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The Muon Puzzle in air showers and its connection to the LHC

Hans Dembinski, TU Dortmund, Germany

Recontres de Blois, October 2021

talk based on

J. Albrecht, L. Cazon, HD, A. Fedynitch, KH. Kampert, T. Pierog, W. Rhode, D. Soldin, B. Spaan, R. Ulrich, M. Unger
The Muon Puzzle in cosmic-ray induced air showers and its connection to the Large Hadron Collider
invited review submitted to Astrophysics and Space Science (2021) arXiv:2105.06148

Overview

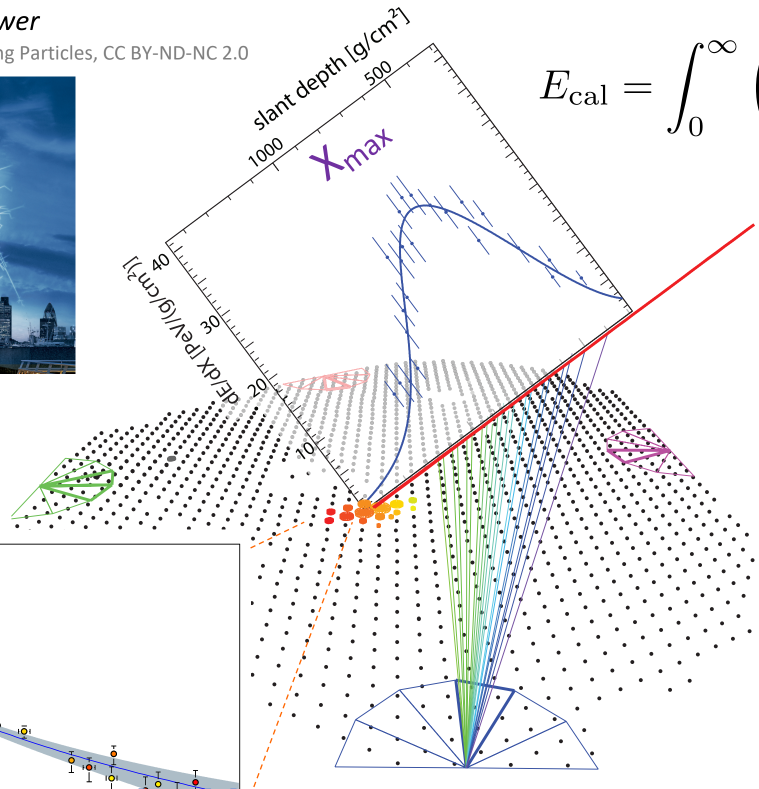
- Muon puzzle in cosmic-ray included air showers
  - Muon excess observed compared to simulations in high-energy showers
- Origin of discrepancy in soft-QCD processes
  - Solution requires to divert less energy to π^0 mesons
  - Need more detailed input from accelerators on forward hadron production
- LHC/SPS experiments provide important reference data
  - Challenge: Limited information on forward hadron production
  - Strangeness enhancement in high-density collisions
    - Key ingredient for solving muon puzzle?
  - Very promising: p-O collisions planned at LHC in 2023/24

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

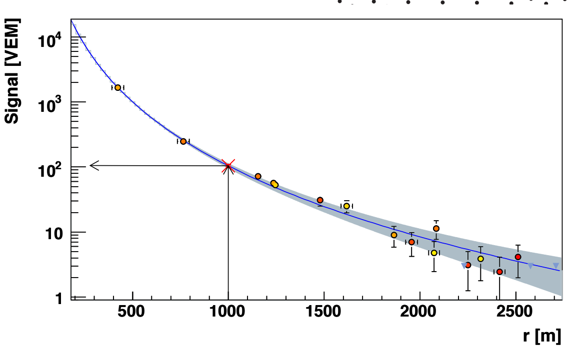


$$E_{\text{cal}} = \int_0^\infty \left(\frac{dE}{dX}\right)_{\text{ionization}} dX$$

- **Direction** from particle arrival times
- **Energy** from size of **eγ component**
- **Mass** from

