Minimally beyond the Standard Model:

Isosinglet vectorlike leptons at e^+e^- colliders

Prudhvi N. Bhattiprolu
prudhvi.bhattiprolu@fi.infn.it

INFN Florence

Florence Theory Group Day
Galileo Galilei Institute
March 19, 2025

Based on arXiv:hep-ph/2308.08386 with
Stephen P. Martin (Northern Illinois U.) and Aaron Pierce (U. Michigan)

All is not well with the Standard Model

Despite being successful and complete with the discovery of the ~ 125 GeV Higgs boson, the Standard Model is plagued by many problems:

All is not well with the Standard Model

Despite being successful and complete with the discovery of the ~ 125 GeV Higgs boson, the Standard Model is plagued by many problems:

- The electroweak hierarchy problem: $M_{\mathrm{weak}}/M_{\mathrm{Planck}} \sim 10^{-16}$

All is not well with the Standard Model

Despite being successful and complete with the discovery of the ~ 125 GeV Higgs boson, the Standard Model is plagued by many problems:

- The electroweak hierarchy problem: $M_{\text{weak}}/M_{\text{Planck}} \sim 10^{-16}$
- The strong CP problem: $|\bar{\theta}| \lesssim 10^{-10}$

All is not well with the Standard Model

Despite being successful and complete with the discovery of the ~ 125 GeV Higgs boson, the Standard Model is plagued by many problems:

- The electroweak hierarchy problem: $M_{\text{weak}}/M_{\text{Planck}} \sim 10^{-16}$
- The strong CP problem: $|\bar{\theta}| \lesssim 10^{-10}$
- Dark matter abundance: $\Omega_{\text{dark}} h^2 \sim 0.12$

All is not well with the Standard Model

Despite being successful and complete with the discovery of the ~ 125 GeV Higgs boson, the Standard Model is plagued by many problems:

- The electroweak hierarchy problem: $M_{\rm weak}/M_{\rm Planck} \sim 10^{-16}$
- The strong CP problem: $|\bar{\theta}| \lesssim 10^{-10}$
- Dark matter abundance: $\Omega_{\rm dark} h^2 \sim 0.12$
- Matter-antimatter asymmetry
- Neutrino masses
- The cosmological constant problem
- ...

SM particle content

Spin	Field	$SU(3)_c \times SU(2)_L \times U(1)_Y$
0	$(H^+ \;\; H^0)$	$(\,\mathbf{1}\,,\,\mathbf{2}\,,\,+\frac{1}{2}\,)$
1/2	$(u_L \;\; d_L)_i$	$(\,\mathbf{3}\,,\,\mathbf{2}\,,\,+\frac{1}{6}\,)$
	$u^\dagger_{Ri}$	$(\,\overline{\mathbf{3}}\,,\,\mathbf{1}\,,\,-\frac{2}{3}\,)$
	$d^\dagger_{Ri}$	$(\,\overline{\mathbf{3}}\,,\,\mathbf{1}\,,\,+\frac{1}{3}\,)$
	$(\nu \;\; e_L)_i$	$(\,\mathbf{1}\,,\,\mathbf{2}\,,\,-\frac{1}{2}\,)$
	$e^\dagger_{Ri}$	$(\,\mathbf{1}\,,\,\mathbf{1}\,,\,+1\,)$
1	g	$(\,\mathbf{8}\,,\,\mathbf{1}\,,\,0\,)$
	$W^\pm, W^0$	$(\,\mathbf{1}\,,\,\mathbf{3}\,,\,0\,)$
	B^0	$(\,\mathbf{1}\,,\,\mathbf{1}\,,\,0\,)$

BSM particle content?

Spin	Field	$SU(3)_c \times SU(2)_L \times U(1)_Y$
0	$(H^+ \quad H^0)$	$(\mathbf{1} , \mathbf{2} , +\frac{1}{2})$
	?	(? , ? , ?)
1/2	$(u_L \quad d_L)_i$	$(\mathbf{3} , \mathbf{2} , +\frac{1}{6})$
	$u^\dagger_{Ri}$	$(\overline{\mathbf{3}} , \mathbf{1} , -\frac{2}{3})$
	$d^\dagger_{Ri}$	$(\overline{\mathbf{3}} , \mathbf{1} , +\frac{1}{3})$
	$(\nu \quad e_L)_i$	$(\mathbf{1} , \mathbf{2} , -\frac{1}{2})$
	$e^\dagger_{Ri}$	$(\mathbf{1} , \mathbf{1} , +1)$
	?	(? , ? , ?)
1	g	$(\mathbf{8} , \mathbf{1} , 0)$
	$W^\pm, W^0$	$(\mathbf{1} , \mathbf{3} , 0)$
	B^0	$(\mathbf{1} , \mathbf{1} , 0)$
	?	(? , ? , ?)

Why not 4$^{\text{th}}$ generation chiral fermions?

