Bottomonium transitions from Belle

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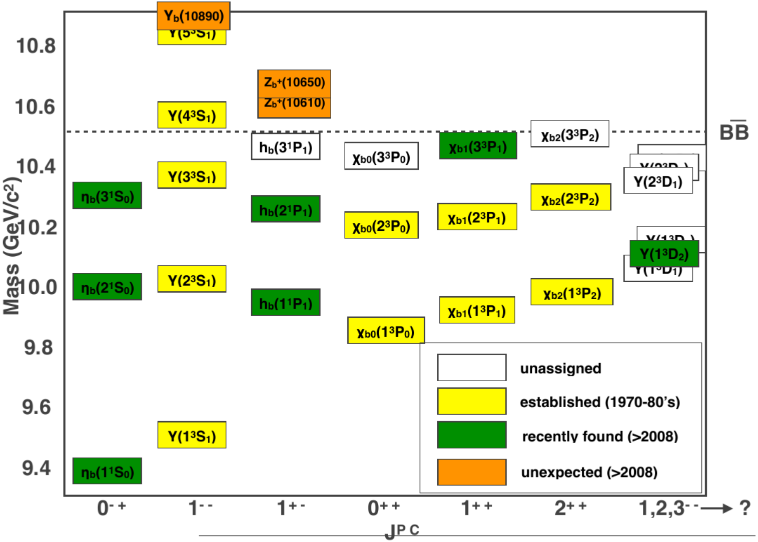
Hadronic transitions

- Last decade has been a fertile era for bottomonium spectroscopy: many missing states and exotica



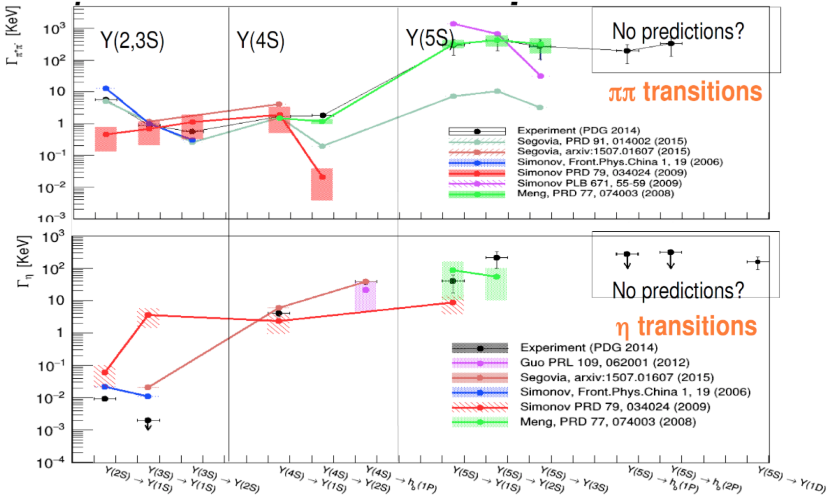
Hadronic transitions

- Important informations on bottomonium given also by the **study of transitions** between its states.
- These transitions can be predicted by effective potential models, rather well established in the case of the dominant radiative transitions
- Instead BRs not well predicted in particular in the 2-body hadronic transitions (η, π^0)
- In quarkonia below open-bottom threshold, should be explained by **QCDME** (analogy with the QED multiple expansion) in terms of momentum of the emitted gluons
- From Heavy Quark Spin Symmetry (HQSS), the spin-flipping η-transtions between bottomonia are suppress by a factor $(\Lambda_{\mathrm{QCD}}/m_b)^2$ comparing to $\pi^+\pi^-$-transitions:

$$\mathcal{R}^{\eta-tran}_{\pi^+\pi^- -tran}(n,m) = \frac{\mathcal{B}(\Upsilon(nS) \to \eta\Upsilon(mS))}{\mathcal{B}(\Upsilon(nS) \to \pi^+\pi^-\Upsilon(mS))} \approx 10^{-3} \tag{1}$$

- Expectations:
  - **suppression of spin-flipping transitions**
    (i.e. mS$\to \eta+$nS wrt mS$\to \pi^+\pi^- +$nS, and mS$\to \pi^+\pi^- +$nP wrt mS$\to \pi^+\pi^-$nS)
  - **further suppression of isospin-violating transitions**
    (i.e. mS$\to \pi^0+$nS wrt others)

