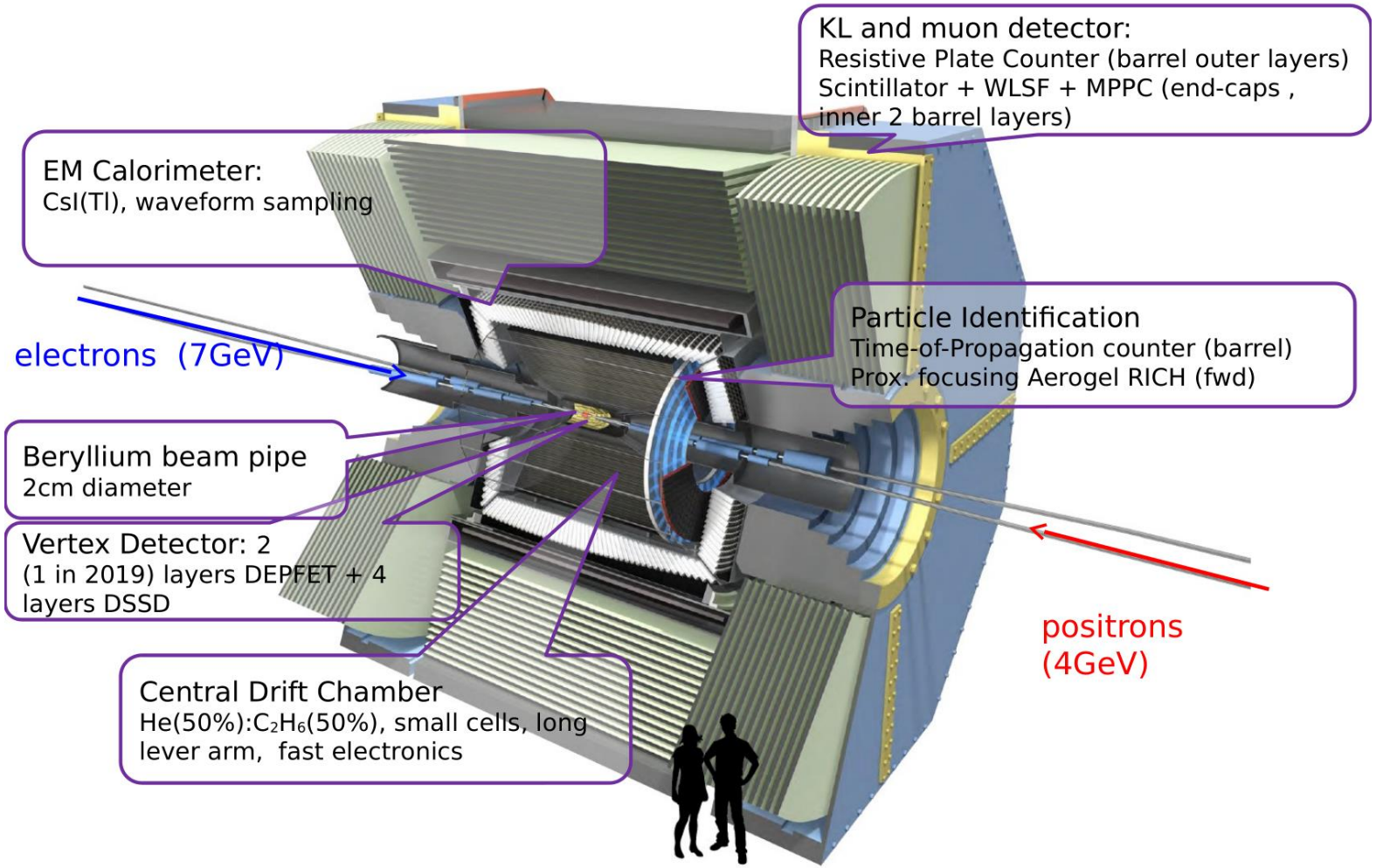
Dark sector study at Belle II

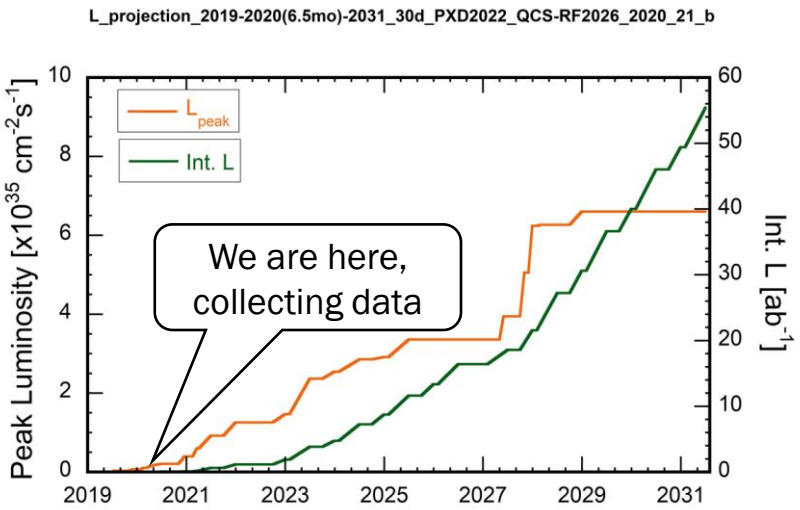
Seokhee Park
KEK IPNS
2020-04-23
(recorded: 2020-04-12)

Belle II experiment



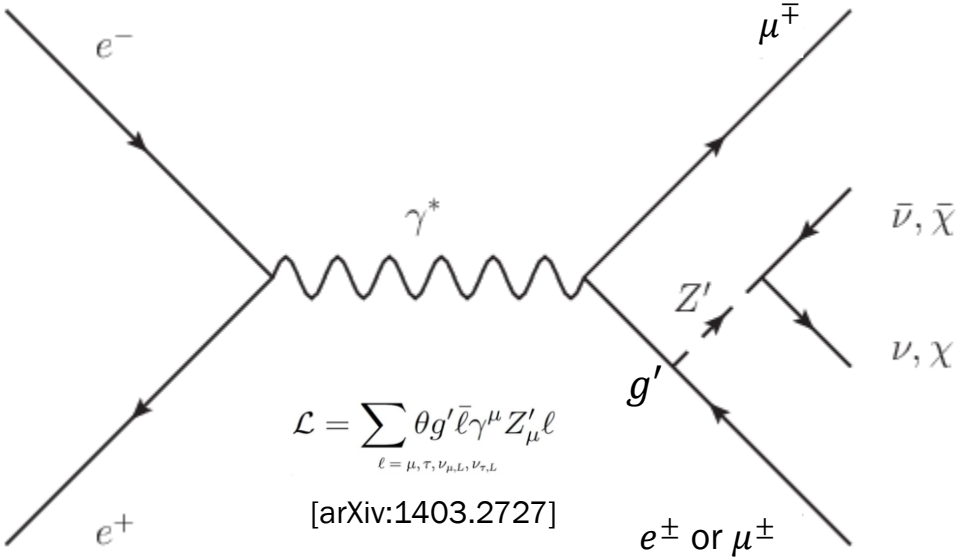
Compare to Belle

- Better detector performance
- Enhanced trigger menu including low multiplicity
  - e.g. Single photon trigger
- Higher luminosity
  - Finally, will be 50 times of Belle



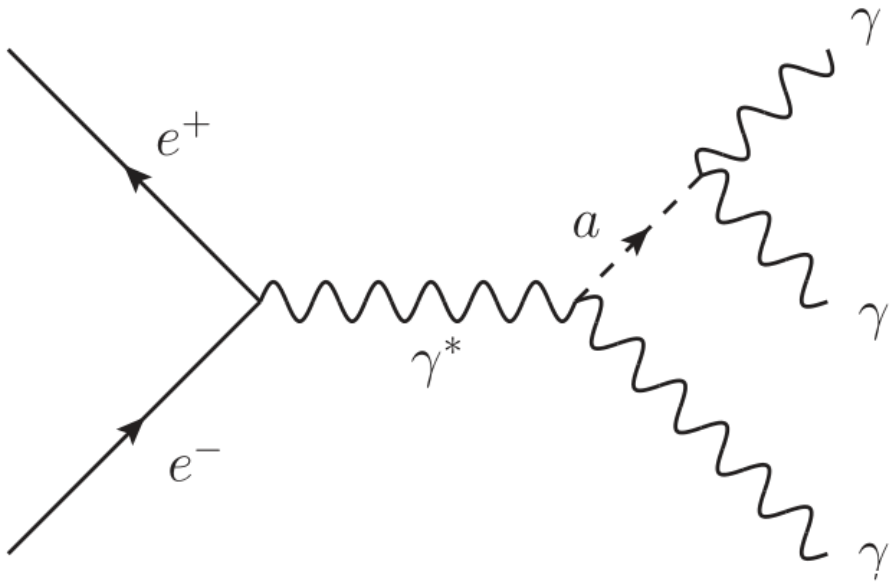
Dark sector study

- Two Belle II physics papers have been published on PRL
  - All of them are related “dark sector”
- Invisible Z' search: PRL 124 (2020) 141801
- Axion-like particle search: PRL 125 (2020) 161806

