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

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U. British Columbia / IPP
October 16, 2019

International Workshop on frontiers in high energy physics, Hyderabad, India

On behalf of the Belle II collaboration

Belle II

Outline

Focus on analyses possible with available (0.5 fb^{-1}) or short term (20 fb^{-1}) data sets, with a few interjections on longer term searches.

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

Quick 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. Collected 6 fb^{-1} this spring, hope for 100 fb^{-1} by summer 2020.

- First Belle II publication (398 authors):

arXiv.org > hep-ex > arXiv:1910.05365

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High Energy Physics – Experiment

Measurement of the integrated luminosity of the Phase 2 data of the Belle II experiment

Belle II Collaboration: F. Abudinén, I. Adachi, P. Ahlburg, H. Aihara, N. Akopov, A. Aloisio, L. Andricek, N. Anh Ky, D. M. Asner, H. Atmacan, T. Aushev, V. Aushev, K. Azmi, V. Babu, S. Baehr, S. Bahinipati, A. M. Bakich, P. Bambade, Sw. Banerjee, S. Bansal, V. Bansal, M. Barrett, J. Baudot, A. Beaulieu, J. Becker, P. K. Behera, J. V. Bennett, E. Bernieri, F. U. Bernlochner, M. Bertemes, M. Bessner, S. Bettarini, V. Bhardwaj, F. Bianchi, T. Bilka, S. Bilokin, D. Biswas, G. Bonvicini, A. Bozek, M. Bračko, P. Branchini, N. Braun, T. E. Browder, A. Budano, S. Bussino, M. Campajola, L. Cao, G. Casarosa, C. Cecchi, D. Červenkov, M.-C. Chang, P. Chang, R. Cheaib, V. Chekelian, Y. Q. Chen, Y.-T. Chen, B. G. Cheon, K. Chilikin, H.-E. Cho, K. Cho, S. Choudhury, D. Cinabro, L. Corona, L. M. Cremaldi, S. Cunliffe, T. Czank, F. Dattola, E. De La Cruz-Burelo, G. De Nardo, M. De Nuccio, G. De Pietro, R. de Sangro, M. Destefanis, S. Dey, A. De Yta-Hernandez, F. Di Capua, S. Di Carlo, J. Dingfelder, Z. Doležal, I. Domínguez Jiménez, T. V. Dong, K. Dort, S. Dubey, S. Duell, S. Eidelman, M. Eliachevitch, T. Ferber, D. Ferlewicz, G. Finocchiaro, S. Fiore, A. Fodor, F. Forti, A. Frey, B. G. Fulsom, M. Gabriel, E. Ganiev, M. Garcia-Hernandez, A. Garmash, V. Gaur et al. (299 additional authors not shown)

(Submitted on 11 Oct 2019)

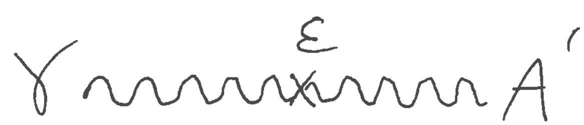
From April to July 2018, a data sample at the peak energy of the $\Upsilon(4S)$ resonance was collected with the Belle~II detector at the SuperKEKB electron-positron collider. This is the first data sample of the Belle~II experiment. Using Bhabha scattering events, we measure the integrated luminosity of the data sample to be $(496.7 \pm 0.3 \pm 3.5)$~pb^{-1} , where the first uncertainty is statistical and the second is systematic. A measurement with digamma events is performed as a cross-check, and the obtained result is in agreement with the nominal result. This work provides a basis for future luminosity measurements at Belle~II.

Comments: 12 pages, 2 figures, the first Belle II Collaboration paper
Subjects: **High Energy Physics - Experiment (hep-ex)**
Cite as: **arXiv:1910.05365 [hep-ex]**
(or **arXiv:1910.05365v1 [hep-ex]** for this version)

Dark sector

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

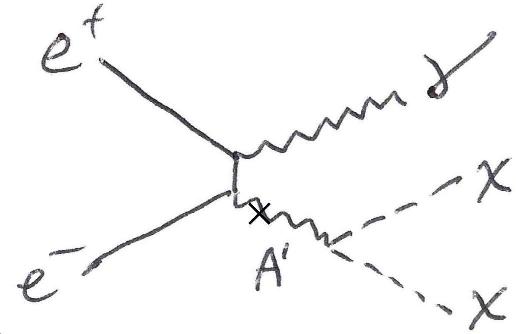
- Simplest dark sector model has a (massive) dark photon A' that mixes with strength ε with ordinary photon.



- 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 A′

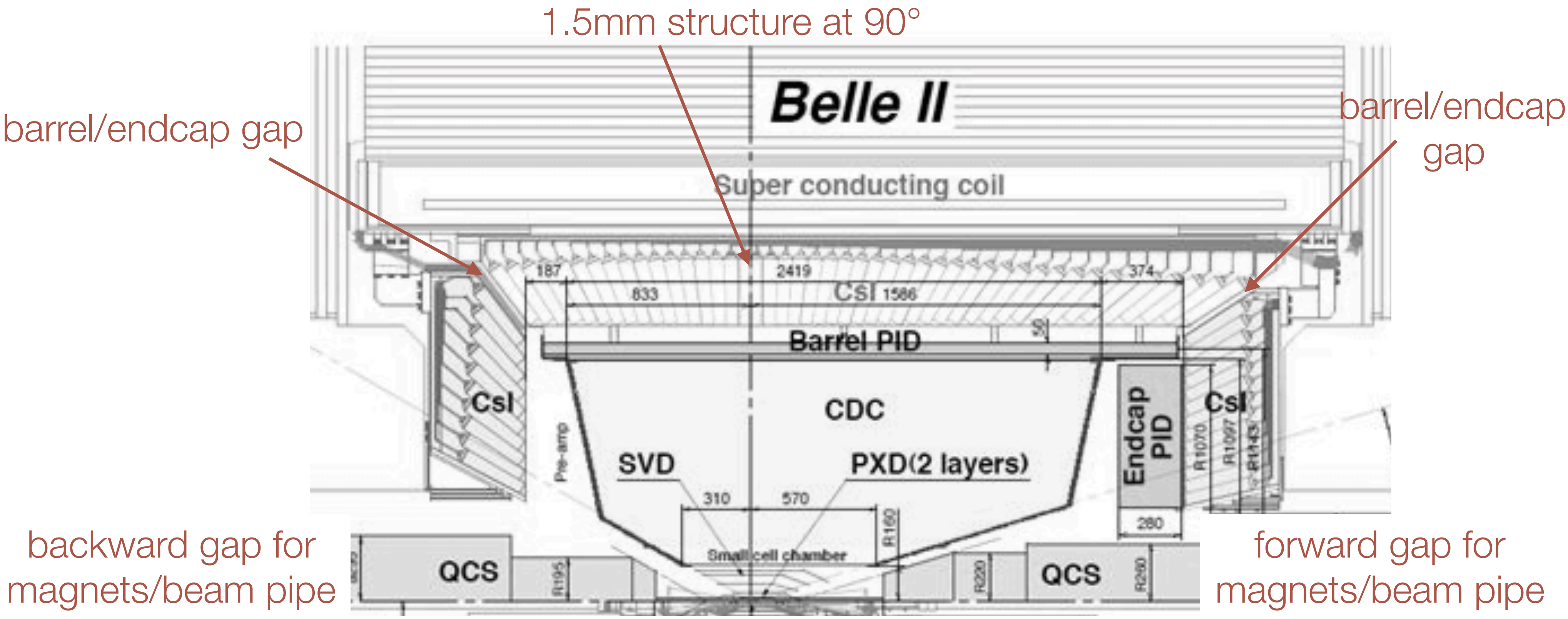


- Can be created in e^+e^- collision; will decay to dark matter if possible.
- On-shell A′ ⇒ signature is monoenergetic photon. Not sensitive to m_χ or χ/A′ coupling.

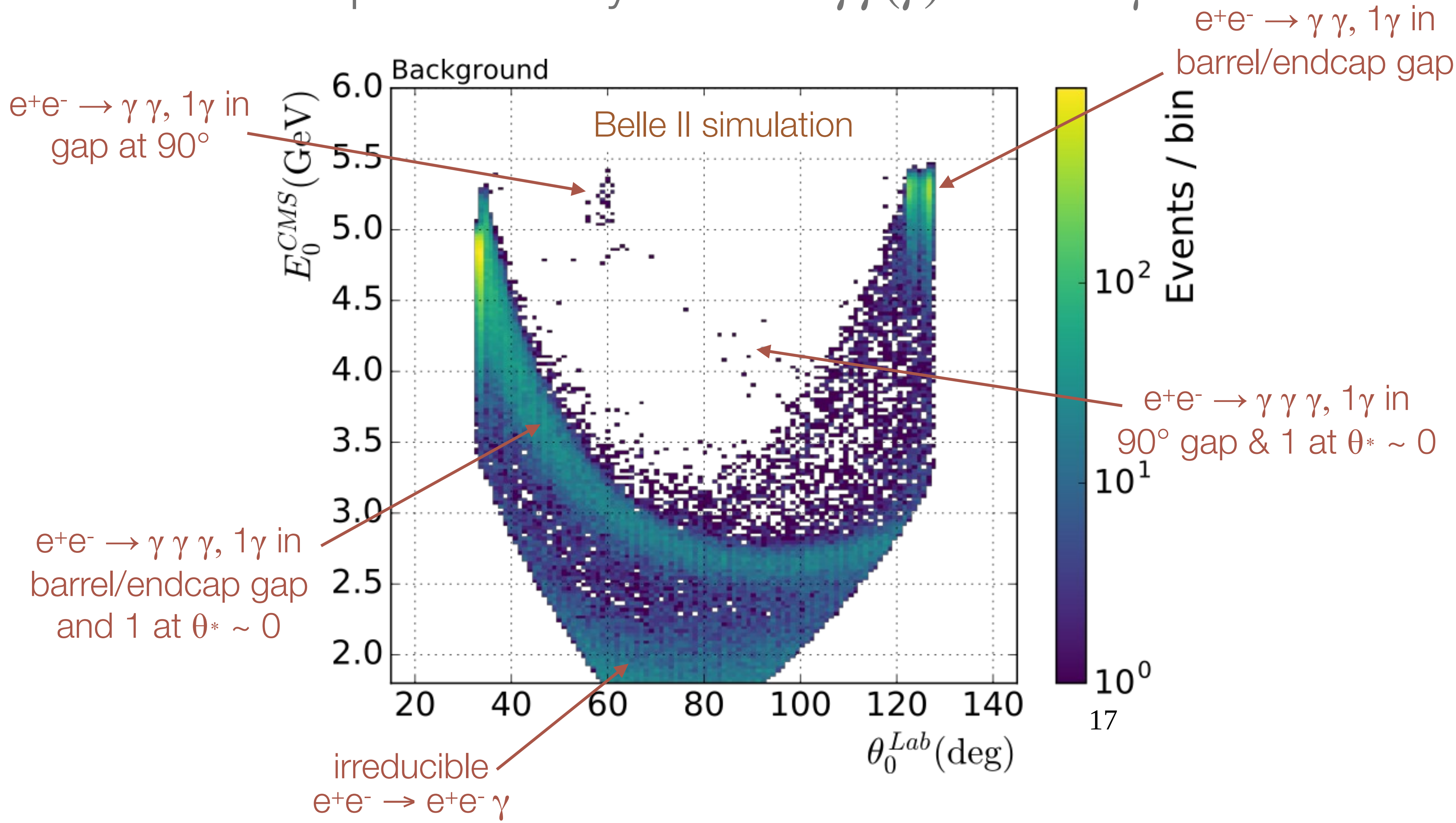
$$E^*_\gamma = E^*_{beam} - \frac{m^2_{A'}}{4E^*_{beam}}$$

- Offshell A′ case (like $e^+e^- \to \gamma\nu\bar{\nu}$) is much harder; no results yet.

