Searches for beyond-the-Standard-Model particles at Belle II

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On behalf of the Belle II collaboration

Outline

Focus on analyses possible with available (0.5 fb^{-1}) or short term (20 fb^{-1}) data sets:

- Invisible decays of the dark photon
- Axion-like particles
- Invisible Z′

One-page summary of Belle II

- Located at the SuperKEKB e^+e^- collider at KEK. "Nano-beams" scheme should give 40× the luminosity of KEKB.

- Belle II is an extensive upgrade of Belle. New tracking, mostly new charged particle ID, new electronics for calorimeter.

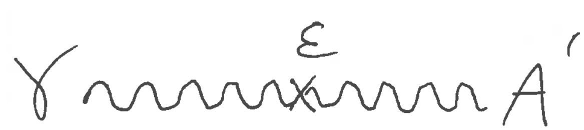
- First colliding beam data (without vertex detectors) in Spring 2018 "Phase 2". 0.5 fb^{-1} recorded.

- Currently commissioning with full detector. Expect a few fb^{-1} by July 1, 100–200 fb^{-1} by summer 2020.

Dark sector

- The absence of discoveries by the LHC or dark matter direct detection experiments motivates interest in models with low-mass dark matter candidates.

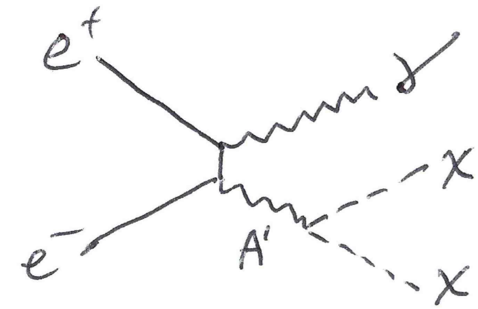
- Simplest dark sector model has a (massive) dark photon A′ that mixes with strength ε with ordinary photon.



- Also includes dark matter particle χ. Stable, neutral under SM forces. Carries dark charge, not electric charge.

B. Holdom, Phys. Lett. B 166, 196 (1986);
M. Pospelov, A. Ritz, and M. B. Voloshin, Phys. Lett. B 662, 53 (2008)

The dark photon

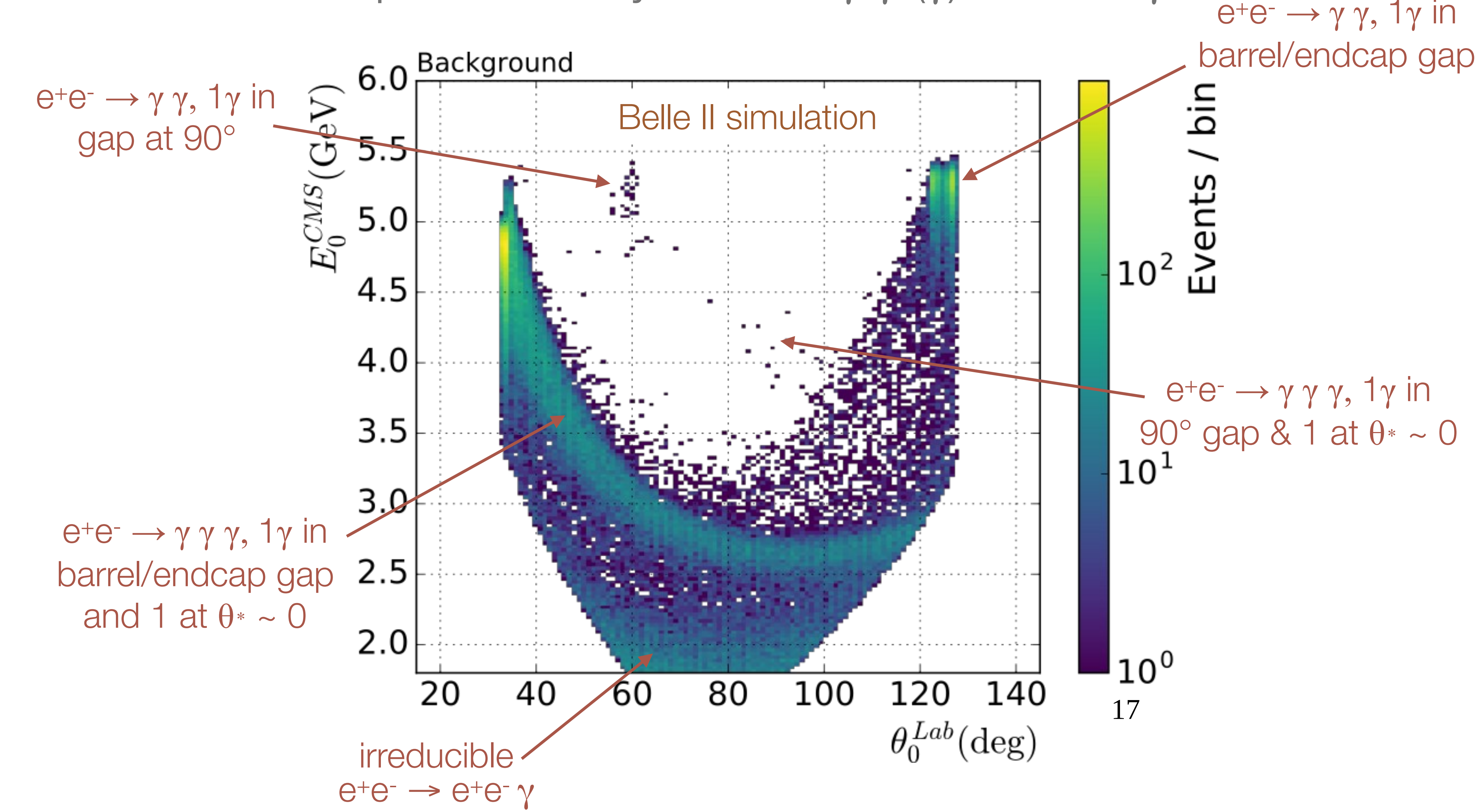


- Can be created in e^+e^- collision; will decay to dark matter if possible.
- On-shell A′ ⇒ signature is monoenergetic photon. Not sensitive to m_χ or χ/A′ coupling.

$$E^*_\gamma = E^*_{beam} - \frac{m^2_{A'}}{4E^*_{beam}}$$

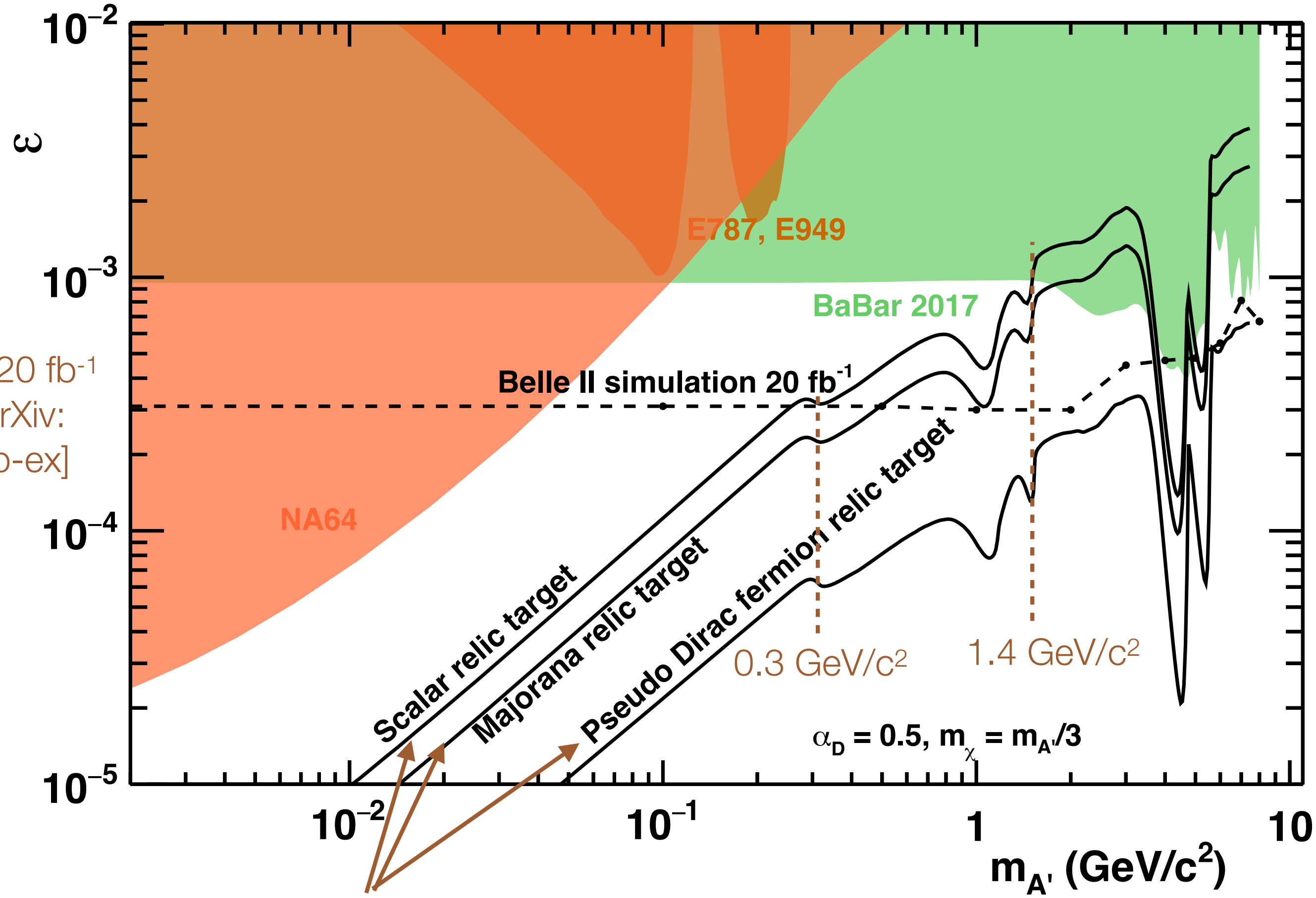
- Finite acceptance & imperfect detector: backgrounds from $e^+e^- \rightarrow \gamma\,\gamma\,(\gamma)$ and $e^+e^- \rightarrow e^+e^-\,\gamma\,(\gamma)$. Cosmics are not negligible.

