Super Flavor Experiments
Belle-II & LHCb Upgrade

P5 meeting at Brookhaven National Laboratory
December 17, 2013

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University of Maryland
Organization of the talk

- What do we hope to learn on New Physics (NP) from the next generation of Heavy Flavor experiments?
  - For TeV scale NP: Can they reveal info on structure of NP?
  - If no TeV scale NP is found: Can they further constrain the scale of NP?

- Belle-II experiment at SuperKEKB:
  - Upgrade of Belle @ KEKB experiment: asymmetric energy $e^+e^-$ collider at $\Upsilon(4S)$, with peak $L = 8 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$; $(\sigma(bb) \sim 1 \text{ nb})$

- Upgrade of LHCb experiment at CERN:
  - Upgrade of the LHCb experiment, forward spectrometer at LHC, to operate at $L = 2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$; $(\sigma(bb) \sim 500 \mu\text{b})$
The past two decades brought tremendous clarity to the CKM picture. Thanks to B factories, Tevatron, LHCb, LQCD, and theory insights.

- The CKM picture of CPV in SM seems to be correct (Nobel 2008)
- Flavor remains the only source of observed CP & T-violations
- Flavor Changing Interactions are now amongst the most precisely determined parts of SM:
  - Severe constraints on possible scenarios of New Physics
How much NP can be accommodated in flavor measurements?

- **Example**: NP constraints from Meson Mixing
  - Fit the CKM parameters allowing modification of mixing Matrix element:
    \[ M_{12} = M_{12}^{SM} \times (1 + h e^{2i\sigma}) \]
  - Determine NP parameter \( h \) & \( \sigma \) for \( B^0_d \) and \( B^0_s \) systems

- **Current data**:
  - \( B_s \) is now on equal ground as \( B_d \) system (Thanks to LHCb results).
  - Data allows NP at 20-30% SM

- **Future**:
  - If consistency with SM persists-
    - LHCb and Belle-II measurements-
      - combined with improved LQCD errors- will constrain the magnitude of NP contribution to \( \sim 5\% \) of SM

\[ h \]
\[ h_s \]
\[ h_d \]

2003

2013

7 fb\(^{-1}\) LHCb
5 ab\(^{-1}\) Belle-II

50 fb\(^{-1}\) LHCb
50 ab\(^{-1}\) Belle-II

Charles, Descotes-Genon, Ligeti et al.
Direct encounter with NP scenarios & parameter space:

Example of $B^0_d \rightarrow \mu^+\mu^-$ vs NP:
sensitive to new scalars in SUSY at large $\tan\beta$

At LHCb upgrade: 50 fb$^{-1}$

Example of $B^- \rightarrow \tau^-\nu$ vs charged Higgs:

$$BR(B \rightarrow \tau^-\nu) = BR_{SM}(B \rightarrow \tau^-\nu) \left( 1 - \frac{m_B^2}{M_H^2} \tan^2 \beta \right)^2$$

Excluded region

Belle-II 50 ab$^{-1}$
Implication of not seeing NP in Flavor (yet)

What do we learn on possible scale of NP?

- NP sensitivity is largely owed to FCNC processes: Forbidden at tree level in SM & Highly suppressed at loop level (GIM & CKM)

NP contribution at very high scale ($\Lambda$), can be comparable to SM amplitude

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} \left( \frac{f(V_{ij}V_{ik}^*)}{M_W^2} \right) + \sum_i \frac{C_{ij}}{\Lambda_{NP}^2} O_{ij}$$

- Isidori, Nir, Perez

- Relative to other probes
  From R. Sundrum at CKM workshop 2012
The Strength of Flavor Physics program rests with its access to a broad set of observables, and their correlated sensitivity to NP models:

In practice:

- Matching improvements in LQCD & other theory inputs also required.
- Precise measurements of CKM parameters and “engineering” channels also needed for data driven control of systematics and validation of theory inputs.
- Belle-II and LHCb coverages, while largely complementary, provide necessary-and healthy- overlap in some areas.

