Dark-sector physics at Belle II

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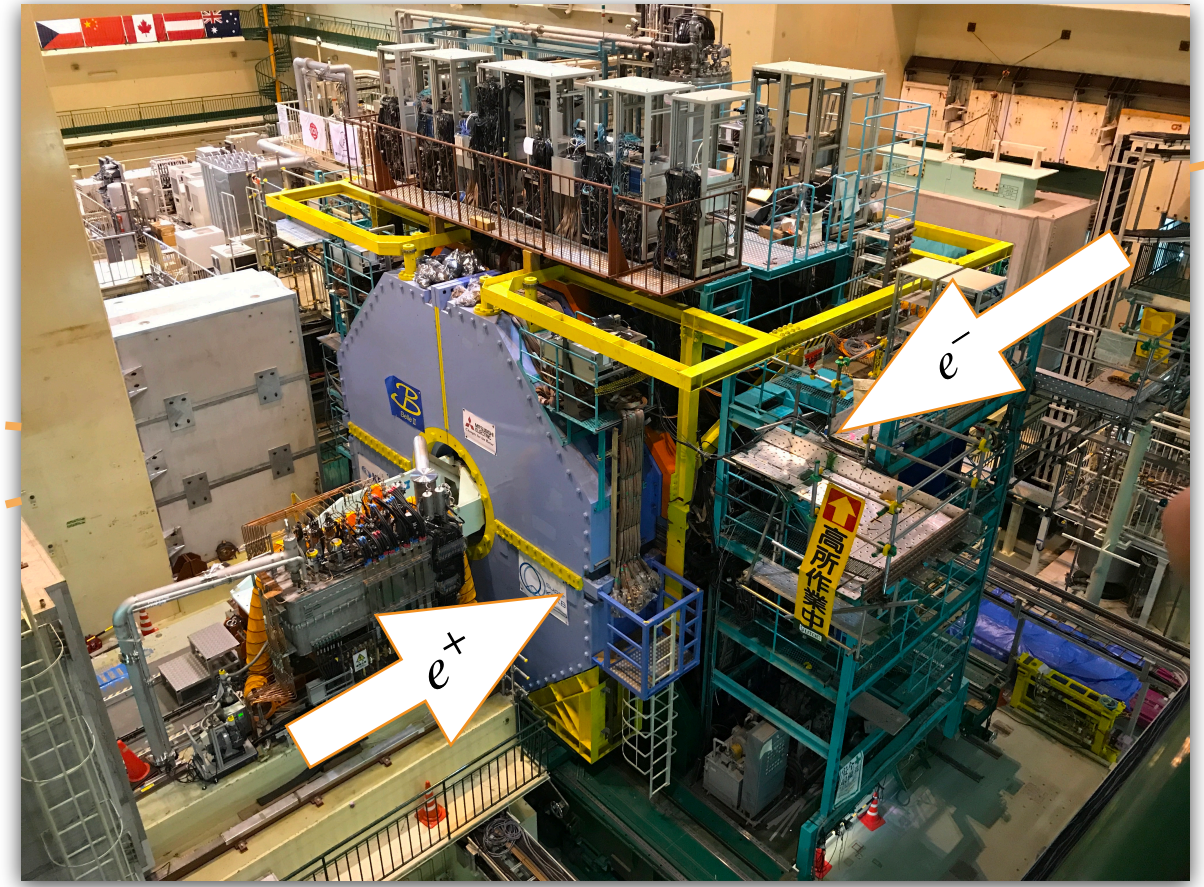
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Exploring Dark Sectors with Belle II

- Next generation B-Factory operating at SuperKEKB asymmetric e^+e^- collider.
  - ➡ $\sqrt{(s)} = 10.58$ GeV corresponding to $\Upsilon(4S)$ resonance.
  - ➡ Targeting 50 ab^{-1} dataset this decade.
- Exploring **Dark Sectors** at the luminosity frontier:

Direct Production:
$e^+e^- \rightarrow X_{Dark}X_{SM}$

Decays:
$B/D/\tau \rightarrow X_{Dark}X_{SM}$



Precision Measurements and Rare Decays:
$e^+e^- \rightarrow X_{SM}$
$B/D/\tau \rightarrow X_{SM}$

The Belle II Detector

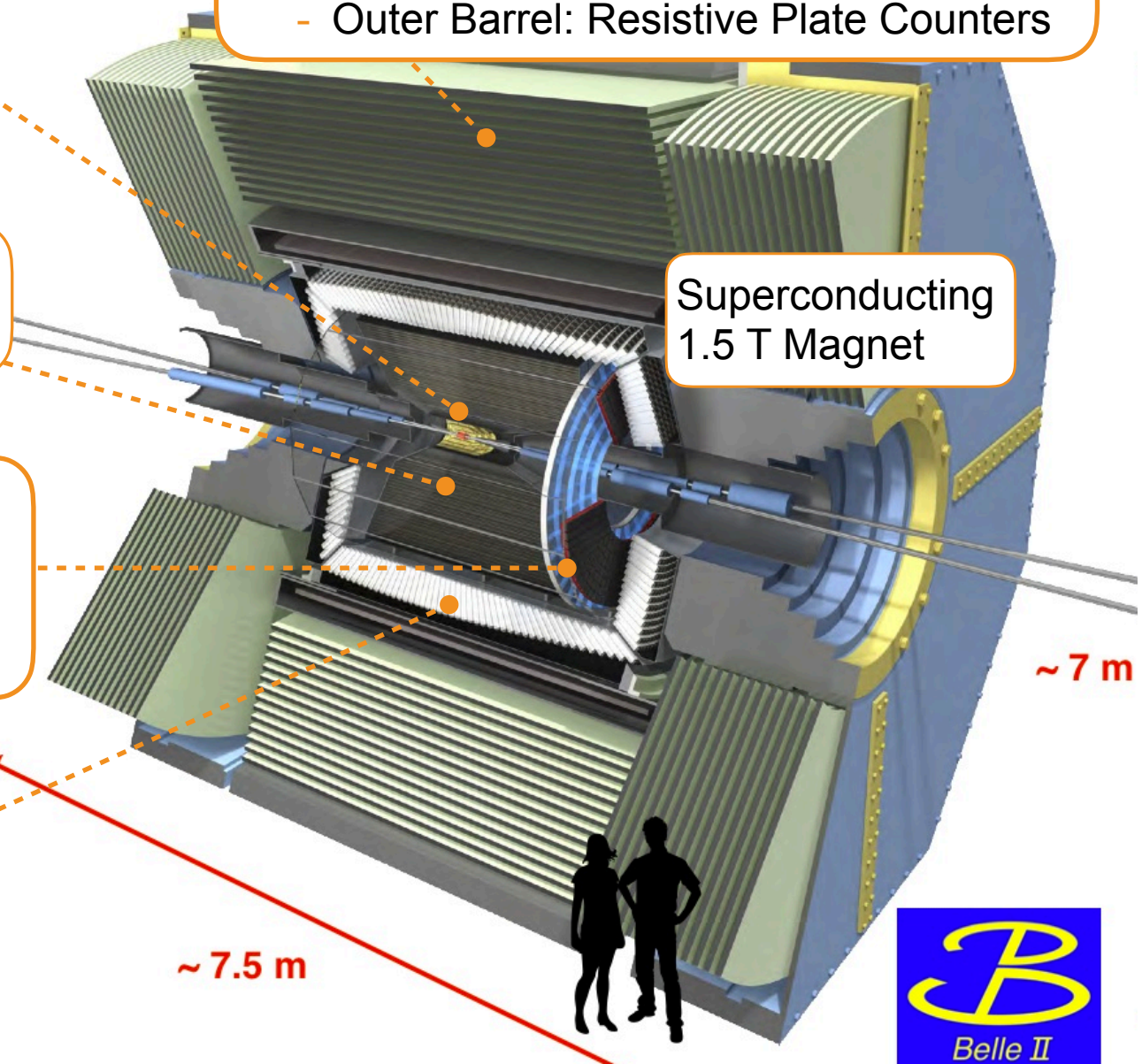
Novel vertexing:
- 2 layer DEPFET pixel detector
- 4 layer double sided silicon strips

New Drift Chamber:
- Larger volume, smaller cells, new electronics

New charged particle identification detectors:
- Barrel:Time-of-Propagation
- Backward Endcap: Cherenkov-based

Upgraded CsI(Tl) Calorimeter:
- Improved timing
- Pulse shape discrimination

New K_L^0/μ detectors
- Inner Barrel/Endcaps: scintillating strips
- Outer Barrel: Resistive Plate Counters



Belle II Dataset and Dark Sector Triggers

- Since first collisions in 2018, total dataset integrated to-date of **180 fb^{-1}.**
  - ➡World record instantaneous luminosity achieved by SuperKEKB (2.9×10^{34} cm^{-2}s^{-1}).
- New “Dark Sector” triggers make this dataset world-unique.

$e^+e^- \to X$ (in acceptance)
~1 MHz
(Dominated by Bhabha and 2γ)

→

Level 1 Hardware Trigger <30 kHz

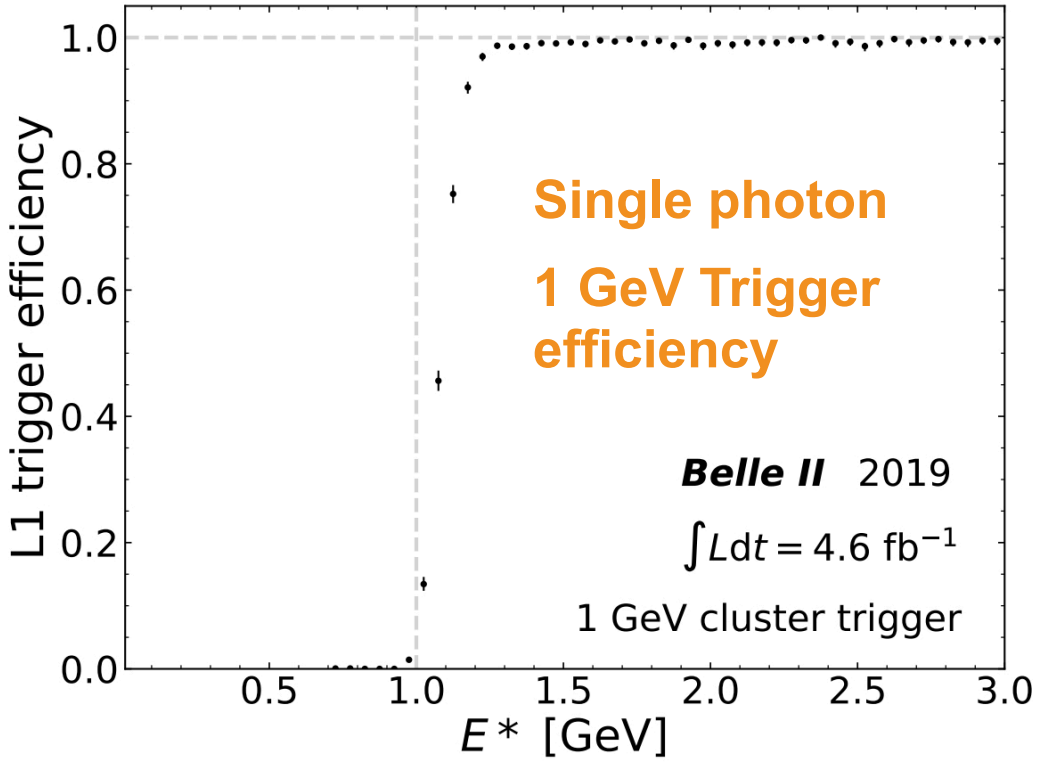
→

High Level Software Trigger <10 kHz

✓**Single photon trigger** operational for entire dataset.
- Not present at Belle.
- **53 fb^{-1}** recorded by BaBar with single photon trigger.

