



THE UNIVERSITY OF BRITISH COLUMBIA



Belle II — IPP Scientist Report

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U. British Columbia / IPP
June 26, 2026

IPP Annual General Meeting 2026

Introduction

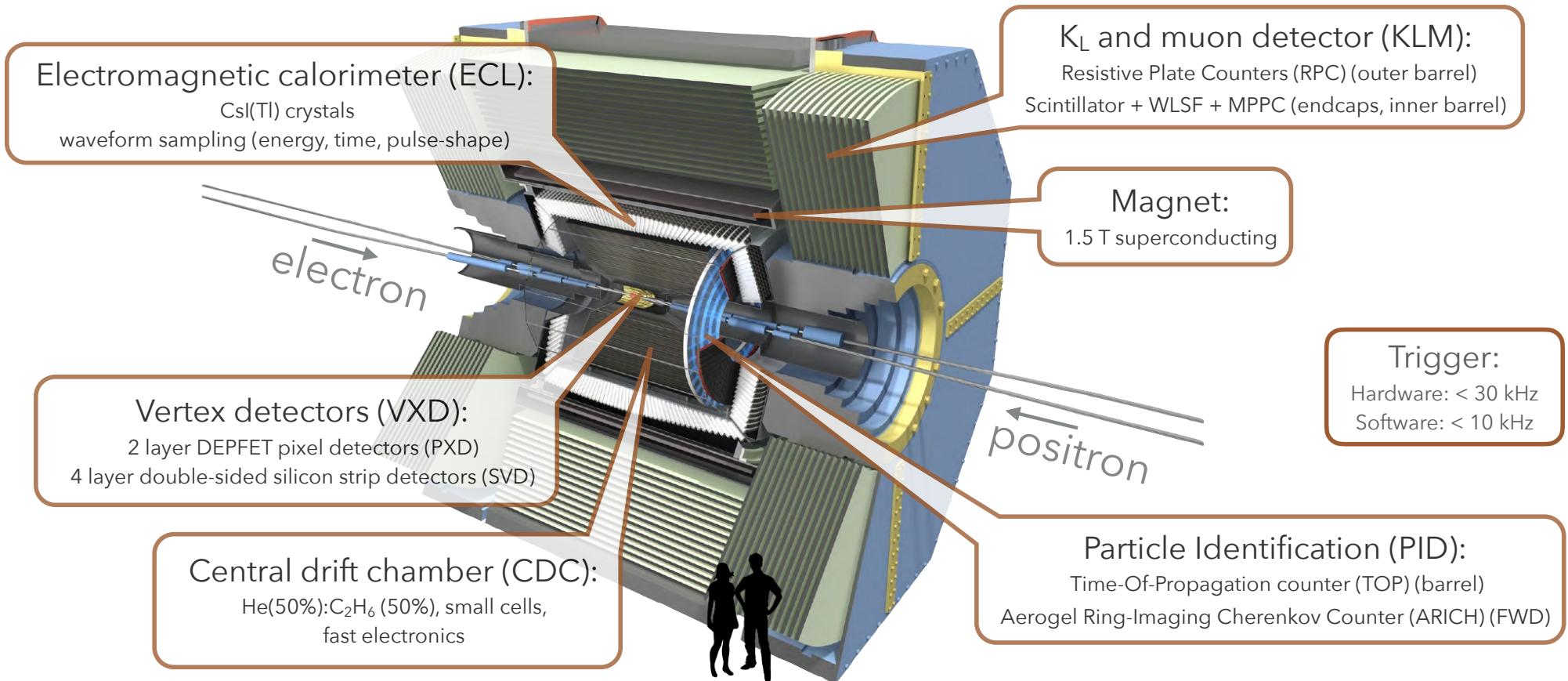
Belle II



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



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



Physics

- Broad physics program:
 - evidence for new physics in modes with solid standard model predictions;
 - Standard model (weak force, hadron spectroscopy...)
 - new particles (dark sector)
- B mesons; charm; tau (including lepton flavour violation); initial-state radiation production of $\pi^+\pi^-$ and such; quarkonium, including new XYZ states.

SuperKEKB

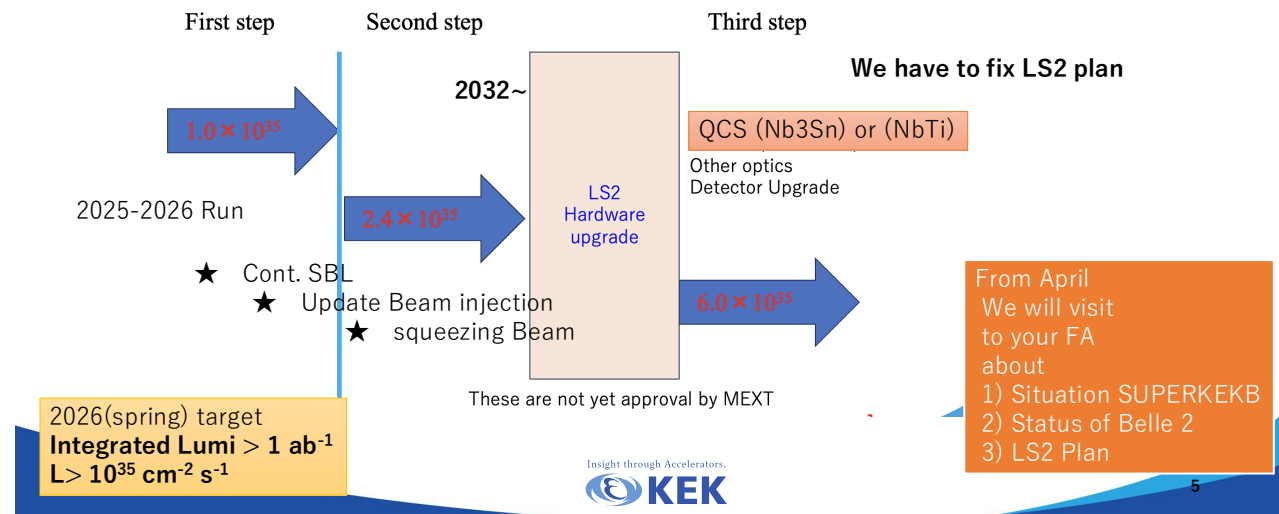
- Operating since 2019. Luminosity goal is $50 \text{ ab}^{-1} = 100\times$ BaBar; $\sim 2\times$ BaBar so far, but with a better detector
- Instantaneous: $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$; target $6 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$.

