Looking at Particle - AntiParticle asymmetry with Heavy Flavors

Toru Iijima
Kobayashi-Maskawa Institute
Nagoya University

February 18, 2019
Talk Outline

- Introduction
- CP violation in the SM
  - Flavor changing quark interaction
- Approaching New Physics with heavy flavors
- LHC and B experiments
- Summary

- Topical session focused on “Mysteries of the matter-antimatter asymmetry in the Universe”.
- Introductory overview for the 2nd KMI school.

- Strong CP (M. Ramsey-Musolf)
- Neutrino (F. di Lodovico)
- Charged leptons (K. Hayasaka)
- Cosmic ray research (S. Haino)
History of the Universe

Big Bang

Inflation

High Energy Cosmic Ray

Particle Accelerator

Dark Energy

Atom

Star

Black Hole

Cosmic Microwave Background

Large Scale Structure

The Origin of Particles and the Universe

10^{-5} s 100 s 3 \times 10^5 y Today
History of the Universe

CP Violation

High Energy Cosmic Ray Particle Accelerator

Dark Energy

Black Hole

Gravitational Wave

Galaxy

Large Scale Structure

The Origin of Particles and the Universe

Big Bang

Inflation

GUT Neutrino

Quark Gluon Plasma

New Physics

Higgs

Cosmic Microwave Background

Dark Matter

10^{-10}s

100 s

3 × 10^5 yr

Today
Physicists believe that equal number of particles and anti-particles are produced from Big Bang. However, anti-particles disappeared somehow, and the present Universe is dominated by matters. Why?
Mystery of Anti-matter Disappearance

Physicists believe that equal number of particles and anti-particles are produced from Big Bang. However, anti-particles disappeared somehow, and the present Universe is dominated by matters. Why?
CP Violation

To make the matter dominated Universe, we need
I. Baryon number violation
II. **CP violation**
III. Loss of thermal equilibrium

[ Sakharov’s 3 conditions ]
Discovery of CPV (1964)

- V. Fitch, J. Cronin et al.

\[ \frac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_L \to \text{all charged})} = (2.0 \pm 0.4) \times 10^{-3} \]
The Standard Model of Particle Physics

Elementary particles make up the Universe
Matter particles (quarks and leptons)
Force mediating particles (bosons) and Higgs!
The Nobel Prize in Physics 2008 was divided, one half awarded to Yoichiro Nambu "for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics", the other half jointly to Makoto Kobayashi and Toshihide Maskawa "for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature."
Kobayashi-Maskawa Theory

- A quark change its flavor by emitting virtual $W$.
- $3 \times 3$ unitarity triangle has 3 rotational angles and one complex phase.

$\begin{align*}
\text{CP Violation} \\
\text{Flavor eigenstate} \\
\text{Mass eigenstate}
\end{align*}$
Unitarity Triangle

unitarity condition

\[ V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = 0 \]
\[ V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \]
\[ V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0 \]

\[ \overline{\rho}(\overline{\eta}) = \left(1 - \frac{\lambda^2}{2}\right)\rho(\eta) \]

\( B \to X_u \ell \nu \)

\( B \to \pi\pi, \rho\pi \)

\( B \to D K \)

\( B \to J/\psi \ K_S \)
B-Factory Experiments

In 2001, the Belle experiment at KEK and the BaBar experiment at SLAC successfully measured CP violation in B meson decays as predicted by the Kobayashi-Maskawa theory.
Confirmation of Kobayashi-Maskawa
Press release from the Academy

“As late as 2001, the two particle detectors BaBar at Stanford, USA and Belle at Tsukuba, Japan, both detected broken symmetries independently of each other. The results were exactly as Kobayashi and Maskawa had predicted almost three decades earlier.”
Latest Results (Summer 2018)
Large Hadron Collider

フランス

ジャンネーブ空港

スイス

周長27 Km

7TeVの陽子と7TeVの陽子を衝突

世界最高エネルギー14TeVの世界
Large Hadron Collider

フランス
ジュネーブ空港
スイス

周長27 Km

7TeVの陽子と7TeVの陽子を衝突
世界最高エネルギー14TeVの世界
Large Hadron Collider

フランス

スイス

ジュネーブ空港

7TeVの陽子と7TeVの陽子を衝突

世界最高エネルギー14TeVの世界

ヒッグス粒子発見!