  depth of shower maximum X_{max}

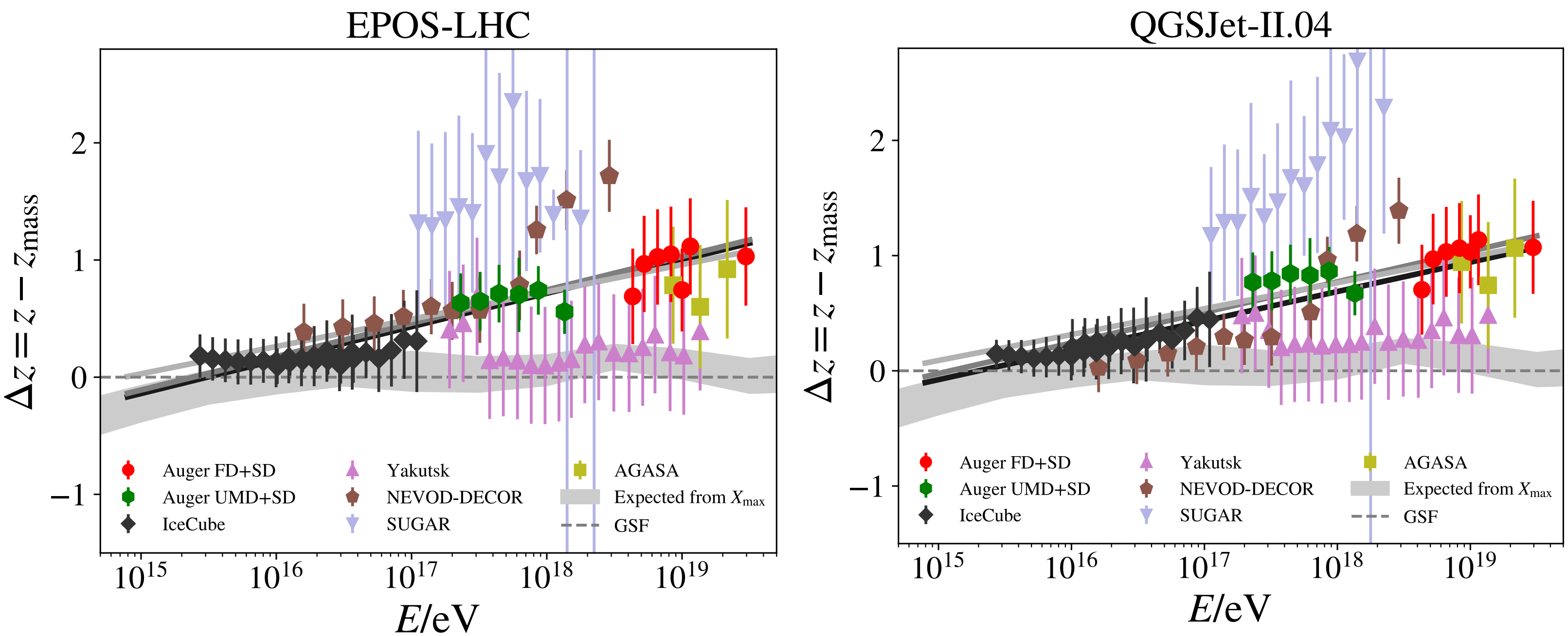
  size of muonic component N_μ



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

Muon deficit in simulated air showers

PoS(ICRC2021)349



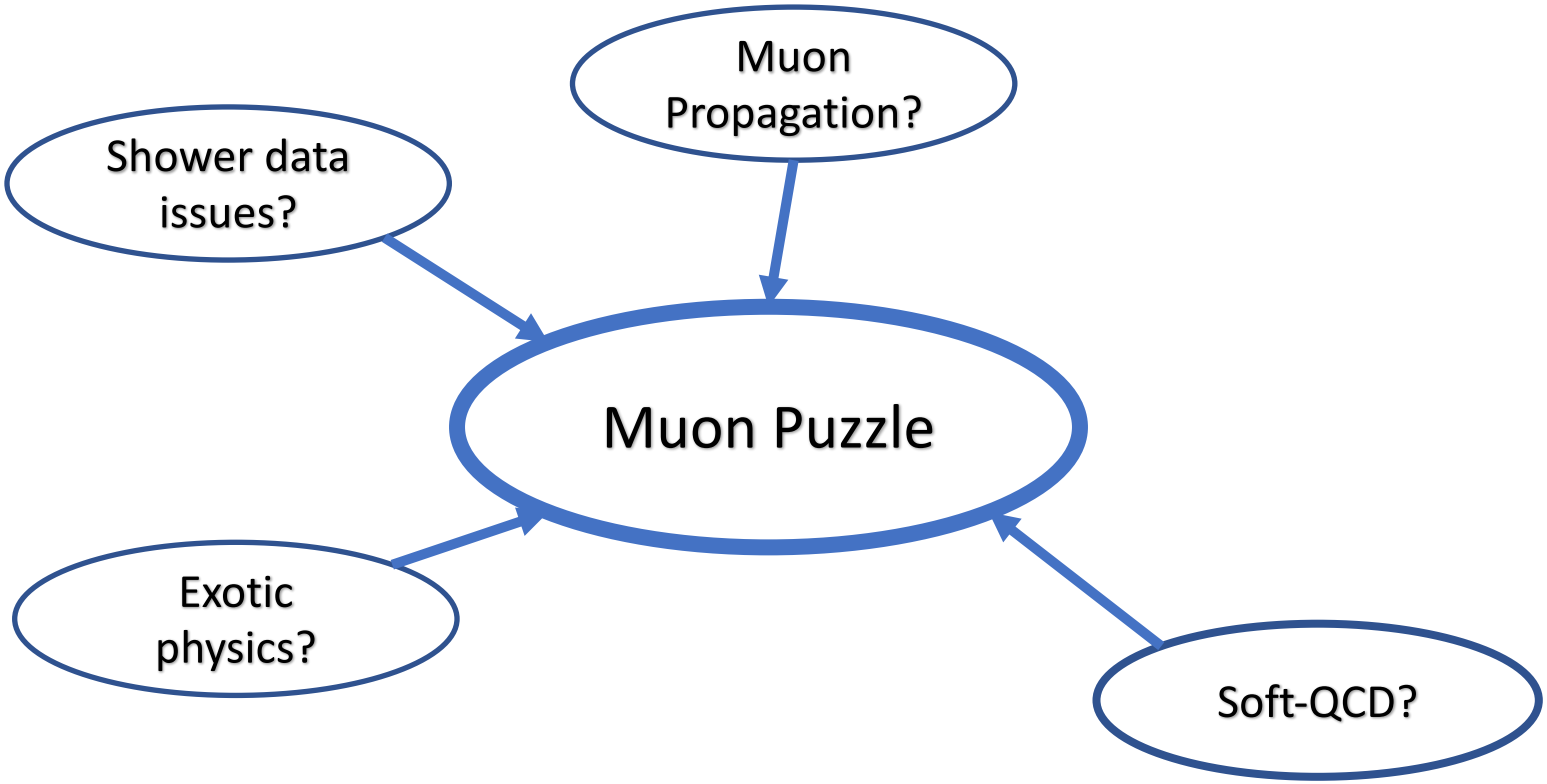
Abstract muon scale
independent of experiment,
dependent on air shower model

$$z = \frac{\ln(N_\mu{}^{\mathrm{det}}) - \ln(N_{\mu_p}{}^{\mathrm{det}})}{\ln(N_{\mu_{\mathrm{Fe}}}{}^{\mathrm{det}}) - \ln(N_{\mu_p}{}^{\mathrm{det}})}$$