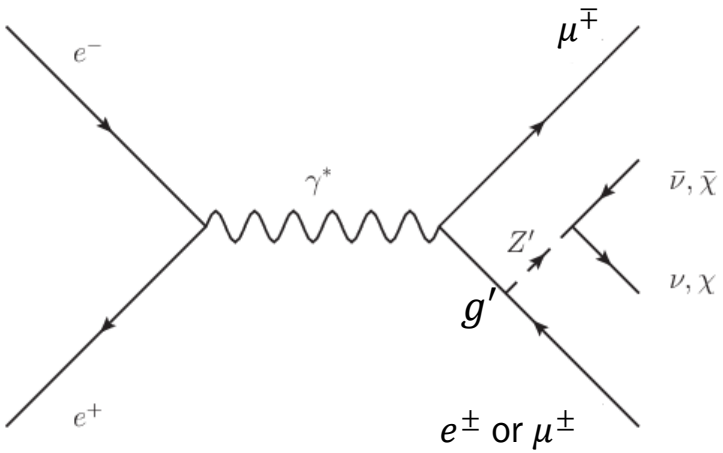


$$\mathcal{L} = \sum_{\ell=\mu,\tau,\nu_{\mu,L},\nu_{\tau,L}} \theta g' \bar{\ell} \gamma^\mu Z'_\mu \ell$$

[arXiv:1403.2727]



Invisible Z' search



- The Z' might be a solution of
  - $R_{K^{(*)}}$ anomaly, LHCb finds 3.1σ deviation
  - $(g-2)_\mu$ anomaly, Fermilab finds 4.2σ deviation
- Two scenarios: $ee \to \mu\mu Z'$ and $ee \to e\mu Z'$ (LFV Z')
- In the analysis, our Z' can decay into invisibles
  - Branching fractions varies with 33% - 100%, depending on the Z' mass
    - In case of $L_\mu - L_\tau$: $$BF(Z' \to \text{invisible}) = \frac{2\Gamma(Z' \to \nu_l \bar{\nu}_l)}{2\Gamma(Z' \to \nu_l \bar{\nu}_l) + \Gamma(Z' \to \mu^+\mu^-) + \Gamma(Z' \to \tau^+\tau^-)}$$
      - $M_{Z'} < 2M_\mu$: $BF = 1$
      - $2M_\mu < M_{Z'} < 2M_\tau$: $BF \simeq 0.5$
      - $M_{Z'} > 2M_\tau$: $BF \simeq 0.33$
  - Or assume $BF(Z' \to \chi_{DM}\bar{\chi}_{DM}) \simeq 1$, much strong coupling to the DM

Event signature

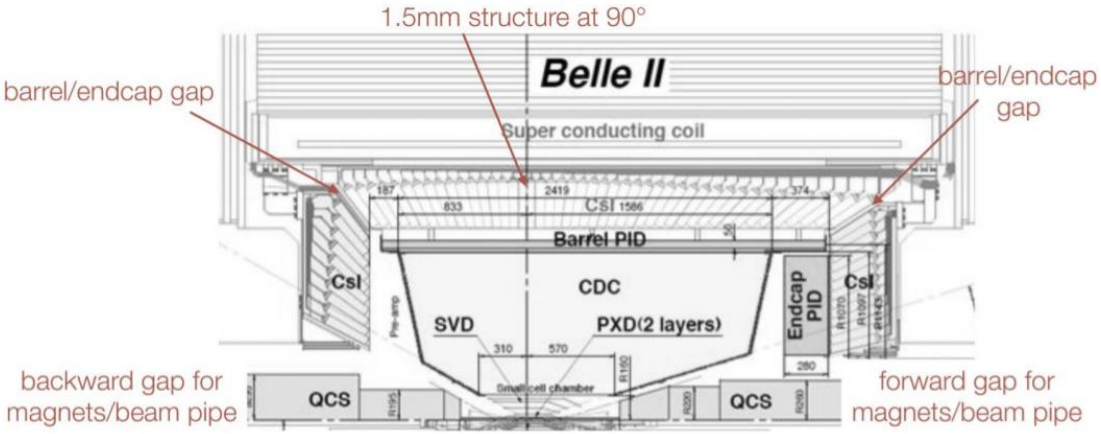
- Events only with exactly two opposite charged tracks ($\mu\mu$ or $e\mu$)
- Minimal activity of ECL → no extra photon
- Missing energy
- Find peak in from the recoil mass of $\mu\mu$ and $e\mu$
  - $M_{rec}^2 = s + M_{\mu\mu,e\mu}^2 - 2\sqrt{s}E_{\mu\mu,e\mu}^*$
  - Recoil mass window: $\pm 2\sigma$ peak of the signal MC
    - $1150\ \mathrm{MeV}$ at $M_{Z'} = 0.5\ \mathrm{GeV}$, $51\ \mathrm{MeV}$ at $M_{Z'} = 6.9\ \mathrm{GeV}$
- The SM backgrounds
  - $e^+e^- \to \mu^+\mu^-(\gamma)$: photon was not reconstructed
  - $e^+e^- \to e^+e^-\mu^+\mu^-$: e^+e^- out of acceptance
  - $e^+e^- \to \tau^+\tau^-(\gamma)$: neutrinos cannot be detected

} Almost no contribution for LFV Z'

Background suppression

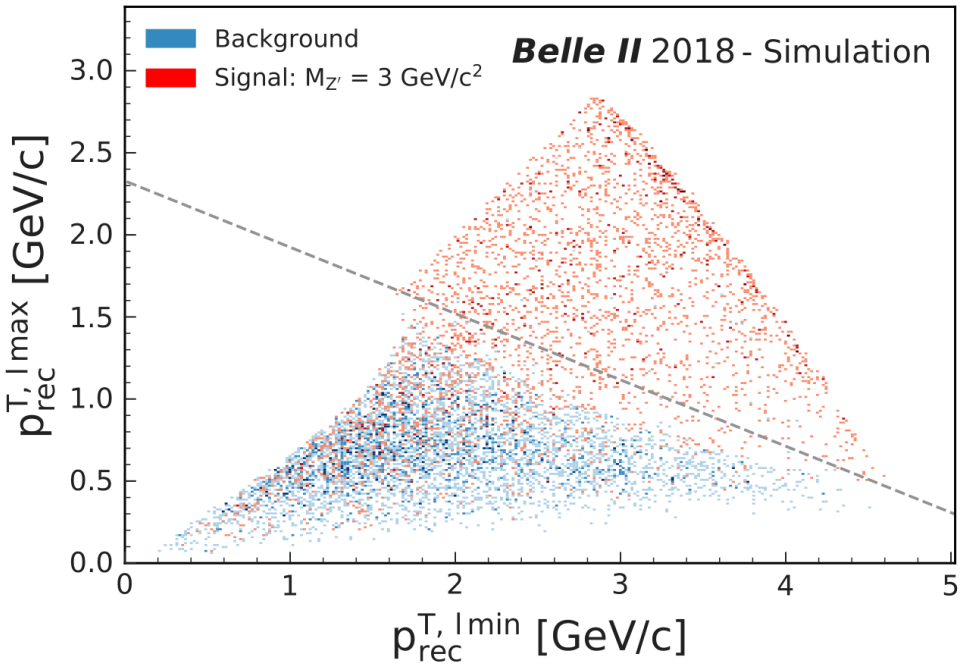
- CDC two-track trigger (including azimuthal opening angle $> 90°$
  - with Bhabha scattering rejection
- Recoil momentum direction: ECL barrel
- ECL based PID (NO KLM at the time)
  - $\mu^{\pm}$: $0.15 < E < 0.4\ \mathrm{GeV}, E/p < 0.4$
  - $e^{\pm}$: $E > 1.5\ \mathrm{GeV}, 0.8 < E/p < 1.2$

