# Highlights from the Sessions on Heavy Flavors and the CKM Matrix

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Paula Collins, Christoph Schwanda

CIPANP 2018
Palm Springs, CA

May 29 - June 3, 2018

# Heavy Flavor and the CKM Matrix

**Lepton Universality Violation** — *Dr. Gerco ONDERWATER*
*Hyatt Regency Indian Wells Conference Center* — 08:00 - 08:35

**Experimental Status of $V_{ub}/V_{cb}$ and the CKM Angle $\gamma$** — *Prof. Abner SOFFER*
*Hyatt Regency Indian Wells Conference Center* — 08:35 - 09:10

**Rare Decays Probing Physics Beyond the Standard Model** — *Dr. Gerco ONDERWATER*
*Hyatt Regency Indian Wells Conference Center* — 14:00 - 14:30

**$B\to \pi\ell\ell$ and $B\to K\ell\ell$ Decay Form Factors from Lattice QCD** — *Dr. Yuzhi LIU*
*Hyatt Regency Indian Wells Conference Center* — 14:30 - 15:00

**Search for LNV by the NA48 Experiment** — *Dr. Cristina BIINO*
*Hyatt Regency Indian Wells Conference Center* — 15:00 - 15:20

**Search for $K^+\to \pi^+ \nu\nu$ at CERN** — *Dr. Bob VELGHE*
*Hyatt Regency Indian Wells Conference Center* — 15:20 - 15:40

**The MEG Experiment: Run I Final Results and Preparation for Run II** — *Dr. Terence LIBEIRO*
*Hyatt Regency Indian Wells Conference Center* — 16:10 - 16:40

**The Mu2e Experiment** — *Dr. Tomonari MIYASHITA*
*Hyatt Regency Indian Wells Conference Center* — 16:40 - 17:10

**PEN Experiment: a Precise Test of Lepton Universality** — *Prof. Dinko POCANIC*
*Hyatt Regency Indian Wells Conference Center* — 17:10 - 17:30

**Improved Search for Heavy Neutrinos and a Test of Lepton Universality in the Decay $\pi \to e \nu$** — *Richard MISCHKE*

**RD and RD*: Theoretical Developments** — *Ryotaro WATANABE*
*Hyatt Regency Indian Wells Conference Center* — 17:50 - 18:10

**Diagnosing New Physics with Lepton Universality Violation and Lepton Flavor Violation** — *Prof. Alakabha DATTA*

**Introduction to the CKM Matrix** — *Wolfgang ALTMANNSHOFER*
*Hyatt Regency Indian Wells Conference Center* — 14:00 - 14:30

**Combined Measurement of the CP Violating Angle $\beta$ by the BaBar and Belle Experiments** — *Dr. Tomonari MIYASHITA*
*Hyatt Regency Indian Wells Conference Center* — 14:30 - 15:00

**Determination of $V_{ub}$ and $V_{cb}$** — *Mr. Matic LUBEJ*
*Hyatt Regency Indian Wells Conference Center* — 15:00 - 15:20

**First Collisions at Belle II** — *Anselm VOSSEN*
*Hyatt Regency Indian Wells Conference Center* — 15:20 - 15:40

**Short-Distance Matrix Elements for $D^0$-Meson Mixing from $N_f=2+1$ Lattice QCD** — *Dr. Chia Cheng CHANG*
*Hyatt Regency Indian Wells Conference Center* — 14:00 - 14:30

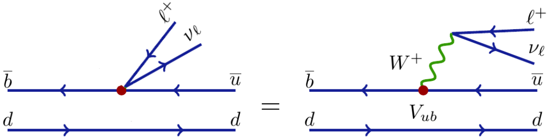
**$B$ and $D$ Meson Leptonic Decay Constants and Quark Masses from Four-Flavor Lattice QCD** — *Carleton DETAR*
*Hyatt Regency Indian Wells Conference Center* — 14:30 - 15:00

**Semileptonic $B_s$ Decays** — *Oliver WITZEL*
*Hyatt Regency Indian Wells Conference Center* — 15:00 - 15:20

**Unify the SU(3) Topological Diagram and Irreducible Representation Amplitudes for B Decays** — *Prof. XIAO-GANG HE*

2 plenary talks + 4 parallel sessions (2 joint with PPHI)
Thank you for all the fantastic contributions!

