第十七届 TeV 物理工作组学术研讨会

Long-lived Searches of Vector-like Lepton and Its Accompanying Scalar at Colliders

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Based on

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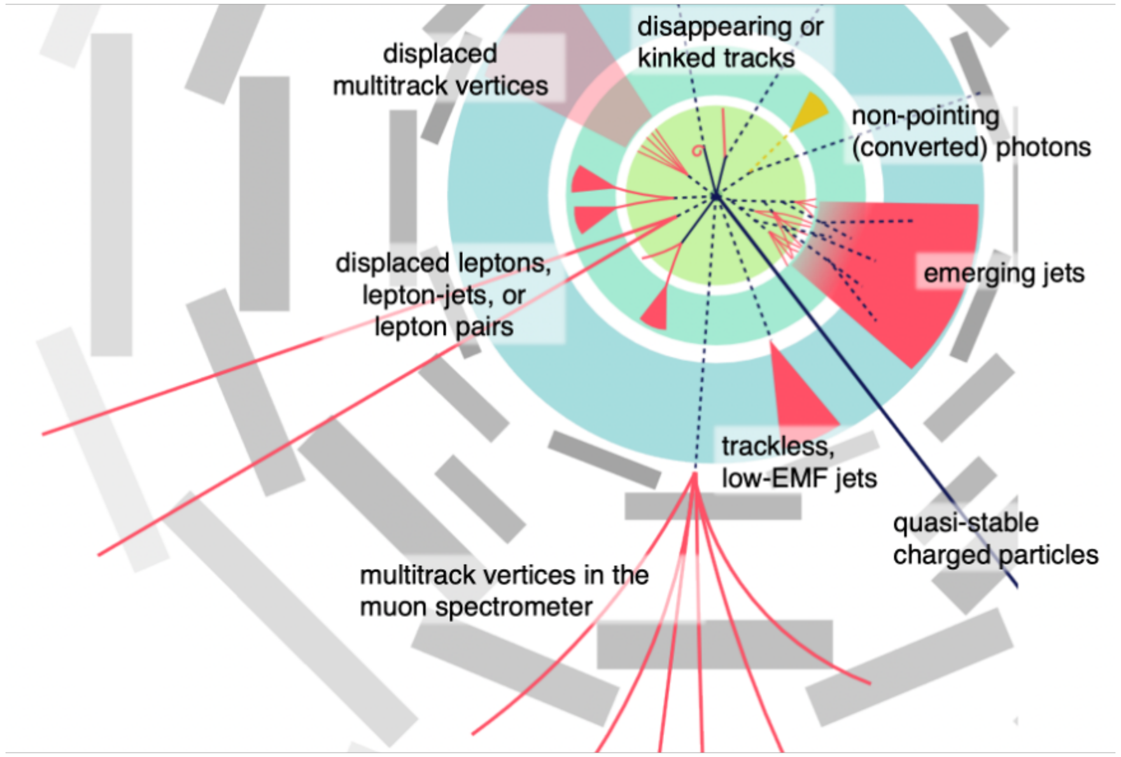
Introduction

- Vector-like fermion:
  non-chiral representation of SM gauge group
- More and more searches for vector-like lepton (VLL):
  but prompt decay 2202.08676. CMS Collaboration 2303.05441. ATLAS Collaboration
- Small chiral mass mixing:
  natural long-lived particle
- Bypass the constraints from Lepton Flavor Violation



ATLAS Collaboration

We consider long-lived singlet VLL and its accompanying scalar.

Models

- Vector-like Lepton Scenario (VLLS)

$$\mathscr{L}^F_{\text{eff}} \supset \bar{F}^0 i D_\mu \gamma^\mu F^0 + \bar{L}^0 i D_\mu \gamma^\mu L^0 + \bar{\ell}^0_R i D_\mu \gamma^\mu \ell^0_R - m^0_F \bar{F}^0 F^0 - m^0_\ell \bar{\ell}^0 \ell^0 - (\delta \bar{F}^0_L \ell^0_R + \text{h.c.})$$

	$F^\pm$	ℓ^0_R
$SU(2)_L$	1	1
$U(1)_Y$	-2	-2

  - diagonalizing the mass terms

$$\mathscr{L}^F_{\text{mass}} = (\bar{F}^0_L, \bar{\ell}^0_L) \begin{pmatrix} m^0_F & \delta \\ 0 & m^0_\ell \end{pmatrix} \begin{pmatrix} F^0_R \\ \ell^0_R \end{pmatrix} = (\bar{F}^0_L, \bar{\ell}^0_L)\, M \begin{pmatrix} F^0_R \\ \ell^0_R \end{pmatrix} = (\bar{F}_L, \bar{\ell}_L)\, U_L M U_R^\dagger \begin{pmatrix} F_R \\ \ell_R \end{pmatrix}$$

