# Tau neutrino oscillations in the far forward rapidities

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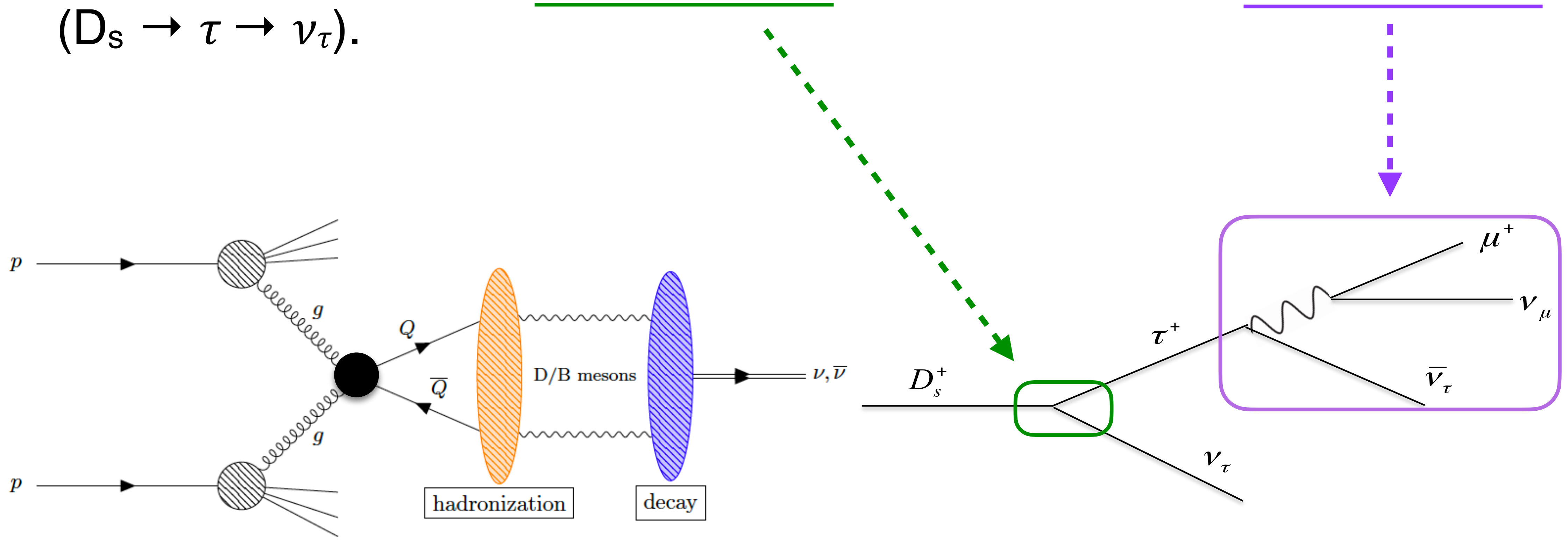
