Torben Ferber (University of British Columbia)

27.09.2017, Flavour and Dark Matter, Heidelberg

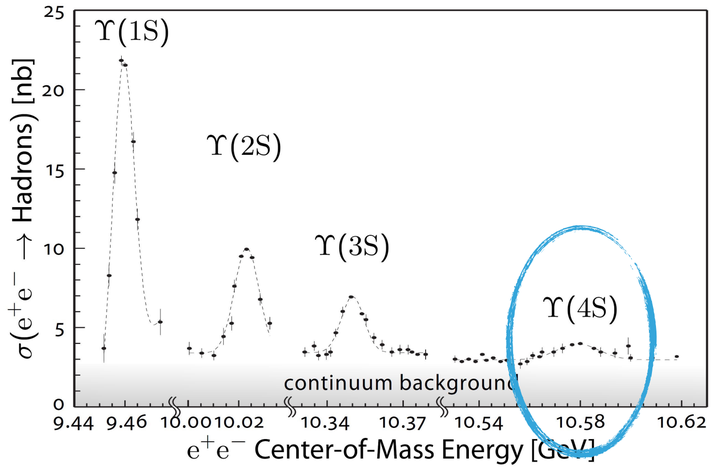
Dark Sector Physics at BaBar and Belle II

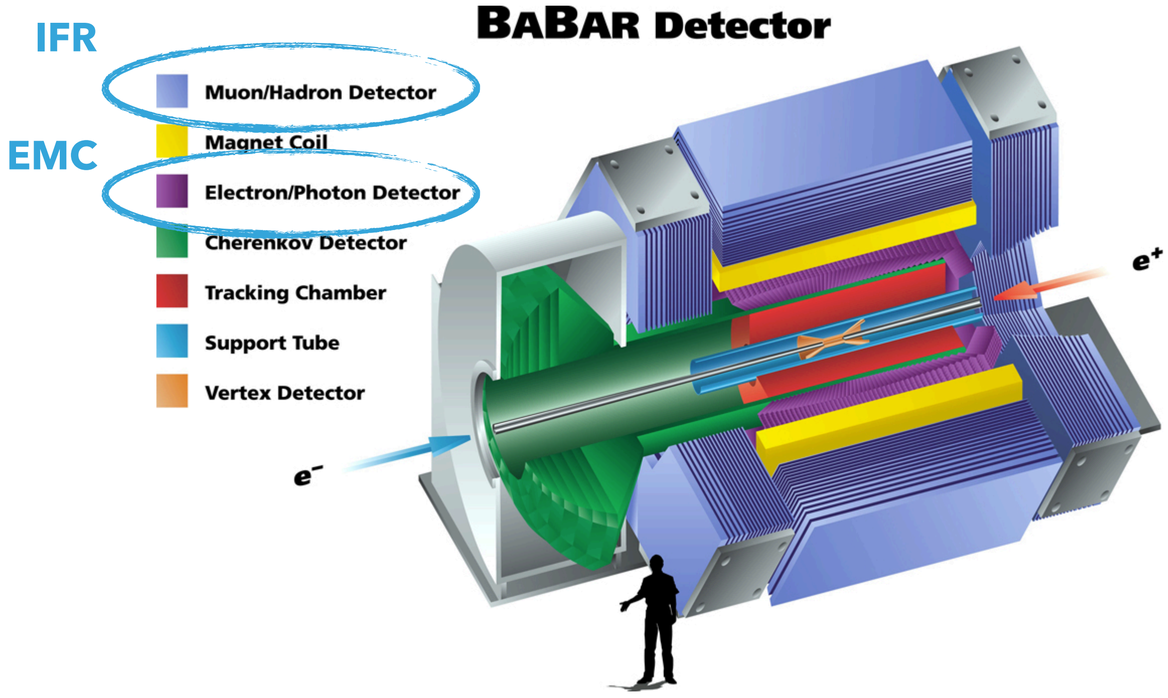
Overview

- Part I: BaBar
  - Experiment overview
  - Dark Photon to Dark Matter
- Part II: Belle II
  - Experiment overview
  - Dark Photon to Dark Matter
  - Axion-Like Particles
  - Other planned searches

BaBar: Experiment

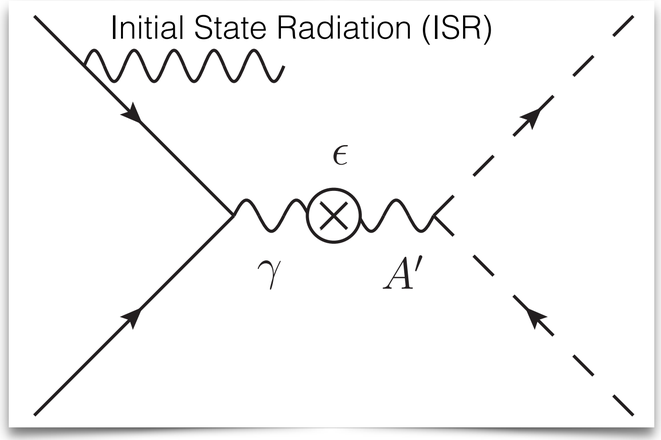
- First generation B-factory:
  BaBar at PEP-II, USA, took
  data until 2008.
- Very high luminosity: ~1.2×10^{34} /cm^2/s
- Collision energy at Y(nS):
  Mainly at E_{CM} = 10.58 GeV.
  BR(Y(4S)→BB) > 96%
- Asymmetric beam energies:
  9 GeV (e^-) / 3.1 GeV (e^+)
  → Boosted $B\bar{B}$ pairs.

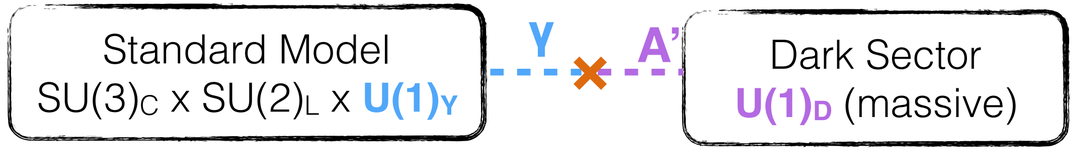




Dark photons: Visible and invisible

- In the Vector Portal, a (massive) Dark Photon A′ can mix with the SM photon with strength ε.
- Searches at BaBar and Belle II assume on-shell A′ decays ($m_{decay} \leq m_{A'}/2$):
  - Mono-energetic ISR photon.
  - Invariant di-lepton mass equals $m_{A'}$.
- If A′ is the not the lightest Dark Sector particle, it will decay into Dark Matter (DM).





*Holdom, Phys. Lett B166, 1986

BaBar: Dark Photons to invisible (``Single photon search'')

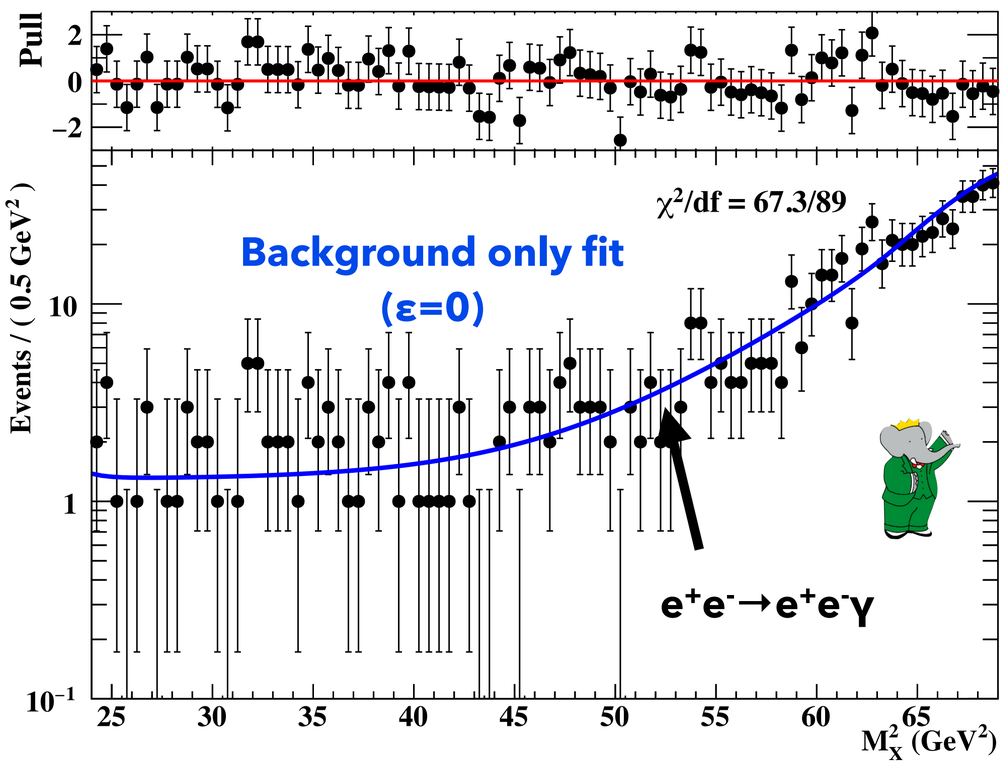
- Single photon trigger was implemented for final BaBar running period (~10% of all data):
  - 48 fb^{-1} for high $m_{A'}$ (low E_γ), mostly at $E^{CM}=\Upsilon(2S)$ and $E^{CM}=\Upsilon(3S)$
  - 53 fb^{-1} for low $m_{A'}$ (high E_γ), (additional 5 fb^{-1} at $E^{CM}=\Upsilon(4S)$).
- Trigger threshold: $E_\gamma^* > 1.5$ GeV. Usable at analysis level: $E_\gamma^* > 1.8$ GeV (calibration issues).
- Signal selection using a BDT with 12 variables, including:
  - Energies and polar angles of highest two energetic γ's.
  - Distance of missing momentum vector to EMC crystal edges.
  - Additional clusters in muon system (IFR).
  - …
- Trained on 3 fb^{-1} $\Upsilon(3S)$ data and simulated signal samples uniform in $m_{A'}$.

