Hadronic interactions in astroparticle physics

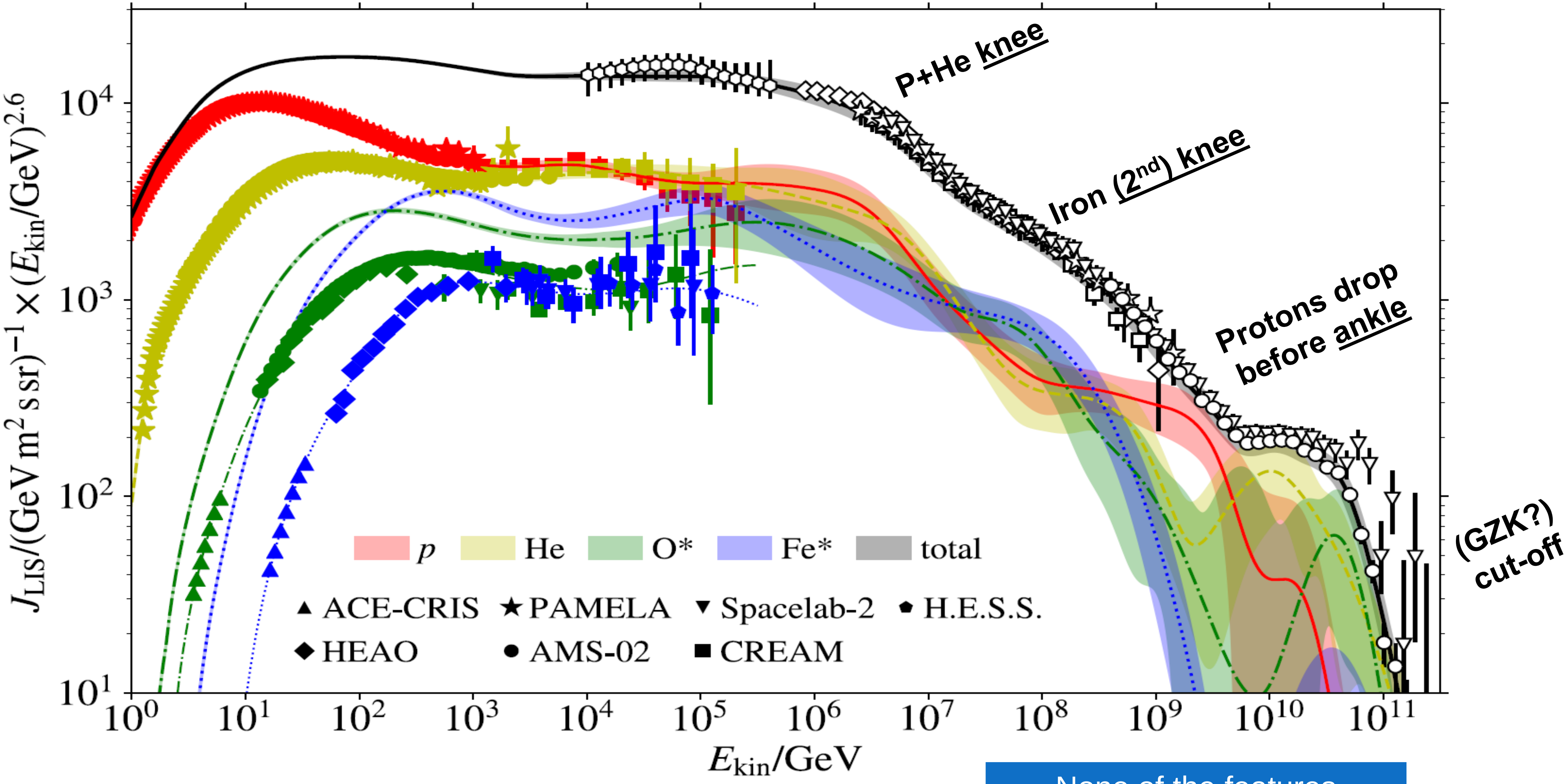
Anatoli Fedynitch
ICRR, University of Tokyo, Japan

December 7, 2020
Connecting high-energy astroparticle physics for origins of cosmic rays and future perspectives

Institute for Cosmic Ray Research
University of Tokyo

Features in cosmic ray observations

Dembinski, AF, Engel, Gaisser, Stanev
PoS(ICRC2017)533 & in prep.

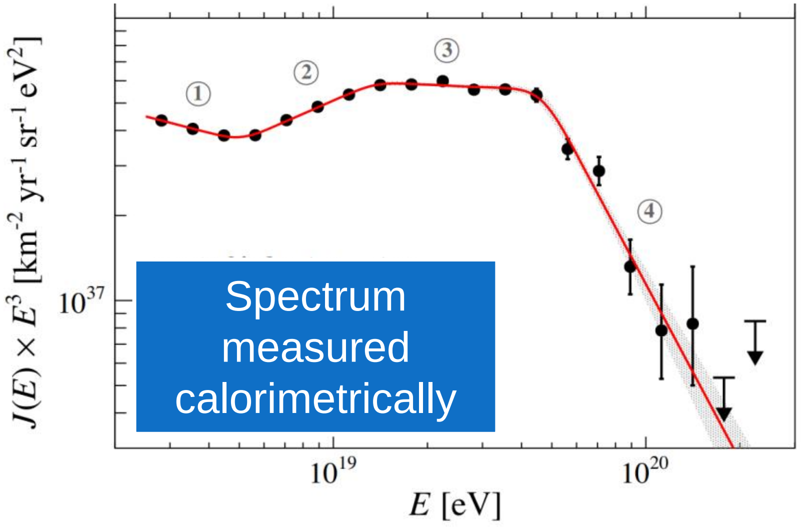


None of the features unambiguously explained

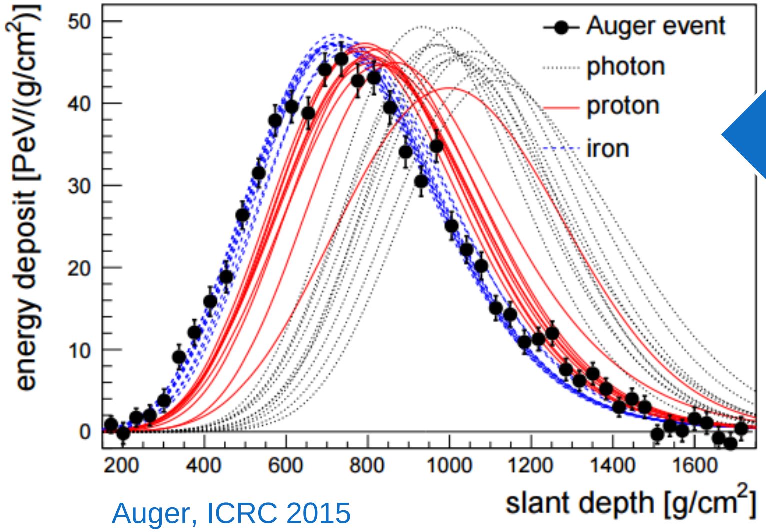
UHECR mass composition

Data

Aab et al. (PAO), PRL 2020



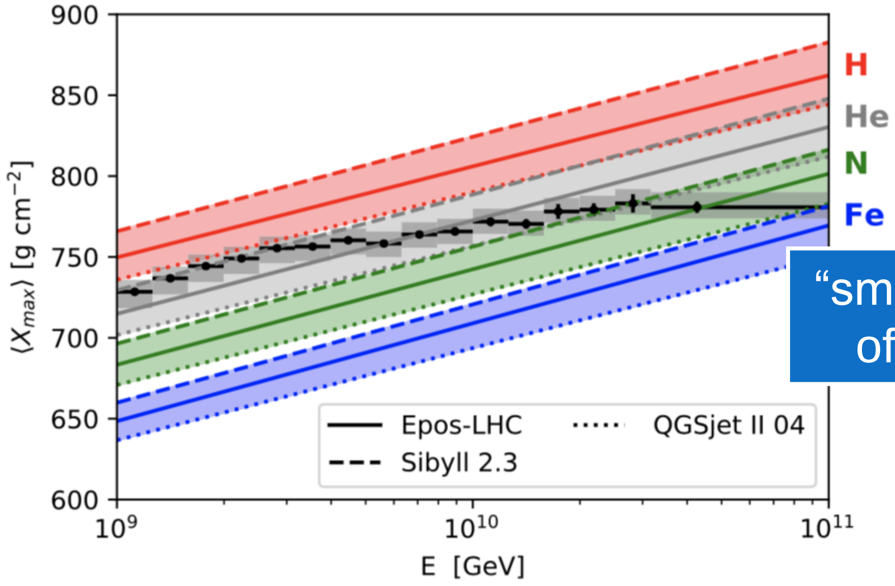
Spectrum measured calorimetrically



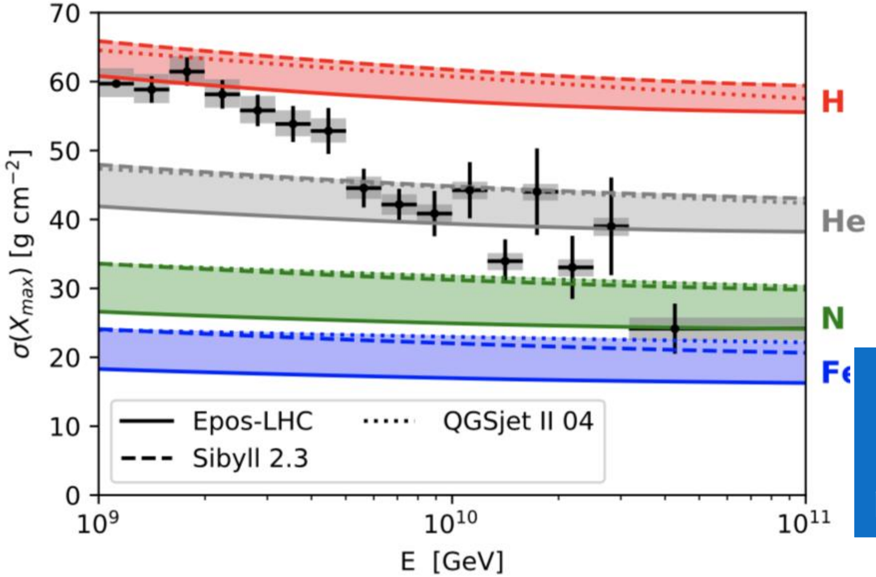
Auger, ICRC 2015

UHECR are nuclei(?)

Model territory



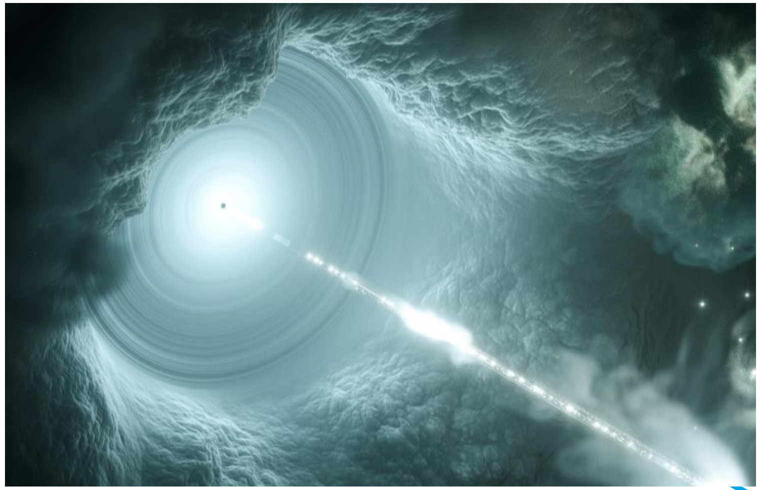
"smooth" increase of mean mass



Decreasing fluctuations → mixture masses

Origin of the features in UHECR spectrum and composition?

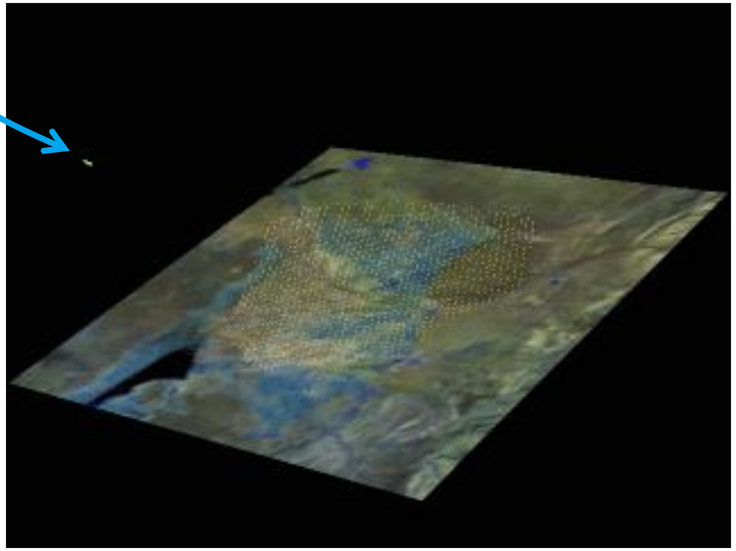
Generic accelerator



Simulate transport of cosmic rays through extragalactic medium

Assume that there is **one dominant type** of UHECR accelerators

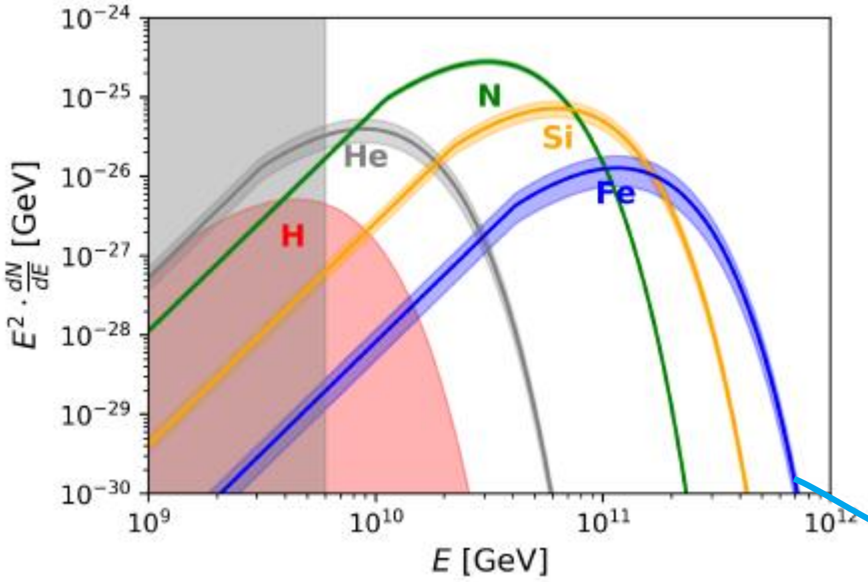
Interpret Pierre Auger data



Heinze, AF, Boncioli, Winter, ApJ 873

Origin of the features in UHECR spectrum and composition?

Rigidity dependent accelerator



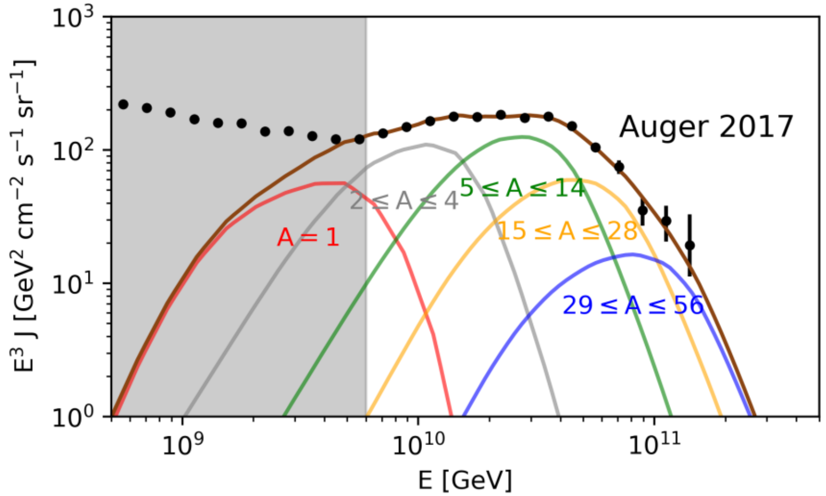
Assumption: there is one dominant source type, accelerating nuclei according to their rigidity (~Z)

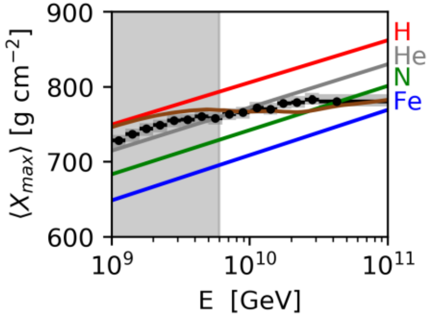
Code: PriNCe = Propagation including Nuclear Cascade equations

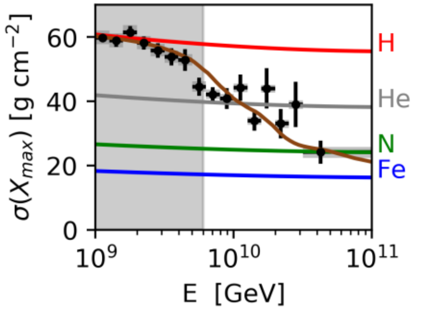
GitHub - joheinze/PriNCe: https://github.com/joheinze/PriNCe

Simulate transport of cosmic rays through extragalactic medium

Fit: free parameters of the accelerator and the evolution m







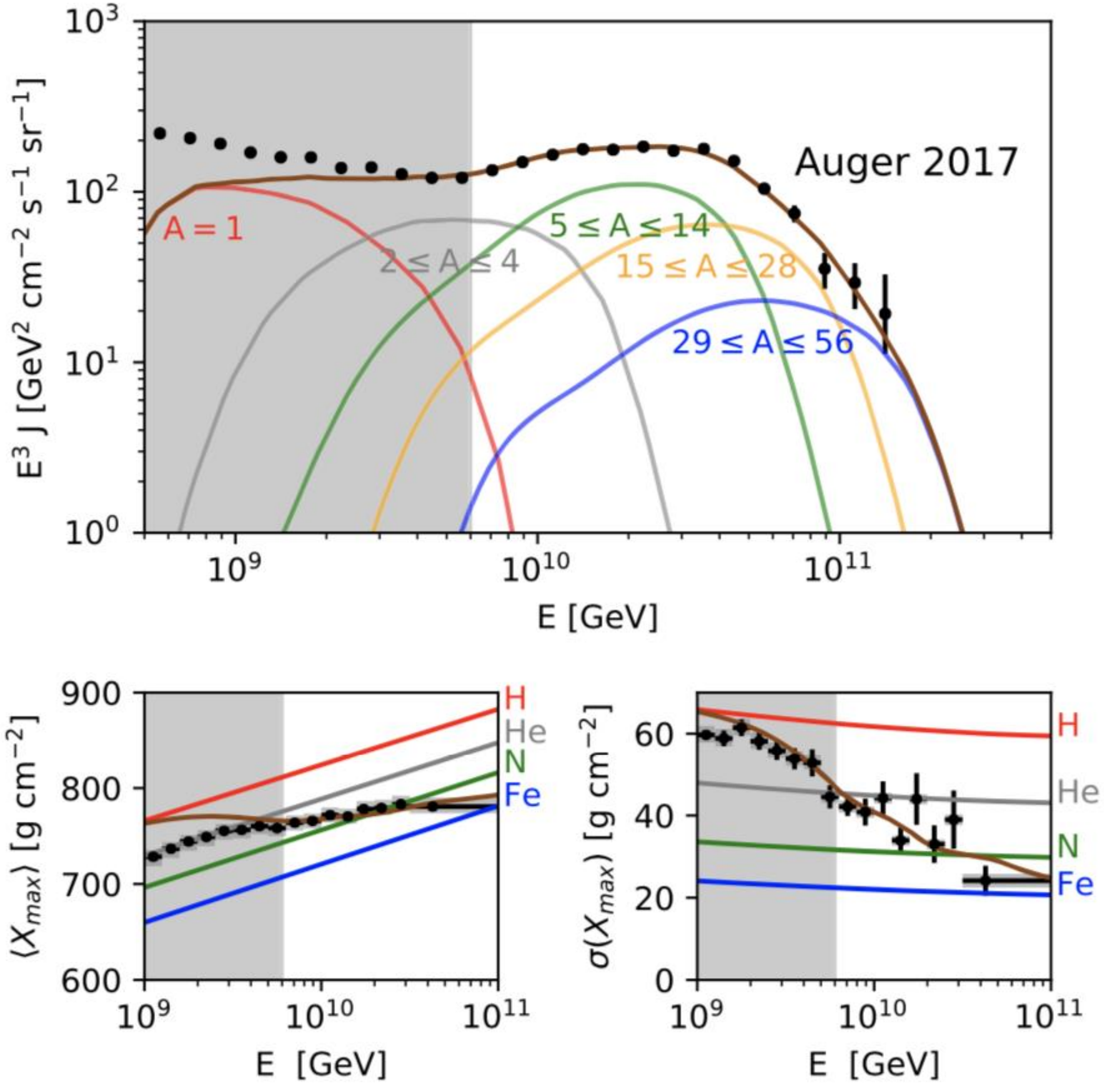
Spectrum:

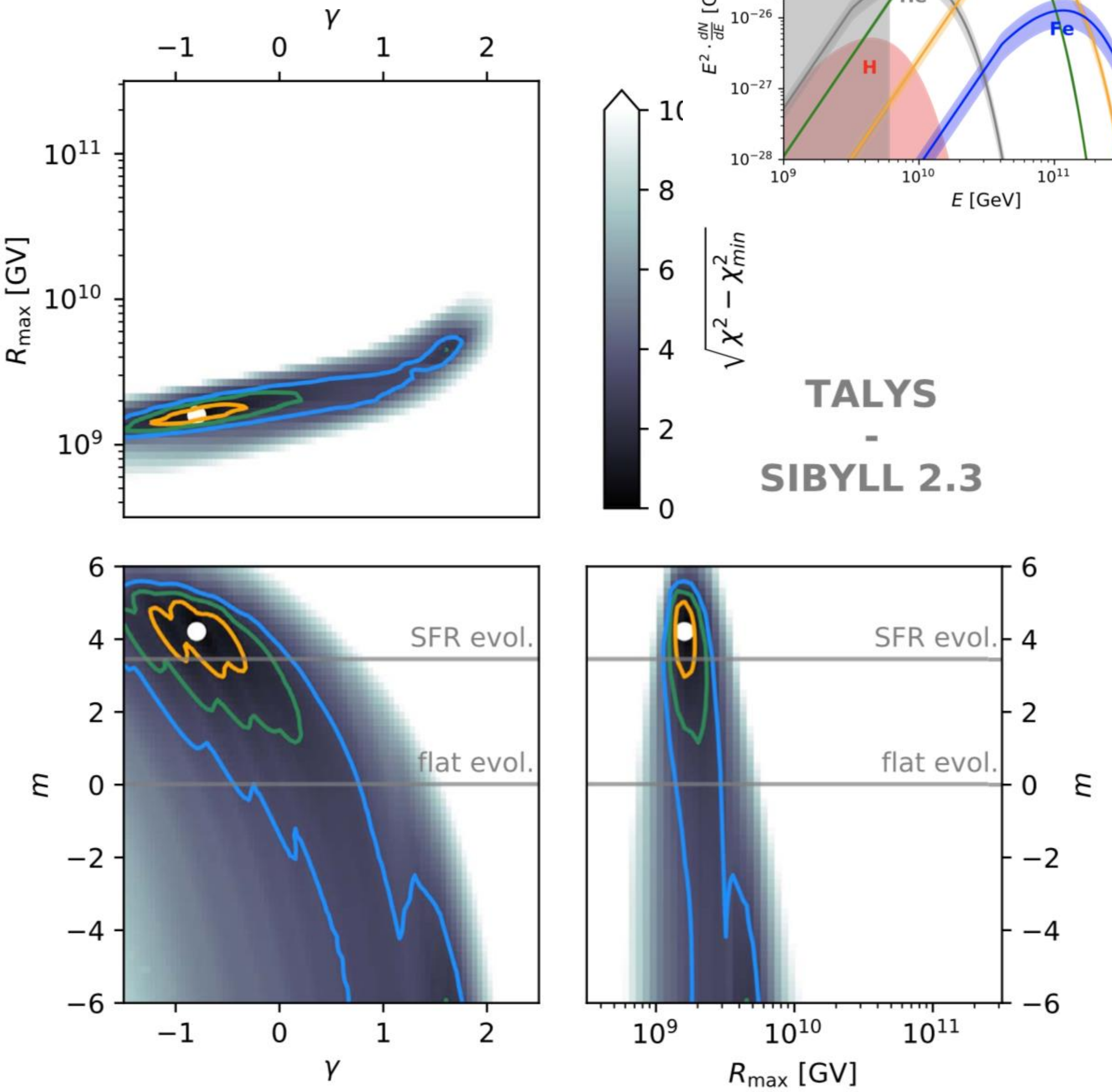
$$J_A(E) = \mathcal{J}_A \left(\frac{E}{10^9 \text{ GeV}} \right)^{-\gamma} \times f_{\text{cut}}(E, Z_A, R_{\text{max}}) \times n_{\text{evol}}(z)$$

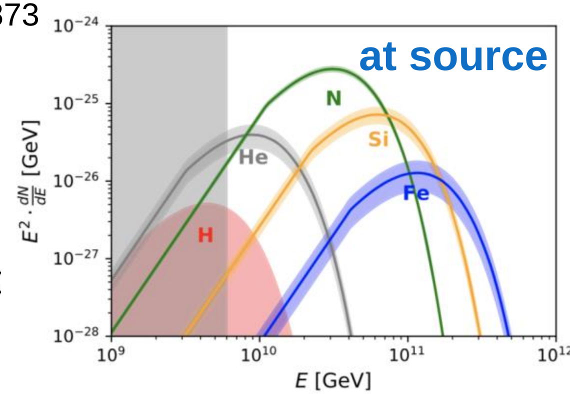
Cosmological density evolution: $n_{\text{evol}}(z) = (1+z)^m$

Heinze, AF, Boncioli, Winter, ApJ 873

Best ‘3D’ fit





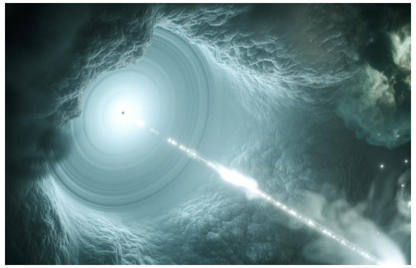


Heinze, AF, Boncioli, Winter, ApJ 873

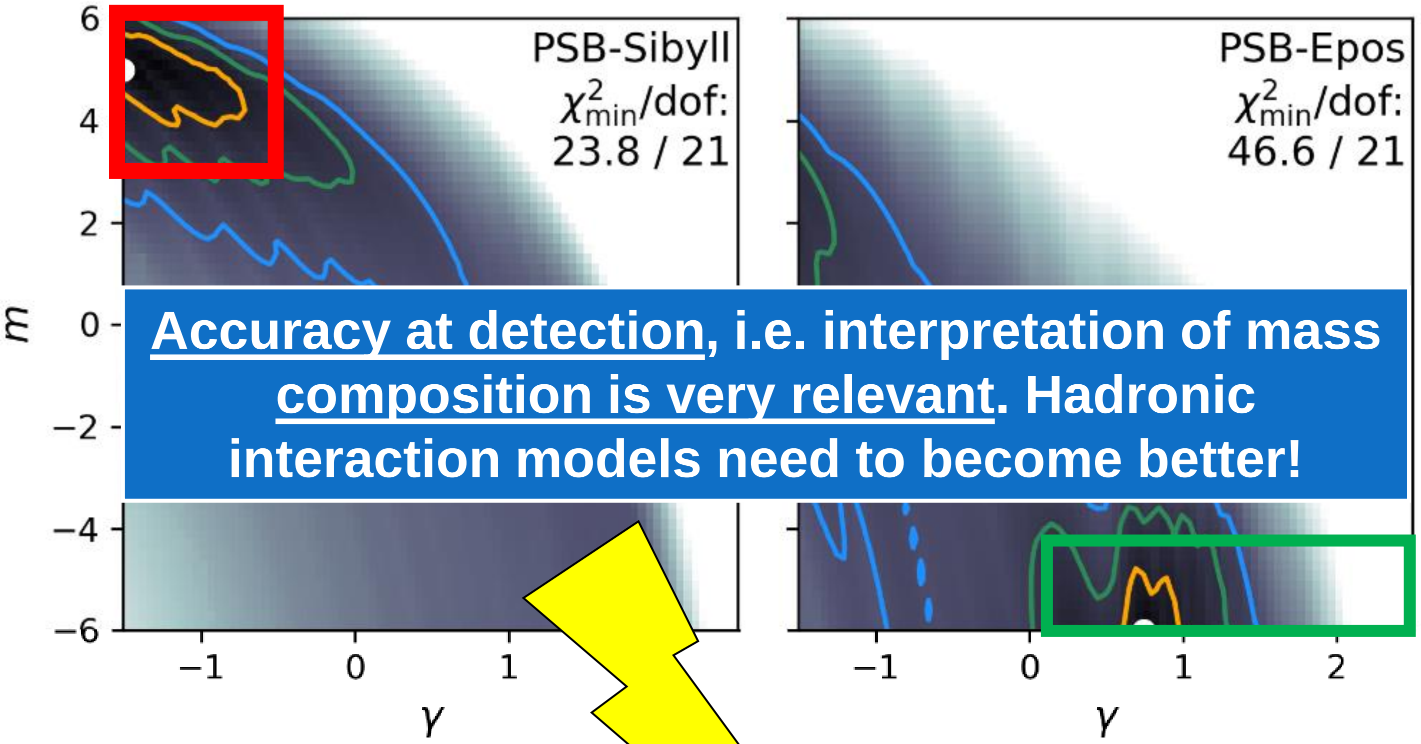
Model dependence of the interpretation

Compared in $\gamma - m$ space

Density evolves like: Stars, Galaxies, Supernovae, AGN



Sibyll 2.3 **Epos-LHC**



<u>Accuracy at detection</u>, i.e. interpretation of mass <u>composition is very relevant</u>. Hadronic interaction models need to become better!

Few strong local sources, or intermediate mass black holes

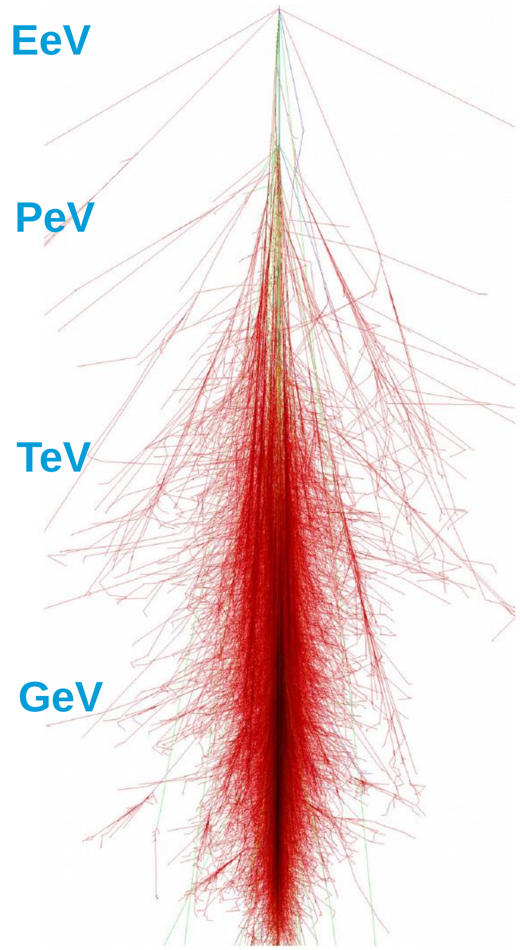
Auger Upgrade may improve the situation within few years.

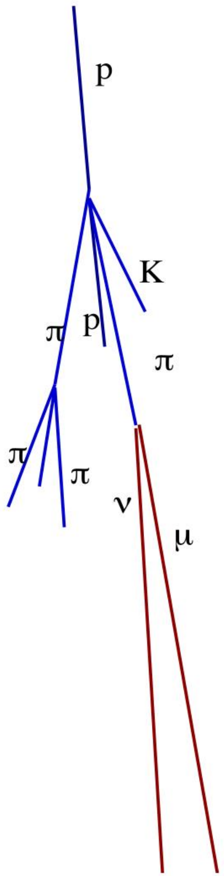
See also: Auger Collaboration JCAP02(2013)026
Auger Collaboration JCAP04(2017)038

Modeling hadronic cascades

- High energies. Some constraints from:
  - colliders
  - air showers
  - theory
- Medium energies. Constraints from:
  - fixed target experiments
  - atmospheric muons
  - atmospheric neutrinos
- Low energies:
  - Constraints from fixed target
  - Modeling “simpler”

100% E in hadrons

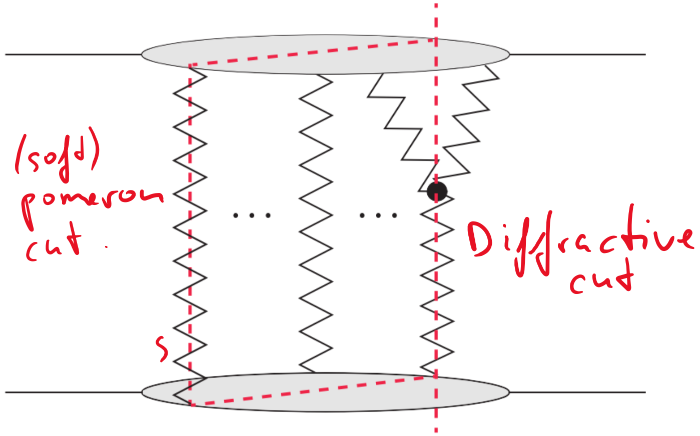


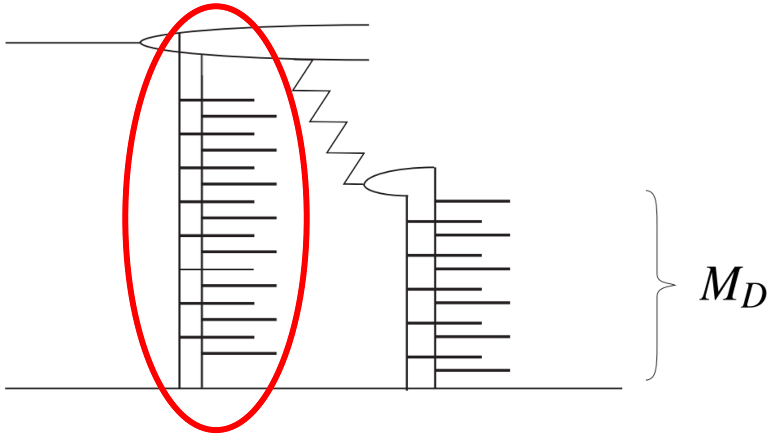


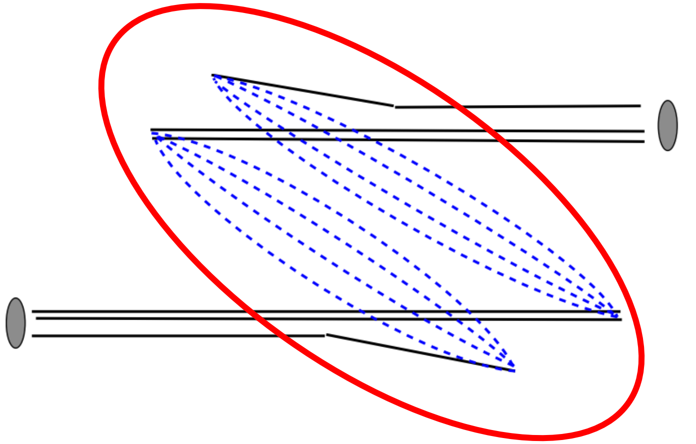
90% E in EM,
10% E in muons

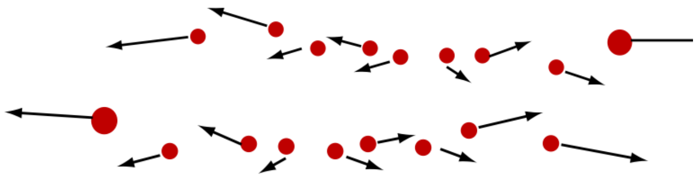
(V. N. Gribov. “A Reggeon Diagram Technique.” Sov. Phys. JETP, volume 53 654, 1968)

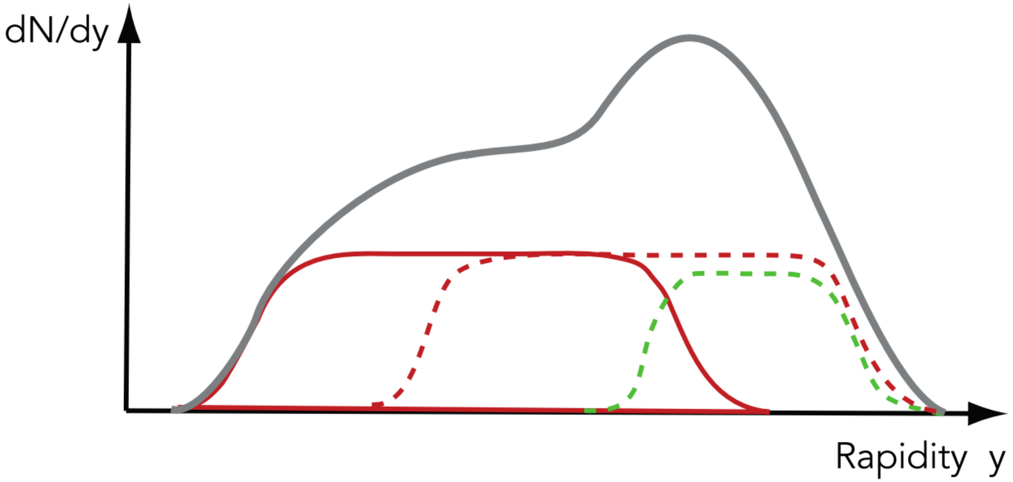
High energies: complicated event topologies

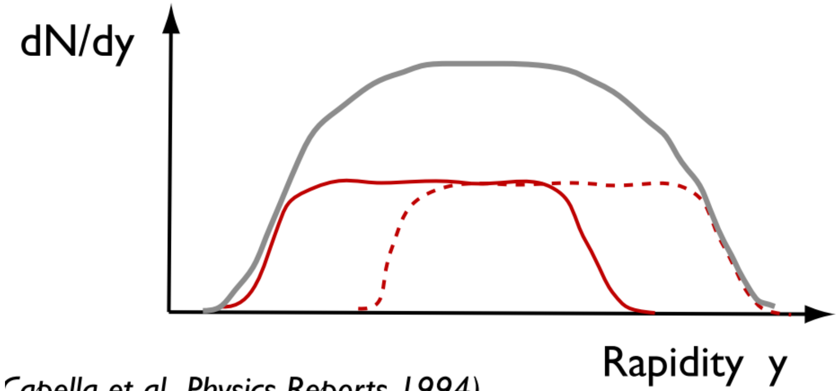






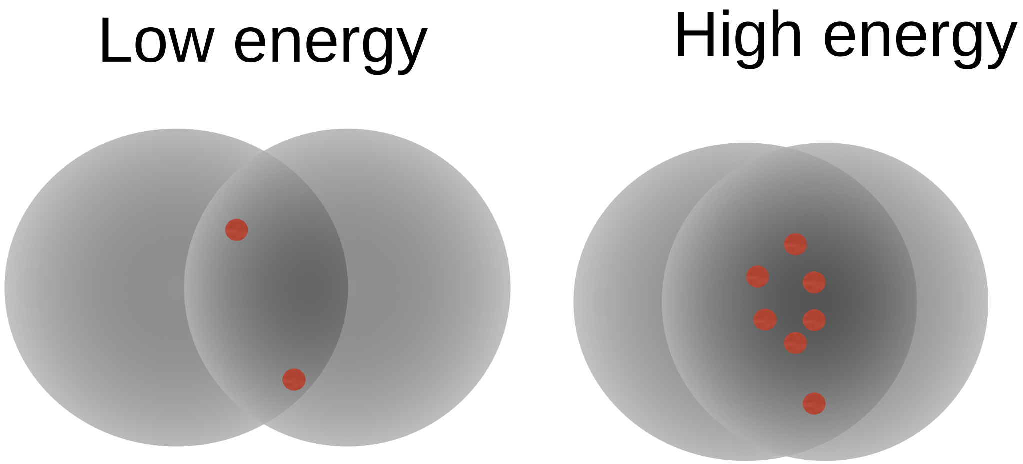






Capella et al., Physics Reports 1994)

Multiple partonic interactions

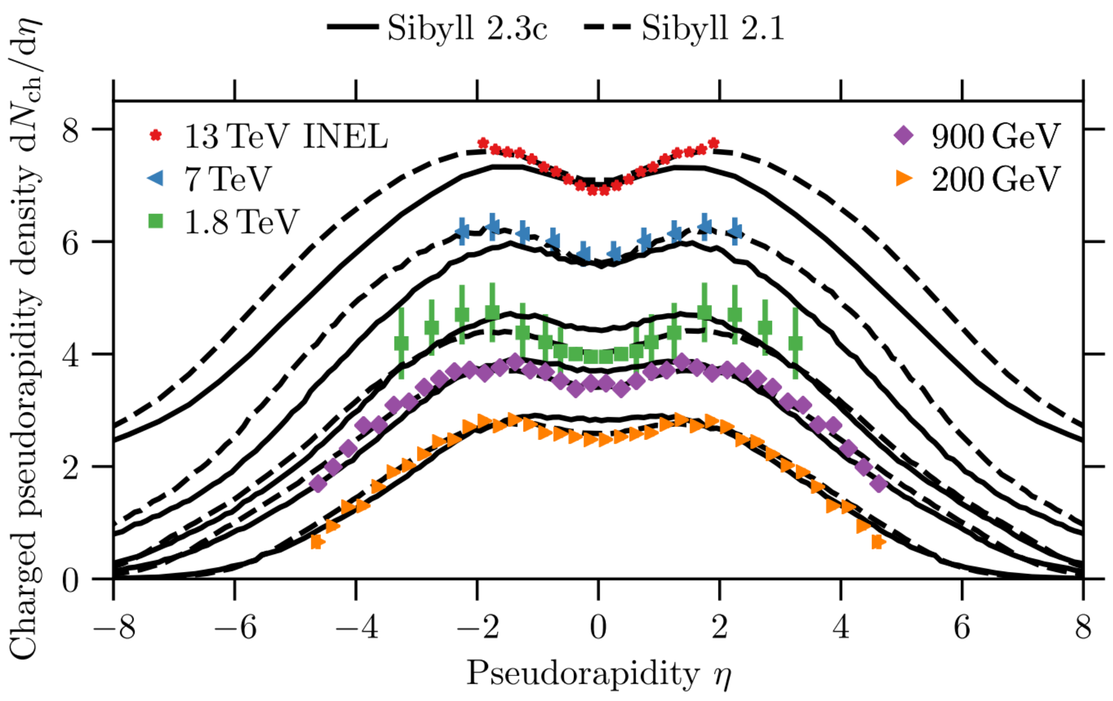


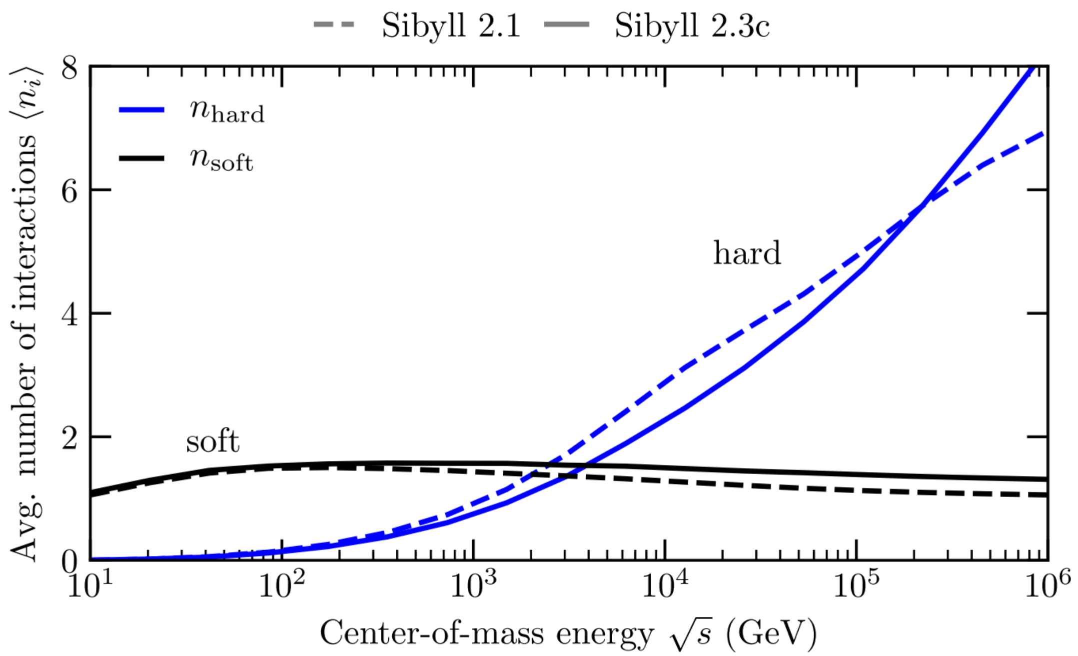
MPI model in DPMJET and SIBYLL

$$\sigma(n_\mathrm{S}, n_\mathrm{H}, \ldots) = \int \mathrm{d}^2\vec{B}\, \frac{(-2\chi_\mathrm{S})^{n_\mathrm{S}}}{n_\mathrm{S}!} \frac{(-2\chi_\mathrm{H})^{n_\mathrm{H}}}{n_\mathrm{H}!} \ldots\ e^{-2\chi}$$

- Phenomenological models for the transverse hadron structure
- SIBYLL + DPMJET models, multiple-cut structure from Eikonal expansion (“optics”)
- Uncorrelated multiple interactions in SIBYLL & DPMJET. Correlations in e.g. PYTHIA through color reconnection, in QGSJET and EPOS through “dynamic” PDFs.