Next phase of Heavy Flavor Physics Program

Example of a possible NP-driven program


<table>
<thead>
<tr>
<th>Observation</th>
<th>AC</th>
<th>RIVV2</th>
<th>AKM</th>
<th>sLL</th>
<th>FBMSSM</th>
<th>LFT</th>
<th>RS</th>
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<td>★</td>
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<td>$B_s \to \mu^+\mu^-$</td>
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<td>$\mu + N \to e + N$</td>
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<td>$d_0$</td>
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<td>$(g - 2)_\mu$</td>
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</tbody>
</table>

NP signature & its structure may be revealed in the pattern of deviations from SM
Physics sensitivity in Key Channels

Belle-II

Will dominate inclusive channels, e.g. b->s γ... unique access to B→Kνν, B→τν, modes with many π^0 or γ, LFV in τ^±→μ^±γ,...Also access to Charm CPV.

LHCb

Will dominate the B^0_s sector, and exclusive decays with charged particles, e.g B→Kμ+μ−... Unique access to B_c & B-baryons & rare charmed decays, LFV in τ^±→μ^±γμ±.
Belle-II at SuperKEKB

Asymmetric Energy $e^+e^-$ collider at goal peak Luminosity $8 \times 10^{35}$ $/cm^2/s$ aiming for 50 $ab^{-1}$

Design based on Nano-beam scheme proposed by P. Raimondi (Frascati), tight focusing, larger crossing angle & higher $I_b$

**Accelerator Upgrade**
- low emittance electron injector
- New positron damping ring
- New vacuum chambers
- New HER and LER lattice and long dipoles for low emittance
- New IR for low $\beta^*$
- Modified and additional RF for higher currents

- Cost ~$400M (+ $50 M detector)

Detail Schedule in backup slides
Belle II Detector

~600 collaborators
100 institutes, 23 countries

SVD: 4 DSSD lyrs → 2 DEPFET lyrs + 4 DSSD lyrs
CDC: small cell, long lever arm
ACC+TOF → TOP+A-RICH
ECL: waveform sampling, pure CsI for end-caps
KLM: RPC → Scintillator +SiPM (end-caps)

KL and muon detector:
Resistive Plate Counter (barrel)
Scintillator + WLSF + MPPC (end-caps)

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

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%):C₃H₆(50%), Small cells, long lever arm, fast electronics

electron (7GeV)

positron (4GeV)
iTOP : An imaging time-of-propagation detector
US Contributions to Belle II

US Belle-II is 43 PhD’s from 13 institutions (PNNL, CMU, Cincinnati, Hawaii, Indiana, Kennesaw State, Luther College, Mississippi, Pittsburgh, S. Carolina, S. Alabama, Virginia Tech, Wayne State)

Funding: DOE (2/3) NSF Seeking-funding

- US contributions to particle identification systems
  - iTOP system (barrel PID) (Providing quartz optical elements)
  - KLM (muon system upgrade, endcap and barrel)
    - Providing replacement of inner layers of BKLM (done)
  - ASICs and front-end electronics
- To provide beamstrahlung monitors for accelerator
- Proposing to lead commissioning detector effort
- US (PNNL) hosting “tier 1” computing facility for Belle II

- The program has received CD0 & CD1 & preparing for CD 2 &3
- Total cost at 15M$ + 15M$ computing (15% of Belle-II computing)
Phase I:
without QCS and Belle II
Jan-May, 2015

Phase II:
with QCS and Belle II
without inner detector
Feb-June, 2016

Phase III:
Physics Run with full Belle II with partial TOP
Starts Oct, 2016
The LHCb Experiment
A Single Arm Spectrometer at LHC
Acceptance: $2 < \eta < 5$

$\sigma_{\text{inel}} \sim 70-80 \text{ mb}$
$\sigma_{cc} \sim 6 \text{ mb (7 TeV)}$
$\sigma_{\tau} \sim 80 \mu \text{b (7 TeV)}$
$\Sigma_{bb} \sim 300 \mu \text{b (7 TeV)}$
$\sigma_{bb} \sim 500 \mu \text{b (14 TeV)}$

$bb$ peaked forward or backward with $\sim 25\%$ in detector acceptance

Access to all species of $B$ hadrons

US Participation: Syracuse (since: 2005); Cincinnati, Maryland, & MIT (since 2012)
Current data & Plan

Since end of 2011, run with $L \sim 4 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ with 50 ns bunch spacing.

