# Isosinglet vectorlike leptons at $e^+e^-$ colliders

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Based on ongoing work with Stephen P. Martin and Aaron Pierce,
arXiv:hep-ph/23xx.xxxxx

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- Lepton colliders: precision studies and indirect searches

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which should be contrasted with the **chiral** $\tau$ leptons in the SM:

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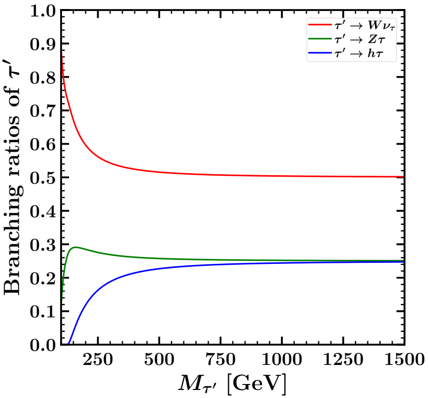
Motivations:

- Many new physics models require vectorlike leptons
- New fermions must be necessarily vectorlike
- Decouple from flavor and EW precision data for higher masses
- Automatically anomaly-free

Assume tiny mass mixing of $\tau'$ and $\tau$:

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



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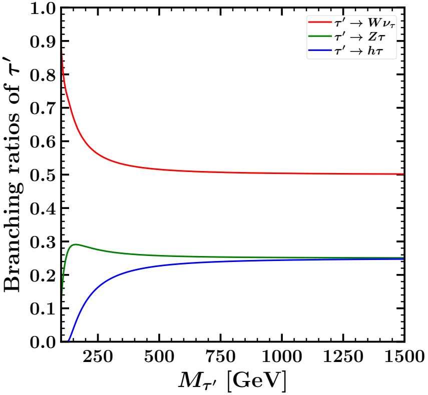


Current 95% CL exclusions:

- $M_{\tau'} < 101.2$ GeV [LEP 0107015]
- 125 GeV $< M_{\tau'} <$ 150 GeV [CMS 2202.08676]

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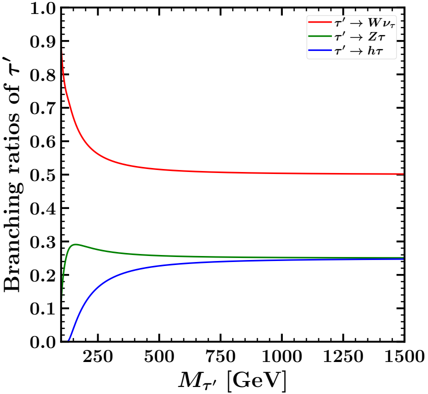


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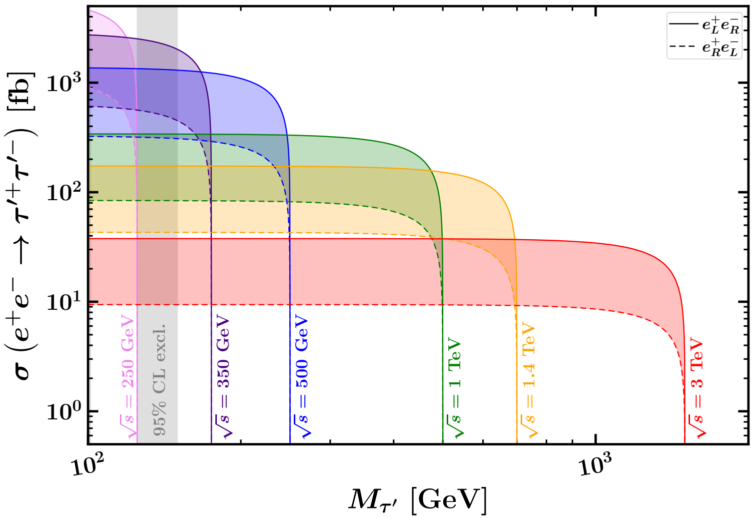
Limited discovery/exclusion reach for $\tau'$ at the

