Dark Matter and ALP Searches at Belle II

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Savino Longo on behalf of the Belle II Collaboration

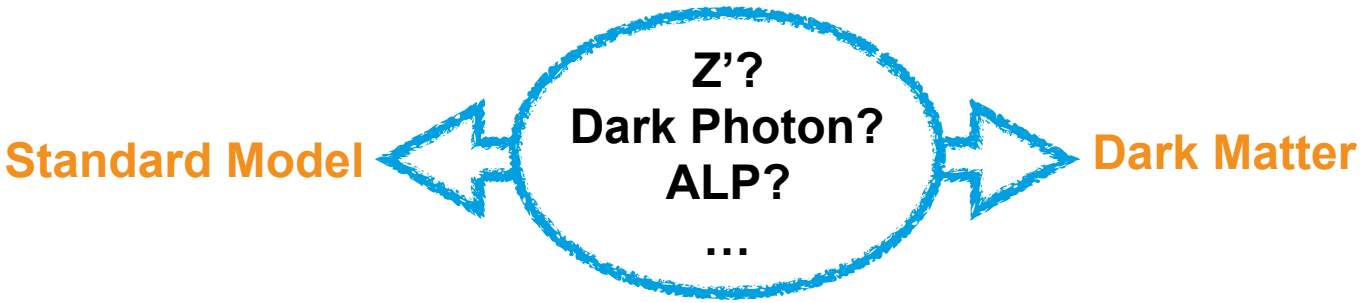
savino.longo@desy.de

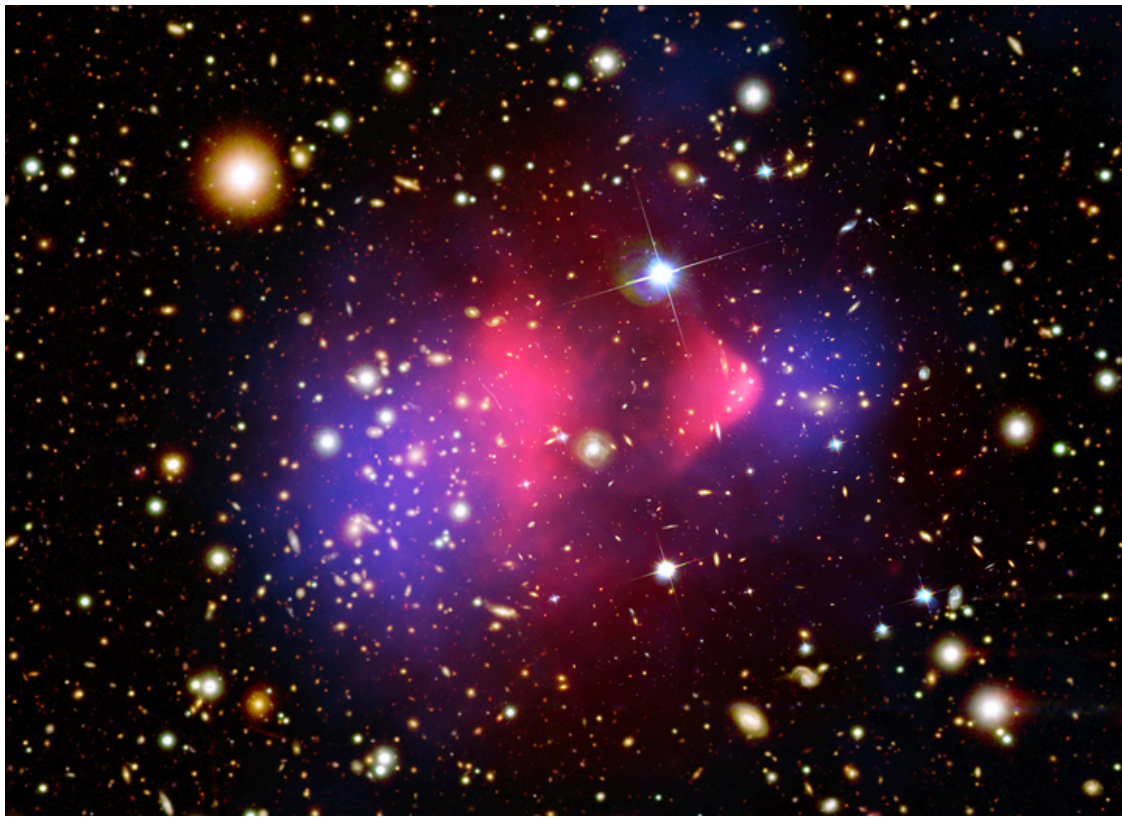
Deutsches Elektronen-Synchrotron (DESY)

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Dark Matter Searches with e^+e^- Collisions

- Indirect evidence for dark matter ranging from galactic to cosmological scales.
- Intensity frontier B-Factories can explore direct production of MeV to GeV scale mediators between Standard Model and Dark Matter/Dark Sectors.



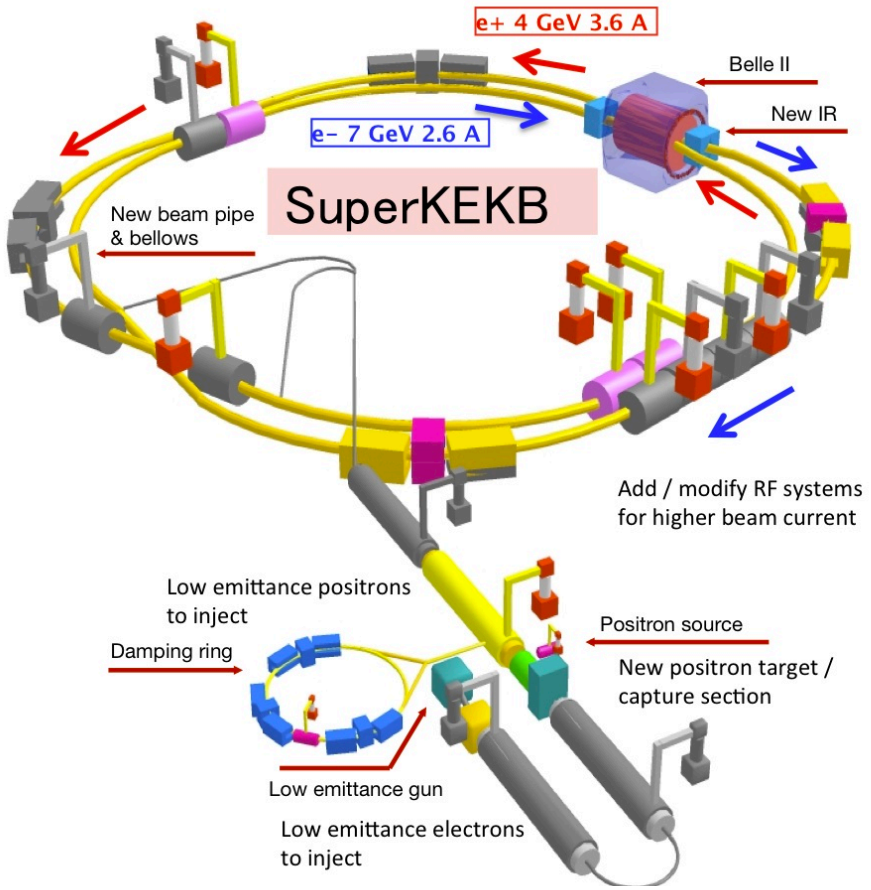


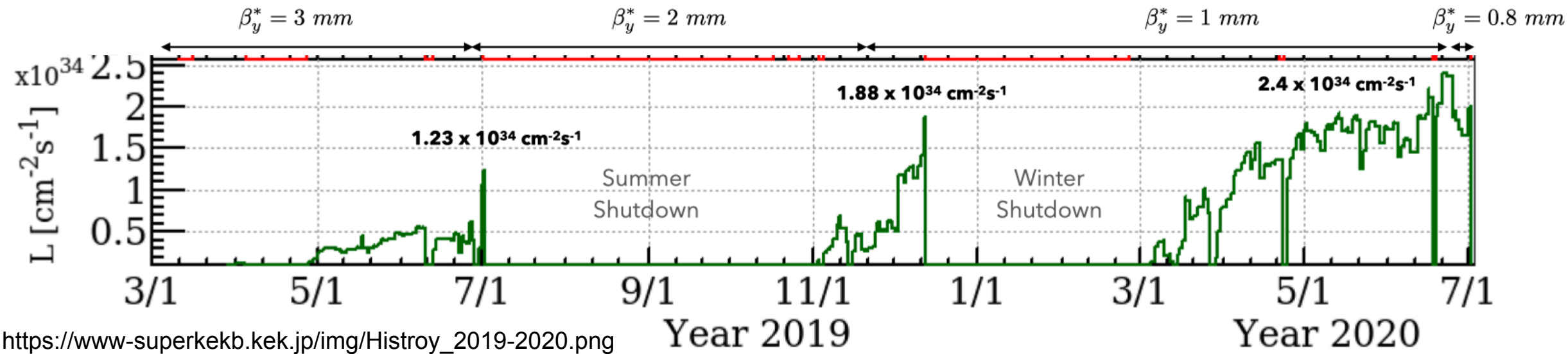
- Several advantages of e^+e^- collision environment for Dark Matter searches:
  - ✓ Well-known initial conditions and hermetic detectors allows for precise determination of missing energy/ momentum.
  - ✓ Minimal background from collision pile-up.
  - ✓ High detection efficiency of charged and neutral particles.