  $*$ E: measured by ECL, p: measured by CDC
- No photon around recoil direction
- Total photon energy $< 0.4\ \mathrm{GeV}$
- No π^0 candidates (reconstructed by two photons)



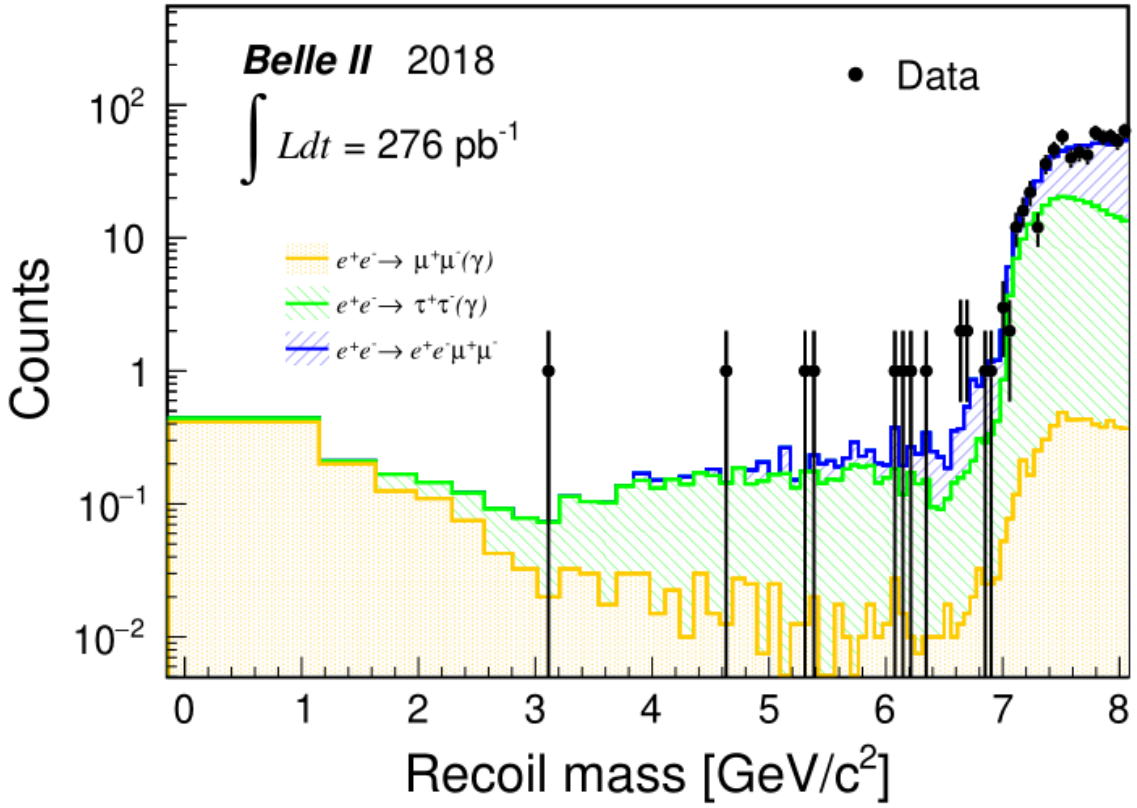
$e^+e^- \to \tau^+\tau^-(\gamma)$ suppression

- After previous selection criteria, $\tau\tau$ background is the dominant one.
- To suppress $\tau\tau$ background, transverse momentums are used
  - $p_{rec}^{T,lmax}$: p^T of recoil momentum in the direction of high momentum lepton
  - $p_{rec}^{T,lmin}$: p^T of recoil momentum in the direction of low momentum lepton
  - $p_{\ell^+\ell^-}^{T}$: p^T of lepton pair
- First, make a linear cut in the plane of $p_{rec}^{T,lmax} - p_{rec}^{T,lmin}$
  - No optimal cut found over 7 GeV $M_{Z'}$
- Simultaneously, $p_{\ell^+\ell^-}^{T} > p_{cut}^{T}$
  - Also, effective to reduce remaining $\mu^+\mu^-$ and $e^+e^-\mu^+\mu^-$ backgrounds.

