New Physics Searches At Belle II

RA-B Day
13.10.2016

Thomas Kuhr
LMU Munich
Search for New Physics

- There must be so far unobserved particles or forces
  - **Direct search:** Production of new particles $\rightarrow$ ATLAS, CMS @ LHC
  - **Indirect search:** Contribution of virtual new particles to observed processed $\rightarrow$ Flavor physics

![Diagram of particle interactions](image-url)
Indirect Search

• Comparison: measurements - standard model predictions
  ➢ Good agreement of measurements so far with SM

  ➔ Contribution of new physics (NP) small:
    \[ |A_{NP}| < |A_{SM}| \]

• Experimentally observable:

  \[ |A_{SM} + A_{NP}|^2 = |A_{SM}|^2 + 2\text{Re}(A_{SM}^*A_{NP}) + |A_{NP}|^2 \]

  ➢ Interference → CP violation
  ➢ In SM suppressed or forbidden processes

  ➔ B mesons offer various possibilities to search for NP
Indirect Search Experiments

- **B factories**: BaBar, Belle
- **Hadron collider experiments**: LHCb, ATLAS, CMS, CDF, D0

- ![Graph showing B(B^0_s \rightarrow \mu^+ \mu^-) values with contours and measurements from ATLAS and CMS.

- Most precision measurements in good agreement with SM
- Stringent NP constraints
- Minimal flavor violation
SuperKEKB

Peak Luminosity Trends ($e^+e^-$ collider)

- $8 \times 10^{35}$ cm$^{-2}$ s$^{-1}$
- Nano beams
Belle II Data

Goal of Belle II/SuperKEKB

- Today: $1 \text{ab}^{-1}$
- 2024: $50 \text{ab}^{-1}$

→ Significantly increased sensitivity for searches for new particles
B Factory

- Reaction: $e^+e^- \rightarrow Y(4S) \rightarrow B^0\bar{B}^0$ (50%), $B^+B^-$ (50%)
  - $m(Y(4S)) = 10.58$ GeV, $2 \times m(B) = 10.56$ GeV

- Oscillation of $B^0$-Mesonen

- Time dependent effect of CP violation

\[ a_f(t) = \frac{\Gamma(\bar{B}^0 \rightarrow f, t) - \Gamma(B^0 \rightarrow f, t)}{\Gamma(\bar{B}^0 \rightarrow f, t) + \Gamma(B^0 \rightarrow f, t)} \approx S \sin(\Delta mt) \]

- Flavor of initial state, time of decay
Measurement of time-dep. CP Violation

→ Asymmetric beam energies

→ Entanglement
  • Decay of one B meson at time $t_{tag}$ in flavor eigenstate $Q \rightarrow$ tagging
  • Other B meson is at time $t_{tag}$ in flavor state $\bar{Q}$
  • Time measurement: $\Delta t = t_{sig} - t_{tag} = \Delta z / c\beta\gamma$

$e^- \rightarrow Y(4S) \rightarrow e^+ e^-$

$B^0_{sig}$

$B^0_{tag}$

$\Delta z$

$\pi^-$

$\pi^+$

$\pi^-$

$\mu^+$

$\mu^-$

$K^0_s$

$\bar{K}^0$

$\bar{Y}(4S)$

$\bar{Y}(4S)$

$PRL\ 108,171802\ (2012)$
Search for New CP Violating Phases

\[ \sin(2\beta_{\text{eff}}) = \sin(2\phi_1^{\text{eff}}) \]
Search for Right-Handed Currents

- $B^0 \rightarrow K^{*0} (\rightarrow K_S \pi^0) \gamma$

  - **SM:**
    - $S_{CP} = 2 \left( \frac{m_s}{m_b} \right) \sin(2\phi_1)$

  - Values up to $0.7 \sin(2\phi_1)$ possible in left-right symmetric NP models
Full Reconstruction

- Full reconstruction of one hadronically decaying B meson
  - Momentum and charge of signal B meson known
  - All remaining particles belong to signal B meson
  - Reconstruction of decays with neutrinos

\[ B^+ \rightarrow K^+ \nu \bar{\nu} \]

Assumption: SM signal

\[ N_{\text{sig}} = 91.5 \pm 32.2 \]
Search for New FCNCs: $B \rightarrow K^{(*)}\nu\bar{\nu}$

