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Physik

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

Hans Dembinski, TU Dortmund, Germany

Astroteilchenphysik Seminar TU Dortmund, Dec 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

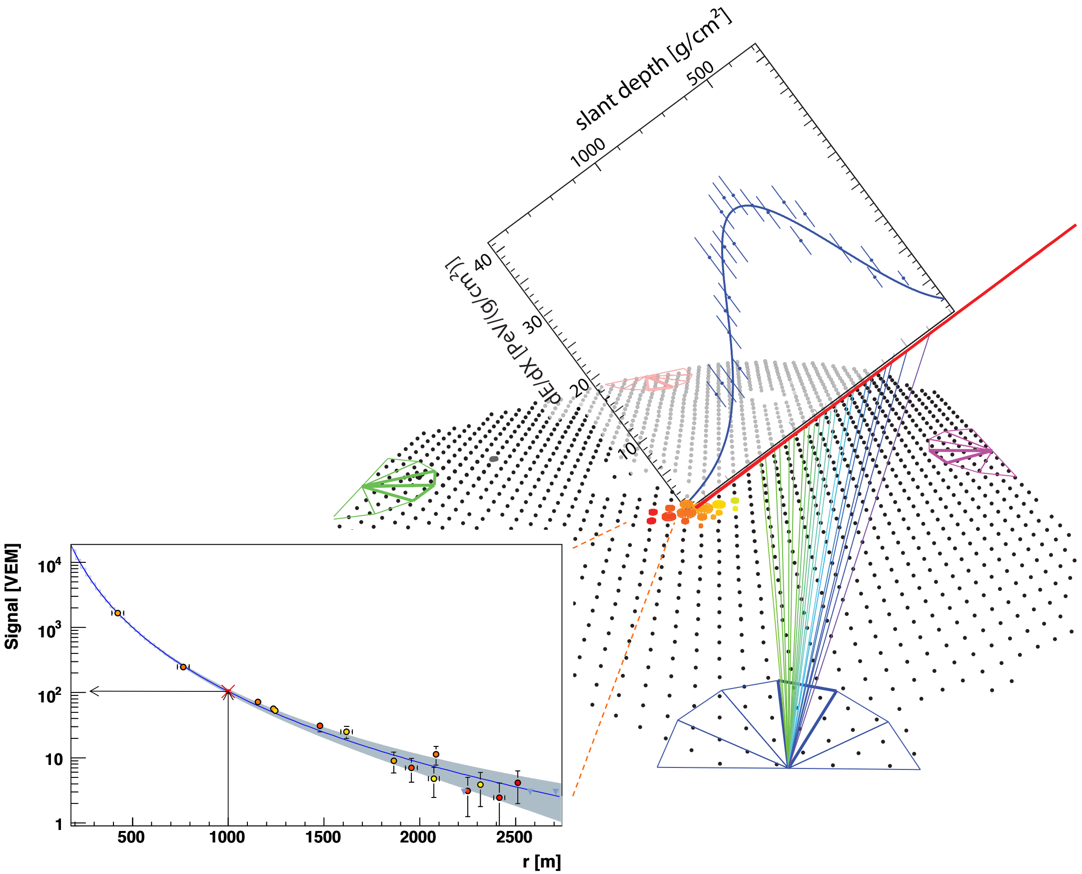
- Muon puzzle in cosmic-ray included air showers
  - Muon excess observed compared to simulations in high-energy showers
  - Best evidence from hybrid observatories
  - Combining data from several experiments boosts significance

