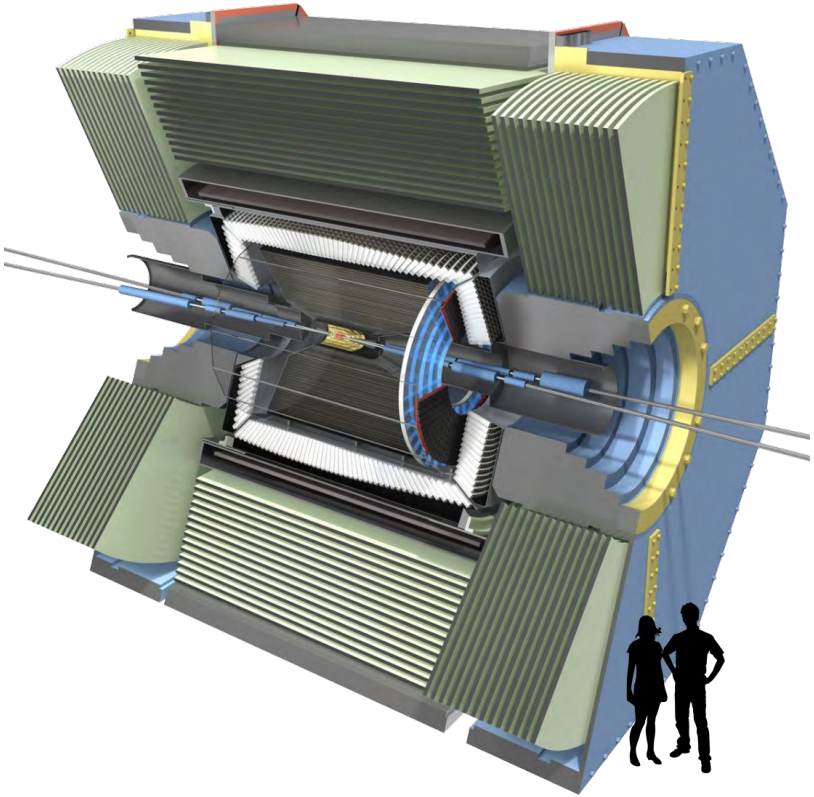


Dark sector physics with Belle II

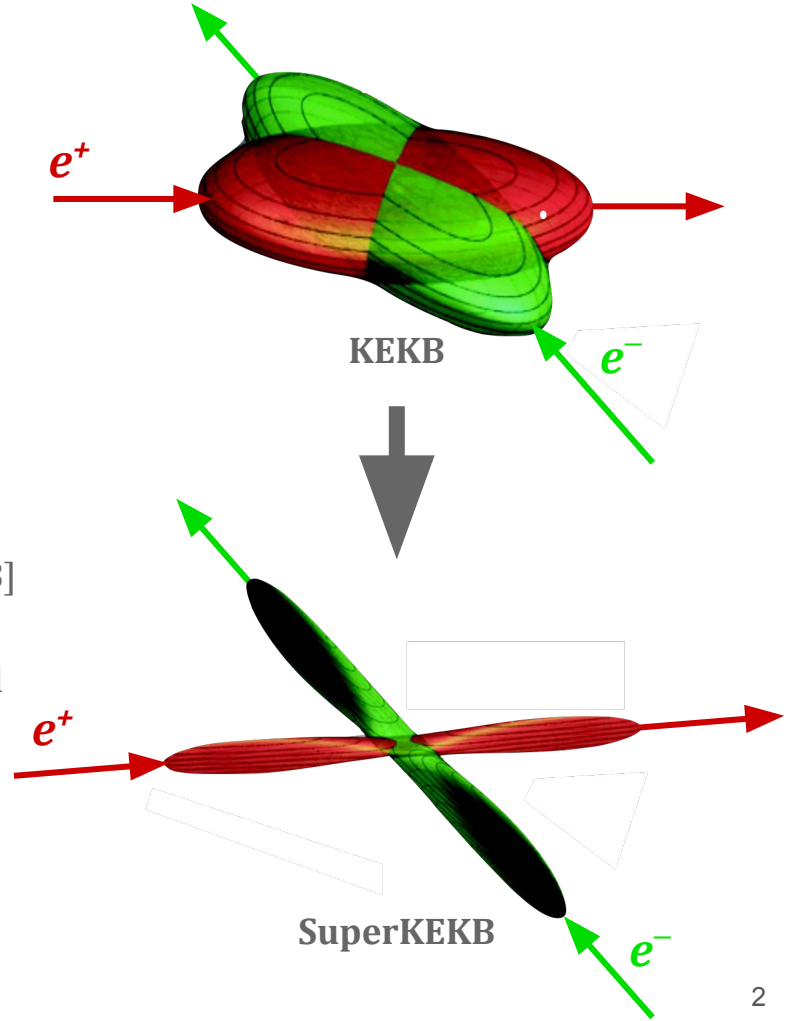
Peter M. Lewis for the Belle II Collaboration
University of Hawai‘i at Mānoa

22 February 2018
UCLA Dark Matter 2018

SuperKEKB

The super ***B*-factory** at KEK

- First-generation *B*-factory at Tsukuba, Japan:
  - KEKB: accelerator (world record luminosity)
  - Belle: detector
- Asymmetric-energy **10.57 GeV** electron-positron collider
- Instantaneous luminosity: **8×10^{35} $cm^{-2}s^{-1}$** [**40** times KEKB]
- Integrated luminosity: **50 ab^{-1}** [**50** times KEKB]
  - **"Nano-beam" scheme** (right, showing **positron** and **electron** bunches crossing)
  - **Doubled beam currents**
- First collisions this spring! Exciting times!



