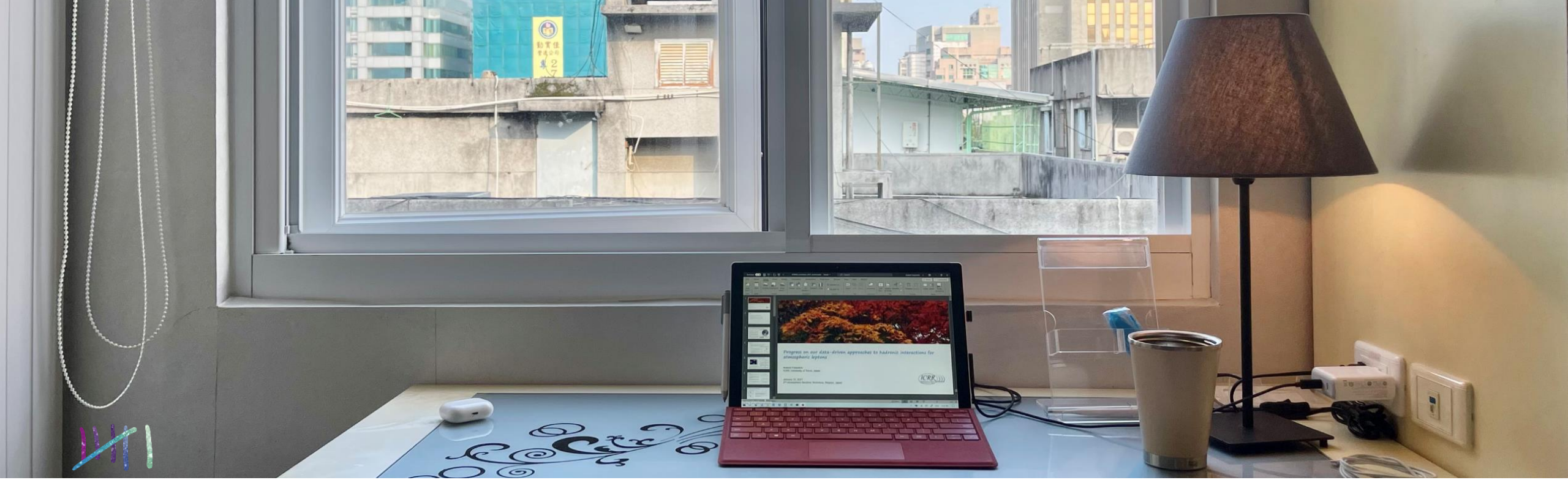


Progress on some data-driven approaches to hadronic uncertainties for atmospheric leptons

Anatoli Fedynitch
ICRR, University of Tokyo, Japan

January 12, 2021
2nd Atmospheric Neutrino Workshop, Nagoya, Japan

ICRR
Institute for Cosmic Ray Research
University of Tokyo

Topics

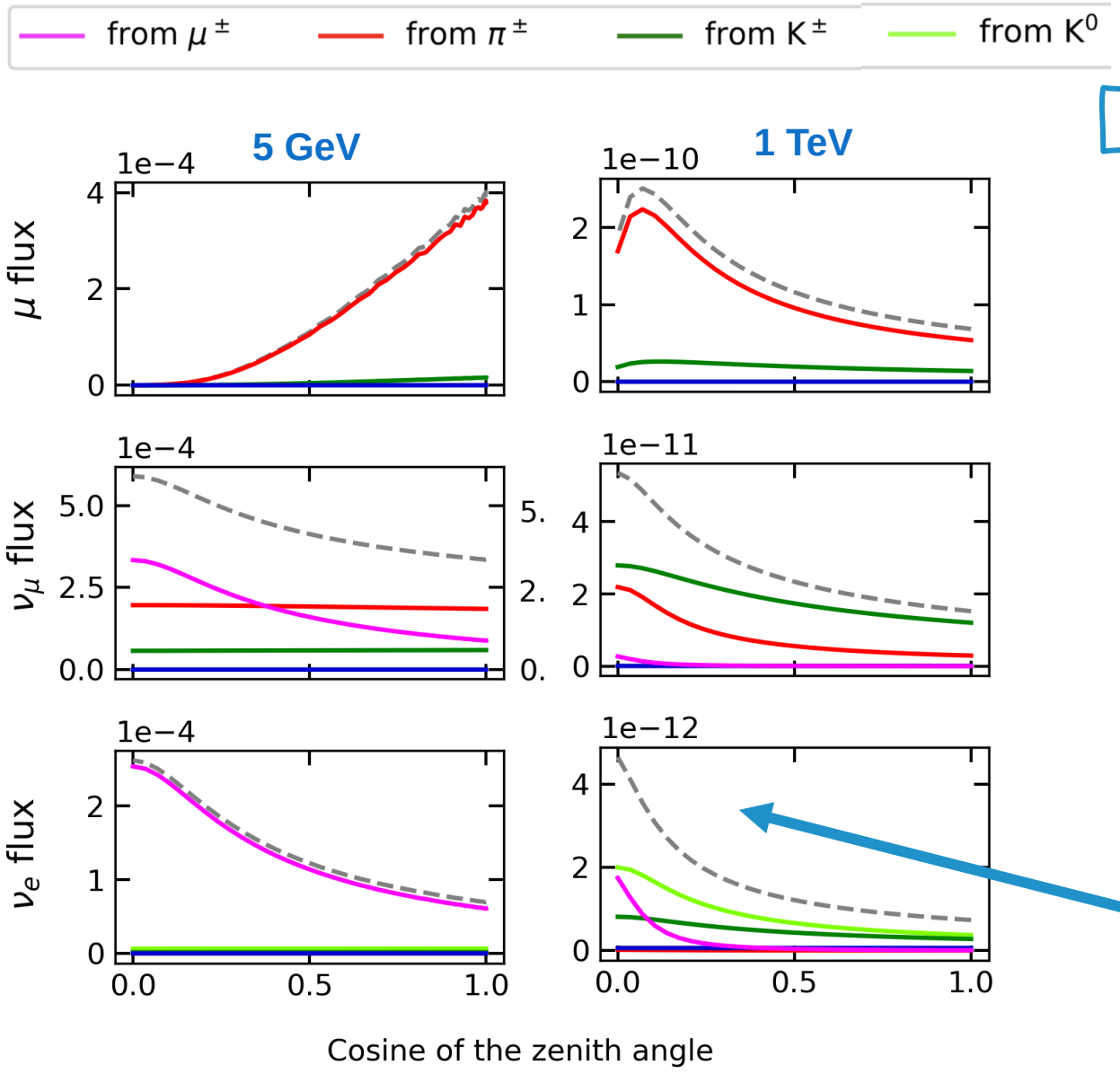
1. Attempt to measure K/Pi ratio with IceCube DeepCore

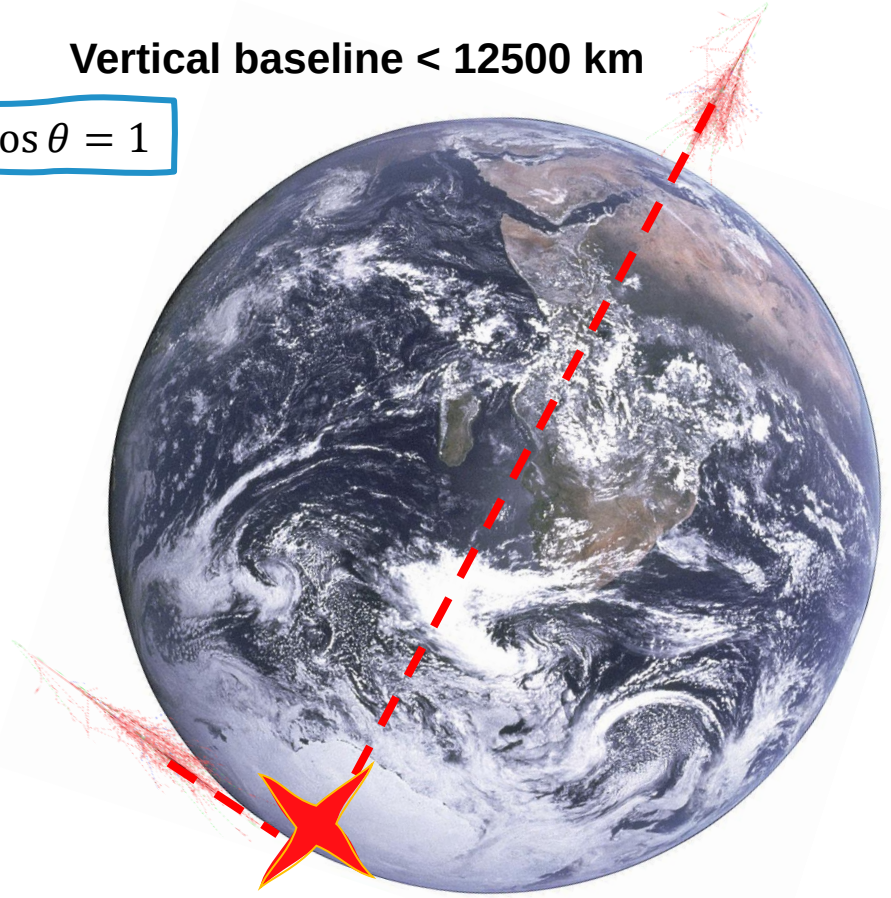
2. Data-driven hadronic interaction model based on accelerator data

3. Constraints from fitting inclusive muon data (mainly problems)

All calculations use the numerical code **MCEq** for all calculations. Visit https://github.com/afedynitch/MCEq

Atmospheric spectrum ←→ hadron components





vertical: $\cos\theta = 1$

horizontal: $\cos\theta = 0$

Various overlapping components

AF, F. Riehn, R. Engel, T.K. Gaisser, T. Stanev, PRD 100 2019

Analytical solution of cascade equations

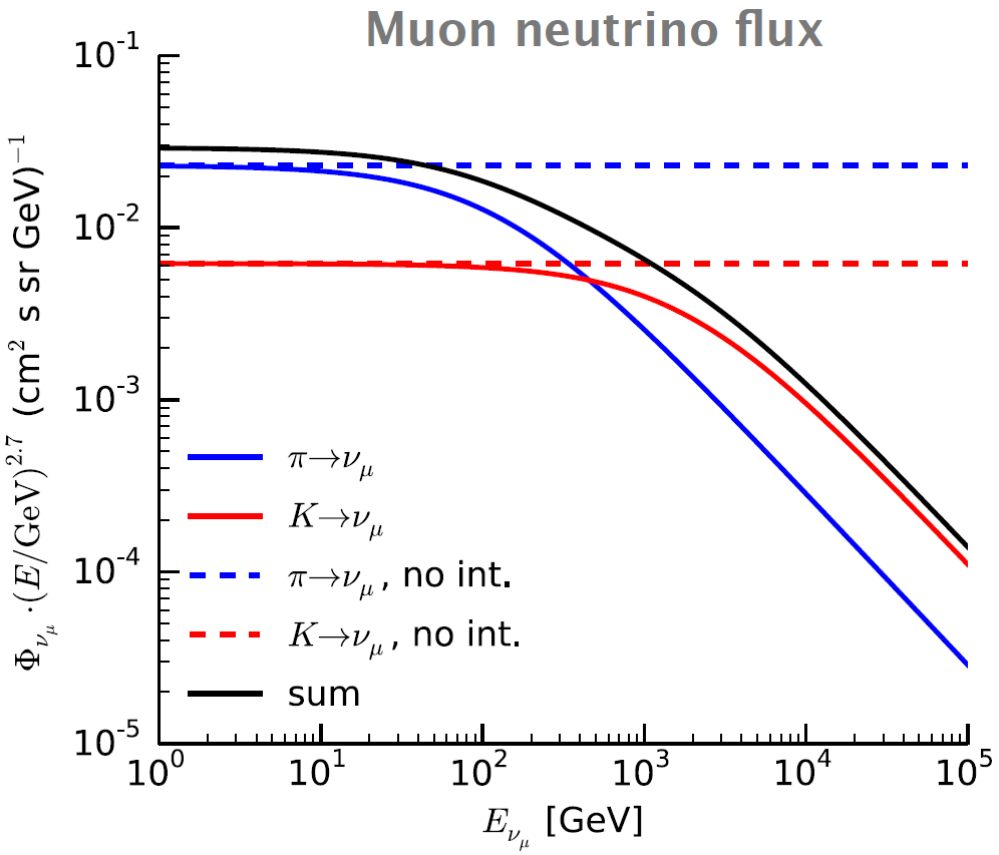
Asymptotic **low-energy solution** (pion interactions negligible)

$$\Phi_\nu(X) \propto E^{-\gamma}$$

Asymptotic **high-energy solution** (pion decays negligible)

$$\Phi_\nu(X) \propto E^{-\gamma-1}$$

Interpolation $$\frac{\Phi_{\text{low}}\Phi_{\text{high}}}{\Phi_{\text{low}} + \Phi_{\text{high}}}$$



$$\Phi_\nu(E) = \frac{\phi_N(E)}{1 - Z_{NN}} \left(\frac{\mathcal{A}_{\pi\nu}}{1 + \mathcal{B}_{\pi\nu} E \cos\theta / \varepsilon_\pi} + \frac{\mathcal{A}_{K\nu}}{1 + \mathcal{B}_{K\nu} E \cos\theta / \varepsilon_K} \right)$$

see book by Gaisser, Engel, Resconi (2016) for full story

Z factors

- In semi-analytical calculations the coefficients A (hadronic model) depend on spectrum weighted moments (Z factors)

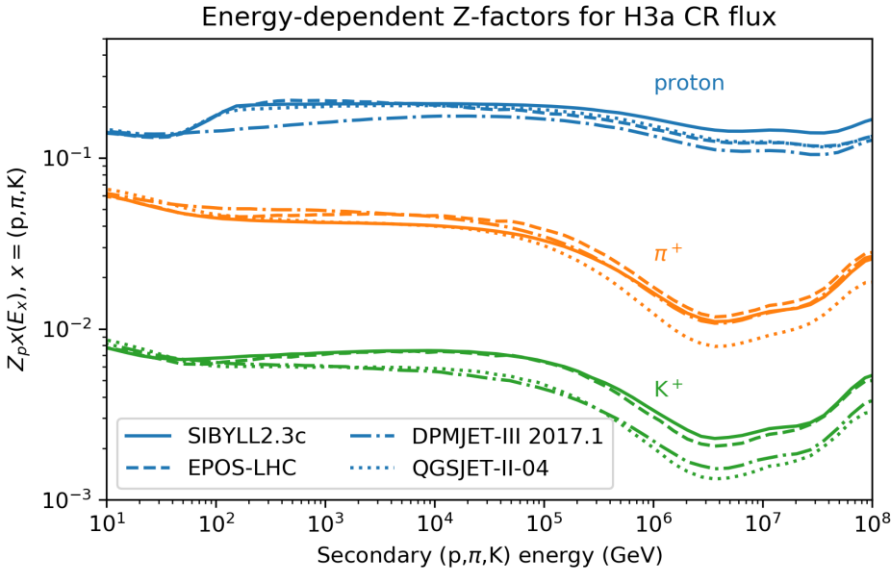
- Simplifying assumptions are energy-independent int. cross sections, particle production and cosmic ray spectral index

- One approach that improves all three issues are energy dependent Z factors (Thunman et al. 1996)

$$\mathcal{A}_{\pi\nu} \equiv Z_{N\pi} \frac{(1-r_\pi)^{\gamma+1}}{(1-r_\pi)(\gamma+1)}$$

$$Z_{N\pi} = \int_0^1 x_L^{\gamma-1} F_{N\pi}(x_L)\, \mathrm{d}x_L = \int_0^1 x_L^{\gamma} \frac{\mathrm{d}n_\pi}{\mathrm{d}x_L}\, \mathrm{d}x_L$$

$$Z_{\mathrm{N}\pi}(E_\pi) = \int_{E_\pi}^{\infty} \mathrm{d}E_{\mathrm{N}} \frac{\Phi_{\mathrm{CR}}(E_{\mathrm{N}})}{\Phi_{\mathrm{CR}}(E_\pi)} \frac{\sigma_{\text{N-air}}(E_{\mathrm{N}})}{\sigma_{\text{N-air}}(E_\pi)} \frac{\mathrm{d}N_{\mathrm{N+air}\to\pi}(E_{\mathrm{N}}, E_\pi)}{\mathrm{d}E_\pi}$$



The K/pi ratio

- The K/pi ratio is simply defined as the ratio of the spectrum weighted moments

where $r(K/\pi) = \frac{Z_{NK}}{Z_{N\pi}}$ [11] is the ratio of kaons to pions produced in the primary cosmic ray interactions.

