Studying hadronic interactions with inclusive atmospheric leptons

CRIS 2016 – Cosmic Ray International Seminar

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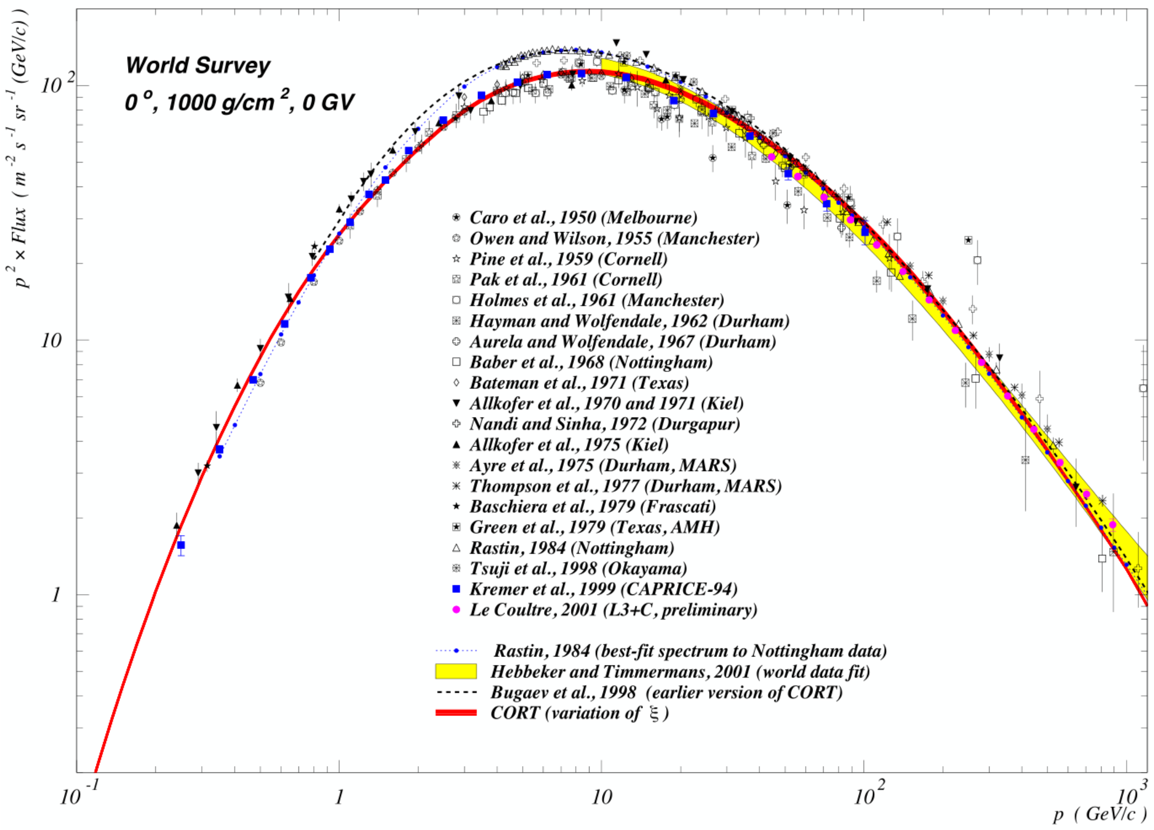
Inclusive atmospheric leptons

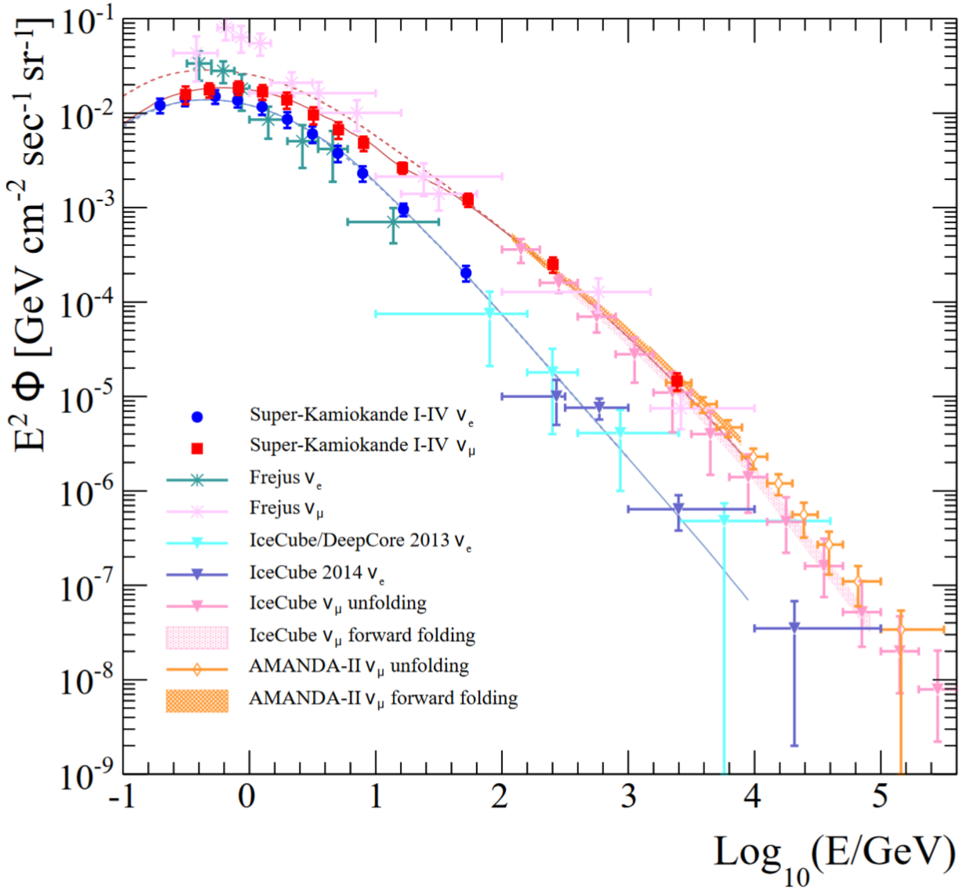
Atmospheric (cosmic) muon flux



decays, E-loss — CR spectrum — Hadronic inter.

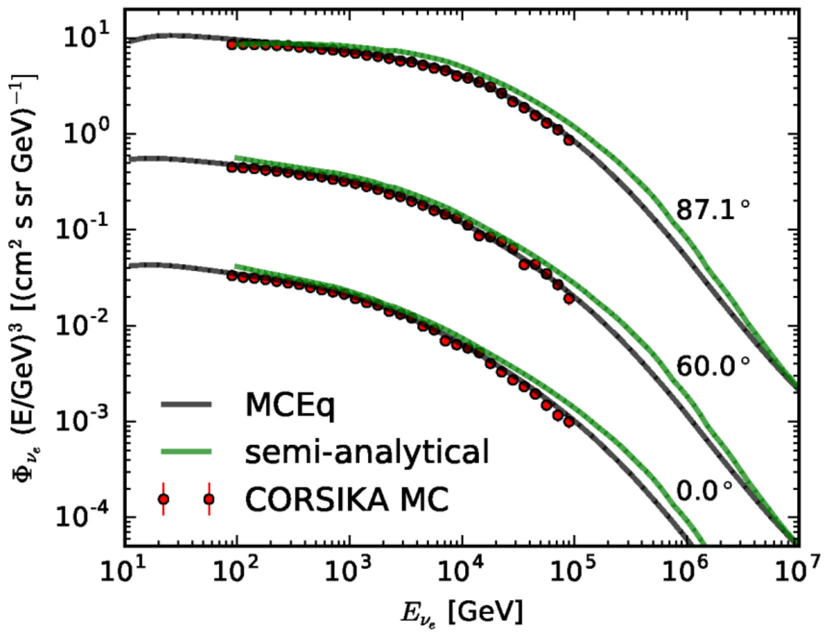
Atmospheric neutrino flux

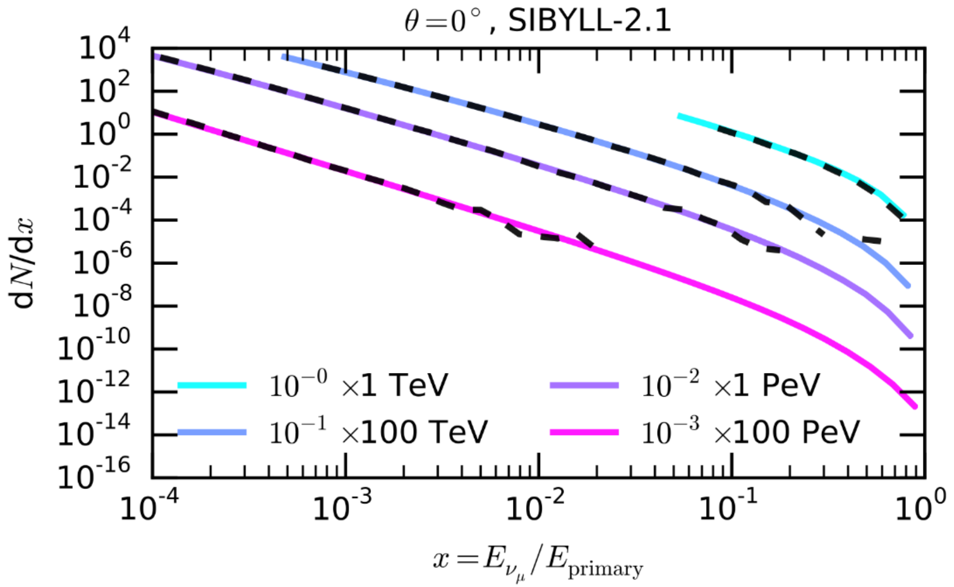
Super-K Coll. (2015), arXiv:1510.08127



oscillations — CR spectrum — Hadronic inter.

