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

Prudhvi N. Bhattiprolu
prudhvib@umich.edu

University of Michigan

Pheno 2023
University of Pittsburgh
May 8

Based on ongoing work with Stephen P. Martin and Aaron Pierce,
arXiv:hep-ph/230x.xxxxx

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

This may not be the case for weakly interacting particles

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

This may not be the case for weakly interacting particles

Consider the example of $SU(2)_L$-singlet **vectorlike** leptons $\tau'$:

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

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

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

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

This may not be the case for weakly interacting particles

Consider the example of $SU(2)_L$-singlet **vectorlike** leptons $\tau'$:

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

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

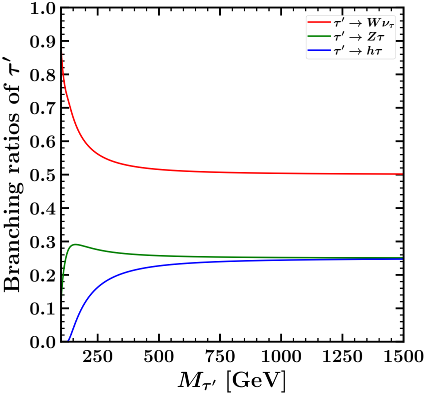
$$\tau_L, \tau^{\dagger}_R \;\sim\; (\mathbf{1}, \mathbf{2}, -1/2) \,+\, (\mathbf{1}, \mathbf{1}, +1)$$

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

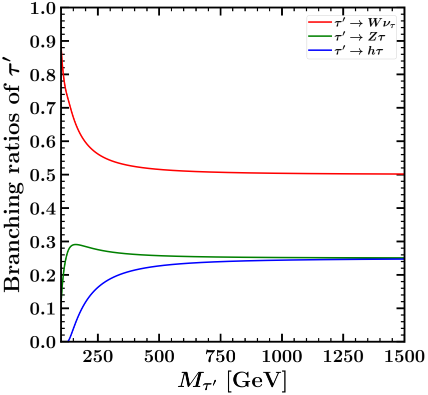
Assume tiny mass mixing of $\tau'$ and $\tau$:

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



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

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

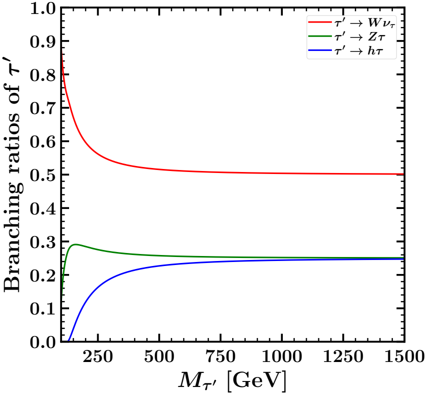



Limited discovery/exclusion reach for $\tau'$ at the

- LHC [Kumar, Martin 1510.03456]
- Future *pp* colliders [PNB, Martin 1905.00498] (See my talk from Pheno 2019!)

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

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

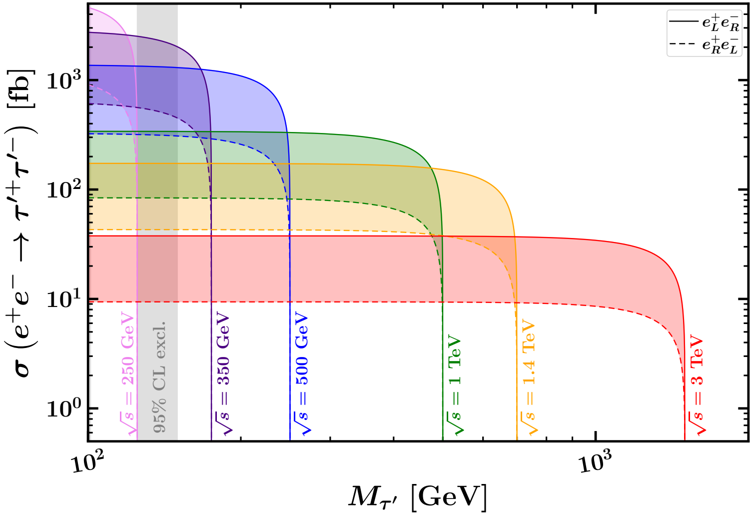



Limited discovery/exclusion reach for $\tau'$ at the

- LHC [Kumar, Martin 1510.03456]
- Future *pp* colliders [PNB, Martin 1905.00498] (See my talk from Pheno 2019!)

