Neutrinos, muons and charm production in the atmosphere*

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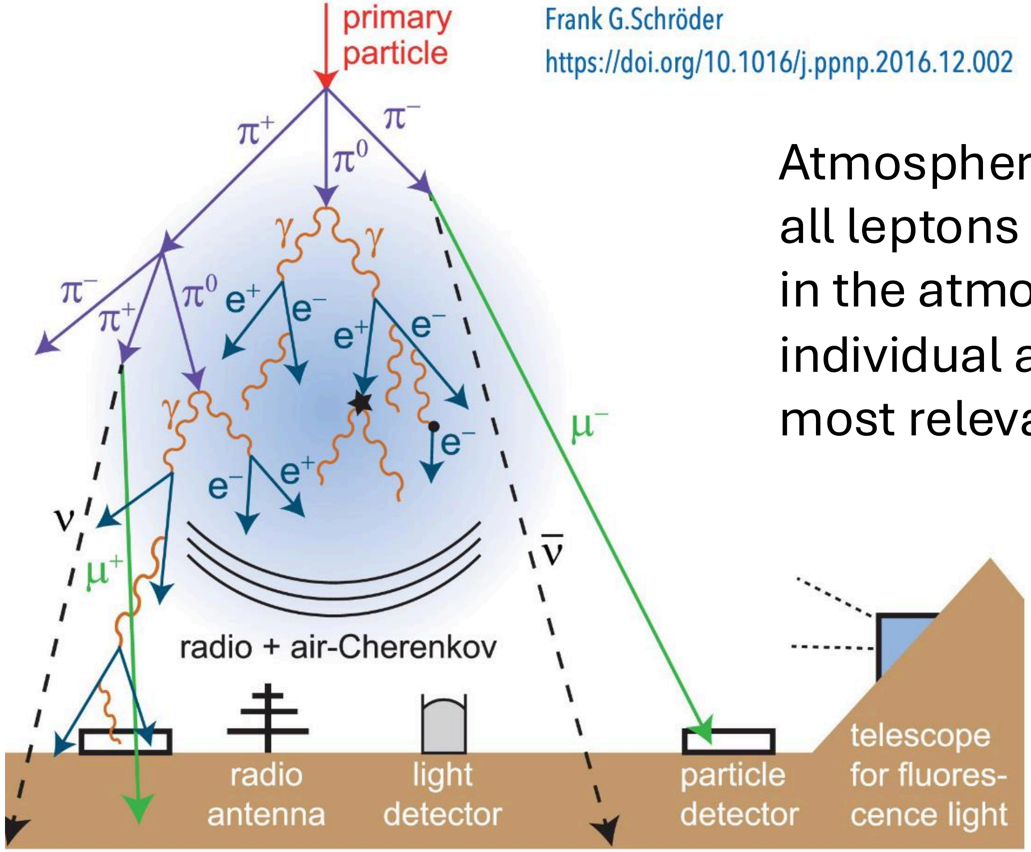
* Das, Garg, Garzelli, Reno, Sigl, arXiv:2512.17886

Atmospheric lepton fluxes

Cosmic rays interact with the atmosphere make to make muons and neutrinos, etc.



Frank G.Schröder
https://doi.org/10.1016/j.ppnp.2016.12.002

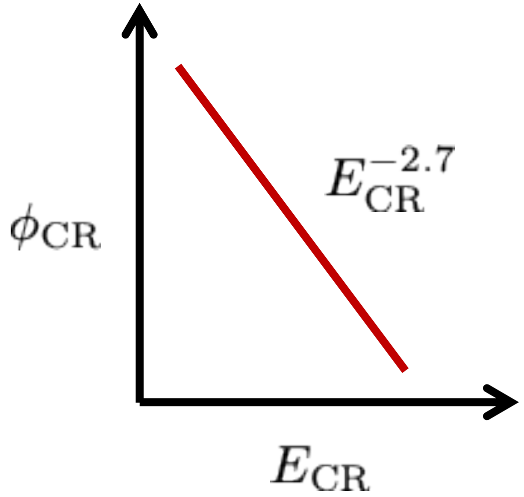
Atmospheric lepton flux: consider flux of all leptons from cosmic ray interactions in the atmosphere, not leptons from one individual air shower. Leading particles most relevant.

atm = atmospheric
not this!

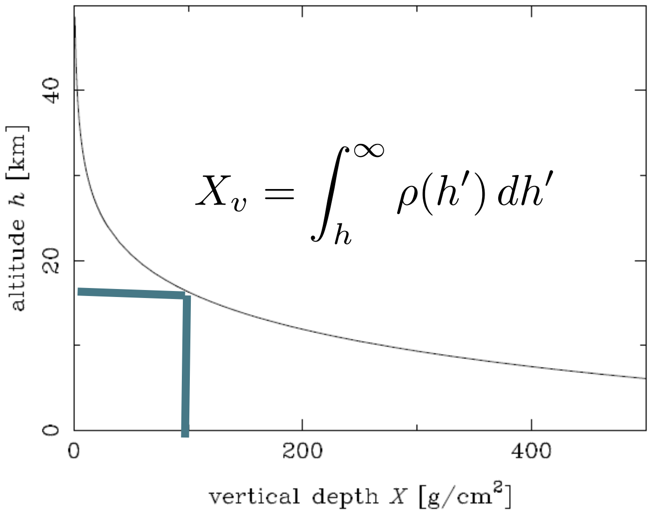
One incident cosmic ray produces an air shower.

Many interactions, spectrum of cosmic rays, consider lepton energy spectrum at the ground.

Cartoon of atm lepton flux above 10 GeV



CRs (nucleons) incident on top of atmosphere pAir, nAir interactions



CRs interact, produce mesons

$\sigma_{N\,\rm air} = 300$ mb $\lambda_N \simeq 80$ g/cm^2

σ nearly independent of E_{CR}

altitude of first interaction (vertical) about h=15 km

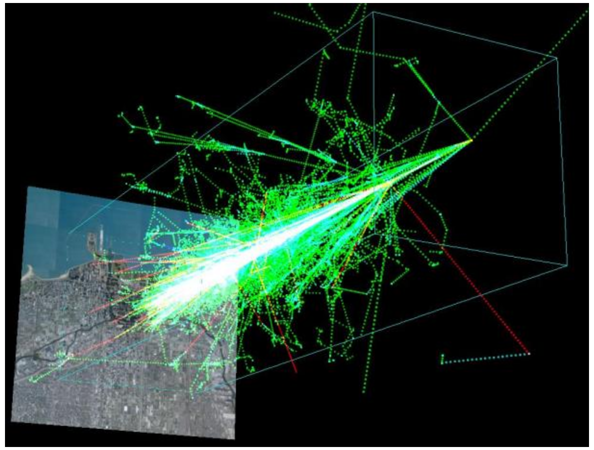
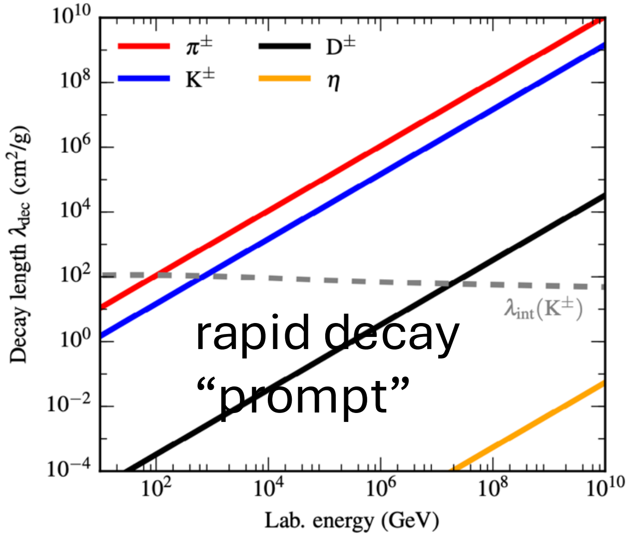


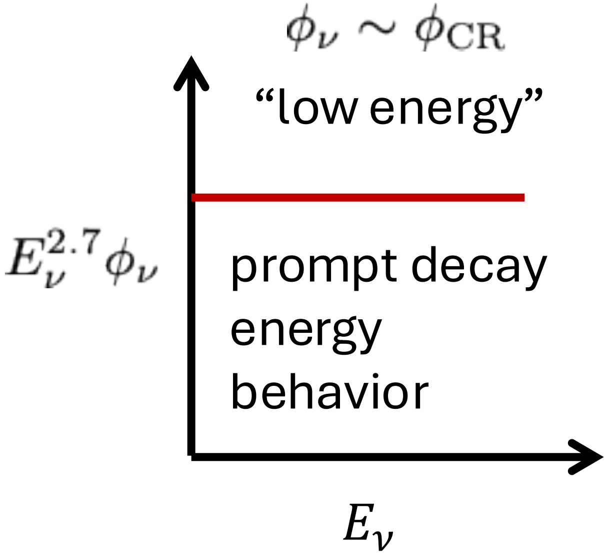
Fig. of Aires simulation of 1 TeV air shower.

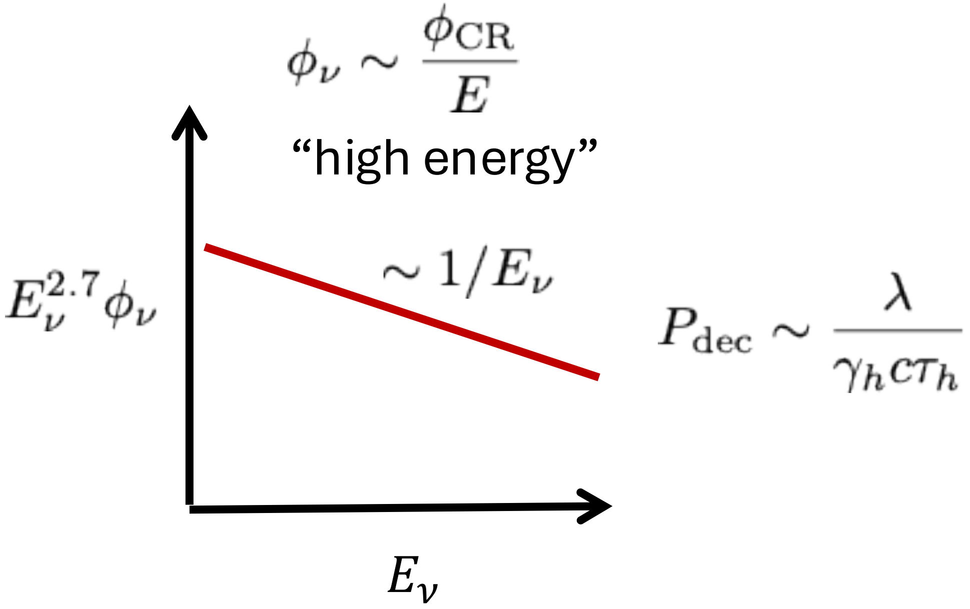
Want all showers, forward, energetic particles at each stage.

