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Dark Photon measurements at Belle II

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U. British Columbia / IPP
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Outline

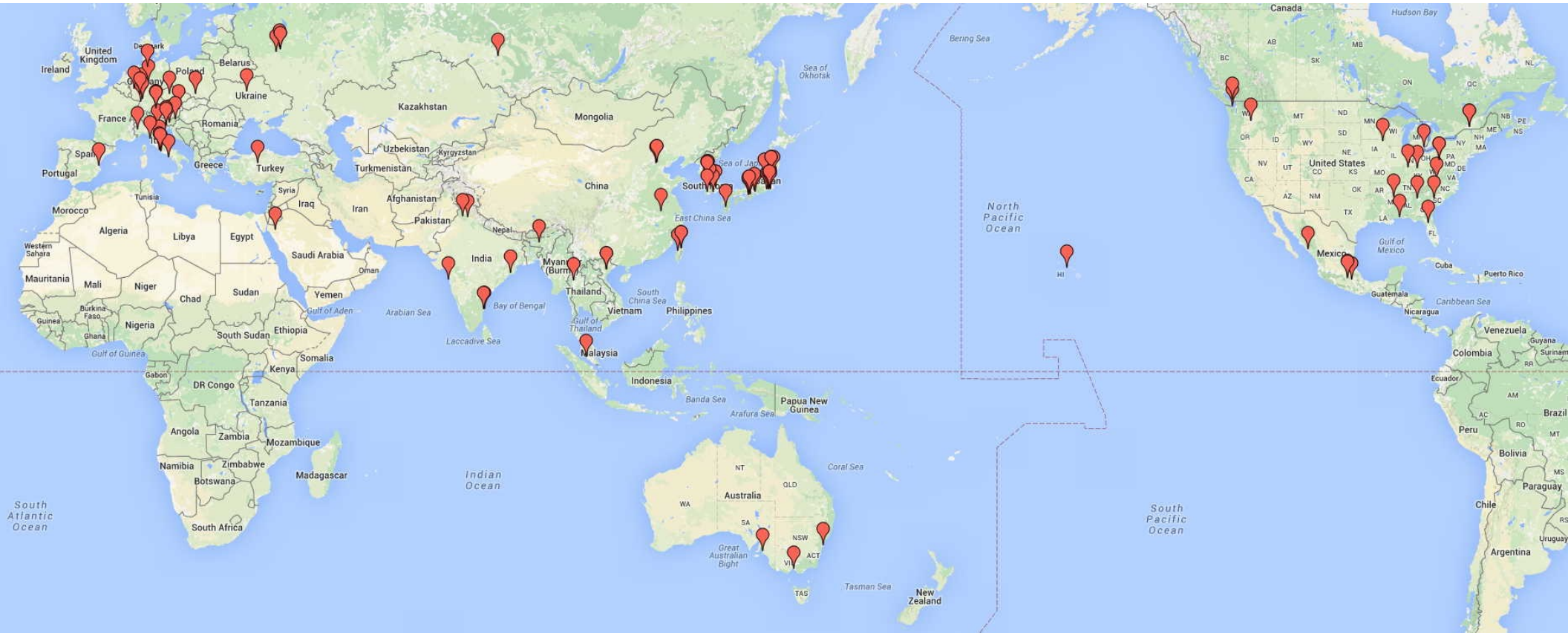
- Belle II: introduction and status
- Invisible decays of the dark photon — single photon measurement
- Dark photon decays to e^+e^- and $\mu^+\mu^-$

Belle II

- Upgrade of Belle, located at the SuperKEKB e^+e^- collider in Tsukuba Japan.

- 40× the peak luminosity of KEKB;
  100× the peak luminosity of PEP-II;
  30× the combined integrated luminosity of BaBar + Belle.

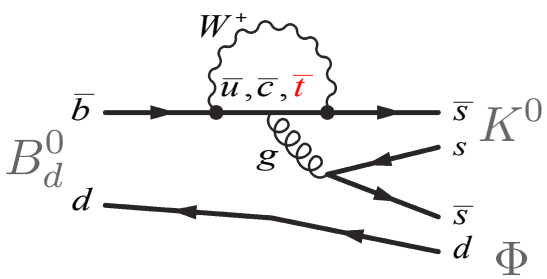
The Belle II collaboration

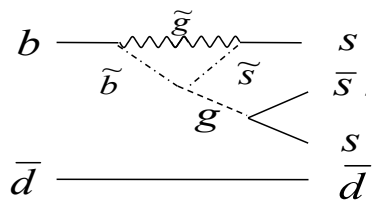


- 674 collaborators, including 376 PhD physicists and 211 graduate students. 25% Japanese.

Physics goals

- To seek evidence for new physics through a wide range of measurements sensitive to the presence of virtual particles.





Standard model process (left) is modified by the SUSY contribution on the right

- Asymmetries, rare decays, forbidden decays. Modes with well-known uncertainties in the standard model.

- And direct searches for new particles—Dark Sector, light Higgs

Schedule

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Press Release

First turns and successful storage of beams in the SuperKEKB electron and positron rings

March 2nd, 2016

High Energy Accelerator Research Organization (KEK)

[Primary research result]

After five years of large-scale upgrade work, SuperKEKB, an electron-positron colliding accelerator at KEK in Japan, has started test operations. SuperKEKB succeeded in circulating and storing beams in the electron and positron rings, which is the first milestone of its commissioning.

