Prompt atmospheric tau neutrino flux

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Included some results from works with A. Bhattacharya, R. Enberg, C. S. Kim, M. H. Reno, I. Sarcevic, A. Stasto, W. Bai, M. Diwan, M. V. Garzelli and F. K. Kumar.

CHUNG-ANG UNIVERSITY
HIGH ENERGY PHYSICS

NuTau2021, September 28 — October 1, 2021

Outline

- Atmospheric neutrinos: conventional vs. prompt
- Essential ingredients as main factors for uncertainty
  - Incident cosmic ray spectrum
  - Heavy quark production cross sections
- Evaluation of the atmospheric neutrino flux
- Resulting fluxes of prompt atmospheric tau neutrinos
- Summary

Atmospheric neutrinos

- Atmospheric neutrinos are produced from the cosmic ray interaction with the nuclei in the Earth's atmosphere.

$$CR(p) + Air \rightarrow \underline{h \text{ (hadrons)}} + X \quad \text{(interaction)}$$

$$\hookrightarrow \nu_a + X' \quad (a = e, \mu, \tau) \quad \text{(decay)}$$

- Conventional neutrinos are from the light hadron decays.
  - $h = \pi^{\pm},\ K^{\pm},\ K_L \ldots$

- Prompt neutrinos are from the heavy flavor hadron decays.
  - $h = D^0(\bar{D}^0),\ D^{\pm},\ D_s^{\pm}, B^{\pm} \ldots$

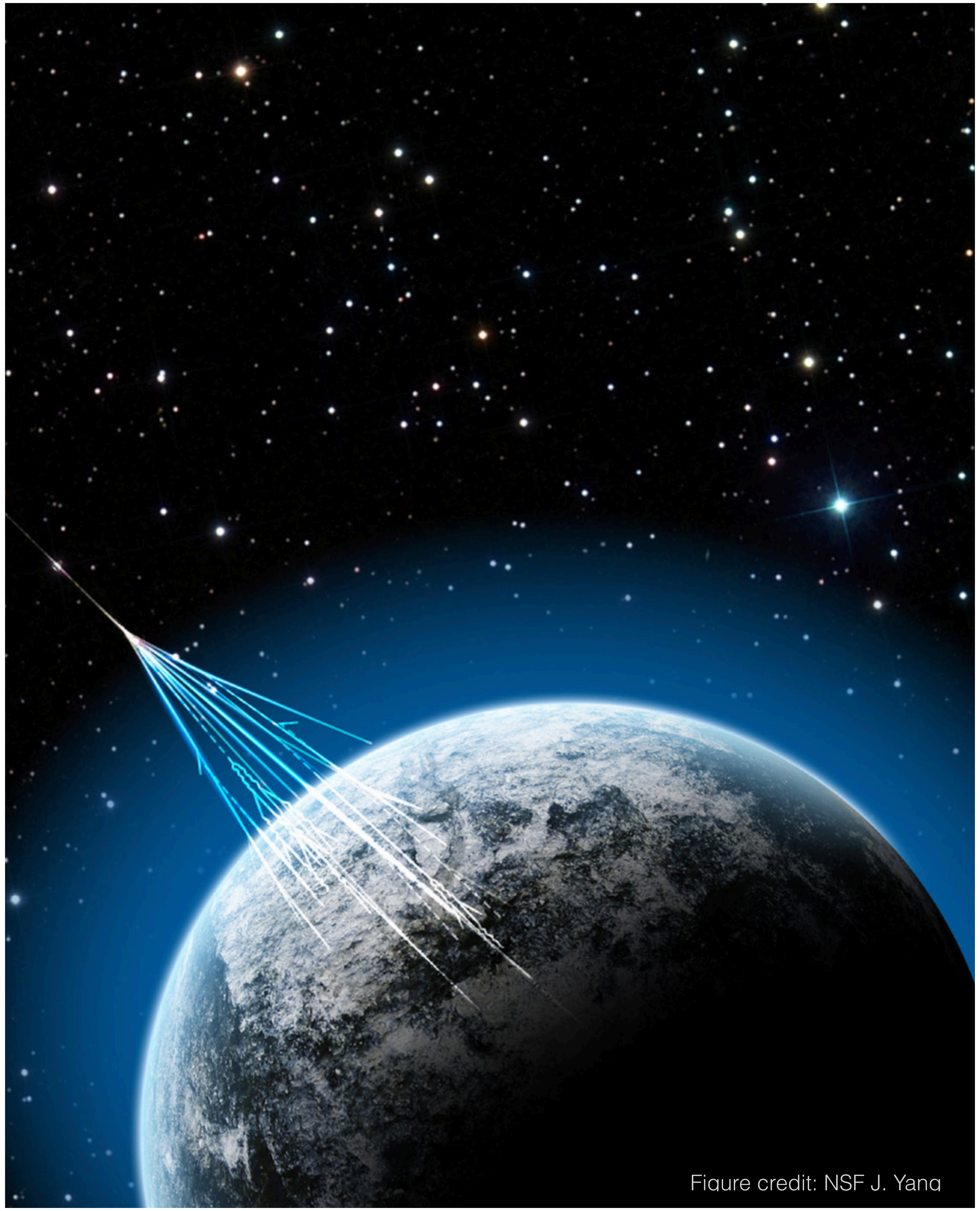
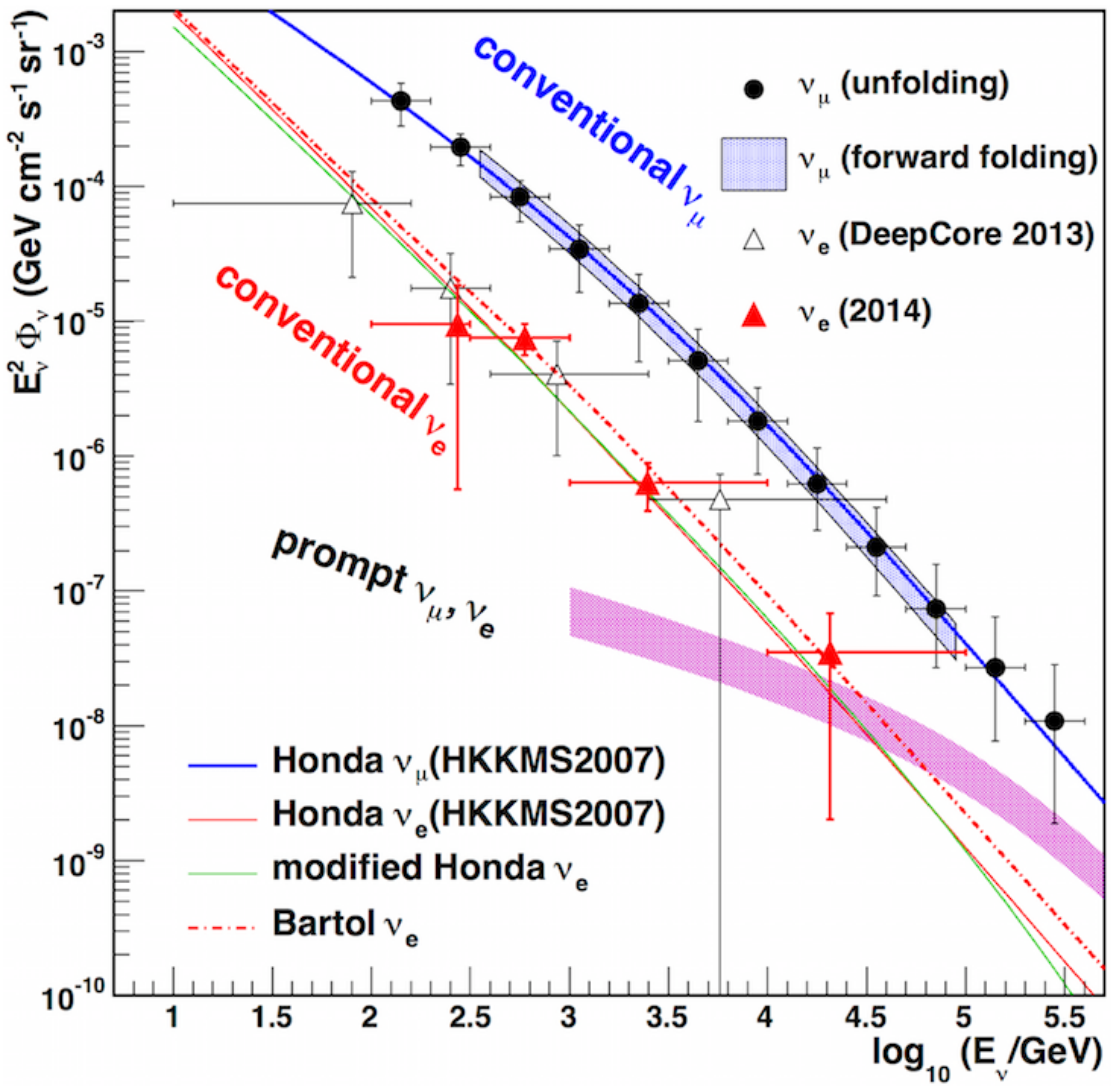