Belle II

Central beam pipe: 2cm diameter, Beryllium with gold coating on inside

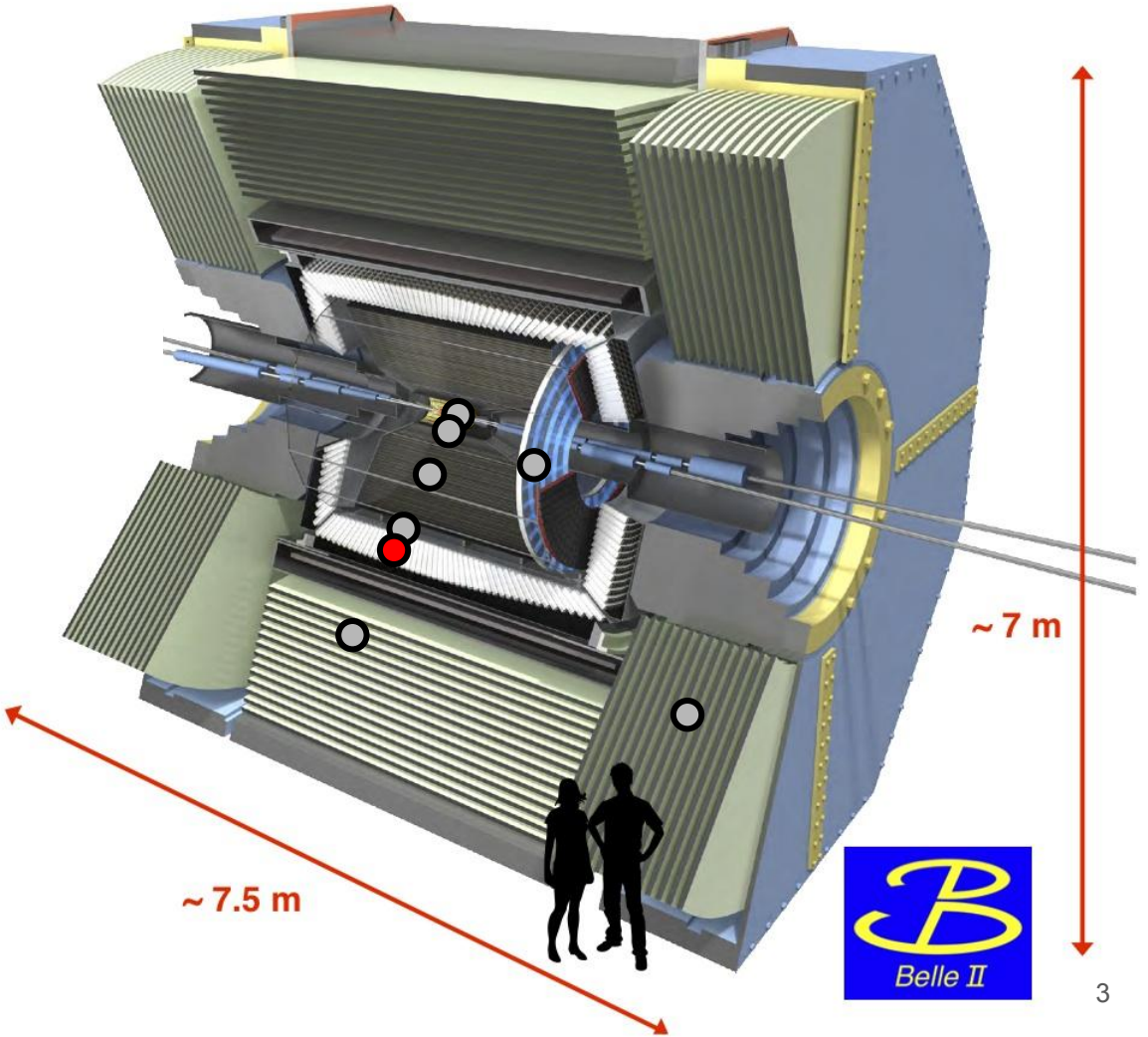
Vertexing: new 2 layers of pixels, 4 double-sided layers of silicon strips

Tracking: 14336-wire drift chamber

PID: time-of-flight (barrel) and proximity focusing aerogel (endcap) Cherenkov detectors

EM calorimetry: CsI(Tl) crystals

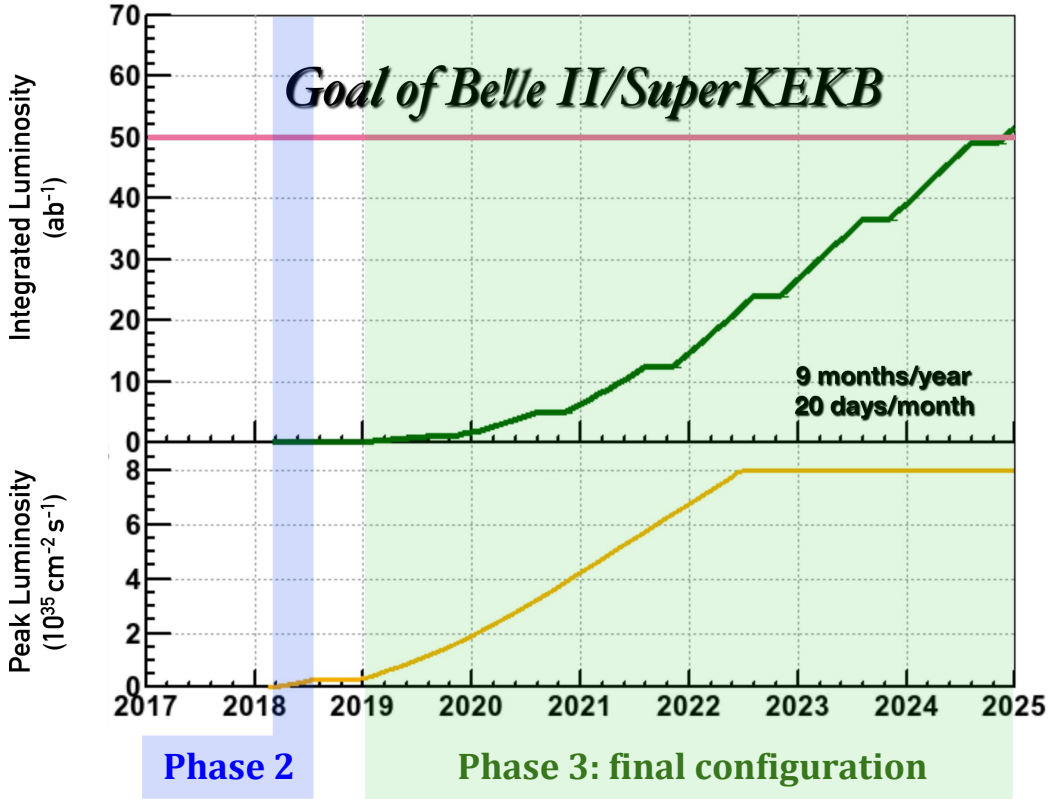
K_L and μ: scintillators (endcap and inner two layers of barrel) and RPCs (remainder of barrel)

