The near and distant future of theoretical flux systematics

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Diffuse Workshop May 11th, 2021

Overview

- Near future:
  - DDM: new hadronic interaction model for atmospheric fluxes
  - The origin of differences between MCEq and Honda
  - Some minor updates on SIBYLL and DPMJET
  - Balloon, surface and shallow-underground muon data for constrains
  - And deep-underground muon fluxes, as well

- More distant future:
  - Data-driven uncertainty estimation of fluxes and uncertainties (GlobalFit ☺)
  - 2D MCEq, geomagnetic cutoff, and more 3D stuff

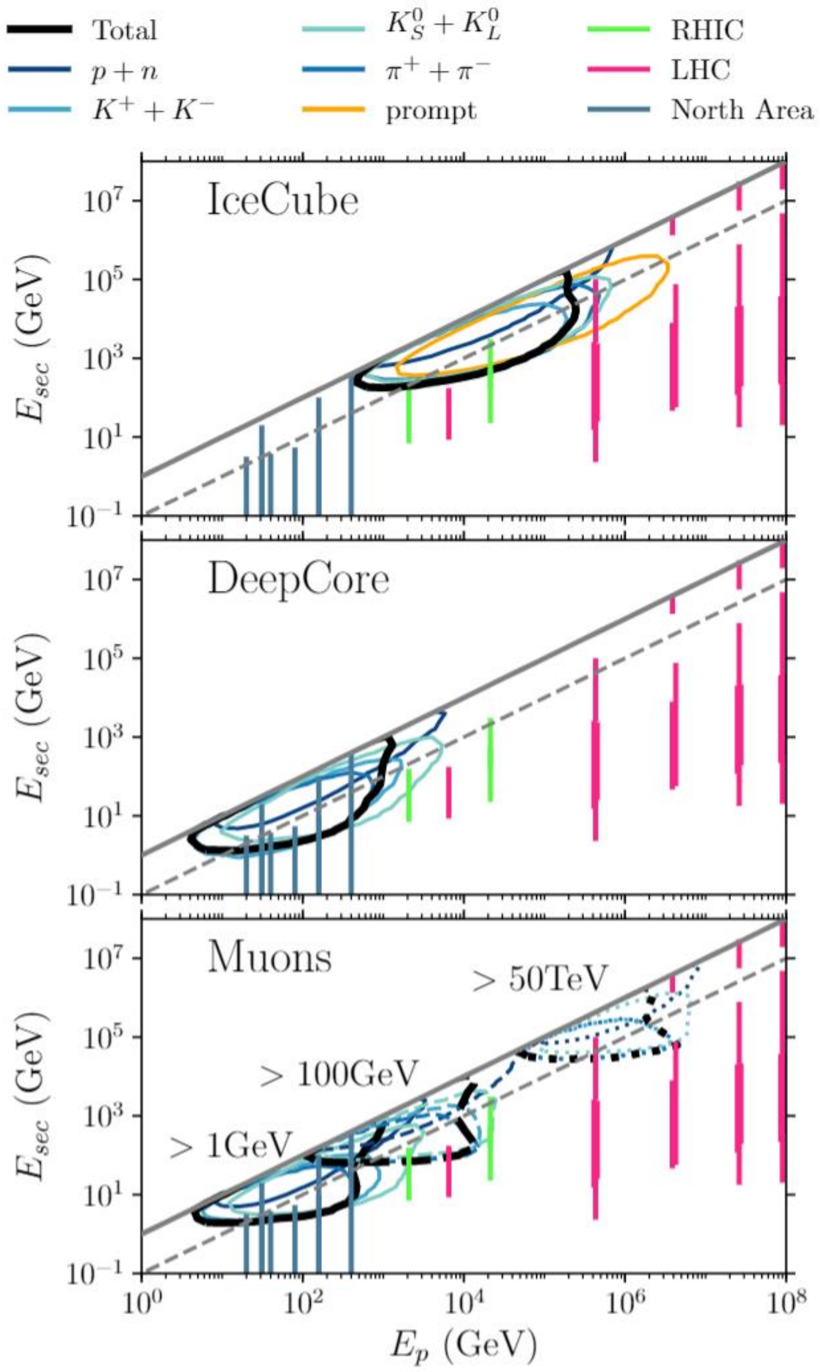
DDM: Data-Driven hadronic interaction Model

1. Take NAxx fixed-target data
2. Transform into x_{lab}, propagate errors
3. Build inclusive hadr. int. model
4. Propagate errors and calculate fluxes

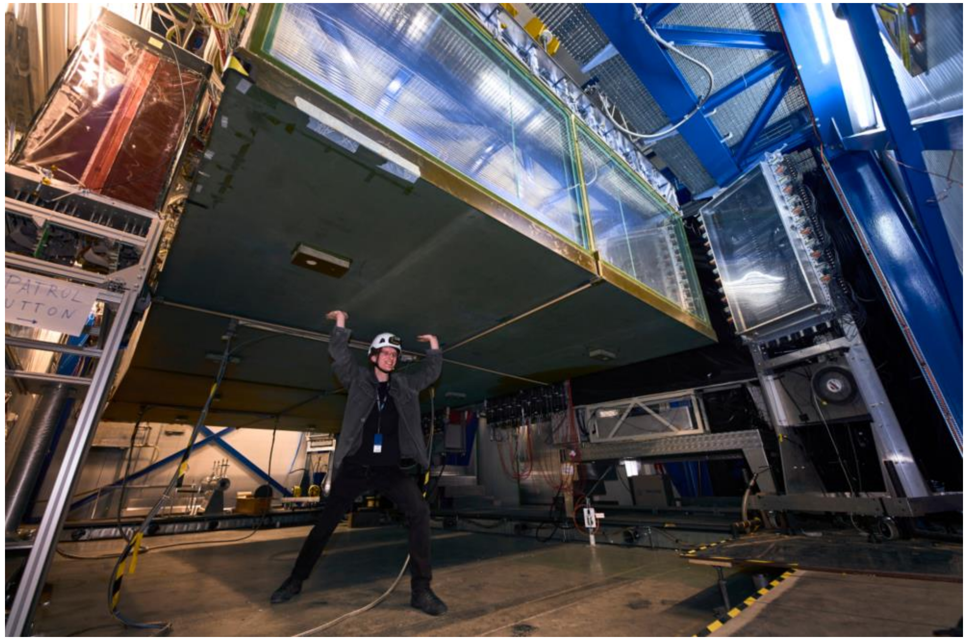
Project with **Matthias Huber** (TUM). However, he left to industry 😭. For the past 1-2 months, I'm plowing through his codes.

