Belle II/SuperKEKB: New Physics and the Next Generation

Tom Browder, University of Hawai‘i at Manoa

Introduction, History and Motivation:
What’s happening in high energy physics?

Some Highlights from First Collisions and the Phase 2 Belle II Pilot Run.

Physics and the Road Ahead to Phase 3, the first Physics run

Conclusion; opportunities for Vietnam

The complex superconducting final focus is partially visible here (before closing the endcap).

Vertex detector before installation
Belle II now has grown to ~800 researchers from 26 countries.

This is rather unique in Japan and Asia. The only comparable example is the T2K experiment at JPARC, which is also an international collaboration. Including one very good one from Vietnam, Dong Van Thanh.

Youth and potential: There are ~267 graduate students in the collaboration.
What is happening these days in high energy physics?

(Personal perspective, based on trips to international conferences and summer schools.)

Typical scenes in Hanoi, Vietnam
2016: US Belle II summer school, @PNNL in Richland, Washington

Friday August 5, 2016 at ICHEP in Chicago, the ATLAS and CMS collaborations announced that the 750 GeV di-photon excess had disappeared in the large Run II 13 TeV dataset.

Some other media headlines on ICHEP:

“Physicists look to the future as new particle dream dies”

“Particle Physics in Mourning”

“The End of the Beginning”
But since then, the silence from the energy frontier has been ominous. 

“The feeling in the field is at best one of confusion and at worst depression,” Adam Falkowski, a particle physicist at the Laboratoire de Physique Théorique d’Orsay in France, wrote recently in an article for the science journal Inference. “These are difficult times for the theorists,” Gian Giudice, the head of CERN’s theory department, said. “Our hopes seem to have been shattered. We have not found what we wanted.”
LHC High pt: Expected Standard Model (SM) $t$-$\bar{t}$-Higgs coupling observed by CMS and ATLAS, SM $Higgs \rightarrow b \bar{b}$ evidence found, no SUSY (SUperSYmmetric) or extra particles.

Dark Matter: No dark matter (DM) signals in Xenon 1T or other leading DM experiments (i.e. DEAP(Canada), LUX (US), PandaX (China))

Neutrinos: Sterile neutrinos at reactors disfavored by Daya Bay results. Planck only needs 3 neutrinos for the CMB (Cosmic Microwave Background). Hints of a normal hierarchy for neutrino masses at NoVa at Fermilab.

This is not what the theorists told us to expect!
“Not found: Any evidence for additional particles. There’s no sugar-coating this one: this was perhaps the greatest hope of most physicists. New particles at scales between 100 GeV and ~2 TeV were sorely hoped for, and at various times, some statistically suggestive evidence emerged for a few candidates. Unfortunately, with more and better data, this tentative evidence evaporated, and now, with Run I and Run II complete, there are not even any good suggestions of where such a new particle might be.

That means it’s important to try new things, including general searches, says Gian Giudice, who heads CERN’s theory department and is not involved in any of the experiments. “This is the right approach, at this point.” (Scientific American, Aug 2018)
Stay calm. Don’t panic!!

The intensity frontier will save you (again) as it has done many times in the past. ($K_L \rightarrow \mu \mu$, $B$ mixing, $A_{FB}(e^+e^- \rightarrow \mu^+ \mu^-)$, Electroweak corrections etc...)

The legend is reborn

Beauty and the Beast
Quantum Mechanical (QM) Finesse versus Brute Force

Energy conservation? \[ \Delta E \Delta t \geq \hbar/2 \]

Banking Analogy (may be easier to understand):
At the Heisenberg Quantum Mechanical bank, customers with no collateral may take out billion Euro loans if they return the full loan within a billionth of a second.

If a beautiful but rare customer takes out such huge loans very frequently, the bank will take notice. Looks odd (or asymmetric) in the bank's special full length mirror.

N.B. Sometimes it is much better to have a large collateral and pay back the loan directly after a longer time.
Time-dependent CP violation is “A Double-Slit experiment” with particles and antiparticles

QM interference between two diagrams

Measures the phase of the $V_{td}$ weak interaction coupling constant or equivalently the phase of $B_d$–anti $B_d$ mixing.
Measurement of $\sin(2\phi_1)/\sin(2\beta)$ in $B\rightarrow$Charmonium $K^0$ modes

Overpowering evidence for CP violation (matter-antimatter asymmetries). >>>>> The phase of $V_{td}$ is in good agreement with Standard Model expectations. This is the phase of $B_d$ mixing.
Critical Role of the B factories in Japan and the US in the verification of the Kobayashi-Maskawa hypothesis was recognized and cited by the Nobel Foundation.

A single irreducible phase accounts for all the matter-antimatter asymmetries in particle physics.

CP violating effects in the B sector are $O(1)$ rather than $O(10^{-3})$ as in the kaon system.
CP Violation is now included in most of the undergraduate particle physics textbooks.

