Calculations of atmospheric neutrinos at intermediate energies

7th International Open Working Group Meeting for Hyper-Kamiokande project

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DESY

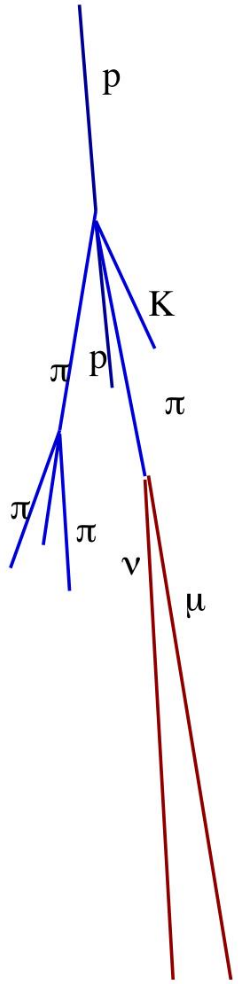
Outline

- Introduction
- One-dimensional calculations
  - via air-shower simulations
  - via numerical integration of cascade equations
- Hadronic interaction models
  - Basic principles
  - Some sources of uncertainties
- Study of hadronic interactions through atmospheric leptons

~~3D and low energy in G. Barr's talk~~

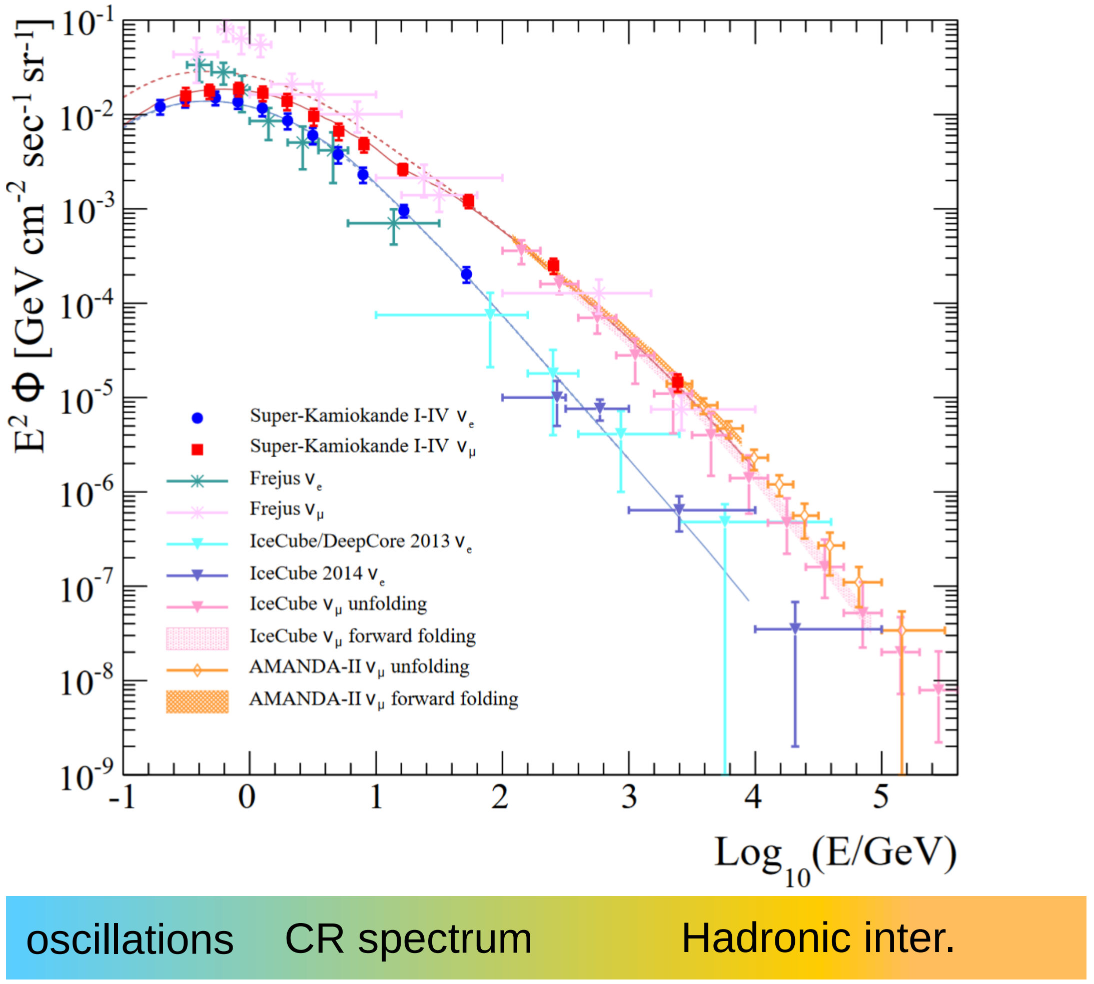
Inclusive atmospheric neutrino flux

- Atmospheric neutrinos are created in decays of hadrons in air-showers
- Inclusive flux stems from integration over all possible energies of primary CR flux
- At high energies, neutrinos follow the trajectory of primary CR
- At low energies, the effect of the lateral extension of the air-shower becomes relevant



Atmospheric neutrino flux

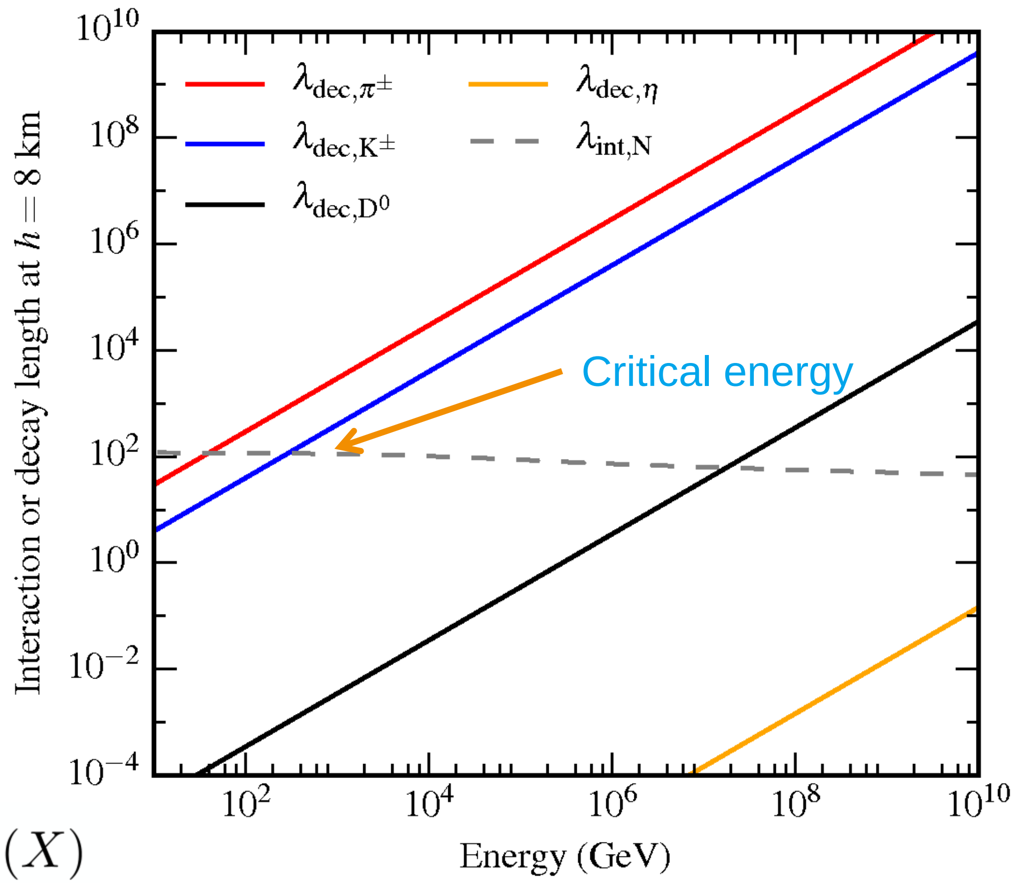
Super-K Coll. (2015), arXiv:1510.08127



Hadronic sources of neutrinos

- Above critical energy, probability for interaction is higher than decay probability
- Flux from one particular hadron species gets attenuated

particle	E_{crit} [GeV]
$\mu^\pm$	1.0
$\pi^\pm$	115
K_L^0	205
$K^\pm$	850
K_S^0	1.2E+05
$D^\pm$	4.3E+07



$$\lambda_{dec,h}(E,X) = \frac{c\tau_h E \rho_{Air}(X)}{m_h c^2} = \frac{E X \cos\theta}{E_{crit,h}}$$

Decay channels

conventional

$$p, A + \text{air} \rightarrow \pi^{\pm}, \pi^{0}, \text{K}^{\pm}, \text{K}^{0}_{\text{S,L}}$$

muons and muon neutrinos

$$\pi^{\pm}, K^{\pm} \rightarrow \mu^{\pm}\nu_{\mu}(\bar{\nu}_{\mu})$$

electron neutrinos

$$K^{\pm}, K^{0}_{L} \rightarrow [\pi^{\pm}, \pi^{0}]e^{\pm}\nu_{e}(\bar{\nu}_{e})$$

prompt

$$p, A + \text{air} \rightarrow \text{D}, \Lambda_{\text{C}} \rightarrow \nu_{\mu}, \nu_{\text{e}}, \mu$$

Subset of dominant decay channels

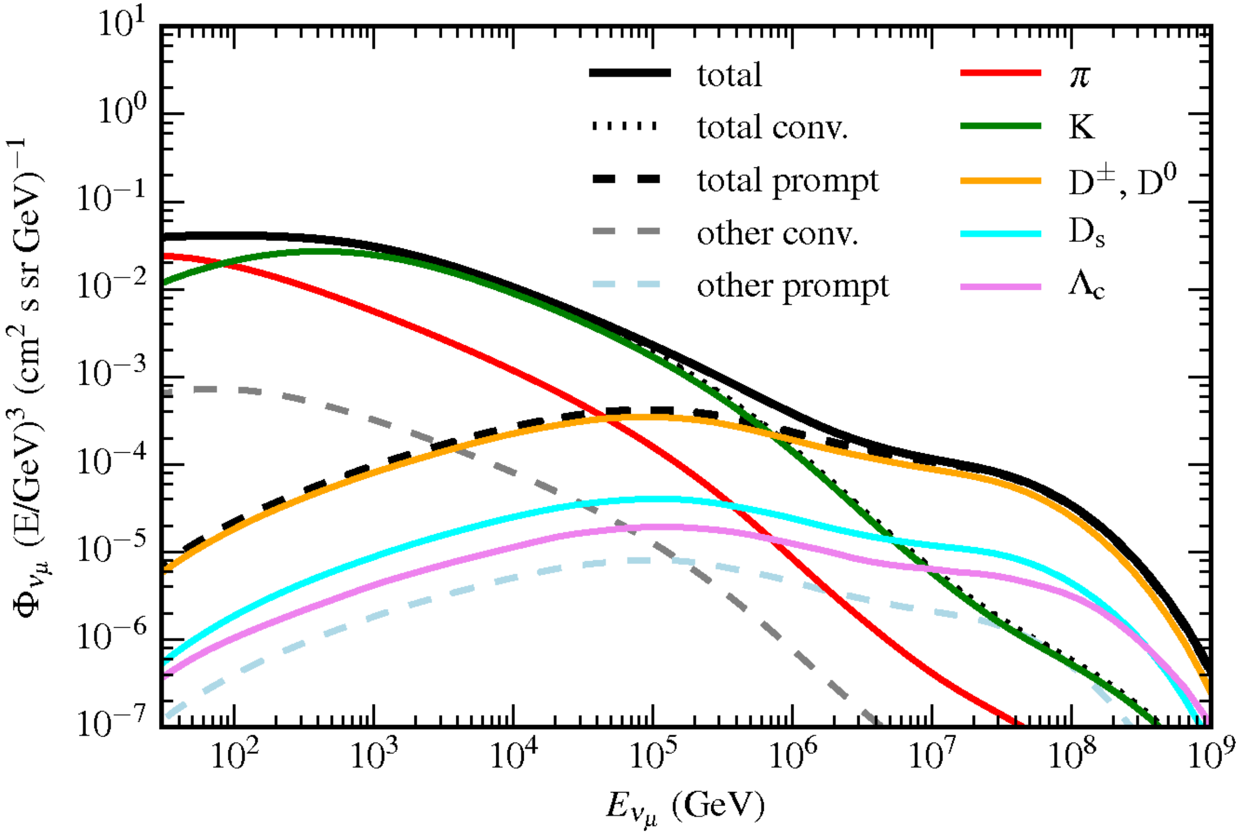
decay channel	branching ratio (BR)
$\mu^{-} \rightarrow e^{-}\bar{\nu}_{e}\nu_{\mu}$	100 %
$\pi^{+} \rightarrow \mu^{+}\nu_{\mu}$	99.9877 %
$K^{0}_{e3} : K^{0}_{L} \rightarrow \pi^{\pm}e^{\mp}\nu_{e}$	40.55 %
$K^{0}_{\mu 3} : K^{0}_{L} \rightarrow \pi^{\pm}\mu^{\mp}\nu_{\mu}$	27.04 %
$K^{+} \rightarrow \mu^{+}\nu_{\mu}$	63.55 %
$K^{+}_{e3} : K^{+} \rightarrow \pi^{0}e^{+}\nu_{e}$	5.07 %
$K^{+}_{\mu 3} : K^{+} \rightarrow \pi^{0}\mu^{+}\nu_{\mu}$	3.353 %
$D^{+} \rightarrow \overline{K}^{0}\mu^{+}\nu_{\mu}$	9.2 %
$D^{0} \rightarrow K^{-}\mu^{+}\nu_{\mu}$	3.3 %

+ charge conjugates

http://pdg.lbl.gov

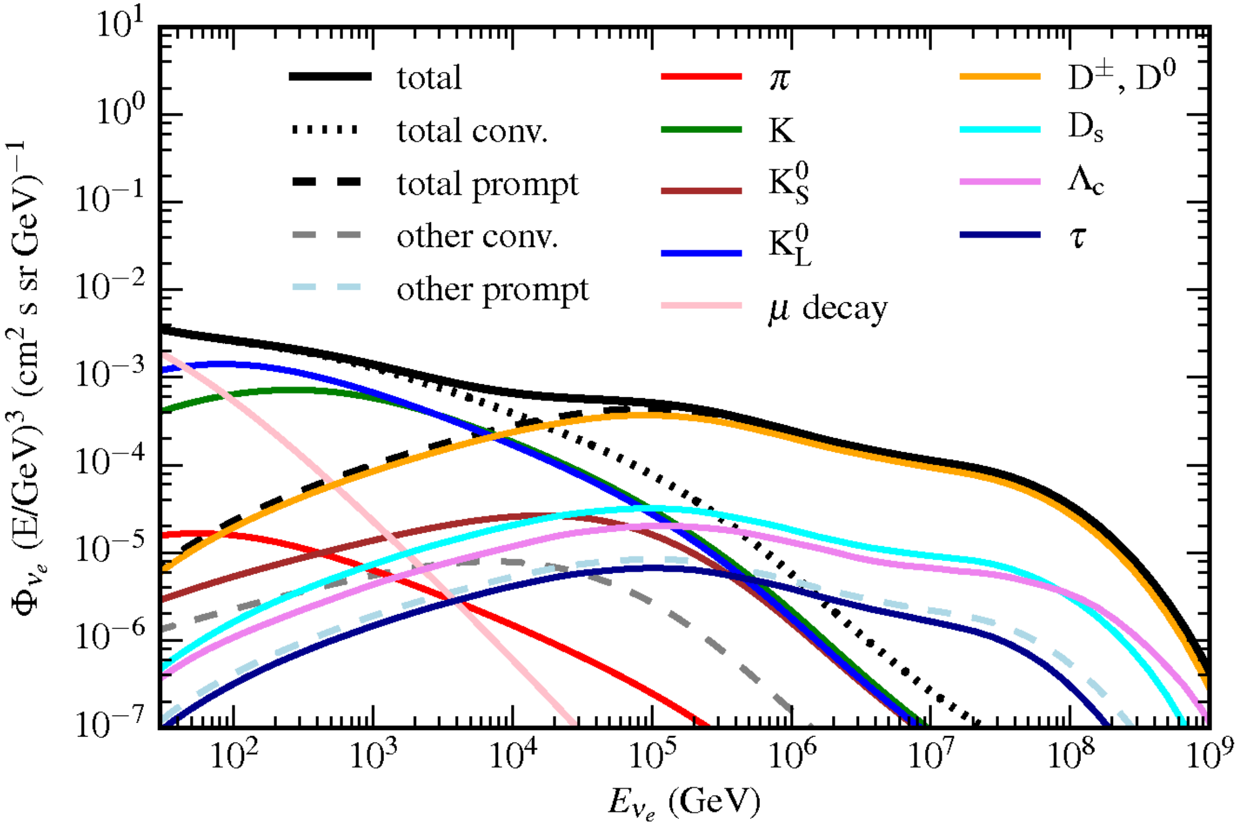
Different production channels depending on energy