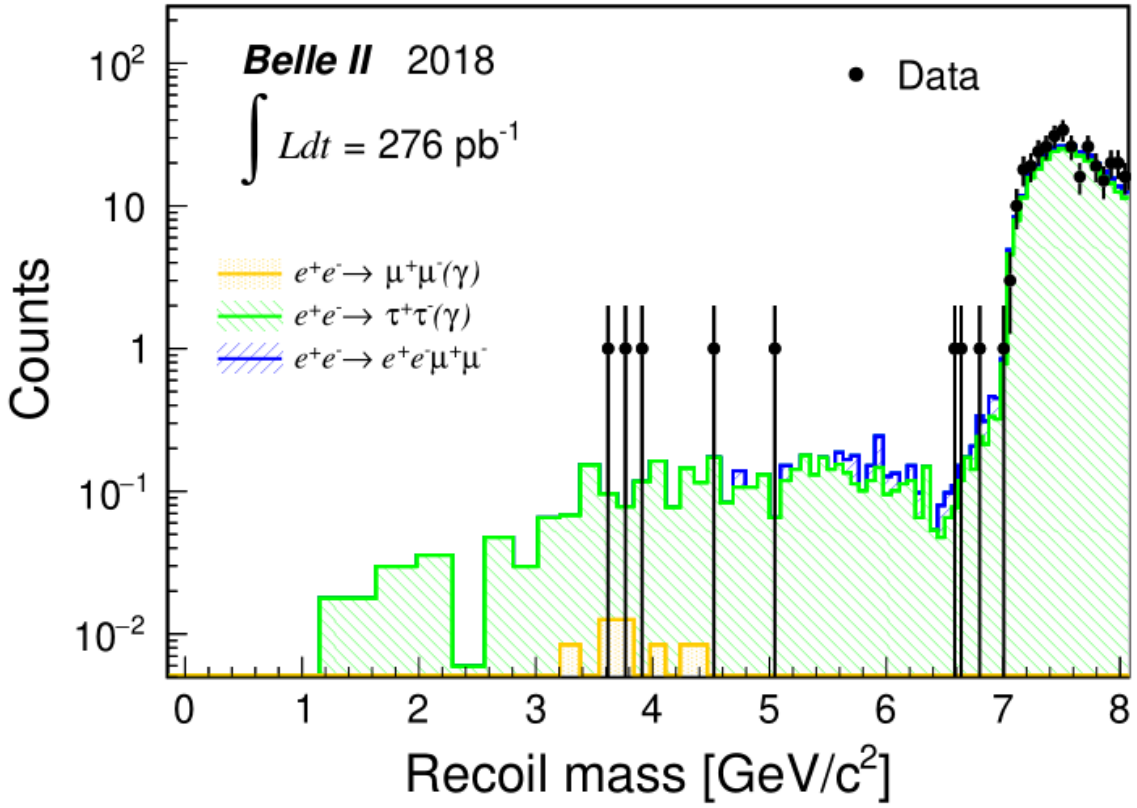


Results

- Recoil mass spectrums



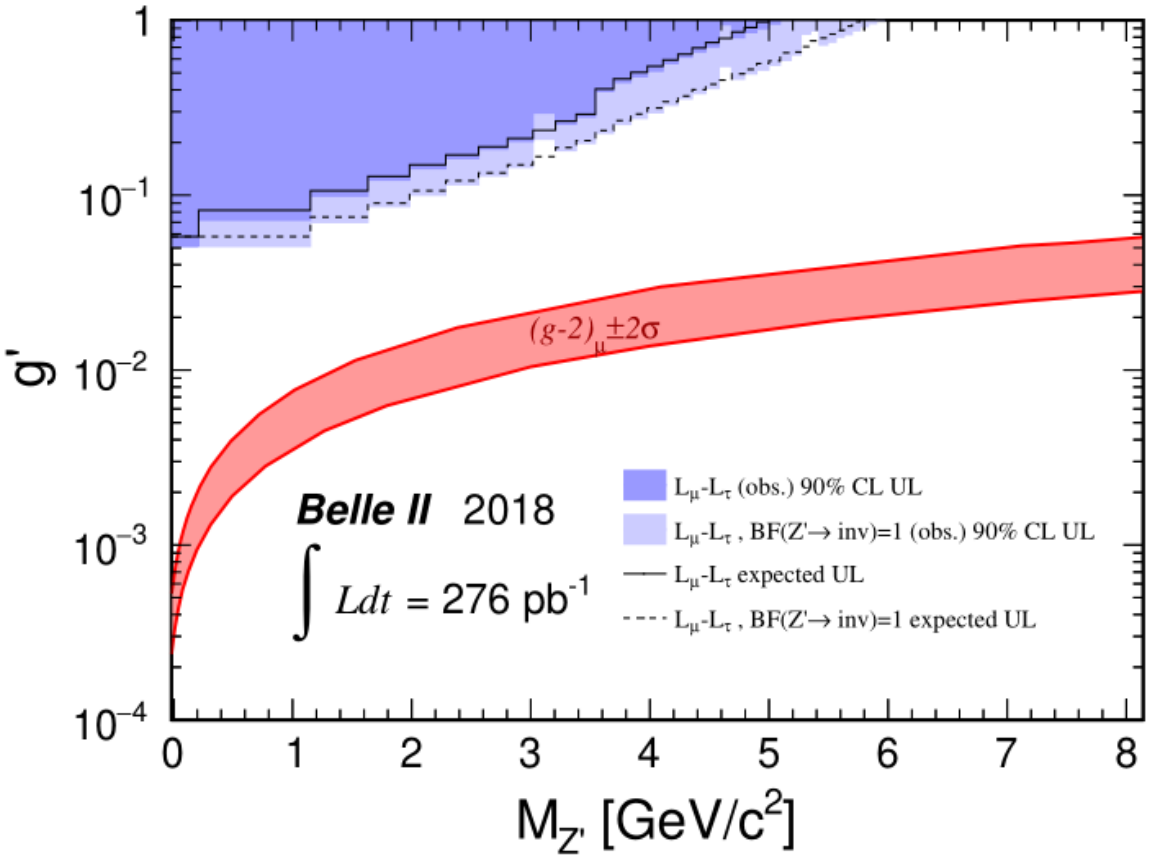
$ee \to \mu\mu Z'$



$ee \to e\mu Z'$

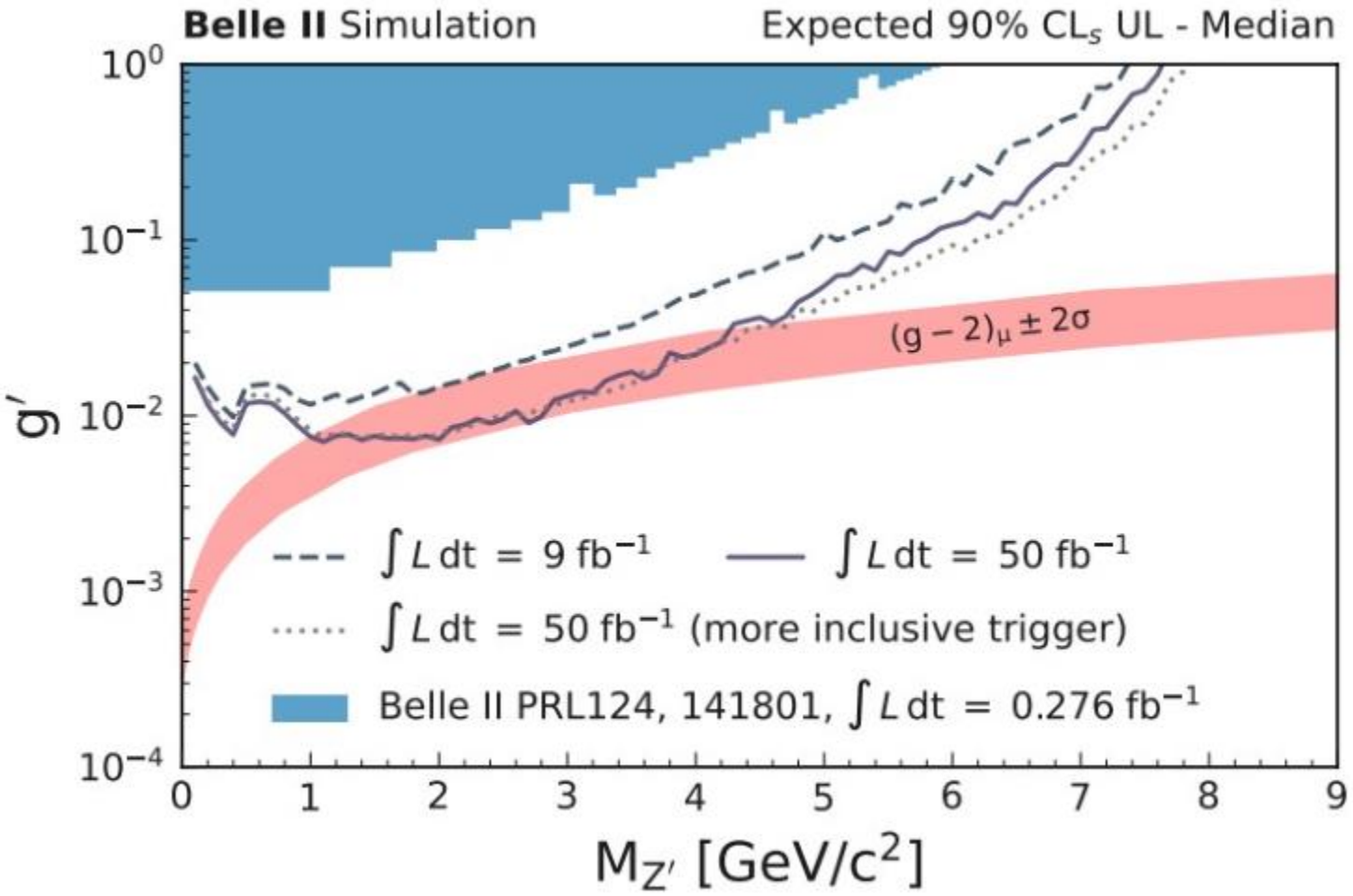
Results

- g' upper limit with 90% confidence level



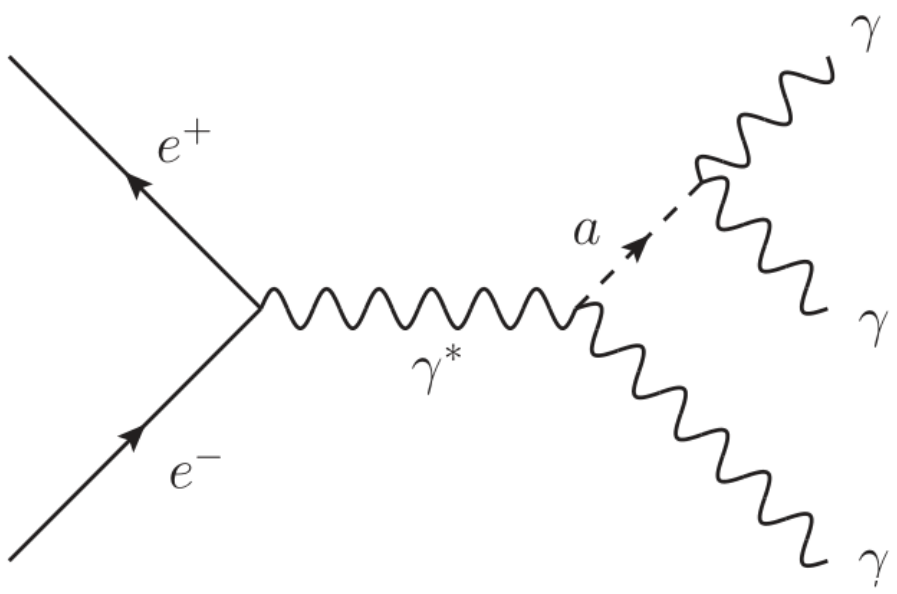
Short term projection

- With more collected data, KLM based μID, new triggers, …

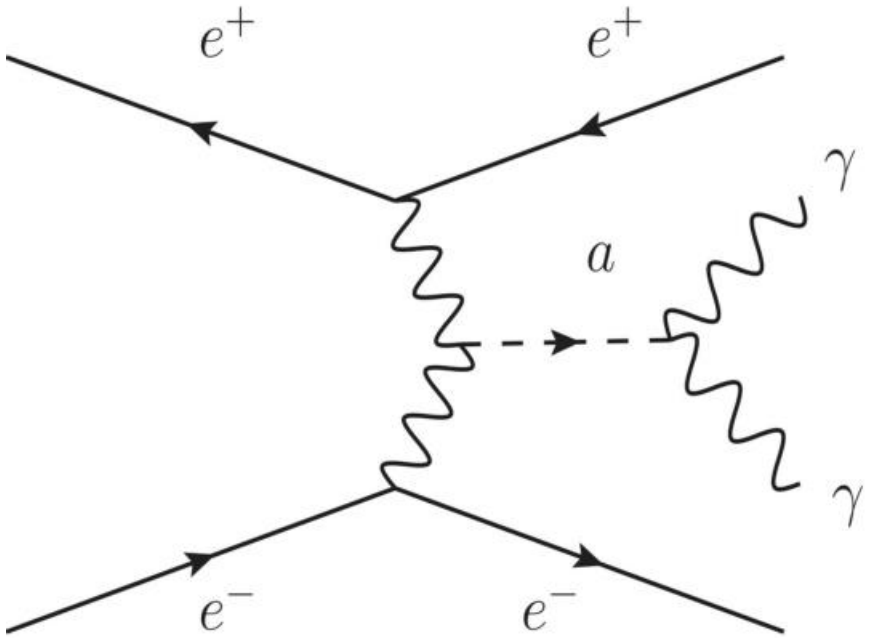