*I will skip the comic book or manga explanation of CP violation.*
I will also not cover the famous competition/race between Belle and BaBar to discover CP violation in the b-sector in 2001.

And I will gloss over the critical role of the original Belle experiment in the 2008 Nobel Prize for Kobayashi and Maskawa.

Sorry this manga is all males.
2015: “Missing Energy Decays” of the B meson

New Frontier: Start of a NP program that will last a decade or more.
Experimentally good for leptonic decays to an accuracy much better than 1%.

\[ \frac{g_\tau}{g_\mu} = 1.0000 \pm 0.0014 \]
But what about semi-leptonic decays of beauty?

To the 1% level, \[ \frac{\Gamma(K^- \to \mu^- \nu)}{\Gamma(K^- \to e^- \nu)} \approx 1 \]

But what about semi-leptonic decays of beauty?

Now can access the 3rd generation of leptons and couple to quarks! Does that make a difference?
Belle

Unexpected competition from LHCb@CERN

Figure 2. Belle (a) and LHCb (b) single event displays illustrating the reconstruction of semileptonic $B$ meson decays: Trajectories of charged particles are shown as colored solid lines, energy deposits in the calorimeters are depicted by red bars. The Belle display is an end view perpendicular to the beam axis with the silicon detector in the center (small orange circle) and the device measuring the particle velocity (dark purple polygon). This is a $\Upsilon(4S) \rightarrow B^+B^-$ event, with $B^- \rightarrow D^0\tau^-\bar{\nu}_\tau$, $D^0 \rightarrow K^-\pi^+$ and $\tau^- \rightarrow e^-\nu_\tau\bar{\nu}_e$, and the $B^+$ decaying to five charged particles (white solid lines) and two photons. The trajectories of undetected neutrinos are marked as dashed yellow lines. The LHCb display is a side view with the proton beams indicated as a white horizontal line with the interaction point far to the left, followed by the dipole magnet (white trapezoid) and the Cherenkov detector (red lines). The area close to the interaction point is enlarged above, showing the tracks of the charged particles produced in the $pp$ interaction, the $B^0$ path (dotted orange line), and its decay $B^0 \rightarrow D^{*+}\tau^-\bar{\nu}_\tau$ with $D^{*+} \rightarrow D^0\pi^+$ and $D^0 \rightarrow K^-\pi^+$, plus the $\mu^-$ from the decay of a very short-lived $\tau^-$. 
Summer 2018 ICHEP:
World Average is still $\sim 4\sigma$ from the Standard Model

\[ R(D^*) = \frac{B(B \rightarrow D^{(*)}\tau\nu)}{B(B \rightarrow D^{(*)}l\nu)} \]
The neutral BEH boson is now firmly established by experimental results from ATLAS and CMS. Now planning for future Higgs flavor factory facilities (e.g. ILC, HL-LHC, CEPC, FCC).

PGU Question: What do these acronyms stand for?

Does the GP (Brout-Englert-Higgs particle) have a “brother” i.e. the charged Higgs?

PGU Question: How would the LHC observe a charged Higgs?

Measurements at Belle II and direct searches at hadron colliders take complementary approaches. N.B. Leptoquarks are also possible.
**Complementarity of e+ e- and LHC**

The current combined $B \rightarrow \tau \nu$ limit places a stronger constraint than direct searches from LHC exps. for the next few years.

Currently inclusive $b \rightarrow s \gamma$ rules out $m_{H^+}$ below $\sim 480$ GeV/c$^2$ range at 95% CL (independent of $\tan\beta$), M. Misiak et al. (assuming no other NP)

Strangely familiar

A new process appears to be modifying one of the standard ways a B meson decays to a K meson. It may involve a new force-carrying particle called a Z’ that avoids creating a short-lived top quark.

**Standard model decay**

- Neutral weak force boson, Z
- Charged weak force boson, W

**Possible new decay**

- Possible new particle, Z'

---

In familiar decays, a whiff of new physics

Deviations in B meson decays provide hints of new particles at the Large Hadron Collider
More QM Leptonic Flavor Billiards

\[ R_{K(*)}(q^2) = \frac{BF(B \rightarrow K^{(*)}\mu^+\mu^-)}{BF(B \rightarrow K^{(*)}e^+e^-)} \]

For experts:
\[ q^2 = M^2(|l^+l^-|) \]

Experts: Angular correlations in \( B \rightarrow K^* l l \) also show deviations from the SM, 4-5\( \sigma \)

\[ R_K \text{ is } \sim 2.6\sigma \text{ from the SM} \]

\[ R_{K^*} \sim 2.1\sigma \text{ (low bin), } 2.5\sigma \text{ (central bin)} \]
“Light DM” sensitivity in \( e^+e^- \rightarrow \gamma + \text{nothing} \)

This is hard. Requires a special new trigger that is being developed for Belle II. Should be tested during Phase III in 2019.
“Light DM” sensitivity in $\gamma$+nothing
The world is waiting for our results.

