# The Belle II Experiment

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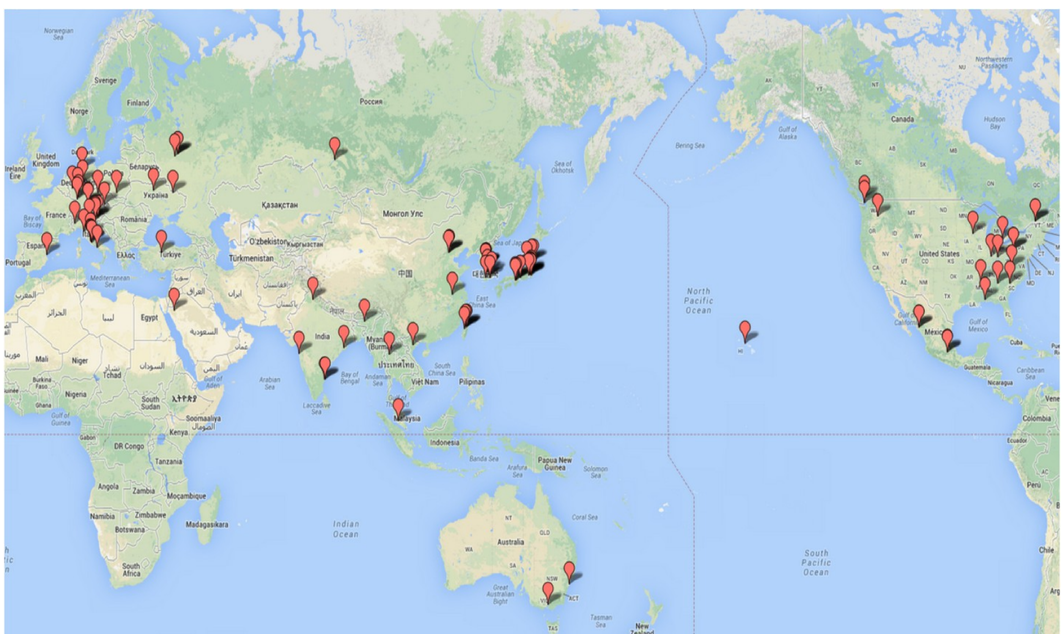
INSTITUTE OF PARTICLE PHYSICS

McGill

# Belle II

The Belle II experiment is a upgrade of Belle at the KEK laboratory

- Target data set of ~30x the combined integrated luminosity of BABAR + Belle
- 750 collaborators, including over 260 graduate students; ~25% Japanese



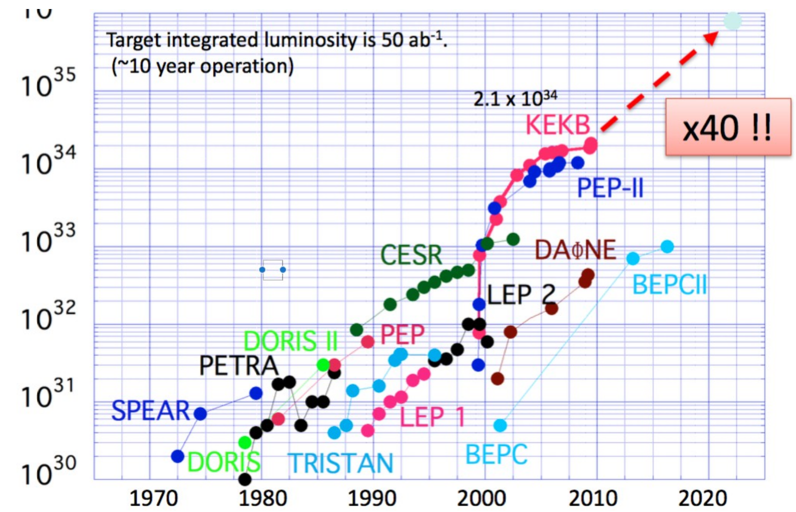
**SuperKEKB** accelerator substantially upgraded to provide beams for Belle II at up to $8 \times 10^{35}$ $cm^{-2}s^{-1}$ luminosity

**First physics collisions to begin in 2018**

# What's so "Super"?

How to get to $8 \times 10^{35}$ $cm^{-2}s^{-1}$ :

- Low-emittance "nanobeam" scheme exploiting ILC and light-source technologies
- Bunch crossings every 6ns (~1.2m spacing)
- Very high charge density bunches (Touschek effect)
- Very high beam currents
- Tiny beamspot at IP



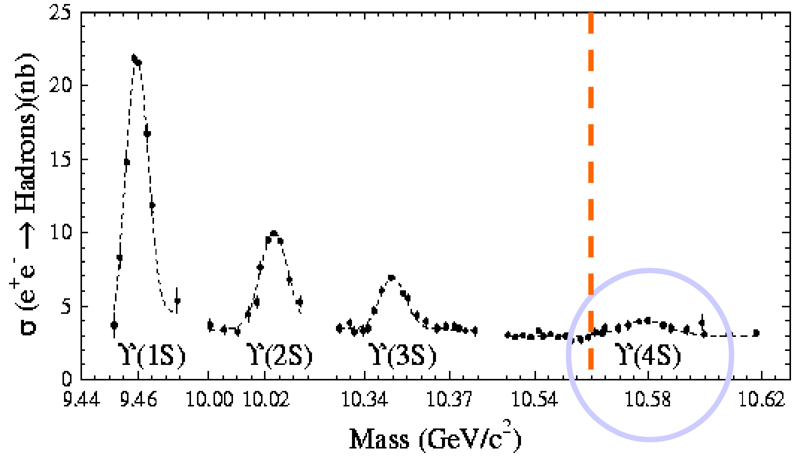

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*}\frac{R_L}{R_{\xi_y}}$$

| | KEKB Achieved LER | KEKB Achieved HER | SuperKEKB LER | SuperKEKB HER |
|---|---|---|---|---|
| RF frequency f [ MHz] | 508.9 | | | |
| # of Bunches N | 1584 | | **2500** | |
| Horizontal emittance εx [nm] | 18 | 24 | 3.2 | 4.6 |
| Beta at IP $\beta x^*/\beta y^*$ [mm] | 1200/5.9 | | 32/**0.27** | 25/**0.30** |
| beam-beam param. ξy | 0.129 | 0.090 | 0.088 | 0.081 |
| Bunch Length Sz [mm] | 6.0 | 6.0 | 6.0 | 5.0 |
| Horizontal Beam Size $sx^*$ [μm] | 150 | 150 | 10 | 11 |
| Vertical Beam Size $sy^*$ [ nm] | 0.94 | | 48 | 62 |
| Half crossing angle φ [ mrad] | 11 | | 41.5 | |
| Beam energy Eb [ GeV] | 3.5 | 8 | 4 | 7.007 |
| Beam currents Ib [A] | 1.64 | 1.19 | **3.6** | **2.6** |
| Lifetime t [min] | 133 | 200 | **6** | **6** |
| Luminosity L [ $cm^{-2}s^{-1}$] | **$2.1 \times 10^{34}$** | | **$8 \times 10^{35}$** | |

# What's so "Super"?

"Inclusive" hadronic and low multiplicity datasets are key features:

- Target data sample has σ of between 5 – 10 nb




$8 \times 10^{35}$ $cm^{-2}s^{-1}$ luminosity yields O(5kHz) of "interesting" physics events

- ~800Hz BB events
- ~30kHz Bhabhas within detector acceptance, plus all the usual beam-related junk
  - Level 1 trigger rejection essential!
  - Probability of multiple collisions per bunch crossing (aka "pileup"): ~0.02%

| Process | σ (nb) |
|---|---|
| bb | 1.1 |
| cc | 1.3 |
| Light quark qq | ~2.1 |
| $\tau^+\tau^-$ | 0.9 |
| $e^+e^-$ | ~40 |