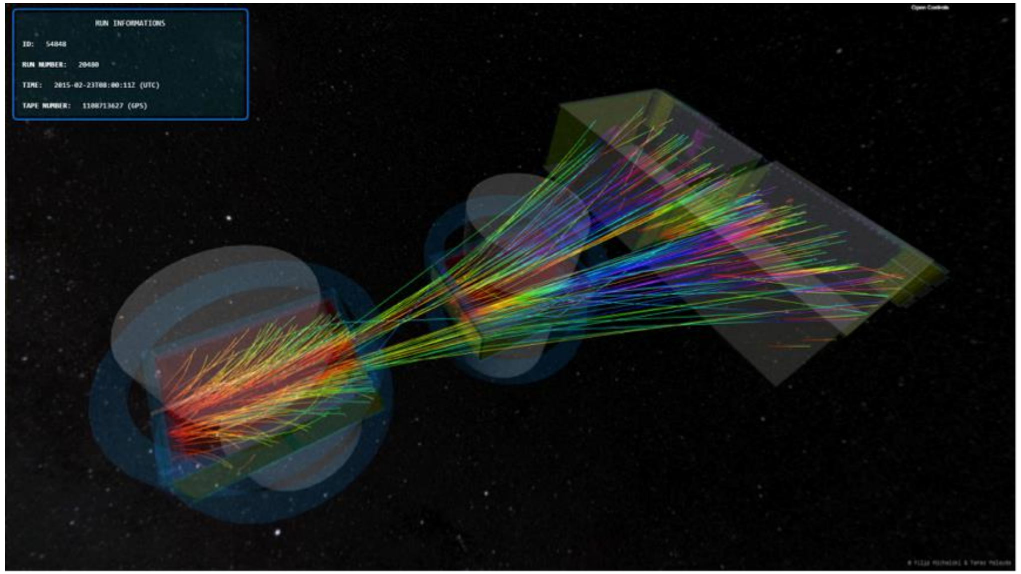
Data from accelerators

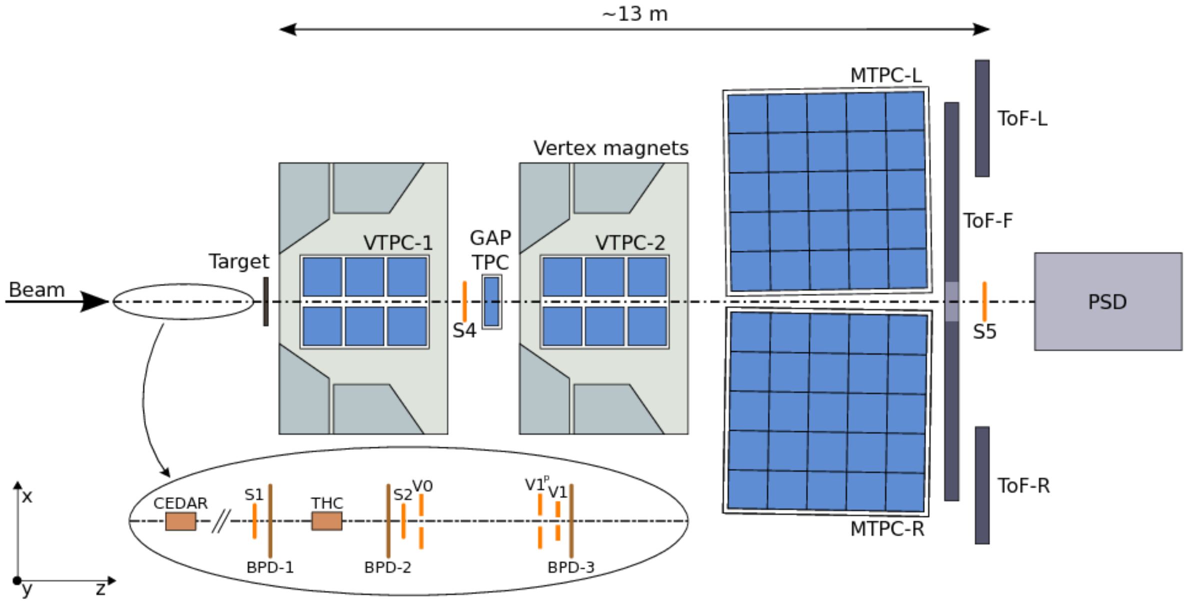
- The lines show **taken** data (not necessarily analyzed) assuming pion secondaries
- Interactions within contours responsible for 90% of the event rate
- IceCube and DeepCore counts from public effective areas
- Atmν in IceCube probes hadronic interactions at $E < E_{LHC.}$
- DeepCore coincides mostly with Super-/Hyper-K from Barr et al.
- Muons: vertical, surface, flux integrated above threshold. Shape of phase-space contours very similar in log-log.



NA61/SHINE, a fixed target experiment



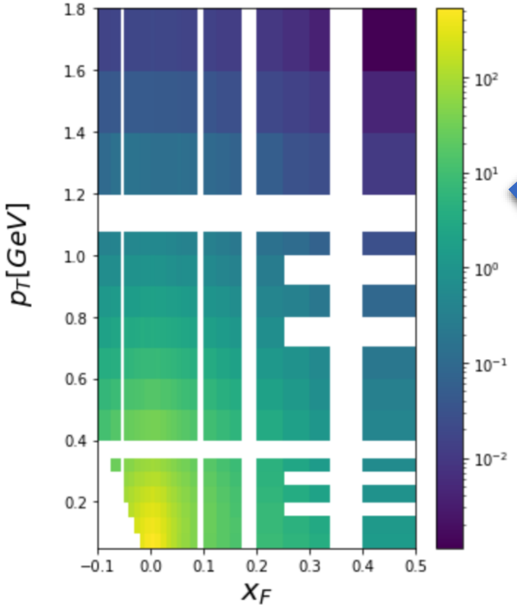




Pictures provided by CERN (home.cern)

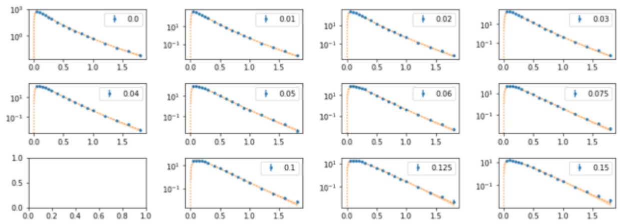
Building the DDM

NA49 proton-carbon @ 158 GeV

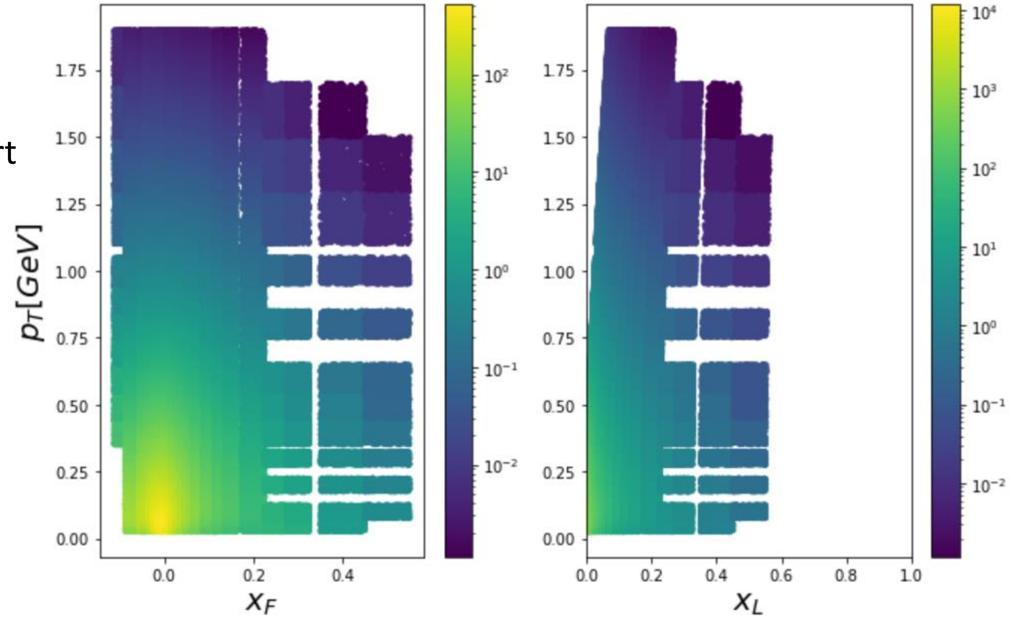


Sample from
x_F = pz/sqrt(s) and convert
into $x_L = E_{secondary}/E_{proj}$

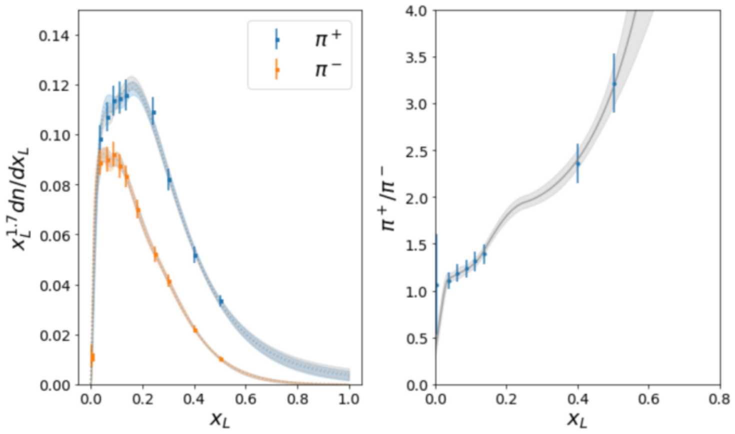
$$x_{Lab} = \frac{E_c}{E_a} = \frac{\gamma\sqrt{m_c^2 + \frac{1}{4}x_F^2 E_{c.m.}^2 + p_{c,T}^{*2}} + \frac{1}{2}\gamma\beta x_F^2 E_{c.m.}}{E_a}$$



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

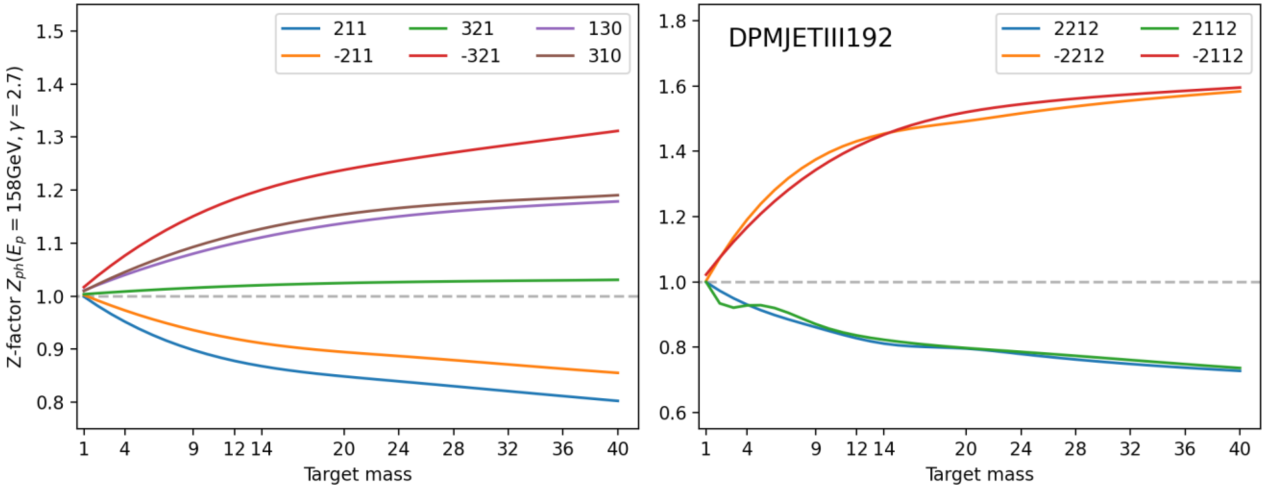


Included data

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

But shouldn’t be much more data around?

