Belle II experiment

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on behalf of the Belle II collaboration

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of the Nucleon,
Kyoto, Japan
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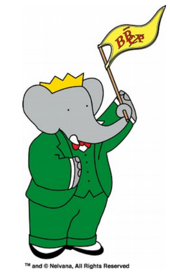
Outline

- From B to Super-B
- Accelerator
- Detector
- Physics
- Getting started

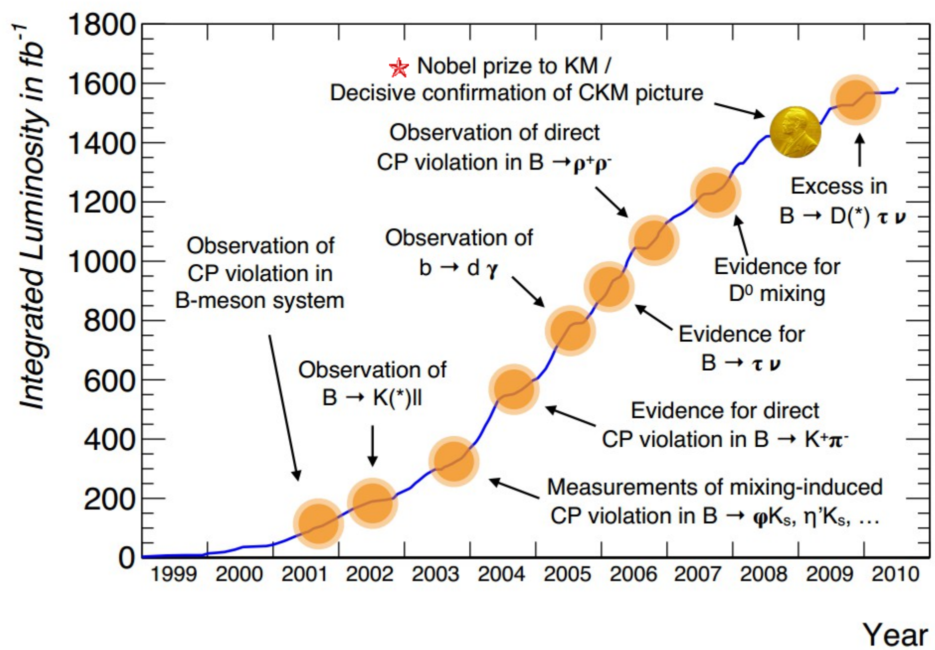
Kobayashi and Maskawa both worked
in Kyoto university when writing
their famous paper.

B-factories

- BaBar: PEP-II e^+e^- collider, SLAC, USA, 1999–2008.
- Belle: KEKB e^+e^- collider, KEK, Tsukuba, Japan, 1999–2010.

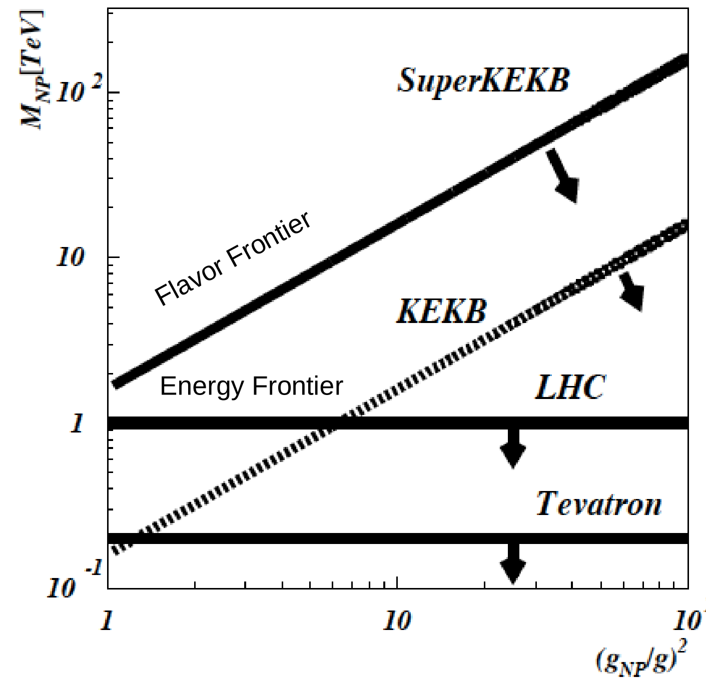


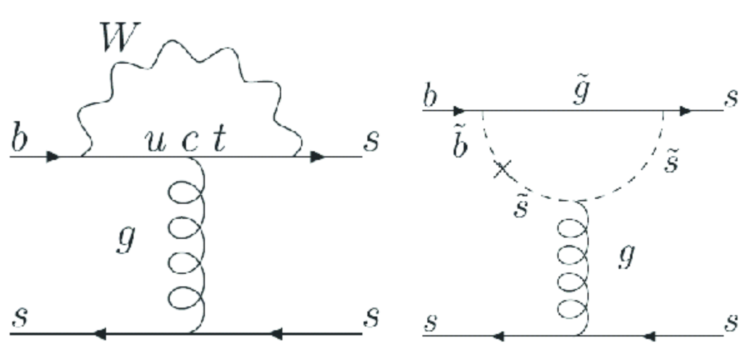
- Combined BaBar and Belle luminosity is ~1.5 ab^{-1} ($1.25*10^9$ $B\overline{B}$ pairs).
- Main focus: *CP*-violation (published in 2001)
  - Also *B*-decays, CKM parameters, quarkonium(-like) states, charm- and τ-physics etc. (see talks by Miyabayashi-san, Kato-san and Y.J.Kwon)
  - 500+ publications from BaBar, 400+ from Belle.
  - But still no observation of the New physics (NP)!



Looking for New physics

- Energy Frontier (direct): Production of new particles from collisions. Limited by beam energy (CMS, ATLAS).
- Flavor Frontier (indirect): Virtual production can probe scales to ~10 TeV or more, but effects are tiny (LHCb, Belle II).
- Virtual NP particles: asymmetries, rare decays, forbidden decays.
- No NP yet – upgrade Belle and KEKB.





Belle II and LHCb

Can Belle II compete with LHCb? Yes.

- Full solid angle detector and clean event environment and well defined initial state of e^+e^- experiment:
  - Missing energy modes are a strength of Belle II and the *B*-factories; powerful constraints on the charged Higgs;
  - Modes with neutrals (although not impossible at LHCb) are another strength of Belle II;
  - Belle II does inclusive modes ($B \to X_S \gamma$, $B \to X_S \ell^+ \ell^-$);
  - Belle II but not LHCb does modes with K_S mesons including a significant fraction of the $b \to s$ penguin modes.

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Quest for high luminosity

- There are two ways to increase luminosity:
  - Increase beam currents
  - Decrease beam size
- SuperKEKB uses ~2x increase in currents and “nano-beams”
- 40x luminosity

Lorentz factor

Beam current

Beam-Beam parameter

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

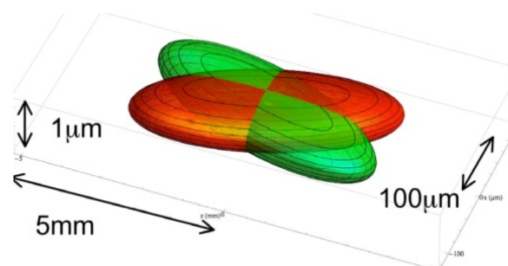
Geometrical reduction factors (crossing angle, hourglass effect)

Beam aspect ratio at IP

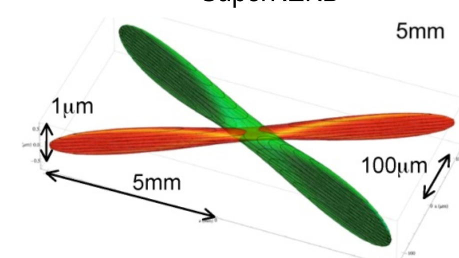
Vertical beta function at IP

Minimum value is limited by hourglass effect

KEKB



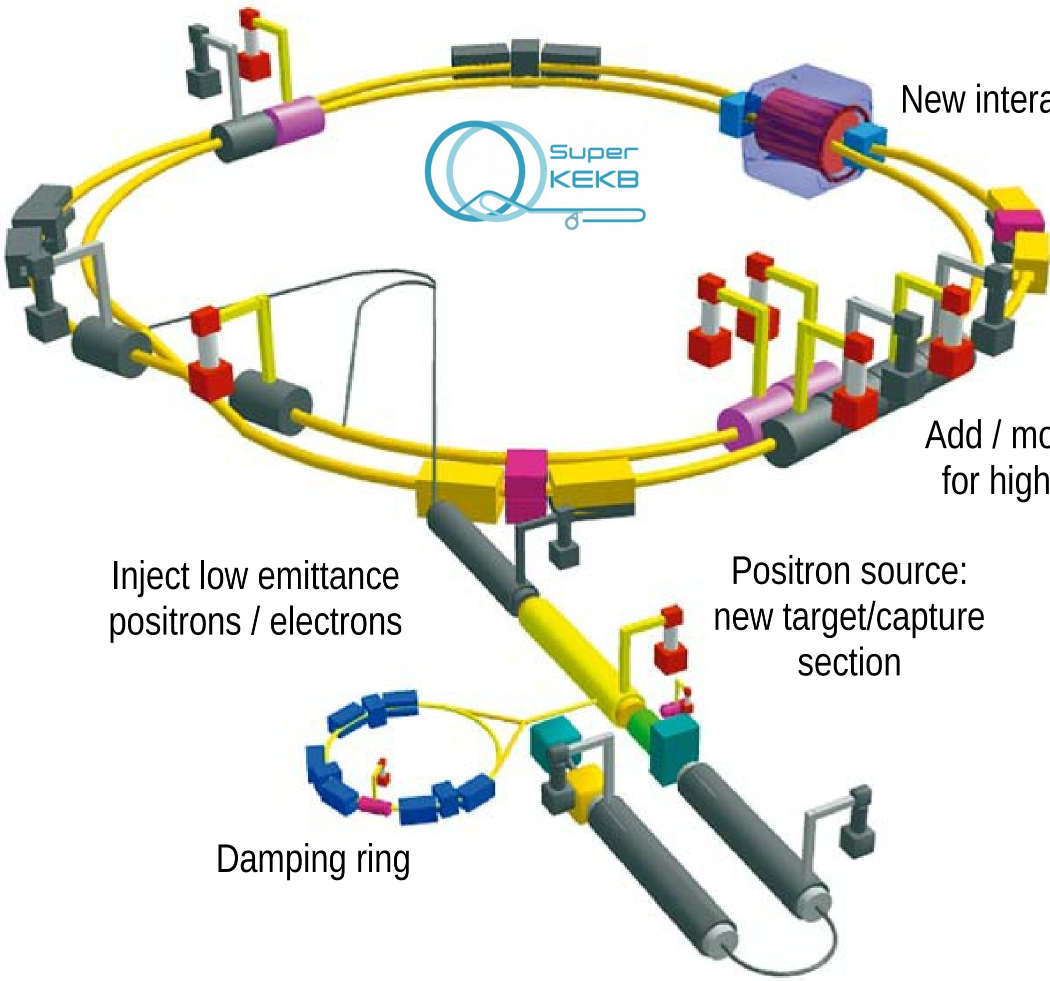
SuperKEKB



	E(GEV) HER/LER	β^*_y(mm) HER/LER	β^*_x(mm) HER/LER	2φ (mrad)	I(A) HER/LER	L ($cm^{-2}s^{-1}$)
KEKB	3.5/8.0	5.9/5.9	120/120	22	1.6/1.2	2.1×10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	83	3.6/2.6	80×10^{34}

SuperKEKB accelerator

A lot of modifications all around the accelerator.



New interaction region

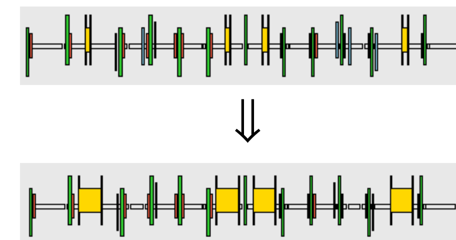
Add / modify RF systems for higher beam current

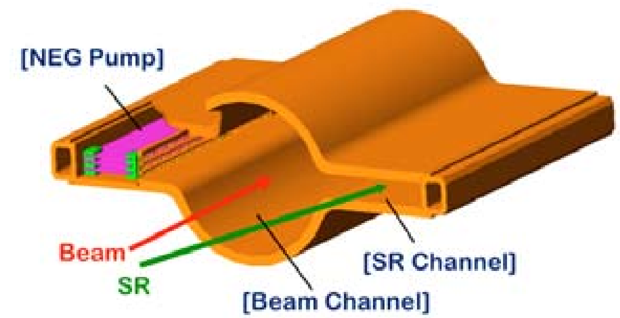
Inject low emittance positrons / electrons

Positron source: new target/capture section

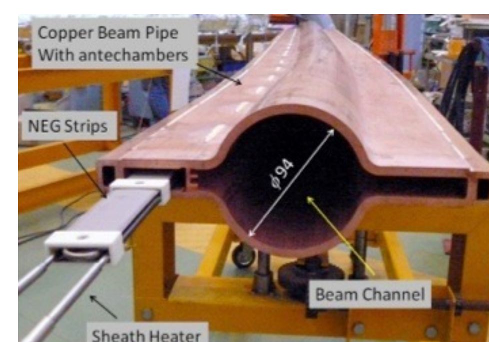
Damping ring

Replace short dipoles with longer ones (LER)





New TiN-coated beam pipe with antechambers



SuperKEKB status

- LER: Approximately 93% of beam pipes in length are renewed.
- HER: Approximately 82% are reused.
- Sub systems, such as cooling water system, compressed air system, were basically reutilized, with necessary upgrades.
- Control system was also reused, but the antique components are updated.