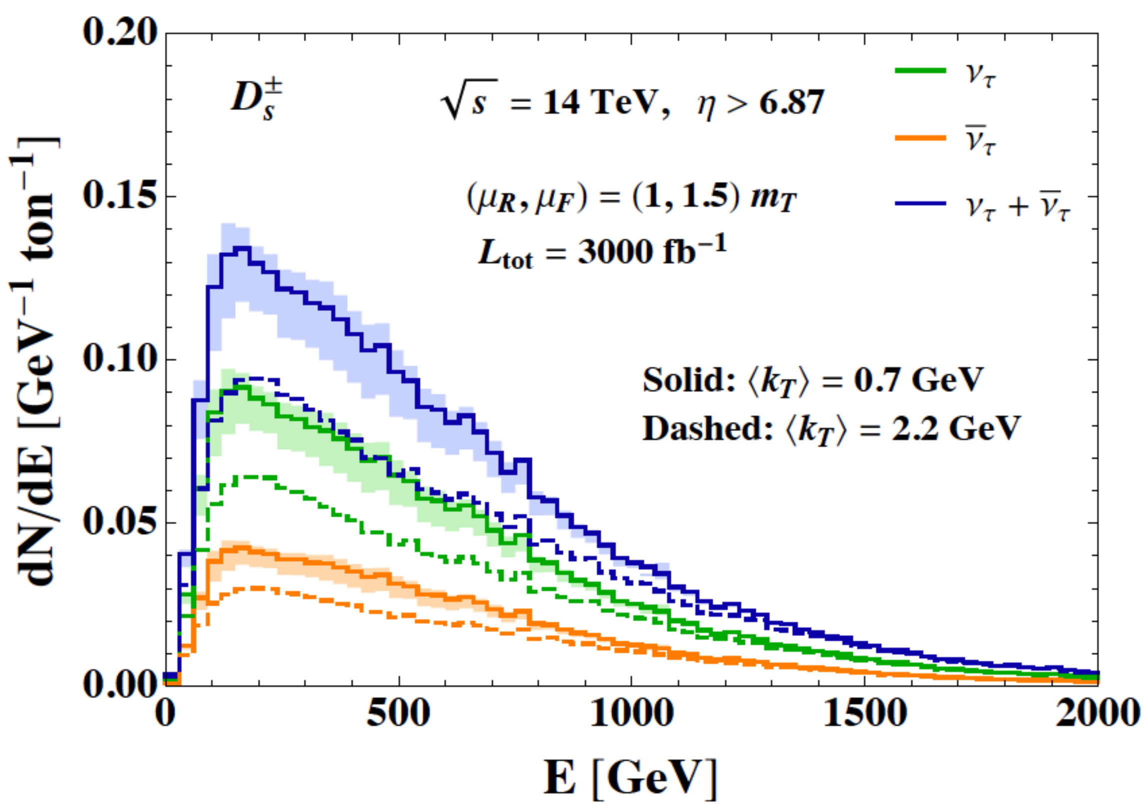
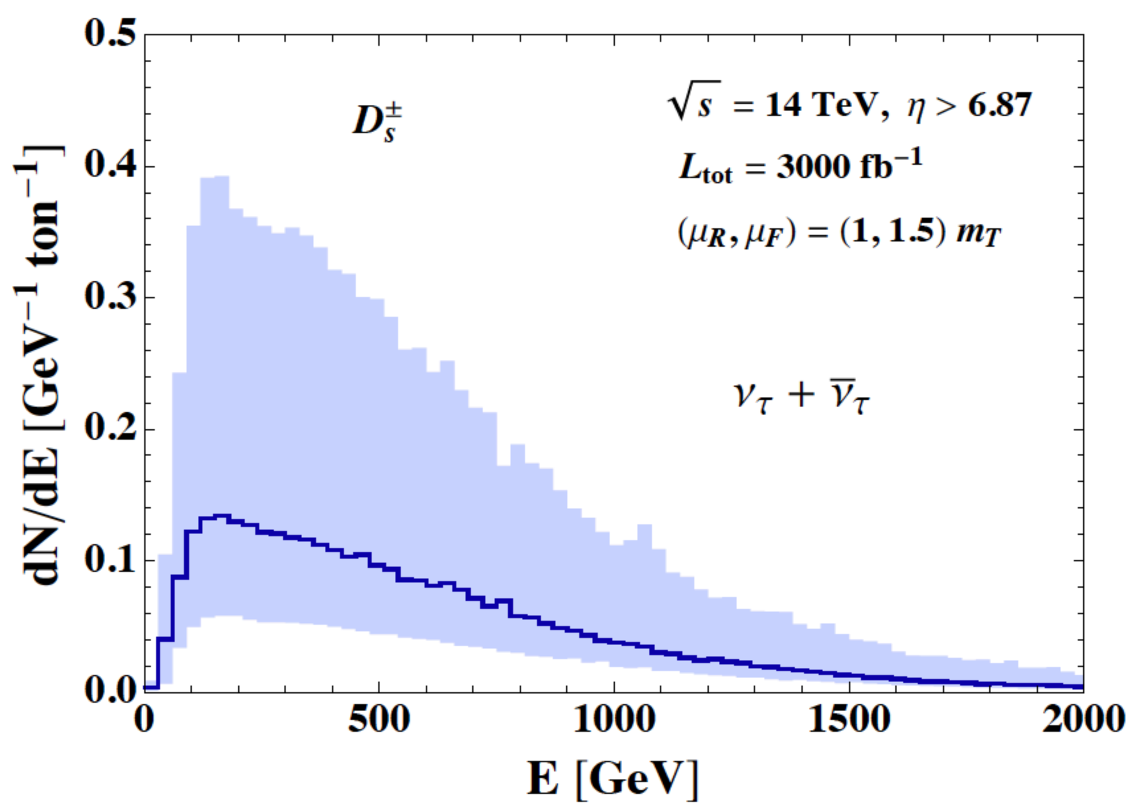
# Production of tau neutrino at the LHC

