Belle II prospects overview

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Purpose of this talk

- brief reminder of Belle II's scope/goals...
- ...in light of what is observed/obtained at LHCb
- ...in light of recent Belle results
- ...in light of phase 2 results

Outline

- Belle II
- CPV and $V_{xb}$, $B \rightarrow \tau \nu$
- $b \rightarrow s \gamma$, $b \rightarrow s l^+ l^-$
- $B \rightarrow D^{(*)} \tau \nu$
- LFV $B$ and $\tau$ decays

precision measurements

rare decays
The Geography of the International Belle II collaboration

Belle II has grown to ∼ 900 researchers from 26 countries
Belle II, a flavour-factory, a rich physics program...

- We plan to collect (at least) 50 ab⁻¹ of e⁺e⁻ collisions at (or close to) the Y(4S) resonance, so that we have:

  - a (Super) B-factory (∼1.1 × 10⁹ B̅B pairs per ab⁻¹)''on resonance" production e⁺e⁻ → Y(4S) → B_d⁰B̅_d⁰, B⁺B⁻

  - 2 B's and nothing else!
  - 2 B mesons are created simultaneously in a L=1 coherent state

  - a (Super) charm factory (∼1.3 × 10⁹ c̅c pairs per ab⁻¹)

  - a (Super) τ factory (∼1.3 × 10⁹ τ⁺τ⁻ pairs per ab⁻¹)

  - with Initial State Radiation, effectively scan the range [0.5 – 10] GeV and measure the e⁺e⁻ → light hadrons cross section very precisely

  - exploit the clean e⁺e⁻ environment to probe the existence of exotic hadrons, dark photons/Higgs, light Dark Matter particles, ...
**Belle(II), LHCb side by side**

**Belle (II)**

\[ e^+ e^- \rightarrow \Upsilon(4S) \rightarrow b \bar{b} \]

at \( \Upsilon(4S) \): 2 \( B \)'s (\( B^0 \) or \( B^+ \)) and nothing else \( \Rightarrow \) clean events

\[ \sigma_{b \bar{b}} \sim 1 \text{nb} \rightarrow 1 \text{ fb}^{-1} \] produces \( 10^6 \) \( B \bar{B} \)

\[ \frac{\sigma_{b \bar{b}}}{\sigma_{\text{total}}} \sim \frac{1}{4} \]

\( b \bar{b} \) production cross-section ~ \( 5 \times \) **Tevatron**, ~ \( 500,000 \times \) BaBar/Belle !!

\[ \frac{\sigma_{b \bar{b}}}{\sigma_{\text{total}}} \text{ much lower than at the } \Upsilon(4S) \]

\( \Rightarrow \) lower reconstruction efficiencies

**B mesons live relatively long**

mean decay length \( \beta_{Y \gamma c} \tau \sim 200 \mu \text{m} \)

**data taking period(s)**

\[ [1999-2010] = 1 \text{ ab}^{-1} \]

(near) **future**

\[ [\text{Belle II from 2018}] \rightarrow 50 \text{ ab}^{-1} \]

**LHCb**

\[ pp \rightarrow b \bar{b} X \]

production of \( B^+, B^0, B_s, B_c, \Lambda_b \ldots \)

but also a lot of other particles in the event

\( \Rightarrow \) lower reconstruction efficiencies

\[ \frac{\sigma_{b \bar{b}}}{\sigma_{\text{total}}} \text{ much higher than at the } \Upsilon(4S) \]

\[ \frac{\sigma_{b \bar{b}}}{\sigma_{\text{total}}} \text{ lower than at the } \Upsilon(4S) \]

\( \Rightarrow \) lower trigger efficiencies

\[ \beta_{Y \gamma c} \tau \sim 7 \text{ mm} \]

**data taking period(s)**

\[ [\text{run I: 2010-2012}] = 3 \text{ fb}^{-1}, \]

\[ [\text{run II: 2015-2018}] = 2 \text{ fb}^{-1} \rightarrow 8 \text{ fb}^{-1} ? \]

\[ [\text{LHCb upgrade from 2020}] \]
SuperKEKB, the first new collider in particle physics since the LHC in 2008 (electron-positron \((e^+ e^-)\) rather than proton-proton \((p-p)\))

**Phase 1**
Background, Optics commissioning
Feb - June 2016
Brand new 3km positron ring

**Phase 2: Pilot run**
Superconducting Final Focus
add positron damping ring
First Collisions \((0.5 \text{ fb}^{-1})\)
April 27 - July 17, 2018

**Phase 3: Physics run**
March 27 - June 30, 2019
Few words on Belle II detector

- collecting 50 ab$^{-1}$ from 2019 to 2025... (or until we get 50 ab$^{-1}$?)

4 DSSD layers $\rightarrow$ 2 pixel layers + 4 DSSD layers
larger radius radius outermost layer (8.8 cm $\rightarrow$ 14 cm)

$K_S$ reconstruction with PXD/SVD: $K^0 \gamma$ TCPV
CDC track + SVD hits in the 1st and 2nd outermost layers
7 cm $\rightarrow$ 12 cm
Precision measurements
The Unitarity Triangle in the year 2027

NB: $\alpha$ with couple of degrees @ Belle II

$\Rightarrow$ major updates for $|V_{ub}|$, $\sin 2\beta$, $\alpha$, $\gamma$
Time–dependent CP asymmetries in decays to CP eigenstates

\[
\frac{dP_{\text{sig}}}{dt}(\Delta t, q) = e^{-|\Delta t|/\tau_B} \left( 1 + q \left( S \sin(\Delta m_d \Delta t) + A \cos(\Delta m_d \Delta t) \right) \right)
\]

Raison d'etre of SVD+PXD
significant resolution improvement for Belle II

A single irreducible phase in the weak interaction matrix accounts for most of the CPV observed in kaons and B's

Critical role of the B factories in the verification of the KM hypothesis
Measurement of $\sin 2\beta$

$\sin(2\beta) \equiv \sin(2\phi_1)$

**WA 2016:** $\beta = (21.9 \pm 0.7)^\circ$

**sin $2\beta$ at Belle II**

<table>
<thead>
<tr>
<th></th>
<th>Belle</th>
<th>Belle II ($50 \text{ ab}^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>$0.667 \pm 0.023 \pm 0.012$</td>
<td>$x.xxxxx \pm 0.0027 \pm 0.0044$</td>
</tr>
<tr>
<td>A</td>
<td>$0.006 \pm 0.016 \pm 0.012$</td>
<td>$x.xxxxx \pm 0.0033 \pm 0.0037$</td>
</tr>
</tbody>
</table>

**anchor of SM**

will be dominated by systematic uncertainties
$\sin 2\beta$ with $b \to s$ penguins

Increasing tree diagram amplitude
Increasing sensitivity to new physics

$J/\psi K^0_S, \psi (2S)K^0_S, \chi_{c1} K^0_S,$
$\eta_c K^0_S, J/\psi K^0_L,$
$J/\psi K^{*0} (K^{*0} \to K^0_S \pi^0)$