Target mass dependence of Z-factors



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- Carbon → air only a 0.1-2% impact
- NA59/SPY has good data from protons on beryllium thin target, needs extrapolation.
- Also target thickness has impact. NA61 data only from carbon thin target usable.
- Data on particle ratios would be useful too, to constrain off-diagonal covariance.
- A collaboration with NA61 would be useful. Partially completed energy ramp study at 31, 60, 80, 120, 158 GeV should nail it down. But NA61/SHINE is traditionally lacking manpower. One energy = 1 PhD student, maybe all required particles.
- There could be more data that we didn’t find. Requirements: angular acceptance, systematic uncertainties, good stats.

Data published by NA61 in rapidity *y* is problematic

$$x_{Lab} \overset{(A.29)}{=} \frac{\gamma\sqrt{m_c^2 + \frac{1}{4}x_F^2 E_{c.m.}^2 + p_{c,T}^{*2}} + \frac{1}{2}\gamma\beta x_F^2 E_{c.m.}}{E_a}$$

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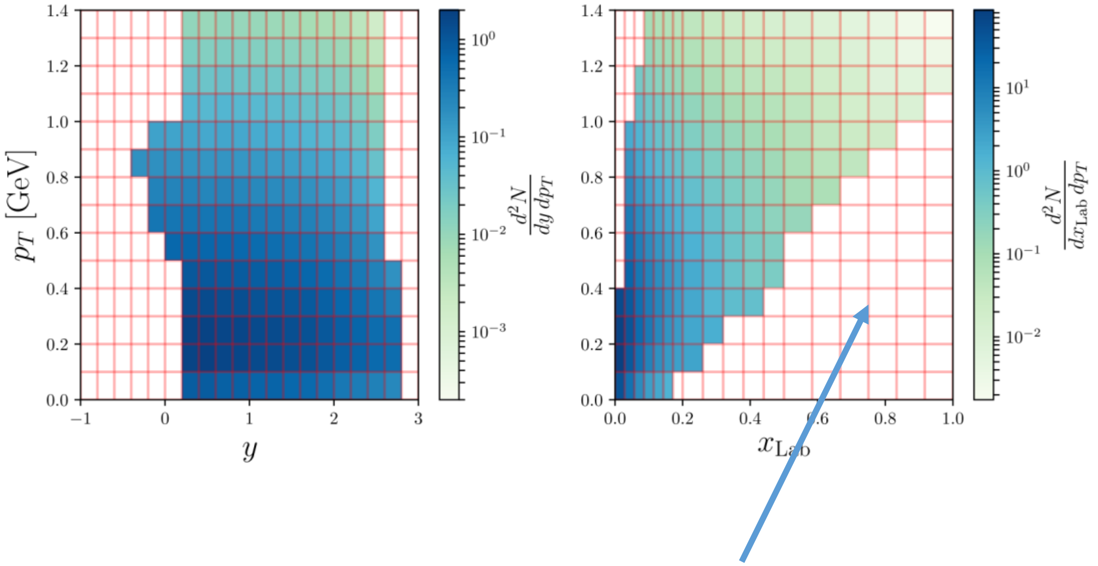

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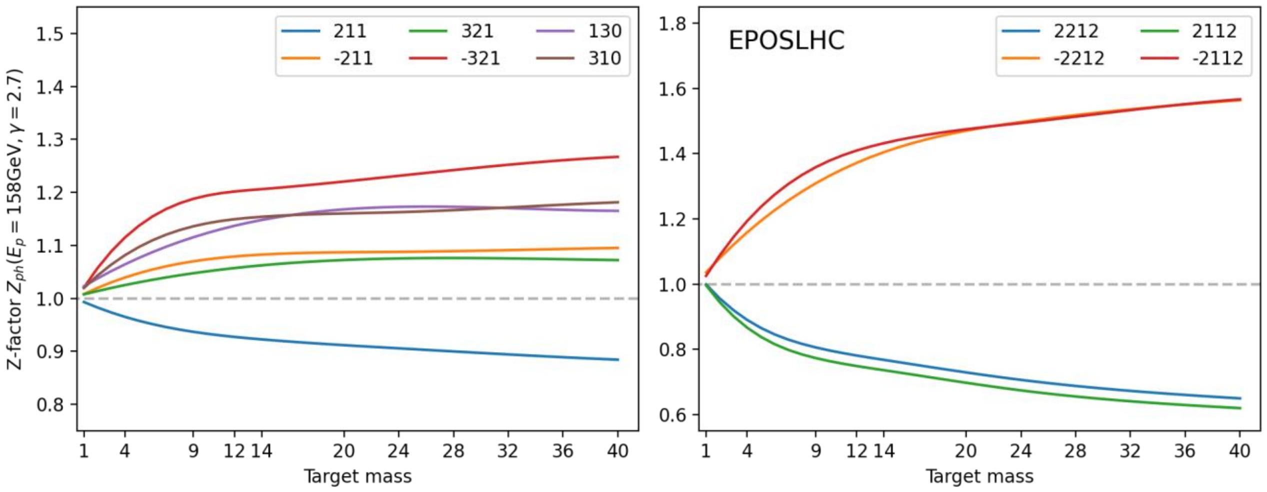

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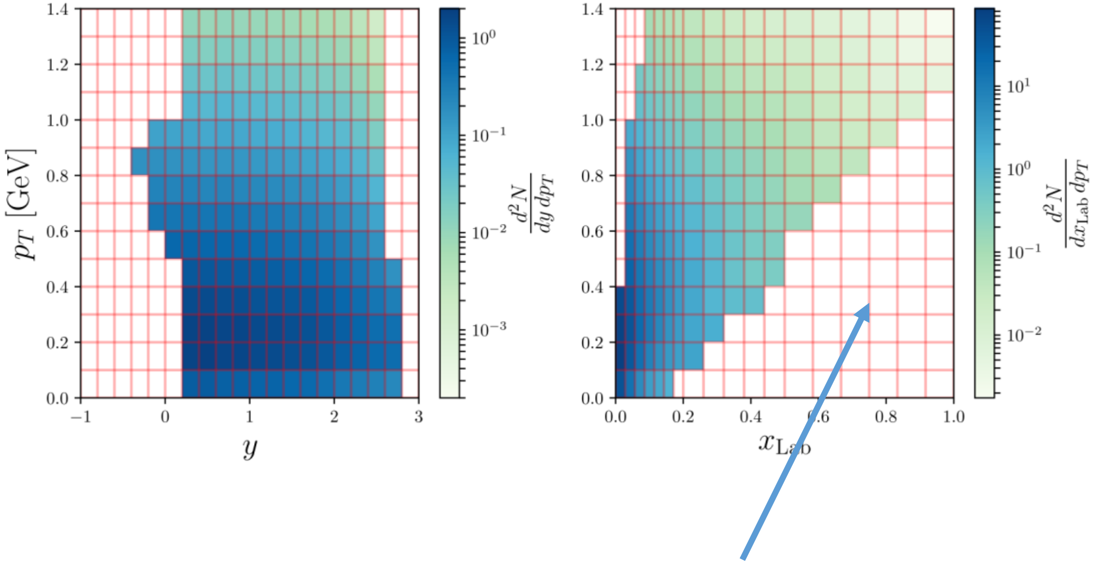

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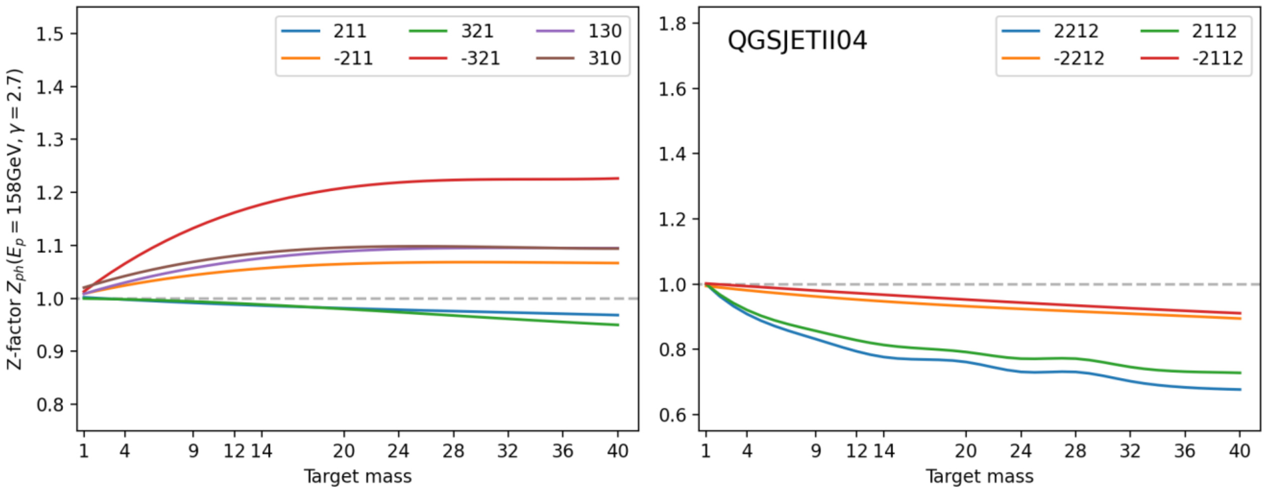

