The Belle II Experiment at SuperKEKB: construction, commissioning and physics prospects

Sven Vahsen, University of Hawaii

... with an acknowledgement to my Belle colleagues, in particular Leo Piilonen, for their contributions
Executive Summary

- Belle @ KEKB and Babar @ PEP-II:
  - Successful B-factory experiments, running until 2010 and 2008
  - Highest $e^+e^-$ luminosities seen to date
  - Rich Physics Legacy. Established KM mechanism as valid description of CP violation in Standard Model

- Belle II @ SuperKEKB: Next generation B-factory
  - Goal: Record 50x larger integrated luminosity than Belle
  - Approved and under construction
  - First physics run expected in 2016
  - Rich physics program, complimentary to LHC, enabled by larger data set
B factories: a success story

- Measurements of CKM matrix elements and angles of the unitarity triangle
- Observation of direct CP violation in B decays
- Measurements of rare decay modes (e.g., $B \to \tau \nu$, $D \tau \nu$)
- $b \to s$ transitions: probe for new sources of CPV and constraints from the $b \to s \gamma$ branching fraction
- Forward-backward asymmetry ($A_{FB}$) in $b \to s l^+ l^-$ has become a powerful tool to search for physics beyond SM.
- Observation of $D$ mixing
- Searches for rare $\tau$ decays
- Observation of new hadrons

Possible also because of unique capabilities of B factories: detection of neutrals, neutrinos, clean event environment.
Belle & Belle II talks at this Conference

1. Leptonic and semileptonic decays at Belle 2013-08-16 17:05:00
2. Measurements of Electroweak Penguins at Belle 2013-08-16 16:25:00
3. Belle II (construction, commissioning and prospects) 2013-08-16 16:18:00
4. Results on New Particles from Belle 2013-08-16 09:10:00
5. Results from Belle's Upsilon(5S) data sample 2013-08-16 08:50:00
6. CP Violation results from Belle 2013-08-15 17:00:00
7. Hadronic B Decays from Belle 2013-08-15 16:00:00
8. Charm mixing and CP Violation at Belle 2013-08-15 14:50:00
9. Particle identification with the iTOP detector at Belle-II 2013-08-15 10:55:00
### Belle physics output (compiled by Simon Eidelman)

<table>
<thead>
<tr>
<th># papers</th>
<th>50-99</th>
<th>100-199</th>
<th>200-299</th>
<th>300-399</th>
<th>400-499</th>
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<table>
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<tr>
<th>N</th>
<th>Title</th>
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<td>1</td>
<td>X(3872)</td>
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<td>739</td>
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<td>Large CPV</td>
<td>2001</td>
<td>618</td>
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<td>3</td>
<td>$B \rightarrow X_s \gamma$</td>
<td>2001</td>
<td>381</td>
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<td>4</td>
<td>CP in $B^0 \bar{B}^0$</td>
<td>2002</td>
<td>326</td>
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<td>5</td>
<td>D0 mixing</td>
<td>2007</td>
<td>292</td>
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<td>6</td>
<td>Y(3945)</td>
<td>2005</td>
<td>290</td>
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<tr>
<td>7</td>
<td>$B \rightarrow \tau \nu$</td>
<td>2006</td>
<td>277</td>
</tr>
<tr>
<td>8</td>
<td>$2c\bar{c}$</td>
<td>2002</td>
<td>272</td>
</tr>
<tr>
<td>9</td>
<td>$b \rightarrow s \gamma$</td>
<td>2004</td>
<td>265</td>
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<tr>
<td>10</td>
<td>$D_s^*(2317), D_{s1}(2460)$</td>
<td>2003</td>
<td>258</td>
</tr>
<tr>
<td>11</td>
<td>$D^{**}$</td>
<td>2004</td>
<td>249</td>
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<tr>
<td>12</td>
<td>Z(4430)</td>
<td>2008</td>
<td>235</td>
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<tr>
<td>13</td>
<td>$D_{sJ}$</td>
<td>2006</td>
<td>221</td>
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<tr>
<td>14</td>
<td>X(3940) in $2c\bar{c}$</td>
<td>2007</td>
<td>204</td>
</tr>
</tbody>
</table>

