Belle II Status and Physics Prospects

Pablo Goldenzweig

(For the Belle II Collaboration)

Les Rencontres De Physique de la Vallée d'Aoste

La Thuile, Italy
March 6-11, 2017

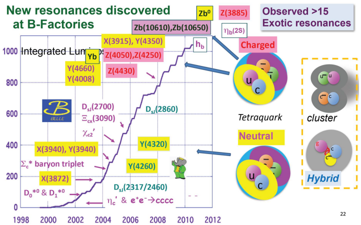
Karlsruhe Institute of Technology

Belle II

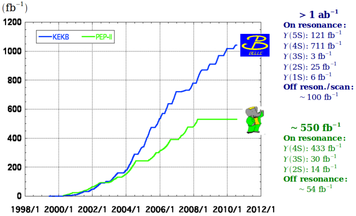
- ***B* factories legacy.**
- **SuperKEKB and Belle II status and timeline.**
- **Selection of tensions with the SM and prospects for Belle II.**

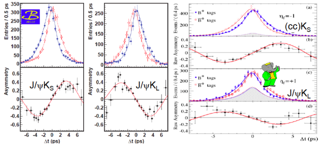
Success of the B factories (1999-2010)

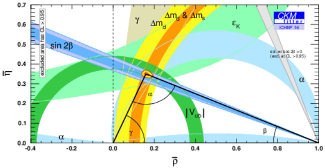
- Spectacular accelerator and detector performance.
- Discovery of CP violation in B decays.
- Confirmation of the CKM picture of flavor physics.
- Discovery of several new particles.
- Probe of rare B decays.
- Limits on New Physics scenarios.



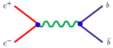
Integrated luminosity of B factories





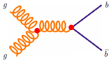


Belle II



- Clean experimental environment.
- Holistic interpretation of events with missing energy (ν).
- Decays with multiple photons.
- Inclusive decays ($B \to X_{s,d}\gamma$).
- Long-lived particles (K_S and K_L).

LHCb



- Large cross section.
- Decays to all charged particle final states.
- Fast mixing.

B2TiP Report (in progress)