Long Plan of SuperKEKB

not yet approved

Three steps are considered.

New Joint Advisory committee will discuss about LS2 plan



Canadian group

- 13 faculty, 3 postdocs, 15 graduate students at 6 institutions.
- I was PI of the NSERC project grant (and BaBar before it) for ~25 years, until April 1, 2026. Now Savino Longo (Manitoba).

Dark Sector

The most compelling question in particle physics

- Much of the universe is composed of matter that does not interact with photons, and is not consistent with the standard model.

Cluster MACS J0025.4-1222. Blue shows mass distribution from gravitational lensing; red shows ordinary matter from x-ray imaging

NASA, ESA, CXC, M. Bradac, and S. Allen



- What is the particle nature of dark matter?

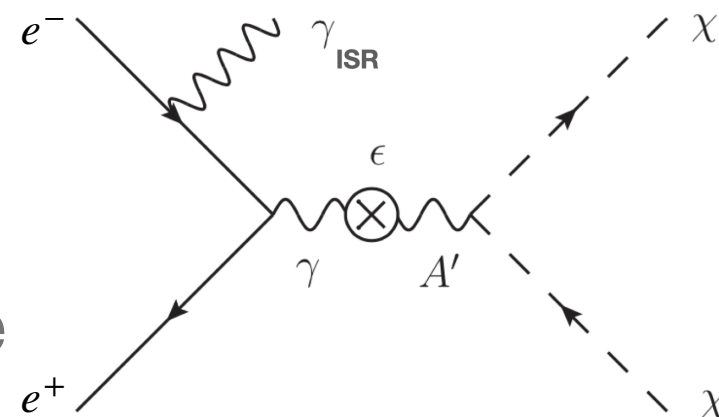
Dark sector and low multiplicity working group

- One of 8 physics working groups. I was the co-convenor from August 2023 – March 2026.
- Searches for direct production of new particles.
- Standard model processes with few particles in the final state.
 - e.g. $e^+e^- \rightarrow \gamma\pi^+\pi^-$
- I will briefly review the analysis topics of my group at UBC.

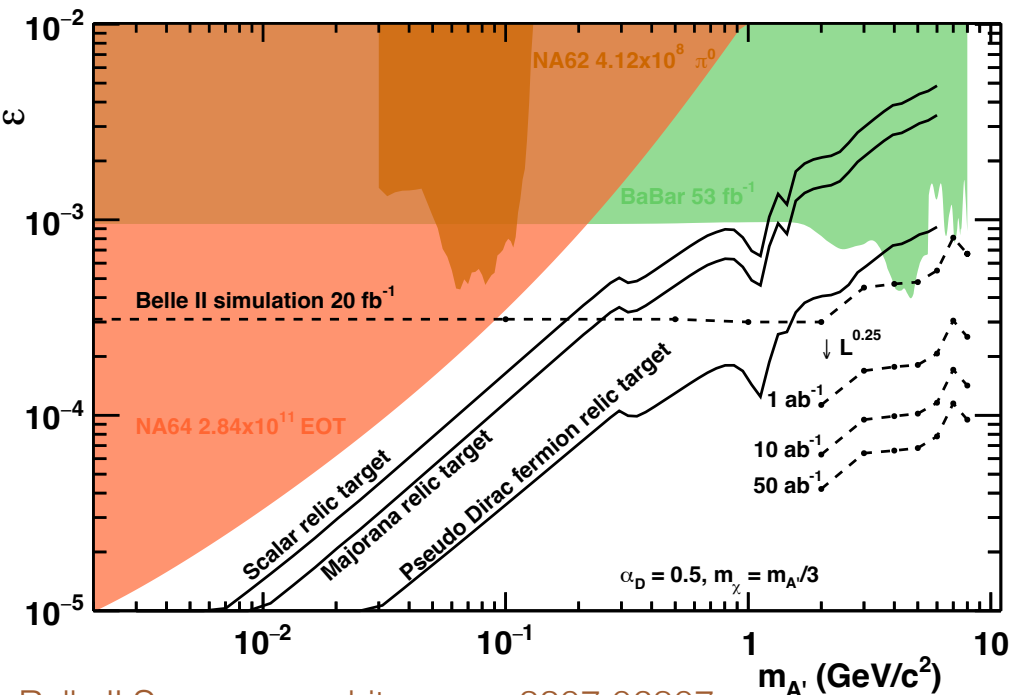
Invisible decays of the dark photon

“single photon analysis”