- L and R transform differently under $SU(2)_L \times U(1)_Y$
- Non-trivial anomaly cancellation constraint
- $M_{\text{SM}_4} = y_{\text{SM}_4} v$, with very large Yukawas to avoid discovery in the past
- Do not decouple from flavor and precision EW (S, T, U) observables
- Do not decouple from Higgs production and decay

Why not 4$^{\text{th}}$ generation chiral fermions?

- L and R transform differently under $SU(2)_L \times U(1)_Y$
- Non-trivial anomaly cancellation constraint
- $M_{\text{SM}_4} = y_{\text{SM}_4} v$, with very large Yukawas to avoid discovery in the past
- Do not decouple from flavor and precision EW (S, T, U) observables
- Do not decouple from Higgs production and decay

LHC ruled out most non-decoupling theories, including new chiral fermions

[See, e.g, A. Lenz, Adv. High Energy Phys. 2013, 910275]

Decoupling theories:

- Vectorlike fermions
- Supersymmetry

Vectorlike fermions

- L and R transform same way
- Automatically anomaly-free
- Get masses mostly from bare electroweak singlet mass terms
- Decouple from flavor and EW precision data like ϵ^2/M^2
- Decouple from Higgs production and decay like ϵ/M

Vectorlike fermions

- L and R transform same way
- Automatically anomaly-free
- Get masses mostly from bare electroweak singlet mass terms
- Decouple from flavor and EW precision data like ϵ^2/M^2
- Decouple from Higgs production and decay like ϵ/M

Required by many BSM models that address:

- Hierachy problem (SUSY, ...)
- Dark matter (SUSY, Singlet-Doublet fermion model, ...)
- Strong CP problem (KSVZ model, ...)
- Baryogenesis [See, e.g., Fairbairn, Grothaus 1307.8011]
- Muon $g-2$ anomaly [See, e.g., Dermisek, Raval 1305.3522]
- ...

- Hadron colliders: best discovery reach
- Lepton colliders: precision studies and indirect searches

- Hadron colliders: best discovery reach
- Lepton colliders: precision studies and indirect searches

This is plausible for strongly-interacting (pair-produced) vectorlike quarks:

$$M_{t'} \geq 1.31 - 1.60 \text{ TeV}$$ [ATLAS 1808.02343, 2210.15413]

$$M_{b'} \geq 1.20 - 1.57 \text{ TeV}$$ [ATLAS 2210.15413, CMS 2008.09835]

$$M_{\psi'_0} \gtrsim 1.5 - 1.7 \text{ TeV}$$ [PNB, G. Elor, R. McGehee, A. Pierce 2210.15653, ATLAS 1902.01636]

where t', b' are assumed to mix with t, b quarks, and ψ'_0 is a long-lived EW-singlet.

- Hadron colliders: best discovery reach
- Lepton colliders: precision studies and indirect searches

This is plausible for strongly-interacting (pair-produced) vectorlike quarks:

$$M_{t'} \geq 1.31 - 1.60 \text{ TeV}$$ [ATLAS 1808.02343, 2210.15413]

$$M_{b'} \geq 1.20 - 1.57 \text{ TeV}$$ [ATLAS 2210.15413, CMS 2008.09835]

$$M_{\psi'_0} \gtrsim 1.5 - 1.7 \text{ TeV}$$ [PNB, G. Elor, R. McGehee, A. Pierce 2210.15653, ATLAS 1902.01636]

where t', b' are assumed to mix with t, b quarks, and ψ'_0 is a long-lived EW-singlet.

But may not be the case for weakly-interacting vectorlike leptons:

$SU(2)_L$-doublet: $M_{\tau'} \geq 1045$ GeV [CMS 2202.08676]

$SU(2)_L$-singlet: $M_{\tau'} \in [101.2, 125]$ or $M_{\tau'} \geq 150$ GeV [LEP 0107015, CMS 2202.08676]

assumed to mix with τ.

Consider $SU(2)_L$-singlet *vectorlike* τ':

$$\tau'_L, \tau'^{\dagger}_R \ \sim\ (\mathbf{1}, \mathbf{1}, -1)\ +\ (\mathbf{1}, \mathbf{1}, +1)$$

in contrast with the *chiral* SM τ

$$\tau_L, \tau^{\dagger}_R \ \sim\ (\mathbf{1}, \mathbf{2}, -1/2)\ +\ (\mathbf{1}, \mathbf{1}, +1)$$

Consider $SU(2)_L$-singlet *vectorlike* τ':