✓**Single muon trigger** using KLM recently introduced.

✓**3D track reconstruction at L1** using neural networks.



Invisibly Decaying Z' Boson

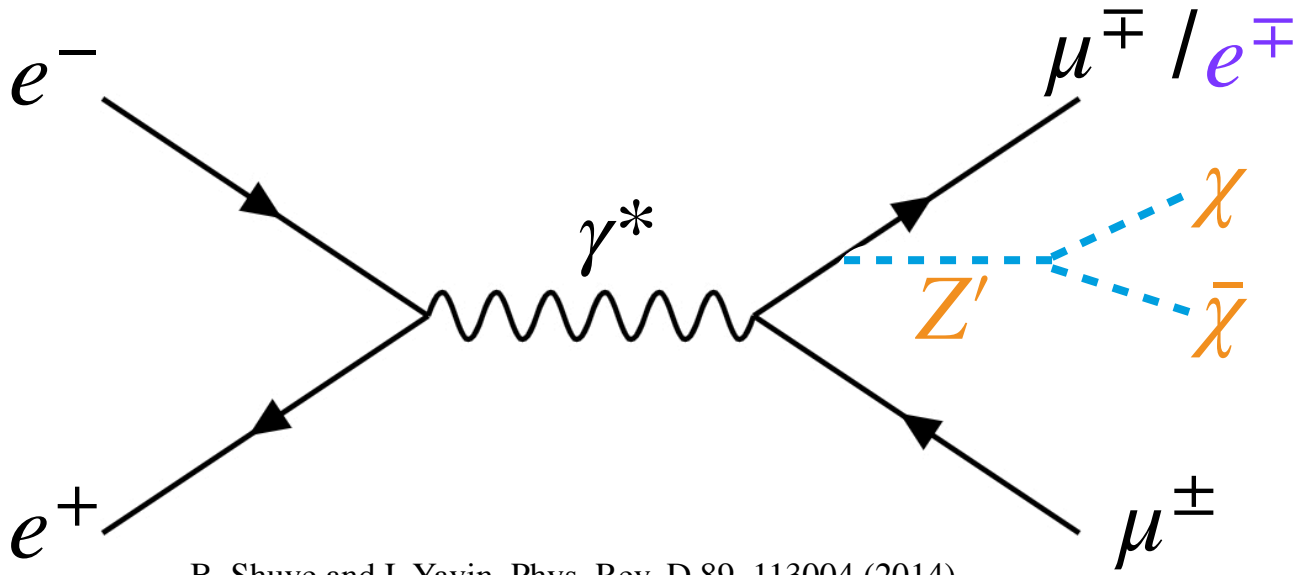
- Z' boson - vector portal mediator between Dark Sector and Standard Model.
  - ➡ Dark Matter, $(g-2)_\mu$, $b \to s\mu^+\mu^-$.
- Consider scenario:
  - ➡ Z' coupling only to 2nd and 3rd generation leptons ($L_\mu - L_\tau$ model).
  - ➡ Z' decays primarily as $Z' \to \chi\bar{\chi}$ (invisible)
- **Hermetic Belle II detector and clean e^+e^- collisions allow precision determination of missing energy!**

Default channel:

$e^+e^- \to \mu^\pm\mu^\mp$ + Missing Energy

Lepton flavour violating channel:

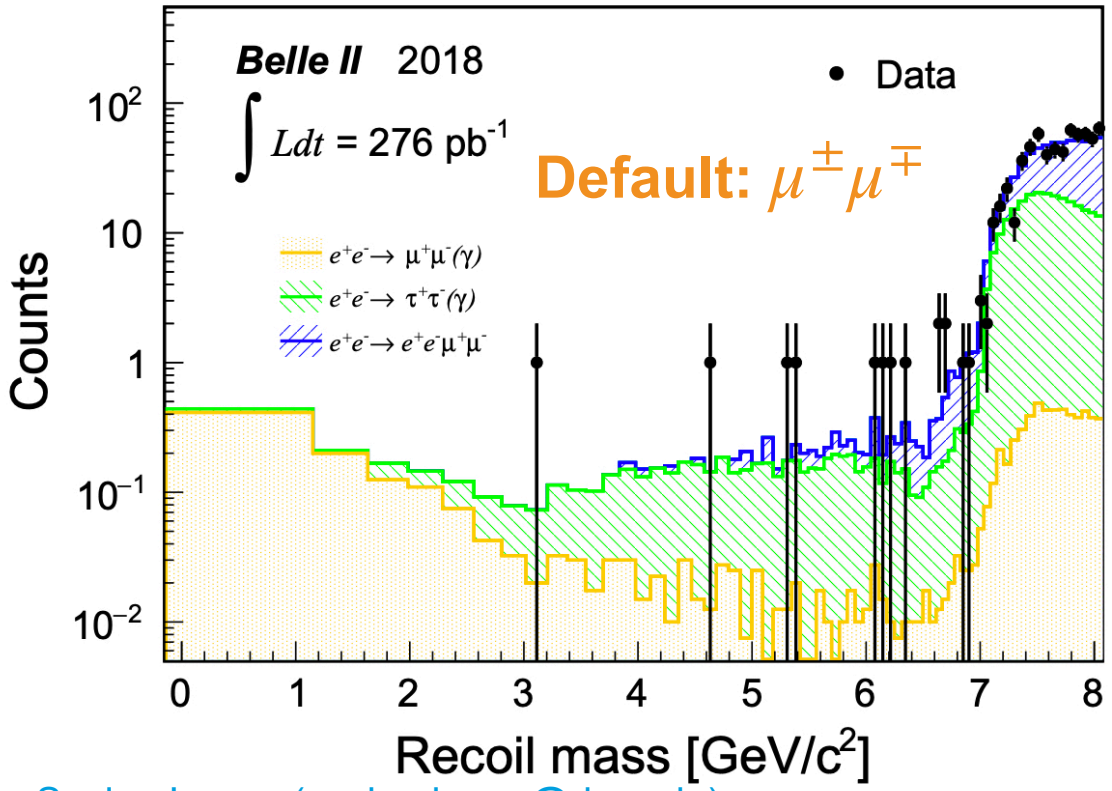
$e^+e^- \to \mu^\pm e^\mp$ + Missing Energy

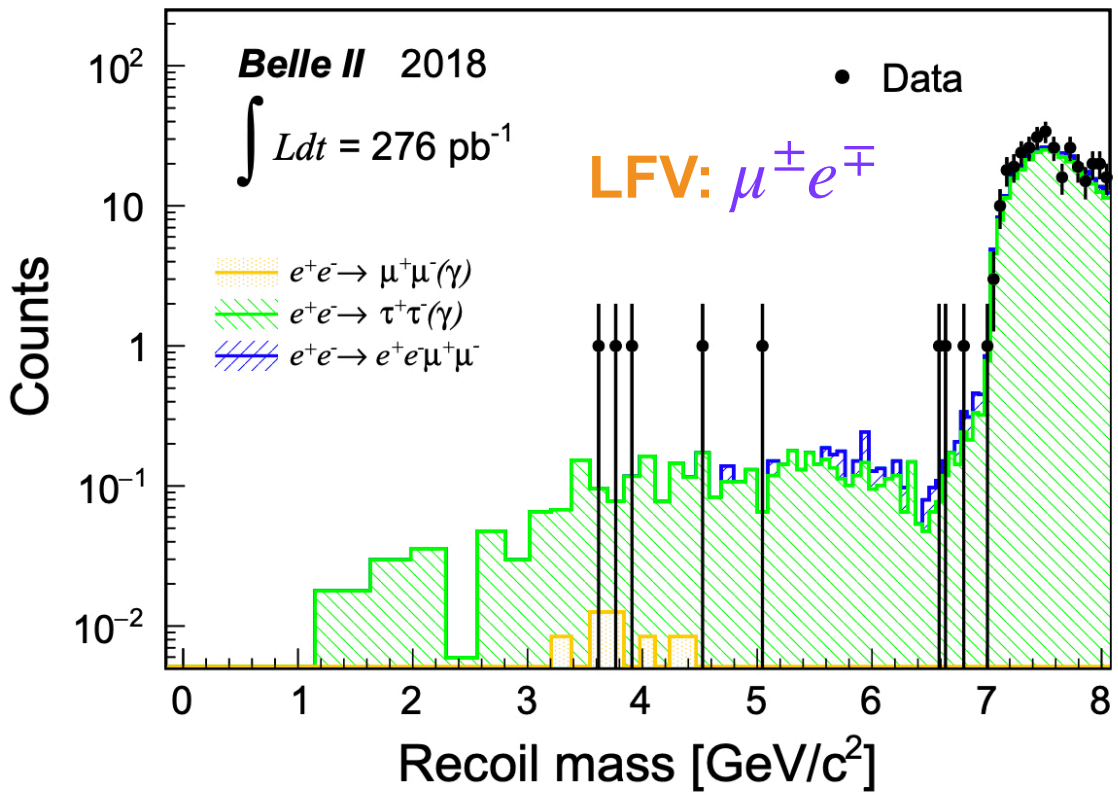


B. Shuve and I. Yavin, Phys. Rev. D 89, 113004 (2014).
W. Altmannshofer, S. Gori, S. Profumo & F. Queiroz. J. High Energy Phys. 12 (2016) 106.
D. Curtin, R. Essig, S. Gori & J. Shelton. J. High Energy Phys. 02 (2015) 157.

Invisibly Decaying Z' Boson Search

- Signal would produce narrow peak in distribution of recoil mass computed from $\mu^{\pm}\mu^{\mp}$(**LFV:** $\mu^{\pm}e^{\mp}$).
- Dominant backgrounds:
  - $e^+e^- \to \tau^+\tau^-$: τ's decay single prong, missing energy from neutrinos.
  - $e^+e^- \to \mu^+\mu^-(\gamma)$, photon is undetected.
- No significant excess observed in either search.

