Search for inelastic Dark Matter at Belle II

FSP Workshop: Long-lived particles at Belle II

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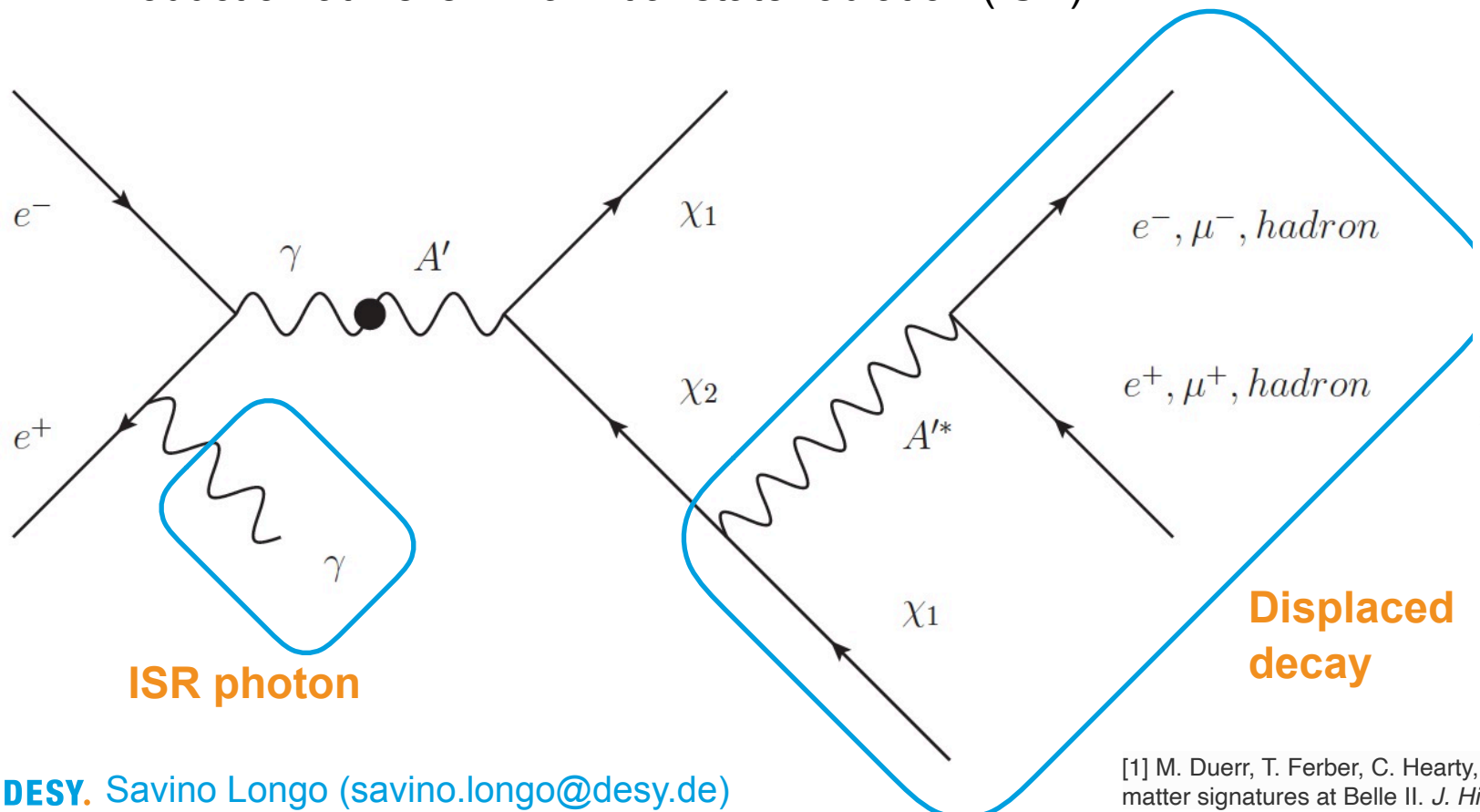
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

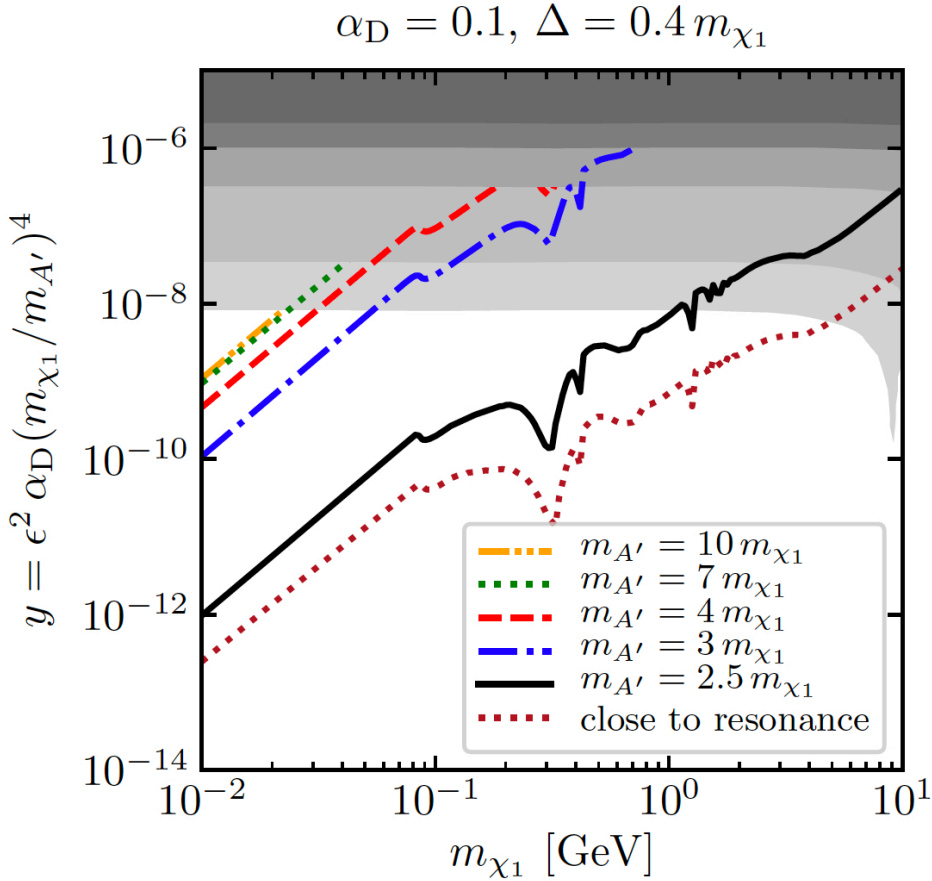
Inelastic Dark Matter (iDM)