- Simulated backgrounds, 40 fb^{-1}, excluding cosmics. Final sample is mostly $e^+e^- \rightarrow \gamma\gamma(\gamma)$ with ≥3γ.



- Goal with early dataset is the world's best sensitivity.
  - extrapolation to full 50 ab^{-1} requires more work on photon inefficiency systematics.

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)

If astronomical dark matter is due to the dark sector, parameters will lie along one of these lines. Derived from E. Izaguirre, G. Krnjaic, P. Schuster, N. Toro, Phys. Rev. Lett. 115, 251301 (2015)

How does Belle II improve on BaBar limits with a smaller dataset?

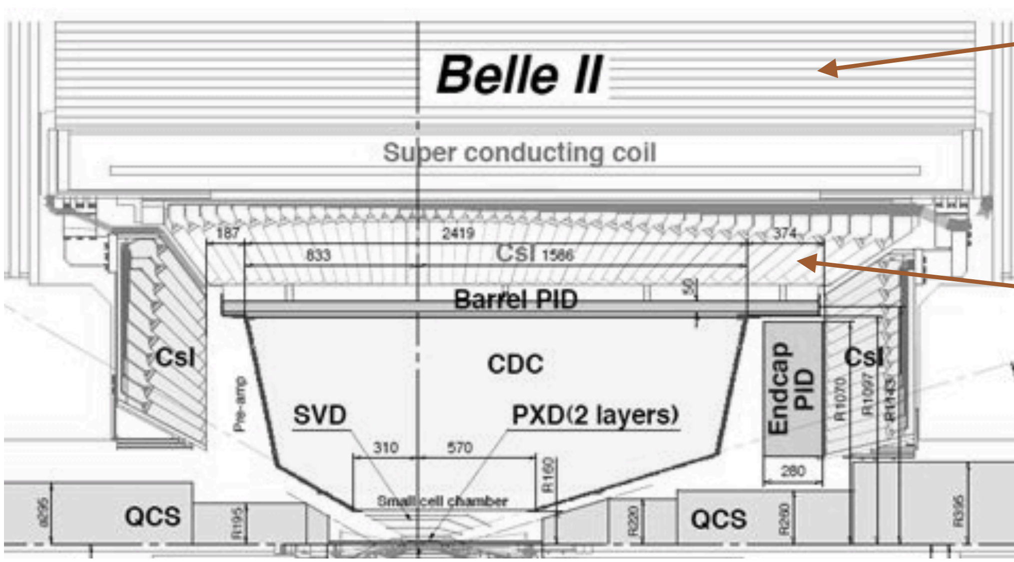
- BaBar calorimeter has projective gaps; Belle II does not.
- Boost of center of mass is smaller and calorimeter is larger ⇒ larger acceptance:

$-0.94 < \cos\theta^* < 0.96$ Belle II

$-0.92 < \cos\theta^* < 0.89$ BaBar

- Largest effect is at small mass / high photon energy. BaBar was not able to quantify the remaining peaking background from $e^+e^- \to \gamma\gamma$. We believe we have a program to do so on Belle II.

- What fraction of photons are missed by the calorimeter? What fraction are then also missed by the muon system?



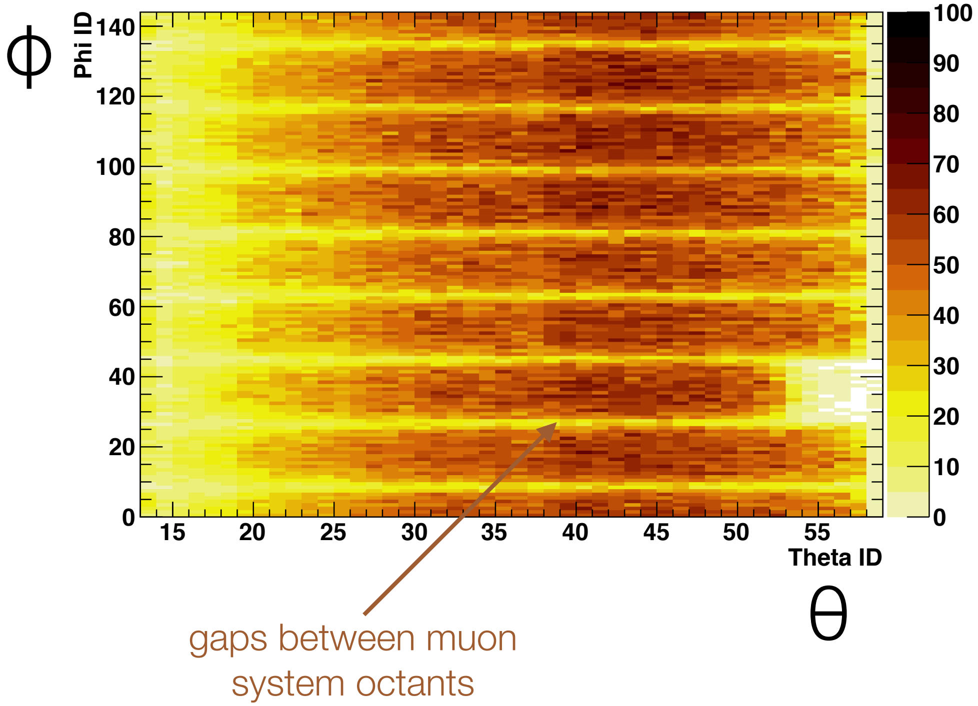
γ not interacting in calorimeter may be detected by muon system

Probability of γ not interacting in 30 cm of CsI = 3.4×10^{-6}. ~9 beam-energy γ per fb^{-1}.