Axion-like particle study

- In this talk, be focused on $g_{a\gamma\gamma}$ coupling



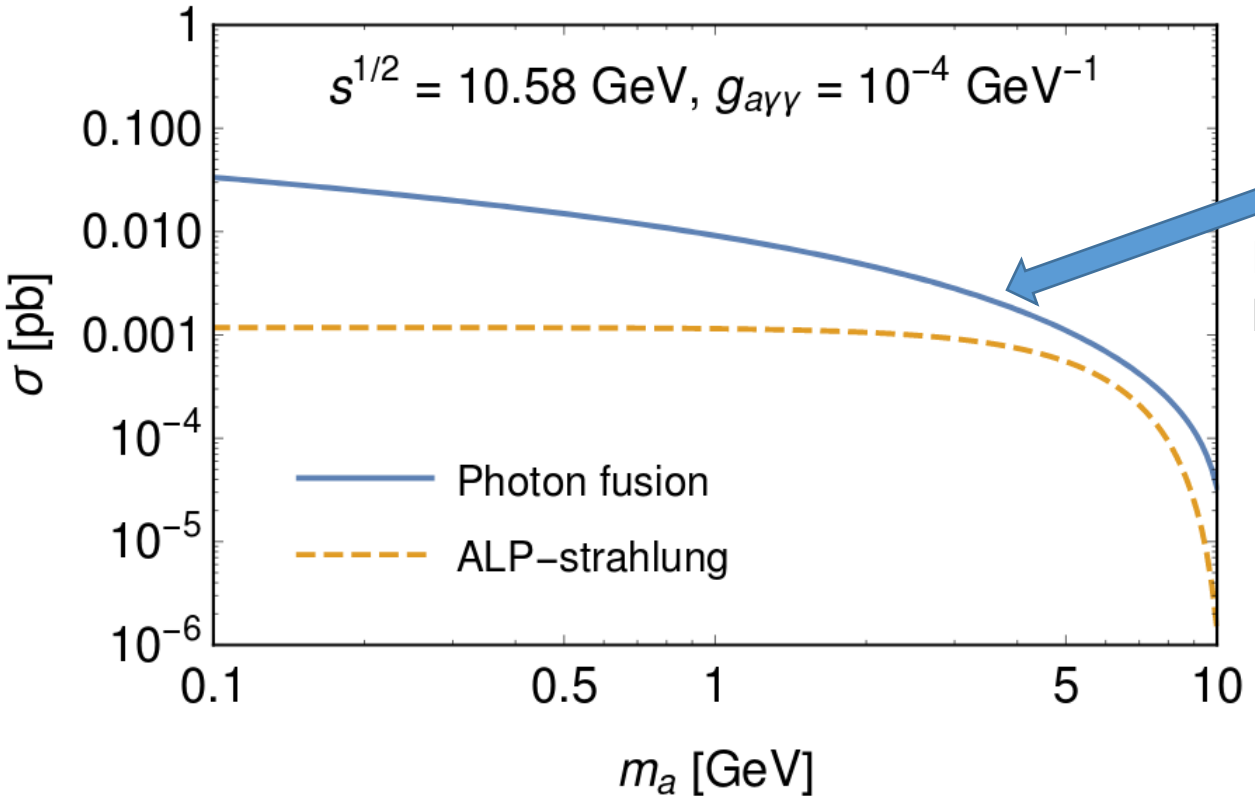
ALP-strahlung



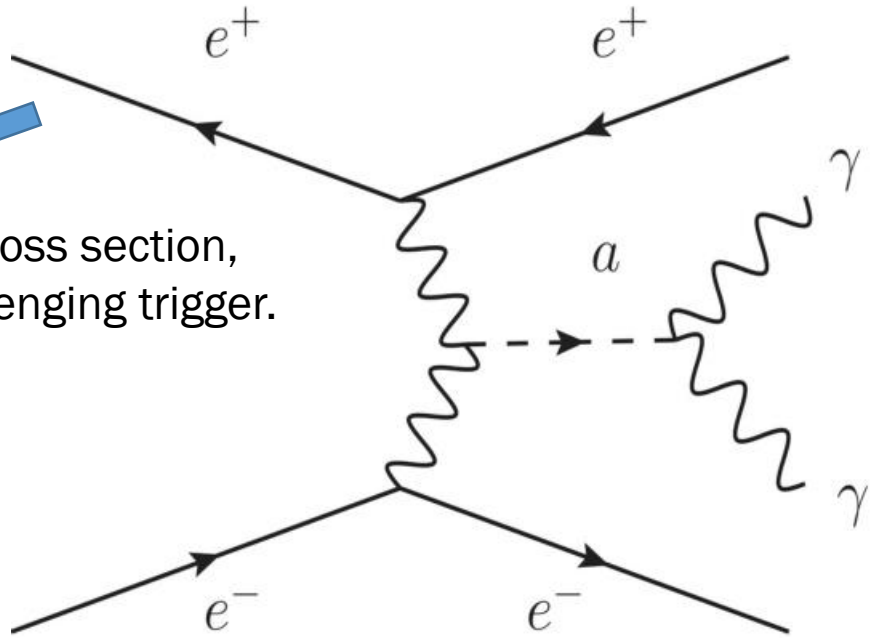
Photon fusion

Axion-like particle study

- In this talk, be focused on $g_{a\gamma\gamma}$ coupling



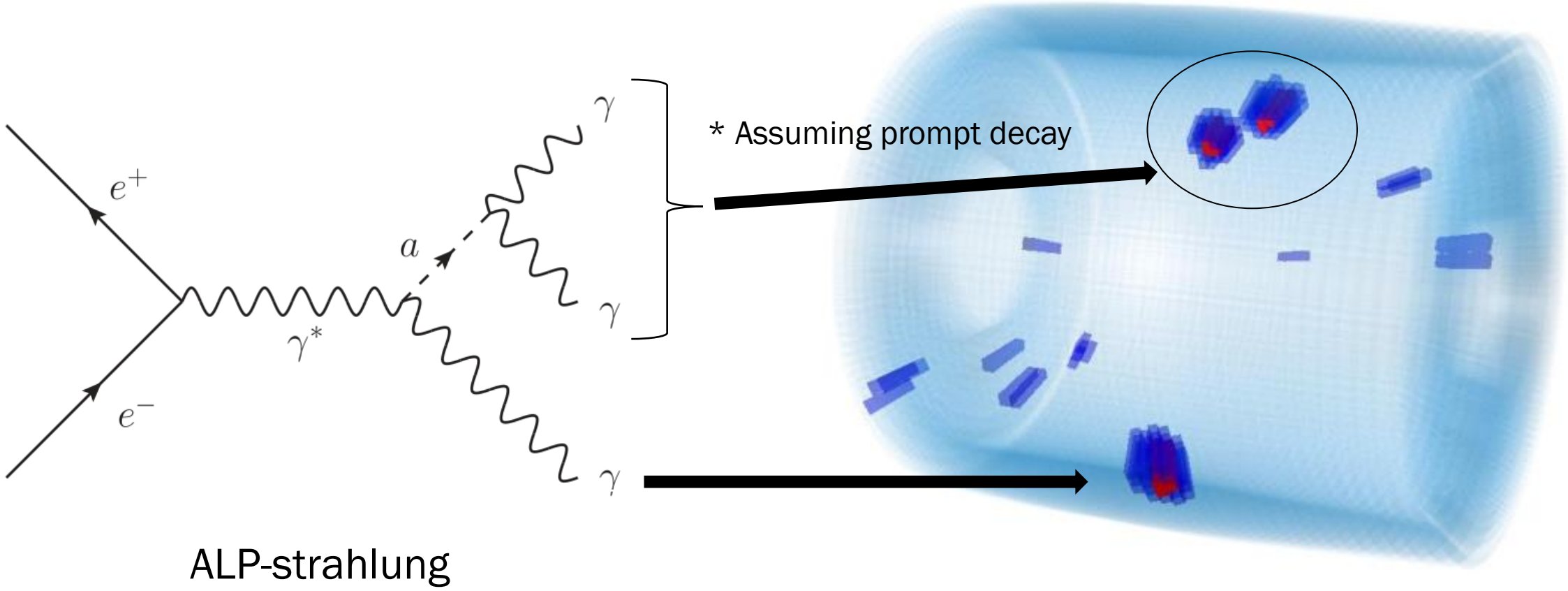
Higher cross section,
but challenging trigger.



