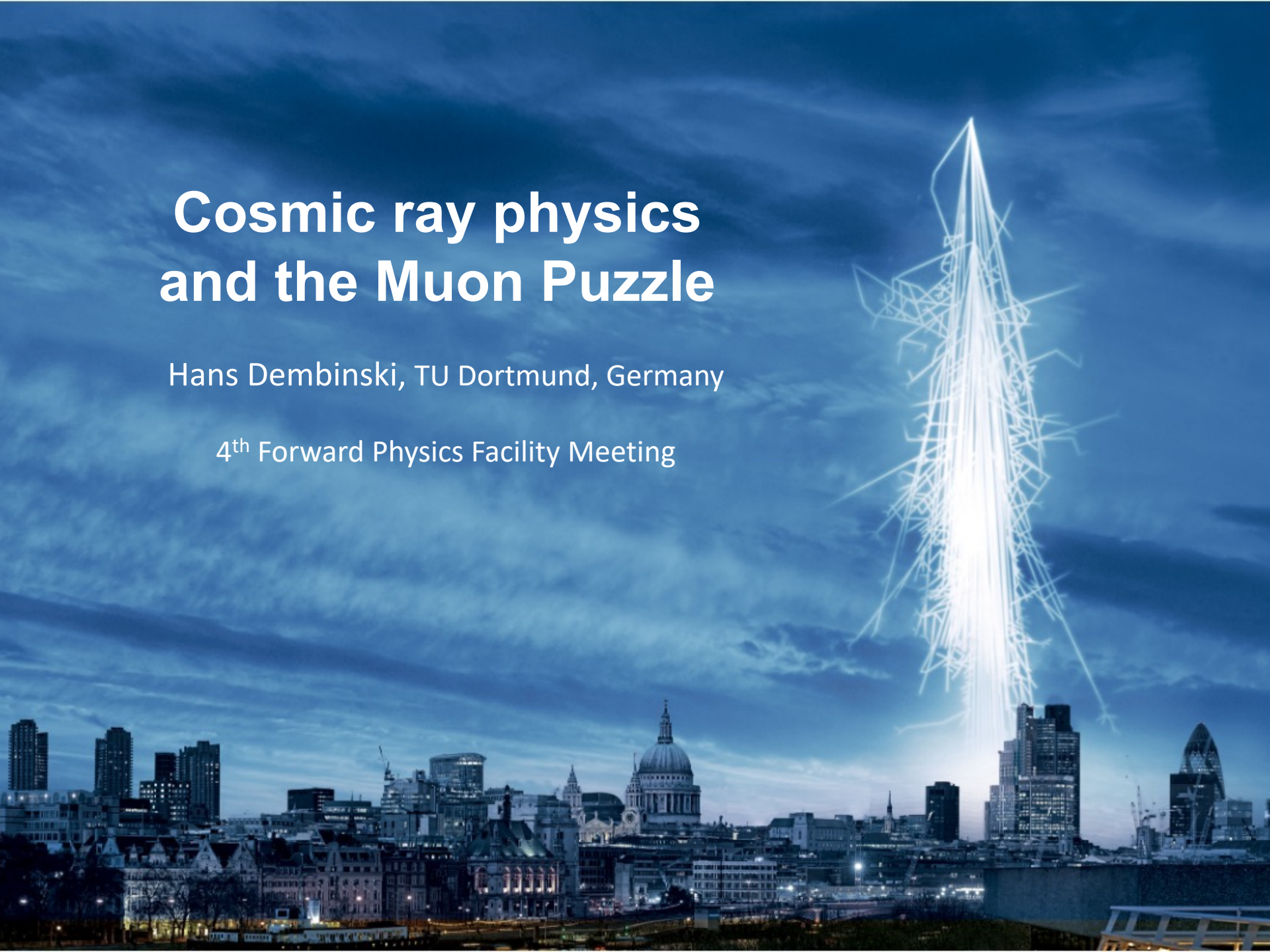


Cosmic ray physics and the Muon Puzzle

Hans Dembinski, TU Dortmund, Germany

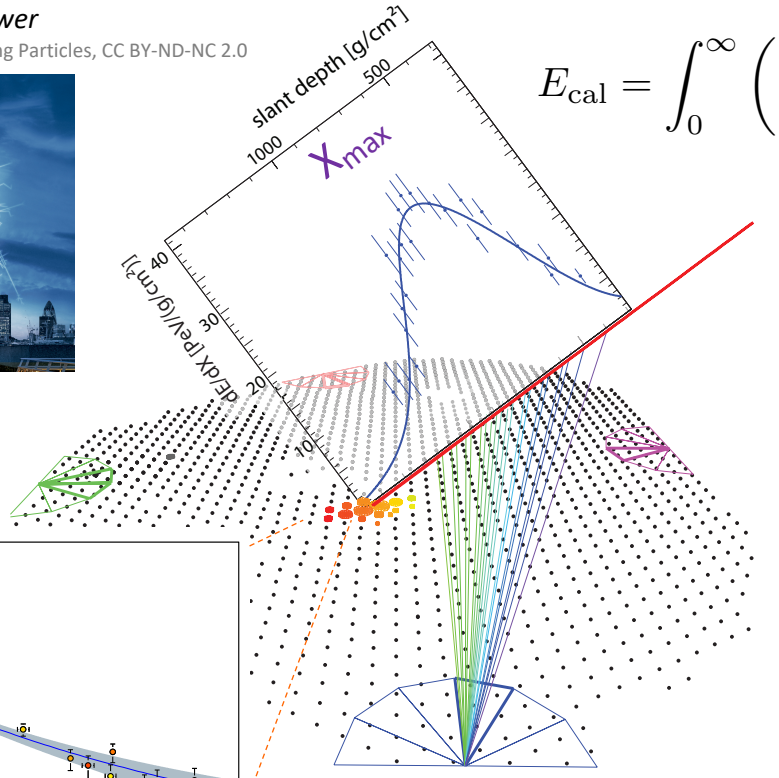
4th Forward Physics Facility Meeting

High-energy cosmic ray detection

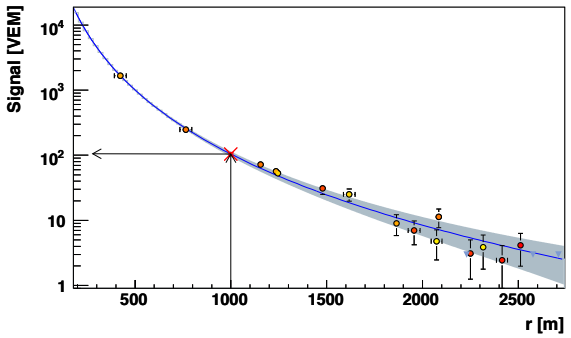
Example: event observed with Pierre Auger Observatory

Artist impression of air shower

Image credit: Rebecca Pitt, Discovering Particles, CC BY-ND-NC 2.0



$$E_{\mathrm{cal}} = \int_0^{\infty} \left(\frac{dE}{dX}\right)_{\mathrm{ionization}} dX$$



Ground signal = **electrons, photons, muons**

- **Direction** from particle arrival times
- **Energy** from size of **eγ component**
- **Mass** from
  depth of shower maximum X_{max}
  size of muonic component N_μ

Mass composition

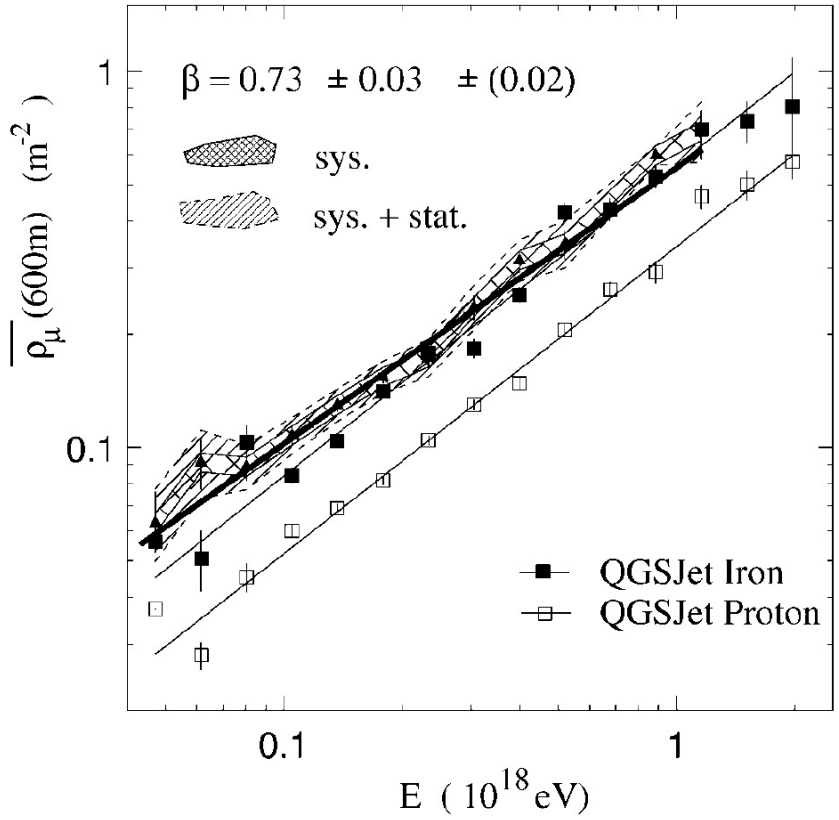
- Strongly constrains theory space on sources
- Important for atm. lepton flux calculation