http://astro.uchicago.edu/cosmus/projects/aires/

Cartoon of atm lepton flux above 10 GeV







hadrons re-interact or decay
8 km alt example here

Fig. from Yanez & Fedynitch,
PRD 107 (2023) 123037

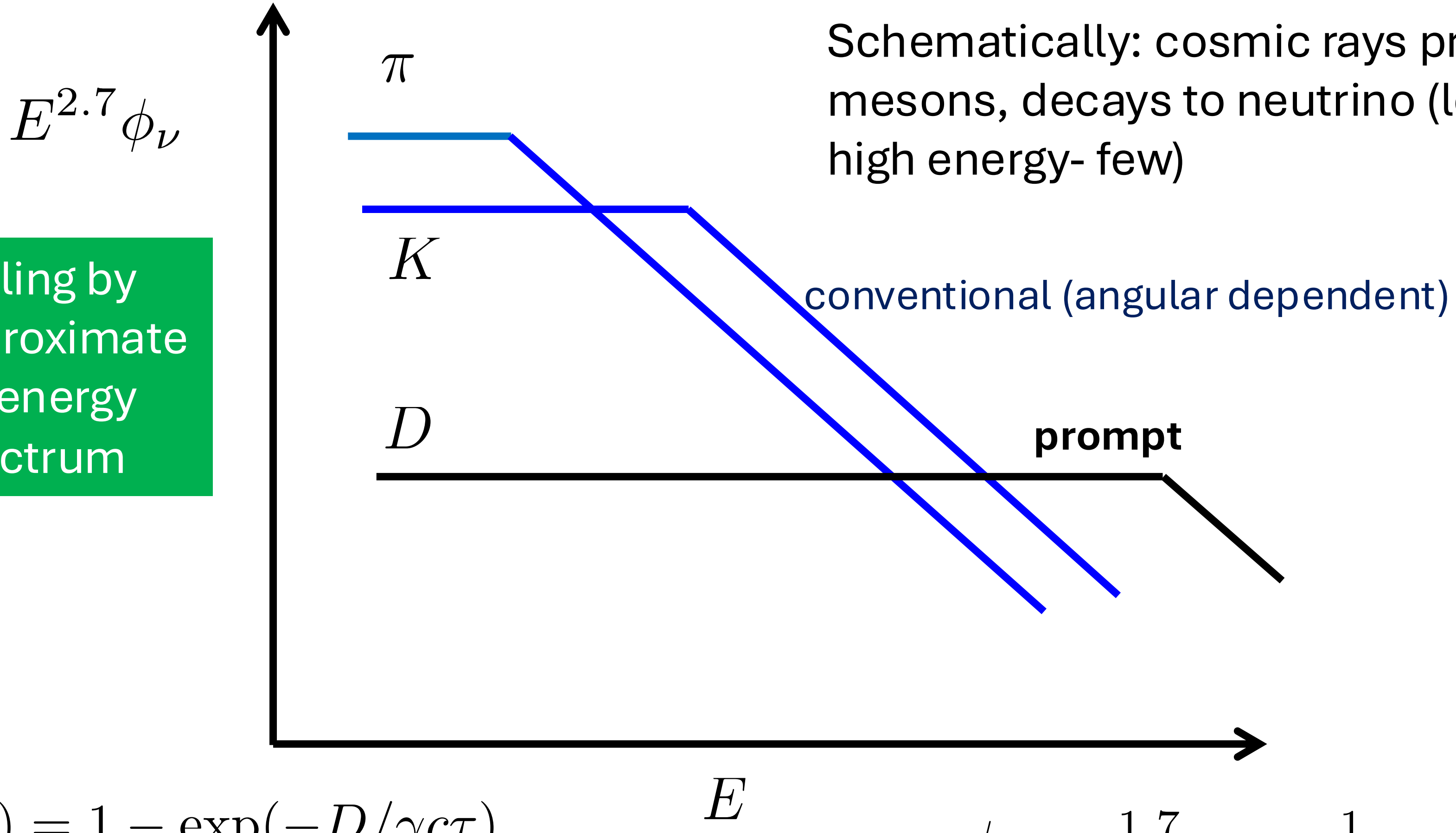
transition from "low energy" to "high energy" depends on lifetime, energy, mass of hadron

Cartoon approximations: power law cosmic ray flux, energy independent hadronic cross sections, Feynman scaling (differential distribution in $x = E_h/E_N$ independent of E_N), vertical, 1-D, column depth factorization.

Atmospheric neutrino fluxes (schematically)

Schematically: cosmic rays produce mesons, decays to neutrino (low energy-all, high energy- few)

Scaling by approximate CR energy spectrum

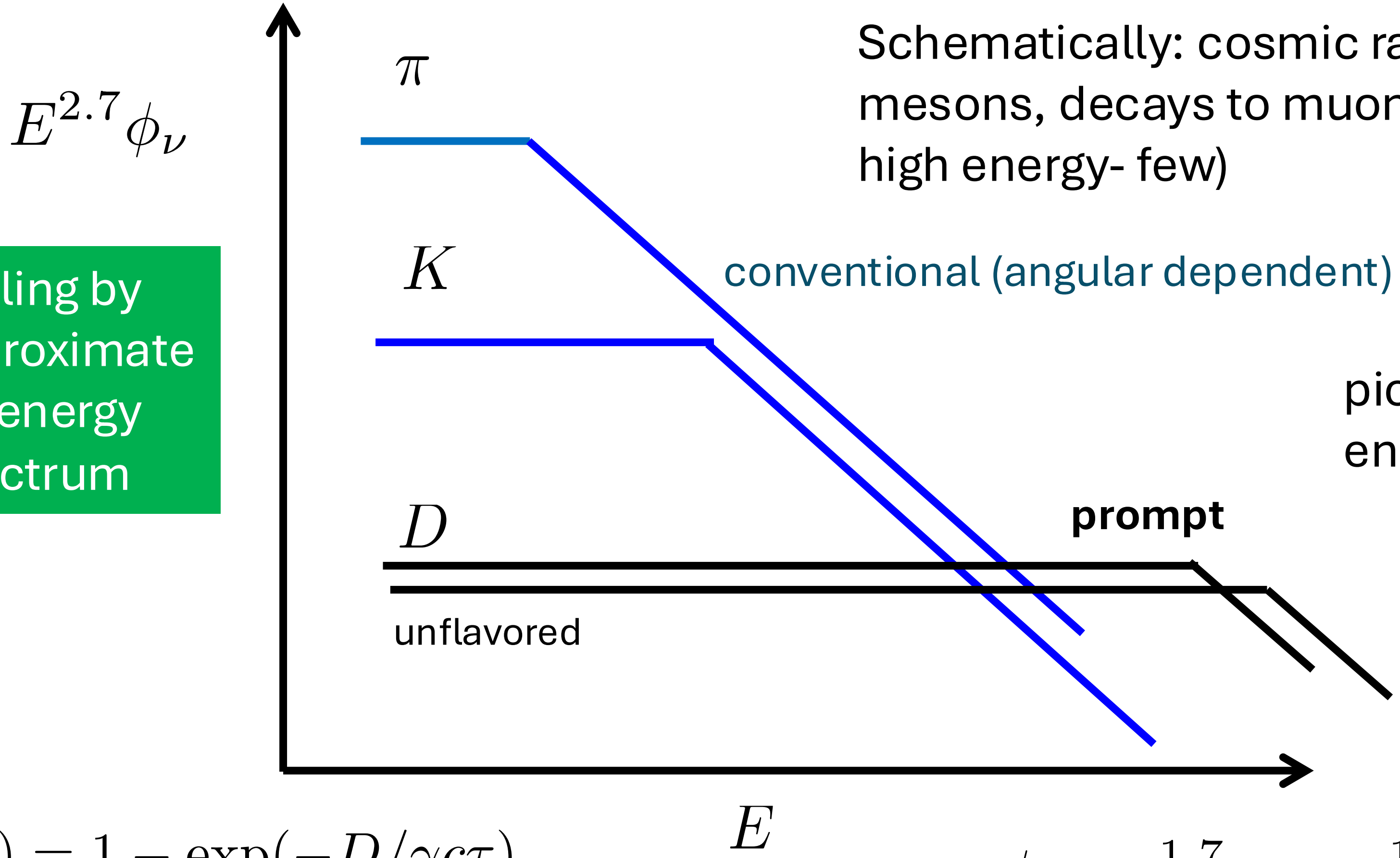


$$P_{decay}(E) = 1 - \exp(-D/\gamma c\tau)$$
$$\simeq D/\gamma c\tau = E_c/E$$

$$\phi \sim \frac{1.7}{E_{\rm GeV}^{2.7}} \frac{1}{\rm cm^2 s\, sr\, GeV}$$

Atmospheric muon fluxes (schematically)

Scaling by approximate CR energy spectrum



Schematically: cosmic rays produce mesons, decays to muon (low energy-all, high energy- few)

pions give almost all energy to muons

$$P_{decay}(E) = 1 - \exp(-D/\gamma c\tau)$$
$$\simeq D/\gamma c\tau = E_c/E$$

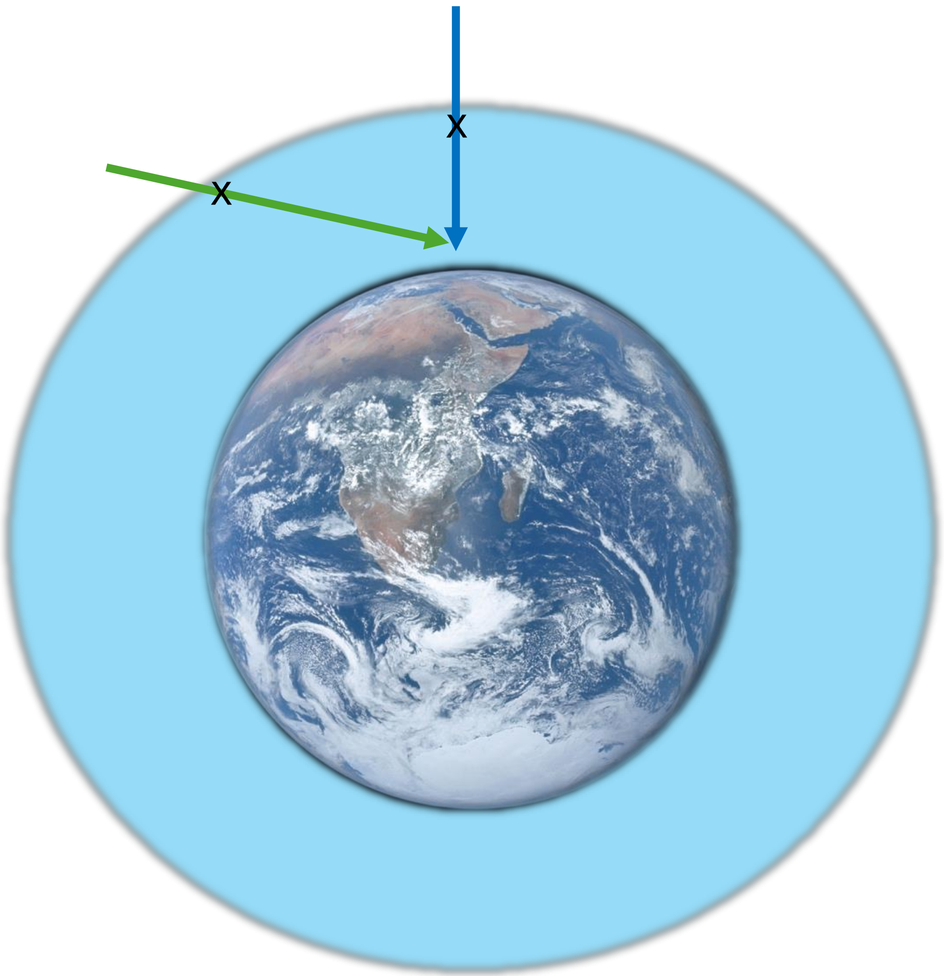
$$\phi \sim \frac{1.7}{E_{\rm GeV}^{2.7}} \frac{1}{\rm cm^2 s\, sr\, GeV}$$

What is the extent to which we can use the prompt muon flux to calibrate charm production/atmospheric neutrino flux?

- Calculation of the flux, MCEq.
- Comparison of neutrino and muon fluxes with data.
- Enhanced charm (let’s call it intrinsic charm).
- Potential for FASER, future Forward Physics Facility input.