$D^{*+}D^-, D^+D^-$
$J/\psi \pi^0, D^{*+}D^{-}$
$\phi K^0, K^+K^-K^0_S,$
$K^0_S K^0_S K^0_S, \eta' K^0, K^0_S \pi^0,$
$\omega K^0_S, f_0(980)K^0_S$

EX–ANOMALY!
First reported in Moriond EW 2002
"$\sin 2\beta$" = $-0.73 \pm 0.64 \pm 0.22$

[PRD 67, 031102 (2003)]
\[ \sin 2\beta \text{ with } b \to s \text{ penguins} \]

\[
\begin{align*}
J/\psi K^0_S, \psi (2S) K^0_S, \chi_{c1} K^0_S, \\
\eta_c K^0_S, J/\psi K^0_L, \\
J/\psi K^0 (K^* \to K^0 \pi^0) \\
D^+ D^-, D^+ D^-
\end{align*}
\]

Increasing tree diagram amplitude

Increasing sensitivity to new physics

\[ \sin(2\beta^{\text{eff}}) = \sin(2\phi_1^{\text{eff}}) \]

More statistics crucial for mode-by-mode studies

- \( f^0_0(980) K^0 \)
- \( \eta K^0 \)
- \( \rho^0 K^0 \)
- \( \omega K^0 \)
- \( \pi^0 K_S^0 \)
- \( \phi K^0 \)
- \( \eta' K^0 \)

\[ \Delta S_{SM} \]

\[ \text{QCDF Beneke, PLB} \text{620}, 143 (2005) \]
\[ \text{SCET/QCDF, Williamson and Zupan, PRD} \text{74}, 014003 (2006) \]
\[ \text{QCDF Cheng, Chua and Soni, PRD} \text{72}, 014006 (2005) \]
\[ \text{SU(3) Gronau, Rosner and Zupan, PRD} \text{74}, 093003 (2006) \]
sin $2\beta$ with $b\to s$ penguins dominated by B-factories

increasing tree diagram amplitude

increasing sensitivity to new physics

Channel | $\int \mathcal{L}$ | Event yield | $\sigma(S)$ | $\sigma(A)$
--- | --- | --- | --- | ---
$\phi K^0$ | 5 ab$^{-1}$ | 5590 | 0.048 | 0.035
$\eta'/K^0$ | 5 ab$^{-1}$ | 27200 | 0.027 | 0.020
$\omega K^0$ | 5 ab$^{-1}$ | 1670 | 0.08 | 0.06
$K_S\pi^0\gamma$ | 5 ab$^{-1}$ | 1400 | 0.10 | 0.12
$K_S\pi^0$ | 5 ab$^{-1}$ | 5699 | 0.09 | 0.10
$\gamma$ measurements from $B^\pm \to D K^\pm$

- Theoretically pristine $B \to D K$ approach
- Access $\gamma$ via interference between $B^- \to D^0 K^-$ and $B^- \to \bar{D}^0 K^-$

**Theoretical Expressions**

**Color Allowed**

$B^- \to D^0 K^- \sim V_{cb} V_{us}^*$

$\sim A \lambda^3$

**Color Suppressed**

$B^- \to \bar{D}^0 K^- \sim V_{ub} V_{cs}^*$

$\sim A \lambda^3 (\rho + i \eta)$

$B^\pm \to D K^\pm$

$B^\pm \to D^* K^\pm, D^* \to D \pi^0$

$B^\pm \to D^* K^\pm, D^* \to D \gamma$

$B^\pm \to D K^{*\pm}$

$B^0 \to D K^{*0}$

$B^\pm \to D K \pi \pi$

$B \to ...$
**γ measurements from B^± → DK^±**

- Theoretically pristine B → DK approach
- Access γ via interference between B^− → D^0 K^− and B^− → D^0 K^−

**Diagram:**

- Color allowed: B^− → D^0 K^− ∼ V_{cb} V_{us}^* ~ A λ^3
- Color suppressed: B^− → D^0 K^− ∼ V_{ub} V_{cs}^* ~ A λ^3(ρ + i η)

**Relative weak phase:** γ

**Relative strong phase:** δ_B

- r_B ≃ 0.1

**Labeling:**

- σ_γ ∼ 6°
- (too) conservative estimate
- long way to go ... (➔ σ_γ = 1° or less?)
## Semileptonic and leptonic

<table>
<thead>
<tr>
<th>Process</th>
<th>Obser.</th>
<th>Theory</th>
<th>Discovery (ab$^{-1}$)</th>
<th>Sys. limit (ab$^{-1}$)</th>
<th>vs LHCb</th>
<th>vs Belle</th>
<th>Anomaly</th>
<th>NP</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B \to \pi l\nu_l$</td>
<td>$</td>
<td>V_{ub}</td>
<td>$</td>
<td>***</td>
<td>-</td>
<td>10</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td>$B \to X_u l\nu_l$</td>
<td>$</td>
<td>V_{ub}</td>
<td>$</td>
<td>**</td>
<td>-</td>
<td>2</td>
<td>***</td>
<td>**</td>
</tr>
<tr>
<td>$B \to \tau \nu$</td>
<td>$Br.$</td>
<td>***</td>
<td>2</td>
<td>50</td>
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<td>***</td>
</tr>
<tr>
<td>$B \to \mu \nu$</td>
<td>$Br.$</td>
<td>***</td>
<td>5</td>
<td>50</td>
<td>***</td>
<td>***</td>
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</tr>
<tr>
<td>$B \to D^{(*)} l\nu_l$</td>
<td>$</td>
<td>V_{cb}</td>
<td>$</td>
<td>***</td>
<td>-</td>
<td>1</td>
<td>***</td>
<td>*</td>
</tr>
<tr>
<td>$B \to X_c l\nu_l$</td>
<td>$</td>
<td>V_{cb}</td>
<td>$</td>
<td>***</td>
<td>-</td>
<td>1</td>
<td>**</td>
<td>**</td>
</tr>
<tr>
<td>$B \to D^{(*)}\tau \nu_{\tau}$</td>
<td>$R(D^{(*)})$</td>
<td>***</td>
<td>-</td>
<td>5</td>
<td>**</td>
<td>***</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td>$B \to D^{(*)}\tau \nu_{\tau}$</td>
<td>$P_{\tau}$</td>
<td>***</td>
<td>-</td>
<td>15</td>
<td>***</td>
<td>***</td>
<td>**</td>
<td>***</td>
</tr>
<tr>
<td>$B \to D^{**} l\nu_l$</td>
<td>$</td>
<td>V_{cb}</td>
<td>$</td>
<td>*</td>
<td>-</td>
<td>-</td>
<td>**</td>
<td>***</td>
</tr>
</tbody>
</table>
Toy MC studies based on Belle II MC, LQCD forecasts estimated at 5 years (5, 10 ab\(^{-1}\)) and 10 years (50 ab\(^{-1}\))

$|V_{ub}|$ from $B \rightarrow \pi \ell \nu$ at Belle II

$|V_{ub}|\pi \ell \nu$ from simultaneous fit for $\mathcal{L} = 5$ ab\(^{-1}\), including lattice forecasts and error scaling.