Muon Puzzle

10^{17} eV

HiRes-MIA experiment
Abu-Zayyad et al. PRL 84 (2000) 4276

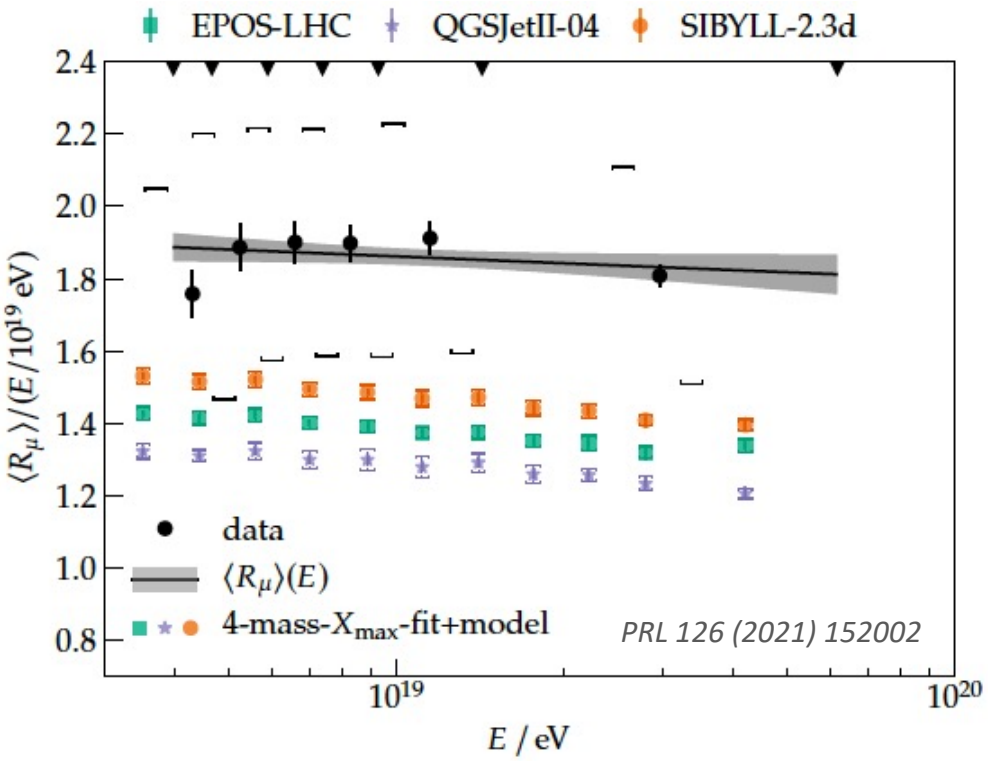
Muon content above simulations
(now outdated)



10^{19} eV

Pierre Auger Observatory
PRD 91 (2015) 032003
PRL 117 (2016) 192001
Eur. Phys. J. C (2020) 80:751
PRL 126 (2021) 152002

Muon content above simulations
(state-of-the-art)

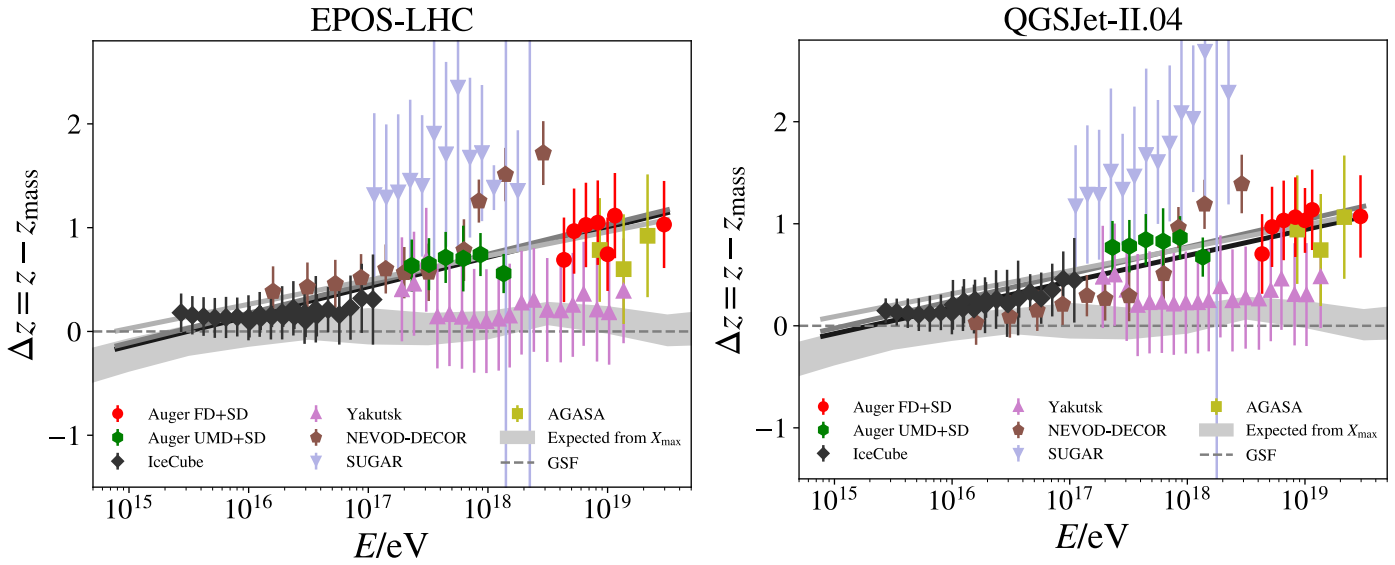


Muon deficit in simulated showers

WHISP publications
EPJ Web Conf. 210 (2019) 02004
PoS ICRC2019 (2020) 214
PoS(ICRC2021)349

Abstract z scale
independent of experiment,
dependent on air shower model

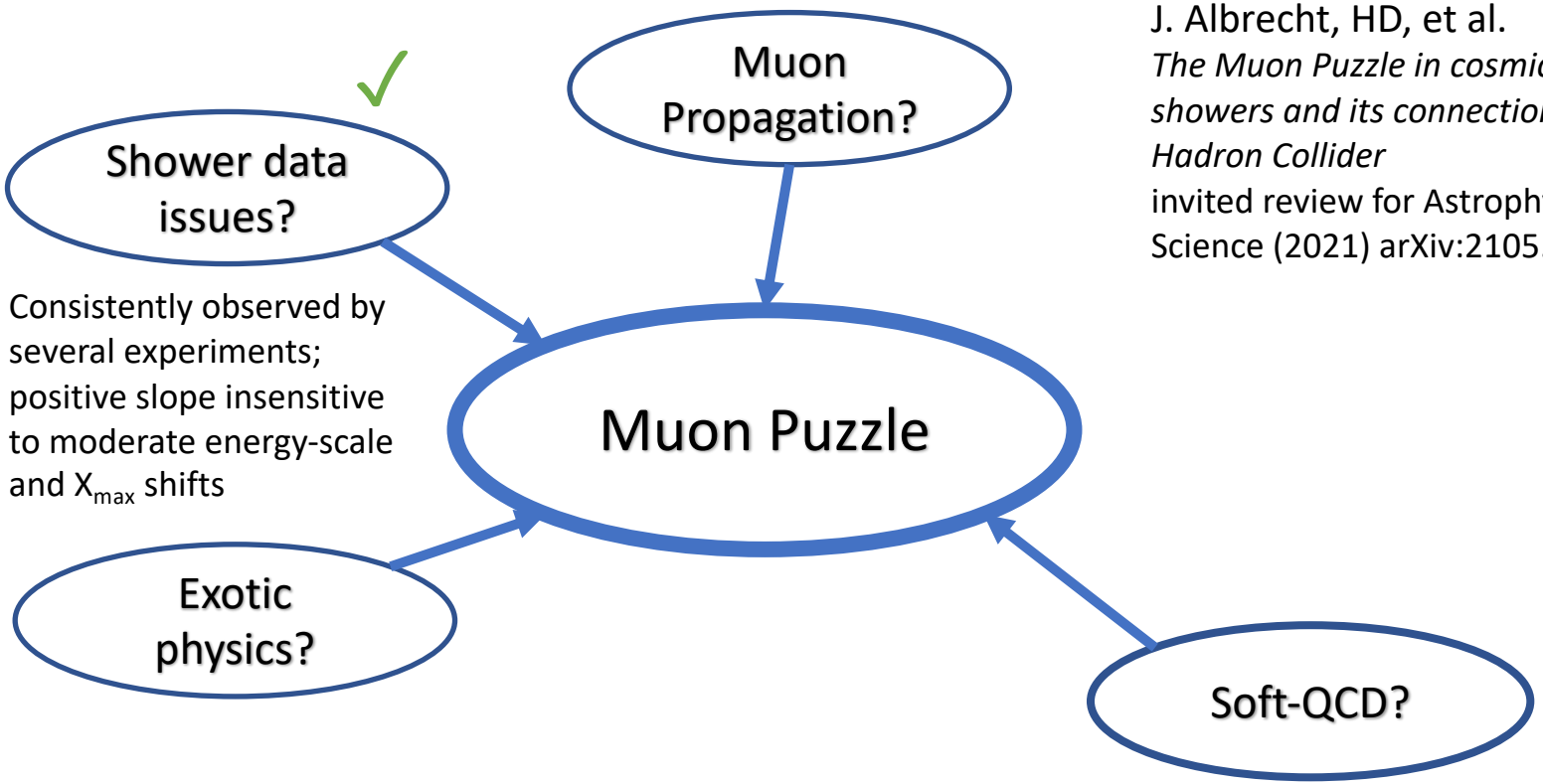
$$z = \frac{\ln\left(N_{\mu}^{\mathrm{det}}\right) - \ln\left(N_{\mu,\boldsymbol{p-sim}}^{\mathrm{det}}\right)}{\ln\left(N_{\mu,\mathbf{Fe-sim}}^{\mathrm{det}}\right) - \ln\left(N_{\mu,\boldsymbol{p-sim}}^{\mathrm{det}}\right)}$$