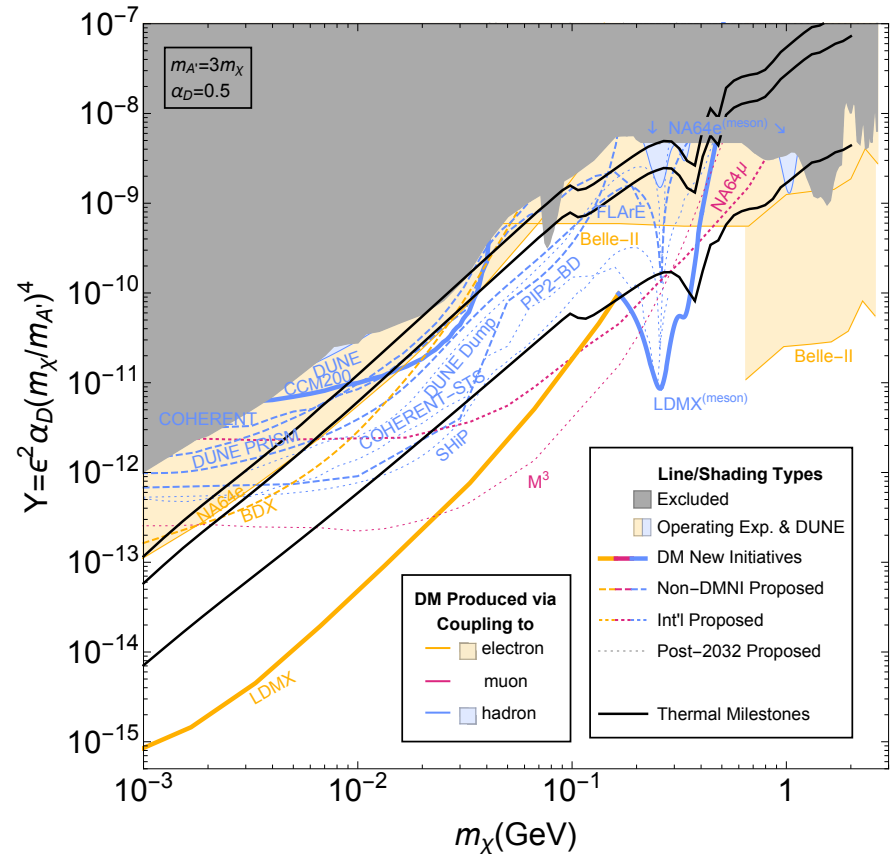
- Dark photon A' mixes with γ , decays to dark matter χ .
- Single photon only in the final state
- Can deduce the mass of the dark photon due to the well-defined initial state: $p_{A'} = p_{e^+} + p_{e^-} - p_{\gamma}$
- Challenge is understanding background from $e^+e^- \rightarrow \gamma\gamma(\gamma)$, where a photon is missed in the detector.
 - especially two body $e^+e^- \rightarrow \gamma\gamma$, which looks identical to a low-mass dark photon.



- Belle II will have unique sensitivity to regions of parameter space consistent with observed dark matter relic density.



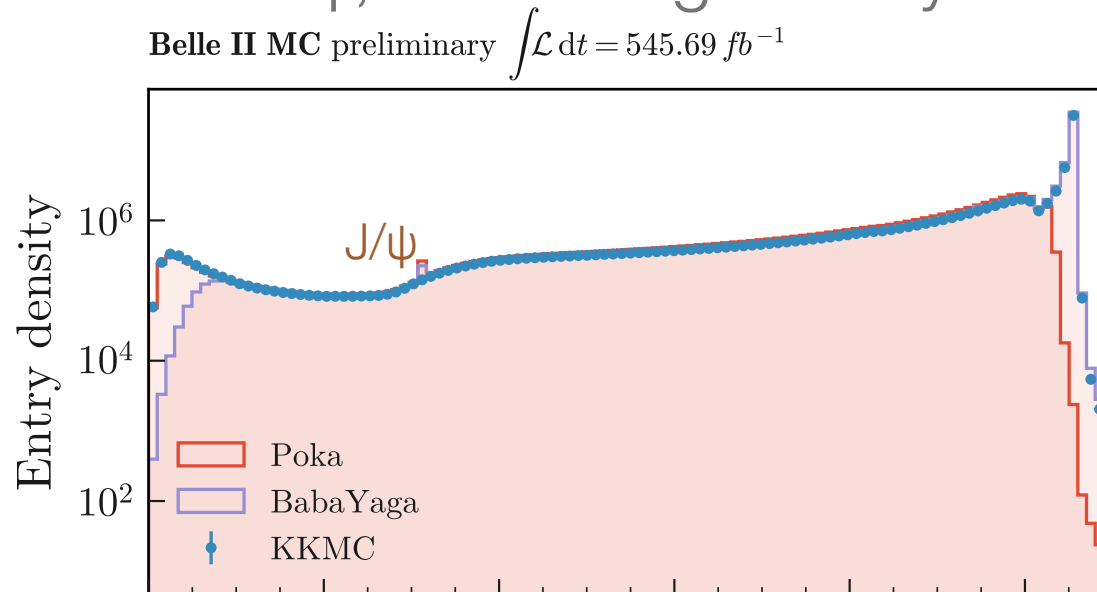
Belle II Snowmass white paper 2207.06307