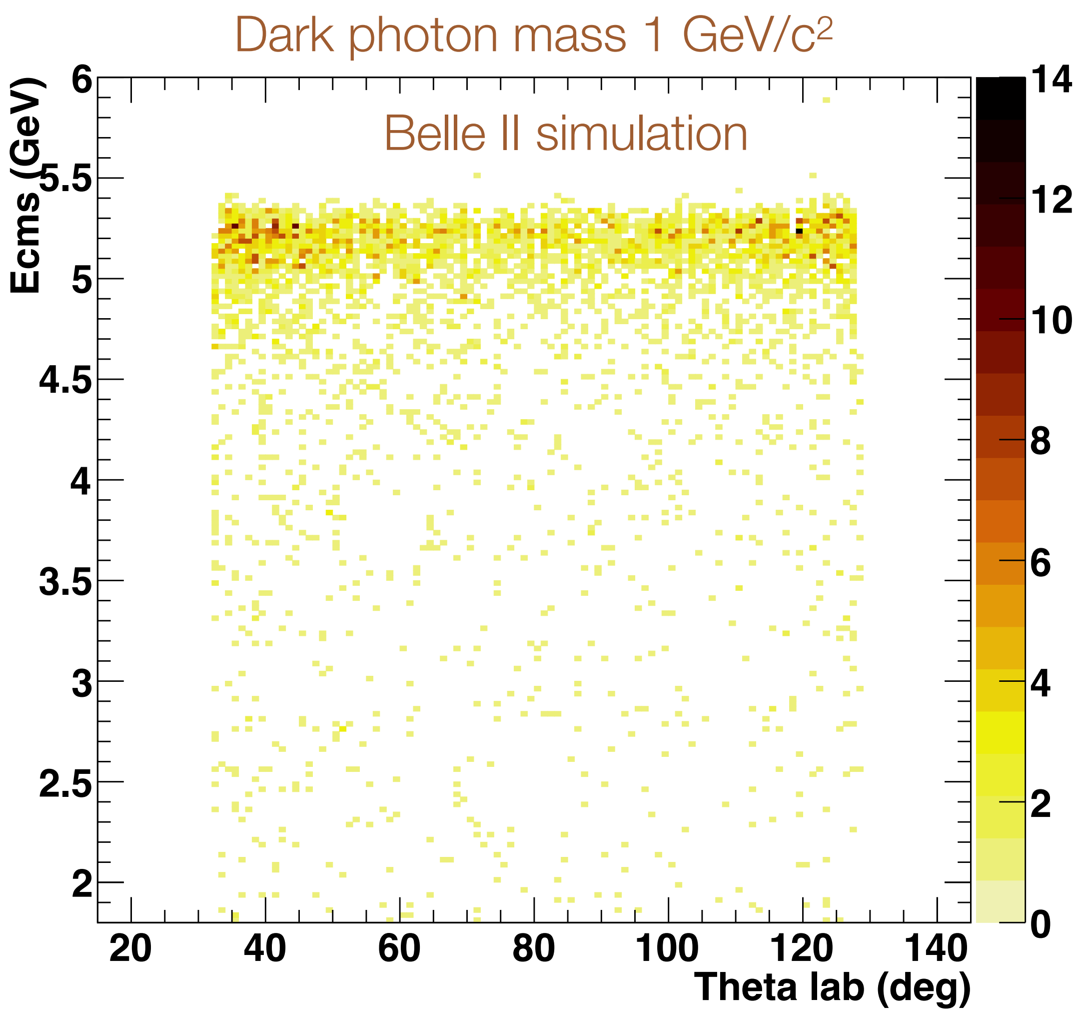
- Finite acceptance & imperfect detector: backgrounds from $e^+e^- \to \gamma\gamma(\gamma)$ and $e^+e^- \to e^+e^-\gamma(\gamma)$. Cosmics are not negligible.



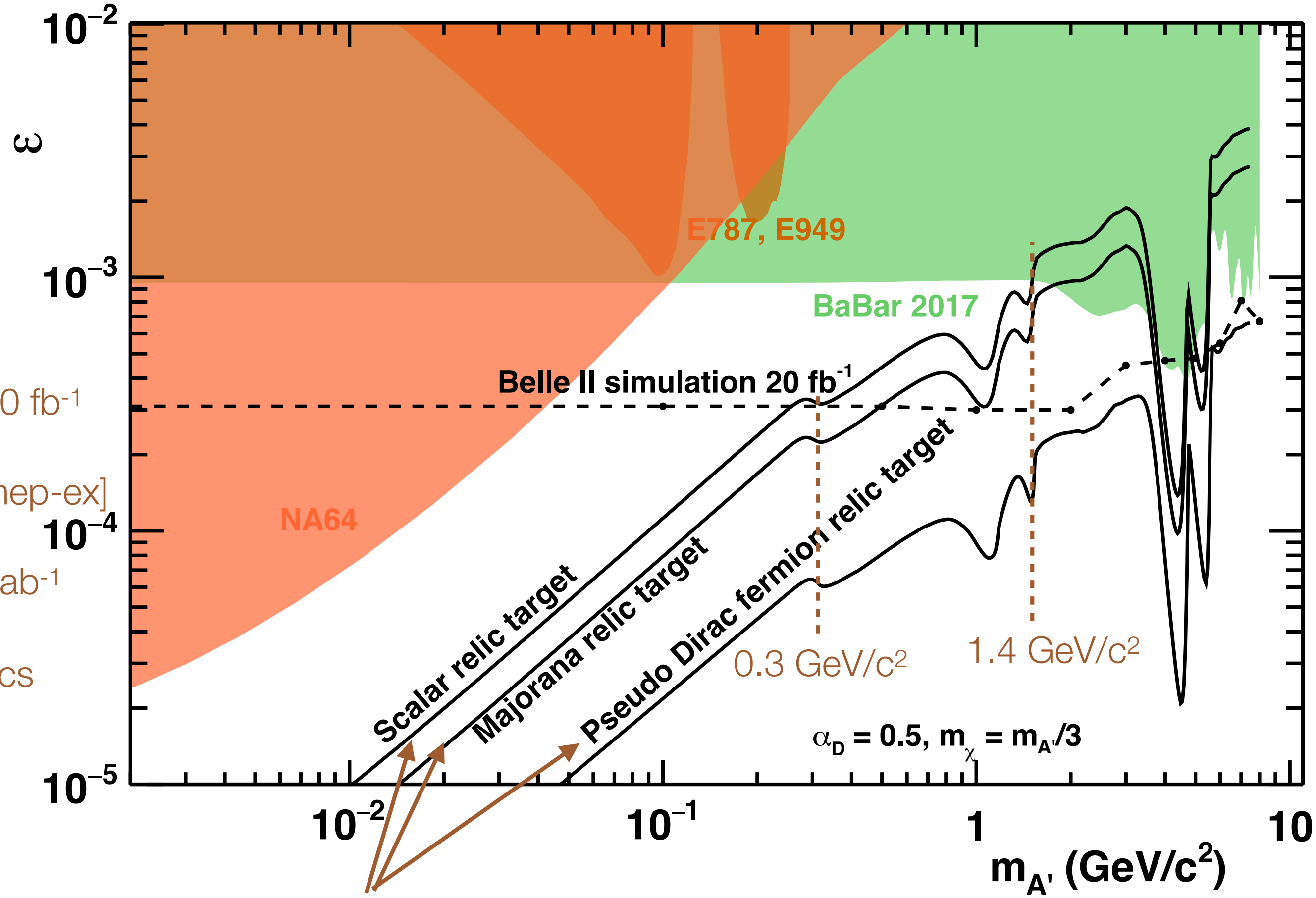
- Simulated backgrounds, 40 fb^{-1}, excluding cosmics. Final sample is mostly $e^+e^- \rightarrow \gamma\gamma(\gamma)$ with ≥3γ.



- Corresponding distribution for simulated signal



- Goal is the world's best sensitivity at low mass with early data. New 0.5 GeV single-photon trigger will extend mass reach to 10 GeV/c², vs 8 GeV/c² for BaBar.