Will restart in 2015 at 13 TeV, with 25 ns bunch spacing (nominal). Expect to reach a total of $\sim 8 \text{ fb}^{-1}$ by 2018.
The LHCb upgrade

The upgrade is designed to run at luminosity of \( (1-2) \times 10^{33} \text{ cm}^{-2}\text{s}^{-1} \); Aiming for 50 fb\(^{-1}\)

- Requires new approach to the LHCb trigger scheme to overcome L0 (1MHz) limitation.

**New Trigger Approach:**
- Remove L0 (hardware) trigger
- Readout the detector at the 40 MHz LHC clock rate
- Move to a fully flexible software trigger

=>> Major upgrade of LHCb detector required: to cope with increase occupancy, data rate and radiation dose, & to preserve efficiency and low ghost rate: Replace all readout electronics, entire tracking system (Vertex locator, upstream & downstream tracking detectors) & upgrade Particle ID system
Upgrade plan

**Tracking system:**
- New VELO (Si strip → Pixel)
- New upstream tracker (UT) (Si)
- New downstream tracker (Sci Fiber - baseline option)

**RICH 1 & RICH 2**
- HPD → MaPMT
- New 40 MHz R/O
- RICH1: new optics
- remove aerogel

**Calorimeter:**
- New 40 MHz R/O
- Lower PMT gain to reduce anode current
- Remove SPD & PS

**Muon System:**
- Remove M1
- M2-5 fine for $1 \times 10^{33}$
- May need upgrade of inner region at $2 \times 10^{33}$
US Contribution to LHCb Upgrade

Construction of new Upstream Tracker (UT)
4 planes of single sided silicon sensors with segmentation optimized for the expected occupancy increase of LHCb upgrade, improved coverage & reduced material budget & new FE and readout electronics to cope with high data rate at 40 MHz readout.

• UT has a key role in High Level Trigger by reducing ghost rate & providing fast momentum measurement

➢ US collaboration: 4 institutions (Cincinnati, Maryland, Syracuse, MIT) (18 Ph.D.’s) all supported by NSF

➢ Upgrade proposal being prepared for submission to NSF
  ➢ NSF Cost at ~$6 M, plus funds from Zurich and Milano (~1.5 MSF)
  ➢ Schedule: 2014(R&D and design)- 2015(start of production & QA), 2018-2019(installation)

➢ US collaboration will continue participation in LHCb operation (2015-2017) and data analysis
2011 - Lol submitted: encouraged by the LHCC to proceed to TDRs

2012 - “Framework TDR” with costing (~57 MSF envelope) and technical options submitted. Endorsed (LHCC) & approved (RB: “LHCb upgrade approved to be part of the long-term exploitation of the LHC”) Submission of Addendum to MoU for Common Projects

2012/13 - R&D towards technical choices

2013/14 - Technical Design Reports & MoUs of sub-systems (updated costs still within the envelope of the FTDR)

2014 - Prototype validation & Engineering Design Reviews

2014/16 - Tendering & serial production

2016/17 - Quality control & acceptance tests

2018/19 - 18 months installation during LS2
Summary

✓ Heavy Flavor Physics has had tremendous progress in the past two decades and remains as one of the most powerful probes of Physics Beyond the Standard Model.

✓ The future of the field will be defined by the Super Flavor experiments, Belle-II & LHCb upgrade, planned for realization by the end of this decade.

✓ US has had a long history of leadership in this field and the participation of US physicists in these off-shore experiments is important to the health of US high energy physics program, as they have significant potential to discover or describe the structure of the physics beyond the Standard Model.
Backup slides
FIG. 10. Hypothetical Stage II fits for NP, assuming that all future experimental results correspond to the current best-fit values of $\bar{\rho}$, $\bar{\eta}$, $h_{d,e}$ and $\sigma_{d,e}$ (with measurement uncertainties as given in Table I, but different central values).
LHCb sensitivity to key flavour channels

Table 1: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the expected sensitivity is given for the integrated luminosity accumulated by the end of LHC Run 1, by 2018 (assuming 5 fb\(^{-1}\) recorded during Run 2) and for the LHCb Upgrade (50 fb\(^{-1}\)). An estimate of the theoretical uncertainty is also given – this and the potential sources of systematic uncertainty are discussed in the text.

