Belle II: flavour physics at the intensity frontier

Jim Libby (IIT Madras)
University of Warwick Seminar
9th October 2018
Overview

- Particle physics and frontiers
- Some flavour history
  - Flavour as a predictor
  - Belle
  - Complementarity with LHCb
- Belle II
  - Highlights of the instrumentation and first results
  - Some physics highlights
- Conclusion
Overview

Probably a Y(4S) event
Overview

arXiv:1808.10567 [hep-ex]

The Belle II Physics Book

E. Kou\textsuperscript{74,\dagger}, P. Urquijo\textsuperscript{142,§,†}, W. Altmannshofer\textsuperscript{132,¶}, F. Beaujean\textsuperscript{78,¶}, G. Bell\textsuperscript{119,¶}, M. Beneke\textsuperscript{111,¶}, I. I. Bigi\textsuperscript{145,¶}, F. Bishara\textsuperscript{147,16,¶}, M. Blanke\textsuperscript{49,50,¶}, C. Bobeth\textsuperscript{110,111,¶},

Probably a Y(4S) event
The standard model
The standard model

1\textsuperscript{st} generation
- everyday matter
- 3 fermions (+3 anti-matter)
- increasing mass

2\textsuperscript{nd} generation
- exotic matter
- 3 fermions (+3 anti-matter)

3\textsuperscript{rd} generation
- force particles

Electro-weak symmetry breaking (mass giving)

Outside of standard model
- gravitational force

6 quarks

6 leptons

12 fermions (+12 anti-matter)

5 bosons (+1 opposite charged W)

- charge
- color charge (r, g, or b)
- mass (eV)
- spin

- strong nuclear force (color charge)
- electromagnetic force
- weak nuclear force
Problems

• **Empirical**
  - Neutrinos are massive
  - Dark matter
  - Dark energy!!!!
  - Matter rather than antimatter
  - Gravity

• **Aesthetic**
  - Why three of everything?
  - Why eighteen parameters?
    - Many with a distinct hierarchy?
  - Why do we need to know them to 18 decimal places?
  - Unification
Frontiers

Energy

Experimental High Energy Physics

Cosmic

Intensity
### ATLAS SUSY Searches - 95% CL Lower Limits

**December 2017**

<table>
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<tr>
<th>Model</th>
<th>Channel</th>
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<th>E_{miss}^{T}</th>
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*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.*
Frontiers

Energy

Experimental High Energy Physics

Cosmic

Intensity
ATLAS SUSY Searches\textsuperscript{*} - 95\% CL Lower Limits

ATLAS Preliminary

[Graph showing WIMP-nucleon cross section vs. WIMP mass with various experiments and their results indicated.]

Simplified models; C. F. for the assumptions made.
Frontiers

Energy

Experimental High Energy Physics

Cosmic

Intensity
ATLAS SUSY Searches - 95% CL Lower Limits

SI WIMP-nucleon cross section [cm$^2$]

Accumulated POT

3.16 x 10$^{21}$ POT

T2K

2017/18

2016/17

2012/13

2015/16

2014/15

2012

2010/11

2010

2014

Nov

Jan

Mar

May

Jul

Month

Simplied models; c.f. refs. for the assumptions made.
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- **CMSSM**
- **2HDM II**
- **RPV SUSY**
Physics HAS A NEW FACE
Physics HAS A NEW FACE
Problems

• **Empirical**
  - Neutrinos are massive
  - Dark matter
  - Dark energy!!!!
  - Matter rather than antimatter
  - Gravity

• **Aesthetic**
  - Why three of everything?
  - Why eighteen parameters?
    - Many with a distinct hierarchy?
  - Why do we need to know them to 18 decimal places?
  - Unification
Flavour physics – history of discovery

- Particle zoo of mesons and baryons discovered in 1950s and early 1960s lead to the quark model
  - up (u)
  - down (d)
  - strange (s)
- An allowed but rare decay such as
  \[ K_L^0(s\bar{d}) \rightarrow \mu^+ \mu^- \]
- Predicted but not seen!