- Growing at $\approx 100$/year
- 375 papers published plus $\approx 30$/year
Searching for New Physics with Belle II

Indirect searches for New Physics complement direct searches at LHC

Flavor changing neutral currents
(virtual contributions of new, heavy particles in loops)

Precision test of CKM unitarity
(search for new CP-violating phases)

Search for New Physics in B decays with $\tau$ leptons
(charged Higgs, ...)

Search for lepton flavor violation in B and $\tau$ decays

For sensitive New Physics searches, need $O(10^2)$ times more data

Belle / KEKB $\Rightarrow$ Belle II / SuperKEKB
> Much more improved measurements

> Overconstrain Unitarity Triangle

> Discrepancy between measurements → new physics?

2012: ~1500 fb⁻¹, Belle + BaBar

Expected constraints at 50 ab⁻¹
Belle II physics prospects: B decays

CP violation in s-Penguins

\[ \Delta S = S(b \rightarrow q\bar{q}s) - S(b \rightarrow c\bar{c}s) = -0.04 \pm 0.04 \]
(HFAG, Summer 2012)

B decays with \( \tau \) leptons

- \( B \rightarrow \tau\nu \) and \( B \rightarrow D^{(*)}\tau\nu \)
- Sensitive to charged Higgs

Belle II (50 ab\(^{-1}\))
5\( \sigma \) discovery

ATLAS 7 TeV (4.6 fb\(^{-1}\))
Belle II physics prospects: Tau and charm

Lepton flavor violation in $\tau$ decays

- strongly suppressed in SM: $\text{BF} \sim 10^{-53-10^{-49}}$
- Possible enhancements in NP models up to $\text{BF} \sim 10^{-9-10^{-7}}$

CP violation in D mixing

- Direct and indirect CPV in $D^0-\bar{D}^0$ mixing

Constraints on indirect CPV parameters
Complementary to LHCb

<table>
<thead>
<tr>
<th>Observable</th>
<th>Expected th. accuracy</th>
<th>Expected exp. uncertainty</th>
<th>Facility</th>
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<tbody>
<tr>
<td>$</td>
<td>V_{us}</td>
<td>[K \to \pi \ell \nu]$</td>
<td>**</td>
</tr>
<tr>
<td>$</td>
<td>V_{cb}</td>
<td>[B \to X_c \ell \nu]$</td>
<td>**</td>
</tr>
<tr>
<td>$</td>
<td>V_{ub}</td>
<td>[B_d \to \pi \ell \nu]$</td>
<td>*</td>
</tr>
<tr>
<td>$\sin(2\phi_1) \ [\bar{c}\bar{c}K_S^0]$</td>
<td>***</td>
<td>$8 \cdot 10^{-3}$</td>
<td>Belle II/LHCb</td>
</tr>
<tr>
<td>$\phi_2$</td>
<td>***</td>
<td>1.5°</td>
<td>Belle II</td>
</tr>
<tr>
<td>$\phi_3$</td>
<td>***</td>
<td>3°</td>
<td>LHCb</td>
</tr>
</tbody>
</table>