$U_L M U_R^\dagger = \text{diag}\,(m_F, m_\ell)$ with $U_L = \begin{pmatrix} \cos\theta_L & -\sin\theta_L \\ \sin\theta_L & \cos\theta_L \end{pmatrix}$ $\quad U_R = \begin{pmatrix} \cos\theta_R & -\sin\theta_R \\ \sin\theta_R & \cos\theta_R \end{pmatrix}$

mixing angle $\quad \tan\theta_R \simeq -\dfrac{\delta}{m^0_F} \quad \tan\theta_L \simeq -\dfrac{m^0_\ell \delta}{(m^0_F)^2} \simeq \dfrac{m^0_\ell}{m^0_F} \tan\theta_R$

$$m_F \simeq m^0_F + \frac{\delta^2}{2m^0_F} \simeq m^0_F \qquad m_\ell \simeq m^0_\ell \left(1 - \frac{1}{2}\left(\frac{\delta}{m^0_F}\right)^2\right)$$

Models

- Vector-like Lepton Scenario (VLLS)

$$\mathscr{L}_{\text{eff}}^{F} \supset \bar{F}(i\partial_\mu - eA_\mu + e\tan\theta_W Z_\mu)\gamma^\mu F - m_F \bar{F}F - m_\ell \bar{\ell}\ell$$

$$+\frac{1}{2}\frac{e}{\sin\theta_W \cos\theta_W}\theta_L Z_\mu(\bar{F}_L\gamma^\mu \ell_L + \mathrm{h.c.}) - \frac{e}{\sqrt{2}\sin\theta_W}\theta_L(W_\mu^+ \bar{\nu}_L \gamma^\mu F_L + \mathrm{h.c.})$$

Decay rate of $F^\pm$:

$$\Gamma(F^\pm \to \nu_\ell W^\pm) = \frac{\theta_L^2 g_W^2}{64\pi}\frac{(m_F^2 - m_W^2)^2(m_F^2 + 2m_W^2)}{m_F^3 m_W^2}$$

$$\Gamma(F^\pm \to \ell^\pm Z) = \frac{\theta_L^2 g_Z^2}{64\pi}\frac{(m_F^2 - m_Z^2)^2(m_F^2 + 2m_Z^2)}{m_F^3 m_Z^2}$$

small $\theta_L \to$ long-lived $F^\pm$

Models

- Vector-like Lepton with Scalar (VLLWS)

$$\mathscr{L}^{\phi}_{\rm Int} \supset -y\phi \bar{F}^0_L \ell^0_R + {\rm h.c.}$$
$$\simeq -y\phi \left(\bar{F}_L \ell_R + \bar{\ell}_R F_L + \theta_R \bar{F} F - \theta_L \bar{\ell} \ell\right)$$

	$F^{\pm}$	ϕ
$SU(2)_L$	1	1
$U(1)_Y$	-2	0

Decay rate of $F^{\pm}$ and ϕ:

$$\Gamma(F^{\pm} \to \phi \ell^{\pm}) = \frac{y^2(m_F^2 + m_\ell^2 - m_\phi^2)\sqrt{\lambda(m_F^2, m_\phi^2, m_\ell^2)}}{32\pi m_F^3}$$

$$\lambda(x, y, z) = x^2 + y^2 + z^2 - 2xy - 2yz - 2zx$$

$$\Gamma(\phi \to \ell^+ \ell^-) = \frac{(y\theta_L)^2 m_\phi (1 - 4m_\ell^2/m_\phi^2)^{3/2}}{8\pi}$$

$$\tau(\phi) \simeq \left(\frac{3 \times 10^{-9}}{y\theta_L}\right)^2 \left(\frac{50\ {\rm GeV}}{m_\phi}\right) {\rm ns}$$

