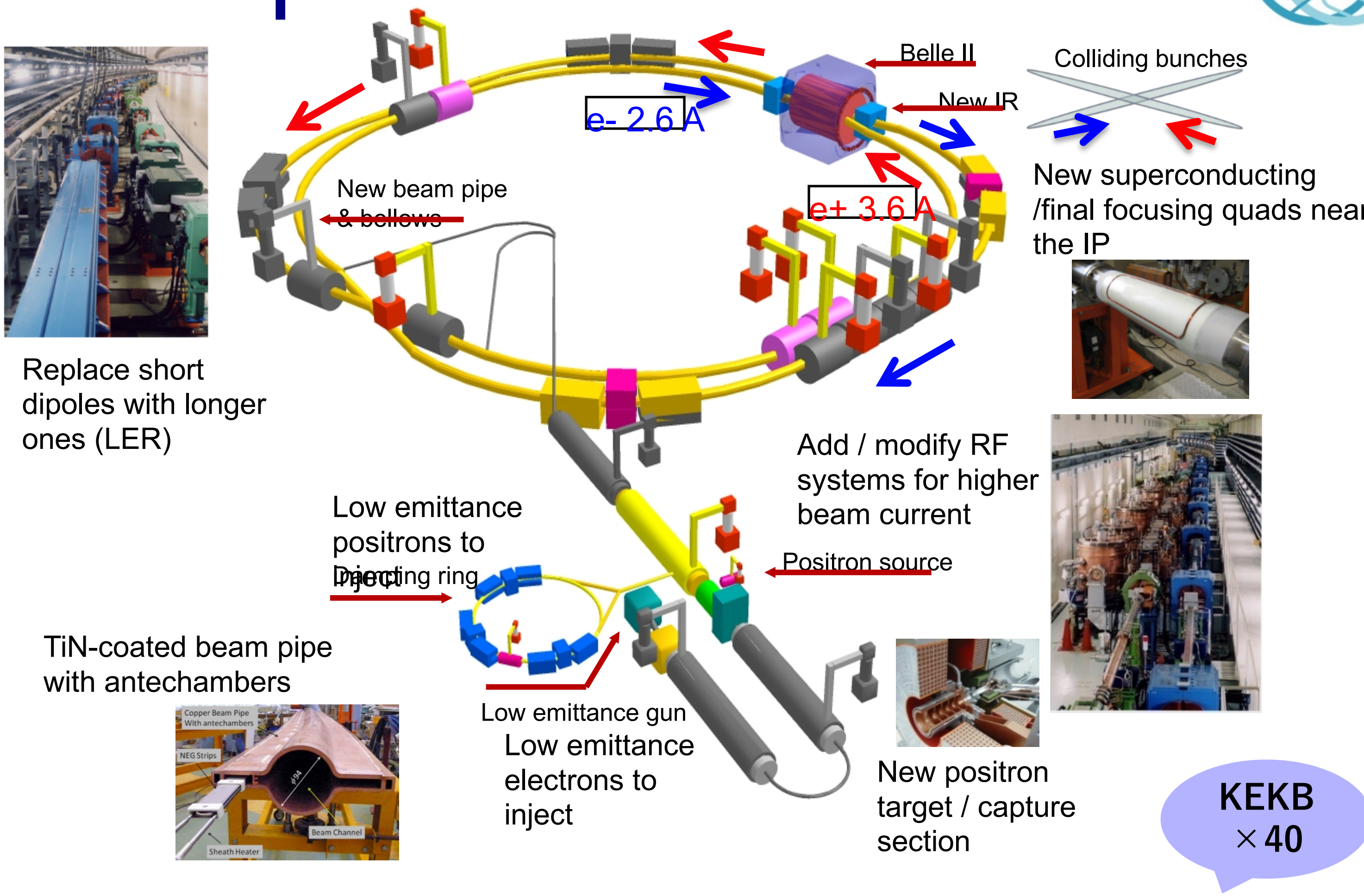
$\Upsilon(2S)$: 14 fb^{-1}

Off resonance:

~ 54 fb^{-1}

In total, more than 1.5 ab^{-1} including 1G $B\overline{B}$ pairs are recorded at B-factories

SuperKEKB collider



- Nano-beam
- Increase currents

Peak luminosity : 2.1×10^{34} $cm^{-2}s^{-1}$ => **8.0×10^{35} $cm^{-2}s^{-1}$**

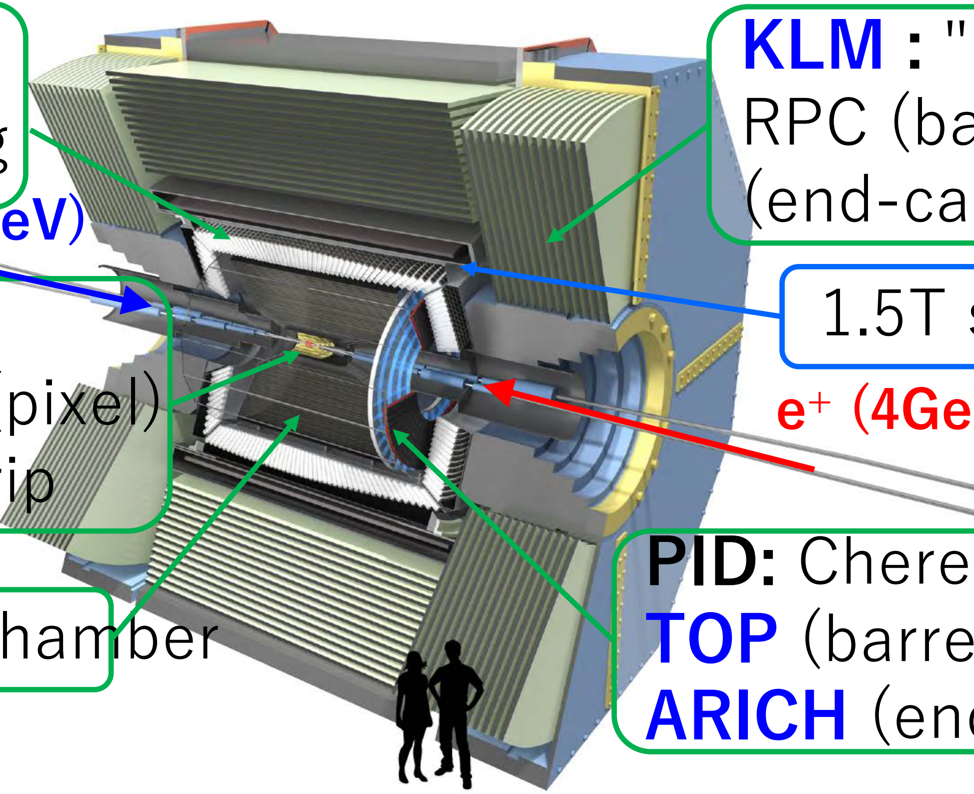
Beam energy : 3.5 / 8.0 GeV => **4.0 / 7.0 GeV**

Boost factor ~2/3

Belle II detector

ECL : CsI (Tl), waveform sampling

KLM : "KL and muon" RPC (barrel) + SiPM (end-cap, inner barrel)



1.5T solenoid coil

VXD :
PXD : DEPFET (pixel)
SVD : Silicon strip

CDC : drift chamber

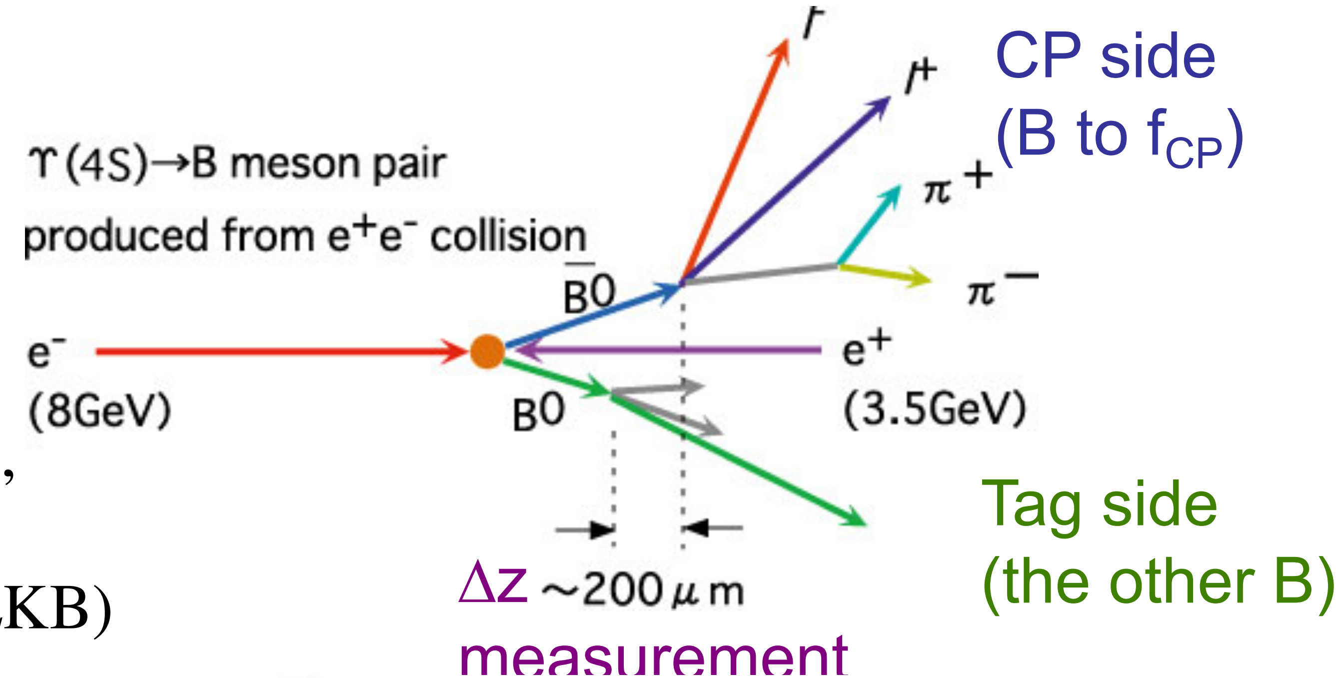
PID: Cherenkov ring image
TOP (barrel): Quarts
ARICH (endcap): Aerogel