New calculation methods

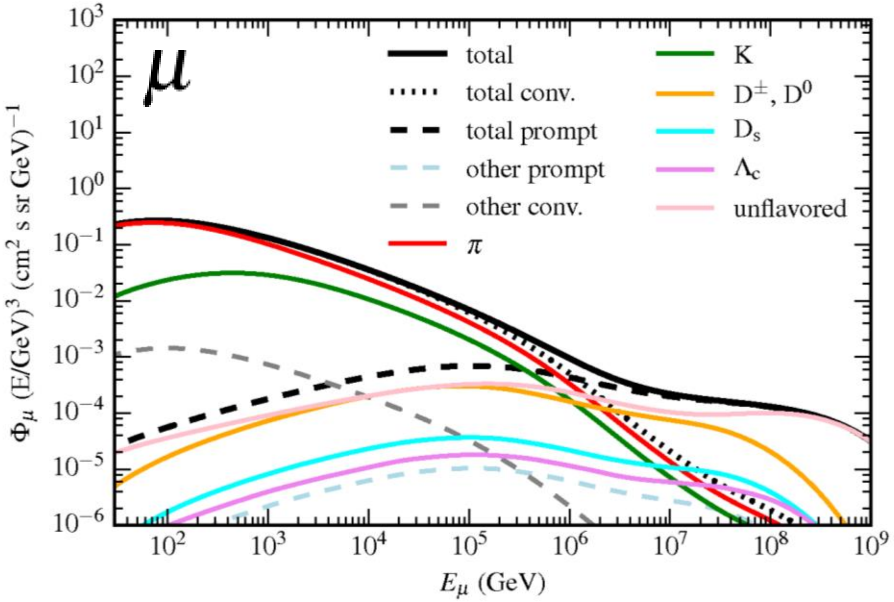




- Accelerated solver of hadronic coupled cascade equations
- Solves simultaneously >6000 equations for individual particle species and energy bins
- Energy range 1 (50) GeV – 10^{11} GeV
- Curved geometry, realistic atmosphere
- Contains tables for common interaction models
- Works also on GPU and multi-core
- Public code MCEq: https://github.com/afedynitch/MCEq

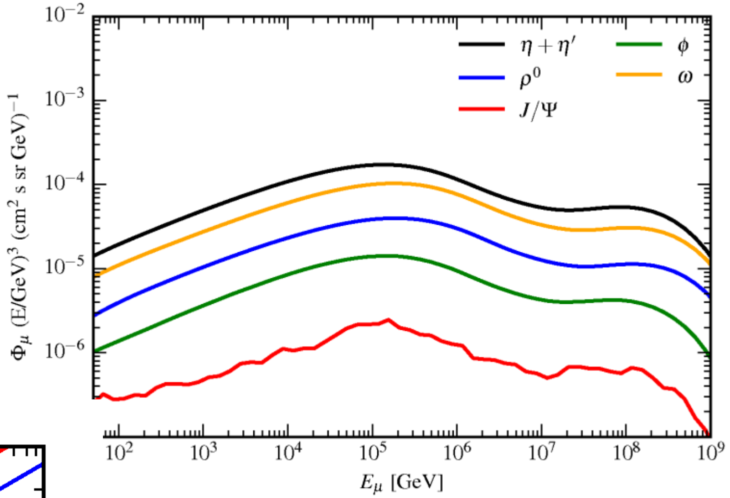
CORSIKA: A. Fedynitch, J. Becker Tjus and P. Desiati, PRD 2012
MCEq: A. Fedynitch, R. Engel, T. K. Gaisser, F. Riehn and S. Todor. PoS ICRC 2015, 1129

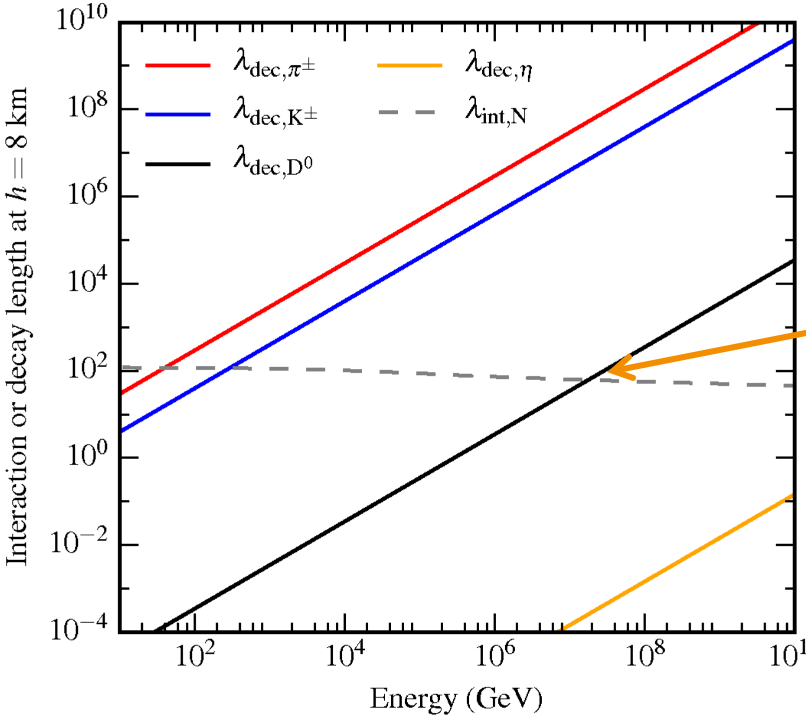
Origin of atmospheric muons



mostly **pion** decay | charm decays | charm interacts | unflavored decays

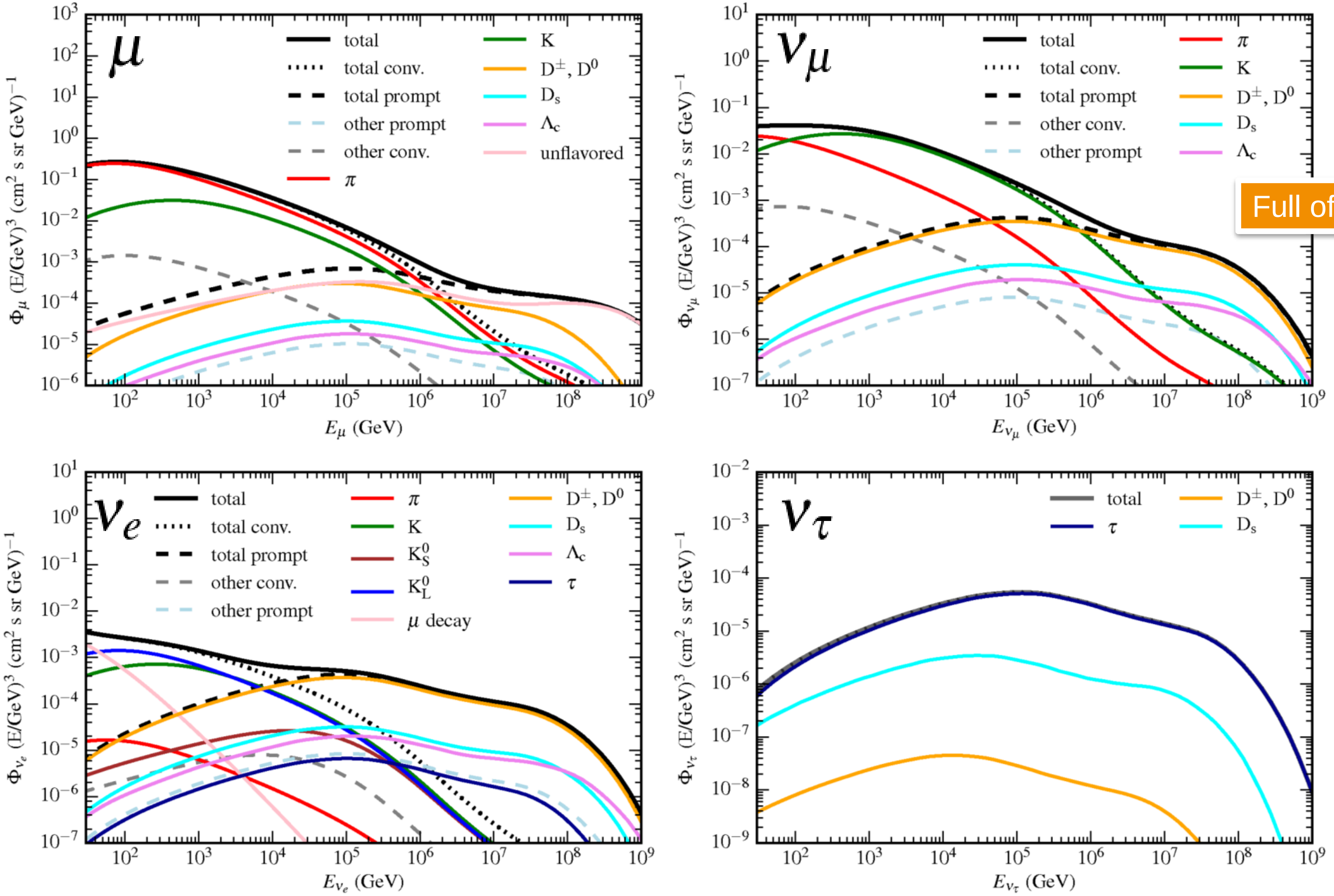
Muons from unflavored hadrons





Critical energy

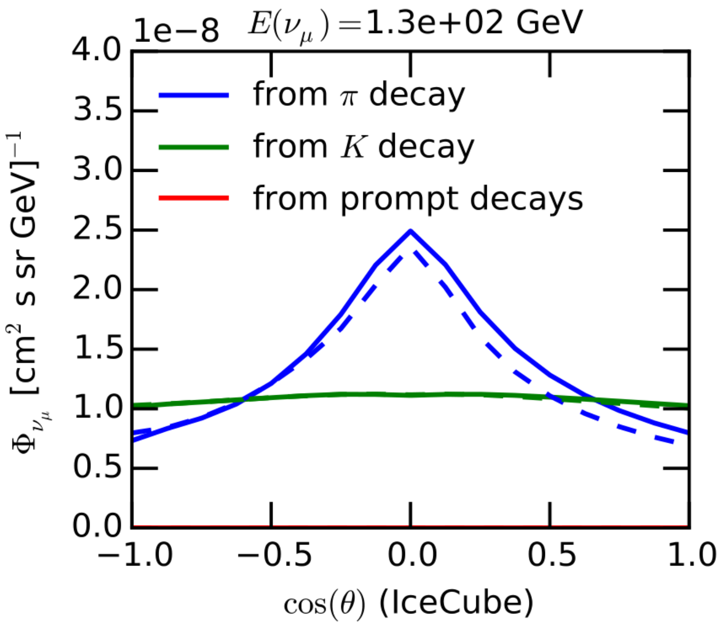
Hadron species taking part in atmospheric lepton production



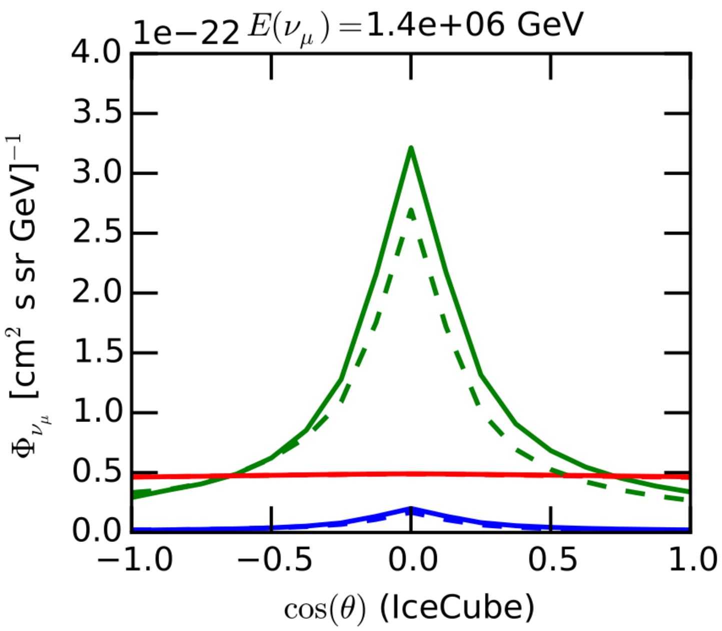
Full of particle physics!