$\delta|V_{ub}|\pi \ell \nu$ estimates for 5, 10 and 50 ab\(^{-1}\):
- Tagged: 3.2, 2.7 and 1.7 %
- Untagged: 2.1, 1.9 and 1.3 %

LQCD forecasts: [A. Kronfeld, T. Kaneko, S. Simula]
**Tauonic B decays: $B \rightarrow \tau \nu$**

- $B_{\text{sig}} \rightarrow \tau \nu$
  - $\tau \rightarrow e \nu, \mu \nu, \nu$
  - $\tau \rightarrow \pi \nu, \pi \pi^0 \nu, 3 \pi \nu$
  (70% of all $\tau$ decays)

- Require no particle and no energy left after removing $B_{\text{tag}}$ & visible particles of $B_{\text{sig}}$

2 HDM (type II): $B(B^+ \rightarrow \tau^+ \nu) = B_{\text{SM}} \times (1 - \frac{m_B^2}{m_{H^+}^2} \tan^2 \beta)^2$

$$B_{\text{SM}}(B^+ \rightarrow \tau^+ \nu) = \frac{G_F^2 m_B m_{\tau}^2}{8 \pi} (1 - \frac{m_{\tau}^2}{m_B^2}) f_B^2 |V_{ub}|^2 \tau_B$$

Uncertainties from $f_B$ and $|V_{ub}|$ can be reduced to $B_B$ and other CKM uncertainties by combining with precise $\Delta m_d$
B → τν status and projections

BaBar semileptonic tagging
(1.7 ± 0.8 ± 0.2) 10^{-4}

BaBar hadronic tagging
(1.83^{+0.53}_{-0.49} ± 0.24) 10^{-4}

Belle semileptonic tagging (old)
(1.54^{+0.38}_{-0.37} +0.29_{-0.31}) 10^{-4}

Belle hadronic tagging
(0.72^{+0.27}_{-0.25} ± 0.11) 10^{-4}

World average
(1.14 ± 0.27) 10^{-4}

Belle semileptonic tagging

not a single observation!!

EX – ANOMALY!

Belle II

<table>
<thead>
<tr>
<th>V_{ub}</th>
<th>B → τν (had. tagged)</th>
</tr>
</thead>
<tbody>
<tr>
<td>711 fb^{-1}</td>
<td>19.0 (7.1, 2.2)</td>
</tr>
<tr>
<td>5 ab^{-1}</td>
<td>7.2 (2.7, 2.2)</td>
</tr>
<tr>
<td>50 ab^{-1}</td>
<td>2.3 (0.8, 2.2)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>V_{ub}</th>
<th>B → τν (SL tagged)</th>
</tr>
</thead>
<tbody>
<tr>
<td>605 fb^{-1}</td>
<td>12.4 (9.0, +3.0_{-4.8})</td>
</tr>
<tr>
<td>5 ab^{-1}</td>
<td>4.3 (3.1, +3.0_{-4.8})</td>
</tr>
<tr>
<td>50 ab^{-1}</td>
<td>1.4 (1.0, +3.0_{-4.8})</td>
</tr>
</tbody>
</table>

observation of B → μν is also expected (from 5 ab^{-1})
The Unitarity Triangle in the year 2025

NB: $\alpha$ with couple of degrees @ Belle II

$\Rightarrow$ major updates for $|V_{ub}|$, $\sin 2\beta$, $\alpha$, $\gamma$
rare B decays
Sensitivity to new physics in rare B decays

T. Hurth et al, arXiv:1603.00865
S. Descotes-Genon et al, arXiv:1510.04239...

NP changes short-distance $C_i$
and/or add new long-distance ops $O'_i$

Model-independent description in effective field theory

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i O_i + C'_i O'_i$$

Left-handed, Right-handed, $\frac{m_s}{m_b}$ suppressed

Wilson coefficients $C_i^{(t)}$ encode short-distance physics, $O_i^{(t)}$ corr. operators

$b \to s\gamma$ $B \to \mu\mu$ $b \to s\ell\ell$

$O_7^{(t)}$ photon penguin

$O_9^{(t)}$ vector coupling

$O_{10}^{(t)}$ axialvector coupling

$O_{5,10}^{(t)}$ (pseudo)scalar penguin
what about inclusive $b \rightarrow s \gamma$?

OFF-resonance data is scaled according to luminosities and subtracted from ON-resonance data.
for $E_γ^* > 1.7$ GeV,

$B(B \to X_s \gamma) = (3.45 \pm 0.15 \pm 0.40) \times 10^{-4}$

$B(B \to X_s \gamma) = (3.49 \pm 0.20) \times 10^{-4}$ (for $E_γ > 1.6$ GeV)

vs

$B(B \to X_s \gamma) = (3.36 \pm 0.23) \times 10^{-4}$ (for $E_γ > 1.6$ GeV)

$B(B \to X_s \gamma) = (3.45 \pm 0.15 \pm 0.40) \times 10^{-4}$

$B(B \to X_s \gamma) = (3.49 \pm 0.20) \times 10^{-4}$ (for $E_γ > 1.6$ GeV)

$B(B \to X_s \gamma) = (3.36 \pm 0.23) \times 10^{-4}$ (for $E_γ > 1.6$ GeV)

[arXiv:1706.07414]

[arXiv:1503.01789]

Charged Higgs bound (2HDM TypeII): $M_{H^+} > 400$ GeV @ 95% C.L.
Found by several experiments (LHCb, BaBar and Belle)

Two observables: $R(D)$ and $R(D^*)$

Charged current

**Tree-level** in the SM

The New Physics must be light

---

Found by LHCb

Many observables: global pattern

Neutral current

1-loop (and CKM-suppressed) in the SM

The New Physics can be heavy
Event reconstruction in $B \to D^{(*)} \tau \nu$ at $B$ factories

**Main signal-background discriminator**

$\mathbf{m}_{\text{miss}}^2 = (p_{ee} - p_{\text{tag}} - p_{D^*} - p_1)^2$

2 HDM (type II):

$$B(B \to D \tau^+ \nu) = G^2_F \tau_B |V_{cb}|^2 f(F_V, F_S, \frac{m_B^2}{m_{H^*}^2} \tan^2 \beta)$$

uncertainties from form factors $F_V$ and $F_S$ can be studied with $B \to D l \nu$ (more form factors in $B \to D^{*} \tau \nu$)
Summary for $B \to D^{(*)} \tau \nu$

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

BaBar

$R(D) = 0.440 \pm 0.058 \pm 0.042$

$R(D^*) = 0.332 \pm 0.024 \pm 0.018$

Belle

$R(D) = 0.375 \pm 0.064 \pm 0.026$

$R(D^*) = 0.293 \pm 0.038 \pm 0.015$

LHCb

$R(D^*) = 0.336 \pm 0.027 \pm 0.030$

average

$R(D) = 0.340 \pm 0.027 \pm 0.013$

$R(D^*) = 0.295 \pm 0.011 \pm 0.008$

difference with SM predictions is at $3\sigma$ level
Hadronic full reconstruction at Belle II