Issues to overcome
- Beam background
- High rate capability
- Boost ~ 2/3

Technical choice
- Finer segmentation, waveform sampling.
- Material change
- Larger angular coverage (CDC, SVD)
- Closer to the IP (PXD) 3 -> 2cm
- Particle ID improve (K/π)(TOP, ARICH)

Originally in order for time-dependent CPV

$\Delta z = \beta\gamma c \Delta t$,
$\beta\gamma = 0.425$(KEKB),
0.56(PEP-II),
0.28(SuperKEKB)



$$A_{CP}(\Delta t) = \frac{\Gamma(\overline{B}^0(\Delta t) \rightarrow f_{CP}) - \Gamma(B^0(\Delta t) \rightarrow f_{CP})}{\Gamma(\overline{B}^0(\Delta t) \rightarrow f_{CP}) + \Gamma(B^0(\Delta t) \rightarrow f_{CP})} = S_{f_{CP}} \sin(\Delta m \Delta t) + A_{f_{CP}} \cos(\Delta m \Delta t)$$

This is very demanding measurement, requires sophisticated detector and analysis methodology!

All these are great benefit

4π general purpose spectrometer with

- High momentum resolution, σ_p/p = 0.3%@1GeV/c.
- Ability to detect γ down to 30 MeV.
- Good γ energy resolution, σ_M =5 MeV for $\pi^0 \to \gamma\gamma$.
- Lepton identification capability, ε>0.9, fake<0.01.
- K/π/p separation capability, ε~0.9, fake<0.1.
- Excellent B decay vertex reconstruction, $\sigma_{\Delta z}$ =80 μm.

+

- World highest luminosity

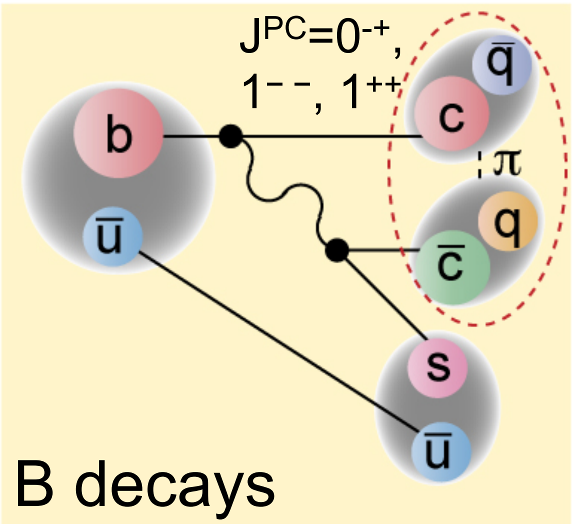
Exploiting the advantages

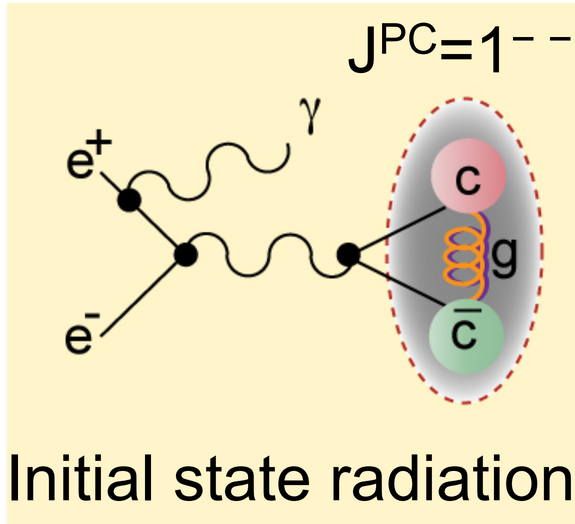
In terms of physics reach to study strong interaction,

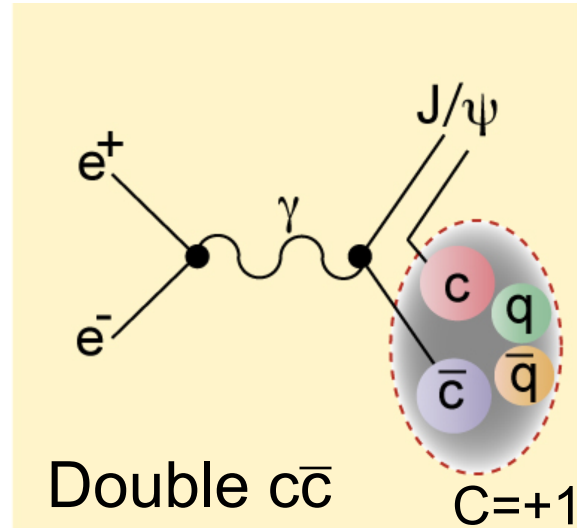
- Variety of the recorded reactions
  - Each process has preference of the quantum numbers.
  - Interplay among several approaches is effective.
- Possibility to access various final state particles
  - Variety of recorded reactions results in variety of final states.
  - To explain an exotic state, each hypothesis has predictions for other decay modes and partner states.

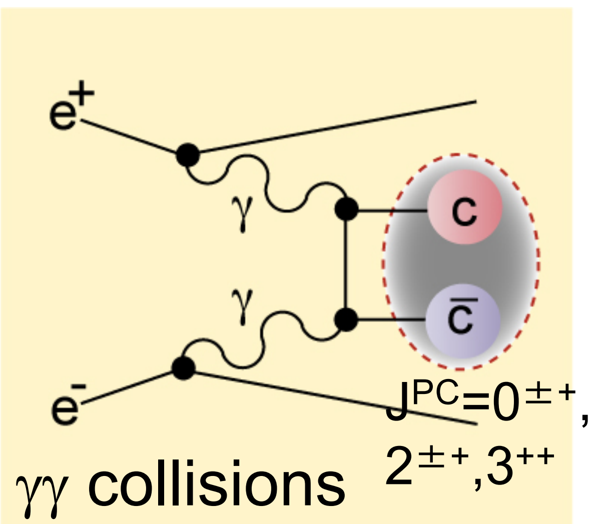
are important.

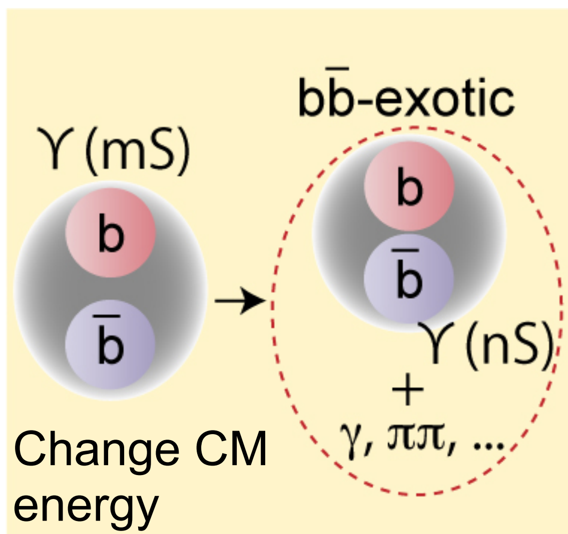
Variety of recorded reactions









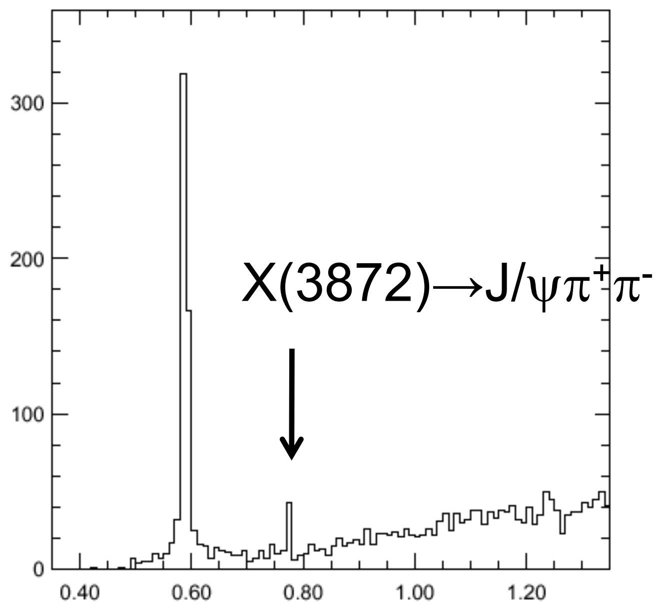


Allowed/favored quantum numbers are different depending on production processes.

