Prompt tau neutrinos at the LHC

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based on the work in collaboration

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Outline

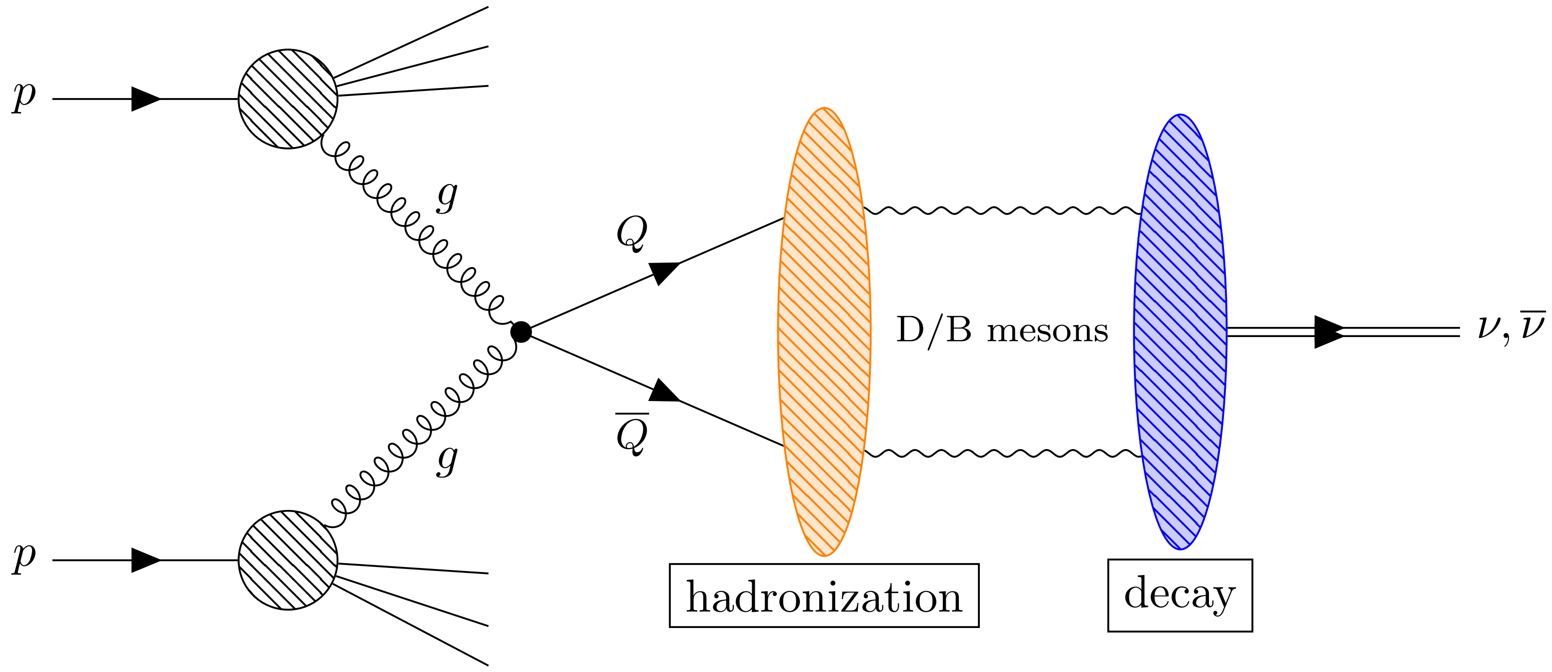
- Potential detection
- Charmed meson production
- Results of neutrino fluxes and events
- Oscillation with sterile neutrinos
- Summary

Prompt neutrinos

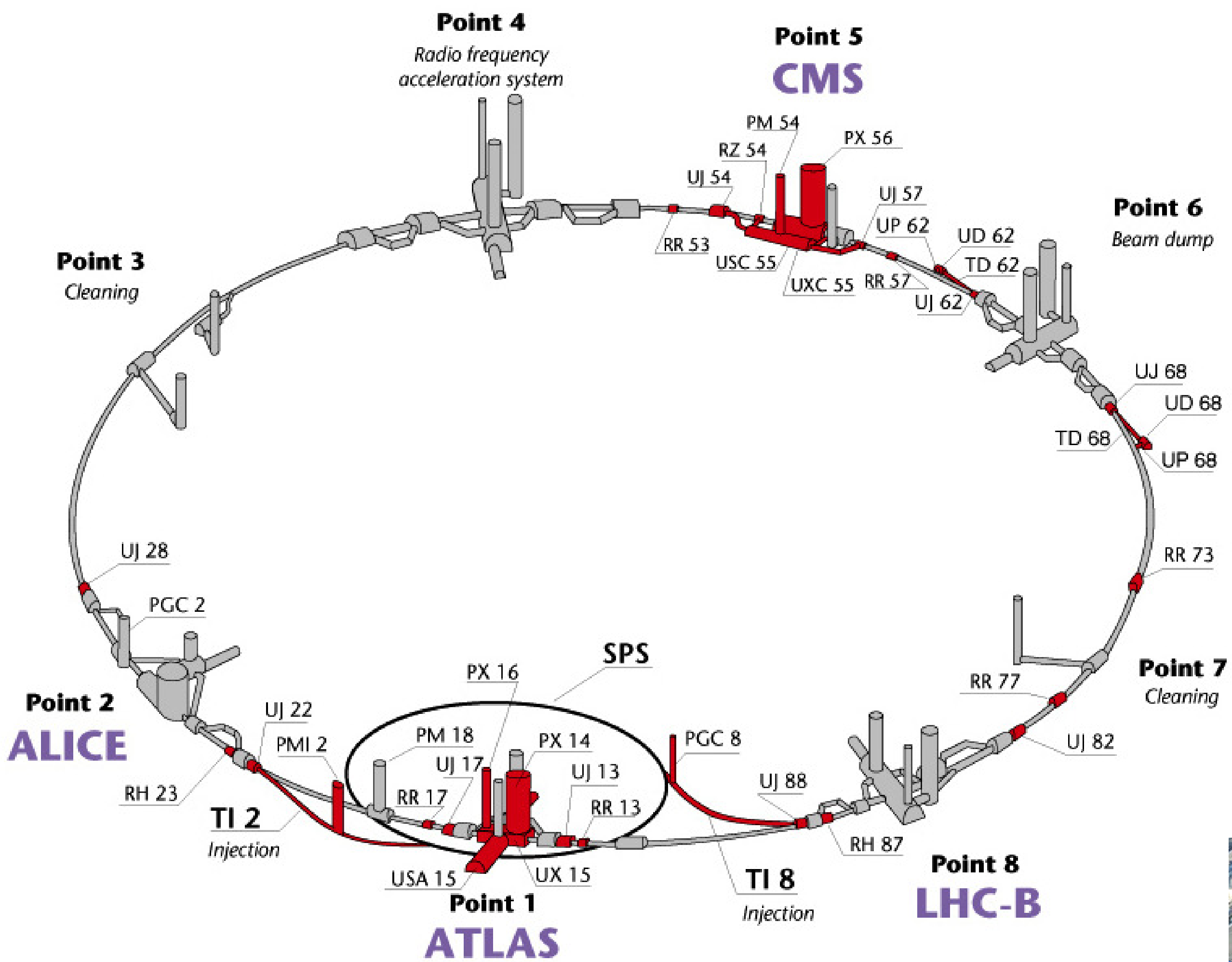
- In pp collision at the LHC, various hadrons are produced.
- A number of neutrinos are produced from subsequent decay of the secondary hadrons.

  e.g.) $\pi, K, D, B \ldots \rightarrow \nu + X$

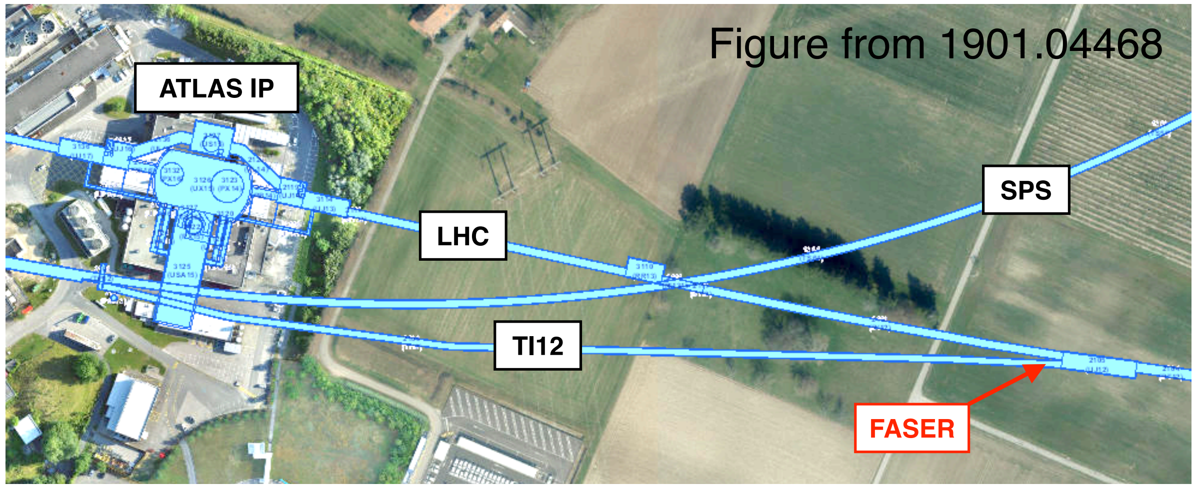
- Neutrinos generated from the decay of charmed/bottom hadrons are called prompt neutrinos.