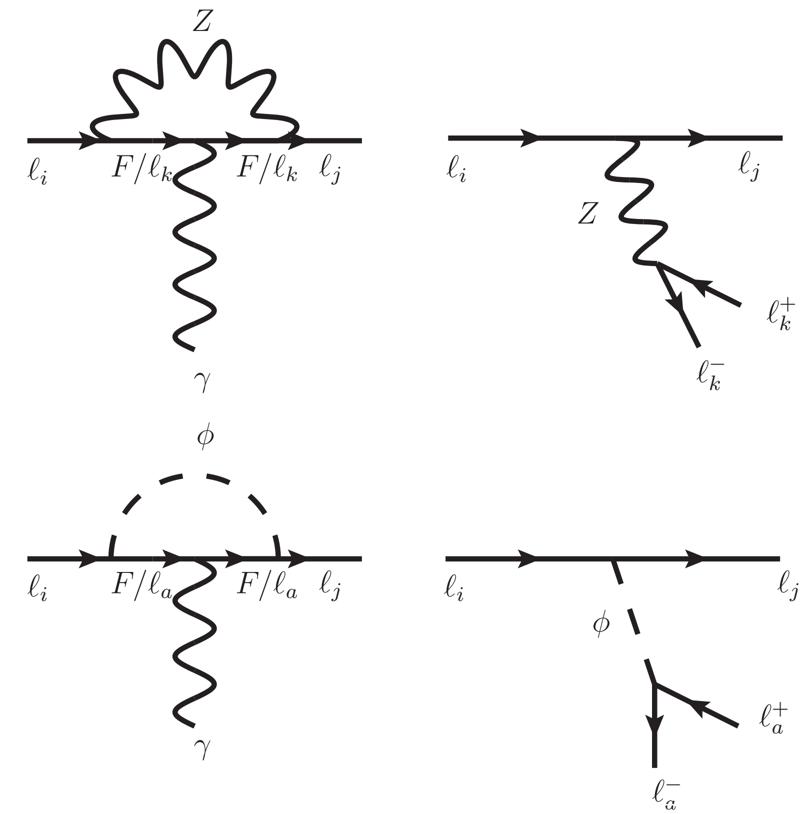
Existing Constraints

- Constraints from Lepton Flavor Violations

Generally, the mass matrix is

$$x_i = U^{\rm SM}_{R,i2}$$

$$M_{\rm mass} = \begin{pmatrix} m_{ee} & m_{e\mu} & m_{e\tau} & 0 \\ m_{\mu e} & m_{\mu\mu} & m_{\mu\tau} & 0 \\ m_{\tau e} & m_{\tau\mu} & m_{\tau\tau} & 0 \\ 0 & \delta & 0 & m_F^0 \end{pmatrix} \longrightarrow M'_{\rm mass} = \begin{pmatrix} m'_e & 0 & 0 & 0 \\ 0 & m'_\mu & 0 & 0 \\ 0 & 0 & m'_\tau & 0 \\ \delta \cdot x_1 & \delta \cdot x_2 & \delta \cdot x_3 & m_F^0 \end{pmatrix}$$



$$\text{Br}(\mu \to eee) < 10^{-12},\ \text{Br}(\tau \to \ell_i \ell_j \ell_j) \lesssim 2.7 \times 10^{-8},\ \text{Br}(\ell_i \to \ell_j \gamma) \lesssim 4.2 \times 10^{-13}$$

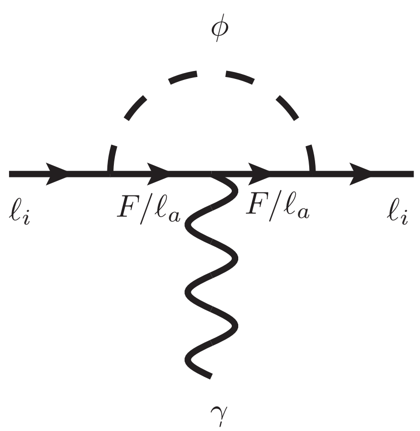
can be easily satisfied in the parameter regions of our LLP study

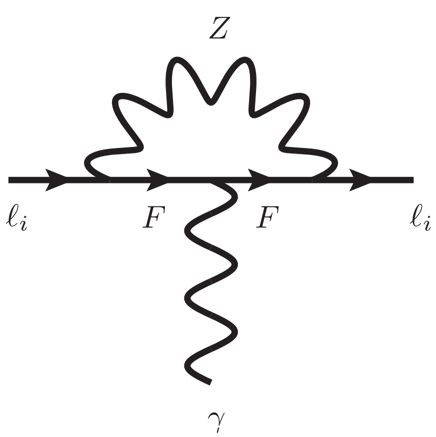
$$\left\{ y\theta_R < 10^{-2},\ y\theta_L < 0.5 \times 10^{-3},\ m_F > 200 \text{ GeV and } m_\phi > 20 \text{ GeV} \right\}$$

In the following phenomenology discussion, we assume ℓ_0 to be SM mass eigenstate.

Existing Constraints

- Constraints from g-2





$$(g-2)_\mu^{\rm BSM} < 2.49 \times 10^{-9}$$
$$(g-2)_e^{\rm BSM} < 9.8 \times 10^{-13}$$

0801.1134. D. Hanneke et al.

2308.06230. D. P. Aguillard et al.

the dominant contribution:

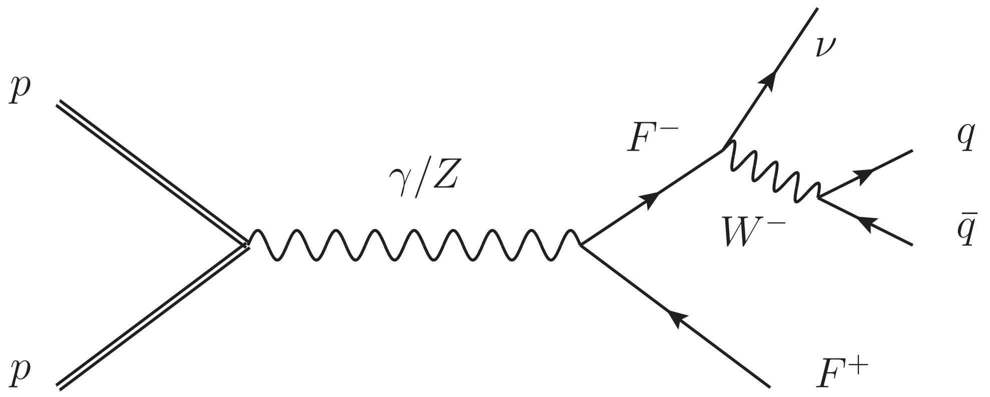
$$(g-2)_{\ell_i}^{F,\phi} \simeq \begin{cases} 2.64 \times 10^{-10} \left(\frac{y}{1}\right)^2 \left(\frac{m_{\ell_i}}{0.1\ \text{GeV}}\right)^2 \left(\frac{200\ \text{GeV}}{m_F}\right)^2 (m_F > m_\phi \gg m_{\ell_i}), \\ 1.32 \times 10^{-10} \left(\frac{y}{1}\right)^2 \left(\frac{m_{\ell_i}}{0.1\ \text{GeV}}\right)^2 \left(\frac{200\ \text{GeV}}{m_F}\right)^2 (m_\phi = m_F \gg m_{\ell_i}), \end{cases}$$