Muon neutrinos



pion decay | kaon decay | charm decay

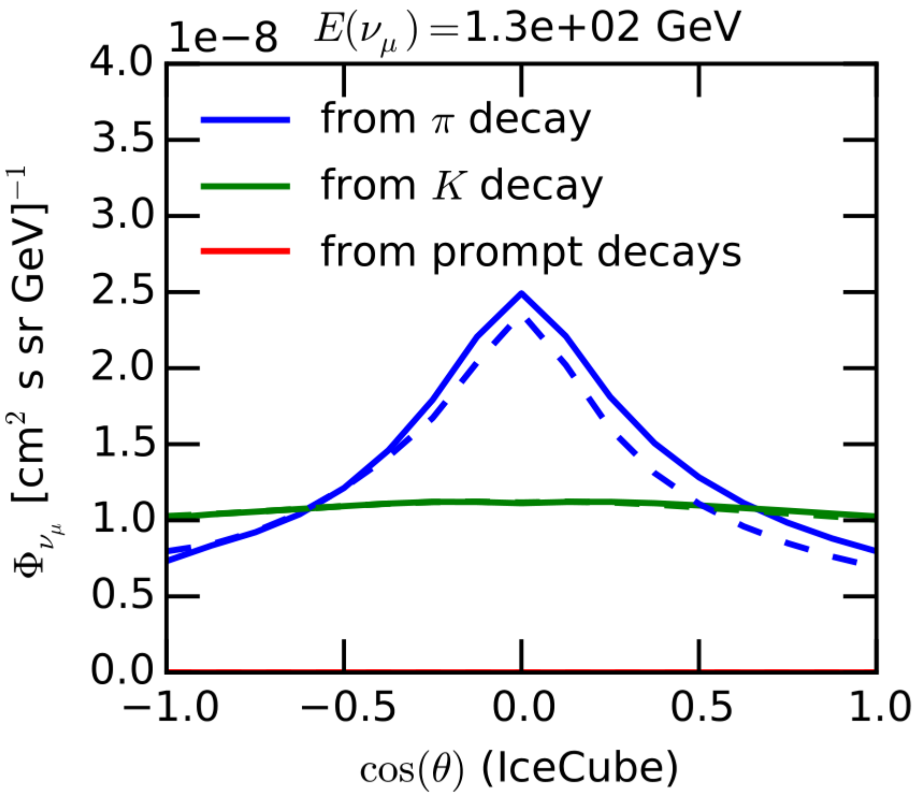
Electron neutrinos



muon decay | kaon decay | charm decay

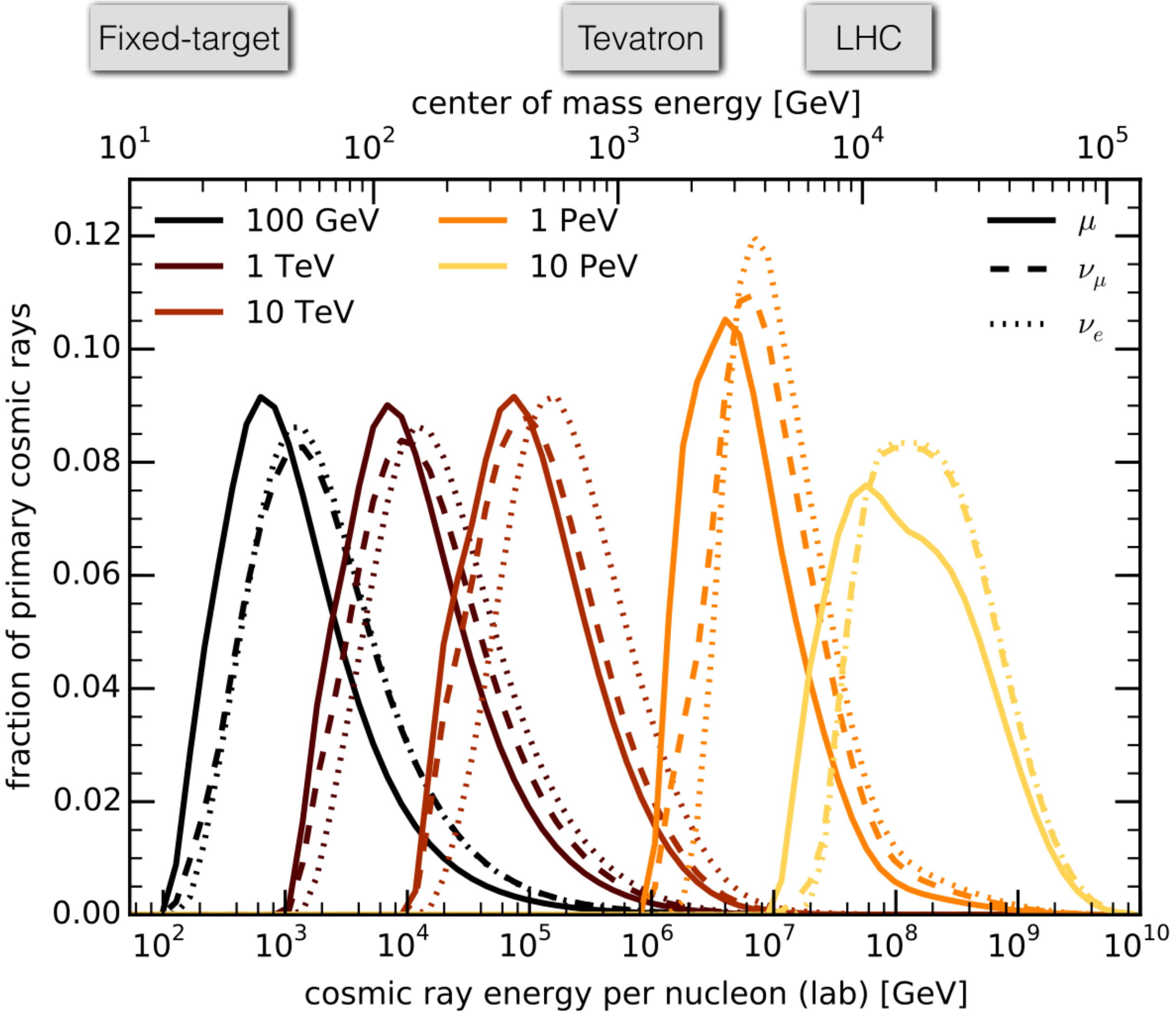
Effect of zenith angle

- Elongated profile of inclined showers reduces interactions
- Vertical leptons come more often from short lived particles
- From horizontal directions longer lived hadrons are less attenuated and can decay into leptons
- Also atmospheric variations



Related cosmic ray energies

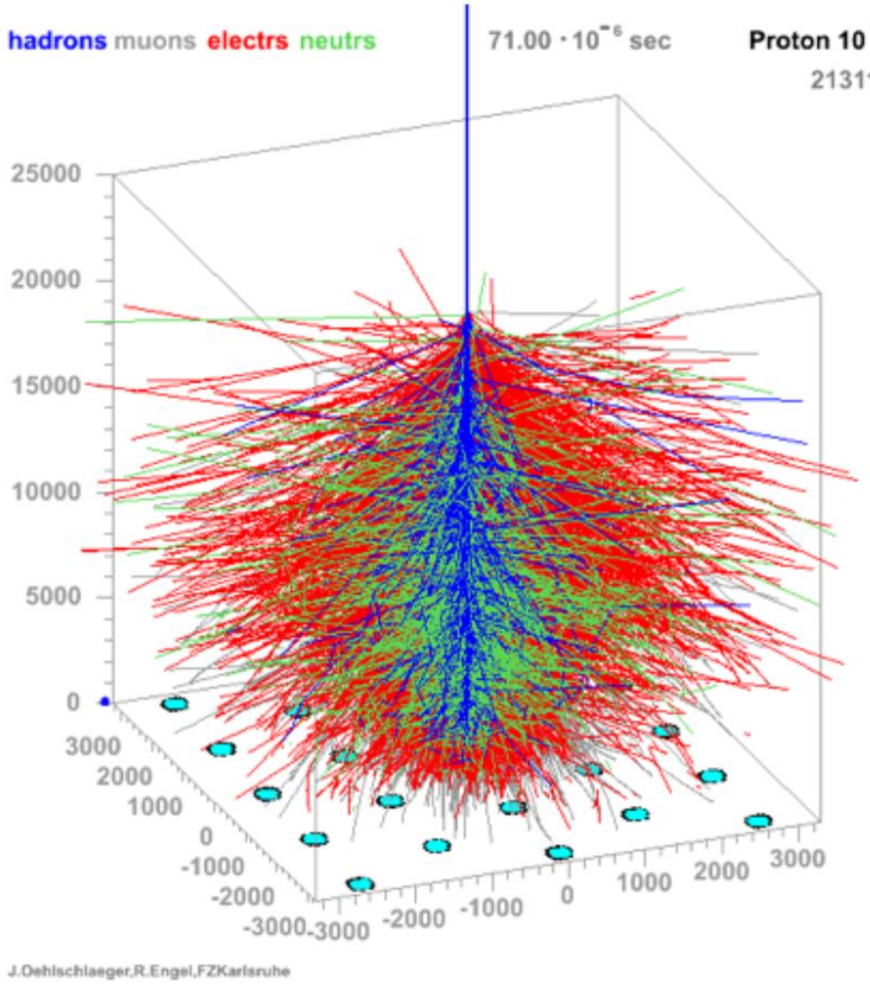
- At least one order of magnitude higher than neutrino energy
- Fluxes relatively well known from direct measurements (PAMELA, AMS, BESS,…)
- Influenced by solar modulation around few GeV
- Super-K already probed CR energies above fixed-target range



One-dimensional calculations

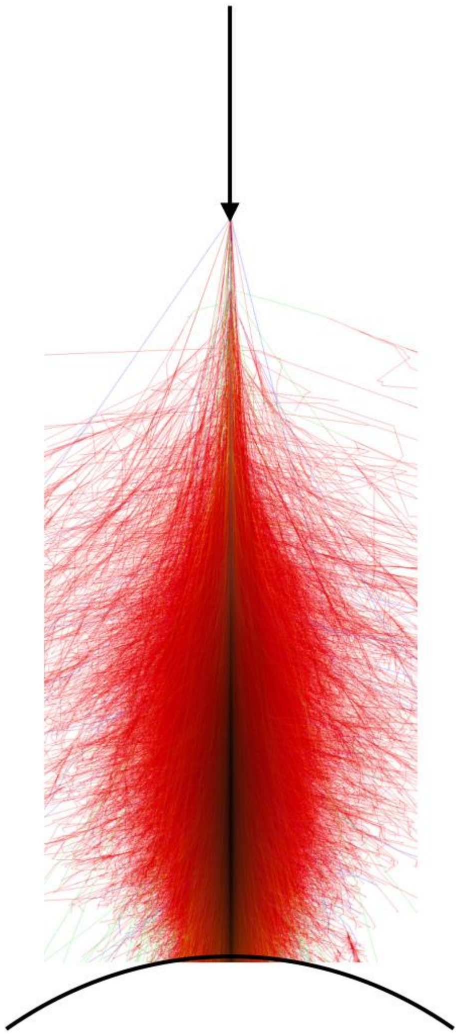
CORSIKA – air-shower simulator

- CORSIKA is a complete air-shower Monte Carlo package
- Contains models of
  - Atmosphere
  - Hadronic interactions (SIBYLL, QGSJET, EPOS, DPMJET)
  - Electromagnetic interactions (EGS4)
- Various extensions, including
  - Cherenkov radiation
  - Radio



https://www.ikp.kit.edu/corsika/

Method



For various “inputs“

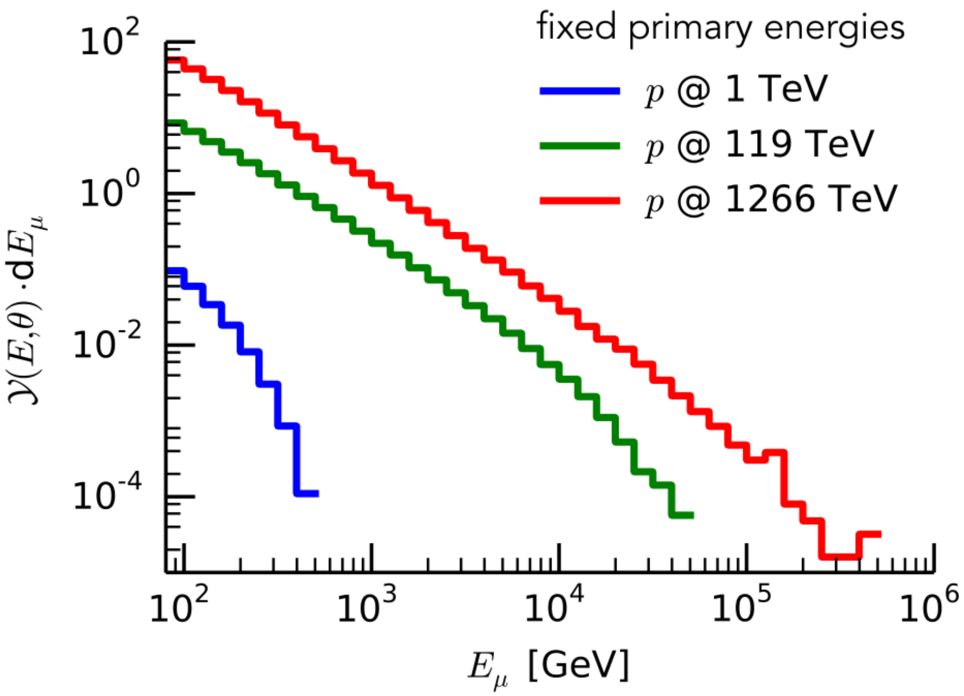
primary spectrum,
zenith angle,
composition