\[ S \quad \bar{d} \quad u \quad W^- \quad W^+ \quad \nu \quad \mu^- \quad \mu^+ \]
Flavour physics – history of discovery

\[ \begin{align*}
\sin \theta_c & \quad S \quad \bar{d} \\
\cos \theta_c + \cos \theta_c & \quad W^- \quad W^+ \\
-\sin \theta_c & \quad S \quad \bar{d} \\
\end{align*} \]

2 \propto \text{Rate} \sim 0

\[ \begin{align*}
\mu^- & \quad \nu \mu^+ \\
\mu^- & \quad \nu \mu^+ \\
\end{align*} \]

Such rare virtual processes tell you about higher energy particles

\[ m_c > m_K \]
ARGUS: B mixing $\Rightarrow$ heavy top

**OBSERVATION OF $B^0-\bar{B}^0$ MIXING**

ARGUS Collaboration

\[ B_i^0 \rightarrow D_{i}^{*} \rightarrow \mu_i^+ \nu_i \]
\[ D_{i}^{*} \rightarrow \pi_i^- \bar{D}^0 \]
\[ \bar{D}^0 \rightarrow K_i^+ \pi_i^- , \]

and

\[ B_2^0 \rightarrow D_{2}^{*} \rightarrow \mu_2^+ \nu_2 \]
\[ D_{2}^{*} \rightarrow \pi_2^0 D^- \]
\[ D^- \rightarrow K_2^+ \pi_2^- \pi_2^- . \]

\[ m_t > 50 \text{ Gev} \]
ARGUS: B mixing $\Rightarrow$ heavy top

$\mu_1^+\nu_1$

$D^+_1 \rightarrow \pi^- D^0$

$D^0 \rightarrow K^+\pi^-$

$m_t > 50$ Gev

CKM matrix

- Two by two mixing matrix proposed Cabibbo

\[
\begin{pmatrix}
 u & c
\end{pmatrix}
\begin{bmatrix}
 \cos \theta_c & \sin \theta_c \\
 -\sin \theta_c & \cos \theta_c
\end{bmatrix}
\begin{pmatrix}
 d \\
 s
\end{pmatrix}
\]
CKM matrix

- Two by two mixing matrix proposed Cabibbo
  - Kobayashi-Maskawa proposed third generation to explain observed CP violation by Cronin and Fitch
- $3 \times 3$ unitary complex matrix
  - 4 parameters
  - 3 mixing angle and 1 phase
- Intergenerational coupling disfavoured

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

Relative magnitude of elements

Responsible for CP violation
Visualising CP violation: the unitarity triangle

1) \[
\begin{pmatrix}
1 - \lambda^2 / 2 & \lambda & A\lambda^3 \left( \rho - i\eta \right)
\\
-\lambda & 1 - \lambda^2 / 2 & A\lambda^2
\\
A\lambda^3 \left[ 1 - (\rho - i\eta) \right] & -A\lambda^2 & 1
\end{pmatrix} + O(\lambda^4)
\]

2) Exploit unitarity (1\textsuperscript{st} and 3\textsuperscript{rd} col.)

3) \[
V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0
\]

\[
\phi_1 = \beta = \arg \left( -\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*} \right)
\]

\[
\simeq \arg \left( \frac{1}{1 - \rho - i\eta} \right)
\]
Belle

- Operation from 1999 to 2010
- $e^+ e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$ for CKM measurements
- Asymmetric energy to allow time-dependent measurements
- Coherent production of $B^0\bar{B}^0$
- Low multiplicity
- Detectors with good tracking, PID and calorimetry
  - plus hermeticity for full event reconstruction/tagging
The Golden Mode

\[ B^0 \rightarrow J / \psi K_S^0 \] sensitive to

\[ \beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) \]

CP violation in the ‘interference of mixing and decay amplitudes’

\[ A_{CP}(\Delta t) = \frac{\Gamma[\bar{B}^0(\Delta t) \rightarrow f] - \Gamma[B^0(\Delta t) \rightarrow f]}{\Gamma[\bar{B}^0(\Delta t) \rightarrow f] + \Gamma[B^0(\Delta t) \rightarrow f]} = S_f \sin(\Delta m_d \Delta t) - C_f \cos(\Delta m_d \Delta t) \]

