Modeling the atmospheric neutrino flux

J.P. Yañez

ν's in the mm era
December 2022

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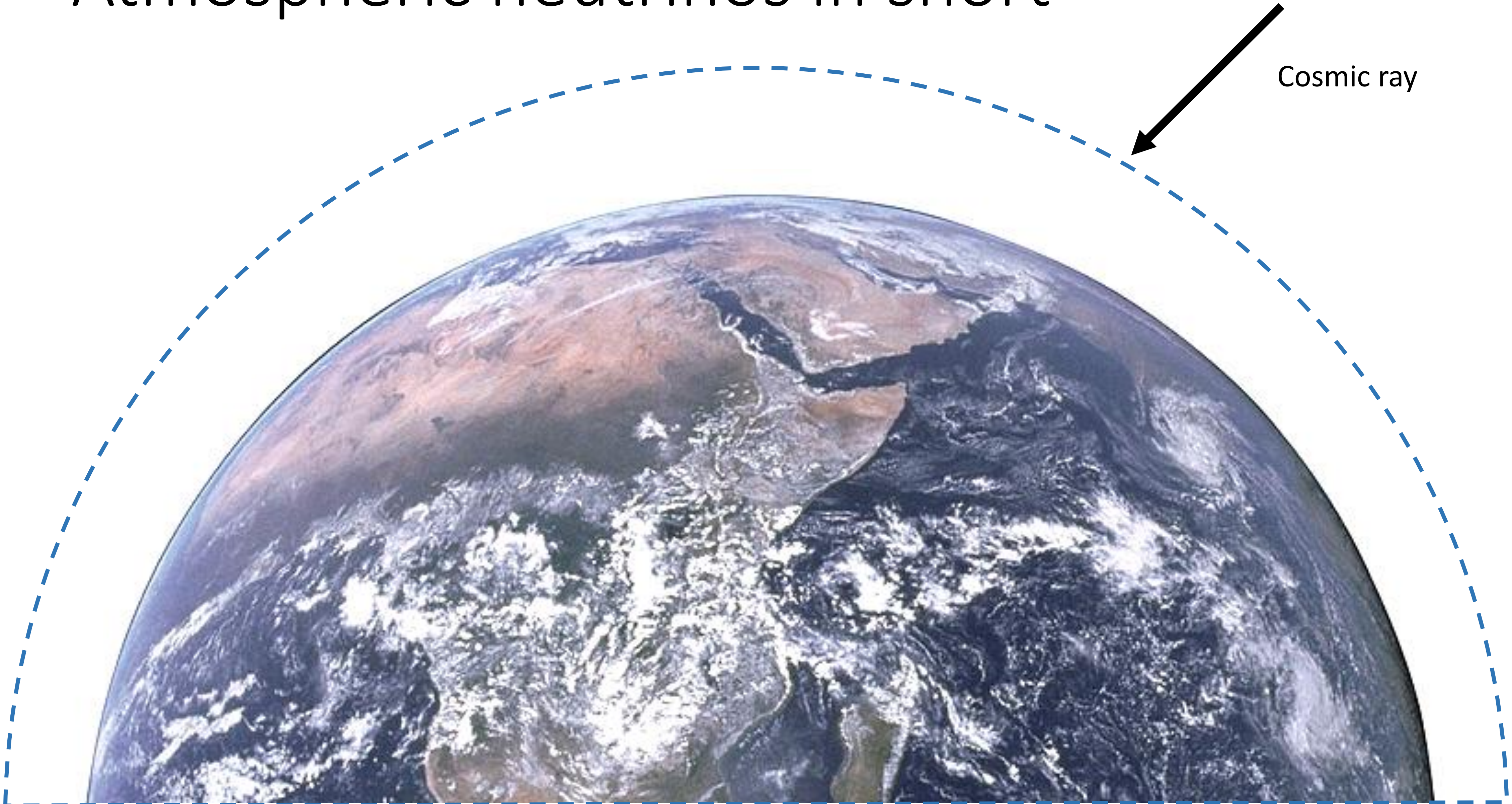
Atmospheric neutrinos in short



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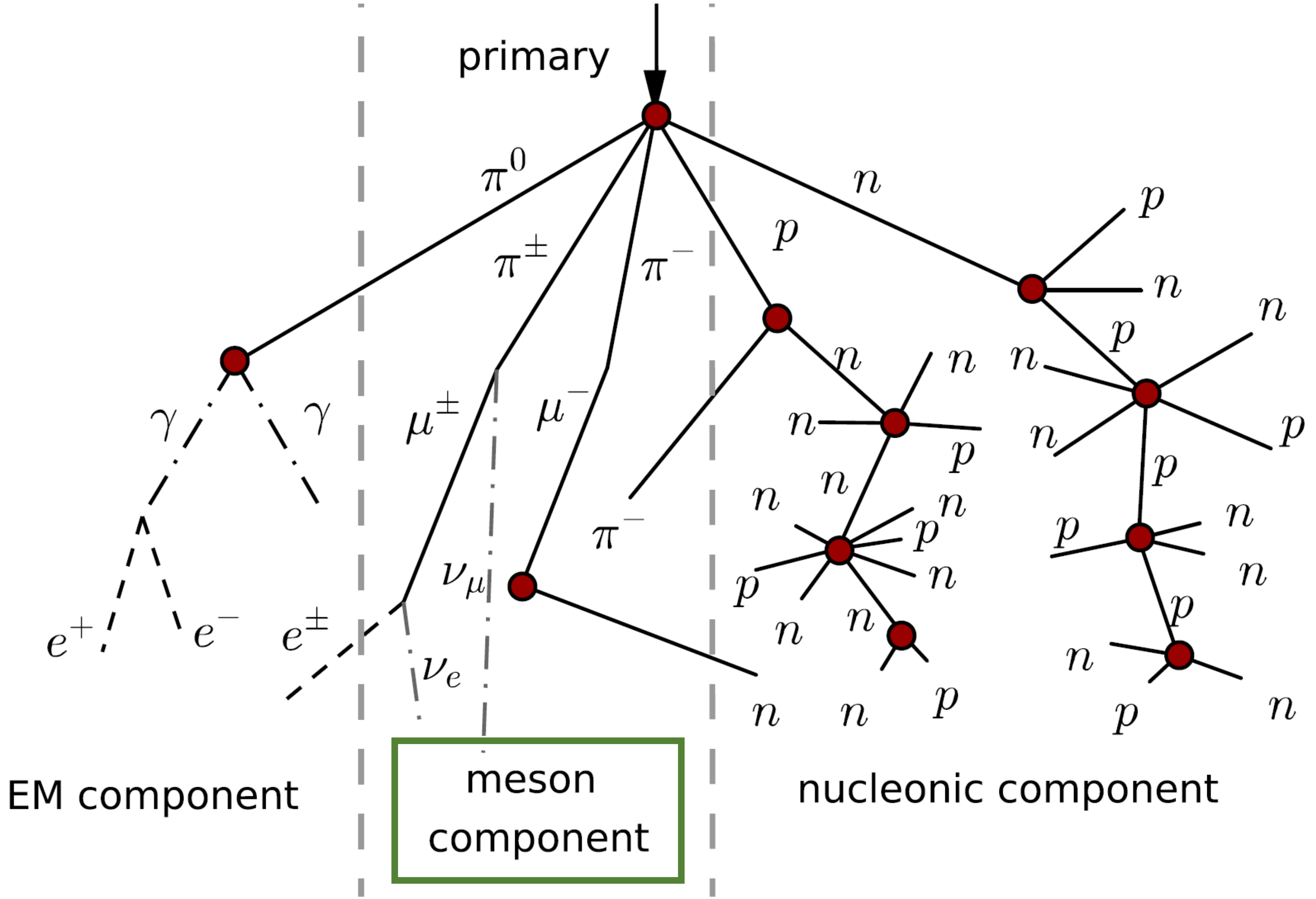
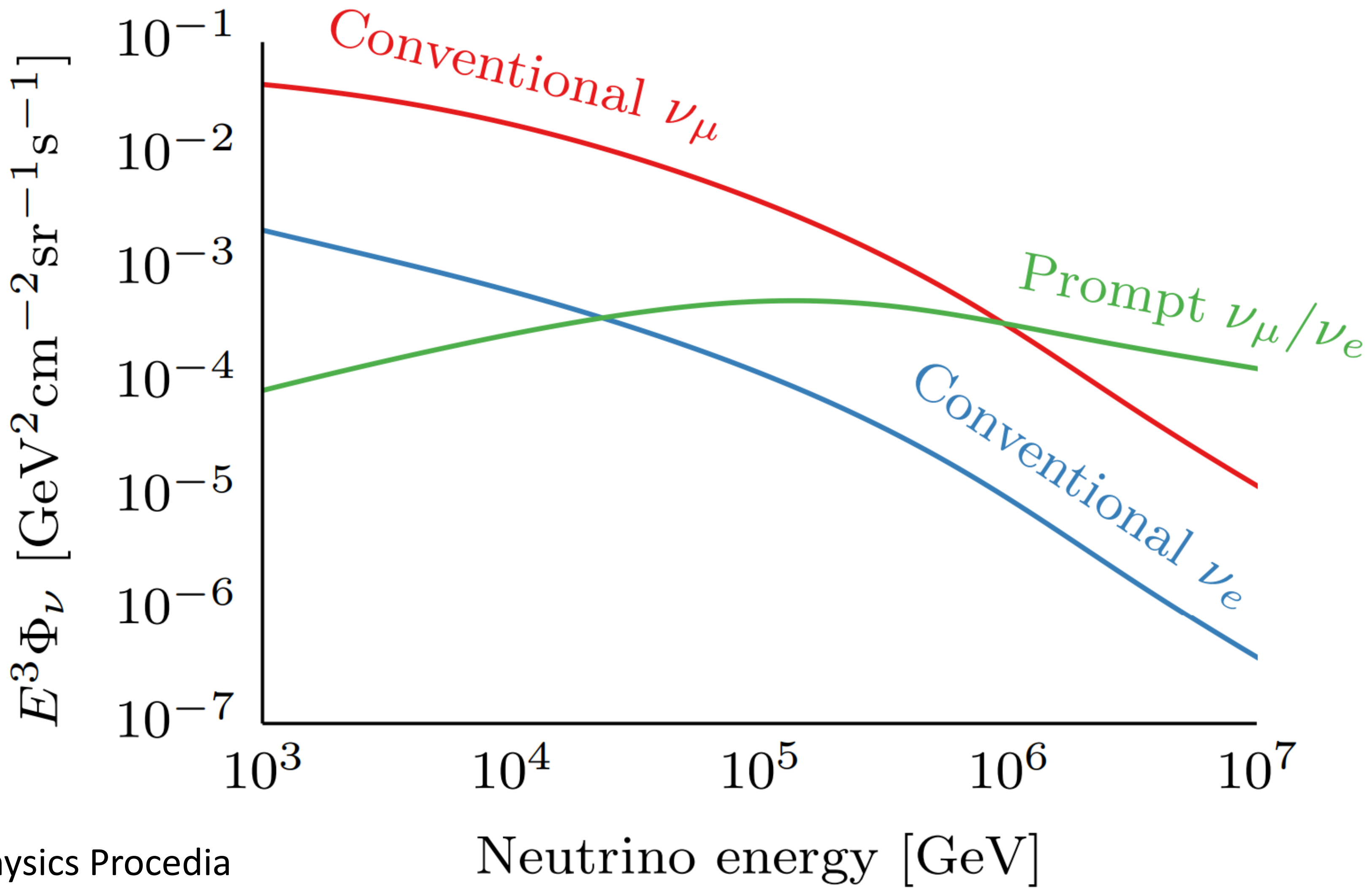


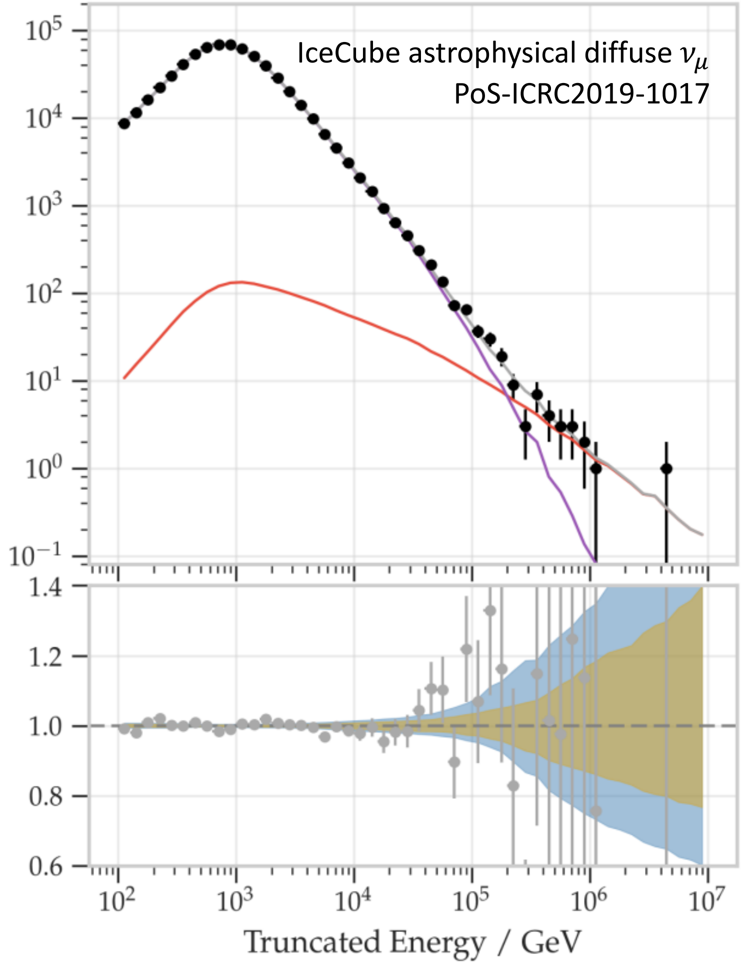
Atmospheric neutrinos in short



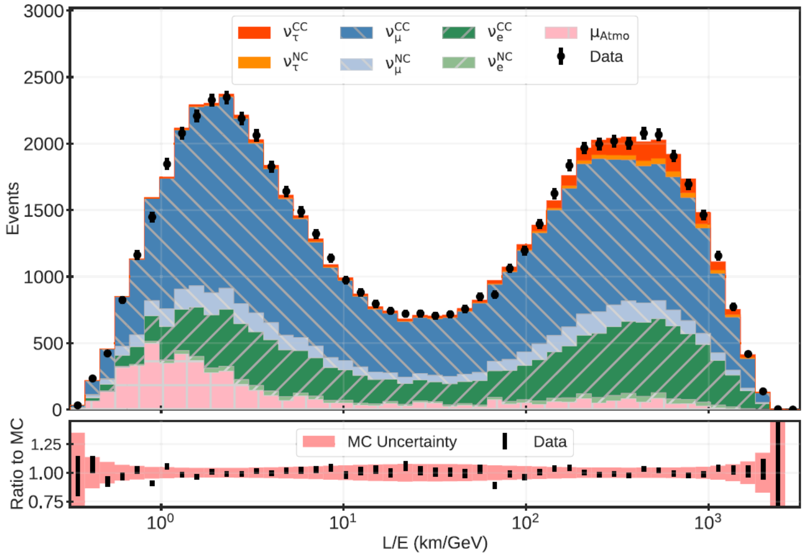
J. van Santen, Physics Procedia Volume 61, 2015, Pages 633-640

NTs need to know atmospheric ν's

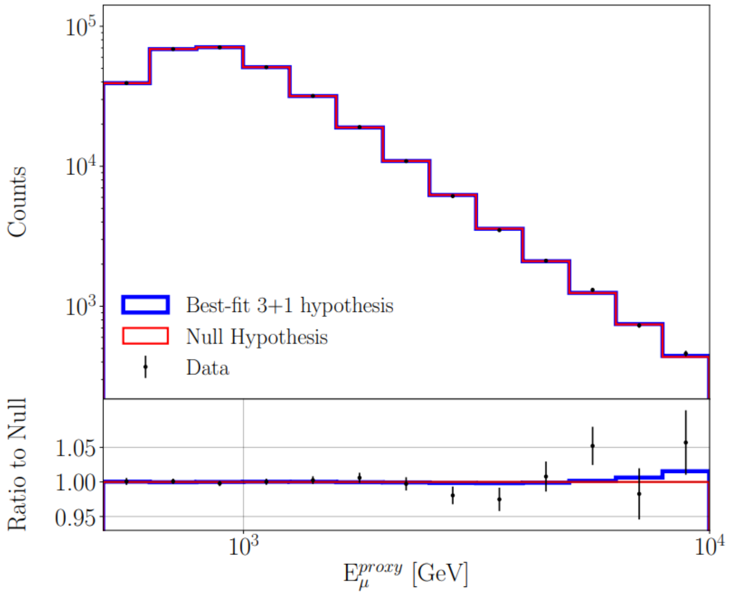
Isolate astrophysical ν



Study physics that modulates atm- ν



IceCube atmospheric neutrino oscillation measurements
PRD 99, 032007 (2019)

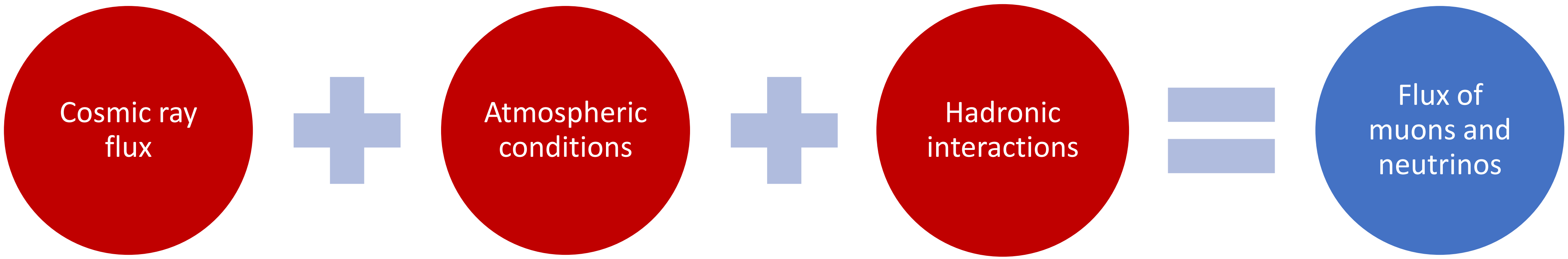


IceCube sterile neutrino search
PRL125, 141801 (2020)

Computing an atm-ν flux (until recently)

- Fitting cosmic ray data to power-law spectra per nuclei (p, He)
- Assuming a shape

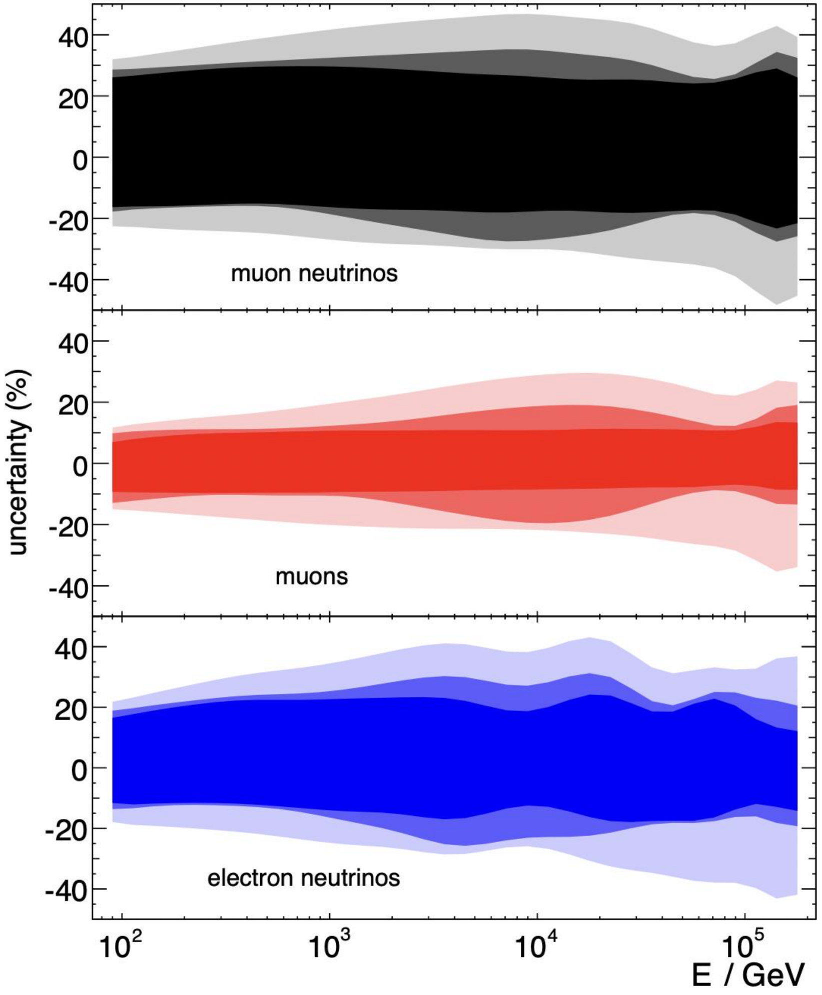
- Micro-physics models to explain interactions (non-perturbative QCD)
- Tuned to data, where available

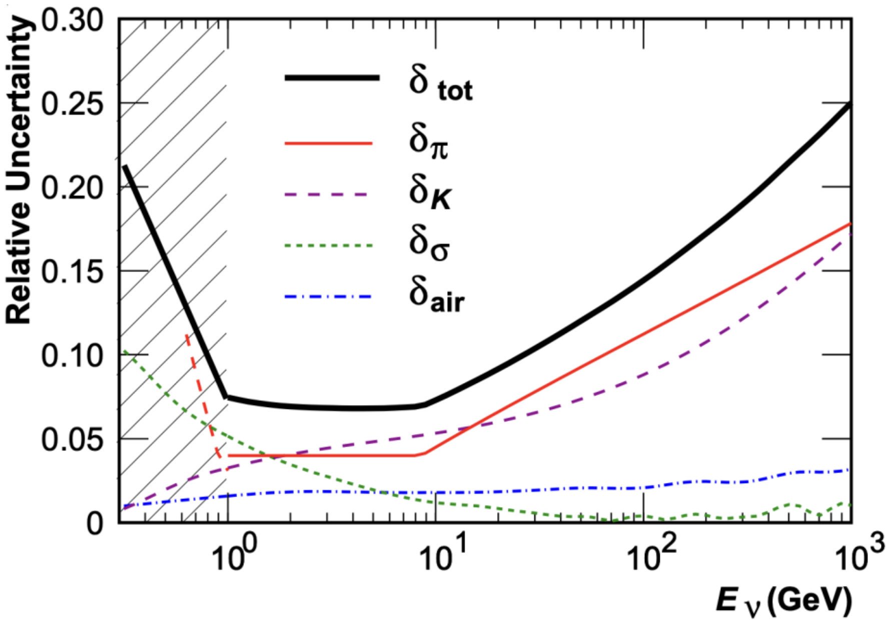


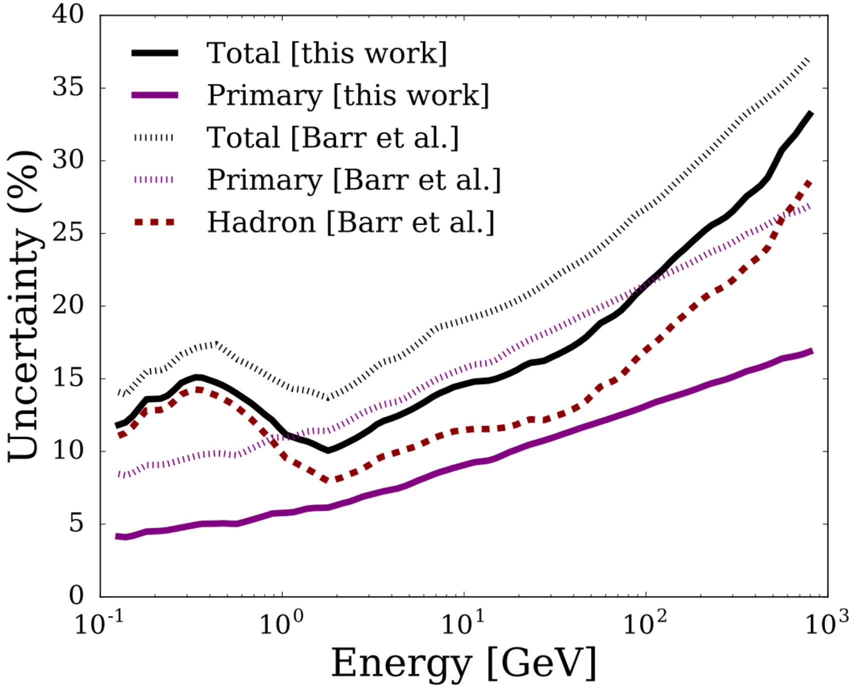
- A few groups with analytical or simulation based code (not open)
- Combine information about physics phenomena over 6-7 decades in energy

Errors

Fedynitch et al., PRD, 2012. Choose different models and estimate band by bracketing







Honda et al. 2006 & Evans et al. 2016:

Uncertainty from eye-balling the description of muon data, and proportional rescaling to neutrino fluxes.