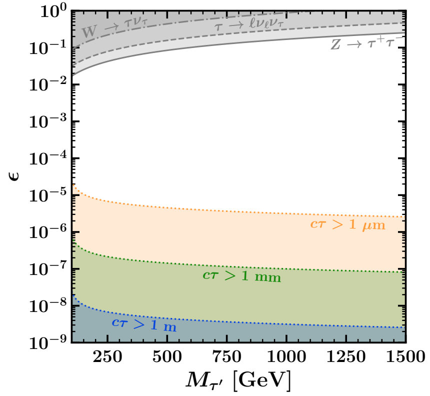
$$\tau'_L, \tau'^{\dagger}_R \;\sim\; (\mathbf{1},\mathbf{1},-1) + (\mathbf{1},\mathbf{1},+1)$$

in contrast with the *chiral* SM τ

$$\tau_L, \tau^{\dagger}_R \;\sim\; (\mathbf{1},\mathbf{2},-1/2) + (\mathbf{1},\mathbf{1},+1)$$

Assume mass mixing of τ' and τ:

$$\mathcal{M} \;=\; \begin{pmatrix} y_\tau v & 0 \\ \epsilon v & M \end{pmatrix}$$



Consider $SU(2)_L$-singlet *vectorlike* τ':

$$\tau'_L, \tau'^{\dagger}_R \;\sim\; (\mathbf{1}, \mathbf{1}, -1) \,+\, (\mathbf{1}, \mathbf{1}, +1)$$

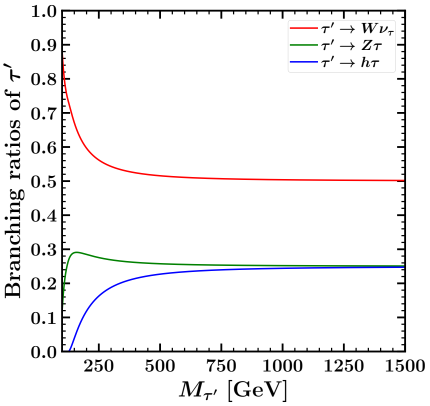
in contrast with the *chiral* SM τ

$$\tau_L, \tau^{\dagger}_R \;\sim\; (\mathbf{1}, \mathbf{2}, -1/2) \,+\, (\mathbf{1}, \mathbf{1}, +1)$$

Assume *tiny* mass mixing of τ' and τ:

$$\mathcal{M} \;=\; \begin{pmatrix} y_\tau v & 0 \\ \epsilon v & M \end{pmatrix}$$

with *prompt* τ' decays



Consider $SU(2)_L$-singlet *vectorlike* τ':

$$\tau'_L, \tau'^{\dagger}_R \;\sim\; (\mathbf{1}, \mathbf{1}, -1) \,+\, (\mathbf{1}, \mathbf{1}, +1)$$

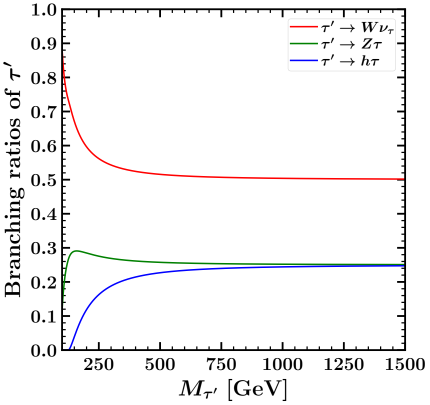
in contrast with the *chiral* SM τ

$$\tau_L, \tau^{\dagger}_R \;\sim\; (\mathbf{1}, \mathbf{2}, -1/2) \,+\, (\mathbf{1}, \mathbf{1}, +1)$$

Assume *tiny* mass mixing of τ' and τ:

$$\mathcal{M} \;=\; \begin{pmatrix} y_\tau v & 0 \\ \epsilon v & M \end{pmatrix}$$

