Conventional and prompt fluxes in neutrino telescopes

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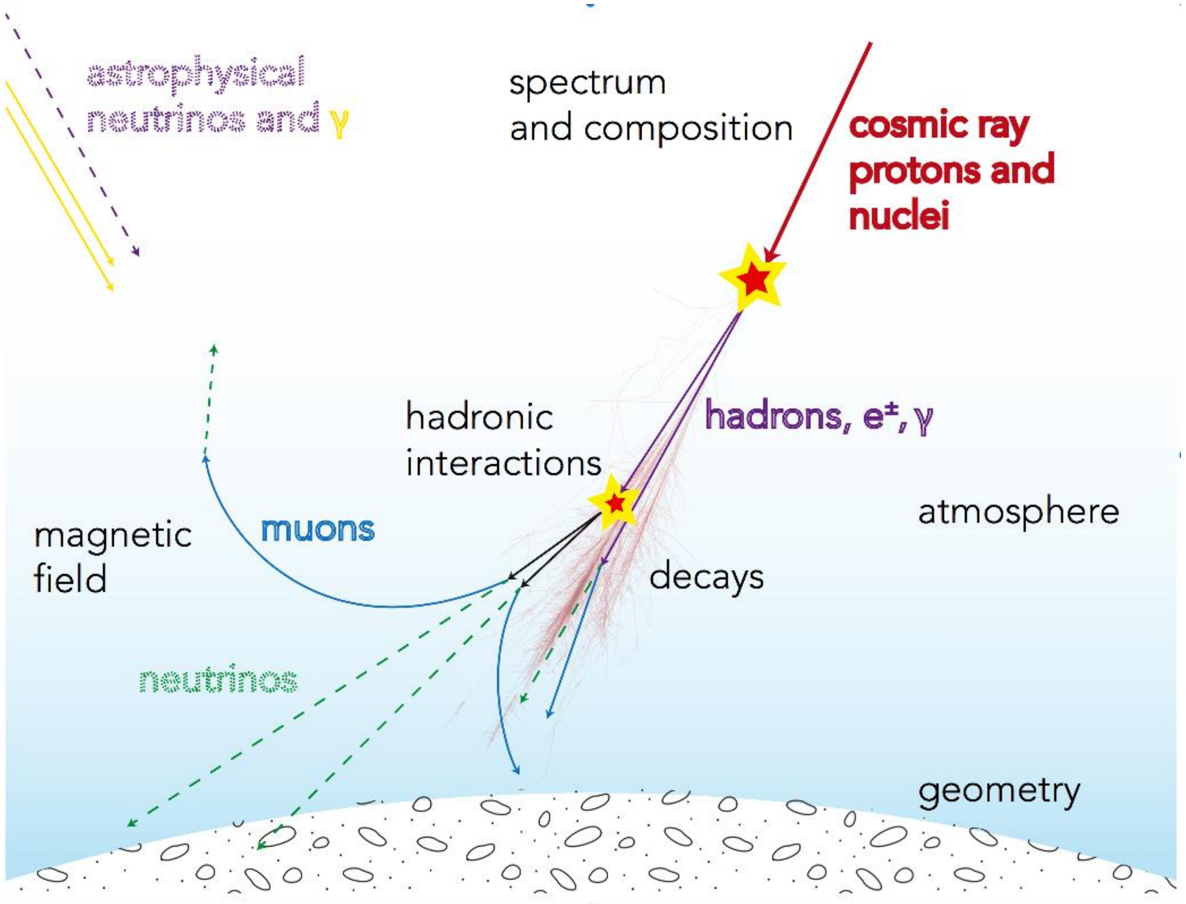
ICRR, University of Tokyo, Japan

October 07
MITP HQHP workshop

Atmospheric neutrinos

Ingredients for high-precision atmospheric neutrino flux calculation



- For <u>high precision</u> calculations all phenomena need accurate modeling

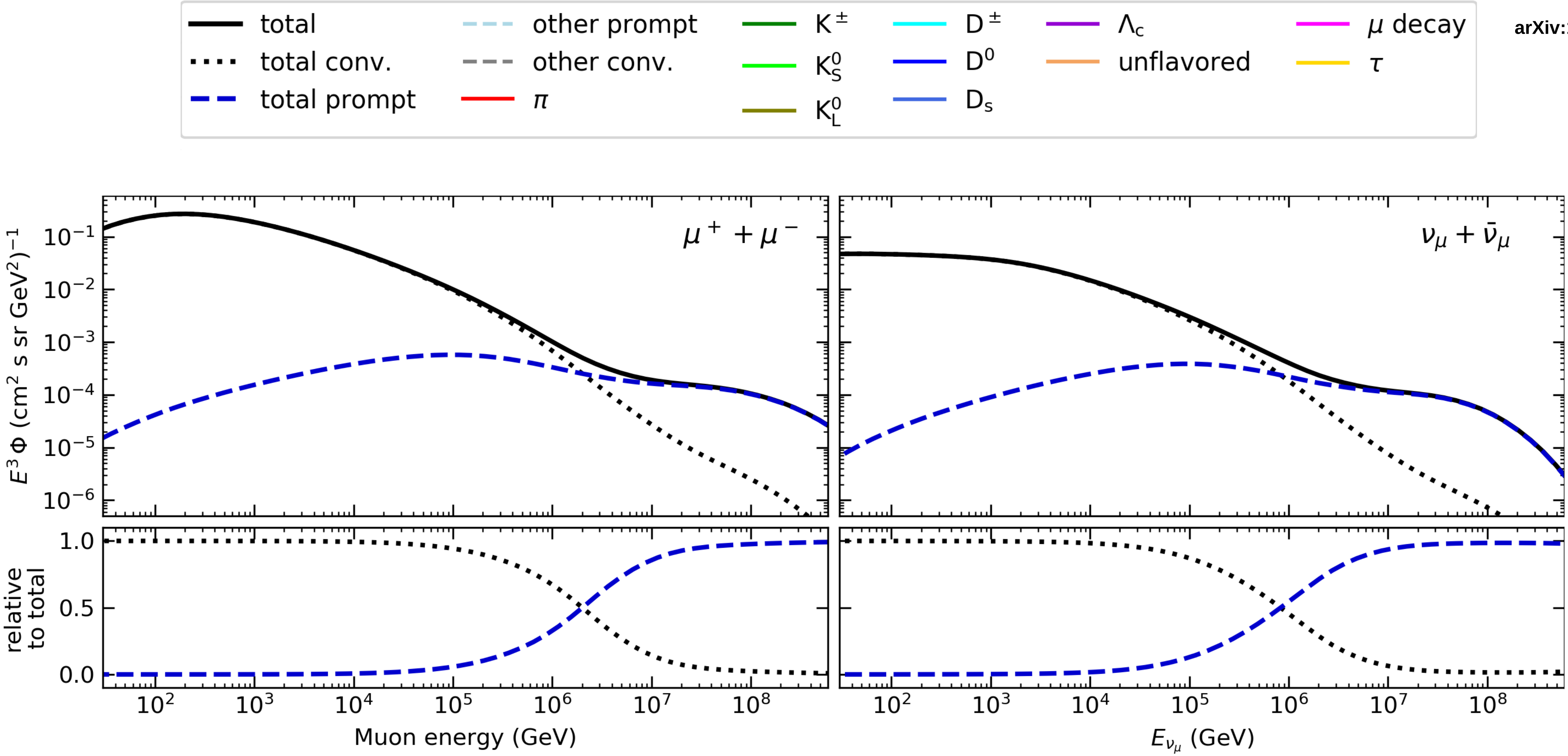
- Uncertain "ingredients":
  - Cosmic ray spectrum and composition
  - Hadronic interactions
  - Atmosphere (dynamic, depends on use case)
  - (Rare) decays
  - Geometry, magnetic fields, solar modulation

- No clear prescription how to handle uncertainties.

- Energy range MeV – EeV!

Hadrons contributing to muonic leptons

arXiv:1806.04140



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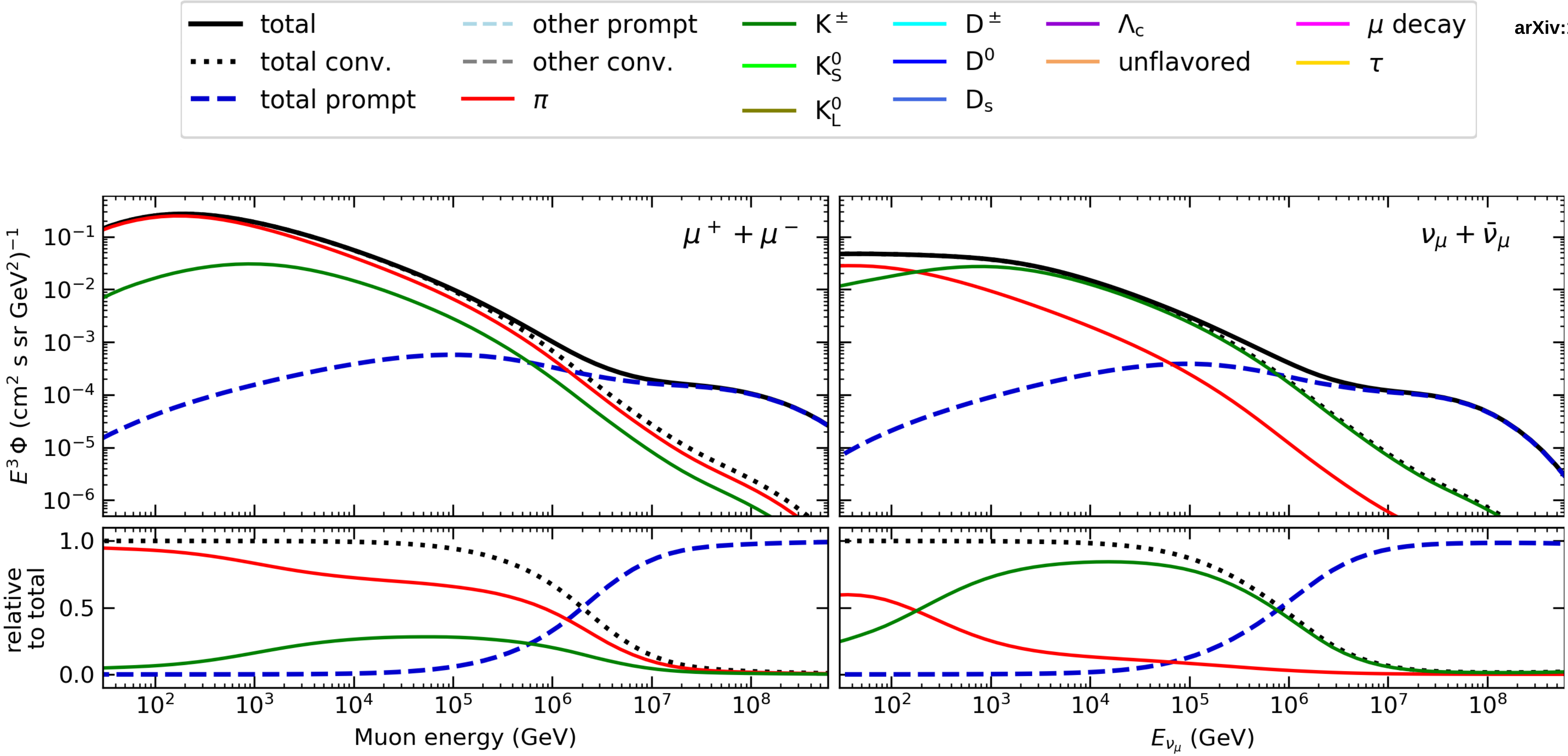

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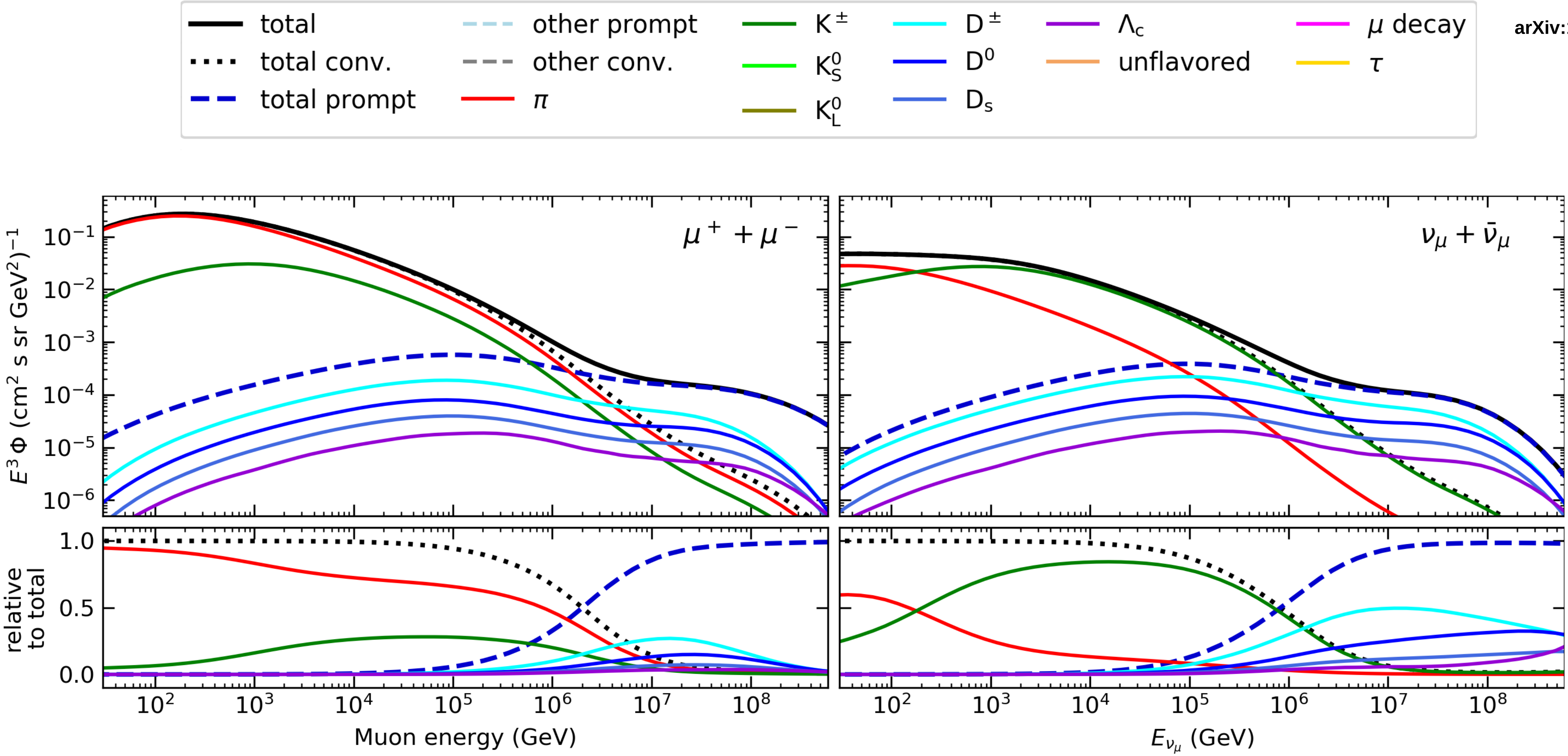

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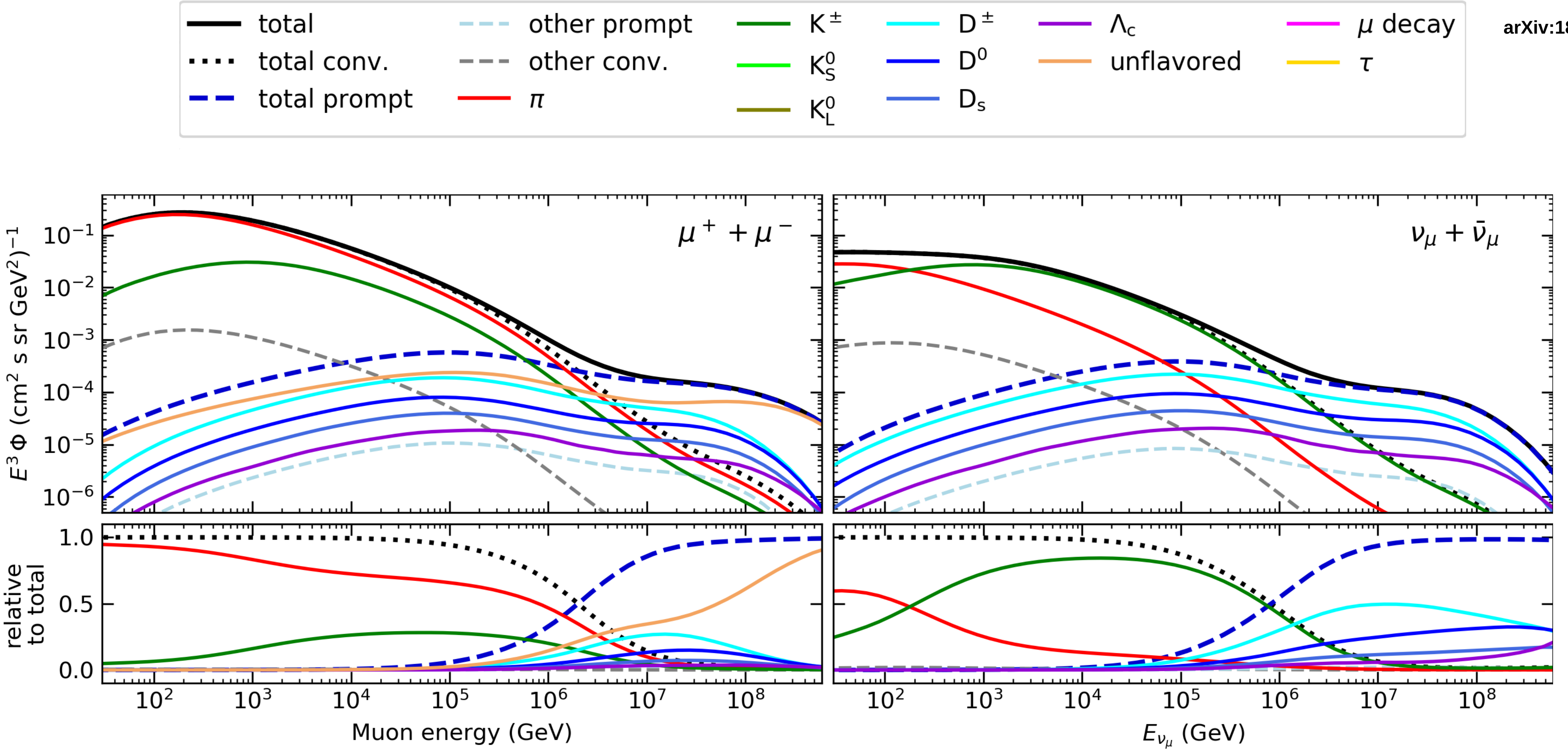

Hadrons contributing to electron and tau neutrinos

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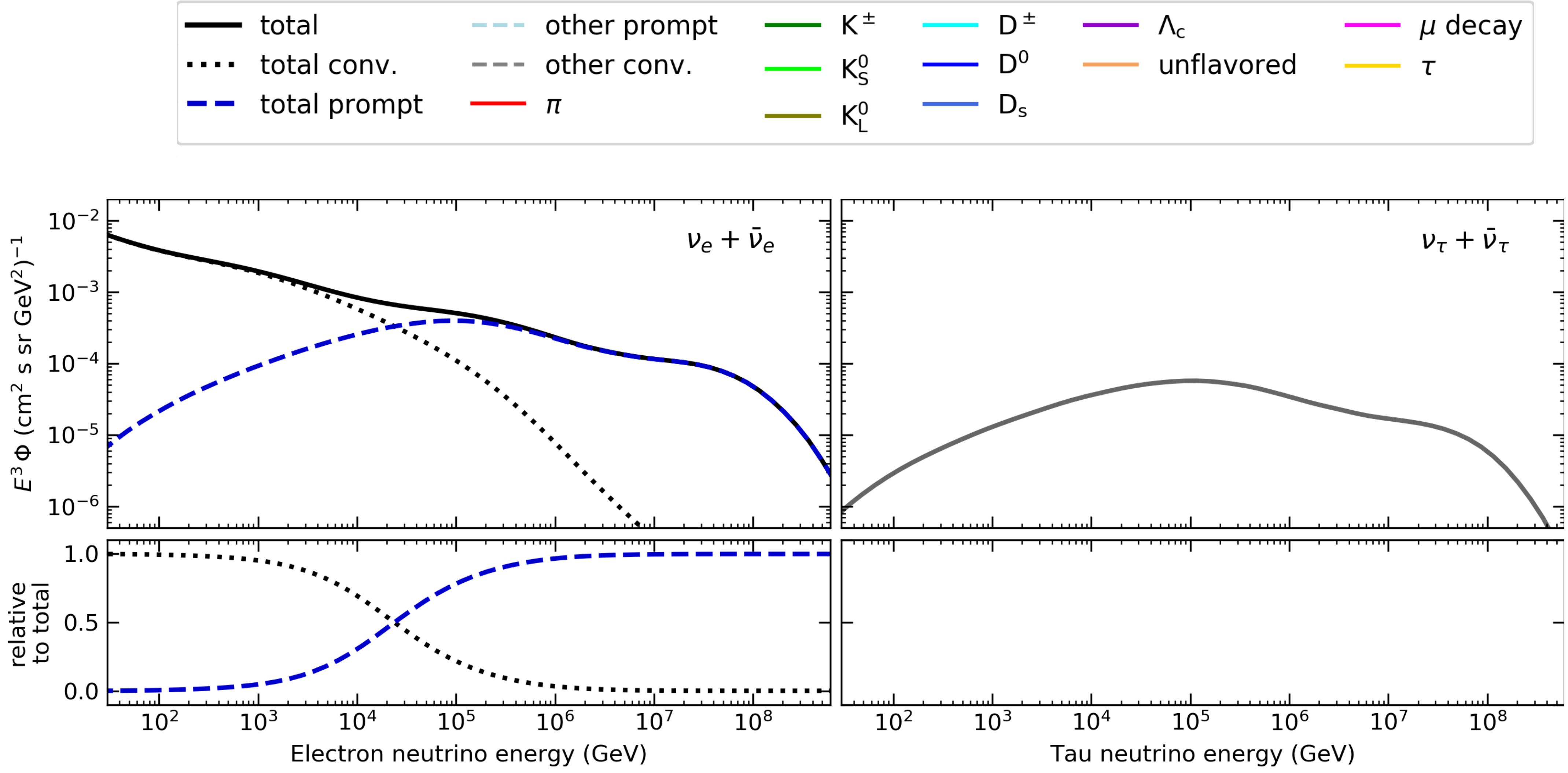

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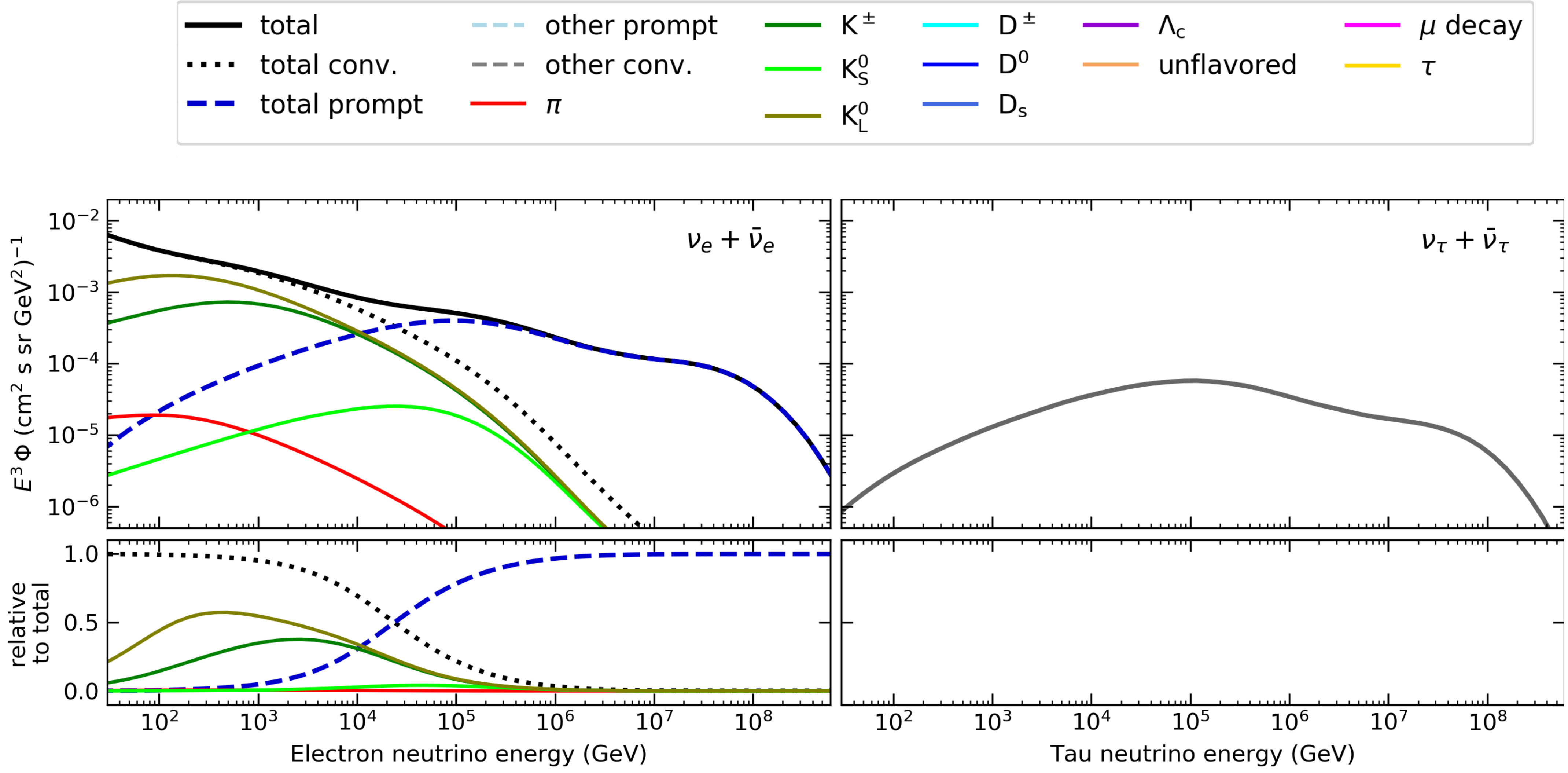