A data-driven, calibrated atm.-ν flux

The Global Spline Fit (GSF)

Dembinski, Fedynitch, Gaisser, ICRC 2017 & H. Dembinski 2019

Data Driven Hadronic interaction model (DDM)

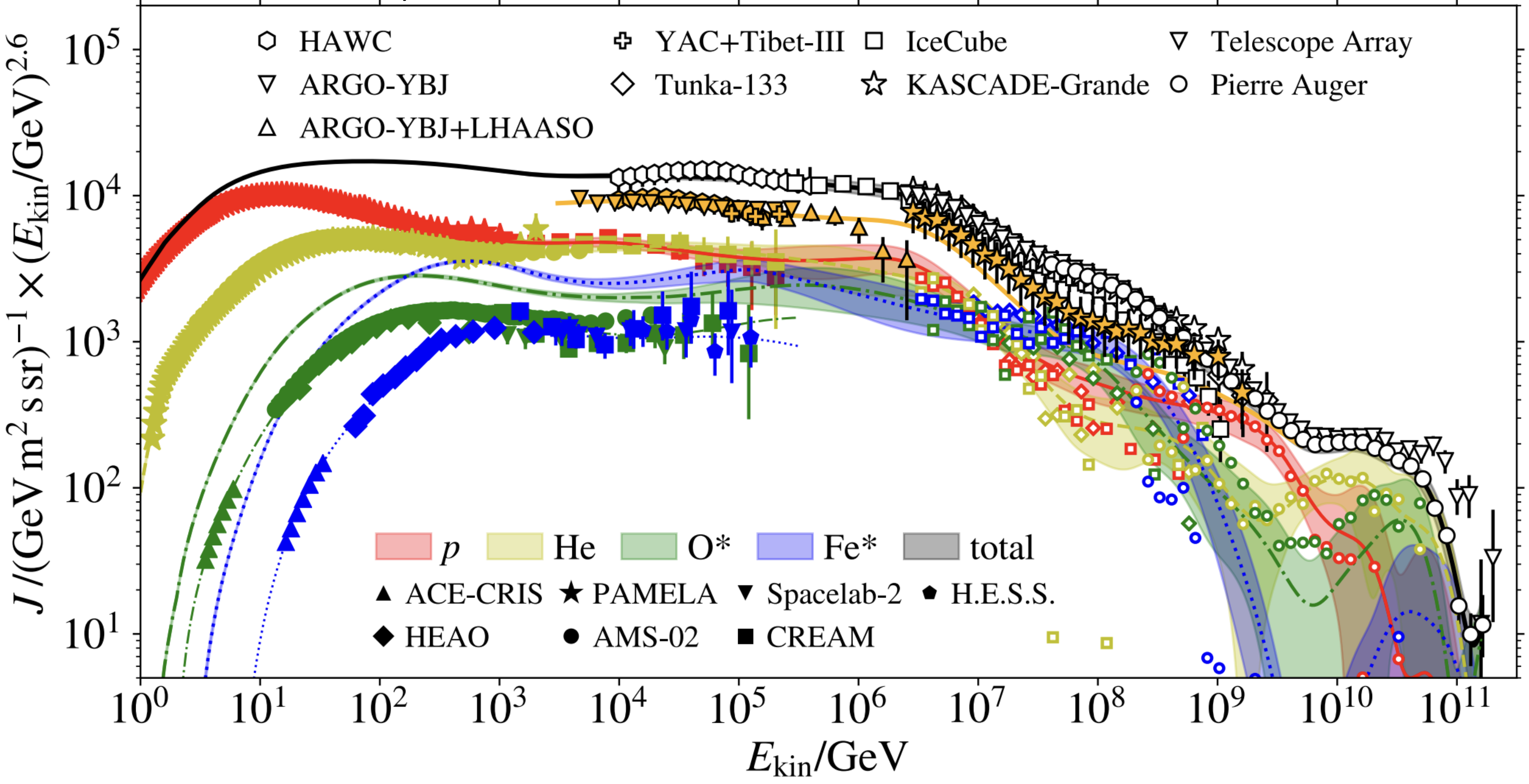
A. Fedynitch, M. Huber PRD 106 (2022)

Calibration of DDM+GSF with muon spectrometer data

J. P. Yañez, A. Fedynitch, ICRC’21 (to appear soon)

The Global Spline Fit (of CR fluxes)

Dembinski, A. Fedynitch, Gaisser, ICRC 2017 & H. Dembinski 2019



Pros:

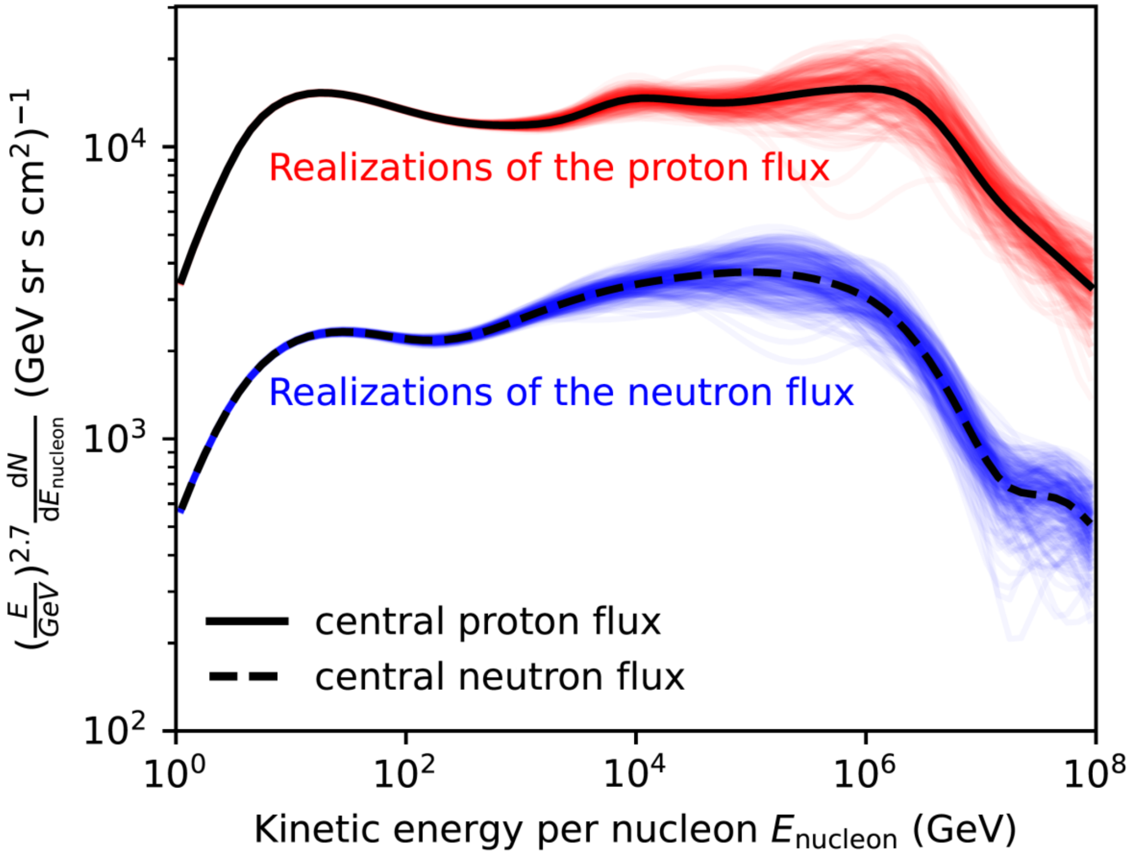
- Parameterizes data
- AND uncertainty
- AND covariance matrix

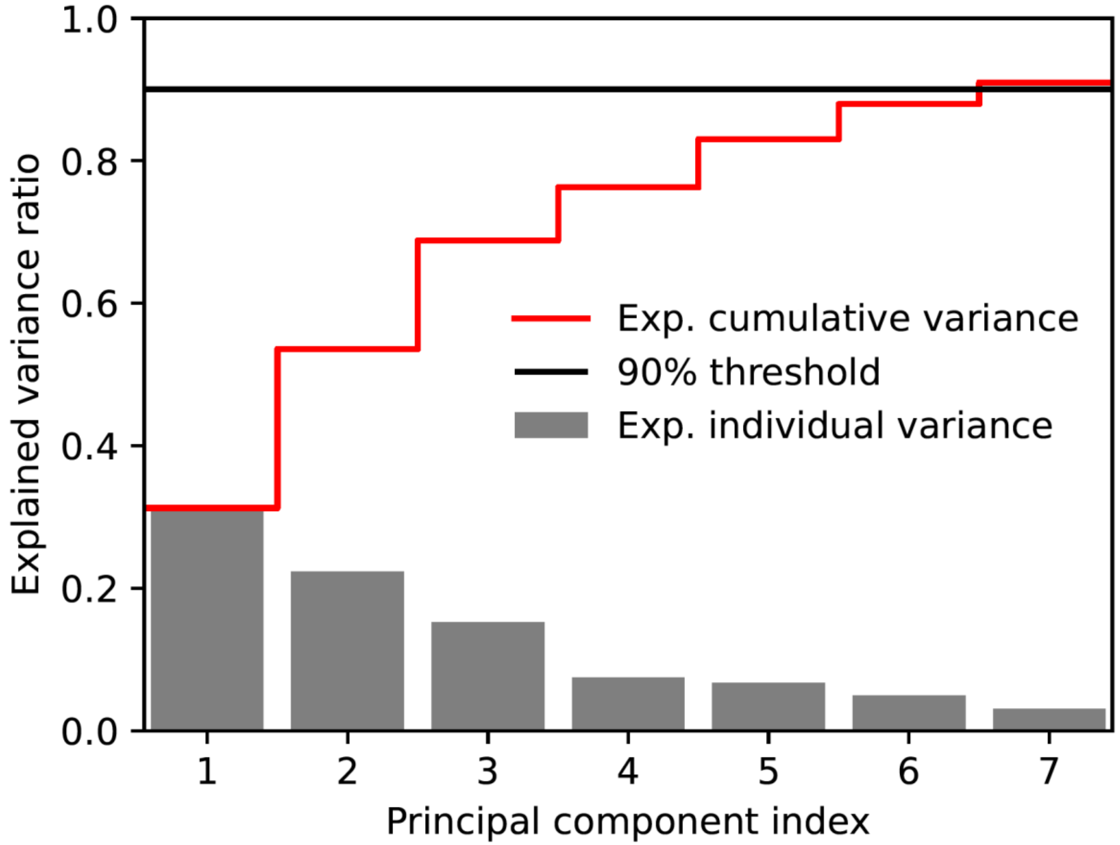
Cons:

- Many parameters
- ~5 * 20 ☺
- Not all equally important for ν fluxes

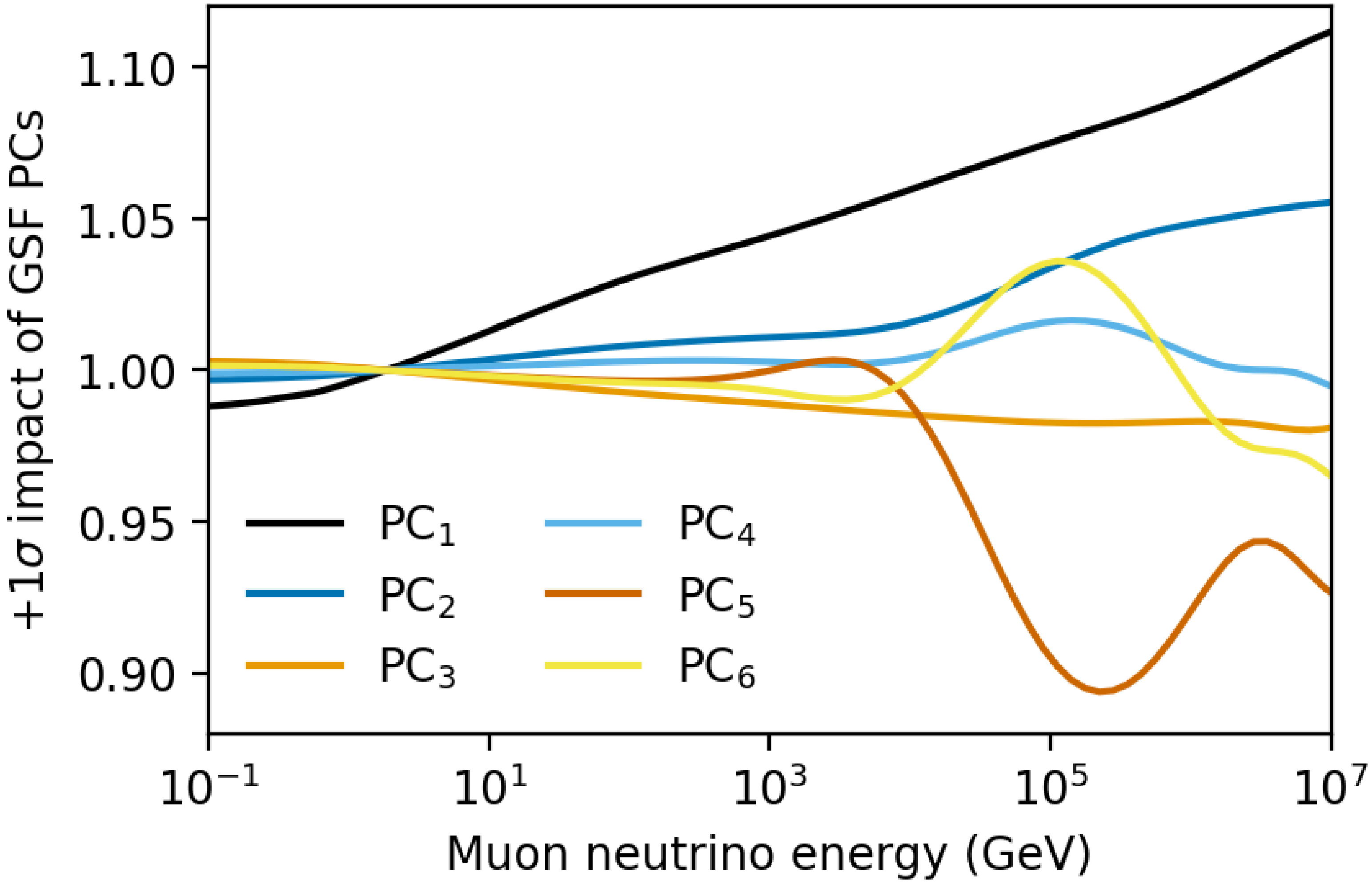
Dimensionality reduction to 6 parameters

New: Parameterizing errors to be accessible via principal component analysis (PCA)





Principal components of CR nucleon fluxes



- Component 1 is a “global” spectral index correction
- Other features possible at ~100 TeV

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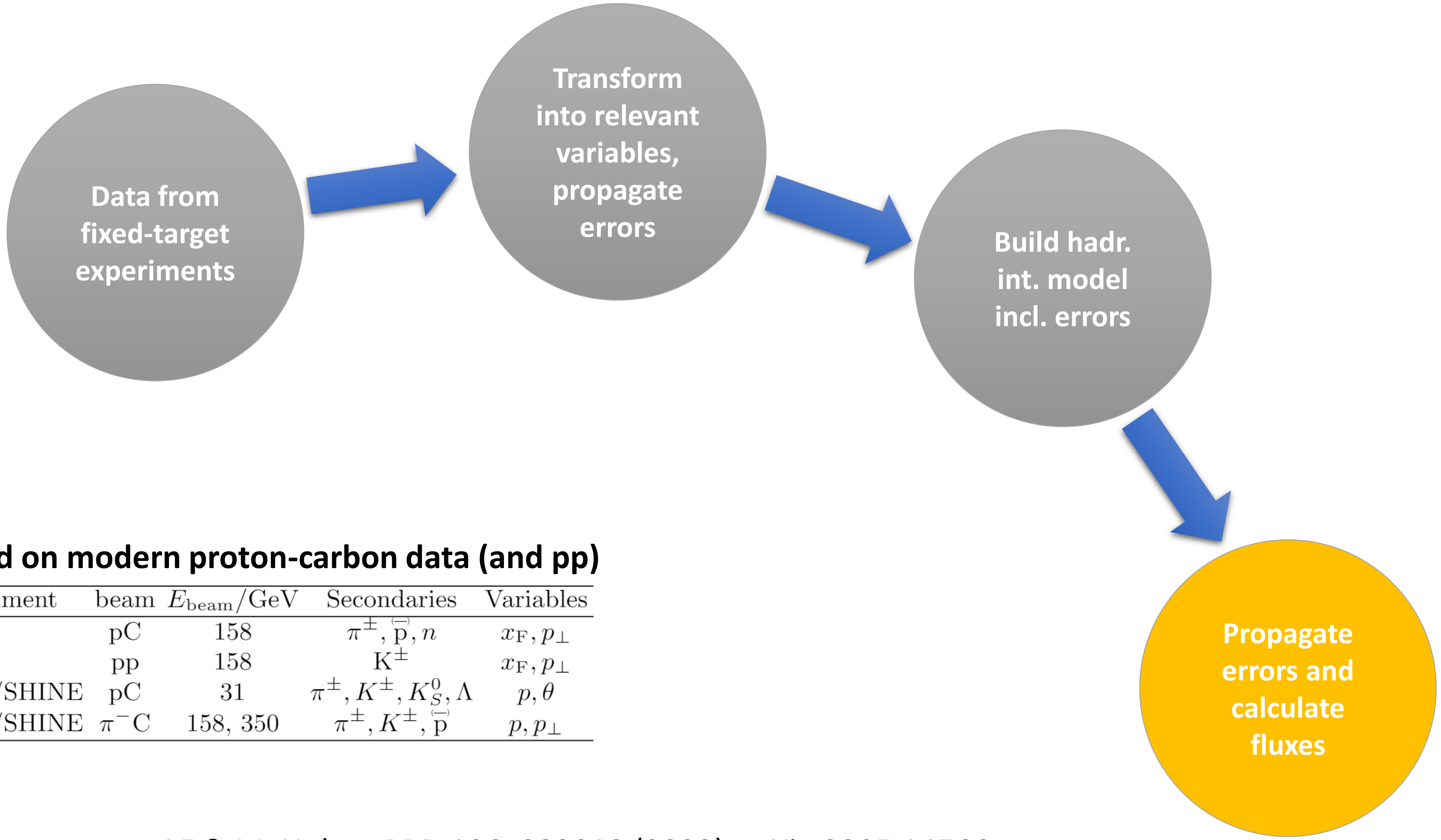
Data-Driven Hadronic Interaction Model

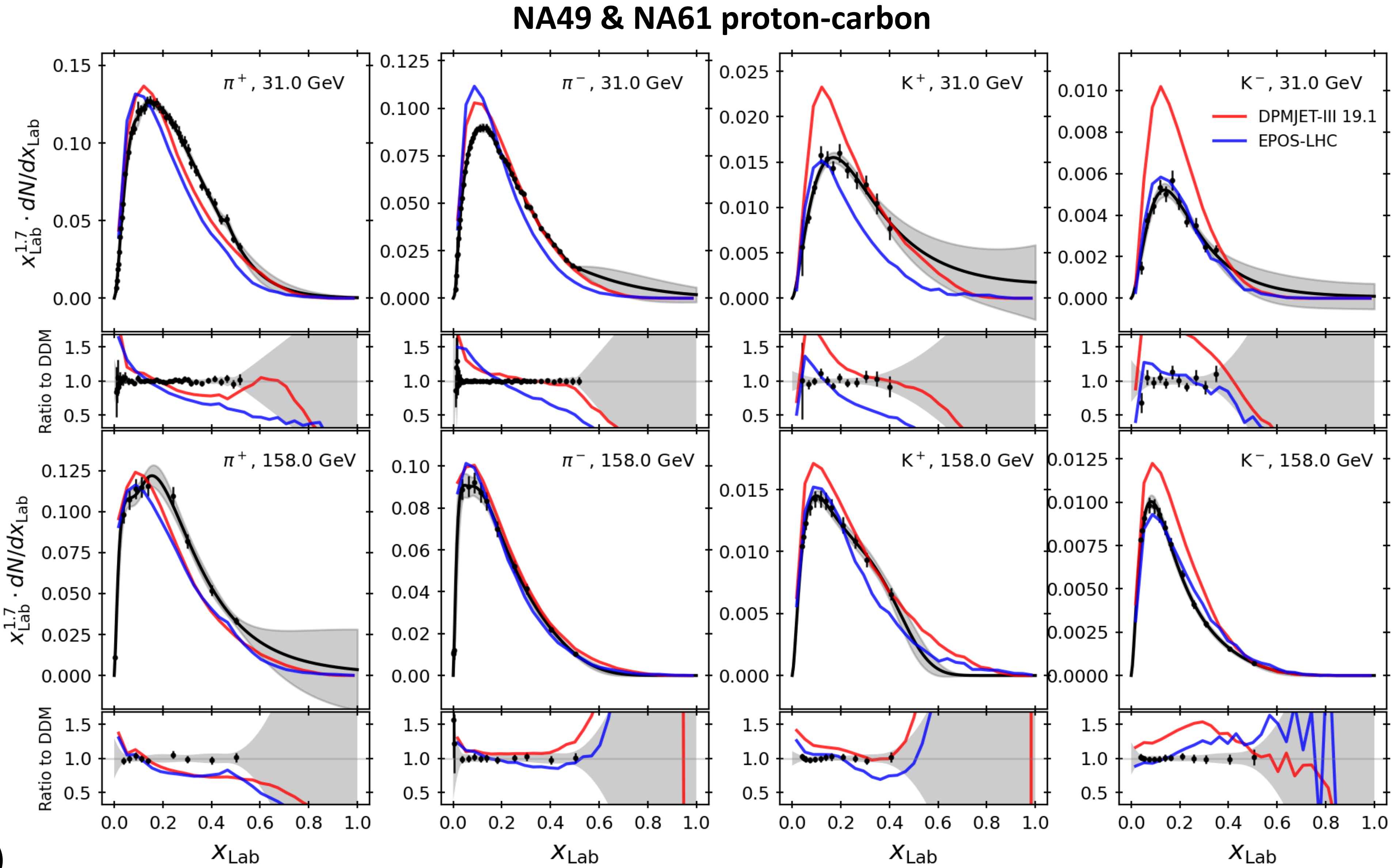


Based on modern proton-carbon data (and pp)

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	$\pi^{\pm}, K^{\pm}, K_S^0, \Lambda$	p, θ
NA61/SHINE	$\pi^{-}\mathrm{C}$	158, 350	$\pi^{\pm}, K^{\pm}, \overset{(-)}{\mathrm{p}}$	$p, p_{\perp}$

