Searching for long-lived particles at Belle II

Zeren Simon Wang 王泽人 (合肥工业大学 HFUT)

ALP: JHEP11(2021)218

Dark photon: JHEP05(2024)094

HNL: JHEP04(2022)057

RPV Bino: JHEP02(2023)224

September 20th, 2025

第四届高能物理理论与实验融合发展研讨会

中国辽宁大连

合肥工業大學
HEFEI UNIVERSITY OF TECHNOLOGY

See also PRD111,035010(2025), JHEP02(2021)211, arXiv:2507.00359, EPJC85(2025)1,66

Motivation

- The LHC has been focusing on searches for heavy new particles; large p_T or MET; NO discovery so far
- Increasingly more attention given to signatures related to long-lived particles (LLPs), among others
- LLP: produced, travel a macroscopic distance, and decay
- Predicted in various BSM scenarios and well motivated
  - $m_\nu \neq 0$
  - DM
  - ...
- LLP candidates: axionlike particle, dark photon, heavy neutral leptons, RPV SUSY bino, inelastic DM, chargino (compressed SUSY), ...
- ALP: strong CP problem, DM candidate, hierarchy problem, EW baryogenesis, ...
- Dark photon: portal connecting visible and dark sectors, DM candidate, ...
- HNLs: non-vanishing neutrino masses (seesaw mechanisms), baryogenesis via leptogenesis, DM candidate, Majorana fermion, ...
- RPV SUSY bino: GeV-scale or even massless bino is allowed with RPV SUSY, hierarchy problem, anomalies, non-vanishing neutrino masses, ...

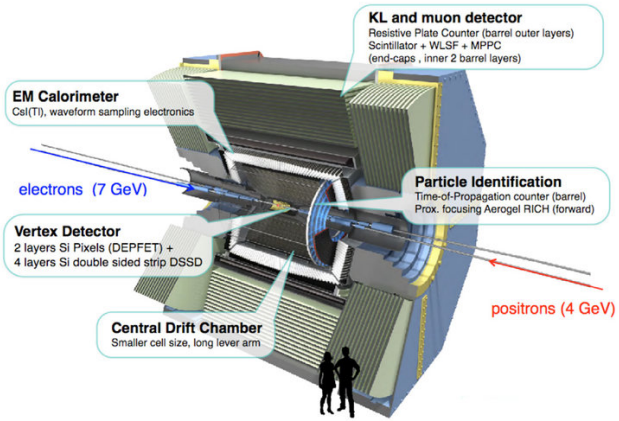
Long lifetime and LLP-search experiments

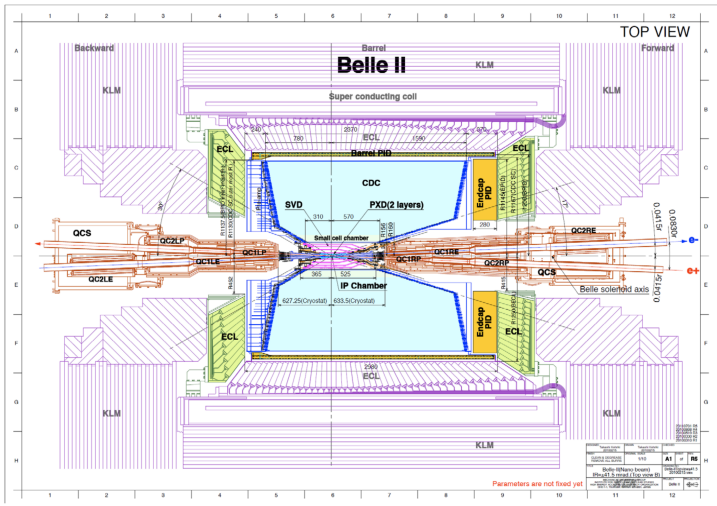
- Causes of the long lifetime:
  - **Feeble** couplings
  - **Heavy** mediators
  - **Small** phase space
  - ...
- Experiments:
  - Beam dumps: PS191, NA62, SHiP, DUNE, ...
  - Neutrino detectors: Super-Kamiokande, IceCUBE, ...
  - Colliders: LEP, BABAR, LHC, Belle II, ...
  - LHC far detectors: FASER(2), MoEDAL-MAPP1(2), MATHUSLA, CODEX-b, ...
  - ...
- Focus of the talk:

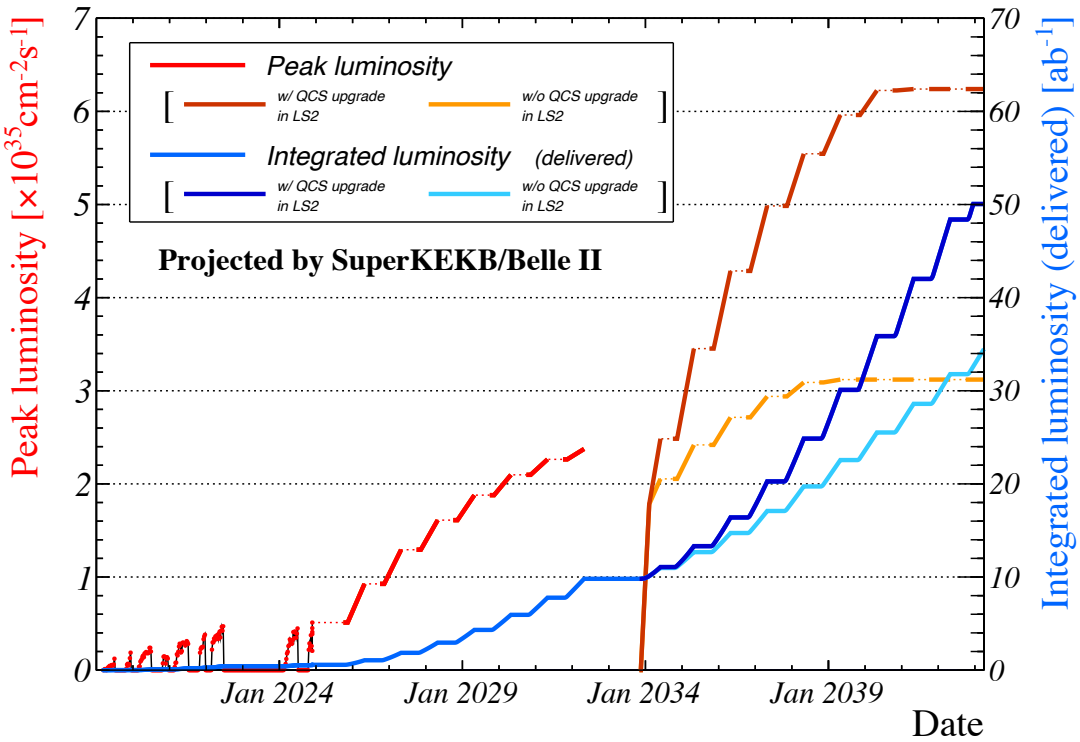
LLP searches at

The Belle II experiment

- Ongoing experiment at the SuperKEKB collider in Tsukuba, Japan
- $E_{e^-} = 7$ GeV & $E_{e^+} = 4$ GeV, $\sqrt{s} = 10.58$ GeV at $\Upsilon(4S)$, *mainly*
- Asymmetric



