Searches for long-lived particles at the $\Upsilon(4S)$

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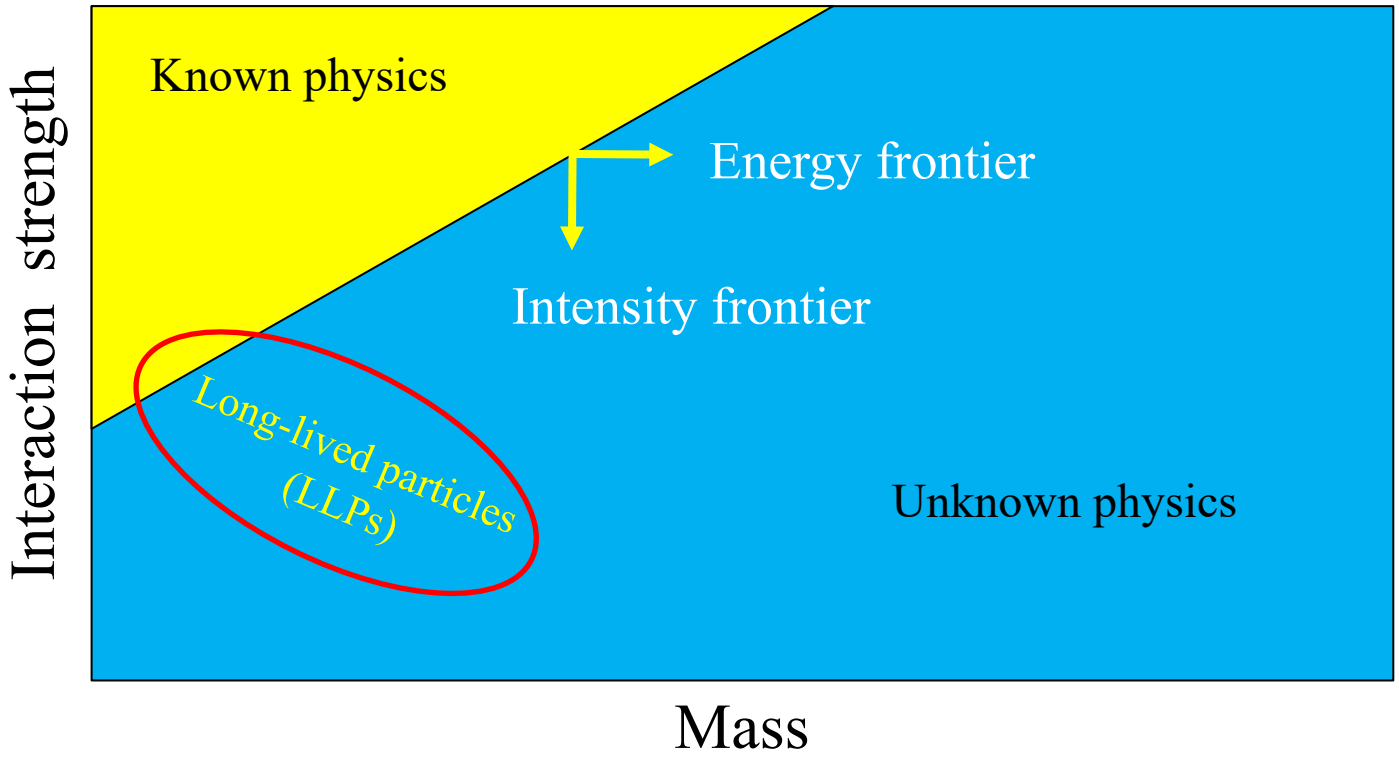
Outline

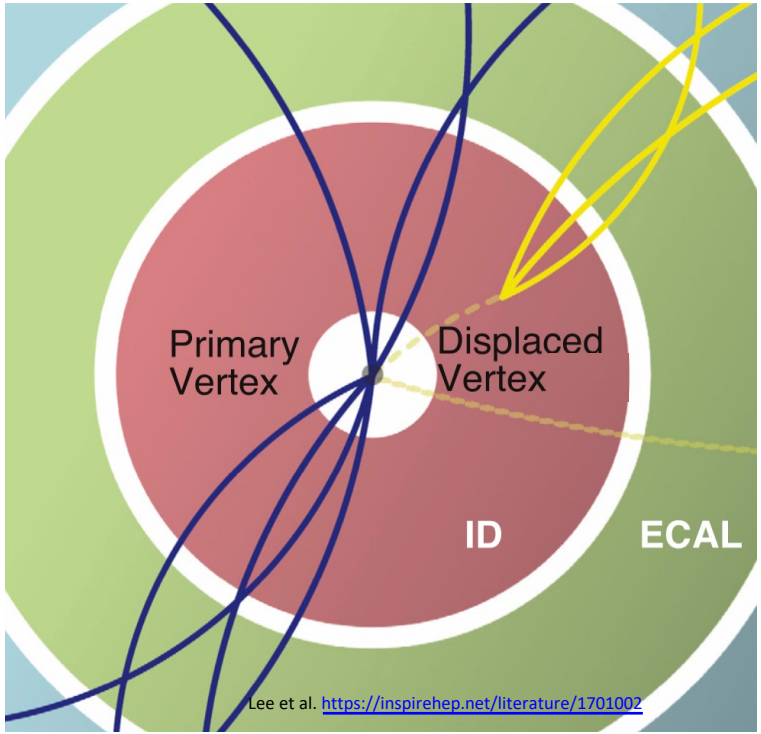
- Long-lived particles (LLPs) in the SM and beyond the SM (BSM)
- The $\Upsilon(4S)$ environment and relevant facilities
- Selected LLP searches at $\Upsilon(4S)$ facilities
- Selected proposals for new searches
- Conclusions

