Isosinglet vectorlike leptons at e^+e^- colliders

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Based on work with Stephen P. Martin and Aaron Pierce
arXiv:hep-ph/2308.08386

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

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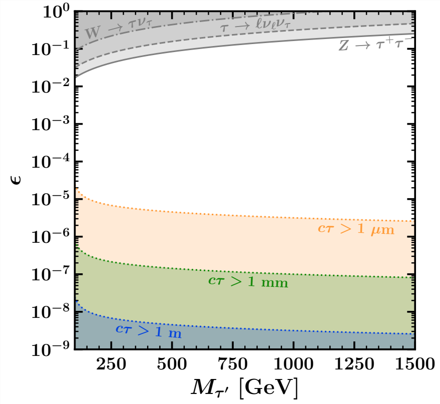
Motivations:

- Many BSM theories require vectorlike leptons
- New fermions must be necessarily vectorlike
- Decouple from flavor and EW precision data with higher masses
- Automatically anomaly-free (unlike chiral fermions)

Assume mass mixing of τ' and τ:

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



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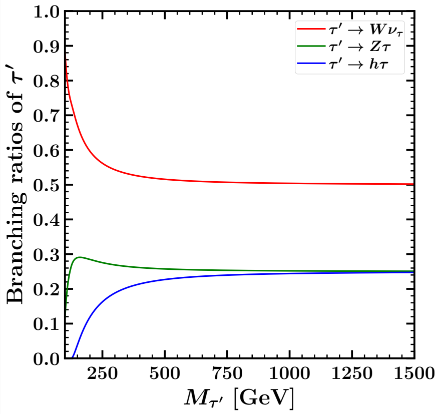
with *prompt* τ' decays



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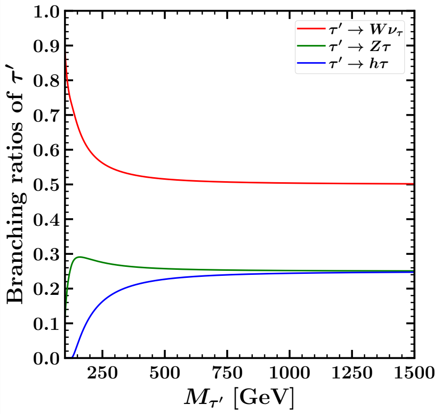
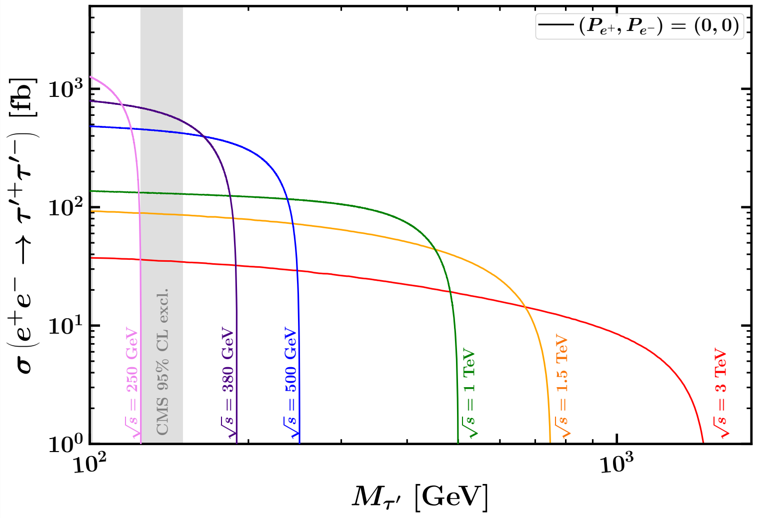
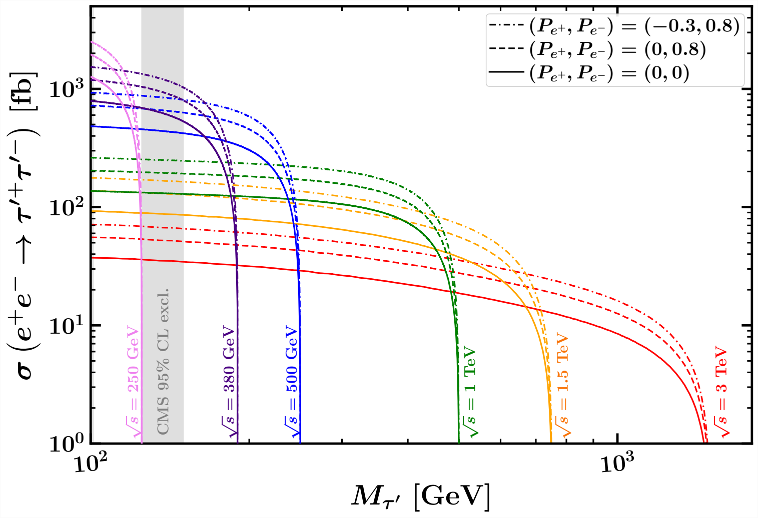