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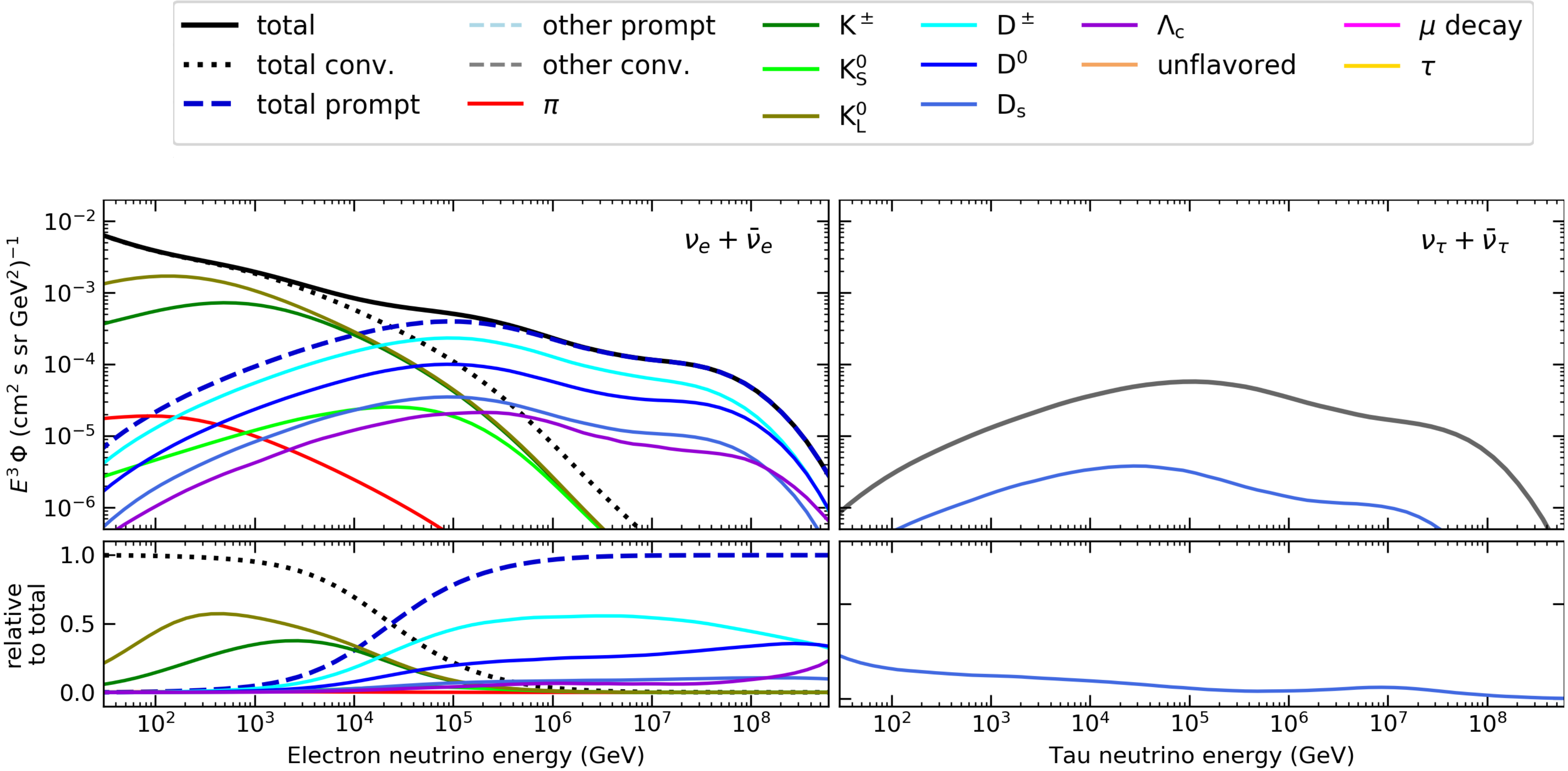

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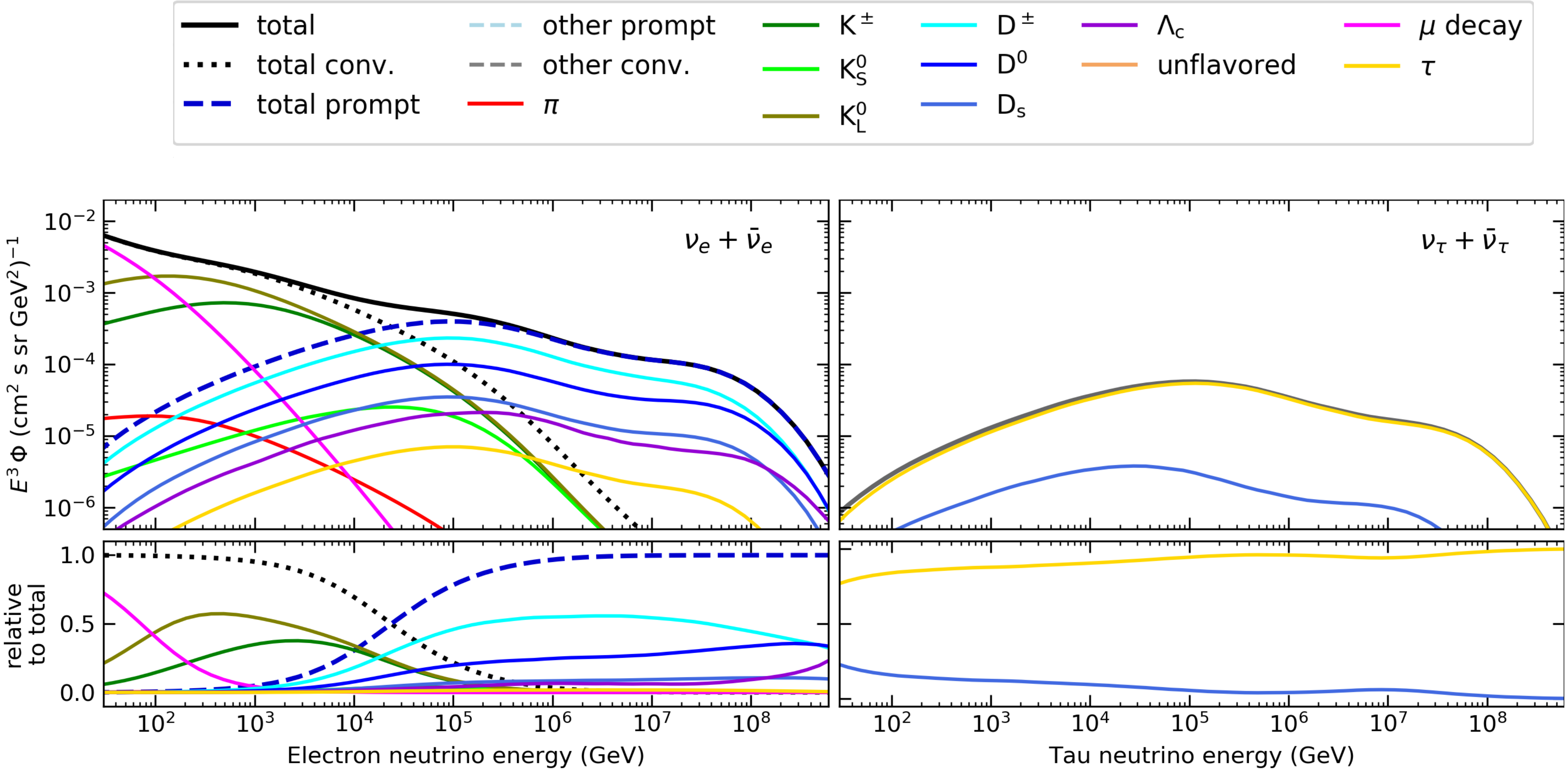
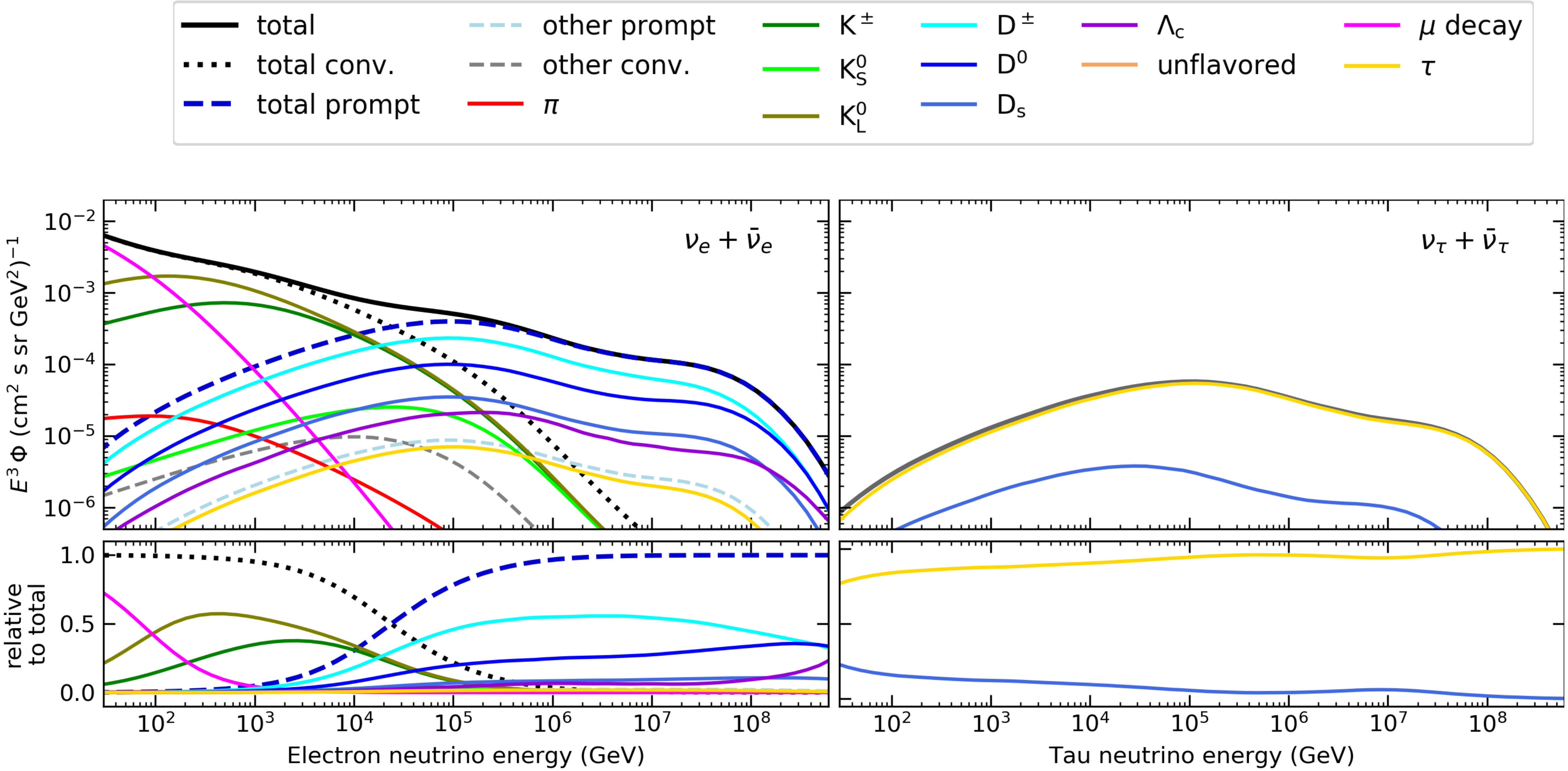
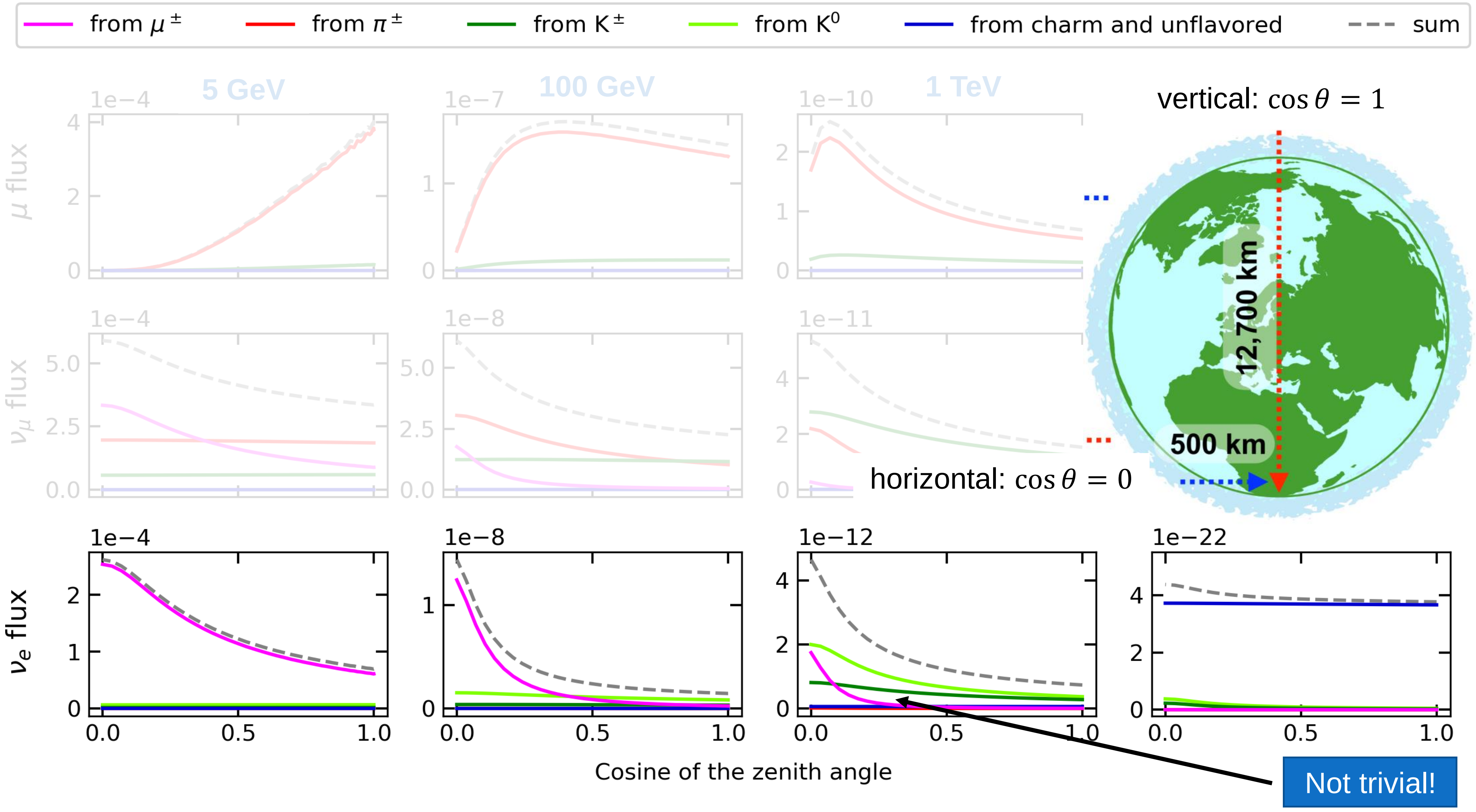


Hadrons contributing to electron and tau neutrinos



arXiv:1806.04140

Different hadronic components shape the zenith distribution



AF, F. Riehn, R. Engel, T.K. Gaisser, T. Stanev, 1806.04140 (2018)

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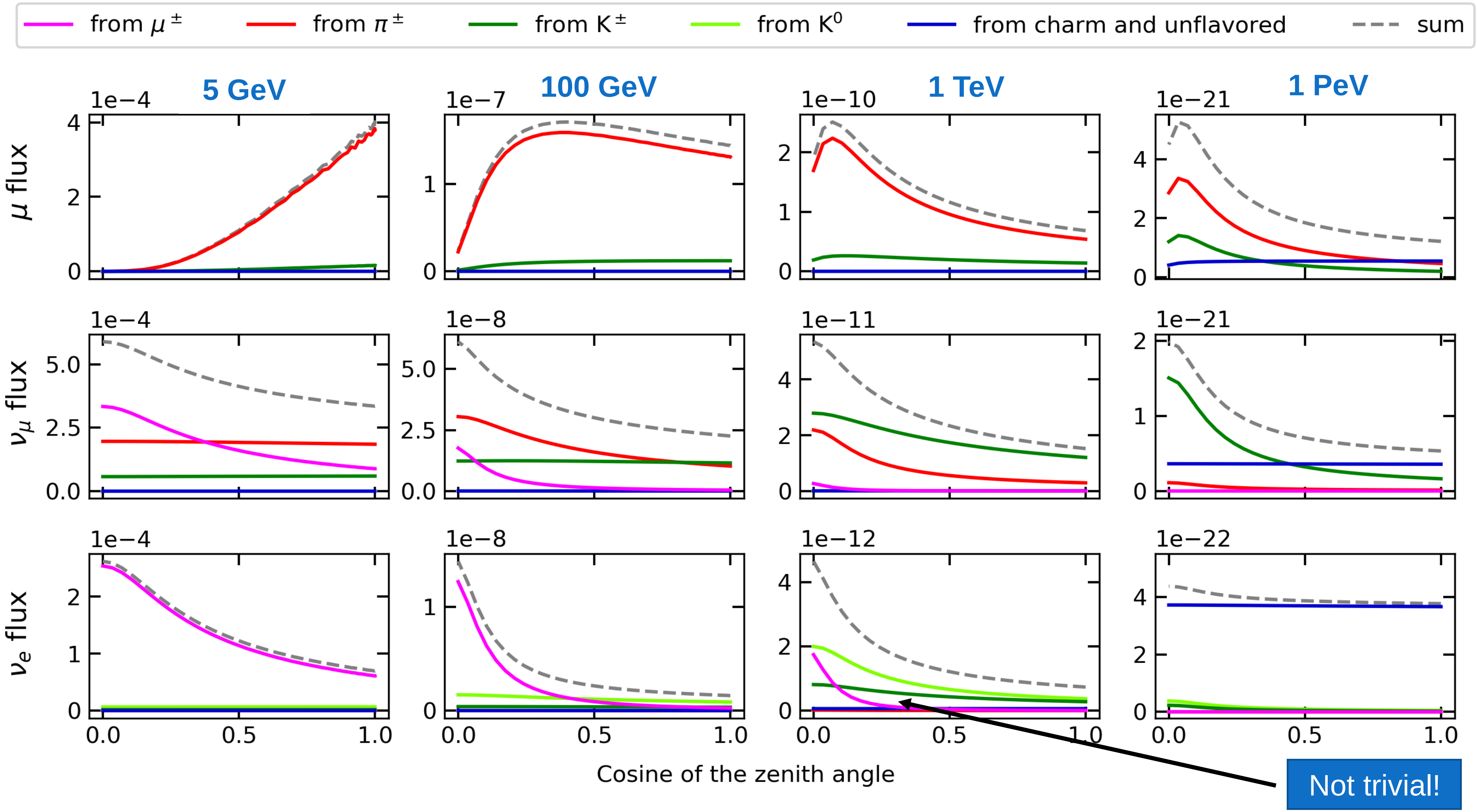

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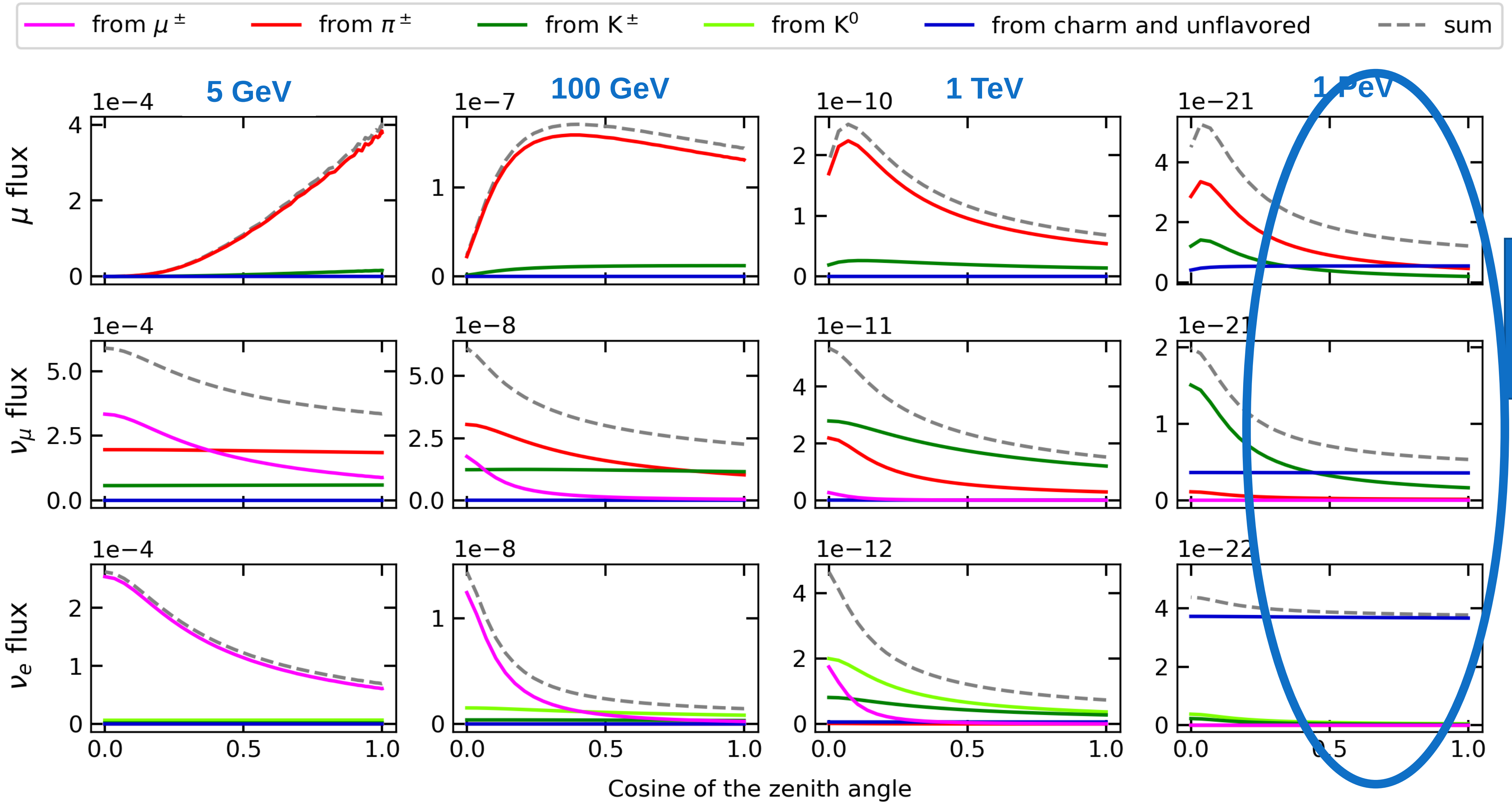


Prompt fluxes only vertical and in ν_e

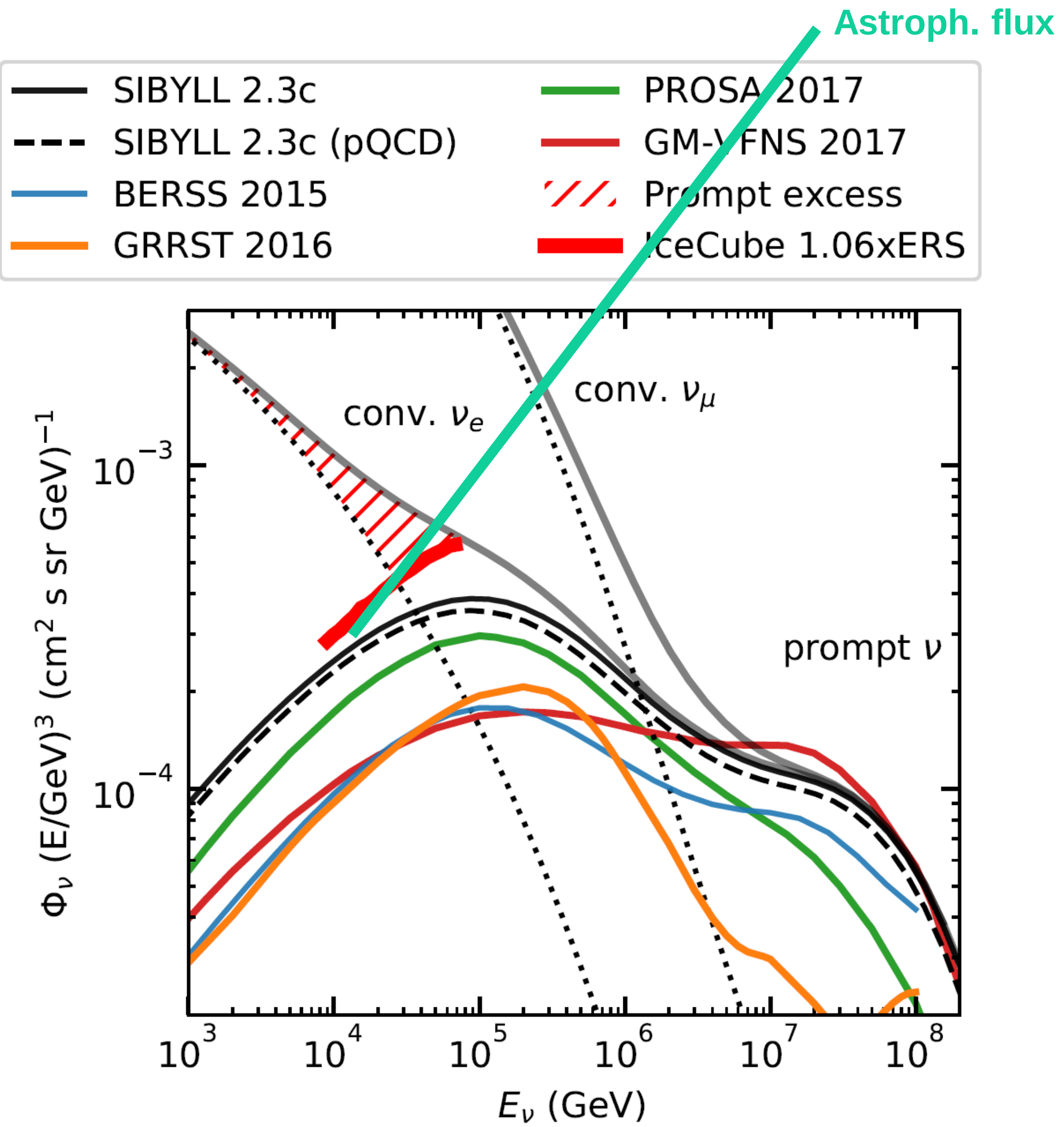
AF, F. Riehn, R. Engel, T.K. Gaisser, T. Stanev, 1806.04140 (2018)

