THE UNIVERSITY OF BRITISH COLUMBIA

INSTITUTE OF PARTICLE PHYSICS

Belle II — past, present, and future

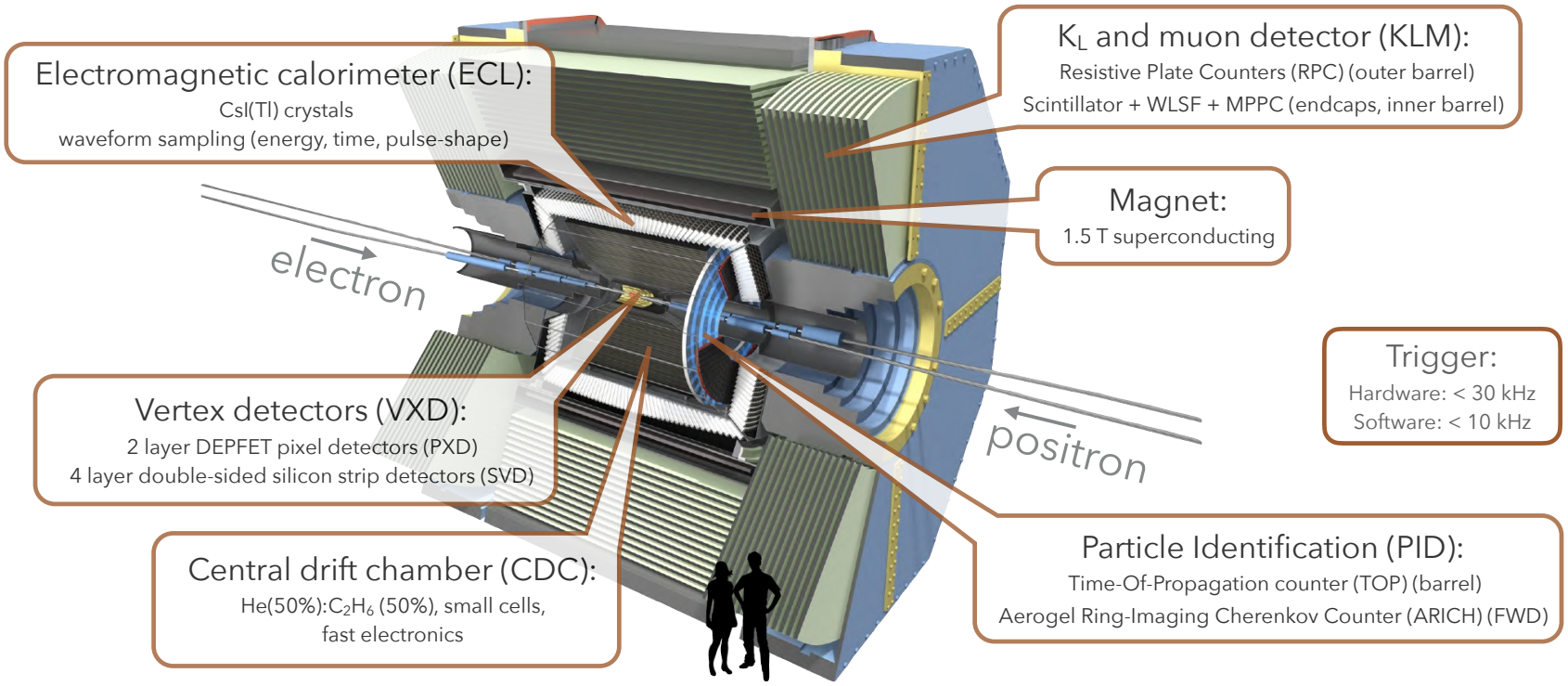
Christopher Hearty
U. British Columbia / IPP
May 28, 2022

Belle II

- Located at the SuperKEKB e^+e^- collider in Japan. Operates at $\sqrt{s}$ = 10.58 GeV (Y(4S)).

- Collecting data since 2019. Luminosity goal is 50 ab^{-1} = 100x BaBar; ~1x BaBar so far.
  - but with a better detector

- Upgrade of Belle: new tracking, particle ID; new calorimeter electronics.



Physics

- Primary goal is to seek evidence for new physics through a wide range of measurements that are sensitive to the presence of heavy virtual particles.
  - asymmetries, rare decays, forbidden decays.

- B physics; charm; tau (including lepton flavour violation); initial-state radiation production of $\pi^+\pi^-$ and other hadronic states; Upsilon decays; new XYZ QCD states.

- Direct searches for beyond-the-Standard-Model particles.
  - first two papers: search for axion-like particles; search for an invisibly-decaying Z′.

Belle II collaboration

- 26 countries, 121 institutions, 1164 collaborators, including 446 PhD physicists & 392 graduate students
  - 560 eligible authors

Canadian group
8 → 9 faculty, 3 postdocs, 14 graduate students

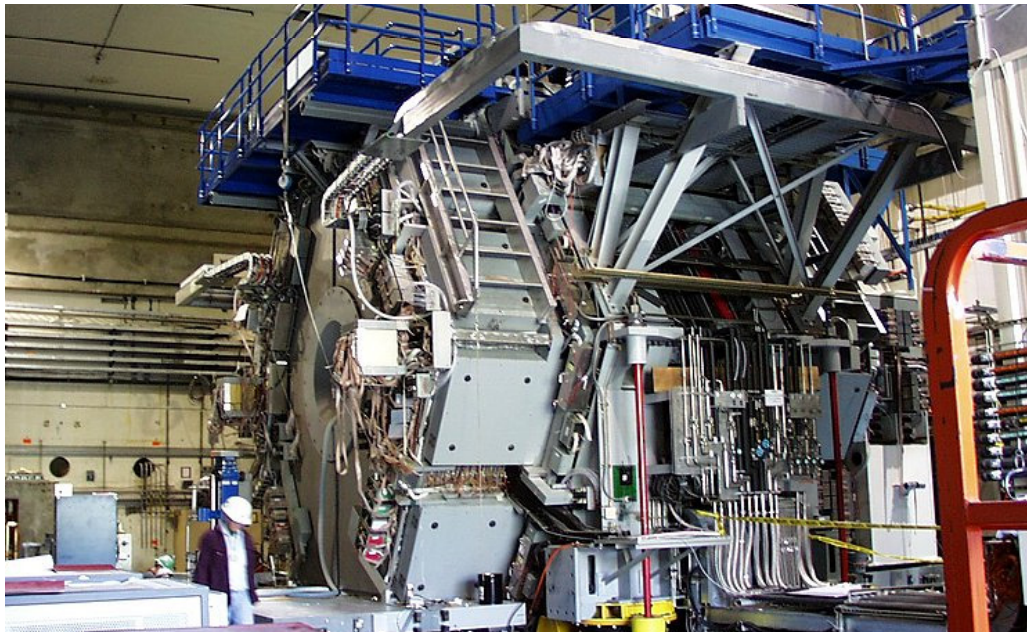
- **UBC**: C. Hearty, J. McKenna
- **Victoria**: J. M. Roney, R. Kowalewski, R. Sobie
- **McGill**: S. Robertson, A. Warburton
- **St. Francis Xavier**: Hossain Ahmed
- **Manitoba**: Savino Longo (as of July 1)

The past

BaBar

- Prior to joining Belle II, most of the current group worked on BaBar.