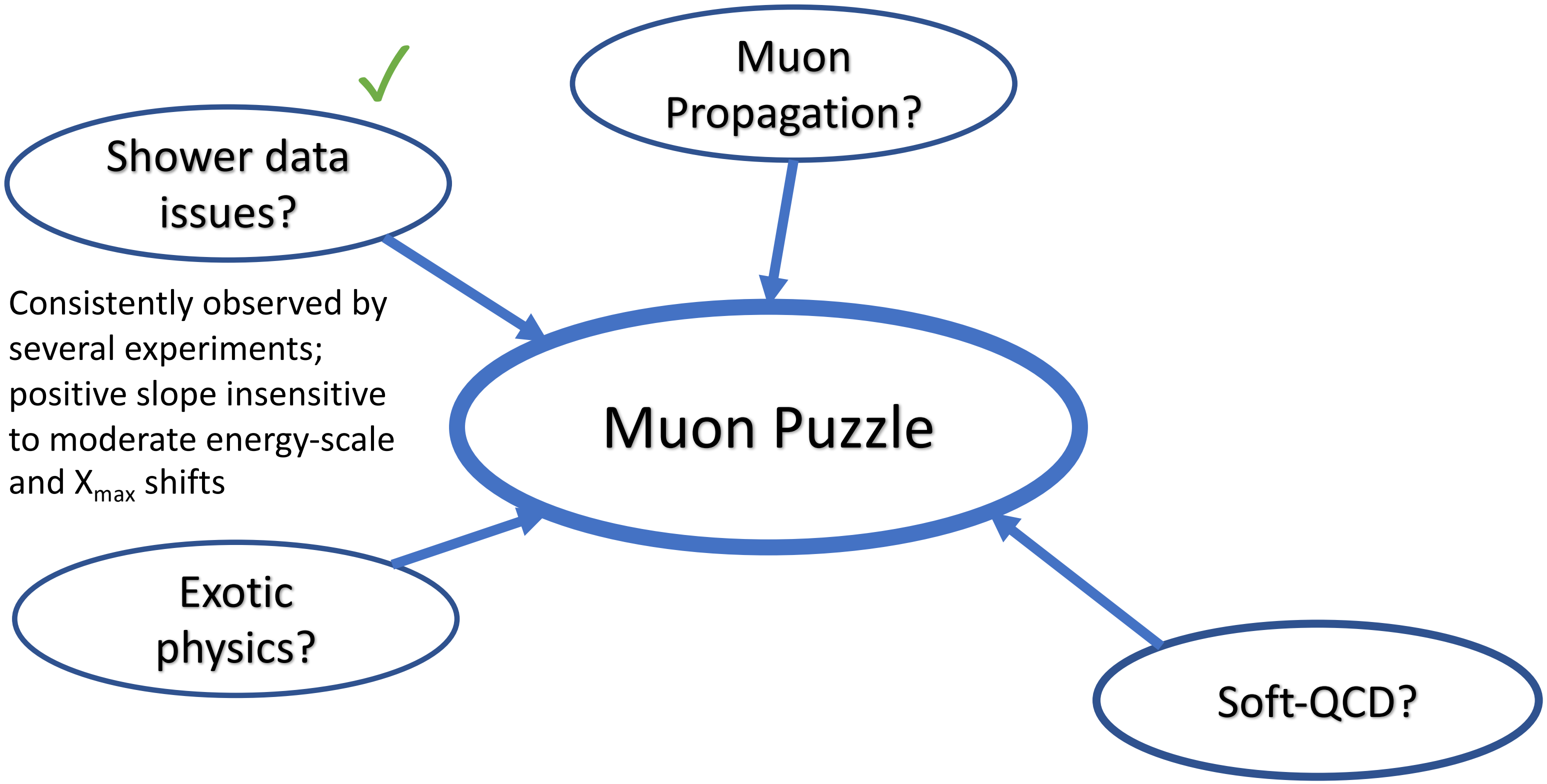
$$z_{\mathrm{mass}} \approx \frac{\langle \ln A \rangle}{\ln 56}$$

- Data combined from 9 air shower experiments by WHISP group
- Line model with slope fitted to $\Delta z = z - z_{\mathrm{mass}}$
  - Correction to $\chi^2/n_{\mathrm{dof}} = 1$ applied to take unexplained spread into account
- Slope is 8σ (10σ) away from zero for EPOS-LHC (QGSJet-II.04)
- Onset of deviation around 40 PeV corresponds to $\sqrt{s} \sim 8$ TeV; in reach of LHC

Attempts to explain muon puzzle

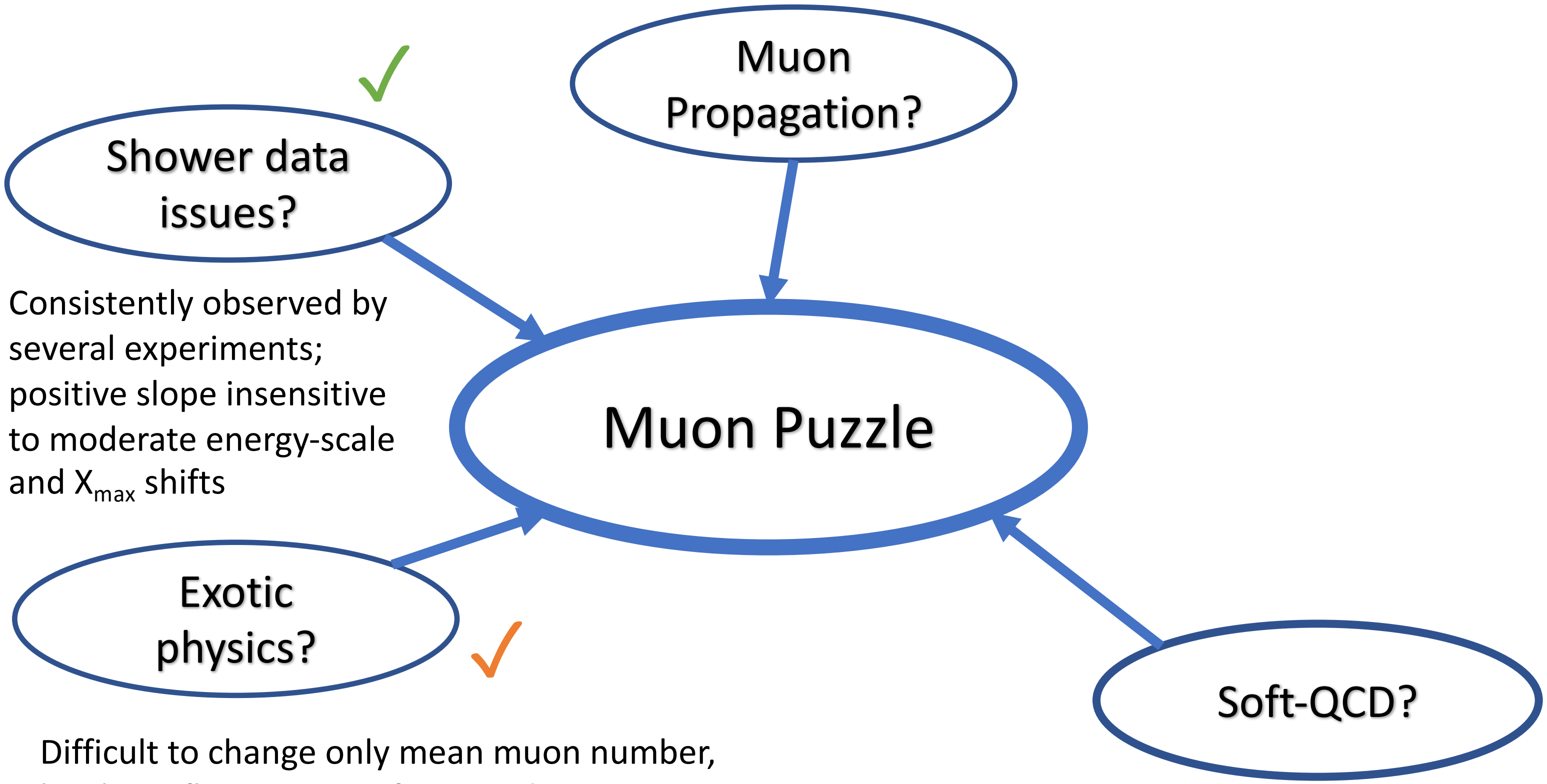


Attempts to explain muon puzzle



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

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., Phys.Rev.Lett. 126 (2021) 15, 152002

Attempts to explain muon puzzle

Muon Puzzle

Shower data issues? ✓

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

Muon Propagation? ✓

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

Exotic physics? ✓

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., Phys.Rev.Lett. 126 (2021) 15, 152002

Soft-QCD?