X(3872) 1658 citations as of Sep. 23rd.

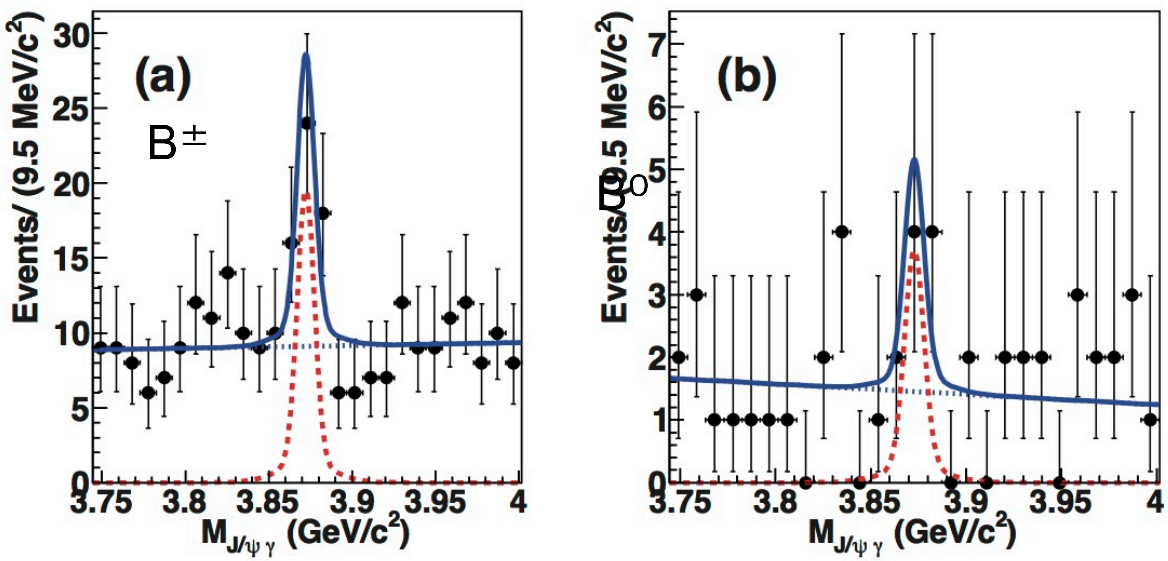
Belle's the most famous discovery

Belle PRL91,261801(2003)



$M_{l+l-\pi+\pi-}$ - M_{l+l-} (GeV)

X(3872)→J/ψ γ; C=+1



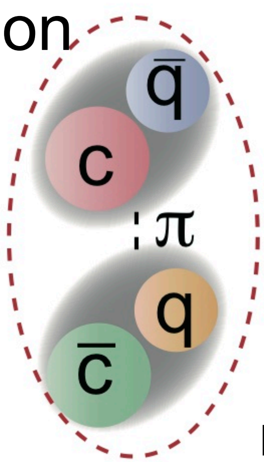
Belle PRL07,091803(2011)

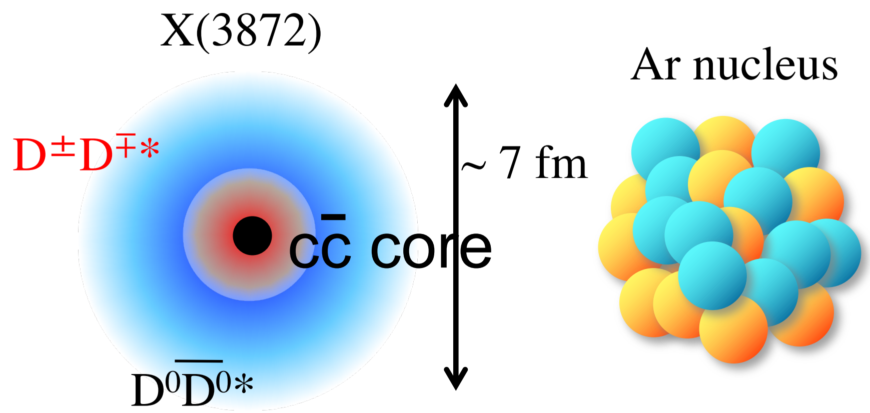
$J^{PC}=1^{++}$ (Belle, BaBar, CDF, LHCb) from $J/\psi\ \pi^+\pi^-$ angular distribution.
(PRL110, 222001(2013) and cited papers)

$Br(X(3872)\rightarrow D^0\overline{D}^{*0})$ is about $Br(X(3872)\rightarrow J/\psi\ \pi^+\pi^-)\times 10$.

Admixture : most plausible interpretation for X(3872)

Meson-meson molecule





E. J. Eichiten et al. Phys. Rev. D 73, 014014 (2006);
A. M. Badalin et al. Phys. Rev.D 85, 031103 (2012);
S. Takeuchi, K. Shimizu and M.Takizawa PTEP2014, 123D01(2014).

$D\bar{D}^*$ component is coupled with the same J^{PC} $c\bar{c}$, $\chi_{c1}(2P)$ (unseen).

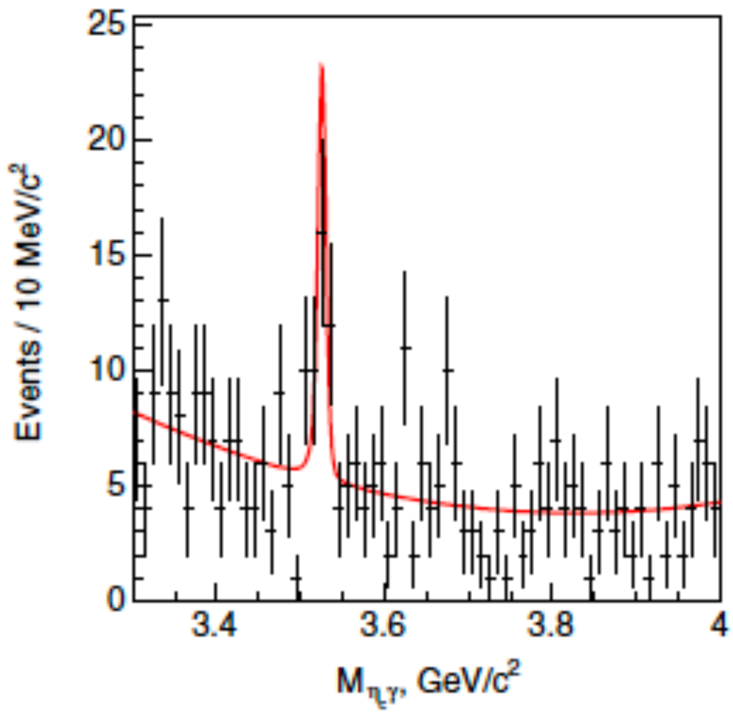
→can explain $Br(X \to D^0\bar{D}^{*0})/Br(X \to J/\psi\ \pi^+\pi^-)$ is about 10.

→D^+D^{*-} component can explain $J/\psi\ \pi^+\pi^-$ and $J/\psi\ \pi^+\pi^-\pi^0$ coexitst.

→pure molecule; too fragile to have prompt produced in Tevatron/LHC.

→another $\chi_{c1}(2P)$ dominant state would become broad.

New observation for charmonium



$B^+ \to h_c K^+$, $h_c \to \gamma\, \eta_c$.

η_c is reconstructed in 11 modes.