- LHC [Kumar, Martin 1510.03456]
- Future *pp* colliders (incl. $\sqrt{s} = 100$ TeV) [PNB, Martin 1905.00498]




- Pair-production mode: $e^+e^- \to \gamma^*, Z^* \to \tau'^+\tau'^-$
- For $M_{\tau'}$ much smaller than $\sqrt{s}$, $\sigma \sim 1/s$ (independent of $M_{\tau'}$)
- Ignoring ISR + beamstrahlung (for now)

## 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!)**

† We used WHIZARD + CIRCE2 in order to account for ISR + beam spectra

‡ For detector simulation, we used `delphes_card_ILD.tcl` based on [ILC Design Report 1306.6329]

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Backgrounds: $t\bar{t}$, $t\bar{t}Z$, $t\bar{t}h$, $WWh$, $WWZ$, $ZZh$, $ZZZ$, ...

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Signal and background events generated at leading order by:
FeynRules → MadGraph5† → Pythia8 → Delphes‡

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Consider 1 TeV ILC with unpolarized beams for demonstration (**Preliminary**)

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## Signal regions with exactly $2\tau$: Reconstruct $Z$ from $e^+e^-/\mu^+\mu^-/jj$ and $h$ from $bb$

- $4\ e/\mu + 2\ \tau$
- $4\ j + 2\ \tau$
- $2\ e/\mu + 2\ j + 2\ \tau$
- $2\ e/\mu + 2\ b + 2\ \tau$
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† There could be more than 2 candidate $Z/h$ in events with $4e/4\mu/4j/4b$.

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Strategy:

- Require both taus $\tau_1, \tau_2$ have opposite-signs
- Reconstruct all candidate $Z/h$ bosons, $B_1$, $B_2$, ...†
- Find various pairings that reconstruct $\tau'$ pair:

$$\tau_1' = (\tau_1, B_k) \text{ and } \tau_2' = (\tau_2, B_\ell)$$

such that the candidate bosons $B_k$, $B_\ell$ are unique

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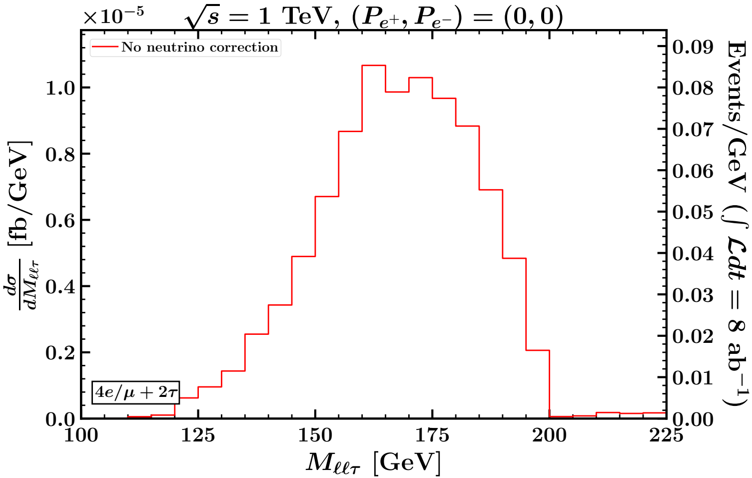

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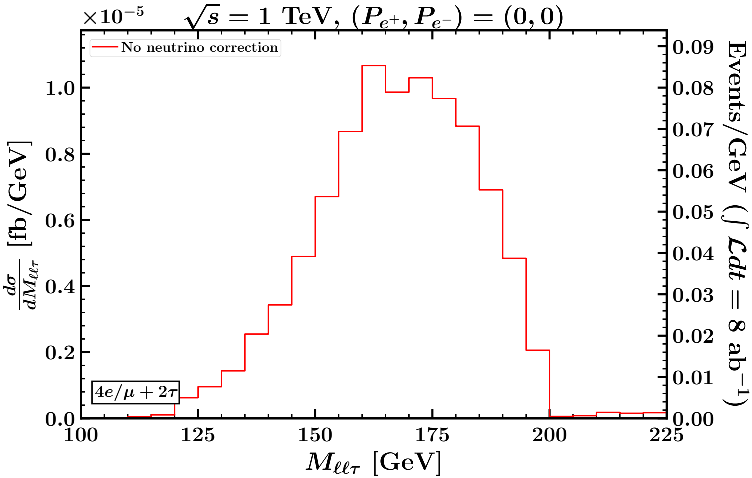