# 1) Determine CKM Matrix Elements



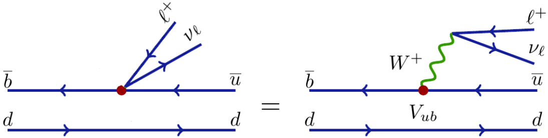

$$A(B \to \pi \ell \nu) \sim G_F \times FF(q^2) \times V_{ub}$$

**measure precisely**

**calculate precisely the SM contribution**

extract CKM matrix elements

# 1) Determine CKM Matrix Elements

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| measure precisely | calculate precisely the SM contribution | extract CKM matrix elements |
|---|---|---|

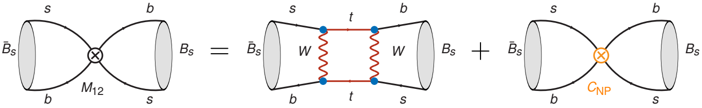
Matic Lubej
(Determination of $|V_{ub}|$ and $|V_{cb}|$ at Belle (II))

Anselm Vossen
(First Collisions at Belle II)

Oliver Witzel
(Semileptonic $B_s$ decays)

Carleton DeTar
(B and D meson leptonic decay constants and quark masses from four-flavor lattice QCD)

Wolfgang Altmannshofer
(Introduction to the CKM Matrix)



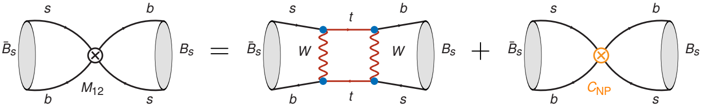

$$M_{12} \sim G_F \frac{g_2^2}{16\pi^2} \frac{m_t^2}{m_W^2} (V_{tb} V_{ts}^*)^2 + \frac{C_{NP}}{\Lambda_{NP}^2}$$

**measure precisely**

**calculate precisely the SM contribution**

**get information on NP coupling and scale**

# 2) Search for New Physics

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**measure precisely**

**calculate precisely the SM contribution**

**get information on NP coupling and scale**

Gerco Oderwater
(Rare Decays at LHCb)

Tomo Miyashita
(Combined Measurement of the CP Violating Angle $\beta$ by the BaBar and Belle Experiments)

Yuzhi Liu
($B \to \pi\ell\ell$ and $B \to K\ell\ell$ decay form factors from Lattice QCD)

Chia Cheng Chang
(Short distance hadronic contributions to D meson mixing from Lattice QCD)

Ryoutaro Watanabe
($R_D$ and $R_{D^*}$: Theoretical Developments)

Alakabha Datta
(Diagnosing New Physics with LUV and LFV B Decays)

## High Precision Lattice Results

# Many Sophisticated Techniques

## How we achieve high precision

- Gluon gauge-field configurations generated with the highly-improved staggered quark (HISQ) formulation for sea quarks.
- HISQ formulation for all valence quarks, including $b$, following HPQCD [Phys. Rev. **D85**, 031503 (2012).]
- Exploit merger of effective theories to carry out extrapolations to the physical point:
  - Heavy-quark effective theory (HQET) to treat heavy-quark discretization effects.
  - Chiral perturbation theory (HMrPQAS$\chi$PT ) to treat the light-quark mass dependence.
  - Symanzik effective theory (SET) to treat light-quark and gluon discretization.
- New minimal renormalon subtraction (MRS) scheme improves HQET for quark mass calculation. [Phys. Rev. **D97**, 034503 (2018)], [Komijani, JHEP **08**, 062 (2017)].
- High statistics: 24 gauge-field ensembles with approximate lattice spacing ranging from 0.03 to 0.15 fm, several values of the light quark masses, including physical values.

(Carleton DeTar in HFCKM 7)

