Super KEKB and Belle II: status and plans

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International Workshop on $e^+e^-$ collisions from $\phi$ to $\psi$
Budker INP, 25 February 2019
Achievements from B factories
Before LHCb

Achievements at Flavor Physics and Exotics:

Luminosity at B Factories (1999-2010)

Two $e^+e^-$ B factories: Belle/KEKB at KEK and BaBar/PEP-II at SLAC

1.5 ab$^{-1}$ data, $1.25 \times 10^9 B\bar{B}$. 

Belle II Experiment
From Belle to Belle II

**KEKB** $\mathcal{L}$ record: $2.1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

**Belle**

- Accelerator: KEKB → SuperKEKB, $\mathcal{L} \times 40!$
- Detector: Belle → Belle II, a new detector with great improved performance.
Belle II Collaboration

- 26 counties/regions
- 113 institutions
- ~900 collaborators
Part I. Status of SuperKEKB and Belle II
SuperKEKB/Belle II schedule

- Overall schedule

- Current schedule

- First collisions on 4/26/2018, 8 years after KEKB and Belle being shut down.
- Phase 2 until July 17th, without inner vertex detector.
- On the way to Phase III: Physics Run will start on 11 March, 2019!
The SuperKEKB accelerator

A lot of new designs

**Luminosity**

\[
L = \frac{\gamma_{\pm}}{2e\gamma_r} \left( 1 + \frac{\sigma_y^*}{\sigma_x^*} \right) \frac{I_{\pm\gamma} R_L}{\beta_y^* R_y}
\]

**Target luminosity:** \(8 \times 10^{35} \text{cm}^{-2}\text{s}^{-1}\)

KEKB \(x\ 40\)!
The final focus: Key of achieving the goal of $L = 0.8 \times 10^{36} \text{ cm}^{-2}\text{s}^{-1}$

The superconducting final focus system

- Effective bunch length is reduced from $\sim 10 \text{ mm}$ (KEKB) to 0.5 mm (SuperKEKB).
- Measured the bunch length in two track events.
- The record the vertical spot size is 400nm with $I \sim 15 \text{ mA}$, goal is $\mathcal{O}(50 \text{ nm})$ with full capability of the QCS system.
- Early Phase 3 will continue with $\beta^* = 3 \text{ mm}$, goal is $\beta^* \sim 0.3 \text{ mm}$.
- Struggling with beam-beam blow-up, a major issue for Phase3.

Large cross angle: $22 \text{ mrad}$ (KEKB) → $83 \text{ mrad}$ (SKB).

X.L. Wang (Fudan)  Belle II Experiment
SuperKEKB achievements at Phase II

Keep on squeezing the two beams with the superconducting final focus $\beta^*_y = 3$ mm.

\[ L_{\text{peak}} = 5.5' \times 10^{33} / cm^2 / sec \]

Phase 2, July 2018

- A long way to go with the superconducting final focus (one order of magnitude in $\beta^*_y$)
- Luminosity tuning had priority. When accelerator physicists became tired, Belle II took data (usually owl shift). Only able to record $0.5 \text{ fb}^{-1}$.
- $L_{\text{max}} = 2.1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ was recorded by KEKB.
Cut view of Belle II detector

- CsI(Tl) EM calorimeter
- Waveform sampling electronics
- 4 layers DSSD → 2 layers PXD (DEPFET) + 4 layers DSSD
- Beryllium beam pipe, 2cm diameter, QCSR and QCSL
- Central Drift Chamber: smaller cell size, long lever arm, fast electronics
- RPC \( \mu \) & \( K_L \) counter: scintillator + Si-PM for end-caps
- Time-of-Flight, Aerogel Cherenkov Counter → Time-of-Propagation counter (barrel), proximity focusing Aerogel RICH (forward)
Detector highlights

PXD and iTOP

Vertex detectors:
- spatial resolution has a factor $\sim 2$ than Belle;
- despite lower Lorentz boost, $O(30\%)$ improvement in separating the B decay vertices!
- $\sim 30\%$ larger acceptance for $K_s$ reconstruction

