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/230x.xxxxx`

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

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which should be contrasted with the **chiral** τ leptons in the SM:

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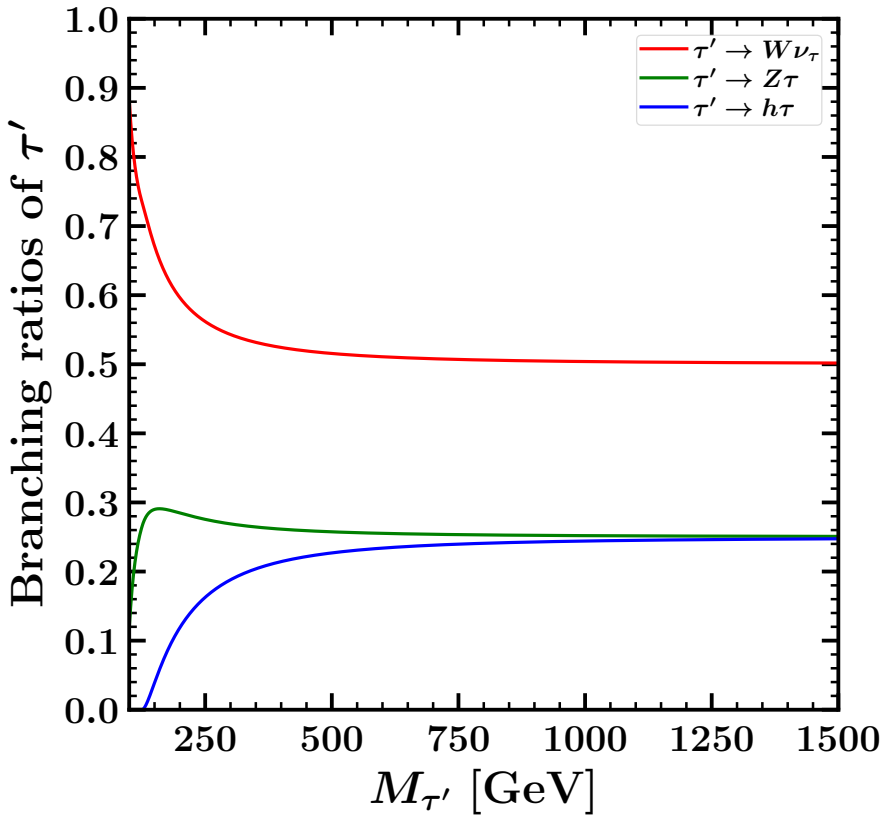
Motivations:

- 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 τ' and τ:

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



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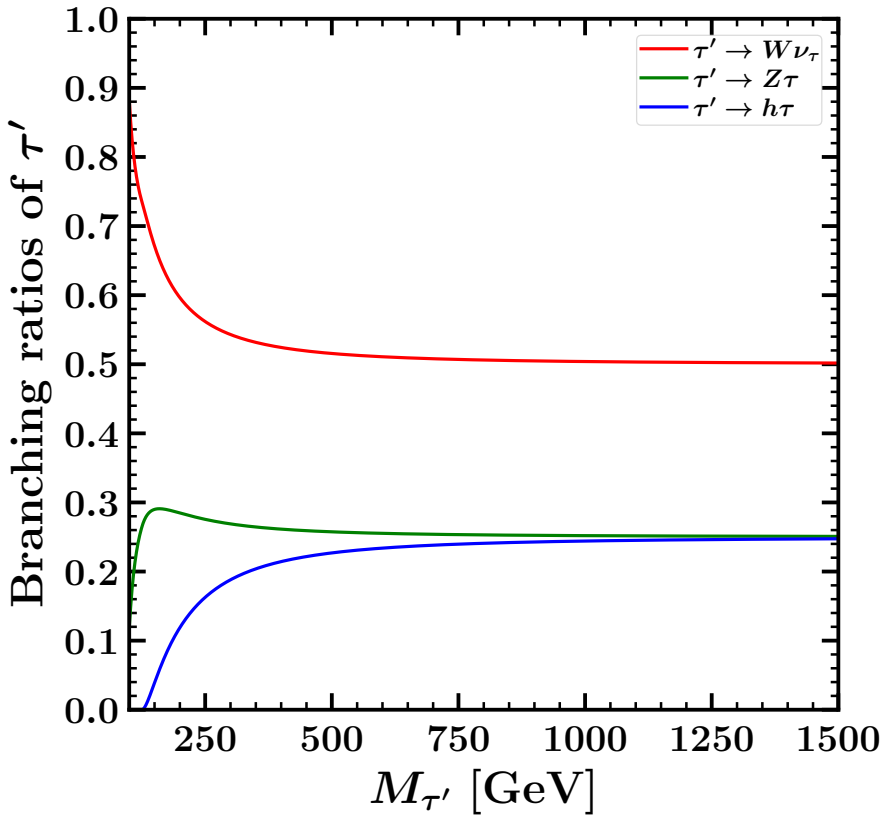

Limited discovery/exclusion reach for τ' at the

- LHC [Kumar, Martin 1510.03456]
- Future pp colliders [PNB, Martin 1905.00498]