BaBar limit, 50 fb^{-1} Phys. Rev. Lett. 119, 131804 (2017)

Belle II projection, 20 fb^{-1} KEK-2018-27, arXiv:1808.10567 [hep-ex]

Extrapolation to 50 ab^{-1} requires study of γ detection systematics

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)

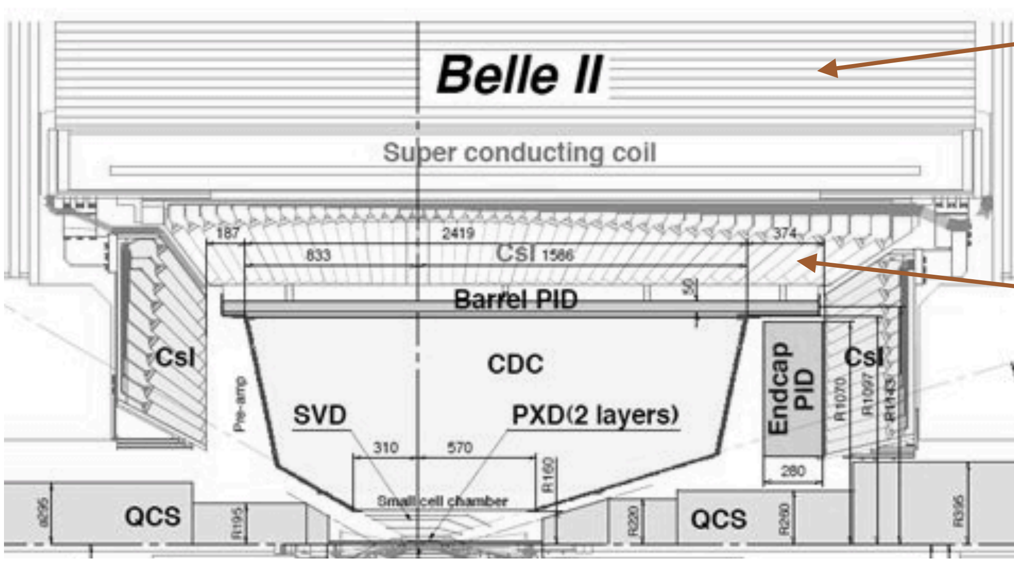
How does Belle II improve on BaBar limits with a smaller dataset?

- BaBar calorimeter has (nearly) 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?



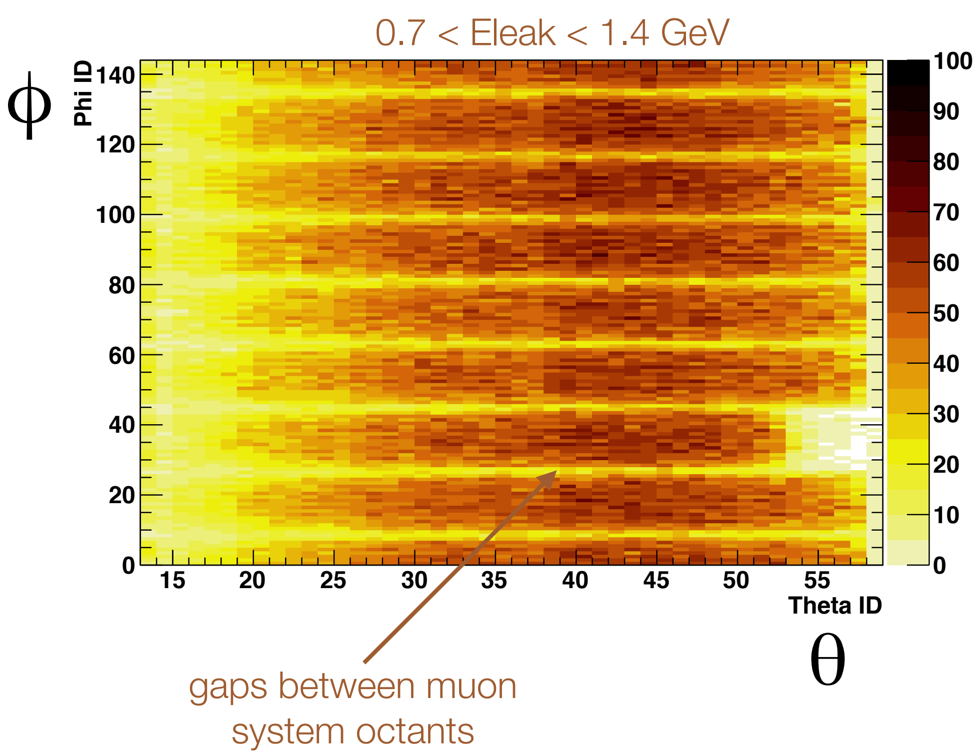
γ not interacting in calorimeter may be detected by muon system

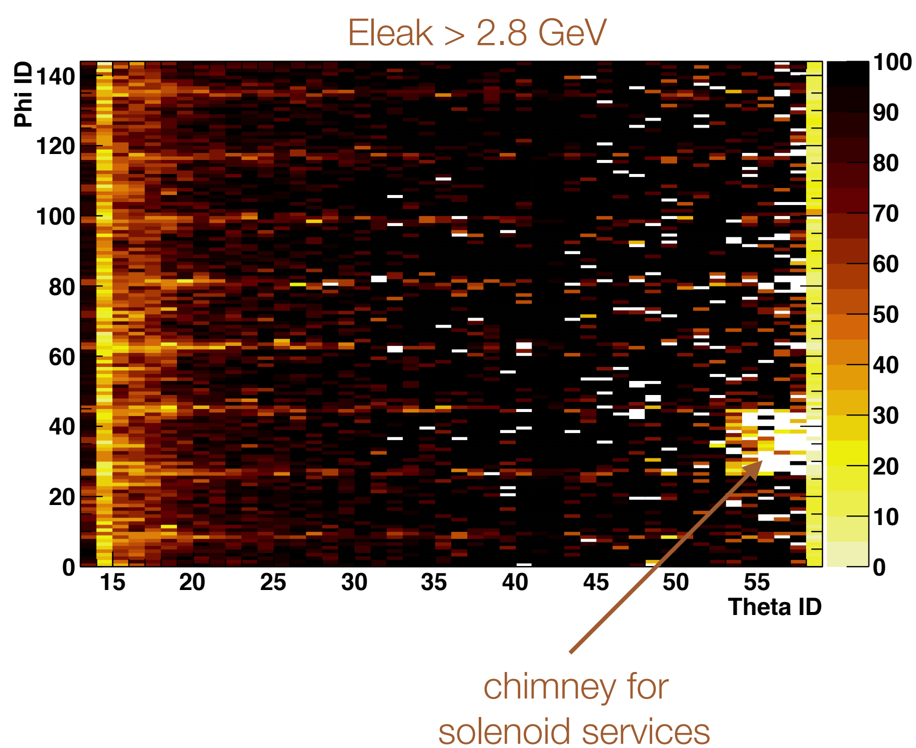
Probability of γ not interacting in 30 cm (16 X_0) of CsI = 3.4×10^{-6}. ~9 beam-energy γ per fb^{-1}.

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.

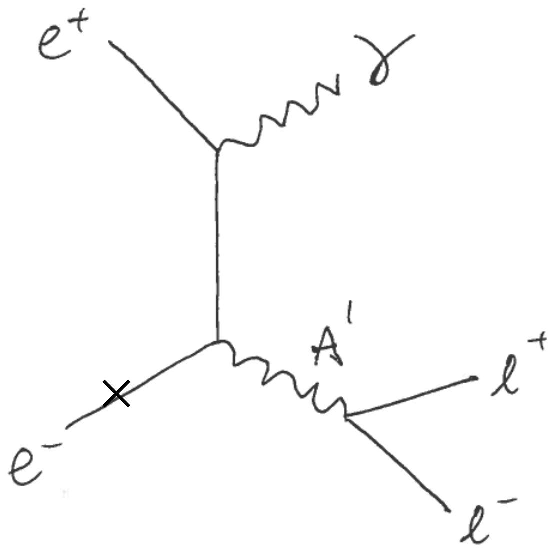
- adjust MC (active detector size/efficiency, inactive material) to agree with data.

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

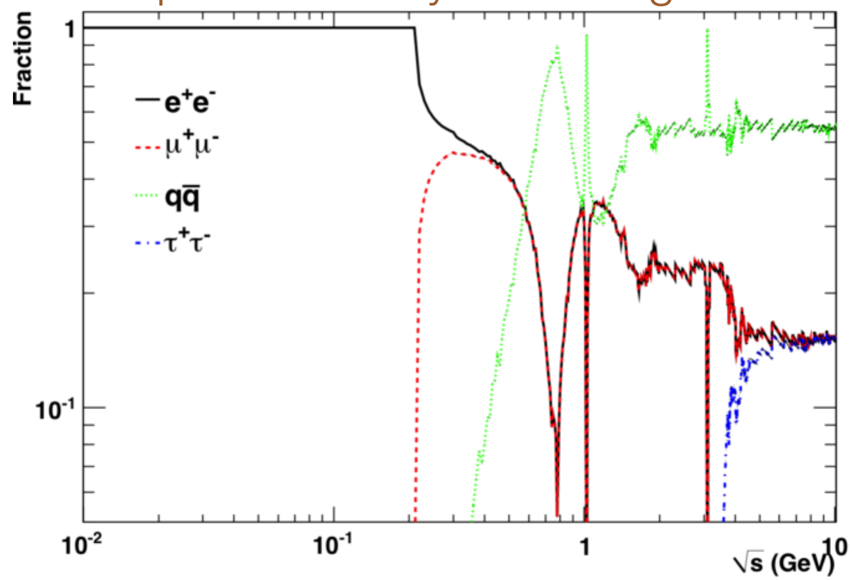




Search for a dark photon decaying to leptonic final states (dark matter decay is not available)