CPV

| $S(B_s \to \psi\phi)$ | ** | 0.01 | LHCb |
| $S(B_s \to \Phi\phi)$ | ** | 0.05 | LHCb |
| $S(B_d \to \Phi K)$ | *** | 0.05 | Belle II/LHCb |
| $S(B_d \to \eta'K)$ | *** | 0.02 | Belle II |
| $S(B_d \to K^*(\to K^0_S\pi^0\gamma))$ | *** | 0.03 | Belle II |
| $S(B_s \to \phi\gamma)$ | *** | 0.05 | LHCb |
| $S(B_d \to \rho\gamma)$ | *** | 0.15 | Belle II |
| $A_{SL}^d$ | *** | 0.001 | LHCb |
| $A_{SL}^s$ | *** | 0.001 | LHCb |
| $A_{CP}(B_d \to s\gamma)$ | * | 0.005 | Belle II |

rare decays

| $B(B \to \tau\nu)$ | ** | 3% | Belle II |
| $B(B \to D\tau\nu)$ | ** | 3% | Belle II |
| $B(B_s \to \mu\nu)$ | ** | 6% | Belle II |
| $B(B_s \to \mu\mu)$ | *** | 10% | LHCb |
| zero of $A_{FB}(B \to K^*\mu\mu)$ | ** | 0.05 | LHCb |
| $B(B \to K^{(*)}\nu\nu)$ | *** | 30% | Belle II |
| $B(B \to s\gamma)$ | *** | 4% | Belle II |
| $B(B_s \to \gamma\gamma)$ | ** | $0.25 \cdot 10^{-6}$ | Belle II (with 5 ab$^{-1}$) |
| $B(K \to \pi\nu\nu)$ | ** | 10% | K-factory |
| $B(K \to e\nu\nu)/B(K \to \mu\nu\nu)$ | *** | 0.1% | K-factory |

charm and $\tau$

| $B(\tau \to \mu\gamma)$ | *** | $3 \cdot 10^{-9}$ | Belle II |
| $|q/p|_D$ | *** | 0.03 | Belle II |
| $\arg(q/p)_D$ | *** | 1.5° | Belle II |

→ Need both LHCb and super B factories to cover all aspects of precision flavour physics


Power of $e^+e^-$, example: Full Reconstruction Method

- Fully reconstruct one of the B mesons to
  - Tag B flavor/charge
  - Determine B momentum
  - Exclude decay products of one B from further analysis

$\rightarrow$ Offline B meson beam!

Powerful tool for B decays with neutrinos

Decays of interest
- $B \rightarrow X_u \ell \nu$
- $B \rightarrow K \nu \nu$
- $B \rightarrow D \tau \nu$, $\tau \nu$
- $B \rightarrow \nu \nu$

Full reconstruction $B \rightarrow D \pi$ etc. (0.1\%\% - 0.3\%)
Search for New Physics at Belle II

✓ Precision CKM unitarity tests

✓ NP effects in $B$ decays with missing energy, such as $B \to \tau \nu$, $B \to D^{(*)}\tau\nu$, $B \to K\nu\nu$, ...

✓ LFV in $B$ and $\tau$ decays

✓ FCNC (via virtual heavy particles in loops)

✓ Charm studies (including exotica)

✓ Dark-sector particles

ν experiments, $g_\mu-2$, $\mu \to e\gamma$, etc.

ν mass and mixing, CPV, and LFV

"A unified and unbiased attack on new physics" - Tom Browder
SuperKEKB is the intensity frontier
40x higher instantaneous luminosity than KEKB

Peak luminosity trends at $e^+e^-$ colliders

Luminosity (cm$^{-2}$ s$^{-1}$)
Strategies for Increasing Luminosity

Nano-beams and a factor of two larger beam currents
KEKB to SuperKEKB

Replace short dipoles with longer ones (LER)

Redesign the lattices of HER & LER to squeeze the emittance

TiN-coated beam pipe with antechambers

Low emittance gun
Low emittance electrons to inject

Damping ring

Low emittance positrons to inject

Add / modify RF systems for higher beam current

Positron source
New positron target / capture section

To obtain x40 higher luminosity
Entirely new LER beam pipe with ante-chamber and Ti-N coating.

Beam pipe is made of aluminum.

Fabrication of the LER arc beam pipe section is completed.
Al ante-chamber before coating

After baking

After TiN coating before baking
All 100 4 m long dipole magnets have been successfully installed in the low energy ring (LER)!

