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Dark sector searches at BaBar and Belle and outlook for Belle II

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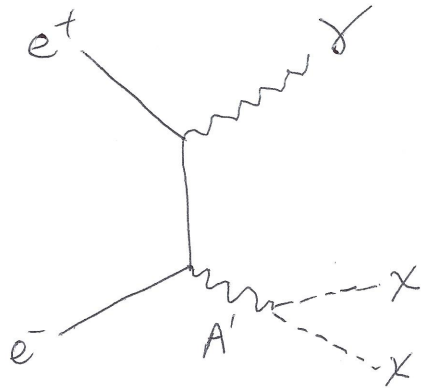
U.S. Cosmic Visions: New Ideas in Dark Matter

Outline

- Search for invisible decays of a dark photon produced in e^+e^- collisions at BaBar.
- Prospects for Belle II: single photon search; axion-like particles.
- Search for muonic dark forces at BaBar.
- Belle: Search for a dark vector gauge boson decaying to $\pi^+\pi^-$ using $\eta \rightarrow \pi^+\pi^- \gamma$ decays .

BaBar single photon search

- Optimized for and interpreted in terms of a dark photon A′ decaying invisibly.



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

- We assume on-shell A′ ($m_\chi < m_{A'}/2$), so signal is a monoenergetic photon.
  - analysis is otherwise not sensitive to m_χ or to the coupling of the χ to the A′.

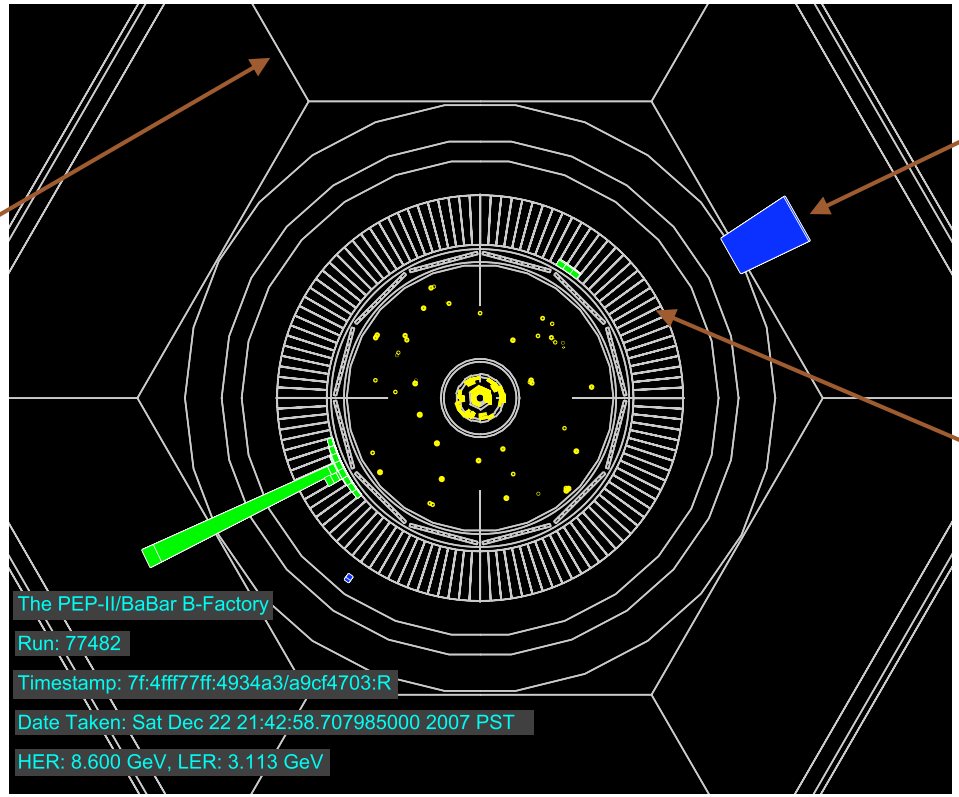
Detector issues — trigger

- Single photon trigger was implemented for final BaBar running period:
  - 48 fb^{-1} for high $m_{A'}$ (low E_γ), mostly Υ(2S) and Υ(3S)
  - 53 fb^{-1} for low $m_{A'}$ (addition 5 fb^{-1} at the Υ(4S)).

- Somewhat complicated, but nominal trigger threshold $E^*_\gamma > 1.5$ GeV; analysis threshold $E^*_\gamma > 1.8$ GeV.
  - trigger calibration issues.

Detector issues — hermeticity

- $e^+e^- \rightarrow \gamma\,\gamma$ event



photon shower detected in muon system (IFR)

no efficiency in muon system near sector boundaries

azimuthal gaps between crystals align with collision point

- Require $|\cos\theta^*|<0.6$ so that both γ are in the calorimeter.

Backgrounds

- $e^+e^- \rightarrow \gamma\,\gamma$, 1 γ not detected.
  - identical to the signal for $m_{A'} < 1.6$ GeV/c^2
  - difficult to quantify this background; not possible to detect a signal.

- $e^+e^- \rightarrow \gamma\,\gamma\,\gamma$, 1 γ not detected, 2nd out of the detector acceptance (typically ~0°).

- $e^+e^- \rightarrow e^+e^-\,\gamma$, both electrons out of acceptance.
  - kinematic limitations on maximum photon energy.

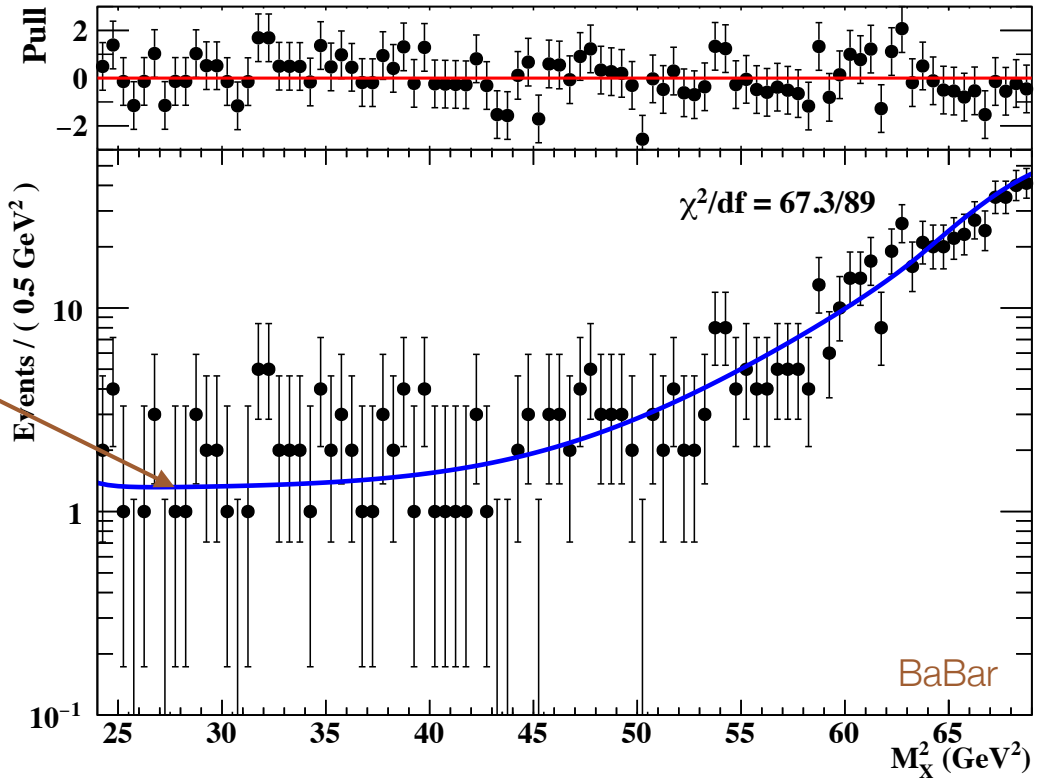
- Beam background photons do not mimic signal, but can be the second photon in a signal event.

Event selection / BDT

- Boosted Decision Tree to distinguish signal and background. 12 items, including:
  - $d\phi$ between signal and 2nd photon;
  - angle between $\vec{p}_{miss}$ and IFR cluster, calorimeter crystal edge, IFR sector boundary
- Training: 3 fb^{-1} of $\Upsilon(3S)$ data, simulated signal with uniform $m_{A'}$.

Mass regions

- High A′ mass region (low γ energy) $m_{A'}$ >5.5 GeV/c^2 is dominated by radiative Bhabha background smooth in recoil mass m_X. Loose cuts on BDT output



