Time-delayed electrons from neutral currents at the LHC

Zeren Simon Wang
(National Tsing Hua University)

arXiv:2107.03203

in collaboration with Kingman Cheung and Kechen Wang

Nov 12th, 2021
Tenth workshop of the LLP Community

NTHU

MOST 科技部
Ministry of Science and Technology

Motivation

- Time-delay feature of the LLP decay products
- Two neutral LLP benchmark scenarios:
  - The lightest neutralinos in the R-parity-violating supersymmetry
  - Heavy neutral leptons (HNLs) in $U(1)$ extensions of the SM
- Similar production and decay topologies

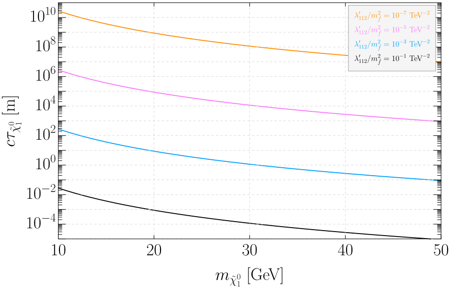
CMS timing detector

- Timing precision upgrades for ATLAS, CMS, and LHCb planned
- Original purpose: reducing pile-up issues at the HL-LHC
- CMS minimum-ionizing-particle (MIP) timing detector (MTD)
- Before ECAL
- Timing resolution: 30 ps

RPV-MSSM

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

- Light ($\mathcal{O}$(GeV)) neutralinos (binolike) still allowed with RPV
- Assume $\tilde{\chi}_1^0$ LSP and degenerate sfermion masses
- Production: $Z \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$ via small Higgsino components
- Decay: $\lambda'_{112} \Rightarrow \tilde{\chi}_1^0 \to \nu_e d\bar{s}, \bar{\nu}_e \bar{d} s, e^- u\bar{d}$, or $e^+ \bar{u} d$
- *Small RPV couplings & $m_{\tilde{\chi}_1^0}$* $\to$ long-lived $\tilde{\chi}_1^0$'s



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

$U(1)_{B-L}$ and $U(1)_X$

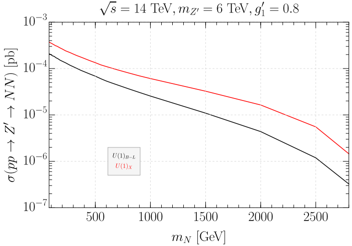
- SM extended w/ $U(1)_X$, a linear combination of SM $U(1)_Y \& U(1)_{B-L}$
- Predicts a new vector boson Z', a new scalar particle Φ, and three right-handed neutrinos

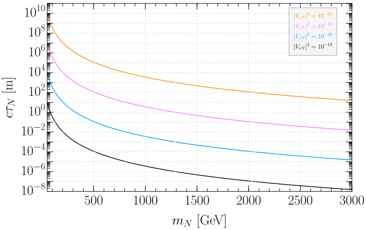
	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_X$
Q_L^i	3	2	$\frac{1}{6}$	$\frac{1}{6}x_H + \frac{1}{3}x_\Phi$
u_R^i	3	1	$\frac{2}{3}$	$\frac{2}{3}x_H + \frac{1}{3}x_\Phi$
d_R^i	3	1	$-\frac{1}{3}$	$-\frac{1}{3}x_H + \frac{1}{3}x_\Phi$
L_L^i	1	2	$-\frac{1}{2}$	$-\frac{1}{2}x_H - x_\Phi$
e_R^i	1	1	-1	$-x_H - x_\Phi$
H	1	2	$\frac{1}{2}$	$\frac{1}{2}x_H$
N^i	1	1	0	$-x_\Phi$
Φ	1	1	0	$2x_\Phi$

- Fix $x_\Phi = 1$, and $x_H = 0 \rightarrow U(1)_{B-L}$ and $x_H = -1.2 \rightarrow$ call $U(1)_X$

HNLs in $U(1)_{B-L}$ and $U(1)_X$

- Production: $Z' \to NN$, assuming only one kinematically relevant N

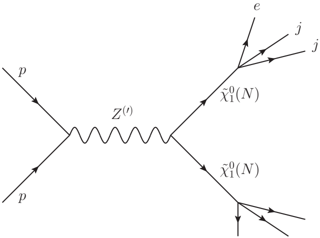


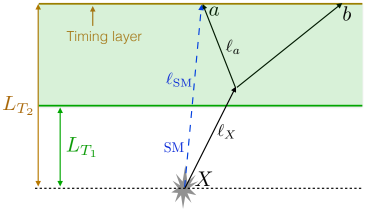


Decay via SM weak currents with the active-heavy neutrino mixing (consider only V_{eN} here)