Prompt ν_μ and ν_e fluxes

- Prompt **muon neutrino flux buried** under conventional and astrophysical flux

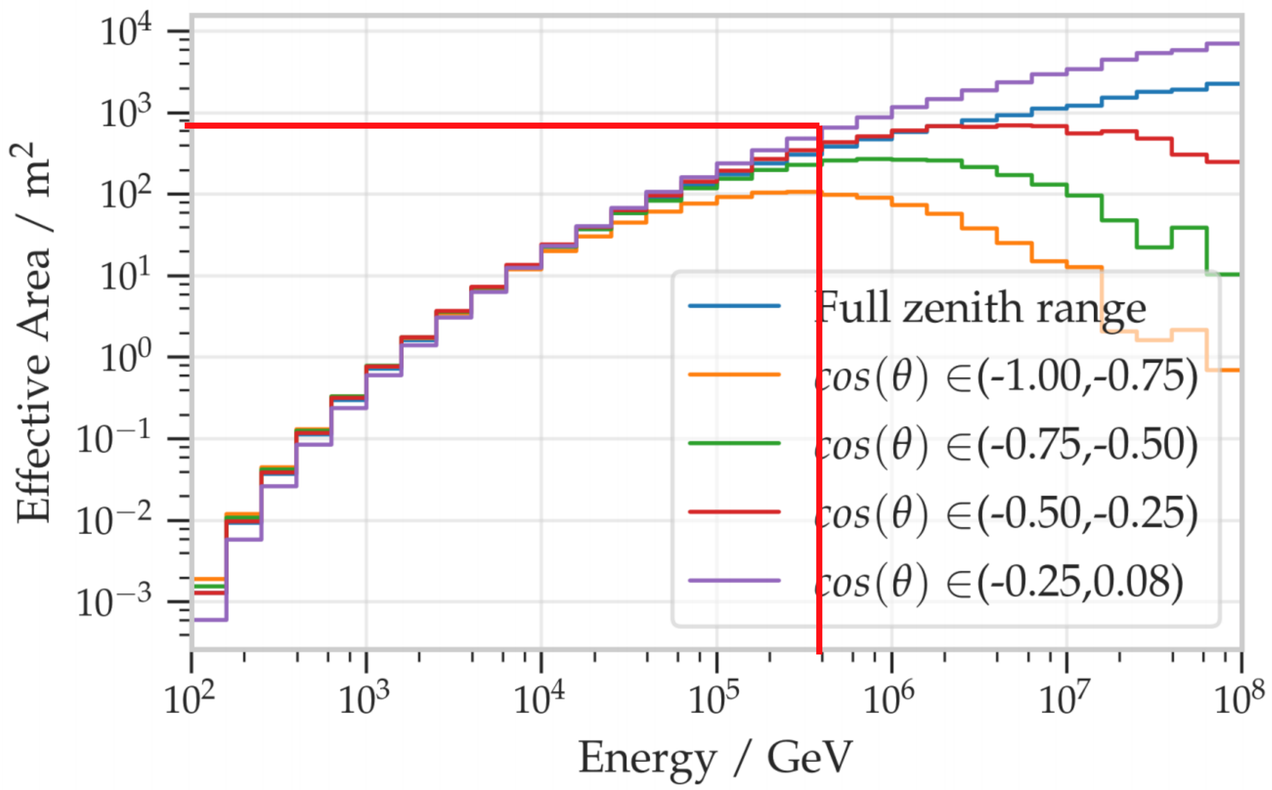
- This depends on the zenith angle (Tom's talk)

- Clear excess over conventional background in electron neutrinos (hatched area)



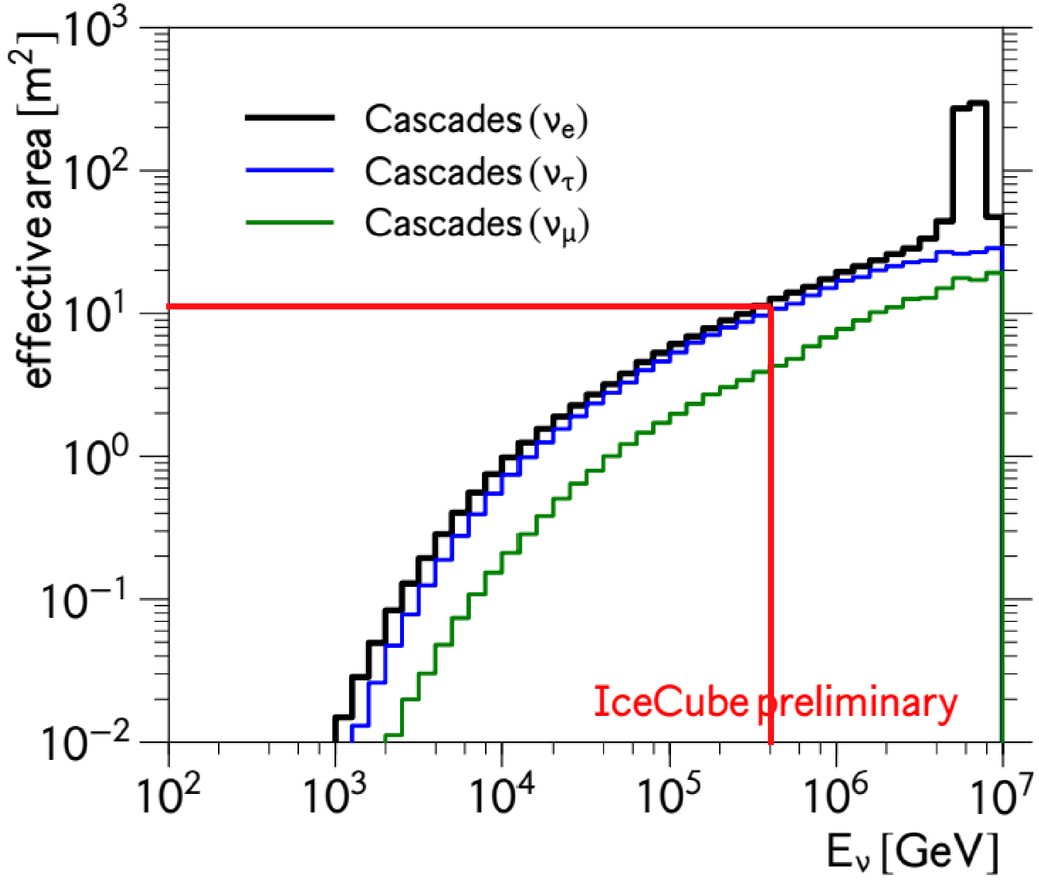
Tracks vs. Cascades effective areas

IceCube, Diffuse NuMu, 10 years



J. Stettner (IceCube Collaboration), ICRC, arxiv: 1908.09551

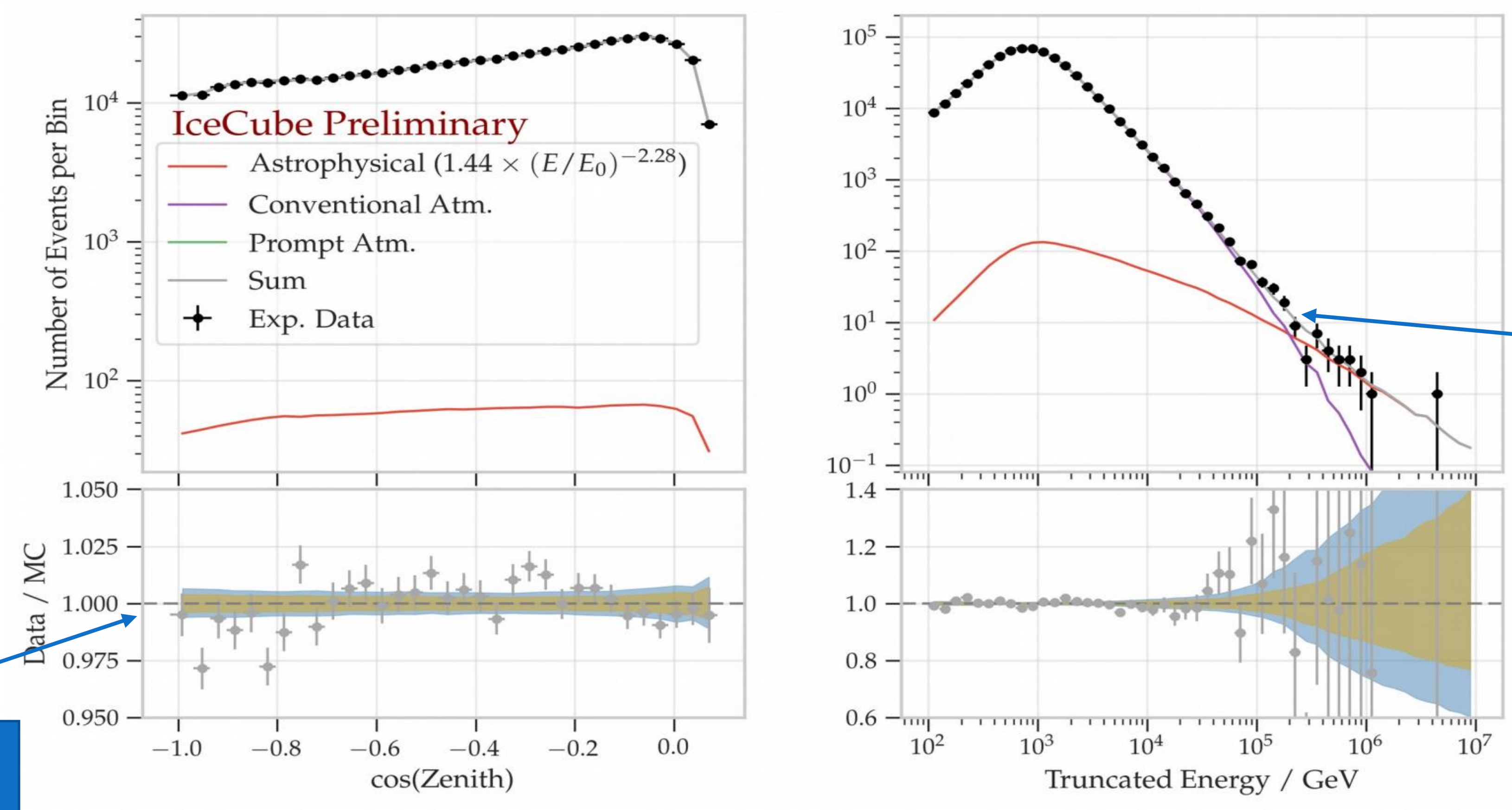
IceCube, Cascades, 4 years



H. Niederhausen (IceCube Collaboration) PoS(ICRC2017)968

IceCube tracks state-of-the-art, latest data

Energy and Zenith Distributions



Best-fit distributions and experimental data (2010-2018)

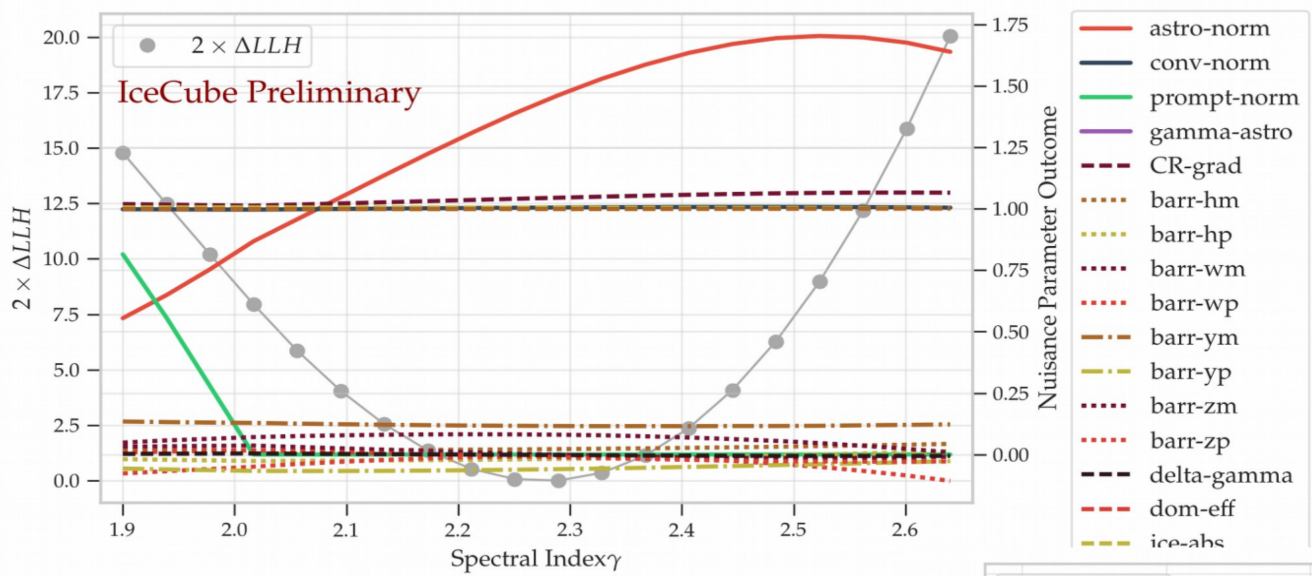
Charm lives here

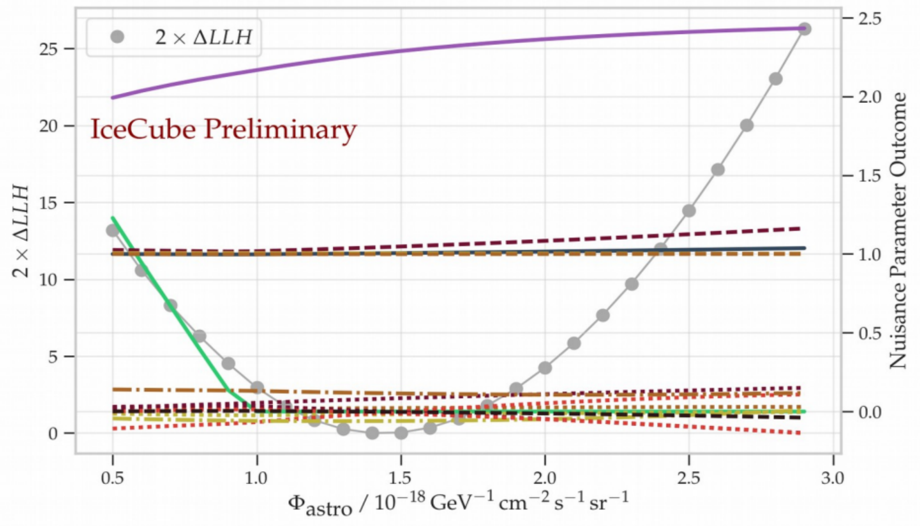
And there, but data currently lower?

Excess of a high-energy component clearly visible
More complex models for the astrophysical component are currently being tested

Prompt flux anti-correlated with astrophysical flux

Astrophysical Parameters and Systematics





One-dimensional profile likelihood scans

→ The two astrophysical parameters are correlated (as expected)

→ Very little correlation with other parameters

→ Only for much harder or smaller astroph. fluxes, a prompt flux is needed to fill the gaps (light green line)

Impact of prompt flux on astrophysical interpretation

- Best-fit astroph. Flux: (no prompt) $$\frac{d\phi_{\nu+\bar{\nu}}}{dE} = (1.44^{+0.25}_{-0.24}) \left(\frac{E}{100\,\mathrm{TeV}}\right)^{-2.28^{+0.08}_{-0.09}} \cdot 10^{-18}\,\mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

- What if a prompt flux is present ?
  Repeated the fit with prompt normalization fixed to 1 x baseline prediction
  → Astro. normalization decreases
  → Spectral index hardens slighlty

- Best-fit astroph. parameters, if prompt=1.0:

ϕ_0 = 1.17 / std. units
γ_{astro} = 2.24

→ Astrophysical flux remains necessary to explain the experimental data

Challenge to advance beyond a single power-law fit

- Two power-law **fit not statistically significant**

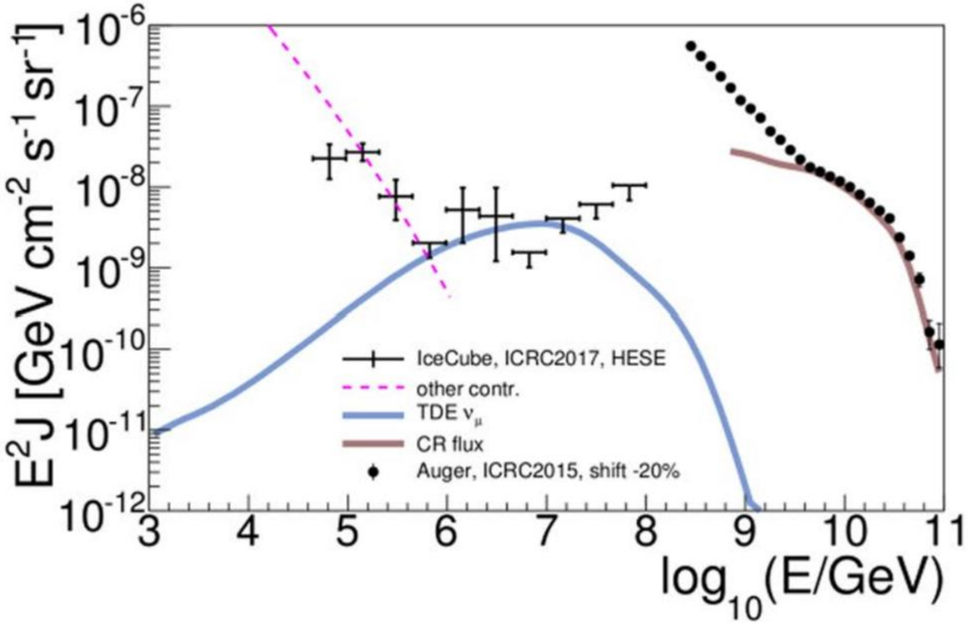
$$\frac{d\Phi_{6\nu}}{dE} = \left[\Phi_{\mathtt{astro1}}\left(\frac{E_\nu}{100\mathrm{TeV}}\right)^{-\gamma_{\mathtt{astro1}}} + \Phi_{\mathtt{astro2}}\left(\frac{E_\nu}{100\mathrm{TeV}}\right)^{-\gamma_{\mathtt{astro2}}}\right] \cdot 10^{-18}\ [\mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}].$$

- Large uncertainty/choice in assumed shape of astrophysical flux

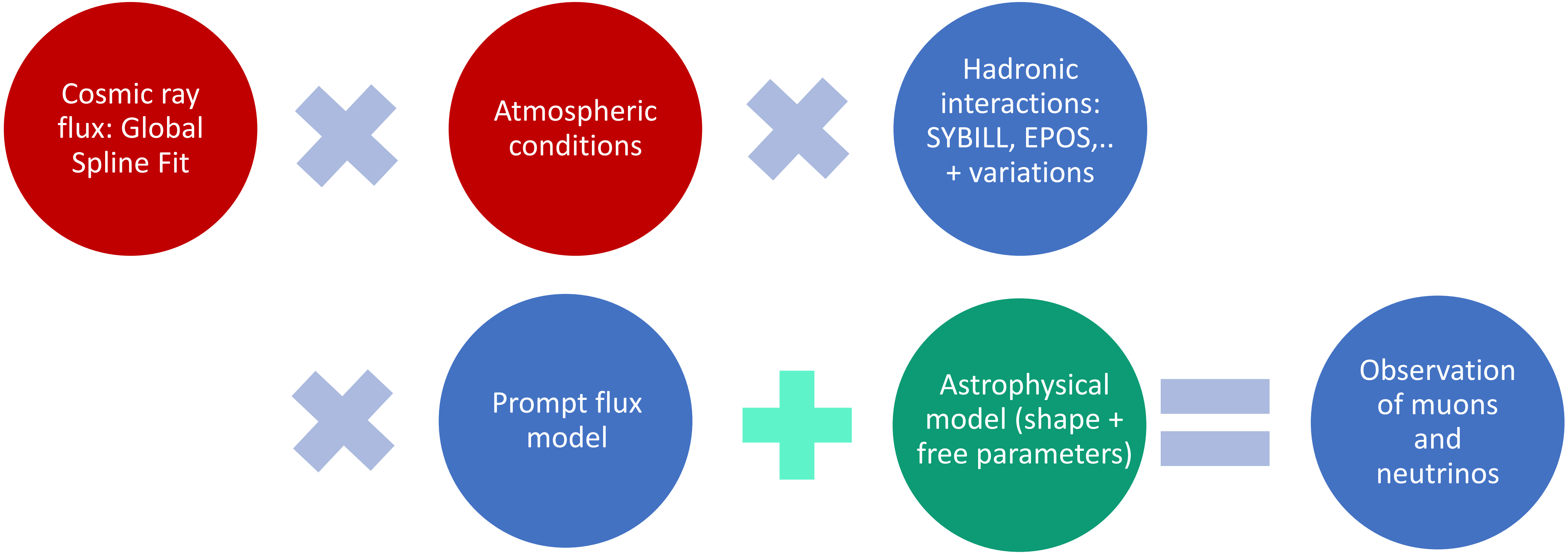
Model	Model only Bayes factor	Model + SPL Bayes factor	Most-likely SPL $\gamma_{\mathtt{astro}}$	Most-likely SPL $\Phi_{\mathtt{astro}}$
Stecker [26]	4.32×10^{-13}	1.45×10^{-10}	$3.97^{+0.54}_{-0.47}$	$4.08^{+1.8}_{-1.13}$
Fang et al. [27]	0.281	0.248	$3.83^{+0.81}_{-0.5}$	$2.56^{+1.28}_{-1.44}$
Kimura et al. (B1) [28]	4.84×10^{-6}	8.38×10^{-7}	$4.5^{+0.5}_{-0.67}$	$0.98^{+1.04}_{-0.98}$
Kimura et al. (B4) [28]	3.44×10^{-4}	0.666	$2.43^{+0.31}_{-0.26}$	$1.39^{+1.18}_{-0.77}$
Kimura et al. (two component) [28]	1.73×10^{-4}	6.12×10^{-6}	$4.15^{+0.84}_{-0.73}$	$0.0^{+0.69}_{-0}$
Padovani et al. [29]	6.20×10^{-11}	3.32×10^{-7}	$3.59^{+0.59}_{-0.34}$	$4.97^{+1.68}_{-1.46}$
Senno et al. [30]	0.256	3.52	$3.67^{+0.57}_{-0.62}$	$3.36^{+1.56}_{-1.34}$
Bartos et al. [31]	1.15×10^{-14}	2.81×10^{-16}	$4.25^{+0.75}_{-0.83}$	$0.0^{+0.49}_{-0}$
Tavecchio et al. [32]	0.0730	1.04	$3.88^{+0.65}_{-0.49}$	$3.7^{+1.39}_{-1.48}$
Biehl et al. [33]	8.66×10^{-7}	0.362	$3.35^{+0.4}_{-0.38}$	$5.09^{+2.07}_{-1.03}$

Austin Schneider (IceCube Collaboration), arXiv:1907.11266

Example for astroph. model:
Biehl et al., Nat. Sci. Rep. 2018



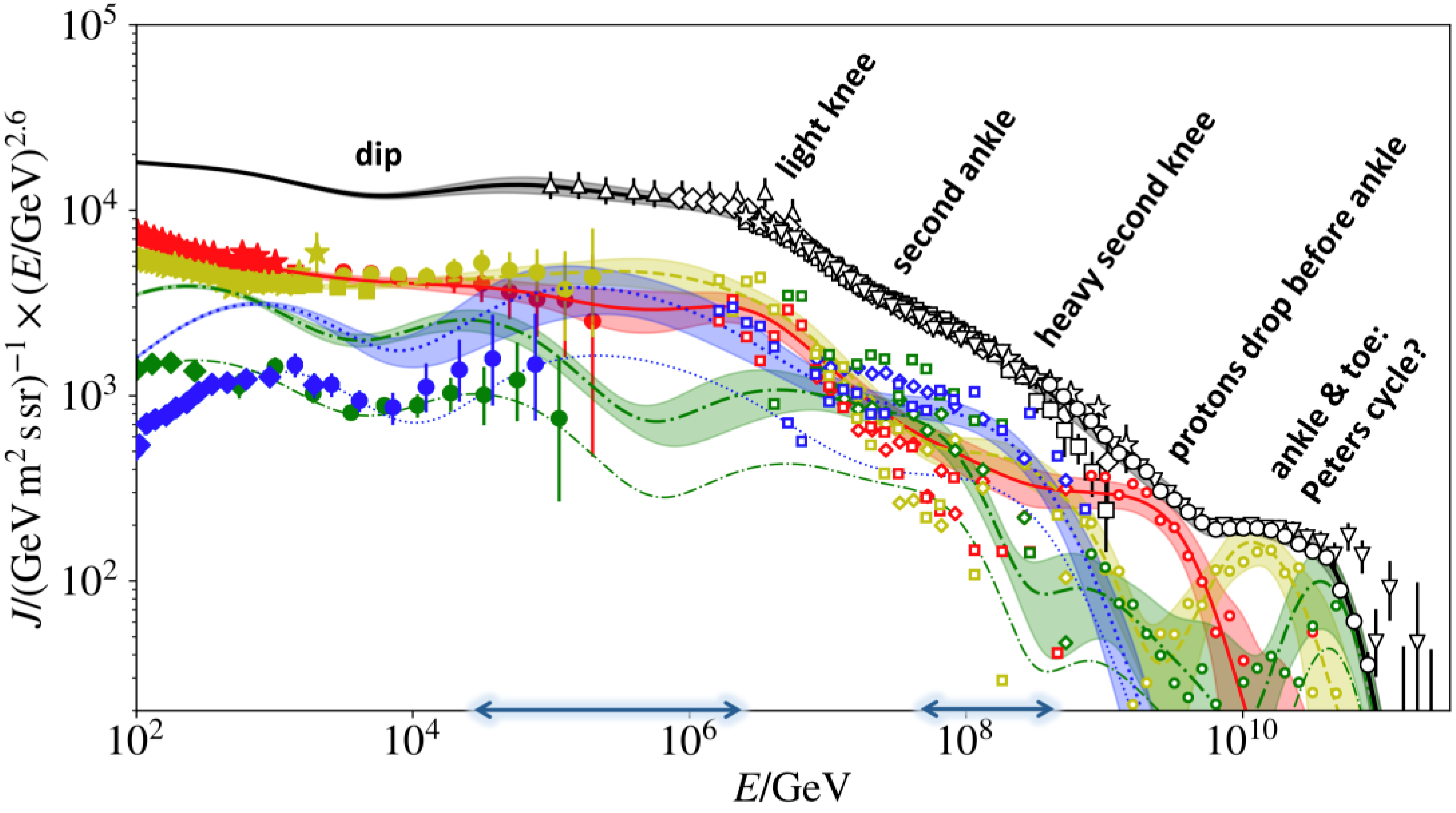
Correct parameterization of uncertainties is a chance to measure prompt fluxes and constrain charm



Circle means central prediction + error band.
Much better: free parameters + covariance matrix.