Dark photon decay branching fractions



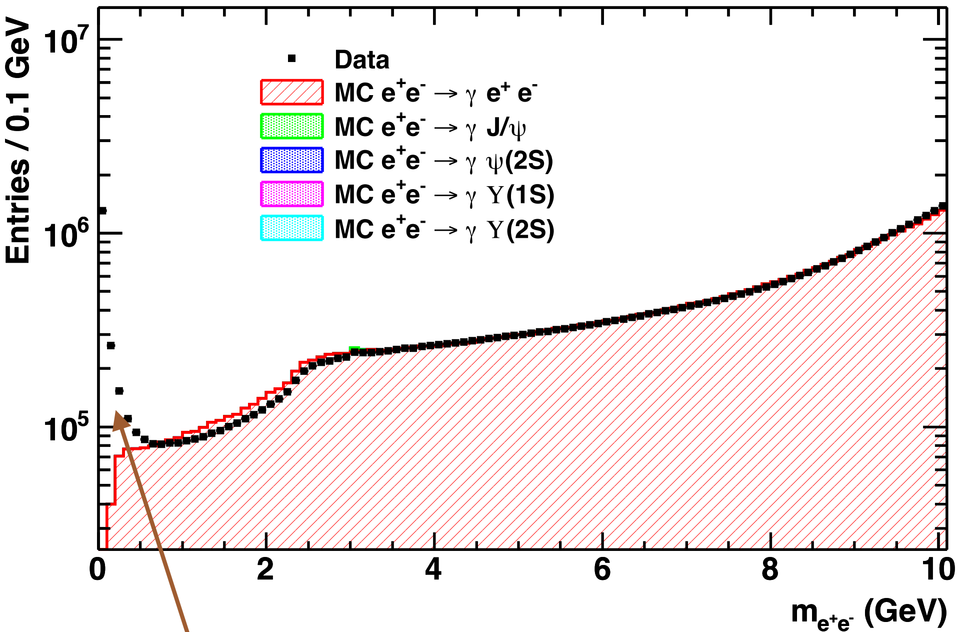
Bertrand Echenard

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

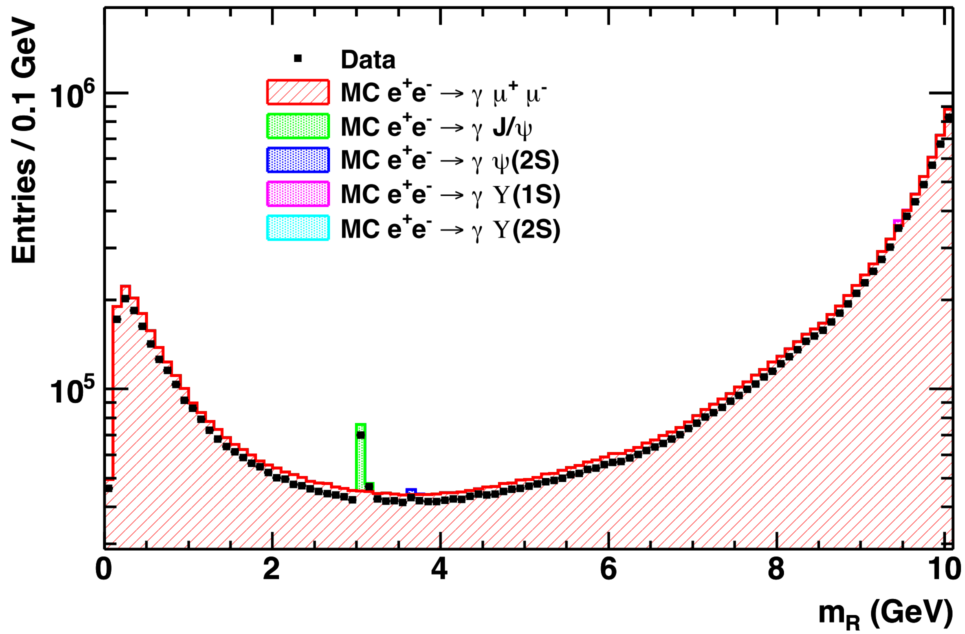
Projected limits for Belle II

- Estimate Belle II limits from BaBar paper.

BaBar search for A′ → e^+e^-



BaBar search for A′ → $\mu^+\mu^-$



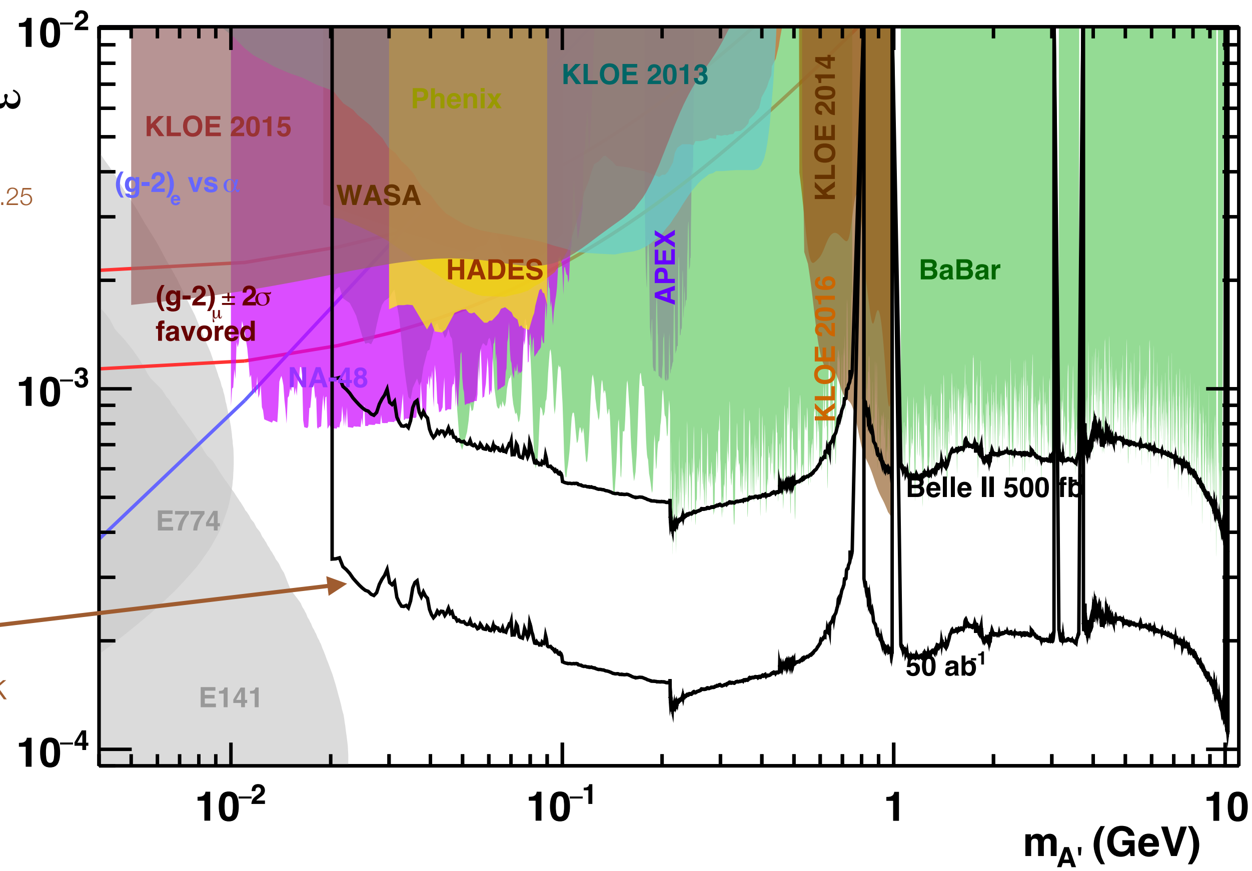
PRL 113, 201801 (2014)

MC used by BaBar does not simulate this configuration; better in BabaYaga

Projected Belle II sensitivity for visible dark photon decays

- Scale BaBar limits assuming twice as good mass resolution and better e^+e^- trigger efficiency.

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



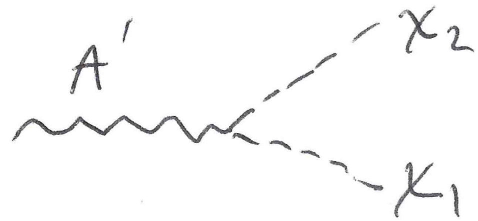
lifetime is non-negligible here; requires some work

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

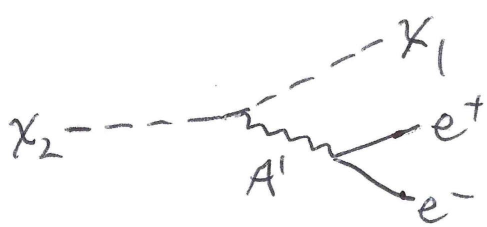
Bertrand Echenard
C. Hearty

Dark photon search in an inelastic dark matter model

- Two dark matter states; A′ couples only to both:



- χ_2 is unstable, and decays to χ_1 plus SM particles:



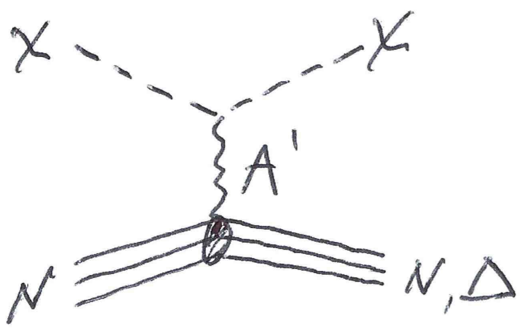
or muons, or hadrons

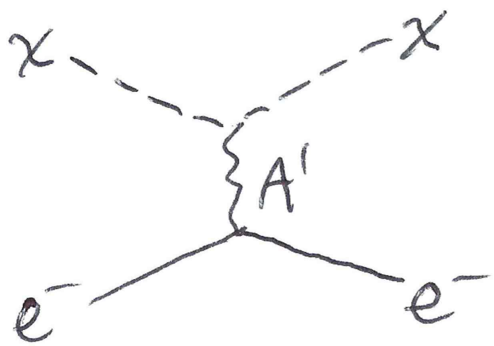
- Thermal relic is χ_1 only.

M. Duerr, T. Ferber, C. Hearty, F. Kahlhoefer, K. Schmidt-Hobert, P. Tunney, "Invisible and displaced dark matter signatures at Belle II", *to be submitted to JHEP*

Direct detection of dark matter

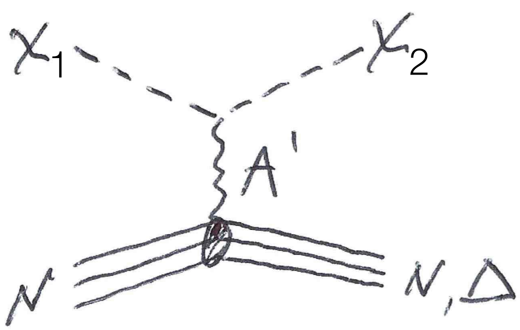
- Direct detection dark matter experiments use nucleon or electron scattering to detect the χ.