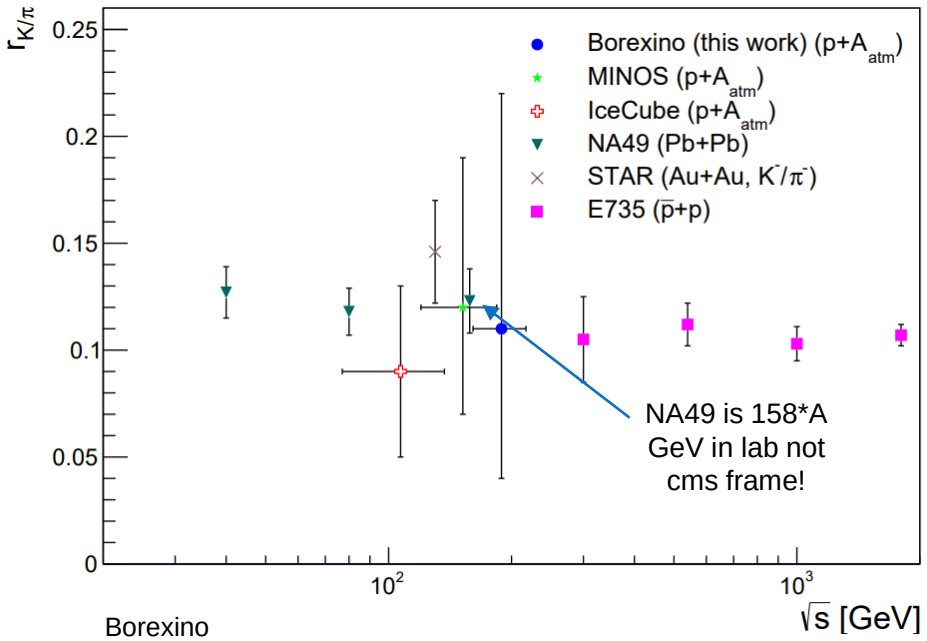
from The atmospheric charged kaon/pion ratio using seasonal variation methods

E.W. Grashorn [e,g,*], J.K. de Jong [c,h], M.C. Goodman [a], A. Habig [f], M.L. Marshak [e], S. Mufson [d], S. Osprey [h], P. Schreiner [b]

Astroparticle Physics 33 (2010) 140–145

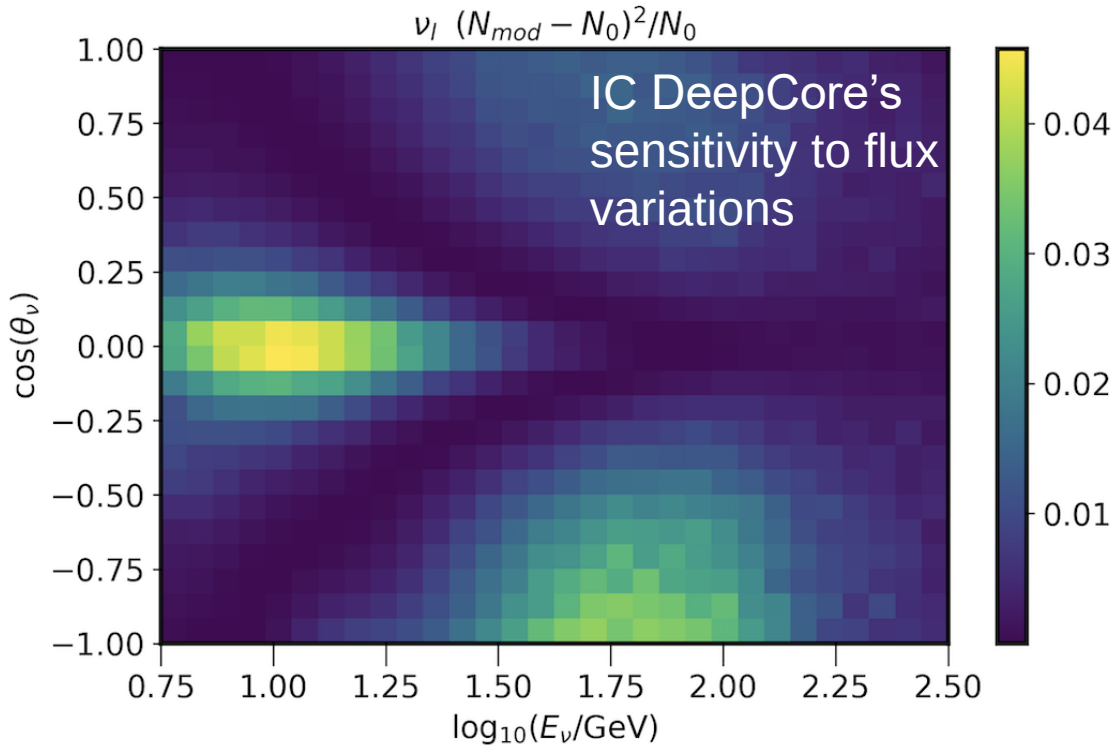
- Side notes:

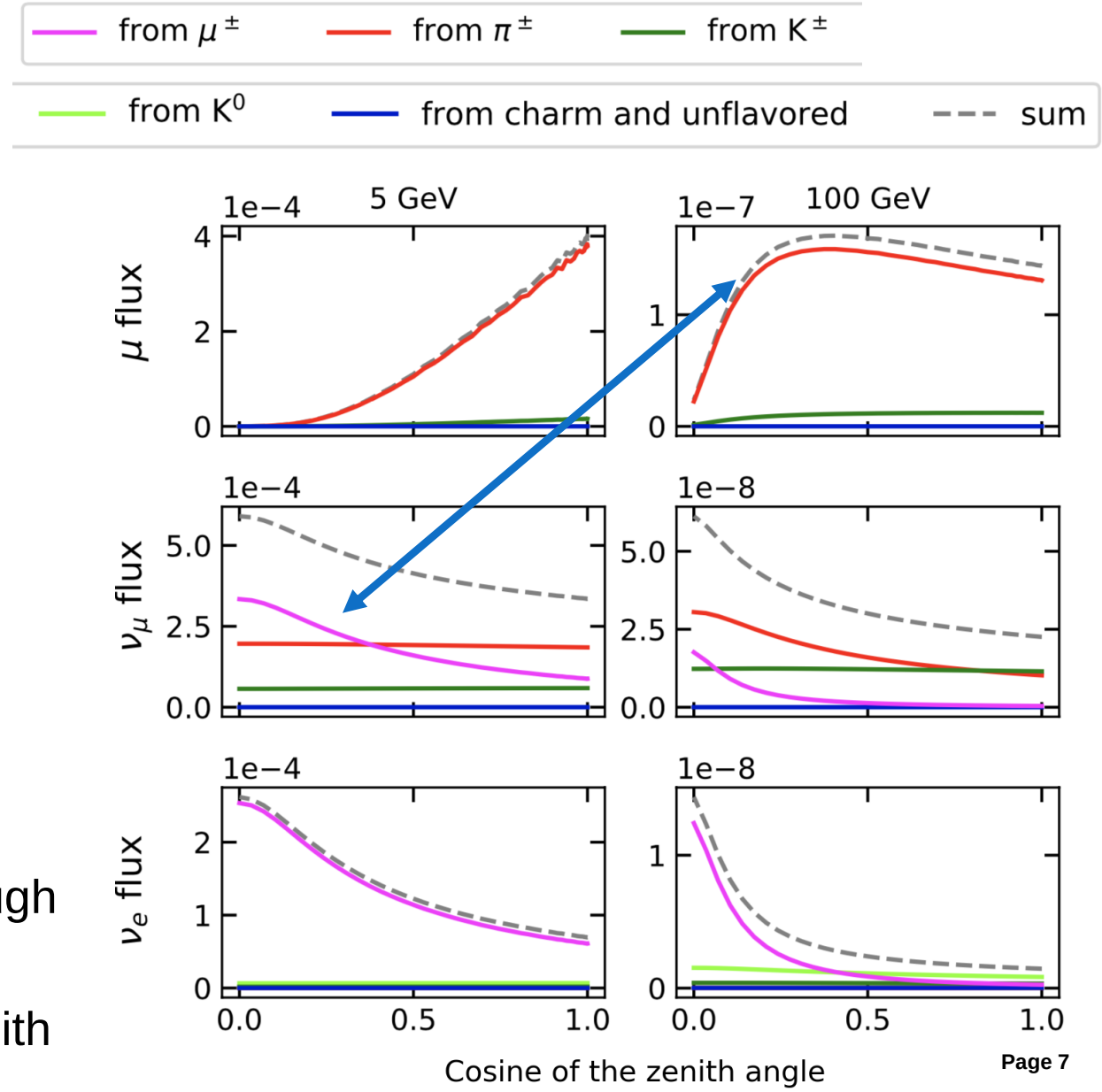
1. The ratio is slightly energy dependent (hadronic int.)
2. Z factors & ratio depend on spectral index of primary CR
3. K/pi ratio can be measured independently from time-integrated flux ”map”
4. And from atmospheric variations: A method using temperature coefficients employed by OPERA, MINOS, LVD, IceCube, etc.



Borexino 1808.04207

Origin of K/pi sensitivity in “low energy” neutrinos

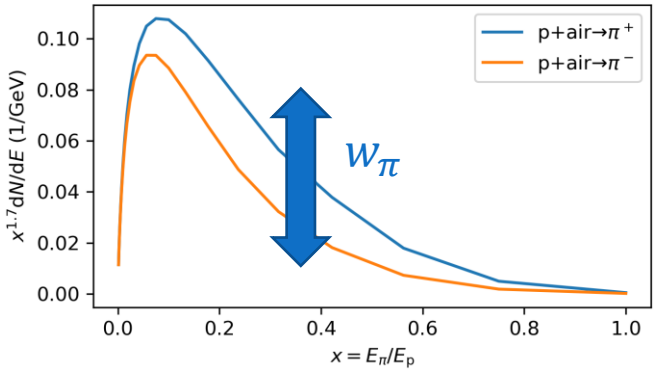


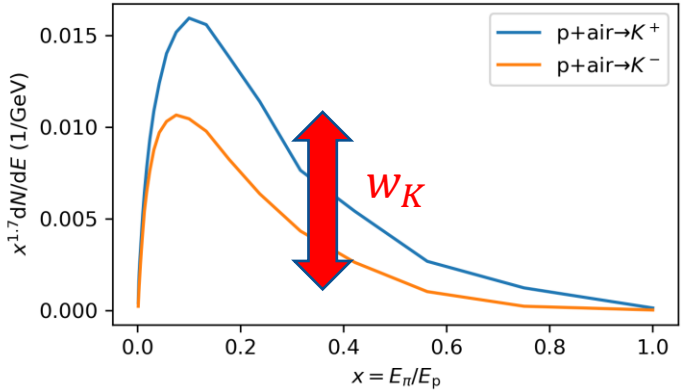


- Electron neutrino at higher E sensitive to K
- Electron neutrino at low E sensitive to pi through muons
- Muon neutrinos sensitive to both in E and zenith

Method: fit one additional parameter

Secondary particle spectrum



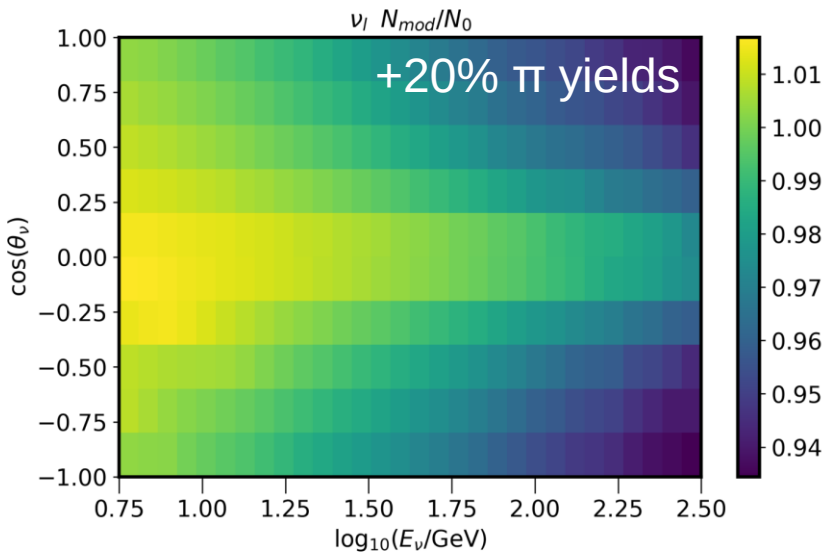


- $Z'_{N\pi} = w_\pi Z_{N\pi}$
- $Z'_{NK} = w_K Z_{NK}$

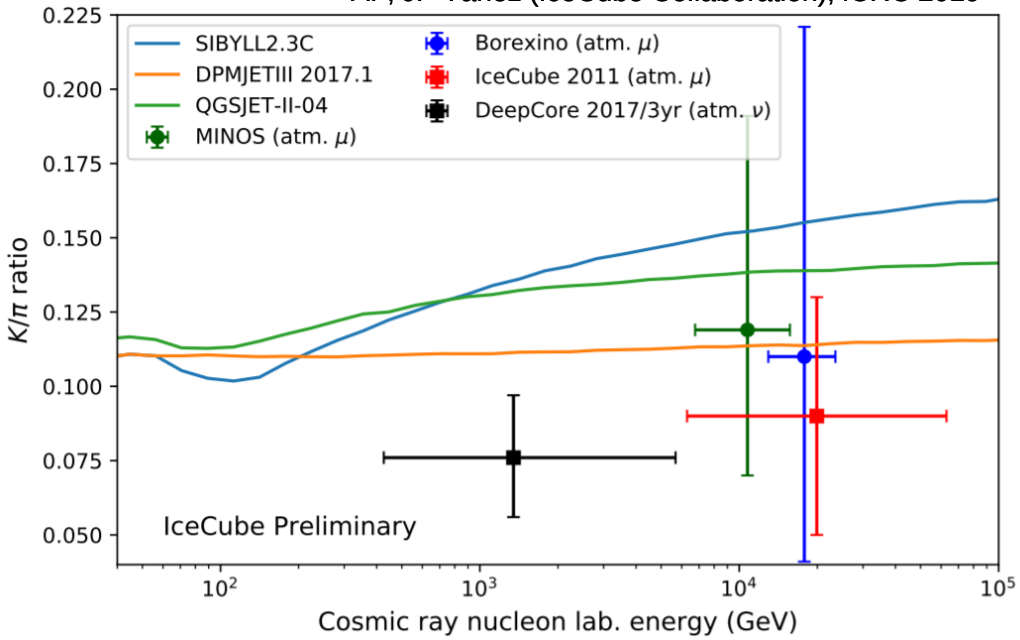
$$r'(K/\pi) = \frac{w_K}{w_\pi} * r\left(K/\pi\right)_{MCEq}$$

- Use one parameter and re-weight the baseline spectrum (normalization drops absorbs the second one)
- Used 3-year sample from Standard Oscillations Analysis
- Also possible to fit separately w_{K+}, w_{K-}, $w_{\pi+}, w_{\pi-}$ but not necessary for $r(K/\pi)$

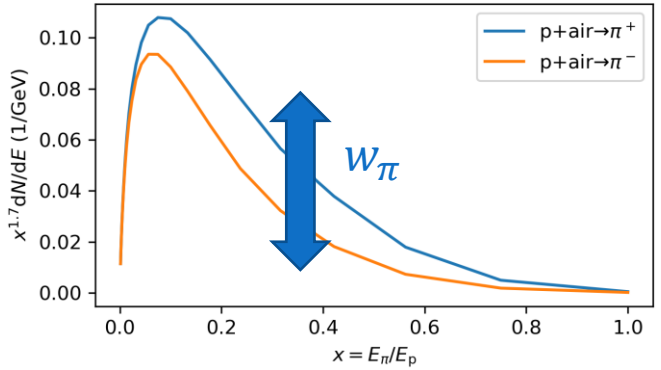
Result

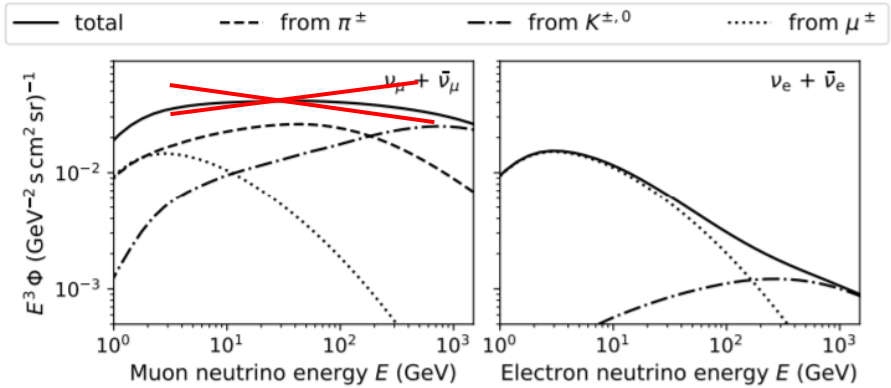


AF, JP Yanez (IceCube Collaboration), ICRC 2019



Variation of particle production yield modifies spectrum and angular distribution





Currently difficult:

- DeepCore < **Energy** < IceCube
- Bias from mis-reconstruction
- Will repeat with new simulation and more data

Constrain ν uncertainties with "global fit" to μ data

Cosmic ray flux: Global Spline Fit [7]

+

Atmospheric conditions

+

Hadronic interactions: SYBILL 2.3c

=

Flux of muons and neutrinos

AMS-02

Experiment	Energy (GeV)	Measurements	Reported unit	Location	Altitude	Zenith range
AMS-02	0.1-2500	Flux & charge ratio	rigidity	28.57°N , 80.65° W	5 m (sea level)	
BESS-TeV	0.6-400	Flux	momentum	36.2°N, 140.1°W	30 m	0-25.8°
CMS	5-1000	Charge ratio	momentum	46.31°N, 6.071°E	420 m	$p\cos\theta_z$
L3+C	20-3000	Flux & charge ratio	momentum	46.25°N, 6.02°E	450 m	0-58°
MINOS	1000-7000	Charge ratio	total energy	47.82°N, 92.24°W	5 m (sea level)	unfolded
OPERA	891-7079	Charge ratio	total energy	42.42°N, 13.51°E	5 m (sea level)	$E\cos\theta^*$

(GeV)

DEIS

Juan Pablo Yanez and AF, launched in 2017, presented at Neutrino 2018 + ICRC 2019

Reweighting method

- New version the cascade code MCEq with improved accuracy at low E
- Cut secondary particle phase-space according to parameters B_i from Barr et al.
- Generate database of fluxes $\Phi(E_\mu)$ and Jacobians

$$\frac{\partial \Phi(E_\mu)}{\partial \mathscr{B}_i} = \frac{\Phi(E_\mu, \mathscr{B}_i = 1+\delta) - \Phi(E_\mu, \mathscr{B}_i = 1-\delta)}{2\delta}$$

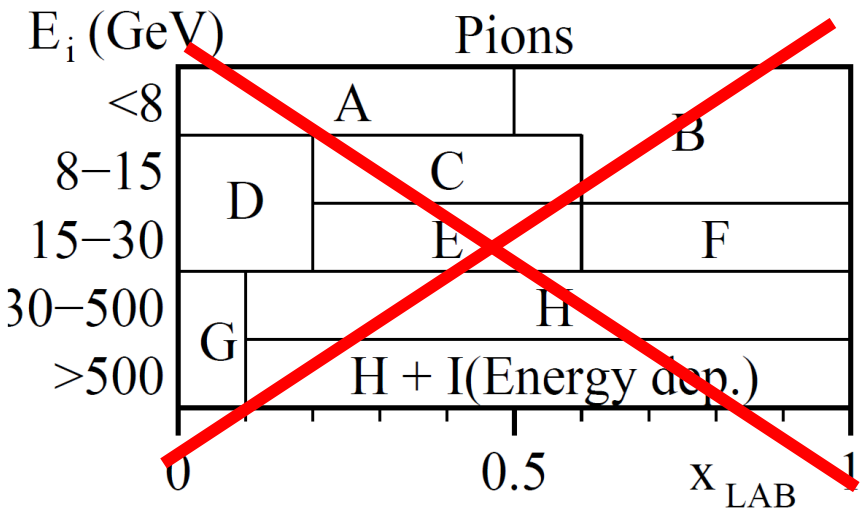
- Fluxes with modifications to B_i can be quickly evaluated in the fit:

$$\Phi(E_\mu, \mathscr{B}_a, \mathscr{B}_b, \dots) = \Phi(E_\mu) + \sum_i \mathscr{B}_i \frac{\partial \Phi(E_\mu)}{\partial \mathscr{B}_i}$$