The Global Spline Fit

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

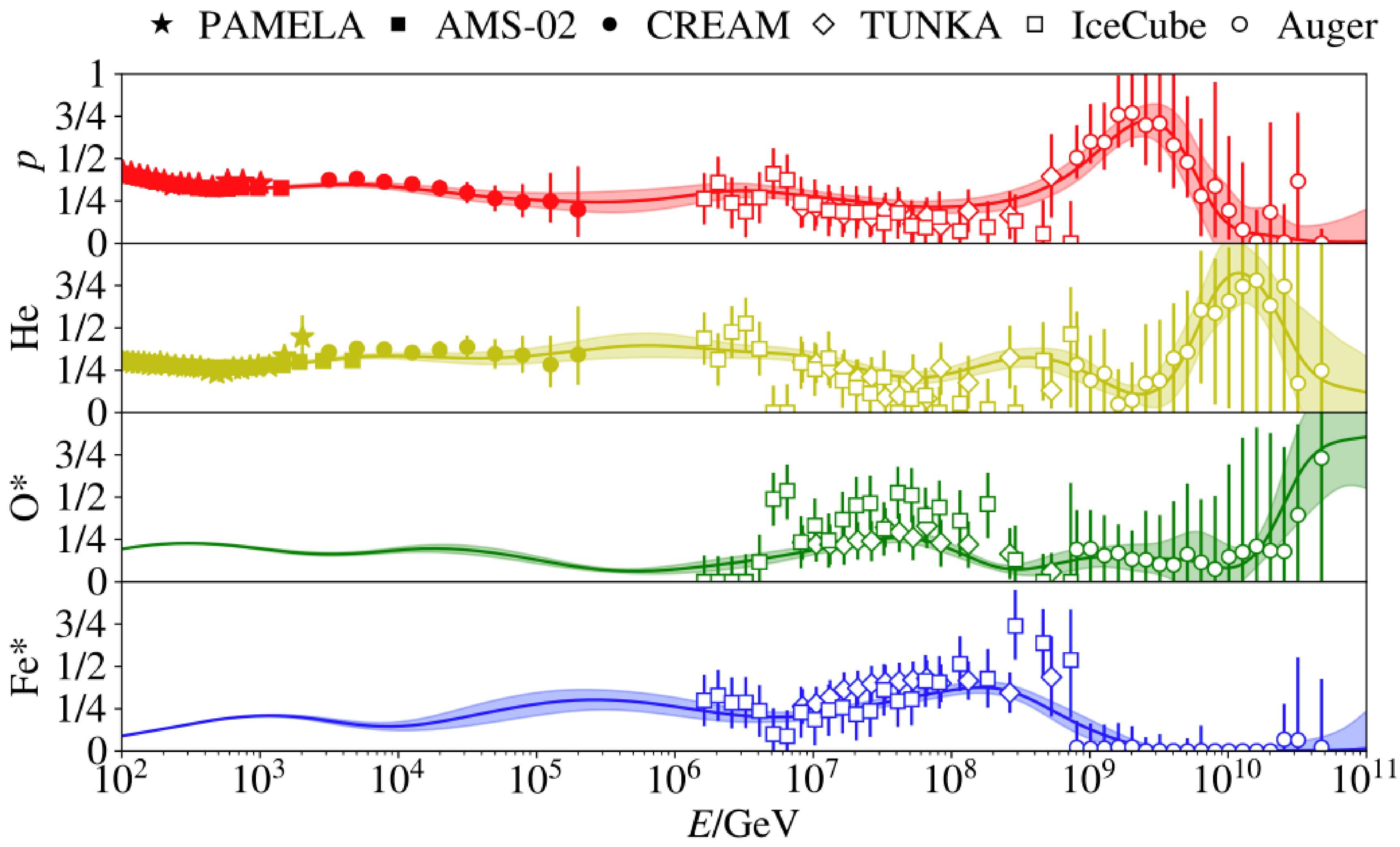


More composition data needed

Fitted composition data

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

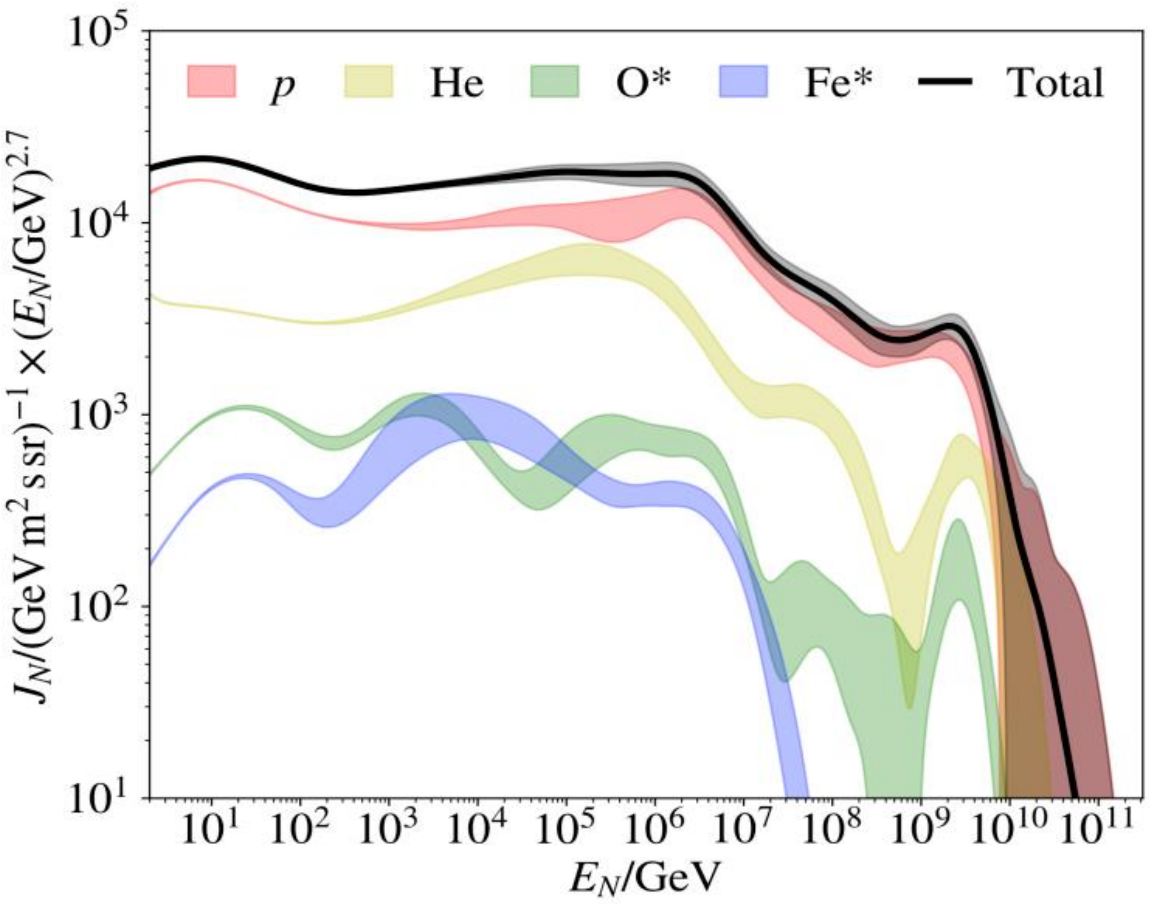
4-mass group experiments



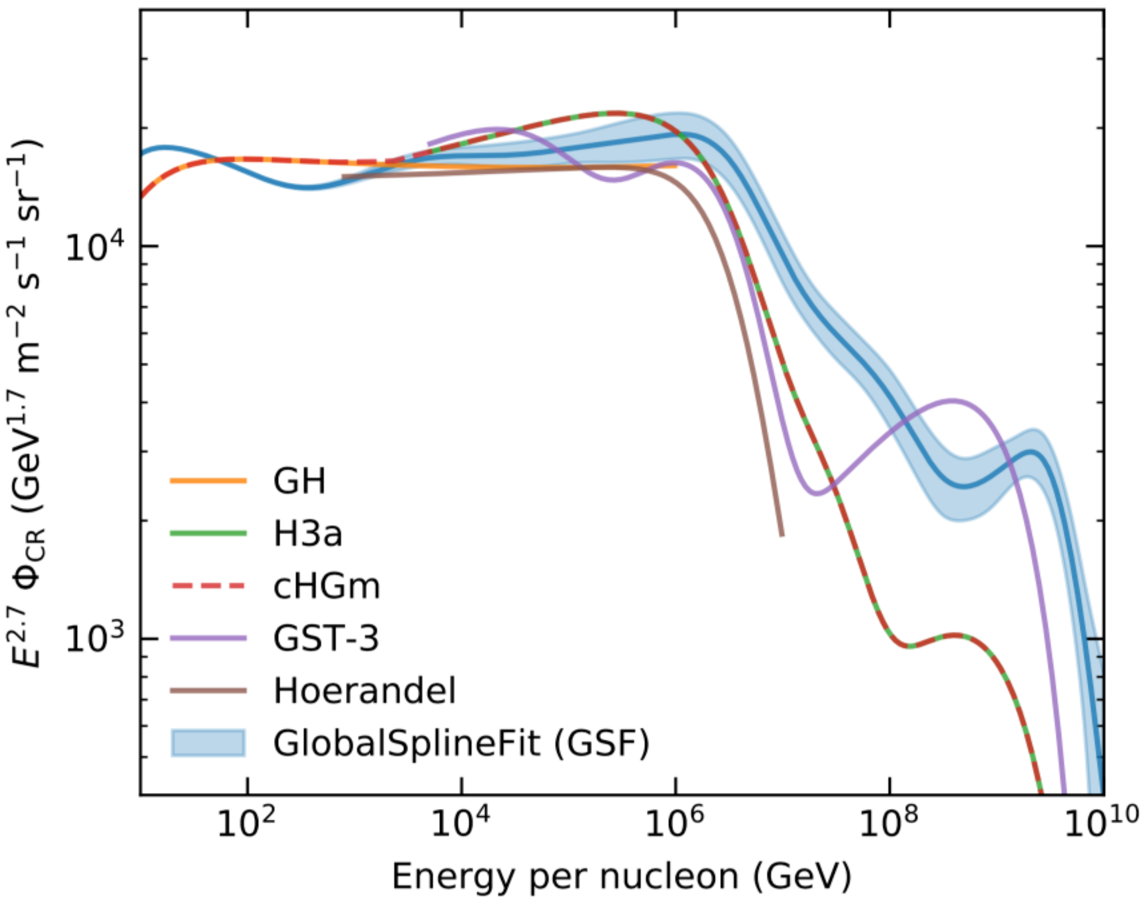
Derived result: nucleon flux

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.

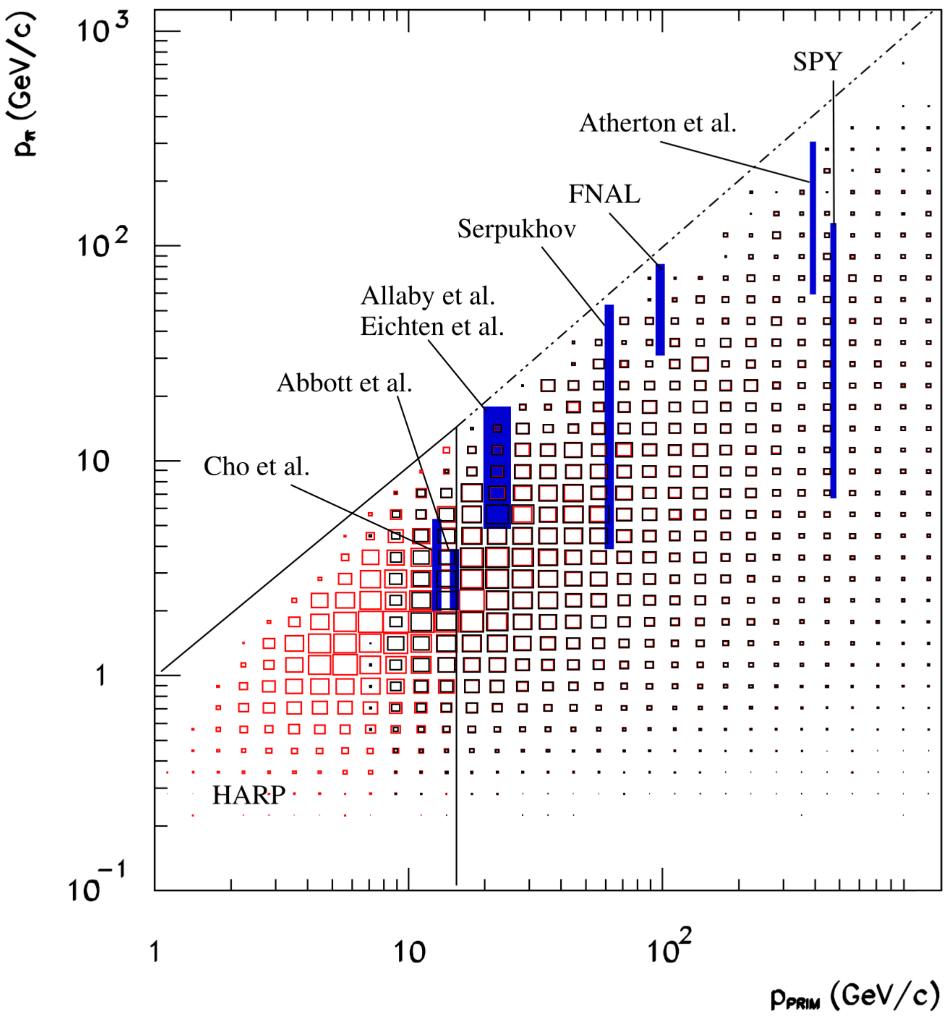


Harder spectrum at the knee due to lighter composition as assumed by 3-population models

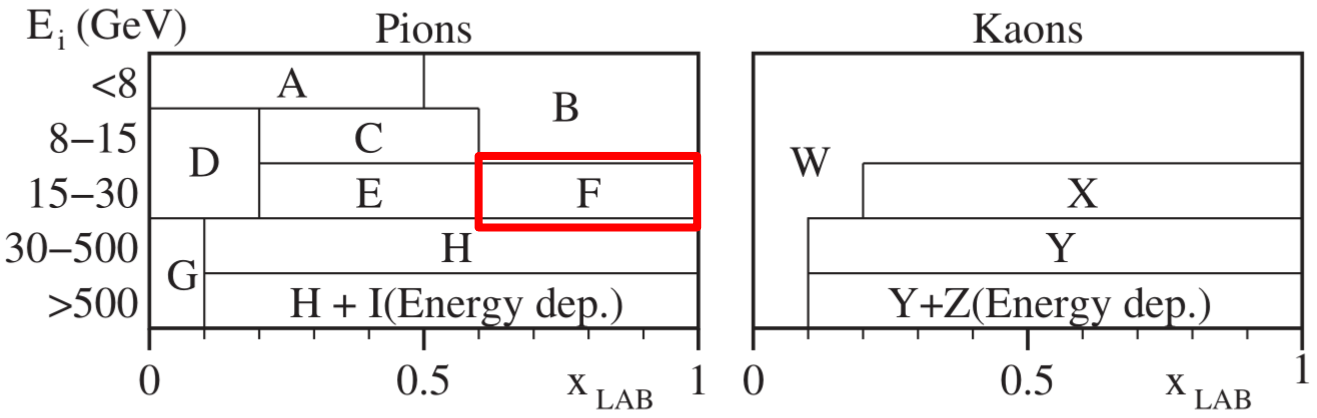
Hadronic uncertainties in new IceCube analyses

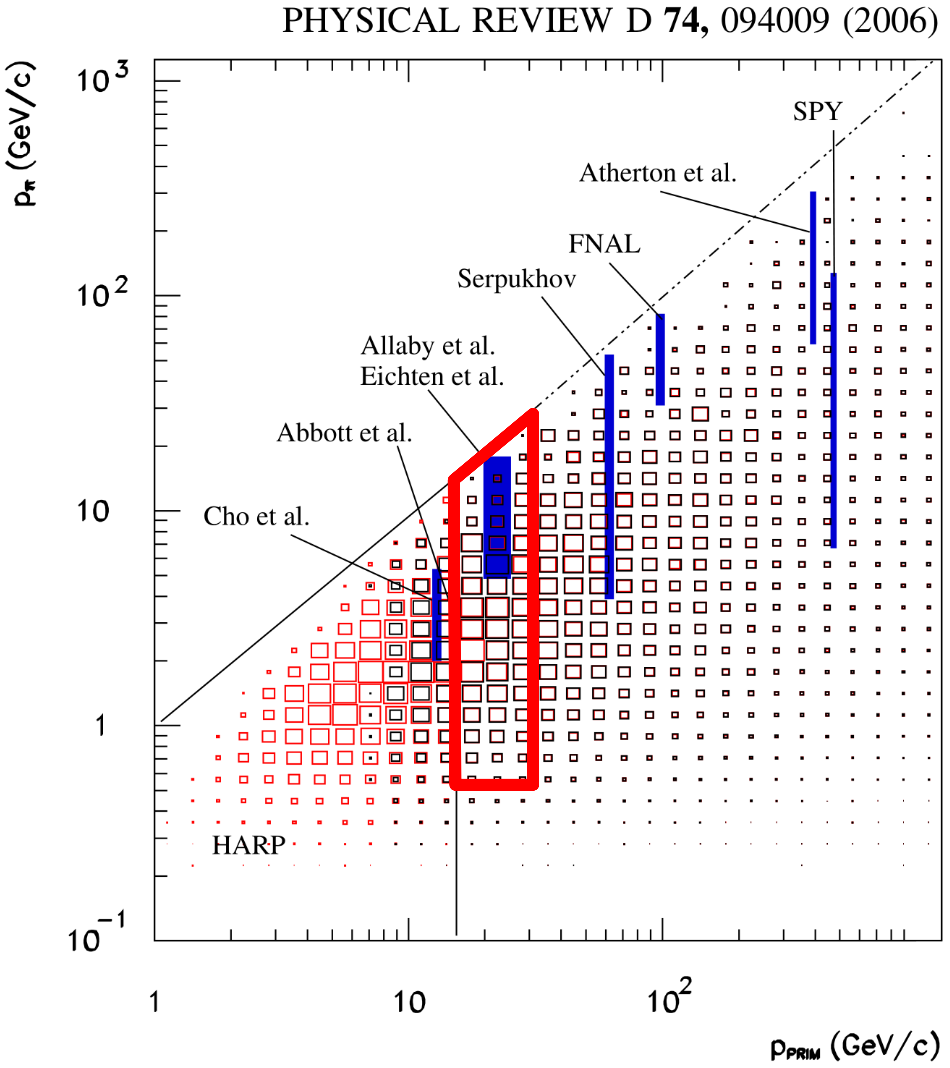
- "*Uncertainties in atmospheric neutrino fluxes*", G. D. Barr, S. Robbins, T. K. Gaisser, and T. Stanev, Phys. Rev. D 74, 094009 (2006) (extensive discussion also in Sanuki et al. PRD 75 (2007)
- Cut phase-space in regions/slices in E_{lab} and x_{lab} and **assign** uncertainty to each slice (uncorrelated)
- Uncertainty assigned by hand and not derived from data. Assignment based on availability of data, not how well the model [TARGET2.1] describes it
- Many "free" parameters with unclear correlations

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

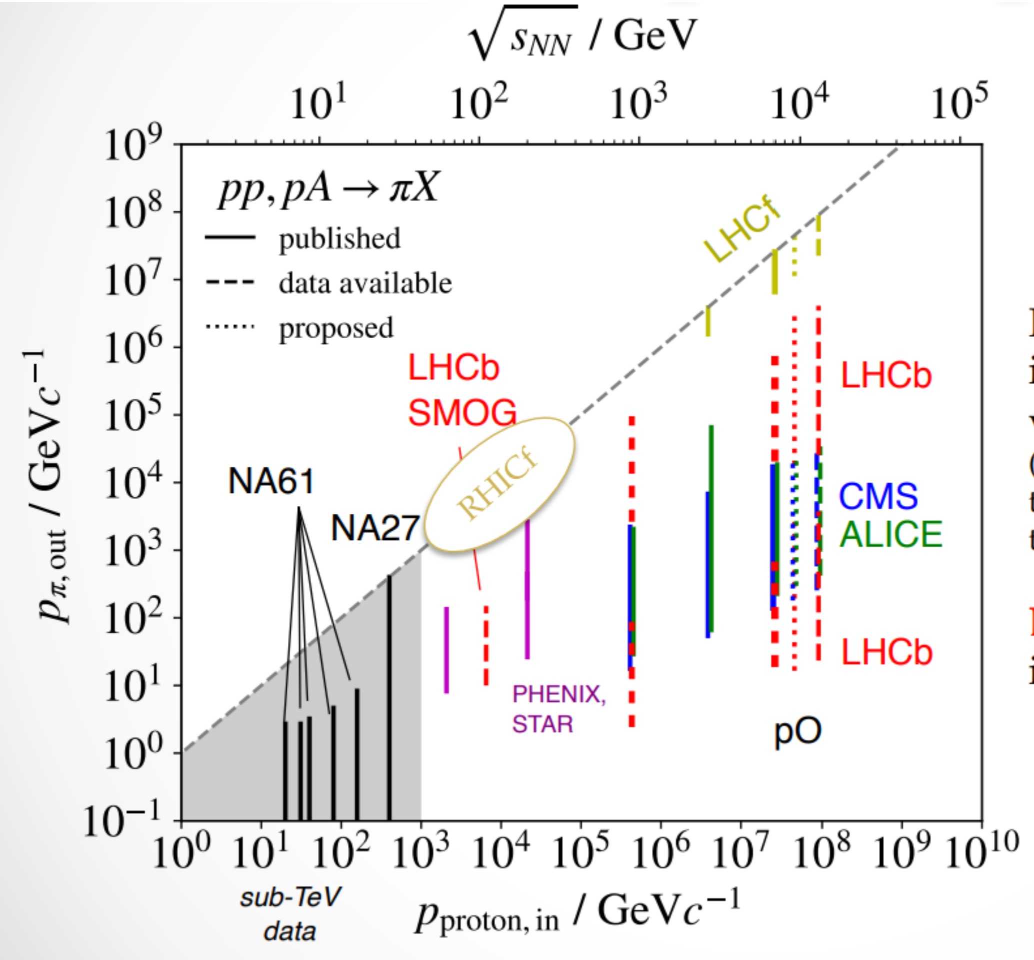


Phase space regions





2019 coverage of phase-space

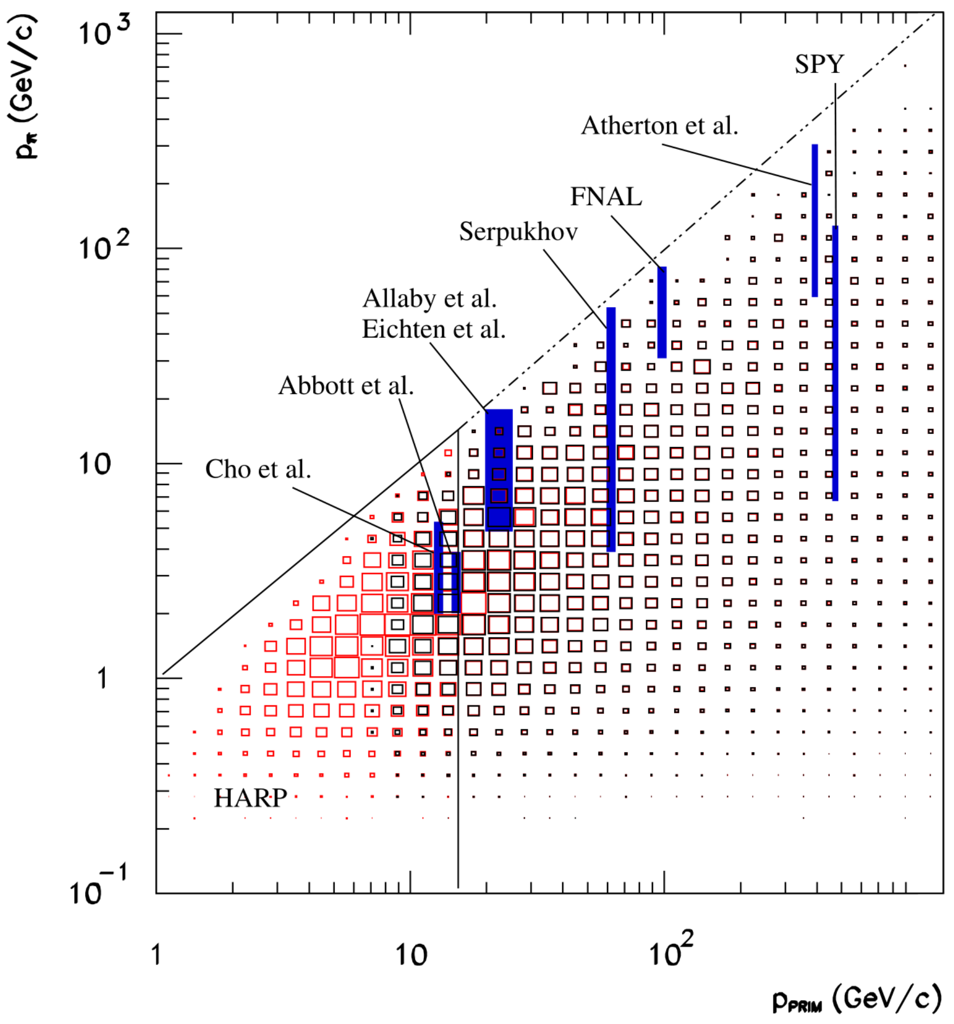


H. Dembinski,
ISVHECRI 2018

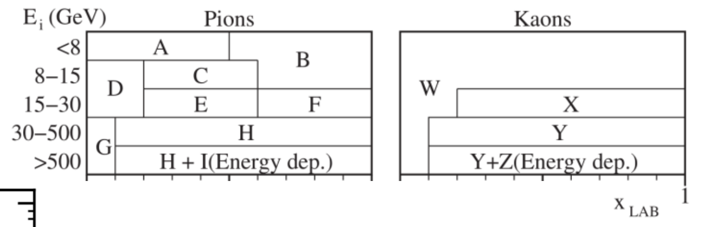
Phase space of air shower interactions as covered by various experiments
(beam-beam collisions transformed to equivalent fixed-target system)