Current 95% CL exclusions:

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




- 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:

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

†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]

## 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!)**

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

†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]

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!)**

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

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

[†]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]

## 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!)**

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

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

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

†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]

## 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!)**

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

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

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

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

[†]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]

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

- $4\ e/\mu + 2\ \tau$
- $4\ j + 2\ \tau$
- $2\ e/\mu + 2\ j + 2\ \tau$
- $2\ e/\mu + 2\ b + 2\ \tau$
- $2\ j + 2\ b + 2\ \tau$
- $4\ b + 2\ \tau$

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

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

- $4\ e/\mu + 2\ \tau$
- $4\ j + 2\ \tau$
- $2\ e/\mu + 2\ j + 2\ \tau$

} $ZZ\tau\tau$

- $2\ e/\mu + 2\ b + 2\ \tau$
- $2\ j + 2\ b + 2\ \tau$

} $Zh\tau\tau$

- $4\ b + 2\ \tau$

} $hh\tau\tau$

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

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

- $4\ e/\mu + 2\ \tau$
- $4\ j + 2\ \tau$
- $2\ e/\mu + 2\ j + 2\ \tau$

} $ZZ\tau\tau$

- $2\ e/\mu + 2\ b + 2\ \tau$
- $2\ j + 2\ b + 2\ \tau$

} $Zh\tau\tau$

- $4\ b + 2\ \tau$

} $hh\tau\tau$

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:

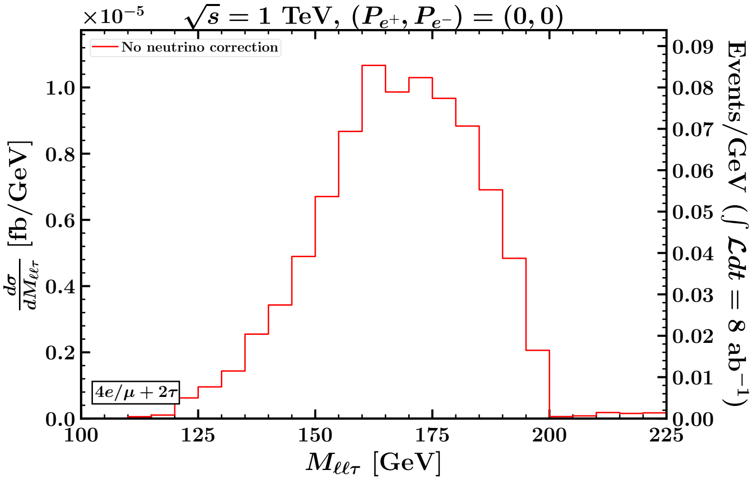
$$\tau'_1 = (\tau_1, B_k) \text{ and } \tau'_2 = (\tau_2, B_\ell)$$

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

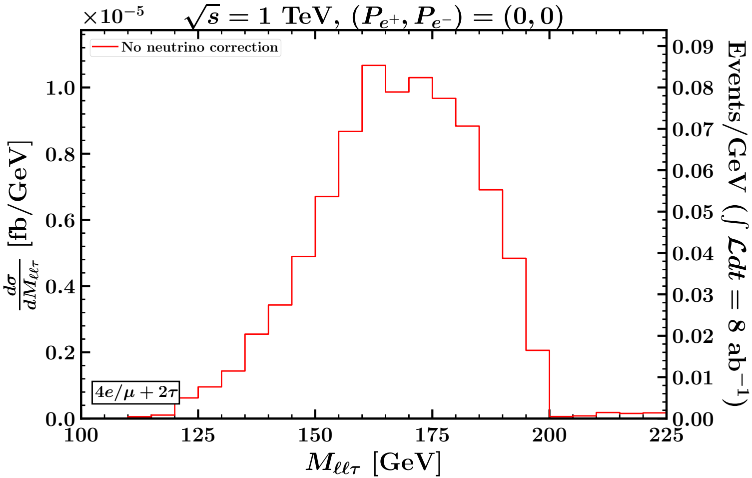
[†] There could be more than 2 candidate $Z/h$ in events with $4e/4\mu/4j/4b$.

