Open questions in atmospheric lepton fluxes

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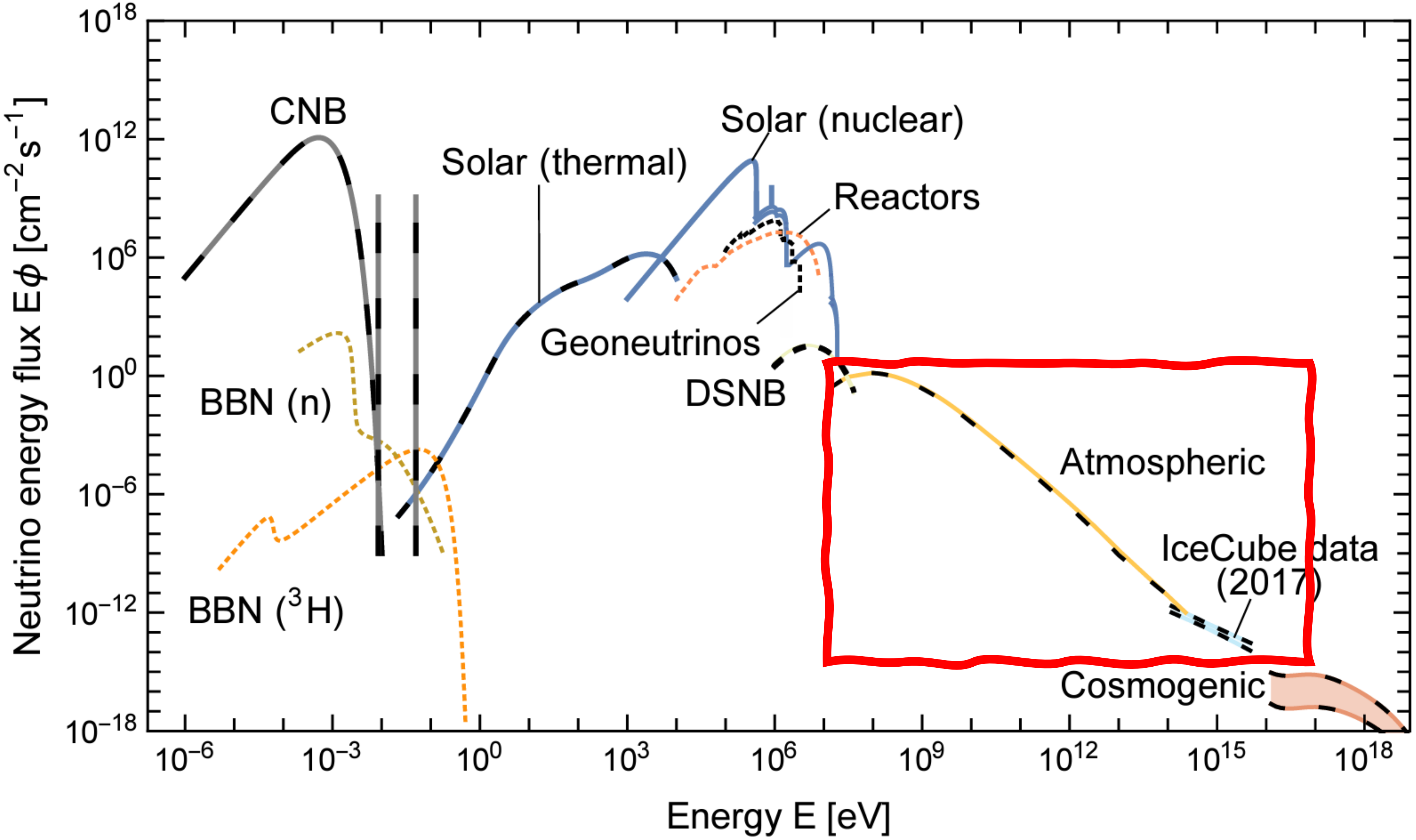
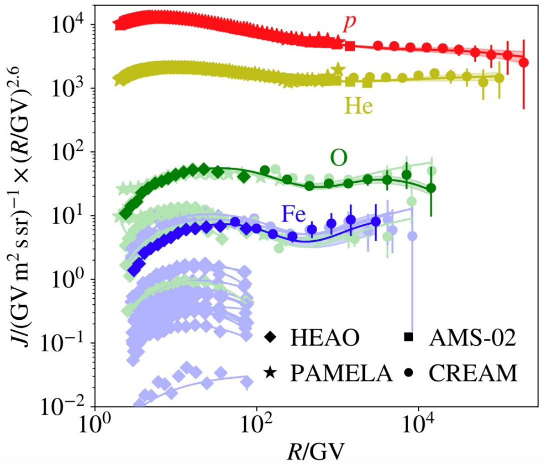
Neutrino spectra at Earth

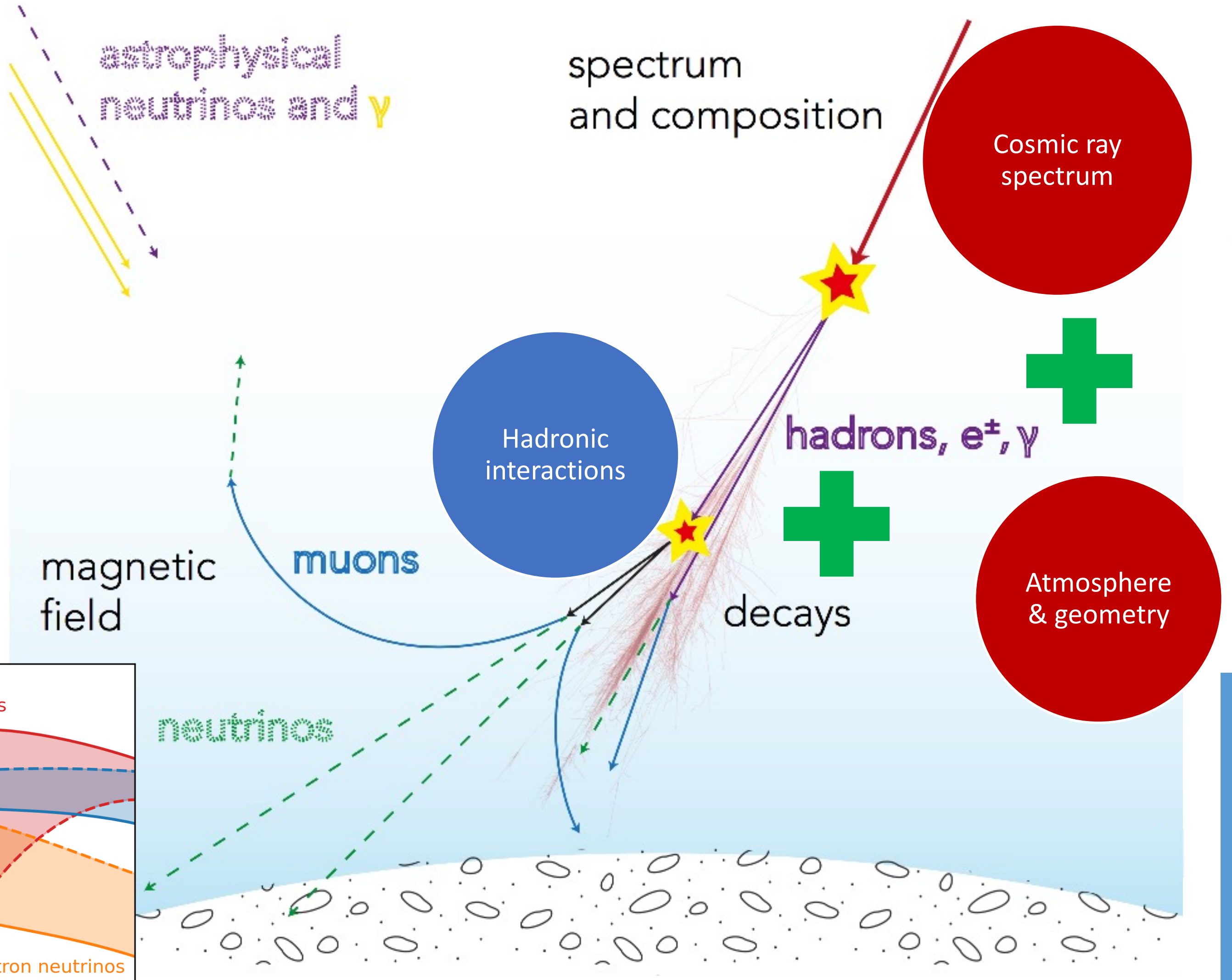
Vitagliano, Tamborra, Raffelt 2019, 1910.11878

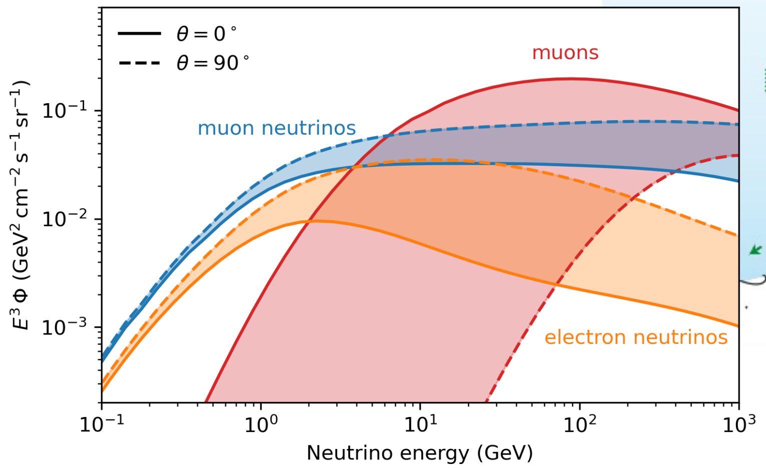


Modeling of inclusive lepton fluxes in the atmosphere



"inclusive" = integrated over CR energy and all other particles at the surface

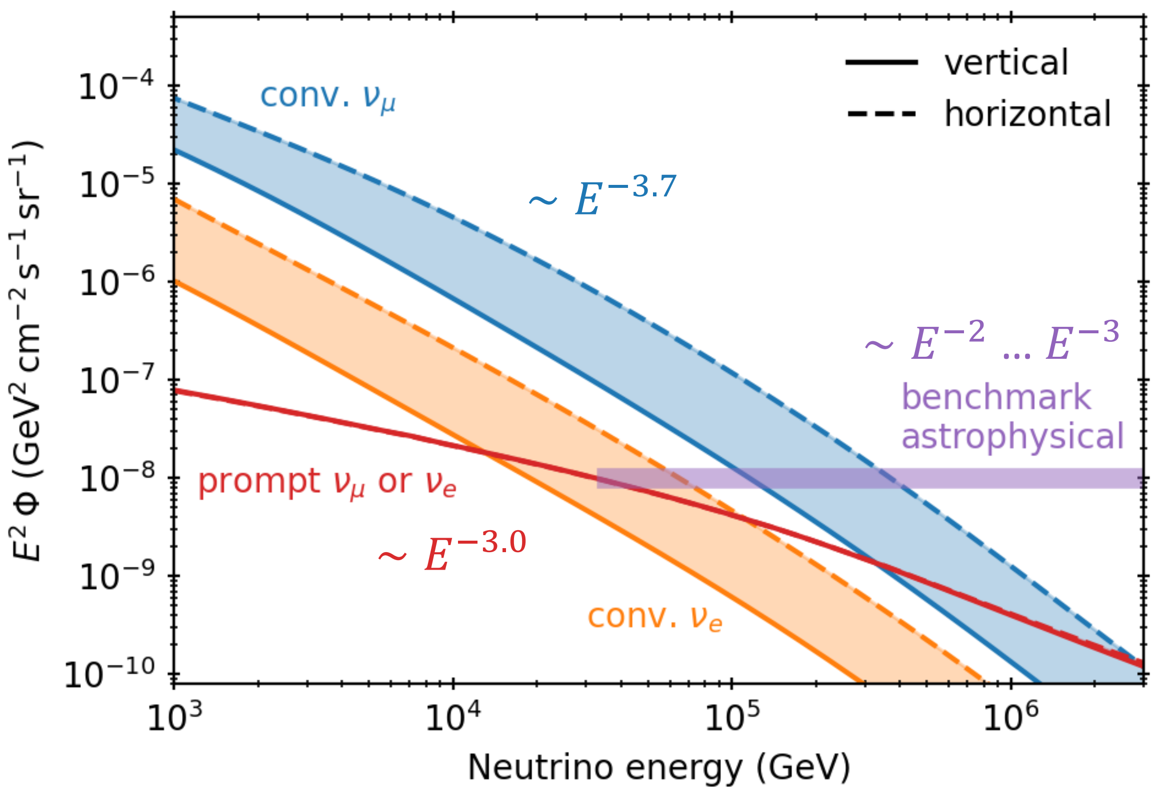




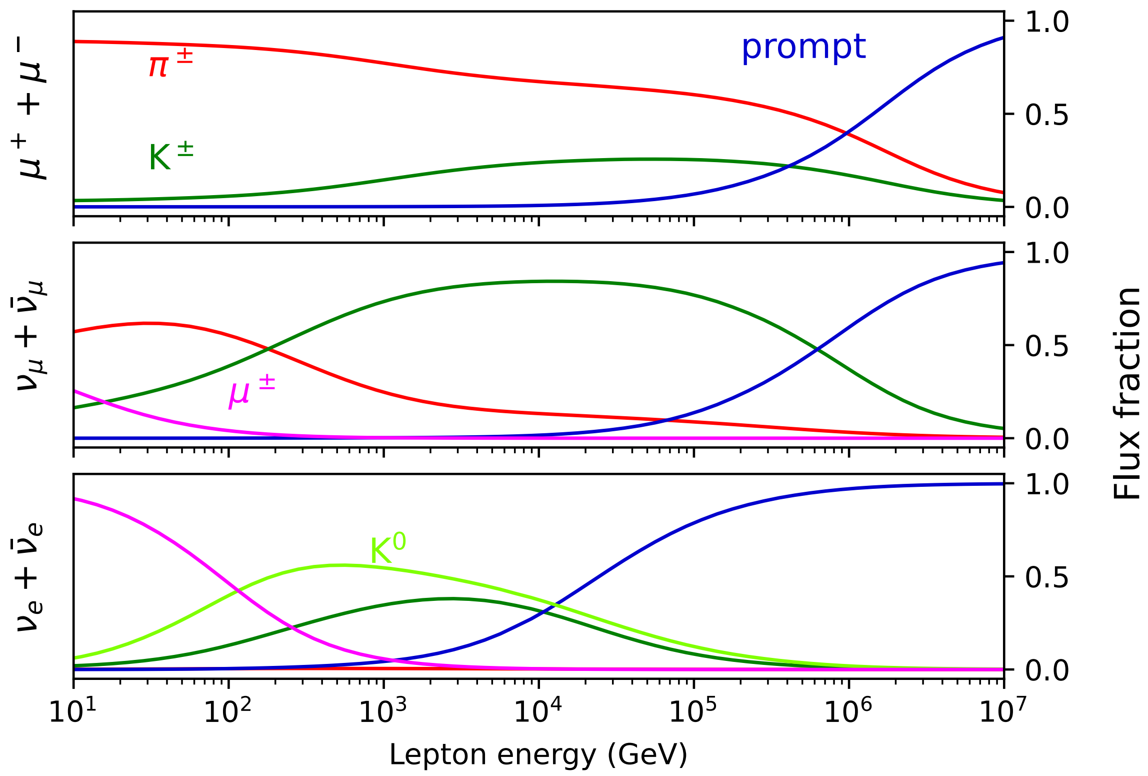
None of these models is founded on a "fundamental" theory/framework.

All are "theory-motivated", "data-driven", or empirical.

Features of high-energy atmospheric muon and neutrino spectra



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



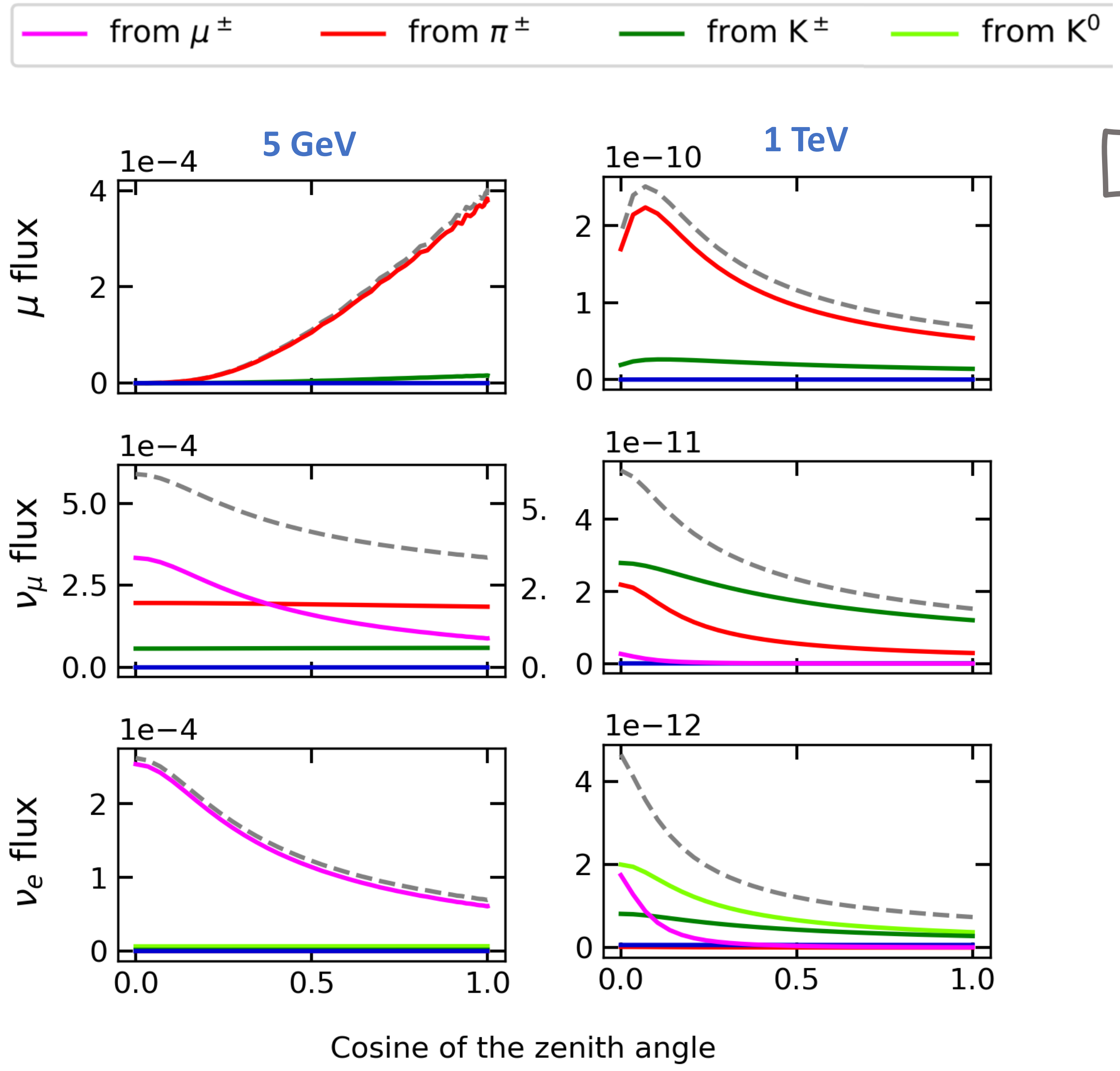
Bands (zenith-enhancement):