The η vs $\pi^+\pi^-$ transitions from $\Upsilon(nS)$: theory vs exp



More hadronic transitions

The partial width in units of keV:

Limited by available channels

$\Upsilon(4S) \to$	
$\Upsilon(1S)\pi^+\pi^-$	1.7 ± 0.2
$\Upsilon(1S)\eta$	4.0 ± 0.8
$\Upsilon(2S)\pi^+\pi^-$	1.8 ± 0.3
$h_b(1P)$	45 ± 7

$\mathcal{B}(\Upsilon(4S) \to \eta\Upsilon(1S)) > \mathcal{B}(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S))$!!!

Limited by available statistics

$\Upsilon(6S) \to$	
$\Upsilon(1S)\pi^+\pi^-$	137 ± 32
$\Upsilon(2S)\pi^+\pi^-$	183 ± 43
$\Upsilon(3S)\pi^+\pi^-$	77 ± 28
$Z_b(10610, 10650)^\pm\pi^\mp$	$1300 - 6600$

$\Upsilon(5S)$ transitions

$\Upsilon(5S) \to$	
$\Upsilon(1S)\pi^+\pi^-$	238 ± 41
$\Upsilon(1S)\eta$	39 ± 11
$\Upsilon(1S)K^+K^-$	33 ± 11
$\Upsilon(2S)\pi^+\pi^-$	428 ± 83
$\Upsilon(2S)\eta$	204 ± 44
$\Upsilon(3S)\pi^+\pi^-$	153 ± 31
$\chi_{b1}(1P)\omega$	84 ± 20
$\chi_{b1}(1P)(\pi^+\pi^-\pi^0)_{\mathrm{non}-\omega}$	28 ± 11
$\chi_{b2}(1P)\omega$	32 ± 15
$\chi_{b2}(1P)(\pi^+\pi^-\pi^0)_{\mathrm{non}-\omega}$	33 ± 20
$\Upsilon_J(1D)\pi^+\pi^-$	~ 60
$\Upsilon_J(1D)\eta$	150 ± 48
$Z_b(10610)^\pm\pi^\mp$	2070 ± 440
$Z_b(10650)^\pm\pi^\mp$	1200 ± 300

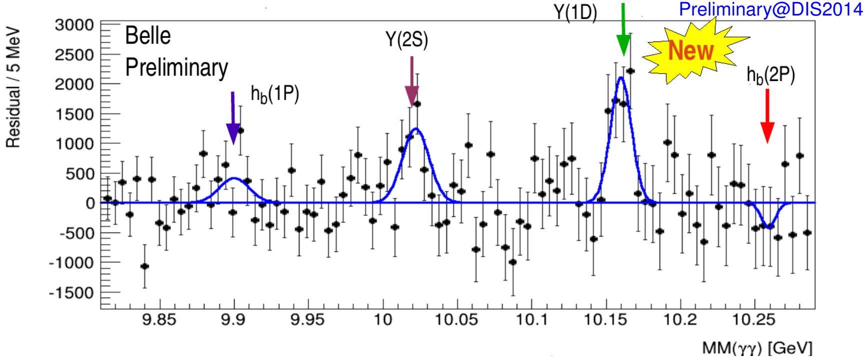
$\pi^+\pi^-$-transition is enhanced by Z_b states.

A full scan (1 MeV$/c^2$ steps, $\int \mathcal{L}dt$) from the $B\bar{B}$ threshold to the maximum availabe energy will give Belle II a unique opportunity to shed light on the hadronization mechanism.