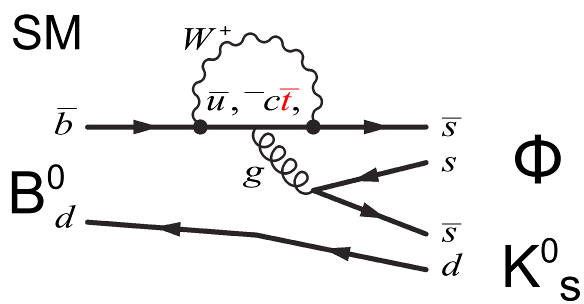
50 $ab^{-1}$ integrated luminosity implies ~55 billion BB pairs in target data sample

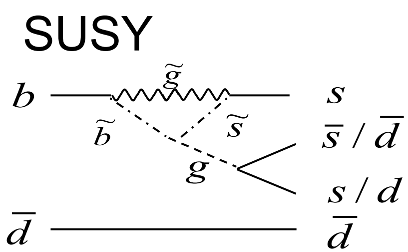
- Analysis sensitivity in B, τ and charm to $O(10^{-9})$ branching fractions

# Belle II physics program

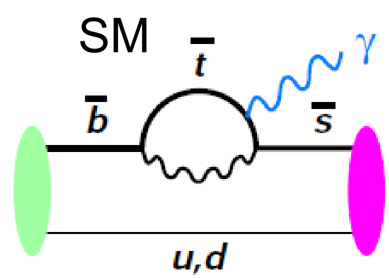
"Heavy flavour" (b, c and τ decays) provides an ideal testing ground for precision probes of physics beyond the Standard Model:

### Hadronic decays:

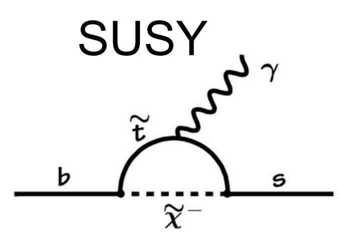


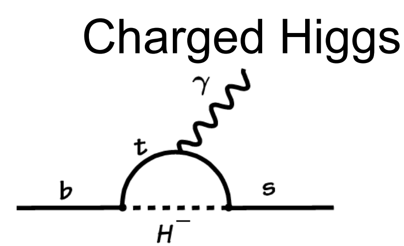




### Electroweak FCNCs:




Precision measurements of one-loop processes can probe new physics mass scales which far exceed direct searches




Many modes and observables with sensitivity to new physics:

- branching fractions, CP asymmetries, kinematic distributions, angular observables and asymmetries

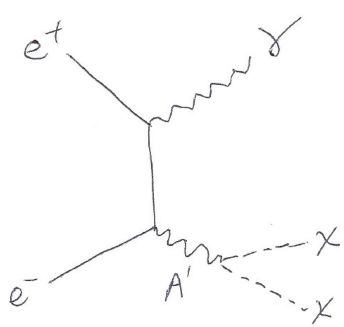
# Exotic searches

Many potential analysis topics beyond the usual "flavour" of B factories

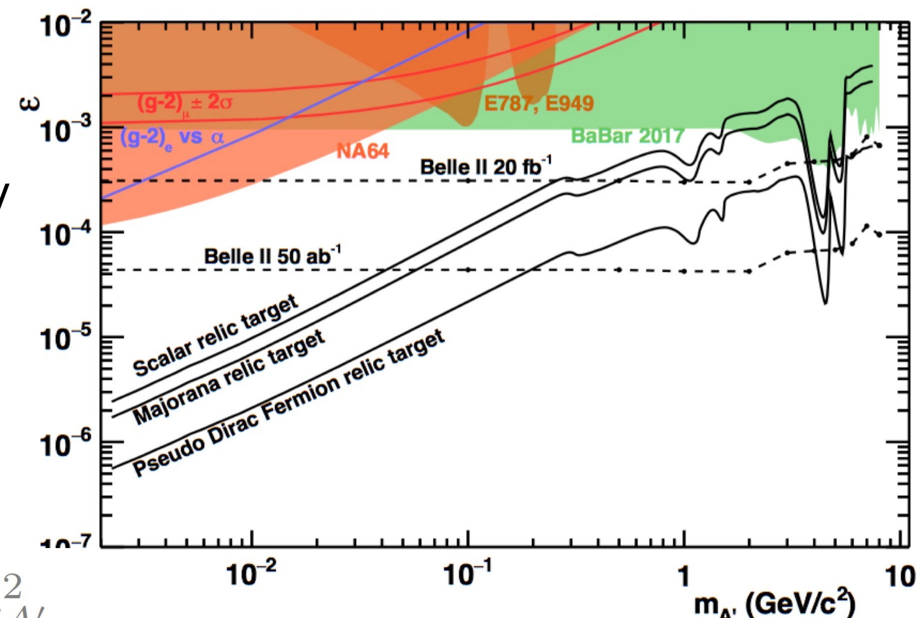
- e.g. dark matter candidates, "dark sector", light Higgs, ALP searches etc.
- typically, these are narrow resonance ("bump hunt") searches in low multiplicity data samples

Invisible decays of a dark photon produced in $e^+e^-$ collisions:

- Signal is a narrow peak in the spectrum of single-photon events
- Requires excellent calorimeter hermeticity and ability to trigger on single photons (down to threshold of E>1GeV)




$$E^*_\gamma = \frac{\sqrt{s}}{2} - \frac{m^2_{A'}}{2\sqrt{s}}$$

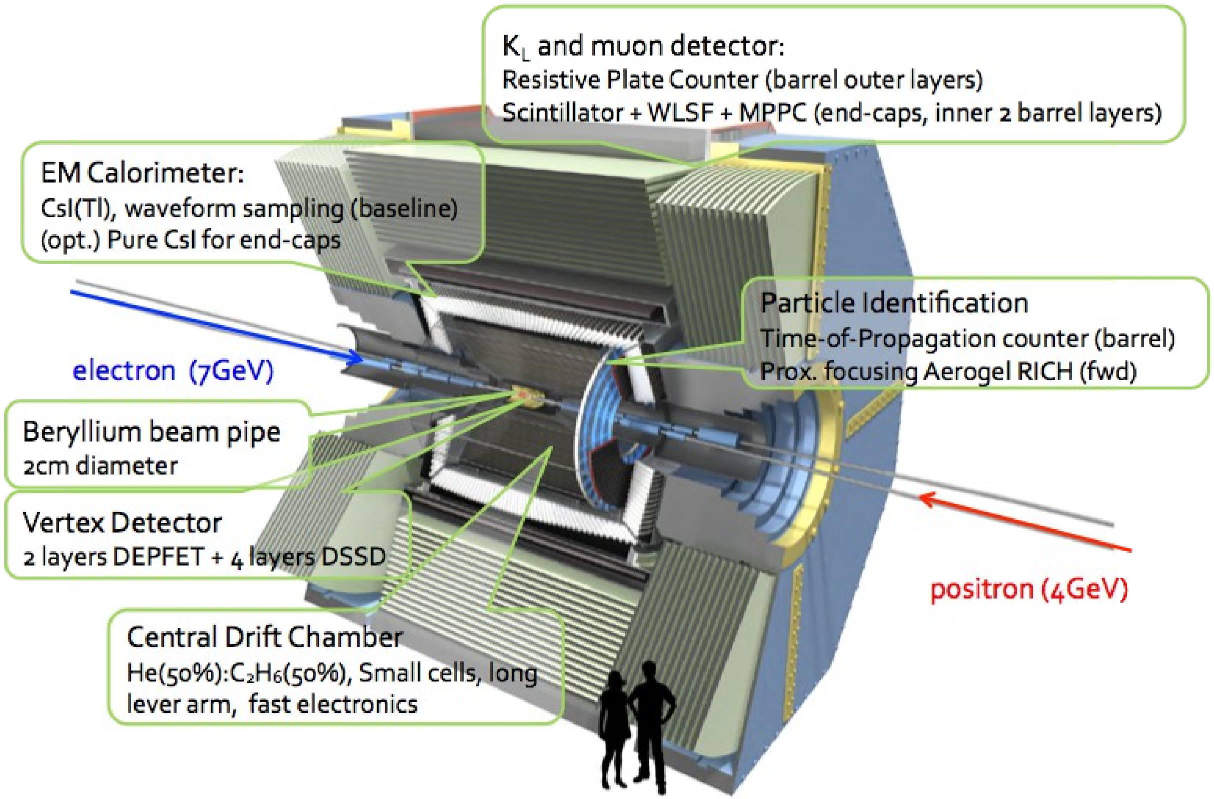



C. Hearty, UBC

# Belle II

Very substantial "upgrades" to the original Belle detector:

- Replacement of beam pipe and redesign of entire inner detector (including vertex detectors and drift chamber)
- New quartz-bar Time-of-Propagation PID in barrel region
- Retain existing CsI(Tl) calorimeter crystals, but front-end electronics, feature extraction and reconstruction software entirely new
- Entirely new software framework and distributed computing environment




**For all intents and purposes, an entirely new experiment**

# Canadian participation

Canadian group joined Belle II experiment in 2013, mostly bridging effort from previous BABAR group

- 10 grant-eligibles at 4 universities, 2 postdocs, 9 grad students:

**UBC:**
C. Hearty, J. McKenna, T. Mattison, **T. Ferber**, **A. Hershon**

**UVic:**
M. Roney, R. Kowalewski, R. Sobie, **A. Sibidanov**,
**A. Beaulieu, S. de Jong, S. Longo , C. Miller**

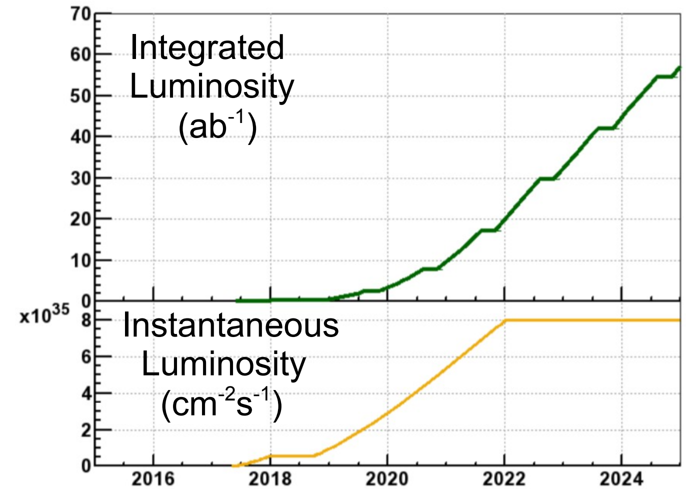
**McGill:**
S. Robertson, A. Warburton, **R. Seddon, A. Fodor,**
**H. Pikhartova, W. Ahmed**

**UdeM:**
J.P. Martin, P. Taras, **N. Starinski**

# Schedule

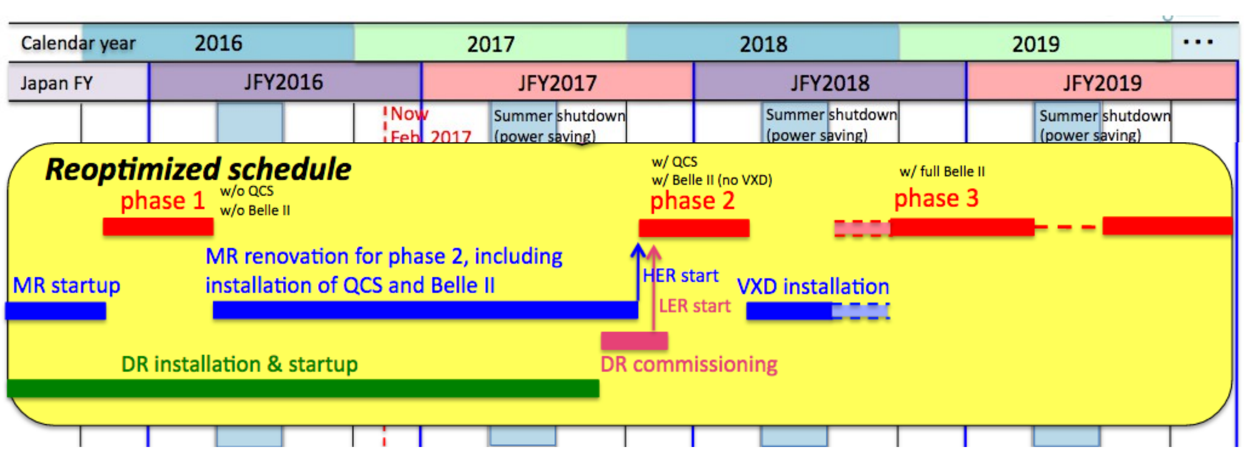
## Commissioning in three phases:

- Phase 1: commissioning began in early 2016, with first turns achieved in March 2016
  - Dedicated “BEAST2” commissioning detector
- Phase 2: commissioning with colliding beams
  - Belle II without silicon tracking detectors; potential for physics data taking




- Phase 3: physics running with full detector beginning in 2018

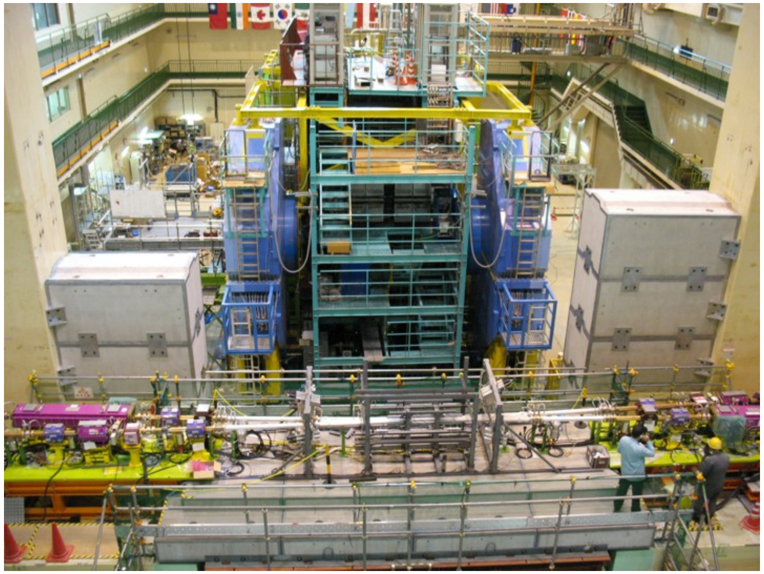
Luminosity to ~8x10$^{35}$ by 2022 with ultimate target of 50 ab$^{-1}$ recorded

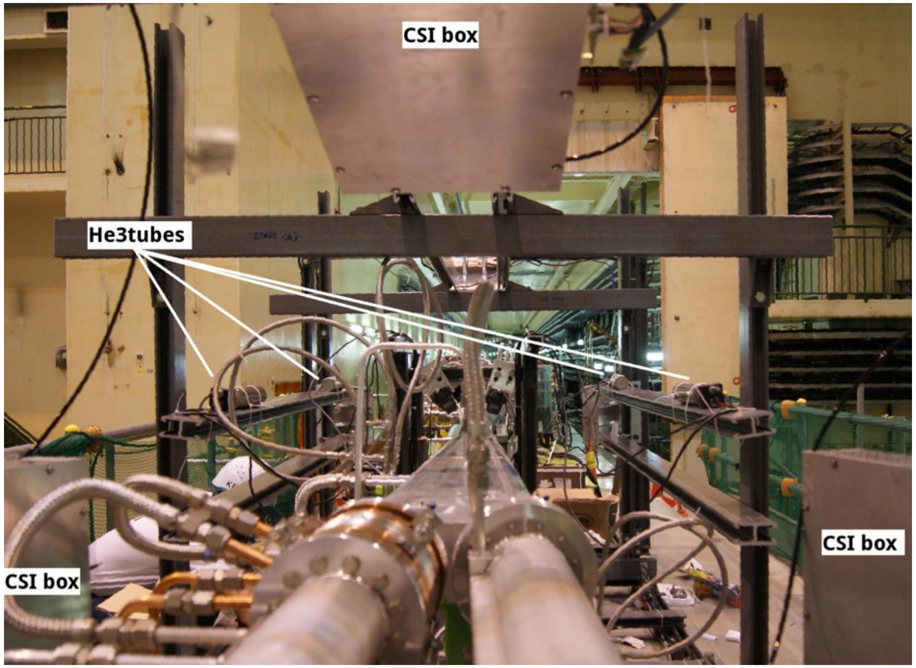


# Phase 1 commissioning

Initial accelerator commissioning performed during 2016 without Belle II detector (and final focus magnets) present