Possible to distinguish mother hadrons

Low energy



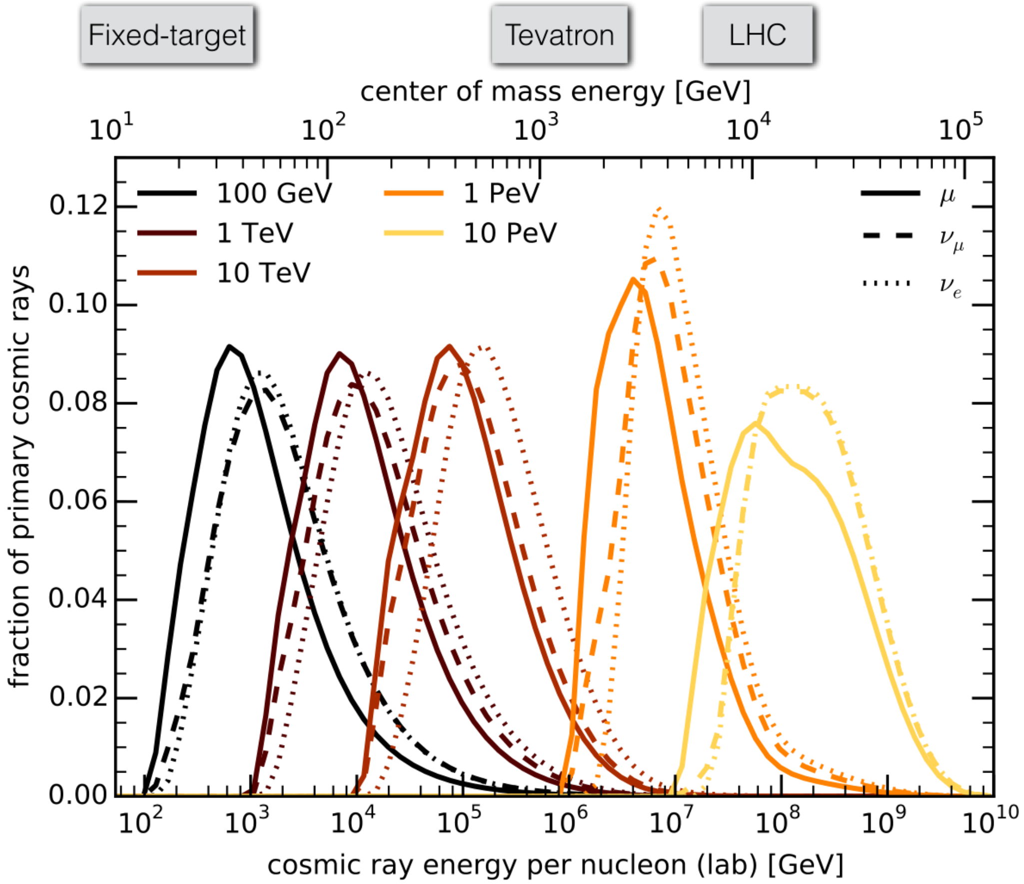
High energy



… through energy and zenith angle

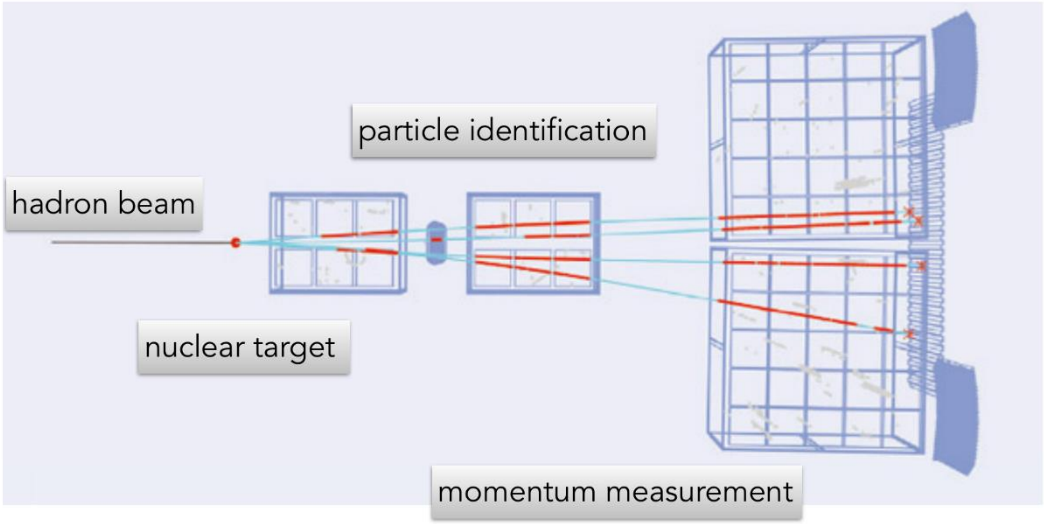
- Elongated profile of inclined showers reduces interactions
- Vertical leptons come more often from short lived particles
- Horizontal from longer lived
- Also atmospheric variations

Why don't accelerators solve all problems?



Energy is not a problem!

NA61/SHRINE



Scattering angle

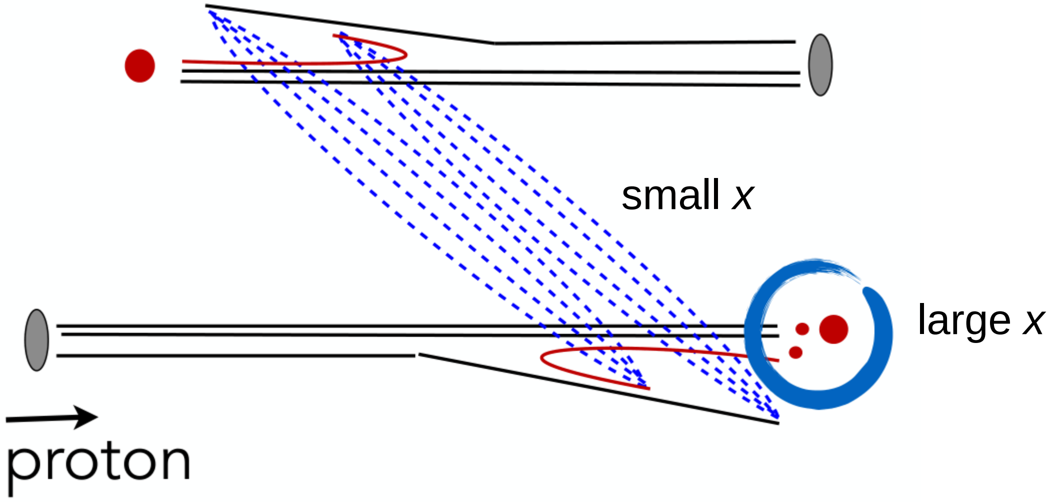
$$p_z \sim \text{TeV} - \text{PeV}$$

$$p_T \sim \text{few GeV}$$

$$x_{\text{lab}} = \frac{E_{\text{secondary}}}{E_{\text{primary}}} \approx \frac{p_{z,\text{secondary}}}{E_{\text{primary}}}$$

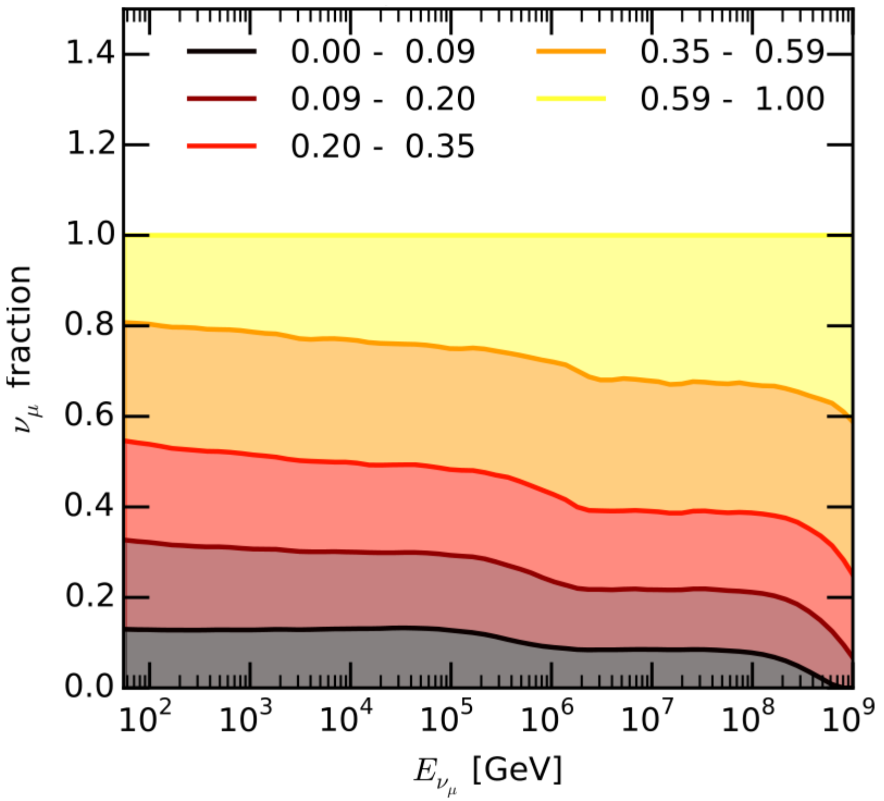
$$\theta = \arccos \frac{p_T}{p_Z}$$

Phase-space: the leading particles are important



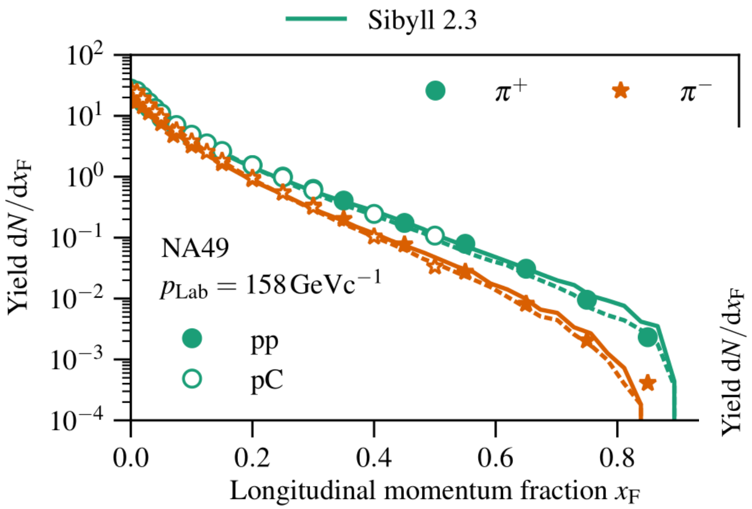
Looking on atmospheric leptons means looking into forward phase-space.