Possible sites for detection



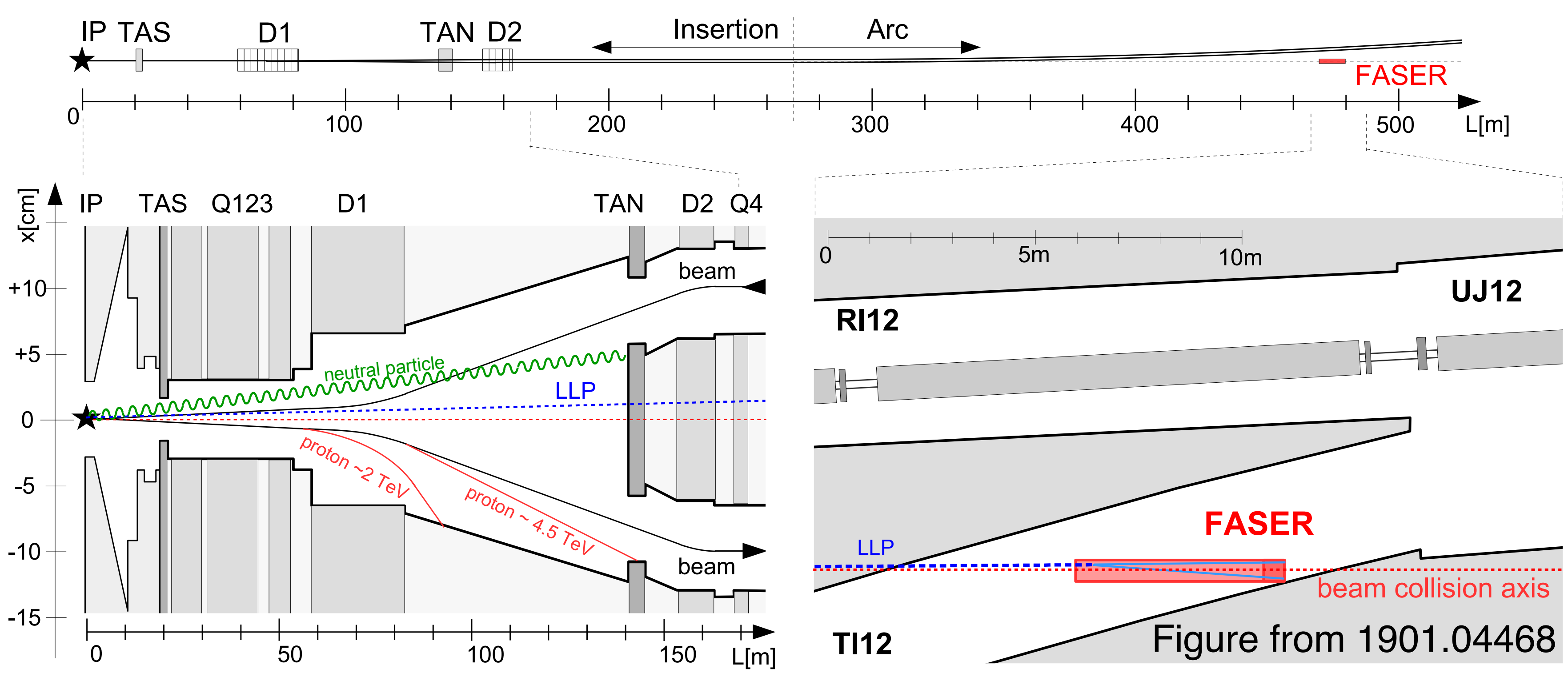
- Near CMS interaction point (IP)
  - 25 m from IP (quadruplet region)
  - 90 &120 m from IP (UJ53 & UJ57)
  - 240 m from IP (PR53 and PR57)
- Near ATLAS IP
  - 480 m from IP (TI18 and TI12)



Ref:1903.06564 (CMS note)
1901.04468 (FASER)

FASER (ForwArd Search ExpeRiment)

- Detector Location: 480 m from ATLAS IP
- Planned with two stages
  - FASER 1: R_d = 10 cm, L_d = 1.5 m, Luminosity = 150 fb^{-1} (during Run 3)
  - FASER 2: R_d = 1.0 m, L_d = 5.0 m, Luminosity = 3000 fb^{-1} (during HL-LHC)
- Rapidity: $\eta \gtrsim 9.2$ for FASER1, $\eta \gtrsim 6.9$ for FASER2



Schematic layout

Neutrino sources at the LHC

- π, K ($c\tau \sim O(1)$ m): do not decay before they reach to the detector at distance of 480 m when $E \gtrsim \sim 9$ (65) GeV for π (K).
- W/Z : neutrinos from weak boson decays are distributed in $|\eta| \lesssim 6$.
- D/B mesons ($c\tau \sim O(100)$ μm)
- Λ_c ($c\tau \sim O(10)$ μm)

➔ Contribute to the neutrino flux for $\eta \gtrsim 6.5$

- ν_τ are only from $D_s^\pm$, $B^\pm$, $B^0(\bar{B}^0)$.

the main source of ν_τ

- Previous works for tau neutrinos at LHC
  - De Rujula et al. Nucl. Phys. B405(1993) 80-108
  - H. K. Park, JHEP 10 (2011) 092
- FASERν (1908.02310)

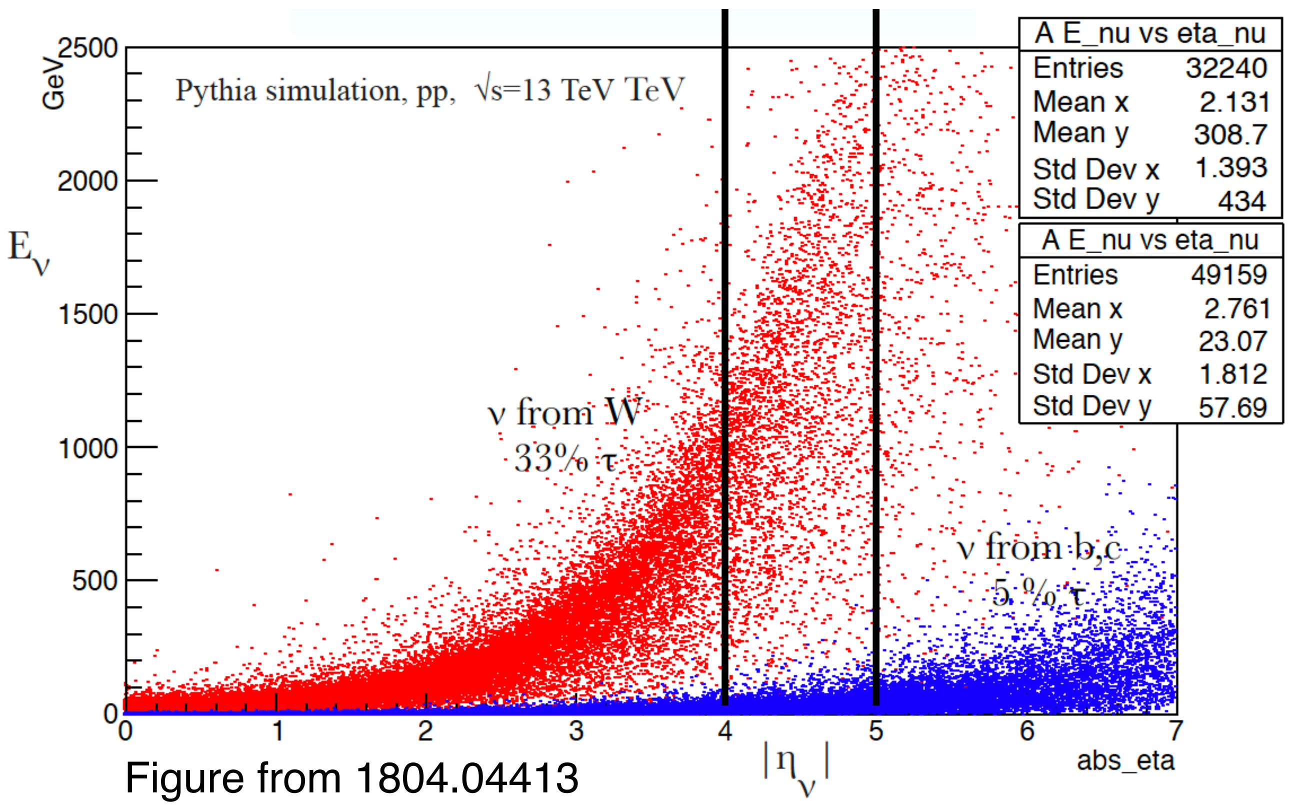


Figure from 1804.04413

Motivation

- Neutrinos in large rapidity region will provide a good opportunity for measurement of neutrino cross section at TeV energies.
- With sizeable number of tau neutrino (ν_τ), it will be possible to test lepton universality in neutrino interaction.
- Abundant ν_τ will help investigate oscillation in/beyond the SM.
  - better understanding of ν_τ CC interaction will be able to reduce the uncertainty due to the tau (τ) decay in the oscillation experiments.
  - possible to probe oscillation between ν_τ and sterile neutrino (ν_s) using the event spectrum.
- To better understand heavy quark production at more forward region than measured by LHCb ➔ useful to explore high energy neutrinos at IceCube and Km3net.

Heavy quark production

- Perturbative QCD with collinear approximation
  - The HQ production cross section (at NLO):

$$\frac{d^2\sigma}{dp_Q^3} = \sum_{i,j=q,\bar{q},g} \int dx_1 dx_2 f_i(x_1, \mu_F^2)\, f_j(x_2, \mu_F^2) \left[\frac{d^3\hat{\sigma}_{ij}(x_1 p_p, x_2 p_p, p_Q, m_Q^2, \mu_F^2, \mu_R^2)}{dp_Q^3} \right]$$

- In collinear approximation, the partons in interaction are assumed to be collinear.
- For very forward kinematic region, small transverse momentum corrections can have important effect on particle's path to the detector.

  ⇒ k_T smearing needs to be incorporated.

