Highlights of the updated hadronic interaction models DPMJET-III and SIBYLL

HAP Workshop | Non-Thermal Universe

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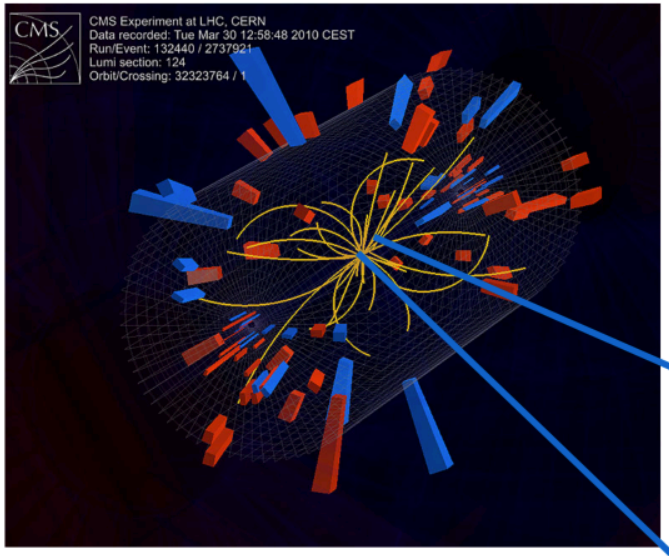
HELMHOLTZ ASSOCIATION

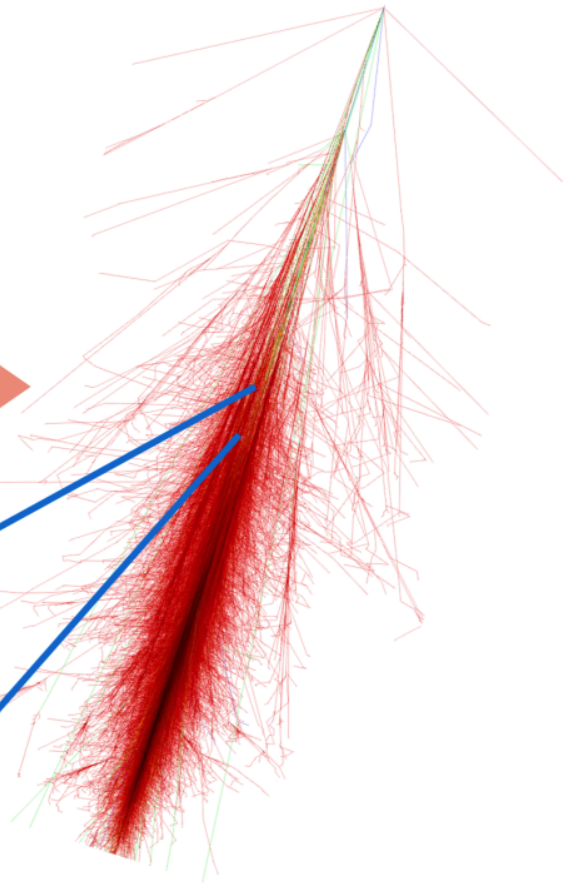
DESY

Hadronic interaction models

Interpretation of cosmic ray measurements **crucially** depends on hadronic interaction models



DPMJET
EPOS
SIBYLL
QGSJet



Detectors have holes!

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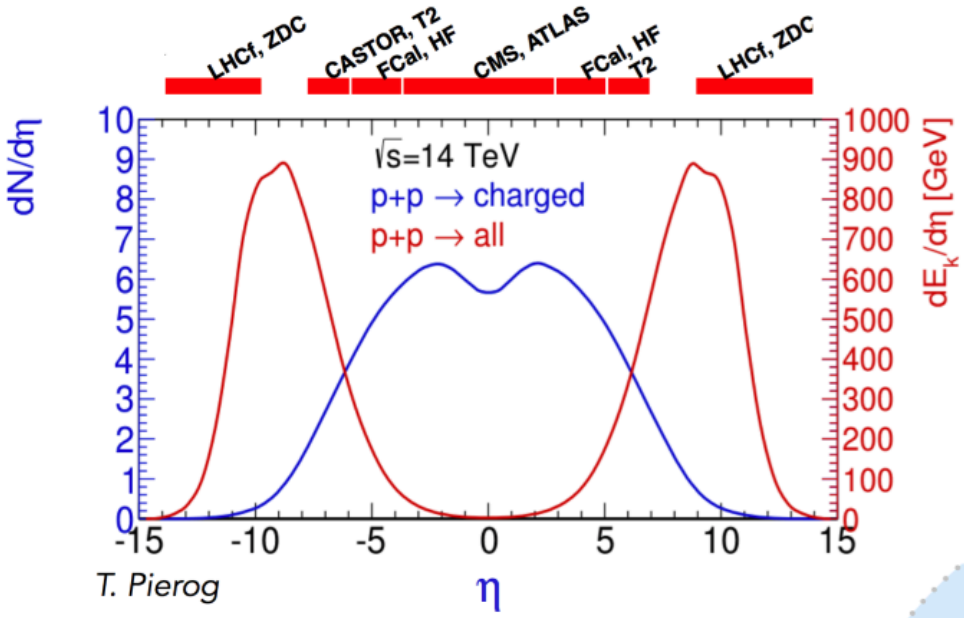
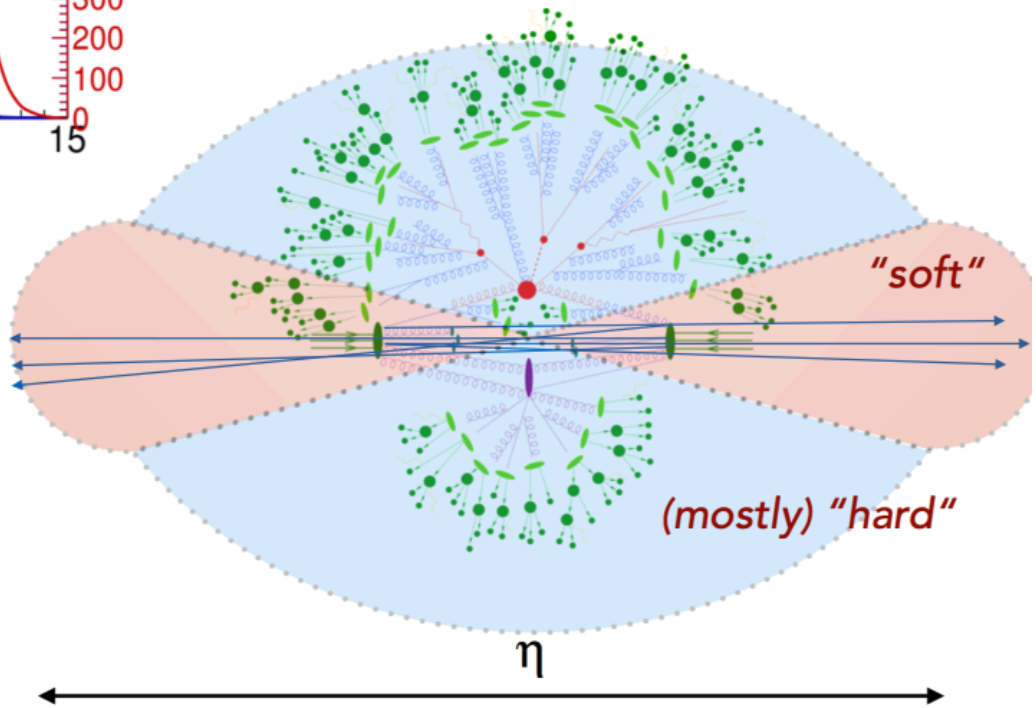
Limited experimental coverage of cosmic ray relevant physics

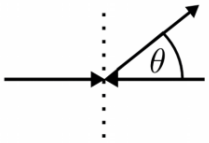


Typical acceptance at LHC

$$x_F = 2p_Z/\sqrt{s} \ll 0.1$$



Most energy is dissipated in not instrumented region!



$$\eta = -\log\tan(\frac{\theta}{2})$$

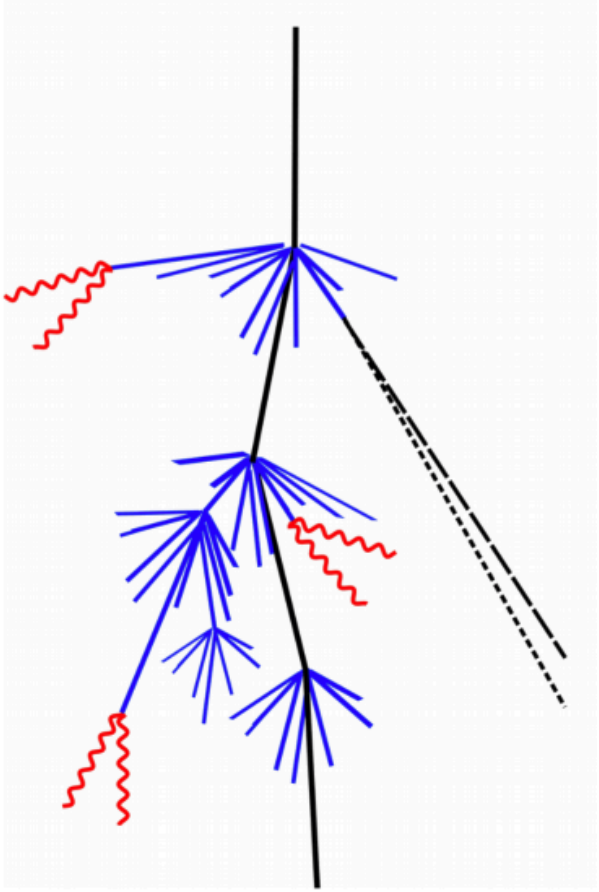
The nuclear Monte Carlo event generator DPMJET-III