MPI impact in data





- Energy scaling:
  - Widening = growth of phase space = longer strings
  - Rise of the central plateau = MPI

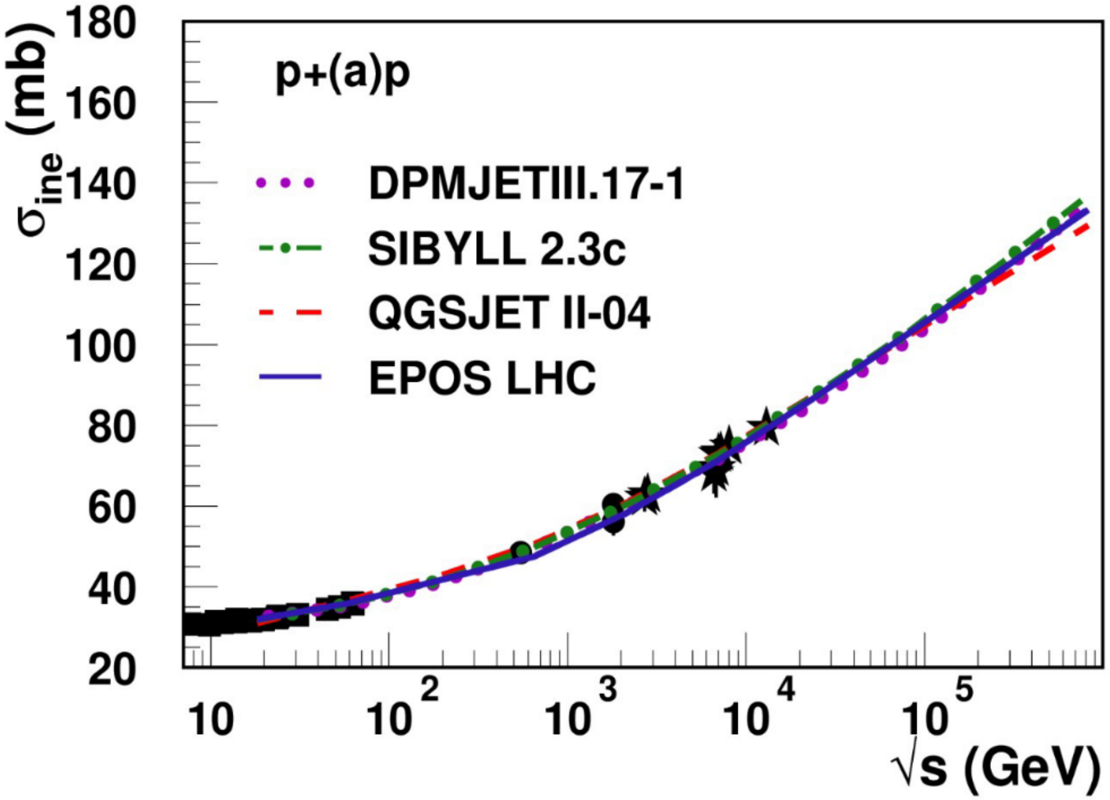
- $n_{MPI} \sim n_{soft} + n_{hard} + n_{semihard} + \ldots$
- Also diffractive topologies

F. Riehn, R. Engel, AF, T. Gaisser, T. Stanev
arXiv:1912.03300, PRD 102

High-energy constraints from LHC on cross section

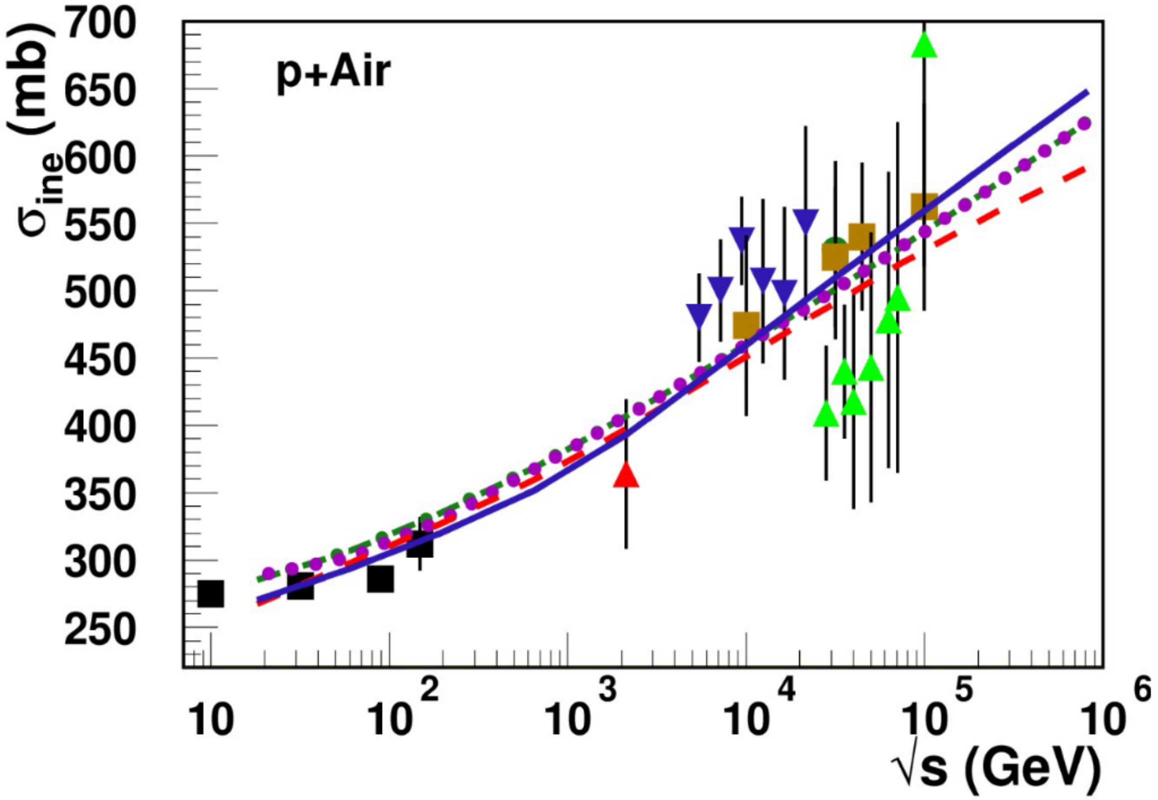
T. Pierog, ISVHECRI 2018

pp



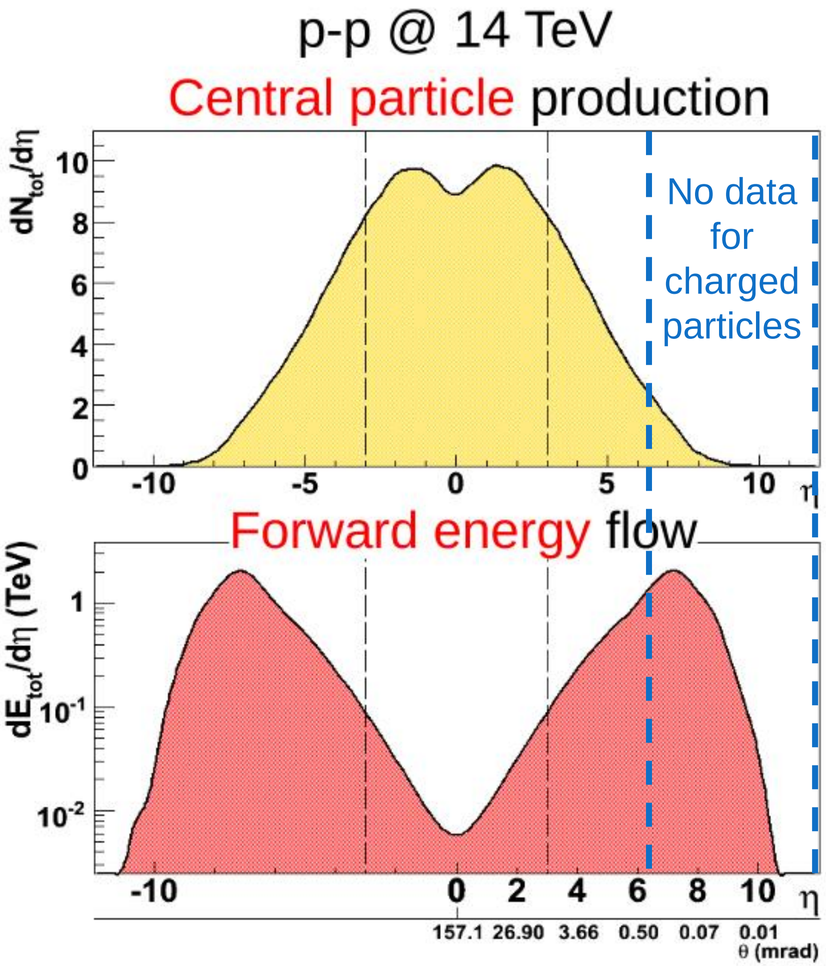
Amplitudes for nucleon-nucleon different in models, but parameters **are well constrained by LHC**

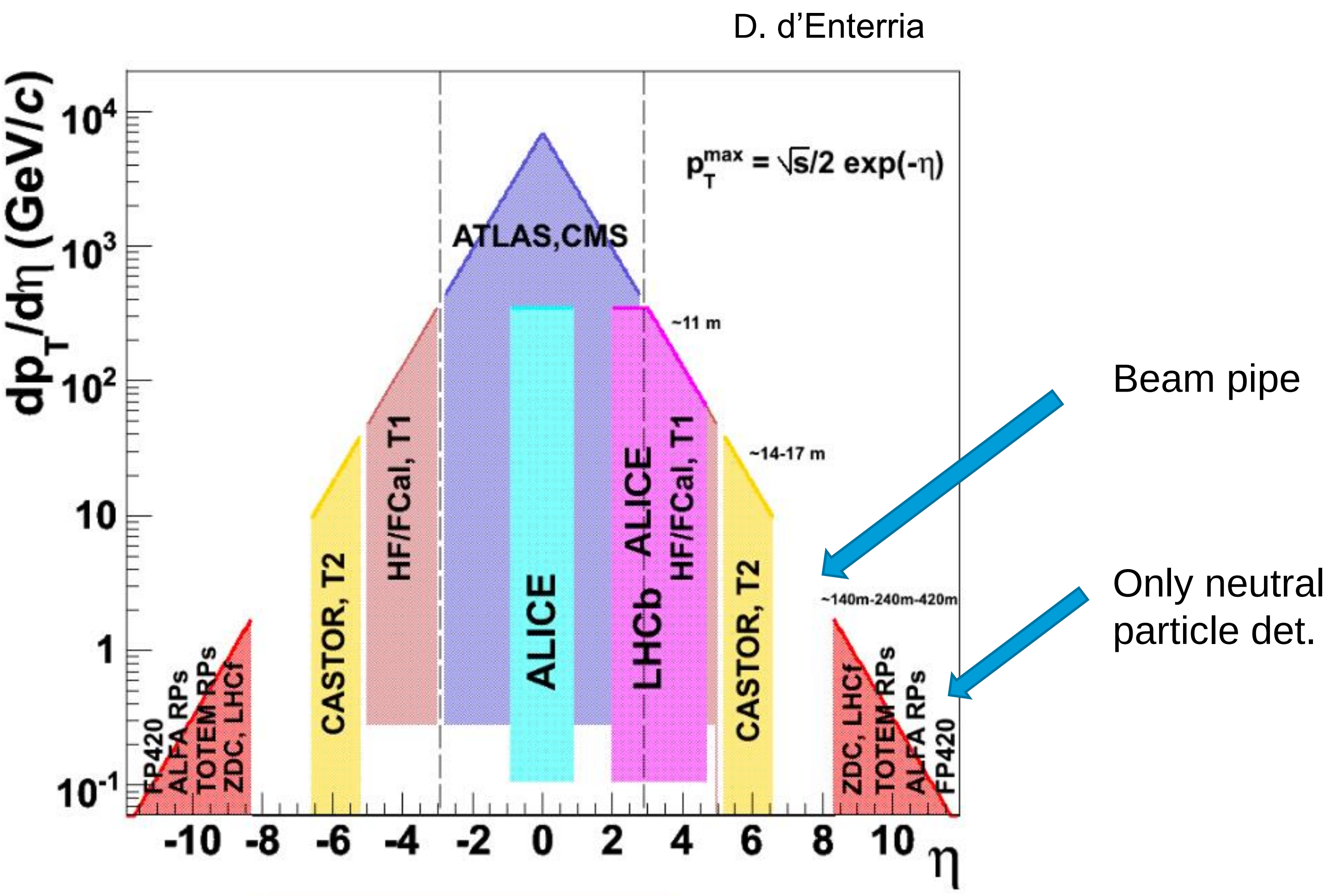
p-Air



Extrapolation uncertainties in conversion from **pp to p-Air**

Other constraints weaker due to phase-space



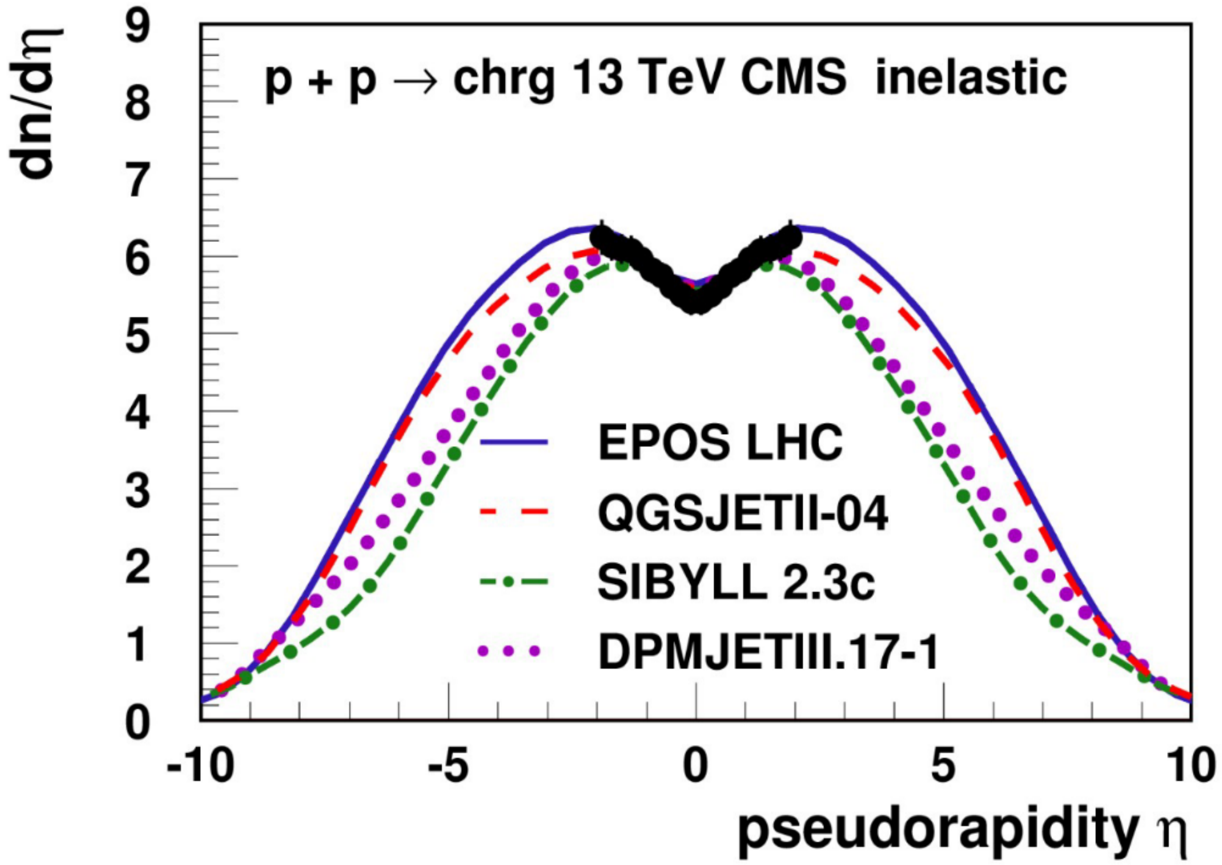


- For hadronic cascades in air, energy transport is crucial
- No data for charged particles available in very forward phase-space
- Models can be indirectly constrained from neutral particle measurements (LHCf/ALFA/TOTEM/RHICf)

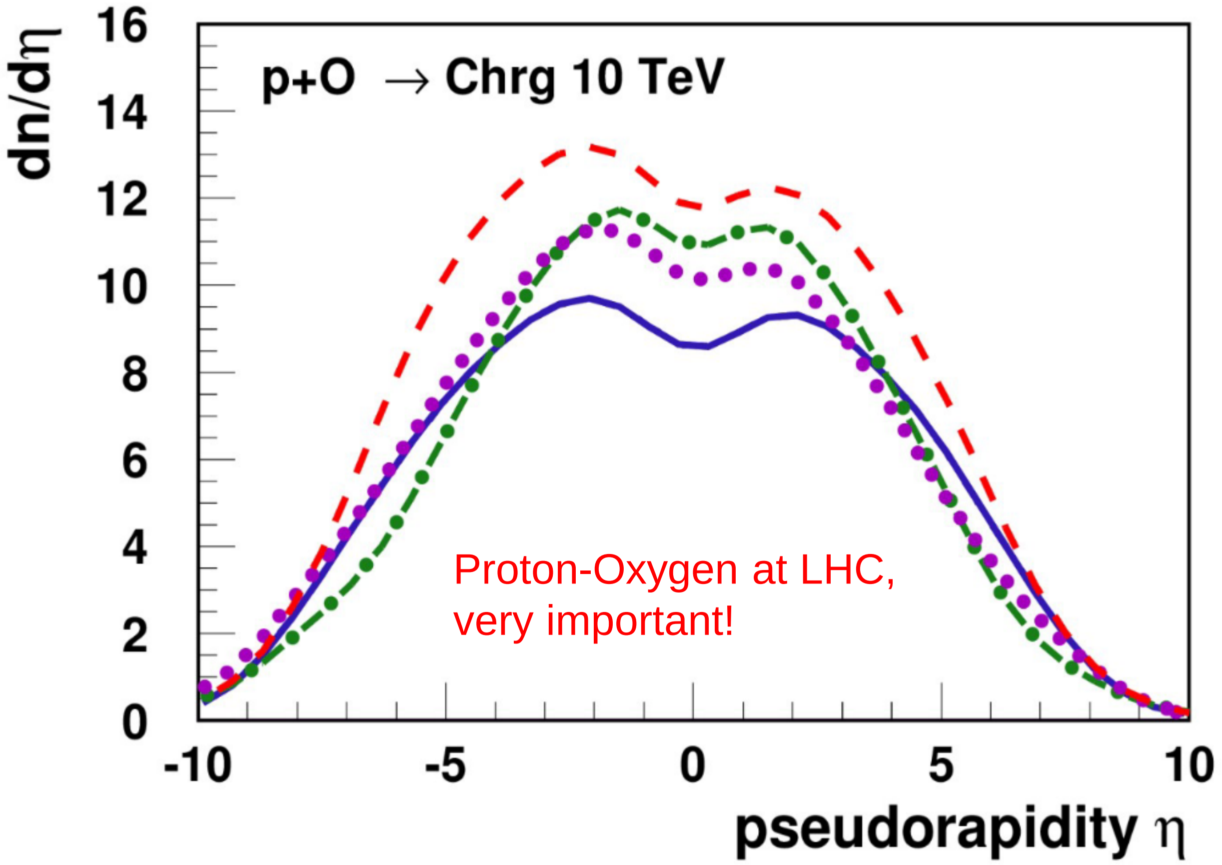
Forward and p-nucleus spectra not well constrained

T. Pierog,
ISVHECRI 2018

pp

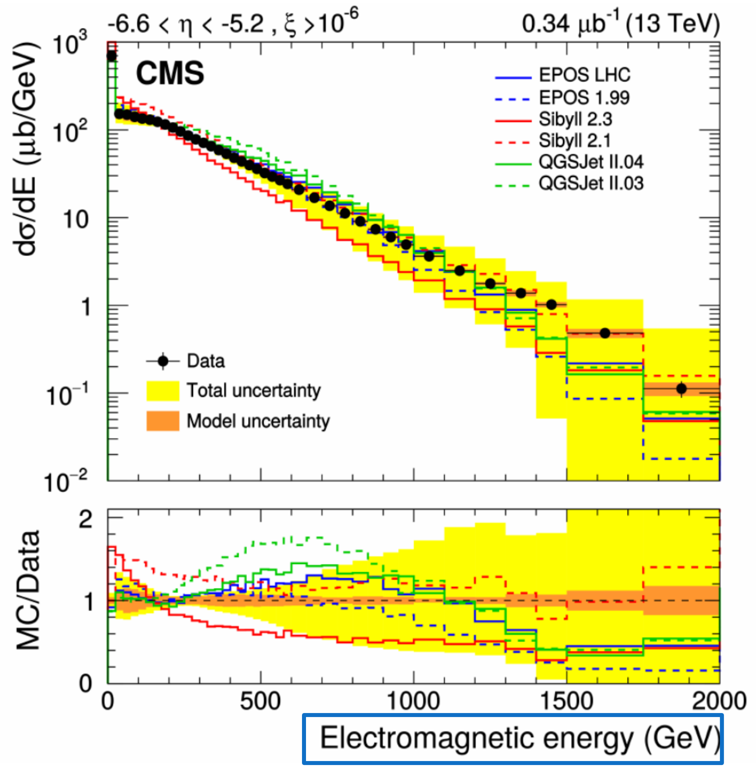


p-Oxygen

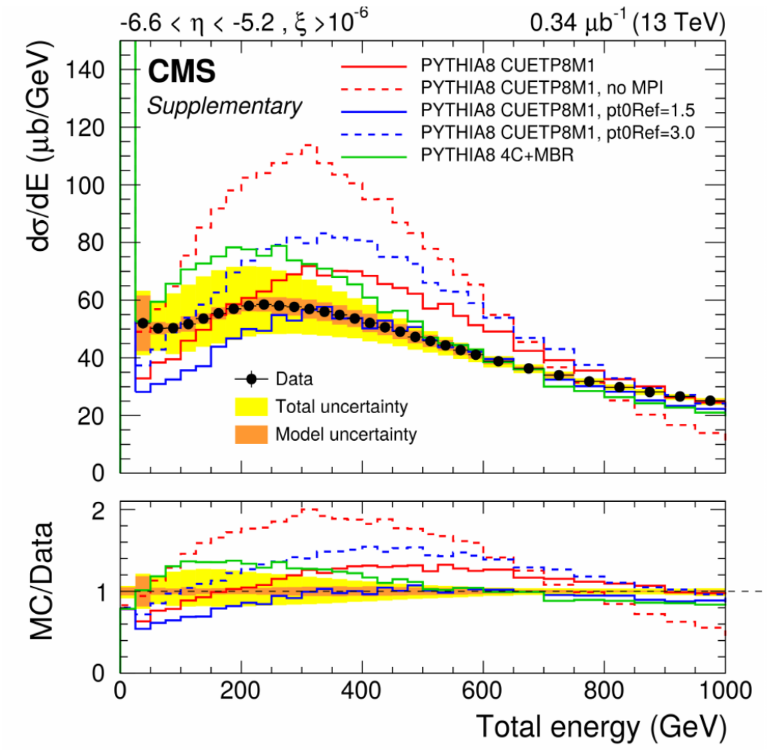


Proton-Oxygen at LHC,
very important!

