Forward production of prompt neutrinos in the atmosphere and at high energy colliders

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(arXiv: 2212.07865)

CHUNG-ANG UNIVERSITY
HIGH ENERGY PHYSICS

CERN Neutrino Platform Pheno Week

Mar. 13-17, 2023

Atmospheric neutrinos

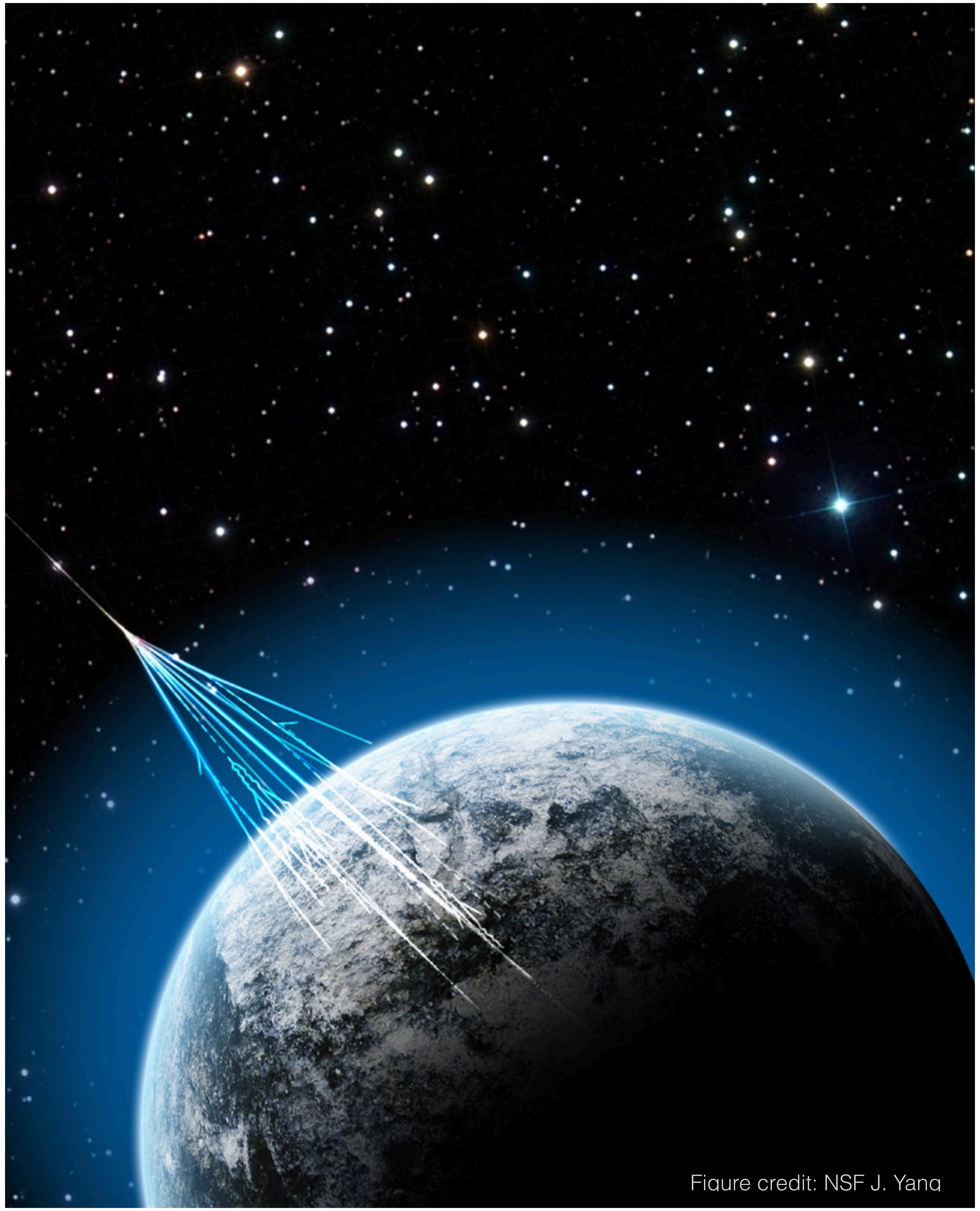
- Neutrinos are produced from high energy hadron collisions.
  - e.g. atmospheric neutrinos