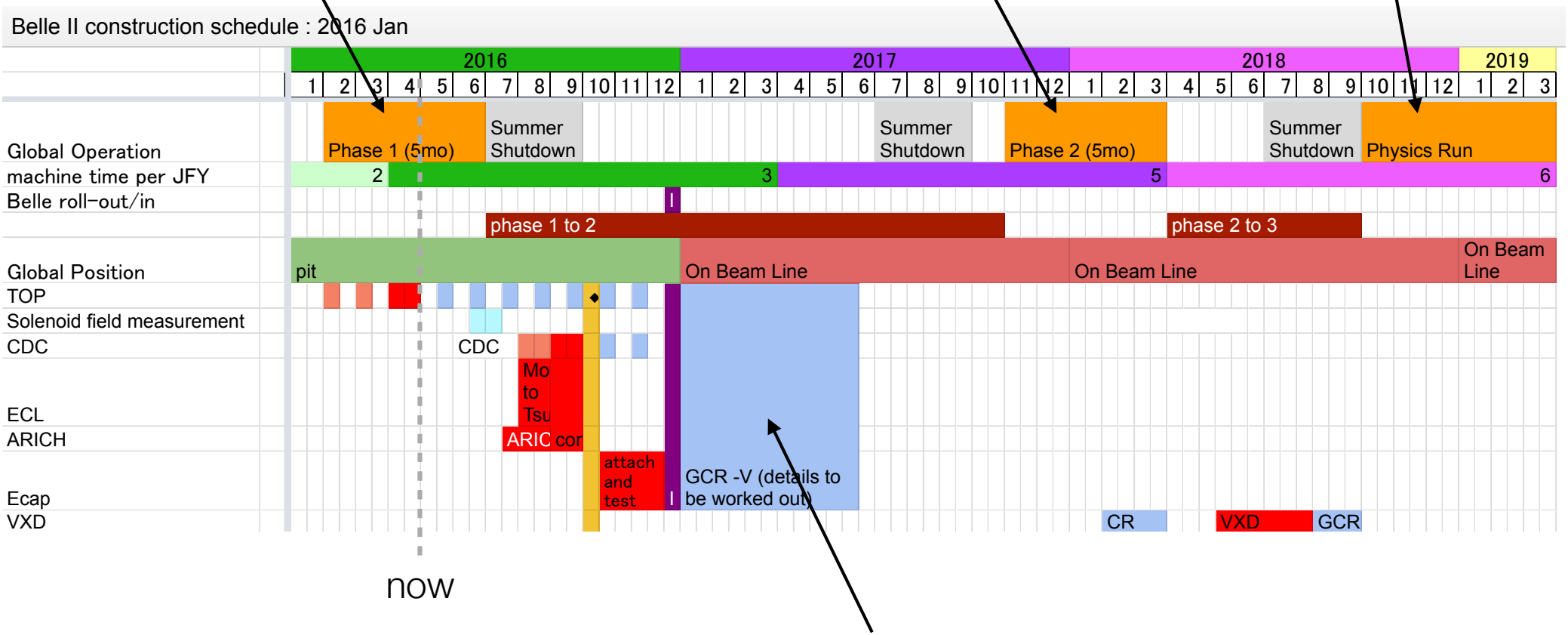
[Synopsis]

On February 1, 2016, the High Energy Accelerator Research Organization (KEK) started test operation of the SuperKEKB electron-positron collider. This machine represents a major upgrade from the previous KEKB accelerator, and is the culmination of years of construction that started in the second half of 2010. On February 10

Phase 1: single beams, commissioning detectors only (no Belle II)

Phase 2: colliding beams, Belle II except vertex detectors

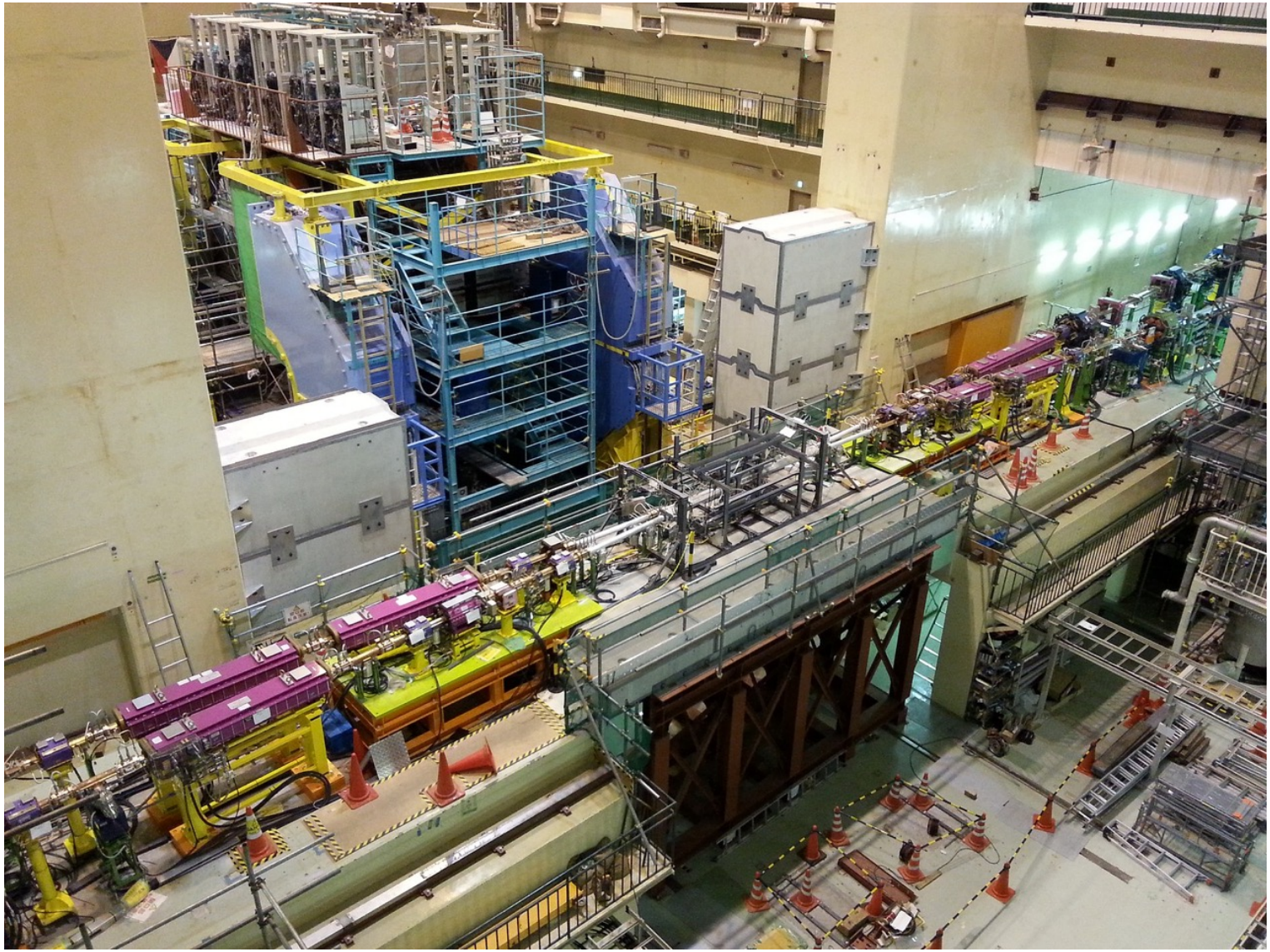
Phase 3: physics, full detector



Global cosmic run (without vertex detectors)