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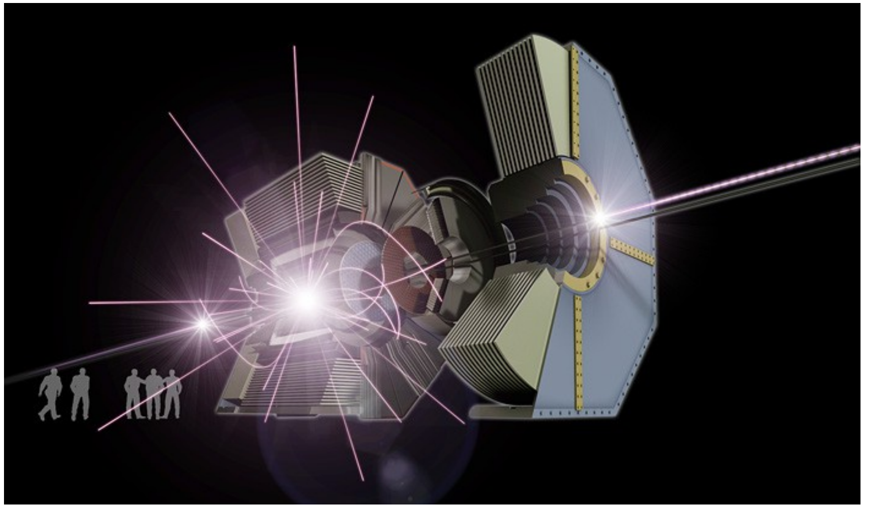
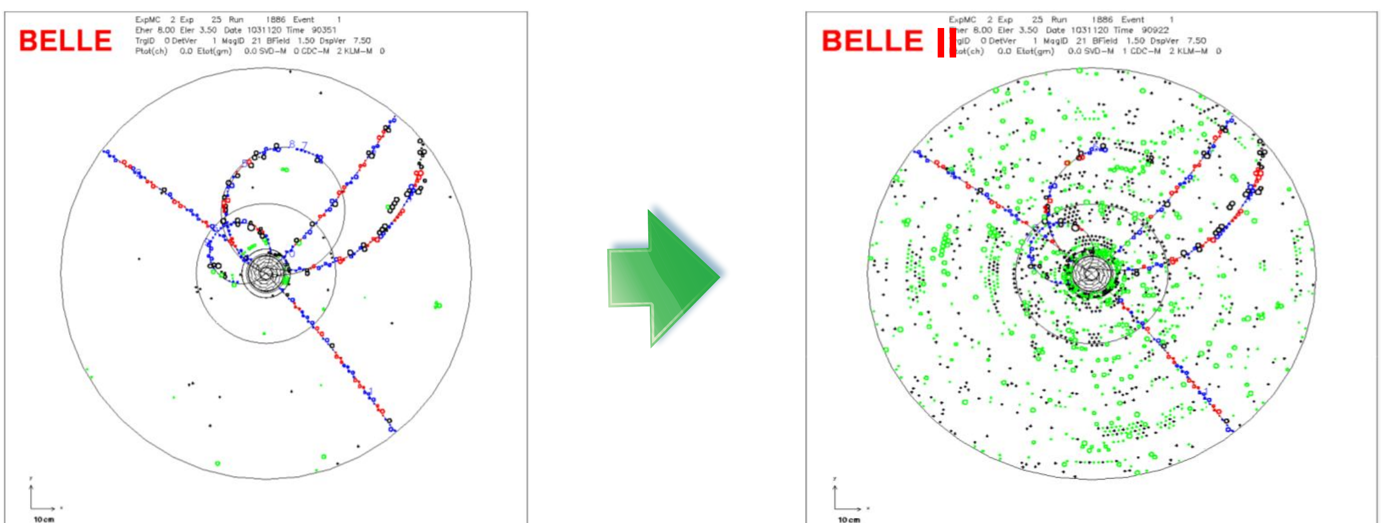


Requirements for detector

- Higher beam-related and QED backgrounds;
- L1 trigger rate 30kHz vs 500Hz for Belle:
  - Stability to high background; fast readout;
  - Better performance (vertex resolution, tracking, PID, esp. improve K/π separation);
  - Less material in front of ECL (for better performance).

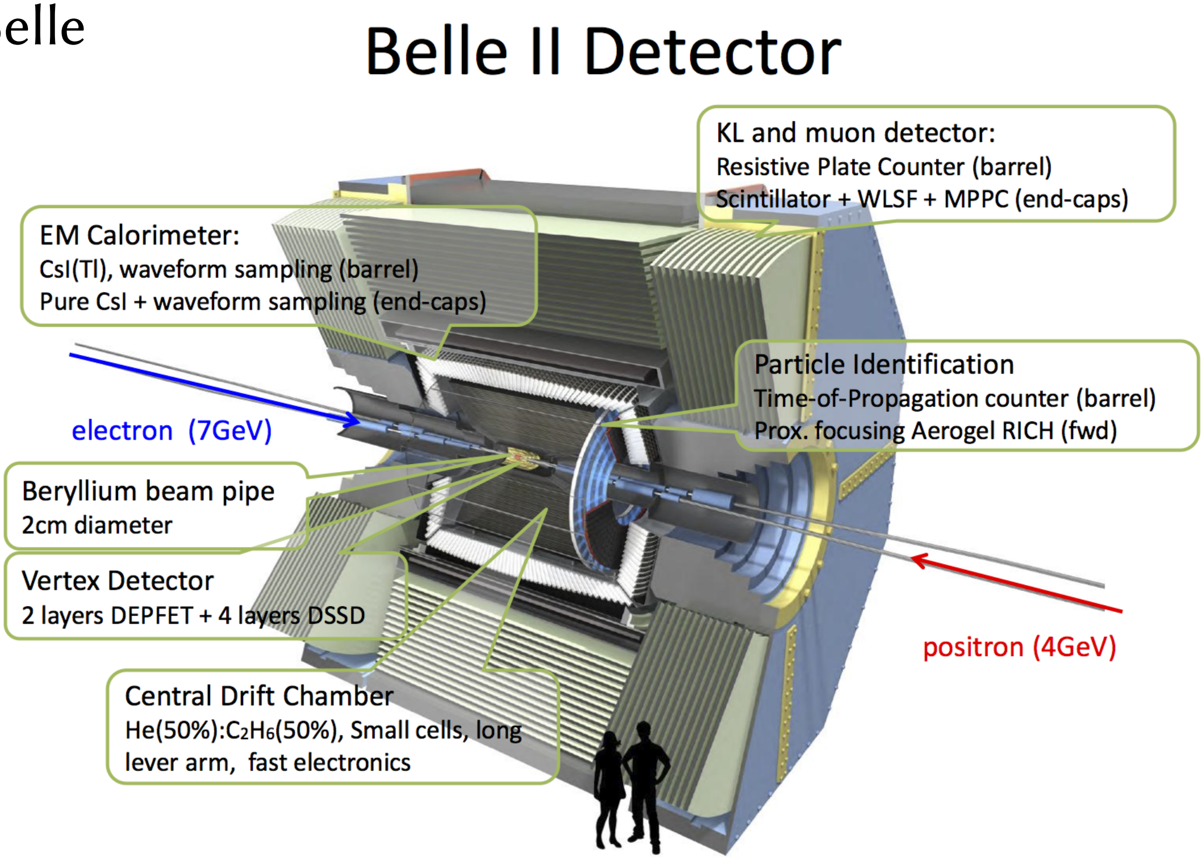


Not a simulation,
just a naive illustration

Belle II detector

Belle II is built on basis of Belle

- Main structure and magnet are reused;
- ECL and KLM are mostly reused;
- Vertex detector, drift chamber, PID, partially KLM are upgraded;
- All electronics are replaced.

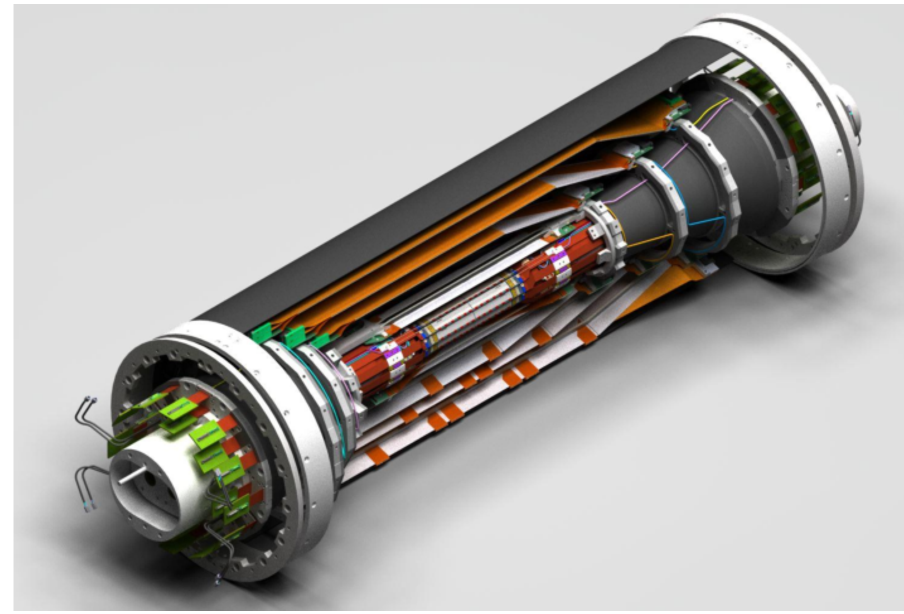


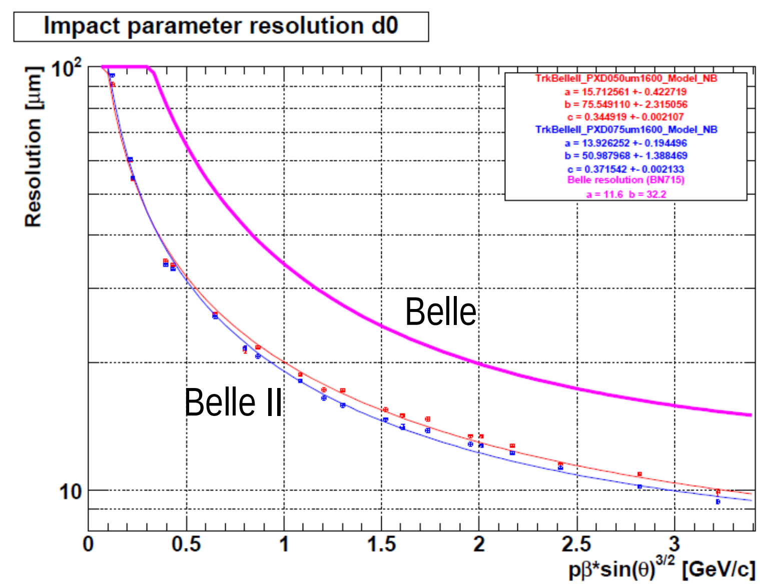
Detector improvements

- Smaller beam pipe radius allows to place the innermost PXD layer closer to the Interaction point (r = 1.4cm)
  - Significantly improves the vertex resolution along z direction.
- Pixel part of the vertex detector, larger SVD and CDC
  - Increases K_S efficiency, improve vertex and timing resolution, better flavor tagging.
- PID: TOP and ARICH
  - Better K/π separation covering the whole range momentum.
- ECL and KLM
  - Improvements in ECL and KLM to compensate for a larger beam background.
- Improved hermeticity.
- Improved trigger and DAQ.