Particle Identification (PID):
- $K - \pi$ separation is fundamental to distinguish among important final states and bkgs;
- crucial ingredient for B flavor tagger;
- expected performance: $K(\pi)$ efficiency $> 90\%$, with $\pi(K)$ fake rate $< 10\%$ for $p < 4$ GeV/c.
Advanced & Innovative Technologies used in Belle II

- Pixelated photo-sensors play a central role. **Collaboration with Industry**
  1. MCP-PMTs in the iTOP
  2. HAPDs in the ARICH
  3. SiPMs in the KLM
  4. DEPFET pixel sensors!

- Waveform sampling with precise timing. **Front-end custom ASICs (Application Specific Integrated Circuits) for all subsystems.**
  1. KLM: TARGETX ASIC
  2. ECL: New waveform sampling backend with good timing
  3. TOP: IRSX ASIC
  4. ARICH: KEK custom ASIC
  5. CDC: KEK custom ASIC
  6. SVD: APV2.5 readout chip adapted from CMS

- DAQ with high performance network switches, large HLT software trigger farm
- a 21\textsuperscript{th} century HEP experiment.
Signals involving photons (ECL)

\[ e^+ e^- \rightarrow \mu^+ \mu^- \gamma \]

Single Photon Lines

Ready for the dark sector!

\[ e^+ e^- \rightarrow \gamma X \]

\[ e^+ e^- \rightarrow \gamma \text{ALPS} \rightarrow \gamma (\gamma \gamma) \]
Signals involving charged tracks

$dE/dx$ from CDC for PID

$J/\psi \rightarrow e^+ e^-$

$J/\psi \rightarrow \mu^+ \mu^-$

Extra cuts:
- $|d0| < 1$
- $|dz| < 3$
- # layers hit > 20
**TOP for Particle Identification: \(K^\pm, \rho\) and \(\pi^\pm\)**

- The charged correlation with the slow pion determines which track is the kaon (or pion)
- Kinematically identified kaon from a \(D^{*+}\) in the TOP.
- Cherenkov \(x\) vs. \(t\) pattern (mapping of the Cherenkov ring):

\[
K^0_S \rightarrow \pi^+ \pi^-
\]
More examples about iTOP

- $K$-ID and $p$-ID

$\phi \rightarrow K^+K^-$ with both the tracks in the TOP acceptance

$\Lambda \rightarrow p\pi$ with the proton candidate in the TOP acceptance

- Rediscovery of $D_s \rightarrow \phi\pi^+$ with $\phi \rightarrow K^+K^-$

![Graphs and diagrams illustrating the examples mentioned above.](image-url)
$B$ mesons from Belle II

- Rediscovery of $B$ mesons in June, shown at ICHEP2018.

- Use the full Phase 2 dataset and apply the FEI (Full Event Interpretation) technique based on boosted decision trees (BDTs, a machine learning technique).
Onwards to Phase 3 and the Physics Run

Inner detector: VXD = PXD+SVD

- PXD installation at KEK around Oct. 2018
- SVD installation, finished in July, 2018
- Successful marriage of the PXD and SVD.
VXD & Endcap Installation and RVC Closure

VXD installation on Nov 21

FWD Endcap push-in on Jan 25

Very good consistency with previous alignment data but bowing of L2 ladders slightly increased after installation
Part II. Prospects of Belle II

- CMK-related Physics
- Search for New Physics
  - $B \rightarrow \tau \nu_{\tau}$
  - $B \rightarrow D^{(*)}\ell\nu$
  - $b \rightarrow s$ transitions
- LFV in $\tau$ decays
- XYZ particles
- ...

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Assumption:
(1) $8 \times 10^{35}$ will be achieved during 4 years (4 x 8 months = 32 months). $\rightarrow \Delta L_{\text{peak}} = 2.5 \times 10^{34}$ per month
(2) Luminosity upgrade plan obeys Morita's plan until 2020 Summer.
(3) Learning curve is a straight line from 2021 (resolution is one month).
(4) Efficiency of integrated luminosity is 70% (includes recorded/delivered, maintenance days, etc.).
(5) 8 months operation per year except for FY2019.
(6) 8 months shutdown in 2020 for PXD and 6 months in 2023 for RF upgrade (from 70% to 100%).

