Hadronic uncertainties of inclusive atmospheric lepton fluxes from fixed-target experiments

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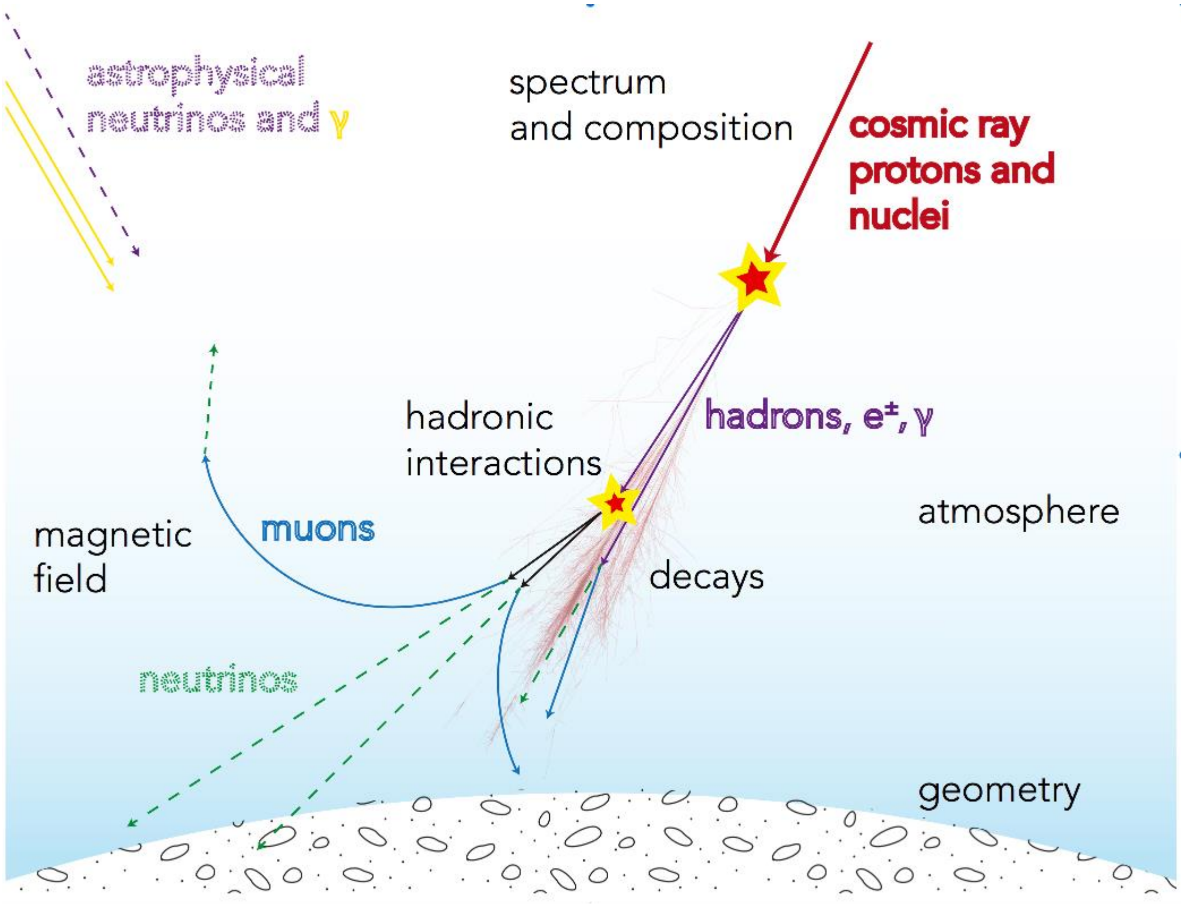
ICRC 2021, 2021/07/16, general forum?

Target audience

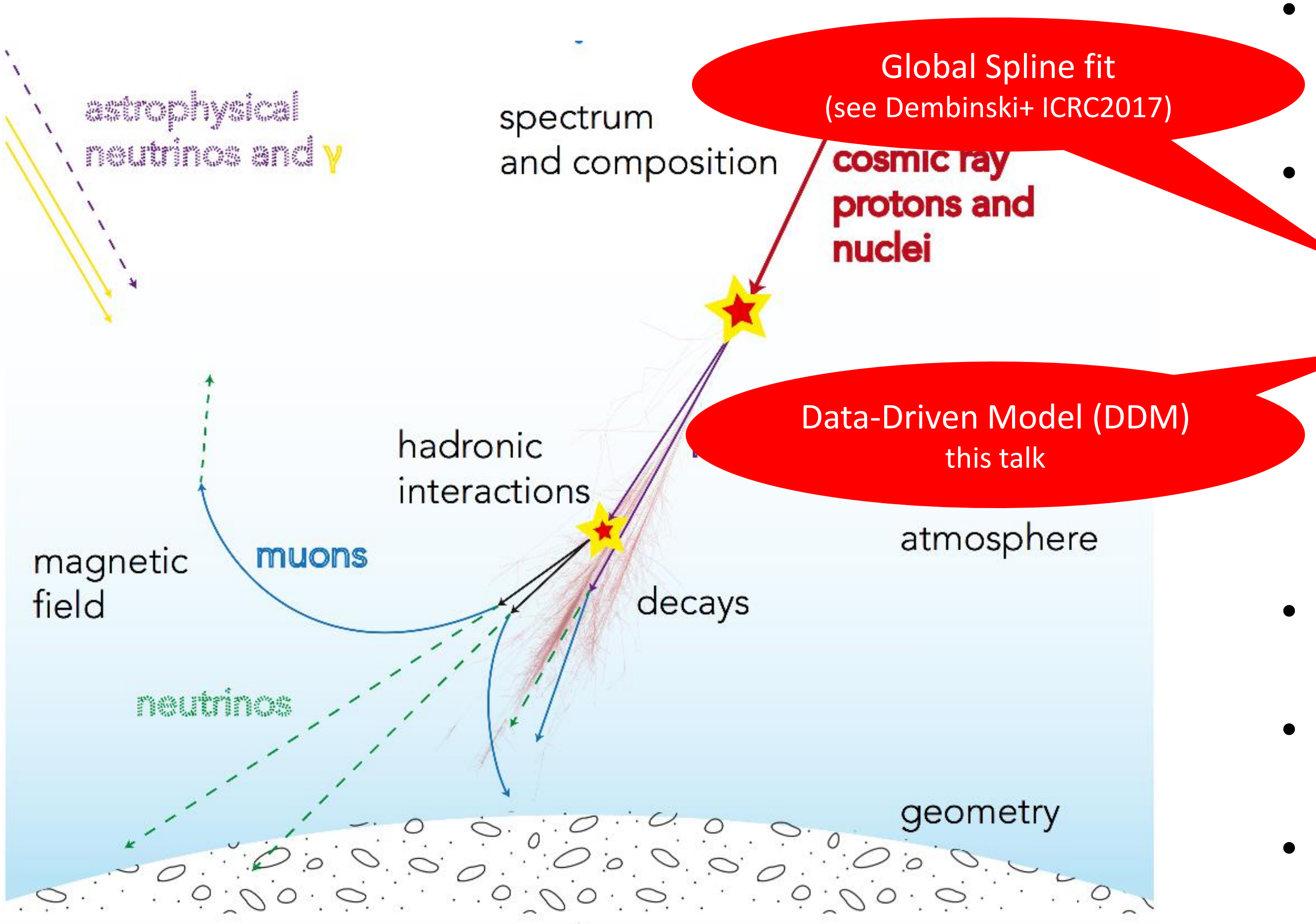
1. Atmospheric neutrino community:
    - Neutrino astronomy
    - Fundamental neutrino properties
    - New physics
2. Cosmic ray community:
    - Direct and indirect cosmic ray flux measurements and modeling
    - Cosmic ray composition
3. Hadronic interaction community:
    - Fixed target and colliders
    - Air showers

High-precision atmospheric lepton calculations



- 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.
- Methods: Monte Carlo, analytical, <u>numerical</u>
- Energy range MeV – EeV!