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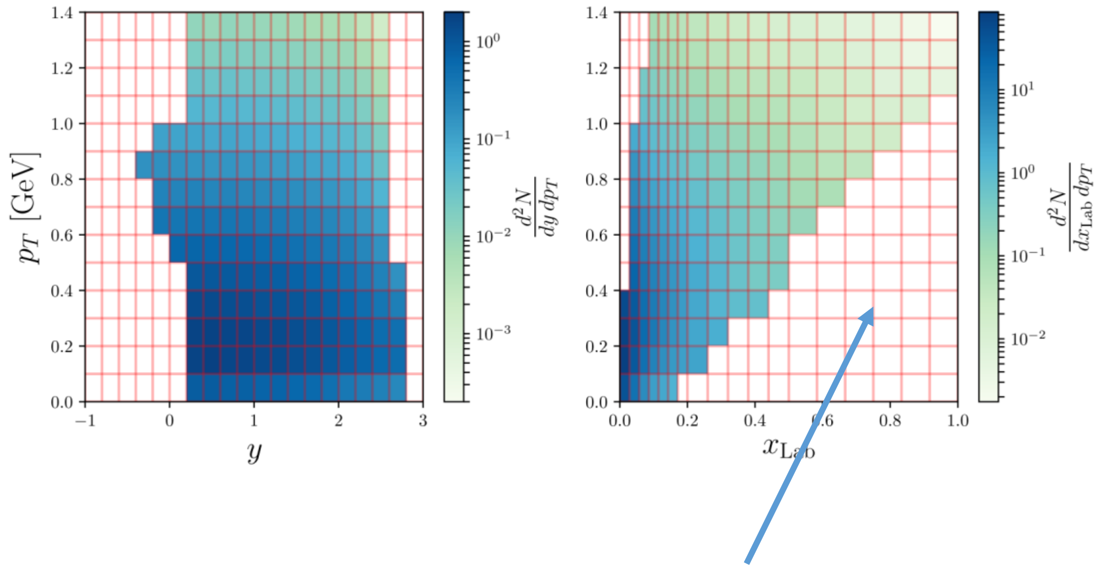

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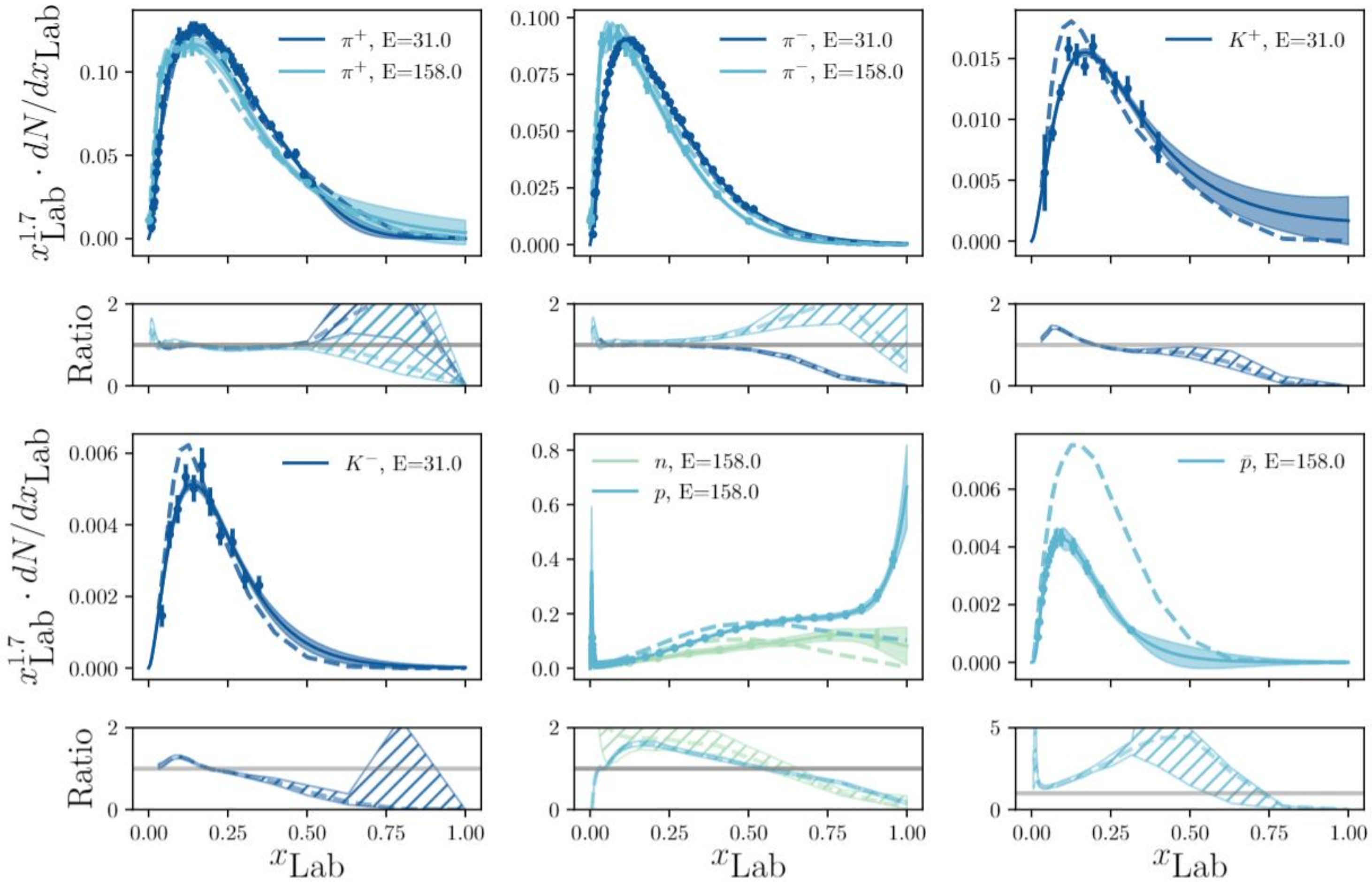
Resulting fits for pC and pi-C



- This is **not the final plot!**
- Dashed curves are from DPMJET-III-19.1
- Uncertainties blow up in absence large x_L data
- The forward protons are compared with bin-averages from MCEq. This effect is not that dramatic in reality and has been corrected
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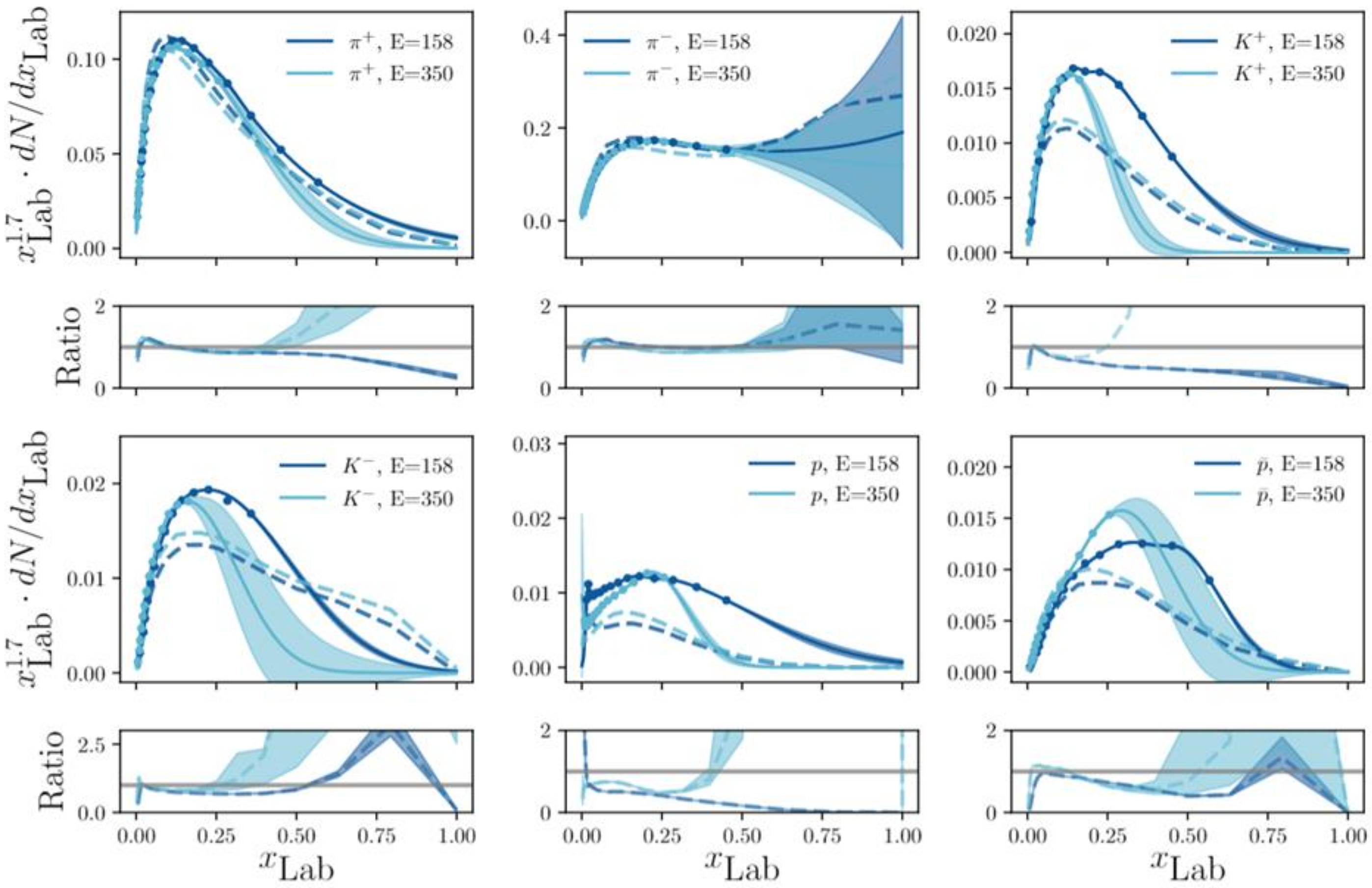