- Collected data at the PEP-II e^+e^- collider at SLAC from 1999–2008. Mostly Y(4S), but also Y(2S) and Y(3S).



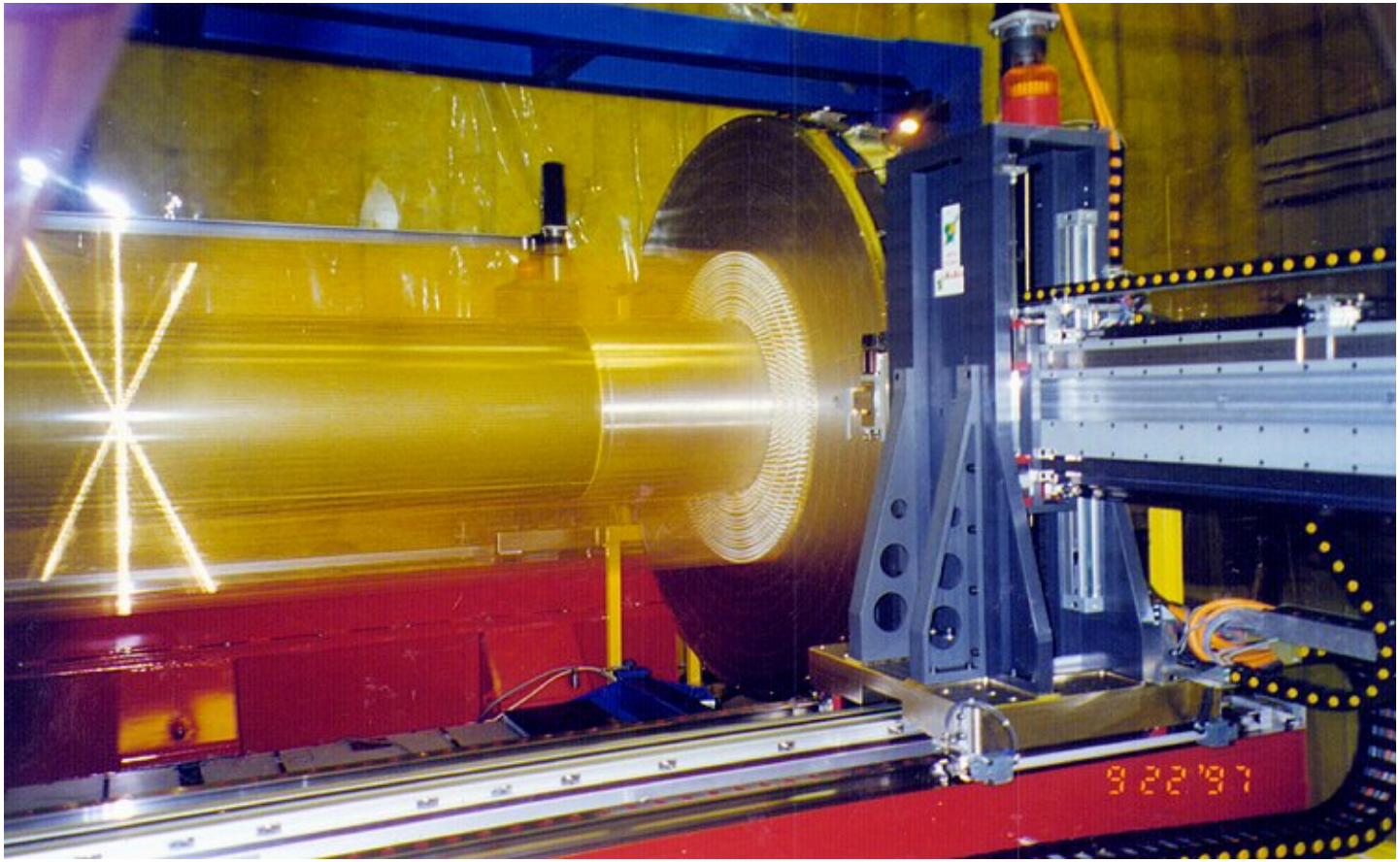
BaBar

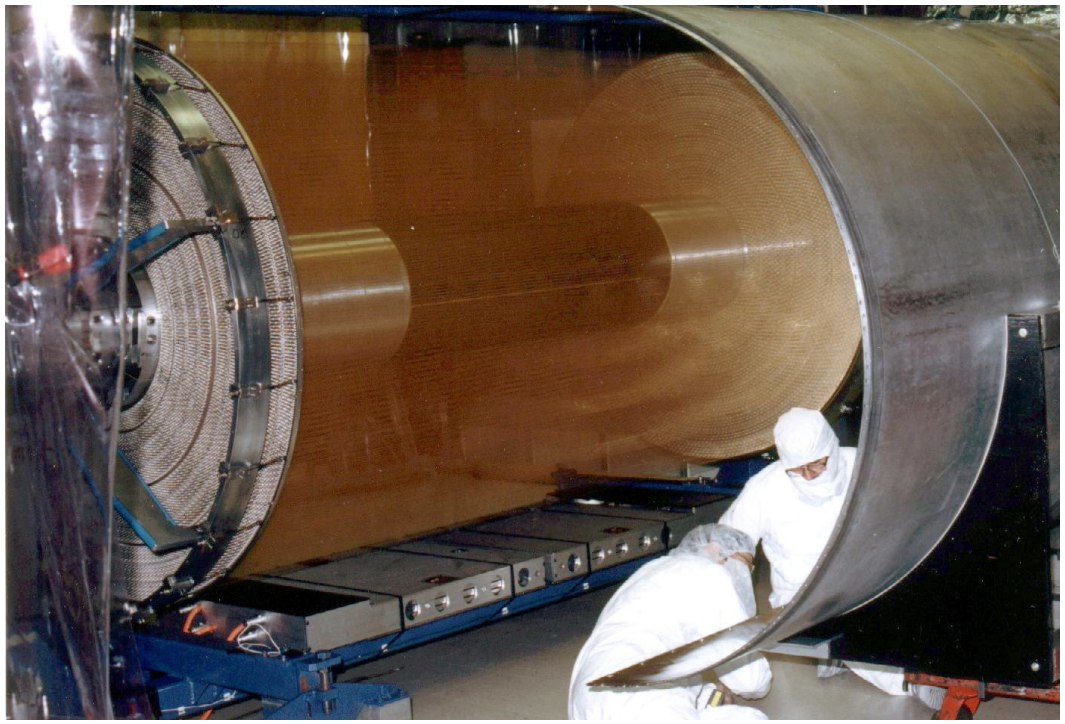
- Along with Belle, observed CP violation in B decay.