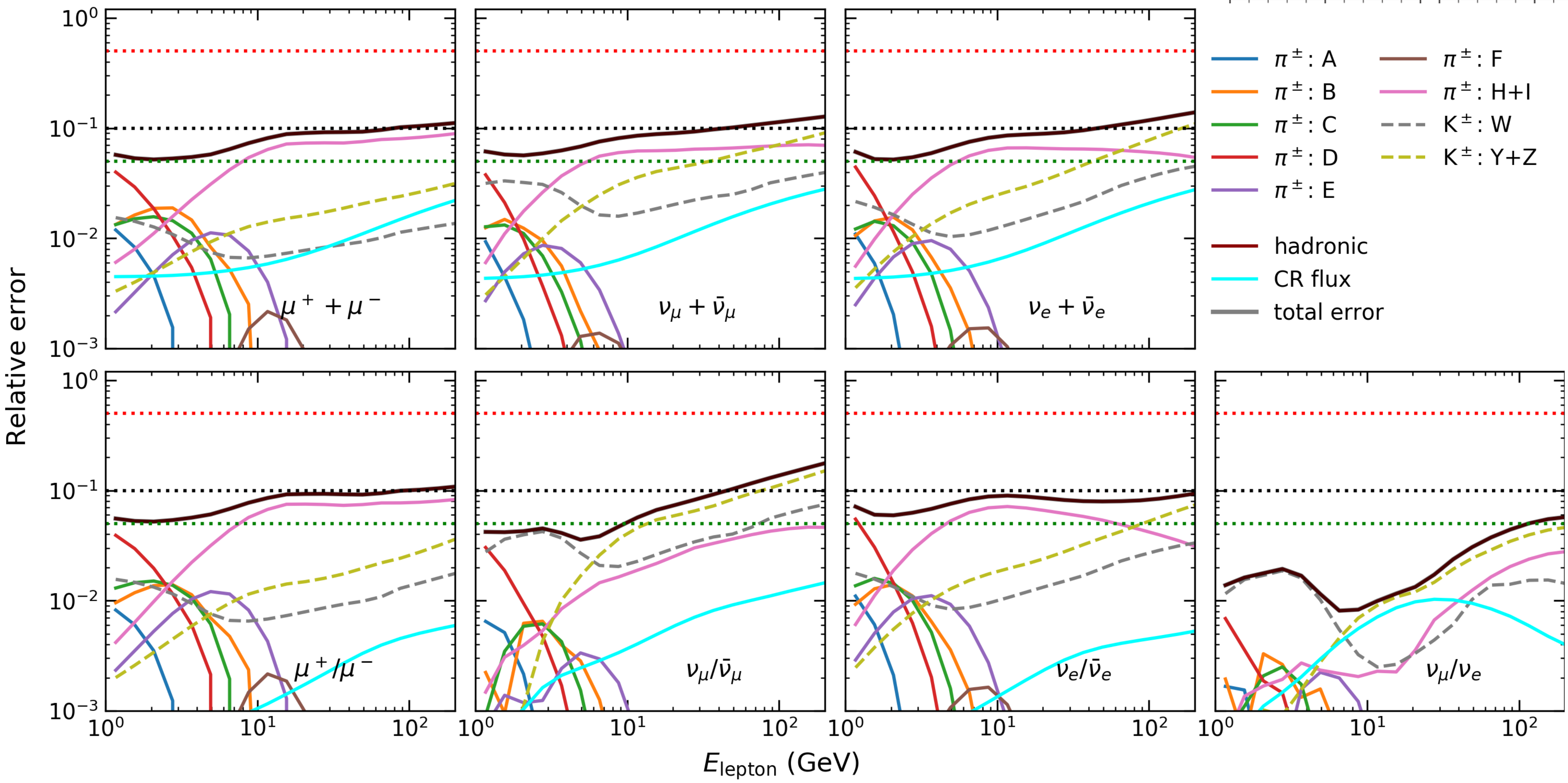
LHCb could significantly increases coverage

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

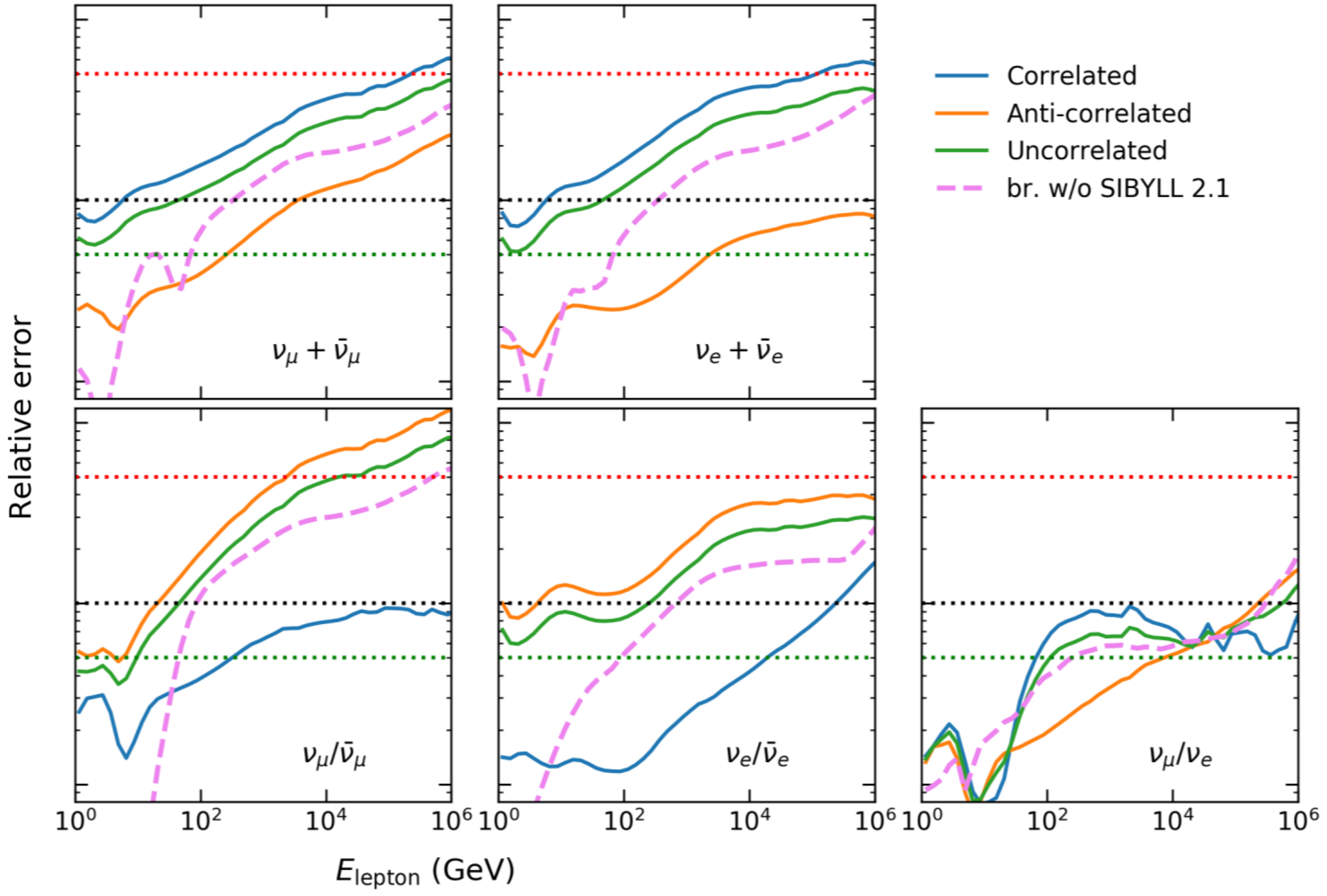


Contribution of individual “Barr groups”





Correlations between phase-space patches unclear

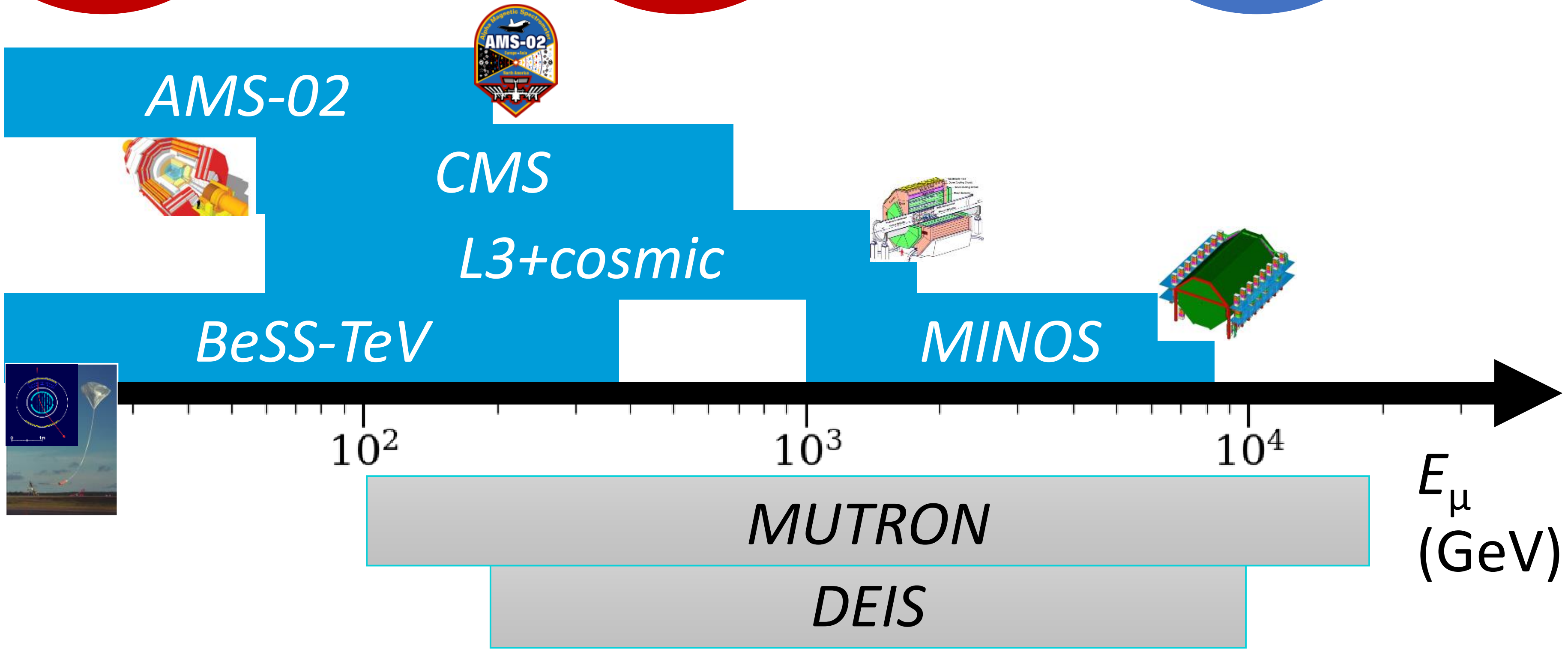


Examples	For one "Barr" - parameters
symmetric	$p\pi^+\uparrow$ $n\pi^+\uparrow$ $p\pi^-\uparrow$ $n\pi^-\uparrow$
asymmetric	$p\pi^+\uparrow$ $n\pi^+\uparrow$ $p\pi^-\downarrow$ $n\pi^-\downarrow$
uncorrelated	$p\pi^+\uparrow$ $n\pi^+0$ $p\pi^-0$ $n\pi^-0$

- The production of charged secondaries is physically not independent
- It is very difficult to extract this information from hadronic interaction models directly

Calibration of 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



Juan Pablo Yanez and AF, Neutrino 2018 + ICRC 2019

Calibration of 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

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, Neutrino 2018 + ICRC 2019

How we did it

- 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

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

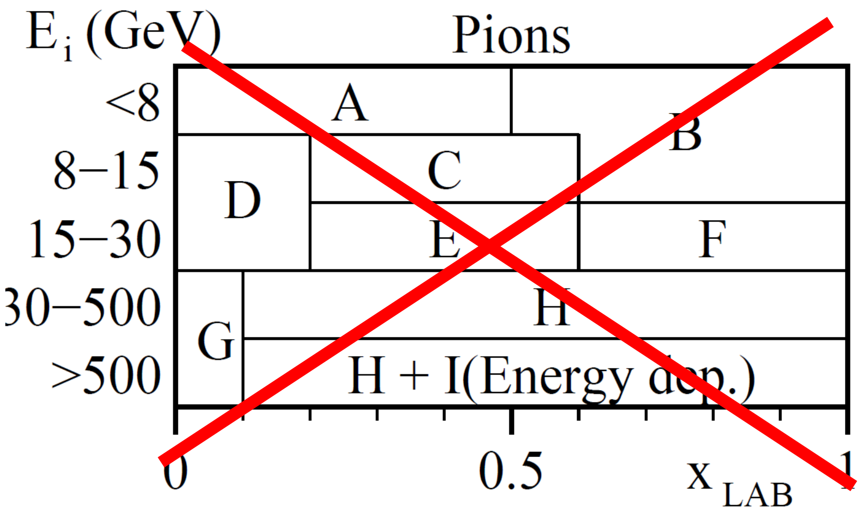
- Fluxes with modifications to B_i can be quickly evaluated in the fit:

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

Juan Pablo Yanez and AF, Neutrino 2018 + ICRC 2019

What we found

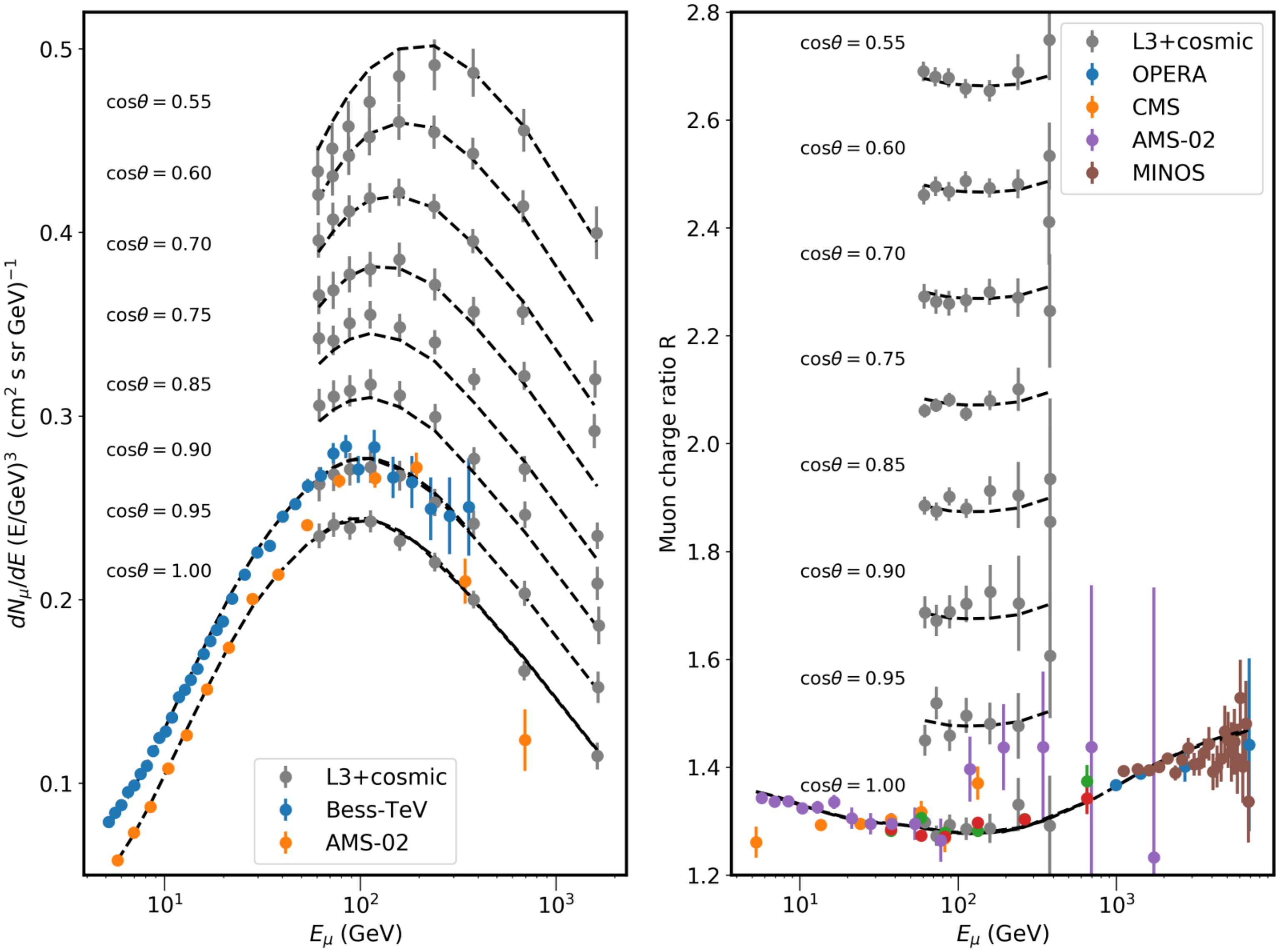
- Original attempt was to use the parameterization of Barr et al.
    1. Found data to be insensitive
    2. Too many correlations
    3. Impossible to constrain



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

Fit results

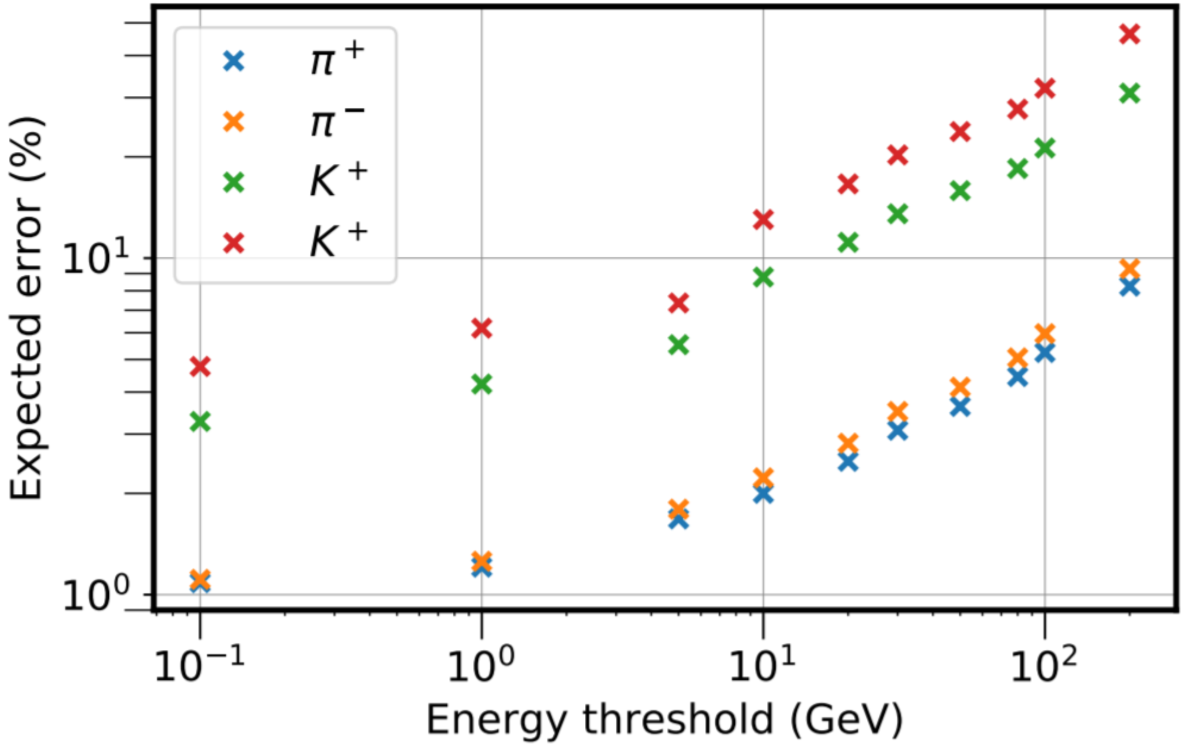
- Some experiments are hard to fit regardless of modifications
- Possible systematic effects not reported
- L3+C – previously “the reference dataset”– is not as good as we thought
- We will include more data and CR flux uncertainties in the next iteration and report later this year
- **This approach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



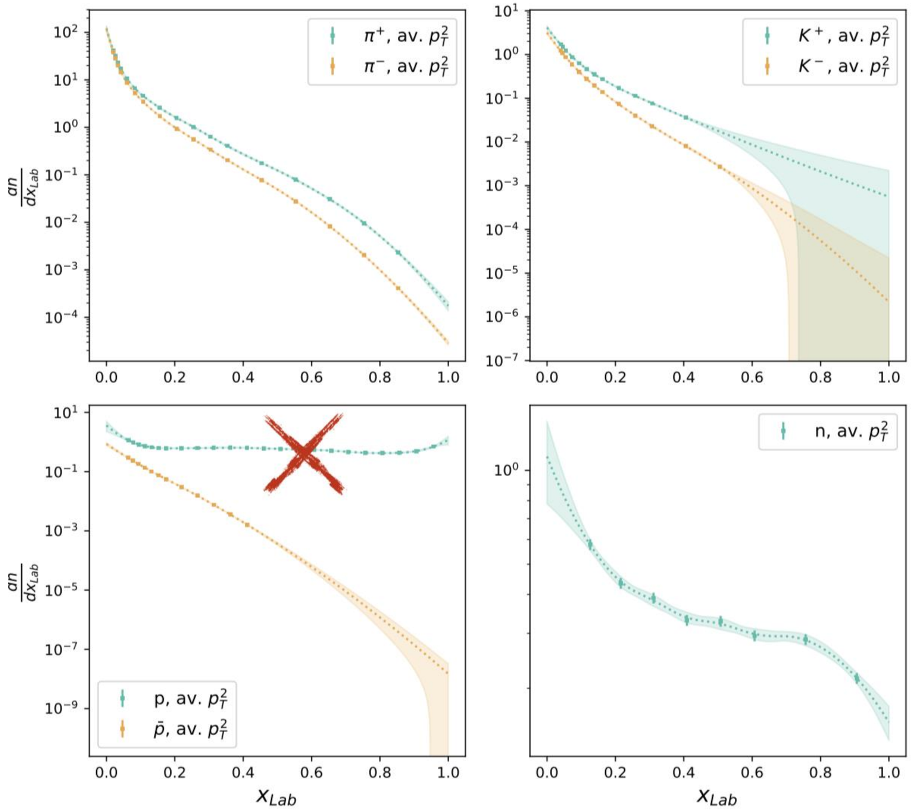
Juan Pablo Yanez and AF, Neutrino 2018 + ICRC 2019

Alternative under investigation: data-driven inclusive interaction model

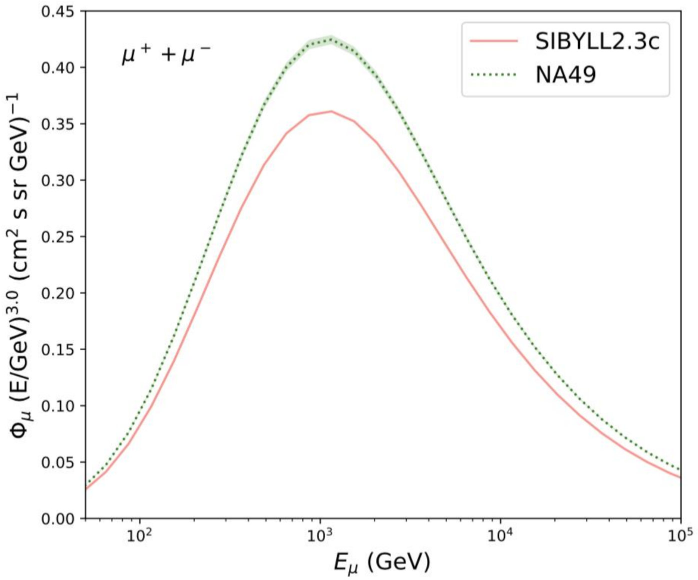
"The SHIn-project"