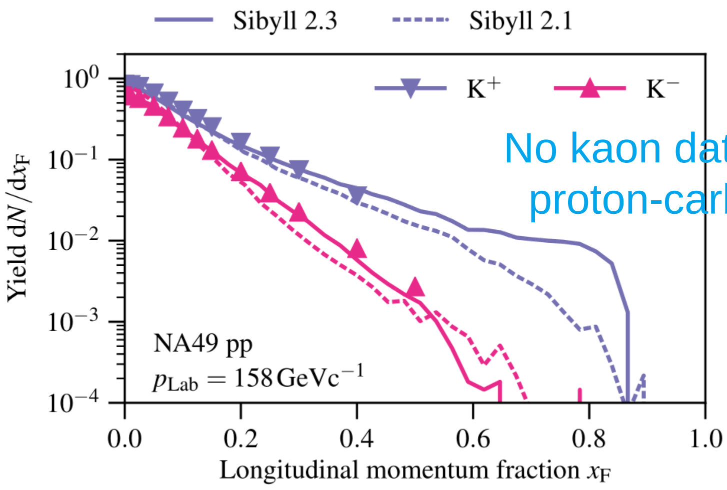
Phase-space regions contributing to inclusive muon neutrino flux



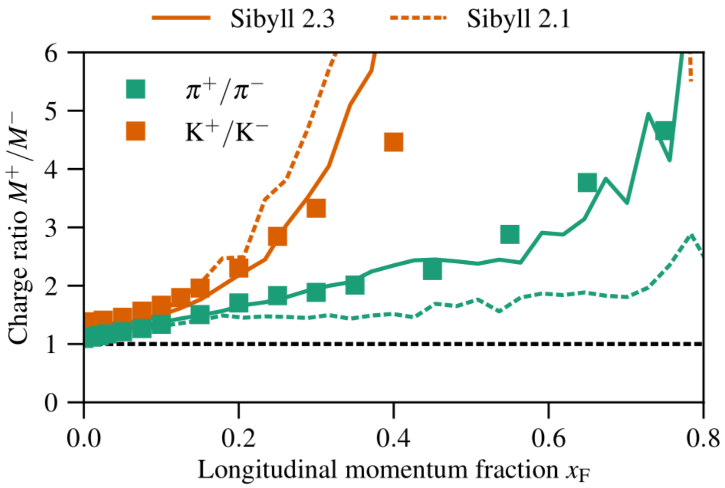
Fedynitch (VLVNT) EPJ Web Conf. 116, 11010 (2016)

Fixed-target data as “anchor”



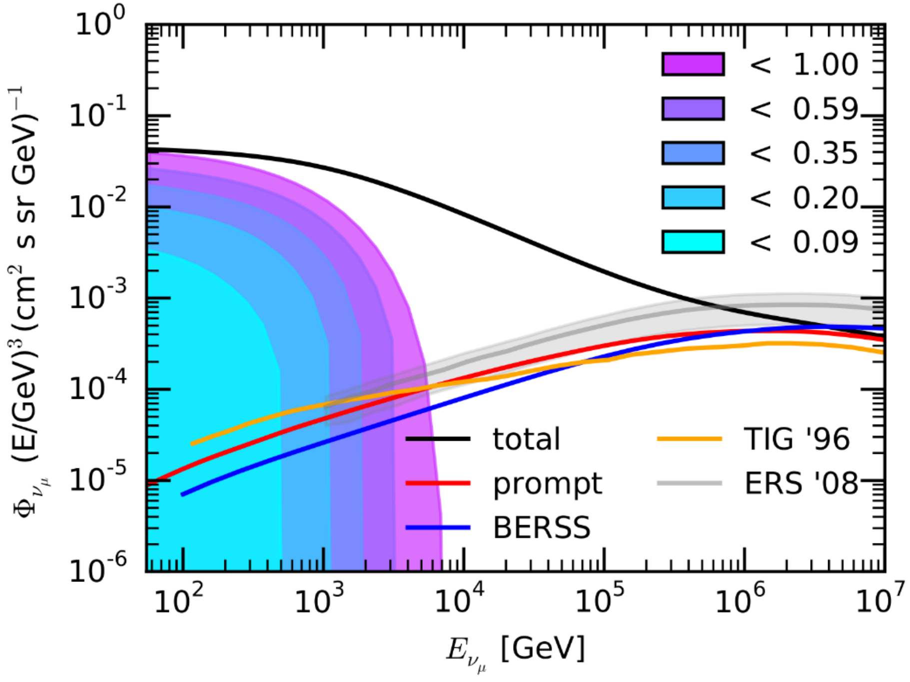


No kaon data for proton-carbon



… but only at low energy

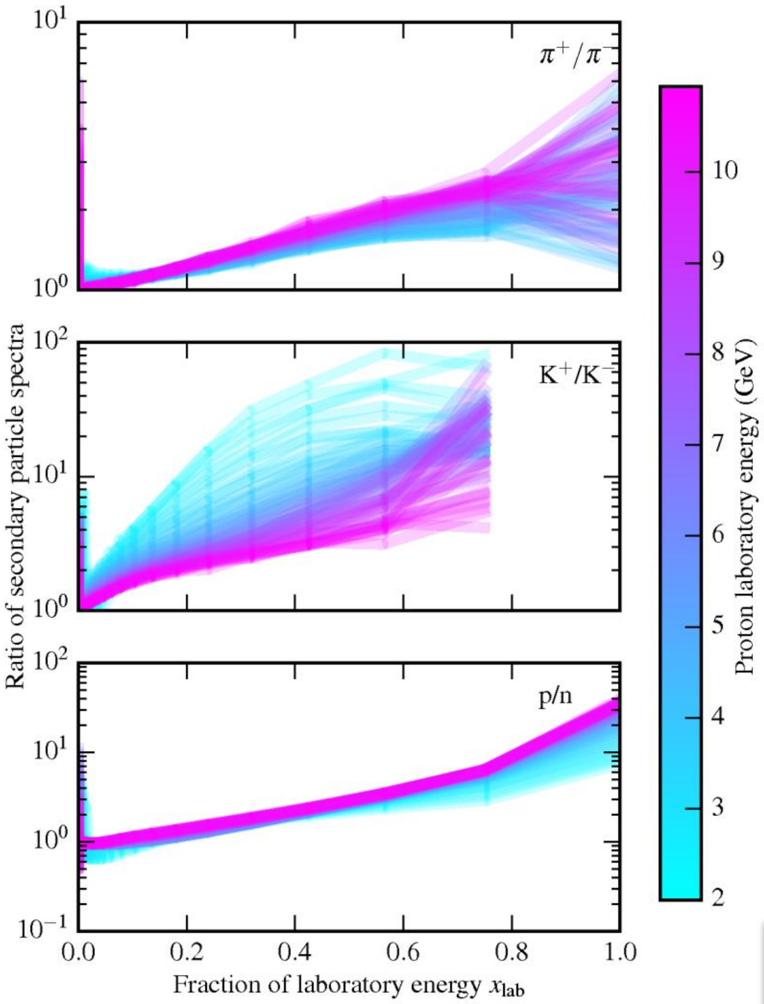
Phase-space coverage from a fixed-target experiment at LHC beam energy



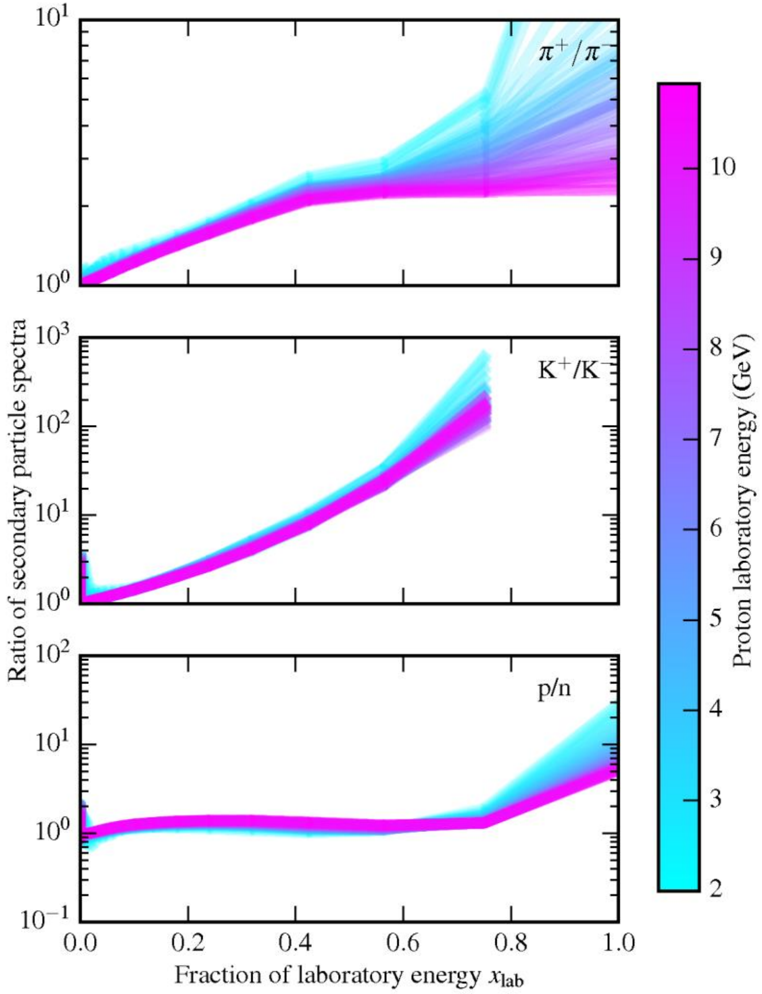
C. Baus et al., PoS ICRC 2015, 407 (2015)

Energy extrapolation?

SIBYLL 2.1 (old)



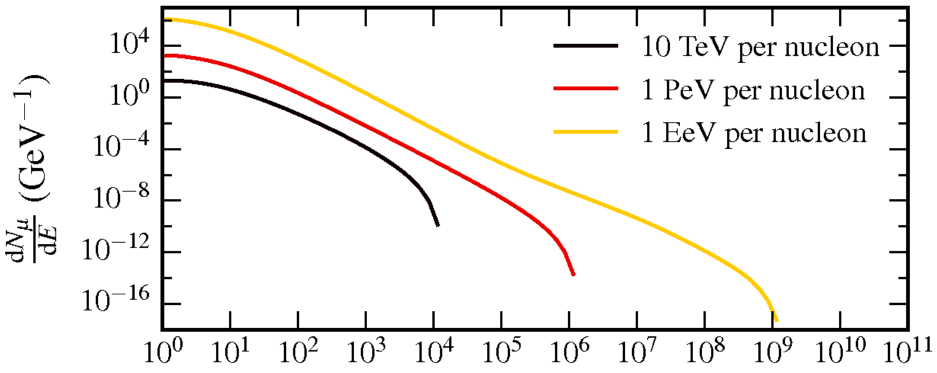
SIBYLL 2.3 (new)