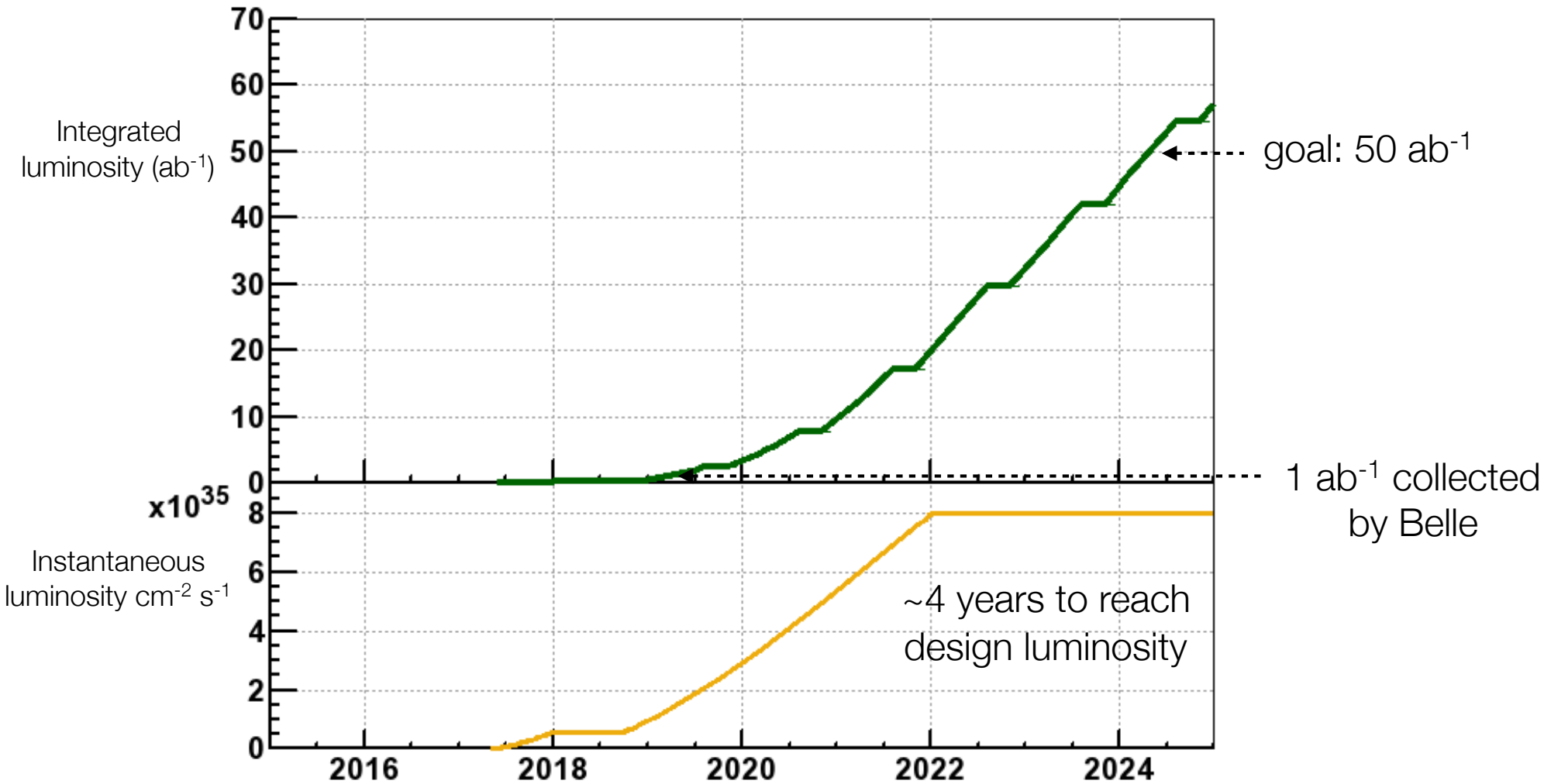
- 0–20 fb^{-1} in Phase 2, 100–200 fb^{-1} in first physics run.

BEAST commissioning detector for Phase 1

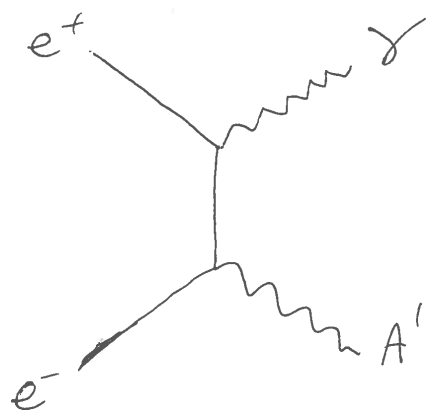


Peter Kodys

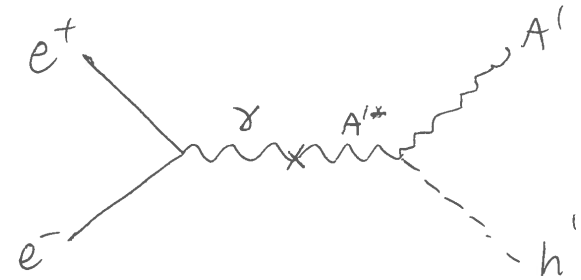
Longer term schedule



Dark photon production mechanisms at Belle II



$$\sigma \propto \epsilon^2 \alpha^2 / E_{CM}^2$$

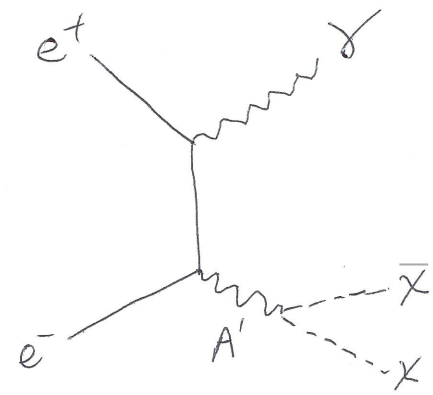


$$\sigma \propto \epsilon^2 \alpha \alpha_D / E_{CM}^2$$

- Lifetime (and decay length) $\propto 1/\left(M_{A'}\epsilon^2\right)$
  For the parameter space we are considering, decays can be considered to be prompt.

Search for a dark photon decaying invisibly

- Dark photon produced in e^+e^- collision will decay almost entirely to a dark fermion pair if kinematically available.



- Simplest case is if the A′ is on-shell ($\sqrt{s} > m_{A'} > 2m_\chi$), in which case the observed final state is a single mono energetic photon.
  - We have not yet studied the off-shell case, but it is clearly more difficult.

BaBar experience

- BaBar recorded 57 fb^{-1} of data with a single photon trigger during the final year of operations. Belle did not record such data.