Figure credit: NSF J. Yang

Conventional vs. Prompt neutrino flux

Conventional	Prompt
$c\tau_{\pi^\pm} \simeq 7.8\,m,\ \ c\tau_{K^\pm} \simeq 3.7\,m,\ \ c\tau_{K_L} \simeq 15.3\,m$ Hadrons can lose energy due to interaction.	$c\tau_{D^\pm} \simeq 312\,\mu m,\ \ c\tau_{D^0} \simeq 123\,\mu m,\ \ c\tau_{D_s^\pm} \simeq 151\,\mu m$ Hadrons decay immediately after being produced, before interaction occurs.
The flux of conventional neutrinos: - rapidly decreases with energy - are well predicted	The flux of prompt neutrinos: - less depends on energy - has large uncertainty.
Flavor ratio $\nu_e : \nu_\mu \neq 1:1\ (\nu_\mu > \nu_e)$	$\nu_e : \nu_\mu = 1:1$
$\pi^{(\pm)} \rightarrow \mu + \nu_\mu$ $K^{(\pm)} \rightarrow \mu + \nu_\mu$ $K_L \rightarrow \pi + l + \nu_l \quad (l = e,\ \mu)$ …	$D^0 \rightarrow l + \nu_l + X \qquad (l = e,\ \mu)$ $D^\pm \rightarrow l + \nu_l + X$ $D_s \rightarrow e + \nu_e + X$ $\rightarrow \tau + \nu_\tau$ B, Λ_c …



Tau neutrinos from natural sources

Astrophysical tau neutrinos

Talks by T. DeYoung and D. Willams

- Astrophysical neutrinos are from the cosmic ray interaction and astrophysical phenomena in the space.
- Tau neutrinos are rarely produced, and the flavor ratio at production is $\nu_e : \nu_\mu : \nu_\tau \simeq 1 : 2 : 0.$
- An expected flavor ratio is $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$ due to oscillation over astronomical distance.

Atmospheric tau neutrinos

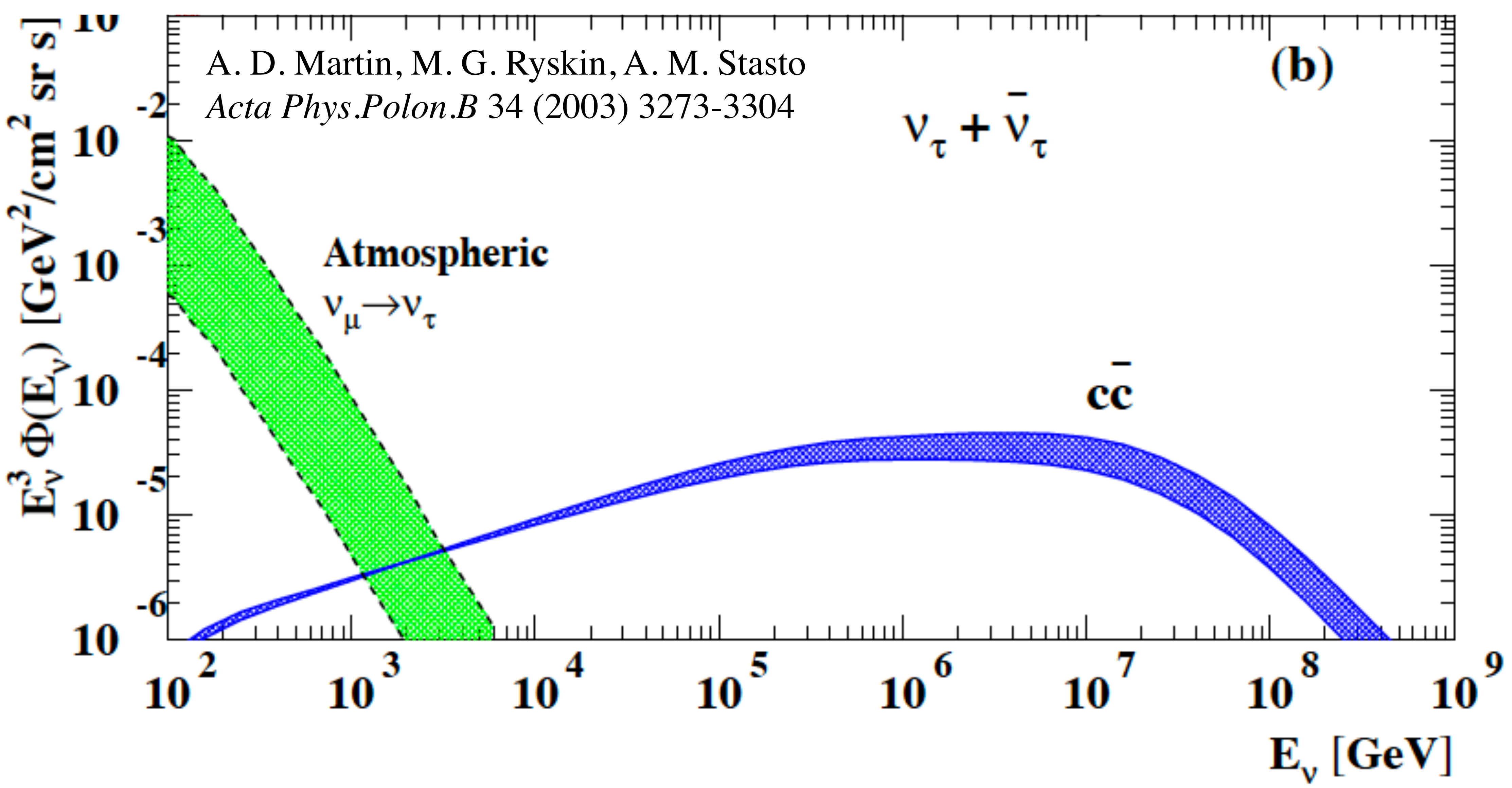
- Conventional component

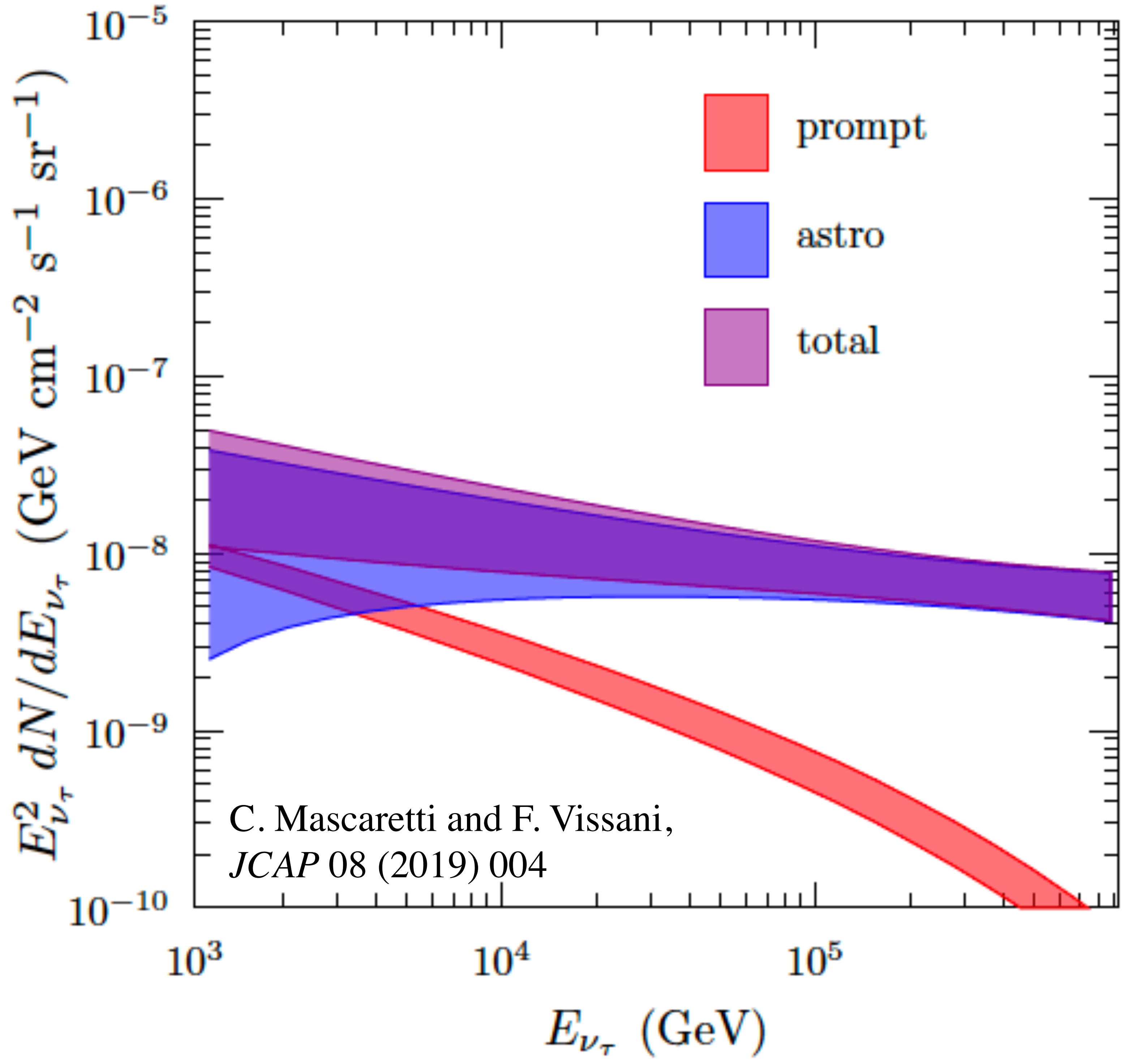
  Talks by T. DeYoung and more on Wednesday morning

  - comes from oscillation of conventional muon neutrinos.
  - The transition from ν_μ to ν_τ from is dominant channel of the atmospheric neutrino oscillation.
- Prompt component
  - directly produced from heavy flavor hadrons (e.g. $D_s \rightarrow \tau + \nu_\tau$, $\tau \rightarrow \nu_\tau + X$)
  - The flux is about an order of magnitude less than the flux of other flavor prompt neutrinos.