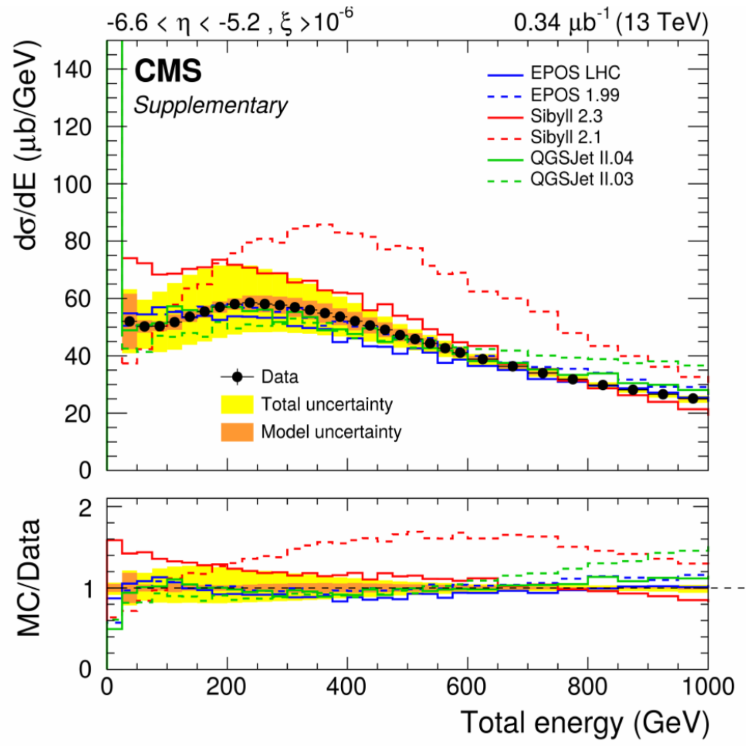
Electromagnetic fraction measurement not yet in CR models



PYTHIA 8 tunes



“Cosmic ray” models

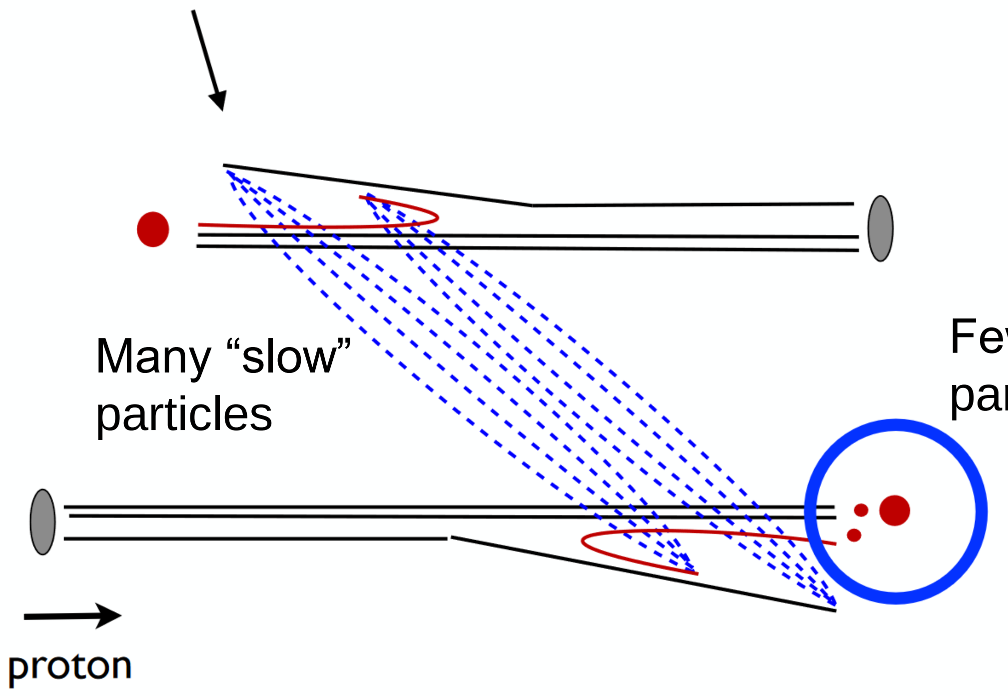


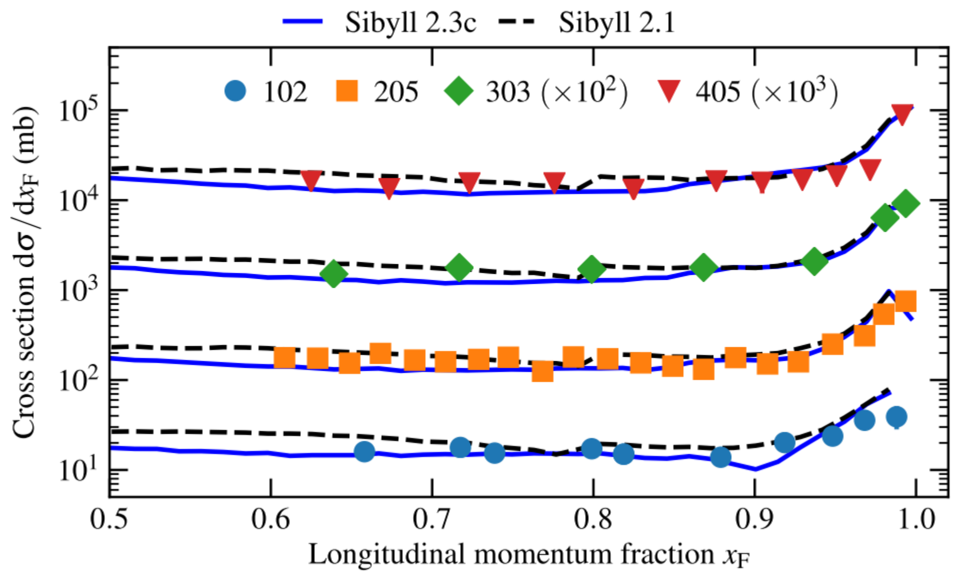
JHEP 08 (2017) 046

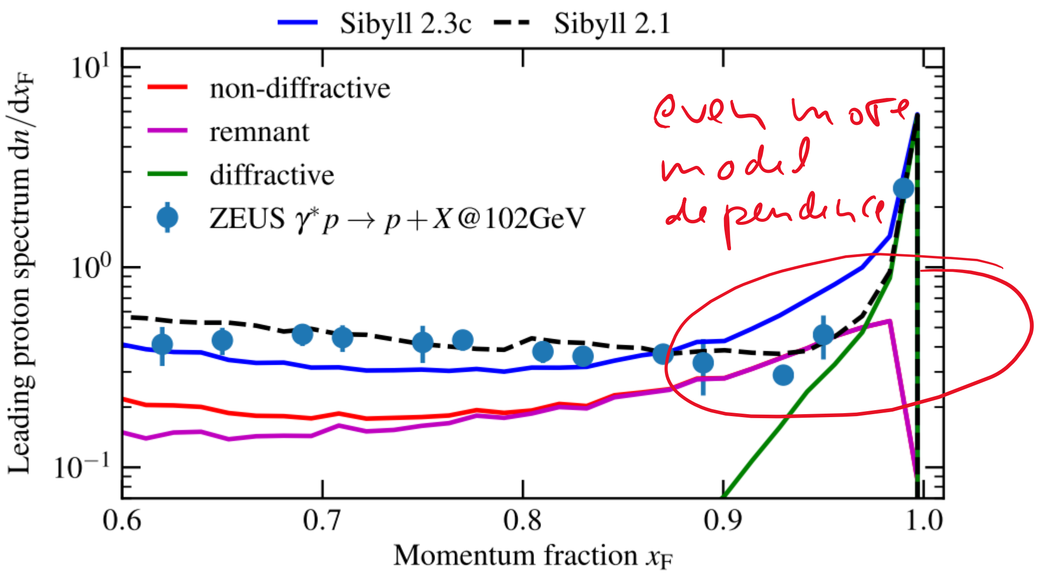
- Measurement constrains <~5% of total interaction energy
- EM energy fraction in SIBYLL 2.3 found to be underestimated in this limited phase space
- None of the cascade models uses these data, yet

F. Riehn, R. Engel, AF, T. Gaisser, T. Stanev
arXiv:1912.03300

Longitudinal spectrum



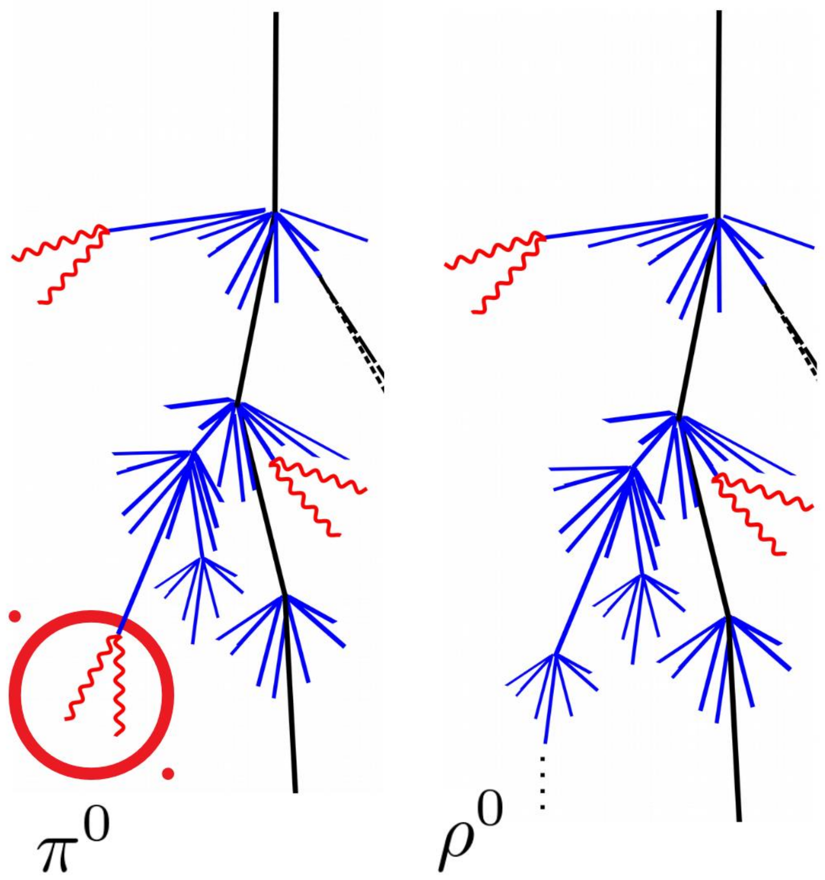


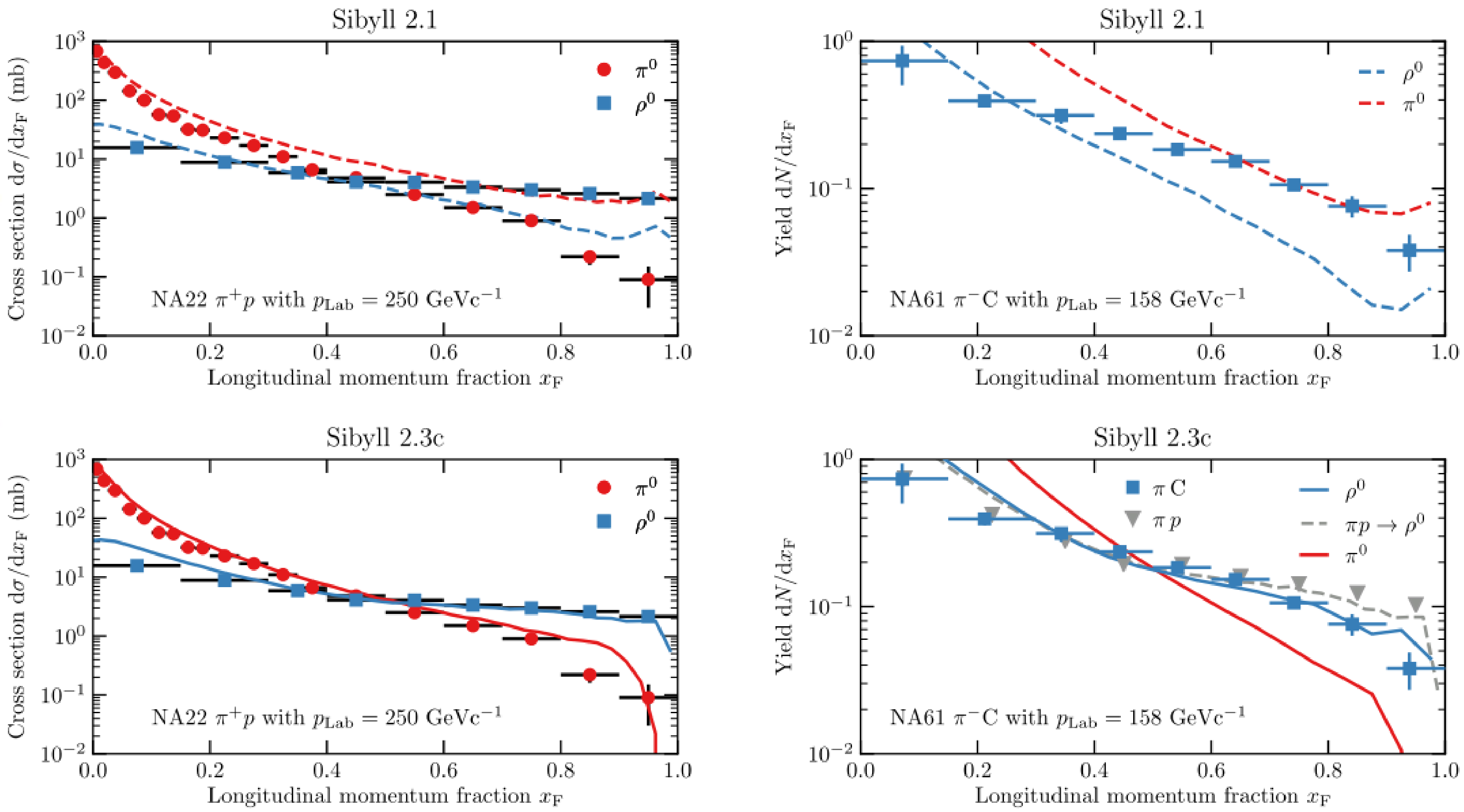


Leading particles crucial to describe energy transfer in particle cascades (air showers)

Improvement in leading rho0 production

F. Riehn, R. Engel, AF, T. Gaisser, T. Stanev
arXiv:1912.03300, PRD 102, 2020

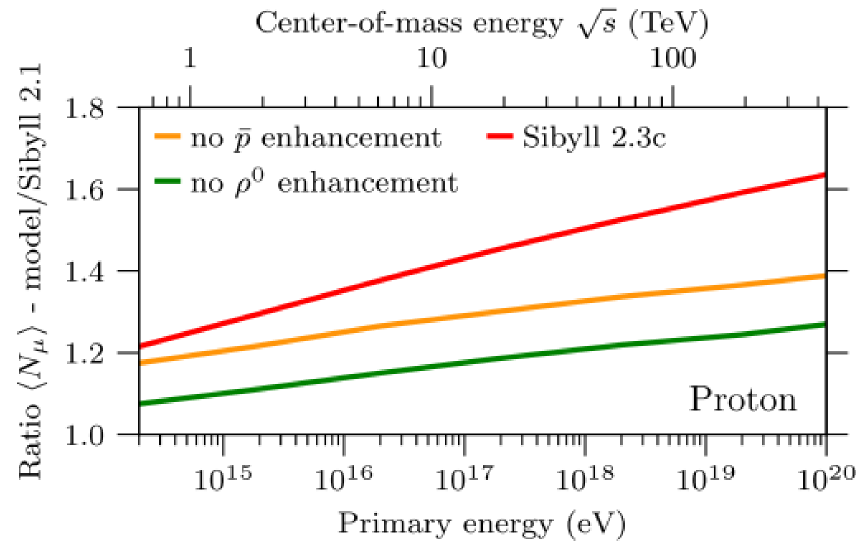


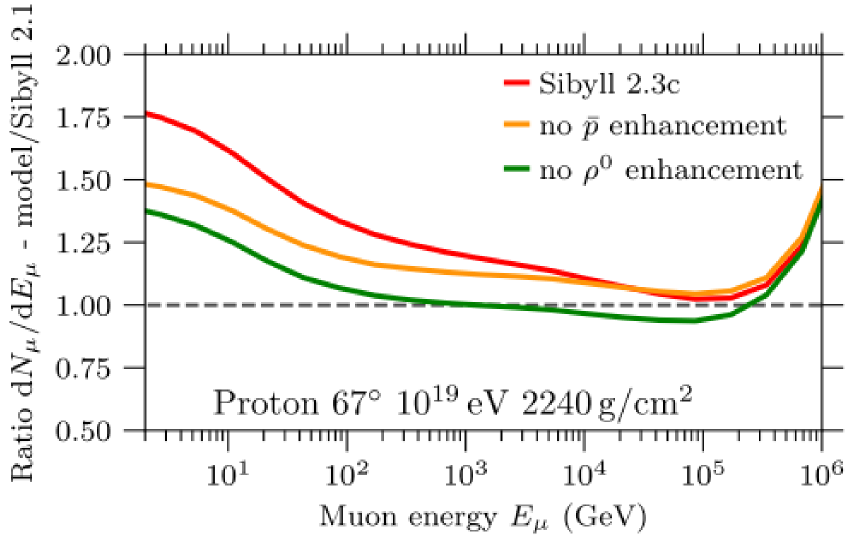


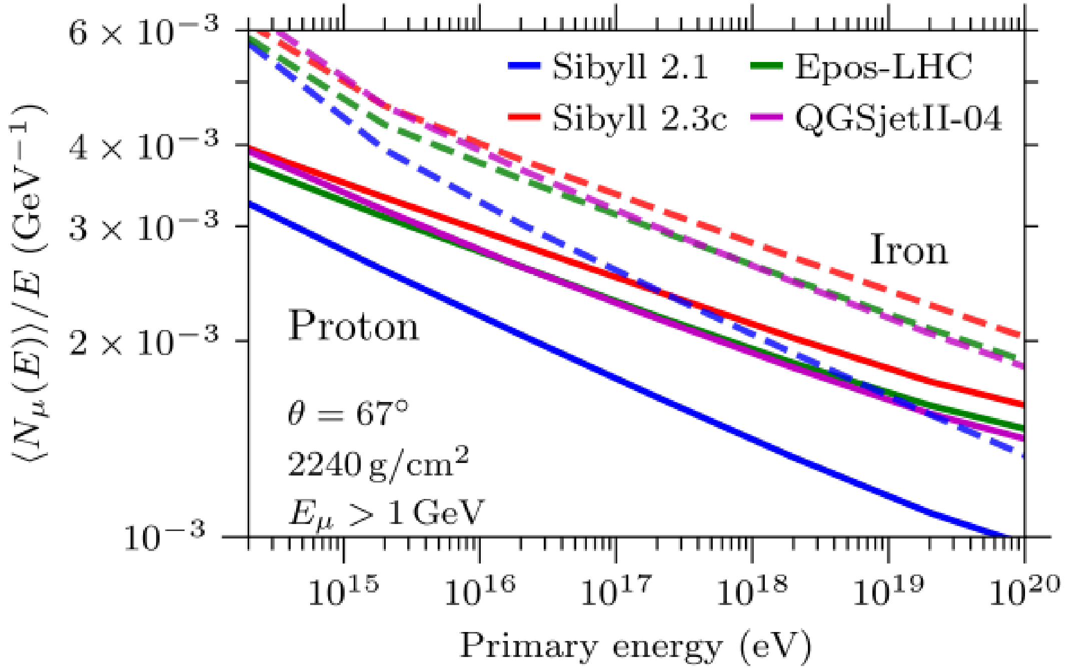
No fixed-target measurement of π^0 production off nulei