($K_S K^+ \pi^-$, $K^+ K^- \pi^0$, $K_S K_S \pi^0$, $K^+K^-K^+K^-$, $K^+K^-K^+K^-$, $\eta' \pi^+\pi^-$, pp, $pp\pi^0$, $pp\pi^+\pi^-$, $\Lambda\Lambda$)

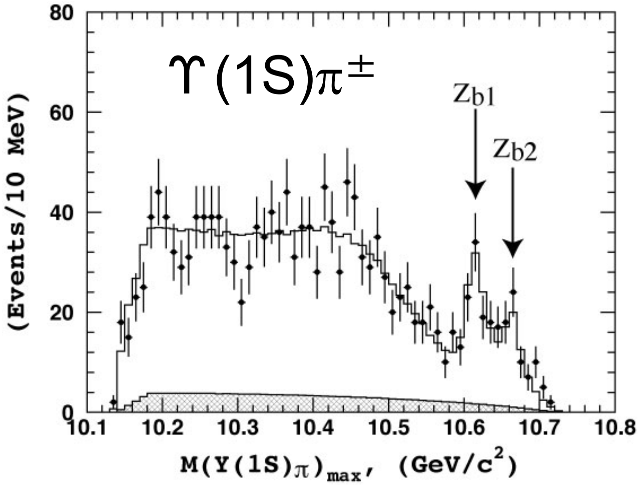
A multivariable analysis technique is introduced to overcome factorization suppression (i.e. low S/N).

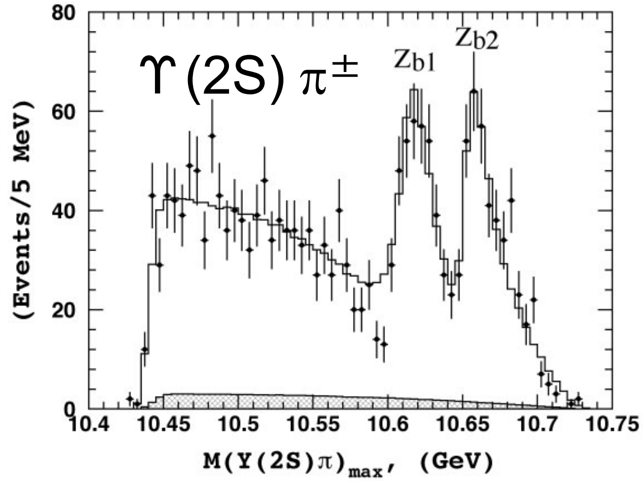
PRD100,012001(2019)

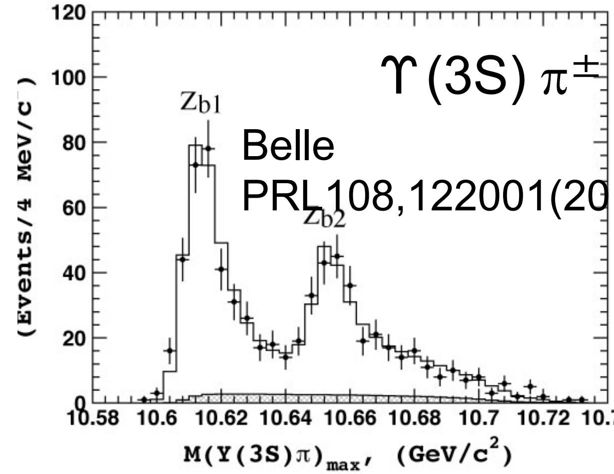
The first evidence of h_c production in B decays.

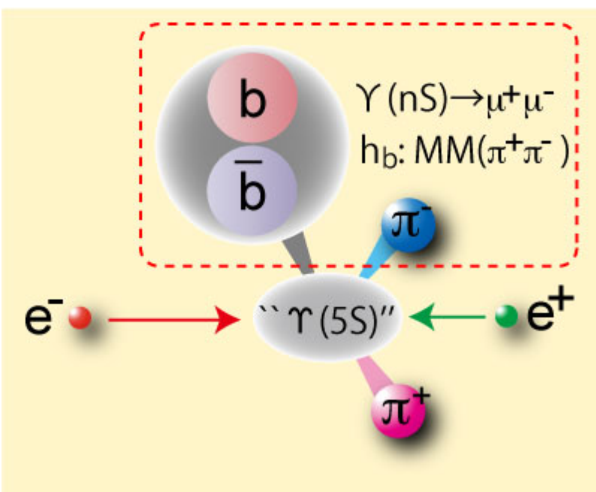
The radiative decays into $\gamma\, \eta_c$ or $\gamma\, \eta_c(2S)$ are important to look for X(3872)'s C-odd partner, this Belle analysis shows that we have passed the first milestone toward such a direction.

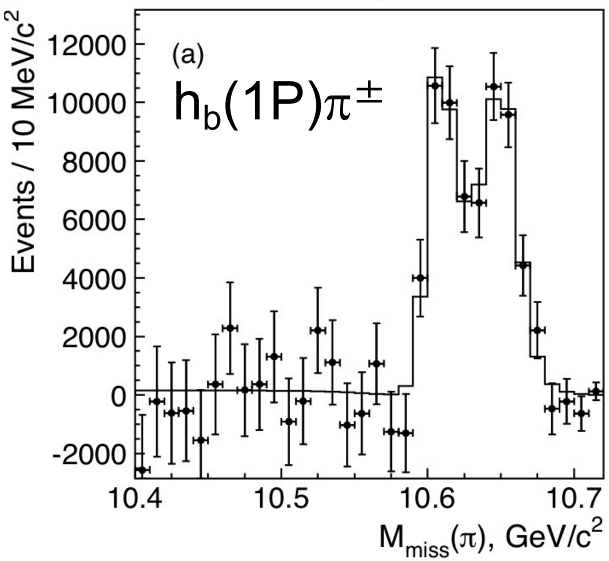
$b\bar{b}\ \pi^{\pm}$ system at $\Upsilon(10860)$