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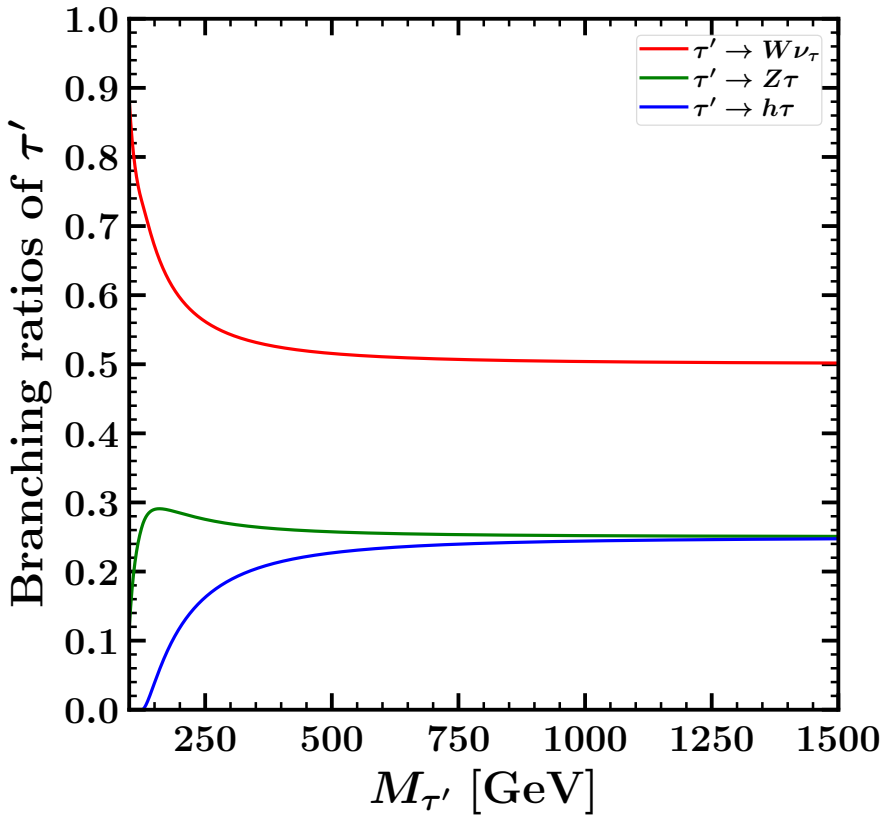

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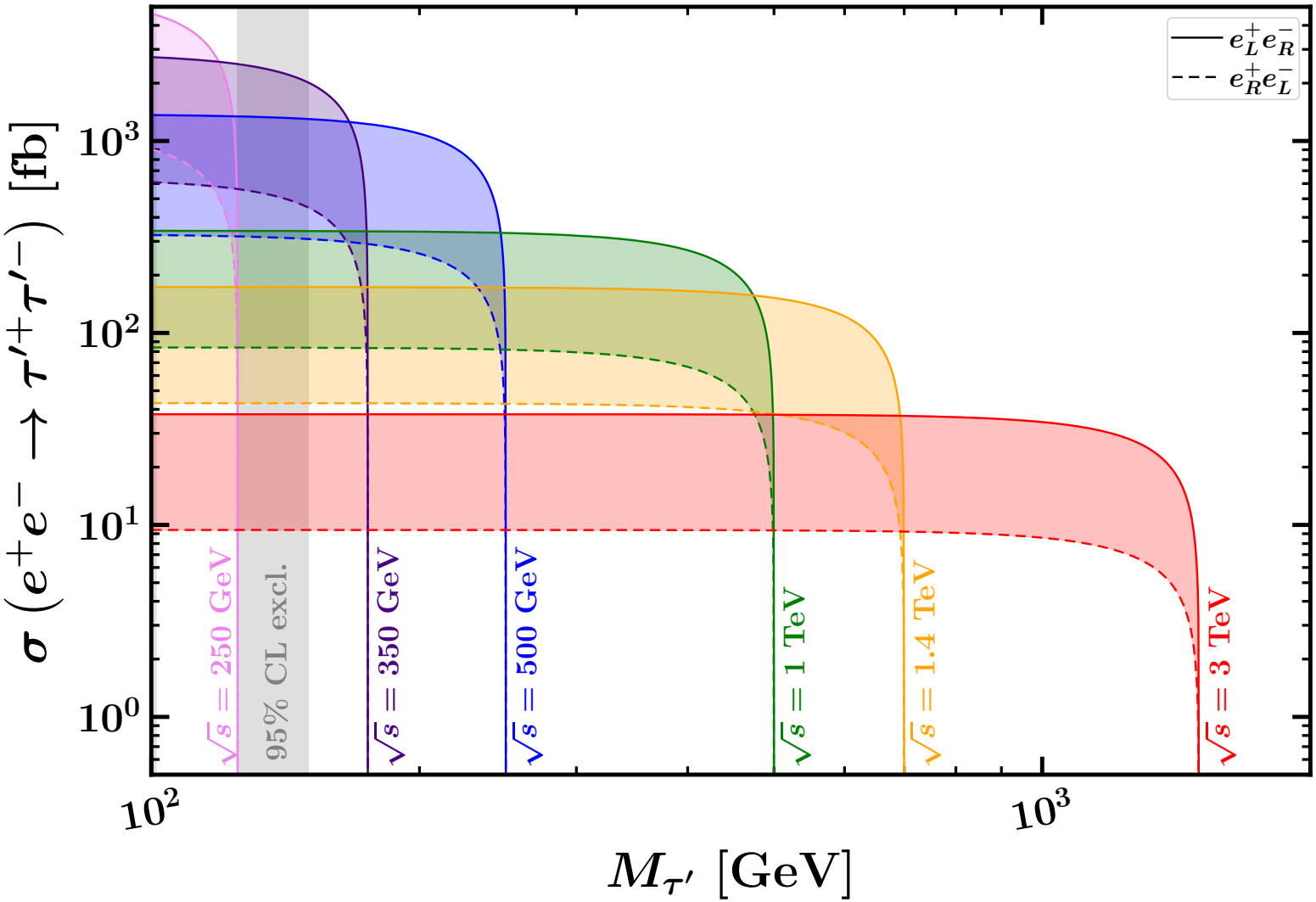
Current 95% CL exclusions:

- $M_{\tau'} < 101.2$ 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]

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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/C^3 with unpolarized beams for demonstration (**Preliminary**)

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

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

- Require both taus τ_1, τ_2 have opposite-signs
- Reconstruct all candidate Z/h bosons, B_1, B_2, ...[†]
- Find various pairings that reconstruct τ' pair:

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

such that the candidate bosons B_k, B_ℓ are unique

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- Use collinear approximation for ν_1 from τ_1 decay:

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

Here, τ_1 is taken to be the τ with highest energy[‡]

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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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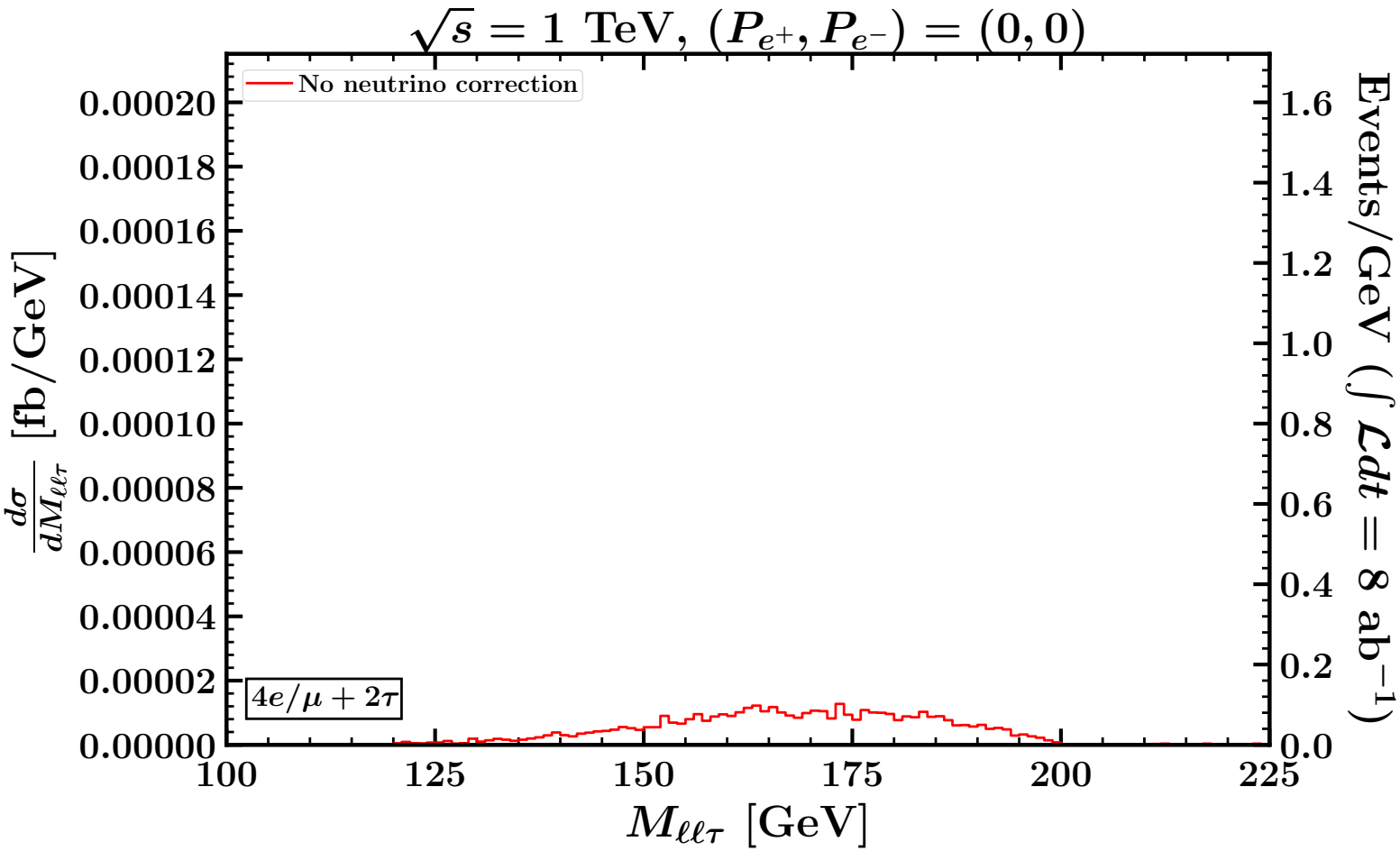
- For each pairing, (τ_1, B_k) and (τ_2, B_ℓ), solve for r by imposing:

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

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

[‡]Except in the events with exactly one Z that decays leptonically, in which case τ_1 in each pairing is relabeled to be the τ that is being paired with the leptonically decaying Z.