From shower muons to QCD

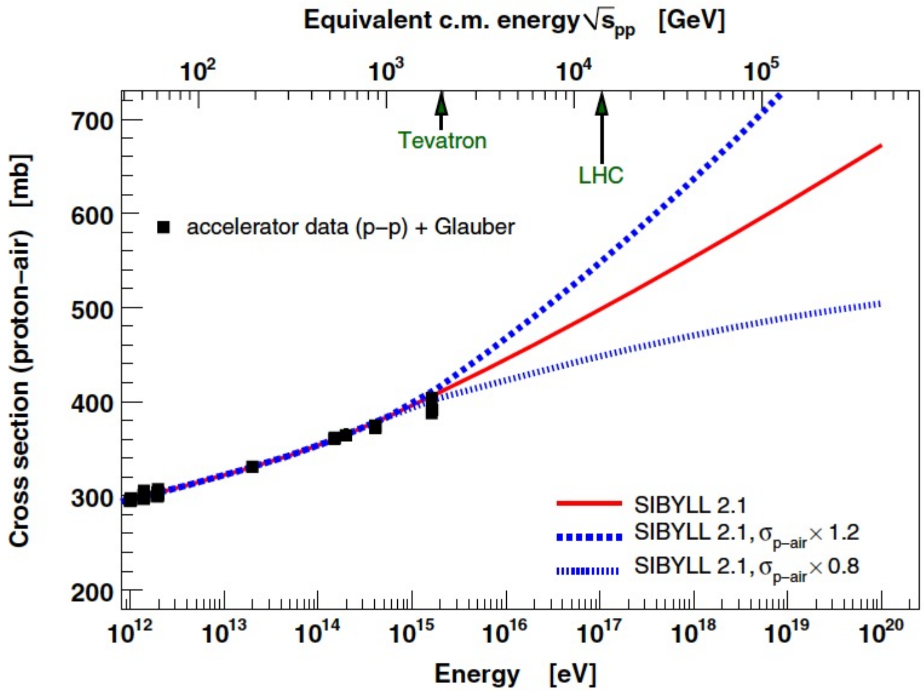
R. Ulrich, R. Engel, M. Unger, PRD 83 (2011) 054026

- 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

$$f(E) = 1 + (f_{19} - 1) \cdot \begin{cases} 0 & E < 1\,\mathrm{PeV} \\ \dfrac{\log_{10}\left(\frac{E}{1\,\mathrm{PeV}}\right)}{\log_{10}\left(\frac{10\,\mathrm{EeV}}{1\,\mathrm{PeV}}\right)} & E \geq 1\,\mathrm{PeV} \end{cases}$$

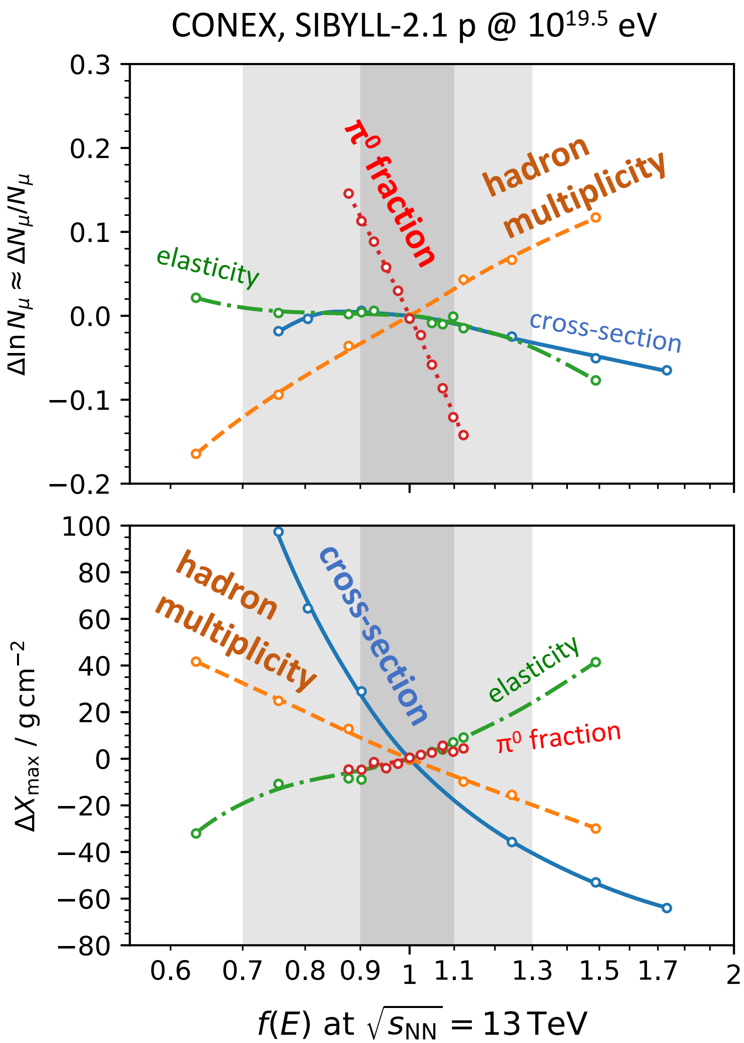
Modified features

- **cross-sections**
  inelastic cross-section of all interactions
- **hadron multiplicity**
  total number of secondary hadrons
- **elasticity** = $E_{\mathrm{leading}}/E_{\mathrm{all}}$
- π^0 **fraction** = 1-α