- Introduces Dark Photon mediator (A') in addition to Dark Matter states χ_1 and χ_2 [1].
  - ➡ χ_1 is stable (relic)
  - ➡ χ_2 is **long-lived** at small values of ϵ (kinetic-mixing coupling), decays via $\chi_2 \to \chi_1 l^+ l^-$.

$$\Delta \equiv m_{\chi_2} - m_{\chi_1}$$

- Unconstrained by direct detection experiments as required χ_1 up-scattering is suppressed.
- Production at Belle II via initial-state-radiation (ISR):





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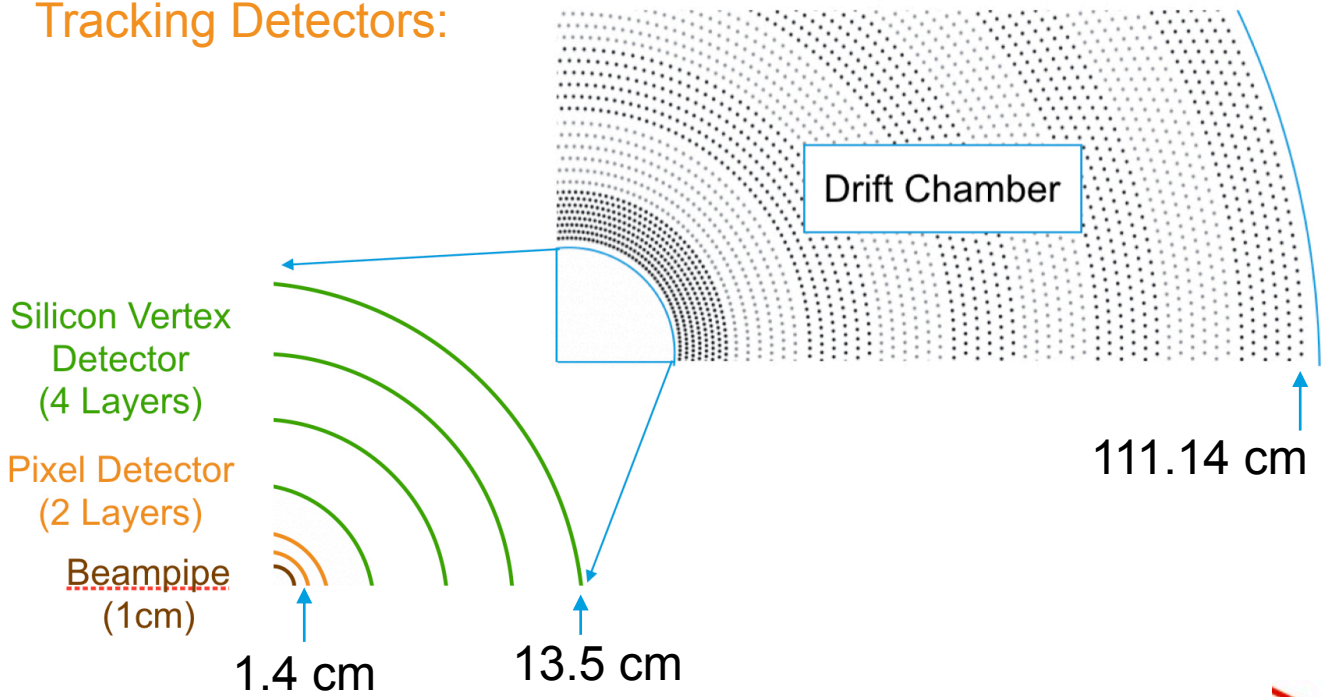
[1] M. Duerr, T. Ferber, C. Hearty, F. Kahlhoefer, K. Schmidt-Hoberg and P. Tunney Invisible and displaced dark matter signatures at Belle II. *J. High Energ. Phys.* **2020,** 39 (2020). https://doi.org/10.1007/JHEP02(2020)039