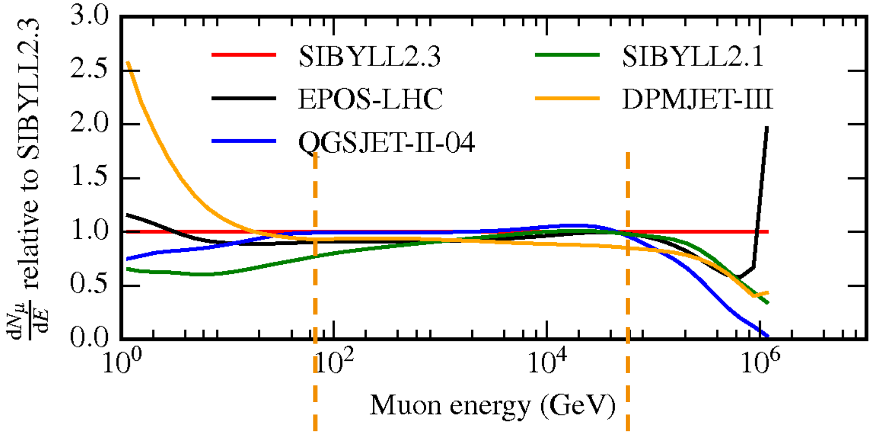


No guidance from accelerators

Big differences among models

Muon yield in single air-shower

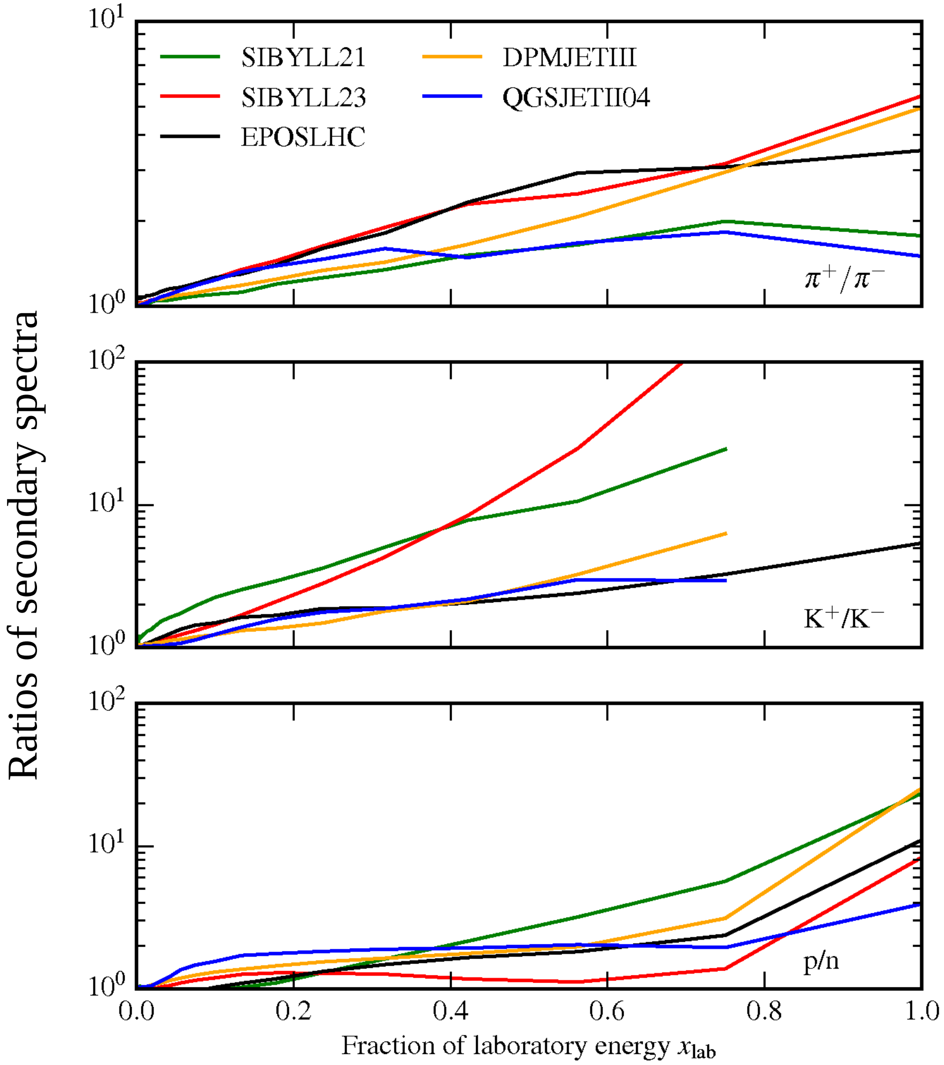




High uncertainty for air-showers

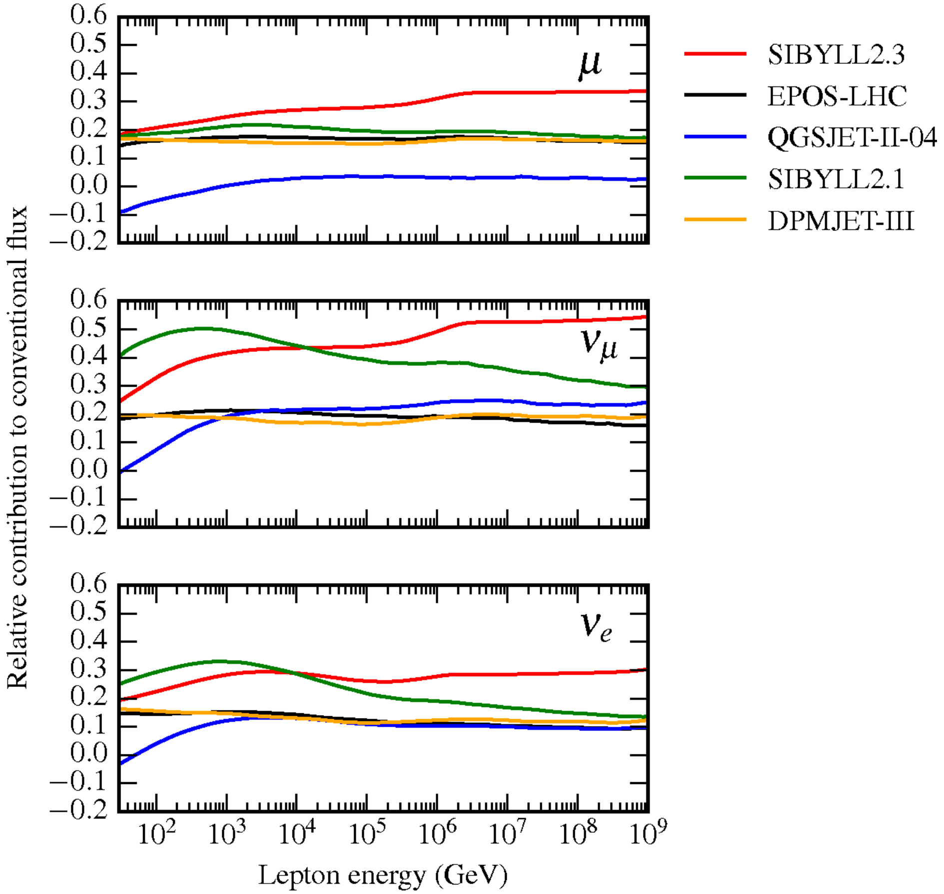
Scaling

High uncertainty for inclusive fluxes

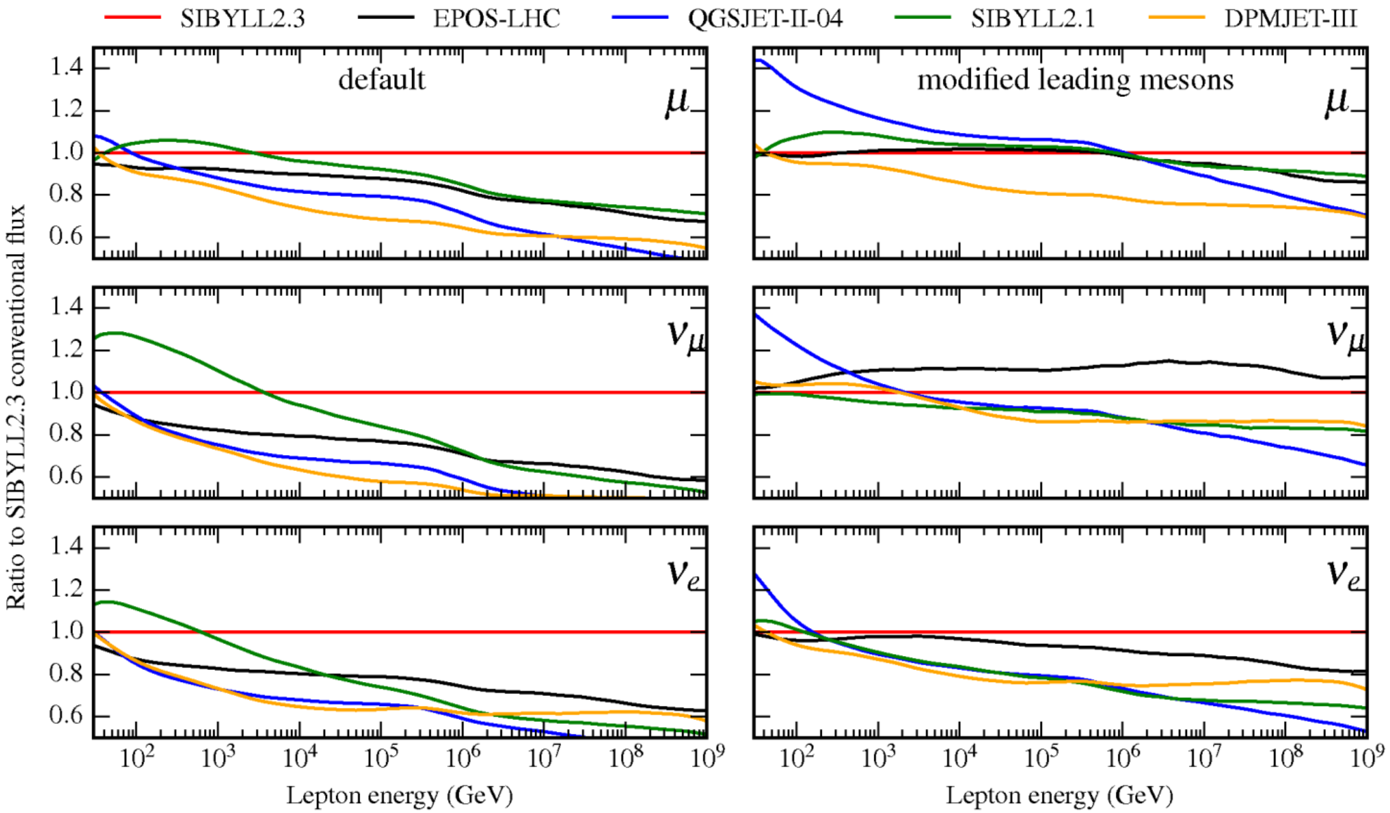


Quantifying the effect

Elimination of leading mesons through setting of (pi+ = pi-,…)