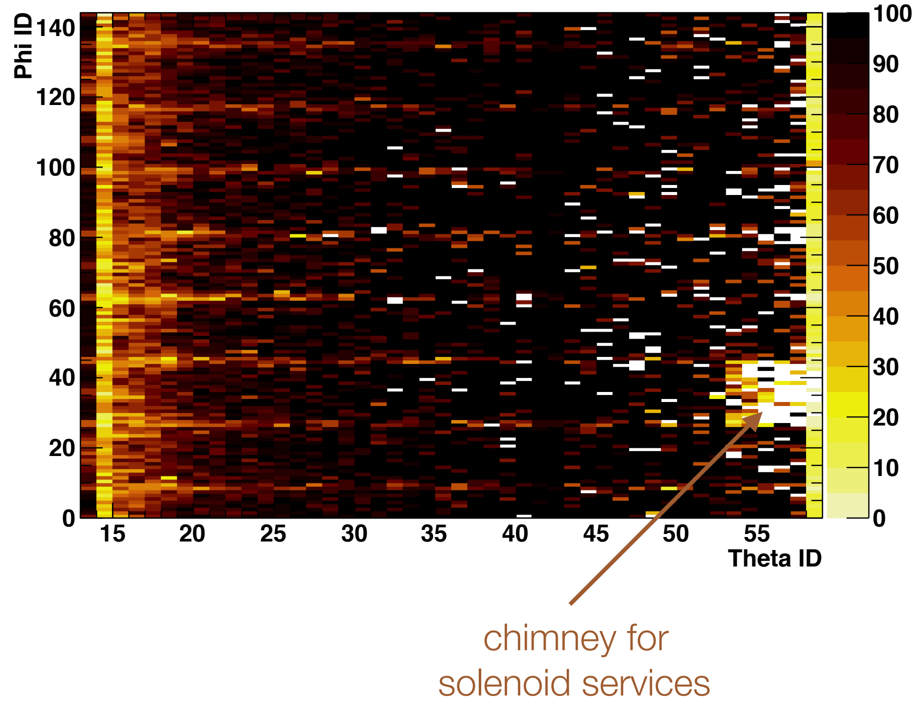
Use $e^+e^- \to \gamma\gamma$ control sample to measure probability that muon system detects photon as a function of energy leaking out of the back of the calorimeter

Belle II simulation, 16 fb^{-1}; each bin = 1 calorimeter crystal

0.7 < Eleak < 1.4 GeV

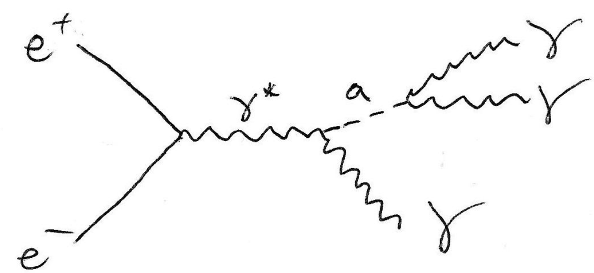


Eleak > 2.8 GeV

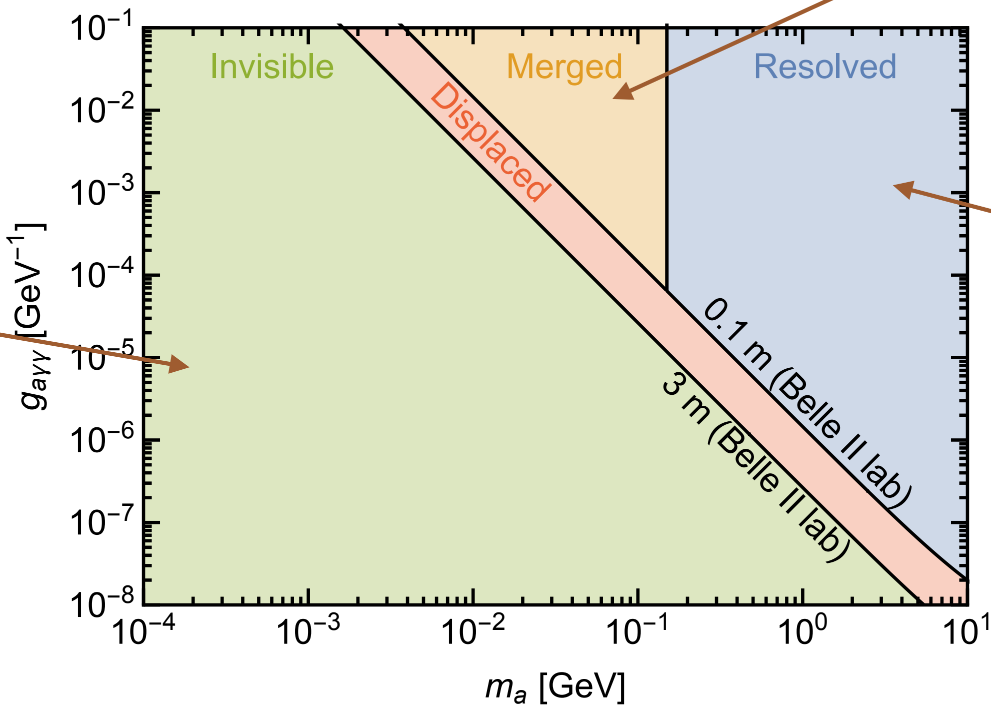


Axion-like particles

- Pseudo-scalars that couple to bosons. No strict relationship between coupling and mass.
- Focus on coupling to photons.



- Different experimental signatures:



Dolan, Ferber, Hearty, Kahlhoefer & Schmidt-Hoberg, JHEP 1712, 094 (2017)

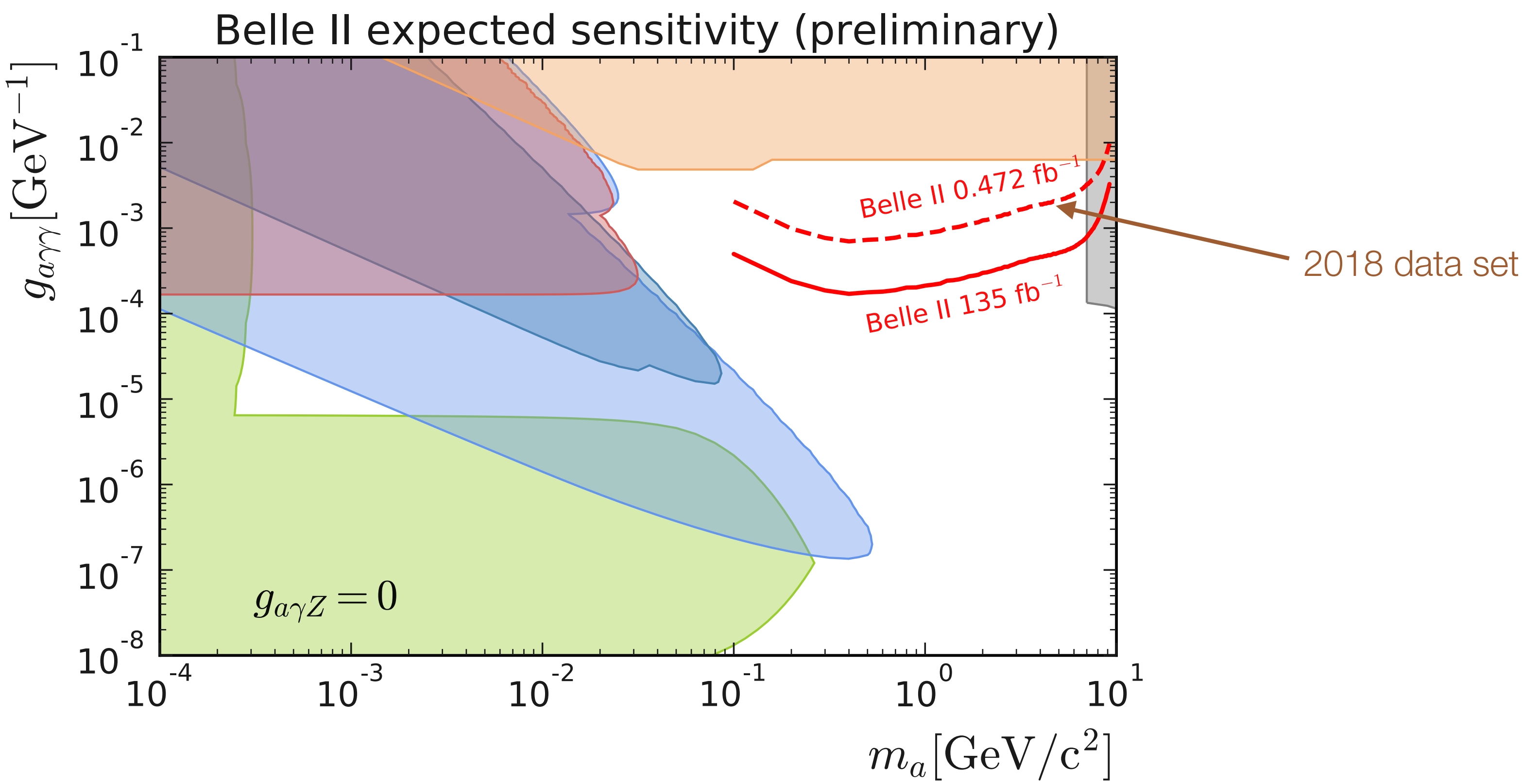
- Three γ signature: bump in invariant mass of $\gamma\gamma$.

