

Forward Neutrinos from Charm at the LHC

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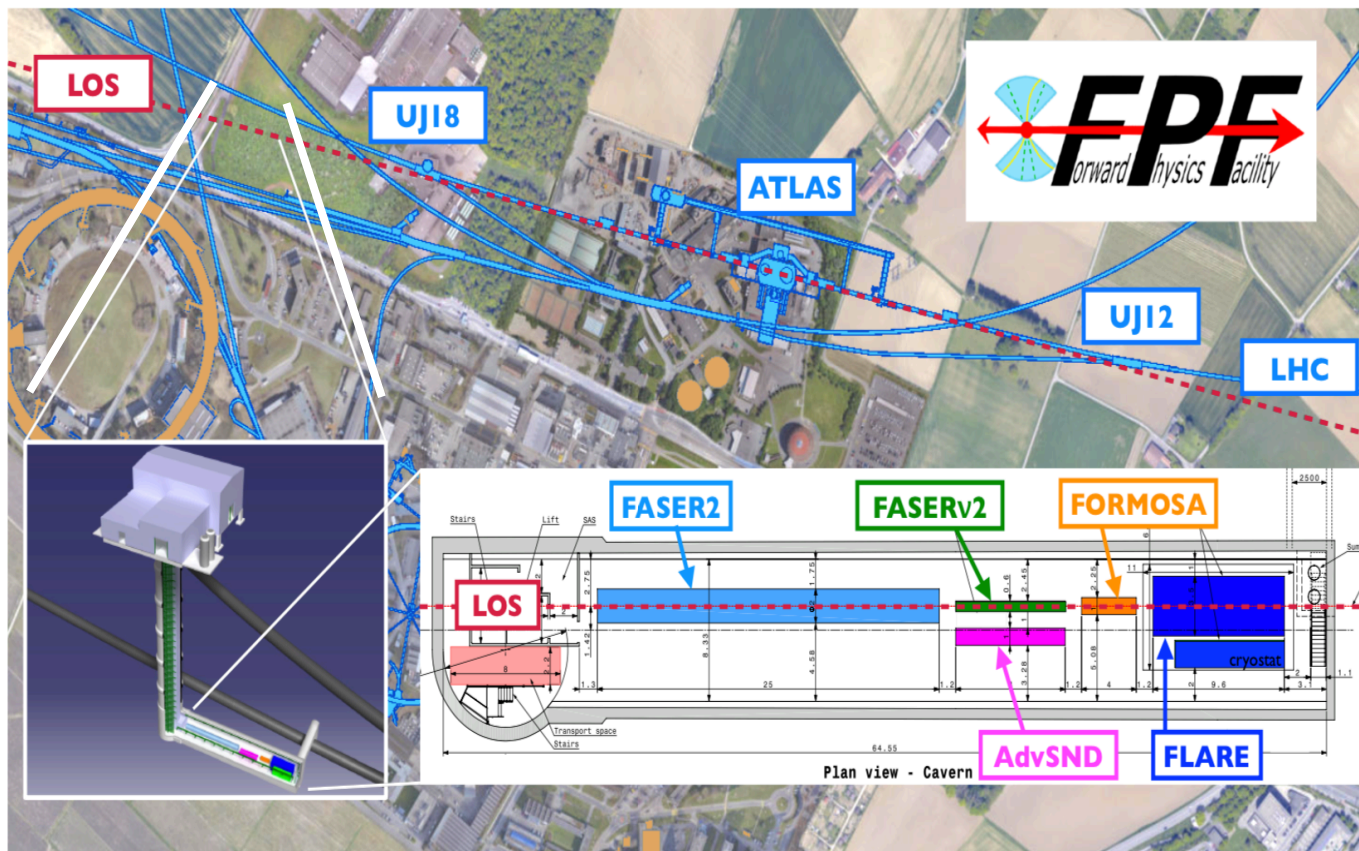
in collaboration with Atri Bhattacharya, Felix Kling and Anna Stasto

See also our results in FPF Papers: J. L. Feng et al., J. Phys.G 50
(2023) 3, 030501 and
L. A. Anchordoqui et al. , Phys. Rept. 968 (2022) 1

The Forward Physics Facility

The Forward Physics Facility (FPF) is a proposal to create a cavern with the space and infrastructure to support a suite of far-forward experiments at the Large Hadron Collider during the High Luminosity era.

FPF experiments will detect about 1M neutrino interactions (1K tau neutrinos) with neutrino energies up to a few TeV



Need the facility infrastructure and detectors designed for Standard Model and BSM Physics.

See talk by Akitaka Ariga

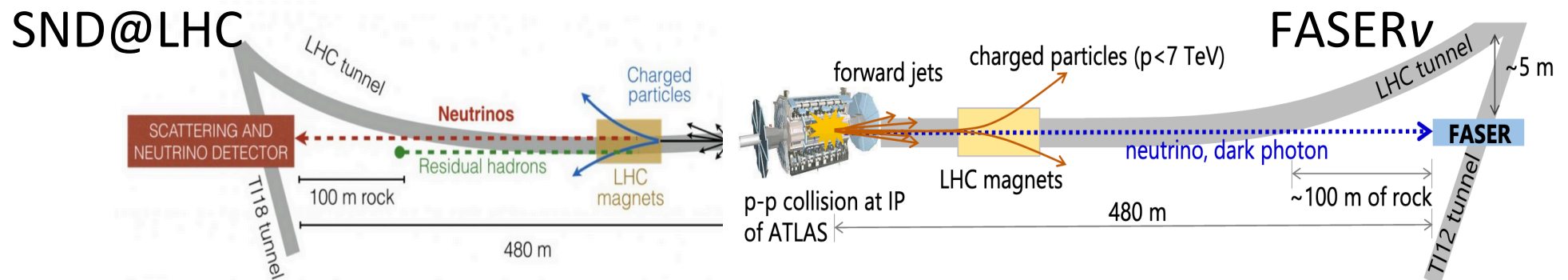
Forward rapidity regions for detectors:

Detector			
Name	Mass	Coverage	Luminosity
FASER ν	1 ton	$\eta \gtrsim 8.5$	150 fb^{-1}
SND@LHC	800kg	$7 < \eta < 8.5$	150 fb^{-1}
FASER ν 2	20 tons	$\eta \gtrsim 8.5$	3 ab^{-1}
FLArE	10 tons	$\eta \gtrsim 7.5$	3 ab^{-1}
AdvSND	2 tons	$7.2 \lesssim \eta \lesssim 9.2$	3 ab^{-1}

Run 3

FASER ν and SND@LHC detectors
are installed

AdvSND (“near”) in range



See talk by Akitaka Ariga

Production of Neutrinos

At LHC (forward detectors: FASERnu ...):

$p + p \rightarrow$ pions, kaons, D-mesons .. \rightarrow neutrinos

Energy of protons 14TeV (LHC beam)

Atmospheric neutrinos:

$p + \text{Air (p)} \rightarrow$ pions, kaons, D-mesons

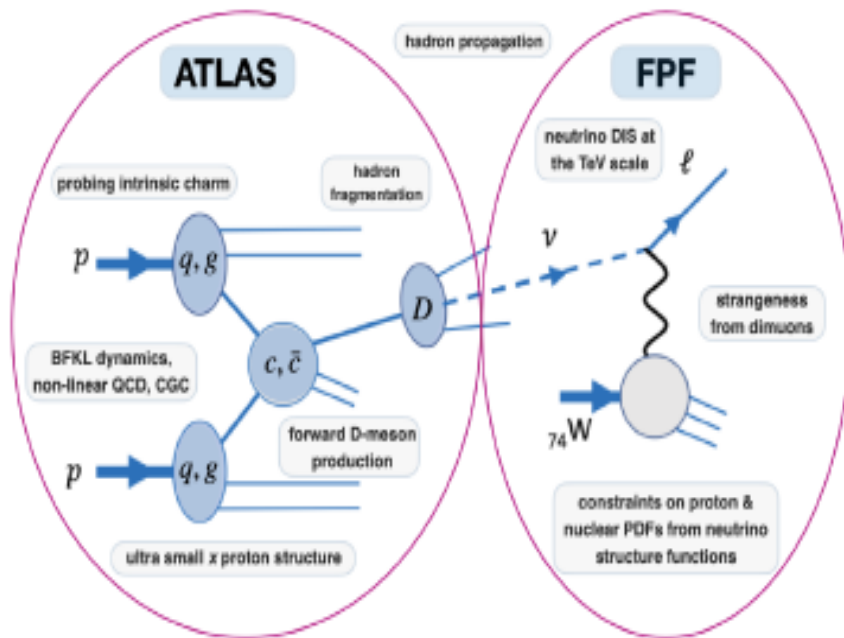
\rightarrow neutrinos

Folding cosmic ray proton spectrum with the production

Astrophysical neutrinos (from AGNs, GRB..)

$p + p$ and $p + \gamma$, folding with the proton energy spectrum

QCD (neutrino production)

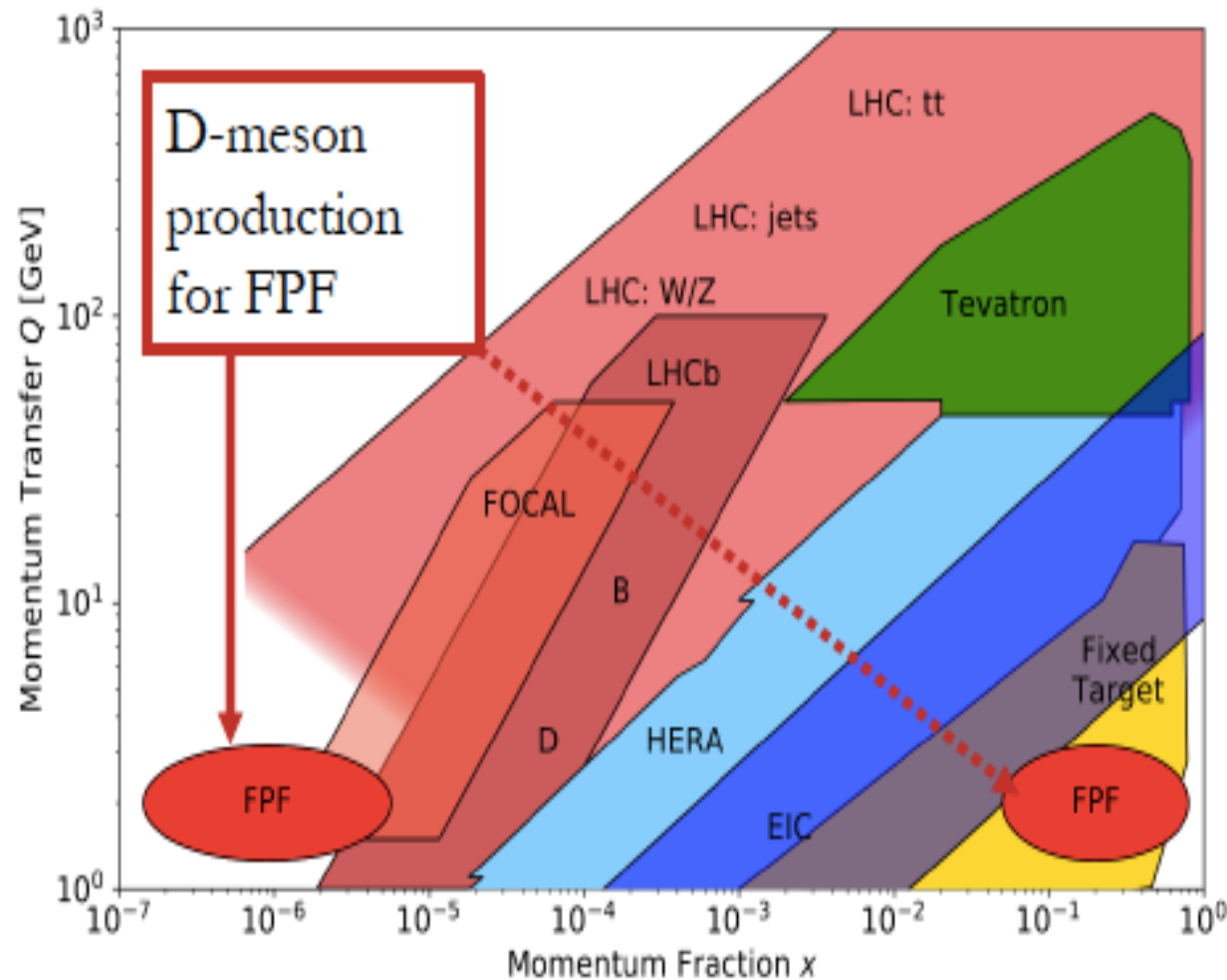


Forward neutrino production is a probe of forward hadron production, BFKL dynamics, PDFs at ultra small x (10^{-7}) and small Q^2