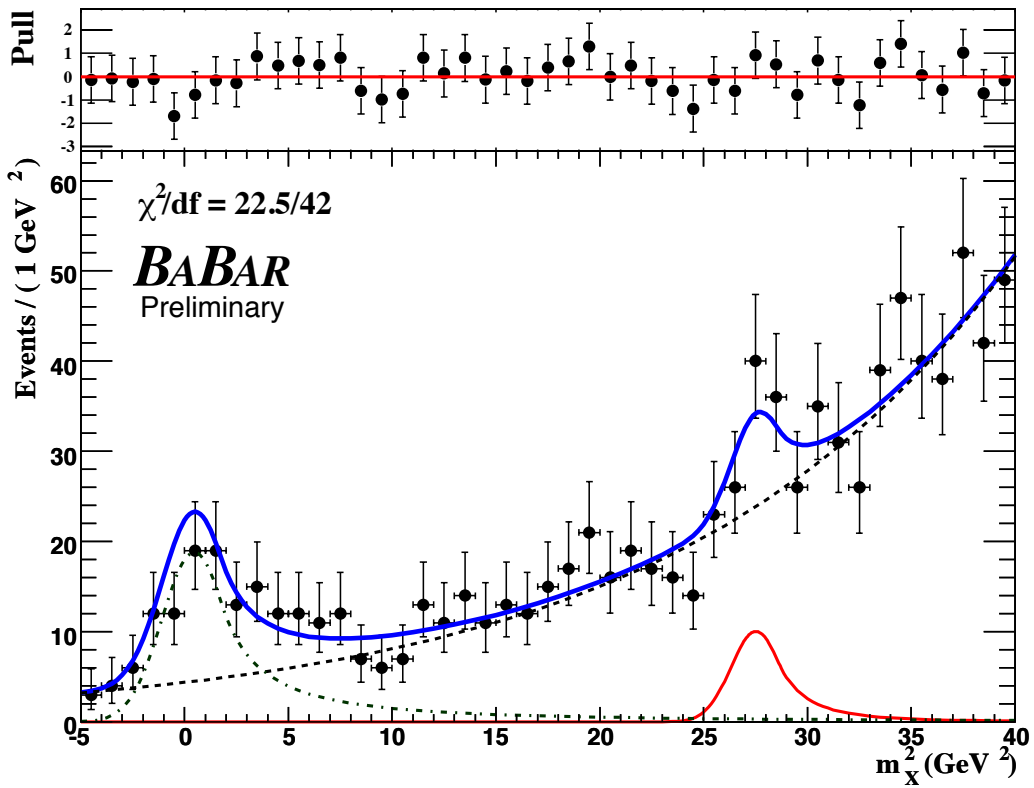
- Trigger rate was ~200 Hz (20 nb), 1/3 of all triggers. Y(4S) cross section ~1 nb.

- 28 fb^{-1} was used in a search for a light Higgs, A^0: $\Upsilon(3S) \rightarrow \gamma A^0$, $A^0 \rightarrow$ invisible.

  - Not published; conference note BaBar-CONF-08/019

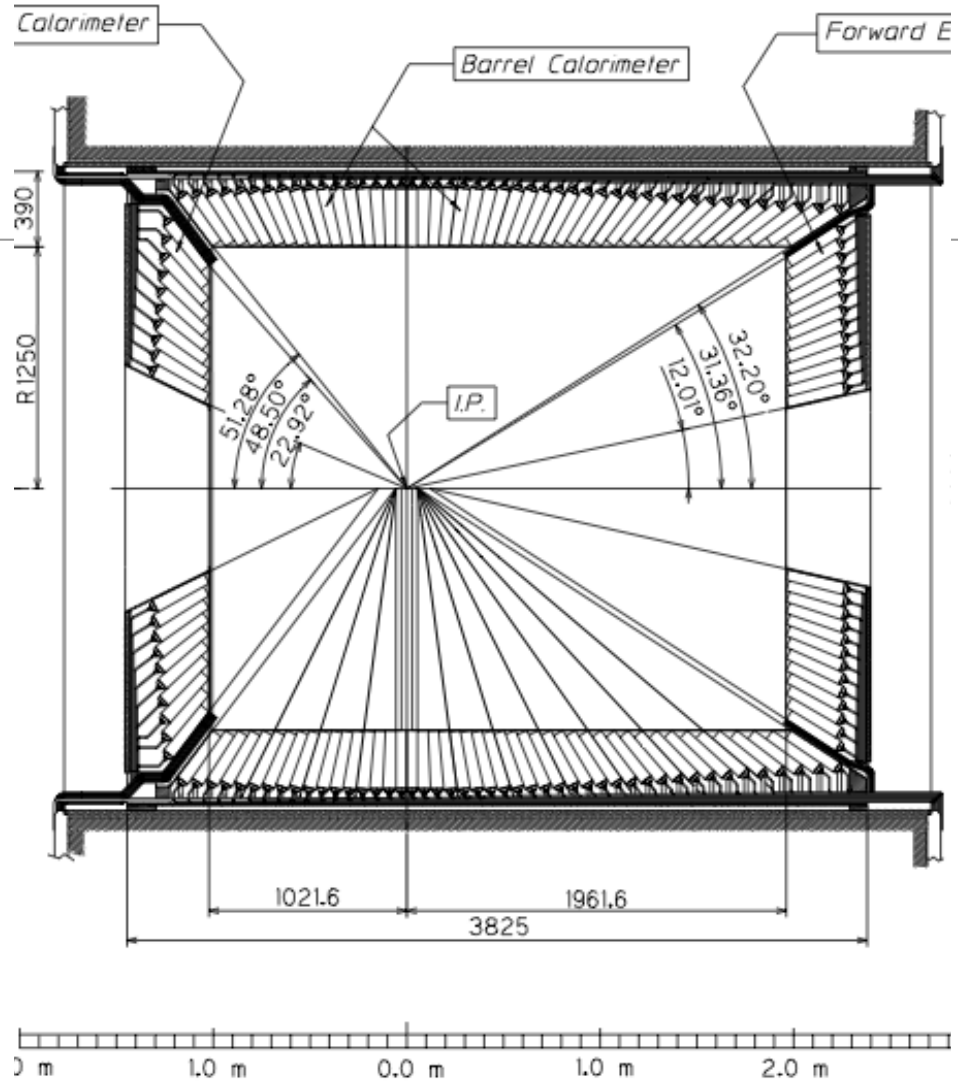
BaBar conference note

- Peaking background from $e^+e^- \rightarrow \gamma\,\gamma$, where one gamma passed through the calorimeter without interacting due to projective cracks between crystals.



BaBar-CONF-08/019

Belle II calorimeter



Hitomi Ikeda
NWU-HEP 99-01

- 8736 CsI(Tl) crystals, typically 5×5×30 cm^3. No projective cracks, except gaps between endcaps and barrel.