- "BEAST2" commissioning detector positioned at nominal IP to evaluate beam backgrounds representative of various Belle II subsystems
  - PIN diodes, diamond detectors, Micro-TPCs, $^3$He tubes, BGO, scintillating crystals (CsI, CsI(TI) and LYSO) and "CLAWS" silicon detectors






- Direct participation in installation, commissioning, data taking and analysis by several Canadian students

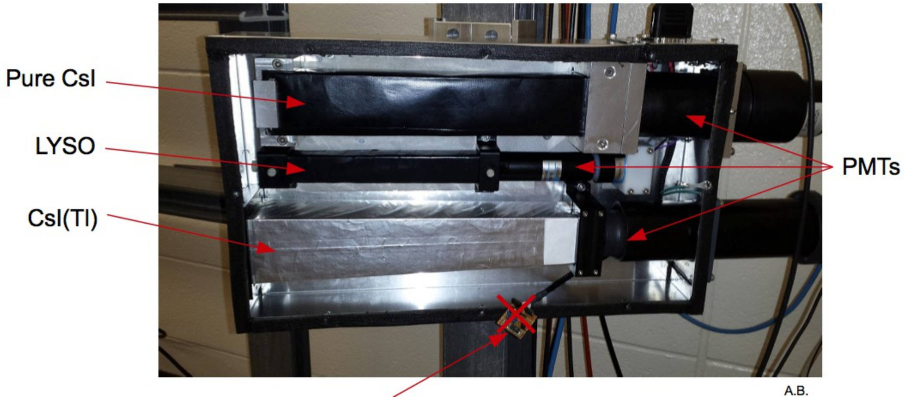
# Canadian phase 1 activities

Canadian groups were responsible for $^{3}$He detectors, and for aspects of scintillating crystal detectors in BEAST phase 1

- $^{3}$**He detectors** to characterize (difficult to simulate) thermal neutrons, which cause aging of ECL photodiodes and other detector components
- **Scintillating crystals** used to measure background photon energy spectrum and injection backgrounds

**NIMA paper describing phase 1 results in preparation**

S. de Jong

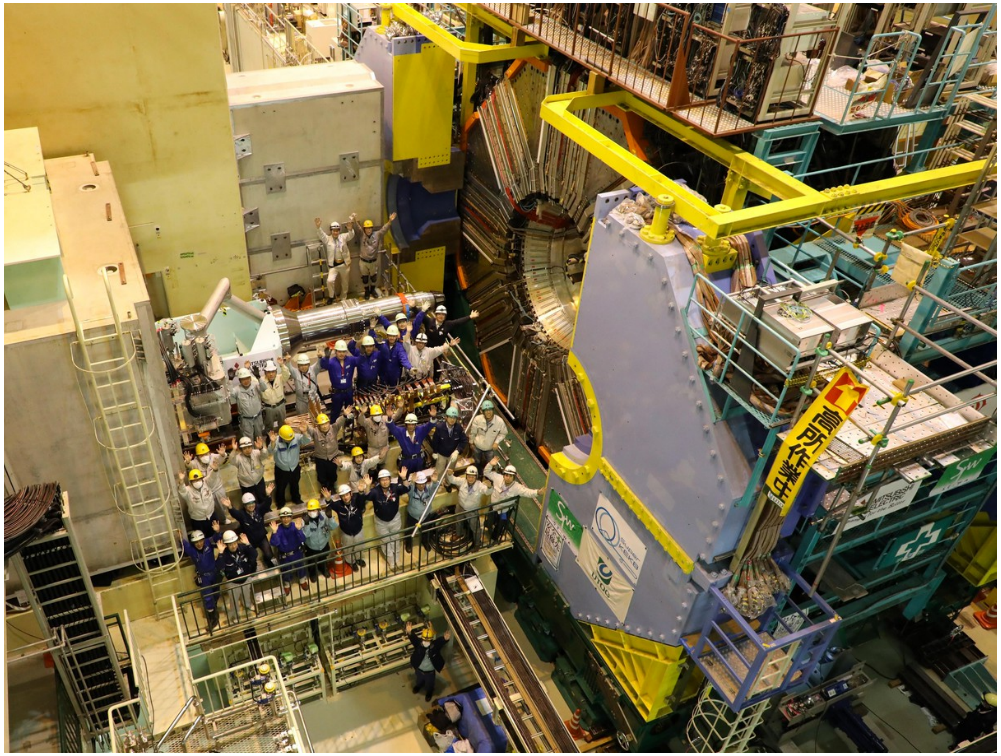


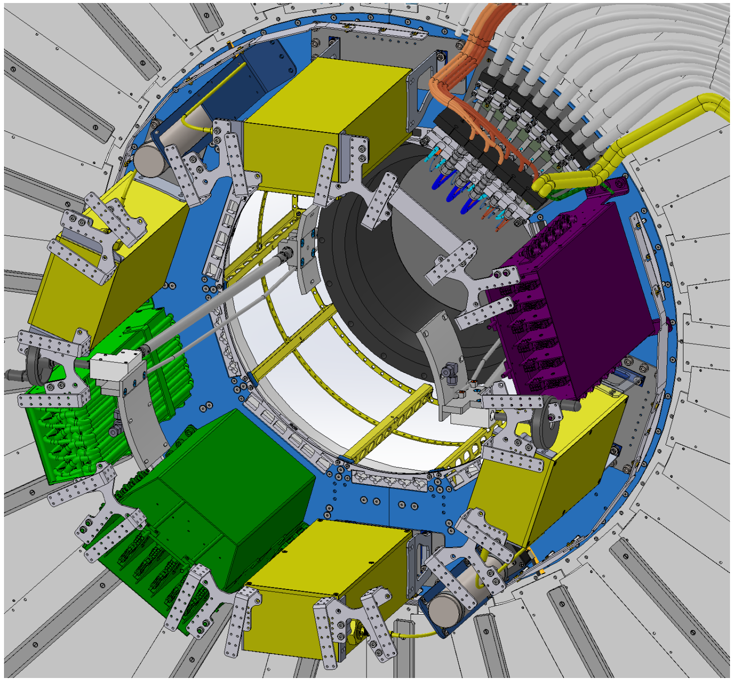

See talks by Caleb Miller and Alex Beaulieu Monday session M2-3

# Phase 2 commissioning

Belle II detector, without silicon vertex detector, rolled into SuperKEKB beamline April 11, 2017

- 2-beam commissioning with collisions beginning in early 2018



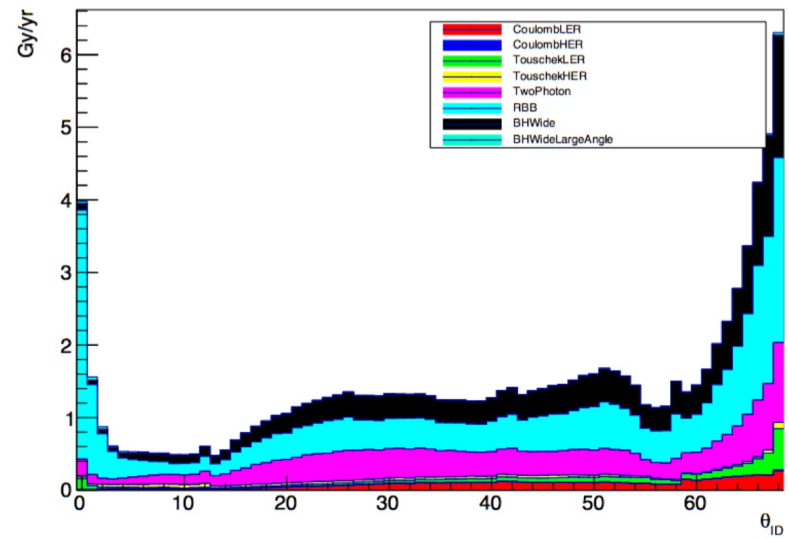


Additional BEAST instrumentation arrayed in central detector region, including Canadian He3 tubes