- Kinematically forbidden (to 1st order) in the inelastic model:

χ_1 energy is insufficient to create the heavier χ_2



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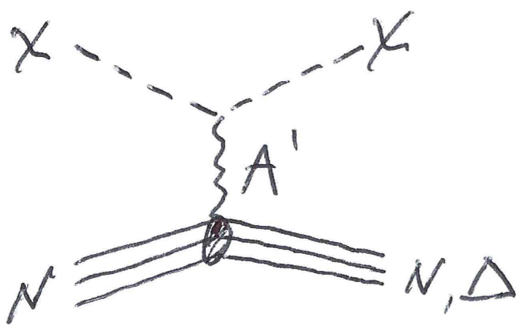

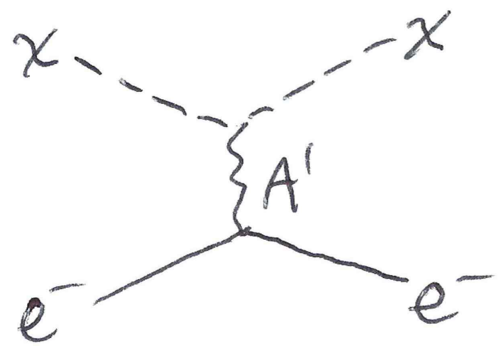

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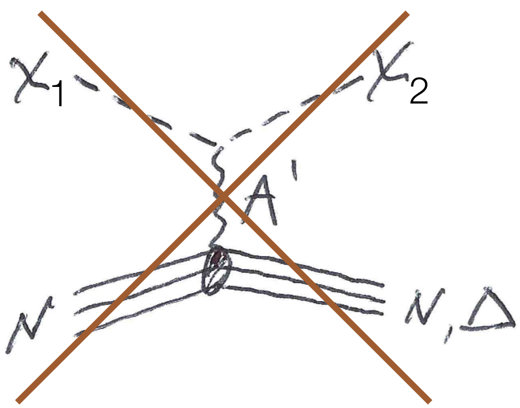
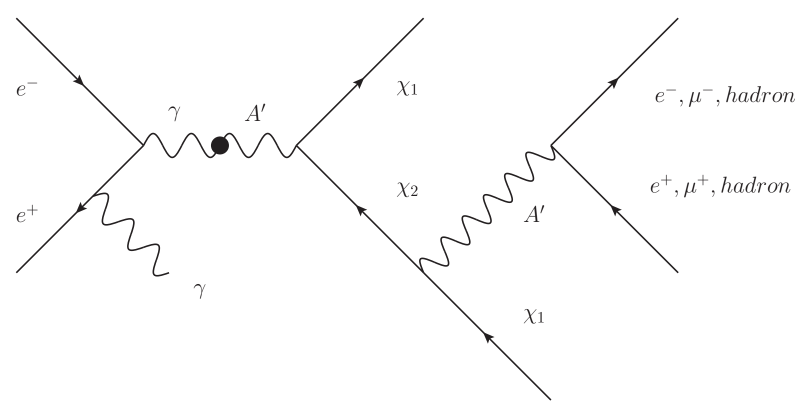
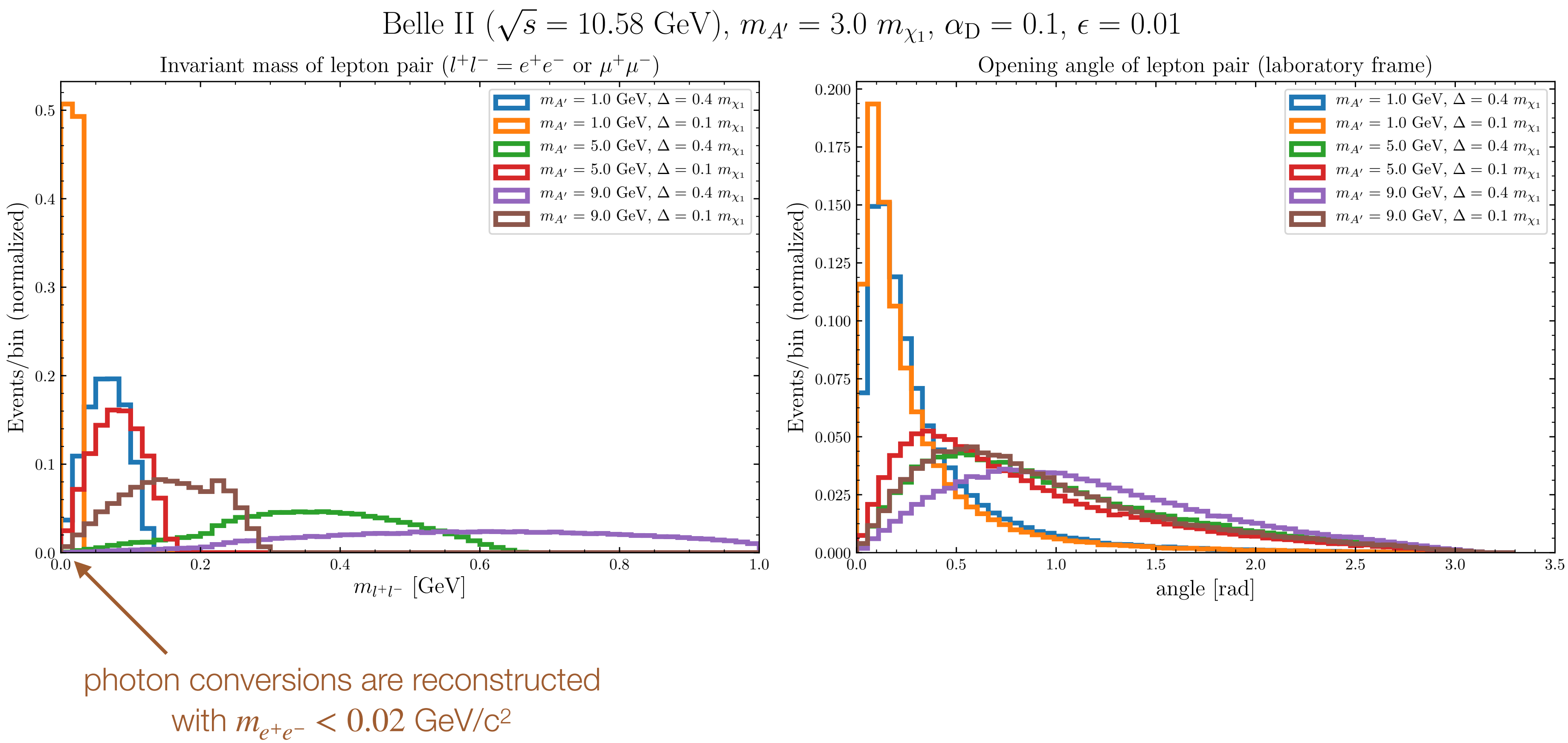


Experimental issues

- A′ production is unchanged.
- Experimental signature can still be a single photon:
  - χ_2 decays outside the detector;
  - or decay is relatively prompt, but is at low angles.
- But often the event includes a displaced e^+e^- pair.



- Many e^+e^- pairs from γ conversions. Kinematics of conversions are quite different from signal, especially at large A′ mass.
  - requires some specialized reconstruction code.



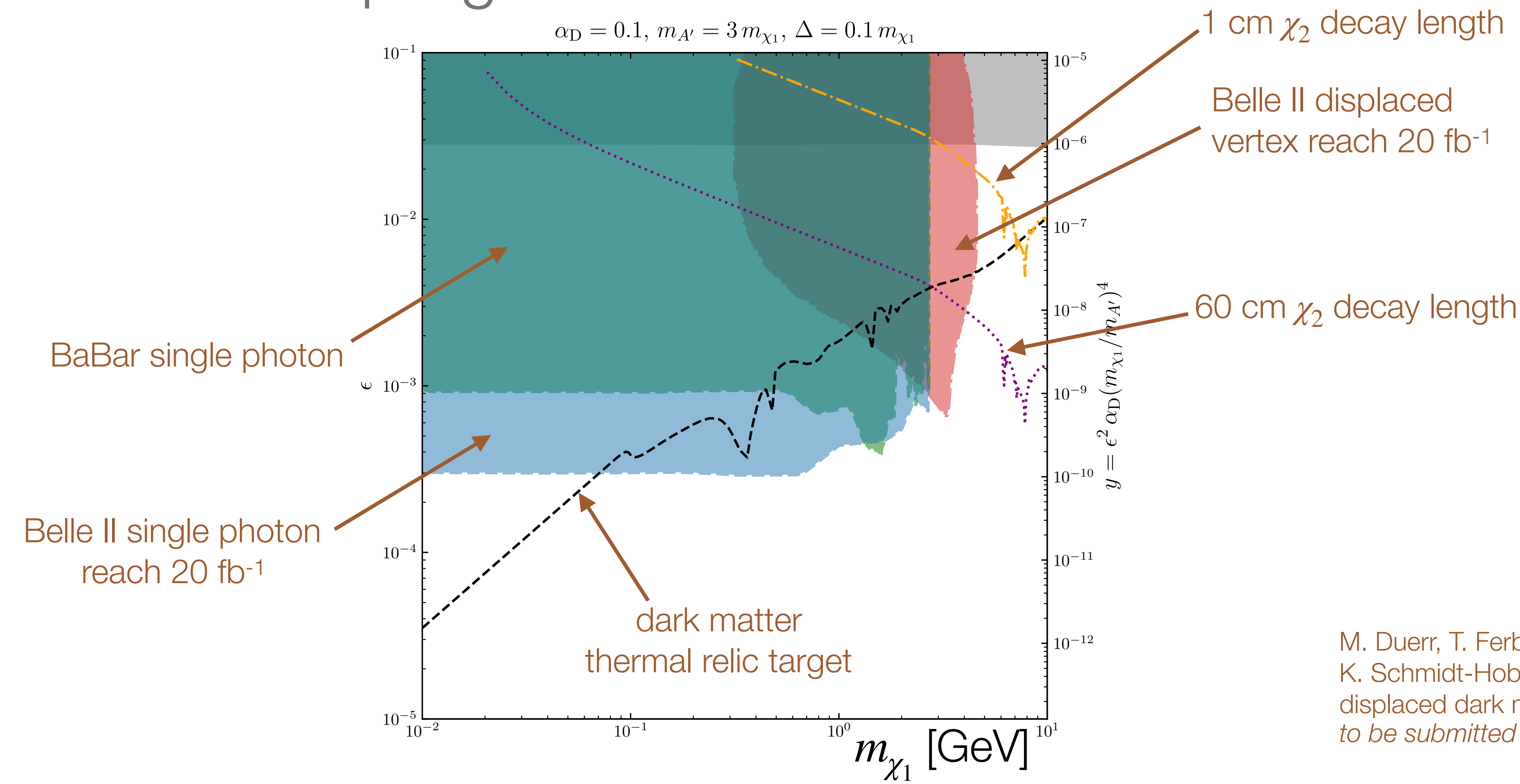
- Displaced vertex is especially important at high dark photon masses = low energy recoil photon.

- Very high backgrounds for single low-energy γ from $e^+e^- \rightarrow e^+e^-\gamma$ with both electrons out of the detector acceptance, but essentially no background for photon plus displaced vertex.

- At high luminosity, existing triggers will be difficult above A′ mass of 8 GeV/c^2. Will need to add a displaced vertex trigger.