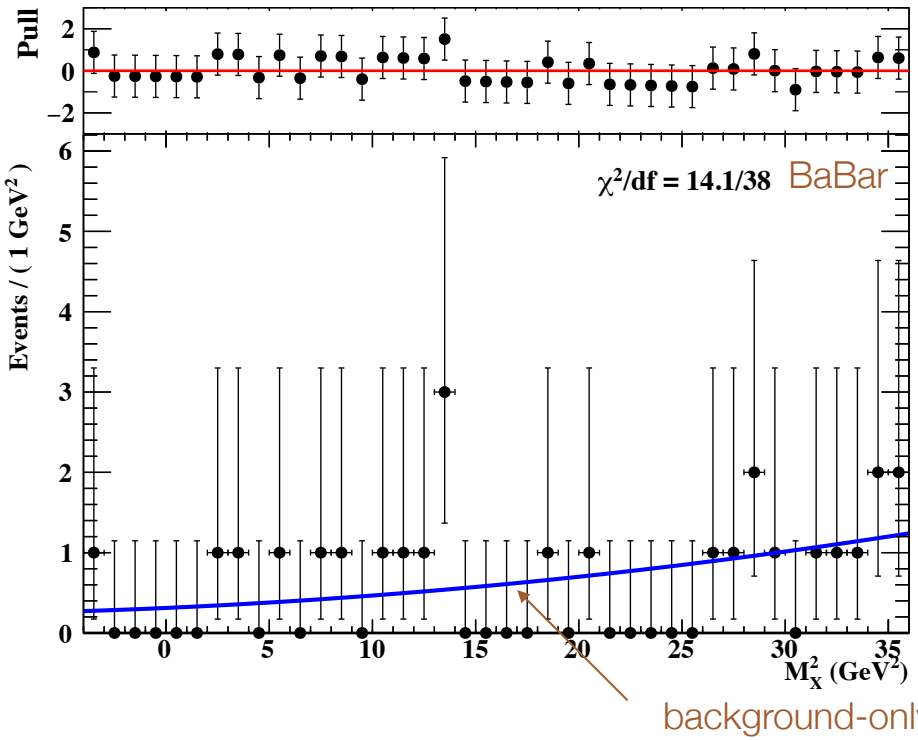
Y(3S) data

background-only shape from BDT<0 events

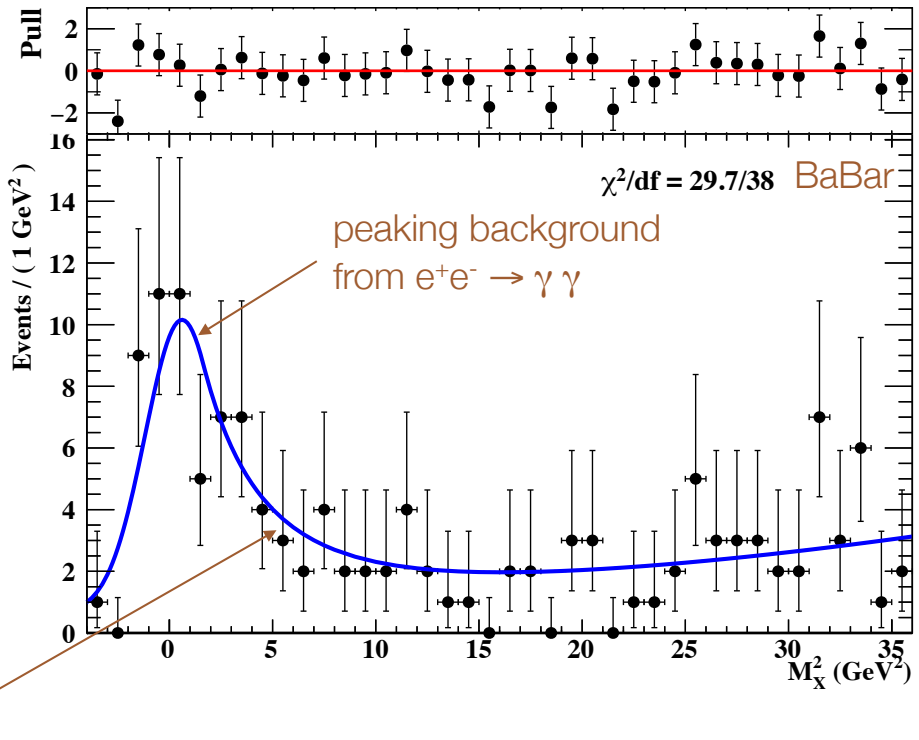
$$m_X^2 \equiv s - 2\sqrt{s}E_\gamma^*$$

- Low mass region has both peaking and smooth backgrounds. Select data using two statistically independent cuts on BDT and θ.

Y(3S) data — tight selection



Y(3S) data — loose′ selection

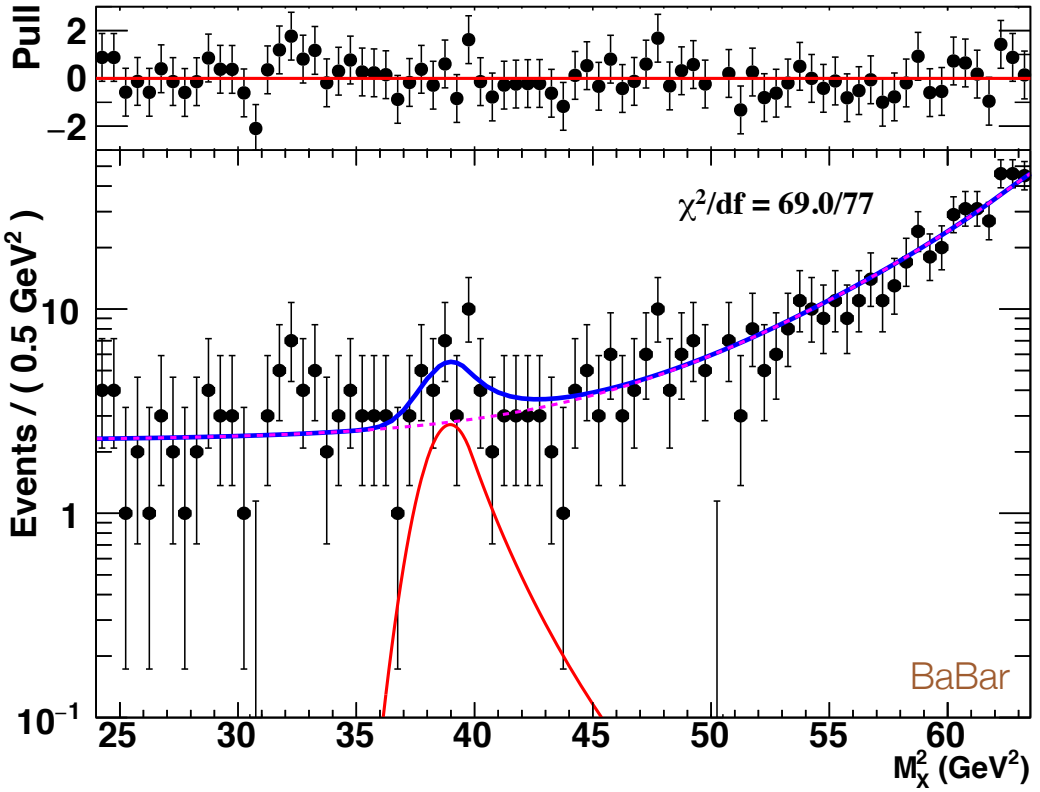


background-only fit

Signal extraction

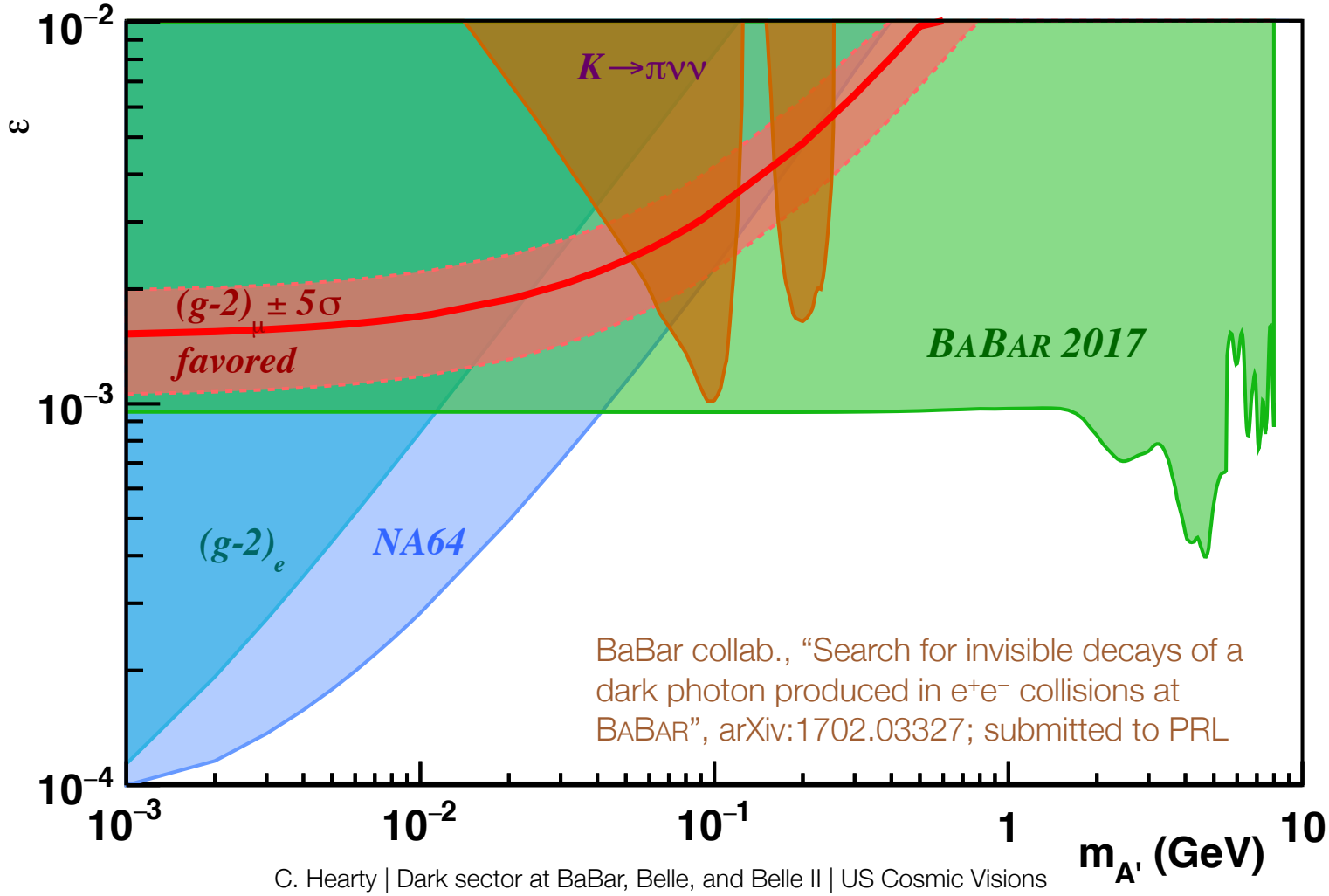
- Fit m_X^2 distribution; float signal, peaking background, and smooth background yields. 166 mass hypotheses.
  - simultaneous fit to 2S, 3S, 4S data, tight and loose.

Fit to Y(2S) + Y(3S) data,
$m_{A'} = 6.21$ GeV/c^2



BaBar exclusion region for invisible decays of a dark photon

- Region preferred by $(g\text{-}2)_\mu$ excluded.