we set $y = 1$ in the following discussion

LLP Signatures at Collider

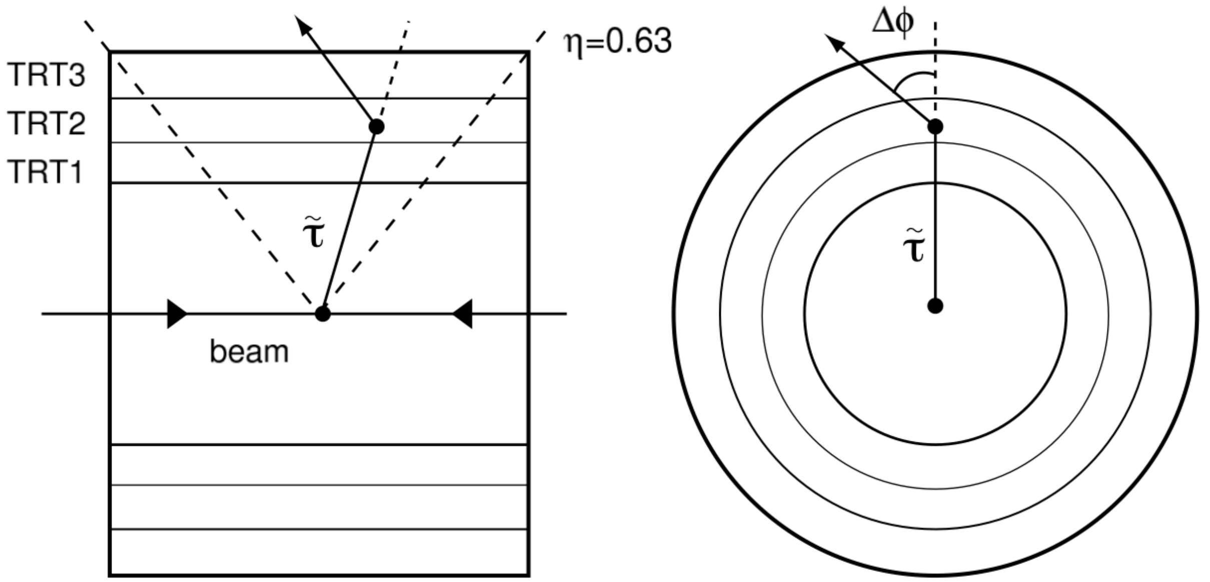
- Long-lived VLL: Kink Signatures

F mixed with μ



Signal process:

$pp \to F^-F^+, F^- \to W^-\nu_e, W^- \to q\bar{q}$



Kink Track in the TRT.

Inner Track
Pixel detector
Semi-conductor tracker (SCT)
Transition radiation tracker (TRT)
563 mm $< R_1 <$ 694 mm
697 mm $< R_2 <$ 860 mm
863 mm $< R_3 <$ 1066 mm