Signature and strategy

- Require at least one of the two LLPs to decay into ejj final state with a macroscopic distance from the IP





arXiv:1805.05957

- $p_T^e > 20$ GeV and $\eta^e < 2.5$ for the leading electron
- LLP decay in the f.v.: $200 < r < 1170$ mm & $|z| < 3040$ mm
- ≥ 1 ISR jet with $p_T^j > 30$ GeV for timestamping the hard collision
- $\Delta t = t^e_{\rm arrival} - t^e_{\rm prompt} > 1{\rm ns}$, $t^e_{\rm arrival} = \frac{l_{\rm LLP}}{\beta_{\rm LLP}} + l_e$

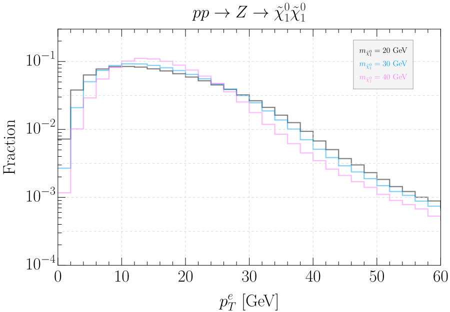
$$N_s^{\tilde{\chi}_1^0} = N^Z \cdot {\rm Br}(Z \to \tilde{\chi}_1^0\tilde{\chi}_1^0) \cdot {\rm Br}(\tilde{\chi}_1^0 \to e^- u\bar{s} \text{ or } e^+\bar{u}s) \cdot 2 \cdot \epsilon^{\tilde{\chi}_1^0}$$

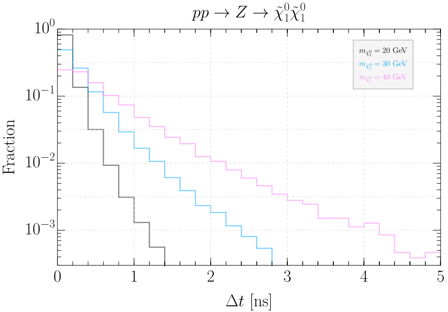
$$N_s^N = \sigma^N \cdot \mathcal{L} \cdot {\rm Br}(N \to ejj) \cdot 2 \cdot \epsilon^N$$

Background

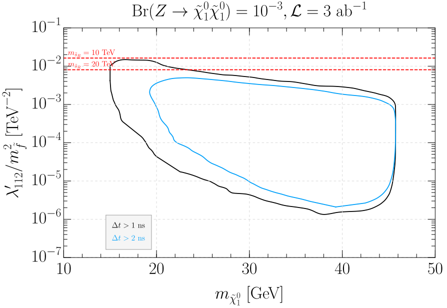
- Follow arXiv:1905.07772
- 1) Finite timing resolution (30 ps) $\rightarrow$ same-vertex (SV) hard collisions of jet and photon production may lead to a fake signal
  - $N_{\text{SV}} = 2 \times 10^{11}$ for the inclusive photon production, as well as jet production ($p_T^j > 30$ GeV) with a jet misidentified as a photon
  - Gaussian smearing $\rightarrow \Delta t > 1$ ns removes all these background events
- 2) Pile-up (PU) events estimated to be 10^7, taking the fraction of jets being trackless as 10^{-3}
  - Gaussian smearing of 190 ps $\rightarrow \Delta t > 1(2)$ ns leads to 0.7 and 0 background events
  - 190 ps derived by the longitudinal spread of the bunch crossing
- Conclusion: $\Delta t > 1$ ns essentially no background
- Show 3-signal-event isocurves as the 95% C.L. exclusion limits

