Complementarity between LHC experiments, Kaon physics, BES III, direct LFV searches, and Belle II

Jernej F. Kamenik
Flavor physics circa 2025: possible scenarios

Now

50 ab$^{-1}$ Belle II

50 ab$^{-1}$ Belle II + LHCb

WA

SM-like

+ discoveries or bounds from high-pT searches

Now

50 ab$^{-1}$ Belle II

50 ab$^{-1}$ Belle II + LHCb

WA

SM-like
Flavor physics circa 2025: possible scenarios

LHC will have pushed the envelope of direct high-mass searches by another factor of few
LHC bad dream scenario: (mini)split SUSY

NP thresholds beyond direct reach

Flavor (&CPV) powerful probes of PeV sfermions
(motivated by Higgs mass)

\[ m_h^2 = m_Z^2 \cos^2 2\beta + \frac{3m_t^2}{4\pi^2v^2} \log \frac{m_t^2}{m_t^2} \]

\[ m_Q^2 = m_{\tilde{q}}^2(\mathbb{I} + \delta_q^L) \]

generic FV \sim O(1)
LHC bad dream scenario: (mini)split SUSY

NP thresholds beyond direct reach

Flavor (&CPV) powerful probes of PeV sfermions

Significant improvements expected in next ~10 yrs

| $m_{\tilde{B}} = m_{\tilde{W}} = 3 \text{ TeV}$, $|m_{\tilde{g}}| = 10 \text{ TeV}$ |
| $\tan\beta$ |
| 10 |
| 30 |

Now

~2025

Best strategy to push beyond?
Who ordered that? Vector-Like Fermions

Do not worsen hierarchy problem.

Can mix with SM chiral fermions

⇒ Z-mediated FCNCs

Strongest bounds from large variety of processes:

\(a\) \(\mu\) to \(e\) conversion; \(b\) \(\tau \to e\pi\); \(c\) \(\tau \to \mu\rho\); \(d\) \(K \to \pi\nu\bar{\nu}\);

\(e\) \(K_L \to \mu^+\mu^-\); \(f\) \(K\) mixing; \(g\) \(B \to \pi\mu^+\mu^-\); \(h\) \(B_d\) mixing;

\(i\) \(B \to X_s\ell^+\ell^-\); \(j\) \(B_s\) mixing; \(k\) \(D \to \mu^+\mu^-\); \(l\) \(D\) mixing; \(m\) \(B_s \to \mu^+\mu^-\)
Who ordered that? Vector-Like Fermions

Do not worsen hierarchy problem.

Can mix with SM chiral fermions

$\Rightarrow$ Z-mediated FCNCs

Strongest bounds from large variety of processes:

1. $\mu$ to $e$ conversion;
2. $\tau \to e\pi$;
3. $\tau \to \mu\rho$;
4. $K \to \pi\nu\bar{\nu}$;
5. $K$ mixing;
6. $B_d \to \mu^+\mu^-$;
7. $B_d$ mixing;
8. $B_s \to \mu^+\mu^-$;
9. $B_s$ mixing;
10. $D \to \mu^+\mu^-$;
11. $D$ mixing.

Best strategy to push beyond?
Outline

Flavor probes of NP post 2025
(+determining SM flavor parameters)

- Beauty
- Charm
- Kaons
- Heavy leptons (τ,μ)