Also works for BSM particle production:
Semi-analytic, see Bhattacharya+ JCAP 10 (2025) 007

Cascade equations



tothemoon.ser.asu.edu/gallery/Apollo/17/

The atmospheric lepton flux (at Earth) depends on energy, angle:

$$X = \int_0^l dl'\, \rho(h(l'))$$

Coupled cascade equations:

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

Production or decay:

this emphasizes leading particle(s)

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

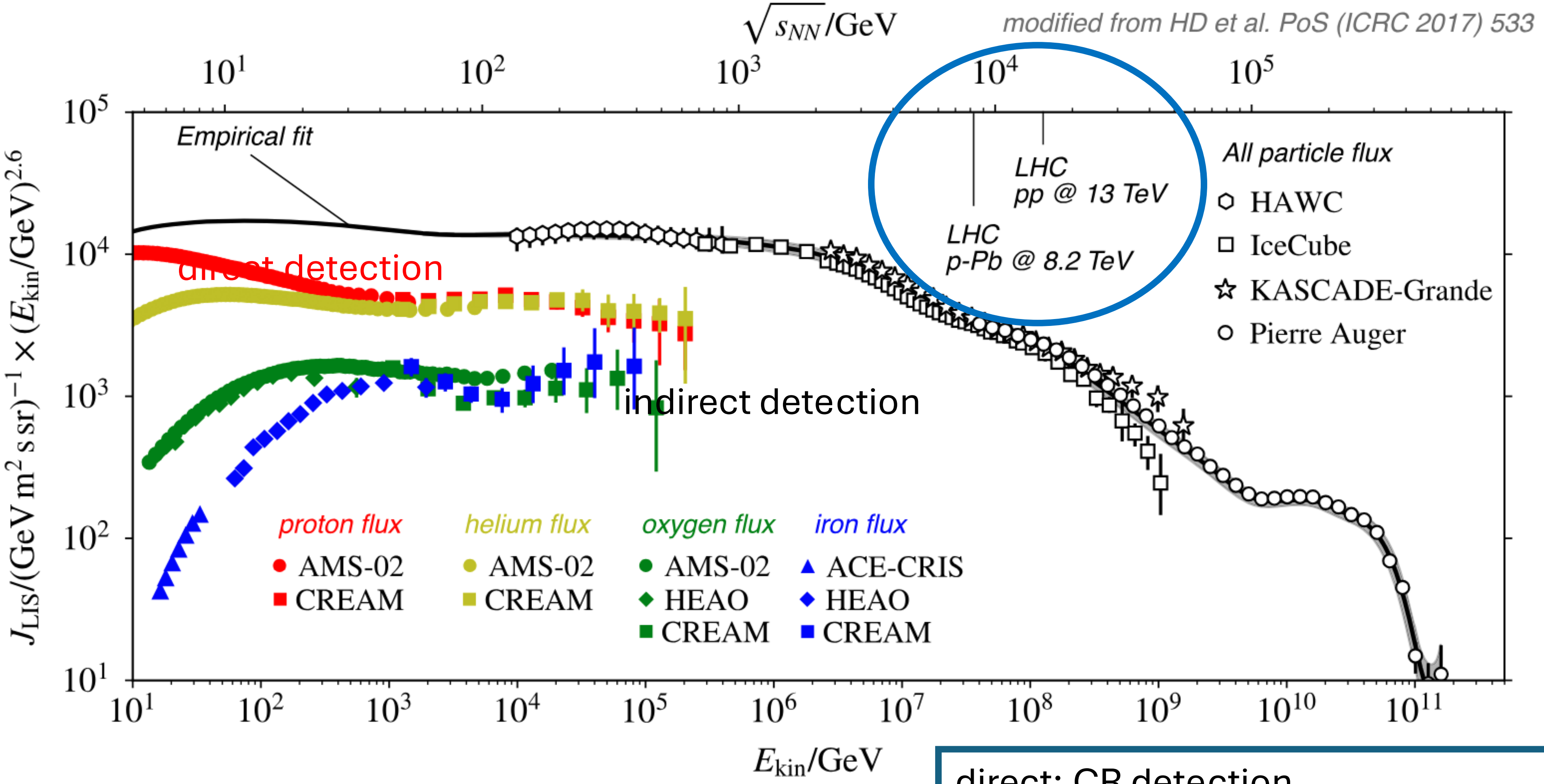
$j = N, \pi, K, D, \ldots, \nu_\mu, \nu_e, \mu$ (also need EM loss term)

Approximations & Uncertainties

- geometry: 1-D – good for >100 GeV for sure
- cosmic ray flux, e.g., composition important
- hadronic interactions
  - hadronic cross sections and Feynman scaling (differential distribution in $x = E_h/E_N$ independent of E_N), limited phase space of measurements
  - prompt flux from charm production, uncertainties
  - prompt flux of muons from unflavored mesons

Cosmic ray flux ($E^{2.6}$ scaling)

Scaling by approximate CR energy spectrum



Albrecht+, Astrophys. and Space Sci (2022) 367: 27

direct: CR detection
indirect: detection of showers they make

Cosmic ray composition

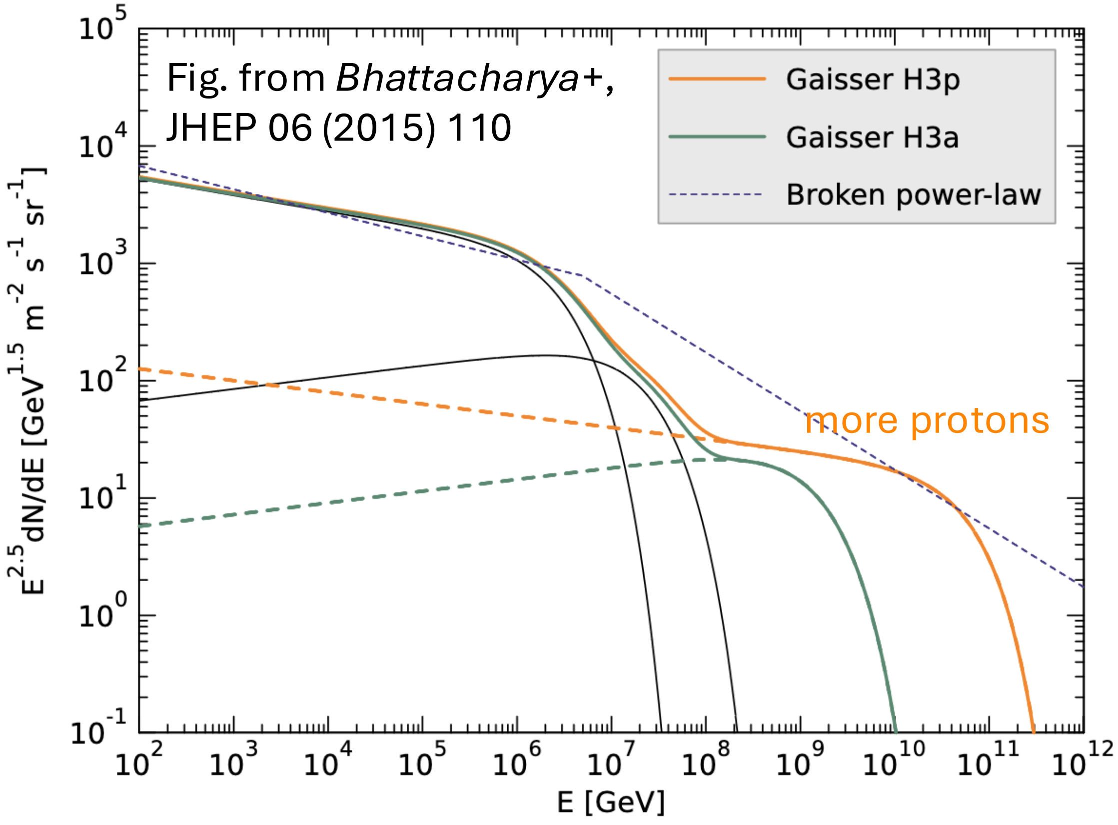
Cosmic ray particle flux (previous slide)

$$\phi_A = \frac{\#}{\mathrm{GeV\,cm^2 s\,sr}} = \frac{dN}{dE_A\, da\, dt\, d\Omega}$$

Cosmic ray nucleon flux

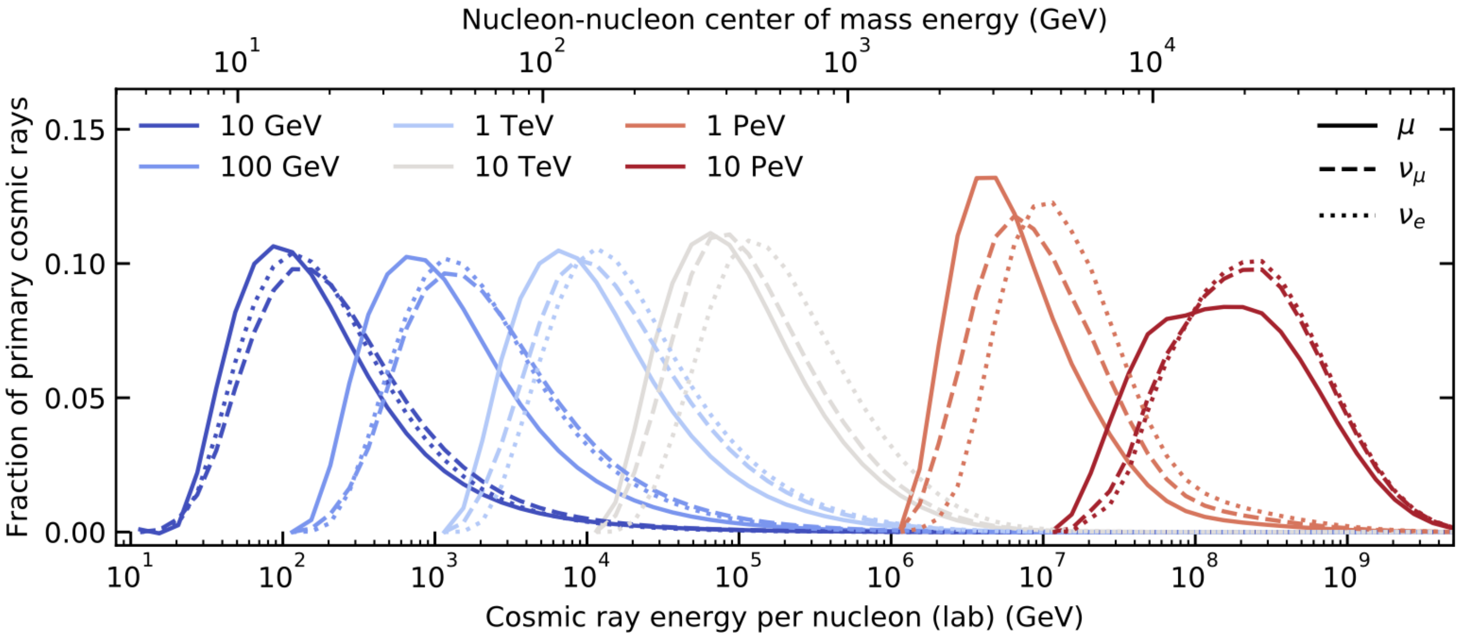
$$\phi_N = A\phi_A(E_A = AE_N)\frac{dE_A}{dE_N}$$
$$= A^2\phi_A(E_A = AE_N)$$

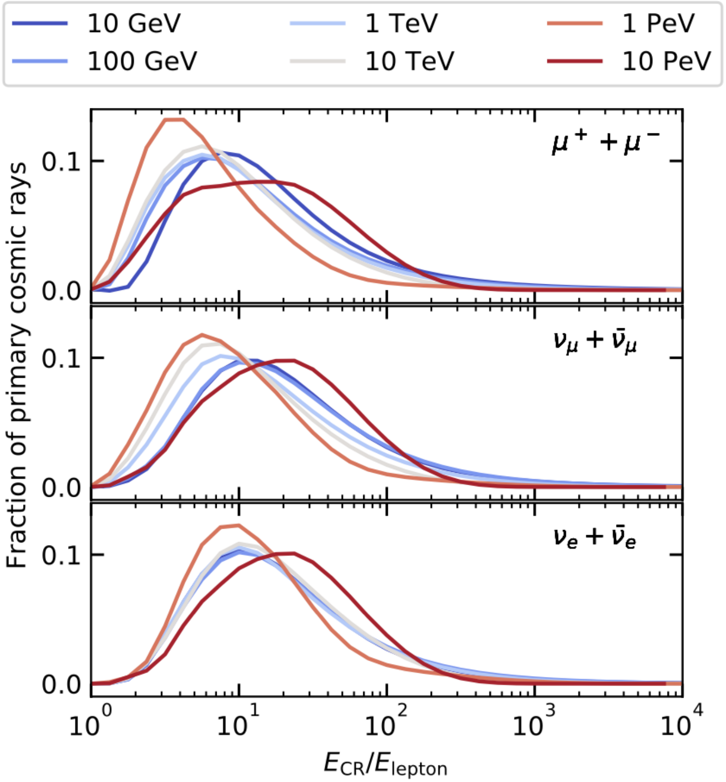
(superposition approximation)



- Broken power law, for apples-to-apples comparisons.
- Clear high energy dependence on composition (more later, not settled).