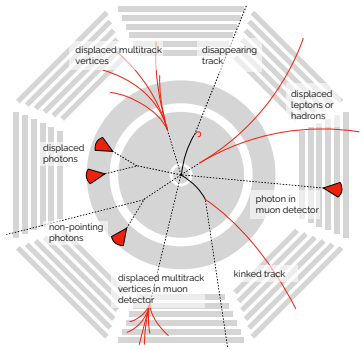




Belle II latest luminosity proj. (*as of Dec. 2024*)

Features of LLP search at Belle II

- Production modes: direct production, B-decays, τ-decays, ...
- Decay modes: leptonic, semi-leptonic, hadronic, ...
- Signatures: displaced vertex, $\not{E}$, displaced γ/ℓ, disappearing track, ...
- Pros:
  - Intensity frontier: $\mathcal{O}(10^{10})$ B and τ
  - Clean, low background levels in general
  - $e^- e^+$ collision, no PDF; initial-state 4-momentum known; full recon.
  - Low-energy $\Rightarrow$ probing large $c\tau$, for fixed $\beta\gamma c\tau \sim$ detector distance from the IP
  - Very low pileup
  - Testing low-mass NP which is usually hard to do at the ATLAS/CMS
  - *Ongoing* experiment, timely
  - ...
- Cons:
  - Not as many B's as at the LHC
  - Can't test high-mass LLP directly
  - No large forward boost to be exploited
  - ...

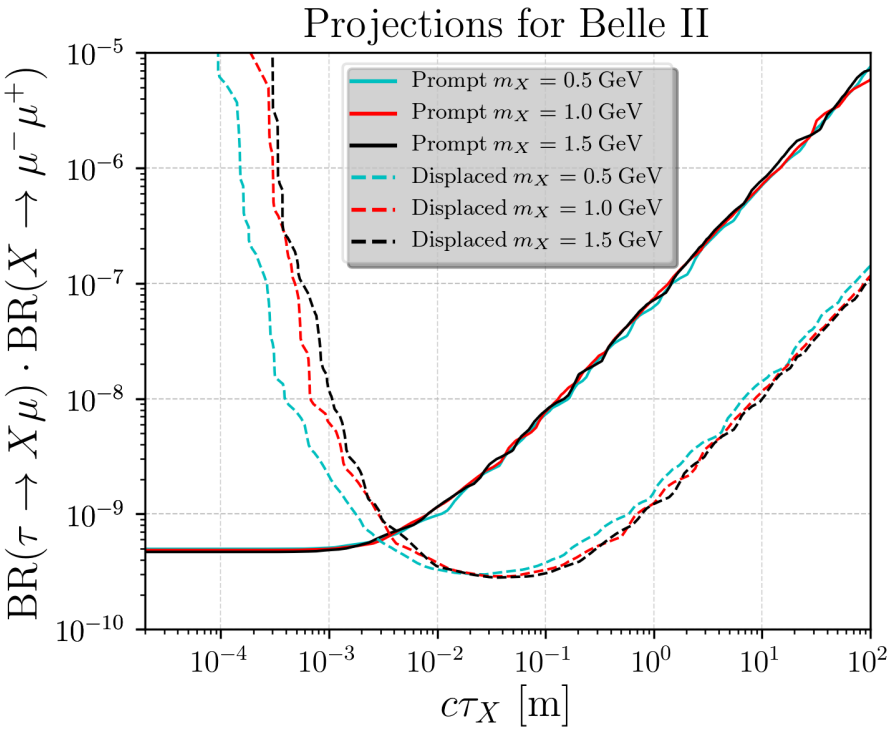


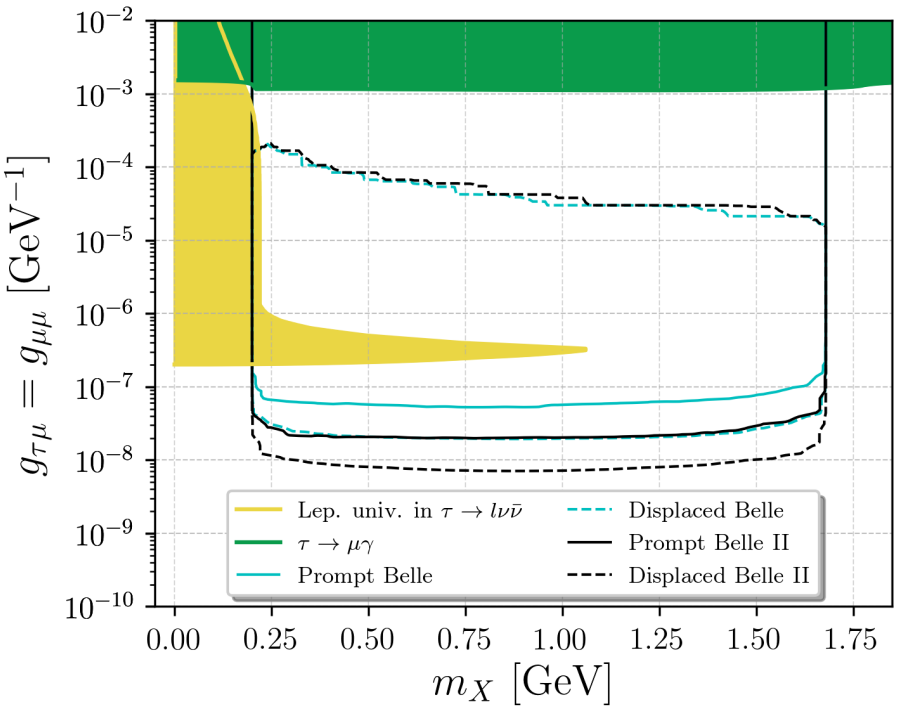
ALP with cLFV, DV

- JHEP11(2021)218
- cLFV: highly sensitive to NP
- Vanishing background
- Leptonic elec. dipole moment

$$\begin{aligned}\mathcal{L}_X &= \partial_\mu X \bar{l}_\alpha g_{\alpha\beta}\gamma^\mu(1+\gamma^5)l_\beta \\ &= -iX\bar{l}_\alpha g_{\alpha\beta}((m_\alpha - m_\beta)+(m_\alpha+m_\beta)\gamma^5)l_\beta\end{aligned}$$

- $(e^-e^+ \overset{\text{SM}}{\to} \tau^-\tau^+, \tau^- \overset{\text{SM}}{\to}$ 1 prong, $\tau^+ \overset{g_{\tau\mu}}{\to} X\mu^+, X \overset{g_{\mu\mu}}{\to} \mu^+\mu^-)$ and C.C.
- Recast a Belle prompt search and propose a DV search