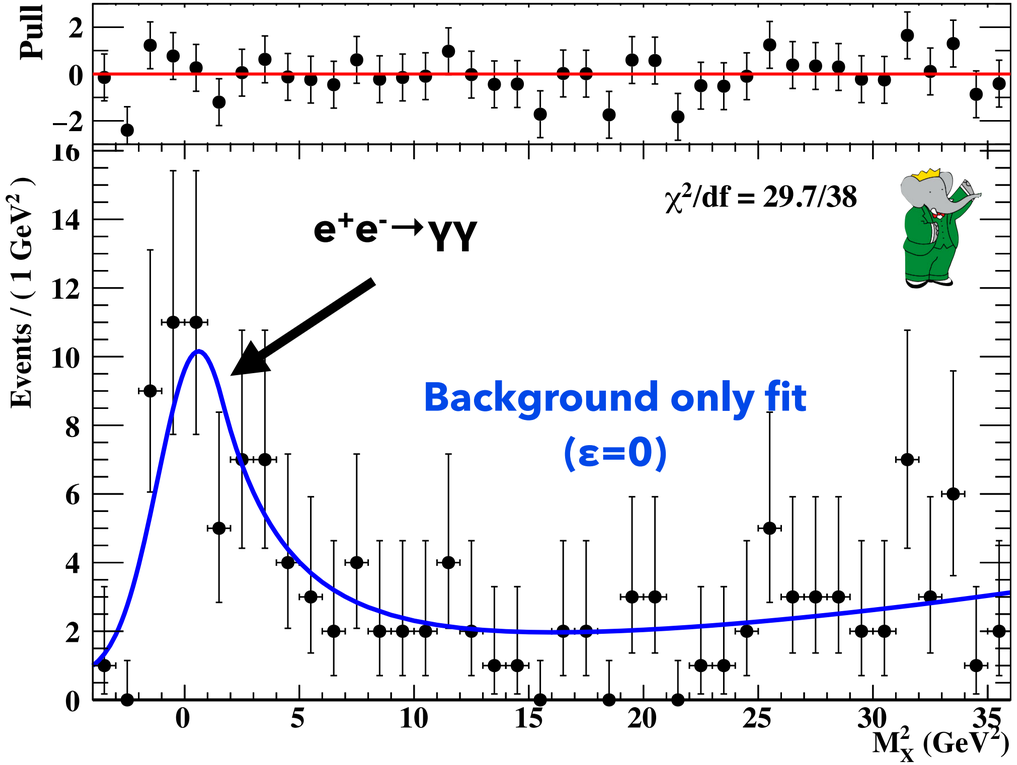
BaBar: Dark Photons to invisible (``Single photon search'')

- Backgrounds:
  - $e^+e^- \to \gamma\gamma$, 1γ undetected: Peaking, identical to the signal for $m_{A'} < 1.6$ GeV/c^2. Photons can escape undetected through azimuthal gaps between calorimeter crystals and other inefficient detector regions.
  - $e^+e^- \to \gamma\gamma\gamma$, 1$\gamma$ undetected, 2nd out of the detector acceptance.
  - $e^+e^- \to e^+e^-\gamma$, both electrons out of the detector acceptance (γ energy limited by kinematics).
  - Beam background photons do not fake signal γ, but can be the 2nd γ in a signal event.
  - Irreducible SM background $e^+e^- \to \nu\nu\gamma$ is negligible.

BaBar: Dark Photons to invisible (``Single photon search'')

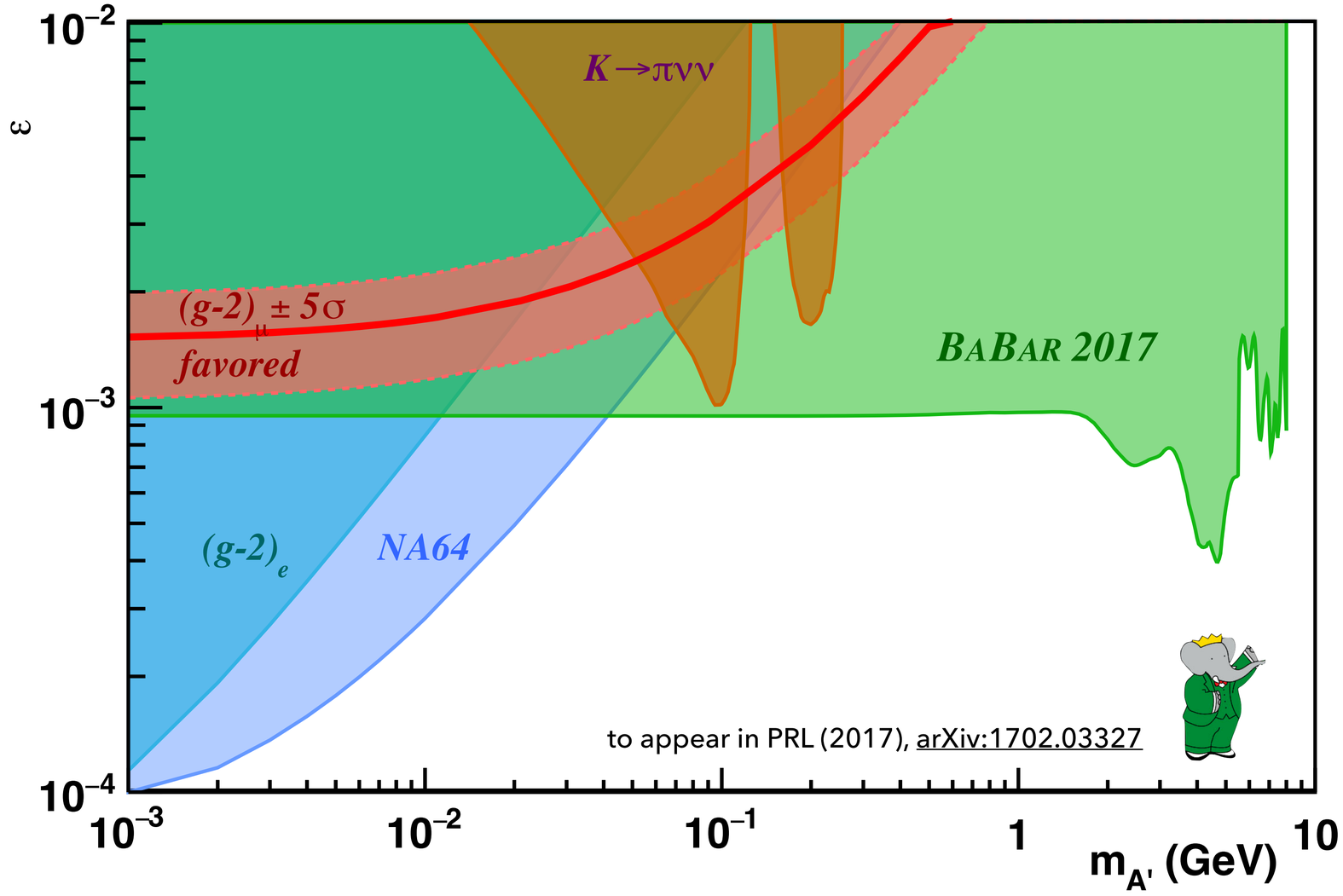
- **High A′ mass region** (low γ energy) $m_{A'}$ >5.5 GeV/c^2 is dominated by radiative Bhabha background smooth in recoil mass.
- **Low A′ mass region** has both peaking and smooth backgrounds. Select data using two statistically independent cuts on BDT and θ.



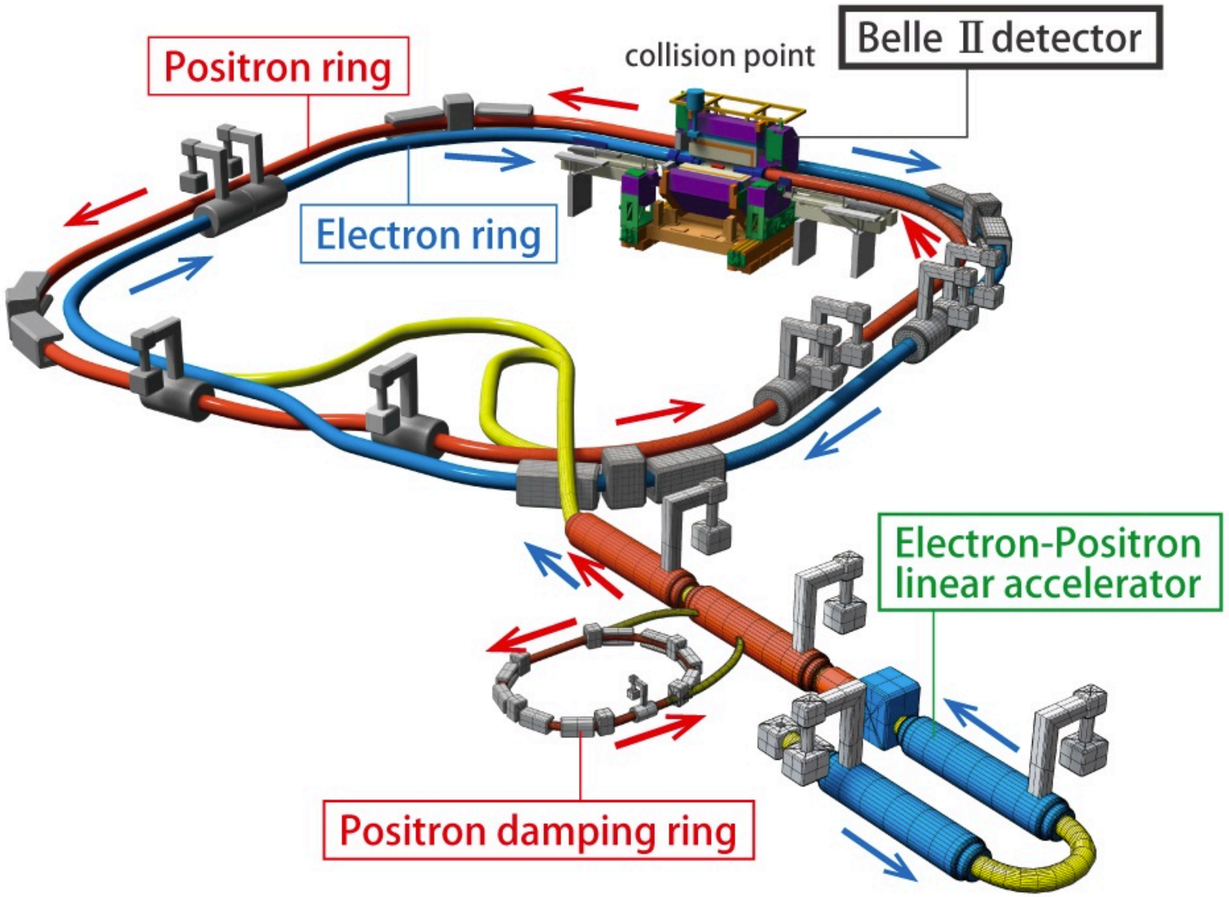


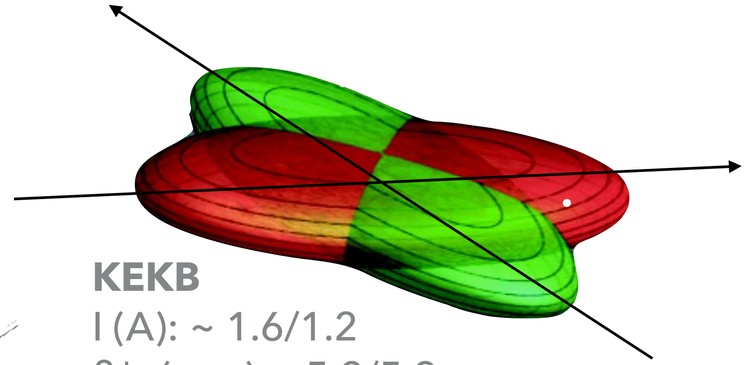
to appear in PRL (2017), arXiv:1702.03327

BaBar: Dark Photons to invisible (``Single photon search'')