An example of an exclusion plot

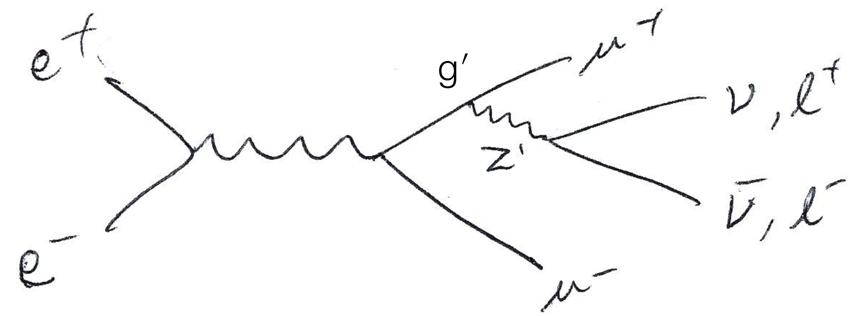
- 5 parameters; many plots required.
  - 3 additional parameters are χ_1 mass, mass difference, and coupling to A′



M. Duerr, T. Ferber, C. Hearty, F. Kahlhoefer, K. Schmidt-Hobert, P. Tunney, "Invisible and displaced dark matter signatures at Belle II", *to be submitted to JHEP*

Search for invisible decays of the Z′

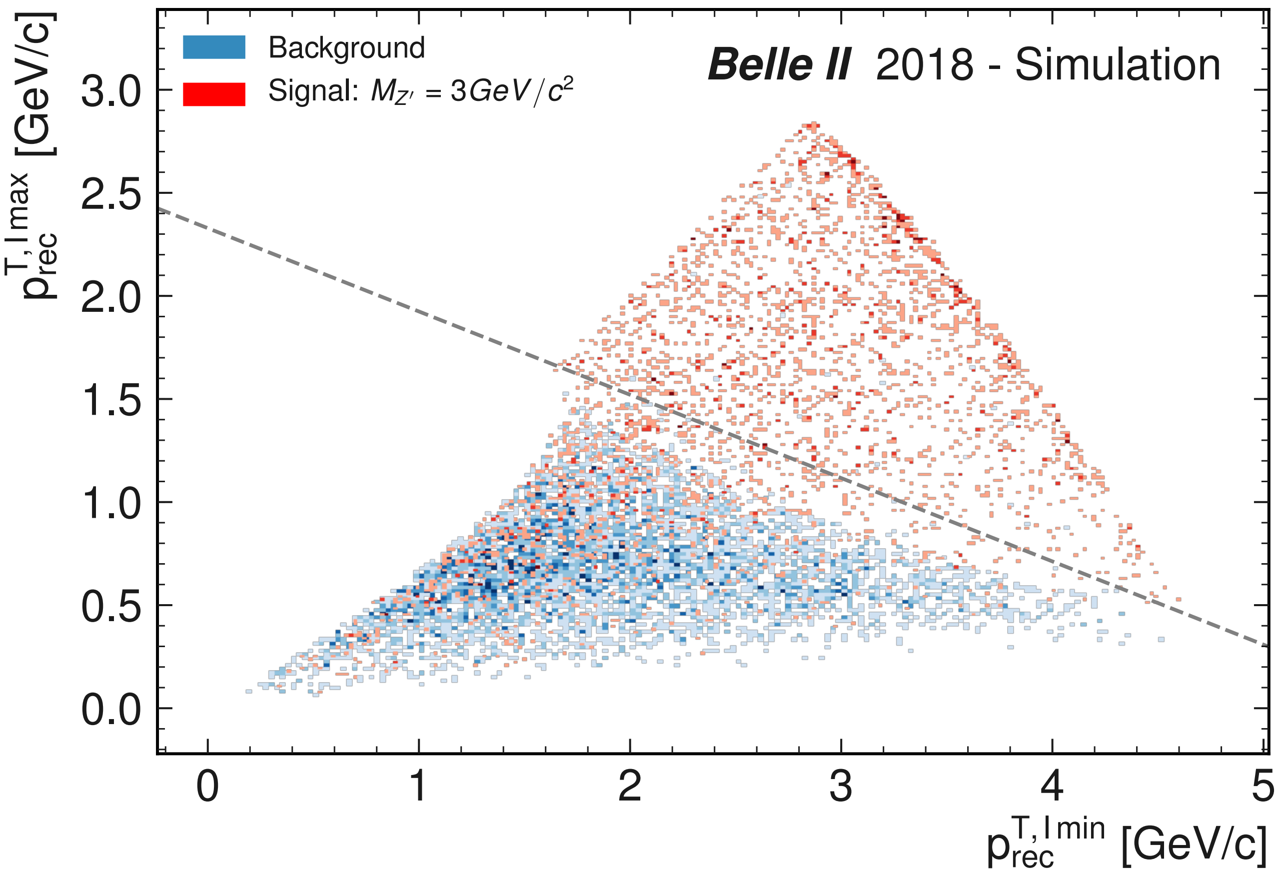
- Gauge boson may have direct couplings to SM (labeled Z′). Z′ that couples to 1st generation is strongly constrained, but not one that couples only to 2nd and 3rd generations. He, Joshi, Lew, Volkas, Phys. Rev. D 43, R22 (1991)



- 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)

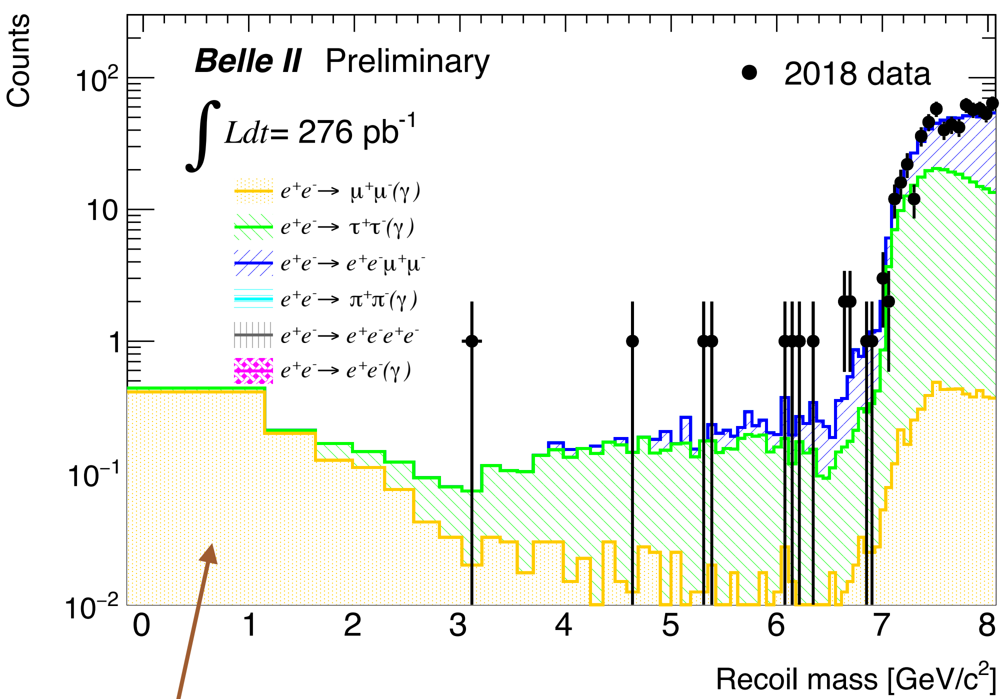
- Signature is $\mu^+\mu^-$ pair with a peak in the missing mass.
- Require $\vec{p}_{miss}$ to point into the calorimeter barrel. Reduce $\tau^+\tau^-$ background with kinematic distributions.



look at transverse Z′ momentum relative to minimum and maximum momentum muon

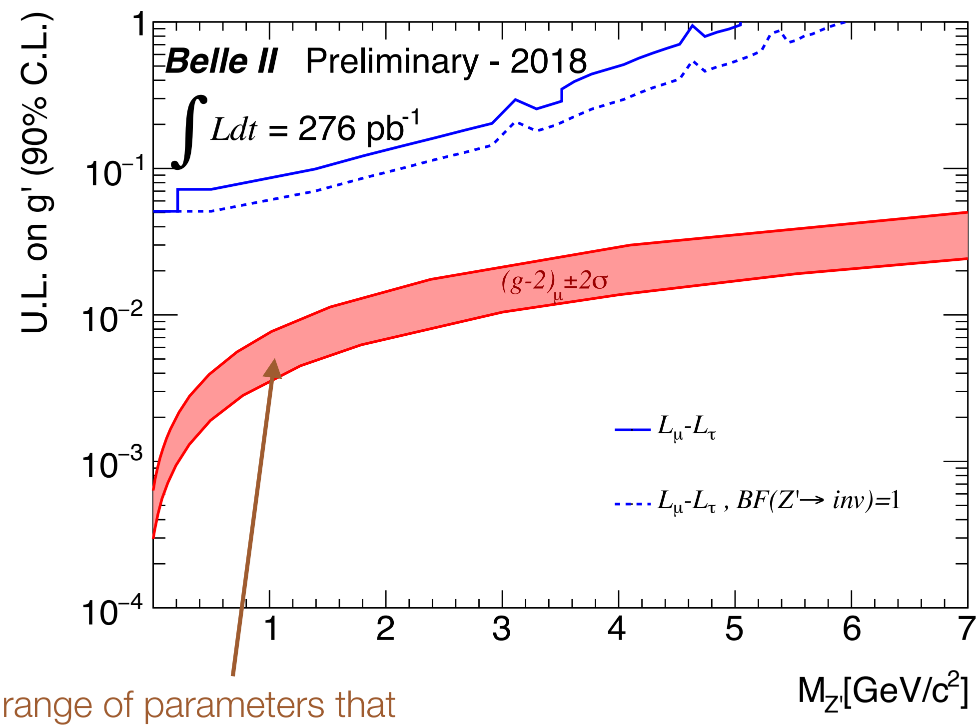
- Belle II can be competitive with 2018 data. Only 276 pb^{-1} is usable due to low trigger efficiency for tracks.