Expected Belle II backgrounds — $\gamma\gamma$

- $e^+e^- \rightarrow (\gamma_{ISR})\gamma\gamma$, where only one photon is detected.

- Irreducible (but calculable) component from ISR. Strongly suppressed by kinematic cuts.
  - generator = BabaYaga

- Need good understanding of photon efficiency (particularly barrel/endcap gaps) when one photon misses and the other is not detected.

- Peaking background from $e^+e^- \rightarrow \gamma\gamma$ is negligible, other than gap regions.

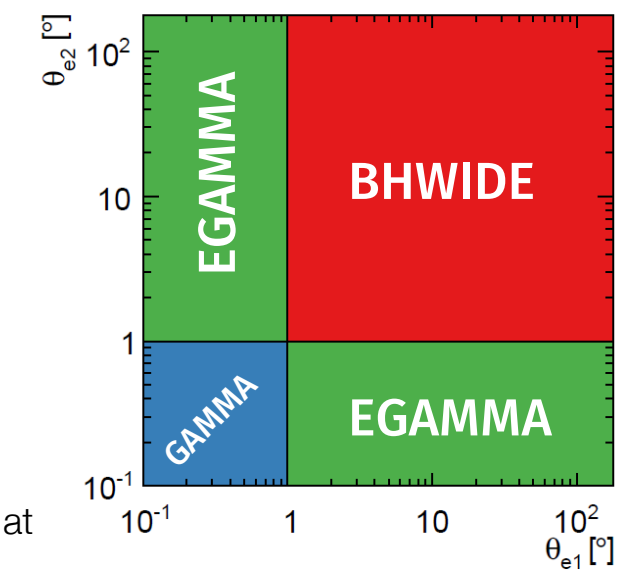
Expected backgrounds — radiative Bhabhas $e^+e^- \rightarrow \gamma(\gamma)e^+e^-$

- Irreducible component when all final state particles except one photon are outside of acceptance.

- Studying this requires two generators:

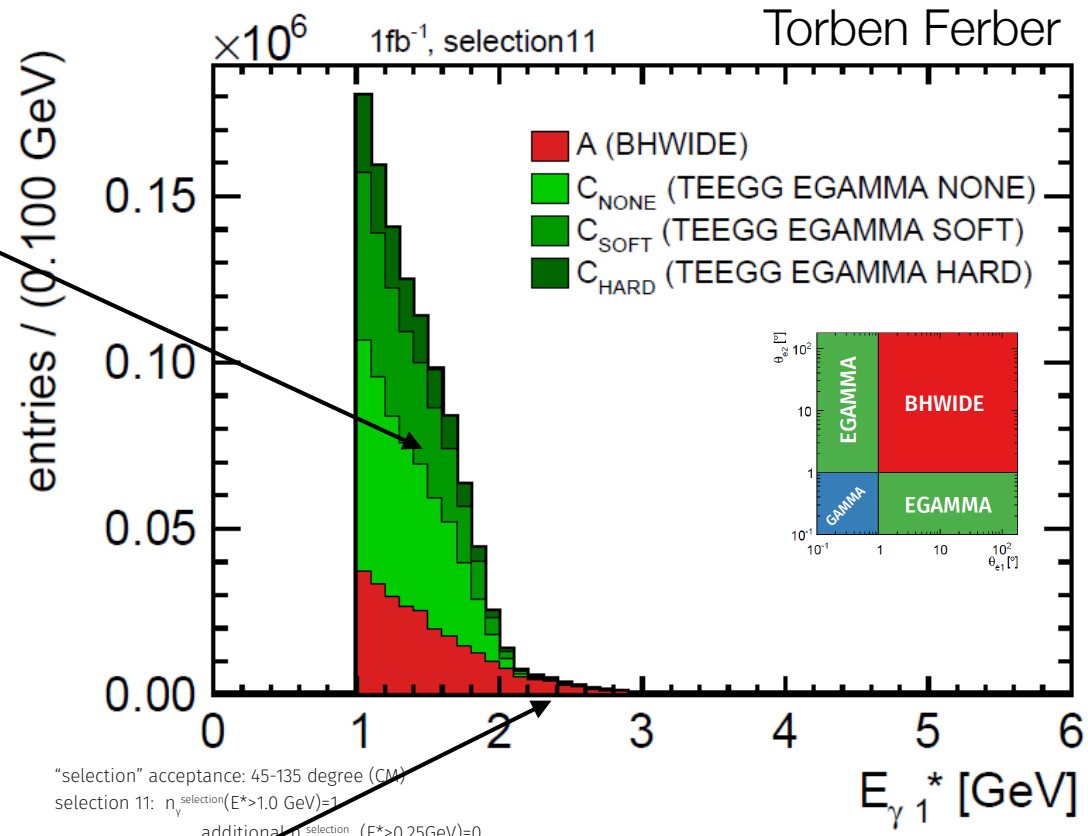
  - BHWide or BabaYaga for “wide angle” scattering: both outgoing electrons are scattered >1 deg

  - TEEGG: at least 1 electron scatters <1 deg (EGAMMA & GAMMA)
    D. Karlen Nucl. Phys. B289 (1987) 23



- $E^* > 1$ GeV in $45° < \theta^* < 135°$ (ECL barrel). Cross section = 1.1 nb.

Dominant process below 2 GeV is one electron at ~0 deg, other outside of detector acceptance