Juan Pablo Yanez and AF, Neutrino 2018 + ICRC 2019

What we found

- Original attempt was to use the parameterization of Barr et al.
    1. Found data to be insensitive
    2. Too many correlations
    3. Impossible to constrain

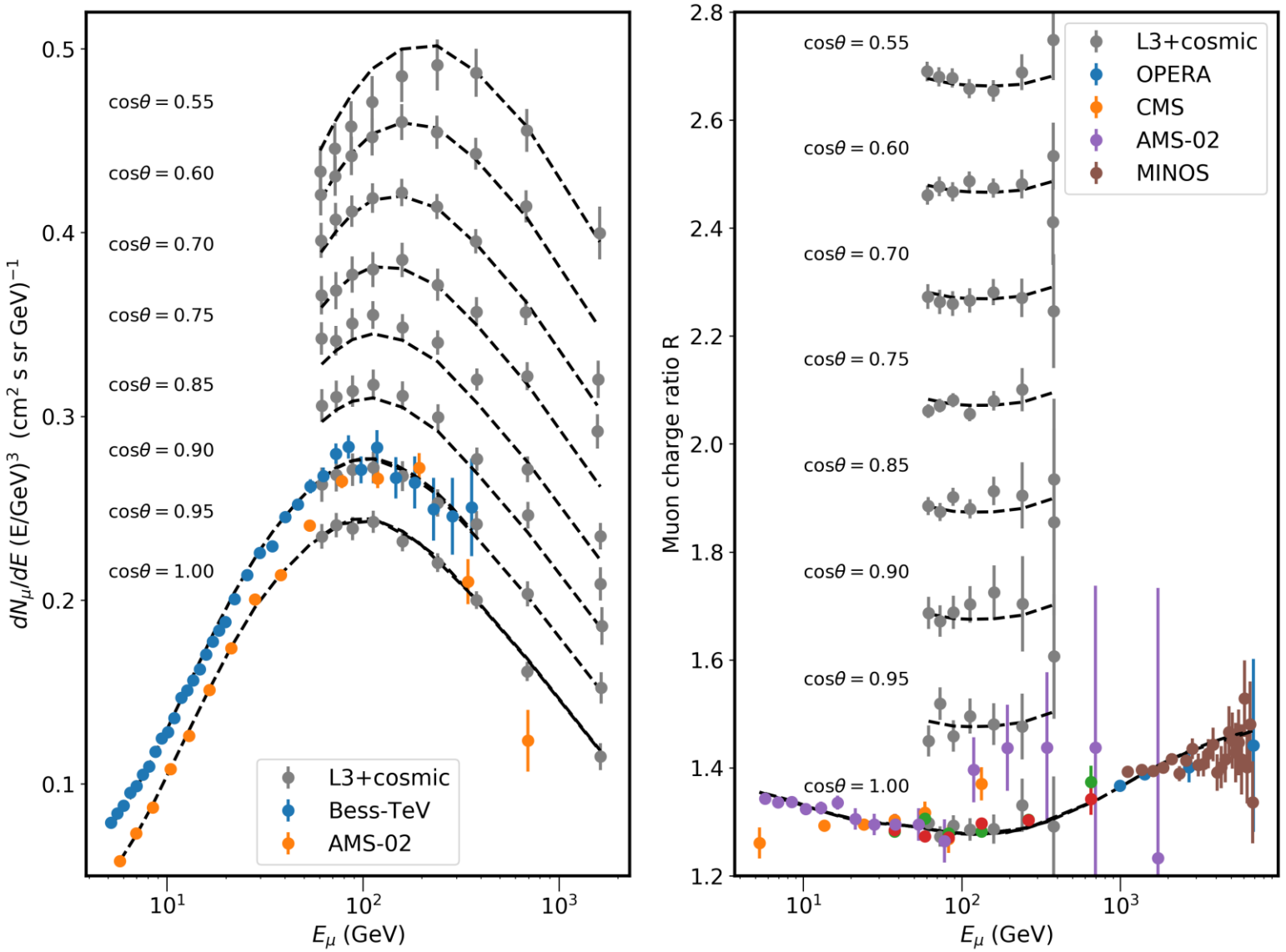


- Simplified to **four parameters**
    - Yields of each meson species
    - Global, energy-independent scales
    - Enough to describe data

Juan Pablo Yanez and AF, Neutrino 2018 + ICRC 2019

Fit results

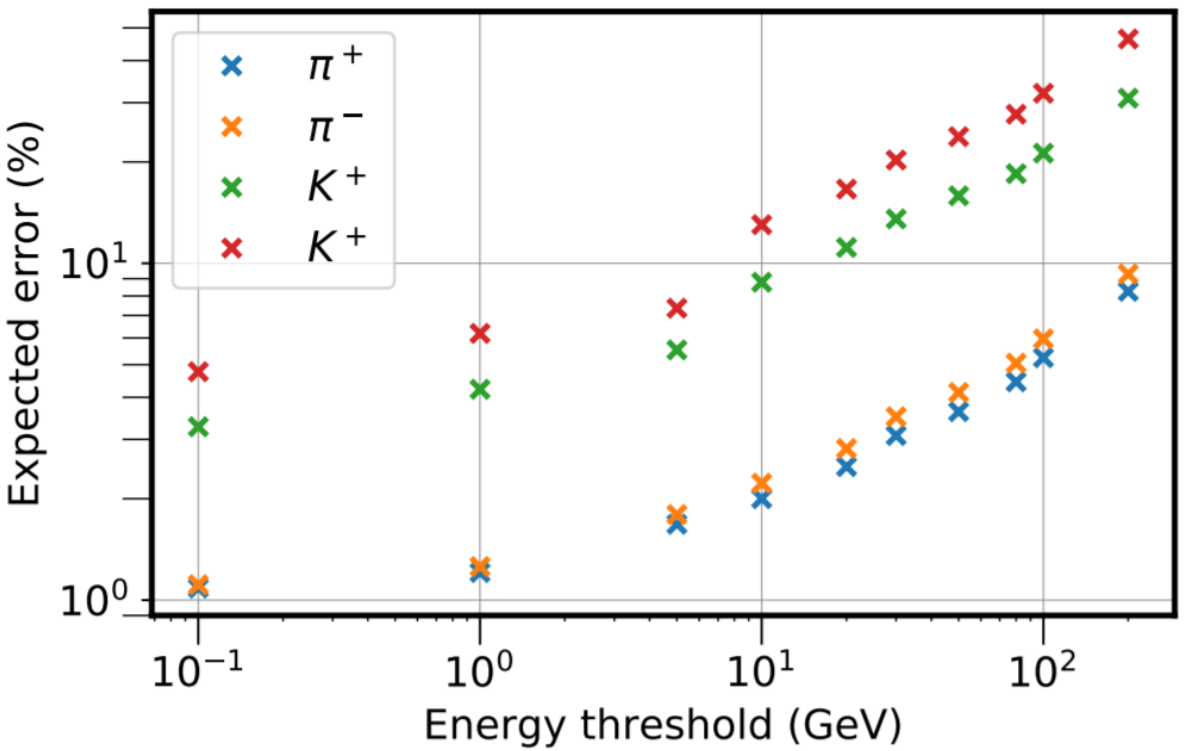
- Some experiments are hard to fit regardless of modifications
- Possible systematic effects not reported
- L3+C – previously “the reference dataset”– is not as good as we thought
- We will include more data and CR flux uncertainties in the next iteration and report later this year
- **This approach limited to < few TeV ☹ lepton energy**



Juan Pablo Yanez and AF, Neutrino 2018 + ICRC 2019

Impact of energy threshold for the fit

- High energy data less sensitive
- This is because the features in the muon spectrum are smooth
- and fit variables become strongly correlated
- More angles are needed
- We're investigating horizontal and high-altitude balloon data



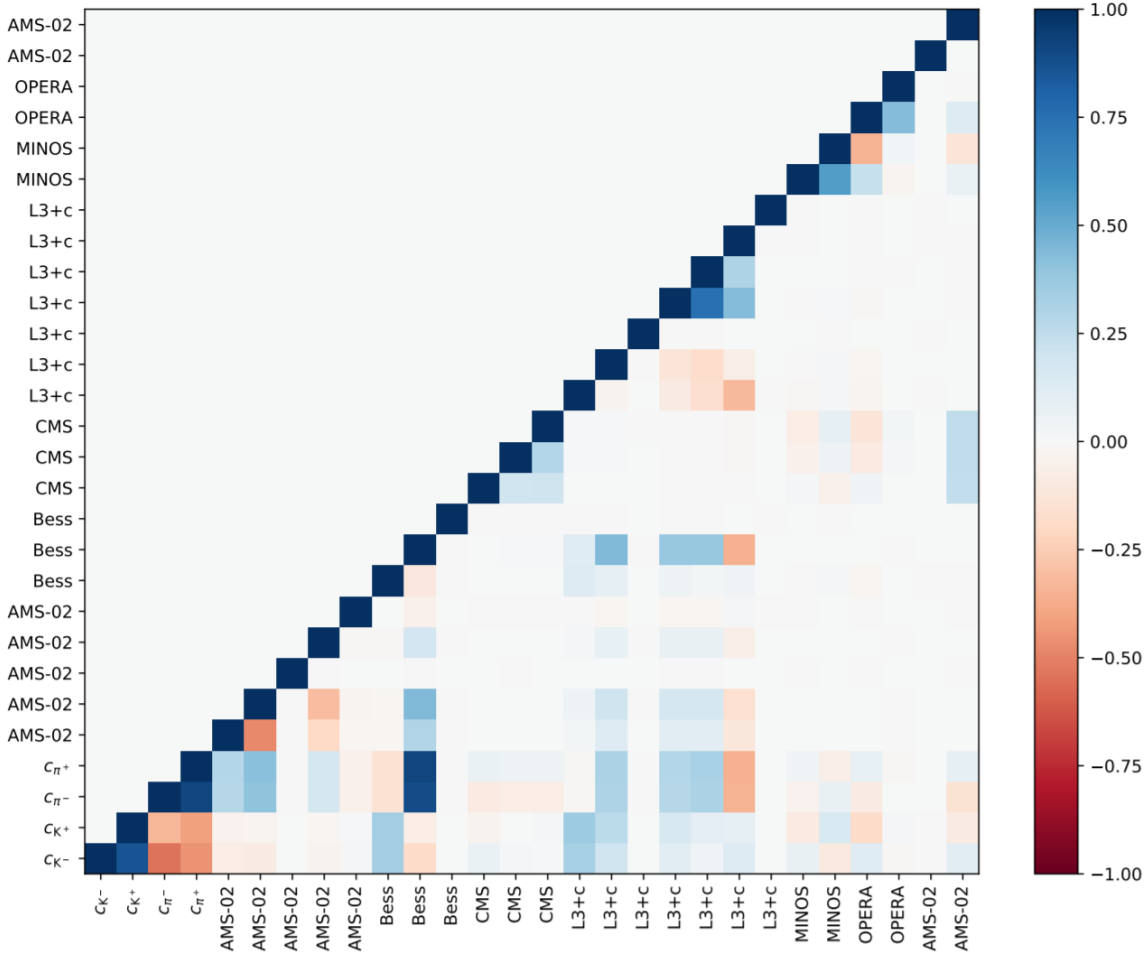
Juan Pablo Yanez and AF, Neutrino 2018 + ICRC 2019

Fit parameters and correlations

- With sufficiently low threshold (5 GeV) the correlations are reduced
- Errors between a few to ten %
- Neutrino flux errors in the range covered by fit comparable to kaon errors

Parameter	Best fit	Error
c_{π^-}	+0.141	±0.017
c_{π^+}	+0.116	±0.016
c_{K^-}	+0.402	±0.073
c_{K^+}	+0.583	±0.055

Thoughts: …in tension with fixed target…qualitative features have to be involved…more digging needed



Juan Pablo Yanez and AF, Neutrino 2018 + ICRC 2019

Learning from fixed target experiments

Take NAxx fixed-target data

Transform into x_{lab}, propagate errors

Build inclusive hadr. int. model

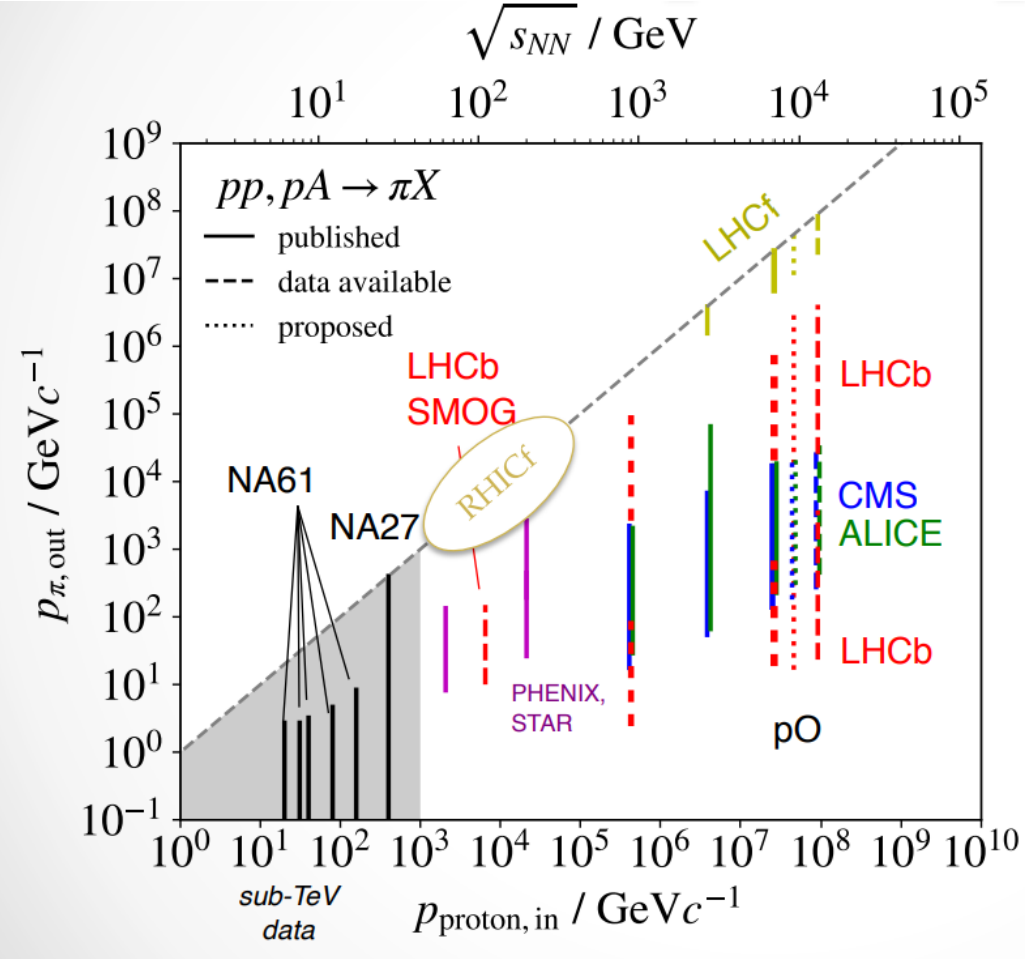
Propagate errors and calculate fluxes

Project with **Matthias Huber** (TUM)

M. Huber and AF, in prep.

Towards constraining flux uncertainties with accelerators

Now



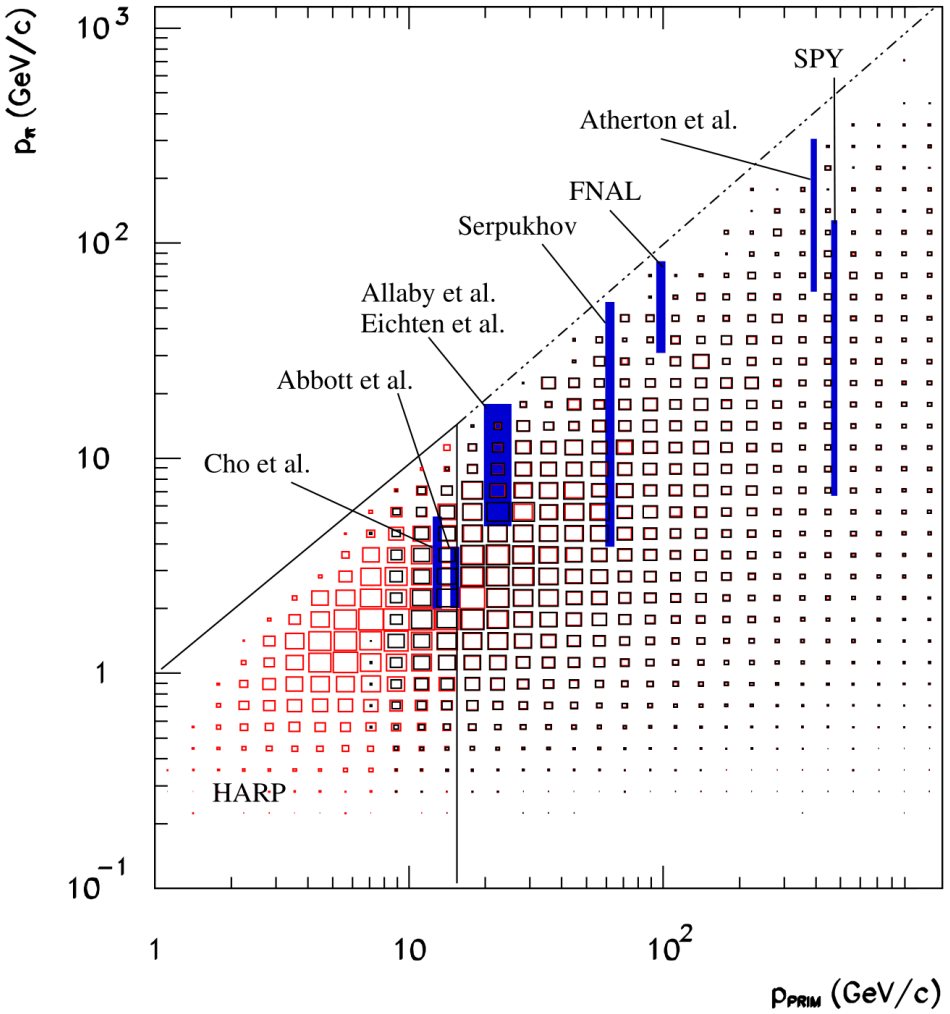
H. Dembinski,
ISVHECRI 2018

Phase space of air shower interactions as covered by various experiments
(beam-beam collisions transformed to equivalent fixed-target system)