Belle II projections for single photon analysis

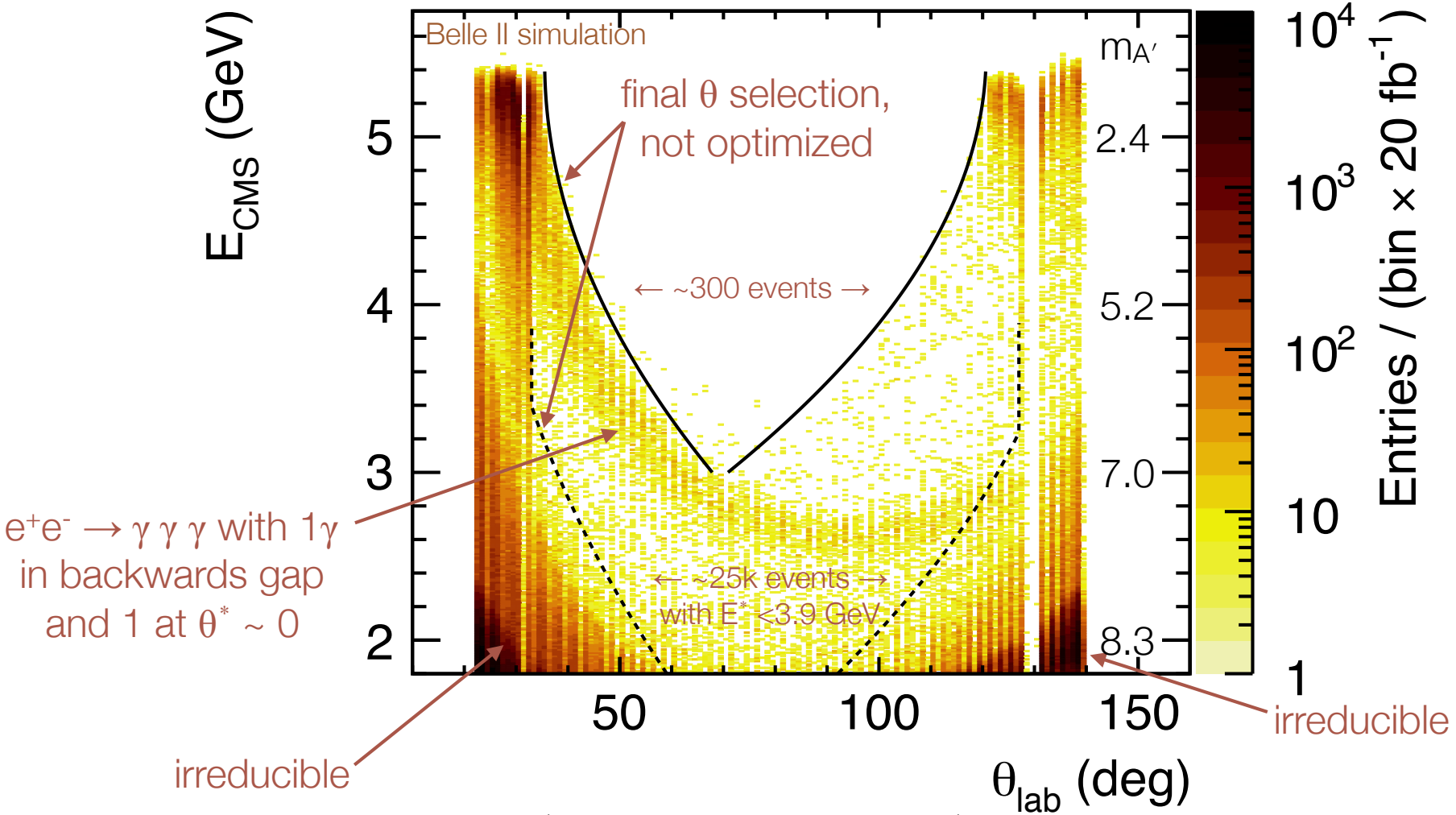
- Schedule (my best estimate, not official):
  - Phase 2 commissioning without vertex detectors: February – July 2018; hope for 20 fb^{-1}. Y(6S) or 4S.
  - Phase 3 commissioning (full detector): Dec. 2018 — June 2019: 200 fb^{-1}? Y(3S)?
- Goal is to produce a useful single photon measurement using the Phase 2 data.

Belle II detector

- Calorimeter is much more hermetic than BaBar:
  - gaps between barrel crystals are not projective
  - coverage is $-0.94 < \cos\theta^* < 0.96$ versus $-0.92 < \cos\theta^* < 0.89$ for BaBar
  - However, there are gaps between the barrel and endcaps in the calorimeter and the muon systems.
- We are aiming for a trigger threshold of $E^* > 1$ GeV.

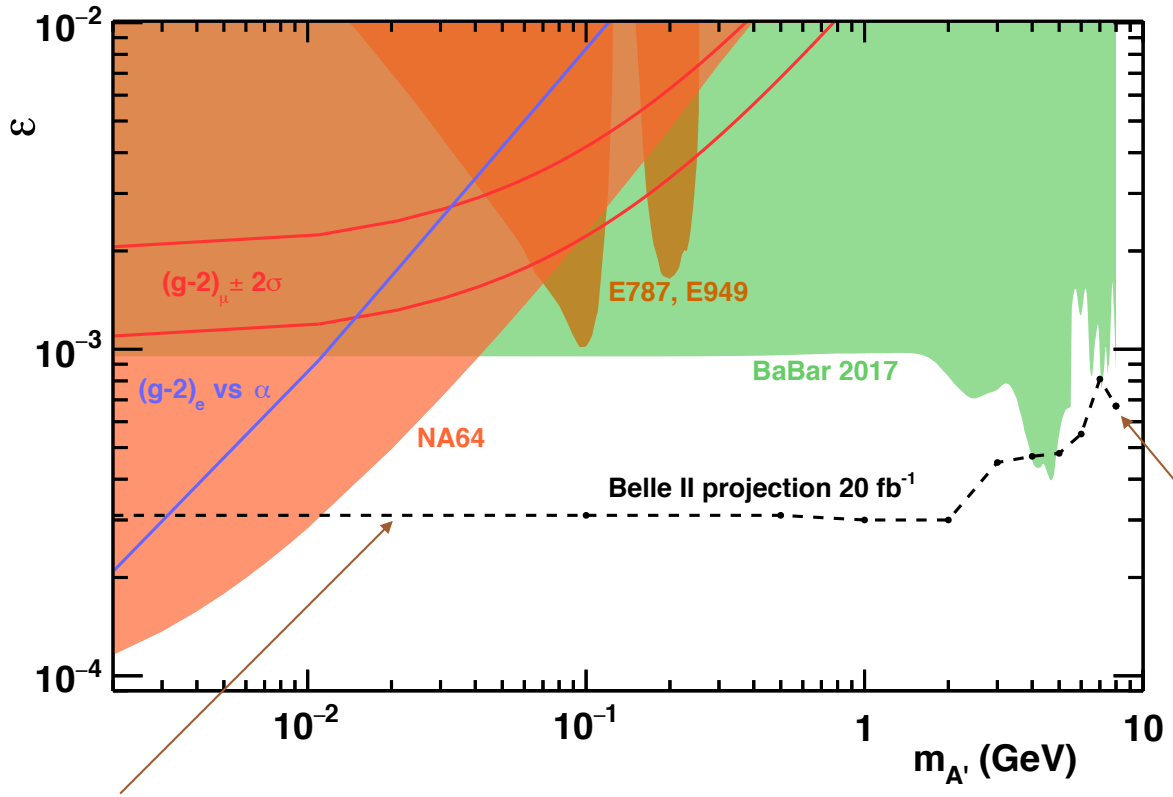
Predicted backgrounds in Belle II single photon analysis for 20 fb^{-1}. Loose selection, not optimized.

- Final sample is almost entirely $e^+e^- \to \gamma\,\gamma\,(\gamma)$ with $\geq 3\gamma$



Projected Belle II exclusion region, 20 fb^{-1}

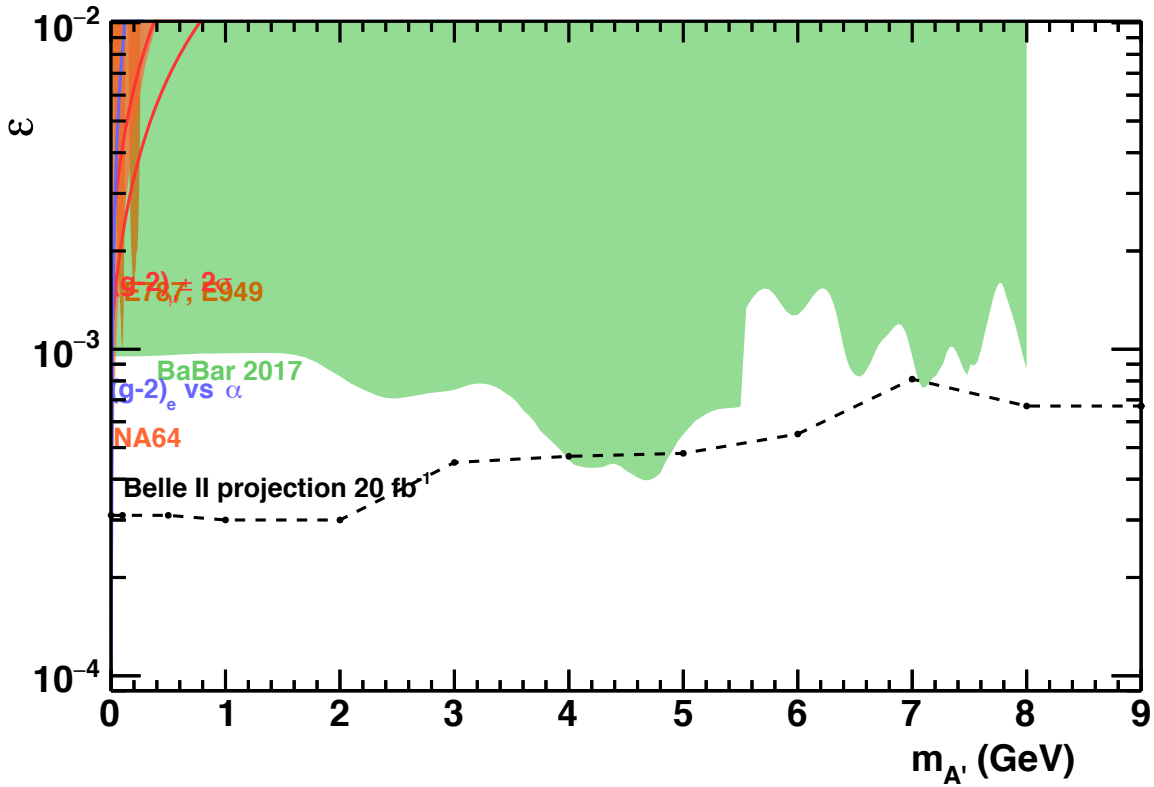
- Assumes we can quantitatively predict background levels.
  - photon efficiency over barrel/endcap gaps.