Cosmic rays – what are the relevant energies?





SIBYLL

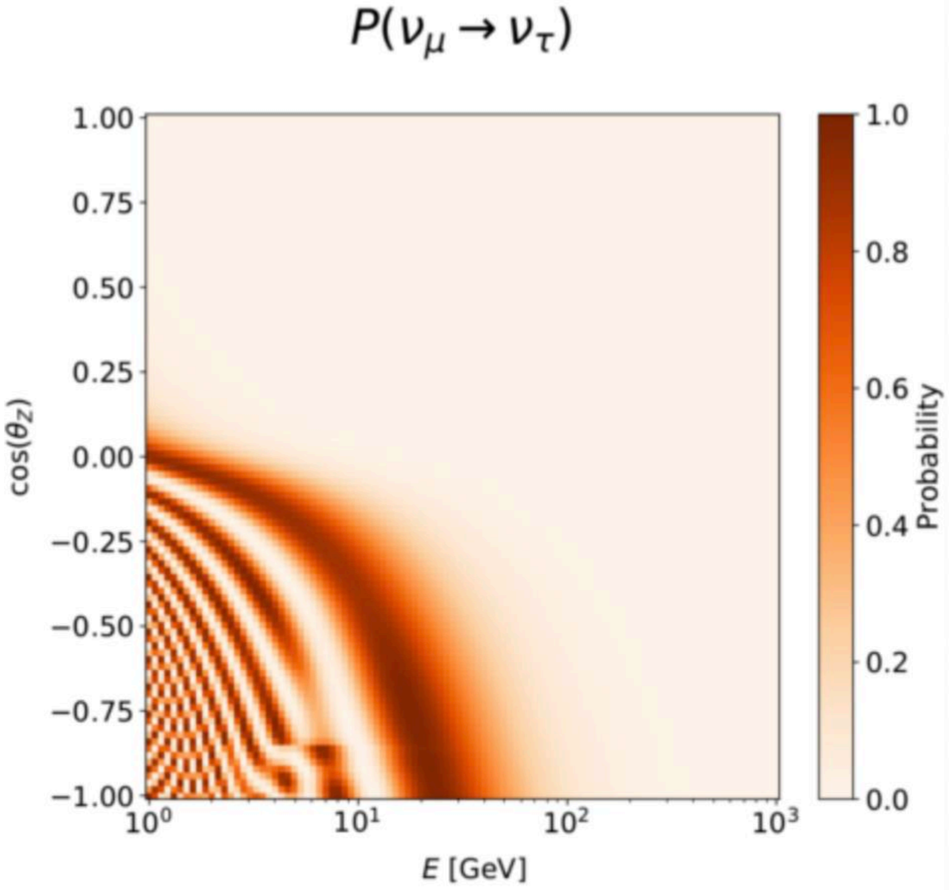
$$\frac{E_{\rm lepton}}{E_{\rm CR}} \simeq 0.1$$

10 GeV leptons, from 20 GeV-2 TeV cosmic rays (dark blue)
1 PeV leptons, from 2 PeV-100 PeV cosmic rays (light red)

Fixed lepton energy in both figures.

Figs. from Fedynitch et al, Phys.Rev.D 100 (2019) 10, 103018

Neutrino propagation



https://nbi.ku.dk/english/research/experimental-particle-physics/icecube/neutrino-oscillation/

Example for propagation in the atmosphere @ 1 TeV:

$$\frac{\Delta m^2/\mathrm{eV}^2 \cdot L/\mathrm{km}}{E/\mathrm{GeV}} \lesssim \frac{10^{-3} \cdot (15-60)}{10^3}$$

We will consider energies (mostly) above 10 TeV.

Energy scaled atmospheric flux (scaling by E^3)

Example: - MCEQ   Fedynitch et al, PRD 100 (2019) 103018

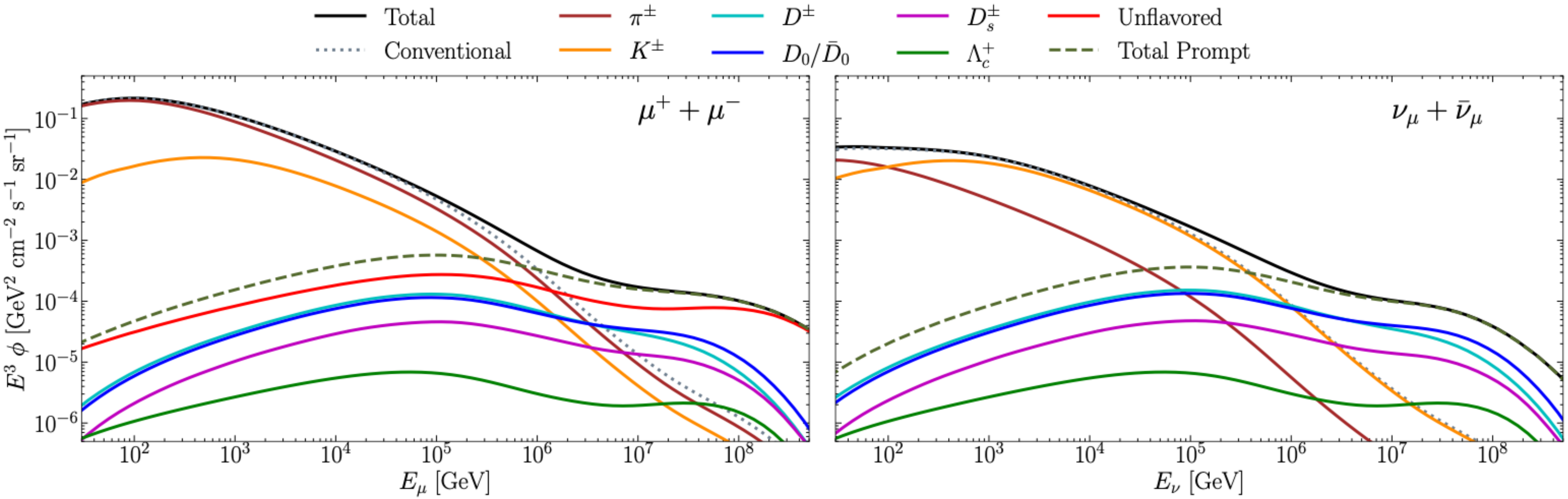


Fig. Laksha Das et al, with MCEq, angle-averaged, SIBYLL 2.3c, H3a (used throughout).

Note: pion to kaon contributions, unflavored meson contribution to muons, charm contributions.

Unflavored mesons to prompt muon flux

unflavored mesons only

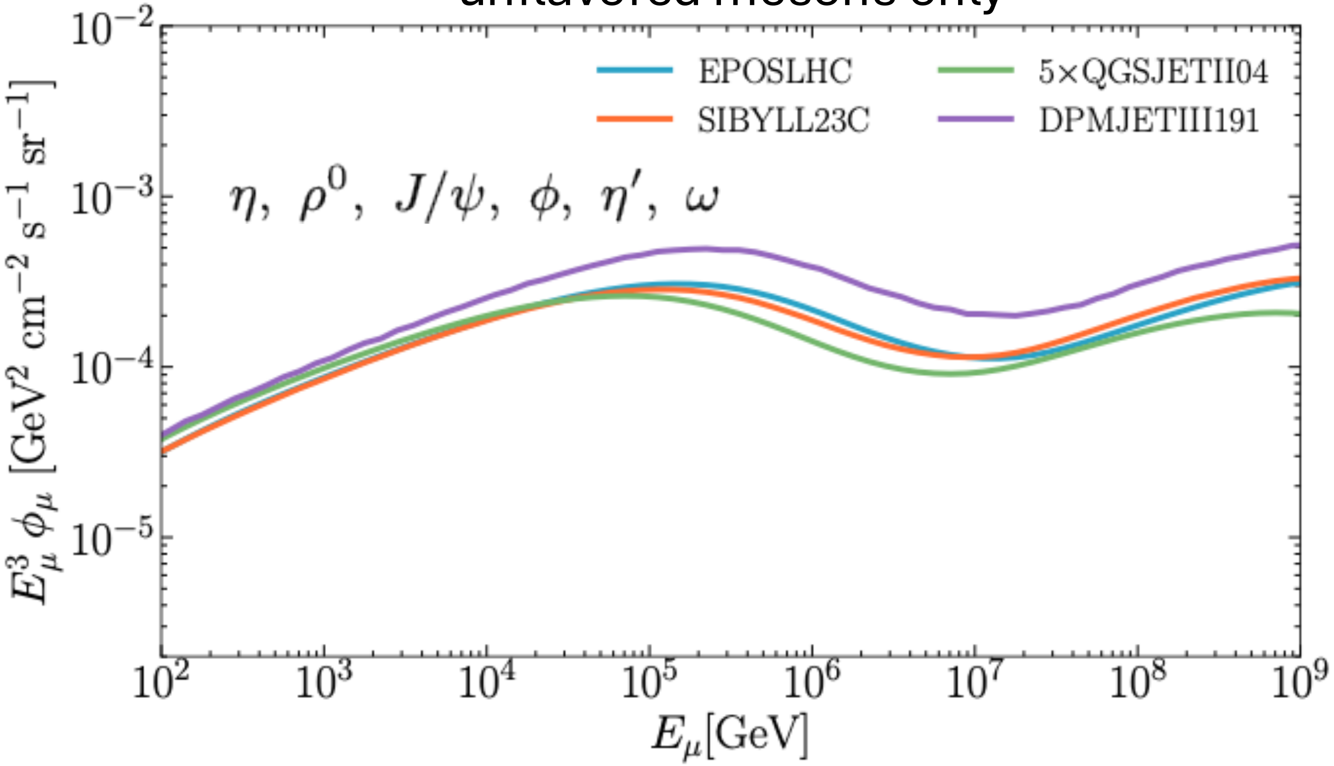


Fig. Laksha Das et al, with MCEq, angle-averaged, H3a.