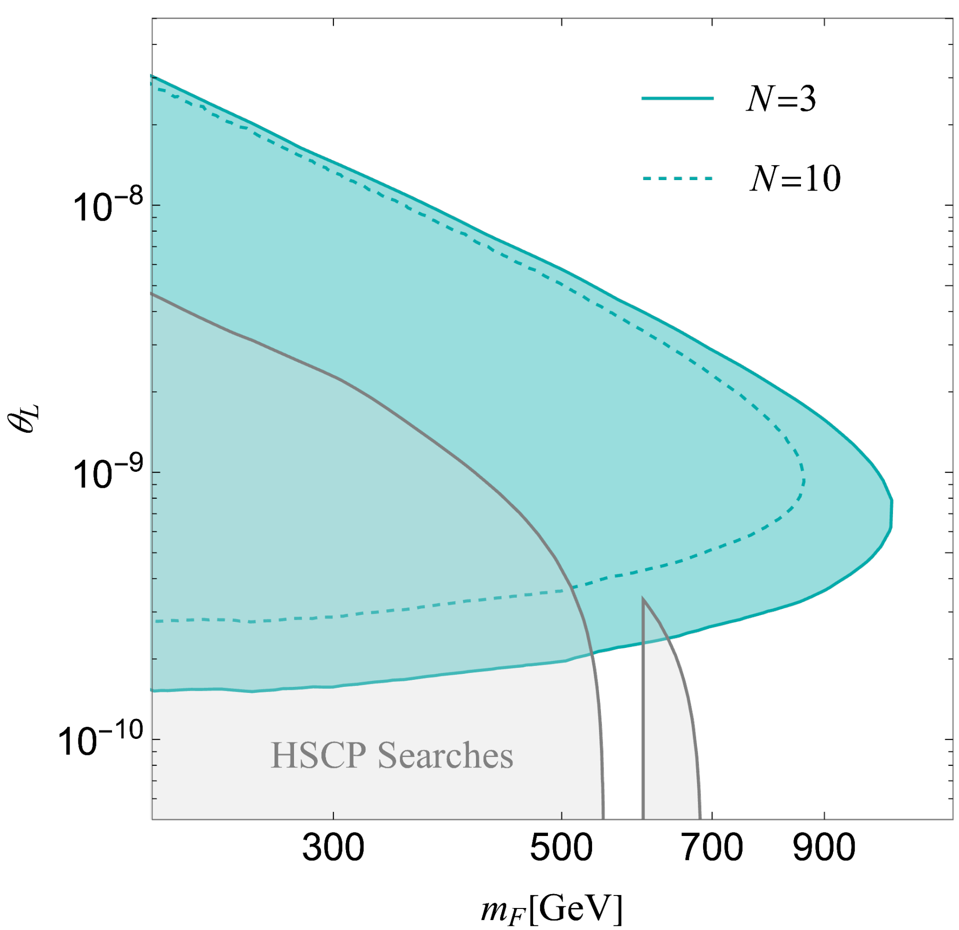
1103.1881. S. Asai et al.

LLP Signatures at Collider

- Long-lived VLL: Kink Signatures

free parameters

$\{m_F, \theta_L\}$



Selection criterions:

$$\text{KT}: p_T^F > 100 \text{ GeV}, |\eta_F| < 0.63, 0.1 < \Delta\phi < \pi/2,$$
$$563 \text{ mm} < r_F < 863 \text{ mm}, |z_F| < 712 \text{ mm},$$
$$p_T^q > 10 \text{ GeV}, |z_F/r_F| > |p_z^\mu/p_T^\mu|$$

HL-LHC: $\sqrt{s} = 13$ TeV, $\mathscr{L} = 3$ ab^{-1}

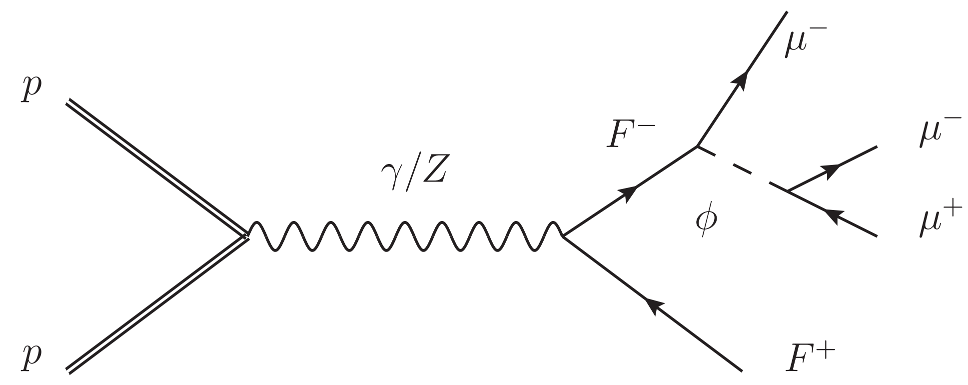
Constraints from the

Heavy Stable Charged Particle searches.

LLP Signatures at Collider

- Long-lived Scalar Particle at HL-LHC

Signal process: $pp \to F^- F^+, F^\pm \to \phi l^\pm, \phi \to l^+ l^-$



Time delay:

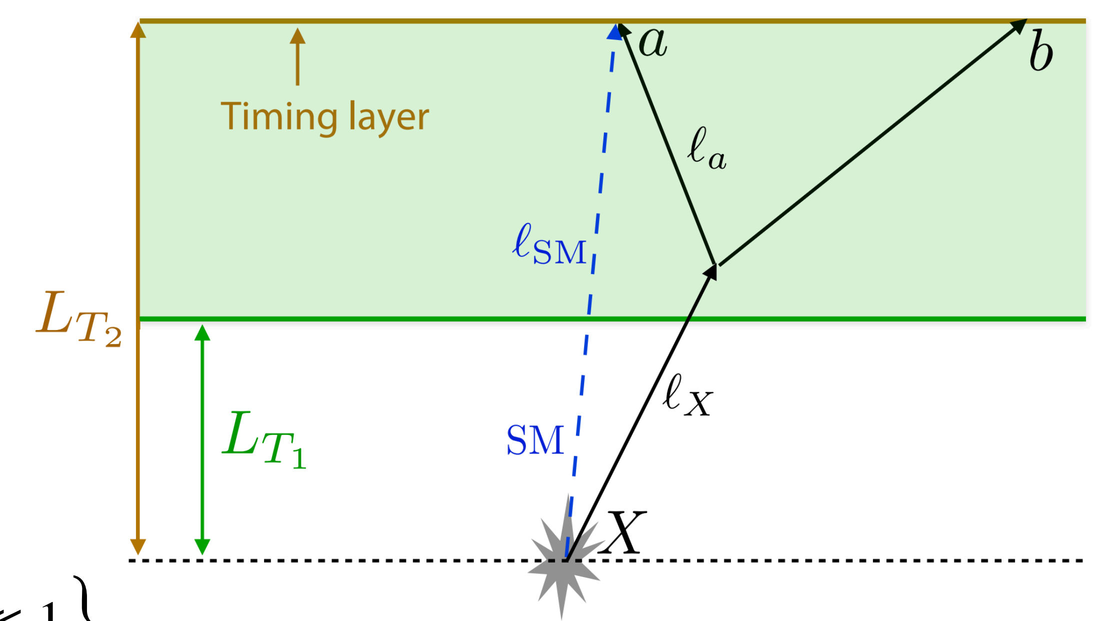
$$\Delta t_\ell = L_\phi/\beta_\phi + L_\ell/\beta_\ell - L_{SM}/\beta_{SM}$$