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

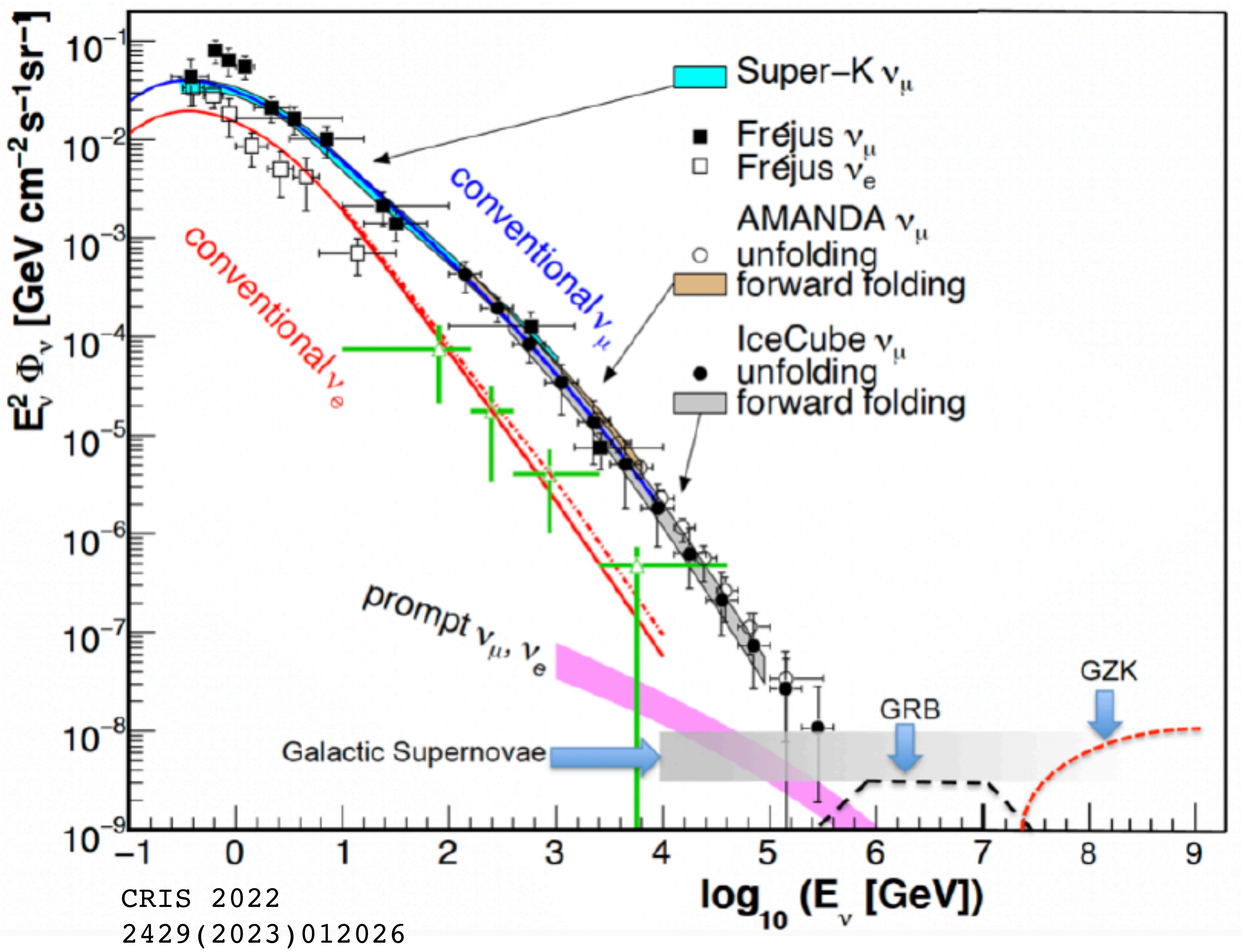
$$\hookrightarrow \nu_a + X' \quad (a = e, \mu, \tau) \quad \text{(decay)}$$