Limited reach for τ' at

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



- Pair-production mode: $e^+e^- \to \gamma^*, Z^* \to \tau'^+\tau'^-$
- Current 95% CL exclusion: 125 GeV $< M_{\tau'} <$ 150 GeV [CMS 2202.08676]



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- $(P_{e^+}, P_{e^-}) = (-0.3, 0.8)$ and $(0, 0.8)$ maximize σ for ILC and CLIC

Signal components: $e^+e^- \to \tau'^+\tau'^- \quad \to \quad ZZ\tau^+\tau^-, \qquad hh\tau^+\tau^-, \qquad Zh\tau^+\tau^-$

$ZW^\pm\tau^\mp + \not{E}, \qquad hW^\pm\tau^\mp + \not{E},$

$W^\pm W^\mp + \not{E}$ **(largest!)**

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)

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$ZW^\pm\tau^\mp + \not{E}, \quad hW^\pm\tau^\mp + \not{E},$
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- $2j + 2b + 2\tau \to Zh\tau\tau$
- $4b + 2\tau \to hh\tau\tau$
- $4j + 1\tau \to ZW\tau\nu_\tau$
- $2j + 2b + 1\tau \to hW\tau\nu_\tau$
- $3j + 1b + 2\tau \to ZZ\tau\tau, Zh\tau\tau$

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

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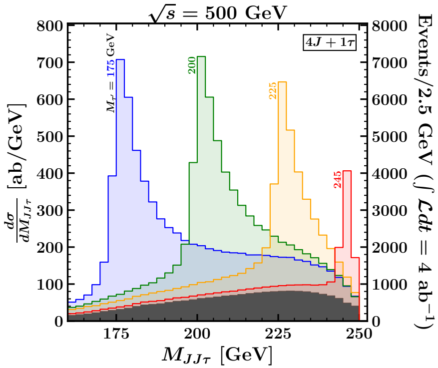

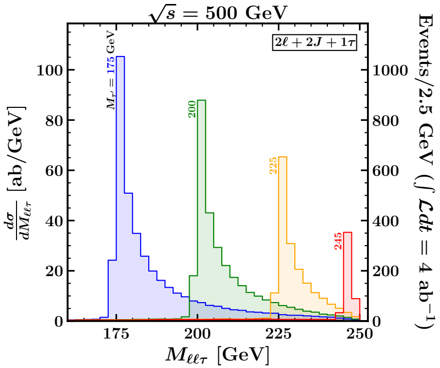

- Events generated at LO while accounting for ISR + beamstrahlung
- Using *collinear approximation* to account for τ-decays
- Since BR($\tau' \to W\nu_\tau$) is the largest, we have best statistics in these SRs
- Backgrounds are (non-)negligible (but still clearly under control)

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

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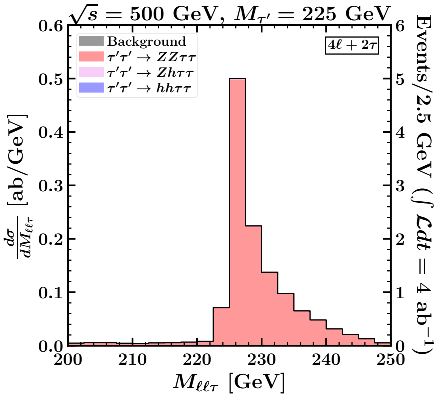
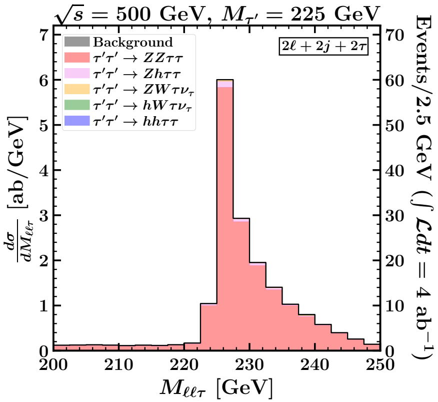
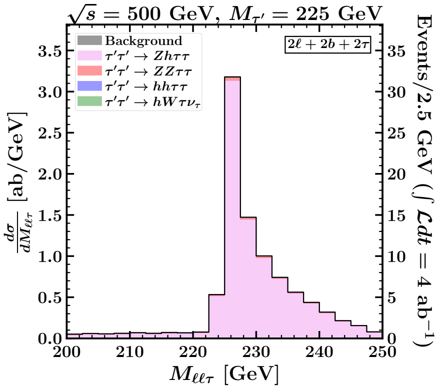
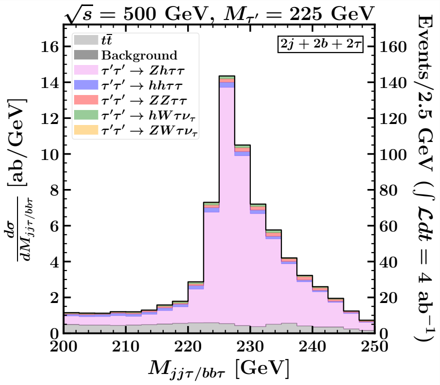