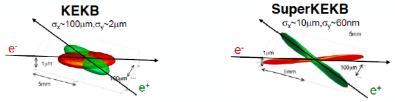
Observables	Expected th. accuracy	Expected exp. uncertainty	Facility (2025)
UT angles & sides			
ϕ_1 [°]	***	0.4	Belle II
ϕ_2 [°]	**	1.0	Belle II
ϕ_3 [°]	***	1.0	Belle II/LHCb
$S(B_s \to J/\psi\phi)$	***	0.01	LHCb
$\lvert V_{cb}\rvert$ incl.	***	1%	Belle II
$\lvert V_{cb}\rvert$ excl.	***	1.5%	Belle II
$\lvert V_{ub}\rvert$ incl.	**	3%	Belle II
$\lvert V_{ub}\rvert$ excl.	**	2%	Belle II/LHCb
CPV			
$S(B \to \phi K^0)$	***	0.02	Belle II
$S(B \to \eta' K^0)$	***	0.01	Belle II
$\beta_s^{\rm eff}(B_s \to \phi\phi)$ [rad]	**	0.1	LHCb
$\beta_s^{\rm eff}(B_s \to K^{*0}\bar{K}^{*0})$ [rad]	**	0.1	LHCb
$\mathcal{A}(B \to K^0\pi^0)[10^{-2}]$	***	4	Belle II
$\mathcal{A}(B \to K^+\pi^-)$ $[10^{-2}]$	***	0.20	LHCb/Belle II
(Semi-)leptonic			
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	**	3%	Belle II
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	**	7%	Belle II
$R(B \to D\tau\nu)$	***	3%	Belle II
$R(B \to D^*\tau\nu)$	***	2%	Belle II/LHCb
Radiative & EW Penguins			
$\mathcal{B}(B \to X_s\gamma)$	**	4%	Belle II
$A_{CP}(B \to X_{s,d}\gamma)$ $[10^{-2}]$	***	0.005	Belle II
$S(B \to K_S^0\pi^0\gamma)$	***	0.03	Belle II
$2\beta_s^{\rm eff}(B_s \to \phi\gamma)$	***	0.05	LHCb
$S(B \to \rho\gamma)$	**	0.07	Belle II
$\mathcal{B}(B_s \to \gamma\gamma)$ $[10^{-6}]$	**	0.3	Belle II
$\mathcal{B}(B \to K^*\nu\bar{\nu})$ $[10^{-6}]$	***	15%	Belle II
$\mathcal{B}(B \to K\nu\bar{\nu})$ $[10^{-6}]$	***	20%	Belle II
$q_0^2 A_{\rm FB}(B \to K^*\mu\mu)$	**	0.05	LHCb/Belle II
$\mathcal{B}(B_s \to \tau\tau)$ $[10^{-3}]$	***	< 2	Belle II
$\mathcal{B}(B_s \to \mu\mu)$	***	10%	LHCb/Belle II
Charm			
$\mathcal{B}(D_s \to \mu\nu)$	***	0.9%	Belle II
$\mathcal{B}(D_s \to \tau\nu)$	***	2%	Belle II
$\Delta A_{CP}(D^0 \to K^+K^-)$ $[10^{-4}]$	**	0.1	LHCb
$A_{CP}(D^0 \to K_S^0\pi^0)$ $[10^{-2}]$	**	0.03	Belle II
$\lvert q/p\rvert(D^0 \to K_S^0\pi^+\pi^-)$	***	0.03	Belle Ii
$\phi(D^0 \to K_S^0\pi^+\pi^-)$ [°]	***	4	Belle II
Tau			
$\tau \to \mu\gamma$ $[10^{-9}]$	***	< 5	Belle II
$\tau \to e\gamma$ $[10^{-9}]$	***	< 10	Belle II
$\tau \to \mu\mu\mu$ $[10^{-9}]$	***	< 0.3	Belle II/LHCb

SuperKEKB Accelerator

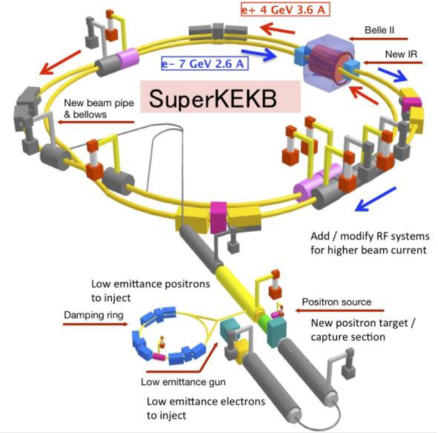
Upgrade for SuperKEKB and Belle II to achieve 40x peak $\mathcal{L}$ under 20x bkgd

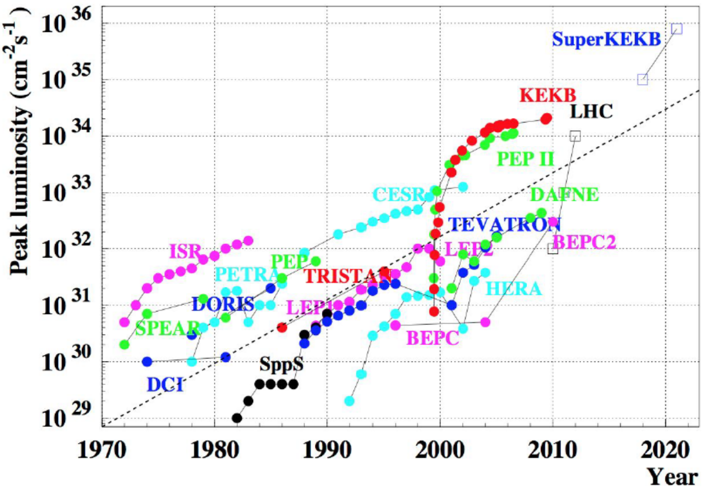
- Reduction in the beam size by 1/20 at the IP.
- Doubling the beam currents.