ATLAS, PLB726, 88 (2013)

Data 2011+2012
SM Higgs boson $m_H=126.8$ GeV (fit)
Bkg (4th order polynomial)

$H \rightarrow \gamma\gamma$

$\sqrt{s} = 7$ TeV $L dt = 4.8$ fb$^{-1}$
$\sqrt{s} = 8$ TeV $L dt = 20.7$ fb$^{-1}$
CP Violation and Mass

\[ Q = +\frac{2}{3} \]

\[ Q = -\frac{1}{3} \]

\[ \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \]

Don’t forget: relevant inputs from LaPce QCD and great work from the Heavy Flavour Averaging Group (hVp://www.slac.stanford.edu/xorg/hfag)

Great success of the Standard Model CKM picture!

– All of the measurements agree in a highly profound way

– In the presence of relevant New Physics effects, the various contours would not cross each other in a single point

But...

Test of CPV origin

Test of mass origin

Yukawa coupling

ATLAS Preliminary

\[ t_s = 13 \text{ TeV}, 36.1 - 79.8 \text{ fb}^{-1} \]

\[ m_{\gamma} = 125.09 \text{ GeV}, |y_{\gamma}| < 2.5 \]

\[ k_{FV} \text{ or } k_{V/V} \]

Particle mass [GeV]
Why do we need go further?
SM explains almost every phenomena so far, but cannot explain

- The Higgs mass (fine tuning problem)
- Grand unification
- Dark matter
- Baryon asymmetry in the Universe
- Origin of the 3 generations

New Physics! @ $O(1 \rightarrow 10) \text{ TeV}$?
Why do we need go further?

SM explains almost every phenomena so far, but cannot explain:

- The Higgs mass (fine tuning problem)
- Grand unification
- Dark matter
- Baryon asymmetry in the Universe
- Origin of the 3 generations

New Physics! @ O(1 → 10) TeV?
Two Ways to Find New Physics

• **Energy Frontier**: produces and detects a new particle directly in collisions of extremely high energy beams.

• **Luminosity Frontier**: measures reactions of known particles very precisely, and finds deviations from the Standard Model predictions.
Importance of Heavy Flavors

- New Physics is unknown.
- We need a variety of approaches to find and know it.
- Heavy flavor particles \((t, b, c, \tau)\) are good probes
  - Sensitive to New Physics
Yukawa couplings to $t, b, \tau$

- Higgs has been discovered, and its couplings to fermions are being measured.
- Couplings to $t, b, \tau$ are just on the stage, and we need more precise measurements to test the SM and also to find NP.

---

See talk by Y. Nakahama
Direct NP Searches

- LHC Run2 (6.5TeV+6.5TeV) completed.
- No NP so far from partial data analyses.
- Extensive analyses for accumulated data (~150fb⁻¹) are underway.

Summer 2018 (mostly 36.1fb⁻¹)

Search for the stop quark of compressed SUSY scenarios in 1-lepton, jets, and missing energy final state

Top quark final states are important part of the LHC NP search program.

See talk by Y. Nakahama
LHC Long-term Plan

Run 1  Run 2  Run 3  HL-LHC
7→8 TeV 13 TeV 14 TeV 14 TeV
30fb⁻¹ 150fb⁻¹ 300fb⁻¹ →3000fb⁻¹

ATLAS upgrade
Phase 1

ATLAS upgrade
Phase 2

See talk by Y. Okumura
SuperKEKB/Belle II

New intensity frontier facility at KEK

- Target luminosity: $L_{\text{peak}} = 8 \times 10^{35} \text{cm}^{-2}\text{s}^{-1}$
  $\Rightarrow \sim 10^{10}$ $\bar{B}B$, $\tau^+\tau^-$ and charms per year!