Impact of corrections on expected muon number

F. Riehn, R. Engel, AF, T. Gaisser, T. Stanev
arXiv:1912.03300, PRD 102, 2020

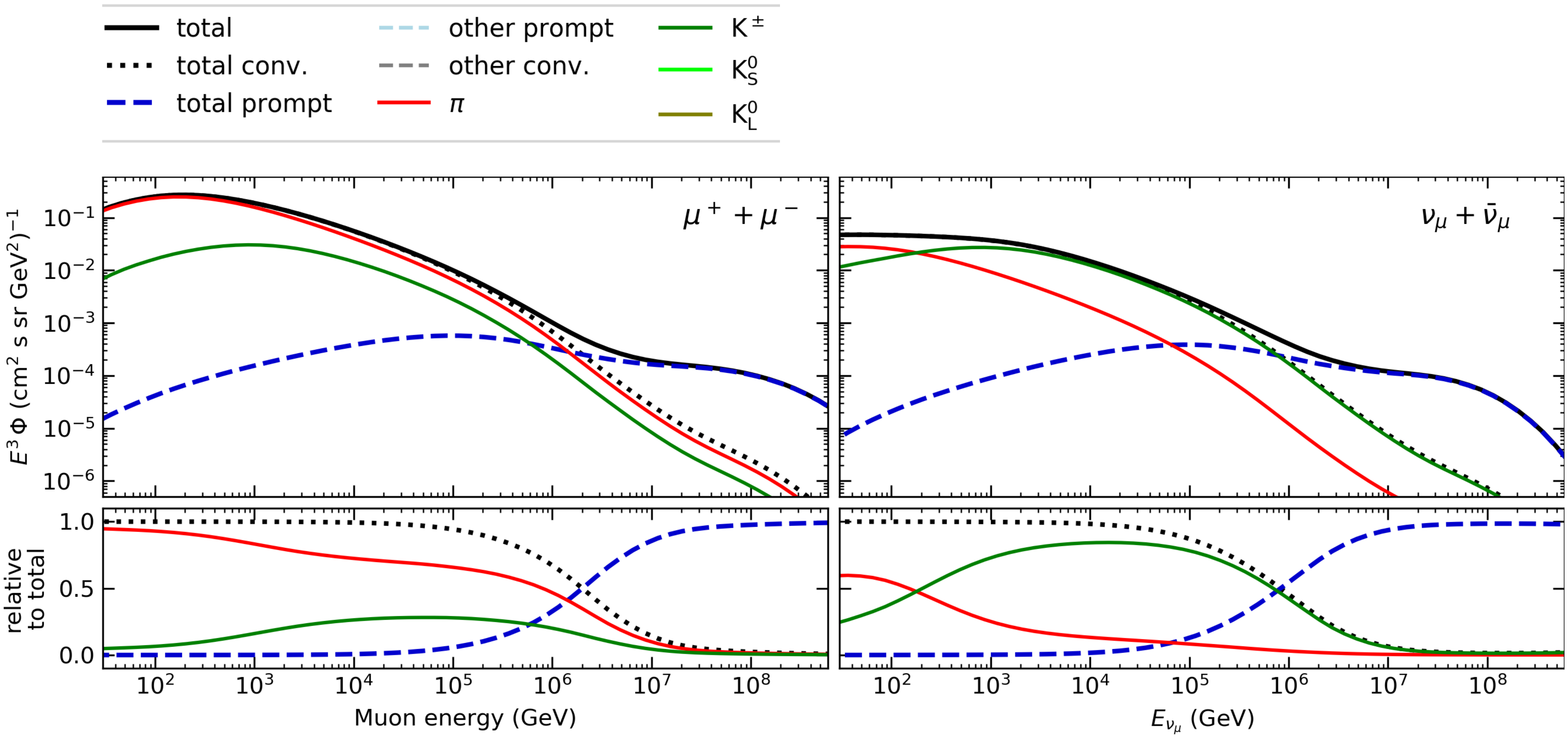






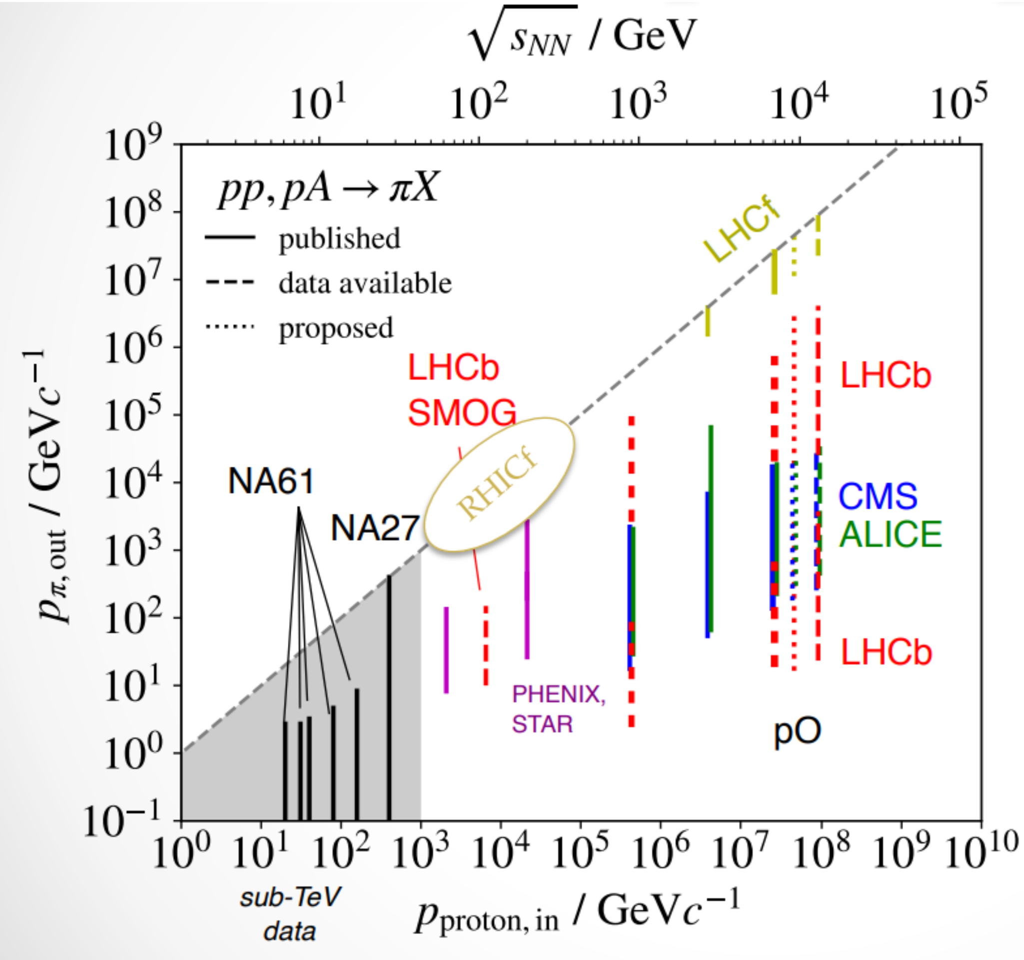
75% more muons in newer models at certain energies

Atmospheric leptons = alternative view on interactions



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

2019 coverage of phase-space

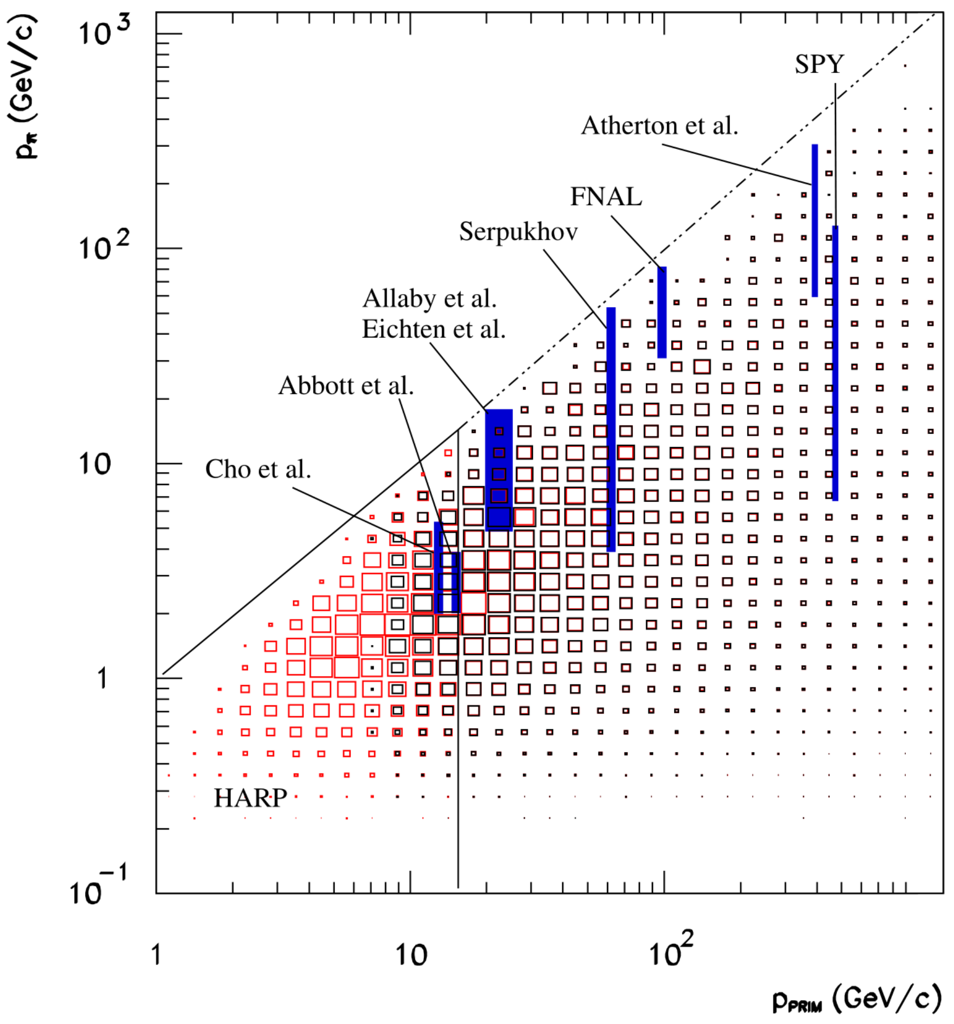


H. Dembinski,
ISVHECRI 2018

Phase space of air shower interactions as covered by various experiments
(beam-beam collisions transformed to equivalent fixed-target system)

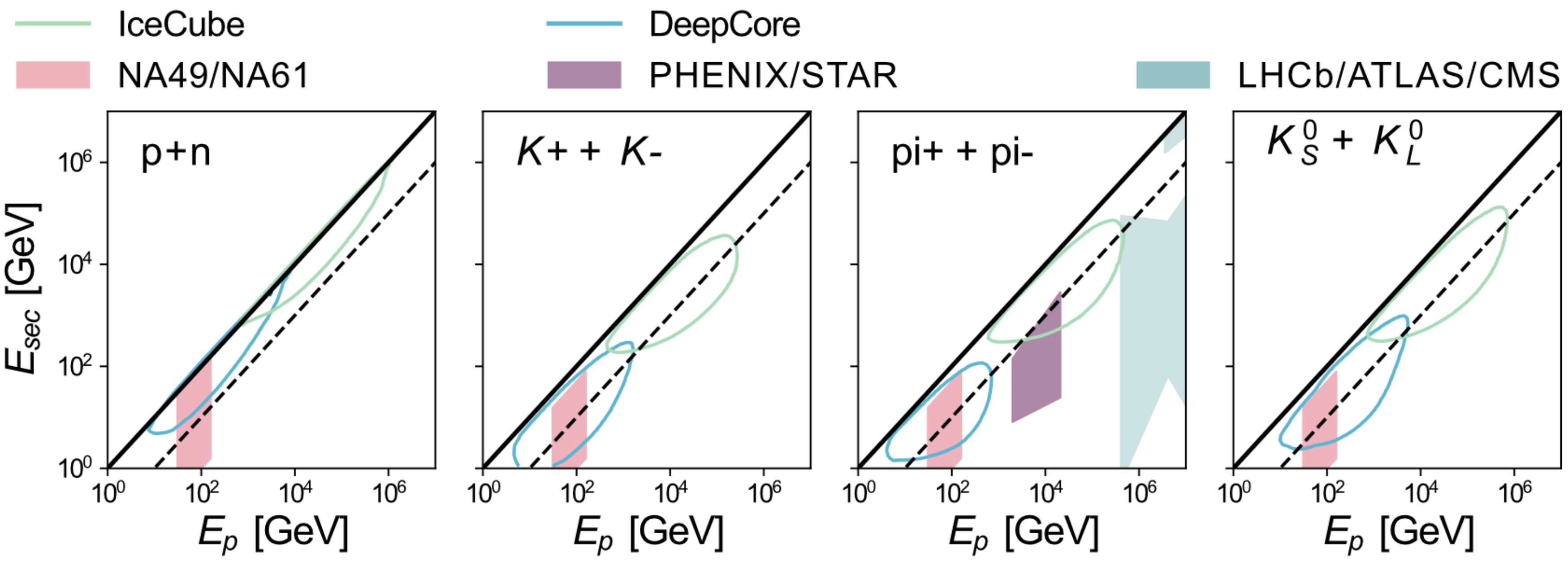
LHCb could significantly increases coverage

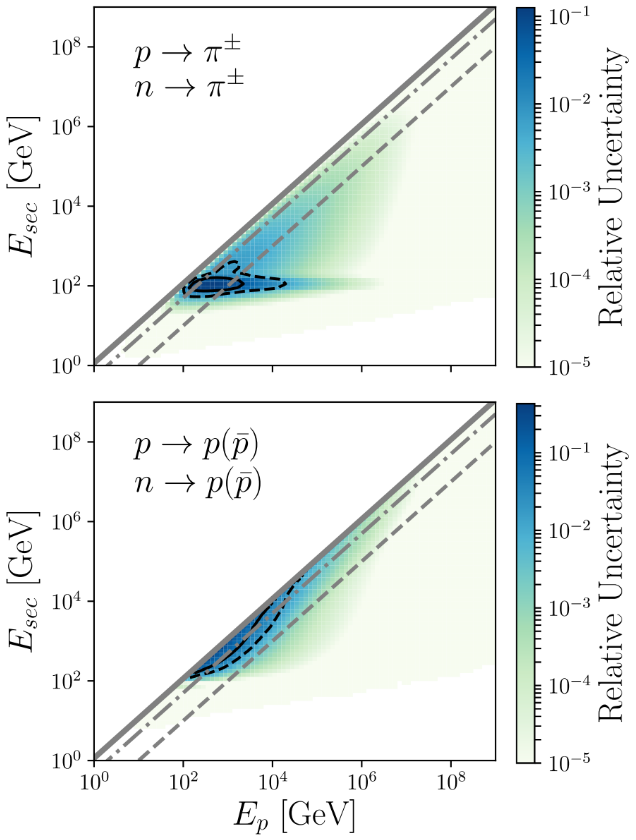
PHYSICAL REVIEW D **74,** 094009 (2006)



Medium energy interactions “visible” in IceCube

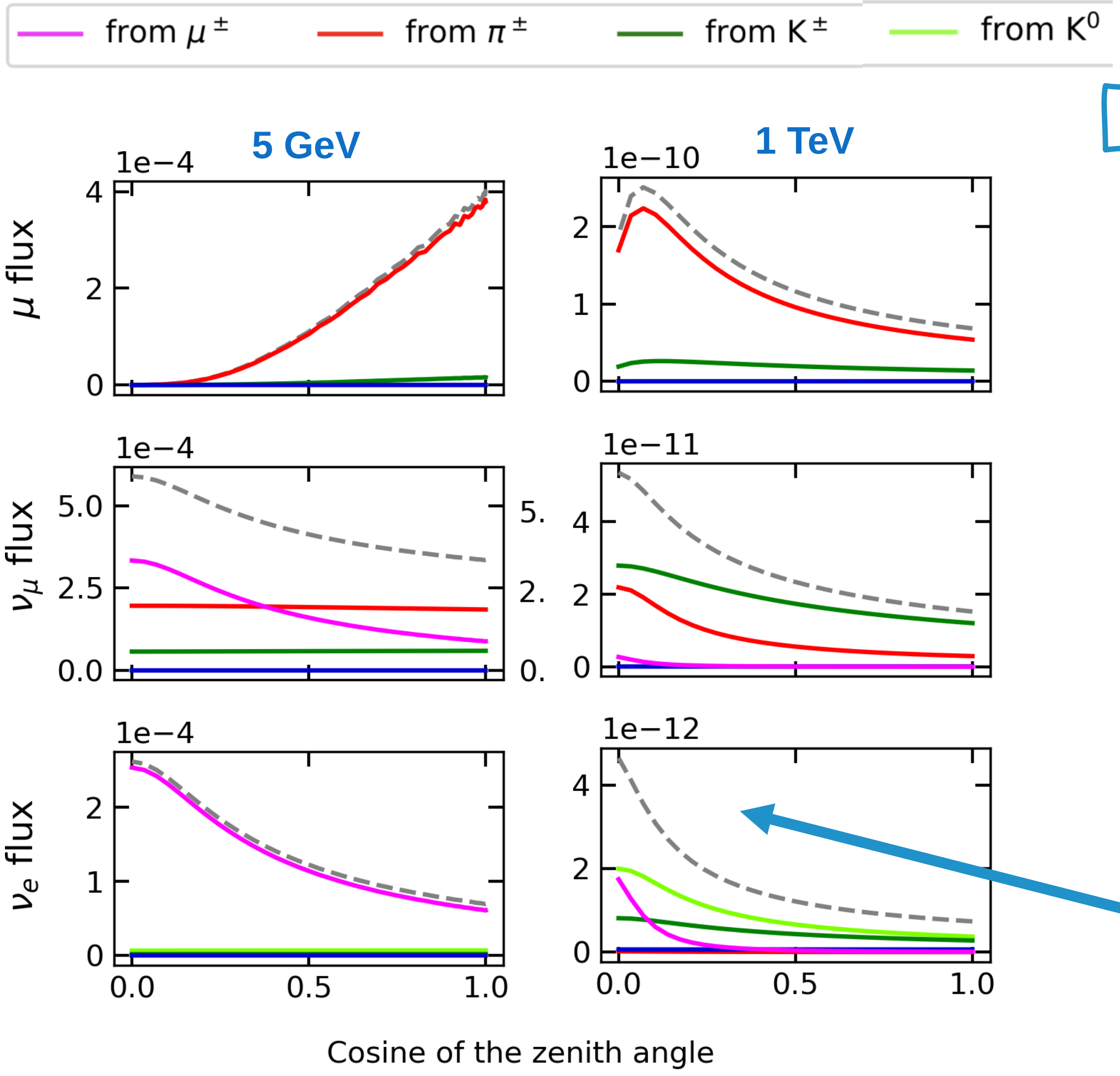
Particle production phase space covered by IceCube & DeepCore up-going tracks





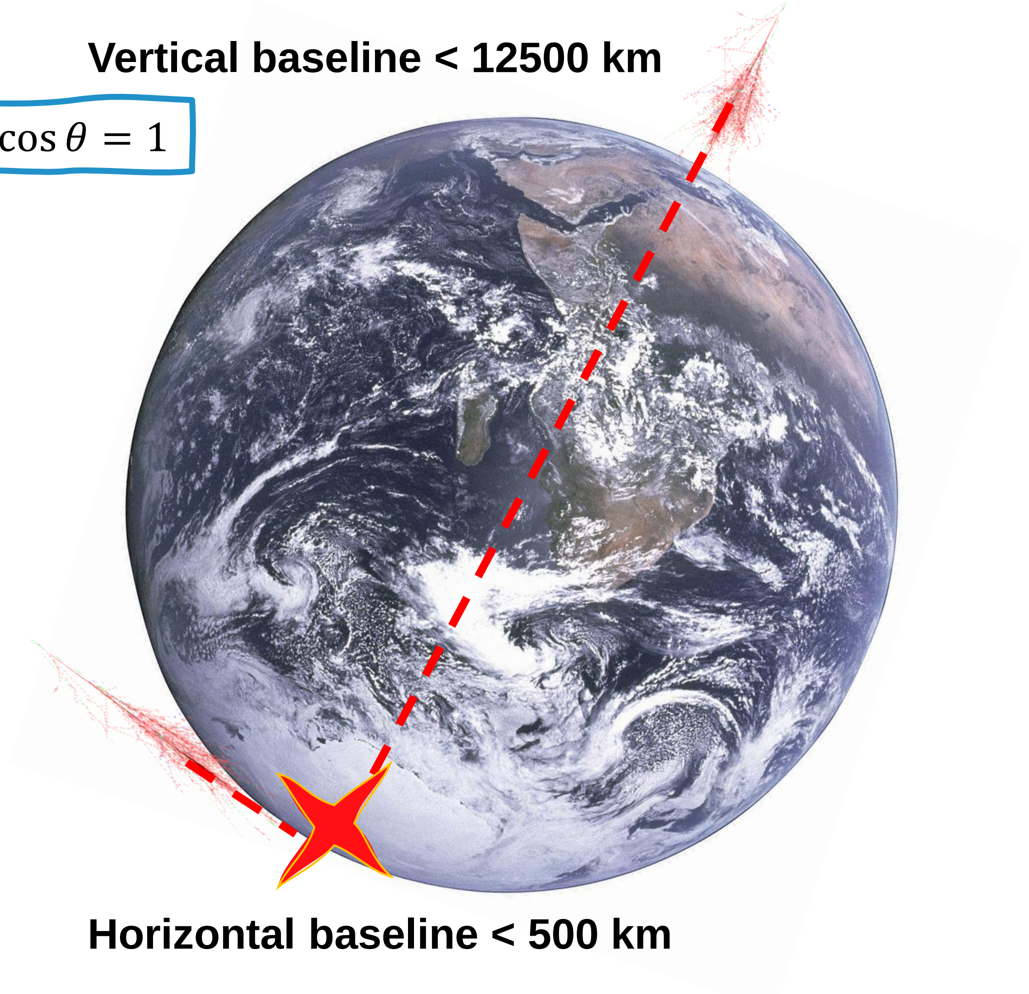
Phase-space contributing to 100 GeV muons

Atmospheric spectrum ←→ hadron components



Vertical baseline < 12500 km

vertical: $\cos\theta = 1$



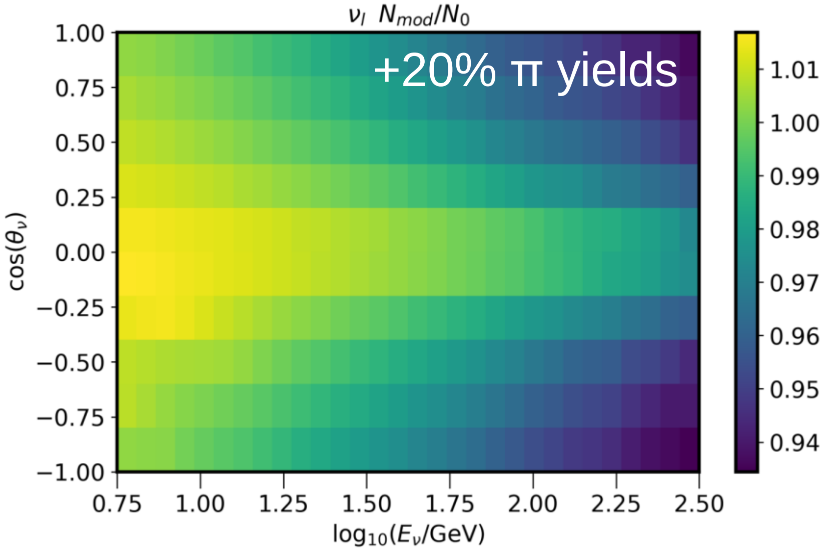
Horizontal baseline < 500 km

Various overlapping components

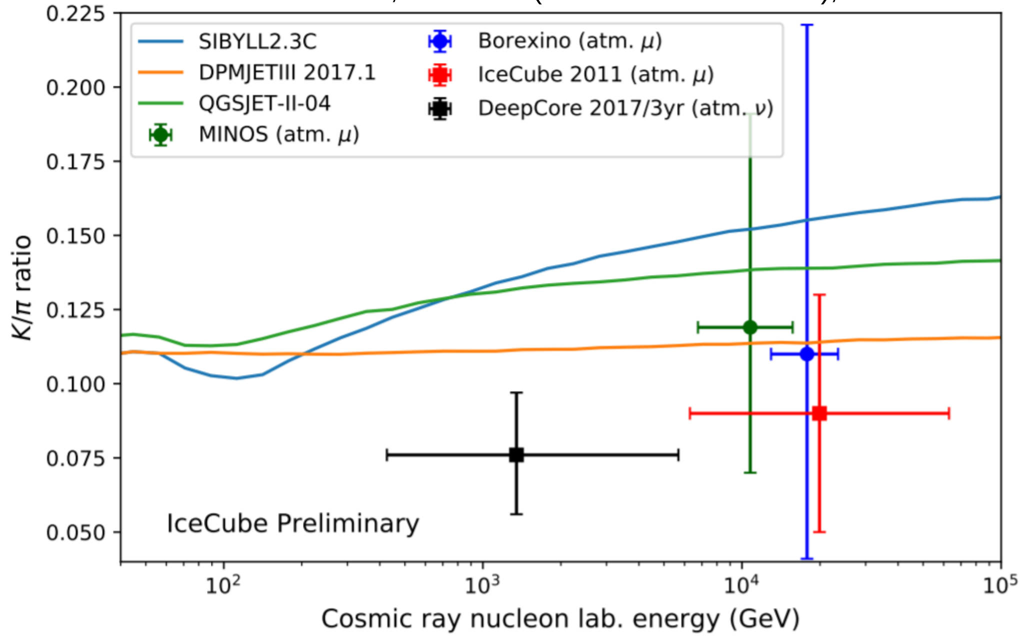
horizontal: $\cos\theta = 0$

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

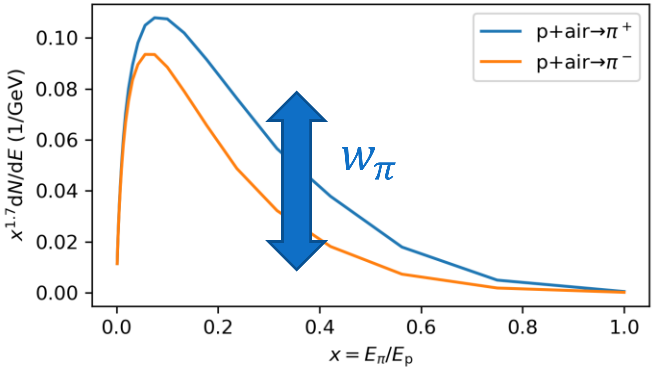
Measure K/pi ratio with angular spectrum in IceCube