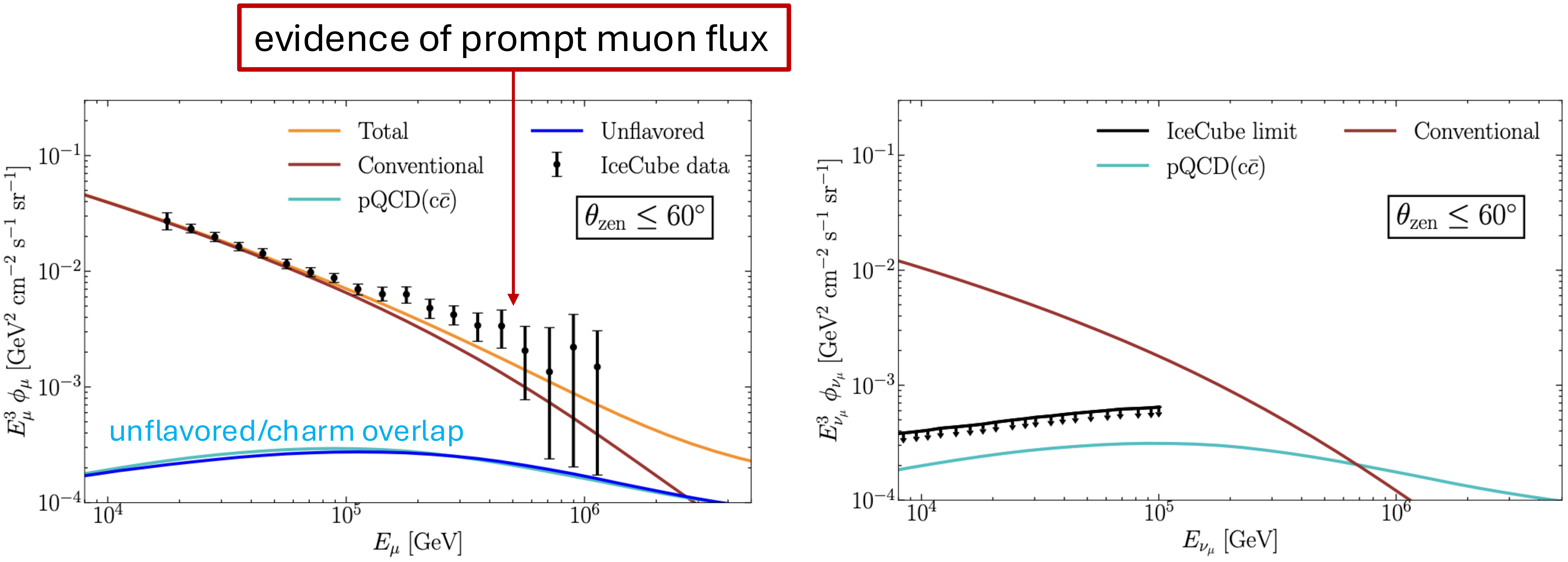
- Can be nearly equal to the prompt flux from charm, or 5x lower (QGSJET).
- Uncertainty interferes with relation between prompt muon and neutrino fluxes.
- From charm only, nearly equal muon and neutrino fluxes.

Role of unflavored mesons:
Illana et al, Astropart.Phys. 34 (2011) 663

Example:

$$B(\eta \to \mu^+\mu^-\gamma) = (3.1 \pm 0.4) \times 10^{-4}$$

Muons

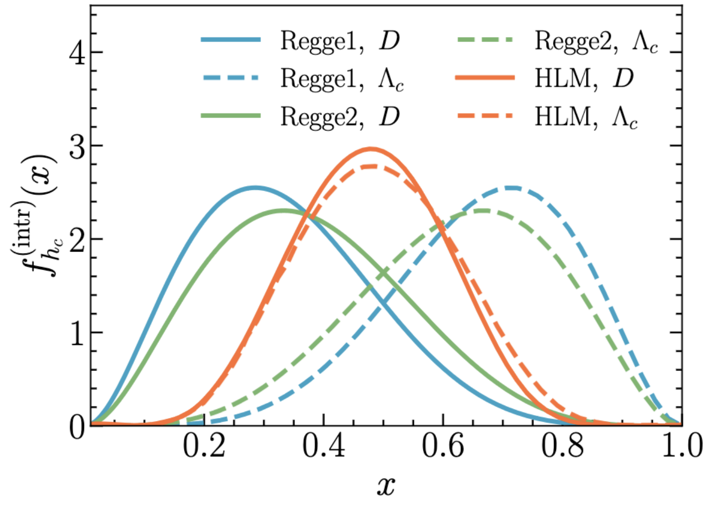


IceCube, muons: 1506.07981, neutrino upper bound: 2512.17760.
Look forward to new muon data.
Used smaller zenith angles because of stated experimental issues with close to the horizon.

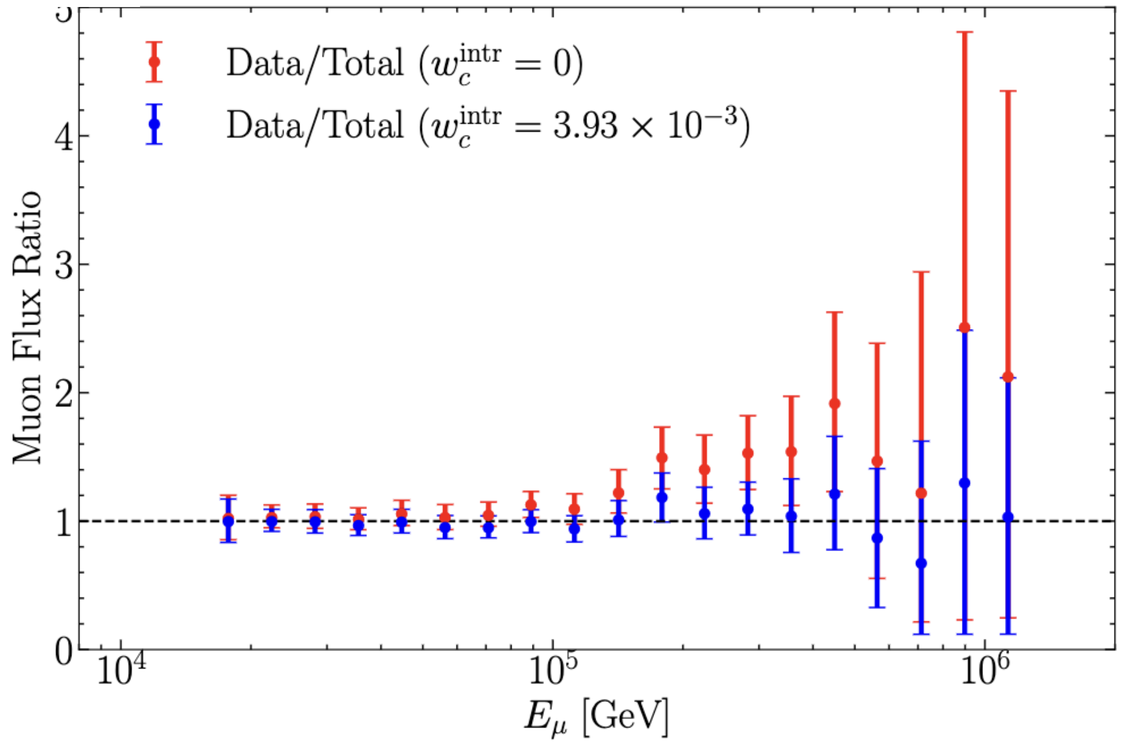
Intrinsic charm - enhance charm contribution to muon flux

$$\frac{d\sigma^{h_c(\mathrm{intr})}_{p-\mathrm{air}}(E_p, x_{h_c})}{dx_{h_c}} = w^c_{\mathrm{intr}}\sigma_{p-\mathrm{air}}(E_p) f^{(\mathrm{intr})}_{h_c}(x_{h_c})$$