In SM \( S_f = \sin 2\beta \) and \( C_f = 0 \) when no CPV in \( f \)
Time-dependent CPV violation

In order to see CPV by interference between decay and mixing.

\[ \Delta z = \beta \gamma c \Delta t, \]
\[ \beta \gamma = 0.425 \text{(KEKB)}, 0.56 \text{(PEP-II)}, \]
\[ \Delta z \sim 200 \mu m \]

Tagging power
\[ = \varepsilon (1 - 2\omega)^2 \]
\[ \approx 30\% \]
Over constraint

Tree level only

Loop-level only

NP at $O(\text{>TeV})$?
Belle achievements

From Abi Soffer: HEPMAD

- Integrated Luminosity in fb^{-1}
- Nobel prize to KM / Decisive confirmation of CKM picture
- Observation of direct CP violation in B \rightarrow \pi^+\pi^-
- Observation of B \rightarrow d\gamma
- Evidence for D^0 mixing
- Evidence for B \rightarrow \tau \nu
- Evidence for direct CP violation in B \rightarrow K^\pm \pi^\mp
- Exotic hadrons
- Observations of mixing-induced CP violation in B \rightarrow \phi K_s, \eta' K_s, ...
- 1st dark searches
- Time reversal asymmetry
- Excess in \bar{B} \rightarrow D^{(*)}\tau \bar{\nu}

>100 unique CPV results

\sim350 papers published after shutdown, 21 in 2018
Belle II: can never have too much of a good thing (x 50 Belle)

- But isn’t LHCb doing this already?

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<tr>
<th>Property</th>
<th>LHCb</th>
<th>Belle II</th>
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<tbody>
<tr>
<td>$\sigma_{b\bar{b}}$ (nb)</td>
<td>$\sim150,000$</td>
<td>$\sim1$</td>
</tr>
<tr>
<td>$\int L , dt , (fb^{-1})$ by $\sim2024$</td>
<td>$\sim25$</td>
<td>$\sim50,000$</td>
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<tr>
<td>Background level</td>
<td>Very high</td>
<td>Low</td>
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<tr>
<td>Typical efficiency</td>
<td>Low</td>
<td>High</td>
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<tr>
<td>$\pi^0, K_S$ reconstruction</td>
<td>Inefficient</td>
<td>Efficient</td>
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<tr>
<td>Initial state</td>
<td>Not well known</td>
<td>Well known</td>
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<tr>
<td>Decay-time resolution</td>
<td>Excellent</td>
<td>Very good</td>
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<tr>
<td>Collision spot size</td>
<td>Large</td>
<td>Tiny</td>
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<tr>
<td>Heavy bottom hadrons</td>
<td>$B_s, B_c, b$-baryons</td>
<td>Partly $B_s$</td>
</tr>
<tr>
<td>$\tau$ physics capability</td>
<td>Limited</td>
<td>Excellent</td>
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<tr>
<td>B-flavor tagging efficiency</td>
<td>3.5 - 6%</td>
<td>36%</td>
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</table>
“Moore’s” Law of Luminosity
The path to higher luminosity

\[ \xi \propto \sqrt{\frac{\beta^*}{\varepsilon}} \]

**Brute force:** Increase beam currents by a factor of 5-10! Increase the beam-beam parameter by a factor of a few (crab cavities). Too hard, too expensive (power, melt beam pipes).
The path to higher luminosity

\[ \xi \propto \sqrt{\frac{\beta^*}{\epsilon}} \]

1. Smaller \( \beta_y^* \) (20x)

2. Increase beam currents (≈2-3x)

**Hourglass condition:**

\[ \beta_y^* \approx \frac{L}{\sigma_x/\phi} \]