# Decay Constants with Sub-Percent Precision!

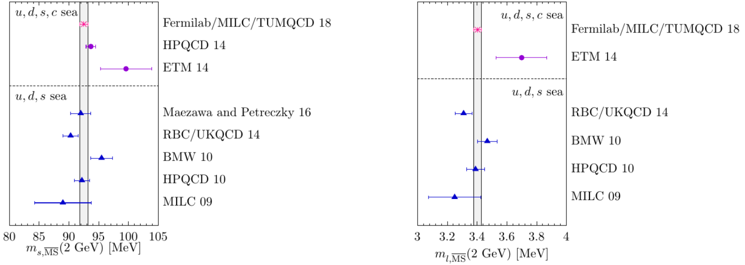
$$
\begin{aligned}
f_{D^0} &= 211.5 \pm 0.3_{\rm stat} \pm 0.3_{\rm sys} \pm 0.2_{f_\pi,{\rm PDG}}\ {\rm MeV} \\
f_{D^+} &= 212.6 \pm 0.3_{\rm stat} \pm 0.3_{\rm sys} \pm 0.2_{f_\pi,{\rm PDG}}\ {\rm MeV} \\
f_{D_s} &= 249.8 \pm 0.3_{\rm stat} \pm 0.3_{\rm sys} \pm 0.2_{f_\pi,{\rm PDG}}\ {\rm MeV} \\
f_{B^+} &= 189.4 \pm 0.8_{\rm stat} \pm 1.1_{\rm sys} \pm 0.3_{f_\pi,{\rm PDG}}\ {\rm MeV} \\
f_{B^0} &= 190.5 \pm 0.8_{\rm stat} \pm 1.0_{\rm sys} \pm 0.3_{f_\pi,{\rm PDG}}\ {\rm MeV} \\
f_{B_s} &= 230.7 \pm 0.8_{\rm stat} \pm 0.8_{\rm sys} \pm 0.2_{f_\pi,{\rm PDG}}\ {\rm MeV}
\end{aligned}
$$

The systematic error includes

- Continuum extrapolation
- Finite volume
- EM contribution to meson masses that are used to fix the quark masses (Decay constants are pure-QCD quantities; EM contributions to the relation between decay constants and physical decay rates are not included here by definition but would be relevant for phenomenology)
- Uncertainty in adjustment for non-equilibration of topological charge

(Carleton DeTar in HFCKM 7)

# Up and Down Masses with Percent Precision!



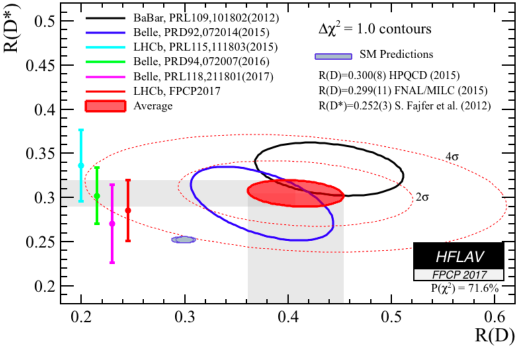

Results for light quark masses in a theory with 4 active flavors.

$$m_{u,\overline{\text{MS}}}(2\text{ GeV}) = 2.118(17)_{\text{stat}}(32)_{\text{syst}}(12)_{\alpha_s}(03)_{f_\pi,\text{PDG}}\text{ MeV},$$
$$m_{d,\overline{\text{MS}}}(2\text{ GeV}) = 4.690(30)_{\text{stat}}(36)_{\text{syst}}(26)_{\alpha_s}(06)_{f_\pi,\text{PDG}}\text{ MeV},$$

(Carleton DeTar in HFCKM 7)

# Flavor Anomalies and New Physics

world average from the heavy flavor averaging group



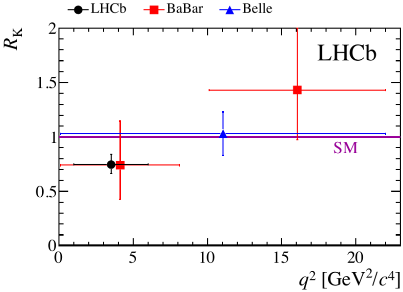

$$R_D = \frac{BR(B \to D\tau\nu)}{BR(B \to D\ell\nu)}$$

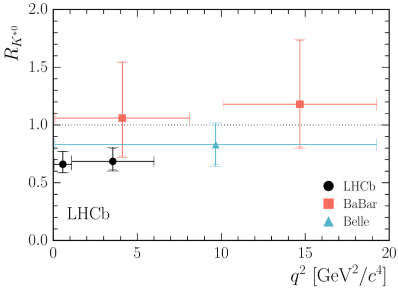
$$R_{D^*} = \frac{BR(B \to D^*\tau\nu)}{BR(B \to D^*\ell\nu)}$$

$\ell = \mu, e$ (BaBar/Belle)
$\ell = \mu$ (LHCb)

$$R_D^{\rm exp} = 0.407 \pm 0.039 \pm 0.024 \ , \qquad R_{D^*}^{\rm exp} = 0.304 \pm 0.013 \pm 0.007$$

Combined discrepancy $\sim 4\sigma$.