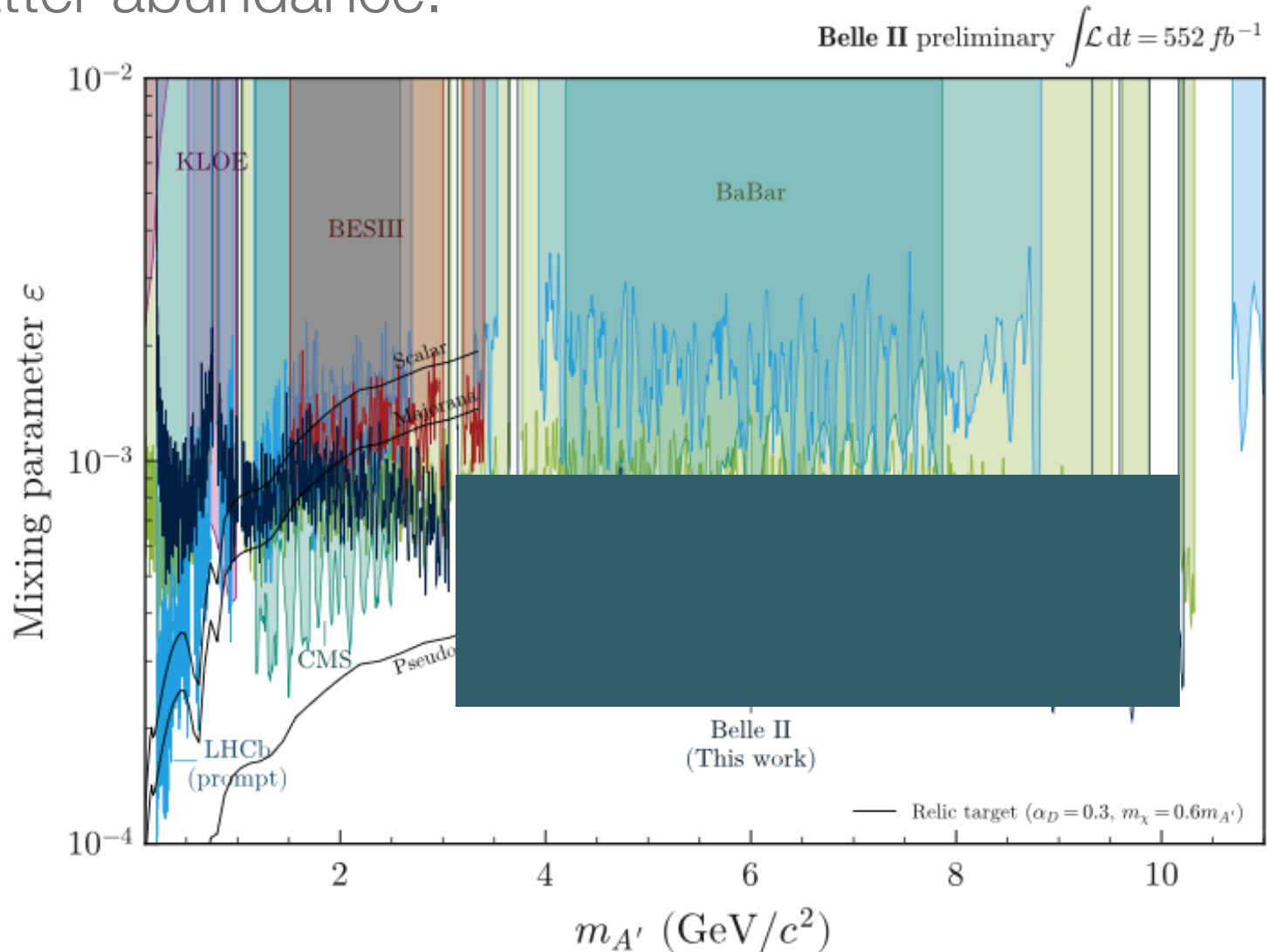
Snowmass RF6 report 2209.04671

Dark photon decaying to muons

- Dark photon will decay to standard model if it cannot decay to dark matter. Signature: narrow peak in the $\mu^+\mu^-$ mass spectrum, on top of a large background.
- Key improvement (compared to BaBar): Do not reconstruct the γ , which is generally at low angle.

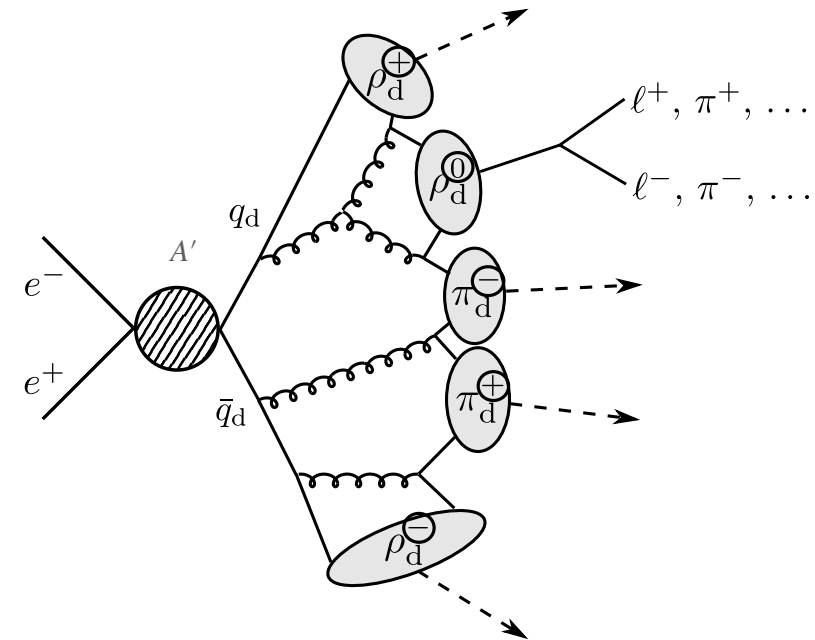


- Belle II will have sensitivity to new regions of parameter space consistent with observed dark matter abundance.



Dark showers

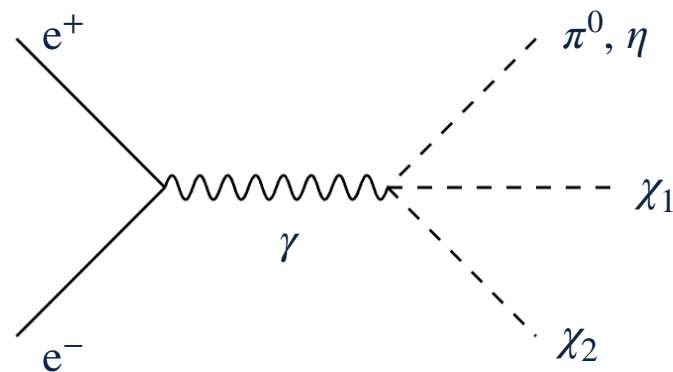
- Dark sector could be more complicated, e.g. dark quarks \Rightarrow dark showers. Mostly invisible, but dark ρ will decay to standard model if it can't decay to dark π .
- Signature: single displaced vertex.
- Challenges: initially extremely high backgrounds from random track overlaps and conversion.
- Ready this summer?



E. Bernreuther et al. Forecasting dark showers at Belle II, 2022

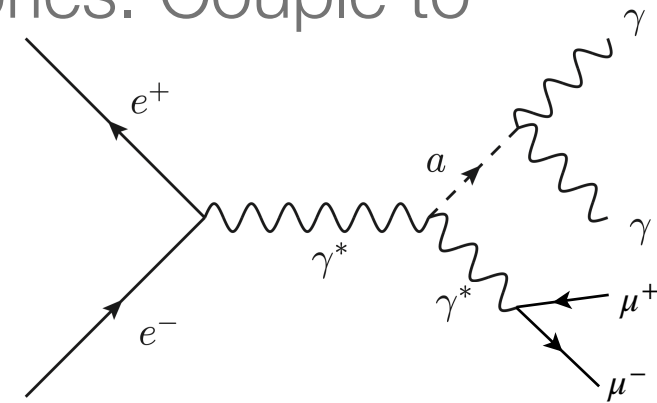
Topological portal to the dark sector

- Phys. Rev. Lett. 134, 111804 proposes new mechanism that links QCD and the dark sector. Four-point interaction between photon, π^0 , and two dark pions.
- Signature: single π^0 or η .
- In progress, but early days.