Why *prompt* atmospheric tau neutrinos?

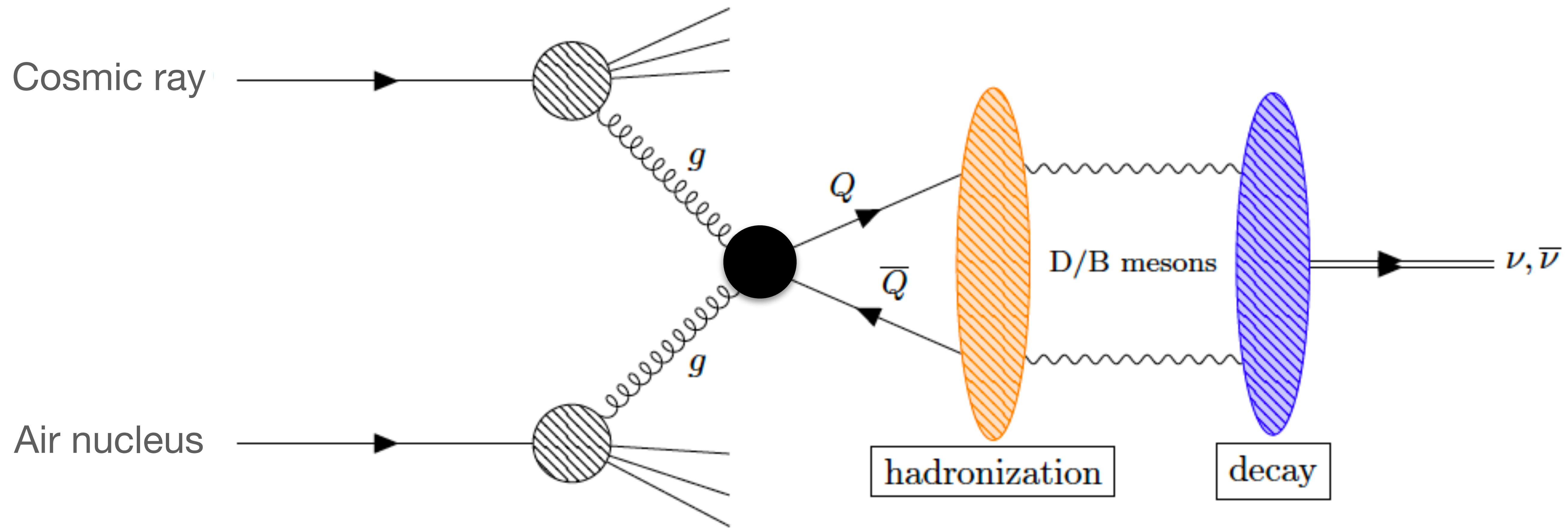
- Interaction study at the TeV energy range that has not been accessible by human-made experiments.
- Background to conventional tau neutrinos from $\nu_\mu \to \nu_\tau$.
- Background to astrophysical neutrinos at $\mathcal{O}(1) \sim \mathcal{O}(10)$ TeV.
  - There is almost no impact as background to astrophysical tau neutrinos for $E_{\nu_\tau} \gtrsim 10^5$ GeV.





Ingredients for evaluation of prompt neutrino fluxes

- Incident cosmic ray flux
- Heavy quark production cross section in pA collision
- Fragmentation functions of heavy quark to hadrons
- Decay rate and distribution
- Atmosphere density, particle propagation in the atmosphere …

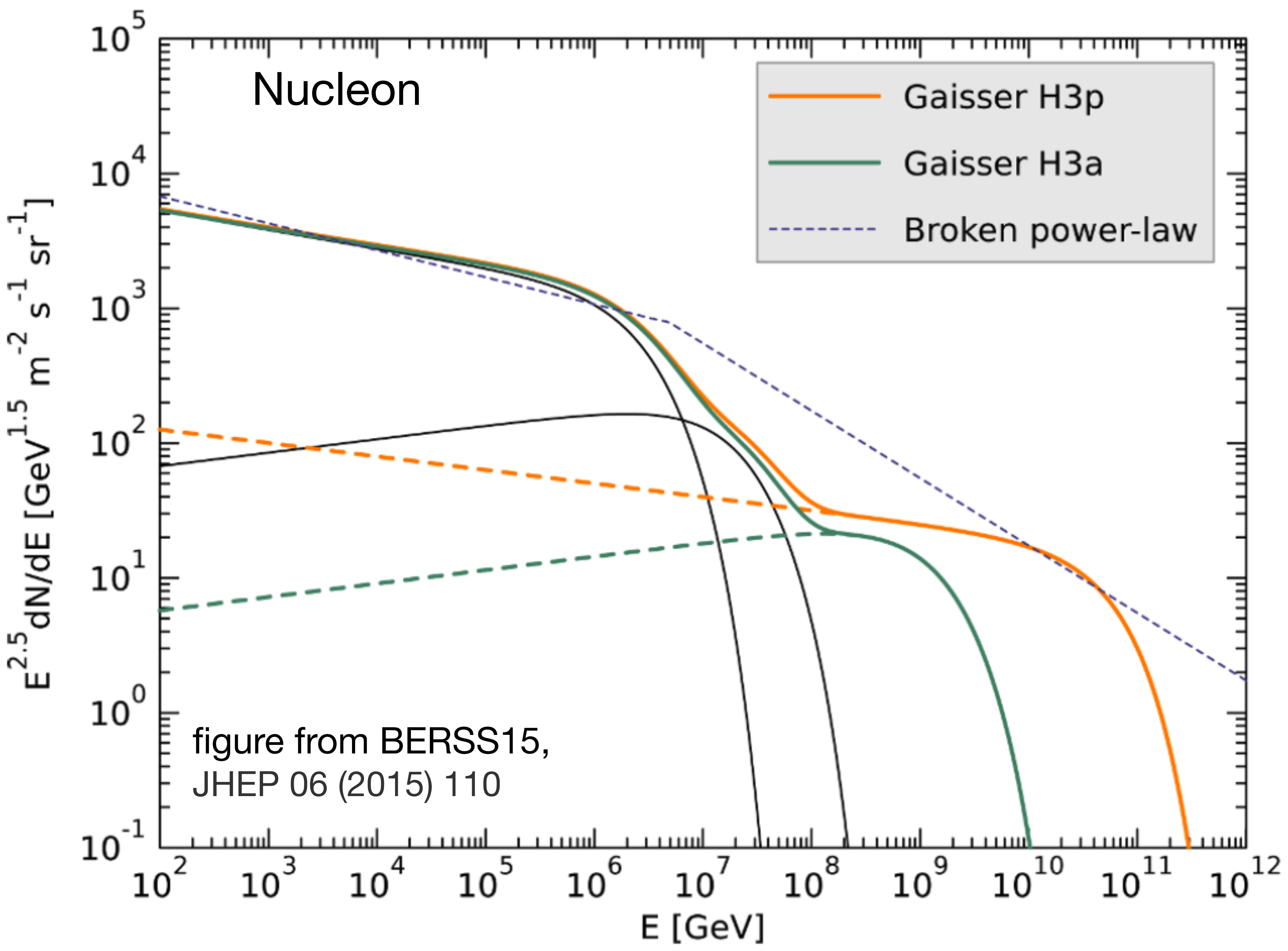


Cosmic ray spectrum

- **Broken Power Law:** all CR particles are protons.