<table>
<thead>
<tr>
<th>Particle</th>
<th># channels (Belle)</th>
<th># channels (Belle II)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^+ / D^{*+} / D_s^+$</td>
<td>18</td>
<td>26</td>
</tr>
<tr>
<td>$D^0 / D^{*0}$</td>
<td>12</td>
<td>17</td>
</tr>
<tr>
<td>$B^+$</td>
<td>17</td>
<td>29</td>
</tr>
<tr>
<td>$B^0$</td>
<td>14</td>
<td>26</td>
</tr>
</tbody>
</table>

- More modes used for tag-side hadronic B than Belle, multiple classifiers

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>MVA</th>
<th>Efficiency</th>
<th>Purity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle v3 (2007)</td>
<td>Cut based</td>
<td>0.1</td>
<td>0.25</td>
</tr>
<tr>
<td>Belle NB (2011)</td>
<td>Neurobayes</td>
<td>0.2</td>
<td>0.25</td>
</tr>
<tr>
<td>Belle II FEI (2017)</td>
<td>Fast BDT</td>
<td>0.5</td>
<td>0.25</td>
</tr>
</tbody>
</table>

- Good performances on Belle II predicted beam background conditions:

Improvement to tagging efficiency in Belle II

Hadronic charged B

Hadronic neutral B

![Graphs showing efficiency vs purity for hadronic charged and neutral B](image)
Projections for Belle II $R(D^{(*)})$

Predictions of uncertainty using hadronic full reconstruction:

<table>
<thead>
<tr>
<th></th>
<th>$\Delta R(D)$ [%]</th>
<th>$\Delta R(D^*)$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Stat</td>
<td>Sys</td>
</tr>
<tr>
<td>Belle 0.7 ab$^{-1}$</td>
<td>14</td>
<td>6</td>
</tr>
<tr>
<td>Belle II 5 ab$^{-1}$</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Belle II 50 ab$^{-1}$</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

Systematic uncertainty dominated by $D^{**}$ and missed soft pions:

- Studies of $D^{**} l\nu$ and $D^{**} \tau\nu$ planned
- Branching ratios and decay modes from data
Other observables from $B \to D^{(*)} \tau \nu$

Additional observables as $P_{\tau}(D^*) (F_L(D^*))$ and $q^2$ distribution can help discriminate between New Physics models.

$P_{\tau}(D^*) = -0.38 \pm 0.51 ^{+0.21}_{-0.16}$

[Belle, arXiv:1612.00529]

![Projections for $P_{\tau}(D^*)$ at Belle II](image)

<table>
<thead>
<tr>
<th>$P_{\tau}(D^*)$</th>
<th>Stat. uncertainty</th>
<th>Sys. uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>at 5 ab$^{-1}$</td>
<td>0.18</td>
<td>0.08</td>
</tr>
<tr>
<td>at 50 ab$^{-1}$</td>
<td>0.06</td>
<td>0.04</td>
</tr>
</tbody>
</table>

![q$^2$ spectrum $B \to D^* \tau \nu$ 50ab$^{-1}$ projection](image)
$B \to D^{(*)} \tau \nu$ and other observables

\[ R(D^{(*)}) = \frac{B(B \to D^{(*)} \tau \nu)}{B(B \to D^{(*)} l \nu)}, \text{ in red} \]

\[ R_{ps} = \frac{\tau_{B^0} B(B \to \tau l \nu)}{\tau_B B(B \to \pi l \nu)}, \text{ in blue} \]

\[ R(\pi) = \frac{B(B \to \pi \tau \nu)}{B(B \to \pi l \nu)}, \text{ in grey} \]

Dashed: Belle II

\[-\mathcal{L}_{\text{eff}} = 2\sqrt{2} G_F V_{qb} \left[ \left( \delta_{\nu \tau,\nu \ell} + C_{V_1}^{(q,\nu \ell)} C_{V_1}^{(q,\nu \ell)} \right) \right. \]
\[ + \sum_{V_2,S_1,S_2,T} C_{X}^{(q,\nu \ell)} C_{X}^{(q,\nu \ell)} \]

where the four-Fermi operators:

\[ O_{V_1}^{(q,\nu \ell)} = (\bar{q}\gamma^\mu P_L b)(\bar{\tau}\gamma_\mu P_L \nu_\ell), \]
\[ O_{V_2}^{(q,\nu \ell)} = (\bar{q}\gamma^\mu P_R b)(\bar{\tau}\gamma_\mu P_L \nu_\ell), \]
\[ O_{S_1}^{(q,\nu \ell)} = (\bar{q} P_R b)(\bar{\tau} P_L \nu_\ell), \]
\[ O_{S_2}^{(q,\nu \ell)} = (\bar{q} P_L b)(\bar{\tau} P_L \nu_\ell), \]
\[ O_{T}^{(q,\nu \ell)} = (\bar{q} \sigma^{\mu \nu} P_L b)(\bar{\tau} \sigma_{\mu \nu} P_L \nu_\ell) \]

[Details in Watanabe et al, B2 TiP32 theory]
\( b\rightarrow s \gamma \) → Decay the \( \gamma \) into 2 leptons

- Start with \( b\rightarrow s \gamma \), pay a factor \( \alpha_{\text{EM}} = \frac{1}{137} \)
- Add an interfering box diagram
- \( b\rightarrow ll s \), very rare in the SM
- \( B(B\rightarrow l l K^*) = (3.3 \pm 1.0) \cdot 10^{-6} \)

- Sensitive to Supersymmetry, Any 2HDM, Fourth generation, Extra dimensions, Axions...
- Ideal place to look for new physics
Test of lepton universality using $B^+ \rightarrow K^{(*)} l^+ l^-$ decays

Model candidates

✧ Model with extended gauge symmetry
  ✓ Effective operator from $Z'$ exchange
  ✓ Extra $U(1)$ symmetry with flavor dependent charge

✧ Models with leptoquarks
  ✓ Effective operator from LQ exchange
  ✓ Yukawa interaction with LQs provide flavor violation

✧ Models with loop induced effective operator
  ✓ With extended Higgs sector and/or vector like quarks/leptons
  ✓ Flavor violation from new Yukawa interactions

Leptoquarks are color-triplet bosons that carry both lepton and baryon numbers

Lot of those models predict also LFV $b \rightarrow s \mu \mu, b \rightarrow s \tau \tau, ...$
First observation

$B^+ \rightarrow K^+ \mu^+ \mu^-$ Event
Situation pre-LHCb

**$B \rightarrow K^* l^+ l^-$ decays**

- Channels: $K^* \rightarrow K^+ \pi^-, K_S^0 \pi^+, K^+ \pi^0$, $l = e$ or $\mu$  
  [Belle, arXiv:0904.0770]