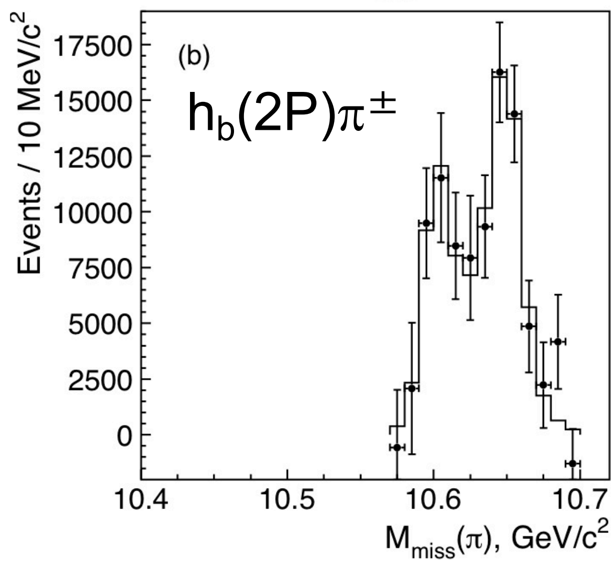












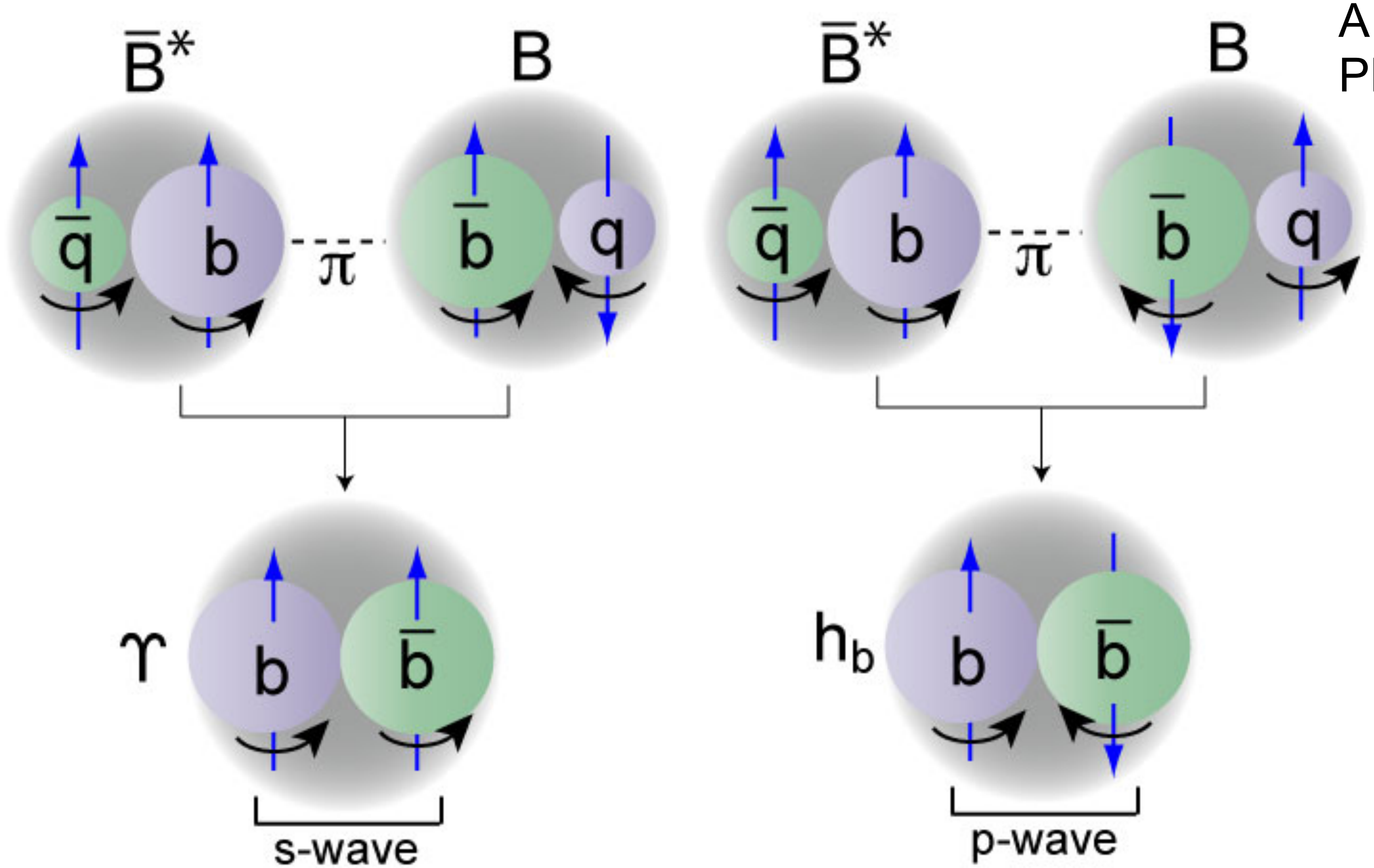
10610 MeV~$M(B\bar{B}^*)$

10650 MeV~$M(B^*\bar{B}^*)$

Z_bs' decay to $B^{(*)}B^*$ found to be dominant.

Belle PRL116,212001(2016)

Molecular picture works

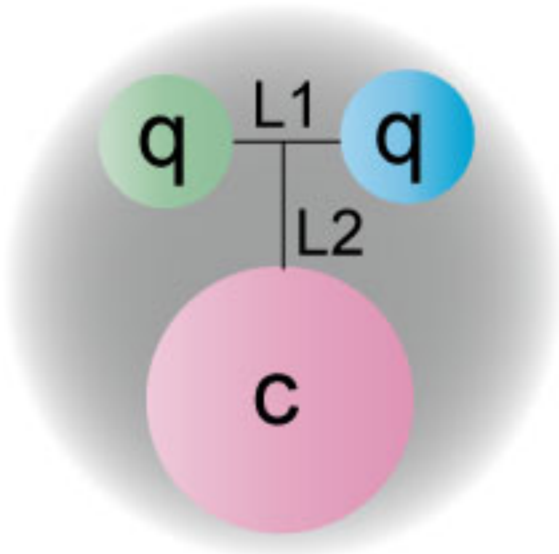


A.E.Bondar et al., PRD84,054010(2011)

Decays to ϒ and h_b can co-exist. Decay into $B^*B^{(*)}$ found to be dominant.
PRL116,212001(2016)
$J^P=1^+$ is supported by Dalitz analysis.
PRD91,072003(2015).

Theoretical predictions given for relevant partner states.
Search for them is likely to require Belle II statistics.

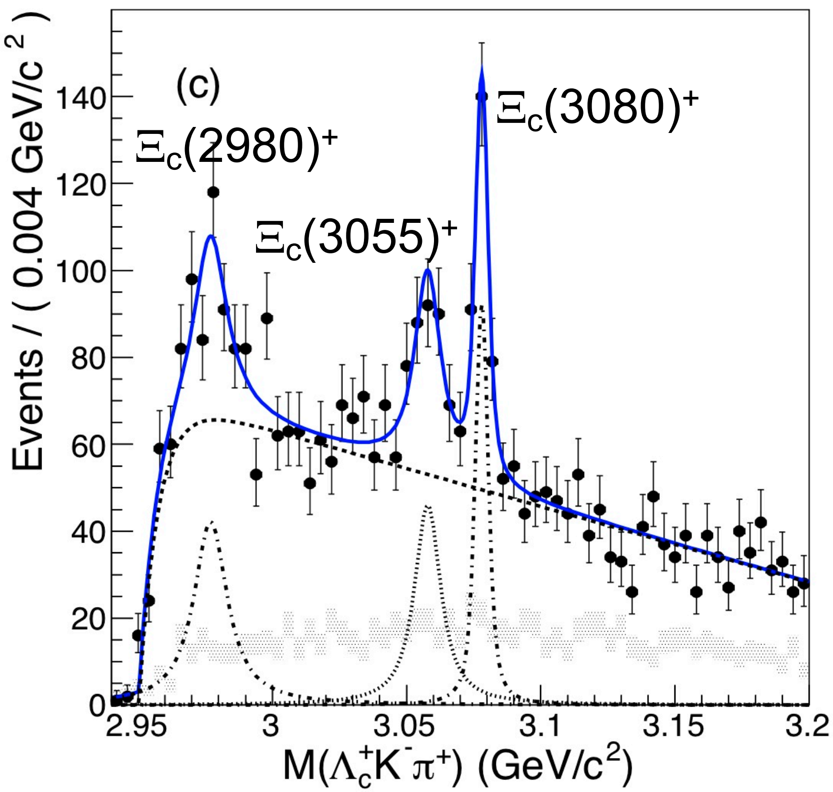
Charm baryon to check "di-quark"



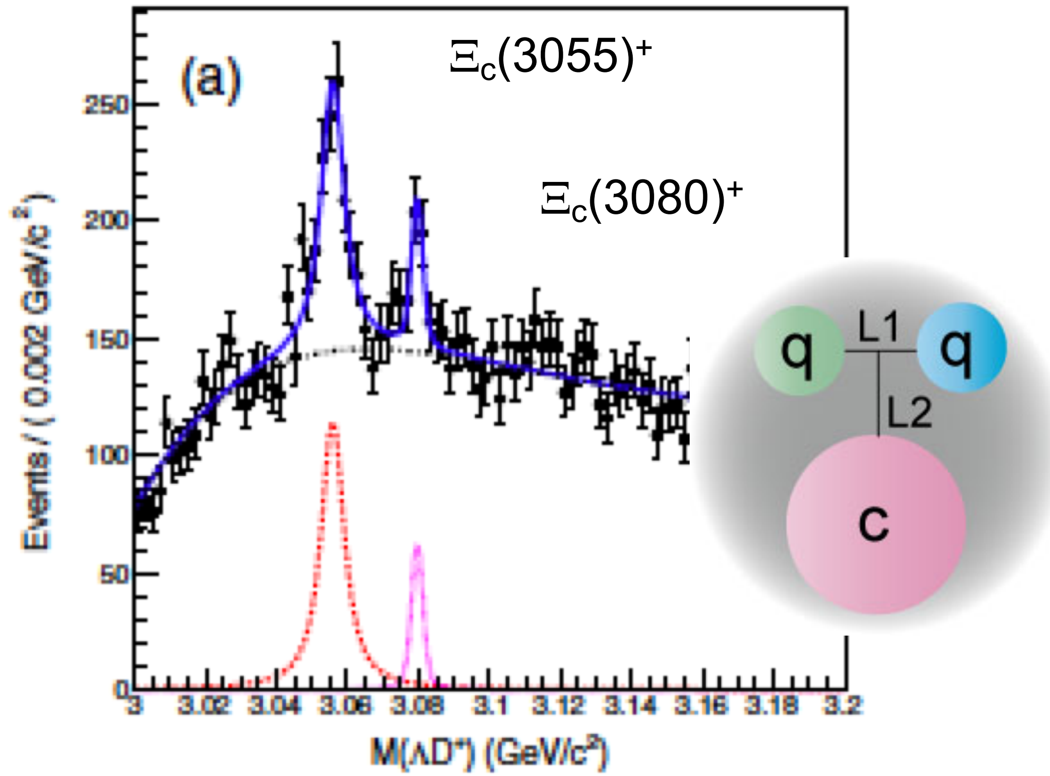
- Thought to be a good place to check if "di-quarks" is behaving as a good degree of freedom to form hadrons.
- One of the constituent quark is heavy, correlation between the remaining light quarks would become clear.
- L_1 : ρ mode, L_2 : λ mode.

To which mode, how much br.?