simulate “average“
air-shower

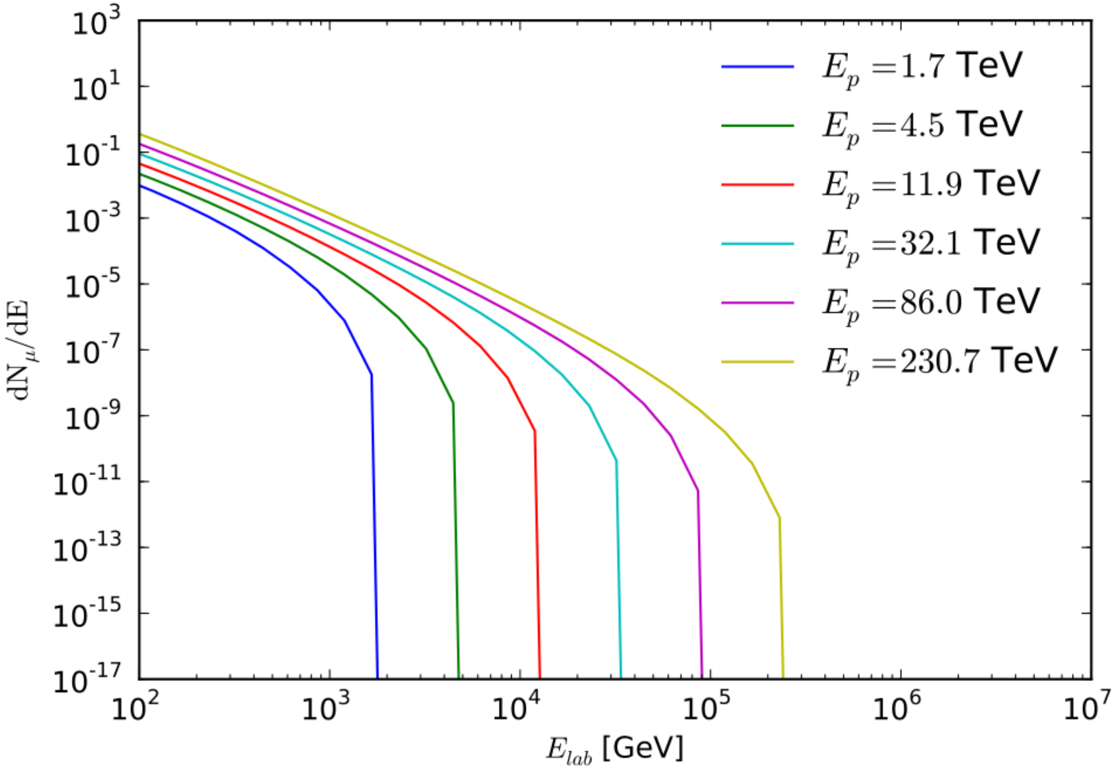
score energy spectrum
of particles in virtual
detector

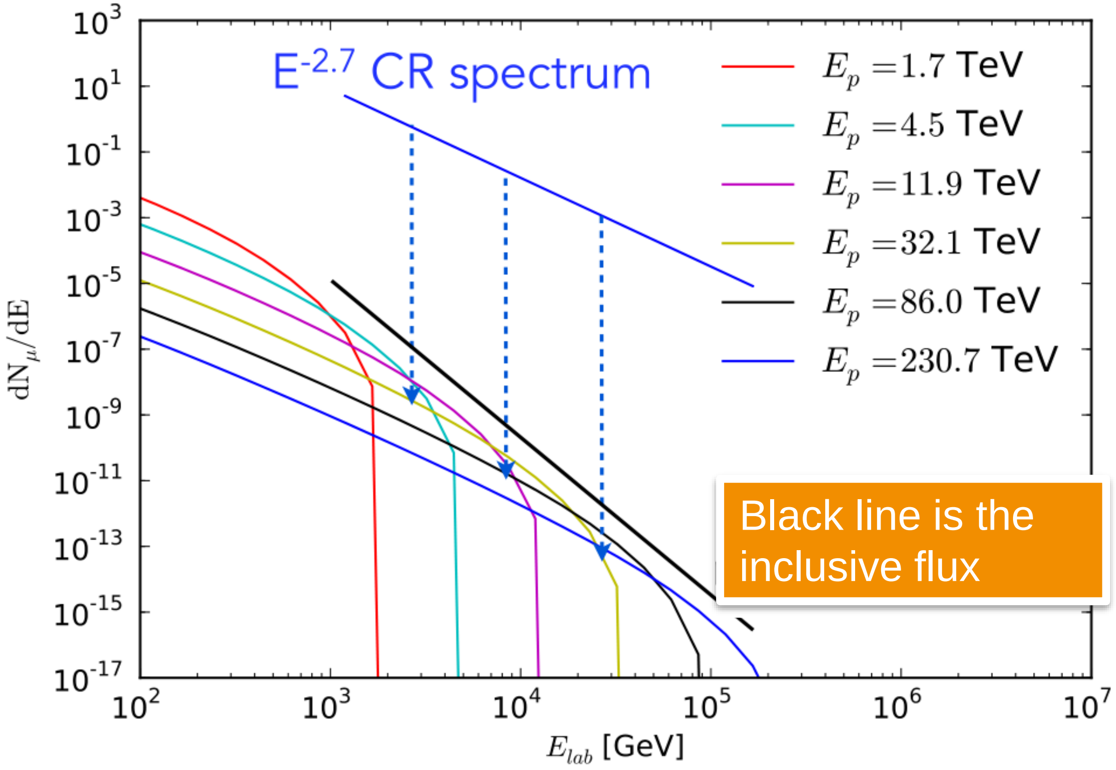
Obtain 1D Yield/Response function

$$\mathcal{Y}(E_0, Z_0, \theta, M, \dots)$$



Convolve yields with primary spectrum





$$\Phi_\mu(E_\mu, \theta) = \sum_p \sum_{E_i} w_p(E_i) \times \mathcal{Y}_{p\to\mu}(E_\mu, E_i, \theta)$$

nuclei/ composition → $\sum_p$

primary spectrum → $w_p(E_i)$

from CORSIKA → $\mathcal{Y}_{p\to\mu}$

$$w_p(E_i) = \frac{1}{N_p(E_i)} \int_{E_i}^{E_{i+1}} \Phi_p(E')dE', \qquad N_p(E_i) = \mathrm{NSHOW}$$

MCEq: Matrix Cascade Equations

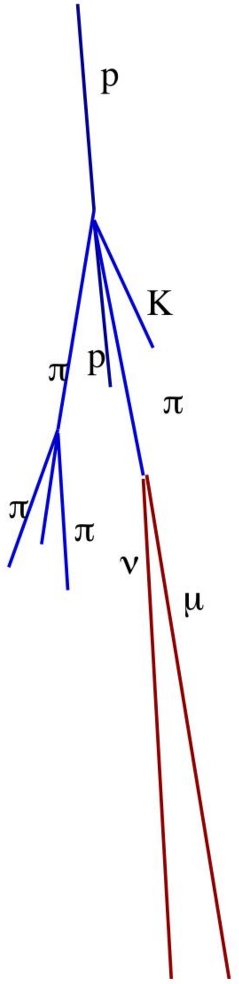
coupled cascade equations

for hadron of type h at (grid-) energy E_i:

$$\frac{\mathrm{d}\phi_h(E_i)}{\mathrm{d}X} = -\frac{\phi_h(E_i)}{\lambda^{(h)}_{int}(E_i)} + \sum_{E_k \geq E_i} \sum_k \frac{c_{k\to h}(E_i,E_k)}{\lambda^{(k)}_{int}(E_k)}\phi_k(E_k) - \frac{\phi_h(E_i)}{\lambda^{(h)}_{dec}(E_i,X)} + \sum_{E_k \geq E_i} \sum_k \frac{d_{k\to h}(E_i,E_k)}{\lambda^{(k)}_{dec}(E_k,X)}\phi_k(E_k)$$

from interaction models: SIBYLL, QGSJET, DPMJET

from PYTHIA 8



flux vector

$$\vec{\phi} = \begin{pmatrix} \phi_p(E_0) \\ \phi_p(E_1) \\ \dots \\ \phi_p(E_N) \\ \phi_n(E_0) \\ \dots \\ \phi_n(E_N) \\ \phi^+_\pi(E_0) \\ \dots \\ \phi_{\bar{\nu}_e}(E_N) \end{pmatrix}$$

Matrix-form

$$\frac{\mathrm{d}}{\mathrm{d}X}\boldsymbol{\phi} = \left[(-\mathbf{1}+\boldsymbol{C})\boldsymbol{\Lambda}_{int} + \frac{1}{\rho(X)}(-\mathbf{1}+\boldsymbol{D})\boldsymbol{\Lambda}_{dec}\right]\boldsymbol{\phi}.$$

geometry & atmosphere

A. Fedynitch, R. Engel, T. K. Gaisser, F. Riehn and S. Todor
PoS ICRC 2015, 1129 (2015), EPJ Web Conf. 99, 08001 (2015) and EPJ Web Conf. 116, 11010 (2016)

Hadrons in MCEq

Leptons

$$\mu^+,\ \mu^-,\ \tau^+,\ \tau^-,\ \nu_e,\ \nu_\mu,\ \nu_\tau,\ \bar{\nu}_e,\ \bar{\nu}_\mu,\ \bar{\nu}_\tau$$

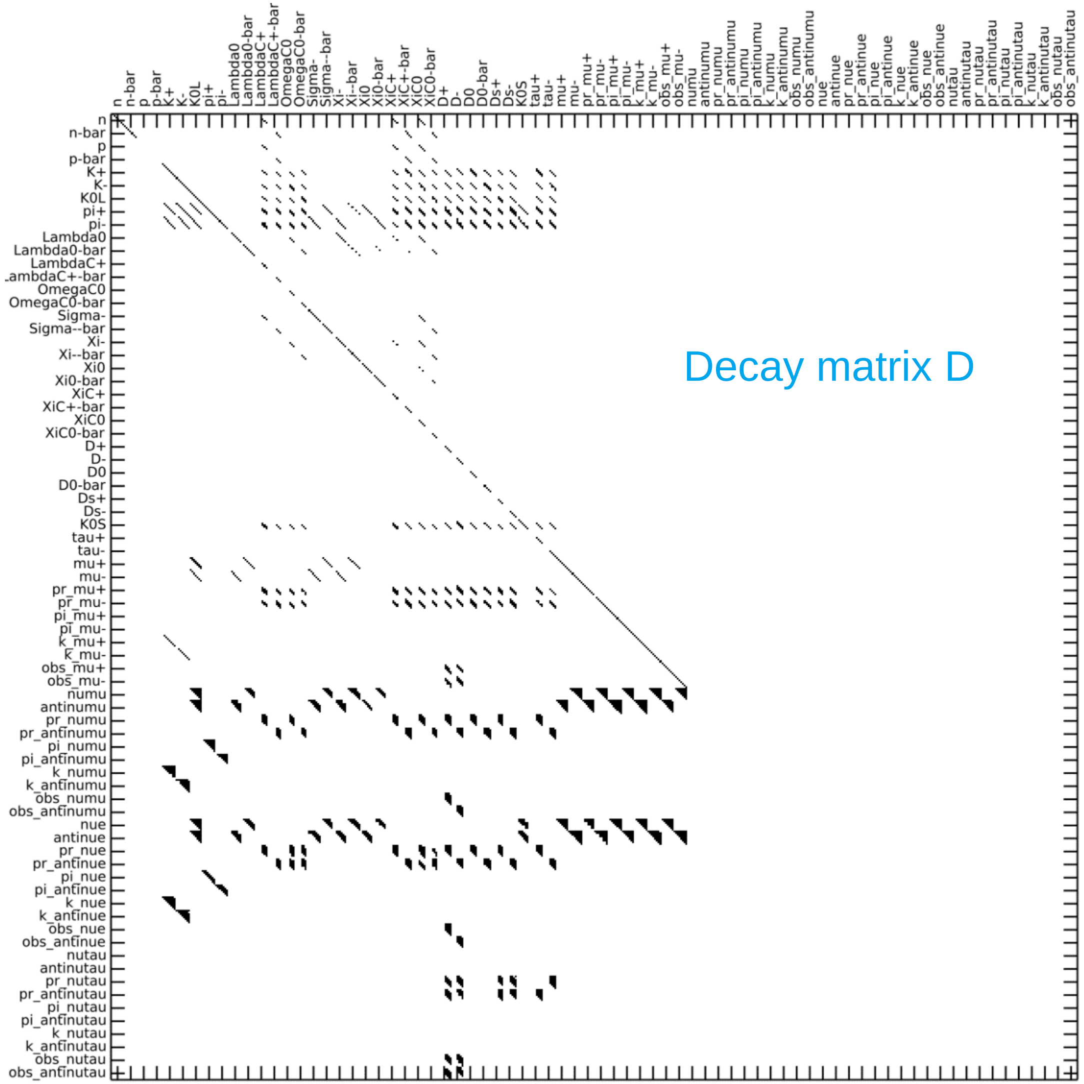
Mesons

$$K^+,\ K^-,\ K_L^0,\ K_S^0,\ \pi^+,\ \pi^-,\ D^+,\ D^-,\ D^0,\ \bar{D}^0,\ D_s^+,\ D_s^-,\ K^{*+},\ K^{*-},$$
$$K^{*0},\ \bar{K}^{*0},\ D^{*+},\ D^{*-},\ D^{*0},\ \bar{D}^{*0},\ \eta,\ \eta^*,\ \eta_C,\ J/\Psi,\ \omega,\ \phi,\ \pi^0,\ \rho^+,\ \rho^-,\ \rho^0$$

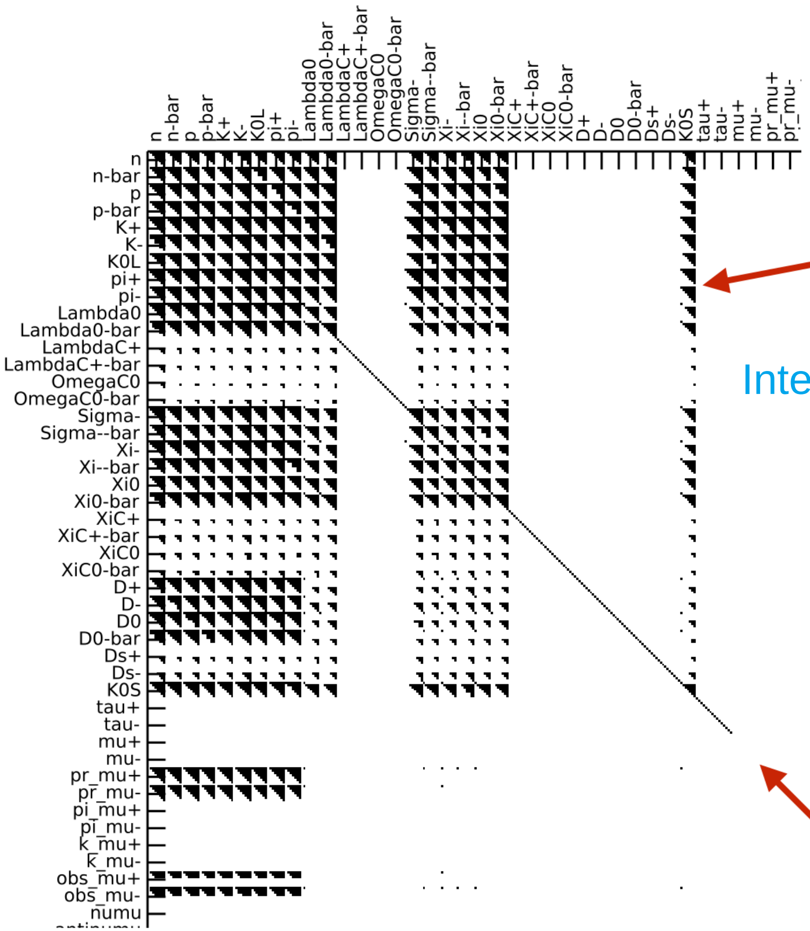
Baryons

$$p,\ \bar{p},\ n,\ \bar{n},\ \Delta^+,\ \Delta^{++},\ \bar{\Delta}^{++},\ \bar{\Delta}^+,\ \Delta-,\ \bar{\Delta}^+,\ \Delta^0,\ \bar{\Delta}^0,\ \Lambda^0,\ \bar{\Lambda}^0,\ \Omega^-,\ \bar{\Omega}^+,$$
$$\Sigma^{*+},\ \bar{\Sigma}^{*-},\ \Sigma^{*-},\ \bar{\Sigma}^{*+},\ \Sigma^{*0},\ \bar{\Sigma}^{*0},\ \Sigma^+,\ \bar{\Sigma}^-,\ \Sigma^0,\ \bar{\Sigma}^0,\ \Lambda_C^+,\ \bar{\Lambda}_C^-,\ \Omega_C^0,\ \bar{\Omega}_C^0,\ \Sigma^-,$$
$$\bar{\Sigma}^+,\ \Xi^-,\ \bar{\Xi}^+,\ \Xi^0,\ \bar{\Xi}^0,\ \Xi_C^+,\ \bar{\Xi}_C^+,\ \Xi_C^0,\ \bar{\Xi}_C^0,\ \Sigma_C^{*+},\ \Sigma_C^{*++},\ \bar{\Sigma}_C^{*--},\ \bar{\Sigma}_C^{*-},\ \Sigma_C^{*0},$$
$$\bar{\Sigma}_C^{*0},\ \Sigma_C^+,\ \Sigma_C^{++},\ \bar{\Sigma}_C^{--},\ \bar{\Sigma}_C^-,\ \Sigma_C^0,\ \bar{\Sigma}_C^0,\ \Xi^{*-},\ \bar{\Xi}^{*+},\ \Xi^{*0},\ \bar{\Xi}^{*0}$$