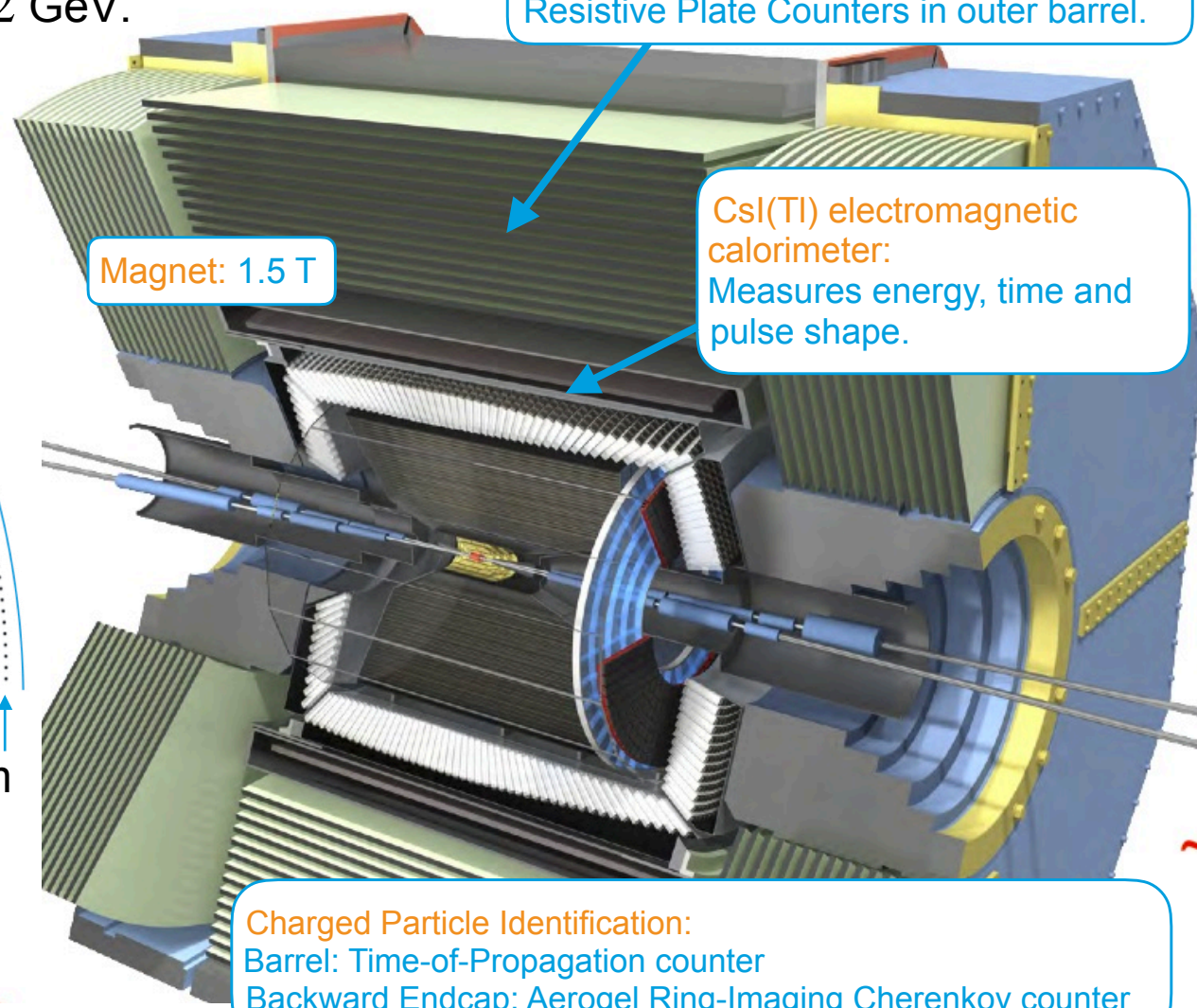
The Belle II Detector

- Operates at the SuperKEKB asymmetric e^+e^- collider, $\sqrt{s} = 10.58$ GeV.
- Dataset to-date of 74 fb^{-1} and counting, with high energy photon trigger enabled.
  - ➡ Records events with at least one photon with $E^{CMS} > 2$ GeV.
- Tracking layers extend radially from 1.4 - 111.14 cm.
- Displaced vertex (V^0) reconstruction via:

  Track finding → Vertex constrained fit

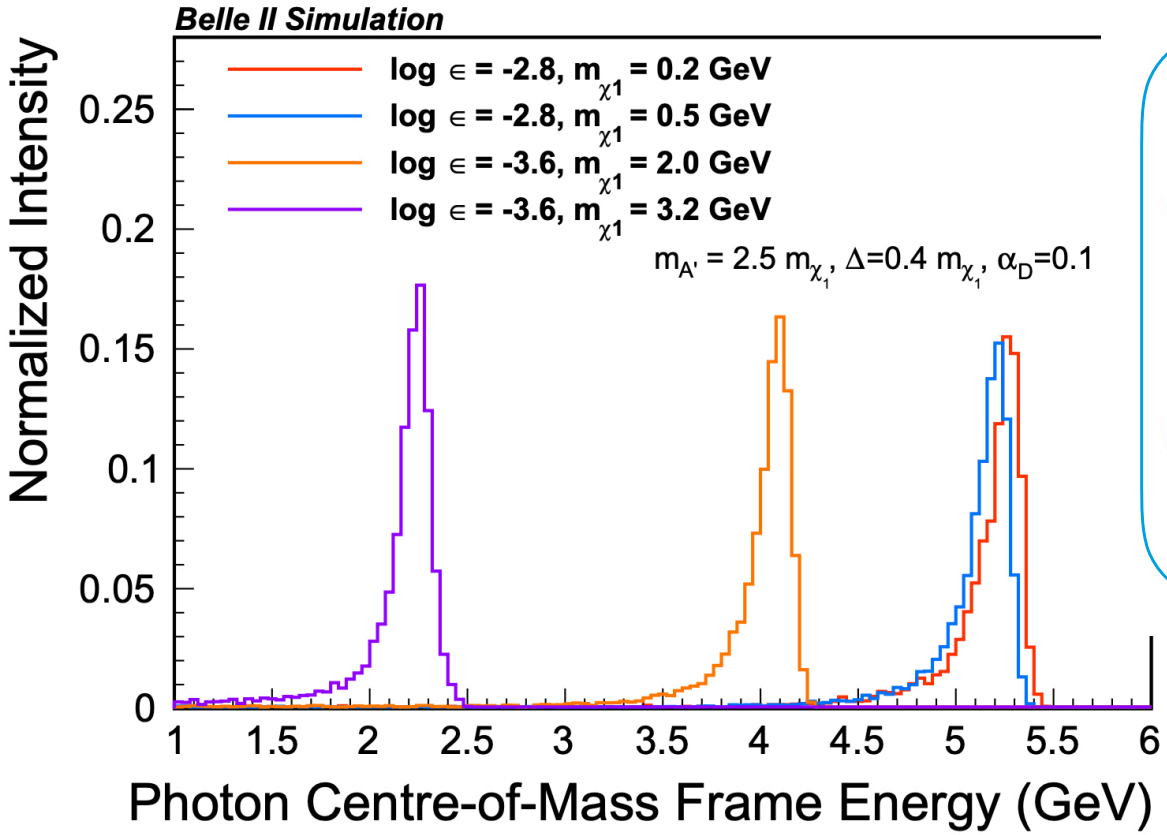
Tracking Detectors:

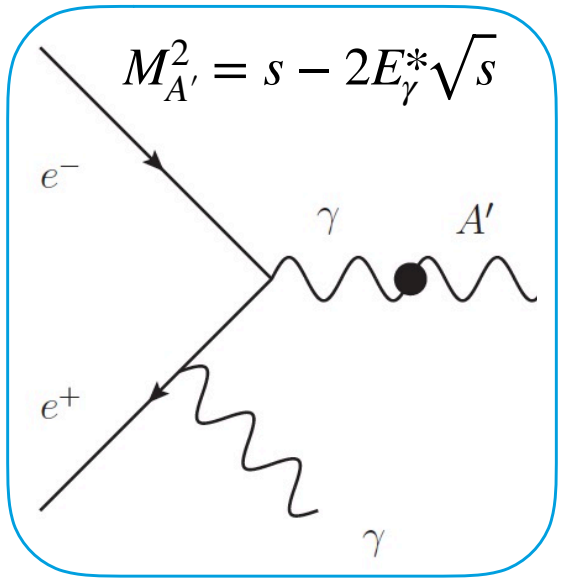


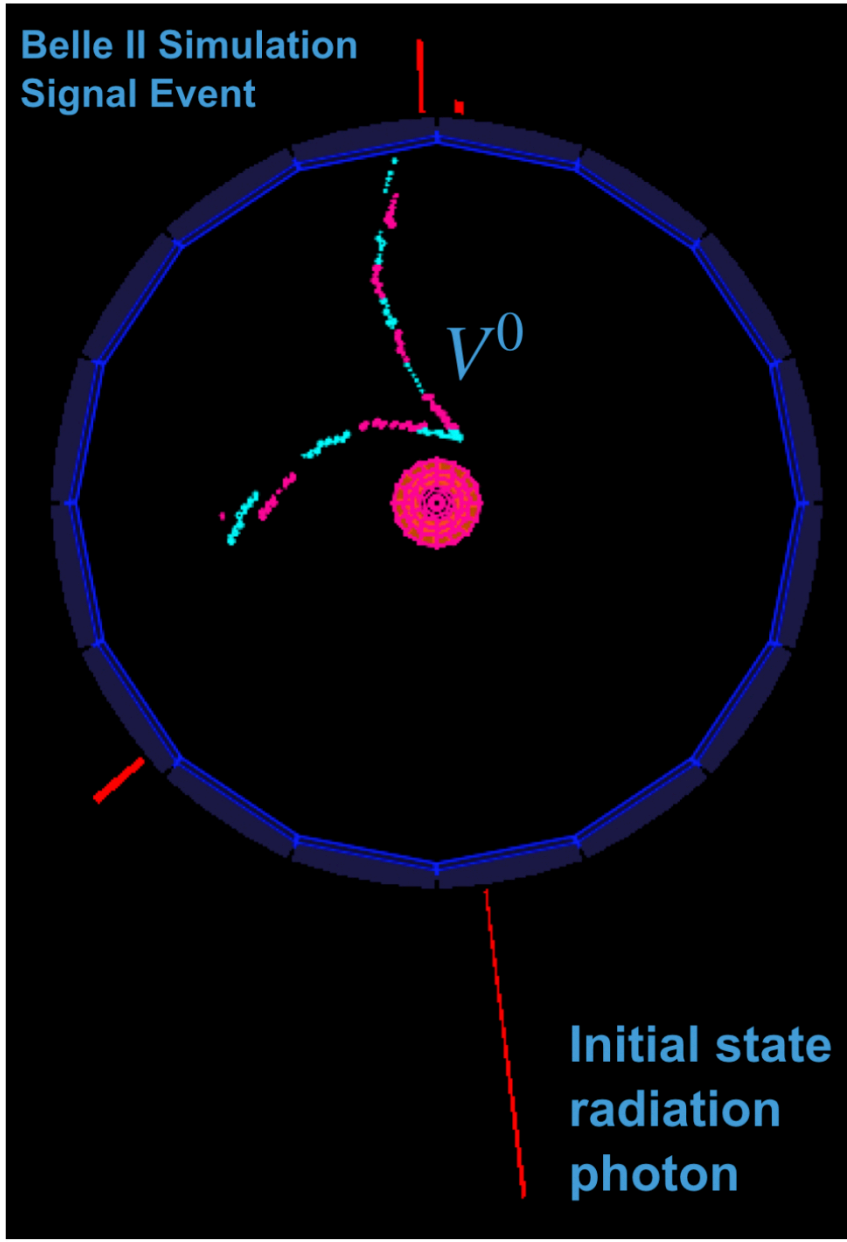


iDM Belle II Detector Signature

- Distinct detector signature containing:
  - ➡ Initial state radiation photon
  - ➡ Displaced vertex which is non-pointing
  - ➡ Missing energy
- Analysis Strategy: Background suppression via V^0 then search for localized peak in distribution of photon energy in CMS frame.