Important implications for high energy neutrino experiments

New kinematic regimes.

forward charm: high rapidity, $x_1 \gg x_2$ in gluon PDF



Charm Production in NLO pQCD using PDFs

The total charm cross section in pQCD is given by:

$$\sigma(pp \rightarrow c\bar{c}X) = \int dx_1 dx_2 G(x_1, \mu^2) G(x_2, \mu^2) \hat{\sigma}_{gg \rightarrow c\bar{c}}(x_1 x_2 s)$$

and differential charm cross section

$$\frac{d\sigma}{dx_F} = \int \frac{dM_{c\bar{c}}^2}{(x_1 + x_2)s} \sigma_{gg \rightarrow c\bar{c}}(\hat{s}) G(x_1, \mu^2) G(x_2, \mu^2)$$

where

$x_1, x_2 :$

$$x_F = x_1 - x_2$$

$$x_F \simeq x_E = E/E'$$

$$x_{1,2} = \frac{1}{2} \left(\sqrt{x_F^2 + \frac{4M_{c\bar{c}}^2}{s}} \pm x_F \right)$$

$$x_1 \simeq x_F \sim 0.1, \quad x_2 \ll 1$$

$$E \sim 10^7 \text{ GeV} \rightarrow x_2 \sim 10^{-6}$$

$$x_{1,2} \sim m_c/2m_p E_\nu$$

For high energies we need gluon PDF for small x , and low Q^2

FONLL program: Cacciari, Greco and Nason, JHEP 05 (1998) 007; Cacciari, Frixione, Nason, JHEP 03 (2001) 006

Calculated in pQCD by matching the Fixed Order NLO terms with NLL high p_T resummation

Charm Production in k_T Factorization Approach

$$\frac{d\sigma}{dx_F}(s, m_Q^2) = \int \frac{dx_1}{x_1} \frac{dx_2}{x_2} dz \delta(zx_1 - x_F) x_1 g(x_1, M_F) \int \frac{dk_T^2}{k_T^2} \hat{\sigma}^{\text{off}}(z, \hat{s}, k_T) f(x_2, k_T^2)$$

x_F is the Feynman variable for the produced heavy quark
 $x_1 g(x_1, M_F)$ is the integrated gluon density on the projectile side, $\hat{\sigma}^{\text{off}}(z, \hat{s}, k_T)$ is the partonic cross section for the process $gg^* \rightarrow Q\bar{Q}$, where g^* is the off-shell gluon on the target side, and $f(x_2, k_T^2)$ is the unintegrated gluon density.

For the unintegrated gluon density, we have used the resummed version of the BFKL evolution which includes important subleading effects due to DGLAP evolution

Resummation of the large powers of $\alpha_s \ln 1/x$ (BFKL) + DGLAP important at small x

Balitsky, Fadin, Kuraev, Lipatov (1977), Martin, Ryskin and **Stasto** (2003), Ciafalone, Colferai, Salam and **Stasto** (2003), Kwiecinski, Martin and **Stasto** (1997), Kutak and Sapeta (2012)

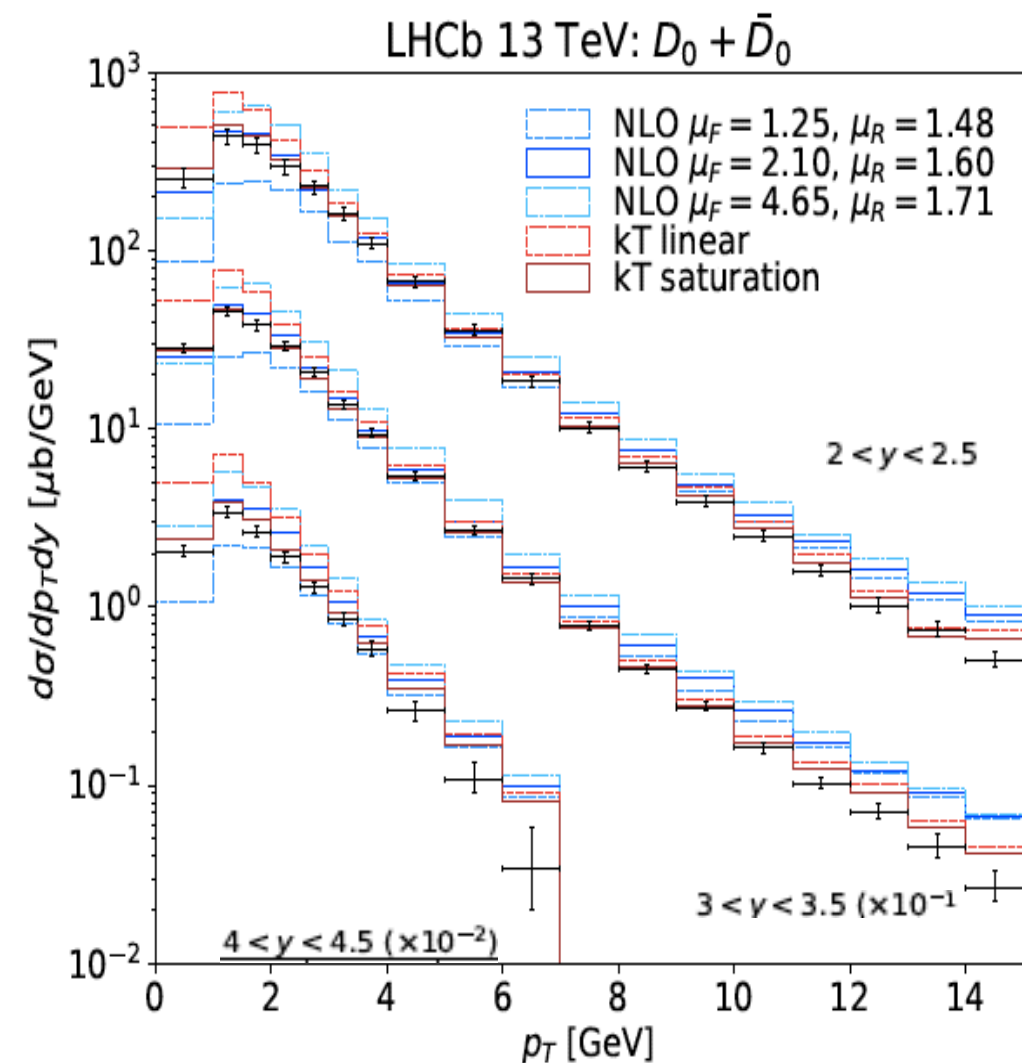
Theoretical uncertainties

Parton distribution functions at small x and small Q^2 (mostly gluons, unconstrained by HERA data), Factorization and Renormalization scale, charm quark mass, Fragmentation function

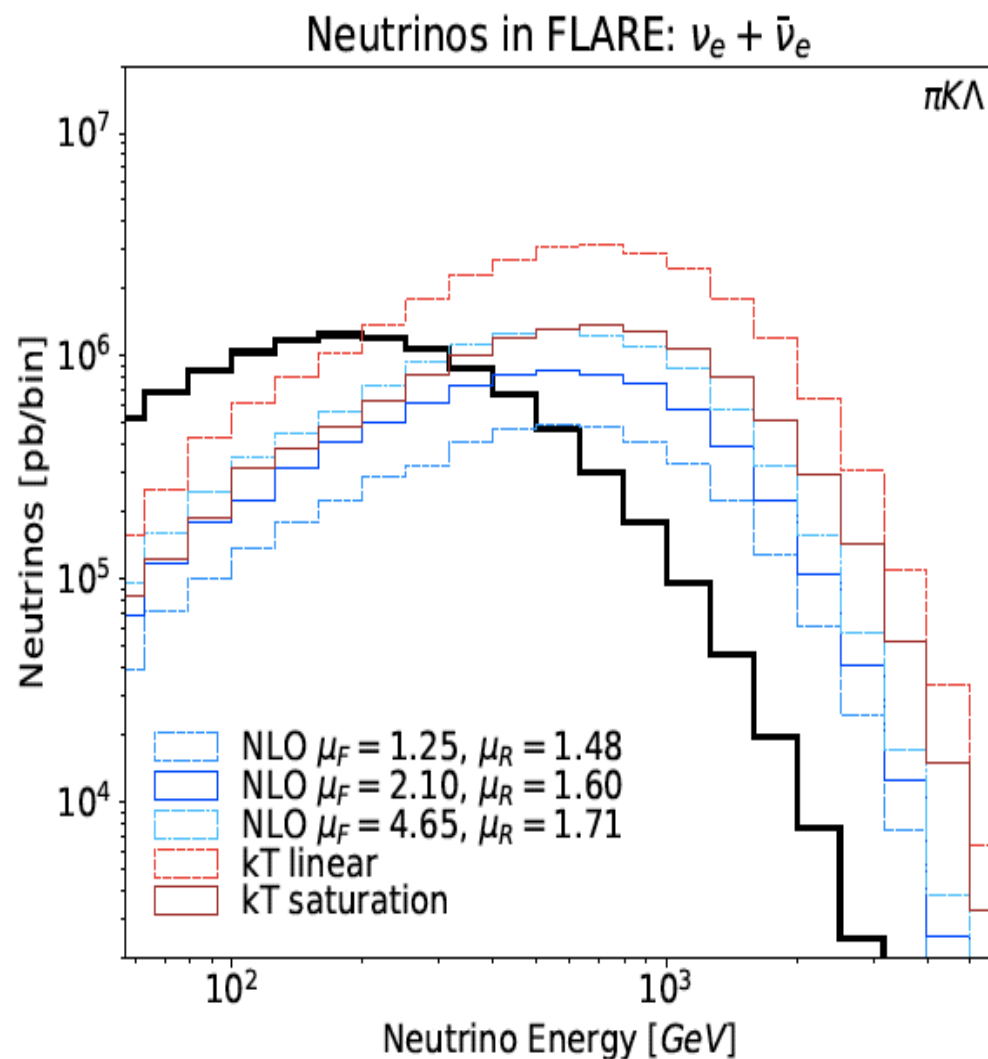
We use LHCb data for D-mesons in different rapidity regions and at several energies to reduce theoretical uncertainties (LHCb data covers rapidity up to 4.5)

k_T factorization approach depends on gluon distribution at large- x , charm quark mass