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<table>
<thead>
<tr>
<th>Observable</th>
<th>Expected th. accuracy</th>
<th>Expected exp. uncertainty</th>
<th>Facility</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>K \to πν\ell\nu</td>
<td>$</td>
<td>**</td>
</tr>
<tr>
<td>$</td>
<td>B \to X_d πν\ell\nu</td>
<td>$</td>
<td>**</td>
</tr>
<tr>
<td>$</td>
<td>B_d \to πν\ell\nu</td>
<td>$</td>
<td>*</td>
</tr>
<tr>
<td>$\sin(2\phi_1)$</td>
<td>***</td>
<td>$8 \cdot 10^{-3}$</td>
<td>Belle II/LHCb</td>
</tr>
<tr>
<td>$\phi_2$</td>
<td>***</td>
<td>1.5°</td>
<td>Belle II</td>
</tr>
<tr>
<td>$\phi_3$</td>
<td>***</td>
<td>3°</td>
<td>LHCb</td>
</tr>
<tr>
<td>$S(B_s \to ψ\phi)$</td>
<td>**</td>
<td>0.01</td>
<td>LHCb</td>
</tr>
<tr>
<td>$S(B_s \to ψK)$</td>
<td>**</td>
<td>0.05</td>
<td>LHCb</td>
</tr>
<tr>
<td>$S(B_d \to ψK)$</td>
<td>***</td>
<td>0.05</td>
<td>Belle II/LHCb</td>
</tr>
<tr>
<td>$S(B_d \to ψK)$</td>
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<td>0.02</td>
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<tr>
<td>$S(B_d \to K^{*}(\to K_3^0\phi^0\gamma))$</td>
<td>***</td>
<td>0.03</td>
<td>Belle II</td>
</tr>
<tr>
<td>$S(B_s \to ψ\gamma)$</td>
<td>***</td>
<td>0.05</td>
<td>Belle II</td>
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<tr>
<td>$S(B_d \to ρ\gamma)$</td>
<td>***</td>
<td>0.15</td>
<td>LHCb</td>
</tr>
<tr>
<td>$A_{SL}^{3}$</td>
<td>**</td>
<td>0.001</td>
<td>LHCb</td>
</tr>
<tr>
<td>$A_{SL}^{1}$</td>
<td>***</td>
<td>0.001</td>
<td>LHCb</td>
</tr>
<tr>
<td>$A_{CT}(B_d \to s\gamma)$</td>
<td>*</td>
<td>0.005</td>
<td>Belle II</td>
</tr>
<tr>
<td>$\tau$ decays</td>
<td>**</td>
<td>3%</td>
<td>Belle II</td>
</tr>
<tr>
<td>$B(\bar{B} \to χ\mu\nu)$</td>
<td>**</td>
<td>3%</td>
<td>Belle II</td>
</tr>
<tr>
<td>$B(\bar{B} \to D\pi\nu)$</td>
<td>**</td>
<td>6%</td>
<td>Belle II</td>
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<tr>
<td>$B(B_d \to μ\nu)$</td>
<td>***</td>
<td>10%</td>
<td>LHCb</td>
</tr>
<tr>
<td>$B(\bar{B} \to μ\nu)$</td>
<td>**</td>
<td>0.05</td>
<td>LHCb</td>
</tr>
<tr>
<td>zero of $A_{FB}(B \to K^*μ\ell\nuμ)$</td>
<td>**</td>
<td>30%</td>
<td>Belle II</td>
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<tr>
<td>$B(\bar{B} \to K_0^0\nu\nu)$</td>
<td>***</td>
<td>4%</td>
<td>Belle II</td>
</tr>
<tr>
<td>$B(\bar{B} \to K\pi\nu\nu)$</td>
<td>***</td>
<td>$0.25 \cdot 10^{-6}$</td>
<td>Belle II (with 5 ab$^{-1}$)</td>
</tr>
<tr>
<td>$B(K \to πν\ell\nu)/B(K \to μν\ell\nu)$</td>
<td>***</td>
<td>10%</td>
<td>$K$-factory</td>
</tr>
<tr>
<td>$B(\bar{B} \to ρ\gamma)$</td>
<td>**</td>
<td>0.1%</td>
<td>$K$-factory</td>
</tr>
<tr>
<td>$A_{FB}(B \to K\mu\nu)$</td>
<td>***</td>
<td>3 · 10^{-9}</td>
<td>Belle II</td>
</tr>
<tr>
<td>$A_{FB}(B \to K\mu\nu)$</td>
<td>***</td>
<td>0.03</td>
<td>Belle II</td>
</tr>
<tr>
<td>$\arg(A_{FB}(B \to K\mu\nu))$</td>
<td>***</td>
<td>1.5°</td>
<td>Belle II</td>
</tr>
</tbody>
</table>

B physics

Precision CKM measurements (in CC dominated processes)

$|V_{cb}|$, $|V_{ub}|$, $\gamma(=\Phi_3)$

Enter all SM predictions of loop observables - limiting factor?

Example: \[ \left| \frac{\Delta \epsilon_K}{\epsilon_K} \right|_{\Delta |V_{cb}| = 0.3 \times 10^{-3}} = 2.2^\circ, \]

$^{1602.08494}$
B physics

Precision CKM measurements (in CC dominated processes)
\[ \Rightarrow |V_{ub}| \]

inclusive measurements theory limited,
final Bellell exclusive precision: \( \sim 2.2\% \)
(assuming matching LatticeQCD)
current LHCb measurement
\[
\frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{\mathcal{B}(\Lambda_b^0 \rightarrow p\mu^-\overline{\nu}_\mu)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+\mu^-\overline{\nu}_\mu)} R_{FF}
\]
\[
\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004 \pm 0.004 \quad \text{Nature Phys. 11 (2015) 743-747}
\]
\( \sim 7.2\% \) uncertainty
B physics