High-precision atmospheric lepton calculations



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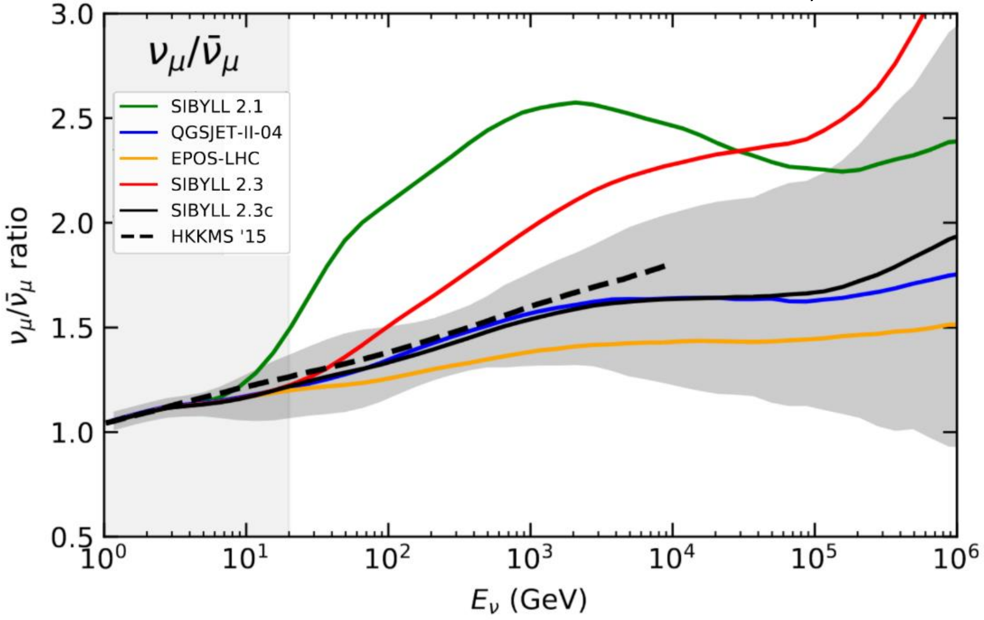
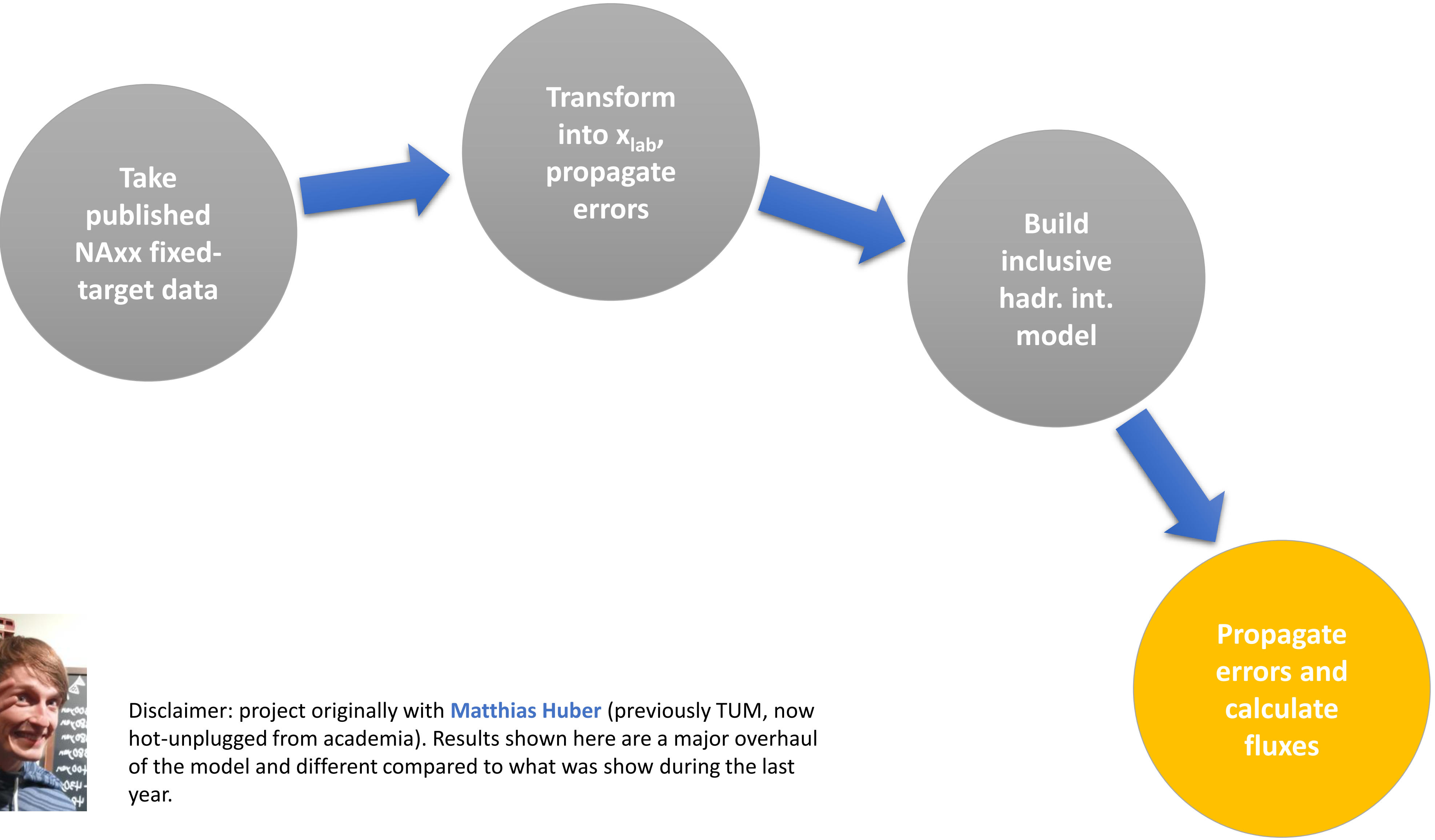
Current state-of-the-art

AF et al., ICRC 2017



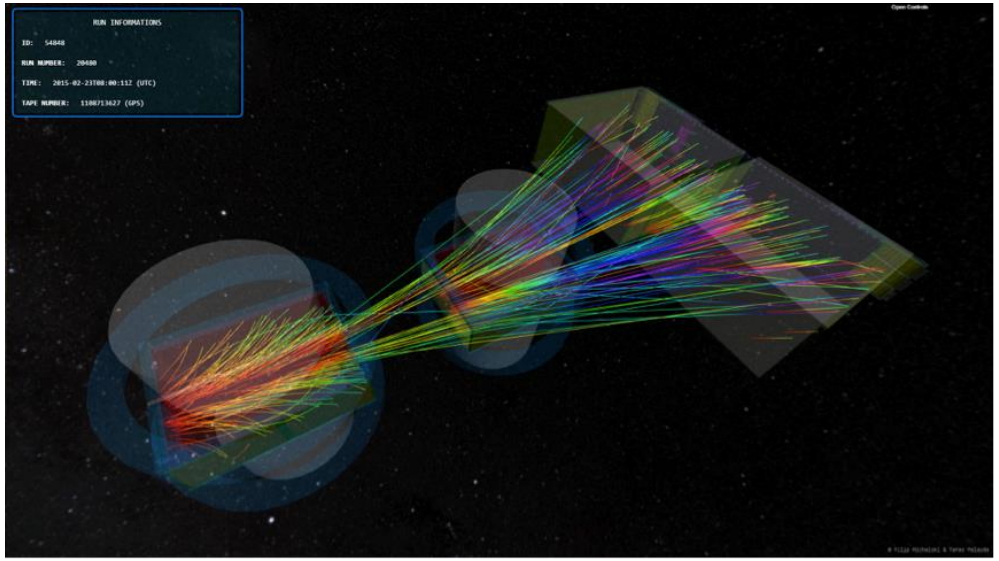
- Hadronic interaction models used in cosmic ray physics SIBYLL, EPOS, QGSJET, DPMJET predictions very different
- **Data-inspired** uncertainties (gray band, Barr et al. 2006 PRD74) are not an envelope of model predictions
- Are these uncertainties over-/underestimated? Are the models wrong?
- How can we make use of high-precision data taken by the CERN North Area NA 49 and 61 experiments <u>beyond inspiration</u>?