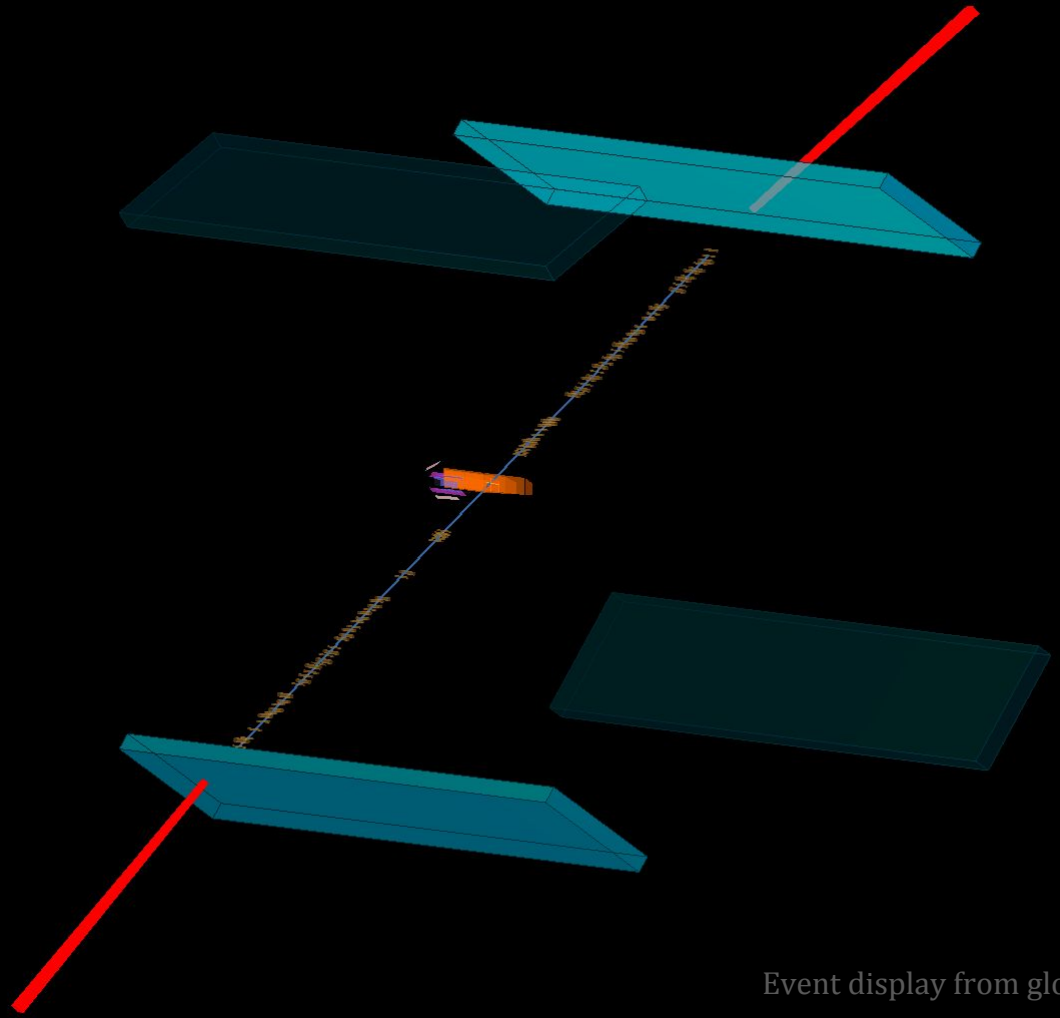


Near-term operations

“Phase 2” run

- 2016: First beams (“Phase 1”)
- Current: global cosmic run
- This spring: “**Phase 2**”
  - Primary purpose: commission nano-beams
  - Target: KEKB instantaneous luminosity (≤**20fb^{-1}** integrated)
  - Vertexing detectors absent
- *But*, with **smart trigger design** we can get competitive dark sector sensitivity:
  - New trigger modes
  - Flexible trigger firmware



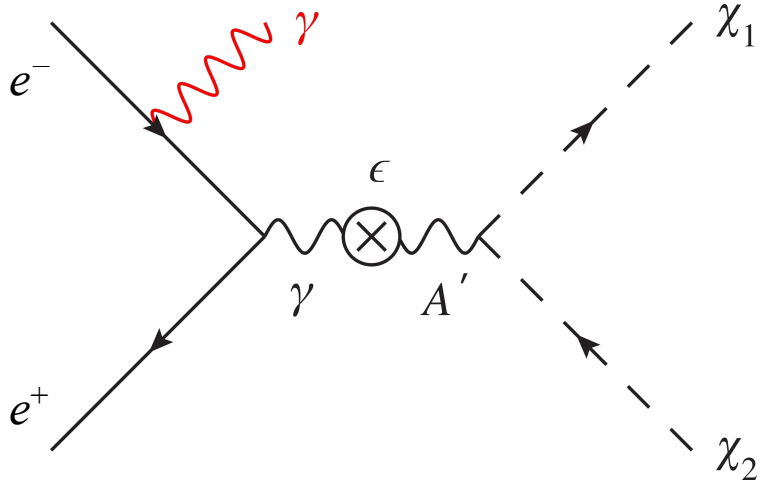


Event display from global Belle II cosmic run (last week)

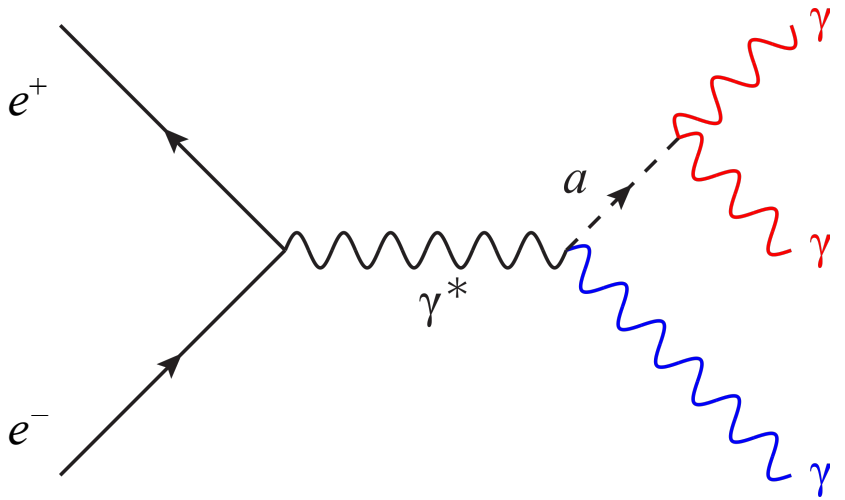
Dark matter searches at Belle II

(Some) Phase 2 physics prospects

- **Vector** portal: dark photon *A'* to invisible



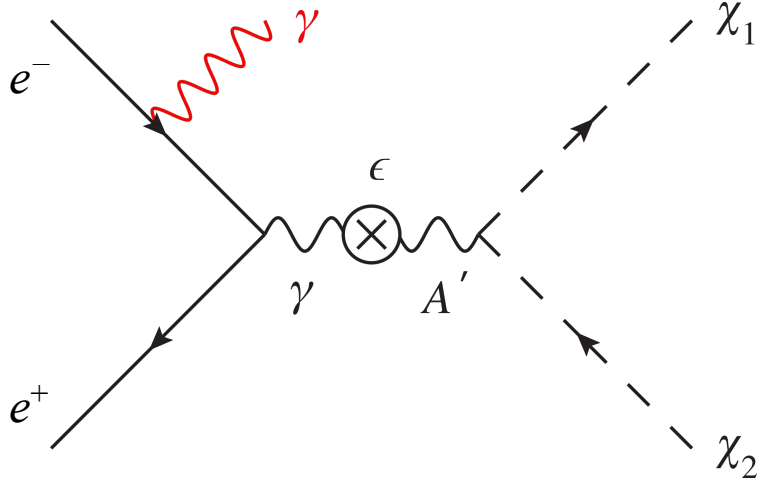
- **Pseudoscalar** portal: axion-like particles *a* (ALPs)