Precision CKM measurements (in CC dominated processes) ⇒ |V_{ub}|

inclusive measurements theory limited, final Bellell exclusive precision: ~2.2% (assuming matching LatticeQCD) current LHCb measurement

\[
\frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{\mathcal{B}(\Lambda_b^0 \rightarrow p\mu^-\bar{\nu}_\mu)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+\mu^-\bar{\nu}_\mu)} R_{FF}
\]

\[
\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004 \pm 0.004 \quad \text{Nature Phys. 11 (2015) 743-747}
\]

~7.2% uncertainty - crucial x-check of discrepancies + angular & spin observables
B physics

Precision CKM measurements (in CC dominated processes)
⇒ |V_{ub}|

inclusive measurements theory limited,
final Belle II exclusive precision: ~2.2%
(assuming matching LatticeQCD)
theoretically cleanest determination:
(uses only isospin)
B physics

Precision CKM measurements (in CC dominated processes)
⇒ \(|V_{ub}|\)

inclusive measurements theory limited,
final Belle II exclusive precision: \(\sim 2.2\%\)
(assuming matching LatticeQCD)
theoretically cleanest determination:
(uses only isospin)

⇒ \(\gamma (=\phi_3)\) theory uncertainty in extraction \(\sim 10^{-7}\)
B physics

LFU in CC B decays

Final BelleII measurements will be systematics limited at precision of 2-3%, comparable to present SM uncertainties.

Look towards other related systems…

Can (in principle) be improved systematically below ~1%
B physics

LFU in CC B decays

Final Belle measurements will be systematics limited at precision of 2-3%, comparable to present SM uncertainties.

LFU in top decays

B physics

LFU in CC B decays

Final BelleII measurements will be systematics limited at precision of 2-3%, comparable to present SM uncertainties.

LFU in top decays at per-mille level at HL-LHC(b)?

Currently known to $O(10\%)$

$$B_e = 13.3(4)(4)\% , \quad B_\mu = 13.4(3)(5)\% , \quad B_\tau = 7.0(3)(5)\% .$$
B physics

$B_{s,d}$ - oscillations

$\Rightarrow \sin 2\beta$, $\alpha$

Final Belle II & LHCb precision comparable & statistically dominated

Theory uncertainties (in $\sin 2\beta$) at $\sim 1\%$
B physics

$B_{s,d} -$ oscillations

$\Rightarrow a_{sl}^{(s,d)}$

Current exp. unc. $\sim 0.5\%$

Will be improved by order of magnitude by Bellell & LHCb

Still order of magnitude above precision of SM predictions:

$$a_{sl}^s = (2.22 \pm 0.27) \times 10^{-5} \text{ for } B_s^0$$

$$a_{sl}^d = (-4.7 \pm 0.6) \times 10^{-4} \text{ for } B^0$$
B physics

Rare FCNC decays

Exclusive rare semileptonic decays already becoming theory limited? (P5’ anomaly)

see e.g. 1212.2263, 1412.3183

Will be probed at Belle II with inclusive decays (theoretically cleaner)
B physics

Rare FCNC decays

Exclusive rare semileptonic decays already becoming theory limited? (P5’ anomaly)

see e.g. 1212.2263, 1412.3183

Focus on th. clean probes

Example: RH-currents
B physics

Rare FCNC decays

LFU ratios in SM known to ~1%

$$R_M[q_{\min}^2, q_{\max}^2] = \frac{\int_{q_{\min}^2}^{q_{\max}^2} dq^2 d\Gamma(B \to M\mu^+\mu^-)}{\int_{q_{\min}^2}^{q_{\max}^2} dq^2 d\Gamma(B \to Me^+e^-)} ,$$

Final BelleII precision <4%
Charm physics

Tests of CKM ($V_{cq}$) in (semi)leptonic D decays will be improved by BESIII, Bellell (theory limited at ~1%)

CPV (in oscillations, in decays) - important interplay with Bellell

⇒ direct CPV in SCS D decays

\[ \Delta A_{CP} \equiv A_{CP}^{K^+K^-} - A_{CP}^{\pi^+\pi^-} \]
Charm physics

Tests of CKM ($V_{cq}$) in (semi)leptonic D decays will be improved by BESIII, Belle II (theory limited at ~1%)

CPV (in oscillations, in decays) - important interplay with Belle II

⇒ direct CPV in SCS D decays

SM expectations uncertain

$|\Delta A_{CP}|_{SM} = R_{P/T}|\text{Im}(\lambda_s/\lambda_d)|\frac{\alpha_s}{\pi} \lesssim 0.1\%$

$\lambda_q \equiv V_{cq}^* V_{uq}$

non-pert QCD, O(few)?
Charm physics

Tests of CKM ($V_{cq}$) in (semi)leptonic D decays will be improved by BESIII, BelleII (theory limited at ~1%)