$1 \text{ ab}^{-1}$ (Belle data size)

1 div. = 4 months
**Belle II Physics Book**

**Belle II Theory Interface Platform (B2TIP)**

**Workshop series, 2015-2018:**

<table>
<thead>
<tr>
<th>WG1</th>
<th>WG2</th>
<th>WG3</th>
<th>WG4</th>
<th>WG5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semileptonic &amp; Leptonic B decays</td>
<td>Radiative &amp; Electroweak Penguins</td>
<td>$\alpha/\varphi_2$ $\beta/\varphi_1$</td>
<td>$\gamma/\varphi_3$</td>
<td>Charmless Hadronic B Decay</td>
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<table>
<thead>
<tr>
<th>WG6</th>
<th>WG7</th>
<th>WG8</th>
<th>WG9</th>
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<tbody>
<tr>
<td>Charm</td>
<td>Quarkonium(-like)</td>
<td>Tau, low multiplicity</td>
<td>New Physics</td>
</tr>
</tbody>
</table>

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**The Belle II Physics Book**

Emi Kou and Phill Urquijo, editors

689 pages  
arXiv: 1808.10567  
submitted to PTEP

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... a fruitful collaboration among theorists and experimentalists
Precise measurements of CKM unitarity triangle

Now

\[ \phi_1 \leftrightarrow \beta \]
\[ \phi_2 \leftrightarrow \alpha \]
\[ \phi_3 \leftrightarrow \gamma \]

with 50 ab\(^{-1}\)
Measuring $|V_{ub}|$ via $B^+ \rightarrow \tau^+ \nu_\tau$

A missing-energy mode

- There is some **tension** at the CKM triangle apex from this measurement vs $\sin 2\phi_1$
- Leveraging fully-reconstructed tag-$B$, there should be **zero excess energy** in the calorimeter

![Graphs showing data and analysis](image)

222 ± 50 (all channels) 3.8$\sigma$
Search for New-Physics (e.g., charged Higgs) in $B^+ \rightarrow \tau^+ \nu_\tau$

$$r = \frac{B_{\text{meas}}(B \rightarrow \tau \nu)}{B_{\text{SM}}(B \rightarrow \tau \nu)} = \left(1 - \frac{m_B^2}{m_H^2} \tan^2 \beta \right)$$

B Factory exclusion plot from $B^+ \rightarrow \tau^+ \nu_\tau$
$B \to D^{(*)} l\nu$: challenge to lepton universality

- Theoretically clean channel in SM
- Charged Higgs can contribute to the decay
- $R(D^{(*)})$ is sensitive parameter to BSM!

$$R(D^{(*)}) = \frac{Br(B \to D^{(*)}\tau\nu)}{Br(B \to D^{(*)}\mu\nu)}$$

<table>
<thead>
<tr>
<th></th>
<th>Exp</th>
<th>SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R(D^*)$</td>
<td>$0.304 \pm 0.013 \pm 0.007$</td>
<td>$0.252 \pm 0.003$</td>
</tr>
<tr>
<td>$R(D)$</td>
<td>$0.407 \pm 0.039 \pm 0.024$</td>
<td>$0.300 \pm 0.008$</td>
</tr>
</tbody>
</table>

4.1σ away from the SM

Belle II should be able to confirm the excess with ~5ab⁻¹ data
New-Physics sensitivity in $b \to s \ell^+ \ell^-$

$$\mathcal{R}(K^{(*)}) = \frac{\mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(B \to K^{(*)}ee)}$$

Note: LHCb value is extrapolated from run-1 result

Belle II: good electron identification
- $K^* e^+ e^- : \sim 200 \text{ events/ab}^{-1}$
- $K^* \mu^+ \mu^- : \sim 280 \text{ events/ab}^{-1}$

Belle II has strong capabilities for electrons and muons.
Belle II will improve sensitivity for many LFV $\tau$ decays