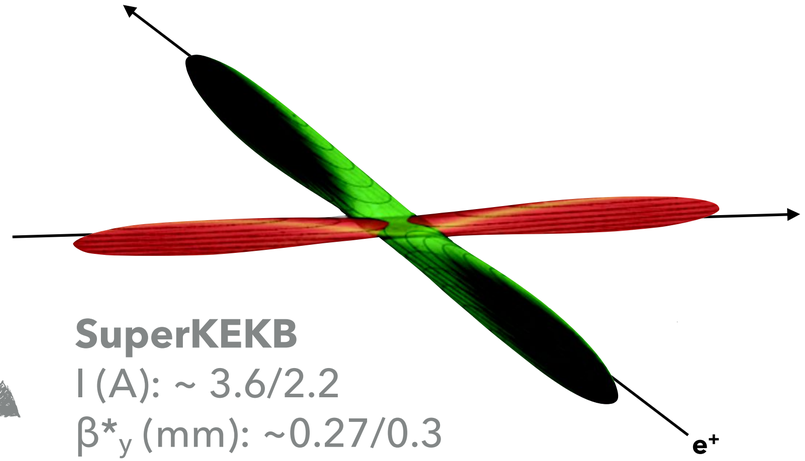


Belle II: SuperKEKB collider



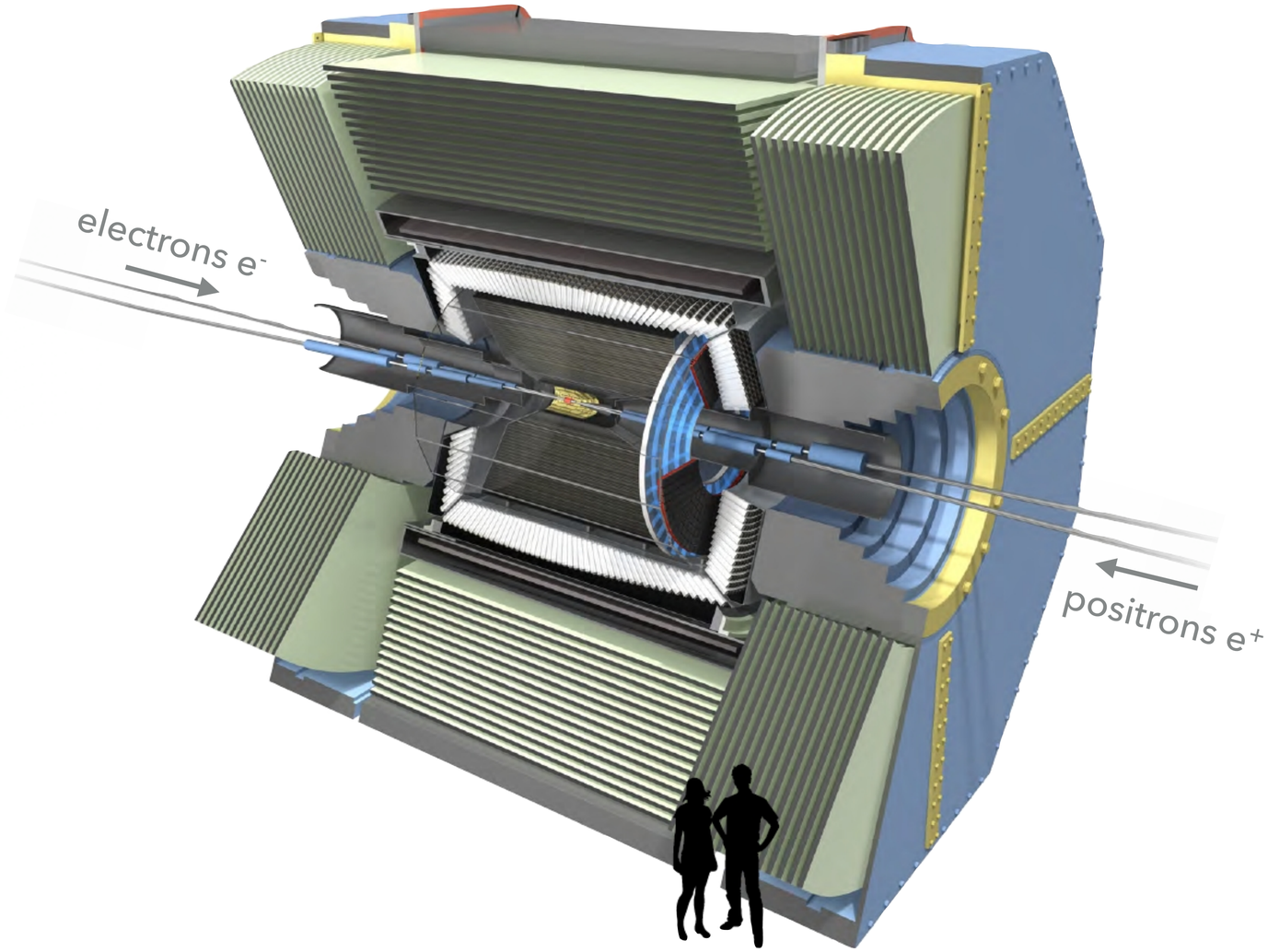


KEKB
I (A): ~ 1.6/1.2
β^*_y (mm): ~5.9/5.9
Crossing angle (mrad): 22



SuperKEKB
I (A): ~ 3.6/2.2
β^*_y (mm): ~0.27/0.3
Crossing angle (mrad): 83

Belle II: Detector

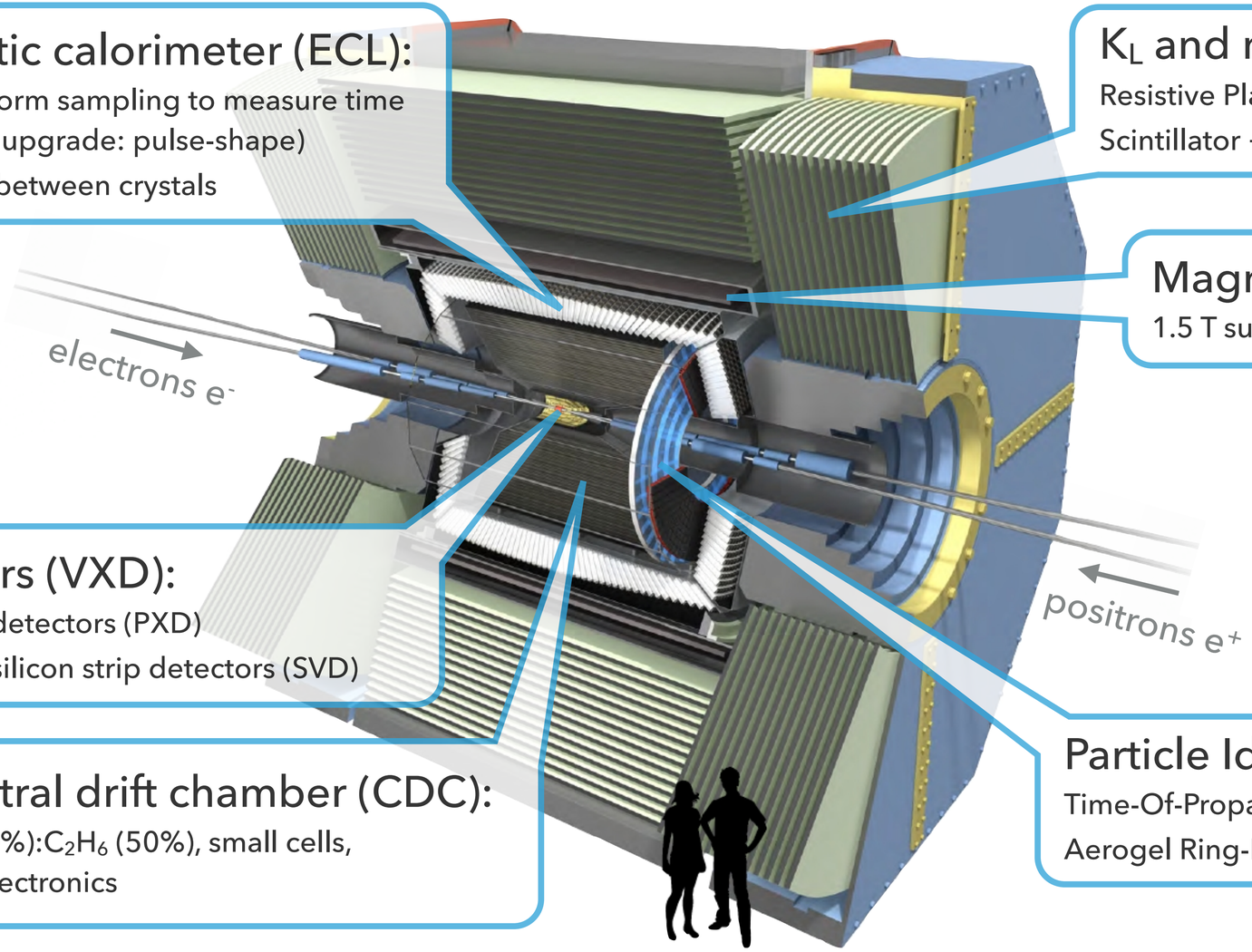


Belle II: Detector

Electromagnetic calorimeter (ECL):
CsI(Tl) crystals, waveform sampling to measure time and energy (possible upgrade: pulse-shape)
Non-projective gaps between crystals

K_L and muon detector (KLM):
Resistive Plate Counters (RPC) (outer barrel)
Scintillator + WLSF + MPPC (endcaps, inner barrel)

Magnet:
1.5 T superconducting

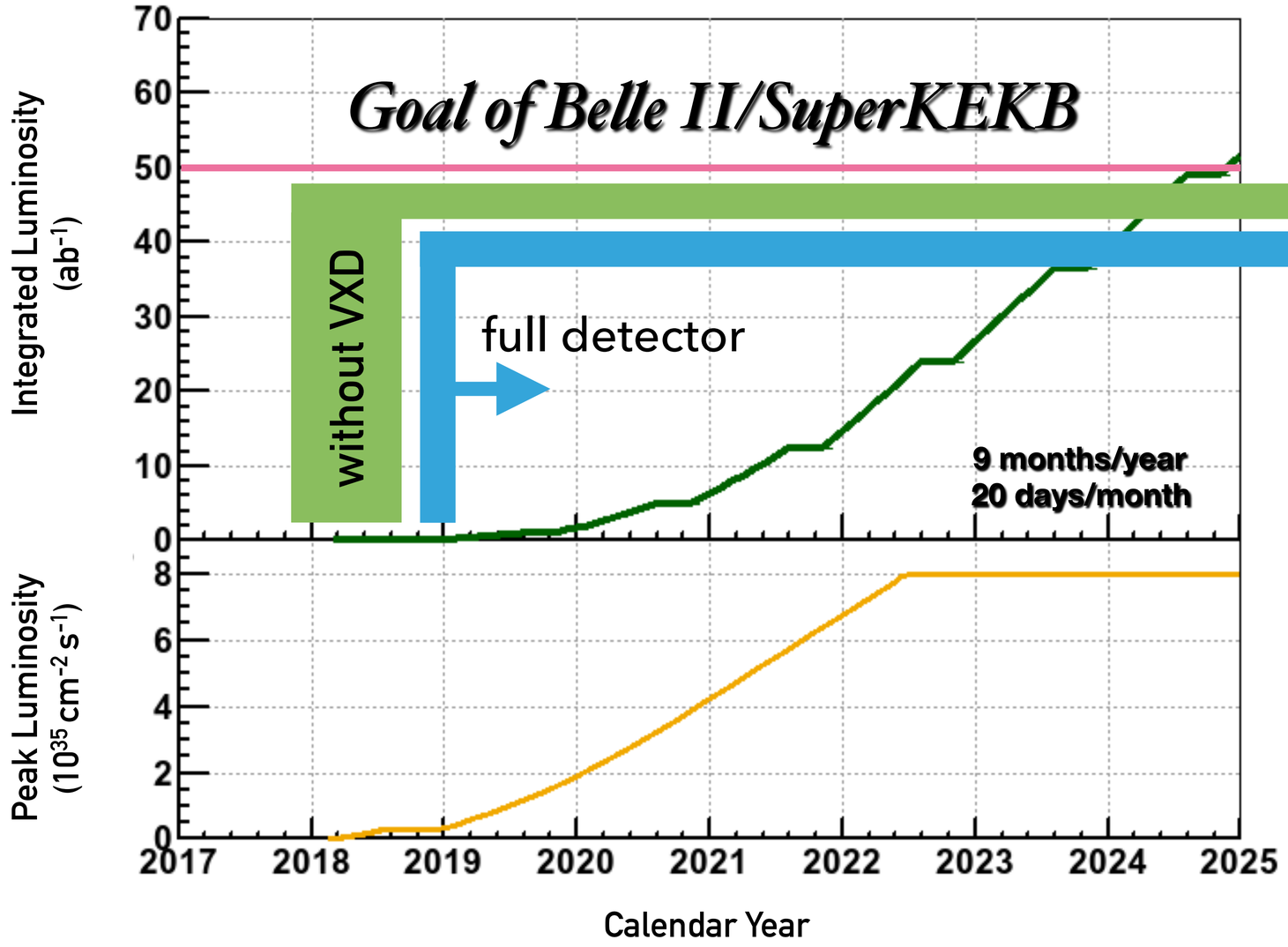


Vertex detectors (VXD):
2 layer DEPFET pixel detectors (PXD)
4 layer double-sided silicon strip detectors (SVD)