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

Fits to proton-carbon data and uncertainties

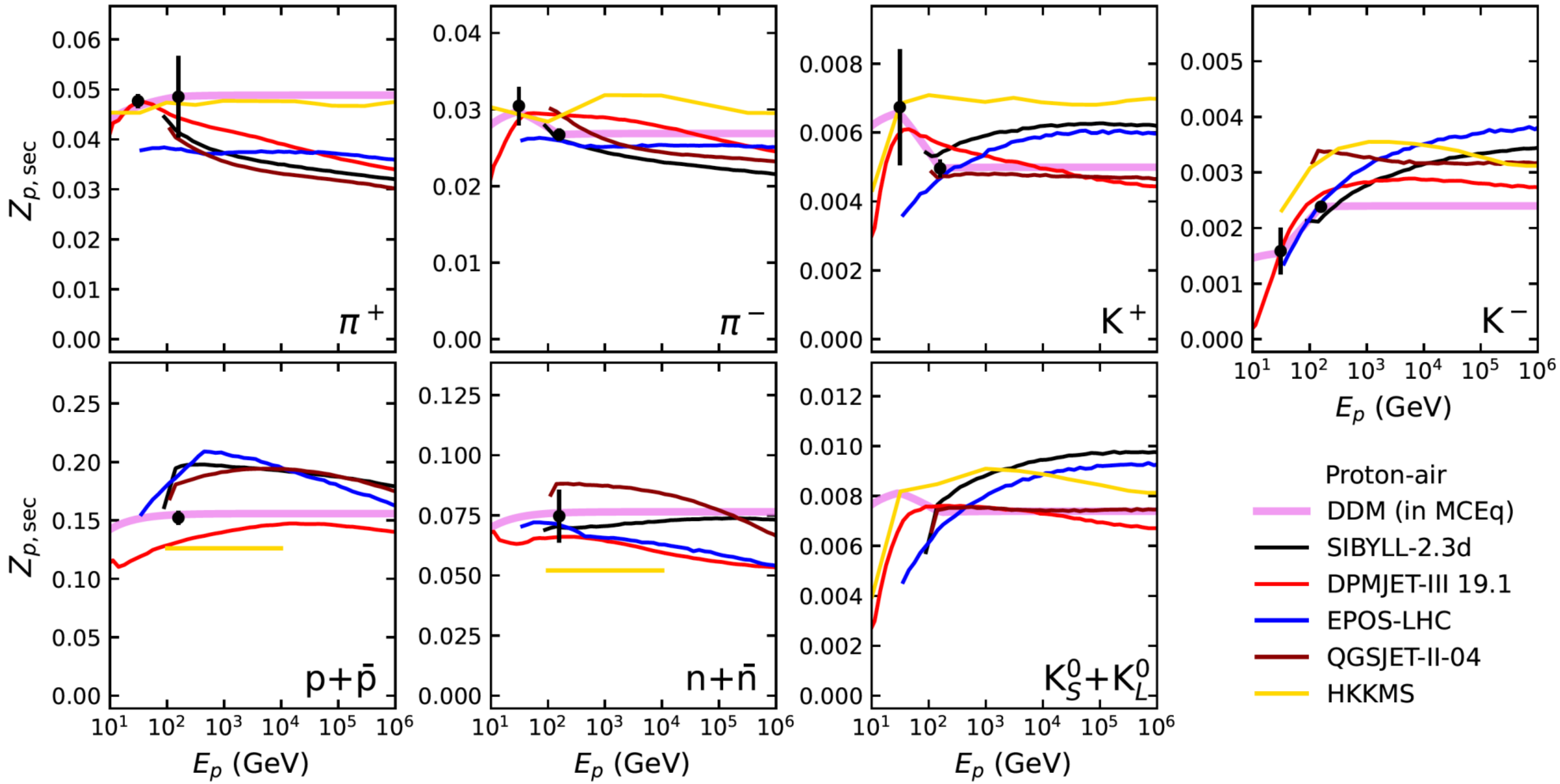


A. Fedynitch,
M. Huber
PRD 106 (2022)

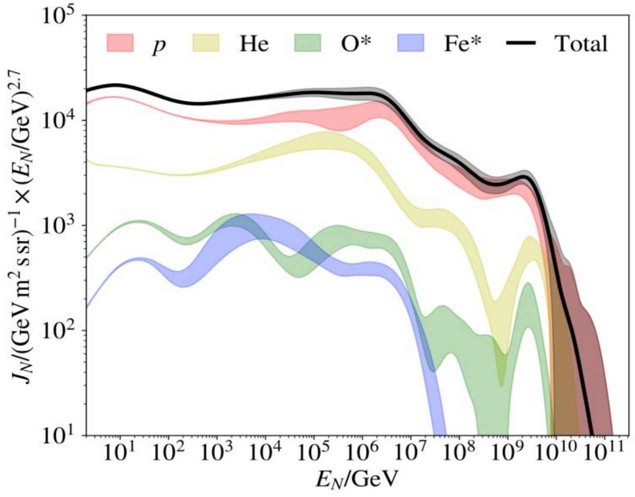
Energy inter- and extrapolation

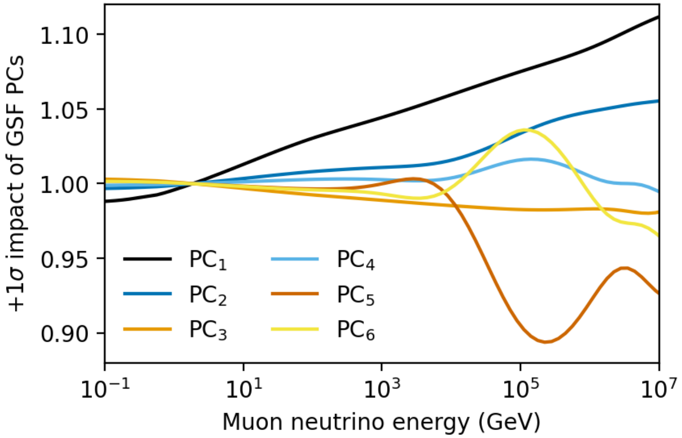
Atm.-flux-relevant phase space →
Spectrum-weighted moment:

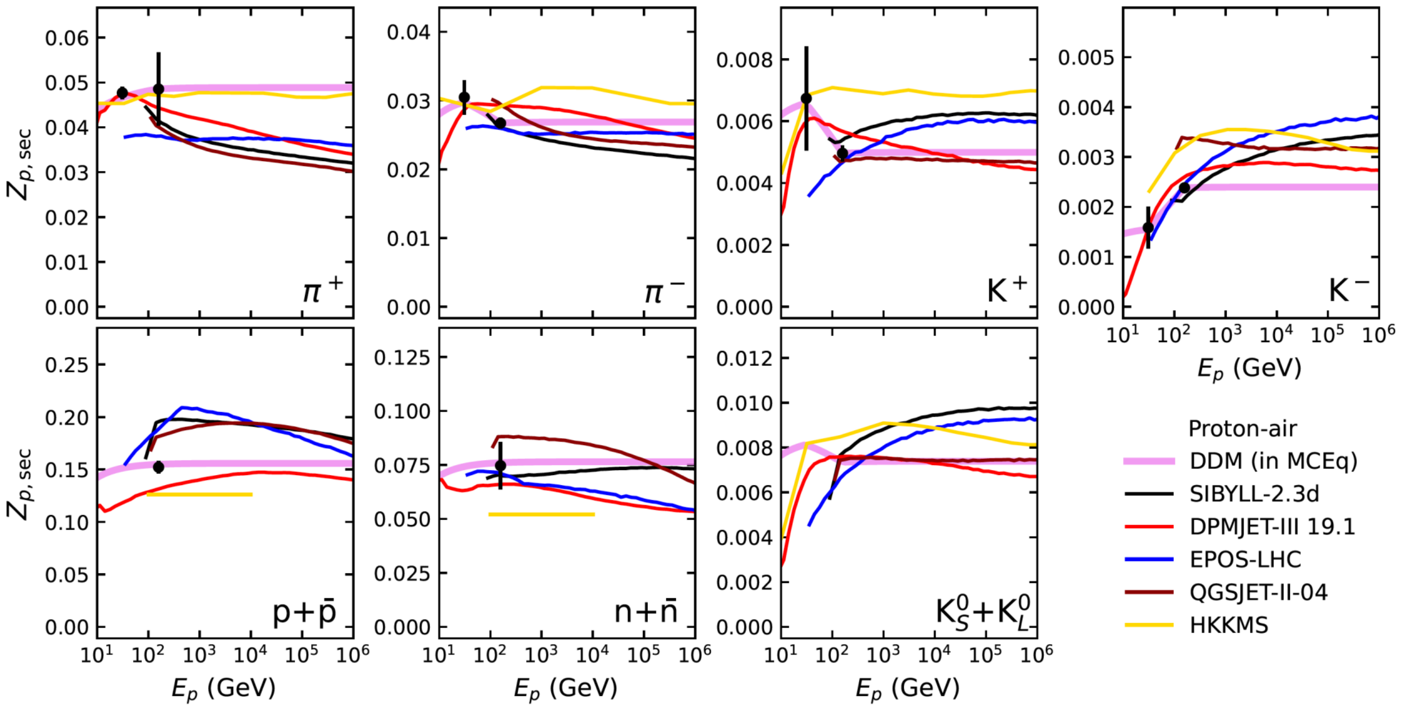
$$Z_{Nh}(E_N) = \int_0^1 dx_{\mathrm{Lab}} \; x_{\mathrm{Lab}}^{\gamma(E_N)-1} \frac{dN_{N\to h}}{dx_{\mathrm{Lab}}}(E_N)$$



Cosmic ray flux: GSF + **Atmospheric conditions** + **Hadronic interactions: DDM** = **Flux of muons and neutrinos**







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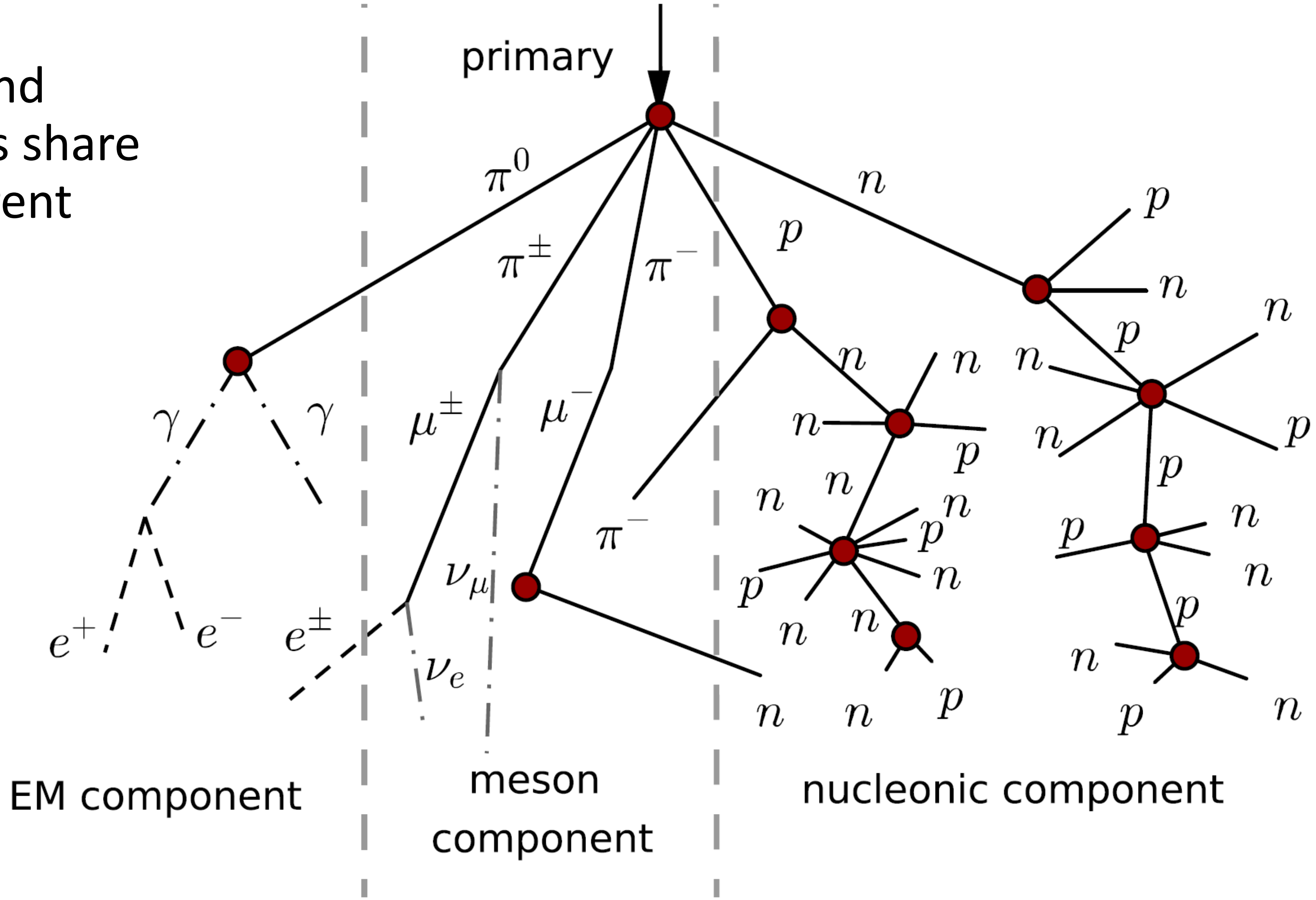
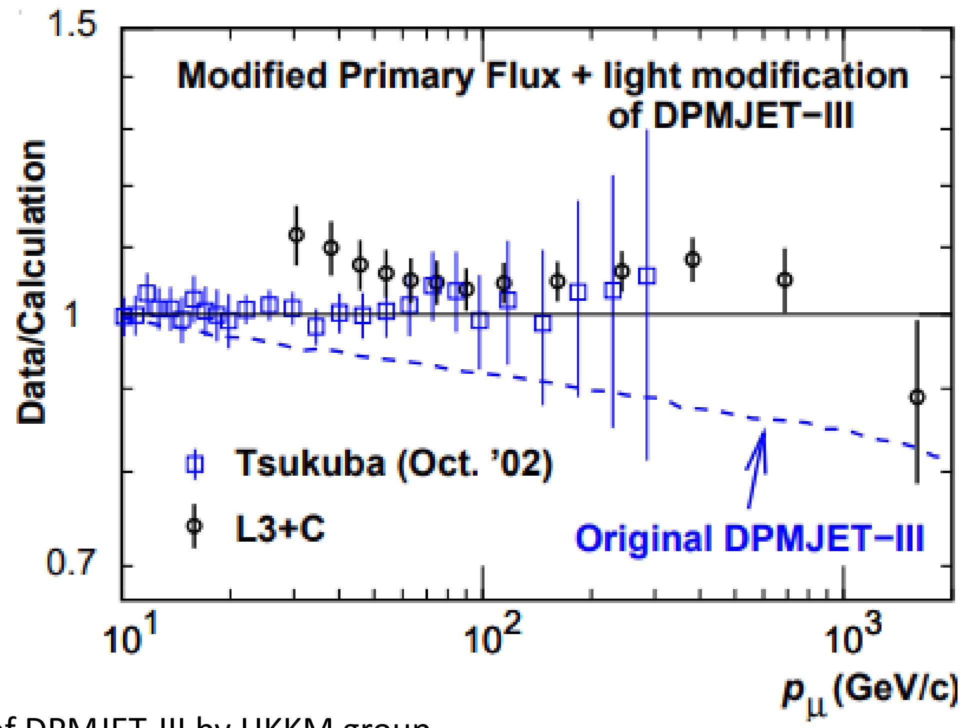
Muons and neutrinos

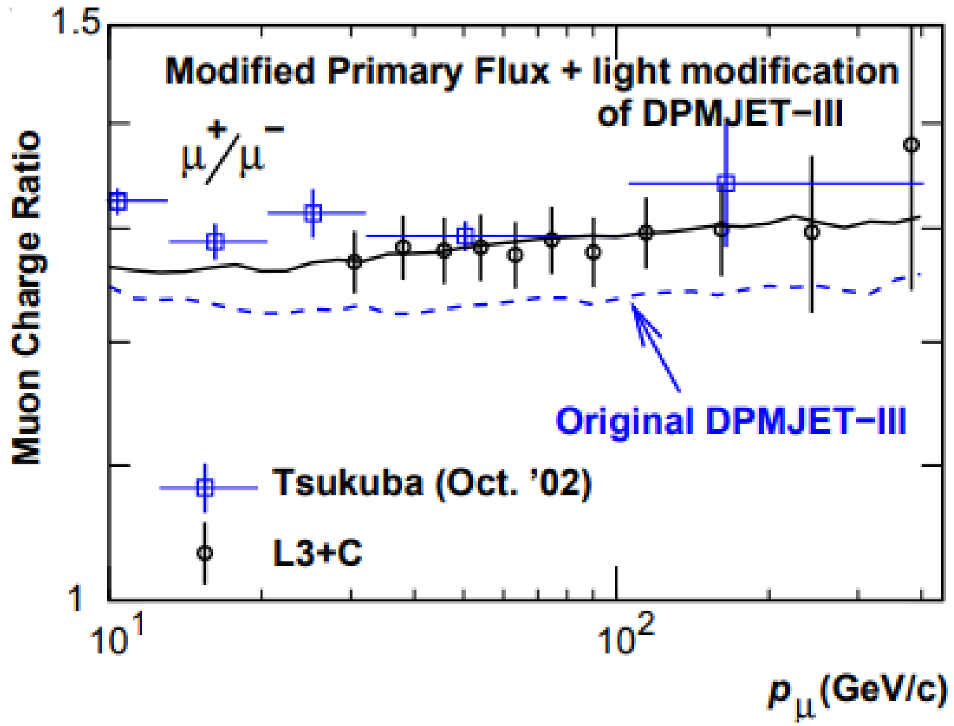
- Muons and neutrinos share same parent mesons



Muon data as calibration

- Muons can be used to calibrate a neutrino flux calculation
- Demonstrated by the HKKM group using muon spectrometer data





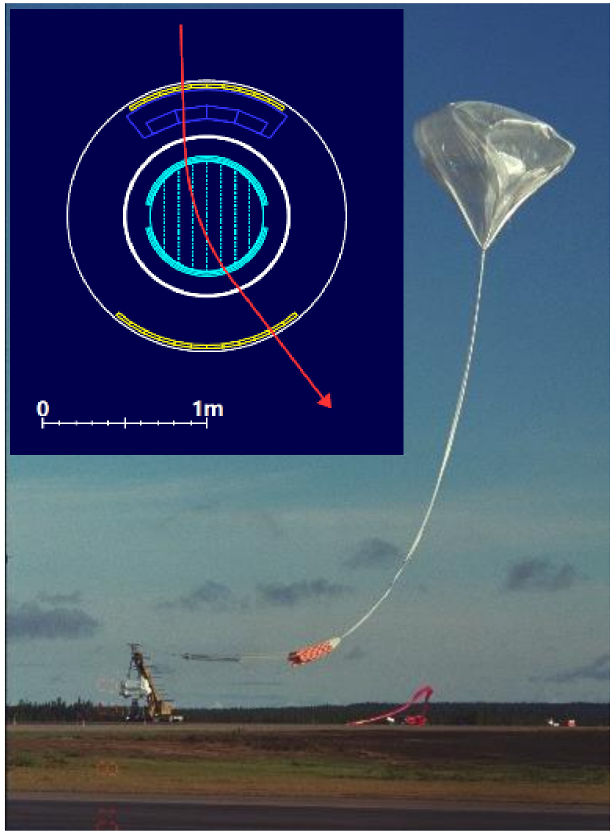
Calibration of DPMJET-III by HKKM group
Phys.Rev.D75:043006,2007

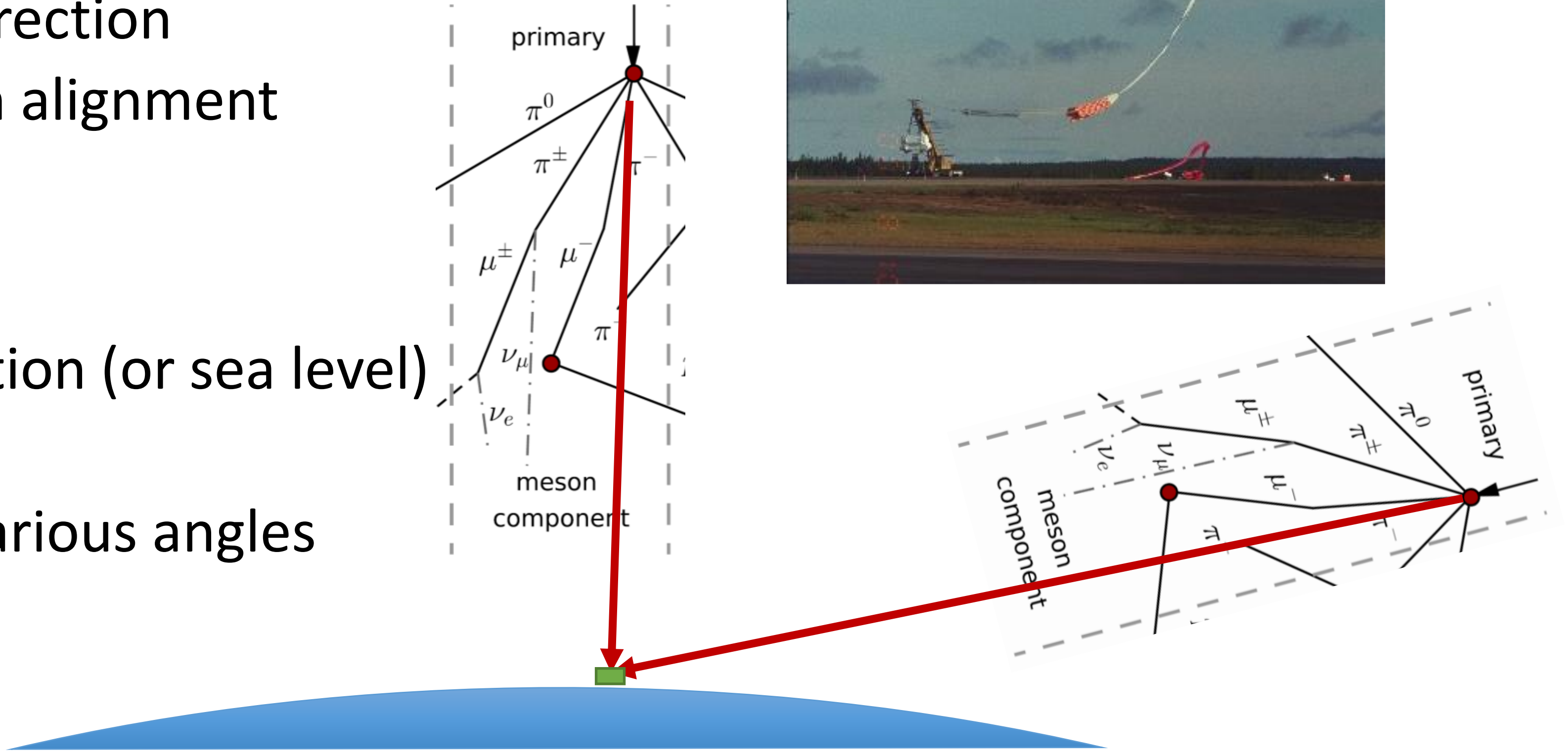
Typical experiment

- Particle tracker in a magnetic field
  - Energy from bending radius
  - Charge from bending direction
  - Incoming direction from alignment

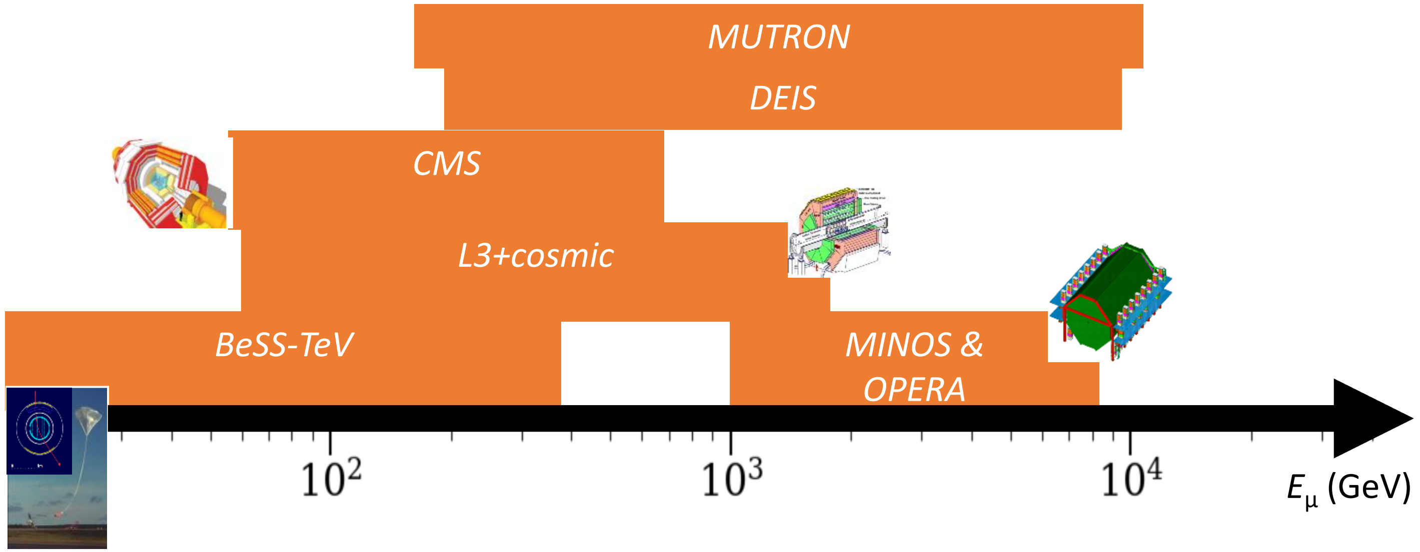
- Quantities reported
  - Flux at experiment location (or sea level)
  - Ratio of μ^+/μ^-
  - Reported vs E and for various angles