Photon fusion

Axion-like particle study

- In this talk, be focused on $g_{a\gamma\gamma}$ coupling

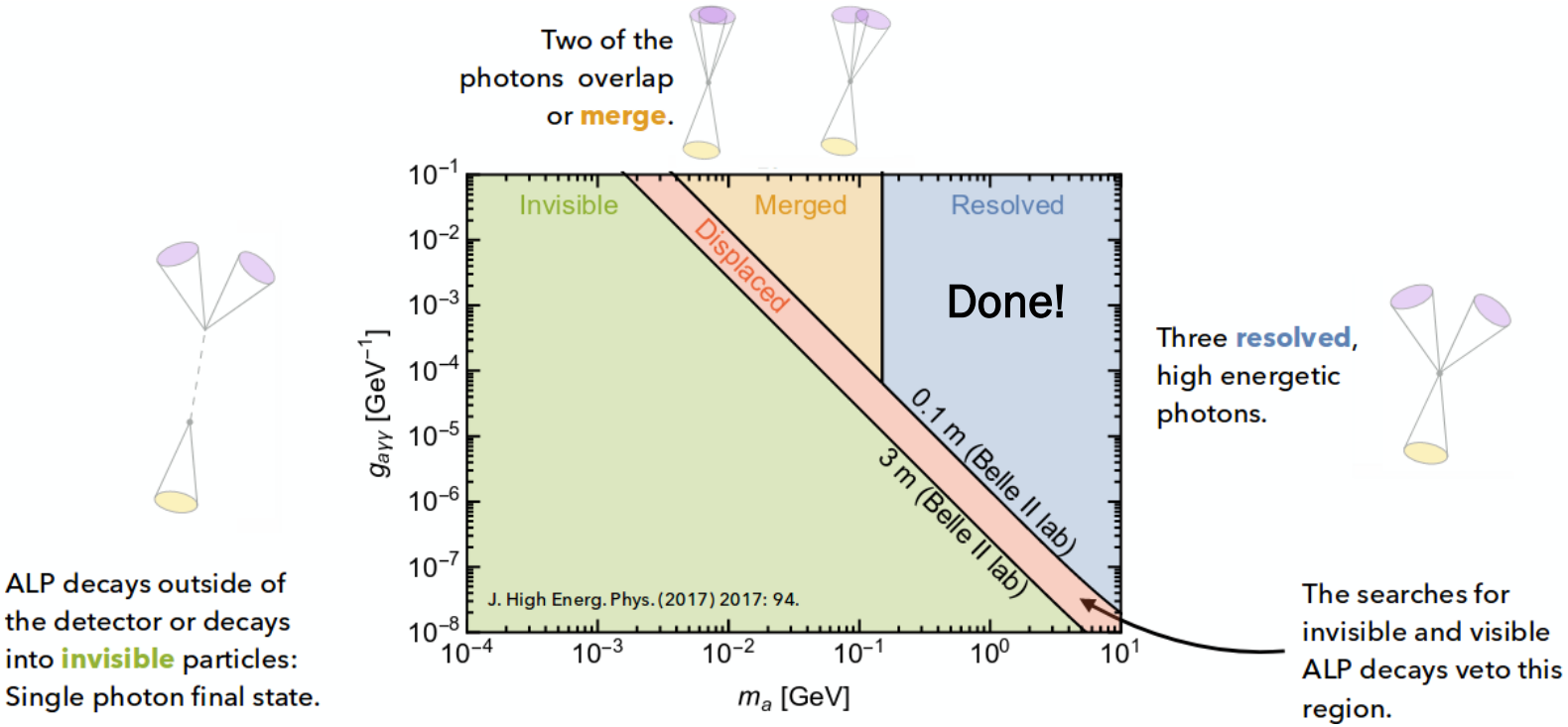


ALP-strahlung

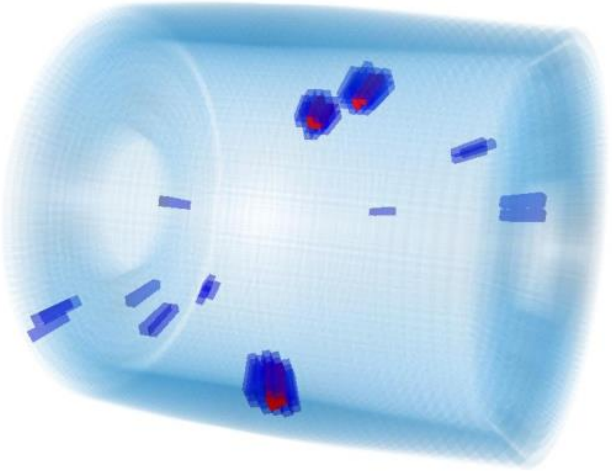
Event signature

- Three photons (Resolved): high m_a
- Two photons (Merged): $m_a < 200$ MeV
- Single photon (invisible)

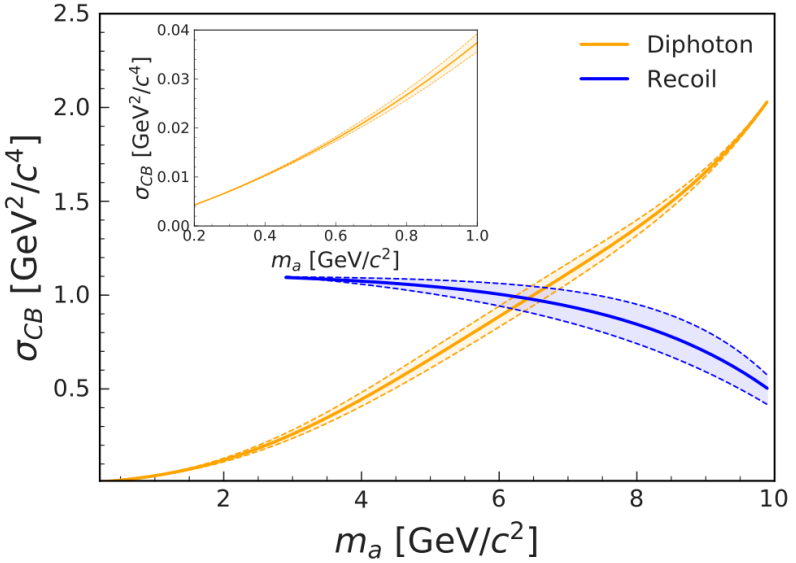
• Three photons (Resolved): high m_a
• Two photons (Merged): $m_a < 200$ MeV
• Single photon (invisible)