free parameters

$$\{m_F, m_\phi, y, \theta_L\}$$

Benchmark parameters setting:

1. $\left\{ m_F/m_\phi = 2,\ 5,\ 10,\ m_F > 200\ \text{GeV},\ \theta_L \ll 1 \right\}$
2. $\left\{ m_\phi \in [20\ \text{GeV}, m_F],\ m_F = 1\ \text{TeV},\ 1.2\ \text{TeV},\ \theta_L \ll 1 \right\}$
3. $\left\{ m_\phi = 100\ \text{GeV},\ 300\ \text{GeV},\ 500\ \text{GeV},\ m_F > 200\ \text{GeV},\ \theta_L \ll 1 \right\}$



1805.05957. Jia Liu et al.

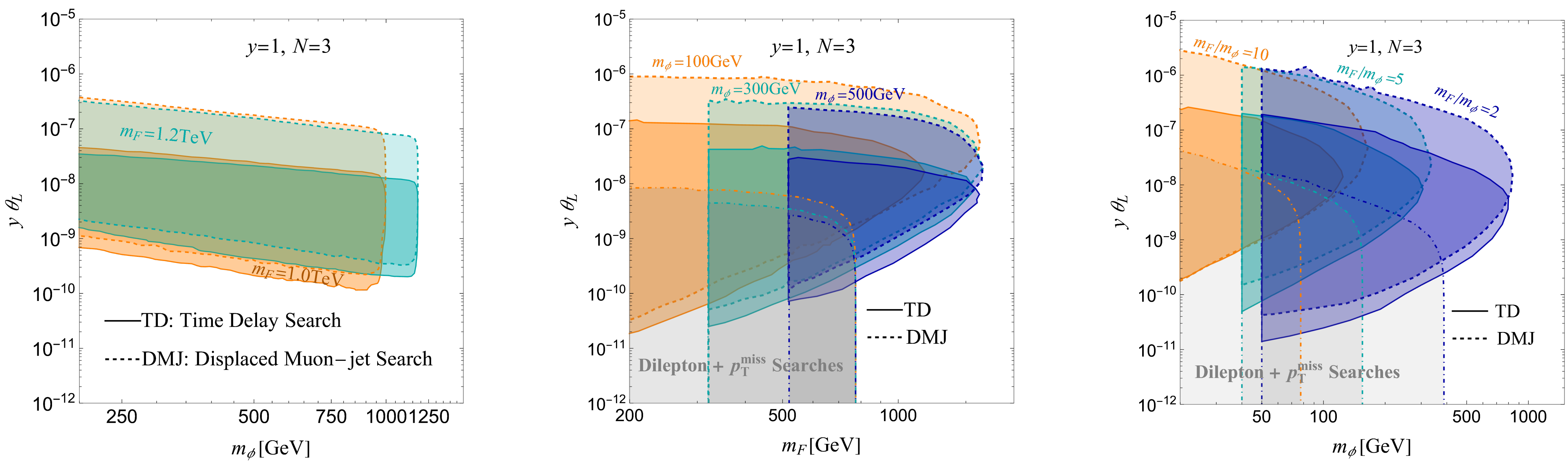
LLP Signatures at Collider

- Long-lived Scalar Particle at HL-LHC

DMJ : $p_T^{\mu,F} > 30$ GeV, $p_T^{\mu,\phi} > 5$ GeV, $r_\phi < 30$ cm, $d_0^{\mu,\phi} > 1$ mm (displaced muon-jets)

TD : $p_T^{\mu,F} > 30$ GeV, $p_T^{\mu,\phi} > 5$ GeV, $|\eta_\mu| < 2.4$, $\Delta t_{\mu,\phi} > 0.3$ ns, 5 cm $< r_\phi < 1.17$ m, $z_\phi < 3.04$ m

CMS Minimum Ionizing Particle (MIP) timing detector



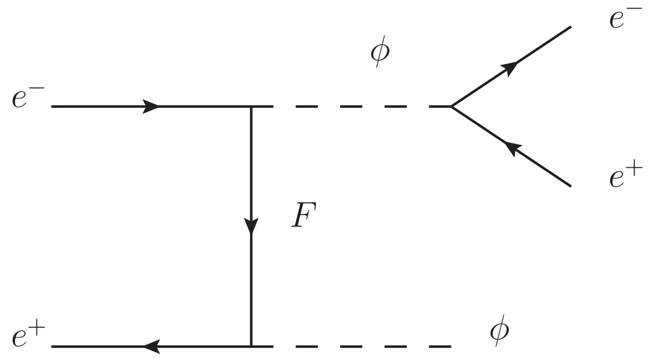
Constraints from dilepton plus missing transverse momentum searches.