- 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



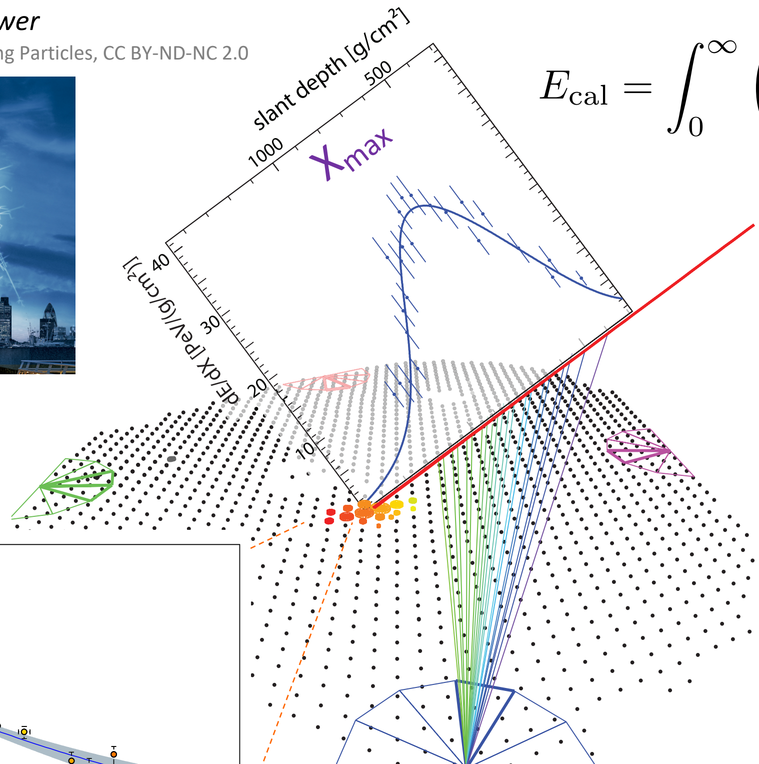
Artist impression of air shower

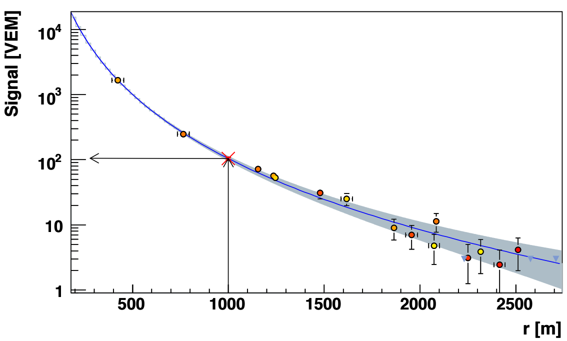
High-energy cosmic ray detection

Example: event observed with Pierre Auger Observatory

Artist impression of air shower

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





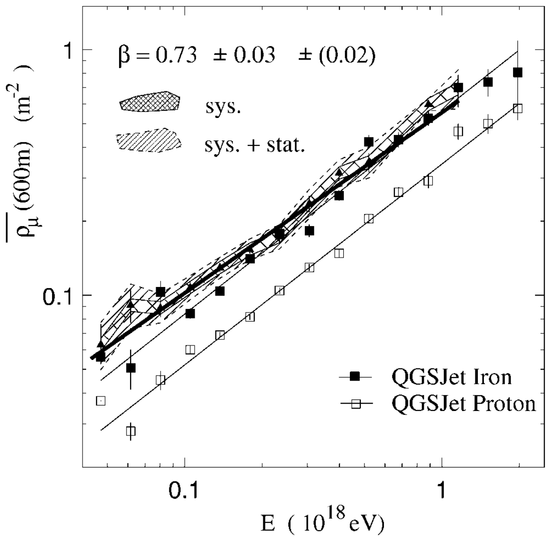
- **Direction** from particle arrival times
- **Energy** from size of **eγ component**
- **Mass** from
  depth of shower maximum X_{max}
  size of muonic component N_{μ}

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

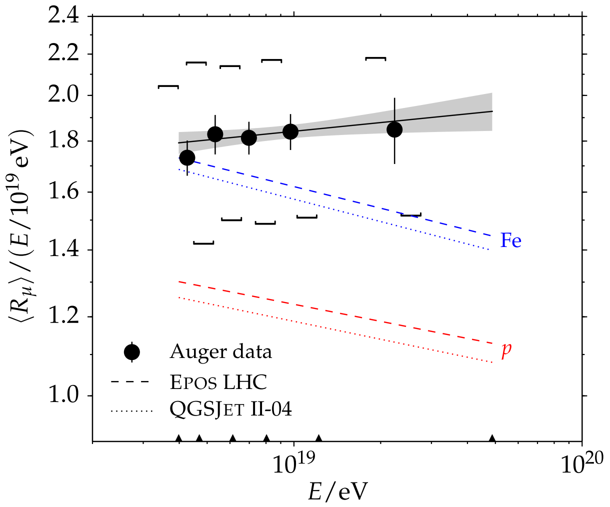
Muon measurements in air showers

- Muons in air showers studied with ground arrays since 1970ies (Haverah Park…)
  - Air shower simulations had to catch up with experiments in early days
- Hybrid experiments ideal: combined longitudinal and ground information
  - 2000: First evidence for muon excess with hybrid detector by HiRes-MIA
    Phys.Rev.Lett. 84 (2000) 4276-4279
  - 2015/16: Evidence for muon excess from Auger up to 3σ
    Phys.Rev.D 91 (2015) 3, 032003
    Phys.Rev.Lett. 117 (2016) 19, 192001

HiRes and MIA collabs. Phys.Rev.Lett. 84 (2000) 4276-4279



Pierre Auger collab. Phys.Rev.D 91 (2015) 3, 032003



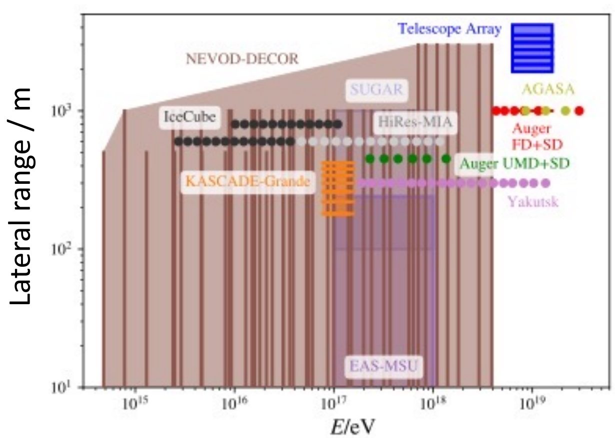
Muon measurements in air showers

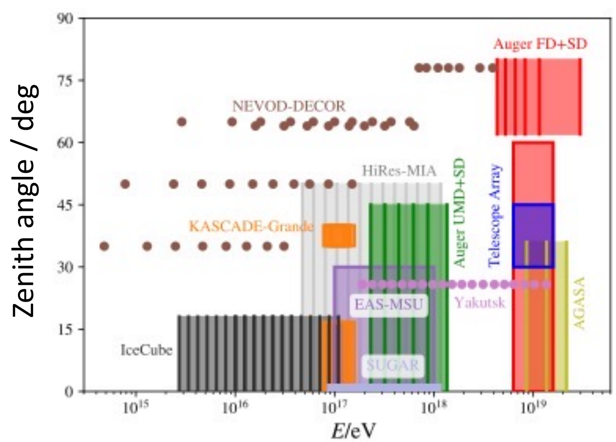
- 2018: Apparently conflicting evidence from different experiments
- Working group on Hadronic Interactions and Shower Physics (WHISP) formed by members of 8 experimental collaborations for UHECR 2018 conference