*Three magnets per day!*

Installing the 4 m long LER dipole **over** the 6 m long HER dipole (remains in place).
Magnet installation

- field measurement
- move into tunnel
- carry on an air-pallet
- carry over existing HER dipole

Installation of 100 new LER bending magnets done

install done

SuperKEKB Status, 7th BPAC, Mar. 11, 2013, K. Akai
Upgrade of RF system to cope with twice beam currents and 2.5 times beam power

RF high power system

1.2 MW CW klystron

Six ARES cavities in D5 moved from HER to LER. HER wiggler magnets were installed close to the ARES.

Superconducting cavities
DR under construction on 18/Dec/2012

Positron Damping Ring (new)

- Tunnel construction under way in 2012-13; half year delay due to budget suspend caused by the earthquake.
- Construction of buildings for DR will start in April this year.
- Fabrication of accelerator components ongoing. Installation starts in 2014.
- DR commissioning will start in 2015.

Inside DR tunnel

Now DR has been buried.
IR magnets overview

Magnet-cryostat in the left
QCSL

Magnet-cryostat in the right
QCSR

in production

design being finalized → in production from summer
Experimental Challenges at High Luminosity

> High background (10-20 times higher than at Belle)
  - Fake hits, pile up, radiation damage

> Higher trigger rate
  - Typical Level1 trigger rate: 20kHz
  - High performance DAQ

> Important improvements
  - Hermeticity for full reconstruction analyses
  - IP and secondary vertex resolution
  - $K_S$ and $\pi^0$ identification efficiency
  - Improve Kaon/pion separation

> Details in TDR *arXiv:1011.0352*
Belle II detector

Higher backgrounds ($\times 20$) $\Rightarrow$ higher occupancy, radiation damage
Higher event rate $\Rightarrow$ faster trigger, DAQ, computing
Special requirements, e.g. low-momentum $\mu$ ID ($b\to s\mu\mu$), hermeticity ($\nu$ reco.)
Particle Identification Devices

Barrel PID: Time of Propagation Counter (TOP)
- Quartz radiator
- Focusing mirror
- Small expansion block
- Hamamatsu MCP-PMT (measure t, x and y)

Endcap PID: Aerogel RICH (ARICH)
- Aerogel radiator
  - n ~ 1.05
- Hamamatsu HAPD + new ASIC
- 200mm Cherenkov photon path
Barrel PID: Time of propagation (TOP) counter

- Cherenkov ring imaging with precise time measurement.
- Device uses internal reflection of Cerenkov ring images from quartz like the BaBar DIRC
- Reconstruct Cherenkov angle from two hit coordinates and the time of propagation of the photon
  - Quartz radiator (2cm)
  - Photon detector (MCP-PMT)
    - Good time resolution $\sim 40$ ps
    - Single photon sensitivity in 1.5 T field
    - Hamamatsu SL10
Detection of **muons and KLs**: Parts of the present RPC system have to be replaced to handle higher backgrounds (mainly from neutrons).

**K_L and muon detector:**
- Resistive Plate Counter (barrel)
- Scintillator + WLSF + MPPC (end-caps + barrel 2 inner layers)

Expected to improve KL and muon detection efficiency beyond Belle performance.
SuperKEKB/Belle II schedule

<table>
<thead>
<tr>
<th>Calendar</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
<th>...</th>
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<tr>
<td>Japan FY</td>
<td>2010</td>
<td>2011</td>
<td>2012</td>
<td>2013</td>
<td>2014</td>
<td>2015</td>
<td>2016</td>
<td>2017</td>
<td>...</td>
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</table>