BESS-TeV spectrometer





New: expand the experimental data sets



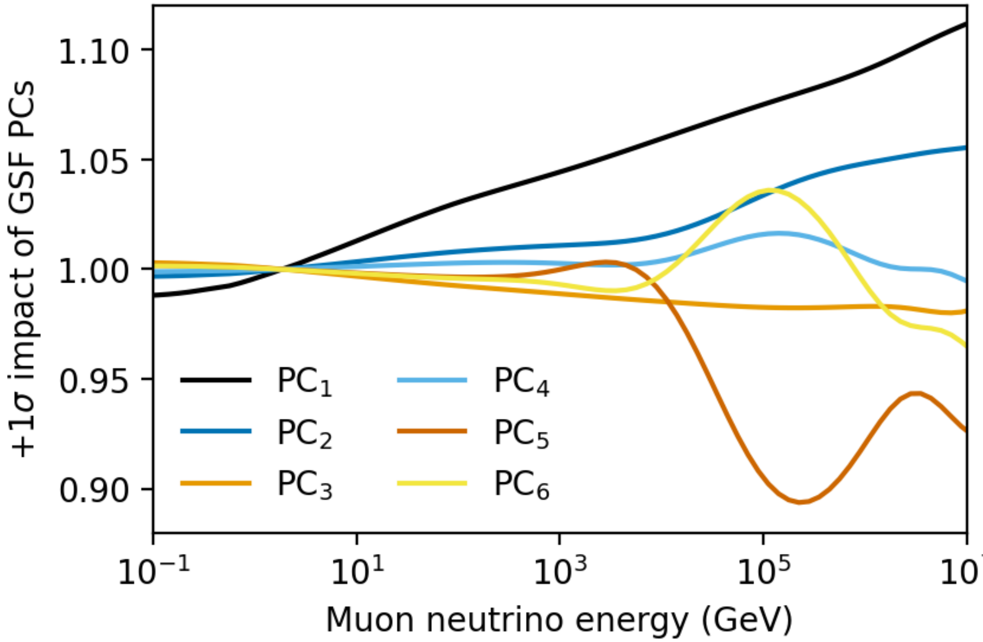
J. P. Yanez & AF, ICRC 2019, to appear very soon

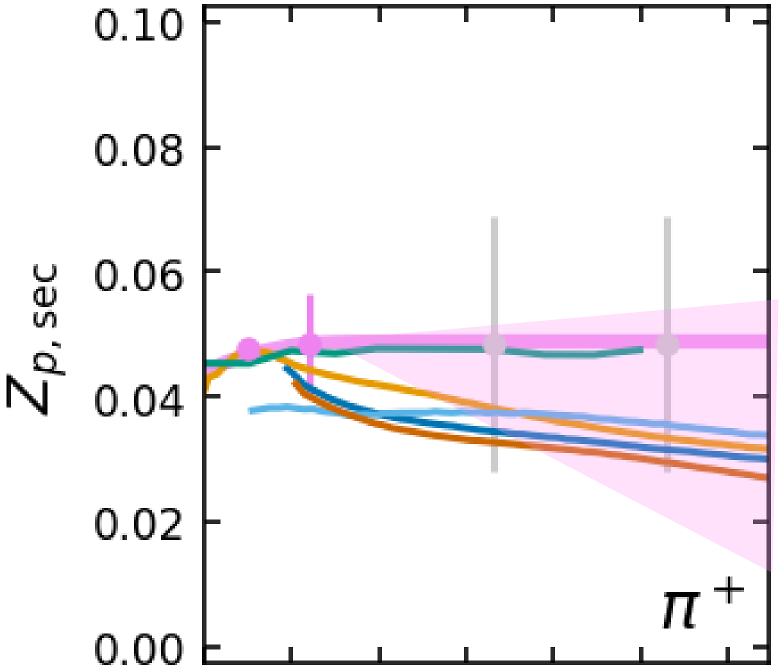
Experiment	Energy (GeV)	Measurements	Unit	Systematics	Location	Altitude	Zenith range
BESS-TeV [21]	0.6-400	Φ_μ	p_μ	C	36.2°N, 140.1°W	30 m	0-25.8°
CMS [22]	5-1000	R_{μ^+/μ^-}	p_μ	Q	46.31°N, 6.071°E	420 m	$p\cos\theta_z$
L3+C [23]	20-3000	Φ_μ,R_{μ^+/μ^-}	p_μ	C	46.25°N, 6.02°E	450 m	0-58°
DEIS [24]	5-10000	Φ_μ	p_μ	Q	32.11°N, 34.80°E	5 m	78.1-90°
MINOS [25]	1000-7000	R_{μ^+/μ^-}	E_μ	C	47.82°N, 92.24°W	5 m	unfolded
OPERA [26]	891-7079	R_{μ^+/μ^-}	E_μ	Q	42.42°N, 13.51°E	5 m	$E\cos\theta^*$

Experiments disclosing systematic uncertainties. Most provide corrrection functions for the data.

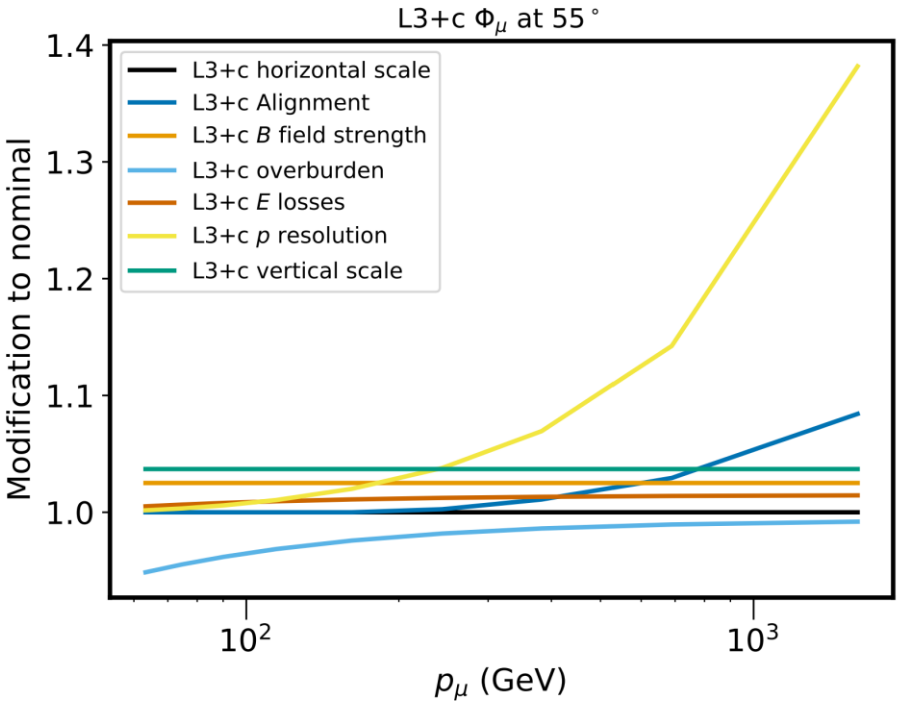
Parameters in the fit

6 parameters from GSF PCA



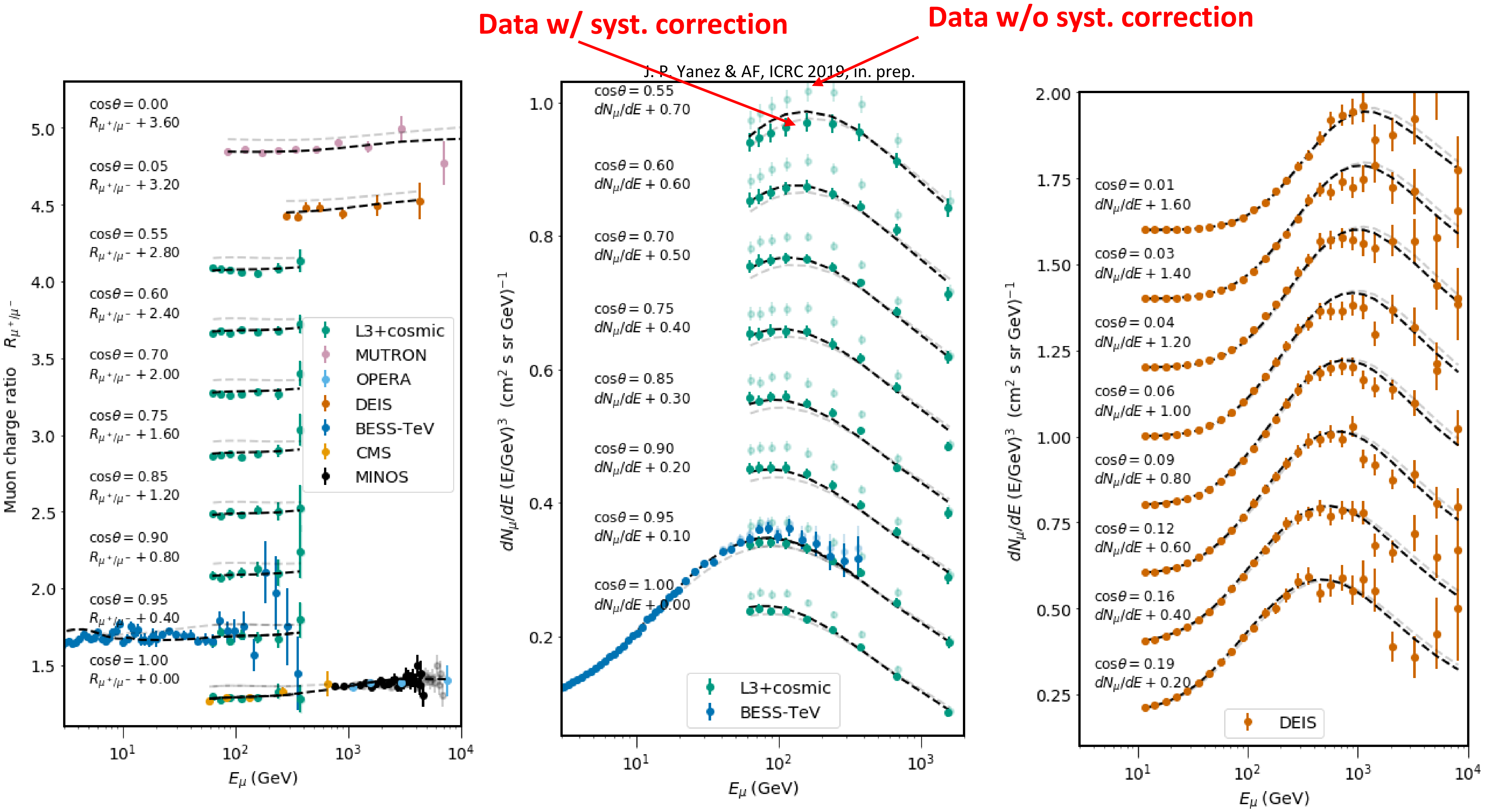


10 parameters from DDM +
8 for high energy "extension"
at 20 TeV, 2 PeV

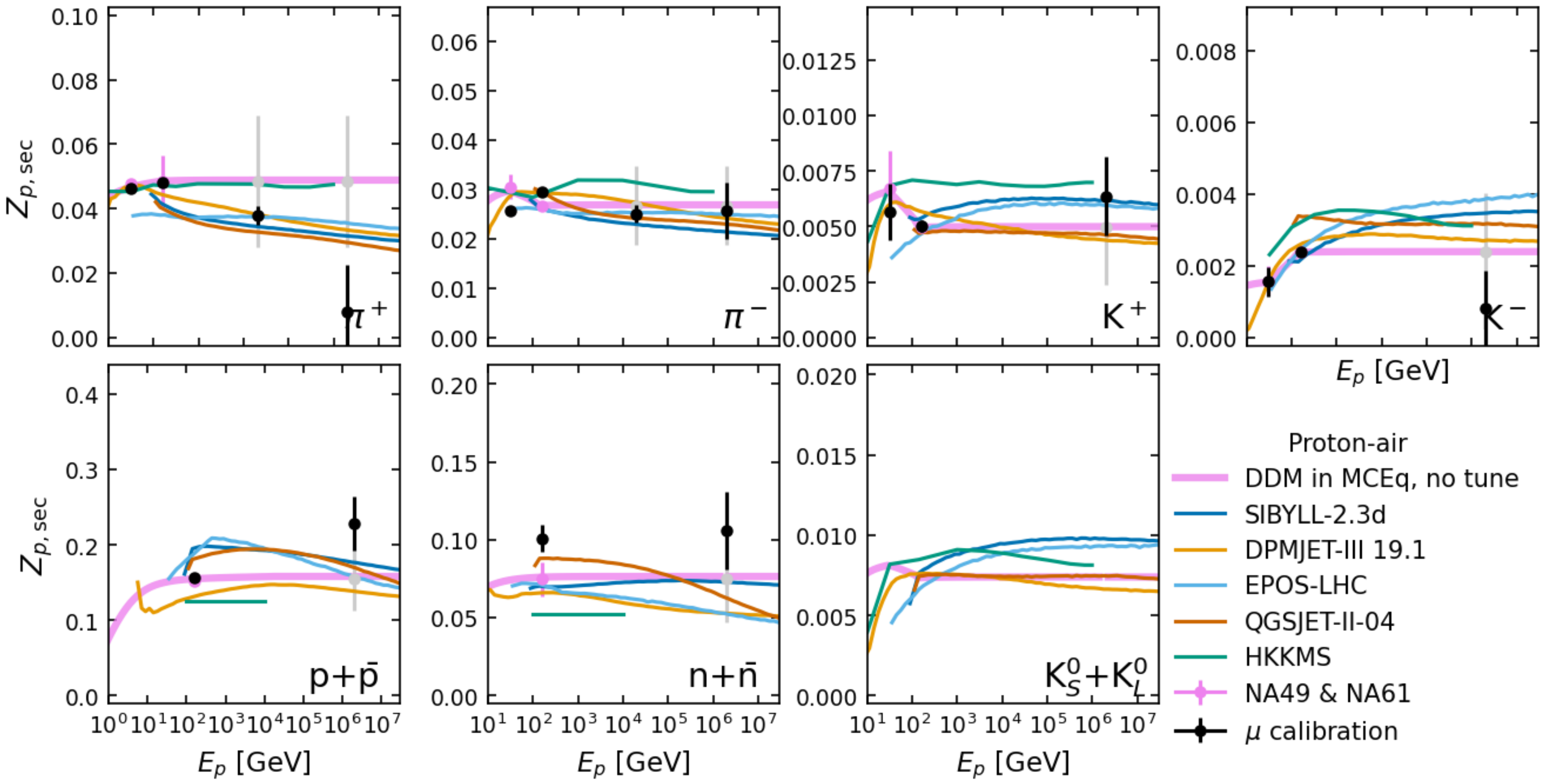


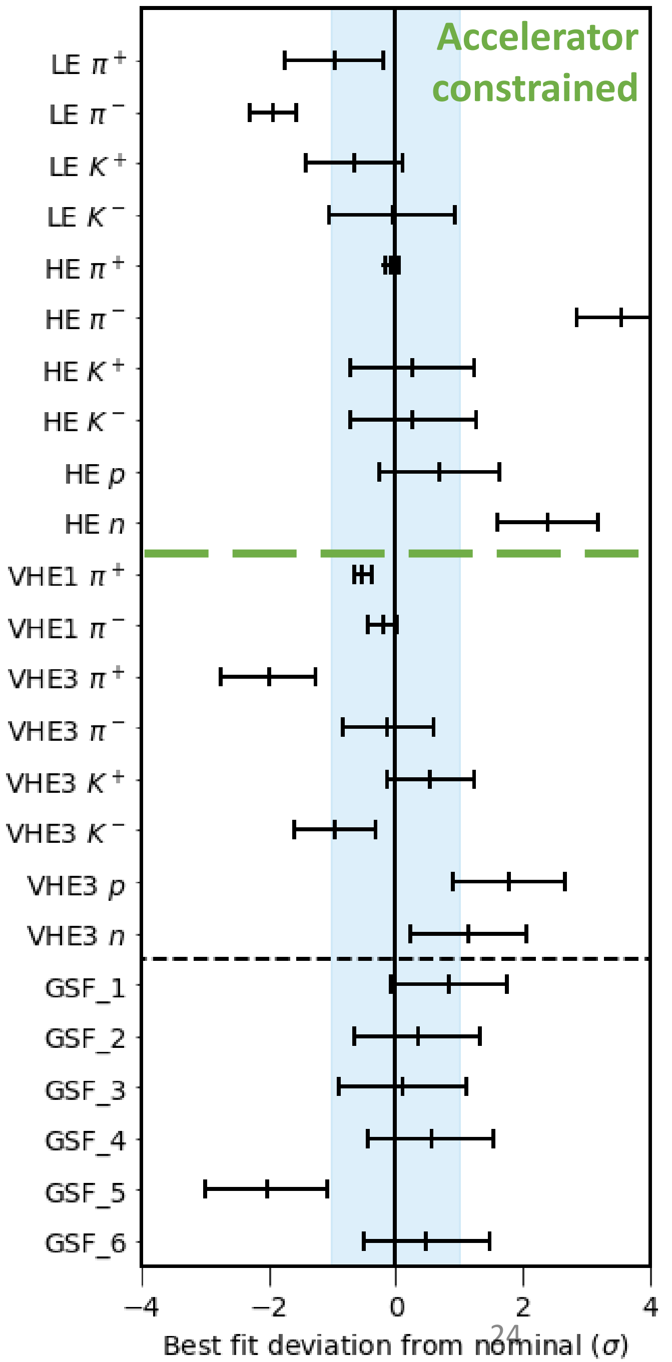
10 correction functions to modify experimental data (if reported by experiments)

Resulting muon fluxes and cross-calibrated data



Fitted parameter values



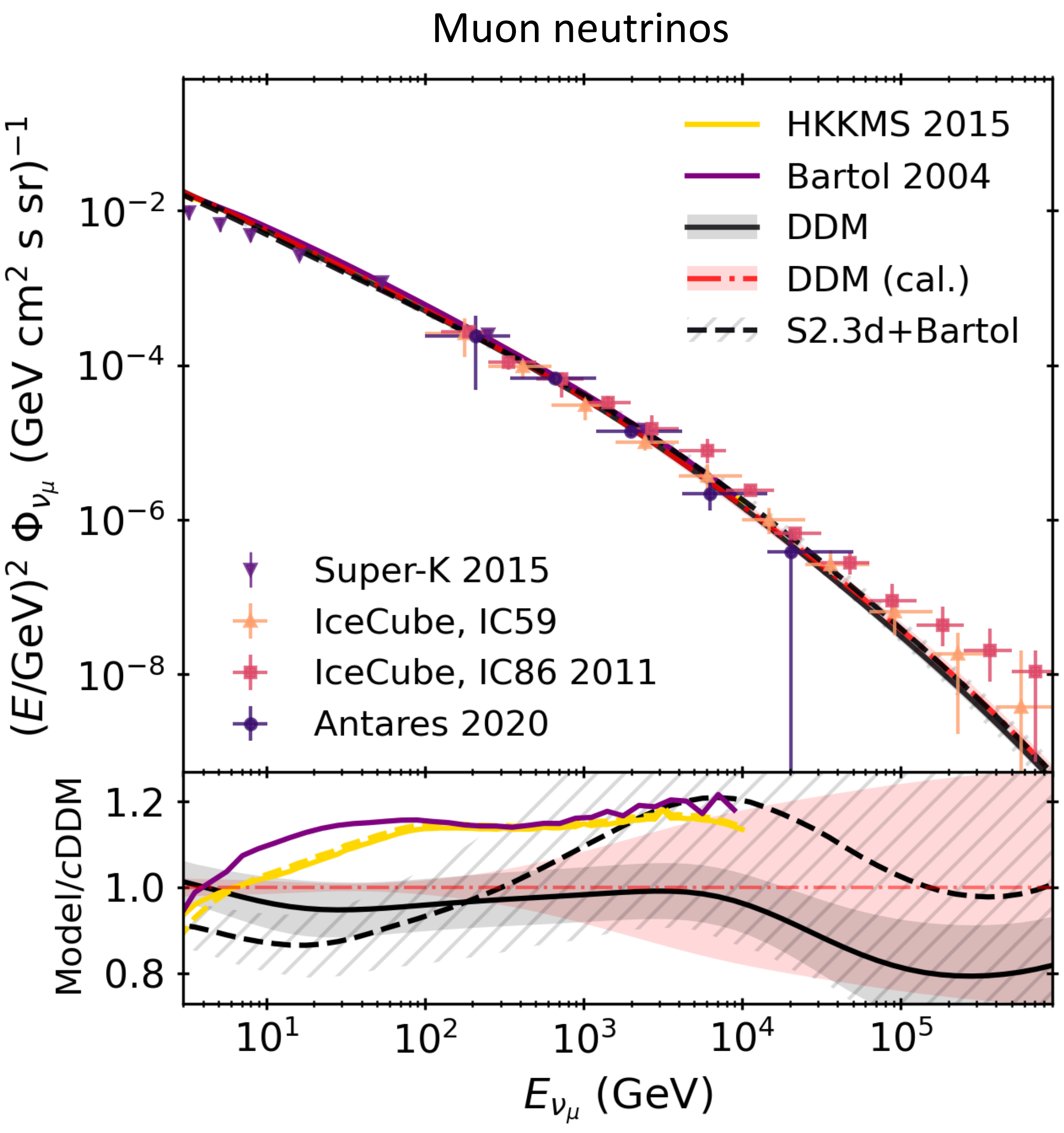


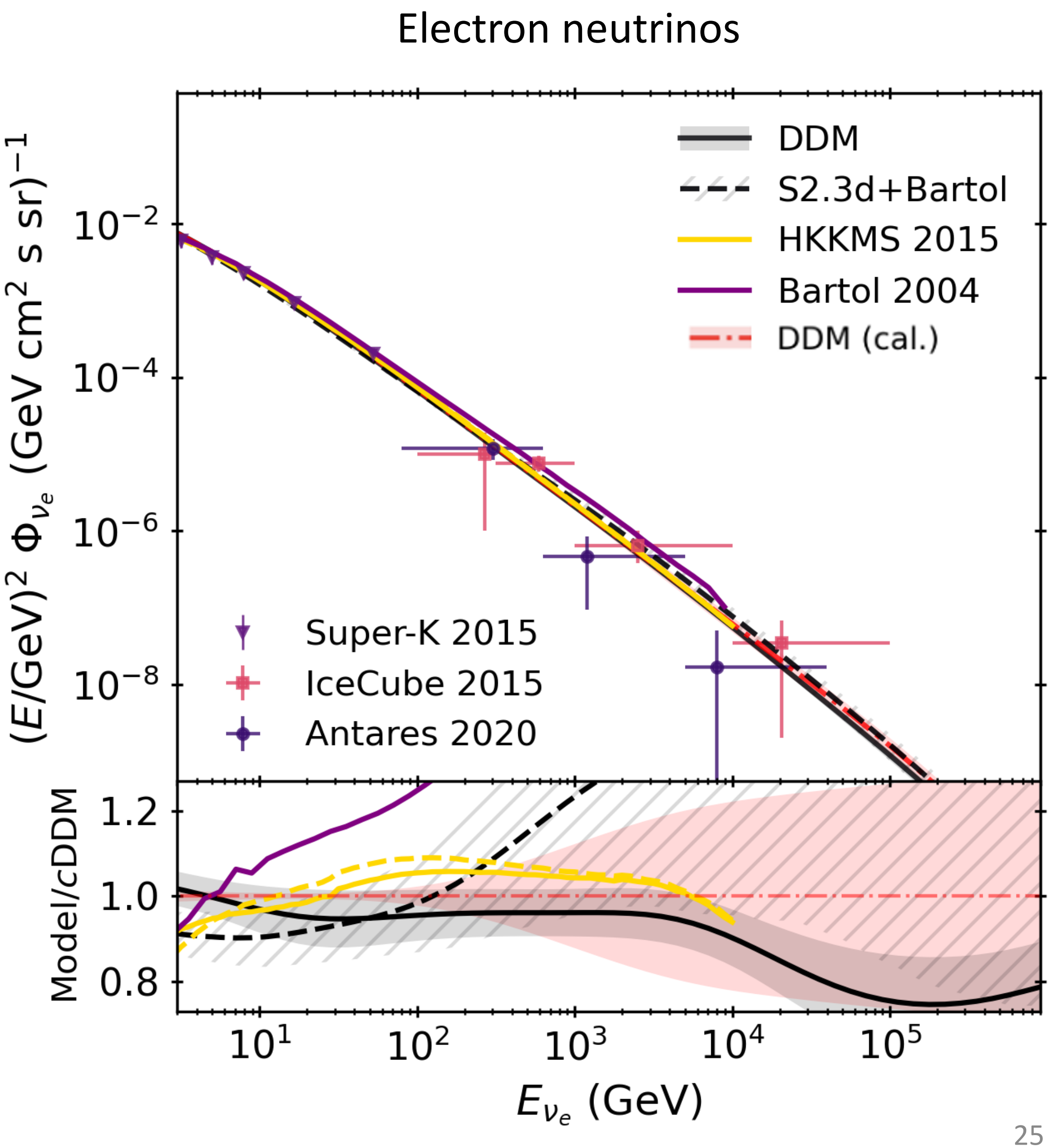
J. P. Yanez & A. Fedynitch, ICRC 2021, appears soon

Neutrino fluxes

hatched area: uncertainty from

Barr et al. PRD74, 094009 (2006) & AF, Huber PRD (2022)



