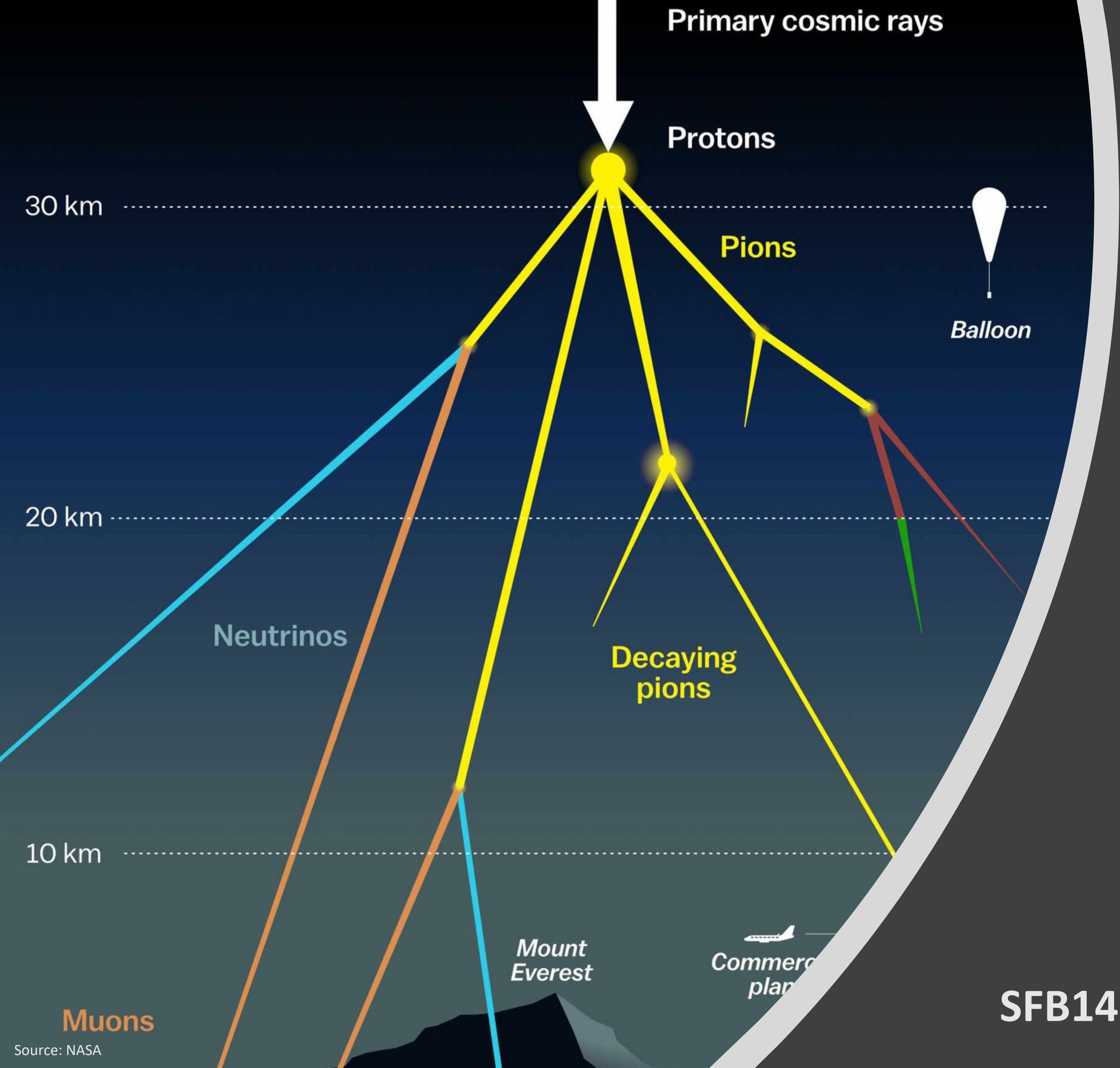


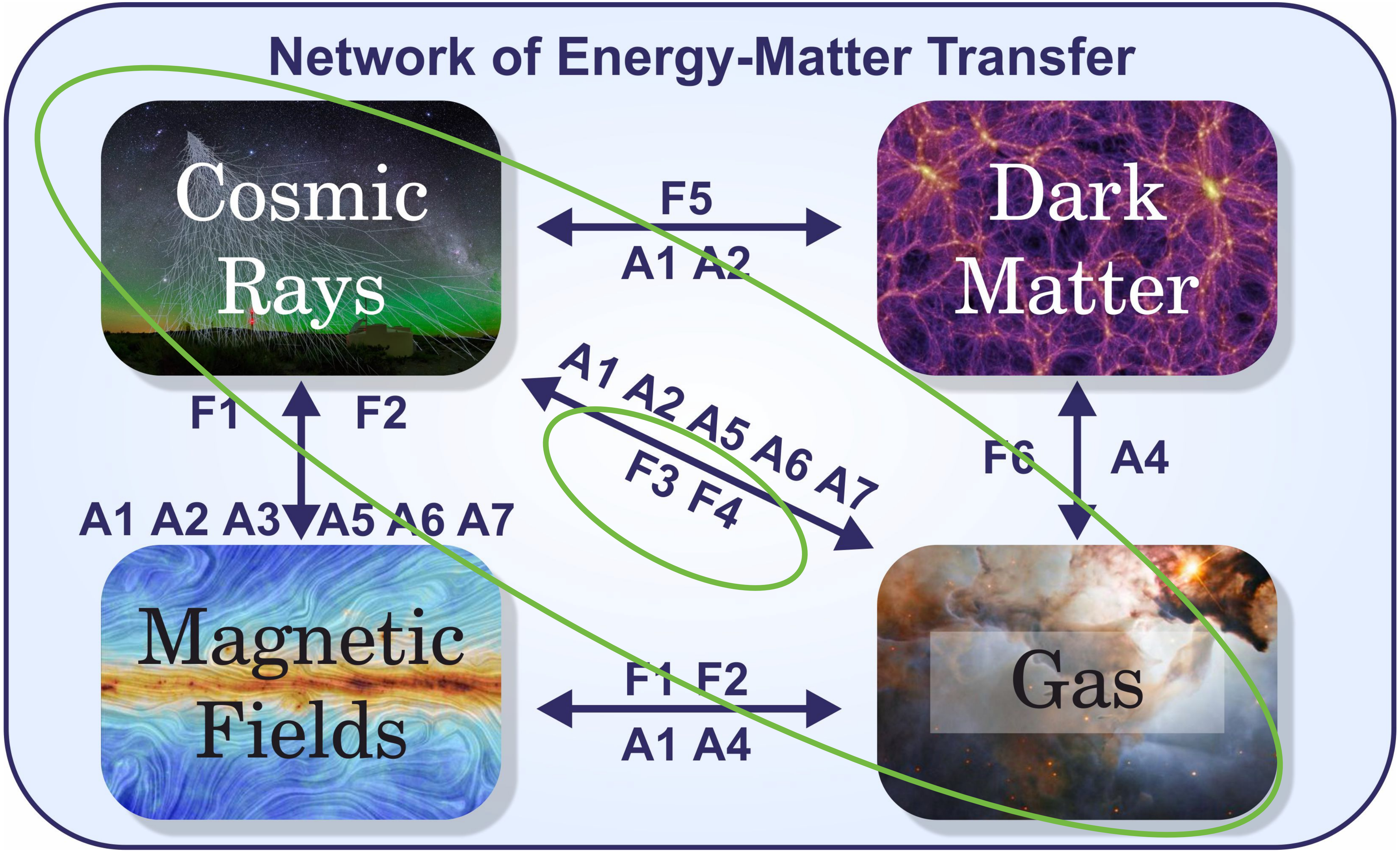
Source: NASA

Constraining production uncertainties of heavy mesons via measurement of the prompt atmospheric component using IceCube