CPV (in oscillations, in decays) - important interplay with BelleII

⇒ direct CPV in SCS D decays

SM expectations uncertain

$$|\Delta A_{CP}|_{SM} = R_P/T |\text{Im}(\lambda_s/\lambda_d)| \frac{\alpha_s}{\pi} \lesssim 0.1\%$$

In future use Lattice, test sum rules

see e.g. 1111.5000

$A_{CP}(D^0 \rightarrow \pi^0\pi^0)$
Tests of CKM ($V_{cq}$) in (semi)leptonic D decays will be improved by BESIII, Bellell (theory limited at $\sim 1\%$).

CPV (in oscillations, in decays) - important interplay with Bellell

$\Rightarrow$ direct CPV in SCS D decays

$\Rightarrow$ CPV in $D^0$ mixing

SM estimates for phase $\phi \sim 0.1^\circ$

Final Bellell sensitivity $\delta\phi \sim 4^\circ$
Charm physics

Tests of CKM ($V_{cq}$) in (semi)leptonic D decays will be improved by BESIII, Belle II (theory limited at ~1%)

CPV (in oscillations, in decays) - important interplay with Belle II

⇒ direct CPV in SCS D decays

⇒ CPV in $D^0$ mixing

⇒ CPV in rare semileptonic D decays (similar to B case)
Kaon physics

Tests of CPV already among most stringent ($\varepsilon_K$, $\varepsilon'$)
Near future improvements mostly due to theory (Lattice)
More progress foreseen in rare decays

$$\Rightarrow K^+ \rightarrow \pi^+ \nu \bar{\nu}, K_L \rightarrow \pi^0 \nu \bar{\nu}$$

Precise SM predictions (dominant parametric unct.)

$$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})_{SM} = 7.81(75)(29) \times 10^{-11}$$
$$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})_{exp} = 17.3^{+11.5}_{-10.5} \times 10^{-11}$$

$$\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu})_{SM} = 2.43(39)(6) \times 10^{-11}$$
$$\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu})_{exp} < 2.6 \times 10^{-8}$$
Kaon physics

Tests of CPV already among most stringent ($\varepsilon_K$, $\varepsilon'$)
Near future improvements mostly due to theory (Lattice)
More progress foreseen in rare decays

$\Rightarrow K^+ \rightarrow \pi^+ \nu \bar{\nu}, K_L \rightarrow \pi^0 \nu \bar{\nu}$

Precise SM predictions (dominant parametric unct.)
Rich NP hunting ground

Example:
Modified $Z$ couplings, in SM convention:

$\Delta^\nu_{L} (Z) = \Delta^\mu_{A} (Z) = \frac{g}{2c_W} = 0.372$
Kaon physics

Tests of CPV already among most stringent ($\varepsilon_K$, $\varepsilon'$)

Near future improvements mostly due to theory (Lattice)

More progress foreseen in rare decays

$$\Rightarrow K^+ \rightarrow \pi^+ \nu \bar{\nu}, K_L \rightarrow \pi^0 \nu \bar{\nu}$$

Precise SM predictions

Rich NP hunting ground

After KOTO & NA62, precision

$$\delta B(K_L) \sim 5\% \quad \delta B(K^+) \sim 10\%$$

competitive to present parametric uncertainties

(UT from rare K decays)
Kaon physics

Tests of CPV already among most stringent ($\varepsilon_K$, $\varepsilon'$)

Near future improvements mostly due to theory (Lattice)

More progress foreseen in rare decays

⇒ $K^+ \rightarrow \pi^+ \nu \bar{\nu}$, $K_L \rightarrow \pi^0 \nu \bar{\nu}$

⇒ rare K decays at HL-LHCb?

<table>
<thead>
<tr>
<th>PDG</th>
<th>Prospects</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_S \rightarrow \mu \mu$</td>
<td>$&lt; 9 \times 10^{-9}$ at 90% CL (LD) $(5.0 \pm 1.5) \cdot 10^{-12}$</td>
</tr>
<tr>
<td>$K_L \rightarrow \mu \mu$</td>
<td>$(6.84 \pm 0.11) \times 10^{-9}$</td>
</tr>
<tr>
<td>$K_S \rightarrow \mu \mu \mu \mu$</td>
<td>$-$</td>
</tr>
<tr>
<td>$K_S \rightarrow ee \mu \mu$</td>
<td>$-$</td>
</tr>
<tr>
<td>$K_S \rightarrow ee$</td>
<td>$-$</td>
</tr>
<tr>
<td>$K_S \rightarrow eeee$</td>
<td>$-$</td>
</tr>
<tr>
<td>$K_S \rightarrow \pi^+ \pi^- \mu^+ \mu^-$</td>
<td>$-$</td>
</tr>
</tbody>
</table>
Kaon physics