LHCb could significantly increases coverage

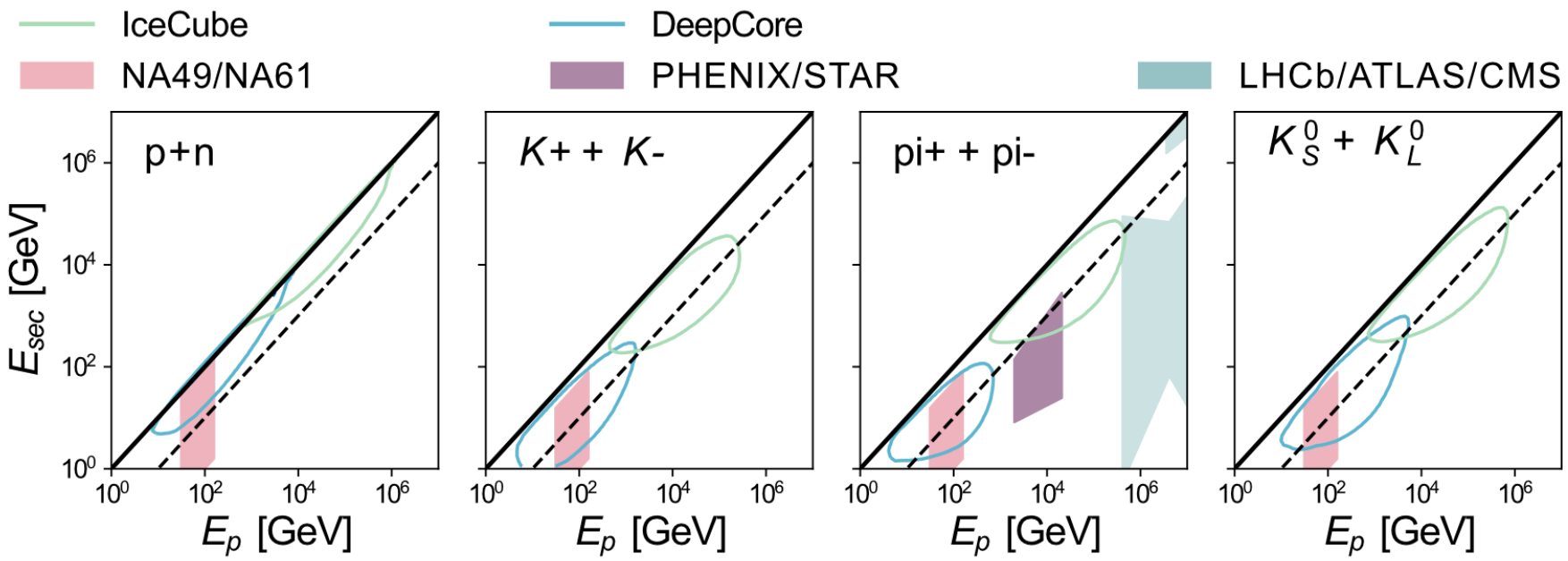
2006

PHYSICAL REVIEW D **74,** 094009 (2006)

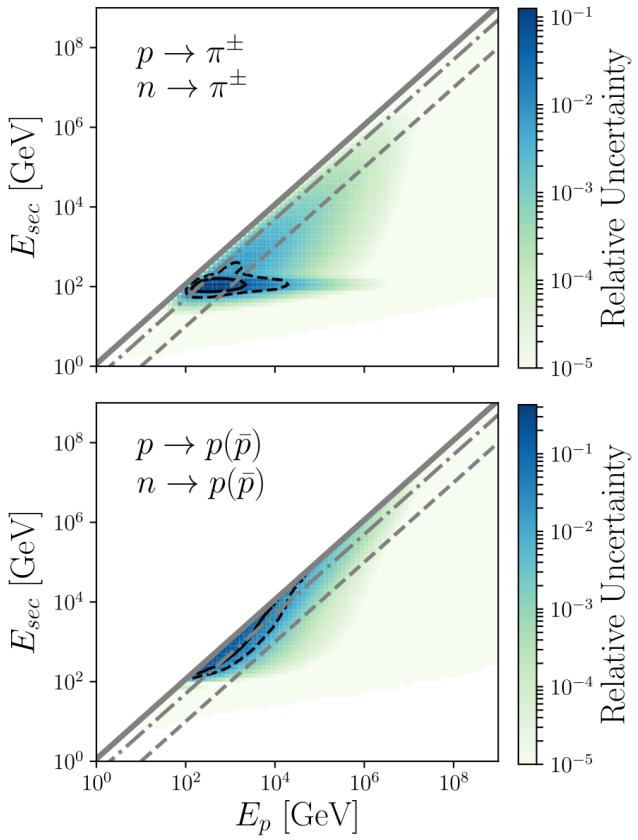


Towards constraining flux uncertainties: neutrino telescopes

Particle production phase space covered by IceCube & DeepCore up-going tracks



Current uncertainty for conventional atmospheric fluxes >30%

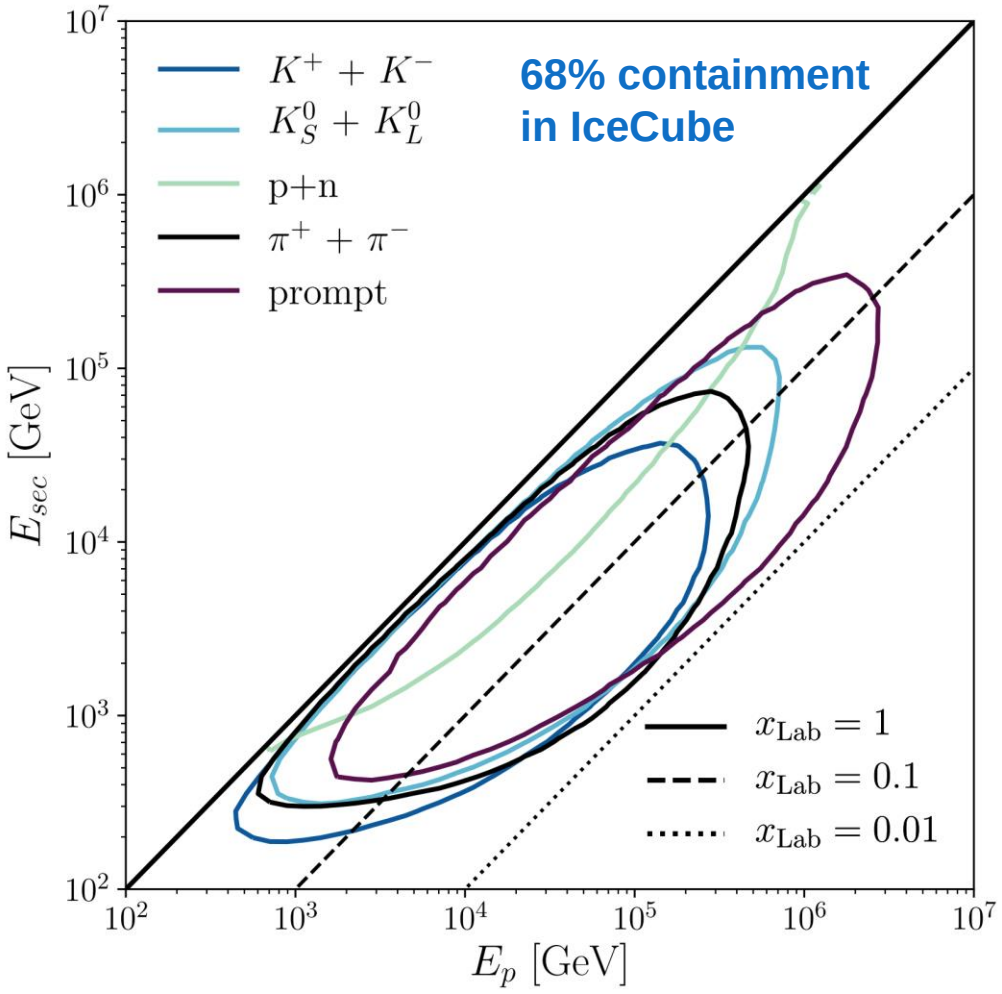


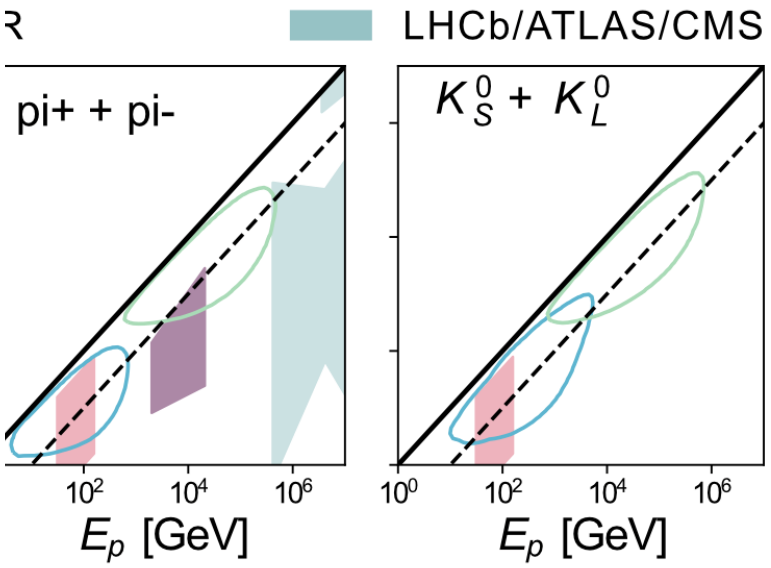
Phase-space contributing to 100 GeV muons

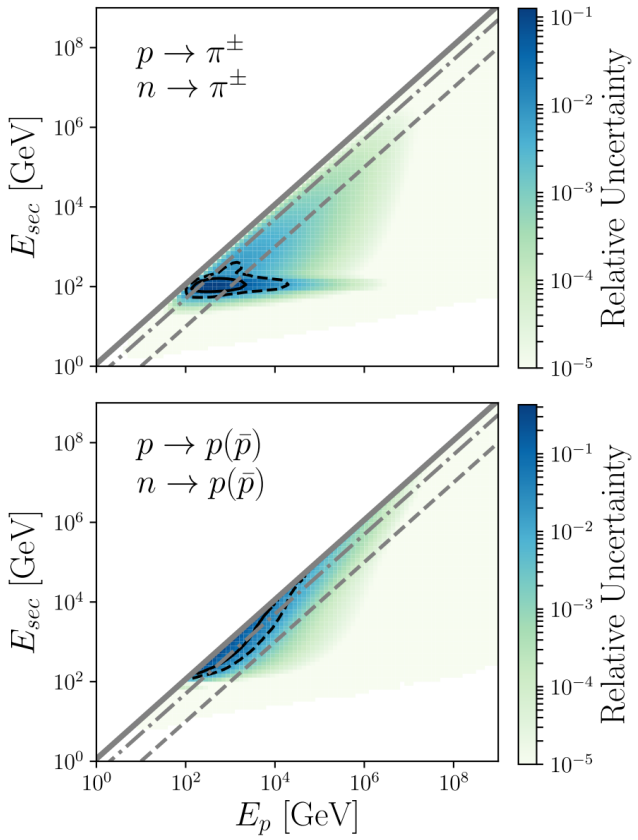
M. Huber and AF,
in prep.

Conventional hadronic interactions in neutrino telescopes

Particle production phase space covered by IceCube & DeepCore up-going tracks



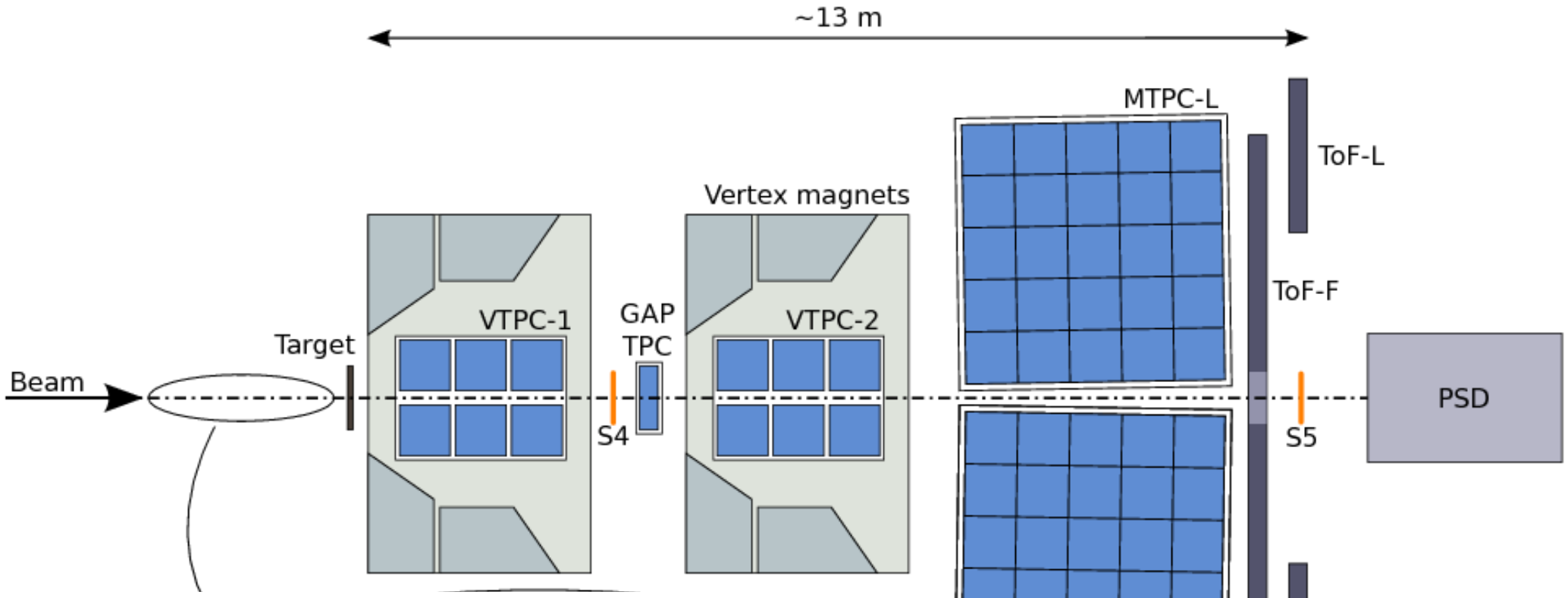




Phase-space contributing to 100 GeV muons

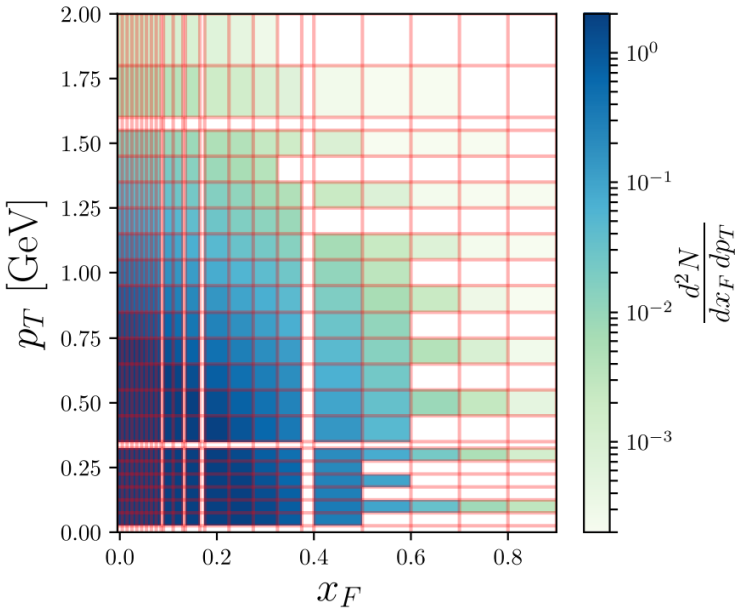
M. Huber and AF, in prep.

