THE BELLE II EXPERIMENT:
STATUS AND PROSPECTS

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UNIVERSITA’ DI PERUGIA & INFN-PG
DISCOVERY OF FLAVOR EXPERIMENTS

CPV in $K^0$ system discovered in 1964 → CKM mechanism and 3rd quark generation

Neutral kaon oscillation predicted in 1955 and established in 1960 and only in 1987 observed in $B^0$ system → charm and top quark masses

$K^0_L$ → $\mu^+\mu^-$ suppression → GIM

PRECISION MEASUREMENTS OF CKM ELEMENTS

$\sin 2\beta = 0.667 \pm 0.023 \pm 0.012$

$A_\psi = 0.006 \pm 0.016 \pm 0.012$

PRL108, 171802 (2012)
B FACTORIES AND THE INTENSITY FRONTIER

Physics of the B Factories
Ed. A.J. Bevan, B. Golob, Th. Mannel, S. Prell, and B.D. Yabsley,

S. Olsen, D. Hitlin, J. Dorfan, F. Takasaki

T. Maskawa, M. Kobayashi
OPEN QUESTIONS

Summer 2018 ICHEP:
World Average is still ~4σ from the Standard Model

\[ R(D^*) = \frac{B(B \to D^{(*)} \tau \nu)}{B(B \to D^{(*)} l \nu)} \quad l = \mu, e \quad \text{LHCb only} \mu \]

\[ R_K = \frac{\text{BR}(B \to K^{(*)} \mu^+ \mu^-)}{\text{BR}(B \to K^{(*)} e^+ e^-)} \]

\[ R_K \approx 2.1\sigma \text{ (low bin), 2.5\sigma (central bin)} \]
COMPLEMENTARITY $e^+e^-$ AND LHC

The current combined $B \rightarrow \tau \nu$ limit places a stronger constraint than direct searches from LHC exps. for the next few years.

Currently inclusive $b \rightarrow s \gamma$ rules out $m_{H^+}$ below $\sim 480$ GeV/c$^2$ range at 95% CL (independent of $\tan\beta$), M. Misiak et al. (assuming no other NP)


For more detail see a dedicated talk at this conference by D. Tonelli
WHAT IS THE GAME AT ASYMMETRIC $e^+e^-$ FACTORIES

**Asymmetric Collider**

- $e^-$ (7 GeV)
- $e^+$ (4 GeV)

- $B$ production
- $B^-$ production

- $\sim 130$ m$\mu$

- The beam energies are asymmetric (7 on 4 GeV)
- The decay distance is increased by around a factor $\sim 7$

**But also some difficulties:**

- $e^+e^-$ cross section about 1000 smaller than hadronic production
- Production of only $B_d$ and $B_u$, $B_s$ is possible at smaller rate, $B_c$ unreachable

**Coherent B Bbar initial state**

**Vertex $\Delta z \rightarrow \Delta t$ in decay proper time**

**Final state can identify flavor, or select CP eigenstate**
Now use the full Phase 2 pilot run dataset and apply the FEI (Full Event Interpretation) technique based on boosted decision trees (BDTs, a machine learning technique).

We now observe ~571 fully reconstructed B mesons (389+182) or an improvement of a factor of ~O(3.6) in overall efficiency by using this advanced analysis method that covers many more decay channels.
Peak Luminosity Trends ($e^+e^-$ collider)

- $10^{36}$
- $10^{35}$
- $10^{34}$
- $10^{33}$
- $10^{32}$
- $10^{31}$
- $10^{30}$

Luminosity vs Year

- KEKB
- PEP-II
- CESR
- DAΦNE
- LEP II
- BEPC-II
- SPEAR
- DORIS
- PETRA
- LEP I

SuperKEKB

40 times higher luminosity
NANO BEAM SCHEME TO INCREASE LUMINOSITY

$$L = \frac{\gamma e^\pm}{2e r_e} \left(1 + \frac{\sigma^*_y}{\sigma^*_x} \right) \frac{I^e_{\pm 0}}{\beta^*_y} \left(\frac{R_L}{R_{\xi_y}}\right)$$

Lorenz factor
Beam current
Lumi. reduction factor (crossing angle)
Tune shift reduction factor (hour glass effect)
Beam size ratio@IP
Classical electron radius
Vertical beta function@IP

1. **Smaller** $\beta_y^*$
2. **Increase beam currents**
3. **Increase** $\xi_y$

"Nano-Beam" scheme

$$\sigma(s) = \sqrt{\epsilon \cdot \beta(s)}$$

Collision with very small spot-size beams

Invented by Pantaleo Raimondi for SuperB
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 positrons to inject