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

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



Conventional vs. Prompt neutrino flux



CRIS 2022
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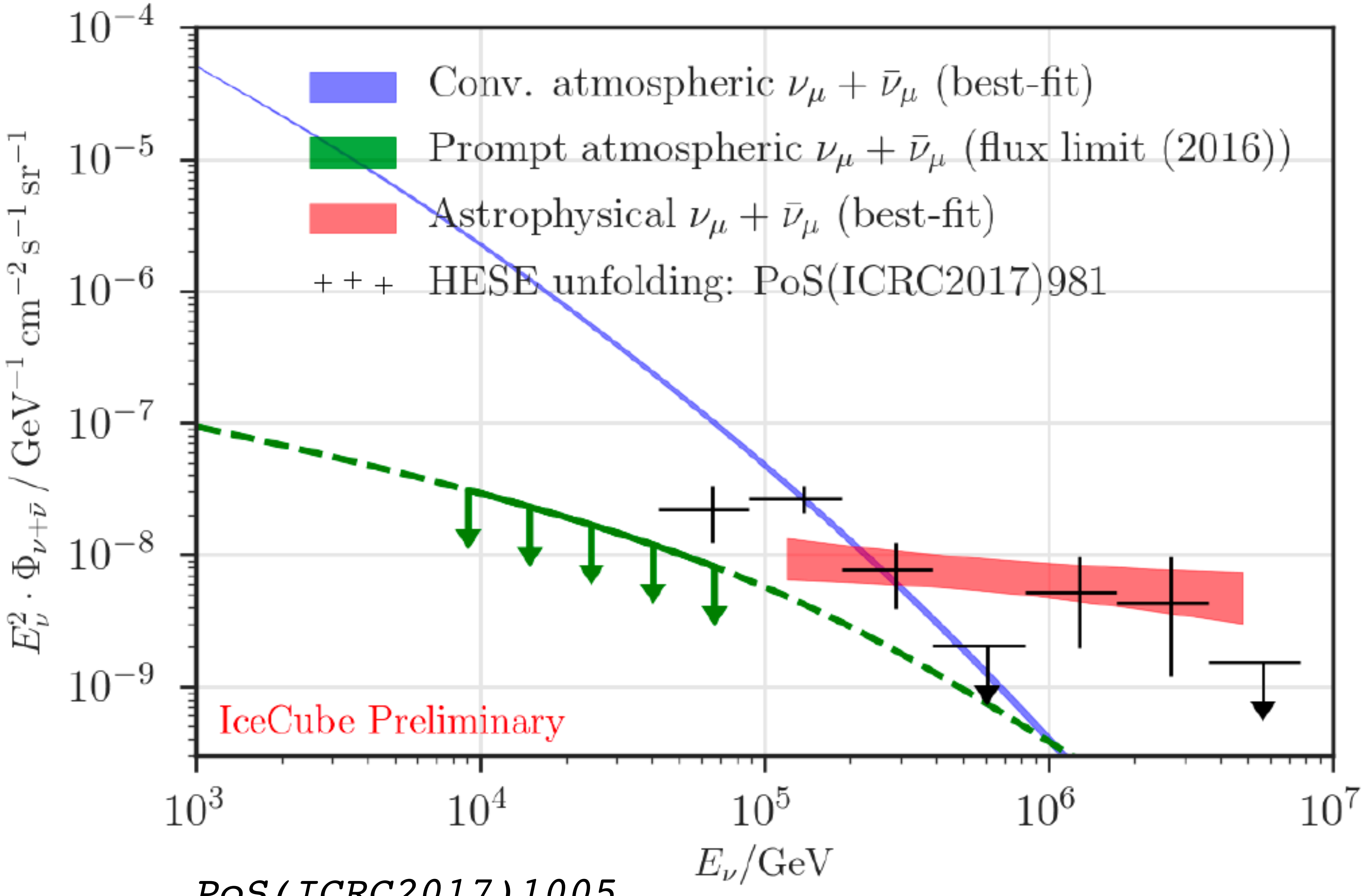
- **Conventional neutrinos**
  - The decay length of pion and kaons is O(1) m ➔ lose energy through interaction.
  - The flux is dominant at low energies, but falls steeply as energy increases.
- **Prompt neutrinos**
  - The decay lengths of charm hadrons: O(10^2) μm
  - Flux less depends on energy.
  - Dominate at very high energy range.

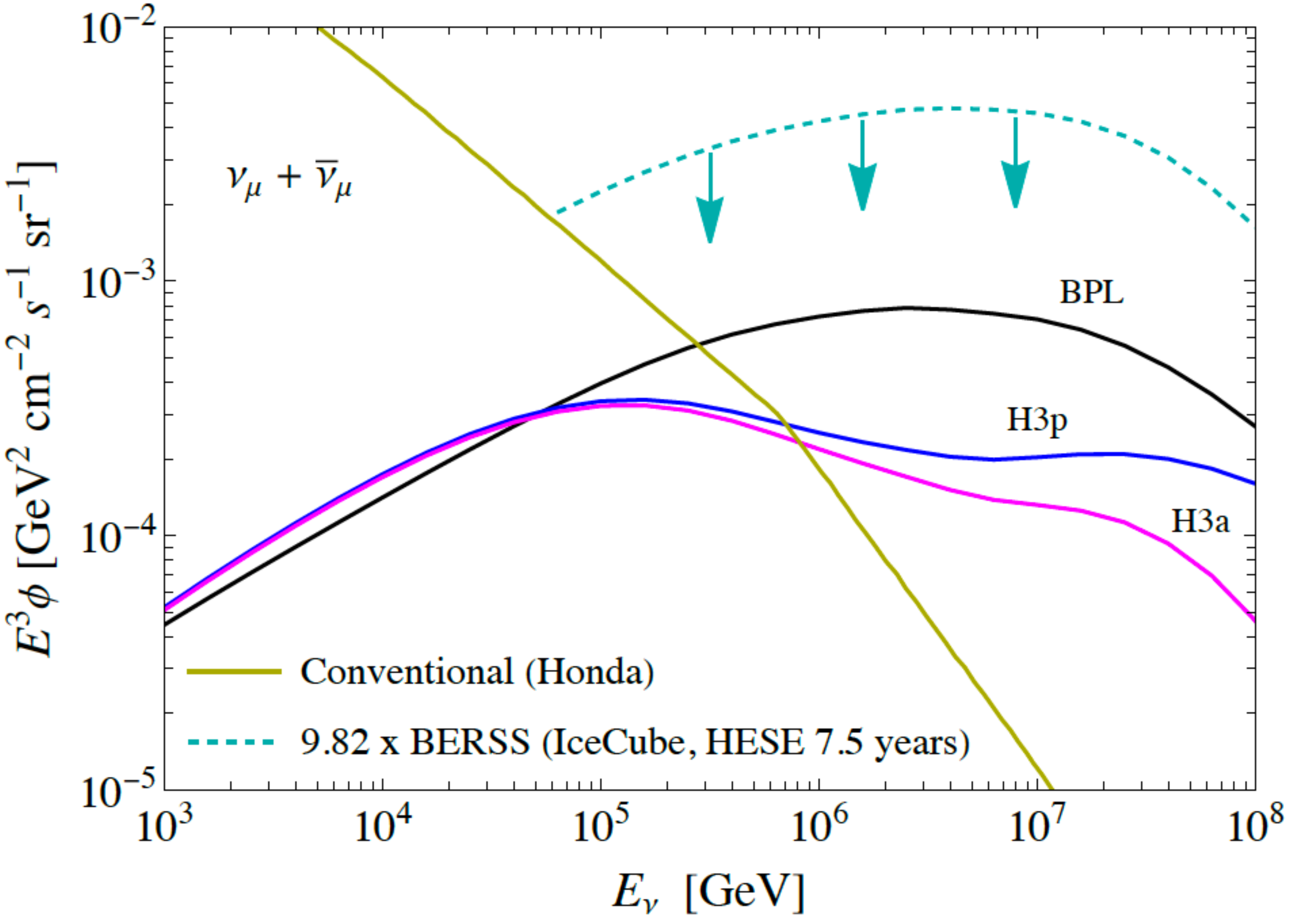
Why prompt atmospheric neutrinos?