83 mrad
SUPERKEKB

- Replace long dipoles with shorter ones in HER
- Low emittance gun
- Redesign the HER arcs to reduce the emittance
- More RF/modify RF systems
- New positron target / capture section
- New IR
- Two separate focusing quads / each 2 beams closer to IP; Superconducting / permanent magnets
- LER e⁻ 2.1 A
- HER e⁺ 3.7 A
- Low emittance positrons
Schedule and status

First collisions, 26 April, 2018

Phase 2 goals:
- Progress toward high luminosity
- Progress toward stable operation

Achievements:
- $L = 5.5 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$
- Collected $\sim 0.5 \text{ fb}^{-1}$ for commissioning & calibration
Super KEKB performance

\( \sigma = 4.5 \text{ mm} \)

\( \sigma = 550 \text{ \(\mu\)m} \)

Measurement at Belle II
Super KEKB performance

Ohnishi-san eeFACT, HKUST

Max 800 mA (HER)

Max 860 mA (LER)

Beam Current

Luminosity

\[ L_{\text{peak}} = 5.55 \times 10^{33} \text{ (not optimized)} \]

1/4 of KEKB
Belle II Collaboration

800 physicists from 25 countries
Belle II

Csl(Tl) EM calorimeter:
- waveform sampling electronics, pure CsI for end-caps

RPC $\mu$ & $K_L$ counter:
- scintillator + Si-PM for end-caps

4 layers DS Si Vertex
Detector →
2 layers PXD (DEPFET),
4 layers DSSD

Central Drift Chamber:
- smaller cell size,
  long lever arm

Time-of-Flight, Aerogel Cherenkov Counter →
Time-of-Propagation counter (barrel),
prox. focusing Aerogel RICH (forward)
Belle II - TOP

Simulation of a 2 GeV pion and kaon interacting in a quartz bar.

K or \( \pi \) of same momentum

16 bar modules arranged in a “roman arch”
Belle II - TOP

At 3 GeV Timing at the ~100 ps level is needed to separate pion and Kaon
Belle II - TOP

At 3 GeV Timing at the ~100 ps level is needed to separate pion and Kaon

ToP signature of kaon identified kinematically via $D^* \rightarrow D^0 \pi^+_s; D^0 \rightarrow K^- \pi^+$

is visibly more consistent with being a kaon than a pion or proton

Phase II data
Belle II – Silicon Vertex Detector

1/8 for Phase II – only one layer of pixels for Phase III

Layers 1-2: Pixel Detector
Layers 3-6: Strip Detector

Closer to IP

“VXD-only” tracking
SVD performance

Belle is a factor two worse than Belle II

Stand alone SVD track finding efficiency good for $K_S$ finding (30% over Belle) and slow $\pi$ from $D^*$
Particle reconstruction

$$\pi^0 \rightarrow \gamma\gamma$$

$$\phi \rightarrow K^+ K^-$$

No TOP

One K IDed by TOP

Both K IDed by TOP
Particle reconstruction

$\phi \rightarrow K^+K^-$

No TOP

One $K$ IDed by TOP

Both $K$ IDed by TOP

$\pi^0 \rightarrow \gamma\gamma$

$K^0_S \rightarrow \pi^+\pi^-$

$\sigma$ 5% larger than MC

$h$ $K$ IDed by TOP
Many charm decays seen including CP eigenstates used in CP violation measurements – reasonable agreement with expectations
Beauty measurements

- We are on the $\Upsilon(4S)$ resonance and recording $B$ anti-$B$ pairs with $\sim 99\%$ efficiency.
- *Not so obvious*: When we change accelerator optics, we remain on $\Upsilon(4S)$.

$$R_2 = \frac{H_2}{H_0}$$

$$H_l = \sum_{i,j} \frac{|P_i| |P_j|}{E_{vis}^2} P_l(\cos \theta_{ij})$$
B meson reconstruction

\[ \Delta E = \frac{E_{CM}}{2} - E_B \]

\[ M_{BC} = \sqrt{\left(\frac{E_{CM}}{2}\right)^2 - \left|\mathbf{p}_B\right|^2} \]

\[ B \rightarrow D^{(*)} h \ (h=\pi, \rho) \] and \[ B \rightarrow J/\psi K^{(*)} \]