Damping ring

New positron target / capture section

Add / modify RF systems for higher beam current
**LUMINOSITY PROFILE**

**Phase I (Feb – June 2016 )**
- Background commissioning detectors (diamond TPC’s, diodes, crystals...)
- Circulated both beams but no collisions;
- Tune accelerator optics, etc.; vacuum scrubbing

**Phase II (2018)**
- First collisions!
- Beam Commissioning
- Background measurements with BEAST II/2
- Full Belle II outer detector without Vertex Detector

**Phase III (2019 →)**
- Physics run
**SCHEDULE**

- First collision April 26th 2018
- Phase 3 has started March 11th

THE SHOW MUST GO ON!!!!
BELLE II DETECTOR

EM Calorimeter: Csl(Tl), waveform sampling

Vertex Detector: 2 (1 in 2019) layers DEPFET + 4 layers DSSD

Beryllium beam pipe 2cm diameter

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

Particle Identification
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (fwd)

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

Electrons (7GeV)

Positrons (4GeV)

SVD: 4 DSSD lyrs → 2 DEPFET lyrs + 4 DSSD lyrs
CDC: small cell, lor
ACC+TOF → TOP+A-RICH
ECL: waveform sampling (+pure CsI for endcaps)
KLM: RPC → Scintillator +MPPC (endcaps, barrel inner 2 lyrs)
>800 members
101 institution
25 countries
First collisions on April 26
\( \beta^* \) successfully squeezed down to \( \beta^* = 2 \text{mm} \)
\( L = 5.54 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1} \)
\( L_{\text{spec}} = 2 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1} \)
Integrated Luminosity (online): 500 pb\(^{-1}\)

\[ e^+e^- \rightarrow \gamma^* \rightarrow B \bar{B} \]
PHASE2: PHOTON RECONSTRUCTION

\[ e^+e^- \rightarrow \mu^+\mu^-\gamma \quad \pi^0 \rightarrow \gamma\gamma \quad \eta \rightarrow \gamma\gamma \]

- Good reconstruction of both single photons and pairs
- Ready for the “dark sector” – single photons

\[ e^+e^- \rightarrow \gamma X \]
\[ e^+e^- \rightarrow \gamma ALP \rightarrow \gamma\gamma \]
PHASE2: TRACKING

\[ K_S \rightarrow \pi^+ \pi^- \]

\[ J / \psi \rightarrow \mu^+ \mu^- , \ J / \psi \rightarrow e^+ e^- \]

- Good tracking efficiency.
**PHASE2: RE-DISCOVERY OF B MESONS**

\[ \Delta E = \frac{E_{cm}}{2} - E_{recon} \]

\[ M_{bc} = \sqrt{\left(\frac{E_{cm}}{2}\right)^2 - p_{recon}^2} \]

**Belle II**

2018 preliminary

\[ \int L \, dt = 472 \text{ pb}^{-1} \]

**VOLUME 50, NUMBER 12**

**PHYSICAL REVIEW LETTERS**

21 MARCH 1983

**Observation of Exclusive Decay Modes of b-Flavored Mesons**

\[ 40.7 \text{ pb}^{-1} \]

**B**-meson decays to final states consisting of a \( D^0 \) or \( D^{**} \) and one or two charged pions have been observed. The charged-\( B \) mass is \( 5270.8 \pm 2.3 \pm 2.0 \) MeV and the neutral-\( B \) mass is \( 5274.2 \pm 1.9 \pm 2.0 \) MeV.
PHYSICS: EARLY PHASE3

- Luminosity will depend on machine and detector performance
- Let’s assume 10 fb⁻¹ by summer 2019

**SEMILEPTONIC**
\[ B \rightarrow \pi \nu \text{ and } \rho \nu \text{ untagged (CLEO saw a signal with } 2.66 \text{ fb}^{-1} \]

**TIME DEPENDENT CP VIOLATION AND CHARM**
- D lifetimes (2 fb⁻¹)
- \[ D^0 \rightarrow K^+ \pi^- , \ D^0 \rightarrow K^+ \pi^- \pi^0 (10 \text{ fb}^{-1}) \]
- B lifetimes (2-10 fb⁻¹)
- Time dependent B mixing (10 fb⁻¹)