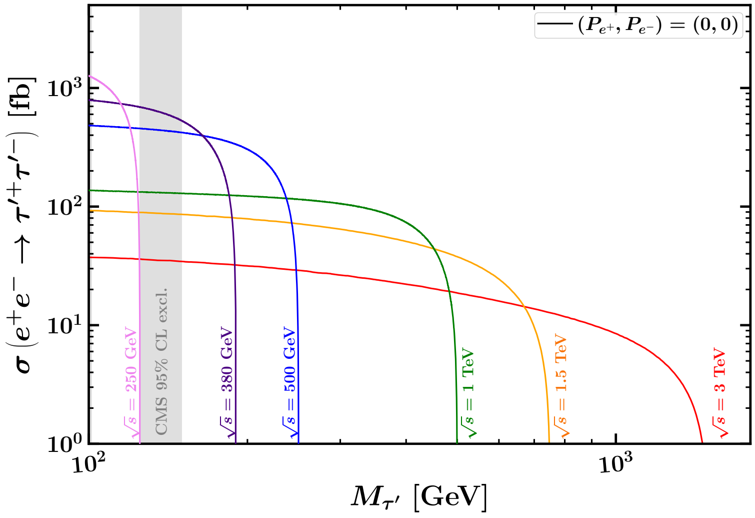
with *prompt* τ' decays



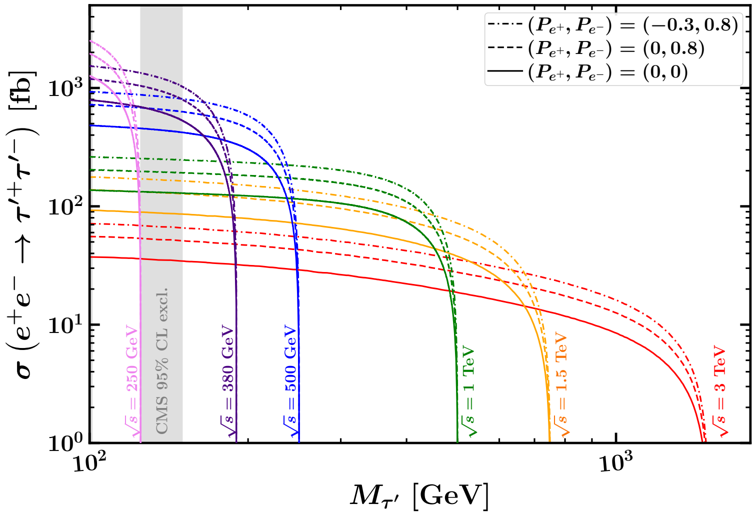
Limited reach for τ' at the

- LHC [N. Kumar, S. P. Martin 1510.03456]
- Future pp colliders [PNB, S. P. Martin 1905.00498]

due to low cross-section and the unfortunately large $\mathrm{BR}(\tau' \to W\nu_\tau)$



- Pair-production mode: $e^+e^- \to \gamma^*, Z^* \to \tau'^+\tau'^-$
- Accounting for the effects of ISR + beamstrahlung



- Pair-production mode: $e^+e^- \to \gamma^*, Z^* \to \tau'^+\tau'^-$
- Accounting for the effects of ISR + beamstrahlung
- $(P_{e^+}, P_{e^-}) = (-0.3, 0.8)$ and $(0, 0.8)$ maximize σ for ILC and CLIC

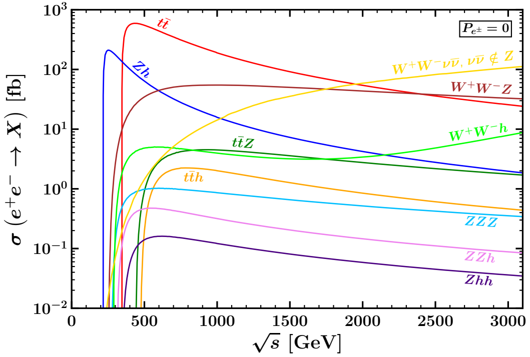
Signal components:

$$e^+e^- \to \tau'^+\tau'^- \to \quad ZZ\tau^+\tau^-, \quad hh\tau^+\tau^-, \quad Zh\tau^+\tau^-$$
$$ZW^\pm\tau^\mp + \not{E}, \quad hW^\pm\tau^\mp + \not{E},$$
$$W^\pm W^\mp + \not{E}$$ **(largest!)**

Signal components:

$$e^+e^- \to \tau'^+\tau'^- \to \quad ZZ\tau^+\tau^-, \quad hh\tau^+\tau^-, \quad Zh\tau^+\tau^-$$
$$ZW^\pm\tau^\mp + \not{E}, \quad hW^\pm\tau^\mp + \not{E},$$
$$W^\pm W^\mp + \not{E}$$ **(largest!)**

SM backgrounds: $t\bar{t}$, $t\bar{t}Z$, $t\bar{t}h$, Zh, Zhh, ZZh, ZZZ, W^+W^-h, W^+W^-Z, and $W^+W^-\nu\bar{\nu}$ with $\nu\bar{\nu} \notin Z$



Signal regions: 15 different signal regions targeting various final states with

$$\begin{aligned} N_\ell + N_j + N_b &= 4 \\ N_\tau &= 1 \text{ or } 2 \end{aligned}$$

Reconstruct Z from $\ell^+\ell^-/jj$, h from bb, and also W from jj if $N_\tau = 1$

E.g.,

- $4\ell + 2\tau$
- $2j + 2b + 2\tau$
- $4b + 2\tau$
- $4j + 1\tau$
- $2j + 2b + 1\tau$
- $3j + 1b + 2\tau$ (& $Z/h/W$ from jb)

Signal regions: 15 different signal regions targeting various final states with

$$\begin{aligned} N_\ell + N_j + N_b &= 4 \\ N_\tau &= 1 \text{ or } 2 \end{aligned}$$

Reconstruct Z from $\ell^+\ell^-/jj$, h from bb, and also W from jj if $N_\tau = 1$

E.g.,

- $4\ell + 2\tau \to ZZ\tau\tau$
- $2j + 2b + 2\tau \to Zh\tau\tau$
- $4b + 2\tau \to hh\tau\tau$
- $4j + 1\tau \to ZW\tau\nu_\tau$
- $2j + 2b + 1\tau \to hW\tau\nu_\tau$
- $3j + 1b + 2\tau \to ZZ\tau\tau, Zh\tau\tau$