Transverse momentum smearing

- In Gaussian approximation of transverse momentum smearing

$$f(k_T) = \frac{1}{\pi\langle k_T^2\rangle} \exp\left(-\frac{k_T^2}{\langle k_T^2\rangle}\right)$$

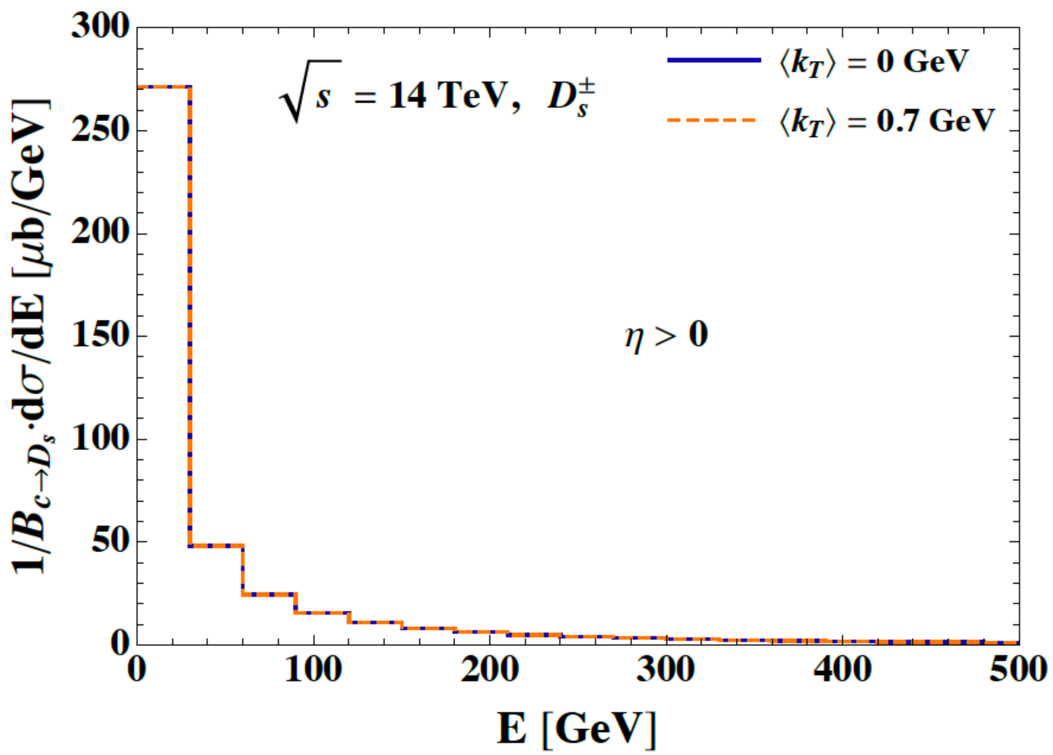
- The heavy quark production cross section with $\langle k_T\rangle$ included:

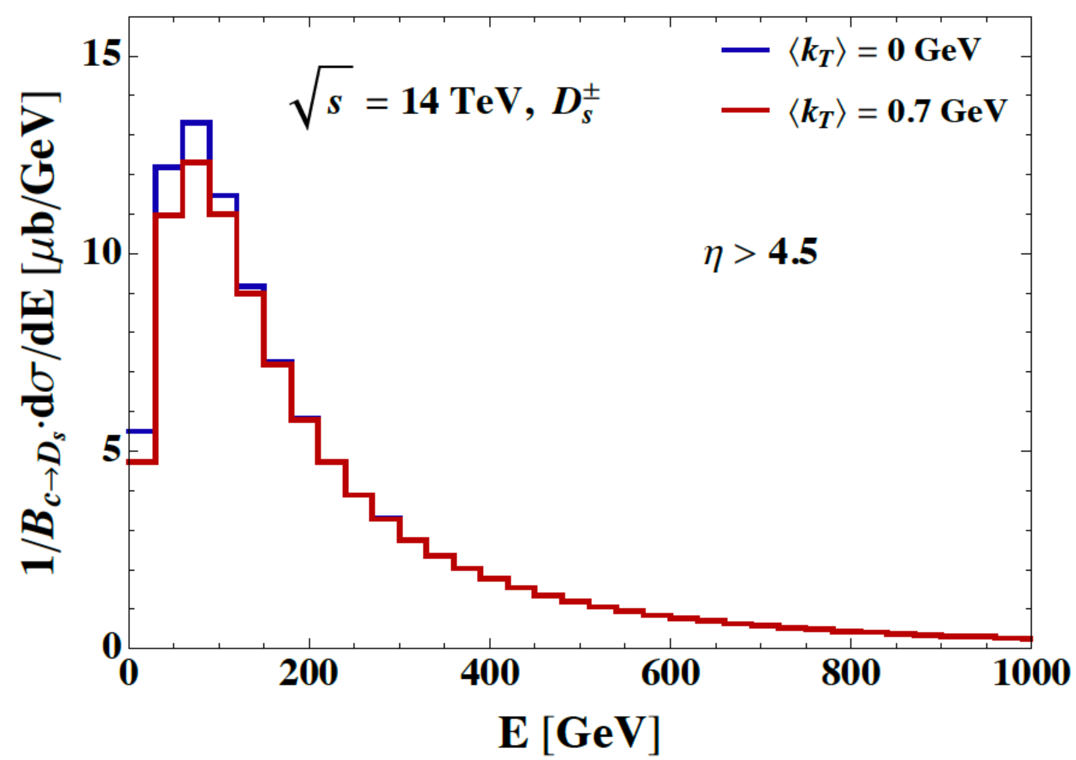
$$dx_1 f_i(x_1, \mu_F^2) \rightarrow dx_1\, d^2k_{T_1}\, f(k_{T_1}) f_i(x_1, \mu_F^2)$$

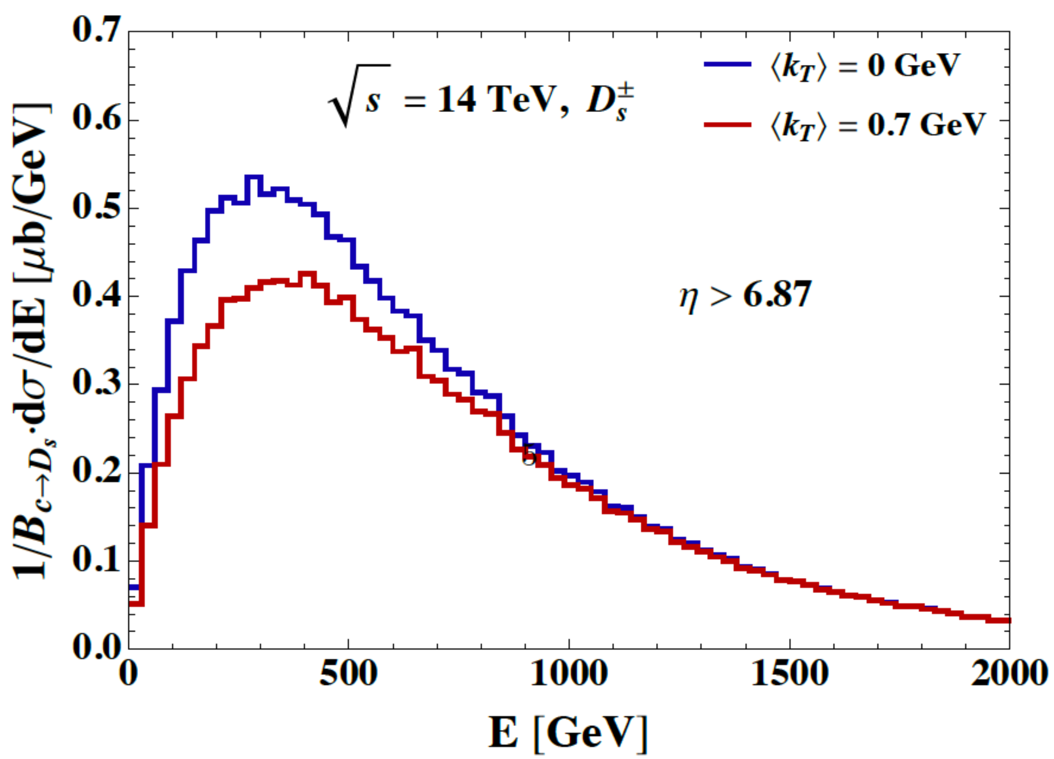
$$\frac{d^2\sigma}{dp_z\, d^2p_T} = \sum_{i,j=q,\bar{q},g} \int d^2k_T \int d^2p'_T\, f(k_T) \frac{d^2\hat{\sigma}}{dp_z\, d^2p_T} \delta^2(p_T - p'_T - k_T)$$

- Transverse momentum smearing:
  - approximate effects of initial state showering
  - Includes intrinsic k_T