**RADIATIVE ELECTROWEAK PENGUINS**
- \[ B \rightarrow K^* \gamma (2 \text{ fb}^{-1}) \text{ rediscovery penguins} \]
- \[ B \rightarrow X_{s\gamma} (10 \text{ fb}^{-1}) \]

**HADRONIC B DECAYS**
- \[ B \rightarrow K\pi (10 \text{ fb}^{-1}) \]
- \[ B \rightarrow \phi K (10 \text{ fb}^{-1}) \]
- \[ B \rightarrow J/\psi K (2-10 \text{ fb}^{-1}) \]
- Time dependent B mixing (10 fb⁻¹)

**DARK SECTOR** physics publications!
New triggers will be used in Belle II to search for dark matter and dark photons.

Single photon trigger with $\sim 1$ GeV threshold to search for dark photon decaying into light dark matter

For more details see dedicated talk at this conference by G. Inguglia
PHYSICS PHASE3: $B \rightarrow D(*)\tau\nu$

- Partial cancellation of theoretical uncertainties related to hadronic effects and measurement systematics.

\[ R(D^*) = \frac{\Gamma(B \rightarrow D(*)\tau\nu)}{\Gamma(B \rightarrow D(*)\ell\nu)} \] (\(\ell = e\) or \(\mu\))

\[ P_{\tau}(D^*) = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-} \] \((\Gamma^\pm\): decay rate of \(\pm\tau\)-helicity)

- Another probe of New Physics

**Belle II 5 ab\(^{-1}\)**

**Very clean theoretical prediction**
PHASE3 PHYSICS PERSPECTIVES

- B2TIP: Belle2 Theory Interface Platform
- A series of joint workshops with theorists
- Belle II Physics book submitted to PTEP

https://inspirehep.net/record/1692393/
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<th>Observables</th>
<th>Expected the. accuracy</th>
<th>Expected exp. uncertainty</th>
<th>Facility (2025)</th>
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| CP Violation |           |                           |                |
| $S(B \rightarrow \phi K^0)$ | *** | 0.02                      | Belle II       |
| $S(B \rightarrow \eta' K^0)$ | *** | 0.01                      | Belle II       |
| $A(B \rightarrow K^0\pi^0)[10^{-2}]$ | *** | 4                         | Belle II       |
| $A(B \rightarrow K^+\pi^-)[10^{-2}]$ | *** | 0.20                      | LHCb/Belle II  |

| (Semi-)leptonic |           |                           |                |
| $B(B \rightarrow \tau \nu)$ | [10^{-6}] | 3%                        | LEPT           |
| $B(B \rightarrow \mu \nu)$ | [10^{-6}] | 7%                        | SL             |
| $R(B \rightarrow D^+\tau\nu)$ | *** | 3%                        | LFUV           |
| $R(B \rightarrow D^+\tau\nu)$ | *** | 2%                        | Bell II/LHCb   |

| Radiative & EW Penguins |           |                           |                |
| $B(B \rightarrow X_s\gamma)$ | ** | 4%                        | EWP            |
| $A_{CP}(B \rightarrow X_s,d\gamma)$ [10^{-2}] | *** | 0.005                     |                |
| $S(B \rightarrow K_S^0\pi^0\gamma)$ | *** | 0.03                      | Belle II       |
| $S(B \rightarrow \rho\gamma)$ | ** | 0.07                      | Belle II       |
| $B(B_s \rightarrow \gamma\gamma)$ [10^{-6}] | ** | 0.3                       | Belle II       |
| $B(B \rightarrow K^+\nu\nu)$ [10^{-6}] | *** | 15%                       | Belle II       |
| $B(B \rightarrow K^0\pi^0\nu\nu)$ [10^{-6}] | *** | 20%                       | Belle II       |
| $R(B \rightarrow K^+\ell\ell)$ | *** | 0.03                      | Belle II/LHCb  |

| Charm |           |                           |                |
| $B(D_s \rightarrow \mu\nu)$ | *** | 0.9%                      | Charm          |
| $B(D_s \rightarrow \tau\nu)$ | *** | 2%                        |                |
| $A_{CP}(D^0 \rightarrow K_{S}^{0}\pi^{0})$ [10^{-2}] | ** | 0.03                      | Belle II       |
| $a/q|p(D^0 \rightarrow K_{S}^{0}\pi^{+}\pi^{-})$ | *** | 0.03                      | Belle II       |
| $\phi(D^0 \rightarrow K_{S}^{0}\pi^{+}\pi^{-})$ [°] | *** | 4                         | Belle II       |

| Tau |           |                           |                |
| $\tau \rightarrow \mu\gamma$ [10^{-10}] | *** | < 50                      | LFV            |
| $\tau \rightarrow e\gamma$ [10^{-10}] | *** | < 100                     |                |
| $\tau \rightarrow \mu\mu\mu$ [10^{-10}] | *** | < 3                       | Belle II/LHCb  |