Signal regions: 15 different signal regions targeting various final states with

$$N_\ell + N_j + N_b = 4$$
$$N_\tau = 1 \text{ or } 2$$

Reconstruct Z from $\ell^+\ell^-/jj$, h from bb, and also W from jj if $N_\tau = 1$

E.g.,

- $4\ell + 2\tau \to ZZ\tau\tau$
- $2j + 2b + 2\tau \to Zh\tau\tau$
- $4b + 2\tau \to hh\tau\tau$
- $4j + 1\tau \to ZW\tau\nu_\tau$
- $2j + 2b + 1\tau \to hW\tau\nu_\tau$
- $3j + 1b + 2\tau \to ZZ\tau\tau, Zh\tau\tau$

Event simulation: At LO while accounting for ISR + beamstrahlung:

FeynRules → Whizard → Pythia8 → Delphes

[Model files at `prudhvibhattiprolu/VLL-UFOs` being used by ATLAS and CMS]

Signal regions: 15 different signal regions targeting various final states with

$$\begin{aligned} N_\ell + N_j + N_b &= 4 \\ N_\tau &= 1 \text{ or } 2 \end{aligned}$$

Reconstruct Z from $\ell^+\ell^-/jj$, h from bb, and also W from jj if $N_\tau = 1$

E.g.,

- $4\ell + 2\tau \to ZZ\tau\tau$
- $2j + 2b + 2\tau \to Zh\tau\tau$
- $4b + 2\tau \to hh\tau\tau$
- $4j + 1\tau \to ZW\tau\nu_\tau$
- $2j + 2b + 1\tau \to hW\tau\nu_\tau$
- $3j + 1b + 2\tau \to ZZ\tau\tau, Zh\tau\tau$

Event simulation: At LO while accounting for ISR + beamstrahlung:

FeynRules → Whizard → Pythia8 → Delphes

[Model files at `prudhvibhattiprolu/VLL-UFOs` being used by ATLAS and CMS]

Goal: Reconstructing mass peaks for various $M_{\tau'}$ in various signal regions

Peak reconstruction:

- Reconstruct Z/h bosons, B_α, and also W bosons, W_β, if $N_\tau = 1$

Peak reconstruction:

- Reconstruct Z/h bosons, B_α, and also W bosons, W_β, if $N_\tau = 1$
- Find all the possible (tau, boson) pairings:

$$\tau_1' \supset (\tau_1, \nu_1, B_\alpha) \text{ and } \tau_2' \supset \begin{cases} (\tau_2, \nu_2, B_\beta) \text{ in SRs with exactly } 2\tau \\ (\nu_2, W_\beta) \text{ in SRs with exactly } 1\tau \end{cases}$$

such that the bosons in τ_1' and τ_2' are distinct

- Use collinear approximation for ν_1 from τ_1 decay:

$$E_{\nu_1} = |\vec{p}_{\nu_1}|, \quad \vec{p}_{\nu_1} = (r-1)\vec{p}_{\tau_1},$$

and obtain the four-momentum of the other neutrino using:

$$E_{\nu_2} = \not{E} - E_{\nu_1}, \qquad \vec{p}_{\nu_2} = \frac{E_{\nu_2}}{|\vec{\not{p}} - \vec{p}_{\nu_1}|} \left(\vec{\not{p}} - \vec{p}_{\nu_1}\right),$$

such that both ν_1 and ν_2 are on-shell.

- Use collinear approximation for ν_1 from τ_1 decay:

$$E_{\nu_1} = |\vec{p}_{\nu_1}|, \quad \vec{p}_{\nu_1} = (r-1)\vec{p}_{\tau_1},$$

  and obtain the four-momentum of the other neutrino using:

$$E_{\nu_2} = \not{E} - E_{\nu_1}, \qquad \vec{p}_{\nu_2} = \frac{E_{\nu_2}}{|\vec{\not{p}} - \vec{p}_{\nu_1}|} \left(\vec{\not{p}} - \vec{p}_{\nu_1}\right),$$

  such that both ν_1 and ν_2 are on-shell.
- For each pairing, solve for r from:

$$p^2_{\tau'_1} \quad = \quad p^2_{\tau'_2}$$

  and impose $E_{\nu_1} \geq 0$ and $E_{\nu_2} \geq 0$

- Use collinear approximation for ν_1 from τ_1 decay:

$$E_{\nu_1} = |\vec{p}_{\nu_1}|, \quad \vec{p}_{\nu_1} = (r-1)\vec{p}_{\tau_1},$$

and obtain the four-momentum of the other neutrino using:

$$E_{\nu_2} = \not{E} - E_{\nu_1}, \qquad \vec{p}_{\nu_2} = \frac{E_{\nu_2}}{|\vec{\not{p}} - \vec{p}_{\nu_1}|} \left(\vec{\not{p}} - \vec{p}_{\nu_1}\right),$$

such that both ν_1 and ν_2 are on-shell.