Matrix forms



Decay matrix D



Interaction matrix C

$$\frac{c_{k\to h}(E_i, E_k)}{\lambda_{int}^{(k)}(E_k)}$$

$$-\frac{\phi_h(E_i)}{\lambda_{int}^{(h)}(E_i)}$$

matrices are sparse → high performance

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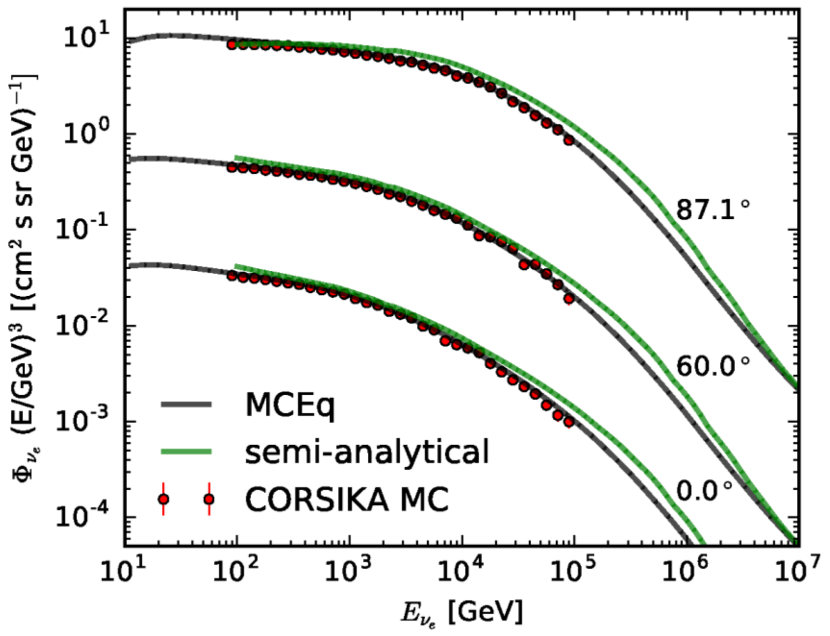
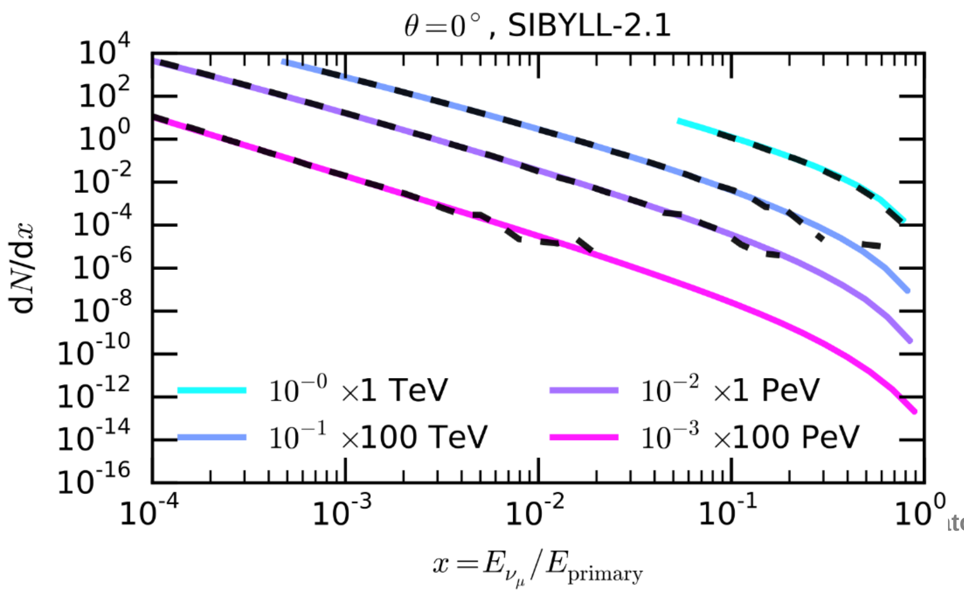
MCEq accuracy as MC, but faster





- 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

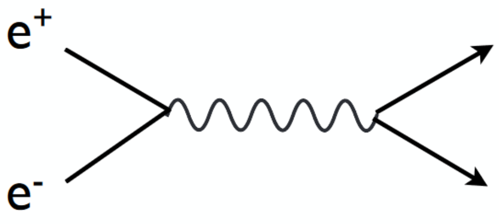
CORSIKA: A. Fedynitch, J. Becker Tjus and P. Desiati, PRD 2012
MCEq: A. Fedynitch, R. Engel, T. K. Gaisser, F. Riehn and S. Todor. PoS ICRC 2015, 1129

Hadronic interaction models

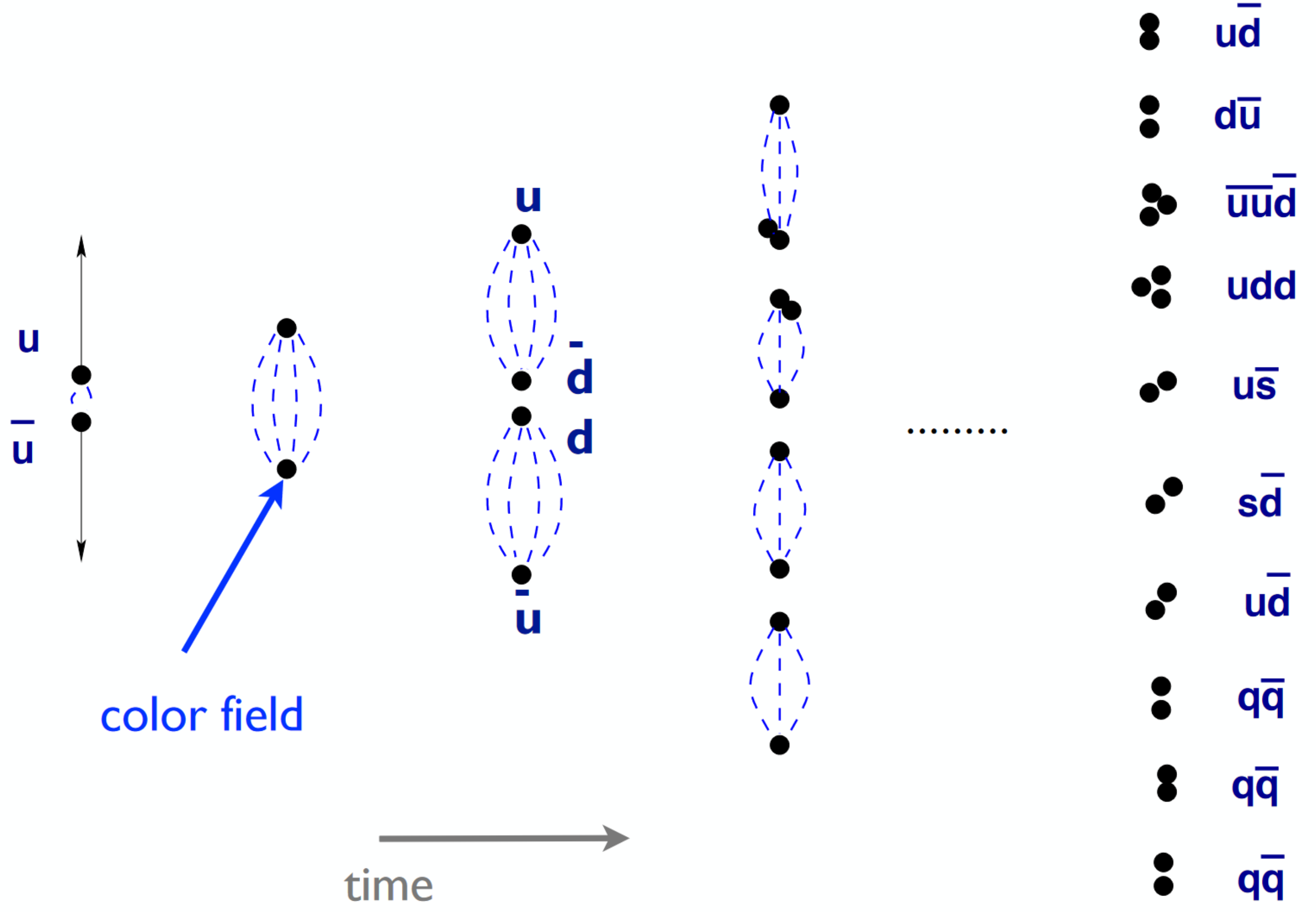
Simplest case: e^+e^- annihilation

(Some slides sourced from R. Engel)