From shower muons to QCD

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

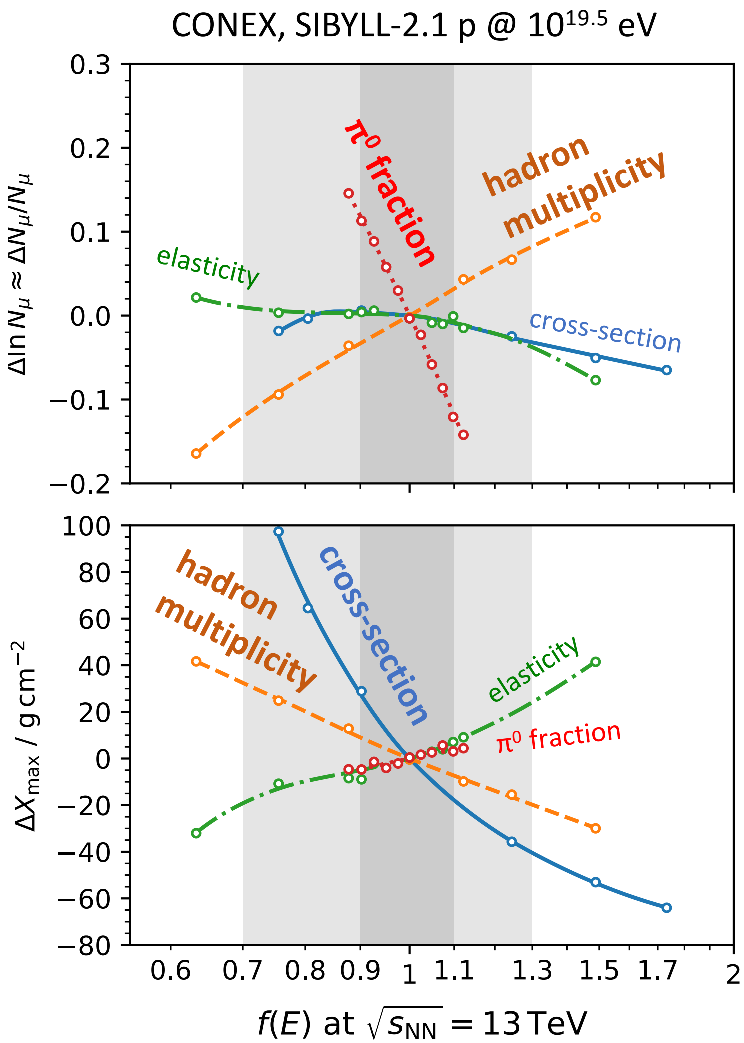


- Number of muons produced, N_μ
  - Very sensitive to π^0 fraction
  - Sensitive to hadron multiplicity
- Depth of shower maximum, X_{max}
  - Very sensitive to cross-section
  - Sensitive to hadron multiplicity
  - Insensitive to π^0 fraction

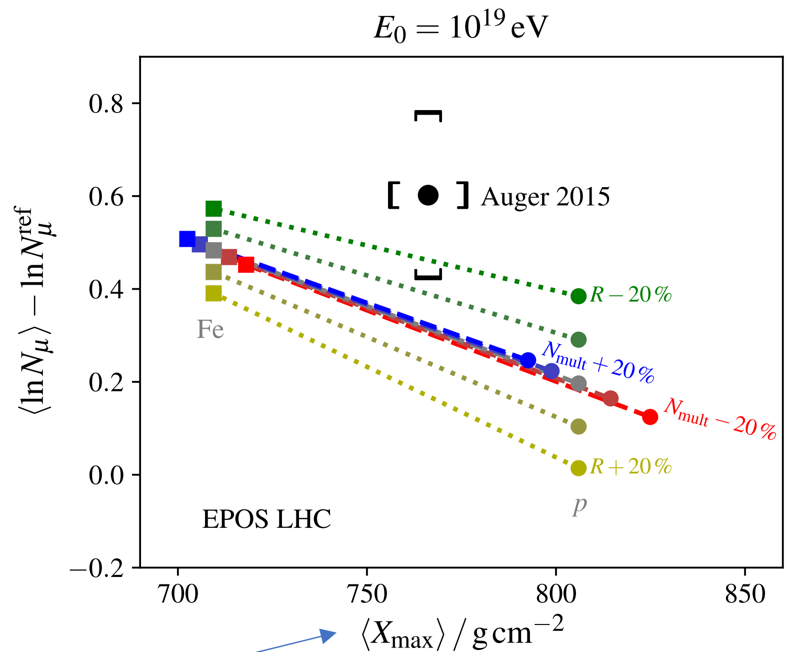
Changing π^0 fraction most promising

From shower muons to QCD

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



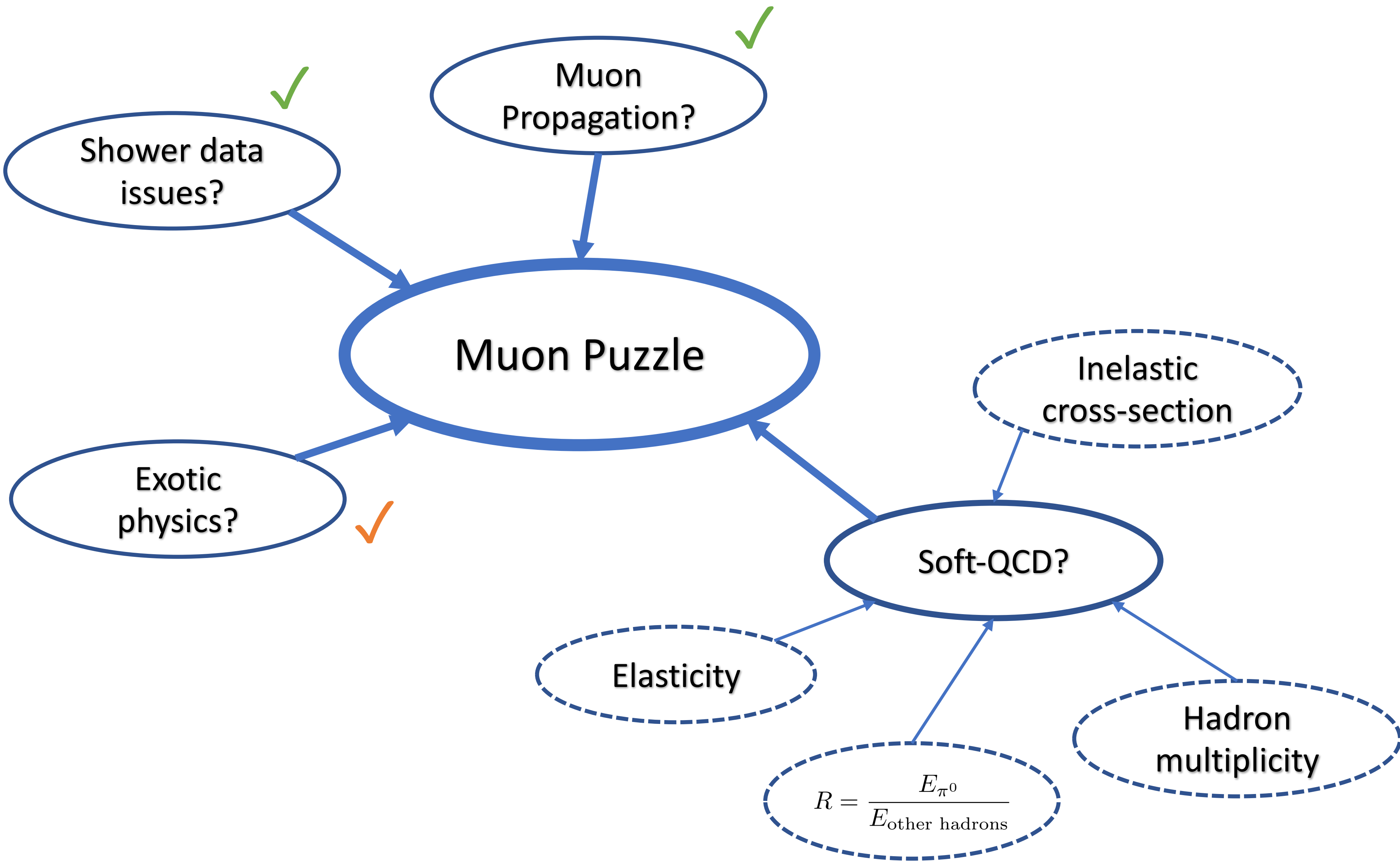
S. Baur, HD, M. Perlin, T. Pierog, R. Ulrich, K. Werner, arXiv:1902.09265