Central drift chamber (CDC):
He(50%):C_2H_6 (50%), small cells, fast electronics

Particle Identification (PID):
Time-Of-Propagation counter (TOP) (barrel)
Aerogel Ring-Imaging Cerenkov Counter (ARICH)

Belle II: Expected luminosity



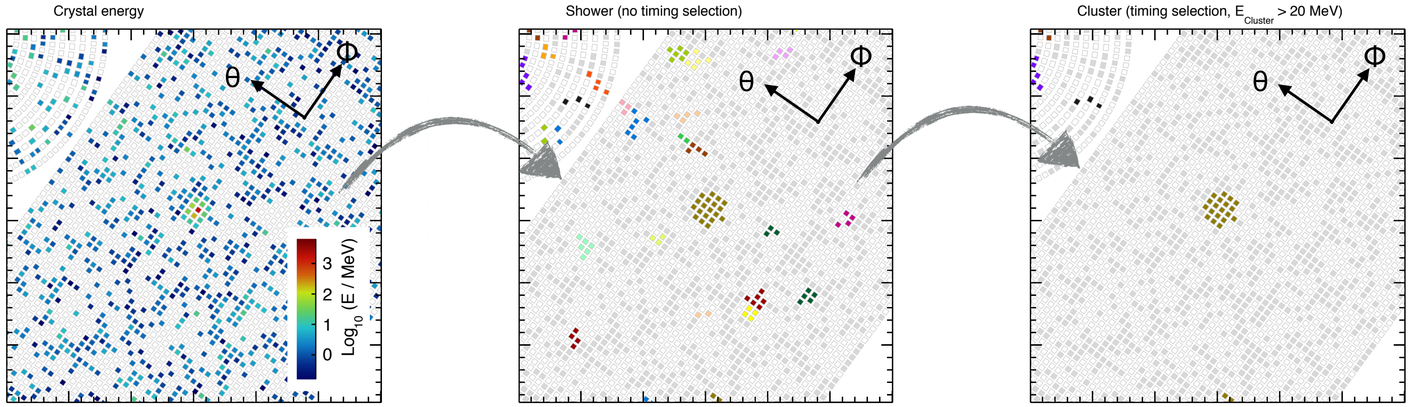
Belle II "Phase 2" goal:
Peak luminosity as at the end of Belle: 1×10^{34} cm^{-2}s^{-1}

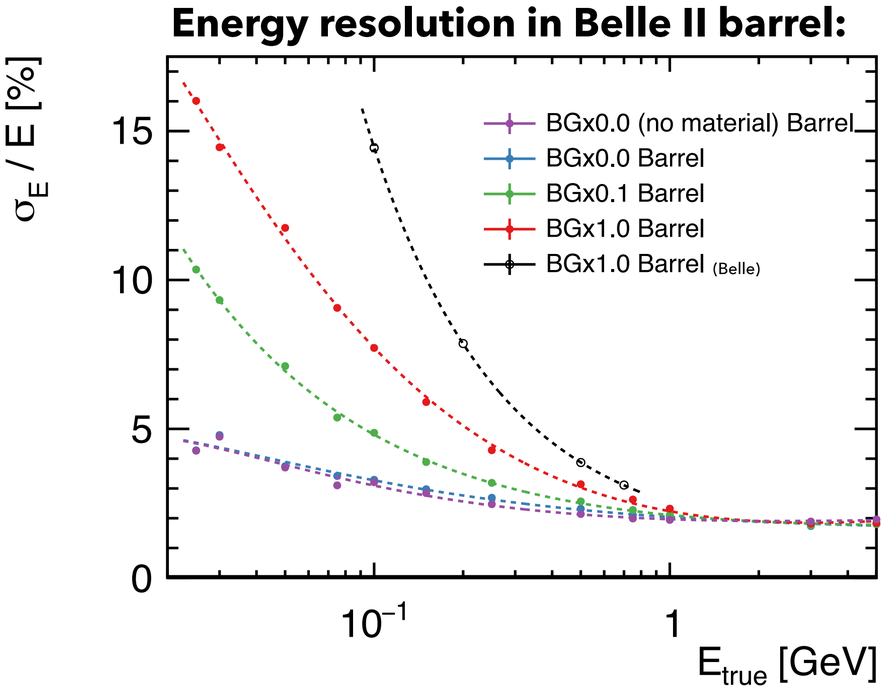
Belle II "Phase 2" dream:
20 fb^{-1} of physics data at the ϒ(4S).

Belle II"Phase 3" goal:
50x the integrated luminosity of Belle: 50ab^{-1} by 2025.

Belle: ~1 ab^{-1}
BaBar: ~0.5 ab^{-1}

Belle II: Expected calorimeter performance



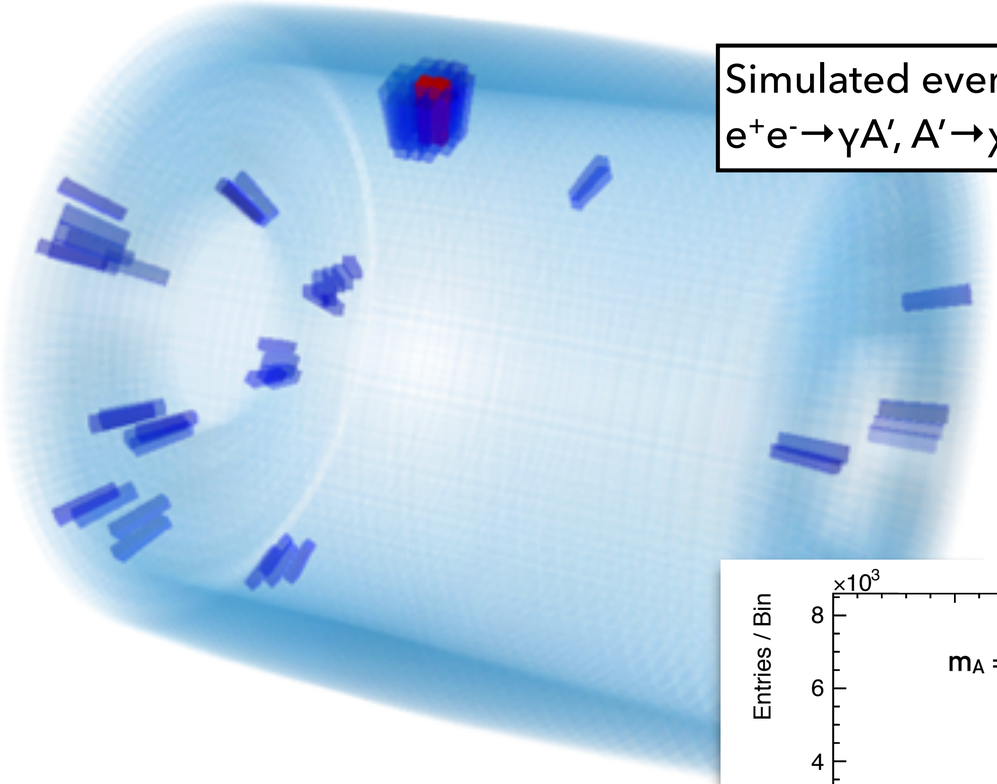


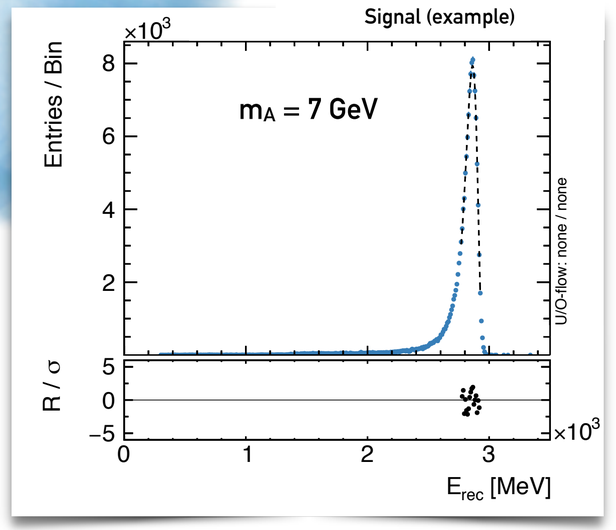
- Effects of beam background:
  - Degrades energy resolution.
  - Radiation damage.
  - Pile-up and increased event size.
  - Physics background.

→ Upgrades of hardware (detector) and software (reconstruction) are crucial.

Belle II: Dark Photons to invisible (``Single photon search'')

- Goal is to produce a competitive single photon measurement using the Phase 2 data (2018):
  - Belle II calorimeter is more hermetic than BaBar's (no projective gaps): Better sensitivity for low mass A' than BaBar.
  - Aim for trigger energy threshold $E_\gamma^* > 1.0$ GeV, at least during initial low luminosity running: Higher mass reach than BaBar.
  - Belle had no triggers for this physics.