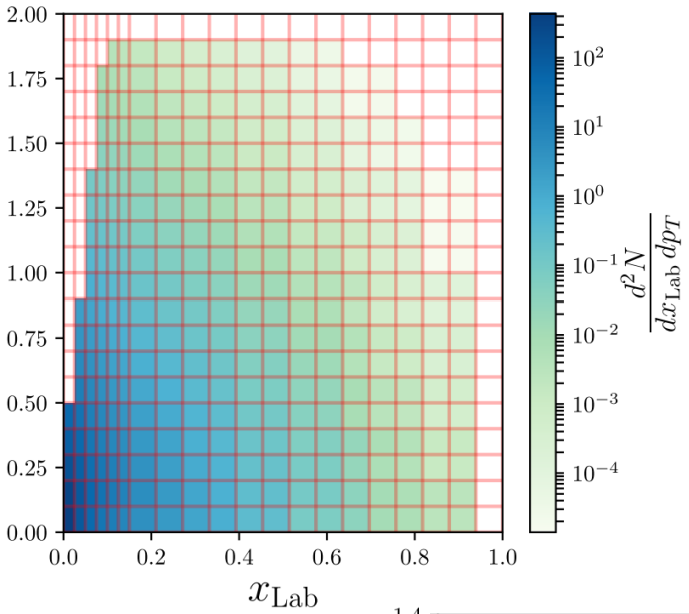
Specialized detectors need specialized analyses



Experiment	Primary	Target	E_{beam} [GeV]	Secondaries	Variables
NA49	p	C	158	$\pi^{\pm}, \overset{(-)}{\text{p}}, n$	x_F
NA61/SHINE	p	C	31	$\pi^{\pm}, K^{\pm}, K^0_S, \Lambda$	p, θ
NA61/SHINE	π^-	C	158, 350	$\pi^{\pm}, K^{\pm}, \overset{(-)}{\text{p}}$	p, p_T

Conversion to longitudinal energy fraction

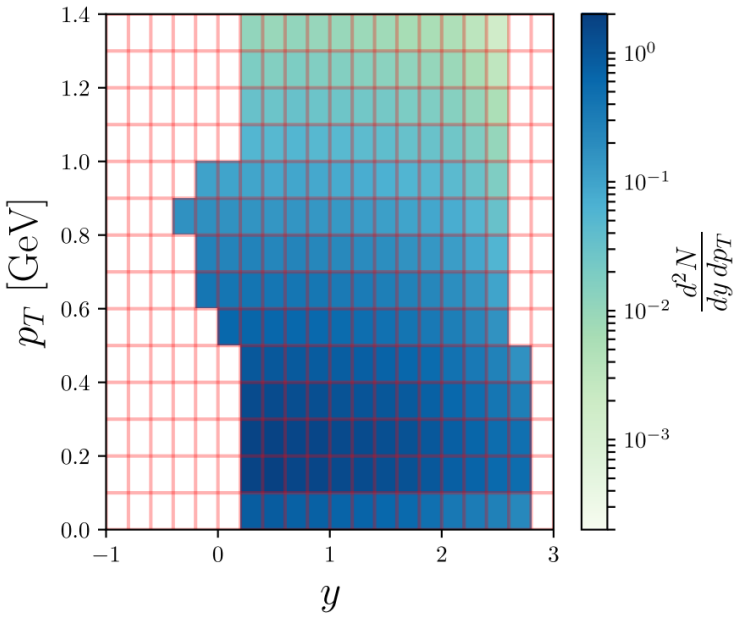


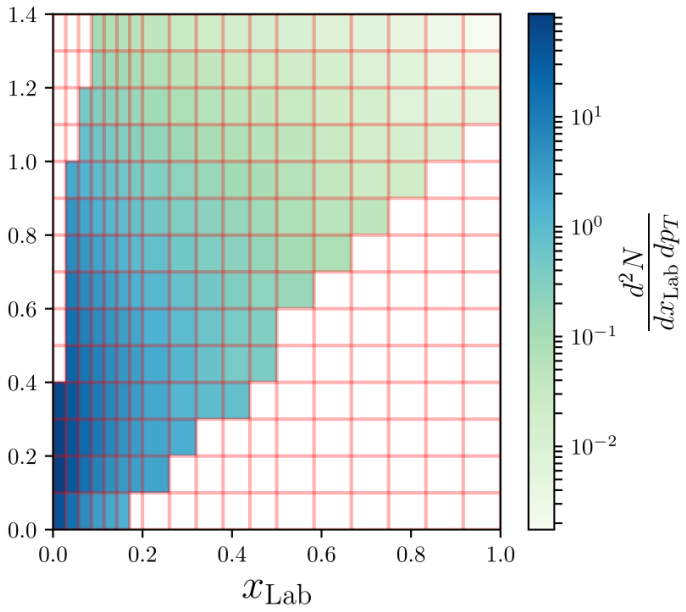


$$x_{Lab} = \frac{\gamma\sqrt{m_c^2 + \frac{1}{4}x_F^2 E_{c.m.}^2 + p_{c,T}^{*2}} + \frac{1}{2}\gamma\beta x_F^2 E_{c.m.}}{E_a}$$

$$= \frac{\gamma\sqrt{m_c^2 + \frac{\tanh^2(y)\left(m_c^2+p_{c,T}^{*2}\right)}{1-\tanh^2(y)} + p_{c,T}^{*2}} + 2\gamma\beta\frac{\tanh^2(y)\left(m_c^2+p_{c,T}^{*2}\right)}{E_{c.m.}\left(1-\tanh^2(y)\right)}}{E_a}$$

$$x_{Lab} = \frac{E_c}{E_a} = \frac{\gamma\sqrt{m_c^2 + \frac{1}{4}x_F^2 E_{c.m.}^2 + p_{c,T}^{*2}} + \frac{1}{2}\gamma\beta x_F^2 E_{c.m.}}{E_a}$$

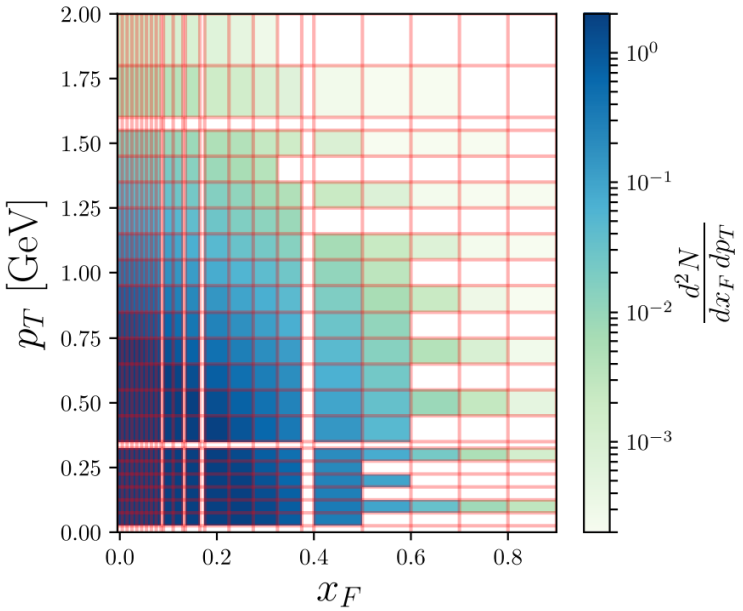


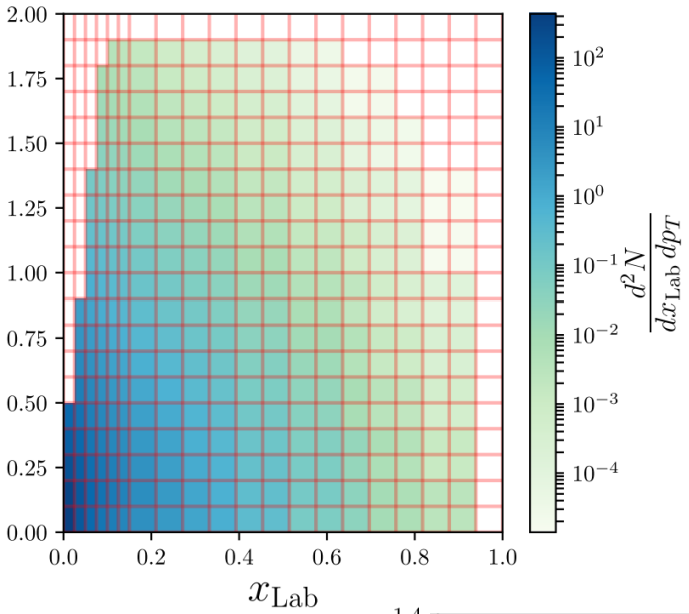


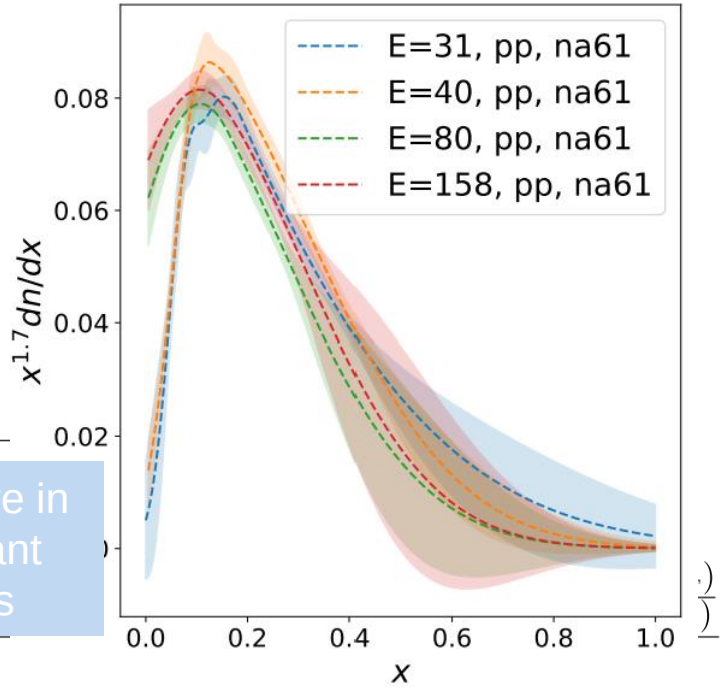
Origin of additional systematic error of 5%

M. Huber and AF,
in prep.

Conversion to longitudinal energy fraction

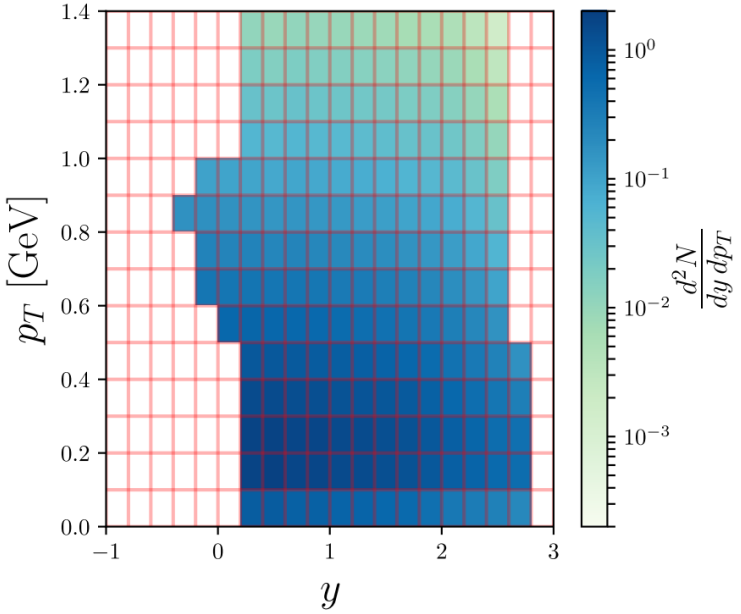


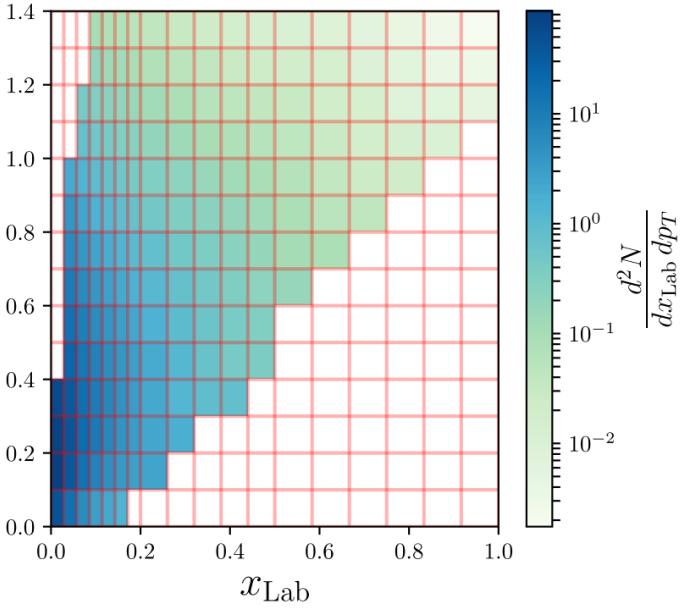




Inconclusive in CR relevant variables

$$x_{Lab} = \frac{E_c}{E_a} = \frac{\gamma\sqrt{m_c^2 + \frac{1}{4}x_F^2 E_{c.m.}^2 + p_{c,T}^{*2}} + \frac{1}{2}\gamma\beta x_F^2 E_{c.m.}}{E_a}$$





Origin of additional systematic error of 5%

M. Huber and AF,
in prep.

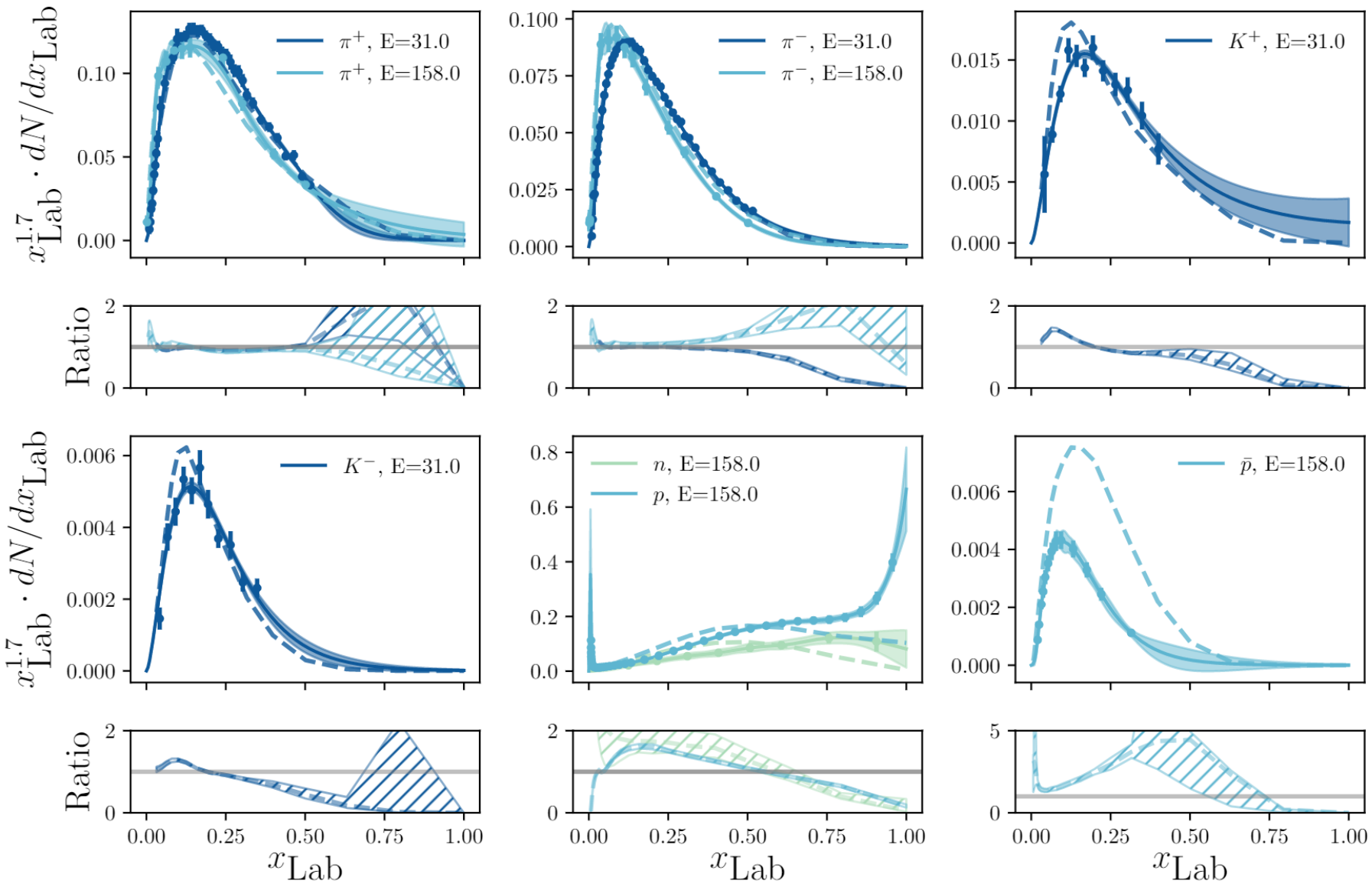
Fitting proton-Carbon data & uncertainty with splines