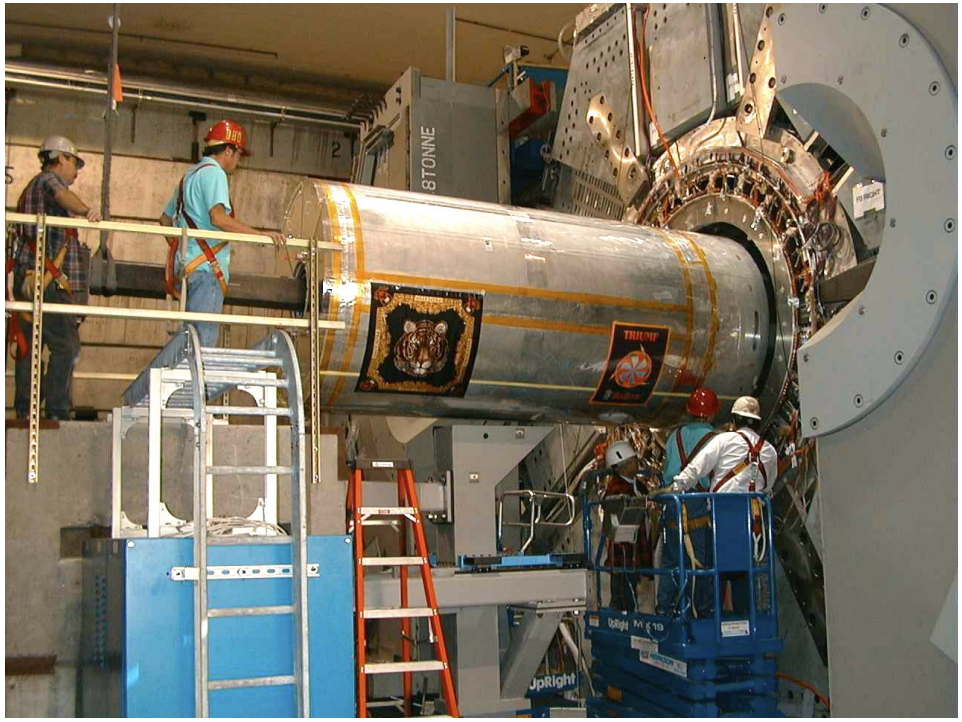
2008 Nobel prize in physics

Construction of the BaBar drift chamber at TRIUMF

- Significant support from TRIUMF, NSERC, US and Italian collaborators.






8TONNE
TRIUMF
UpRight

- Canadians made up only ~3% of BaBar, but had a significant role in management
  - Mike Roney continues as BaBar spokeperson;
  - Chris Hearty, Mike Roney, and Steve Robertson were physics analysis coordinators;
  - Janis McKenna, Mike Roney, and Chris Hearty were run coordinators.
  - Five physics working group convenors: charmonium, tau, leptonic B and c, semileptonic.

- Canadian analysis leadership in semileptonic B decays; tau physics; charmonium; light Higgs

PRL **107,** 221803 (2011) PHYSICAL REVIEW LETTERS week ending 25 NOVEMBER 2011

Search for Hadronic Decays of a Light Higgs Boson in the Radiative Decay $\Upsilon \to \gamma A^0$

J. P. Lees,[1] V. Poireau,[1] V. Tisserand,[1] J. Garra Tico,[2] E. Grauges,[2] M. Martinelli,[3a,3b] D. A. Milanes,[3a] A. Palano,[3a,3b] M. Pappagallo,[3a,3b] G. Eigen,[4] B. Stugu,[4] D. N. Brown,[5] L. T. Kerth,[5] Yu. G. Kolomensky,[5] G. Lynch,[5] H. Koch,[6] T. Schroeder,[6] D. J. Asgeirsson,[7] C. Hearty,[7] T. S. Mattison,[7] J. A. McKenna,[7] R. Y. So,[7] A. Khan,[8] V. E. Blinov,[9] A. R. Buzykaev,[9] V. P. Druzhinin,[9] V. B. Golubev,[9] E. A. Kravchenko,[9] A. P. Onuchin,[9] S. I. Serednyakov,[9] Yu. I. Skovpen,[9] E. P. Solodov,[9] K. Yu. Todyshev,[9] A. N. Yushkov,[9] M. Bondioli,[10] D. Kirkby,[10] A. J. Lankford,[10] M. Mandelkern,[10] D. P. Stoker,[10] H. Atmacan,[11] J. W. Gary,[11] F. Liu,[11] O. Long,[11] G. M. Vitug,[11] C. Campagnari,[12] T. M. Hong,[12] D. Kovalskyi,[12] J. D. Richman,[12] C. A. West,[12] A. M. Eisner,[13] J. Kroseberg,[13] W. S. Lockman,[13] A. J. Martinez,[13] T. Schalk,[13] B. A. Schumm,[13] A. Seiden,[13] C. H. Cheng,[14] D. A. Doll,[14] B. Echenard,[14] K. T. Flood,[14] D. G. Hitlin,[14]

PRL **104,** 021802 (2010) PHYSICAL REVIEW LETTERS week ending 15 JANUARY 2010

Searches for Lepton Flavor Violation in the Decays $\tau^\pm \to e^\pm\gamma$ and $\tau^\pm \to \mu^\pm\gamma$

B. Aubert,[1] Y. Karyotakis,[1] J. P. Lees,[1] V. Poireau,[1] E. Prencipe,[1] X. Prudent,[1] V. Tisserand,[1] J. Garra Tico,[2] E. Grauges,[2] M. Martinelli,[3a,3b] A. Palano,[3a,3b] M. Pappagallo,[3a,3b] G. Eigen,[4] B. Stugu,[4] L. Sun,[4] M. Battaglia,[5] D. N. Brown,[5] B. Hooberman,[5] L. T. Kerth,[5] Yu. G. Kolomensky,[5] G. Lynch,[5] I. L. Osipenkov,[5] K. Tackmann,[5] T. Tanabe,[5] C. M. Hawkes,[6] N. Soni,[6] A. T. Watson,[6] H. Koch,[7] T. Schroeder,[7] D. J. Asgeirsson,[8] C. Hearty,[8] T. S. Mattison,[8] J. A. McKenna,[8] M. Barrett,[9] A. Khan,[9] A. Randle-Conde,[9] V. E. Blinov,[10] A. D. Bukin,[10,*] A. R. Buzykaev,[10] V. P. Druzhinin,[10] V. B. Golubev,[10] A. P. Onuchin,[10] S. I. Serednyakov,[10] Yu. I. Skovpen,[10] E. P. Solodov,[10]

PRL **102,** 132001 (2009) PHYSICAL REVIEW LETTERS week ending 3 APRIL 2009

Evidence for $X(3872) \to \psi(2S)\gamma$ in $B^\pm \to X(3872)K^\pm$ Decays and a Study of $B \to c\bar{c}\gamma K$

