Searching for long-lived light neutralinos at future lepton colliders

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Motivation

- New-Physics models including SUSY predict new heavy fields
- No new fundamental particles found yet at the LHC
- More stringent limits placed on NP models, e.g. $m_{\tilde{q},\tilde{g}} \gtrsim 1$ TeV
- LHC focus: **promptly decaying** NP particles
- New Physics in the form of Long-lived Particles (LLPs)?

LLP and future lepton colliders

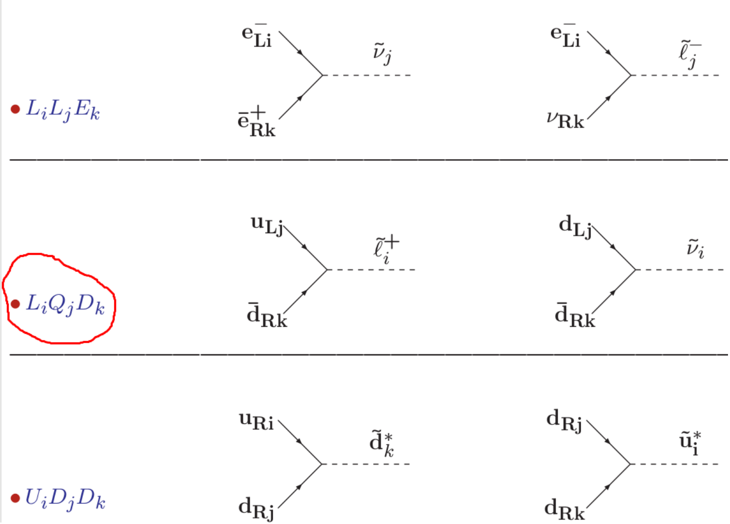
- LLPs: produced, travel a macroscopic distance, and then decay $\rightarrow$ Displaced Vertices, ...
- LLPs appear in many extensions of the SM: heavy neutral lepton, dark photon, neutralino, light Higgs, ...
- Often motivated by the small neutrino masses or dark matter
- Causes of the long lifetime:
  - **Feeble** couplings
  - **Heavy** mediators
  - **Small** phase space
  - ...
- CEPC/FCC-ee: large and clean samples of Higgs and Z-bosons may decay to LLPs

In this talk:

- Focus on long-lived lightest neutralinos in the R-parity-violating supersymmetry coupled to Z-bosons

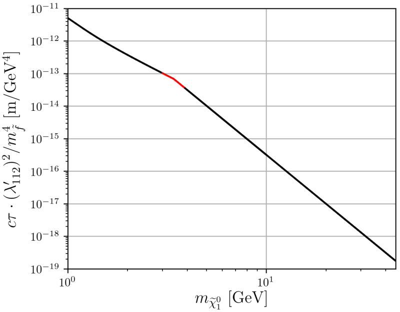
RPV-MSSM

$$W_{\not R_p} = \mu_i H_u \cdot L_i + \frac{1}{2}\lambda_{ijk} L_i \cdot L_j \bar{E}_k + \lambda'_{ijk} L_i \cdot Q_j \bar{D}_k + \frac{1}{2}\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$



RPV-MSSM

- Light ($\mathcal{O}$(GeV)) neutralinos (binolike) still allowed with RPV
- Assume $\tilde{\chi}_1^0$ LSP and degenerate sfermion masses
- *Small RPV couplings & $m_{\tilde{\chi}_1^0}$* $\rightarrow$ long-lived $\tilde{\chi}_1^0$'s
- Assume λ'_{112} only
- $m_{\tilde{\chi}_1^0} \sim \mathcal{O}(\text{GeV}) : \tilde{\chi}_1^0 \rightarrow \begin{cases} (K_L^0, K_S^0, K^*) + (\nu_e, \bar{\nu}_e), \text{ invisible mode,} \\ (K^\pm, K^{*\pm}) + e^\mp, \text{ visible mode,} \end{cases}$
- heavier: $\tilde{\chi}_1^0 \rightarrow e^\mp/\nu_e + jj : c\tau_{\tilde{\chi}_1^0} \simeq (3.2\text{ m})\left(\frac{m_{\tilde{f}}}{1\text{ TeV}}\right)^4 \left(\frac{10\text{ GeV}}{m_{\tilde{\chi}_1^0}}\right)^5 \left(\frac{0.01}{\lambda'_{112}}\right)^2$



Production: $Z \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0$ via small Higgsino components
BR($Z \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0$) $\lesssim 0.1\%$

Independent parameter:
$m_{\tilde{\chi}_1^0}$, $\lambda'_{112}/m_{\tilde{f}}^2$, Br($Z \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0$)

Future lepton colliders and the Z-pole mode

- LHC has been a huge success
- Next-generation e^-e^+ colliders: CEPC, FCC-ee, ILC, etc.
- $\sqrt{s} = 91.2$ GeV (Z-pole), 160 GeV (WW mode), 240 GeV (Higgs mode), etc.