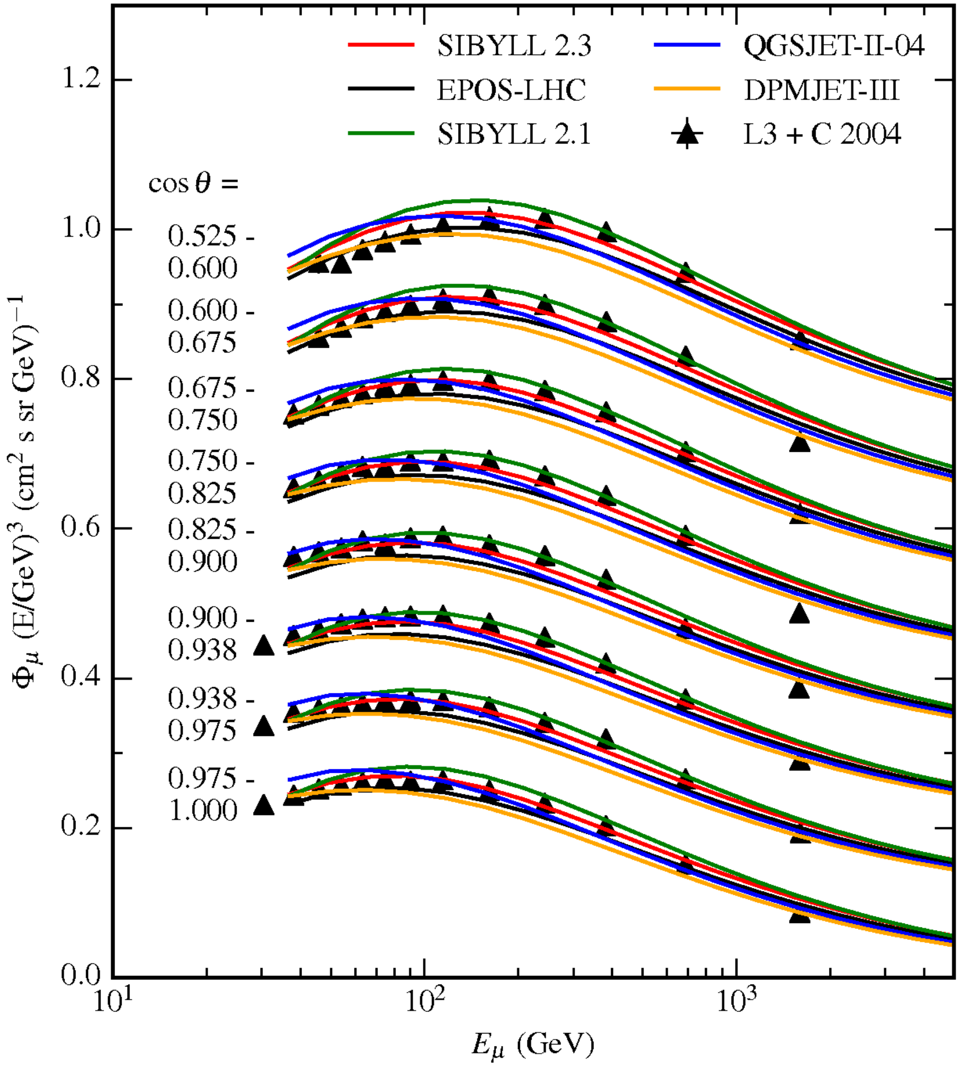
Modeling of leading particle effect contributes to large uncertainties



Larger effect in SIBYLL compared to other models

Interpretation of atmospheric muon data

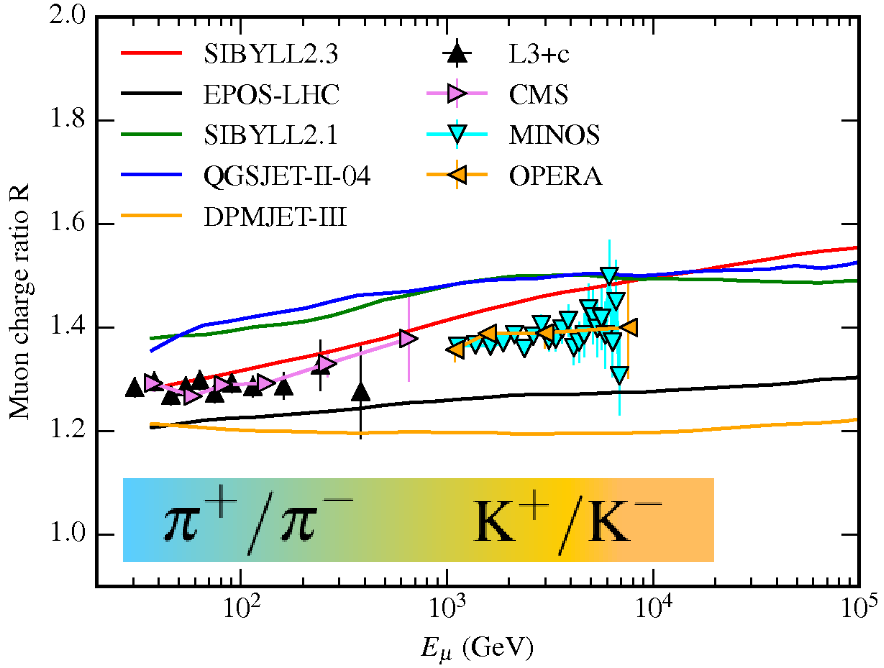
- Flux at sub-TeV probes primary interactions < 10 TeV
- Current models bracket the measurement
- The description of fixed-target data had straight impact on the muon flux prediction (from tuning of SIBYLL 2.3)
- SIBYLL 2.3 achieves a good description
- SIBYLL 2.1 is upper and DPMJET-III lower “bound”



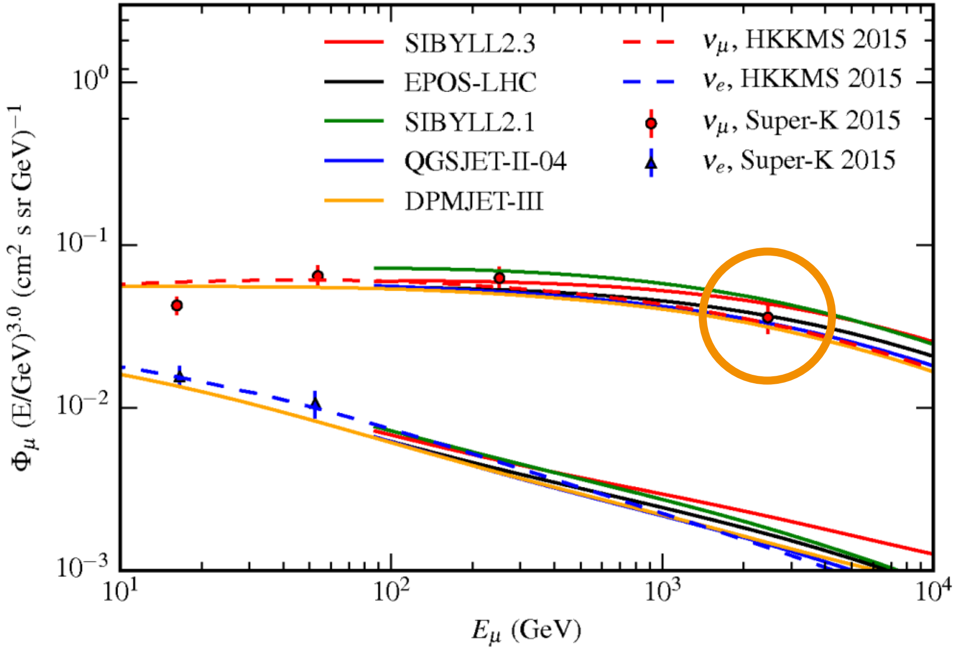
This measurement helps to adjust pions.

How to adjust kaons?

- Muon neutrino flux becomes dominated by kaon decays above 100's GeV - few TeV
- Muon charge ratio sensitive to leading particle effect, observed in K⁺/K⁻ from associated production $\mathrm{p} + N \rightarrow \Lambda + \mathrm{K}^+$
- SIBYLL 2.3 is the only model, qualitatively reproducing charge ratio



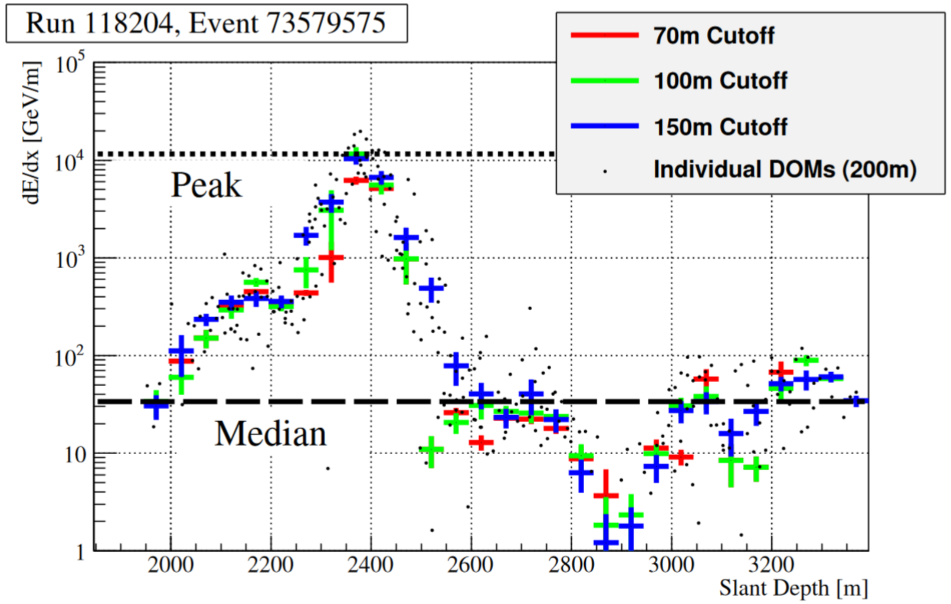
Super-K Coll. (2015), arXiv:1510.08127

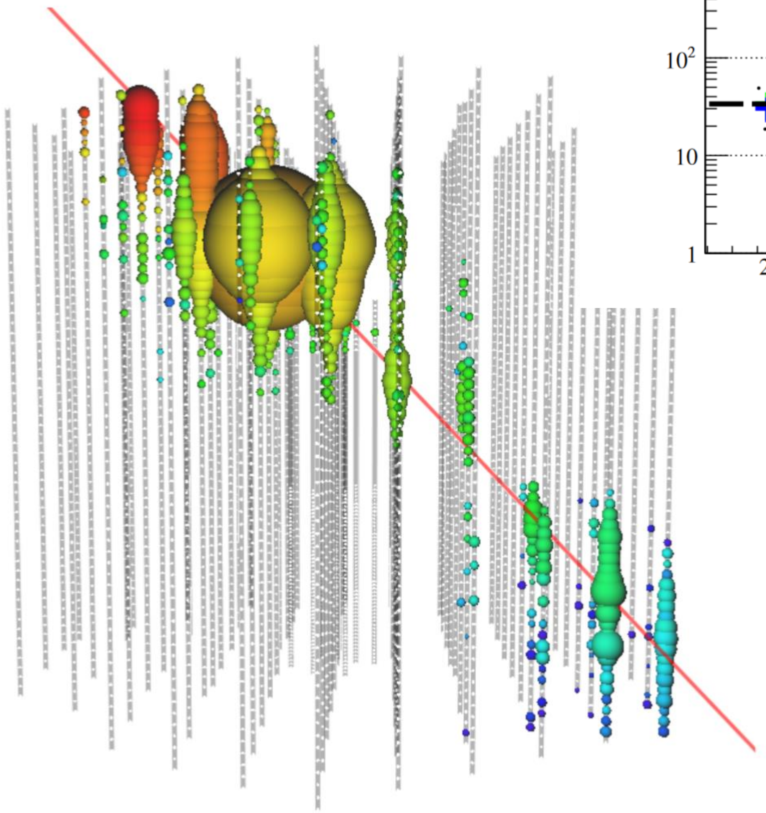


Modeling of kaons in SIBYLL 2.3 likely needs more adjustment

Muon flux measurement in IceCube

- Muon energy is reconstructed via energy loss pattern
- Big stochastic losses are attributed to single high energy muons
- Small, continuous losses are a signature for muon bundles
- Observable is $E_{\mathrm{mult}} \sim \sum_{N_\mu} E_\mu$