Low-mass axion-like particle

- Axion-like particles (similar to the QCD axion) appear in many beyond-the-standard-model theories. Couple to gauge bosons. Photons in this case.
- Published Belle II search could not reach low masses due to backgrounds and poor resolution in γ + axion-like-particle final state.
- Hope is that muons address both issues.



Encyclopedia of particle physics

- New project to provide an entry-level introduction to a wide-range of topics. I have wrote the chapter on the search for dark matter at accelerators, along with my ex-postdoc Torben Ferber.
 - available August.

Searches for dark matter at accelerators

Torben Ferber^a and Christopher Hearty^{b,c}, ^a Karlsruhe Institute of Technology, Institute of Experimental Particle Physics, Karlsruhe, Germany; ^b Department of Physics and Astronomy, University of British Columbia, Vancouver, BC, Canada; and ^c Institute of Particle Physics, Edmonton, AB, Canada

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<https://doi.org/10.1016/B978-0-443-26598-3.00056-0>

Trigger

High-level trigger

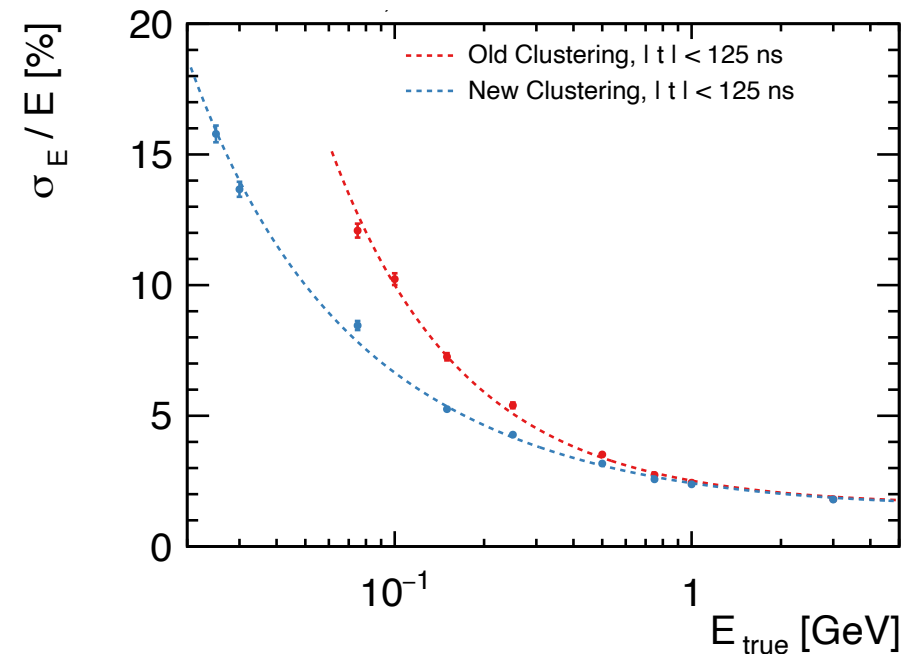
- Second level of trigger, uses almost full reconstruction. Reduces 15 kHz level 1 trigger rate to ~ 1 kHz.
- I am responsible for developing, writing, and maintaining the high-level trigger menu (i.e., what events do we keep)
- Challenge is on the dark sector / low multiplicity side. Recent additions include displaced vertex; single π^0 .
- Primary focus recently has been on ensuring good efficiency in the face of reduction in drift chamber performance (backgrounds, aging, helium shortages).