- DPMJET-III
  - supports hadron-hadron, photon-hadron, photon-photon, hadron-nucleus and nucleus-nucleus
  - from few GeV (lab) up to UHECR energies
  - light and heavy nuclei (>^{235}U) via Glauber, intra-nuclear cascade,…
  - is the main hadronic model for high energies and nucleus-nucleus interactions in FLUKA
- Individual hadron-/photon-nucleon interaction modeled with recently updated PHOJET minimum-bias model
- Under test in upcoming versions of FLUKA, CORSIKA, MCEq
- … soon available as standalone at https://dpmjetiii.hepforge.org

A. Fedynitch and R. Engel,
CERN-Proceedings-2015-001

DPMJET-III cascade mode

- Accepts most of the hadrons as projectiles
- Initialization in run-time, on demand
- Projectiles without known cross sections mapped to closest related particle combination (with valence exchange)
- Low minimal energy (no low-E model necessary)
- Relatively fast (wrt. EPOS-LHC or QGSJET-II-04)

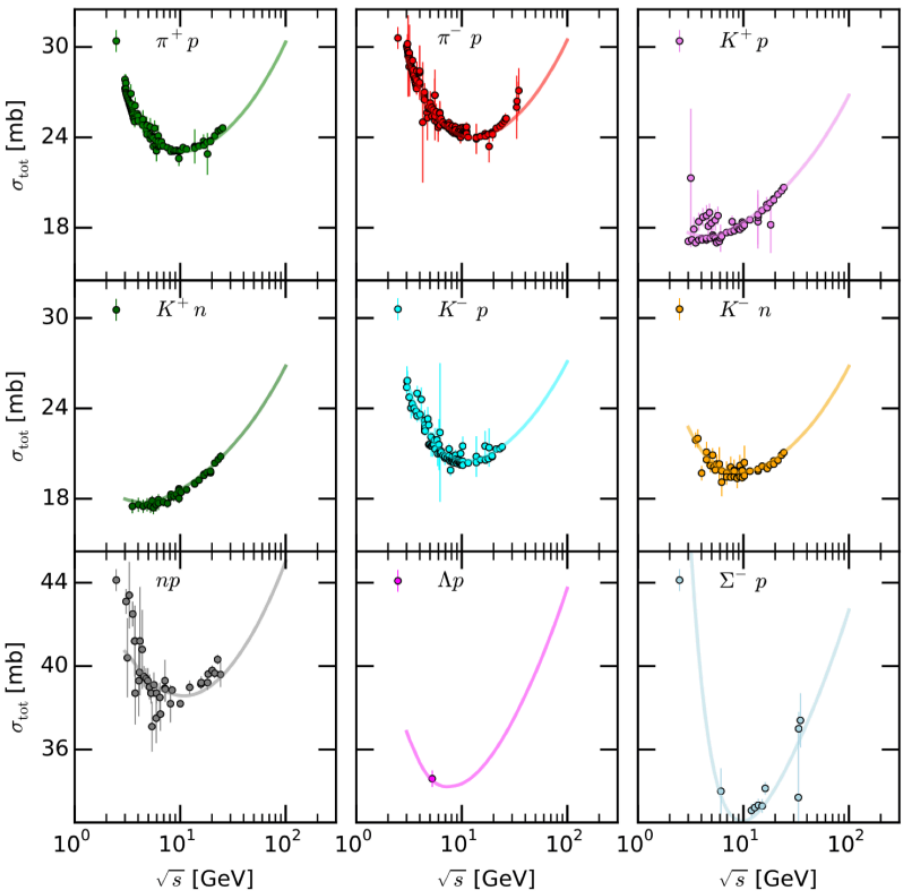


→ Can be used in air-shower Monte Carlo (CORSIKA)

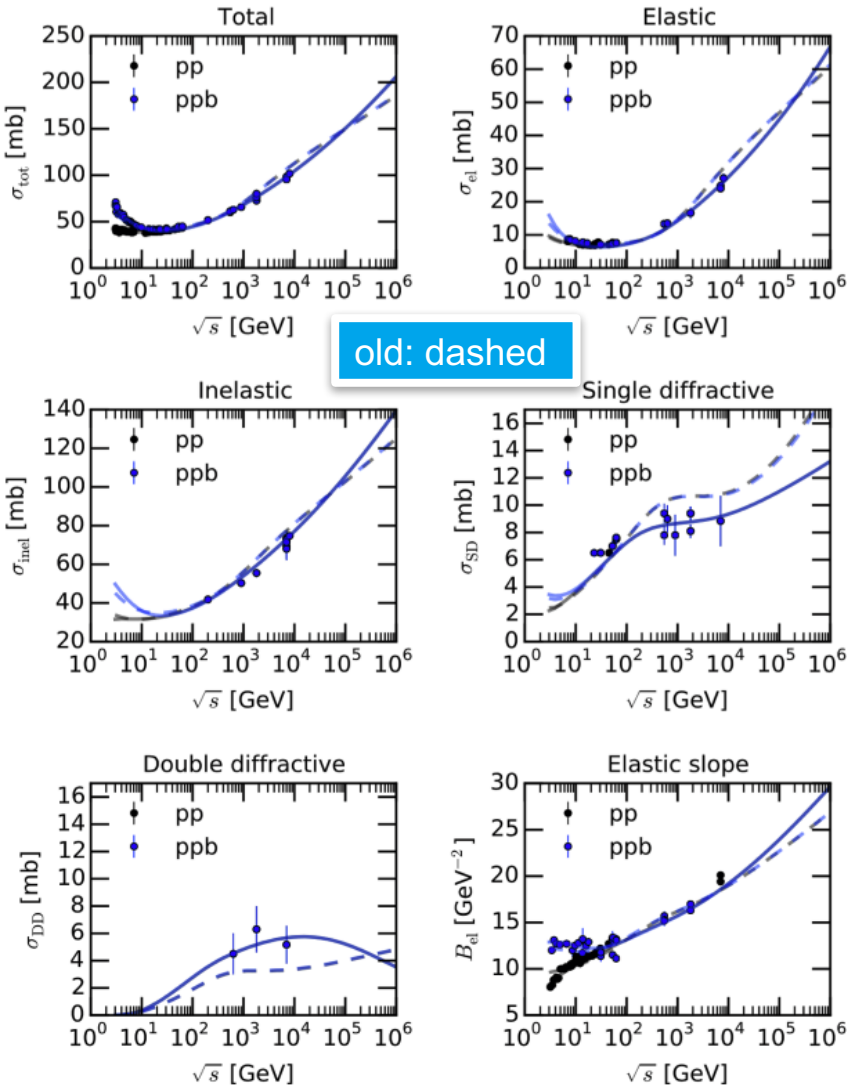
→ Can be used in FLUKA without workarounds