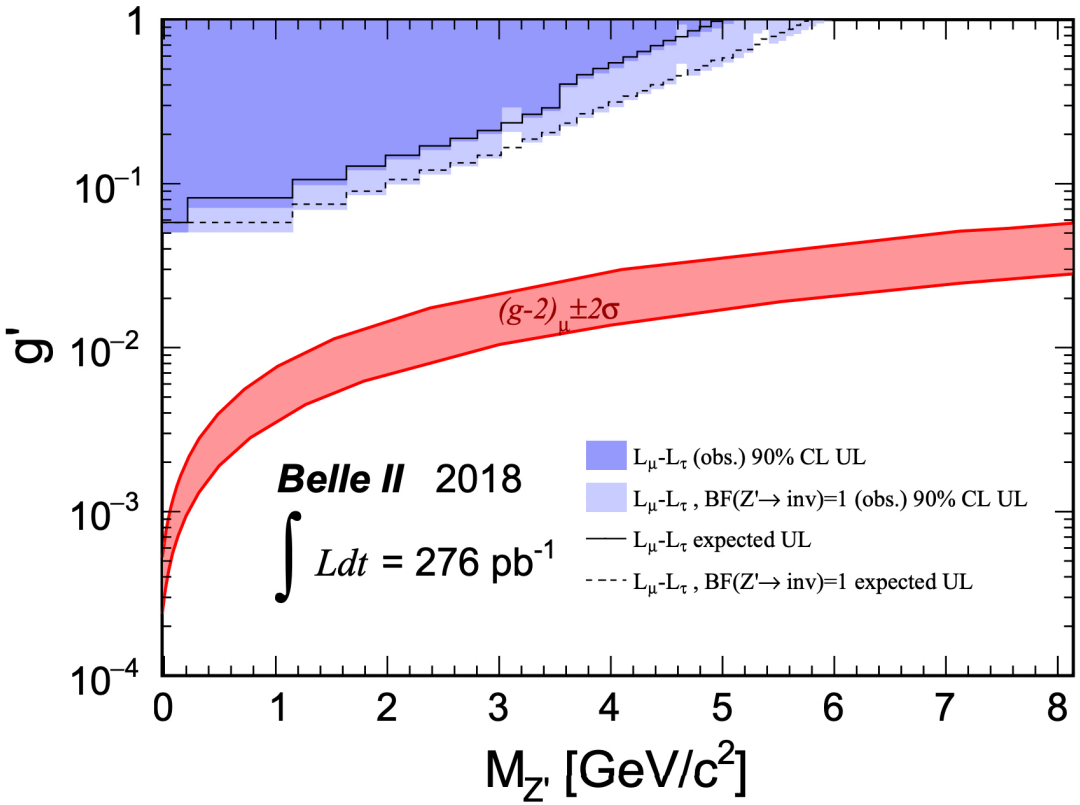




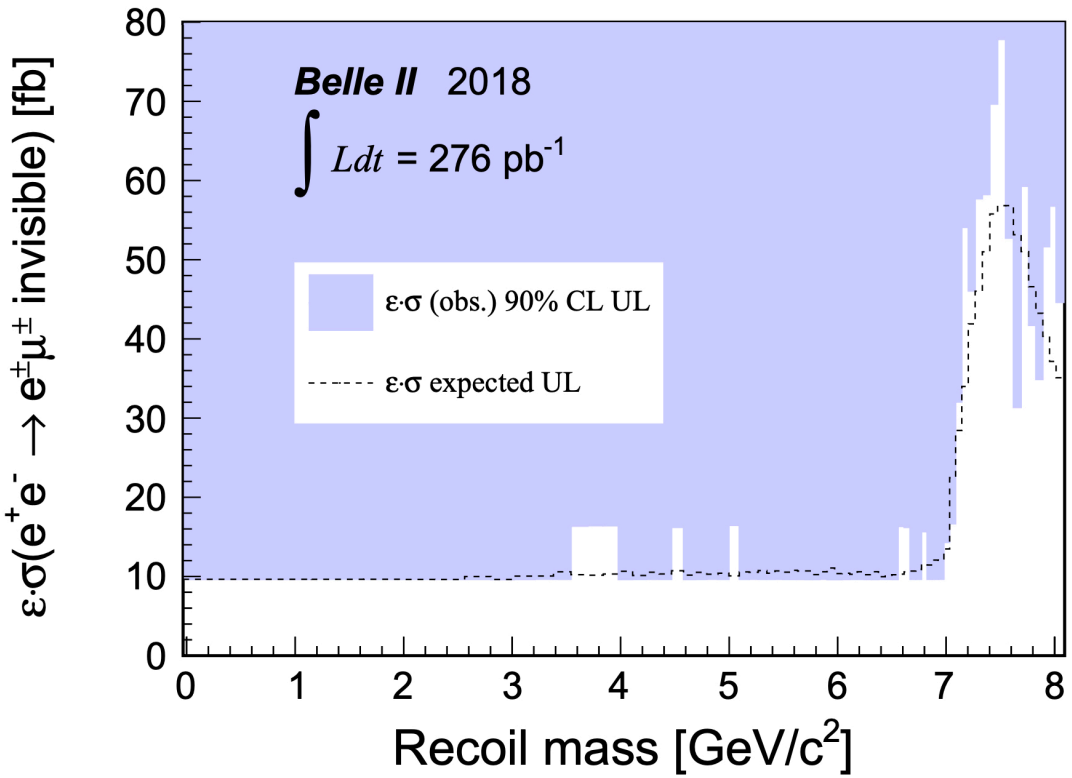
Z' Boson Limits and Exclusions

- 90% CL upper limits set on Z'-SM coupling (g') excluding strengths from 1 down to 5×10^{-2}.
- LFV search sets first model independent limits on the $\epsilon \times \sigma[e^+e^- \to e^\pm\mu^\mp$ invisible] down to 10 fb.
- Results published: I. Adachi et al. (Belle II Collaboration) Phys. Rev. Lett. 124, 141801

Default: $\mu^\pm\mu^\mp$

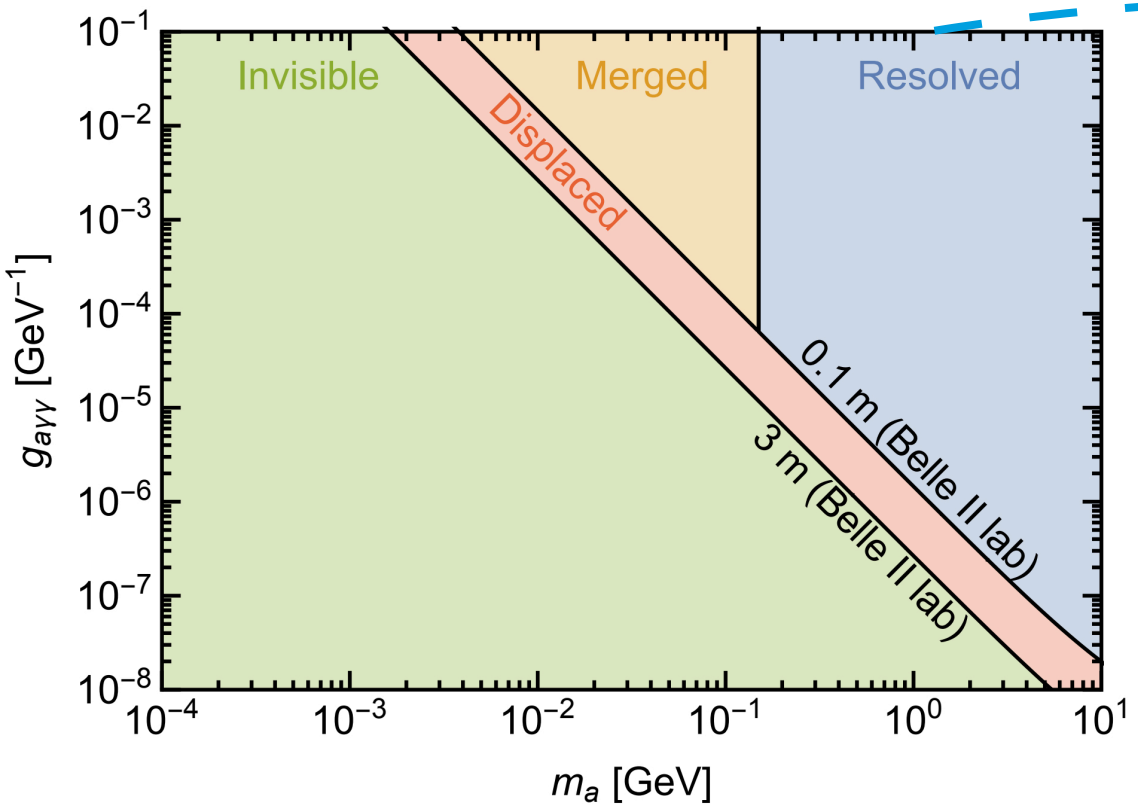


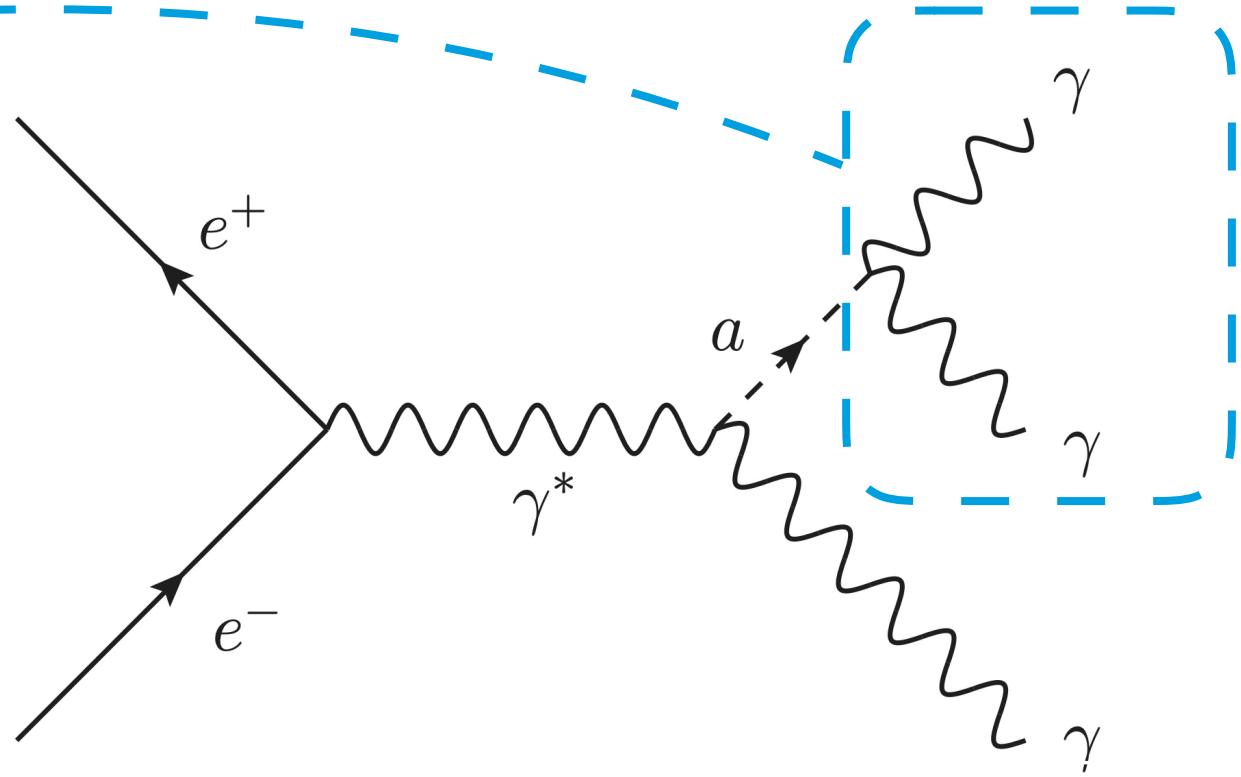
LFV: $\mu^\pm e^\mp$



Axion-Like Particles (ALP)

- GeV-scale ALPs (a) - pseudoscalar portal mediator between Dark Sector and Standard Model.
- If ALP-photon coupling ($g_{a\gamma\gamma}$) dominates, $B(a \to \gamma\gamma) \approx 100\,\%$.
- Search targets mass region where ALP decay is prompt and photons can be well resolved by Belle II.