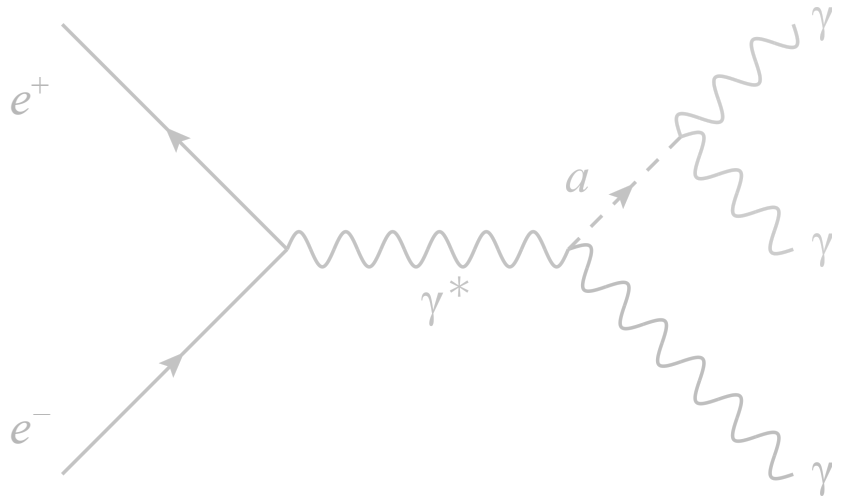


Dark matter searches at Belle II

(Some) Phase 2 physics prospects

- **Vector** portal: dark photon A' to invisible
- **Pseudoscalar** portal: axion-like particles a (ALPs)

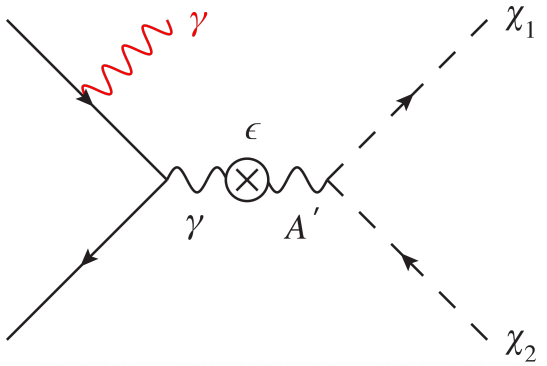


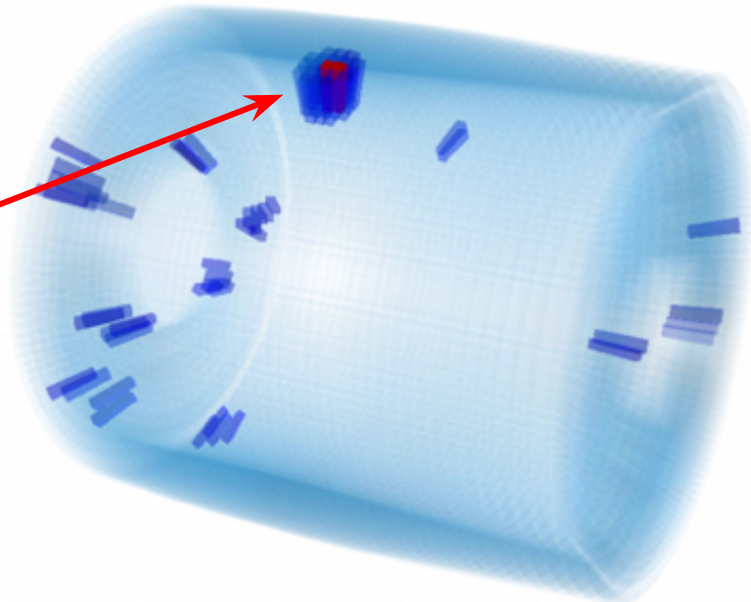


Dark photon to invisible

A distinctive signature

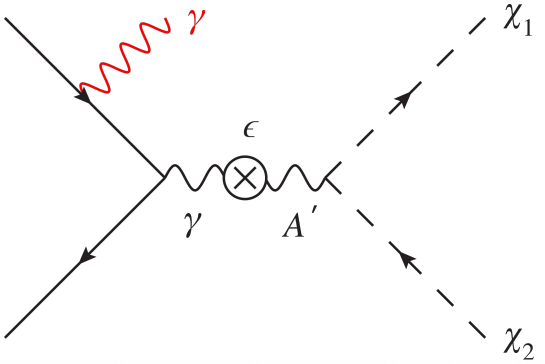
- **Single photon** from initial state radiation
- SM photon mixes with massive dark photon *A'*
- If DM is light enough, *A'* decays to invisible light DM particles
- **Signature:**
  - Single, mono-energetic, high-*E* photon
  - Peak in recoil mass (dark photon mass)





Simulated calorimeter event with reducible background

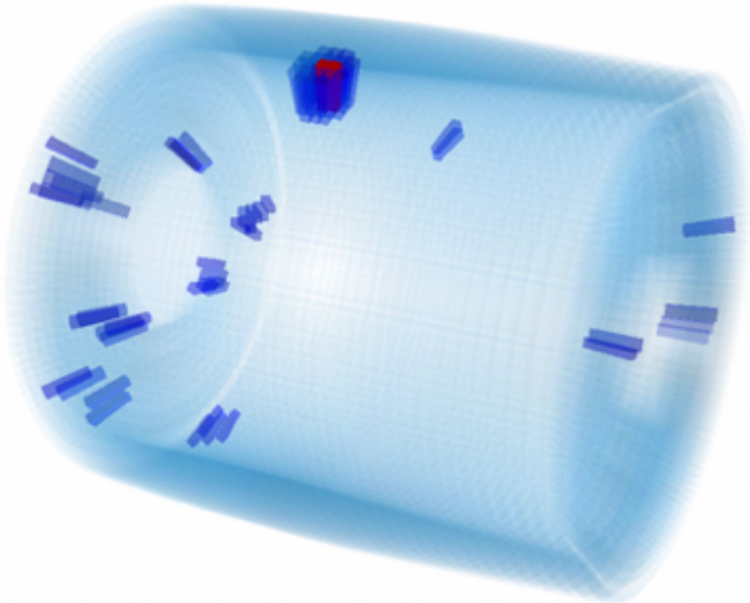
Dark photon to invisible



A special trigger

- **Single-photon trigger:**
  - None in Belle
  - Only for short time in BaBar ($53 fb^{-1}$)
- **Advantages over BaBar**:
  - More-hermetic calorimeter
    - Larger calorimeter coverage
    - Photons cannot escape between crystals due to a slight rotation in θ and ϕ
  - Lower energy asymmetry