- Large non-peaking background from $e^+e^- \to \gamma\gamma\gamma$.

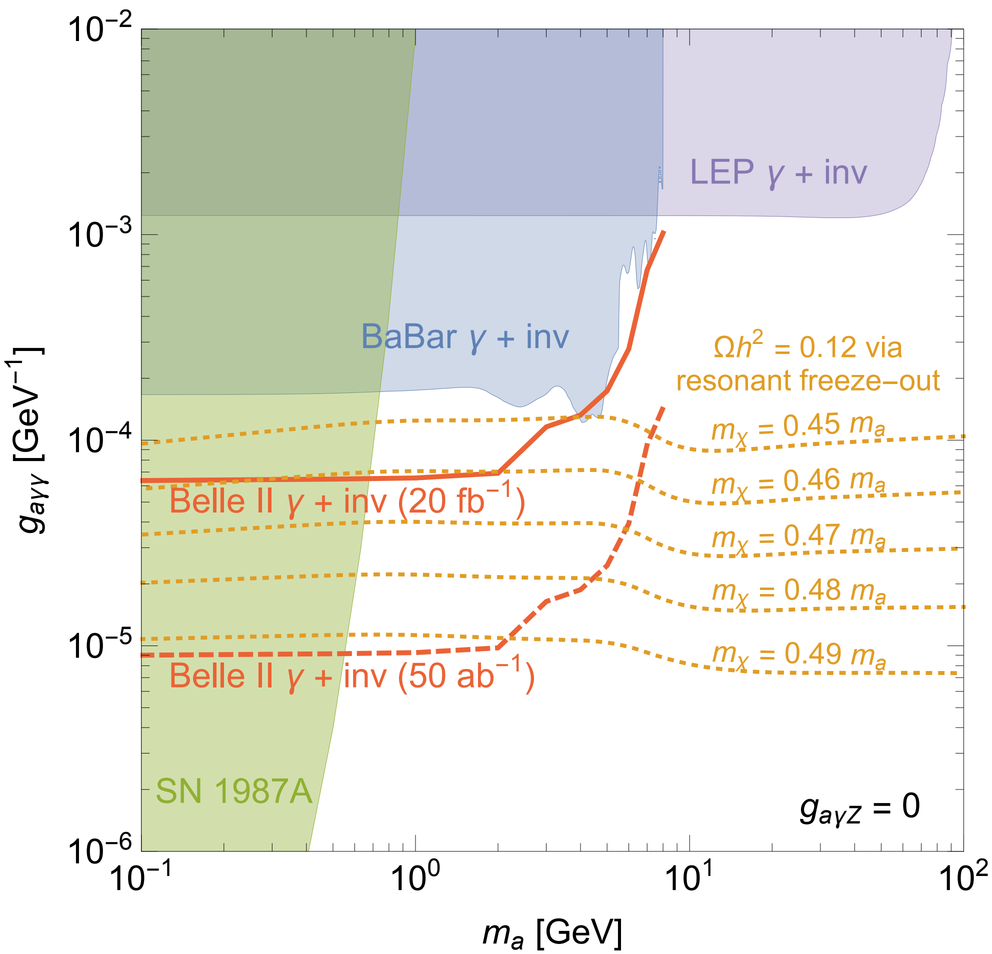
- Largest peaking background is $e^+e^- \to \gamma\omega, \omega \to \pi^0\gamma$. Also $e^+e^- \to \gamma\pi^0$ and $e^+e^- \to \gamma\eta$.

Expected sensitivity

- No published results, so Belle II can be competitive with the 472 pb^{-1} data from 2018.



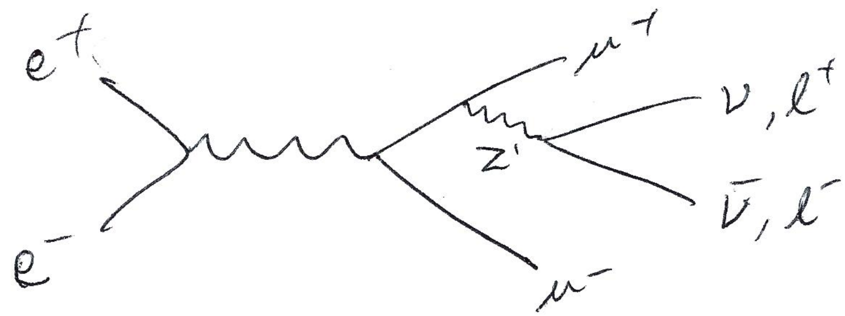
- If ALP decays to dark matter, single γ search is relevant. ALP mediation of SM / dark matter interaction could explain observed abundance if $m_a \approx 2m_\chi$.



JHEP 1712, 094 (2017)

Search for invisible decays of the Z′

- Dark gauge boson may have direct couplings to SM (labeled Z′). Z′ that couples to 1st generation is strongly constrained, but not one that couples only to 2nd and 3rd generations. He, Joshi, Lew, Volkas, Phys. Rev. D 43, R22 (1991)



- If $m_{Z'} < 2m_\mu$, decay is to neutrinos only. Also possible that decay to dark matter is dominant.

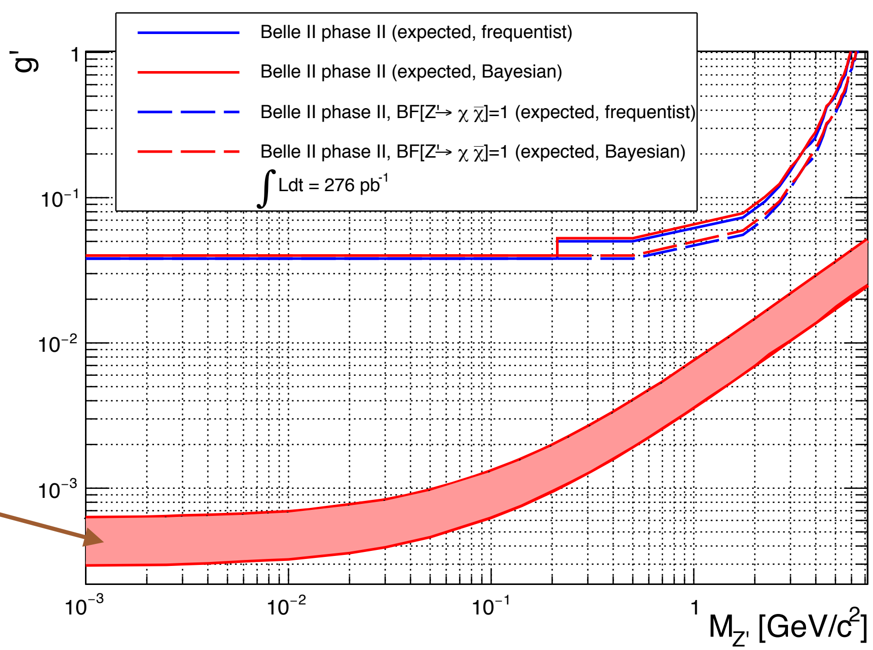
- BaBar searched for $4\mu^\pm$ final state, but no existing limits for invisible final state. Phys. Rev. D94, 011102(R) (2016)

- Signature is $\mu^+\mu^-$ pair with a peak in the missing mass.

- Require $\vec{p}_{miss}$ to point into the calorimeter barrel. Reduce $\tau^+\tau^-$ background with kinematic distributions.
  - low $m_{Z'}$ background is from $e^+e^- \to \mu^+\mu^-\gamma\gamma$.

- Belle II can be competitive with 2018 data. Only 276 pb^{-1} is usable due to low trigger efficiency for tracks.