# ECL Beam Backgrounds

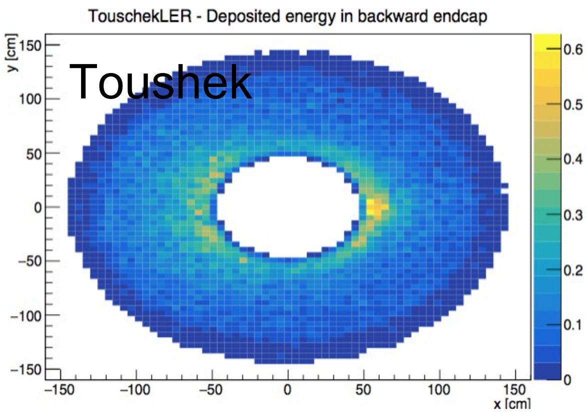
High background rates and radiation dose can negatively impact ECL performance through damage and high occupancies

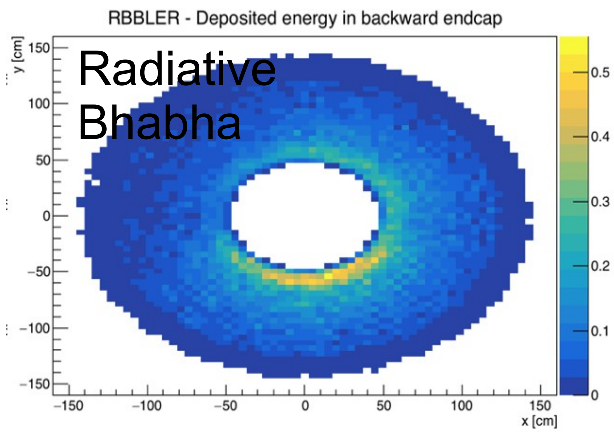
- Large contributions from Toushek, and beam gas contributions in early running, and low-angle radiative Bhabha events as luminosity increases




GEANT4 simulation studies to assess impact and to understand sources

- Different sources impact different ECL regions:



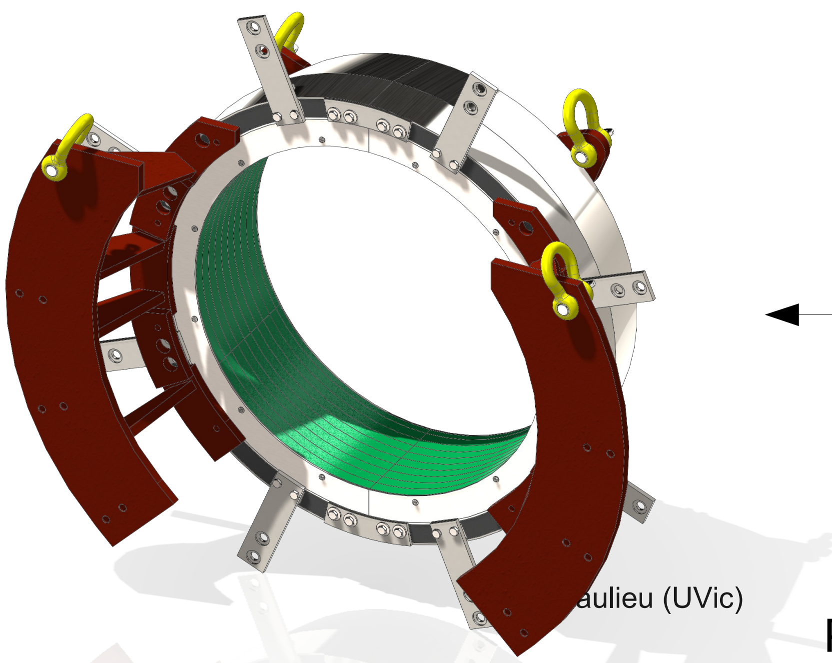



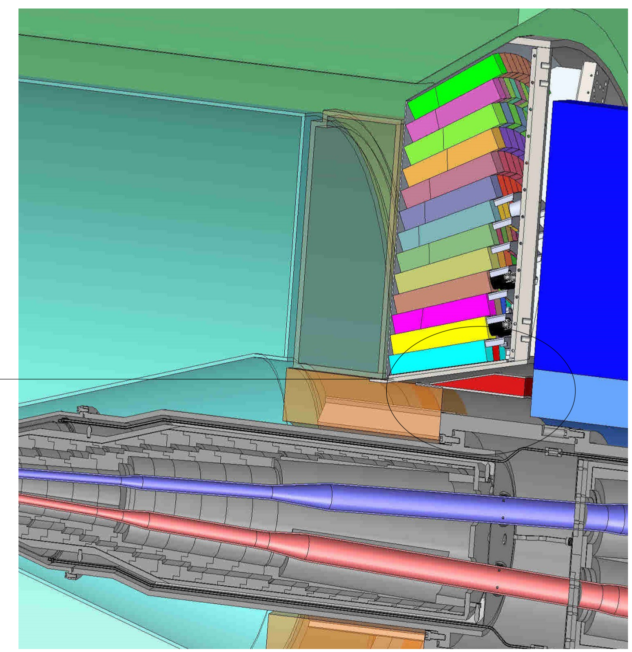

Andrea Fodor (McGill)
Sam DeJong (UVic)

# Background Shielding

Simulation studies suggest that high ECL background rates can be reduced by lead/HDPE shield between endcaps and beam line

- Optimization (materials + shape) and mechanical design by A. Beaulieu (UVic)
- Shields will be installed along with ECL endcaps for phase 2 commissioning and remain for life of experiment



Predicted performance [vs Belle shields]:

- Radiation dose reduced by **20%**
- Neutron f lux reduced by **59%**

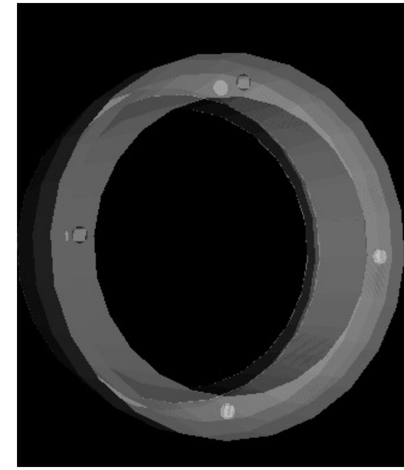
# Background Shielding

Recently delivered to KEK

- Will be installed over the next several months, in time for Phase 2 commissioning

Recesses drilled in HDPE to house Canadian-built beam background monitors

# Beam background monitors

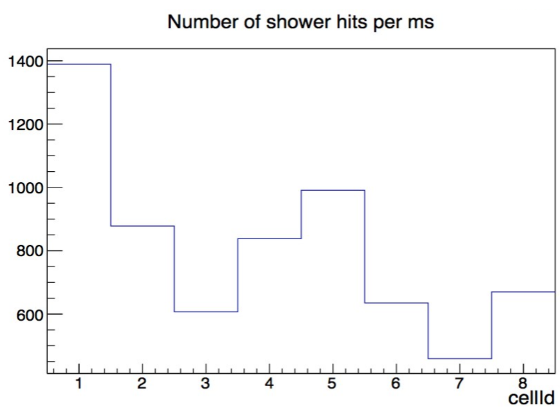


Need for live monitoring of fast beam background resulting from "trickle injection"