$$L = \frac{\gamma_{e\pm}}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{e\pm}\xi_y^{e\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$



- *First turns achieved Feb. 2016*
- *Beam-background studies ongoing*





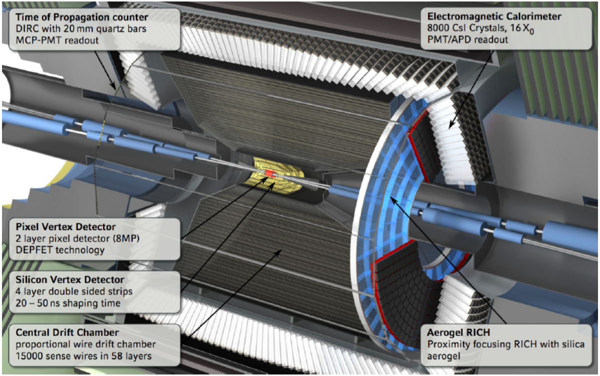
Targets:

Instantaneous luminosity $\mathbf{8 \times 10^{35} cm^{-2} s^{-1}}$

Integrated luminosity **50ab^{-1} by 2024**

Targeted improvements:

- *Increase K_S^0 efficiency.*
- *Improve IP and secondary vertex resolution.*
- *Improve K/π separation.*
- *Improve π^0 efficiency.*
- *Add particle ID and μ ID in endcaps.*



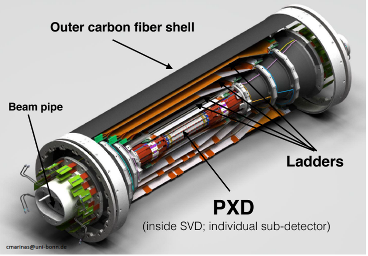
Vertex Detector

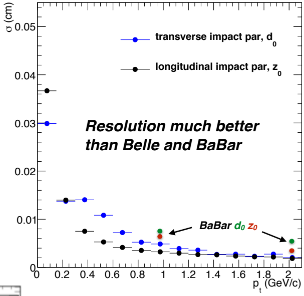
Si pixel (2 layers) and strip (4 layers):

- 1^{st} pixel layer at $r = 14mm$ to IP

  [Belle at $r = 20mm$]

  Improves vertex resolution along z-axis

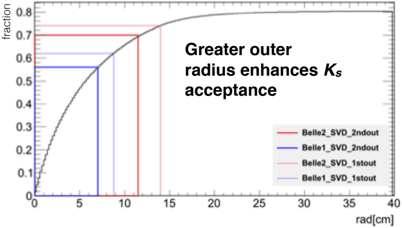




- Larger SVD w/outer layer at $r = 135mm$.

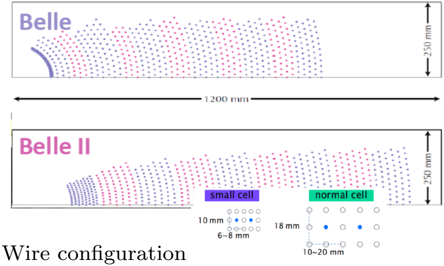
  [Belle at $r = 88mm$]

  Higher fraction of K_S' with vertex hits improves vertex resolution



Central Drift Chamber:

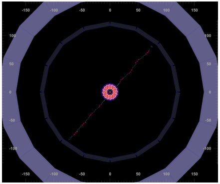
- Larger outer radius of 1111mm (Belle 863mm) allows for improved p resolution.
- Smaller cells with lower occupancy and capacity for higher hit rate.