- Two orders lower, down to $10^{-9}$ or $10^{-10}$ level
- Improve the sensitivity for search for LFV, which may be related to some experiments like neutrinoless double-beta decays.
Processes for $XYZ$

- Color-suppressed B-meson decays
- Two-photon fusion processes
- Double charmonium production
- Initial-state radiation

**FIG. 12.** Processes that produce $c\bar{c}$ pairs in $e^+e^-$ collisions near $E_{c.m.} = 10.6$ GeV: (a) $B \to K(c\bar{c})$ decays, (b) two-photon fusion processes, (c) $e^+e^-$ annihilation into $c\bar{c}c\bar{c}$, and (d) initial state radiation.

- $\Upsilon(1, 2, 3S)$ decays, continuum productions and energy scan can be used to study $XYZ$ too.
- Uniquely measurable at Belle II: Two-photon fusion, Double-charmonium production, and Initial-state radiation
Current heavy quarkonium(-like) spectroscopies
Summary

- Belle II has finished the detector construction.
- Belle II had the first collisions on April 26, 2018, and the Phase 2 was until July 17th.
- The Phase 2 got very impressive results from both the SuperKEKB accelerator and the Belle II detector.
- \[ L_{peak} = 0.55 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \] was achieved in Phase II.
- The nano-beam scheme is working well and the Belle II detector has very good performance!
- Belle II is going to start physics running in 2019, coming back the game.
- \[ 0.8 \times 10^{36} \text{ cm}^{-2}\text{s}^{-1} \] will make Belle II a luminosity revolution experiment, and open new windows for various physics topics.
  - Search for New-Physics in \( B \rightarrow \tau \nu_\tau \), \( B \rightarrow D(\ast)l\nu \), \( b \rightarrow s \) transitions and LFV, etc.
  - Figure out the nature of exotic states, charmonium-like and bottomonium-like states.

Thank you!
Back-up
## Nano-beam parameters of SuperKEKB

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LER (e+)</th>
<th>HER (e-)</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy</td>
<td>$E$</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>Half Crossing Angle</td>
<td>$\phi$</td>
<td></td>
<td>41.5</td>
</tr>
<tr>
<td>Horizontal Emittance</td>
<td>$\varepsilon_x$</td>
<td>3.2(2.7)</td>
<td>2.4(2.3)</td>
</tr>
<tr>
<td>Emittance ratio</td>
<td>$\varepsilon_y / \varepsilon_x$</td>
<td>0.40</td>
<td>0.35</td>
</tr>
<tr>
<td>Beta Function at the IP</td>
<td>$\beta^<em>_x / \beta^</em>_y$</td>
<td>32 / 0.27</td>
<td>25 / 0.41</td>
</tr>
<tr>
<td>Horizontal Beam Size</td>
<td>$\sigma_x^*$</td>
<td>10.2(10.1)</td>
<td>7.75(7.58)</td>
</tr>
<tr>
<td>Vertical Beam Size</td>
<td>$\sigma_y^*$</td>
<td>59</td>
<td>59</td>
</tr>
<tr>
<td>Betatron tune</td>
<td>$\nu_x/\nu_y$</td>
<td>45.530/45.570</td>
<td>58.529/52.570</td>
</tr>
<tr>
<td>Momentum Compaction</td>
<td>$\alpha_c$</td>
<td>$2.74 \times 10^{-4}$</td>
<td>$1.88 \times 10^{-4}$</td>
</tr>
<tr>
<td>Energy Spread</td>
<td>$\sigma_\varepsilon$</td>
<td>$8.14(7.96) \times 10^{-4}$</td>
<td>$6.49(6.34) \times 10^{-4}$</td>
</tr>
<tr>
<td>Beam Current</td>
<td>$I$</td>
<td>3.60</td>
<td>2.62</td>
</tr>
<tr>
<td>Number of Bunches/ring</td>
<td>$n_b$</td>
<td>2503</td>
<td></td>
</tr>
<tr>
<td>Energy Loss/turn</td>
<td>$U_0$</td>
<td>2.15</td>
<td>2.50</td>
</tr>
<tr>
<td>Total Cavity Voltage</td>
<td>$V_c$</td>
<td>8.4</td>
<td>6.7</td>
</tr>
<tr>
<td>Synchrotron Tune</td>
<td>$\nu_s$</td>
<td>-0.0213</td>
<td>-0.0117</td>
</tr>
<tr>
<td>Bunch Length</td>
<td>$\sigma_z$</td>
<td>6.0(4.9)</td>
<td>5.0(4.9)</td>
</tr>
<tr>
<td>Beam-Beam Parameter</td>
<td>$\xi_y$</td>
<td>0.0900</td>
<td>0.0875</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$L$</td>
<td>$8 \times 10^{35}$</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>KEKB Achieved</th>
<th>SuperKEKB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (GeV) (LER/HER)</td>
<td>3.5/8.0</td>
<td>4.0/7.0</td>
</tr>
<tr>
<td>$\xi_y$</td>
<td>0.129/0.090</td>
<td>0.090/0.088</td>
</tr>
<tr>
<td>$\beta^*_y$ (mm)</td>
<td>5.9/5.9</td>
<td>0.27/0.41</td>
</tr>
<tr>
<td>$I$ (A)</td>
<td>1.64/1.19</td>
<td>3.60/2.62</td>
</tr>
<tr>
<td>Luminosity ($10^{34}$cm$^{-2}$s$^{-1}$)</td>
<td>2.11</td>
<td>80</td>
</tr>
</tbody>
</table>
**Pixel Vertex Detector (PXD)**