→ Could be implemented in, e.g., GEANT 4

Interaction cross sections

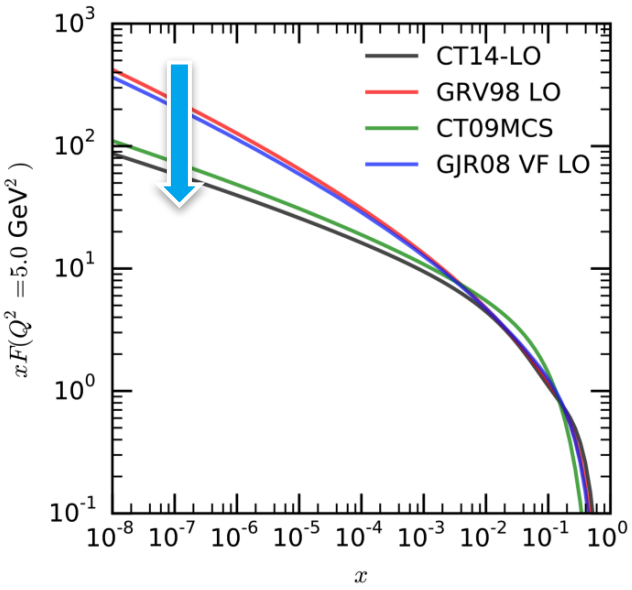


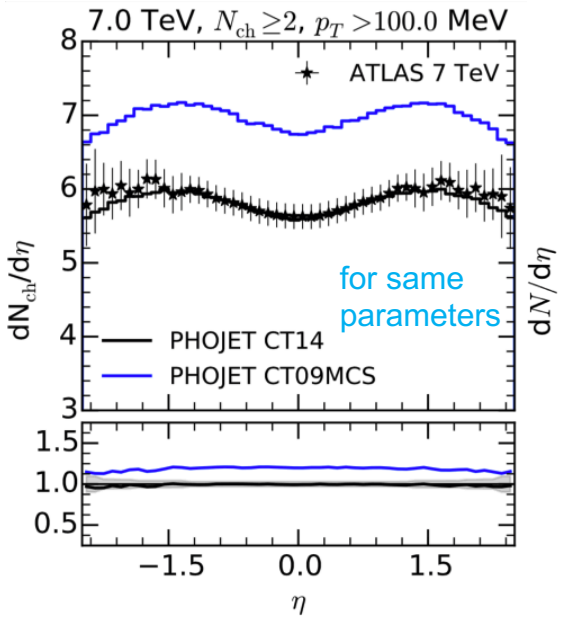
LHC data restricts high energy behavior

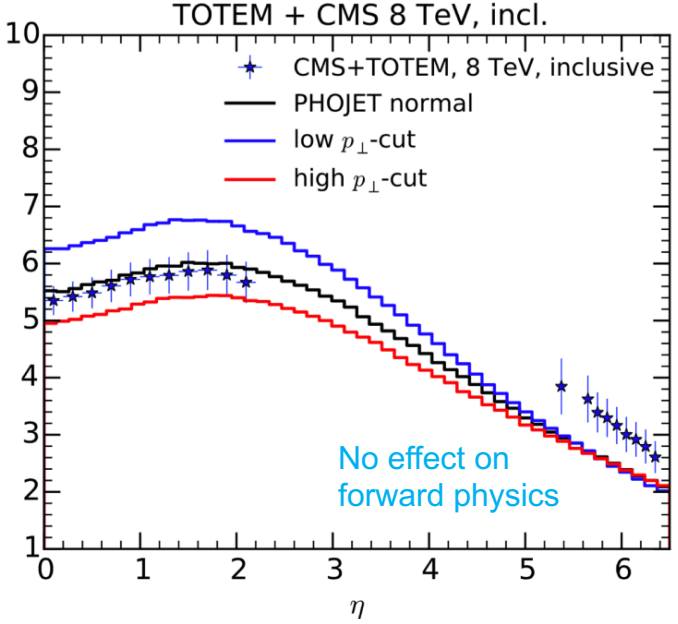


old: dashed

Modern parton distribution functions







Hard cross section: $$\sigma_{QCD} = \sum_{i,j,k,l} \frac{1}{1+\delta_{kl}} \int dx_1\, dx_2 \int_{p_\perp^{\mathrm{cutoff}}} dp_\perp^2\, f_i(x_1,Q^2)\, f_j(x_2,Q^2)\, \frac{d\sigma_{i,j\to k,l}}{dp_\perp}$$

- CT14LO parton distribution functions for hard scatterings (instead of GRV94/98)
- Significantly improved description of LHC distributions

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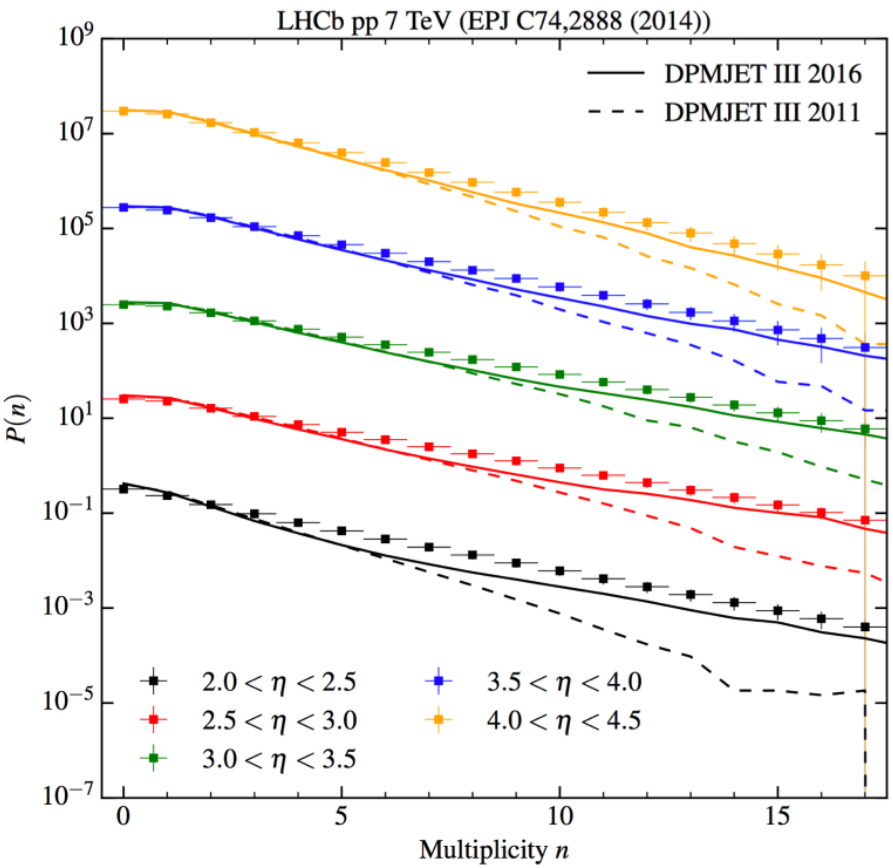
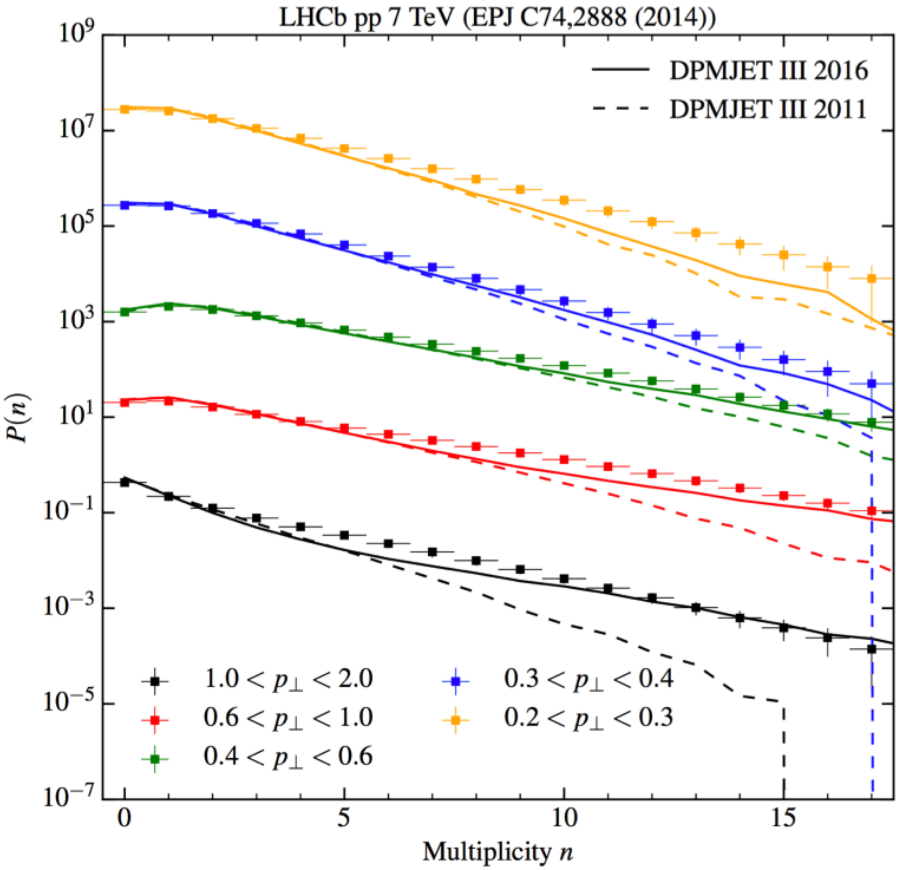
Improvement at LHC energies

angular distributions

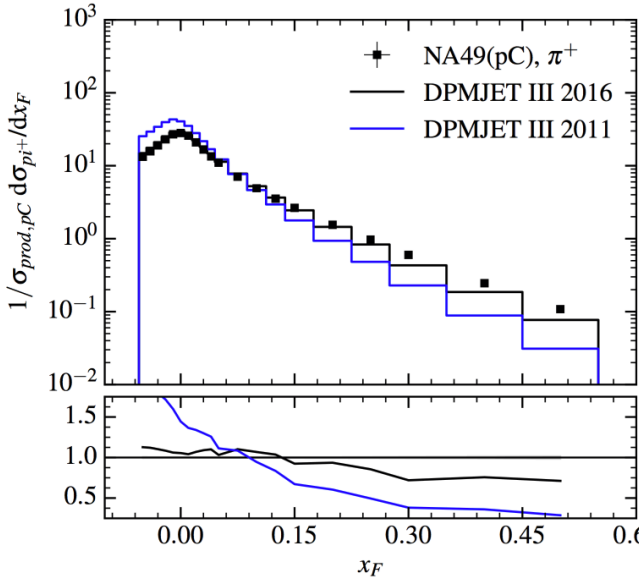


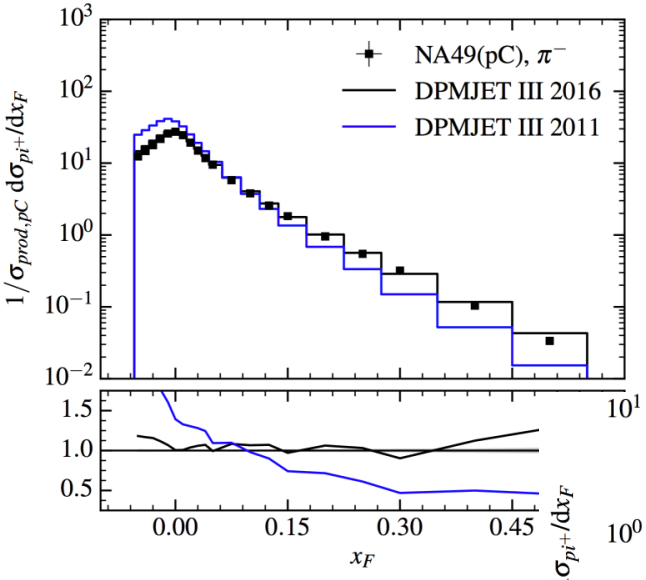
pT distributions



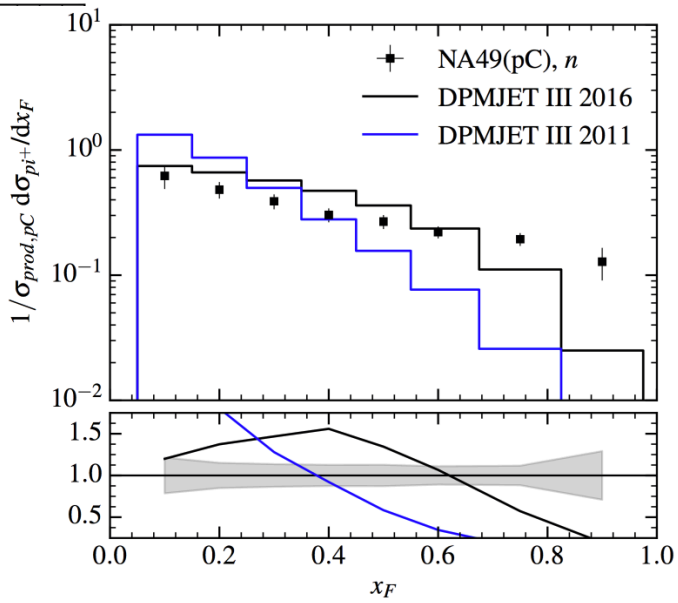
…also for many other measurements

DPMJET at fixed-target energies





proton-Carbon
E_{lab} = 158 GeV



- Incremental improvement for p, n, π, K, ν, Λ
- Baryon spectra as problematic as in SIBYLL 2.1
- "Soft" interactions need more work