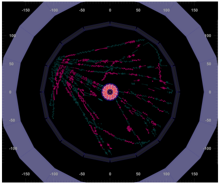
Wire configuration

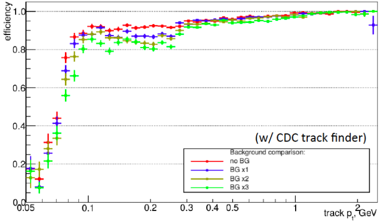
Full readout of the CDC

Single track



Showering event





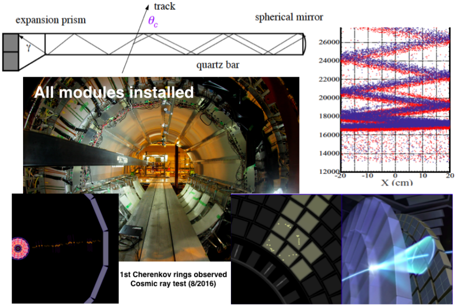
Simulated track reconstruction efficiency

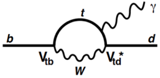
Stable performance for up to 3x predicted beam BG

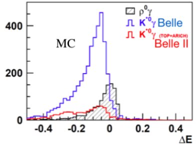
(Preliminary)

Two RICH systems covering full momentum range

- Barrel: Time of Propagation (TOP) counter (16 modules).
  - ⇒ *Measure x-y position of Cherenkov γ's and their arrival time.*
- Forward Endcap: Aerogel Ring Imaging Cherenkov detector (ARICH)
  - ⇒ *Proximity focusing with silica aerogel (4σ separation at $1 - 3.5$ GeV/c)*

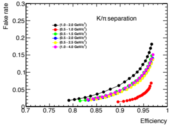


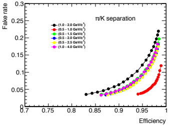




The background $B \to K^*\gamma$ (Belle/Belle II) $\approx 30x$ more abundant than $B \to \rho\gamma$.

Average ϵ_K vs. π fake rate improved: Fake rate decreases by ≈ 3 for the same ε w.r.t. Belle

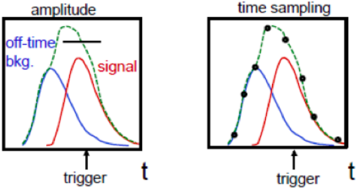


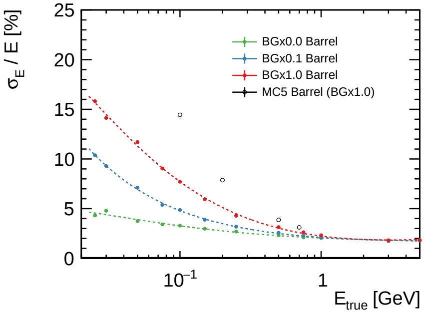


Electromagnetic Calorimeter

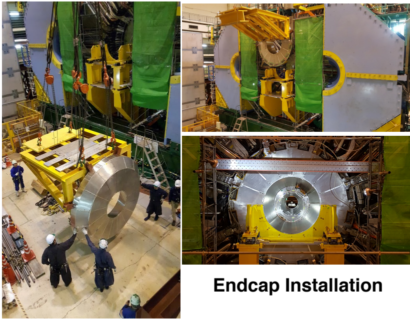
Re-usage of Belle's CsI(TI) crystal calorimeter, but with new electronics with 2MHz wave form sampling to compensate for the larger beam-related backgrounds and the long decay time of CsI(TI) signals.

⇒ *Resolution much better at Belle II*



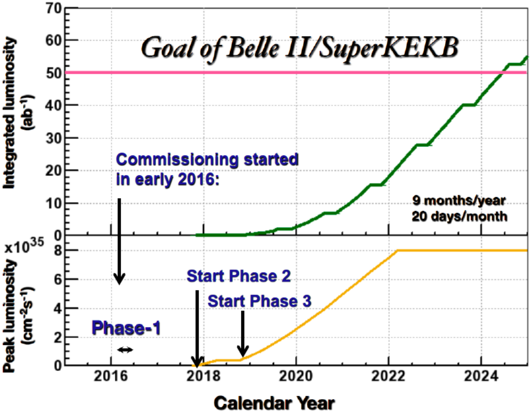


Peak energy resolution in the ECL barrel as a function of true photon energy



Endcap Installation

Roadmap



Phase 1 (completed):

- Circulate beams (no collisions.)
- Tune optics, vacuum scrubbing, and beam background studies.