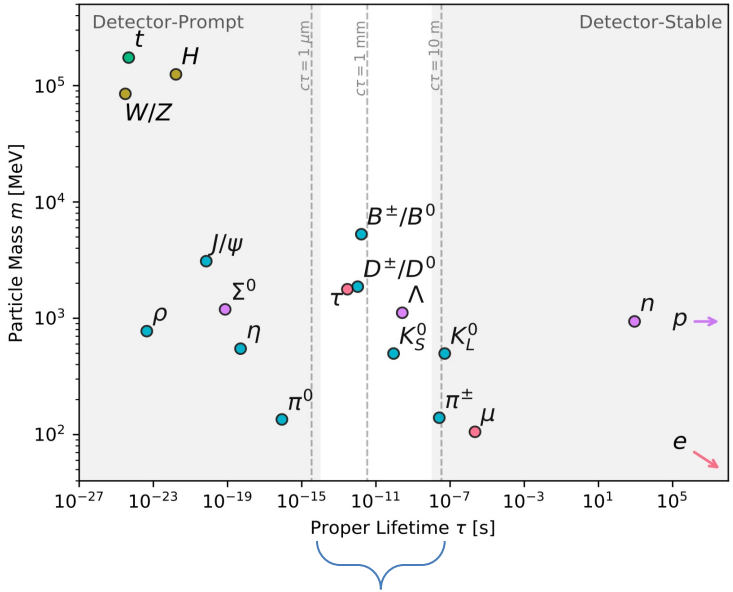
Where to search for new physics



Long-lived particles (LLPs)

LLPs: decay in the inner detector tracking volume, forming a displaced vertex (DV):

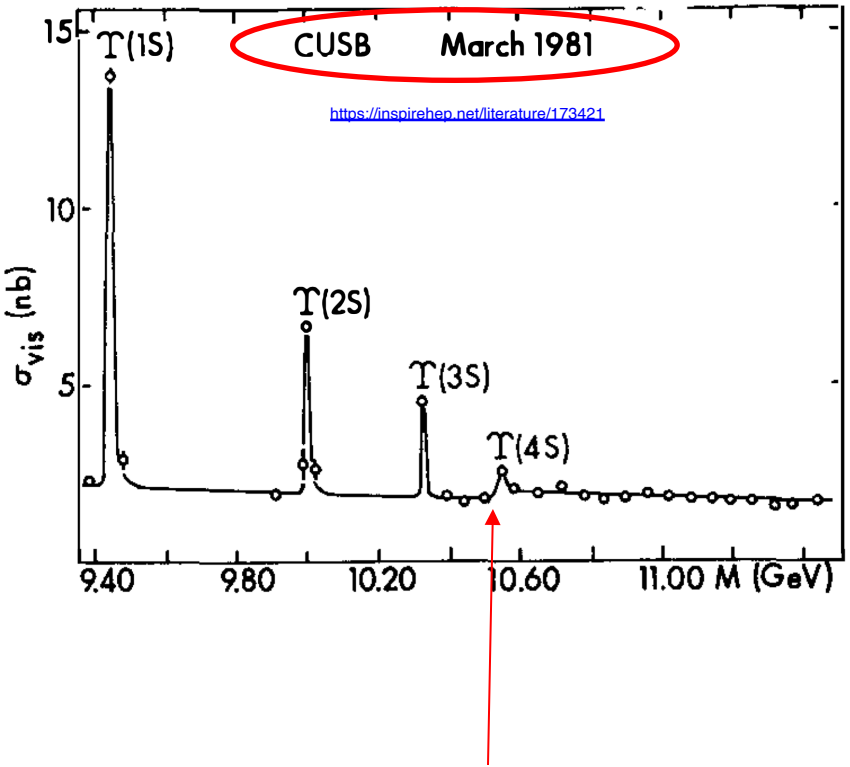




The SM also has LLPs, but few.

Therefore, the DV signature strongly suppresses background.

… at the the $\Upsilon(4S)$



Cross sections at the $\Upsilon(4S)$

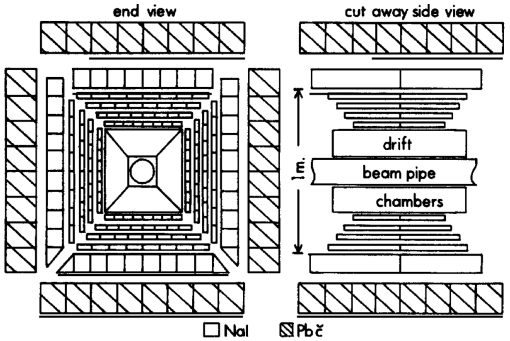
- $e^+e^- \to B\bar{B}$: 1.1 nb
- $e^+e^- \to c\bar{c}$: 1.3 nb
- $e^+e^- \to \tau^+\tau^-$: 0.9 nb
- QED processes, e.g., $e^+e^- \to \gamma\gamma$

Various options for BSM-particle searches.