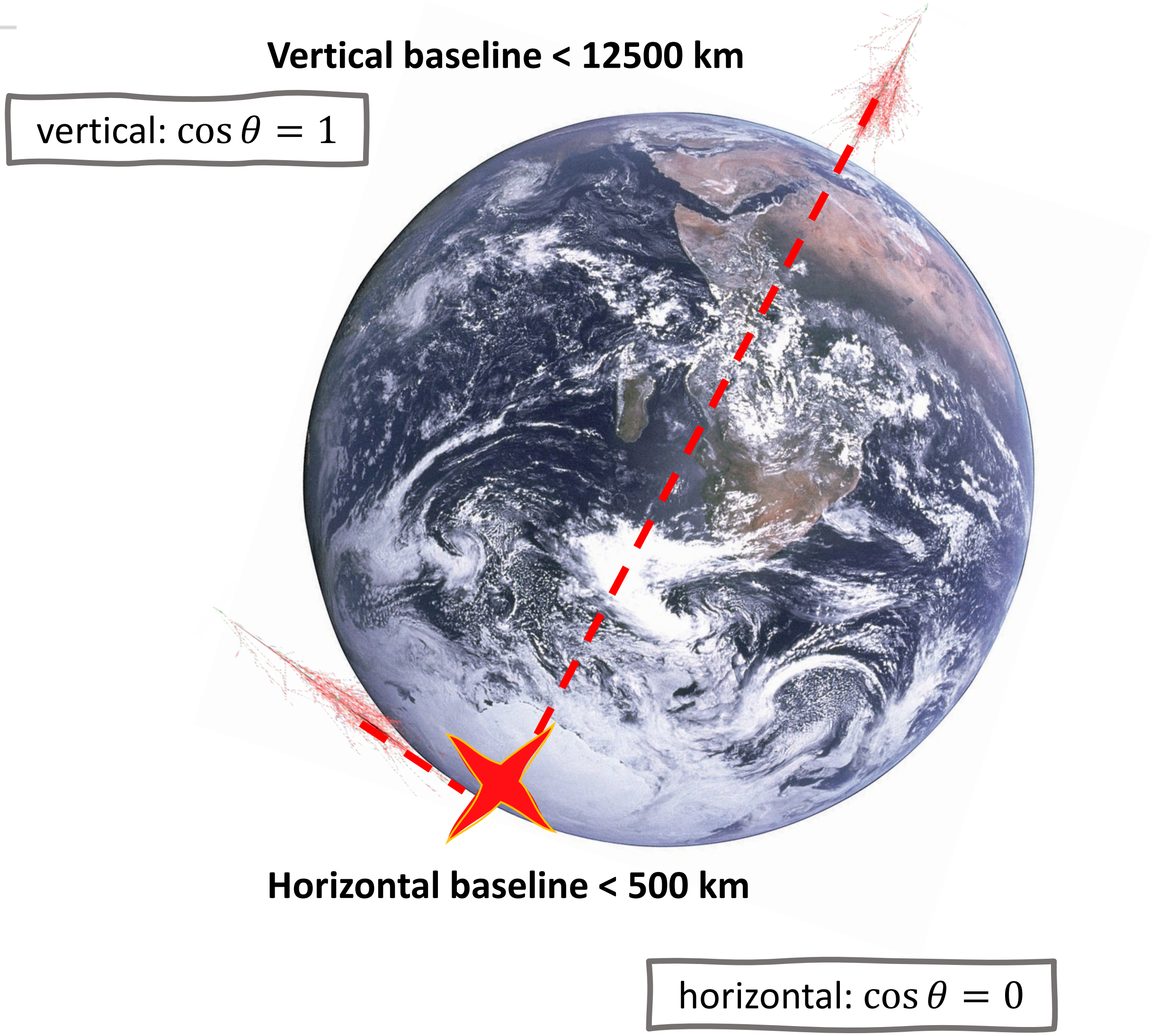
- Lower boundary $\cos\theta = 1$, vertical
- Upper boundary $\cos\theta = 0$, horizontal

Different weight of hadrons in lepton production, due to:

- Hadron production cross sections
- Branching ratio & decay kinematics

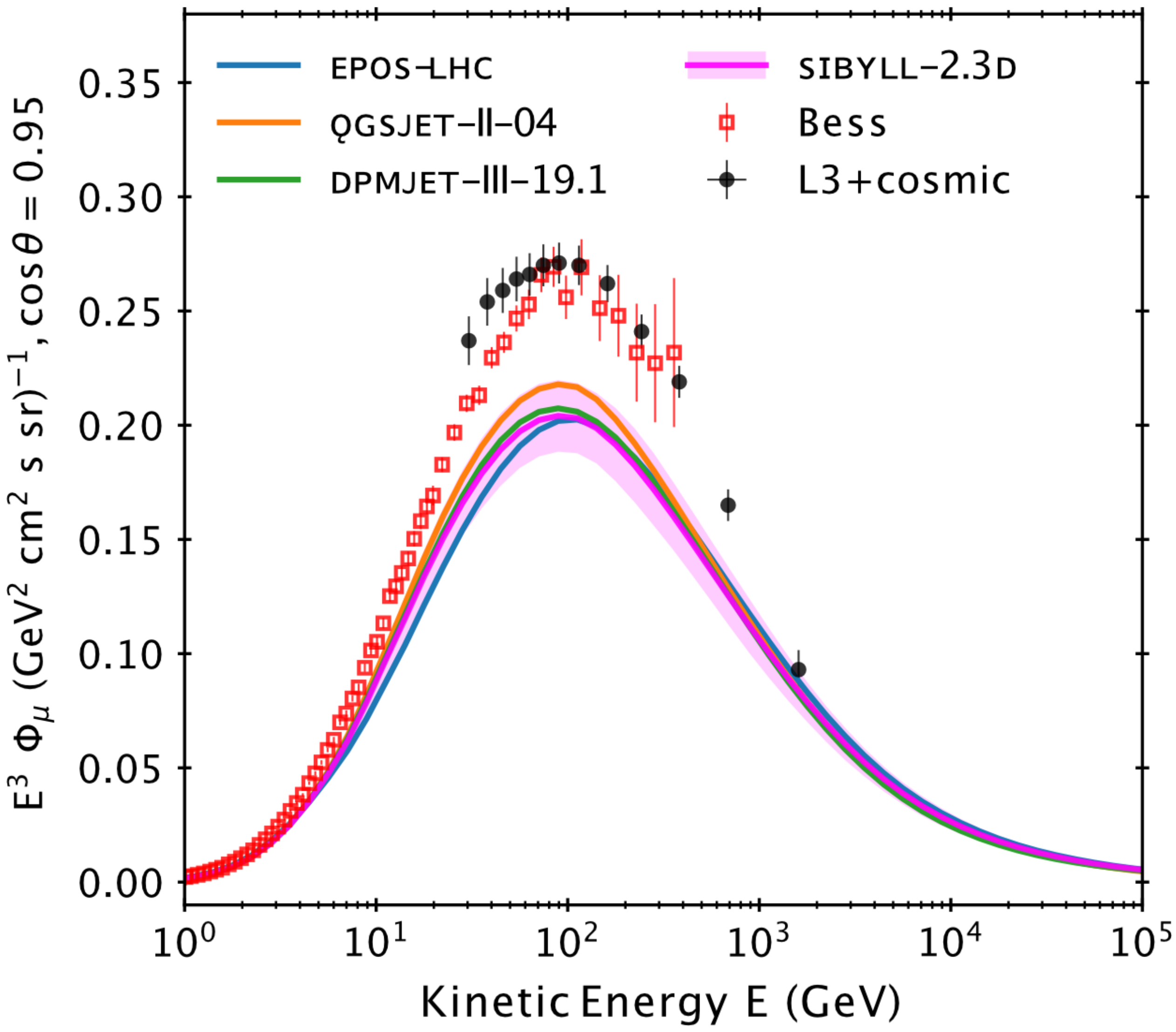
Zenith angle dependence at higher-E is sensitive to hadron production





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

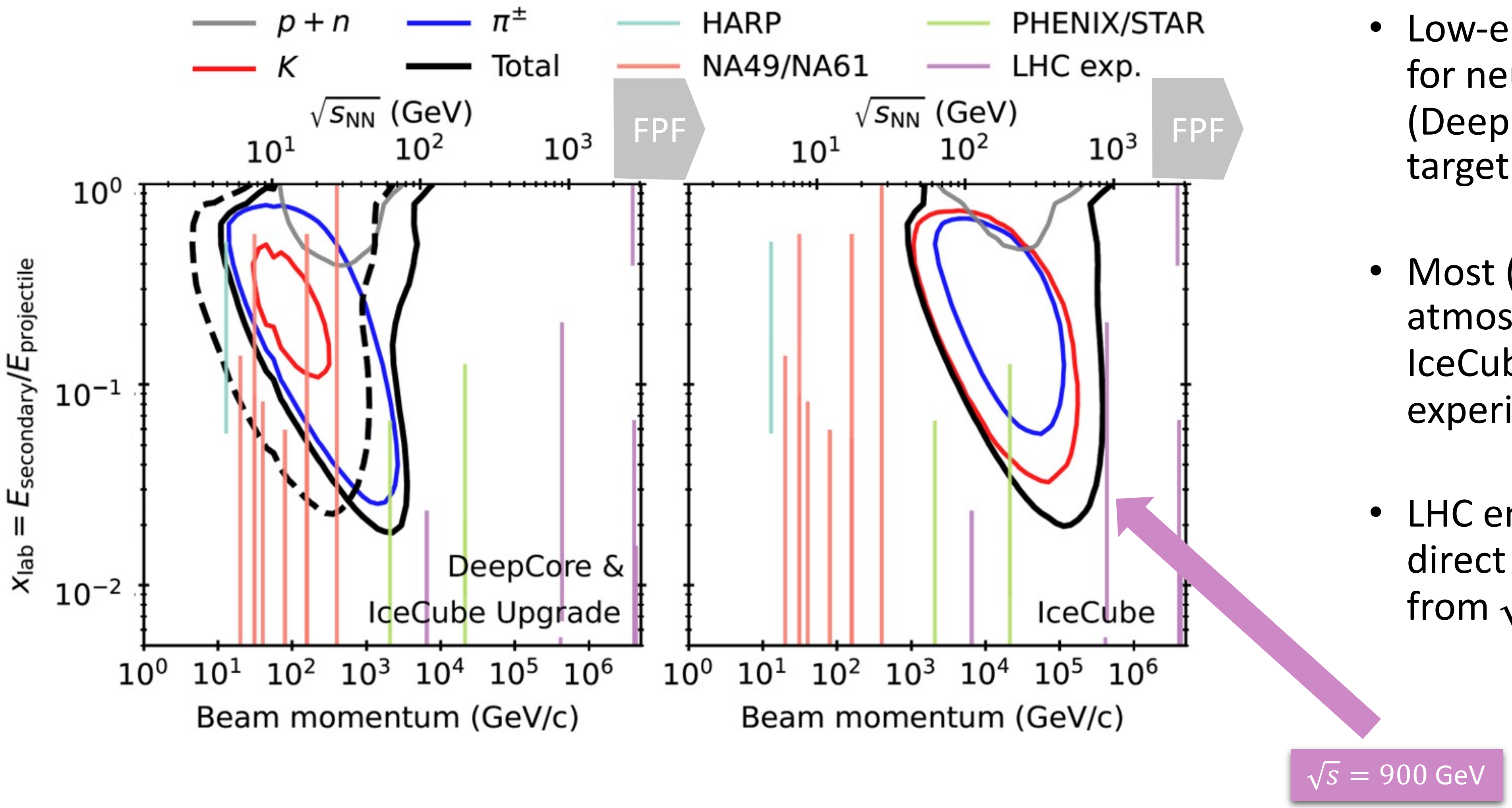
But surface muons never looked great… (known for > 10 years or >> longer)



- Calculations (MCEq) that use recent (or old) hadronic interaction models and recent cosmic ray flux measurements are **lower than data (~30%)**
- This is not entirely new but…
- Cosmic ray fluxes are very much constrained by AMS, CALET, etc. up to multi-TeV energies
- Hadronic interaction models have been tuned to LHC data (but not in the relevant forward phase space) so could be the reason
- Cascade codes (CORSIKA 7/8, MCEq, or FLUKA) have been +- cross checked and are not the origin

Hadron production phase space seen by neutrino detectors

AF & M. Huber, arXiv:2205.14766

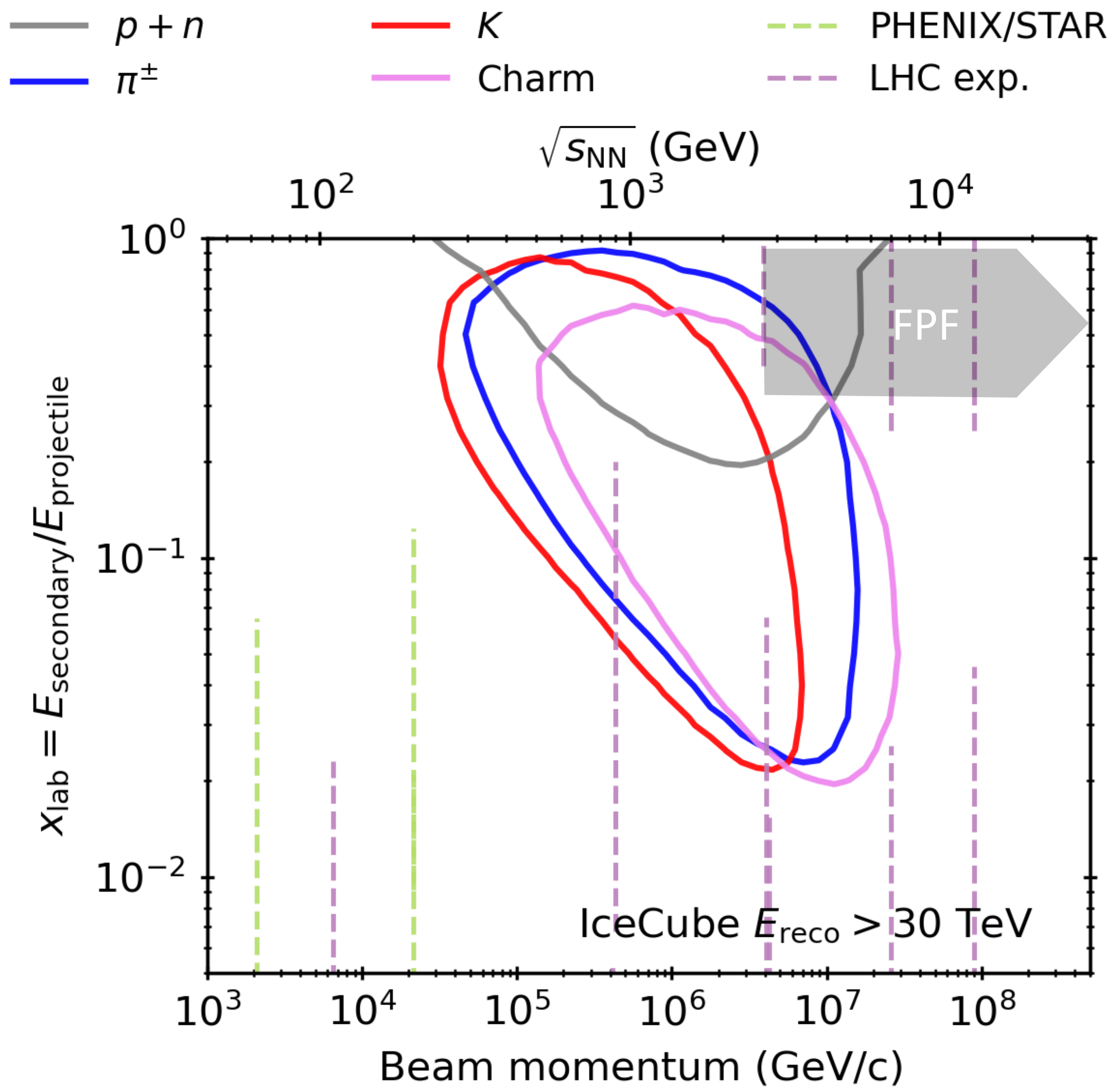


- Low-energy range, relevant for neutrino oscillations (DeepCore), covered by fixed target data
- Most (high-energy) atmospheric neutrinos in IceCube not covered by any experiment
- LHC energies are too high, direct constraints possible from $\sqrt{s} = 900$ GeV

Contours = 90% of neutrino events in full detectors

Hadron prod. phase space relevant for characterization of prompt and astro neutrinos

- At 10 - 100 TeV atmospheric and astrophysical fluxes are similar → strong model dependence → **large syst. uncertainty**
- Reduction of atm. systematics crucial to reveal prompt flux
- **More in Lu Lu's talk after mine**
- FPF's energy range might be a bit high for direct constraints (in p-Oxygen)
- Nonetheless, indirectly we may learn something, such as **about Feynman scaling for charged hadrons**