Annihilation at high energy

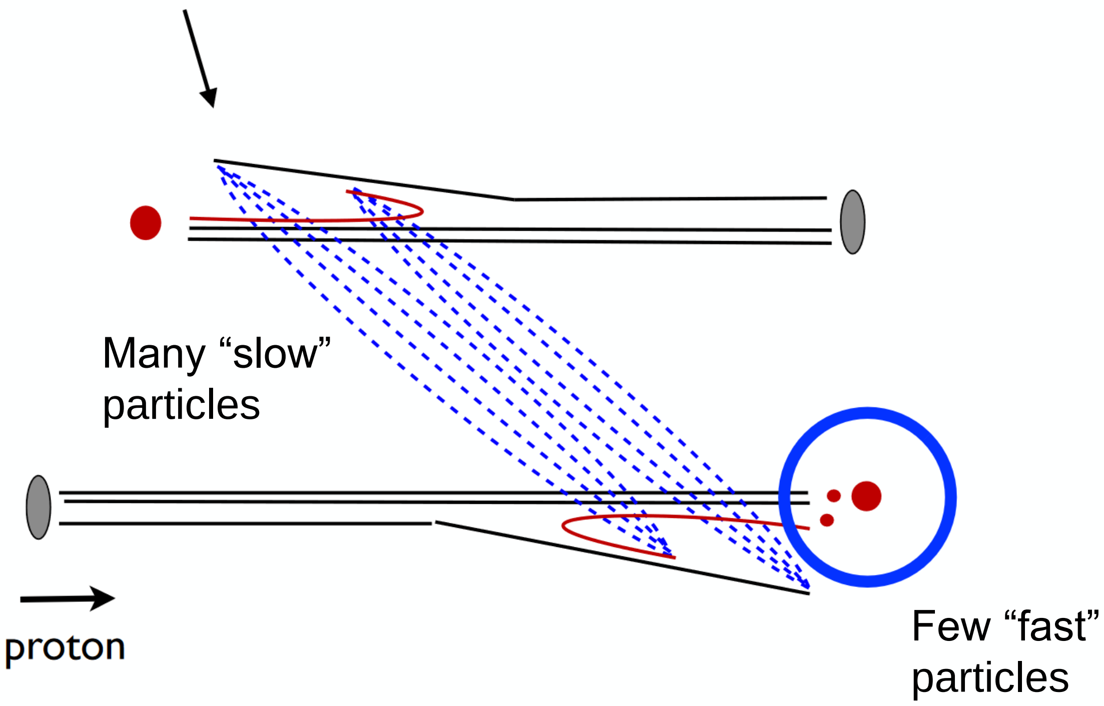


Quarks together are color-neutral system



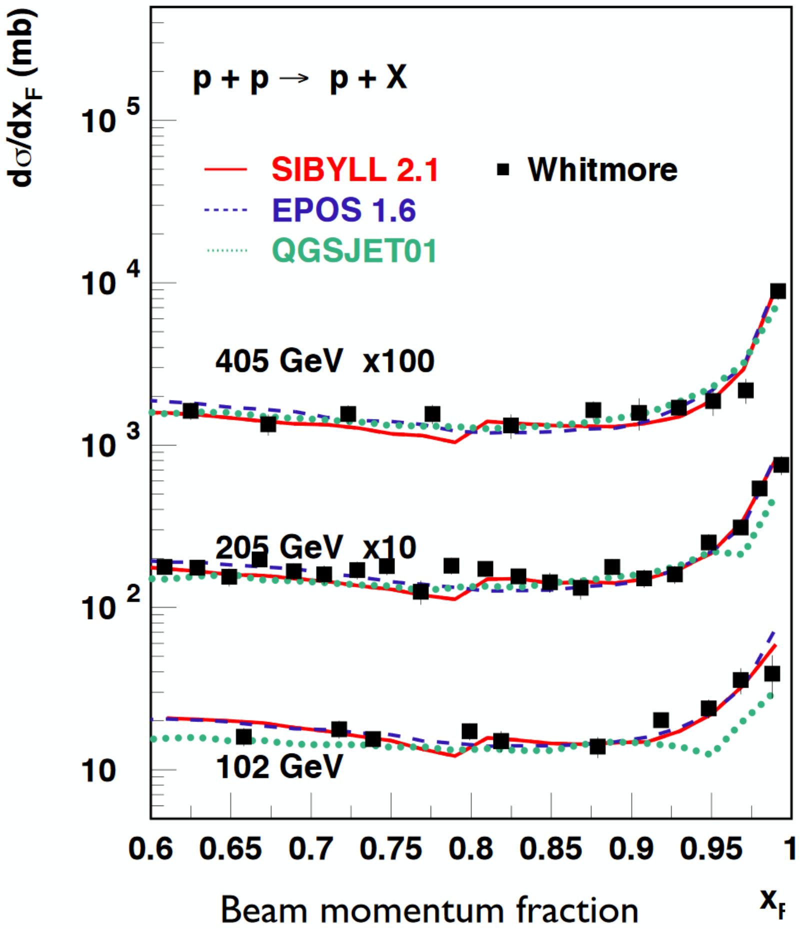
String fragmentation tuned to e^+e^-

Leading particle effect

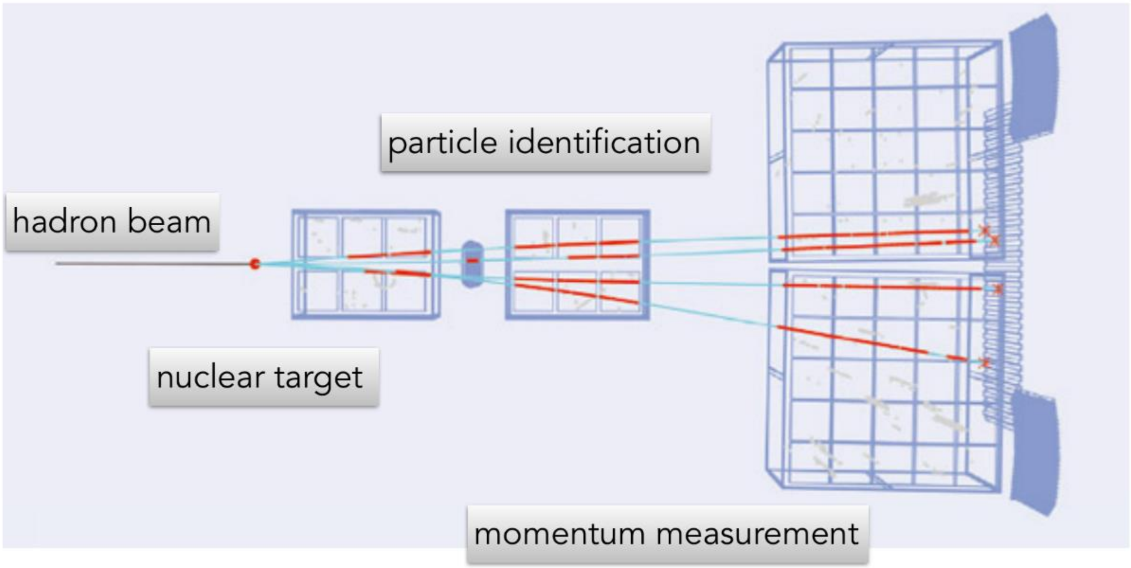


Fluctuations: Generation of sea quark anti-quark pair and leading/excited hadron

Leading particle effect



Phase-space for atmospheric lepton production



Scattering angle

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

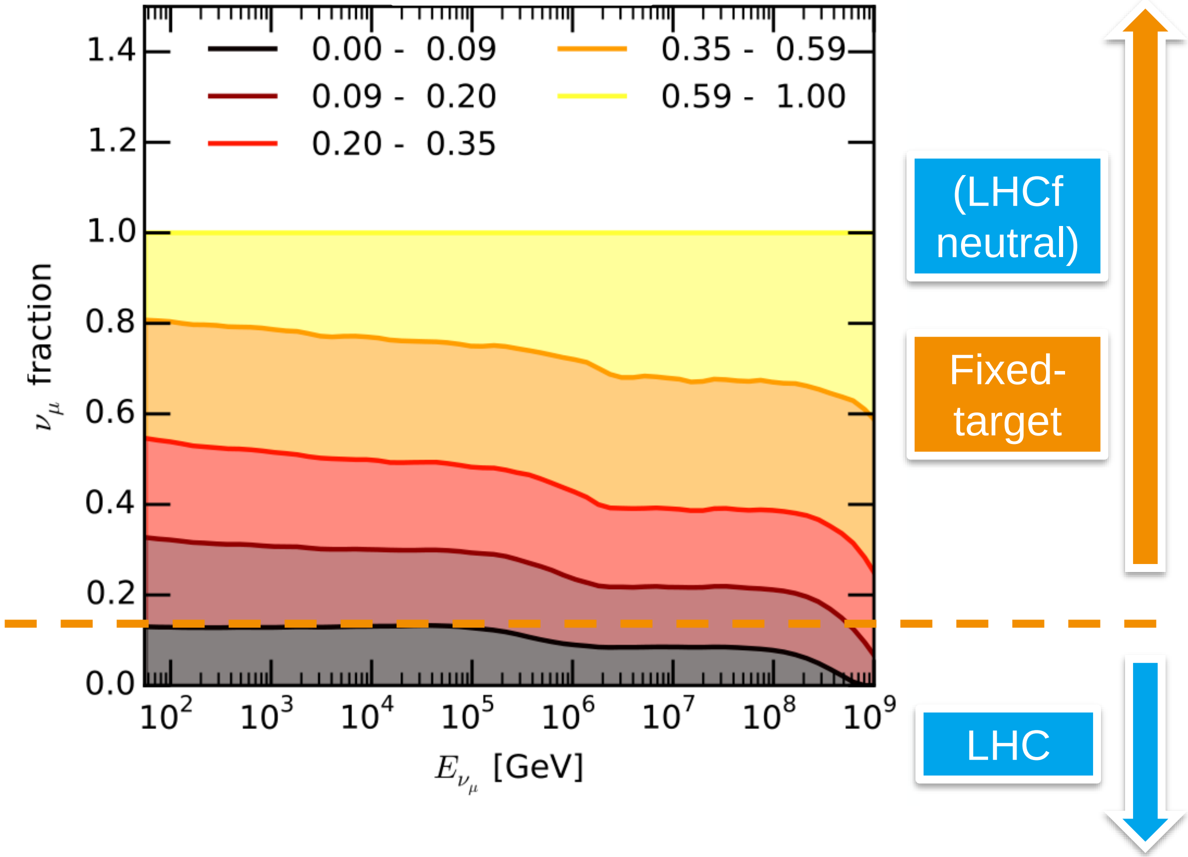
$$p_T \sim \text{few GeV}$$

$$\theta = \arctan \frac{p_T}{p_z}$$

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

Most atmospheric leptons come from forward phase-space.

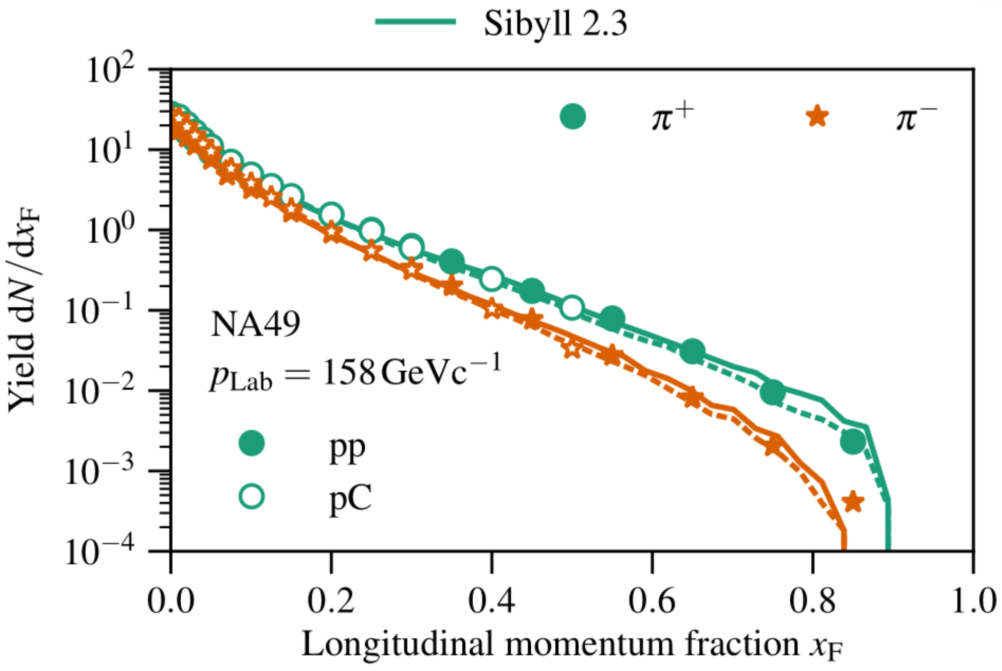
Phase-space regions contributing to inclusive muon neutrino flux

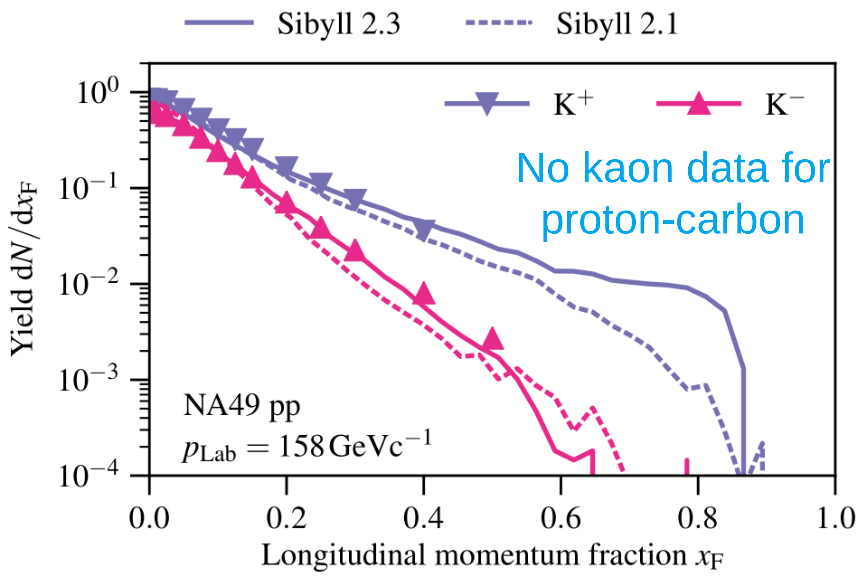


Fedynitch (VLVNT) EPJ Web Conf. 116, 11010 (2016)

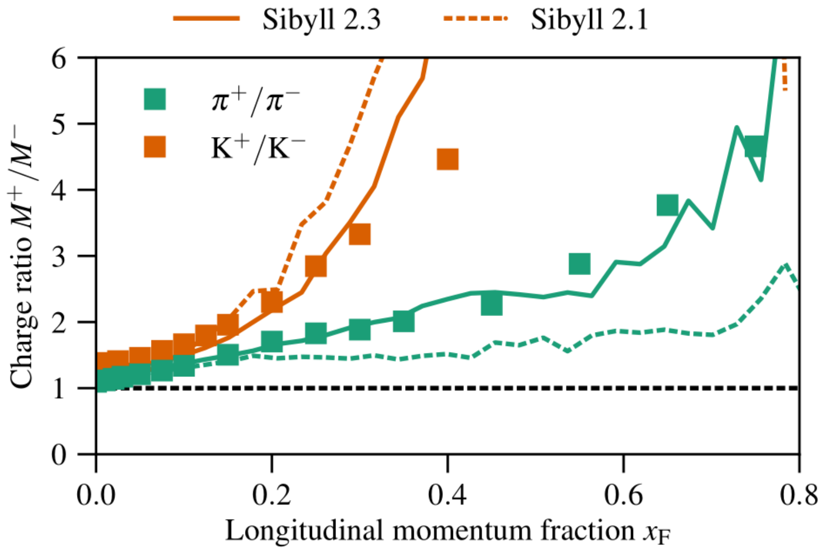
Fixed-target data as “anchor” for tuning of models