- In pp collisions at the LHC, various hadrons are produced and subsequently decay producing many neutrinos.
- Tau neutrinos are from the decays of $D_s$ and B mesons.
- The $D_s$ is a main source of tau neutrinos and it produces tau neutrinos through the direct decay ($D_s \to \nu_\tau$) and the chain decay ($D_s \to \tau \to \nu_\tau$).



# Event rate spectrum




| | $\nu_\tau$ | $\bar{\nu}_\tau$ | $\nu_\tau + \bar{\nu}_\tau$ | $\nu_\tau + \bar{\nu}_\tau$ | | | | |
|---|---|---|---|---|---|---|---|---|
| $(\mu_R,\ \mu_F)$ | $(1,\ 1.5)\ m_T$ | | | $(1,\ 1.5)\ m_T$ | | | $(0.5,\ 1.5)\ m_T$ | $(1,\ 0.75)\ m_T$ |
| $\langle k_T \rangle$ | 0.7 GeV | | | 0 GeV | 1.4 GeV | 2.2 GeV | 0.7 GeV | |
| $D_s$ | 2451 | 1191 | 3642 | 3799 | 3261 | 2735 | 11008 | 1716 |
| $B^{\pm,0}$ | 96 | 46 | 142 | 144 | 137 | 127 | 214 | 115 |
| Total | 2547 | 1237 | 3784 | 3943 | 3398 | 2862 | 11222 | 1831 |

$\langle k_T \rangle$: Transverse momentum smearing

in the lead detector with $R_d$ = 1 m and $L_d$ = 1 m

# Sterile neutrinos at FPF of the LHC

- With abundant tau neutrinos and their broad energy distributions, one can probe oscillation by observing any distortion in the energy spectrum of $\nu_\tau$ events.

- For the baseline and the neutrino energy range at forward physics facilities (FPF), oscillations between active neutrinos in the SM will not be noticeable.

- Therefore, deficit or excess in the observed event spectrum can be interpreted as oscillation between tau neutrinos and sterile neutrinos.

# Potential mass and mixing

- Sterile neutrinos are searched in a wide mass range depending on motivations. For example, oscillation experiments search for mostly eV scale sterile neutrinos and the mixing angles are constrained for $\Delta m^2_{41} \simeq O(10^{-2}) - 10\,\mathrm{eV}^2$.

- Oscillation probability in the 3+1 scenario:

$$P(\nu_\alpha \to \nu_\beta) \simeq \delta_{\alpha\beta} - 4(\delta_{\alpha\beta} - |U_{\beta n_\nu}|^2)|U_{\alpha n_\nu}|^2 \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

- Condition for noticeable signal : $\dfrac{\Delta m^2 L}{4E} \sim \dfrac{\pi}{2}$
  - $L = 480$ m, $m_4 = 20$ eV ($\Delta m^2 = 400$ eV$^2$) $\Rightarrow E_\nu \sim 155$ GeV
  - $L = 480$ m, $m_4 = 30$ eV ($\Delta m^2 = 900$ eV$^2$) $\Rightarrow E_\nu \sim 350$ GeV