Revamped collider hunts for cracks in the fundamental theory of physics

Experiment smashes electrons into positrons to search for unseen particles and problems with overarching physics framework.

Elizabeth Gibney

https://www.nature.com/articles/d41586-018-00162-x
SuperKEKB, the first new collider in particle physics since the LHC in 2008 (electron-positron ($e^+e^-$) rather than proton-proton (pp))

Some items to note:
1) Brand-new positron damping ring (commissioned spring 2018).

2) New 3 km positron ring vacuum chamber (commissioned in 2016). Optics and vacuum scrubbing this spring.

3) New complex superconducting final focus (commissioned this spring 2018).
SuperKEKB/Belle II Luminosity Profile

Belle/KEKB recorded $\sim1000$ fb$^{-1}$. Now have to change units on y-axis to ab$^{-1}$

Beam currents only a factor of two higher than KEKB (~PEP-II)

“nano-beams” are the key; vertical beam size is 50nm at the IP

N.B. To realize this steep turn-on, requires close cooperation between Belle II and SuperKEKB [and some international collaboration on the accelerator, including the US and Europe].

Vietnam: The old 1 ab$^{-1}$ Belle dataset can be analyzed by Belle II collaborators.
**Some Belle II jargon**

**Phase 1**: Simple background commissioning detector (diodes, diamonds TPCs, crystals...). No final focus. Only *single* beam background studies possible [started in Feb 2016 and completed in June 2016.]

**Phase 2**: More elaborate inner background commissioning detector (VXD samples). **Full Belle II outer detector**. Full superconducting final focus. *No vertex detectors*. **Collisions !** [Phase 2 collisions: April 26-July 17, 2018]
Antimatter-matter annihilation in Tsukuba, Japan

Probably \( e^+e^- \rightarrow \gamma^* \rightarrow q\bar{q} \)
The scene at the experimental control room in Tsukuba Hall B3

This is scientific history in the making: SuperKEKB/Belle II joins DORIS/ARGUS, CESR/CLEO, and PEP-II/BaBar and KEKB/Belle
Welcome to the world of large crossing angle nano-beams!

As expected, the effective bunch length is reduced from ~10 mm (KEKB) to 0.5 mm (SuperKEKB)

We measure this in two track events in Belle II data.
How do we measure the vertical height of nanobeams?

Ans: Width of Luminosity scans with diamond detectors

1. For early Phase 3, we will continue with $\beta_y^* = 3\text{mm}$

2. The record is 400 nm and beam currents of only $\sim 15\text{mA}$

Heading downwards but still struggling with beam-beam blow-up (a major issue for Phase 3 too.)
Keep on squeezing the two beams with the superconducting final focus $\beta_y^*=3\text{mm}$, making sure that the two “thin pancakes” are well aligned. One then adds beam current.....

$$L_{\text{peak}} = 5.5 \times 10^{33} \text{ / cm}^2 / \text{sec}$$

PEP-II design luminosity $3 \times 10^{33}$

Phase 2, July 2018

N.B. Still a long way to go with the superconducting final focus (one order of magnitude in $\beta_y^*$)

Luminosity tuning has priority. When accelerator physicists become tired, Belle II does commissioning or takes data (usually owl shift only). Only able to record ~0.5 fb$^{-1}$ during Phase 2 pilot run.
Belle II Detector ("A Universal Spectrometer")

**BEAST (Background commissioning detector)**

**KLong and muon detector:**
- Resistive Plate Chambers (barrel outer layers)
- Scintillator + WLSF + SiPM’s (end-caps, inner 2 barrel layers)

**EM Calorimeter:**
- CsI(Tl), waveform sampling (barrel + endcap)

**Vertex Detector**
- 2 layers DEPFET + 4 layers DSSD

**Central Drift Chamber**
- He(50%):C$_2$H$_6$(50%), small cells, long lever arm, fast electronics (Core element)

**Beryllium beam pipe**
- 2cm diameter

**Particle Identification**
- TOP detector system (barrel)
- Prox. focusing Aerogel RICH (fwd)

**Electrons (7 GeV)**

**Positrons (4 GeV)**
The paths of Cherenkov photons from a 2 GeV pion and kaon interacting in a TOP quartz bar. (Japan, US, Slovenia, Italy)

Incoming track

**Barrel Particle Identification (uses Cherenkov radiation)**

**Vertexing/Inner Tracking**

- Beampipe $r=10$ mm
- DEPFET pixels (Germany, Czech Republic…)
  - Layer 1 $r=14$ mm
  - Layer 2 $r=22$ mm
- DSSD (double sided silicon detectors)
  - Layer 3 $r=38$ mm (Australia)
  - Layer 4 $r=80$ mm (India)
  - Layer 5 $r=115$ mm (Austria)
  - Layer 6 $r=140$ mm (Japan)

+ Poland, Korea
Advanced & Innovative Technologies used in Belle II

Pixelated photo-sensors play a central role
- MCP-PMTs in the iTOP
- HAPDs in the ARICH
- SiPMs in the KLM
- Collaboration with Industry

DEPFET pixel sensors

Waveform sampling with precise timing is “saving our butts”.
Front-end custom ASICs (Application Specific Integrated Circuits) for all subsystems
→ DAQ with high performance network switches, large HLT software trigger farm
→ a 21st century HEP experiment.