Naive attempt: Pick a pairing that minimizes $|M_{\tau_1'} - M_{\tau_2'}|$ and plot $(M_{\tau_1'} + M_{\tau_2'})/2$ (choosing $M_{\tau'} = 200$ GeV)

Naive attempt: Pick a pairing that minimizes $|M_{\tau_1'} - M_{\tau_2'}|$ and plot $(M_{\tau_1'} + M_{\tau_2'})/2$ (choosing $M_{\tau'} = 200$ GeV)



Naive attempt: Pick a pairing that minimizes $|M_{\tau'_1} - M_{\tau'_2}|$ and plot $(M_{\tau'_1} + M_{\tau'_2})/2$ (choosing $M_{\tau'} = 200$ GeV)




- 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 $Z$.

## 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[‡]

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

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

[†] 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 $Z$.

## 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[‡]

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

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

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

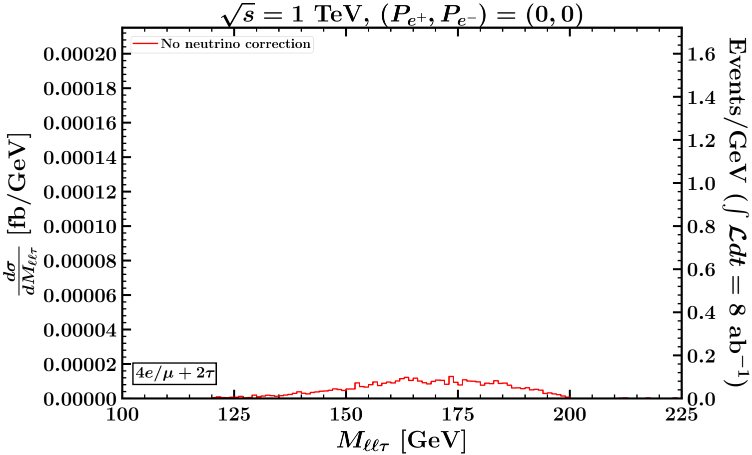
$$\left(p^\mu_{B_k} + p^\mu_{\tau_1} + p^\mu_{\nu_1}\right)^2 = \left(p^\mu_{B_\ell} + p^\mu_{\tau_2} + \not{p}^\mu - p^\mu_{\nu_1}\right)^2$$

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

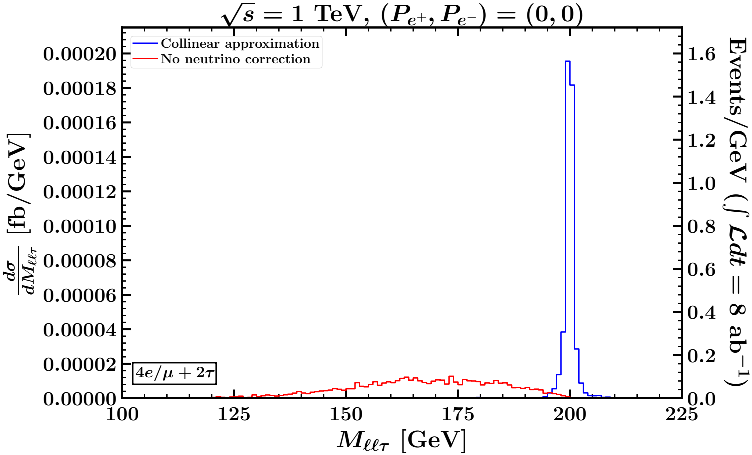
[†] Additionally, for candidate $Z/h$ bosons reconstructed from ($b$) jets, rescale the 4-momenta of each ($b$) jet by a common factor such that their invariant mass is exactly $M_{Z/h}$

[‡] 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 $Z$.