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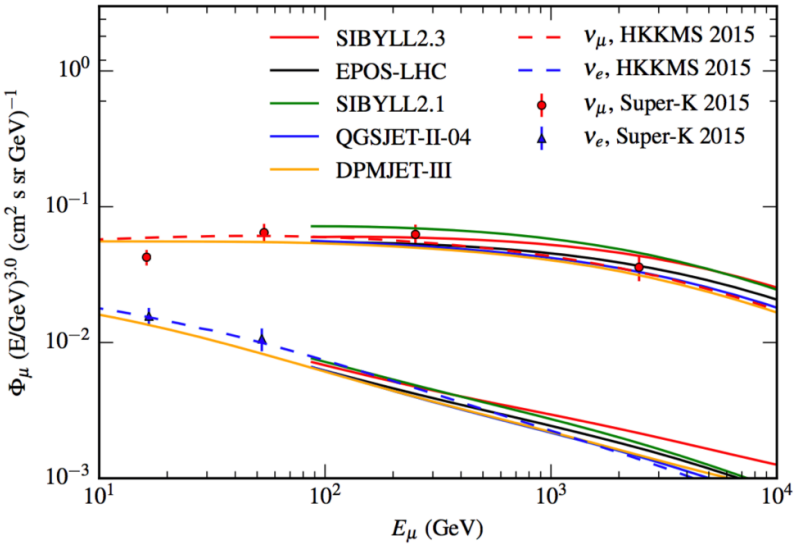
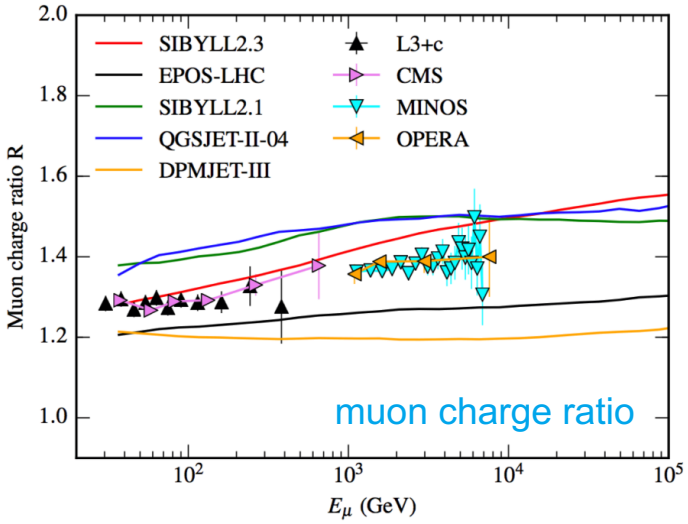
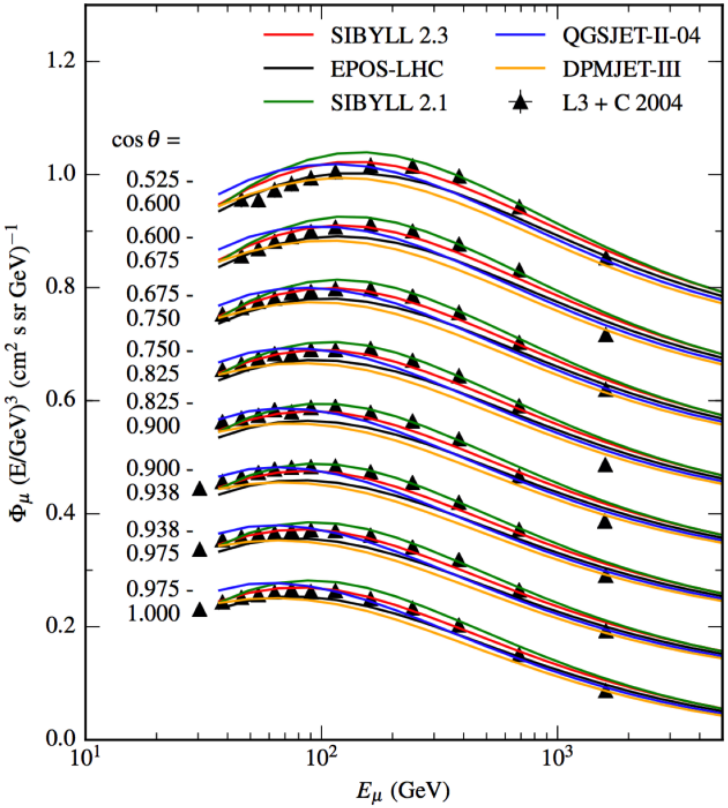
Inclusive lepton fluxes with DPMJET-III and SIBYLL

atmospheric neutrinos





atmospheric muons



- Just the beginning of CR studies with DPMJET
- No air-shower predictions, yet

AF, R. Engel, T. K. Gaisser, F. Riehn and S. Todor. PoS ICRC 2015, 1129 (2015)

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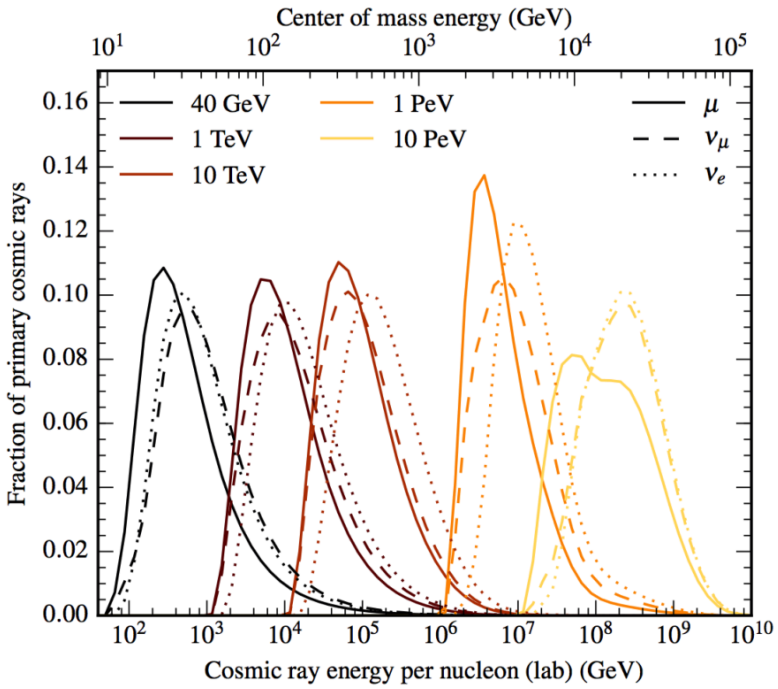
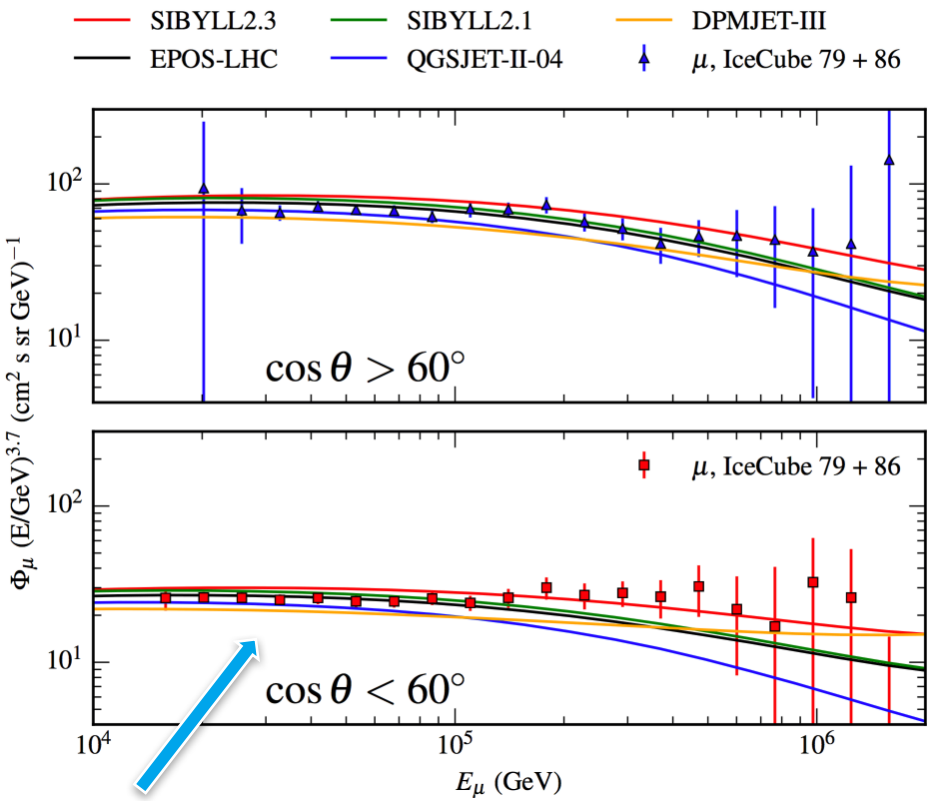
Explore energy extrapolation via CR “beam”