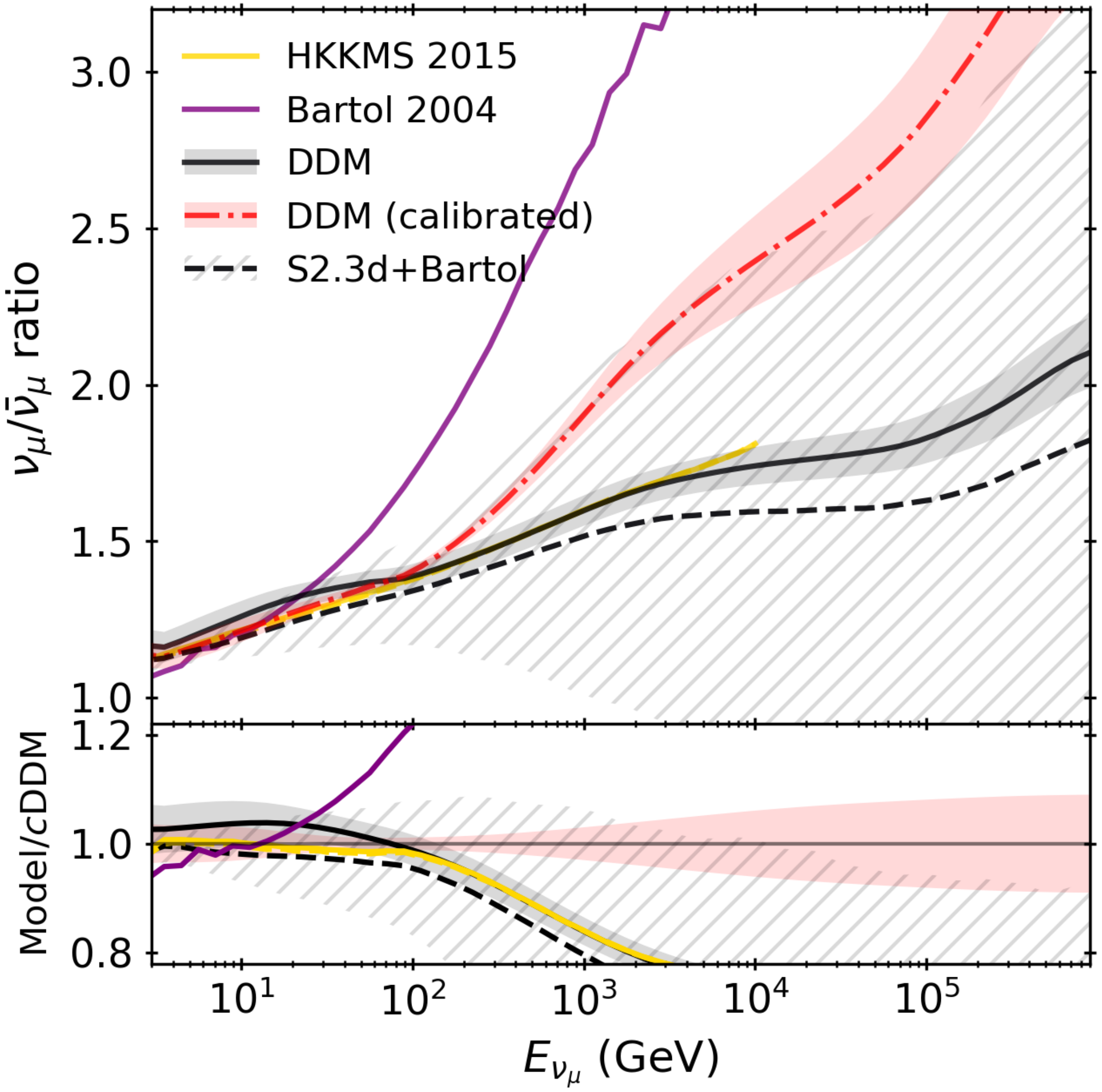


Neutrino ratios

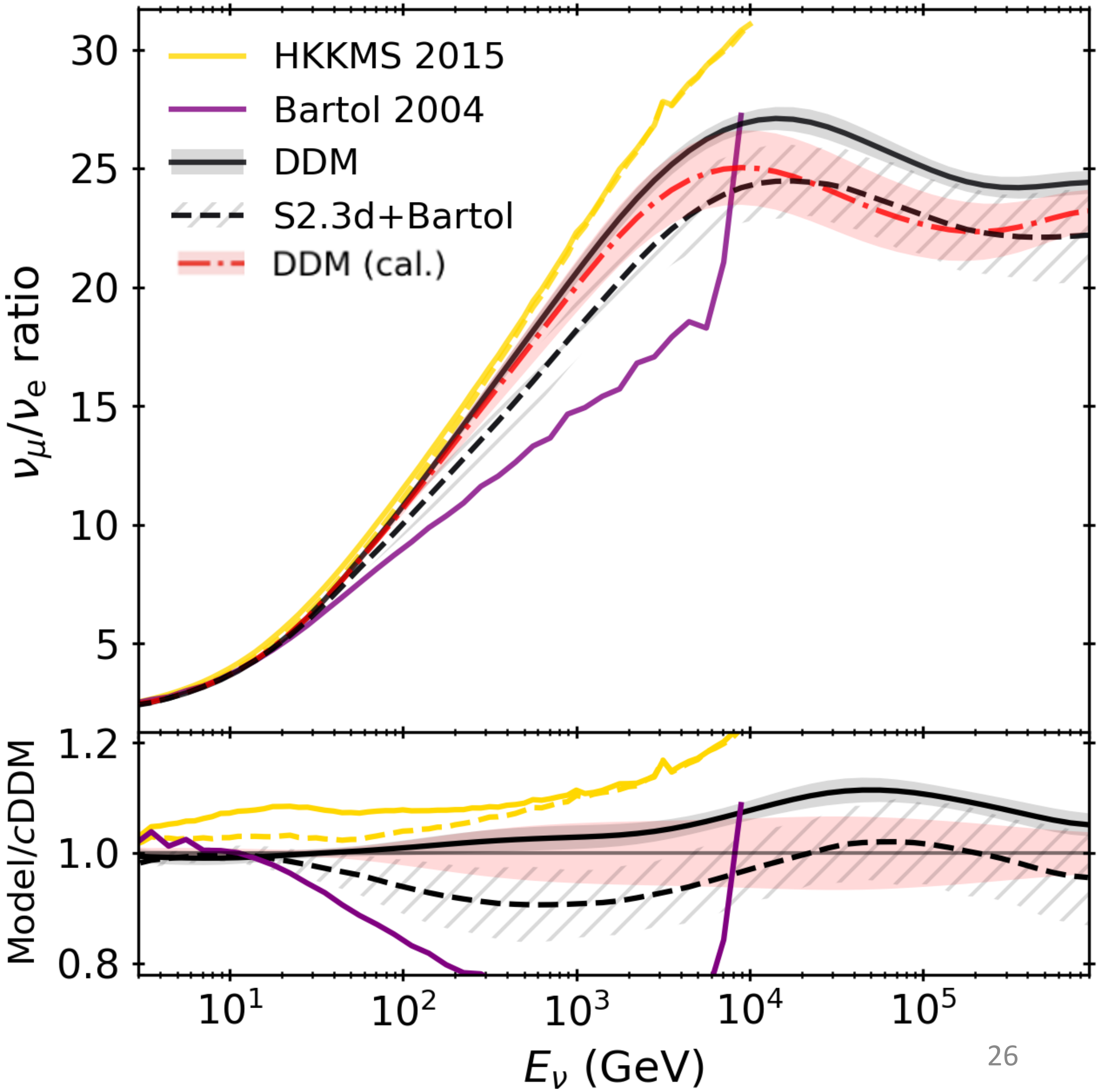
hatched area: uncertainty from

Barr et al. PRD74, 094009 (2006) & AF, Huber PRD (2022)

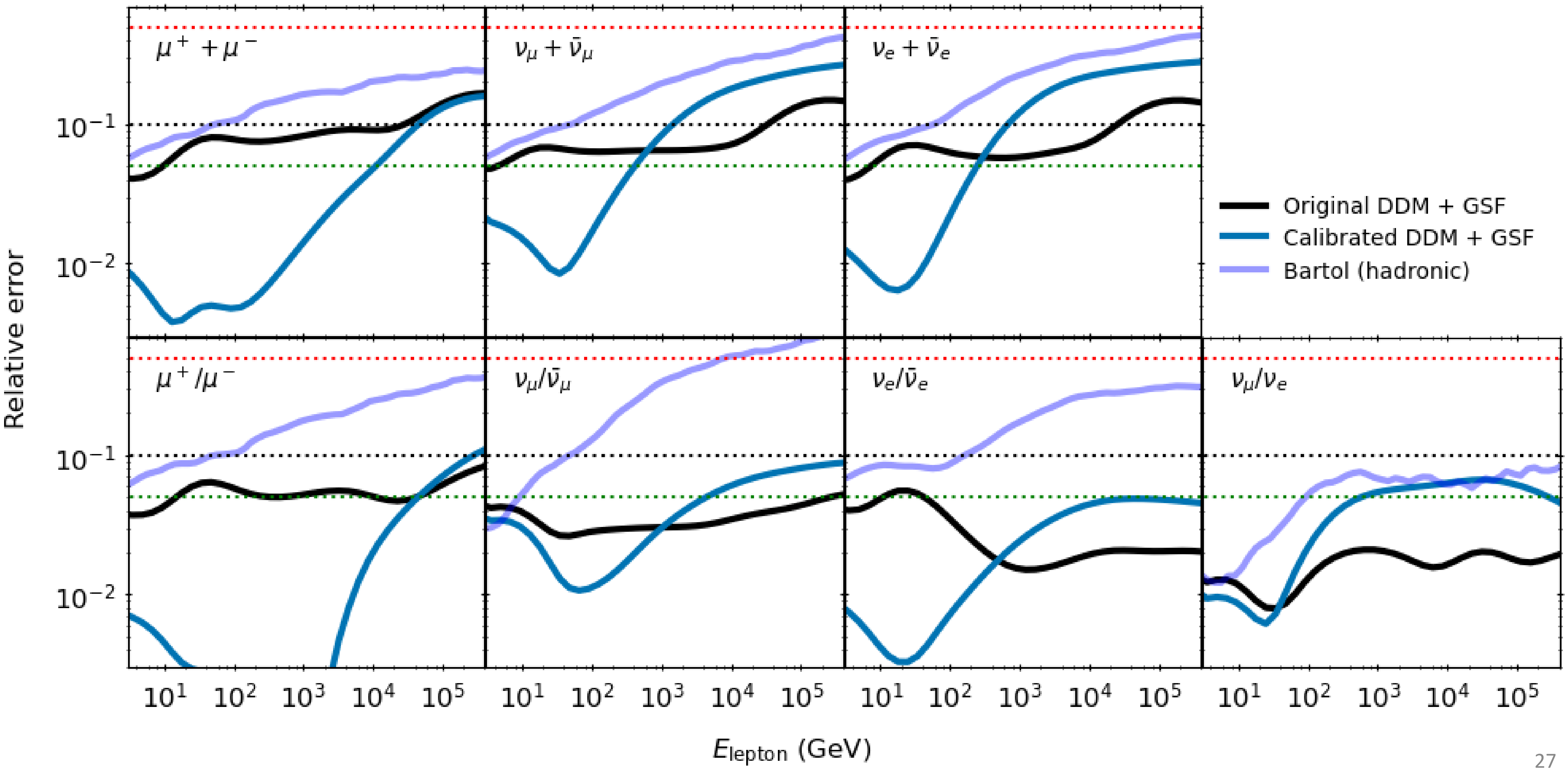
Numu/numubar ratio



Flavor ratio



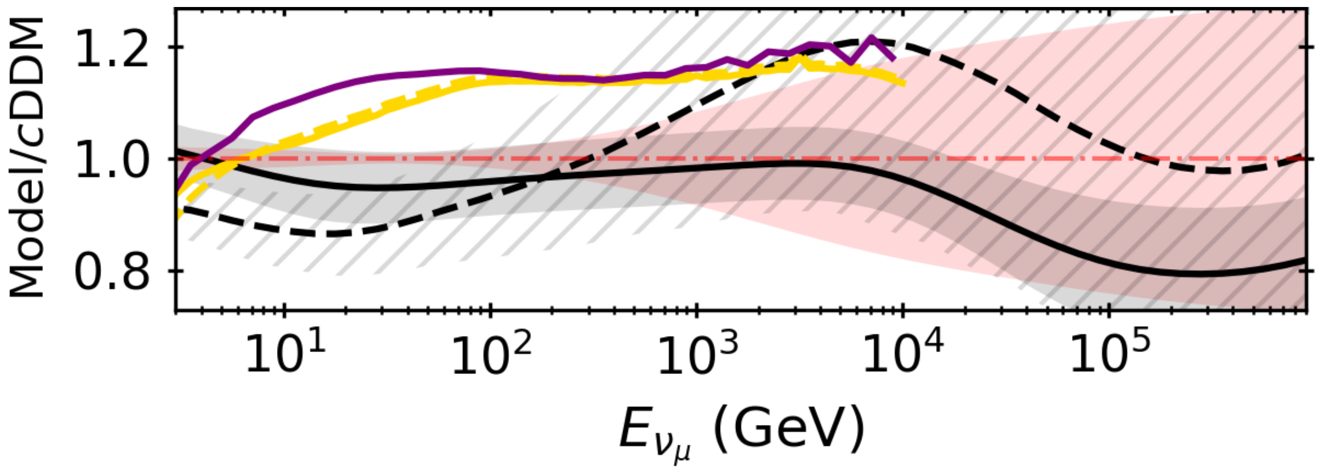
Total uncertainty from DDM + GSF + muon fit



J. P. Yanez & A. Fedynitch, ICRC 2021, appears soon

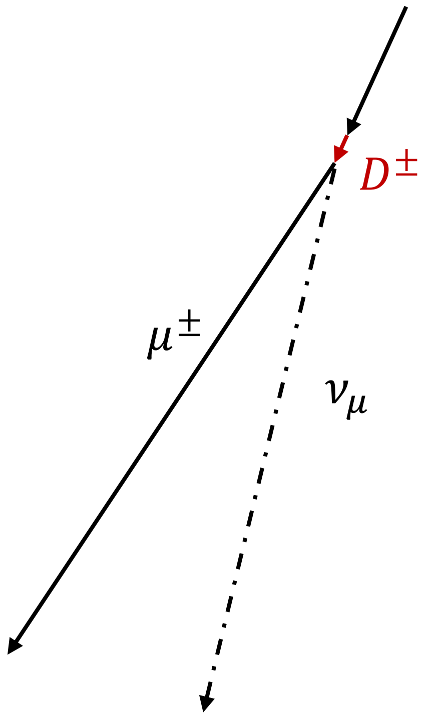
Features

- Constrained by data
  - New measurements can be included, update calculation
- Using open source tool: MCEq
  - Implementation and physics assumptions are transparent
- Gives access to the full covariance matrix
  - Users can compute how uncertainties modify the flux

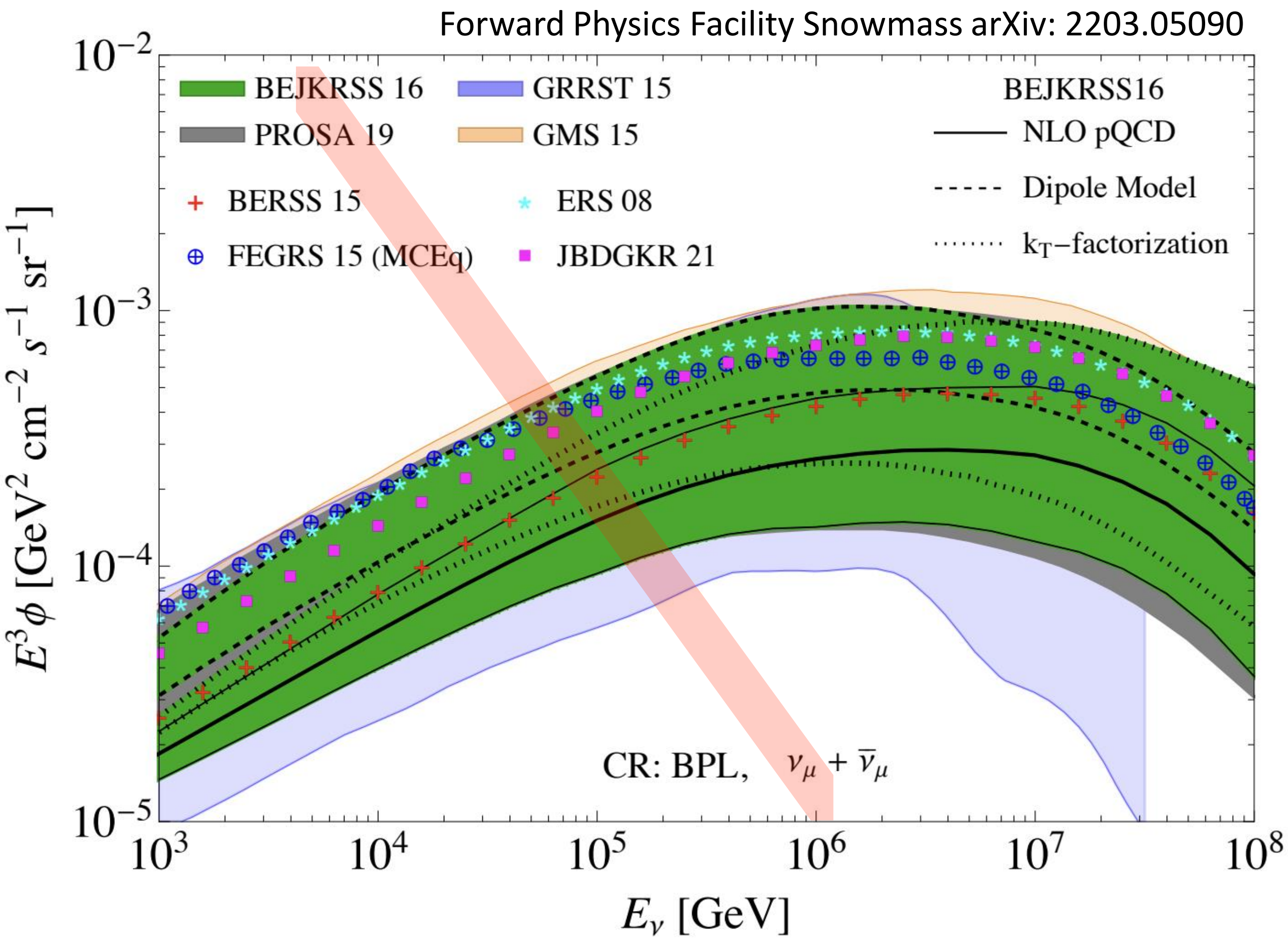


What about the prompt component?

Spoiler: We still don't know



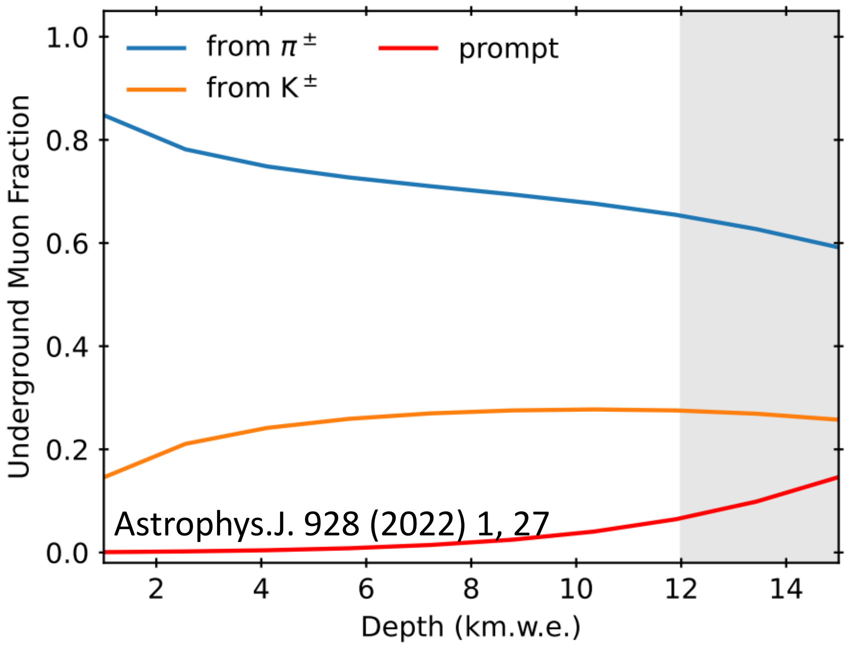
The problem of prompt



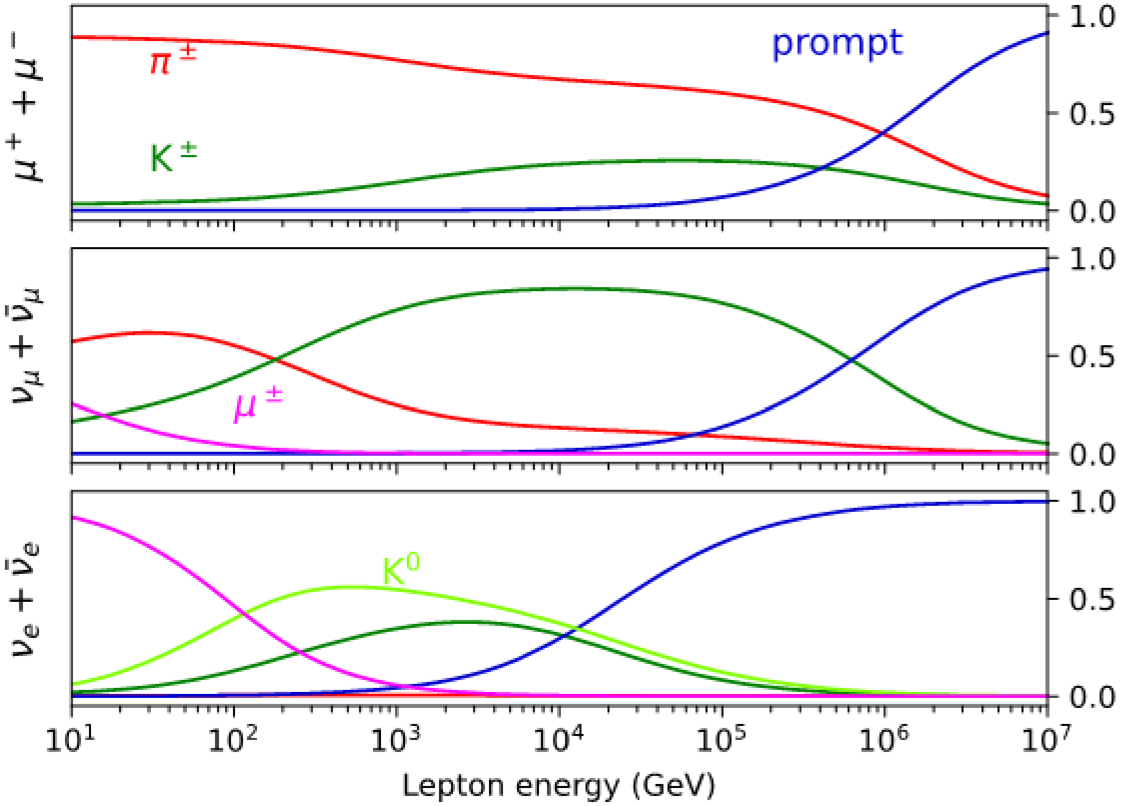
- Expected to dominate atm. ν flux above 100 TeV – 1 PeV but **not yet observed**
- Predictions have issues
  - Large uncertainties from pQCD
  - pQCD might be incomplete (intrinsic charm)
  - The fragmentation (c → D) function is a choice
- No hadronic data available to directly constrain the models

Constraints from muons

- Prompt muons have more production channels than ν
- No spectrometer data at PeV energies where prompt dominates
- How about deep underground experiments?