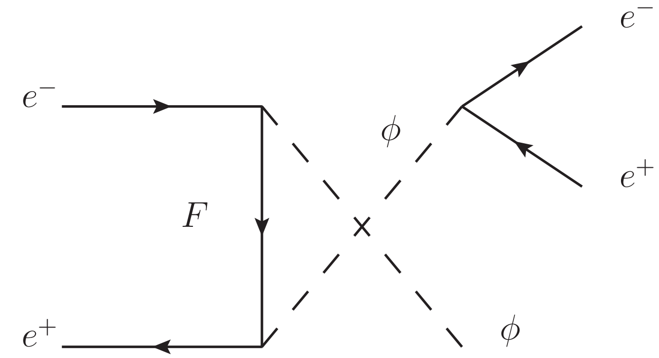
LLP Signatures at Collider

- Long-lived Scalar Particle at CEPC

F mixed with e

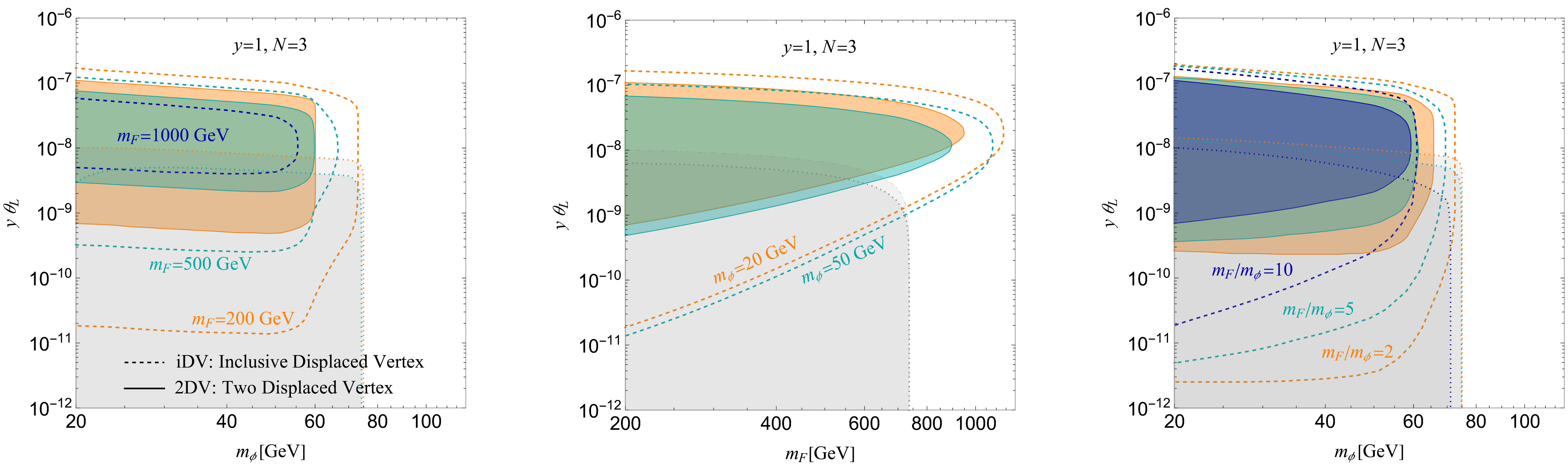
(displaced vertex)





$$\text{DV} - \text{CEPC}: \quad 10\ \text{cm} < |d_\phi \cdot \sin\theta_i| < 1.8\ \text{m},\ |d_\phi \cdot \cos\theta_i| < 2.35\ \text{m},$$

$$p_T^{e_i} > 30\ \text{GeV},\ m_{e_1 e_2}(m_\phi) > 20\ \text{GeV},\ 1 > \Delta R > 0.01$$



CEPC: $\sqrt{s} = 240\ \text{GeV},\ \mathscr{L} = 5.6\ \text{ab}^{-1}$

Summary

- We explore the potential long-lived signatures of VLLs $F^{\pm}$ or their subsequent decay products ϕ.

- For the long-lived $F^{\pm}$, we use the kink track method at the ATLAS detector, which shows good sensitivities for $m_F \in [200,950]$ GeV, with coupling around $10^{-10} < \theta_L < 10^{-7}$.