Tests of CPV already among most stringent ($\varepsilon_K$, $\varepsilon'$)

Near future improvements mostly due to theory (Lattice)

More progress foreseen in rare decays

$$\Rightarrow K^+ \rightarrow \pi^+ \nu \bar{\nu}, K_L \rightarrow \pi^0 \nu \bar{\nu}$$

$$\Rightarrow$$ rare K decays at HL-LHCb?

could probe NP related to B LFU anomalies

sensitivity beyond $10^{-11}$?

see e.g. 1601.00970
Heavy leptons

rare tau decays
rare muon decays + conversion in nuclei
relative rates depend on UV dynamics & flavor structure
⇒ dipole-dominance

$$\mathcal{L}_{CLFV} = \frac{m_\ell}{\Lambda_{NP}^2} \bar{\ell}_R (\sigma \cdot F) \ell'_L$$

G. Signorelli, FPCP2013
Heavy leptons

rare tau decays
rare muon decays + conversion in nuclei
relative rates depend on UV dynamics & flavor structure
⇒ dipole-dominance
⇒ realistic models generate more ops.

$$\mathcal{L}_{CLFV} = \frac{m_\ell}{\Lambda_{NP}^2 (1 + \kappa)} \bar{\ell}_R (\sigma \cdot F) \ell'_L$$

$$+ \frac{\kappa}{\Lambda_{NP}^2 (1 + \kappa)} \bar{\ell}_L \gamma_\mu \ell'_L \bar{f}_L \gamma^\mu f_L$$
Heavy leptons

rare tau decays
rare muon decays + conversion in nuclei
relative rates depend on UV dynamics & flavor structure
⇒ dipole-dominance
⇒ realistic models generate more ops.

\[ \mathcal{L}_{CLFV} = \frac{m_\ell}{\Lambda_{NP}^2(1 + \kappa)} \bar{\ell}_R (\sigma \cdot F) \ell' \]

\[ + \frac{\kappa}{\Lambda_{NP}^2(1 + \kappa)} \bar{\ell}_L \gamma_\mu \ell'_L \bar{f}_L \gamma^\mu f_L \]

Figure 3: Sensitivity of a \( \mu \to eee \) experiment that is sensitive to branching ratios \( 10^{-14} \) and \( 10^{-16} \), and of a \( \mu \to e \) search that is sensitive to a branching ratio of \( 10^{-13} \) and \( 10^{-14} \), to the new physics scale \( \Lambda \) as a function of \( \kappa \), as defined in Eq. (3). Also depicted is the currently excluded region of this parameter space.
Heavy leptons

rare tau decays
rare muon decays + conversion in nuclei
relative rates depend on UV dynamics & flavor structure
CLFV ~null test of SM

\[ \mathcal{B}(\mu \rightarrow e\gamma) \sim \alpha \frac{m_\nu^4}{m_W^4} \sim 10^{-52} \]

Huge exp. progress expected by factor \(O(10^{-2} - 10^{-5})\)
Heavy leptons

rare tau decays
rare muon decays + conversion in nuclei
relative rates depend on UV dynamics & flavor structure
CLFV ~null test of SM

At Belle II also CLFV tau decays
Conclusions

Expect tremendous progress in flavor sensitivity to NP at the end of BelleII, many key measurements will be systematics or theory limited

clear motivation for $\gamma$, CPV in D, $B_{s,d}$ mixing, rare $B_{s,d}$ decays at HL-LHC

SM quasi null tests remain clear targets

CLFV in muon, tau & meson interactions,
complementarity between BelleII, HL-LHC(b), kaon, lepton experiments
Backup
Complementarity between LHC experiments and the rest of the world

Jernej F. Kamenik
LHC luminosity prospects

<table>
<thead>
<tr>
<th></th>
<th>LHC era</th>
<th>HL-LHC era</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS, CMS</td>
<td>25 fb⁻¹</td>
<td>100 fb⁻¹</td>
</tr>
<tr>
<td>LHCb</td>
<td>3 fb⁻¹</td>
<td>8 fb⁻¹</td>
</tr>
</tbody>
</table>

• LHC is delivering luminosity at an incredibly high pace in Run-2 – Prospects in the table above might be conservative.

• Note that beauty production cross section roughly doubles passing from 7 to 13-14 TeV pp collisions.

• LHCb upgrade comes already after Run-2, whereas the HL (phase-2) ATLAS and CMS upgrades come after Run-3.