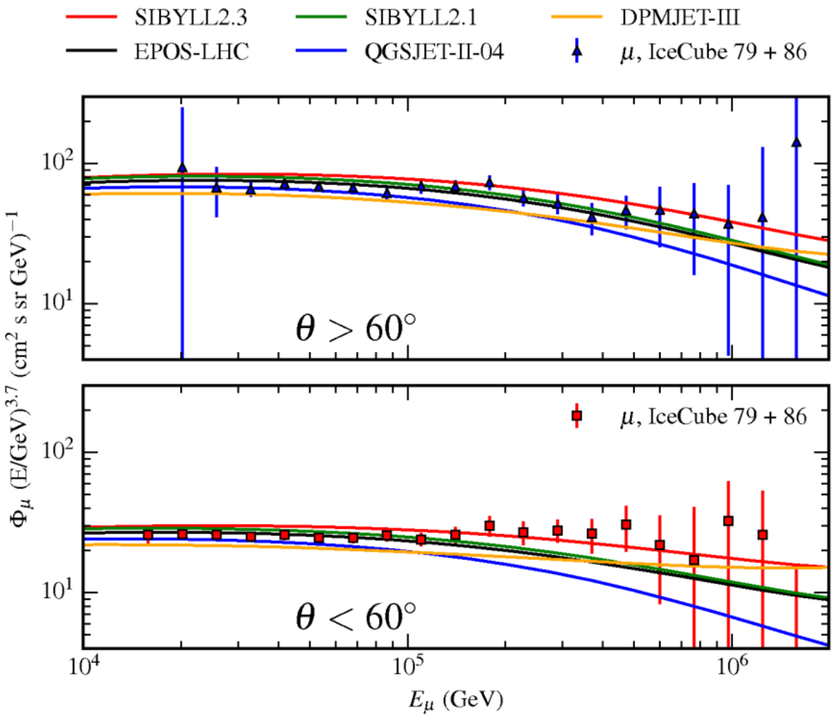


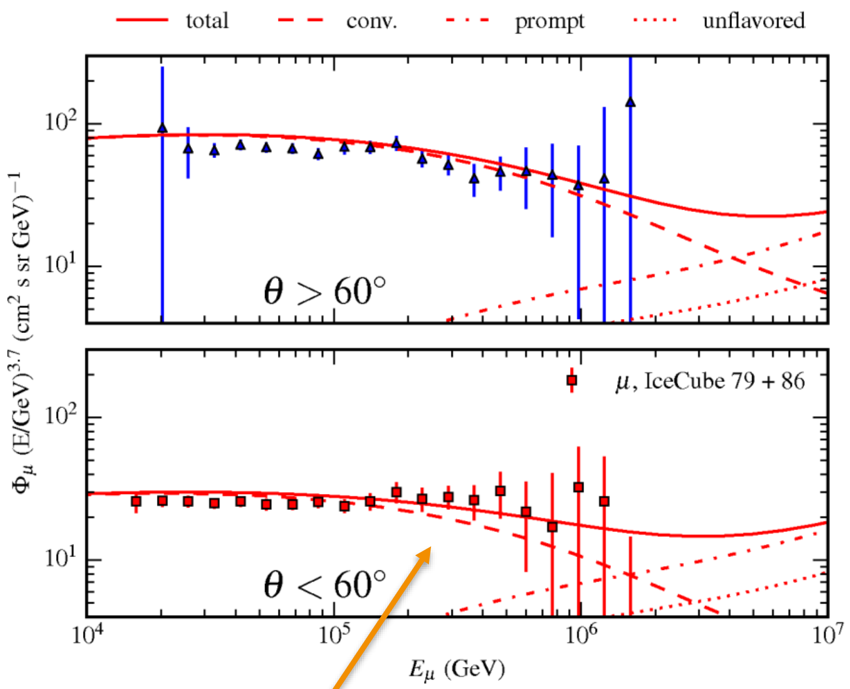


"Characterization of the Atmospheric Muon Flux in IceCube"
M. G. Aartsen et al. [IceCube Collaboration], Astropart. Phys. 78, 1 (2016)

Implications for hadronic models

- Models bracket horizontal muons
- Shape in vertical muons only described by SIBYLL 2.3 (with prompt)
- Unflavored component not significant at this energy



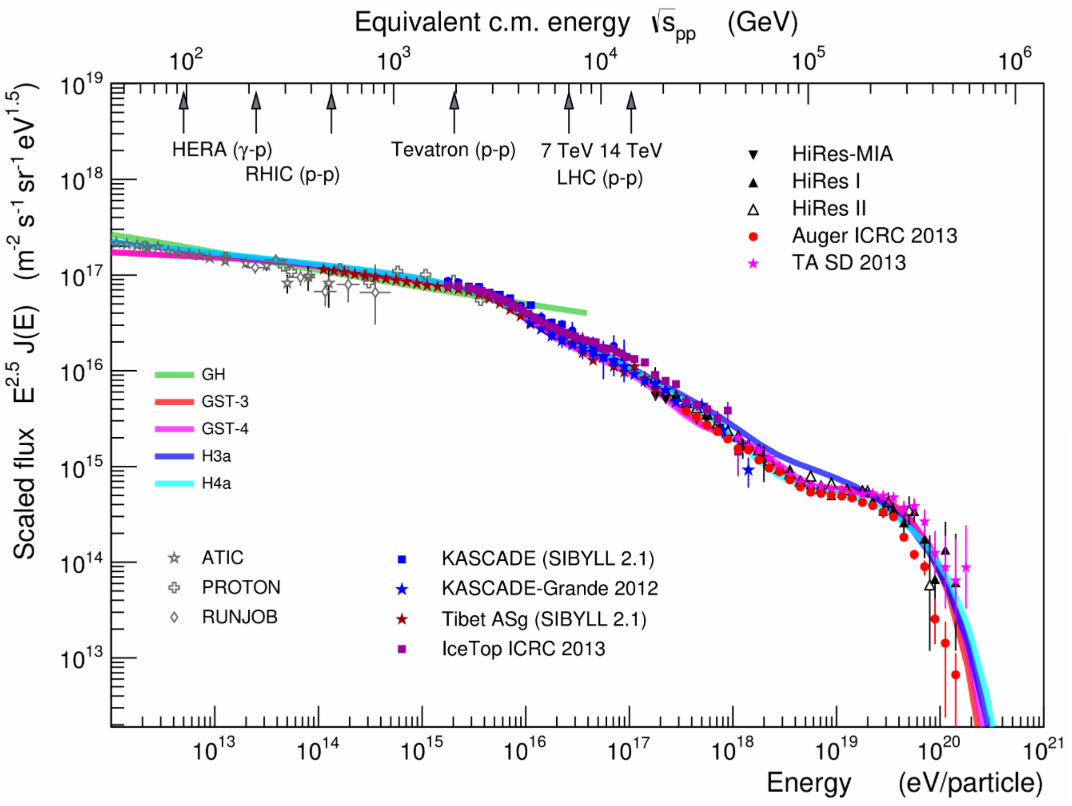


Kaons only

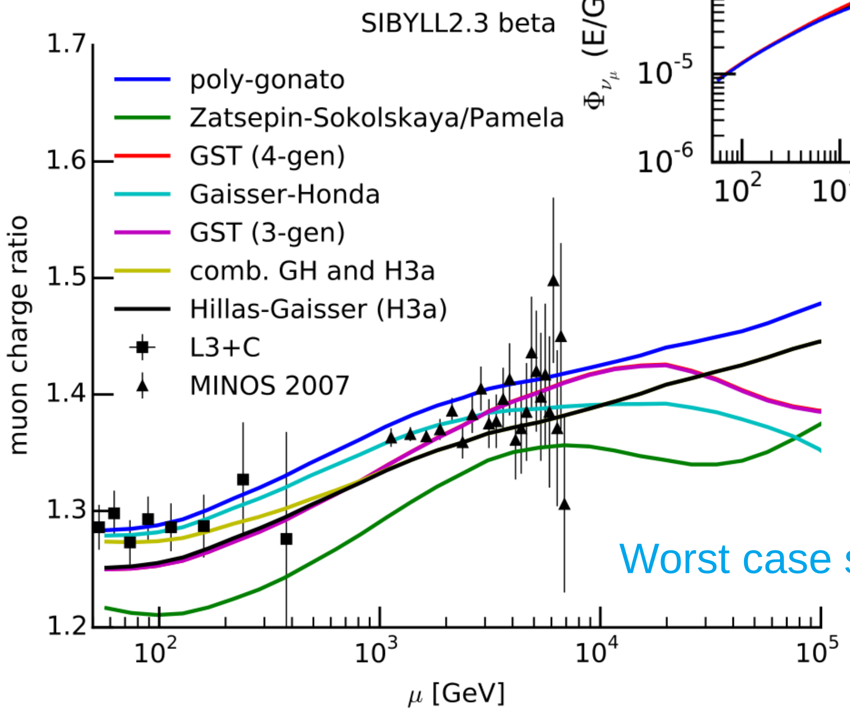
Prompt flux??

“Characterization of the Atmospheric Muon Flux in IceCube”
IceCube Collaboration, Astropart. Phys. 78, 1 (2016)

Interpretation ambiguity from the primary flux

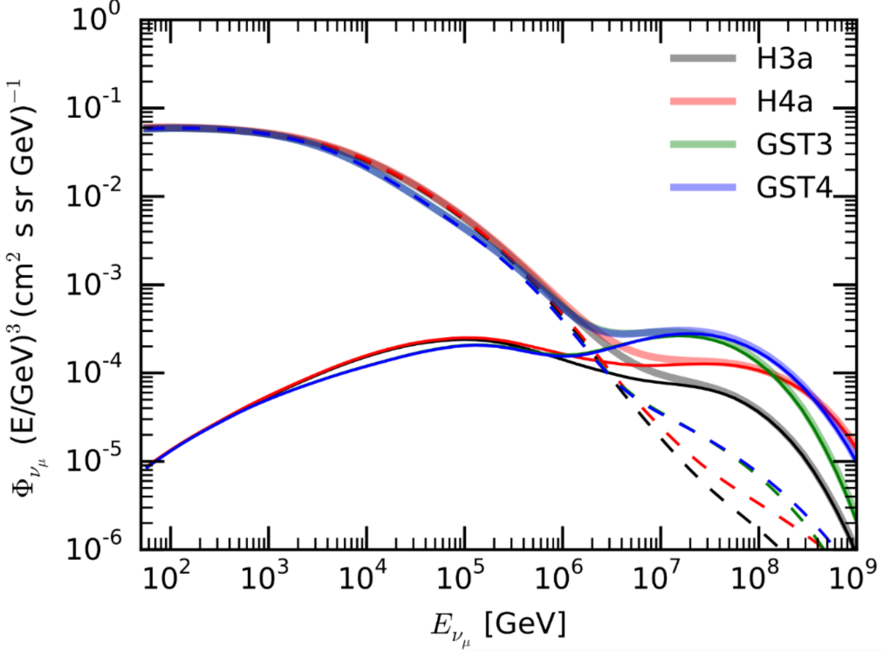


Recent direct data from e.g. PAMELA and AMS-02 will reduce model uncertainties



Worst case scenario!