IceCube, Astropart. Phys. 78, 1 (2016)

Relation between primary nucleon energy and inclusive lepton energy



Muon flux measurement by IceCube



LHC energy probed by μ & ν around 100 TeV

Forward particle physics beyond reach of current detectors at accelerators

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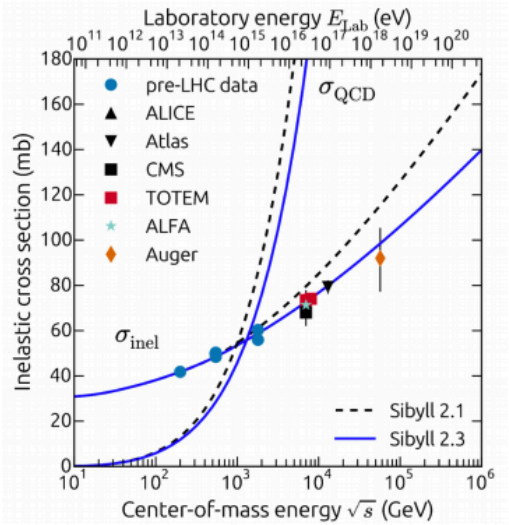
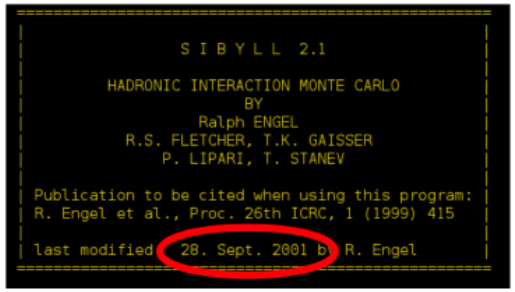
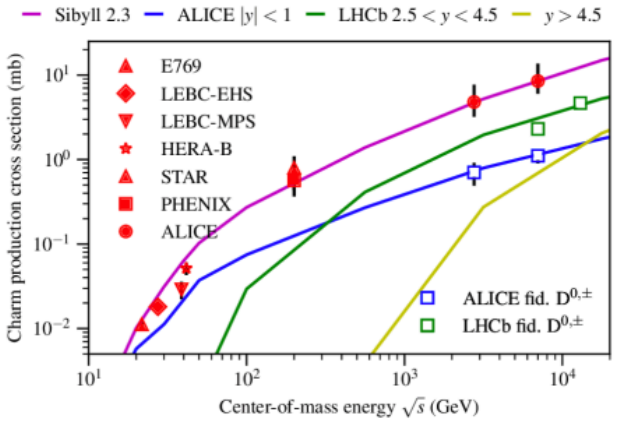
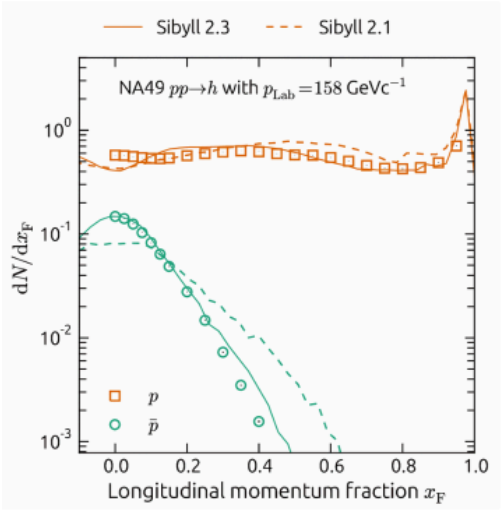
Improvements in SIBYLL 2.3 at a glance

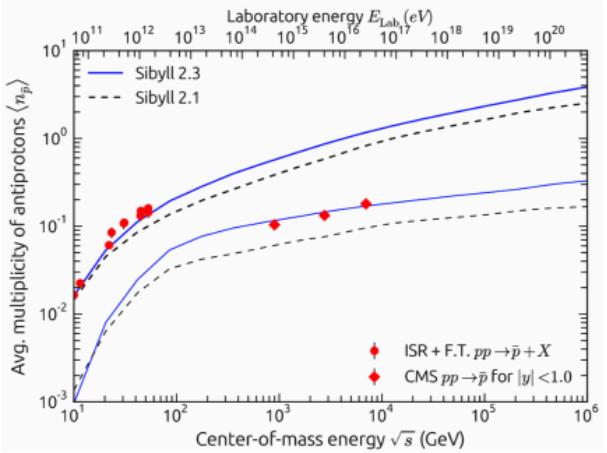








- Interaction cross sections
- Charm production
- Leading particles
- Baryon production
- …

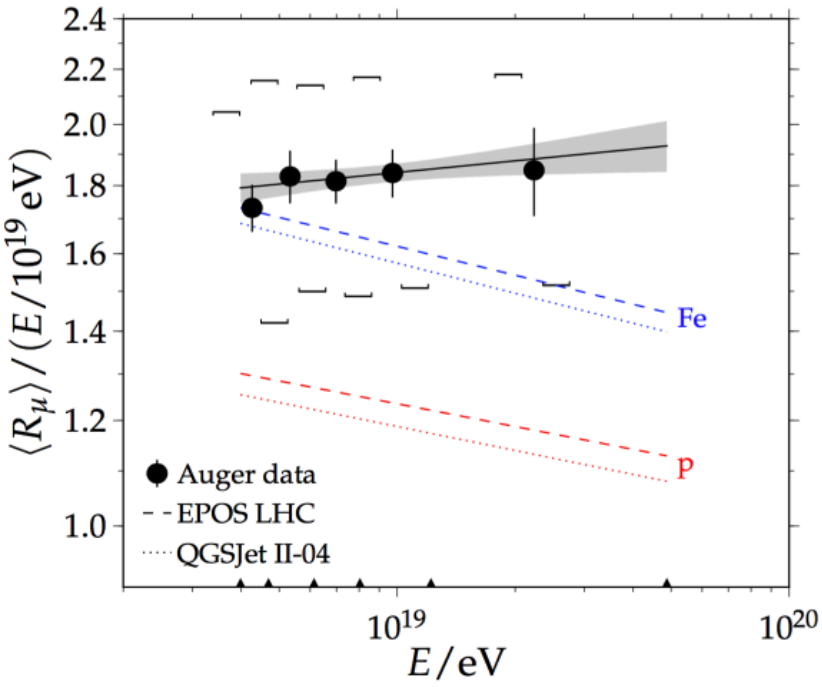


By Felix Riehn & Ralph Engel!

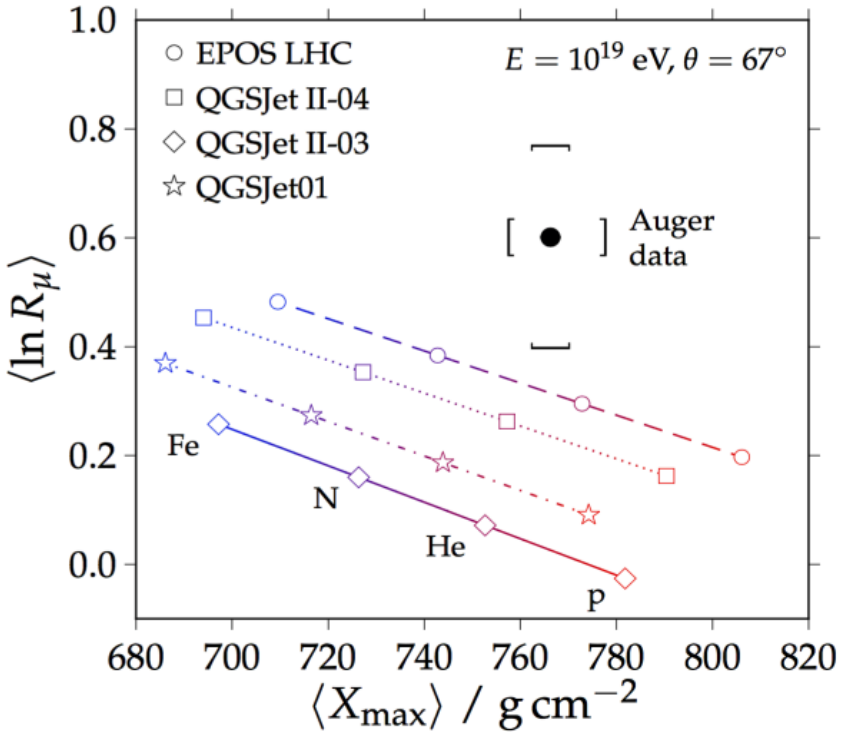
F. Riehn, R. Engel, A. Fedynitch, T. K. Gaisser and T. Stanev. PoS ICRC 2015, 1129 (2015), 1510.00568

The “muon mystery”

muon number in inclined showers θ > 60°



Combination of information on mean X_{max} and muon number at ground



Something is really inconsistent
[hadronic interaction models]