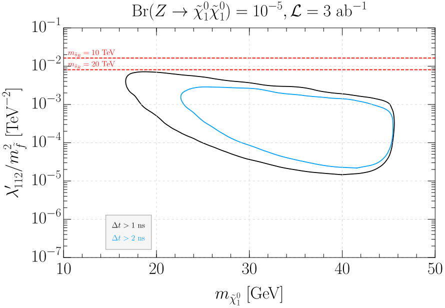
Numerical results: light neutralinos

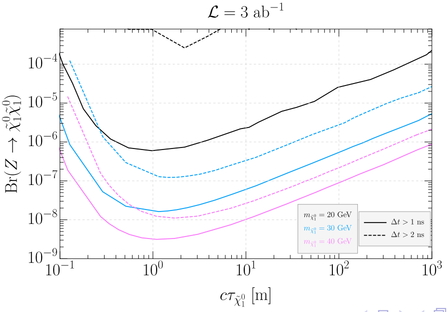




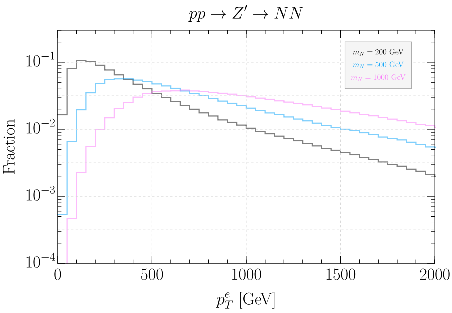
Numerical results: light neutralinos

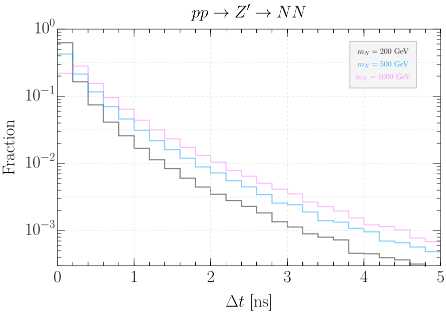




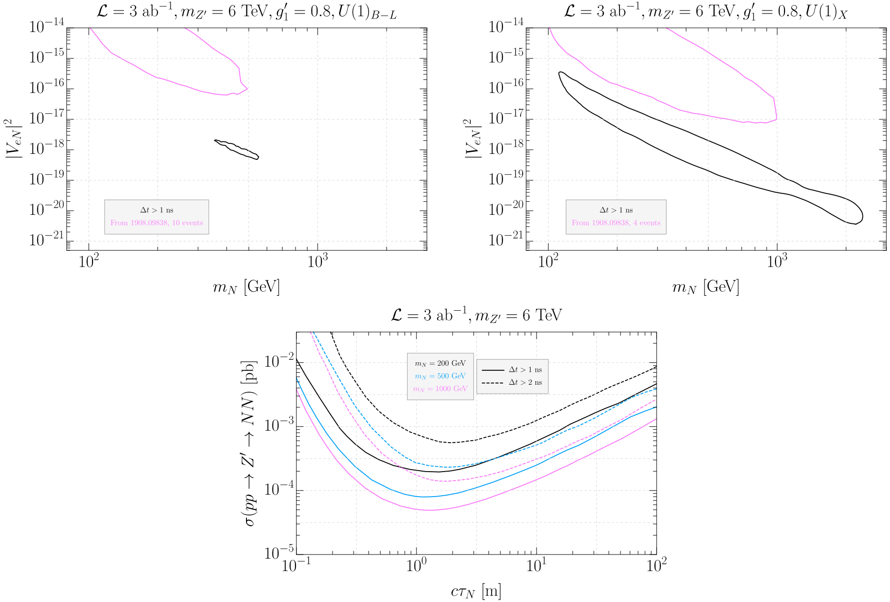


Numerical results: HNLs





Numerical results: HNLs



Summary

- Upcoming upgrades in the timing precision detectors at the ATLAS, CMS, LHCb, etc.
- Using timing information to probe LLPs
- Studied two scenarios of neutral LLPs with similar signatures
  - $\tilde{\chi}_1^0$ in the RPV-SUSY
  - HNLs in $U(1)$ extensions of the SM
- Strong limits predicted, complementary to other search strategies
- In particular interesting for heavy ($\gtrsim \mathcal{O}(10$ GeV$)$) LLPs

Thank You!

Back-up slides

R-parity and the RPV-MSSM

In general, the MSSM superpotential includes the following operators:

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

Lepton Number Violation & Baryon Number Violation

$\Rightarrow$ too fast proton decay rate!

$\Rightarrow$ An implicit ingredient of the MSSM: $\underline{R_p \text{ conservation (RPC)}}$

$$R_p = (-1)^{3(B-L)+2S}$$

B : *baryon number*, L : *lepton number*, S : *spin*

- SM fields: $R_p = +1$, superpartners: $R_p = -1$
- Forbids all the terms in $W_{\not R_p}$
- Renders the lightest supersymmetric particle (LSP) a stable cold DM candidate

(Partly) New Yukawa-like couplings

- $L_i L_j E_k$

- $L_i Q_j D_k$

- $U_i D_j D_k$

Final efficiencies