Image: https://chandra.harvard.edu/photo/2006/1e0657/1e0657.jpg

SuperKEKB Collider

- Asymmetric e^+e^- collider at $\Upsilon(4S)$ resonance ($\sqrt{s} = 10.58$ GeV).
- Nano-beams to boost instantaneous luminosity, targeting 40x increase relative KEKB.
- Design luminosity of 8×10^{35} cm^{-2}s^{-1}.
- Peak of 2.4×10^{34} cm^{-2}s^{-1} achieved in 2020 (world record).
- Continuous injection.





https://www-superkekb.kek.jp/img/Histroy_2019-2020.png

The Belle II Detector

Vertex Detectors:
DEPFET pixel detector (2 layers)
Double-sided silicon strip detector (4 layers)

Electromagnetic calorimeter:
CsI(Tl) crystals, crystal gaps offset from IP, waveform sampling electronics.
Measures energy, time and pulse shape.

Magnet:
1.5T superconducting

Drift Chamber:
He(50%):C_2H_6(50%), Larger size relative to Belle, smaller cells, new electronics.

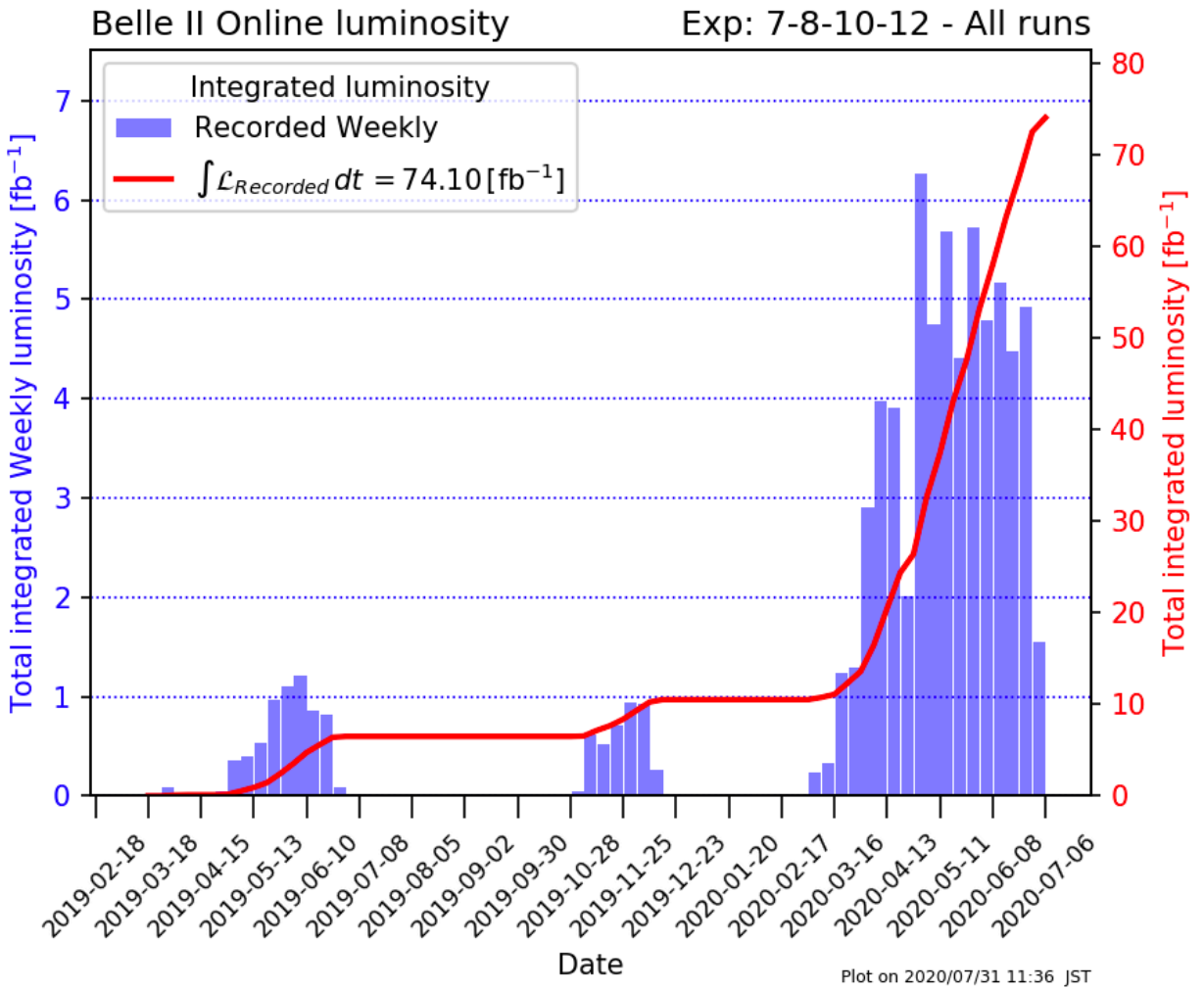
K_L^0/μ Detector:
Inner Barrel/Endcaps: Scintillating Strips
Outer Barrel: Resistive Plate Counters

Charged Particle Identification:
Barrel: Time-of-Propagation counter
Backward Endcap: Aerogel Ring-Imaging Cherenkov counter

DESY. Savino Longo (savino.longo@desy.de)

Belle II Integrated Luminosity

- First physics data arrived in 2018 with 0.5 fb^{-1} commissioning run.
  - ➡ One octant of vertex detector installed.
- Steady operations throughout 2019/2020, current dataset is ~ 74 fb^{-1}.
  - ➡ Vertex detector installed.
- Specialized low multiplicity triggers for Dark Sector searches (eg. single photon), are enabled in entire dataset.
  - ➡ Belle did not have single photon trigger, and BaBar had only for ~10% of dataset.



Single Photon Level 1 Triggers:

- At least one photon with $E_{CMS} > 2$ GeV
- One $E_{CMS} > 1$ GeV photon in barrel + no other energetic photons
- One $E_{CMS} > 0.5$ GeV photon in central barrel + no other energetic photons

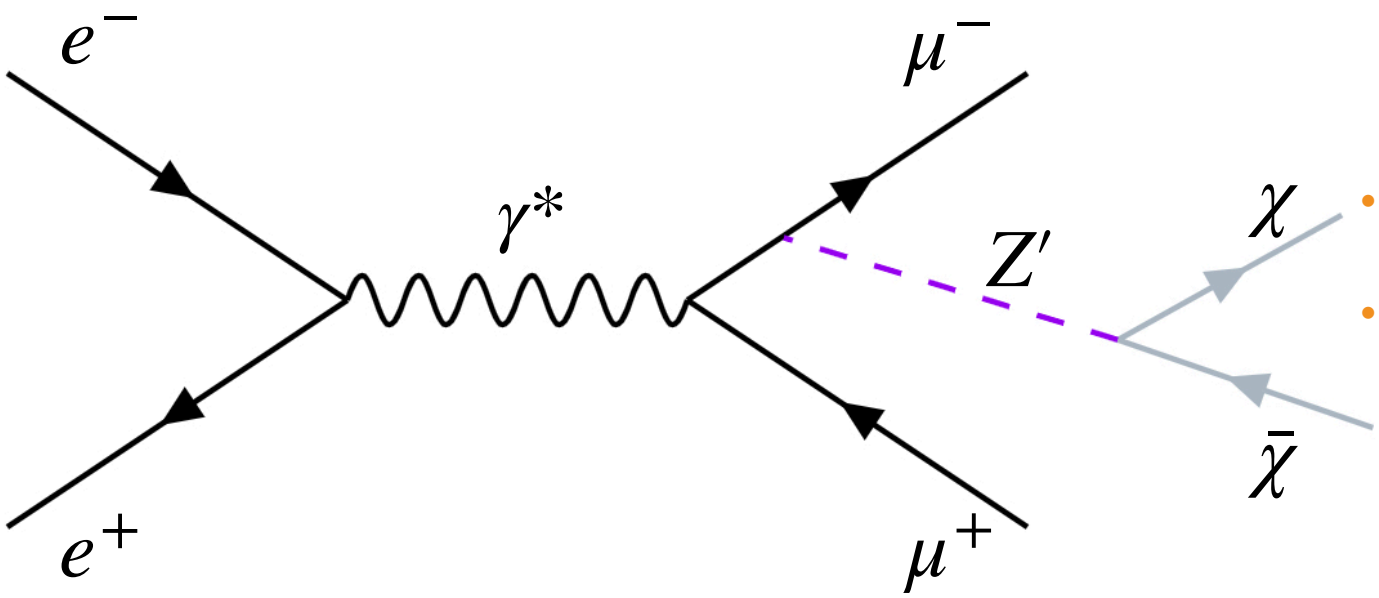
Search for Z’ and LFV Z’

Search for Z'

- Search for Z' mediator which couples only to 2nd and 3rd generation leptons ($L_\mu - L_\tau$ model).
- Could address Dark Matter, $(g-2)_\mu$ and $b \to s\mu^+\mu^-$ anomalies.

B. Shuve and I. Yavin, Phys. Rev. D 89, 113004 (2014).
W. Altmannshofer et al, J. High Energy Phys. 12 (2016) 106.
D. Curtin et al, J. High Energy Phys. 02 (2015) 157.