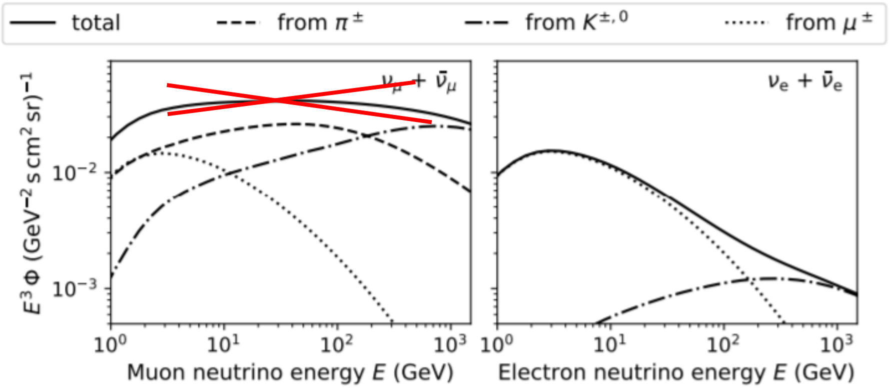


AF, JP Yanez (IceCube Collaboration), ICRC 2019



Variation of particle production yield modifies spectrum and angular distribution





- DeepCore < **Energy** < IceCube
- Bias from mis-reconstruction
- Will repeat with new MC and 7yr data sample

Calibration of ν uncertainties with “global fit” to μ data

Cosmic ray flux: Global Spline Fit [7] + Atmospheric conditions + Hadronic interactions: SYBILL 2.3c = Flux of muons and neutrinos

Experiment	Energy (GeV)	Measurements	Reported unit	Location	Altitude	Zenith range
AMS-02	0.1-2500	Flux & charge ratio	rigidity	28.57°N , 80.65° W	5 m (sea level)	
BESS-TeV	0.6-400	Flux	momentum	36.2°N, 140.1°W	30 m	0-25.8°
CMS	5-1000	Charge ratio	momentum	46.31°N, 6.071°E	420 m	$p \cos \theta_z$
L3+C	20-3000	Flux & charge ratio	momentum	46.25°N, 6.02°E	450 m	0-58°
MINOS	1000-7000	Charge ratio	total energy	47.82°N, 92.24°W	5 m (sea level)	unfolded
OPERA	891-7079	Charge ratio	total energy	42.42°N, 13.51°E	5 m (sea level)	$E \cos \theta^*$

(GeV)

DEIS

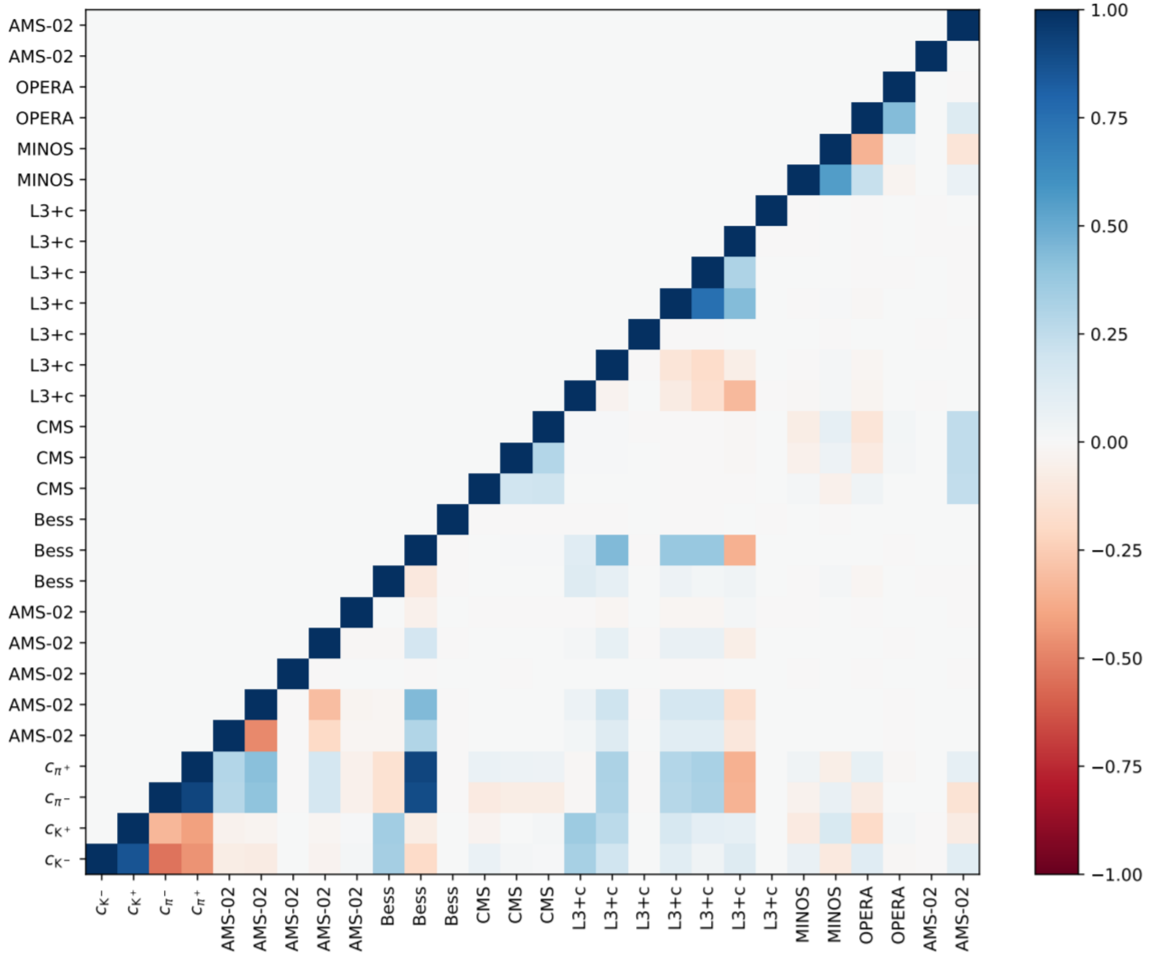
Juan Pablo Yanez and AF, launched in 2017, presented at Neutrino 2018 + ICRC 2019

Fit parameters and correlations

- With sufficiently low threshold (5 GeV) the correlations are reduced
- Errors between a few to ten %
- Neutrino flux errors in the range covered by fit comparable to kaon errors

Parameter	Best fit	Error
c_{π^-}	+0.141	±0.017
c_{π^+}	+0.116	±0.016
c_{K^-}	+0.402	±0.073
c_{K^+}	+0.583	±0.055

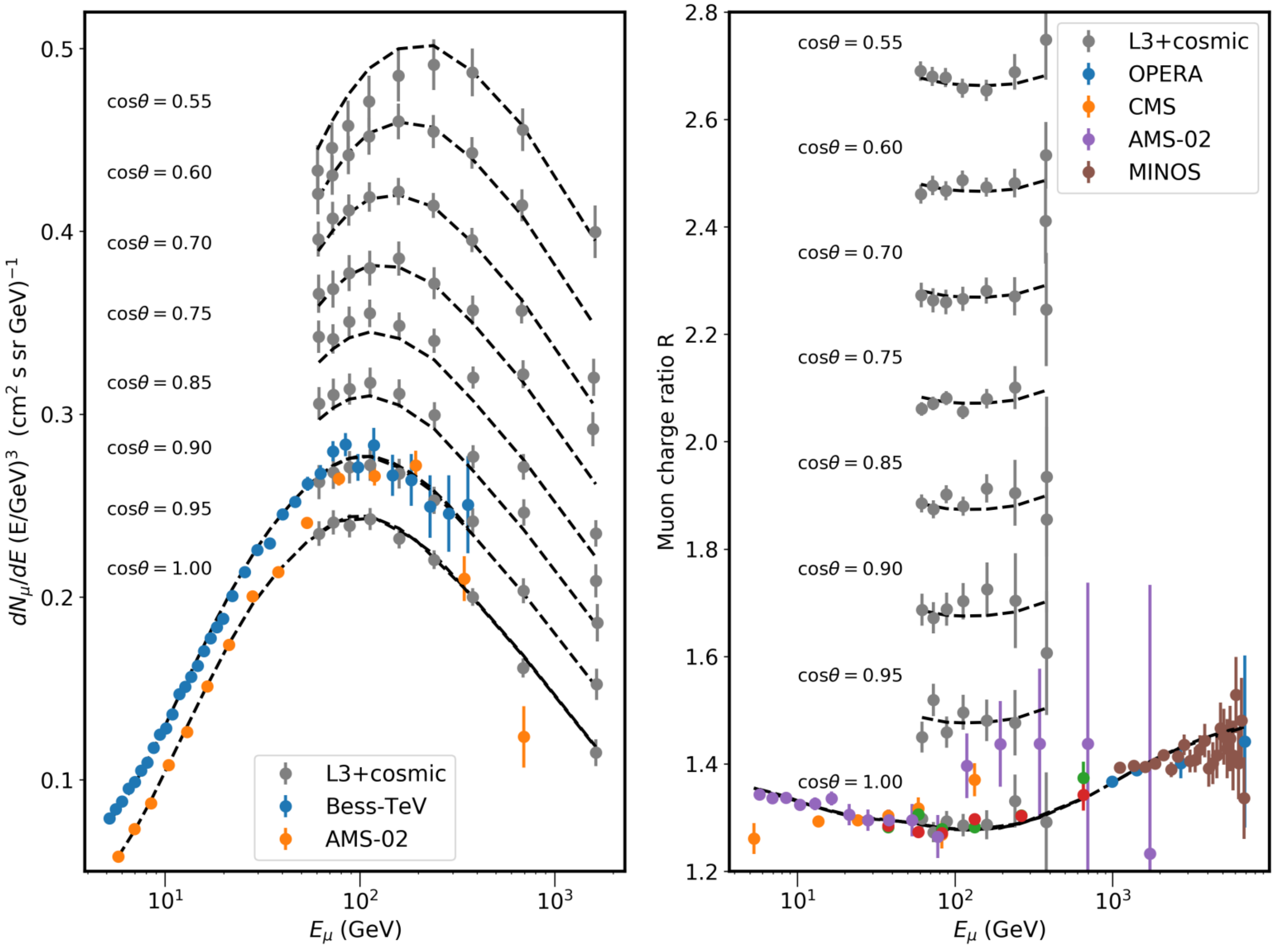
Thoughts: hard to believe…in tension with fixed target…qualitative features have to be involved…more digging needed



Juan Pablo Yanez and AF, Neutrino 2018 + ICRC 2019

Fit results

- Some experiments are hard to fit regardless of modifications
- Possible systematic effects not reported
- L3+C – previously “the reference dataset”– is not as good as we thought
- Hard to obtain robust fits, not all uncertainties sufficiently parameterized



Juan Pablo Yanez and AF, Neutrino 2018 + ICRC 2019

Learning from specialized accelerator experiments

Take NAxx fixed-target data

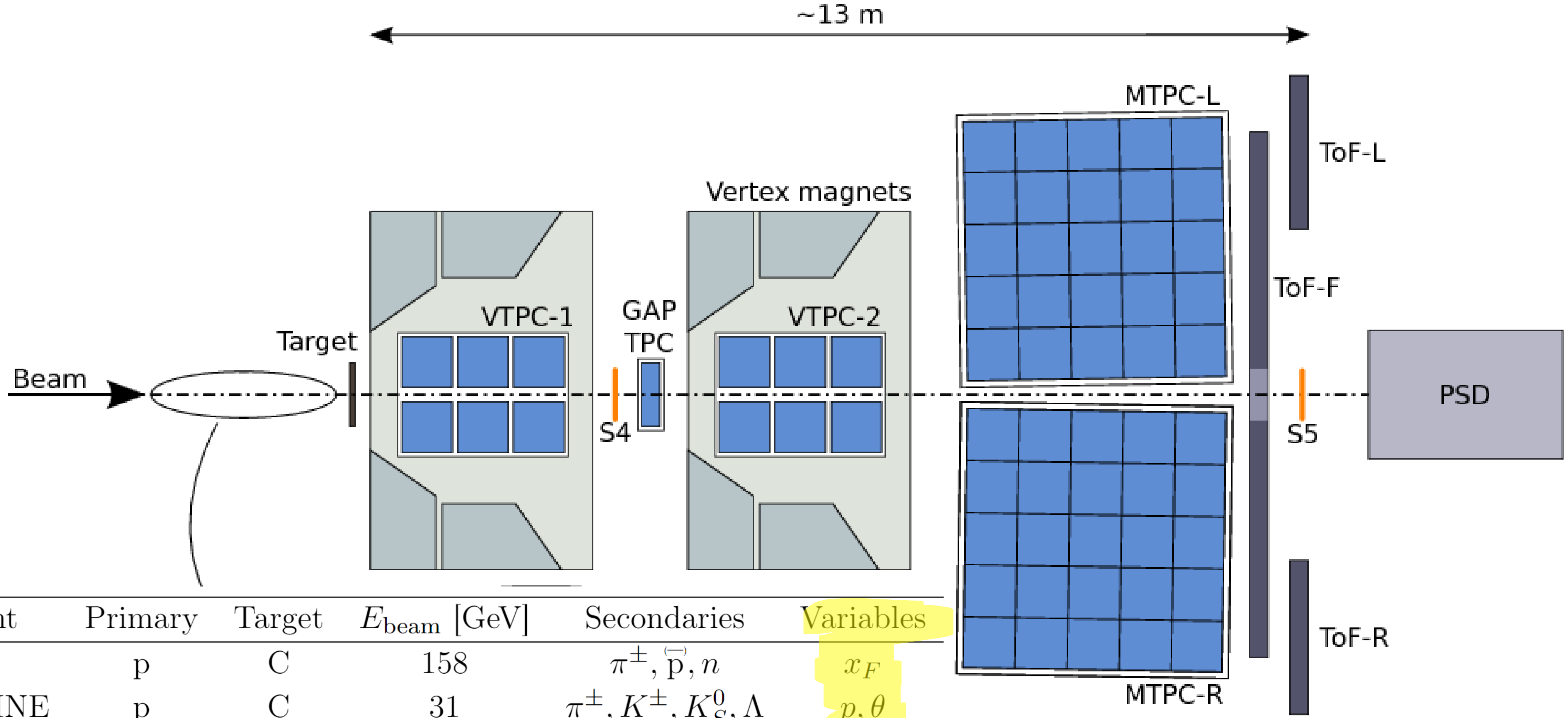
→ Transform into x_{lab}, propagate errors

→ Build inclusive hadr. int. model

→ Propagate errors and calculate fluxes

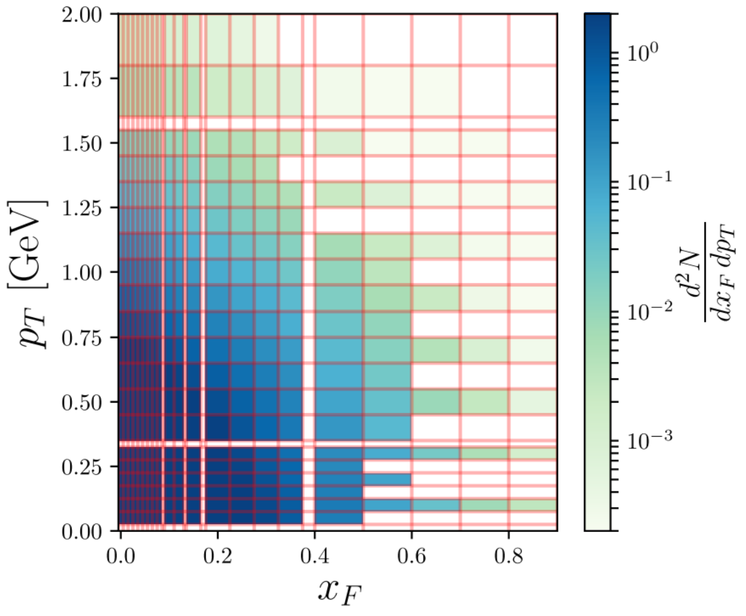
Project with **Matthias Huber** (TUM)

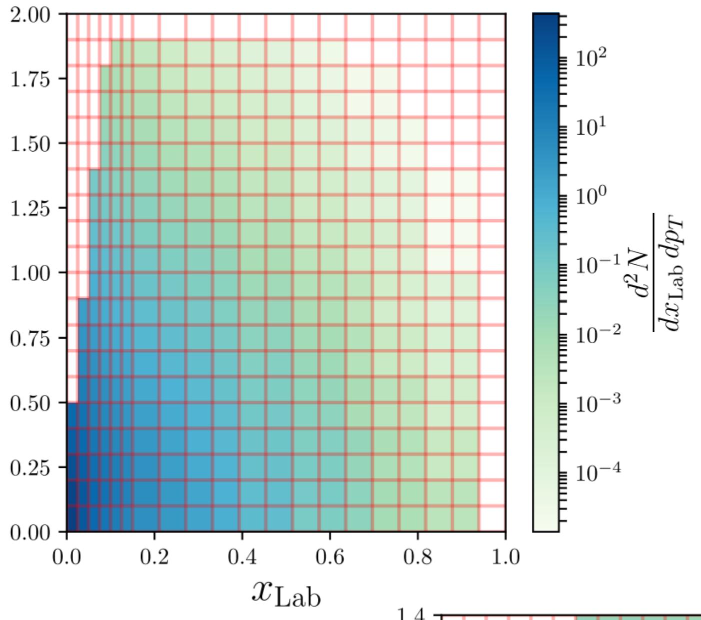
Specialized detectors: fixed-target experiments



Experiment	Primary	Target	E_{beam} [GeV]	Secondaries	Variables
NA49	p	C	158	$\pi^\pm, \overset{(-)}{\mathrm{p}}, n$	x_F
NA61/SHINE	p	C	31	$\pi^\pm, K^\pm, K^0_S, \Lambda$	p, θ
NA61/SHINE	π^-	C	158, 350	$\pi^\pm, K^\pm, \overset{(-)}{\mathrm{p}}$	p, p_T

Conversion to longitudinal energy fraction

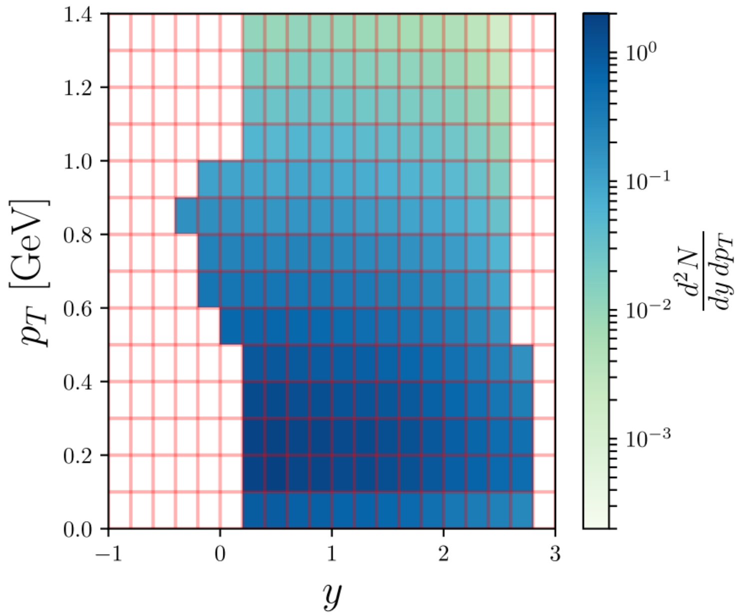


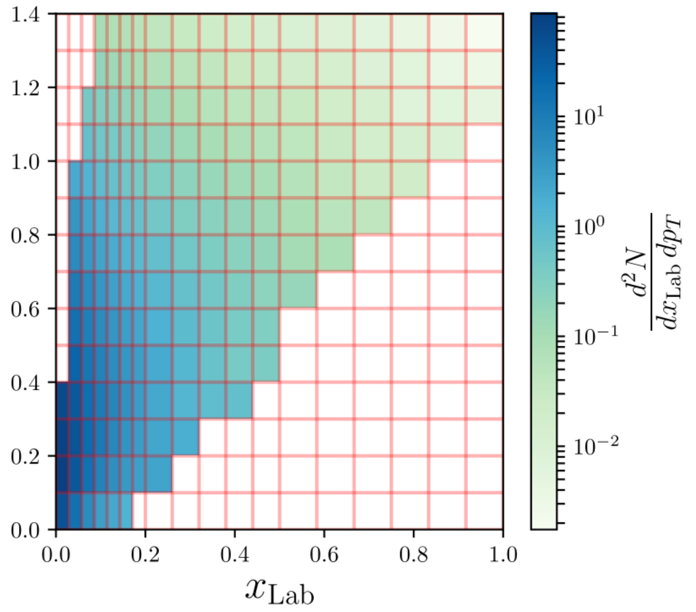


$$x_{Lab} = \frac{\gamma\sqrt{m_c^2 + \frac{1}{4}x_F^2 E_{c.m.}^2 + p_{c,T}^{*2}} + \frac{1}{2}\gamma\beta x_F^2 E_{c.m.}}{E_a}$$

$$= \frac{\gamma\sqrt{m_c^2 + \frac{\tanh^2(y)\left(m_c^2+p_{c,T}^{*2}\right)}{1-\tanh^2(y)} + p_{c,T}^{*2}} + 2\gamma\beta\frac{\tanh^2(y)\left(m_c^2+p_{c,T}^{*2}\right)}{E_{c.m.}\left(1-\tanh^2(y)\right)}}{E_a}$$