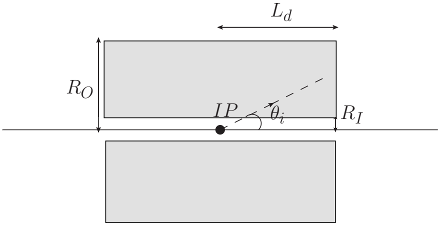
production		on-shell Z-boson
$\sqrt{s}$ [GeV]		91.2
N_Z	CEPC	7×10^{11}
	FCC-ee	5×10^{12}
$\mathcal{L}^{\text{int}}$	CEPC	16 ab^{-1}
	FCC-ee	150 ab^{-1}

- $e^-e^+ \to Z \to \tilde{\chi}_1^0\tilde{\chi}_1^0$, with $\tilde{\chi}_1^0 \to ljj$ or νjj at the parton level

General calculation procedure

Total No. of $\tilde{\chi}_1^0$:	$N_{\tilde{\chi}_1^0} = 2\, N_Z \cdot \text{BR}(Z \to \tilde{\chi}_1^0 \tilde{\chi}_1^0)$
Ave. decay prob. in f.v.:	$\left\langle P[\tilde{\chi}_1^0 \text{ in f.v.}] \right\rangle = \frac{1}{N^{\text{MC}}_{\tilde{\chi}_1^0}} \sum_{i=1}^{N^{\text{MC}}_{\tilde{\chi}_1^0}} P[(\tilde{\chi}_1^0)_i \text{ in f.v.}]$
Individual decay prob.:	$P[(\tilde{\chi}_1^0)_i \text{ in f.v.}]$
No. of obs. decays:	$N^{\text{obs}}_{\tilde{\chi}_1^0} = N_{\tilde{\chi}_1^0} \cdot \left\langle P[\tilde{\chi}_1^0 \text{ in f.v.}] \right\rangle \cdot \text{BR}(\tilde{\chi}_1^0 \to \text{ visible})$

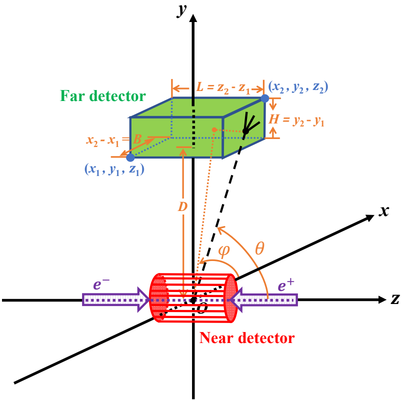
Near detector

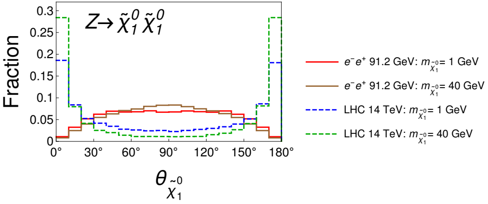


Detector	R_I [mm]	R_O [m]	L_d [m]	V [m^3]
CEPC	16	1.8	2.35	47.8
FCC-ee IDEA	17	2.0	2.0	50.3

$$\begin{aligned} P[(\tilde{\chi}_1^0)_i \text{ in f.v.}] &= e^{-L_i/\lambda_i^z} \cdot (1 - e^{-L_i'/\lambda_i^z}) \\ L_i &\equiv \min(L_d, |R_I/\tan\theta_i|), \\ L_i' &\equiv \min(L_d, |R_O/\tan\theta_i|) - L_i \\ \lambda_i^z &= \beta_i^z\, \gamma_i\, c\tau_{\tilde{\chi}_1^0} \end{aligned}$$