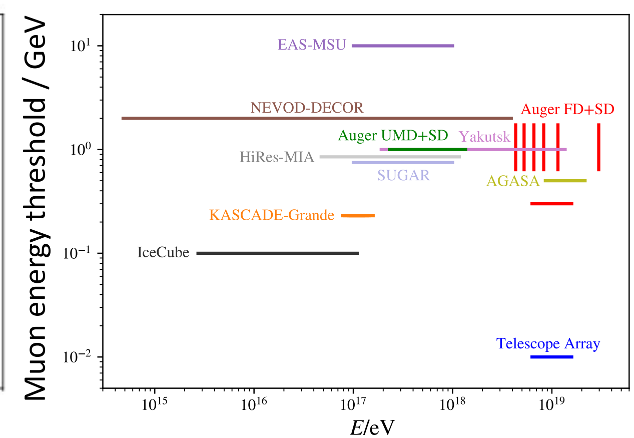
  EAS-MSU, NEVOD-DECOR, IceCube, KASCADE-Grande, Pierre Auger Observatory, SUGAR, Telescope Array, Yakutsk EAS Array

- Goal: Combine diverse set of muon measurements
  - New for ICRC2021: AGASA data, updated data from IceCube, Auger, SUGAR
    PoS(ICRC2021)326

PoS(ICRC2021)349







z-scale and energy-scale calibration

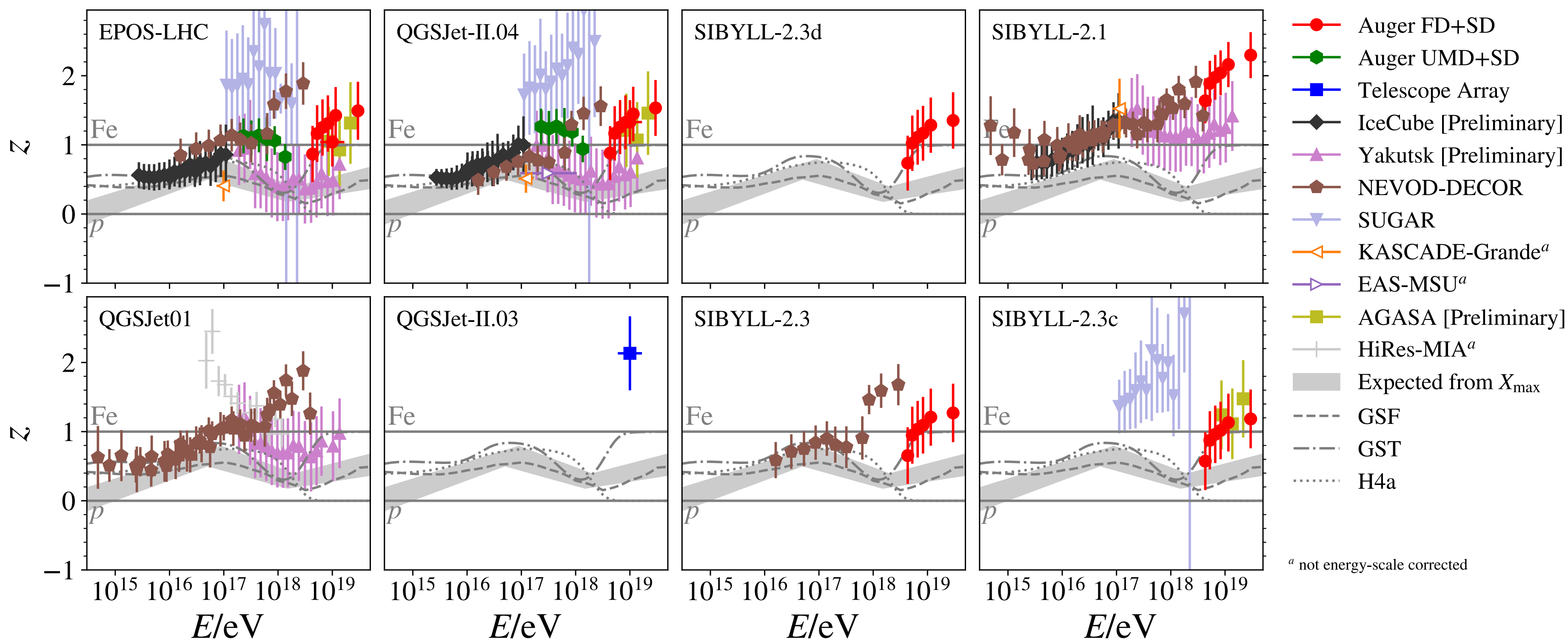
Abstract muon scale
independent of experiment,
dependent on air shower model