PRD89,052003(2014)

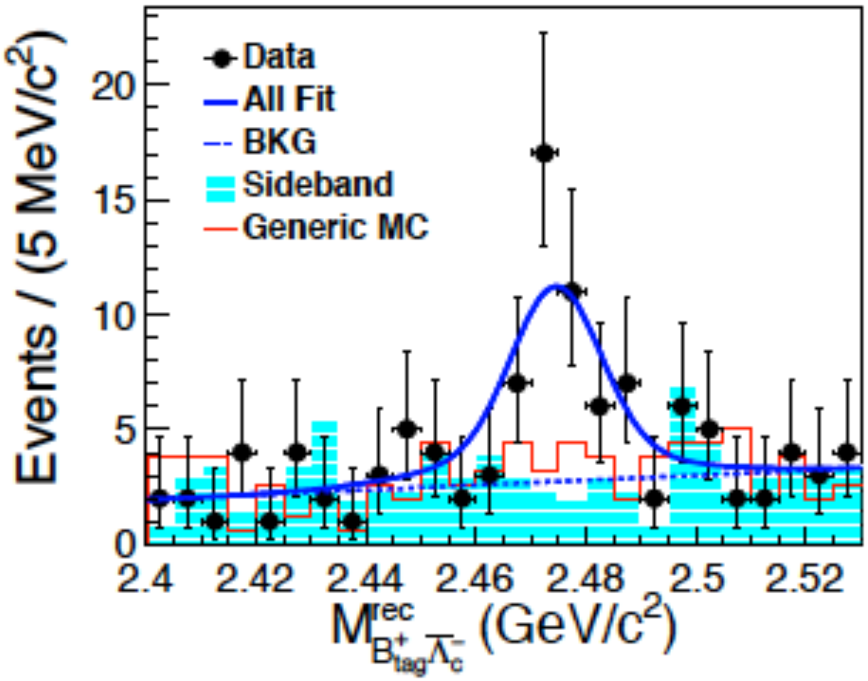


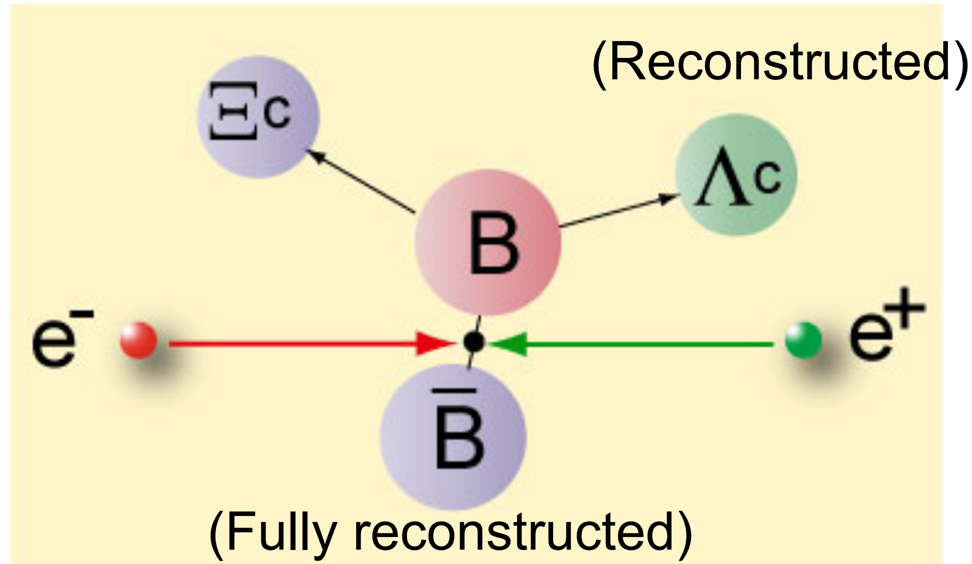
PRD94,032002(2016)



"charm baryon + light hadron" or "charm meson + baryon" ?
Very important info., just started to be got in our hand.
For J^P determination, higher statistics needed.

$B^- \to \Lambda_c^- \, \Xi_c^0$ with missing mass technique and absolute Ξ_c^0 Br.





PRL122,082001(2019)

$Br(B^- \to \Lambda_c^- \, \Xi_c^0) = (9.51 \pm 2.10 \pm 0.88) \times 10^{-4}$

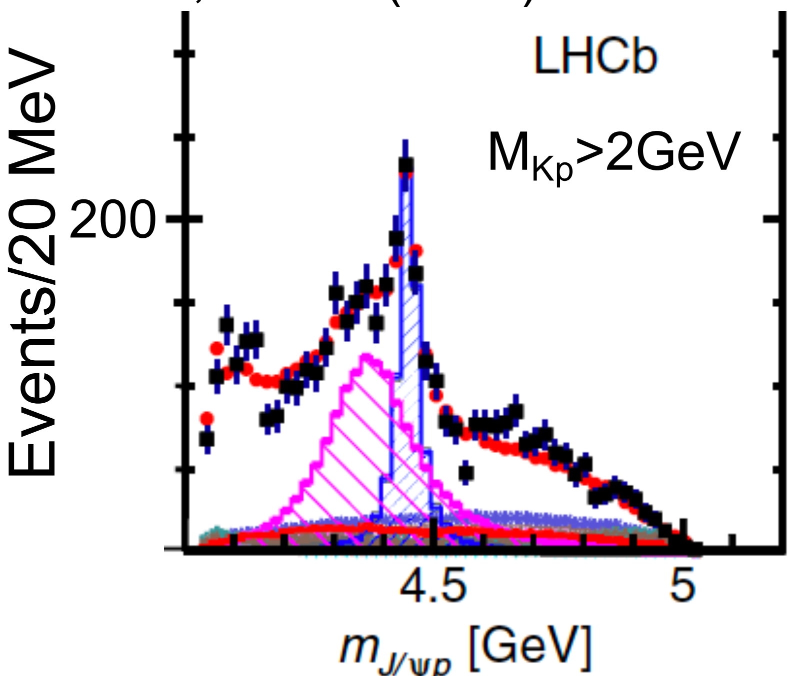
$Br(\Xi_c^0 \to \Xi^- \pi^+) = (1.80 \pm 0.50 \pm 0.14)\%$

$Br(\Xi_c^0 \to \Lambda K^- \pi^+) = (1.17 \pm 0.37 \pm 0.09)\%$

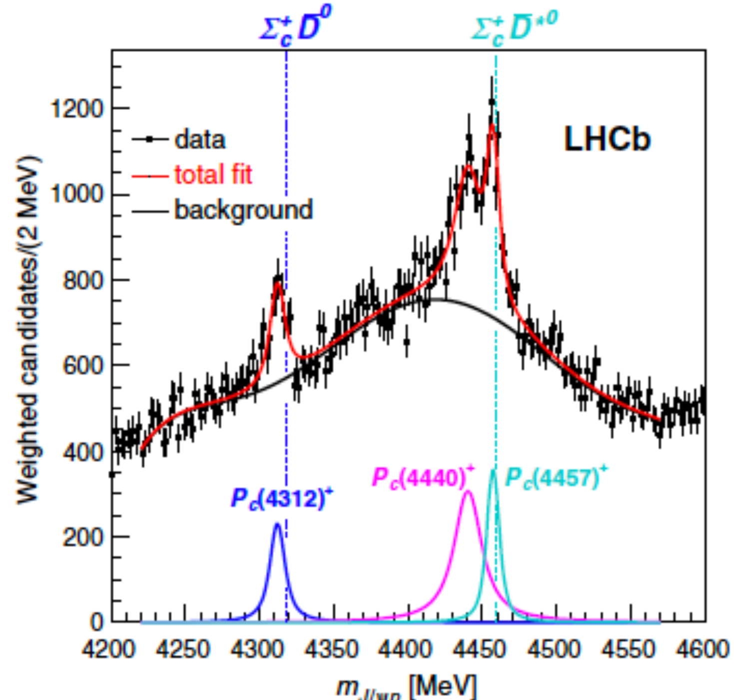
$Br(\Xi_c^0 \to p K^+ K^- \pi^+) = (0.58 \pm 0.23 \pm 0.05)\%$

Higher statistics physics reach (an example at LHCb)

PRL115,072001(2015)



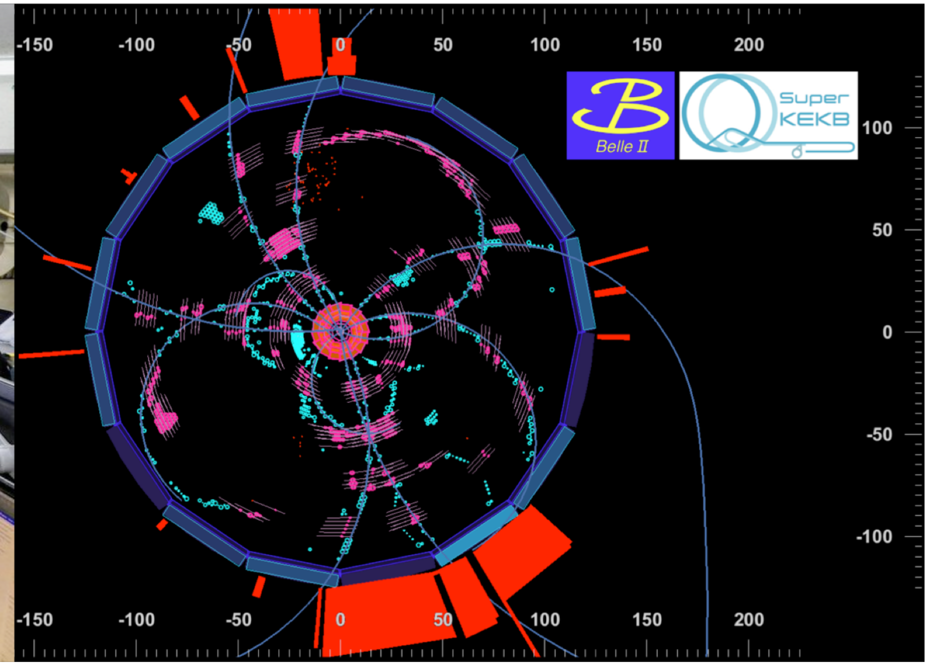
PRL122,222001(2019)



In 2015, 3/fb (√s=7 and 8 TeV)
26k $\Lambda_b \rightarrow J/\psi K^- p$ events
Two P_c^+ states claimed.