- Pick a pairing that minimizes $|\vec{p}_{\text{total}}|$ and plot invariant mass of τ_1, B_k and the reconstructed ν_1 (example below for $M_{\tau'} = 200$ GeV)



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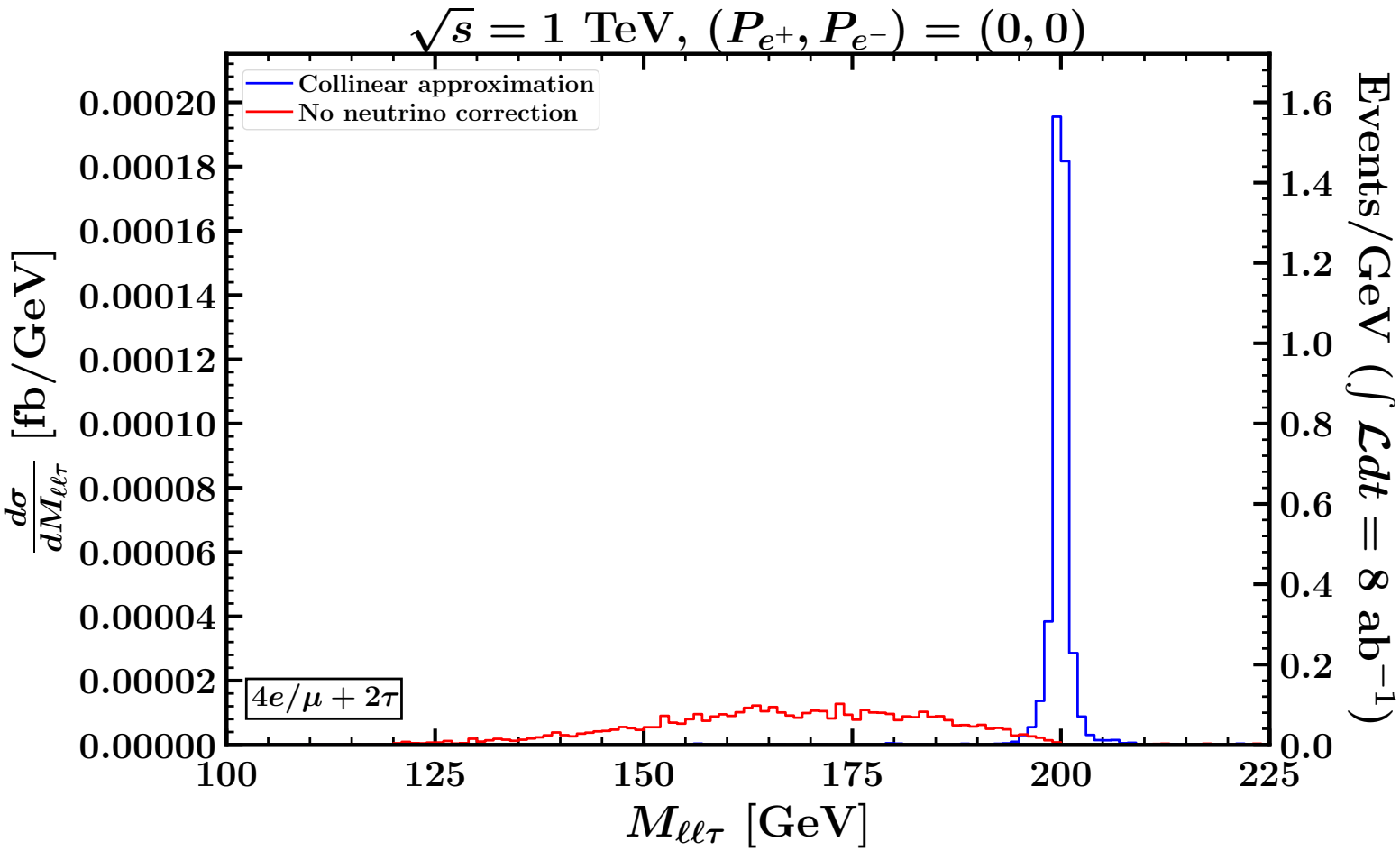
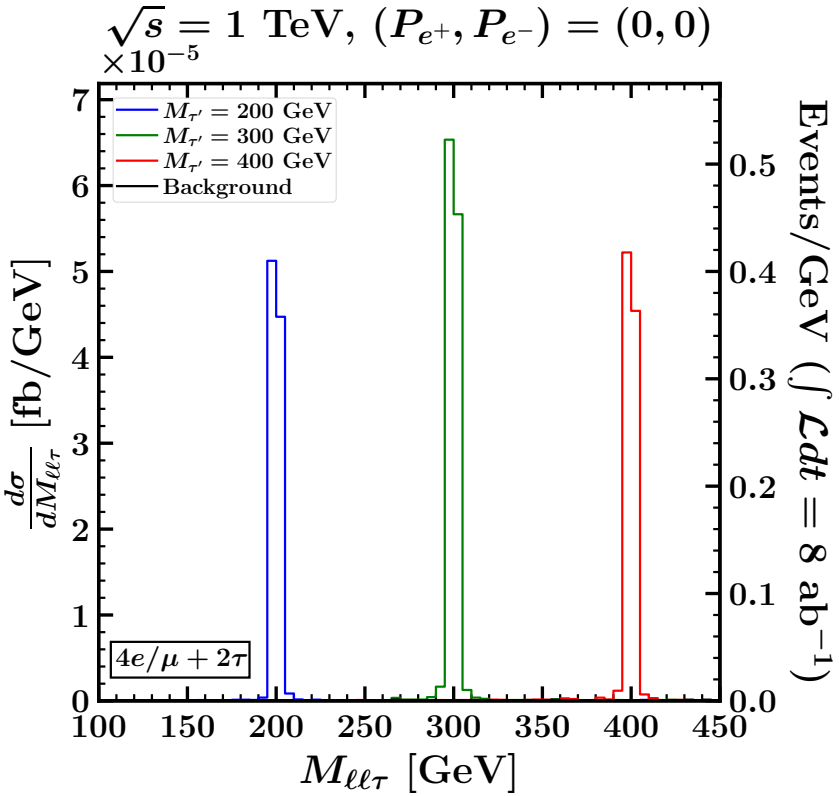
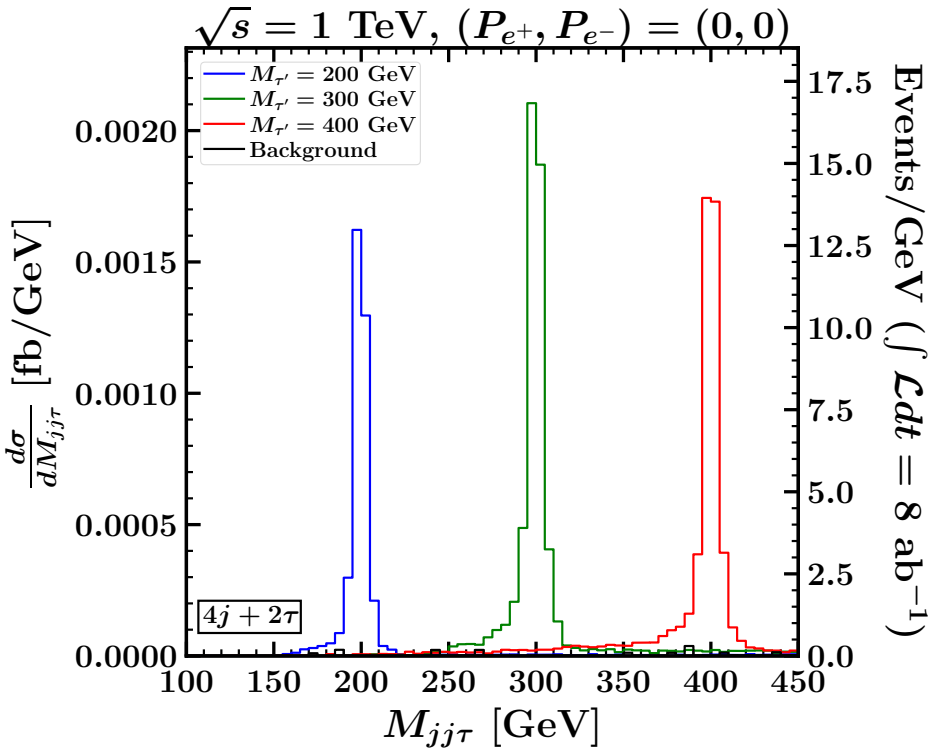