ECL - Physics			
filter Elab gt 0.3 plus 3 others with Elab gt 0.18 plus no clust with Ecms gt 2.0	21 (42.86%)	21 (42.86%)	1.0
filter Elab gt 0.5 plus 2 others with Elab gt 0.18 plus no clust with Ecms gt 2.0	4 (8.16%)	4 (8.16%)	1.0
filter gel Estartgt2 GeV neutral clst 2232 or 130145 not gg2clst ee2clst eeleg eeBremB	0 (0.00%)	0 (0.00%)	1.0
filter gel Estartgt2 GeV neutral clst 32130 not gg2clst eeleglclst eelegltrk eeBremB	3 (6.12%)	3 (6.12%)	1.0
ECL - Potentially Prescaled			
filter 0.3ltEstar max clustlt2 GeV plus 2 others gt 0.2 GeV	0 (0.00%)	24 (48.98%)	100.0
filter 1 electron Estartgt1 GeV clust in 45115 and no other clust Estartgt0.3 GeV	0 (0.00%)	3 (6.12%)	10.0
filter 1 electron Estartgt1 GeV clust in 32130 and no other clust Estartgt0.3 GeV	0 (0.00%)	3 (6.12%)	100.0
filter 1 Estartgt1 GeV cluster no other cluster Estartgt0.3 GeV	0 (0.00%)	8 (16.33%)	200.0
filter 1 photon Estartgt1 GeV clust not low not 45115 no other clust Estartgt0.3 GeV	0 (0.00%)	0 (0.00%)	50.0
filter gg2clst	0 (0.00%)	0 (0.00%)	100.0
filter gel Estartgt2 GeV chrg clst 22145 not gg2clst ee2clst eeleg	0 (0.00%)	8 (16.33%)	50.0
filter ggEndcapLoose	0 (0.00%)	0 (0.00%)	1.0
filter n2GeVPhotonBarrelgel	0 (0.00%)	1 (2.04%)	100.0
filter n2GeVPhotonEndcapgel	0 (0.00%)	0 (0.00%)	50.0
filter Estartgt2 GeV cluster	0 (0.00%)	10 (20.41%)	100.0
filter ECLMuonPair	0 (0.00%)	0 (0.00%)	10.0
CDC - Physics			
filter ge3 looseB tracks inc 1 tightB not ee2leg	5 (10.20%)	5 (10.20%)	1.0
filter ge3 trackC not ee2leg	4 (8.16%)	4 (8.16%)	1.0
filter 2 looseB tracks inc 1 tightB q==0 pstarmaxlt0.8 GeVc not eexx	2 (4.08%)	2 (4.08%)	1.0
filter 2 looseB tracks 0.8ltpstarmaxlt4.5 GeVc not ee2leg eelegltrk eexx	40 (81.63%)	40 (81.63%)	1.0
filter 2 looseB tracks pstarmaxgt4.5 GeVc not ee2leg eelegltrk eelegle eeBremB muonPairVB	1 (2.04%)	1 (2.04%)	1.0
CDC - Potentially Prescaled			
filter 2 loose tracks pstarmaxlt0.8 GeVc	0 (0.00%)	2 (4.08%)	100.0
filter 2 loose tracks 0.8ltpstarmaxlt4.5 GeVc	0 (0.00%)	39 (79.59%)	100.0
filter 2 loose tracks pstarmaxgt4.5 GeVc	0 (0.00%)	1 (2.04%)	500.0
filter gel tight track	0 (0.00%)	49 (100.00%)	1000.0
filter 2 looseC tracks inc 1 tightB q==0 pstarmaxlt0.8 GeVc not eexx	0 (0.00%)	2 (4.08%)	100.0
filter 2 trackC 0.8ltpstarmaxlt4.5 GeVc not ee2leg eelegltrk eexx	0 (0.00%)	42 (85.71%)	100.0
filter 2 trackC pstarmaxgt4.5 GeVc not ee2leg eelegltrk eelegle eeBremB muonPairVB	0 (0.00%)	1 (2.04%)	100.0
Targeted Physics Lines			
filter 1 photon Estartgt1 GeV clust in 45115 and no other clust Estartgt0.3 GeV	2 (4.08%)	2 (4.08%)	1.0
filter 1 photon Estartgt1 GeV clust in 32130 and no other clust Estartgt0.3 GeV	2 (4.08%)	2 (4.08%)	1.0
filter 1 photon Estartgt0.5 GeV clust in 4498 and no other clust Estartgt0.3 GeV	1 (2.04%)	1 (2.04%)	1.0
filter ggBarrelLoose	0 (0.00%)	0 (0.00%)	1.0
filter singleTagLowMassB	0 (0.00%)	0 (0.00%)	1.0
filter singleTagHighMassB	0 (0.00%)	0 (0.00%)	10.0
filter b2b phi photons	0 (0.00%)	0 (0.00%)	1.0
filter displaced vertex	0 (0.00%)	0 (0.00%)	1.0
filter single diPhoton	0 (0.00%)	0 (0.00%)	1.0
QED / Control Samples			
filter ee flat 0 19	0 (0.00%)	0 (0.00%)	62.0
filter ee flat 19 22	0 (0.00%)	0 (0.00%)	36.0
filter ee flat 22 25	0 (0.00%)	0 (0.00%)	30.0
filter ee flat 25 30	0 (0.00%)	0 (0.00%)	10.0
filter ee flat 30 35	0 (0.00%)	0 (0.00%)	36.0
filter ee flat 35 45	0 (0.00%)	0 (0.00%)	30.0
filter ee flat 45 60	0 (0.00%)	0 (0.00%)	10.0
filter ee flat 60 90	0 (0.00%)	0 (0.00%)	4.0
filter ee flat 90 180	0 (0.00%)	0 (0.00%)	2.0
filter selectees	0 (0.00%)	0 (0.00%)	20.0
filter seleelleglclst	0 (0.00%)	2 (4.08%)	1000.0
filter seleellegltrk	0 (0.00%)	4 (8.16%)	1000.0
filter eexxSelectB	0 (0.00%)	1 (2.04%)	4.0
filter eexxHighP	1 (2.04%)	1 (2.04%)	1.0
filter radiative BhabhaB	1 (2.04%)	2 (4.08%)	4.0
filter selectmumu	2 (4.08%)	2 (4.08%)	1.0
filter selectmumuC	2 (4.08%)	2 (4.08%)	1.0
filter single muon	1 (2.04%)	9 (18.37%)	10.0
filter cosmic	0 (0.00%)	0 (0.00%)	1.0
filter rad Bhabha ltrkB	0 (0.00%)	0 (0.00%)	4.0
filter Bhabha one cluster	0 (0.00%)	0 (0.00%)	10.0
Level 1 Passthrough			
filter L1 trigger	0 (0.00%)	49 (100.00%)	1000.0
filter passthrough l1 trigger delayed bhabha	0 (0.00%)	0 (0.00%)	1.0
filter passthrough l1 trigger random	0 (0.00%)	0 (0.00%)	1.0
filter passthrough l1 trigger poisson	0 (0.00%)	0 (0.00%)	1.0
filter L1 Bhabha veto	0 (0.00%)	0 (0.00%)	10.0
filter L1 Bhabha select	0 (0.00%)	0 (0.00%)	100.0
filter L1 trigger nn info	0 (0.00%)	0 (0.00%)	8.0
filter passthrough l1 trigger f	0 (0.00%)	0 (0.00%)	1.0
filter dummy	0 (0.00%)	0 (0.00%)	1000.0
Prescaled Vetoes			
filter eeleg	0 (0.00%)	0 (0.00%)	1000.0
filter eeleglclst	0 (0.00%)	0 (0.00%)	1000.0
filter eelegle	0 (0.00%)	0 (0.00%)	1000.0
filter eelegltrk	0 (0.00%)	0 (0.00%)	1000.0
filter ee2clst	0 (0.00%)	0 (0.00%)	1000.0
filter ee2leg	0 (0.00%)	0 (0.00%)	1000.0
filter eeBremB	0 (0.00%)	0 (0.00%)	1000.0
filter eexx	0 (0.00%)	0 (0.00%)	1000.0
filter muonPairVB	0 (0.00%)	0 (0.00%)	1000.0