<table>
<thead>
<tr>
<th>Type</th>
<th>Observable</th>
<th>LHC Run 1</th>
<th>LHCb 2018</th>
<th>LHCb upgrade</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>B(_s^0) mixing</td>
<td>(\phi_s(B_{s}^0 \rightarrow J/\psi \phi)) (rad)</td>
<td>0.05</td>
<td>0.025</td>
<td>0.009</td>
<td>~0.003</td>
</tr>
<tr>
<td></td>
<td>(\phi_s(B_{s}^0 \rightarrow J/\psi f_0(980))) (rad)</td>
<td>0.09</td>
<td>0.05</td>
<td>0.016</td>
<td>~0.01</td>
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<tr>
<td></td>
<td>(A_{s}(B_{s}^0)) (10(^{-3}))</td>
<td>2.8</td>
<td>1.4</td>
<td>0.5</td>
<td>0.03</td>
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<tr>
<td>Gluonic penguin</td>
<td>(\phi_{s}^{\text{eff}}(B_{s}^0 \rightarrow \phi \phi)) (rad)</td>
<td>0.18</td>
<td>0.12</td>
<td>0.026</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>(\phi_{s}^{\text{eff}}(B_{s}^0 \rightarrow K^{*0}K^{*0})) (rad)</td>
<td>0.19</td>
<td>0.13</td>
<td>0.029</td>
<td>&lt;0.02</td>
</tr>
<tr>
<td></td>
<td>(2\beta_{s}^{\text{eff}}(B_{s}^0 \rightarrow \phi K_{S}^0)) (rad)</td>
<td>0.30</td>
<td>0.20</td>
<td>0.04</td>
<td>0.02</td>
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<tr>
<td>Right-handed currents</td>
<td>(\phi_{s}^{\text{eff}}(B_{s}^0 \rightarrow \phi \gamma))</td>
<td>0.20</td>
<td>0.13</td>
<td>0.030</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td></td>
<td>(\tau_{s}^{\text{eff}}(B_{s}^0 \rightarrow \phi \gamma)/\tau_{B_{s}})</td>
<td>5%</td>
<td>3.2%</td>
<td>0.8%</td>
<td>0.2%</td>
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<tr>
<td>Electroweak penguin</td>
<td>(S_{3}(B_{s}^0 \rightarrow K^{*0}\mu^{+}\mu^{-}); 1 &lt; q^{2} &lt; 6 \text{ GeV}^2/c^4)</td>
<td>0.04</td>
<td>0.020</td>
<td>0.007</td>
<td>0.02</td>
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<td></td>
<td>(q^{2}<em>{\text{AFB}}(B</em>{s}^0 \rightarrow K^{*0}\mu^{+}\mu^{-}))</td>
<td>10%</td>
<td>5%</td>
<td>1.9%</td>
<td>~7%</td>
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<tr>
<td></td>
<td>(A_{1}(K\mu^{+}\mu^{-}); 1 &lt; q^{2} &lt; 6 \text{ GeV}^2/c^4)</td>
<td>0.14</td>
<td>0.07</td>
<td>0.024</td>
<td>~0.02</td>
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<tr>
<td></td>
<td>(B(B^{+} \rightarrow \pi^{+}\mu^{+}\mu^{-})/B(B^{+} \rightarrow K^{\pi}\mu^{+}\mu^{-}))</td>
<td>14%</td>
<td>7%</td>
<td>2.4%</td>
<td>~10%</td>
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<td>Higgs penguin</td>
<td>(B(B_{s}^0 \rightarrow \mu^{+}\mu^{-})(10^{-9}))</td>
<td>1.0</td>
<td>0.5</td>
<td>0.19</td>
<td>0.3</td>
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<td></td>
<td>(B(B_{s}^0 \rightarrow \mu^{+}\mu^{-})/B(B_{s}^0 \rightarrow \mu^{+}\mu^{-}))</td>
<td>220%</td>
<td>110%</td>
<td>40%</td>
<td>~5%</td>
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<tr>
<td>Unitarity triangle</td>
<td>(\gamma(B \rightarrow D^{(<em>)}K^{(</em>)}))</td>
<td>7°</td>
<td>4°</td>
<td>1.1°</td>
<td>negligible</td>
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<td>(\gamma(B_{s}^0 \rightarrow D_{s}^{\pm}K_{\pm}))</td>
<td>17°</td>
<td>11°</td>
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<td>(\beta(B^{0} \rightarrow J/\psi K_{S}^{0}))</td>
<td>1.7°</td>
<td>0.8°</td>
<td>0.31°</td>
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<tr>
<td>Charm</td>
<td>(A_{1}(D^{0} \rightarrow K^{+}K^{-})(10^{-4}))</td>
<td>3.4</td>
<td>2.2</td>
<td>0.5</td>
<td>–</td>
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<tr>
<td></td>
<td>(\Delta A_{CP}(10^{-3}))</td>
<td>0.8</td>
<td>0.5</td>
<td>0.12</td>
<td>–</td>
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Belle-II sensitivity in key flavour channels