VXD=PXD+SVD

- Layers 1-2: Pixel detectors (PXD)
  - DEPFET pixels
  - 50µm thick
  - r=14mm and 22mm (vs 20mm minimum for Belle)
- Layers 3-6: Strip detectors (SVD)
  - 4 layers of DSSD detectors, well tested at Belle
  - Largest radius 135mm (vs 88mm for Belle)
- Dedicated PXD preDAQ for data rate reduction from ~8M channels (matching against tracks from SVD+CDC)

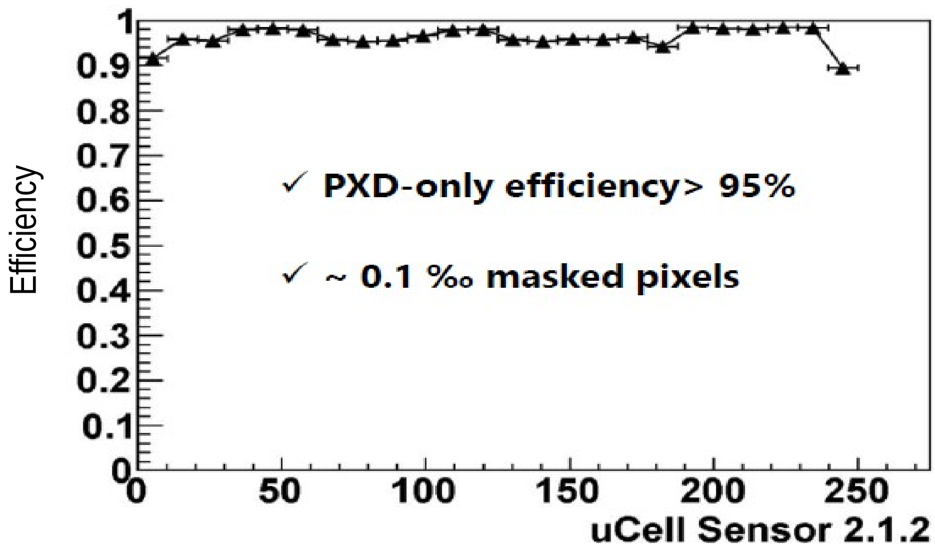




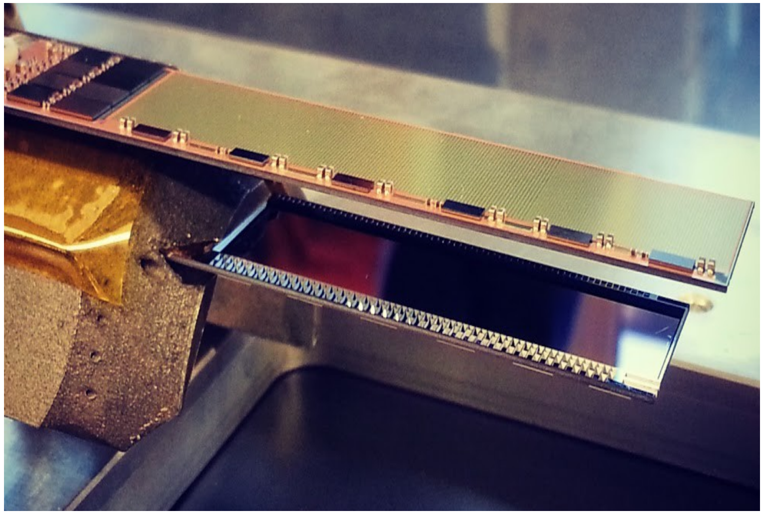
VXD beam test in DESY

- Combined beam test of PXD and SVD
- Also test of DAQ, software, DB, CO_2 cooling, slow control, environmental sensors
- e^- beam, momentum 2-5GeV
- B-field in PCMag: 0-1T
- Total of ~340 runs in 4 weeks

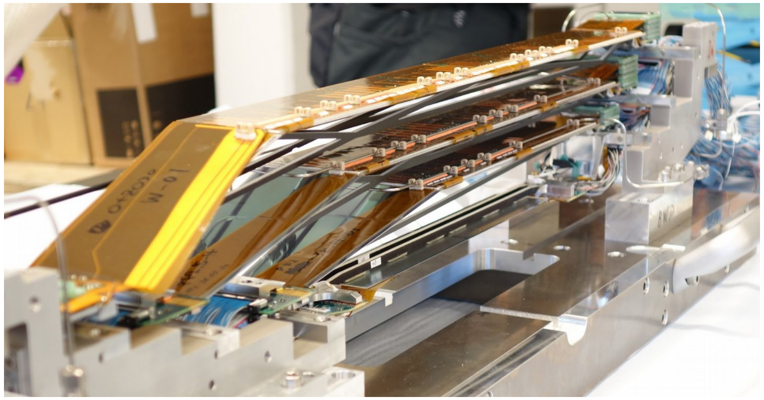
Overall the campaign was a great success for the VXD!



2 PXD half-ladders (L1-L2)



4 SVD ladders (L3-L6)

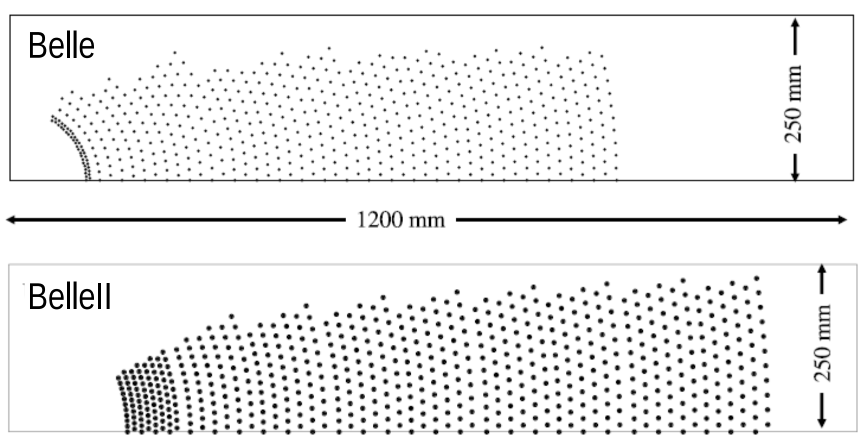


CDC

- Belle II Central Drift Chamber (CDC) is larger than that of Belle.
- Smaller drift cells with sense wires and more layers allow better charged track reconstruction and dE/dx measurement compared to Belle.
- Faster readout electronics

	Belle	Belle II
Radius of inner boundary (mm)	88	168
Radius of outer boundary (mm)	863	1111
Number of layers	50	56
Number of sense wires	8400	14336
Gas	HeC_2H_6	HeC_2H_6
Diameter of a sense wire (μm)	30	30

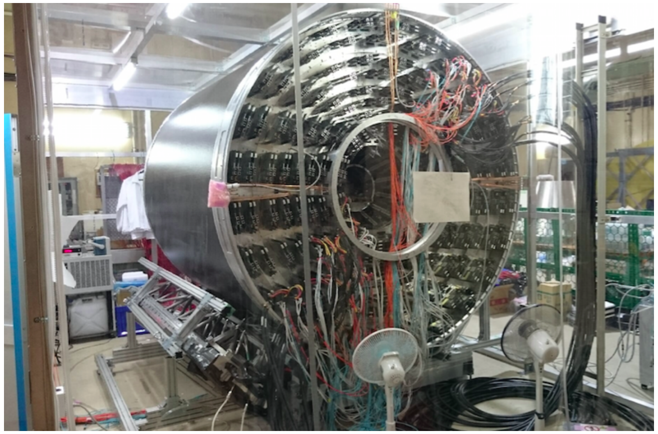
Wire Configuration

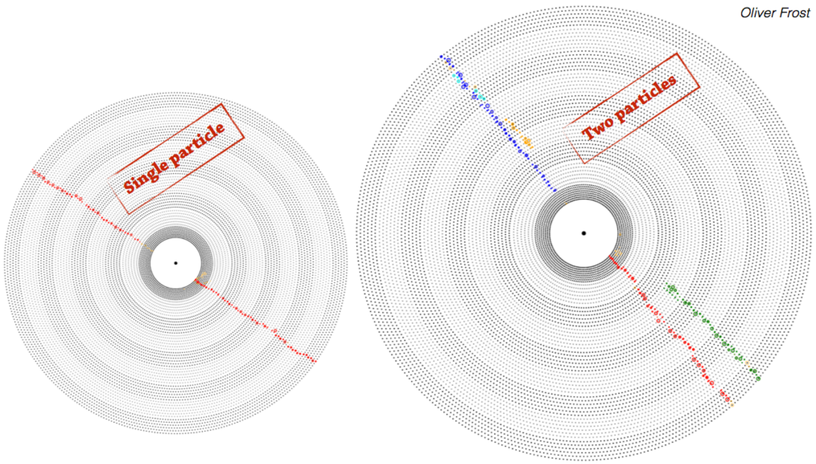


CDC status

- CDC construction is complete, CDC moved to the experimental hall next to Belle II detector.
- Cosmic ray test is ongoing, next is DAQ integration.
- The new CDC track finder is able to identify tracks on cosmic rays events with an efficiency close to 100% (i.e. each triggered event contains at least one track).
- A few interesting events with more than one particles are also correctly reconstructed. All the CDC hits are represented.
- The hits belonging to the same track are in same color.

CDC in the experimental hall



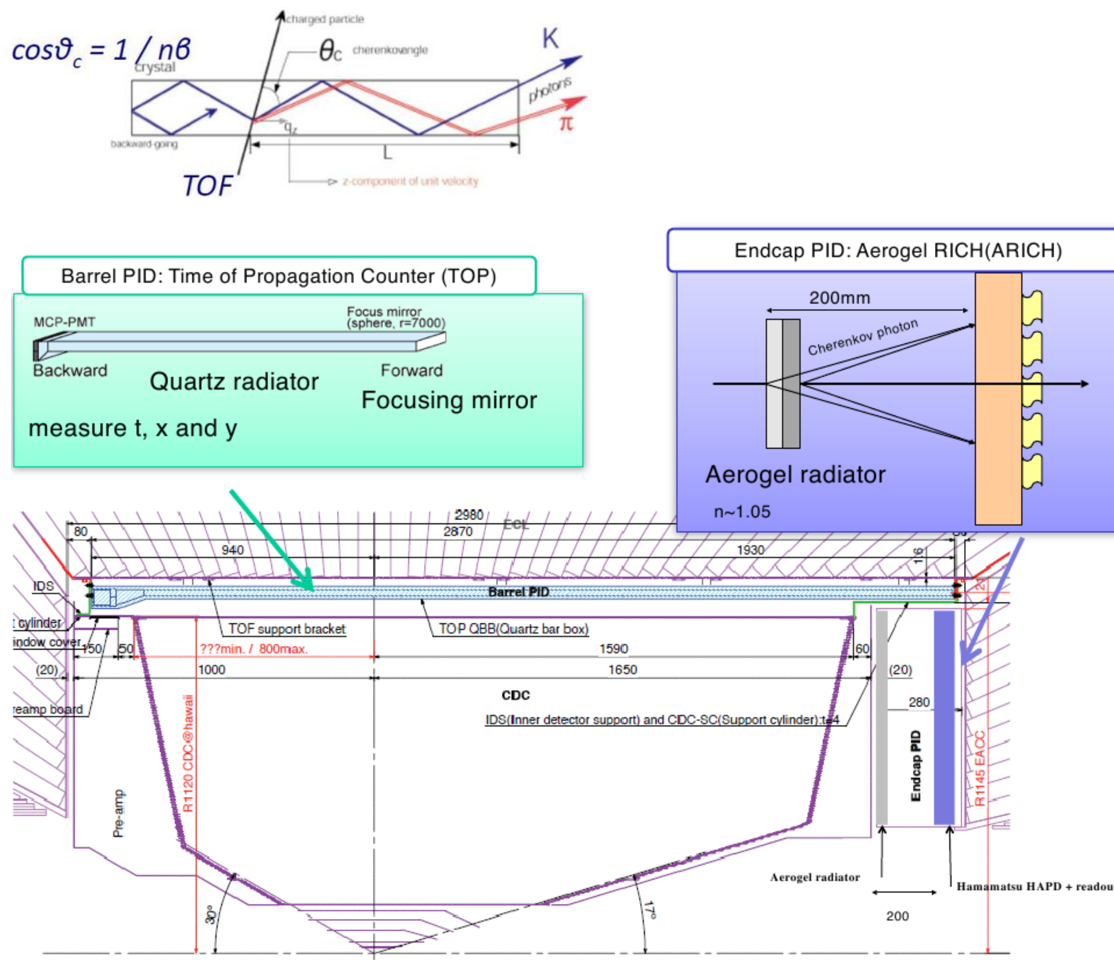


PID: TOP+ARICH

Two Cherenkov detectors for particle identification (mainly K and π)

- Barrel: Time of Propagation (TOP)
- Endcap: Aerogel Ring-Imaging Cherenkov (ARICH)

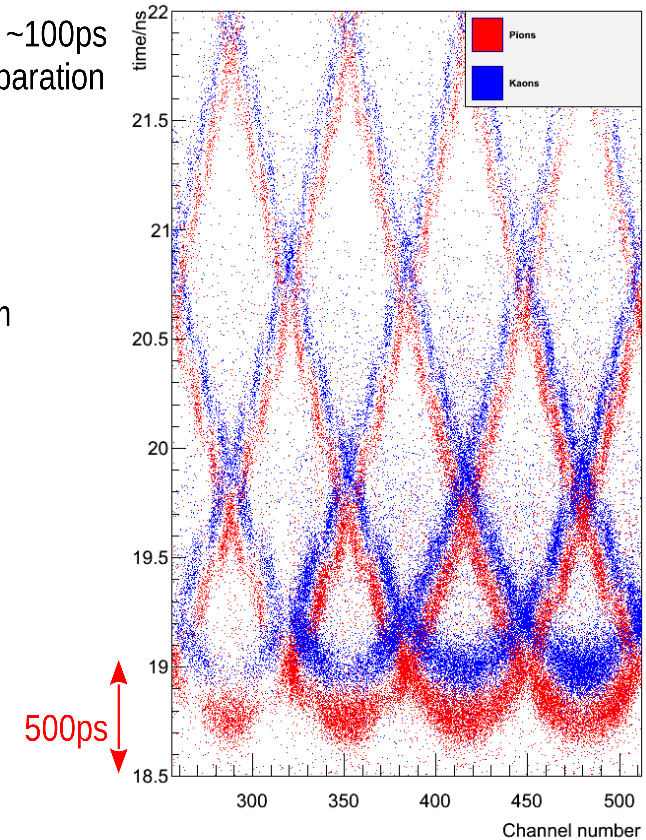
Much thinner than PID in Belle, less material in front of calorimeter.