Reach masses of 9.1–9.5 GeV/c^2 with lower trigger threshold (vs 8 GeV/c^2 for BaBar)

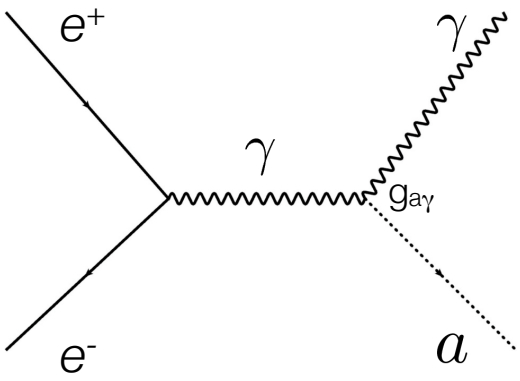
better calorimeter hermeticity to suppress $e^+e^- \to \gamma\,\gamma$

Projected Belle II exclusion region, 20 fb^{-1}

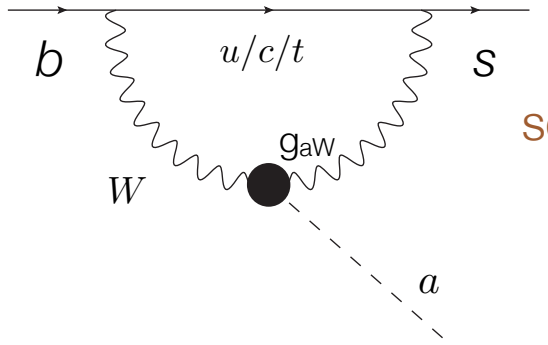


Belle II search for Axion-like particles (ALP, a)

- Production mechanisms:



K. Mimasu & V. Sanz, "ALPs at Colliders", JHEP 1506 (2015) 173



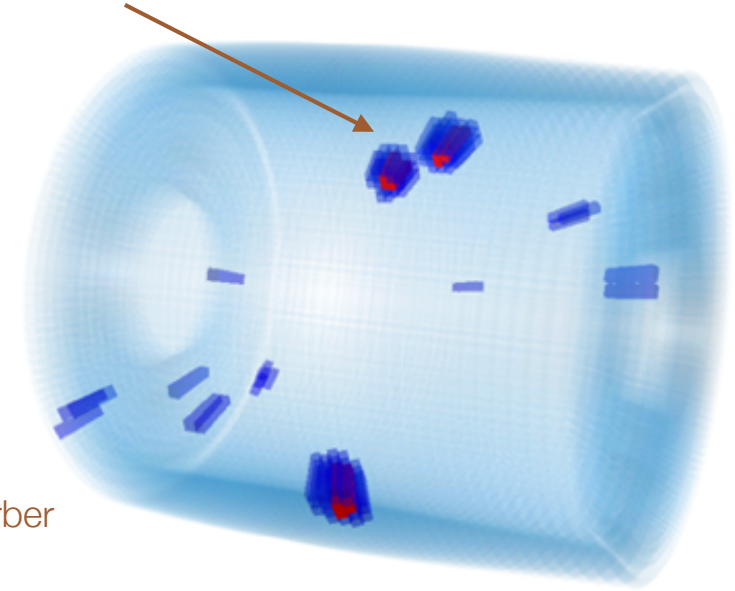
E. Izaguirre, T. Lin, and B. Shuve, "A New Flavor of Searches for Axion-Like Particles", arXiv 1611.09355

see backup slides

- ALP decays to a pair of photons (but could be long lived).

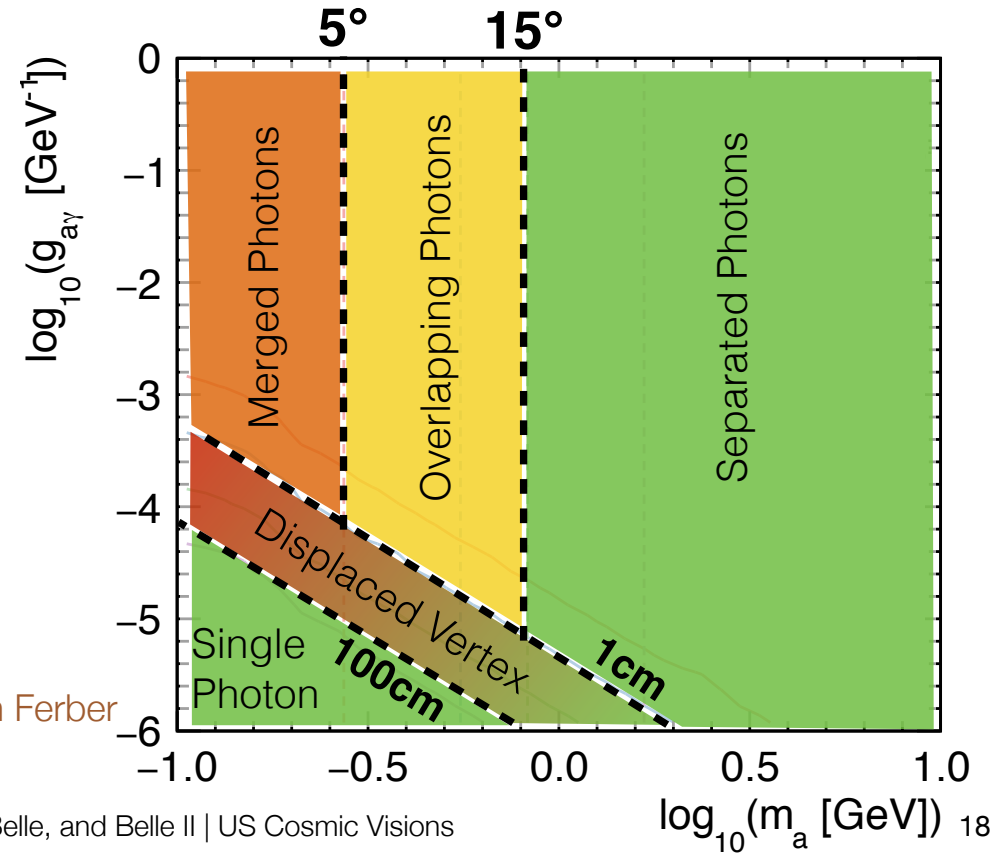
- Decay photons in $e^+e^- \to a\gamma$ could overlap in the trigger and look like $\gamma\gamma$. Large prescales applied to existing BaBar and Belle data sets.
  - Belle II trigger should be able to keep these events.

level 1 trigger may not separate these two clusters



Torben Ferber

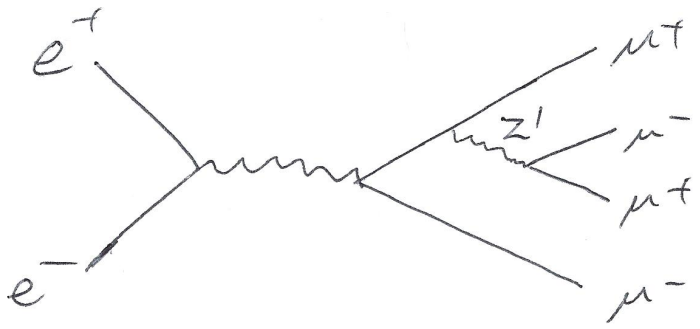
Different experimental signatures for $e^+e^- \to a\gamma$ search



Torben Ferber

Search for muonic dark forces at BaBar

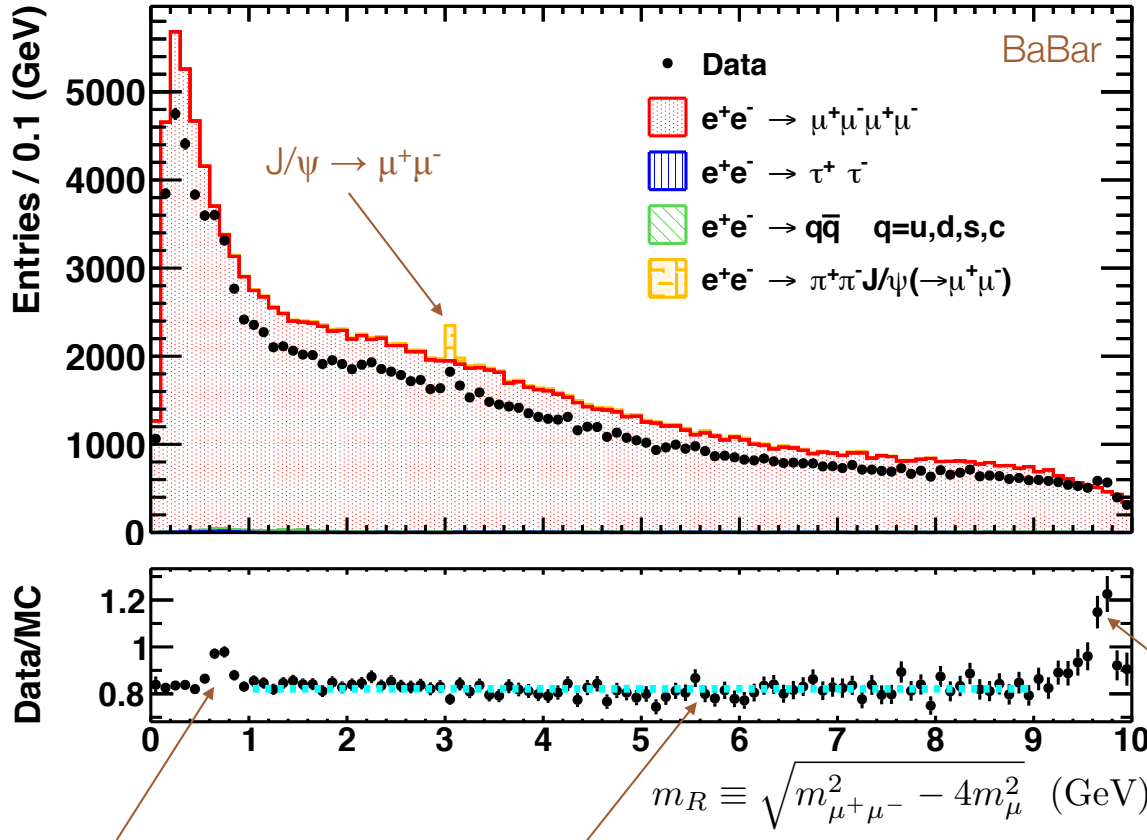
- Dark gauge boson Z′ couples only to 2nd and 3rd generations. Results are much less constrained; could explain muon g-2.



final state = 4 muons

- 514 fb^{-1} mostly at Y(4S), but also Y(3S), Y(2S), off-peak.

- Plot all four $\mu^+\mu^-$ mass combinations per event, and look for a narrow peak on a smooth background.