D-meson production at LHCb in different rapidity regions

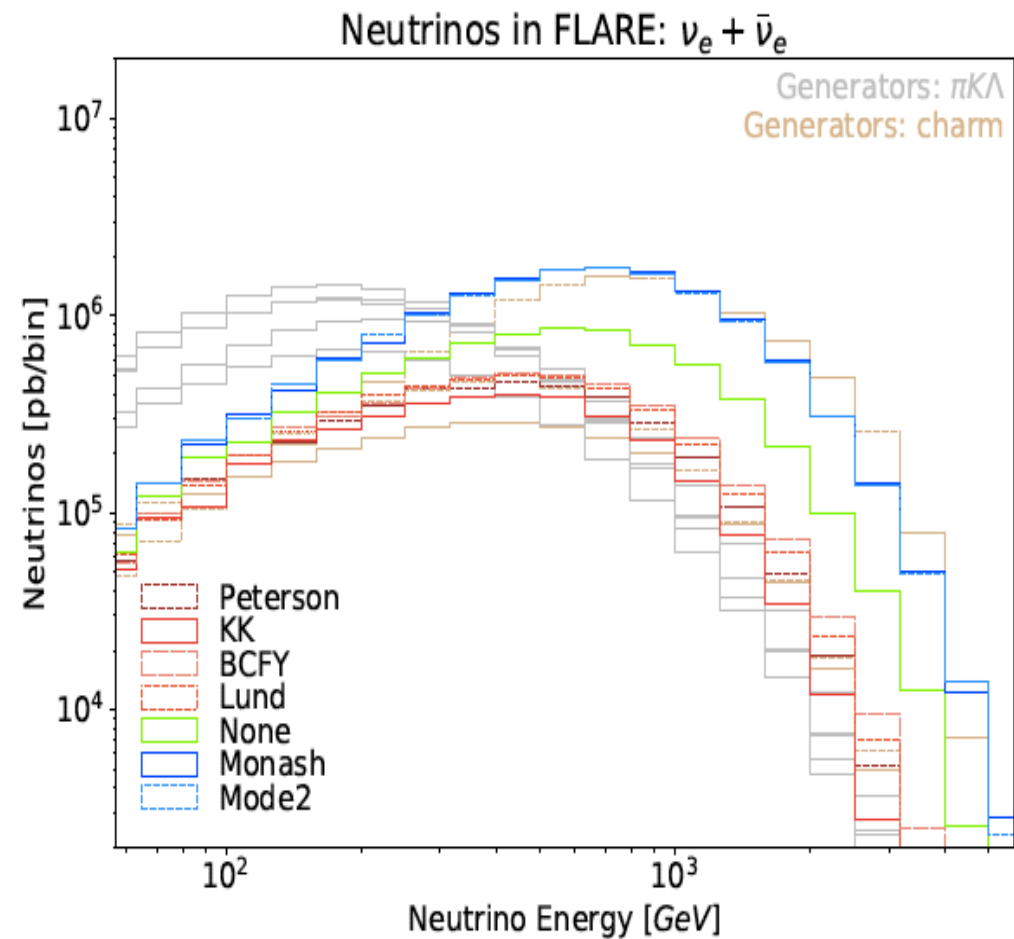
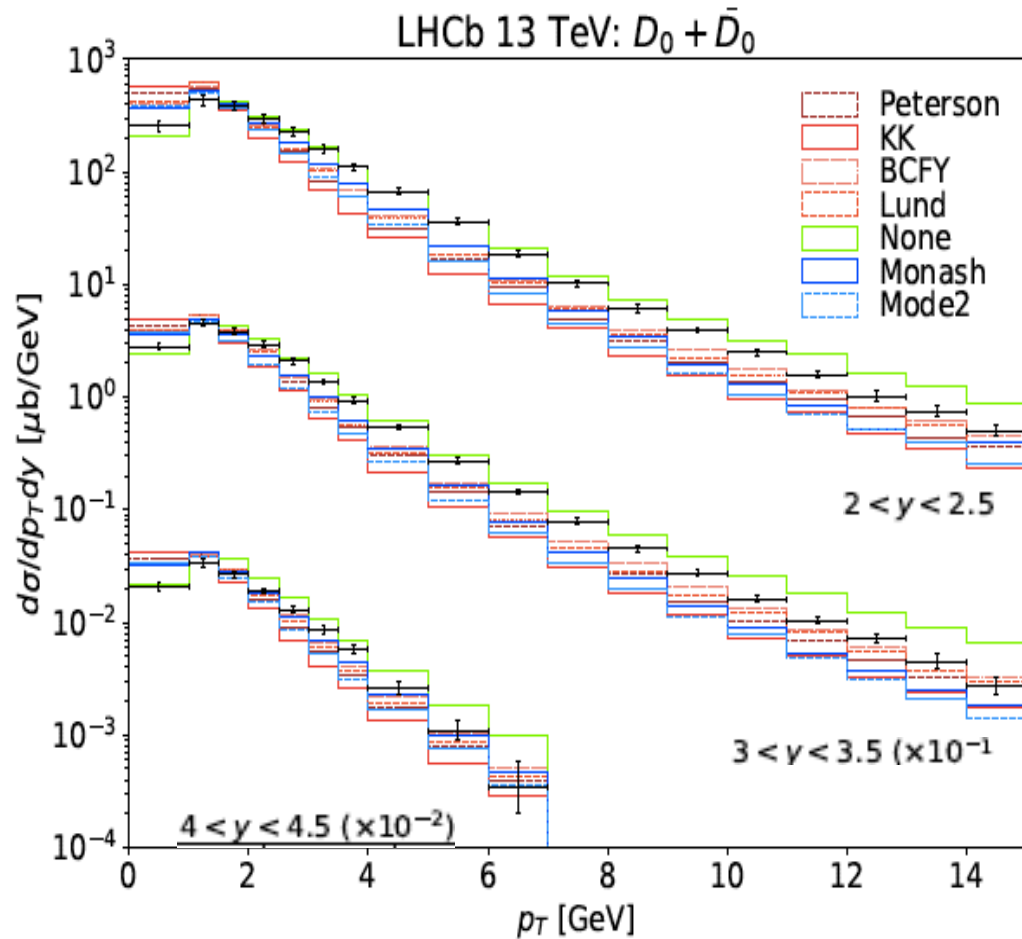


Neutrinos from D-meson decays

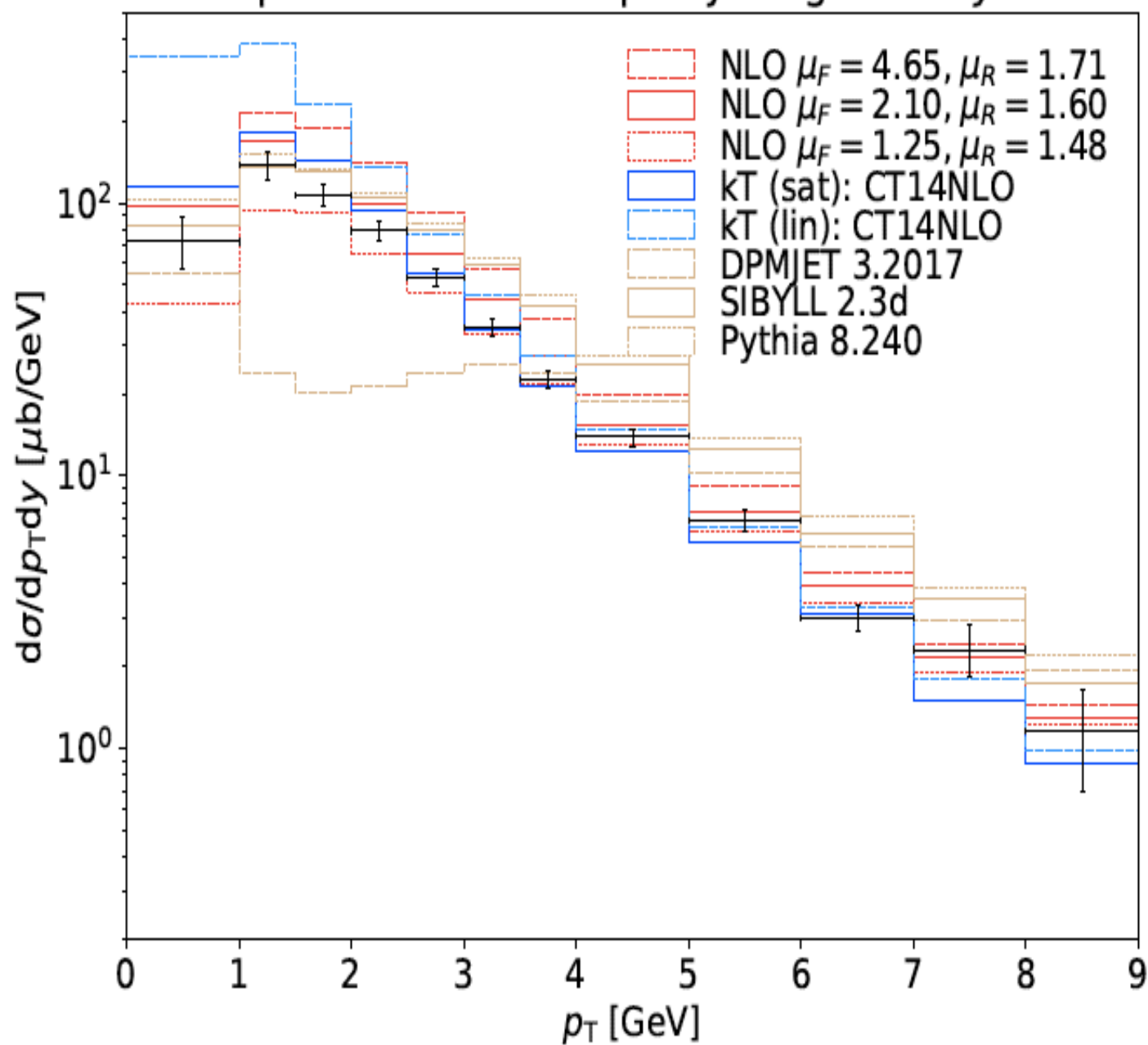


Neutrinos with energy above 300 GeV come predominantly from charm.