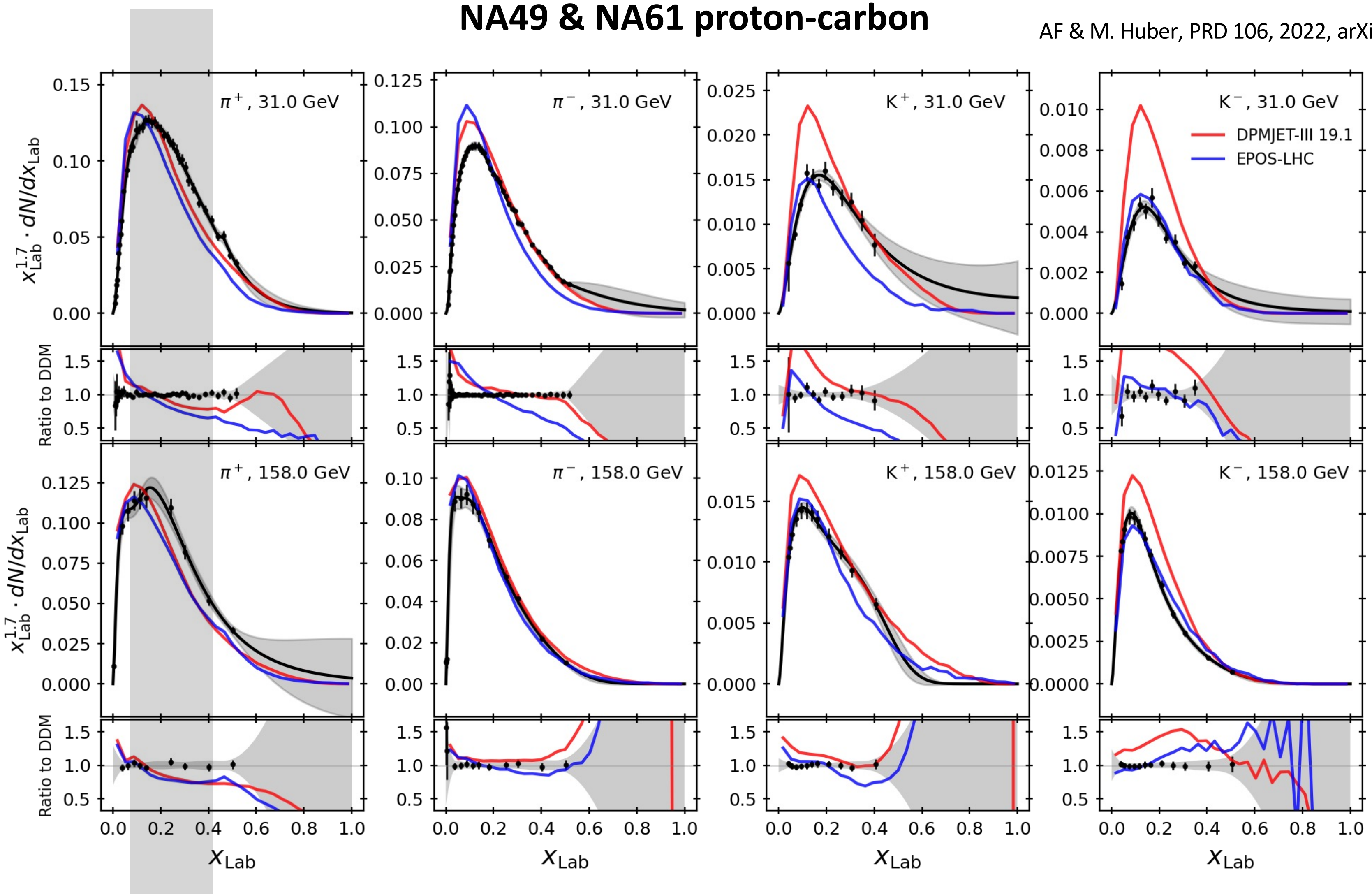


Contours = 90% of muon neutrino events above threshold in reconstructed energy in IceCube

Data-driven model (DDM) built in incl. cross sections

NA49 & NA61 proton-carbon

AF & M. Huber, PRD 106, 2022, arXiv:2205.14766

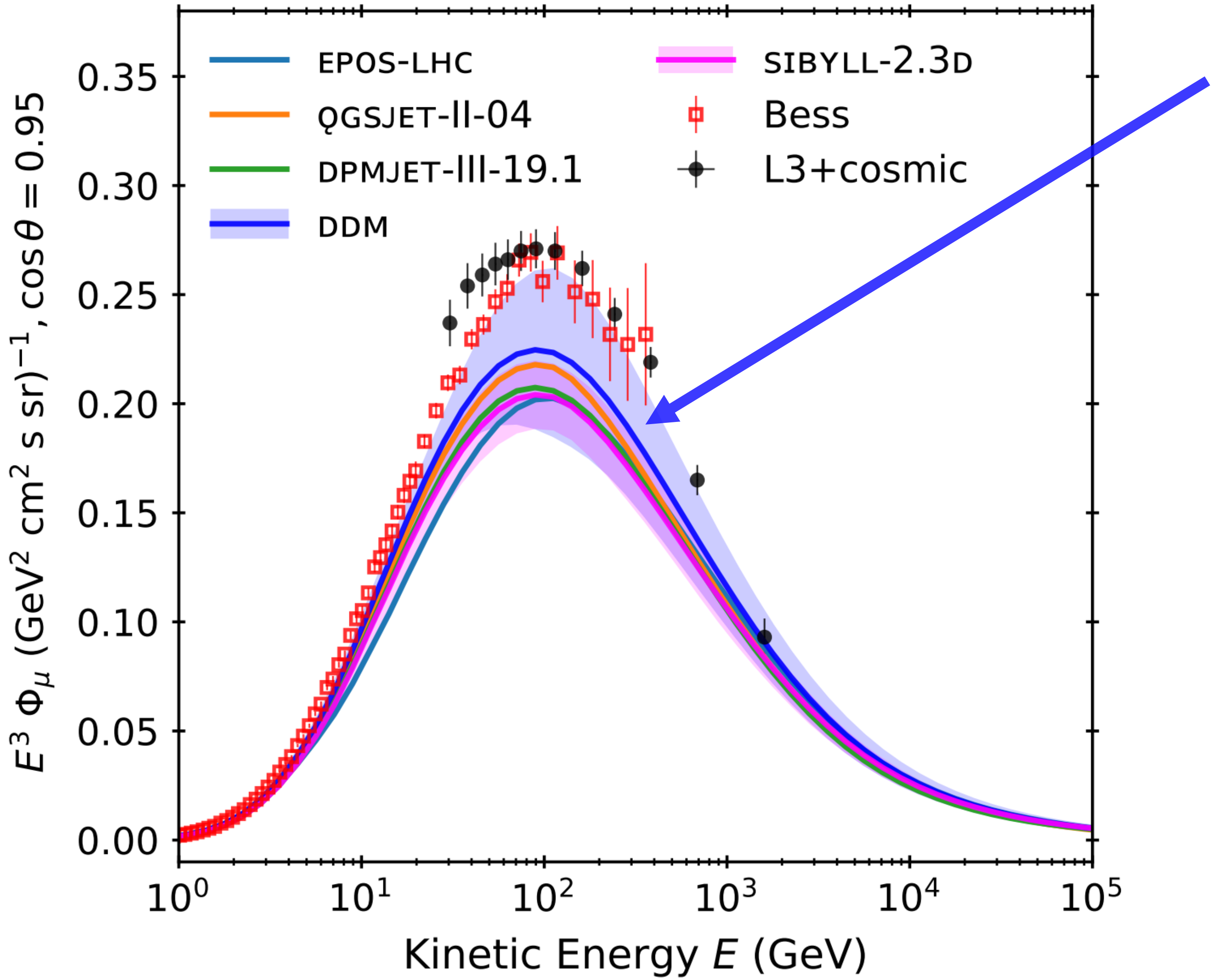


- **Uncertainties conservatively scale up** in absence of forward data
- K^{+-} data at 158 GeV extrapolated from pp→pC
  - → + 5-7% error from MC
- Carbon to air correction < 1%
- + proton and neutron secondaries , & π^- projectiles (not shown)
- Neutron (and π^+ projectiles) via isospin relations
- K^0 via isospin

Relevant phase space is $0.1 < x_{Lab} < 0.4$, contributes most to the weighted integral

AF & M. Huber, PRD, arXiv:2205.14766
AF, Woodley, Piro, ApJ 2022 arXiv:2109.11559

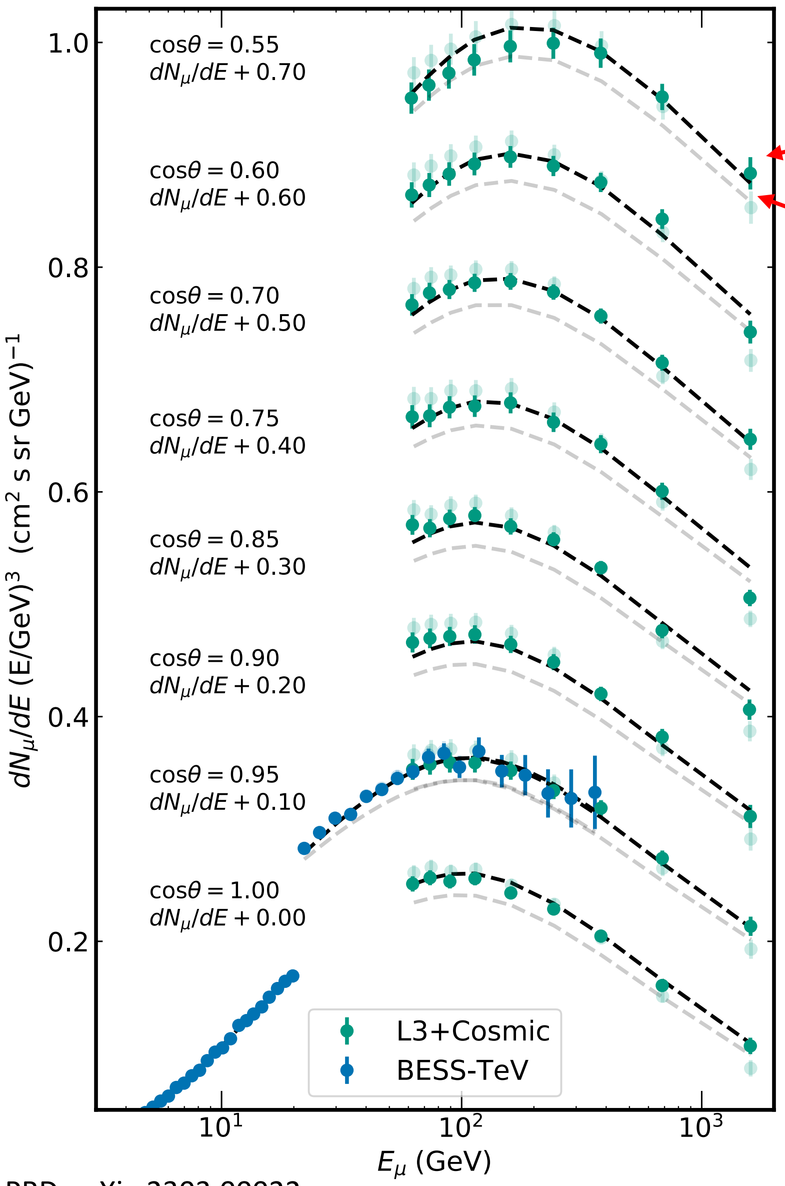
Atmospheric muon fluxes from DDM + GSF



- DDM is built using fixed target/spectrometer data (NA49/61)
- GSF: interpolates direct CR experiments (incl. AMS → few % error)
- Muon observations barely compatible within "pessimistic" error estimate of DDM
- Central prediction compatible with hadronic interaction models → the models can not be that wrong!
- Next question: how should a model look like, which is compatible with muon data? → **daemonflux**