Projected Belle II limits



range of parameters that would explain muon g-2. Will be challenging, even with 50 ab^{-1}

Summary

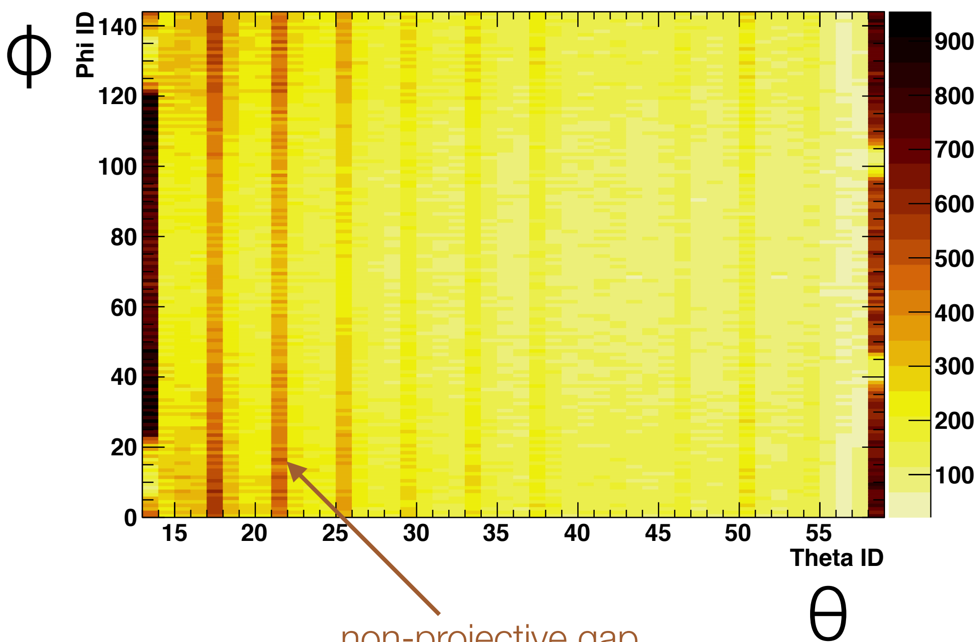
- Searches for the direct production of low-mass new particles are a priority for the early running period of Belle II.
- Several topics are candidates for early publications. In particular, excellent calorimeter performance enables a competitive single photon analysis.
- Large number of other searches require more complex analyses or larger data sets.

Backup

$e^+e^- \to \gamma\gamma$ control sample to study photon detection in muon system: probes per crystal as a function of leakage energy

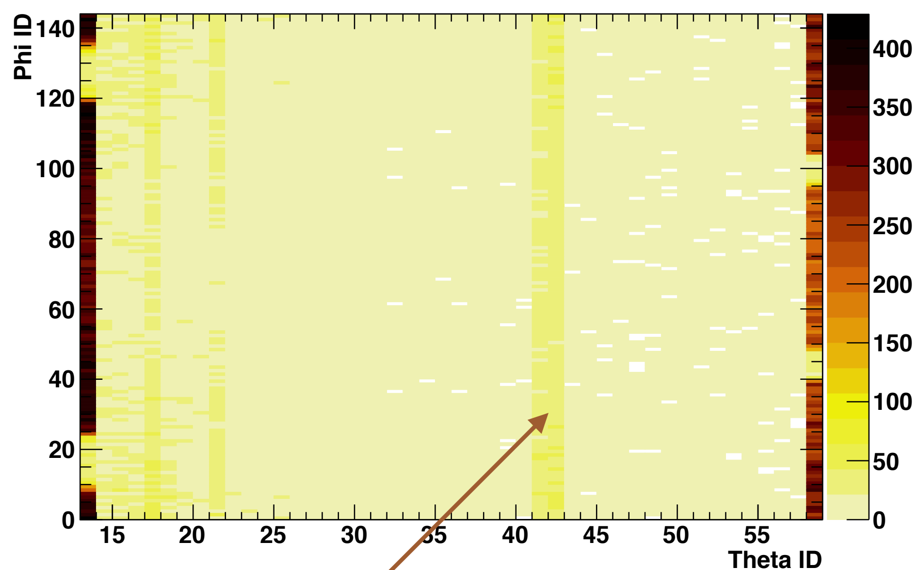
Belle II simulation, 16 fb^{-1}; each bin = 1 calorimeter crystal

0.7 < Eleak < 1.4 GeV



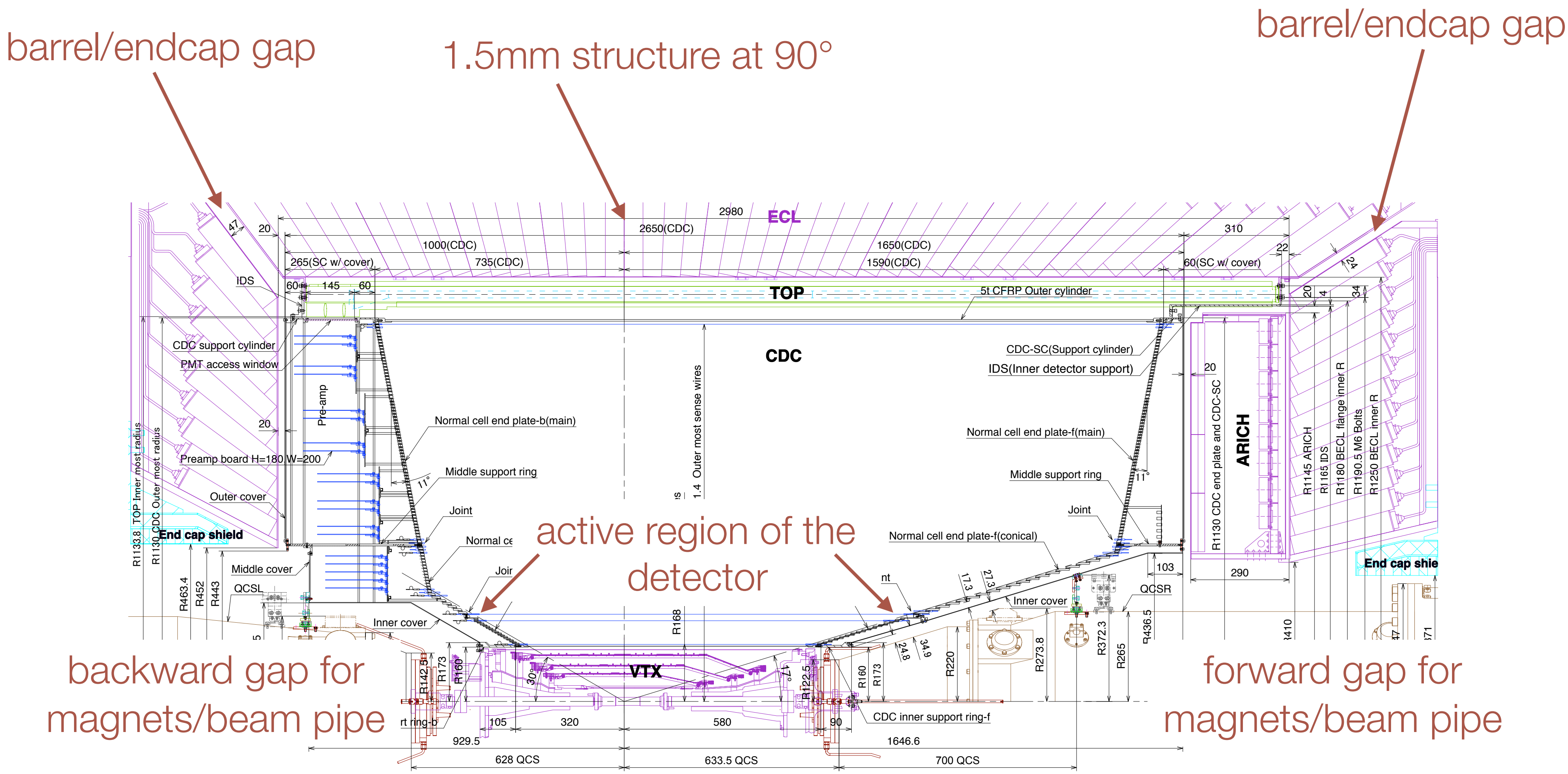
non-projective gap between crystals, plus crystal stagger