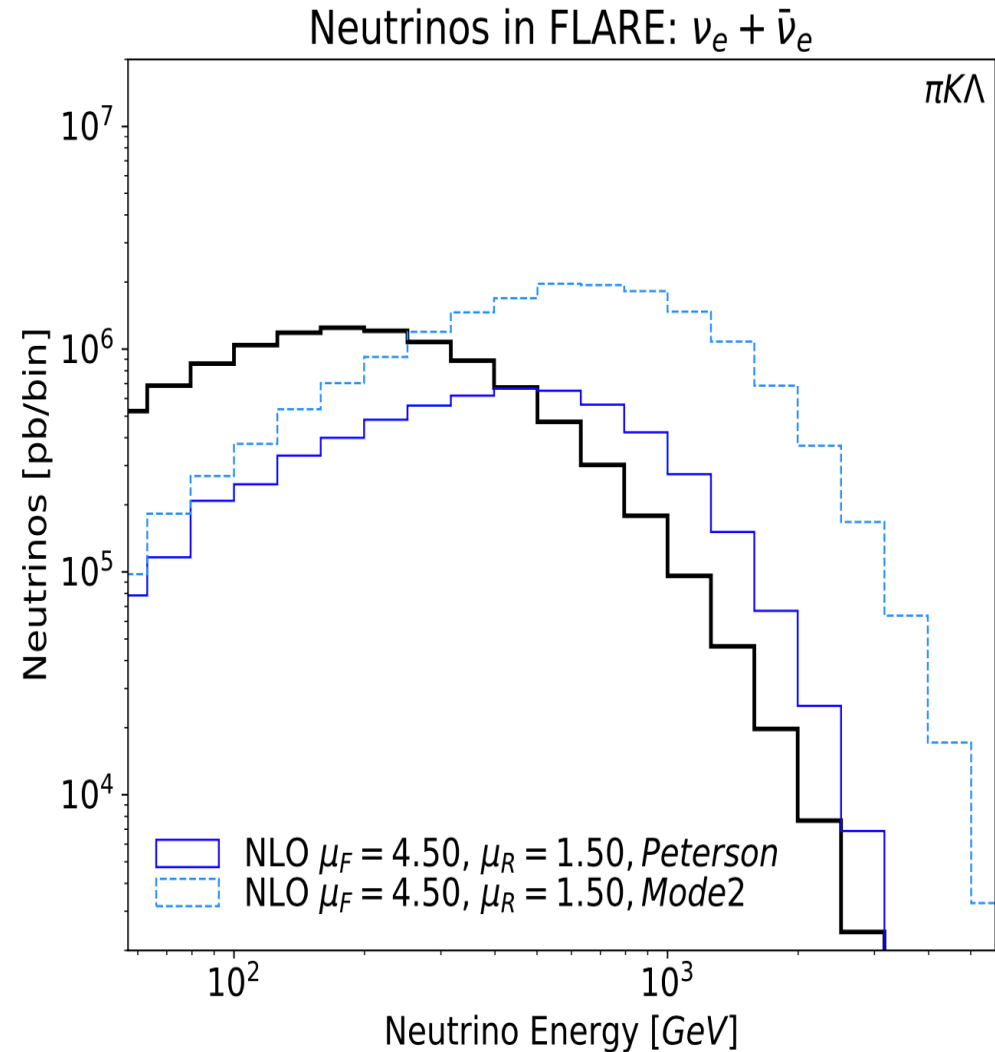
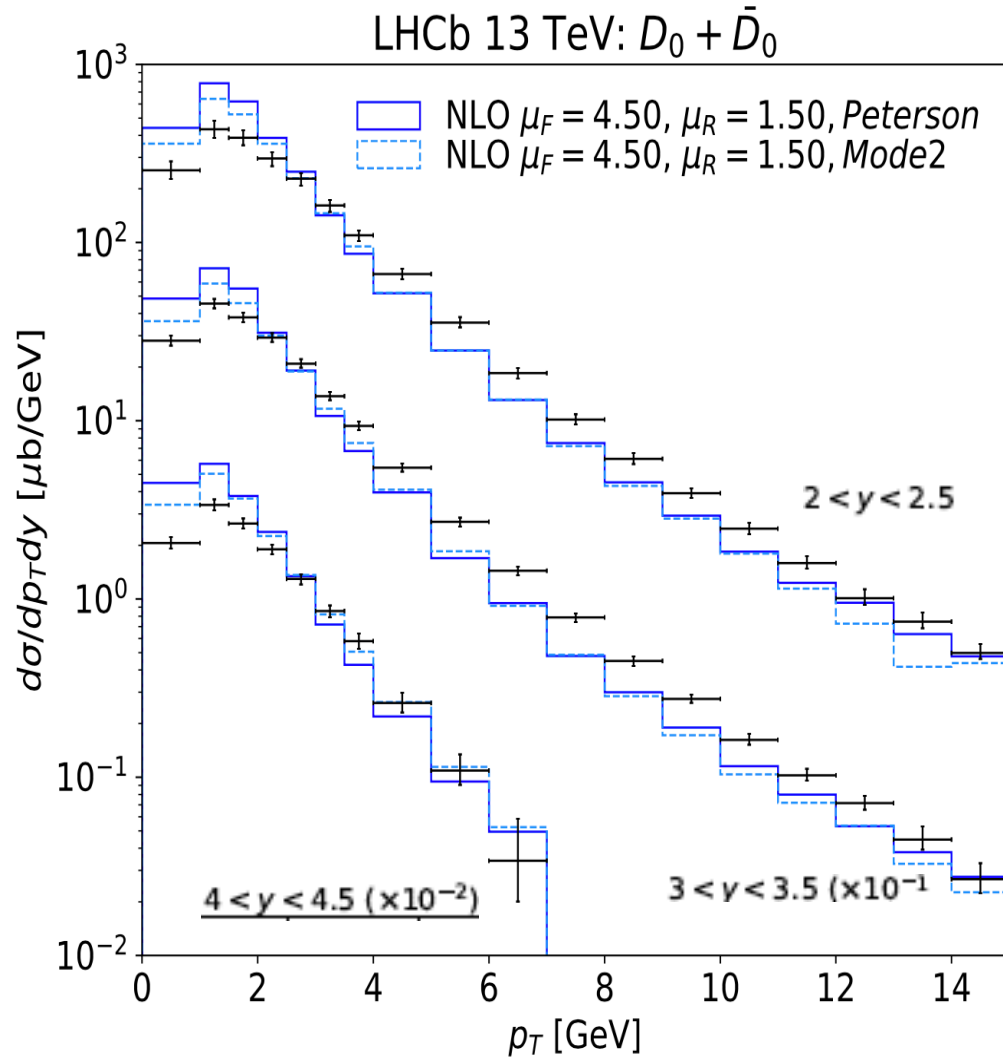
Fragmentation Functions



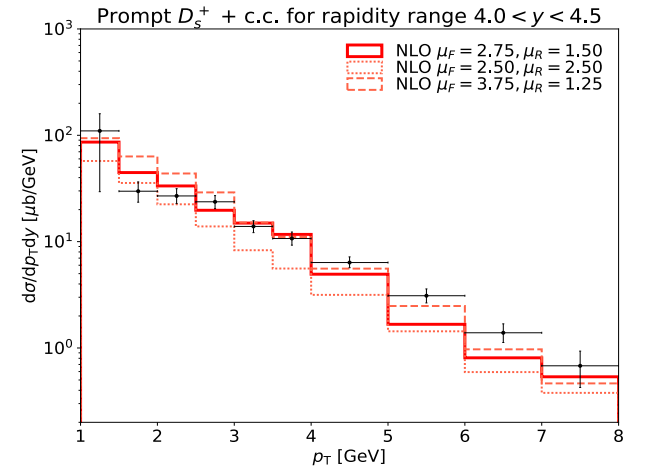
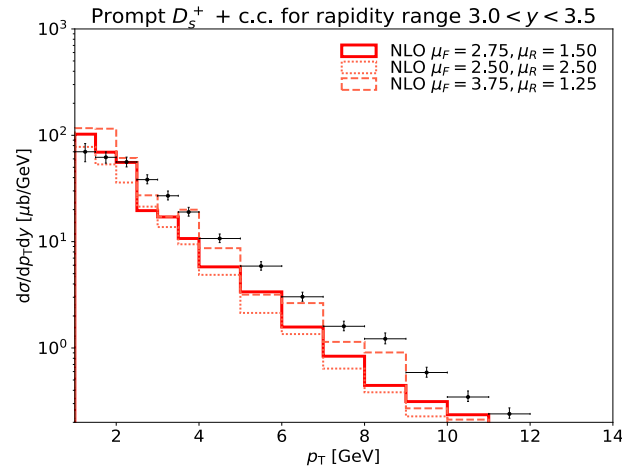
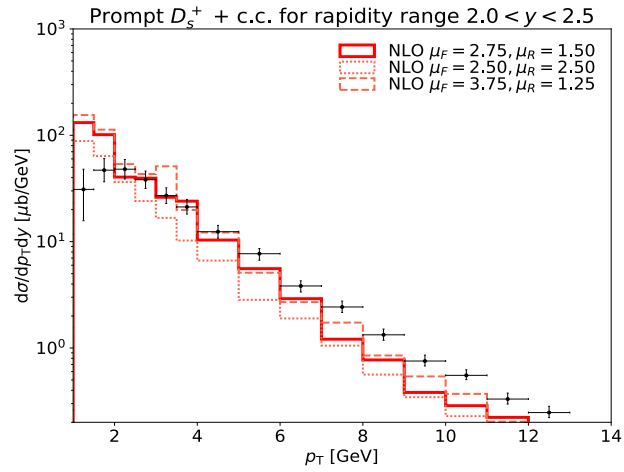
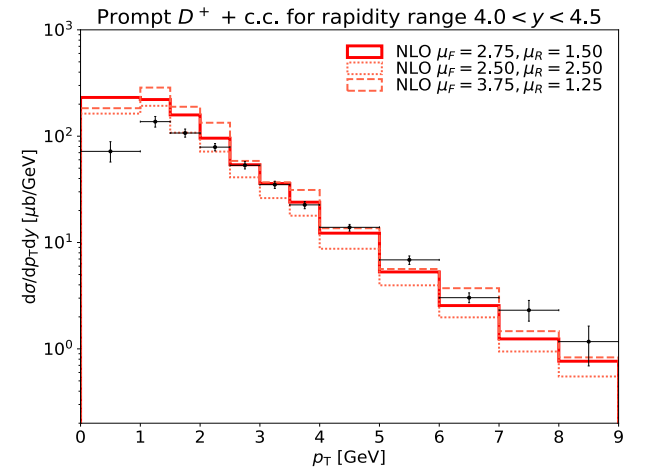
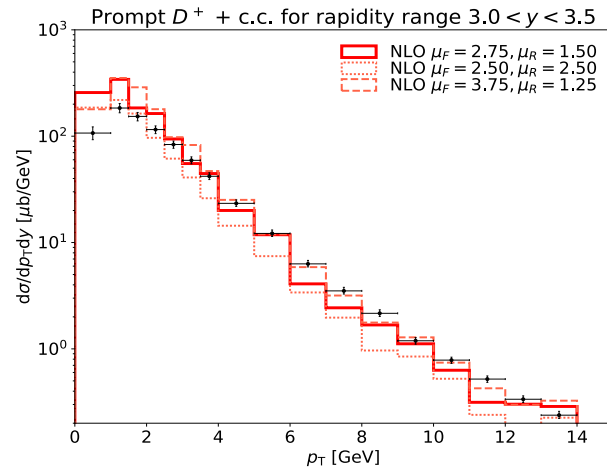
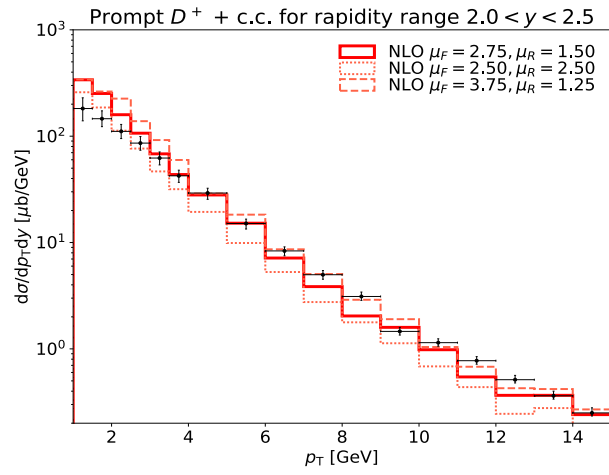
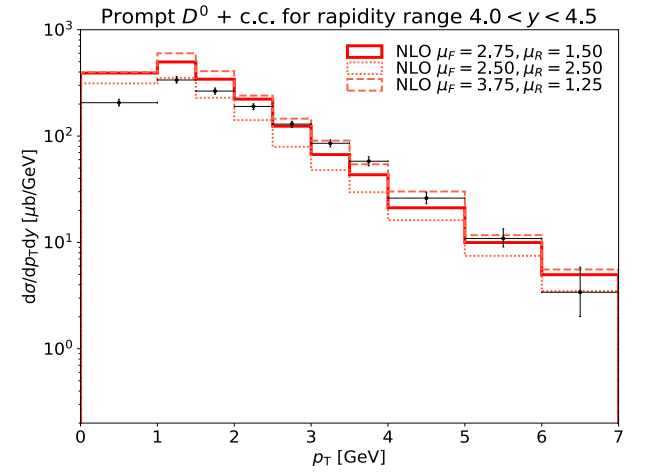
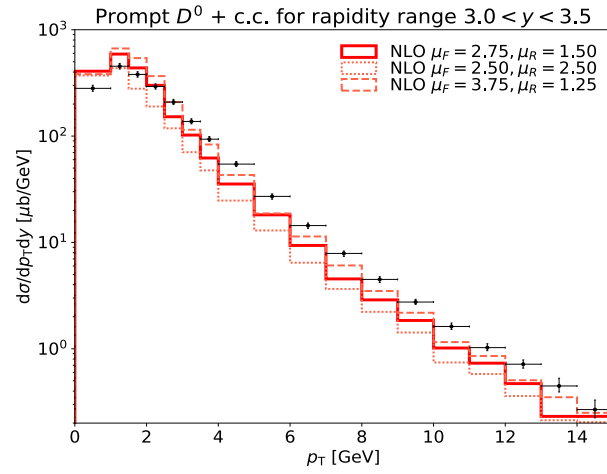
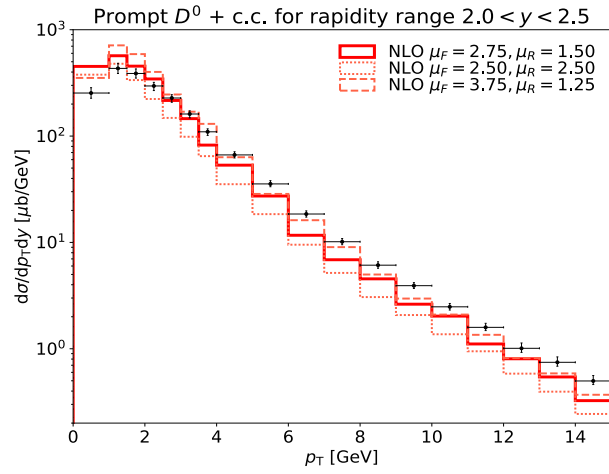
Prompt D^+ + c.c. for rapidity range $4.0 < y < 4.5$