Daemonflux: GSF+DDM calibrated to surface muon measurements

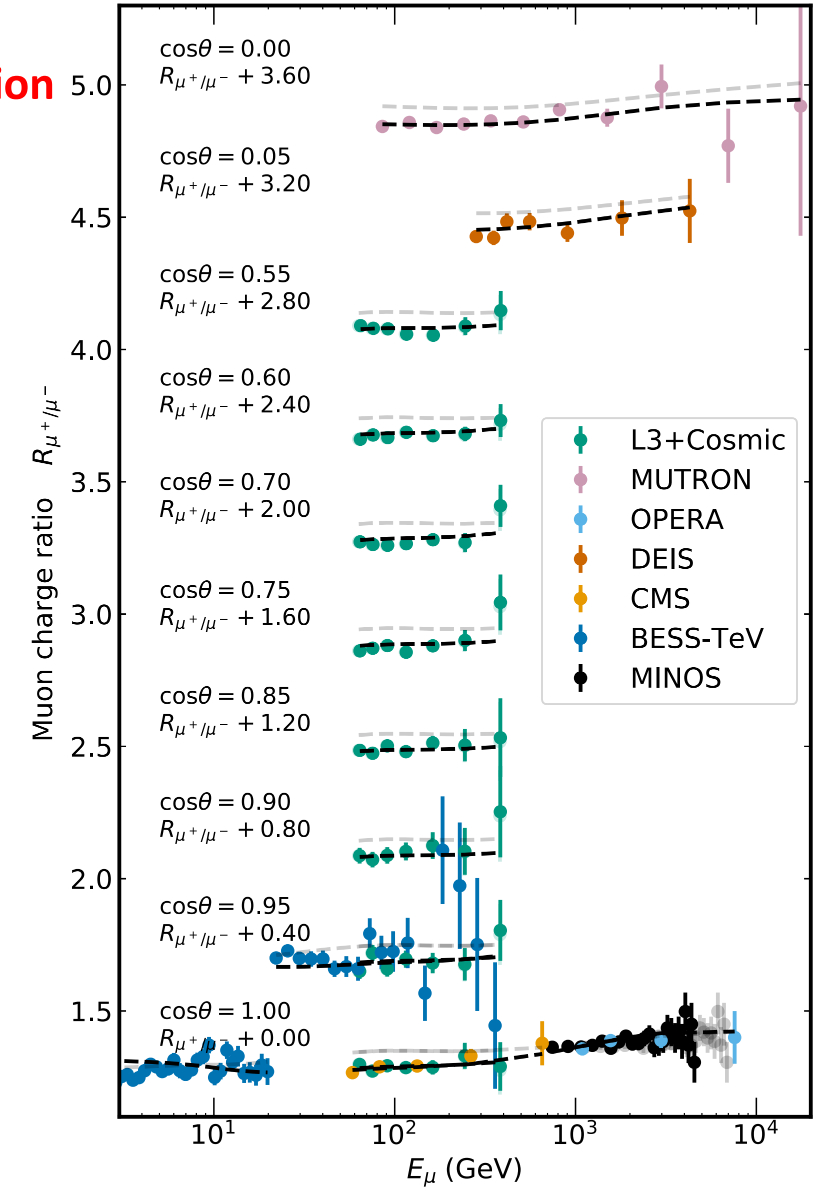
Muon flux



Data w/ syst. correction

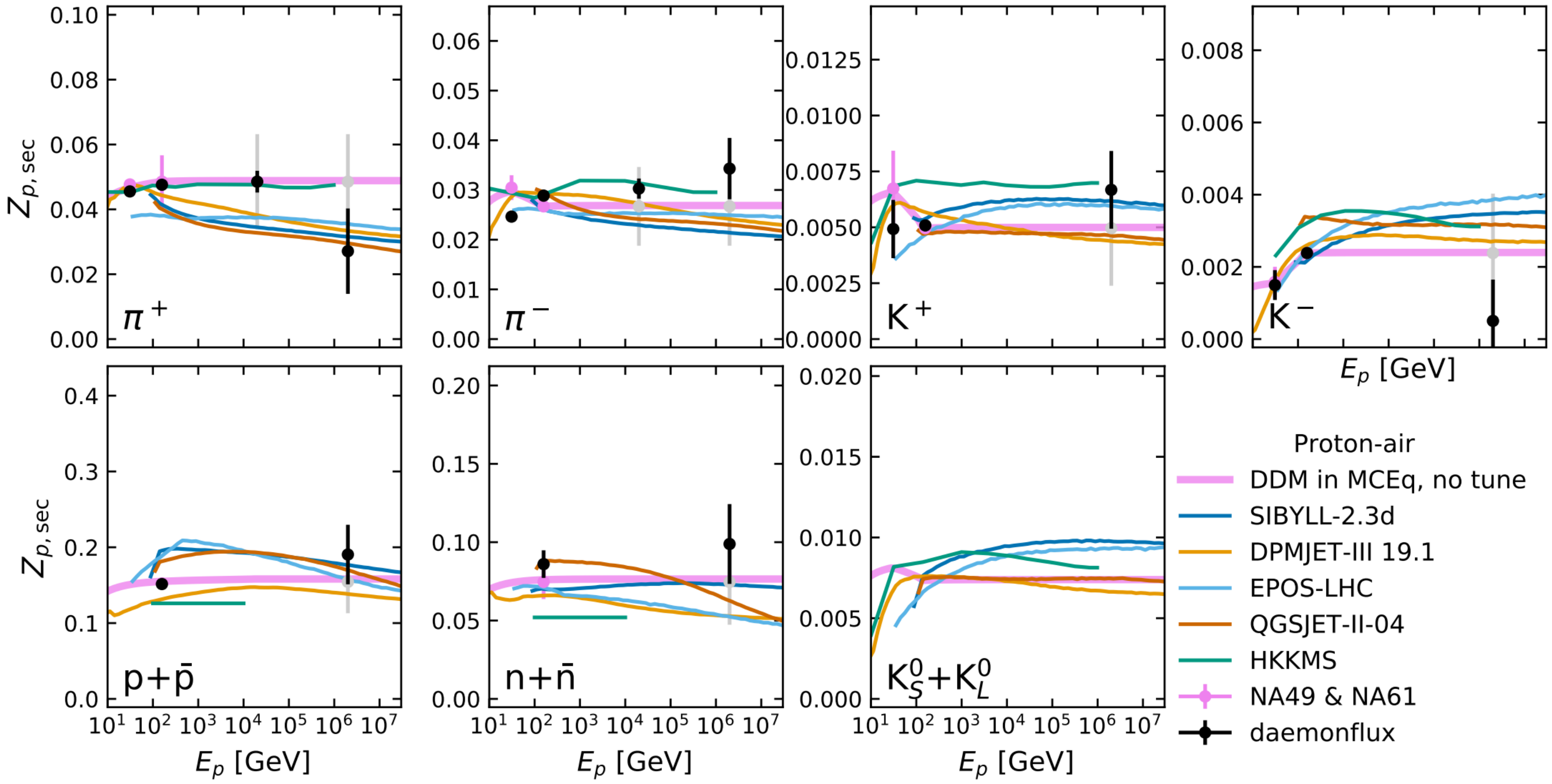
Data w/o syst. correction

Muon charge ratio



J. P. Yanez & AF, PRD, arXiv:2303.00022

What muons tell about energy dependence of forward particle yields



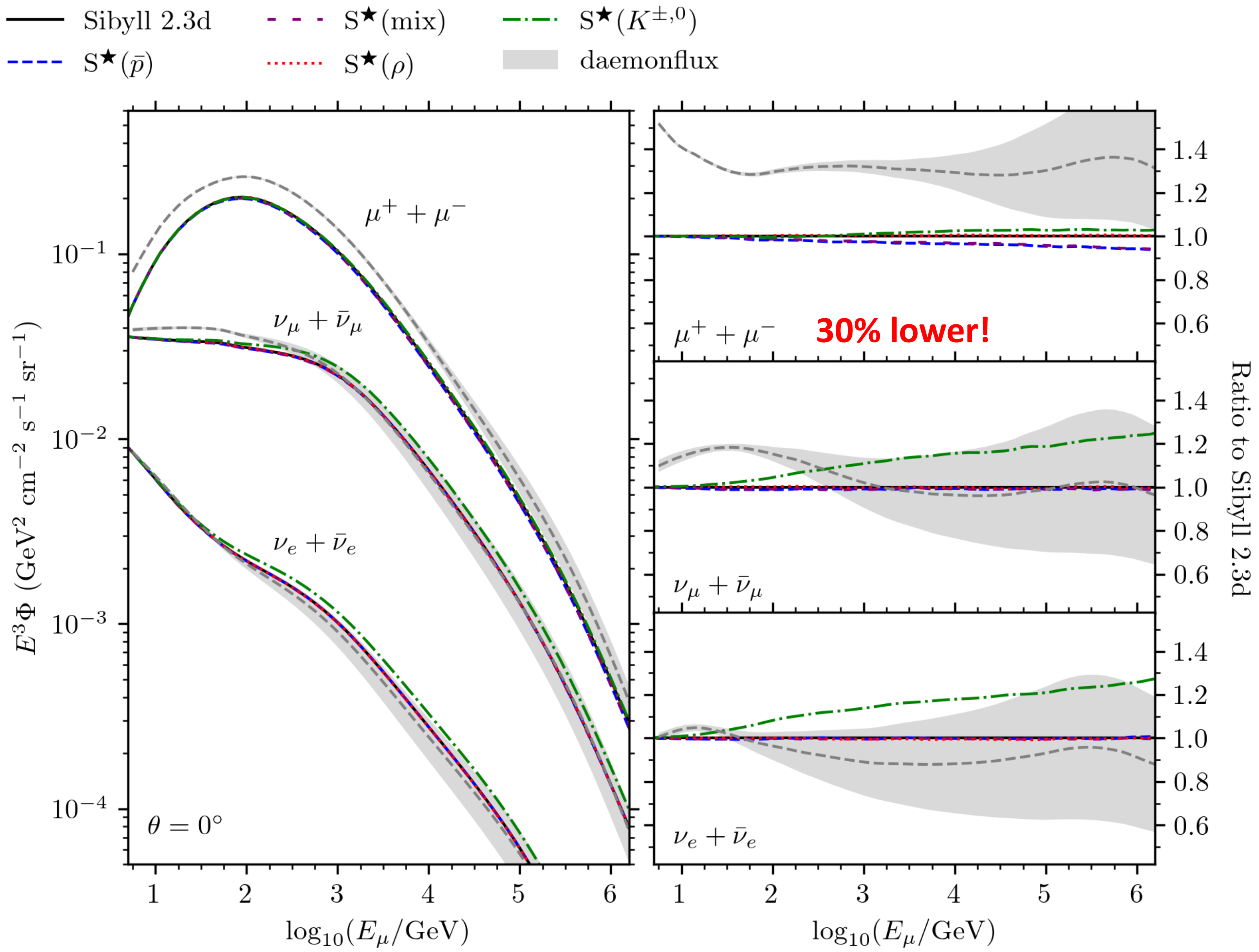
- Daemonflux uses 1 or 2 cross section "shapes" from 31 & 158 GeV
- Priors (errorbars) constrained by errors from fixed target data
- Interpolates linearly in log(E) between those
- DDM assumes Feynman scaling (shape of longitudinal spectrum constant = pink thick line)
- More degrees of freedom added to **daemonflux** such that Feynman scaling can be violated
- **Black**

Atm.-flux-relevant phase space → CR-Spectrum-weighted moment:

$$Z_{\mathrm{N}h}(E_{\mathrm{N}}) = \int_0^1 \mathrm{d}x_{\mathrm{Lab}}\; x_{\mathrm{Lab}}^{\gamma(E_{\mathrm{N}})-1} \frac{\mathrm{d}N_{\mathrm{N}\to h}}{\mathrm{d}x_{\mathrm{Lab}}}(E_{\mathrm{N}})$$

SIBYLL* vs data-driven muon-calibrated model (daemonflux)

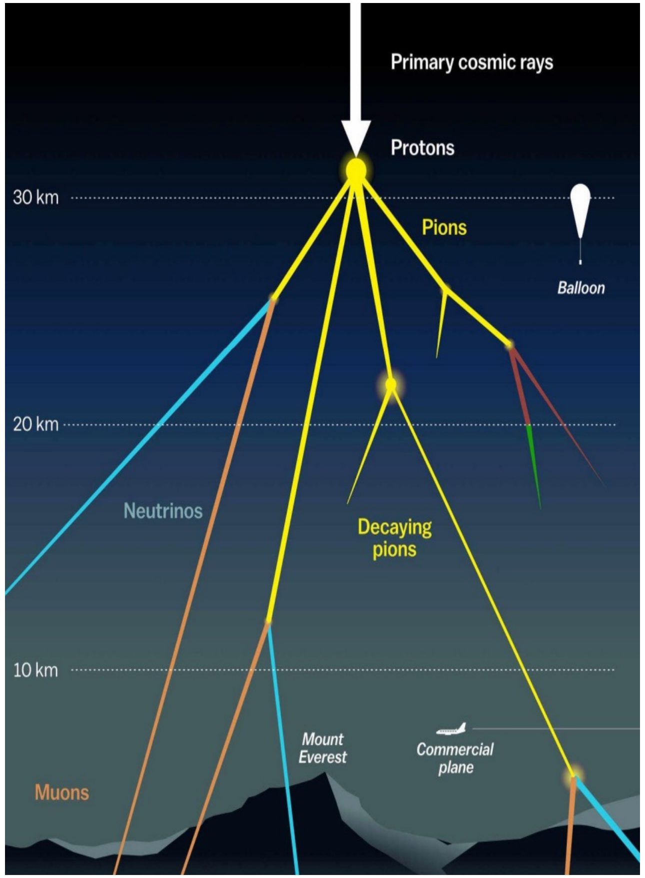
F. Riehn, AF, R. Engel,
accepted, to appear soon

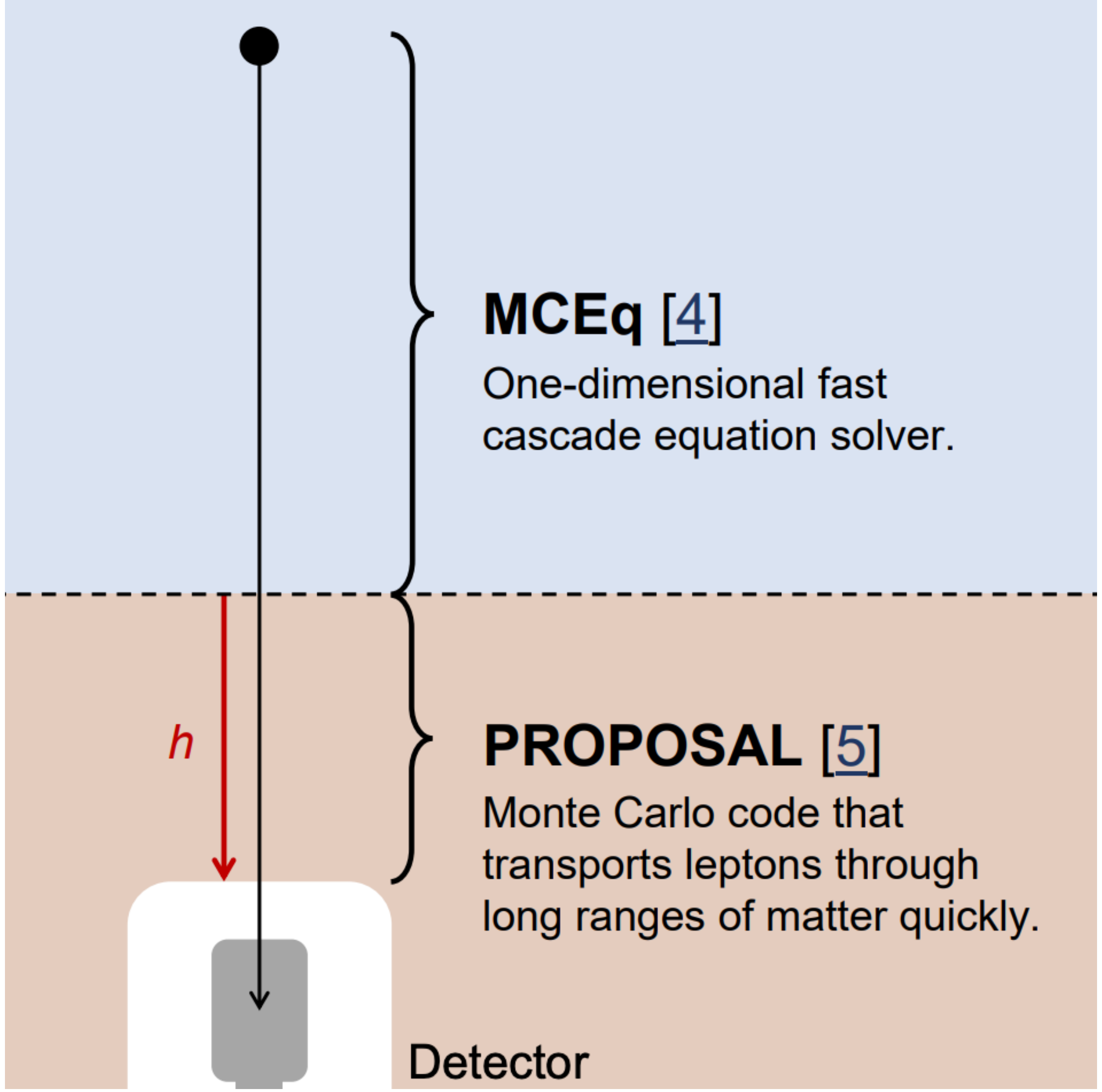


- SIBYLL*: set of modifications to SIBYLL-2.3d to solve the muon excess UHECR **(see R. Engel's talk)**
- SIBYLL* has similar inclusive fluxes as the other models +-10%
- Interestingly, neutrino fluxes are predicted by daemonflux not different from SIBYLL estimates
- But until now, no neutrino data sensitive to the flux normalization…
- **Could FASER/FPF measure the pi + K (0.1 < x_F < 0.4) neutrinos to this precision?**
- **→ can determine if 30% excess is due to hadronic int. or from CR flux**

High energy constraints from underground μ?

W. Woodley (UofA), TeVPa 2022

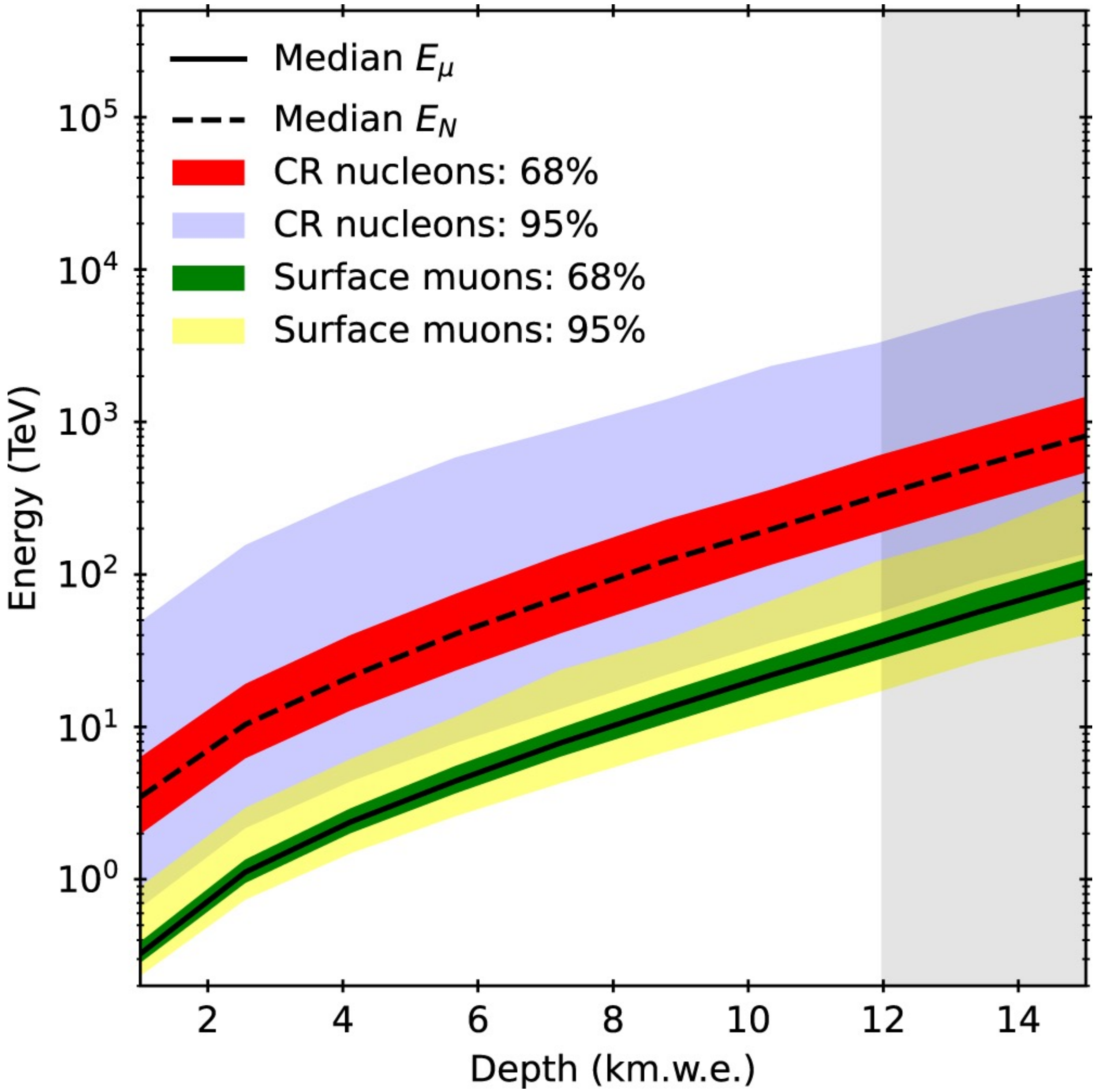




AF, **W. Woodley**, M.-C. Piro, *ApJ* **928** 27 (2022)

W. Woodley, TeVPa 2022 and Woodley, AF, Piro in prep.

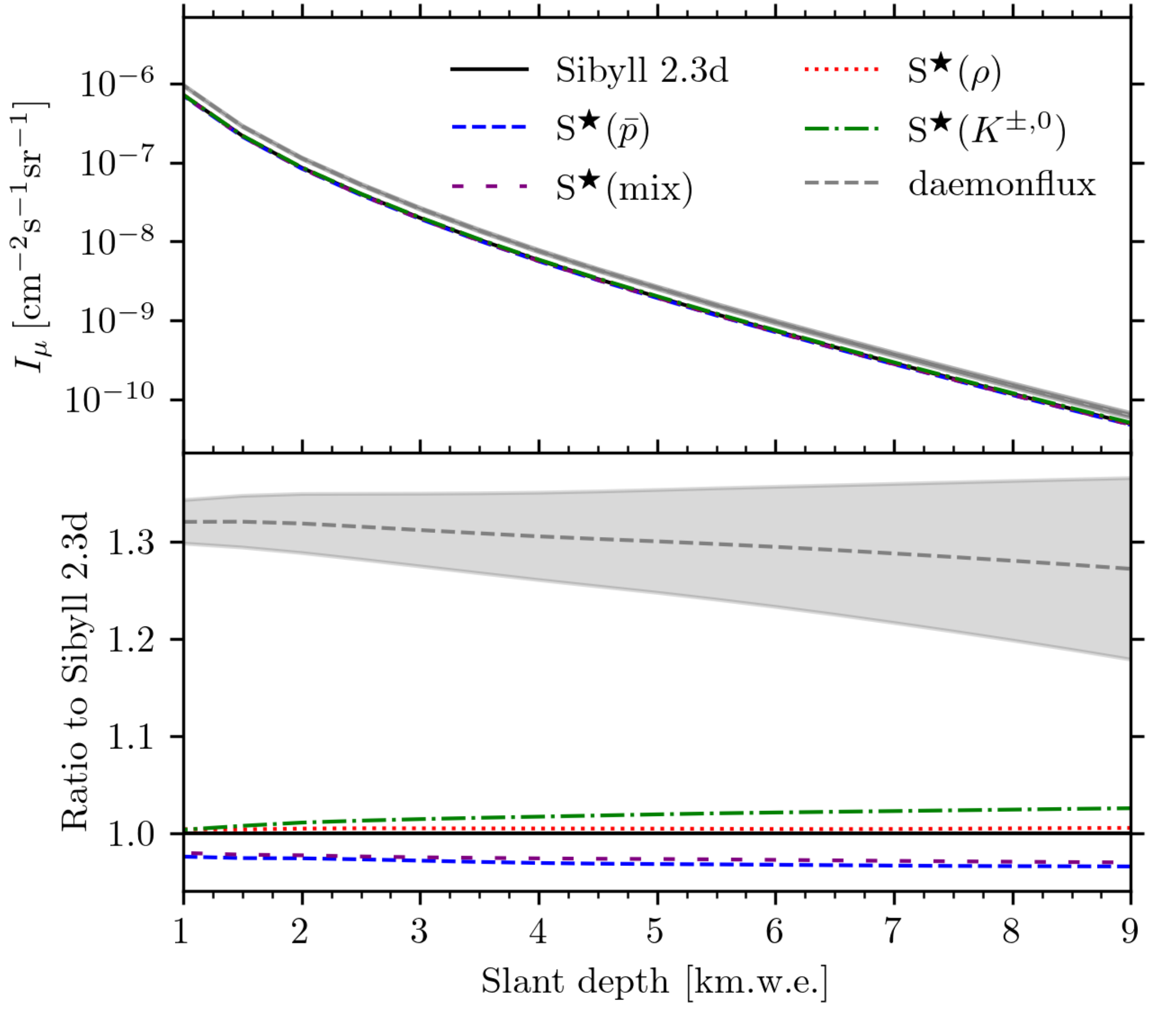
Relation of depth to surface and CR energy