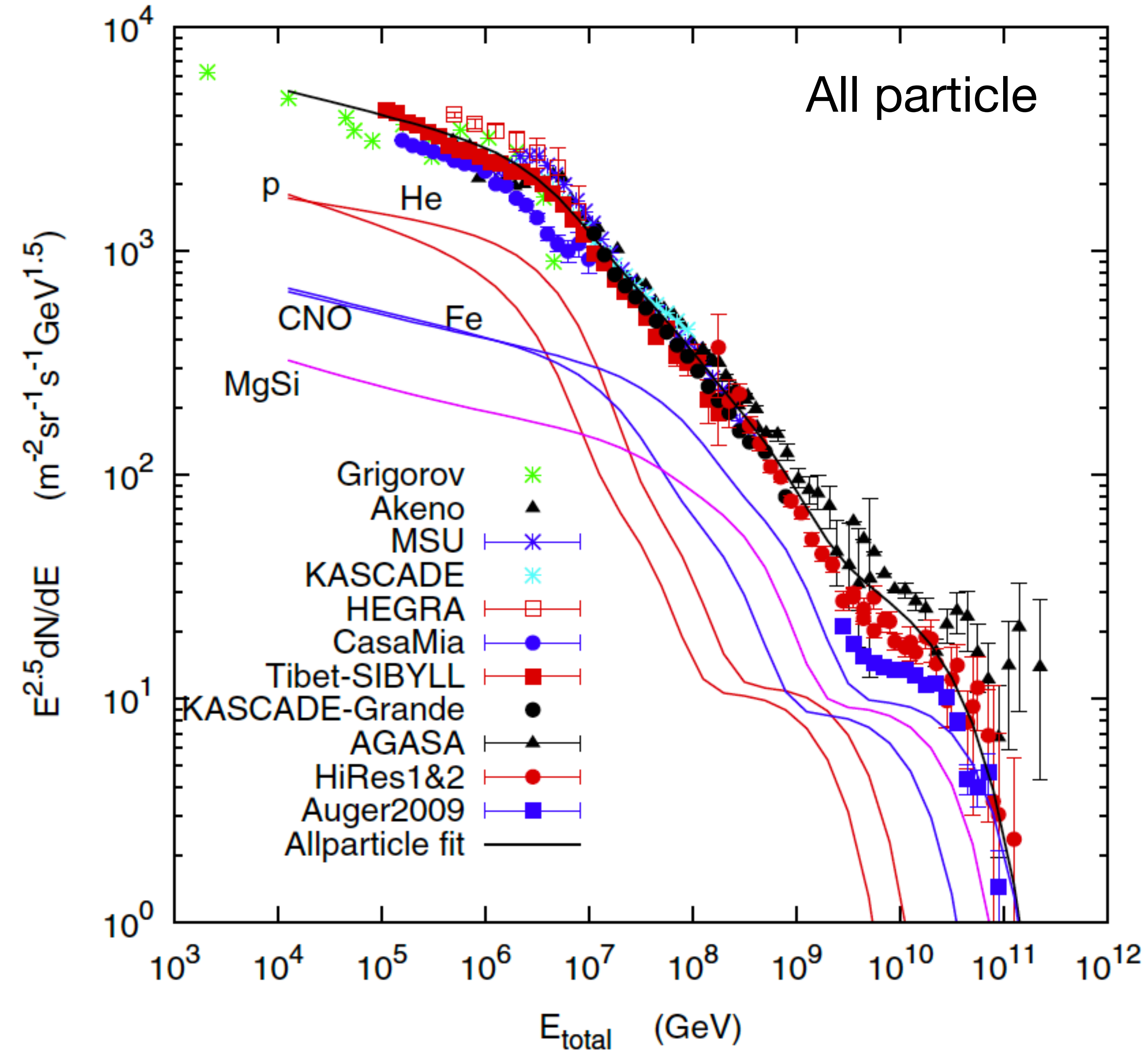
$$\phi_N(E) = \begin{cases} 1.7E^{-2.7} & \text{for } E < 5\cdot 10^6 \text{ GeV} \\ 174E^{-3} & \text{for } E > 5\cdot 10^6 \text{ GeV} \end{cases}$$

- H3p - all protons in extragalactic population.
- H3a - mixed composition in extra galactic population.



- Parameterizations by Gaisser
  - source populations: SN remnants, other galactic and extra galactic sources
  - multi nuclear species

T. K. Gaisser,
Astropart. phys. 35 (2012) 801



Cross sections for heavy flavor production

- Perturbative QCD with collinear approximation
  - The cross section is given by convolution of the hard cross section and parton distribution functions (PDF).

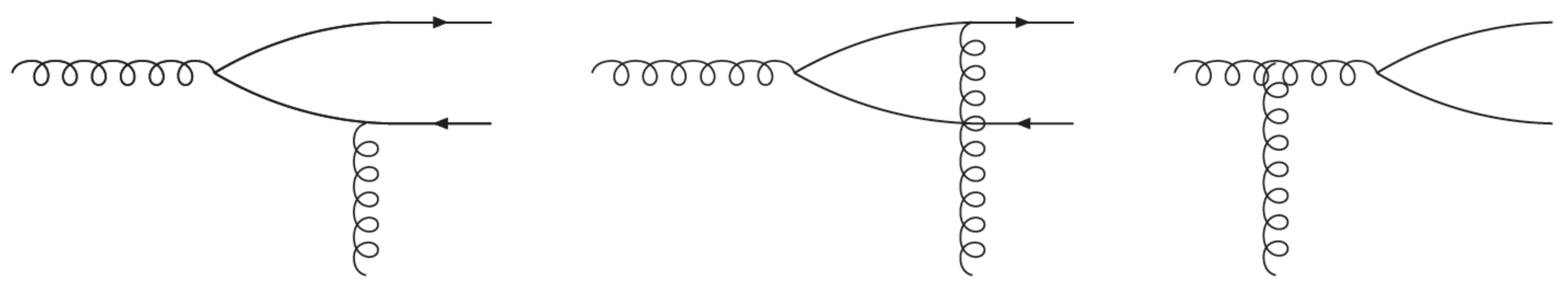
$$\sigma(pp \to q\bar{q}X) = \sum_{i,j=q,\bar{q},g} \int dx_1 dx_2 f_i(x_1, \mu_F^2)\, f_j(x_2, \mu_F^2)\, \hat{\sigma}_{ij\to q\bar{q}}(\hat{s}, \mu_F^2, \mu_R^2, \dots)$$

  - Need the PDFs at small-x region, where not constrained by the experimental data.

- Dipole model

$$\sigma(pp \to q\bar{q}X) \simeq \int dy\, x_1 g(x_1, M_F) \sigma^{gp\to q\bar{q}X}(x_2, M_R, Q^2)$$

$$\sigma^{gp\to q\bar{q}X}(x, M_R, Q^2) = \int dz\, d^2\vec{r}\, |\Psi_g^q(z, \vec{r}, M_R, Q^2)|^2 \sigma_d(x, \vec{r})$$



$|\Psi_g^q|^2$: Gluon fluctuation into the quark-antiquark pair (color dipole)

σ_d : Interaction of the color-dipole with the target particle (dipole cross section)

Cross sections for heavy flavor production

- k_T factorization (or hybrid formalism)

$$\sigma(pp \to q\bar{q}X) = \int \frac{dx_1}{x_1}\frac{dx_2}{x_2}\, dz\, dx_F\, \delta(zx_1 - x_F)\, x_1 g(x_1, M_F) \quad \longleftarrow \text{collinear approximation for the incoming parton from cosmic rays}$$

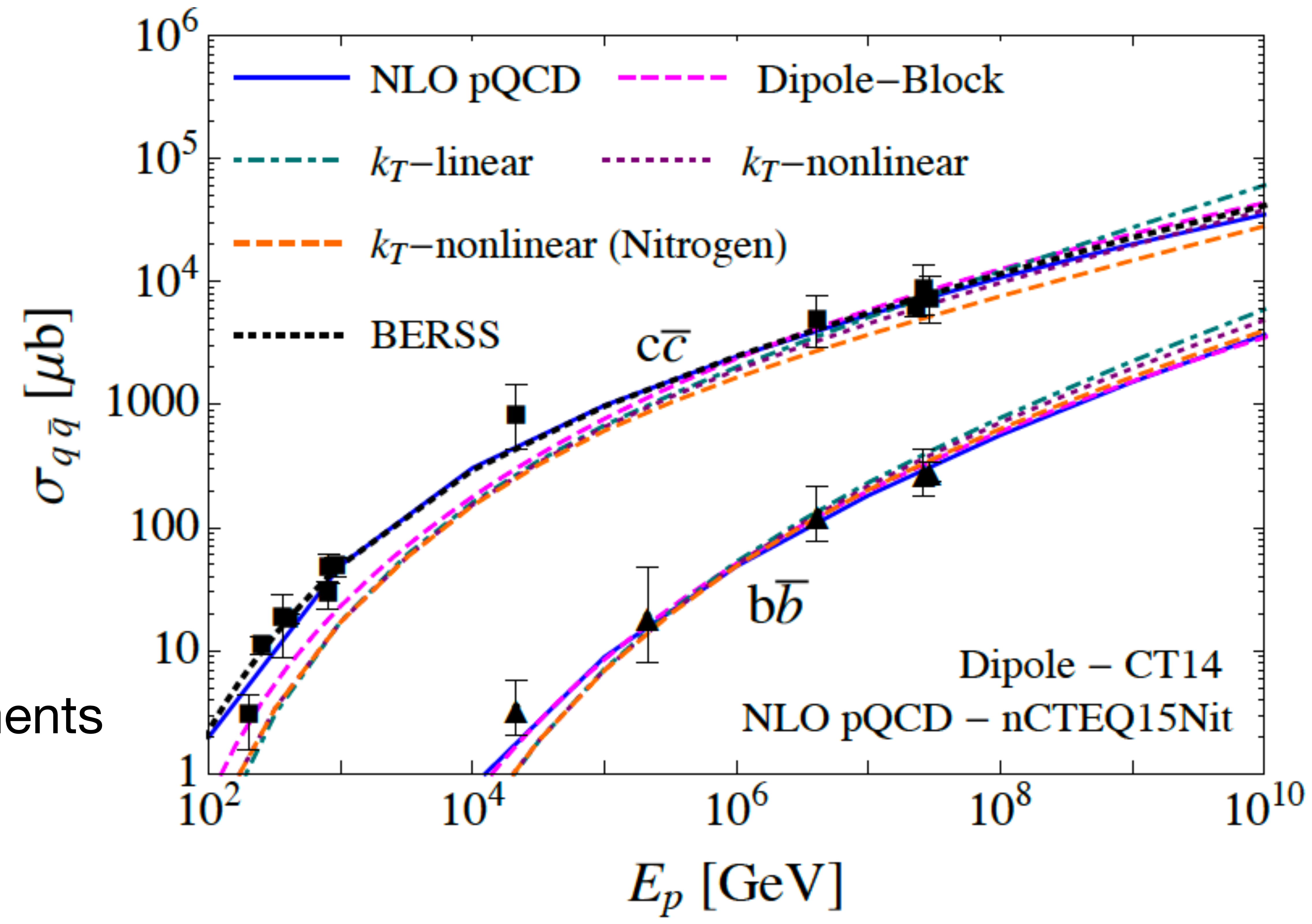
$$\times \int \frac{dk_T^2}{k_T^2} \hat{\sigma}^{\rm off}(z, \hat{s}, k_T)\, f(x_2, k_T^2) \quad \longleftarrow k_T \text{ factorization for the small-}x\text{ parton from target nucleus}$$