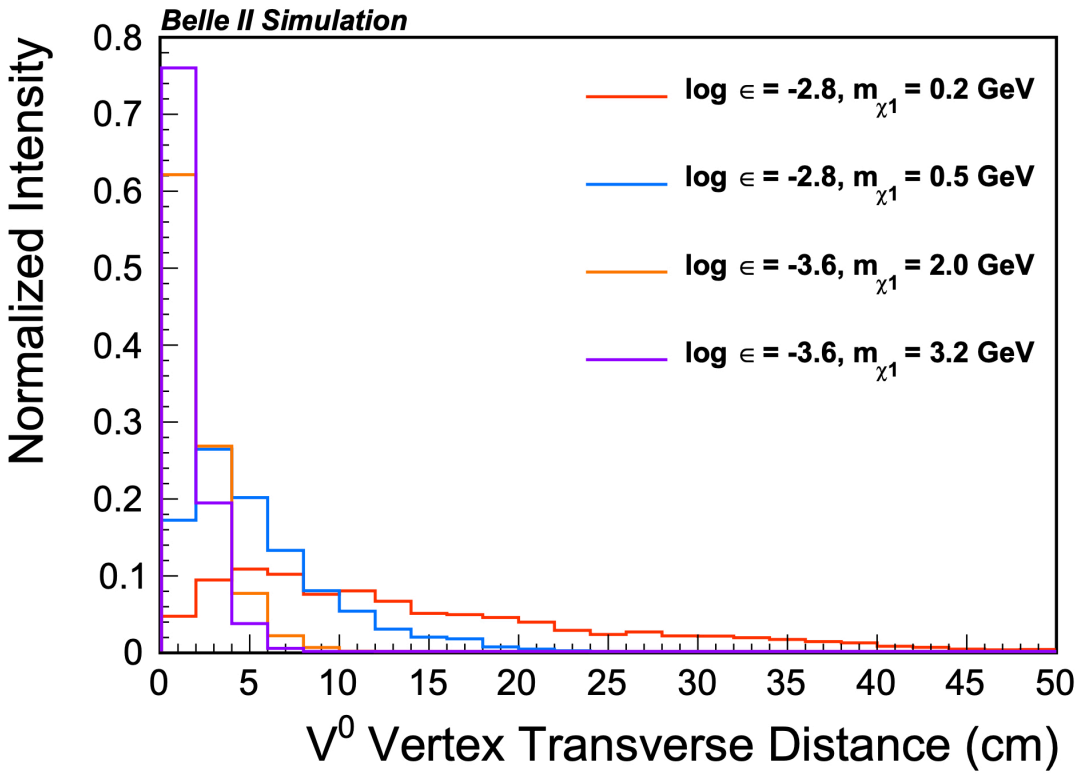


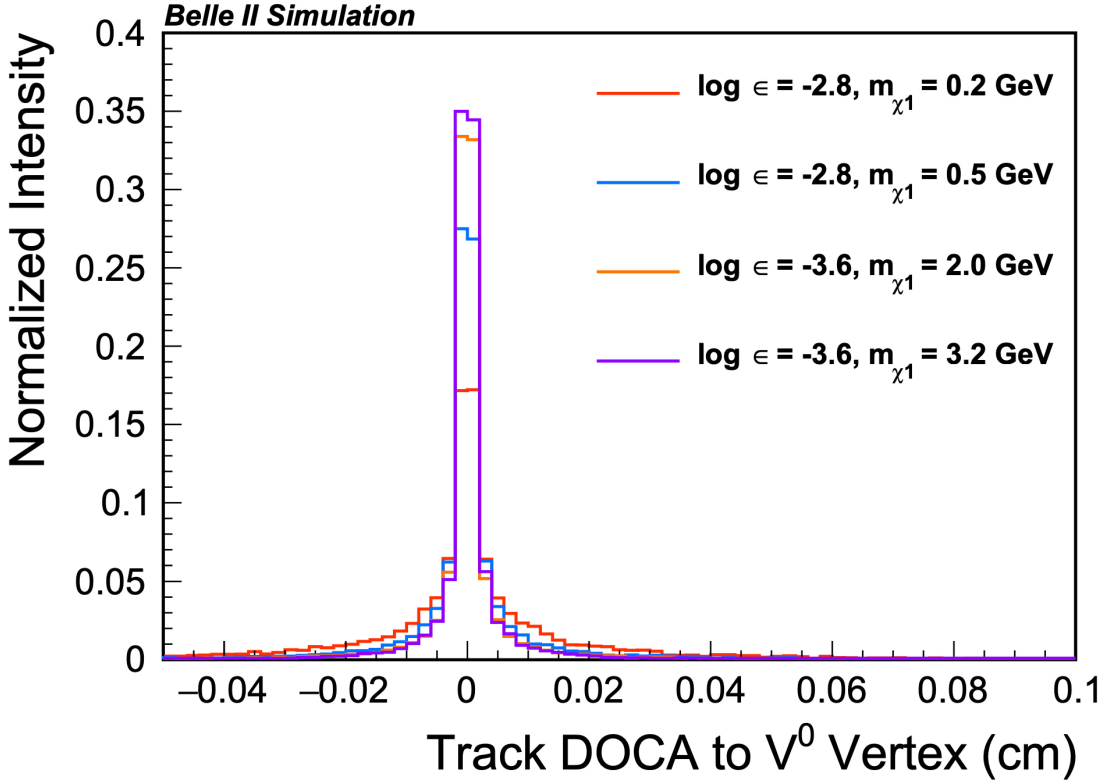


iDM V^0 Reconstruction

- Analysis covers range of χ_2 decay lengths. Selection requires V^0 transverse displacement of > 0.5 cm.
- Track Distance of Closest Approach (DOCA) peaks at zero, demonstrating V^0's are well reconstructed.
  - ➡ Track finding of <0.1 GeV/c tracks with large displacements challenging, limits reach for $\Delta/m_{\chi 1} < 0.2$ models.
- Additional quality requirements:
  - ➡ Vertex is in central region with good tracking coverage.
  - ➡ Radius of first tracking detector layer of tracks is not before vertex location.

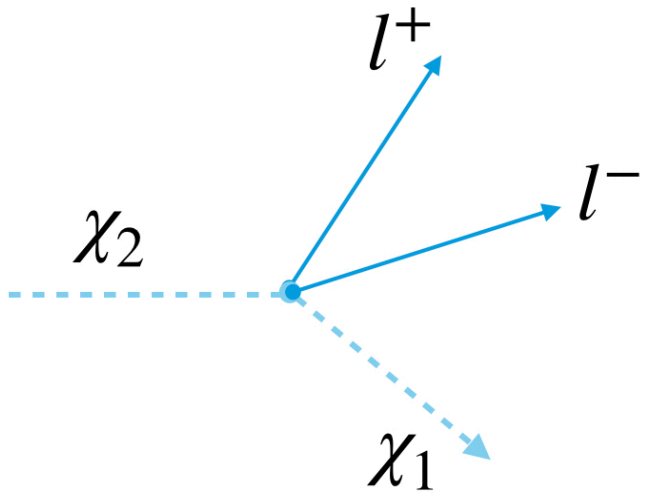
$$\chi_2 \rightarrow \chi_1 l^+ l^-$$

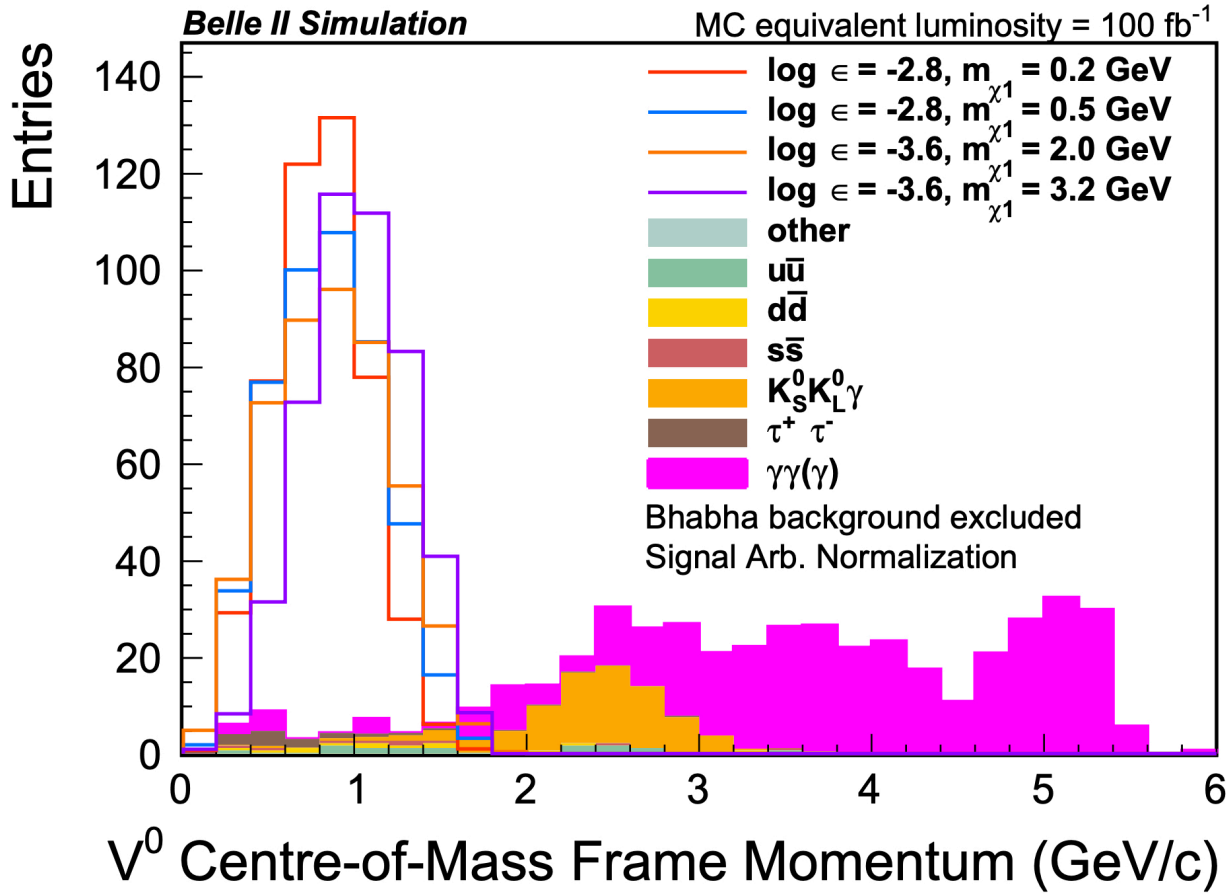




Background Suppression

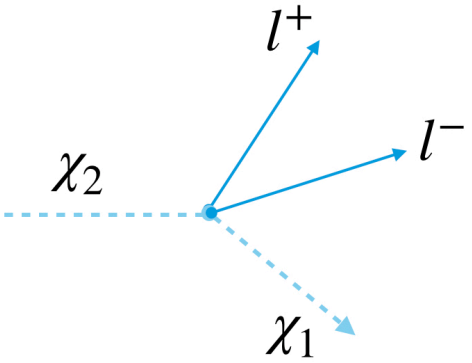
- Displaced l^+l^- vertex rejects significant majority of prompt $e^+e^- \to f^+f^-(\gamma)$ backgrounds.
- Backgrounds with displaced signatures arise from:
  - ➡ $e^+e^- \to \gamma\gamma(\gamma)$: Photon conversion or photo-nuclear interactions
  - ➡ $e^+e^- \to K_S^0 K_L^0(\gamma)$: K_S^0 decays
- Plot shows V^0 momentum after selection, excluding cut on V^0 momentum.
- Undetected χ_1 emitted in $\chi_2 \to \chi_1 l^+l^-$ lowers momentum of signal V^0 relative to backgrounds.