<table>
<thead>
<tr>
<th>Observable</th>
<th>Belle II sens. (50 ab⁻¹)</th>
<th>SM¹</th>
<th>comment</th>
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</thead>
<tbody>
<tr>
<td>Hadronic $b \to s$ transitions</td>
<td></td>
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<tr>
<td>$S(B \to \phi K_S)$</td>
<td>0.03</td>
<td>0.03 ± 0.02</td>
<td></td>
</tr>
<tr>
<td>$S(B \to \eta' K_S)$</td>
<td>0.02</td>
<td>0 ± 0.015</td>
<td></td>
</tr>
<tr>
<td>$S(B \to f_0 K_S)$</td>
<td>0.03</td>
<td>0 ± 0.015</td>
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<tr>
<td>Radiative/electroweak $b \to s$ transitions</td>
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<td></td>
</tr>
<tr>
<td>$S(B \to K_S\pi^0\gamma)$</td>
<td>0.03</td>
<td>−0.04 ± 0.1</td>
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<tr>
<td>$Br(B \to X_s\gamma)$ (×10⁻⁴)</td>
<td>0.13</td>
<td>3.2 ± 0.2</td>
<td>inclusive $Br$</td>
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<tr>
<td>$Br(B \to K\nu\bar{\nu})$ (×10⁻⁶)</td>
<td>1.0</td>
<td>3.6 ± 0.5</td>
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<tr>
<td>$A_{FB}(B \to K^+\ell^+\ell^-)$</td>
<td>0.03</td>
<td>−0.10 ± 0.02</td>
<td>for $0 \leq q^2 \leq 4.3$ GeV²</td>
</tr>
<tr>
<td>Radiative $b \to d$ transitions</td>
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<tr>
<td>$S(B \to \rho\gamma)$</td>
<td>0.15</td>
<td>&lt; 0.05</td>
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<tr>
<td>Leptonic $B$ decays</td>
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<tr>
<td>$Br(B \to \tau\nu)$ (×10⁻⁵)</td>
<td>0.04</td>
<td>1.1 ± 0.2</td>
<td></td>
</tr>
<tr>
<td>LFV in $\tau$ decays (U.L. at 90% C.L.)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>$Br(\tau \to \mu\gamma)$ (×10⁻⁹)</td>
<td>3</td>
<td>0</td>
<td></td>
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<tr>
<td>$B_s$ physics</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>$Br(B_s \to \gamma\gamma)$ (×10⁻⁶)</td>
<td>0.3</td>
<td>0.7 ± 0.3</td>
<td>with 5 ab⁻¹ of data</td>
</tr>
<tr>
<td>$A_{SL}$ (×10⁻³)</td>
<td>5</td>
<td>0.23 ± 0.06</td>
<td>at $\Upsilon(5S)$</td>
</tr>
<tr>
<td>$D$ meson mixing and CPV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$x$ (×10⁻⁴)</td>
<td>4</td>
<td>SM expectations</td>
<td></td>
</tr>
<tr>
<td>$y$ (×10⁻⁴)</td>
<td>3</td>
<td>difficult to</td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>q/p</td>
<td>$</td>
<td>0.03</td>
</tr>
<tr>
<td>$\text{Arg}(</td>
<td>q/p</td>
<td>)$ (°)</td>
<td>1.5</td>
</tr>
<tr>
<td>$A_{CP}(D^0 \to K^+K^-)$ (×10⁻⁴)</td>
<td>6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Some expected accuracies of selected physics observables at Belle II with a 50 ab⁻¹ data sample. The second column gives approximate expectations within the SM along with theoretical uncertainties.