- The small x resummation is incorporated in the unintegrated PDF.

❖ Part of references

- Dipole model
  - G. Soyez, Phys. Lett. B 655 (2007) 32, “Saturation QCD predictions with heavy quarks at HERA”
  - M. M. Block, L. Durand and P. Ha, Phys. Rev. D 89 (2014) 094027
  - J.L. Albacete, N. Armesto, J.G. Milhano, P. Quiroga-Arias and C.A. Salgado, AAMQS: Eur. Phys. J. C 71 (2011) 1705
- k_T factorization
  - S. Catani, M. Ciafaloni and F. Hautmann, Nucl. Phys. B 366 (1991) 135
  - J.C. Collins and R.K. Ellis, Nucl. Phys. B 360 (1991) 3

Total cross sections for heavy flavor production

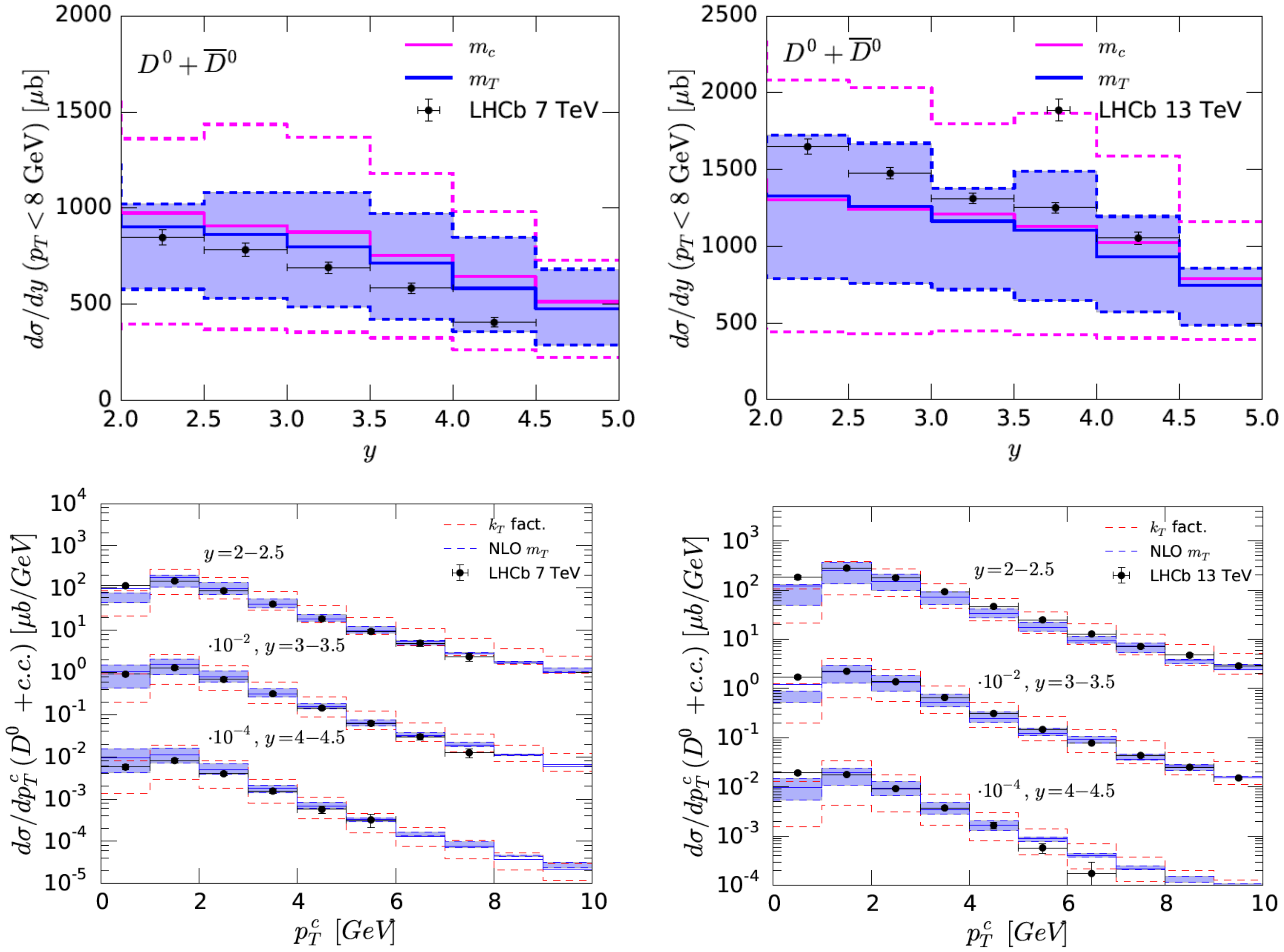


- Low energy data
  - Fixed target experiments
- High energy data
  - RHIC (STAR, PHENIX)
  - LHC (ALICE, ATLAS, LHCb)

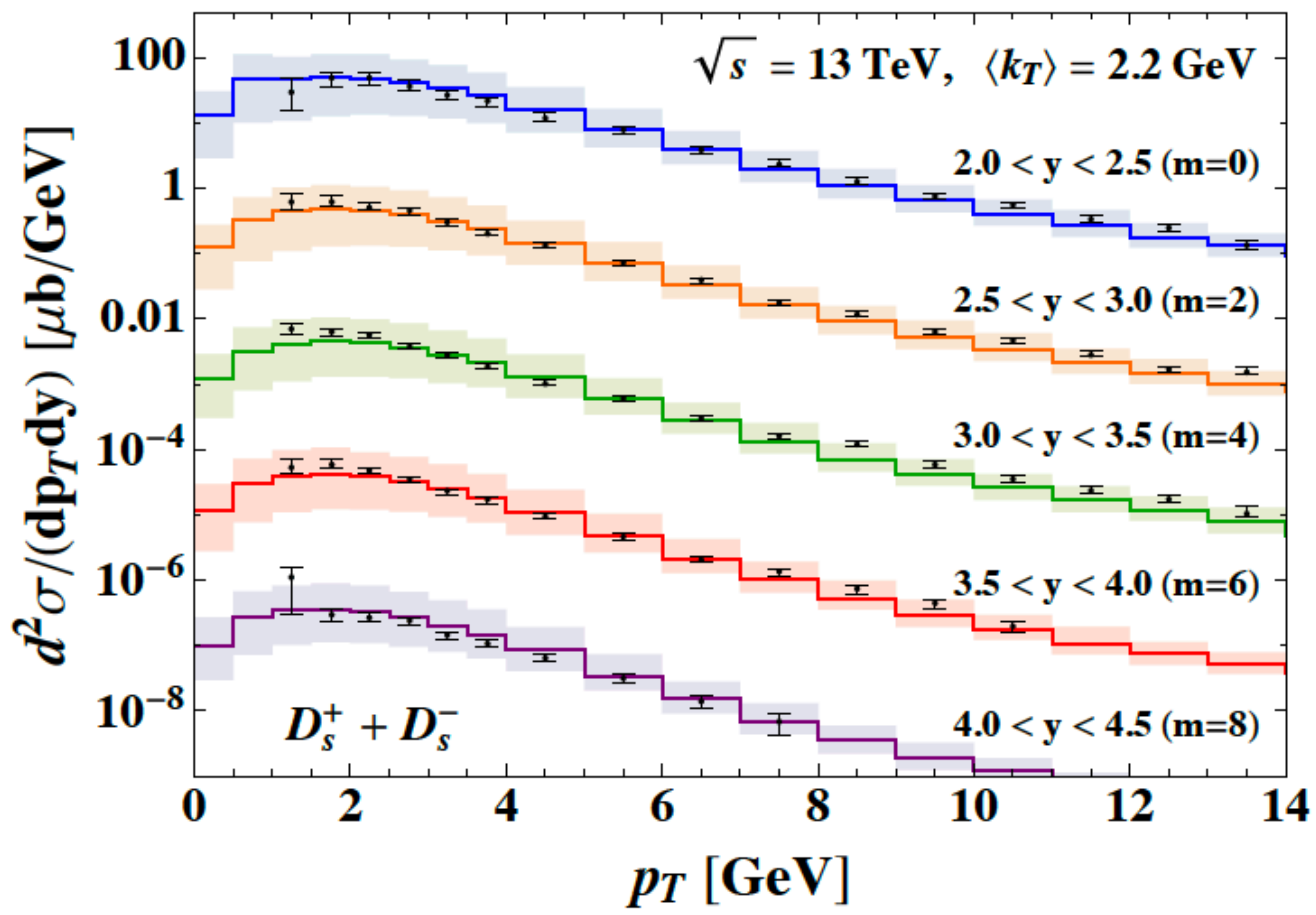
A. Bhattacharya, R. Enberg, YSJ, C. S. Kim, M. H. Reno, I. Sarcevic, A. Stasto (BEJKRSS), JHEP11 (2016) 167

- The total cross sections from all models are well matched with the experimental data at high energy range.