Illustration: $q^2 \in [0.0, 2.0] \text{ GeV}^2$

- $R_{K^*} = 0.83 \pm 0.17 \pm 0.08$
- $R_K = 1.03 \pm 0.19 \pm 0.06$

\[ \left[ \frac{3}{2} F_L \cos^2 \theta_{K^*} + \frac{3}{4} (1 - F_L)(1 - \cos^2 \theta_{K^*}) \right] \times \epsilon(\cos \theta_{K^*}) \]

\[ \left[ \frac{3}{4} F_L (1 - \cos^2 \theta_{B\ell}) + \frac{3}{8} (1 - F_L)(1 + \cos^2 \theta_{B\ell}) + A_{FB} \cos \theta_{B\ell} \right] \times \epsilon(\cos \theta_{B\ell}) , \]
\( R_K, R_K^* \)...

for the whole \( q^2 \) range: of course excluding the \( \psi \)...

\[
R_{K^*} = 0.83 \pm 0.17 \pm 0.08 \\
R_K = 1.03 \pm 0.19 \pm 0.06
\]

[Belle, arXiv:0904.0770]


5σ confirmation possible with Belle II 20 ab\(^{-1}\)
$B \rightarrow K^{(*)} \tau \tau$

q$^2$ range for predictions for $B \rightarrow H \tau^+ \tau^-$: from $4 m_{\tau}^2 \left( \sim 12.6 \text{ GeV}^2 \right)$ to $(m_B - m_H)^2$

to avoid contributions from resonant decay through $\psi(2S)$, $B \rightarrow H \psi(2S)$, $\psi(2S) \rightarrow \tau^+ \tau^-$

predictions restricted to $q^2 > 15 \text{ GeV}^2$:

$B(B^+ \rightarrow K^+ \tau^+ \tau^-)_{\text{SM}} = (1.22 \pm 0.10) \times 10^{-7}$

$B(B^0 \rightarrow K^0 \tau^+ \tau^-)_{\text{SM}} = (1.13 \pm 0.09) \times 10^{-7}$

$B(B^+ \rightarrow K^{*+} \tau^+ \tau^-)_{\text{SM}} = (0.99 \pm 0.12) \times 10^{-7}$

$B(B^0 \rightarrow K^{*0} \tau^+ \tau^-)_{\text{SM}} = (0.91 \pm 0.11) \times 10^{-7}$

$B(B \rightarrow K \tau^+ \tau^-)_{\text{SM}} = (1.20 \pm 0.12) \times 10^{-7}$

$B(B \rightarrow K^* \tau^+ \tau^-)_{\text{SM}} = (0.98 \pm 0.10) \times 10^{-7}$
\( B \rightarrow K^{(*)} \tau \tau \)

strategy used: B fully reconstructed (had tag), \( \tau^+ \rightarrow l^+ \nu_l \nu_\tau \)

background: mostly \( B \rightarrow D^{(*)} l \nu_l \), \( D^{(*)} \rightarrow K l \nu_l' \)

\[ B(B^+ \rightarrow K^+ \tau^+ \tau^-) < 2.25 \times 10^{-3} \text{ at } 90\% \text{ CL} \]

<table>
<thead>
<tr>
<th>Observables</th>
<th>Belle 0.71 ab(^{-1}) (0.12 ab(^{-1}))</th>
<th>Belle II 5 ab(^{-1})</th>
<th>Belle II 50 ab(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{Br}(B^+ \rightarrow K^+ \tau^+ \tau^-) \cdot 10^5 )</td>
<td>&lt; 32</td>
<td>&lt; 6.5</td>
<td>&lt; 2.0</td>
</tr>
<tr>
<td>( \text{Br}(B^0 \rightarrow \tau^+ \tau^-) \cdot 10^5 )</td>
<td>&lt; 140</td>
<td>&lt; 30</td>
<td>&lt; 9.6</td>
</tr>
<tr>
<td>( \text{Br}(B^0_z \rightarrow \tau^+ \tau^-) \cdot 10^4 )</td>
<td>&lt; 70</td>
<td>&lt; 8.1</td>
<td>–</td>
</tr>
</tbody>
</table>
and more...

\[ B \rightarrow K^{(*)} \nu \bar{\nu} \]

- **Standard Model:**
  - Flavour changing neutral current prohibited at tree level
  - Measurement of \( B \rightarrow K^{(*)} \nu \bar{\nu} \) would allow high accuracy extraction of \( B \rightarrow K^{(*)} \) form factors
  - SM estimate of branching fraction known to \( \sim 10\% \) uncertainty

- **New Physics:**
  - Contribution from NP may be similar in size to SM contributions, decreasing time required to make discovery.
  - Light dark matter scenarios:
    - \( B \rightarrow K \nu \bar{\nu} \) is identical in the detector to \( B \rightarrow K + \text{invisible searches for light dark matter} \)
    - Increased \( B \rightarrow K \nu \bar{\nu} \) branching ratio may suggest a light dark matter component

### Projected precision on branching ratios at 50 ab\(^{-1}\) Belle II data, with FEI hadronic tag

<table>
<thead>
<tr>
<th>Mode</th>
<th>Stat. uncertainty</th>
<th>Total uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B^+ \rightarrow K^+ \nu \bar{\nu} )</td>
<td>9.5%</td>
<td>10.7%</td>
</tr>
<tr>
<td>( B^+ \rightarrow K^{*+} \nu \bar{\nu} )</td>
<td>7.9%</td>
<td>9.3%</td>
</tr>
<tr>
<td>( B^+ \rightarrow K^{*0} \nu \bar{\nu} )</td>
<td>8.2%</td>
<td>9.6%</td>
</tr>
</tbody>
</table>

Standard model observations of these modes could be made with \( \sim 18\) ab\(^{-1}\)
LFV in B decays
LFV $b \to sll'$ decays

Glashow, Guadagnoli and Lane, 1411.0565, LUV $\Rightarrow$ LFV, such as $B \to K \mu e$, $K \mu \tau$ could also be generated...