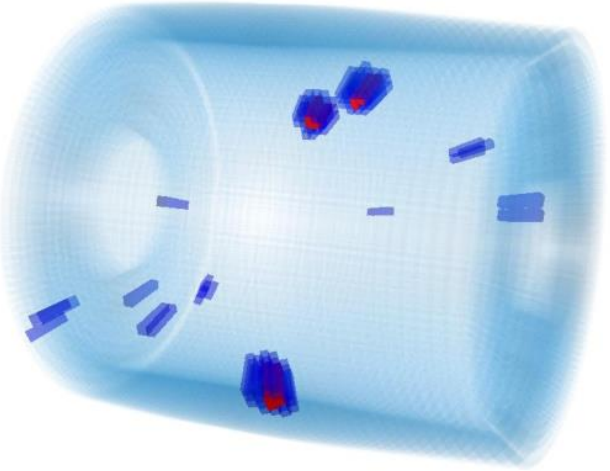
Event signature



- Monoenergetic photon against the $a \to \gamma\gamma$
- Three most energetic photons are accepted in barrel ECL
- No good charged track
- Find peak in from the $M^2_{\gamma\gamma}$ or M^2_{rec} of the rest photon
  - $M^2_{rec} = s - 2\sqrt{s}E^*_{rec}$ where $E^*_{rec} = \frac{s-m_a^2}{2\sqrt{s}}$
  - Choose a more sensitive variable
  - $M^2_{\gamma\gamma}: 0.2 < m_a < 6.85$ GeV, $M^2_{rec}: 6.85 < m_a < 9.7$ GeV
- Dominant backgrounds
  - $\gamma\gamma(\gamma)$: The most dominant
  - $e^+e^-(\gamma)$: Second dominant



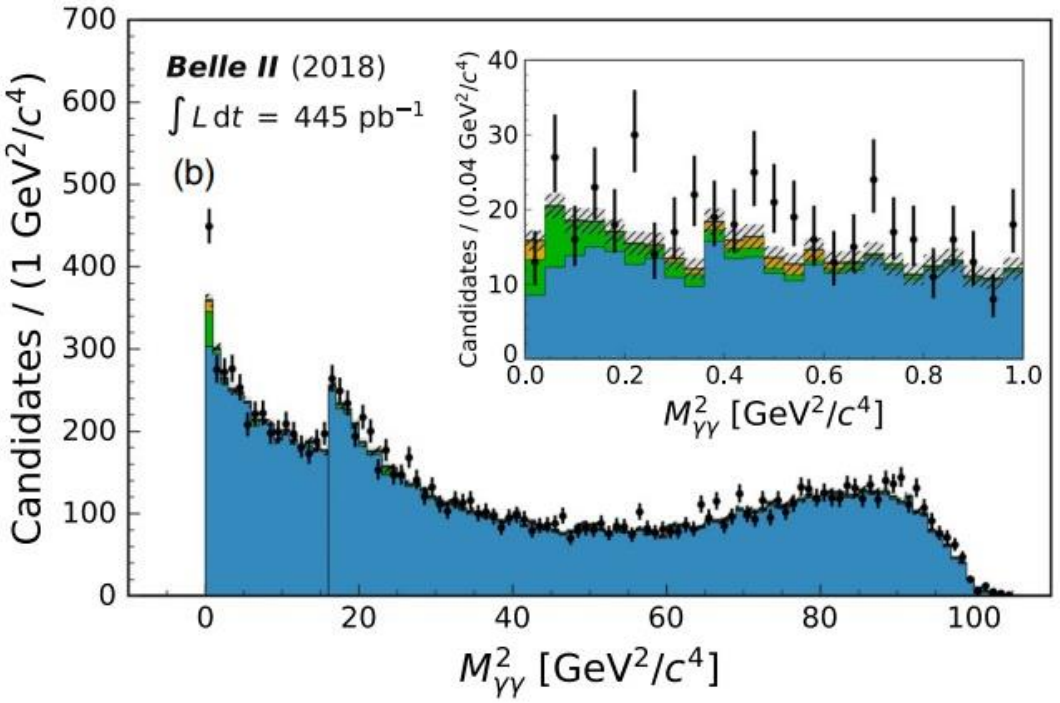
Background suppression

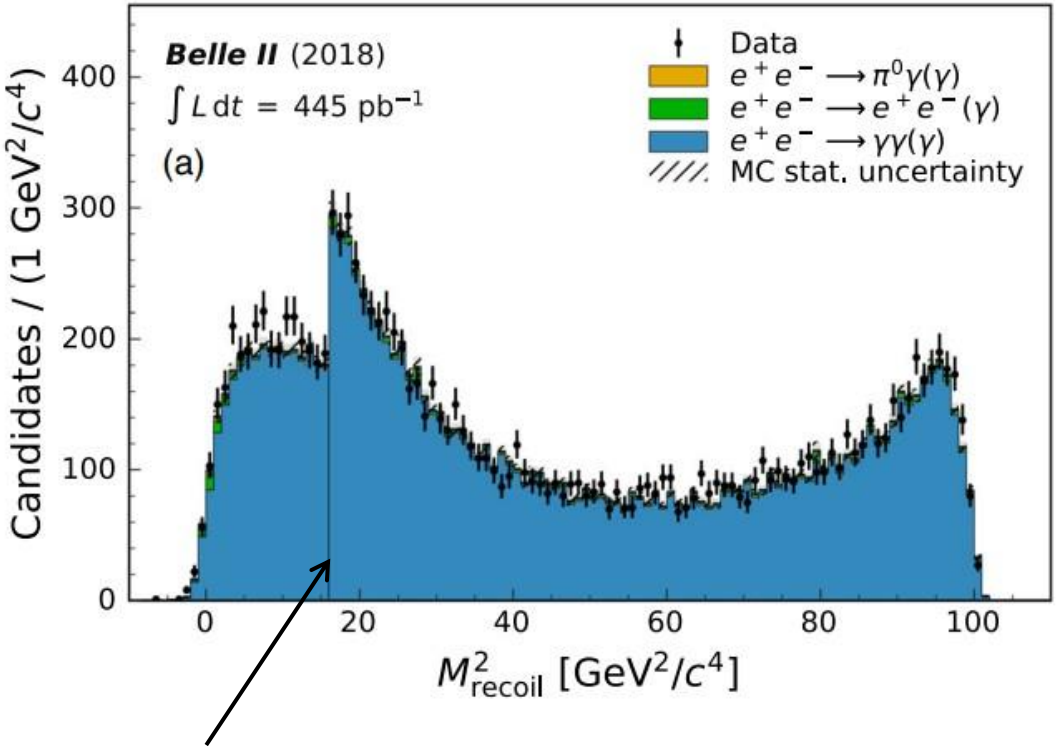


- All photons with $E_\gamma^* > 0.65\ \mathrm{GeV} (m_a > 4\ \mathrm{GeV})$
  or $E_\gamma^* > 1.00\ \mathrm{GeV} (m_a < 4\ \mathrm{GeV})$
- Photon detection time to reduce beam backgrounds
- $0.88\sqrt{s} < M_{\gamma\gamma\gamma} < 1.03\sqrt{s}$ to reduce cosmic rays, two photon processes, etc.
- Separation angle between two photons to reduce photon conversion
  - Both polar and azimuthal angles
- Multivariate Zernike moments of shower shapes to reduce neutral hadrons and particles which is not originated from the interaction point