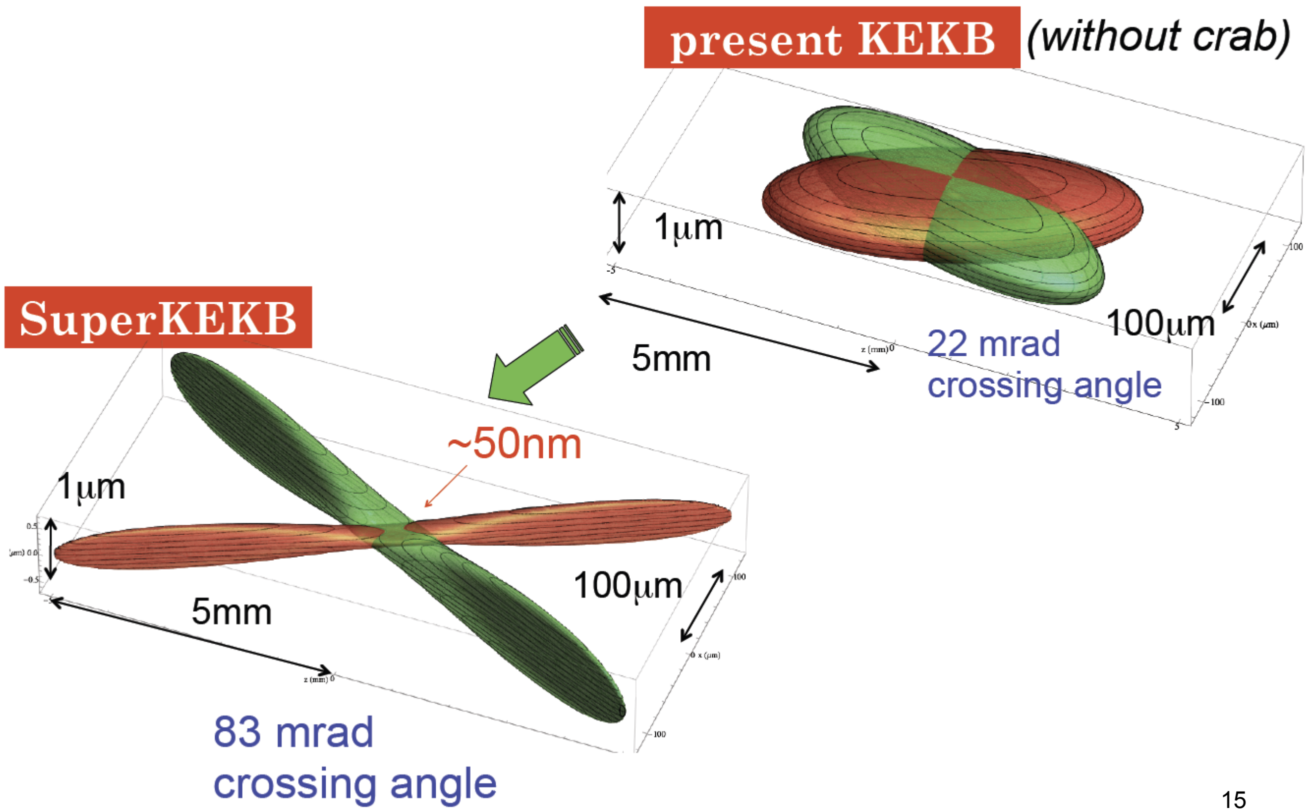
Eleak > 2.8 GeV

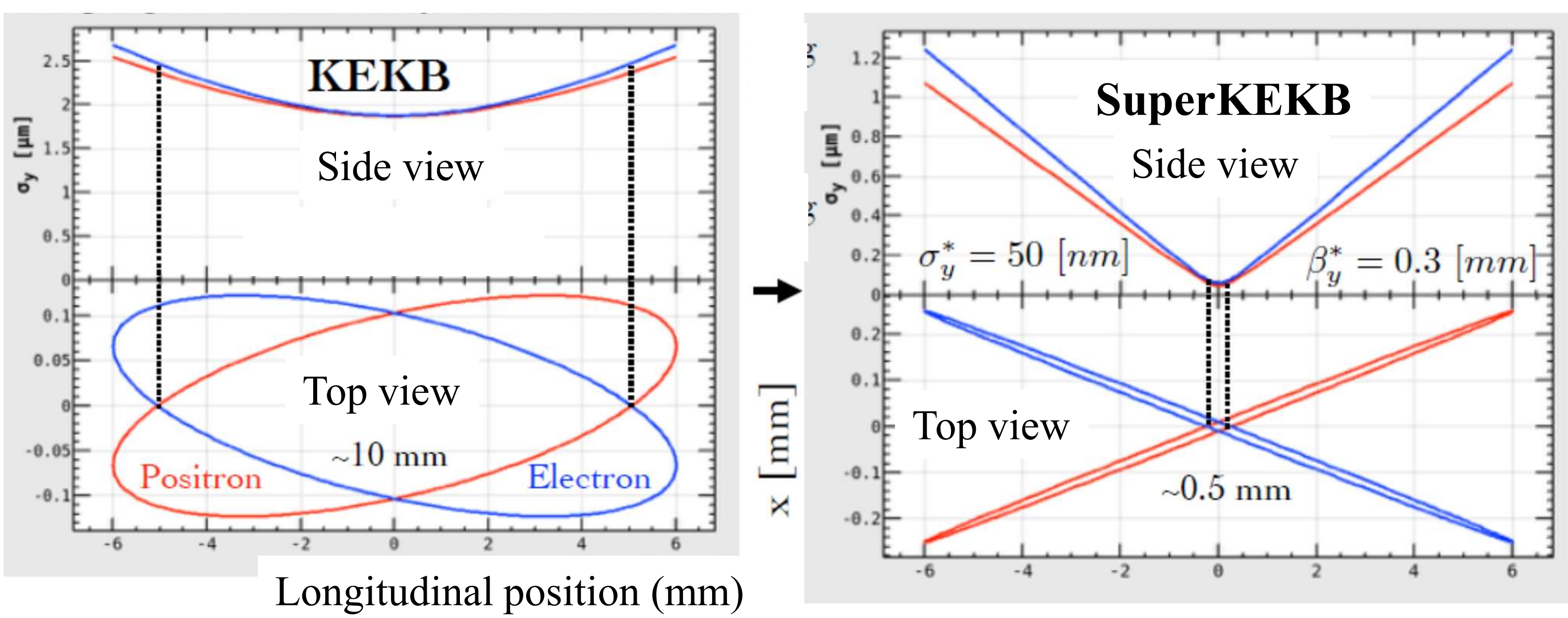


projective gap at 90°

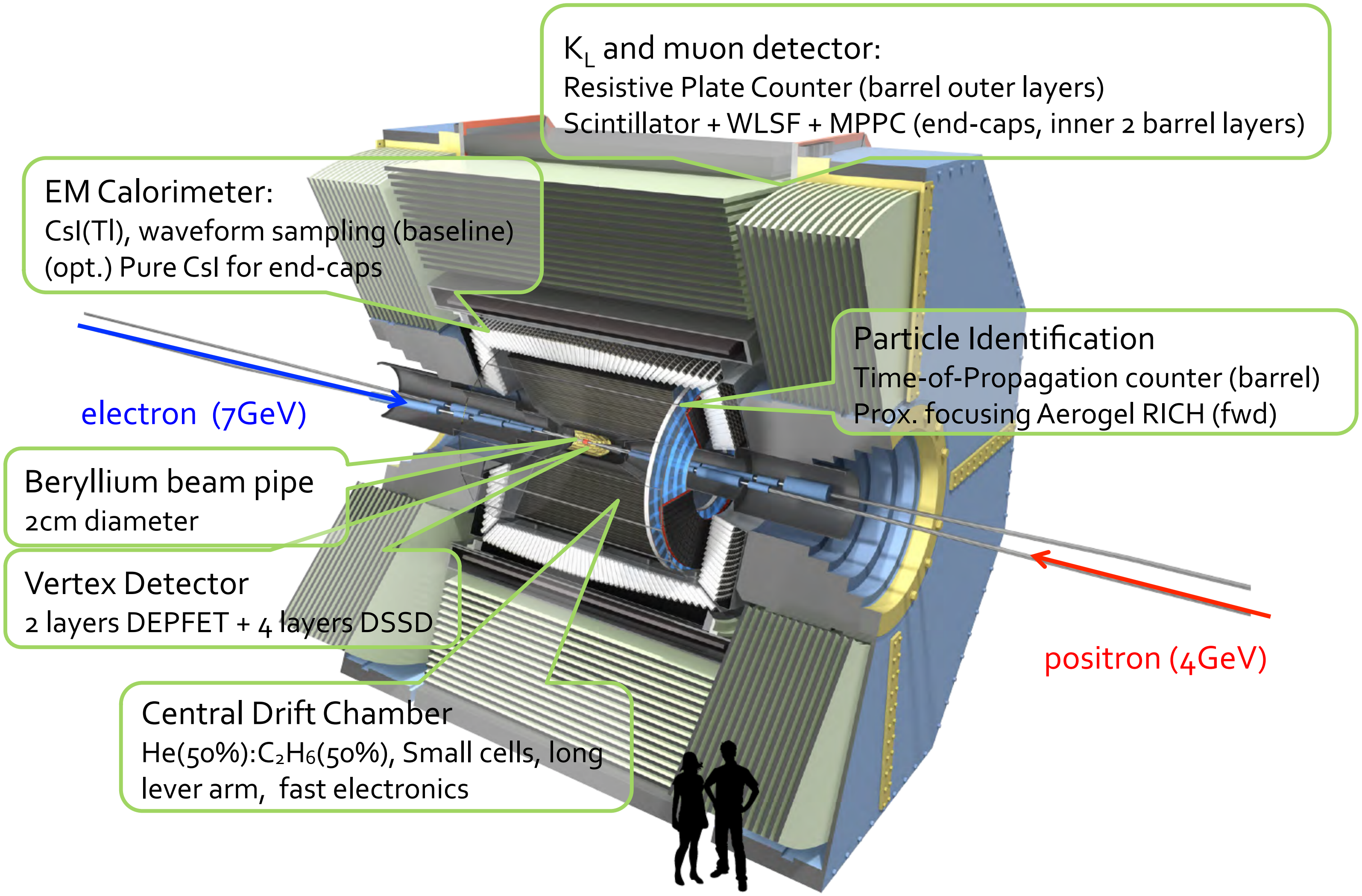
Sources of detector inefficiency




present KEKB (without crab)
1μm
5mm
100μm
22 mrad crossing angle
SuperKEKB
~50nm
1μm
5mm
100μm
83 mrad crossing angle
15


KEKB
Side view
Top view
~10 mm
Positron
Electron
SuperKEKB
Side view
$\sigma_y^* = 50\ [nm]$
$\beta_y^* = 0.3\ [mm]$
Top view
~0.5 mm
x [mm]
Longitudinal position (mm)

The Belle II detector