Above 2 GeV, both $e^{\pm}$ are scattered at wide angles

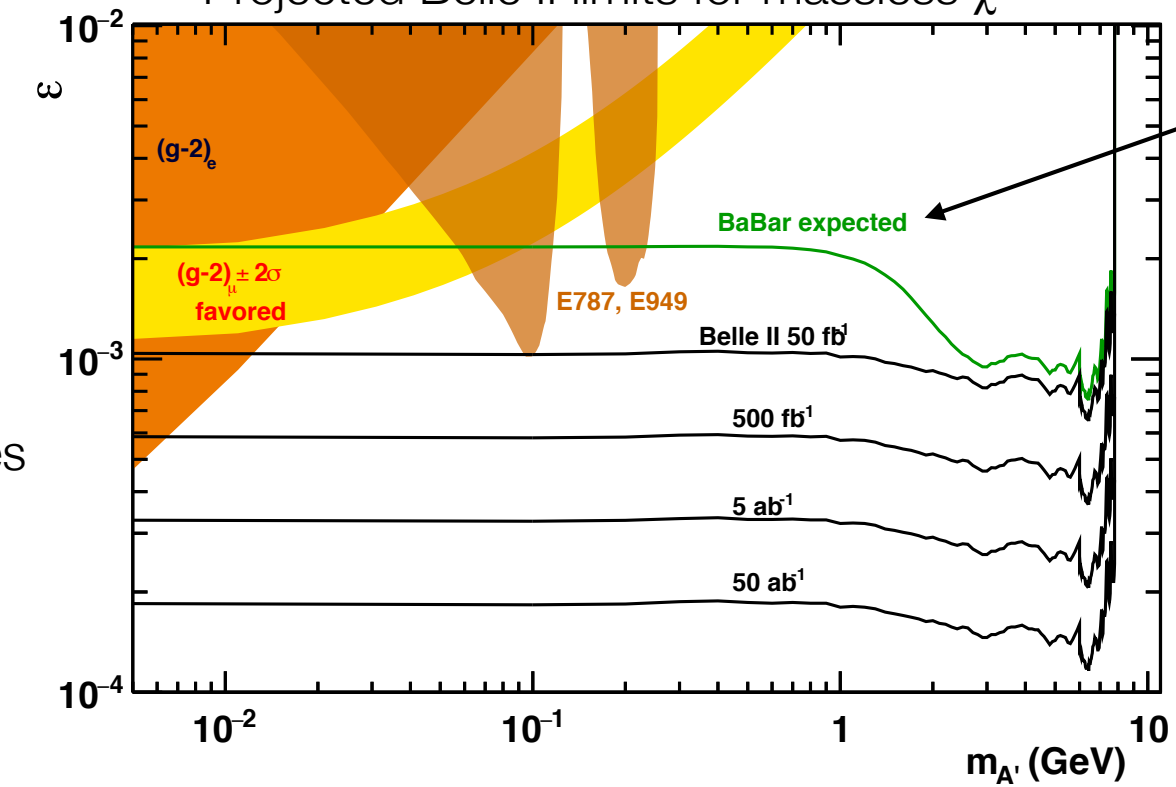
Signal event generation

- MadGraph used by BaBar and so far by Belle II
- We are working on implementing $e^+e^- \to \gamma A'$ in BabaYaga, which should correctly handle ISR, FSR, and interference with SM processes.
  - Not included in the MadGraph generation.

Projection

- Extrapolating from BaBar preliminary result; correct for different angular distribution of signal; improved systematic error at low mass.

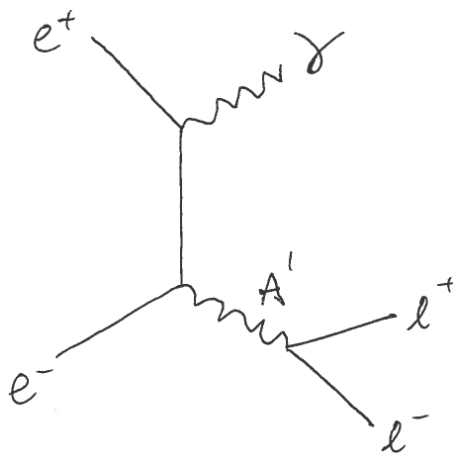
Projected Belle II limits for massless χ



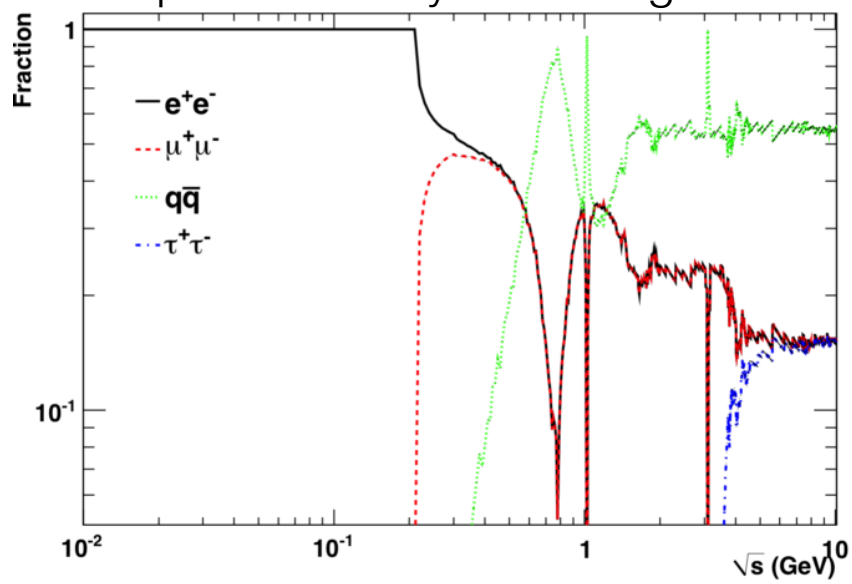
28 fb^{-1} sample

limit on ε improves as $L^{0.25}$

Search for Dark Photon decaying to leptonic final states



Dark photon decay branching fractions



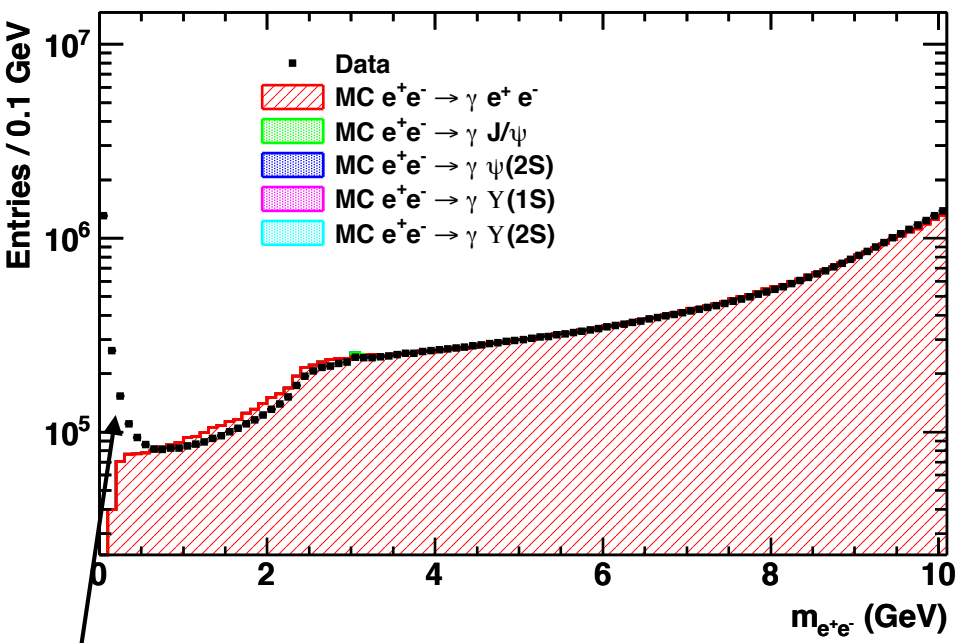
Bertrand Echenard

- Final state is photon plus lepton pair. Large SM backgrounds, particularly in electron final state.
- Muon final state is dominant above threshold due to lower backgrounds.