A. Crivellin et al, 1706.08511
**LFV B→K*1l' decays**

[Belle, arXiv:1807.03267]

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\varepsilon$ (%)</th>
<th>$N_{\text{sig}}$</th>
<th>$N_{\text{sig}}^{\text{UL}}$</th>
<th>$B^{\text{UL}}$ (10$^{-7}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \to K^{*0}\mu^+e^-$</td>
<td>8.8</td>
<td>$-1.5^{+4.7}_{-4.1}$</td>
<td>5.2</td>
<td>1.2</td>
</tr>
<tr>
<td>$B^0 \to K^{*0}\mu^-e^+$</td>
<td>9.3</td>
<td>$0.40^{+4.8}_{-4.5}$</td>
<td>7.4</td>
<td>1.6</td>
</tr>
<tr>
<td>$B^0 \to K^{*0}\mu^\pm e^\mp$ (combined)</td>
<td>9.0</td>
<td>$-1.18^{+6.8}_{-6.2}$</td>
<td>8.0</td>
<td>1.8</td>
</tr>
</tbody>
</table>

$B(B^0 \to K^{*0}\mu^+e^-) < 1.2 \times 10^{-7}$ at 90\% CL

$B(B^0 \to K^{*0}\mu^+e^-) < 1.6 \times 10^{-7}$ at 90\% CL

**Belle II can get 90\% UL at 10$^{-8}$ level with 50 ab$^{-1}$**
$R(D^*)$ and $b \to s \mu \mu \Rightarrow B \to K \tau \mu$

L. Calibbi et al, arXiv:1709.00692

**Key Features of PS$^3$**

**common to all PS-type models**
- TeV-scale LQ, colour-octet vector and $Z'$
- decent fit to low-energy data
- large $\tau \to \mu$ LFV effects

**specific to PS$^3$**
- hierarchical symmetry breaking pattern relates
  flavour-dependent LQ couplings
  to Yukawa hierarchies
- LQ coupling also to right-handed fermions
LFV $B \rightarrow K\tau l$ decays

[BaBar, arXiv:1204.2852]

strategy used: $B$ fully reconstructed (had tag), $\tau^+ \rightarrow l^+\nu_l\nu_\tau, (n\pi^0)\pi\nu$, with $n \geq 0$ using momenta of $K, l$ and $B$, can fully determine the $\tau$ four-momentum

\[
B(B^+ \rightarrow K^+\tau^-\mu^+) < 4.5 \times 10^{-5} \text{ at } 90\% \text{ CL, } B(B^+ \rightarrow K^+\tau^+\mu^-) < 2.8 \times 10^{-5} \text{ at } 90\% \text{ CL}
\]

(also results for $B \rightarrow K^+\tau^\pm e^\mp, B \rightarrow \pi^+\tau^\pm\mu^\mp, B \rightarrow \pi^+\tau^\pm e^\mp$ modes)


<table>
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<tr>
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<th>Belle 0.71 ab(^{-1}) (0.12 ab(^{-1}))</th>
<th>Belle II 5 ab(^{-1})</th>
<th>Belle II 50 ab(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Br}(B^+ \rightarrow K^+\tau^\pm e^\mp) \cdot 10^6$</td>
<td>--</td>
<td>--</td>
<td>&lt; 2.1</td>
</tr>
<tr>
<td>$\text{Br}(B^+ \rightarrow K^+\tau^\pm\mu^\mp) \cdot 10^6$</td>
<td>--</td>
<td>--</td>
<td>&lt; 3.3</td>
</tr>
<tr>
<td>$\text{Br}(B^0 \rightarrow \tau^\pm e^\mp) \cdot 10^5$</td>
<td>--</td>
<td>--</td>
<td>&lt; 1.6</td>
</tr>
<tr>
<td>$\text{Br}(B^0 \rightarrow \tau^\pm\mu^\mp) \cdot 10^5$</td>
<td>--</td>
<td>--</td>
<td>&lt; 1.3</td>
</tr>
</tbody>
</table>

⇒ can we do better? combining hadronic tag with inclusive tag?
⇒ can do $K^*\tau e$, $K^*\tau\mu$ with similar sensitivity...
more observables...

C. Hati et al, arXiv:1806.10146

A. Datta et al, arXiv:1609.09078: interesting modes are $\tau \rightarrow 3\mu$, and $Y(3S)\rightarrow \mu \tau$
cLFV: beyond the Standard Model

\[ \mathcal{B}_{\nu SM}(\tau \to \mu \gamma) = \frac{3\alpha}{32\pi} \left| U_{\tau i} U_{\mu i} \frac{\Delta m^2}{m_W^2} \right|^2 < 10^{-40} \]

\[ \mathcal{L} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^6} O_i^{(6)} + \ldots \]

<table>
<thead>
<tr>
<th>Model</th>
<th>Reference</th>
<th>( \tau \to \mu \gamma )</th>
<th>( \tau \to \mu \mu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM + ν oscillations</td>
<td>EPJ C8 (1999) 513</td>
<td>10^{-40}</td>
<td>10^{-40}</td>
</tr>
<tr>
<td>SM + heavy Maj νR</td>
<td>PRD 66 (2002) 034008</td>
<td>10^{-9}</td>
<td>10^{-10}</td>
</tr>
<tr>
<td>Non-universal Z</td>
<td>PLB 547 (2002) 252</td>
<td>10^{-8}</td>
<td>10^{-8}</td>
</tr>
<tr>
<td>SUSY SO(10)</td>
<td>PRD 68 (2003) 033012</td>
<td>10^{-8}</td>
<td>10^{-10}</td>
</tr>
<tr>
<td>mSUGRA+seesaw</td>
<td>PRD 66 (2002) 115013</td>
<td>10^{-7}</td>
<td>10^{-9}</td>
</tr>
<tr>
<td>SUSY Higgs</td>
<td>PLB 566 (2003) 217</td>
<td>10^{-10}</td>
<td>10^{-7}</td>
</tr>
</tbody>
</table>

...also Υ(nS) LFV decays
Belle II's first steps...
phase 2 \rightarrow phase 3

B rediscovery program

Phase 2, BEAST II collision + partial Belle II

First collisions May to July
\sim 500 \, \text{pb}^{-1}

Goal of Belle II/SuperKEKB

Phase 3, physics run

9 months/year
20 days/month

First studies of performance of hadronic tagging in Belle II data
**Belle II detector**

- EM Calorimeter: CsI(Tl)
  - waveform sampling
- K_L and muon detector
  - Resistive Plate Counter (barrel)
  - Scintillator + WLSF + MPPC (endcaps)
- Vertex Detector
  - 2 layers DEPFET + 4 layers DSSD (phase 3)
- Particle Identification
  - Time–Of–Propagation counter (barrel)
  - Prox. focusing Aerogel RICH
- Central Drift Chamber
  - He (50%):C_2H_6 (50%)
  - small cells, long level arm, fast electronics
\[ \phi \rightarrow K^+ K^- \]

with PID

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

with PID

\[ K_S^0 \rightarrow \pi^+ \pi^- \]

\[ \pi^0 \rightarrow \gamma \gamma \]
Spring 2019, first phase 3 physics run

Only 2 months of collisions

\[ L(\text{peak}) \sim 5.5 \times 10^{33}/\text{cm}^2/\text{sec} \]
\[ (\beta_y^* = 3 \text{ mm}) \]

\[ L(\text{SuperKEKB peak}) \sim 1.2 \times 10^{34}/\text{cm}^2/\text{sec} \]
\[ (\beta_y^* = 2 \text{ mm}) \]

Comparable to PEP–II best but bkgs \( \times 3 \) too large to turn on Belle II
Rediscovering beauty: \( B \to D^{(*)} h \ldots \)

Results for 2.6 \( fb^{-1} \)

\[
\Delta E = E_{CM}/2 - E_{\text{recon}}
\]