- $4\ell + 2\tau$ and $2\ell + 2j + 2\tau$ SRs provide a pure sample of $ZZ\tau\tau$ final state

Similarly,





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

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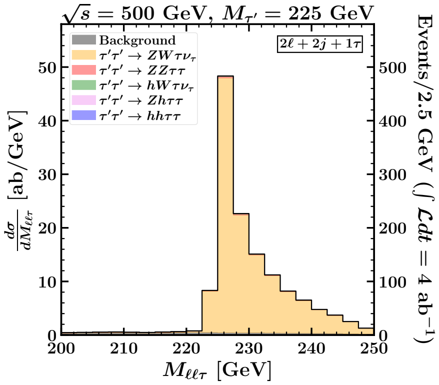
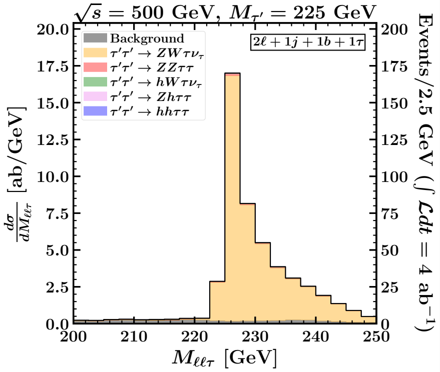
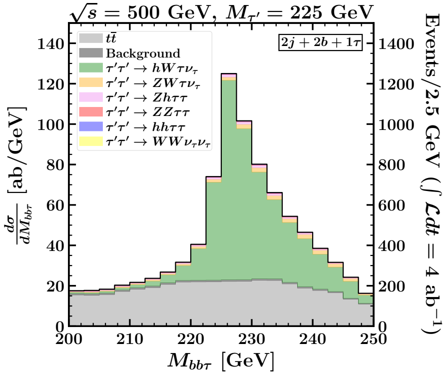
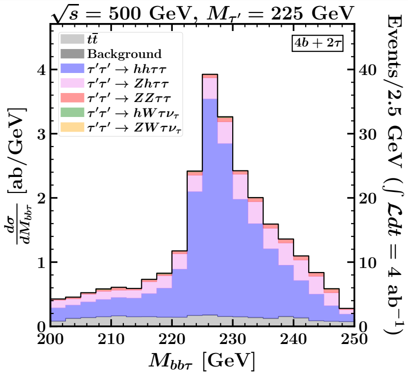




- $2\ell + 2j + 1\tau$ and $2j + 1j + 1b + 1\tau$ SRs provide a pure sample of $ZW\tau\nu$ final state

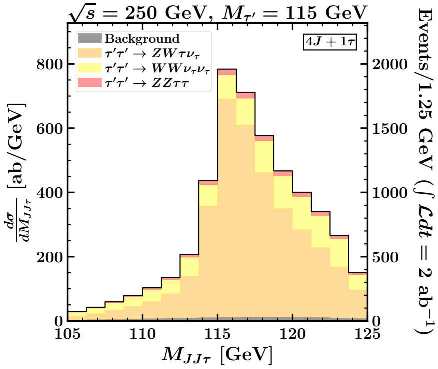
Similarly,

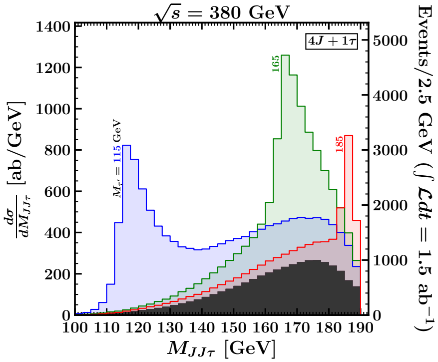




- $2j + 2b + 1\tau$ ($4b + 2\tau$) SR provides a (relatively) pure sample of $hW\tau\nu$ ($hh\tau\tau$) final state

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

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- Considered an example of weak isosinget vectorlike leptons that are well-motivated
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e^+e^- collider may act as a discovery machine for particles with only electroweak interactions that have limited reach at a hadron collider!