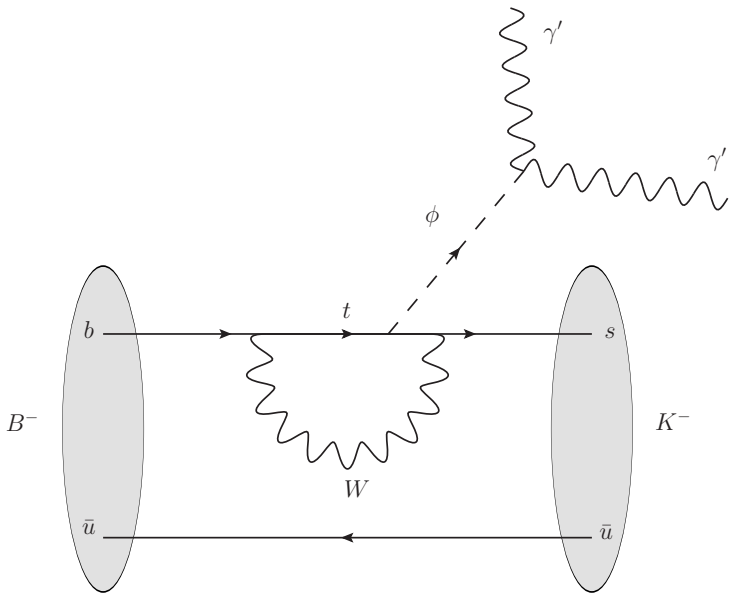


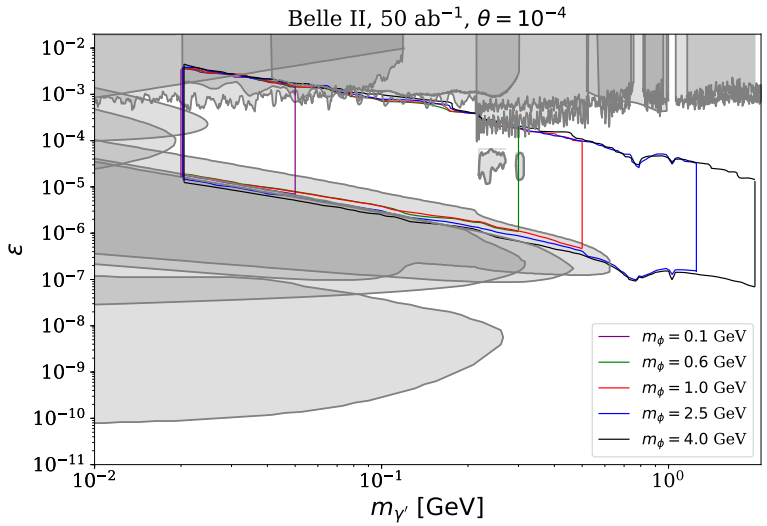
Dark photons from a light scalar, DV

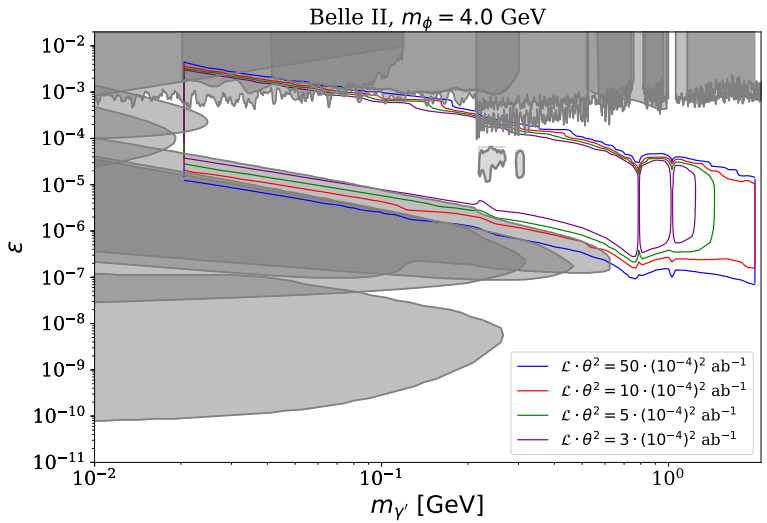
- JHEP05(2024)094
- Signal final states: $\gamma' \to e^+e^-,\ \mu^+\mu^-,\ \pi^+\pi^-,\ K^+K^-$
- Require 2 displaced vertices
- Vanishing background
- $\theta = 10^{-4}, \mathrm{BR}(\phi \to \gamma'\gamma') \simeq 100\%$

- Short-lived ϕ and long-lived γ'

$$\mathcal{L}_{\mathrm{int}} = g' m_{\gamma'} \phi \gamma'_\mu \gamma'^\mu - \epsilon e \gamma'_\mu J^\mu_{\mathrm{EM}} + \sum_f \frac{m_f \theta}{v} \phi \bar{f} f$$