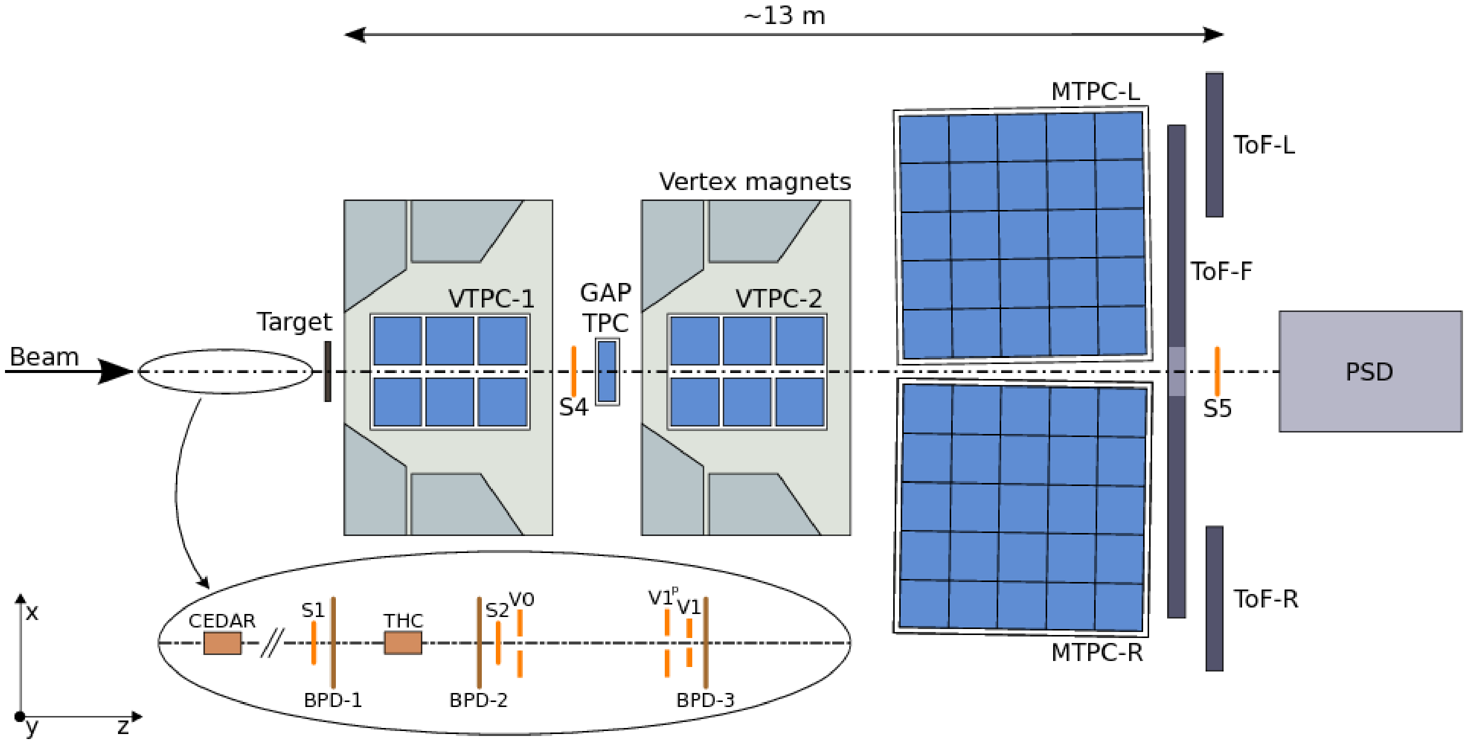
DDM: Data-Driven hadronic interaction Model



Disclaimer: project originally with **Matthias Huber** (previously TUM, now hot-unplugged from academia). Results shown here are a major overhaul of the model and different compared to what was show during the last year.

NA61/SHINE

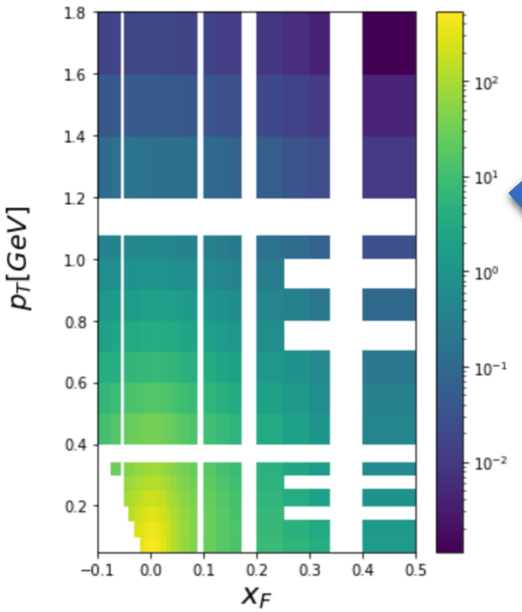




Pictures by CERN (home.cern)

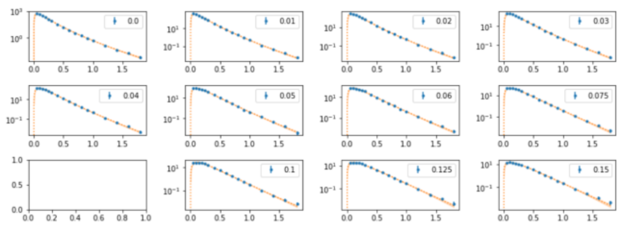
Building the DDM

NA49 proton-carbon @ 158 GeV

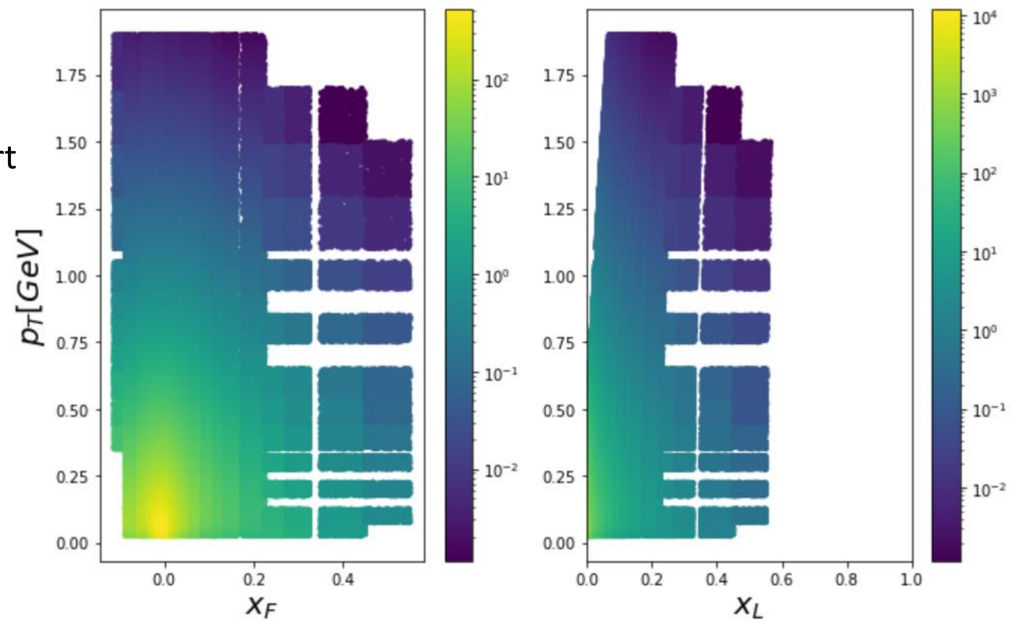


Sample from
x_F = pz/sqrt(s) and convert
into x_L = $E_{secondary}/E_{proj}$

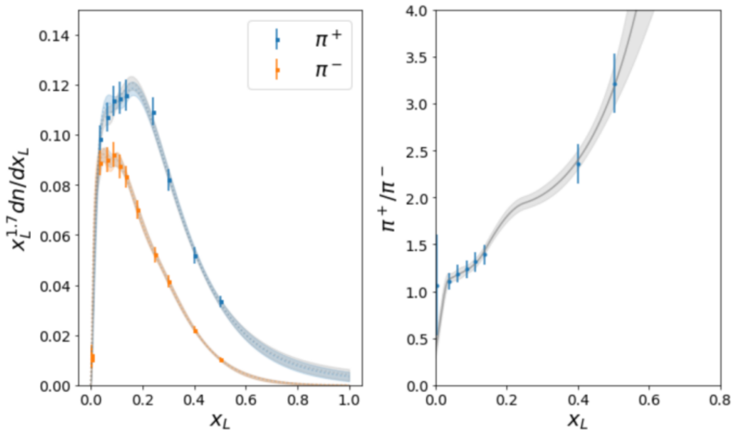
$$x_{Lab} = \frac{E_c}{E_a} = \frac{\gamma\sqrt{m_c^2 + \frac{1}{4}x_F^2 E_{c.m.}^2 + p_{c,T}^{*2}} + \frac{1}{2}\gamma\beta x_F^2 E_{c.m.}}{E_a}$$