KLM (TARGETX ASIC)
ECL (New waveform sampling backend with good timing)
TOP (IRSX ASIC)
ARICH (KEK custom ASIC)
CDC (KEK custom ASIC)
SVD (APV2.5 readout chip adapted from CMS)

New methods of neutron detection with TPC’s for the background. Directions!
The B-anti B meson pairs at the Upsilon(4S) are produced in a coherent, *entangled* quantum mechanical state.

\[ |\Psi\rangle = |B^0(t_1,f_1)\bar{B}^0(t_2,f_2)\rangle - |B^0(t_2,f_2)\bar{B}^0(t_1,f_1)\rangle \]

Need to measure decay times to observe CP violation (particle-antiparticle asymmetry). (PGU: Why is there a minus sign above ?)

One B decays \( \rightarrow \) collapses the flavor wavefunction of the other anti-B.

(Exercise: Show one B must decay before the other can mix)

**Asymmetric Collider**

The beam energies are asymmetric (7 on 4 GeV)

*The decay distance is increased by around a factor \( \sim 7 \)*
Most of the Belle II detector subsystems are working well. Some nice examples of signals involving photons.

\[ e^+ e^- \rightarrow \mu^+ \mu^- \gamma \]

Single Photon Lines

Ready for the dark sector!

\[ e^+ e^- \rightarrow \gamma X \]
\[ e^+ e^- \rightarrow \gamma ALP \rightarrow \gamma (\gamma \gamma) \]
Most of the Belle II detector subsystems are working well. Here are some *signals* involving charged tracks.

\[ K_S \rightarrow \pi^+\pi^- \quad \int L \, dt = \sim 5 \text{ pb}^{-1} \]

Belle II 2018 Preliminary

No vertex cuts

\[ J/\psi \rightarrow \mu^+\mu^- \quad J/\psi \rightarrow e^+e^- \]

\[ \mu_x = 3.0649 \pm 0.0030 \]
\[ \text{nbkg} = 1038 \pm 53 \]
\[ \text{nsig} = 54 \pm 11 \]

\[ \mu_x = 3.0930 \pm 0.0017 \]
\[ \text{nbkg} = 476 \pm 24 \]
\[ \text{nsig} = 108 \pm 14 \]
The signal peaks are charm in continuum not B’s.

Clearly illustrates the capabilities of Belle II and the potential for charm physics and the building blocks of B mesons.
TOP Particle Identification

\[ D^{*+} \rightarrow D^0 \pi^+_s; D^0 \rightarrow K^- \pi^+ \]

N.B. The charge correlation with the slow pion determines which track is the kaon (or pion)

Kinematically identified kaon from a D^{*+} in the TOP; Cherenkov x vs t pattern (mapping of the Cherenkov radiation ring)
No kaons identified

One kaon identified in the TOP.

Both kaons identified in the TOP.

Another example of TOP particle identification with early calibration and alignment.

$$\phi \rightarrow K^- K^+ \text{ inclusive}$$

FIG. 7: $m(K^+K^-)$ distributions for runs with TOP calibration (run number up to 2531). Tracks are required to be in the TOP acceptance. Top: No PID requirement. Middle: $L L(K)^{TOP} > L L(\pi)^{TOP}$ for one of the tracks. Bottom: $L L(K)^{TOP} > L L(\pi)^{TOP}$ for both tracks.
Example of unique capabilities in the Phase 2 pilot run

**CP Eigenstate:** $D^0 \rightarrow K_S\pi^0$

Comment from LHCb colleagues: “This would be impossible at LHCb.”
More matter-antimatter annihilation in Tsukuba: Another event from Belle II’s first evening

\[ e^+ e^- \rightarrow \gamma^* \rightarrow B \bar{B} \]

A potential e+ e- → B anti-B candidate
**Event Topology** tells us we are seeing B’s.

B pairs produced at rest in the CM with no extra particles.