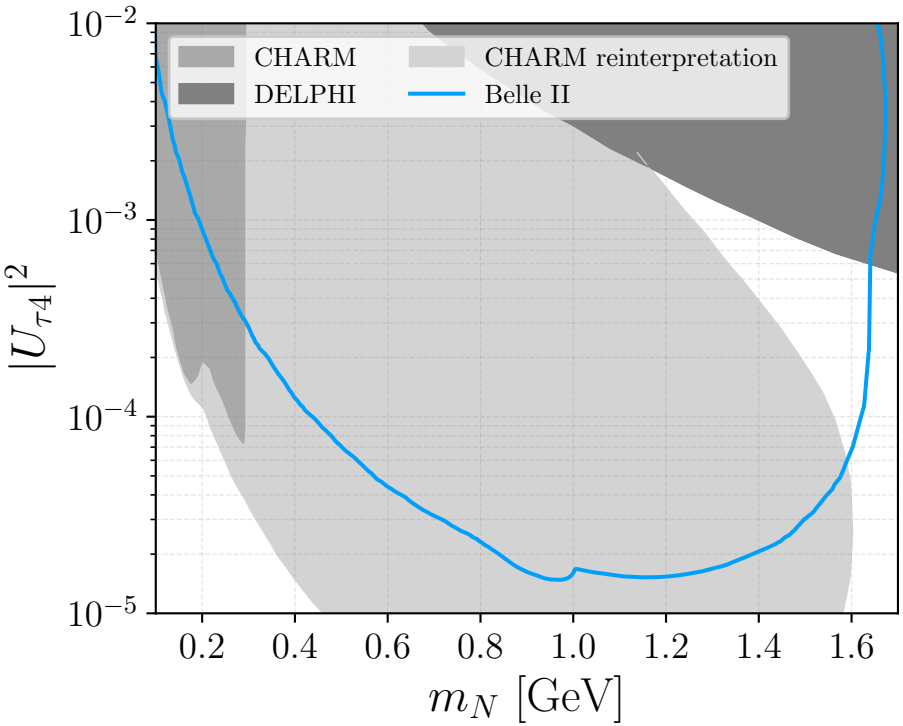




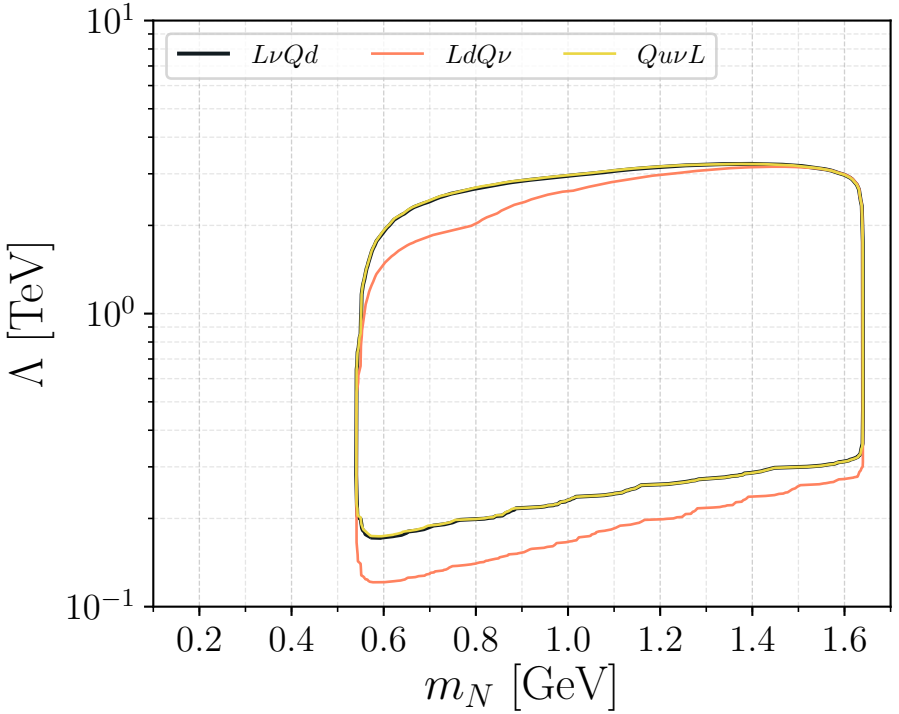
HNL in EFT, DV

- JHEP04(2022)057
- Minimal & EFT
- $ee \to \tau\tau$, τ-decays
- Op. $\Rightarrow$ prod. & decay
- DV reconstruction

Class 1	$\psi^2 H^3$	Class 4	ψ^4
$\mathcal{O}_{L\nu H}$	$(\bar{L}\nu_R)\tilde{H}(H^\dagger H)$	$\mathcal{O}_{du\nu e}$	$(\bar{d}_R\gamma^\mu u_R)(\bar{\nu}_R\gamma_\mu e)$
Class 2	$\psi^2 H^2 D$	$\mathcal{O}_{Qu\nu L}$	$(\bar{Q}u_R)(\bar{\nu}_R L)$
$\mathcal{O}_{H\nu e}$	$(\bar{\nu}_R\gamma^\mu e_R)(\tilde{H}^\dagger iD_\mu H)$	$\mathcal{O}_{L\nu Qd}$	$(\bar{L}\nu_R)\epsilon(\bar{Q}d_R)$
Class 3	$\psi^2 HF$	$\mathcal{O}_{LdQ\nu}$	$(\bar{L}d_R)\epsilon(\bar{Q}\nu_R)$
$\mathcal{O}_{\nu W}$	$(\bar{L}\sigma_{\mu\nu}\nu_R)\tau^I\tilde{H}W^{I\mu\nu}$	$\mathcal{O}_{L\nu Le}$	$(\bar{L}\nu_R)\epsilon(\bar{L}e_R)$
$\mathcal{O}_{\nu B}$	$(\bar{L}\sigma_{\mu\nu}\nu_R)\tilde{H}B^{\mu\nu}$		



Minimal scenario



Some dim-6 operators

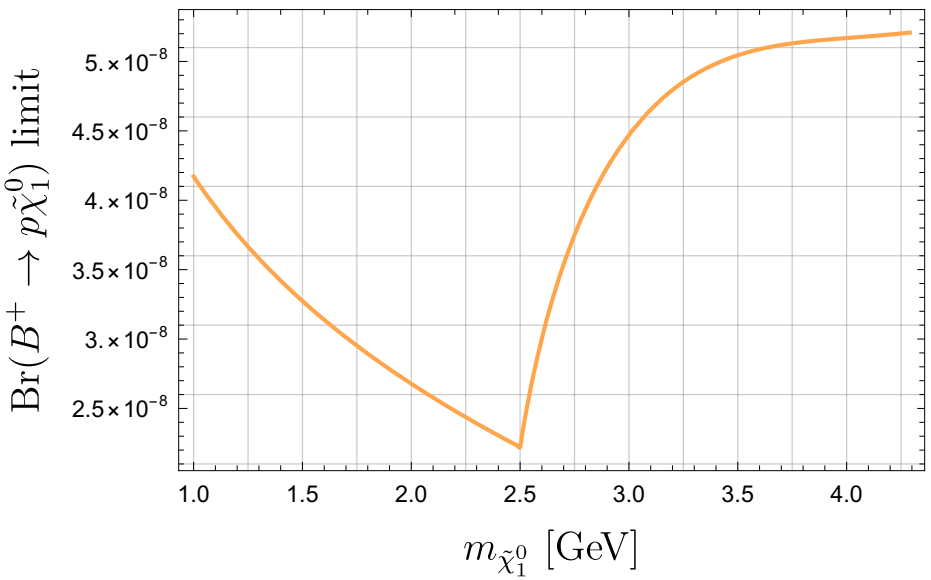
See also PRD111, 035010(2025) for another HNL-study at Belle II