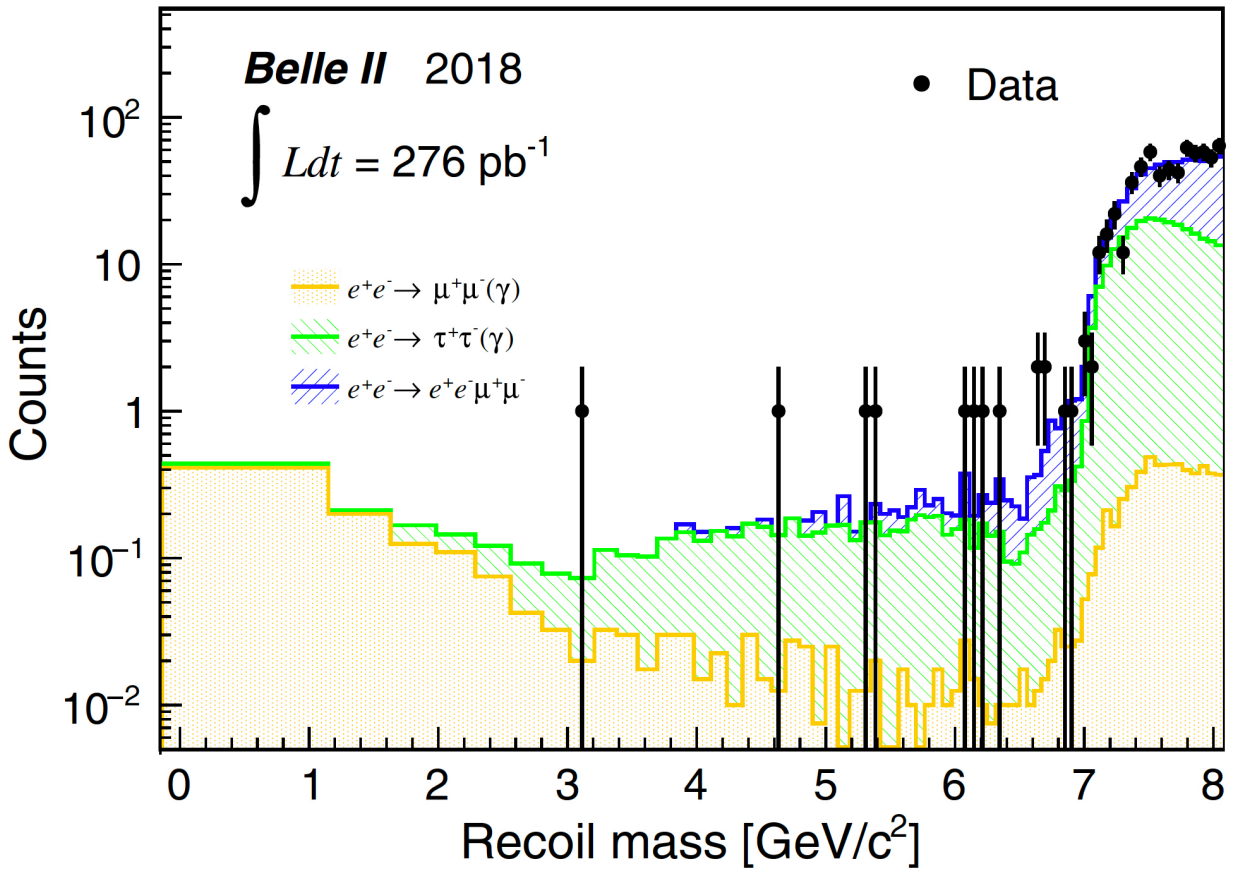
- Production at Belle II by final state radiation of muon, search channel: $e^+e^- \to \mu^+\mu^- Z', Z' \to$ Invisiable

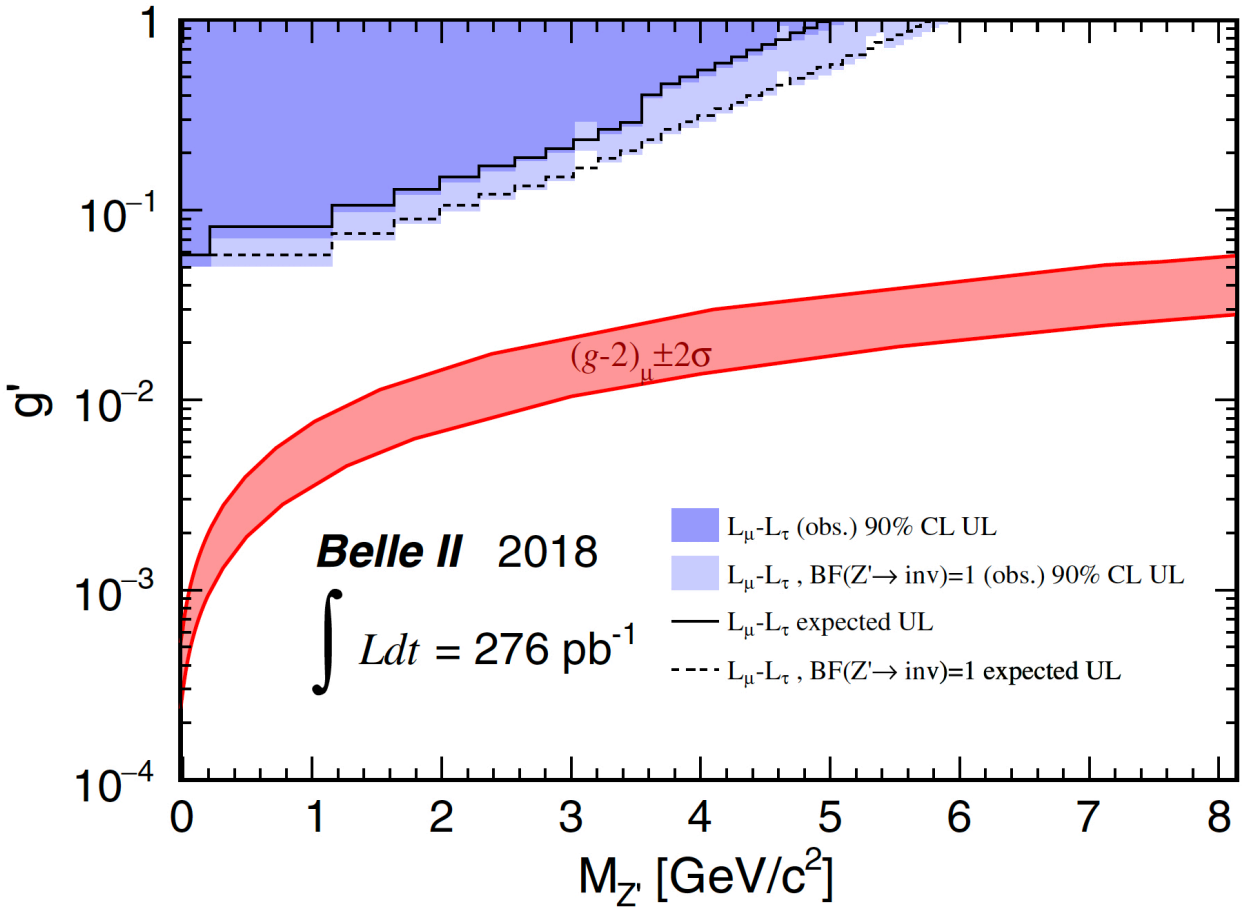


- Belle II signature:
  - ➡ Missing energy + dimuon pair.
- Search for peak in recoil mass of muons.
- Backgrounds:
  - ➡ $e^+e^- \to \mu^+\mu^-(\gamma)$: Do not reconstruct photon
  - ➡ $e^+e^- \to \tau^+\tau^-(\gamma)$: Neutrinos escape detector
  - ➡ $e^+e^- \to e^+e^-\mu^+\mu^-$: e^+e^- not in acceptance

Search for Z' Results

- Search conducted with 0.276 fb^{-1} of commissioning data.
- No excess observed, Belle II is first experiment to set limits on Z' coupling, g', for $Z' \rightarrow$ Invisible
- Published in: **Phys. Rev. Lett. 124, 141801 (2020)**





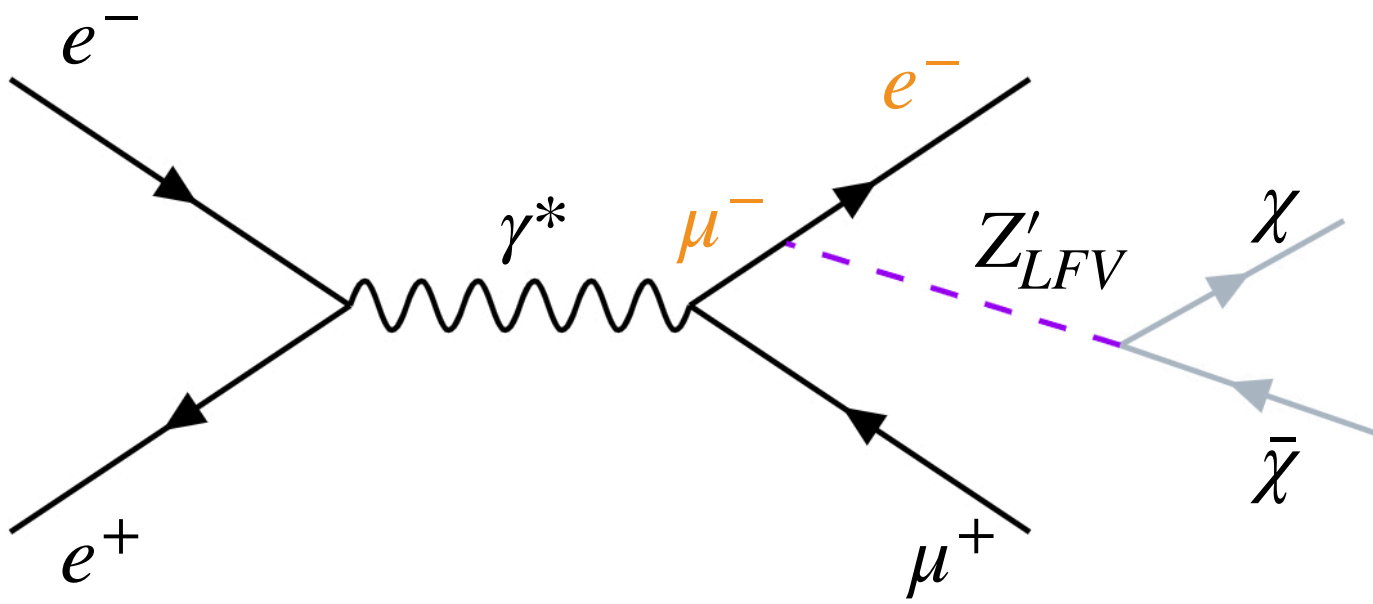
Search for Lepton Flavour Violating Z'

- Z' with LFV $e - \mu$ coupling discussed in literature as Dark Matter candidate.