We are on the 4S.
We have *rediscovered* the B meson!

\[ \Delta E = \frac{E_{cm}}{2} - E_{\text{recon}} \]

\[ M_{bc} = \sqrt{\left(\frac{E_{cm}}{2}\right)^2 - p_{\text{recon}}^2} \]

**History**

1983:

\[ \int L \, dt = 250 \, \text{pb}^{-1} \]

**Volume 50, Number 12**  
**Physical Review Letters**  
21 March 1983

Observation of Exclusive Decay Modes of \( b \)-Flavored Mesons  

\( 40.7 \, \text{pb}^{-1} \)

\( B \)-meson decays to final states consisting of a \( D^0 \) or \( D^{**} \) and one or two charged pions have been observed. The charged-\( B \) mass is \( 5270.8 \pm 2.3 \pm 2.0 \) MeV and the neutral-\( B \) mass is \( 5274.2 \pm 1.9 \pm 2.0 \) MeV.
Now use the full Phase 2 pilot run dataset and apply the FEI (Full Event Interpretation) technique based on boosted decision trees (BDTs, a machine learning technique)

We now observe \( \sim 571 \) fully reconstructed B mesons (389+182) or an improvement of a factor of \( \sim O(3.6) \) in overall efficiency by using this advanced analysis method that covers many more decay channels.

Further improvement (X 2) is definitely possible (PID, low p tracking will play a major role).

B2NOTE-2018-031-1,
W. Sutcliffe, F. Bernlochner
Impact parameter resolution in the Phase 2 pilot run with the BEAST2 VXD

\[ \frac{1}{N} \langle \Delta N/10 \mu m \rangle \]

\[ \sigma_{68} = 12.1 \mu m \]
\[ \sigma_{68} = 20.5 \mu m \]

\[ \sigma_{68}^{\text{measured}} = 12.1 \pm 0.2 \text{ (stat)}^{+0.1}_{-0.3} \text{ (syst)} \mu m, \]
\[ \sigma_{\text{expected}} = 9.9 \pm 0.2 \text{ (stat)} \mu m. \]
Onwards to Phase 3 and the Physics Run

The VXD has now been installed.
Restart Belle II data taking in mid-March 2019.

SVD +x half-shell, Jan 2018 KEK

PXD layer 1 ladders, Feb 2018

SVD -x half-shell, July 2018, KEK

First PXD half-shell being tested at DESY, July 2018
“Full sized” pixel detector module 0

75 μm thick
Installation of VXD into Belle II (Nov 21, 2018)
Early Phase 3 Physics (March-June, 2019) Plan

We assume a plausible scenario with three months in which we integrate luminosity: (2 fb$^{-1}$, 4 fb$^{-1}$, 4 fb$^{-1}$) + 1 fb$^{-1}$ continuum or $\sim$11 fb$^{-1}$ for Lepton-Photon 2019 in Toronto, Canada. All detector subsystems, DAQ and trigger will be operating well. Software, calibrations and computing will be ready.

Semileptonic
- $B \rightarrow \pi \ell \nu$ and $\rho \ell \nu$ untagged (CLEO saw a signal with 2.66 fb$^{-1}$)

Time Dependent CP Violation/Charm
- D lifetimes (2 fb$^{-1}$)
- Doubly Cabibbo suppressed $D^0 \rightarrow K^+ \pi^-$, $D^0 \rightarrow K^+ \pi^- \pi^0$ (10 fb$^{-1}$)
- B lifetimes (2-10 fb$^{-1}$)
- Time dependent B-anti B mixing (10 fb$^{-1}$)

Radiative/Electroweak Penguins
- $B \rightarrow K^* \gamma (b \rightarrow s)$ (2 fb$^{-1}$) rediscover penguins
- $B \rightarrow Xs \gamma (b \rightarrow s)$ ($\sim$10 fb$^{-1}$ depending on off-resonance data taking)

Hadronic B decays (not time dependent)
- $B \rightarrow K \pi (b \rightarrow u)$ (10 fb$^{-1}$)
- $B \rightarrow \Phi K (b \rightarrow s)$ (10 fb$^{-1}$)
- $B \rightarrow J/\psi K$ (with more significance 2-10 fb$^{-1}$)

++ Dark Sector Physics Publications

P. Urquijo et al.
• Belle II will explore New Physics on the Luminosity or Intensity Frontier. This is different and complementary to the LHC high $p_T$ experiments, which operate on the Energy Frontier. *Time for a paradigm shift?*

• There is competition and complementarity with LHCb (@CERN)

• We are ready to start a long physics run in the Super Factory mode (Phase 3) in March 2019. This requires *high-efficiency* data-taking by Belle II and *extensive running* by Super KEK-B, soon to be the world’s highest luminosity accelerator.

• The world is waiting for our results. (First ones expected at LP2019)

• There are excellent opportunities for collaborators from Vietnam
First PXD was flown to Japan (business class). This PXD half-shell being installed at KEK, last week.
Belle II will explore New Physics on the Luminosity or Intensity Frontier. This is different and complementary to the LHC high $p_T$ experiments, which operate on the Energy Frontier. *Time for a paradigm shift?*

- There is competition and complementarity with LHCb (@CERN)

- We are ready to start a long physics run in the Super Factory mode (Phase 3) in March 2019. This requires *high-efficiency* data-taking by Belle II and *extensive running* by Super KEK-B, soon to be the world’s highest luminosity accelerator.