A light $\tilde{\chi}_1^0$ from B, RPV SUSY, $\not{E}$

- JHEP02(2023)224
- $\tilde{\chi}_1^0$ bino
- λ''_{113}, BNV

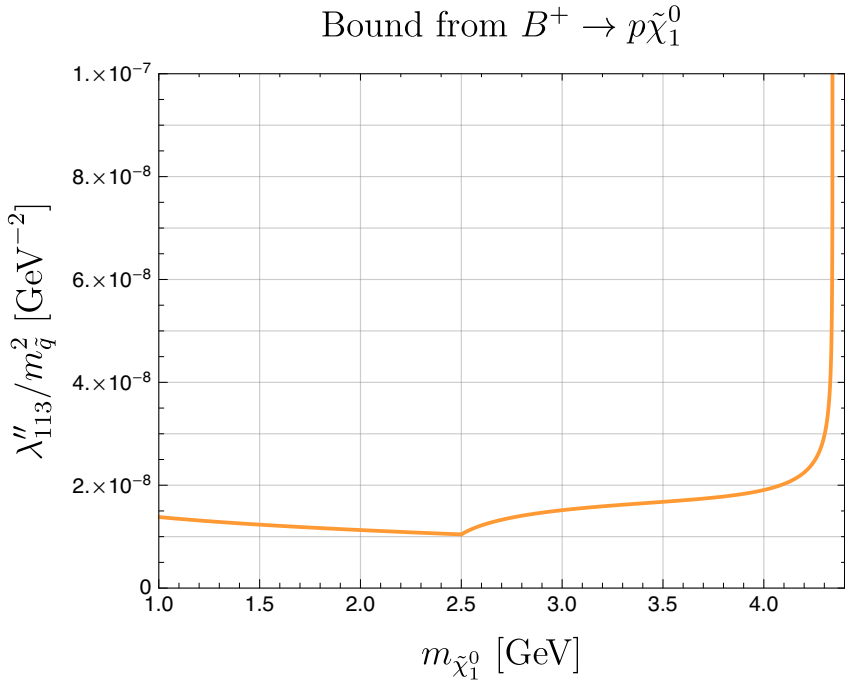
$$\mathcal{L}_{\text{RPV}} \supset \sum_{i,j=1}^{2} \lambda''_{ij3}\, \epsilon_{abc} \left(\tilde{u}^*_{Ria}\, \bar{d}_{Rjb}\, b^C_{Rc} + \tilde{d}^*_{Rja}\, \bar{u}_{Rib}\, b^C_{Rc} + \tilde{b}^*_{Ra}\, \bar{u}_{Rib}\, d^C_{Rjc} \right) + \text{h.c.}$$

- Production: $B^+ \xrightarrow{\lambda''_{113}} p\tilde{\chi}_1^0$



Obtained by re-scaling bgd level in a BABAR search for $\text{Br}(B^+ \to K^+ \nu\bar{\nu})$

- Signature: tagged B+p + $\not{E}$



Based on the left plot

Searched for at BABAR

See also JHEP02(2021)211, arXiv:2507.00359, EPJC85(2025)1,66 for other bino-studies at Belle II

Summary

- No new heavy resonances have been found yet at the LHC
- Searching for (light) long-lived particles becomes more important
- Very few, $\mathcal{O}(1)$, LLP exp. searches at B-factories exist
- Focus on Belle II for LLP searches
- Unique advantages: clean, low background, ongoing exp., full reconstruction, sensitivity to large $c\tau$, testing low-mass LLP, ...
- Multiple potential studies:
  - Prod.: direct prod., rare decays of B-mesons and τ-leptons
  - Signatures: DV, $\not{E}$, ...
  - Rare processes: cLFV, FCNC, LNV, BNV, tiny coupling, high NP-scale suppression (EFT), ...
  - Belle II $B^+ \to K^+ \nu\bar{\nu}$ excess
  - See also the back-up slides
  - ...

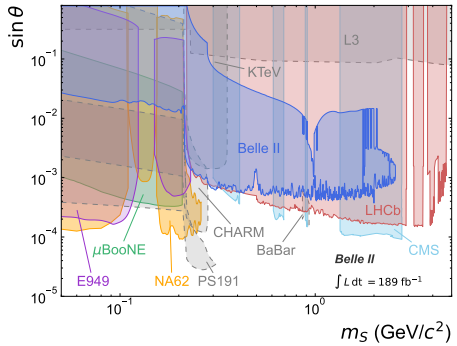
Thank You! 谢谢!

Back-up slides

Detector modeling for LLP searches at Belle II

- Using Vertex Detector and Tracker
- Specific for DV searches:
  - Fiducial volume for DV searches:
    $-40 < z < 120$ cm & $1(10) < r < 80$ cm
  - $r > 1$ cm or 10 cm, depending on background level & search strategy
  - Displaced-tracking efficiency:
    $\epsilon = 100\%$ at $r = 0$ cm and $\epsilon = 0\%$ at $r = 80$ cm
- PID efficiencies: flat or estimated from Belle II publications

Past *B*-factory LLP searches



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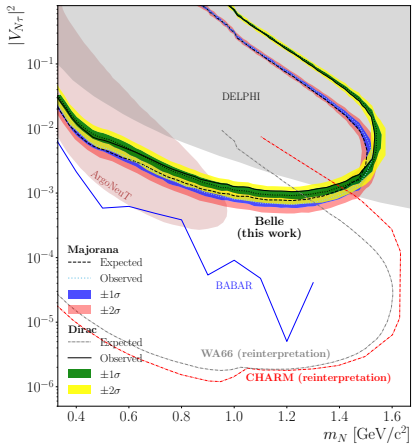

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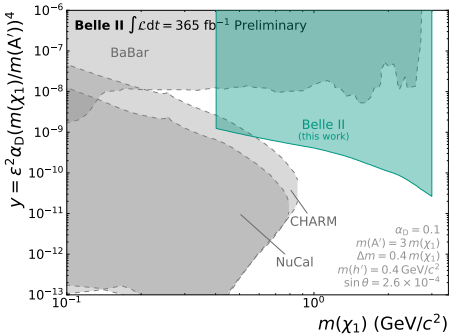

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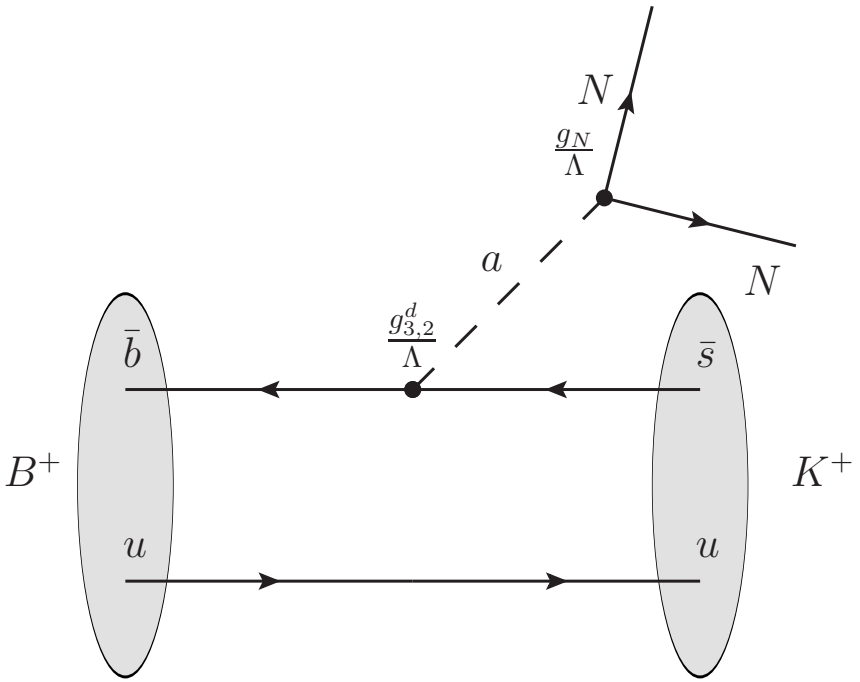
1. PRD87,071102(2013): *Search for heavy neutrinos at Belle*, Belle
2. PRL114,171801(2015): *Search for long-lived particles in e^+e^- collisions*, BaBar
3. PRD108,L111104(2023): *Search for a long-lived spin-0 mediator in $b \to s$ transitions at the Belle II experiment*, Belle II
4. PRD109,L111102(2024): *Search for a heavy neutral lepton that mixes predominantly with the tau neutrino*, Belle
5. arXiv:2505.09705: *Search for a dark Higgs boson produced in association with inelastic dark matter at the Belle II experiment*, Belle II