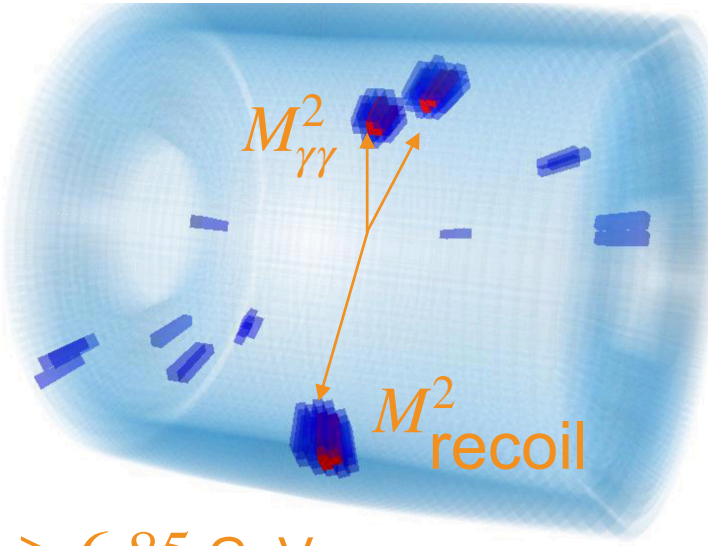




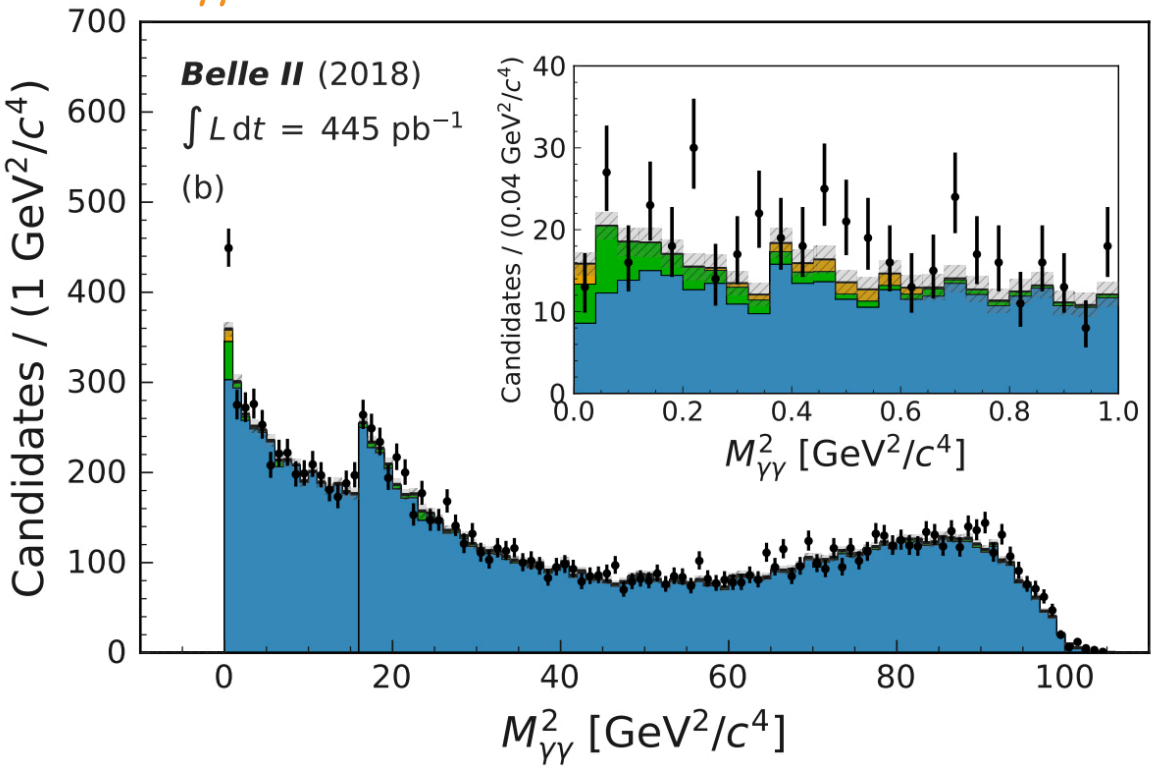
M. Dolan, T. Ferber, C. Hearty, F. Kahlhoefer & K. Schmidt-Hoberg, J. High Energy Phys. 12, 094 (2017).

Searching for Axion-Like Particles

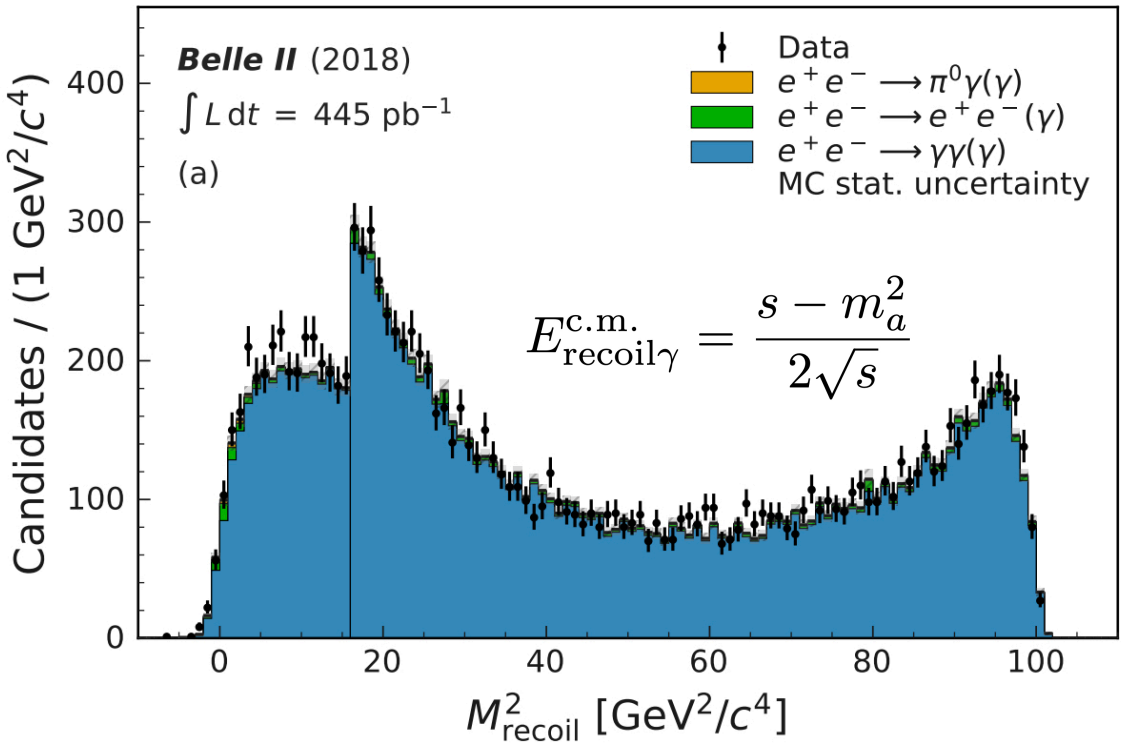
- Select events that have three photons with invariant mass consistent with the collision $\sqrt{s}$.
- Search for narrow peak in M^2_{recoil} or $M^2_{\gamma\gamma}$ (optimized for ALP resolution)
  - ➡Largest background from $e^+e^- \to \gamma\gamma(\gamma)$