- Can do better: account for the missing four-momentum of each $\tau_i$ carried by neutrinos $\nu_i$

## Better attempt:[†]

- Use collinear approximation for $\nu_1$ from $\tau_1$ decay:

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

Here, $\tau_1$ is taken to be the $\tau$ with highest energy[‡]

[†]Additionally, for candidate $Z/h$ bosons reconstructed from ($b$) jets, rescale the 4-momenta of each ($b$) jet by a common factor such that their invariant mass is exactly $M_{Z/h}$

[‡]Except in the events with exactly one $Z$ that decays leptonically, in which case $\tau_1$ in each pairing is relabeled to be the $\tau$ that is being paired with the leptonically decaying $Z$.

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- Use total missing $\not{E}$ (inferred from $\sqrt{s}$) to obtain

$$E_{\nu_2} = \not{E} - E_{\nu_1}, \quad \vec{p}_{\nu_2} = \frac{E_{\nu_2}}{|\vec{p}_{\tau_2}|}\ \vec{p}_{\tau_2}$$

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- For each pairing, $(\tau_1, B_k)$ and $(\tau_2, B_\ell)$, solve for $r$ by imposing:

$$\left(p^\mu_{B_k} + p^\mu_{\tau_1} + p^\mu_{\nu_1}\right)^2 = \left(p^\mu_{B_\ell} + p^\mu_{\tau_2} + \not{p}^\mu - p^\mu_{\nu_1}\right)^2$$

  and compute $\vec{p}_{\text{total}} = \vec{p}_{\text{visible}} + \vec{p}_{\nu_1} + \vec{p}_{\nu_2}$

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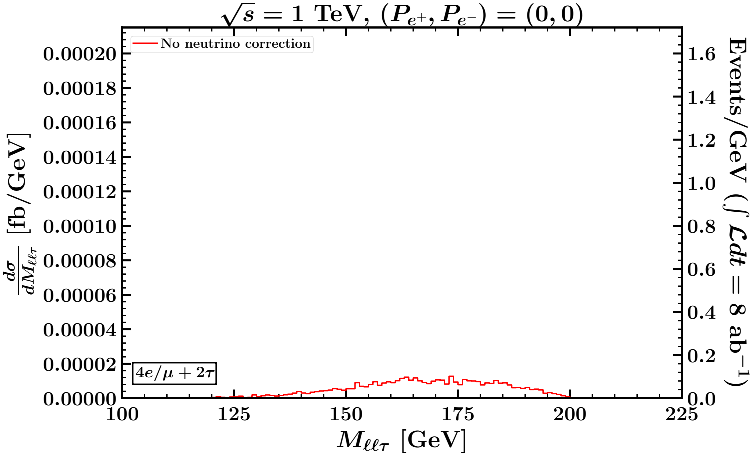