The effect of $\langle k_T \rangle$ by rapidity

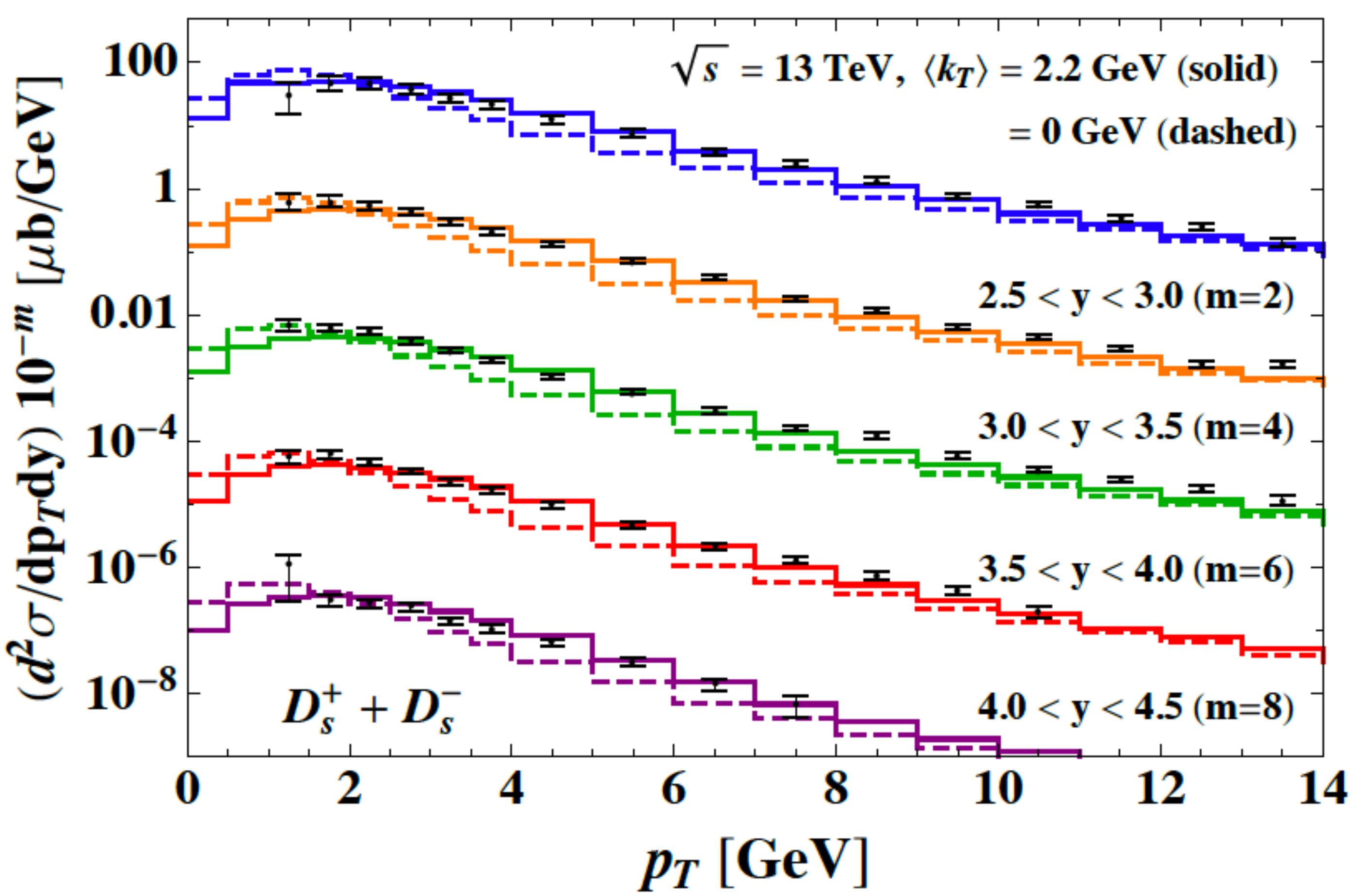






- $\langle k_T \rangle$ has more impact at larger rapidity region.
- $\langle k_T \rangle$ reduces the amount of the particle toward the detector direction.

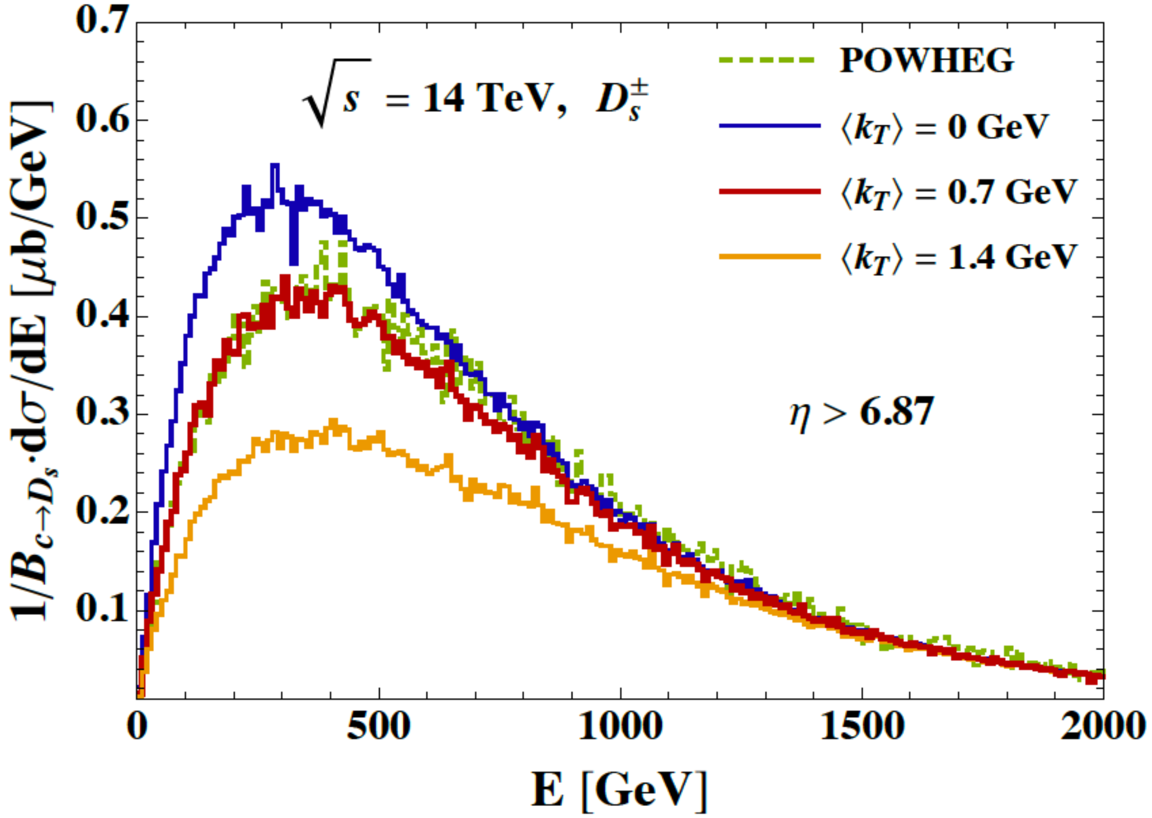
Comparison with LHCb (p_T distribution)

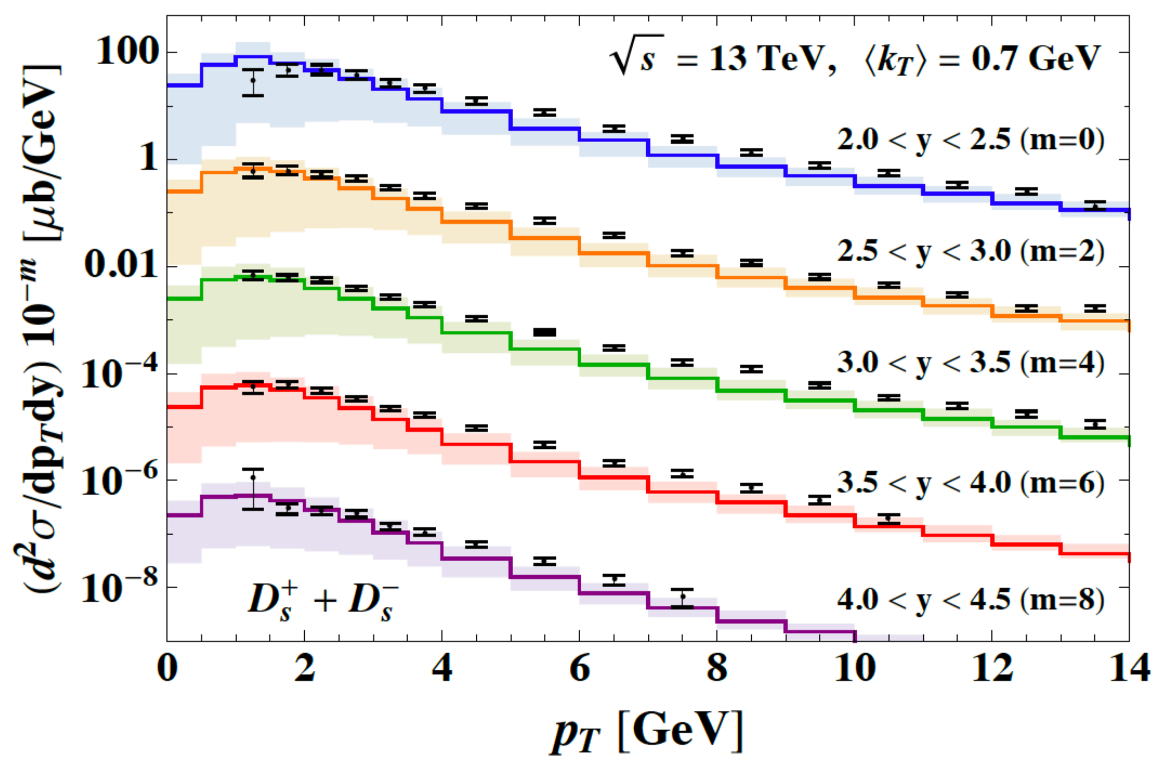


- By comparing NLO pQCD evaluation with the LHCb data for the total and differential cross sections, the relevant scales is obtained as $(\mu_R, \mu_F) = (1.0, 1.5)\, m_T$.
- Non-zero $\langle k_T \rangle$ makes fit better to the measurement.
- $\langle k_T \rangle$ = 2.2 GeV fairly well describes the overall data, but still not optimal for low p_T range.

Determination of $\langle k_T \rangle$

Preliminary

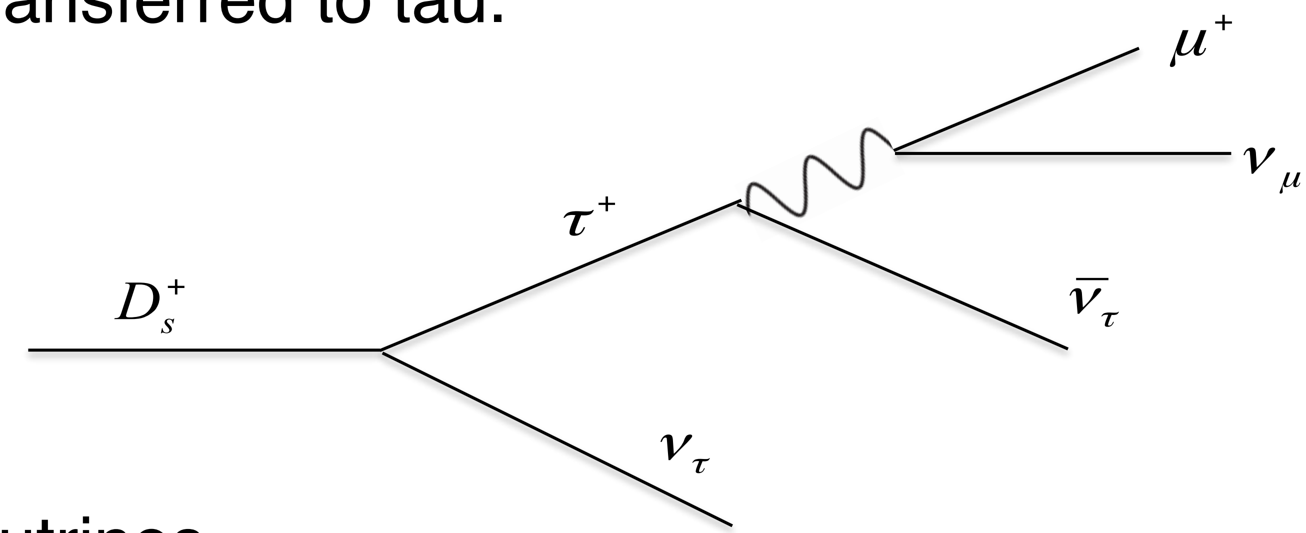




- The default value: $\langle k_T \rangle$ = 0.7 GeV guided by POWHEG simulation.
- The uncertainty range by the scales is too broad at the low p_T region. Instead, we take $0 < \langle k_T \rangle < 1.4$ GeV.