Bondar et al. **Mod. Phys. Lett. A32(2017), 1750025**

η transitions from $\Upsilon(5S)$

- η reconstructed in $\eta \to \gamma\gamma$, look at the missing mass spectrum, after combinatorial background subtraction



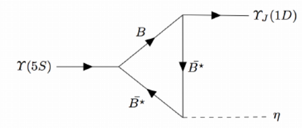
- In particular, $\mathcal{B}(\Upsilon(5S) \to \eta\Upsilon(1D))$ in compatible with the prediction (via triangular meson loops)

  Wang et al., PRD94, 094039(2016)

- Observation of $\Upsilon(5S) \to \eta\Upsilon(1D)$

  $\mathcal{B}(\Upsilon(5S) \to \eta\Upsilon(1D)) = (2.8 \pm 0.7 \pm 0.4) \times 10^{-3}$

- Now finalizing the result on the branching fractions



Investigations on the $\Upsilon(1D)$ triplet

- Not resolving the $\Upsilon(1D)$ triplet (resolution $\sim$ mass splitting)
- Signal in $M^2_{\rm miss}(\gamma\gamma)$: 3 Crystal Ball functions, with free relative fractions f_1, f_2 that are precisely predicted in
  Wang et al., PRD94, 094039(2016)
- m_2 fixed to world average, ΔM_{ij} fixed to different values between 3 and 15 MeV$/c^2$ (reasonable according to calculations and observations)
  $\Delta M_{12} = m_2 - m_1, \ \Delta M_{23} = m_3 - m_2$

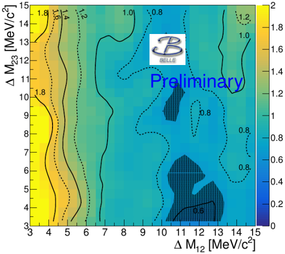
$$\mathcal{F}_{1D} = \frac{N_{1D}}{1+f_1+f_2}\cdot[\mathcal{C}_2(m_2)+f_1\mathcal{C}_1(m_1)+f_3\mathcal{C}_3(m_3)], \quad (2)$$

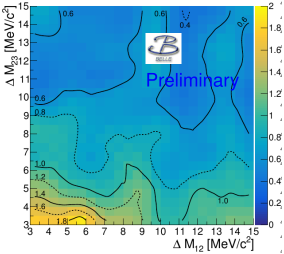
with

$$f_1 = \frac{\mathcal{B}[\Upsilon(5S)\to\eta\Upsilon(1D_1)]}{\mathcal{B}[\Upsilon(5S)\to\eta\Upsilon(1D)_2]}(=0.68)_{theory} \quad (3)$$

$$f_3 = \frac{\Upsilon(5S)\to\eta\Upsilon(1D_3)}{\mathcal{B}[\Upsilon(5S)\to\eta\Upsilon(1D_2)]}(=0.13)_{theory} \quad (4)$$

- Values returned by the fit in any of these configurations are compatible with 0
- 90% C.L. ULs on f_1, f_3 as a function of ΔM_{12} and ΔM_{23}
- f_1 favored value excluded in 3 regions where
  $10 < \Delta M_{12} < 13$ MeV$/c^2$



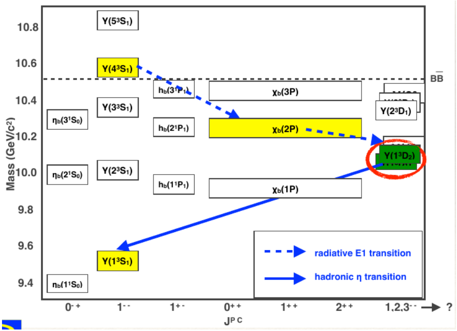


To be submitted to EPJ-C

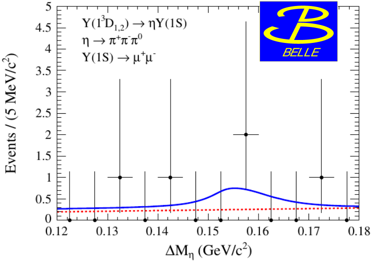
$\Upsilon(1D) \to \eta\Upsilon(1S)$

- $\eta \to \pi^+\pi^-\pi^0$ and $\pi^0 \to \gamma\gamma$, $\Upsilon(1S) \to \mu^+\mu^-$
- Predicted to be enhanced with respect to the transition $\Upsilon(1D) \to \pi^+\pi^-\Upsilon(1S)$ by the axial anomaly in QCD

Voloshin PLB562, 68(2003)



Belle: PRD96,052005(2017)



- $\Upsilon(1D)$ could be produced via double-radiative transitions from $\Upsilon(4S)$ through $\chi_{bJ}(2P)$ states
- $\mathcal{B}(\Upsilon(4S) \to \gamma\gamma\Upsilon(1D)) \times \mathcal{B}(\Upsilon(1D) \to \eta\Upsilon(1S)) < 2.3 \times 10^{-5}$ at 90% C.L.