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)

Peak reconstruction:

- Find all the possible (tau, boson) pairings:

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

  and 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:

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

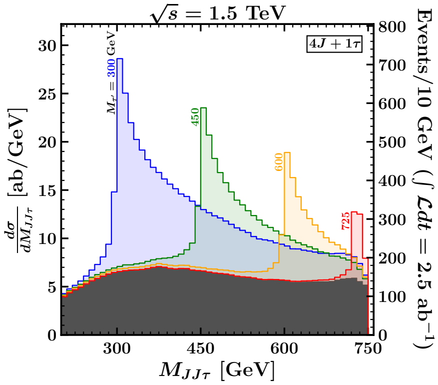
  such that both ν_1 and ν_2 are on-shell.
- For each pairing, solve for r from:

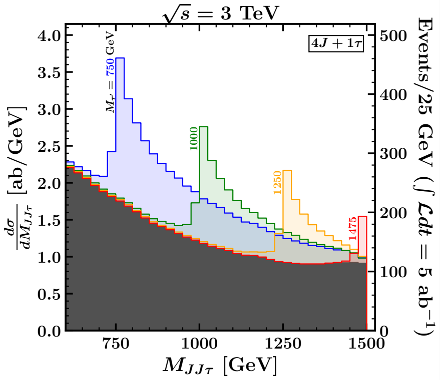
$$p^2_{\tau_1'} = p^2_{\tau_2'}$$

  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

$$M^{\text{reco}}_{\tau'} = \sqrt{p^2_{\tau_1'}}$$

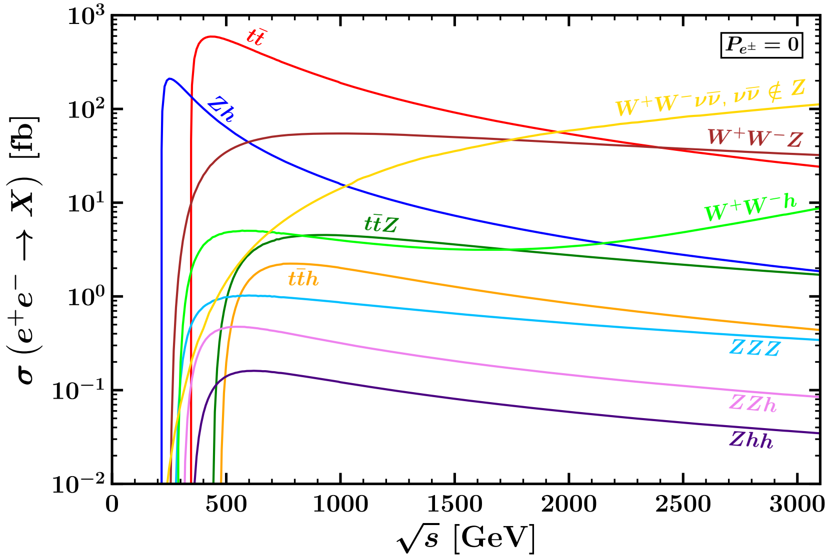
At $\sqrt{s} = 1.5$ and 3 TeV:



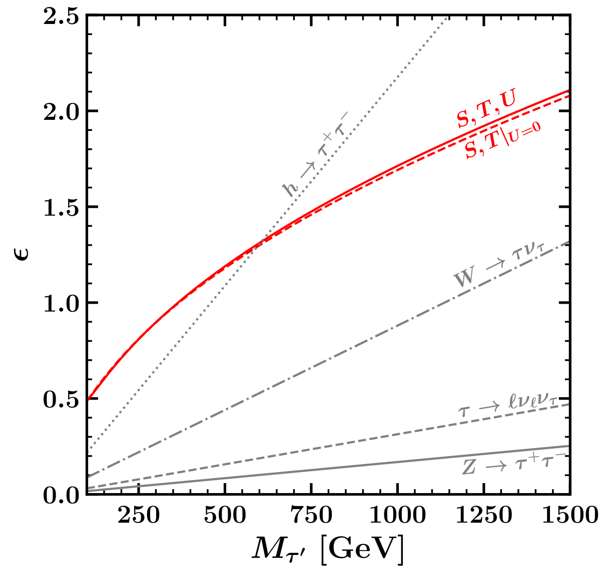


- Since the production cross section falls with $\sqrt{s}$, a lack of adequate statistics can be an issue in some signal regions
- Backgrounds can be more significant, but with a smooth mass distribution that should be under good theoretical control

SM backgrounds:



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