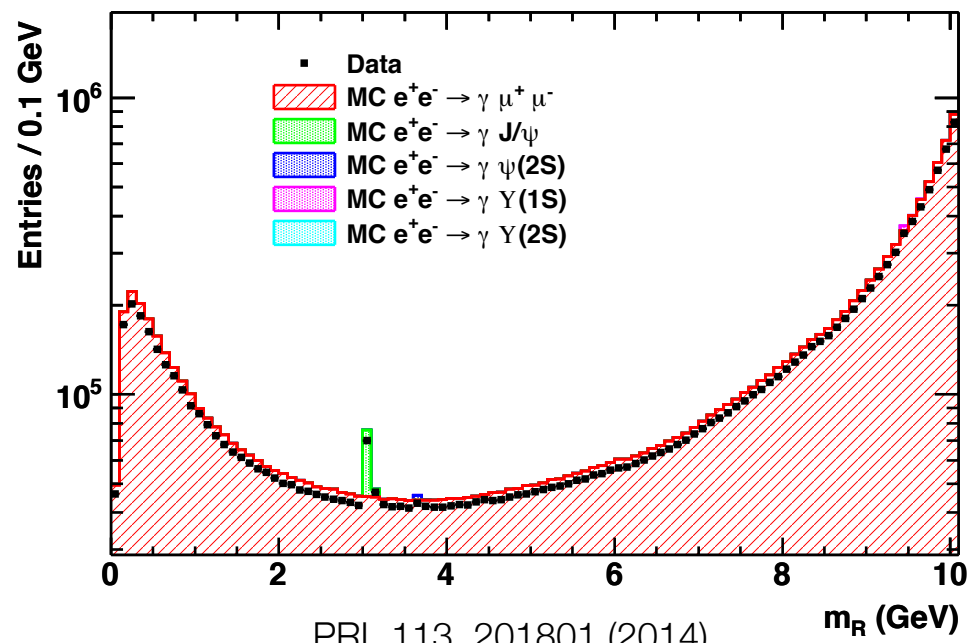
Projected limits for Belle II

- Estimate Belle II limits from BaBar paper

e^+e^-



$\mu^+\mu^-$



PRL 113, 201801 (2014)

BHWide does not simulate this configuration; better in BabaYaga

Considerations for projection

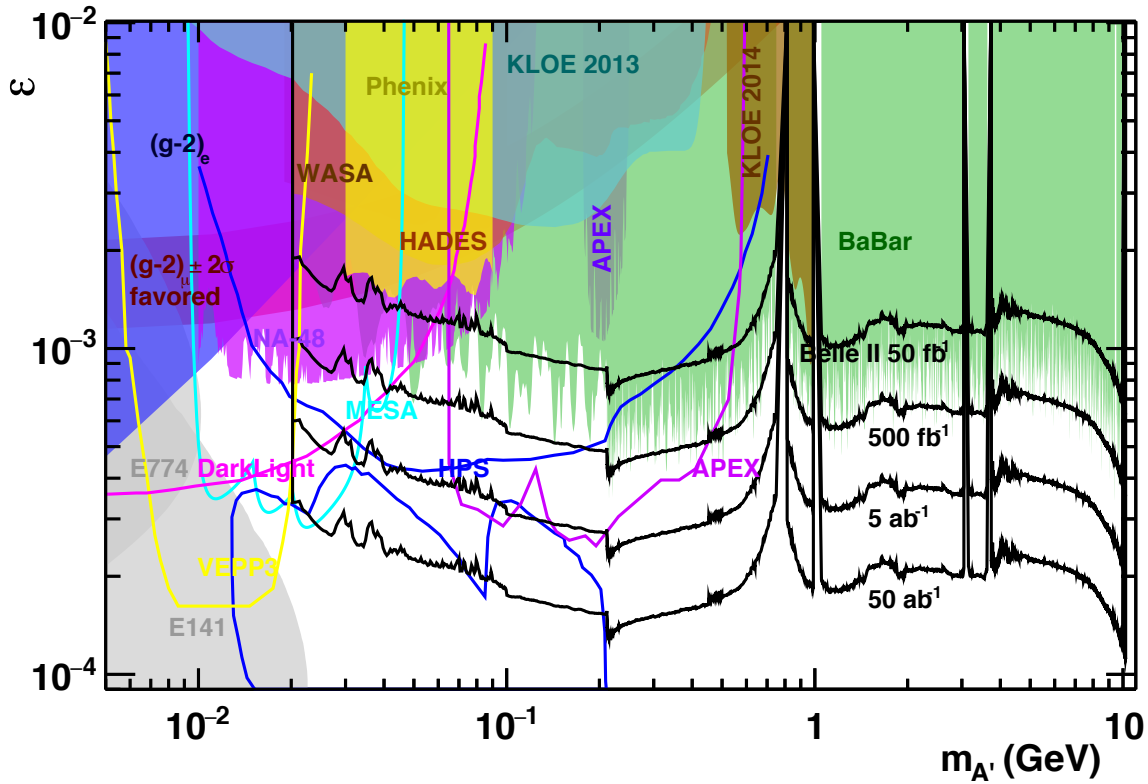
- Limit on epsilon improves as luminosity$^{0.25}$
- Assume improvement in efficiency of e^+e^- final state (BaBar efficiency in e^+e^- was half of $\mu^+\mu^-$ due to trigger)
- Belle II mass resolution should be 2× BaBar: radius of drift chamber is 1130 mm vs 800 mm.