B. Aubert,[1] M. Bona,[1] Y. Karyotakis,[1] J. P. Lees,[1] V. Poireau,[1] E. Prencipe,[1] X. Prudent,[1] V. Tisserand,[1] J. Garra Tico,[2] E. Grauges,[2] L. Lopez,[3a,3b] A. Palano,[3a,3b] M. Pappagallo,[3a,3b] G. Eigen,[4] B. Stugu,[4] L. Sun,[4] G. S. Abrams,[5] M. Battaglia,[5] D. N. Brown,[5] R. N. Cahn,[5] R. G. Jacobsen,[5] L. T. Kerth,[5] Yu. G. Kolomensky,[5] G. Lynch,[5] I. L. Osipenkov,[5] M. T. Ronan,[5,*] K. Tackmann,[5] T. Tanabe,[5] C. M. Hawkes,[6] N. Soni,[6] A. T. Watson,[6] H. Koch,[7] T. Schroeder,[7] D. Walker,[8] D. J. Asgeirsson,[9] B. G. Fulsom,[9] C. Hearty,[9] T. S. Mattison,[9] J. A. McKenna,[9] M. Barrett,[10] A. Khan,[10] V. E. Blinov,[11] A. D. Bukin,[11] A. R. Buzykaev,[11] V. P. Druzhinin,[11] V. B. Golubev,[11] A. P. Onuchin,[11] S. I. Serednyakov,[11] Yu. I. Skovpen,[11] E. P. Solodov,[11] K. Yu. Todyshev,[11] M. Bondioli,[12] S. Curry,[12] I. Eschrich,[12] D. Kirkby,[12]

PRL **97,** 211801 (2006) PHYSICAL REVIEW LETTERS week ending 24 NOVEMBER 2006

Measurement of the $B \to \pi l \nu$ Branching Fraction and Determination of $|V_{ub}|$ with Tagged B Mesons

B. Aubert,[1] R. Barate,[1] M. Bona,[1] D. Boutigny,[1] F. Couderc,[1] Y. Karyotakis,[1] J. P. Lees,[1] V. Poireau,[1] V. Tisserand,[1] A. Zghiche,[1] E. Grauges,[2] A. Palano,[3] J. C. Chen,[4] N. D. Qi,[4] G. Rong,[4] P. Wang,[4] Y. S. Zhu,[4] G. Eigen,[5] I. Ofte,[5] B. Stugu,[5] G. S. Abrams,[6] M. Battaglia,[6] D. N. Brown,[6] J. Button-Shafer,[6] R. N. Cahn,[6] E. Charles,[6] M. S. Gill,[6] Y. Groysman,[6] R. G. Jacobsen,[6] J. A. Kadyk,[6] L. T. Kerth,[6] Yu. G. Kolomensky,[6] G. Kukartsev,[6] G. Lynch,[6] L. M. Mir,[6] T. J. Orimoto,[6] M. Pripstein,[6] N. A. Roe,[6] M. T. Ronan,[6] W. A. Wenzel,[6] P. del Amo Sanchez,[7] M. Barrett,[7] K. E. Ford,[7] T. J. Harrison,[7] A. J. Hart,[7] C. M. Hawkes,[7] S. E. Morgan,[7] A. T. Watson,[7] T. Held,[8] H. Koch,[8] B. Lewandowski,[8] M. Pelizaeus,[8] K. Peters,[8] T. Schroeder,[8] M. Steinke,[8] J. T. Boyd,[9] J. P. Burke,[9] W. N. Cottingham,[9] D. Walker,[9] T. Cuhadar-Donszelmann,[10] B. G. Fulsom,[10] C. Hearty,[10] N. S. Knecht,[10] T. S. Mattison,[10] J. A. McKenna,[10] A. Khan,[11] P. Kyberd,[11] M. Saleem,[11]

PRL **95,** 142001 (2005) PHYSICAL REVIEW LETTERS week ending 30 SEPTEMBER 2005

Observation of a Broad Structure in the $\pi^+\pi^- J/\psi$ Mass Spectrum around 4.26 GeV/c^2

B. Aubert,[1] R. Barate,[1] D. Boutigny,[1] F. Couderc,[1] Y. Karyotakis,[1] J. P. Lees,[1] V. Poireau,[1] V. Tisserand,[1] A. Zghiche,[1] E. Grauges,[2] A. Palano,[3] M. Pappagallo,[3] A. Pompili,[3] J. C. Chen,[4] N. D. Qi,[4] G. Rong,[4] P. Wang,[4] Y. S. Zhu,[4] G. Eigen,[5] I. Ofte,[5] B. Stugu,[5] G. S. Abrams,[6] M. Battaglia,[6] A. B. Breon,[6] D. N. Brown,[6] J. Button-Shafer,[6] R. N. Cahn,[6] E. Charles,[6] C. T. Day,[6] M. S. Gill,[6] A. V. Gritsan,[6] Y. Groysman,[6] R. G. Jacobsen,[6] R. W. Kadel,[6] J. Kadyk,[6] L. T. Kerth,[6] Yu. G. Kolomensky,[6] G. Kukartsev,[6] G. Lynch,[6] L. M. Mir,[6] P. J. Oddone,[6] T. J. Orimoto,[6] M. Pripstein,[6] N. A. Roe,[6] M. T. Ronan,[6] W. A. Wenzel,[6] M. Barrett,[7] K. E. Ford,[7] T. J. Harrison,[7] A. J. Hart,[7] C. M. Hawkes,[7] S. E. Morgan,[7] A. T. Watson,[7] M. Fritsch,[8] K. Goetzen,[8] T. Held,[8] H. Koch,[8] B. Lewandowski,[8] M. Pelizaeus,[8] K. Peters,[8] T. Schroeder,[8] M. Steinke,[8] J. T. Boyd,[9] J. P. Burke,[9] N. Chevalier,[9] W. N. Cottingham,[9] T. Cuhadar-Donszelmann,[10] B. G. Fulsom,[10] C. Hearty,[10] N. S. Knecht,[10] T. S. Mattison,[10] J. A. McKenna,[10] A. Khan,[11] P. Kyberd,[11] M. Saleem,[11] L. Teodorescu,[11]