- $L_{\text{int}} > 50 \text{ ab}^{-1}$

- Rich physics program
  - Search for New Physics through processes sensitive to virtual heavy particles.
  - New QCD phenomena ($XYZ$, new states including heavy flavors) + more

The first particle collider after the LHC!
10 years later from KM’s Nobel Prize, we are starting a new experiment SuperKEKB/Belle II to search for new phenomena beyond KM.
10 years later from KM’s Nobel Prize, we are starting a new experiment SuperKEKB/Belle II to search for new phenomena beyond KM.
First Collision!
0:38, April 26, 2018

First hadronic event, April 26 2018
First Collision!
0:38, April 26, 2018
First Collision!
0:38, April 26, 2018
Advantage of e⁺e⁻ Flavor Factory

- Clean environment
  - Efficient detection of neutrals (\(\gamma, \pi^0, \eta, \ldots\))
- Quantum correlated \(B^0\bar{B}^0\) pairs
  - High effective flavor tagging efficiency: ~34% (Belle II) \(\leftrightarrow\) ~3% (LHCb)
- Large sample of \(\tau\) leptons
  - Search for LFV \(\tau\) decays at \(O(10^{-9})\)
- Full reconstruction tagging possible
  - A powerful tool to measure;
    - \(b \to u\) semileptonic decays (CKM)
    - decays with large missing energy
- Systematics different from LHCb
  - Two experiments are required to establish NP
Advantage of $e^+e^-$ Flavor Factory

- Clean environment
- Efficient detection of neutrals ($\gamma$, $\pi^0$, $\eta$, …)
- Quantum correlated $B_0B_0$ pairs
- High effective flavor tagging efficiency: ~34% (Belle II) ~3% (LHCb)
- Large sample of $\tau$ leptons
- Search for LFV $\tau$ decays at $O(10^{-9})$
- Full reconstruction tagging possible
- A powerful tool to measure;
  - $b \to u$ semileptonic decays (CKM)
  - decays with large missing energy

---

pp collision
large production rate

$\times$

$e^+e^-$ collision
low background

Powerful!

Clean!

---

TOYOTA FCV
NOW ON MARKET!
Role of the Belle II Experiment

• Complementary to direct search in LHC high $P_T$ programs.
• Reach in mass scale is not limited by the collision energy.
• Depend on NP flavor violating couplings.
Key Measurements at Belle II

- CPV in $b \to s$ penguin decays
- FCNC
- Tauonic decays
- LFV $\tau$ decays

Ultimate measurements down to theory error!
Physics w/ b-quark

We know this old road...

Mt. New Physics?

by Hiroshige Utagawa (1797-1858)
B-\overline{B} Mixing and Top Quark

Mt > 50 GeV/c²
**CKM fit w/ Belle II + LHCb**

<table>
<thead>
<tr>
<th>Input</th>
<th>Current WA</th>
<th>SM value Belle II</th>
<th>SM value Belle II + LHCb</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda$</td>
<td>$0.8227^{+0.0136}_{-0.0136}$</td>
<td>$+0.0025$</td>
<td>$+0.0024$</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>$0.22543^{+0.00042}_{-0.00031}$</td>
<td>$-0.0027$</td>
<td>$-0.0028$</td>
</tr>
<tr>
<td>$\tilde{\rho}$</td>
<td>$0.1504^{+0.0121}_{-0.0062}$</td>
<td>$0.00036$</td>
<td>$0.00035$</td>
</tr>
<tr>
<td>$\tilde{\eta}$</td>
<td>$0.3540^{+0.0069}_{-0.0076}$</td>
<td>$-0.00030$</td>
<td>$-0.00040$</td>
</tr>
</tbody>
</table>