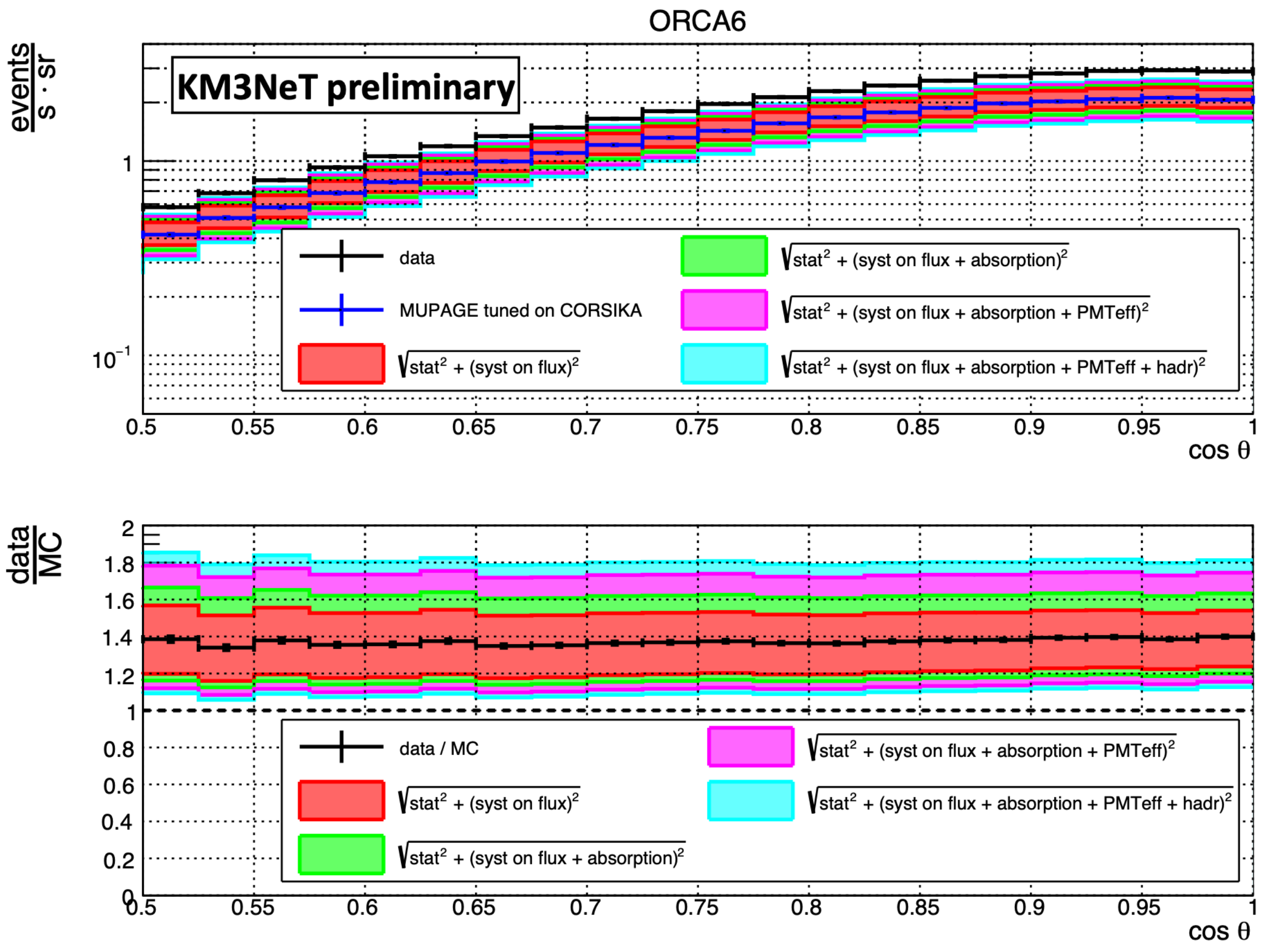


AF, W. Woodley, M.-C. Piro, *ApJ* **928** 27 (2022)

Daemonflux vs models underground/-water

A. Romanov et al. (KM3NeT), PoS(ICRC2023) 338

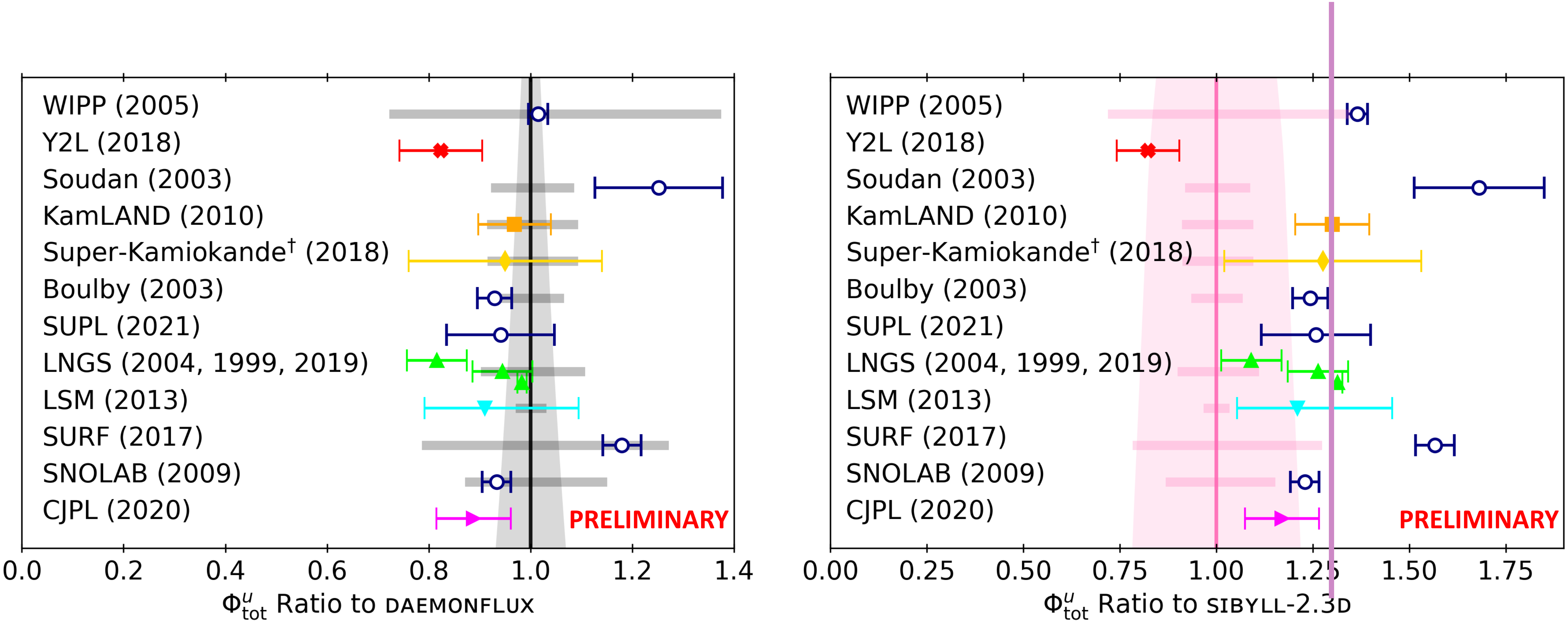




> 30% discrepancy confirmed using independent analysis and tools pipeline using underwater detector.

F. Riehn, AF, R. Engel, to appear soon

Total muon fluxes underground: “simple” measurement



- Measurement almost model independent
- Calculations difficult (chem. rock composition, density, overburden topography)
- Final result will change (a bit), pls don’t use these plots

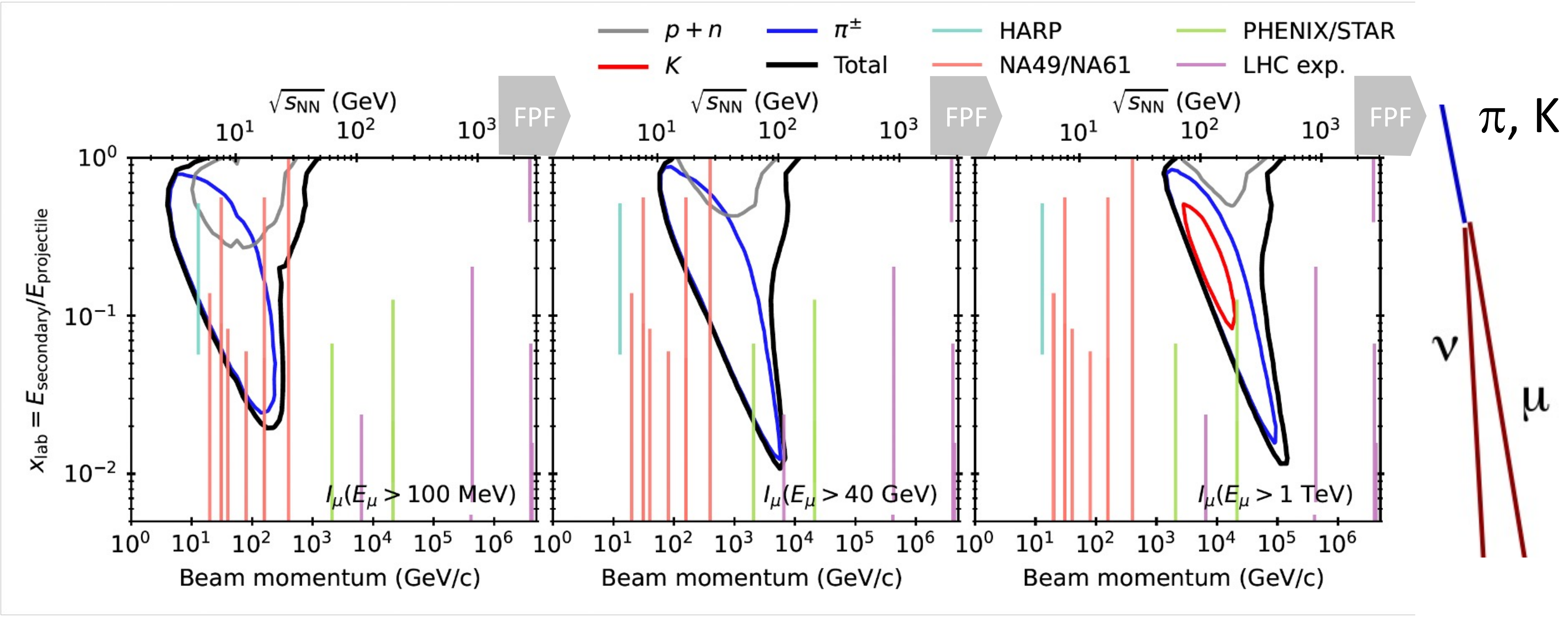
Woodley, AF, Piro, shown at PoS(ICRC2023) 338, paper to appear soon

Summary

- Atm. Leptons are a different channel to study very forward hadronic interactions (mostly p-air)
- “Differences“ seen in comparisons with muon data at the surface and underground
- Validation/calibration via muon surface fluxes very challenging if performed rigorously!
  (old data and docs)
- **Models 30-35% lower than muon data above a few tens of GeV**
- Discrepancy in neutrinos (more sensitive to kaon production) experimentally not established
- Can the FPF constrain the pion + kaon yields within **$0.1 < x_F < 0.4$** in p-O or pp interactions?
- Origin of discrepancies different from the muon excess in air showers (SIBYLL*)
- Current work is on understanding data

Related muon production phase space

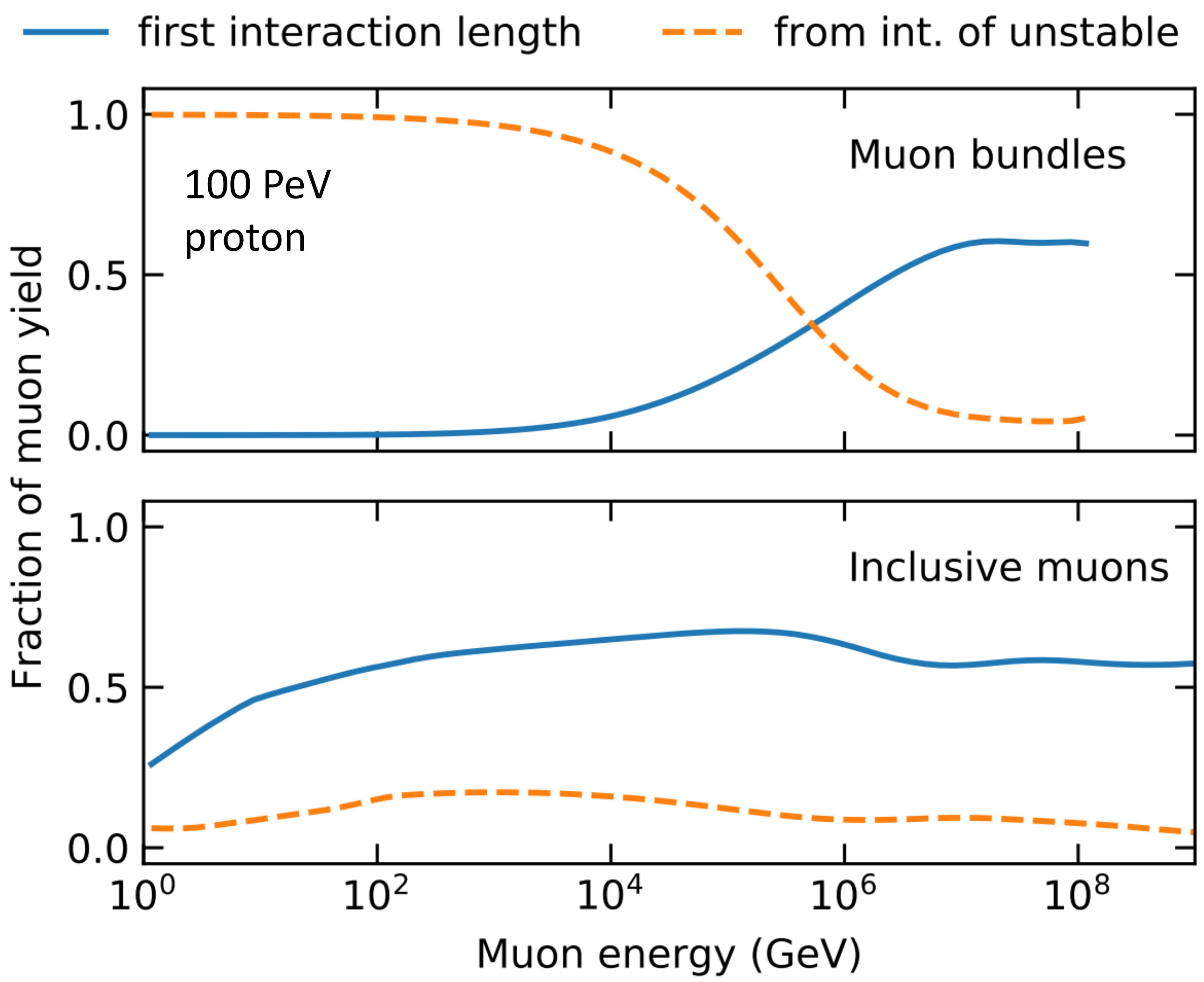
AF & M. Huber, arXiv:2205.14766



Contours = 90% of integral flux above indicated threshold

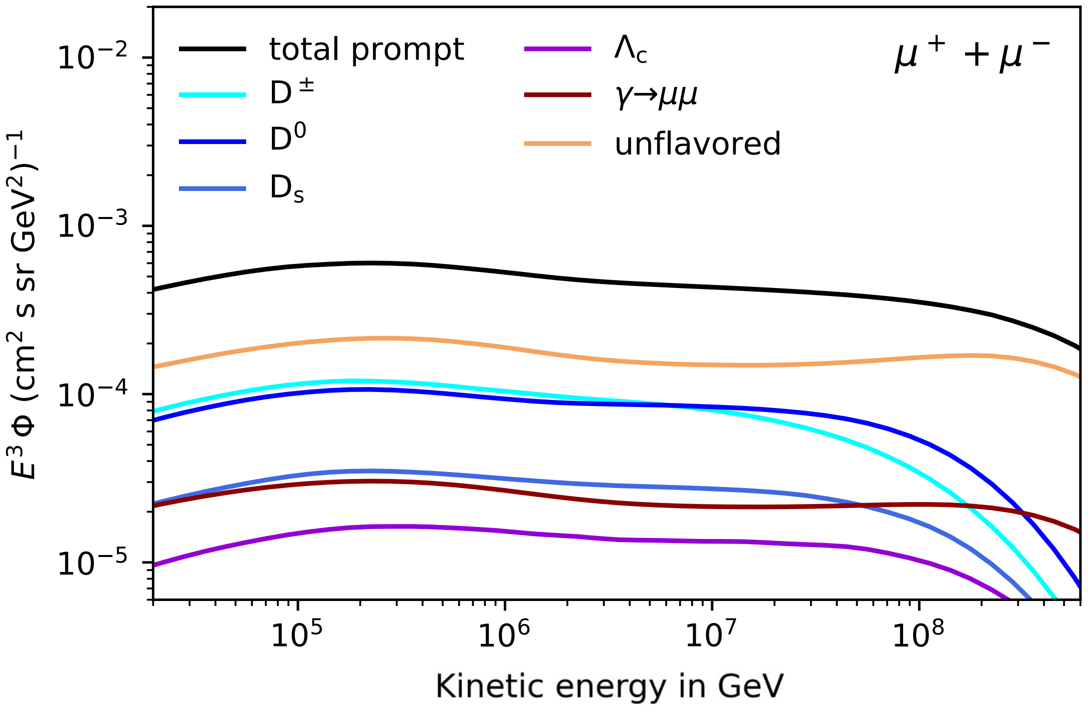
Atm. leptons != air showers: different “astroparticle observable”

- Inclusive fluxes sensitive to ”first interaction”
- Air shower muons at the surface mostly from pion interactions
- Reason: competition between falling CR flux vs falling forward cross section
- Problems in incl. leptons distinct should be distinct from air showers