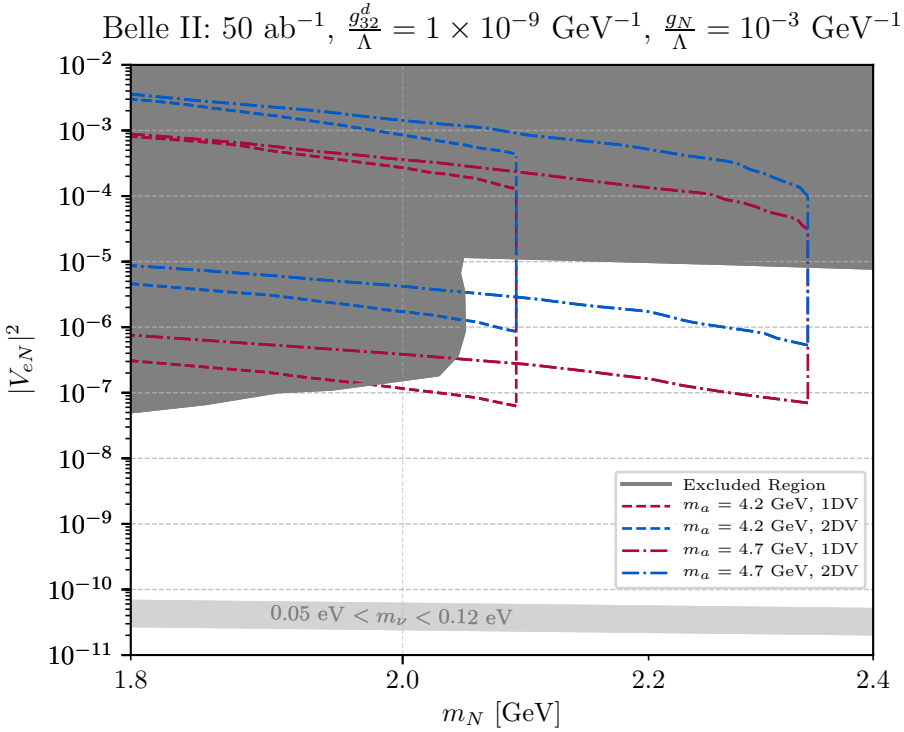
HNLs from an ALP, DV(s)

- PRD111, 035010(2025)
- ALP with FCNC & long-lived N

$$\mathcal{L}_a = \frac{1}{2}\partial_\mu a\,\partial^\mu a - \frac{1}{2}m_a^2 a^2 + \frac{\partial_\mu a}{\Lambda}\sum_q\sum_{i,j} g^q_{i,j}\bar{q}_i\gamma^\mu q_j + \frac{\partial_\mu a}{\Lambda}\, g_N \overline{N}\gamma^\mu\gamma_5 N$$

- Choices of fid. vol. & final states $\Rightarrow$ vanishing background
- $B^+ \xrightarrow{g^d_{3,2}} K^+ a$, $a \xrightarrow{g_N} NN$
- N decays via mixing V_{eN}
- Search strategies: 1DV & 2DV

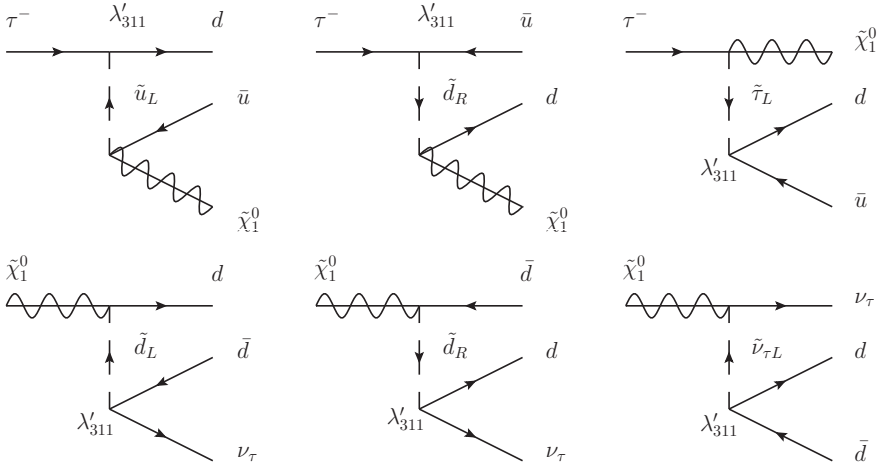


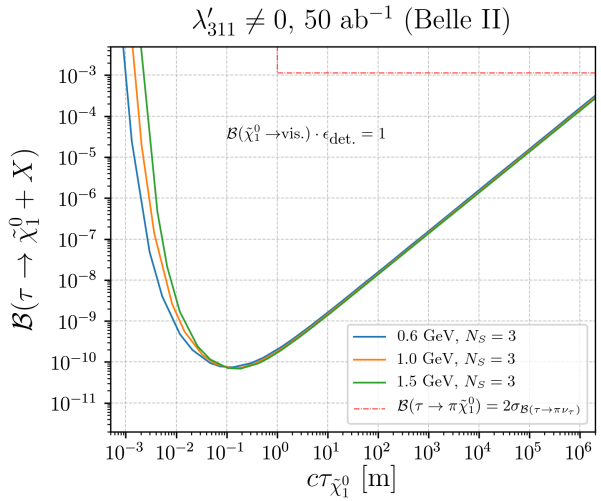


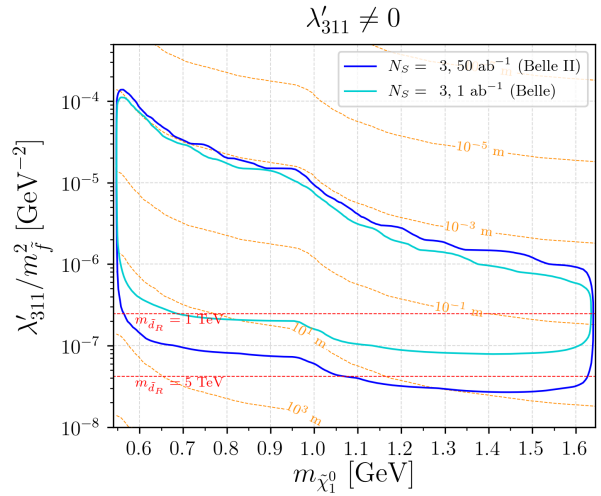
A light $\tilde{\chi}_1^0$ from τ, RPV SUSY, DV