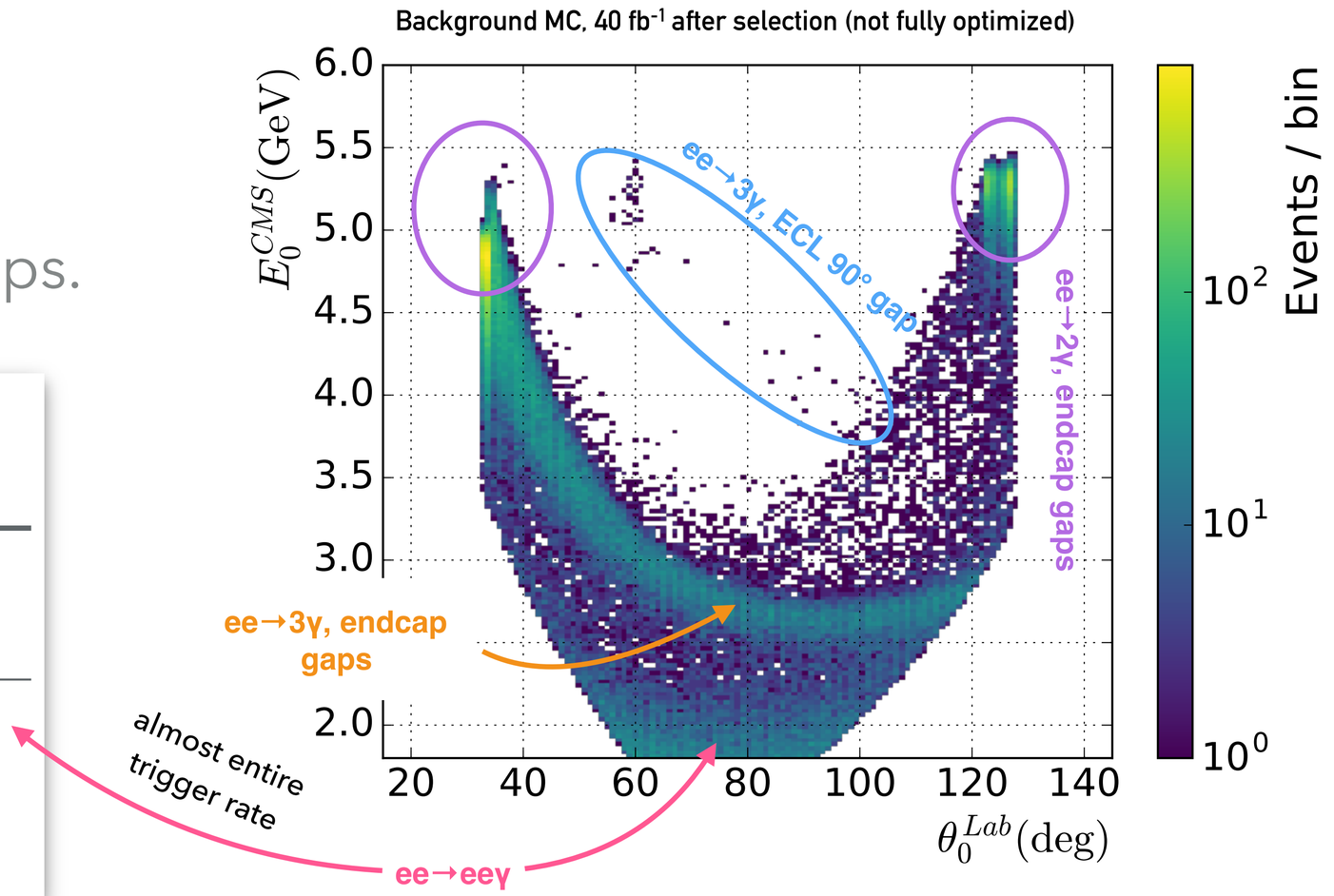


Belle II: Dark Photons to invisible (``Single photon search'')

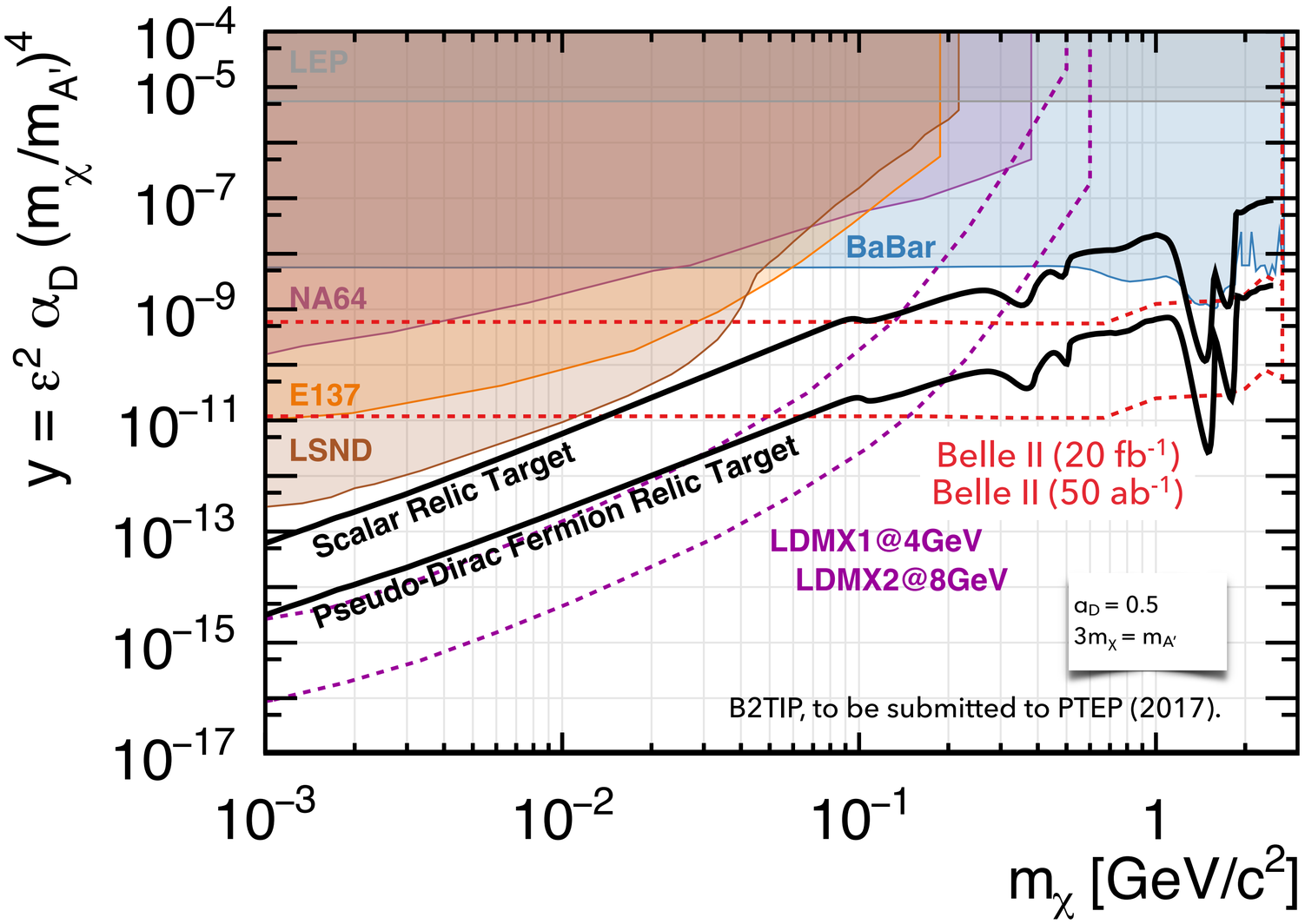
- Qualitatively the same backgrounds as in the BaBar analysis, but:
  - Almost no backgrounds from ee→γγ outside the endcap gaps.

Trigger	Rate at full luminosity [kHz]
1 GeV* E*>1 GeV and second cluster E* < 0.3 GeV	4 kHz (barrel) 7 kHz (endcaps)
2 GeV* E*>2 GeV and Bhabha veto	5 kHz (barrel)

Belle II MC Preliminary (BG16), C. Hearty

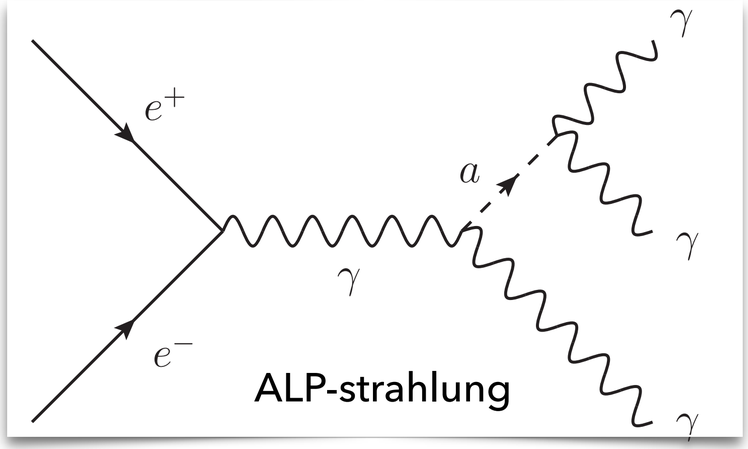


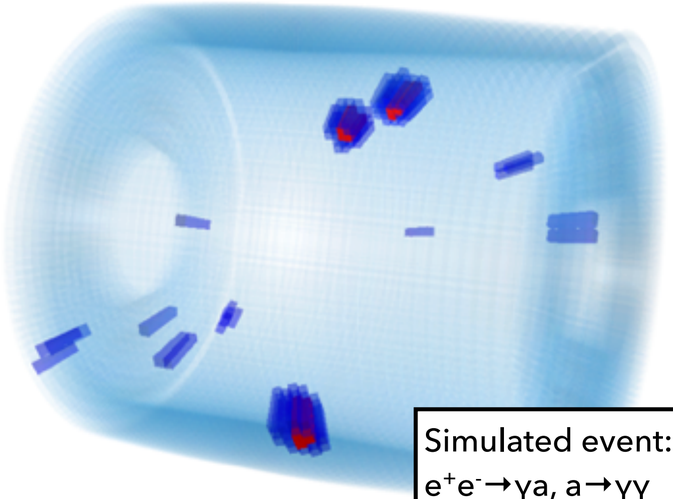
Belle II: Dark Photons to invisible (``Single photon search'')



Belle II: Axion-Like Particles (ALPs)

- Axion-like particles (ALPs) are pseudo-scalars and couple to bosons. Unlike Axions, ALPs have no relation between mass and coupling.
- They can be Dark Matter candidates, Dark Sector mediators, and they appear in many BSM scenarios.
- Focus on coupling to photons ($g_{a\gamma\gamma}$) in this talk. B-decays give access to coupling to charged bosons (not in this talk).

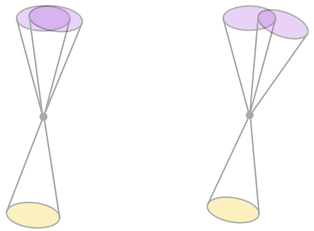


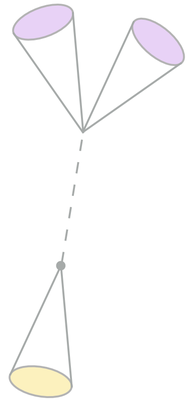


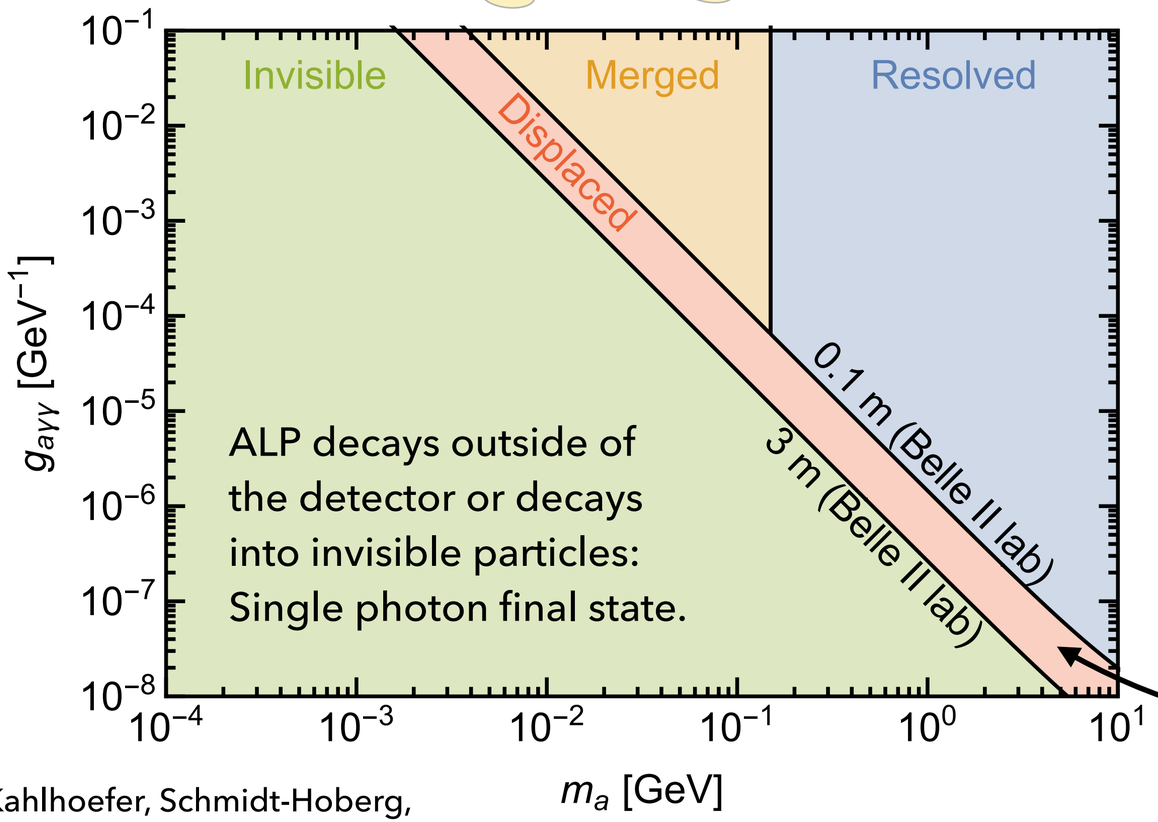
Simulated event:
$e^+e^- \to \gamma a$, $a \to \gamma\gamma$
(m_a=1 GeV)

Belle II: Axion-Like Particles decaying into two photons or Dark Matter

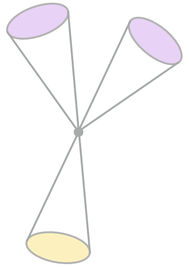
Two of the photons overlap or merge.