PoS(ICRC2017)1005

- Expected crossover energy:
  $100 \text{ TeV} \lesssim E_\nu \lesssim 1 \text{ PeV}$
- Background to astrophysical neutrinos

Main inputs — cosmic ray spectrum



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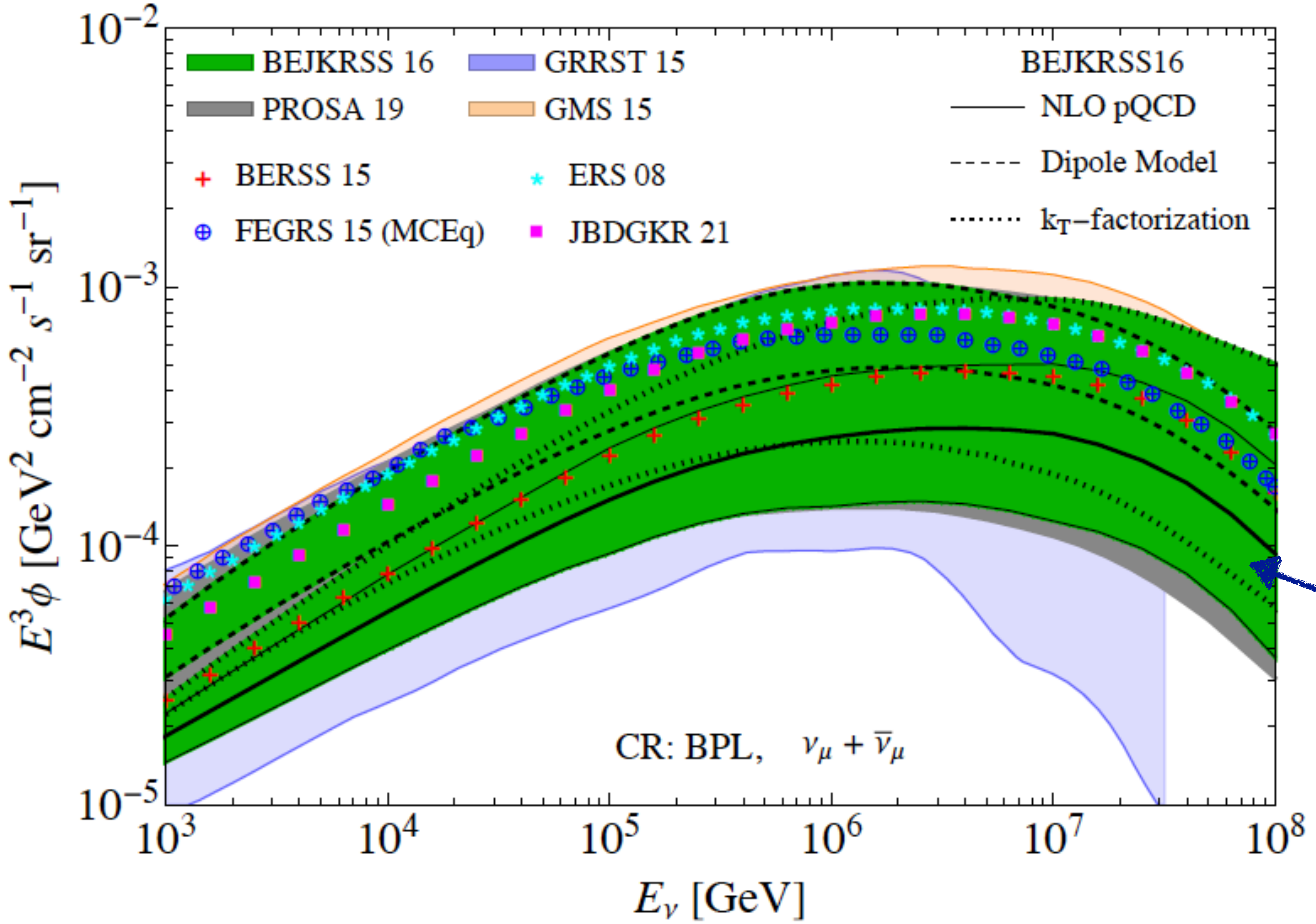
- BPL (Broken Power Law)