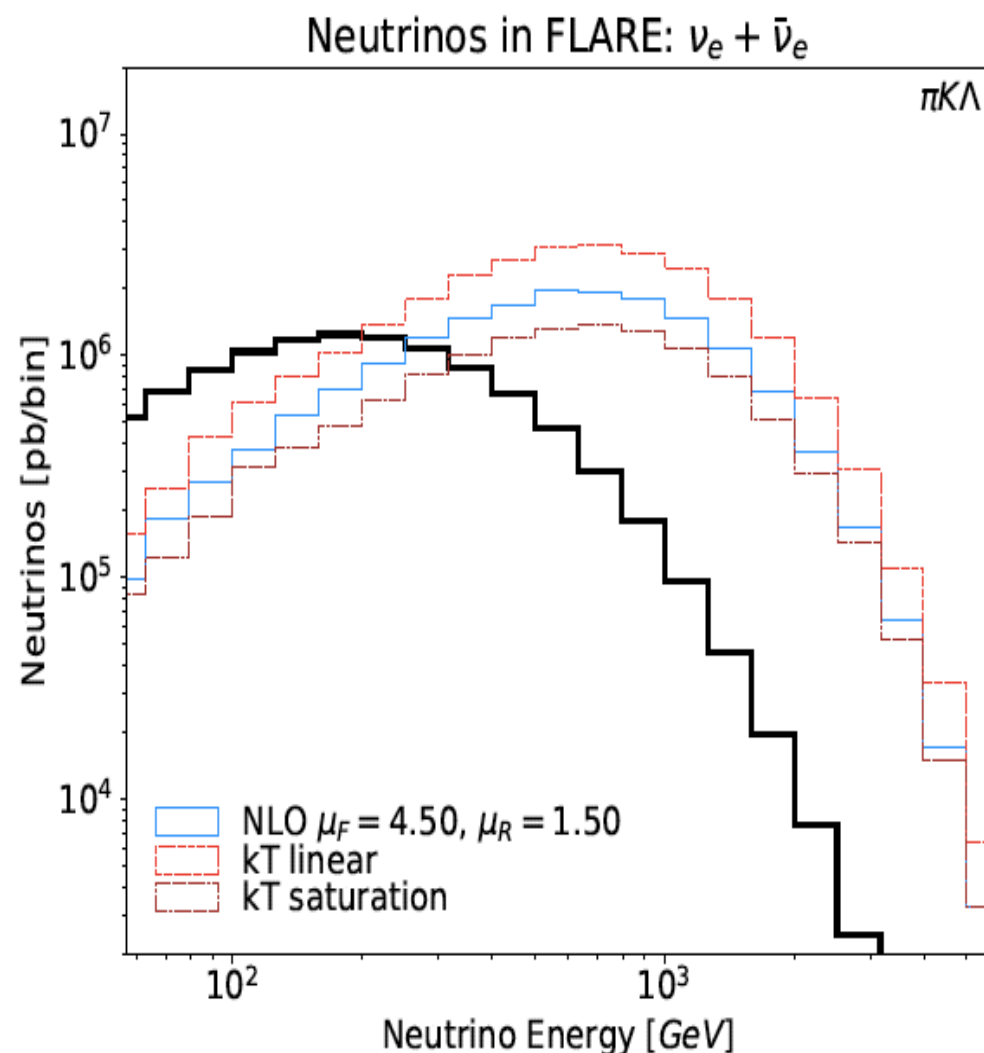
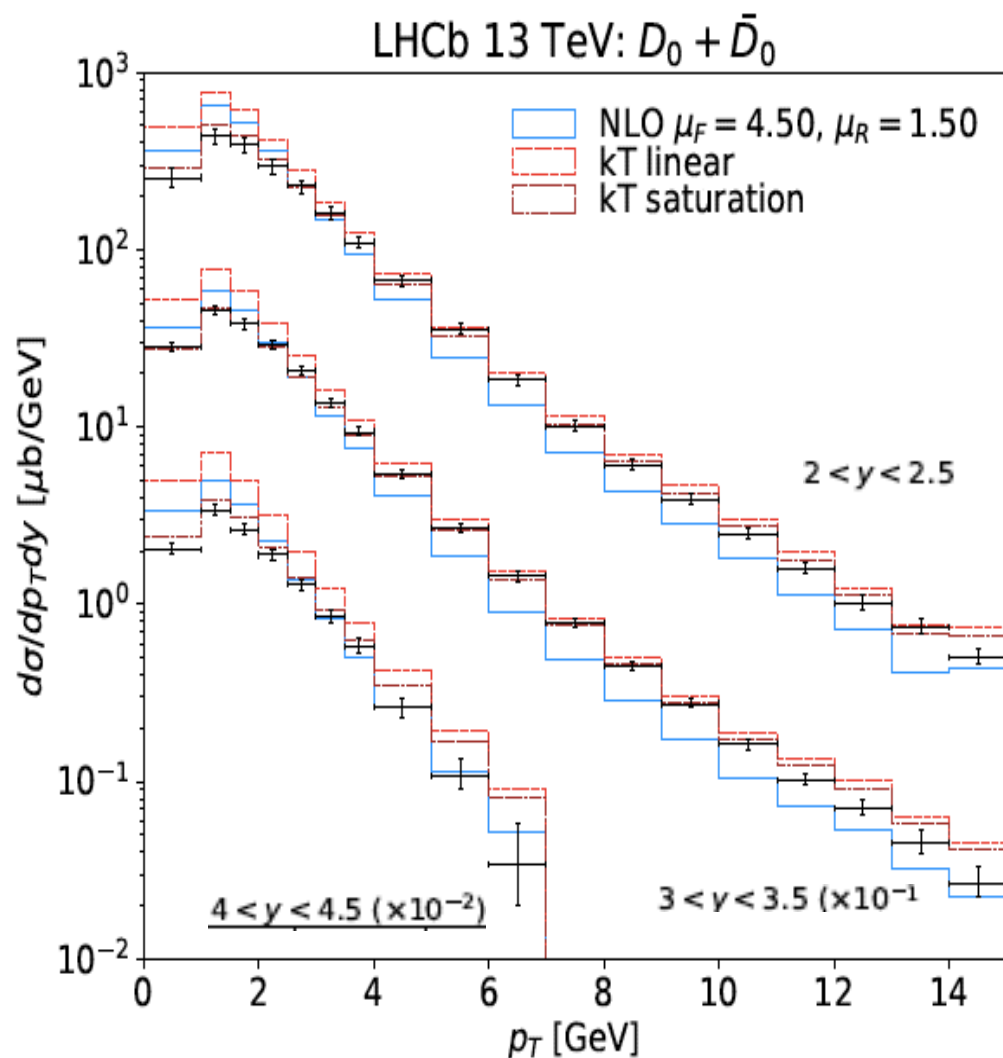
NLO with different fragmentation functions



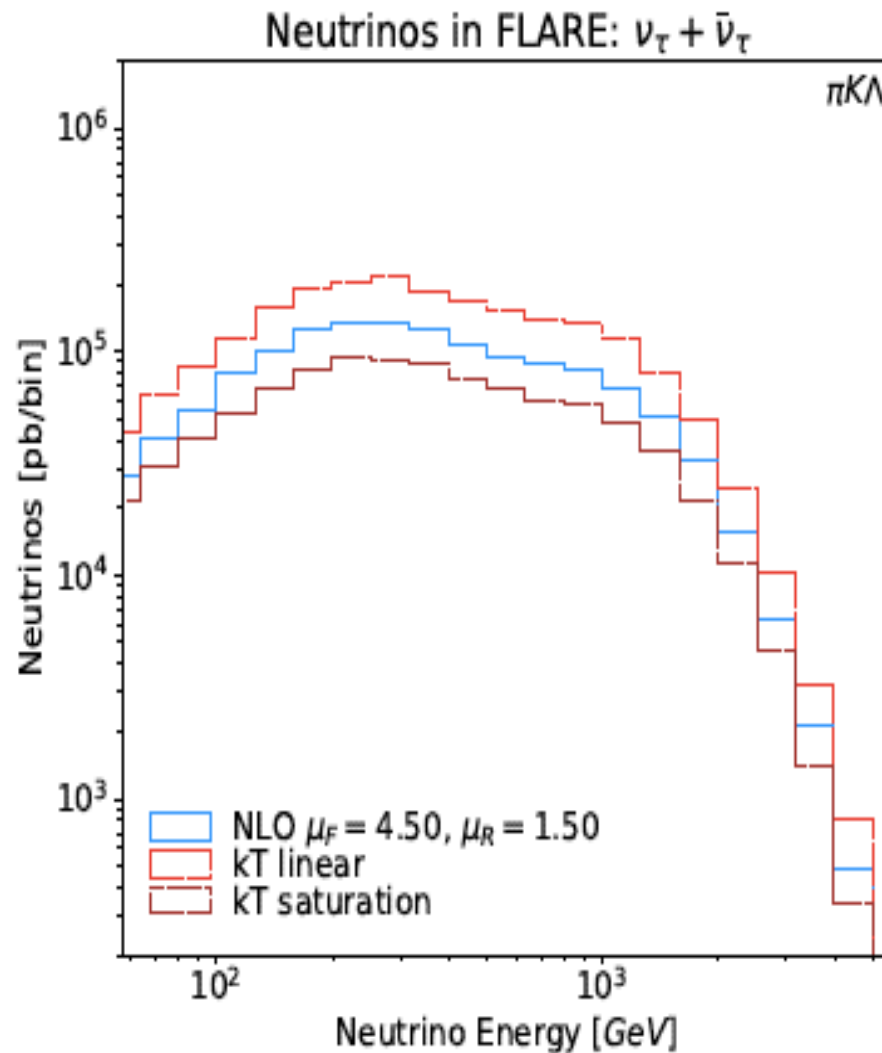
Similar results for LHCb but very different neutrino flux in FLARE