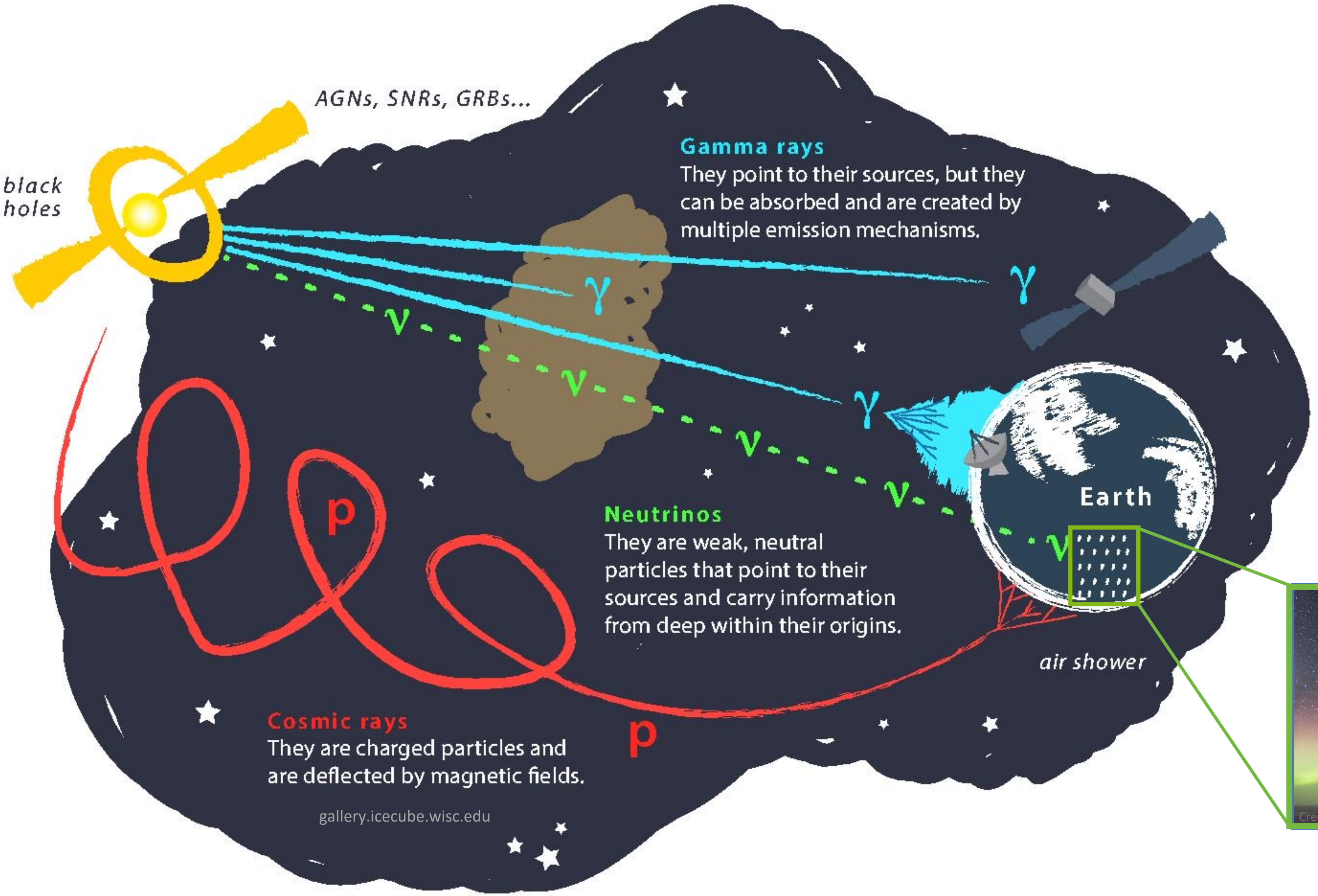
- F3 -

Ludwig Neste, Mirco Hünnefeld and Pascal Gutjahr

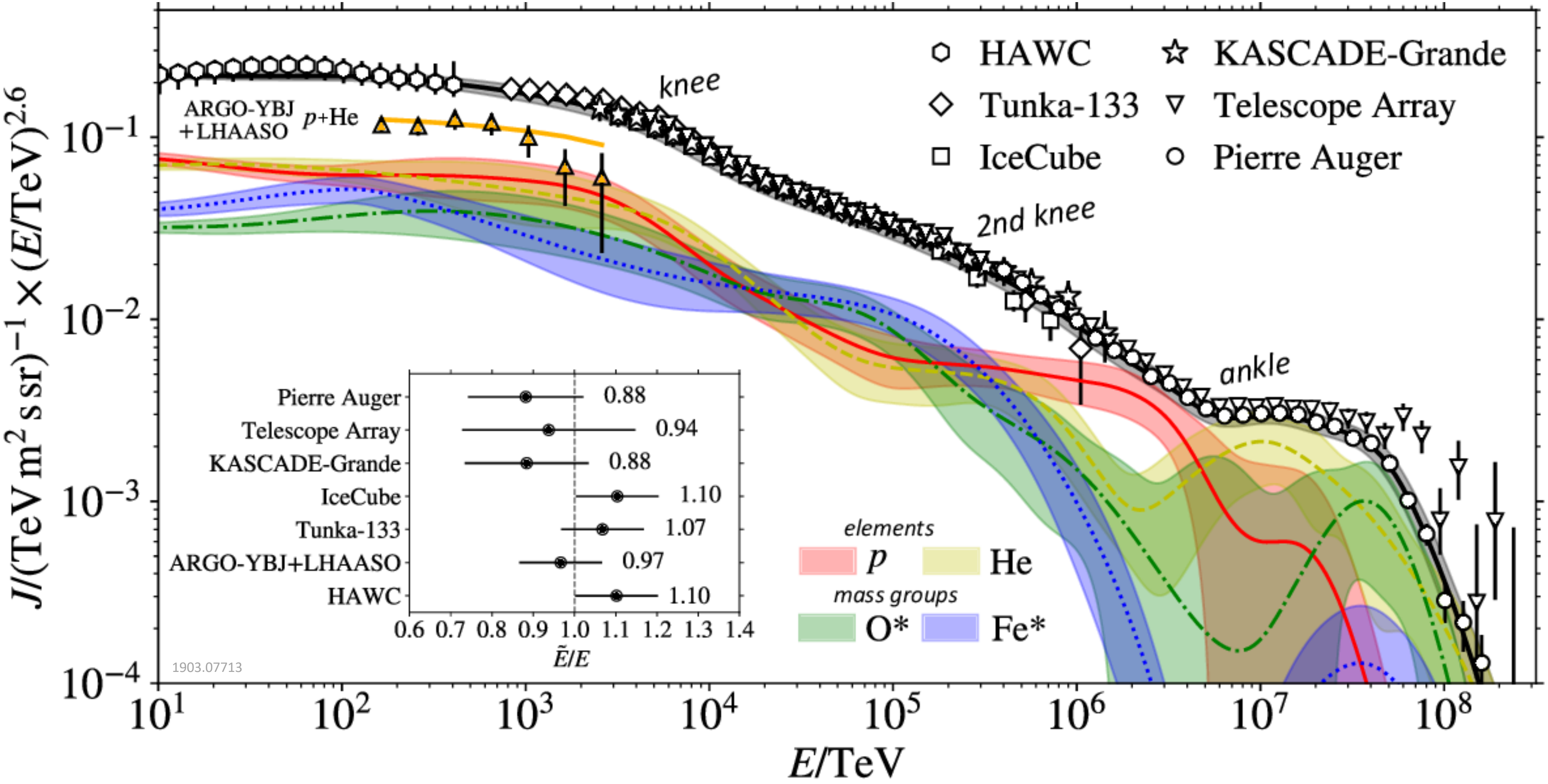
SFB1491 General Assembly, Dortmund 2023


Network of Energy-Matter Transfer
Cosmic Rays
Dark Matter
Magnetic Fields
Gas
F5
A1 A2
F1
F2
A1 A2 A3 A5 A6 A7
A1 A2 A5 A6 A7
F3 F4
F6
A4
F1 F2
A1 A4