Phase 2:

- First collisions.
- Beam commissioning.
- Physics run with Belle II w/o VXD on $\Upsilon(4S)$ (& possibly $\Upsilon(6S)$).
- New triggers for exotic dark signatures.

Phase 3:

- Luminosity tuning.
- Physics run with full Belle II.

Many open questions and as-yet unobserved processes awaiting Belle II data...

Belle, PRD 87, 031103(R) (2013)

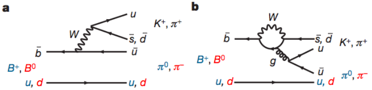
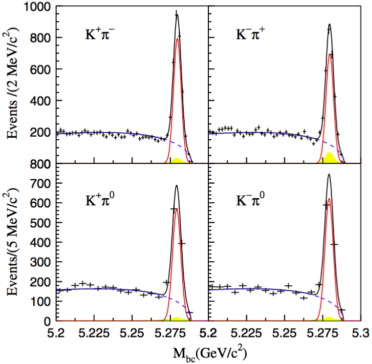


Figure 17.4.4. The dominant Tree-level (a) and Penguin-loop (b) Feynman diagrams in the two-body decays $B \to K\pi$ and $B \to \pi\pi$ (Lin, 2008).



Measurements of $DCPV$ in $B^+ \to K^+\pi^0$ found to be different than in $B^0 \to K^+\pi^-$, *contrary to naive expectation from the presence of electroweak penguin diagrams.*

$$\mathcal{A}_{K^+\pi^0} - \mathcal{A}_{K^+\pi^-} = 0.112 \pm 0.027 \pm 0.007 \quad (4\sigma)$$

The difference could be due to:

- Neglected diagrams contributing to B decays (theoretical uncertainty is still large).
  $K^+\pi^- : T + P + P_{EW}^C$
  $K^+\pi^0 : T + P + C + P_{EW} + P_{EW}^C + A$
- Some unknown NP effect that violates Isospin.

$\Rightarrow$ *In combination with other $K\pi$ measurements and with the larger Belle II dataset, strong interaction effects can be controlled and the validitiy of the SM can be tested in a model-independent way.*

$B \to K\pi$: Test of sum rule

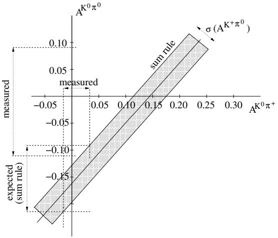
Test-of-sum (isospin) rule for NP nearly free of theoretical uncertainties, where the SM can be tested by measuring all observables: [Proposed by: PLB 627, 82(2005), PRD 58, 036005(1998)]

$$I_{K\pi} = \mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$

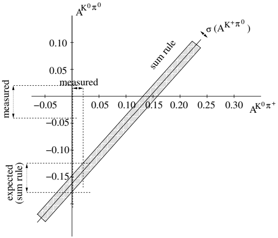
$$I_{K\pi} = -0.270 \pm 0.132 \pm 0.060 \quad (1.9\sigma)$$

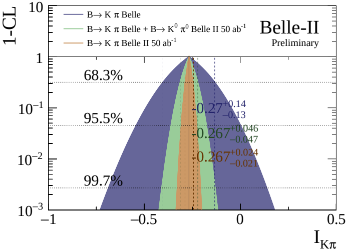
Isospin sum rule can be presented as a band in the $\mathcal{A}_{K^0\pi^0}$ vs. $\mathcal{A}_{K^0\pi^+}$ plane.