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



Fit dn/dx_L with splines, get covariance matrix



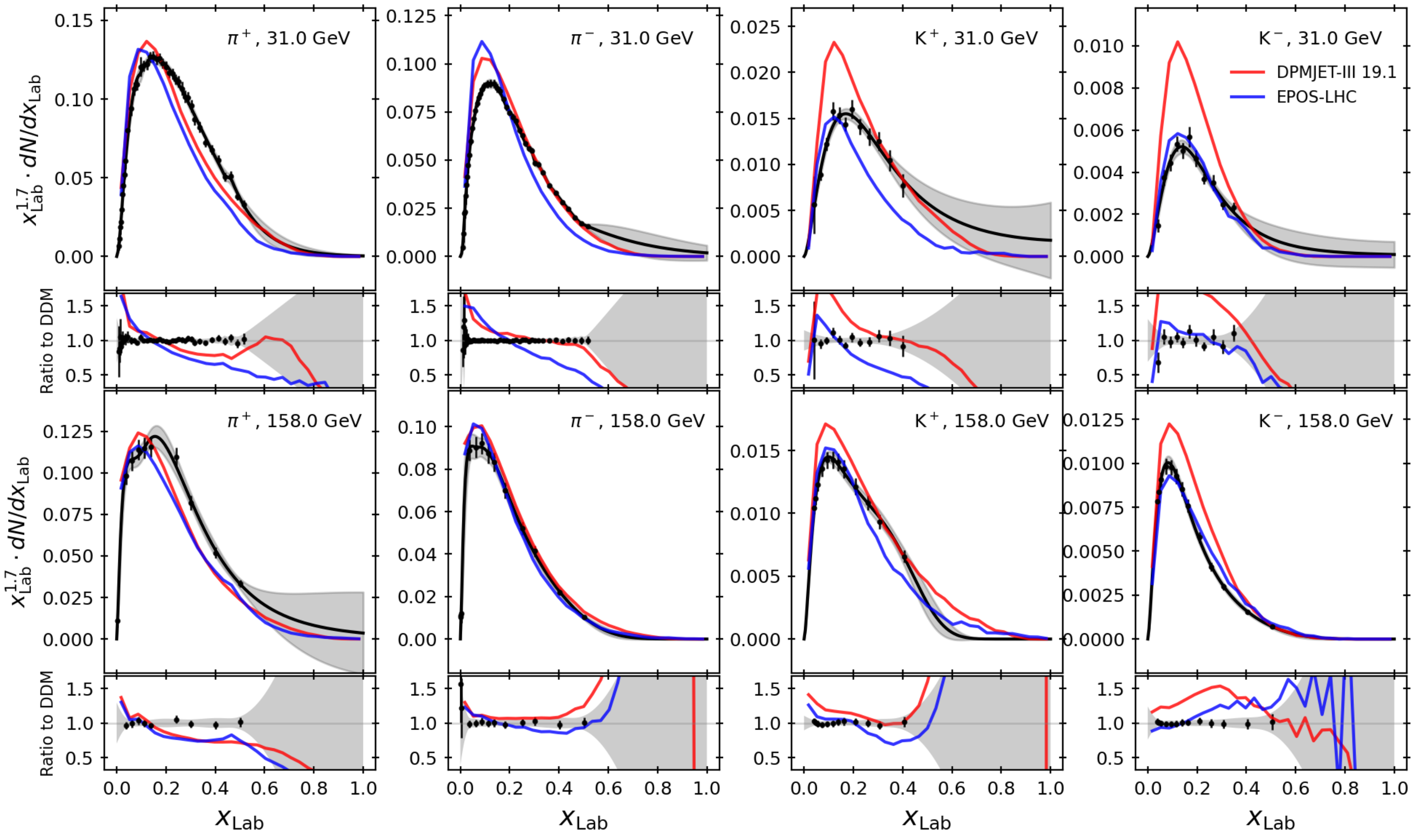
Included data

Experiment	beam	E_{beam}/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	π^-C	158, 350	$\pi^\pm, K^\pm, \overset{(-)}{\mathrm{p}}$	$p, p_\perp$

(In the next iteration we would like to include new results from NA61 and old results from NA59 that require Be->C extrapolation.

Fits of proton-carbon data

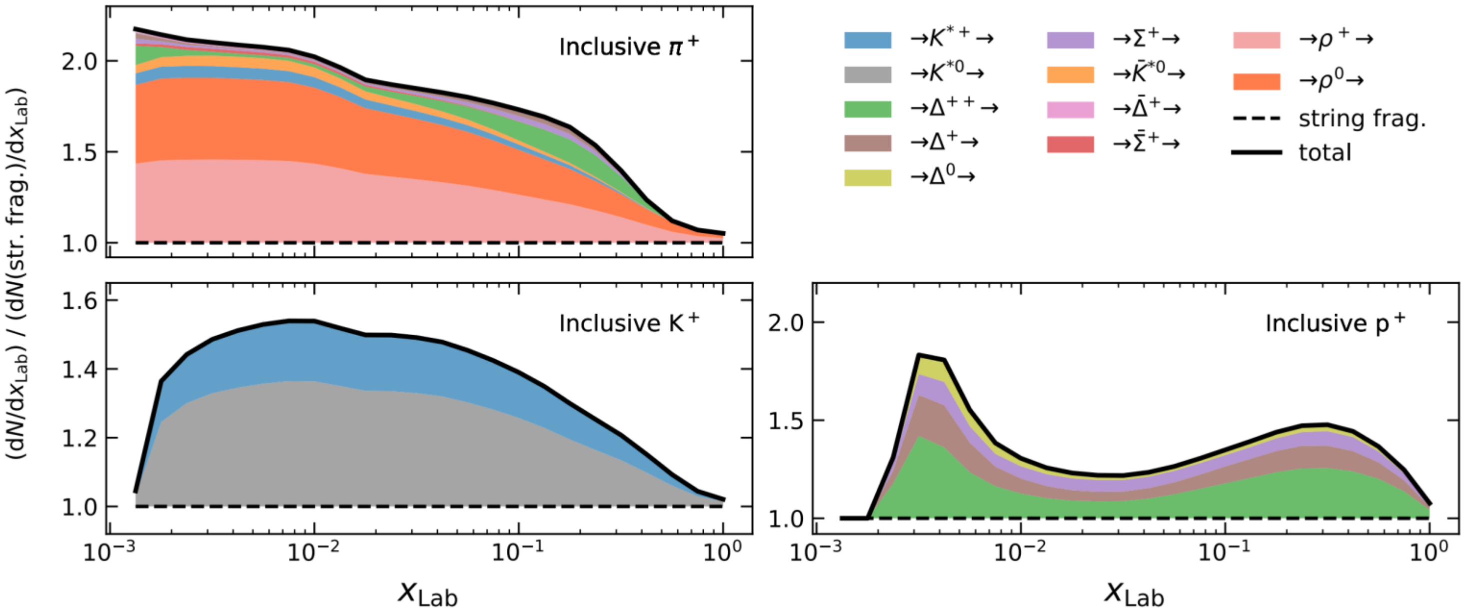
NA49 & NA61 proton-carbon



- Performed in log(dN/dx) using linear (π^+ &π^-@31 GeV) cubic splines (rest) with s>0
- **Uncertainties consistently blow up** in absence of x_L data
- Covariance matrix via hesse, multiplied by 2 to contain most of the data's error bars
- Models weak for π^+ (both energies) and K^- at 158 GeV
- An additional data point at large x would add very significant constraints
- K+- data fit at 158 GeV corrected from pp→pC, based on average of 4 hadronic interaction models (work in progress)