- For each pairing, solve for r from:

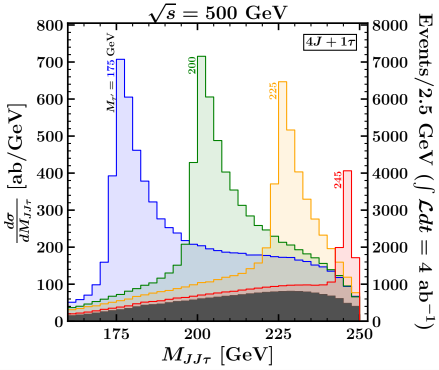
$$p^2_{\tau'_1} = p^2_{\tau'_2}$$

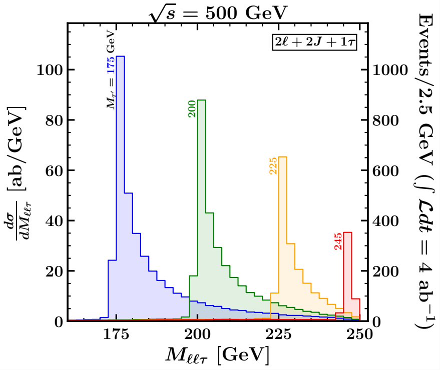
and impose $E_{\nu_1} \geq 0$ and $E_{\nu_2} \geq 0$

- If multiple pairings survive, pick a pairing that minimizes $|\vec{p}_{\text{total}}|$ and

$$M^{\text{reco}}_{\tau'} = \sqrt{p^2_{\tau'_1}}$$

Mass peaks: Consider a 500 GeV e^+e^- collider with unpolarized beams ...

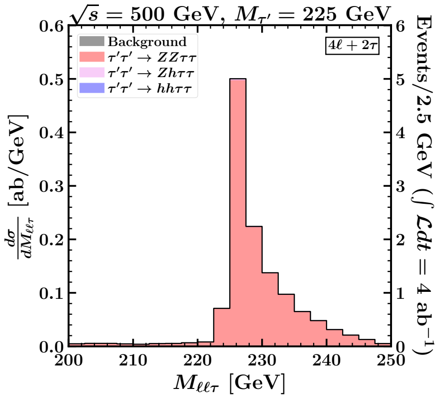


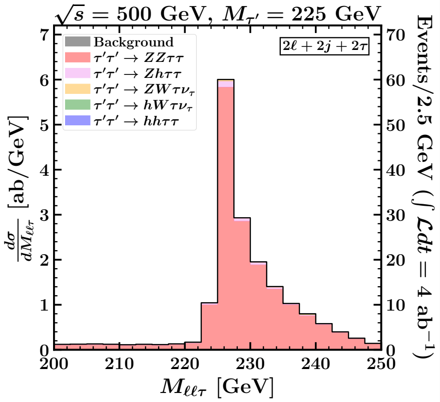


- Since BR($\tau' \to W\nu_\tau$) is the largest, we have far better statistics in these SRs
- Backgrounds are (non-)negligible (but still clearly under control)
- Similar peak reconstructions also possible in all SRs with 2τ

Branching ratios: If τ' indeed discovered, the heights of mass peaks in various SRs can be used to determine τ' branching ratios!

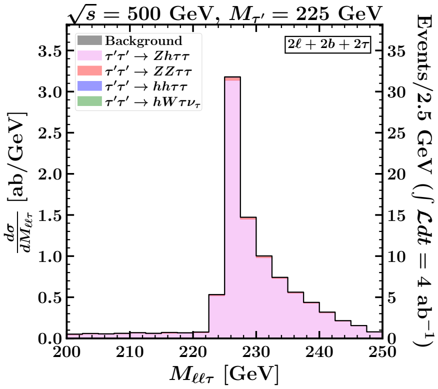
Branching ratios: If τ' indeed discovered, the heights of mass peaks in various SRs can be used to determine τ' branching ratios!

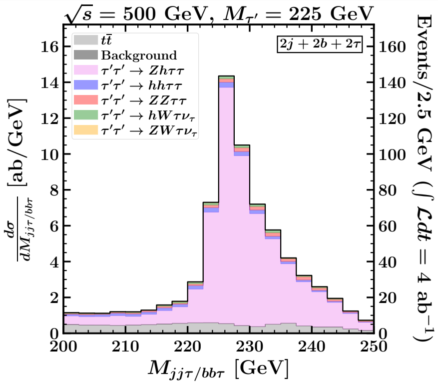




- $4\ell + 2\tau$ and $2\ell + 2j + 2\tau$ SRs provide a pure sample of $ZZ\tau\tau$ final state