Decay to tau neutrinos

- The D_s meson is the main source of the tau neutrinos with $\mathrm{Br}\,(D_s \to \tau + \nu_\tau) \sim 5.5\,\%$.
- The D_s decay produces two tau neutrinos: by direct decay ($D_s \to \nu_\tau$) and by chain decay ($D_s \to \tau \to \nu_\tau$).
- About 90% of D_s energy is transferred to tau.



- B^0, $B^\pm$ also decays to tau neutrinos.

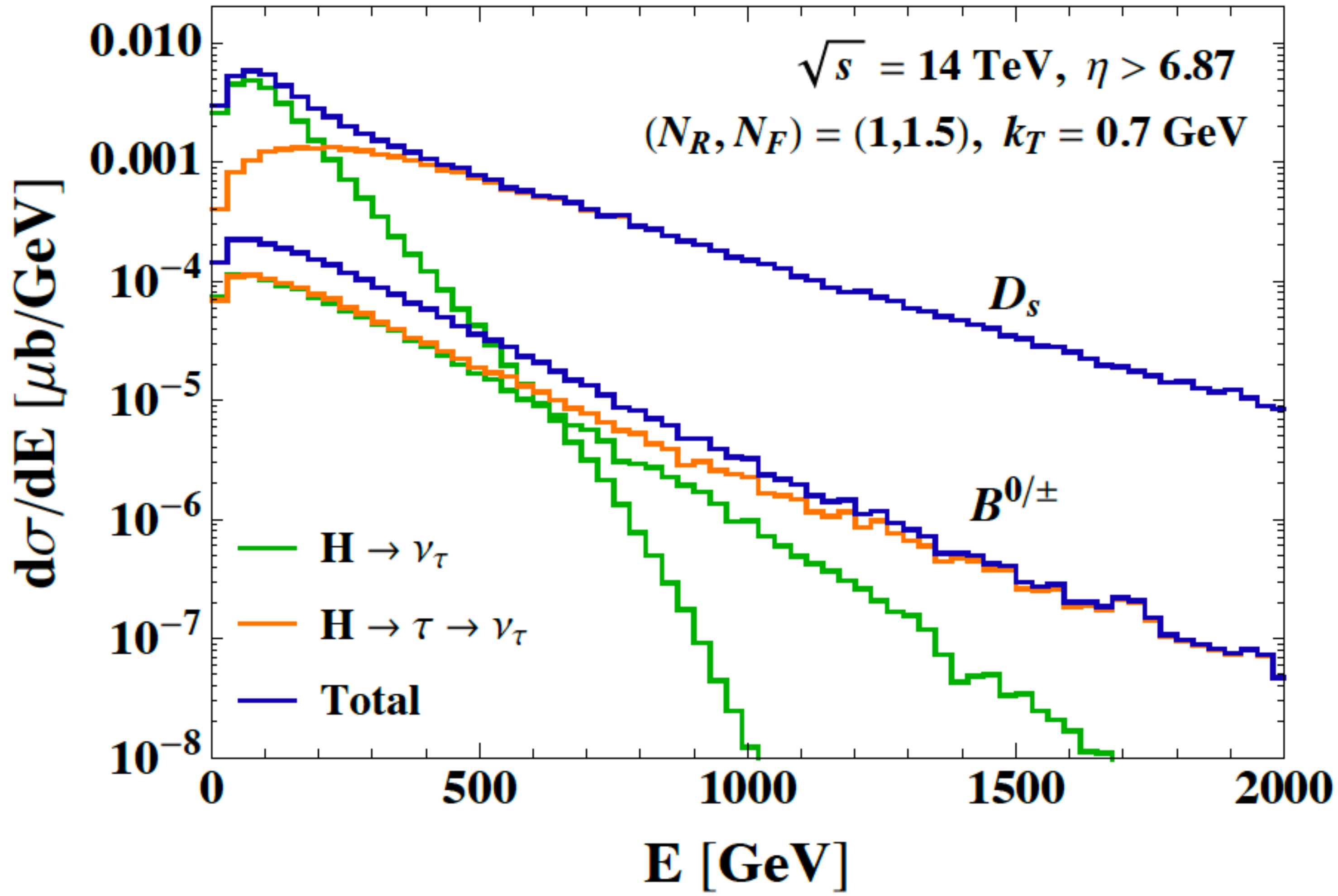
$$\mathrm{Br}\,(B^+ \to \bar{D}^0\tau^+\nu_\tau) = 0.7\,\%$$

$$\mathrm{Br}\,(B^+ \to \bar{D}^*(2007)^0\tau^+\nu_\tau) = 1.88\,\%$$

$$\mathrm{Br}\,(B^0 \to D^-\tau^+\nu_\tau) = 1.08\,\%$$

$$\mathrm{Br}\,(B^0 \to D^*(2010)^-\tau^+\nu_\tau) = 1.57\,\%$$

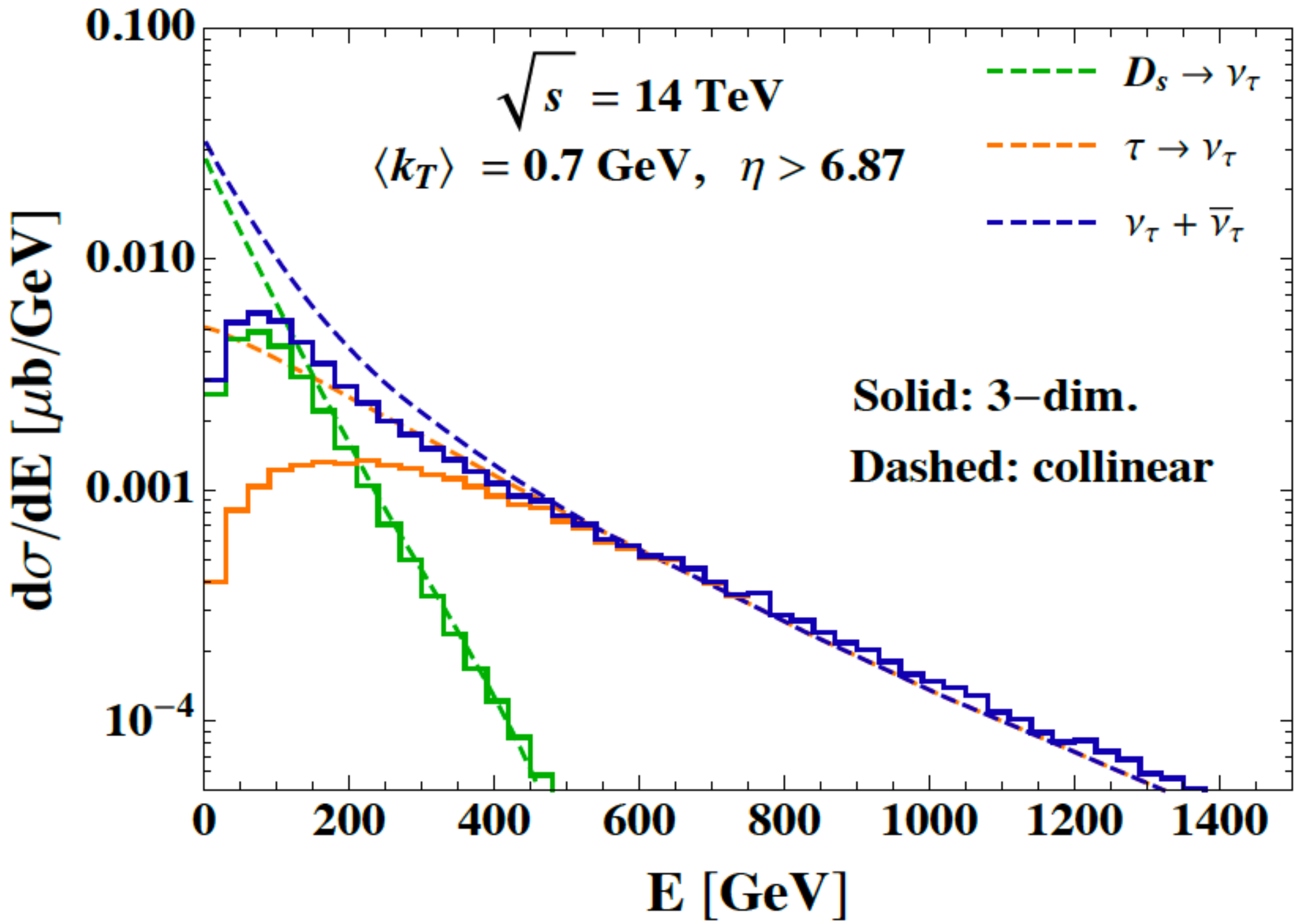
Differential cross sections for ν_τ production



Preliminary

- $\frac{d\sigma}{dE} \times \mathscr{L}$: total flux of neutrinos incoming to the detector area.
- 3-dimensional decay are considered.