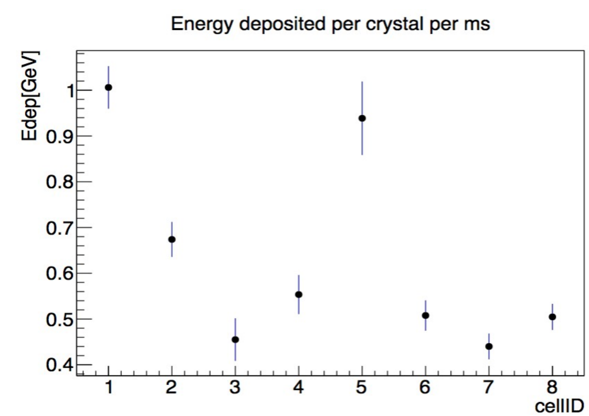
- Lost beam particles produce high detector rates as individual bunches are topped up during live data-taking
  - Backgrounds synchronous with accelerator revolution frequency and decay over many 100's of turns

2016 RTI request (PI A. Warburton, McGill) to fund hardware for 8 fast crystal scintillator beam background monitors

- Provide fast feedback directly to SuperKEKB control room for accelerator tuning
- Continuous monitoring of "steady state" background rates in vicinity of ECL endcaps




Simulation studies by A. Fodor (McGill)



# Beam background monitors

LYSO scintillating crystals with attached PMT imbedded in HDPE of shields

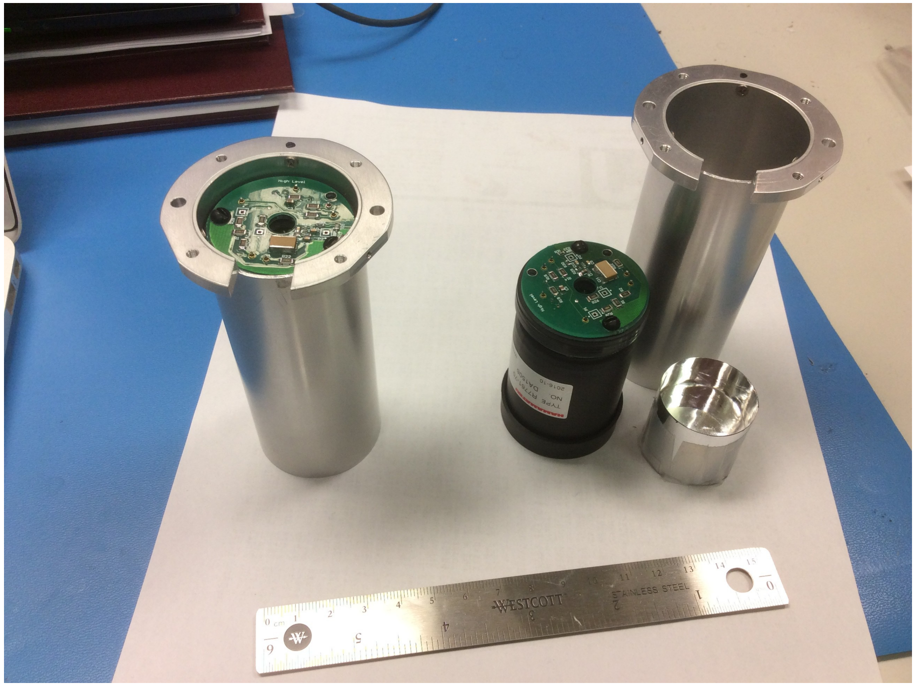
- No other active elements in interaction region area due to high radiation flux; readout via differential amp off-detector
- ADC sampling at ~258MHz synchronous with beam revolution frequency to give sensitivity to individual* beam bunches

Design and construction by UdeM group:

Jean-Pierre Martin,
Nikolai Starinski,
Yanik Landry-Ducharne,
Wen Chao Chen,
Paul Taras

Provides bunch-dependent signals to SuperKEKB control room via EPICS

- 4 monitors to be installed for Phase 2 commissioning; remainder to built/installed for Phase 3



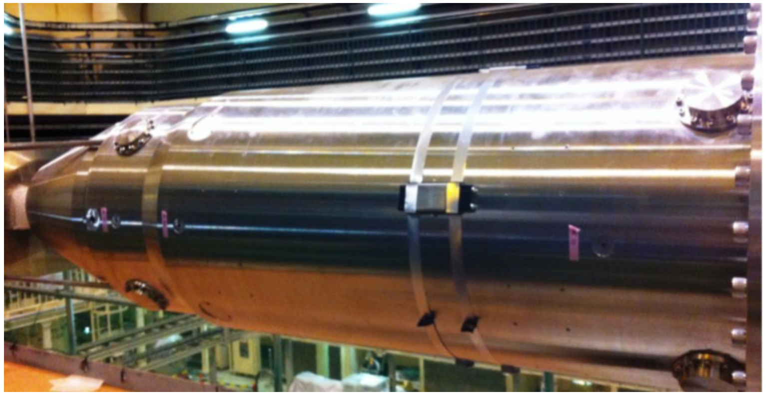

* LYSO time resolution larger than ~4ns bunch separation, but injected bunches separated by at least 100ns

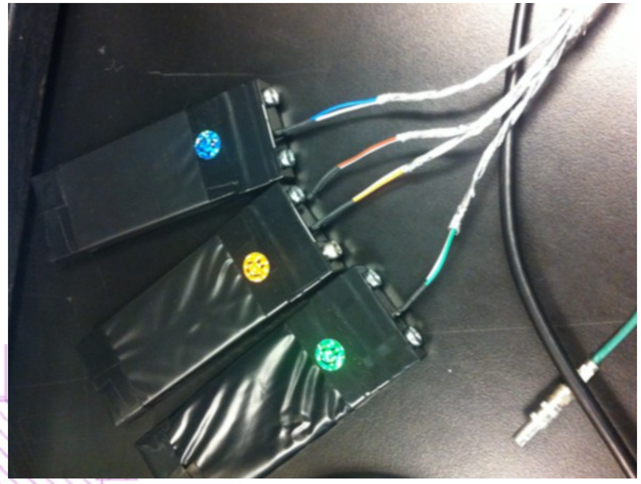
# More background monitors

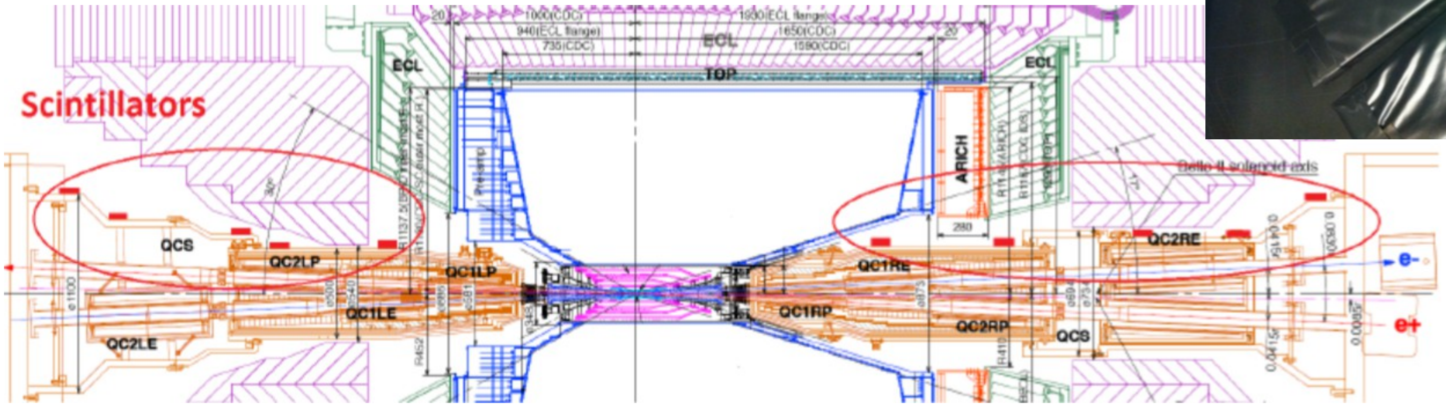
McGill collaboration with NWU (Japan) and KEK to design and build background counters adjacent to the beam line