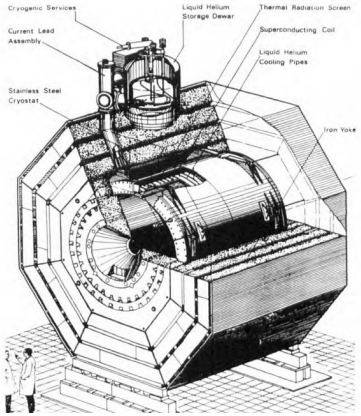
$e^+e^- \to \Upsilon(4S)$ experiments

Gen 1

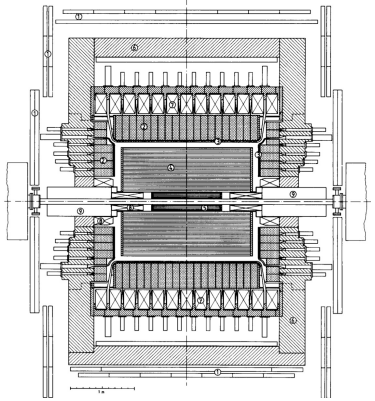
CUSB 1979-1990



CLEO 1979-2003

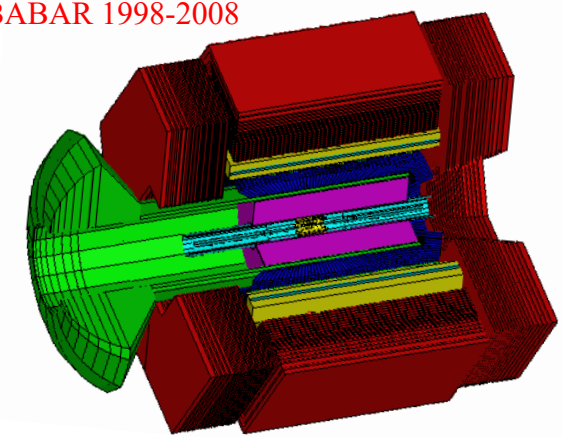


ARGUS 1982-1992

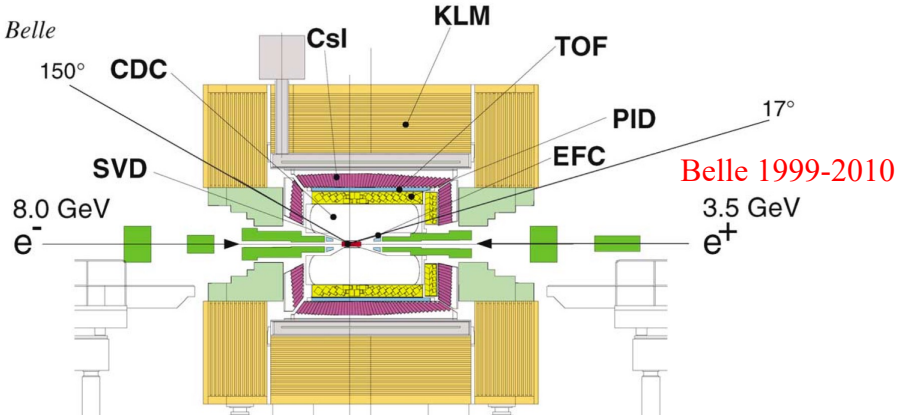


Gen 2
(B factories)

BABAR 1998-2008



Belle 1999-2010

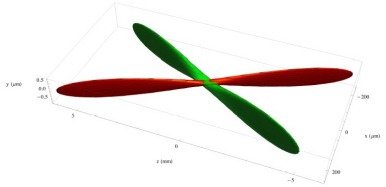


Belle II (since 2018)

SuperKEKB collider

Design $L = 6{\times}10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

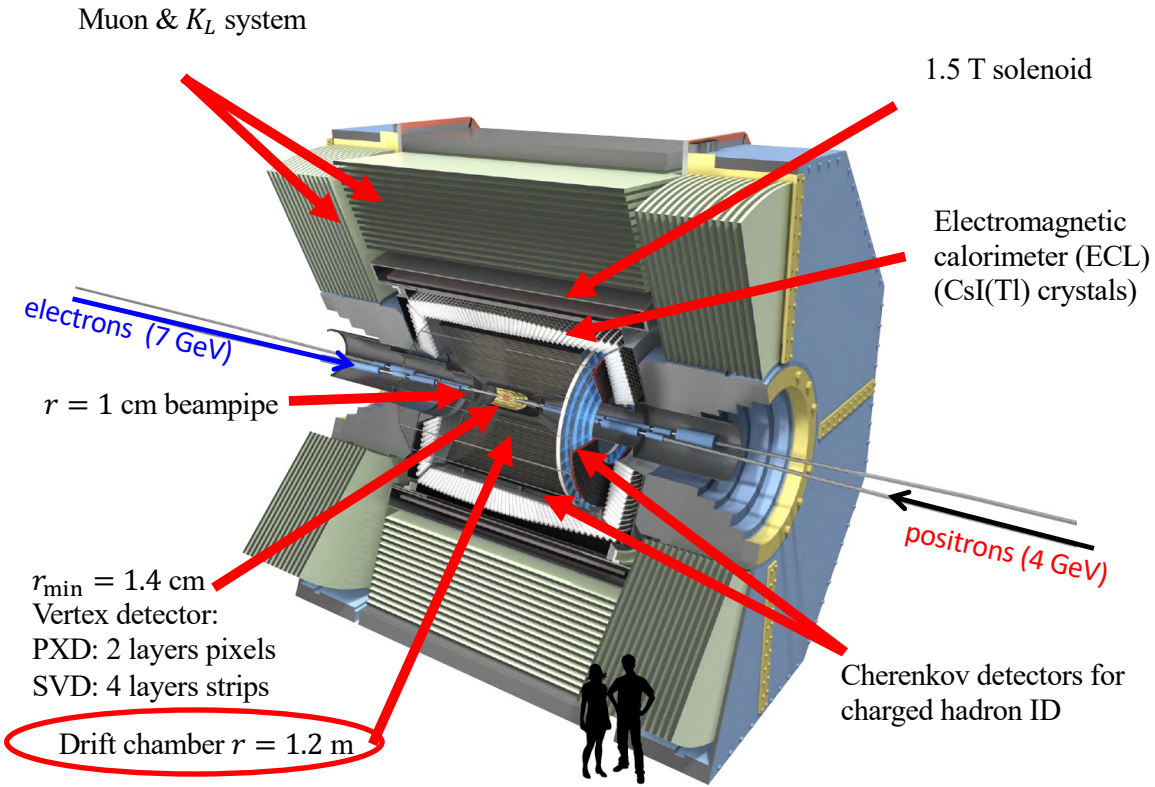
Design $\int L\,dt = 50\ \mathrm{ab}^{-1}$