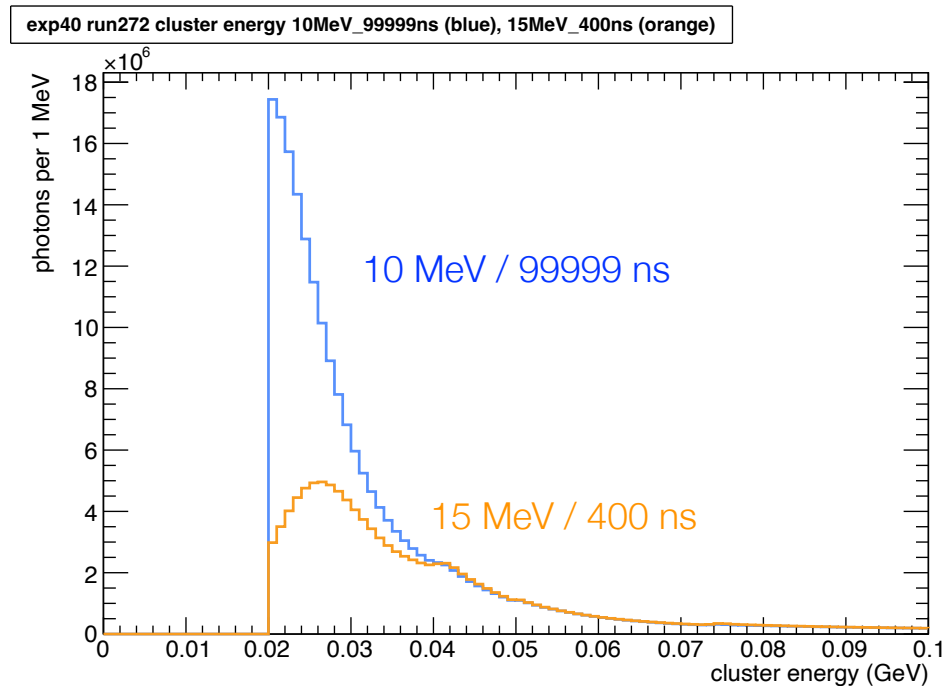
Calorimeter / Neutrals

Calorimeter

- 8736 CsI(Tl) crystals.
- Canada is part of the calorimeter group, with responsibility for reconstruction software and calibration.
- Reconstruction software was largely written by my postdoc Torben Ferber.

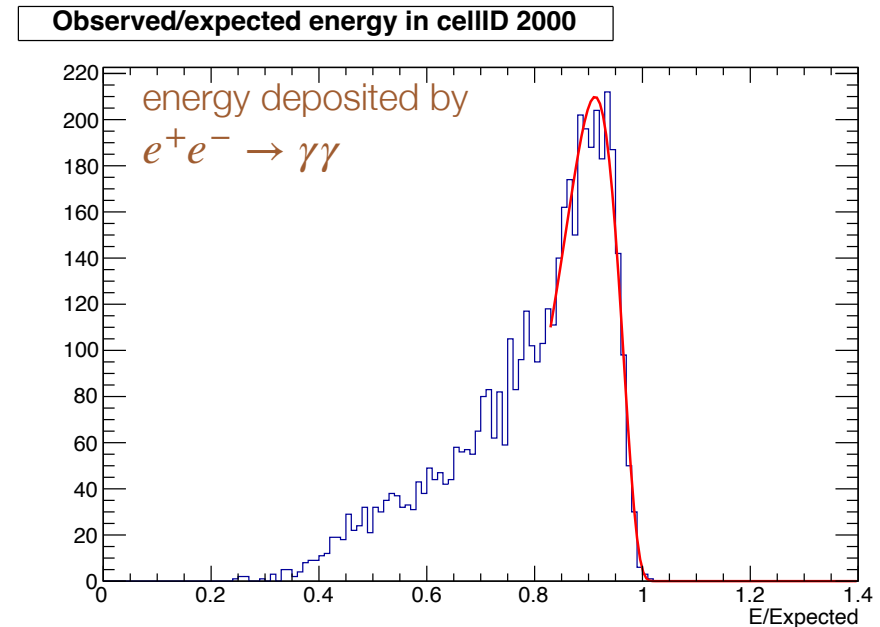


- My focus for the past ~2 years has been on improving the speed, efficiency, and purity of the reconstruction in light of higher beam backgrounds than originally expected.
- 50% reduction in fake clusters; 30% less disk space; 3% increase in low-energy real clusters.