data sim

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

sim sim

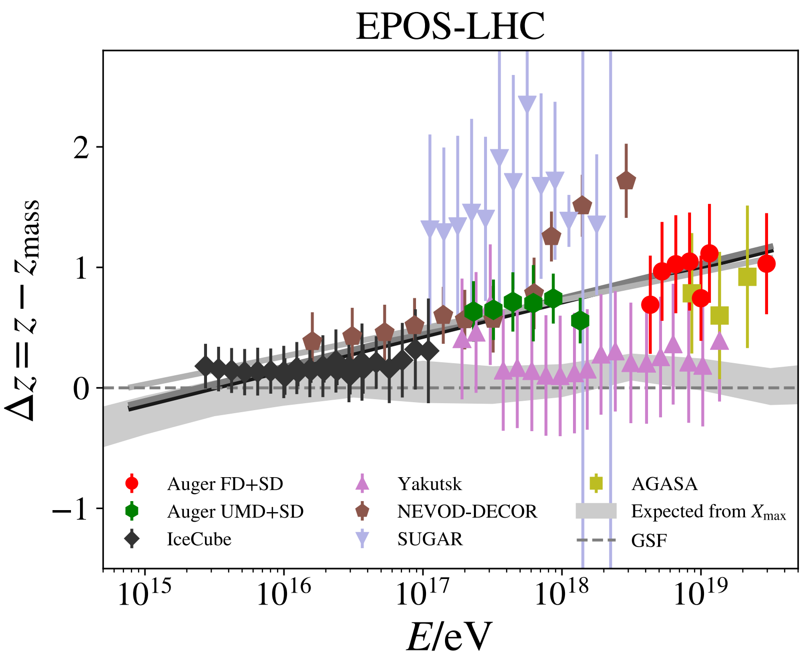
PoS(ICRC2021)349

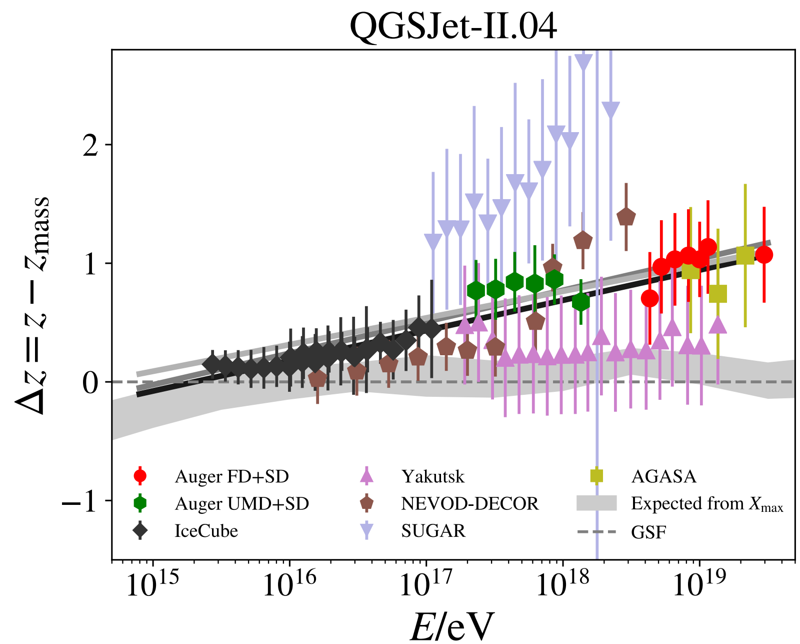


- Original data adjusted with energy-scale cross-calibration (this figure)
- Removes relative systematic shifts between experiments

Muon deficit in simulated showers

PoS(ICRC2021)349





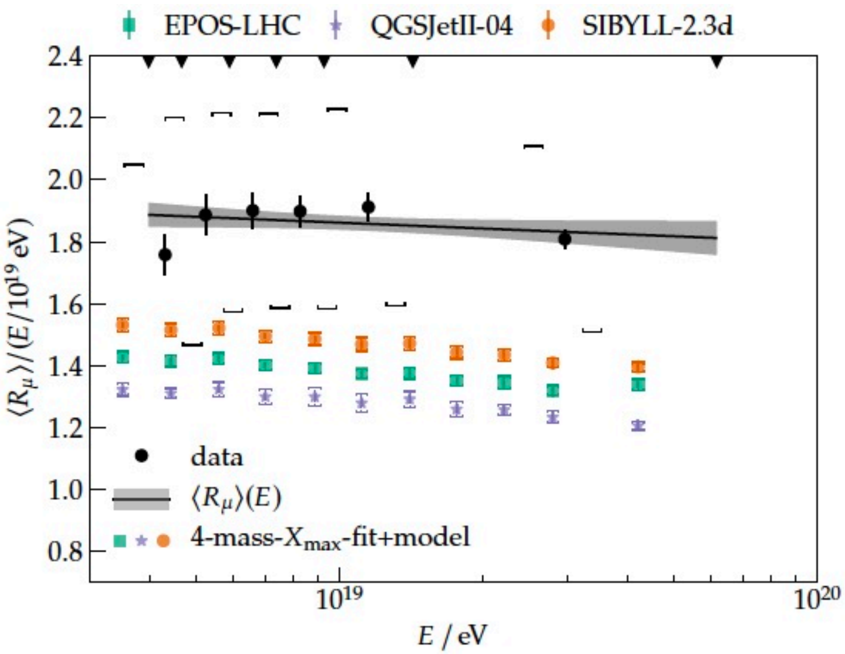
$$z = \frac{\ln(N_{\mu}^{\mathrm{det}}) - \ln(N_{\mu_p}^{\mathrm{det}})}{\ln(N_{\mu_{\mathrm{Fe}}}^{\mathrm{det}}) - \ln(N_{\mu_p}^{\mathrm{det}})}$$