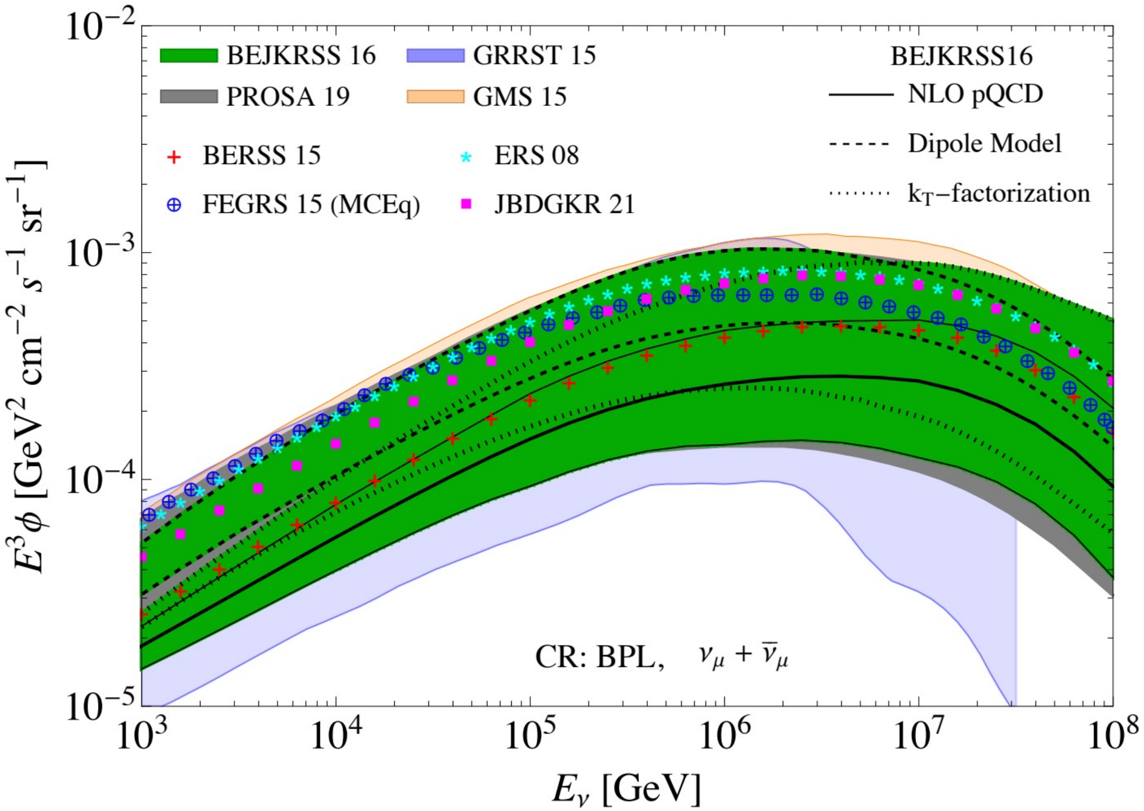


Above 100 TeV: territory of the (undiscovered) prompt muons and neutrinos

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



Forward Physics Facility Snowmass arXiv: 2203.05090

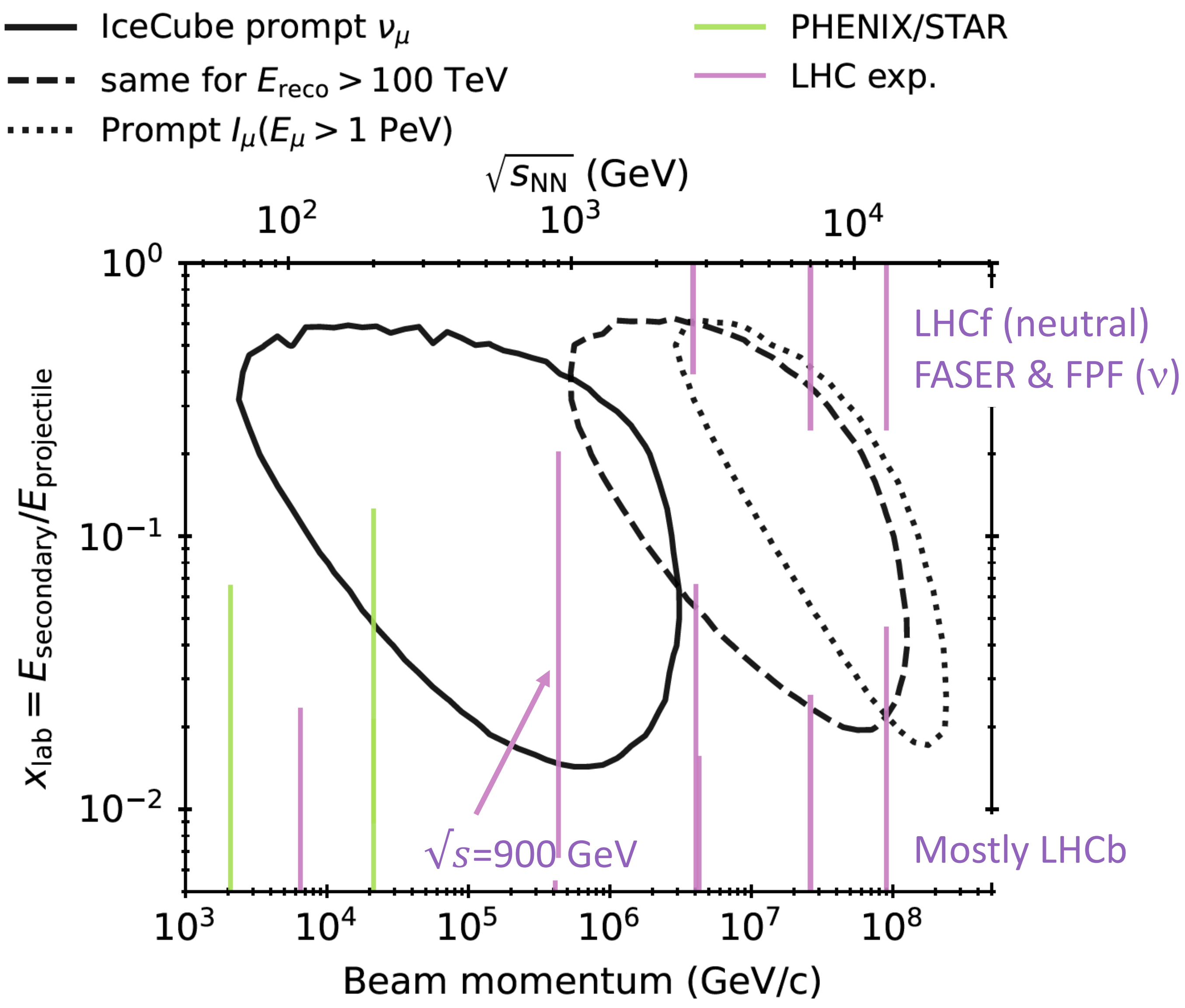


Prompt muons more production channels than prompt neutrinos:

- Rare decays of unflavored mesons *e.g.*, $\eta \to \mu^+\mu^-$
- EM pair production $\gamma \to \mu^+\mu^-$

- Large uncertainties from pQCD
- pQCD might be incomplete (intrinsic charm)
- The fragmentation (c $\to D$) function is a choice

Charm production cross section inaccessible to present-day colliders



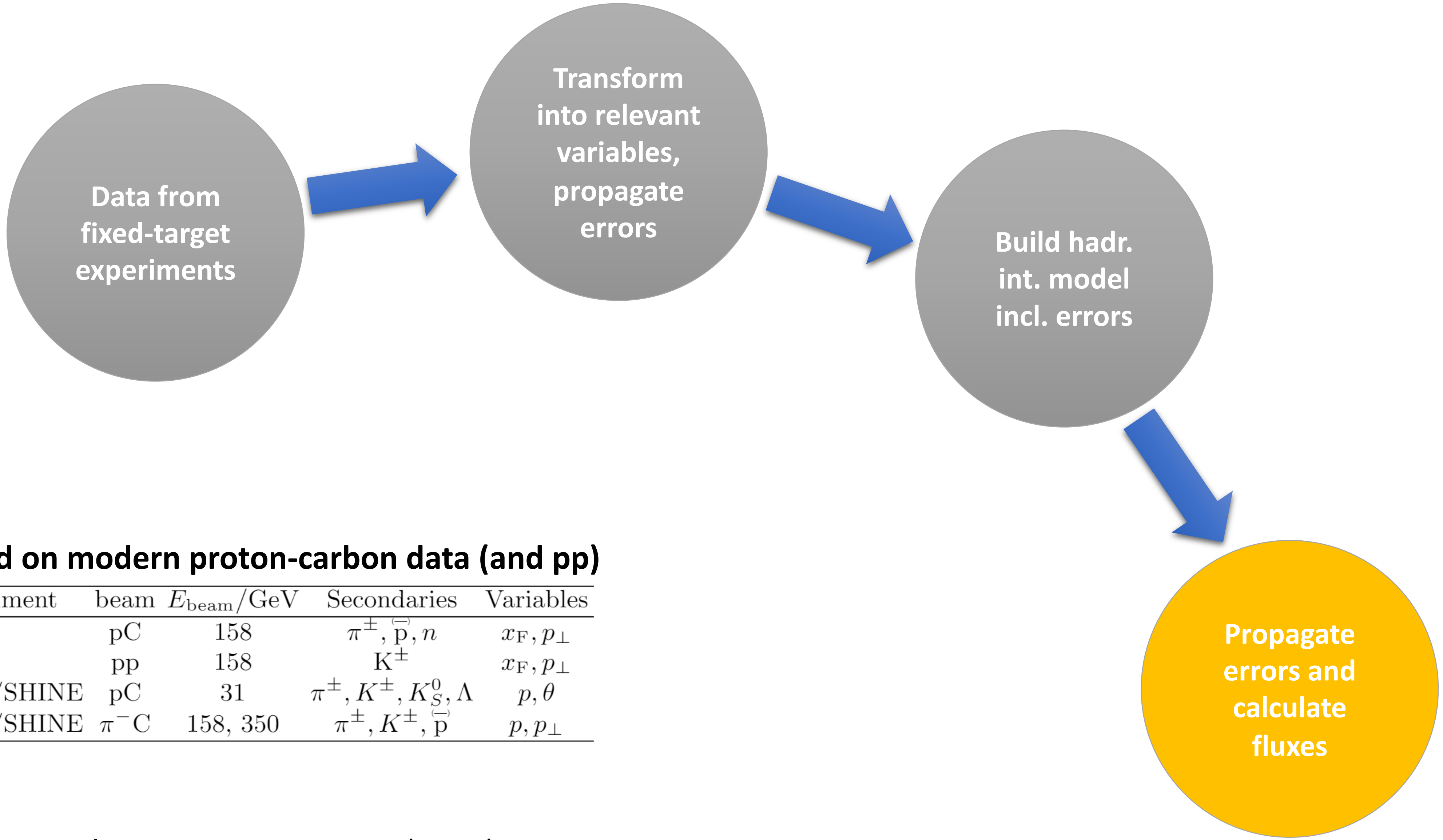
- Each line represents a collider running at fixed $\sqrt{s}$
- Gap in x between LHC coverage is due to the beam pipe
- Detectors need particle ID capability & sufficient luminosity
- Indirect constraints from new forward detectors like FASER and the proposed FPF (see 2203.05090)
- New insights expected from proton-oxygen collisions in Run3

Neutrino contours: 90% events in IceCube

Muon contours: 90% of integral flux

AF & M. Huber, arXiv:2205.14766

Data-Driven Hadronic Interaction Model (DDM)



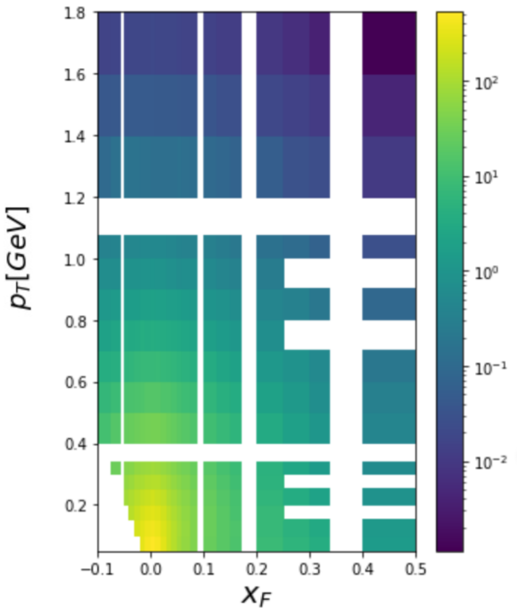
Based on modern proton-carbon data (and pp)

Experiment	beam	$E_{\mathrm{beam}}/\mathrm{GeV}$	Secondaries	Variables
NA49	pC	158	$\pi^{\pm}, \overset{(-)}{\mathrm{p}}, n$	$x_{\mathrm{F}}, p_{\perp}$
NA49	pp	158	$\mathrm{K}^{\pm}$	$x_{\mathrm{F}}, p_{\perp}$
NA61/SHINE	pC	31	$\pi^{\pm}, K^{\pm}, K^0_S, \Lambda$	p, θ
NA61/SHINE	$\pi^{-}\mathrm{C}$	158, 350	$\pi^{\pm}, K^{\pm}, \overset{(-)}{\mathrm{p}}$	$p, p_{\perp}$

AF & M. Huber, PRD 106, 083018 (2022), arXiv:2205.14766

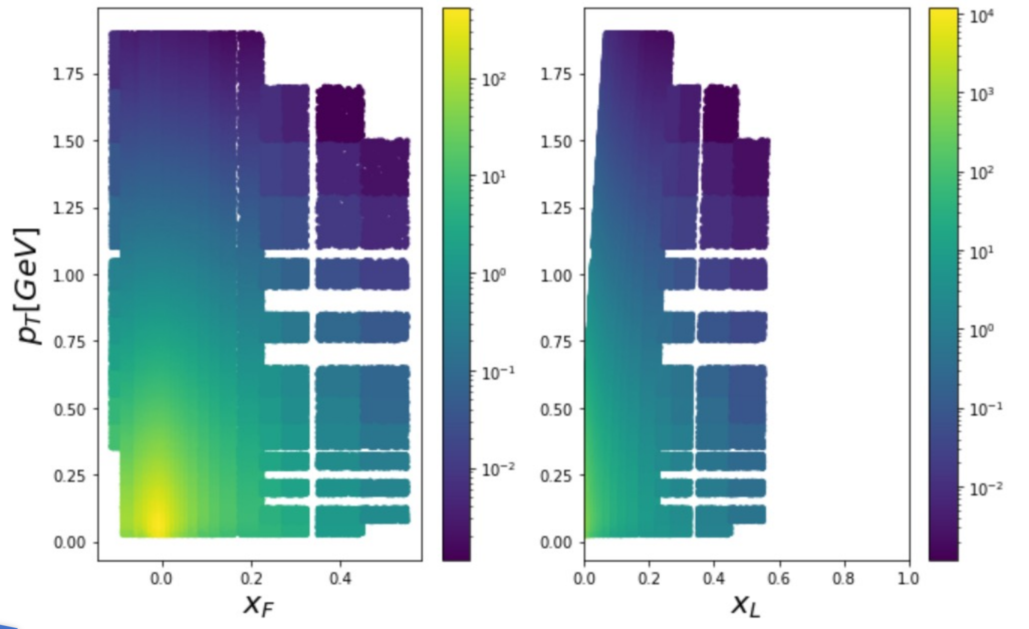
Building the DDM

NA49 proton-carbon @ 158 GeV

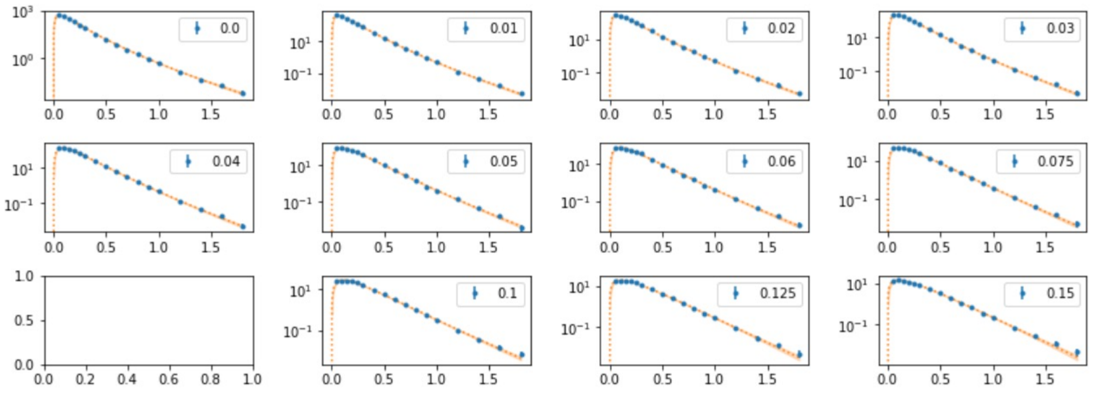


Sample from
x_F = pz/sqrt(s) and convert into $x_L = E_{secondary}/E_{proj}$

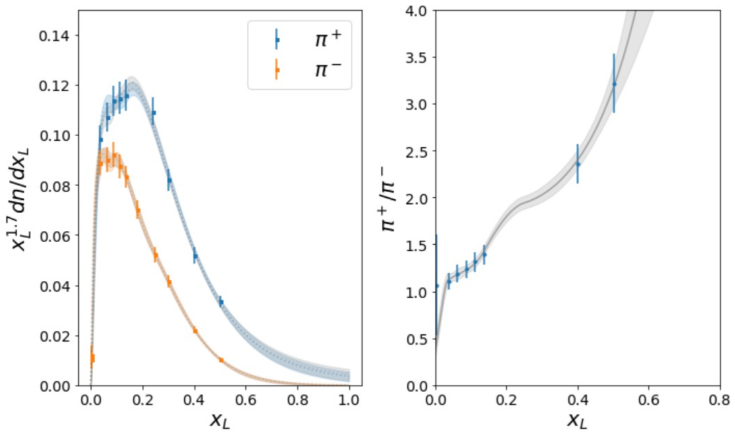
$$x_{Lab} = \frac{E_c}{E_a} = \frac{\gamma\sqrt{m_c^2 + \frac{1}{4}x_F^2 E_{c.m.}^2 + p_{c,T}^{*2}} + \frac{1}{2}\gamma\beta x_F^2 E_{c.m.}}{E_a}$$