Why is it so difficult to just make better models

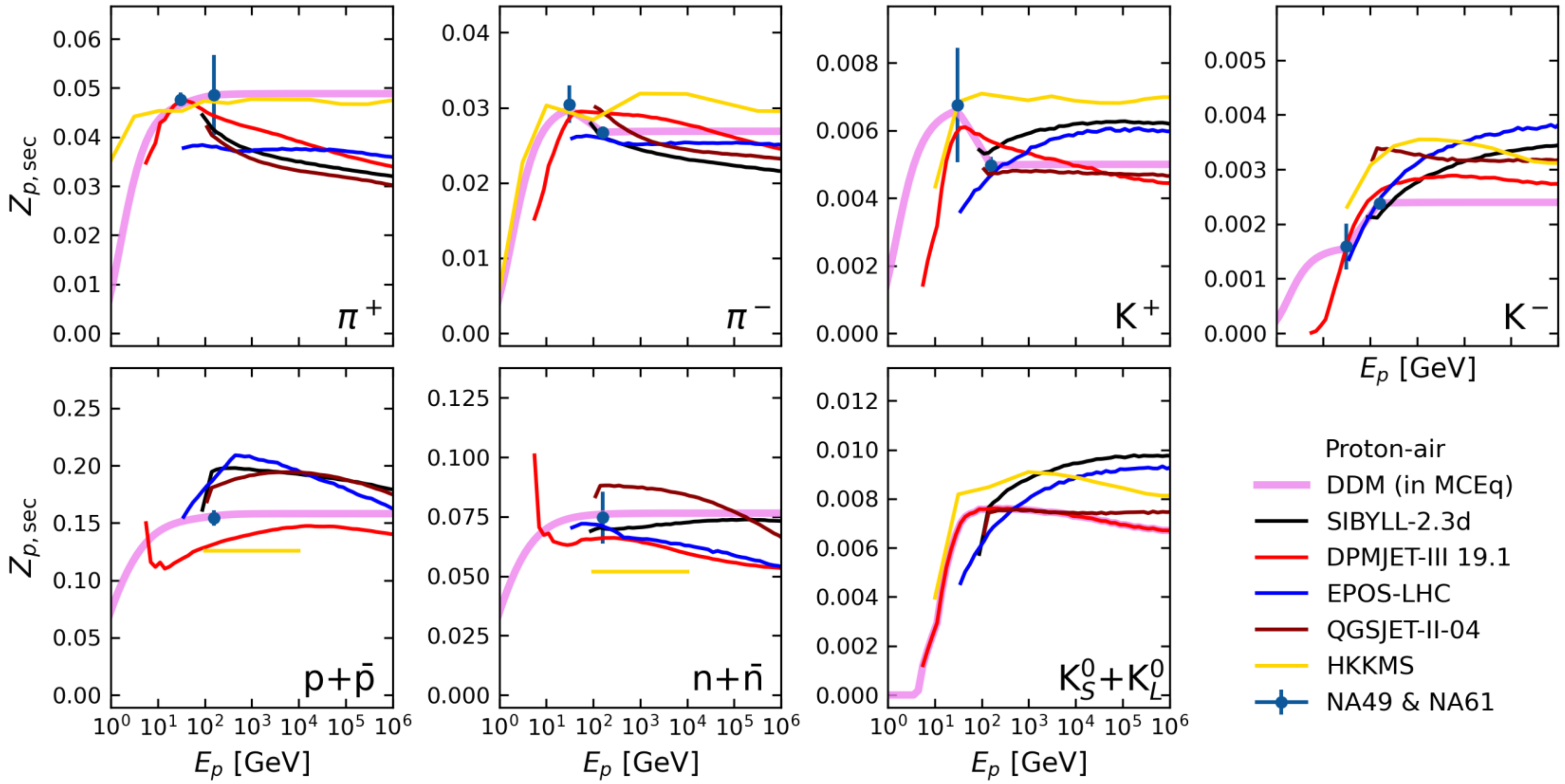
Feed-down from higher-mass states



AF et al. PRD 100 (2019)

- We tried (see Fedynitch et al. PRD 100 (2019) and Riehn et al. PRD102 (2020))
- A major problem is the definition of what “pions” or “kaons” are, since a large fraction originates from feed-down of higher mass states
- For cascades in the atmosphere, the definition coincides with that of NA49/61 that only correct for longer lived strange particles like Λ
- Older data from accelerators may not be useful, since it is not corrected for feed-down (see e.g. epic papers by S. Wenig and H.G. Fischer from NA49)
- For most interaction models the inclusive (pion) yields are a superposition of ρ, Δ etc., which are explicitly produced in the model’s fragmentation routines
- There are no “easy to tune” free parameters

Assembling the model + assumptions

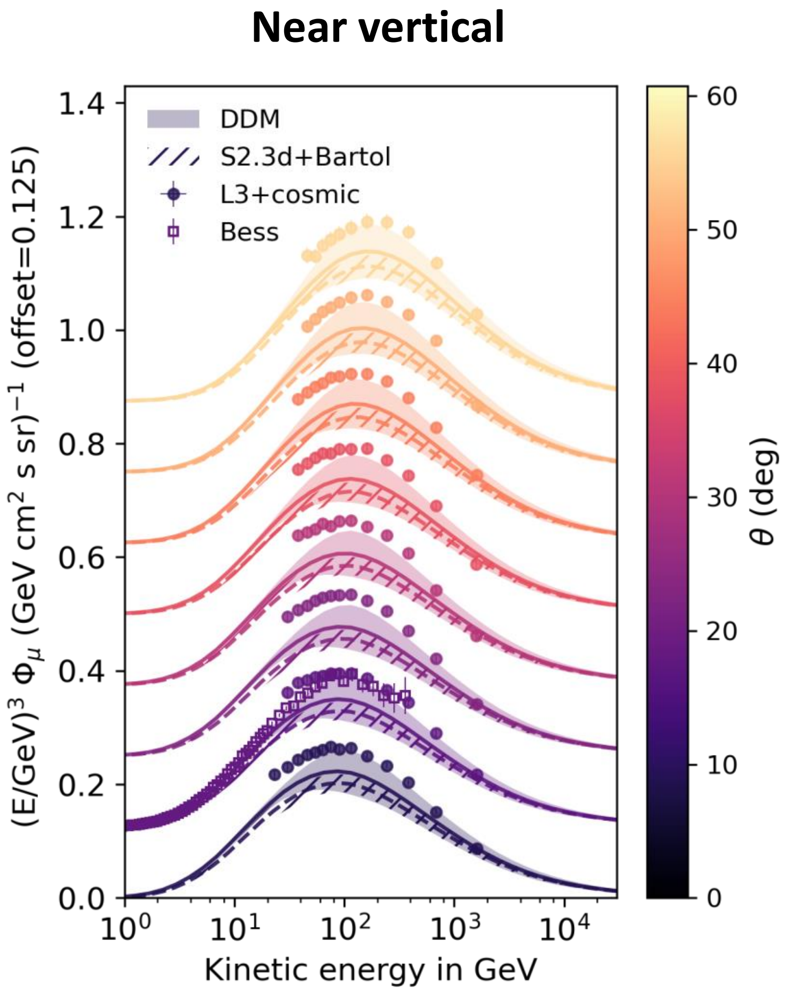


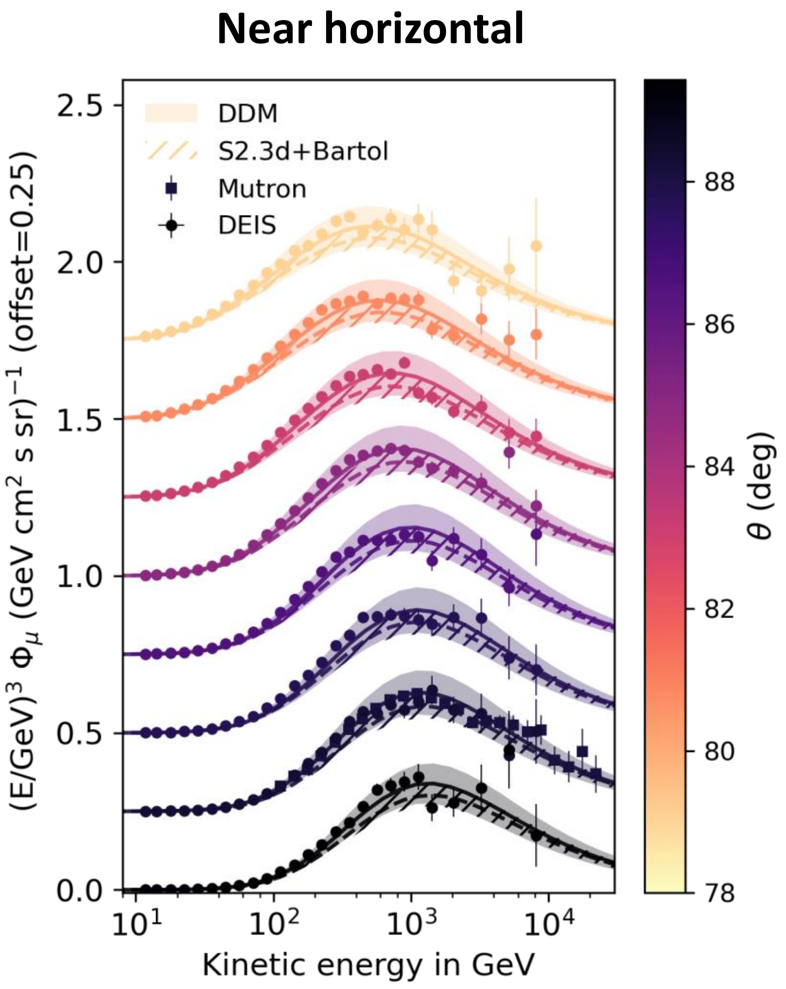
- The spectrum weighted moments (Z-factors) simplify discussion on relevant particle yields
- **Main assumption: Feynman scaling** beyond 158 GeV
- OK assumption for inclusive fluxes due to the x^γ in the integral and suppression of small x values
- DDM interpolates between 31 and 158 GeV data linearly in log(E_p)
- The error on the data (blue dots) originates from the fits (Slide 10)
- This version of DDM **may potentially** underestimate kaons due to threshold effects still present at 158 GeV
- Higher-energy data from NA59 may contain additional hints