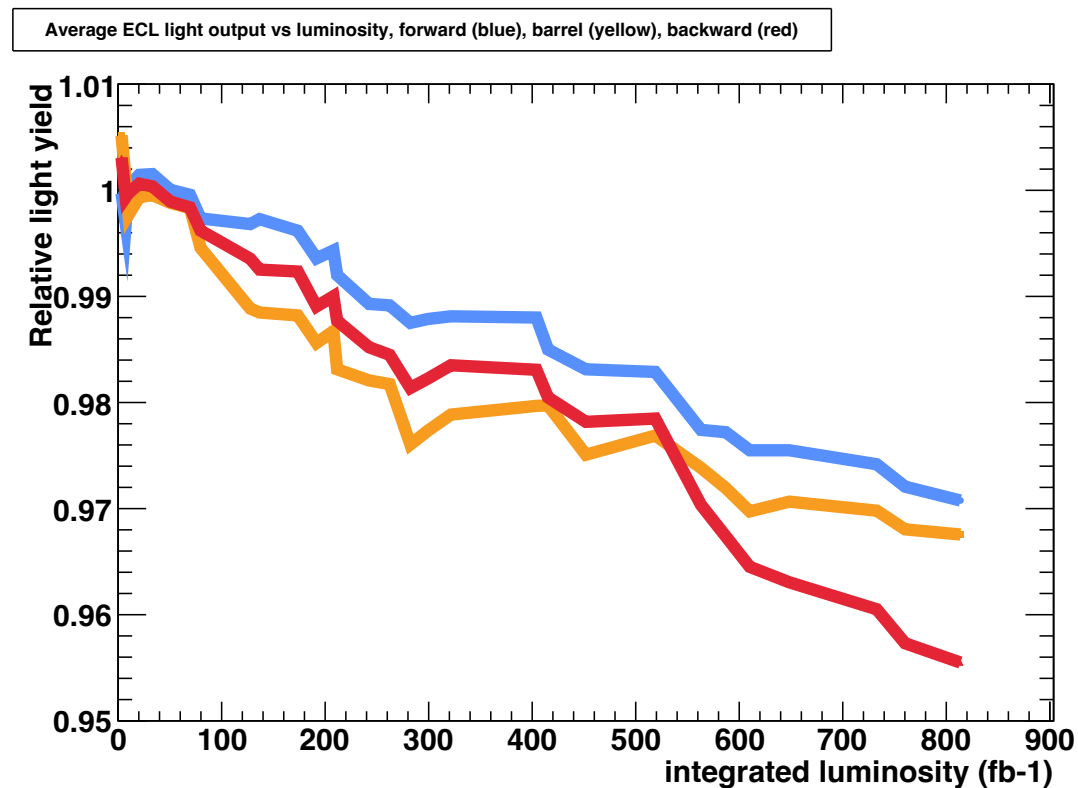


Calibration

- I am responsible for calorimeter calibration.
 - with Savino Longo, McGill student, and much work by my previous postdoc Ewan Hill.
- Energy and timing response of individual crystals; hadronic pulse shape parameters.
- Impact of background on clustering parameters.



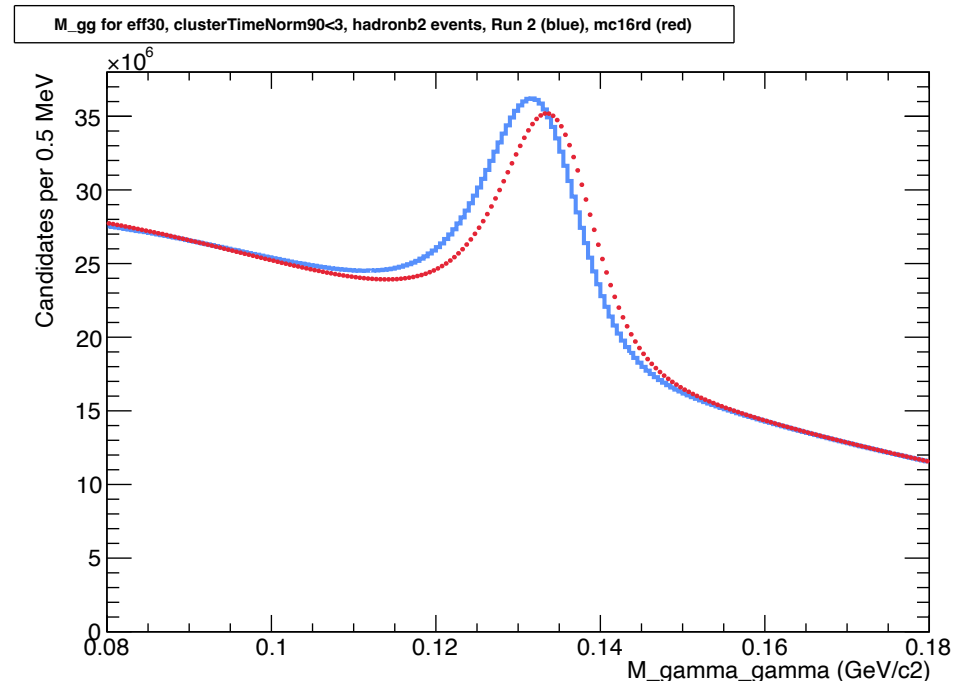
- Operationally, we calibrate “buckets” of data recorded between SuperKEKB maintenance days, 2–4 weeks.
- Challenge: calibrations have started to fail due to backgrounds and drift chamber performance.



Neutrals performance group

- I have just started a term as co-convener.
- Provides corrections and uncertainties for data/MC reconstruction differences, primarily for photons ($\pi^0 \rightarrow \gamma\gamma$). Energy bias, photon efficiency, timing.

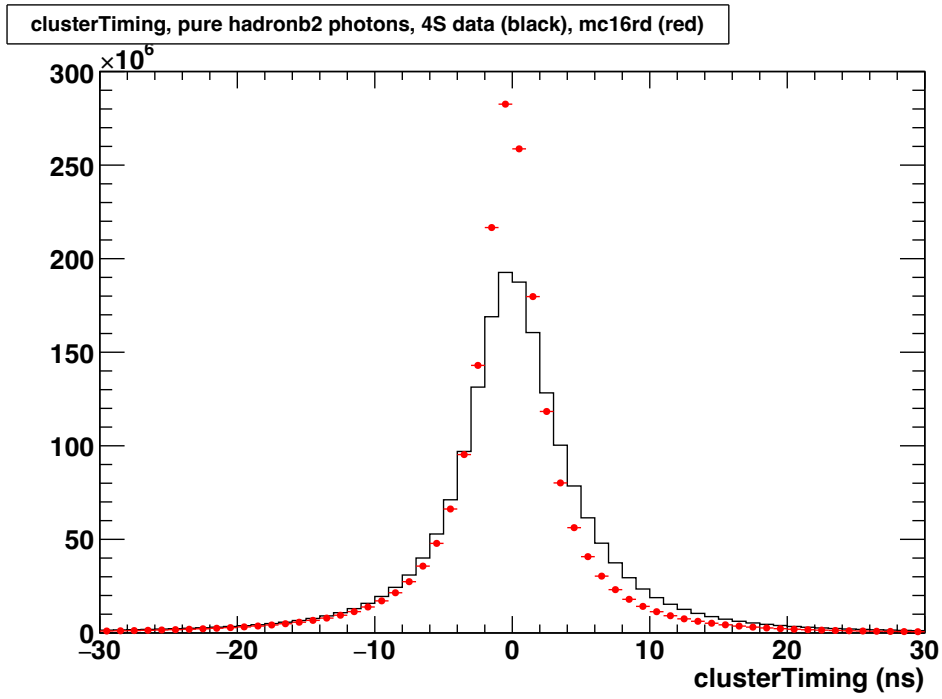
π^0 peak in data and MC
before bias correction



Photon timing

- Real detector has 8736 individually made crystals. Simulation has 8736 perfect crystals.
- I have characterized the timing response of each crystal in data and in simulation as a function of energy and background level.
- Result is a timing variable with significantly better agreement between data and simulation.

Original timing distribution



corrected variable