$$z_{\mathrm{mass}} \approx \frac{\langle \ln A \rangle}{\ln 56}$$

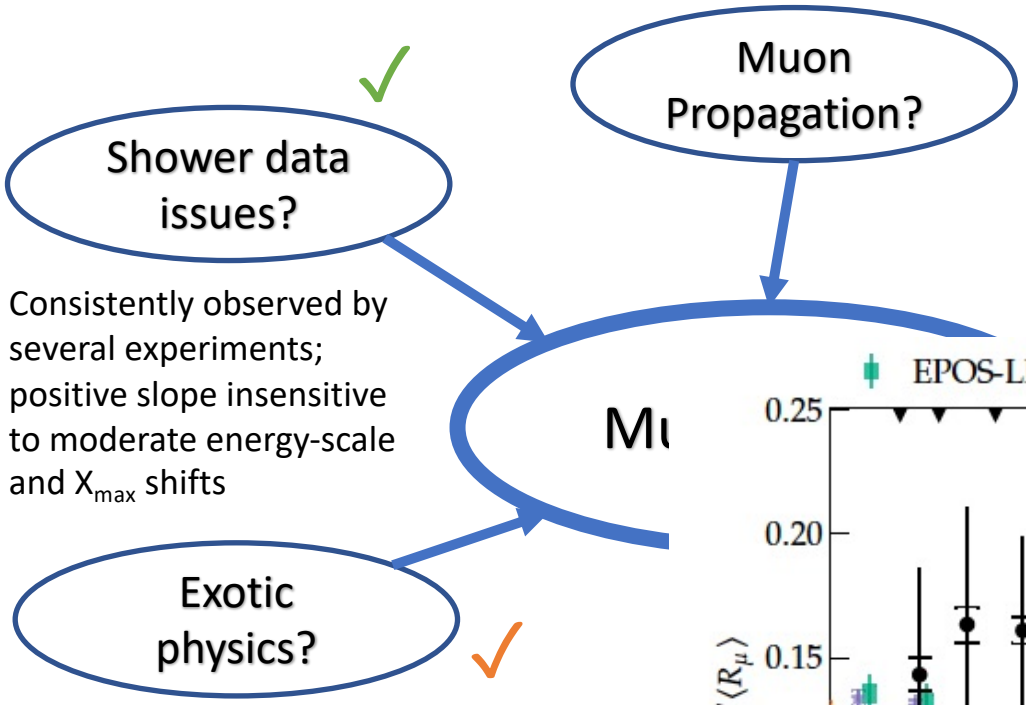
- Meta-analysis of muon data from **nine** air shower experiments
- Re-calibrated original data and convert it to abstract z scale
- Subtract z_{mass}, prediction from mass composition measurements
- Slope of line model is 8σ (10σ) away from zero
- Onset of deviation around 40 PeV corresponds to $\sqrt{s} \sim 8$ TeV; **in reach of LHC**

Attempts to explain muon puzzle



J. Albrecht, HD, et al.
The Muon Puzzle in cosmic-ray induced air showers and its connection to the Large Hadron Collider
invited review for Astrophysics and Space Science (2021) arXiv:2105.06148

Attempts to explain muon puzzle

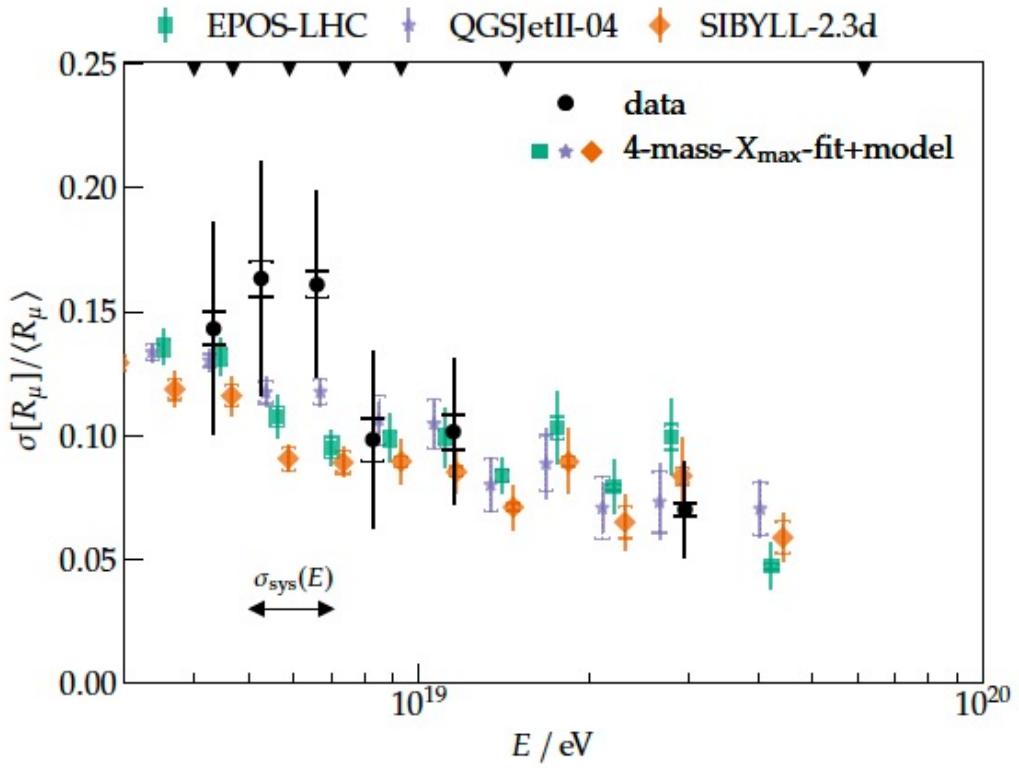


Consistently observed by several experiments; positive slope insensitive to moderate energy-scale and X_{max} shifts

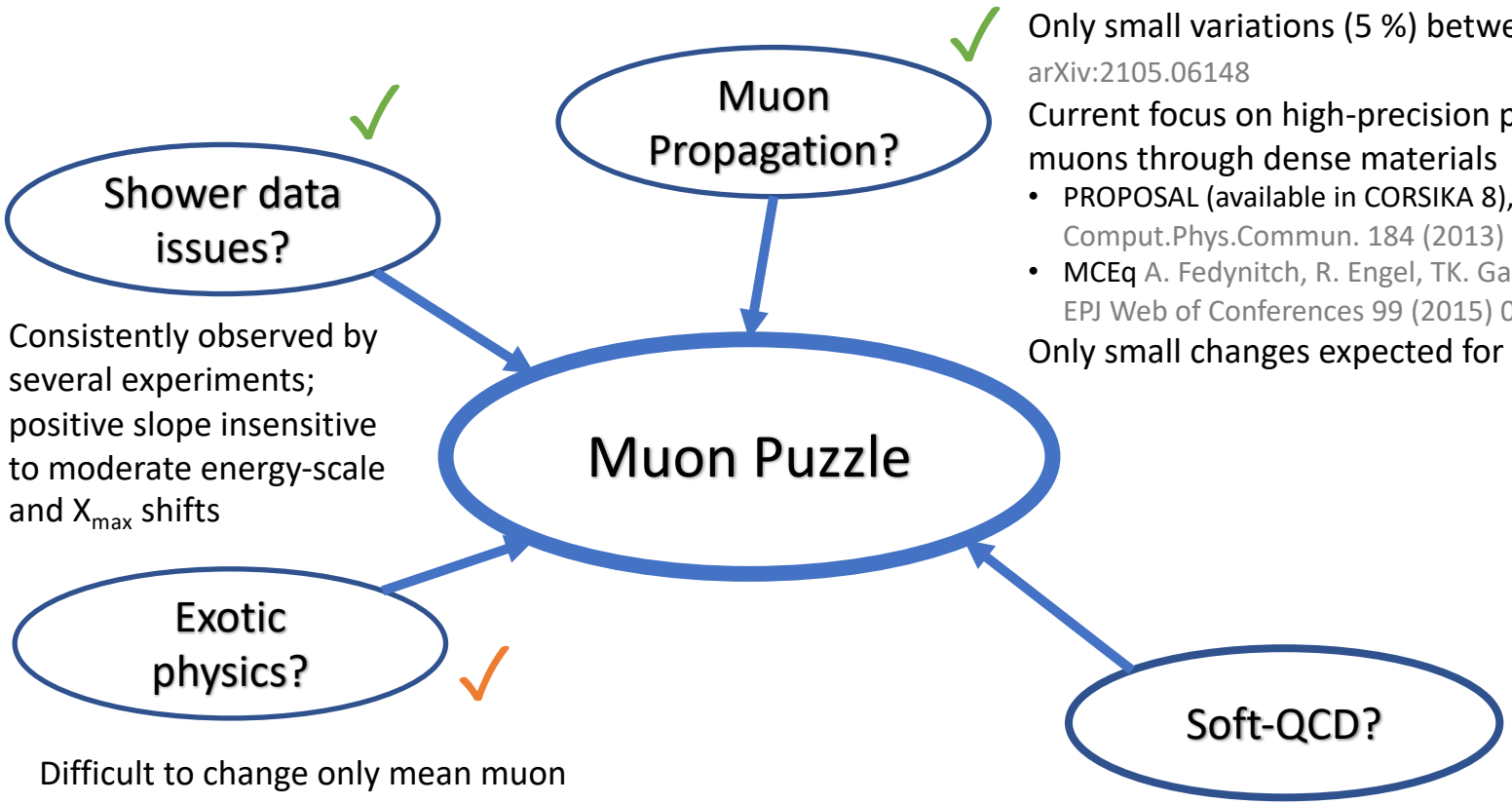
Difficult to change only mean muon number, but keep fluctuations of X_{max} and N_μ same; early onset of muon discrepancy

First measurement of muon fluctuations Pierre Auger collab., PRL 126 (2021) 15, 152002

J. Albrecht, HD, et al.
The Muon Puzzle in cosmic-ray induced air showers and its connection to the Large Hadron Collider
invited review for Astrophysics and Space Science (2021) arXiv:2105.06148



Attempts to explain muon puzzle



Only small variations (5 %) between shower codes arXiv:2105.06148

Current focus on high-precision propagation of TeV muons through dense materials

- PROPOSAL (available in CORSIKA 8), JH. Koehne et al. Comput.Phys.Commun. 184 (2013) 2070-2090
- MCEq A. Fedynitch, R. Engel, TK. Gaisser, T. Stanev, EPJ Web of Conferences 99 (2015) 08001