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

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

DDM+ GSF vs data: muon fluxes

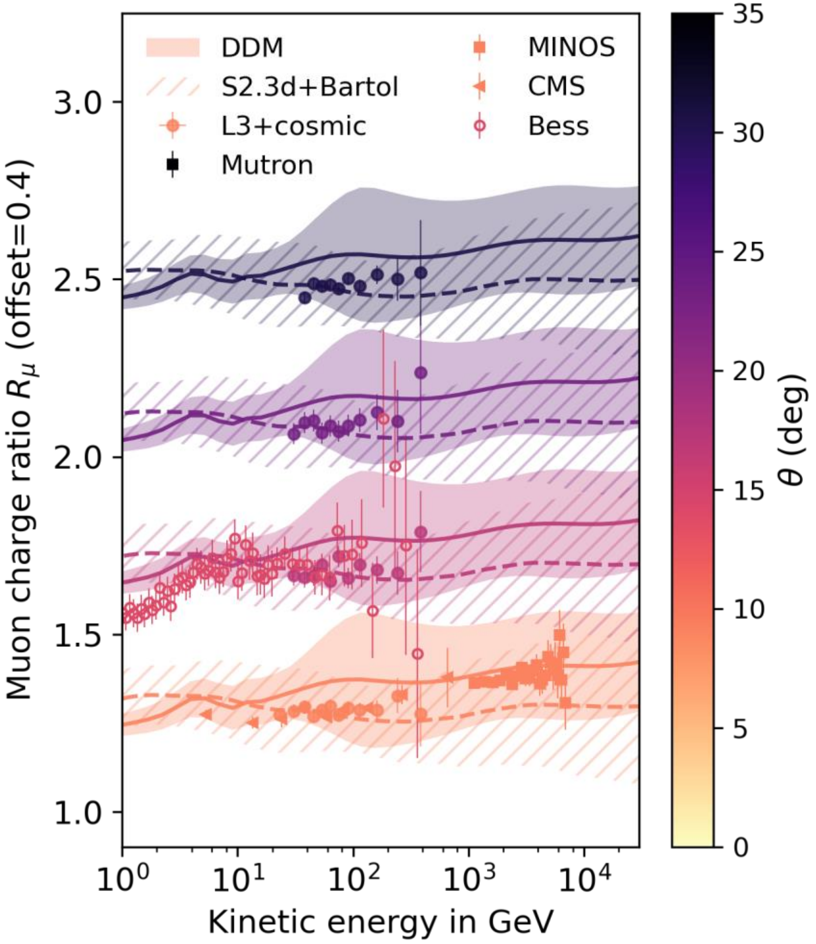




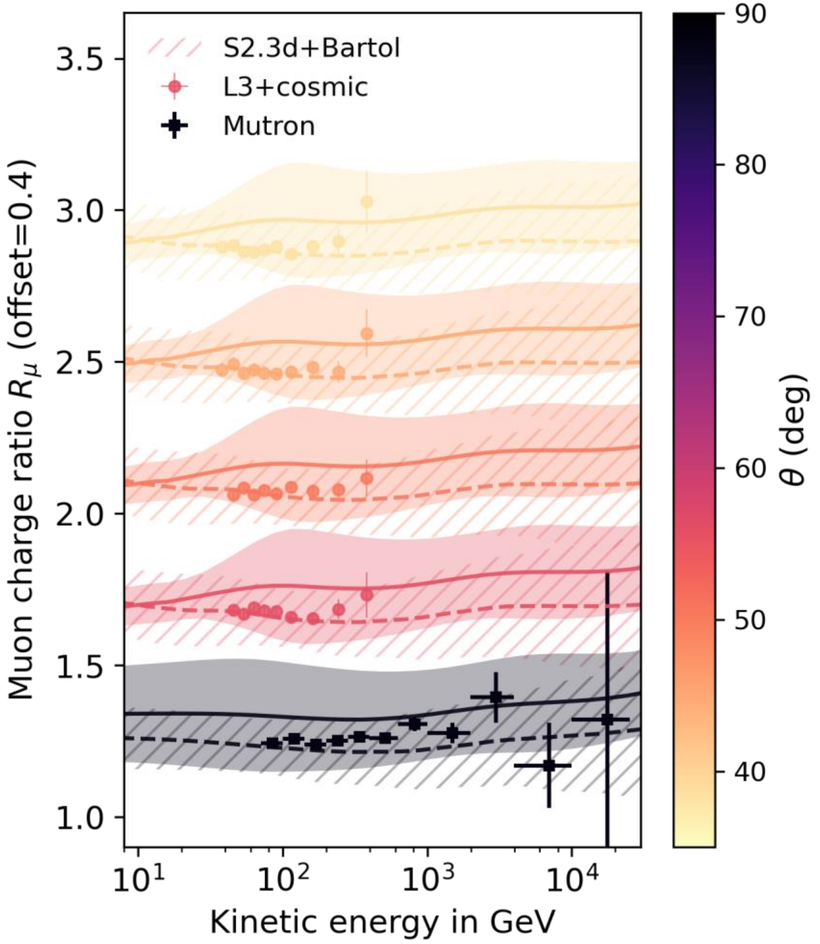
- Previous estimate from ICRC2017: SIBYLL + Bartol error propagation (hatched)
- Calculation and error propagation with MCEq
- Data without systematics. L3c and Bess allow for some normalization shift. DEIS has large systematics.
- Indication for tension between vertical and near-horizontal data may indicate that
  - Feynman scaling is not a good assumption
  - More likely: The primary flux (GSF) needs to be pulled within its uncertainties (up <~TeV and softened beyond that). Needs revisiting…
- Data has smaller uncertainties than the model → constraints can be obtained from muon data