**DEpleted P-channel FET**

- **PXD:**
  - Excellent spatial granularity ($\sigma \sim 15\mu m$), low material (0.16% $X_0$ for layer_1)
  - **But**, significant amount of background hits, huge data rate.

- **SVD:**
  - Precise time (2 ~ 3 ns RMS)
  - **But**, has ambiguities in space due to 1D strip.

Combining both yields a very powerful device!
Particle Identification in Belle II

- Cherenkov ring imaging with precise time measurement.
- Device uses internal reflection of Cherenkov ring images from quartz like DIRC of BaBar
- Cherenkov angle reconstruction from two hit coordinates and time of propagation of photons

**Barrel PID: Time of Propagation Counter (iTOP)**

- Small expansion block
- Hamamatsu MCP-PMT (measure t, x and y)

**Quartz radiator**

**Focusing mirror**

16 Quartz radiators
2.6m x 45cm x 2cm
Excellent surface accuracy

**MCP-PMT**

- Hamamatsu 16ch MCP-PMT
- Good TTS (<35ps) & enough lifetime
- Multialkali photo-cathode $\rightarrow$ SBA

**Table 7.1: Baseline quartz bar specifications.**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>$(440 \pm 0.15) \times (1200 \pm 0.5) \times (20 \pm 0.10)$ mm$^3$</td>
</tr>
<tr>
<td>Material</td>
<td>Synthetic fused silica (e.g., Corning 7980, Shin-etsu Suprasil)</td>
</tr>
<tr>
<td>Index tolerance</td>
<td>$\pm 0.001$</td>
</tr>
<tr>
<td>Flatness</td>
<td>10$\lambda$ over full aperture</td>
</tr>
<tr>
<td>Roughness (r.m.s.)</td>
<td>5 Å</td>
</tr>
<tr>
<td>Angle between planes</td>
<td>$(90 \pm 1/60)$ degree</td>
</tr>
<tr>
<td>Chamfer size</td>
<td>$&lt; 0.20$ mm</td>
</tr>
</tbody>
</table>
Aerogel RICH
Endcap PID

- RICH with a novel "focusing" radiator
- Two layer radiator
  - Employ multiple layers with different $n$
  - Cherenkov images from individual layers overlap on the photon detector

Cherenkov angle distribution

$6.6 \sigma \pi/K$ at 4 GeV/c!
**$K_L$ & Muon detector (KLM)**

- WLS fiber in each strip
- Hamamatsu MPPC at one fiber end
- Mirrored far fiber end
- **Endcap:**
  - One layer: 75 strips (4cm)/sector
  - 5 segments ($\times$ 15 strips)
  - Two orthogonal layer = superlayer
  - Total area $\sim$ 1400 m$^2$
- **Barrel:**
  - Two superlayers
  - Each layer has two modules: forward and backward
  - Each module has 80 $\sim$ 100 strips
  - 32 modules totally.