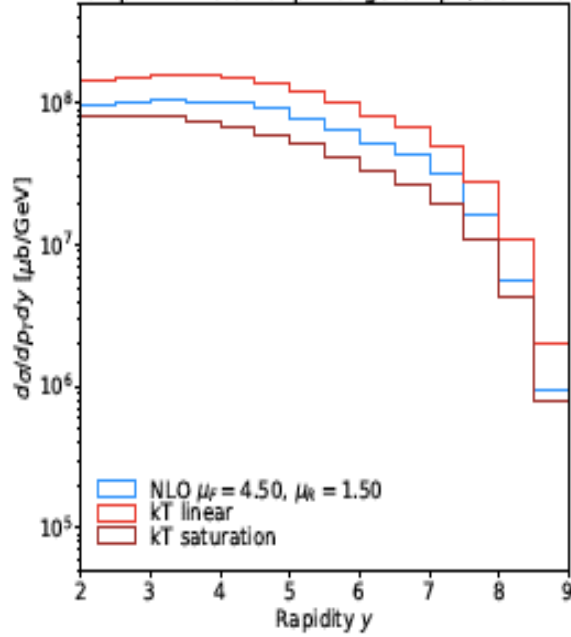
NLO and kT distributions at LHCb and neutrino fluxes at FASER (Peterson Fragmentation function)



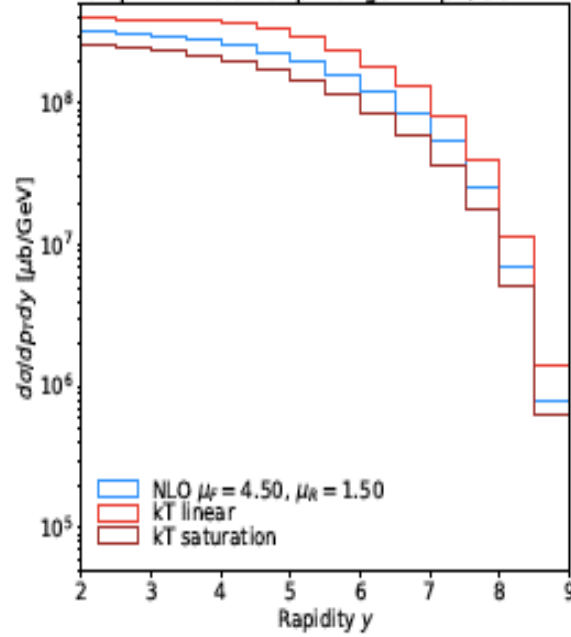
Tau neutrino flux from charm



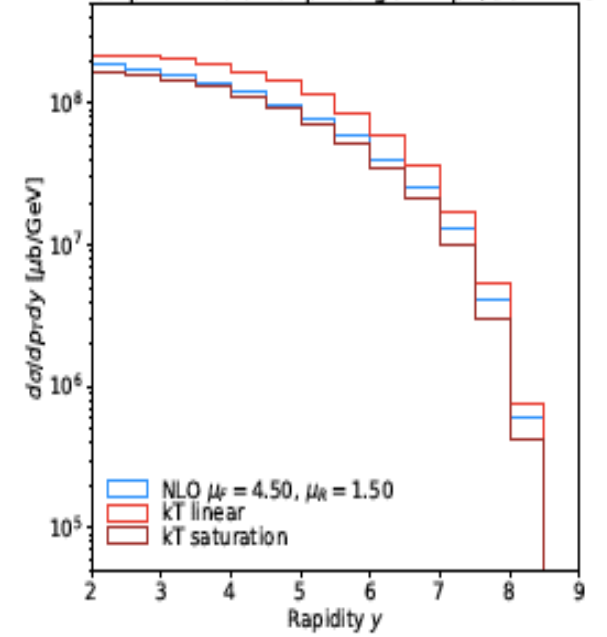
Prompt $D^+ + \text{c.c.}$ for pt range $0 < p_T/\text{GeV} < 0.5$



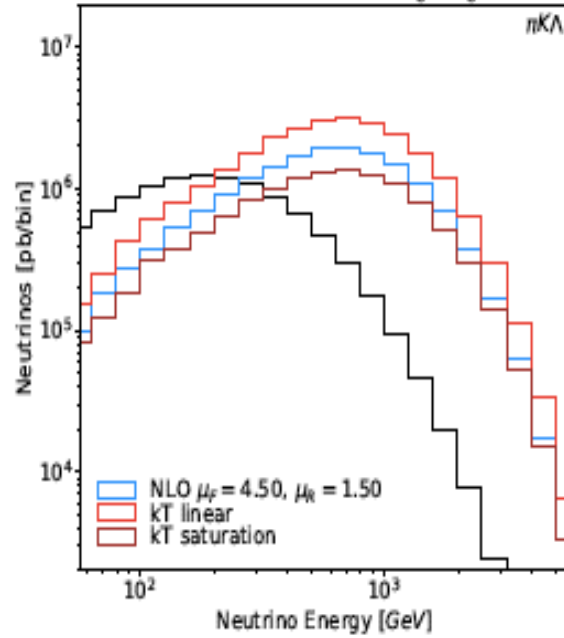
Prompt $D^+ + \text{c.c.}$ for pt range $1 < p_T/\text{GeV} < 1.5$



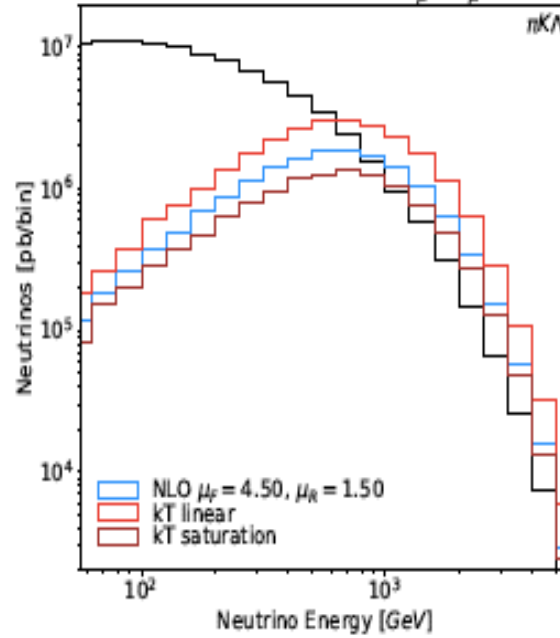
Prompt $D^+ + \text{c.c.}$ for pt range $2 < p_T/\text{GeV} < 2.5$



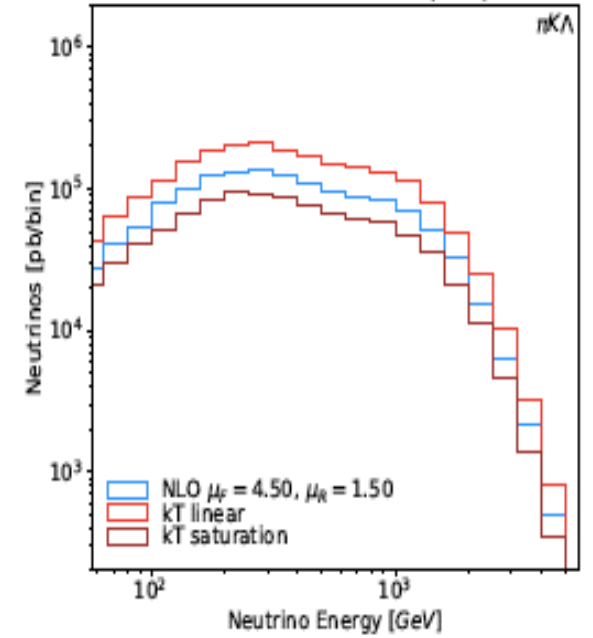
Neutrinos in FLARE: $\nu_e + \bar{\nu}_e$



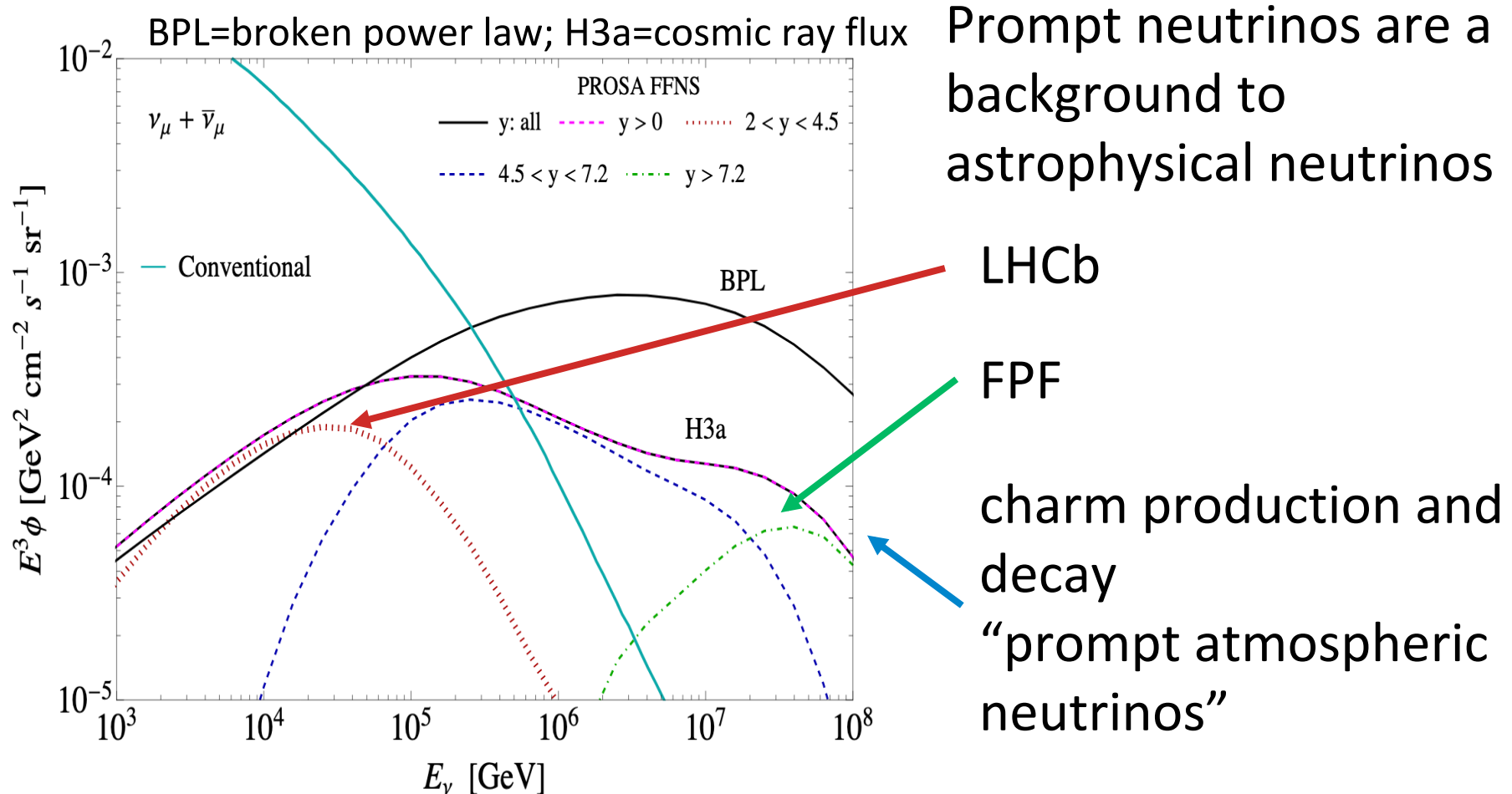
Neutrinos in FLARE: $\nu_\mu + \bar{\nu}_\mu$