$$R_{K^{(*)}} = \frac{BR(B \to K^{(*)}\mu\mu)}{BR(B \to K^{(*)}ee)}$$

$$R_K^{[1,6]} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

$$R_{K^*}^{[0.045,1.1]} = 0.66^{+0.11}_{-0.07} \pm 0.03$$

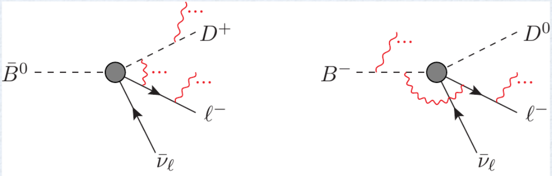
$$R_{K^*}^{[1.1,6]} = 0.69^{+0.11}_{-0.07} \pm 0.05$$

3 observables
deviating by $\sim 2\sigma - 2.5\sigma$
from the SM predictions

# Could We Be Missing a Standard Model Effect?

**[2] Radiative correction** **Kitahara et al., 1803.05881**

**Another development. Soft-photon effects depend on lepton mass, which leads to corrections even in RD(*)**




**Soft-photon corrections to RD result in**

**(1) leading to RD^+ ≠ RD^0**

**(2) depending on photon energy cut**

**(3) non-negligible constructive contribution to RD, at most 4〜6%**

(Ryoutaro Watanabe in HFCKM/PPHI 2)

# Many Possible New Physics Explanations

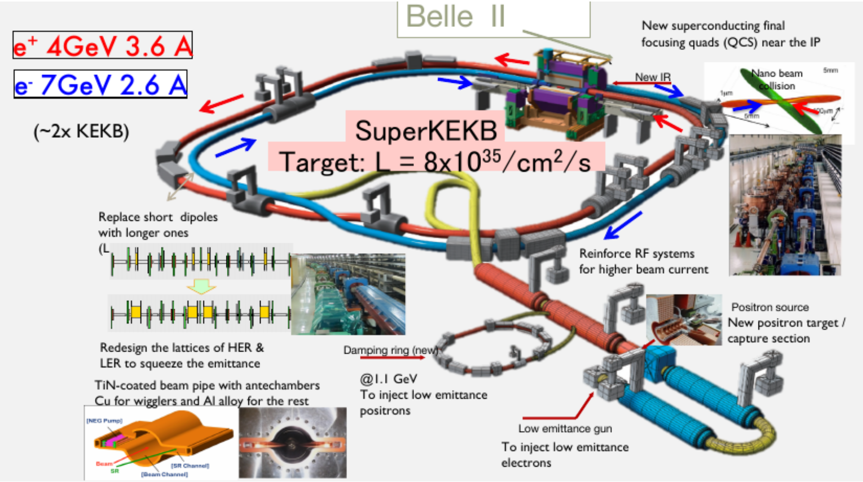
- (i) a vector boson ($VB$) that transforms as $(\mathbf{1}, \mathbf{3}, 0)$ under $SU(3)_C \times SU(2)_L \times U(1)_Y$, as in the SM.
- (ii) an $SU(2)_L$-triplet scalar leptoquark ($S_3$) $[(\mathbf{3}, \mathbf{3}, -2/3)$.
- (iii) an $SU(2)_L$-singlet vector leptoquark ($U_1$) $[(\mathbf{3}, \mathbf{1}, 4/3)$.
- $SU(2)_L$-triplet vector leptoquark ($U_3$) $[(\mathbf{3}, \mathbf{3}, 4/3)]$.

- Note to simply explain $b \to s\ell^+\ell^-$ we can have $Z'$ $(\mathbf{1}, \mathbf{1}, 0)$ from $U(1)$. One can consider both $(\mathbf{1}, \mathbf{3}, 0)$ and $(\mathbf{1}, \mathbf{1}, 0)$.

(Alakabha Datta in HFCKM/PPHI 2)