I. Galon and J. Zupan, J. High Energy Phys. 05 (2017) 083.
I. Galon, A. Kwa, and P. Tanedo, J. High Energy Phys. 03 (2017) 064.

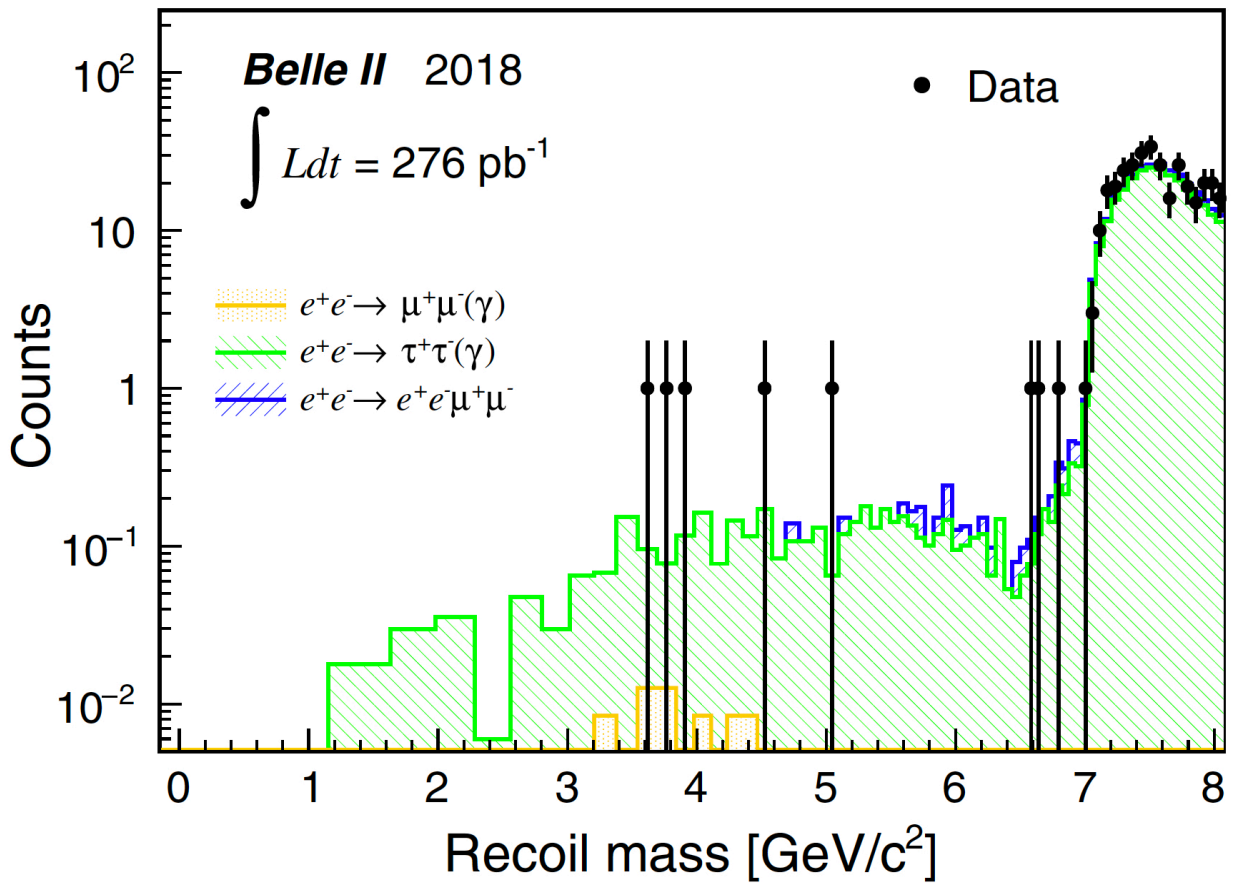
- Model independent search for $e^+e^- \rightarrow e^\pm\mu^\mp +$ missing energy completed by Belle II.
- Belle II signature:
  - ➡ Missing energy + one muon and one electron.
- Search for peak in recoil mass of leptons.
- $e^\pm\mu^\mp$ final state allows for significant background suppression relative standard Z' search.
- Main background:

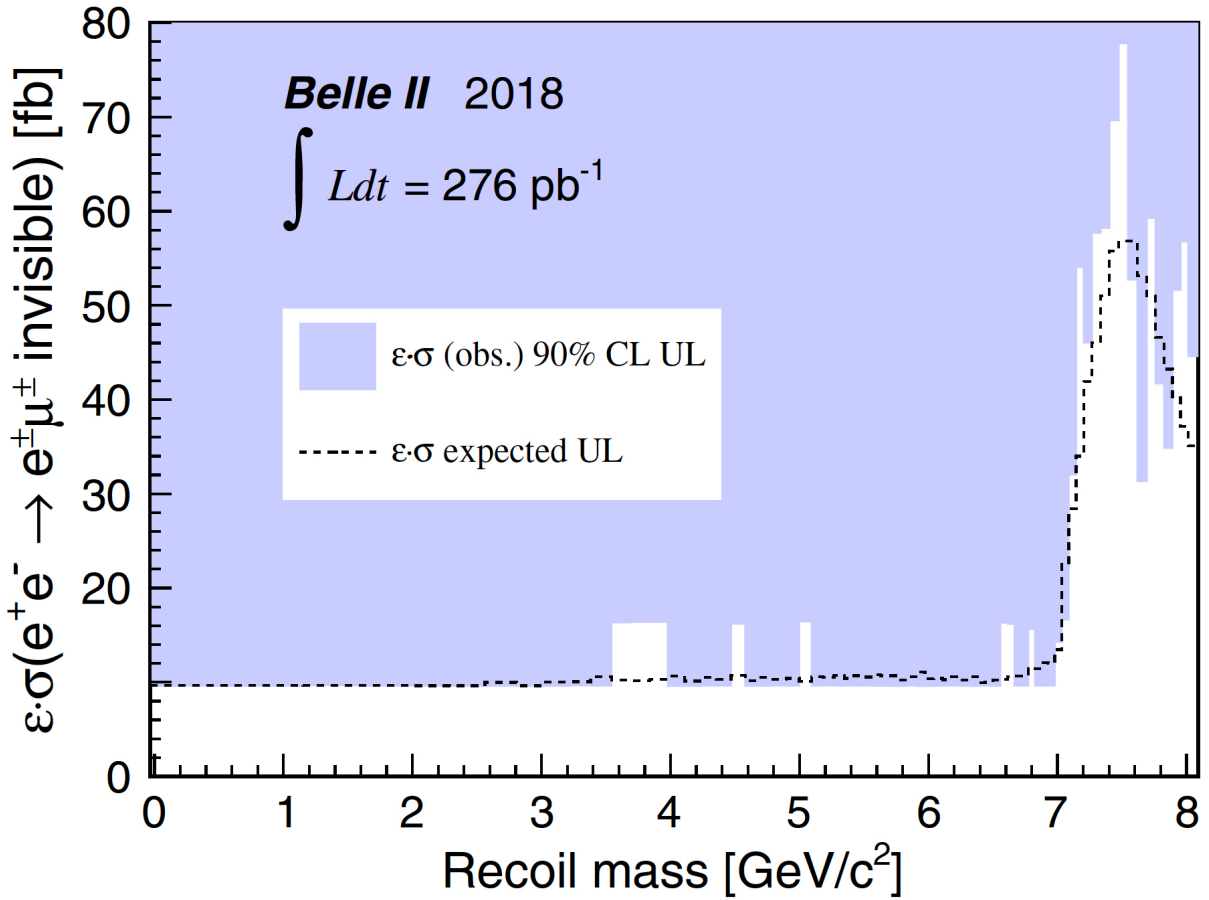
$$e^+e^- \rightarrow \tau^+\tau^-(\gamma)$$



LFV Z' Search Results

- Search conducted with 0.276 fb^{-1} of commissioning data.
- No excess observed, first experiment to set limits on cross-section for $e^+e^- \to e^\pm\mu^\mp +$ missing energy
- Published in: **Phys. Rev. Lett. 124, 141801 (2020)**