Belle II projection for leptonic final states

Upper limit on ε
superscript 0 ⇒ BaBar value

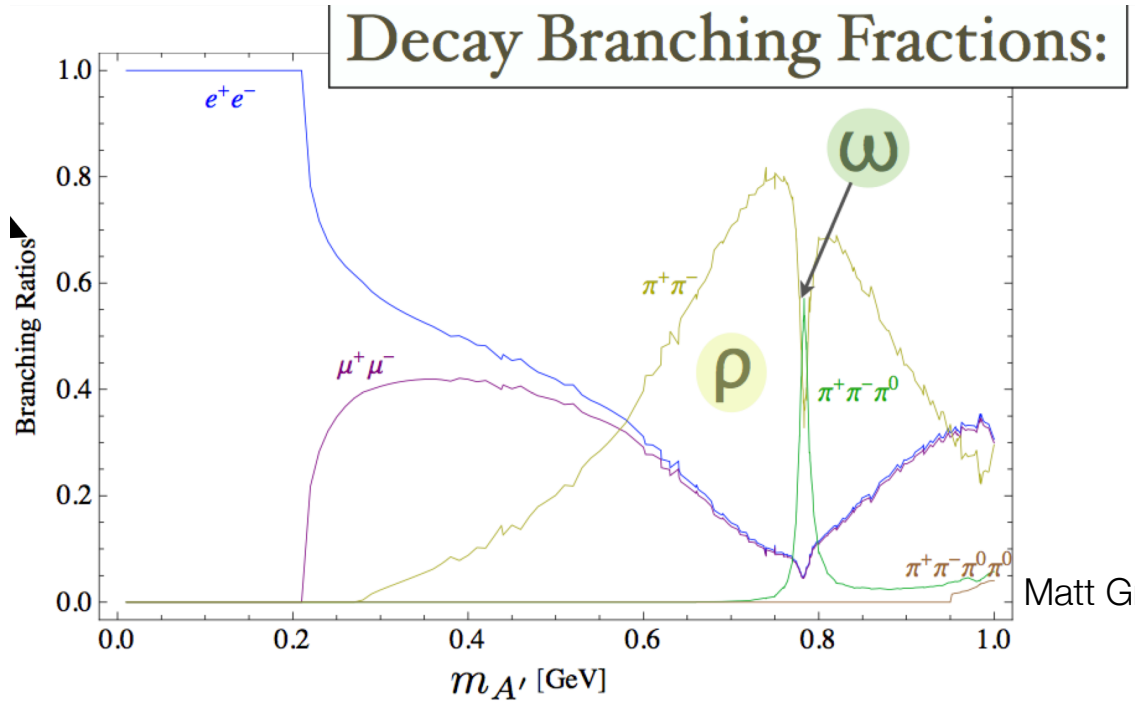
$$\frac{U_\epsilon}{U_\epsilon^0} = \left(\frac{\mathcal{L}^0}{\mathcal{L}} \frac{\Delta_M}{\Delta_M^0} \frac{\epsilon_{\ell\ell}^0}{\epsilon_{\ell\ell}} \right)^{0.25}$$

Bertrand Echenard
Chris Hearty



- I would be interested in updated projections for other experiments.

Hadronic final state



Matt Graham

- Might be worth looking at hadronic final states to cover the regions excluded in the BaBar plot.
  - KLOE-2: "Limit on the production of a new vector boson in $e^+e^- \rightarrow U\gamma$, $U \rightarrow \pi^+\pi^-$ with the KLOE experiment", Phys. Lett. B (in press)

Low multiplicity triggers

- Current focus of the low-multiplicity physics group.
- Maximum level 1 trigger rate at full luminosity corresponds to a cross section of 38 nb.
- Designing separate single photon triggers for calorimeter endcaps and barrel with at least two energy thresholds for maximum flexibility.
  - recall BaBar level 3 single photon rate = 20 nb.

- We may be able to support triggers at initial (low) luminosity that we can't use at full luminosity. e.g. $\Upsilon(2S) \rightarrow \pi^+\pi^- \Upsilon(1S)$, $\Upsilon(1S) \rightarrow$ invisible
  - this work is needed to establish whether or not there is a case for running at the $\Upsilon(2S)$.

Summary

- Goal is that the search for dark photon decaying invisibly will be one of the earliest Belle II measurements, possibly even during Phase 2 running starting in late 2017.
- The Belle II calorimeter and tracking are improvements over BaBar.
- Wider range of event generators (wrt BaBar) helps with projections.
- Our current focus is on developing the triggers to enable these measurements.

Backup

Final focus quadrupoles are the critical accelerator component for Phase 2

- QCSL magnet cryostat was set in the Super. Cryo. Vac. Experimental Laboratory at Dec. 25 and 26, 2015.

K. AKAI, SuperKEKB status, schedule and plans, Feb. 1, 2016 @B2GM 23

Invisible decays of the Y(1S)

- Searches for invisible decays of Y resonances may not be strongly motivated by dark sector models, but are sensitive to some models of low mass dark matter.

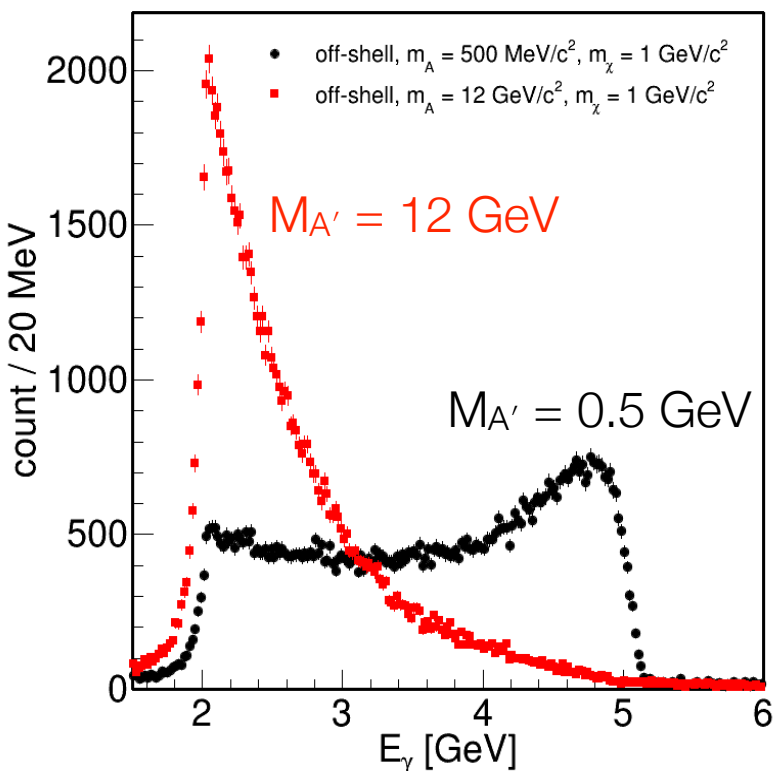
- BaBar searched for Y(2S) → $\pi^+\pi^-$ Y(1S), Y(1S) → invisible
  PRL 103, 251801 (2009)

  - 23 fb^{-1} @ Y(3S) = 4.2M Y(1S)

- We could match this dipion-tagged Y(1S) production with 3.4 fb^{-1} @ Y(2S). The trigger (and analysis) is very challenging.

Invisible decays, off-shell A′

- Depending on the dark sector masses, the process $e^+e^- \to \gamma\chi\chi$ could occur through a virtual A′. In this case, the $\chi\chi$ invariant mass does not peak.



Igal Jaegle

- Requires a good understanding of the rates and invariant mass distributions of the high-rate standard model backgrounds.

- A specialized detector would do a better job.