Current data



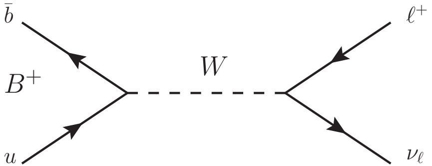
Belle II $\mathcal{L} = 50\text{ab}^{-1}$





→ Most demanding measurement is $K^0\pi^0$ final state. With Belle II, the uncertainty on $\mathcal{A}(B \to K^0\pi^0)$ from time-dep. analyses is expected to reach $\sim 4\%$

⇒ *Sufficient for NP studies.*



In the SM, annihilation process mediated by $W^\pm$

$$\mathcal{B}(B^+ \to \ell^+ \nu_\ell)_{\mathrm{SM}} = \frac{G_F^2 m_B m_\ell^2}{8\pi}\left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

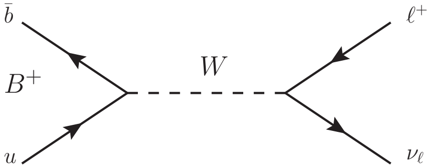
$\mathcal{B}(l=\tau) > \mathcal{B}(l=\mu) > \mathcal{B}(l=e)$
$\mathcal{O}(10^{-4})$ $\mathcal{O}(10^{-7})$ $\mathcal{O}(10^{-11})$

f_B: B meson decay constant. *Can be calculated from Lattice QCD*.

V_{ub}: CKM matrix element. *Can be measured from $b \to ul\nu$ decays.*

Both can also be obtained from a CKM global fit.

Leptonic B decays



In the SM, annihilation process mediated by $W^\pm$

$$\mathcal{B}(B^+ \to \ell^+\nu_\ell)_{\rm SM} = \frac{G_F^2 m_B m_\ell^2}{8\pi}\left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

$\mathcal{B}(l=\tau) > \mathcal{B}(l=\mu) > \mathcal{B}(l=e)$
$\mathcal{O}(10^{-4})$ $\mathcal{O}(10^{-7})$ $\mathcal{O}(10^{-11})$

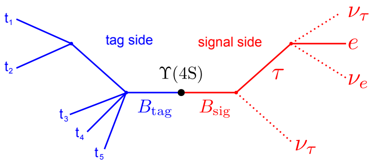
f_B: B meson decay constant. *Can be calculated from Lattice QCD.*

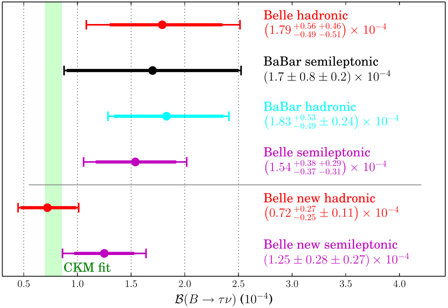
V_{ub}: CKM matrix element. *Can be measured from $b \to ul\nu$ decays.*

Both can also be obtained from a CKM global fit.

In a type-II two-Higgs-doublet model

$$\mathcal{B}(B^+ \to \tau^+\nu_\tau) = \mathcal{B}(B^+ \to \tau^+\nu_\tau)_{\rm SM} \times \left|1 - \frac{\tan^2\beta}{m_{H^\pm}^2} m_B^2\right|^2$$

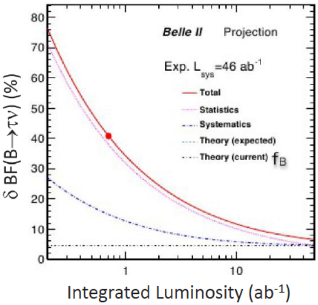




Current measurements approach

$$\mathcal{B}(B^+ \to \tau^+\nu_\tau)_{\text{CKM}} = (0.821^{+0.034}_{-0.028}) \times 10^{-4}$$

Belle II at 50ab^{-1} is expected to achieve $\approx 6\%$ precision.



(Projection from new Belle hadronic tag result)

+ *New Full Event Interpretation algorithm for tag-side reconstruction*

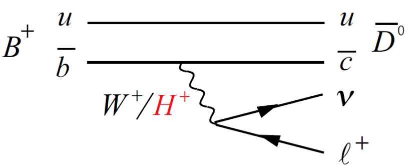
Hadronic tag:

$\epsilon(B^0_{tag}) = 0.33\%$ Belle II $\epsilon(B^+_{tag}) = 0.36\%$

$\epsilon(B^0_{tag}) = 0.19\%$ Belle I $\epsilon(B^+_{tag}) = 0.28\%$

Semileptonic decay $B \to D^{(*)}\tau\nu$

- Larger $\mathcal{B}$ and less theoretical uncertainty than $B^+ \to \tau^+\nu_\tau$.
- New Physics could change the ratios $\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(\overline{B}\to D^{(*)}\tau\nu)}{\mathcal{B}(\overline{B}\to D^{(*)}\ell\nu)}$.
- Effect could be different for D and D^*.