Comparison with LHCb data (NLO pQCD)



A. Bhattacharya, R. Enberg, YSJ, C. S. Kim, M. H. Reno, I. Sarcevic, A. Stasto (BEJKRSS), JHEP11 (2016) 167



YSJ, W. Bai, M. Diwan, M. V. Garzelli, M. H. Reno, JHEP 06 (2020) 032

How to evaluate the atmospheric neutrino flux

Cascade equation and Z-moment method

- Cascade equations describe the propagation of high energy particles in the atmosphere.

$$\frac{d\phi_j(E,X)}{dX} = -\frac{\phi_j(E,X)}{\lambda_j(E)} - \frac{\phi_j(E,X)}{\lambda_j^{\mathrm{dec}}(E)} + \sum S(k \to j)$$

$$X(\ell,\theta) = \int_\ell^\infty d\ell' \rho(h(\ell',\theta))$$

$$\rho = \rho_0 \exp(-h/h_0)$$

$$h_0 = 6.4\,\mathrm{km} \quad \rho_0 h_0 = 1300\,\mathrm{g/cm^2}$$

- Z-moments for production/decay of the particle:

$$Z_{kj}(E) = \frac{\lambda_k(E)}{\phi_k(E,X)} S(k \to j) \simeq \int_E^\infty dE' \frac{\phi_k(E')}{\phi_k(E)} \frac{\lambda_k(E)}{\lambda_k(E')} \frac{dn(k \to j; E', E)}{dE}$$

with an approximation $\phi_k(E,X) \simeq \phi_k(E)\, f(X)$

- Z-moment depends only on the energy.

$$\frac{1}{\sigma_{kA}(E')} \frac{d\sigma(kA \to jY; E', E)}{dE} \quad \text{(interaction)}$$

$$\frac{1}{\Gamma_k(E')} \frac{d\Gamma(k \to jY; E', E)}{dE} \quad \text{(decay)}$$

How to evaluate the atmospheric neutrino flux

- Approximate solutions according to the energy range:

$$\phi_{h\to\nu}^{\rm low}(E) = \sum_h \frac{Z_{Nh}Z_{h\nu}}{1-Z_{NN}}\phi_N^0(E) \quad (E \ll \epsilon_h)$$

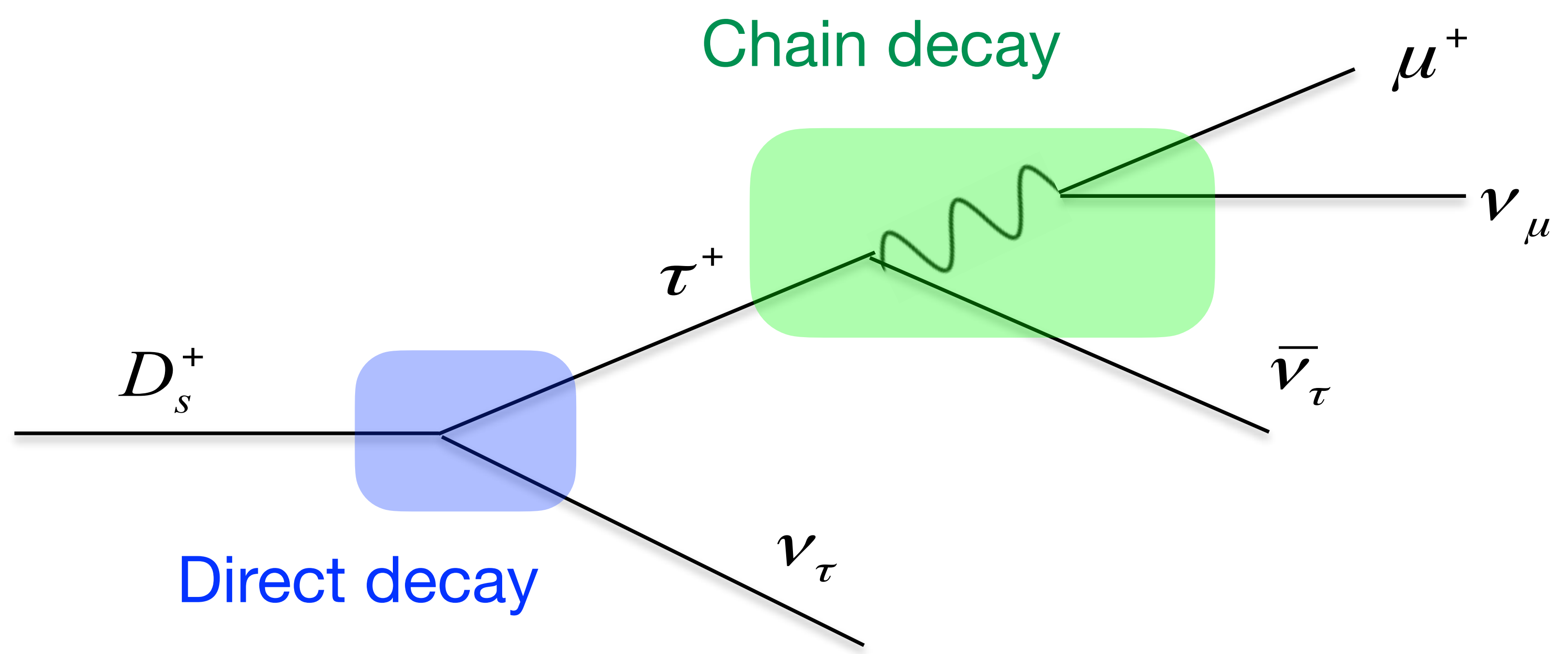
$$\phi_{h\to\nu}^{\rm high}(E) = \sum_h \frac{Z_{Nh}Z_{h\nu}}{1-Z_{NN}}\frac{\ln(\Lambda_h/\Lambda_N)}{1-\Lambda_N/\Lambda_h}\frac{\epsilon_h}{E}\phi_N^0(E) \quad (E \gg \epsilon_h)$$

$$\Longrightarrow \quad \boxed{\phi_\nu(E) = \sum_h \frac{\phi_{h\to\nu}^{\rm low}\,\phi_{h\to\nu}^{\rm high}}{(\phi_{h\to\nu}^{\rm low} + \phi_{h\to\nu}^{\rm high})}}$$

- ϵ_h: the critical energy at which $\lambda_h^{\rm int} = \lambda_h^{\rm dec}$.
- $\Lambda_k = \lambda_k/(1-Z_{kk})$
- ϕ_N^0 : incident cosmic ray spectrum

❋ Neutrino flux can be obtained by interpolating the two solutions.