Three resolved, high energetic photons.



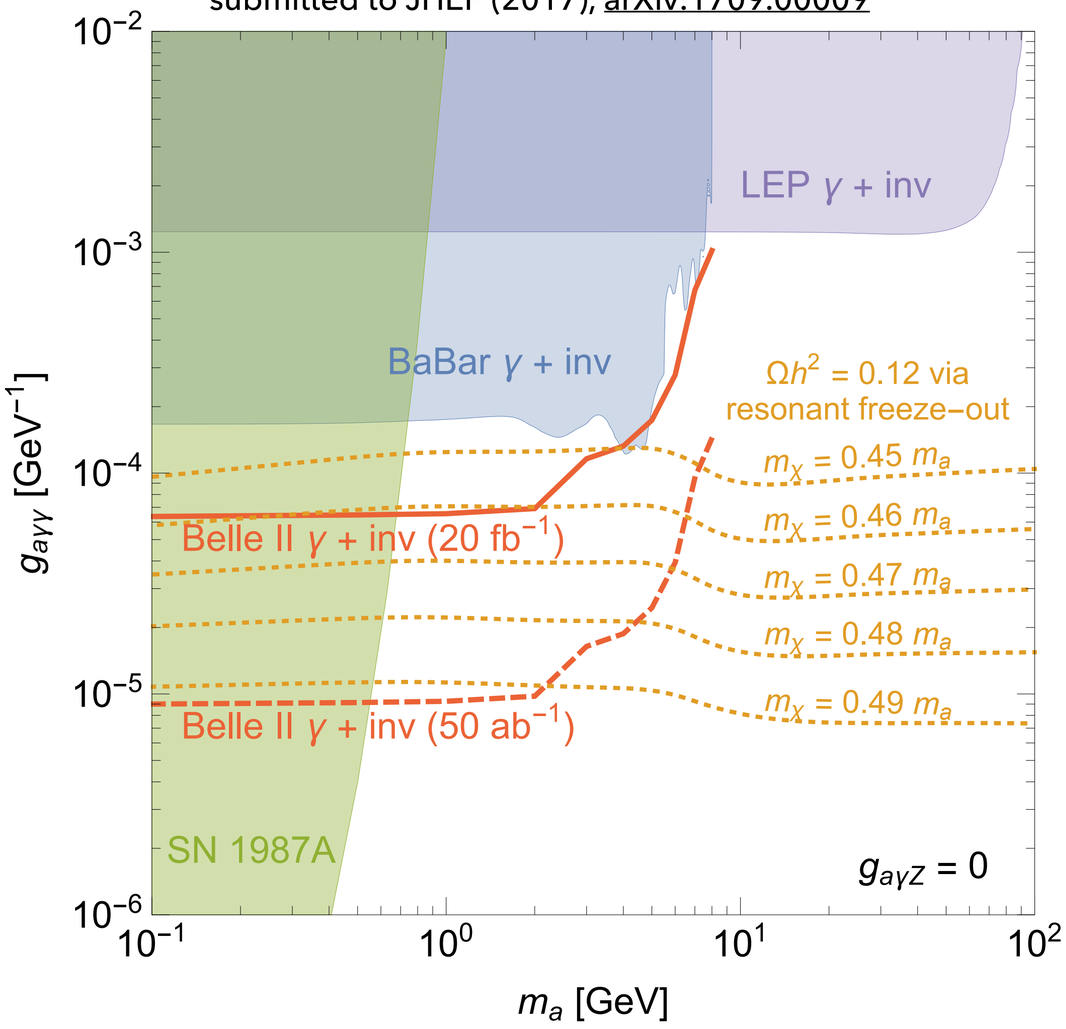
Nominal analyses veto long-lived topologies.

Dolan, Ferber, Hearty, Kahlhoefer, Schmidt-Hoberg, submitted to JHEP (2017), arXiv:1709.00009

Belle II: ALPs decaying into Dark Matter

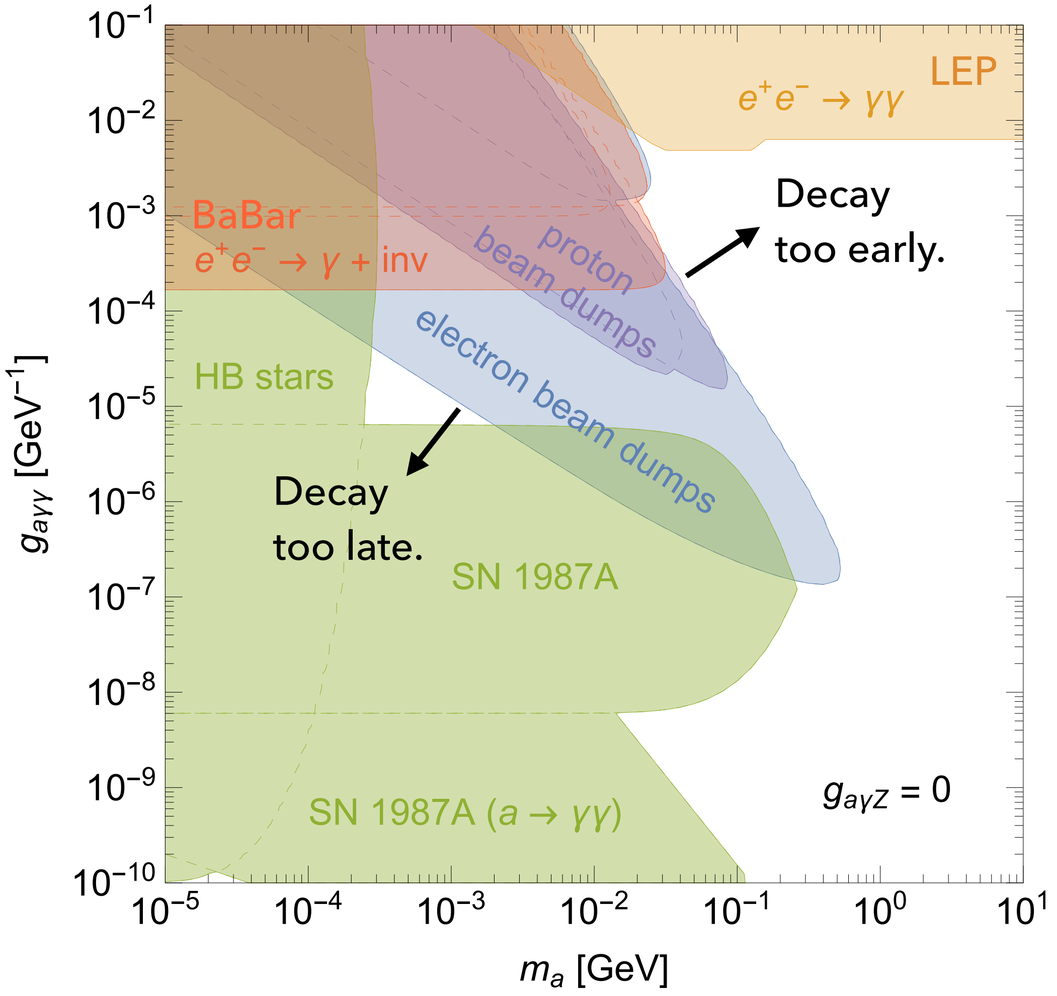
- ALP decays can be invisible because the ALP decays outside of the detector or because the ALP decays into an invisible final state: Dark Matter.
- We re-interpreted BaBar's Dark Photon analysis in terms of ALPs decaying into Dark Matter.
- We studied the Belle II sensitivity for ALPs decaying into Dark Matter.

Dolan, Ferber, Hearty, Kahlhoefer, Schmidt-Hoberg, submitted to JHEP (2017), arXiv:1709.00009