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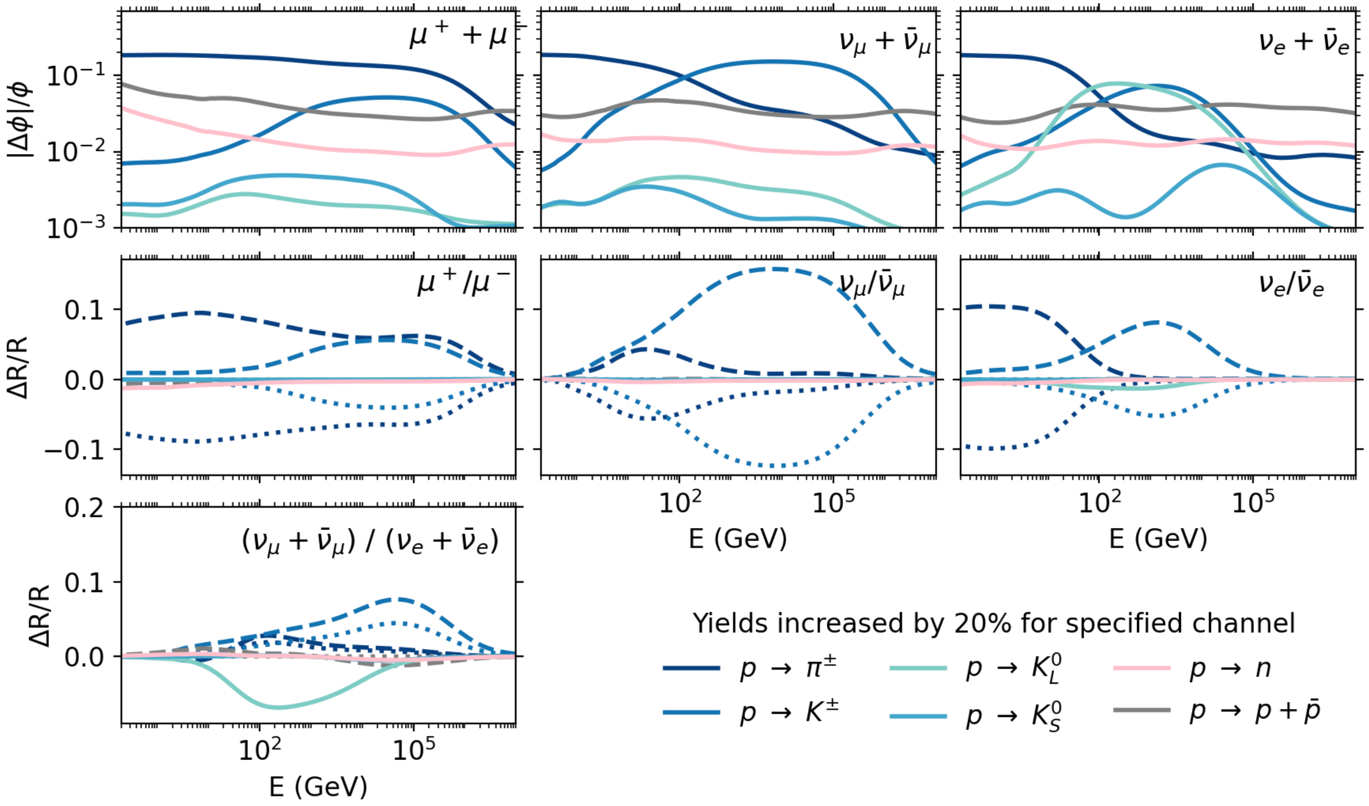
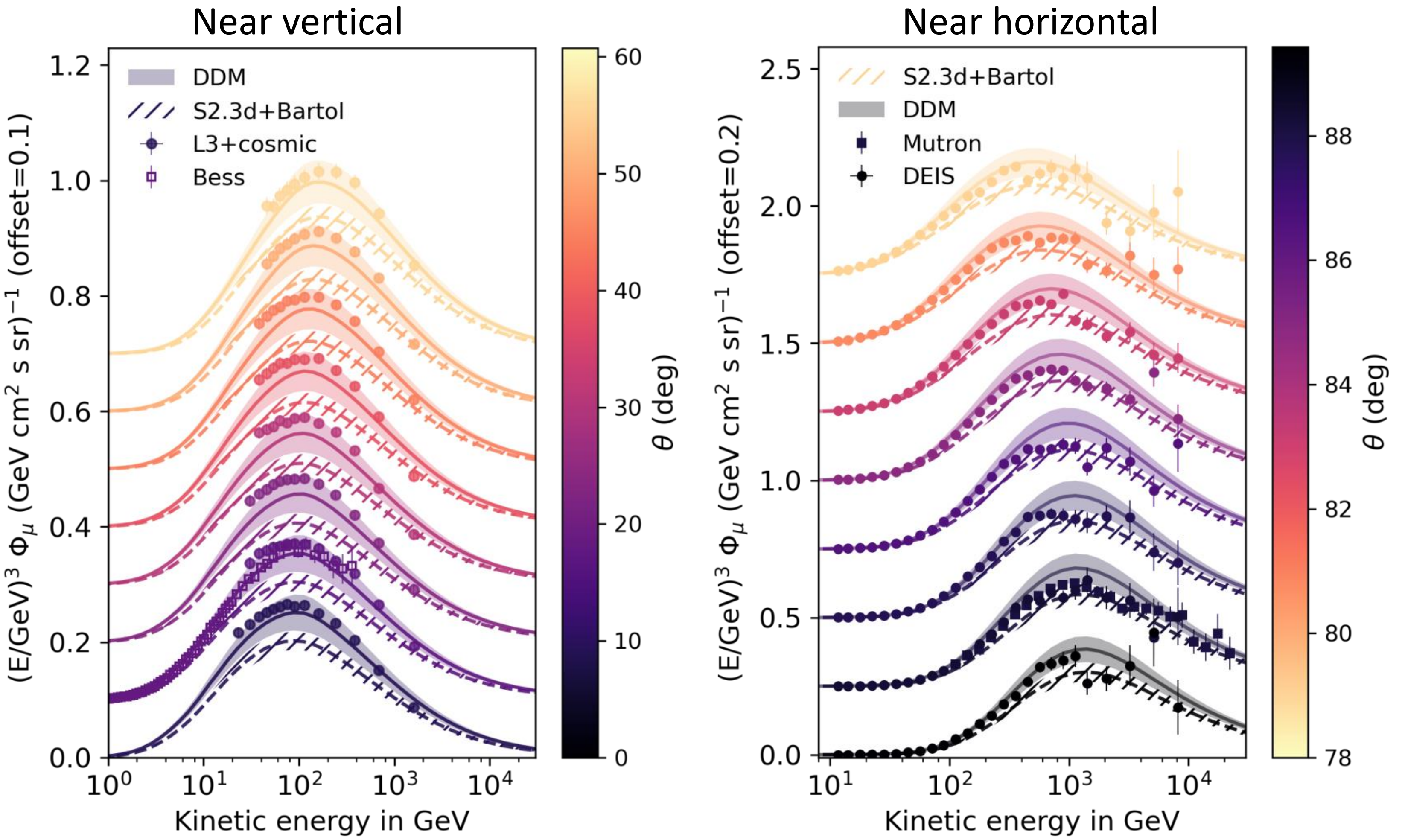
Impact of individual channels on uncertainty