Beamspot size

$6 \times 0.06 \times 150\ \mu\mathrm{m}^3$

Belle II detector

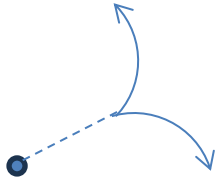


Selected completed searches

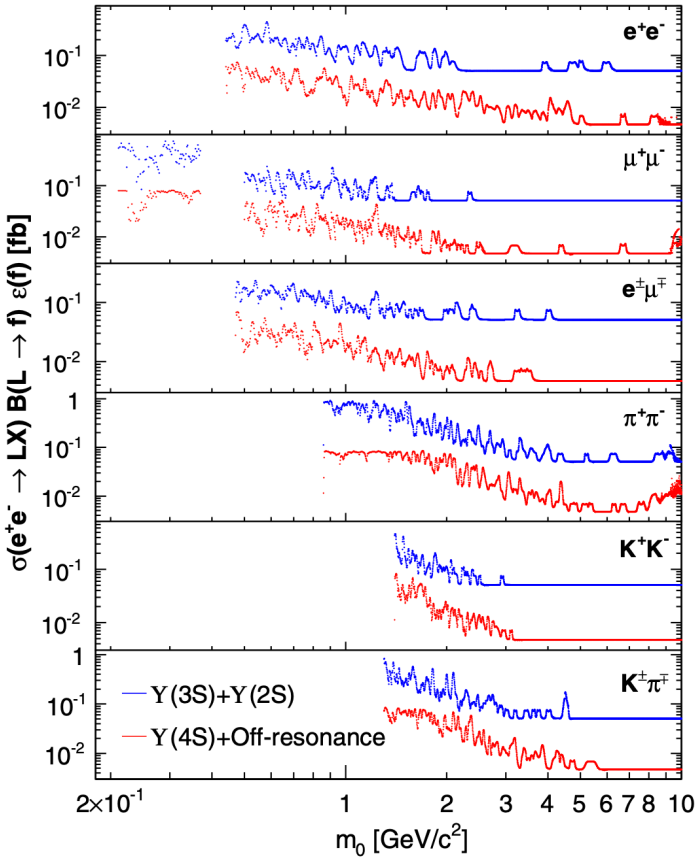
Generic LLP decaying to two charged particles

BABAR, PRL 114, 171801 (2015)

- $\int L\,dt = 489\ \text{fb}^{-1}$
- Required:
  - 2-lepton or 2-hadron vertex significantly displaced from interaction point (IP)
  - 2-track momentum pointing back to the IP



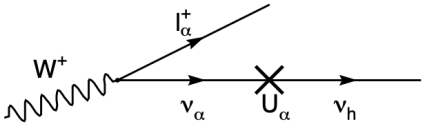
- Model-independent interpretation: assuming only that the LLP decays to two charged particles
- Set limits on the product of cross section and branching fraction by track species

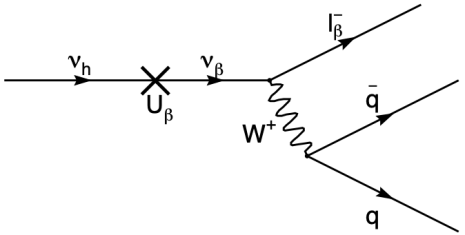


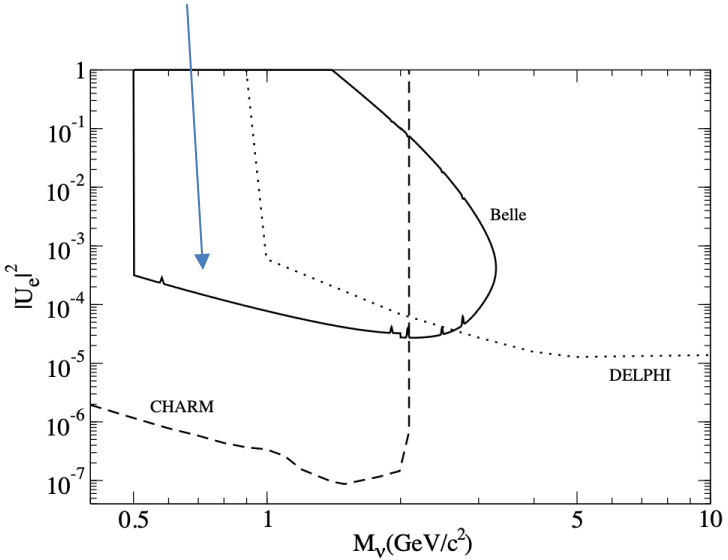
Long-lived heavy neutral lepton (HNL)