Only small changes expected for GeV muons in air

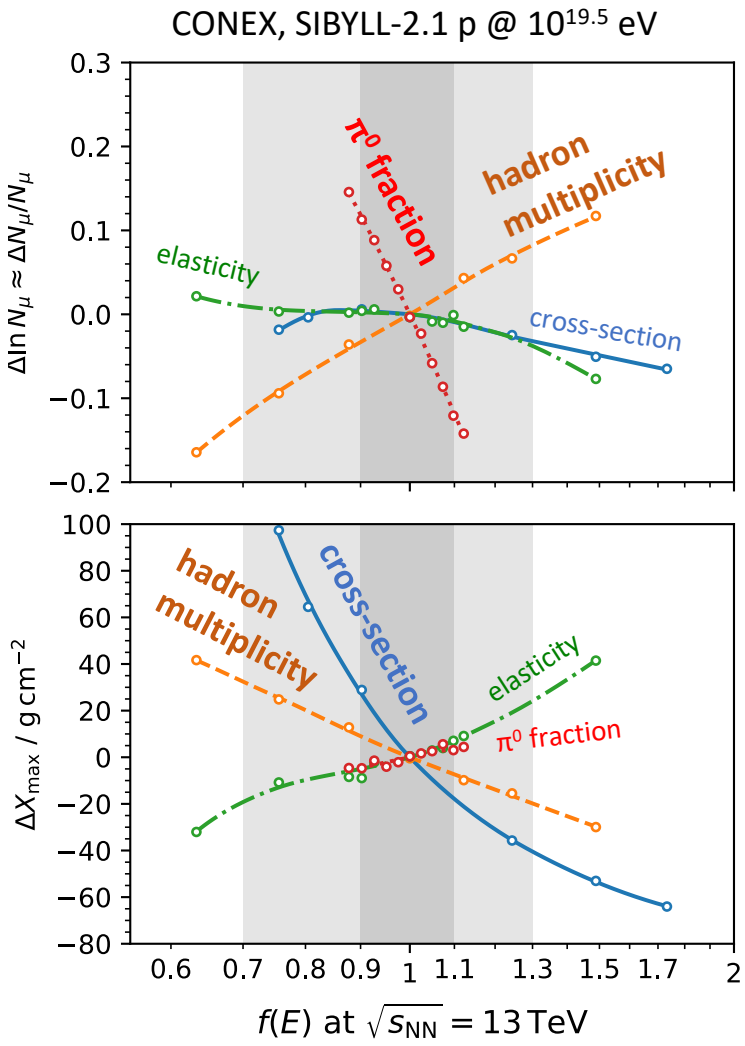
Consistently observed by several experiments; positive slope insensitive to moderate energy-scale and X_{max} shifts

Difficult to change only mean muon number, but keep fluctuations of X_{max} and N_{μ} same; early onset of muon discrepancy

First measurement of muon fluctuations Pierre Auger collab., PRL 126 (2021) 15, 152002

From shower muons to QCD

R. Ulrich, R. Engel, M. Unger, PRD 83 (2011) 054026



- Modify hadronic features in SIBYLL-2.1 and other models with energy-dependent factor $f(E)$
- Study effect in $10^{19.5}$ eV shower simulations

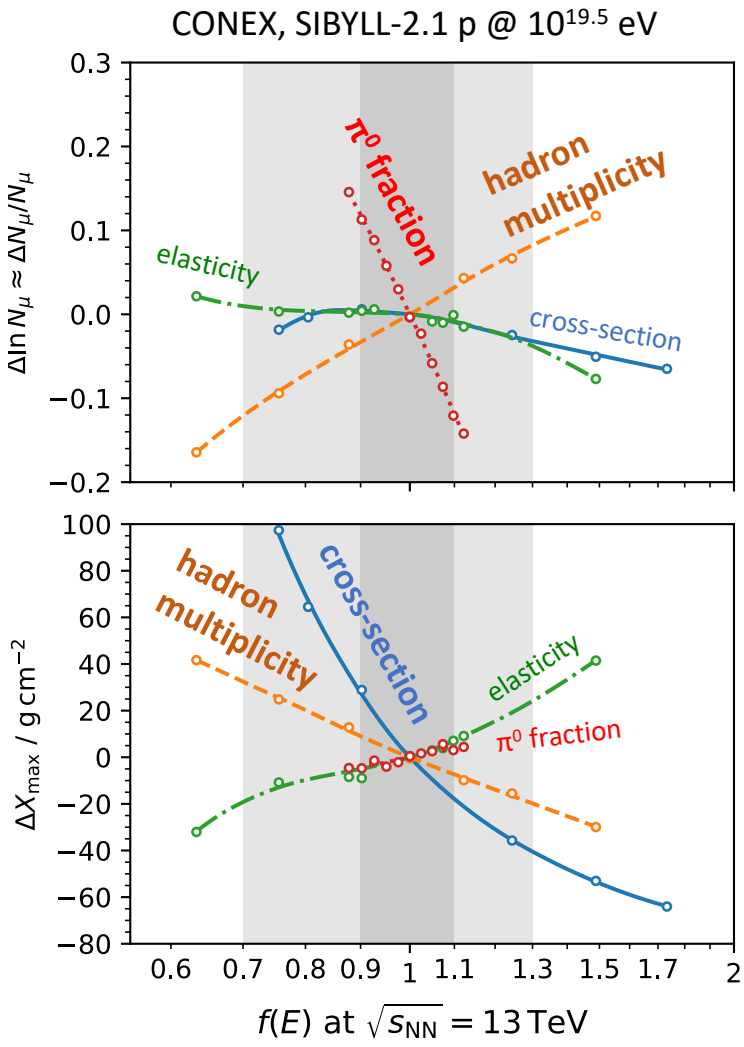
- Number of muons produced, N_μ
  - Very sensitive to π^0 fraction
  - Sensitive to hadron multiplicity

- Depth of shower maximum, X_{max}
  - Very sensitive to cross-section
  - Sensitive to hadron multiplicity
  - Insensitive to π^0 fraction

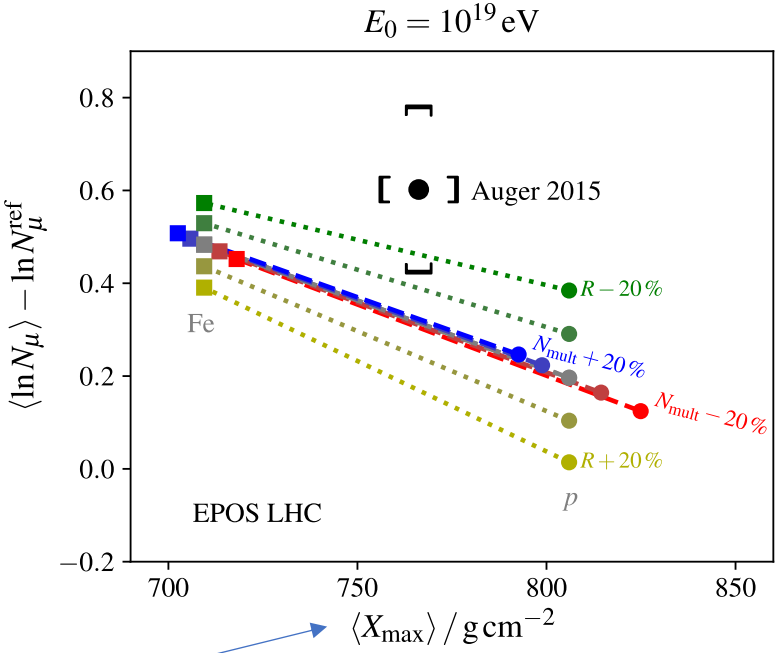
Changing π^0 fraction most promising

From shower muons to QCD

R. Ulrich, R. Engel, M. Unger, PRD 83 (2011) 054026



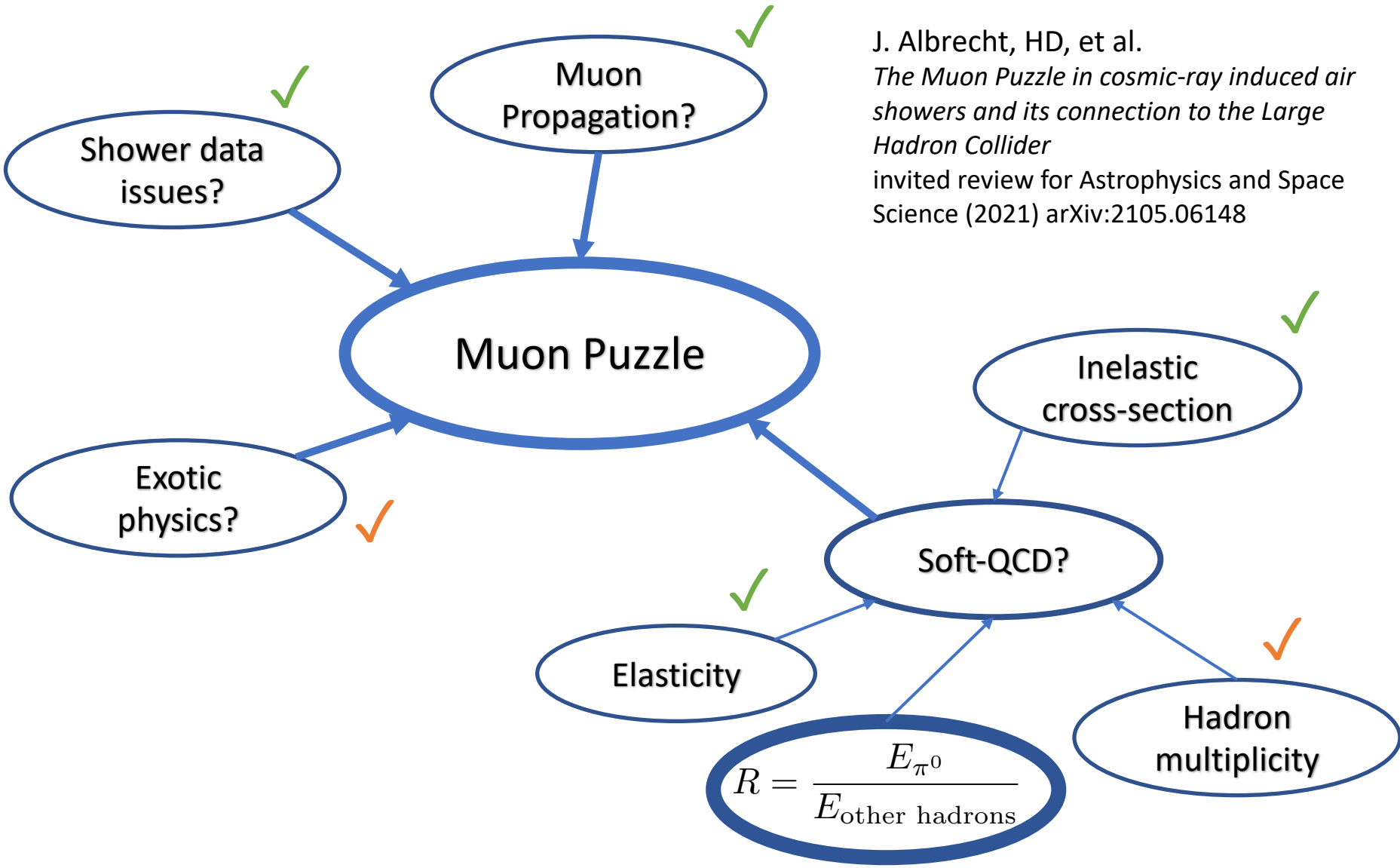
S. Baur, HD, M. Perlin, T. Pierog, R. Ulrich, K. Werner, arXiv:1902.09265



$$R = \frac{E_{\pi^0}}{E_{\text{other hadrons}}}$$

- Only changes to *R* can solve muon puzzle
- Small changes have large effect,
  R needs to be known to about 5 %