Auger, Phys.Rev. D91 (2015) 032003

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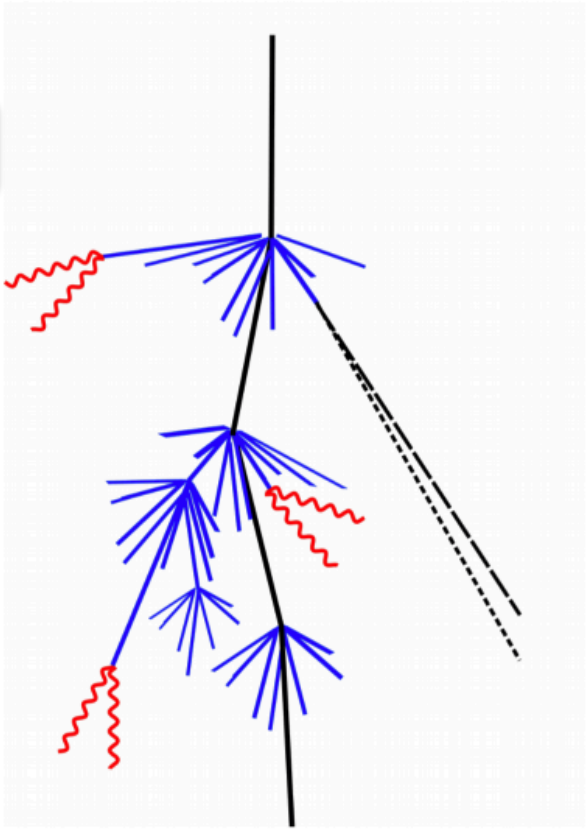
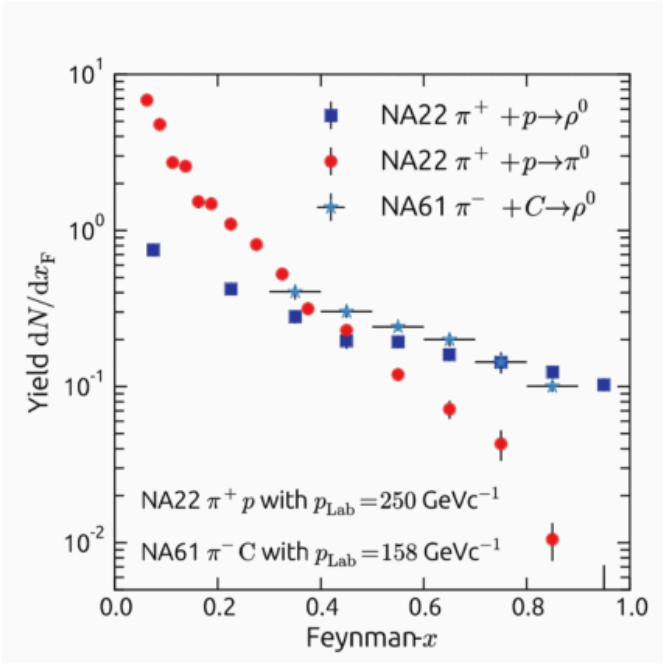
More (low-energy) muons?

Pion interactions!

$$\pi^{\pm} + \text{Air} \rightarrow \rho^{0}$$

$$\pi^{\pm} + \text{Air} \rightarrow \pi^{0}$$





More (low-energy) muons?

Pion interactions!

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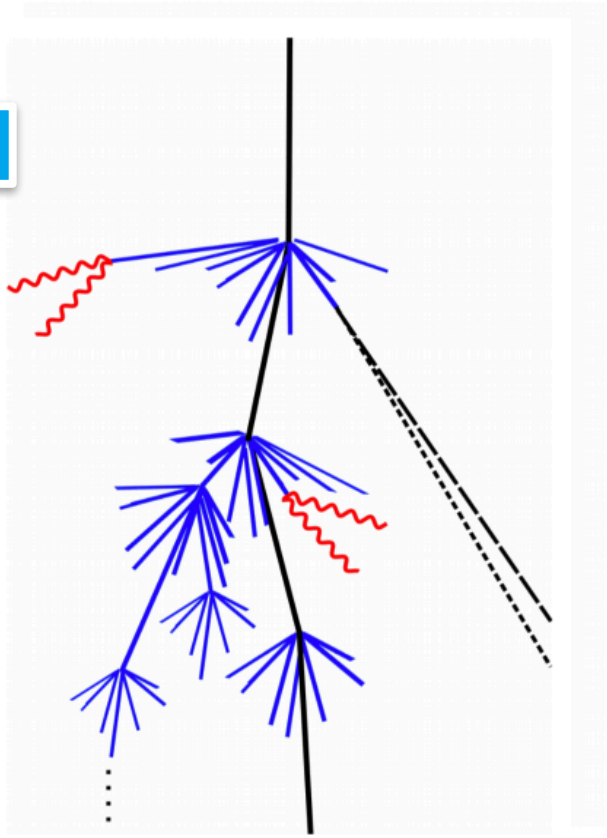
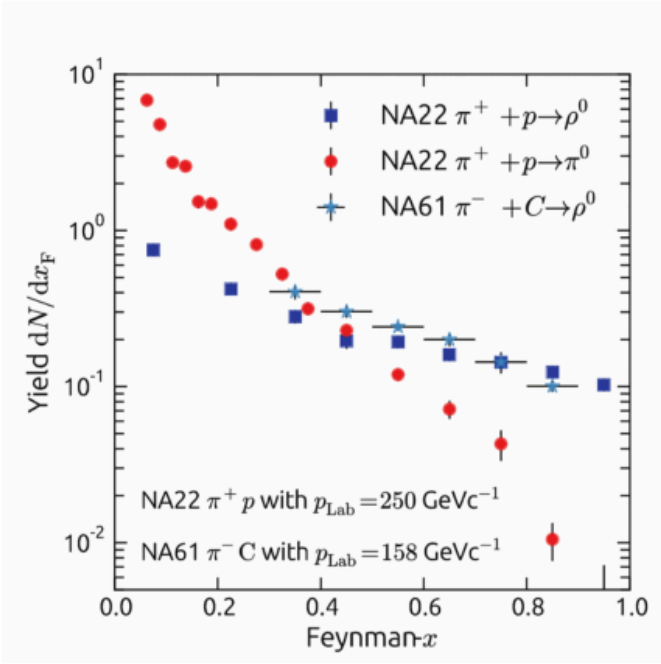
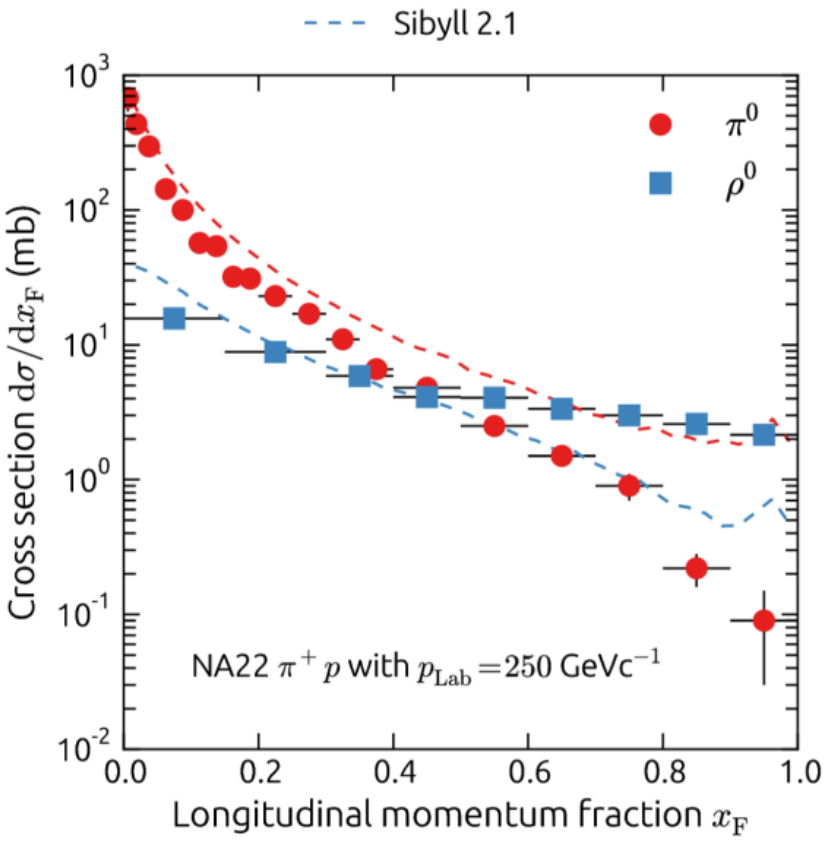