Collinear approx. vs. 3-dim in decay

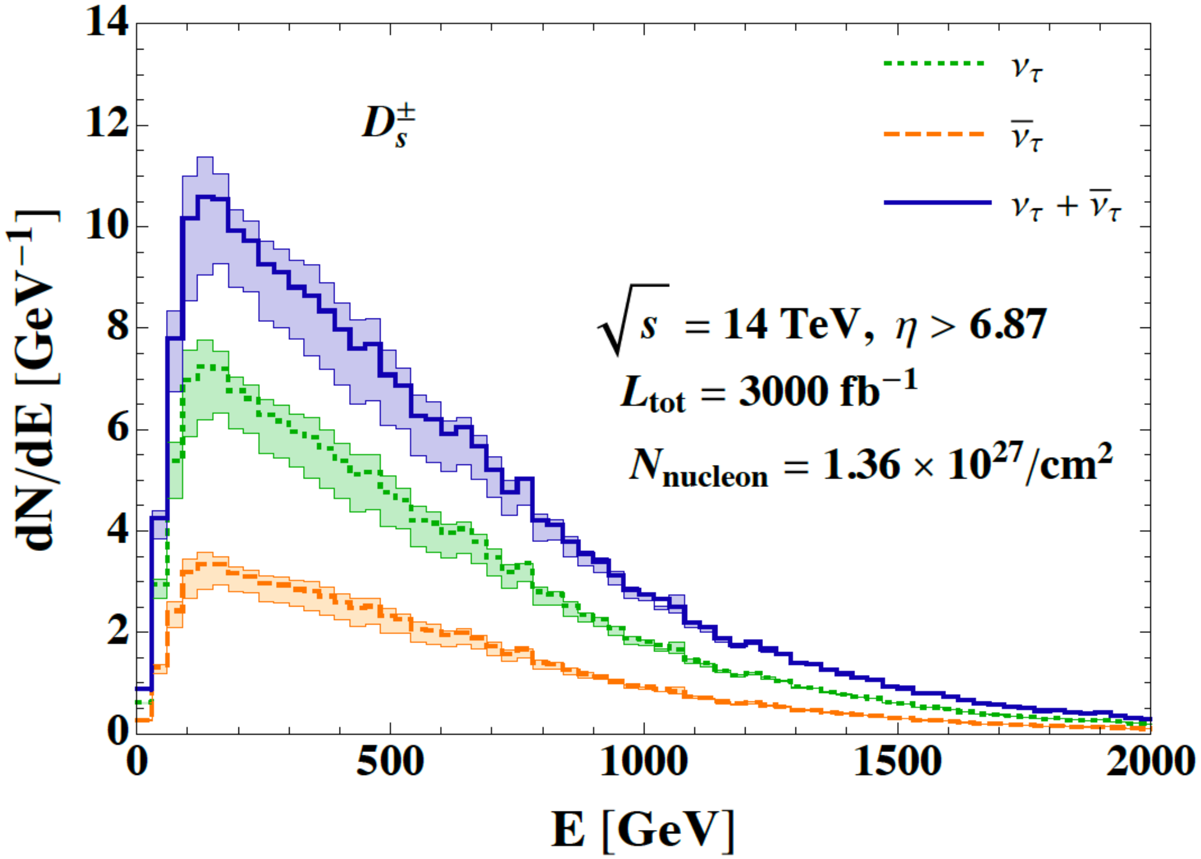


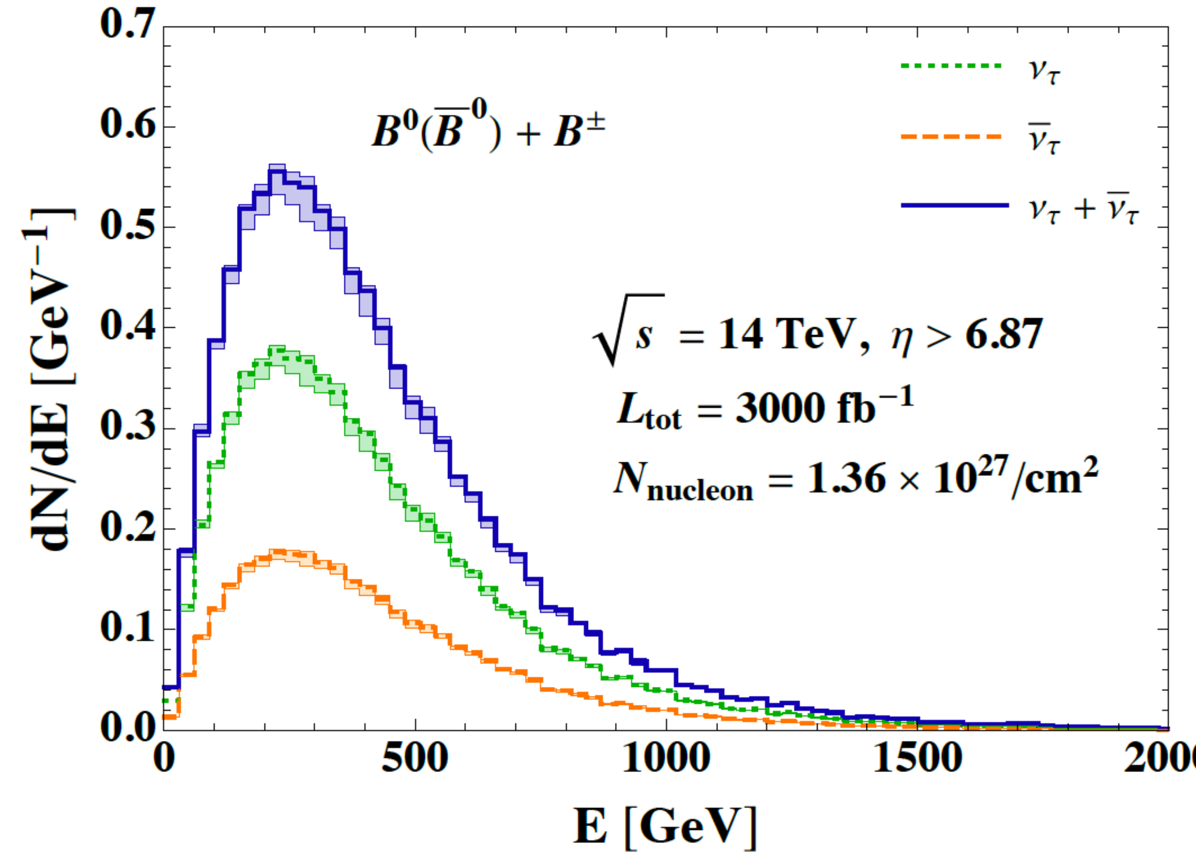
Preliminary

- 3D decay consideration reduce the number of tau neutrinos reached to the detector by ~ 20%.

Event rate

Preliminary





$\langle k_T \rangle$ = 0.7 TeV

$\eta > 6.87$	ν_τ	$\bar{\nu}_\tau$	$\nu_\tau + \bar{\nu}_\tau$ (k_T= 1.4, 0)
D_s	4901	2382	7283(6523, 7597)
$B^{\pm,0}$	193	92	285 (274 , 289)
Total	5094	2474	7568 (6797 , 7886)

- Contribution from B is ~ 4 %.
- Events with $\langle k_T \rangle$= 2.2 GeV is 5725, which is ~ 20% less than prediction with $\langle k_T \rangle$ = 0.7 GeV.

Oscillation with sterile neutrinos

Sterile neutrinos at FASER

- Sterile neutrinos are searched in a wide mass range depending on motivations.
- Oscillation experiments search for mostly eV scale sterile neutrinos and the mixing angles are constrained for $\Delta m^2_{41} \simeq O(10^{-2}) - 10\,\mathrm{eV}^2$.
- With the abundant tau neutrinos and broad energy spectrum, the FASER can investigate oscillation between ν_τ and ν_s.
    - For the baseline and the neutrino energy range, FASER will not be sensitive to oscillation between the SM neutrinos. Therefore, deficit or excess in the observed event spectrum can be interpreted as oscillation with sterile neutrinos.
    - The larger mass range of sterile neutrinos can be probed.

Potential mass and mixing

- Oscillation probability in two flavour approximation:

$$P(\nu_\alpha \to \nu_\beta) \simeq \sin^2 2\theta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

- Condition for noticeable signal :

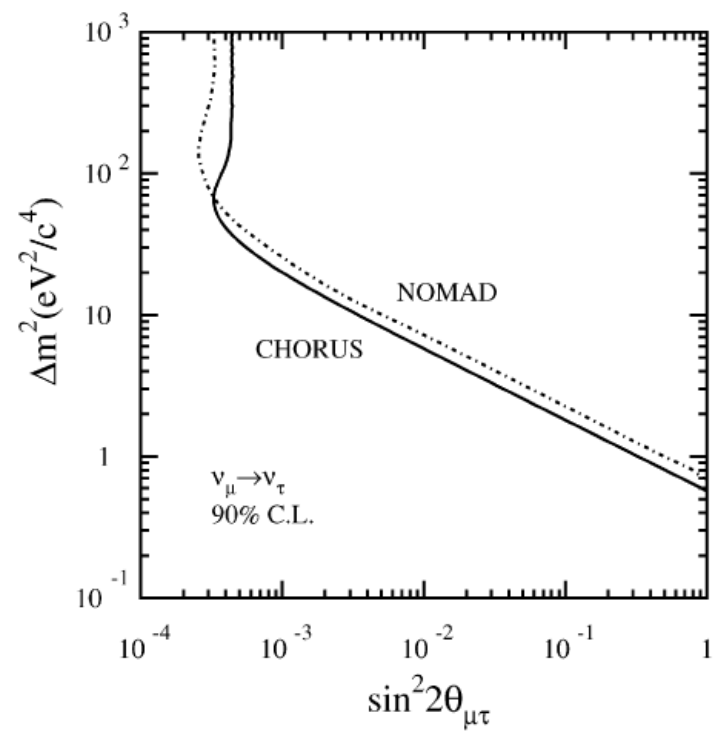
$$\frac{\Delta m^2 L}{4E} \sim \frac{\pi}{2}$$

- For the baseline 480 m and neutrinos with
  - E ~ 170 GeV ⇒ $\Delta m_s^2 \sim 440\ \mathrm{eV}^2$ $(m_s \sim 20\ \mathrm{eV})$
  - E ~ 350 GeV ⇒ $\Delta m_s^2 \sim 900\ \mathrm{eV}^2$ $(m_s \sim 30\ \mathrm{eV})$