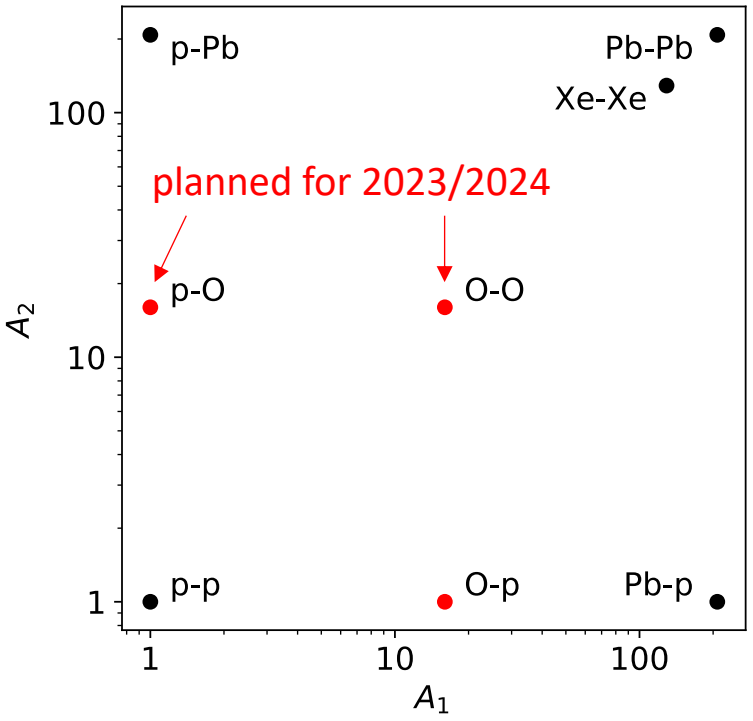
Attempts to explain muon puzzle



J. Albrecht, HD, et al.
The Muon Puzzle in cosmic-ray induced air showers and its connection to the Large Hadron Collider
invited review for Astrophysics and Space Science (2021) arXiv:2105.06148

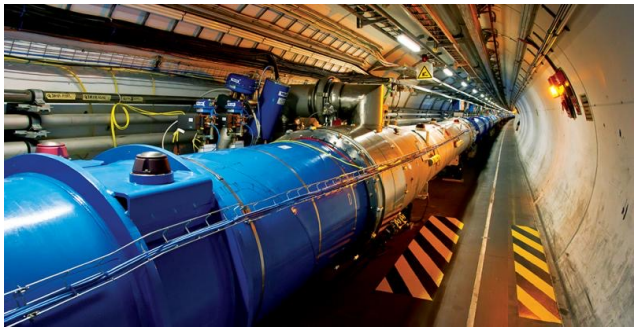
Collisions at the LHC and air showers

Collision systems at the LHC
Run 3: p-p @ 14 TeV, p-O @ 10 TeV

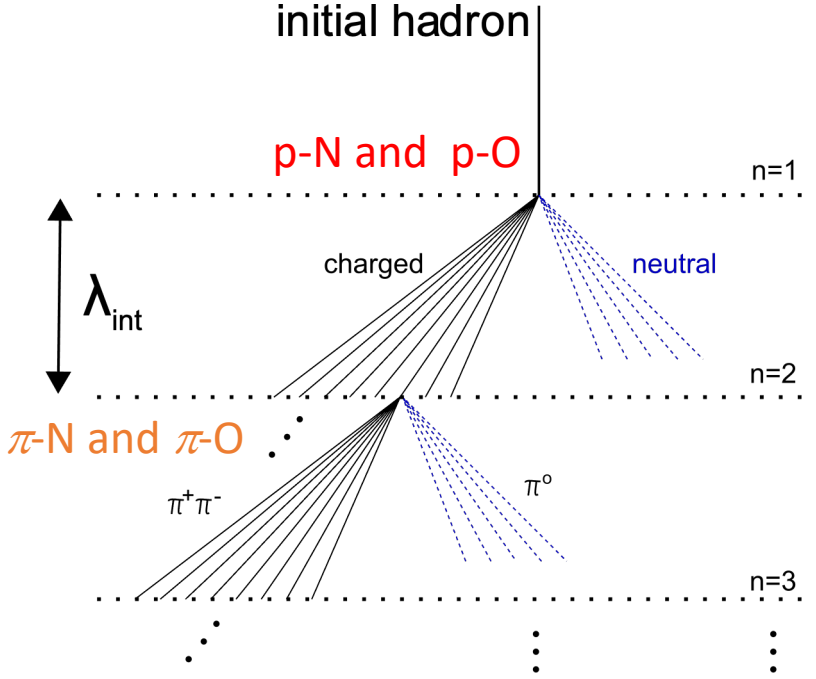


Fixed target data at sub-TeV (LHCb only)

- p+(p,...,O,N,...) @ 0.11 TeV
- Pb+(p,...,O,N,...) @ 0.07 TeV
- O+O, O+p @ 0.08 TeV (in Run 3)



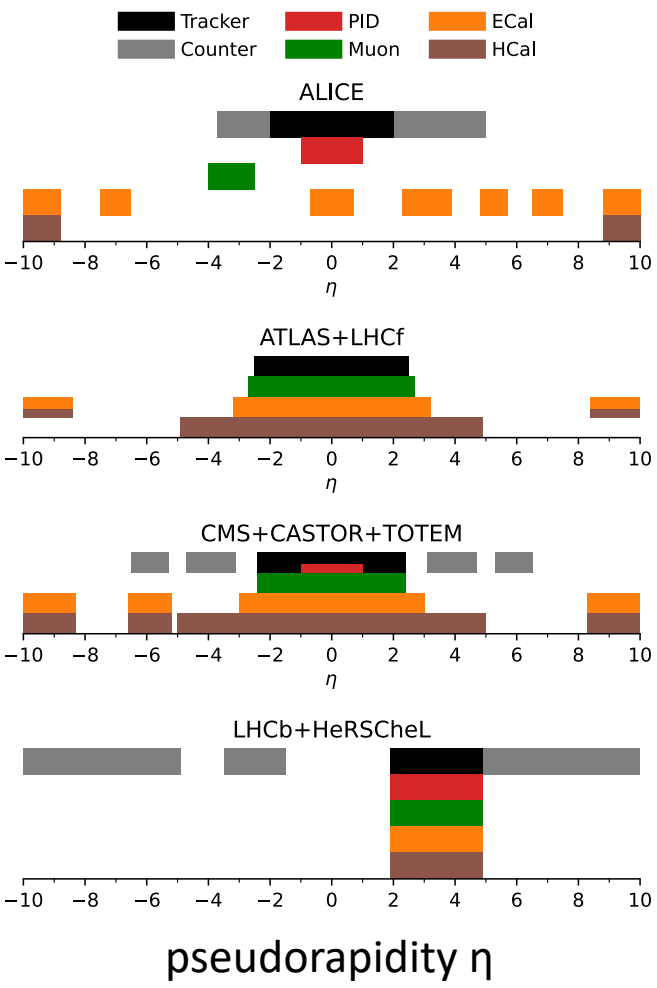
Air shower collision systems

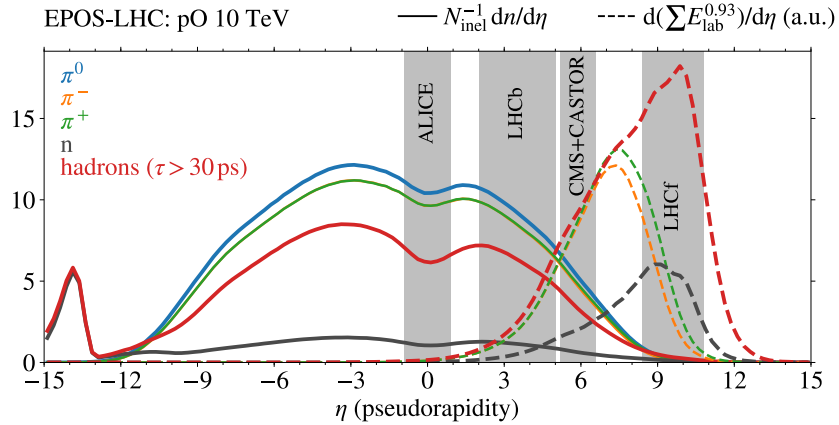


p-O collisions mimic air shower interactions

LHC experiments and Muon Puzzle

arXiv:2105.06148





- Most LHC experiments focus on |η| < 2 region
- Forward capabilities |η| > 2
  - ALICE (counters)
  - CMS-CASTOR: calorimeter
  - TOTEM
  - LHCb: full tracking and PID
  - LHCf: neutral particles
  - **FPF**