Solid + shade:
Spline fit

Dashed:
SIBYLL2.3d @ 158 GeV
DPMJET-III-191 @ 31 GeV

Data:
CERN, SPS
NA49 and NA61

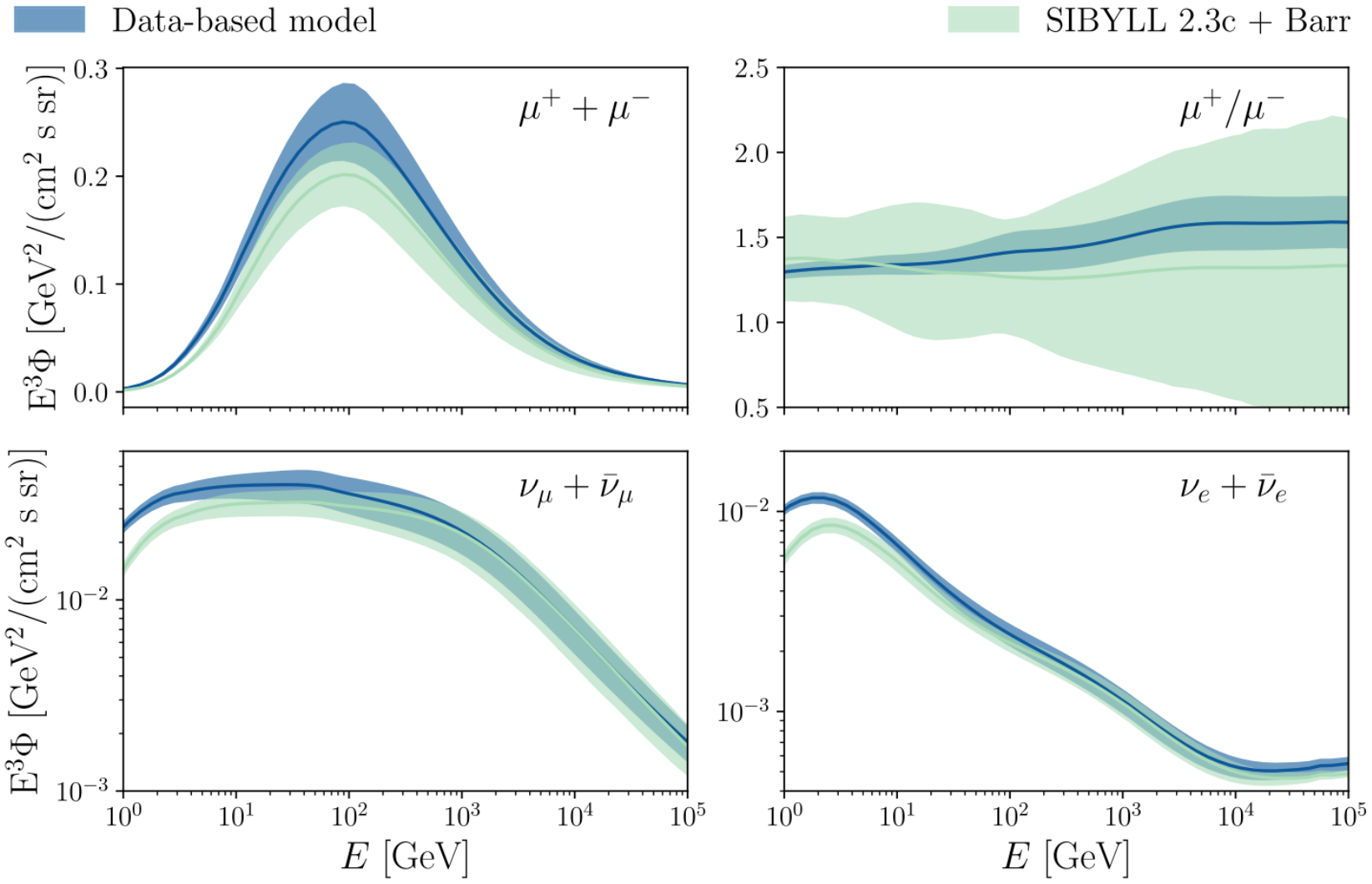
same for pion-Carbon data



M. Huber and AF,
in prep.

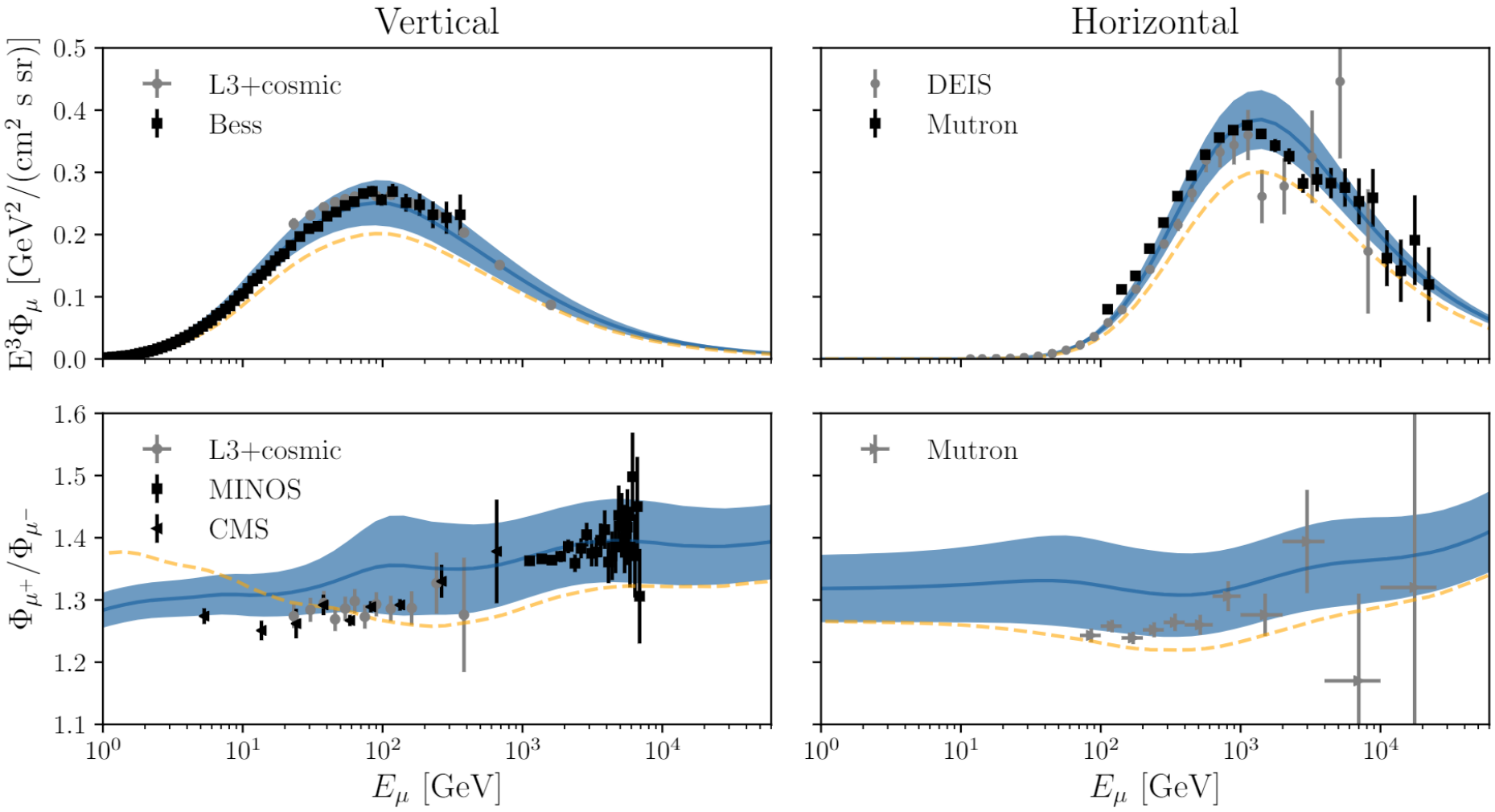
Impact on prediction uncertainties

AF et al., ICRC 2017 + Barr 2006, PRD 74



M. Huber and AF,
in prep.

Good muon spectrum description from fixed-target data



M. Huber and AF,
in prep.

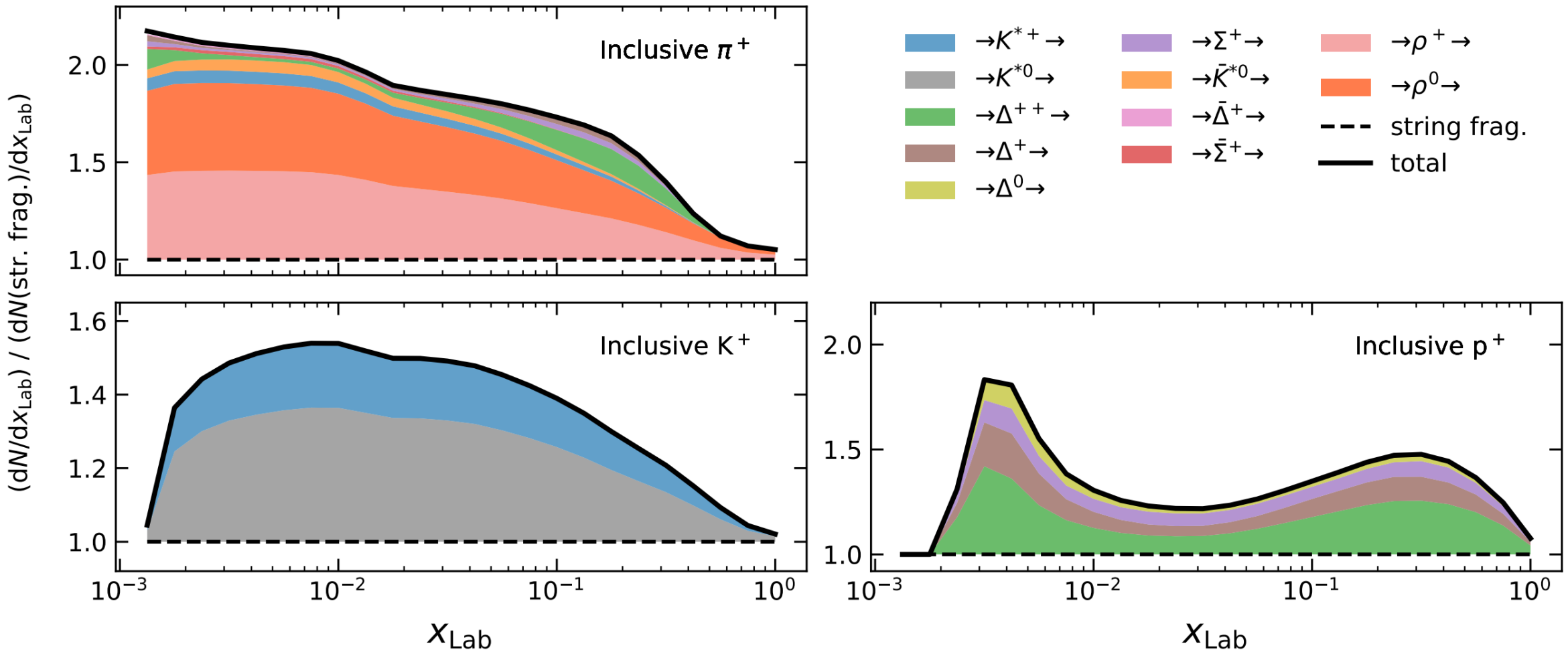
…but many nasty details regarding extrapolation uncertainties to consider.

Conclusions

- We have investigated three different methods to use data for constraining hadronic uncertainties
- With the (software) technology in development, we will be able to perform a global combined fit to muons, neutrinos and accelerator data
- It's a long path though…
- Next steps:
  - The IceCube DeepCore measurement will be updated to the new sample, as soon as the time critical analyses have been performed. Will be done either by seniors (us) or an interested student.
  - One master student in UofA is working on the muon fit with Juan Pablo Yanez and me, we are considering different parameterizations and try to find an underestimated error that biases our analysis.
  - Matthias Huber and I are writing up the accelerator data fit. It works, but many open questions remain. In particular, different data analyses would be required from NA61 in x_Lab/x_F.

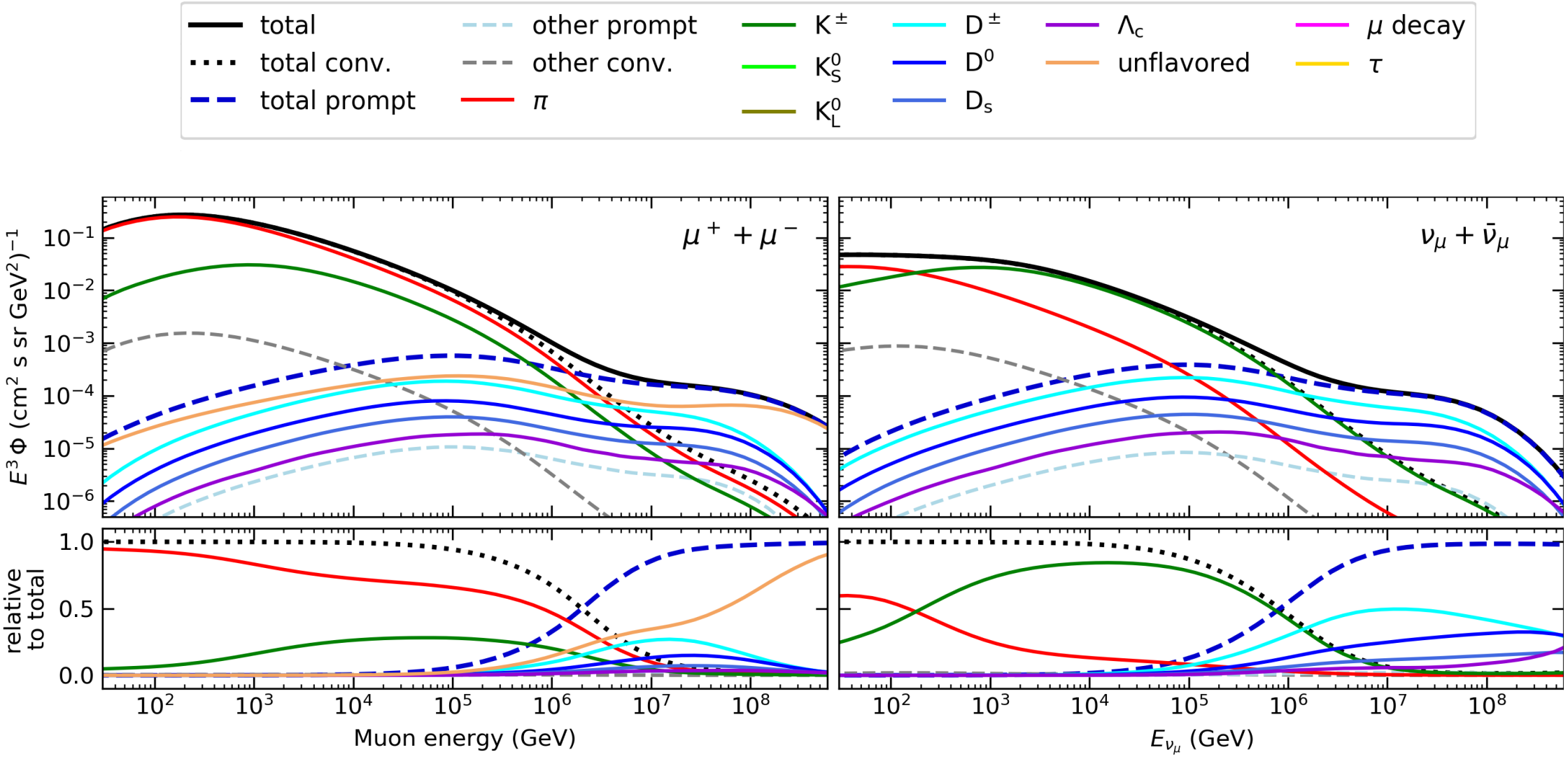
…difficult to interpret

arXiv:1806.04140



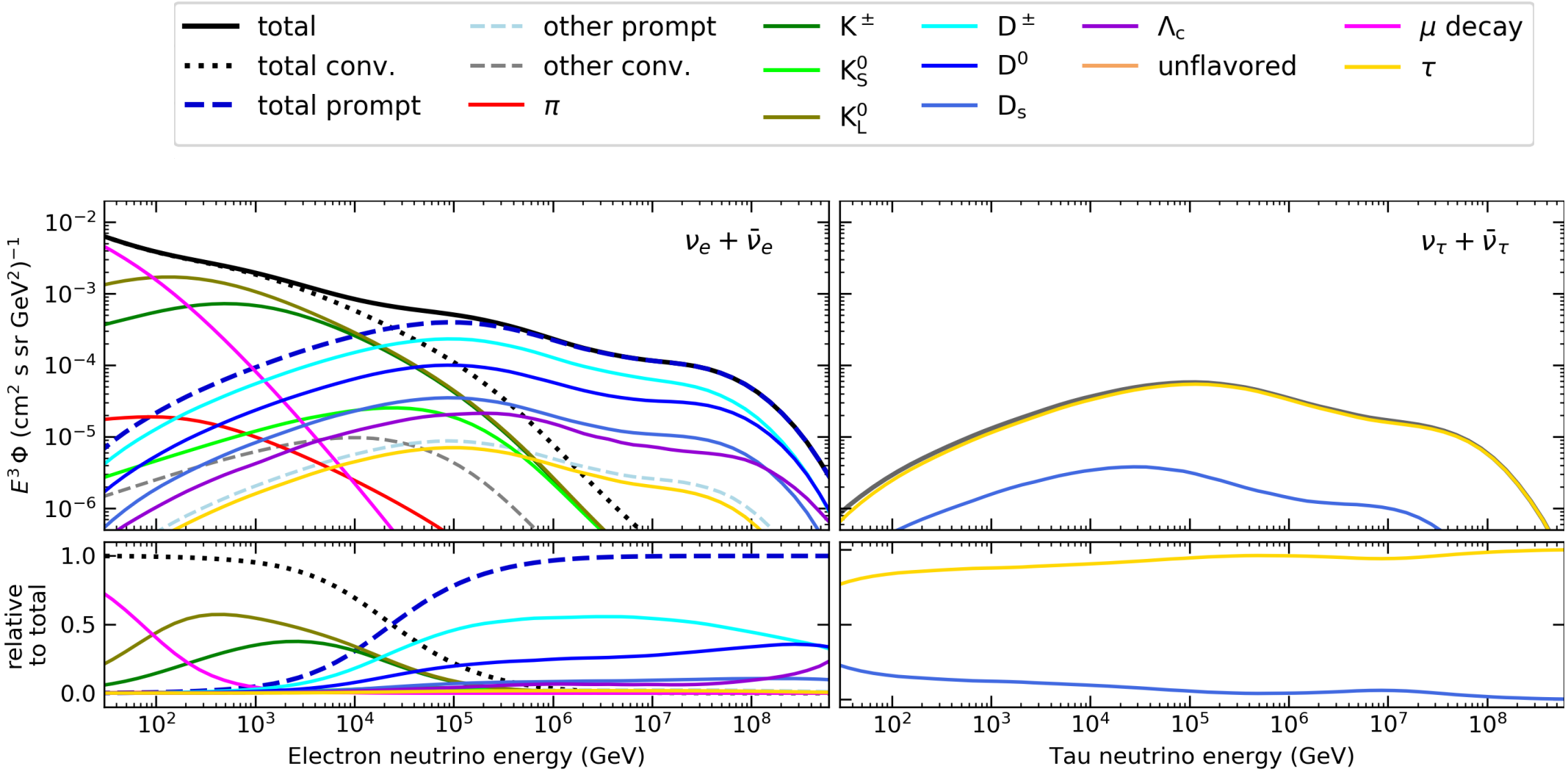
No simple tuning/systematic parameters within one interaction model! Many features related to each other.