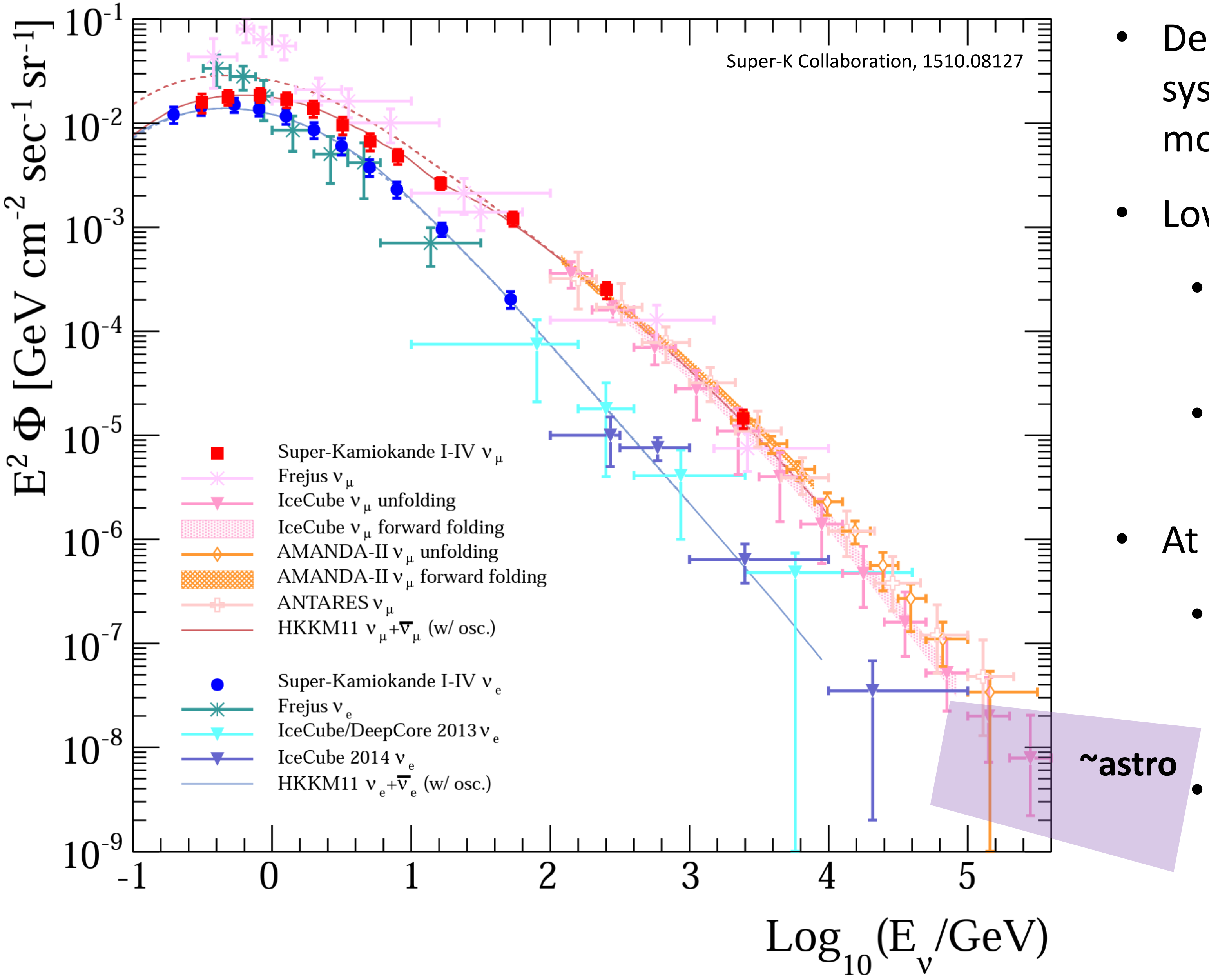
Fit dn/dx_L with splines, get covariance matrix



Fit pT in each x_F bin using $$\frac{dn}{dp_\perp} = a_0 p_\perp^{a_1}\ e^{a_2 p_\perp^{a_3}}$$

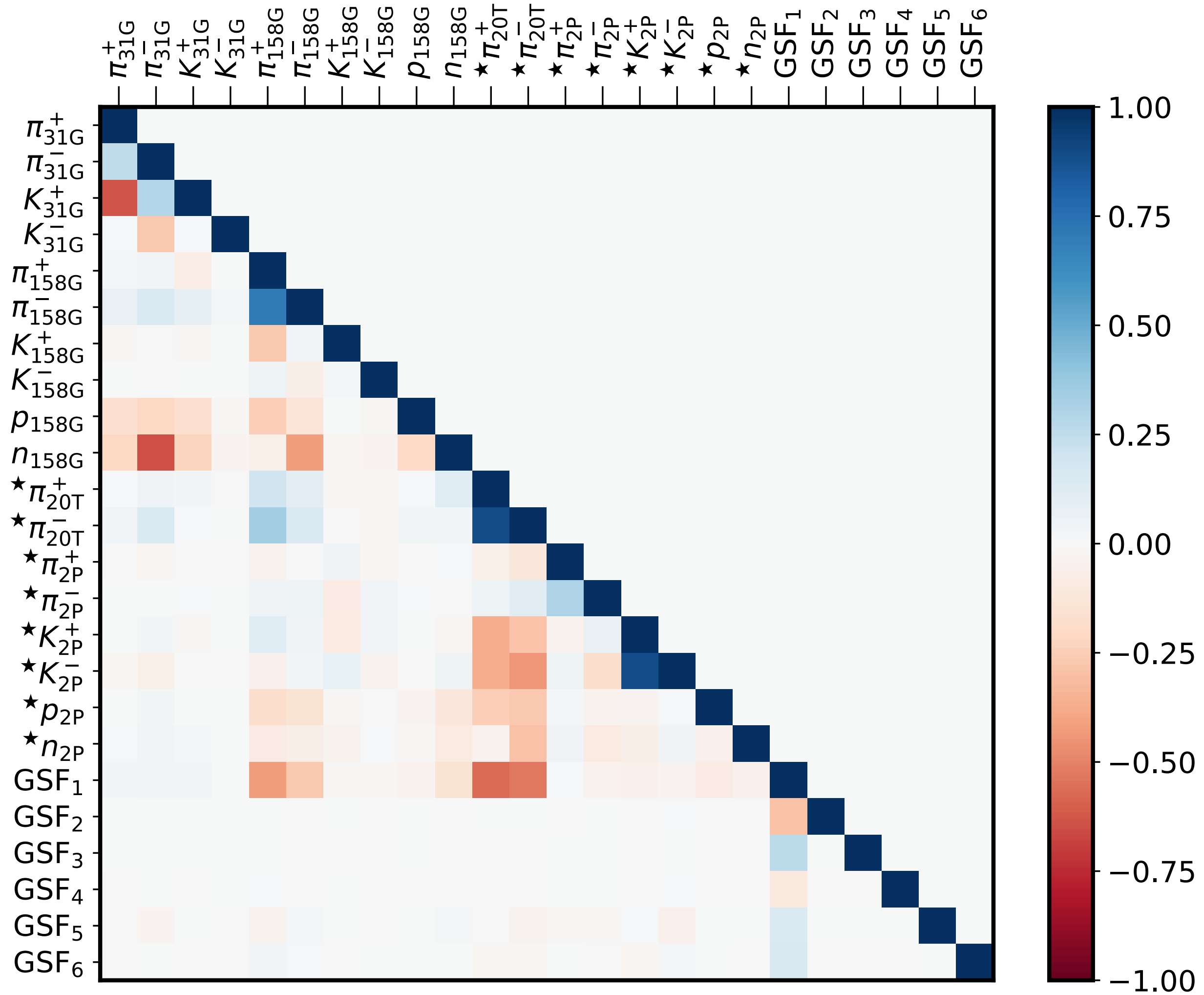


Measurements of atm. neutrinos



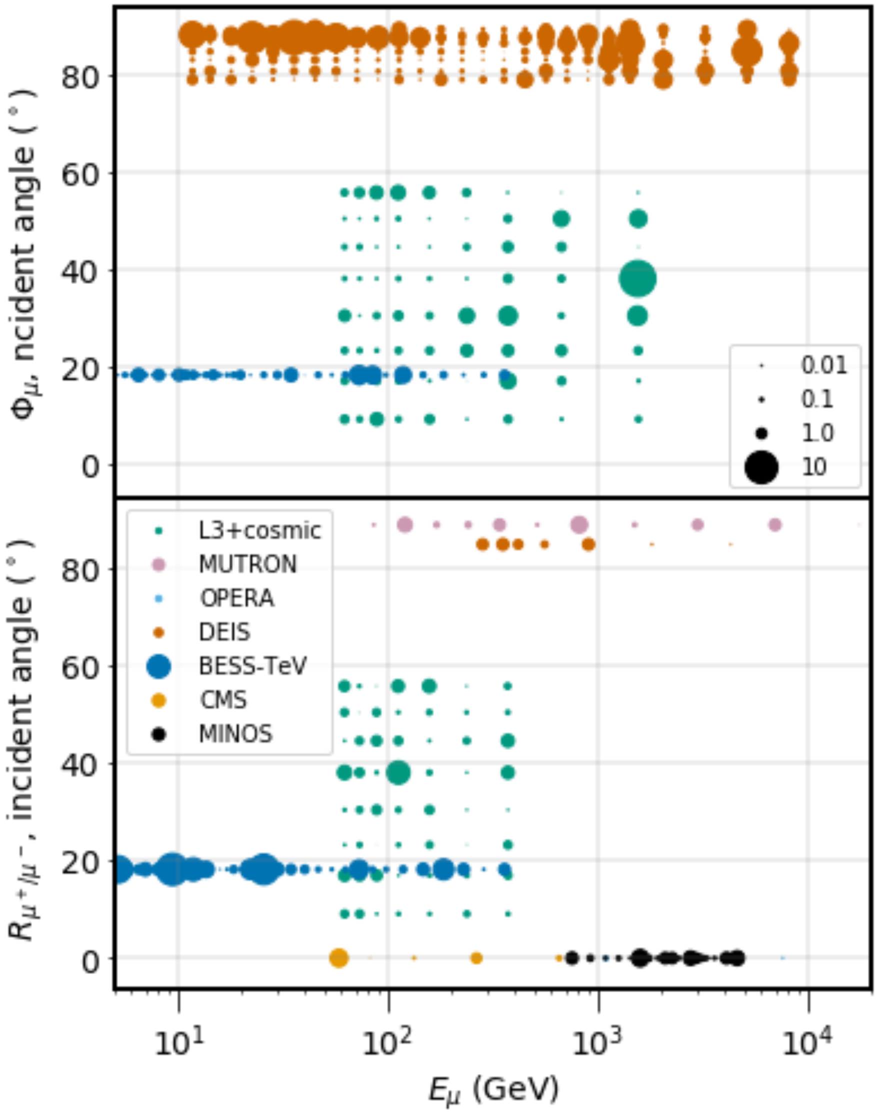
- Degeneracy between detector systematics, cross section, assumed flux model and oscillation parameters
- Low energies:
  - Cross section models uncertain -> uncertain norm and spectrum
  - Faint and complex signal -> syst. errors
- At high energies:
  - Muon track from numu charged current not contained withing detectors -> bad energy res.
  - Electron neutrino measurements suffer from lack statistics and neutral current background -> bad stats

Fit quality



Physics parameter part of the correlation matrix: Total 34 parameters: 18 hadrons + 6 GSF + 10 experimental