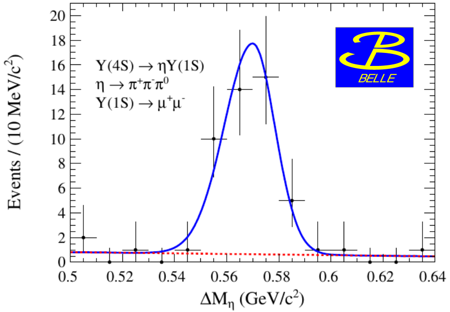
$\Upsilon(4S) \to \eta\Upsilon(1S)$

Belle: PRD96,052005(2017)

- With the same approach and a similar event selection.
- Fit to $\Delta M_\eta = M_{\pi^+\pi^-\gamma\gamma\mu^+\mu^-} - M_{\mu^+\mu^-} - M_{\pi^+\pi^-\gamma\gamma}$
- Confirmation of the enhancement with respect to dipion transition

$$\mathcal{R} = \frac{\mathcal{B}(\Upsilon(4S) \to \eta\Upsilon(1S))}{\mathcal{B}(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S))} \quad (5)$$

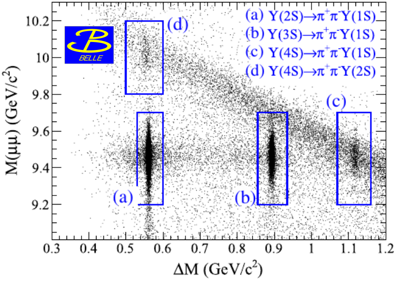
- Confirm the enhancement of $\Upsilon(4S) \to \eta\Upsilon(1S)$ via spin-flip transition.



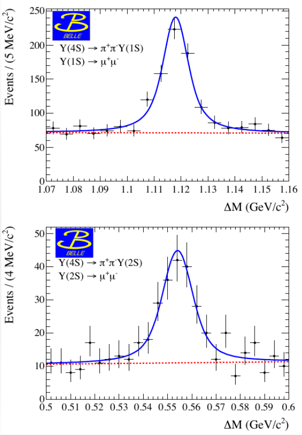
Measurement	Result	PDG value
$\mathcal{B}(\Upsilon(4S) \to \eta\Upsilon(1S))$	$(1.70 \pm 0.23 \pm 0.08) \times 10^{-4}$	$(1.96 \pm 0.28) \times 10^{-4}$
$\mathcal{R}$	$2.07 \pm 0.30 \pm 0.11$	2.41 ± 0.42

Dipion transitions

- Measurement of dipion transitions also provided
- Fit to $\Delta M = M_{\pi^+\pi^-\mu^+\mu^-} - M_{\mu^+\mu^-}$



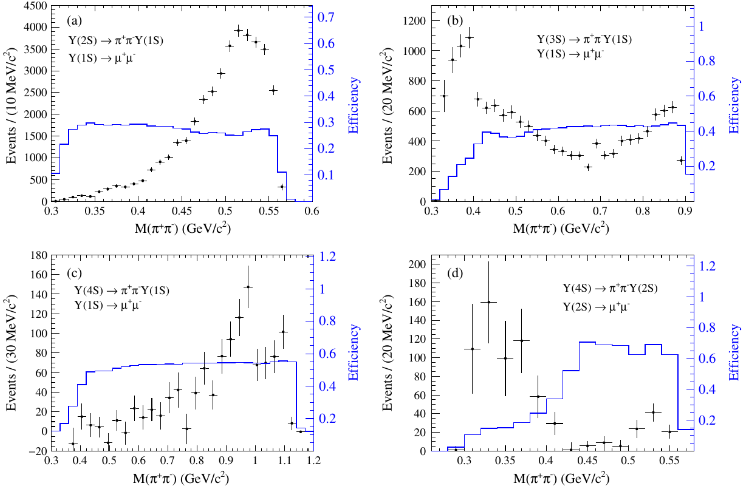
Belle: PRD96, 052005(2017)