- JHEP02(2021)211
- $\tilde{\chi}_1^0$ bino
- $\lambda'_{311}/m_{\tilde{f}}^2$, LNV

$$W_{\text{RPV}} = \epsilon_i L_i \cdot H_u + \frac{1}{2}\lambda_{ijk} L_i \cdot L_j \bar{E}_k + \lambda'_{ijk} L_i \cdot Q_j \bar{D}_k + \frac{1}{2}\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$







- $\tau^\pm \xrightarrow{\lambda'_{311}} \tilde{\chi}_1^0 + \pi^\pm/\rho^\pm$
- $\tilde{\chi}_1^0 \xrightarrow{\lambda'_{311}} \nu_\tau + \pi^0/\rho/\omega/\eta/\eta'$
- $\eta/\eta' \to$ charged particles, DV reconstruction

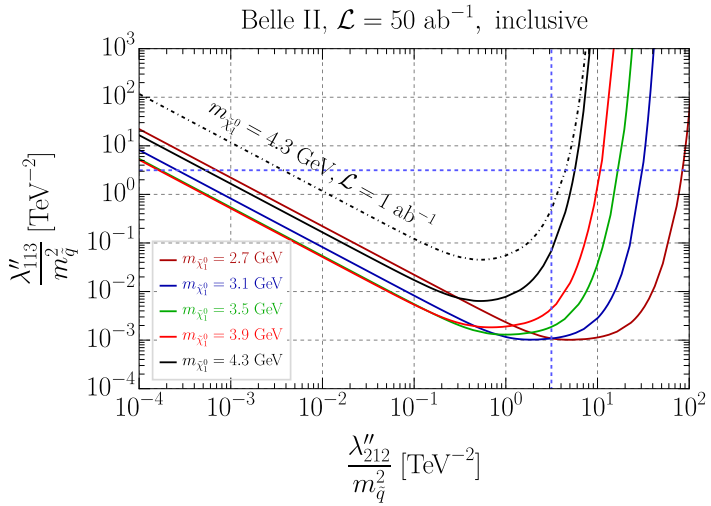
A light $\tilde{\chi}_1^0$ from B, RPV SUSY, DV

- arXiv:2507.00359
- $\tilde{\chi}_1^0$ bino
- λ''_{113} & λ''_{212}, BNV

$$\mathcal{L}_{\text{RPV}} \supset \sum_{i,j,k=1}^{3} \lambda''_{ijk}\,\epsilon_{abc}\left(\tilde{u}^*_{Ria}\,\bar{d}_{Rjb}\,d^C_{Rkc} + \tilde{d}^*_{Rja}\,\bar{u}_{Rib}\,d^C_{Rkc} + \tilde{d}^*_{Rka}\,\bar{u}_{Rib}\,d^C_{Rjc}\right) + \text{h.c.}$$

- Production: $B^+ \xrightarrow{\lambda''_{113}} p\tilde{\chi}_1^0$
- Decays: $\tilde{\chi}_1^0 \xrightarrow{\lambda''_{212}} \Sigma_c^0\bar{K}^0, \Omega_c^0 K^0, \Lambda_c^+ K^-, \Xi_c^+\pi^-, \Xi_c^0\pi^0, +\text{c.c.}$
- One inclusive analysis (and two exclusive analyses)

- Reconstruct $p+ \geq 3$ tracks from the DV
- Track-recon. eff. estimated with TrackEff
- Vastly outperforms current limits (not shown in the plot)



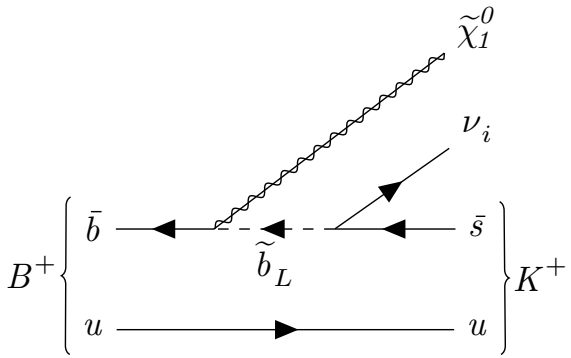
A massless $\tilde{\chi}_1^0$ in RPV SUSY & $B^+ \to K^+ \nu\bar{\nu}$ at Belle II

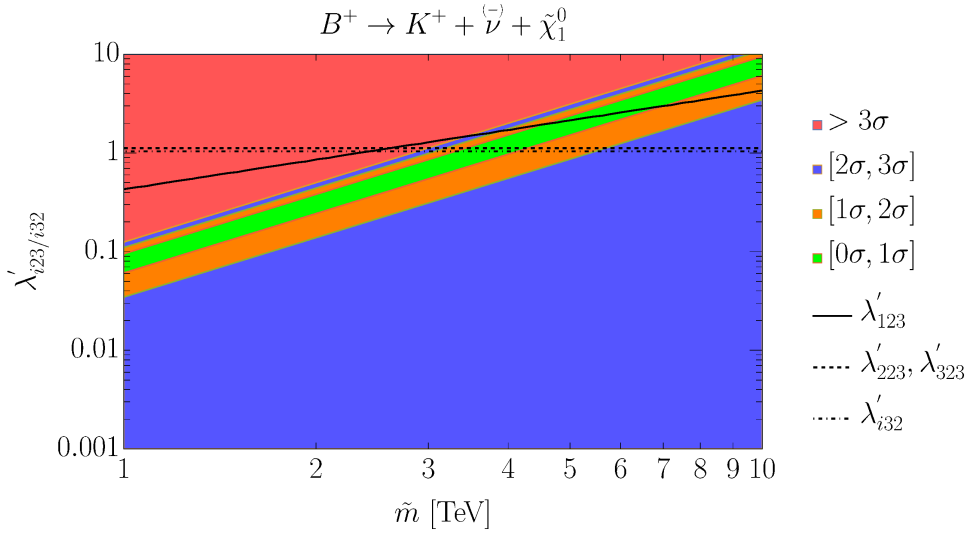
- EPJC85(2025)1,66
- $\tilde{\chi}_1^0$ bino
- λ', LNV

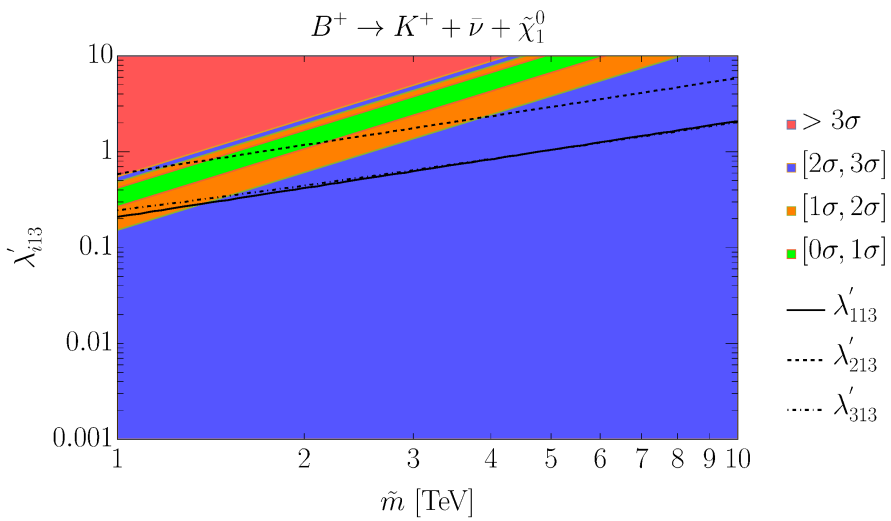
$$\mathrm{BR}^{\mathrm{exp}}(B^+ \to K^+ + \nu + \bar{\nu}) = (2.3 \pm 0.7) \times 10^{-5}, \text{ measured at Belle II}$$

$$\mathrm{BR}^{\mathrm{SM}}(B^+ \to K^+ + \nu + \bar{\nu}) = (5.6 \pm 0.4) \times 10^{-6}, \text{ lower by } 2.7\sigma$$