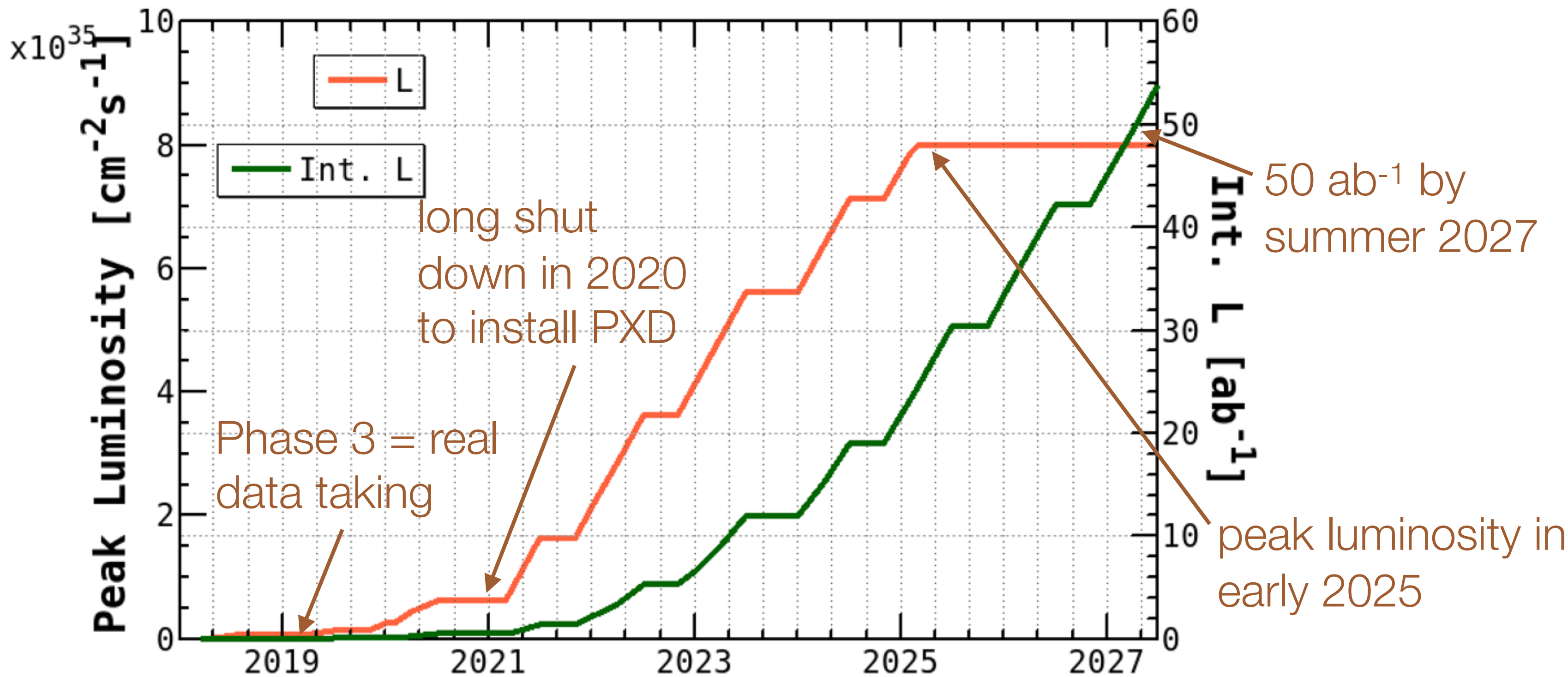


- Reusing solenoid, iron, part of muon system, calorimeter crystals. Remainder optimized for rates and high backgrounds

Longer term run plan

- Phase 3 commissioning started in March 2019.
  - new collimators should give much lower backgrounds.

- Then ~8 years of data taking for full data set.

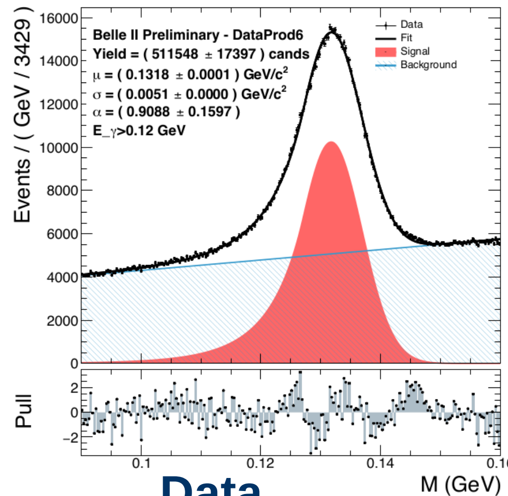


Calorimeter performance in 2018 data

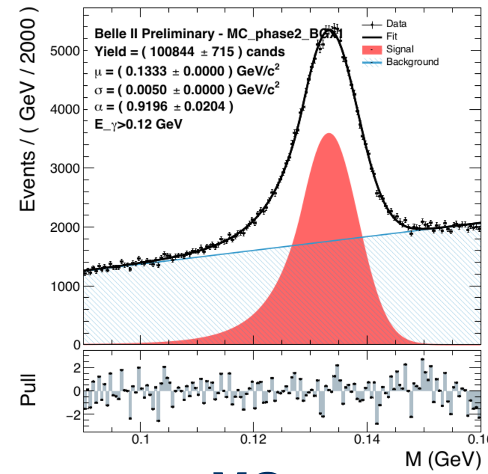
- Sufficient data to tune calorimeter performance.