- Might lose some events where ν not actually collinear with τ
- Collinear approximation holds better for larger $M_{\tau'}$ (next slide)





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

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

- $2\ e/mu + 2\ j + 1\ \tau$
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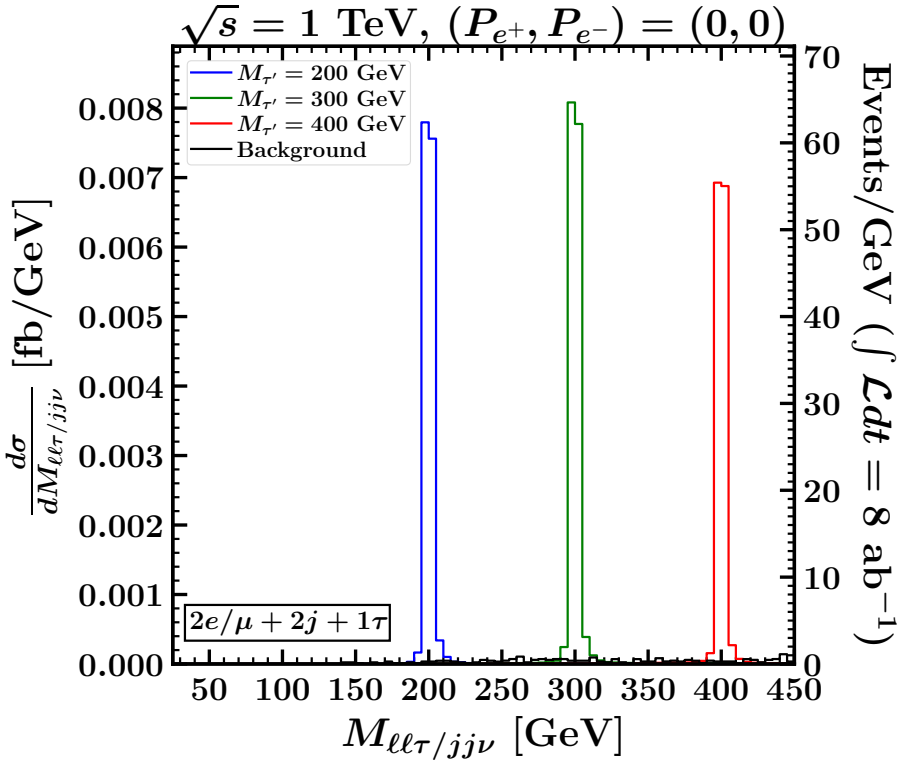
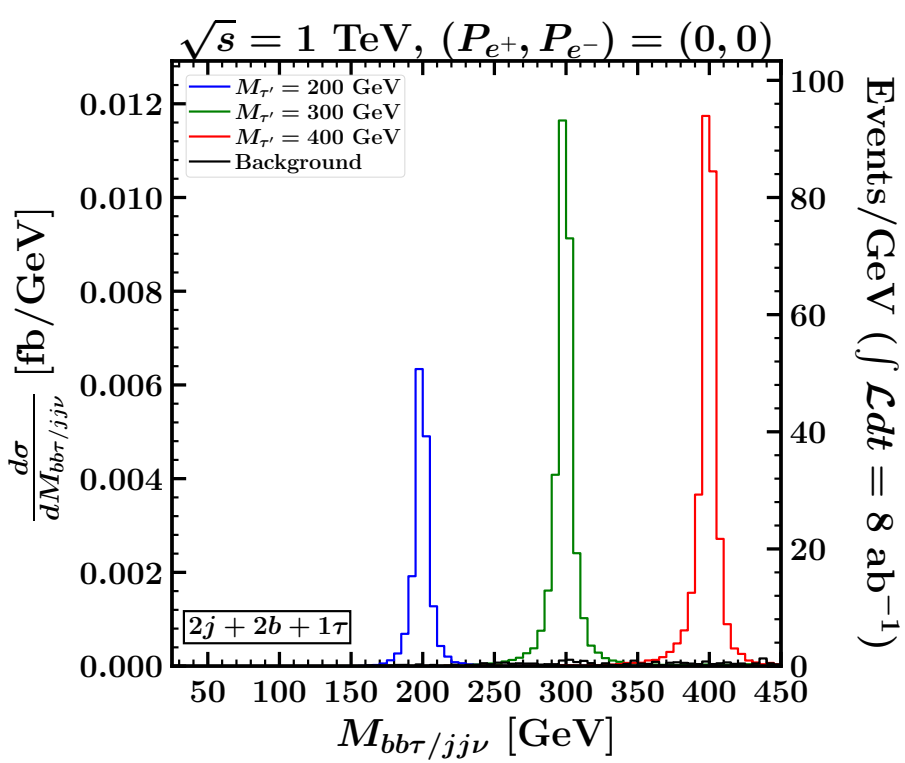
Strategy:

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

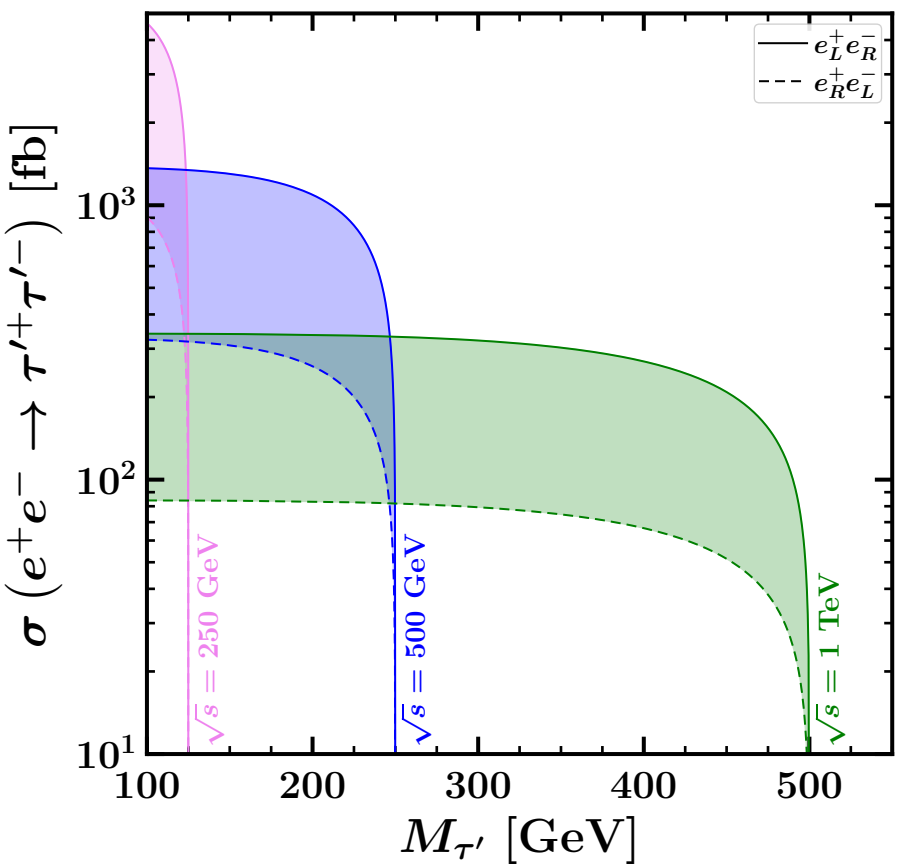




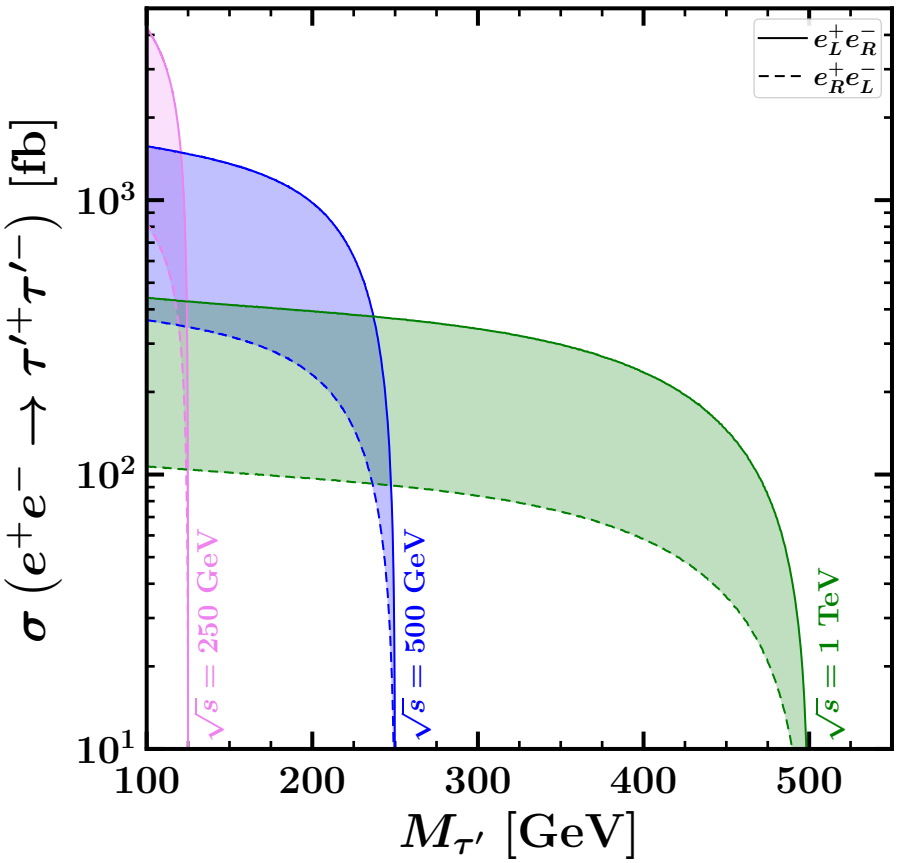
- Backgrounds slightly larger than SRs with 2τ but still very sub-dominant
- Since BR($\tau' \to W\nu_\tau$) is the largest, we have far better statistics in these SRs