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

- Parameterizations by Gaisser
  (Astropart. phys. 35 (2012) 801)
  - Multi nuclear species, three different origins
  - H3p: All protons in extragalactic origin
  - H3a: mixed composition in extragalactic origin

Main inputs — heavy flavor hadron production



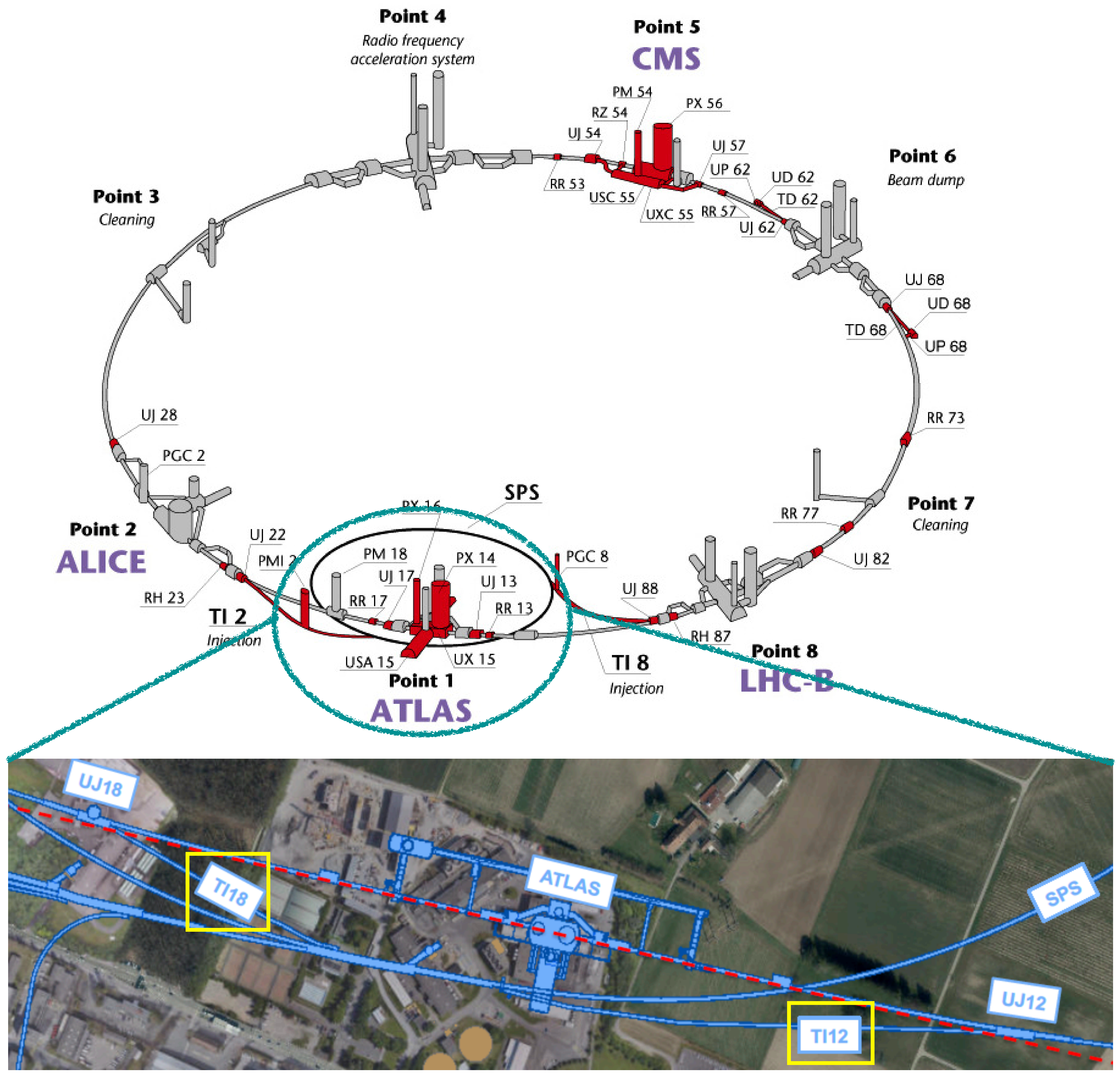
- Predictions with BPL CR spectrum
- Uncertainty is mostly related to heavy flavor hadron production.