Large mass of τ adds sensitivity to additional helicity amplitude.

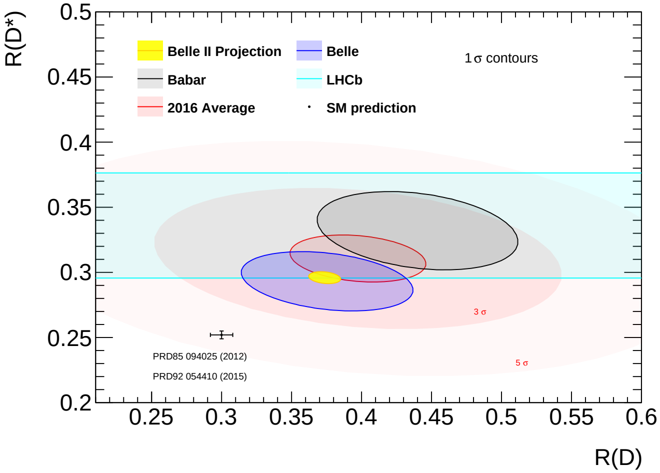
$$\frac{d\Gamma}{dq^2} = \frac{G_F^2|V_{cb}|^2|p|q^2}{96\pi^3 m_B^2}\left(1-\frac{m_\tau^2}{q^2}\right)^2\left[\left(|H_{++}|^2+|H_{--}|^2+|H_{00}|^2\right)\left(1+\frac{m_\tau^2}{2q^2}\right)+\frac{3}{2}\frac{m_\tau^2}{q^2}|H_{t0}|^2\right]$$

A charged Higgs (2HDM type II) of spin 0 couples to the τ and will only affect H_{t0}:

$$H_{t0}^{2\text{HDM}} = H_{t0}^{\text{SM}} \times \left(1 - \frac{\tan^2\beta}{m_{H^\pm}^2}\frac{q^2}{1\mp m_c^2/m_b^2}\right)$$

This could enhance or decrease the ratios $R(D^*)$ depending on $\frac{\tan^2\beta}{m_{H^\pm}^2}$

$\overline{B} \to D^{(*)}\tau\overline{\nu}$ with Belle II



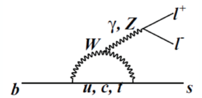
- Very clean prediction from theory.
- World average 4σ away from SM.
- Belle II can achieve $\approx 3\%$ precision.

Belle combination includes: PRD 92, 072014 (2015), PRD 94, 072007 (2016), arXiv:1612.00529.

Electroweak penguin decays $b \to s\, l^+ l^-$

- Within the SM, decays proceed via one loop diagram:
  JHEP0712:040,2007

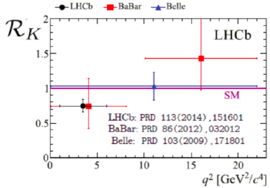
$$\mathcal{R}_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)} = 1.00030^{+0.00010}_{-0.00007}$$



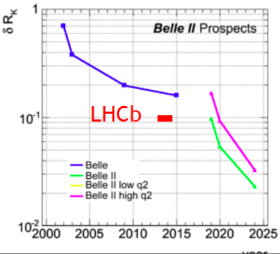
- LHCb reported a 2.6σ deviation for the dilepton invariant mass squared region $1 < q^2 < 6$ GeV$^4/c^2$:

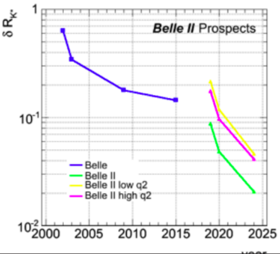
$$\mathcal{R}_K = 0.745^{+0.090}_{-0.074} \pm 0.036$$