• LHCb is starring to consider a phase-2 upgrade for Run 5+.

*Assumes a future LHCb upgrade to raise the instantaneous luminosity to $2 \times 10^{34}$ cm⁻² s⁻¹.

Vagnoni @ ICHEP’16
### LHCb sensitivity

<table>
<thead>
<tr>
<th>Type</th>
<th>Observable</th>
<th>Current precision</th>
<th>LHCb 2018</th>
<th>Upgrade (50 fb(^{-1}))</th>
<th>Theory uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B_s^0) mixing</td>
<td>(2\beta_s (B_s^0 \to J/\psi \phi))</td>
<td>0.10 [138]</td>
<td>0.025</td>
<td>0.008</td>
<td>(\sim 0.003)</td>
</tr>
<tr>
<td></td>
<td>(2\beta_s (B_s^0 \to J/\psi f_0(980)))</td>
<td>0.17 [214]</td>
<td>0.045</td>
<td>0.014</td>
<td>(\sim 0.01)</td>
</tr>
<tr>
<td></td>
<td>(a_s^2)</td>
<td>(6.4 \times 10^{-3}) [43]</td>
<td>0.6 \times 10^{-3}</td>
<td>0.2 \times 10^{-3}</td>
<td>0.03 \times 10^{-3}</td>
</tr>
<tr>
<td>Gluonic penguins</td>
<td>(2\beta_s^{\text{eff}} (B_s^0 \to \phi\phi))</td>
<td>–</td>
<td>0.17</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>(2\beta_s^{\text{eff}} (B_s^0 \to K^*0K^0))</td>
<td>–</td>
<td>0.13</td>
<td>0.02</td>
<td>&lt; 0.02</td>
</tr>
<tr>
<td></td>
<td>(2\beta_s^{\text{eff}} (B^0 \to \phi K_s^0))</td>
<td>0.17 [43]</td>
<td>0.30</td>
<td>0.05</td>
<td>0.02</td>
</tr>
<tr>
<td>Right-handed currents</td>
<td>(2\beta_s^{\text{eff}} (B_s^0 \to \phi\gamma))</td>
<td>–</td>
<td>0.09</td>
<td>0.02</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td></td>
<td>(\tau^{\text{eff}} (B_s^0 \to \phi\gamma)/\tau_{B_s^0})</td>
<td>–</td>
<td>5%</td>
<td>1%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Electroweak penguins</td>
<td>(S_3 (B^0 \to K^{*0}\mu^+\mu^-; 1 &lt; q^2 &lt; 6 \text{ GeV}^2/\text{c}^4))</td>
<td>0.08 [67]</td>
<td>0.025</td>
<td>0.008</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>(s_0 A^{\text{FB}} (B^0 \to K^{*0}\mu^+\mu^-))</td>
<td>25% [67]</td>
<td>6%</td>
<td>2%</td>
<td>7%</td>
</tr>
<tr>
<td></td>
<td>(A_1 (K^0\mu^+\mu^-; 1 &lt; q^2 &lt; 6 \text{ GeV}^2/\text{c}^4))</td>
<td>0.25 [76]</td>
<td>0.08</td>
<td>0.025</td>
<td>(\sim 0.02)</td>
</tr>
<tr>
<td></td>
<td>(\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-))</td>
<td>25% [85]</td>
<td>8%</td>
<td>2.5%</td>
<td>(\sim 10%)</td>
</tr>
<tr>
<td>Higgs penguins</td>
<td>(\mathcal{B}(B_s^0 \to \mu^+\mu^-))</td>
<td>(1.5 \times 10^{-9}) [13]</td>
<td>0.5 \times 10^{-9}</td>
<td>0.15 \times 10^{-9}</td>
<td>0.3 \times 10^{-9}</td>
</tr>
<tr>
<td></td>
<td>(\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-))</td>
<td>–</td>
<td>(\sim 100%)</td>
<td>(\sim 35%)</td>
<td>(\sim 5%)</td>
</tr>
<tr>
<td>Unitarity triangle</td>
<td>(\gamma (B \to D^*(\ast)K^{(\ast)}))</td>
<td>(\sim 10–12^\circ) [244, 258]</td>
<td>4(^{\circ})</td>
<td>0.9(^{\circ})</td>
<td>negligible</td>
</tr>
<tr>
<td>angles</td>
<td>(\gamma (B_s^0 \to D_sK))</td>
<td>–</td>
<td>11(^{\circ})</td>
<td>2.0(^{\circ})</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>(\beta (B^0 \to J/\psi K_s^0))</td>
<td>0.8(^{\circ}) [43]</td>
<td>0.6(^{\circ})</td>
<td>0.2(^{\circ})</td>
<td>negligible</td>
</tr>
<tr>
<td>Charm</td>
<td>(A_T)</td>
<td>(2.3 \times 10^{-3}) [43]</td>
<td>0.40 \times 10^{-3}</td>
<td>0.07 \times 10^{-3}</td>
<td>–</td>
</tr>
<tr>
<td>(CP) violation</td>
<td>(\Delta A_{CP})</td>
<td>(2.1 \times 10^{-3}) [18]</td>
<td>0.65 \times 10^{-3}</td>
<td>0.12 \times 10^{-3}</td>
<td>–</td>
</tr>
</tbody>
</table>
Belle II sensitivity