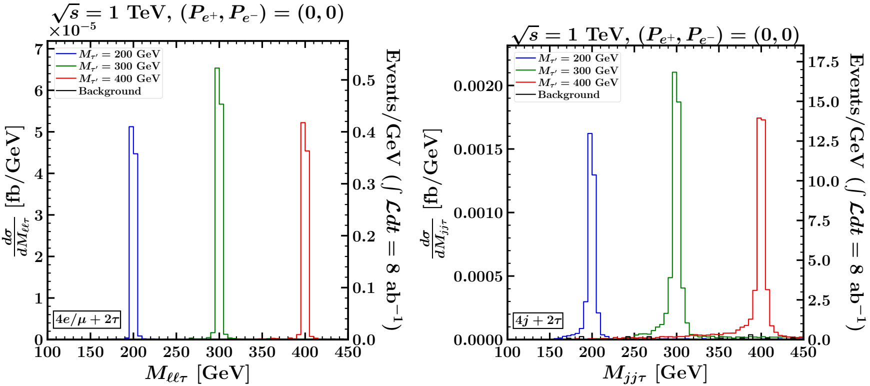
Better attempt: Pick a pairing that minimizes $|\vec{p}_{\text{total}}|$ and plot invariant mass of $(\tau_1, B_k)$ and the reconstructed $\nu_1$



Better attempt: Pick a pairing that minimizes $|\vec{p}_{\text{total}}|$ and plot invariant mass of $(\tau_1, B_k)$ and the reconstructed $\nu_1$




- 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 $jj$

- $2\ e/mu + 2\ j + 1\ \tau$
- $2\ j + 2\ b + 1\ \tau$

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

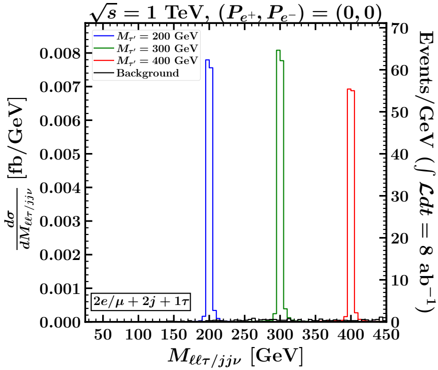
- $2\ e/mu + 2\ j + 1\ \tau$ } $ZW\tau\nu_\tau$
- $2\ j + 2\ b + 1\ \tau$ } $hW\tau\nu_\tau$

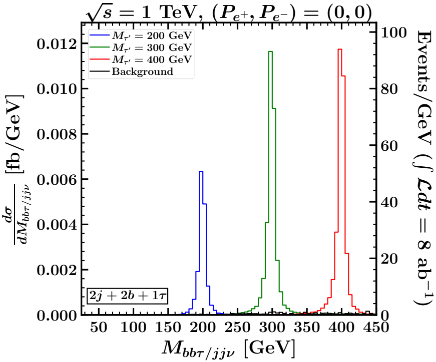
Signal regions with exactly $1\tau$: Reconstruct $Z$ from $e^+e^-/\mu^+\mu^-$, $h$ from $bb$, and $W$ from $jj$

- $2\ e/mu + 2\ j + 1\ \tau$ } $ZW\tau\nu_\tau$
- $2\ j + 2\ b + 1\ \tau$ } $hW\tau\nu_\tau$