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





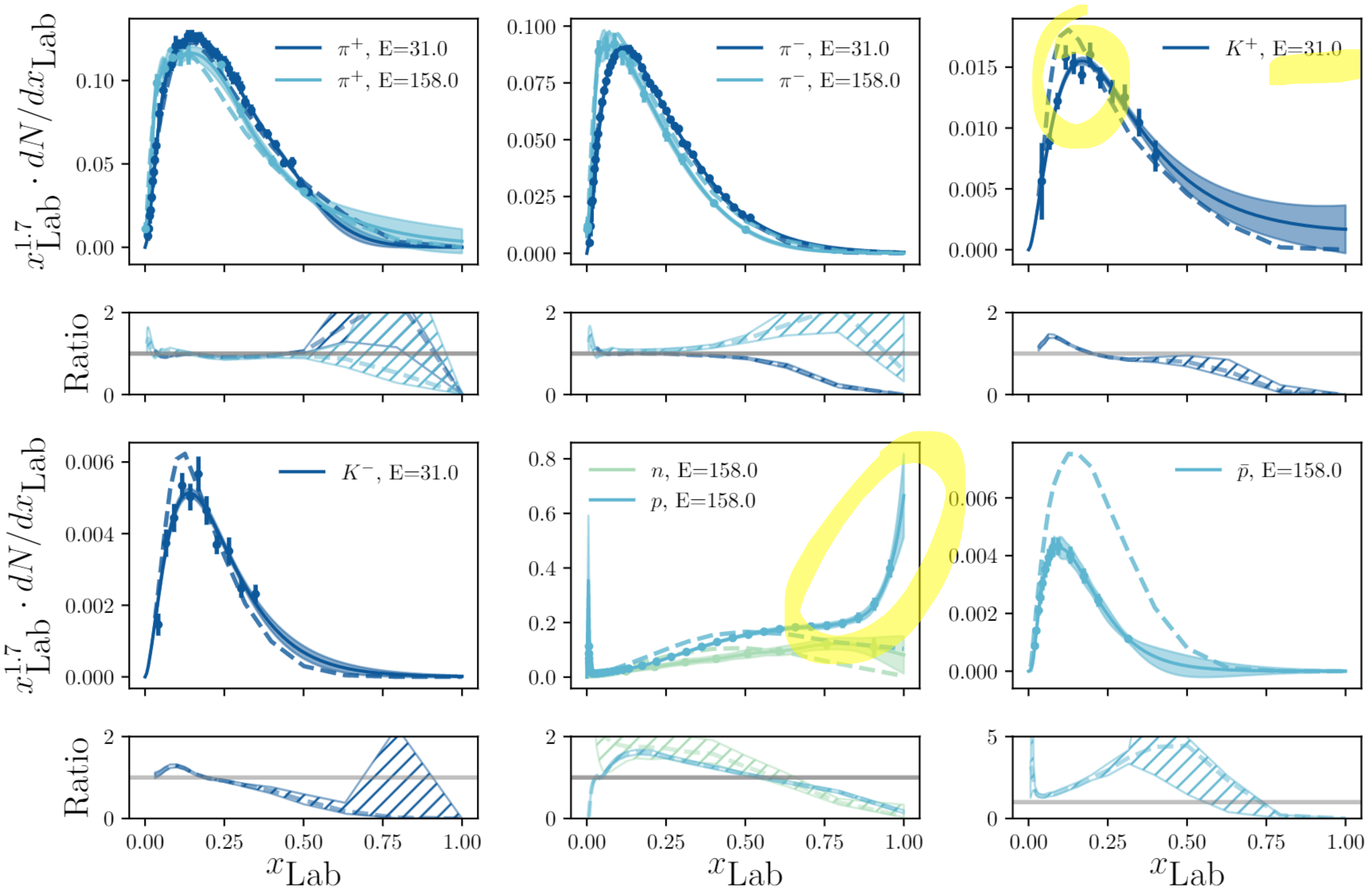
Origin of additional systematic error of 5%

Fitting proton-Carbon data & uncertainty with splines

Solid + shade:
Spline fit

Dashed:
SIBYLL2.3d @ 158 GeV
DPMJET-III-191 @ 31 GeV

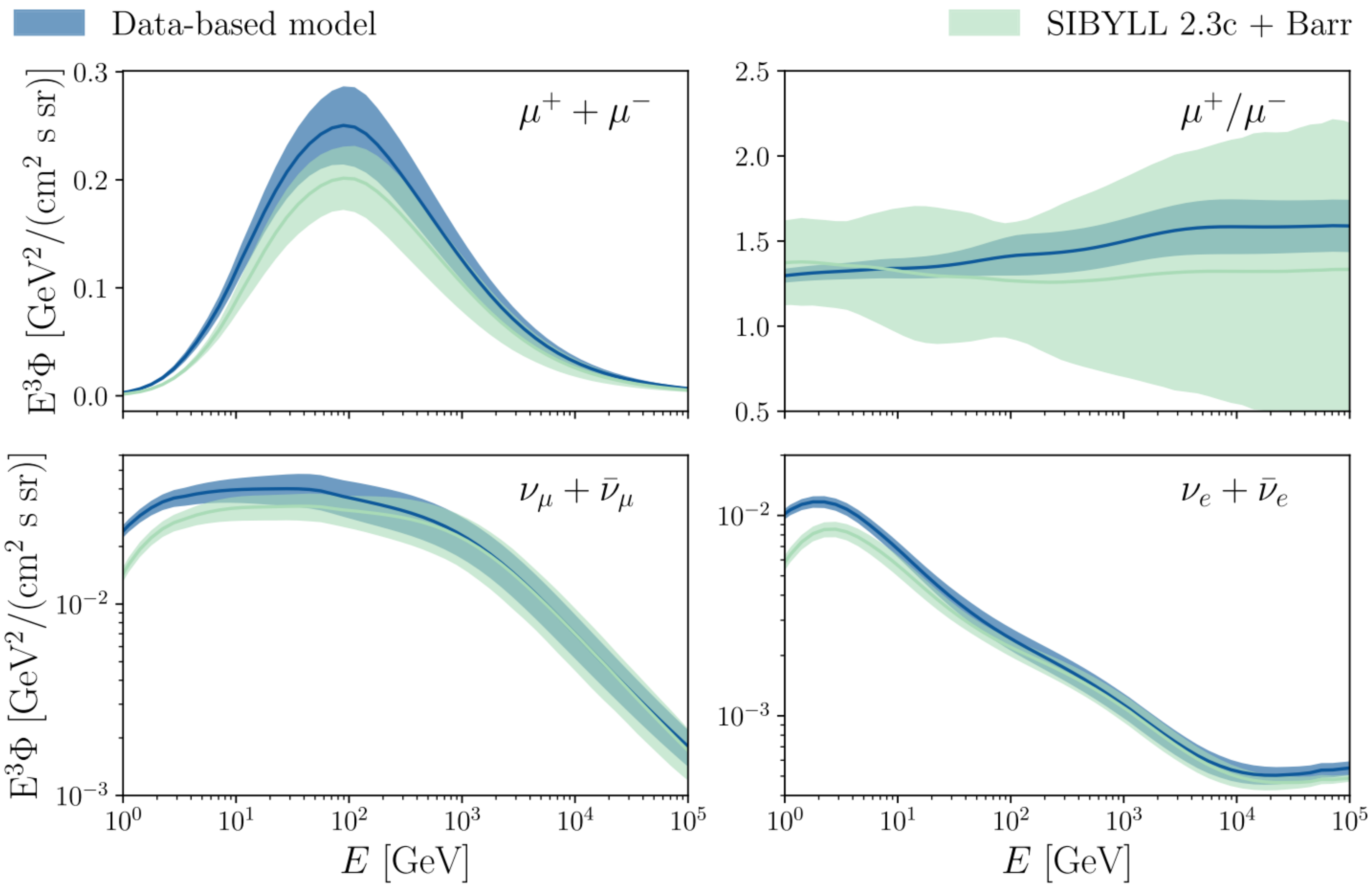
Data:
CERN, SPS
NA49 and NA61



M. Huber and AF,
in prep.

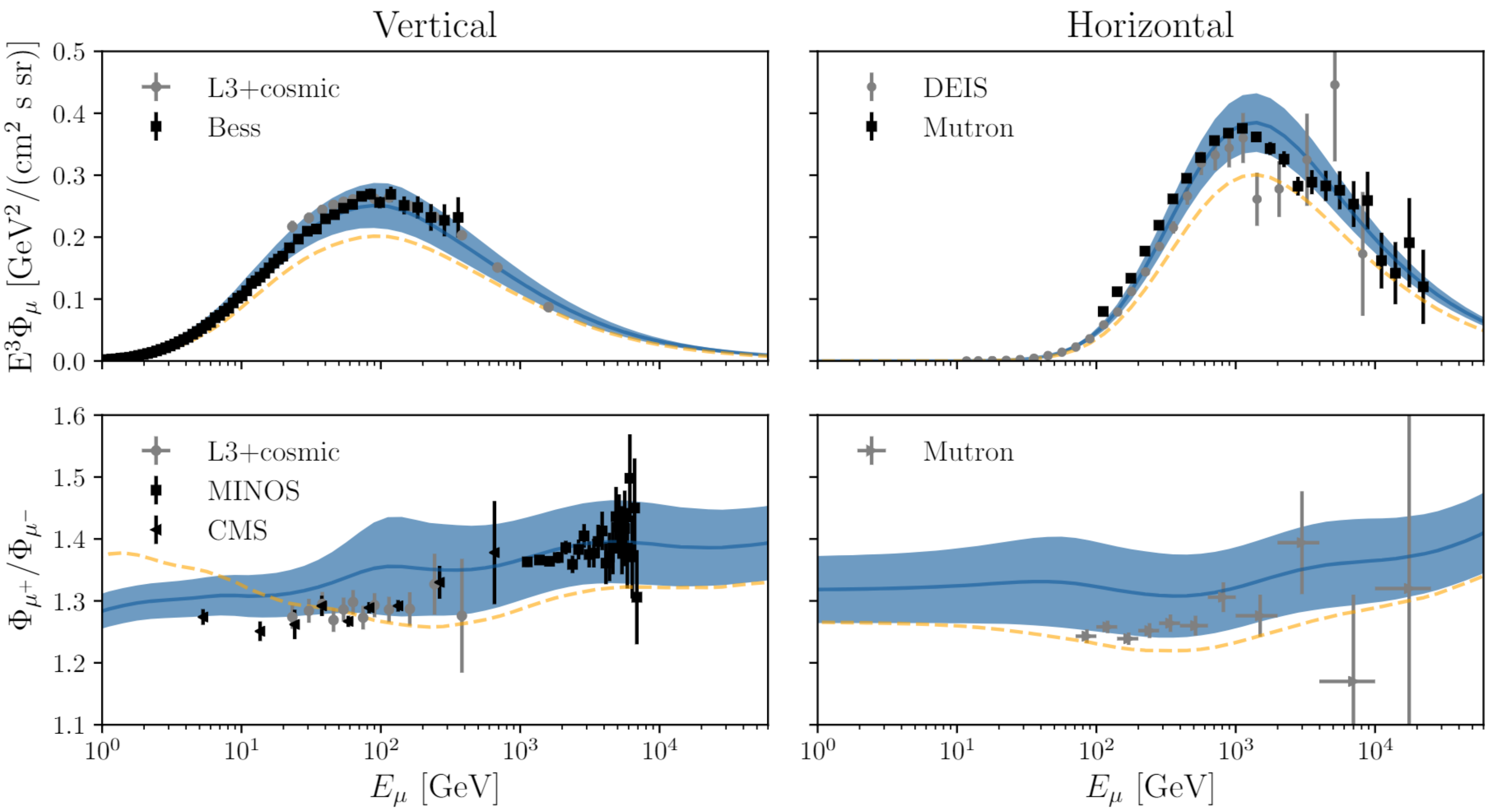
Impact on prediction uncertainties

AF et al., ICRC 2017 + Barr 2006, PRD 74



M. Huber and AF,
in prep.

Good muon spectrum description from fixed-target data



M. Huber and AF, in prep.

…but many nasty details regarding extrapolation uncertainties to consider.

Conclusions

- Astrophysical interpretation of (U)HECR depends on hadronic models
- Plenty of data but rigorous approaches to build or improve models using these data are missing
- Combinations of different sensitive observables will notably constrain the very important “medium energies”

- **What's your targeted physics in next decades? (on this topic)**
  - Reduce atmospheric neutrino flux uncertainties for neutrino observatories and Hyper-K
  - Figure out where in the phase space experimental constraints can reduce ambiguities in UHECR interpretations (understand which observables are crucial for next generation UHECR experiments)

- What we need to accomplish?
  - Develop better methods to incorporate results from particle physics experiments (LHC, RHIC, EIC, NA61) in cascade simulations including realistic uncertainties
  - Re-analyze some fixed target data in CR-relevant kinematic variables
  - Create a new lighter hadronic model that is from scratch built “to fit”

- and take-home messages (optional):
  - There is a lot of work to do!

Model for extragalactic transport of UHECR

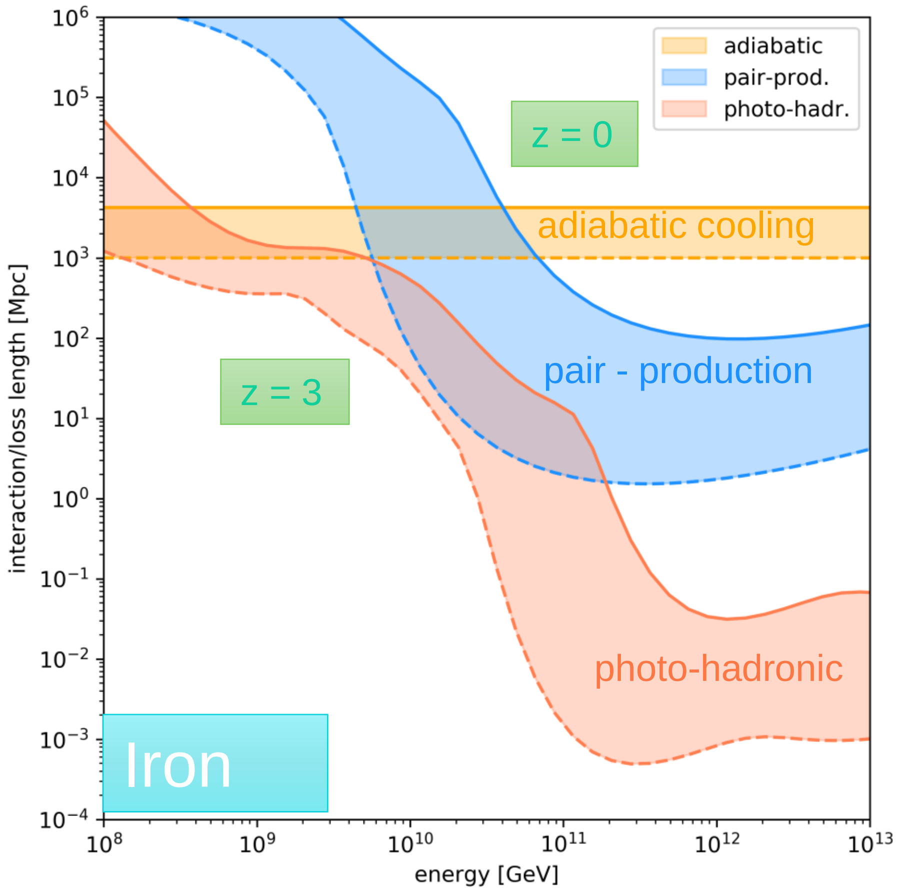
$$\partial_t Y_i(E,z) = +\partial_E(HEY_i) - \partial_E\left(\frac{dE}{dt}Y_i\right) - \Gamma_i Y_i + \sum_j Q_{j\to i} + \mathcal{L}_i$$

comoving particle density | adiabatic cooling | pair - production | photo-nuclear | Injection

- Initial injection of **nuclei up to iron**
- Disintegration (Giant Dipole Resonance + photo-meson production, nuclear fragmentation)
- About 50 species × size of E-grid (~150) coupled partial differential equations (~8000)
- All coefficients **time and energy dependent**

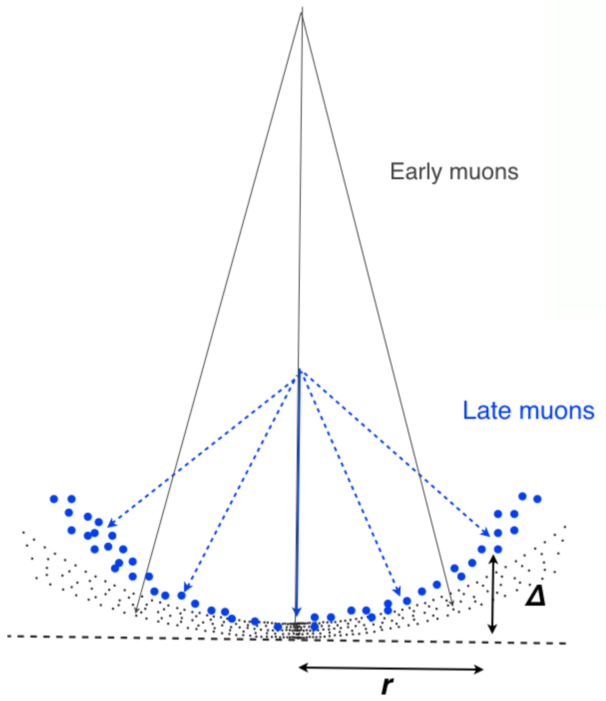
New code:
PriNCe = Propagation including Nuclear Cascade equations

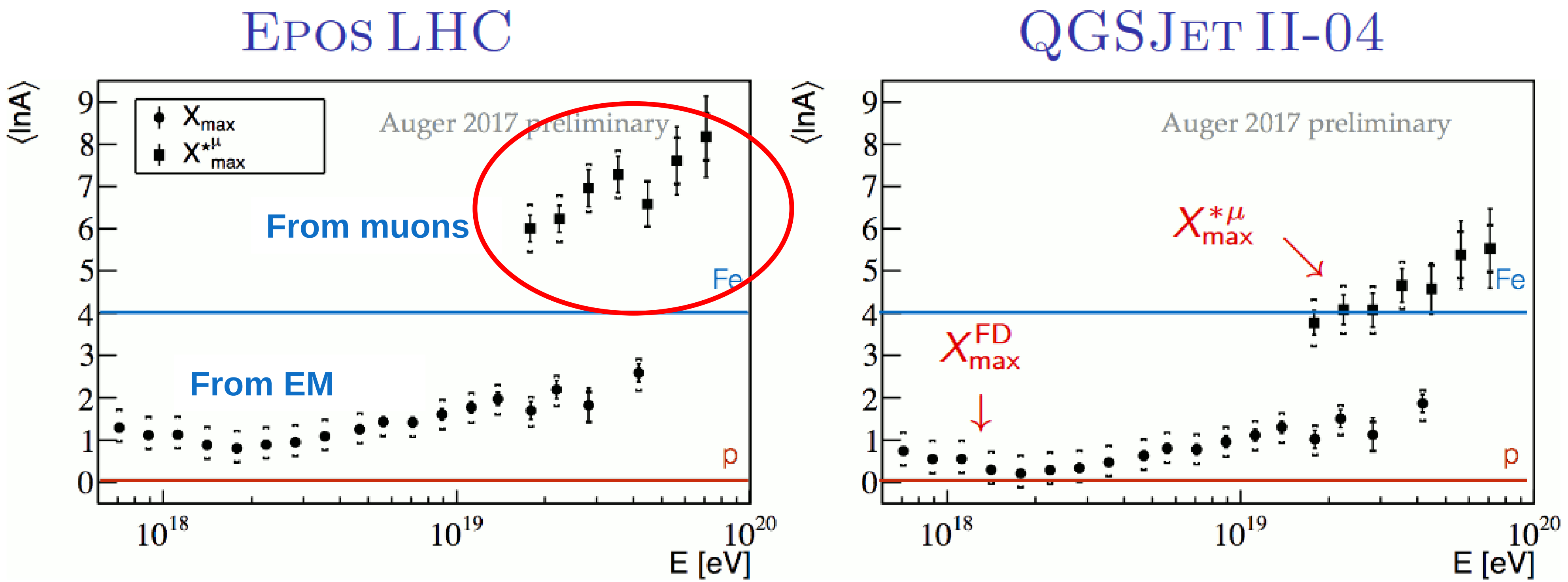
GitHub - joheinze/PriNCe: https://github.com/joheinze/PriNCe