<table>
<thead>
<tr>
<th>Observables</th>
<th>Belle (2014)</th>
<th>Belle II 5 ab(^{-1}) 50 ab(^{-1}) [ab(^{-1})]</th>
<th>(\mathcal{L}_s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\sin 2\beta)</td>
<td>0.667 ± 0.023 ± 0.012 ± 0.012 ± 0.008</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>(\alpha)</td>
<td>±2°</td>
<td>±1°</td>
<td></td>
</tr>
<tr>
<td>(\gamma)</td>
<td>±14°</td>
<td>±6°</td>
<td>±1.5°</td>
</tr>
<tr>
<td>(S(B \to \phi K^0))</td>
<td>0.90 ± 0.09</td>
<td>±0.053 ± 0.018 &gt;50</td>
<td></td>
</tr>
<tr>
<td>(S(B \to \eta' K^0))</td>
<td>0.68 ± 0.07 ± 0.03</td>
<td>0.028 ± 0.011 &gt;50</td>
<td></td>
</tr>
<tr>
<td>(S(B \to K^0\overline{K}^0 K^0\overline{K}^0))</td>
<td>0.30 ± 0.32 ± 0.08</td>
<td>±0.100 ± 0.033 44</td>
<td></td>
</tr>
<tr>
<td>(</td>
<td>V_{cb}</td>
<td>) incl.</td>
<td>±2.4%</td>
</tr>
<tr>
<td>(</td>
<td>V_{cb}</td>
<td>) excl.</td>
<td>±3.6%</td>
</tr>
<tr>
<td>(</td>
<td>V_{ub}</td>
<td>) incl.</td>
<td>±6.5%</td>
</tr>
<tr>
<td>(</td>
<td>V_{ub}</td>
<td>) excl. (had. tag.)</td>
<td>±10.8%</td>
</tr>
<tr>
<td>(</td>
<td>V_{ub}</td>
<td>) excl. (untag.)</td>
<td>±9.4%</td>
</tr>
<tr>
<td>(B(B \to \tau \nu)) ([10^{-6}])</td>
<td>96 ± 26</td>
<td>±10% ±5% 46</td>
<td></td>
</tr>
<tr>
<td>(B(B \to \mu \nu)) ([10^{-6}])</td>
<td>&lt;1.7</td>
<td>5(\sigma) &gt;5(\sigma) 50</td>
<td></td>
</tr>
<tr>
<td>(R(B \to D \tau \nu))</td>
<td>±16.5%</td>
<td>±5.6% ±3.4% 4</td>
<td></td>
</tr>
<tr>
<td>(R(B \to D^* \tau \nu))</td>
<td>±9.0%</td>
<td>±3.2% ±2.1% 3</td>
<td></td>
</tr>
<tr>
<td>(B(B \to K^{\pm} \nu \overline{\nu})) ([10^{-6}])</td>
<td>&lt;40</td>
<td>±30% &gt;50</td>
<td></td>
</tr>
<tr>
<td>(B(B \to K^{+} \nu \nu)) ([10^{-6}])</td>
<td>&lt;55</td>
<td>±30% &gt;50</td>
<td></td>
</tr>
<tr>
<td>(B(B \to X_\tau \gamma)) ([10^{-6}])</td>
<td>±13%</td>
<td>±7% ±6% &lt;1</td>
<td></td>
</tr>
<tr>
<td>(A_{CP}(B \to X_\tau \gamma))</td>
<td>±0.01</td>
<td>±0.005 8</td>
<td></td>
</tr>
<tr>
<td>(S(B \to K_\tau^0 \pi^0 \gamma))</td>
<td>±0.10 ± 0.31 ± 0.07 ± 0.11 ± 0.035 &gt;50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(S(B \to \rho \gamma))</td>
<td>±0.83 ± 0.65 ± 0.18 ± 0.23 ± 0.07 &gt;50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(C_7/C_9 (B \to X_\tau \ell \ell))</td>
<td>~20%</td>
<td>10% 5%</td>
<td></td>
</tr>
<tr>
<td>(B(B_s \to \gamma \gamma)) ([10^{-6}])</td>
<td>&lt; 8.7</td>
<td>±0.3</td>
<td></td>
</tr>
<tr>
<td>(B(B_s \to \tau^+ \tau^-)) ([10^{-3}])</td>