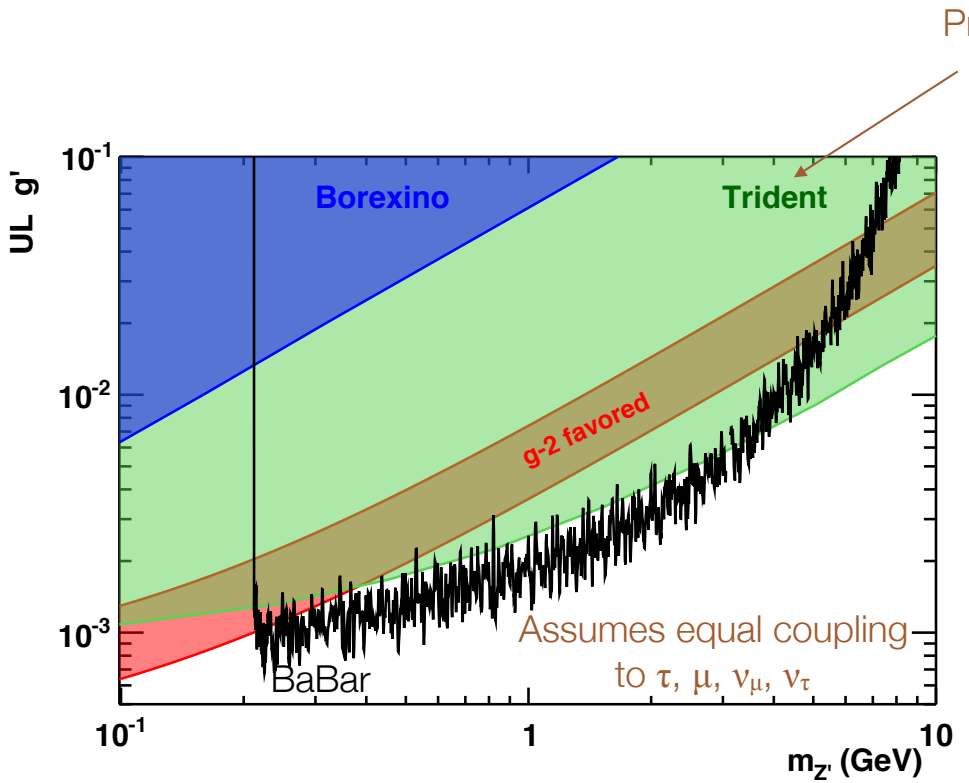
other candidates in ρ^0 events

$e^+e^- \to \pi^+\pi^-\rho^0$; $\rho^0 \to \pi^+\pi^-$
$e^+e^- \to \mu^+\mu^-\rho^0$

blue line = overall correction for ISR, tracking, PID etc

BABAR collab., "Search for a muonic dark force at BABAR", Phys. Rev. D94, 011102(R) (2016)

- No significant signal. Excludes this model as an explanation for muon g-2 for Z′ heavy enough to decay to muons.



- Belle II will study $e^+e^- \rightarrow \mu^+\mu^- Z'$ ($Z' \rightarrow$ invisible), but no results yet. Better hermeticity helps compared to BaBar

Search for a dark vector gauge boson U′ decaying to $\pi^+\pi^-$ using $\eta \to \pi^+\pi^-\gamma$ decays by Belle

- Dark sector vector gauge boson that couples predominantly to quarks. S. Tulin, Phys. Rev. D 89, 114008 (2014)

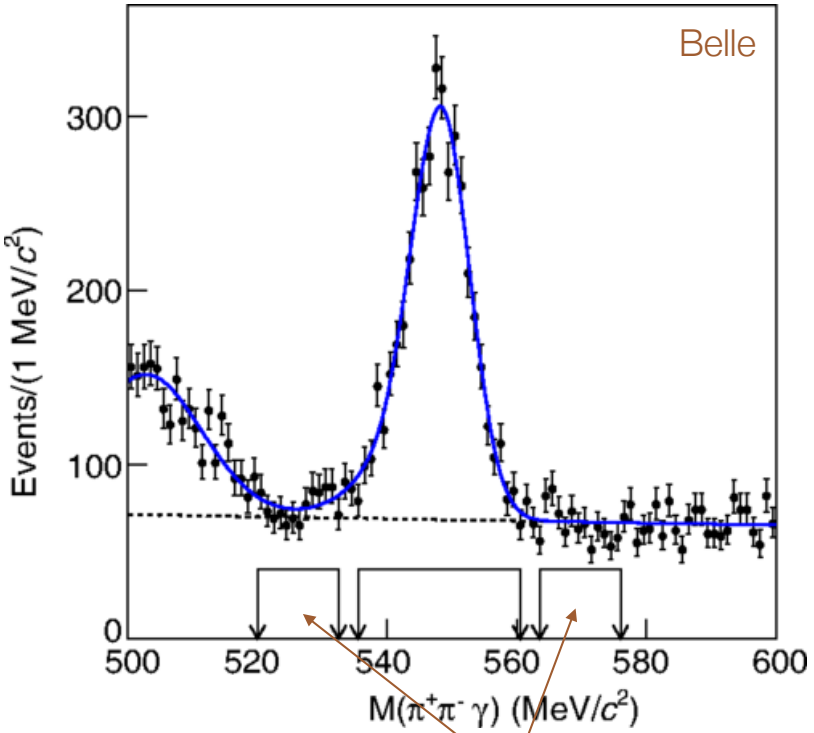
- Decay chain: $D^{*+} \to D^0\pi^+$

$D^0 \to K_s\eta$

$\eta \to U'\gamma$

$U' \to \pi^+\pi^-$

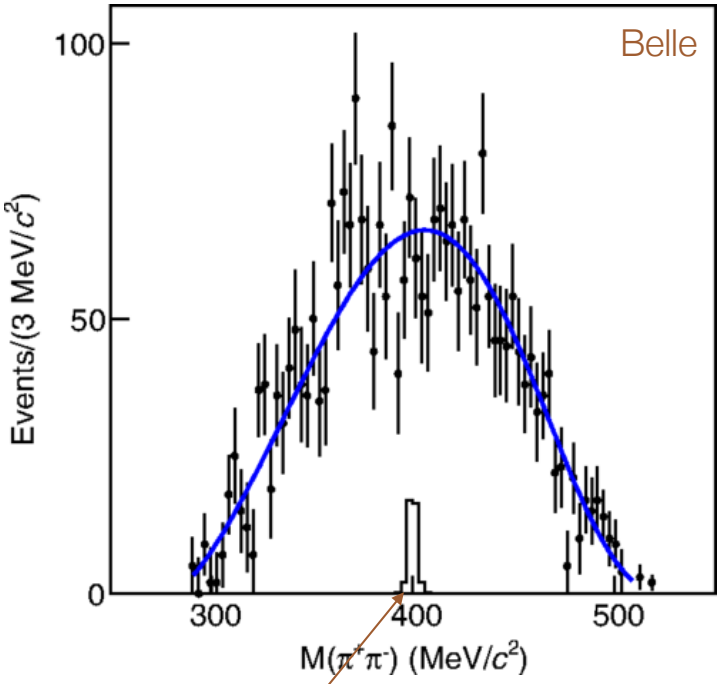
slow pion and K_s give a clean signature



Belle Collab, “Search for a dark vector gauge boson…”, Phys. Rev. D94, 092006 (2016)

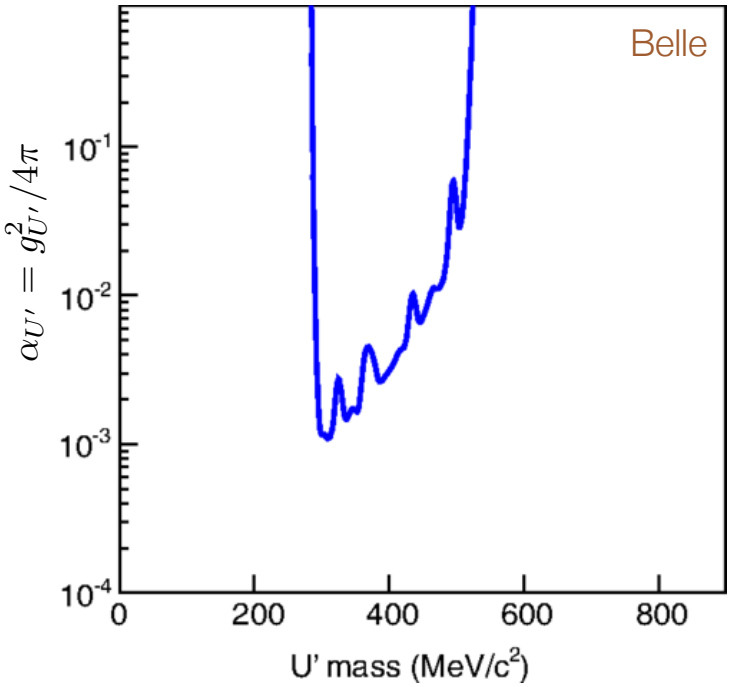
- Look for a peak in the $\pi^+\pi^-$ mass distribution on top of the smooth background. No evidence for signal.

sideband-subtracted mass distribution



400 Mev/c^2 signal

exclusion limits on coupling constant $g_{U'}$ between U′ and quarks



Summary

- BaBar single photon search excludes g-2 region of parameter space.

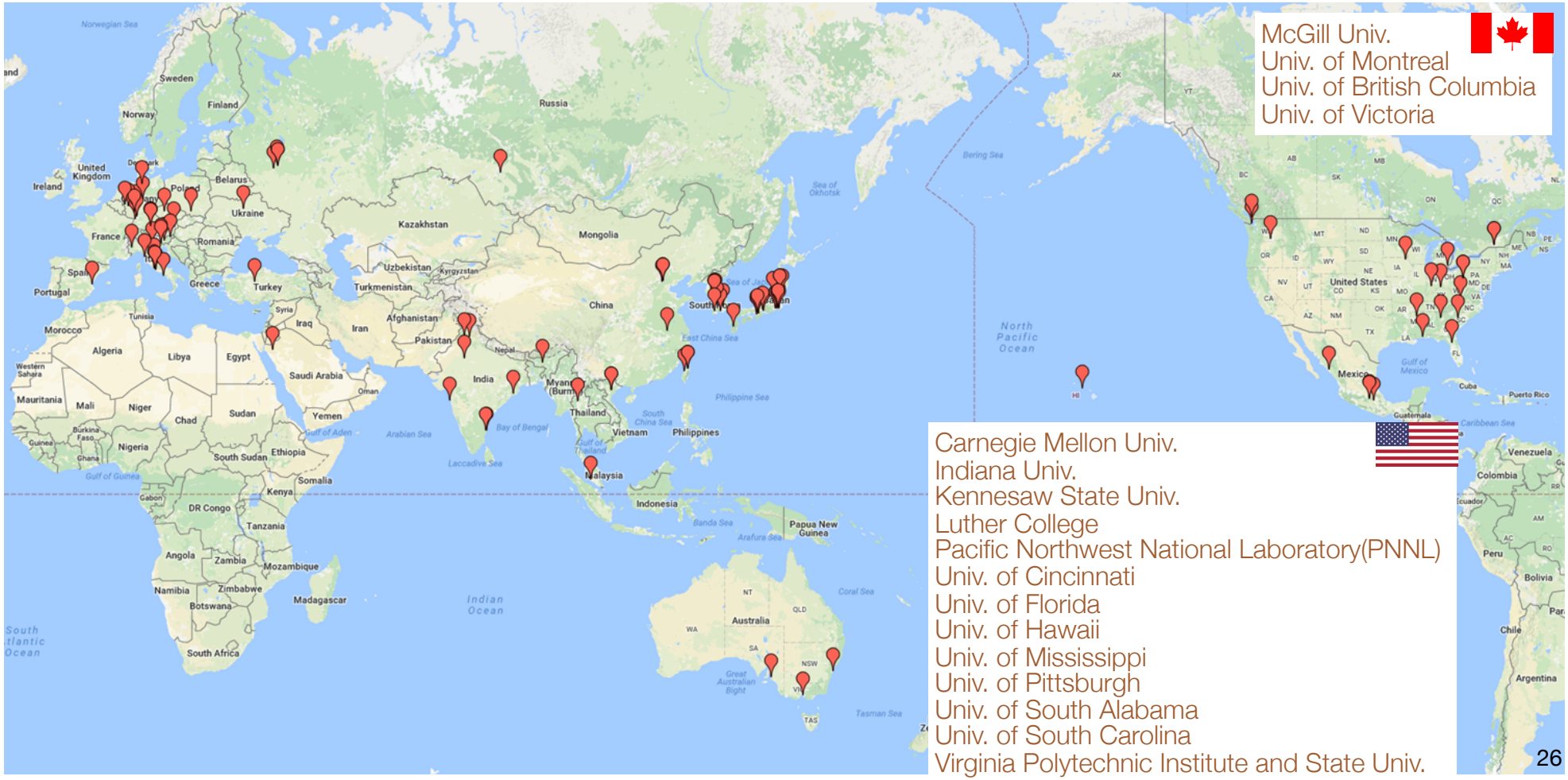
- Belle II will achieve useful limits in this mode with initial data set. Possibly for ALP searches as well. Improvements in searches for visible dark photon decays (backup slides) will require luminosity.