Neutrinos in FLARE: $\nu_\tau + \bar{\nu}_\tau$



Astroparticle physics connections – prompt atmospheric neutrinos

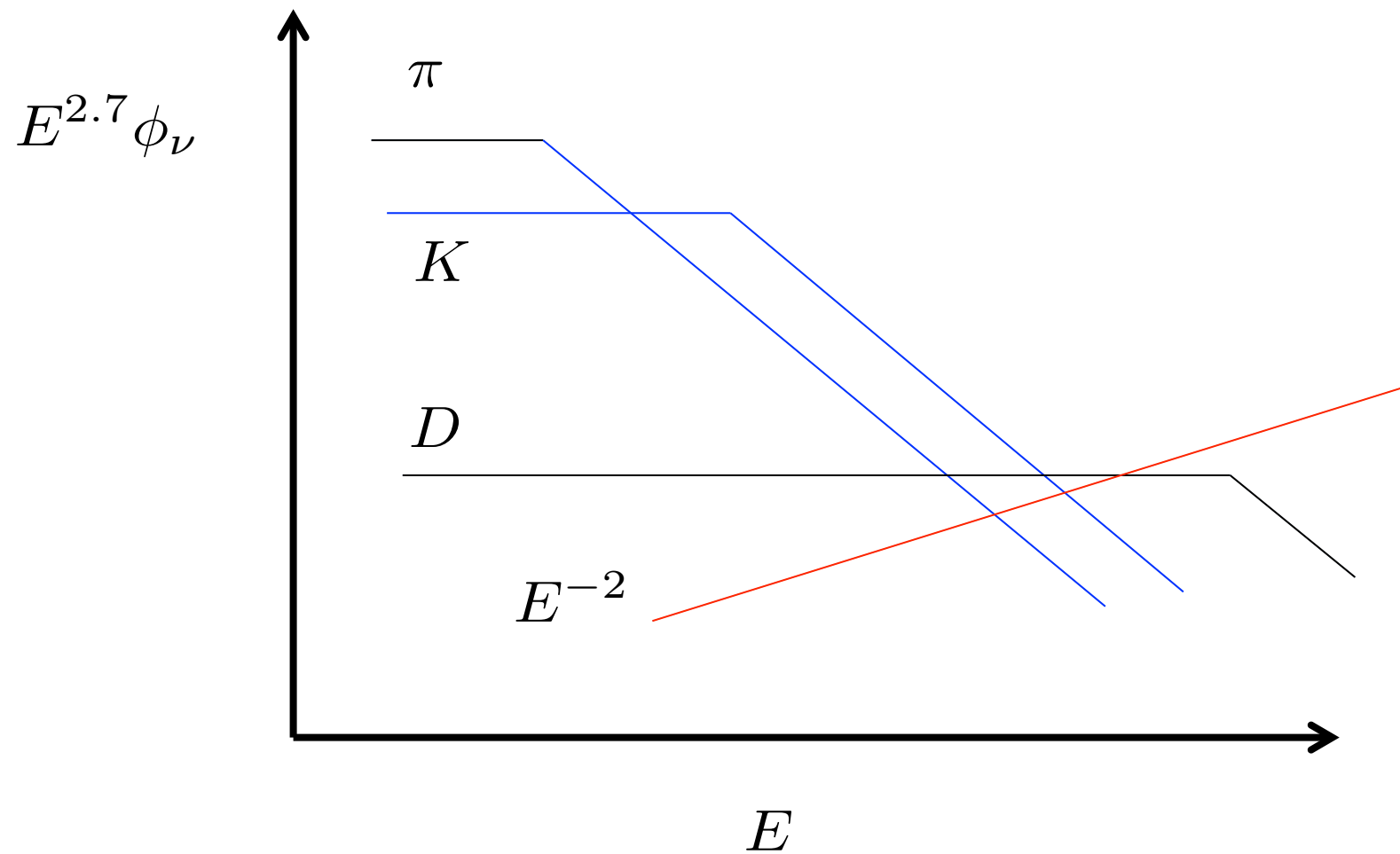


Bai, Diwan, Garzelli, Jeong, Kumar and Reno, arXiv:2212:07865;
J. L. Feng et al., J. Phys.G 50 (2023) 3, 030501

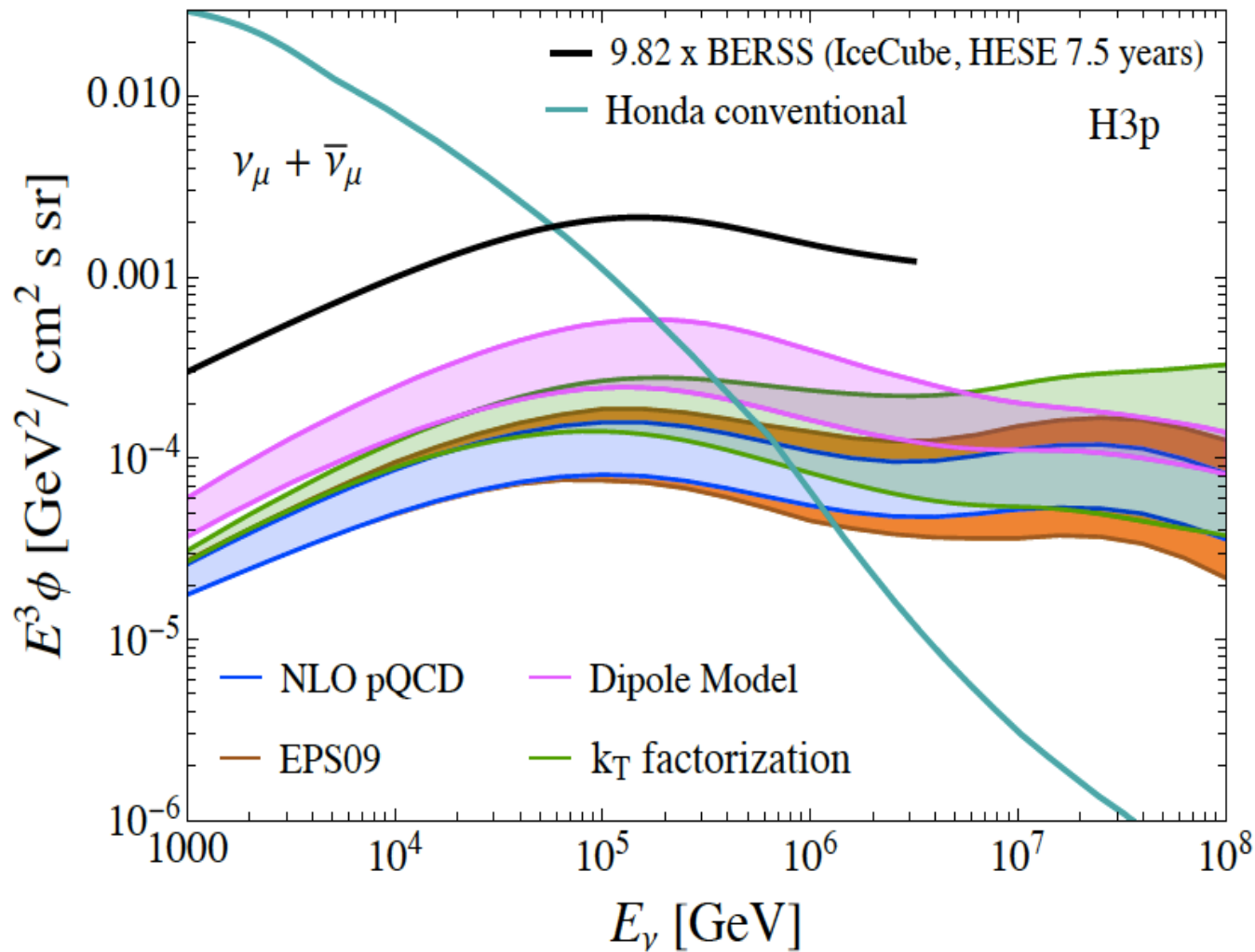
Prompt neutrino flux

- Hadrons containing heavy quarks (*charm or bottom*) are **extremely short-lived**:
 - ⇒ decay before losing much energy
 - ⇒ neutrino energy spectrum is harder
- However, production cross-section is much smaller
- There is a cross-over energy above which prompt neutrinos dominate over the conventional flux
- This is called the atmospheric *prompt neutrino flux*

Schematically



Prompt Neutrino Flux



A. Bhattacharya, R. Enberg, Y.S. Jeon, M.H. Reno, I. Sarcevic and A. Stasto, JHEP 11 (2016) 167

Conclusion

High energy muon and electron neutrinos and all of tau neutrinos produced in the forward region, come from the decay of charmed mesons. Forward neutrinos are probe of QCD at small x and small Q^2 .