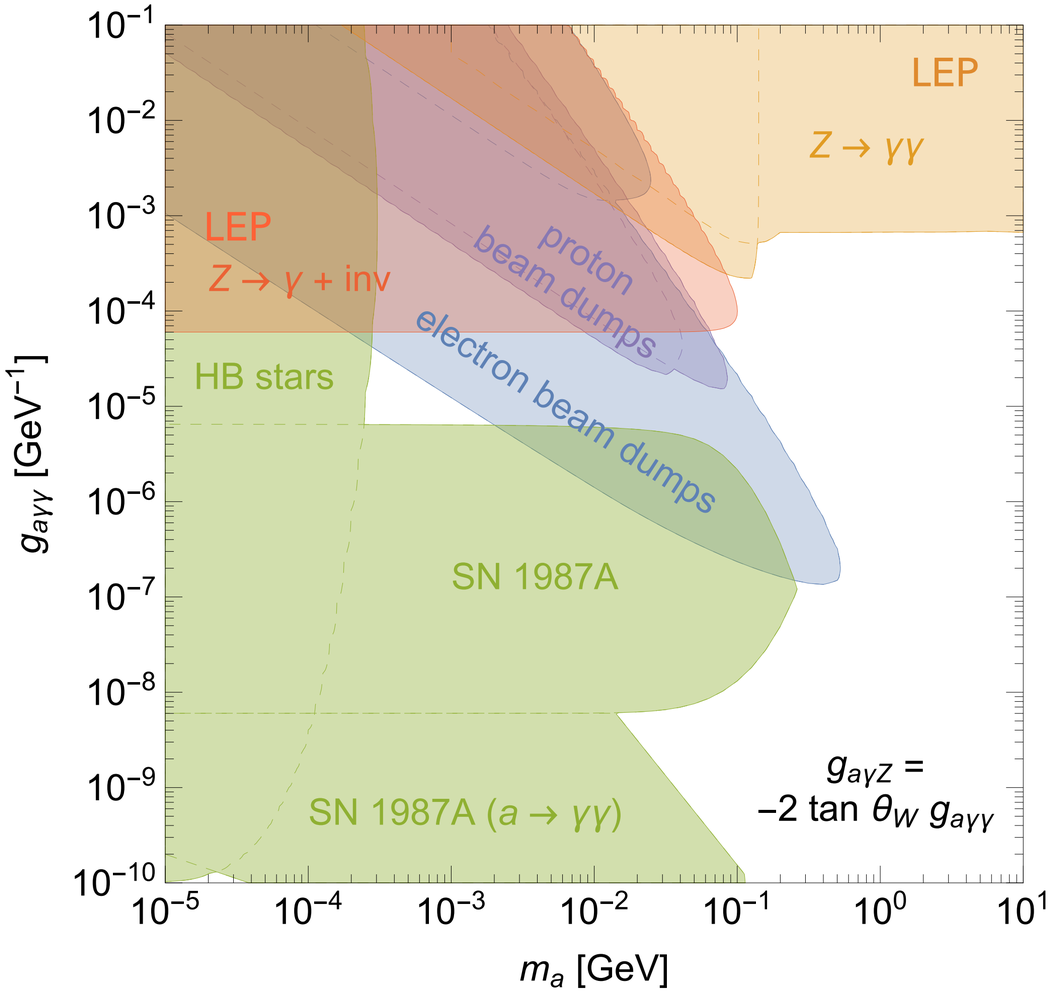


Belle II: Axion-Like Particles, revised constraints

only couplings to γ's



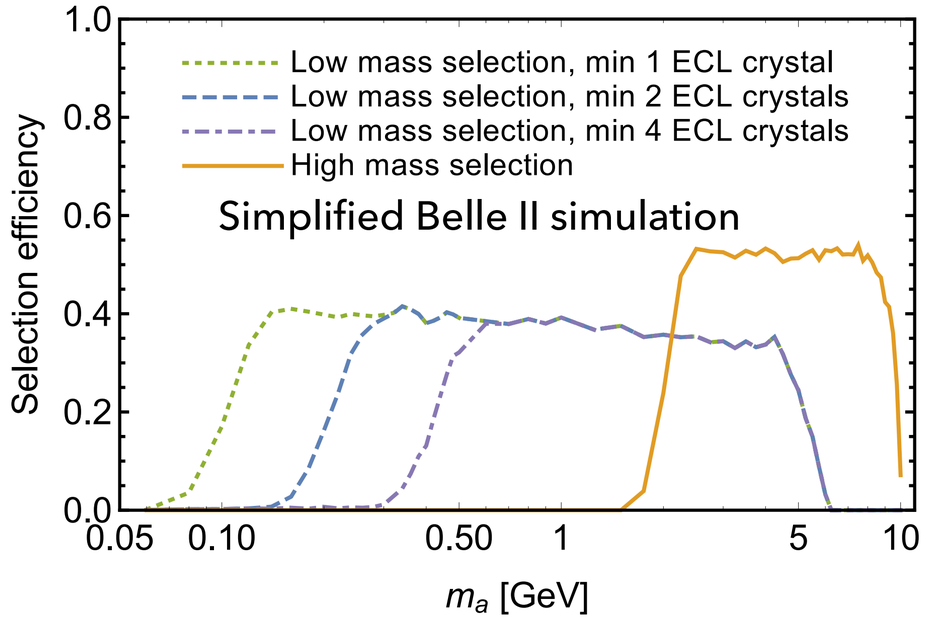
with couplings to Z's



Dolan, Ferber, Hearty, Kahlhoefer, Schmidt-Hoberg, submitted to JHEP (2017), arXiv:1709.00009

Belle II: ALPs decaying into two Photons

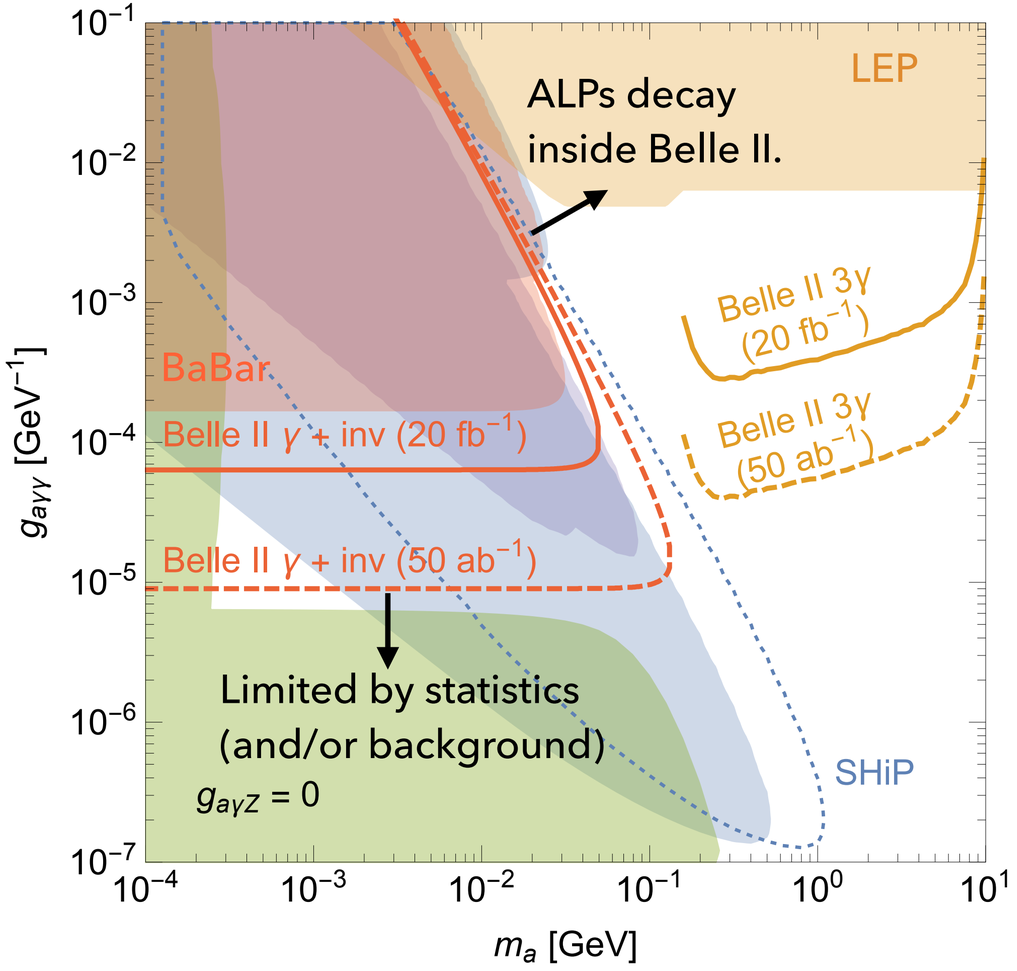
- Select events with three ECL clusters with $m_a \geq 0.2$ GeV and search for a bump in the invariant 2γ mass spectrum.
- Main backgrounds:
  - $e^+e^- \to \gamma\gamma\gamma$ (reduced by helicity cuts)
  - $e^+e^- \to \gamma\gamma$ + beam background γ (reduced by timing cuts)
  - $e^+e^- \to \gamma\gamma$, $\gamma \to e^+e^-$ outside of tracking volume (reduced by angular cuts)



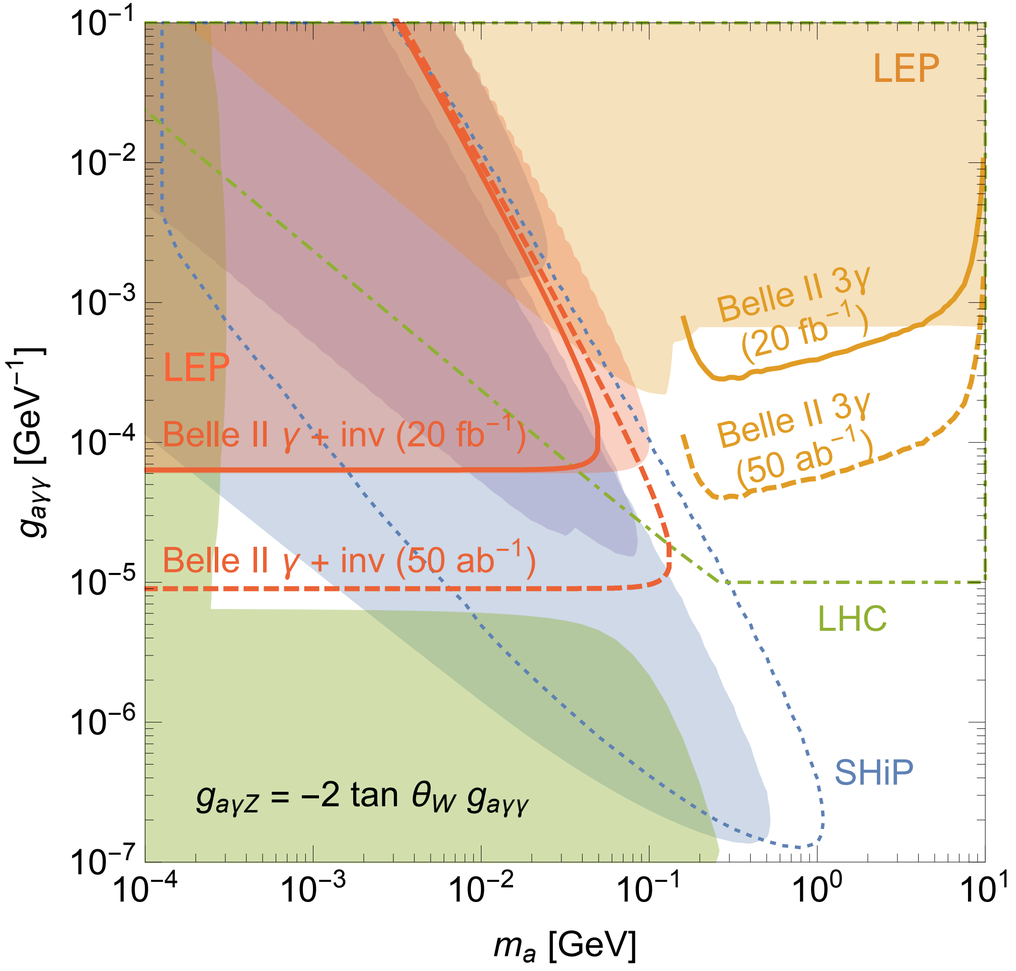
- Trigger: For small ALP masses, events look like $e^+e^- \to \gamma\gamma$ events.
  - At BaBar/Belle: Prescaled at L1.
  - At Belle II: Delay trigger decision, no prescale at L1.

Belle II: Axion-Like Particles, future experiments for visible decays

only couplings to γ's



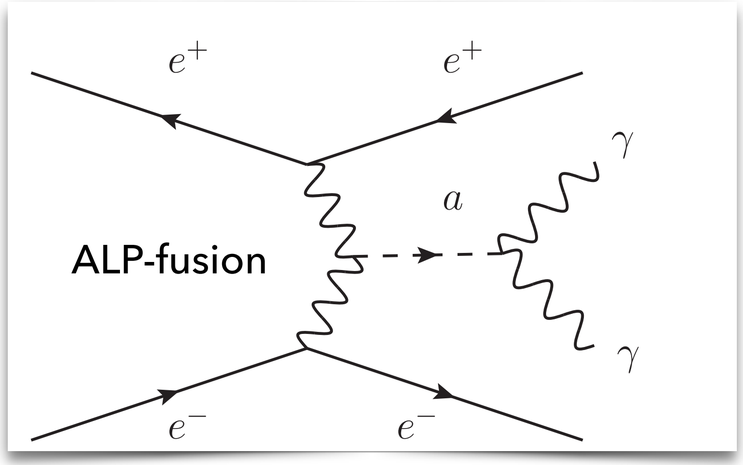
with couplings to Z's

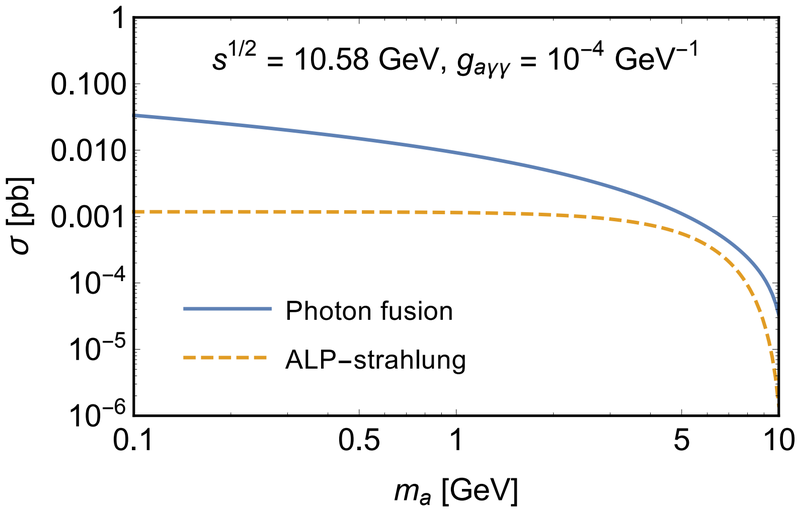


Dolan, Ferber, Hearty, Kahlhoefer, Schmidt-Hoberg, submitted to JHEP (2017), arXiv:1709.00009

Belle II: ALPs below 200 MeV?