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

2200 fully reconstructed hadronic B decays

Show capacity for charm physics in \( e^+ e^- \to c \bar{c} \)

- \( D^0, D^+, D^* \)
- Cabibbo favoured and suppressed modes

... for B- physics

- hadronic modes from \( b \to c \), including modes with neutrals and \( K_S^0 \)
- semileptonic decay modes from \( b \to c \)
Observation of $B^- \rightarrow D^0 K^-$

No PID

With high momentum PID

Demonstration of Belle II high momentum PID on a decay mode to be used for future determinations of the unitarity angle $\gamma$ (a. k. a. $\phi_3$)

$N(DK) = 38 \pm 8$, fit gives $6 \sigma$

$D^0$ lifetime ($D^0 \rightarrow K \pi$)

$t_{D^0} = 370 \pm 40$ (stat) fs
Conclusion

- Few tantalizing results on rare decays in B sector covered in this talk... but much more in B decays: LFV searches, $B \rightarrow K^{(*)}\nu\bar{\nu}$, $B \rightarrow \tau\nu, \mu\nu$...
  
  also in charm, charmonium, bottomonium, light Higgs, $\tau$, DS, kaon sectors...

- Definitely not only complementary, but stimulating competition between (super) B-factories and LHCb (upgrade):
  
  - for the expected: results on $B_{(s)} \rightarrow \mu\mu$, $B \rightarrow K^{*}\mu\nu$, $B_s \rightarrow J/\psi\phi$, $\gamma$ angle...
  
  - for the less expected: results on $|V_{ub}|$, $D^*\tau\nu$...

<table>
<thead>
<tr>
<th></th>
<th>LHC era</th>
<th>HL-LHC era</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1 (2010-12)</td>
<td>3 fb$^{-1}$</td>
<td></td>
</tr>
<tr>
<td>Run 2 (2015-18)</td>
<td>8 fb$^{-1}$</td>
<td></td>
</tr>
<tr>
<td>Run 3 (2020-22)</td>
<td>23 fb$^{-1}$</td>
<td>46 fb$^{-1}$</td>
</tr>
<tr>
<td>Run 4 (2025-28)</td>
<td></td>
<td>100 fb$^{-1}$</td>
</tr>
<tr>
<td>Run 5+ (2030+)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
$B \rightarrow K^* (K^0_S \pi^0) \gamma$

time-dependent CPV

$K_S$ trajectory

$B$ vertex

IP profile

control sample is $J/\psi K^0_S$!!

[467 MBB]
[arXiv:0807.3103]

[535 MBB]
[hep-ex/0608017]

$K^* \gamma S_{CP}$ vs $C_{CP}$

HFAG Moriond 2014 PRELIMINARY

$S_{K^* \gamma} = -0.16 \pm 0.22$

$A_{K^* \gamma} = +0.04 \pm 0.14$

HFAG CKM 2014 PRELIMINARY
Mixing-induced CP violation

Remember $B^0 \to J/\psi K^0_s$:

What about $B^0 \to \gamma K^0_s \pi^0$?

In SM mainly $B^0 \to K^0_s \pi^0 \gamma_R$ and $\bar{B}^0 \to K^0_s \pi^0 \gamma_L$: $K^0_s \pi^0 \gamma$ behaves like an effective flavor eigenstate, $\Rightarrow$ mixing-induced CP violation is expected to be small $S \sim -2(m_s/m_b)\sin(2\phi_1)$.
In SM, the photon from $b \to s \gamma$ is (mostly) lefthanded (polarized).
⇒ Mixing induced (time-dependent) CPV does not occur in $B \to f_{CP} \gamma$

**SM**: $S_{CP}^{K^*\gamma} \sim -\left(2m_s/m_b\right)\sin2\beta \sim -0.04$

**Left-Right Symmetric Models**: $S_{CP}^{K^*\gamma} \sim 0.5$

[D. Atwood et al., PRL 79, 185 (1997)]
Constraints on NP from radiative B decays

At Belle II, expect significant improvement in the determination of $A_{CP}(t)$ in $K_S^0\pi^0\gamma$

- **Belle II SVD larger than Belle** ($6 \rightarrow 11.5 \text{ cm}$)

  $\Rightarrow$ 30% more $K_S$ with vertex hits available, effective tagging eff. 13% better

### Expected errors for $S$ measurements of $K_S^0\pi^0\gamma$ and $\rho^0\gamma$

<table>
<thead>
<tr>
<th>Mode</th>
<th>5 ab$^{-1}$</th>
<th>50 ab$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_S^0\pi^0\gamma$</td>
<td>0.09</td>
<td>0.030</td>
</tr>
<tr>
<td>$\rho^0\gamma$</td>
<td>0.19</td>
<td>0.064</td>
</tr>
</tbody>
</table>

HFLAV

$S_{CP}^{K^0\gamma} = -0.16 \pm 0.22$

$A_{CP}^{K^0\gamma} = +0.04 \pm 0.14$
Belle results for both ee and $\mu \mu$

[Belle, arXiv:1612.05014]

$B \to K^* ee$

$B \to K^* \mu \mu$

2.6$\sigma$ from SM for $\mu \mu$ mode, 1.1$\sigma$ for ee mode
**Inclusive di-lepton, B→X_s l^+ l^-** (at Belle II)

<table>
<thead>
<tr>
<th>Observables</th>
<th>Belle 0.71 ab⁻¹</th>
<th>Belle II 5 ab⁻¹</th>
<th>Belle II 50 ab⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Br(B → X_s l^+ l^-) ([1.0, 3.5] GeV²)</td>
<td>29%</td>
<td>13%</td>
<td>6.6%</td>
</tr>
<tr>
<td>Br(B → X_s l^+ l^-) ([3.5, 6.0] GeV²)</td>
<td>24%</td>
<td>11%</td>
<td>6.4%</td>
</tr>
<tr>
<td>Br(B → X_s l^+ l^-) (&gt; 14.4 GeV²)</td>
<td>23%</td>
<td>10%</td>
<td>4.7%</td>
</tr>
<tr>
<td>A_CP(B → X_s l^+ l^-) ([1.0, 3.5] GeV²)</td>
<td>26%</td>
<td>9.7%</td>
<td>3.1%</td>
</tr>
<tr>
<td>A_CP(B → X_s l^+ l^-) ([3.5, 6.0] GeV²)</td>
<td>21%</td>
<td>7.9%</td>
<td>2.6%</td>
</tr>
<tr>
<td>A_CP(B → X_s l^+ l^-) (&gt; 14.4 GeV²)</td>
<td>21%</td>
<td>8.1%</td>
<td>2.6%</td>
</tr>
<tr>
<td>A_FB(B → X_s l^+ l^-) ([1.0, 3.5] GeV²)</td>
<td>26%</td>
<td>9.7%</td>
<td>3.1%</td>
</tr>
<tr>
<td>A_FB(B → X_s l^+ l^-) ([3.5, 6.0] GeV²)</td>
<td>21%</td>
<td>7.9%</td>
<td>2.6%</td>
</tr>
<tr>
<td>A_FB(B → X_s l^+ l^-) (&gt; 14.4 GeV²)</td>
<td>19%</td>
<td>7.3%</td>
<td>2.4%</td>
</tr>
<tr>
<td>Δ_CP(A_FB) ([1.0, 3.5] GeV²)</td>
<td>52%</td>
<td>19%</td>
<td>6.1%</td>
</tr>
<tr>
<td>Δ_CP(A_FB) ([3.5, 6.0] GeV²)</td>
<td>42%</td>
<td>16%</td>
<td>5.2%</td>
</tr>
<tr>
<td>Δ_CP(A_FB) (&gt; 14.4 GeV²)</td>
<td>38%</td>
<td>15%</td>
<td>4.8%</td>
</tr>
</tbody>
</table>