$M^2_{\gamma\gamma}$: $m_a < 6.85$ GeV

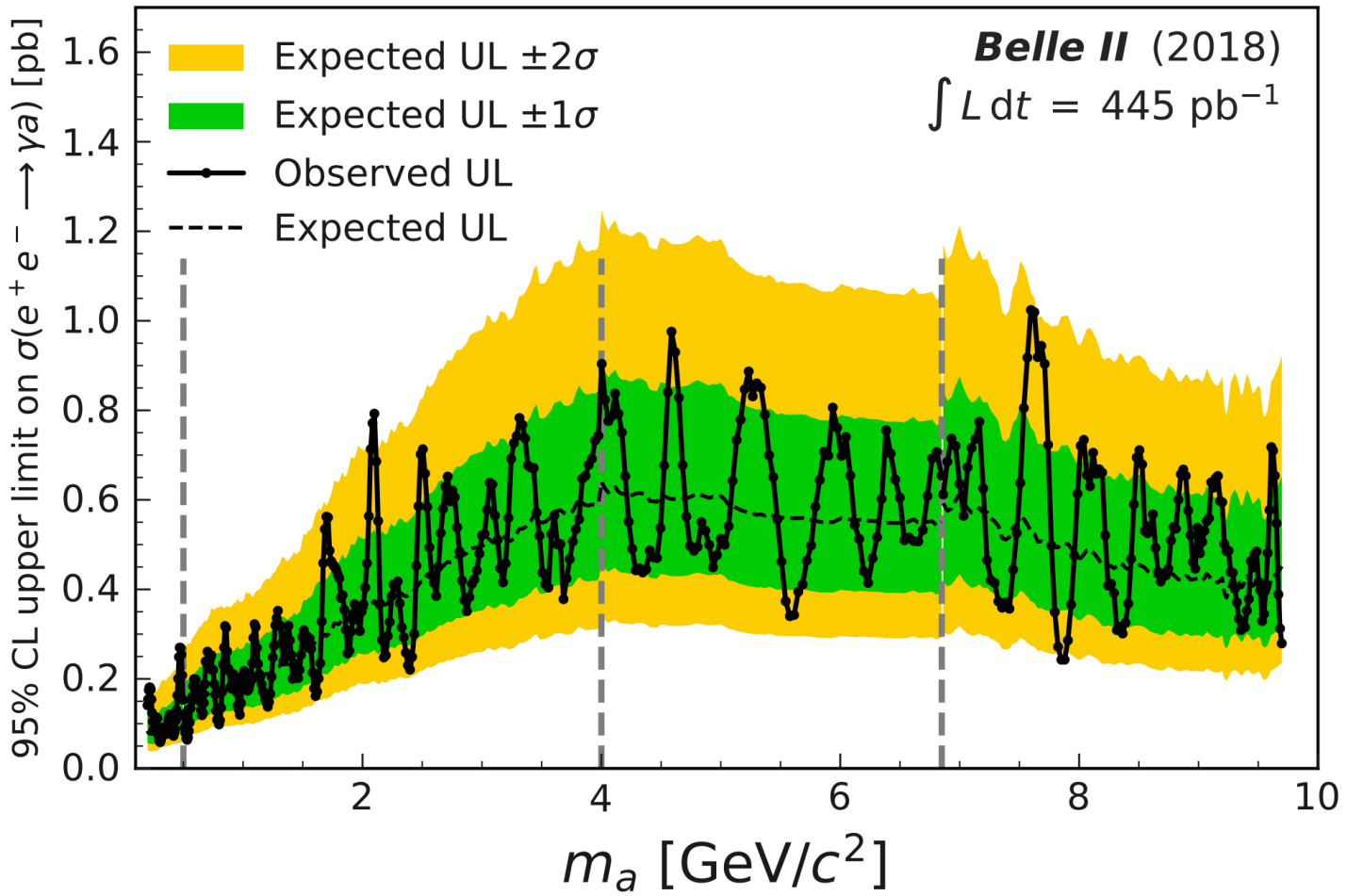


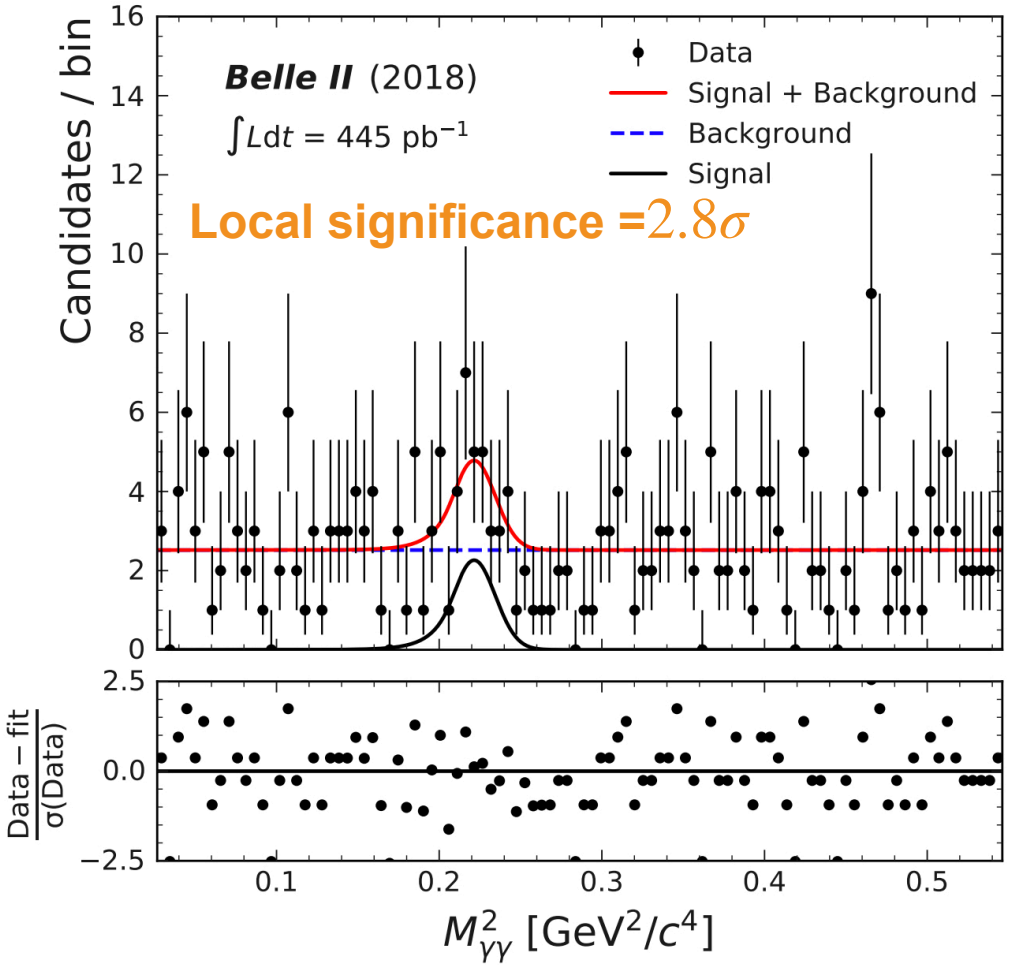
M^2_{recoil} : $m_a \geq 6.85$ GeV



ALP Search Results

- Search spanned $0.2 < m_a < 9.7$ GeV/c^2.
- No significant excess observed.
  - ➡ Largest local significance at $m_a = 0.477$ GeV/c^2 corresponding to 2.8σ.

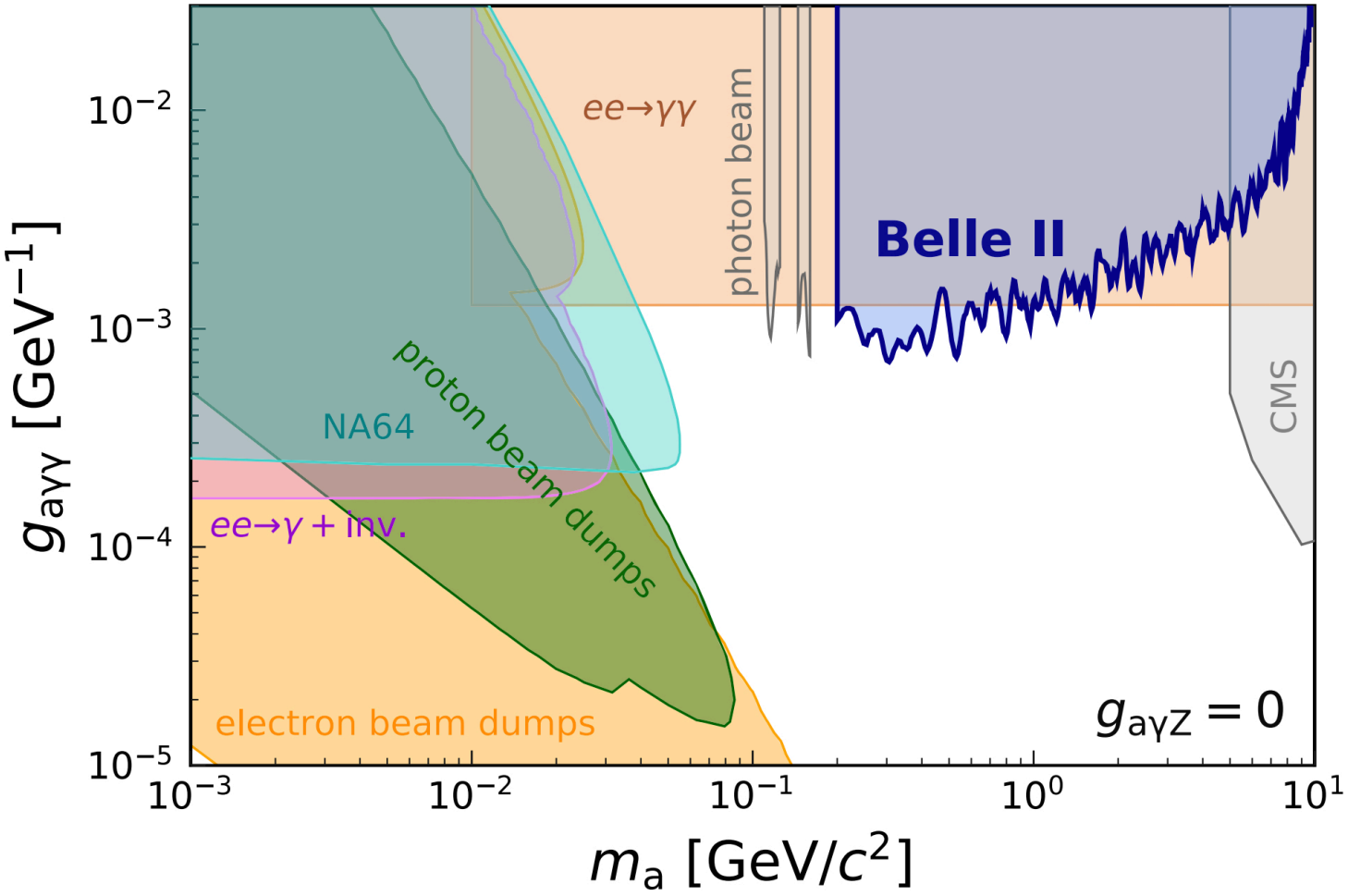




Exclusion on ALP-Photon Coupling

- Upper limit (95% CL) set on ALP-photon coupling reaching below 10^{-3}.
  - ➡Limits exceed recast from $e^+e^- \to \gamma\gamma$ analysis by LEP-II.
- Results published: F. Abudinén et al. (Belle II Collaboration) Phys. Rev. Lett. 125, 161806 (2020)

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



Inelastic Dark Matter

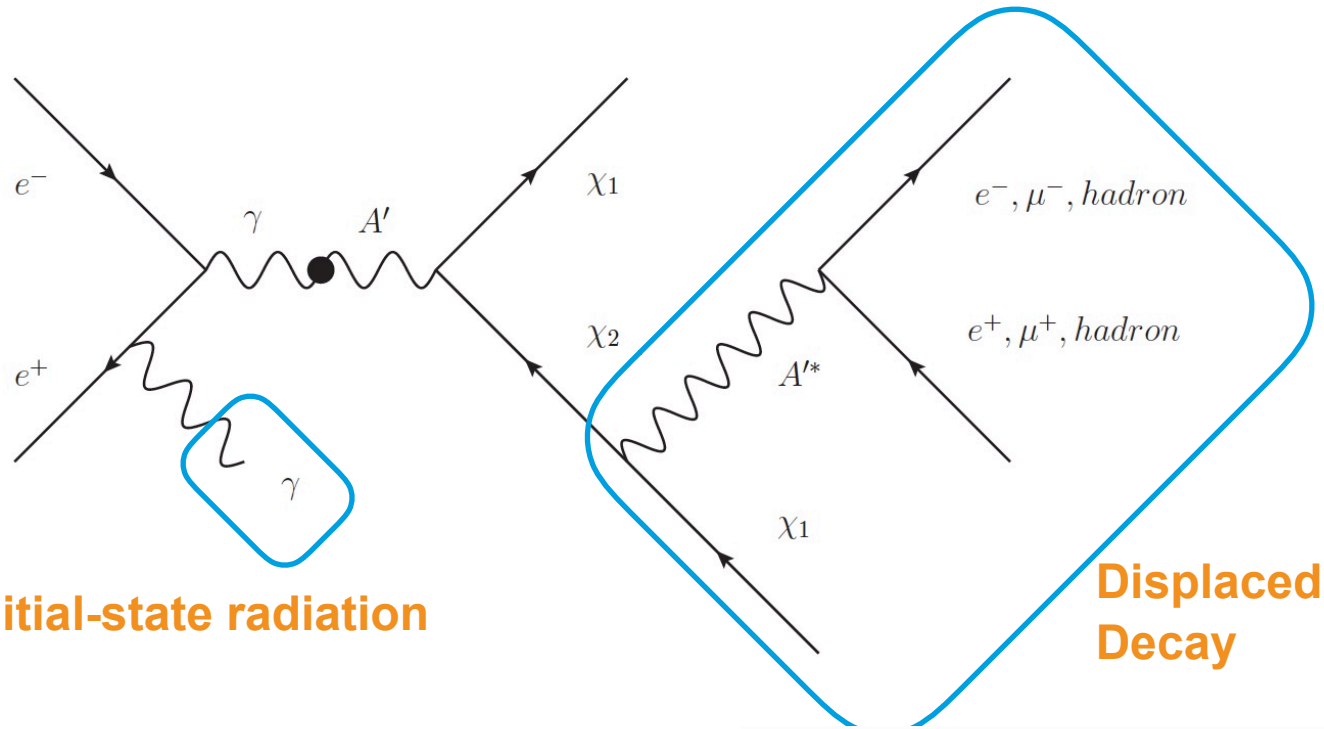
- **Expanded Dark Sector** with two Dark Matter states:

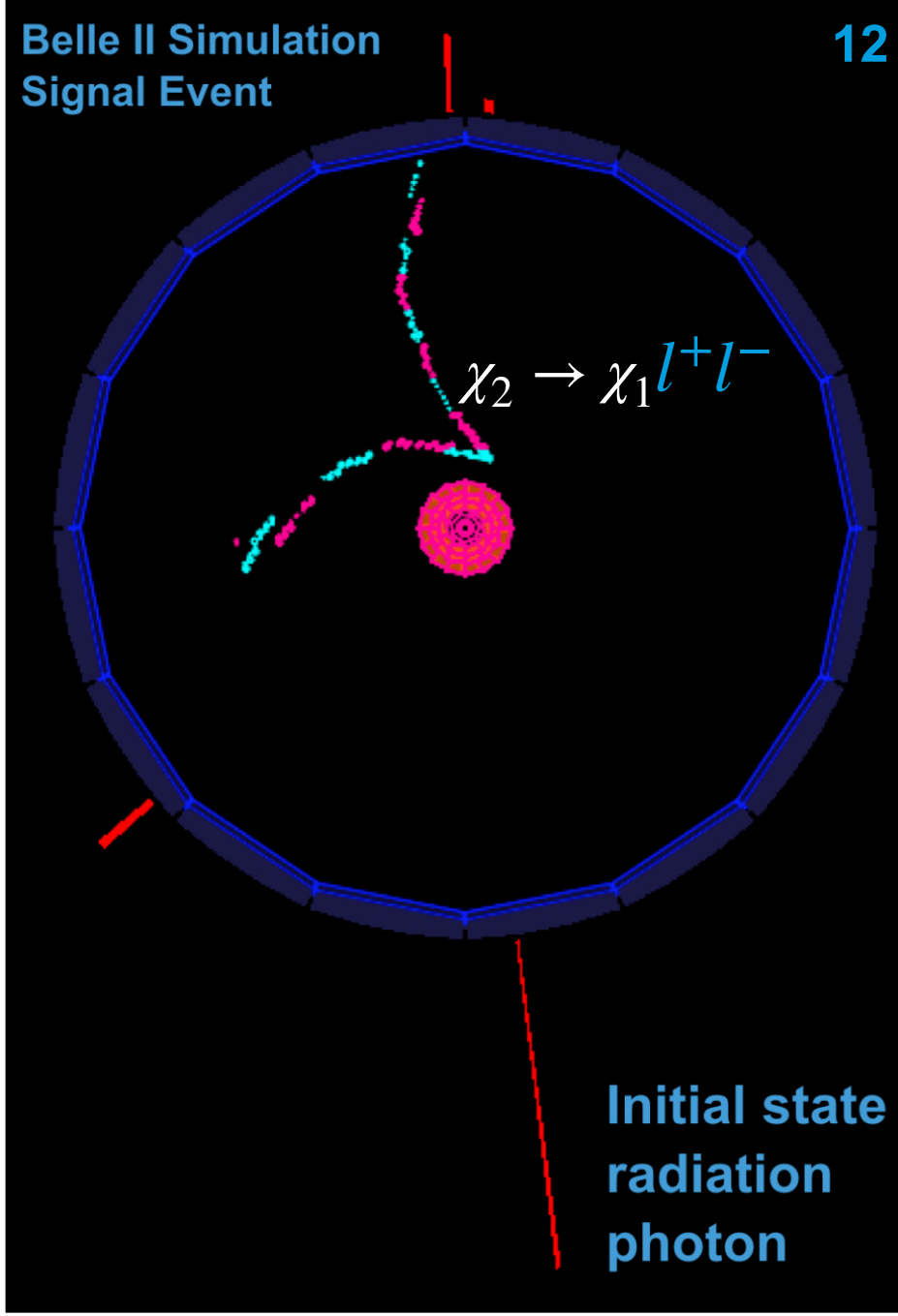
  χ_1 - Relic DM

  χ_2 - **Long-lived particle**

  - Decays as $\chi_2 \to \chi_1 l^+ l^-$, $l^\pm$ = SM fermion

- Vector portal coupling to SM via Dark Photon, A', mediator.



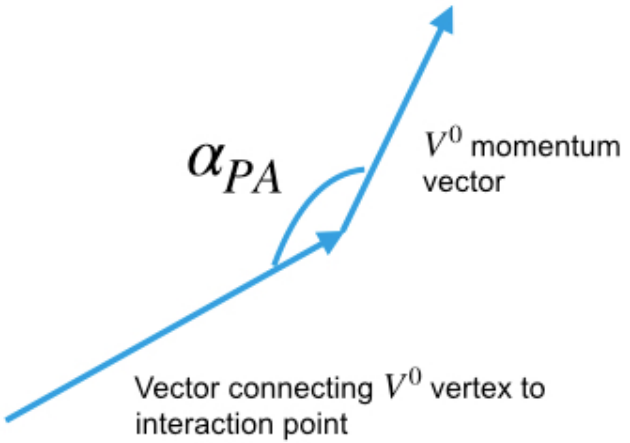


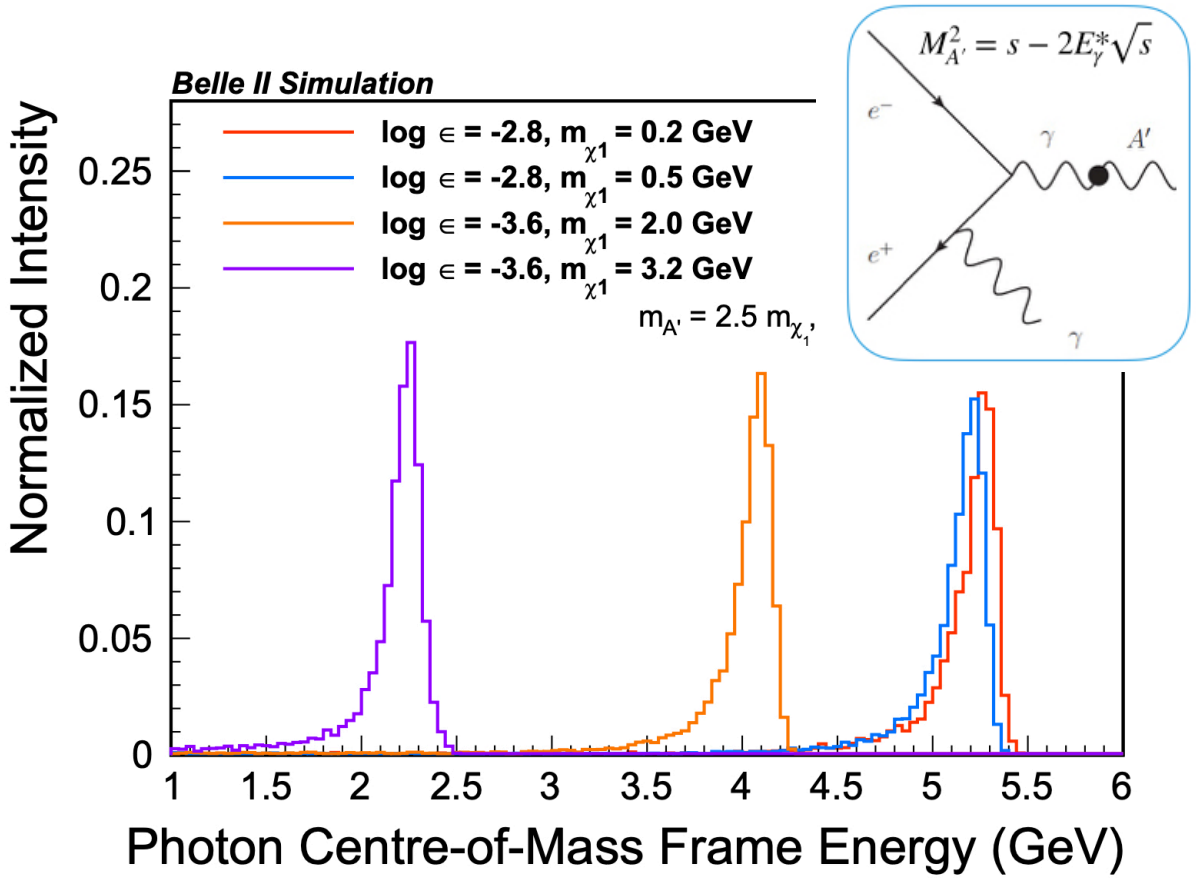
DESY. Savino Longo (savino.longo@desy.de)

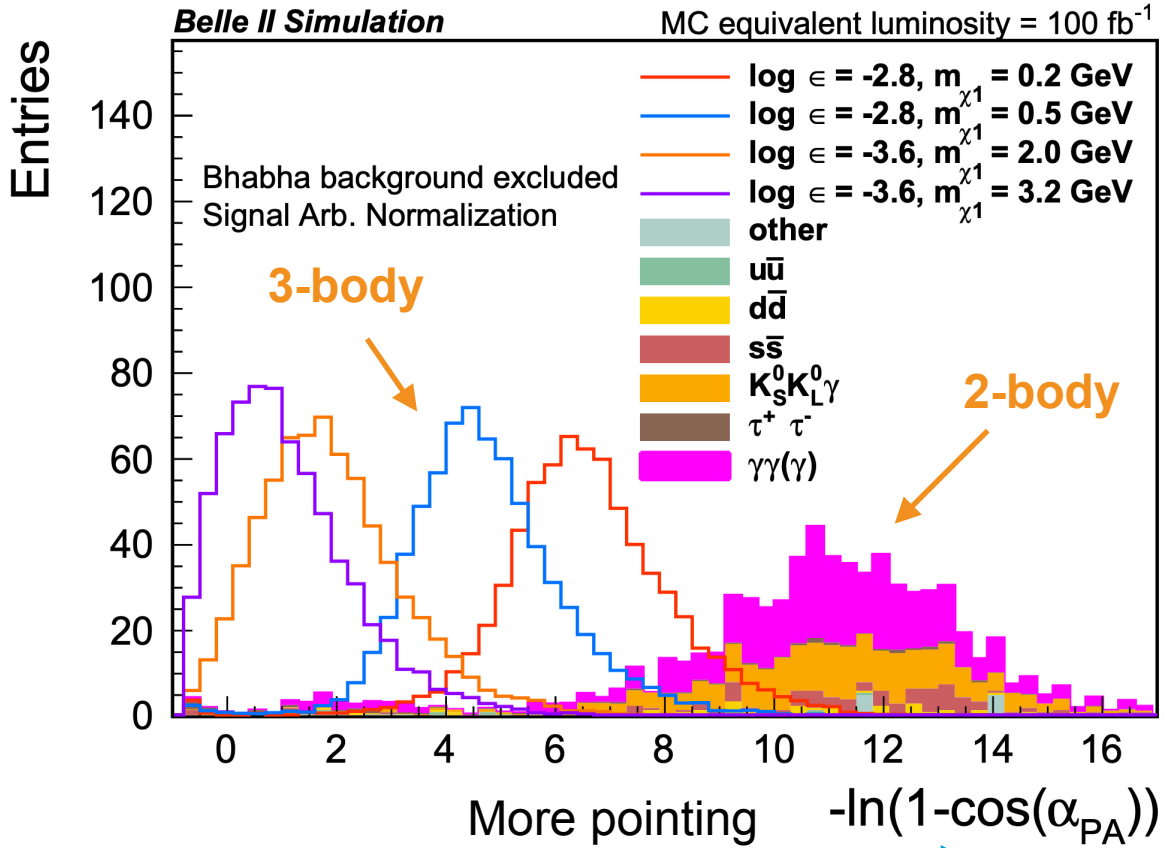
M. Duerr, T. Ferber, C. Hearty, F. Kahlhoefer, K. Schmidt-Hoberg & P. Tunney. J. High Energ. Phys. **2020,** 39.
M. Duerr, T. Ferber, C. Garcia-Cely, C. Hearty & K. Schmidt-Hoberg. J. High Energ. Phys. 2021, 146.

Inelastic Dark Matter Search

- Background suppression using leptons from displaced χ_2 decay vertex.
  - ➡ **Missing energy** in $\chi_2 \to \chi_1 l^+ l^-$ allows for suppression of $\gamma \to e^+e^-$ and $K_S^0 \to \pi^+\pi^-$.
- Search for peak in recoil mass of ISR photon.