Belle II Phase 2 run with single-photon trigger should be competitive

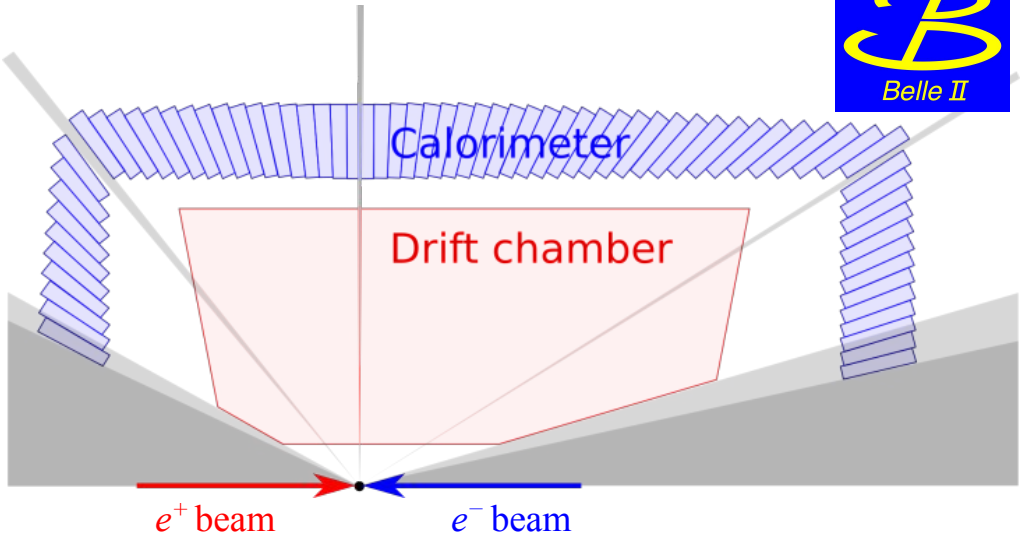


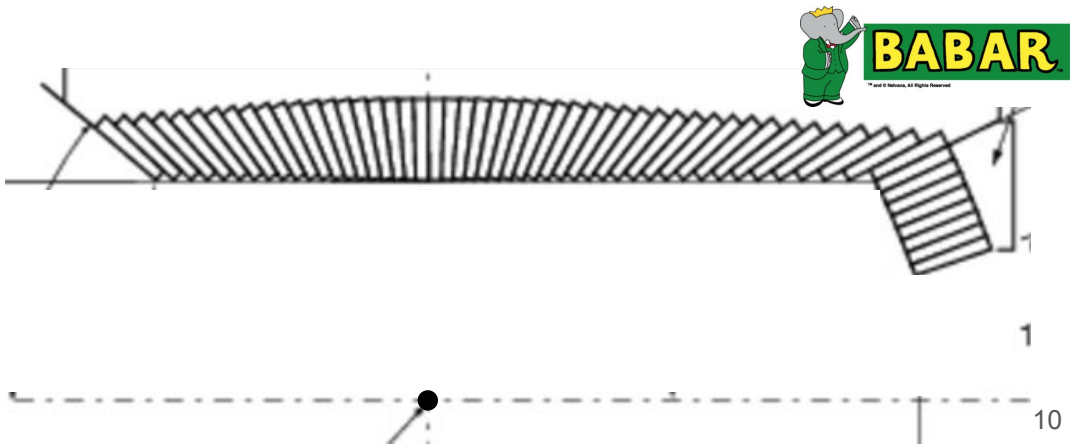
Simulated calorimeter event with reducible background

Dark photon to invisible

Backgrounds

- **~No** true physics backgrounds
- Missing particle backgrounds:
  - $e^+e^- \rightarrow \gamma\gamma(\gamma)$
  - Radiative Bhabha $e^+e^- \rightarrow e^+e^-\gamma$
- Final state particles get “lost” in cracks (top)
  - BaBar had no backwards endcap calorimeter and cracks between each crystal (bottom)