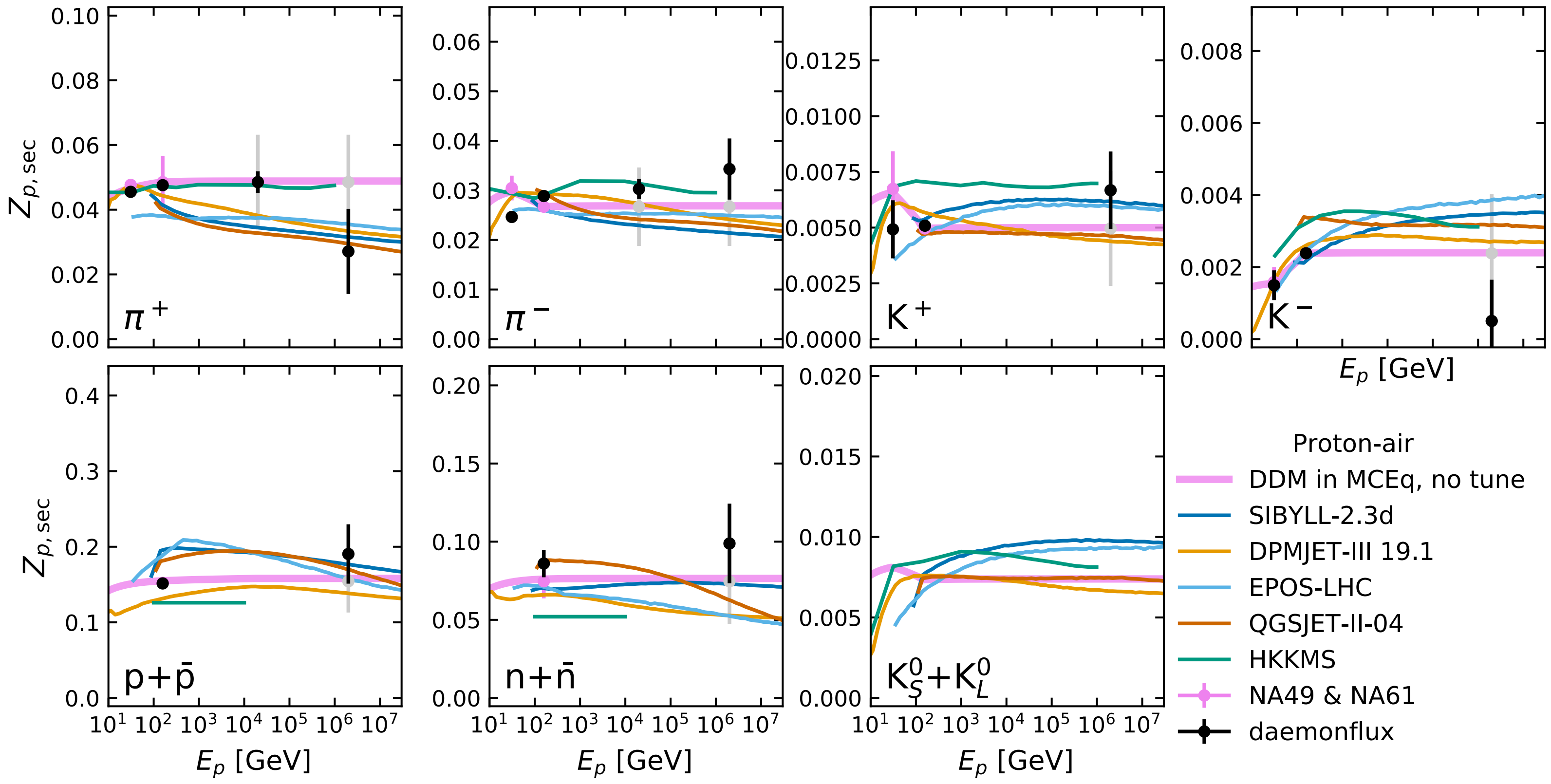
Contribution to Chi2

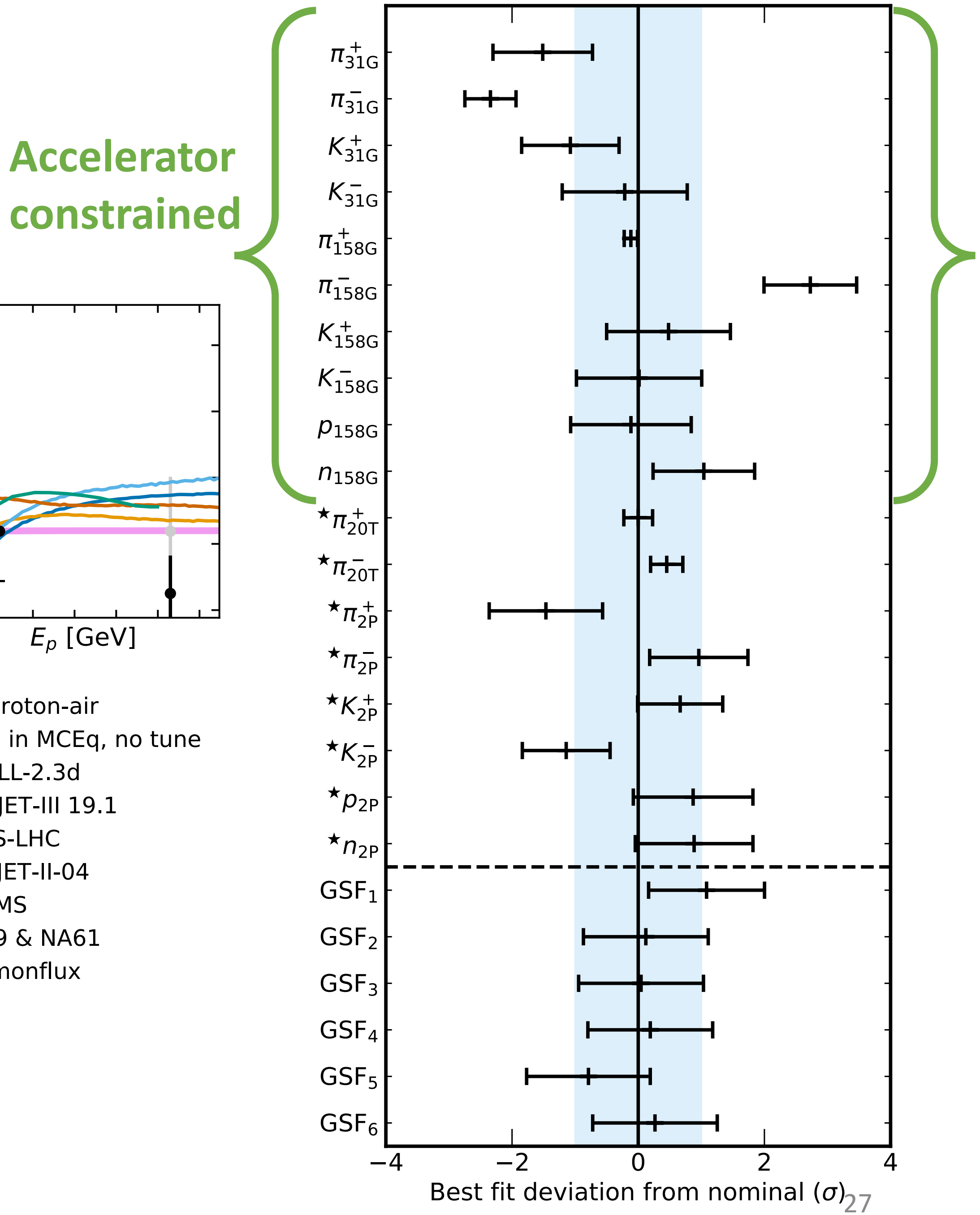


Chi^2 199/ 217 dof (approximate)
P-value = 81%

J. P. Yanez & AF, arXiv:2303.00022

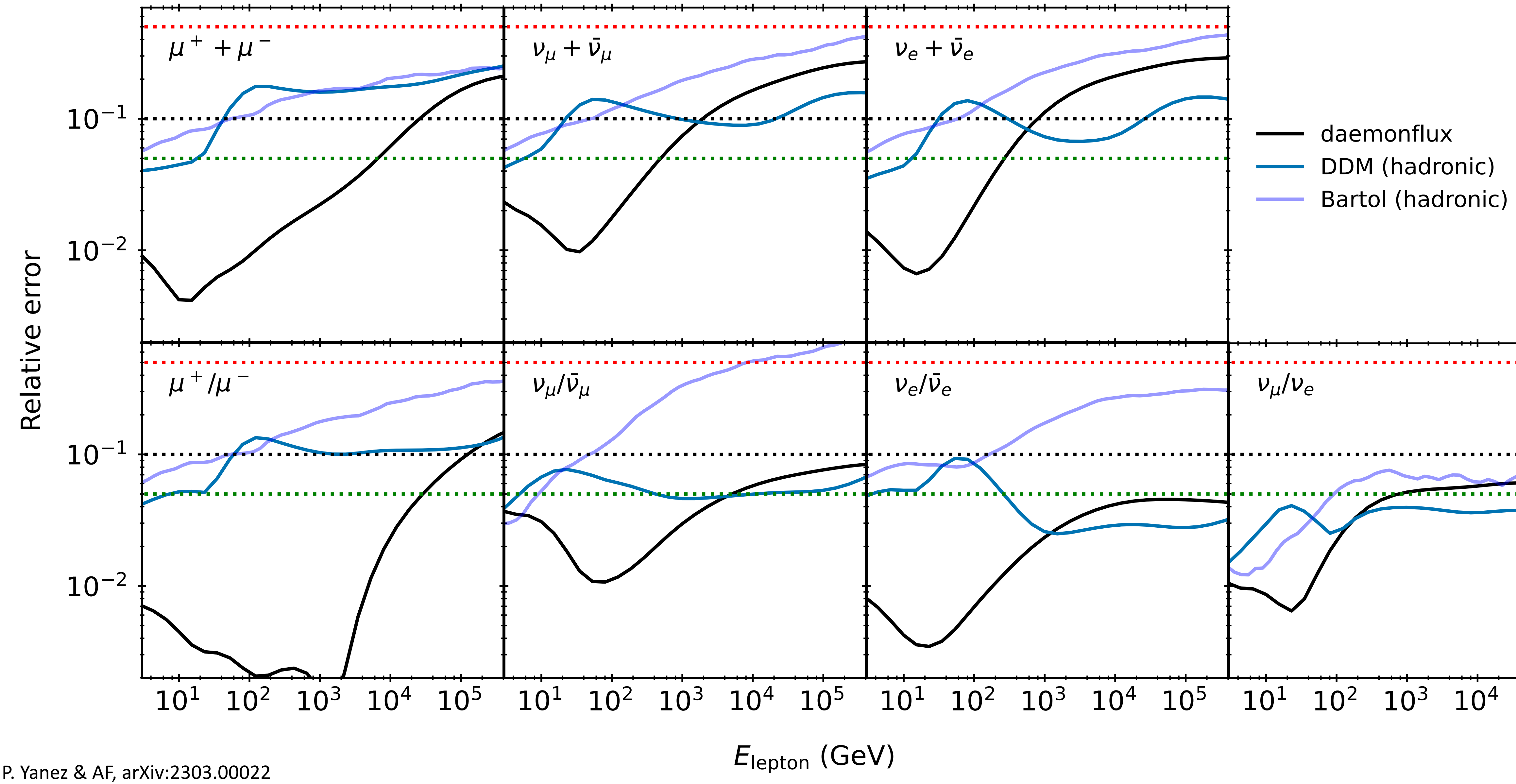
Fitted parameter values





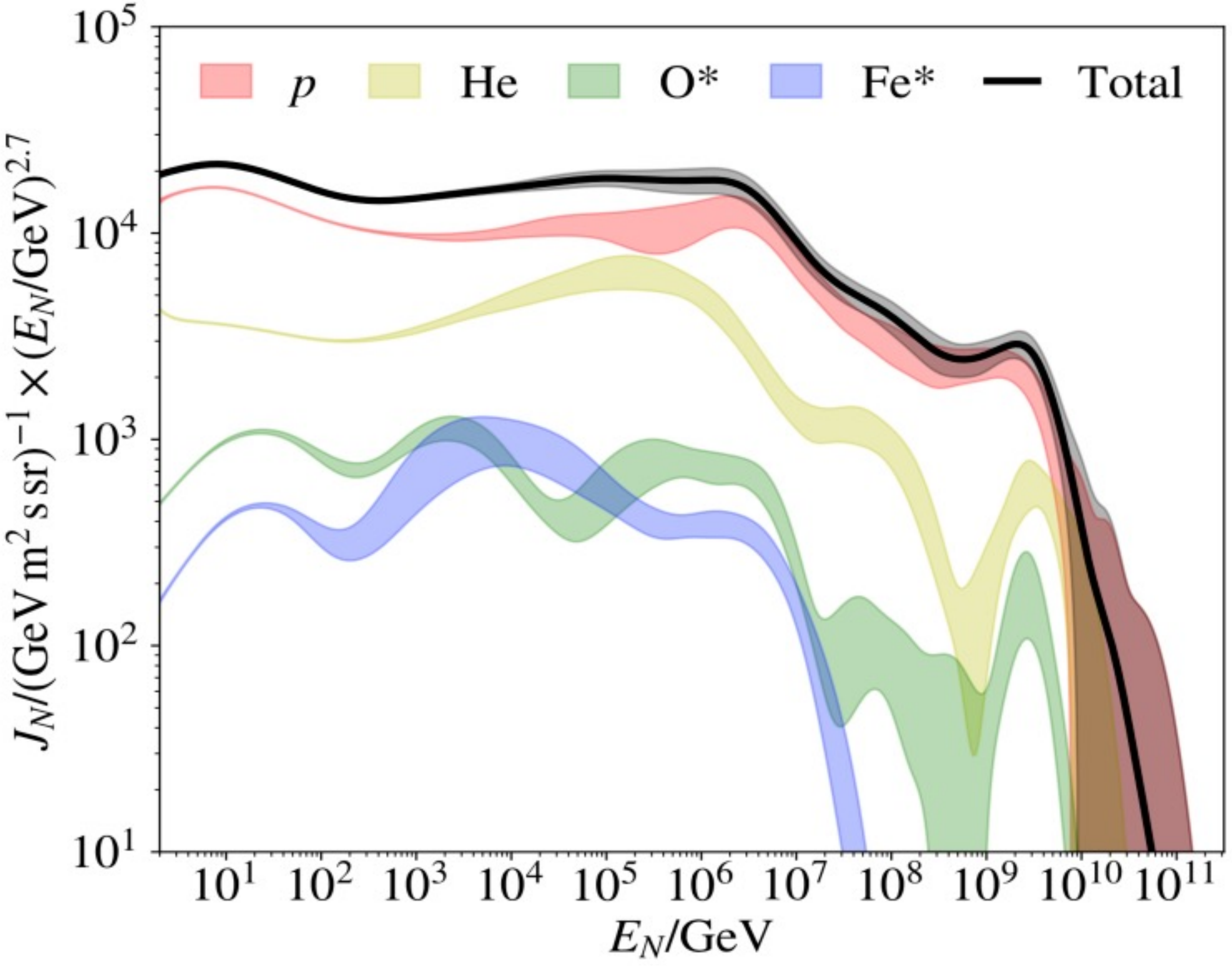
J. P. Yanez & AF, arXiv:2303.00022

Total uncertainty of daemonflux (DDM+GSF+Fit)



J. P. Yanez & AF, arXiv:2303.00022

The Global Spline Fit – nucleon fluxes (MCEq input)



- Most contribution from proton and helium flux
- Correlations between H and He affect
  - CR neutron fraction
  - Muon charge ratio
  - Neutrino/Antineutrino ratio

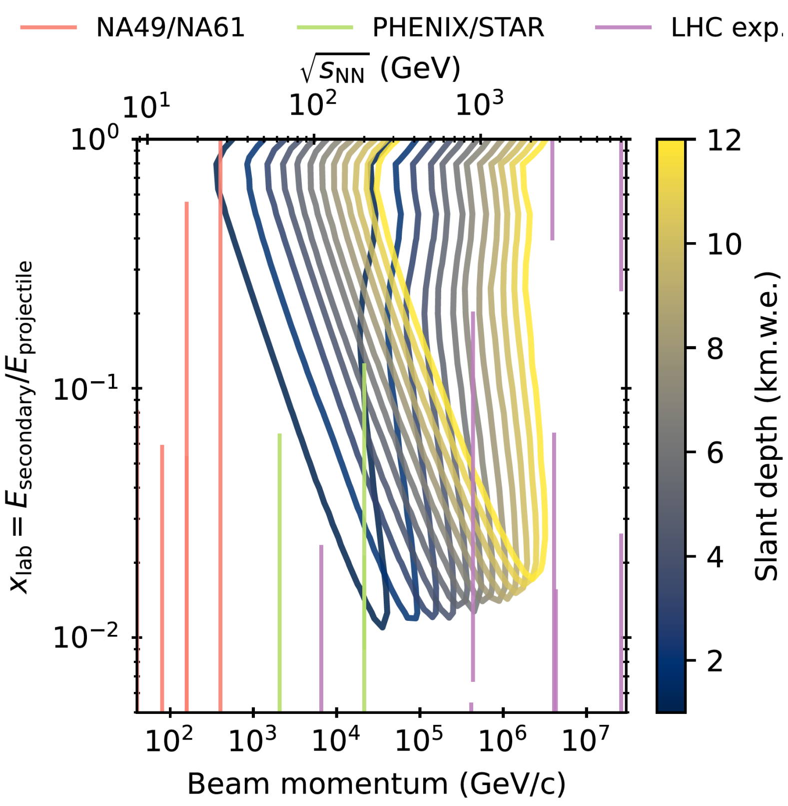
→ Need to model two correlated components

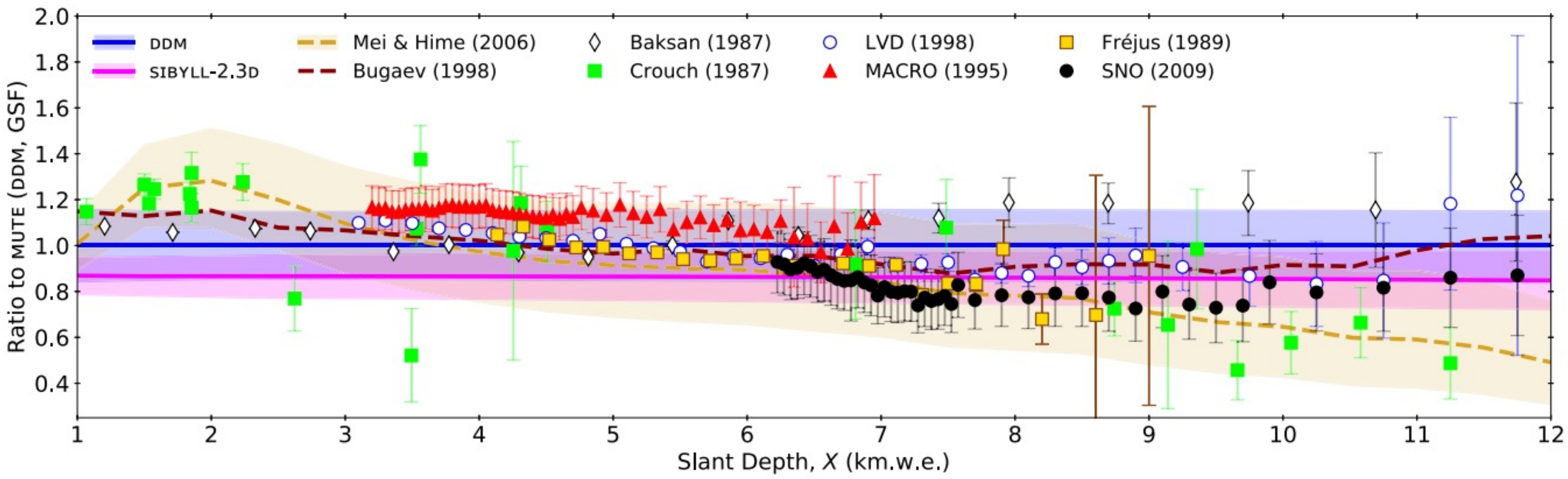
→ technically ~80 parameters

AF, Dembinski, Engel, Riehn, Gaisser, Stanev ICRC 2017

Underground data constraining if systematics understood

AF, **W. Woodley**, M.-C. Piro, *ApJ* **928** 27 (2022)





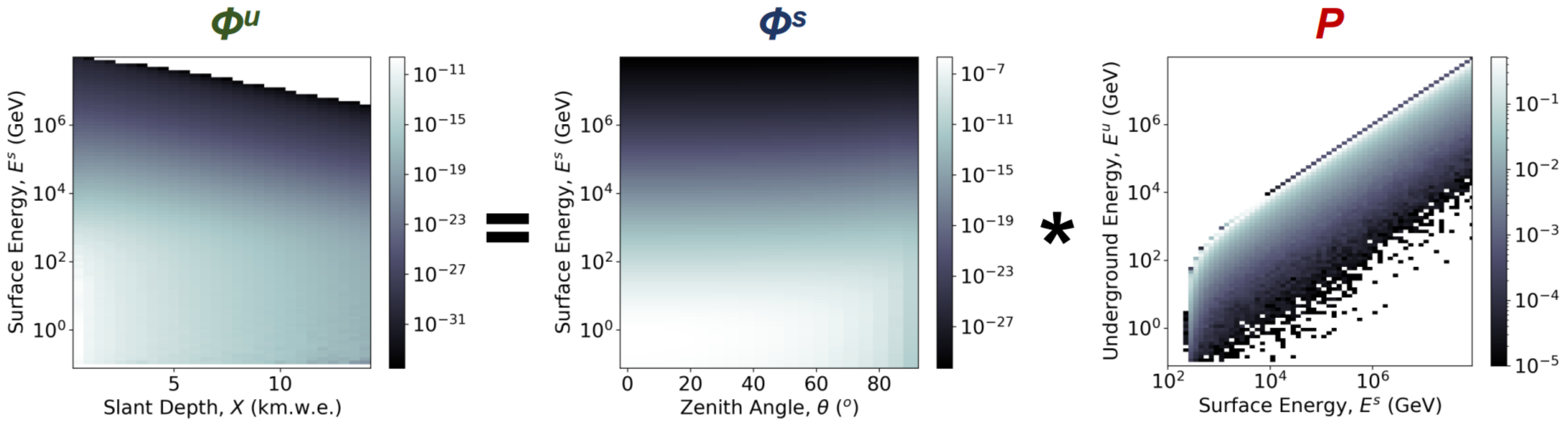
- Vertical equivalent rate, total underground muon rate, 2D distributions and seasonal variations for labs under mountains (paper in prep for ICRC)
- Underground muon charge ratio (not unfolded) (MINOS?)
- New fast code by William Woodley (MUTE) https://github.com/wjwoodley/mute
- Attempt combined fit with surface muons → nail down high energy uncertainties
- **Challenge: survey experimental data with explicit systematic uncertainties**

MUTE (Muon inTnsity codE): fast convolutions

AF, **W. Woodley**, M.-C. Piro, *ApJ* **928** 27 (2022)
W. Woodley, TeVPa 2022 and Woodley, AF, Piro in prep.

https://github.com/wjwoodley/mute

$$\Phi^u(E_j^u, X_k, \theta_k) = \sum_i \Phi^s(E_i^s, \theta_k) P(E_i^s, E_j^u, X_k) \left(\frac{\Delta E_i^s}{\Delta E_j^u}\right)$$



MUTE
Underground Fluxes

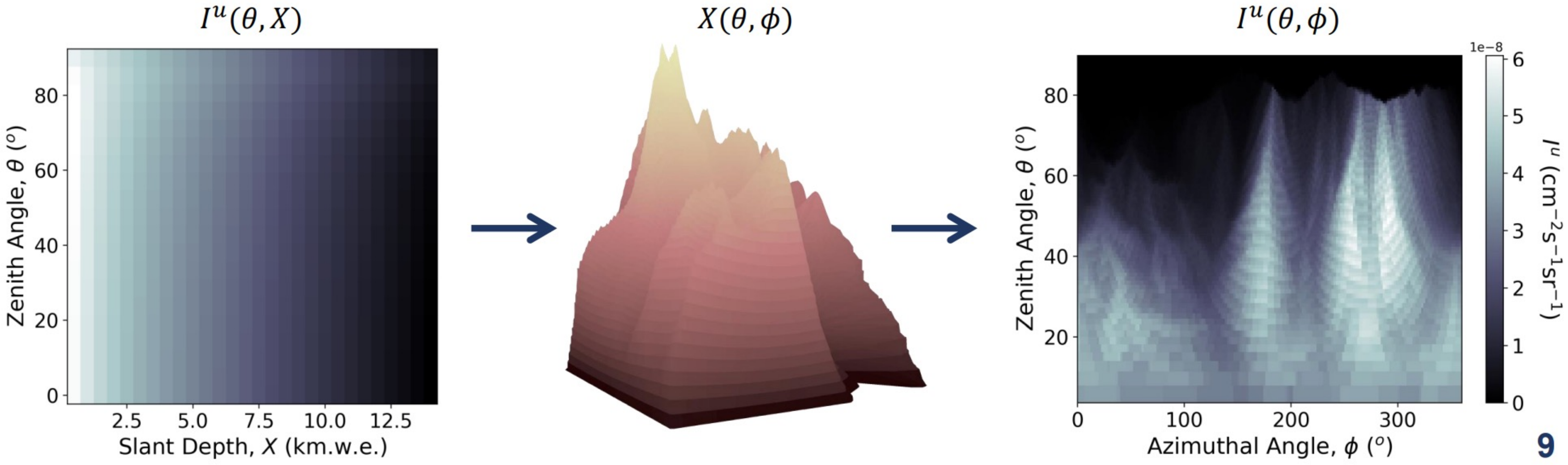
MCEq
Surface Fluxes

PROPOSAL
Transfer Tensor

MUTE (Muon inTnsity codE): Muon flux for labs under mountains

https://github.com/wjwoodley/mute

$$\Phi^u = \iint_\Omega I^u(X(\theta,\phi),\theta)\mathrm{d}\Omega$$



W. Woodley, TeVPa 2022