Can constrain R

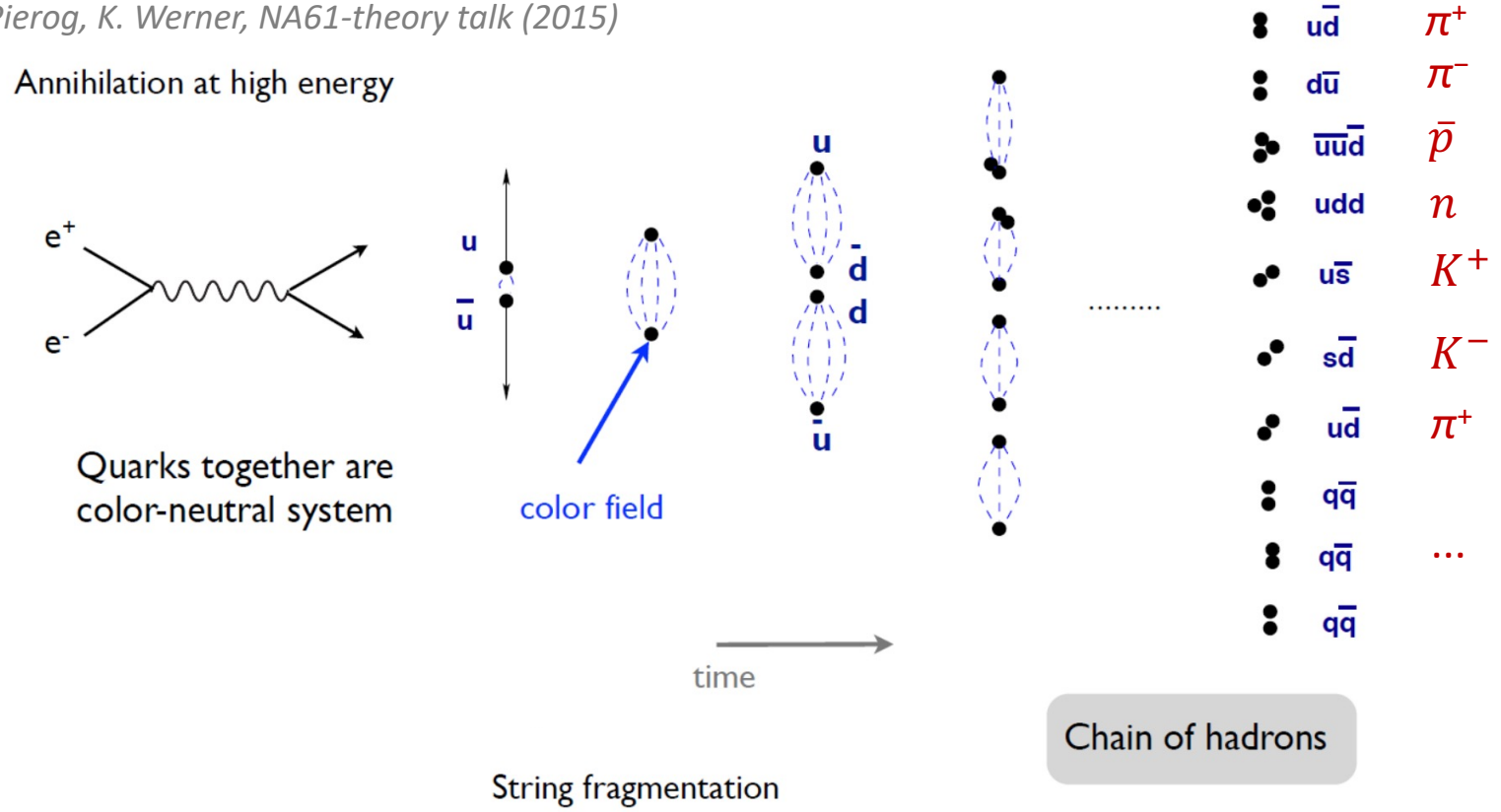
$$R = \frac{E_{\pi^0}}{E_{\text{other hadrons}}}$$

Possibilities to reduce energy ratio *R*

- Difficult to change *R* within standard QCD
  - String fragmentation universal → hadron ratios universal
  - Iso-spin symmetry: $\pi^+ : \pi^- : \pi^0 \sim 1 : 1 : 1$

Probabilities to generate quark pairs independent of collision details

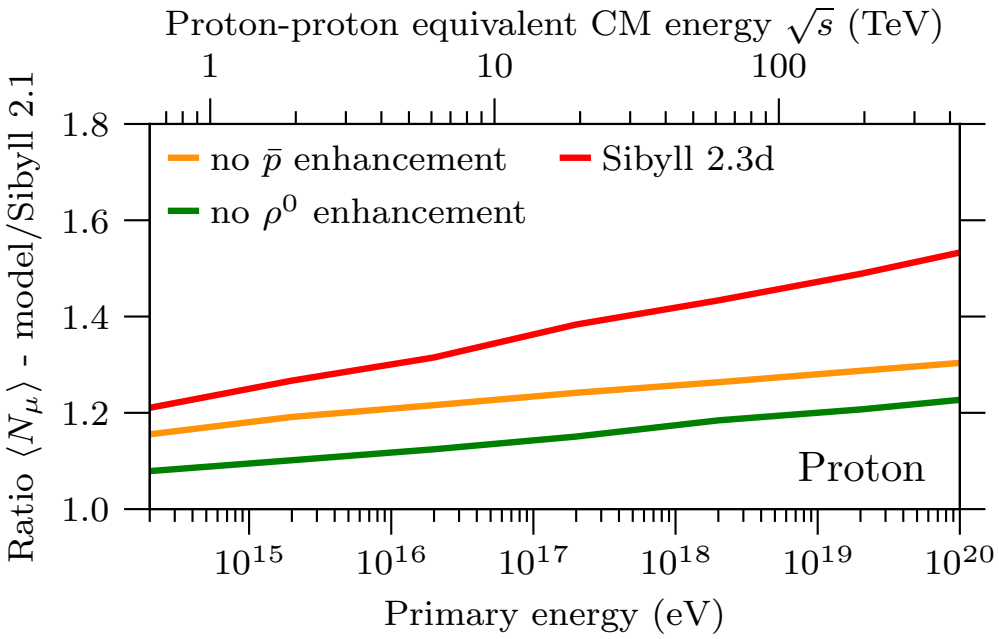
T. Pierog, K. Werner, NA61-theory talk (2015)



Possibilities to reduce energy ratio *R*

- Difficult to change *R* within standard QCD
- Option: Enhanced forward baryon and ρ^0 production in π-air collisions

M. Unger for NA61/SHINE, PoS ICRC2019 (2020) 446
R. Prado for NA61/SHINE, EPJ Web Conf. 208 (2019) 05006
F. Riehn, R. Engel, A. Fedynitch, TK. Gaisser, T. Stanev, Phys.Rev.D 102 (2020) 6, 063002

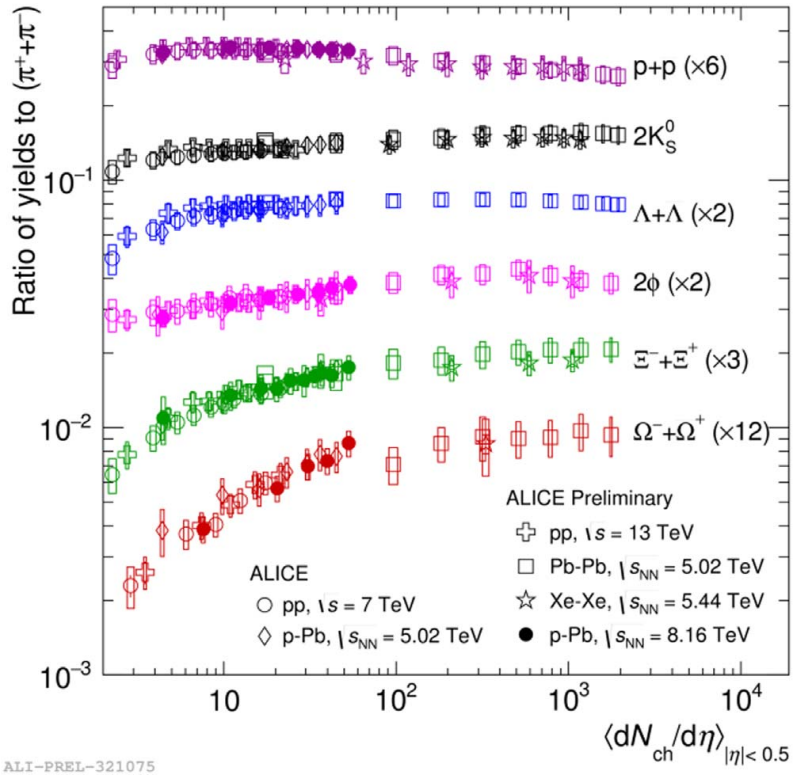


- More baryons and ρ^0 → less π^0 → more muons in air showers
- Large increase of muon number in SIBYLL model, but not enough to solve muon puzzle

Possibilities to reduce energy ratio *R*

- Difficult to change *R* within standard QCD
- Option: Enhanced forward baryon and ρ^0 production in π-air collisions
- Option: Enhanced strangeness production

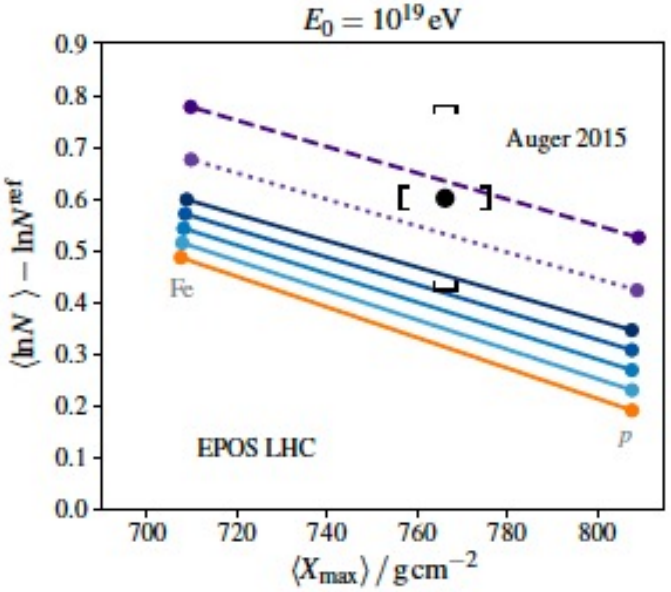
M. Vasileiou for ALICE, Phys. Scr. 95 (2020) 064007