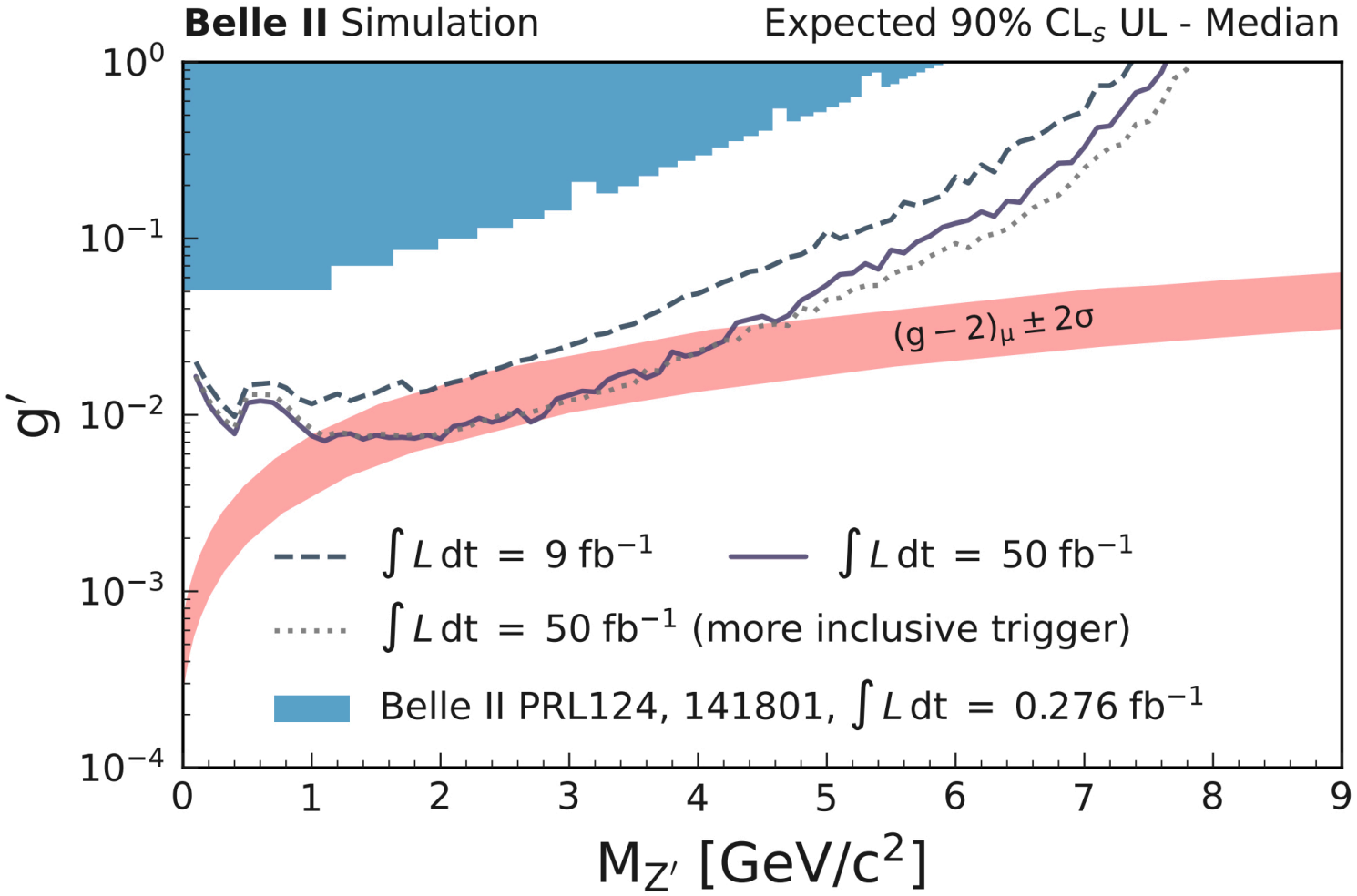




Future Reach of Z' Searches

- Full Belle II dataset is already over 200 times that used for first Z' searches.
- Larger dataset and improvements in detector/trigger performance are predicted to already significantly extend sensitivity compared to initial search.

Update with current full dataset is in progress.



Search for Axion-Like Particles

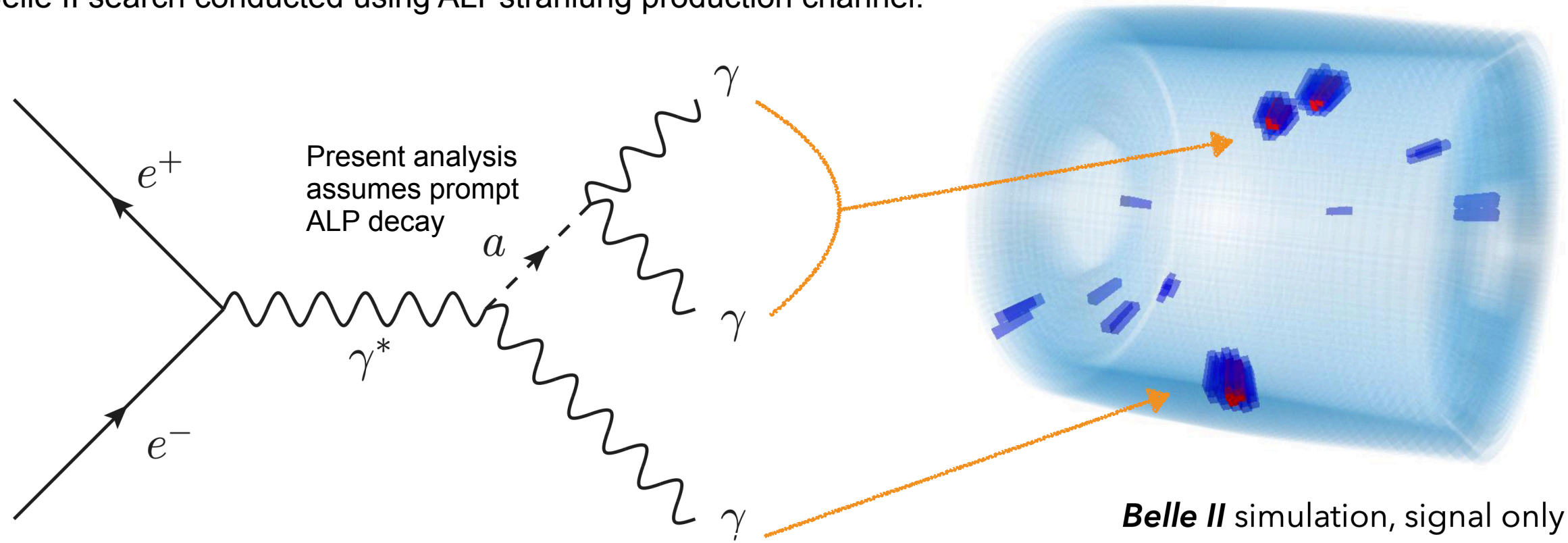
Search for Axion-Like Particles

- Axion-Like Particles (ALPs) are pseudoscalars, a, which couple to Standard Model bosons via, $g_{a\gamma Z}$ and/or $g_{a\gamma\gamma}$. Belle II focus on $g_{a\gamma\gamma}$.

M. J. Dolan et al., J. High Energy Phys. 12, 094 (2017).

- ALPs with mass in the MeV-GeV range could be mediators to Dark Sectors and also could impact $(g-2)_\mu$.

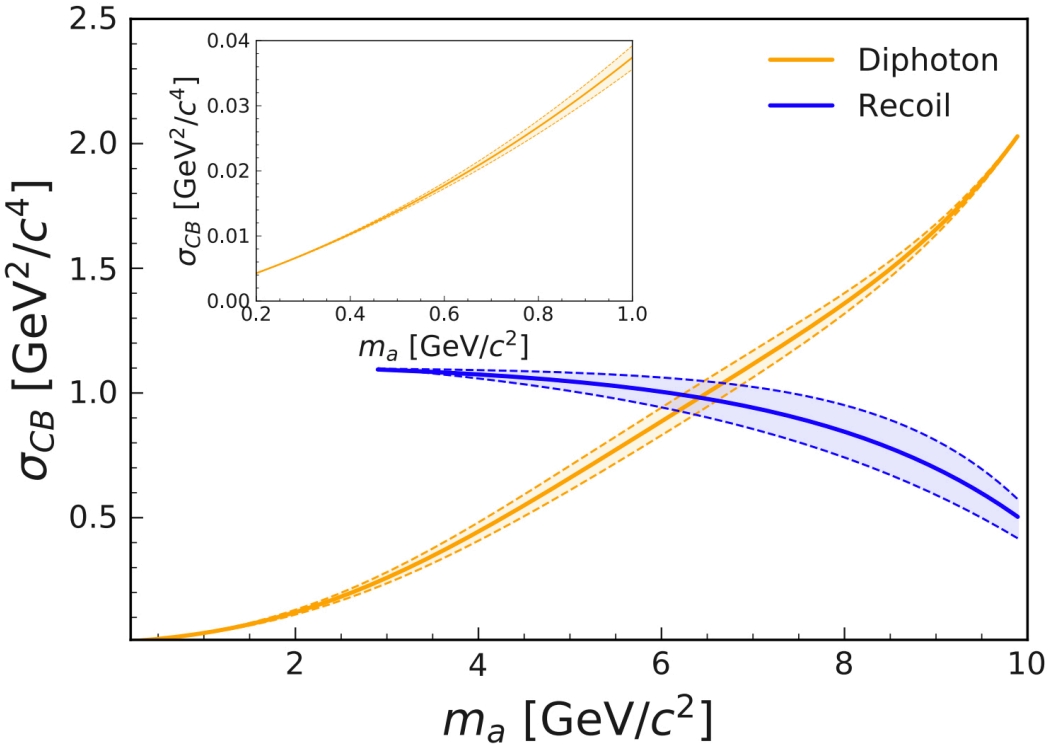
- Belle II search conducted using ALPstrahlung production channel:

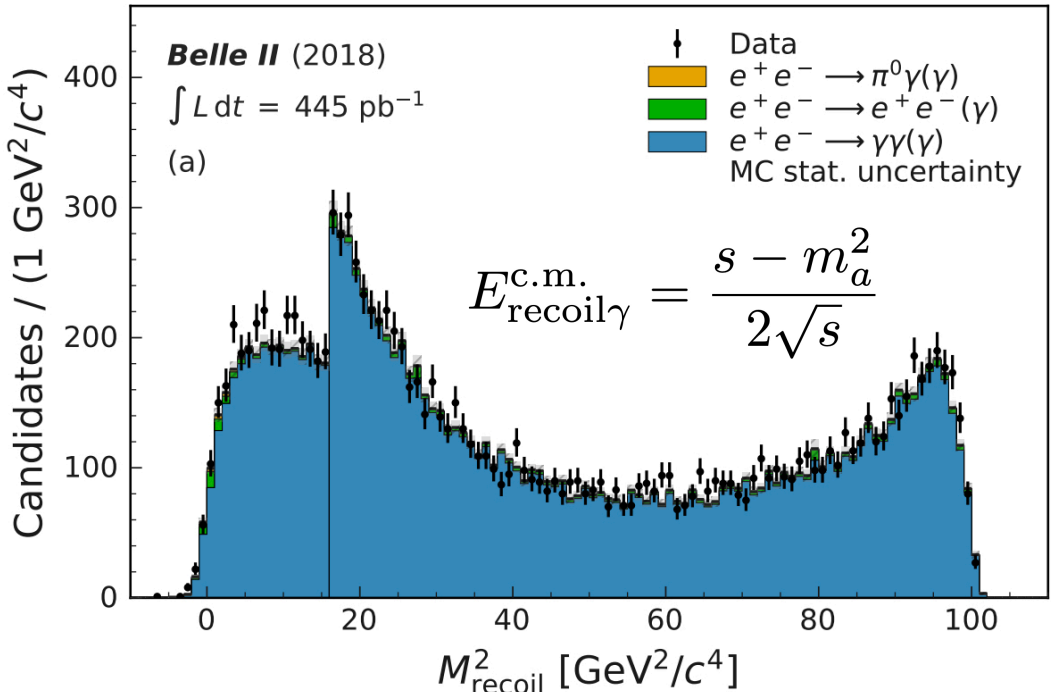


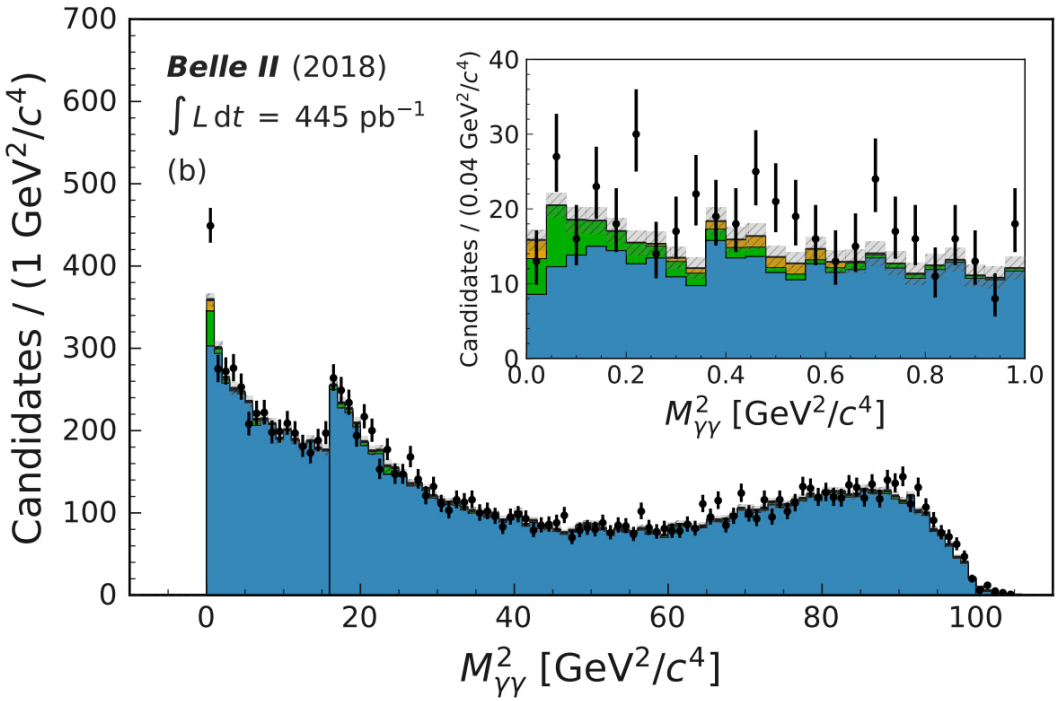
ALP Search

- Select fully neutral events consisting of 3 well-isolated photons with total invariant mass consistent with $\sqrt{s}$.

- Search strategy optimized to maximize ALP sensitivity.
  - ➡ High ALP mass: Search M_{recoil} spectrum.
  - ➡ Low ALP mass: Search $M_{\gamma\gamma}$ spectrum.