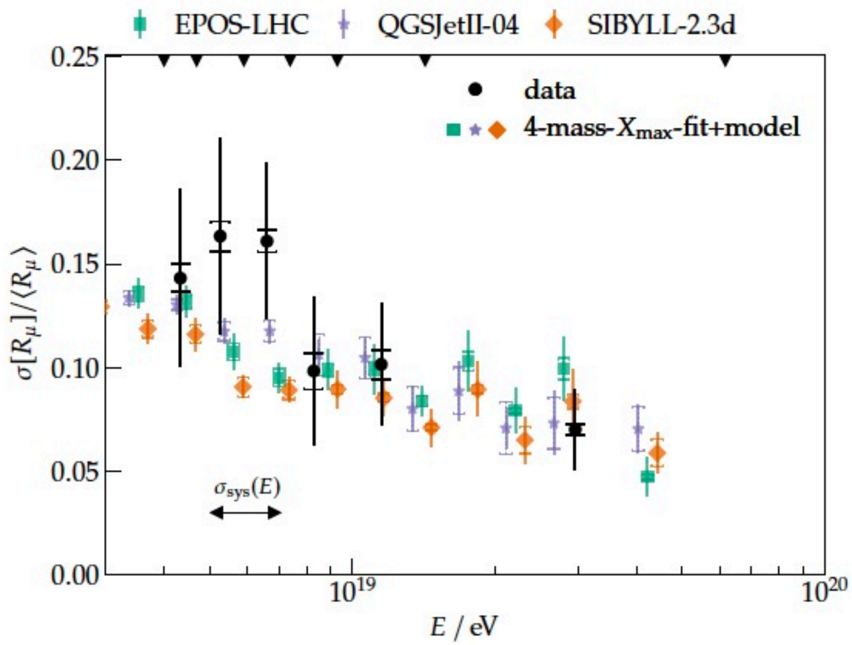
$$z_{\mathrm{mass}} \approx \frac{\langle \ln A \rangle}{\ln 56}$$

- 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

Muon number fluctuations

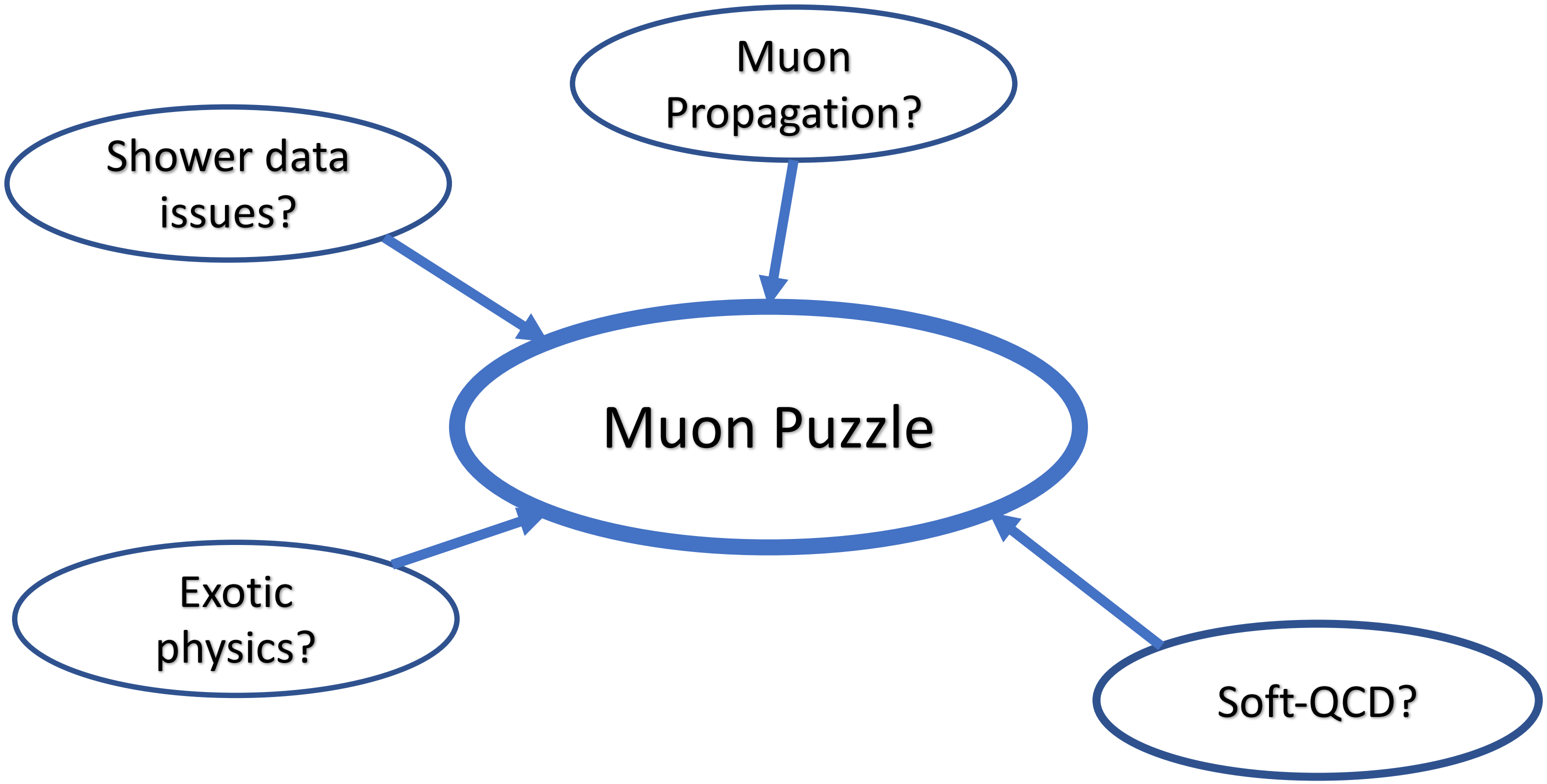
Pierre Auger collab., Phys.Rev.Lett. 126 (2021) 15, 152002





- First measurement of mean and **variance** of muon number distribution
- Variance of muon number consistent with current model predictions; mean deviates
- Constrains scenarios in which only first (or second) interaction is modified, e.g. in model with violation of Lorentz-invariance PoS(ICRC2021)340