PRL **94,** 101801 (2005) PHYSICAL REVIEW LETTERS week ending 18 MARCH 2005

Search for the Decay $B^+ \to K^+\nu\bar{\nu}$

B. Aubert,[1] R. Barate,[1] D. Boutigny,[1] F. Couderc,[1] J.-M. Gaillard,[1] A. Hicheur,[1] Y. Karyotakis,[1] J. P. Lees,[1] V. Tisserand,[1] A. Zghiche,[1] A. Palano,[2] A. Pompili,[2] J. C. Chen,[3] N. D. Qi,[3] G. Rong,[3] P. Wang,[3] Y. S. Zhu,[3] G. Eigen,[4] I. Ofte,[4] B. Stugu,[4] G. S. Abrams,[5] A. W. Borgland,[5] A. B. Breon,[5] D. N. Brown,[5] J. Button-Shafer,[5] R. N. Cahn,[5] E. Charles,[5] C. T. Day,[5] M. S. Gill,[5] A. V. Gritsan,[5] Y. Groysman,[5] R. G. Jacobsen,[5] R. W. Kadel,[5] J. Kadyk,[5] L. T. Kerth,[5] Yu. G. Kolomensky,[5] G. Kukartsev,[5] G. Lynch,[5] L. M. Mir,[5] P. J. Oddone,[5] T. J. Orimoto,[5] M. Pripstein,[5] N. A. Roe,[5] M. T. Ronan,[5] V. G. Shelkov,[5] W. A. Wenzel,[5] M. Barrett,[6] K. E. Ford,[6] T. J. Harrison,[6] A. J. Hart,[6] C. M. Hawkes,[6] S. E. Morgan,[6] A. T. Watson,[6] M. Fritsch,[7] K. Goetzen,[7] T. Held,[7] H. Koch,[7] B. Lewandowski,[7] M. Pelizaeus,[7] M. Steinke,[7] J. T. Boyd,[8] N. Chevalier,[8] W. N. Cottingham,[8] M. P. Kelly,[8] T. E. Latham,[8] F. F. Wilson,[8] T. Cuhadar-Donszelmann,[9] C. Hearty,[9]

SuperB

- A detour on the way from BaBar to Belle II.

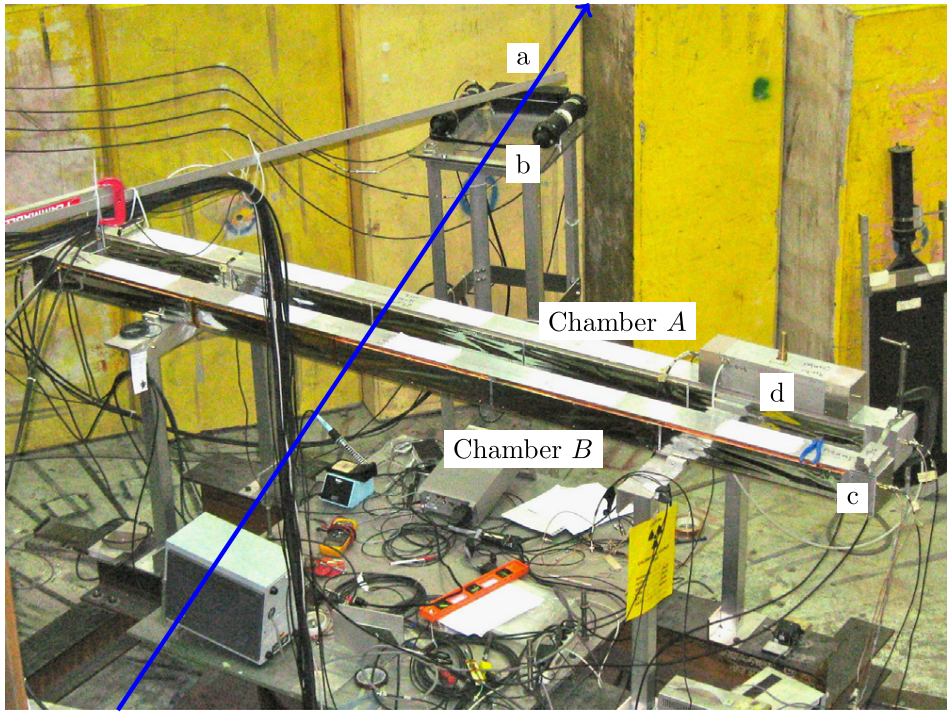
- SuperB was a high-luminosity B factory to be built near Frascati.
  - primarily Y(4S), but also ψ(3770)
  - polarized e^- beam

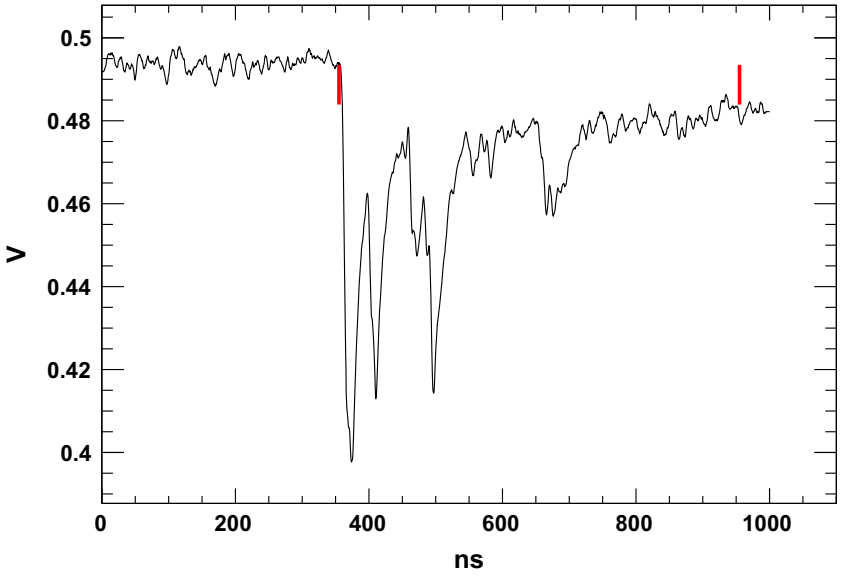
- Cancelled 2012.

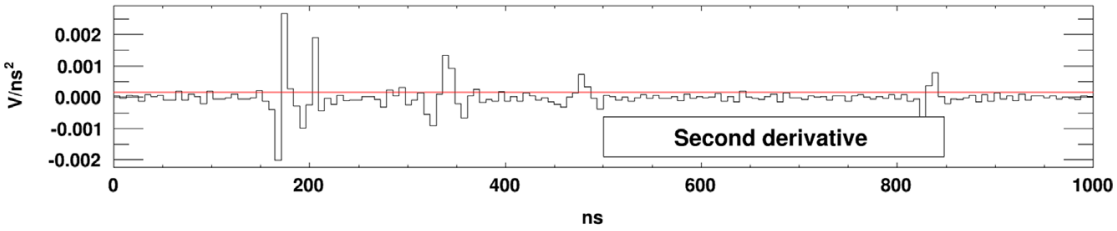
- Very nice place to work.

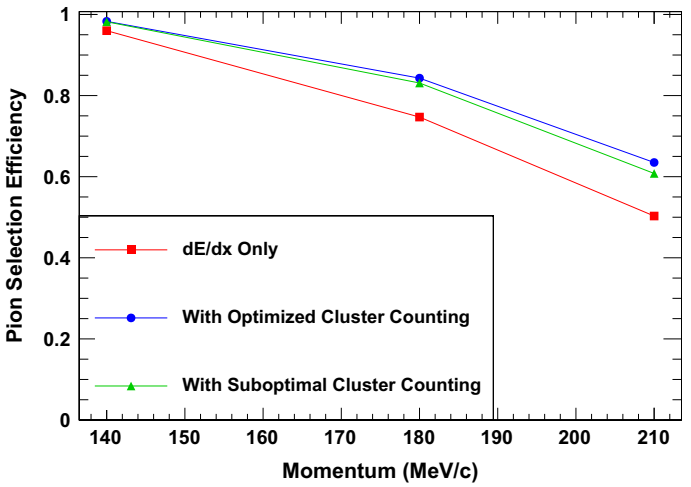
- Together with the Frascati group, the Canadian group was intending to build the drift chamber.