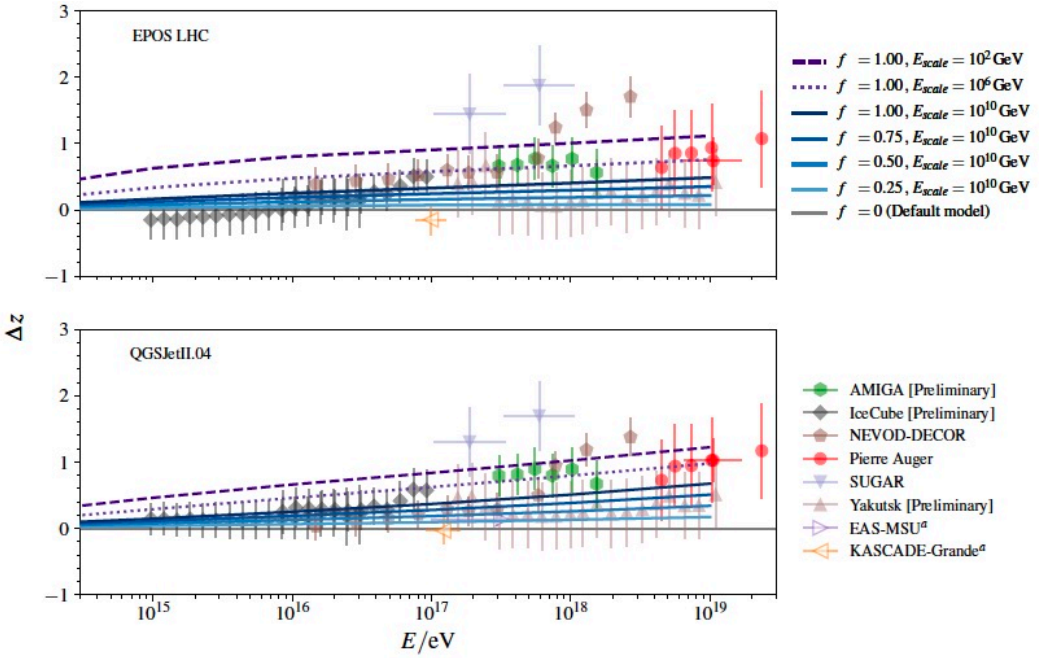


- ALICE discovered universal enhancement of strangeness production in *pp*, *p*Pb, PbPb
  ALICE, Nature Phys. 13 (2017) 535
- More strangeness → less π^0
  → more muons in air showers
  $R \approx 0.41 - 0.45$ (low density)
  $R \approx 0.34$ (high density) (≈ -20 %!)
  arXiv:1902.09265
- Enhancement seems to depend **only** on density of charged particles → predictive power!
- Open question: Does it extend forward to $\eta \gg 1$?

Strangeness and shower muons

S. Baur, HD, M. Perlin, T. Pierog, R. Ulrich, K. Werner, arXiv:1902.09265 PoS(ICRC2021)469

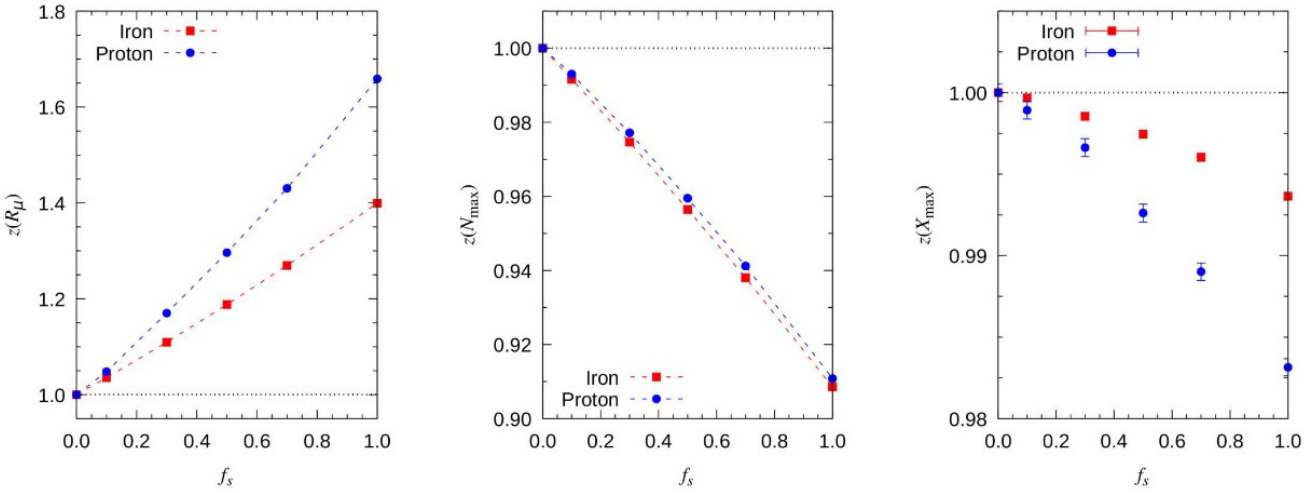




- Core/corona model needed to describe ALICE data and can potentially solve Muon Puzzle
- Constrained by CMS-CASTOR measurements of *R*, and by ongoing LHCb analyses
- Can be tested further with future data on forward strangeness production, e.g. K/π ratio

Strangeness and shower muons

- **Sergio Sciutto:** Study of impact on modified hadron composition in air shower simulations on air shower features
- Assumption: strangeness enhancement is solution to Muon Puzzle
- Toy model: Swap out fraction f_s of π with K in air shower simulation (either all or only forward produced)



Results from AIRES+ Sibyll 2.3d + $\pi \longrightarrow K$ swap, for varying swapping probabilities f_s. 10^{19} eV proton and iron showers inclined 67°. $E_{\mathrm{pmin}} = 1$ PeV.

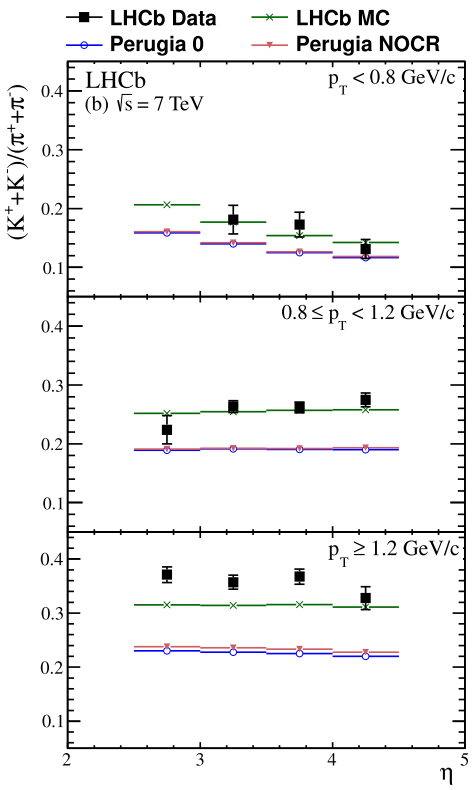
- Can fix Muon Puzzle without violating good agreement of other shower parameters
- Testable: Predictions for FPF show sizeable changes in neutrino flux contribution from K

LHCb: Forward identified hadron spectra

Hadron ratios

LHCb, EPJC (2012) 72:2168

p-p @ 0.9, 7 TeV



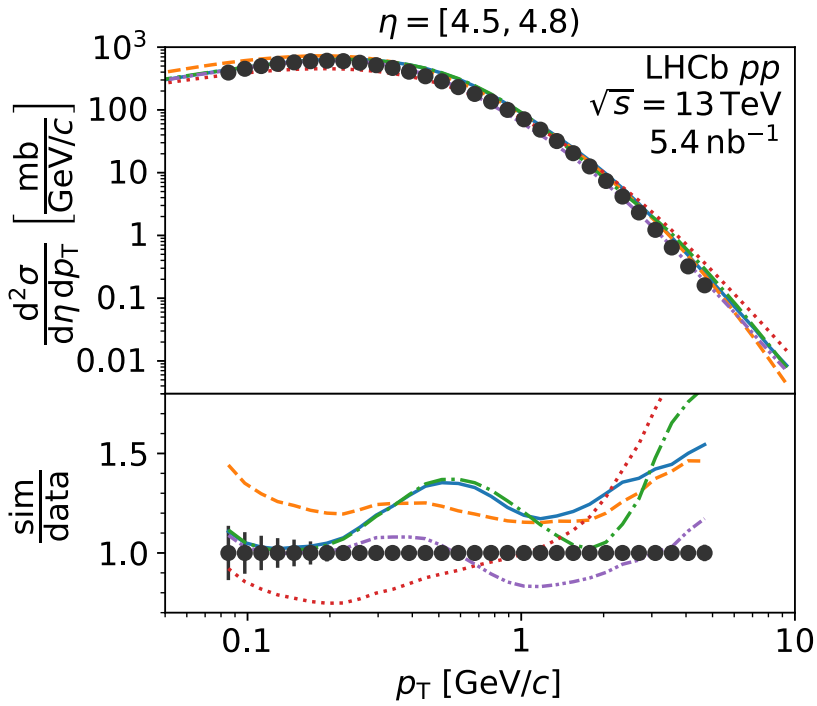
Prompt charged particles

LHCb-PAPER-2021-010, arXiv:2107.10090

p-p @ 13 TeV

LHCb-PAPER-2021-015, arXiv:2107.10090

p-p, p-Pb @ 5 TeV



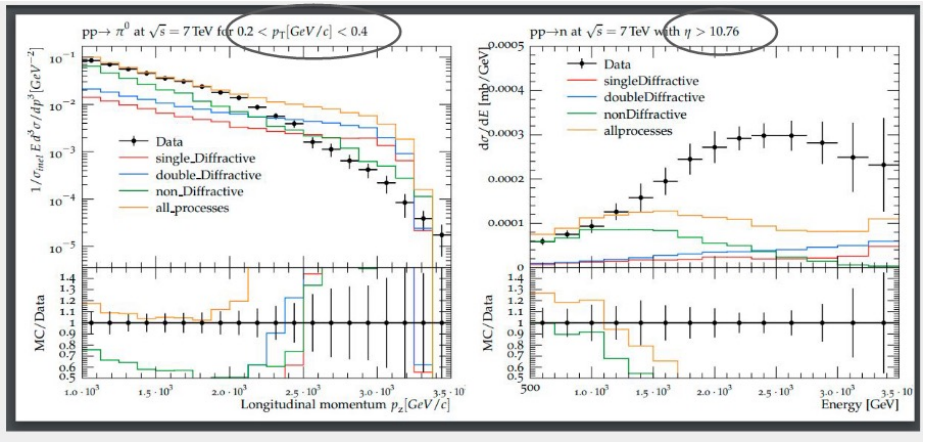
- Just published: precise measurements of charged particle density at 1-2 % level
- *R* constrained by π, K, p ratios measured in p-p at 0.9 and 7 TeV; analysis of 13 TeV data in progress
- Potential of fixed target studies: $\bar{p}$ production in p-He at 0.11 TeV LHCb, PRL 121 (2018) 22, 222001