Attempts to explain muon puzzle



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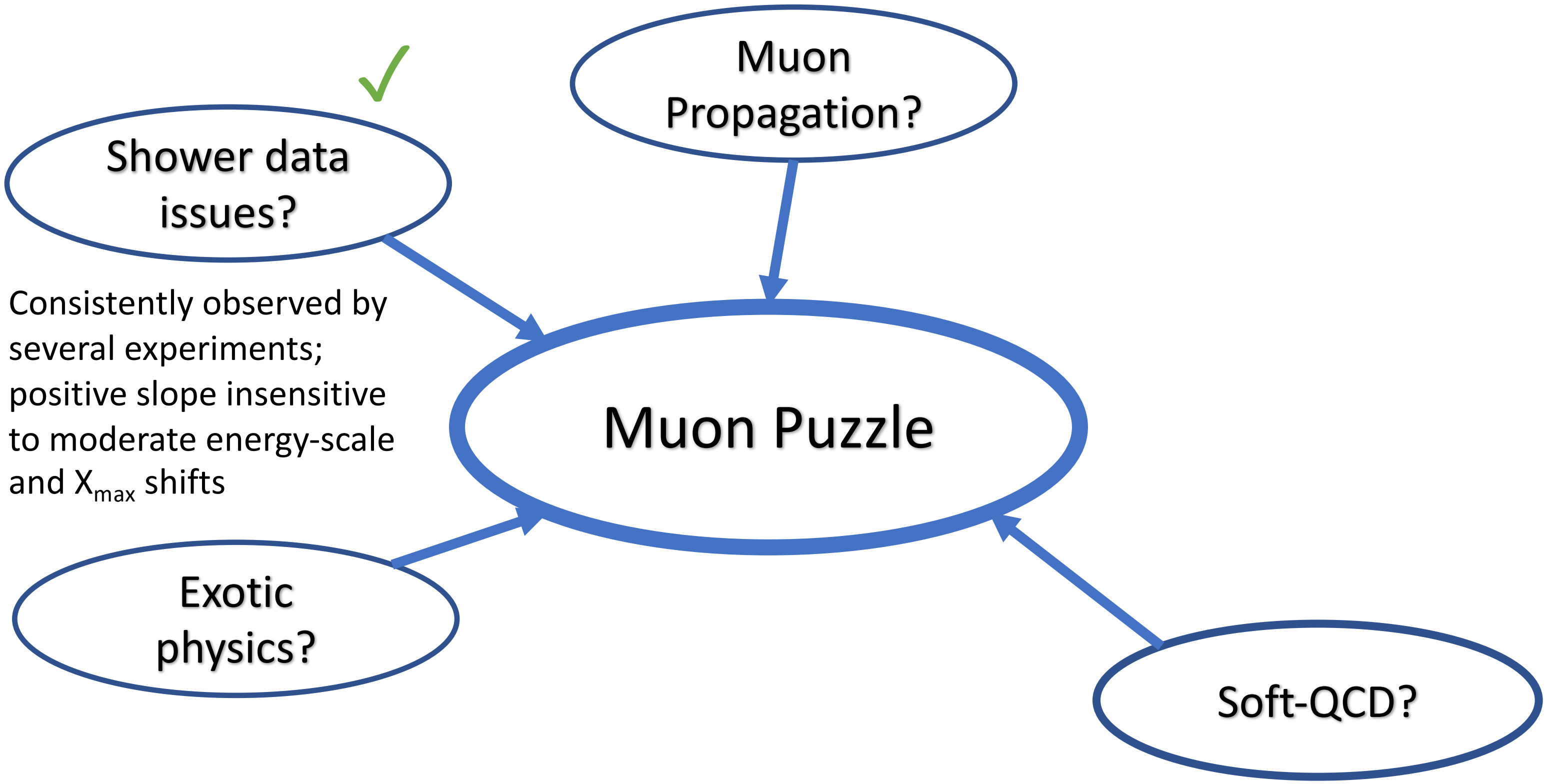
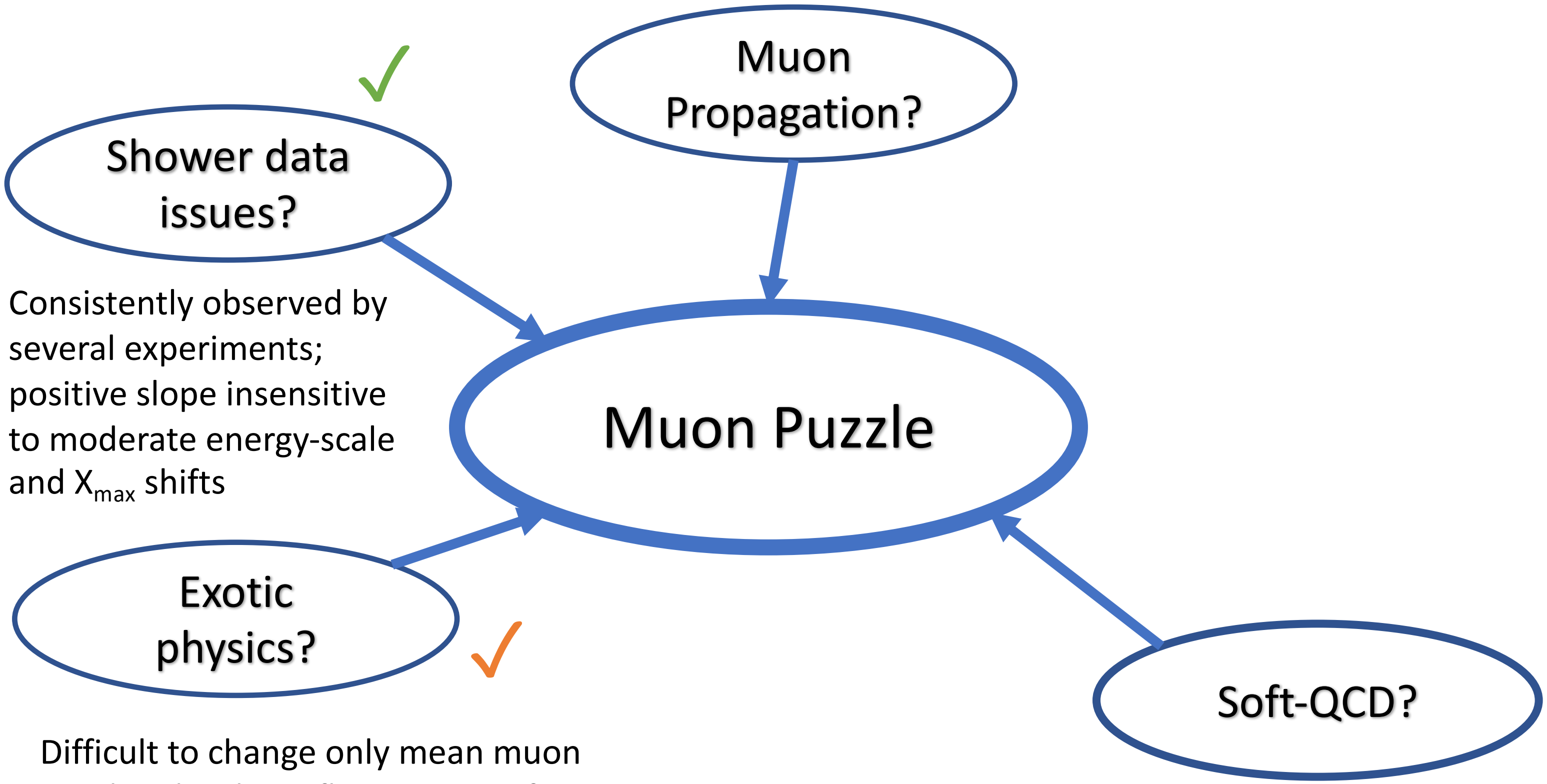