π^0 reconstruction

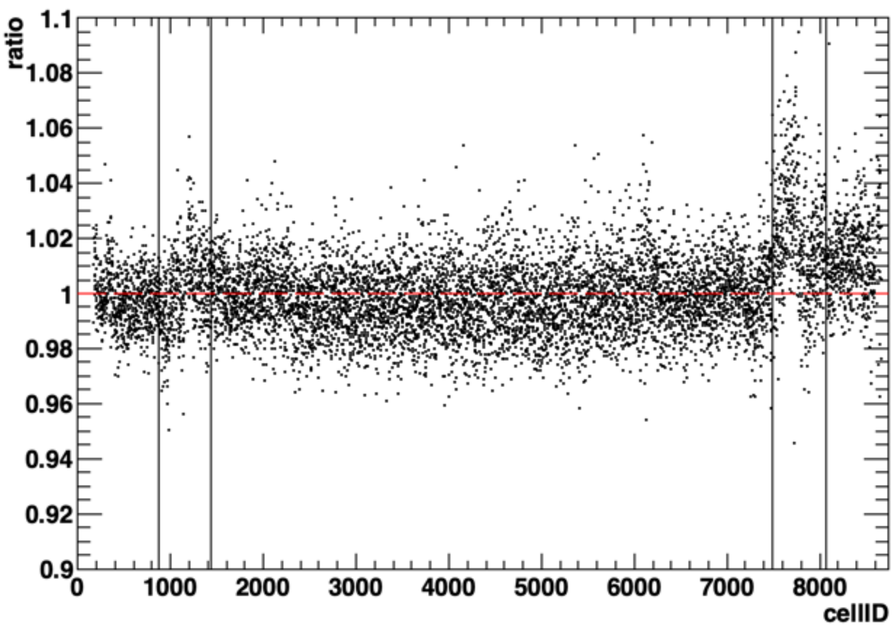
peak location good to 1%
resolution within 2%



Data



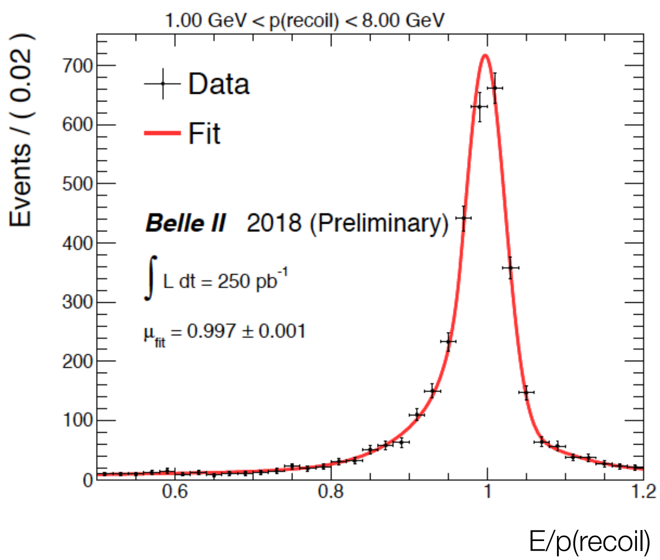
MC



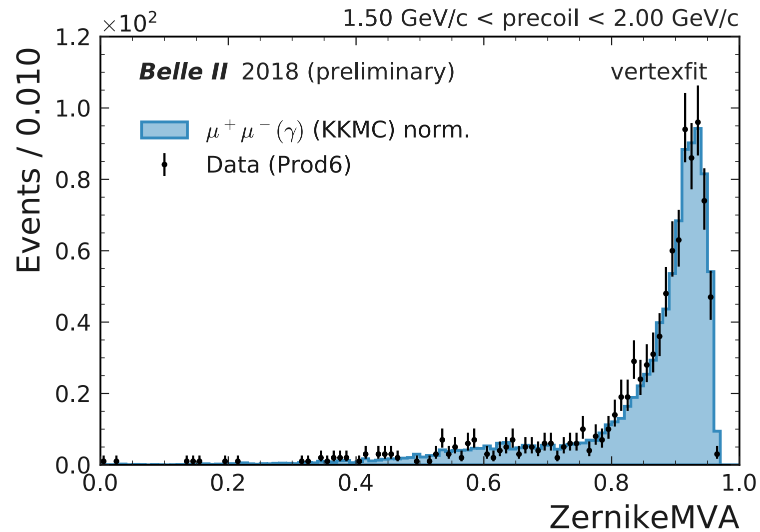
Comparison between calibration using Bhabhas and $\gamma\gamma$ events

- γ control sample, $e^+e^- \to \mu^+\mu^-\gamma$

Ratio of observed to predicted energy

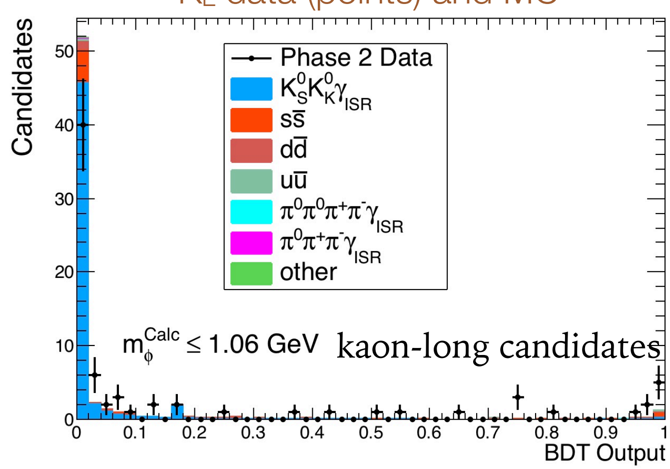


Multivariate shower shape, MC and data

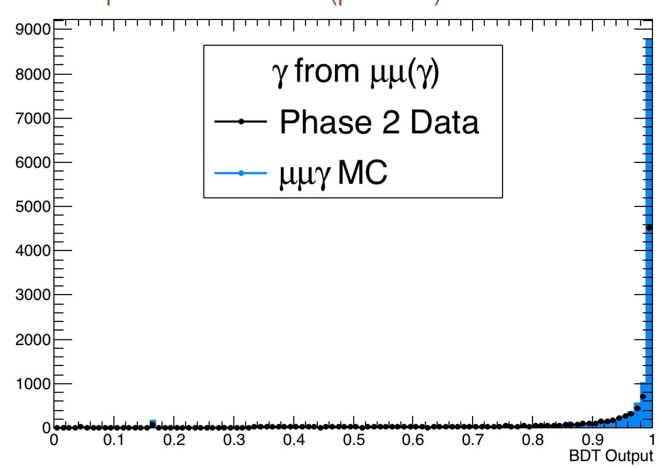


- Progress in hadron identification using new pulse-shape discrimination tools (Savino Longo)

K_L data (points) and MC

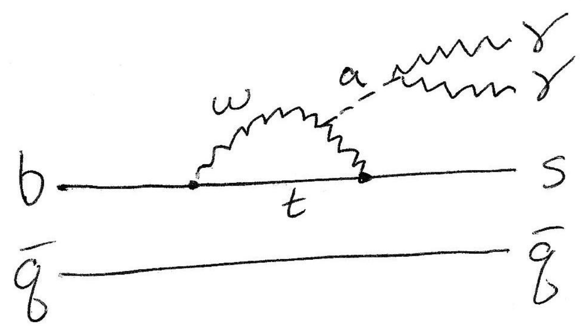


photons data (points) and MC



Searches for Axion-like particles in B decay

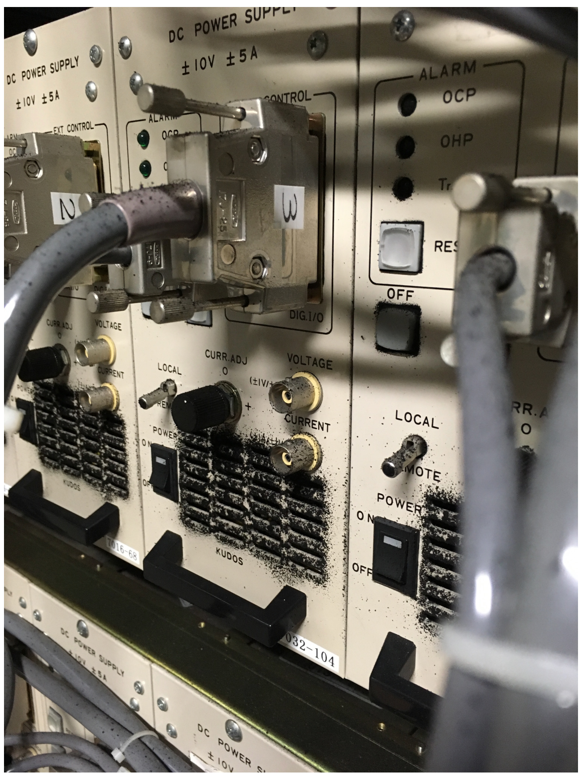
- ALP can be produced in radiative penguin B decays.
  - Sensitive to both γ and $W^{\pm}$ couplings.



- Similar to $B \rightarrow K\pi^0$ analyses; will need a few ab^{-1} to be competitive with Belle and BaBar data sets.

Soot in klystron gallery

- Fire was in accelerating structure test facility Nextef.
- Cleanup of klystron gallery took ~4 weeks.



- Path for cosmics to reach calorimeter without KLM or calorimeter vetos