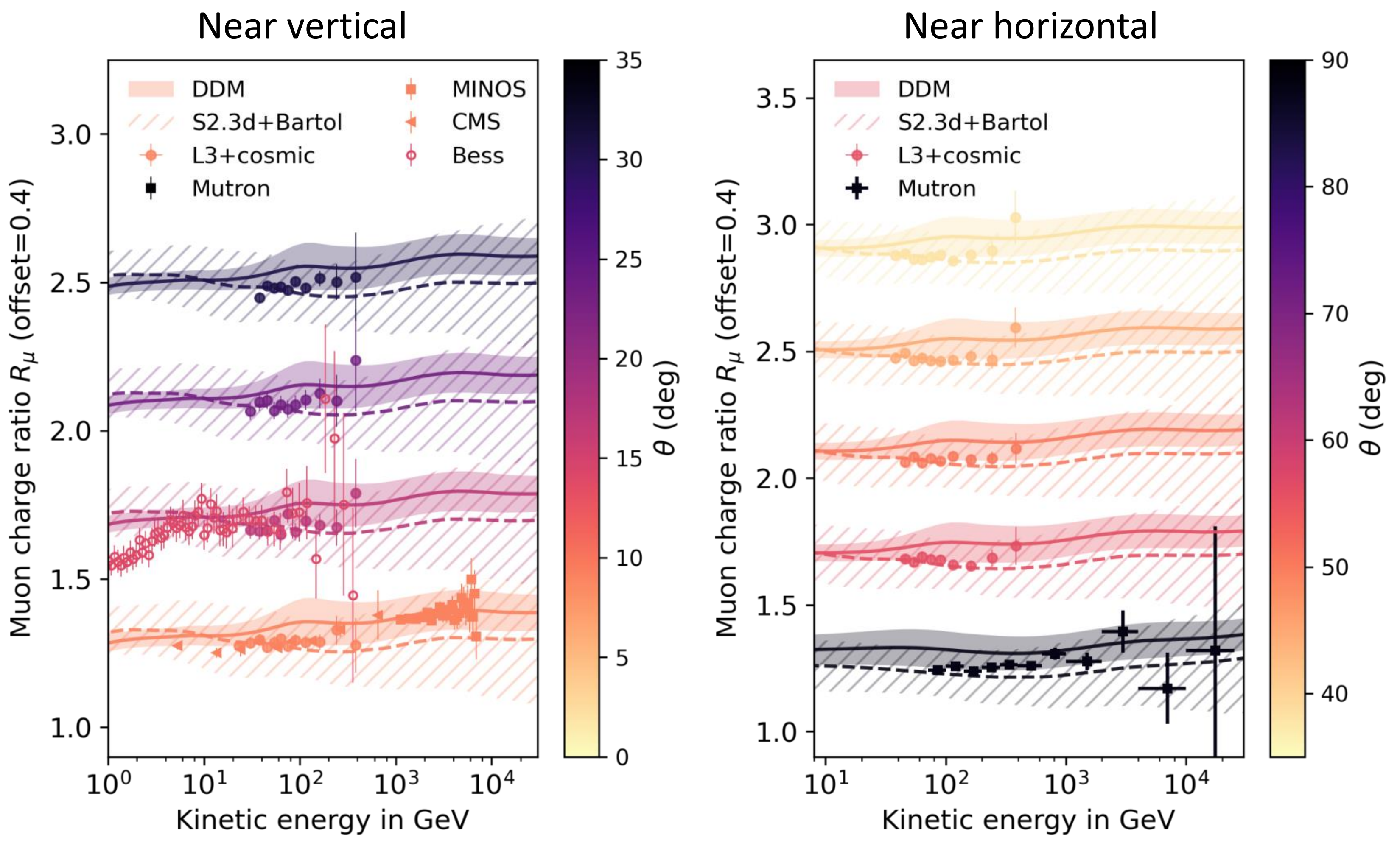
- Large effect from nucleons (pink and gray) cancels out in ratios
- No prompt considered
- Dashed curves are + and – charged mesons
- Mostly as expected, except the role of nucleons
- I'm not yet fully convinced of the nucleons

DDM+ GSF vs data: muon fluxes



- Hatched line is SIBYLL + Barr parameters (Bartol-Parameters maybe?)
- Shaded bands DDM uncertainties, propagated from splines with MCEq
- DDM uncertainty larger than Bartol
- Data without systematics. L3c and Bess allow for 10-15% normalization shift
- BESS perfectly described without additional corrections or syst. pulls
- DEIS and Mutron are both from the 1980s, with good papers.
- Both indicate a softening of the spectrum

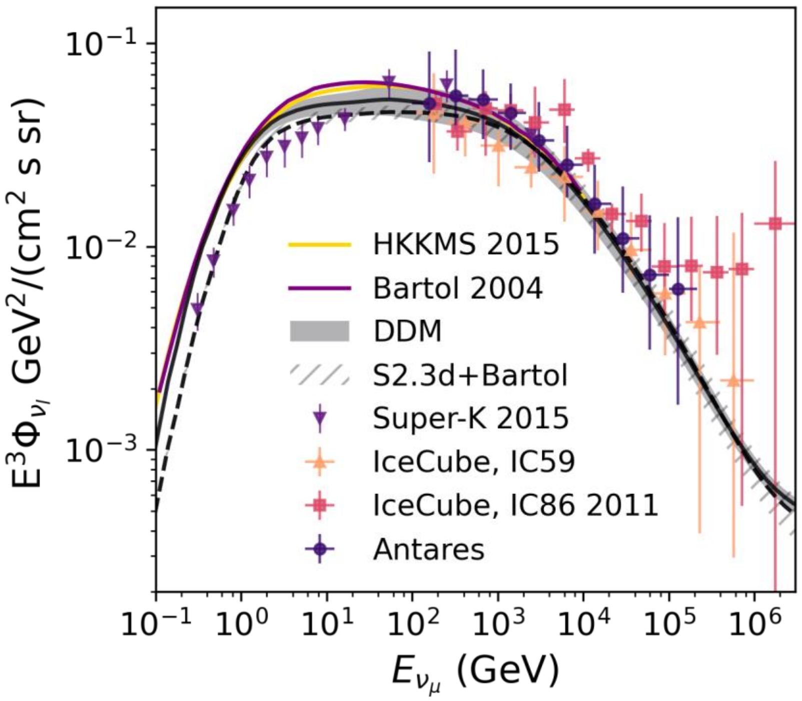
DDM+ GSF vs data: muon charge ratio



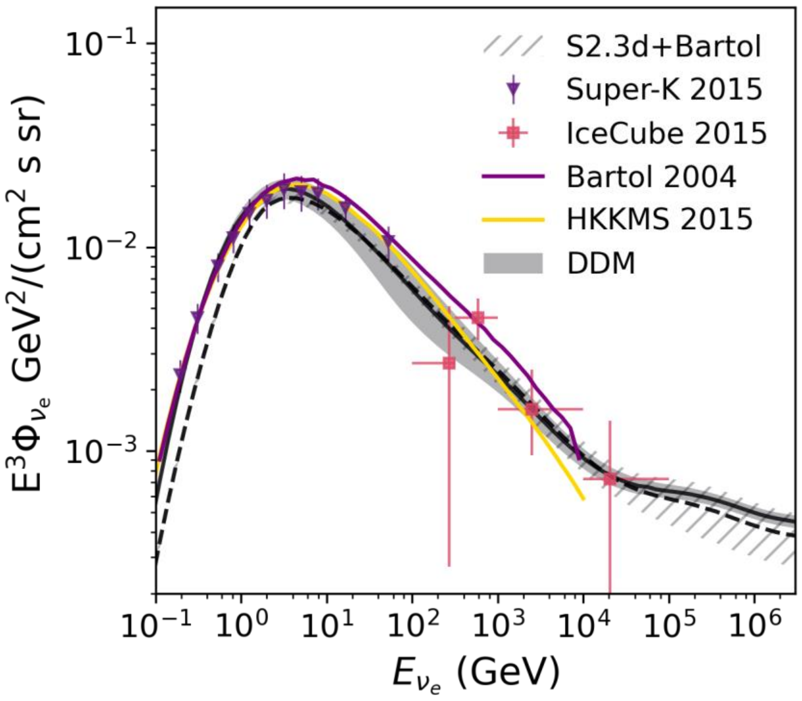
- Reasonable description
- BESS data @ 13 deg (costh=0.95), well described between 5-50 GeV → Projectile E<300 GeV
- At E > 100 GeV description worse. Indication of energy dependent effect?
- Same for higher energy near-horizontal
- At lower energies maybe low-E model effect or geomagnetic cutoff
- Data is within model uncertainties