NA49 pp data (158GeV)

Experiment	Interaction	E_p [GeV]	yields
NA49	pp	158	$\pi^{\pm}, K^{\pm}, \overset{(-)}{\mathrm{p}}, n$
NA49	pC	158	$\pi^{\pm}, \overset{(-)}{\mathrm{p}}, n$
NA61/SHINE	pC	31	$\pi^{\pm}, K^{\pm}, K^0_S, \Lambda$
NA61/SHINE	pp	20, 31, 40, 80, 158	$\pi^{\pm}, K^{\pm}, \overset{(-)}{\mathrm{p}}$
NA61/SHINE	$\pi^- C$	158, 350	ρ^0, ω, K^{*0}
NA61/SHINE (upcoming)	$\pi^- C$	158, 350	$\pi^{\pm}, K^{\pm}, \overset{(-)}{\mathrm{p}}$



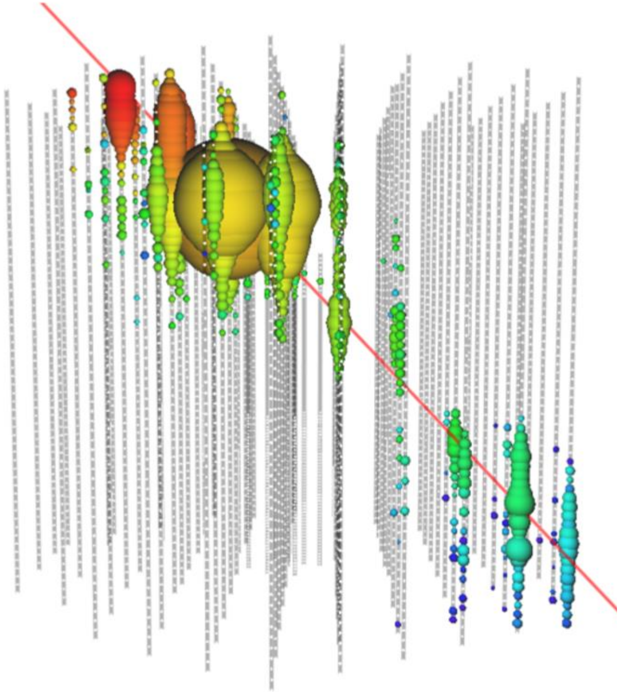
p+p → part+X



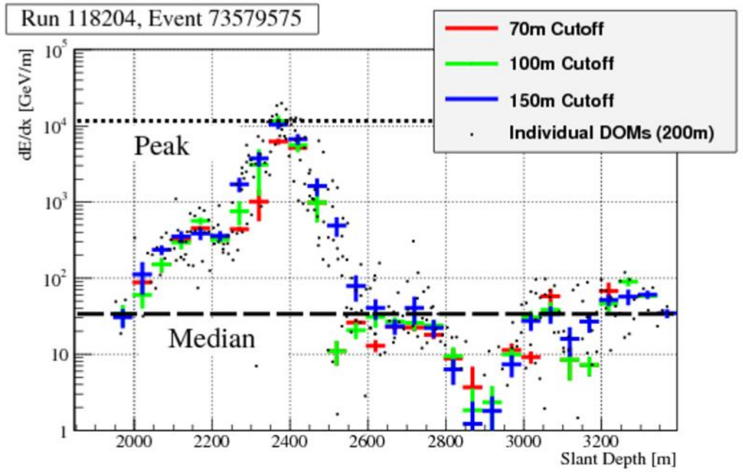
Matthias Huber

High-energy muons in IceCube

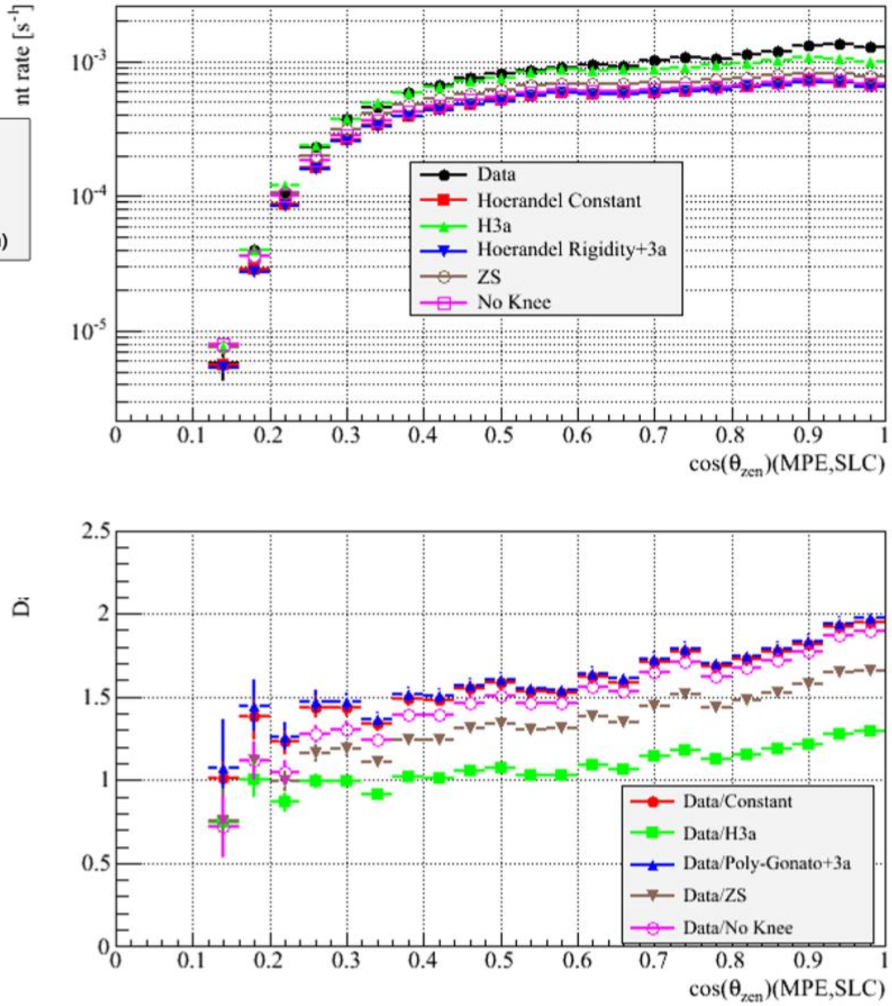
See talk by D. Soldin at UHECR 2018



Energy loss pattern



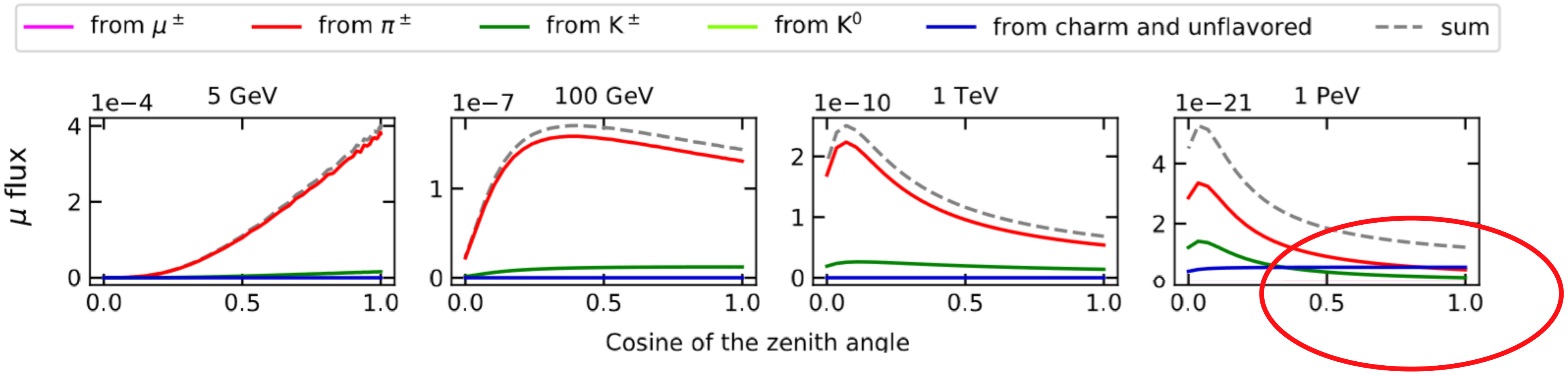
Angular distribution has tilt



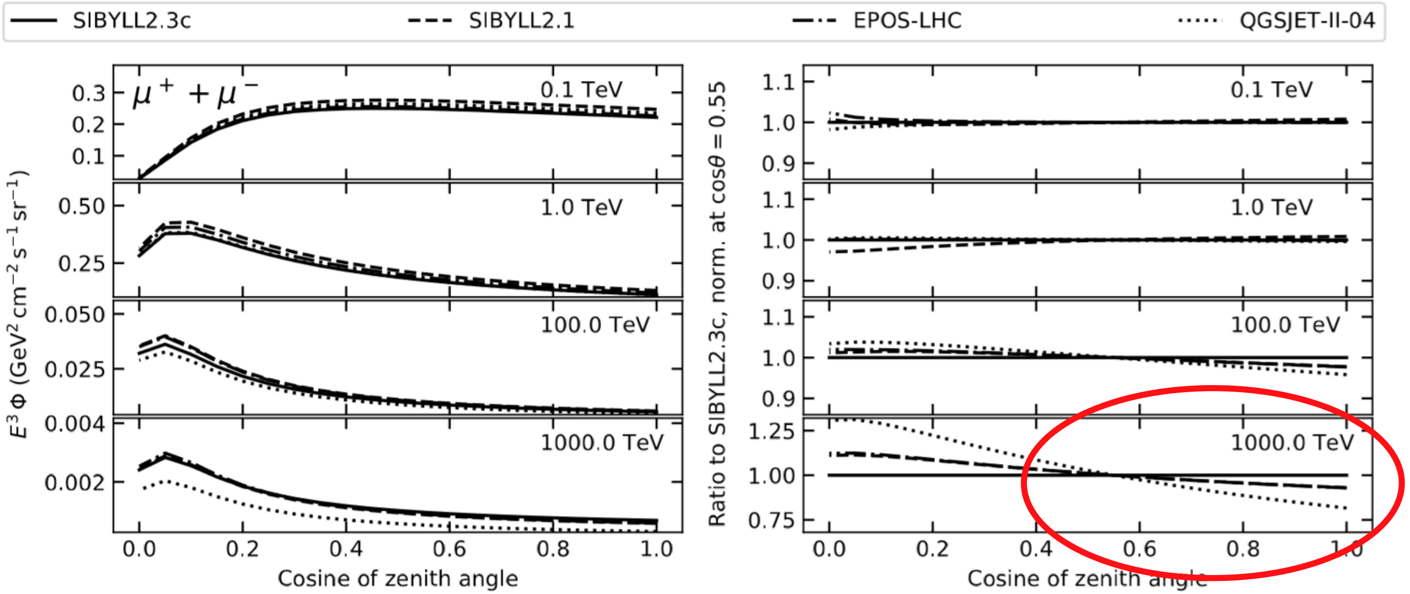
- Energy loss pattern sensitive to muon multiplicity and energy
- Angular distribution of muon bundles always tilted compared to MC
- Neither hadronic interactions nor cosmic ray models can explain this
- Maybe unknown detector systematics

IceCube, Astropart. Phys. 78 (2016)

Possible origin from prompt muons (not necessarily charm)



- First **indication** that zenith shift is a signature of **prompt muons**
- But! **Other processes** contribute
  - Muon pair production $\gamma \rightarrow \mu^+\mu^-$
  - Quasi-elastic vector meson production $\gamma + A \rightarrow (\rho, \omega, \phi) + A' \rightarrow$ **hadrons + X**
- The "electromagnetic" processes might be under better control and thus would allow for constraining the contribution of charm (50%)
- **Tilt in the zenith distribution is simple to measure**



Conclusions and future path

- Current atmospheric neutrino detectors cover **9 orders of magnitude** in energy (MeV-PeV) → **challenge** for modeling!
- **High-precision** (and high-performance) scheme to take **uncertainties self-consistently** into account **is available** through MCEq (https://github.com/afedynitch/MCEq), but good/realistic parameterizations are under investigation
- **Data-driven techniques** can constrain some of the expected/known uncertainties, but is this a consistent scheme? What do we learn?
- Measurement of the prompt flux unlikely to happen in a model-independent way for the present generation of detectors
- Help creating a better likelihood for the (global) fit
- Build KM3Net

Transport equations (hadronic cascade equations)

System of coupled non-linear PDE for each particle species *h :*

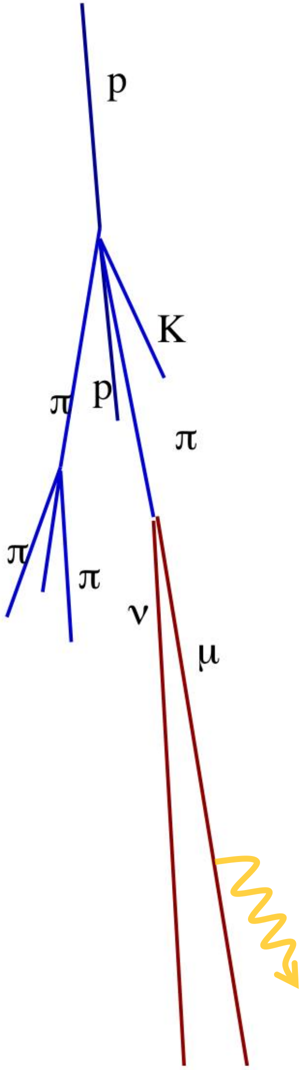
$$\frac{\mathrm{d}\Phi_h(E,X)}{\mathrm{d}X} = -\frac{\Phi_h(E,X)}{\lambda_{\mathrm{int},h}(E)}$$ Interactions with air

$$-\frac{\Phi_h(E,X)}{\lambda_{\mathrm{dec},h}(E,X)}$$ Decays

$$-\frac{\partial}{\partial E}(\mu(E)\Phi_h(E,X))$$ Continuous losses

$$+\sum_k \int_E^{\infty} \mathrm{d}E_k \frac{\mathrm{d}N_{k(E_k)\to h(E)}}{\mathrm{d}E} \frac{\Phi_k(E_k,X)}{\lambda_{\mathrm{int},k}(E_k)}$$ Re-injection from interactions

$$+\sum_k \int_E^{\infty} \mathrm{d}E_k \frac{\mathrm{d}N^{\mathrm{dec}}_{k(E_k)\to h(E)}}{\mathrm{d}E} \frac{\Phi_k(E_k,X)}{\lambda_{\mathrm{dec},k}(E_k,X)}$$ Re-injection from decays



$$X(h_0) = \int_0^{h_0} \mathrm{d}\ell \; \rho_{\mathrm{air}}(\ell)$$

Transport equations (hadronic cascade equations)

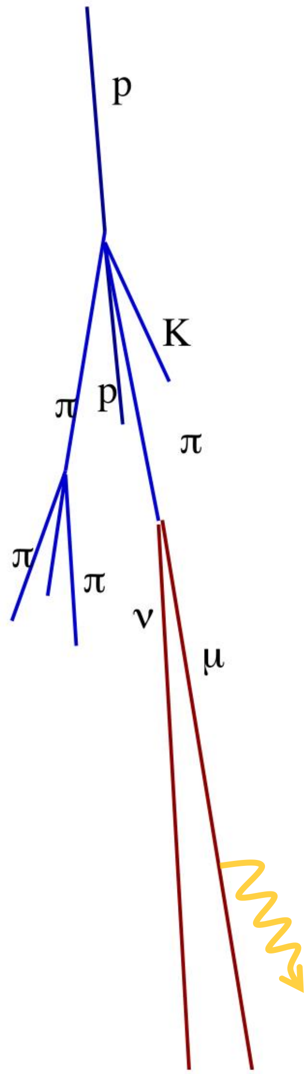
System of coupled non-linear PDE for each particle species *h* :

$$
\begin{aligned}
\frac{\mathrm{d}\Phi_h(E,X)}{\mathrm{d}X} = & -\frac{\Phi_h(E,X)}{\lambda_{\mathrm{int},h}(E)} && \text{Interactions with air} \\
& -\frac{\Phi_h(E,X)}{\lambda_{\mathrm{dec},h}(E,X)} && \text{Decays} \\
& -\frac{\partial}{\partial E}(\mu(E)\Phi_h(E,X)) && \text{Continuous losses} \\
& +\sum_k \int_E^\infty \mathrm{d}E_k \frac{\mathrm{d}N_{k(E_k)\to h(E)}}{\mathrm{d}E}\frac{\Phi_k(E_k,X)}{\lambda_{\mathrm{int},k}(E_k)} && \text{Re-injection from interactions} \\
& +\sum_k \int_E^\infty \mathrm{d}E_k \frac{\mathrm{d}N^{\mathrm{dec}}_{k(E_k)\to h(E)}}{\mathrm{d}E}\frac{\Phi_k(E_k,X)}{\lambda_{\mathrm{dec},k}(E_k,X)} && \text{Re-injection from decays}
\end{aligned}
$$

cosmic ray physics

atmospheric physics

particle physics



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cosmic ray physics

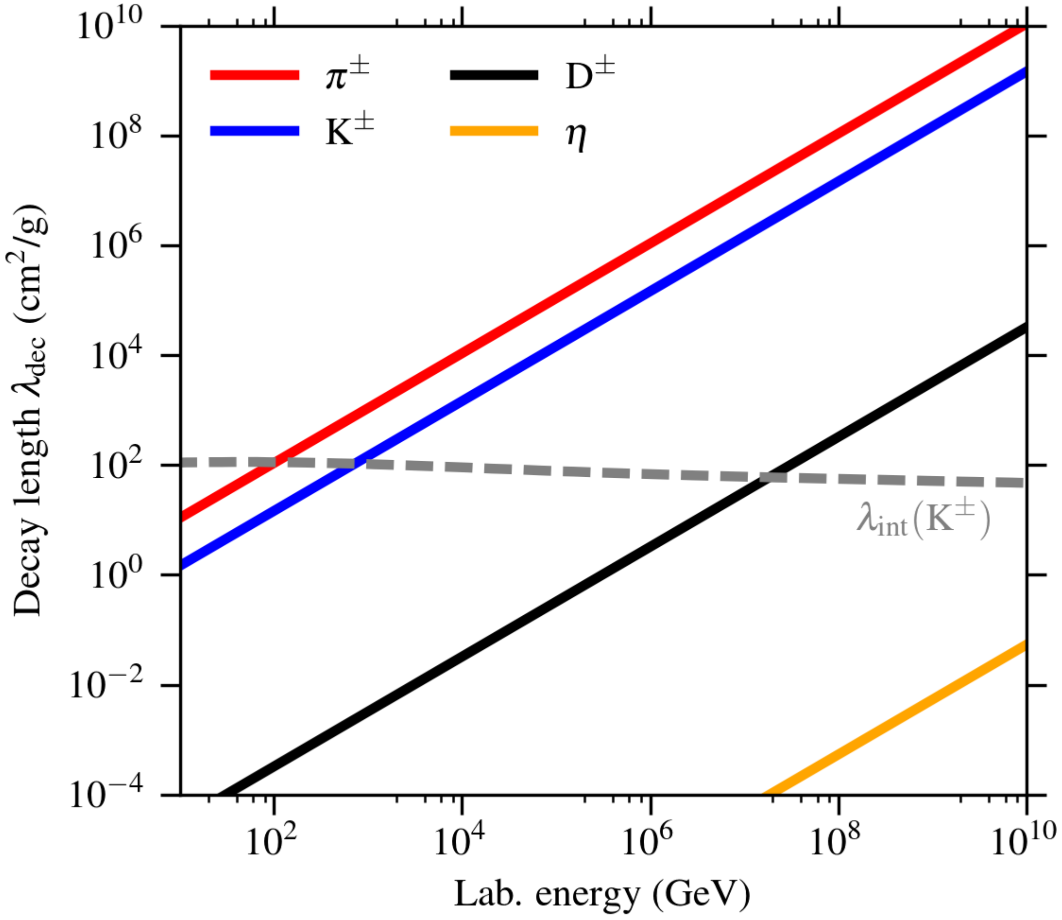
Interactions with air

Decays

atmospheric physics

Continuous losses

particle physics



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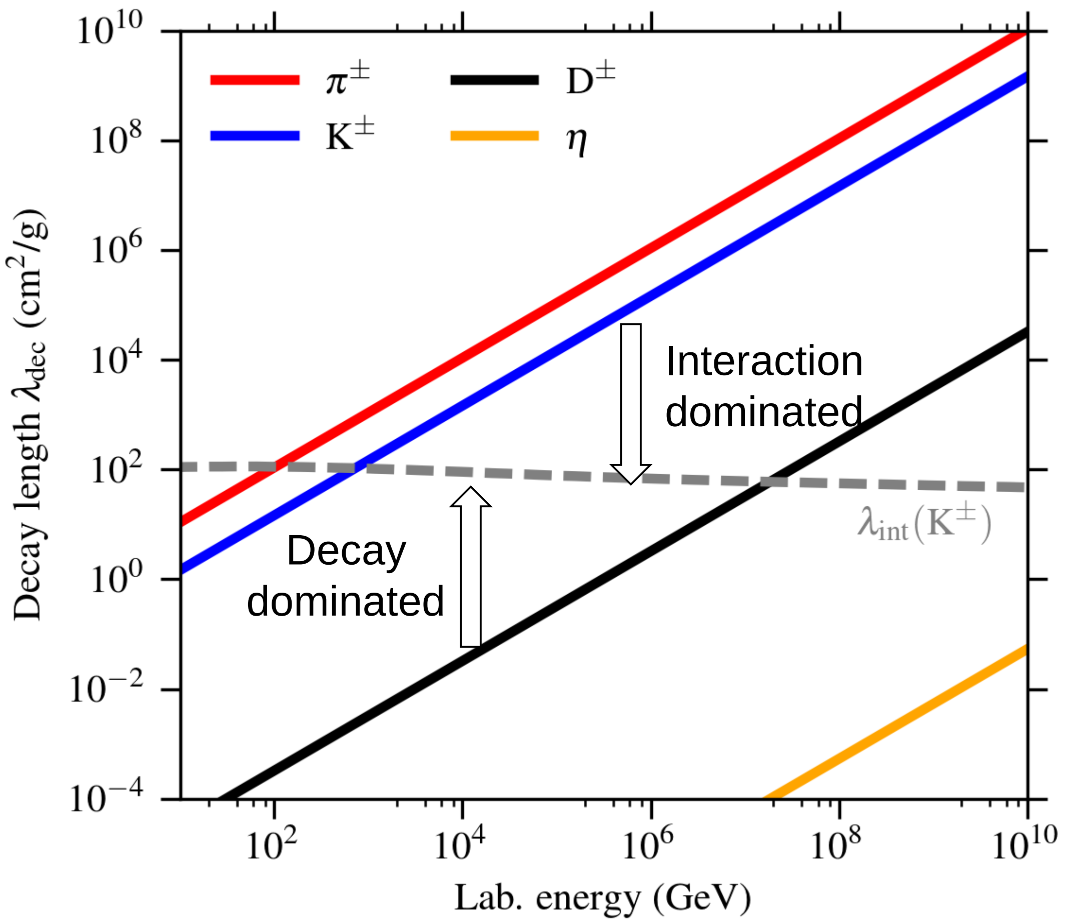


$$X(h_0) = \int_0^{h_0} \mathrm{d}\ell\ \rho_{\mathrm{air}}(\ell)$$

MCEq: Matrix Cascade Equations

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)

$$\frac{\mathrm{d}\Phi_h(E,X)}{\mathrm{d}X} = -\frac{\Phi_h(E,X)}{\lambda_{\mathrm{int},h}(E)} - \frac{\Phi_h(E,X)}{\lambda_{\mathrm{dec},h}(E,X)} - \frac{\partial}{\partial E}(\mu(E)\Phi_h(E,X)) + \sum_\ell \int_E^\infty \mathrm{d}E_\ell \frac{\mathrm{d}N_{\ell(E_\ell)\to h(E)}}{\mathrm{d}E}\frac{\Phi_\ell(E_\ell,X)}{\lambda_{\mathrm{int},l}(E_\ell)} + \sum_\ell \int_E^\infty \mathrm{d}E_\ell \frac{\mathrm{d}N^{\mathrm{dec}}_{\ell(E_\ell)\to h(E)}}{\mathrm{d}E}\frac{\Phi_\ell(E_\ell,X)}{\lambda_{\mathrm{dec},l}(E_\ell,X)}$$

$$\frac{\mathrm{d}\Phi^h_{E_i}}{\mathrm{d}X} = -\frac{\Phi^h_{E_i}}{\lambda^h_{\mathrm{int},E_i}} - \frac{\Phi^h_{E_i}}{\lambda^h_{\mathrm{dec},E_i}(X)} - \vec{\nabla}_i(\mu^h_{E_i}\Phi^h_{E_i}) + \sum_{E_k\geq E_i}^{E_N}\sum_\ell \frac{c_{\ell(E_k)\to h(E_i)}}{\lambda^\ell_{\mathrm{int},E_k}}\Phi^\ell_{E_k} + \sum_{E_k\geq E_i}^{E_N}\sum_\ell \frac{\mathrm{d}_{\ell(E_k)\to h(E_i)}}{\lambda^\ell_{\mathrm{dec},E_k}(X)}\Phi^\ell_{E_k}$$