The flux of tau neutrinos from D_s meson

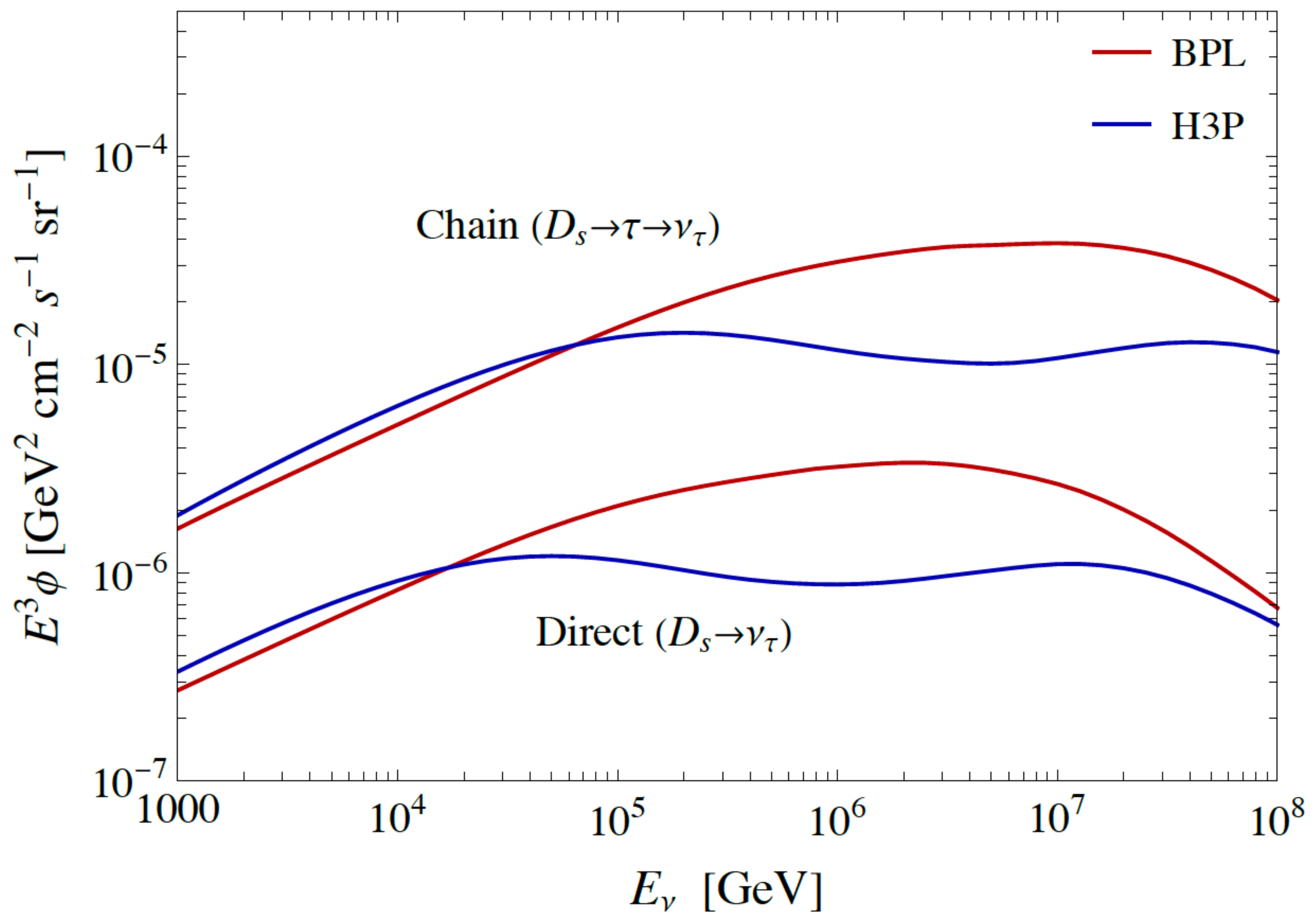


- Main process of prompt tau neutrino production is the D_s meson decays.
  - Direct decay: $\mathrm{Br}\,(D_s \to \tau + \nu_\tau) \sim 5.5\,\%$
  - Chain decay: $\mathrm{Br}\,(\tau \to \nu_\tau\, e\, \nu_e) \sim 17.8\,\%\,,\ \mathrm{Br}\,(\tau \to \nu_\tau\, \mu\, \nu_\mu) \sim 17.4\,\%\,,$ $\mathrm{Br}\,(\tau \to \nu_\tau\, \pi) \sim 10.8\,\%\ \ldots$

- Z-decay moments for ν_τ from D_s meson:

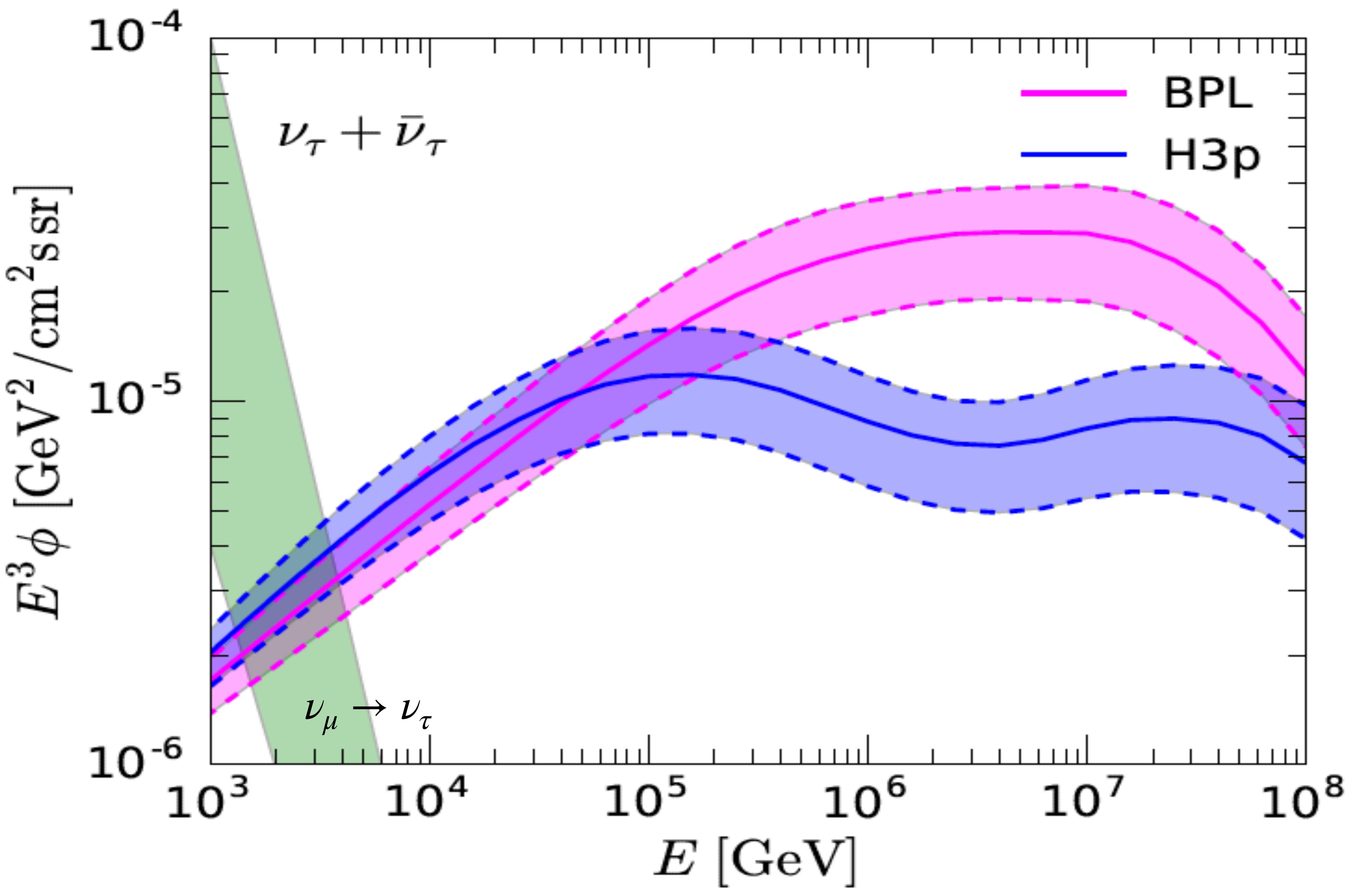
$$Z^{(direct)}_{D_s\nu_\tau}(E) = \int_E^\infty dE_D \frac{\phi_D(E_D)}{\phi_D(E)} \frac{E}{E_D} \frac{dn_{D_s\to\nu_\tau}}{dE}(E_D, E)$$

$$Z^{(chain)}_{D_s\nu_\tau}(E) = \int_E^\infty dE_D \int_E^{E_D} dE_\tau \frac{\phi_D(E_D)}{\phi_D(E)} \frac{E}{E_D} \frac{dn_{D_s\to\tau}}{dE_\tau}(E_D, E_\tau) \frac{dn_{\tau\to\nu_\tau}}{dE}(E_\tau, E)$$