Hadrons contributing to muonic leptons



AF, F. Riehn, R. Engel, T.K. Gaisser, T. Stanev, PRD 100 2019

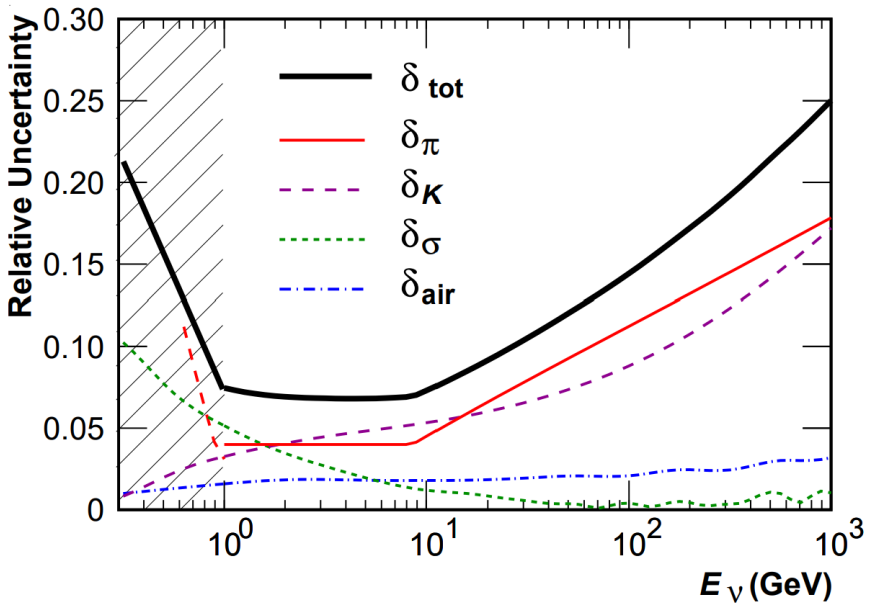
Hadrons contributing to electron and tau neutrinos



AF, F. Riehn, R. Engel, T.K. Gaisser, T. Stanev, PRD 100 2019

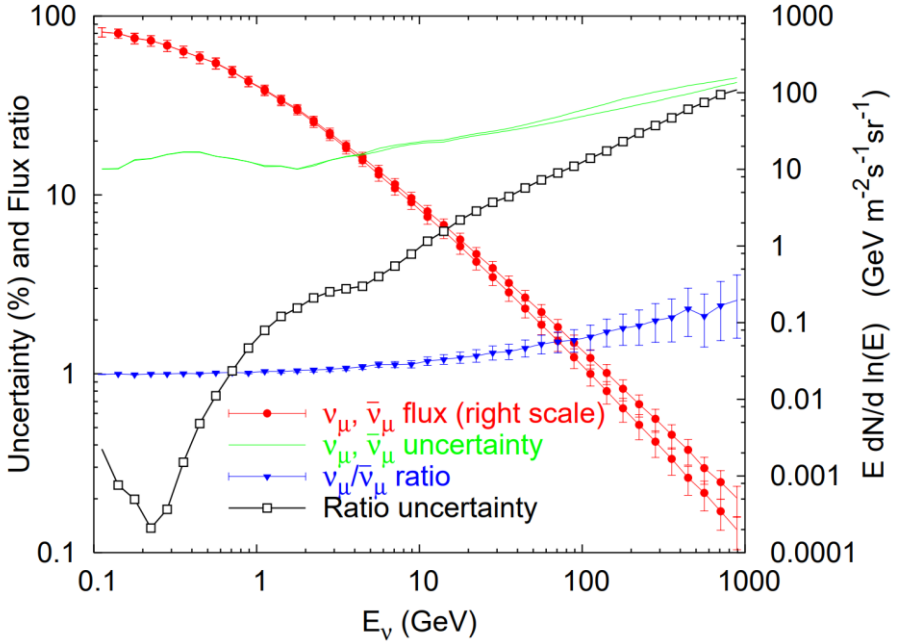
Flux uncertainties status

T. Sanuki & HKKM, 2006



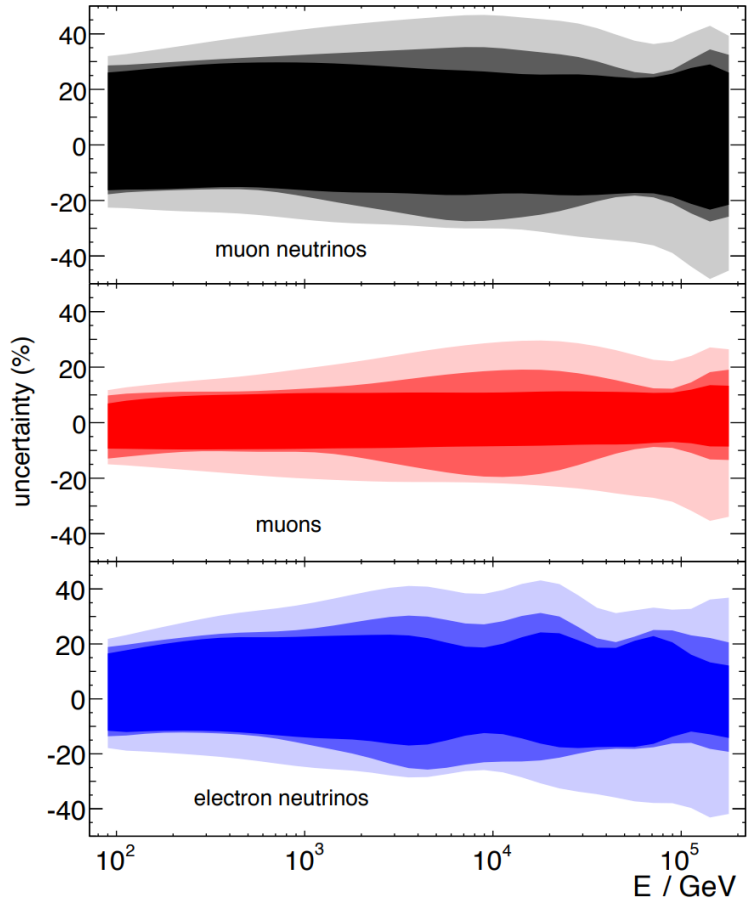
- Derive corrections from **muon data**
- Below 1 GeV all muons decay in flight → method unconstrained

G. Barr et al. (Bartol), 2006



- Uncertainty from **assessment of accelerator and CR data**
- Current state-of-the-art (used by most except SK)

AF, Becker Tjus, Desiati (CORSIKA), 2012

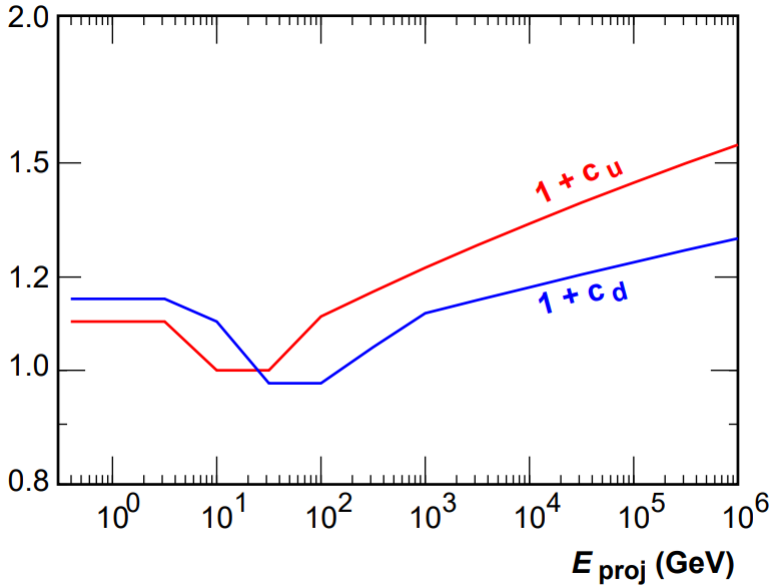


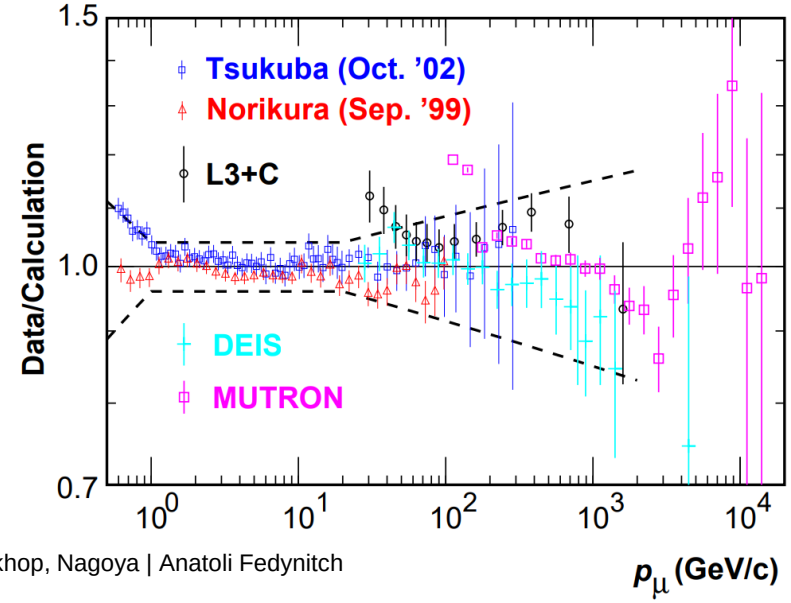
- Based on **"bracketing" of hadronic** (air-shower) and CR **models**
- Same result with post-LHC models (SIBYLL2.3, EPOS, QGSJET-II-04)
- Comparable with "Barr-scheme"

Hadronic uncertainties: HKKM approach

- Use **isospin-symmetry-inspired relation** between secondary hadrons and **valence quarks**=(constituent quark/parton model = 70's)
- Allow for energy-dependent re-scaling to fit muon observations
- Many free**, not necessarily physically motivated**, parameters
- Fit muon data **for fixed CR flux (GH)**, error bars from eye-ball fit
- → **Likely** results in the best normalization from all the available flux calculations

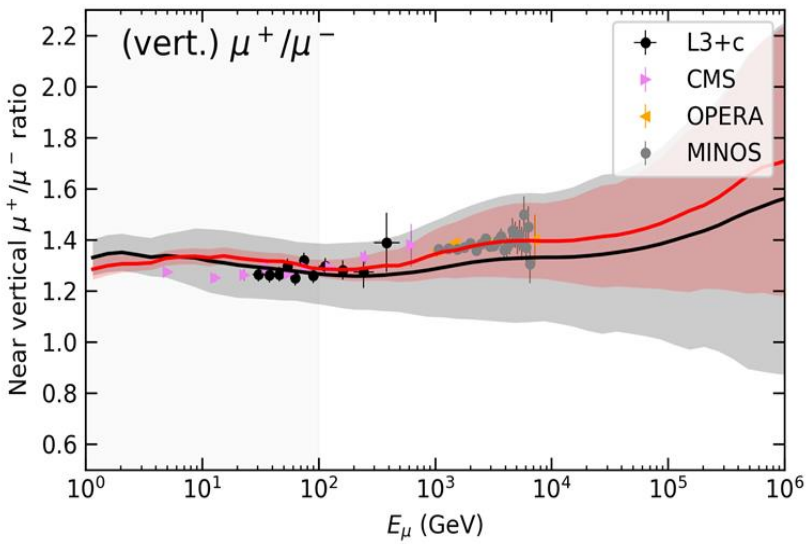
HKKM, PRD (2007)

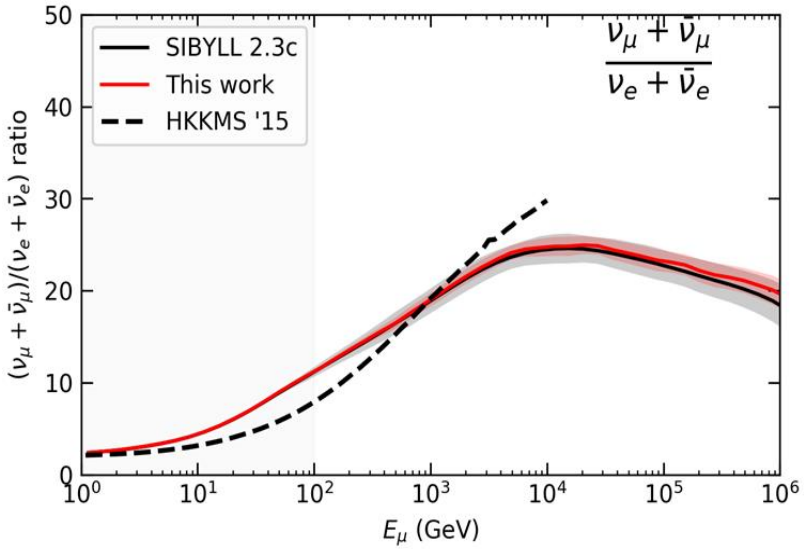


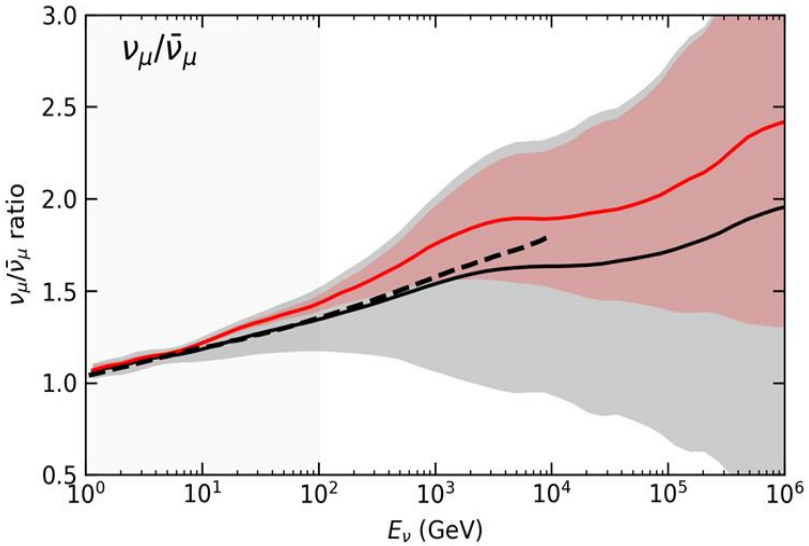


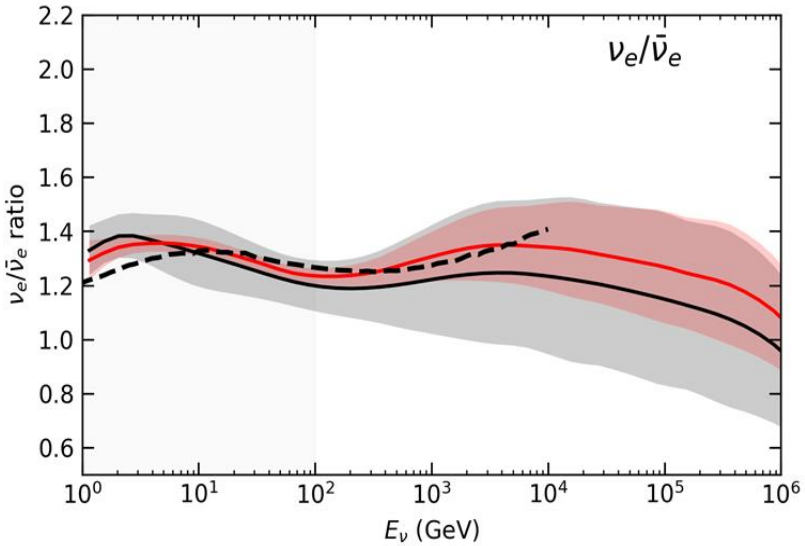
$$< E_{\pi^+} > \;=\; (1 + c_u) < E^0_{\pi^+} > \qquad (u\bar{d})$$
$$< E_{\pi^-} > \;=\; (1 + c_d) < E^0_{\pi^-} > \qquad (d\bar{u})$$
$$< E_{\pi^0} > \;=\; (1 + (c_u + c_d)/2) < E^0_{\pi^0} > \qquad ((u\bar{u} - d\bar{d})/2)$$
$$< E_{K^+} > \;=\; (1 + c_u) < E^0_{K^+} > \qquad (u\bar{s})$$
$$< E_{K^-} > \;=\; < E^0_{K^-} > \qquad (s\bar{d})$$
$$< E_{K^0} > \;=\; (1 + c_d) < E^0_{K^0} > \qquad (d\bar{s})$$
$$< E_{\bar{K}^0} > \;=\; < E^0_{\bar{K}^0} > \qquad (s\bar{d})$$