- The world is waiting for our results. (First ones expected at LP2019)
Backup Slides
“Now then, shall we start the experiment?”

“さぁ、実験を始めようか。Sa, jikken o hajimeyou ka.”

Sento Kiryu (桐生 戦兎 Kiryū Sento), theoretical scientist and character in the “Kamen Rider Build” TV show

東都先端物質学研究所 Toutu Sendan Busshitsuakukui Kenkyūsho (an imaginary research institute in the TV show)

https://en.wikipedia.org/wiki/Kamen_Rider

Thanks to Hiro Nakayama
Physics Competition and Complementarity

<table>
<thead>
<tr>
<th>Year</th>
<th>Run III</th>
<th>Run IV</th>
<th>Run V</th>
</tr>
</thead>
<tbody>
<tr>
<td>2019</td>
<td>LS2</td>
<td>LS3</td>
<td>LS4</td>
</tr>
<tr>
<td>2020</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2021</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2022</td>
<td>LHCb 40 MHz UPGRADE I</td>
<td>LHCb Consolidate: Upgr I b</td>
<td>LHCb UPGRADE II</td>
</tr>
<tr>
<td></td>
<td>$L = 2 \times 10^{33}$</td>
<td>$L = 2 \times 10^{33}$</td>
<td>$L = 1 - 2 \times 10^{34}$</td>
</tr>
<tr>
<td>2023</td>
<td>ATLAS Phase I Upgr</td>
<td>ATLAS Phase II UPGRADE</td>
<td>HL-LHC</td>
</tr>
<tr>
<td></td>
<td>$L = 2 \times 10^{34}$</td>
<td></td>
<td>$L = 5 \times 10^{34}$</td>
</tr>
<tr>
<td>2024</td>
<td>CMS Phase I Upgr</td>
<td>CMS Phase II UPGRADE</td>
<td>ATLAS</td>
</tr>
<tr>
<td></td>
<td>$300 \text{ fb}^{-1}$</td>
<td></td>
<td>$3000 \text{ fb}^{-1}$</td>
</tr>
<tr>
<td>2025</td>
<td>Belle II</td>
<td>$L = 8 \times 10^{35}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$5 \text{ ab}^{-1}$</td>
<td>$50 \text{ ab}^{-1}$</td>
<td></td>
</tr>
<tr>
<td>2026</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2027</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2028</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2029</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2030</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2031</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2032</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2033</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2034+</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Belle II
- $L = 5 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1}$ achieved!
- Physics with VXD in 2019

Outside perspective: Belle II inserted into the CERN global schedule. [slide from a plenary talk by Niels Tuning, ICHEP 2018 in Seoul, Korea]
Examples of Physics Competition and Complementarity

Use publicly available LHCb projections.
Results from Global Fits to Data (CKMFitte Group)

Great progress on $\varphi_3$ or $\gamma$ (first from B factories and now in the last four years from LHCb). These measure the phase of $V_{ub}$.

Similar results from UTFIT

Great progress on $\phi_3$ or $\gamma$ (first from B factories and now in the last four years from LHCb). These measure the phase of $V_{ub}$.

But a 10-20% NP amplitude in $B_d$ mixing is perfectly compatible with all current data.

Extrapolation to 50 ab$^{-1}$

NP/SM amplitude ratio

Looks good (except for an issue with $|V_{ub}|$).
How can we establish NP in $B \rightarrow K^* l^- l^+$?

Ans: Observe and measure the rate for $B \rightarrow s \nu \overline{\nu}$ and thus isolate the Z penguin ($C_9$) at Belle II.

B2SS exercise: Draw the Feynman diagram for this process. Draw this for two cases: kaon and $K^*$ in the final state.

<table>
<thead>
<tr>
<th>Mode</th>
<th>$B [10^{-6}]$</th>
<th>Efficiency $N_{\text{Backg.}}$</th>
<th>$N_{\text{Sig-exp.}}$</th>
<th>Statistical Error</th>
<th>Total Error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$B \rightarrow K^+ \nu \overline{\nu}$</td>
<td>$5.68 \times 10^{-4}$</td>
<td>21</td>
<td>3.5</td>
<td>23%</td>
</tr>
<tr>
<td></td>
<td>$B^0 \rightarrow K^0_S \nu \overline{\nu}$</td>
<td>$0.84 \times 10^{-4}$</td>
<td>4</td>
<td>0.24</td>
<td>110%</td>
</tr>
<tr>
<td></td>
<td>$B^+ \rightarrow K^{*+} \nu \overline{\nu}$</td>
<td>$1.47 \times 10^{-4}$</td>
<td>7</td>
<td>2.2</td>
<td>21%</td>
</tr>
<tr>
<td></td>
<td>$B^0 \rightarrow K^{*0} \nu \overline{\nu}$</td>
<td>$1.44 \times 10^{-4}$</td>
<td>5</td>
<td>2.0</td>
<td>20%</td>
</tr>
<tr>
<td></td>
<td>$B \rightarrow K^* \nu \overline{\nu}$ combined</td>
<td></td>
<td></td>
<td></td>
<td>15%</td>
</tr>
</tbody>
</table>
What’s Ahead?