BEJKRSS16 (JHEP11 (2016) 167) :

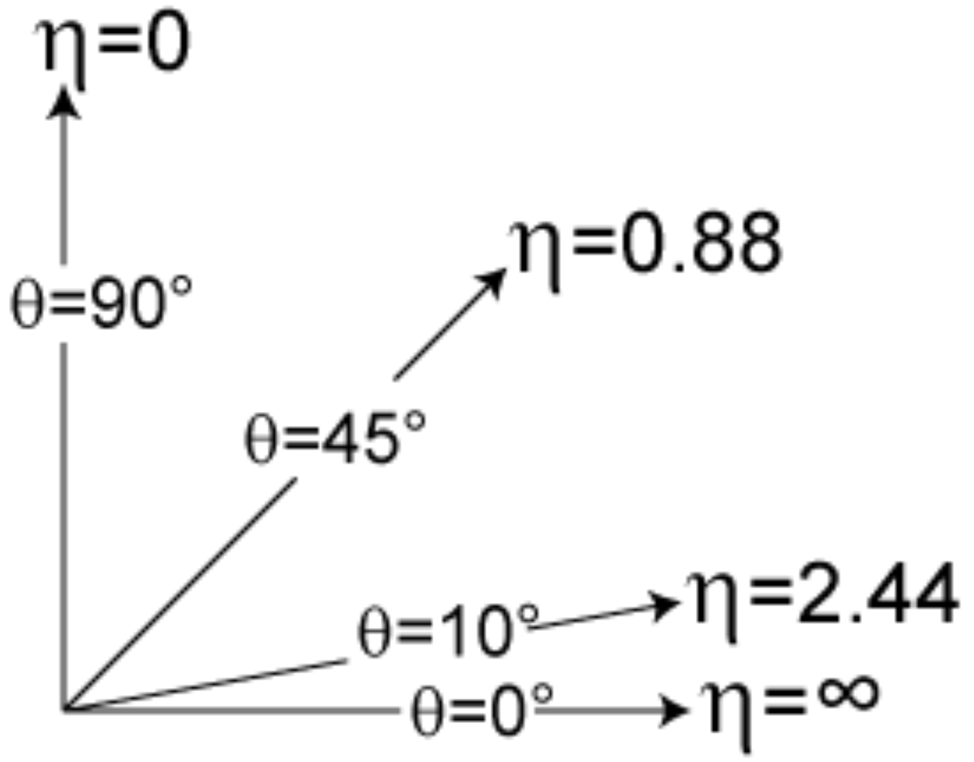
includes the different models for heavy quark production.