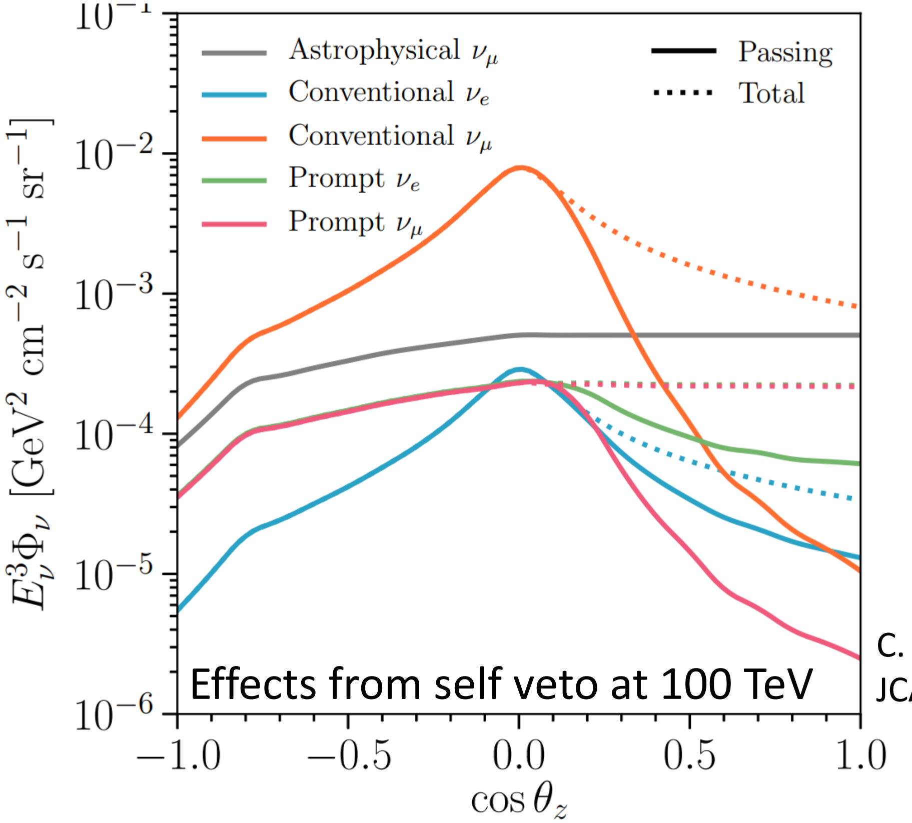
Fraction of flux coming from each meson



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

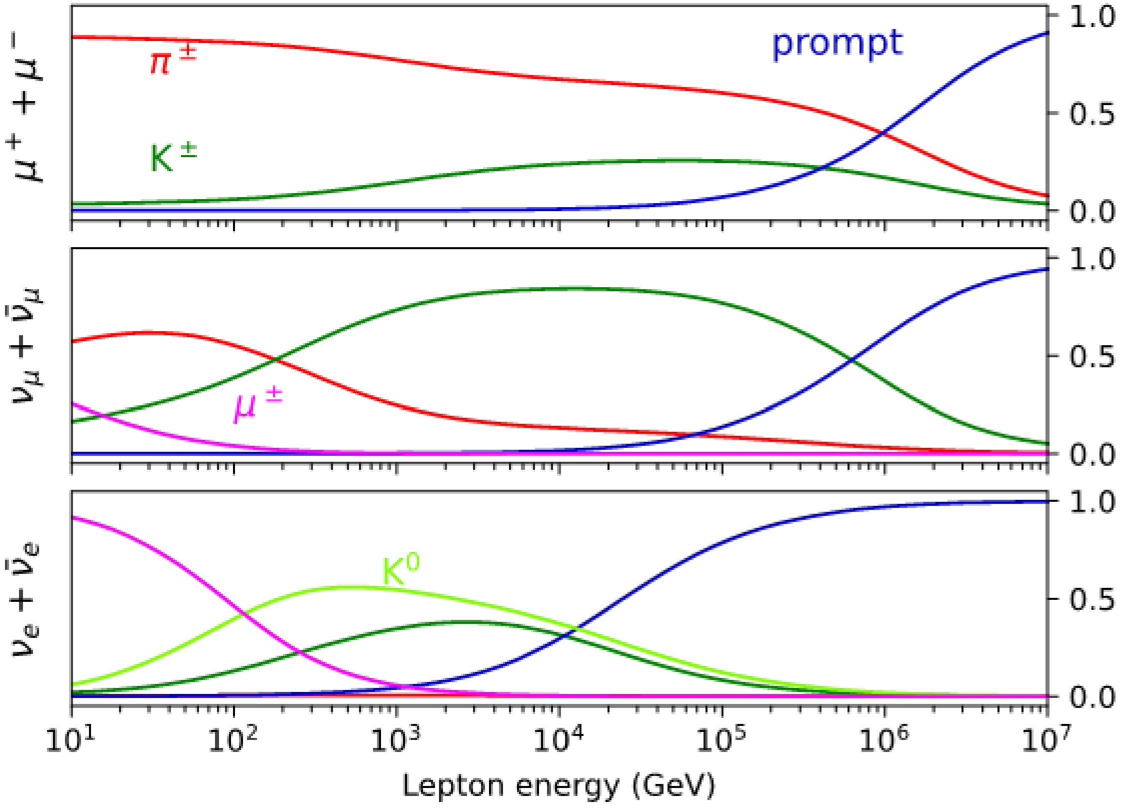
Constraints from ν

- The ν_e channel is dominant at 10's TeV
- The ν_μ channel is degenerate with $\Phi_{\nu\ \mathrm{astro}}$
- Self-veto rejects prompt, breaks degeneracy



C. Arguelles et al
JCAP 07 (2018) 047

Fraction of flux coming from each meson

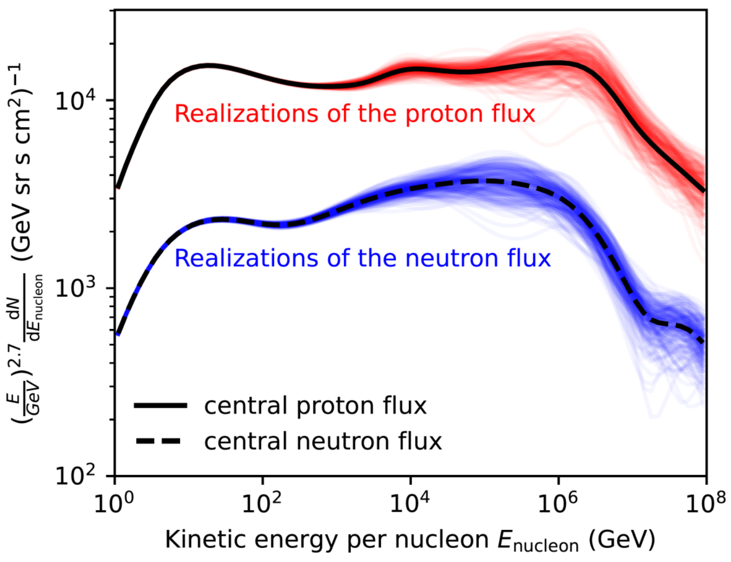


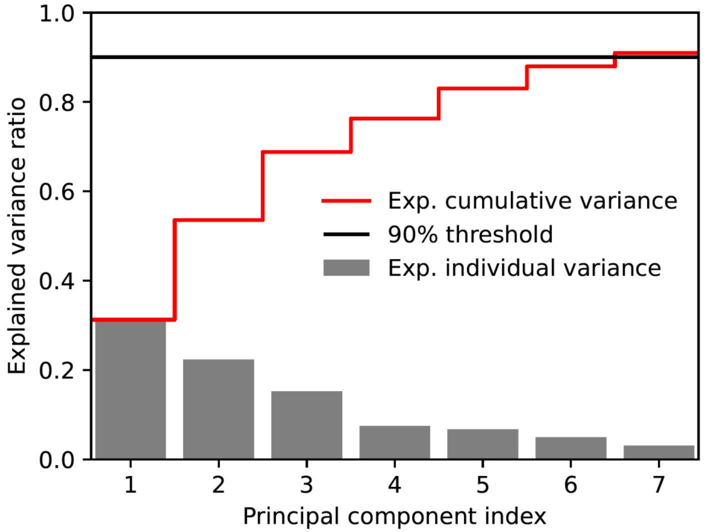
A. Fedynitch, F. Riehn, R. Engel, T.K. Gaisser, T. Stanev
PRD 100 2019

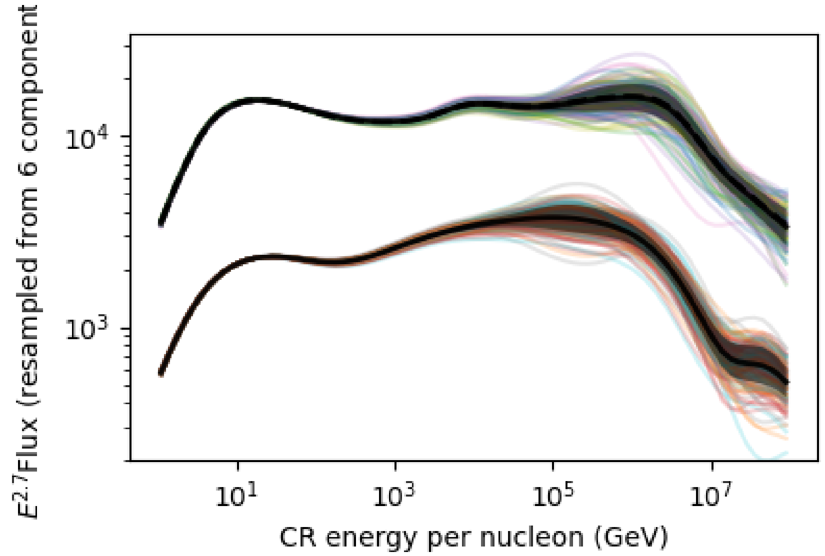
Conclusions

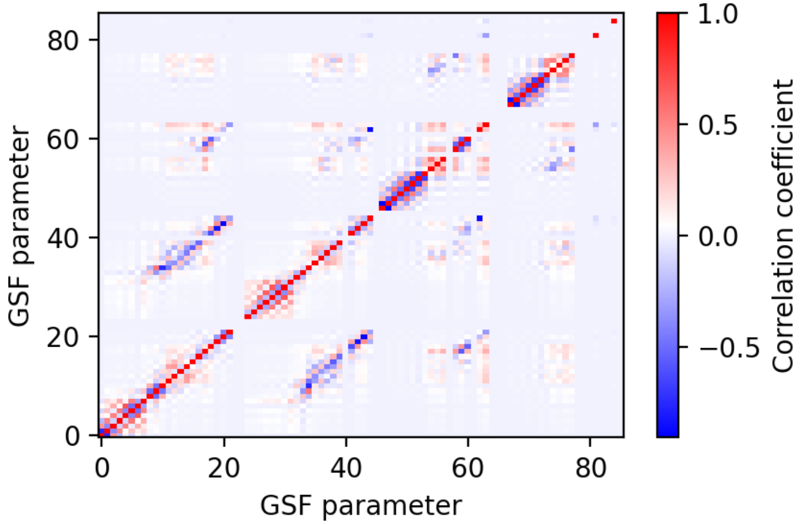
- Data-driven atm-ν flux available from few GeV to PeV (DDM+GSF)
  - Calculated with MCEq, can be reproduced independently
- The muon calibration adjusts flux and reduces errors
  - Mainly constrain pion yields
  - Error < 10% for $E_\nu < 1\ \mathrm{TeV}$, going to 30% at PeV
  - Users will get full access to calibrated flux and corresponding errors
  - Future: will include data from underground experiments, higher energy
- Prompt – existing data could be enough to measure it
  - Tight constraints on conventional component achieved
  - Underground muon data sets could help
  - Exploit neutrino measurements with self-veto + cascades + tracks

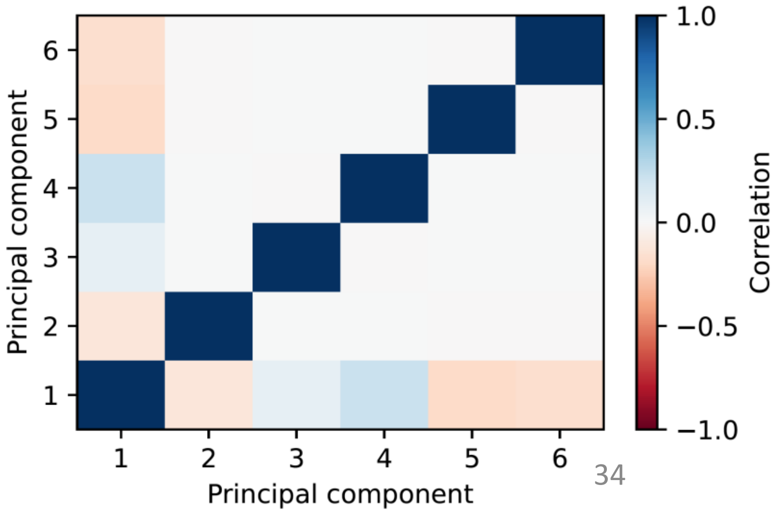
Dimensionality reduction to 6 parameters



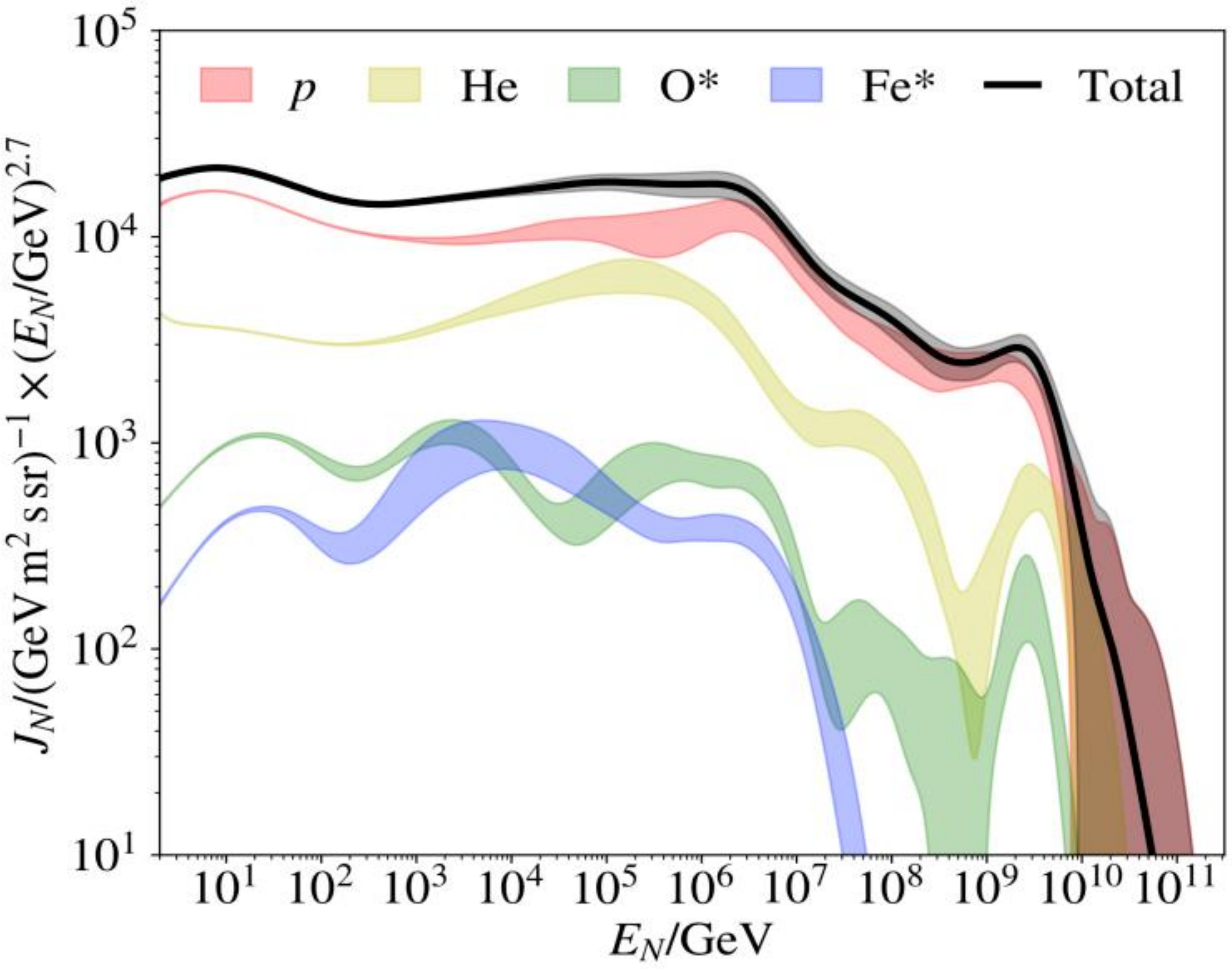








The Global Spline Fit – nucleon fluxes (MCEq input)



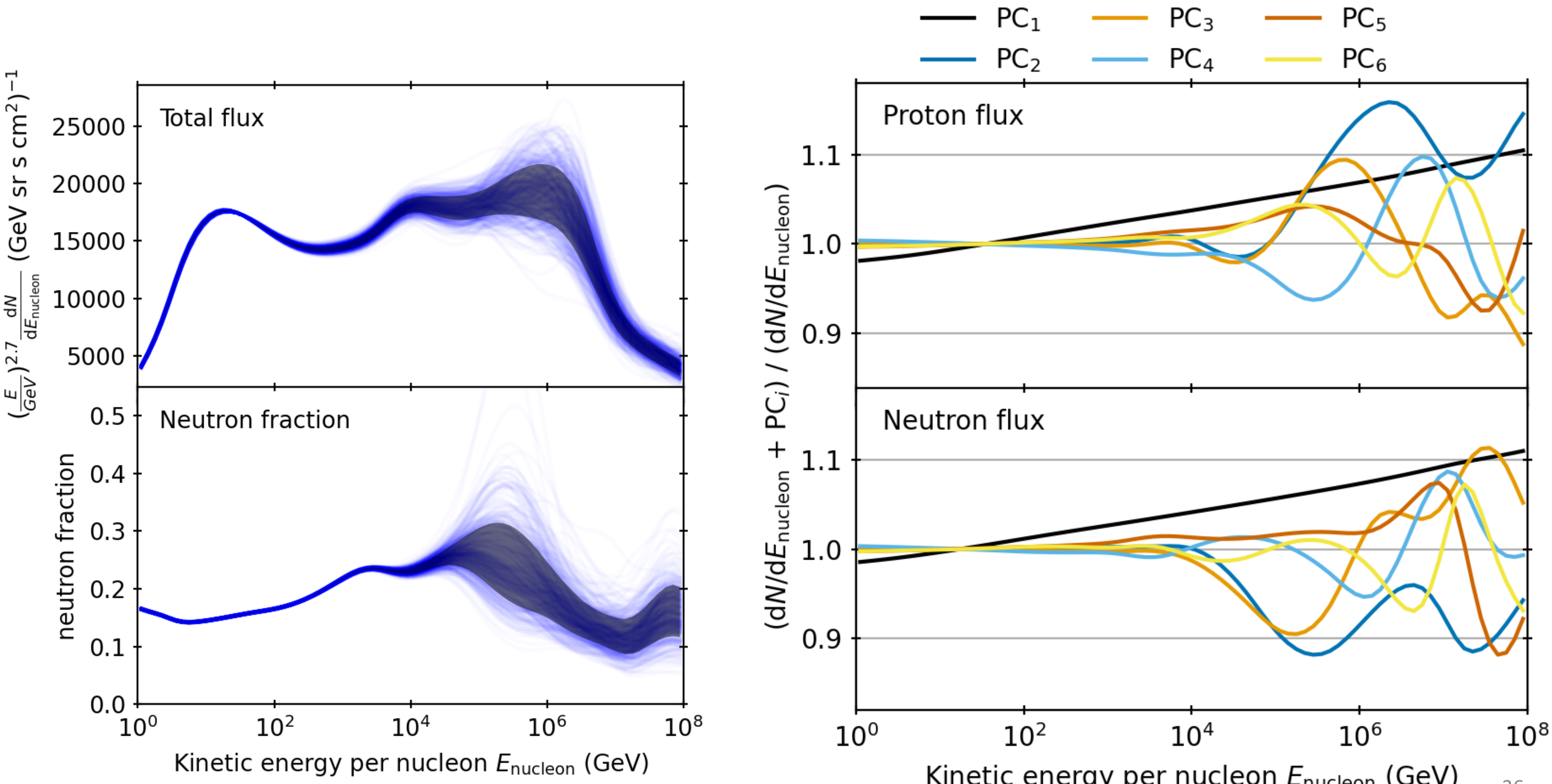
- Most contribution from proton and helium flux
- Correlations between H and He affect
  - CR neutron fraction
  - Muon charge ratio
  - Neutrino/Antineutrino ratio

→ Need to model two correlated components

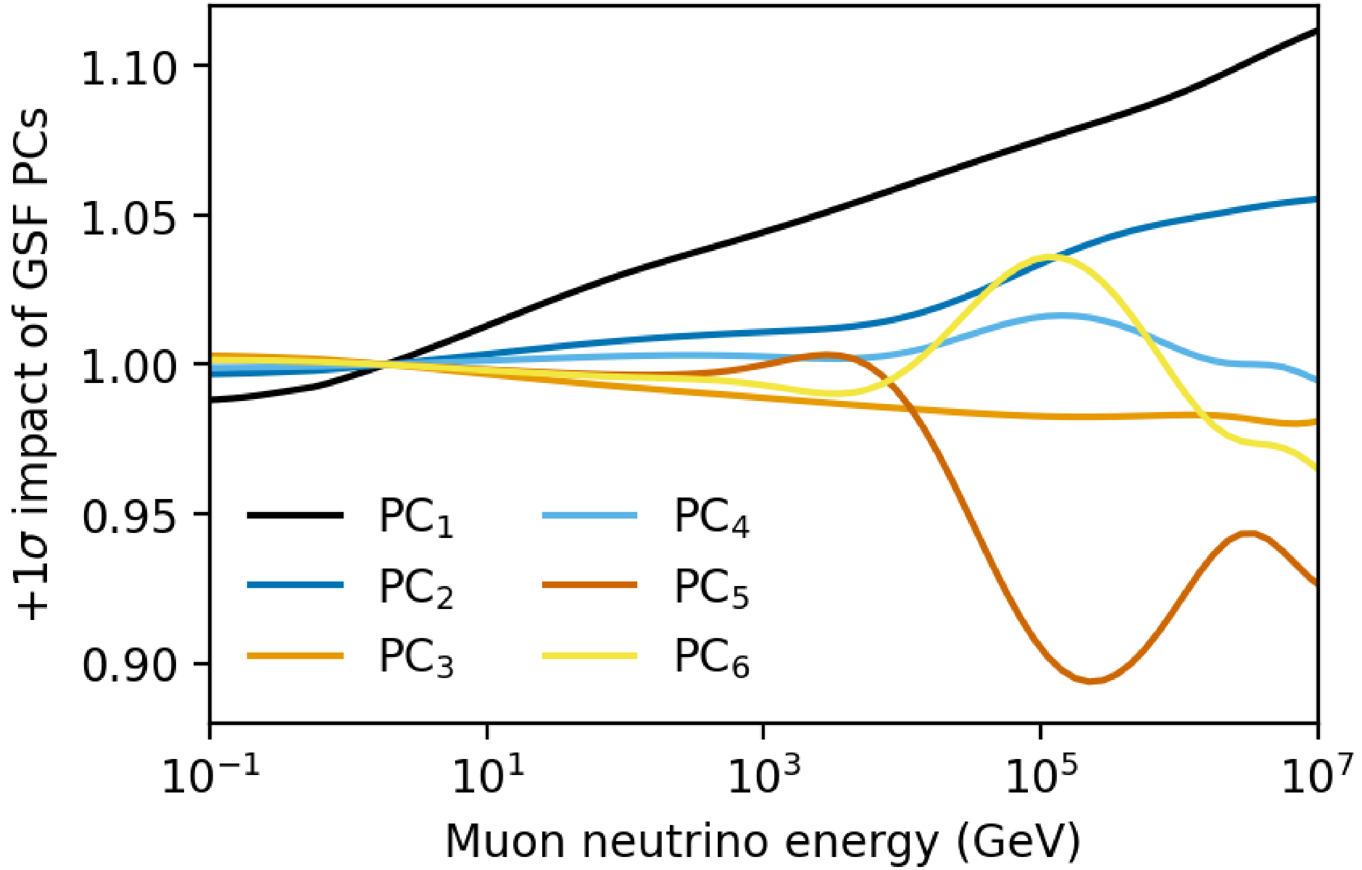
→ technically ~80 parameters

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

GSF-PCA


Total flux
Neutron fraction
$(\frac{E}{GeV})^{2.7} \frac{dN}{dE_{nucleon}}$ (GeV sr s cm^2)$^{-1}$
25000
20000
15000
10000
5000
neutron fraction
0.5
0.4
0.3
0.2
0.1
0.0
10^0
10^2
10^4
10^6
10^8
Kinetic energy per nucleon $E_{nucleon}$ (GeV)
PC_1
PC_2
PC_3
PC_4
PC_5
PC_6
Proton flux
Neutron flux
$(dN/dE_{nucleon} + PC_i) / (dN/dE_{nucleon})$
1.1
1.0
0.9
Kinetic energy per nucleon $E_{nucleon}$ (GeV)

Principal components of CR nucleon fluxes



- Figure shows **zenith-averaged muon neutrinos**
- Component 1 is a “global” spectral index correction
- Sum of components can reproduce 90% allowed shapes from the 1-sigma range of GSF
- How accurate is the GSF error?