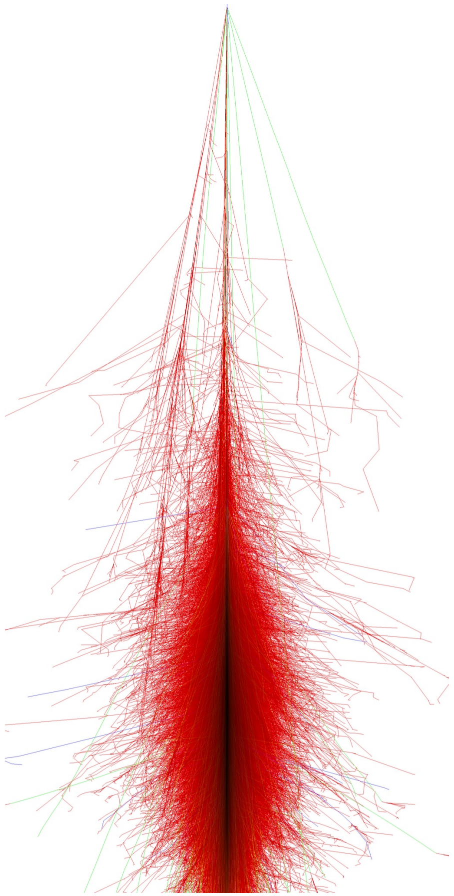
Astroparticle physics



Cosmic ray flux

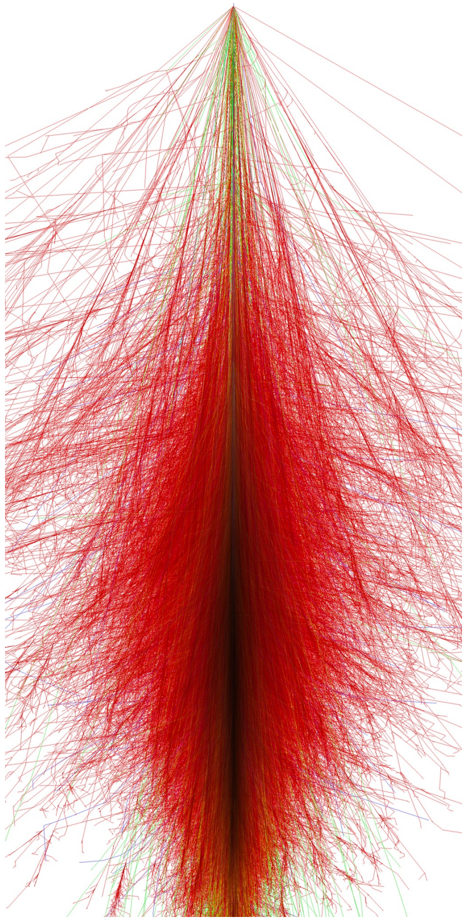


Air shower – 10 TeV

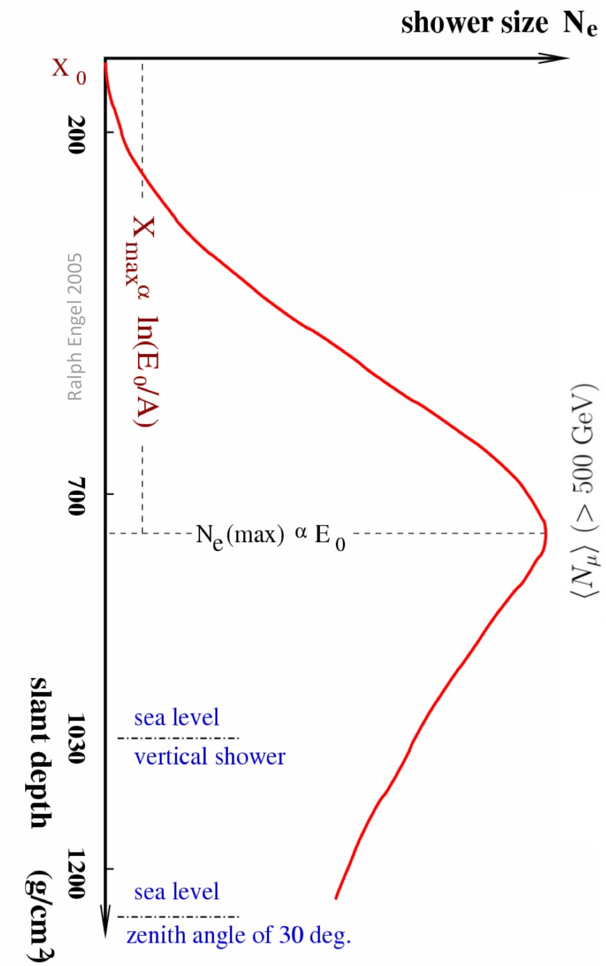


Proton

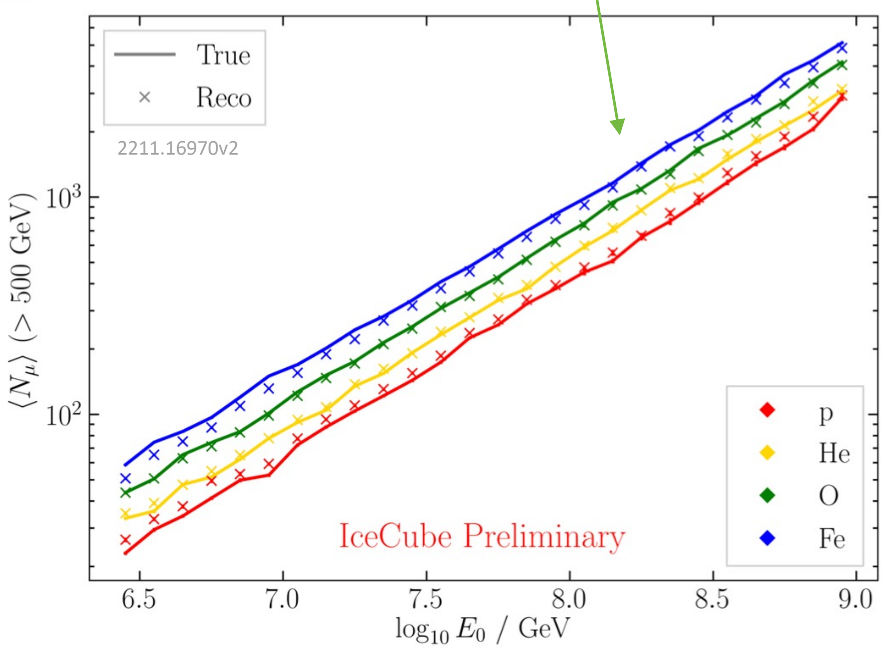
zeuthen.desy.de



Iron

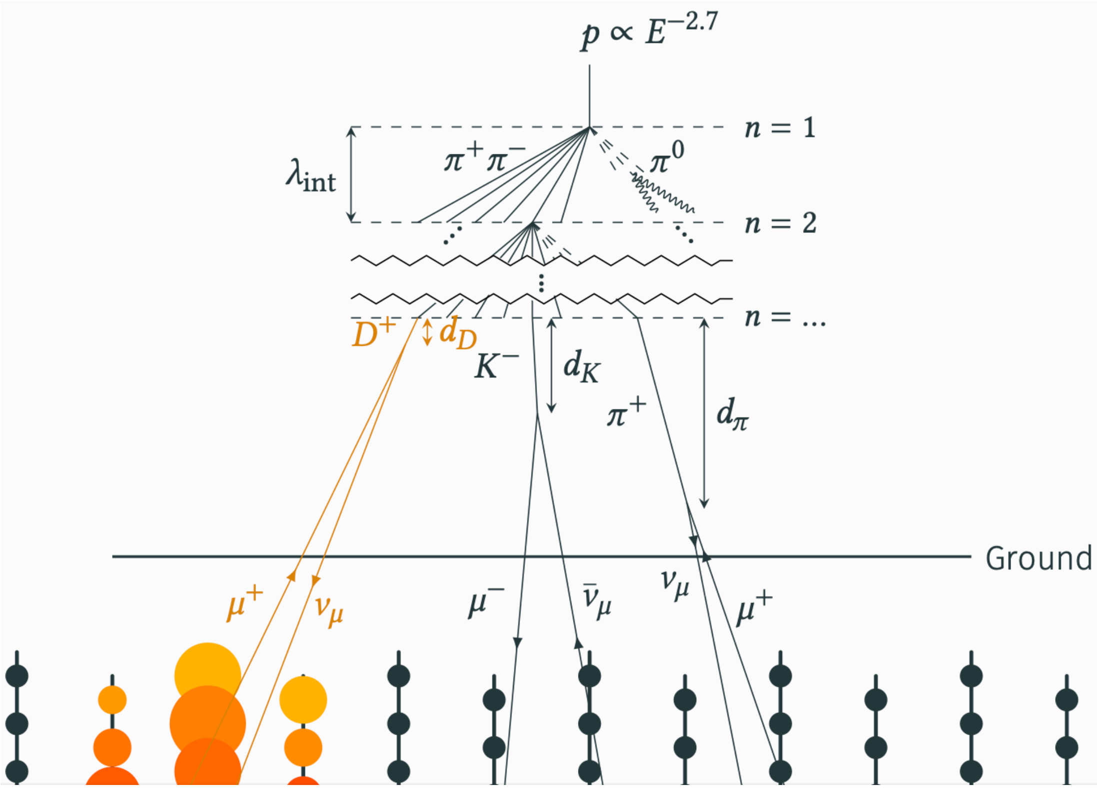


"muon bundles"



Muon flux: Definition of prompt

$$\Phi_{tot} = \Phi_{prompt} + \Phi_{conventional}$$

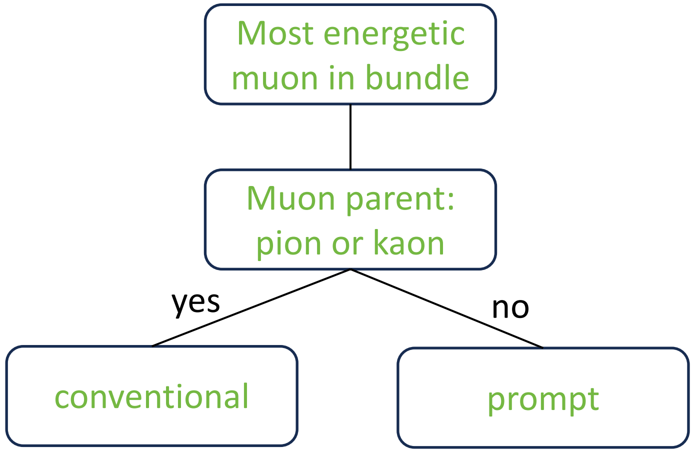


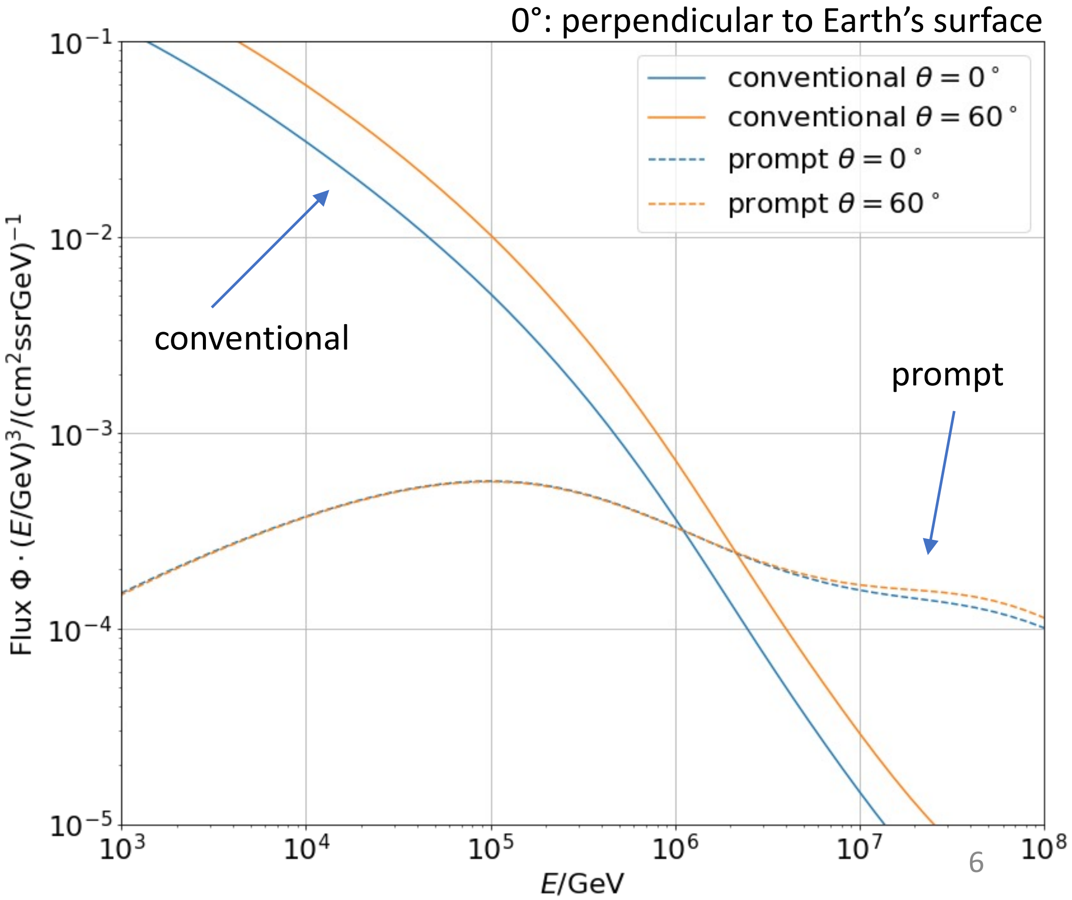
prompt component:

$$\underset{\propto E^{-2.7}}{p} \rightarrow \overbrace{D^+}^{\tau = 1.04\cdot 10^{-12}\,\mathrm{s}} \rightarrow \bar{K}^0 + \underset{\propto E^{-2.7}}{\mu^+} + \nu_\mu$$

Conventional component:

$$\underset{\propto E^{-2.7}}{p} \rightarrow \overbrace{\pi^+}^{\tau = 2.6\cdot 10^{-8}\,\mathrm{s}} \rightarrow \underset{\propto E^{-3.7}}{\mu^+} + \nu_\mu$$





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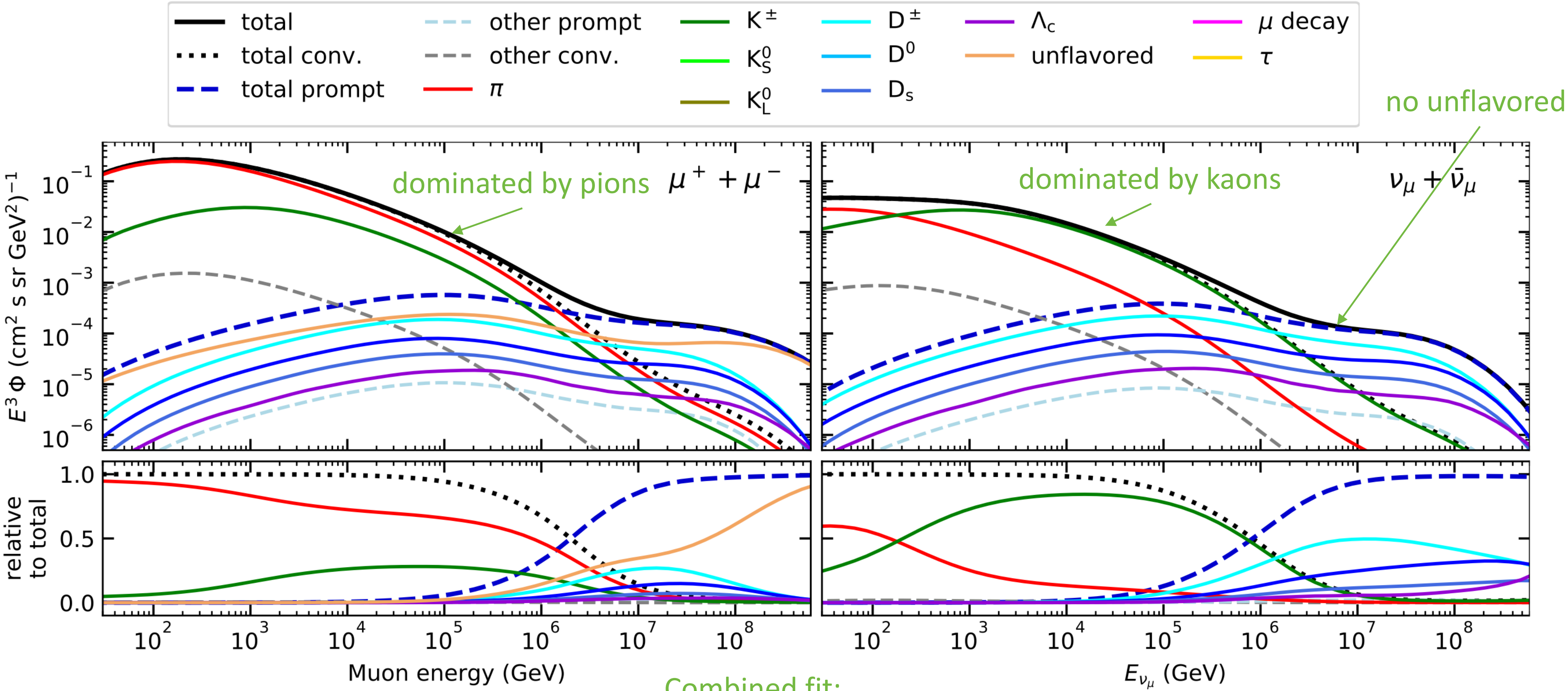
Prompt atmospheric muons and neutrinos

10.1103/PhysRevD.100.103018



Combined fit:

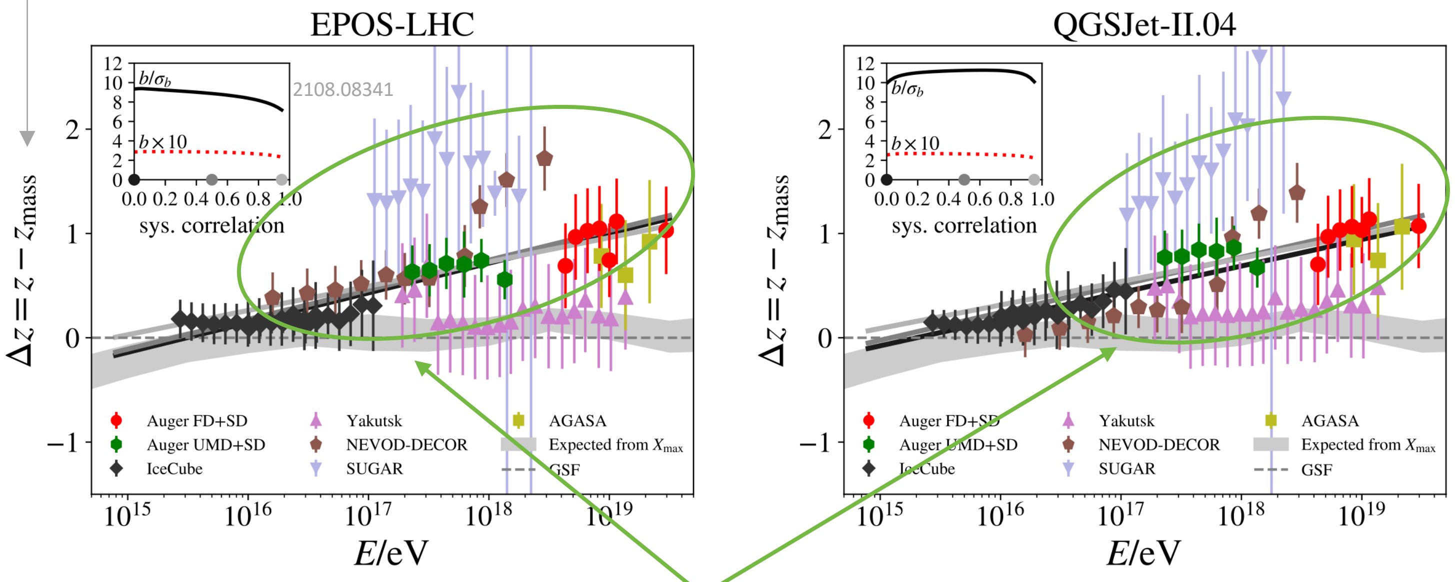
- handle on pion/kaon ratio
- handle on charmed mesons