… but only at low energy, unclear how to extrapolate



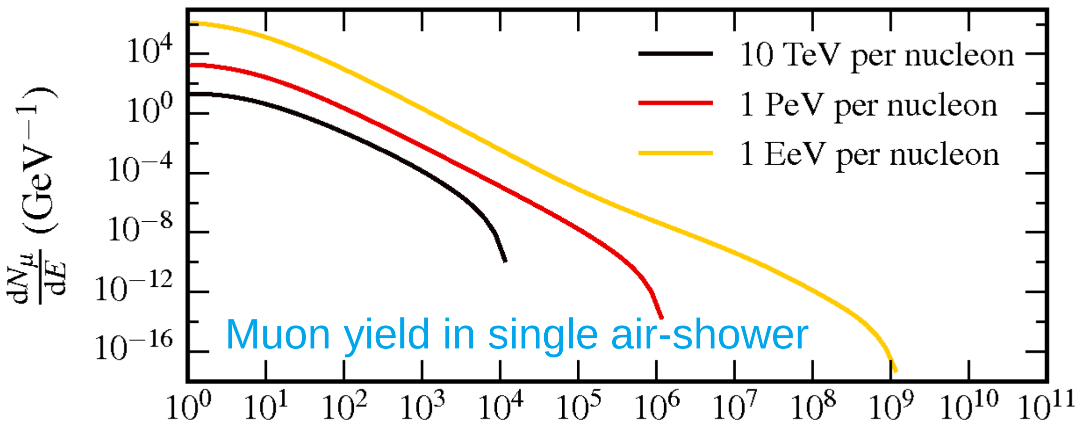


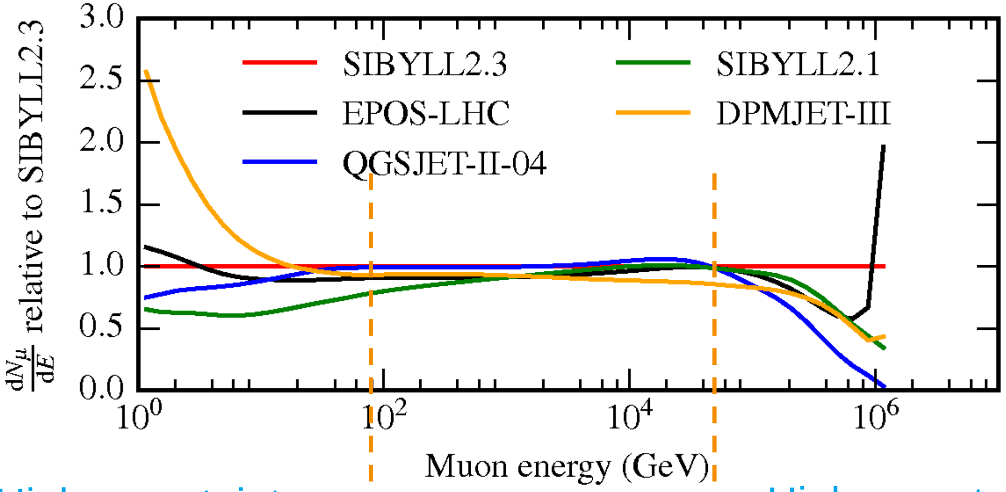
No kaon data for proton-carbon



F. Riehn, R. Engel, A. Fedynitch, T. K. Gaisser and T. Stanev. arXiv:1510.00568, PoS ICRC 2015, 1129 (2015)

Energy extrapolation results in large uncertainties among models

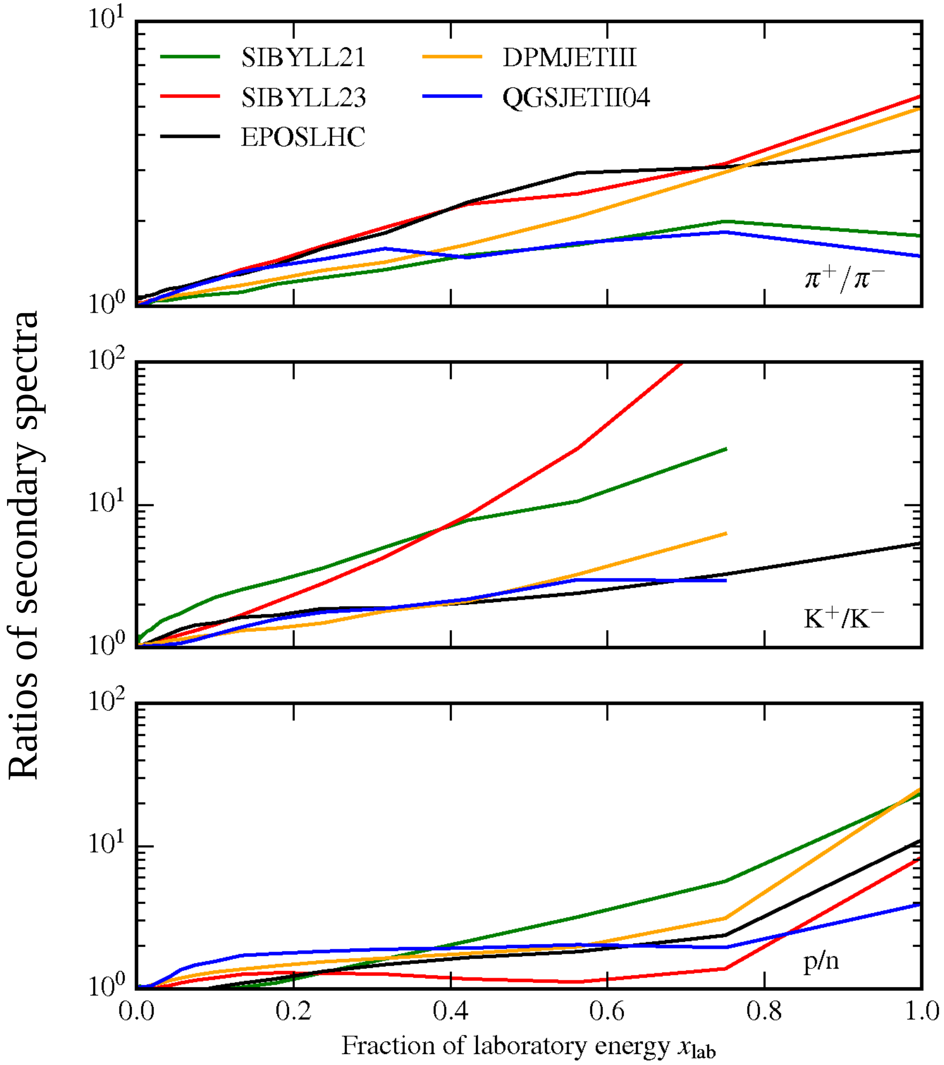




High uncertainty for air-showers

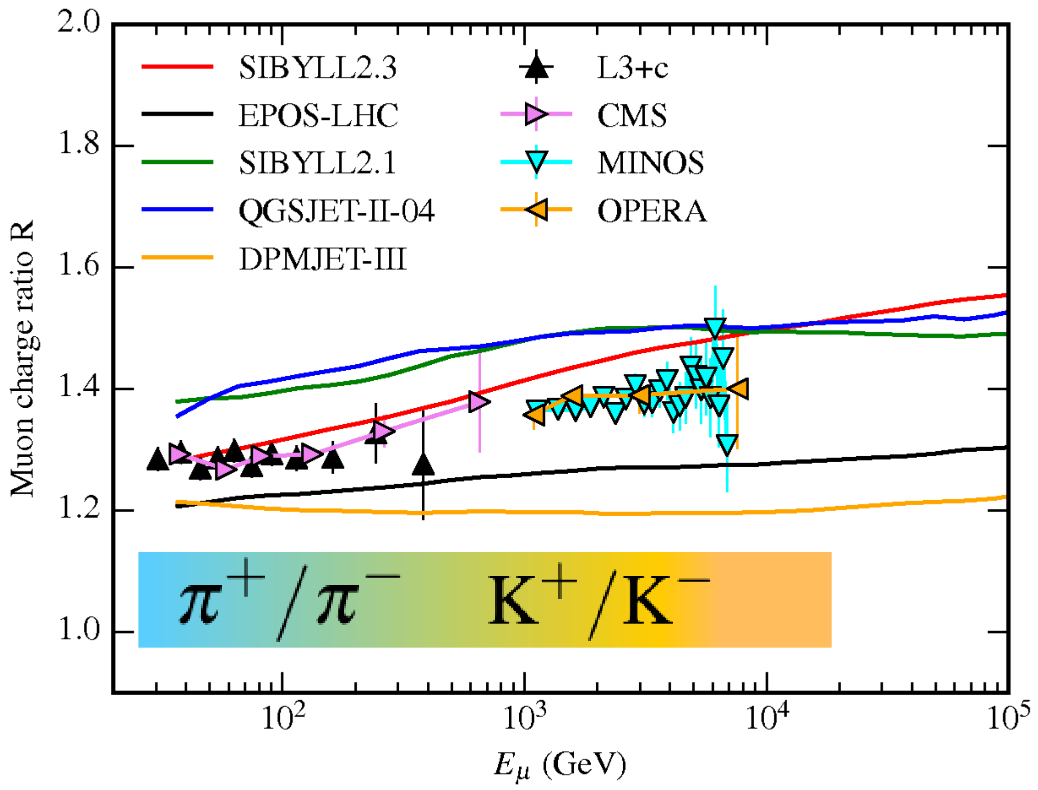
Scaling

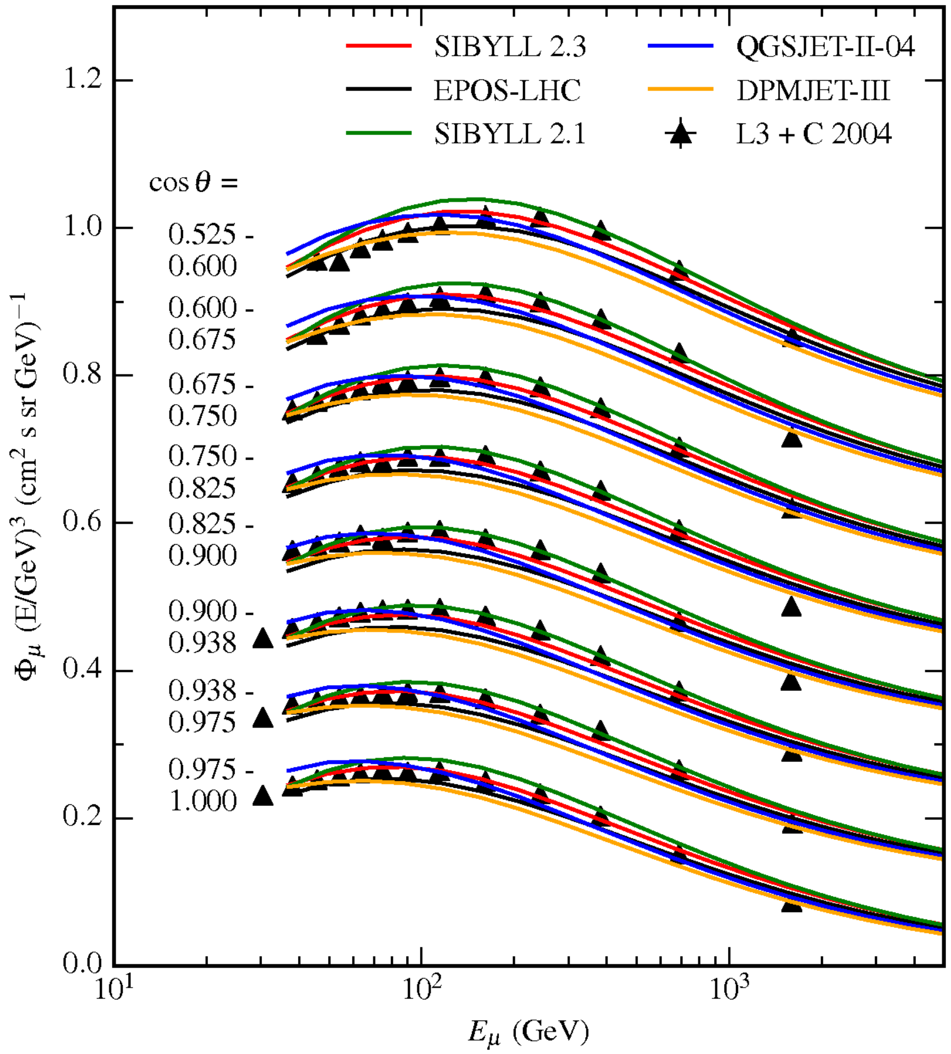
High uncertainty for inclusive fluxes



Study of hadronic interactions through atmospheric leptons

Interpretation of atmospheric muon data





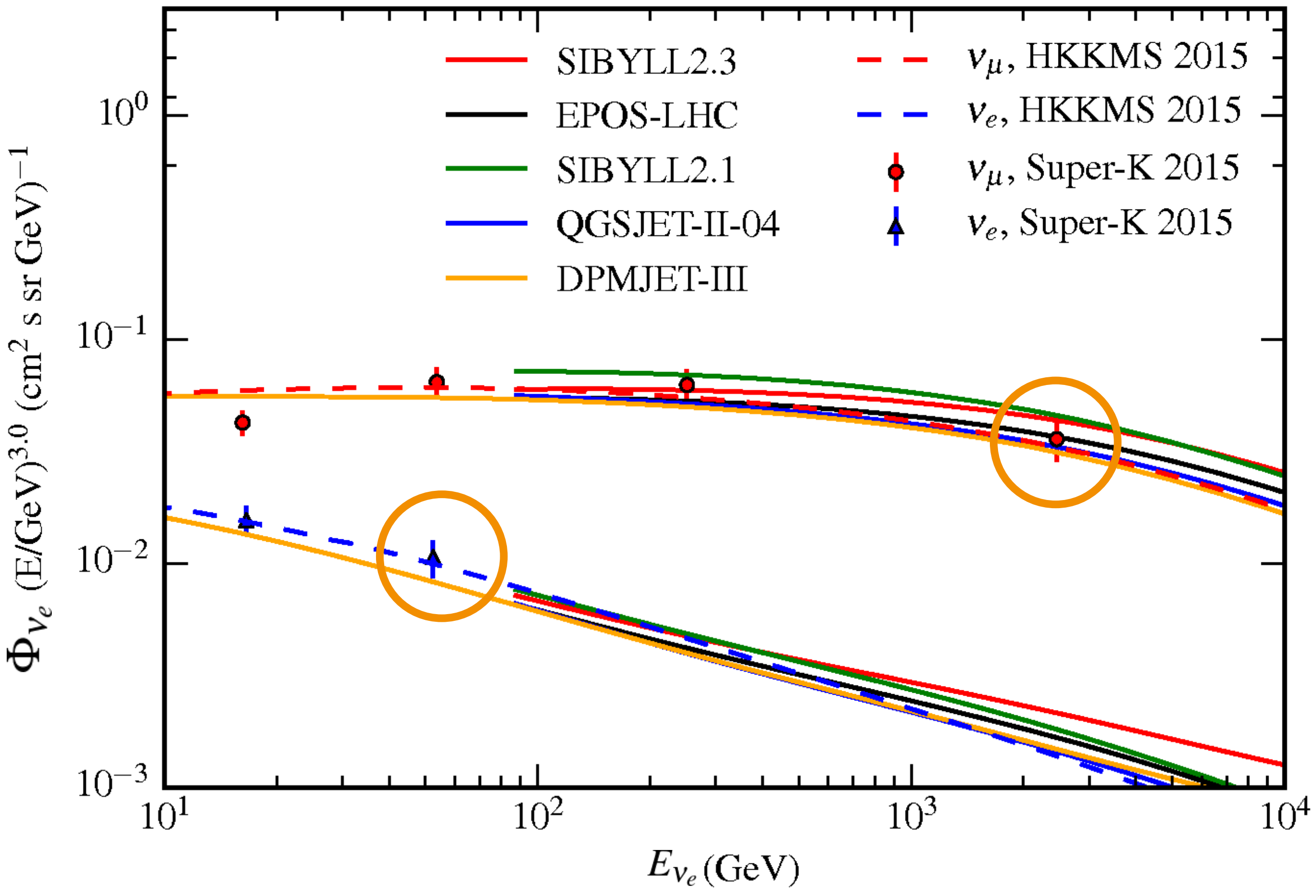
- Flux at TeV probes primary interactions ~10 TeV
- These measurements help to adjust pions and kaons separately
- L3+c highest E, high-precision flux measurement

What about neutrinos?

- Neutrinos above 100 GeV come from kaon decays
- Electron neutrinos also from K^0_L
- Neutrino ratios and fluxes constrain extrapolation uncertainties
- Neutrino/anti-neutrino ratio as important as muon charge ratio

HKKMS: M. Honda et al., PRD 2015

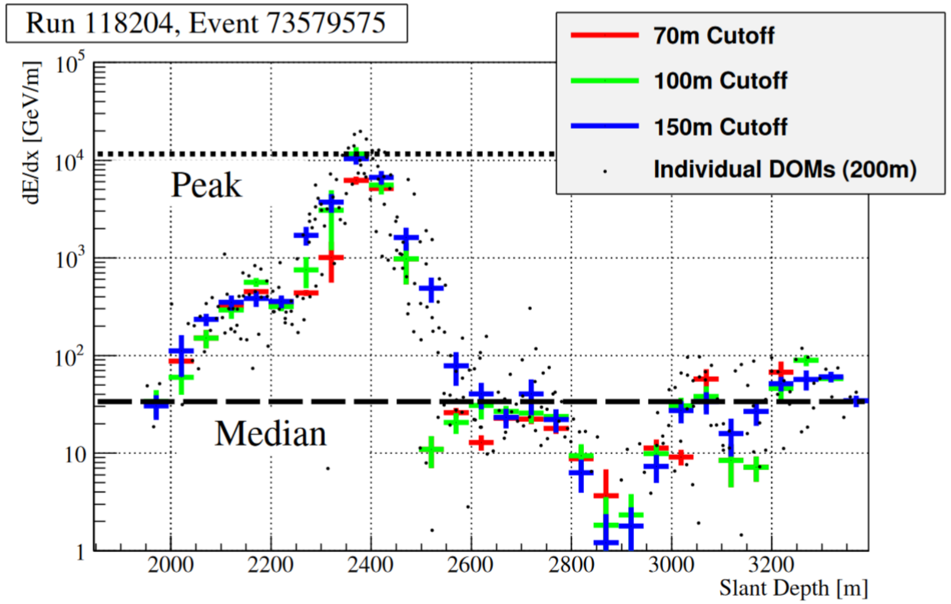
Data: Super-K Coll. (2015), arXiv:1510.08127

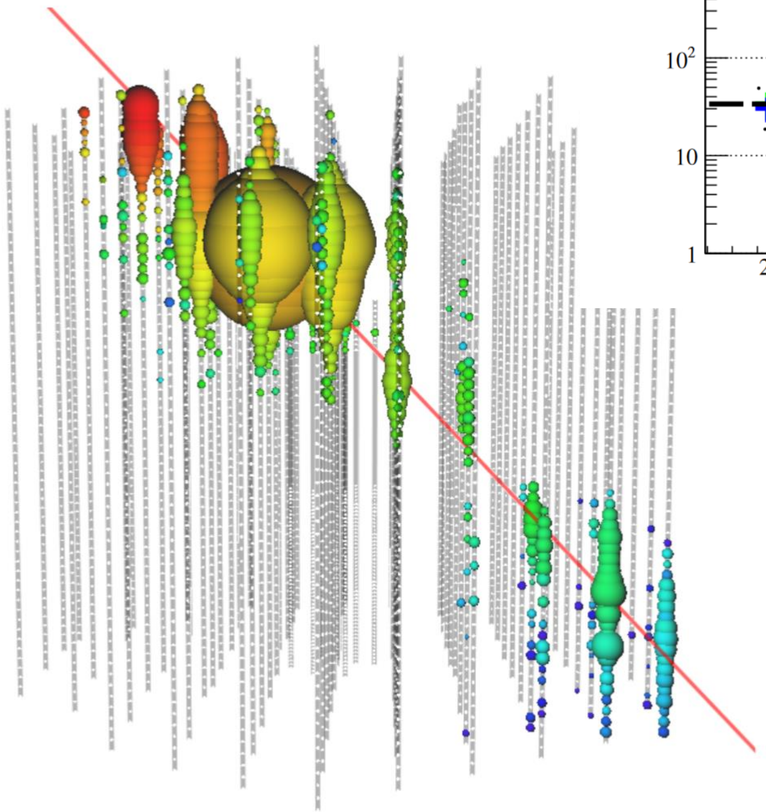


Energy behavior of kaons in SIBYLL disfavored by SK data

Muon flux measurement with IceCube

- Example of a measurement for which the detector was not designed for
- 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