- Decay with flavor changing neutral current (FCNC)
- No tree diagram in SM

→ **SM prediction:**
  
  $\text{BR}(B^+ \rightarrow K^+\nu\bar{\nu}) = (4.4 \pm 0.7) \times 10^{-6}$  Buchalla, NPPS 209, 137
  
  $\text{BR}(B^+ \rightarrow K^{*+}\nu\bar{\nu}) = (6.8^{+1.0}_{-1.1}) \times 10^{-6}$  Altmannshofer et al, JHEP 0904, 022

- Sensitive to new physics
New Physics in $B \to K^{(*)}\nu\bar{\nu}$

$C_{L/R}^\nu$:
left/right
handed
Coupling

\[ \frac{-\text{Re}(C_L^\nu C_R^{\nu*})}{|C_L^\nu|^2 + |C_R^\nu|^2} \]

\[ \epsilon = \frac{\sqrt{|C_L^\nu|^2 + |C_R^\nu|^2}}{|(C_L^\nu)_{\text{SM}}|} \]

Altmannshofer et al, JHEP 0904, 022
Search for New Invisible Particles

- Same experimental signature of $B \to K^{(*)}\nu\bar{\nu}$ and $B \to K^{(*)} +$ invisible particles (S)

  ➔ Can be distinguished from $K\nu\bar{\nu}$ if new particles have mass

  ➔ Requires measurement of $q^2 = m^2(\nu\bar{\nu})$
Search for Multiple Higgs Bosons

World average of $R(D), R(D^*)$ 4.0$\sigma$ away from SM pred.

Incompatible with 2HDM of type II
Example of Theoretical Explanation

2HDM of type X with additional non-standard Yukawa couplings

PRL 116, 081801 (2016)

FIG. 6: Left: Allowed regions in the $\epsilon_{32}^{u}$-plane from $\mathcal{R}(D)$ (blue) and $\mathcal{R}(D^*)$ (yellow) for $\tan \beta = 50$, $m_{H^+} = 200$ GeV, and $\epsilon_{33}^{\ell} = 0$. The scaling of the allowed region for $\epsilon_{32}^{u}$ with $\tan \beta$ and $m_{H^+}$ is the same as for $\epsilon_{31}^{u}$. $e^u$ is given at the matching scale $m_{H^+}$. Right: Allowed regions in the $\epsilon_{32}^{u} \frac{\tan \beta (100 \text{ GeV})^2}{m_{H^+}^2}$ plane for $\epsilon_{33}^{\ell} = 0$ (yellow), $\frac{m_{\tau}}{2v}$ (blue), $\frac{3m_{\tau}}{2v}$ (red) and $\frac{2m_{\tau}}{v}$ (green).

Also $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ can be easily explained by additional $t-c$–Higgs couplings. Combining these $t-c$ couplings with a light $H$ the decay rate for $t \to Hc$ can be in a testable range for the LHC.
More New Physics Searches

Lepton flavor violation

B(τ → μγ) 90% CL upper limit [10⁻⁹]:
45 (~0.5 ab⁻¹) → 5 (50 ab⁻¹)

CP violation in D⁰ mixing

Precision of |q/p|:
0.16 (~0.5 ab⁻¹) → 0.05 (50 ab⁻¹)
## Important Measurements for NP Search

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

### CPV

<table>
<thead>
<tr>
<th>Observable</th>
<th>Expected th. accuracy</th>
<th>Expected exp. uncertainty</th>
<th>Facility</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S(B_s \to \psi \phi)$</td>
<td>**</td>
<td>0.01</td>
<td>LHCb</td>
</tr>
<tr>
<td>$S(B_s \to \phi \phi)$</td>
<td>**</td>
<td>0.05</td>
<td>LHCb</td>
</tr>
<tr>
<td>$S(B_d \to \phi K)$</td>
<td>***</td>
<td>0.05</td>
<td>Belle II/LHCb</td>
</tr>
<tr>
<td>$S(B_d \to K^*(\to K_0^0(\pi^0)(\gamma))$</td>
<td>***</td>
<td>0.03</td>
<td>Belle II</td>
</tr>
<tr>
<td>$S(B_s \to \phi \gamma)$</td>
<td>***</td>
<td>0.05</td>
<td>LHCb</td>
</tr>
<tr>
<td>$A_{SL}^d$</td>
<td>***</td>
<td>0.15</td>
<td>Belle II</td>
</tr>
<tr>
<td>$A_{SL}^s$</td>
<td>***</td>
<td>0.001</td>
<td>LHCb</td>
</tr>
<tr>
<td>$A_{CP}(B_d \to s \gamma)$</td>
<td>*</td>
<td>0.005</td>
<td>Belle II</td>
</tr>
</tbody>
</table>