- Very rich physics program in the next few years
CONCLUSIONS

• Belle II has completed the initial data taking (Phase 2)
  Understanding the machine and the backgrounds
  Detector and software checkout
  Initial physics

• Belle II will explore New Physics on the Intensity Frontier in a complementary way w.r.t. LHC high $p_T$ experiments, in a healthy competition with LHCb

• We are ready to start a long physics run in the Super Factory mode (Phase 3) from yesterday!
  This requires high-efficiency data-taking by Belle II and extensive running by Super KEK-B, soon to be the world’s highest luminosity accelerator.

• Particle Physics community is waiting for our results ➔ first at LP2019
## SUPERKEKB DESIGN PARAMETERS

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<th>parameters</th>
<th>KEKB</th>
<th>SuperKEKB</th>
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<td>LER</td>
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<td>Beam energy $E_b$</td>
<td>3.5</td>
<td>8</td>
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<td>Half crossing angle $\phi$</td>
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<td>Horizontal emittance $\varepsilon_x$</td>
<td>18</td>
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<td>Emittance ratio $\kappa$</td>
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<td>Beta functions at IP $\beta_x^<em>/\beta_y^</em>$</td>
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<td>Beam currents $I_b$</td>
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<td>beam-beam parameter $\xi_y$</td>
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<tr>
<td>Luminosity $L$</td>
<td>$2.1 \times 10^{34}$</td>
<td>$8 \times 10^{35}$</td>
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- 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
- Consequence $\beta_y$: decrease 0.42 $\rightarrow$ 0.28
### Physics Competition and Complementarity

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</tr>
</tbody>
</table>

- **Belle II**
  - \( L = 5 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1} \) achieved!
  - Physics with VXD in 2019
## GLOBAL SCHEDULE

### Ongoing status and JFY2018 plan

**Phase 1**
- MR startup
- MR renovation for phase 2, including installation of QCS and Belle II
- DR installation & startup

**Phase 2**
- HER start
- LER start
- VXD installation

**Phase 3**
- W/ Belle II
- W/ full Belle II
- Phase 3 operation 9 months / year

### Table

<table>
<thead>
<tr>
<th>Calendar year</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
<th>2019</th>
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<td>JFY2017</td>
<td>JFY2018</td>
<td>JFY2019</td>
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<tr>
<td></td>
<td>Summer shutdown (power saving)</td>
<td>Summer shutdown (power saving)</td>
<td>Summer shutdown (power saving)</td>
<td>Summer shutdown (power saving)</td>
<td>...</td>
</tr>
</tbody>
</table>

### Timeline

- **Phase 2 started April 26, 2018**
- **Phase 3 start Mar. 11, 2019**
- **Operation** Mar. 11, 2019 to 9:00 Jul. 1, 2019
- **Summer shutdown** Jul. 1, 2019 to Early autumn 2019 (end Sep-Oct)
- **Operation** Early autumn 2019 to ~Christmas
- **Winter shutdown** ~Christmas to Early 2020 (Jan-Feb)
- **Operation** Early 2020 (Jan-Feb) to 9:00 Jul. 1, 2020
- **Shutdown 2020** Jul. 1, 2020 to Depending on the amount of Belle II/superKEKB consolidation works

### Notes

- **12/03/2019**
- **2019**

---

**La Thuile 2019**
# E+E- CROSS SECTIONS

## Cross section @ Y(10580)

<table>
<thead>
<tr>
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<th>Cross-section (nb)</th>
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<tbody>
<tr>
<td>$e^+e^-$</td>
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<tr>
<td>$b\bar{b}$</td>
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</tr>
<tr>
<td>$c\bar{c}$</td>
<td>1.30</td>
</tr>
<tr>
<td>$s\bar{s}$</td>
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<tr>
<td>$u\bar{u}$</td>
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<tr>
<td>$d\bar{d}$</td>
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<tr>
<td>$\tau^+\tau^-$</td>
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<tr>
<td>$\mu^+\mu^-$</td>
<td>1.16</td>
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<tr>
<td>$e^+e^-$</td>
<td>$\sim$ 40</td>
</tr>
</tbody>
</table>

R = $\sigma(e^+e^- \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$

La Thuile 2019