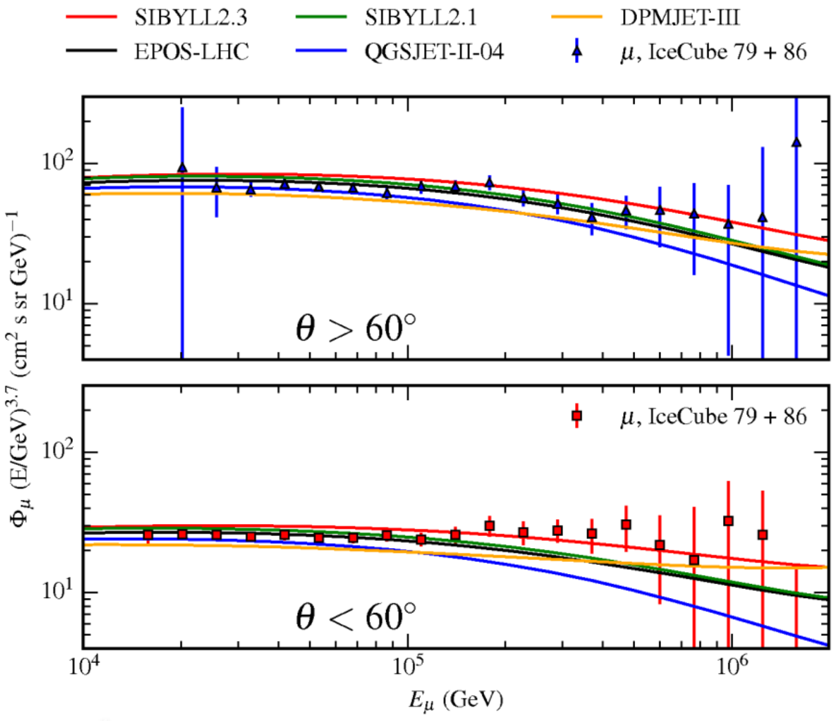


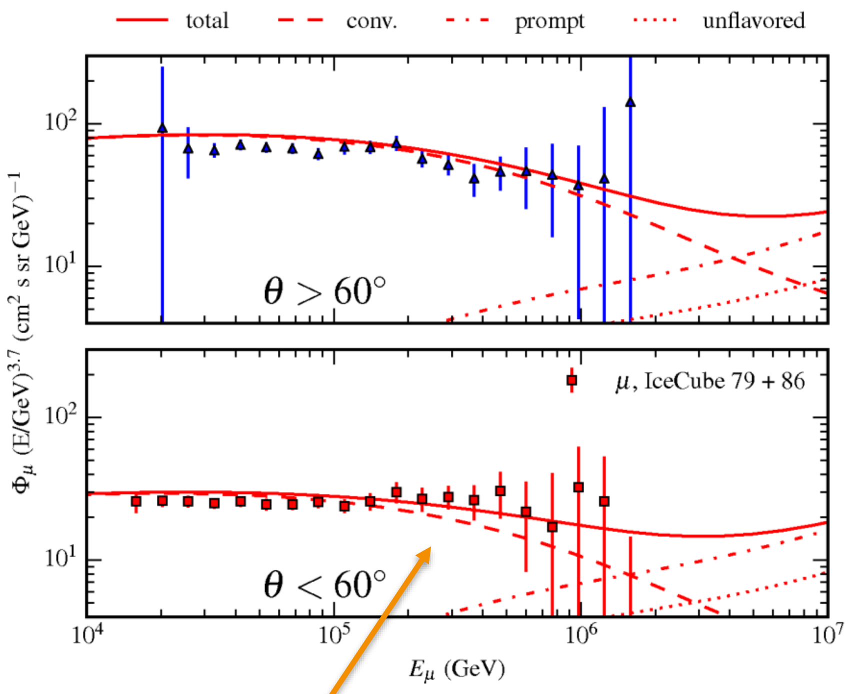


“Characterization of the Atmospheric Muon Flux in IceCube”
M. G. Aartsen et al. [IceCube Collaboration], Astropart. Phys. 78, 1 (2016)

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

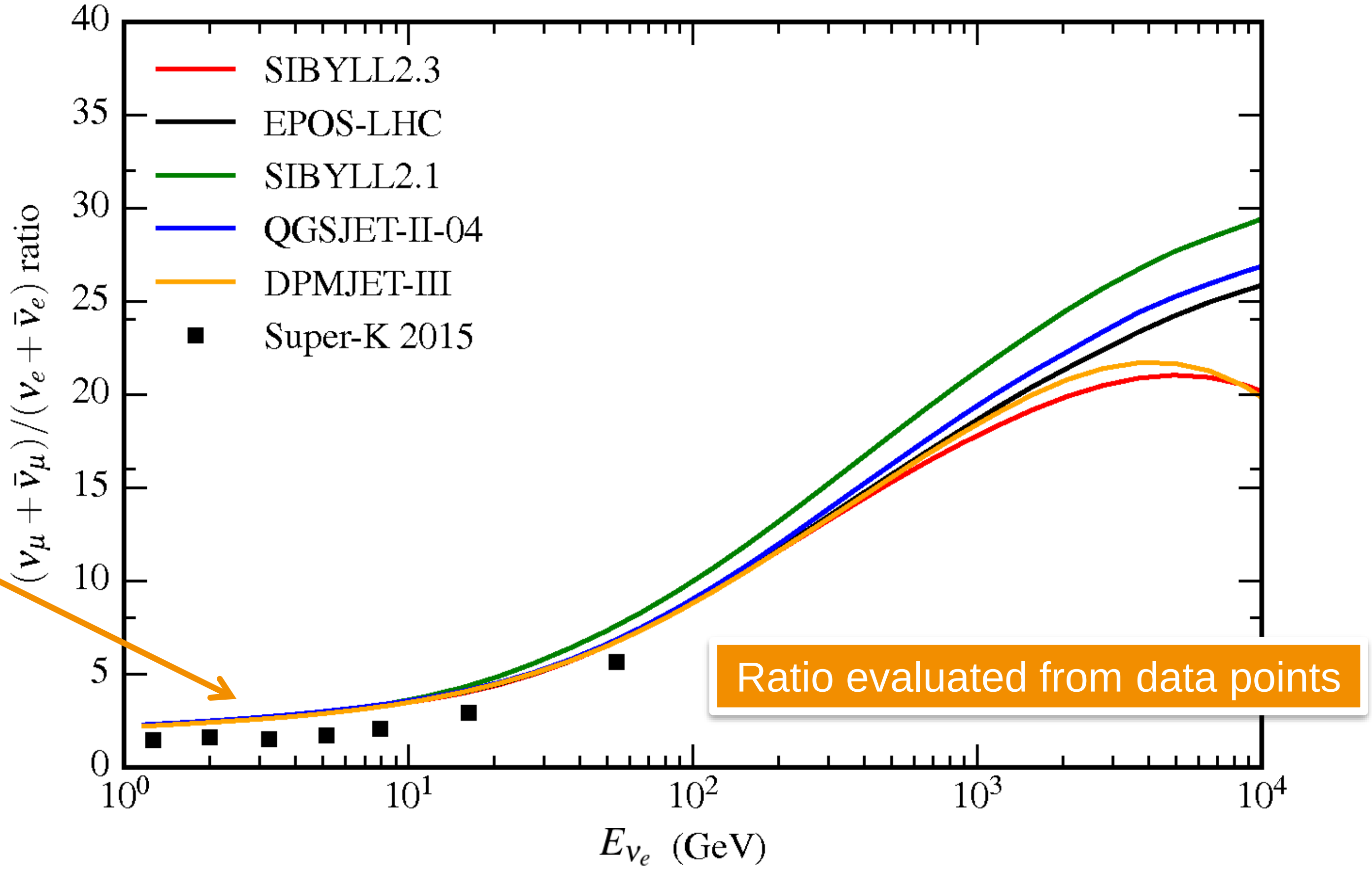
Prompt flux??

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

Current limitations of MCEq

- Missing “straight-forward to implement” features, precise for E > 30-60 GeV
  - Muon energy loss
  - Neutrino oscillations
- Possible upgrades
  - Geomagnetic cut-off
  - Curved trajectories due to magnetic field
  - 3D simulations
- The advantage of MCEq is possibility to evaluate all kinds of systematics, since code is open and very fast

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



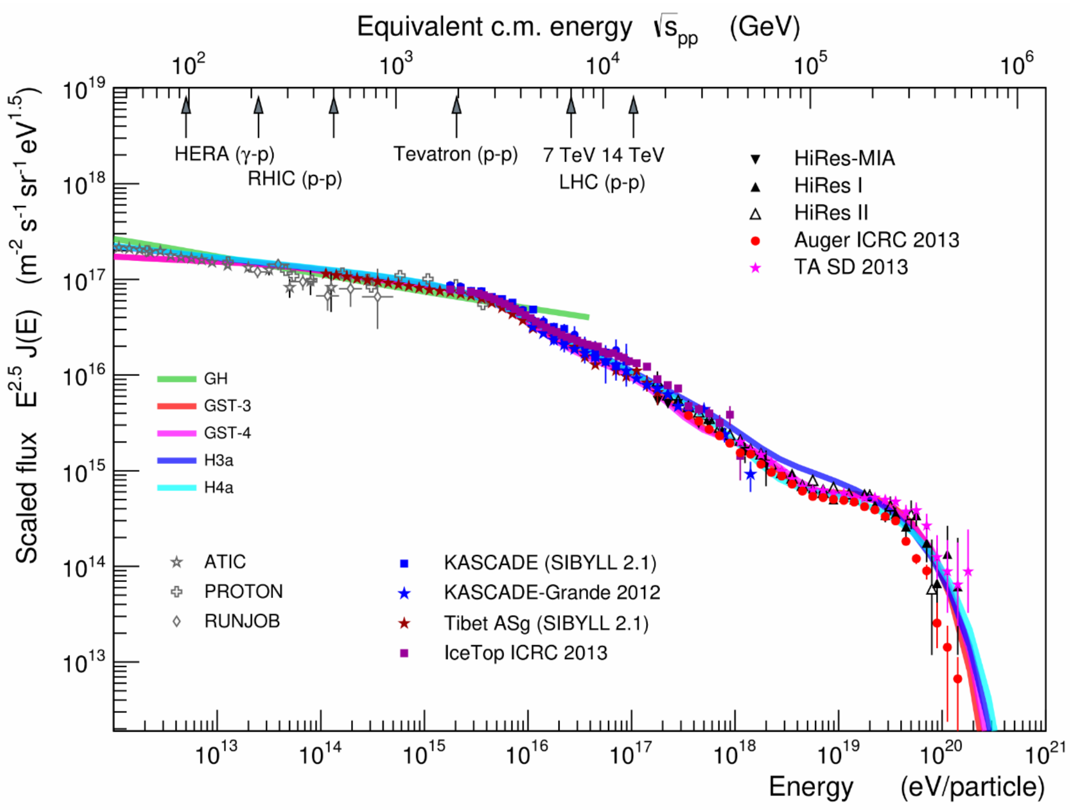
Conclusions

- Hadronic interactions can be studied with atmospheric muons and neutrinos
- Inclusive fluxes probe forward phase-space at energies beyond reach of fixed-target experiments
- Unique source of constraints for the energy dependence for charged leading particles
- MCEq can be extended to lower energies with increased precision

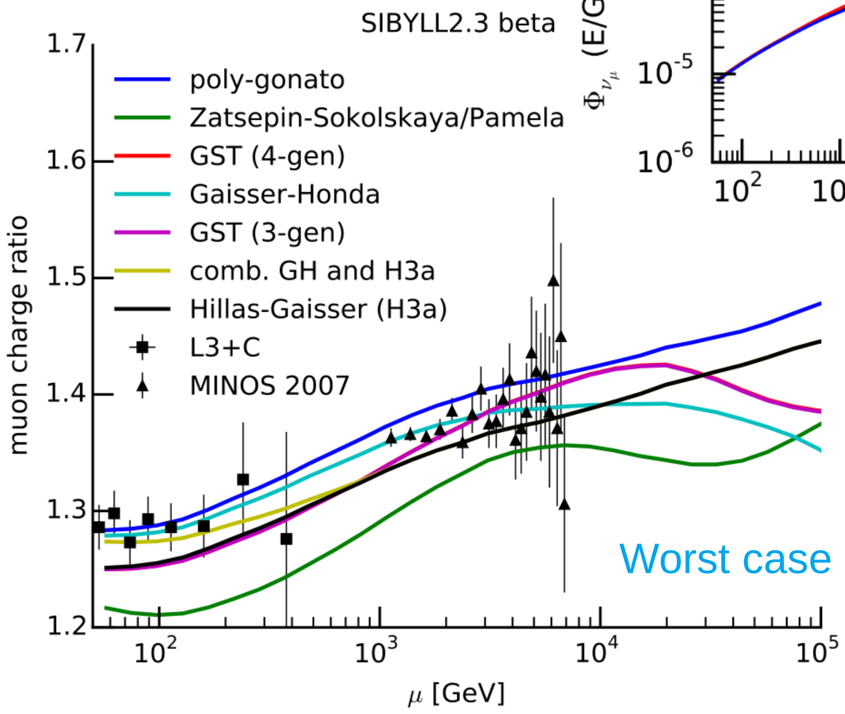
Questions:

- Can Hyper-K supersede Super-K in energy range and/or precision?
- What about muons?