DDM+ GSF vs data: neutrino fluxes

Muon neutrinos+antineutrinos

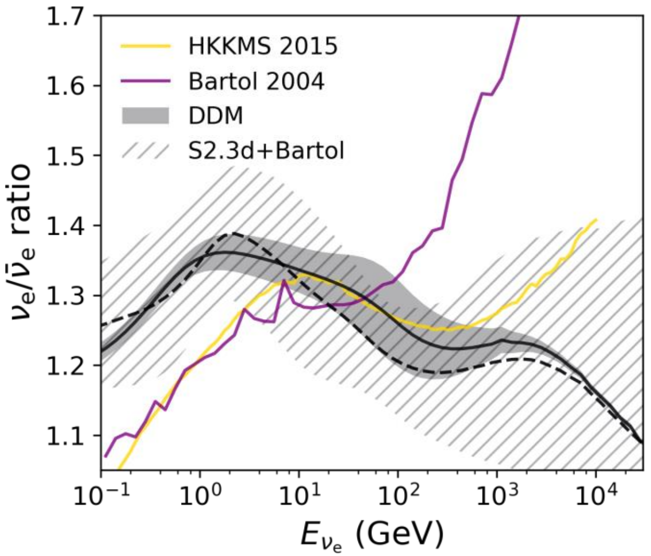


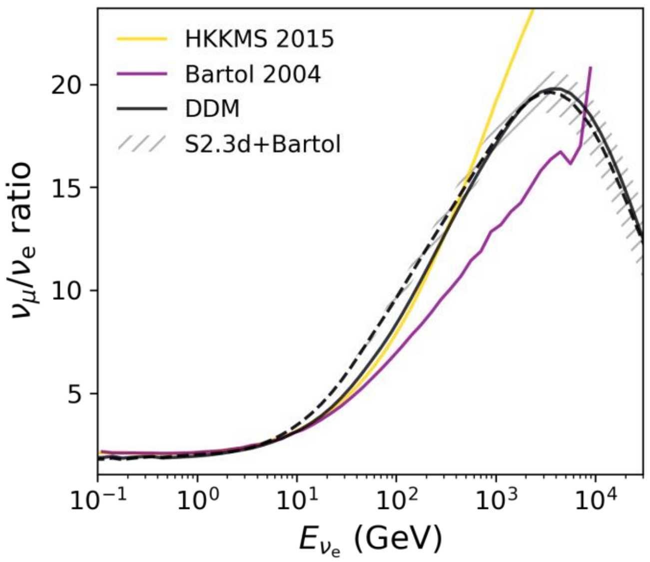
Electron neutrinos+antineutrinos

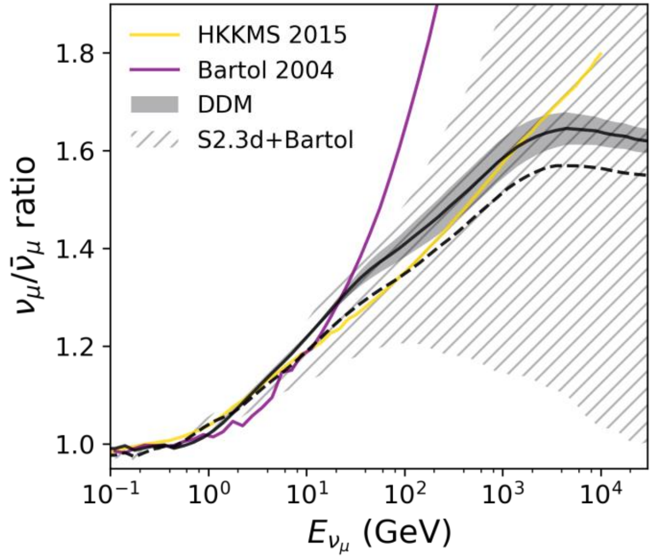


- DDM much close to Honda, identical at low energies
- Angular distribution at E<3 GeV should not be correct (will mention it later)
- Numu model line not corrected for disappearance
- Different spectral index than SIBYLL + Bartol

DDM+ GSF vs data: neutrino ratios

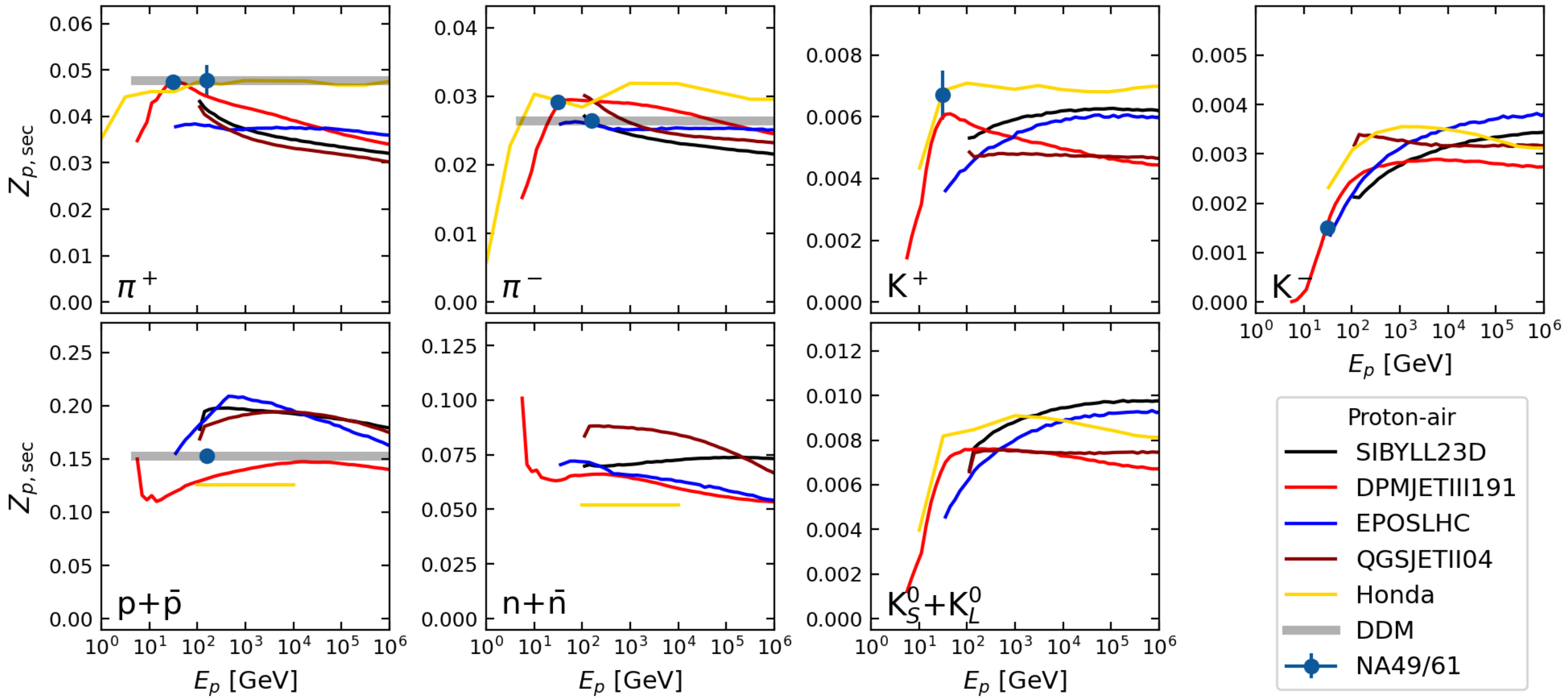






- Ratio uncertainties much smaller in DDM than Bartol
- Flavor ratio uncertainties not (yet) shown, requires to a re-run of entire error propagation chain
- There is CR flux uncertainty and energy extrapolation uncertainty, which will impact higher energies.