Figure from the FPF white paper, arXiv: 2203.05090

Forward experiments during the Run 3

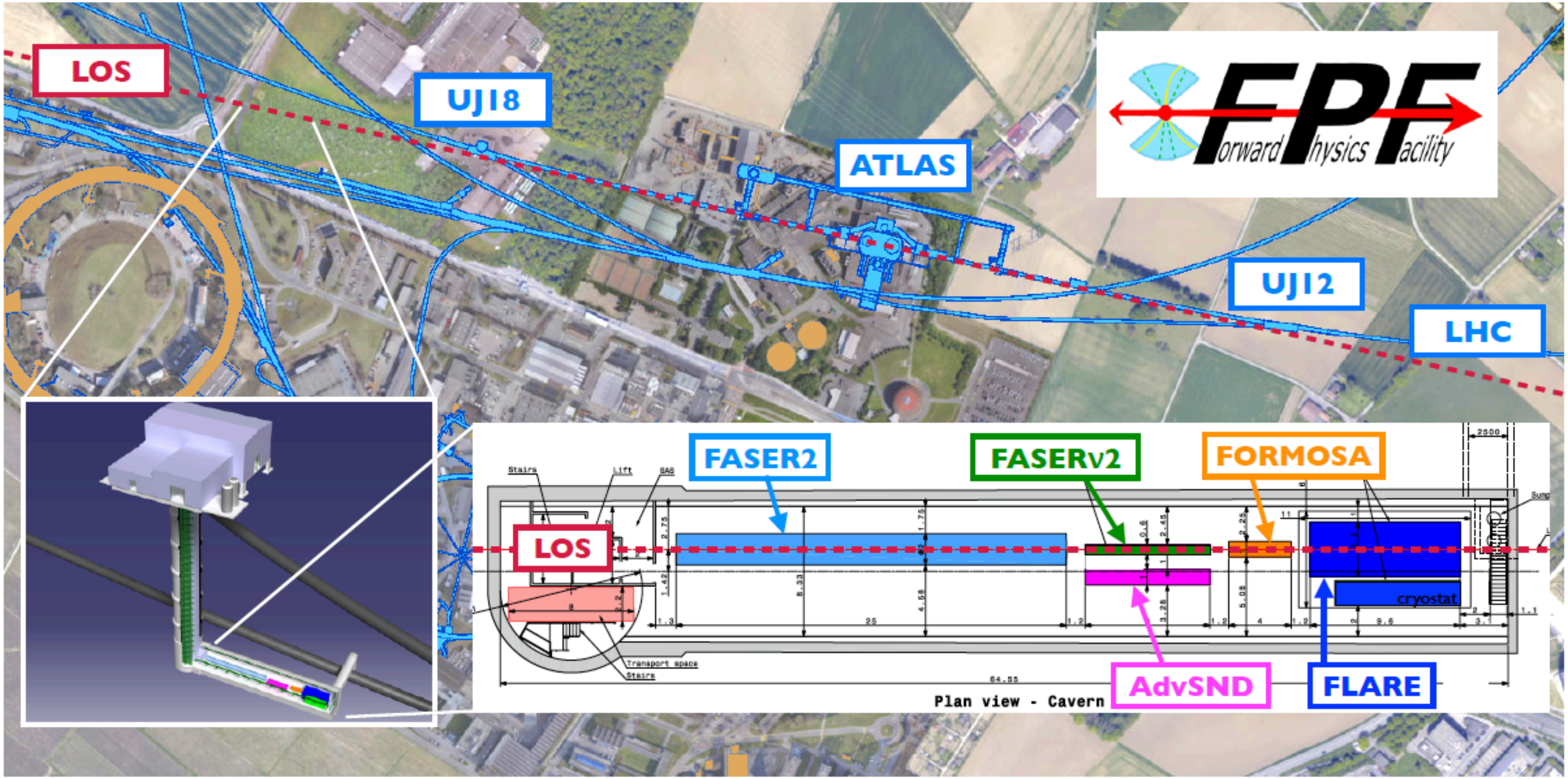


- The first phase experiments have launched.
  - FASERν ($\eta > 8.5$)
  - SND@LHC ($7.2 < \eta < 8.4$)
- Both experiments are installed at 480 m distance from the ATLAS interaction point.
- Pseudorapidity: $\eta = -\ln\left[\tan\frac{\theta}{2}\right]$



See Akitaka Ariga's talk on Wednesday

Forward Physics Facility (FPF, High-Luminosity)



J.Phys.G 50 (2023) 3, 030501 (arXiv: 2203.05090)

Expected neutrino events at the forward experiments

J.Phys.G 50 (2023) 3, 030501 (arXiv: 2203.05090)

Detector				Number of CC Interactions		
Name	Mass	Coverage	Luminosity	$\nu_e+\bar{\nu}_e$	$\nu_\mu+\bar{\nu}_\mu$	$\nu_\tau+\bar{\nu}_\tau$
FASERν	1 ton	$\eta \gtrsim 8.5$	150 fb^{-1}	901 / 3.4k	4.7k / 7.1k	15 / 97
SND@LHC	800kg	$7 < \eta < 8.5$	150 fb^{-1}	137 / 395	790 / 1.0k	7.6 / 18.6
FASERν2	20 tons	$\eta \gtrsim 8.5$	3 ab^{-1}	178k / 668k	943k / 1.4M	2.3k / 20k
FLArE	10 tons	$\eta \gtrsim 7.5$	3 ab^{-1}	36k / 113k	203k / 268k	1.5k / 4k
AdvSND	2 tons	$7.2 \lesssim \eta \lesssim 9.2$	3 ab^{-1}	6.5k / 20k	41k / 53k	190 / 754

increased by about 2 times

- The rapidity coverage of the detectors at the FPF is similar to the experiments for the Run 3.
- The increased detector/target mass and the luminosity yields about two order of magnitude larger number of events than the first phase experiments.
- At the FPF, large number of neutrinos can be detected for all three flavor neutrinos.

- The forward physics facility at the LHC can detect abundant number of prompt neutrinos.
    - Forward production of prompt neutrinos is related with small-x physics.
    - Prompt neutrino study at the LHC allows to investigate the QCD at small x region.

See Ina Sarcevic's talk on Thursday

- Question: (how) can the prompt neutrino study at the LHC help to improve prediction of the prompt atmospheric neutrino flux?