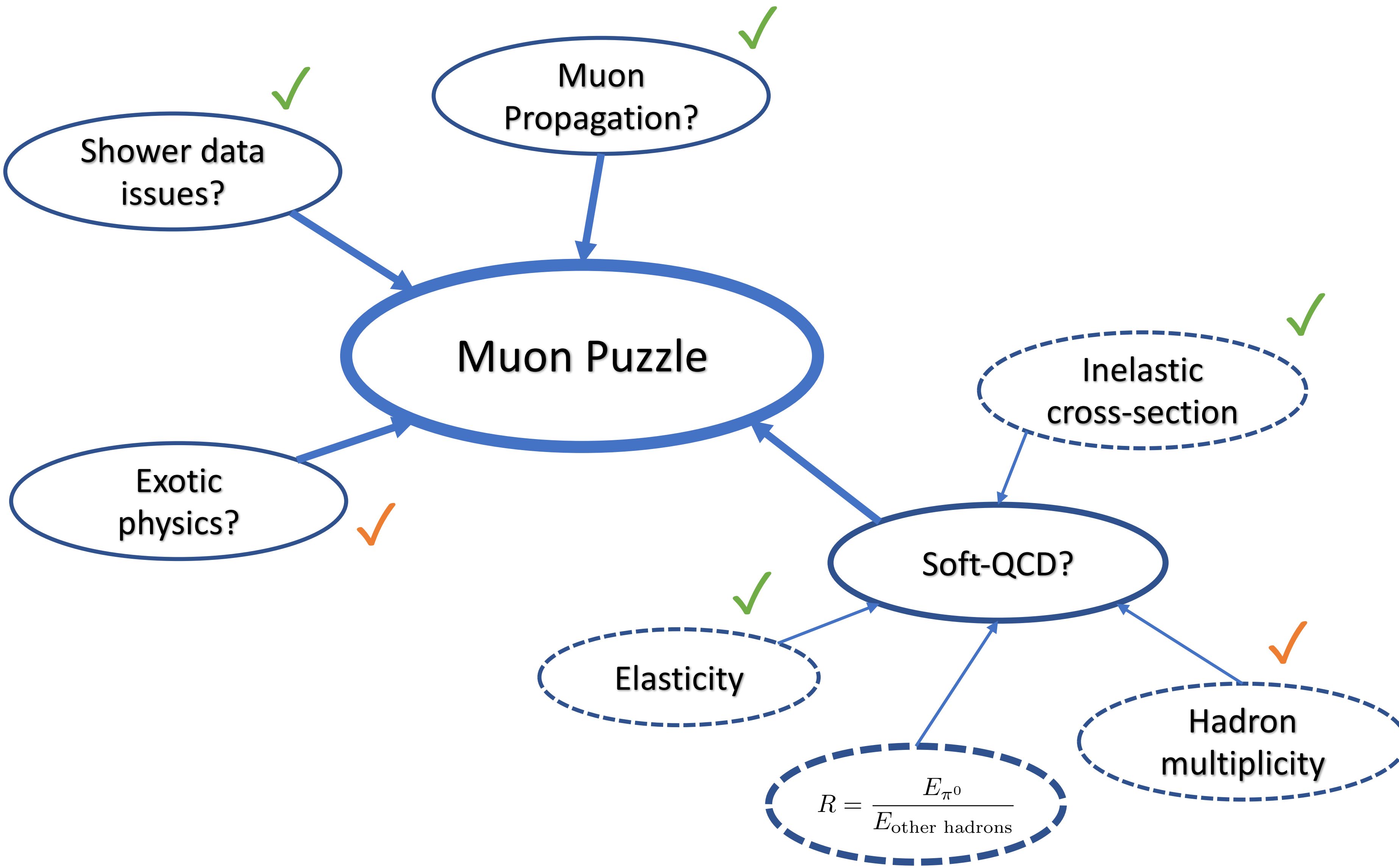
$$R = \frac{E_{\pi^0}}{E_{\text{other hadrons}}}$$