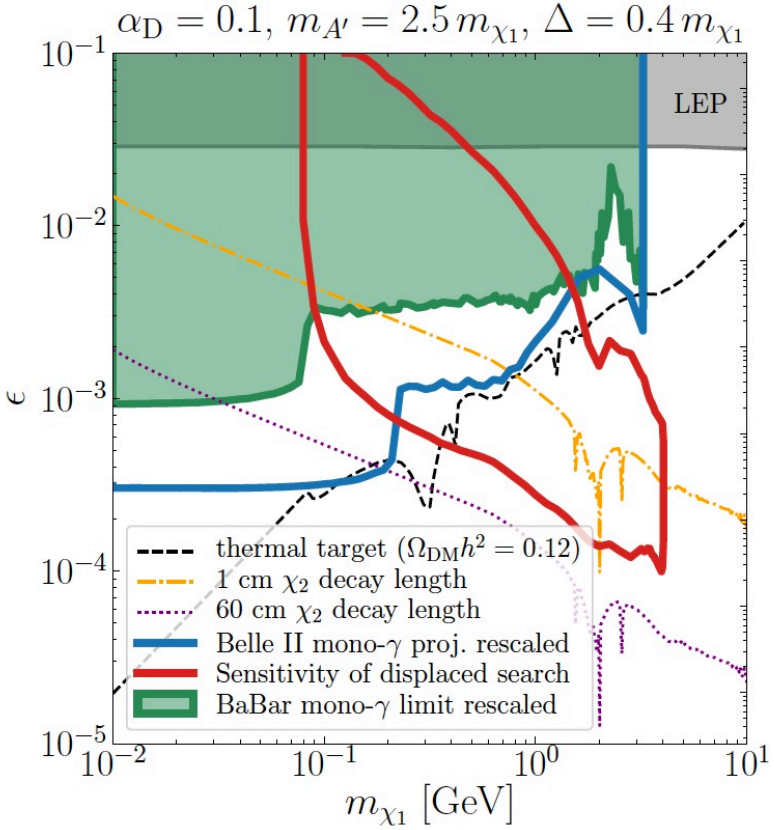


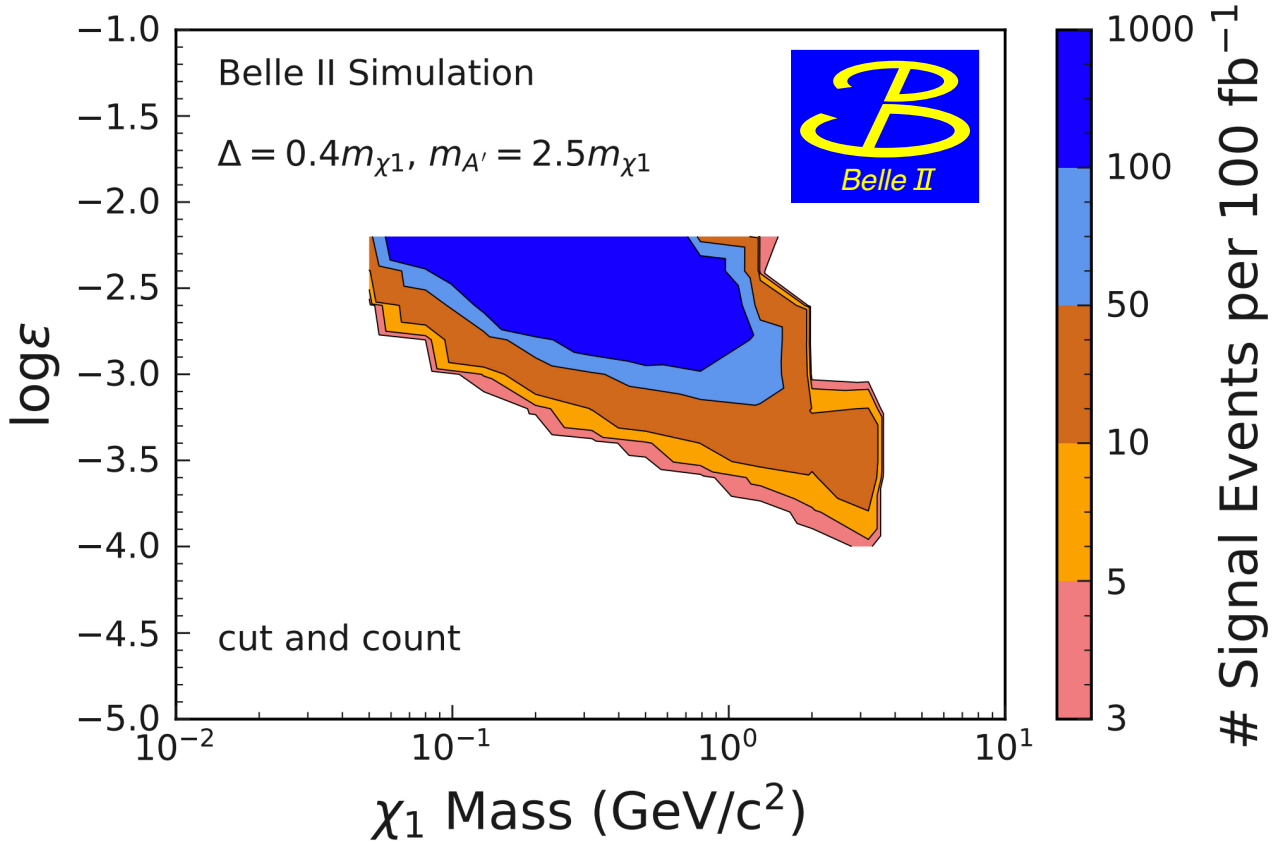




Inelastic Dark Matter Prospects

- With current Belle II dataset expect to probe Dark Sector-Standard Model couplings down to $10^{-3} - 10^{-4}$.
- Search will also constrain extended iDM models featuring Dark Higg Bosons.





M. Duerr, T. Ferber, C. Hearty, F. Kahlhoefer, K. Schmidt-Hoberg and P. Tunney. J. High Energ. Phys. **2020,** 39.
M. Duerr, T. Ferber, C. Garcia-Cely, C. Hearty & K. Schmidt-Hoberg. J. High Energ. Phys. 2021, 146.

Conclusions

- The Belle II experiment is exploring Dark Sectors at the luminosity frontier.
- New Dark Sector triggers enabled to target unique low-multiplicity final states.
- World-leading limits published on Z' boson and ALP's:

  ➡ I. Adachi et al. (Belle II Collaboration) Phys. Rev. Lett. 124, 141801 (2020)

  ➡ F. Abudinén et al. (Belle II Collaboration) Phys. Rev. Lett. 125, 161806 (2020)

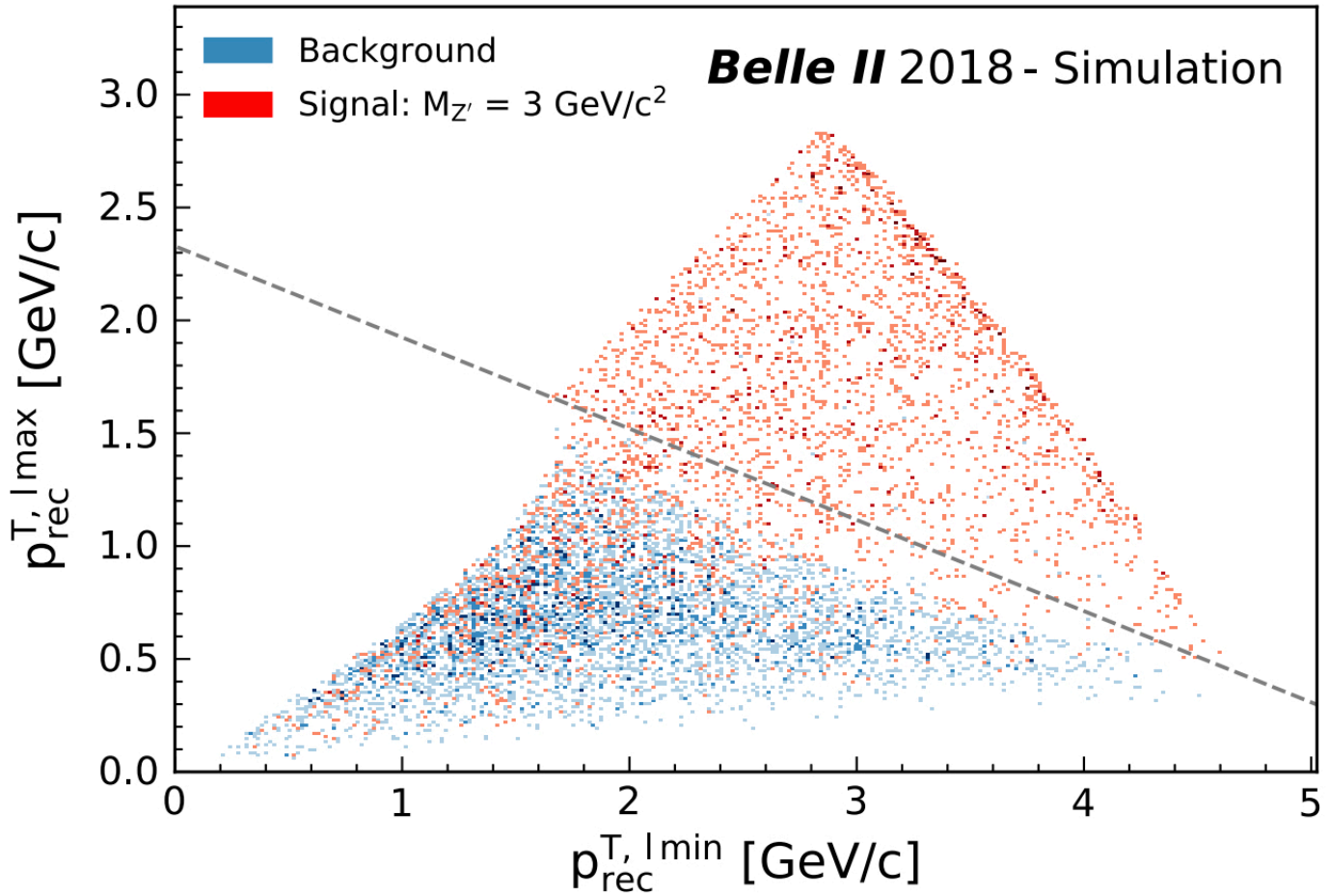
- New Inelastic Dark Matter analysis in progress, targeting expanded Dark Sectors with long-lived particles.

Thanks!