Results

- M^2 spectrums

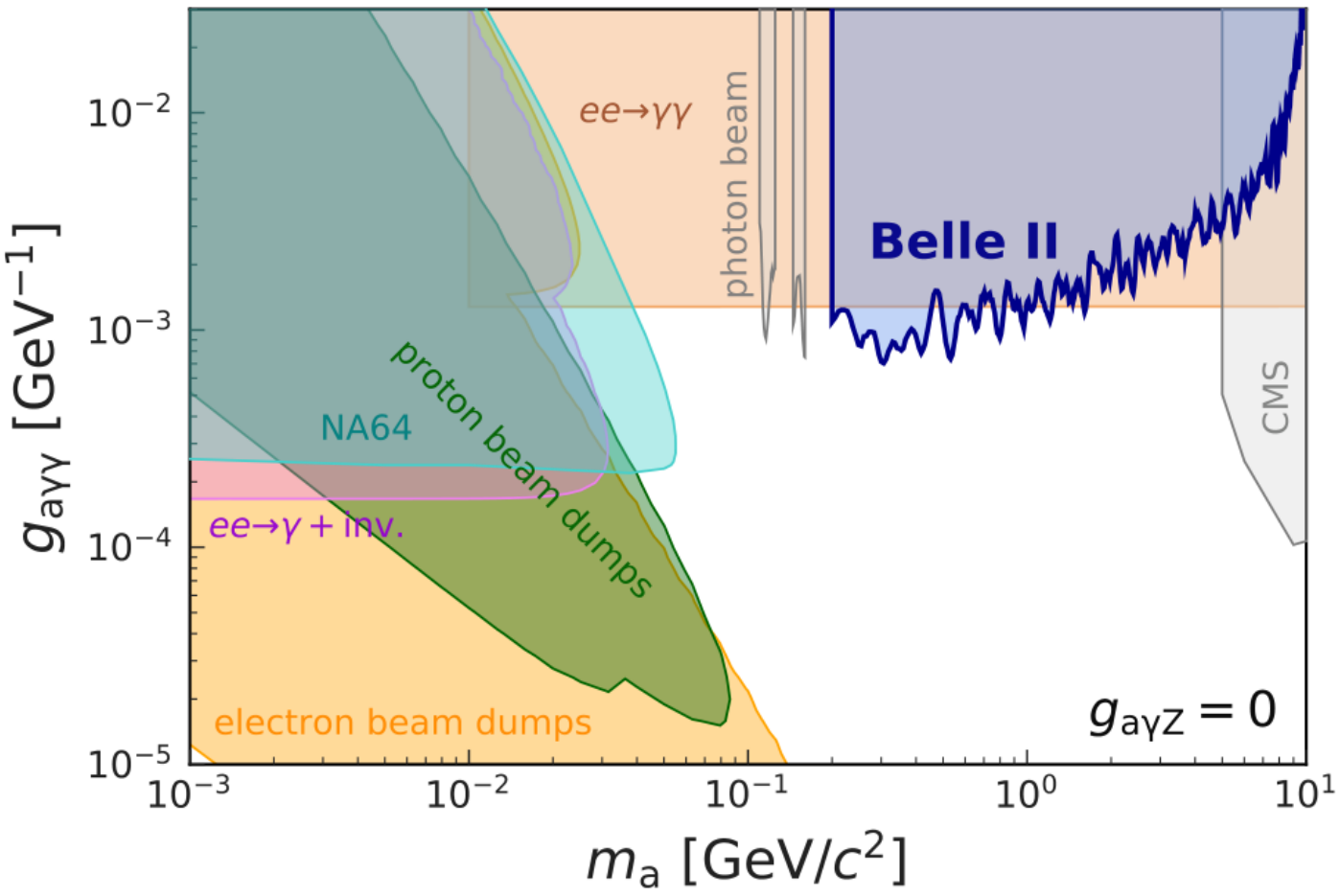




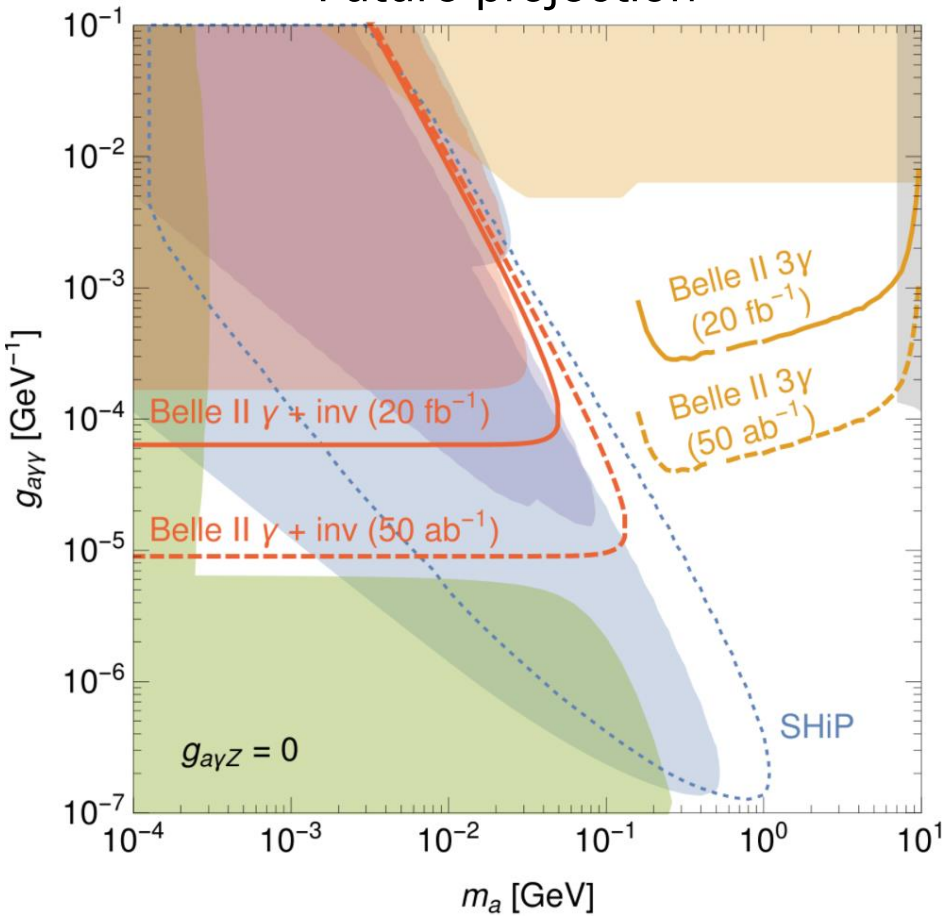
* Due to photon selection change

Results

- $g_{a\gamma\gamma}$ upper limit with 95% confidence level

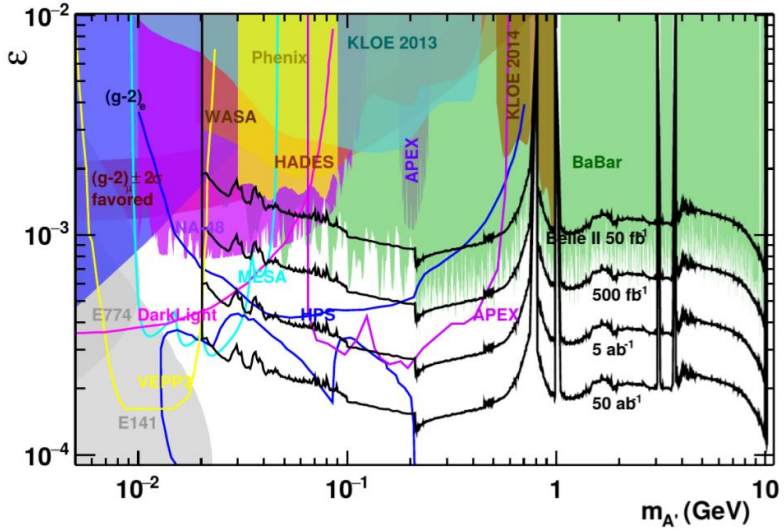


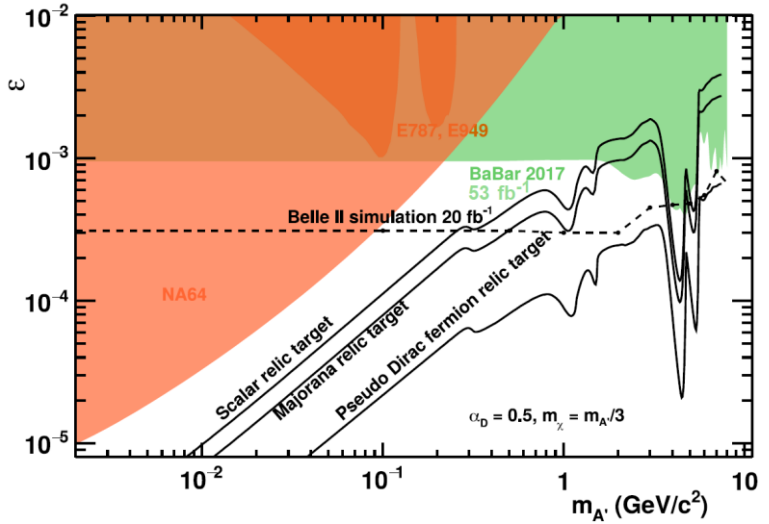
Future projection



Another dark sector searches

- $B \to K\nu\nu \leftarrow$ coming soon!
- Dark Higgs-strahlung: $e^+e^- \to A'h', h' \to A'A'$
- Two minimal dark photon searches
  - $e^+e^- \to A'\gamma, A' \to \ell^+\ell^-$ or inv.
- Visible Z'
- $e^+e^- \to \tau^+\tau^- S$
- $B \to KS$ with displaced vertex
- $B \to Ka$
- ...and more!





Summary

- Two dark sector papers were published using Belle II 2018 data
  - $Z' \rightarrow \mathrm{inv.}$ search with and without LFV
  - ALP searches with three photons
- With more data, both channels give more sensible results for the NP
  - Especially, Z' can reach the $(g-2)_\mu$ anomaly very soon
- Many dark sector related results will appear

KEEP YOUR EYES ON BELLE II,
THANK YOU!