“Missing Energy Decay” in a Belle II GEANT4 MC simulation

Signal: $B \to K \nu \nu$

tag mode: $B \to D\pi; D \to K\pi$

View in r-z

Zoomed view of the vertex region in r-phi
Belle II can do both inclusive and exclusive. Equally strong capabilities for electrons and muons.
What’s ahead: τ Lepton Flavor Violation

**Belle II** will push many limits below $10^{-9}$; LHCb, CMS and ATLAS have very limited capabilities.

LHC high pt: The modes $\tau \rightarrow \mu \gamma$ and $\tau \rightarrow \mu h^+ h^-$ provide important constraints on $H \rightarrow \mu \tau$

*Note vertical log-scale (50 ab$^{-1}$ assumed for Belle II; 3 fb$^{-1}$ result for LHCb*
Not so obvious: When we change accelerator optics, we remain on the Upsilon(4S) resonance.

Event Topology (fits to $R_2$) tells us we are seeing $B$’s

Not so obvious: When we change accelerator optics, we remain on the Upsilon(4S) resonance.

PGU exercise: Why is the 4S broad while the other three are narrow?

Technical note: $R_2 = H_2/H_0$

$$H_l = \sum_{i,j} \frac{|P_i||P_j|}{E_{\text{vis}}^2} P_l(\cos \theta_{ij})$$
FIG. 2: SuperKEKB and LHCb integrated luminosity projections in fb$^{-1}$ and ab$^{-1}$ respectively.
More examples of Physics Competition and Complementarity

FIG. 6: Projected precision for various measurements of semileptonic $B$ decays.

Use publicly available LHCb projections.
“We need more data !!”

Signal of 
~312 events

Belle I data. S. Wehle et al. (Belle collab)  
arXiv: 1612.05014, published in PRL
Systematics from charmonium resonances in ArXiv:1603.04355

$c\bar{c}$ bound states added: $J/\psi$, $\psi(2S)$, $\psi(3770)$, $\psi(4040)$, $\psi(4160)$, $\psi(4415)$.

$\text{Observable} \quad \text{=} \quad \text{Form-factors} \quad + \quad \text{Kruger & Sehgal parametrization}$

Asymmetries decrease in high $q^2$ region
makes observable $\omega_1$ unphysical

Random variation of each strong phases

Conclusions about the presence of NP unchanged
Results from Global Fits to Data (CKMFitter Group)

**PGU Question:**
What are the x and y axes?

**PGU Question:** What is $\varepsilon_K$? Why is the band so broad?

**PGU Question:** What is $\Delta m_d, \Delta m_s$? What is their ratio in terms of CKM parameters?

**PGU Question:** Why is the region for $V_{ub}$ a circular disk?

**PGU Question:** Where are the measurements of $B \rightarrow J/\psi \ K$? Why are there two associated regions?
What do the acronyms LER and HER stand for?

Why aren’t the electron and positron beam energies equal?

Why is a larger current stored in the positron beam?

BTW, the LHC uses p p collisions rather than proton-anti proton collisions as at the Fermilab Tevatron and earlier hadron colliders. Why?
PGU: What is the GIM (Glashow Illiopoulos-Maiani) Mechanism?  
Or GIM suppression? What is an FCNC (Flavor Changing Neutral Current)?

Hint:
“Tsukuba, we have a Problem”
(apologies to Tom Hanks, Apollo 13)

The CP Violation predicted by Kobayashi and Maskawa is too small by \( \sim 10 \) orders of magnitude in the Standard Model.

What does this mean?

“Tsukuba: we need some New Physics”
FIG. 5: Projected precision for various measurements of direct CP violation.
## Machine Parameters