Measurement	Result	PDG value
$\mathcal{B}(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S))$	$(8.2 \pm 0.5 \pm 0.4) \times 10^{-5}$	$(8.1 \pm 0.6) \times 10^{-5}$
$\mathcal{B}(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(2S))$	$(7.9 \pm 1.0 \pm 0.4) \times 10^{-5}$	$(8.6 \pm 1.3) \times 10^{-5}$
$\sigma_{\rm ISR}(\Upsilon(2S))$	$(17.36 \pm 0.19 \pm 0.69)$ pb	(17.1 ± 0.3) pb
$\sigma_{\rm ISR}(\Upsilon(3S))$	$(28.9 \pm 0.5 \pm 1.3)$ pb	(28.6 ± 0.5) pb

The ISR cross section $\sigma_{\rm ISR}$ is based on $\mathcal{B}^{\rm PDG}(\Upsilon(2S,3S) \to \pi^+\pi^-\Upsilon(1S))$

$M_{\pi^+\pi^-}$ in the $\pi^+\pi^-$-transitions

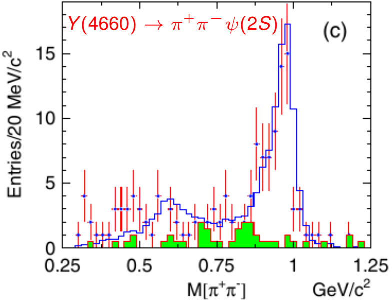


- Double peaked structure in $\Upsilon(4S) \to \pi^+\pi^-\Upsilon(2S)$ and $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$, enhancement near $M_{\pi^+\pi^-}$ threshold.
- $f_0(980)$ in $\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S)$???

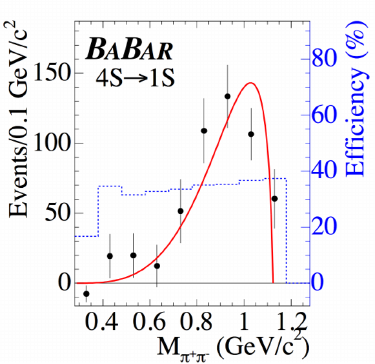
Belle: PRD96,052005(2017)

$f_0(980)$ in $\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S)$

- Behaviour not seen in previous data at the $\Upsilon(4S)$.
- However, $f_0(980)$ signals were observed in $Y(4260) \to \pi^+\pi^- J/\psi$ and $Y(4660) \to \pi^+\pi^-\psi(2S)$.



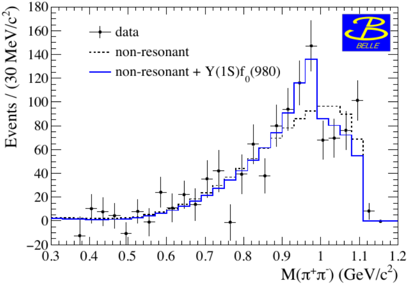
Belle: PRD91,112007(2015)



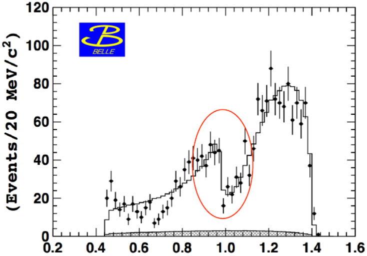
BaBar: PRL96, 232001(2006)

$f_0(980)$ in $\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S)$

- Major interest comes from $\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S)$ dipion invariant mass.
- very similar to what observed at the $\Upsilon(5S)$:



Belle: PRD96,052005(2017)