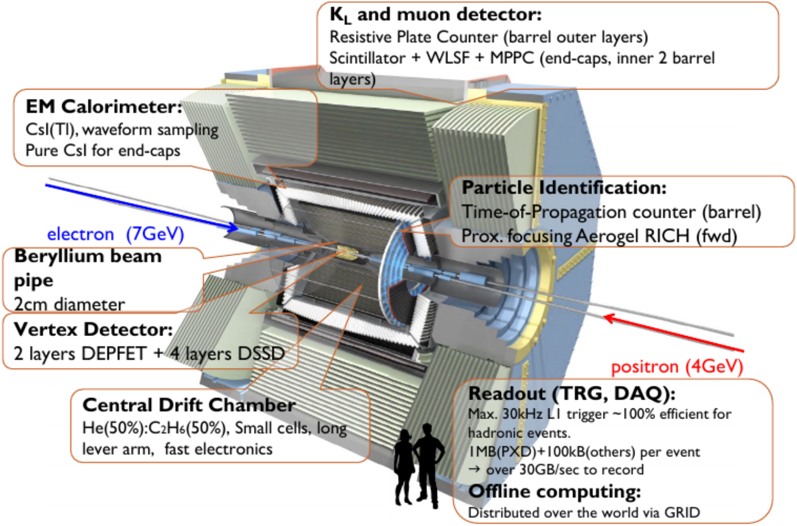
# First Collisions at Belle II

# The Machine: SuperKEKB



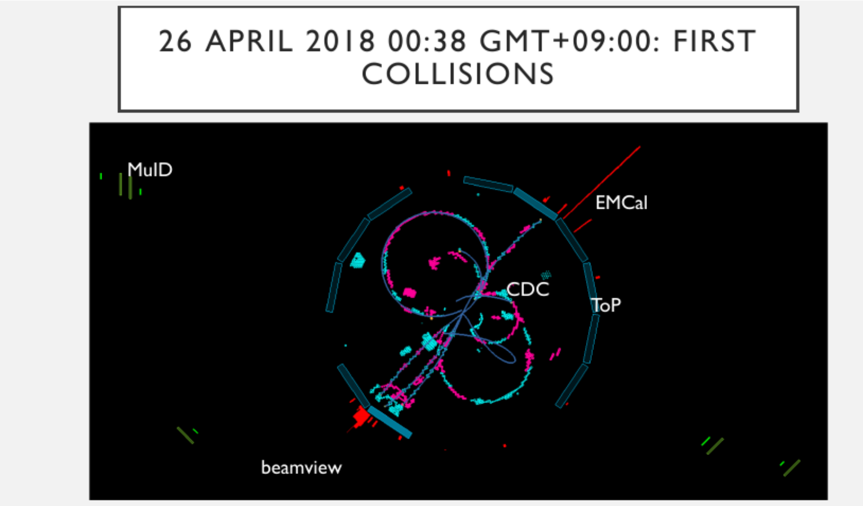

(Anselm Vossen in HFCKM 3)

# The Detector: Belle II



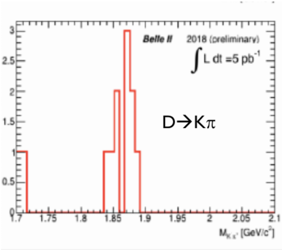

(Anselm Vossen in HFCKM 3)

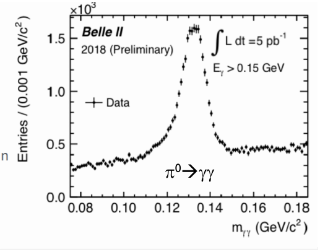
# First Collisions

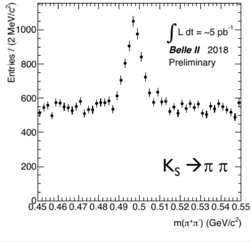



(Anselm Vossen in HFCKM 3)

# First Bumps!



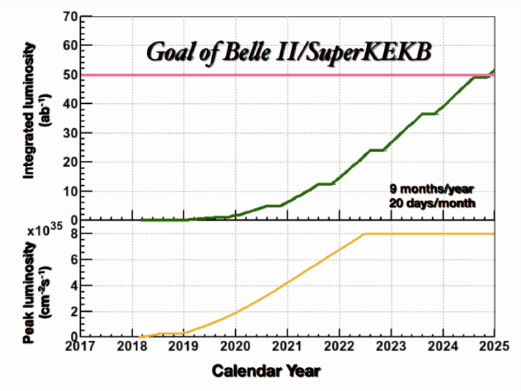




D mesons | pions | Kaons

(Anselm Vossen in HFCKM 3)

# Current Status and Schedule

- Phase I (complete)
  - Accelerator commissioning
- Phase 2 (now)
  - First collisions (20±20 $fb^{-1}$)
  - Partial detector
  - Background study
  - Physics possible
- Phase 3 ("Run I", early 2019)
  - Nominal Belle II start
- **Ultimate goal: 50 $ab^{-1}$**




(Anselm Vossen in HFCKM 3)

# Summary

- CKM picture of flavor and CP violation gives overall a consistent picture at the $\sim 10\%$ level ...
- ... but, over the last few years, several anomalies appeared (e.g. $R_{K^{(*)}}$, $R_{D^{(*)}}$)
- Lattice QCD calculations continue to provide invaluable input with higher and higher precision
- Expect many exciting results from LHCb and Belle II in the near future