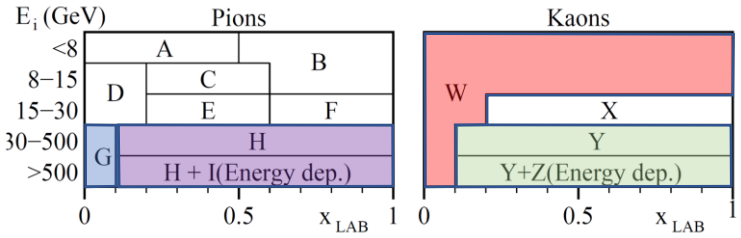
Results of the preliminary fit

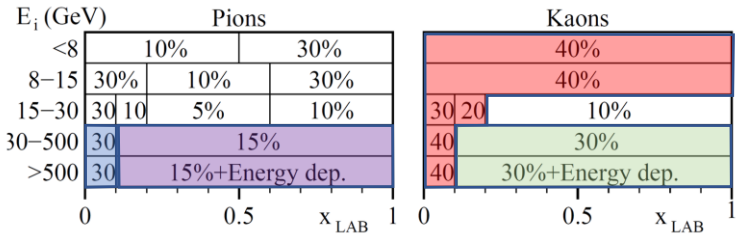






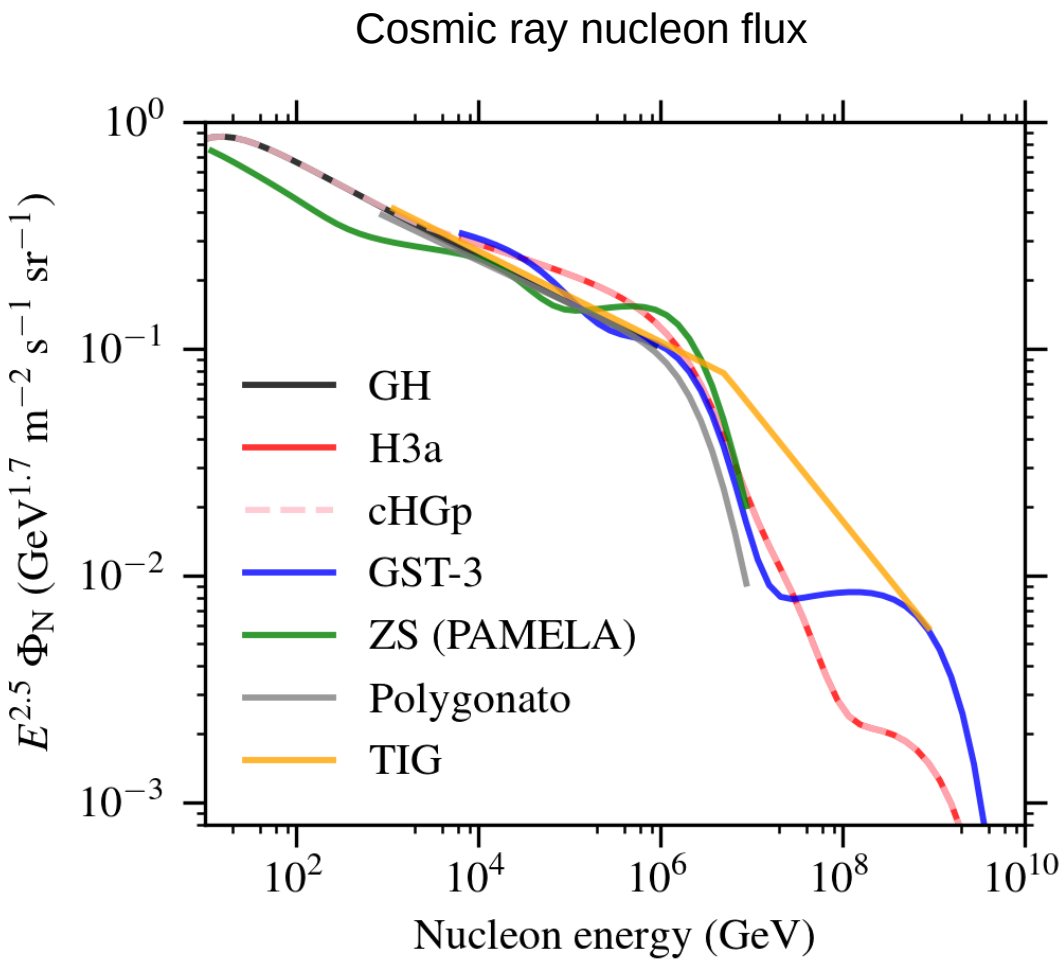


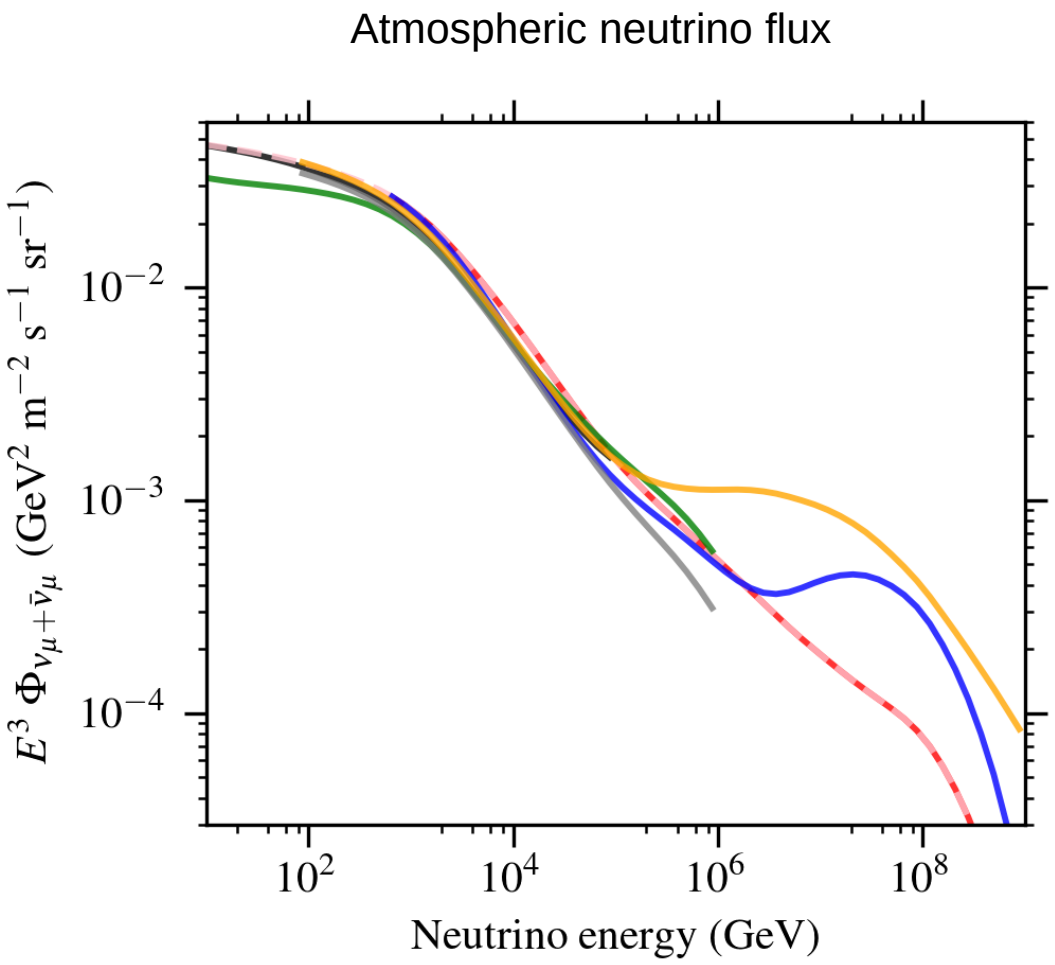




Name	value, error
π^+: G	0.13±0.10
π^+: H	0.30±0.03
K^+: W	0.14±0.08
K^+: Y	0.47±0.07
π^-: G	0.44±0.08
π^-: H	0.16±0.04
K^-: W	0.20±0.10
K^-: Y	0.11±0.07

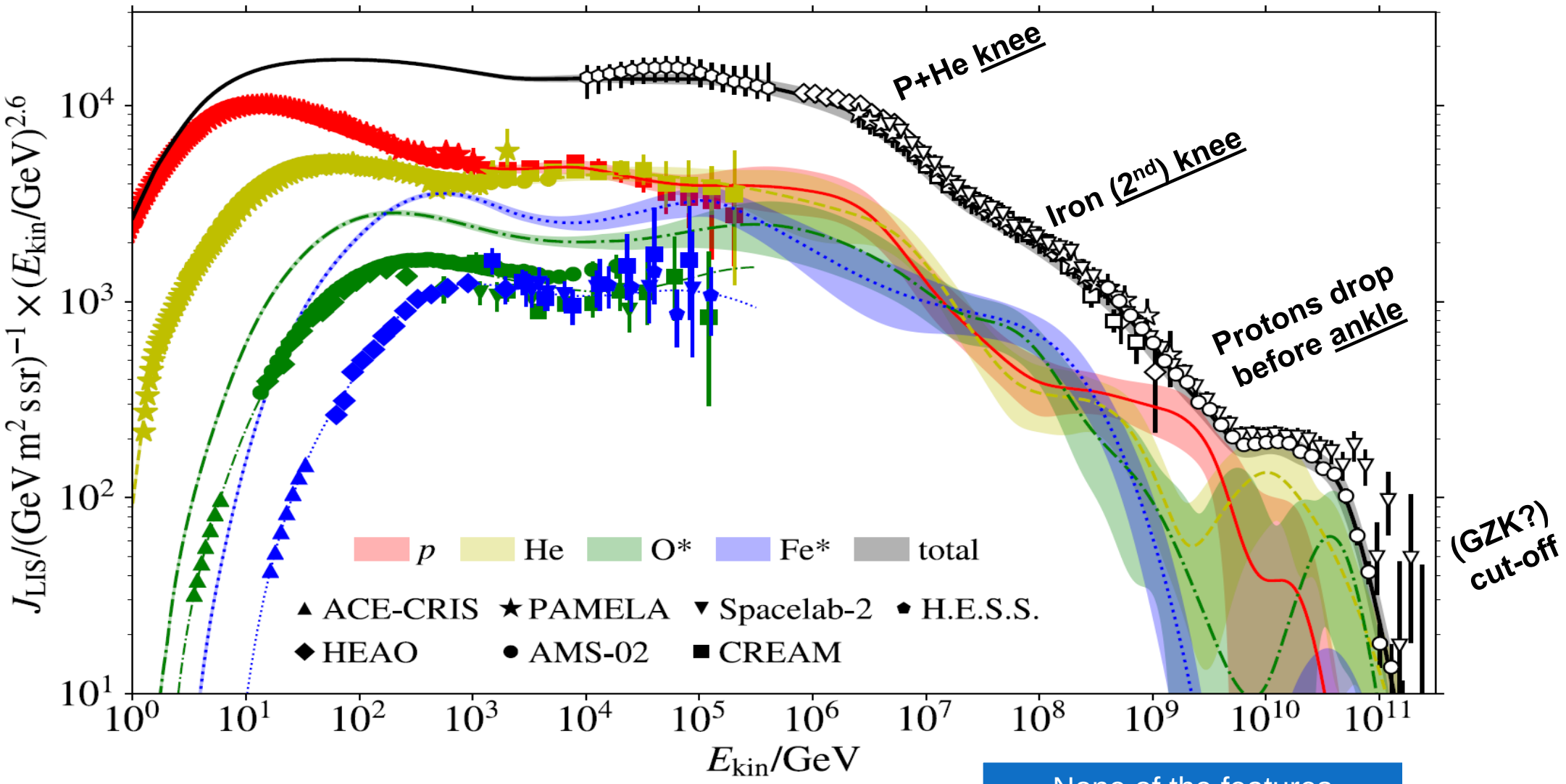
Cosmic ray flux uncertainties – ‘bracketing’ overestimates





Cosmic Ray observations

Dembinski, AF, Engel, Gaisser, Stanev
PoS(ICRC2017)533 & in prep.

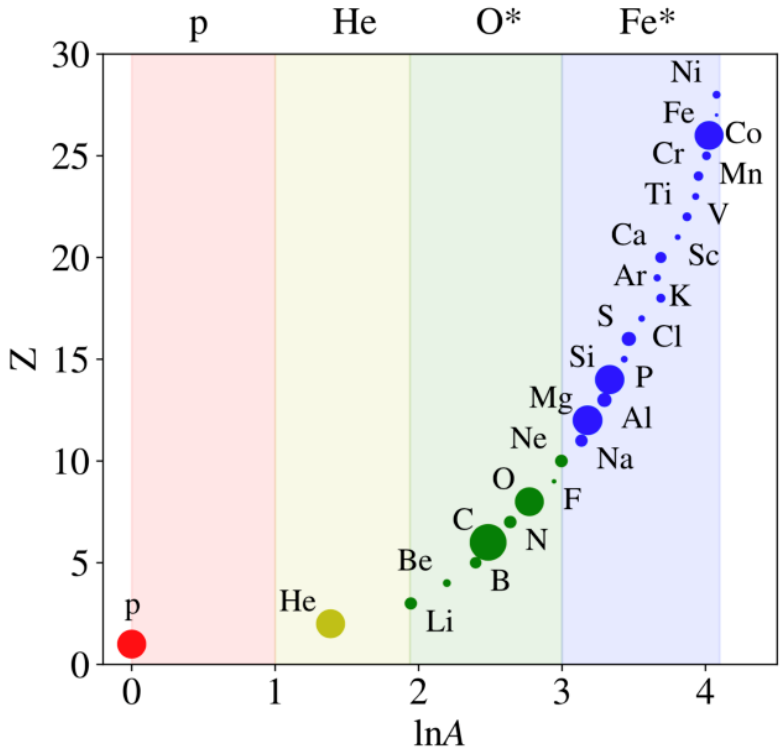


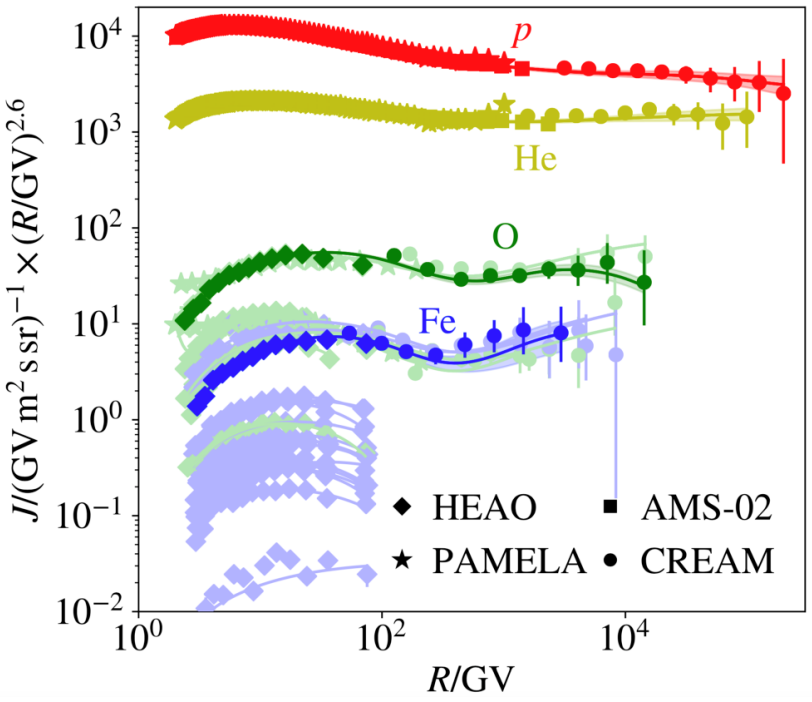
None of the features unambiguously explained!

Global Spline Fit – fit to direct & indirect observations

H. Dembinski, AF, T. Gaisser
PoS(ICRC2017)533

- Fit **four** independent mass groups, which cover equal ranges in lnA: proton (p), helium (He), oxygen group (O*), and iron group (Fe*)
- Assumption: this holds **at all energies**
- One leading element *L* per group described by smooth spline curve
- Other elements *j* in a group kept in constant ratio: $J_j(R)/ J_L(R) = const.$



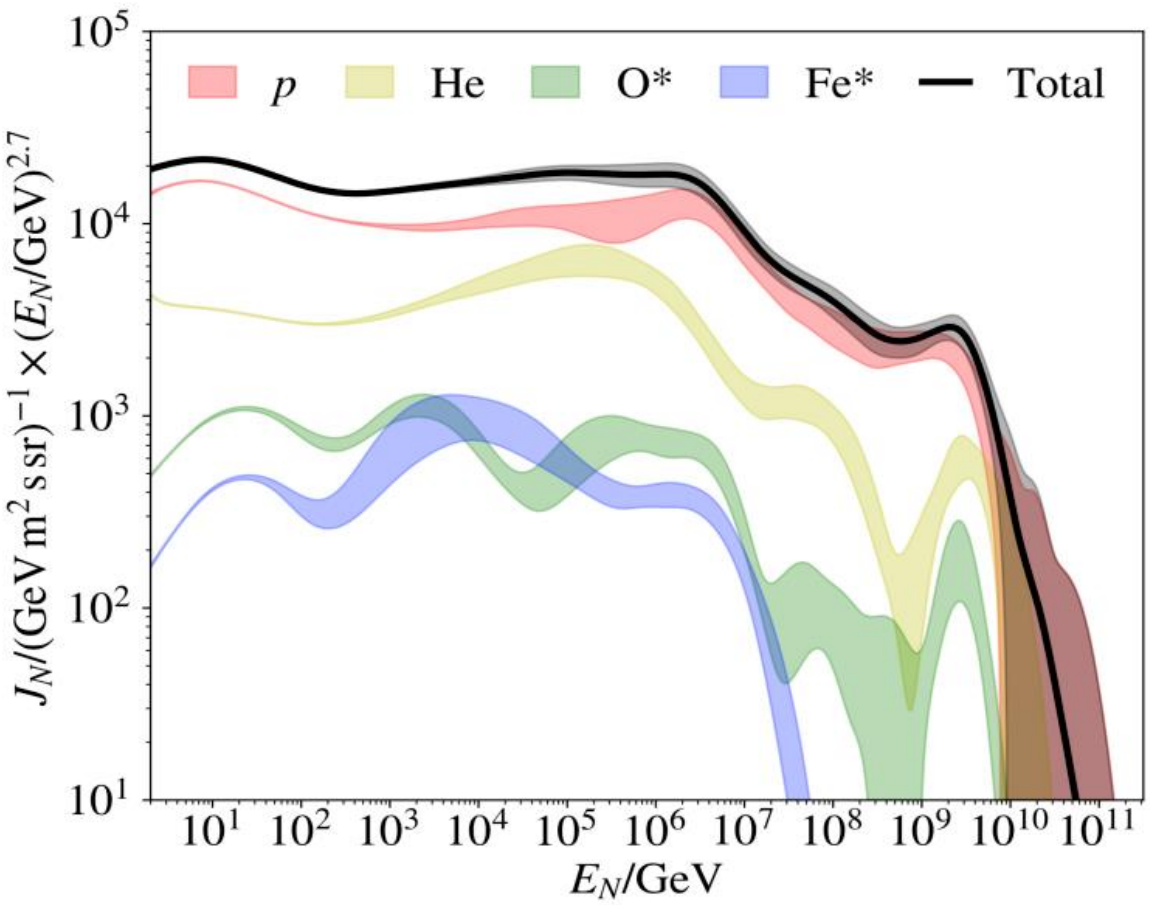


Mass sensitivity of air-shower experiments is ~ lnA

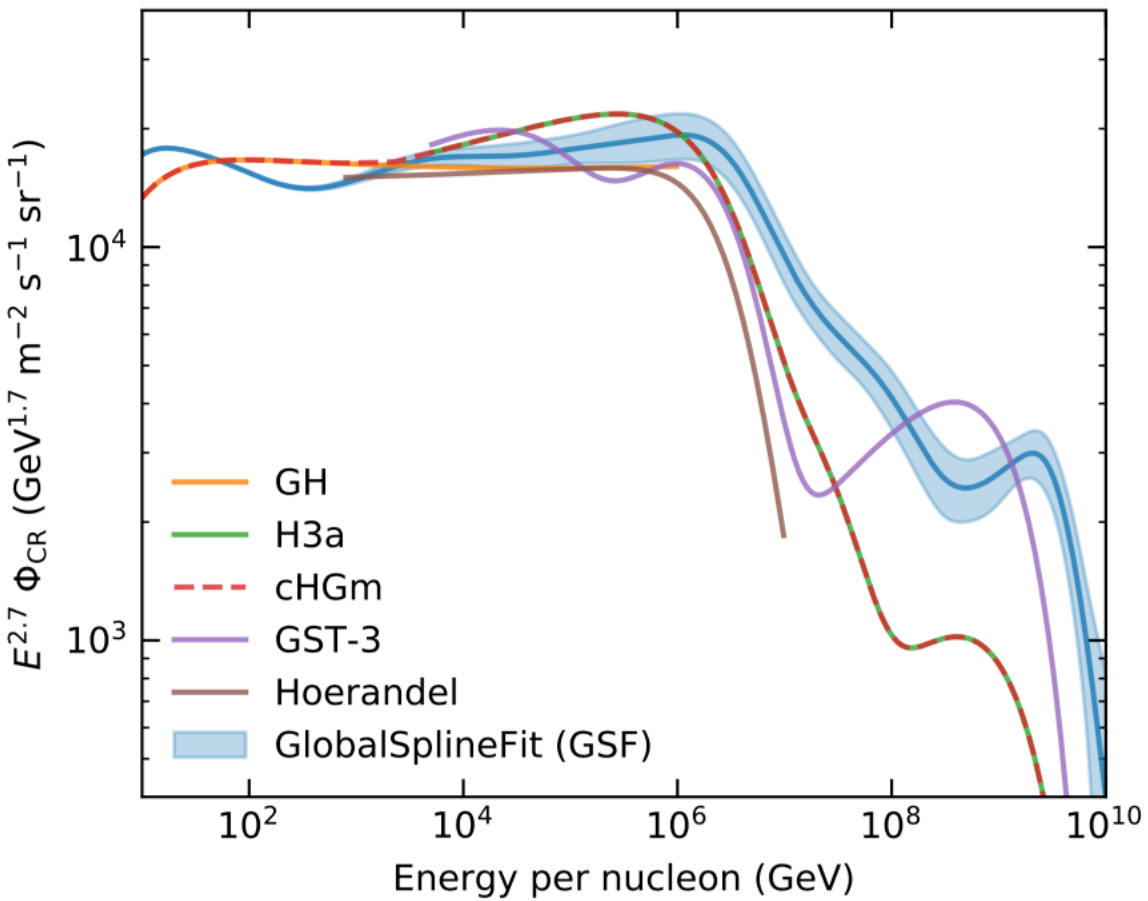
Derived result: nucleon flux

Dembinski, AF, Engel, Gaisser, Stanev
PoS(ICRC2017)533 & in prep.

AF et al, PoS(ICRC2017)1019



Dominated by proton flux. Details of sub-leading elements not important.



Harder spectrum at the knee due to lighter composition as assumed by 3-population models