DDM+ GSF vs data: muon charge ratio

Near vertical



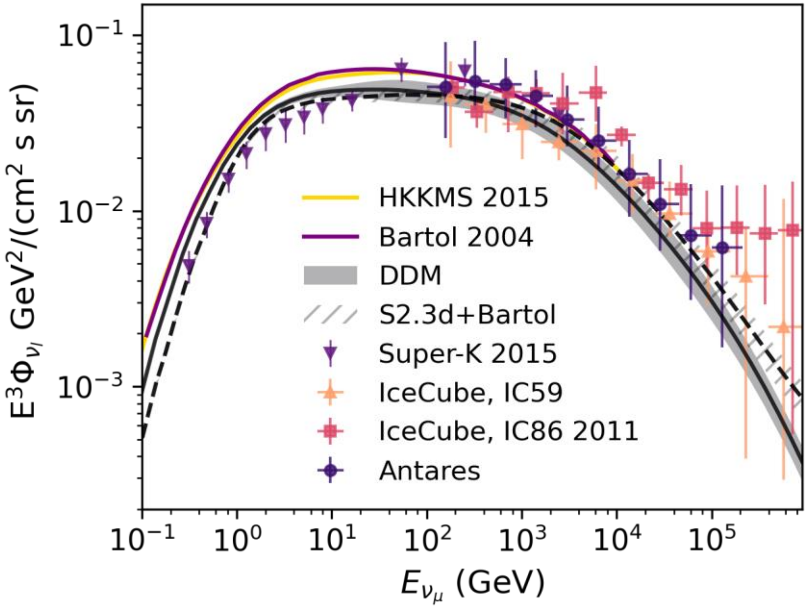
Near horizontal



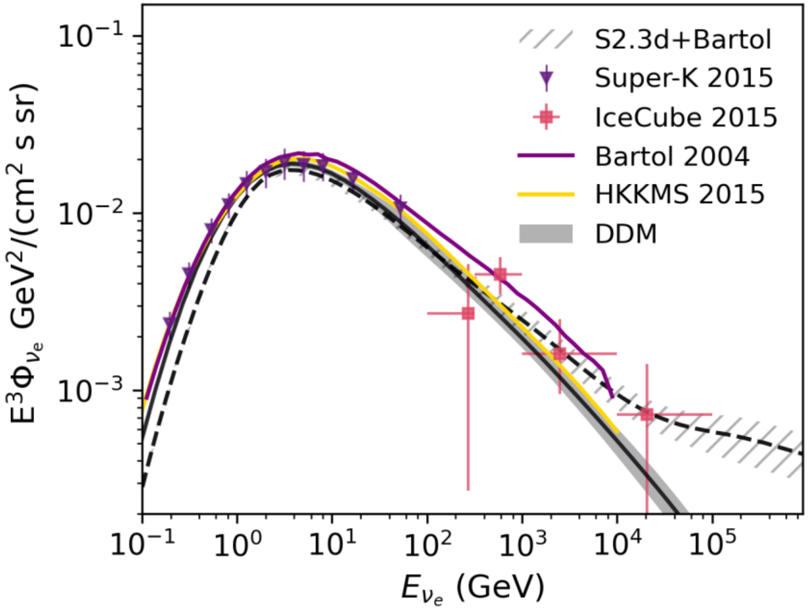
- Data is within uncertainties
- BESS data @ 13 deg (costh=0.95), well described between 5-50 GeV → Projectile E<300 GeV
- Same for higher energies @ near-horizontal
- No geomagnetic effects included that may affect lower energy measurements of Bess
- No primary neutron fraction uncertainty included that may affect the charge ratio
- Also, data has smaller uncertainties than the model → constraints over a wide energy range on neutrino ratios possible

DDM+ GSF vs data: neutrino fluxes

Muon neutrinos+antineutrinos



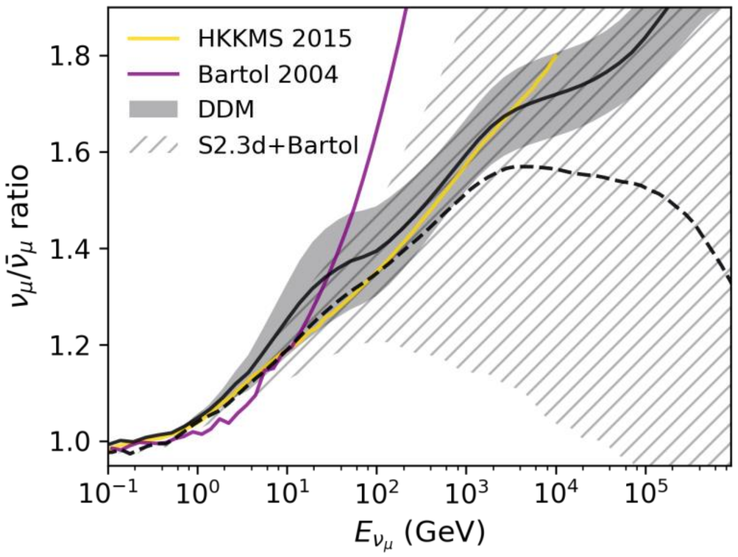
Electron neutrinos+antineutrinos

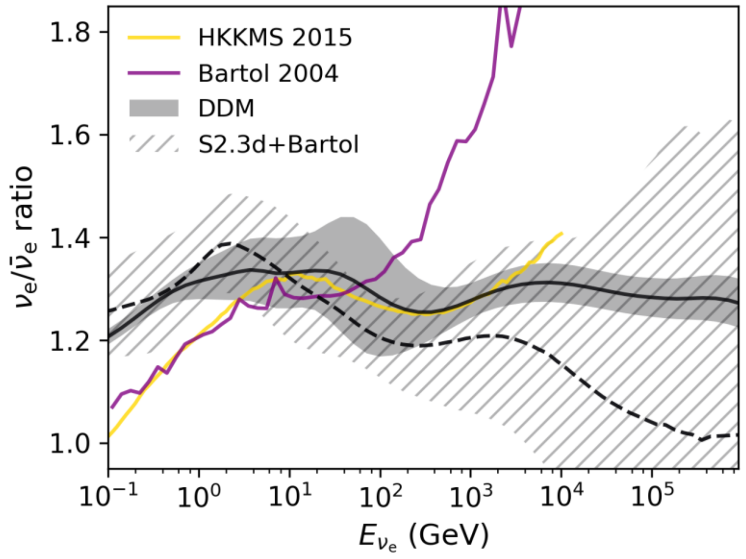


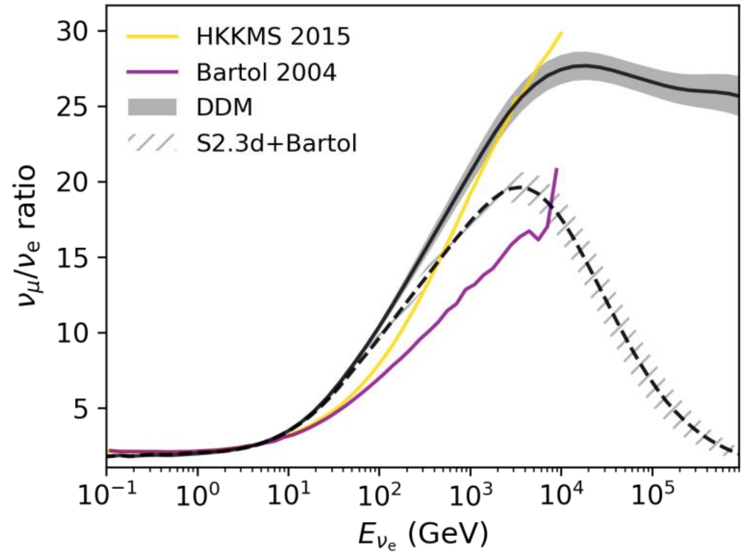
- Above few GeV DMM is compatible with SIBYLL2.3d+Bartol uncertainties
- At lower energy larger impact from more low-energy muons
- Models not corrected for muon neutrino disappearance (left figure)
- Good compatibility with SK data for electron neutrinos at low energies
- Prompt (hardening at high energy) only SIBYLL, DDM only conventional
- On top is CR flux uncertainty, which will affect E> 100 GeV

DDM+ GSF vs data: neutrino ratios

Neutrino-antineutrino ratios







Flavor ratio

- Neutrino antineutrino ratio compatible over a wide energy range with HKKMS within error
- At low energy notable improvement compared to Bartol errors due to NA61 31 GeV dataset
- Error on ratios at 100 MeV — GeV may be slightly underestimated due to extrapolation in DDM below 31 GeV
- Flavor ratio above 20 GeV significantly different due to less kaons in DDM wrt HKKMS or Bartol 2004