→ Data motivated nuissance parameters

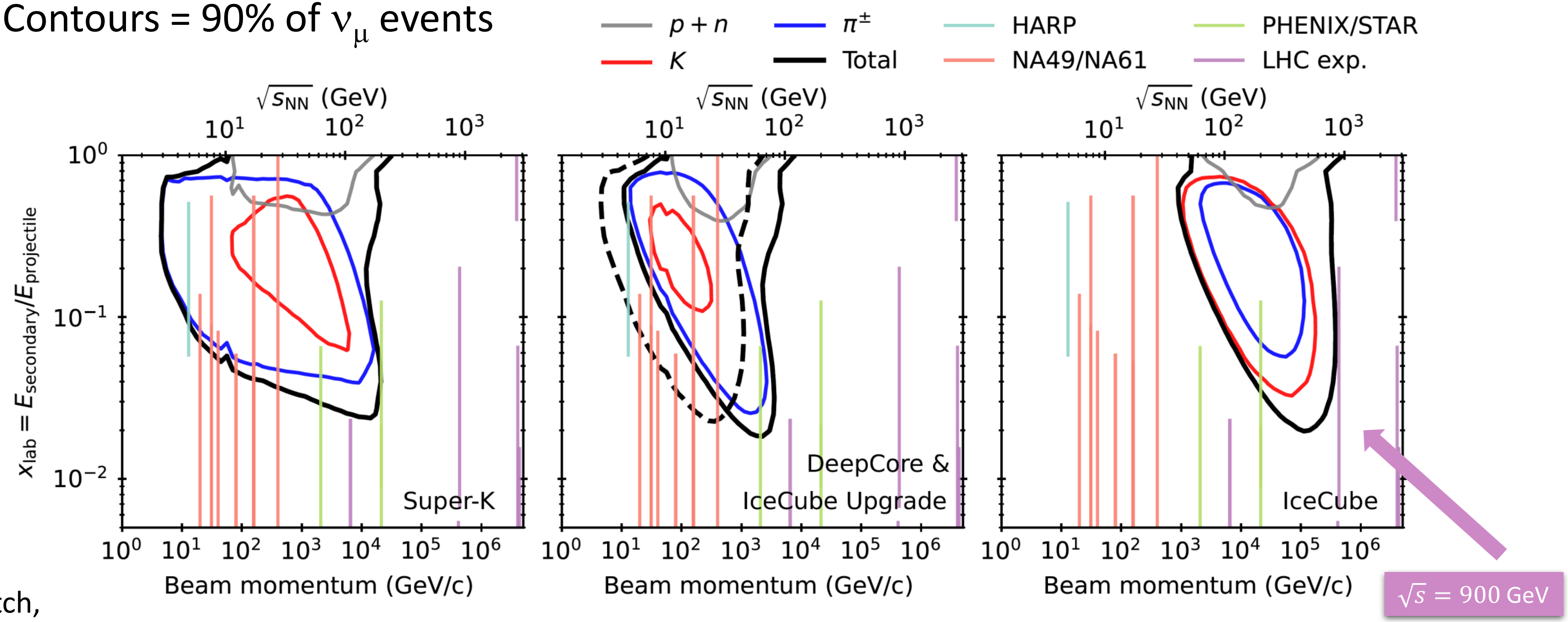
→ CR nucleon flux represented by weighted sum of 6 weakly base vectors

→ GSF can be dynamically updated if new data comes in

→ **Optimal CR nucleon flux model for neutrino flux calculations**

Hadron production phase space relevant for NTs

Contours = 90% of ν_μ events



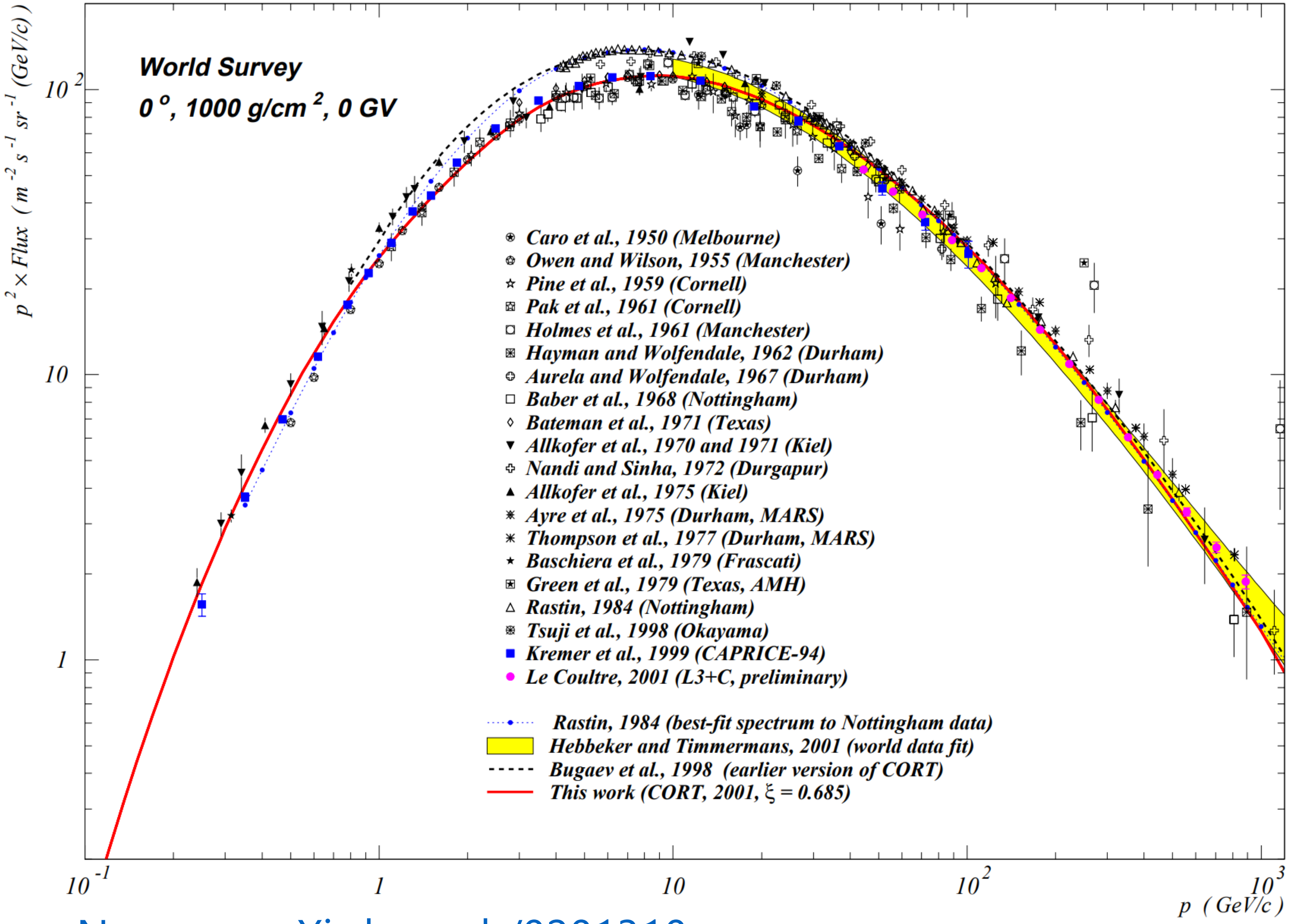
A. Fedynitch,
M. Huber
PRD 106 (2022)

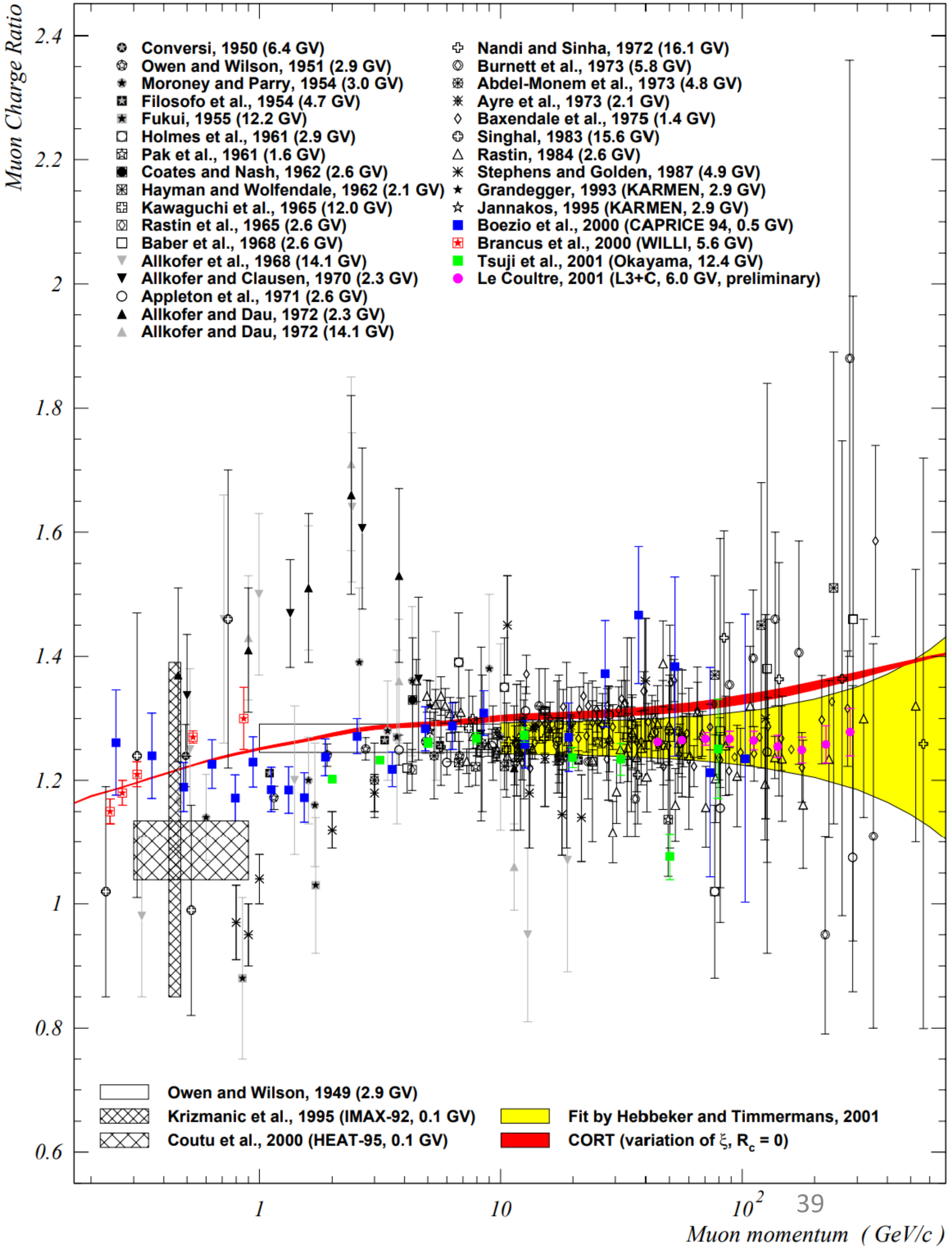
SK: sum of ν_μ FC and PC

DeepCore :
tracks, E_{reco} < 60 GeV (osc.)

IceCube Northern Tracks

Data as of 2002





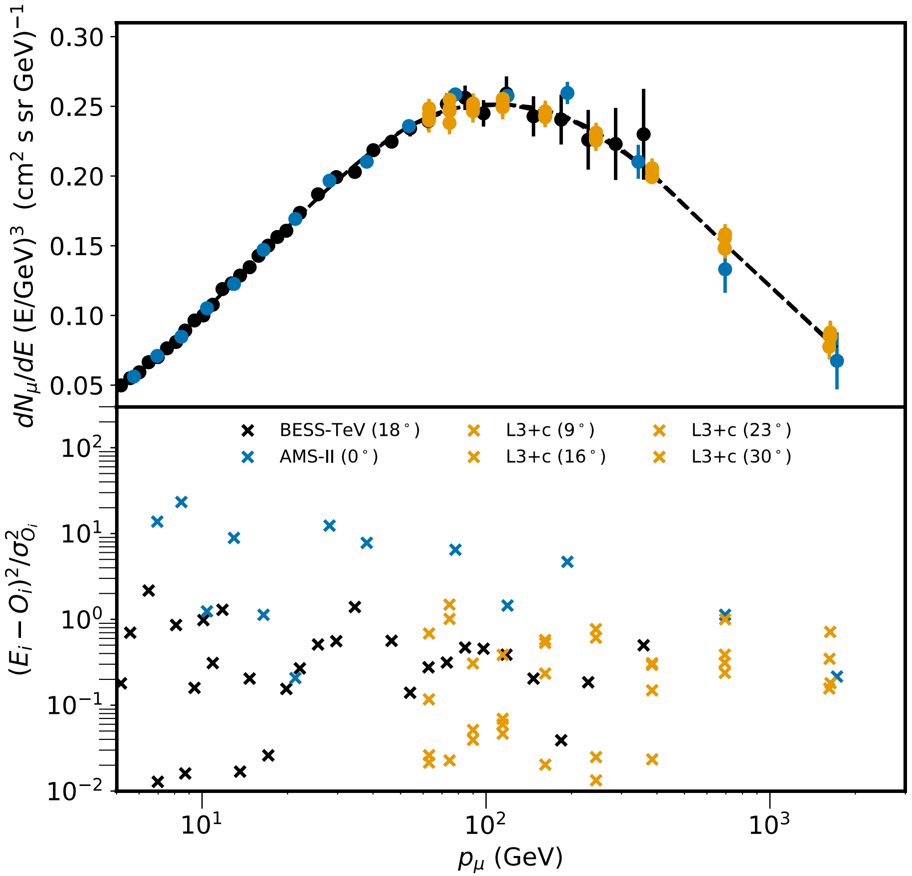
[Naumov, arXiv:hep-ph/0201310](arXiv:hep-ph/0201310)

Surveying the muon fluxes literature

- We looked at most data from muon spectrometers above some 5 GeV
  - Muon fluxes and muon charge ratio (μ^+/μ^-)

Requirements for use

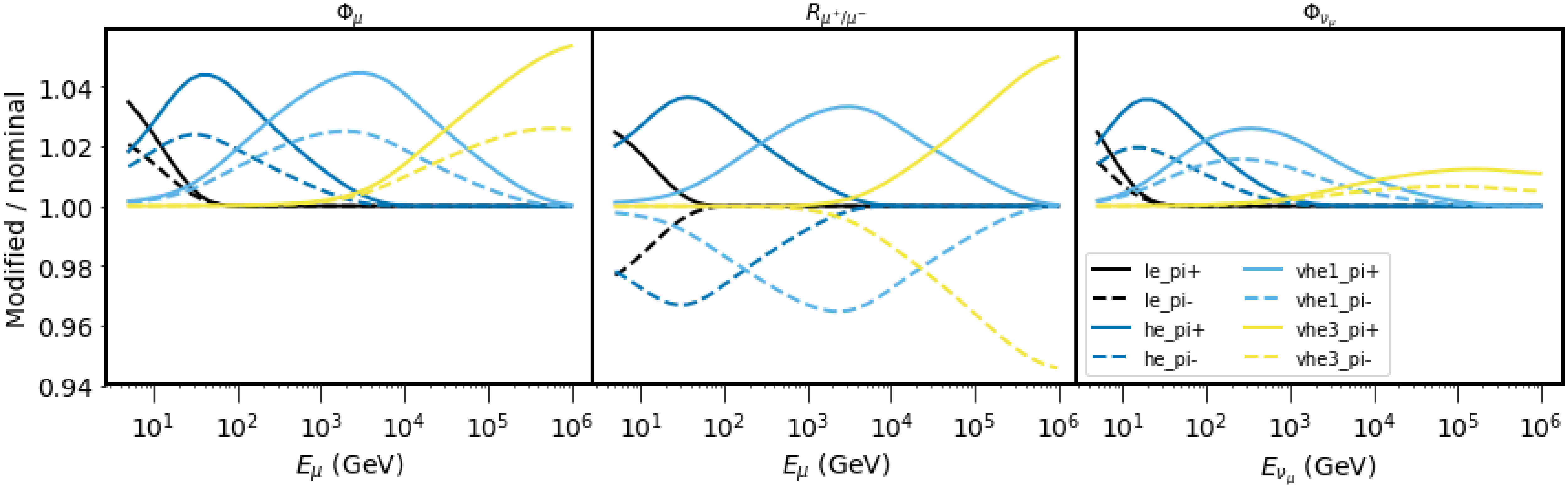
- Detailed description of detector and operating conditions
- Corrections applied to the data (e.g. extrapolation from underground to sea level)
- Muon fluxes: Systematic uncertainties explained in detail



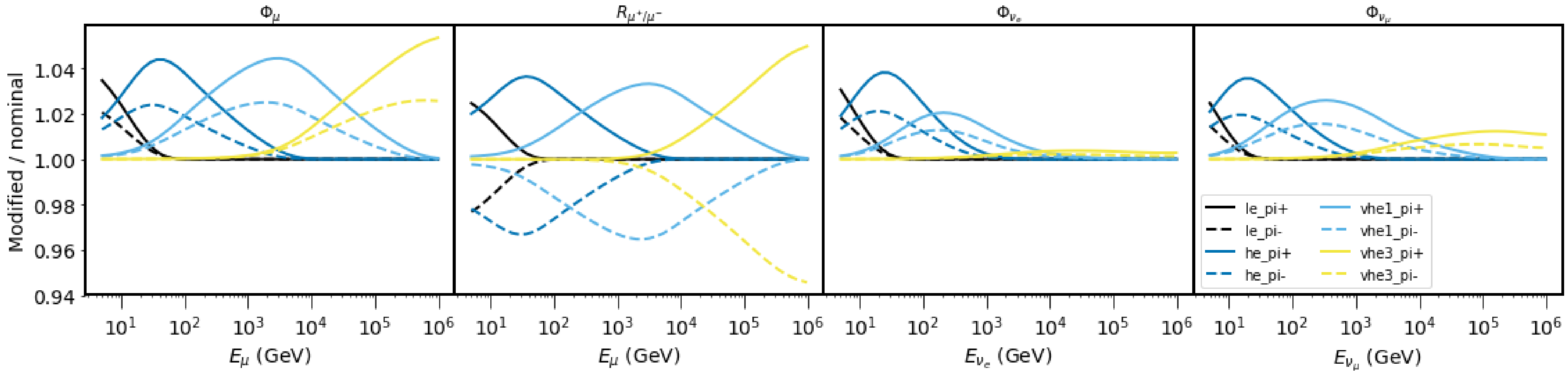
Experiments, we believe are not compatible or statistically not significant with each other include: AMS, MARS, MUTRON,

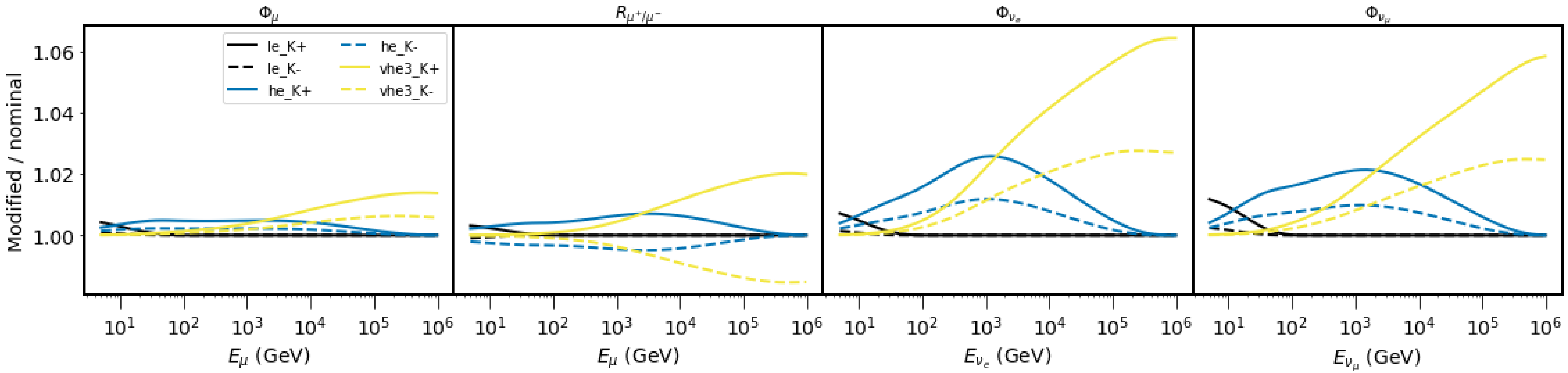
Example of DDM parameter impact

Projectile proton E:
le_: 31 GeV NA61
he_: 158 GeV NA49
vhe1_: 20 TeV extrp.
vhe3_: 2 PeV extrp.



Choice of parameters and extrapolation from “DDM energies”





Projectile proton E:
le_: 31 GeV NA61
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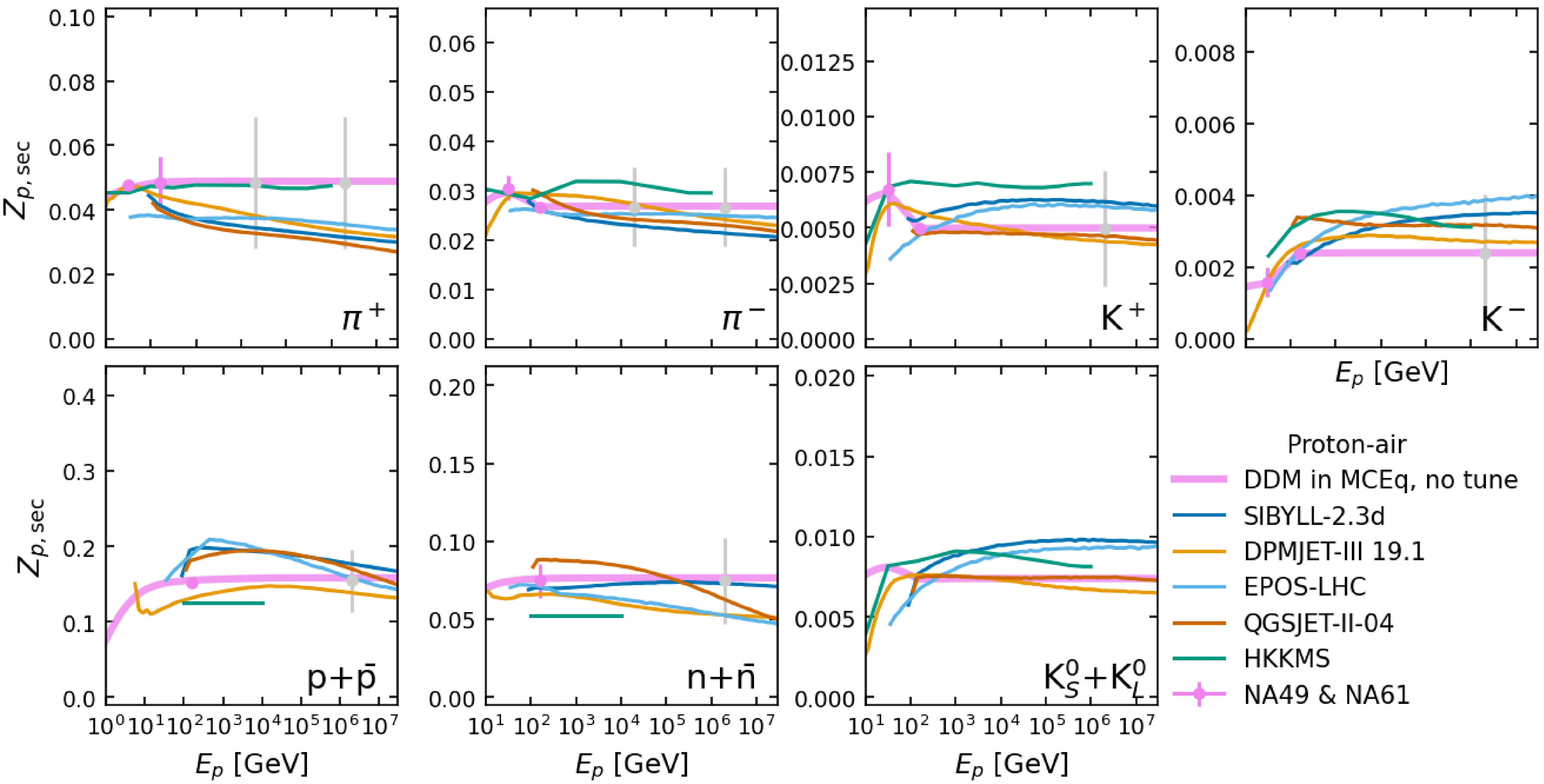
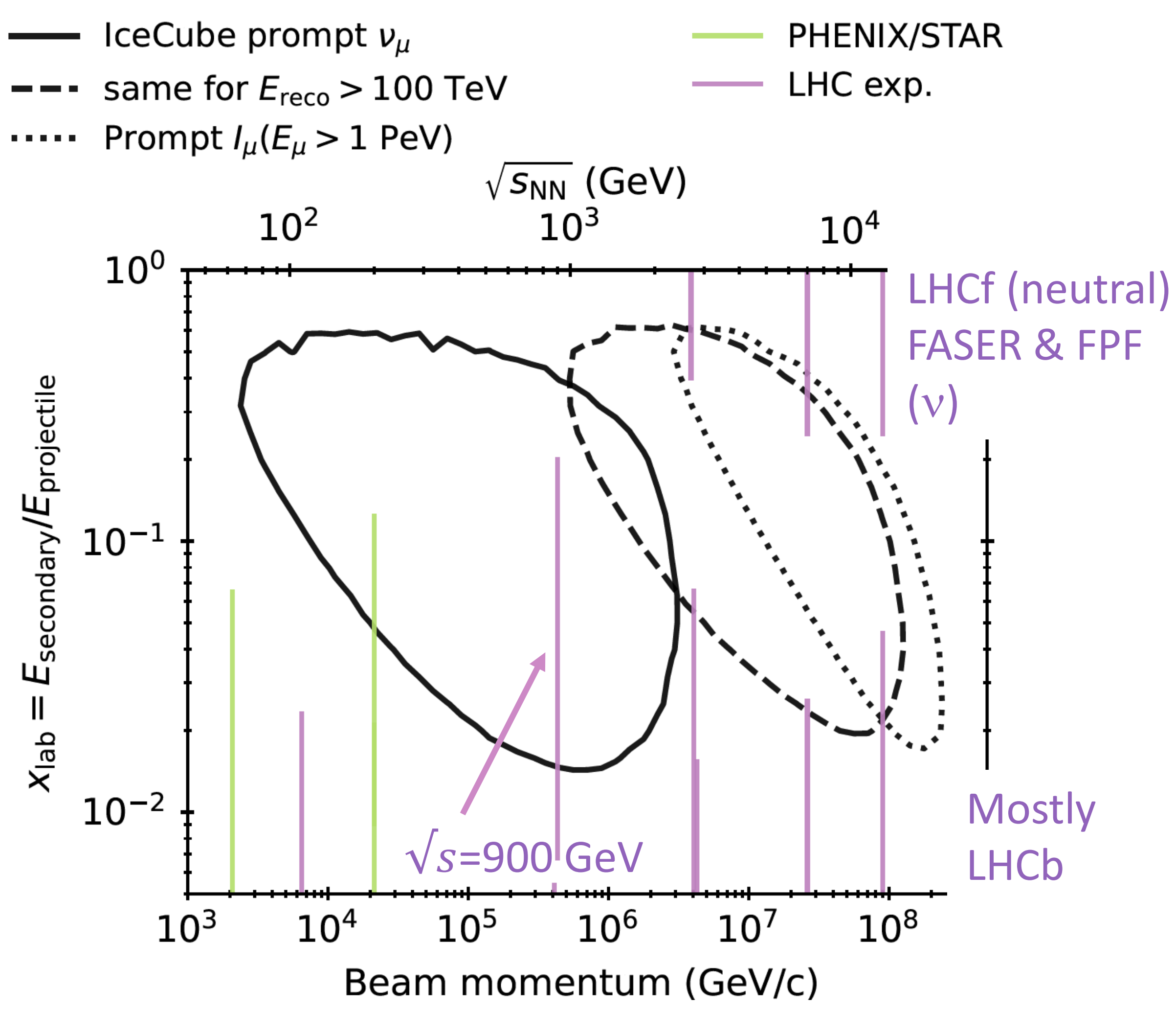