$$p + A \to \bar{D}^0 + \Lambda_c + X$$
$$n + A \to D^- + \Lambda_c + X$$

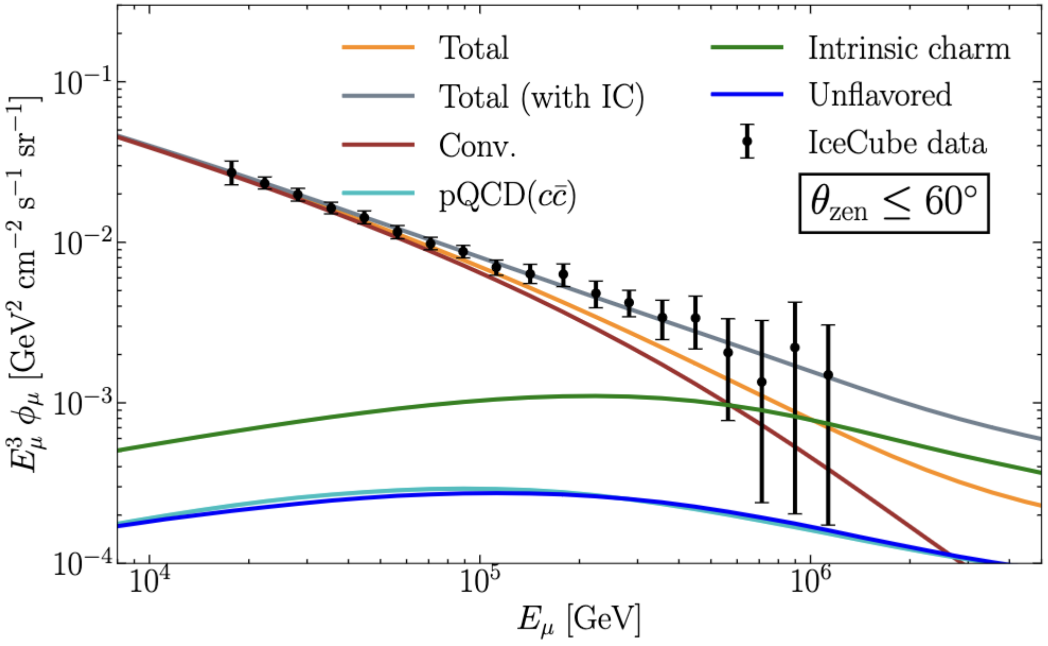


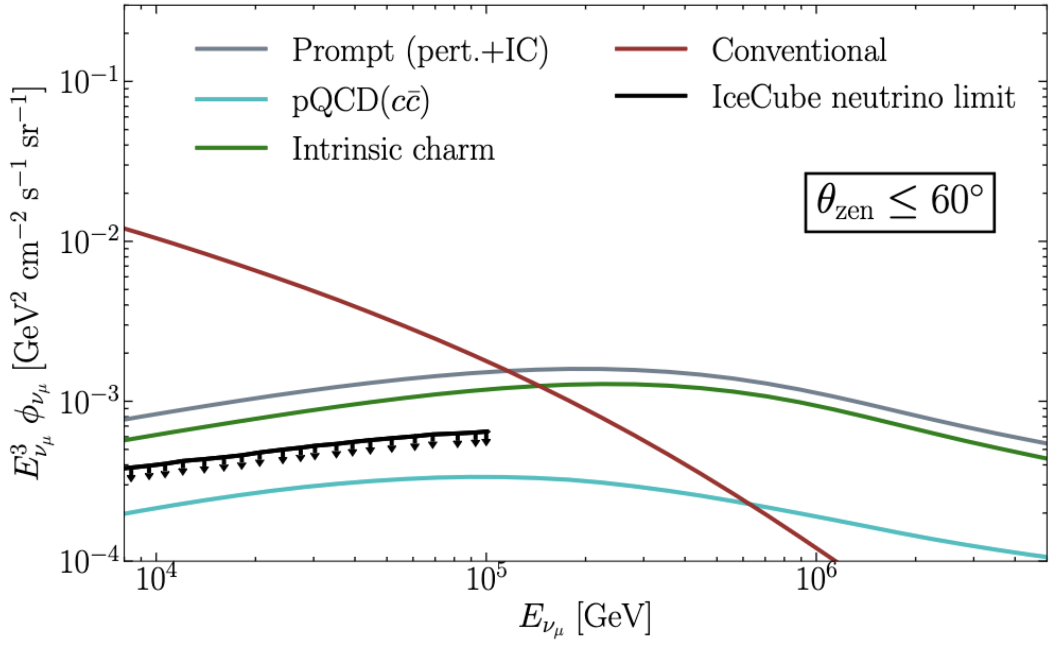
Muon flux: Data/Total



Intrinsic charm saturates prompt muons – exceeds neutrino bounds

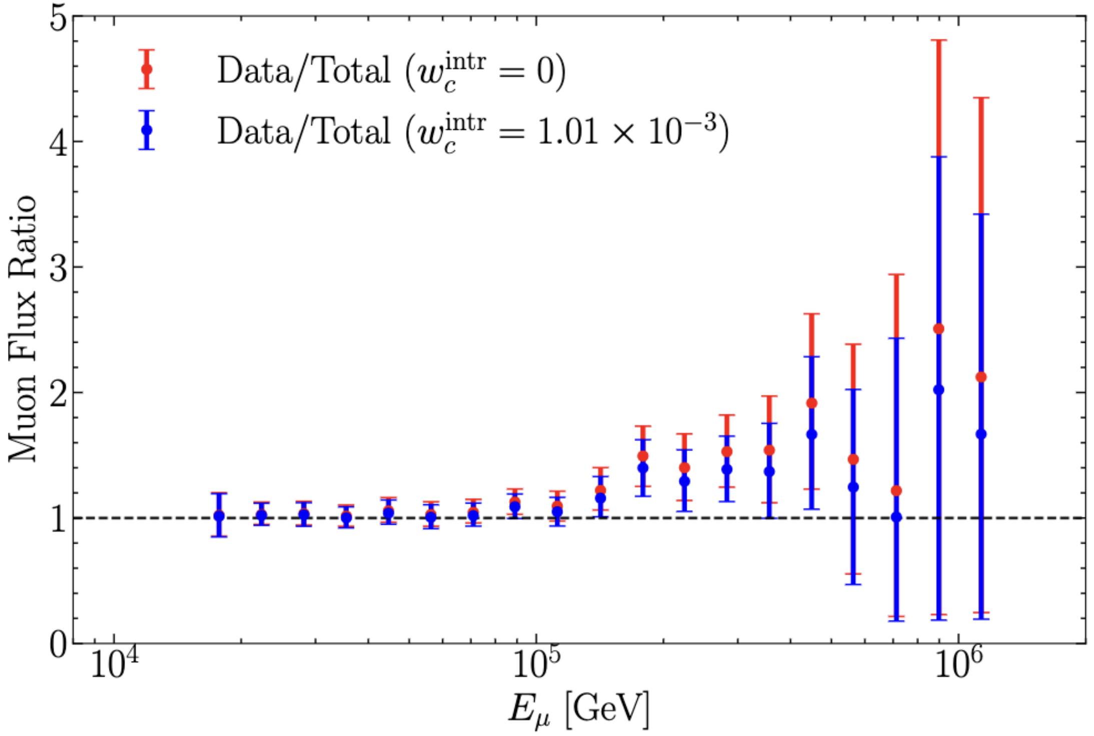
too much charm (above IceCube upper bound)



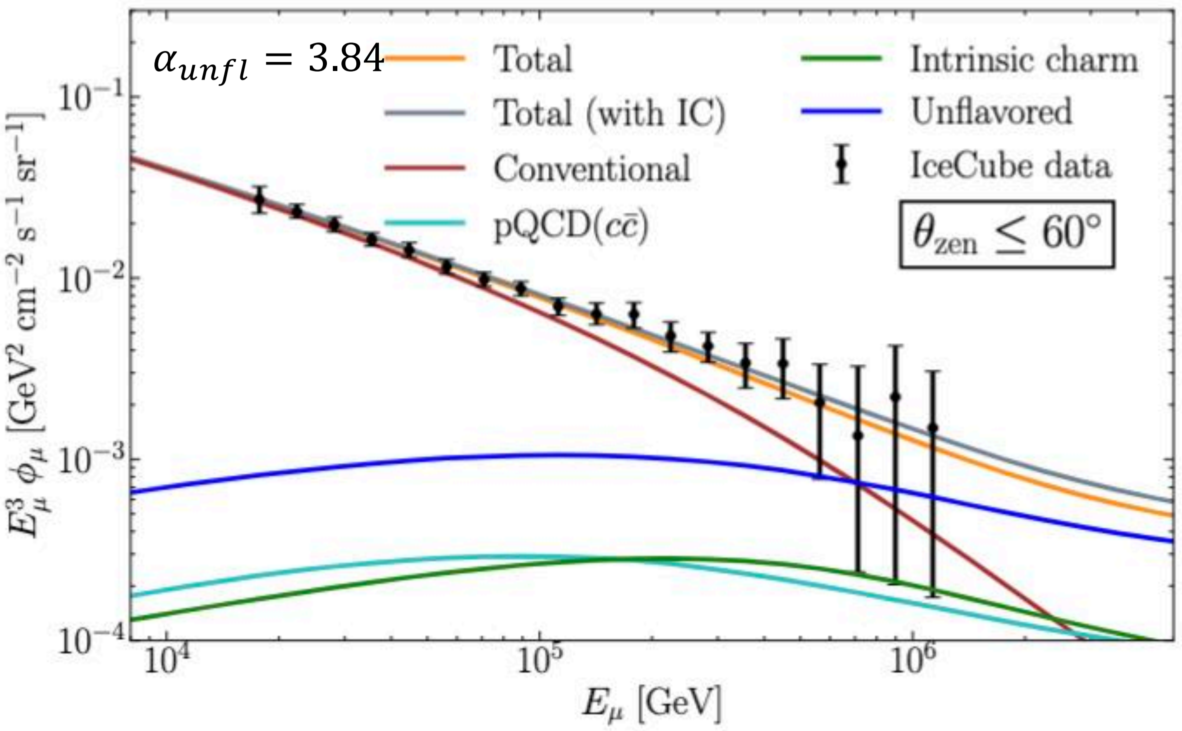


Unflavored light meson enhancements + IC

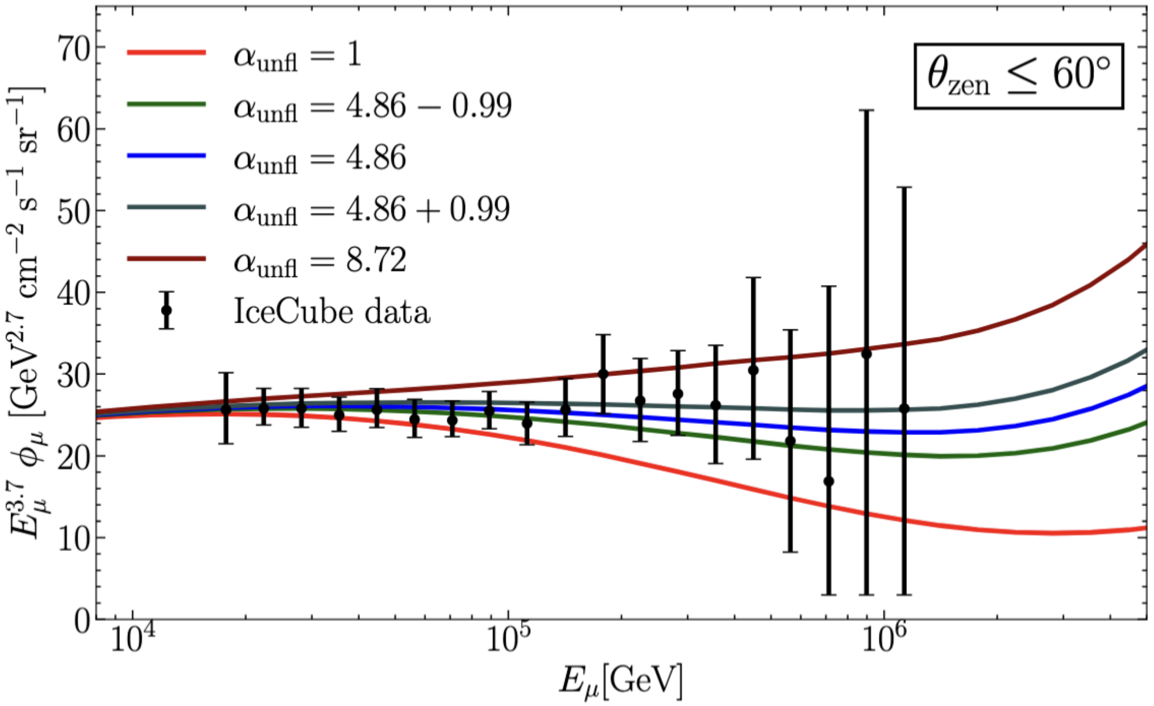
no unflavored light meson enhancement



$$\phi_\mu^{\mathrm{unfl}} = \alpha_{\mathrm{unfl}}\, \phi_\mu^{\mathrm{MCEq,unfl}}$$



Unflavored light meson enhancement (only)



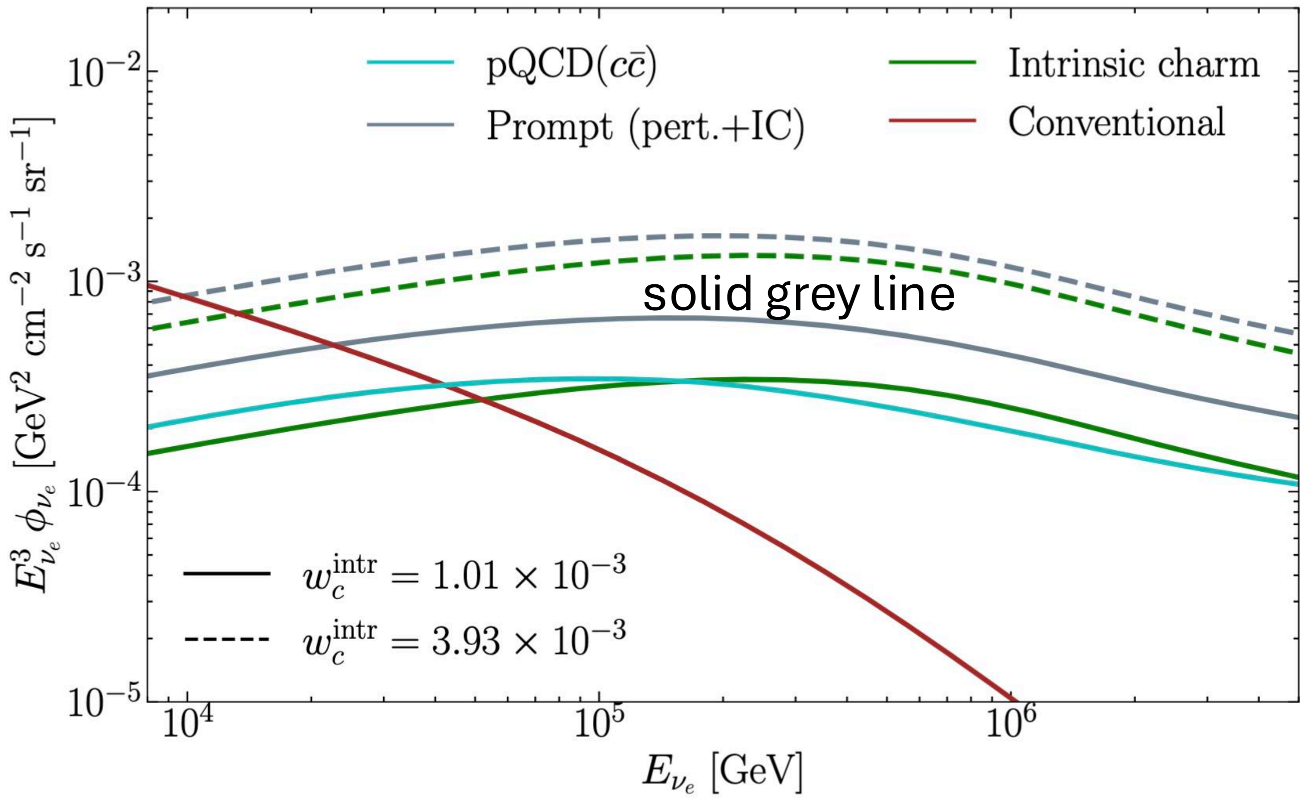
Best fit – with no enhanced charm production is alpha=4.86.
Figure shows a range of values for alpha.