- 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



Attempts to explain muon puzzle



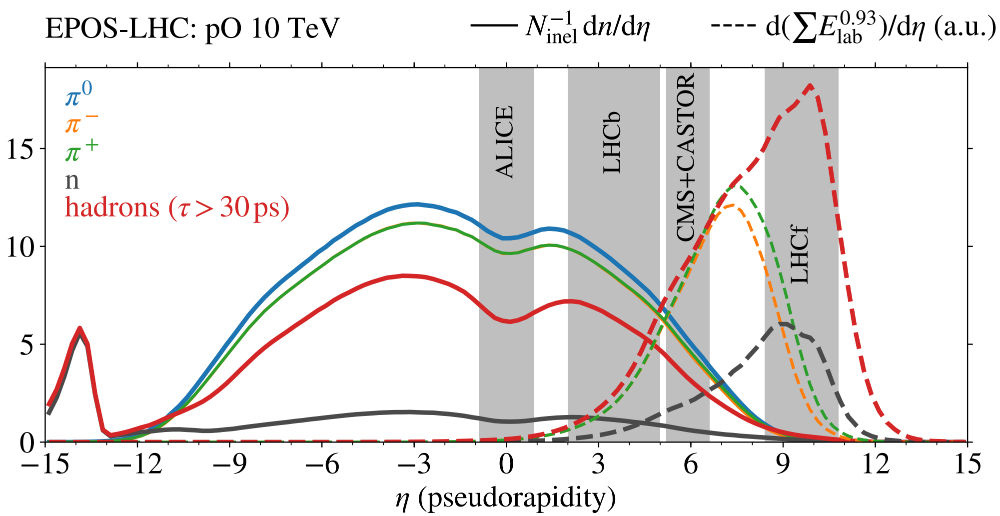
LHC experiments and Muon Puzzle

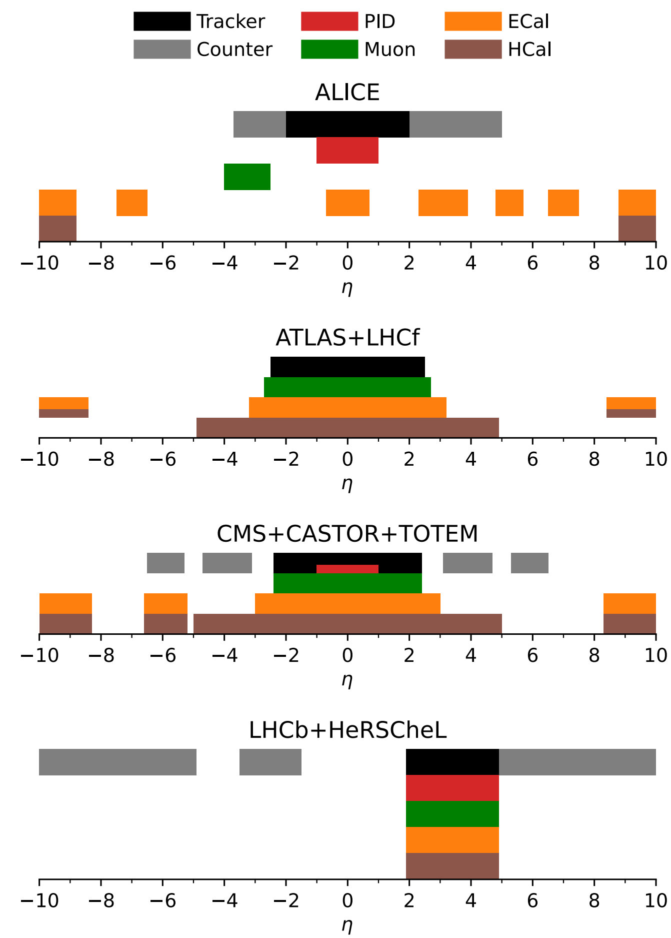
arXiv:2105.06148

„Muon production weight“

how many muon would be produced in shower by secondaries in this collision

PoS(ICRC2021)46





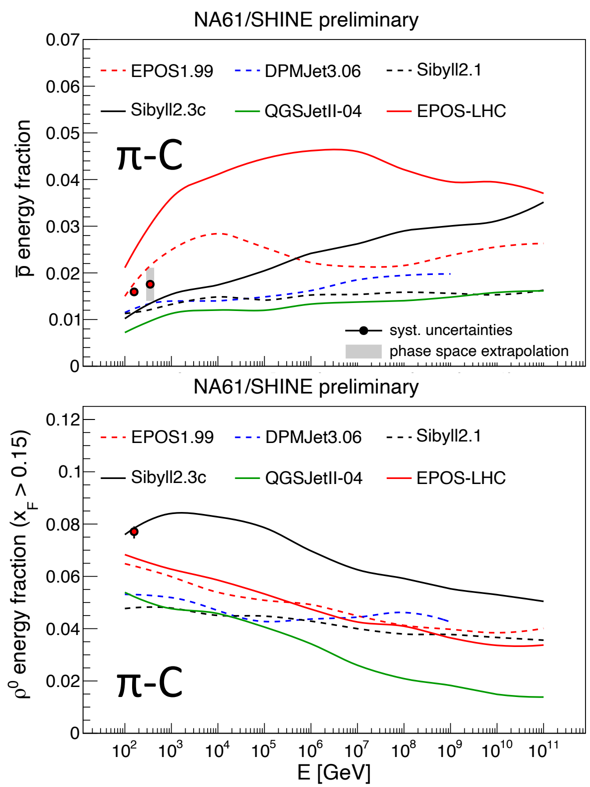
pseudorapidity η

- Forward capabilities |η| > 2
    - ALICE, TOTEM: counters
    - CMS-CASTOR: Calorimeters for eγ and hadrons
    - LHCb: full tracking and PID at 2 < η < 5
    - LHCf: neutral particles η > 8

Possibilities to reduce energy ratio *R*

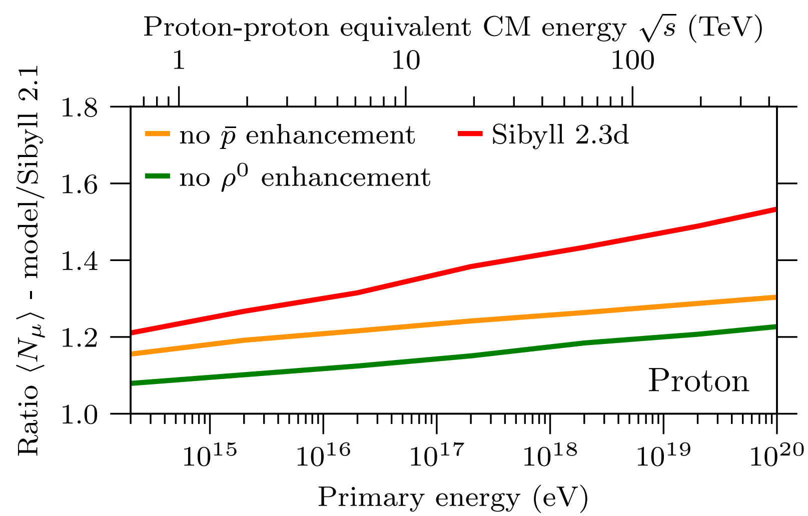
- Difficult to change *R* within standard soft-QCD
  - Fragmentation of strings and excited nuclear remnant believed to be universal
  - Iso-spin symmetry fixes ratio of neutral to charged pions
- Option 1: Changes to baryon production and ρ^0 production in π-air collisions
- Option 2: Strangeness enhancement

M. Unger for NA61/SHINE, PoS ICRC2019 (2020) 446
R. Prado for NA61/SHINE, EPJ Web Conf. 208 (2019) 05006



Lab energy (fixed-target)

F. Riehn, R. Engel, A. Fedynitch, TK. Gaisser, T. Stanev, Phys.Rev.D 102 (2020) 6, 063002



- Large increase of muon number compared to SIBYLL 2.1, but not enough to solve muon puzzle
- No data for pion interactions at $\sqrt{s}$ > 100 GeV