**Current world average**

**Belle II projection @ 50ab$^{-1}$**
CKM fit w/ Belle II + LHCb

Relative amplitude (h) phase (σ)

\[ M_{12}^{d,s} = (M_{12}^{d,s})_{SM} \times (1 + h_{d,s} e^{2i\sigma_{d,s}}) \]
B-\bar{B} Mixing and New Physics

\[ \bar{B}^0 \rightarrow W^\pm \rightarrow W^+ \rightarrow B^0 \]

\[ h = 1.5 \frac{|C_{ij}|^2 (4\pi)^2}{|\lambda_{ij}^t|^2 G_F \Lambda^2} \approx \frac{|C_{ij}|^2}{|\lambda_{ij}^t|^2} \left( \frac{4.5 \text{ TeV}}{\Lambda} \right)^2, \]

\[ \sigma = \arg(C_{ij}\lambda_{ij}^{t*}), \]

\[ \lambda_{ij}^{t} = V_{ti}^* V_{tj} \]

\[ \frac{C_{ij}^2}{\Lambda^2} (\bar{q}_{i,L} \gamma^\mu q_{j,L})^2, \]

Mass reach (CKM-like): \( O(1) \text{ TeV} \rightarrow O(10) \text{ TeV} \)!
Some theoretical issues

• Hadronic uncertainties to extract fundamental quantities from experimentally measured rates.
  
  • Ex. $|V_{c(u)b}|$ from $\Gamma(B \rightarrow X_{c(u)} l \nu)$.
  
  • Form factors $f(B \rightarrow D)$, $f(B \rightarrow \pi \nu)$
  
  • Inclusive vs Exclusive
  
  • Need more theoretical investigations.
CP Violation by New Physics

Belle II can measure types of B meson decays which rarely happen (~ one per million B decays), known as “Penguin” decays.

Q: Does CP violation in “Penguin” decays deviates from the SM?

A. Gaz is leading the physics analysis in Belle II
Time-dependent CPV

- Larger acceptance for $K_S$ decay vertex +30%

- Improved vertex resolution
  $\sigma(Z) \sim 18 \mu m \ @ \ Belle \ II \ \leftrightarrow \ \sim 61 \mu m \ @ \ Belle$

  $\rightarrow$ less systematic error
Belle II projection for $\sin 2\phi_1^{\text{eff}}$ from $b \to s\bar{s}s$ processes
Time-dep. CPV in $b \rightarrow s,d + \gamma$

- In SM, photon from $b \rightarrow s,d + \gamma$ is almost left-handed.
- Right-handed photon causes interference, and large CPV.

**SM prediction**

$$S(B \rightarrow V\gamma) \simeq -\frac{2m_s}{m_b} \sin 2\phi_1$$

$$|S(B \rightarrow K^{*}\gamma)| \leq 0.02$$

$$|S(B \rightarrow \rho\gamma)| \sim 0$$

**SUSY models**

Belle measurement

Belle II detector (improved for $K_s$ vertex)
Lepton non-Universality (tree)

There are 3 modes in the B meson weak decay into the lepton final states; \( B \rightarrow D \, e \, \nu \), \( D \, \mu \, \nu \), \( D \, \tau \, \nu \).

Q: Are they just the same (as in the SM)?

Hints of deviations in recent BaBar, Belle, LHCb data …
Deviation from SM slightly decreased from 4.1 → 3.8σ, mainly due to change in theoretical SM prediction.
Belle II Projections

- Lepton universality violation may be established even with 5ab$^{-1}$ (2020).
- High statistics data will provide more detailed information, such as $\tau$ polarization, $q^2$ distribution, to discriminate type of NP.