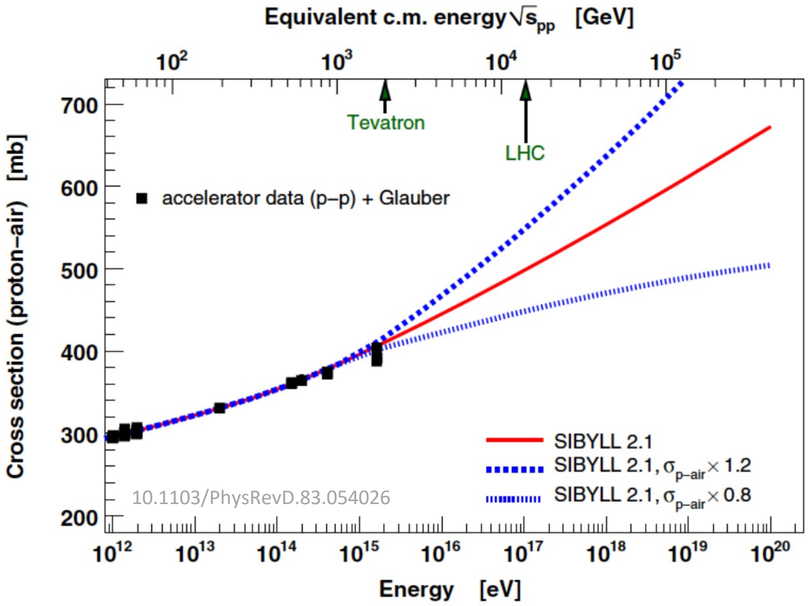
Muon Puzzle and model uncertainties

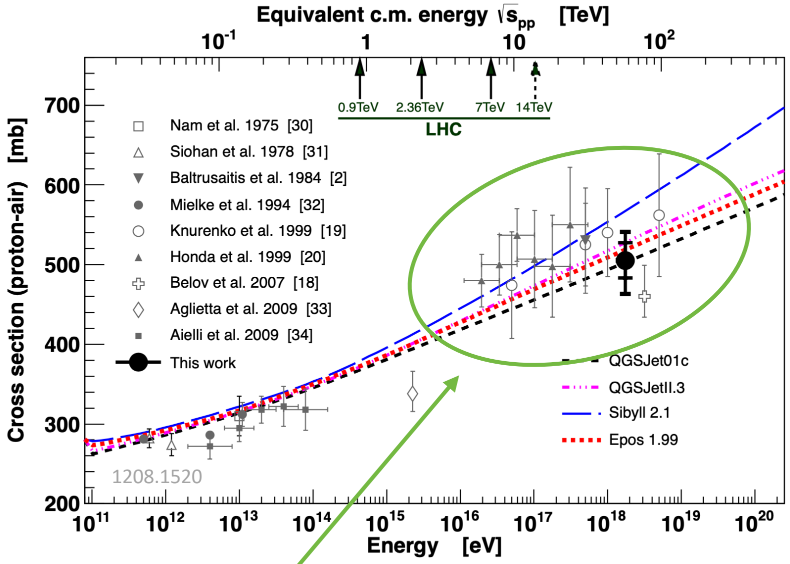
"muon number"

Expected z ("muon number")

$$z = \frac{\ln\langle N_\mu\rangle - \ln\langle N_\mu\rangle_p}{\ln\langle N_\mu\rangle_{Fe} - \ln\langle N_\mu\rangle_p}$$







- More muons measured than simulated for E > 40 PeV ~ cms 8 TeV
- Large uncertainties at E > 10 PeV

F3/F4 Overview

- F3 (“Prompt lepton production in hadronic interactions”)
- F4 (“Cross sections and hadronic interactions in particle- and astroparticle physics”)

F3.1 (W. Rhode, IceCube)

Deliverables:

- Year 1/2:
  - Establish analysis framework for prompt muon measurement
  - First (preliminary) results will be produced
  - Upgrade MC generators for necessary comparisons and alignments to F3 and F4
- Year 3/4:
  - Continue systematic studies for prompt muon measurement
  - Publication of prompt muon measurement
  - Further work on unifying F3/4 results for MC generators

First: Atmospheric prompt muons

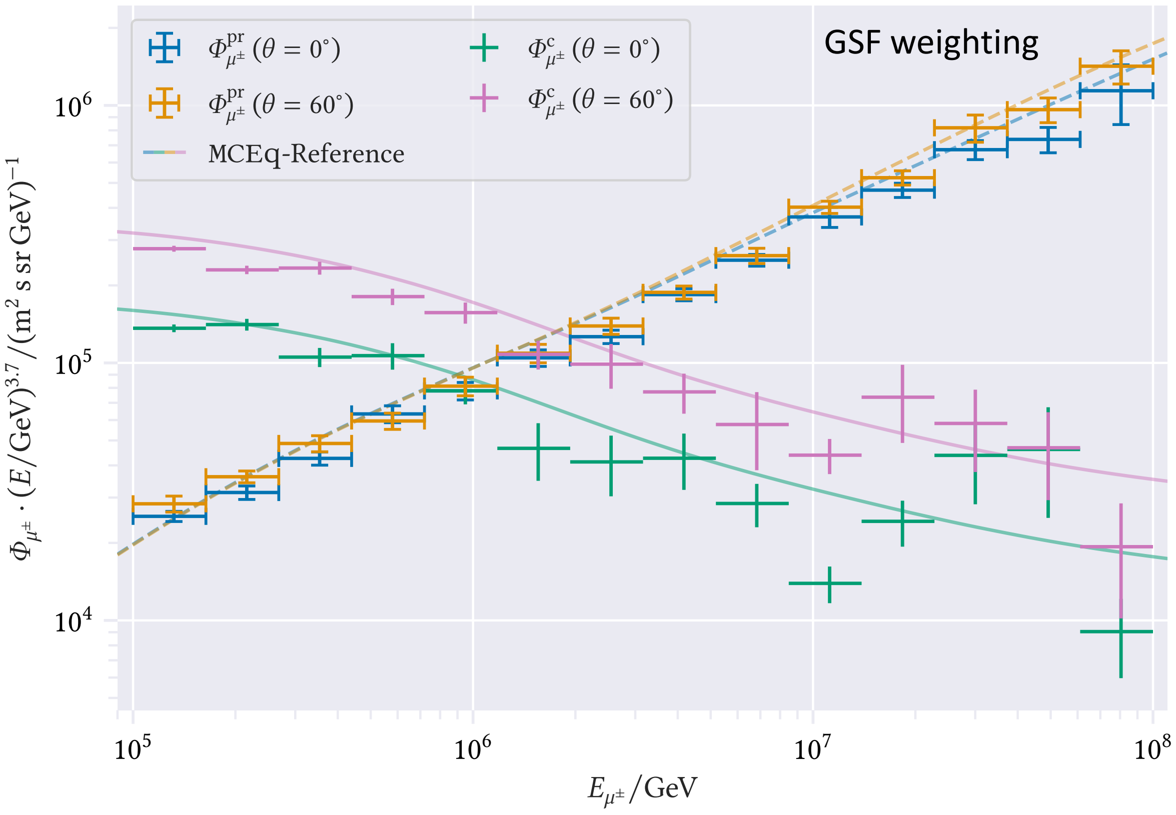
1) Detect prompt component of the atmospheric muon flux
   - Measure the normalization
   - Get handle on hadronic interaction models
2) Unfold a muon energy spectrum

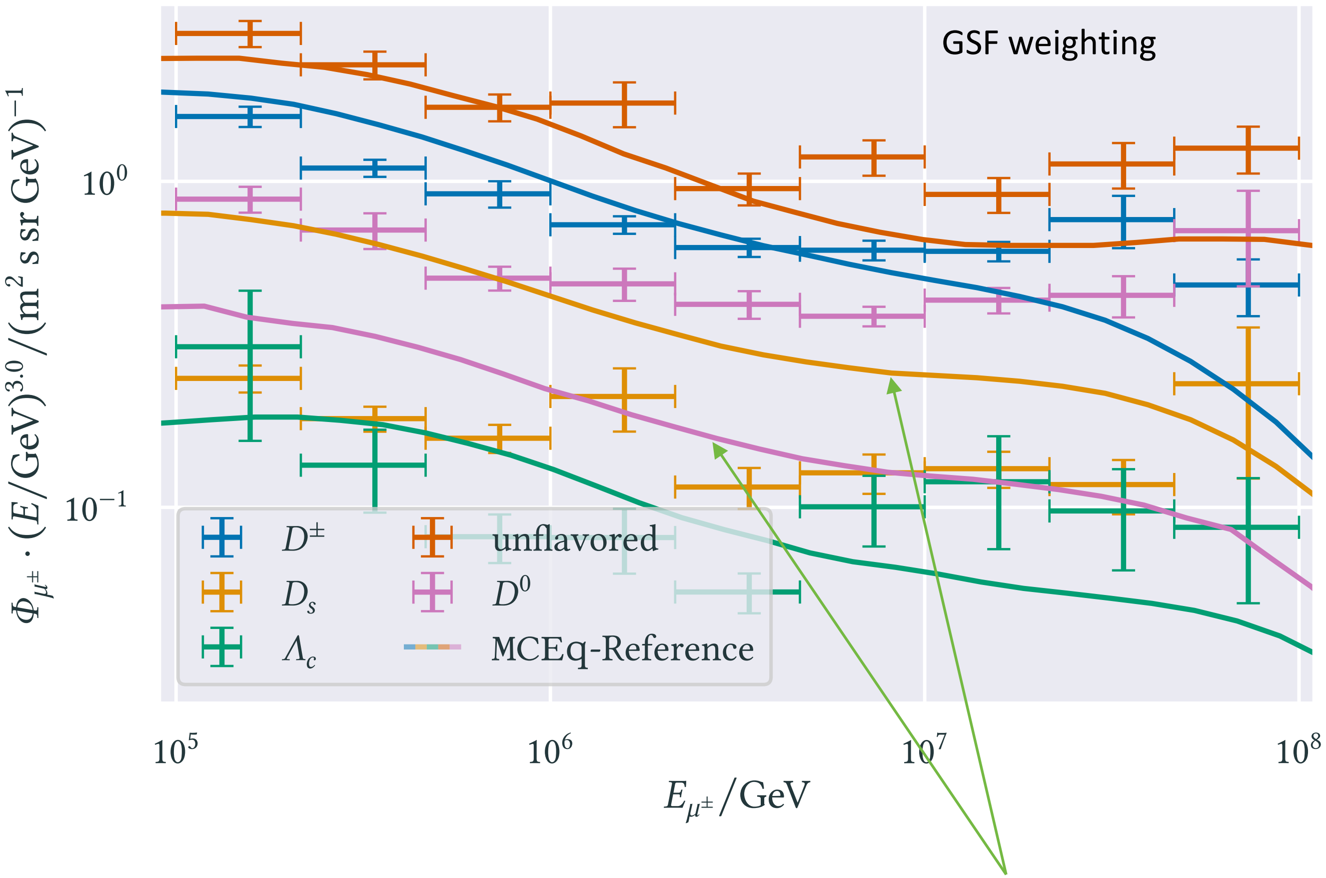
Idea:

- New CORSIKA simulations with extended history
- Tag muons by parent → prompt or conventional
- Scale amount of prompt particles
  - Scaling saves time and resources instead of doing multiple simulations with different interaction models
  - Perform forward fit of the prompt normalization

CORSIKA 7 tagging and MCEq comparison

MCEq: tool to numerically solve the cascade equations that describes the evolution of particle densities as they propagate through a gaseous, dense medium
https://github.com/mceq-project/MCEq

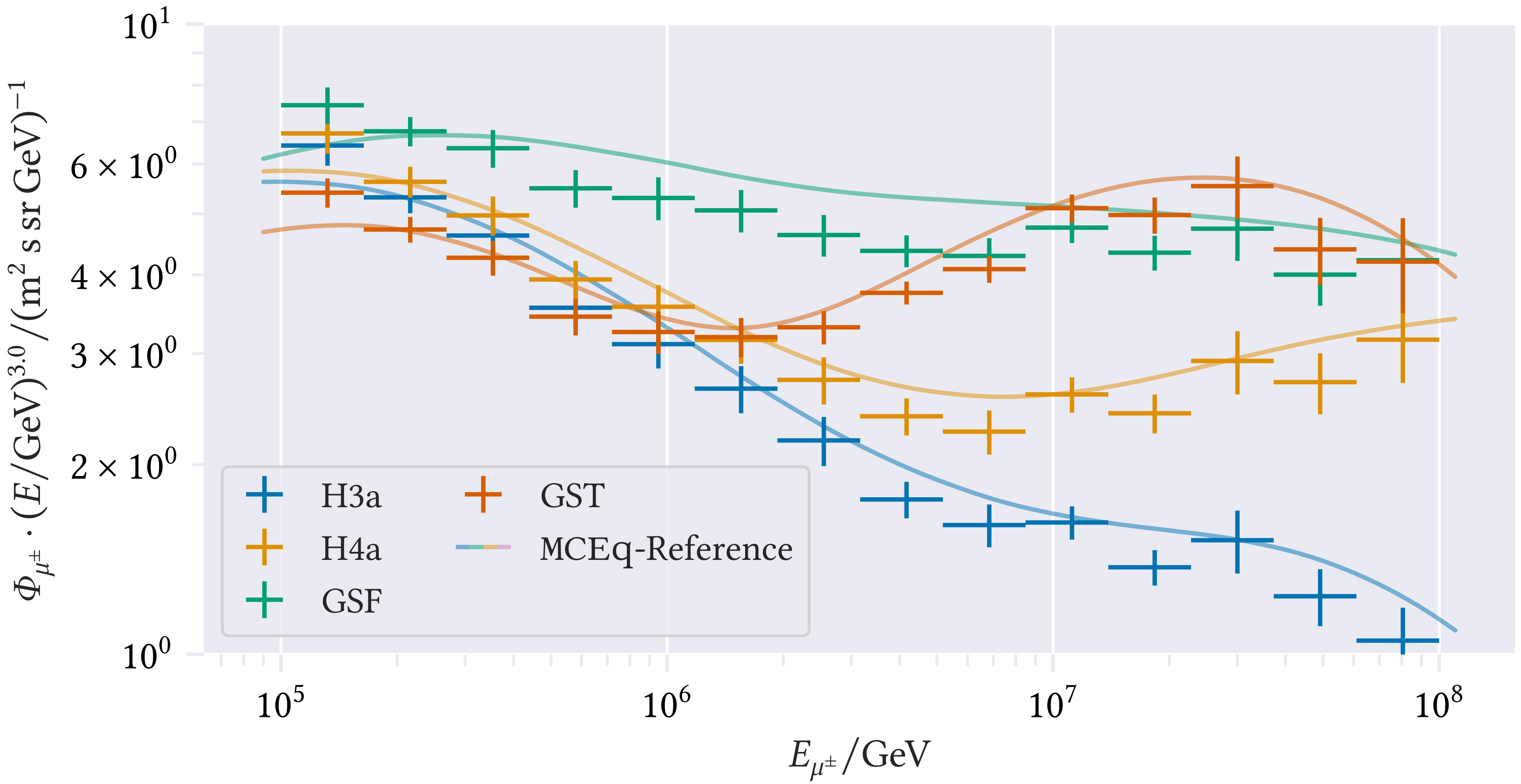




- Good agreement in total prompt and conv muon flux

- D^0 and D_s are swapped here but this is fixed in MCEq

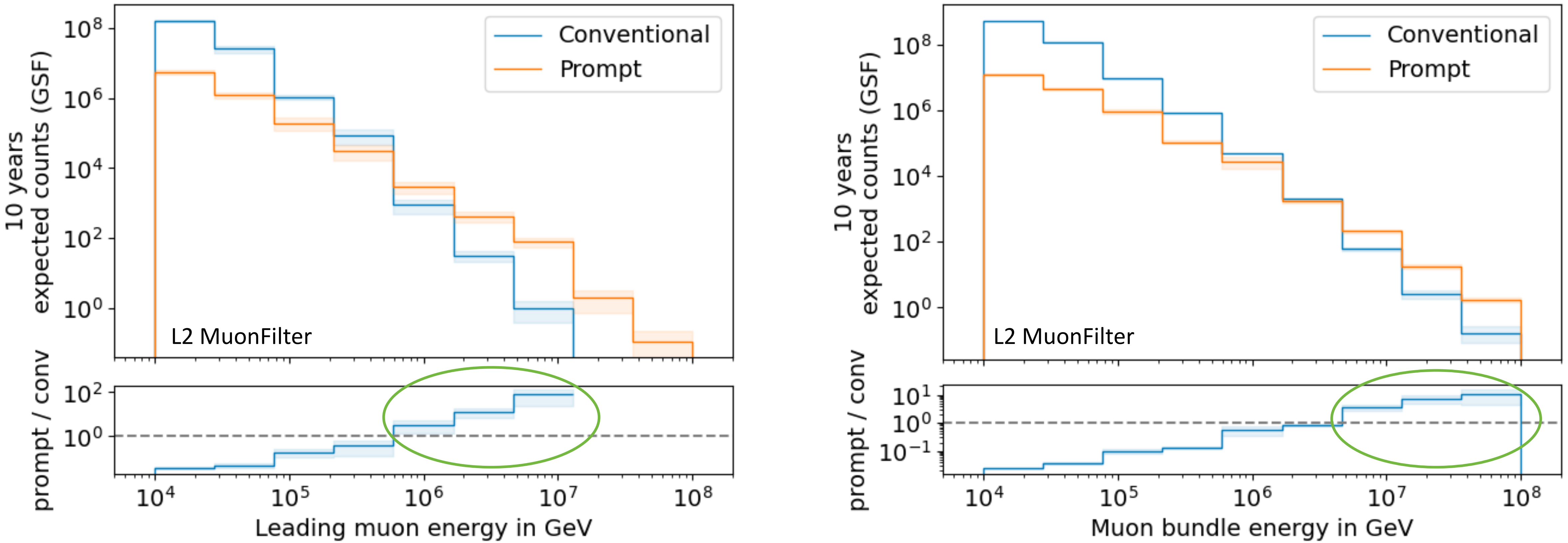
Agreement for different primary models



Pseudo analysis

Expected muons for 10 years: leading vs. bundle energy (GSF)