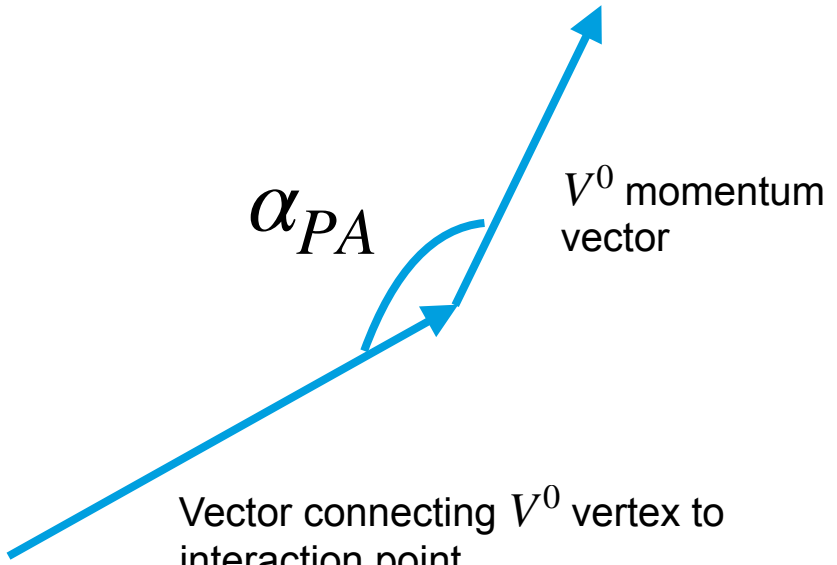


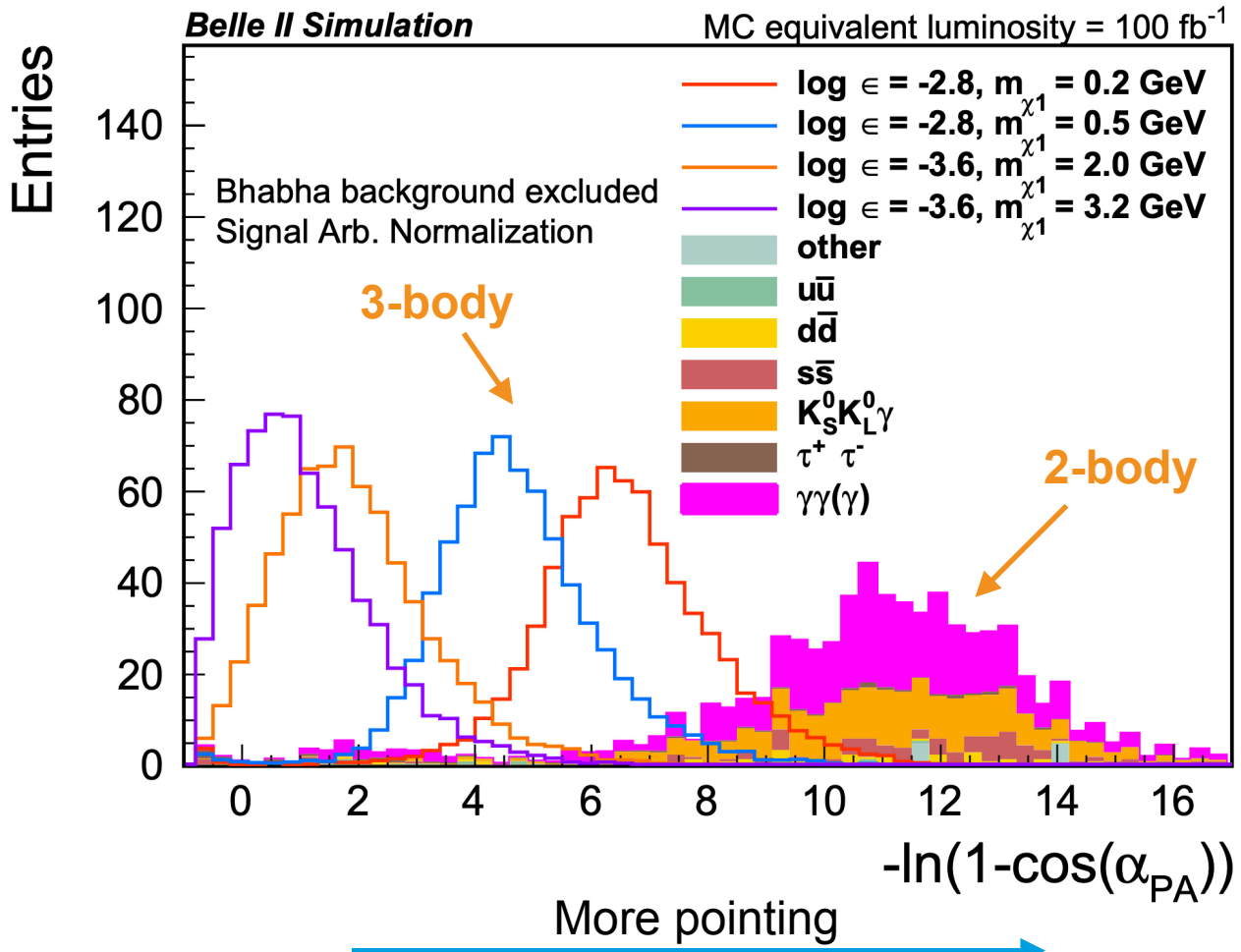


V^0 Pointing Angle

- Pointing angle, α_{PA}, is power tool for background suppression.
  - ➡ Plot shows V^0 pointing angle after selection, excluding cut on pointing angle.
- Background V^0's are mainly from 2-body processes.
- 3-body nature of iDM decay produces a non-pointing V^0.
- Significant suppression of K_S^0 and photon conversions achieved without mass window veto.