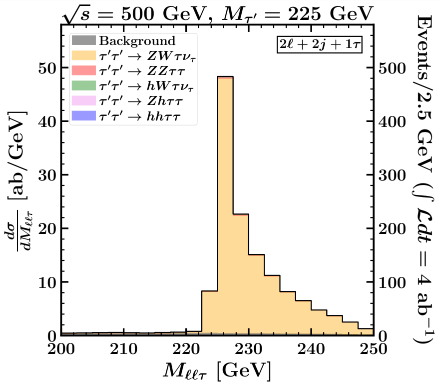
Similarly,

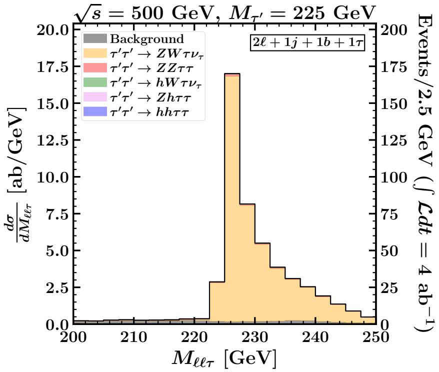




- $2\ell + 2b + 2\tau$ and $2j + 2b + 2\tau$ SRs provide a pure sample of $Zh\tau\tau$ final state

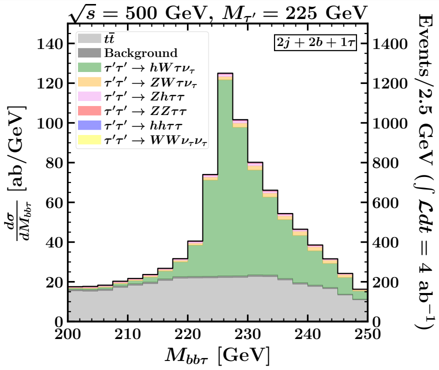
Similarly,

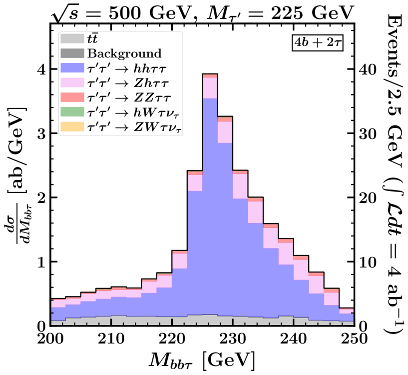




- $2\ell + 2j + 1\tau$ and $2j + 1j + 1b + 1\tau$ SRs provide a pure sample of $ZW\tau\nu$ final state

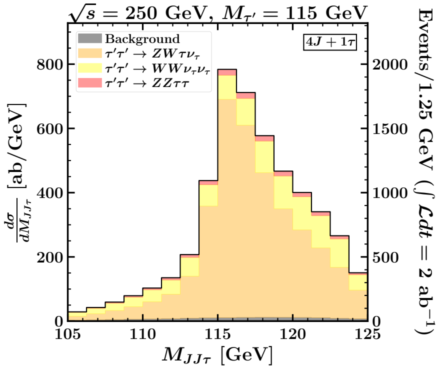
Similarly,

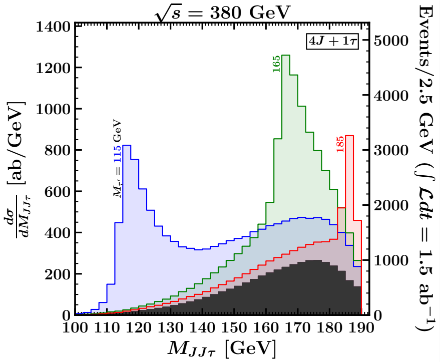




- $2j + 2b + 1\tau$ ($4b + 2\tau$) SR provides a (relatively) pure sample of $hW\tau\nu$ ($hh\tau\tau$) final state

Both Higgs and top factories can also act as discovery machines!





- For $M_{\tau'} < M_h + M_\tau$, since $\tau' \to h\tau$ is not accessible, we also reconstruct Z from bb

Conclusions

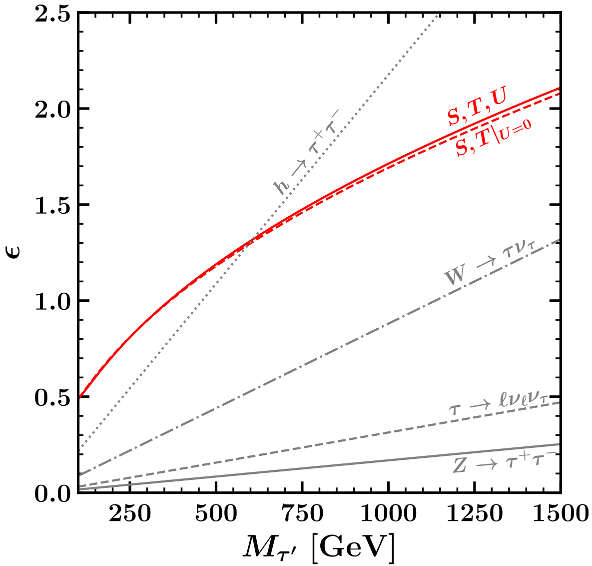
- Considered an example of weak isosinget vectorlike leptons that are well-motivated
- Demonstrated that its mass peaks can be reconstructed in various signal regions up to close to the kinematic limit
- Heights of the mass peaks in various signal regions can in turn give a handle on the branching ratios