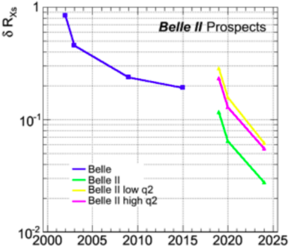
  Phys. Rev. Lett. **113** 151601 (2016)



- Electron mode challenging for LHCb.
- Electrons and muons have the same ε at Belle II:
  $\Rightarrow$ *Both low and high q^2 regions possible.*





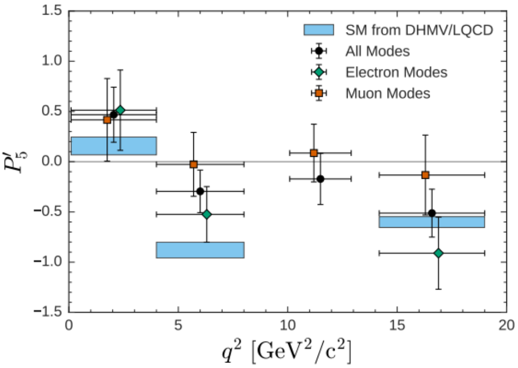


New lepton-flavour-dependent angular analysis by Belle

CKM 2016 (To appear in PRL)

- Largest deviation of 2.6σ from the SM for the muon channel for $4 < q^2 < 8\ \mathrm{GeV}^4/c^2$.
- Electron channel deviation of 1.1σ.

- Belle II and LHCb will be comparable for this process.
- Belle II will be able to perform an isospin comparison of K^{*+} and K^{*0}, or the ground states K.



Absolute error on P_5'

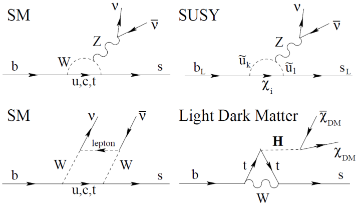
q^2 (GeV^2)	Belle	Belle II (50ab^{-1})
0.10 - 4.00	0.416	0.059
4.00 - 8.00	0.277	0.040
10.09 - 12.00	0.344	0.049
14.18 - 19.00	0.248	0.033

Karlsruhe Institute of Technology

Belle II

⇒ The ultimate test of Belle II

- Theoretically clean due to a maximum of one electromagnetically interacting charged particle in the final state, as opposed to $K^{(*)}l^+l^-$ decays.
- Several new physics models (SUSY, non-standard Z coupling) could enhance these decays.

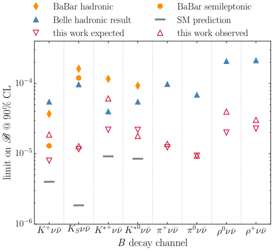


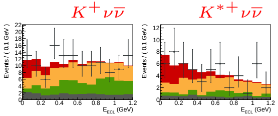
Projections from Belle hadronic tag result ⇒

CKM 2016 (Preliminary)

This work = Belle Semi-leptonic tag

arXiv:1702.03224 (Submitted to PRD)





mode	$\mathcal{B}_{SM}[10^{-6}]$	$N_{Sig-exp.}(50ab^{-1})$	Statistical error	Total Error
$B^+ \to K^+\nu\bar{\nu}$	4.68	245	20%	22%
$B^0 \to K^0_S\nu\bar{\nu}$	2.17	22	94%	94%
$B^+ \to K^{*+}\nu\bar{\nu}$	10.22	158	21%	22%
$B^0 \to K^{*0}\nu\bar{\nu}$	9.48	143	20%	22%
$B \to K^*\nu\bar{\nu}$ combined			15%	17%

Summary

- The SuperKEKB accelerator is operational and beam background studies are under way.
- The Belle II detector construction is nearing completion.
- Physics with partial detector scheduled for late 2017.
- Full detector to begin taking data in 2018.
- Many open questions to address.
- Broad program to search for NP with flavor observables.