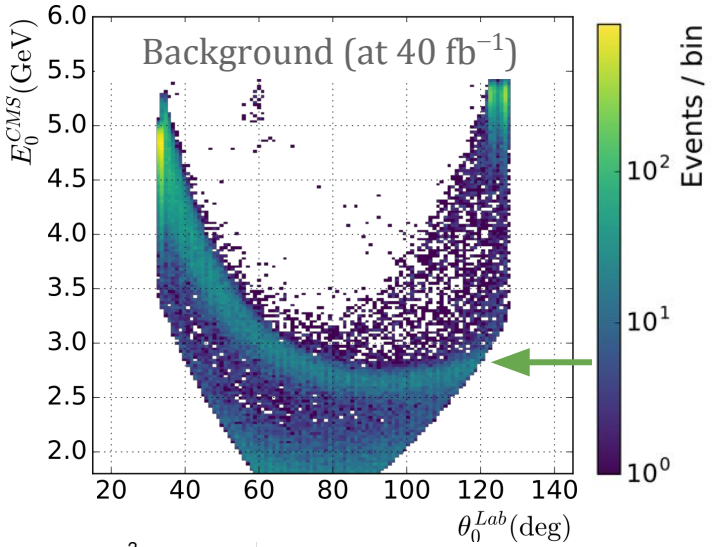


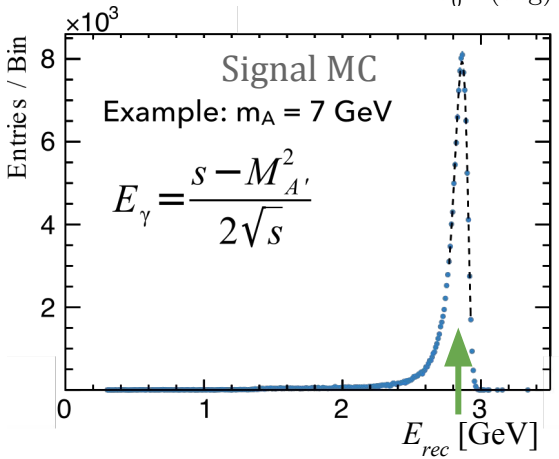


Dark photon to invisible

Phase 2 expectations

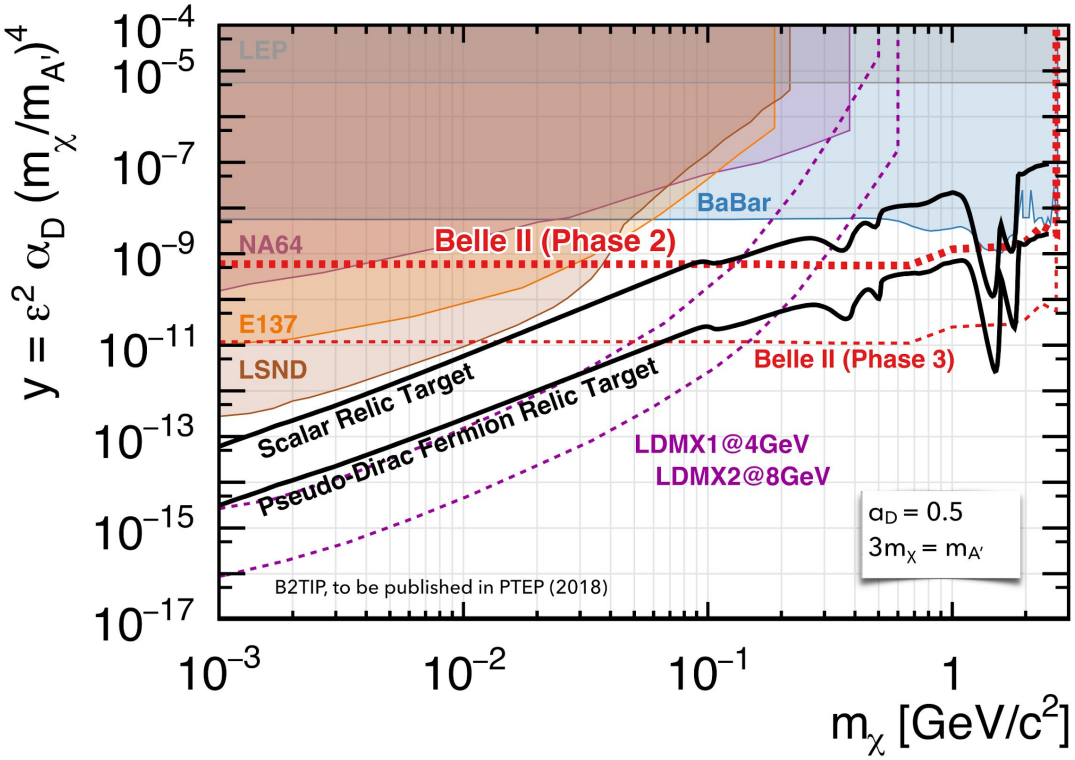
- **Single-photon trigger**
  - Exactly one cluster >1GeV, none other >300MeV
  - Rate dominated by $e^+e^- \rightarrow e^+e^-\gamma$
  - Single-photon trigger **~0.5kHz** [of **8kHz** max]
  - May be able to use in Phase 3
- **Handling backgrounds**
  - Peaking $e^+e^- \rightarrow \gamma\gamma(\gamma)$ dominates analysis (right)
  - The key: quantify photon efficiency
- **Key strength**
  - Low backgrounds → good sensitivity for **low-mass** dark photons





Belle II MC with 1.8GeV single-photon trigger

Dark photon to invisible: projected sensitivity



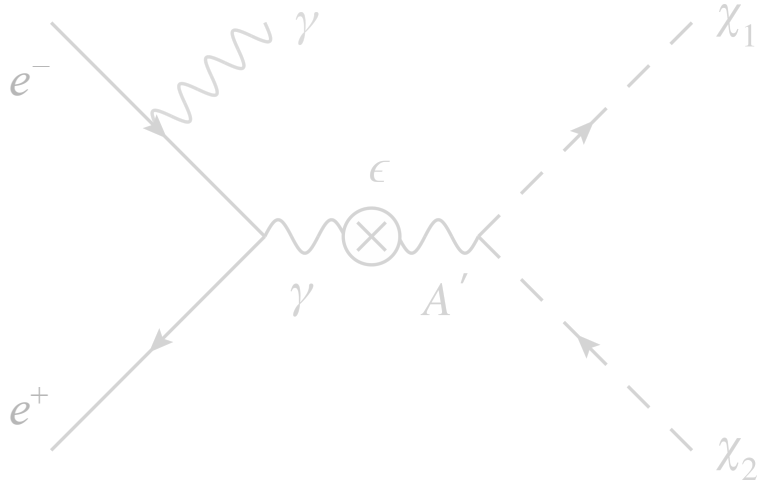
J. Alexander et al. (2016), arXiv:1608.08632
Natalia Toro, private comm. (2017)
J.P. Lees et al., BaBar (2017), arXiv:1702.0332
B2TIP, to be submitted in PTEP (2018)

Disclaimer: relic density lines assume a standard cosmological history and that there is only a single component of dark matter, which only interacts via dark photon exchange.

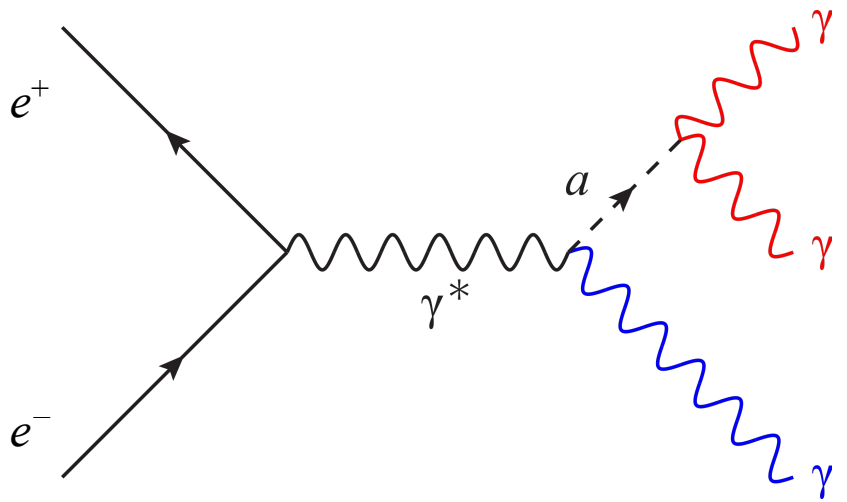
Dark matter searches at Belle II

(Some) Phase 2 physics prospects

- **Vector** portal: dark photon A' to invisible



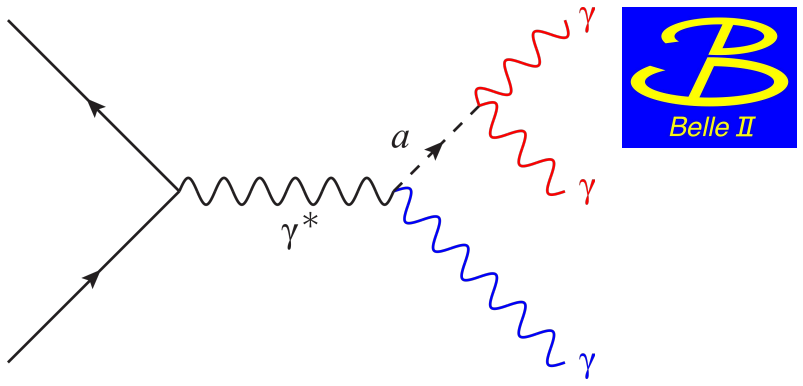
- **Pseudoscalar** portal: axion-like particles a (ALPs)