Could this be related to the muon puzzle in cosmic ray air showers (not enough muons in VHE showers)?

$B(\rho^0 \rightarrow \pi^+\pi^-)$ = 100% (approx.)
This is a contribution to conventional muon flux, but rare decays could contribute to prompt muons.

Soldin+, https://arxiv.org/pdf/2509.15426, tuned SIBYLL*.

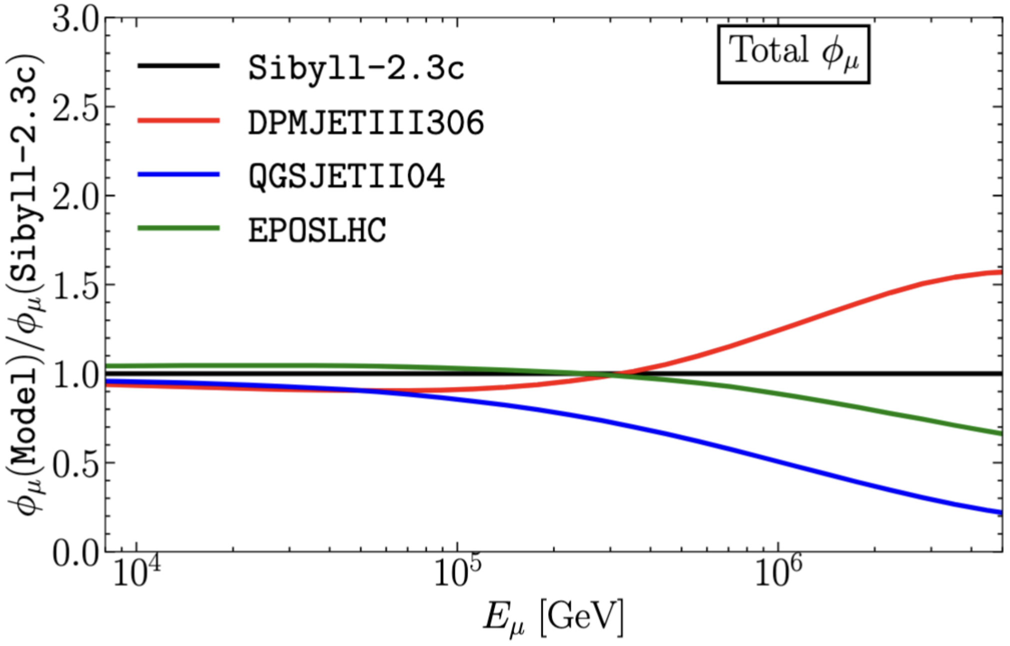
Electron neutrinos

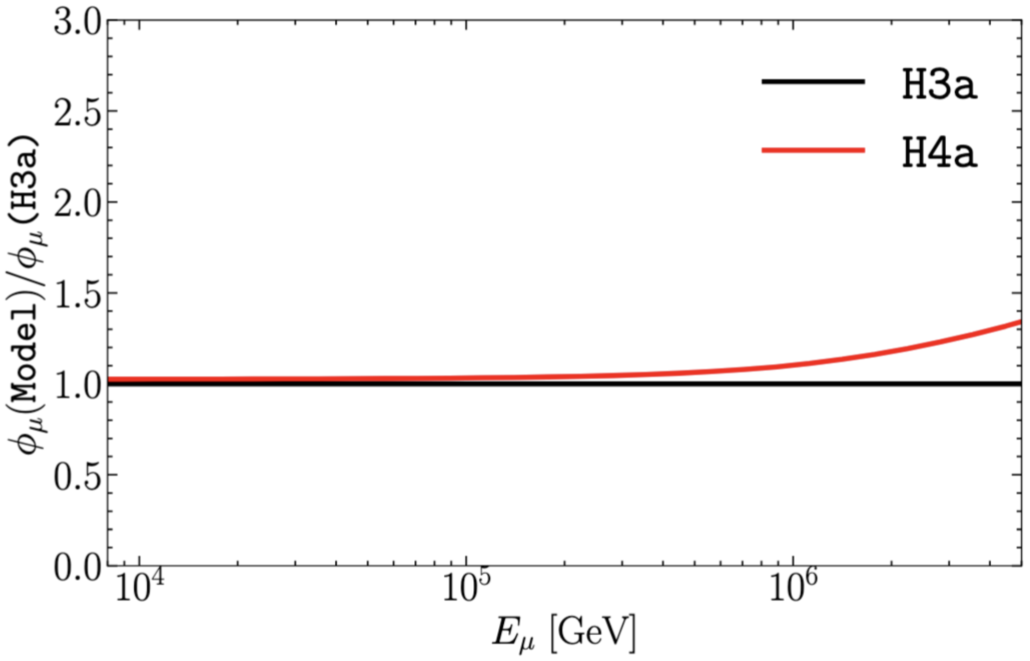


Solid grey line saturates the IceCube upper bound. (Dashed lines exceed.)

Electron neutrino prompt flux emerges at a lower energy than muon neutrino prompt flux.

Uncertainties include MC (charm production), cosmic ray flux





We are investigating other cosmic ray flux models (composition).

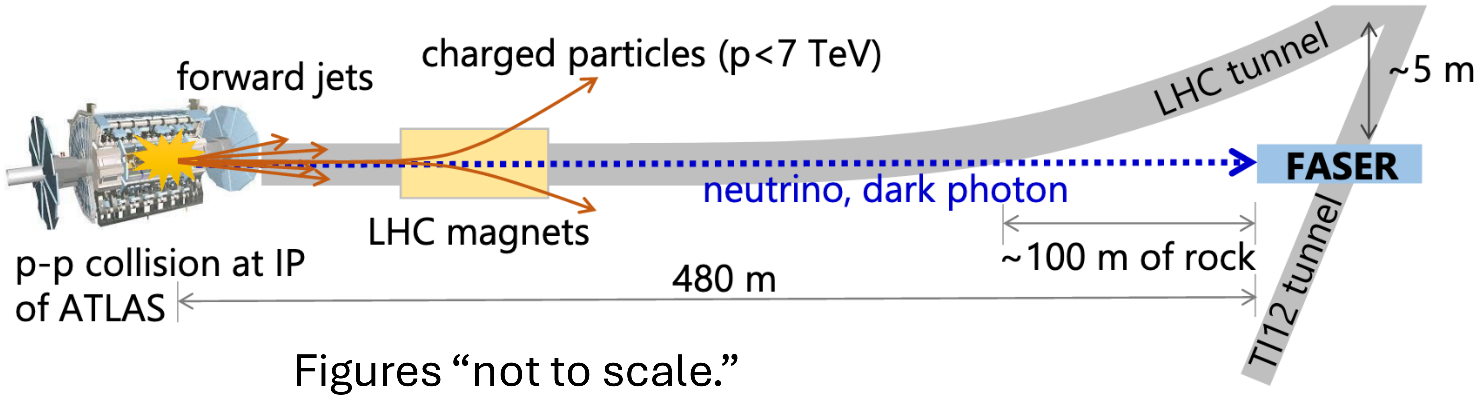
Neutrinos @ LHC Run 3

Both experiments installed, in T12 and T18 existing injector tunnels on either side of the ATLAS IP.

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

θ	η
0°	∞
0.1°	7.04
[illegible]	[illegible]

FASERν

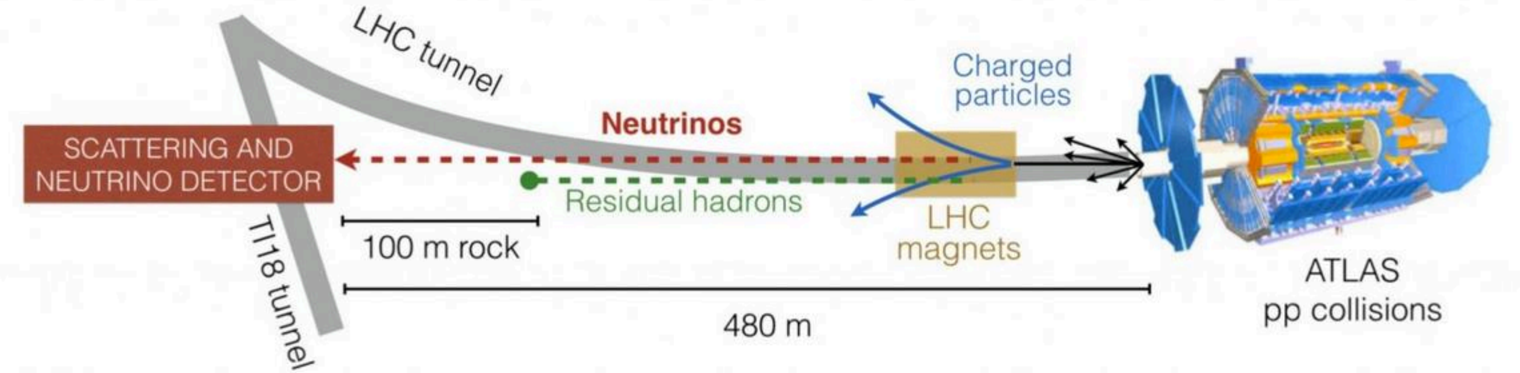


Figures “not to scale.”