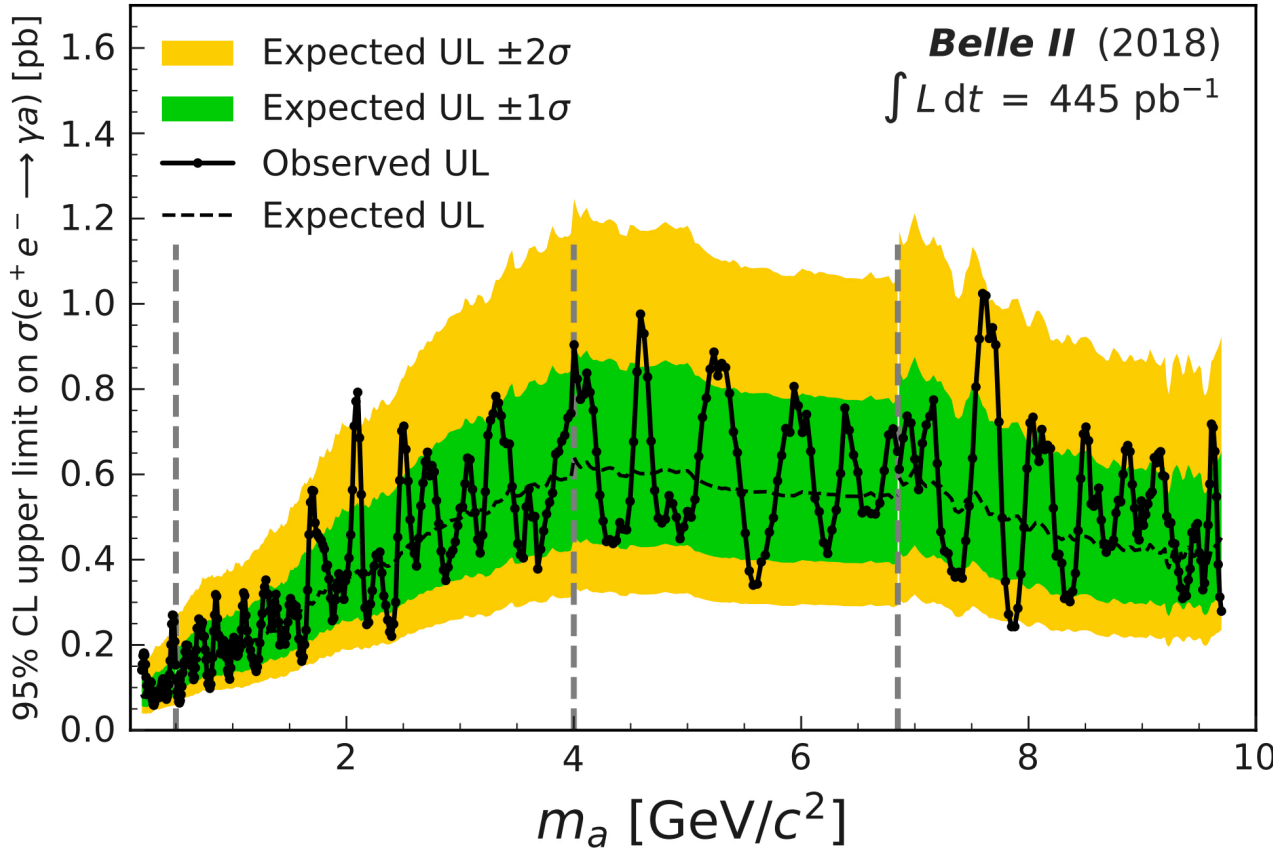


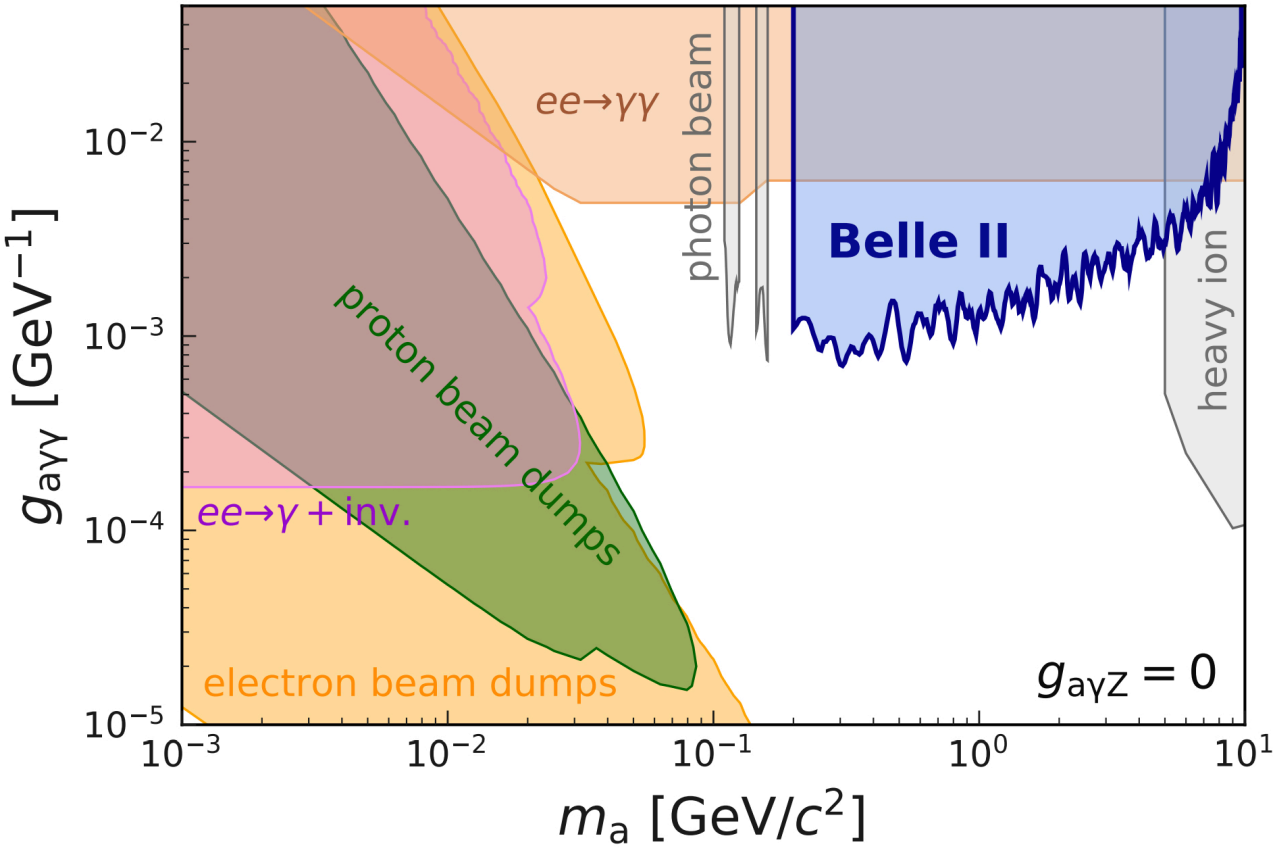


ALP Search Results

- Search conducted with 0.445 fb^{-1} of commissioning data.
- No excess observed, limits set on ALP coupling to photons.
- Submitted to PRL. Preprint: **arXiv: 2007.13071**

$$\sigma_a = \frac{g_{a\gamma\gamma}^2 \alpha_{\mathrm{QED}}}{24}\left(1 - \frac{m_a^2}{s}\right)^3$$

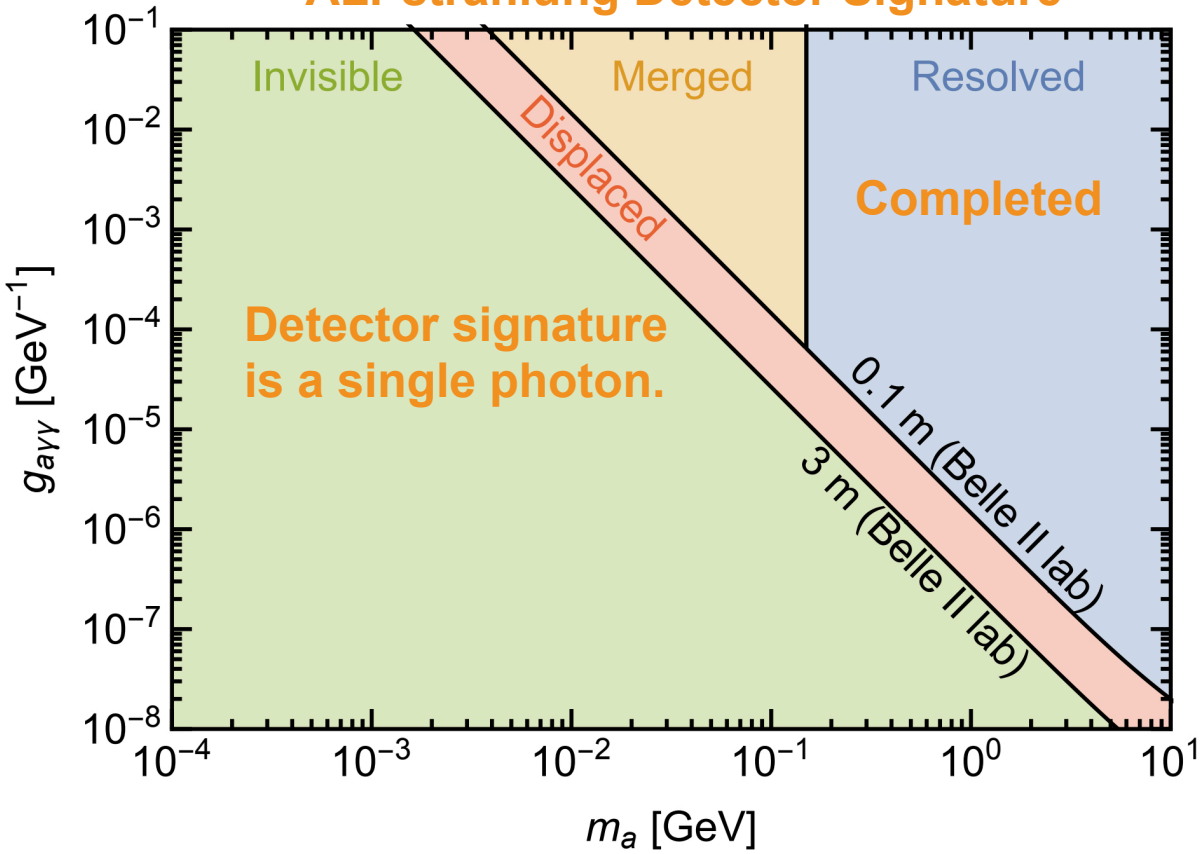




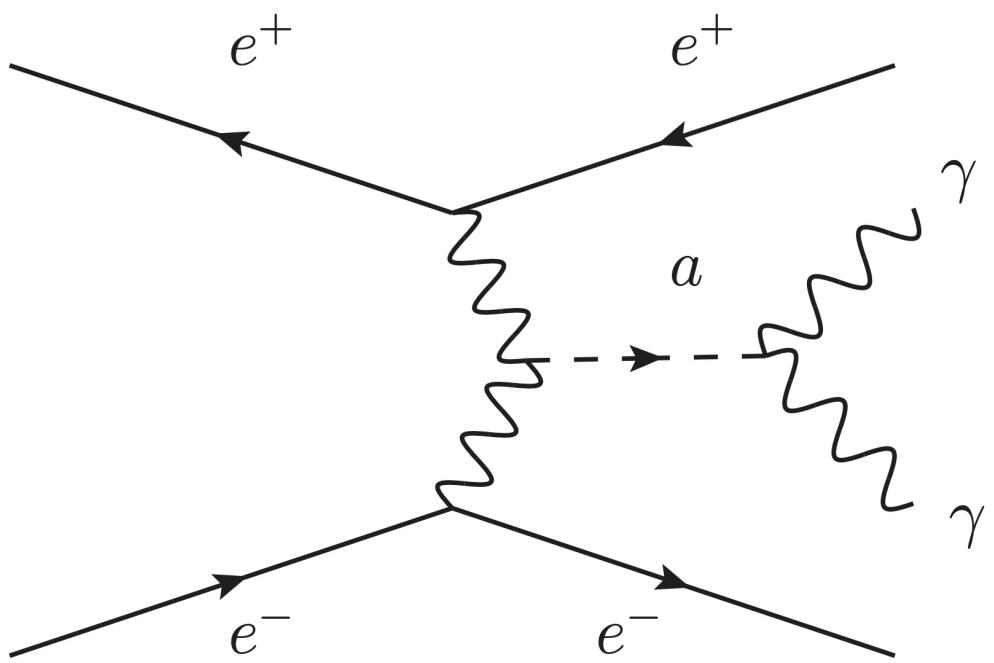
Extending ALP Searches at Belle II

- For ALP mass below ~0.2 GeV, ALPstrahlung channel limited. Photons from $a \to \gamma\gamma$ are merged in calorimeter.
- Photon fusion is an alternate production channel to search low mass region. Trigger is however challenging.
- At very low masses and small couplings ALP is long-lived, ALPstrahlung detector signature becomes single photon.