Conclusions

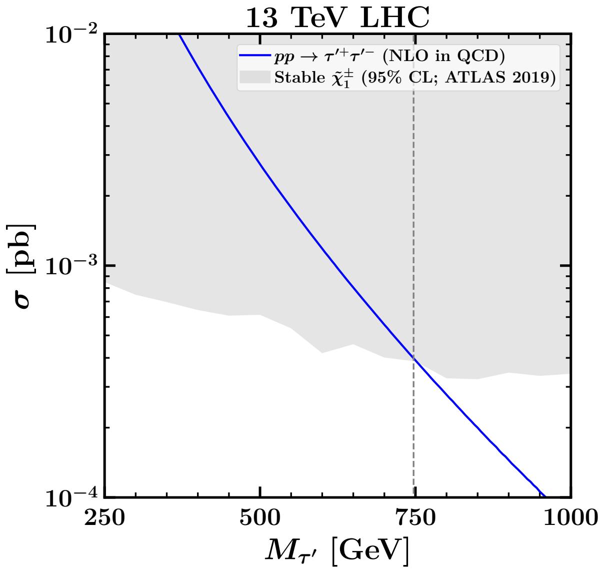
- Considered an example of weak isosinget vectorlike leptons that are well-motivated
- Demonstrated that its mass peaks can be reconstructed in various signal regions up to close to the kinematic limit
- Heights of the mass peaks in various signal regions can in turn give a handle on the branching ratios

e^+e^- collider may act as a discovery machine for particles with only electroweak interactions that have limited reach at a hadron collider!

Precision electroweak:



If τ' is stable over detector lengths, then it can be inferred that $M_{\tau'} \gtrsim 750$ GeV based on the $-dE/dx$ and time of flight measurements in searches for long lived charginos at the LHC



Partonic pair-production cross-section $\hat{\sigma}(e^+e^- \to \tau'^+\tau'^-)$:

$$\hat{\sigma} = \frac{2\pi\alpha^2}{3}(\hat{s} + 2M_{\tau'}^2)\sqrt{1 - 4M_{\tau'}^2/\hat{s}}\Big[|a_L|^2(1 - P_{e^-})(1 + P_{e^+}) + |a_R|^2(1 + P_{e^-})(1 - P_{e^+})\Big],$$

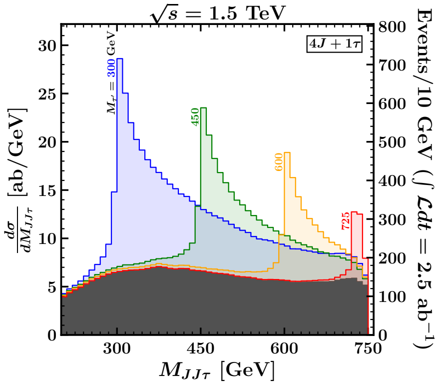
where the left-handed and right-handed amplitude coefficients are

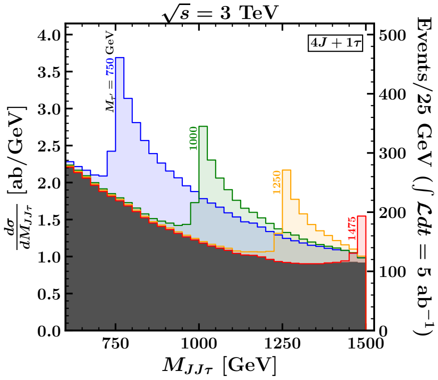
$$a_L = \frac{1}{\hat{s}} + \frac{1}{c_W^2}(s_W^2 - 1/2)\frac{1}{\hat{s} - M_Z^2},$$

$$a_R = \frac{1}{\hat{s}} + \frac{s_W^2}{c_W^2}\frac{1}{\hat{s} - M_Z^2}.$$

- $P = 1$ and -1 corresponding to pure right-handed and left-handed polarizations
- Since $|a_L| < |a_R|$ for $\sqrt{\hat{s}} > 93$ GeV, we see that the production cross-section is maximized when P_{e^-} is positive (and, if available, when P_{e^+} is negative)

At $\sqrt{s} = 1.5$ and 3 TeV:





- Since the production cross section falls with $\sqrt{s}$, a lack of adequate statistics can be an issue in some signal regions
- Backgrounds can be more significant, but with a smooth mass distribution that should be under good theoretical control