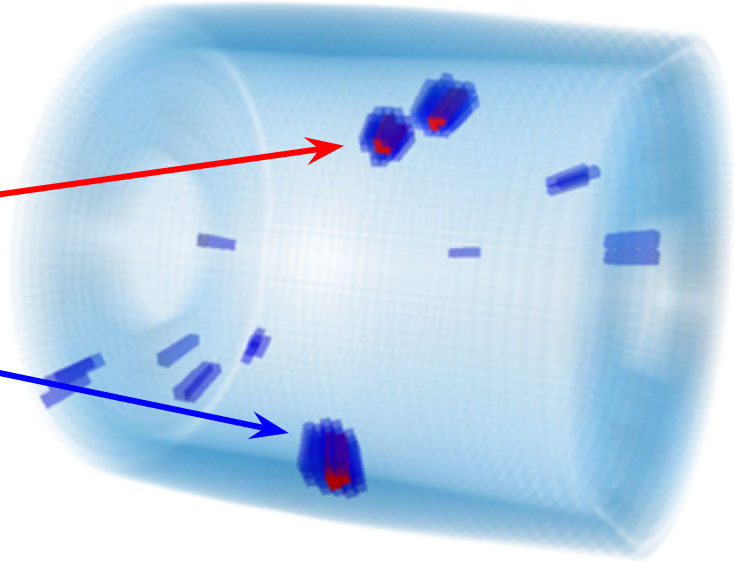


Axion-like particles

Three-photon final state

- ALPs couple to bosons
  - No relation between mass and coupling
  - **Photon** coupling $g_{a\gamma\gamma}$ targetable in Phase 2
- Signature
  - Three photons > 0.1GeV in calorimeter
  - Pair of photons from $a \rightarrow \gamma\gamma$
  - Single **recoil photon**
- Search for a
  - Bump in invariant $\gamma\gamma$ mass spectrum
  - Multiplicity of three; we don't know which photon is which



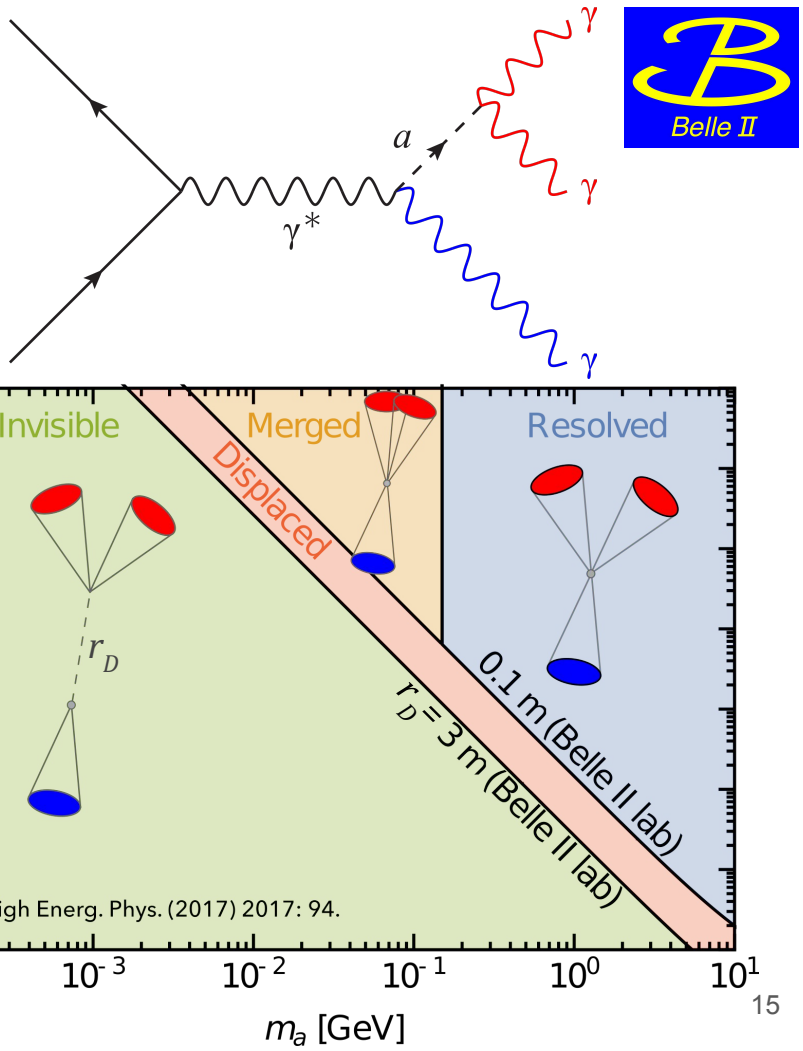


Simulated calorimeter event with reducible background

ALPs

Calorimeter signature

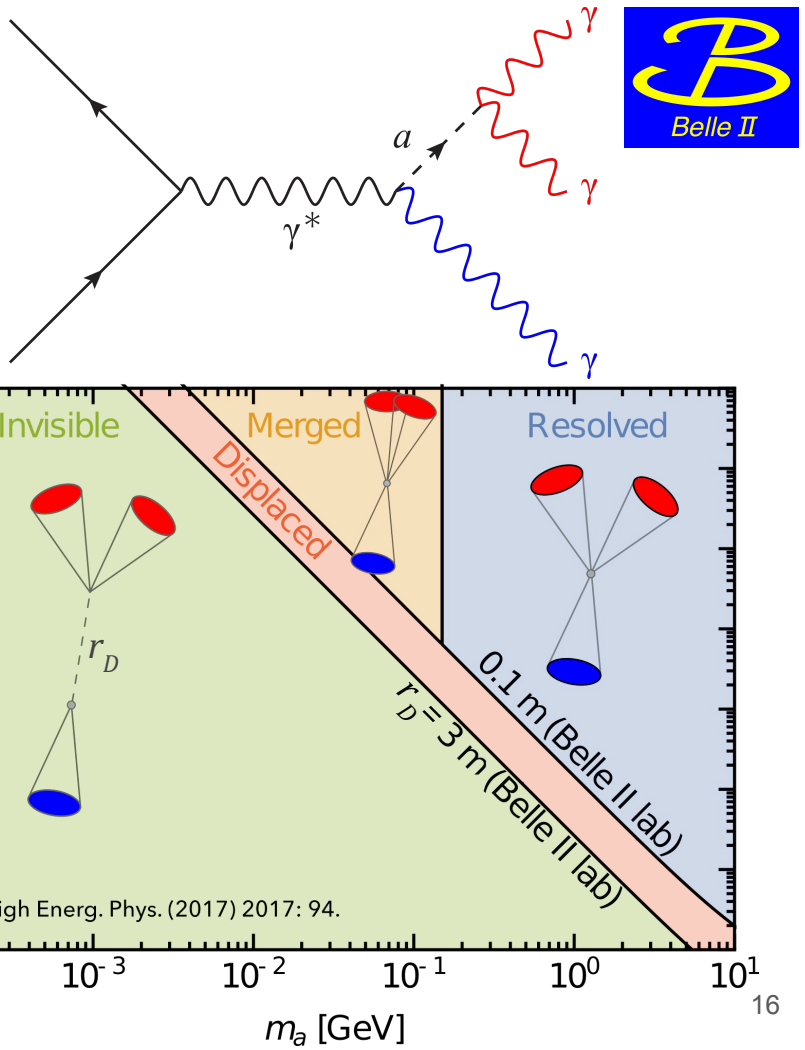
- Mass m_a and coupling $g_{a\gamma\gamma}$ determine
  - Displacement from collision point (r_D)
  - Opening angle θ of decay photons
- Four signatures:
  - **Resolved**: prompt decay, large θ
  - **Merged**: prompt decay, small θ
  - **Displaced**: (ignore; indistinguishable from $e^+e^- \to \gamma\gamma$)
  - **Invisible**: decay outside Belle, single-photon final state