Very forward LHCf measurements

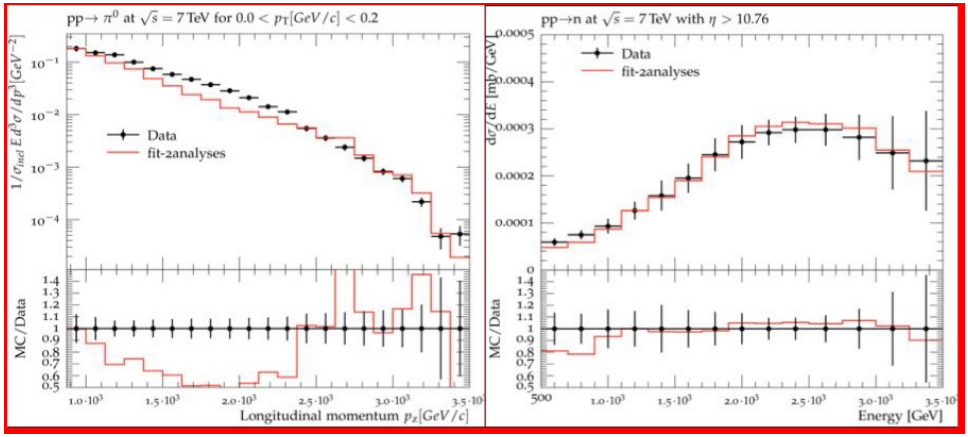
- LHCf: zero degree calorimeters (η > 8) around ATLAS to detect neutral particles
  - *R* constrained by photon, π^0, neutron production cross-sections in p-p, p-Pb from 0.9 to 13 TeV
  - π^0 production also important for forward neutrino fluxes: most neutrinos from π, K decays
  - Plans to study strangeness production via $K^0_S \longrightarrow 4\gamma$ (requires large samples) PoS(ICRC2021)301

- **Max Fieg:** Tuning Pythia for the FPF
- Tuned PYTHIA to LHCf data on π^0, neutron
- PYTHIA not optimised for forward; poor predictions
- But with tuning can describe data
- Attempts to estimate uncertainty of tune

PYTHIA: Before tuning



After tuning

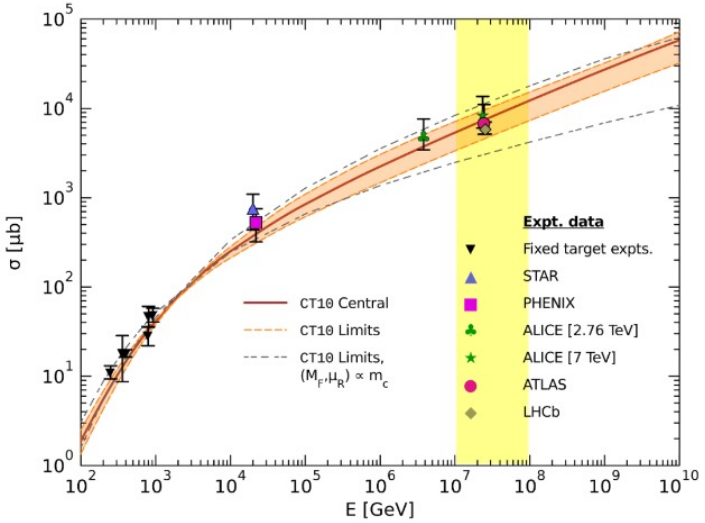


Prompt atmospheric leptons

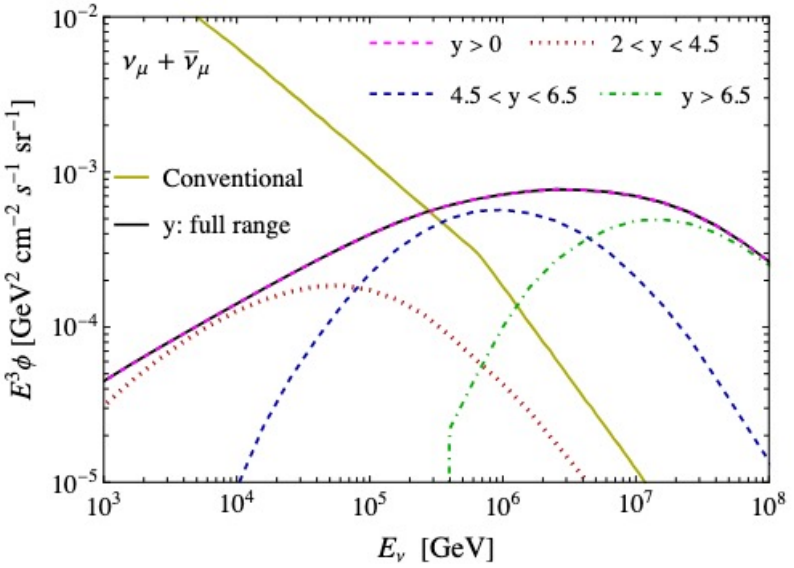
Pions $\pi^{\pm}$, π^{0} [$\tau \sim 10^{-8}$ s]
Kaons $K^{\pm}$, K^{0} [$\tau \sim 10^{-8}$ s]
Conventional

Charmed mesons $D^{\pm}$, D^{0} [$\tau \sim 10^{-12}$ s]
Prompt

- **Contributions: Tim Ruhe** and **Atri Bhattacharya**
- Prompt atmospheric component linked primarily to forward charm production
- pp interactions at 10^{7}-10^{8} GeV lab → sqrt(s) = 4-14 TeV (LHC)
- Studying prompt production requires measurements at LHC with y > 4.5, i.e. LHCb or higher
- Challenges/uncertainties: charm hadronization, charm mass, theory scales



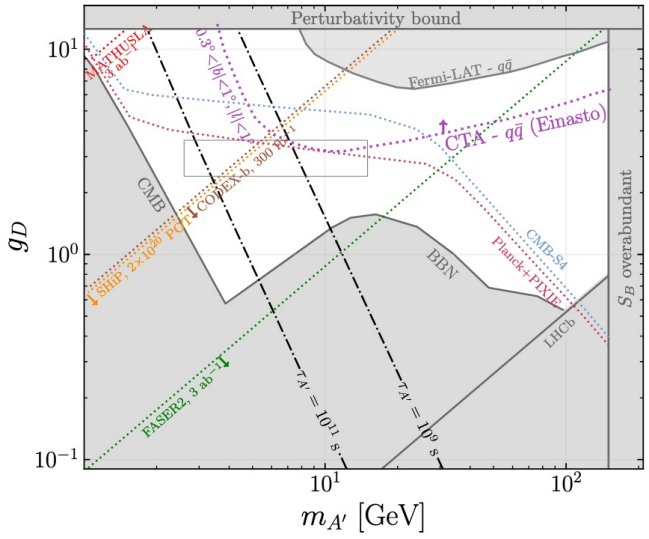
Y.S. Jeong et al. + Honda et al.
from L. Achordoqui et al. arXiv:2109.10905



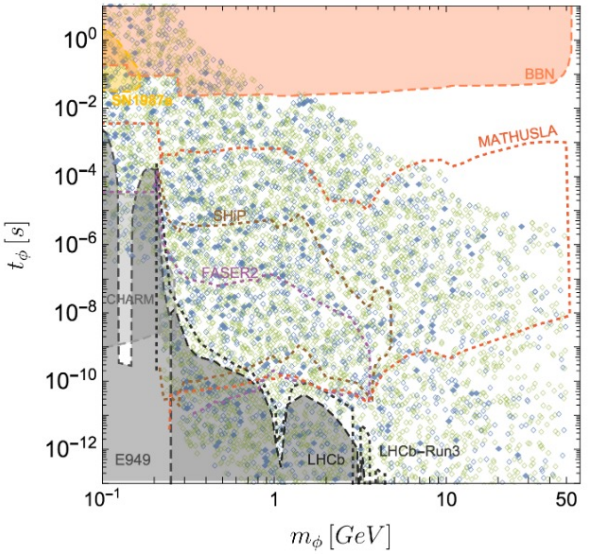
Further contributions

- BSM theories in which detectable long-lived particles (LLP) are produced
- **Tanmay Poddar:** Freeze-in sterile neutrino dark matter in a class of U(1)' models with inverse seesaw
- **Maxim Laletin:** Dark matter freeze-in from semi-production
- **Krzysztof Jodlowski:** Searching for rich dark sectors in the FPF through secondary production and in indirect dark matter searches

Krzysztof Jodlowski



Maxim Laletin



Summary & outlook

- Muon Puzzle in air showers
  - Excess in mean muon number observed with 8σ over simulation
- Origin of muon discrepancy
  - Most likely an issue in forward soft QCD
  - Very sensitive to em/had energy ratio *R* in forward region η ≫ 2
    - Key to Muon Puzzle: strangeness/baryon production?
    - Precise forward measurements needed

$$R = \frac{E_{\pi^0}}{E_{\text{other hadrons}}}$$

- FPF very sensitive to K/π ratio & forward prompt charm
- LHC pilot run with p-O collisions planned for 2023/24
- More precise muon data from future air shower experiments

AugerPrime PoS(ICRC2021)270
IceCube surface extension and Gen2 PoS(ICRC2021)314
TAx4 PoS(ICRC2021)203
NEVOD-DECOR extension
GRAND PoS(ICRC2021)1181
GCOS PoS(ICRC2021)027