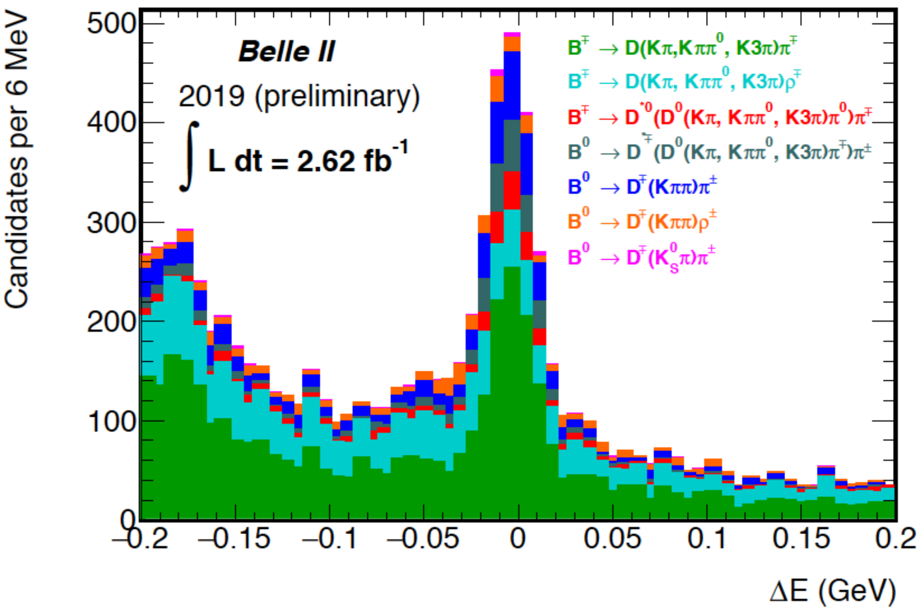
In 2019, 3/fb + 6/fb (√s=13 TeV)
246k $\Lambda_b \rightarrow J/\psi K^- p$ events
Three P_c^+ states appeared.

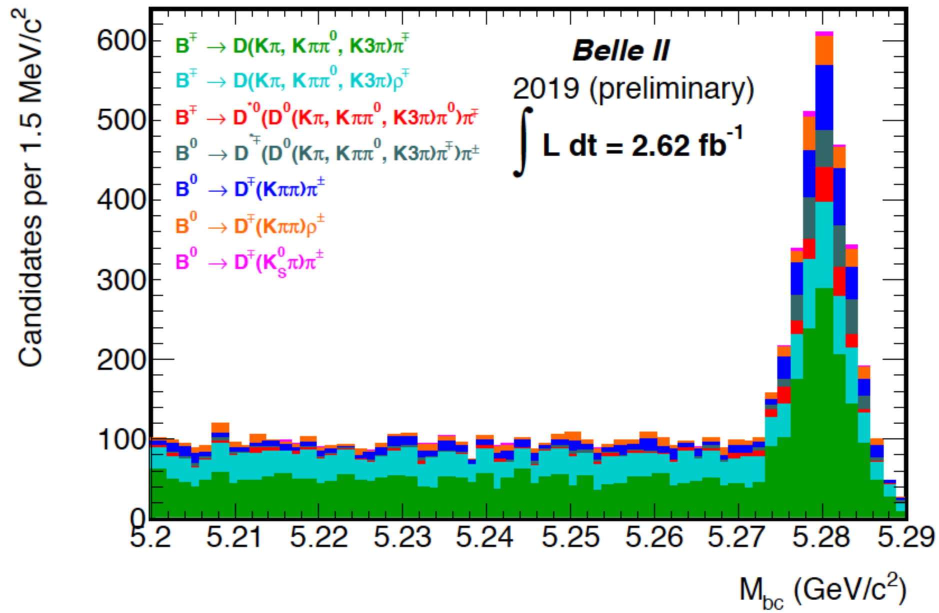
Beam collision with vertex detector
2019 March 25th 19:44 JST



- The vertex detector system has been installed 2018 autumn, now Belle II is fully equipped (except for partial 2nd layer vertex pixel detectors).
- Beam operation resumed 2019 Mar. 11th.

Fully reconstructed B mesons





$\Delta E = (E_{CM}/2) - E_{rec}$

$M_{bc} = \{ (E_{CM}/2)^2 - P_{rec}^{\ 2} \}^{1/2}$

We got 22k fully reconstructed B decay events from ~ half of 2019 Mar.-Jun. run data : 2.6/fb.

Not only charged Kaons and pions but also neutrals and K_S are efficiently reconstructed.

For GPDs and GPAs

Nowadays, Generalized Parton Distribution (GPD) and Generalized Parton Amplitude (GPA) are intensively discussed. (Parton distribution as a func. of x : 1D, here 3D dist. considered.)

S.Kumano et al., PRD97,014020(2018)

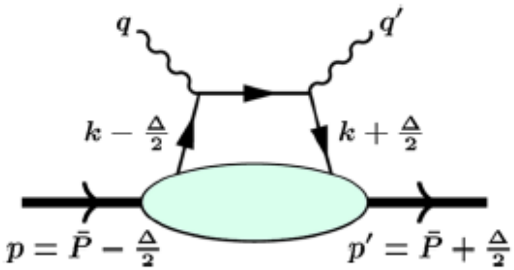


FIG. 2. Kinematics for GPDs in deeply virtual Compton scattering process.

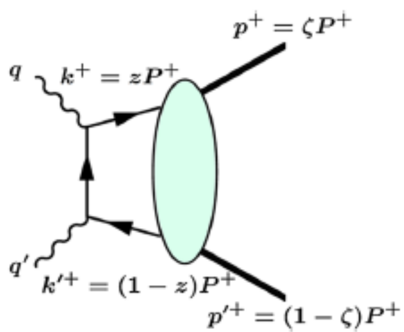
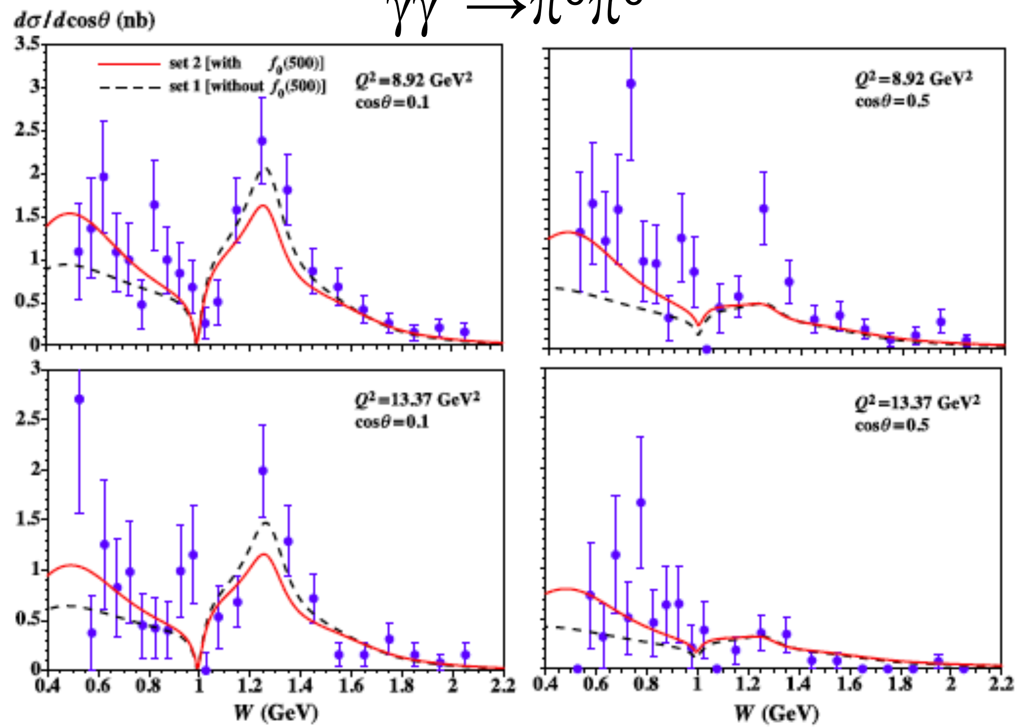


FIG. 3. Kinematics for GDAs in two-photon process $\gamma^* + \gamma \to h + \bar{h}$. This process corresponds to the $s - t$ crossed one of the Compton scattering process in Fig. 2.