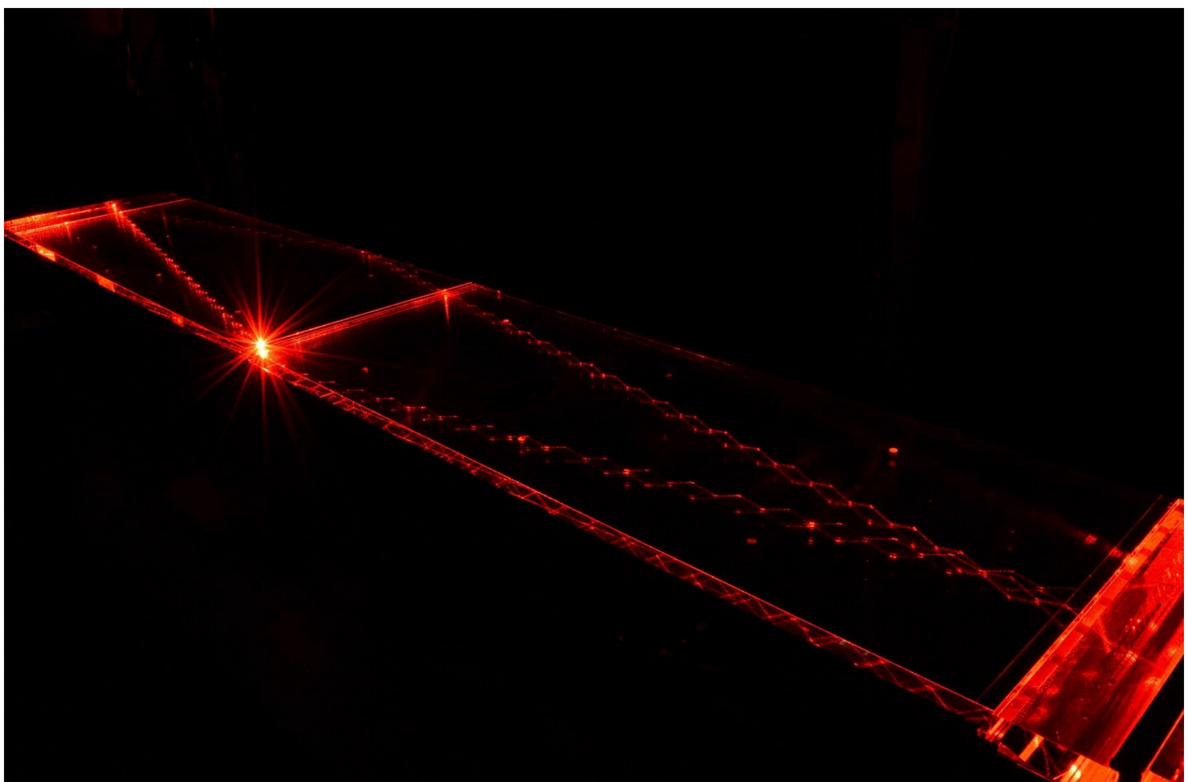
TOP status

- All TOP modules installed in May.
- Comissioning with cosmic rays and DAQ tests are ongoing.

TOP: at 3GeV timing ~100ps is needed for K/π separation



Full internal reflection of laser beam inside TOP quartz module

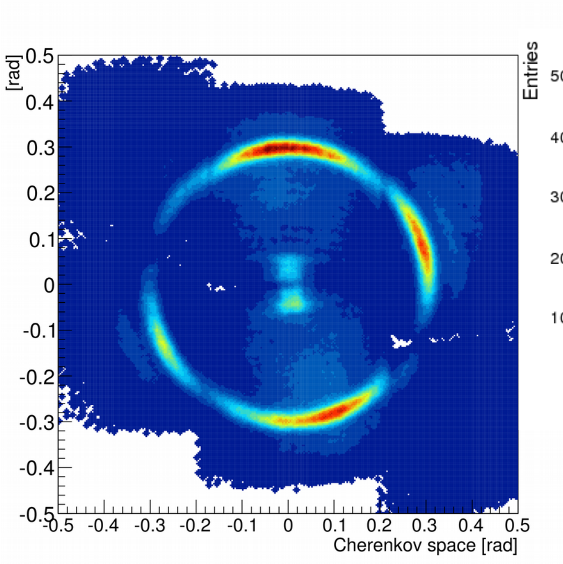


	Belle	Belle II (sim)
K eff	88%	94%
π fake rate	9%	4%

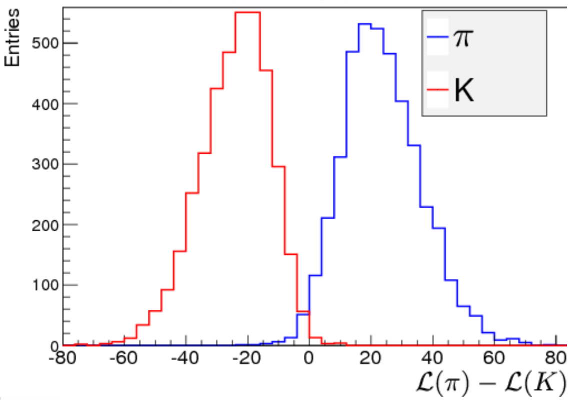
ARICH status

- K/π separation at 5σ
- Radiator: Aerogel n=1.045-1.055
- Transmission length >40mm
- Photon detection: Hybrid Avalanche Photo Detectors (HAPD)
- 420 units, 144 channels each
  Gain = $7*10^5$, QE > 28%
- Production/assembly state, installation schedule under discussion.

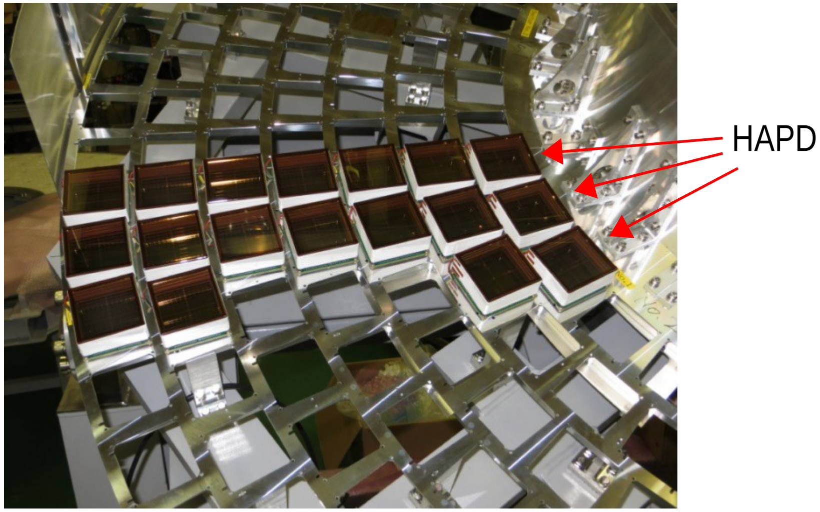
ARICH testbeam



ARICH simulation:
likelihood of K/π ID

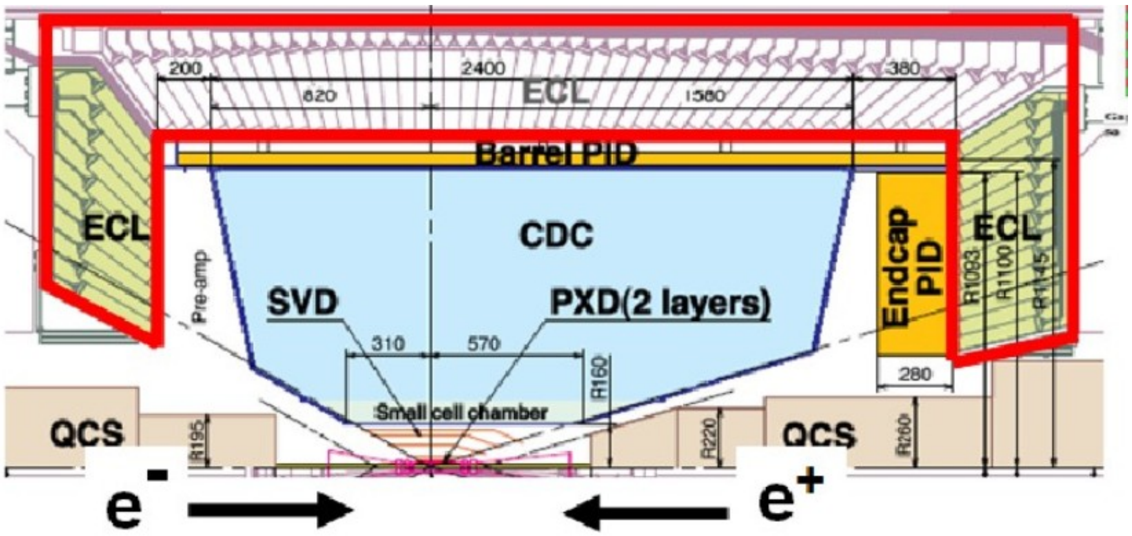


Partially assembled ARICH ring



ECL

- Belle II electromagnetic calorimeter (ECL) reuses Belle CsI (TI) crystals and installs improved readout electronics with a waveform sampling to compensate for higher beam-related background.
- R&D to replace in future endcap crystals with pure CsI with faster light emission and smaller light yield.
- ECL readout electronics was installed and DAQ integration tests are going on.

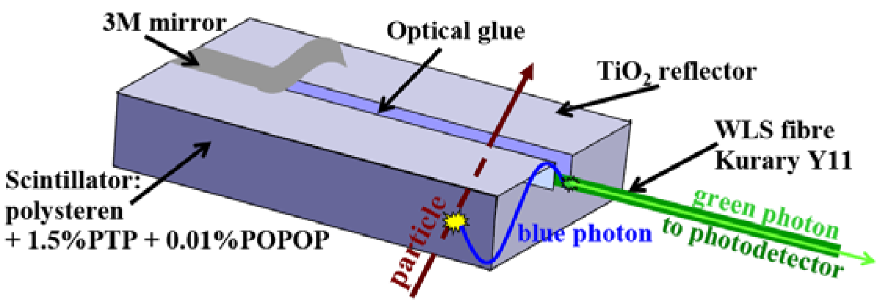


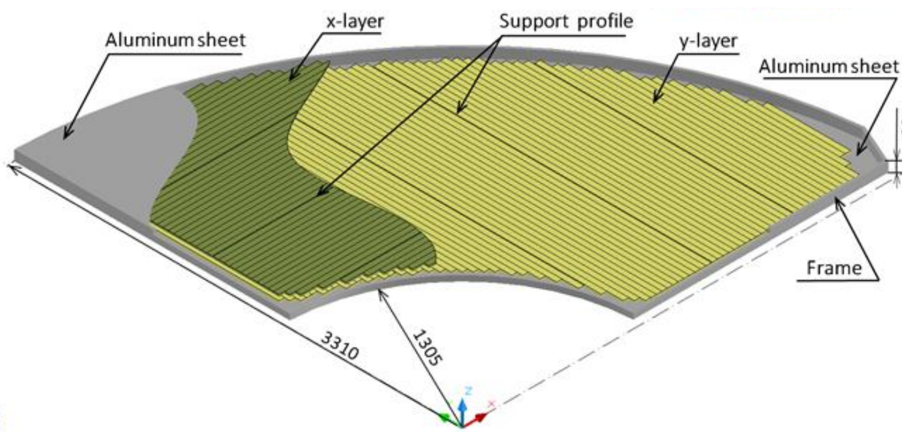
KLM

The outermost detector for $K_L - \mu$ detection

- Endcap muon detecton based on RPC will not work at design luminosity and higher background. The inner barrel layers efficiencies would also be small.
- Replace RPCs in the endcaps and two inner barrel layers with scintillator strips with WLS fibers and MPPC detectors.
- KLM installation was completed, ~⅛ of the readout electronics were installed and DAQ integration tests are going on.