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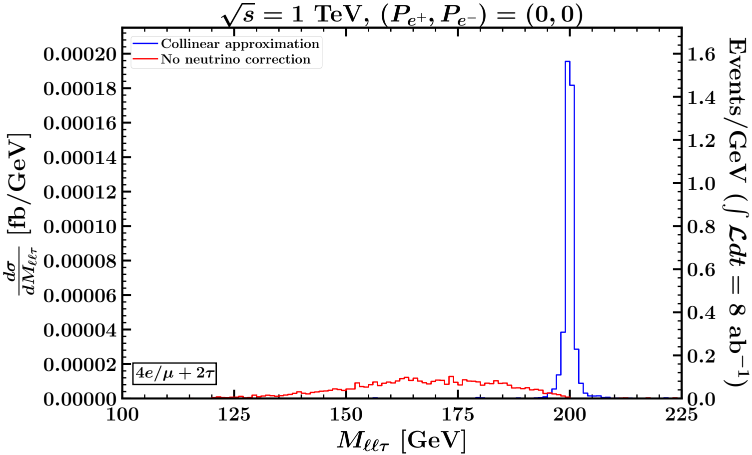
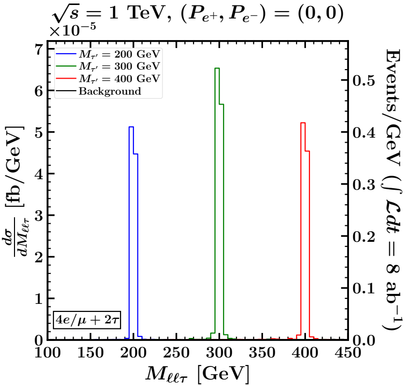
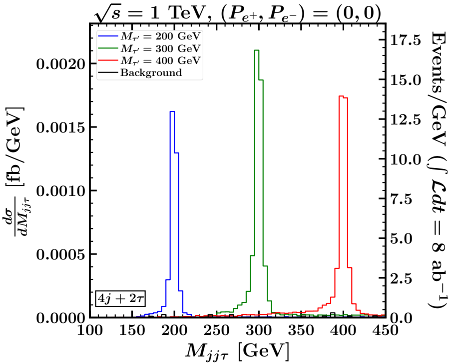



- Might lose some events where $\nu$ not actually collinear with $\tau$
- Collinear approximation holds better for larger $M_{\tau'}$ (examples below)




- Backgrounds seem very small (at least with processes included so far)
- Similar peak reconstructions also possible in all the other signal regions with $2\tau$ (not shown here)

Signal regions with exactly $1\tau$: Reconstruct $Z$ from $e^+e^-/\mu^+\mu^-$, $h$ from $bb$, and $W$ from $jj$

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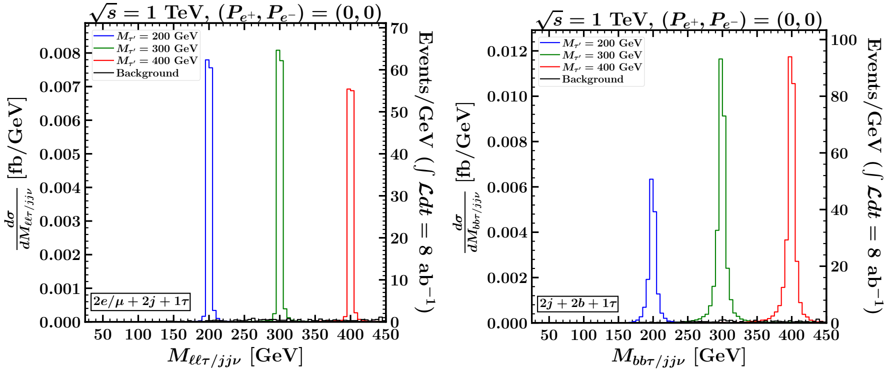
- $2\ j + 2\ b + 1\ \tau$ } $hW\tau\nu_\tau$

Strategy:

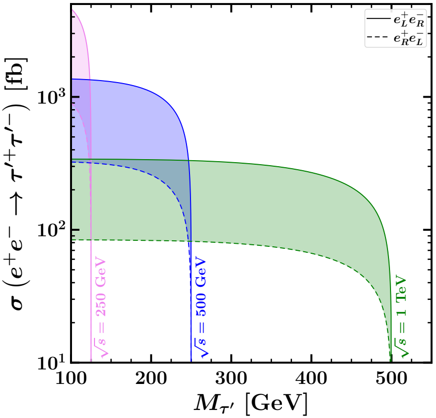
- Similar to the signal regions with $2\tau$, except there is only one tau
- No ambiguity in finding the correct pairing: $\tau$ (and its associated neutrino $\nu$) is always paired with $Z/h$