Consistently observed by several experiments; positive slope insensitive to moderate energy-scale and X_{max} shifts

Attempts to explain muon puzzle

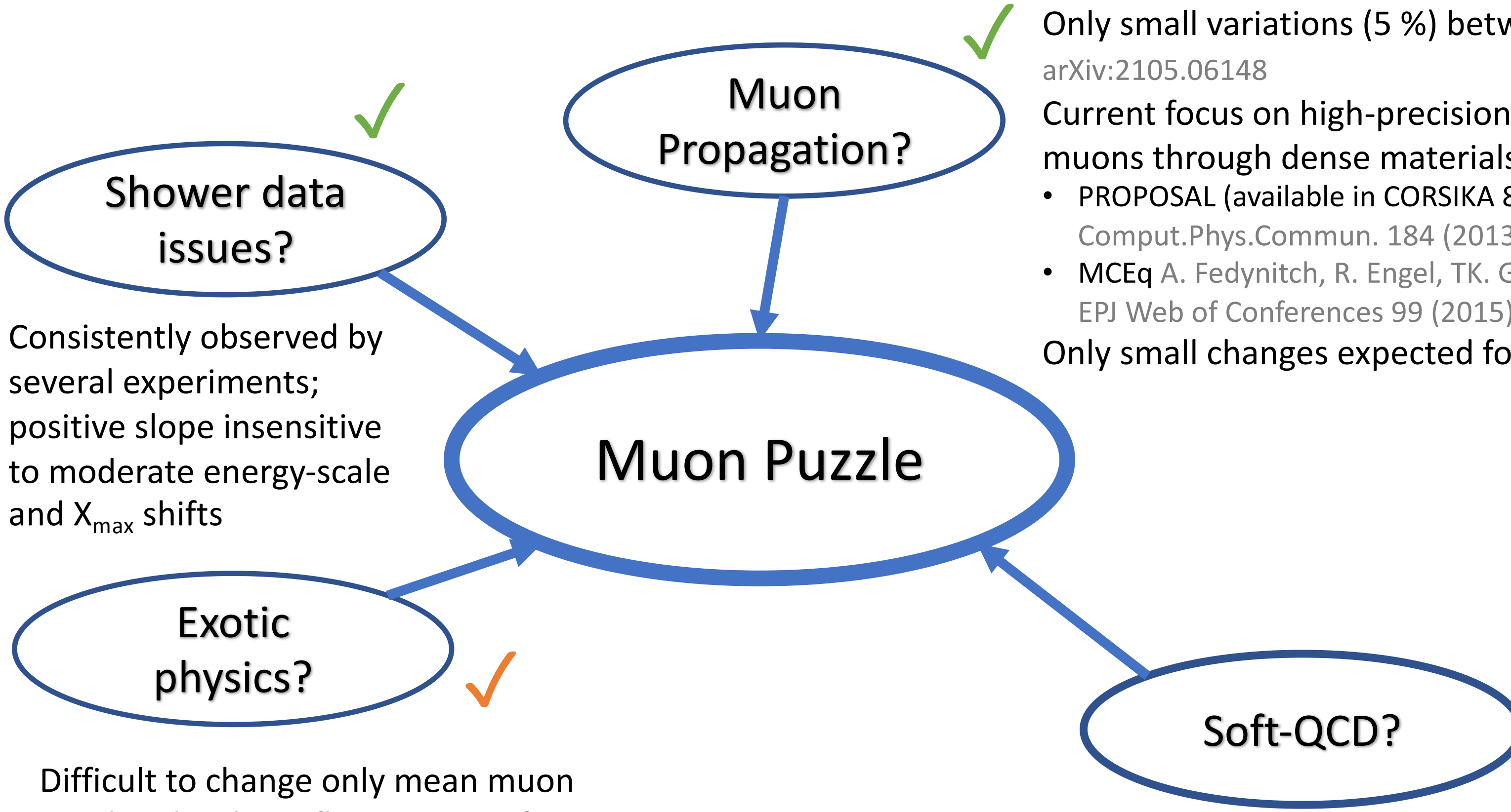


Consistently observed by several experiments; positive slope insensitive to moderate energy-scale and X_{max} shifts