ALPstrahlung Detector Signature



Photon Fusion ALP production

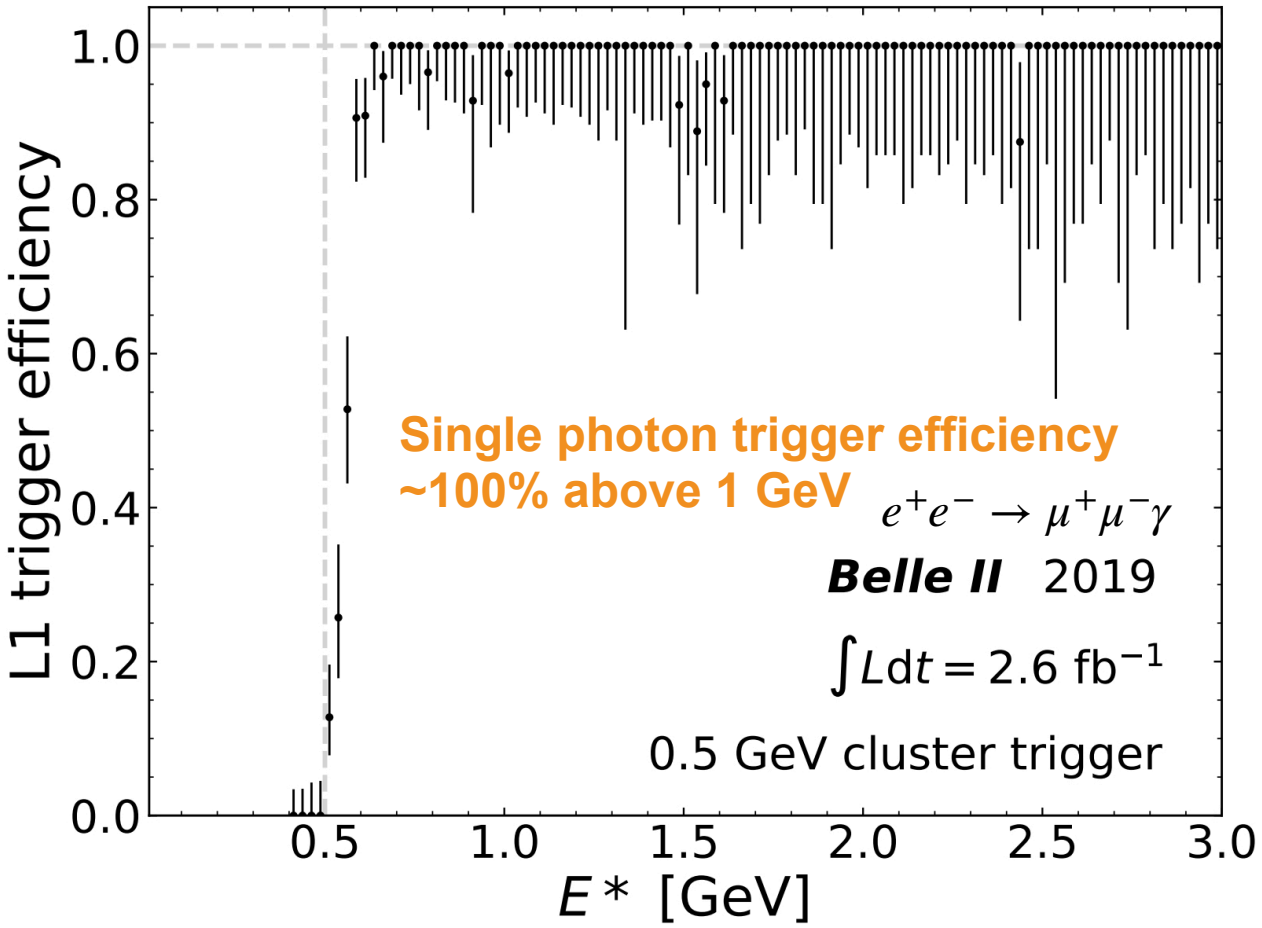


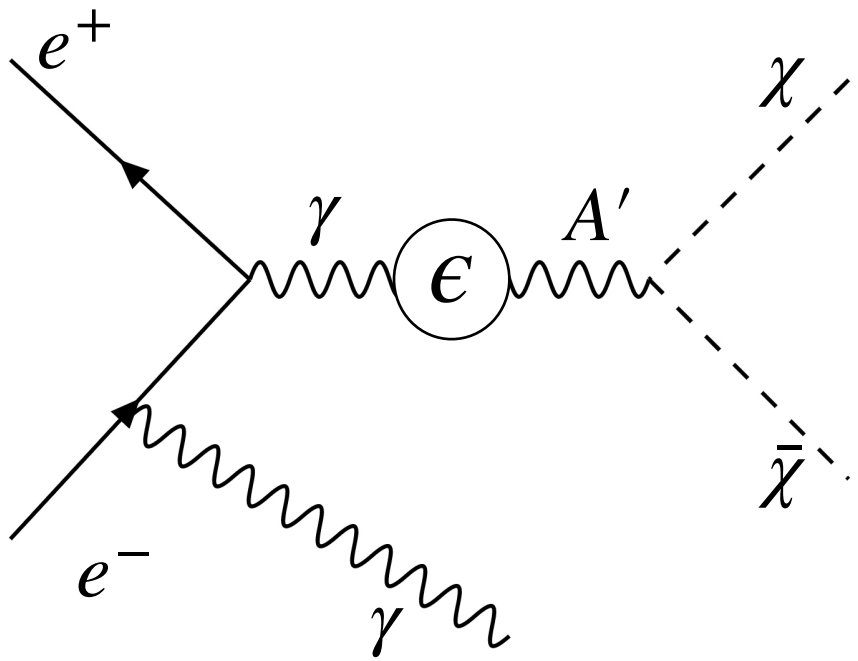
M. J. Dolan et al., J. High Energy Phys. 12, 094 (2017).

Single Photon Search

Single Photon Search

- Search for massive Dark Photon, A', which mixes with Standard Model photon.
- Detector signature is a single initial-state radiation photon.





- Single photon trigger is crucial:
  - ➡ Maintaining acceptable rate challenging due to beam-induced backgrounds

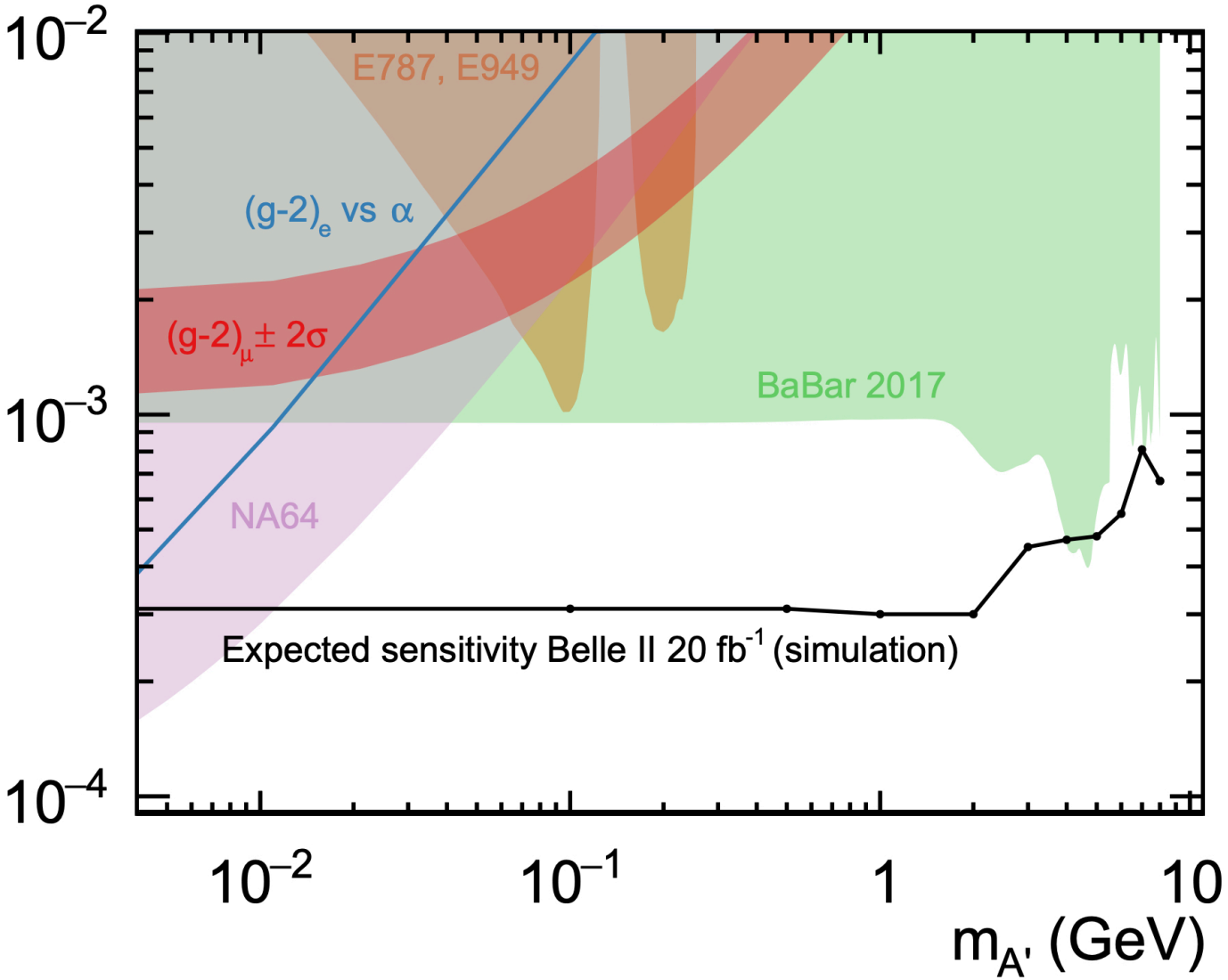
Projected Sensitivity

- BaBar published single photon search in 2017 using $53\ \text{fb}^{-1}$. J. P. Lees et al., Phys. Rev. Lett. 113, 201801 (2014).
- Main backgrounds:

$$e^+e^- \to \gamma\gamma(\gamma)$$

$$e^+e^- \to e^+e^-(\gamma)$$

- Calorimeter coverage critical to suppress backgrounds.
- Belle II calorimeter features configuration where crystal gaps are offset from IP. Photons cannot escape between crystal boundaries.
  - ➡ Significant improvement in background rejection. Belle II very competitive, even with smaller dataset.



E. Kou et al. PTEP 2019 (2019) 123C01

Conclusions

- Intensity frontier B-Factories are a unique setting to search for direct production of MeV-GeV scale Dark Matter and Dark Sector mediators.
- Belle II has completed searches for Z' and axion-like particles using < 0.5 fb^{-1}.

  Z' and LFV Z': **I. Adachi et al. (Belle II Collaboration) Phys. Rev. Lett. 124, 141801 (2020)**

  ALPs Search: Accepted in PRL, preprint: **arXiv: 2007.13071**
- Single photon search is in progress. L1 trigger efficiency measured to be ~100% above 1 GeV.
- Total dataset is now 74 fb^{-1} and counting, many exciting updates ahead!

Thanks!

Extra Slides

$e^+e^- \to \tau^+\tau^-(\gamma)$ Suppression in Z' Search

- Missing energy in signal arises from Z' radiation off a final state muon.
- In background missing energy arises from both tracks due to neutrinos in tau decays.
- This difference allows the lepton kinematics to be used to suppress backgrounds from $e^+e^- \to \tau^+\tau^-(\gamma)$.