[Belle II Prospects](arXiv:1808.10567)
Rediscovering charm: $D^{*+} \rightarrow D \pi^+$, $D \rightarrow K^- \pi^+$, $K^- \pi^+ \pi^0$, $K^- \pi^+ \pi^- \pi^+$
Dark Sector Physics

exploit the clean $e^+e^-$ environment to probe the existence of exotic hadrons, dark photons/Higgs, light Dark Matter particles, ...

dark photon $A'$ mixes with SM photon $\gamma$ with strength $\epsilon$

search for a dark photon decaying invisibly, and the search for an axion-like particle may be possible even in "Phase 2"
\(B_s \rightarrow \mu \mu\): ultra rare processes...

loop diagram + suppressed in SM + theoretically clean = an excellent place to look for new physics

higher-order FCNC allowed in SM

\[B(B_s \rightarrow \mu^+ \mu^-)=(3.65 \pm 0.23) \times 10^{-9}\]
\[B(B_d \rightarrow \mu^+ \mu^-)=(1.06 \pm 0.09) \times 10^{-10}\]

[Bobeth et al, PRL 112 (2014) 101801]

same decay in theories extending the SM (some of NP scenarios may boost the \(B \rightarrow \mu \mu\) decay rates)
$B_{(s)} \rightarrow \mu \mu$: ultra rare processes...

"I'm too old for limits, I want to see signals"
(Francis Halzen)
**B_s → μ⁺ μ⁻ results**

CMS and LHCb (LHC run I) 6 most sensitive bins

\[ B(B_s^0 → μ^+ μ^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9} \]

**first observation**: 6.2σ significance

\[ B(B^0 → μ^+ μ^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10} \]

**first evidence**: 3.0σ significance

---

**SM**: heavy state decays to \( μ^+ μ^- \)

**first lifetime measurement**:

\[ \tau(B_s → μ^+ μ^±) = 2.04 \pm 0.44 \pm 0.05 \text{ ps} \]

\[ B(B^0_\text{s} → μ^+ μ^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9} \] (7.8σ significance)

\[ B(B^0 → μ^+ μ^-) < 3.4 \times 10^{-10} @ 90\% \text{ CL} \]
Constraints on NP models

From D. Straub, arXiv:1205.6094
B → D(*)τν

1,768 decay chains

○ 2D unbinned fit to $m^2_{\text{miss}}$ and $p_1^*$
○ fitted samples
  - 4 D(*)l samples (D^0 l, D^*0 l, D^+ l and D^*+ l)
  - 4 D(*)π^0 l control samples (D** (1/τ)ν)

⇒ Dτν and D^*τν clearly observed
$B \rightarrow D^{(*)} \tau \nu$ [BaBar, PRL 109, 101802 (2012)]

- combined $3.4 \sigma$ away from SM
- doesn't fit 2HDM Type II
\[ B \to D^{(*)} \tau \nu \text{ at Belle} \] [Belle, arXiv:1507.03233]

(projections for large \( M_{\text{miss}}^2 \) region, \( N(D\tau\nu) \sim 300, N(D^{*}\tau\nu) \sim 500 \))

\[ B \to D^+ \tau \nu \]

\[ B \to D^0 \tau \nu \]

\[ B \to D^{*+} \tau \nu \]

\[ B \to D^{*0} \tau \nu \]

\[ R(D) = 0.375 \pm 0.064 \pm 0.026 \]
\[ R(D^*) = 0.293 \pm 0.038 \pm 0.015 \]

(disagreement with SM at 1.5\( \sigma \))

(stat error only!)

[disagreement with SM at 1.5\( \sigma \)]
Summary for $B \to D^{(*)} \tau \nu$ in 2016

$$R(D^{(*)}) = \frac{BF(B \to D^{(*)} \tau \nu_\tau)}{BF(B \to D^{(*)} l \nu_l)}$$

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$R(D)$</th>
<th>$R(D^*)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaBar</td>
<td>$0.440 \pm 0.058 \pm 0.042$</td>
<td>$0.332 \pm 0.024 \pm 0.018$</td>
</tr>
<tr>
<td>Belle</td>
<td>$0.375 \pm 0.064 \pm 0.026$</td>
<td>$0.293 \pm 0.038 \pm 0.015$</td>
</tr>
<tr>
<td>LHCb</td>
<td>$0.336 \pm 0.027 \pm 0.030$</td>
<td></td>
</tr>
</tbody>
</table>

Average difference with SM predictions is at $4.0\sigma$ level

[Belle, arXiv:1607.07923]

Semileptonic tagging ($B \to D^{*+} l^- \nu$)

$R(D^*) = 0.302 \pm 0.030 \pm 0.011$
$B \to D^* \tau \nu$ at Belle

[Belle, arXiv:1612.00529]

$\tau$ polarization result using:

- $\tau^- \to \pi^- \nu_\tau, \rho^- \nu_\tau$ are good polarimeter for $\tau$ polarization

\[
P_{\tau}(D^*) = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-}
\]

$P_{\tau}(D^*)_{SM} = -0.497 \pm 0.013$


- $\theta_{hel}$ = angle of $\tau$ daughter meson momentum with respect to direction opposite to momentum of $\tau \nu$ system in $\tau$ rest frame

\[
\frac{1}{\Gamma(D^*)} \frac{d\Gamma(D^*)}{d\cos \theta_{hel}} = \frac{1}{2} \left[ 1 + \alpha P_{\tau}(D^*) \cos \theta_{hel} \right]
\]

\[
\alpha = 1 \text{ for } \tau^- \to \pi^- \nu_\tau
\]

\[
\alpha = 0.45 \text{ for } \tau^- \to \rho^- \nu_\tau
\]

$P_{\tau}(D^*) = -0.38 \pm 0.51^{+0.21}_{-0.16}$

$R(D^*) = 0.270 \pm 0.035^{+0.028}_{-0.025}$

hadronic decays of $\tau$: $\tau^- \to \pi^- \nu_\tau, \rho^- \nu_\tau$

hadronic tagging

$\tau$ polarizations

$D^{(*)}$ leptonic with hadronic tagging, arXiv:1507.03233

$D^*$ with semileptonic tagging, arXiv:1607.07923

hadronic tagging