**MPPC:** Hamamatsu
1.3 $\times$ 1.3 mm 667 pixels
(used in T2K Near Detector)
The tracking system

<table>
<thead>
<tr>
<th>Component</th>
<th>Type</th>
<th>Configuration</th>
<th>Readout</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam pipe</td>
<td>Beryllium double-wall</td>
<td>Cylindrical, inner radius 10 mm, 10 μm Au, 0.6 mm Be, 1 mm coolant (paraffin), 0.4 mm Be</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PXD</td>
<td>Silicon pixel (DEPFET)</td>
<td>Sensor size: 15×100 (120) mm², pixel size: 50×50 (75) μm², 2 layers: 8 (12) sensors</td>
<td>10 M</td>
<td>impact parameter resolution</td>
</tr>
<tr>
<td>SVD</td>
<td>Double sided Silicon strip</td>
<td>Sensors: rectangular and trapezoidal strip pitch: 50(p)/160(n) - 75(p)/240(n) μm, 4 layers: 16/30/56/85 sensors</td>
<td>245 k</td>
<td>$\sigma_{z_0} \sim 20 \mu m$</td>
</tr>
<tr>
<td>CDC</td>
<td>Small cell drift chamber</td>
<td>56 layers, 32 axial, 24 stereo r = 16 - 112 cm, - 83 ≤ z ≤ 159 cm</td>
<td>14 k</td>
<td>$\sigma_{\rho \phi} = 100 \mu m, \sigma_z = 2 mm$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\sigma_{p_t}/p_t = \sqrt{(0.2%)p_t^2 + (0.3%/\beta)^2}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\sigma_{p_t}/p_t = \sqrt{(0.1%)p_t^2 + (0.3%/\beta)^2}$ (with SVD)</td>
</tr>
</tbody>
</table>

X.L. Wang (Fudan)  
Belle II Experiment
CKM and Unitarity Triangle from B Decays

- Flavor physics described by the CKM unitary matrix $V_{ckm}$.
- Standard parametrisation in complex plane:
  - Sides $\rightarrow$ Amplitudes $\rightarrow$ Branching fractions
  - Angle $\rightarrow$ Phase $\rightarrow$ CPV
- All angles can be accessed at B-factories $\rightarrow$ precise determination of unitary triangle

- $\phi_1 = \beta$: $b \rightarrow c\bar{c}s$, $q\bar{q}s$
  - $B^0 \rightarrow J/\psi K^0_s$
  - $B^0 \rightarrow \phi K^0_s$
  - $B^0 \rightarrow \eta' K^0_s$
- $\phi_2 = \alpha$: $b \rightarrow u\bar{u}d$
  - $B^0 \rightarrow \pi\pi$
  - $B^0 \rightarrow \rho\rho$
  - $B^0 \rightarrow \rho\pi$
- $\phi_3 = \gamma$: $b \rightarrow c\bar{u}s$
  - $B^\pm \rightarrow D K^\pm$
Is there NP in $B \rightarrow D^{(*)} l \nu$?

Missing-energy mode; multiple neutrinos in final state

Tagged analysis:

- full or partial reconstruction
- measure $q^2$ distribution, angular distribution, $\tau$ polarization, ...

Standard Model:

- lepton universality
- hadronic uncertainties $\approx$ cancel (manageable)
Is there NP in $B \rightarrow D^{(*)} l\nu$?