Observed recoil mass spectrum



low $m_{Z'}$ background is from radiative muon pairs

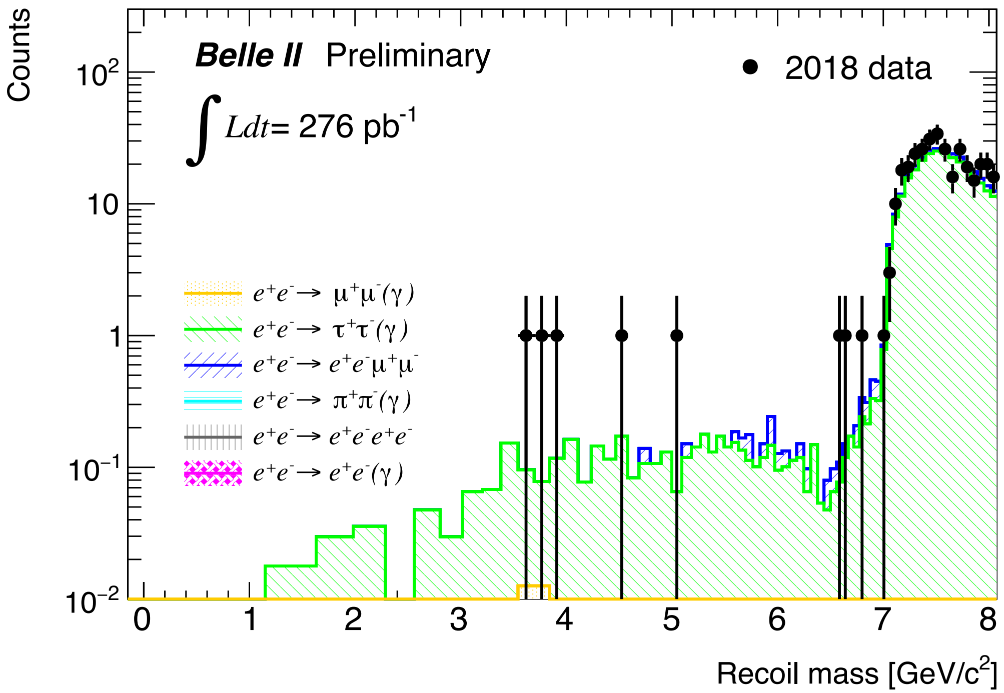
Corresponding upper limits



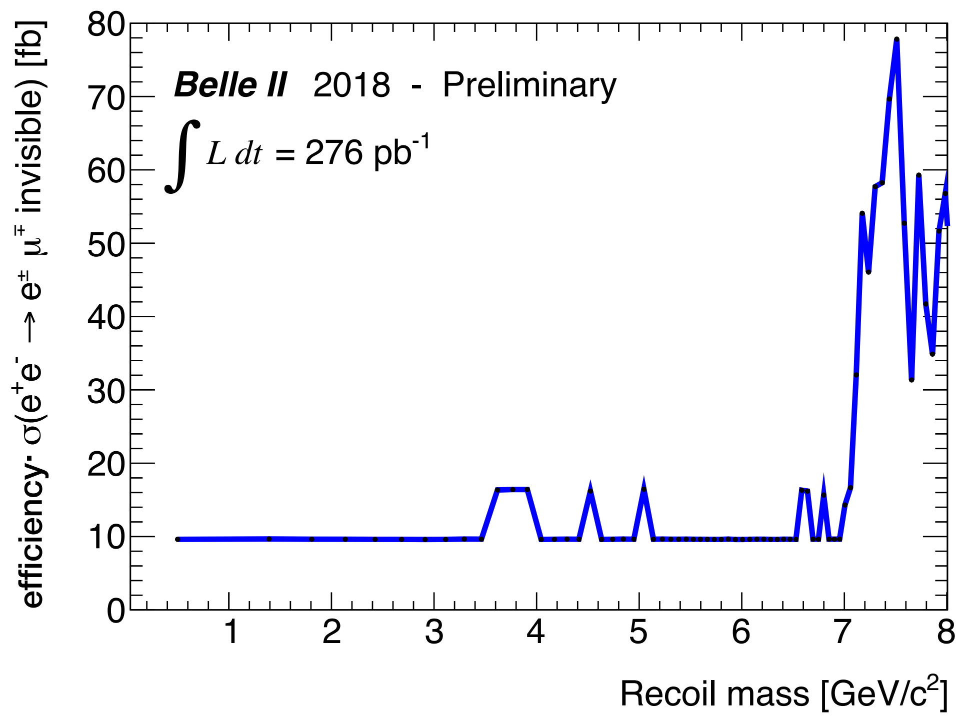
range of parameters that would explain muon g-2. Will be challenging, even with 50 ab^{-1}

- Also search for a Lepton-Flavour Violating variation, with $e^{\pm}\mu^{\mp}$ plus missing momentum.

Observed recoil mass spectrum



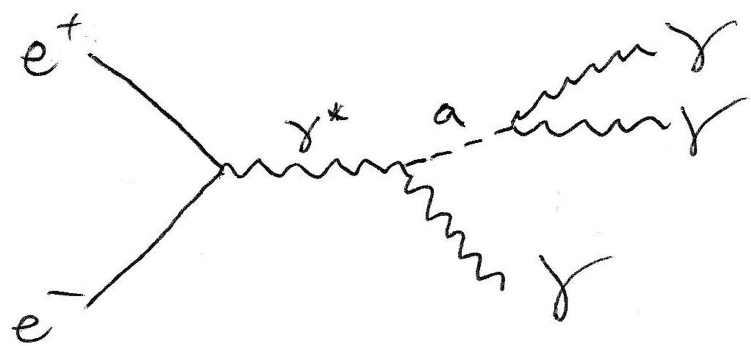
Upper limits on observed cross section, LFV Z′



Axion-like particles

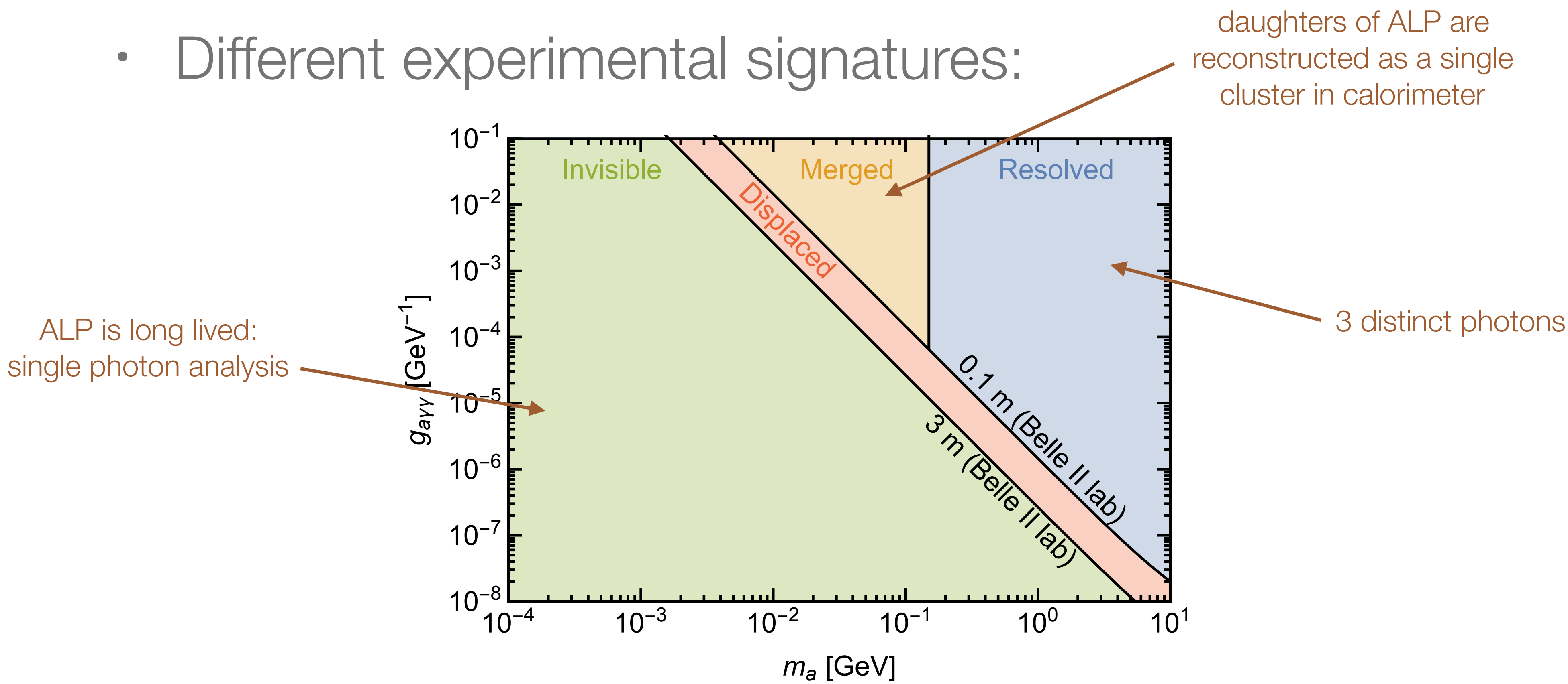
- Pseudo-scalars that couple to bosons. No strict relationship between coupling and mass.

- Focus on coupling to photons.



Dolan, Ferber, Hearty, Kahlhoefer & Schmidt-Hoberg, "Revised constraints and Belle II sensitivity for visible and invisible axion-like particles", JHEP 1712, 094 (2017)

- Different experimental signatures:



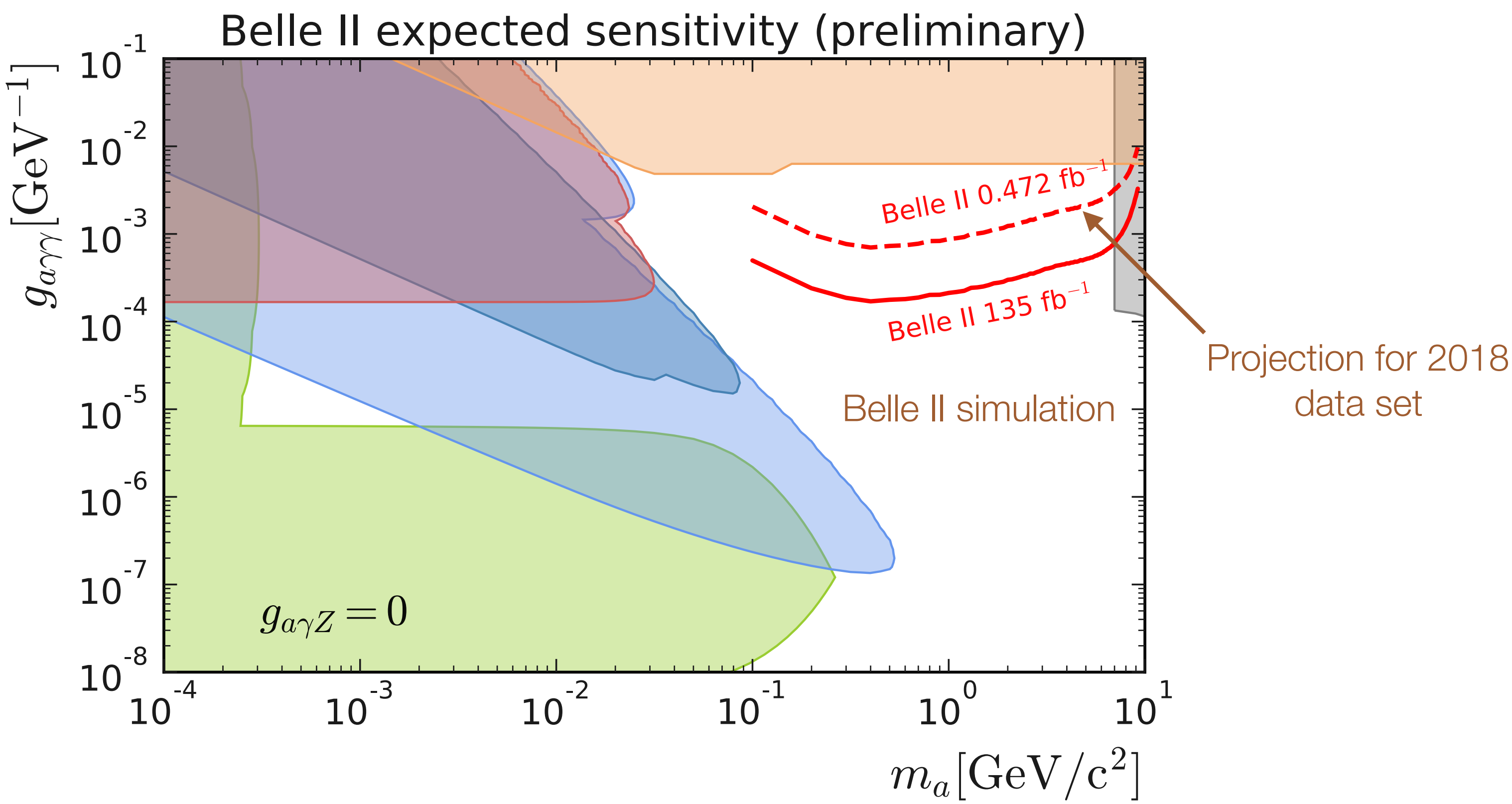
- Three γ signature: bump in invariant mass of $\gamma\gamma$.

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

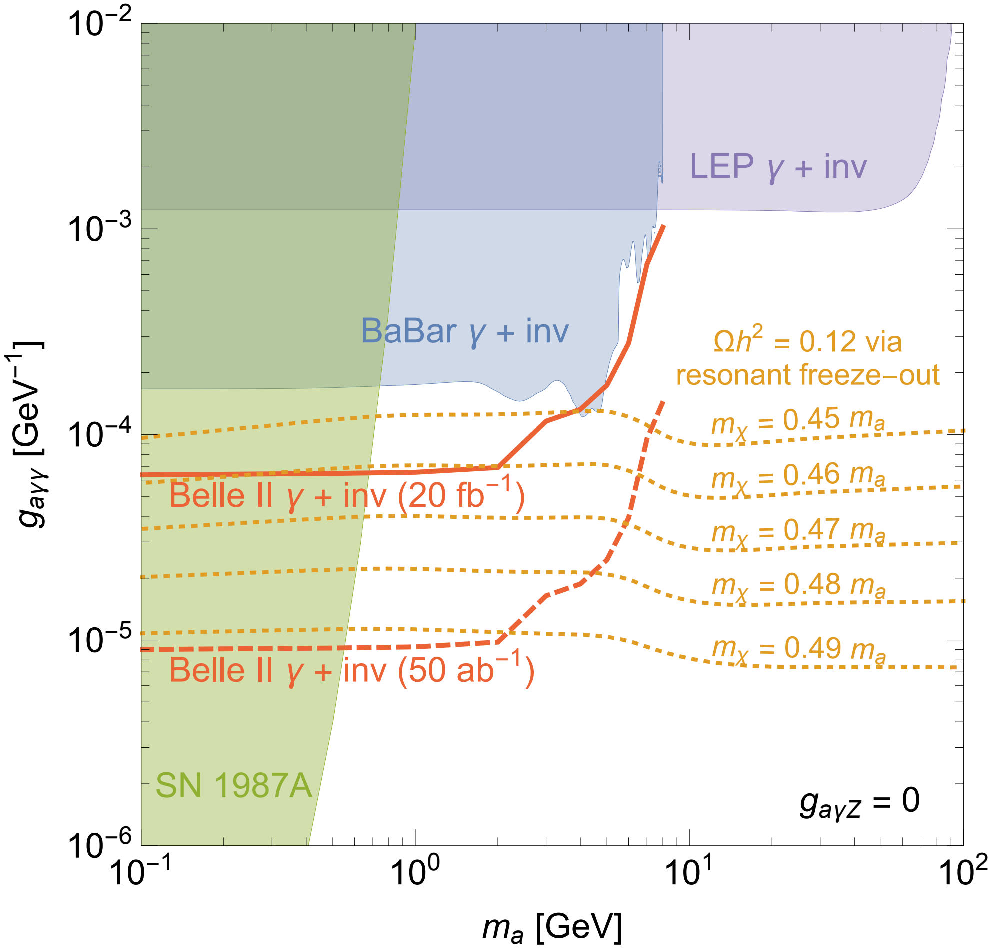
- Largest peaking background is $e^+e^- \to \gamma\omega, \omega \to \gamma\pi^0$. Also $e^+e^- \to \gamma\pi^0$ and $e^+e^- \to \gamma\eta$.

Expected sensitivity

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



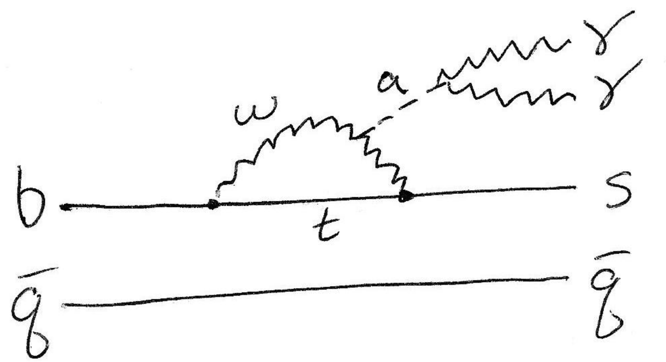
- If ALP decays to dark matter, single γ search is relevant. ALP mediation of SM / dark matter interaction could explain observed abundance if $m_a \approx 2m_\chi$.



JHEP 1712, 094 (2017)

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.

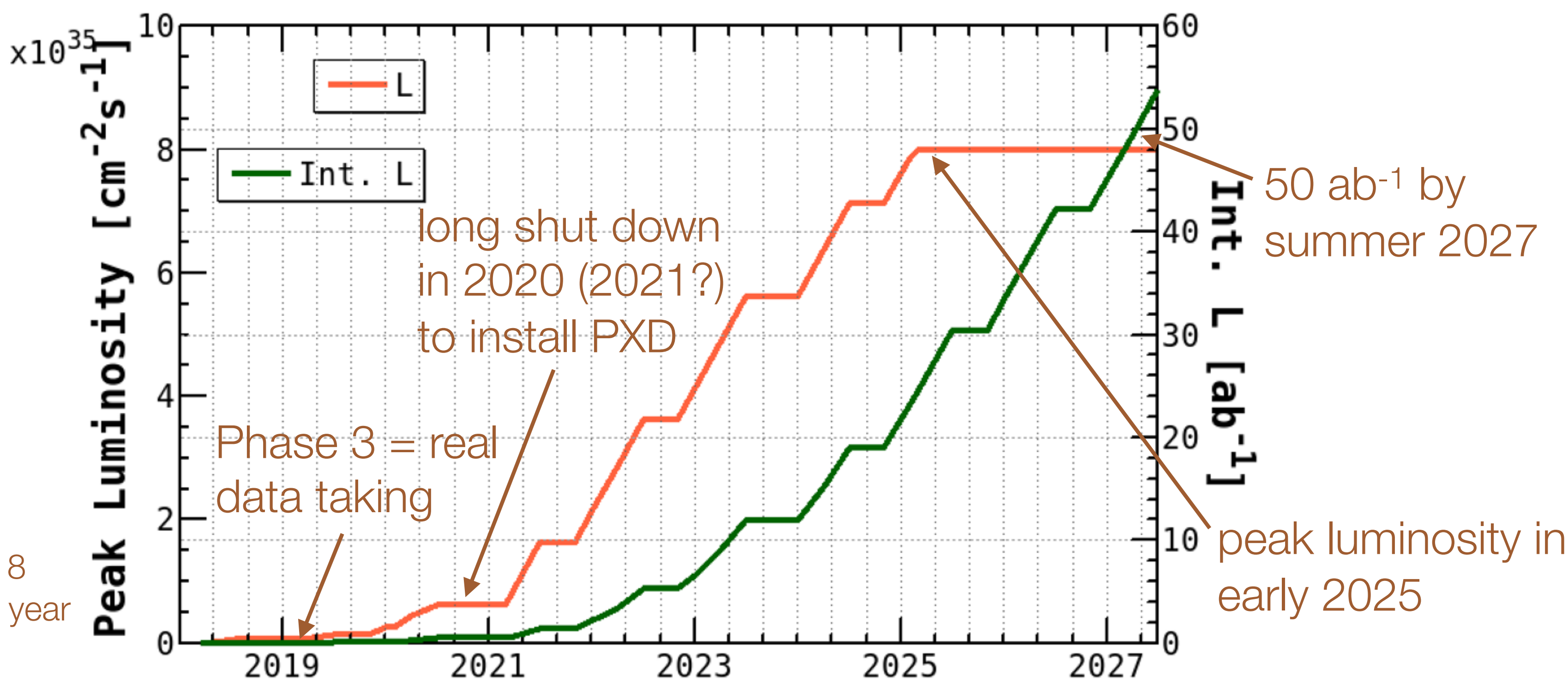


- Similar to $B \to K\pi^0$ analyses; will need a few ab^{-1} to be competitive with Belle and BaBar data sets.

Longer term Belle II run plan

- Hope to surpass Belle integrated luminosity summer 2021 (depends on PXD installation).

- Full dataset by summer 2027.



plan is based on 8 months running per year

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.