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 $Z/h$

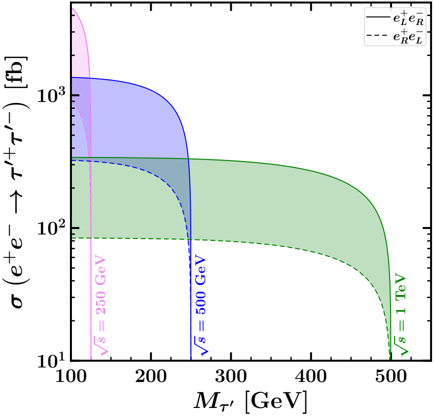




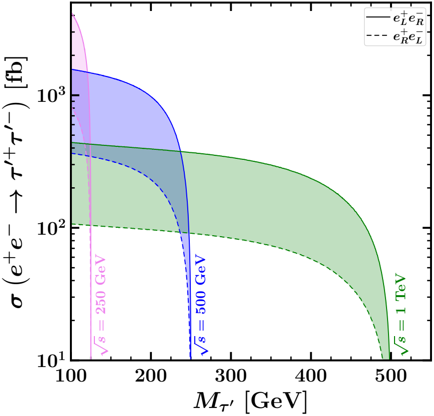

- Backgrounds slightly larger than SRs with $2\tau$ but still very sub-dominant
- Since BR($\tau' \to W\nu_\tau$) is the largest, we have far better statistics in these SRs

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

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

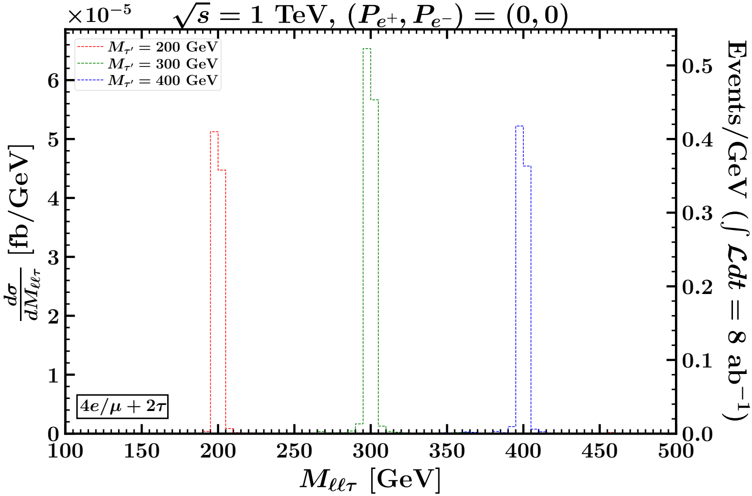



**ISR + beamstrahlung**

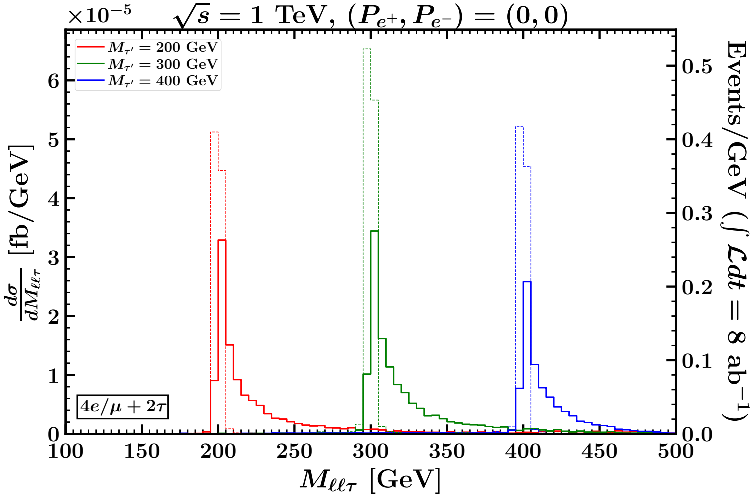



- Right: Since $\hat{\sigma} \sim 1/\hat{s}$ for $s \gg M_{\tau'}^2$, slightly enhanced cross sections for small $M_{\tau'}$

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



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




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

Conclusions:

- Considered an example of weak isosinget vectorlike leptons that are well-motivated
- Demonstrated that its mass peaks can be reconstructed

Conclusions:

- Considered an example of weak isosinget vectorlike leptons that are well-motivated
- Demonstrated that its mass peaks can be reconstructed
- 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
- 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!