<table>
<thead>
<tr>
<th>2017/September/1</th>
<th>LER</th>
<th>HER</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>E</strong></td>
<td>4.000</td>
<td>7.007</td>
<td>GeV</td>
</tr>
<tr>
<td><strong>I</strong></td>
<td>3.6</td>
<td>2.6</td>
<td>A</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>2,500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bunch Current</td>
<td>1.44</td>
<td>1.04</td>
<td>mA</td>
</tr>
<tr>
<td>Circumference</td>
<td>3,016.315</td>
<td></td>
<td>m</td>
</tr>
<tr>
<td>$\varepsilon_x/\varepsilon_y$</td>
<td>3.2(1.9)/8.64(2.8)</td>
<td>4.6(4.4)/12.9(1.5)</td>
<td>nm/μm (zero current)</td>
</tr>
<tr>
<td>Coupling</td>
<td>0.27</td>
<td>0.28</td>
<td></td>
</tr>
<tr>
<td>$\beta_x^<em>/\beta_y^</em>$</td>
<td>32/0.27</td>
<td>25/0.30</td>
<td>mm</td>
</tr>
<tr>
<td>Crossing angle</td>
<td>83</td>
<td></td>
<td>mrad</td>
</tr>
<tr>
<td>$\alpha_p$</td>
<td>3.20x10^{-4}</td>
<td>4.55x10^{-4}</td>
<td></td>
</tr>
<tr>
<td>$\sigma_p$</td>
<td>7.92(7.53)x10^{-4}</td>
<td>6.37(6.30)x10^{-4}</td>
<td>(zero current)</td>
</tr>
<tr>
<td>$\nu_c$</td>
<td>9.4</td>
<td>15.0</td>
<td>MV</td>
</tr>
<tr>
<td>$\sigma_z$</td>
<td>6(4.7)</td>
<td>5(4.9)</td>
<td>mm</td>
</tr>
<tr>
<td>$\nu_s$</td>
<td>-0.0245</td>
<td>-0.0280</td>
<td></td>
</tr>
<tr>
<td>$\nu_x/\nu_y$</td>
<td>44.53/46.57</td>
<td>45.53/43.57</td>
<td></td>
</tr>
<tr>
<td>$U_0$</td>
<td>1.76</td>
<td>2.43</td>
<td>MeV</td>
</tr>
<tr>
<td>$T_{x,y}/T_z$</td>
<td>45.7/22.8</td>
<td>58.0/29.0</td>
<td>msec</td>
</tr>
<tr>
<td>$\xi_x/\xi_y$</td>
<td>0.0028/0.0881</td>
<td>0.0012/0.0807</td>
<td></td>
</tr>
<tr>
<td>Luminosity</td>
<td>8x10^{35}</td>
<td></td>
<td>cm^{-2}s^{-1}</td>
</tr>
</tbody>
</table>
Belle II has a modern DAQ and readout system

Item to note: Note ROI (Region of Interest) for PXD data volume.

Item to note: Front-end readout electronics and Gb fiber optic link (Belle2link) to the back-end.

More on G. Varner’s B2SS talk.

Item to note: Note ROI (Region of Interest) for PXD data volume.
Performance of CDC dE/dx particle identification with early calibrations in the hadronic event sample.

Extra cuts:
- |d0| < 1
- |dz| < 3
- # layers hit > 20

Jake Bennett, Roy Briere et al.
Endcap particle identification via Aerogel RICH (ARICH)
A Challenge to Lepton Universality in B Meson Decays

Gregory Ciezarek¹, Manuel Franco Sevilla², Brian Hamilton³, Robert Kowalewski⁴, Thomas Kuhr⁵, Vera Lüth⁶, Yutaro Sato⁷

One of the key assumptions of the Standard Model of fundamental particles is that the interactions of the charged leptons, namely electrons, muons, and taus, differ only because of their different masses. While precision tests comparing processes involving electrons and muons have not revealed any significant violation of this assumption, recent studies involving the higher-mass tau lepton have resulted in observations that challenge lepton universality at the level of four standard deviations. A confirmation of these results would point to new particles or interactions, and could have profound implications for our understanding of particle physics.
Outer Detector Highlights

Belle II Jargon/Acronym Check

KLM = [KLong- Muon] detector (Endcap and Barrel) [RPC = Resistive Plate Chamber];

  EKLM = Endcap KLM; BKLM= Barrel KLM

CsI(Tl) crystals (measures energies of photons et al.)
  (ECL = Electromagnetic Calorimeter)

Barrel PID  Distinguishes kaons from pions/Cherenkov radiation
  (iTOP = imaging Time Of Propagation)

Endcap PID  Distinguishes kaons from pions/Cherenkov radiation
  (ARICH = Aerogel Ring Imaging Cherenkov)

CDC = Central Drift Chamber (provides momenta).  Via tracking in a 1.5 T B field.
History/Background:
The Flagship Measurement for the “old” B Factories

At the Upsilon(4S), we produce pairs of QM entangled B anti-B pairs in a C=-1 state.

Exercises:
1) Why do time-integrated asymmetries vanish at the 4S?
2) Verify the $\beta\gamma$ factors

Boost factors and asymmetric energies:

- PEPII/BaBar $\beta\gamma=0.56$;
  $(9 \times 3.1 \text{ GeV})$

- KEKB/Belle $\beta\gamma=0.43$;
  $(8.0 \times 3.5 \text{ GeV})$

SuperKEKB/Belle II $\beta\gamma=0.284$
$(7.0 \times 4.0 \text{ GeV})$;
smaller boost but improved LER lifetime and backgrounds; better acceptance for “missing energy” decays