- Array of 40 plastic scintillators read out by MPPCs
- Real-time monitoring of rates; provided to Belle II shifters and SuperKEKB operators via EPICS

See talk by H. Pikhartova
Monday M2-3





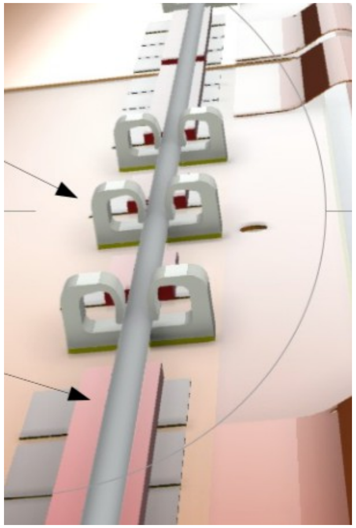


# Detector Material Studies

Detector material degrades tracking/vertexing resolution due to multiple scattering in inner detectors

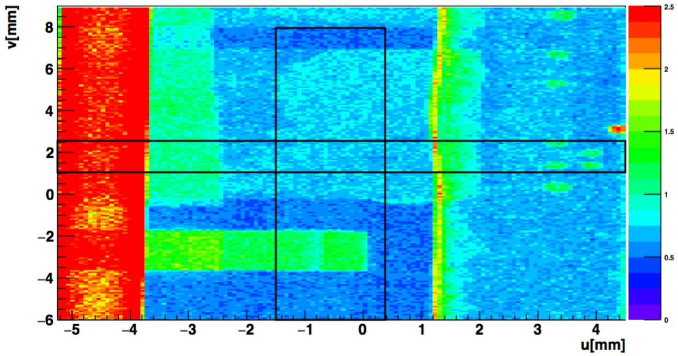
- Collaboration with U of Gottingen to validate simulation model of silicon vertexing detectors (PXD and SVD)
- Precision beam scattering measurements of tracking modules using AIDA beam telescope to produce material “thickness” measurements

See talk by W. Ahmed Monday M2-3



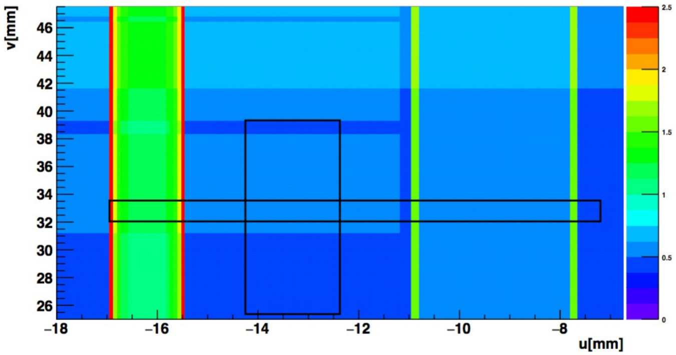
Comparisons with (and improvement of) simulated material model by W. Ahmed (McGill)

- Sensitivity to sub-0.1% of a radiation length




Measurement

Simulation

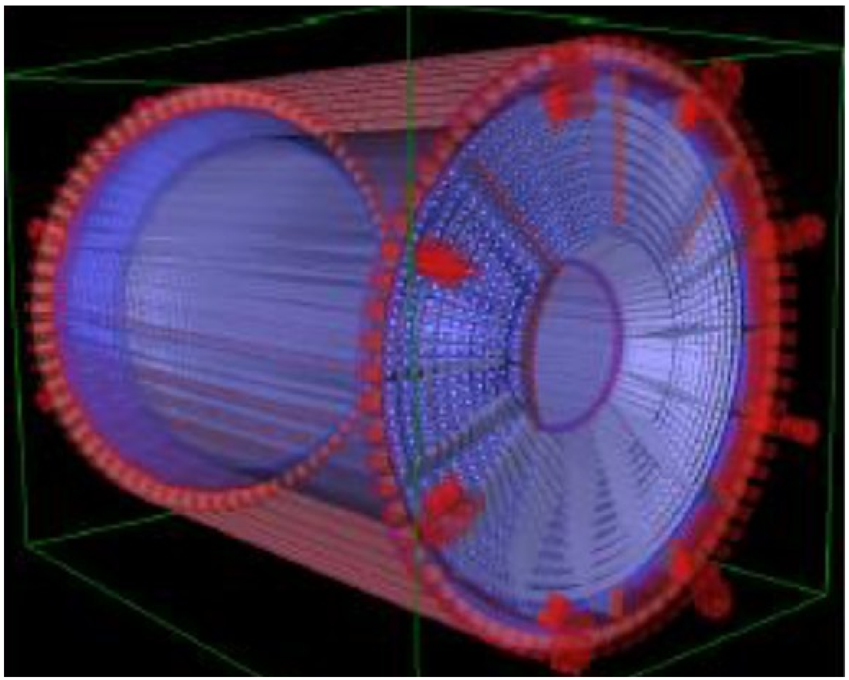



Additional “data driven” validation will be performed during Phase 3

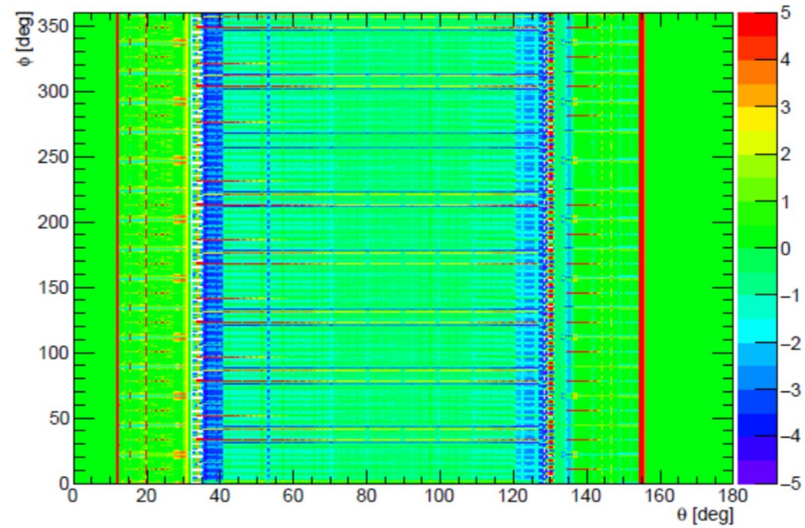
# ECL Simulation

Canadian groups are responsible for the calorimeter simulation and reconstruction software

- Improvements to ECL simulation model to correct crystal geometries and structural material    (A. Sibidanov UVic)