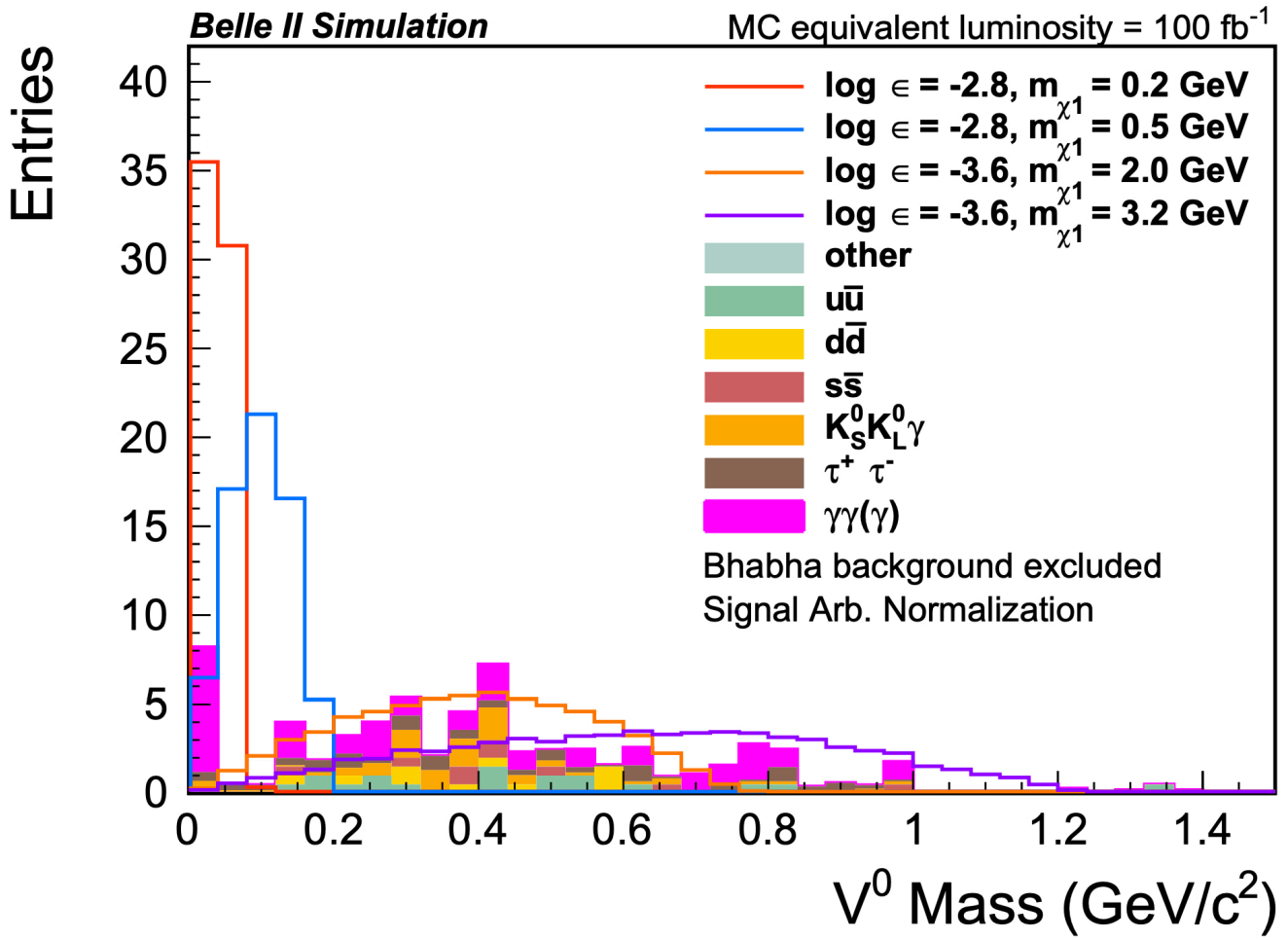




Remaining Background and V^0 Mass Threshold

- Distribution of V^0 invariant mass shown for backgrounds after selection with different signal models overlaid.
- Source of V^0 in backgrounds remaining after selections found to be:
  - ➡ $e^+e^- \to \gamma\gamma(\gamma)$: Photon conversion (peak at zero) or photo-nuclear interactions (high mass)
  - ➡ $e^+e^- \to K_S^0 K_L^0(\gamma)$: K_S^0 decays

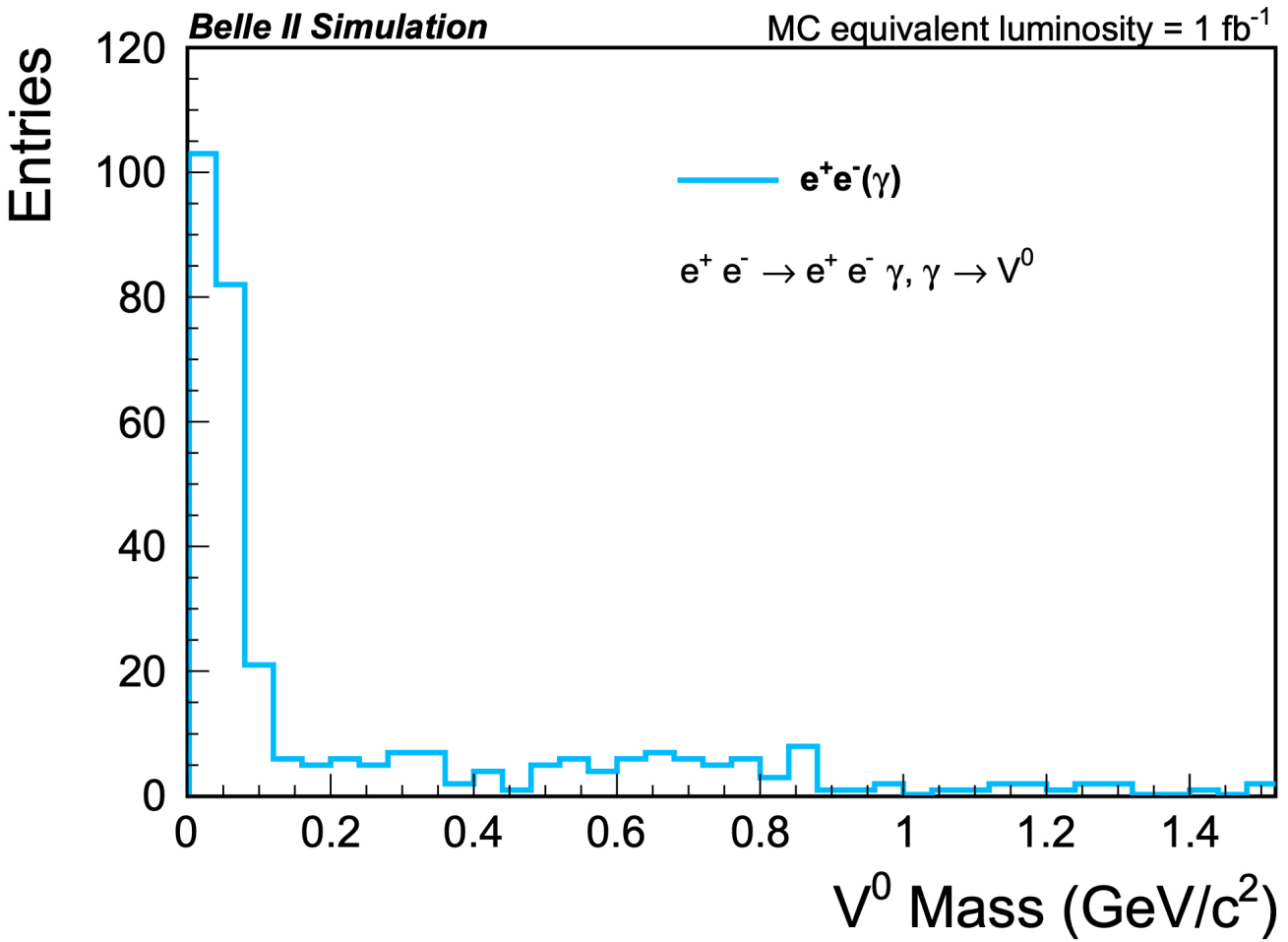
- V^0 mass distribution of signal has property that $m_{V^0} < \Delta$, where $\Delta = m_{\chi 2} - m_{\chi 1}$
  - ➡ Maximize sensitivity to given iDM model by final cut of $m_{V^0} < \Delta$ to reject backgrounds with high mass V^0's.