State (or flux) vector

$$\vec{\Phi} = \left(\vec{\Phi}^{\mathrm{p}} \quad \vec{\Phi}^{\mathrm{n}} \quad \vec{\Phi}^{\pi^+} \quad \ldots \quad \vec{\Phi}^{\bar{\nu}_\mu} \quad \ldots\right)^T$$

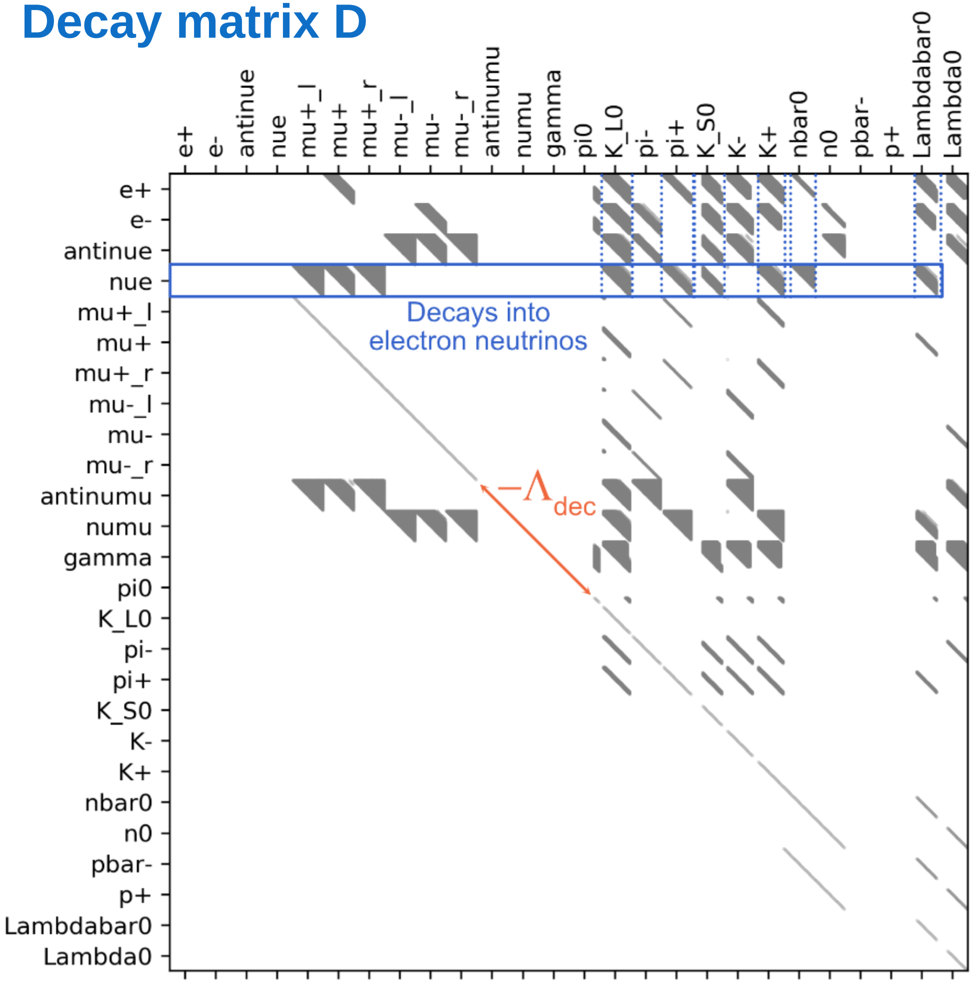
$$\vec{\Phi}^{\mathrm{p}} = \left(\Phi^{\mathrm{p}}_{E_0} \quad \Phi^{\mathrm{p}}_{E_1} \quad \cdots \quad \Phi^{\mathrm{p}}_{E_N}\right)^T$$

“Matrix form”

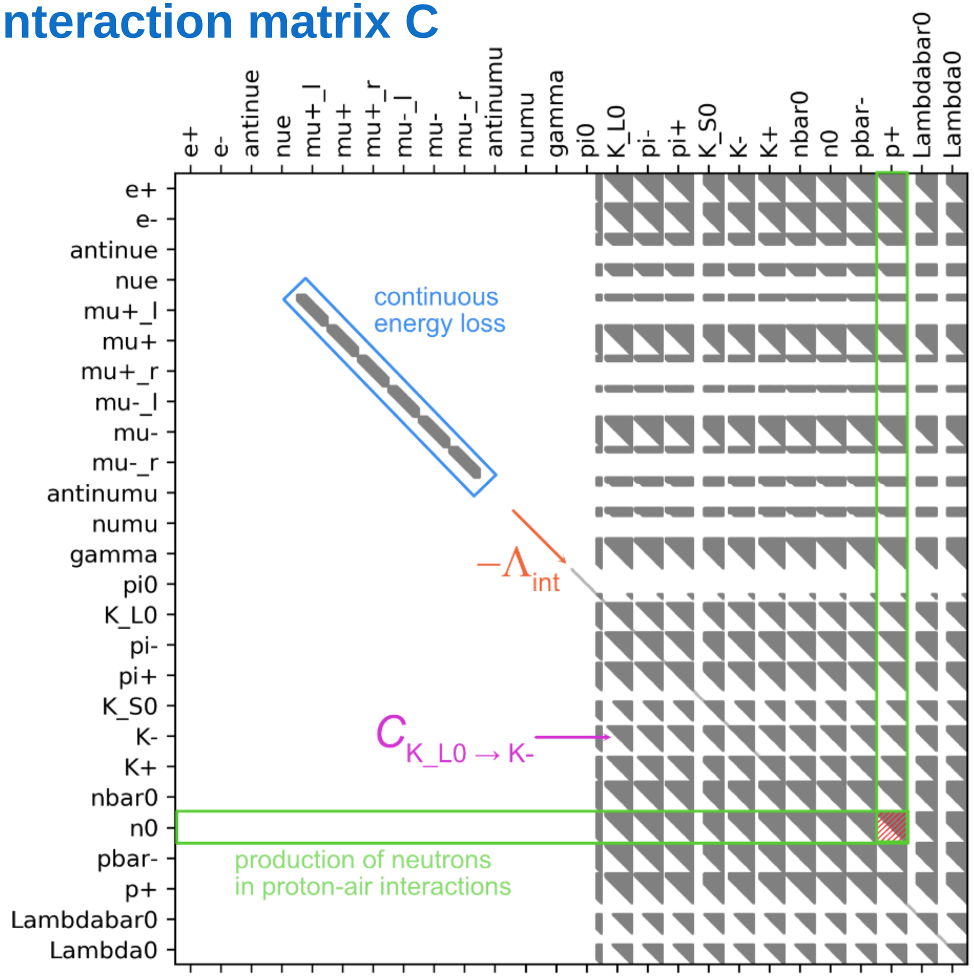
$$\frac{\mathrm{d}}{\mathrm{d}X}\vec{\Phi} = -\vec{\nabla}_E(\mathrm{diag}(\vec{\mu})\vec{\Phi}) + (-\mathbf{1}+\mathbf{C})\mathbf{\Lambda}_{\mathrm{int}}\vec{\Phi} + \frac{1}{\rho(X)}(-\mathbf{1}+\mathbf{D})\mathbf{\Lambda}_{\mathrm{dec}}\vec{\Phi}$$

Sparse matrix structure

Decay matrix D

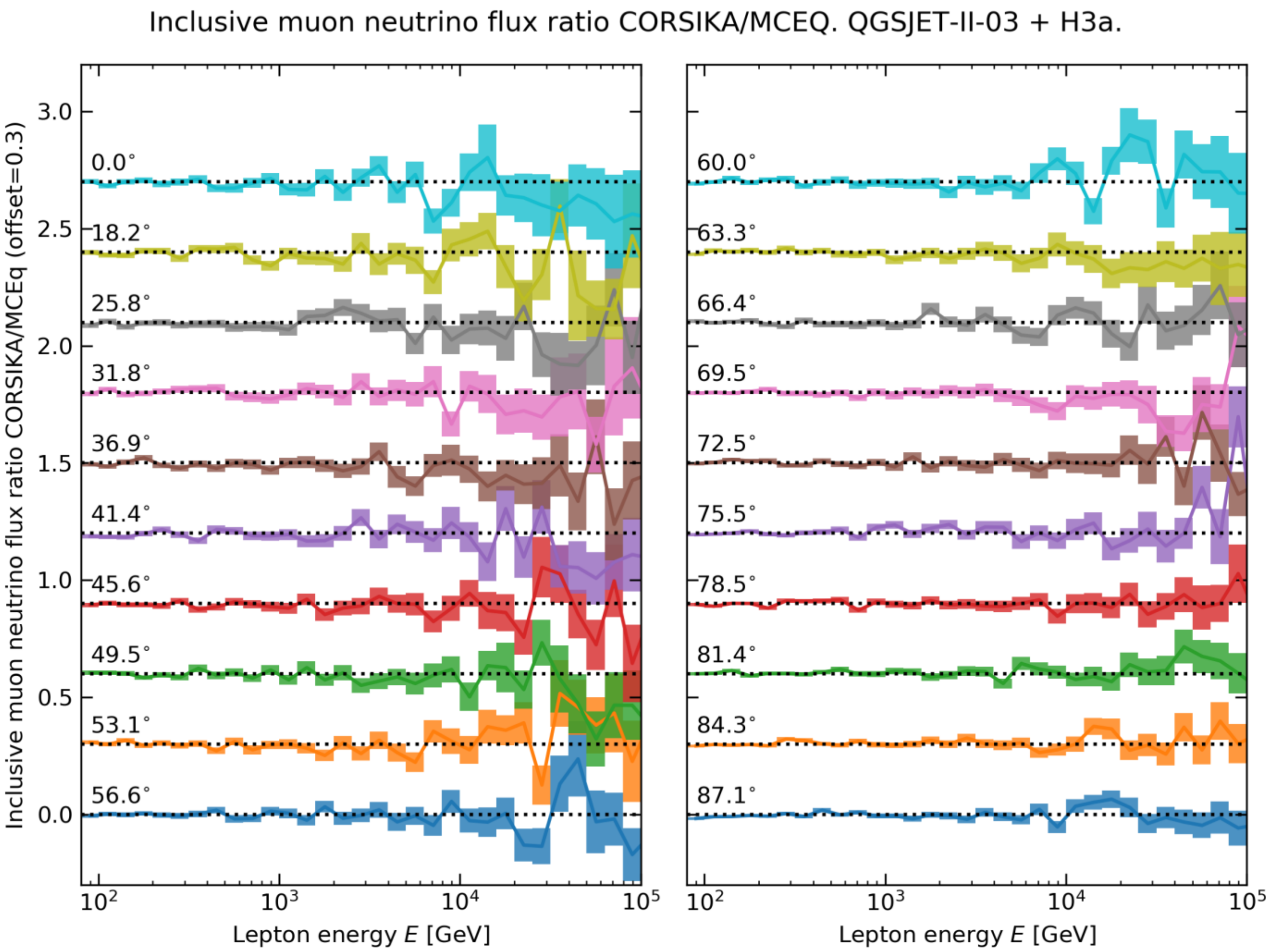


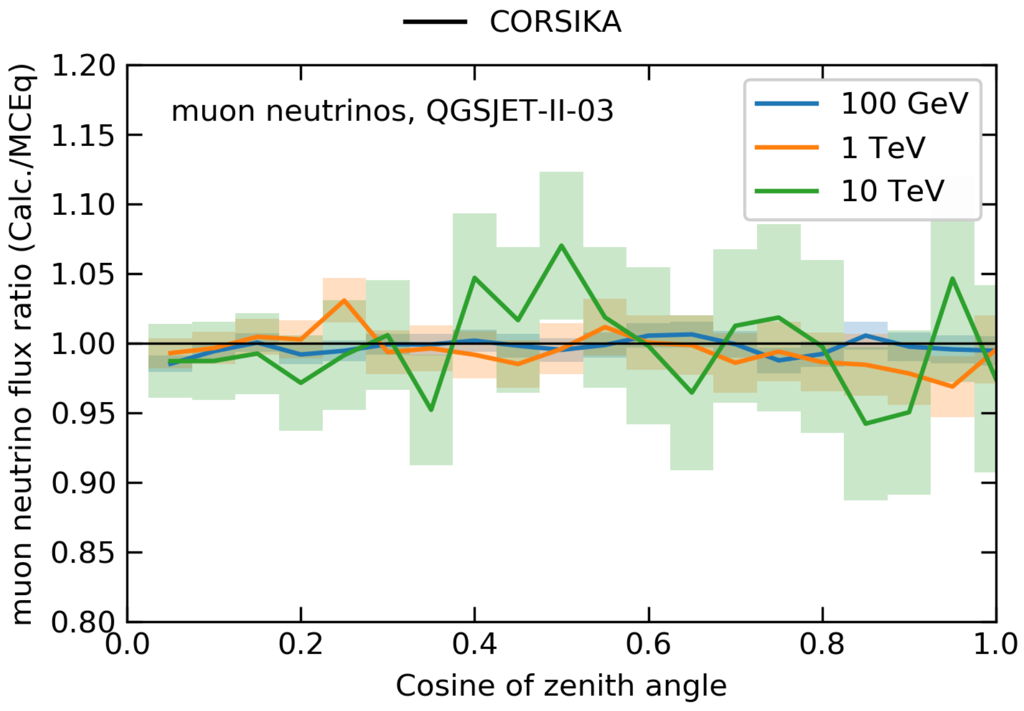
Interaction matrix C



matrices are sparse → high performance

MCEq vs (thinned) CORSIKA calculation in 1D



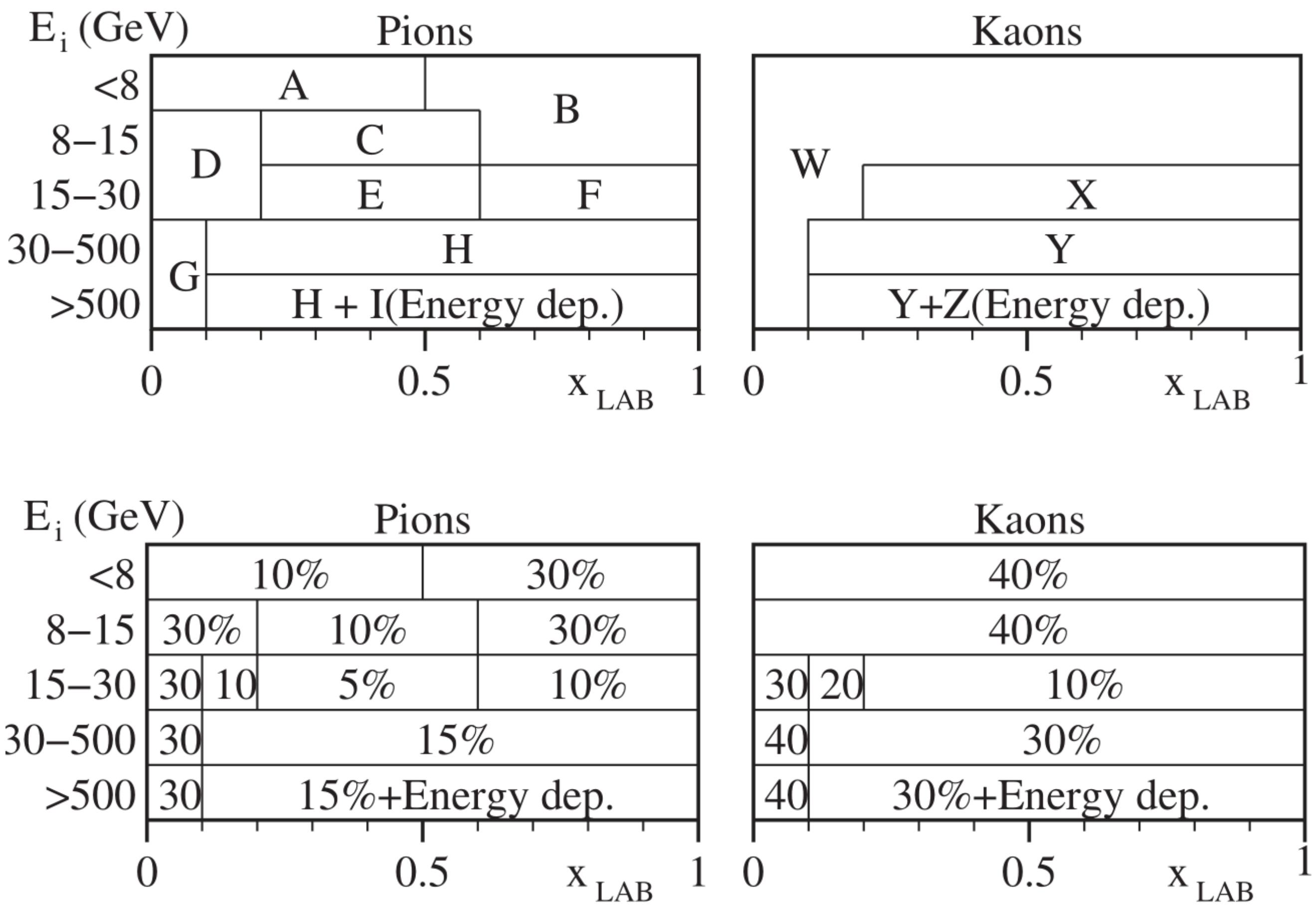


> BSD licensed @ https://github.com/afedynitch/MCEq

CORSIKA: A. Fedynitch, J. Becker Tjus and P. Desiati, PRD 2012
MCEq: Code paper, AF, R. Engel, in prep. for submission

MCEq-based implementation

"Barr regions"



- Compute partial derivatives wrt. phase-space regions (Taylor expansion), i.e. $\frac{\partial \Phi_\nu}{\partial W}$
- No correlations between phase-space regions (as in Barr et al.) or add. correlations

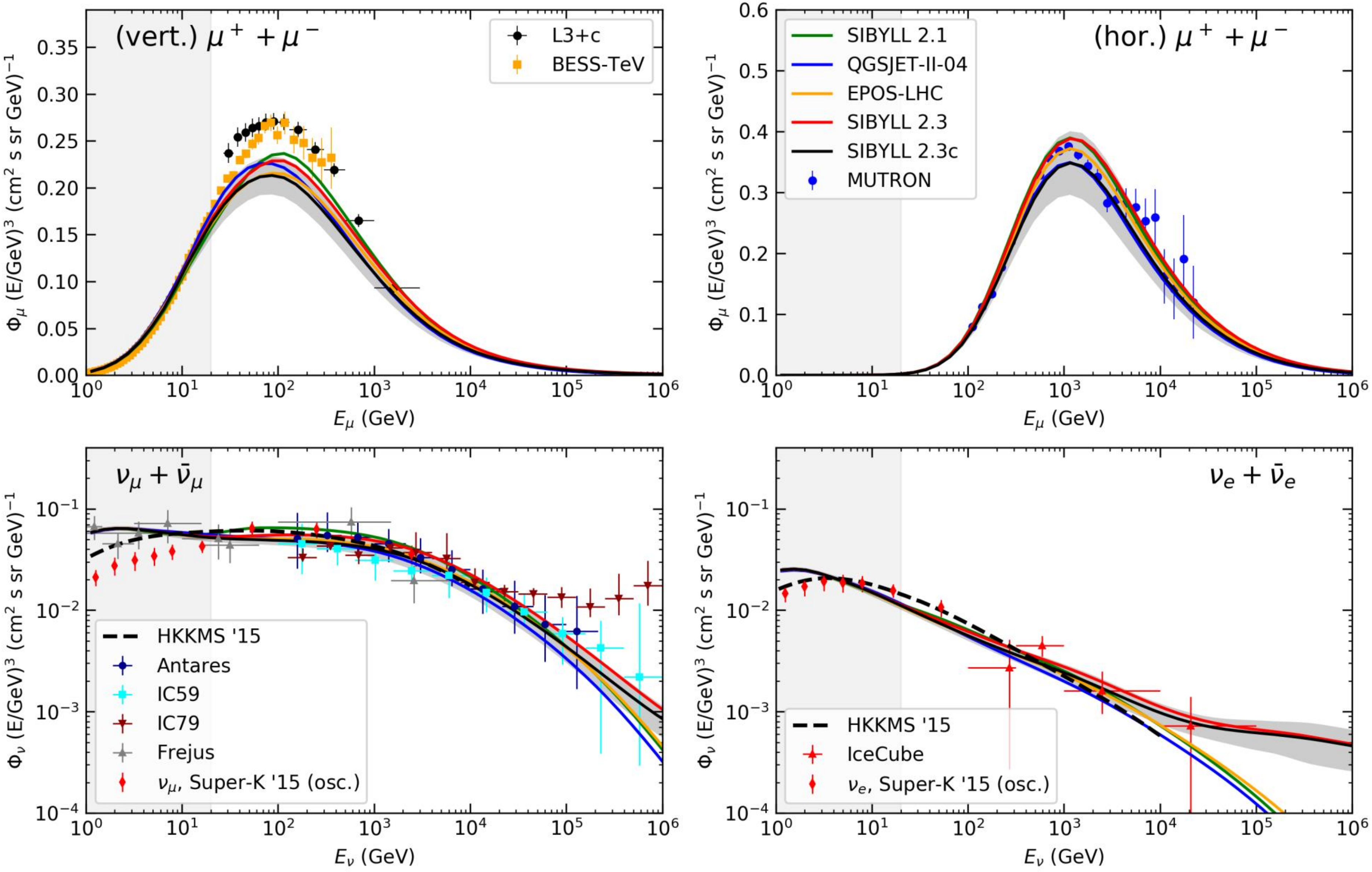
Elements of Jacobian (numerical)

$$J_{E_i j} = \frac{\partial \Phi_\nu(E_i)}{\partial p} = \frac{\Phi_\nu(\delta p_j +) - \Phi_\nu(\delta p_j -)}{2\delta p_j}$$

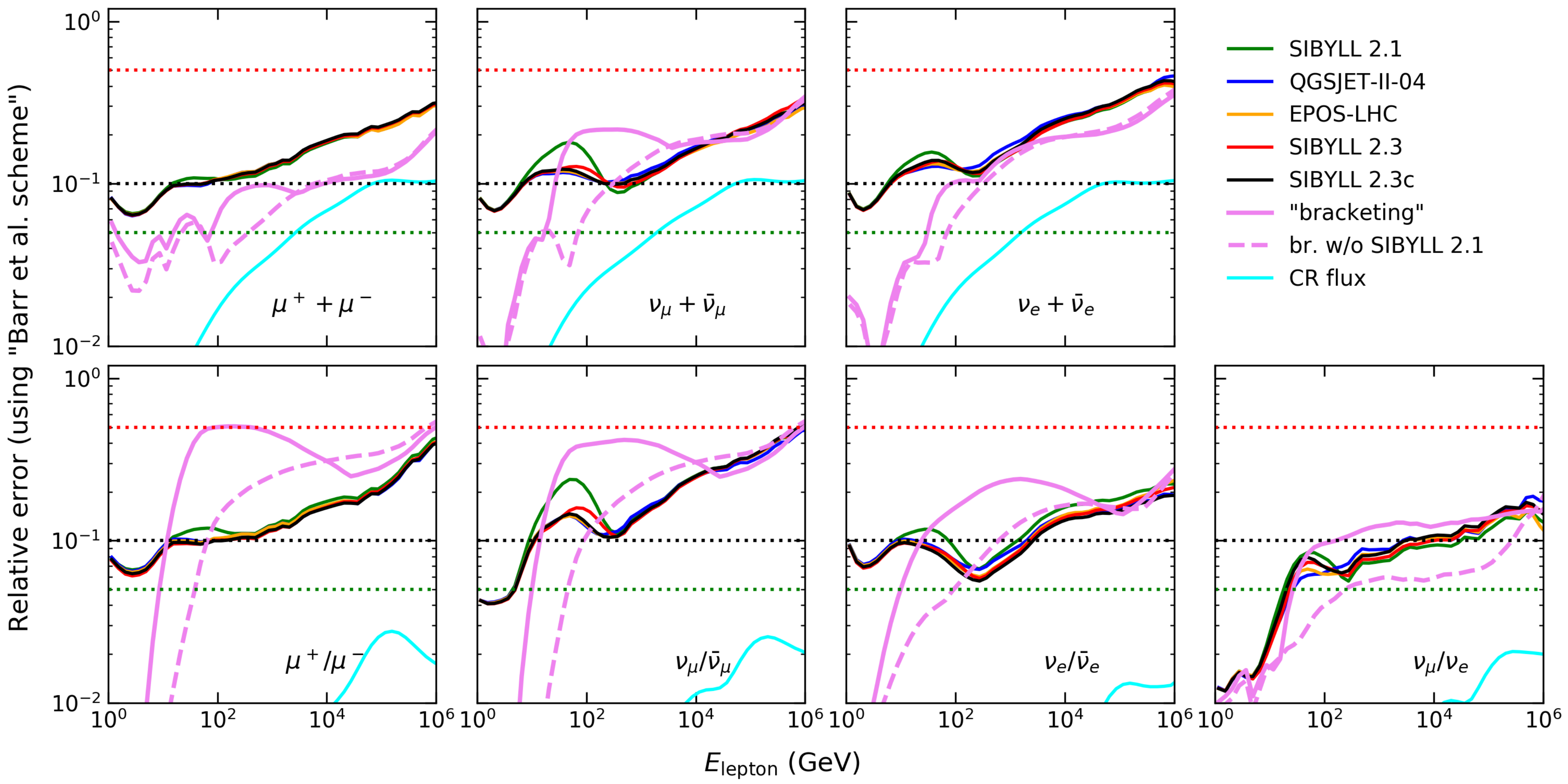
Error propagation

$$\mathrm{cov}[\Phi_\nu(E_i), \Phi_\nu(E_j)] = \sum_{mn} J_{E_i m} J_{E_j n} \mathrm{cov}[p_m, p_l]$$