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

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

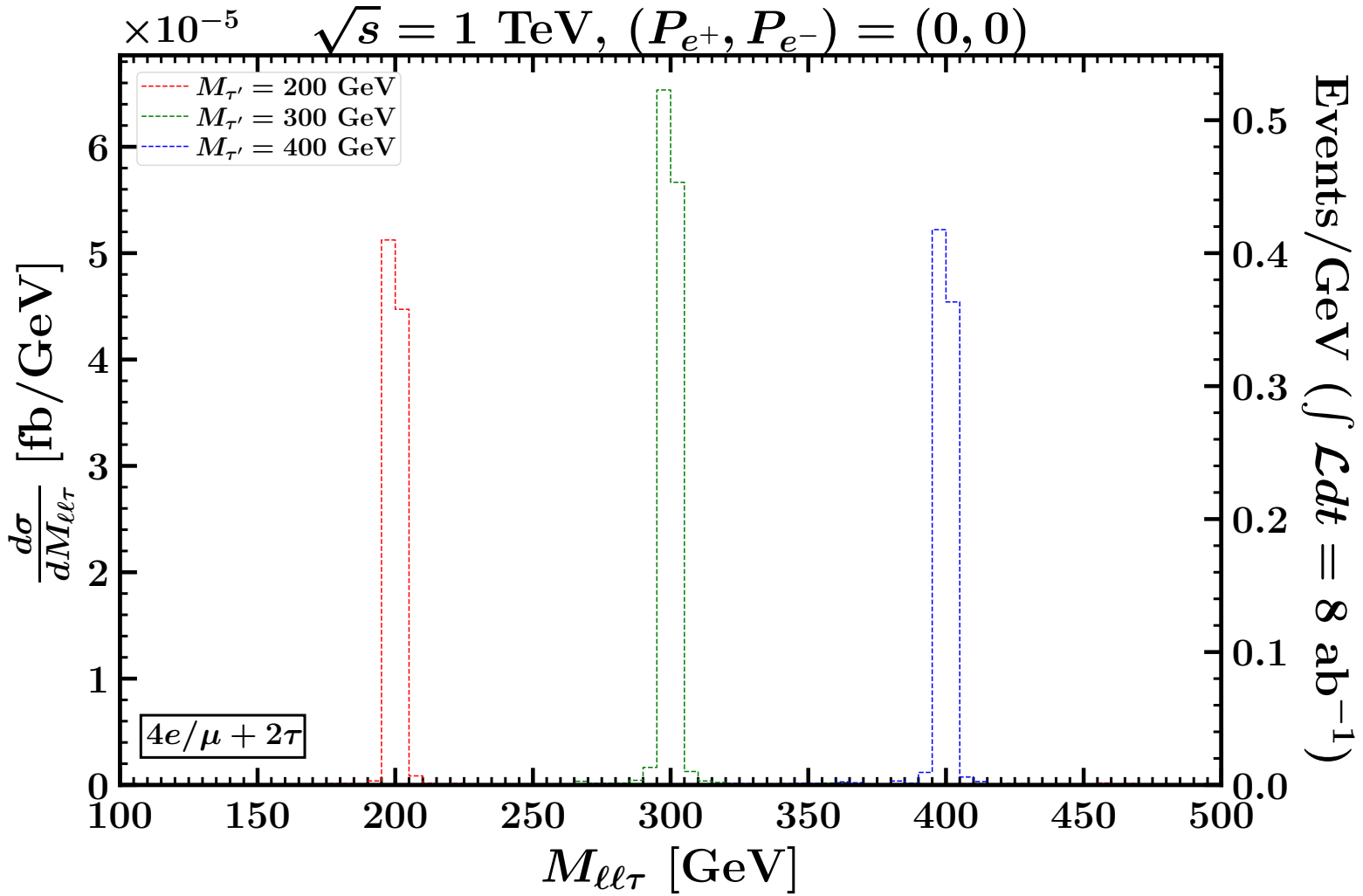


ISR + beamstrahlung



- 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



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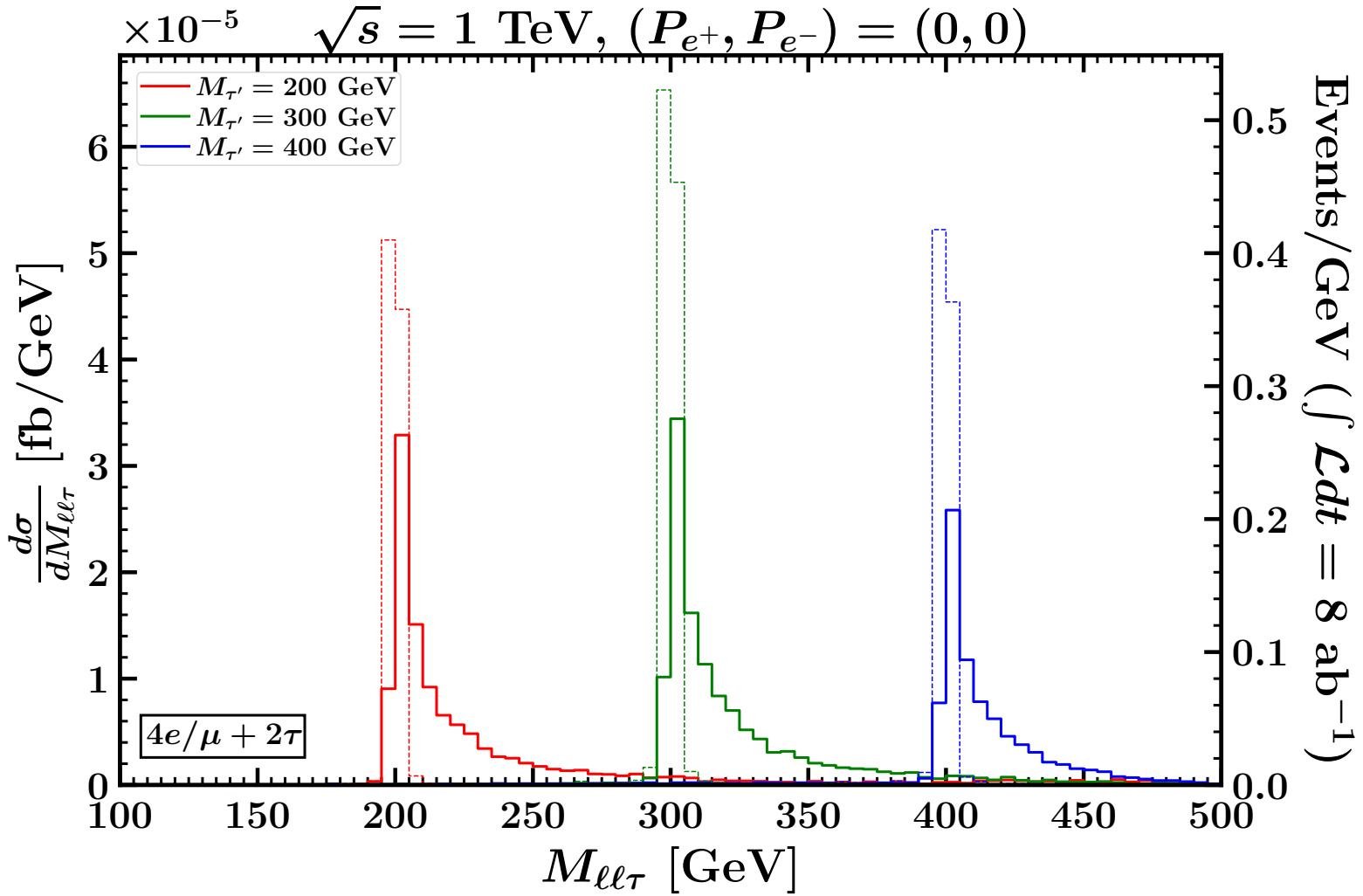

- Distributions more spread out but still peak $\sim M_{\tau'}$

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- Demonstrated that its mass peaks can be reconstructed

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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!