$Z_{p,\mathrm{sec}}$
E_p [GeV]
π^+
π^-
K^+
K^-
$p+\bar{p}$
$n+\bar{n}$
$K^0_S+K^0_L$
Proton-air
DDM in MCEq, no tune
SIBYLL-2.3d
DPMJET-III 19.1
EPOS-LHC
QGSJET-II-04
HKKMS
NA49 & NA61

The problem of prompt



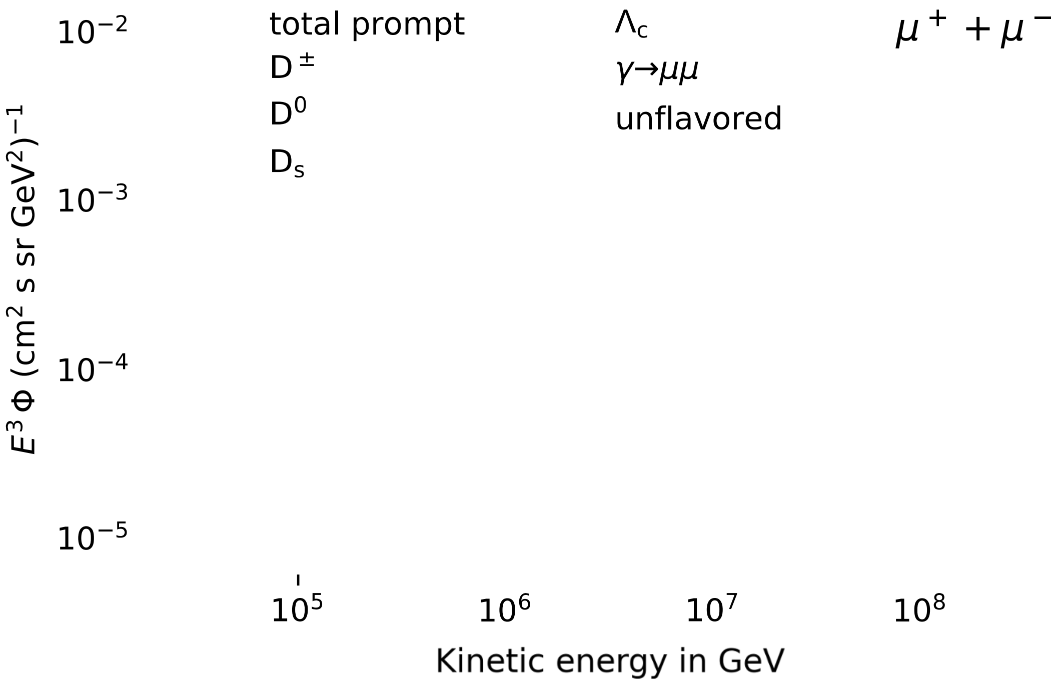
- Expected to dominate atm. ν flux above 100 TeV – 1 PeV but **not yet observed**

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

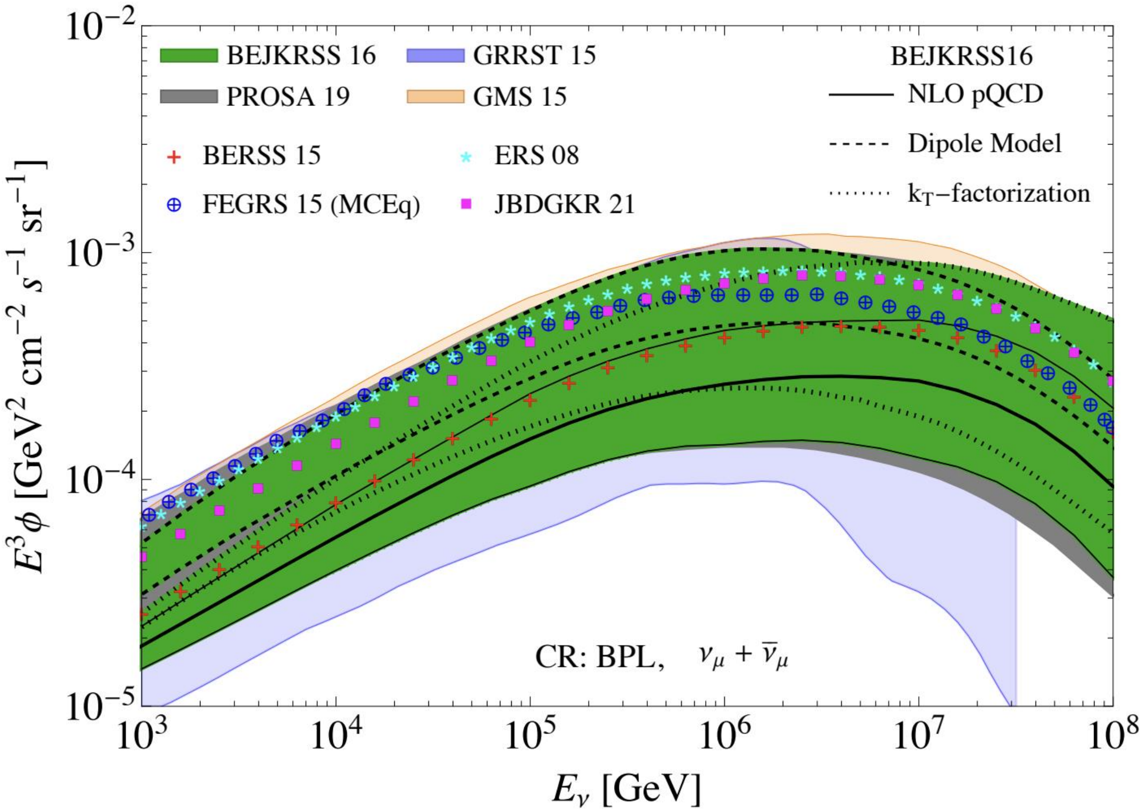
- No hadronic data available to directly constrain the models

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

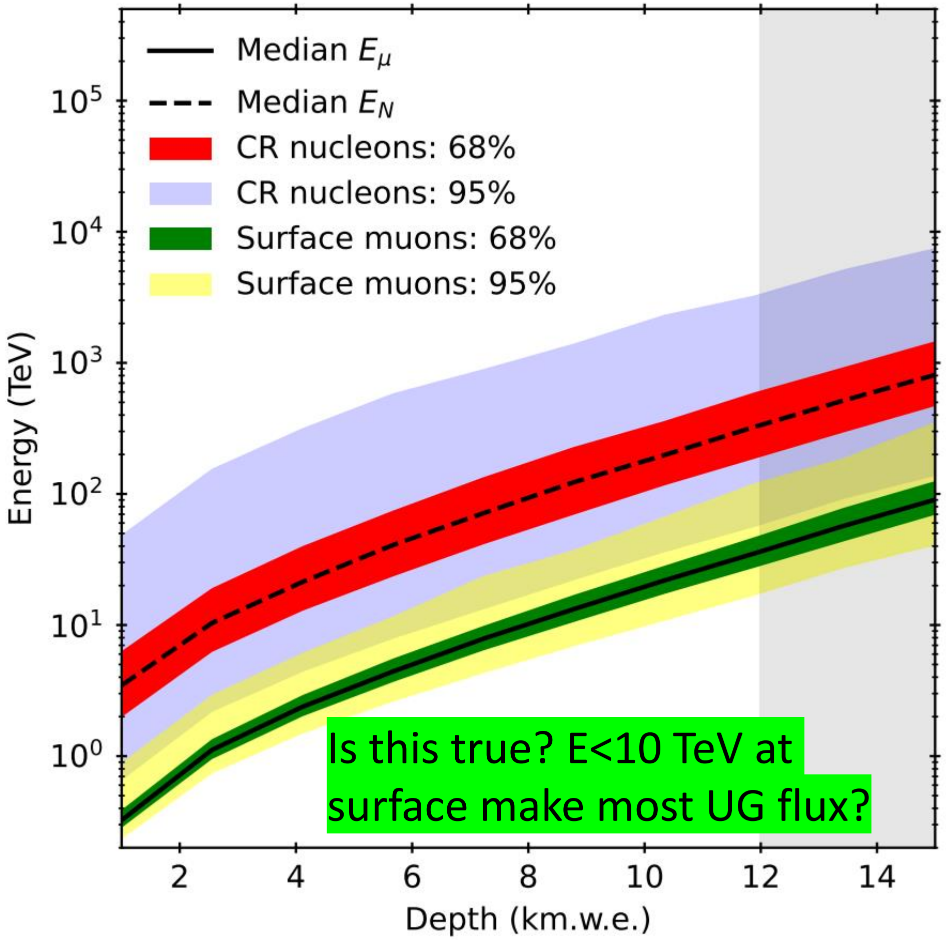


Figure 4. Energies of surface and cosmic ray (CR) nucleons contributing to the muon rate underground, shown for the SIBYLL-2.3D hadronic interaction model and the GSF primary flux model. The coloured bands show the energy ranges that result in 68% and 95% of the underground muon rate respectively. At depths larger than 12 km.w.e. the rate becomes dominated by neutrino-induced muons through charged-current interactions as indicated by the grey band.

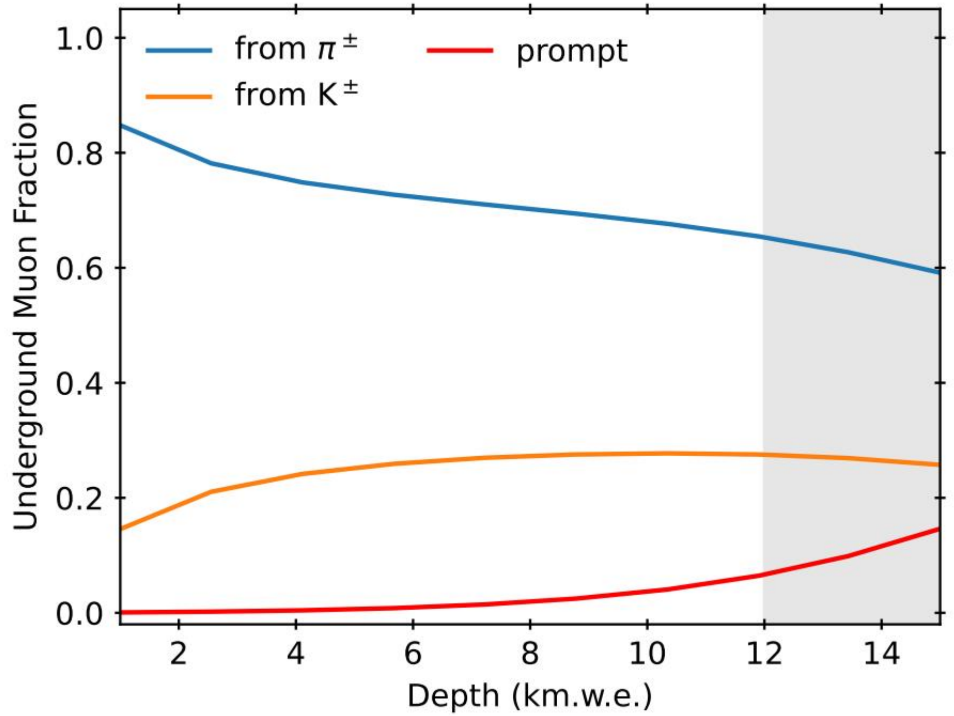
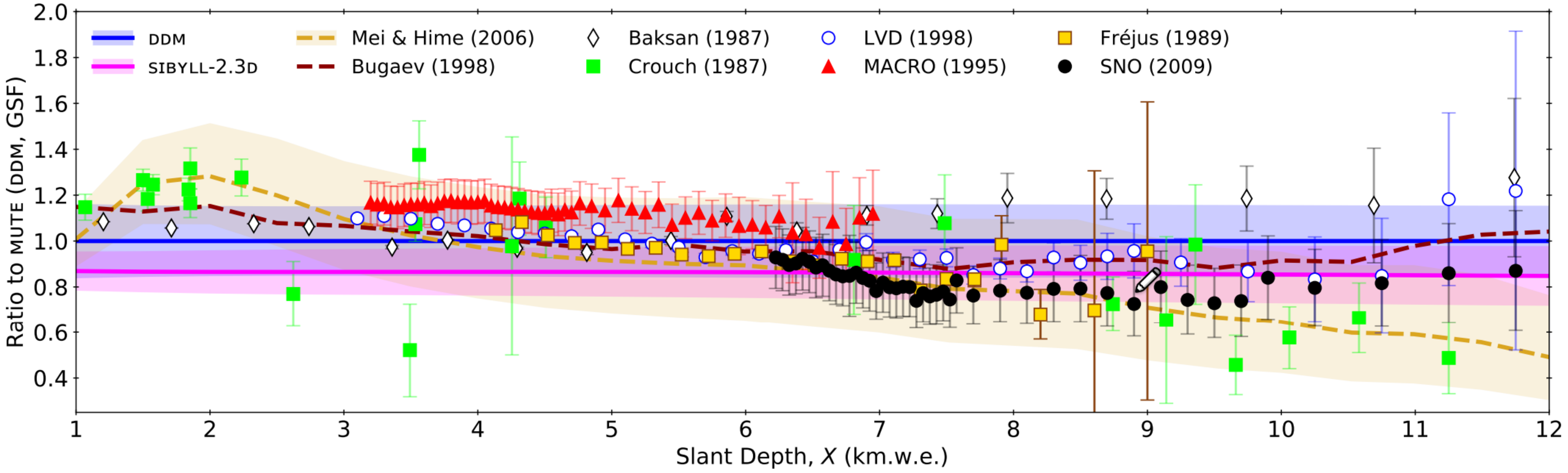
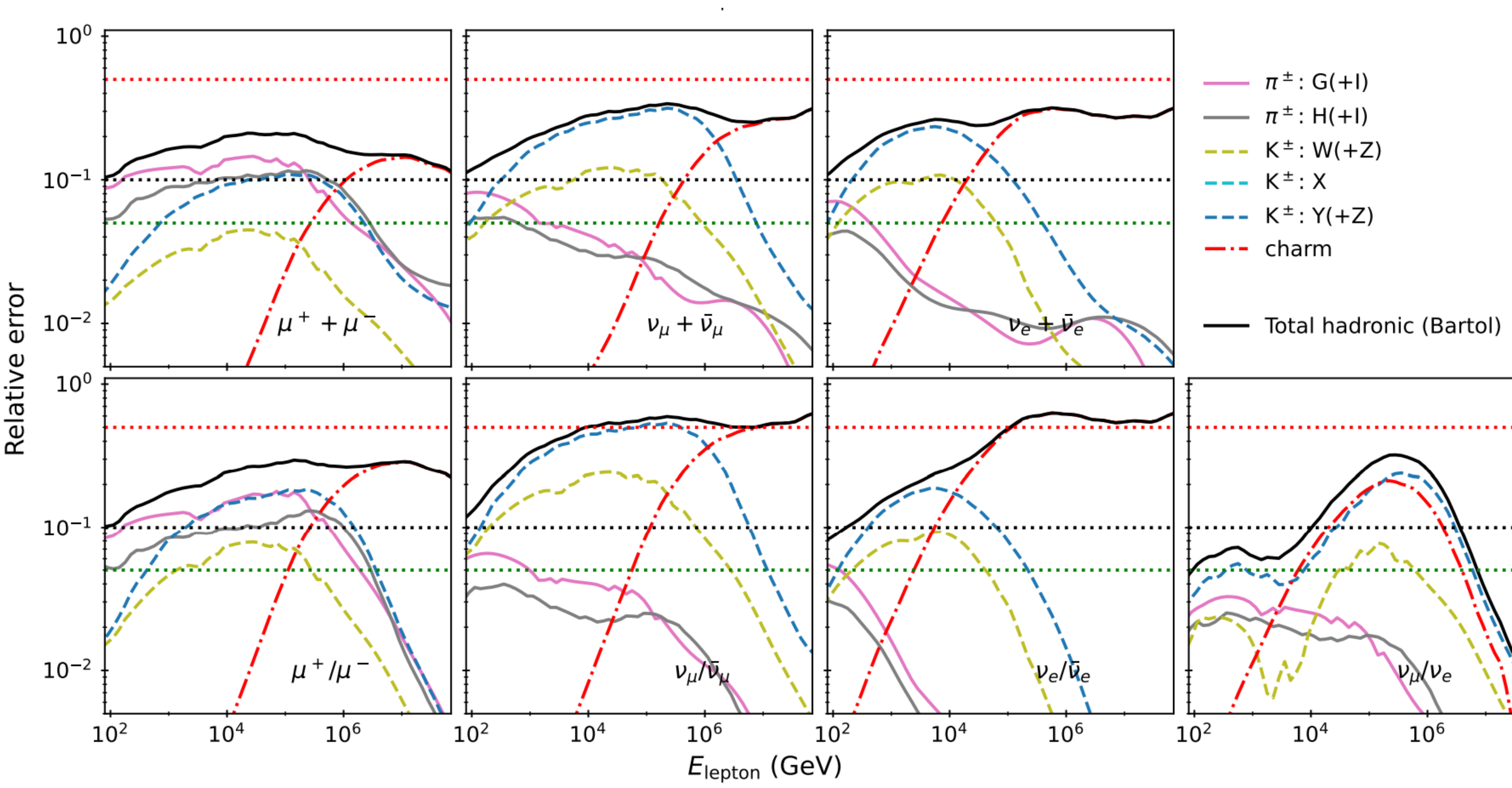


Figure 5. Fraction of parent mesons contributing to the vertical-equivalent underground intensity of muons, calculated with SIBYLL-2.3D and GSF primary flux. Since deep underground muons sample TeV surface energies, the kaon contribution is at its maximum of $\sim 20\%$. The charm model in SIBYLL-2.3D yields a $\sim 10\%$ prompt muon component below depths where neutrino-induced muons contribute (grey band).

Underground muons

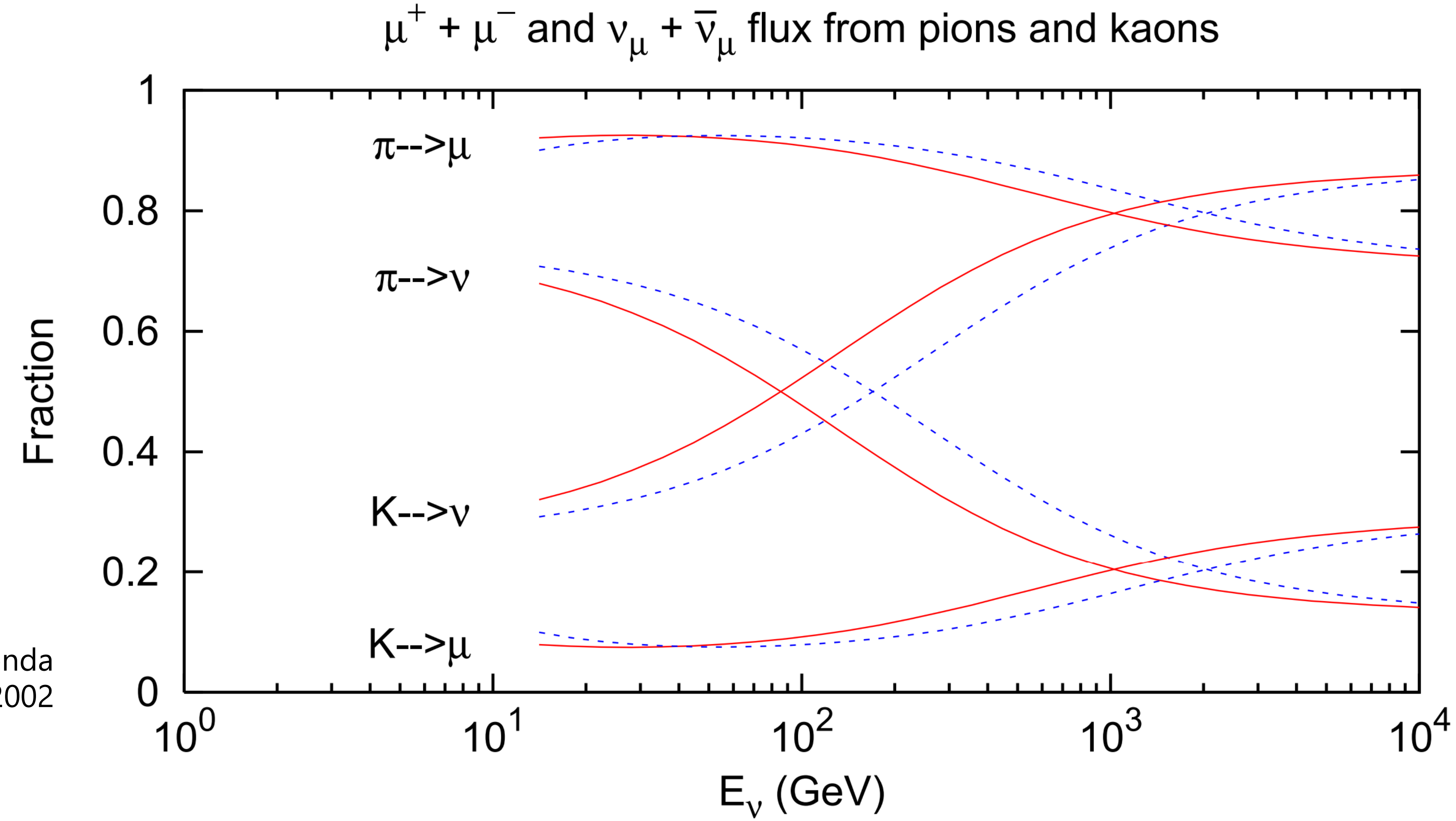




Relative error
E_{lepton} (GeV)
$\pi^\pm$: G(+I)
$\pi^\pm$: H(+I)
K$^\pm$: W(+Z)
K$^\pm$: X
K$^\pm$: Y(+Z)
charm
Total hadronic (Bartol)
$\mu^+ + \mu^-$
$\nu_\mu + \bar{\nu}_\mu$
$\nu_e + \bar{\nu}_e$
μ^+/μ^-
$\nu_\mu/\bar{\nu}_\mu$
$\nu_e/\bar{\nu}_e$
ν_μ/ν_e

Muon data as calibration

- Muons at all energies mainly come from pion component



Gaisser and Honda
Ann.Rev.Nucl.Part.Sci.52:153-199,2002