- $W_{\not L} = \lambda'_{ijk} L_i Q_j \bar{D}_k$
- Consider a massless bino
- $B^+ \to K^+ + \overset{(-)}{\nu} + \tilde{\chi}_1^0$



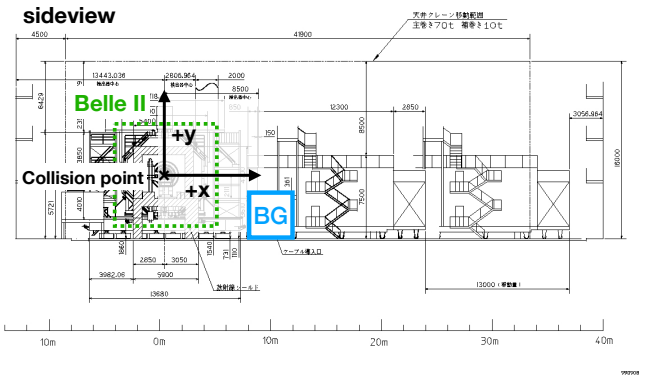


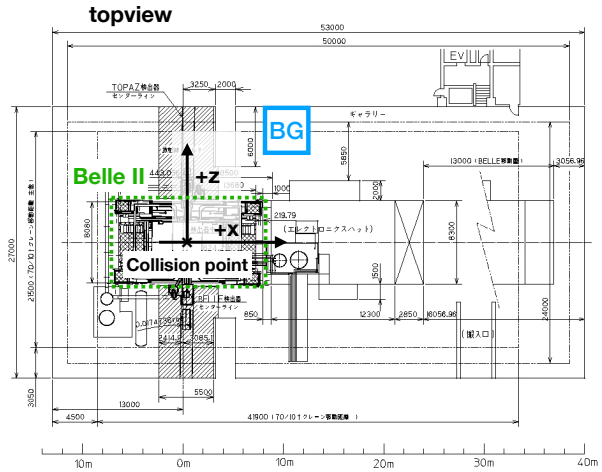


Far detectors at Belle II

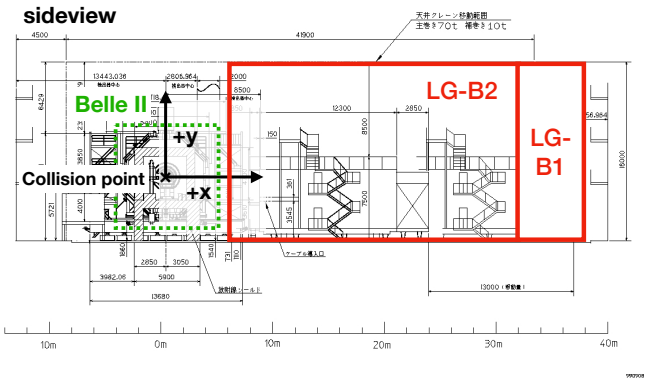
arXiv:2105.12962

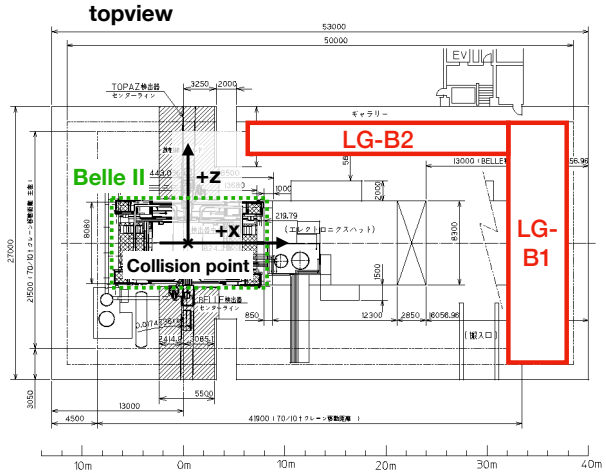
Baby-GAZELLE:





L-GAZELLE:



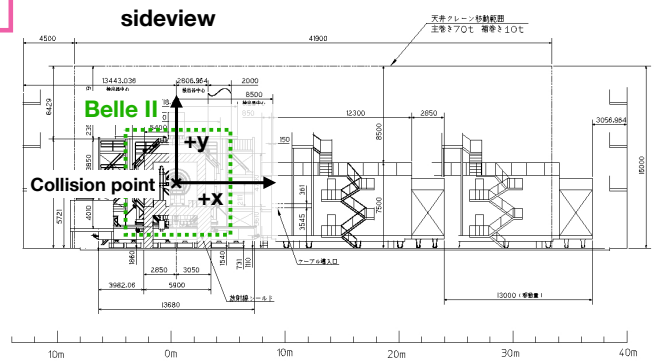


- See also arXiv:2202.11714

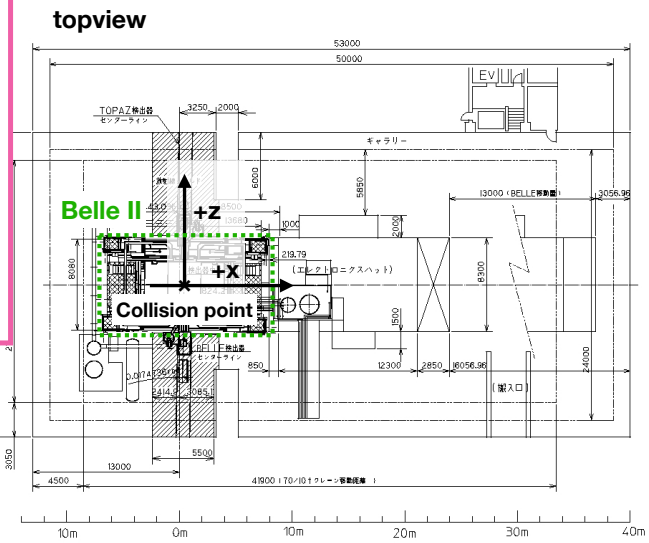
GODZILLA at Belle II

arXiv:2105.12962

GZ



GZ



Sensitivities to HNLs at far detectors

arXiv:2105.12962