Far detectors





Far detectors

	V [m^3]	B [m]	H [m]	L [m]	(x_1, y_1, z_1) [m]	(x_2, y_2, z_2) [m]	D [m]	θ [°]
FD1	5.0×10^3	10	10	50	(5, -5, -25)	(15, 5, 25)	5	[11.3, 168.7]
					(10, -5, -25)	(20, 5, 25)	10	[21.8, 158.2]
FD2	8.0×10^5	200	20	200	(-100, 50, 50)	(100, 70, 250)	50	[11.3, 54.5]
					(-100, 100, 100)	(100, 120, 300)	100	[18.4, 50.2]
FD3	8.0×10^5	200	20	200	(-100, 50, -100)	(100, 70, 100)	50	[26.6, 153.4]
					(-100, 100, -100)	(100, 120, 100)	100	[45.0, 135.0]
FD4	8.0×10^5	100	80	100	(-50, 50, -50)	(50, 130, 50)	50	[45.0, 135.0]
					(-50, 100, -50)	(50, 180, 50)	100	[63.4, 116.6]
FD5	3.2×10^6	200	80	200	(-100, 50, -100)	(100, 130, 100)	50	[26.6, 153.4]
					(-100, 100, -100)	(100, 180, 100)	100	[45.0, 135.0]
FD6	8.0×10^7	1000	80	1000	(-500, 50, -500)	(500, 130, 500)	50	[5.7, 174.3]
					(-500, 100, -500)	(500, 180, 500)	100	[11.3, 168.7]
FD7	8.0×10^5	2000	20	20	(-1000, 50, -10)	(1000, 70, 10)	50	[78.7, 101.3]
					(-1000, 100, -10)	(1000, 120, 10)	100	[84.3, 95.7]
FD8	8.0×10^5	20	20	2000	(-10, 50, -1000)	(10, 70, 1000)	50	[2.9, 177.1]
					(-10, 100, -1000)	(10, 120, 1000)	100	[5.7, 174.3]

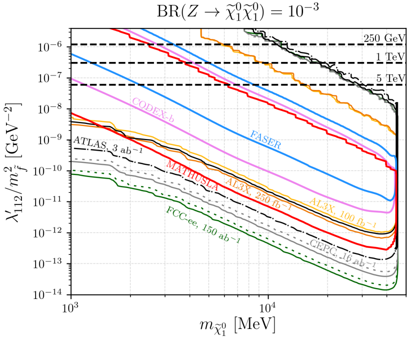
Far detectors

	D [m]	$\epsilon^{Z\to\tilde{\chi}_1^0\tilde{\chi}_1^0}\cdot c\tau$ [m]	$\frac{\epsilon^{Z\to\tilde{\chi}_1^0\tilde{\chi}_1^0}}{\epsilon_{\text{CEPC}}^{Z\to\tilde{\chi}_1^0\tilde{\chi}_1^0}}+1$
FD1	5	6.6×10^{-2}	2.3
	10	3.2×10^{-2}	1.7
FD2	50	6.3×10^{-2}	2.3
	100	3.3×10^{-2}	1.7
FD3	50	1.5×10^{-1}	4.1
	100	7.0×10^{-2}	2.4
FD4	50	1.9×10^{-1}	4.8
	100	7.1×10^{-2}	2.5
FD5	50	4.8×10^{-1}	10.8
	100	2.3×10^{-1}	5.7
FD6	50	1.2	26.2
	100	1.0	22.4
FD7	50	2.9×10^{-2}	1.6
	100	1.4×10^{-2}	1.3
FD8	50	4.8×10^{-2}	2.0
	100	2.3×10^{-2}	1.5

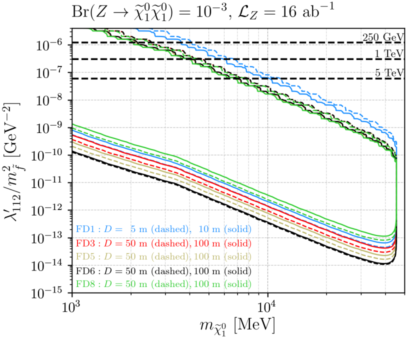
Background

- Vanishing background for the far detectors
- Background for the near detector:
  - Semi-leptonic decays of neutral SM mesons produced from Z-decays: $D^0 \to K^{\pm} l \nu_l$
  - Can be rejected by imposing a minimal radius requirement of the displaced vertex at $\sim$ several cm (e.g. 10 cm)
  - At a Z-pole lepton collider such background events are much less boosted than at the LHC, less likely to fake the signal
- Show 3-signal-event isocurves for both near and far detectors

Results

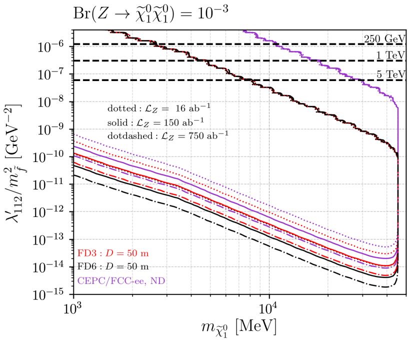


BR($Z \to \tilde{\chi}_1^0\tilde{\chi}_1^0$) = 10^{-3}
250 GeV
1 TeV
5 TeV
CODEX-b
FASER
ATLAS, 3 ab^{-1}
MATHUSLA
AL3X, 250 fb^{-1}
AL3X, 100 fb^{-1}
FCC-ee, 150 ab^{-1}
CEPC, 16 ab^{-1}
$\lambda'_{112}/m_{\tilde{f}}^2$ [GeV^{-2}]
$m_{\tilde{\chi}_1^0}$ [MeV]