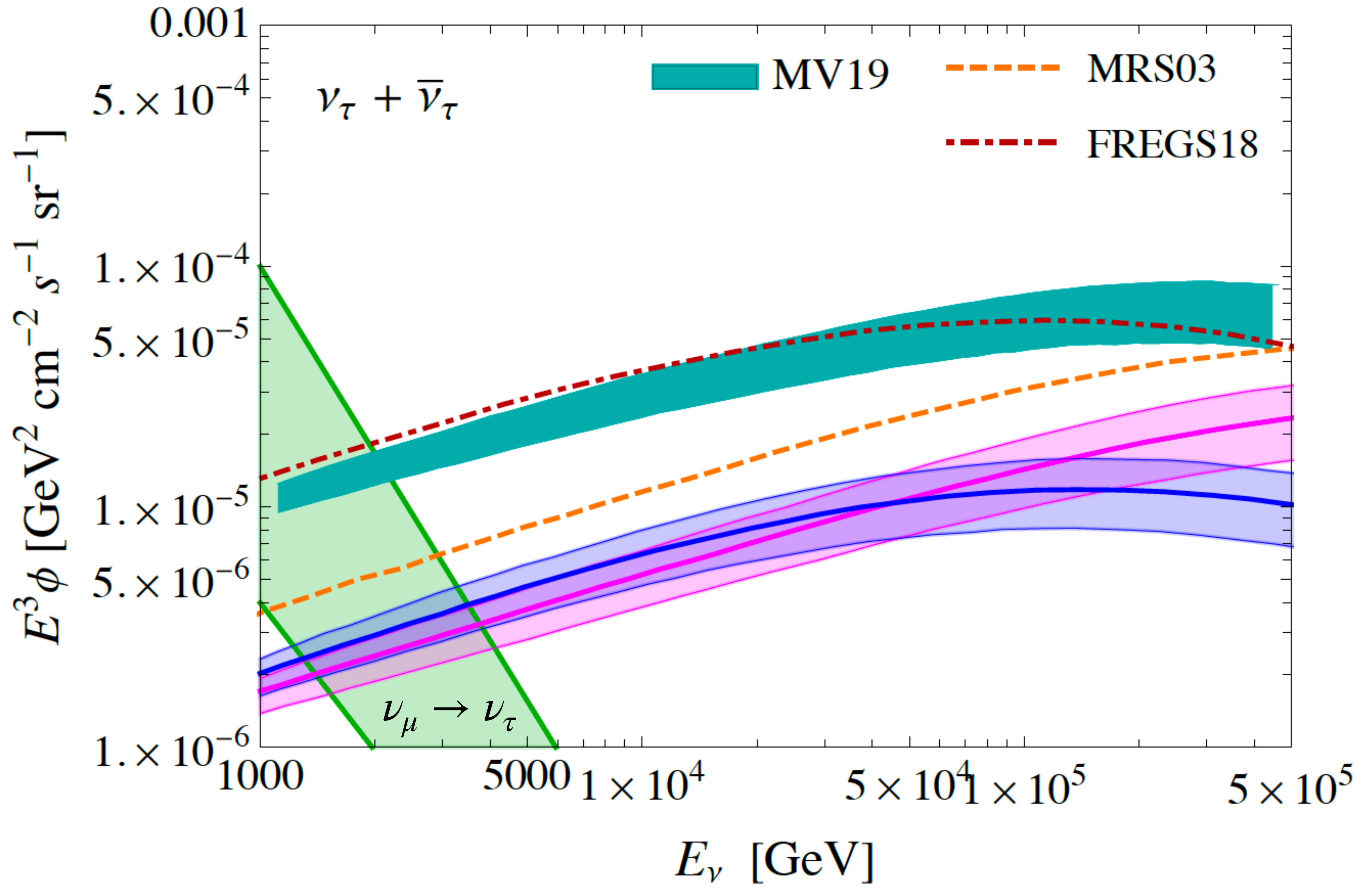
Prompt atmospheric tau neutrino flux ($\nu_\tau + \bar{\nu}_\tau$)

A. Bhattacharya, R. Enberg, YSJ, C. S. Kim, M. H. Reno, I. Sarcevic, A. Stasto (BEJKRSS), JHEP11 (2016) 167



- The cosmic ray spectrum impact on the shape of the fluxes for $E \gtrsim 100\,\mathrm{TeV}$.
- The shaded band is from the QCD scale variations.
- Different frameworks for heavy quark production yield difference by a factor of 3~6 at TeV energies.
- The prompt neutrino flux for tau neutrinos is about 10 % of that for muon neutrinos.

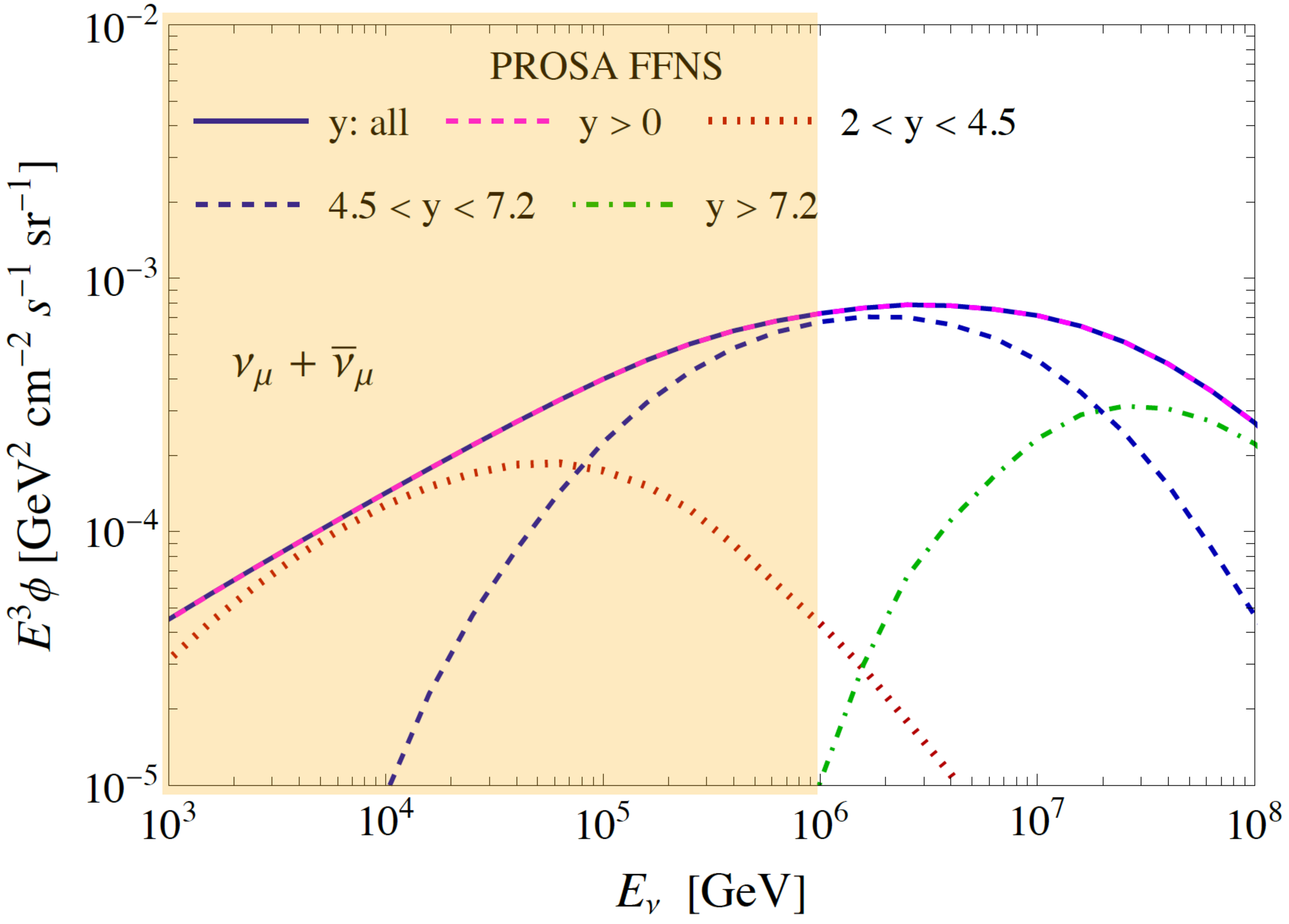
Prompt atmospheric tau neutrino flux $(\nu_\tau + \bar{\nu}_\tau)$



- BEJKRSS
  - NLO pQCD with nuclear correction
  - BPL & H3p for CR spectrum
- MRS03: Martin, Ryskin, Stasto, Acta Phys. Pol. B 34, 3273 (2003)
  - Dipole model with BPL
- FREGS18: Fedynitch et. al., PRD 100 103018 (2019)
  - MCEQ with SIBYLL-2.3c with H3a
- MV19: Mascaretti and Vissani, *JCAP* 08 (2019) 004
  - MCEQ with SIBYLL-2.3c
  - Different cosmic ray spectrum and model of atmosphere from other evaluations above. (See also 1906.05197)

✷ MCEQ (Matrix Cascade EQuation): Numerical method to solve coupled cascade equation
https://github.com/afedynitch/MCEq

Forward experiments at the LHC



YSJ, W. Bai, M. Diwan, M. V. Garzelli, F. K. Kumar, M. H. Reno,
PoS (ICRC2021) 1218 and work in progress

- The prompt atmospheric neutrinos below $E_\nu \lesssim 1\,\mathrm{PeV}$ are from the hadrons produced in the rapidity range $y < 7.2$.
- The LHCb experiment has the measurement data for the rapidity range of $2 < y < 4.5$.
- Two upcoming forward experiments at the LHC during the Run 3 (2022-2024) will probe more forward region.
  - SND@LHC ($7.2 < y < 8.6$)
  - FASERν ($y \gtrsim 8.9$)

talks by F. Kling and A. De Roeck
Also see talk by M. V. Garzelli for tau neutrino predictions

- If future experiments cover the rapidity range between the LHCb and new forward experiments, it will be useful for better prediction for prompt atmospheric tau neutrinos.

Summary

- The prompt atmospheric tau neutrinos are only directly produced neutrinos from the natural sources.
- The prompt atmospheric tau neutrinos can be important for the study of interaction and oscillation with atmospheric and possibly astrophysical neutrinos at TeV energy range.
- Theoretical uncertainty for the flux of prompt neutrinos are large and depends on many factors. Most prominent uncertainty for tau neutrinos is from the heavy quark production cross sections by QCD.
- For more precise predictions,
  - need to better understand the pA interaction, e.g) QCD, nuclear effect, fragmentation …
  - need more data at more forward region.
- Future potential forward experiments can help to improve theoretical prediction on the prompt atmospheric tau neutrino flux.

Thank you for your attention