Possibilities to reduce energy ratio *R*

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- Option 1: Changes to baryon production and ρ^0 production in π-air collisions
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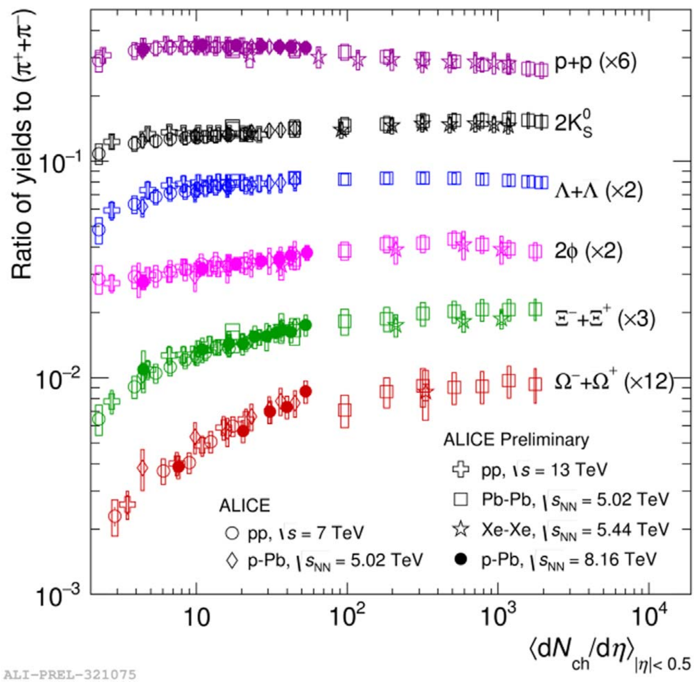
M. Vasileiou for ALICE, Phys. Scr. 95 (2020) 064007



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

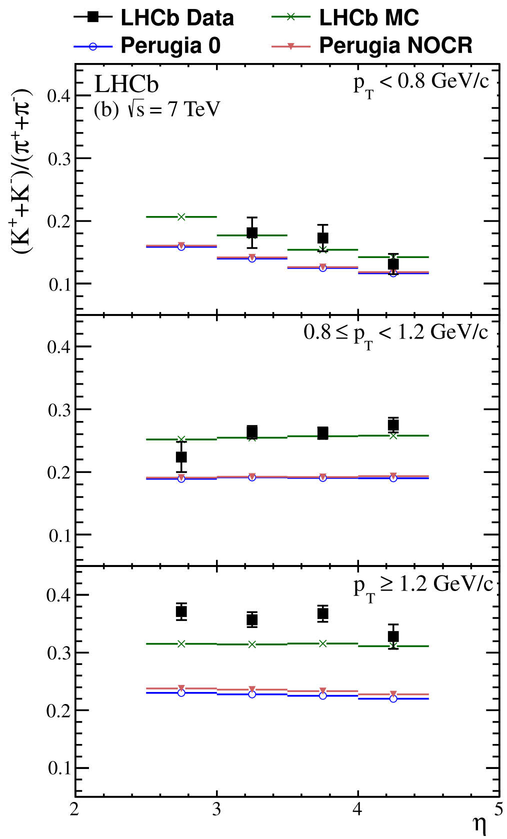
- Enhancement seems to depend **only** on density of charged particles produced in the event → predictive power!

- Open question: Does it extend forward to η ≫ 1?
  Results from CMS/CASTOR inconclusive
  CMS, Eur.Phys.J. C79 (2019) no.11, 893

Forward spectra of identified hadrons

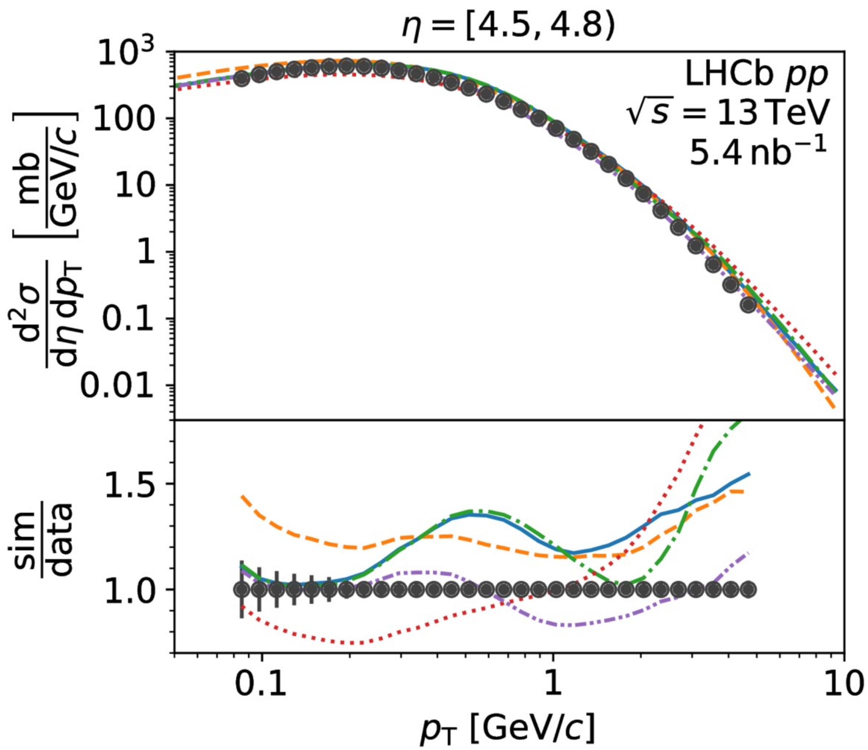
LHCb, EPJC (2012) 72:2168

p-p @ 7 TeV



LHCb-PAPER-2021-010 [arXiv:2107.10090]

p-p @ 13 TeV



- LHCb: forward spectrometer with particle identification 2 < η < 5
- *R* constrained by π, K, p ratios measured in p-p at 0.9 and 7 TeV; working on 13 TeV data
- Precise measurement of charged particle density in p-p at 13 TeV
  - Analysis will be extended to identified hadron spectra

Summary & outlook

- Muon Puzzle in air showers
  - Excess in mean muon number observed with 8σ over simulation
  - Early onset around 40 PeV ($\sqrt{s} \sim 8$ TeV) in reach of LHC
  - Muon number fluctuations consistent with model predictions; constrains exotic explanations

- Origin of muon discrepancy
  - Most likely an issue in forward **soft-QCD**
  - Very sensitive to energy ratio *R* in forward region $\eta \gg 2$
    - Constrained only by few LHC experiments: CMS-CASTOR, LHCb, LHCf
    - Key to Muon Puzzle: statistical hadronization in high-density collisions?
  - Sensitive to charged particle spectra
    - Well constrained by LHC p-p data now, still large model spread for p-O
    - Important also for X_{max} prediction

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

- LHC measurements with p-O collisions in 2023/24
  - Will resolve large model spread in charged particle density
  - Need to study hadron composition & strangeness production over wide η range