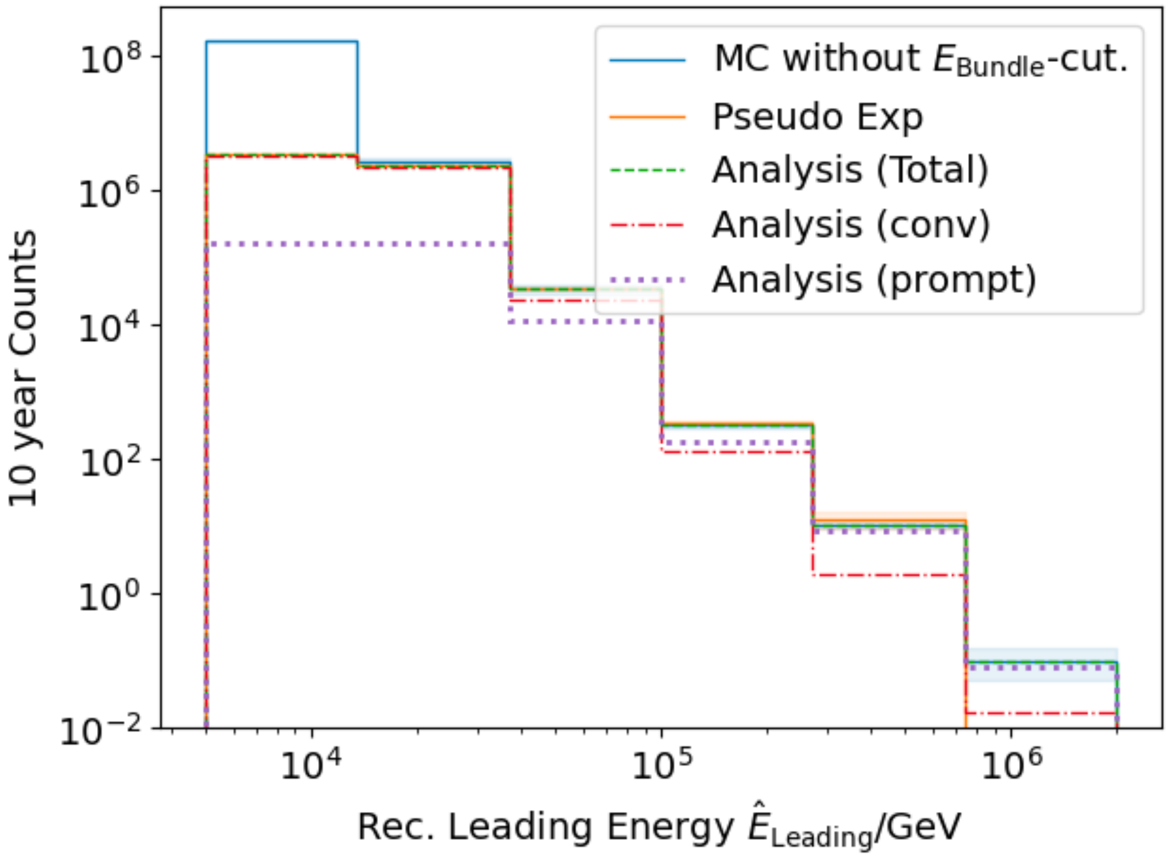
- leading: energy of most energetic muon in a muon bundle
- bundle: sum of energies of all muons of the bundle

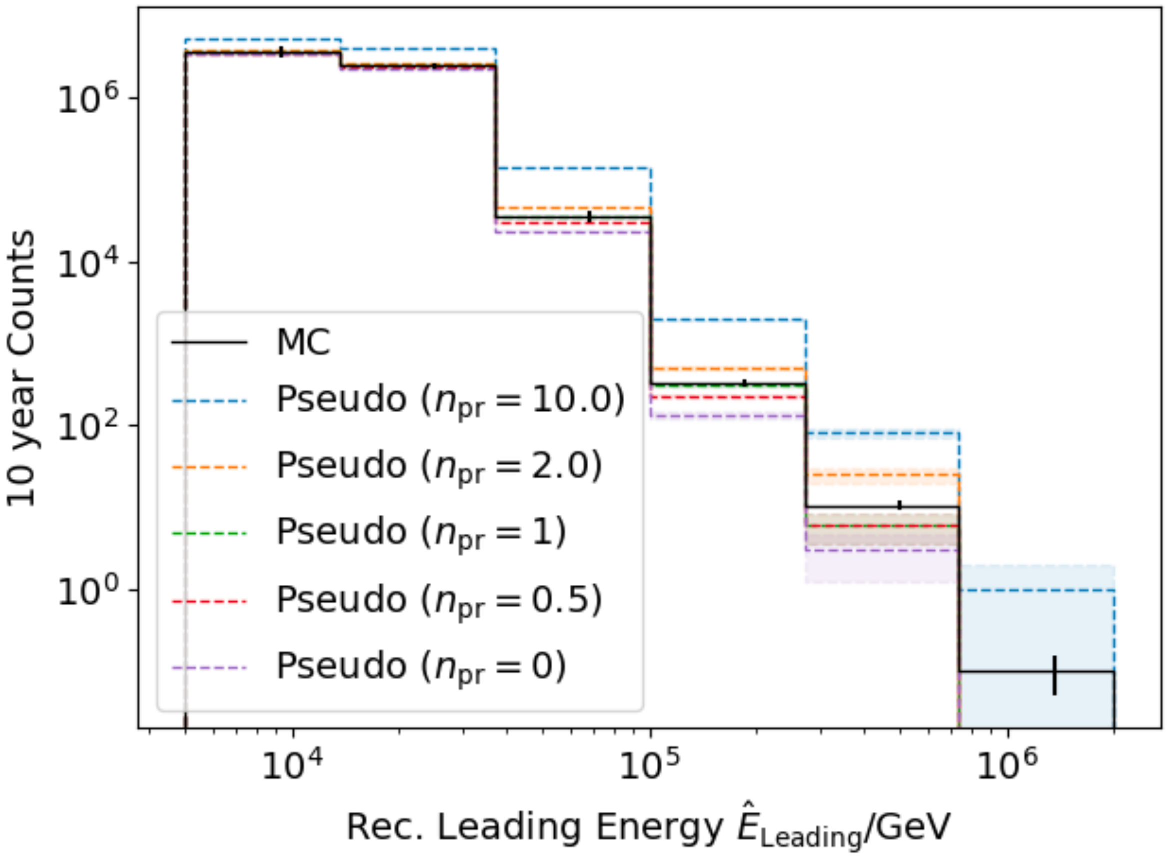


- ➢ Both leading and bundle energy are sensitive to detect prompt
- ➢ Leading muon energy is more sensitive

Pseudo data sampling

Cuts:
L2 MuonFilter
Bundle energy > 100 TeV





- Tagging allows scaling of prompt by factor n_{pr}

Poisson likelihood fit performed in leading muon energy

Cuts:
L2 MuonFilter
Bundle energy > 100 TeV

Prompt scaling/normalization

Conv norm = 1

MC counts per bin i

$$C_1^{\mathrm{MC}} = n_{\mathrm{pr}} C_1^{\mathrm{MC,pr}} + n_{\mathrm{conv}} C_1^{\mathrm{MC,conv}}, \ldots, C_M^{\mathrm{MC}} = n_{\mathrm{pr}} C_M^{\mathrm{MC,pr}} + n_{\mathrm{conv}} C_M^{\mathrm{MC,conv}}$$

Experimental counts

$$p\left(C_i\right) = p_{\mathrm{poisson}}\left(C_i; \lambda\left(n_{\mathrm{pr}}\right) = C_i^{\mathrm{MC}}\left(n_{\mathrm{pr}}\right)\right) = \frac{\lambda\left(n_{\mathrm{pr}}\right)^{C_i} e^{-\lambda\left(n_{\mathrm{pr}}\right)}}{C_i!}$$

With a constant conv norm:
bin counts depend only on prompt norm
= expectation value per bin

Maximize likelihood

$$\mathscr{L}\left(n_{\mathrm{pr}}\right) = \prod_{i=1}^{M} p\left(C_i; n_{\mathrm{pr}}\right)$$

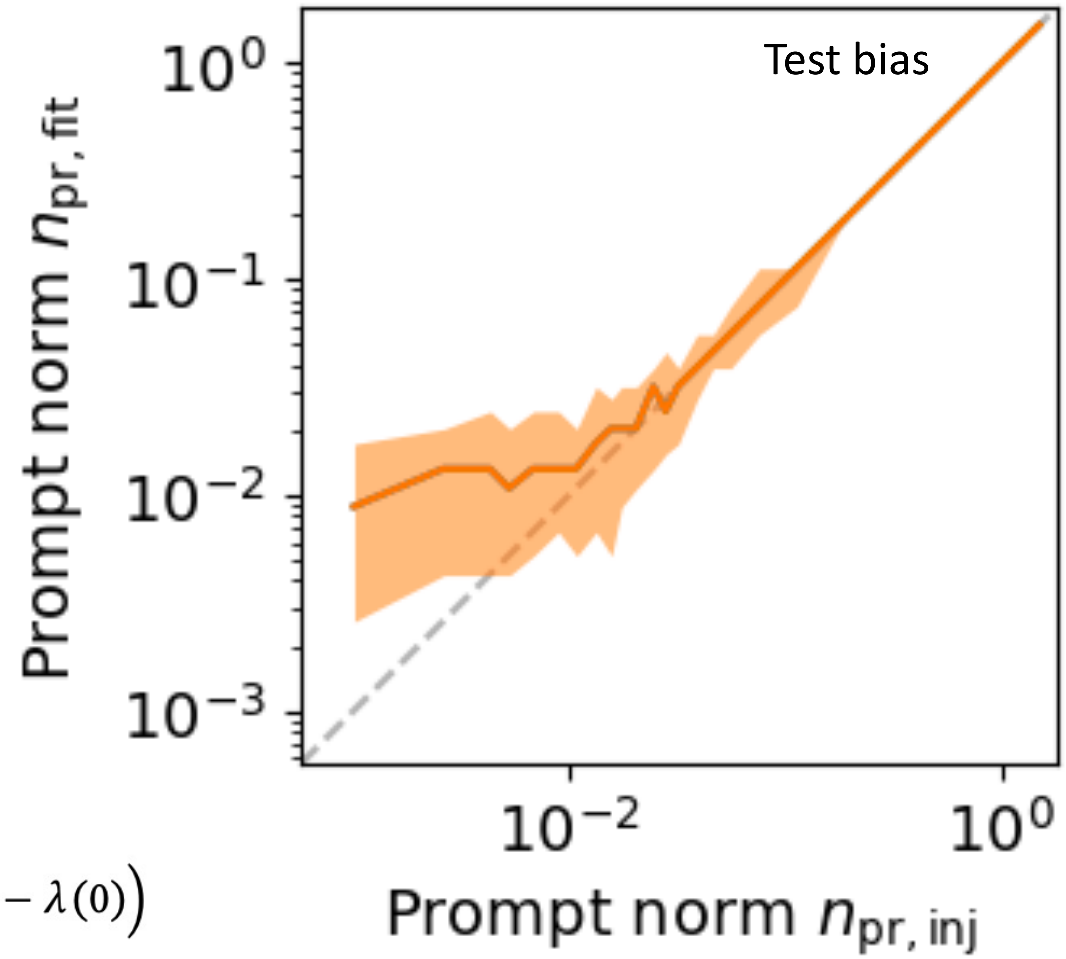
Easier:
minimize negative
log-likelihood

$$-\ln \mathscr{L} = -\sum_{i=1}^{M} C_i \ln \lambda\left(n_{\mathrm{pr}}\right) - \lambda\left(n_{\mathrm{pr}}\right) - \ln C_i!$$

$$\Lambda = -2 \ln \frac{\mathscr{L}\left(n_{\mathrm{pr}} = \hat{n}_{\mathrm{pr}}\right)}{\mathscr{L}\left(n_{\mathrm{pr}=0}\right)} = -2 \sum_{i=1}^{M} C_i \left(\ln \lambda\left(\hat{n}_{\mathrm{pr}}\right) - \ln \lambda(0)\right) - \left(\lambda\left(n_{\mathrm{pr}}\right) - \lambda(0)\right)$$