W. Ahmed




Difference (in $X/X_0$) relative to old model

# ECL reconstruction

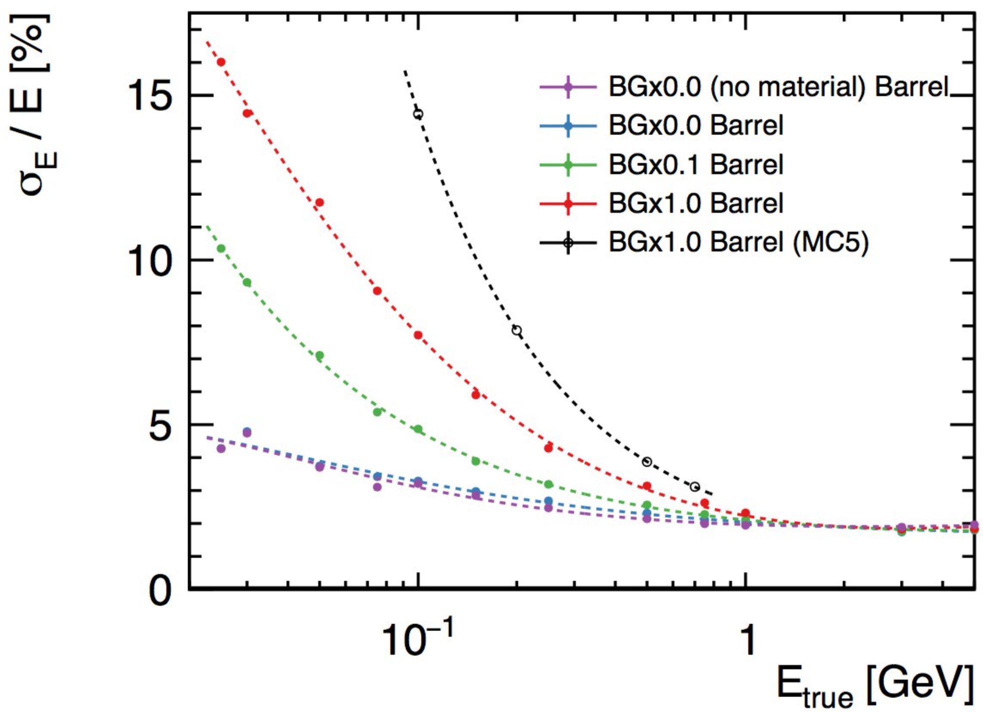
Although calorimeter crystals and photodetectors remained the same as for Belle, ECL readout electronics were upgraded to support fast shaping and feature extraction

- Necessary to cope with high background rates

ECL reconstruction software rewritten entire from scratch:

- More robust clustering, including particle hypothesis-based clustering
- New shower shape variables for improved hadron/photon separation
- Preparations for calibration in upcoming cosmic and Phase 2 running

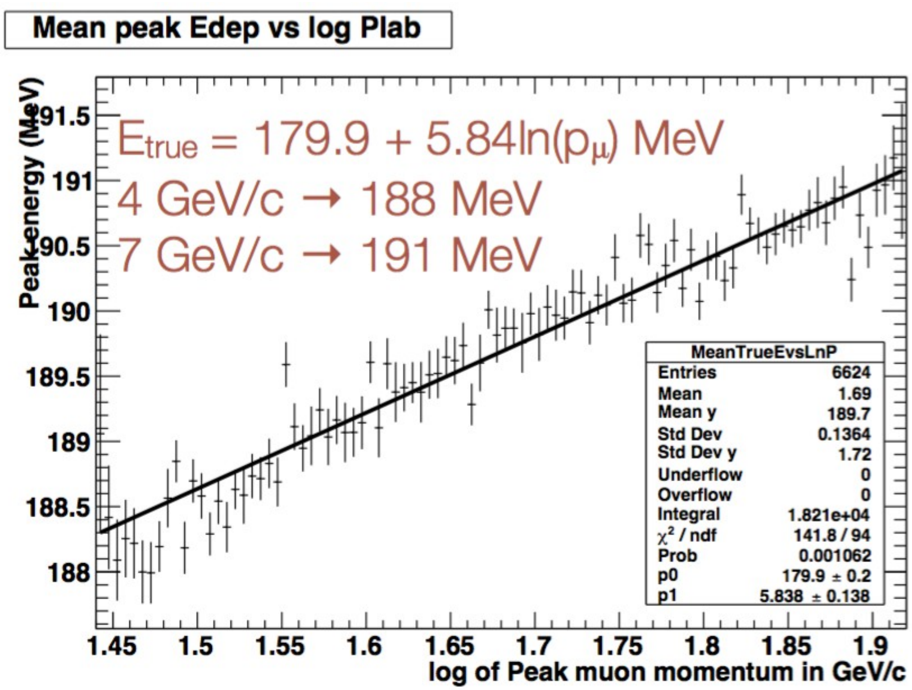
T. Ferber (UBC)



# Calibration

Calorimeter requires calibration a various points in the reconstruction chain (single crystal, cluster, object etc.)

- Single crystal calibration based on dimuon events in data; simulation studies by C. Hearty
- Studies in progress also for Bhabhas, γγ (A. Hershenhorn, T. Ferber)

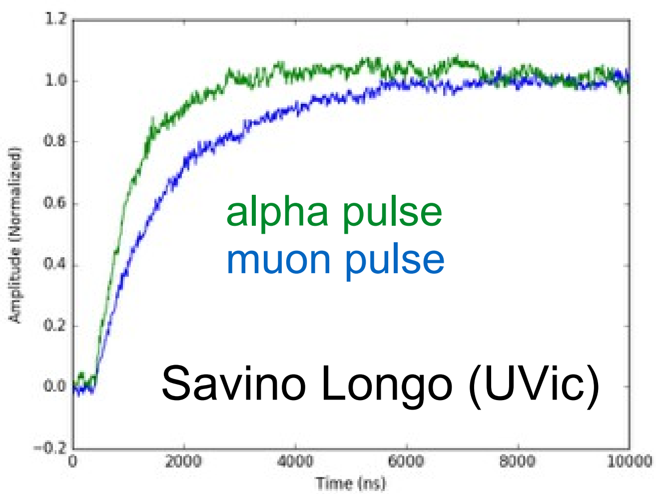



Sub-1% calibration of barrel crystals possible in Phase 2 with ~4$fb^{-1}$ of data

# Pulse shape discrimination

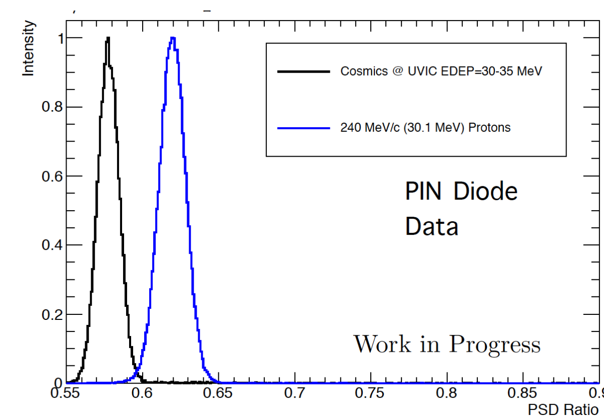
Study of CsI(Tl) pulse shape to discriminate neutral hadrons ($K_L$) from photons:

- Proof of concept from TRIUMF testbeam using ECL crystal assembly with PIN diode and preamp



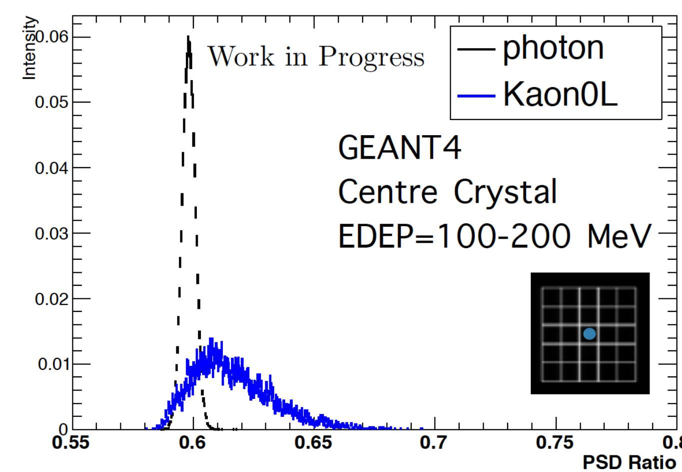

Characterize pulses with ratio of charge at t=1.2 μs and t=7.4 μs

$$R_{\mathrm{PSD}} = \frac{Q(1.2\mu s)}{Q(7.4\mu s)}$$




Technique has not previously been used at B factories

- Performance will be tested in-situ during Phase 2 commissioning




Simulation of photon and $K_L$ pulse shapes

# Summary

**Very exciting time for Belle II right now**

- Phase 1 commissioning completed, with first collisions anticipated during 2018

Canadian group heavily involved in commissioning activities

- Beam background simulation, measurements and monitors
- Design and construction of shielding

Major impact on calorimeter performance due to improvements in simulation, reconstruction and calibration

**Hope to have first colliding-beam data to show by next congress!**