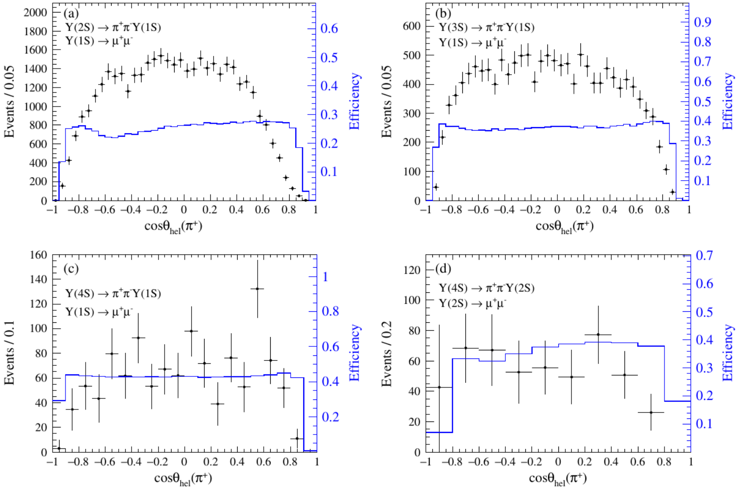


Belle: PRL108, 122001(2012)

- Recently predicted by theory: Chen et al., PRD95, 034022(2017)
- An amplitude model including a resonant $f_0(980)$ contribution is preferred by data (2.8σ)
- Addition of $f_2(1270)$ does not improve the description

$\cos\theta_{hel}$ from $\pi^+\pi^-$-transitions of $\Upsilon(4S)$

$\cos\theta_{hel}$: helicity angle of the π^+ candidate.



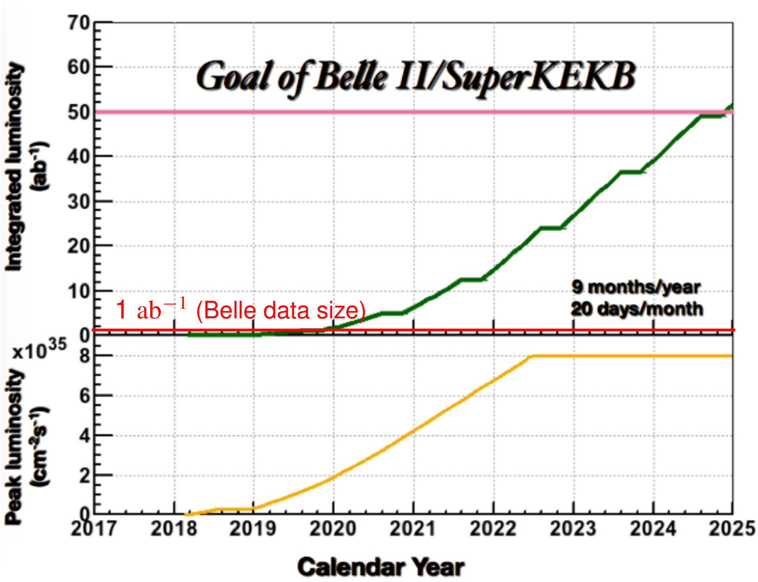
Belle: PRD96,052005(2017)

Questions

- $\Upsilon(1D)$ triplet
- $\mathcal{R} = \frac{\Upsilon(5S)\to\eta\Upsilon(nS)}{\Upsilon(5S)\to\pi^+\pi^-\Upsilon(nS)_{\mathrm{non-Z_b}}}$
- $\Upsilon(1D) \to \eta\Upsilon(1S)$
- $M_{\pi^+\pi^-}$ in $\Upsilon(4S) \to \pi^+\pi^-\Upsilon(2S)$
- ...

The precision of the measurements should be increased with a larger data sample!
$\to$ Belle II

Profile of SuperKEKB luminosity and Belle II data sample



For more details about Belle II status, see Dr. Hua YE's talk on Friday.

Summary

- Hadronic transitions are a key ingredient in understanding bottomonium and QCD description of matter
- Belle has recently given a solid contribution, with many achievements in the topic:
  - Observation of $\Upsilon(5S) \to \eta\Upsilon(1D)$
  - Confirmation of the enhancement of $\Upsilon(4S) \to \eta\Upsilon(1S)$ with respect to $\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S)$
  - Measurement of/search for other η transitions
  - Precise measurement of $\Upsilon(4S)$ dipion transitions and first indication for a resonant contribution in $\Upsilon(4S) \to f_0(980)\Upsilon(1S)$
- And many more results are likely to come in the future with Belle2.