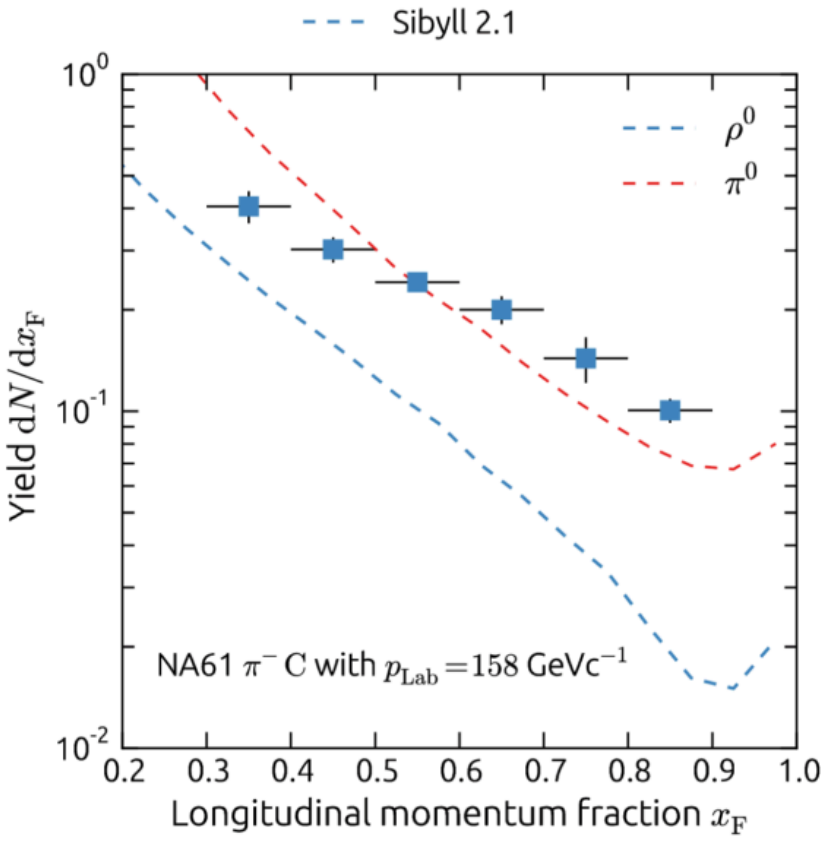


Leading vector mesons

pion - proton



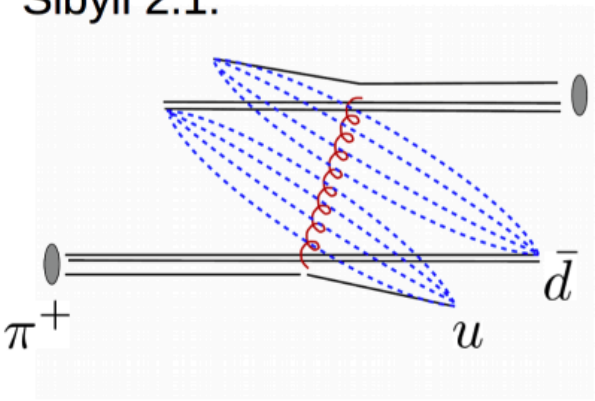
pion - Carbon



Incorrect leading meson!

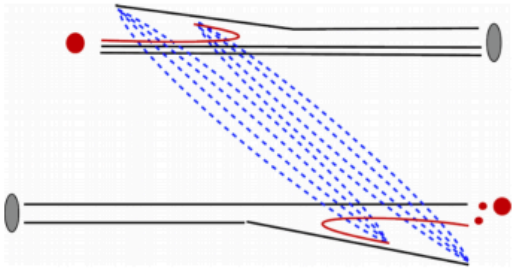
New degrees of needed in microscopic model

Sibyll 2.1:

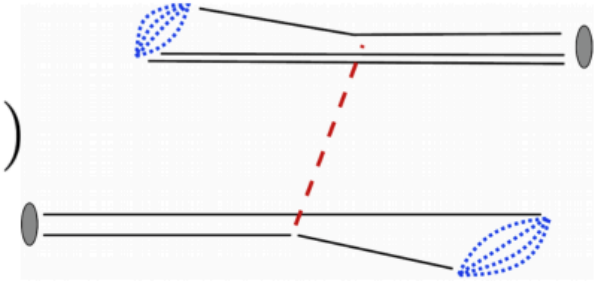


$$R_{\rho^0}/R_{\pi^0} = 0.3$$

Sibyll 2.3:

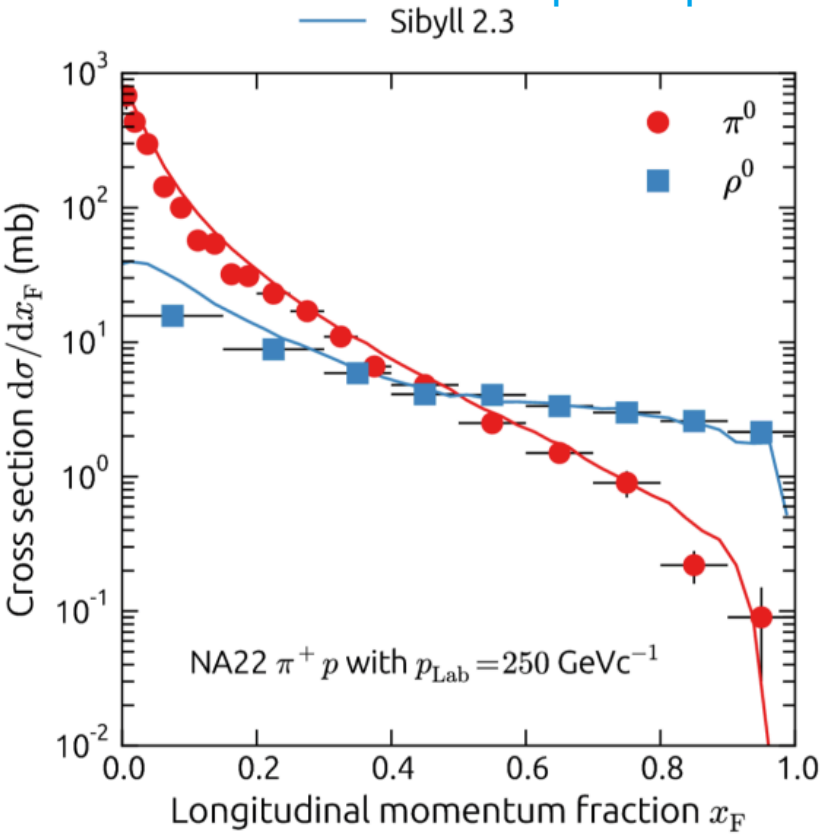


$$R_{\rho^0}/R_{\pi^0} = f(x_{\mathrm{F}})$$

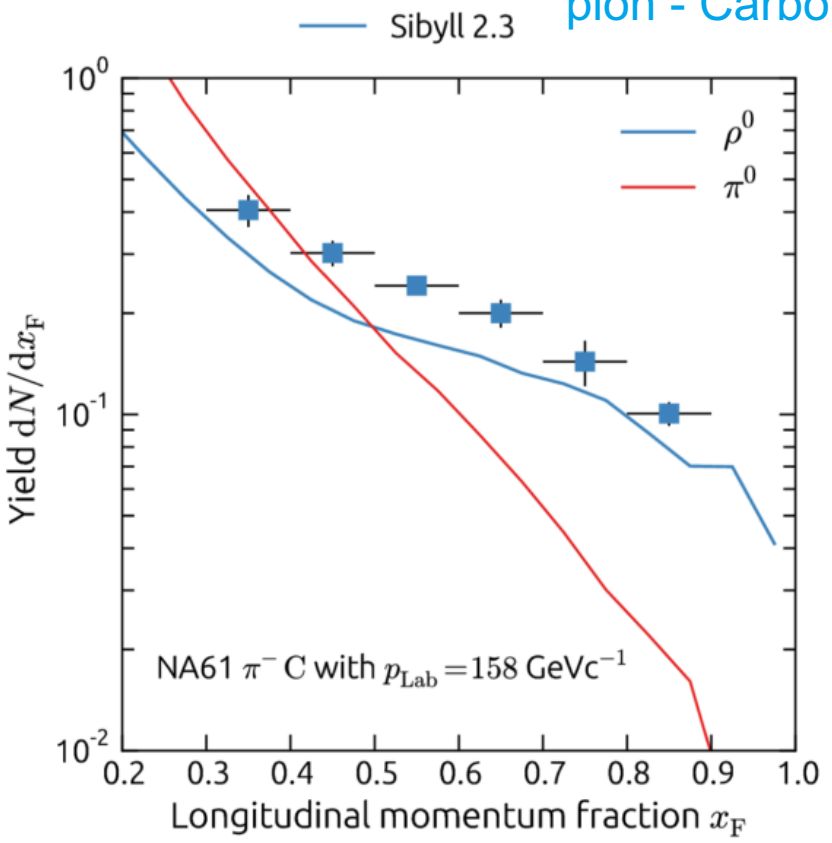


Leading vector mesons

pion - proton

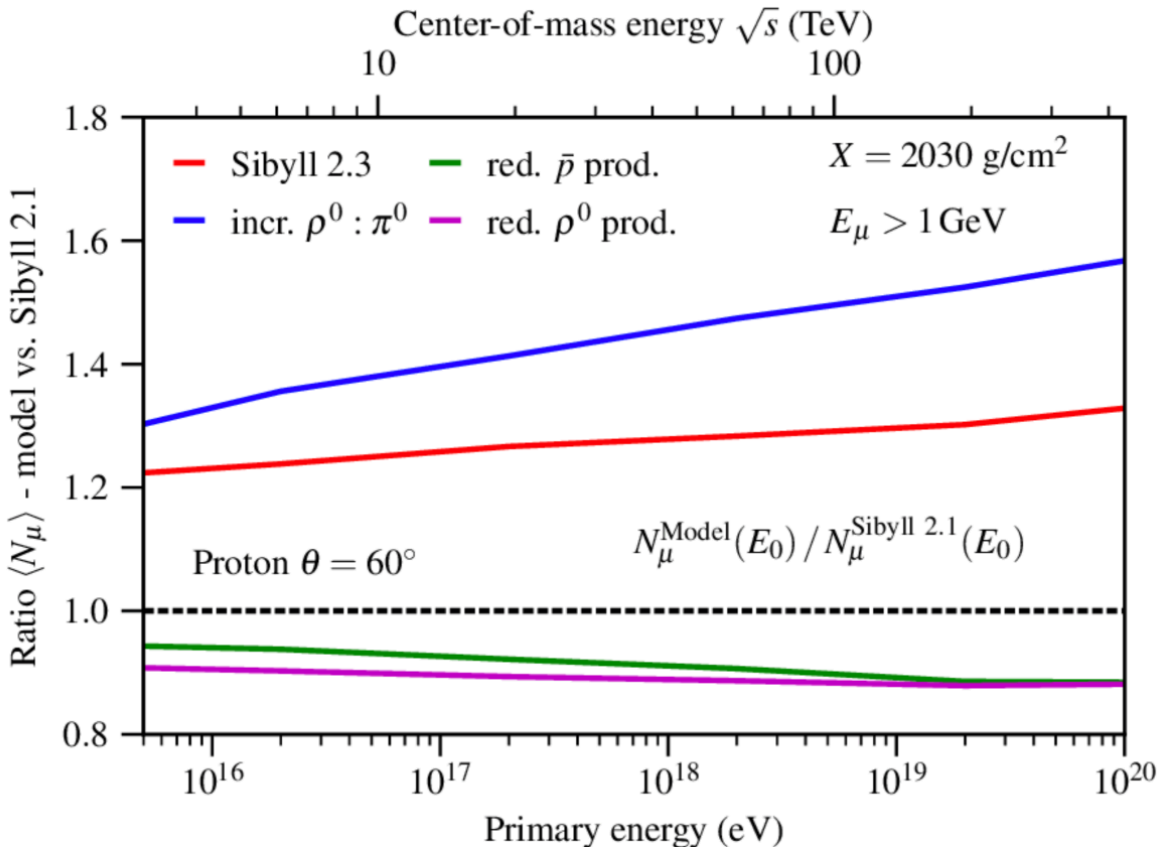


pion - Carbon



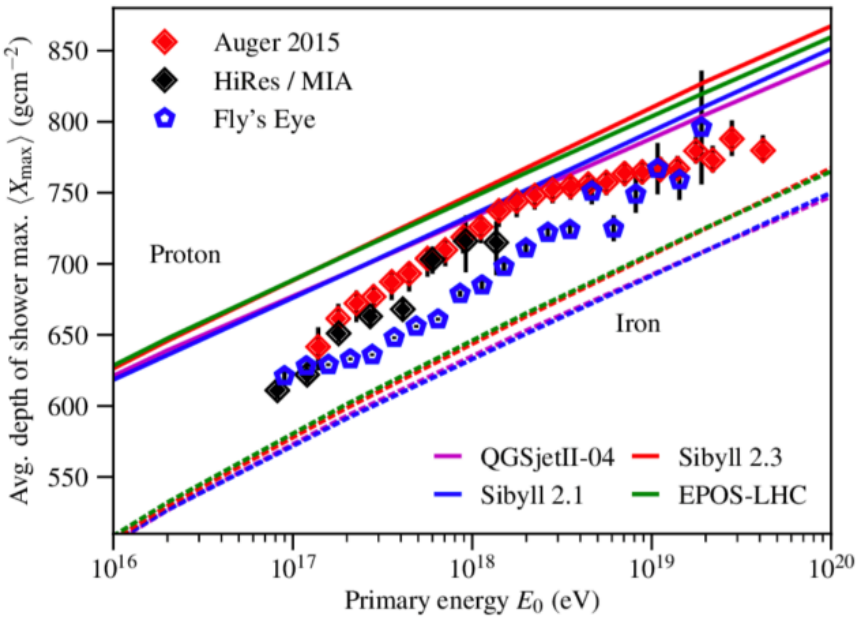
Significantly improved description!

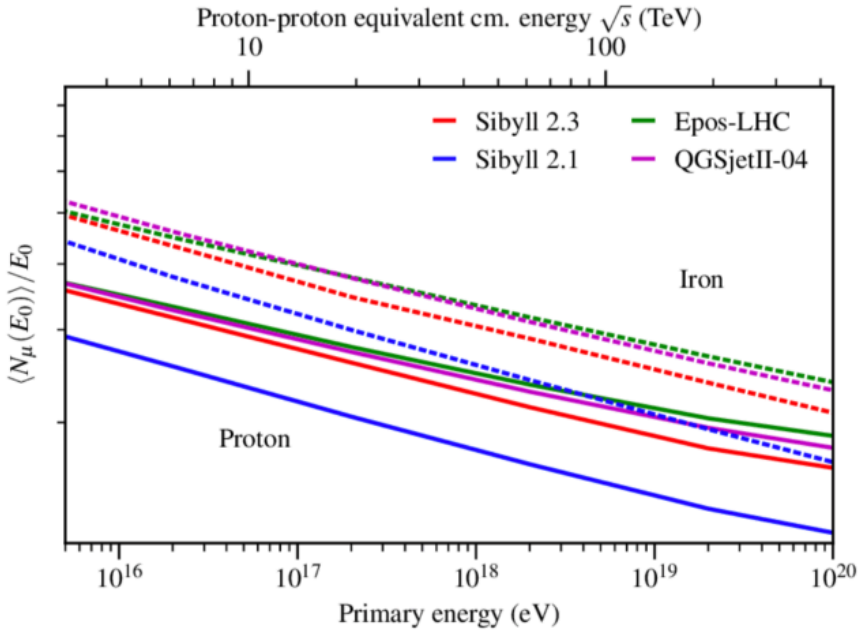
Impact on number of muons



20-30% more muons

New predictions





Deeper showers with more muons

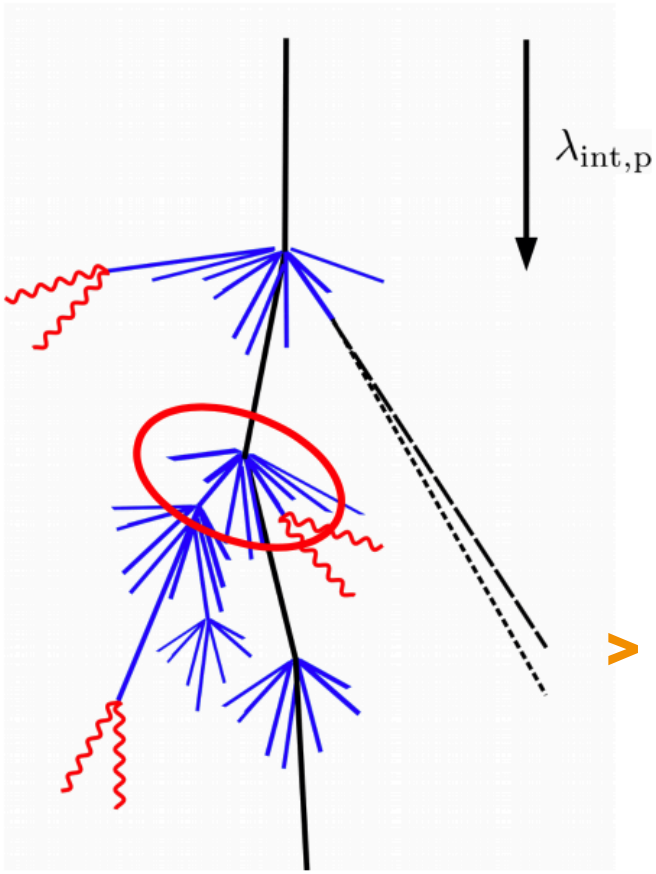
Conclusion

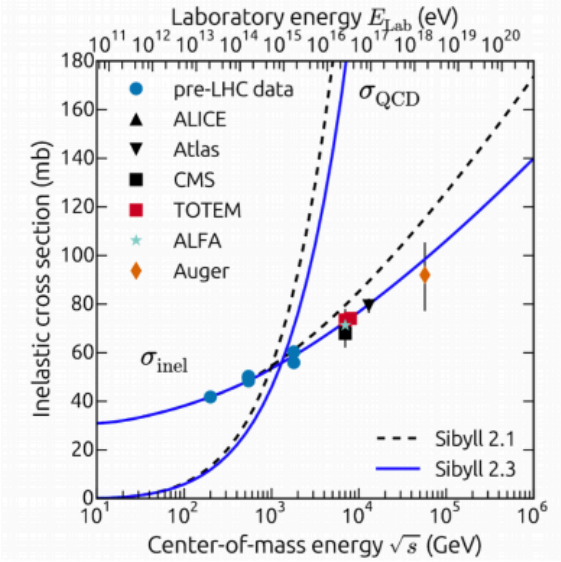
- Significant improvements in the description of hadronic interactions in both models DPMJET-III and SIBYLL 2.3
- DPMJET-III is technically ready for cosmic ray physics, first calculations with inclusive leptons show promising performance
- SIBYLL 2.3 changes notably air-shower predictions in muon number and X_{max}
- It also includes a new model for charm production/prompt neutrinos (not mentioned in this talk)

What's next?

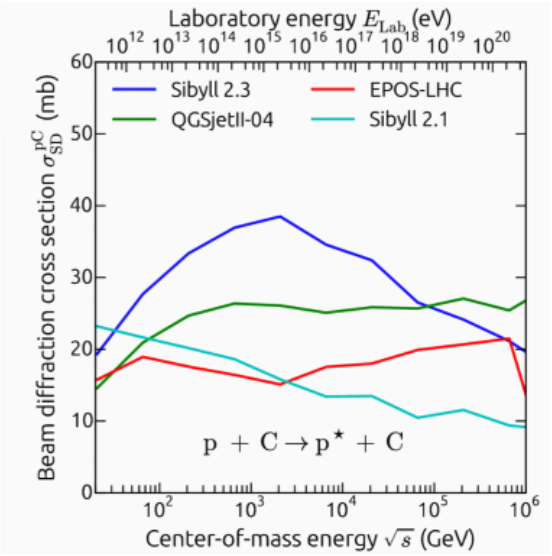
- Extrapolation of non-perturbative models to high energies?
- Re-iteration expected after deeper analysis of CR data with new models
- Nucleus-nucleus interactions, pions, kaons and baryons at fixed target energies need more attention in DPMJET-III

Deeper X_{max}





- Interactions more elastic
  - nuclear Diffraction
  - harder leading particles



Impact on X_{max}