Installation of KLM





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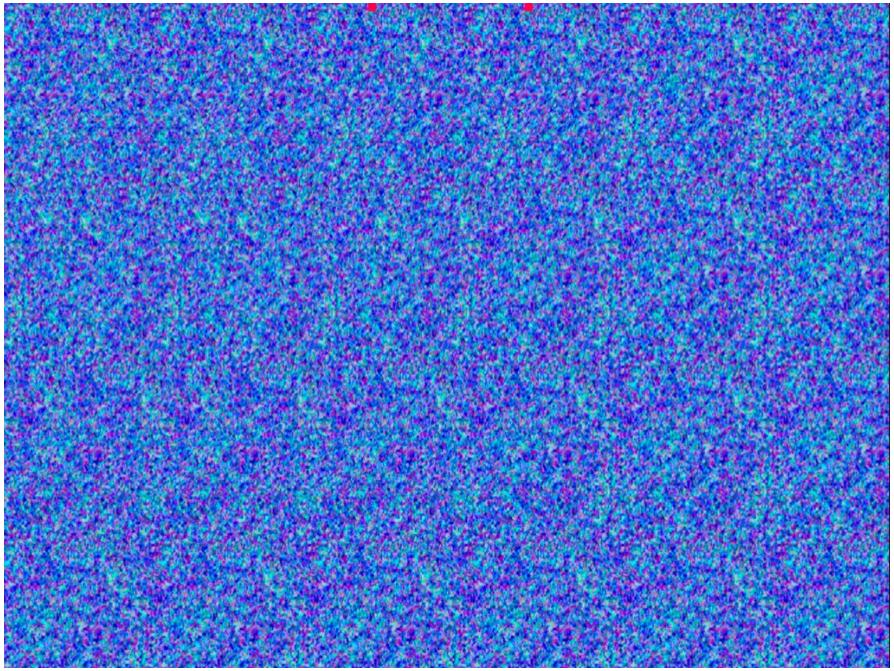
Credit: Nature Methods, Le Maho, et. al.

Physics at Belle II

Since NP is not discovered yet, its manifestations are unknown. We should look everywhere. Our focus is on

- Precise CKM measurements,
- CPV in quarks and charged leptons,
- Missing energy studies:
  - $B \longrightarrow \ell\nu$,
  - $B \longrightarrow D^{(*)}\tau\nu$,
- Charged LFV: $\tau \longrightarrow \ell\gamma$, $\tau \longrightarrow \ell\ell\ell$, $\ell = e, \mu$,
- Quarkonium,
- Low multiplicity events.

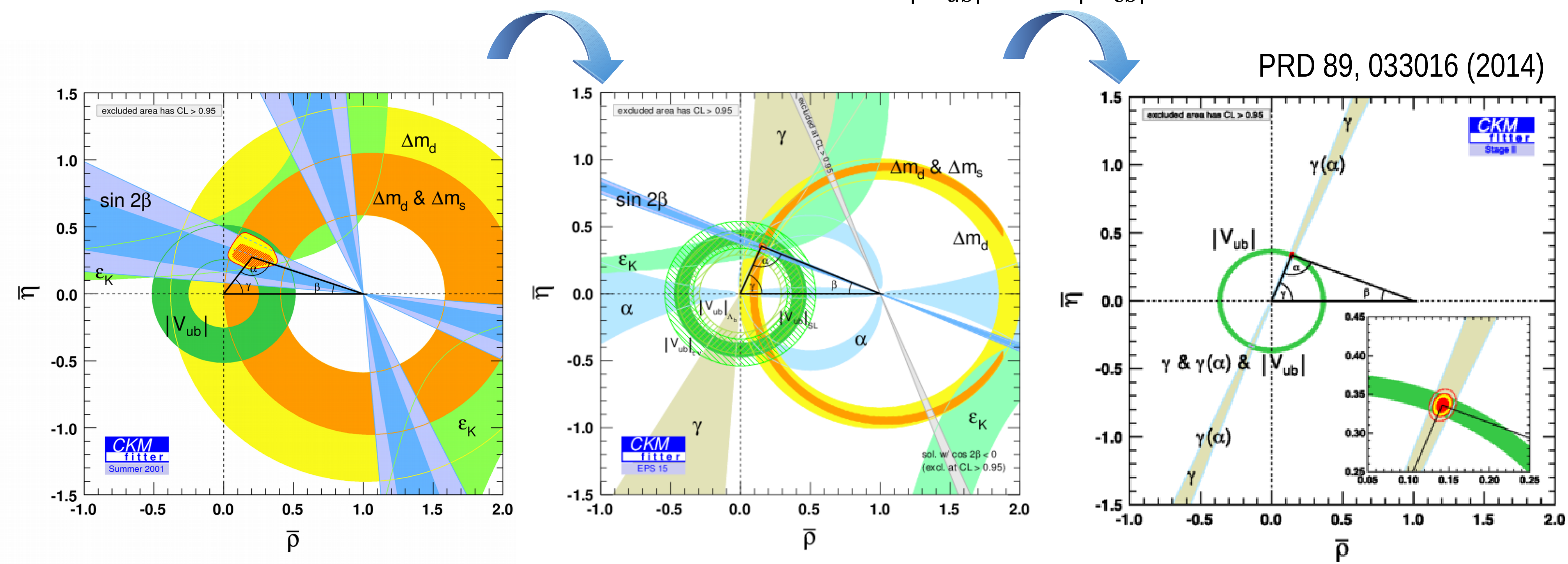


Just noise? Look closer!

Unitary triangle

- Unitary triangle changed dramatically in *B*-factories era.
- But is it really a triangle? Current $\alpha+\beta+\gamma = (175\pm9)^\circ$ (PDG), Belle II expects to improve the precision to $\alpha\sim0.3^\circ$, $\beta\sim1.0^\circ$, $\gamma\sim1.5^\circ$.
- Improvement in precision should help to resolve the tension between inclusive and exclusive measurements of $|V_{ub}|$ and $|V_{cb}|$.

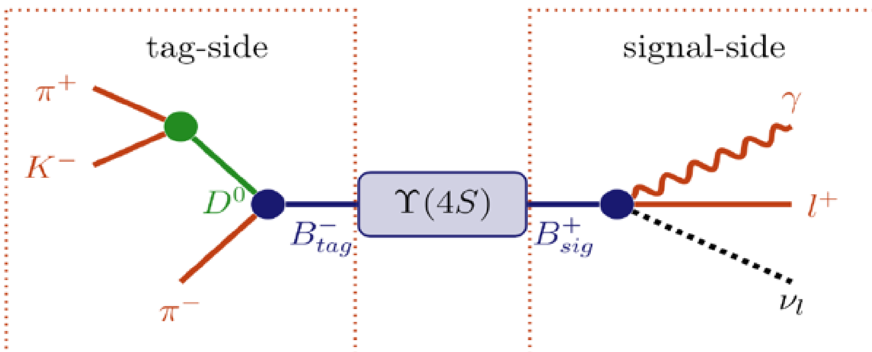
PRD 89, 033016 (2014)



Reconstruction with tagging

- At Belle (II) events are clean are well separated from each other; we reconstruct the whole event:

$$e^+e^- \to \Upsilon(4S) \to B_{\mathrm{tag}}B_{\mathrm{sig}}$$



Purity

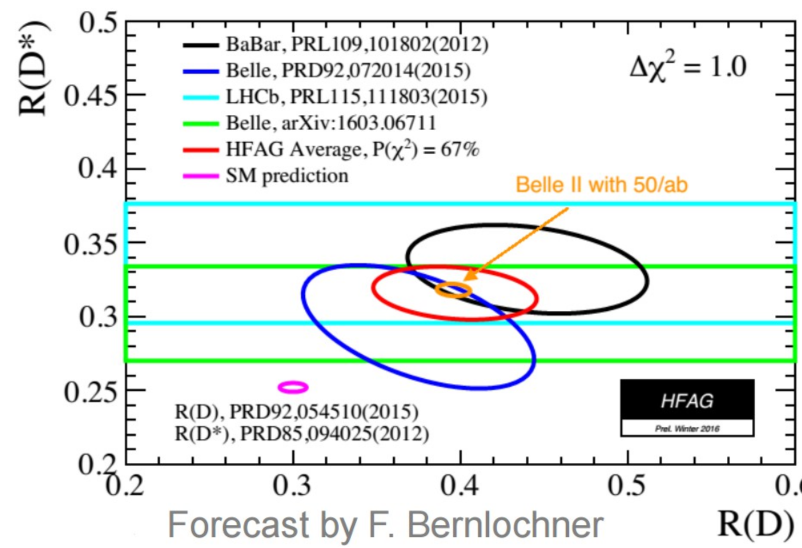
Efficiency

Inclusive	**Semileptonic**	**Hadronic**
$B \to$ anything	$B \to D^{(*)}\ell\nu$	$B \to$ hadrons
ε≈O(2%)	ε≈O(0.2%)	ε≈O(0.1%)
High background		Low background
		P(B)

Example:

$B \to D^{(*)}\tau\nu_\tau$

Now 4σ deviation from the SM

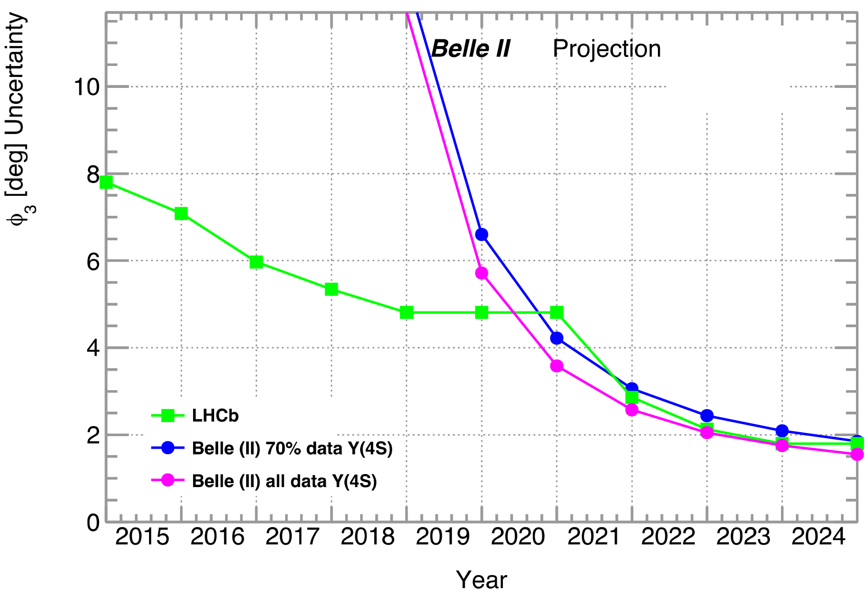


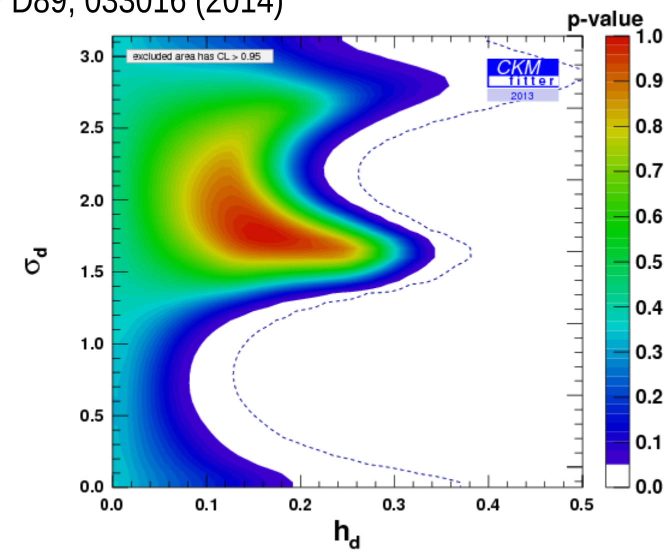
Physics at 50 ab^{-1}

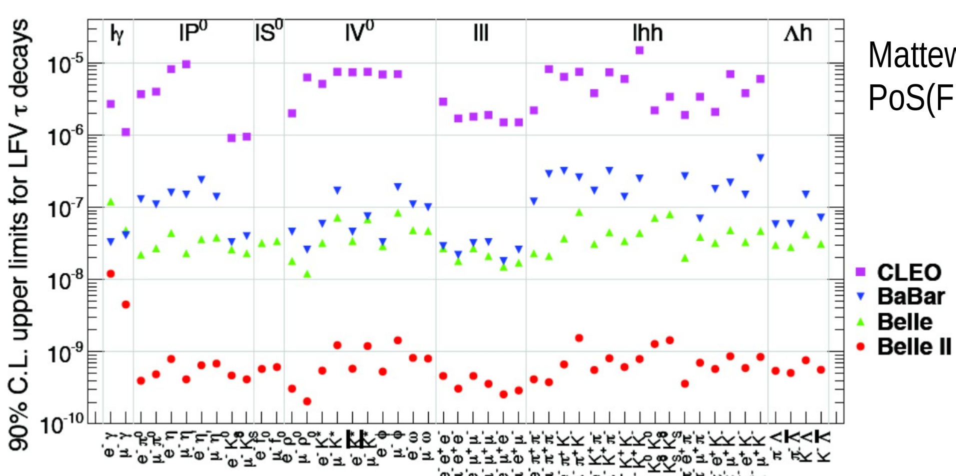
Parameterize NP contributions to the $B_{d,s}$ mixing amplitudes as