- Superior particle identification by using cluster counting as well as dE/dx.
  - successful beam test at TRIUMF M11 line.









Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Improved particle identification using cluster counting in a full-length drift chamber prototype

Jean-François Caron [a,*], Christopher Hearty [a], Philip Lu [a], Rocky So [a], Racha Cheaib [b], Jean-Pierre Martin [c], Wayne Faszer [d], Alexandre Beaulieu [e], Samuel de Jong [e], Michael Roney [e], Riccardo de Sangro [f], Giulietto Felici [f], Giuseppe Finocchiaro [f], Marcello Piccolo [f]

Nuclear Instruments and Methods in Physics Research A 735 (2014) 169–183

- Unfortunately, we joined Belle II too late to implement the concept there.

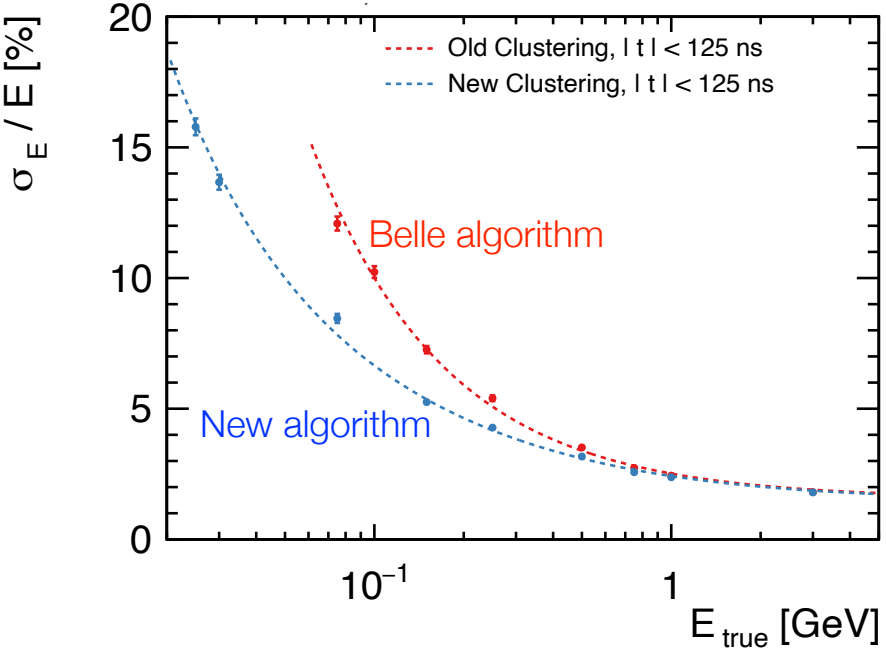
The present

Canadian activities on Belle II

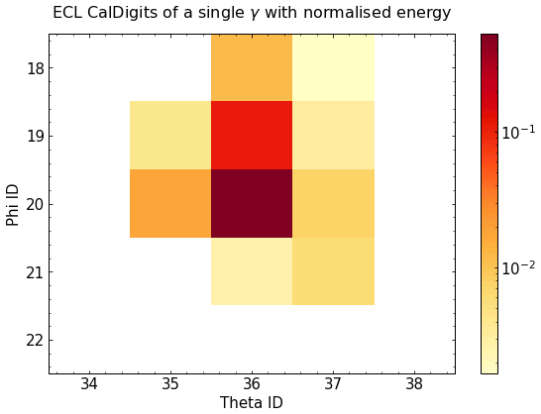
- We did not join early enough to take on a hardware project, but we did join the calorimeter group.
- Responsible for
  - Calorimeter calibration
  - Calorimeter software
  - Trigger menu / high-level trigger algorithms

- Significant contributions:
  - Computing
  - Collaboration organization.
    - Mike Roney is executive board chair;
    - I was chair of institutional board;
    - speakers committee; publications committee.
  - Physics

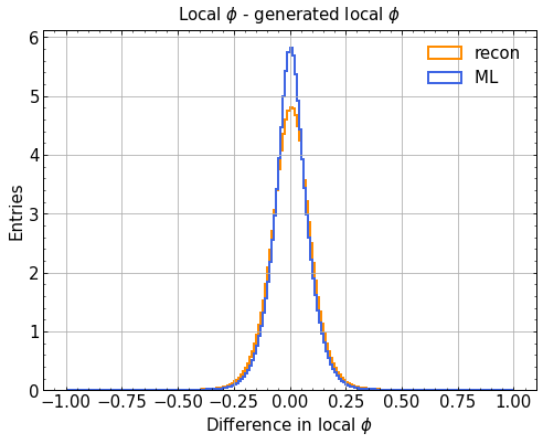
Energy resolution as a function of energy

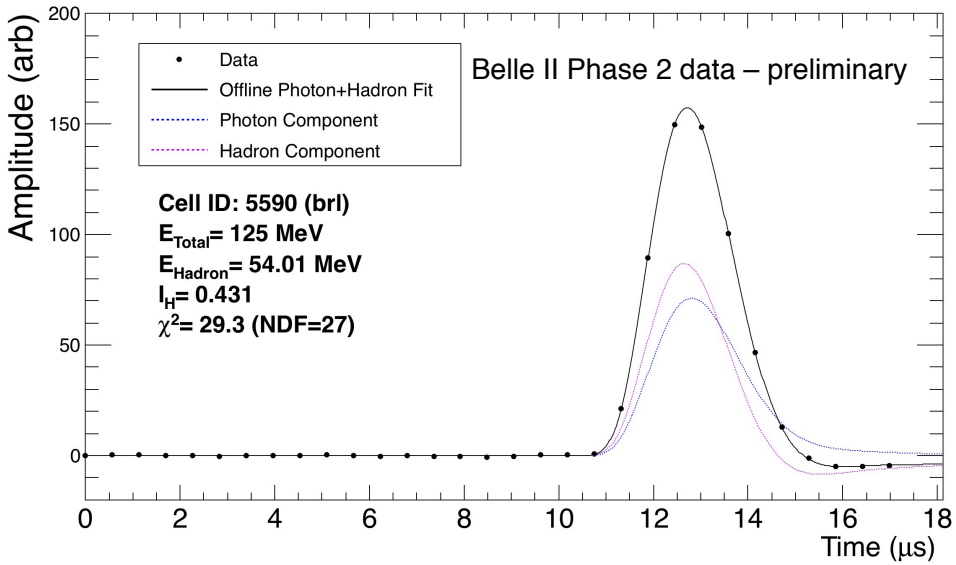


Torben Ferber (postdoc) wrote new reconstruction software designed for higher luminosity



Miho Wakai is developing NN tools for position resolution = better mass resolution for high-momentum π^0





Savino Longo uses waveform time structure to distinguish hadrons from photons: new particle ID capability for Belle II

Canadian contribution to Belle II computing

- Approximately 10% of offline computing from Compute Canada; simulation production.