- Large number of additional searches are possible; Z′, U′, h′…
  - dark Higgs searches are almost background-free (backup slides); will improve linearly with luminosity.

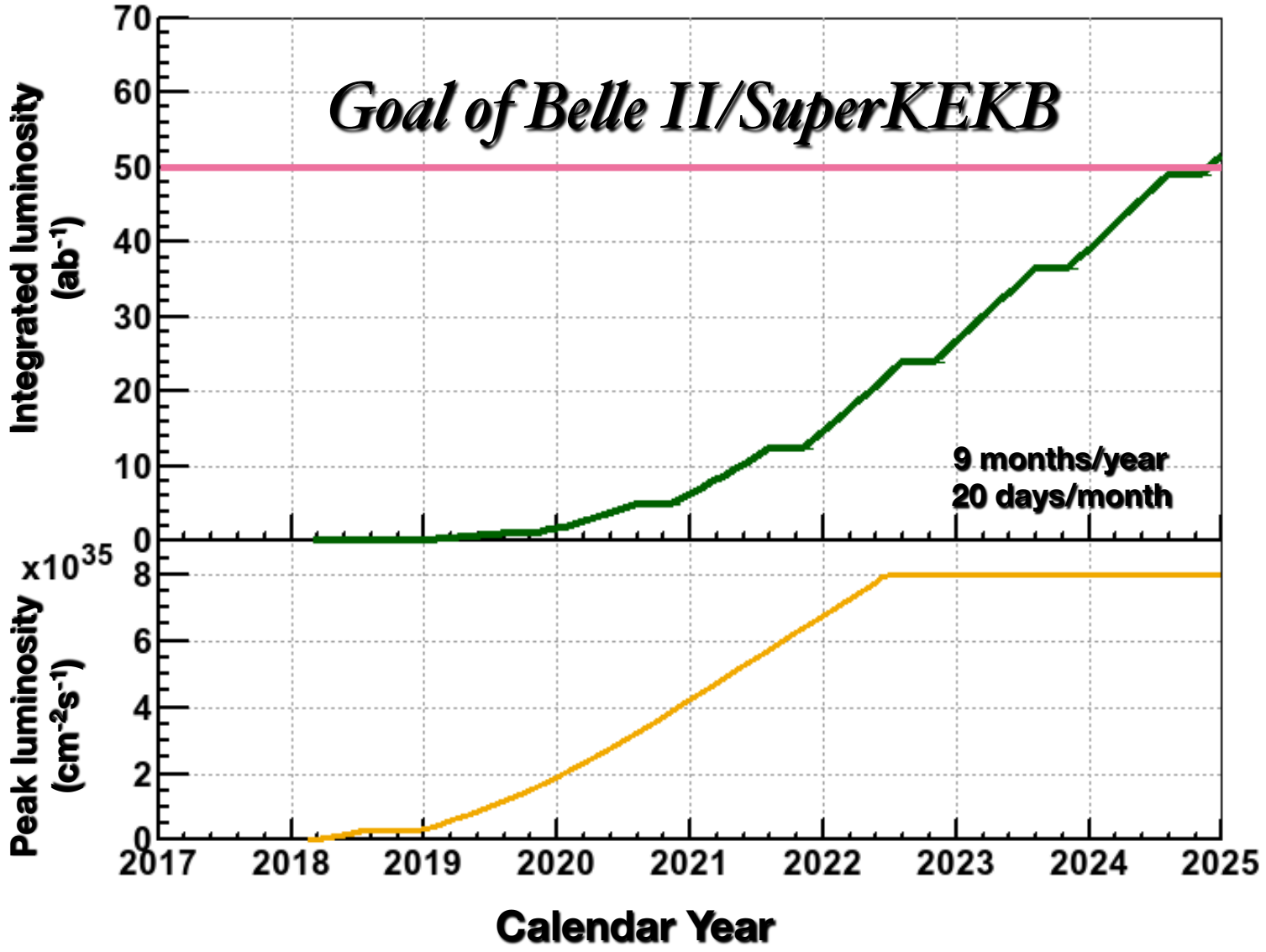
Backup

Belle II collaboration

- 23 countries, 100 institutions, 750 collaborators, including 380 PhD physicists & 260 graduate students.



SuperKEKB luminosity projection

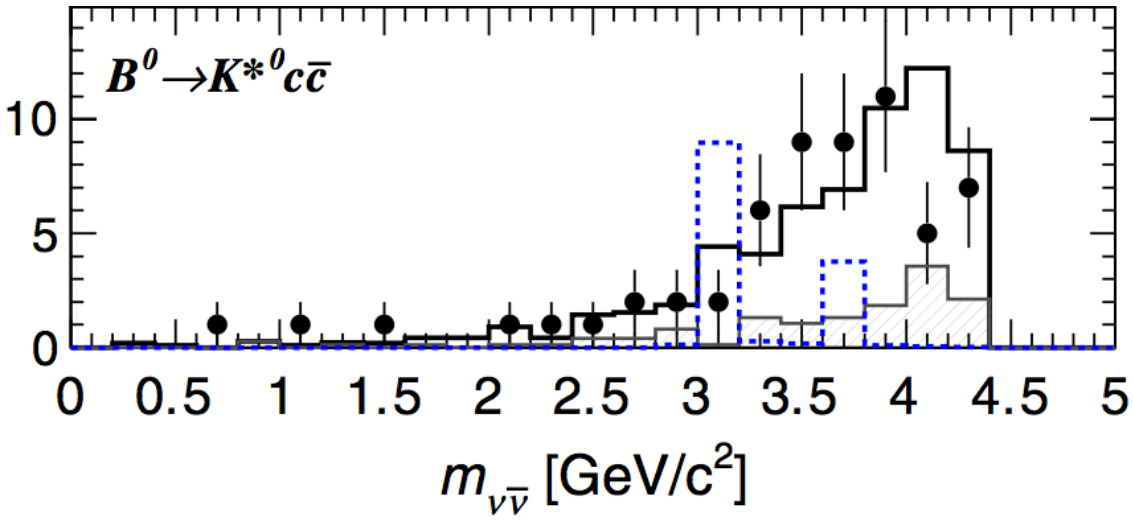


Event selection / BDT

- Boosted Decision Tree to distinguish signal & background
  - quality and θ of γ
  - E and θ of 2nd γ, dϕ with signal;
  - total extra energy
  - distance of $\vec{p}_{miss}$ to calorimeter crystal edge, IFR sector boundary, IFR cluster
- Training: 3 fb^{-1} of Υ(3S) data, signal MC with uniform $m_{A'}$.

Search for ALP in B decay

- B → $K^{(*)}$a , a → invisible: BaBar has published
  B → $K^{(*)}$J/ψ, J/ψ → invisible
  - same dataset could be used for arbitrary a′ mass.



BABAR collab., "Search for B→ $K^{(*)}\nu\nu$ and invisible quarkonium decays", Phys. Rev. D87, 112005 (2013)

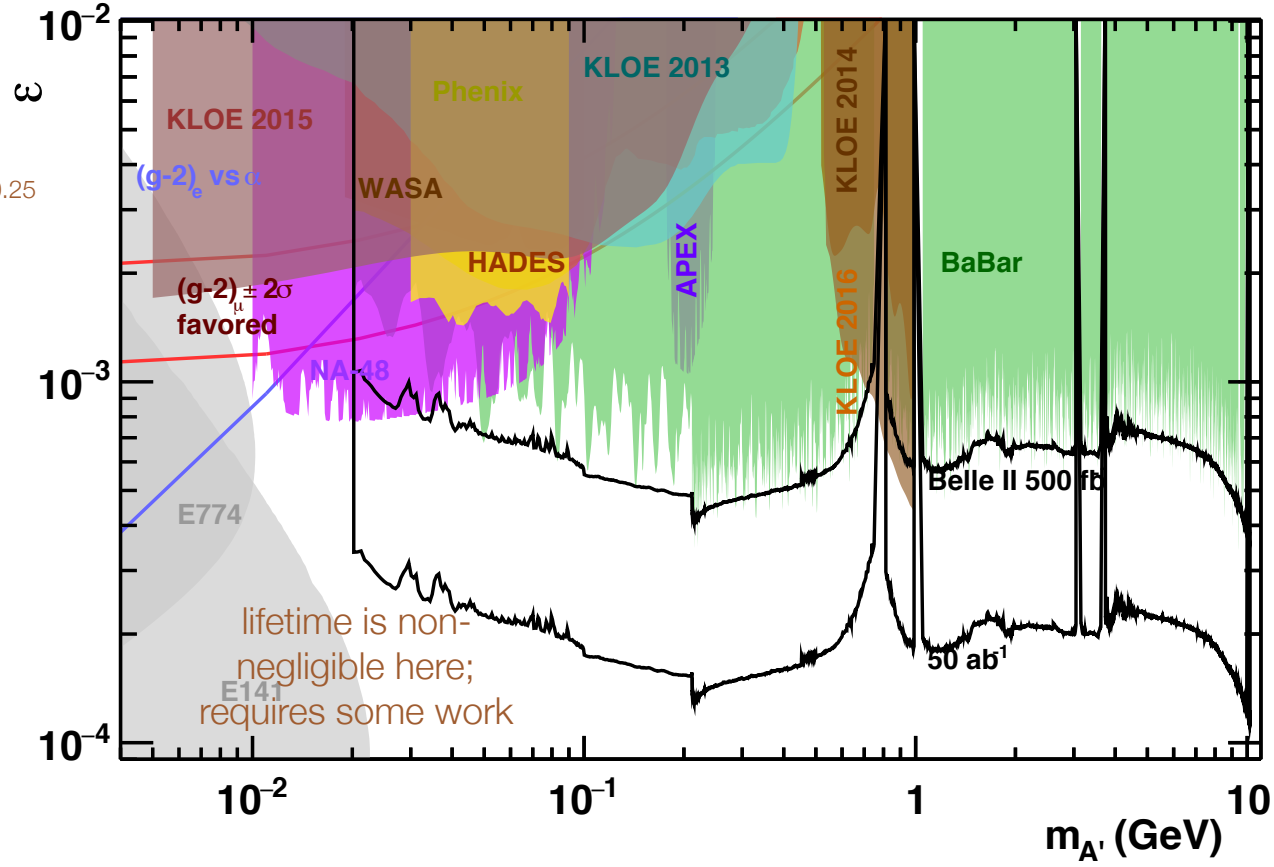
- a → γ γ is similar to $K^{(*)}\pi^0$, previously published.