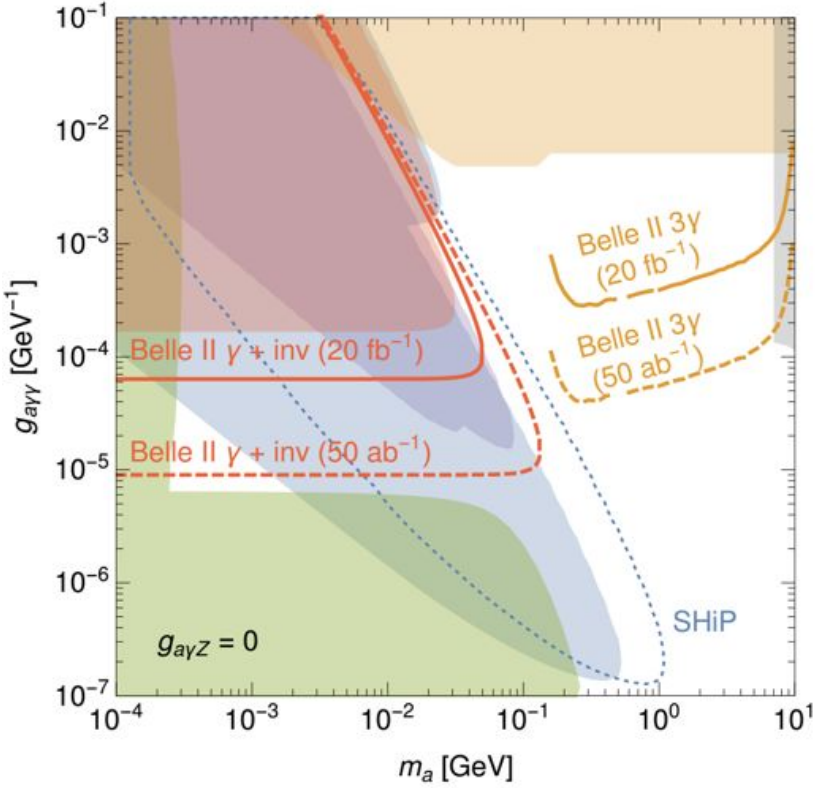
ALPs

Phase 2 considerations

- **Backgrounds**
  - $e^+e^- \to \gamma\gamma(\gamma)$ with 0 or 1 γ from beam background
  - **Resolved**: $e^+e^- \to \pi^0\gamma,\ \eta\gamma,\ \eta'\gamma$
- **Trigger**
  - **Resolved:** relax $e^+e^- \to \gamma\gamma$ prescale in trigger
  - **Invisible**: single-photon trigger (also captures prompt $a \to$ invisible)



ALPs: projected sensitivity



M. J. Dolan, T. Ferber, C. Hearty, F. Kahlhoefer, K. Schmidt-Hoberg, *Revised constraints and Belle II sensitivity for visible and invisible axion-like particles*. J. High Energy Phys. (2017) 2017: 94

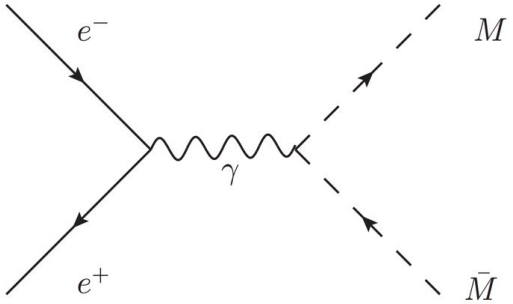
Conclusions

Belle II dark sector

- Belle II has **unique** sensitivity to ALPs and dark photons, even in low-luminosity **Phase 2**:
  - Specially designed triggers
  - Lower background than BaBar
  - Complementary to searches at SHiP and LHC
- Other Phase 2 dark-sector searches could include:
  - Dark photon → pseudo-Dirac DM
  - Off-shell *A'* decays
  - Magnetic monopoles with small magnetic charges (additional slides)
  - Muonic dark force with dark boson *Z'*: $e^+e^- \rightarrow \mu^+\mu^- Z'$, $Z' \rightarrow$ invisible
- **Phase 3** (to final luminosity)
  - Can use Phase 2 trigger for early Phase 3 runs too
  - Dark photon coupling to leptons: $A' \rightarrow l^+l^-$
  - A lot more...

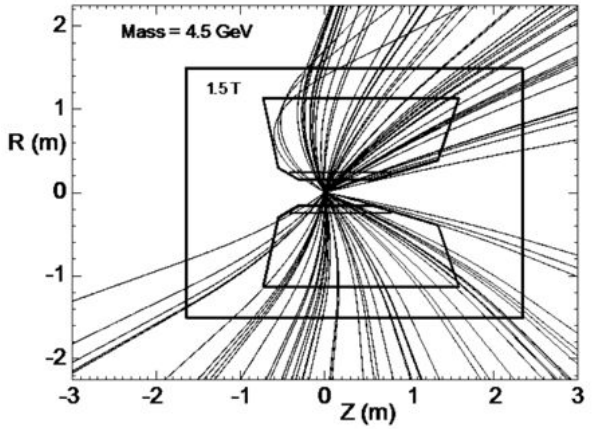
Thank you!

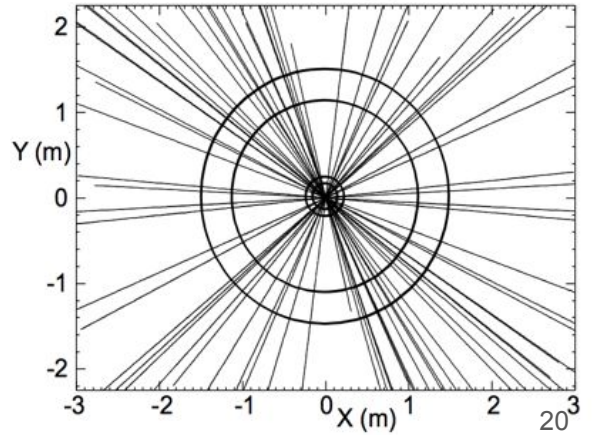
Magnetic monopoles



Another Phase 2 specialty

- Search for magnetons with small magnetic charge
- **Distinct signature** in drift chamber: seen on-end, tracks will be **straight**
- **Special trigger**:
  - Trigger on any track that crosses all cells of inner drift chamber
  - Trigger in Phase 3 may be too tight
- Detection efficiency is **high**: 40-97%, depending on magneton mass





arXiv: 1707.05295