Potential mass and mixing

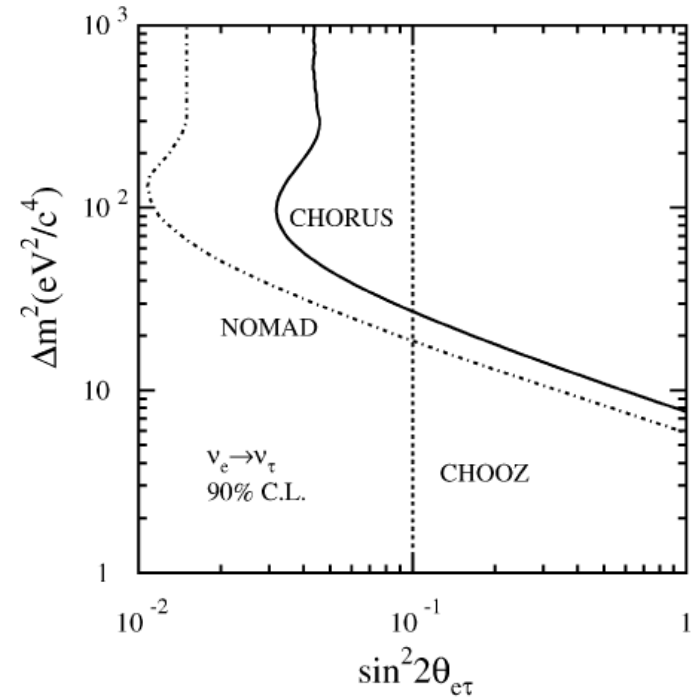
- Among the existing constraints on $\Delta m^2 \gtrsim 100\ \mathrm{eV}^2$, the strongest constraint is from NOMAD as

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



- The testable parameter sets for mixing angle:

$$|U_{e4}|^2 = 0.04,\ |U_{\mu 4}|^2 = 10^{-3},\ |U_{\tau 4}|^2 = 0.08$$
$$|U_{e4}|^2 = 0.02,\ |U_{\mu 4}|^2 = 5 \cdot 10^{-4},\ |U_{\tau 4}|^2 = 0.15$$



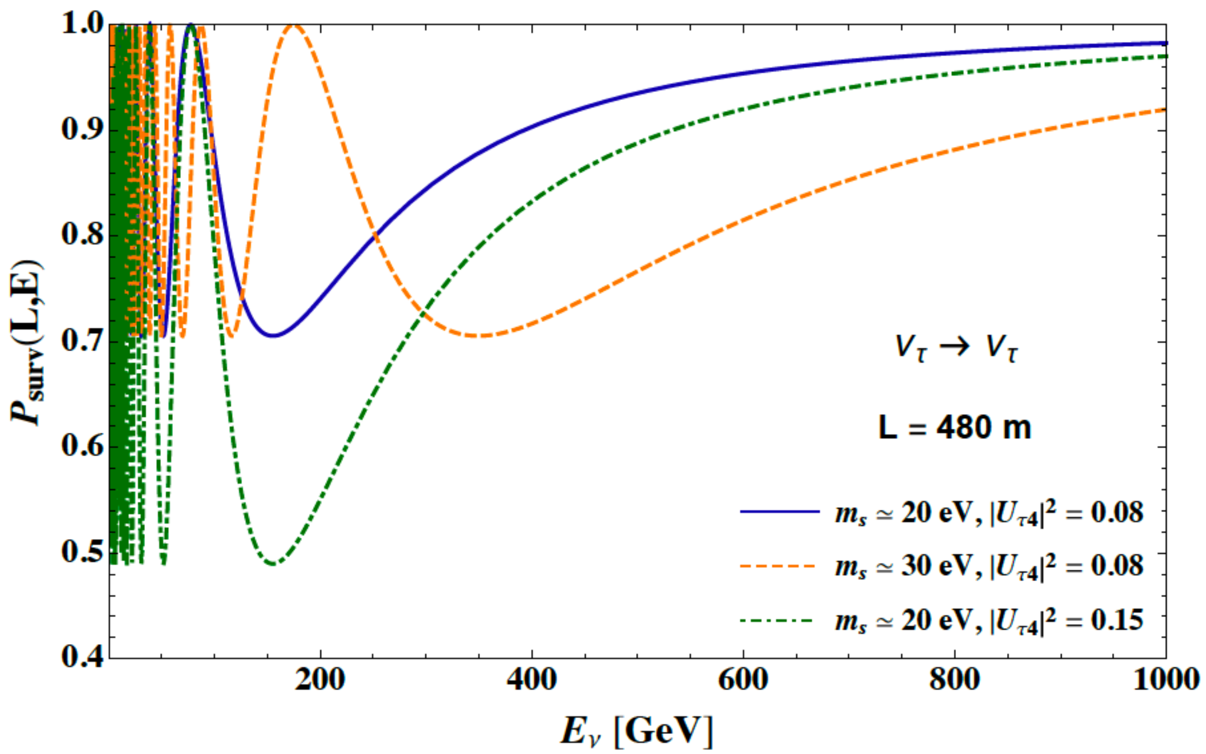
Oscillation probability in the 3+1 model

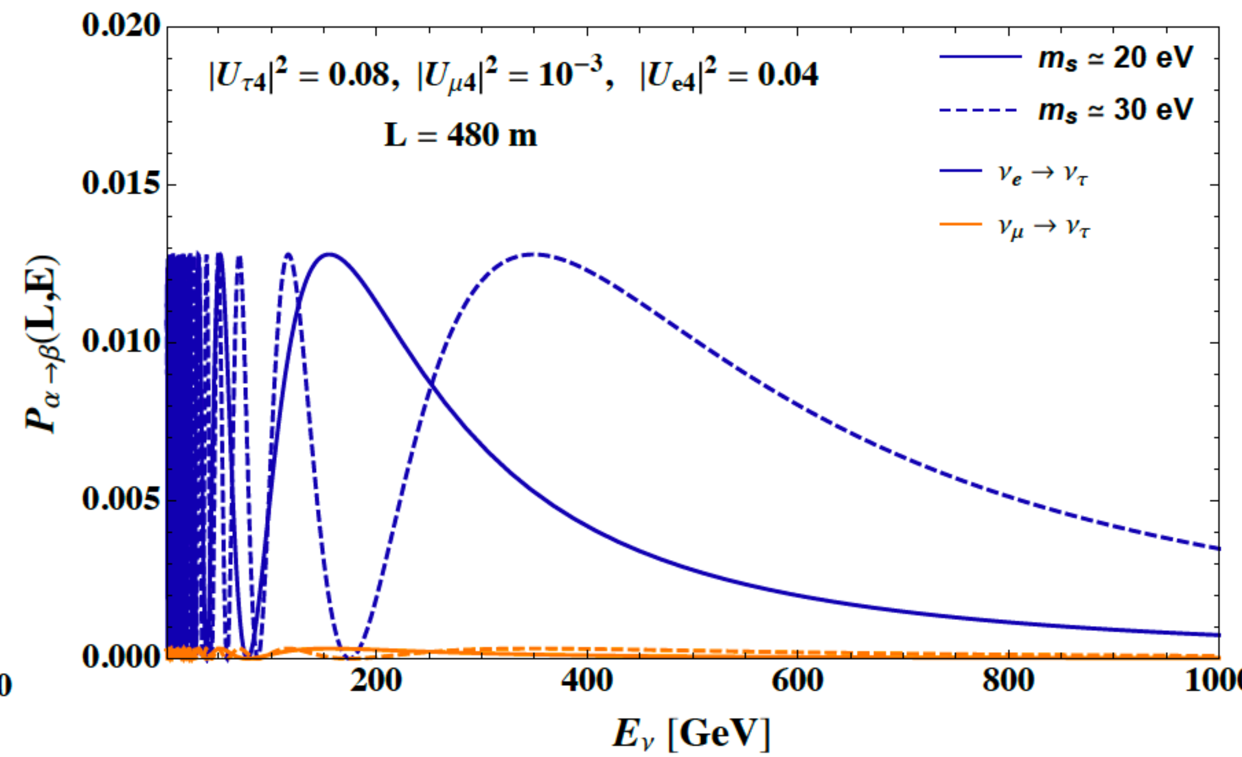
- The oscillation probability in two flavour approximation

$$P(\nu_\alpha \to \nu_\alpha) \simeq 1 - 4(1 - |U_{\alpha 4}|^2)|U_{\alpha 4}|^2 \sin^2\left(\frac{\Delta m^2 L}{4E}\right) \quad \text{(disappearance)}$$

$$P(\nu_\alpha \to \nu_\beta) \simeq 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2 \sin^2\left(\frac{\Delta m^2 L}{4E}\right) \quad \text{(appearance)}$$

Preliminary



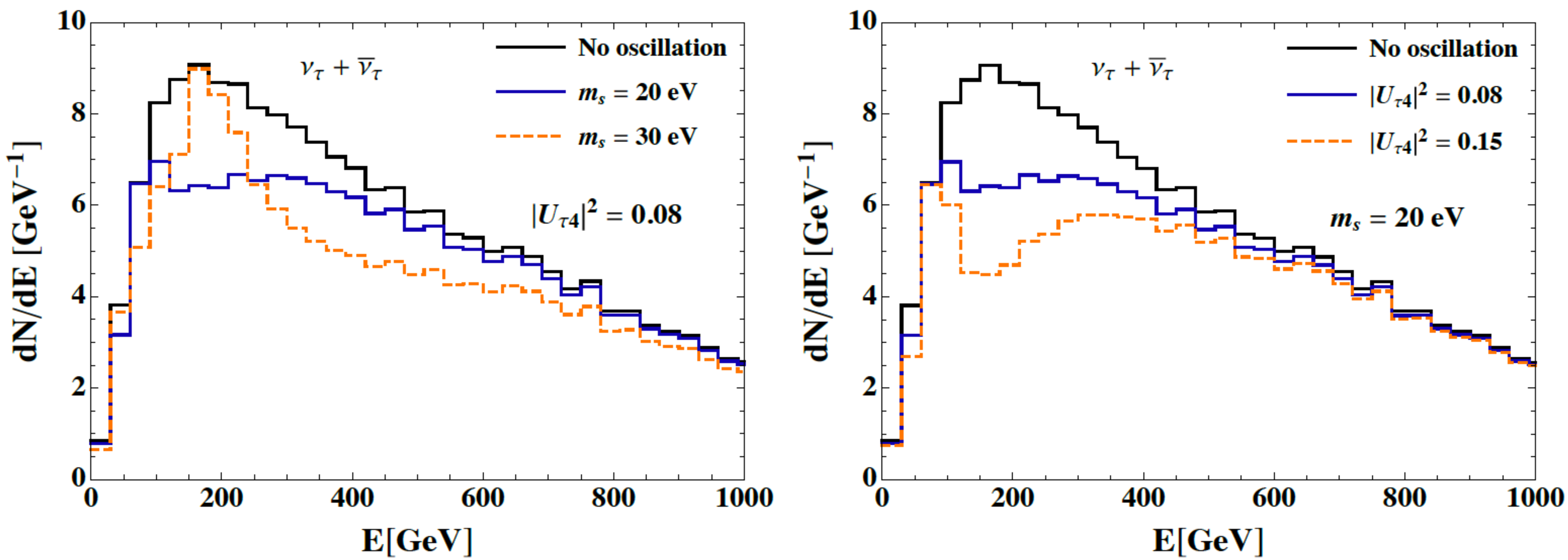


- Probability of appearance is much less than disappearance, but due to the large flux of muon/electron neutrinos it could affect the spectrum.