We use fits to LHCb data to constraint QCD parameters. FASER (FPF) will probe different kinematic region, providing information about importance of non-linear effects and saturation that is relevant in the forward region

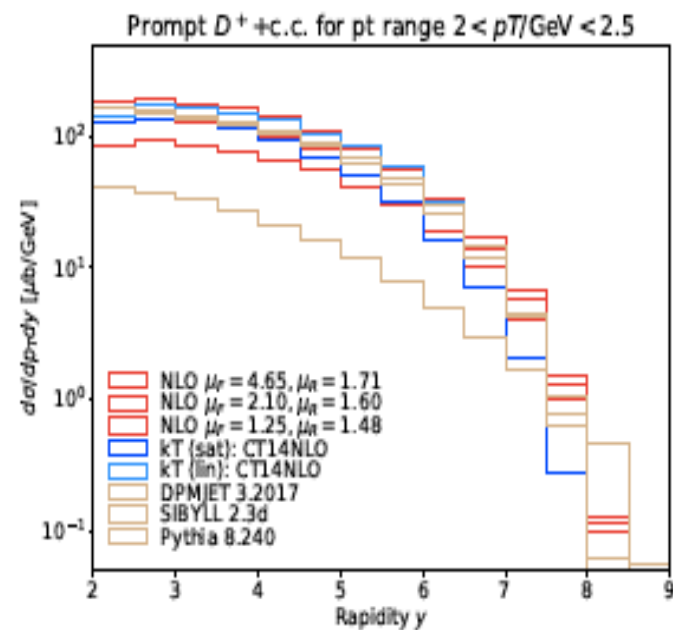
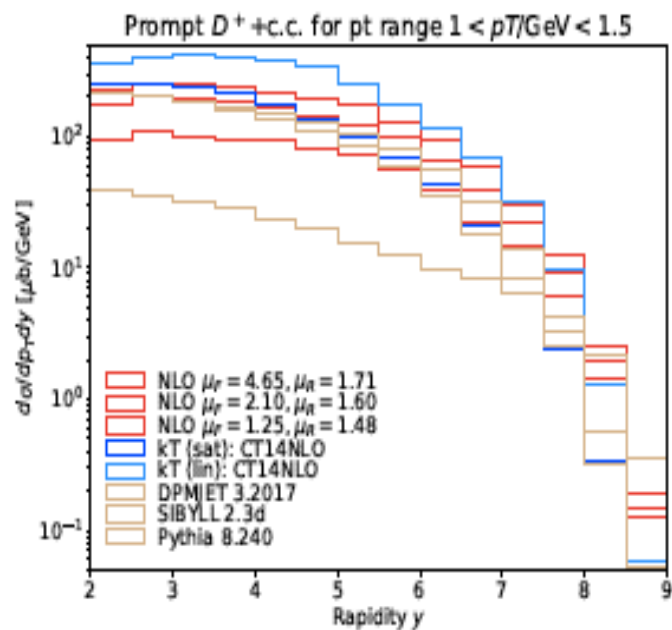
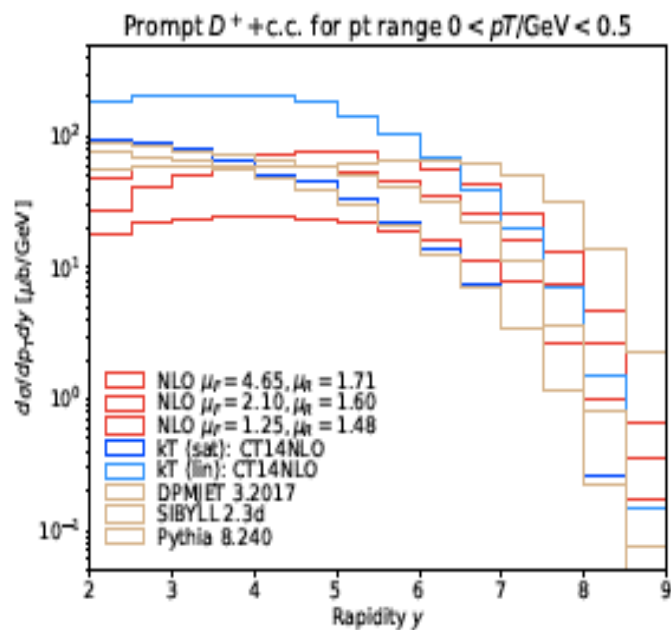
Prompt atmospheric neutrino flux has the same QCD input, but it is folded with the cosmic ray flux. Connection to forward neutrino production at the

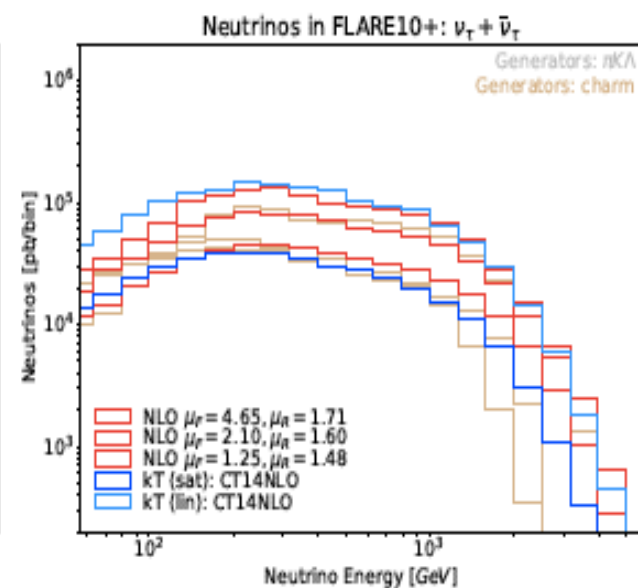
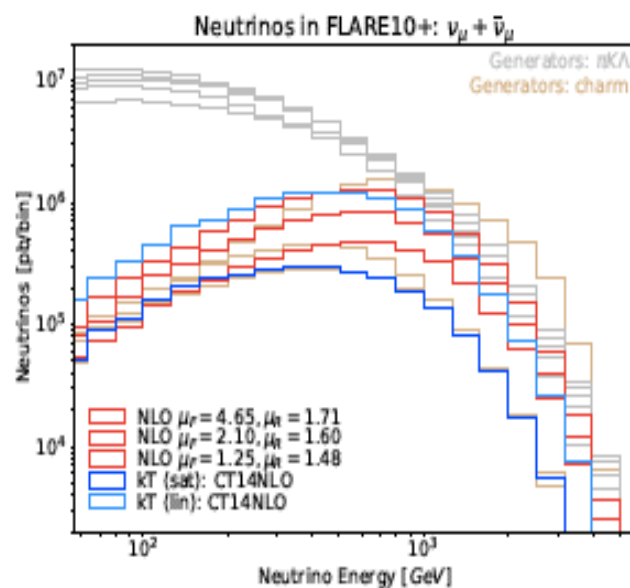
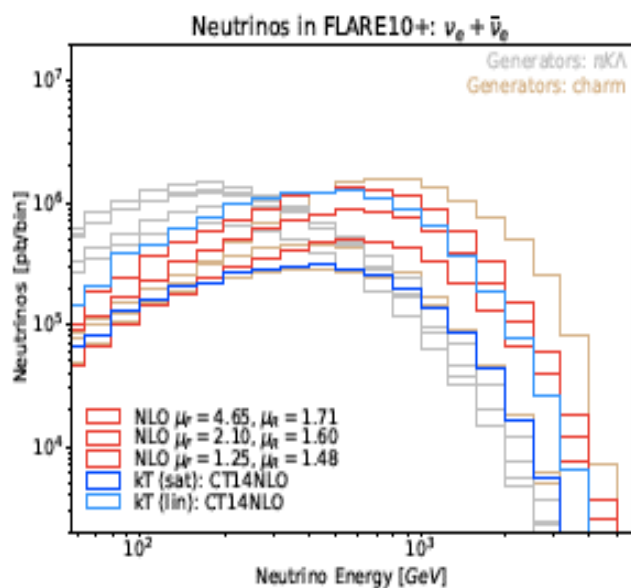
HL-LHC, i.e. measurements with FASER can reduce theoretical uncertainties in the prediction of the prompt neutrino flux

It is important to pursue Forward Physics Facility Program at HL-LHC and Neutrino telescopes such as IceCube-Gen2, km3Net.. Study correlations between these experiments, as well as multimessengers (gamma rays, cosmic rays, etc)

Backup Slides

Experiments The FPF is uniquely suited to exploit physics opportunities in the far-forward region, because it will house a diverse set of experiments, each optimized for particular physics goals. The envisioned experiments and their physics targets are shown in Fig. 2. FASER2, a magnetic spectrometer and tracker, will search for light and weakly-interacting states, including long-lived particles, new force carriers, axion-like particles, light neutralinos, and dark sector particles. FASER ν 2 and Advanced SND, proposed emulsion and electronic detectors, respectively, will detect $\sim 10^6$ neutrinos and anti-neutrinos at TeV energies, including $\sim 10^3$ tau neutrinos, the least well-understood of all known particles. FLArE, a proposed 10-tonne-scale noble liquid detector, will detect neutrinos and also search for light dark matter. And FORMOSA, a detector composed of scintillating bars, will provide world-leading sensitivity to millicharged particles and other very weakly-interacting particles across a large range of masses.



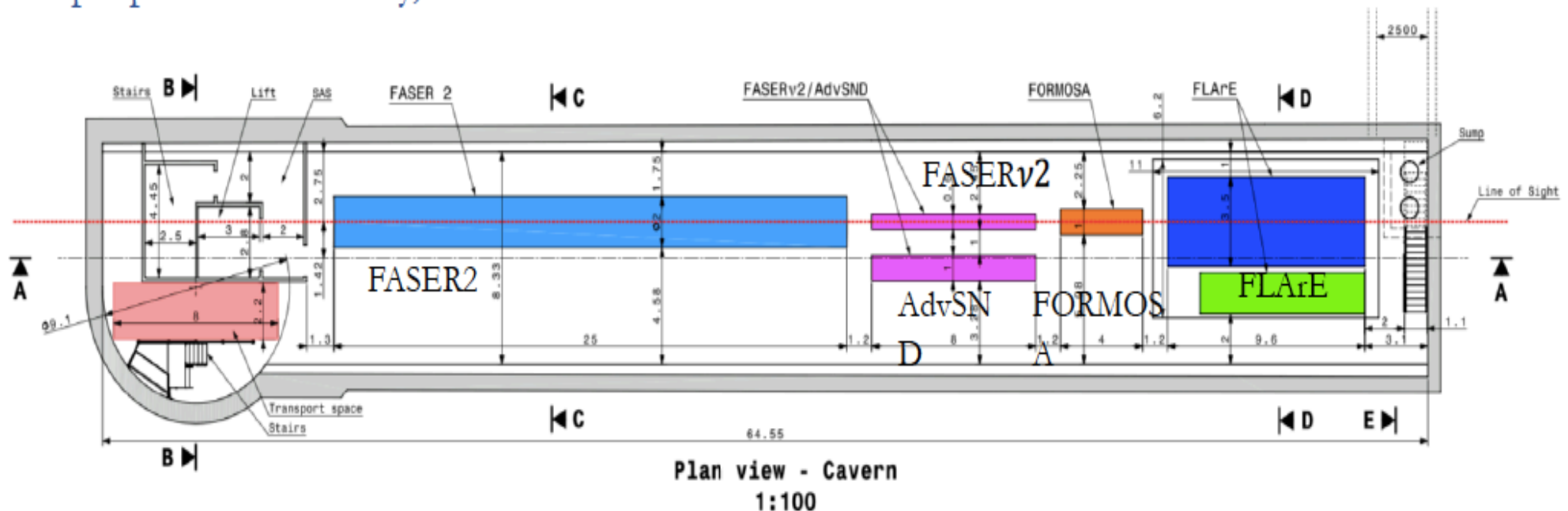


Proposed Experiments

- FLArE – *neutrinos*, LArTPC
- FORMOSA – Forward MicroCharge Search, BSM search, plastic scintillator

In a purpose-built facility, would like this:

- FASER2 – BSM search, magnetized spectrometer
- FASERv2 – *neutrinos*, emulsion-based
- AdvSND (and AdvSND2) – *neutrinos*, electronic, calorimeters



Short white paper 2109.10905