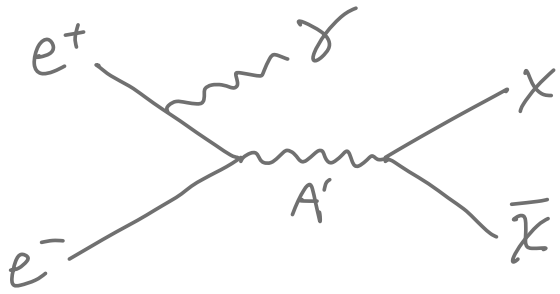
- Canadian data center will store and process 15% of the 2nd copy of the raw data.

- Funded by CFI in November 2020. $2M in CFI funds. $3M in-kind funding from collaboration computing resources; no provincial funds.
  - Randy Sobie (PI) + other faculty.

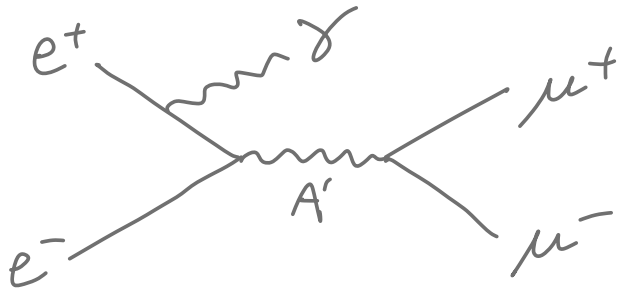
Dark sector / dark photons

- Wide range of “dark sector” models address dark matter and/or various anomalies. Particularly simple model that can explain observed relic densities has dark matter χ and a dark photon A′.

- Can be produced at Belle II.



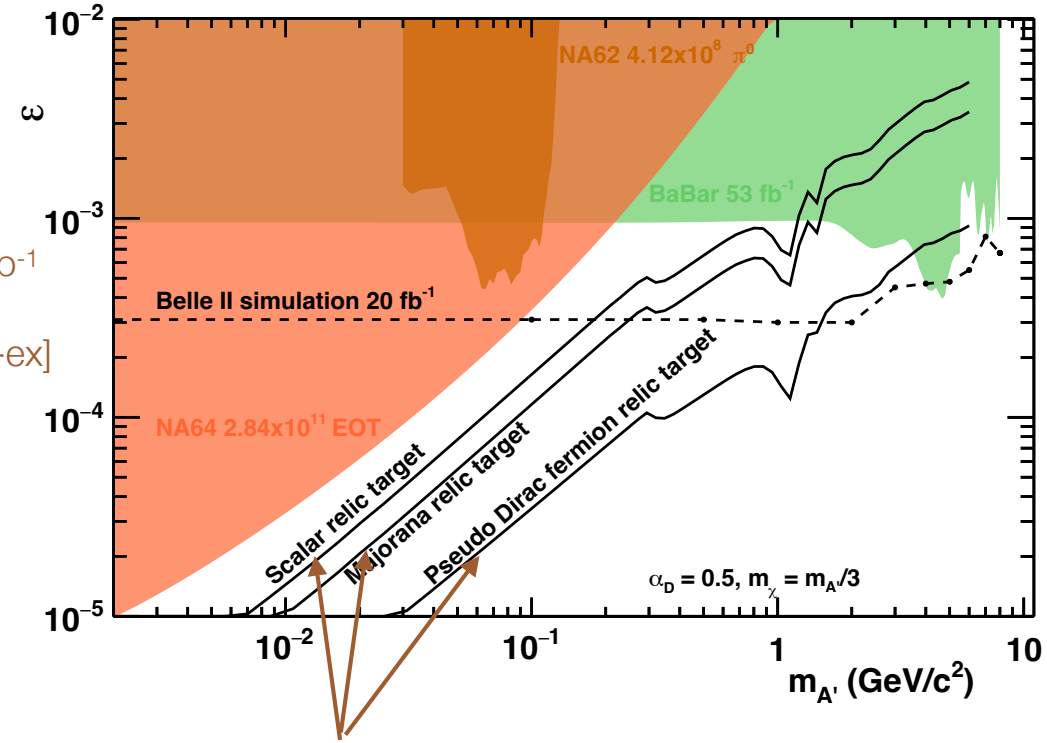
only the γ is visible in Belle II



the γ and both muons are visible

Limits on dark sector parameters from BaBar and projections for Belle II

- Initial analysis will have sensitivity to parameter space that would explain observed dark matter properties.



Belle II projection, 20 fb^{-1}
KEK-2018-27,
arXiv:1808.10567 [hep-ex]

BaBar limit, 50 fb^{-1}
Phys. Rev. Lett. 119,
131804 (2017)

These parameters predict astronomical dark matter.
Derived from E. Izaguirre, G. Krnjaic, P. Schuster,
N. Toro, Phys. Rev. Lett. 115, 251301 (2015)