# Potential mass and mixing

- Among the existing constraints on $\Delta m^2 \gtrsim 100\ \mathrm{eV}^2$, the strongest constraints are from NOMAD and Troitsk tritium beta decay experiments.
  - NOMAD ($\Delta m^2 \simeq m_4^2 \gtrsim 30\ \mathrm{eV}^2$):

$$\sin^2 2\theta_{\mu\tau} \simeq 4|U_{\mu 4}|^2 |U_{\tau 4}|^2 < 3.3\times 10^{-4},$$
$$\sin^2 2\theta_{e\tau} \simeq 4|U_{e4}|^2 |U_{\tau 4}|^2 < 1.5\times 10^{-2},$$
$$\sin^2 2\theta_{\mu e} \simeq 4|U_{\mu 4}|^2 |U_{e4}|^2 < 1.4\times 10^{-3}$$

  - Troitsk tritium beta decay:

$$|U_{e4}|^2 < 6.7\times 10^{-3} \text{ for } m_4 = 20\ \mathrm{eV}$$

- Our parameter choice:

$$m_4 = 20\ \mathrm{eV},\ |U_{\tau 4}|^2 = 0.15,$$
$$|U_{e4}|^2 = 6\times 10^{-3},\ |U_{\mu 4}|^2 = 5\times 10^{-4}$$

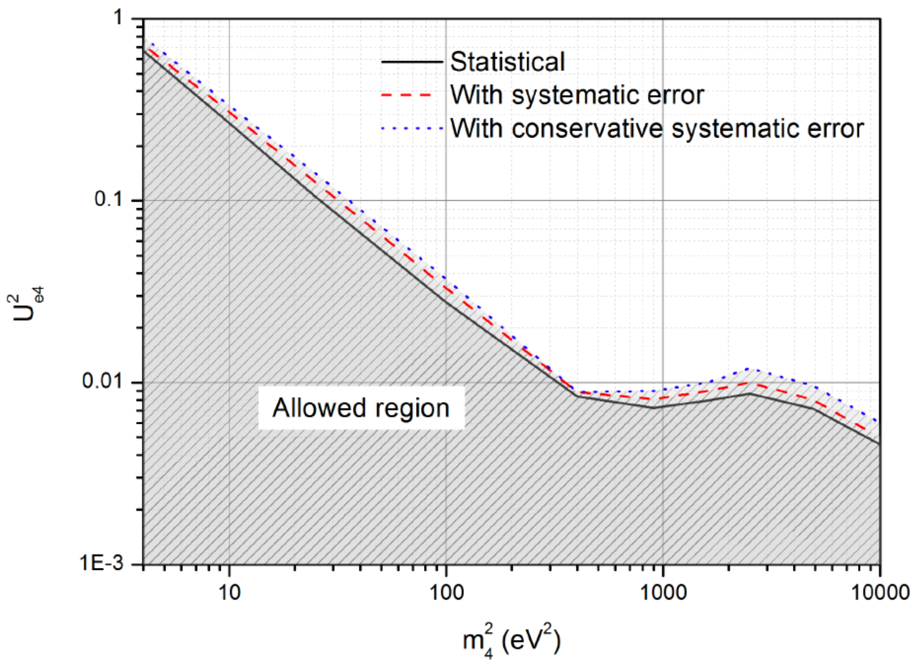
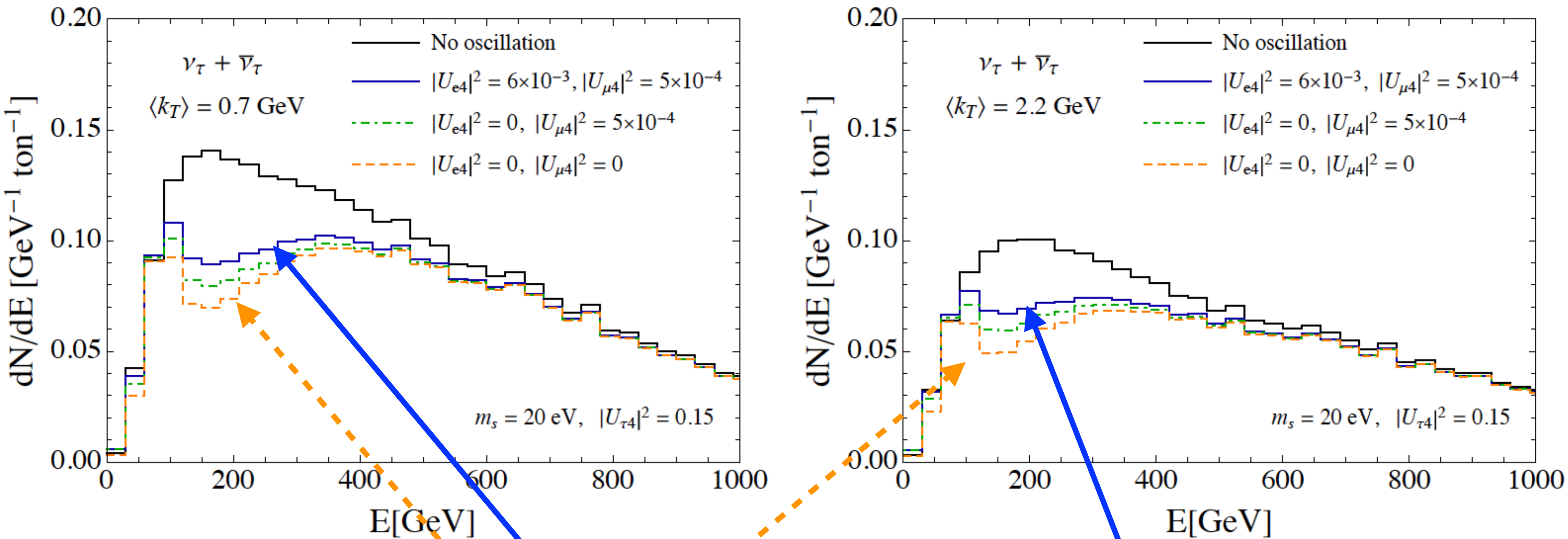