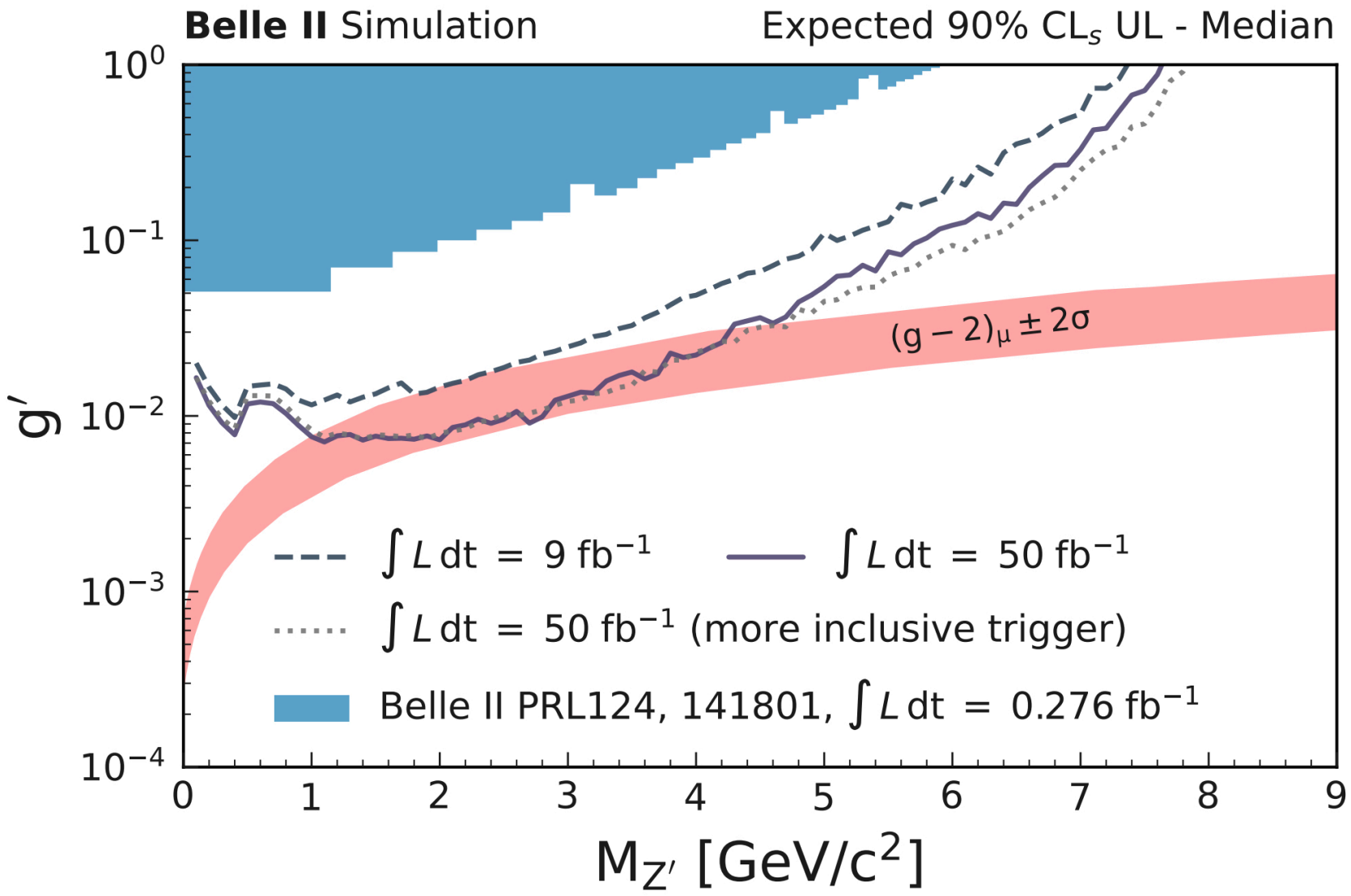
Extra Slides

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



Future Reach of Z' Searches



ALP Resolution

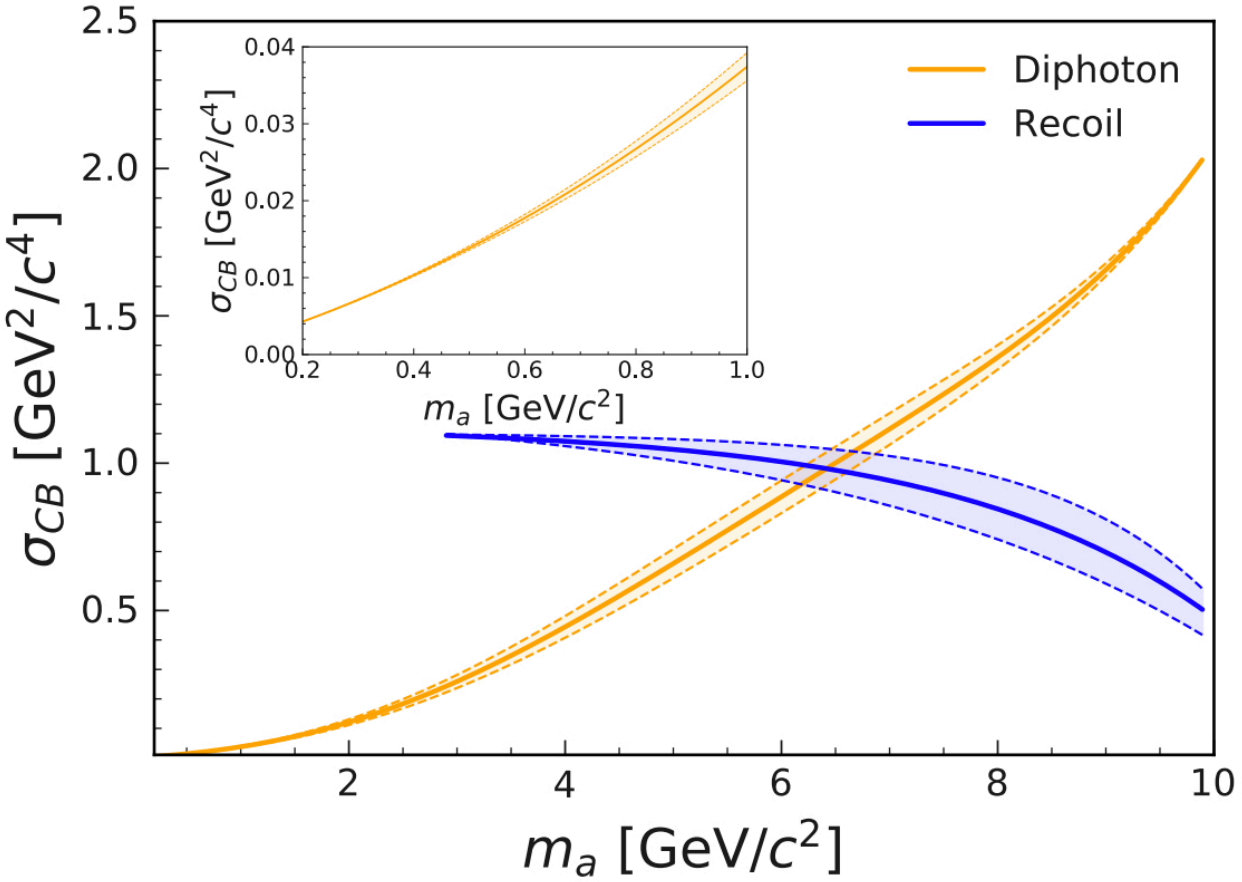
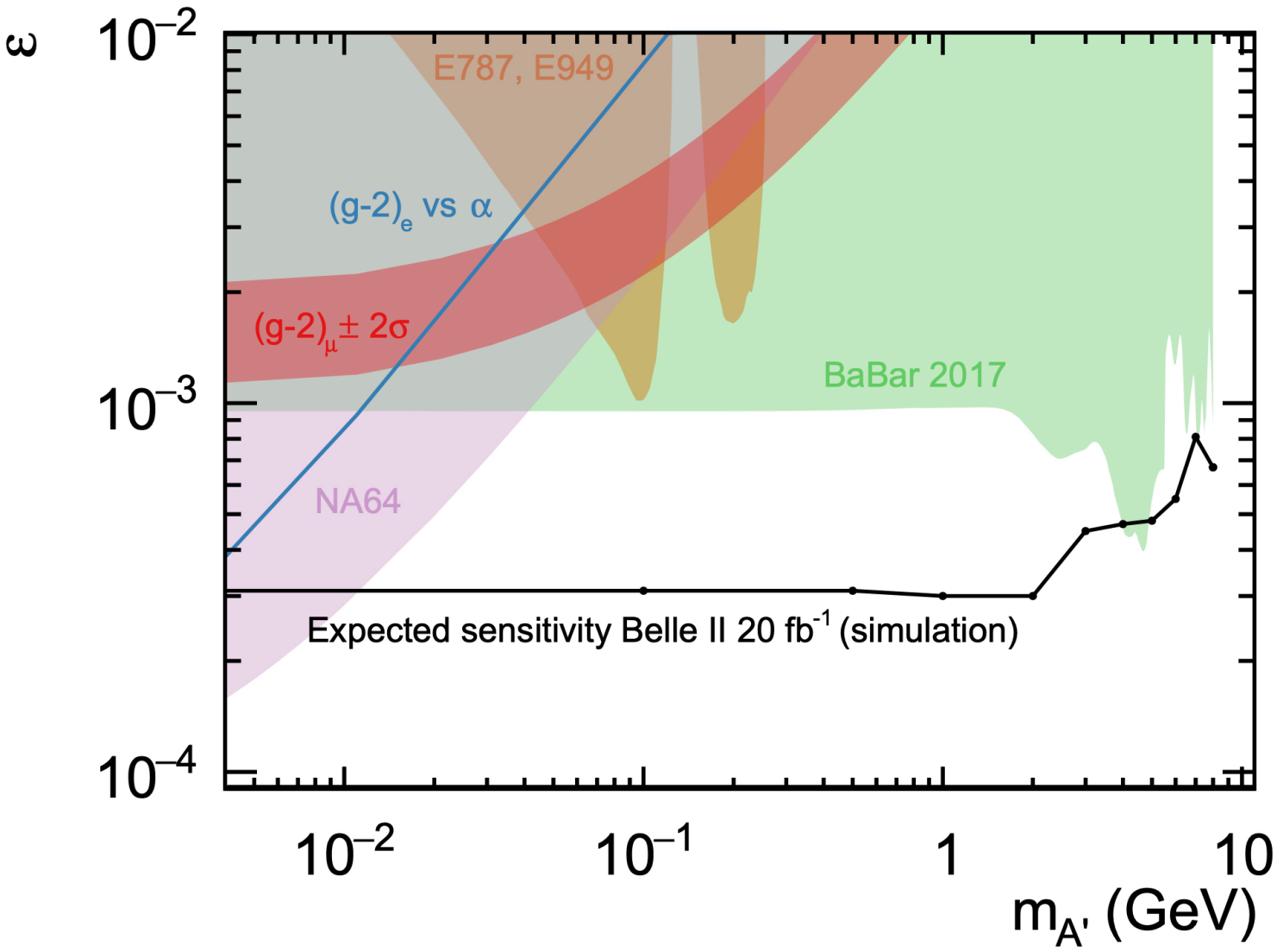
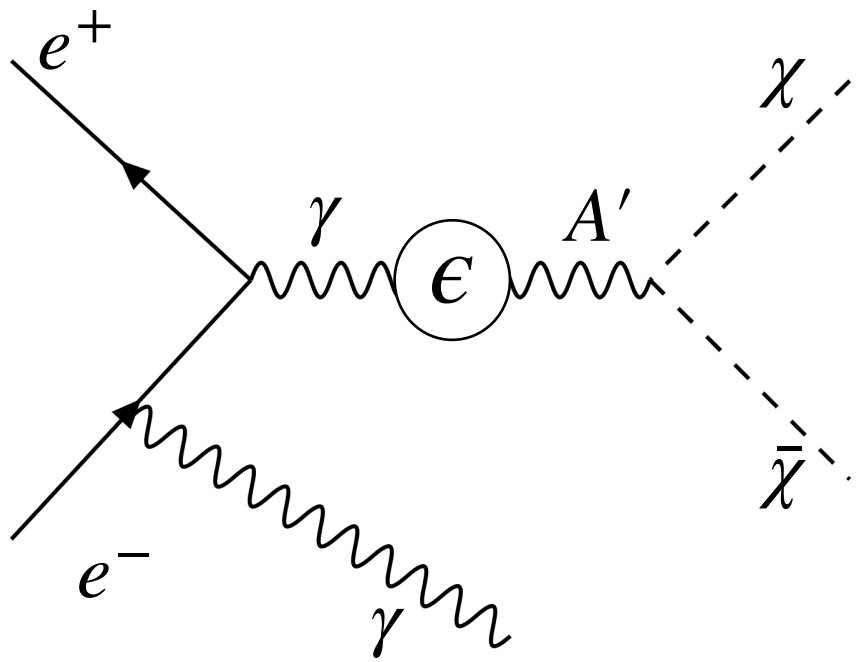


FIG. 2. $M^2_{\gamma\gamma}$ and M^2_{recoil} resolutions with uncertainty as a function of ALP mass m_a. The inset shows an enlargement of the low-mass region $m_a < 1\,\text{GeV}/c^2$.

Projected Reach of Dark Photon Search





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