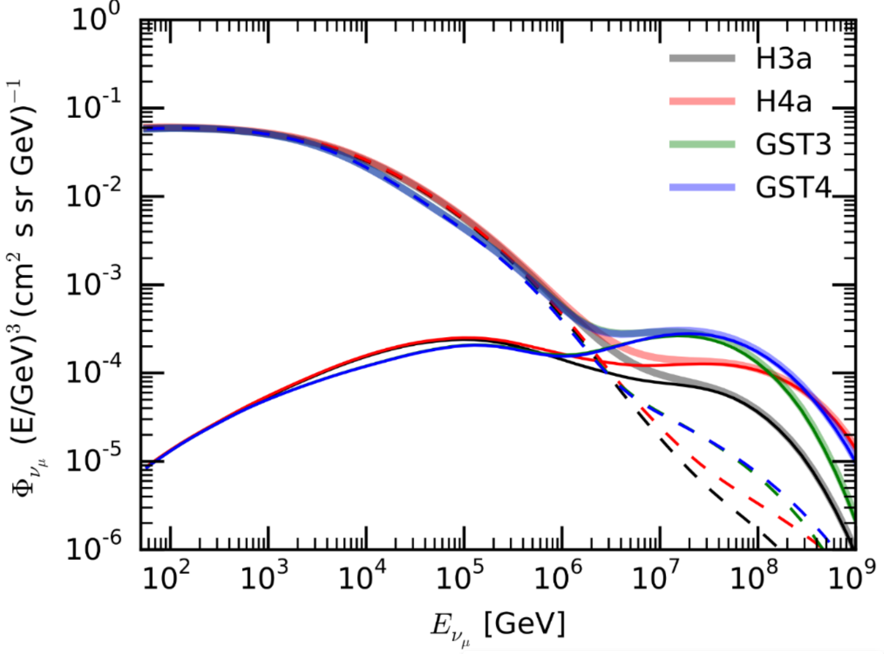
Interpretation ambiguity from the primary flux



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



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

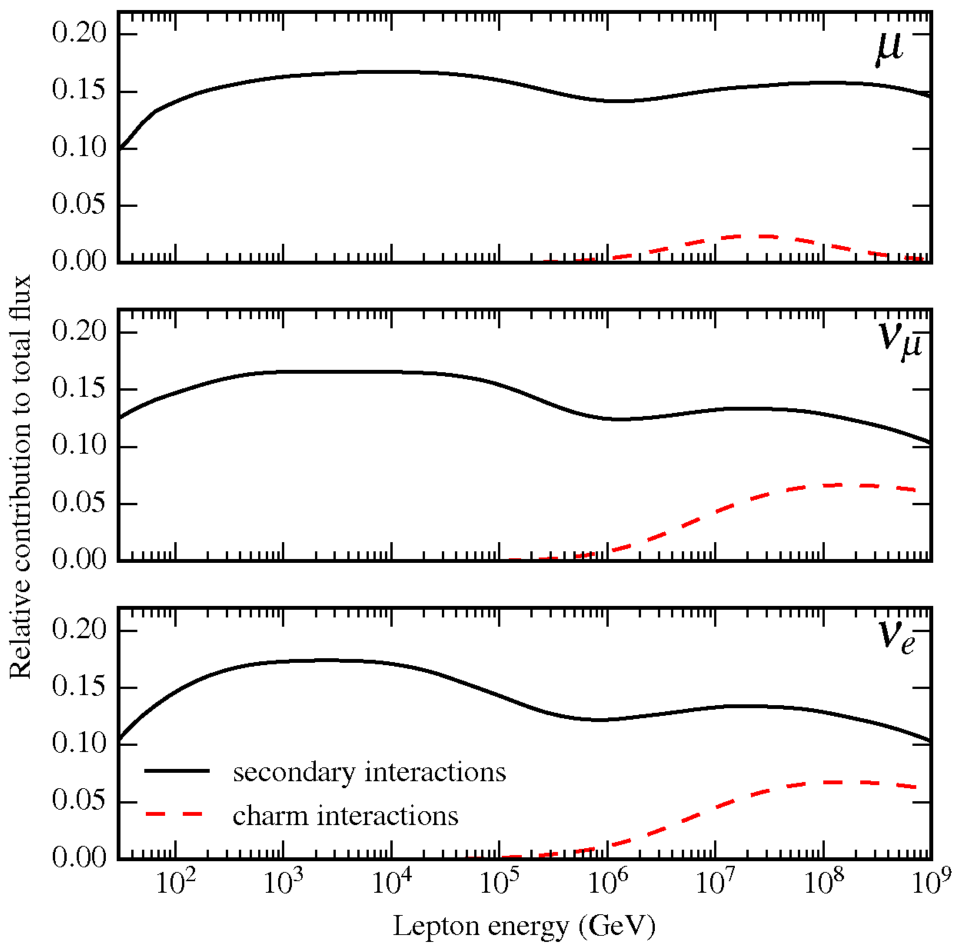


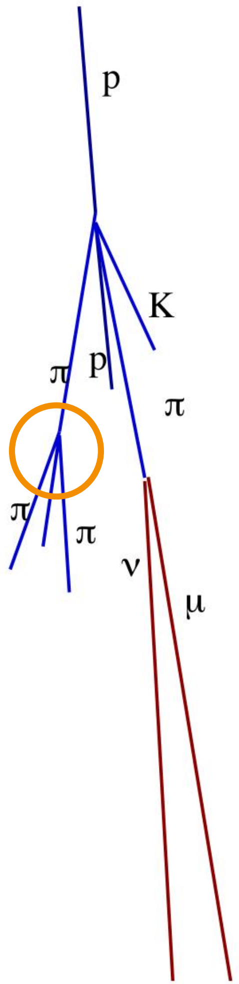
High composition uncertainty at UHE

Worst case scenario!

Interpretation ambiguity from secondary interactions

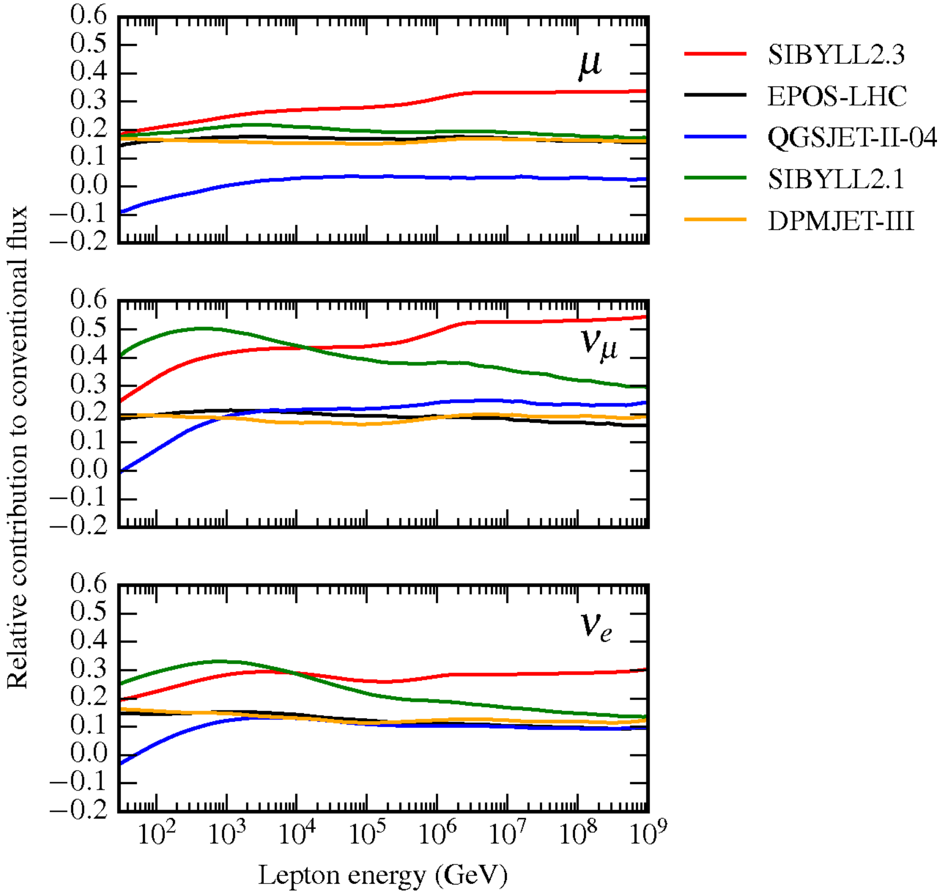
- Effect is larger than expected (< 5%)
- Leading particles change depending on projectile
- Other, indirect, production channels become more important, such as vector mesons



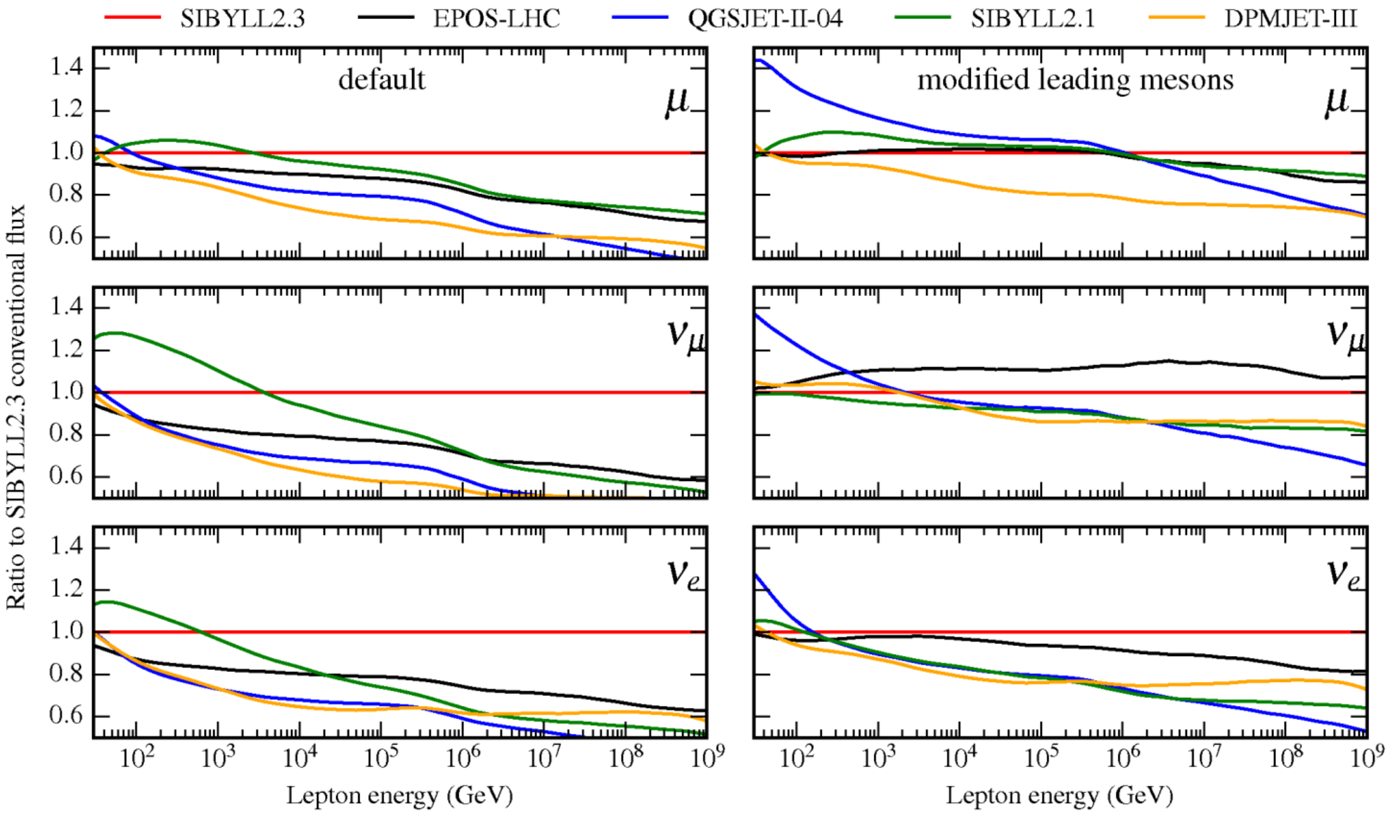


Quantifying the effect

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



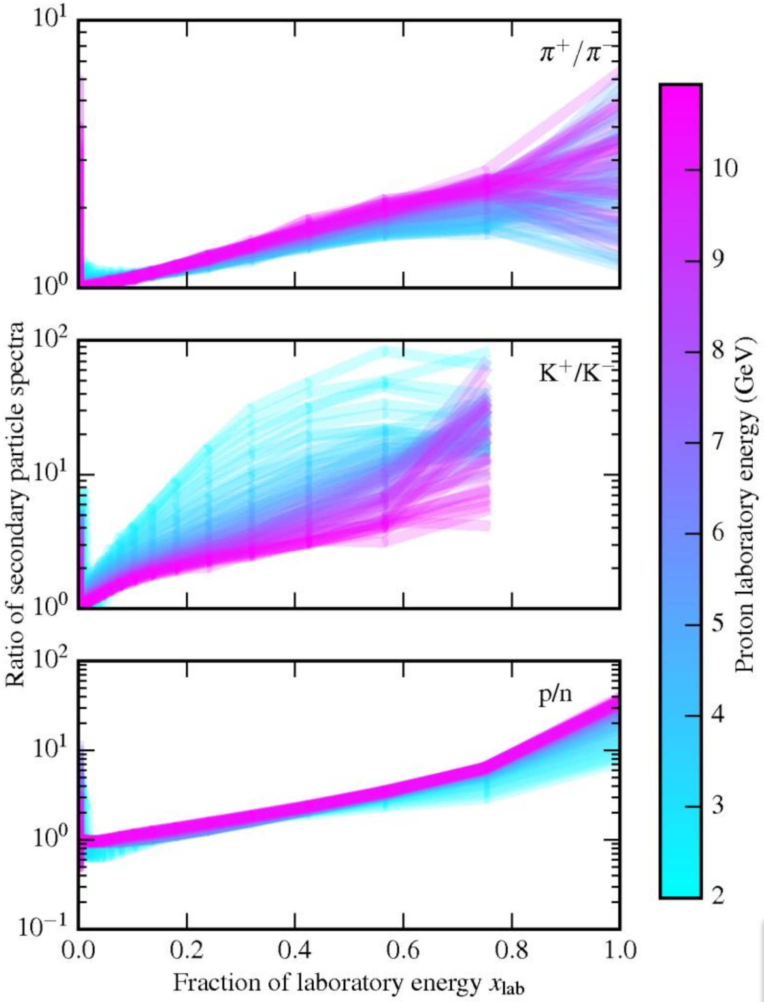
Modeling of leading particle effect contributes to large uncertainties



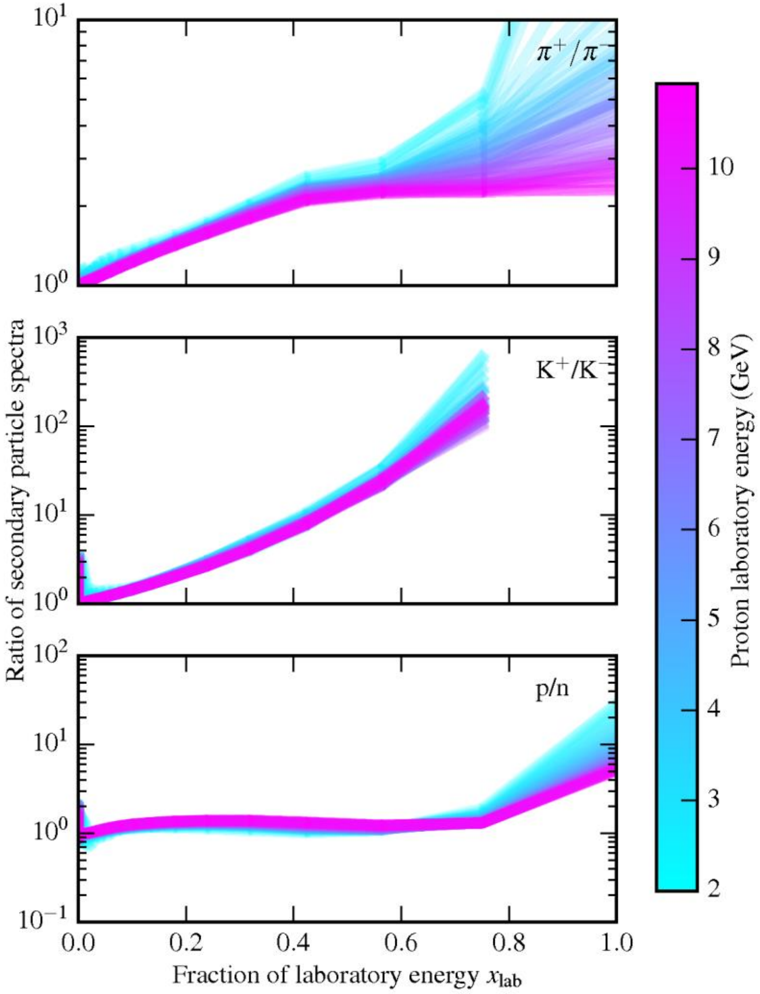
Larger effect in SIBYLL compared to other models

Energy extrapolation?

SIBYLL 2.1 (old)



SIBYLL 2.3 (new)



No guidance from accelerators