Event spectrum of ν_τ (disappearance)

- $\left.\frac{dN_{\nu_\tau}}{dE}\right|_{\mathrm{surv}} = \frac{dN_{\nu_\tau}}{dE} P(\nu_\tau \to \nu_\tau)$ (for only disappearance)

Preliminary



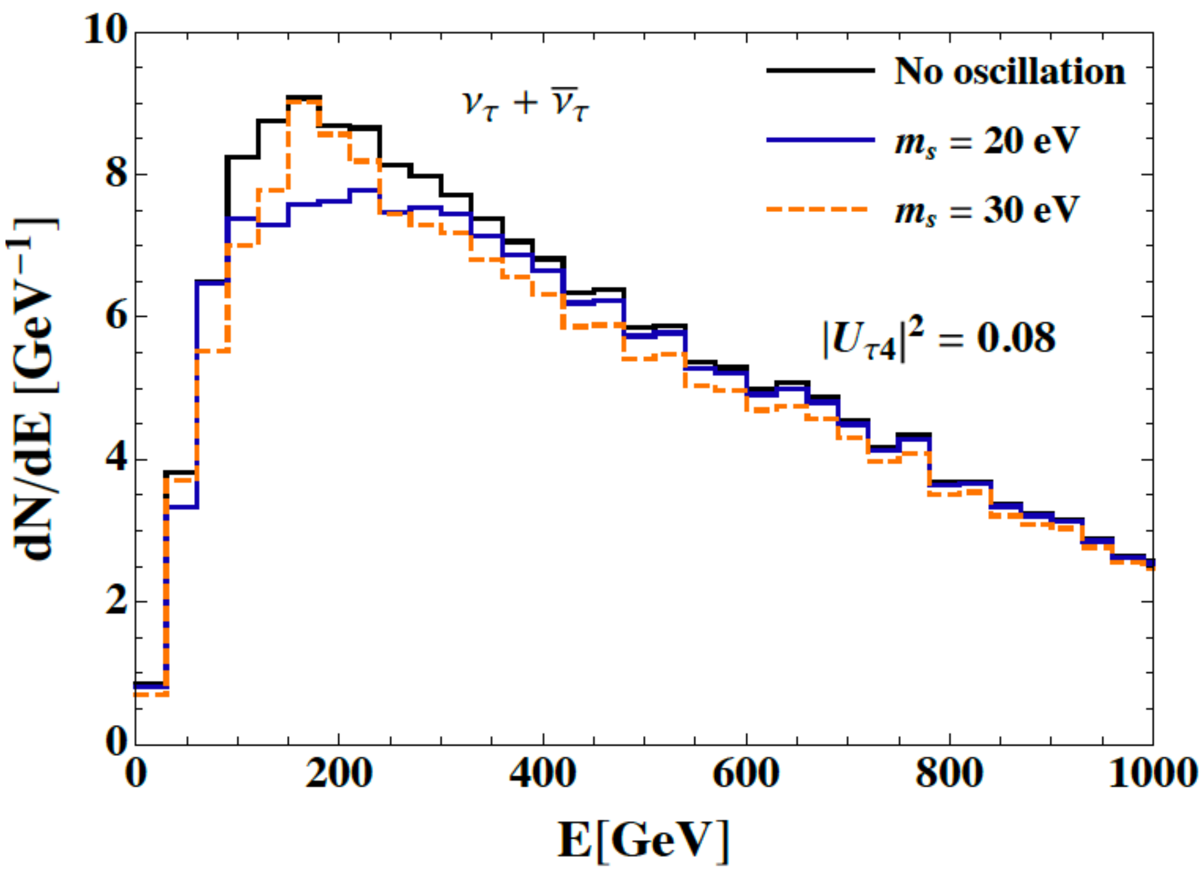
Representative parameter sets

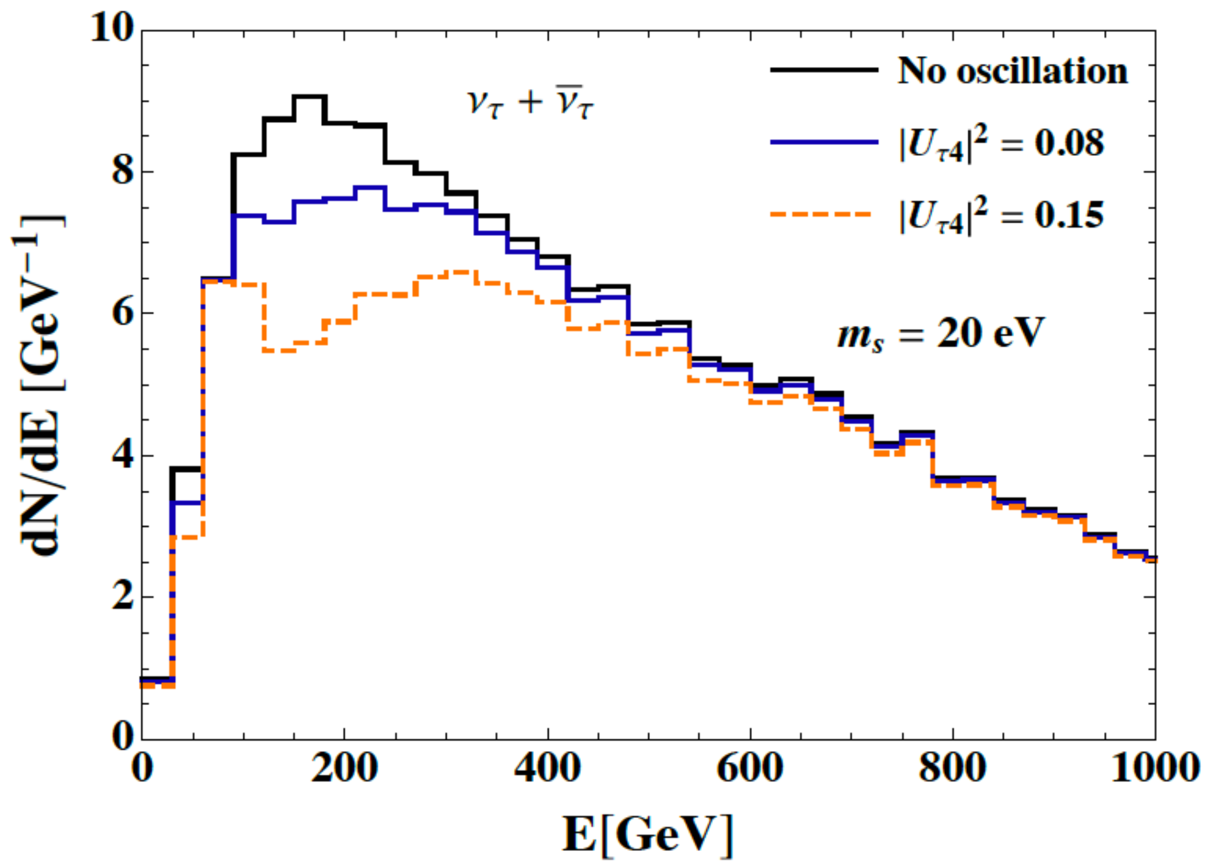
$$\Delta m^2 = 20\,\mathrm{eV}^2 \text{ and } 30\,\mathrm{eV}^2, \;\; |U_{\tau 4}|^2 = 0.08 \text{ and } 0.15$$

Event spectrum of ν_τ

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

Preliminary





- All neutrinos here are prompt neutrinos.

Representative parameter sets

$\Delta m^2 = 20\,\mathrm{eV}^2 \quad |U_{e4}|^2 = 0.04,\ |U_{\mu 4}|^2 = 10^{-3},\ |U_{\tau 4}|^2 = 0.08$

$\&\ 30\ \mathrm{eV}^2, \quad |U_{e4}|^2 = 0.02,\ |U_{\mu 4}|^2 = 5 \cdot 10^{-4},\ |U_{\tau 4}|^2 = 0.15$

Summary

- We have investigated tau neutrinos that could be measured at very forward detector, focusing on the 2nd stage of the FASER experiment with total luminosity $\mathscr{L}_{\rm int} = 3{,}000\ {\rm fb}^{-1}$.
- The expected tau neutrino events are about 7-8000 and their energy scale will be in O(100) GeV - O(1) TeV.
- The FASER will be an opportunity for the first detection of neutrino from a collider and the highest energy neutrinos from the laboratory accelerator experiments.
- With abundant tau neutrinos, their detection will contribute to the precise study of tau neutrino interaction including TeV scale and the heavy flavour production in the forward region.
- The FASER will also make it possible to explore the larger mass sterile neutrino ($\Delta m_s^2 > 100\ {\rm eV}^2$) than usually probed by oscillation experiments.