### Rare decays

<table>
<thead>
<tr>
<th>Observable</th>
<th>Expected th. accuracy</th>
<th>Expected exp. uncertainty</th>
<th>Facility</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B(B \to \tau \nu)$</td>
<td>**</td>
<td>3%</td>
<td>Belle II</td>
</tr>
<tr>
<td>$B(B \to D \tau \nu)$</td>
<td>**</td>
<td>3%</td>
<td>Belle II</td>
</tr>
<tr>
<td>$B(B_d \to \mu \nu)$</td>
<td>**</td>
<td>6%</td>
<td>Belle II</td>
</tr>
<tr>
<td>$B(B_s \to \mu \nu)$</td>
<td>**</td>
<td>10%</td>
<td>LHCb</td>
</tr>
<tr>
<td>zero of $A_{FB}(B \to K^* \mu \mu)$</td>
<td>**</td>
<td>0.05</td>
<td>LHCb</td>
</tr>
<tr>
<td>$B(B \to K^{(*)} \nu \nu)$</td>
<td>***</td>
<td>30%</td>
<td>Belle II</td>
</tr>
<tr>
<td>$B(B \to s \nu \nu)$</td>
<td>**</td>
<td>4%</td>
<td>Belle II</td>
</tr>
<tr>
<td>$B(B_s \to \gamma \gamma)$</td>
<td>**</td>
<td>0.25 - $10^{-6}$</td>
<td>Belle II (with 5 ab$^{-1}$)</td>
</tr>
<tr>
<td>$B(K \to \pi \nu \nu)$</td>
<td>**</td>
<td>10%</td>
<td>$K$-factory</td>
</tr>
<tr>
<td>$B(K \to e \nu \nu)/B(K \to \mu \nu \nu)$</td>
<td>***</td>
<td>0.1%</td>
<td>$K$-factory</td>
</tr>
</tbody>
</table>

### Charm and $\tau$

<table>
<thead>
<tr>
<th>Observable</th>
<th>Expected th. accuracy</th>
<th>Expected exp. uncertainty</th>
<th>Facility</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B(\tau \to \mu \gamma)$</td>
<td>***</td>
<td>$3 \cdot 10^{-9}$</td>
<td>Belle II</td>
</tr>
<tr>
<td>$</td>
<td>g/p</td>
<td>_D$</td>
<td>***</td>
</tr>
<tr>
<td>$\arg(g/p)_D$</td>
<td>***</td>
<td>1.5°</td>
<td>Belle II</td>
</tr>
</tbody>
</table>

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Figure 1: Towards New Standard Model in 12 Steps.
Buras, Girrbach, arXiv:1306.3775

Isidori, Nir, Perez
First Turns!

Press Release

First turns and successful storage of beams in the SuperKEKB electron and positron rings

March 2nd, 2016

High Energy Accelerator Research Organization (KEK)
SuperKEKB / Belle II Startup

- **Phase 1**, Feb-Jun 2016
  - Circulate both beams, no collisions
  - Accelerator tuning
  - **Background measurements with BEAST detector**

- **Phase 2**, starts end of 2017 for few months
  - Collisions
  - Accelerator tuning
  - **Background measurements and first physics with Belle II detector w/o vertex detectors**

- **Phase 3**, starts end of 2018
  - Physics running with full Belle II detector
BEAST Detector

Belle and the BEAST

Belle II will eventually roll in on a pair of railroad tracks
Installation of QCS-L in August
Installation of QCS-L in August

- Item
Summary

➢ There must be new physics
➢ Search for NP by detecting virtual particles in flavor changing processes
   ▪ CP violation, rare decays
➢ Need much more data to find or exclude NP
✔ 50 ab\(^{-1}\) with nano-beam scheme at SuperKEKB
✔ Start of Belle II data taking in 2018
➢ Unique opportunities for search for new physics with unprecedented precision
➢ Complementary to searches at LHC
Backup
Belle II Detector