$M^{d,s}_{12}=(M^{d,s}_{12})_{CM}x(1+h_{d,s}\exp(2i\sigma_{d,s}))$

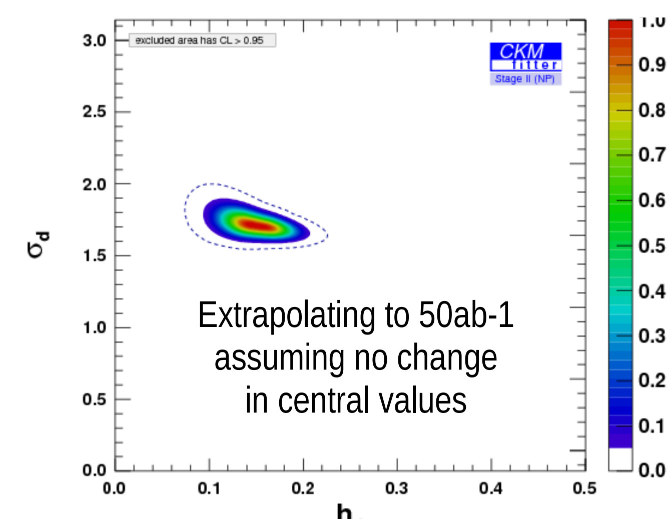
Phys Rev D89, 033016 (2014)







Mattew Barrett
PoS(FPCP2015)049



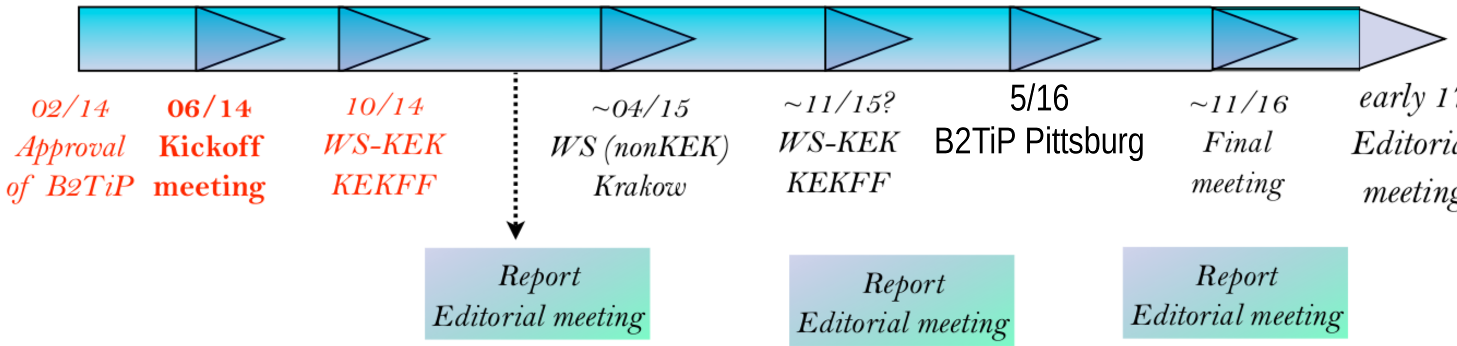
Physics at 50 ab^{-1}

Belle II
Note 21
9th Belle PAC
P.Urquijo talk

	Observables	Belle or LHCb* (2014)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}	LHCb 8 fb^{-1}(2018)	LHCb 50 fb^{-1}
UT angles	$\sin 2\beta$	$0.667 \pm 0.023 \pm 0.012 (1.4^\circ)$	0.7°	0.4°	1.6°	0.6°
	α [$^\circ$]	85 ± 4 (Belle+BaBar)	2	1		
	γ [$^\circ$] $(B \to D^{(*)}K^{(*)})$	68 ± 14	6	1.5	4	1
	$2\beta_s(B_s \to J/\psi\phi)$ [rad]	$0.07 \pm 0.09 \pm 0.01^*$			0.025	0.009
Gluonic penguins	$S(B \to \phi K^0)$	$0.90^{+0.09}_{-0.19}$	0.053	0.018	0.2	0.04
	$S(B \to \eta' K^0)$	$0.68 \pm 0.07 \pm 0.03$	0.028	0.011		
	$S(B \to K^0_S K^0_S K^0_S)$	$0.30 \pm 0.32 \pm 0.08$	0.100	0.033		
	$\beta_s^{\rm eff}(B_s \to \phi\phi)$ [rad]	$-0.17 \pm 0.15 \pm 0.03^*$			0.12	0.03
	$\beta_s^{\rm eff}(B_s \to K^{*0}\bar{K}^{*0})$ [rad]	$-$			0.13	0.03
Direct CP in hadronic Decays	$\mathcal{A}(B \to K^0\pi^0)$	$-0.05 \pm 0.14 \pm 0.05$	0.07	0.04		
UT sides	$\lvert V_{cb}\rvert$ incl.	$41.6 \cdot 10^{-3}(1 \pm 2.4\%)$	1.2%			
	$\lvert V_{cb}\rvert$ excl.	$37.5 \cdot 10^{-3}(1 \pm 3.0\%_{\rm ex.} \pm 2.7\%_{\rm th.})$	1.8%	1.4%		
	$\lvert V_{ub}\rvert$ incl.	$4.47 \cdot 10^{-3}(1 \pm 6.0\%_{\rm ex.} \pm 2.5\%_{\rm th.})$	3.4%	3.0%		
	$\lvert V_{ub}\rvert$ excl. (had. tag.)	$3.52 \cdot 10^{-3}(1 \pm 10.8\%)$	4.7%	2.4%		
Leptonic and Semi-tauonic	$\mathcal{B}(B \to \tau\nu)$ [10^{-6}]	$96(1 \pm 26\%)$	10%	5%		
	$\mathcal{B}(B \to \mu\nu)$ [10^{-6}]	< 1.7	20%	7%		
	$R(B \to D\tau\nu)$ [Had. tag]	$0.440(1 \pm 16.5\%)^\dagger$	5.6%	3.4%		
	$R(B \to D^*\tau\nu)^\dagger$ [Had. tag]	$0.332(1 \pm 9.0\%)^\dagger$	3.2%	2.1%	...	
Radiative	$\mathcal{B}(B \to X_s\gamma)$	$3.45 \cdot 10^{-4}(1 \pm 4.3\% \pm 11.6\%)$	7%	6%		
	$A_{CP}(B \to X_{s,d}\gamma)$ [10^{-2}]	$2.2 \pm 4.0 \pm 0.8$	1	0.5		
	$S(B \to K^0_S\pi^0\gamma)$	$-0.10 \pm 0.31 \pm 0.07$	0.11	0.035		
	$2\beta_s^{\rm eff}(B_s \to \phi\gamma)$	$-$			0.13	0.03
	$S(B \to \rho\gamma)$	$-0.83 \pm 0.65 \pm 0.18$	0.23	0.07		
	$\mathcal{B}(B_s \to \gamma\gamma)$ [10^{-6}]	< 8.7	0.3	$-$		
Electroweak penguins	$\mathcal{B}(B \to K^{*+}\nu\overline{\nu})$ [10^{-6}]	< 40	< 15	30%		
	$\mathcal{B}(B \to K^{+}\nu\overline{\nu})$ [10^{-6}]	< 55	< 21	30%		
	C_7/C_9 $(B \to X_s\ell\ell)$	$\sim$20%	10%	5%		
	$\mathcal{B}(B_s \to \tau\tau)$ [10^{-3}]	$-$	< 2	$-$		
	$\mathcal{B}(B_s \to \mu\mu)$ [10^{-9}]	$2.9^{+1.1*}_{-1.0}$			0.5	0.2

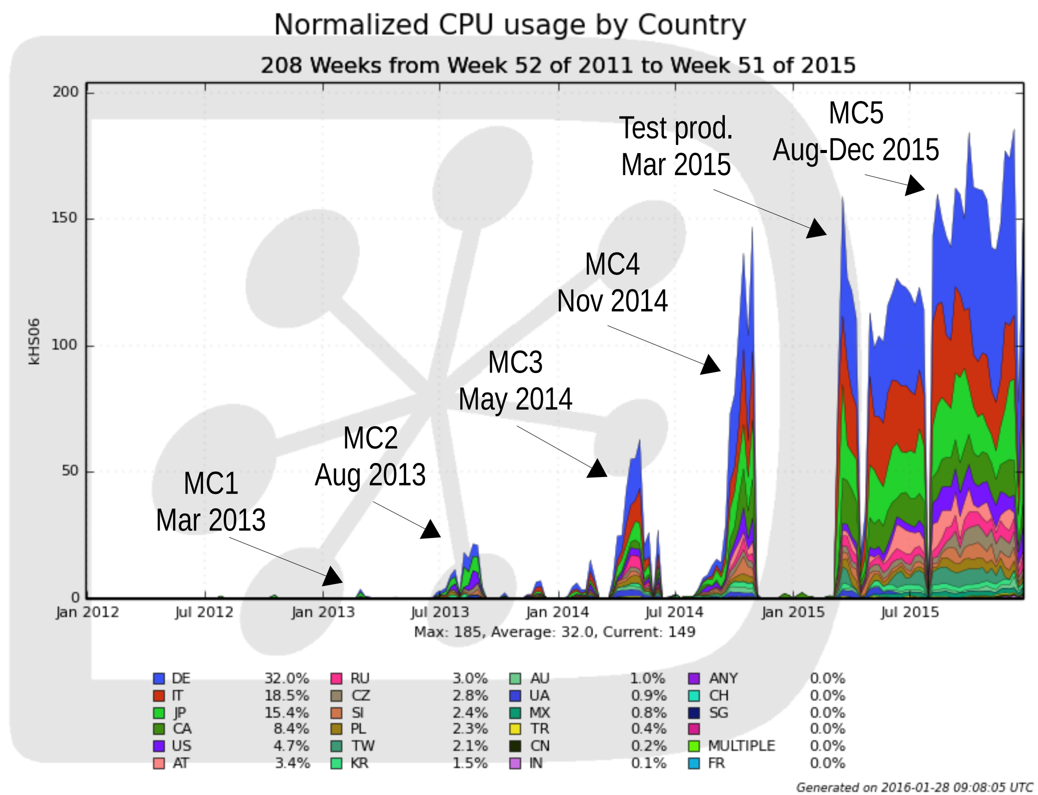
Theoretical workshops

- Series of experimental-theoretical workshops for development of Belle II physics program "Belle II Theory Interface Platform" (B2TiP).
- It is a joint effort of both theorists and experimentalists to have a close communication.
- Aim at delivering a full report in spring 2017.
- The last workshop was held in Pittsburgh in May 23-26.
- 9 working groups: semileptonic and leptonic *B* decays, radiative and EWP *B* decays, time dependent CPV, Phi 3, hadronic *B* decays, charm, quarkonium, low multiplicity, new physics.



Software and MC

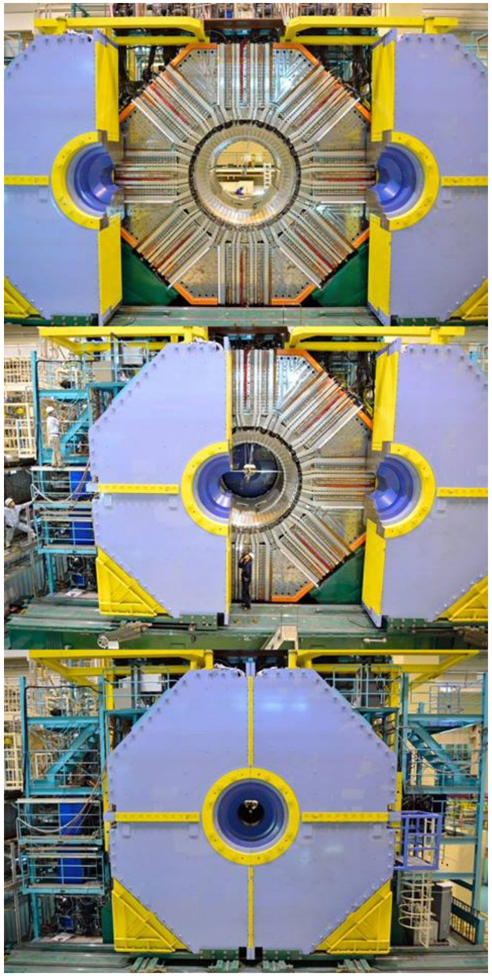
- Belle II analysis software framework (basf2) is being actively developed.
- 5 MC (6th has started) campaigns to estimate, measure, mitigate, and protect against beam backgrounds.
- Sample MC analyses with the new software.
- Belle II uses GRID for computing. ~40 computing sites in 18 countries (Australia, Austria, Canada, China, Czeck R., France, Germany, India, Italy, Japan, Korea, Poland, Russia, Slovenia, Taiwan, Turkey, Mexico, USA).