Mar. 2013

Detector upgrade to Belle II

Belle roll out

Dismantling KEKB

Fabrication and tests of ring components

Install and set up

Electricity and cooling facility

MR & DR buildings

DR tunnel

Jan. 2015

Belle II roll in

QCS install

VXD install

Accelerator tuning

BEAST

Physics run

Upgraded Linac operation for SuperKEKB, PF, PF-AR

SuperKEKB operation

KEKB operation

Linac

Linac upgrade / operation for PF&PF-AR
Beam Exorcisms for A Stable ExperimentT
a.k.a. Commissioning Detector

- BEAST II Commissioning detector will characterize radiation near SuperKEKB interaction point during beam commissioning
  - Ensure radiation levels safe before Belle roll-in
  - Measure individual beam background components, to validate / tune simulation
  - System test of Belle II subdetectors and systems (beam abort, VXD cooling, occupancy, etc)

KEKB commissioning detector
- BEAST – in 1998
Timeline & goal

Goal of Belle II/SuperKEKB

Plan to reach 50 ab\(^{-1}\) by end of 2022

Commissioning starts in early 2015.

Shutdown for upgrade

>21 countries/regions, 76 institutions, ~480 collaborators
Very successful $e^+e^-$ B Factories: Belle and BaBar

Major upgrade: SuperKEKB and Belle II

- 50 times larger integrated luminosity compared to Belle
  - Challenges to both accelerator and detector

- Fully approved and construction is ongoing

- First physics run in 2016

- New era of discoveries, complementary to LHC
BACKUP SLIDES
### Machine design parameters

<table>
<thead>
<tr>
<th>parameters</th>
<th>KEKB</th>
<th></th>
<th>SuperKEKB</th>
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<tr>
<td></td>
<td>LER</td>
<td>HER</td>
<td>LER</td>
<td>HER</td>
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<tr>
<td>Beam energy</td>
<td>$E_b$</td>
<td>3.5</td>
<td>8</td>
<td>4</td>
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<tr>
<td>Half crossing angle</td>
<td>$\varphi$</td>
<td>11</td>
<td></td>
<td>41.5</td>
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<tr>
<td>Horizontal emittance</td>
<td>$\varepsilon_x$</td>
<td>18</td>
<td>24</td>
<td>3.2</td>
</tr>
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</table>
| Emittance ratio               | $\kappa$   | 0.88 | 0.66 | 0.37 | 0.40 |%
| Beta functions at IP         | $\beta_x^*/\beta_y^*$ | 1200/5.9 |     | 32/0.27 | 25/0.30 | mm
| Beam currents                 | $I_b$      | 1.64 | 1.19 | 3.60 | 2.60 | A
| beam-beam parameter          | $\xi_y$    | 0.129 | 0.090 | 0.0881 | 0.0807 | cm$^{-2}$s$^{-1}$
| Luminosity                    | $L$        | $2.1 \times 10^{34}$ | | $8 \times 10^{35}$ |

- **Nano-beams and a factor of two more beam current** to increase luminosity
- **Large crossing angle**
- **Change beam energies** to solve the problem of short lifetime for the LER
Strategies for increasing luminosity

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

(1) Smaller \( \beta_y^* \)
(2) Increase beam currents
(3) Increase \( \xi_y \)

“Nano-Beam” scheme

Collision with very small spot-size beams

Invented by Pantaleo Raimondi for SuperB
Belle II Detector – vertex region

Beryllium beam pipe
2cm diameter

Vertex Detector
2 layers DEPFET + 4 layers DSSD
**Vertex Detector**

<table>
<thead>
<tr>
<th>Detector</th>
<th>Layer</th>
<th>Distance (mm)</th>
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<tbody>
<tr>
<td><strong>Beam Pipe</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DEPFET</td>
<td>Layer 1</td>
<td>14mm</td>
</tr>
<tr>
<td></td>
<td>Layer 2</td>
<td>22mm</td>
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<tr>
<td></td>
<td>Layer 3</td>
<td>38mm</td>
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<td></td>
<td>Layer 4</td>
<td>80mm</td>
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<td></td>
<td>Layer 5</td>
<td>115mm</td>
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<td></td>
<td>Layer 6</td>
<td>140mm</td>
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<tr>
<td><strong>DSSD</strong></td>
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</tr>
</tbody>
</table>