Summary

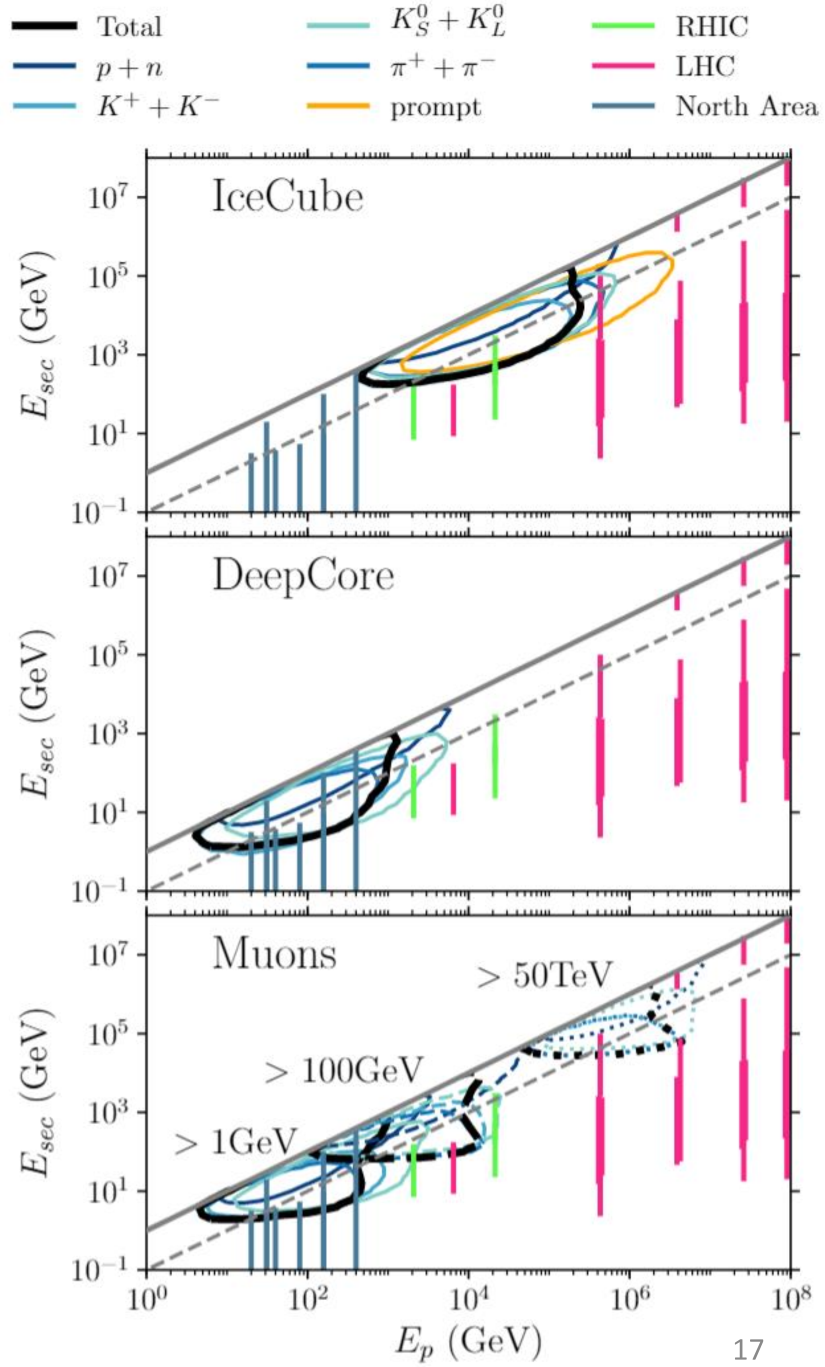
- This new Data-Driven Model (DDM) attacks the largest source of uncertainty in atmospheric neutrino flux calculations. Data from fixed-target accelerators **and** its uncertainties have been successfully parameterized with splines.
- The resulting errors on the lepton fluxes and ratios considerably shrink at low energies and high energies, staying compatible at tens — hundreds GeV with the previous reference (Barr et al.)
- The main sources of the remaining uncertainty are π^+ at somewhat larger x_L and charged kaon measurements on carbon target and at higher energy.
- The impact on atmospheric neutrino oscillation analyses needs requires study, and I offer to help with extracting most from this model.

Outlook

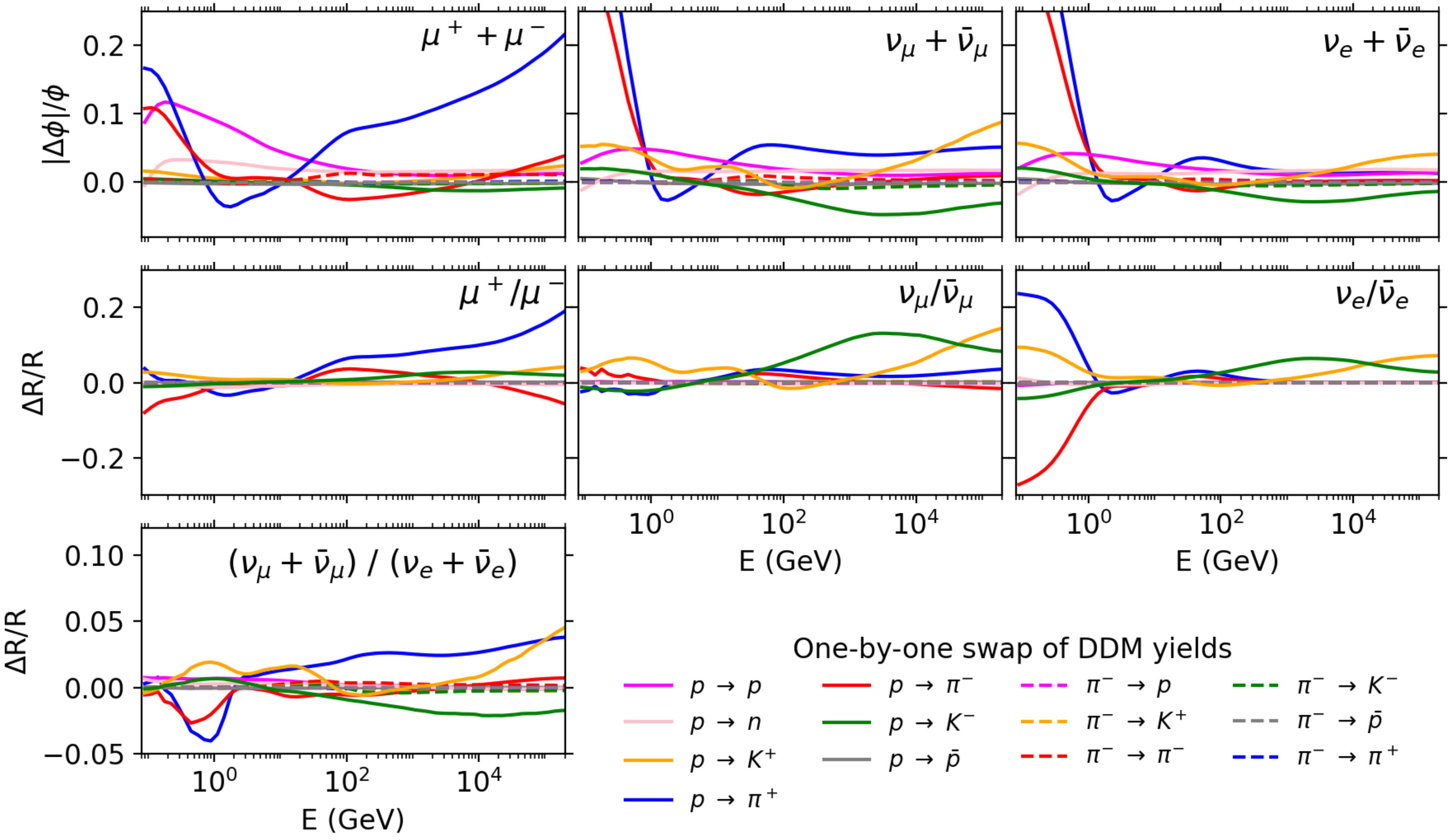
- Upcoming data from NA61 taken at different energies between ~10 – 158 GeV and (hopefully analyzed in the same way) may constrain the lower energies more significantly → expect 3-5% uncertainty. At higher energy, the NA59 data may add crucial constraints after extrapolation from Be→C.
- The model can be calibrated using inclusive muon measurements from surface spectrometers, see this talk by J.P. Yanez
- At higher energies, deep underground muon intensity data will provide further constraints using the methods presented in W. Woodley's talk
- The characterization of primary cosmic ray flux uncertainties will be crucial to obtain the best model.

Atm. leptons <-> accelerators

- Contours show phase-space probed by atmospheric muon and neutrino experiments
- The lines show **taken** data (not necessarily analyzed) assuming pion secondaries
- Interactions within contours responsible for 90% of the event rate
- Atmν in IceCube probes hadronic interactions at $E < E_{LHC.}$
- DeepCore probes same phase-space as Super-/Hyper-K
- Muons: vertical, surface, flux integrated above threshold



Impact of individual DDM channels



- Exchanging only one channel of a DPMJET prediction
- Largest impact from π^+ and K^- as expected from sub-panels on Sl. 10
- Only small differences for most ither channels: DPMJET (also, SIBYLL and QGSJET) similar to DDM
- Large impact on low energy muons → hence also neutrinos from muon decay
- Baryon distributions can shift production depth that matters for unstable particles such as muons