Reconstructed > 200 B events
A FEW PHYSICS PROSPECTS
$B \to K^*(892) l^+ l^-$

- This is a rare flavour changing neutral current process
- The four-body final state allows differential distributions to be probed
  - Large new physics contributions possible as they appear via interference c.f. forward-backward asymmetries in $e^+e^-$
- Also variation with the invariant mass of the $l^+l^-$ system - $q^2$
Goal is to measure this 4D differential distribution and extract the coefficients from data to compare to the SM predictions

Much work on defining observables with minimal theoretical uncertainties

Let us focus on $S_5$ which get normalized as $P_5' = \frac{S_5}{\sqrt{F_L (1 - F_L)}}$ to minimize form factor uncertainties
Angular Asymmetries based on 2398±57 $B \to K^*\mu\mu$ events

3.7 $\sigma$ disagreement with Standard Model

Other analyses of the data also show inconsistency i.e. RH currents at large $q^2$
Smaller sample than LHCb, but e and μ
Tests of LUV more in a moment
Lepton Universality Violation (LUV)

\[
R_H = \frac{\int \frac{d\Gamma(B \to H\mu^+\mu^-)}{dq^2} \ dq^2}{\int \frac{d\Gamma(B \to H\mu^+\mu^-)}{dq^2} \ dq^2},
\]

2-3 standard deviations for \( H = K \) and \( K^* \)
Belle II predictions

Graph showing the prediction for the ratio $R(K^*)$ (1 < $q^2$ < 6 GeV/c²) [% Uncertainty] over years from 2017 to 2024. The graph includes projections for different data scenarios:
- 70% data $Y(4S)$, 6 months, slow ramp-up
- 70% data $Y(4S)$, full 9 months
- LHCb estimate

The graph includes a projection (Feb 2018) with a noted NP 5σ.
Semi-tauonic decays

- Tree level in the SM but allows lepton universality tests
- Measure ratios to reduce theoretical and experimental uncertainties

\[
R(D) = \frac{\Gamma(\overline{B} \to D\tau\nu)}{\Gamma(\overline{B} \to D\ell\nu)} \quad R(D^*) = \frac{\Gamma(\overline{B} \to D^*\tau\nu)}{\Gamma(\overline{B} \to D^*\ell\nu)}
\]

- Babar reported an anomalous result PRL 109, 101802 (2012) much activity since
Belle results

- Tag signal by fully reconstructing or identifying a semileptonic (SL) decay of the other B
- Then use residual energy in ECL, missing mass, multivariates and/or lepton momentum to separate signal
- LHCb also in the game using their vertexing prowess

- Average 3.9σ from SM
- Several NP ideas but it is hard to get all the anomalies in a single framework
Belle II predictions

- More modes for tagging Full Event Interpretation

>5000 modes!
Belle II predictions

- More modes for tagging Full Event Interpretation

>5000 modes

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Many other measurements

- CKM metrology
  - \( \frac{\phi_3}{\gamma} \) - 1.5 degrees
    - Same from LHCb
  - \( V_{ub} \) – 1.2%
- Other rare decays
  - \( B \to \tau\nu \) - 1.5-2.0%
  - \( B \to \mu\nu \) - 5%
  - \( B \to X_s l^+l^- \) - \( R_X \) 3-5%
  - \( b \to s\tau\tau \), \( b \to s\nu\nu \) and LFV versions
- CPV – gluonic penguins
  - \( B \to \eta' K^0_s \sin 2\phi_1 \) to 0.02
  - LFV \( \tau \to \mu\gamma \) 10\(^{-9}\) limit at 90% C.L
- + charm, XYZ spectroscopy, dark photon
Conclusion

- Particle physics is tackling its problems on three complementary frontiers
  1. Energy
  2. Cosmic
  3. Intensity

- Flavour physics has played a significant role in the development of the Standard Model

- Belle II is a project that will continue flavour physics at the intensity frontier until the middle of the next decade along with LHCb
  - First collisions this year much more to come..