Figure from A. I. Belesev et. al., J.Phys. G 41 (2014) 015001

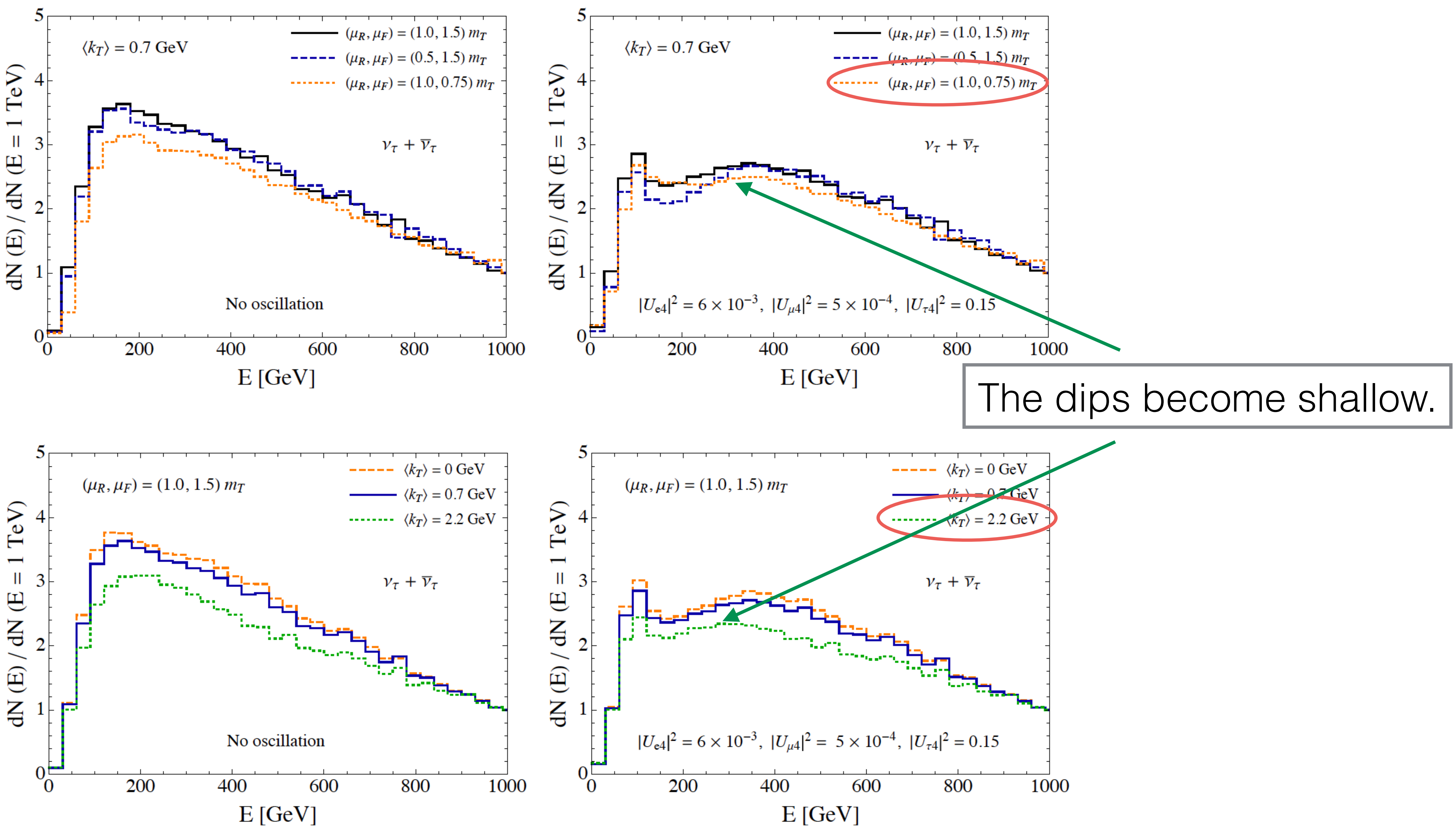
# Event spectrum with oscillations




$$\left.\frac{dN_{\nu_\tau}}{dE}\right|_{\rm surv} = \frac{dN_{\nu_\tau}}{dE} P(\nu_\tau \to \nu_\tau) + \frac{dN_{\nu_\mu}}{dE} P(\nu_\mu \to \nu_\tau) + \frac{dN_{\nu_e}}{dE} P(\nu_e \to \nu_\tau)$$

- Muon and electron neutrinos are from heavy flavor hadrons as well as kaon and pions.
- Representative parameter set: $\Delta m^2 = 400\,\mathrm{eV}^2$ $(m_4 = 20$ eV$)$, $|U_{e4}|^2 = 6\cdot10^{-3}$, $|U_{\mu4}|^2 = 5\cdot10^{-4}$, $|U_{\tau4}|^2 = 0.15$

# Event spectrum with oscillations




If the observed spectrum is close to that of the lower limit of scale uncertainty and high $\langle k_T \rangle$ value, the dip could be more ambiguous.

# Conclusion

- In the far-forward region ($\eta > 6.87$), tau neutrino events are expected to number in thousands and spread over GeV - O(1) TeV energy range in a m-length detector during the HL-LHC phase ($\mathscr{L}_{\rm int} = 3{,}000\ {\rm fb}^{-1}$).
- Abundant neutrino events and the broad energy spectrum will provide an opportunity to explore the O(10) eV mass range of sterile neutrinos and constrain the mixing parameters.
- The energy point of a dip in the observed spectrum will be able to constrain the mass of sterile neutrino that can be probed in this forward region.
- Uncertainties in heavy flavor production make it challenging to distinguish the oscillation effect in the 3+1 model. Suppression of $|U_{e4}|$ and $|U_{\mu 4}|$ could relieve the difficulty. Further dedicated study is under development.

*Thank you for your attention*