Kinematic regions for prompt atmospheric neutrinos

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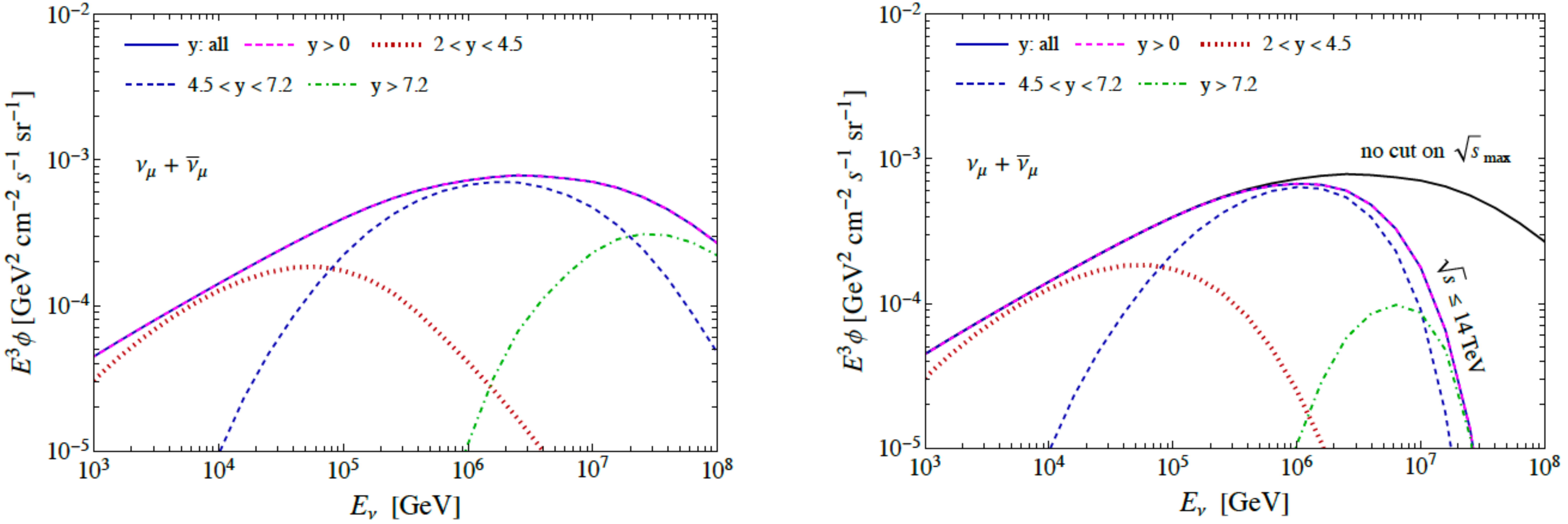
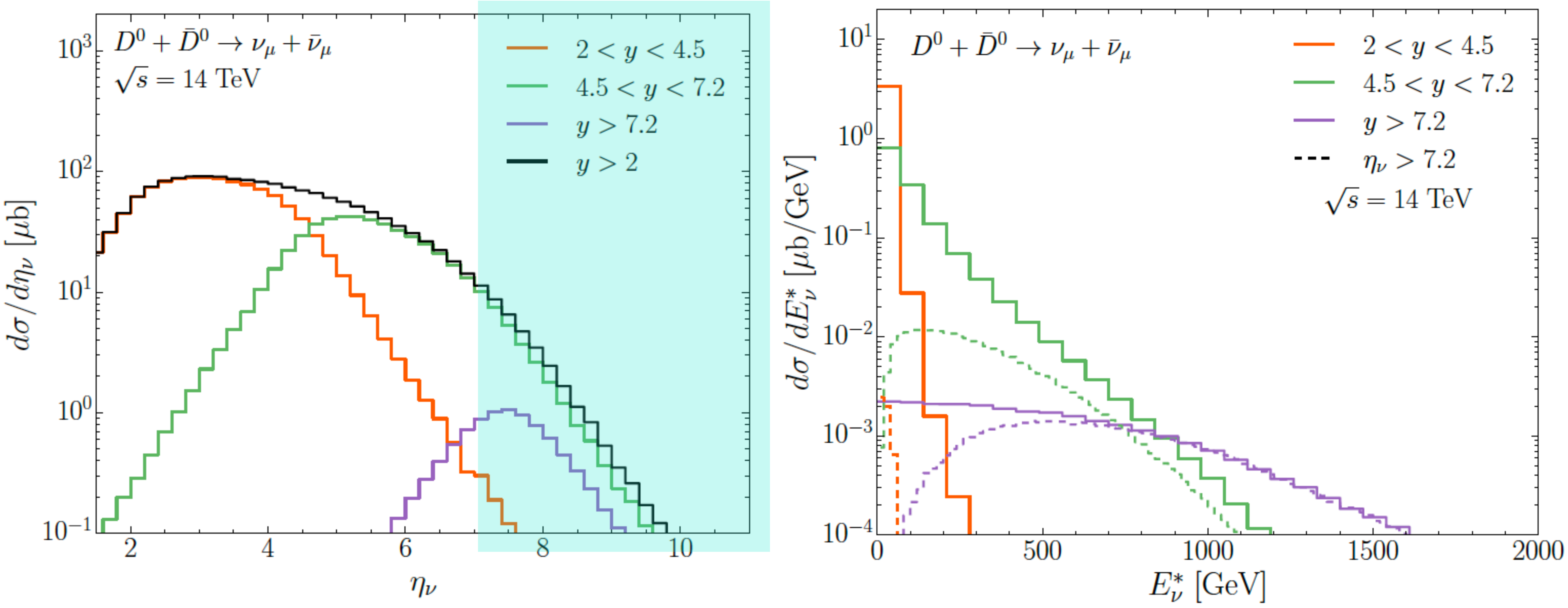


- The three rapidity ranges: $2 < y < 4.5$ (LHCb coverage), $4.5 < y < 7.2$, $y > 7.2$ (forward experiments)
- The produced neutrinos with $\sqrt{s} \leq 14$ TeV are distributed up to $E_\nu \sim 10^7$ GeV.
- Prompt atmospheric neutrinos for $E_\nu \gtrsim 10^5$ GeV are mainly from charm hadrons produced in $y > 4.5$.

LHC neutrinos with neutrino rapidity



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Concluding remarks

- Relevant kinematic region for atmospheric prompt neutrinos was investigated in terms of collider variables, CM collision energy $\sqrt{s}$ and charm hadron rapidity y.
  - The LHC energy covers the atmospheric neutrino energy range where the cross-over between conventional and prompt fluxes occurs.
  - Charm hadrons produced in $4.5 < y < 7.2$, which produce most prompt atmospheric neutrinos in the transition region, substantially contribute to the prompt neutrinos at the FPF of the LHC.
- The prompt neutrino measurement at the forward experiments of the LHC will be able to provide neutrino data that can probe proton structure (e.g. low-x PDFs) and constrain the QCD evaluations for heavy flavor hadron production.
- The LHC can play important roles in constraining/improving theoretical predictions of prompt atmospheric neutrino fluxes.

Thank you for your attention