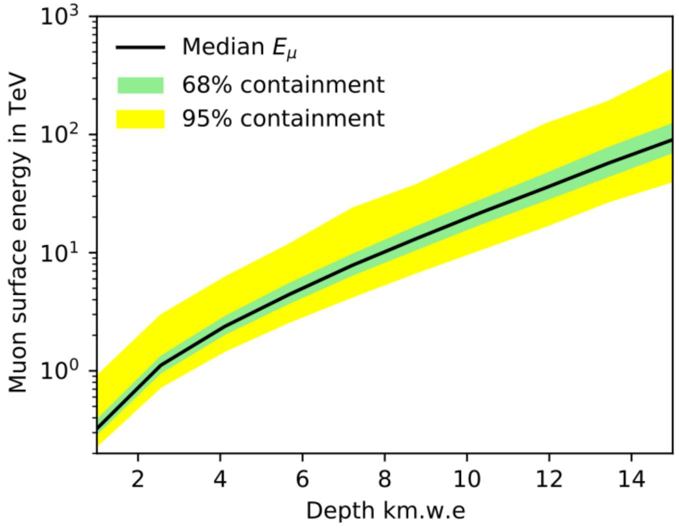
The meat: Z-factors

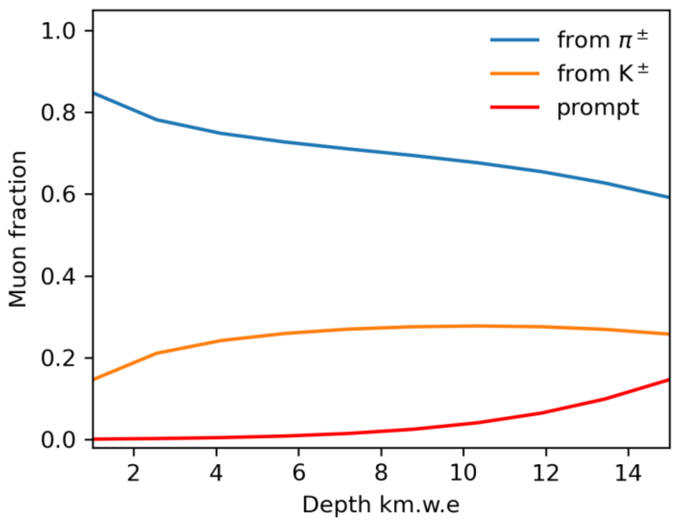


- Honda assumes scaling
- All models don't obey scaling
- DPMJET looks like the best model, but it's not in fluxes → crucial energy range above NA49/61
- Phase-space plot on slide 3 shows this
- Many reasons for scaling violation in models, and likely different reasons in each models
- Some speculation: valence-sea configurations increase too rapidly for soft strings, remnant excitation is not a good solution for baryon spectra, less diffraction than we think, etc..

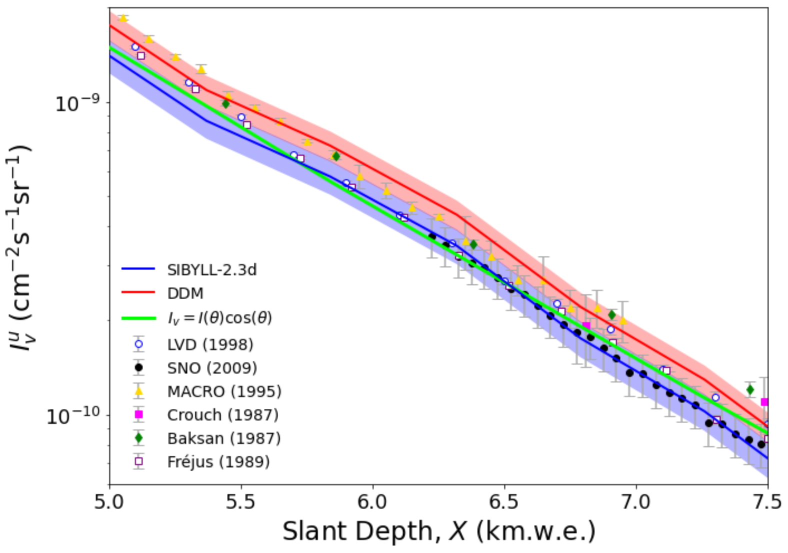
What's next and how to gain certainty?

Deep underground muons sensitive to 1-100 TeV range





Vertical muon intensity

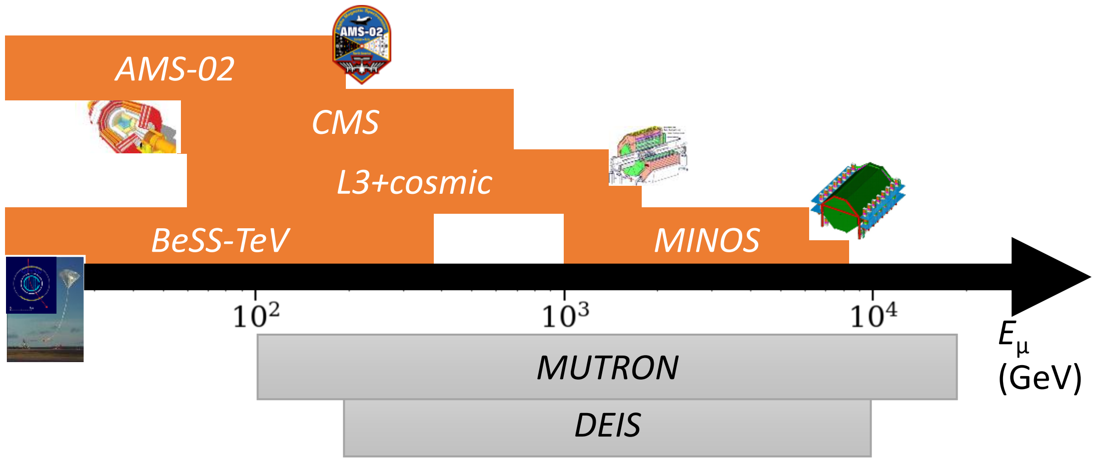


- At shallower depths, DDM is excellent
- At large depths, SIBYLL provides a god description
- Truth will be in-between
- Stay tuned
- Also, G. Barr mentioned that he wants to trigger MINOS to publish the true underground charge ratio, avoiding many of the systematics
- There is more underground data, but analyses without specific goals

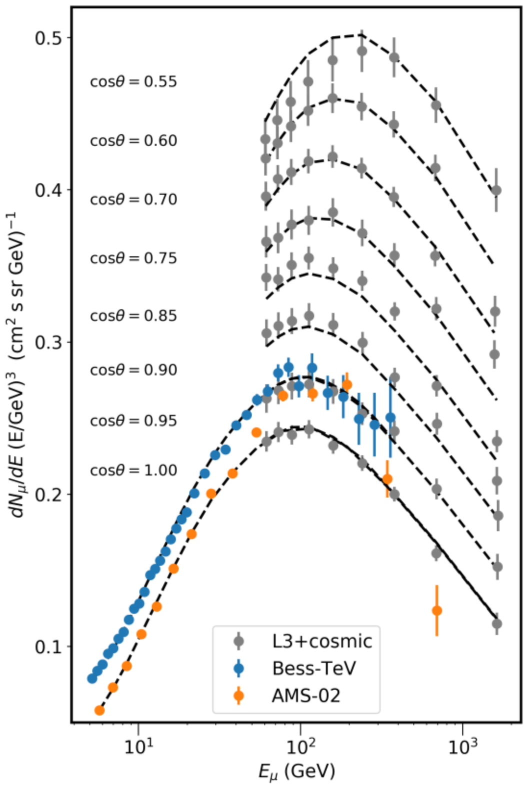
Project with W. Woodley and M.-C. Piro (UofA). Will be presented at CAP and ICRC. Paper near completion.

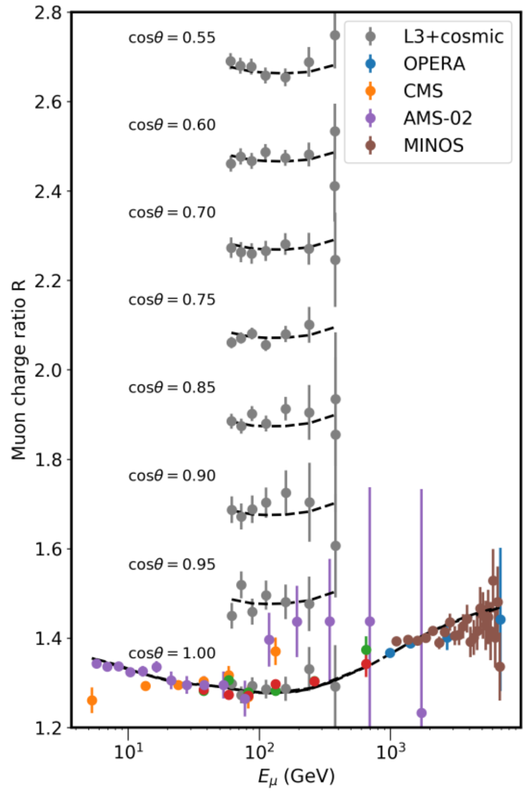
How to learn from muon data?

Cosmic ray flux: Global Spline Fit [7] + Atmospheric conditions + Hadronic interactions: DDM = Flux of muons and neutrinos



Project with Juan Pablo Yanez, update soon (ICRC).





Final words

- Some new data-driven techniques have been developed
- The DDM model behaves in general well and produces conclusive results
- An interesting issue is the violation of Feynman scaling that seems indicated by muon data
- However, this can also be related to cosmic ray spectrum. A joint fit with GSF, may constrain flux anyways.
- Data available with errors smaller than current uncertainties!
- At low energies, a 3D calculation is on the way. Tetiana Kozynets (NBI) has reported on the progress. More at ICRC.
- There are many things to do, help is welcome.

Other minor issues

- Difference between SIBYLL 2.3c and 2.3d: almost none for fluxes, just pi0
- DPMJET-III in MCEq: K0L and K0S buggy matrices
- Fix implemented in MCEq > 1.3.4:
  config.adv_set['fix_dpmjet_neutral_kaons’] = True
- Due to synchronization with FLUKA 4 CERN, DPMJET-III params will slightly change, minor impact, no breakthroughs.