Problem with mass sensitive observables

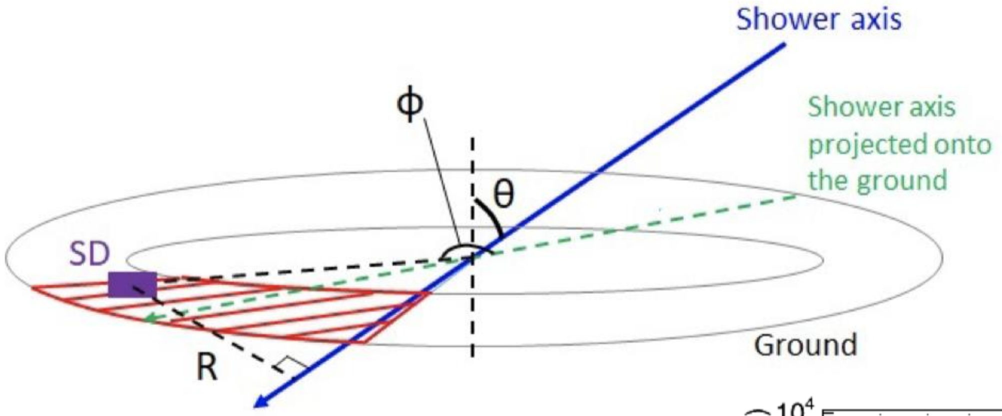
R. Prado, ISVHECRI 2018

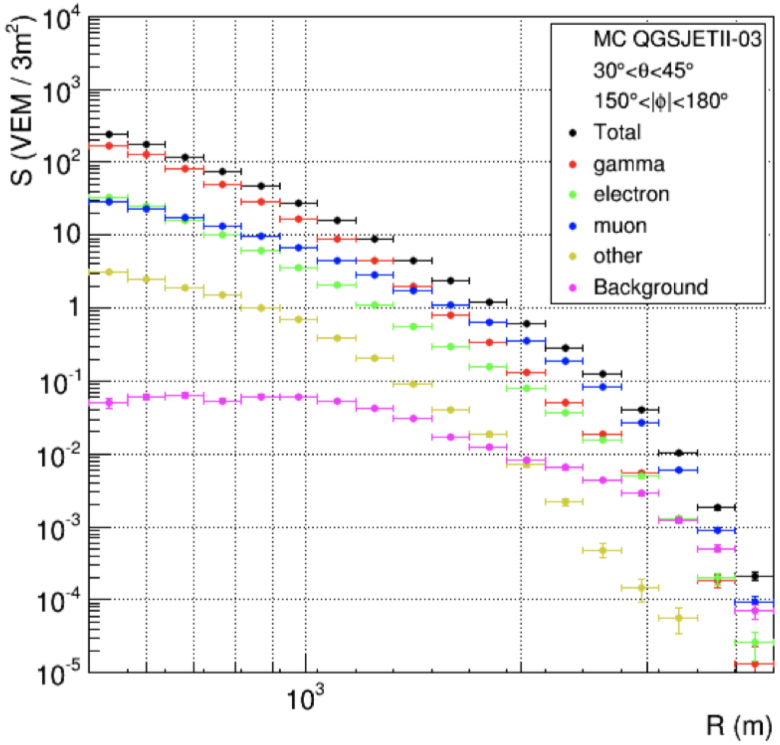


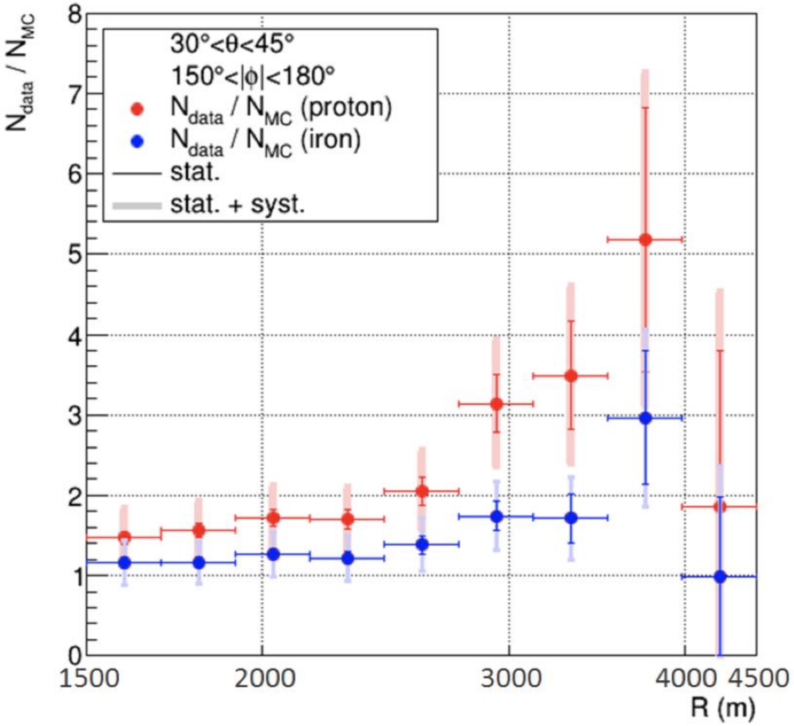


Telescope Array can sees muon deficit

Takeishi (TA), UHECR 2018

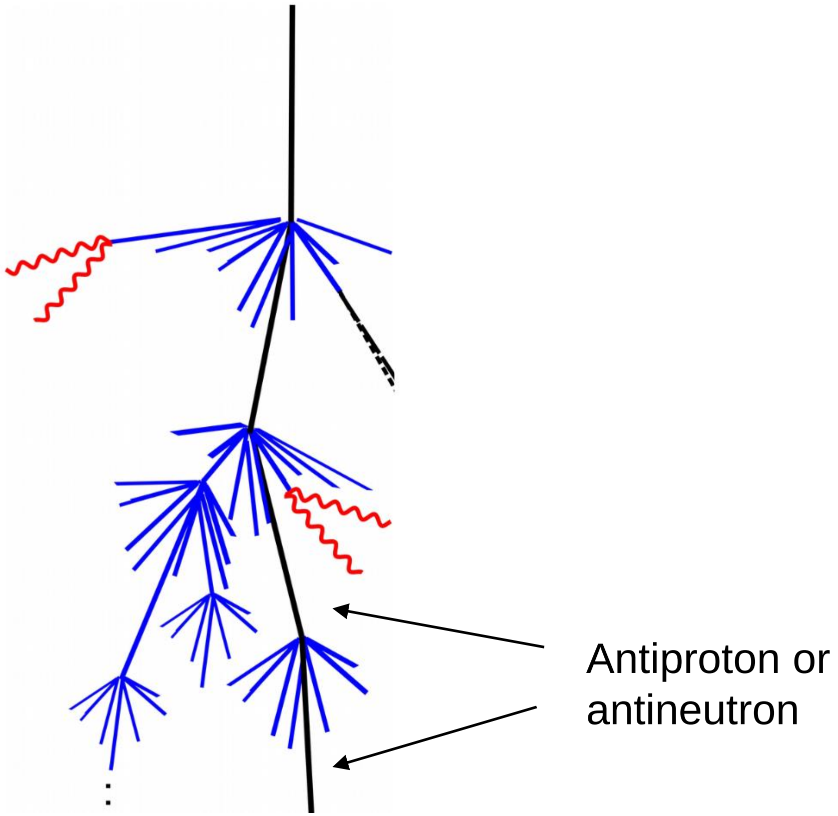






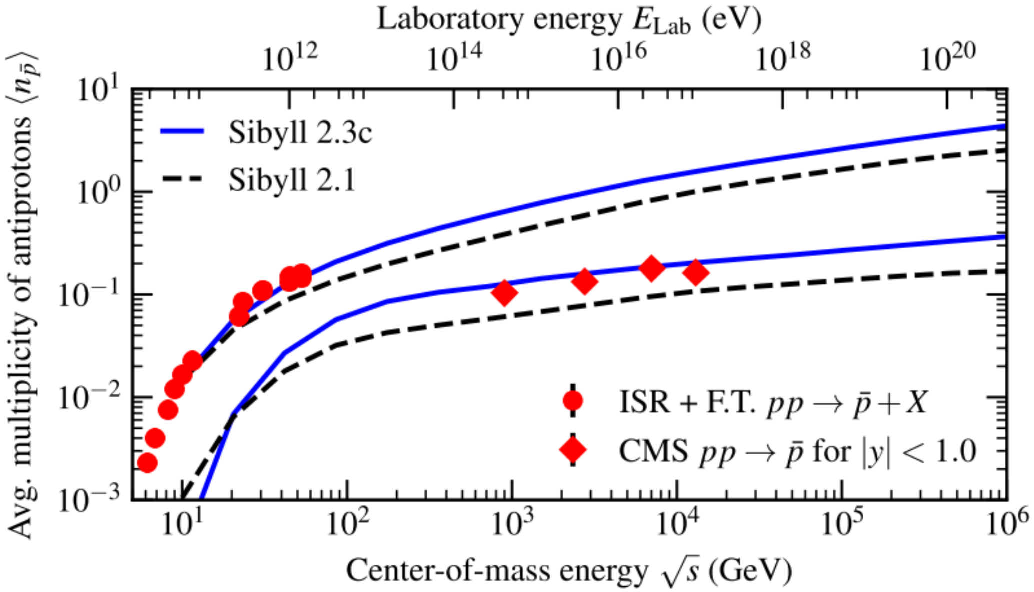
More low-energy muons through anti-baryons production

F. Riehn, R. Engel, AF, T. Gaisser, T. Stanev
arXiv:1912.03300, PRD 102, 2020



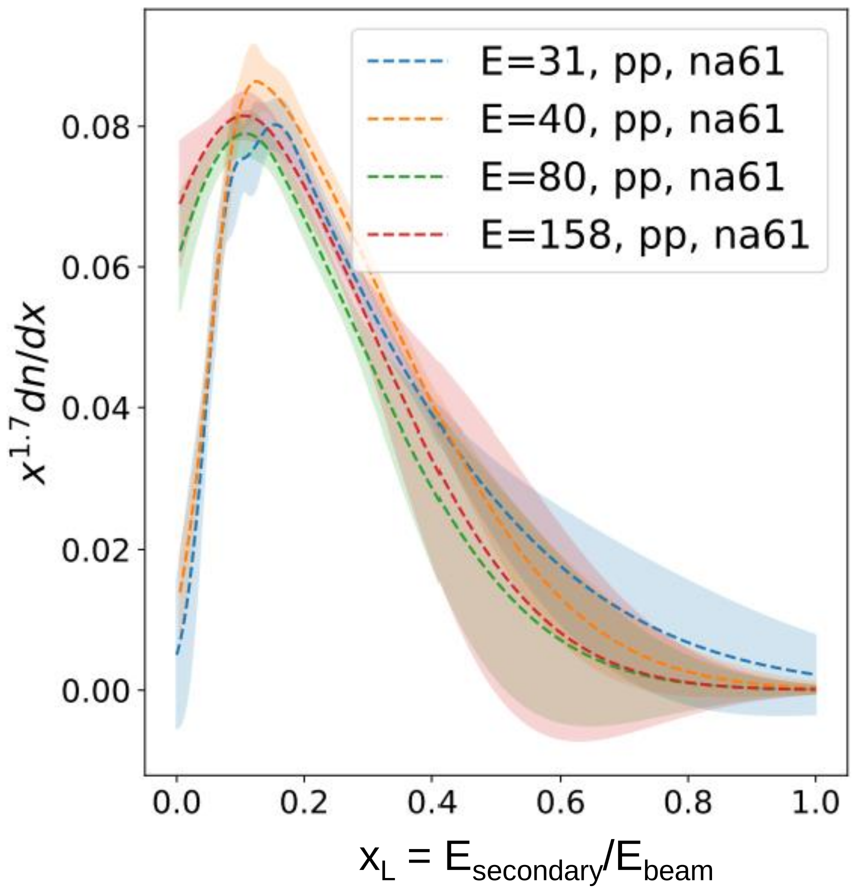
Baryon number conservation results in cascade regeneration:

- Each interaction yields at least one baryon
- These baryons re-interact, producing more pions
- Production was off in older models



NA61 pp "energy-scan" problematic

NA61, proton-proton → pi-

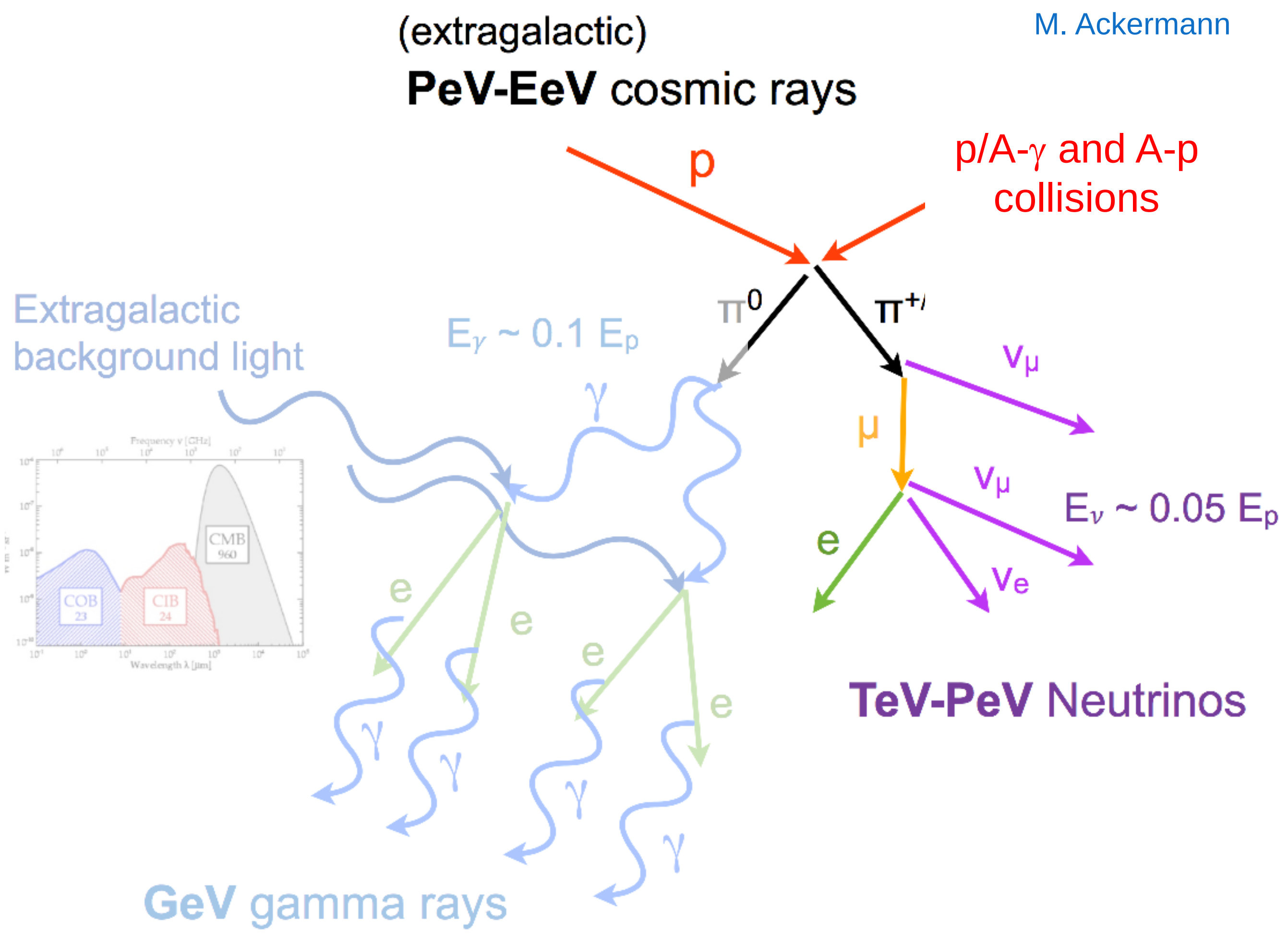


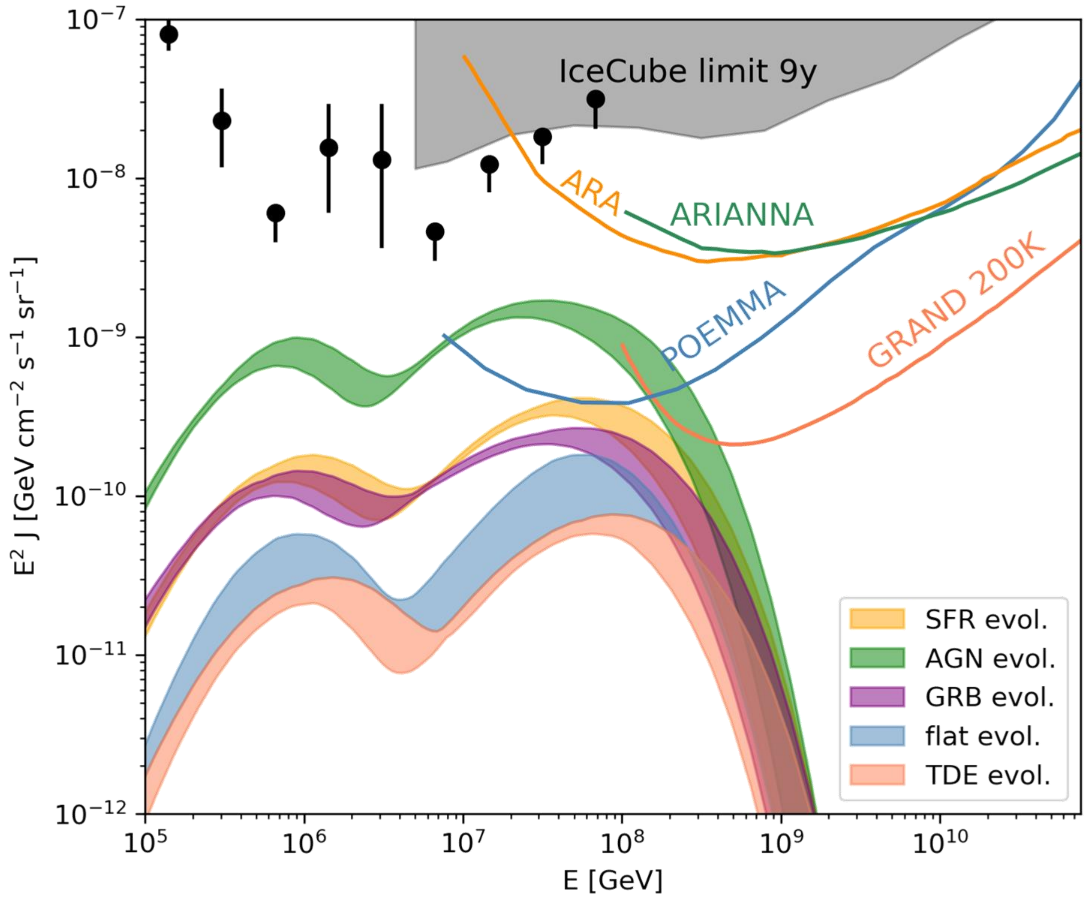
- Data originally in rapidity: y-p_T plane
- Phase-space coverage and statistics not good, many empty bins → fits and conversion problematic
- Disagreement with NA49 when converted to longitudinal phase-space variable
- Large errors when propagated to muon & neutrino fluxes

M. Huber and AF, in prep.

Heinze, AF, Boncioli, Winter, ApJ 873

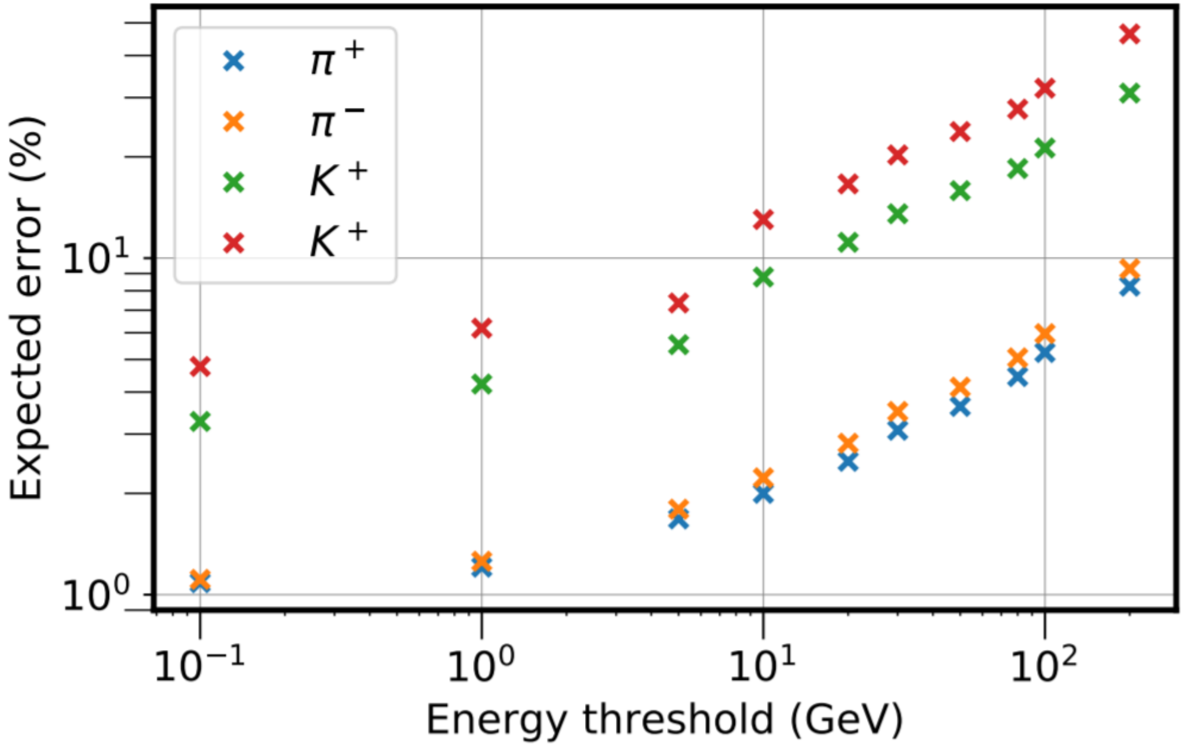
Additional multi-messenger constraints on UHECR sources?





Impact of energy threshold for the fit

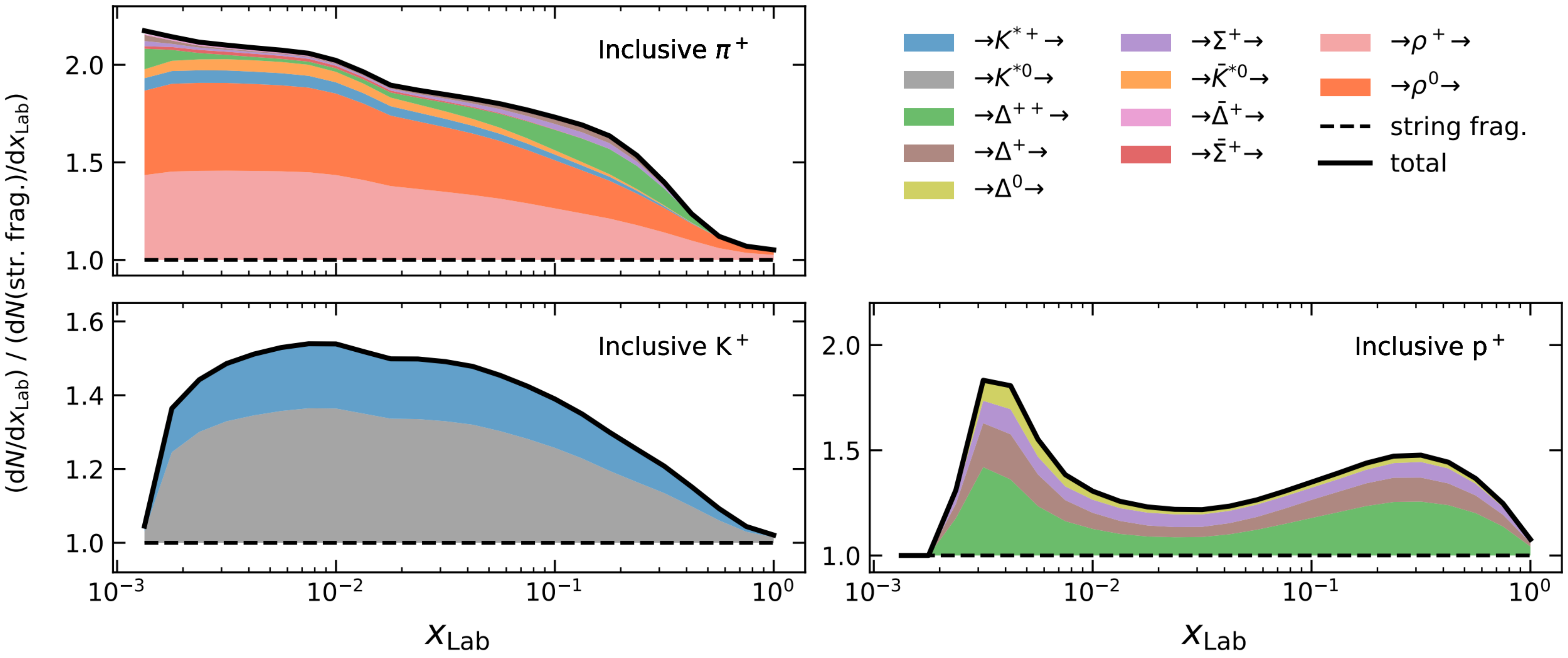
- High energy data less sensitive
- …because **the features in the muon spectrum are smooth**
- and fit variables become strongly correlated
- More angles needed
- We're investigating horizontal and high-altitude balloon data



Juan Pablo Yanez and AF, Neutrino 2018 + ICRC 2019

…difficult to interpret

arXiv:1806.04140



No simple tuning/systematic parameters within one interaction model! Many features related to each other.