Test statistic for Wilks' theorem

Null hypothesis: no prompt



- ➢ Bias starts at a prompt normalization of 0.1

Discovery potential and sensitivity

Cuts:
L2 MuonFilter
Bundle energy > 100 TeV

Expectation for 1 year:

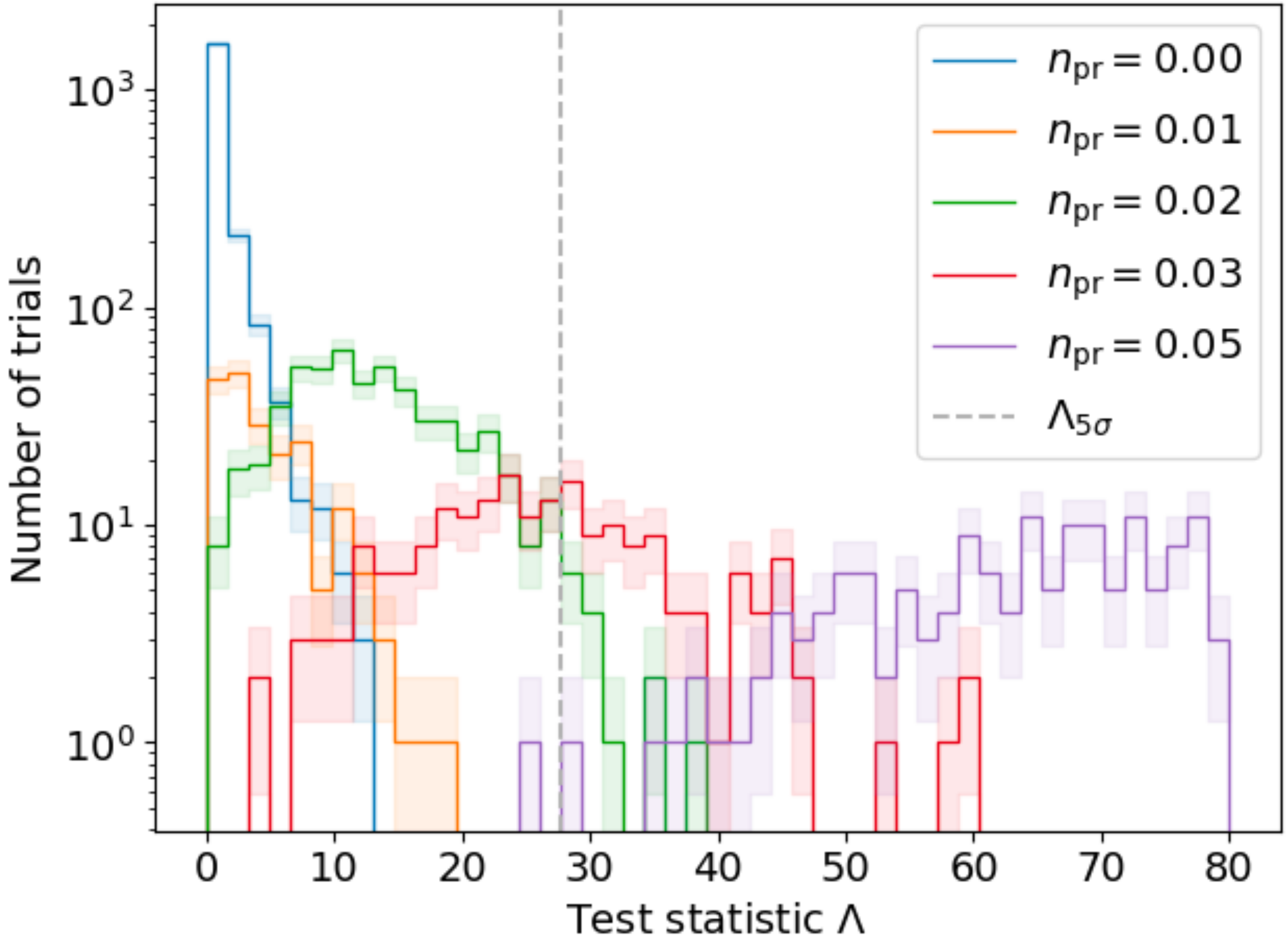
- 5 sigma discovery potential: 0.102 ± 0.005
- Sensitivity: 0.024 ± 0.001

Expectation for 10 years:

- 5 sigma discovery potential: 0.032 ± 0.001
- Sensitivity: 0.007 ± 0.000

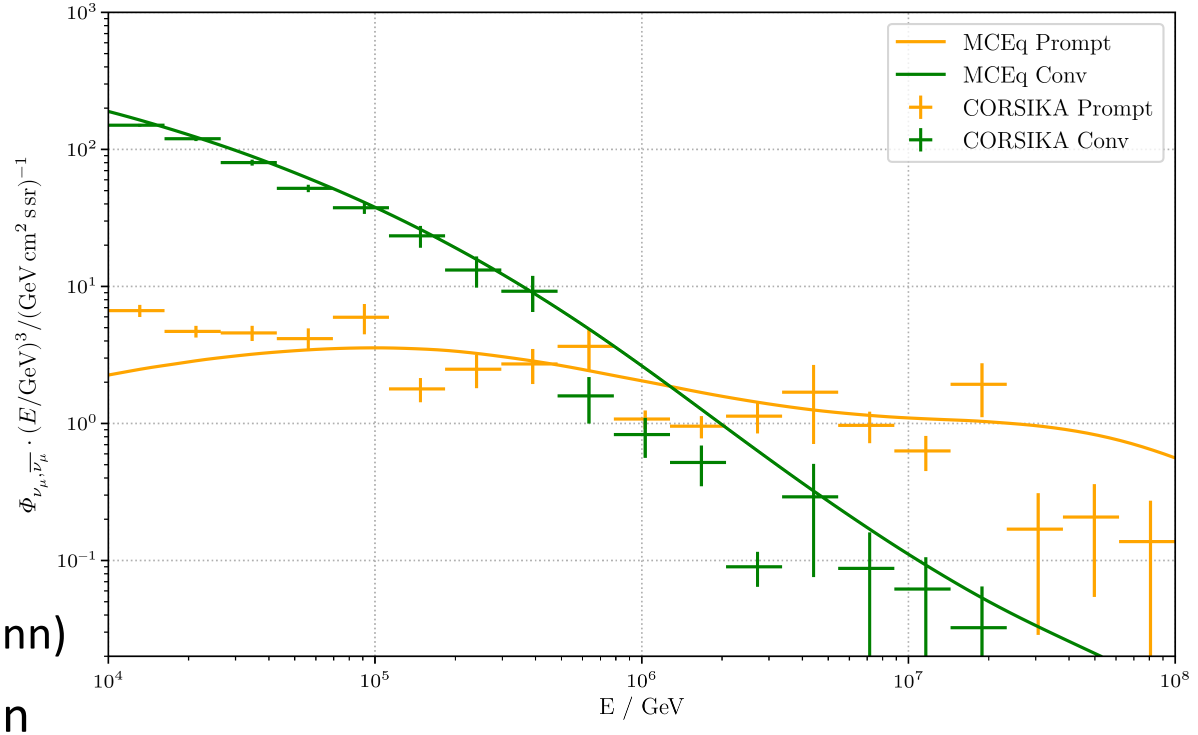
Caution:

- Limited MC statistics -> events are oversampled in pseudo dataset
- No systematic uncertainties



Conclusion and outlook

- ☑ CORSIKA 7 test simulations
  - ☑ Prompt identification
  - ☑ MCEq comparison
  - ★ Few-author paper in progress (publish early 2024)
- ☑ First analysis chain for prompt muon normalization
- ★ Proceed analysis…(systematics etc.)
- ❑ IceCube prompt muons paper (publish early 2025)
- ❑ Prompt neutrino analysis
  - ★ Tagging and MCEq comparison in progress (Lars Bollmann)
- ❑ Combined fit (prompt muons + neutrinos)…future plan



F3/F4 Dortmund Meeting:

- https://nextcloud.e5.physik.tu-dortmund.de/index.php/s/J5WGYQ6wBb9ndJM

do we want to use this again?