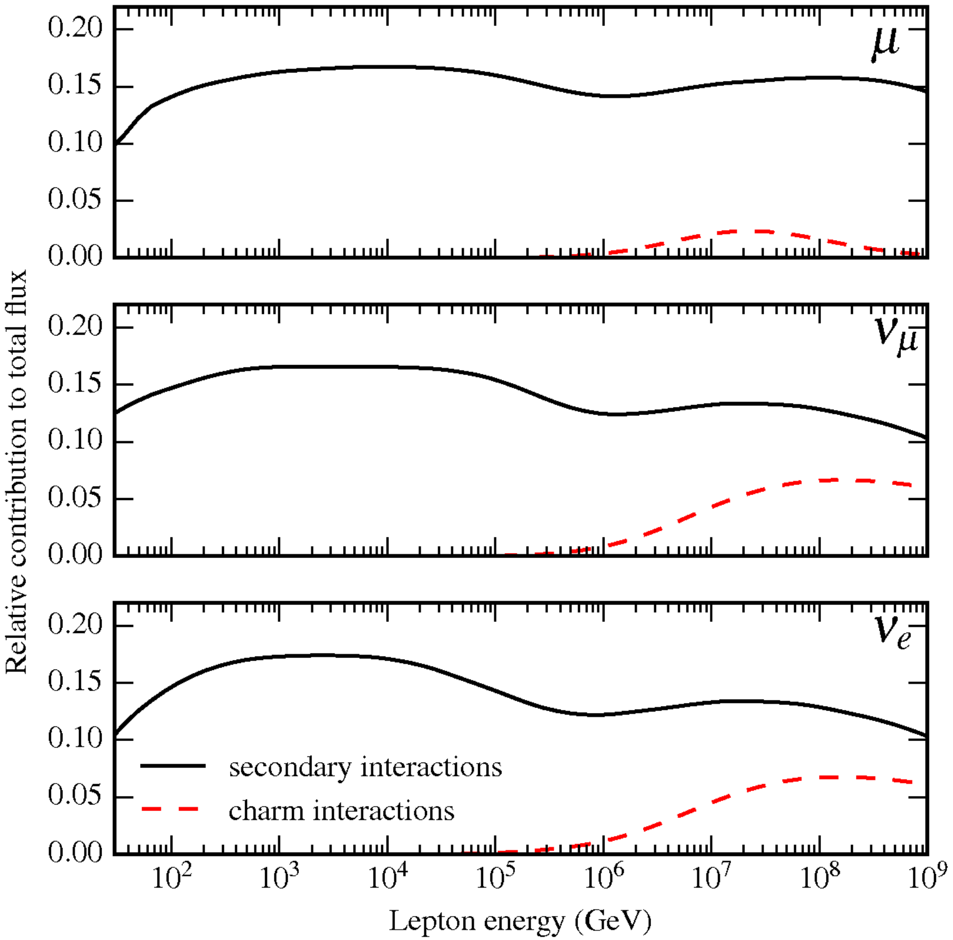
A. Fedynitch, R. Engel, T. K. Gaisser, F. Riehn and S. Todor. PoS ICRC 2015, 1129

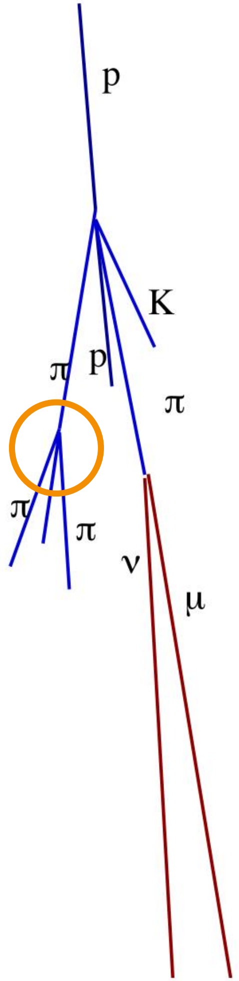


High composition uncertainty at UHE

Interpretation ambiguity from secondary interactions

- Effect is larger than expected (< 5%)
- Leading particles change depending on projectile
- Other, indirect, production channels become more important, such as vector mesons

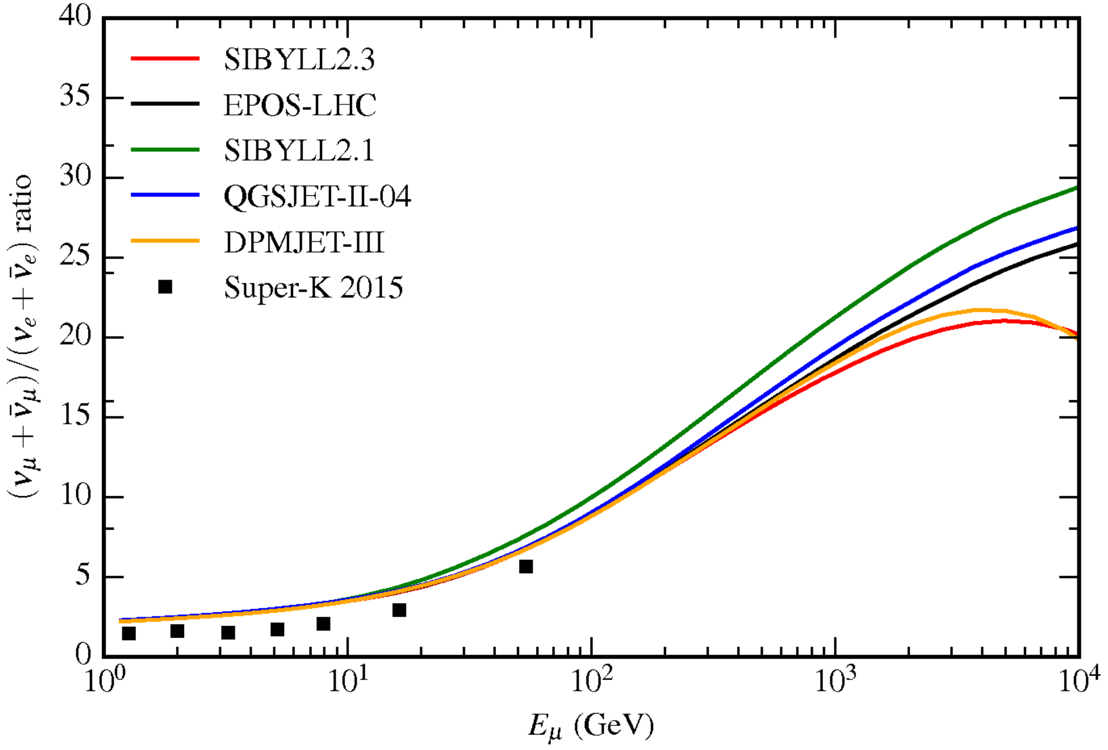




Conclusion and outlook

- Studying hadronic interactions using inclusive lepton measurements is possible
- Unique source of constraints for the energy dependence of the leading particle effect
- Studied particle production phase-space is very forward and inaccessible to colliders
- Feedback into air-shower simulations through tuning of interaction models
- Neutrino detectors have already published some relevant measurements of atmospheric neutrinos **and** muons at very high energies
- SIBYLL 2.3 is the only model which takes into account atmospheric lepton data
- EPOS-LHC has good overall agreement, except for the muon charge ratio
- DPMJET-III currently under test as a cosmic ray hadronic interaction model

Measurement of flavor ratio not reproduced without oscillations



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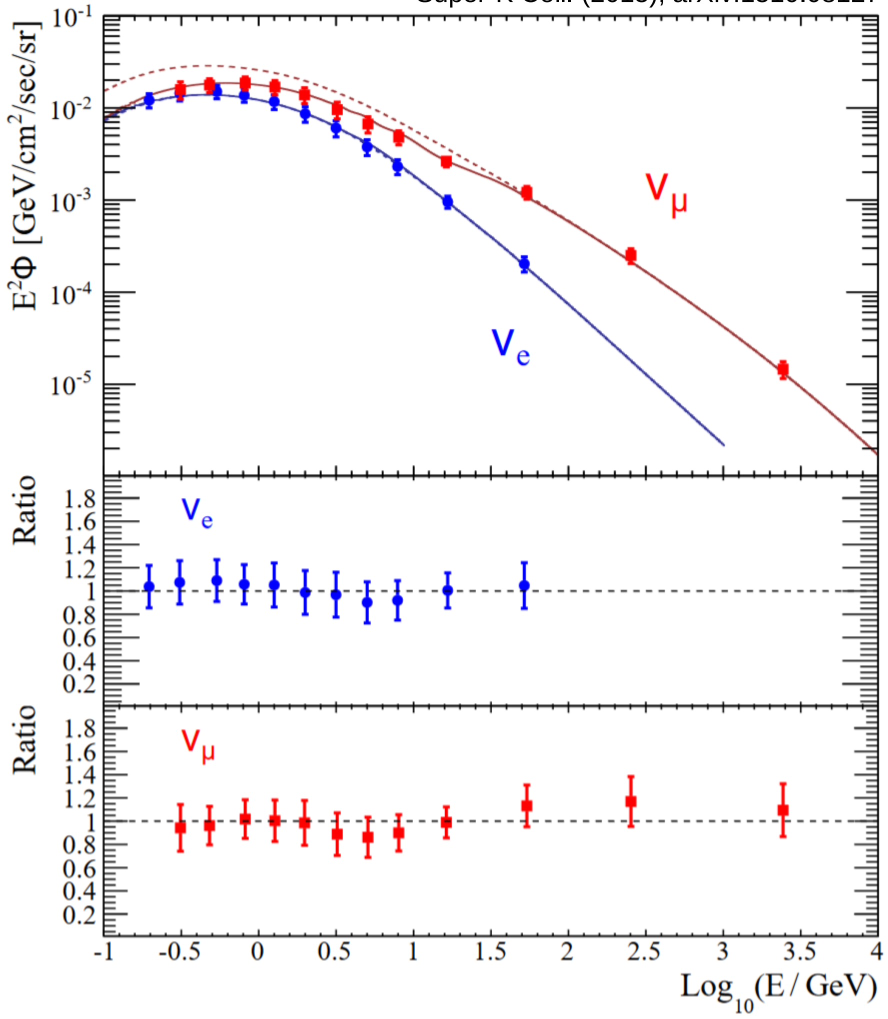

Our current calculation does not include oscillations and energy loss, yet.