Data Validation Strategy

- V^0's in remaining $e^+e^- \to \gamma\gamma(\gamma)$ background originate from photon conversion or photo-nuclear interaction.
- Data validation ongoing with control sample: $e^+e^- \to e^+e^-(\gamma), \gamma \to V^0$

- Plot shows simulation prediction for invariant mass of V^0's selected in control sample.
- Control sample will be used to validate in data and simulation,
  - ➡ Rates of V^0's from photons which pass iDM selection
  - ➡ V^0 momentum and position resolutions
  - ➡ Potential for material map veto



Inelastic Dark Matter Belle II Prospects

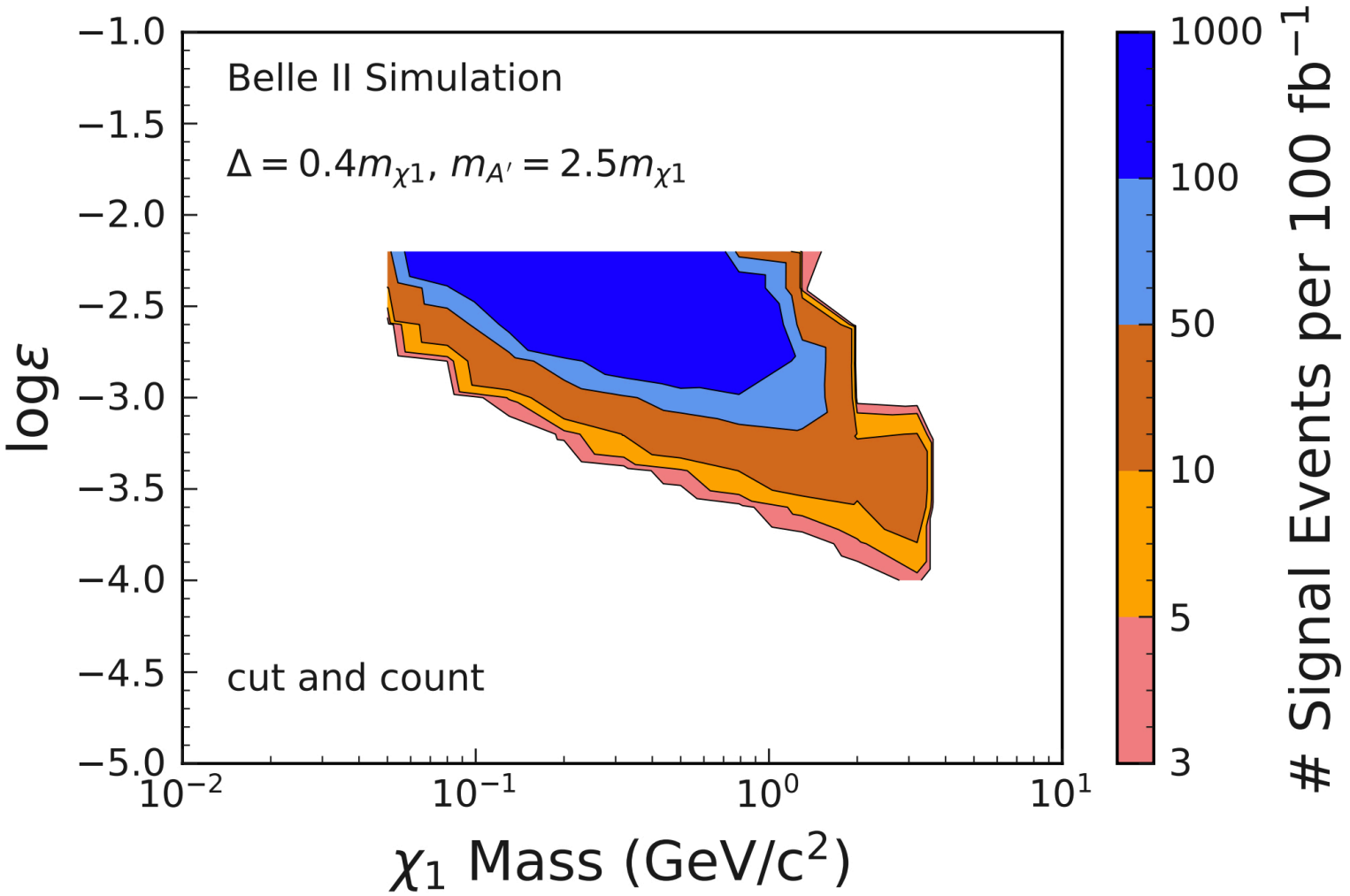
- Signal yield estimated per $100\ \text{fb}^{-1}$ determined by counting number of signal events in ISR photon window. Note final analysis plans to perform template fit of ISR photon energy spectrum to measure yield.

- Drop in yield at small epsilon driven mainly by cross section.

- Maximum reach of χ_1 mass limited by 2 GeV trigger threshold.

  ➡ New Belle II displaced vertex trigger under consideration to extend reach.

- Predictions consistent with [1], Belle II can explore large region of new iDM parameter space.



Conclusions

- Belle II search for inelastic Dark Matter is enabled by new low multiplicity high energy photon triggers.
- iDM features a long-lived particle detector signature.
- Displaced vertex from LLP decay allows for significant background suppression.
- Primary background component after selections is from $e^+e^- \to \gamma\gamma(\gamma)$, data validation studies ongoing using $e^+e^- \to e^+e^-(\gamma), \gamma \to V^0$.
- Using 2020/2021 dataset, Belle II plans to explore new regions of iDM parameter space.