	2016	2017	2018	2019	2020	2021	2022	2023	2024
Tape (PB)	1.04	2.26	3.6	16.88	39.09	81.09	132.02	182.94	233.86
Disk (PB)	4.07	8.52	9.25	33.72	47.94	80.84	120.73	160.62	200.51
CPU (kHS)	219	310	357	506	653	749	1035	1262	1489

Outline

- From B to Super-B
- Accelerator
- Detector
- Physics
- Getting started

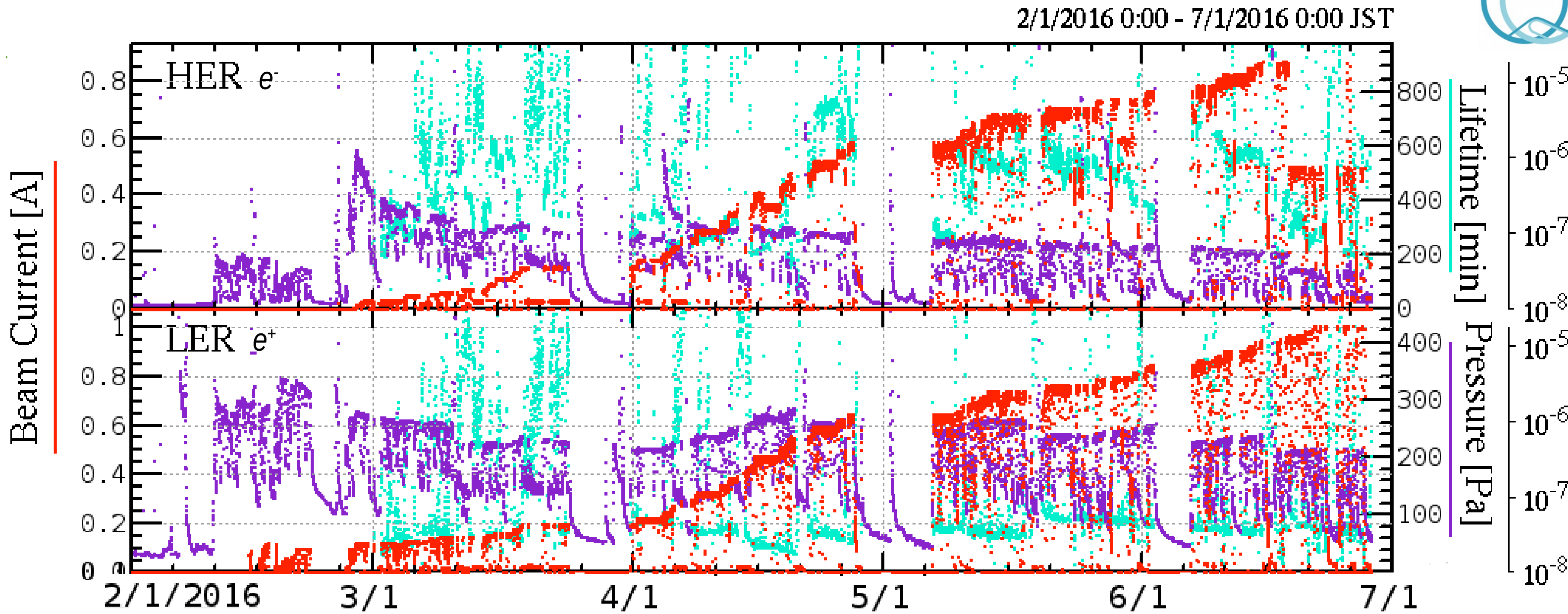


SuperKEKB phase 1

SuperKEKB first started in February and worked until June (Phase 1).

- Startup of each hardware system
- Establish beam operation software tools
- Preparation for installation of Belle-II detector
  - Enough vacuum scrubbing
    - Request from Belle II group: ~1 month vacuum scrubbing with beam current of 0.5~1A (360~720Ah).
  - Beam background study with test detector (named BEAST)
- High beam current operation
  - Find and solve problems associated with high beam current operation
- Optics study w/o IR (no detector solenoid)
  - Low emittance tuning
- Other machine studies

SuperKEKB phase 1 history



HER injection tuning

Short break for injector work

Short break

Short break
Solenoid installation at belleows (LER)

LER injection tuning

BT tuning

No collisions. Achieved currents:

HER: 870 mA, 5.7×10^{-8} Pa, ~200 min. (6/17)

LER: 1010mA, 4.7×10^{-7} Pa, ~60 min. (6/22)

SuperKEKB phase 1 results

- Faster startup than KEKB…
  - KEKB beam currents achieved after first 3 months

    LER: ~300mA, HER: ~200mA
  - SuperKEKB beam currents achieved after first 3 months

    LER: ~650mA, HER: ~590mA
- Compared with KEKB…
  - Each hardware component has been upgraded with experiences at KEK and has worked fine (RF, Magnet, Vacuum…)
  - The bunch-by-bunch feedback system has more effectively suppressed instabilities.
  - Operational tools (such as closed orbit correction system) has worked fine based on experiences at KEKB.
  - Less machine troubles than KEKB so far.

BEAST II

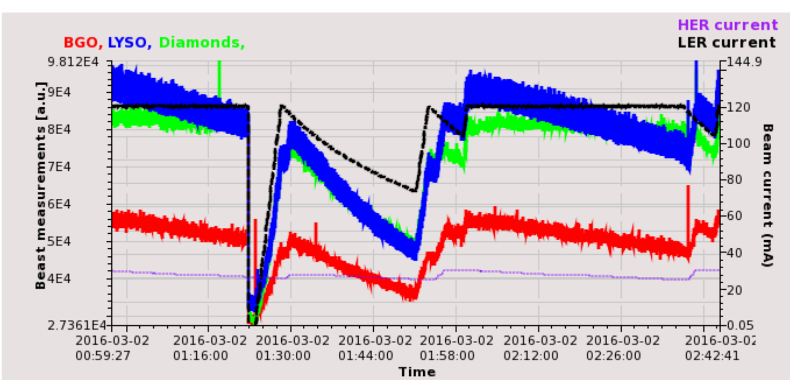
- Due to high beam currents, small beam size and higher luminosity, predicted SuperKEKB Beam background is 40 times higher than at KEKB.
- Background is reduced by installing moveable collimators and adding shielding near the final focus magnets.
- **B**eam **E**xorcism for a **S**table **E**xperimen**T** II (BEAST II): measure and characterize beam background for safe roll-in of Belle II.
- Provide feedback to SuperKEKB.
- First comparison of simulation with experimental data.
- Seven independent BEAST II sub-detectors to measure beam loss backgrounds

System	Number of detectors	Measurement
"CLAWS" scintillator	8	Injection background
Diamonds	4	Ionizing radiation dose
PIN Diodes	64	Neutral vs charged ionizing dose
BGO	8	Luminosity
Crystals	6 CsI(Tl) 6 CsI 6 LYSO	EM energy spectrum
He-3 tubes	4	Thermal neutron flux
Micro TPCs	2	Fast neutron flux

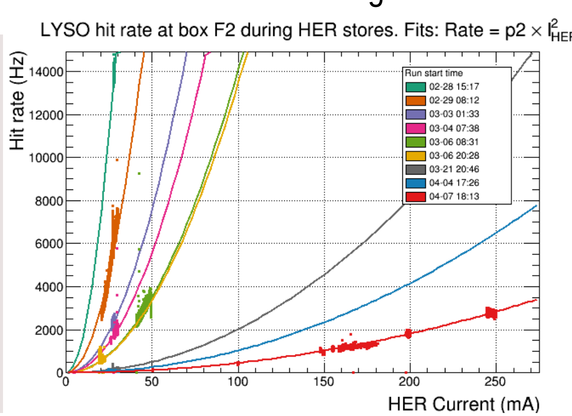
BEAST II results

- Early stage: LER/HER first turns seen by BEAST sensors.
- Vacuum scrubbing progress seen by BEAST sensors.
- “Vacuum burst”(dust capture) events seen by BEAST sensors.
- Provide “live” display of injection BG.
- Collimators are proven to reduce BEAST BG (incl. injection BG).
- Analysis of the results and comparison with simulation is ongoing.

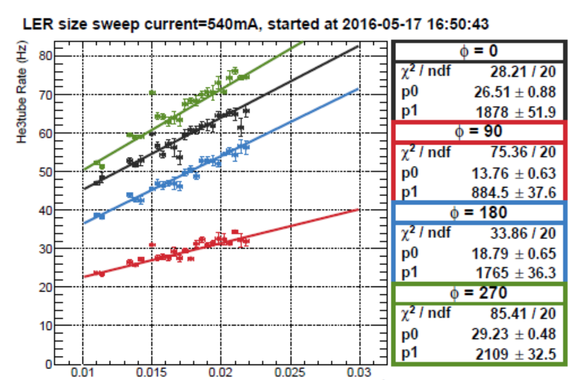
BEAST II Online monitor display



HER baking



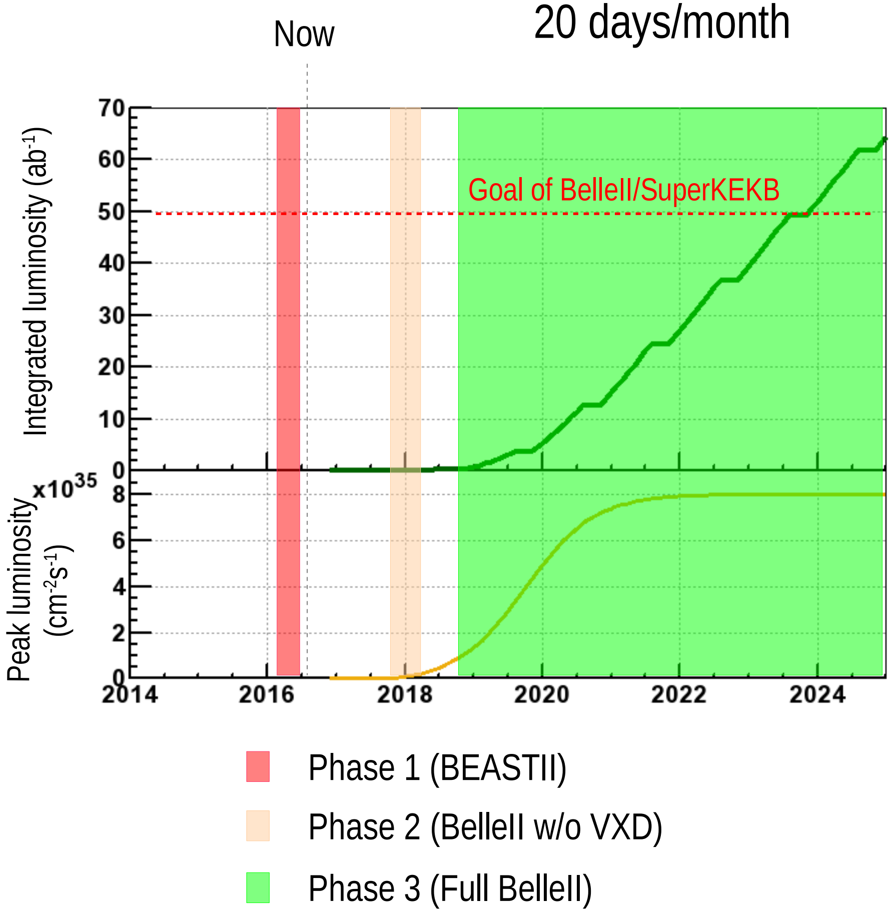
LER Touschek study



Schedule

- July 2016 – May 2017
  - QCS installation, cooling etc
- October 2016 – June 2017
  - CDC, ARICH installation
- December 2016
  - Belle II roll in
- November 2017 – March 2018
  - Phase 2 operation
  - Beta function squeezing, collision tuning
  - Belle II w/o VXD physics run
- April – June 2018
  - VXD installation
- October 2018 – ...
  - Full Belle II detector physics run

Expected running time:
9 months/year
20 days/month



Summary

- TOP, ECL, KLM are installed. CDC is ready for installation. DAQ tests of individual systems with cosmic rays and their integration are ongoing.
- PXD, SVD, ARICH are in production/assembly state.
- Accelerator Phase 1 completed. SuperKEKB has been successfully switched on. It reached 1.01A current in the LER and 0.87A in the HER. Getting ready for Phase 2 with partial Belle II detector (w/o VXD) in 2017.
- Physics run is scheduled to start on 2018.
- Reach and promising physics program is further refined and extended in collaboration with theorists.