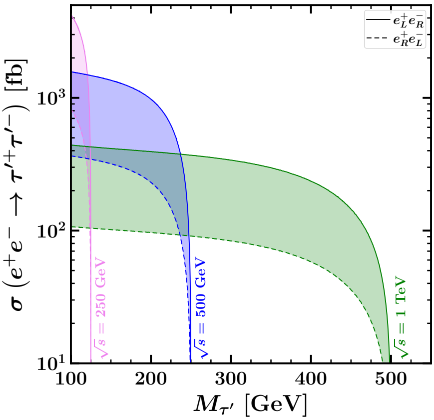

- Backgrounds slightly larger than SRs with $2\tau$ but still very sub-dominant
- Since BR($\tau' \to W\nu_\tau$) is the largest, we have far better statistics in these SRs

For more realistic peak reconstructions, one should also account for ISR and beamstrahlung

$\sqrt{\hat{s}} = \sqrt{s}$

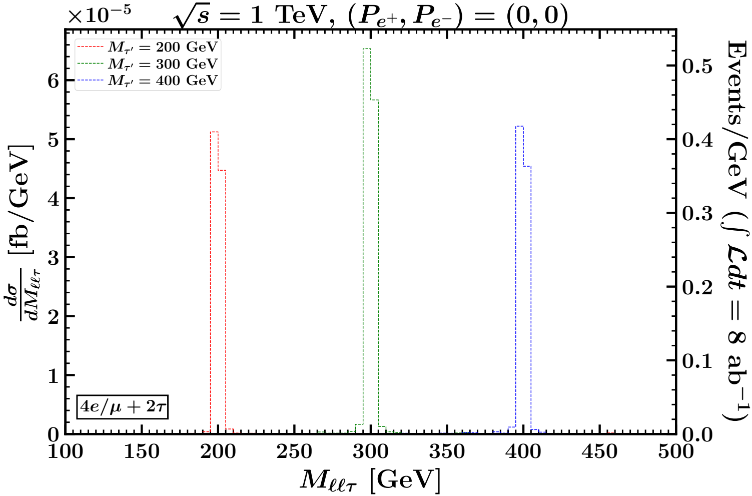



**ISR + beamstrahlung**




- Right: Since $\hat{\sigma} \sim 1/\hat{s}$ for $s \gg M^2_{\tau'}$, slightly enhanced cross sections for small $M_{\tau'}$

Peak reconstruction with ISR and beamstrahlung: Consider, e.g., $4e/\mu + 2\tau$ signal region



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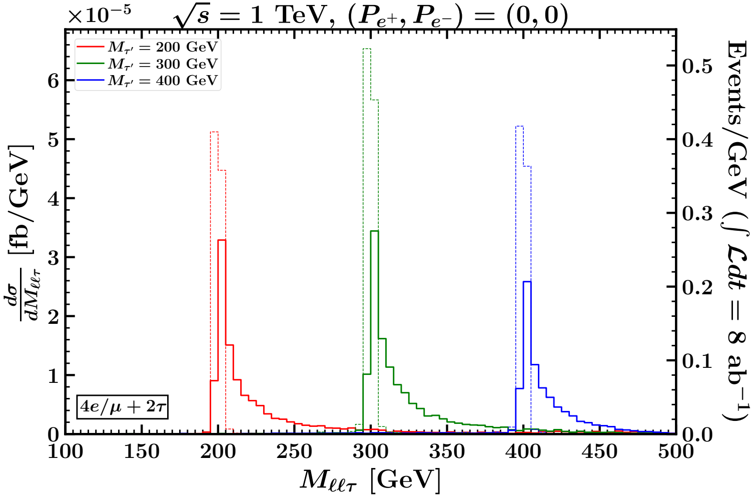


- Distributions more spread out but still peak $\sim M_{\tau'}$

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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!