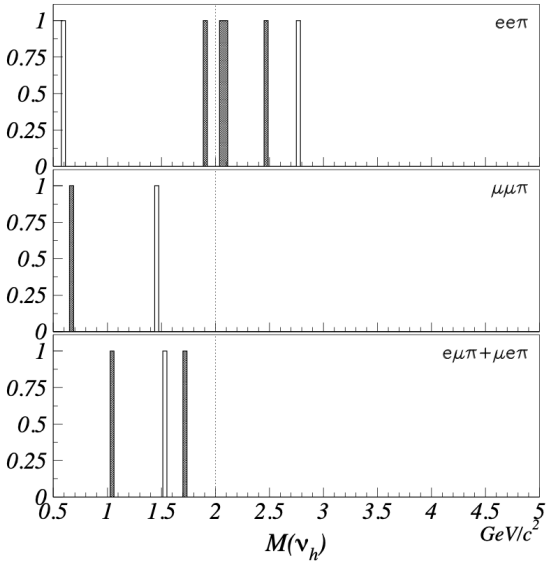
Belle PRD 95 (2017) 099903

- HNL produced from W^* in meson decay via mixing with ν
- Very little background
- Limits mostly covered by previous experiments





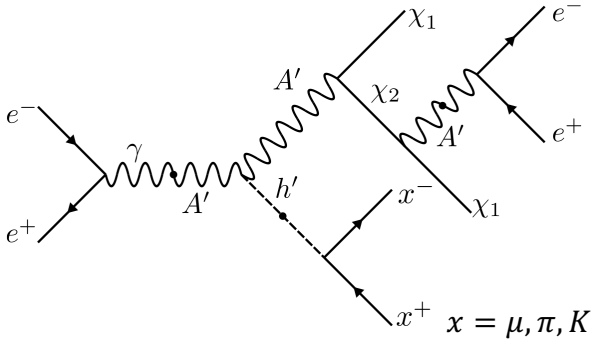




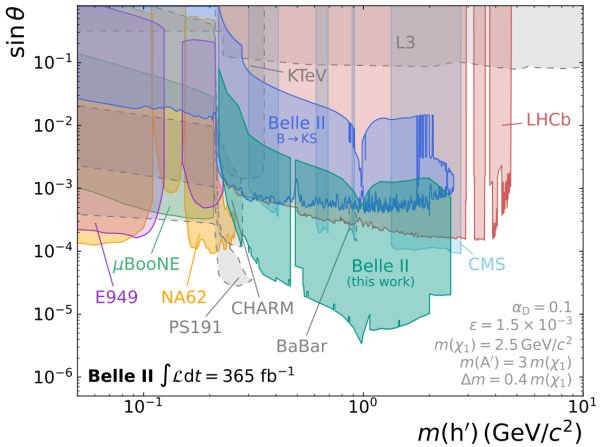
Dark photon and Higgs with inelastic dark matter

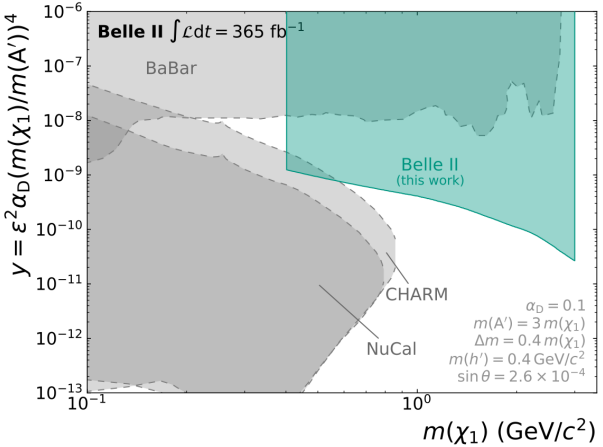
Belle II, PRL 135, 131801 (2025)

- 365 fb^{-1}
- Require:
  - 4 tracks, at least 1 DV
  - DVs point back to the IP
  - Missing energy
- Find: 8 $\pi^+\pi^-$, 1 K^+K^-, 0 $\mu^+\mu^-$ events, consistent with background.