**Mechanical mockup of pixel detector**

**DEPFET pixel sensor**

**Charge Distribution**

S/N ~ 40

**DEPFET sensor: very good S/N**

[DEPFET: http://aldebaran.hll.mpg.de/twiki/bin/view/DEPFET/WebHome](http://aldebaran.hll.mpg.de/twiki/bin/view/DEPFET/WebHome)
SVD Mechanical Mockup

Gearing up for ladder production!
Expected performance

Significant improvement in vertex resolution!

$\sigma = a + \frac{b}{p\beta\sin^\gamma\theta}$

Pixel detector close to the beam pipe

Less Coulomb scattering

Significant improvement in $\delta S(K_s\pi^0\gamma)$

B decay point reconstruction with $K_s$ trajectory

Larger radial coverage of SVD
Main tracking device: small cell drift chamber

Central Drift Chamber
He(50%):C₂H₆(50%), small cells, long lever arm, fast electronics
Central drift chamber

- **Extended** outer radius
- **Smaller cells** near beampipe
- **Faster** readout electronics

⇒ **Improved** p and dE/dx resolution

$\sigma_p/p \sim 0.3\% + 0.1\% \times p(\text{GeV})$ in $B=1.5T$

$\sigma (\text{dE/dx}) \sim 6\%$

<table>
<thead>
<tr>
<th></th>
<th>Belle</th>
<th>Belle II</th>
</tr>
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<tbody>
<tr>
<td>Innermost sense wire</td>
<td>$r=88\text{mm}$</td>
<td>$r=168\text{mm}$</td>
</tr>
<tr>
<td>Outermost sense wire</td>
<td>$r=863\text{mm}$</td>
<td>$r=1111.4\text{mm}$</td>
</tr>
<tr>
<td>Number of layers</td>
<td>50</td>
<td>56</td>
</tr>
<tr>
<td>Total sense wires</td>
<td>8400</td>
<td>14336</td>
</tr>
<tr>
<td>Gas</td>
<td>He:C$_2$H$_6$</td>
<td>He:C$_2$H$_6$</td>
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<td>Sense wire</td>
<td>W(φ30μm)</td>
<td>W(φ30μm)</td>
</tr>
<tr>
<td>Field wire</td>
<td>Al(φ120μm)</td>
<td>Al(φ120μm)</td>
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</tbody>
</table>
Belle II CDC

Wire Configuration

Present CDC

Upgrade CDC

250 mm

1200 mm

Much bigger than in Belle!

Wire stringing in a clean room

- thousands of wires,
- 1 year of work...
Pattern in the coordinate-time space ('ring') of a pion hitting a quartz bar with ~80 MAPMT channels.

Time distribution of signals recorded by one of the PMT channels: different for π and K (~shifted in time).
Aerogel RICH (endcap PID)

Clear Cherenkov image observed

Cherenkov angle distribution

6.6 $\sigma$ $\pi/K$ at 4GeV/c!

RICH with a novel “focusing” radiator – a two layer radiator

Employ multiple layers with different refractive indices $\rightarrow$ Cherenkov images from individual layers overlap on the photon detector.
RICH with a focusing radiator

Increases the number of photons without degrading the resolution

**4cm aerogel single index**

**2+2cm aerogel**

→ NIM A548 (2005) 383
EM calorimeter: upgrade needed because of higher rates (barrel: **electronics**, endcap: electronics and CsI(Tl) $\rightarrow$ pure CsI) and radiation load (endcap: CsI(Tl) $\rightarrow$ pure CsI)

EM Calorimeter:
CsI(Tl), waveform sampling (barrel)
Pure CsI + waveform sampling (end-caps)