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

**Beryllium beam pipe**
- 2cm diameter

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

**Central Drift Chamber**
- He(50%):C$_2$H$_6$(50%), small cells, long lever arm, fast electronics

**K$^-$ and muon detector:**
- Resistive Plate Counter (barrel)
- Scintillator + WLSF + MPPC (end-caps)

**Particle Identification**
- Time-of-Propagation counter (barrel)
- Proximal focusing Aerogel RICH (fwd)

**Tracking**
- Calorimeter
- Magnet
- Vertex detector
- Muon detector
- Photon
- Charged particle
- Tracking
- Calorimeter
CP Violation → Interference

\[ q \rightarrow q' \quad V_{qq'} \quad \text{CP} \quad \bar{q} \rightarrow \bar{q}' \quad V^*_{qq'} \]

\[ B^0_s \quad f_{CP} \quad \bar{B}^0_s \quad \text{CP} \quad \bar{B}^0_s \quad f_{CP} \quad B^0_s \]
Direct $\mathcal{CP}$ in $B \to K\pi$

Sum rule:

$$\Delta A(K^0\pi^0) = \frac{A_f(K^+\pi^-) + A_f(K^0\pi^+) B(K^0\pi^+) \tau_{B^0}}{B(K^+\pi^-) \tau_{B^+}} =$$

$$+ \frac{A_f(K^+\pi^0) 2B(K^+\pi^0) \tau_{B^0}}{B(K^+\pi^-) \tau_{B^+}} + \frac{A_f(K^0\pi^0) 2B(K^0\pi^0)}{B(K^+\pi^-)}.$$ 

\[50 \text{ ab}^{-1}\]

\[\Delta A(K^0\pi^0): 0.15\]

\[\Delta A(K^0\pi^0): 0.042\]
Rare Decay: $B \to \tau \nu$

- **SM:**
  \[
  B(B^+ \to \tau^+ \nu) = \frac{G_F^2 m_B m_{\tau}^2}{8\pi} \left(1 - \frac{m_{\tau}^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B
  \]

- **Two Higgs doublet model:**
  \[
  B(B^+ \to \tau^+ \nu) = B(B^+ \to \tau^+ \nu)_{SM} \left(1 - \frac{m_B^2}{m_H^2} \tan^2 \beta\right)^2
  \]

**Expected sensitivity with 50 fb$^{-1}$:**
\[
\sigma(BR)/BR_{SM} = 3%
\]
### Projections for CKM Metrology

<table>
<thead>
<tr>
<th></th>
<th>Belle</th>
<th>BaBar</th>
<th>Global Fit CKMfitter</th>
<th>LHCb Run-2</th>
<th>Belle II 50 ab⁻¹</th>
<th>LHCb Upgrade 50 fb⁻¹</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \varphi_1: \text{ccs} )</td>
<td>0.9°</td>
<td>0.9°</td>
<td>0.6°</td>
<td>0.3°</td>
<td>0.3°</td>
<td>v. small.</td>
<td></td>
</tr>
<tr>
<td>( \varphi_2: \text{uud} )</td>
<td>4° (WA)</td>
<td>2.1°</td>
<td></td>
<td>1°</td>
<td></td>
<td>~1-2°</td>
<td></td>
</tr>
<tr>
<td>( \varphi_3: \text{DK} )</td>
<td>14°</td>
<td>3.8°</td>
<td>4°</td>
<td>1.5°</td>
<td>1°</td>
<td>negl.</td>
<td></td>
</tr>
<tr>
<td>(</td>
<td>V_{cb}</td>
<td>) inclusive</td>
<td>1.7%</td>
<td>2.4%</td>
<td></td>
<td>1.2%</td>
<td></td>
</tr>
<tr>
<td>(</td>
<td>V_{cb}</td>
<td>) exclusive</td>
<td>2.2%</td>
<td></td>
<td></td>
<td>1.4%</td>
<td></td>
</tr>
<tr>
<td>(</td>
<td>V_{ub}</td>
<td>) inclusive</td>
<td>7%</td>
<td>4.5%</td>
<td></td>
<td>3.0%</td>
<td></td>
</tr>
<tr>
<td>(</td>
<td>V_{ub}</td>
<td>) exclusive</td>
<td>8%</td>
<td></td>
<td></td>
<td>2.4%</td>
<td></td>
</tr>
<tr>
<td>(</td>
<td>V_{ub}</td>
<td>) leptonic</td>
<td>14%</td>
<td></td>
<td></td>
<td>3.0%</td>
<td></td>
</tr>
</tbody>
</table>