- For ALP masses below ~200 MeV, the decay photons are reconstructed as one ECL cluster even in offline analysis. Currently under study:
  - Untagged (electrons not seen) ALP fusion production has a much higher cross section and produces ALPs with less boost (difficult to trigger).
  - Shower shapes for merged cluster are different, MVA based reconstruction has better separation power (but events have to pass L1 trigger).
  - Pair conversion of one decay photon costs statistics, but yields a distinctive four particle final state.





Dolan, Ferber, Hearty, Kahlhoefer, Schmidt-Hoberg, submitted to JHEP (2017), arXiv:1709.00009

Belle II: Other planned Dark Sector and exotic searches

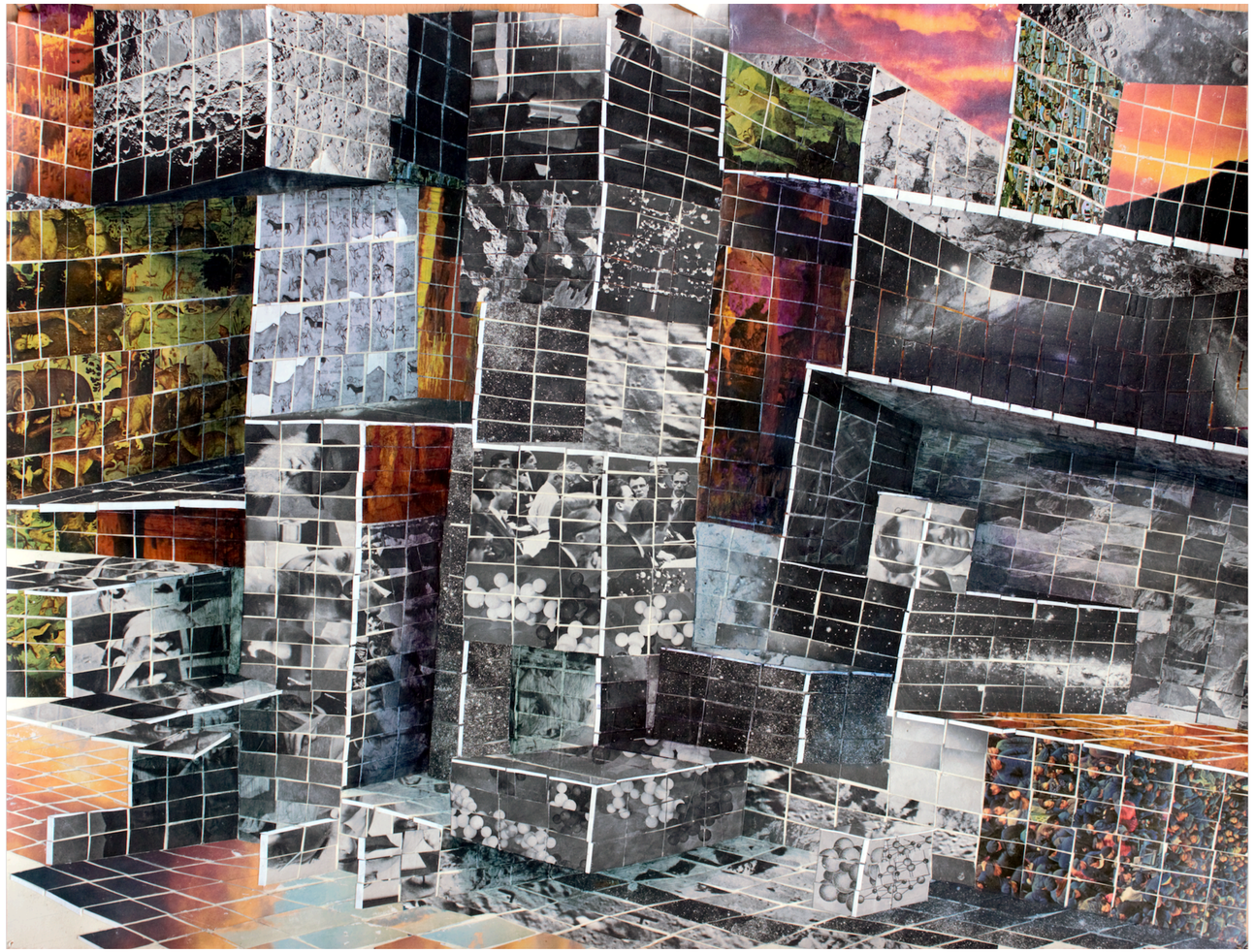
- Search for Dark Photons decaying into pseudo-Dirac DM: ***
  - $A' \rightarrow \chi_1\chi_2$, $\chi_2 \rightarrow \chi_1 A'$, $A' \rightarrow e^+e^-$.
- Off-shell A′ decays. ***
- Long-lived neutral particle decays.
- Visible Dark Photon decays.
- Dark Scalar: $e^+e^- \rightarrow \tau^+\tau^- S$, $S \rightarrow \ell^+\ell^-$
- Magnetic monopoles with small magnetic charges. ***
- Invisible $\Upsilon(1S)$ decays via $\Upsilon(3S) \rightarrow \Upsilon(1S)\pi^+\pi^-$ (Requires beam energies at $\Upsilon(3S)$).
- Muonic Dark Force:
  - $e^+e^- \rightarrow \mu^+\mu^- Z'$, $Z' \rightarrow \mu^+\mu^-$
  - $e^+e^- \rightarrow \mu^+\mu^- Z'$, $Z' \rightarrow$ Invisible ***
- Dark Higgs
- …

*** Possible during Phase 2 (2018 data)

Summary

- BaBar single photon search excludes g-2 region of parameter space.
- Still ongoing Dark Sector searches in BaBar and Belle.
- The Belle II search for light dark matter is competitive with BaBar already with expected 2018 data due to the more hermetic calorimeter and better triggers.
- The early running of Belle II offers possibilities for many unique physics analyses in the Dark Sector.
- Belle II Physics Book in preparation* (Belle II detector, simulation, software, analysis tools, physics program incl. dark sectors), to be submitted to PTEP (2017).

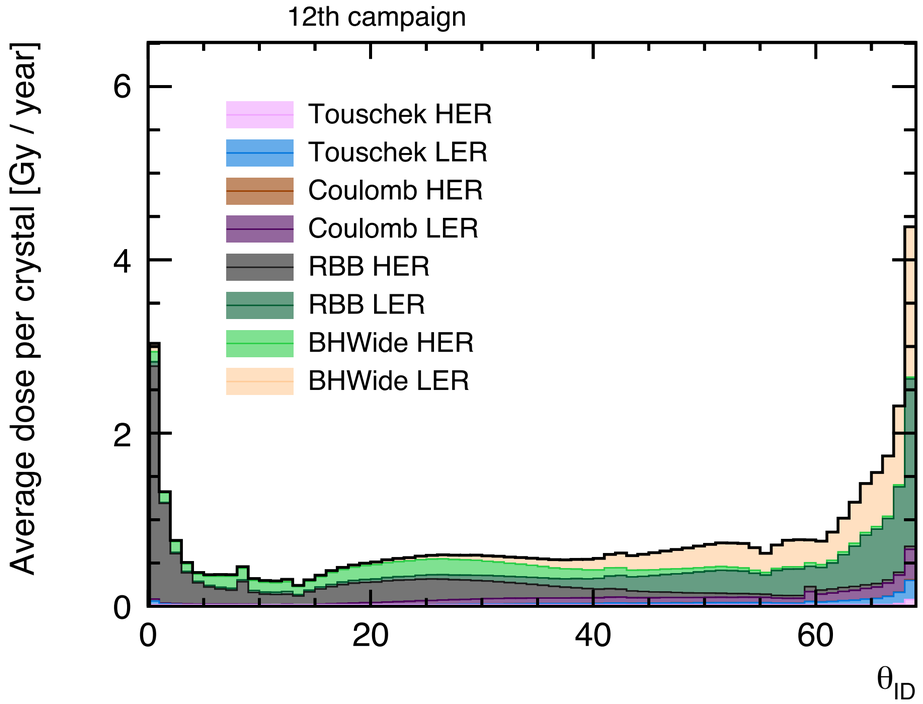
* https://confluence.desy.de/display/BI/B2TiP+ReportStatus

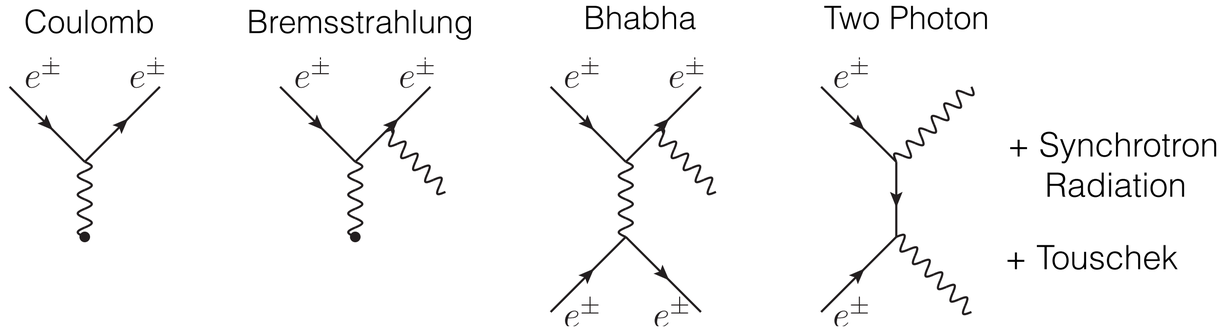


``Leaning out of windows'' (E. Zack/V. Kwan/T. Ferber/J. Roman)
Outreach project of TRIUMF, UBC and Emily Carr University
Exhibition Jan 25 – Feb 8, 2018 (Vancouver)

Additional information

Beam backgrounds at Belle II





- Degrades calorimeter resolution.
- Radiation damage.
- Pile-up and event size.
- Physics background.

Triggers

Trigger	Rate at full luminosity [kHz]
1 GeV* E*>1 GeV and second cluster E* < 0.3 GeV	4 kHz (barrel) 7 kHz (endcaps)
2 GeV* E*>2 GeV and Bhabha veto	5 kHz (barrel)

Belle II MC Preliminary (BG16), C. Hearty