Backup

Belle II collaboration

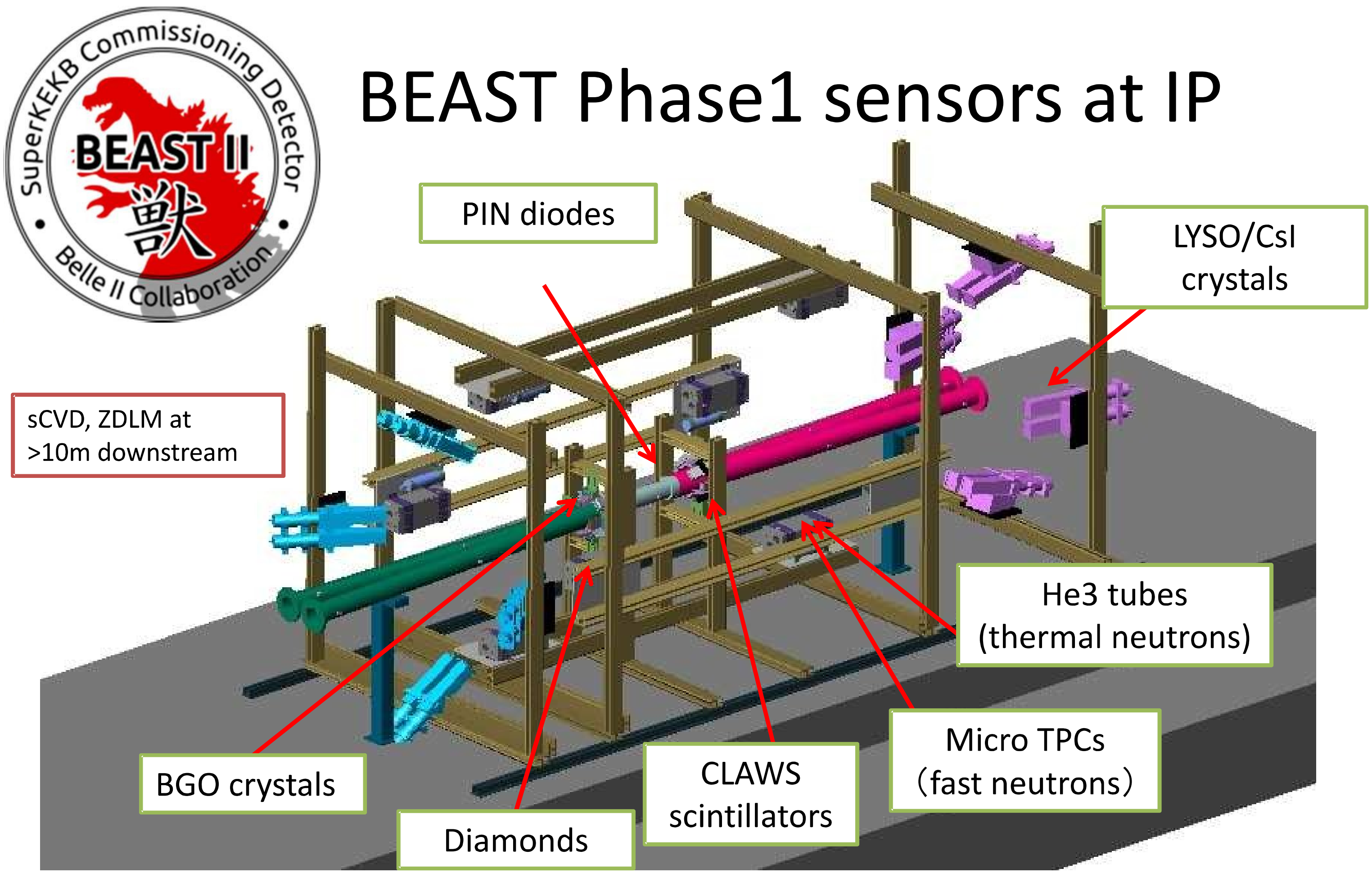
https://www.belle2.org

Formed in 2008 on basis of the Belle collaboration.

631 collaborators, 100 institutions, 23 countries/regions.

BEASTII schematic view

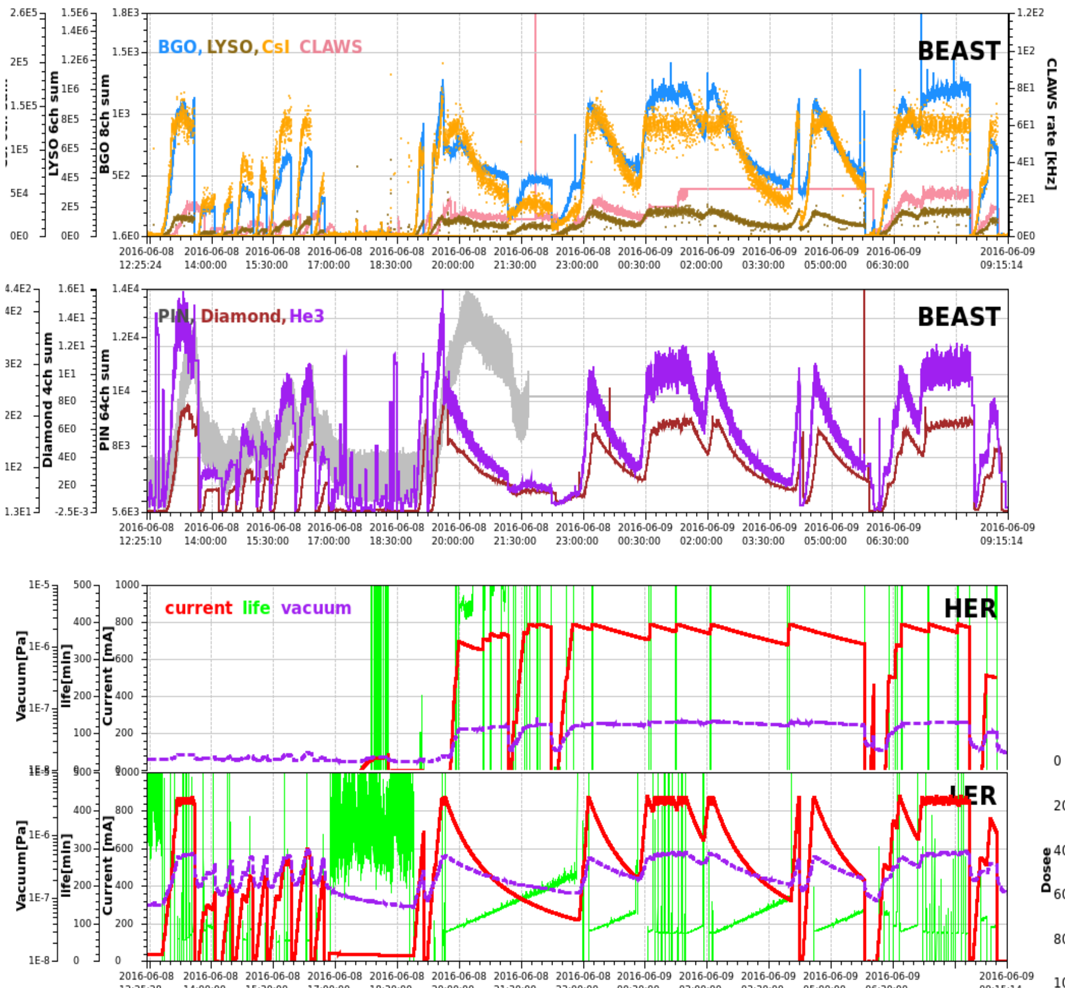
BEAST Phase1 sensors at IP

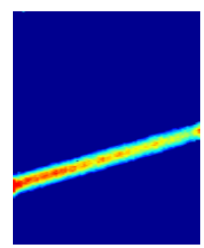


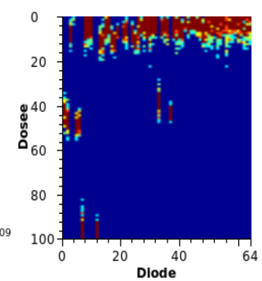
Various measurements (fast charged particle, high-energy photons, thermal/MeV neutron, dosimetry, etc..) to **validate beam loss simulation**

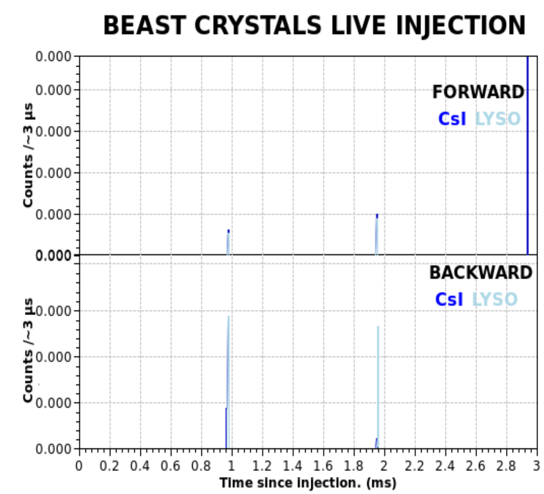
BEASTII run monitor

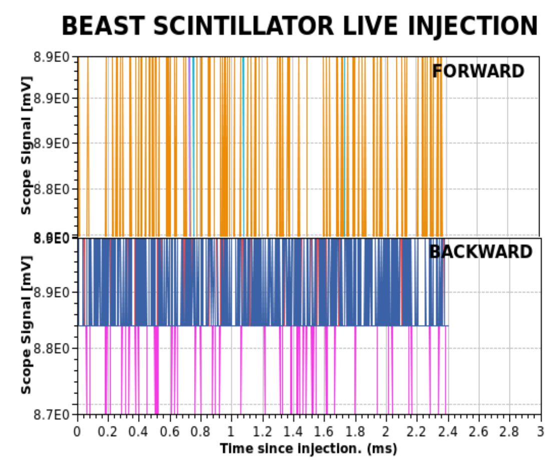
Good time resolution
injection BG monitors







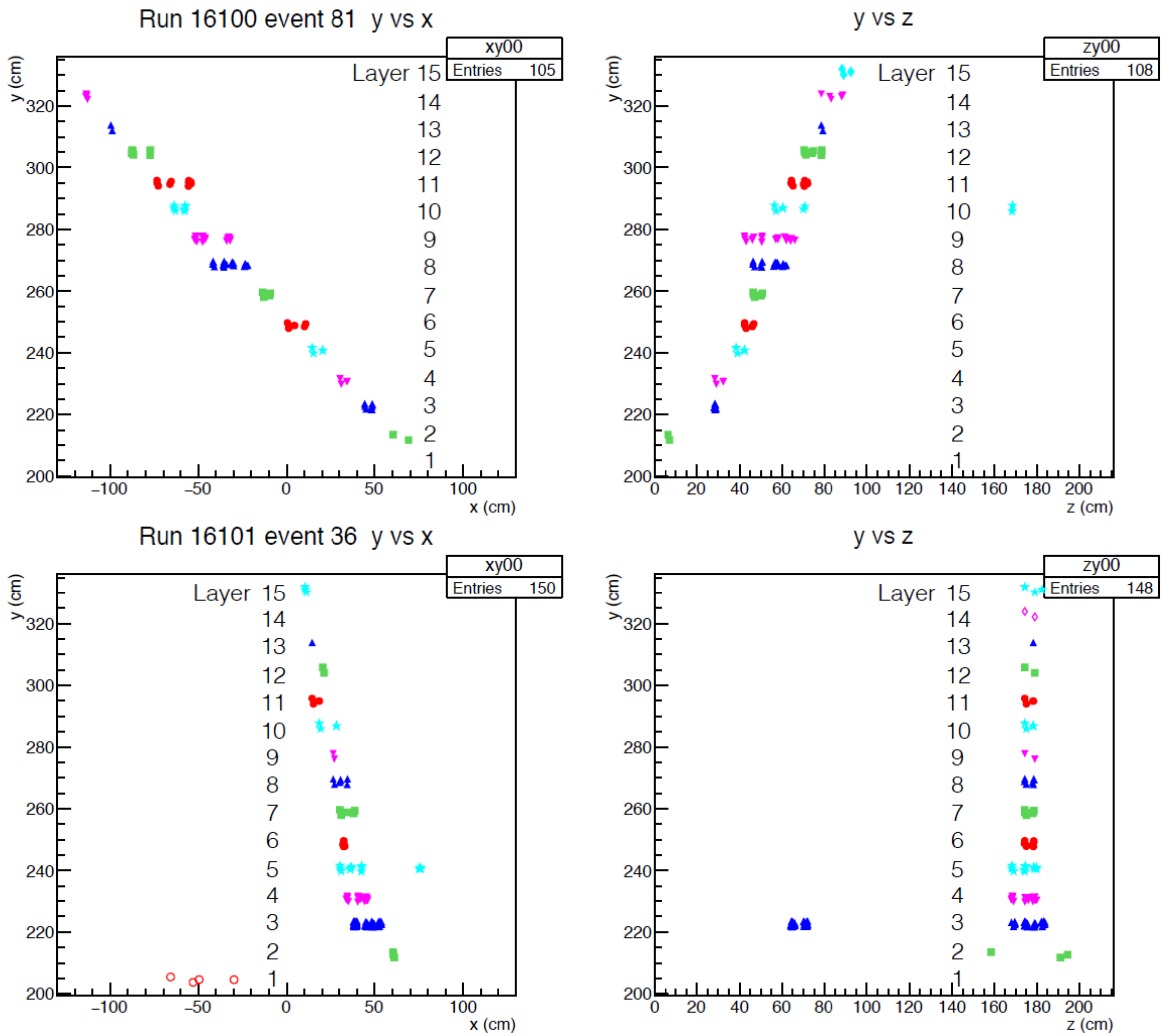




Directional neutron detection

KLM tracks

As of June 21, we now see cosmic-ray tracks 😄



PXD module size