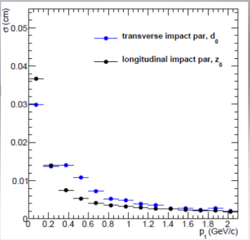
Thank you!

Backup

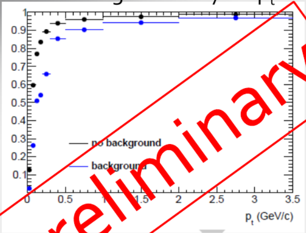
Expected performance of Belle II

Belle II works similar to or better than Belle despite ~20 times higher beam background

IP resolution

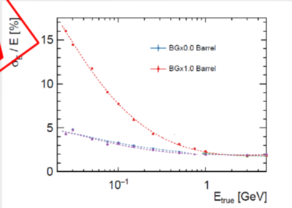


Tracking efficiency vs. p_t

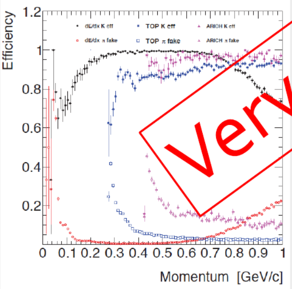


Energy resolution

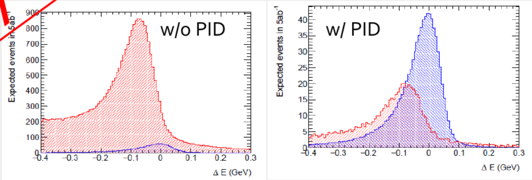
Better w/ no background, worse w/ background



K/π PID

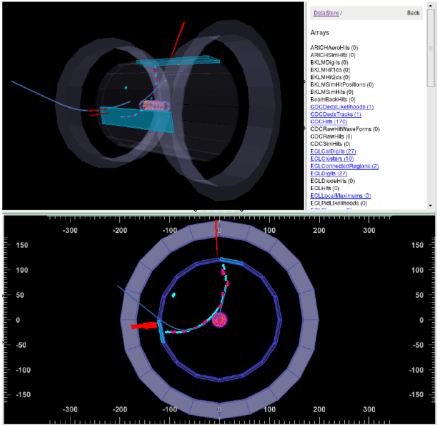


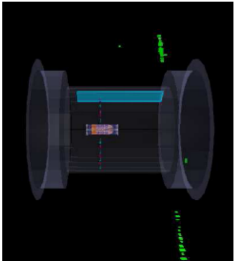
$B^0 \to \rho^0\gamma$ vs. $K^{*0}\gamma$

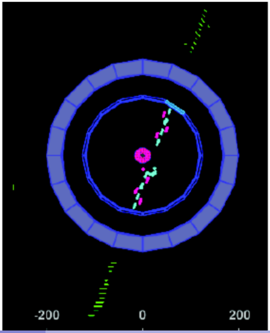


From Prof. Ushiroda's talk at LP2017.

Cosmic ray run (June, 2017)



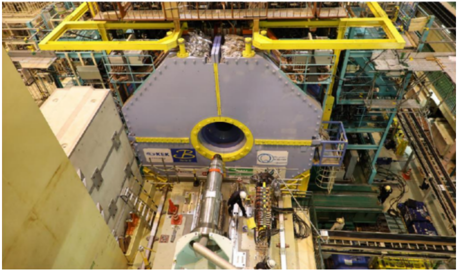




- Systems included: CDC, TOP, ECL, KLM
- Magnetic field: 1.5T

Phase II

Belle II roll in, 11/4/2017



Commissioning of accelerator and sub-detectors

- Start beginning of 2018, duration about 5 months.
- Beam collisions with focusing magnets (QCS).
- Target luminosity is 10^{34} $cm^{-2}s^{-1}$, which is KEKB level.
- 20-40 fb^{-1} data for physics analyses.
- W/o vertex detector dependent measurements.

What can be done with Phase 2 data?

- Background studies
- Detector and trigger performance studies
- Simulation validation
- Exercising of calibration and alignment procedures
- Reconstruction algorithm tuning
- Physics measurements

The first collision is expected in Feb. 2018, about 8 years after KEKB being shut down.