- Belle II will eventually repeat these with much higher statistics.

Projected Belle II sensitivity for visible dark photon decays

- No real analysis yet; projected limits scaled from BaBar, assuming twice as good mass resolution.

Upper limit on ε scales as luminosity $L^{0.25}$



BaBar collab., PRL 113, 201801 (2014), 514 fb^{-1}

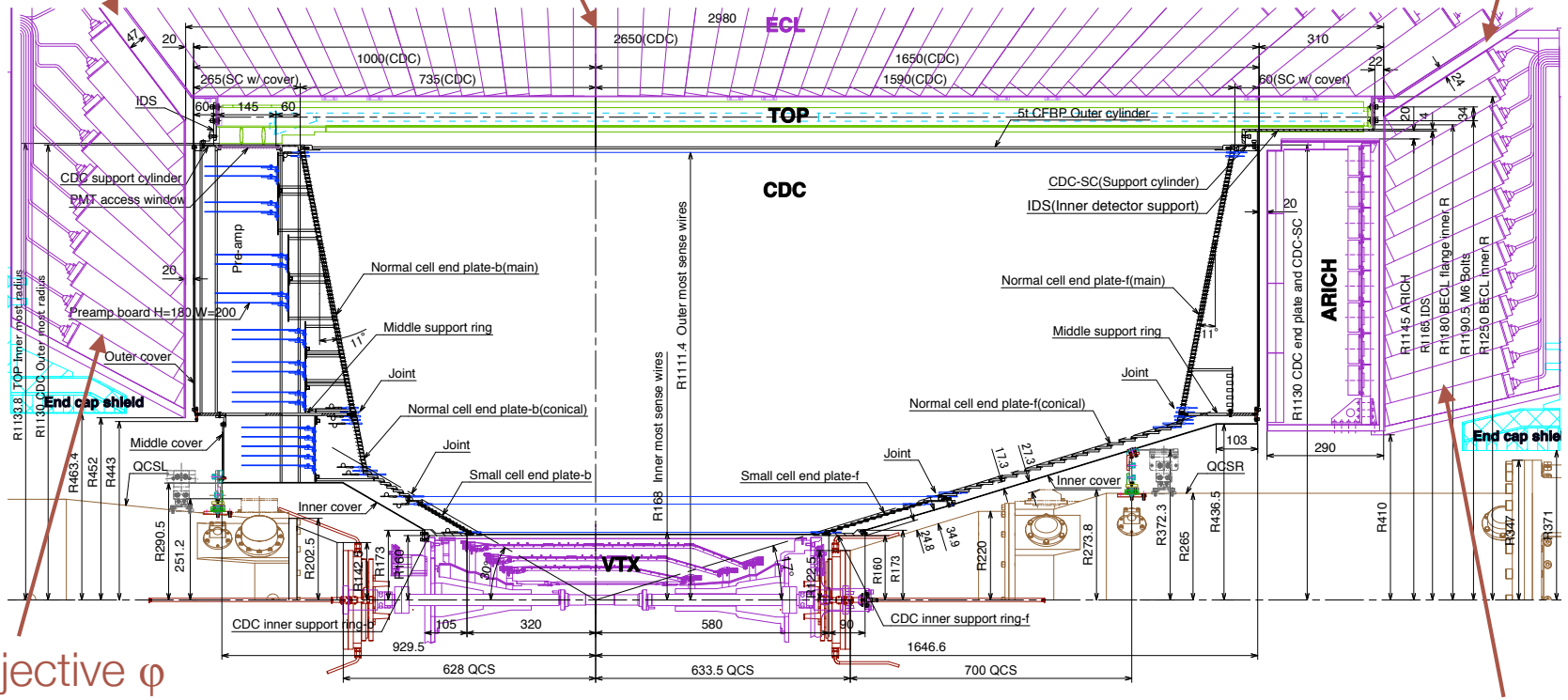
Bertrand Echenard
Chris Hearty

Sources of calorimeter inefficiency (in order of importance)