- More observables (distributions)!
  - $P(\tau), P(D^*)$
  - $d\Gamma/dq^2, d\Gamma/dp_{D^*(s)}, d\Gamma/dp_e, \ldots$

- More modes!
  - $B \rightarrow \pi \tau \nu$,
  - $B_s \rightarrow D_s \tau \nu$ (at 5S runs), \ldots

Will soon hit the systematic limit!
Lepton non-Universality (loop)

Hints of deviations in recent LHCb data ...

\[ R(K) = \frac{Br(B \rightarrow K\mu\mu)}{Br(B \rightarrow Kee)} \]
\[ = 0.745^{+0.09}_{-0.07} \pm 0.036 (1 < q^2 < 6\text{GeV}^2) \]

\[ R(K^*) = \frac{Br(B \rightarrow K^*\mu\mu)}{Br(B \rightarrow K^*ee)} \]
\[ = 0.66^{+0.11}_{-0.07} \pm 0.03 (0.045 < q^2 < 1.1\text{GeV}^2) \]
\[ = 0.69^{+0.11}_{-0.07} \pm 0.05 (1.1 < q^2 < 6\text{GeV}^2) \]

Precision at Belle II : \(~3\%\) at 50ab\(^{-1}\) and also inclusive measurement (less theory ambiguity) possible.
Lepton Flavor Violation

SuperKEKB produces also a lot of tau-leptons, which can be studies in detail by Belle II.

Q: Does the tau-lepton changes to the muon or electron, similarly to the case of the neutrino (neutrino oscillation).

\[ \nu_e \leftrightarrow \nu_\mu \leftrightarrow \nu_\tau \]

neutrino oscillation

are there decays like

\[ \tau \rightarrow \mu \gamma \, ? \]
\[ \tau \rightarrow e \gamma \, ? \]
Is Lepton Non-universality the clue to NP?
Testing B anomalies at ATLAS/CMS (e.g. LQ model)

- The Leptoquark (LQ) model is a favored model, which can explain observed anomalies consistently: $P5'$, $R_K(*)$, $R(D(*))$
- Coupling to 3rd gen. $>$ to 2nd gen. $>>$ to 1st gen.

E.g.: scalar leptoquark

\[ b \xrightarrow{g_{1L}^{33}} LQ \xrightarrow{g_{1R}^{23}} c \]

\[ 2\sqrt{2}G_F V_{cb} C_{LQ_2} = -\frac{g_{1L}^{33} g_{1R}^{23*}}{M_{S_1}^2} \]

Once B anomalies are confirmed, it would be interesting to see results of ATLAS/CMS w/ 300fb$^{-1}$
Work by Nagoya Theory Group

- Building a model, which can explain the “B anomalies”, and predict and suggest tests at LHC.

![Diagram showing SM and H-/W' reactions testable at LHC]

- Reaction testable at LHC

Predictions for H- in this model excluded.

W’ can be tested with more data.
World Research Unit for Heavy Flavor Particle Physics ("WPI-next")

SuperKEKB/Belle II
- Toru Iijima
  - B, Tau Physics
  - Exotic hadrons

LHC-ATLAS
- Makoto Tomoto
  - Top physics
  - Higgs

Theory
- Junji Hisano
  - Flavor Physics
  - Dark Matter

Alessandro Gaz
Kodai Matsuoka
Yuji Omura
Gino Isidori (Zurich)
Yu Nakahama

Peter Krizan (Ljubljana)
Tim Gershon (Warwick)
R&D for ATLAS Muon Trigger

HL-LHC advanced muon trigger
Realized high speed muon track trigger by processing 1M channel signals with large-scale FPGA.
Belle II Experiment

- Deal with higher background (10-20×), radiation damage, higher occupancy, higher event rates (L1 trigg. 0.5→30 kHz)
- Improved performance and hermeticity

Nagoya group takes leading roles: Particle ID, Computing, Physics analyses

T.I will be the spokesperson from June, 2019.
Summary

- The CPV phenomena observed in flavor changing quark interactions (in $K, B$ decays so far) can be explained by the Kobayashi-Maskawa.
- But, we are still far from explaining the Matter-Antimatter asymmetry in the Universe.
- Search for New Physics is the clue to investigate more the issue.
- Researches on heavy flavors are important in coming years.

High Energy Frontier

LHC/ATLAS

- 7-8 TeV
- 13 TeV
- 13-14 TeV
- HL-LHC

High Luminosity Frontier

SuperKEKB/Belle II

- 1st collision!
- Critical test of SM
- NP Discovery
- Test of NP models
- New SM?