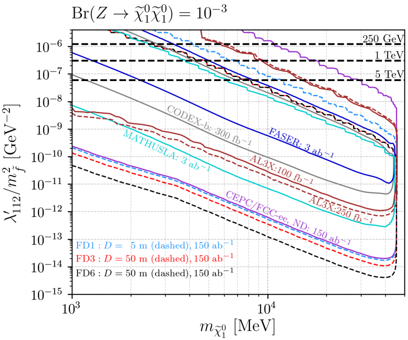


Br($Z \to \tilde{\chi}_1^0\tilde{\chi}_1^0$) = 10^{-3}, $\mathcal{L}_Z$ = 16 ab^{-1}
250 GeV
1 TeV
5 TeV
FD1 : D = 5 m (dashed), 10 m (solid)
FD3 : D = 50 m (dashed), 100 m (solid)
FD5 : D = 50 m (dashed), 100 m (solid)
FD6 : D = 50 m (dashed), 100 m (solid)
FD8 : D = 50 m (dashed), 100 m (solid)
$\lambda'_{112}/m_{\tilde{f}}^2$ [GeV^{-2}]
$m_{\tilde{\chi}_1^0}$ [MeV]

Results



$\mathrm{Br}(Z \to \tilde{\chi}_1^0 \tilde{\chi}_1^0) = 10^{-3}$
250 GeV
1 TeV
5 TeV
dotted : $\mathcal{L}_Z =$ 16 ab^{-1}
solid : $\mathcal{L}_Z =$ 150 ab^{-1}
dotdashed : $\mathcal{L}_Z =$ 750 ab^{-1}
FD3 : $D = 50$ m
FD6 : $D = 50$ m
CEPC/FCC-ee, ND
$\lambda'_{112}/m_{\tilde{f}}^2$ [GeV^{-2}]
$m_{\tilde{\chi}_1^0}$ [MeV]



$\mathrm{Br}(Z \to \tilde{\chi}_1^0 \tilde{\chi}_1^0) = 10^{-3}$
250 GeV
1 TeV
5 TeV
CODEX-b: 300 fb^{-1}
FASER: 3 ab^{-1}
MATHUSLA: 3 ab^{-1}
AL3X:100 fb^{-1}
AL3X:250 fb^{-1}
CEPC/FCC-ee, ND: 150 ab^{-1}
FD1 : $D =$ 5 m (dashed), 150 ab^{-1}
FD3 : $D =$ 50 m (dashed), 150 ab^{-1}
FD6 : $D =$ 50 m (dashed), 150 ab^{-1}
$\lambda'_{112}/m_{\tilde{f}}^2$ [GeV^{-2}]
$m_{\tilde{\chi}_1^0}$ [MeV]

Conclusions

- LLP as potential new physics beyond the Standard Model
- Benchmark model: long-lived lightest neutralinos in the RPV-SUSY
- Future Z-factories provide a large and clean sample of Z-bosons
- $Z \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$, and $\tilde{\chi}_1^0$ decays via λ'_{112}
- CEPC and FCC-ee expected to outperform LHC experiments
- Installing a far detector at future lepton colliders in the perpendicular direction can be promising
- Further benchmark model studies of LLPs with far detectors at CEPC/FCC-ee: heavy neutral leptons and light scalar in PRD 101 (2020) 075046

Thank You!

MC simulation

- $\underline{Z\text{-boson}}$ generation:
  - Decays of the SM Z-bosons are hard-coded in `Pythia8`
  - `New-Gauge-Boson Processes` of `Pythia8`: pure Z'-bosons with the same mass and couplings as the SM Z-boson, decaying to a pair ot new fermions

Experimental upper bound on $\Gamma(Z \to \tilde{\chi}_1^0 \tilde{\chi}_1^0)$

- Upper bound of $\text{BR}(Z \to \chi_1^0 \chi_1^0) \lesssim 0.1$ % at 90 % c.l., determined from the LEP measurement uncertainty of the insivible width.
- Higgsino mass μ is now excluded by ATLAS up to $\mu \simeq 130$ GeV. [1712.08119]
- Cross check:
  use the model *MSSMTriRpV* from `SARAH-4.12.2`. Perform numerical calculations with `SPheno-4.0.3`:

  $$M_2 = 500 \text{ GeV}, \mu = 130 \text{ GeV}, \tan\beta = 10,$$

  for mass $m_{\chi_1^0} \ll m_Z/2 \Rightarrow \text{BR}(Z \to \chi_i^0 \chi_j^0) \simeq 0.06\%$.
- Treat $\text{BR}(Z \to \chi_1^0 \chi_1^0)$ as a free parameter.