1. barrel/endcap gap

4. 1.5mm structure at 90°

2. barrel/endcap gap

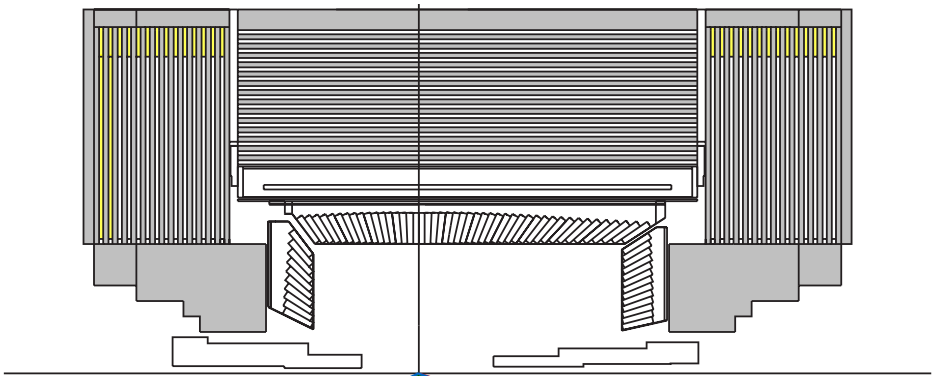


3. projective φ cracks in endcaps

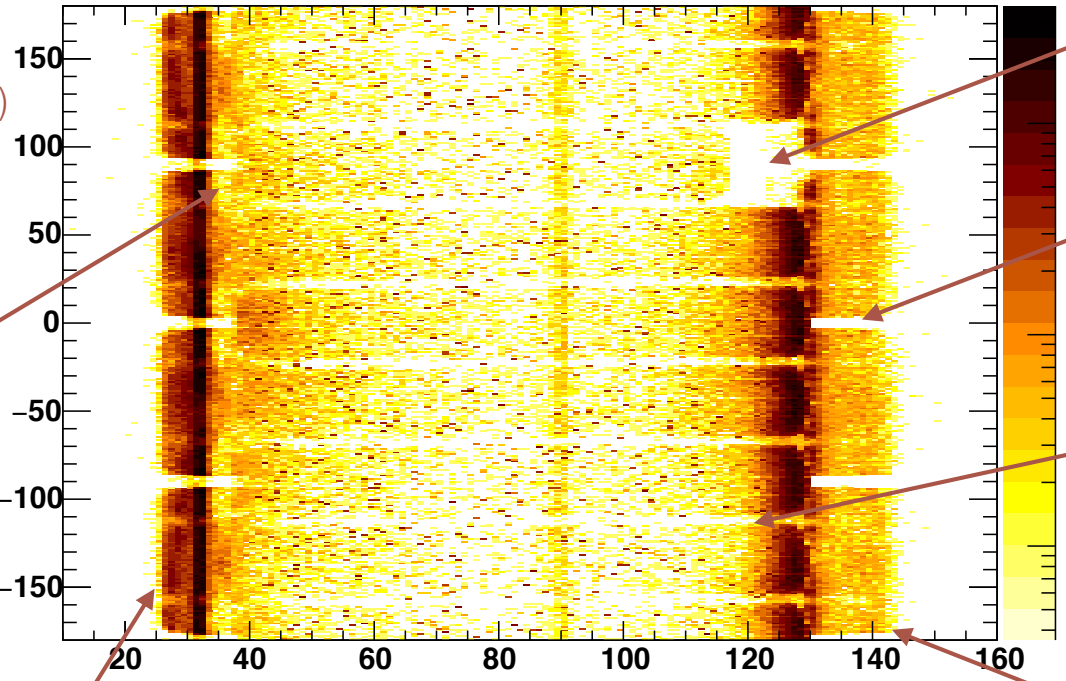
3. projective φ cracks in endcaps

5. γ non-conversion 3×10^{-6}

Sources of muon detector inefficiency



φ_{lab} vs θ_{lab} of all KLM clusters in $e^+e^- \to \gamma\,\gamma\,(\gamma)$



chimney

endcap sector boundary

endcap/barrel transition

barrel sector boundary

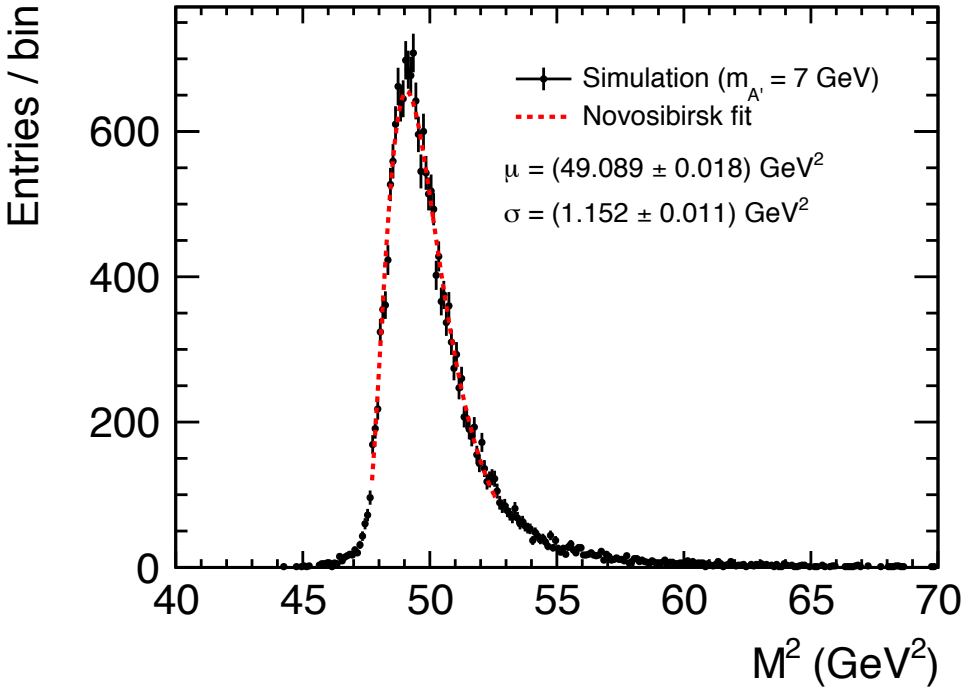
no KLM behind innermost ECL endcaps

no KLM behind innermost ECL endcaps

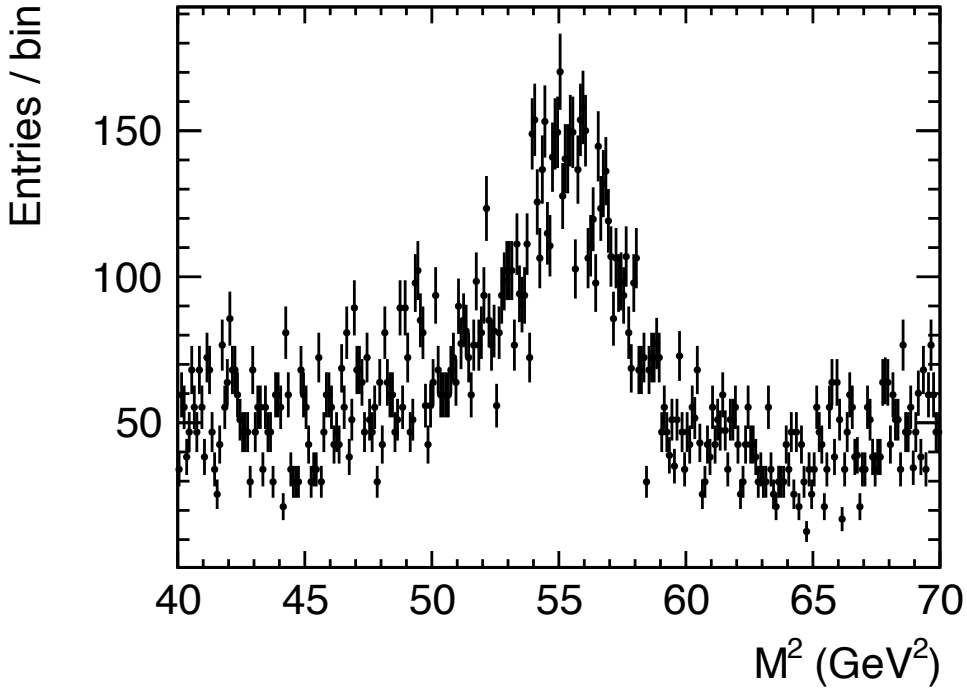
Signal extraction

- Correlation between E_γ and θ in backgrounds produces pseudo peaks in the m_X distribution.

Signal, $m_{A'}$ = 7 GeV/c^2

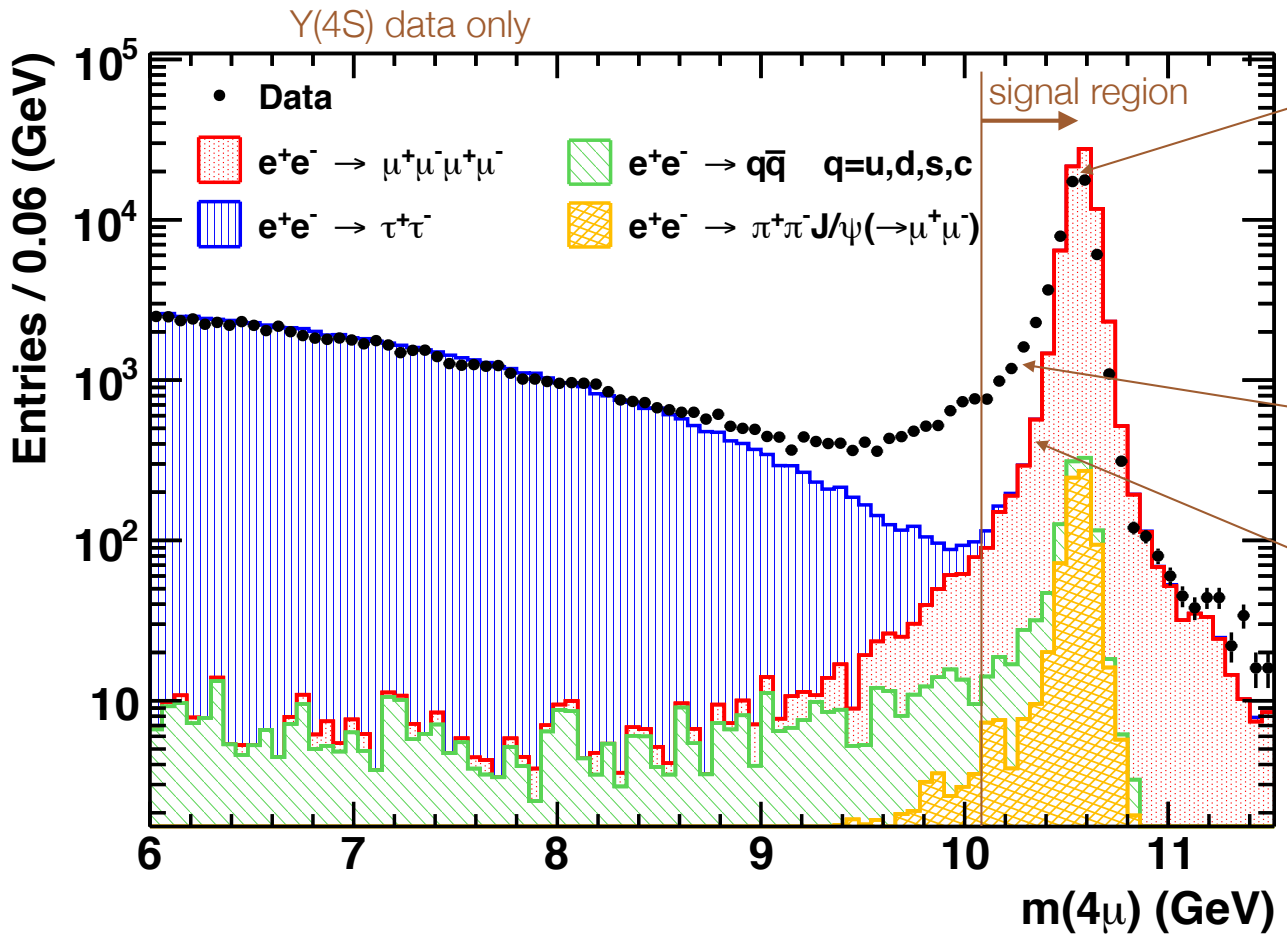


Background, 20 fb^{-1}



- Essential to study photon efficiency near endcap/barrel gaps to establish this correlation.

- Four tracks (two identified as muons) consistent with √s.

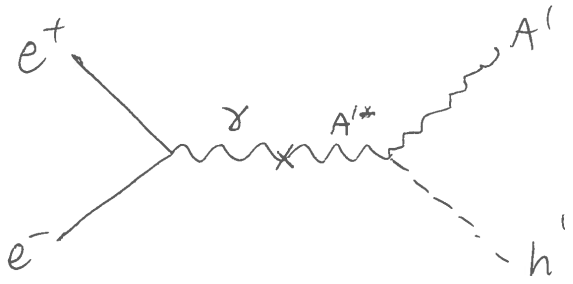


Dominant background is $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$

Initial state radiation causes low-side tail in data

MC (DIAG36) does not include initial state radiation. In general, neither does MadGraph (signal MC)

Searches for dark Higgs at e^+e^- colliders



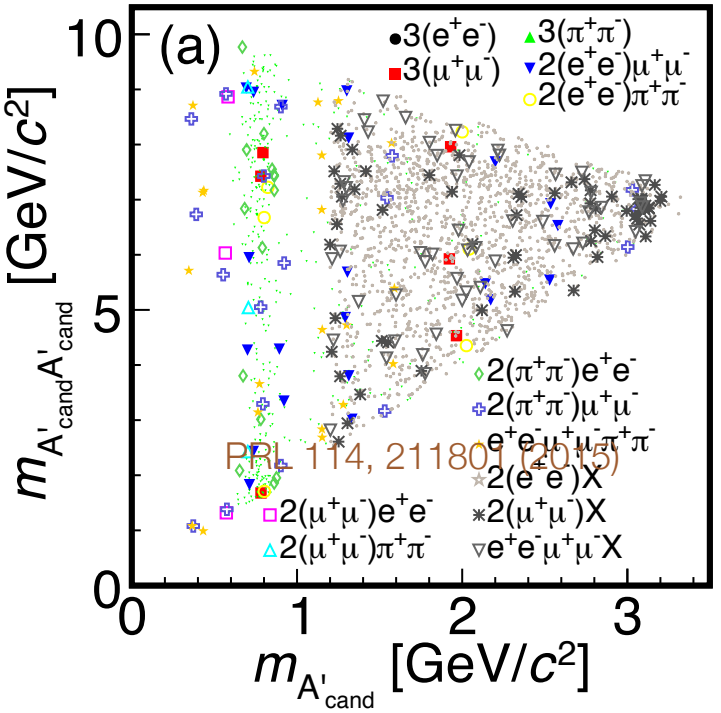
- $h' \rightarrow A'A'$ (6 track final state) or

  BaBar collab, Phys. Rev. Lett. 108, 211801 (2012)
  Belle collab, Phys. Rev. Lett. 114, 211801 (2015)

  h' is long lived, if $m_{h'} < m_{A'}$

  KLOE collab, Phys. Lett. B 747, 365 (2015)

- $3A'$ analysis is almost background-free. Comparing Belle and BaBar, limits on $\alpha_D\varepsilon^2$ improve as $1/\mathscr{L}$. Belle II will have very good sensitivity.



PRL 114, 211801