FASERν 1.2 ton, 25 cm x 25cm

on axis, $\eta > 8.5$

SND@LHC



https://www.epfl.ch/labs/lphe/en/4266-2/

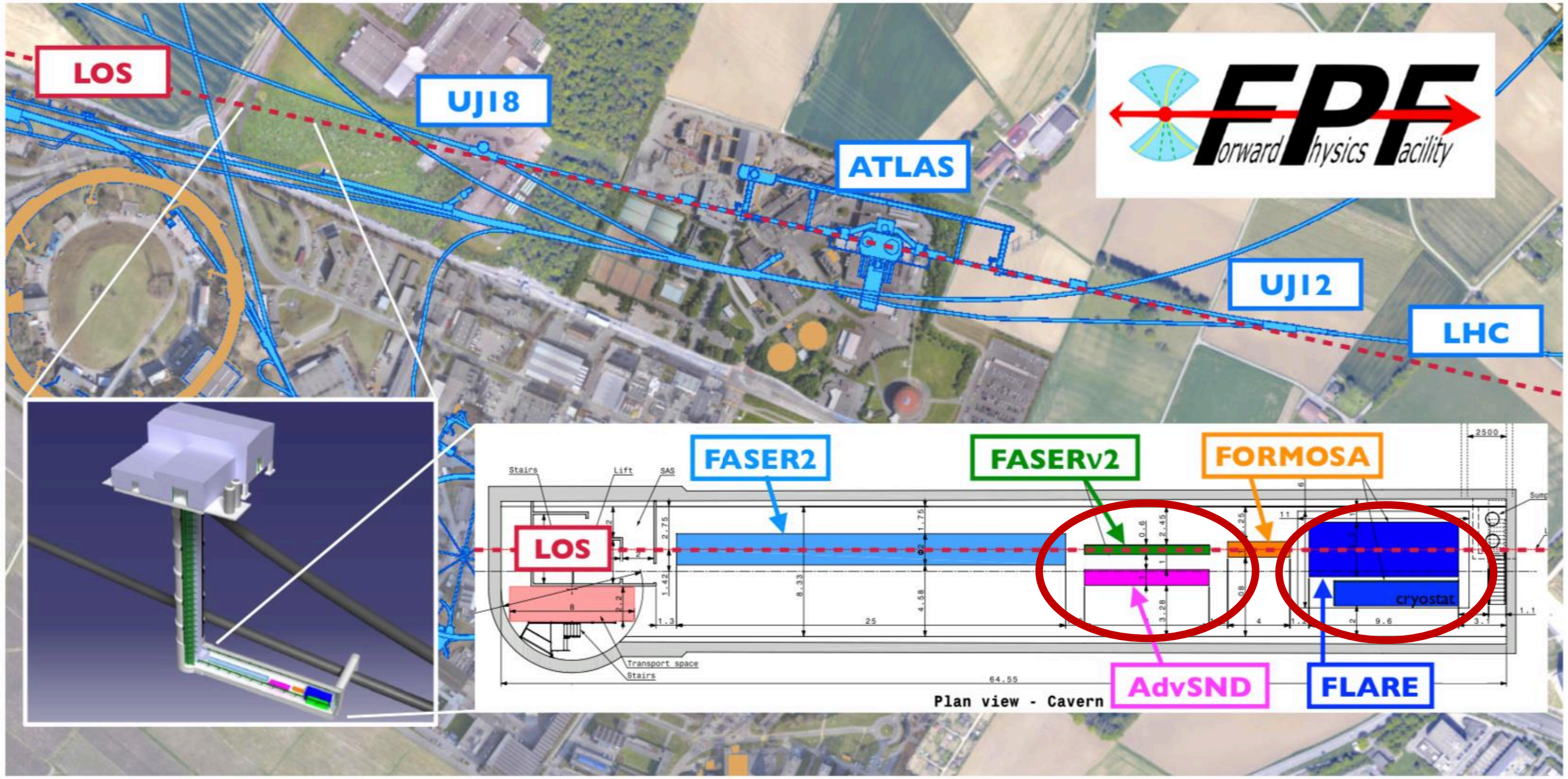
SND@LHC 800 kg, 39 cm x 39 cm

off axis, $8.5 > \eta > 7$

150 fb^{-1}

Purpose-built Forward Physics Facility

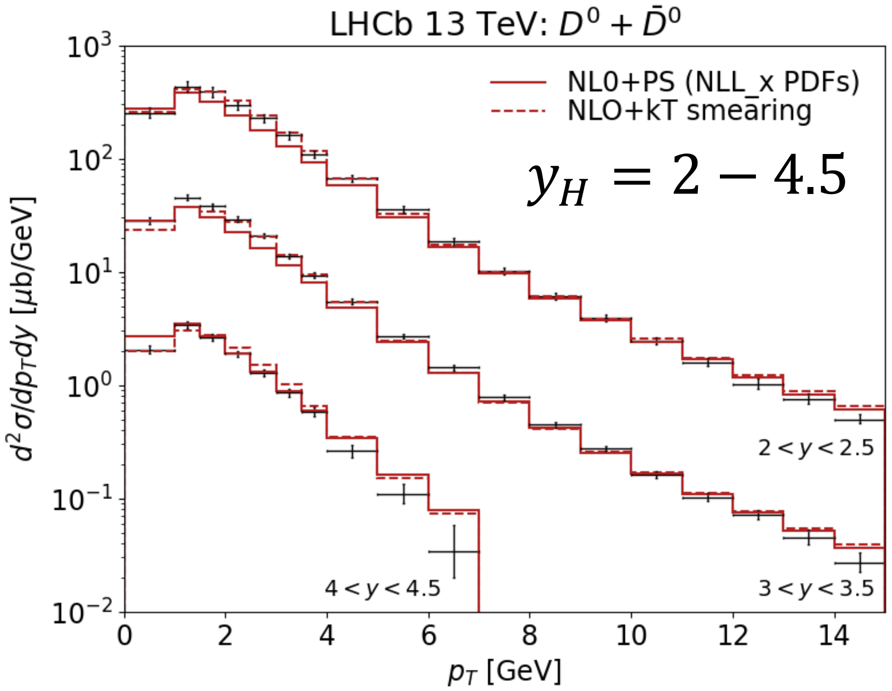
Underground facility ~620 m far forward from the ATLAS IP, shielded by concrete and rock. FPF experiments to detect $\sim 10^6$ neutrino interactions, energies up to a few TeV.

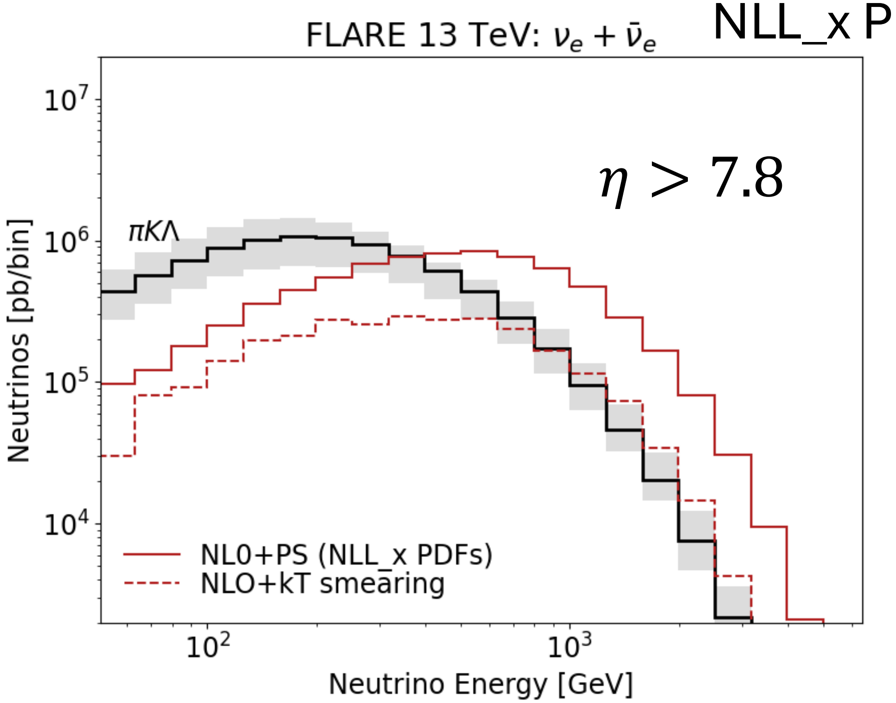


- Detectors designed for Standard Model and BSM Physics.
- Neutrino detection at FASERv2, AdvSND and FLArE.
- Snowmass White Paper: J.Phys.G 50 (2023) 3, 030501

See also, Anchordoqui et al., 2109.10905 (Phys. Rept.); Anchordoqui et al., Nucl.Phys.B 1026 (2026) 117398

Future contraints: FPF neutrino fluxes





Differences in histograms: primarily in PDFs, one has NLL_x PDFs sum $\ln(1/x_2)$.

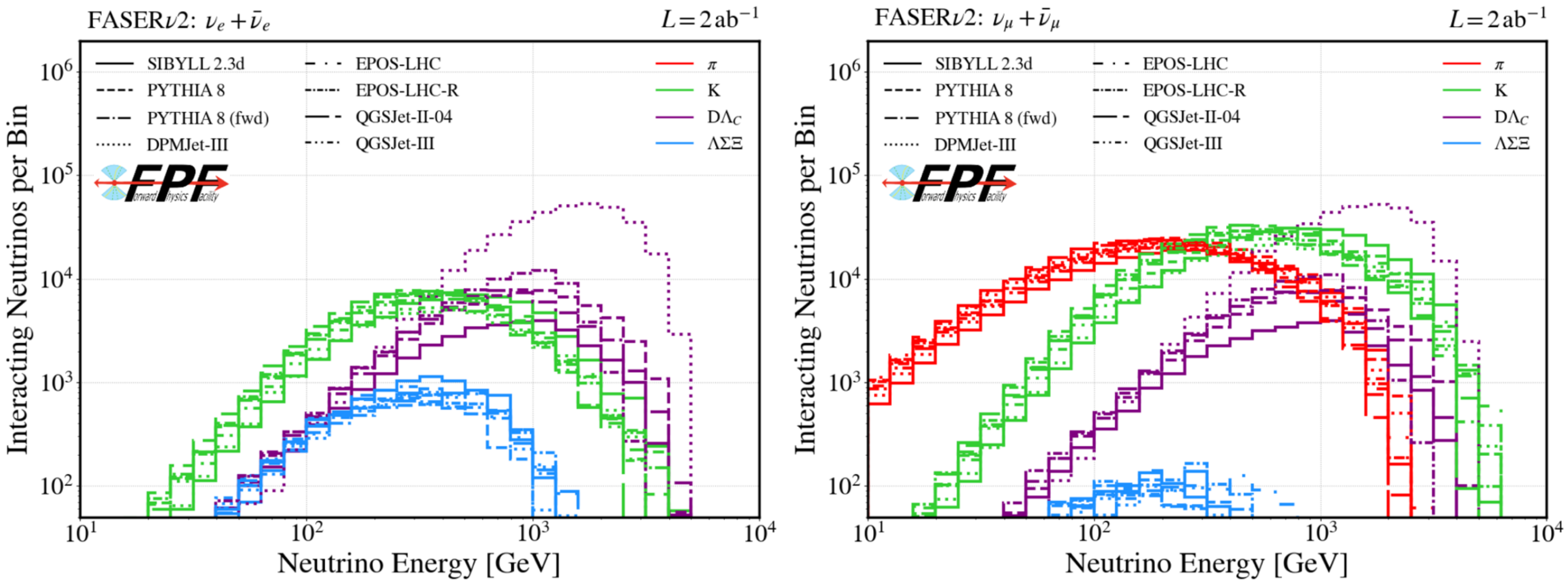
Direct input to prompt atm nu flux requires measurements past LHCb rapidity.

Histograms almost the same for most of LHCb range.

NLO+kT smearing; L. Buonocore and L. Rottoli (2023) NLO+PS (NLL_x PDFs)

FPF neutrinos

Soldin+, https://arxiv.org/pdf/2509.15426, see also tuned SIBYLL*, Anchordoqui+, https://arxiv.org/pdf/2510.26260



Other references on FPF neutrinos from charm in perturbative QCD:
Bai, Diwan, Garzelli et al, JHEP 06 (2022) 148, JHEAp 34 (2022) 212
FPF-prompt atmospheric neutrino connection:
Bai, Diwan, Garzelli et al, JHEP 10 (2023) 142

Final remarks

- We can’t use muons to normalize the prompt contribution to muon neutrinos because light, unflavored mesons have (small) prompt contributions to the muon flux.
- There could be enhanced charm (or our perturbative charm could be close to the upper range of uncertainties).
- In the standard evaluation, there is a missing component to the prompt muon flux. It can’t be from charm because IceCube prompt neutrino bounds would be violated.
- Neutrino flux measurements from forward physics experiments will refine our understanding of forward charm production, reduce uncertainties in the prompt atmospheric neutrino (and muon) fluxes.