The future

Belle II outlook

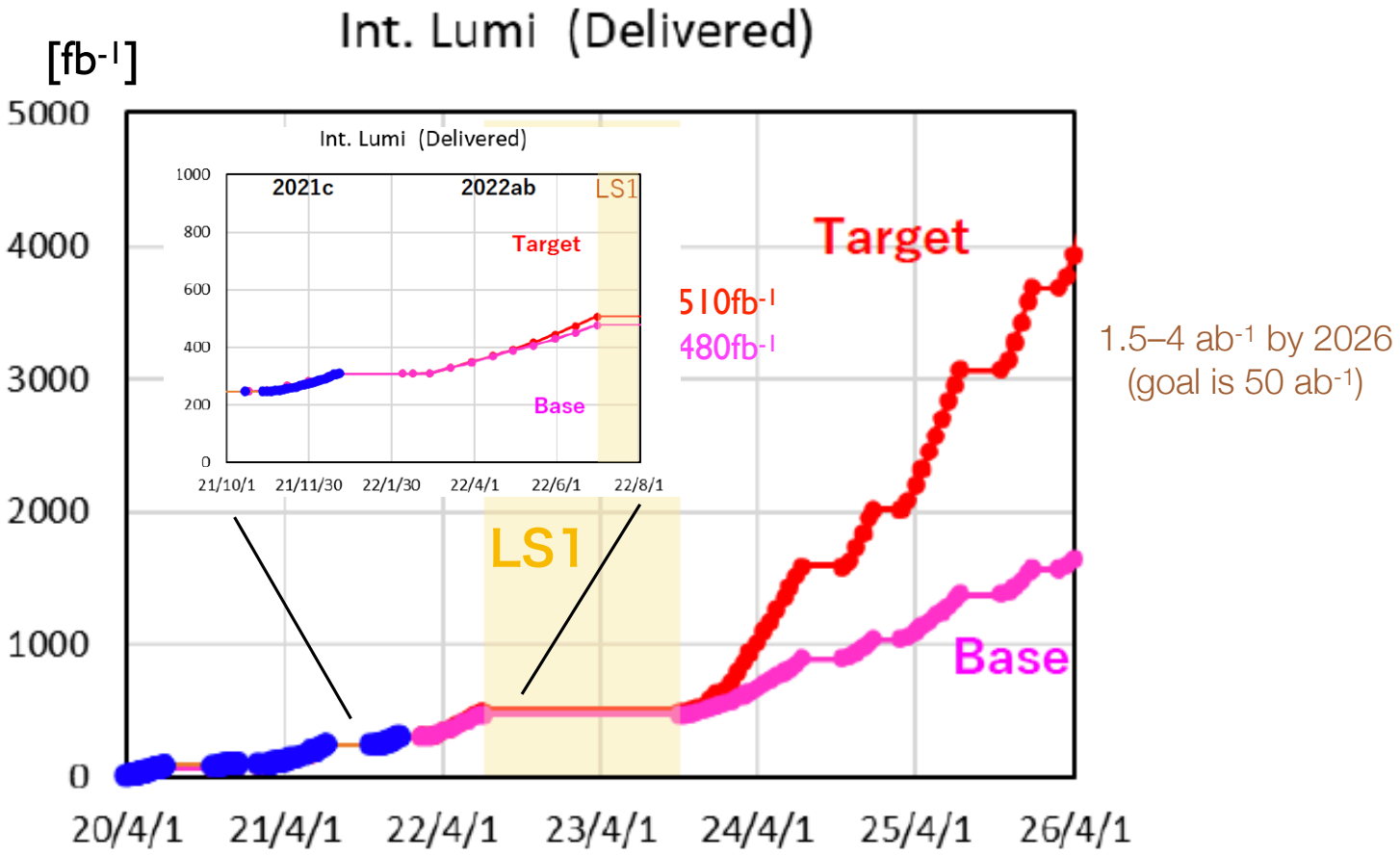
- We start a 15-month shutdown to install a new 2-layer pixel detector in July 2022.
  - also some accelerator work.

- Planning for a second long shut down 2026/2027, primarily for accelerator upgrades. Current design of final focus cannot achieve desired peak luminosity.

- SuperKEKB international task force will put forward recommendations this fall.
  - electricity costs indicate a solution other than current.

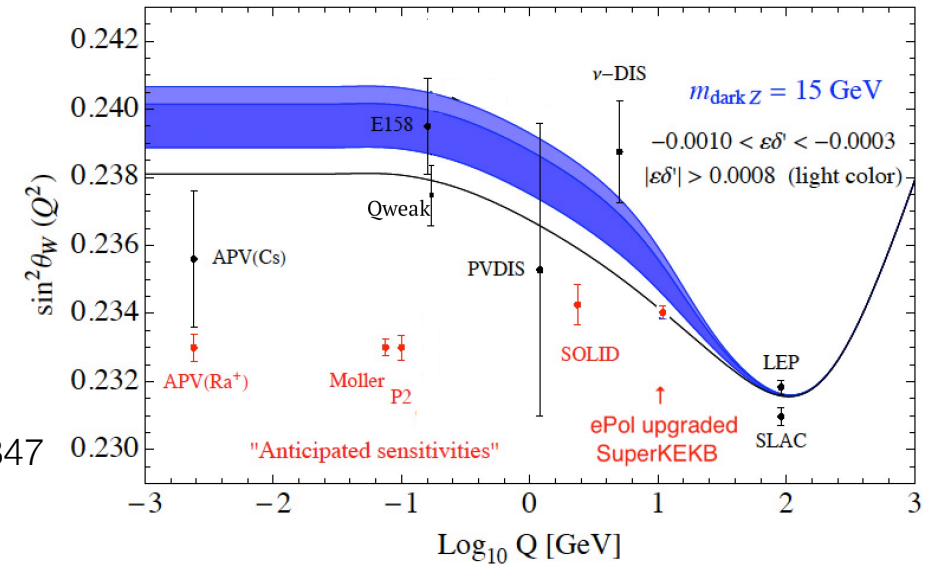
SuperKEKB luminosity projection

- Peak instantaneous luminosity 4×10^{34} $cm^{-2}s^{-1}$ (world record), 8% of design.



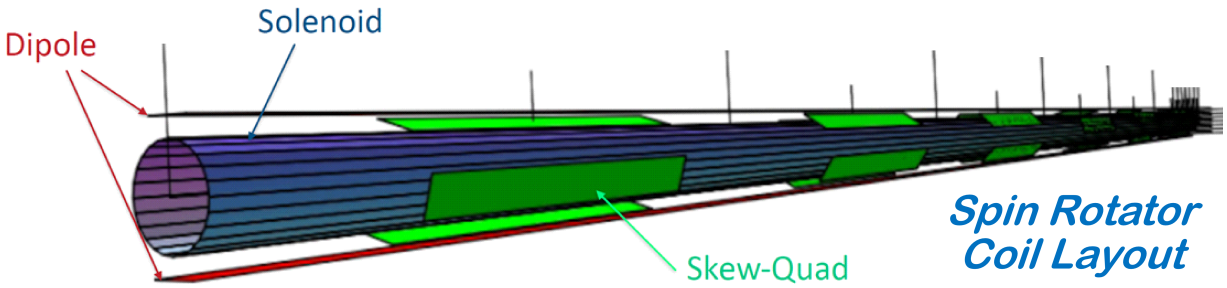
Polarized electron beam for SuperKEKB — "Chiral Belle"

- In parallel with the studies of luminosity upgrades, Mike Roney is putting together a proposal to polarize the e- beam.
- Enable measurements of $\sin^2\theta_W$ in e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$, $c\bar{c}$, and $b\bar{b}$ with precision similar to LEP/SLD, but at a new energy scale.
- Sensitive to new physics, e.g. parity-violating dark Z.



arXiv:2205.12847

- Will replace existing dipoles with combined function spin-rotators. Can be made transparent to the rest of the SuperKEKB lattice.



Combined function spin rotator magnets proposed by Uri Weinands

- Conceptual design underway. Goal would be installation before the end of the decade.

Snowmass 2021 White Paper
Upgrading SuperKEKB with a Polarized Electron Beam: Discovery Potential and Proposed Implementation

April 13, 2022

US Belle II Group [1]
and
Belle II/SuperKEKB e- Polarization Upgrade Working Group [2]

Corresponding Author(s):
Swagato Banerjee (swagato.banerjee@louisville.edu)
J. Michael Roney (mroney@uvic.ca)

arXiv:2205.12847