<td>&lt; 2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Observables</th>
<th>Belle (2014)</th>
<th>Belle II 5 ab(^{-1}) 50 ab(^{-1}) [ab(^{-1})]</th>
<th>(\mathcal{L}_s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B(D_s \to \mu \nu))</td>
<td>5.31 ± 10(^{-3})(1 ± 0.053 ± 0.038)</td>
<td>±2.9%</td>
<td>±(0.9%-1.3%) &gt;50</td>
</tr>
<tr>
<td>(B(D_s \to \tau \nu))</td>
<td>5.70 ± 10(^{-3})(1 ± 0.037 ± 0.054)</td>
<td>±3.5%-4.3%</td>
<td>±(2.3%-3.6%) 3-5</td>
</tr>
<tr>
<td>(y_{CP} \cdot 10^{-2})</td>
<td>1.11 ± 0.22 ± 0.11</td>
<td>±(0.11-0.13)</td>
<td>±(0.05-0.08) 5-8</td>
</tr>
<tr>
<td>(A_T \cdot 10^{-2})</td>
<td>±0.03 ± 0.20 ± 0.08</td>
<td>±0.10</td>
<td>±(0.03-0.05) 7-9</td>
</tr>
<tr>
<td>(A^{\overline{D}_s^0 \pi^0 - 10^{-2}})</td>
<td>±0.32 ± 0.21 ± 0.09</td>
<td>±0.11</td>
<td>±0.06 15</td>
</tr>
<tr>
<td>(A^{\overline{D}_s^0 \pi^0 - 10^{-2}})</td>
<td>±0.55 ± 0.36 ± 0.09</td>
<td>±0.17</td>
<td>±0.06 &gt;50</td>
</tr>
<tr>
<td>(A^{\overline{D}_s^0 \pi^0 - 10^{-2}})</td>
<td>±5.6</td>
<td>±2.5</td>
<td>±0.8 &gt;50</td>
</tr>
<tr>
<td>(x_{K_s \overline{K}^0 \tau^-} \cdot 10^{-2})</td>
<td>0.56 ± 0.19 ± 0.07</td>
<td>±0.14</td>
<td>±0.11 3</td>
</tr>
<tr>
<td>(y_{K_s \overline{K}^0 \tau^-} \cdot 10^{-2})</td>
<td>0.30 ± 0.15 ± 0.08</td>
<td>±0.08</td>
<td>±0.05 15</td>
</tr>
<tr>
<td>(</td>
<td>q/p</td>
<td>_{K_s \overline{K}^0 \tau^-} \cdot 10^{-2})</td>
<td>0.90 ± 0.16 ± 0.06</td>
</tr>
<tr>
<td>(\phi_{K_s \overline{K}^0 \tau^-} \cdot 10^{-2})</td>
<td>±6 ± 11</td>
<td>±6</td>
<td>±4 10</td>
</tr>
<tr>
<td>(A^{\overline{D}_s^0 \pi^0 - 10^{-2}})</td>
<td>±0.03 ± 0.64 ± 0.10</td>
<td>±0.29</td>
<td>±0.09 &gt;50</td>
</tr>
<tr>
<td>(A^{\overline{D}_s^0 \pi^0 - 10^{-2}})</td>
<td>±0.10 ± 0.16 ± 0.09</td>
<td>±0.08</td>
<td>±0.03 &gt;50</td>
</tr>
<tr>
<td>(Br(D^0 \to \gamma \gamma) \cdot 10^{-6})</td>
<td>&lt;1.5</td>
<td>±30% ±25% 2</td>
<td></td>
</tr>
</tbody>
</table>

\(\tau \to \mu \gamma\) \([10^{-6}]\) | < 45 | ±14.7 | ±4.7 |
\(\tau \to e \gamma\) \([10^{-6}]\) | < 120 | ±39 | ±12 |
\(\tau \to \mu \mu \mu\) \([10^{-5}]\) | < 21.0 | ±3.0 | ±0.3 |
Light NP @ HL-LHCb

Rare FCNC decays as portals to light dark sectors
Bump/resonance search in $q^2$ spectrum (below charm threshold in B decays):
- axion-like particles, scalar DM-SM mediators

Search for LNV in same-sign di-leptons
- light Majorana neutrinos

Complementarity with Beam dump experiments

Also direct Dark photon searches, Light scalar searches