Computation of error bands through error propagation

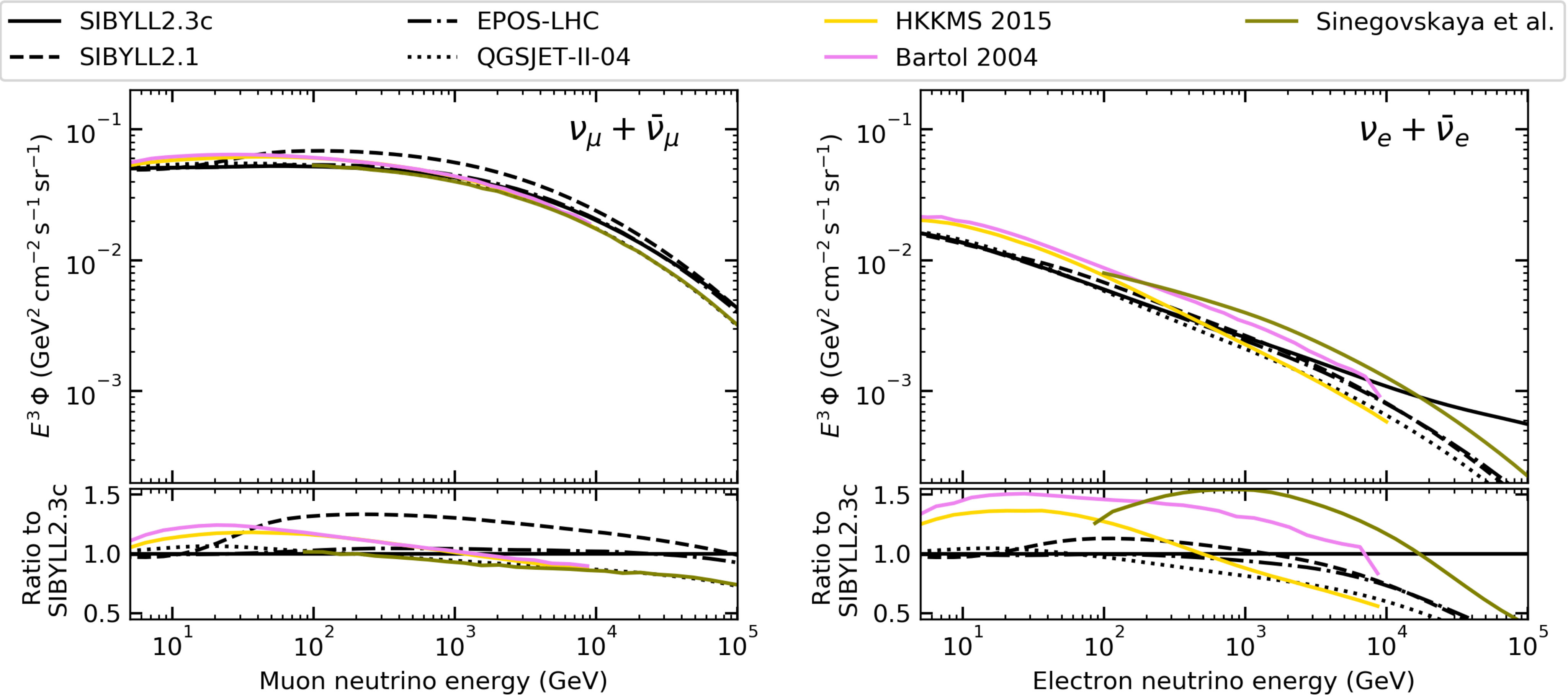


Computation of error bands through error propagation



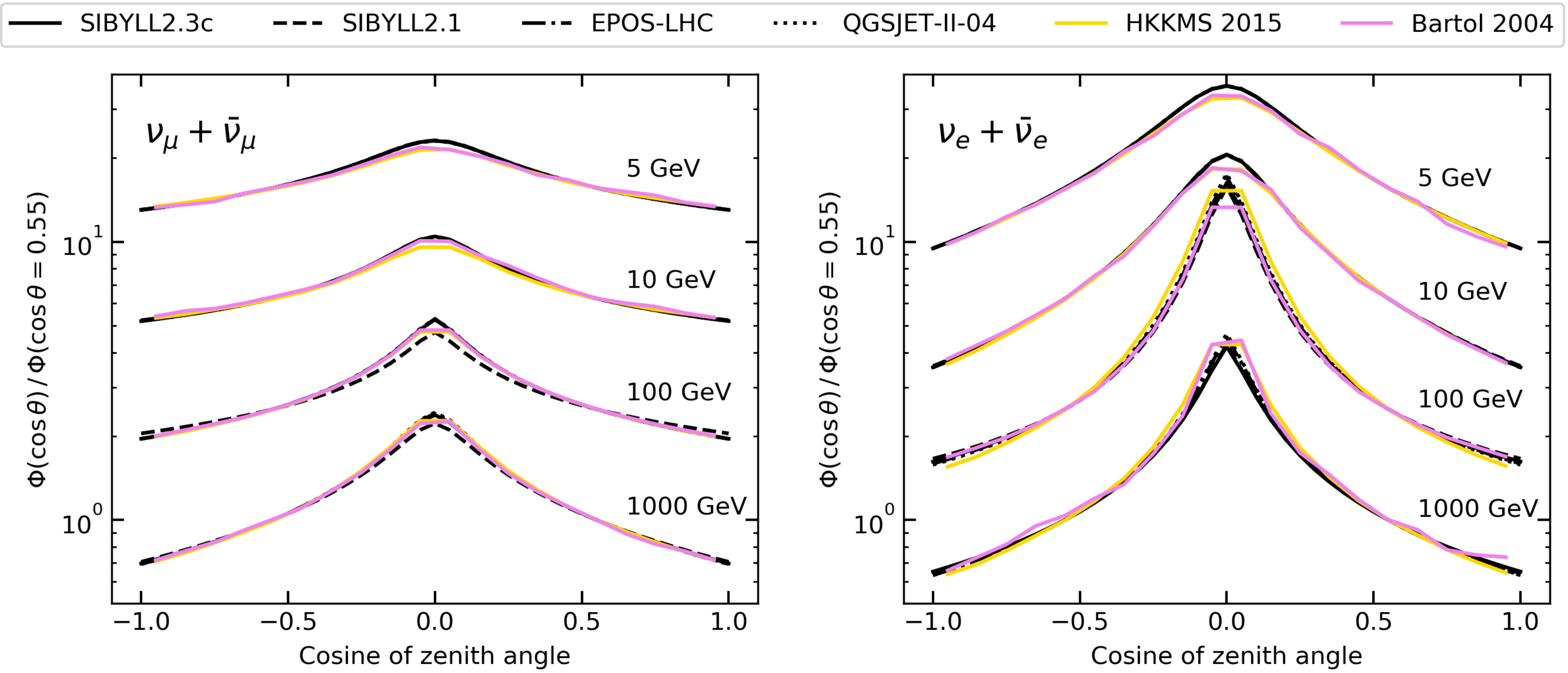
MCEq vs. traditional calculations

HKKMS: M. Honda et al., PRD 92 (2015)
Bartol: G. Barr et al., PRD 70 (2004)
Sinegovskaya et al. PRD 91 (2015)
MCEq: AF, R. Engel in prep.



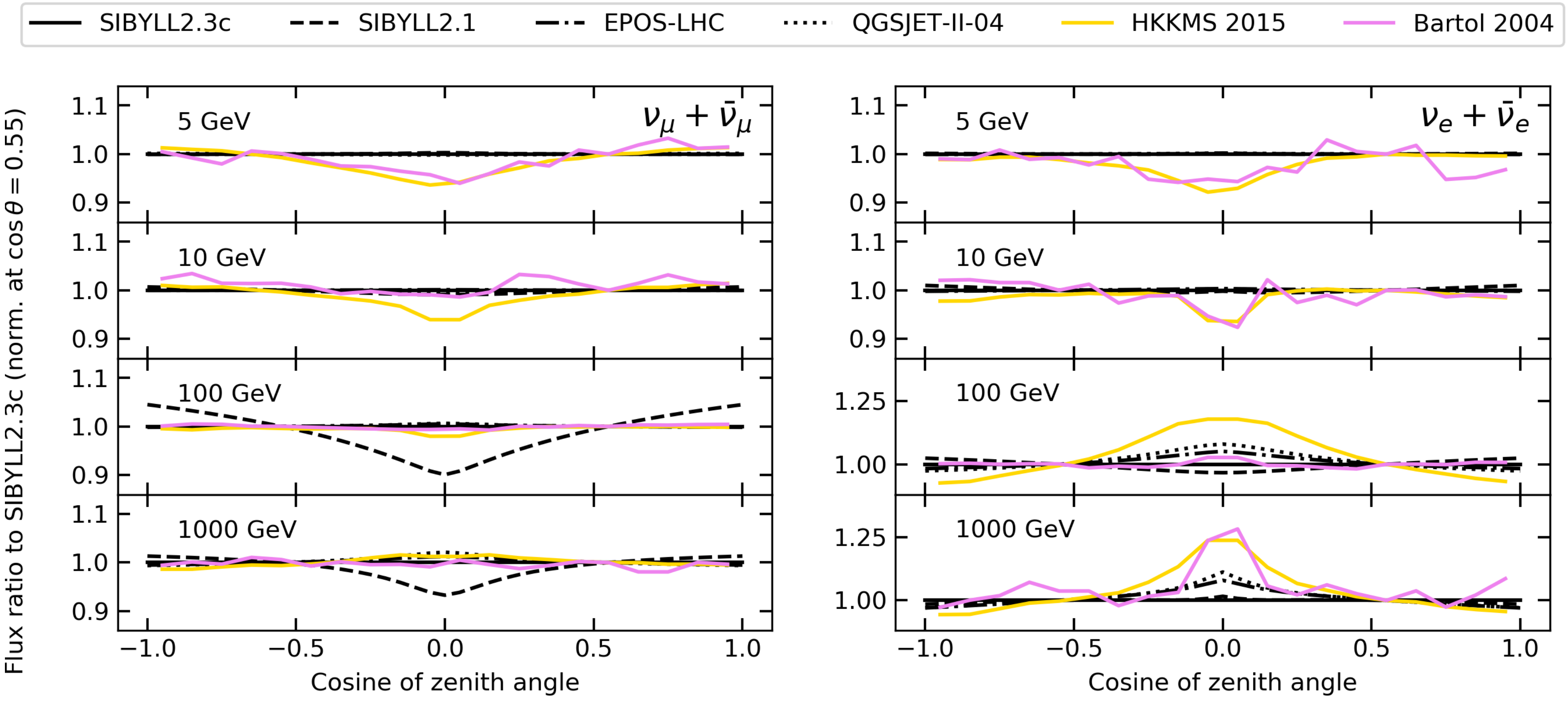
- Old 2002 (GH) primary model for HKKMS and Bartol, H3a for the rest
- Data can not discriminate between calculations
- Shown are zenith and azimuth averages

Hadronic model dependence of zenith distributions



- Good agreement above tens of GeV for muon neutrinos
- Some tension between calculations at the horizon in electron neutrinos
- Affected by K/Pi, K^{+-}/K^0_L ratios

Hadronic model dependence of zenith distributions



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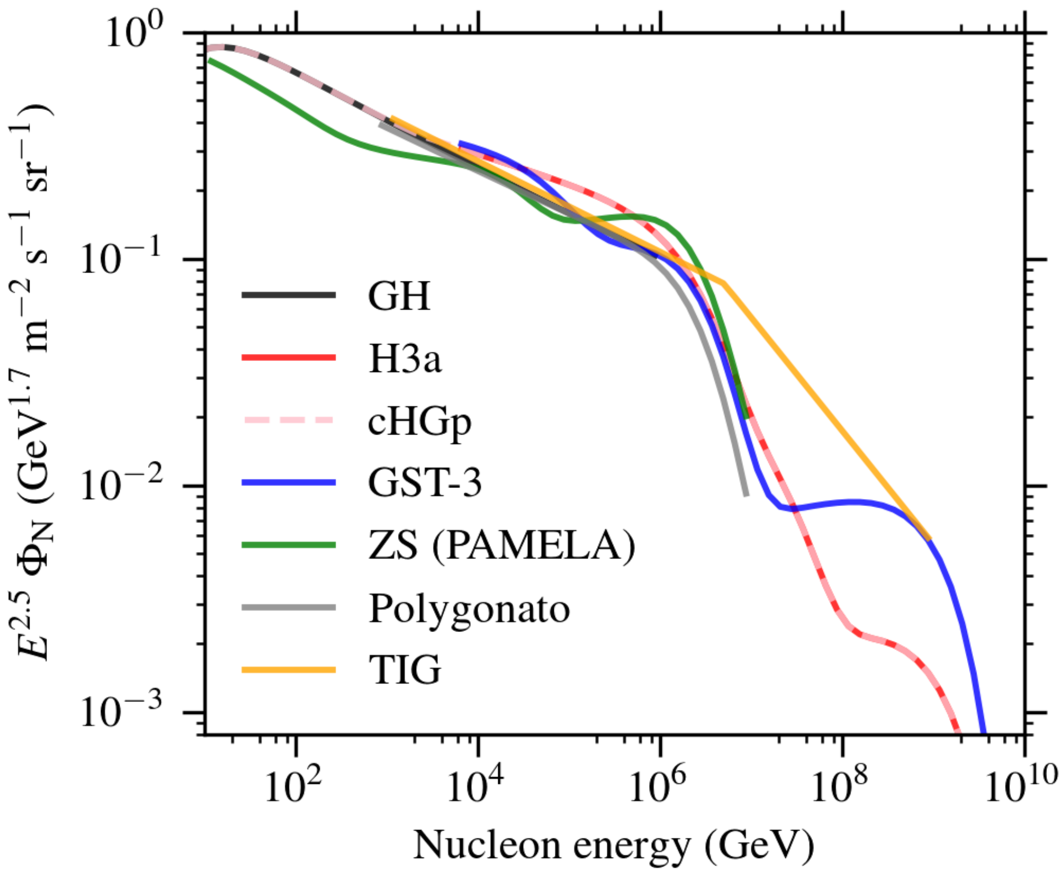
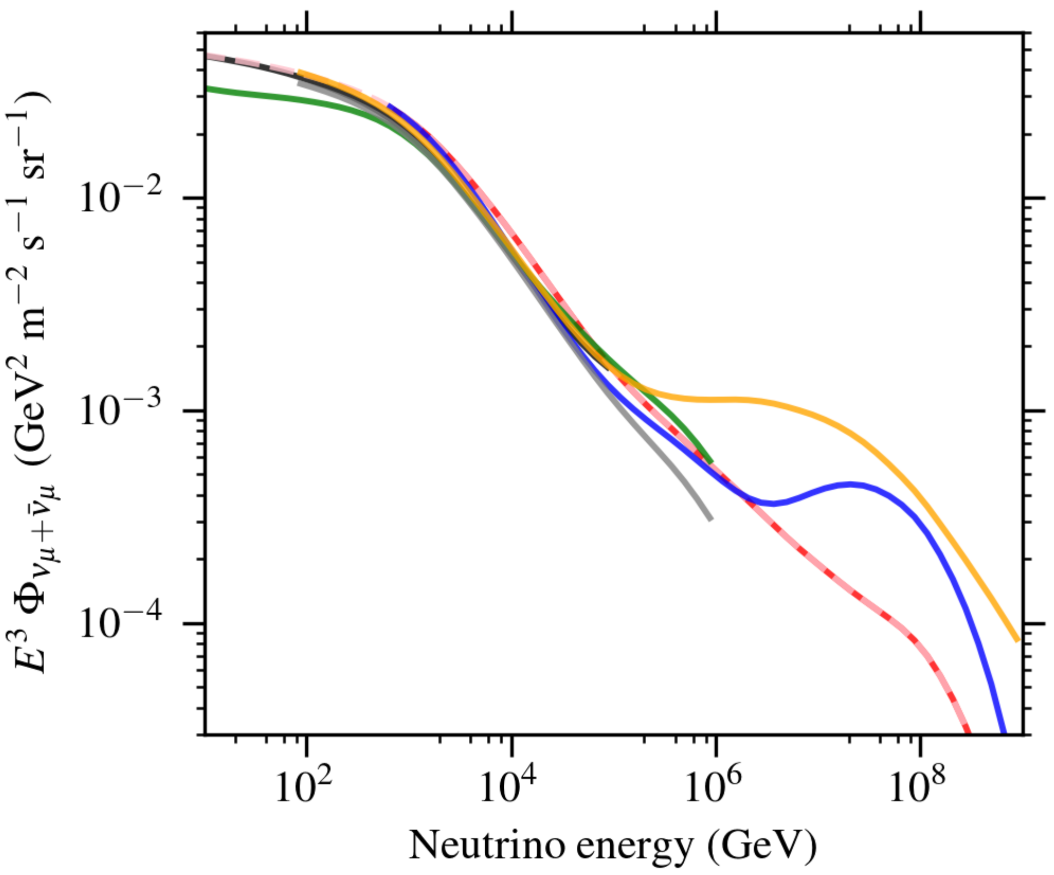
AF, F. Riehn, R. Engel, T.K. Gaisser, T. Stanev, 1806.04140 (2018)

Cosmic ray flux uncertainties – ‘bracketing’ overestimates

Cosmic ray nucleon flux



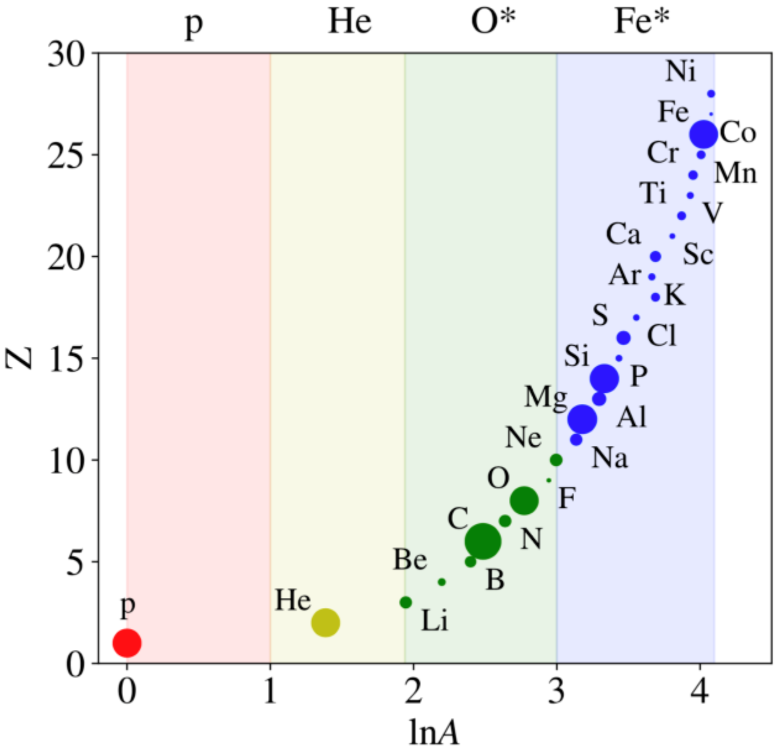
Atmospheric neutrino flux

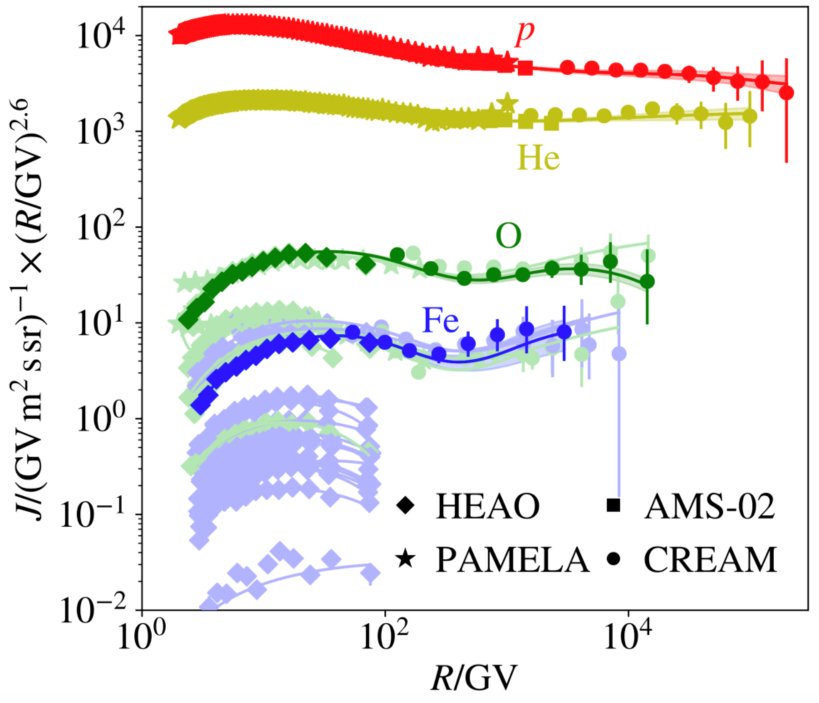


Global Spline Fit – fit to direct & indirect observations

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: $J_j(R)/ J_L(R) = const.$



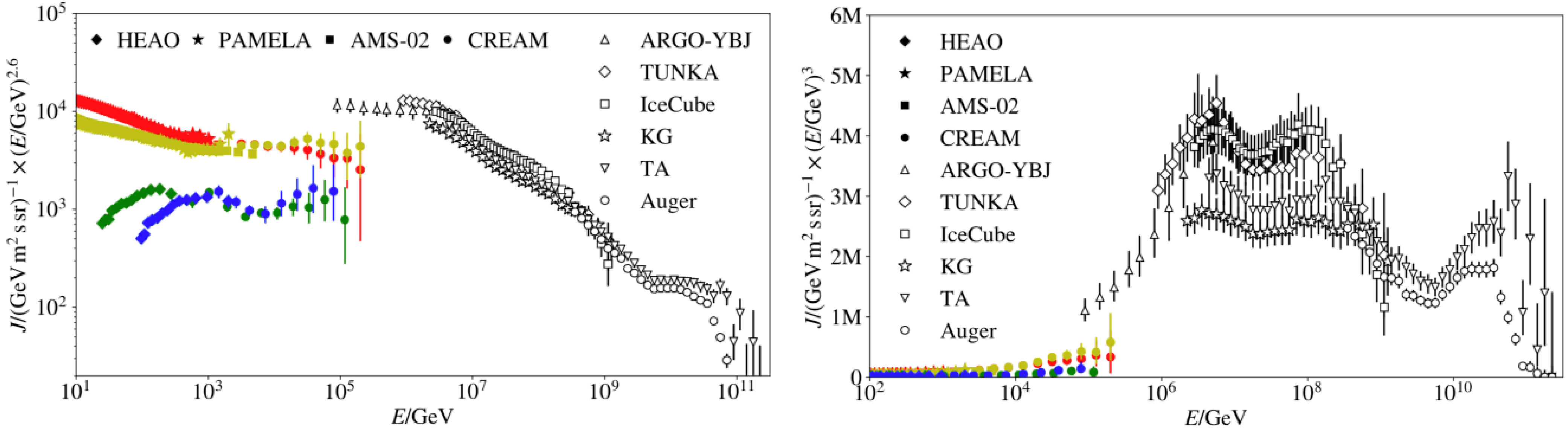


Mass sensitivity of air-shower experiments is ~ lnA

Handling energy-scale uncertainty

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

Original data



- The determination of **energy scale in air-shower experiments is uncertain**
- This is caused by inconsistencies of **hadronic interaction models**
- Fit adjusts energy scales **within systematic uncertainties** of the experiment

$$\tilde{J}(\tilde{E}) = J(E)\frac{\mathrm{d}E}{\mathrm{d}\tilde{E}} = J\left(\frac{\tilde{E}}{1+z_E}\right)\frac{1}{1+z_E}$$

Flux distortion caused by energy-scale offset z_E

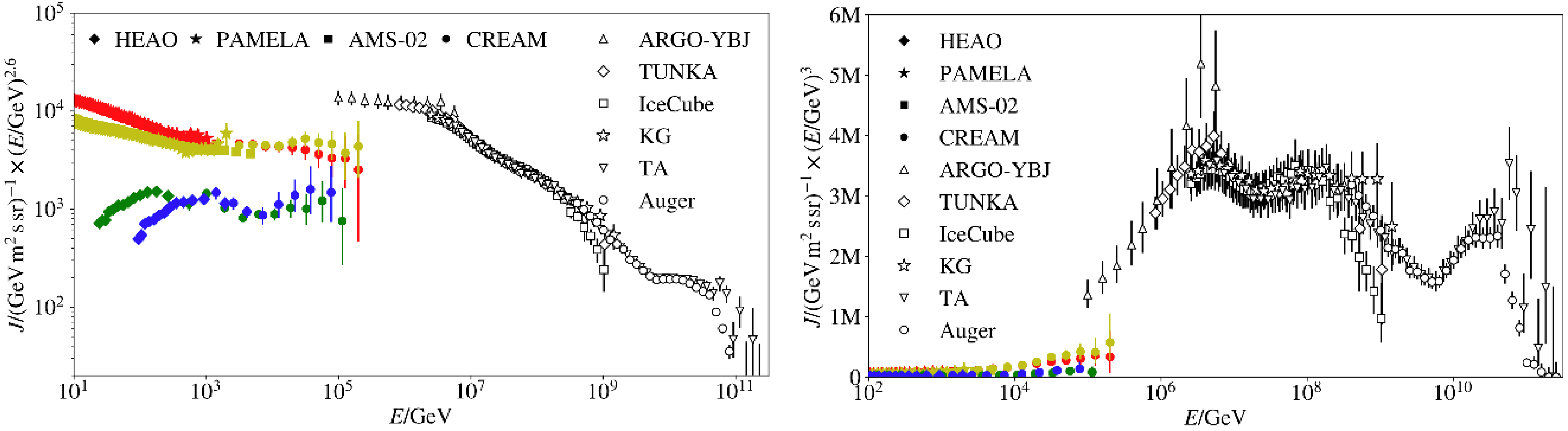
$$S = \sum_i z_i^2 + \sum_j \left(\frac{z_{Ej}}{(\sigma[E]/E)_j}\right)^2$$

Flux residuals Energy-scale offset residuals

Handling energy-scale uncertainty

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

Adjusted data



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Flux residuals   Energy-scale offset residuals