$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \rightarrow D^{(*)} \tau^{−} \bar{\nu}_{\tau})}{\mathcal{B}(\bar{B} \rightarrow D^{(*)} \ell^{−} \bar{\nu}_{\ell})}$$

---

**Graphical Analysis:**

- **Data Points:**
  - BaBar, PRL109,101802(2012)
  - Belle, PRD92,072014(2015)
  - LHCb, PRL115,111803(2015)
  - Belle, PRD94,072007(2016)
  - Belle, PRL118,211801(2017)
  - LHCb, PRL120,171802(2018)
  - Average

- **Plot Details:**
  - $\Delta\chi^2 = 1.0$ contours
  - $R(D) = 0.299 \pm 0.003$
  - $R(D^{*}) = 0.258 \pm 0.005$

---

**Statistical Significance:**

- **4σ Discrepancy:**
  - 4σ discrepancy between SM and measurements

---

*HFLAV Summer 2018: $P(\chi^2) = 74\%$*
**Belle II prospects for New Physics (I)**

<table>
<thead>
<tr>
<th>Process</th>
<th>Observable</th>
<th>Theory</th>
<th>Sys. limit (Discovery) [ab$^{-1}$]</th>
<th>vs LHCb</th>
<th>vs Belle</th>
<th>Anomaly</th>
<th>NP</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B \rightarrow \pi \ell \nu$</td>
<td>$</td>
<td>V_{ub}</td>
<td>$</td>
<td>***</td>
<td>10-20</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td>$B \rightarrow X_s \ell \nu$</td>
<td>$</td>
<td>V_{ub}</td>
<td>$</td>
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<td>$B \rightarrow \tau \nu$</td>
<td>$Br.$</td>
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<td>&gt;50 (2)</td>
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<td>$B \rightarrow \mu \nu$</td>
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<td>$B \rightarrow D^{(*)} \ell \nu$</td>
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<td>$B \rightarrow D^{(*)} \tau \nu$</td>
<td>$P_\tau$</td>
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<td>$B \rightarrow D^{(*)} \ell \nu$</td>
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<tr>
<th>Process</th>
<th>Observable</th>
<th>Theory</th>
<th>Sys. limit (Discovery) [ab$^{-1}$]</th>
<th>vs LHCb</th>
<th>vs Belle</th>
<th>Anomaly</th>
<th>NP</th>
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<tbody>
<tr>
<td>$B \rightarrow K^{(*)} \pi \nu$</td>
<td>$Br., F_L$</td>
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<td>$S_{K^{0} \pi \gamma}$</td>
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<td>$S_{\rho \gamma}$</td>
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<tr>
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<tr>
<td>$B \rightarrow X_{s} l^{+} l^{-}$</td>
<td>$R_{X_{s}}$</td>
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<td>$R(K^{(*)})$</td>
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<td>$B_{u(s)} \rightarrow \gamma \gamma$</td>
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# Belle II New-Physics potential in $b \to s$ transitions

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<tr>
<th>Observables</th>
<th>Experimental Sensitivity</th>
<th>Multi-Higgs Models ($\S 17.2$)</th>
<th>generic SUSY</th>
<th>MFV ($\S 17.3$)</th>
<th>$Z'$ models ($\S 17.6.1$)</th>
<th>gauged flavour ($\S 17.6.2$)</th>
<th>3-3.1 ($\S 17.6.3$)</th>
<th>left-right ($\S 17.6.4$)</th>
<th>leptoquarks ($\S 18.2.1$)</th>
<th>compositeness ($\S 17.7$)</th>
<th>dark sector ($\S 16.1$)</th>
<th>Sum</th>
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<tbody>
<tr>
<td>$B \to K(\ast) \ell \ell$ angular</td>
<td>**</td>
<td>x</td>
<td>x</td>
<td>**</td>
<td>x</td>
<td>**</td>
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<td>$R(K^\ast), R(K)$</td>
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<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>**</td>
<td>x</td>
<td>**</td>
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<td>x</td>
<td>x</td>
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<td>x</td>
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<td>***</td>
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<td>x</td>
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<td>x</td>
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<td>***</td>
<td>*</td>
<td>x</td>
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*** Belle II  
** Belle II + LHCb  
* LHCb  

× unlikely  
□ not studied