**Experiment**  
- No result  
- Moderate precision  
- Precise  
- Very Precise  

**Theory**  
- Moderate precision  
- Clean / LQCD  
- Clean
Tokyo (40 mins by Tsukuba Exps)
Accelerator Design: Nano Beam Scheme

Invented by Pantaleo Raimondi for SuperB

\[ L = \frac{\gamma \pm 1}{2er_e} \left( 1 + \frac{\sigma_y^*}{\sigma_x^*} \right) I_{\pm, y} \xi_{y, \pm} \frac{R_L}{R_{\xi, y}} \]

Beam-BEAM parameter: \( \xi_y \propto \sqrt{\left( \beta_y^*/\epsilon_y \right)} \)

Geometrical reduction factors (crossing angle, hourglass effect)

Lorentz factor

Beam current

Beam aspect ratio at IP

Vertical beta function at IP

<table>
<thead>
<tr>
<th></th>
<th>E (GeV)</th>
<th>( \beta^*_y ) (mm)</th>
<th>( \beta^*_x ) (cm)</th>
<th>( \varphi ) (mrad)</th>
<th>I (A)</th>
<th>L (cm(^2)s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>KEKB</td>
<td>3.5/8.0</td>
<td>5.9/5.9</td>
<td>120/120</td>
<td>11</td>
<td>1.6/1.2</td>
<td>2.1 x 10(^34)</td>
</tr>
<tr>
<td>SuperKEKB</td>
<td>4.0/7.0</td>
<td>0.27/0.30</td>
<td>3.2/2.5</td>
<td>41.5</td>
<td>3.6/2.6</td>
<td>80 x 10(^34)</td>
</tr>
</tbody>
</table>
SuperKEKB Upgrade

- Replace short dipoles with longer ones (LER)
- New beam pipe & bellows
- TiN-coated beam pipe with antechambers
- Redesign the lattices of HER & LER to squeeze the emittance
- New superconducting/permanent final focusing quads near the IP
- Low emittance electrons to inject
- Low emittance positrons to inject
- New positron target / capture section
- Add / modify RF systems for higher beam current
- New IR
- Belle II
- Low emittance gun
- Positron source
- New beam pipe & bellows
Belle II Detector Challenges

➢ Higher background → radiation damage, occupancy
➢ Higher event rate → trigger, DAQ, computing
• Low momentum particle reconstruction and ID, hermeticity
➢ Detector has to be upgraded for SuperKEKB conditions to achieve equal or better performance than at KEKB
Belle II Detector Compared with Belle
Belle II Collaboration

~680 members
100 institutions
23 countries
Belle II Organization

Outreach Committee
Chair: Toru Iijima

Speakers Committee
Chair: Alan Schwartz

Institutional Board
Chair: Christopher Hearty
Institutional representatives

Management
Spokesperson: Thomas Browder
Project Manager: Yutaka Ushiroda
Financial Officer: Yoshihide Sakai

Executive Board
Chair: Francesco Forti

Financial Board
Chair: Yoshihide Sakai
National representatives

Detector
Technical coordinator: Peter Krizan (acting)
Integration leaders: Ichiro Adachi (outer)
Shuji Tanaka (inner)

Data Production
Coordinator: Jako Bennett
Deputy: Karim Trabelsi

Operations
Run coordinator: Shoji Uno

Software
Coordinator: Thomas Kuhr

Computing
Coordinator: Takenori Hara

Physics
Coordinator: Philip Urquijo

VXD
Commissionsing
C. Mamar, K. Nakamura

Online integration
Sand, M. Kaufman

Data processing
T. Harai, K. Hata

Analysis Software & tool validation
A. Zupanc

Combined Particles
F. Semenov

Evgen
F. Semenov

Radiative Electroweak Physics
A. Ichikawa

Belle II Organization

LMU Thomas Kuhr


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