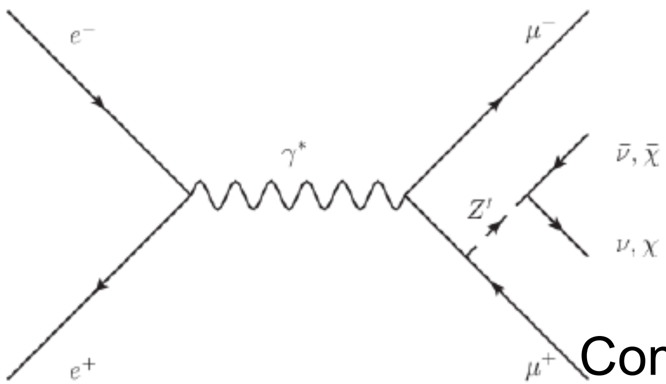
$\gamma\gamma^* \to \pi^0\pi^0$

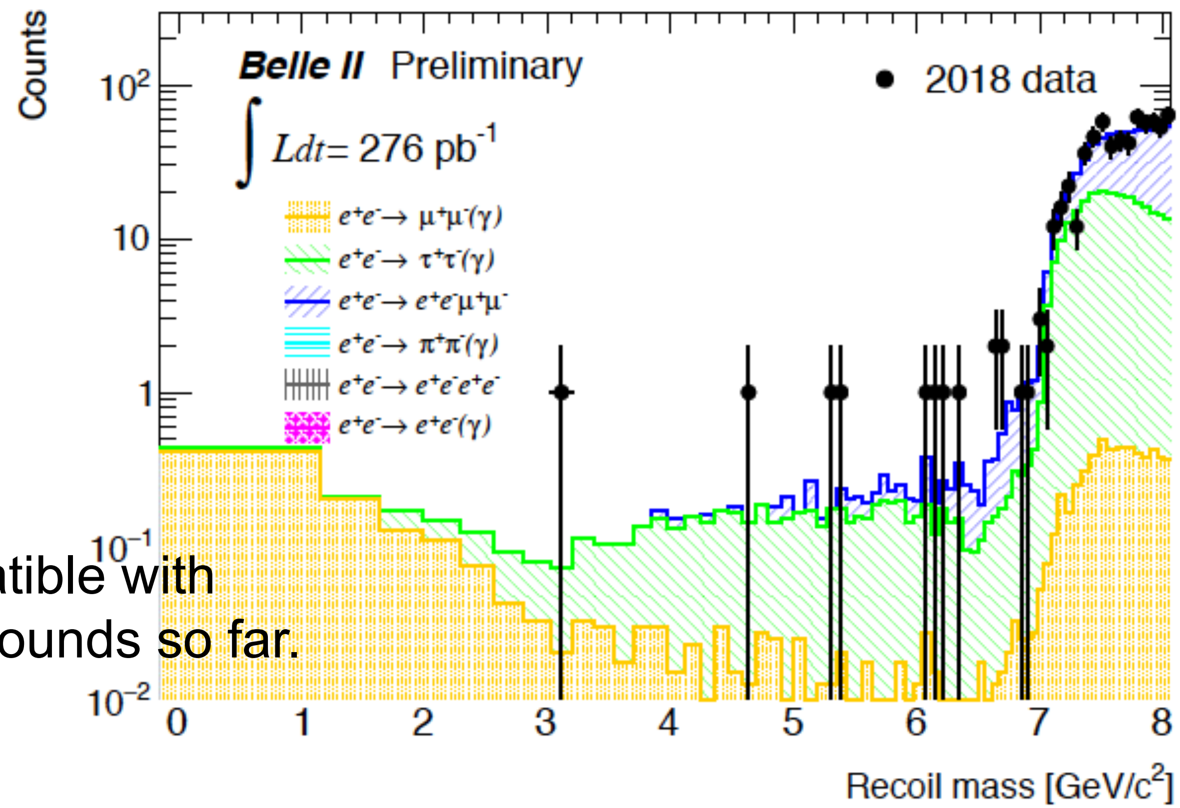


Data : PRD86,092007(2012), PRD93,032003(2016)

Low multiplicity events are properly taken

Search for $e^+e^- \to \mu^+\mu^- Z'$, $Z' \to$ invisible



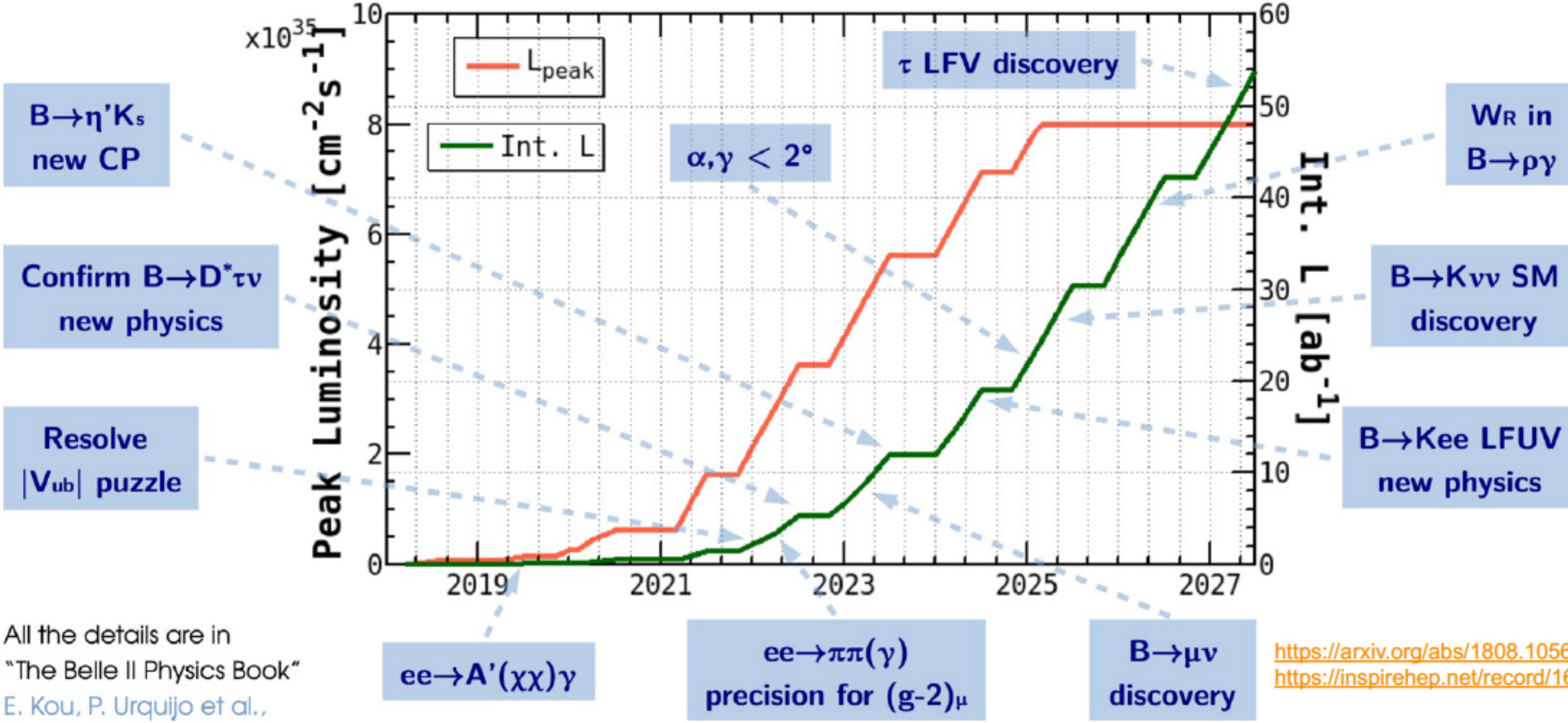


Compatible with backgrounds so far.

Trigger logic to accept low multiplicity events is properly functioning.
Improvement in $\gamma\gamma^* \to hh$ at Belle II is promising.

Next runs and prospects

Note : Physics cases are based on some assumptions ..



All the details are in
"The Belle II Physics Book"
E. Kou, P. Urquijo et al.,

https://arxiv.org/abs/1808.10567
https://inspirehep.net/record/1692393/

Summary

- At intensity frontier e^+e^- experiments, variety of recorded reactions and accessibility for various decay modes continue to be exploited.
- For quarkonium(-like) XYZ states
  - Other decay modes and Partner searches need more data.
  - Production of h_c in B decay confirmed.
- Charmed baryons to test “di-quark” picture.
  - J^P determination need more data.
  - Ξ_c absolute branching fractions have been measured.
- Low multiplicity events are also properly taken.
- SuperKEKB/Belle II next beam run starts soon, Oct.