- Tight limits on →
  - dark-SM Higgs mixing
  - dark-sector U(1) coupling





Selected proposed searches

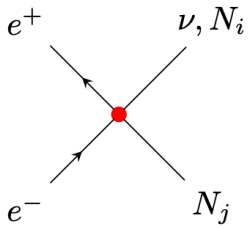
2 heavy neutral leptons within νSMEFT

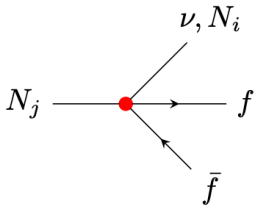
Bolton et al., 2609.04332

- Consider effective operators advantageous for HNL production in e^+e^- collisions

$\psi^2 X$	
Q_{NNB}	$g'(\bar{N}^c\sigma^{\mu\nu}N)B_{\mu\nu}$

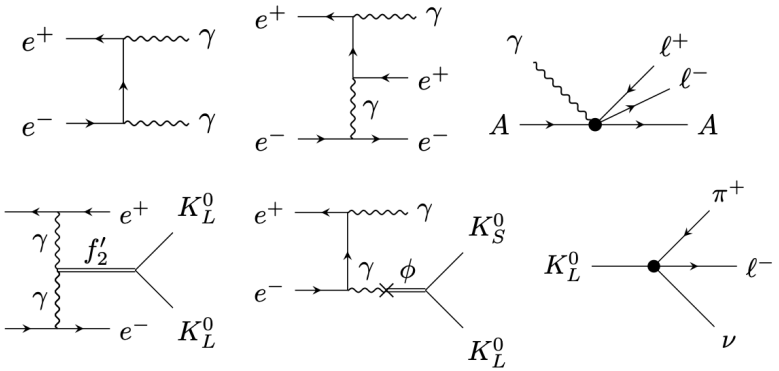
$\psi^2 HX$		ψ^4	
Q_{NB}	$g'(\bar{l}\sigma^{\mu\nu}N)\tilde{H}B_{\mu\nu}$	Q_{lN}	$(\bar{l}\gamma_\mu l)(\bar{N}\gamma^\mu N)$
Q_{NW}	$g(\bar{l}\sigma^{\mu\nu}\tau^I N)\tilde{H}W^I_{\mu\nu}$	Q_{eN}	$(\bar{e}\gamma_\mu e)(\bar{N}\gamma^\mu N)$
$\psi^2 H^2 D$		Q_{lNle}	$(\bar{l}^j N)\epsilon_{jk}(\bar{l}^k e)$
Q_{HN}	$(\bar{N}\gamma_\mu N)(H^\dagger i\overleftrightarrow{D}^\mu H)$		
Q_{HNe}	$(\bar{N}\gamma_\mu e)(\tilde{H}^\dagger iD^\mu H)$		





- Suggest to require events with only a dilepton DV, missing energy, & minimal calorimeter activity

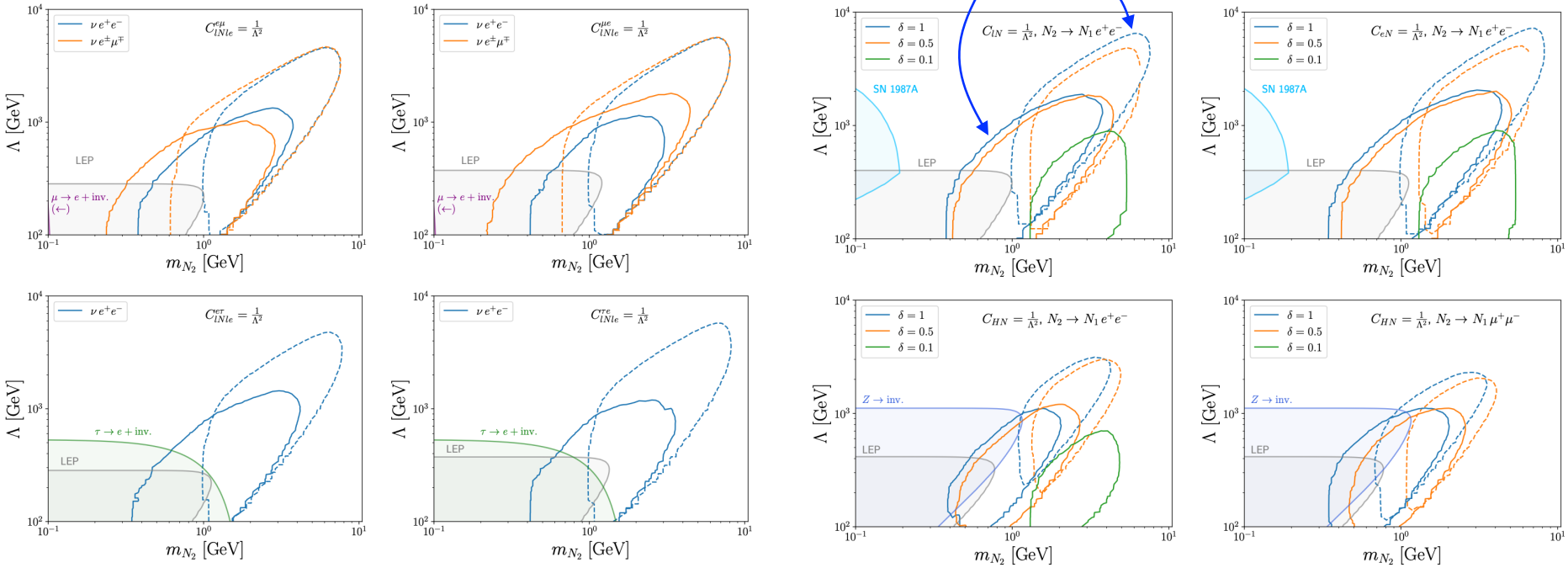
- Cuts to suppress background from γ conversion, K_L^0 decays:



2 heavy neutral leptons within νSMEFT

Bolton et al., 2609.04332

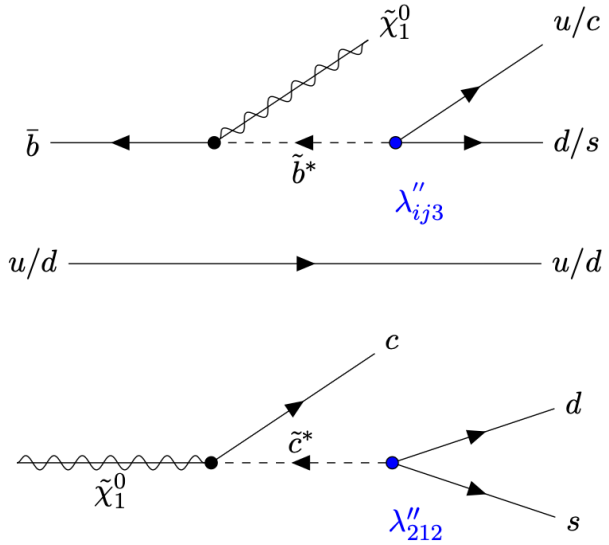
- High sensitivity expected:
  - Shown here for 50 ab^{-1}
  - But sensitivity for 1 ab^{-1} is only 2.7 times weaker



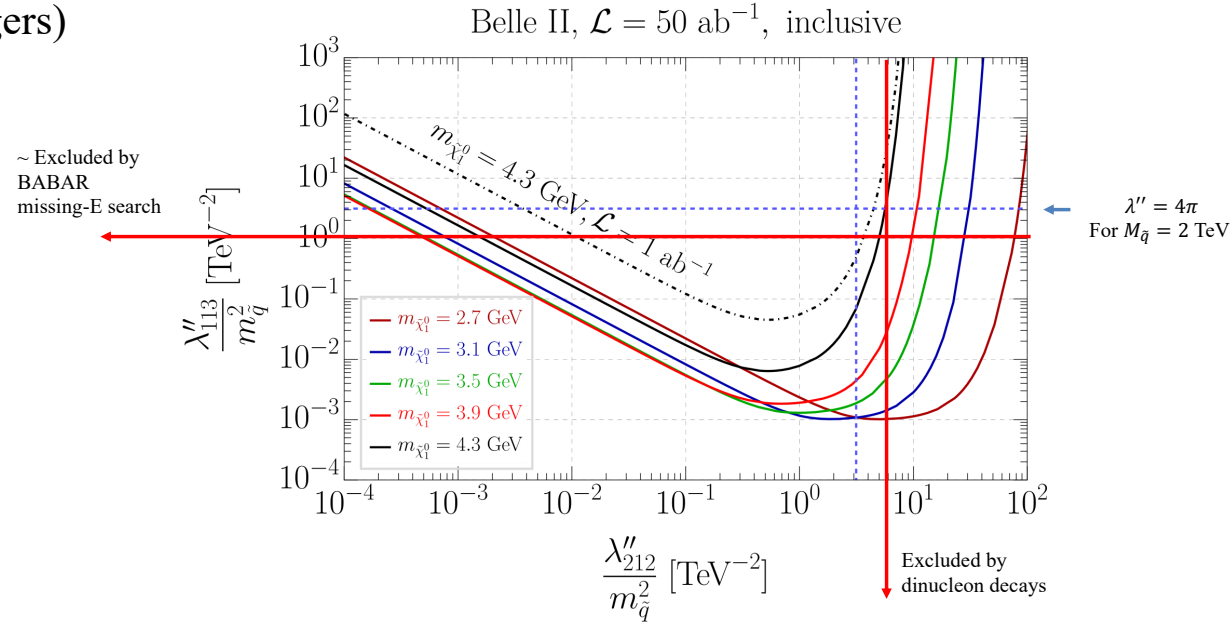
Long-lived neutralinos with R-parity violation

Bertholet et al. JHEP 10 (2025) 076

- Scenario:
  - Squarks heavier than LHC limits (1.85 TeV)
  - RPV
  - ~ GeV $\tilde{\chi}_1^0$ (too light for LHC triggers)

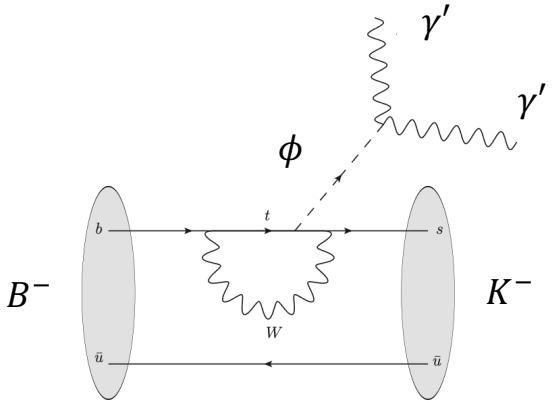


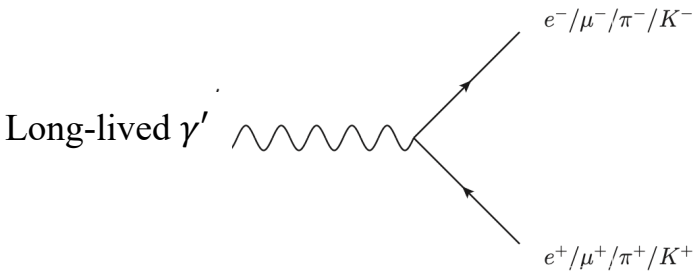
High sensitivity
(tight projected limits):