- For the long-lived scalars ϕ, we use the displaced muon-jet and time-delay methods, which show good sensitivities for $m_F \in [200,1200]$ GeV, with coupling around $10^{-11} < y\theta_L < 10^{-6}$. Moreover, CEPC has good performance for $m_\phi < 70$ GeV and $m_F < 1000$ GeV through the displaced vertex method.

Thanks!

References

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Backup

- More on LFV

The unitary matrix which diagonalizing the general mixed mass matrix

$$U'_L \simeq \begin{pmatrix} 1-\frac{1}{2}r_{1a}^2\theta_L^2 & x_1x_2r_{12}\theta_R^2 & x_1x_3r_{13}\theta_R^2 & -x_1r_{1a}\theta_L \\ -x_1x_2r_{12}\theta_R^2 & 1-\frac{1}{2}r_{2a}^2\theta_L^2 & x_2x_3r_{23}\theta_R^2 & -x_2r_{2a}\theta_L \\ -x_1x_3r_{13}\theta_R^2 & -x_2x_3r_{23}\theta_R^2 & 1-\frac{1}{2}r_{3a}\theta_L^2 & -x_3r_{3a}\theta_L \\ x_1r_{1a}\theta_L & x_2r_{2a}\theta_L & x_3r_{3a}\theta_L & 1-\frac{1}{2}\theta_L^2(r_{1a}^2x_1^2+r_{2a}^2x_2^2+r_{3a}^2x_3^2) \end{pmatrix}$$

$$U'_R \simeq \begin{pmatrix} 1-\frac{1}{2}\theta_R^2 & x_1x_2r_{12}\theta_R^2 & x_1x_3r_{13}\theta_R^2 & -x_1\theta_R \\ -x_1x_2\theta_R^2 & 1-\frac{1}{2}\theta_R^2 & x_2x_3r_{23}\theta_R^2 & -x_2\theta_R \\ -x_1x_3\theta_R^2 & -x_2x_3\theta_R^2 & 1-\frac{1}{2}\theta_R^2 & -x_3\theta_R \\ x_1\theta_R & x_2\theta_R & x_3\theta_R & 1-\frac{1}{2}\theta_R^2(x_1^2+x_2^2+x_3^2) \end{pmatrix}$$

$$r_{ij} \equiv m_{\ell_i}/m_{\ell_j}$$

$$r_{ia} \equiv m_{\ell_i}/m_{\ell_a}$$

Backup

- More on LFV

  - If ϕ interaction comes from flavor eigenstates

$$\mathcal{L}_{\rm eff}^{\phi} = y\phi(\bar{e}_L^0, \bar{\mu}_L^0, \bar{\tau}_L^0, \bar{F}_L^0)\begin{pmatrix} 0000 \\ 0000 \\ 0000 \\ 0100 \end{pmatrix}\begin{pmatrix} e_R^0 \\ \mu_R^0 \\ \tau_R^0 \\ F_R^0 \end{pmatrix} + {\rm h.c.} = y\phi(\bar{e}'_L, \bar{\mu}'_L, \bar{\tau}'_L, \bar{F}'_L)\begin{pmatrix} 00\,0\,0 \\ 00\,0\,0 \\ 00\,0\,0 \\ x_1x_2x_3 0 \end{pmatrix}\begin{pmatrix} e'_R \\ \mu'_R \\ \tau'_R \\ F'_R \end{pmatrix} + {\rm h.c.}.$$

leads to

$${\rm Br}(\ell_i \to \ell_j\gamma) \simeq \frac{\pi^3\alpha_{\rm EM}(y^2x_ix_j)^2}{3G_F^2}\frac{\left(m_F^6 - 6m_F^4m_\phi^2 + 3m_F^2m_\phi^4 + 2m_\phi^6 + 12m_F^2m_\phi^4\ln\left(\frac{m_F}{m_\phi}\right)\right)^2}{\left(m_F^2 - m_\phi^2\right)^8}$$

$$y < 6.8 \times 10^{-4}\left(\frac{1}{x_1}\right)^{1/2}\left(\frac{1}{x_2}\right)^{1/2}\left(\frac{m_F}{200\ {\rm GeV}}\right)$$

Backup

- More on LFV
  - If ϕ interaction comes from SM mass eigenstates

$$\mathrm{Br}(\ell_a \to \ell_i \gamma) \simeq \frac{\pi^3 \alpha_{\mathrm{EM}} (x_i x_a r_{ia} y^2 \theta_R^2)^2}{3 G_F^2} \frac{\left(m_F^6 - 6 m_F^4 m_\phi^2 + 3 m_F^2 m_\phi^4 + 2 m_\phi^6 + 12 m_F^2 m_\phi^4 \ln\left(\frac{m_F}{m_\phi}\right)\right)^2}{\left(m_F^2 - m_\phi^2\right)^8}$$

$$\simeq 3.5 \times 10^{-15} \left(\frac{x_i}{1}\right)^2 \left(\frac{x_a}{1}\right)^2 \left(\frac{r_{ia}}{10^{-3}}\right)^2 \left(\frac{y\theta_R}{10^{-2}}\right)^4 \left(\frac{200\ \mathrm{GeV}}{m_F}\right)^4 .$$