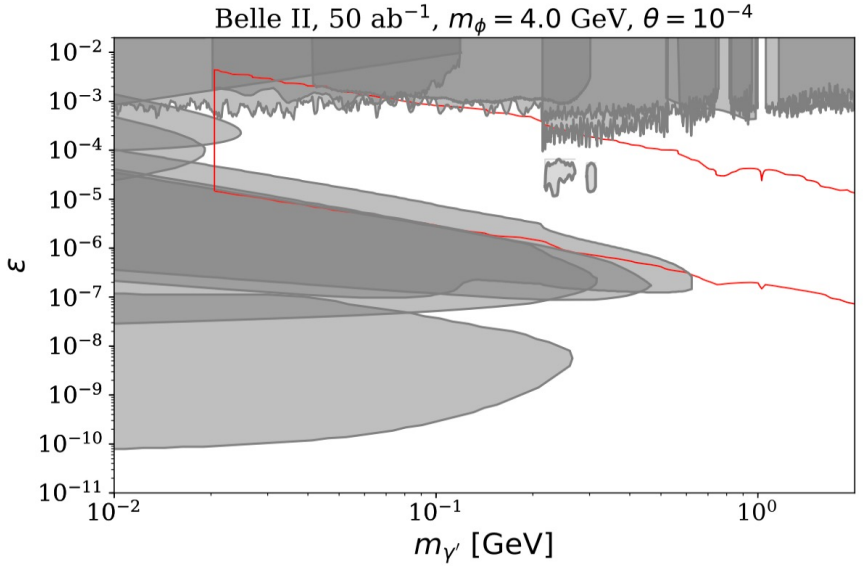
Long-lived dark photon with a dark Higgs

Cheung et al. JHEP 05 (2024) 094



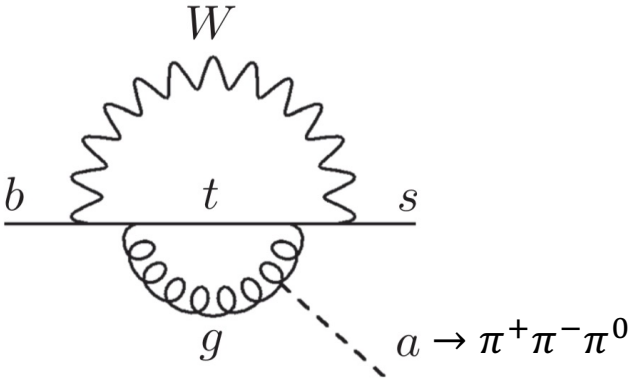


- Strong background suppression:
  - full reconstruction of a B^- meson
  - at least 1 DV from the long-lived dark photons
- Sensitivity to dark-photon kinetic mixing:



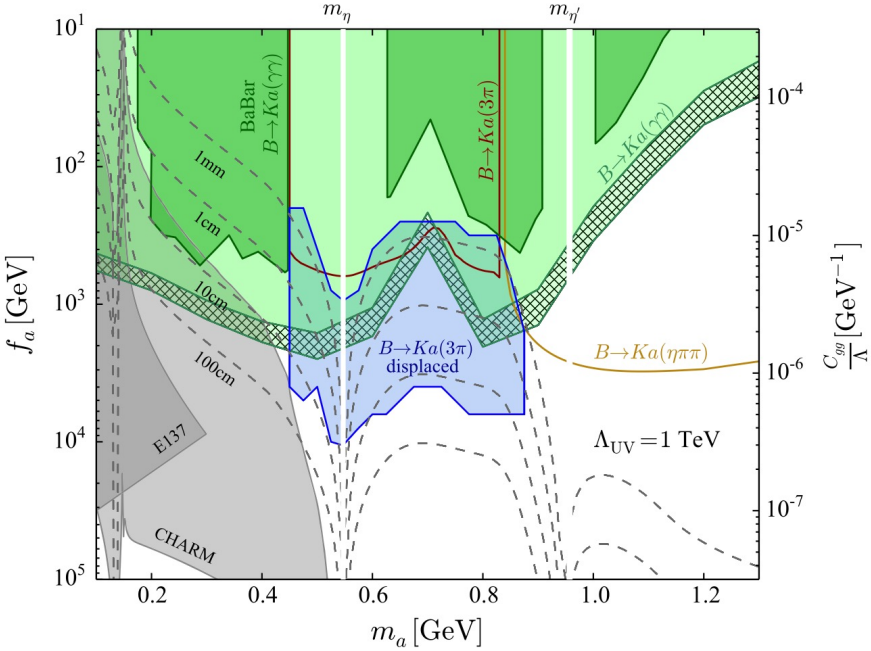
Long-lived axion

Bertholet et al. PRD 105, L071701 (2022)



- Strong background suppression:
  - full reconstruction of a B^- meson
  - DV from the axion

- High expected sensitivity highlights advantage of an LLP search:



Conclusions

- $e^+e^- \rightarrow \Upsilon(4S)$ machines ("B factories") can perform unique BSM particle searches
  - e^+e^- annihilations
  - B-meson decay
  - τ-lepton decay
- Searches for long-lived particles enable strong background suppression → high sensitivity
- Belle II has started exploring this landscape
- New ideas and proposals are constantly created
  - Note: Belle II also performs BSM-particle searches not involving a DV, not included in this talk