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



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

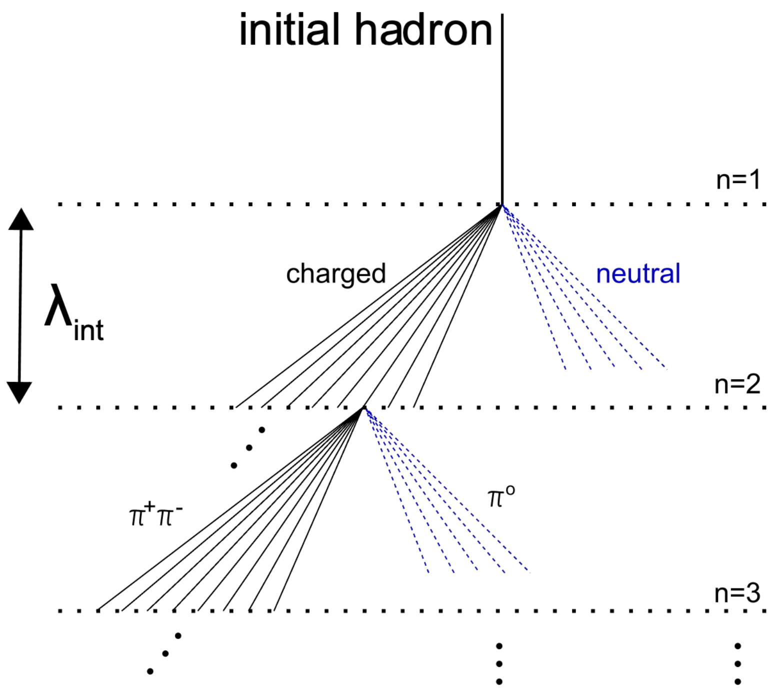
Difficult to change only mean muon number, but keep fluctuations of X_{max} and N_{μ} same;
early onset of muon discrepancy

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

From shower muons to QCD

Heitler-Matthews model of air shower

J. Matthews, Astropart. Phys. 22 (2005) 387-397



Cascade stops after 5-10 steps (energy-dependent)

Muons detected in air shower arrays produced at end of hadronic cascade when π (and K) decay

$$N_\mu(E, A) = A^{(1-\beta)} \left(\frac{E}{\xi_h}\right)^\beta$$

E … energy of cosmic ray
A … mass of cosmic ray
ξ_h … critical energy

$$\text{with } \beta = \frac{\ln(\alpha\, N_\text{mult})}{\ln N_\text{mult}} \approx 0.9$$

α … fraction of charged pions among all pions

exactly 2/3 in Heitler-Matthews model

N_{mult} … hadron multiplicity

From shower muons to QCD

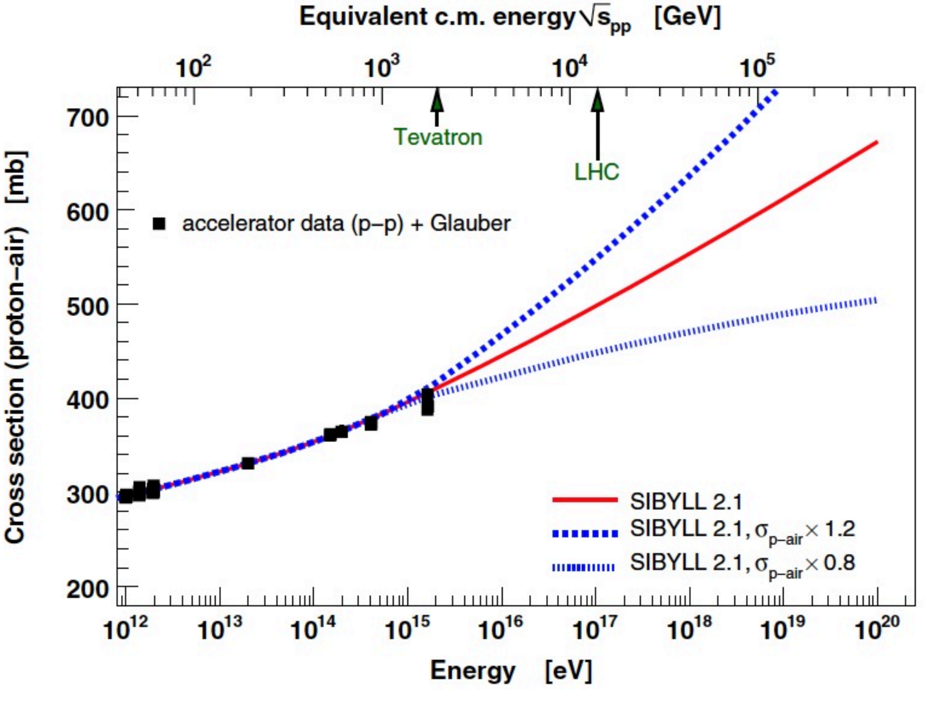
R. Ulrich, R. Engel, M. Unger, PRD 83 (2011) 054026

- 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

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

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



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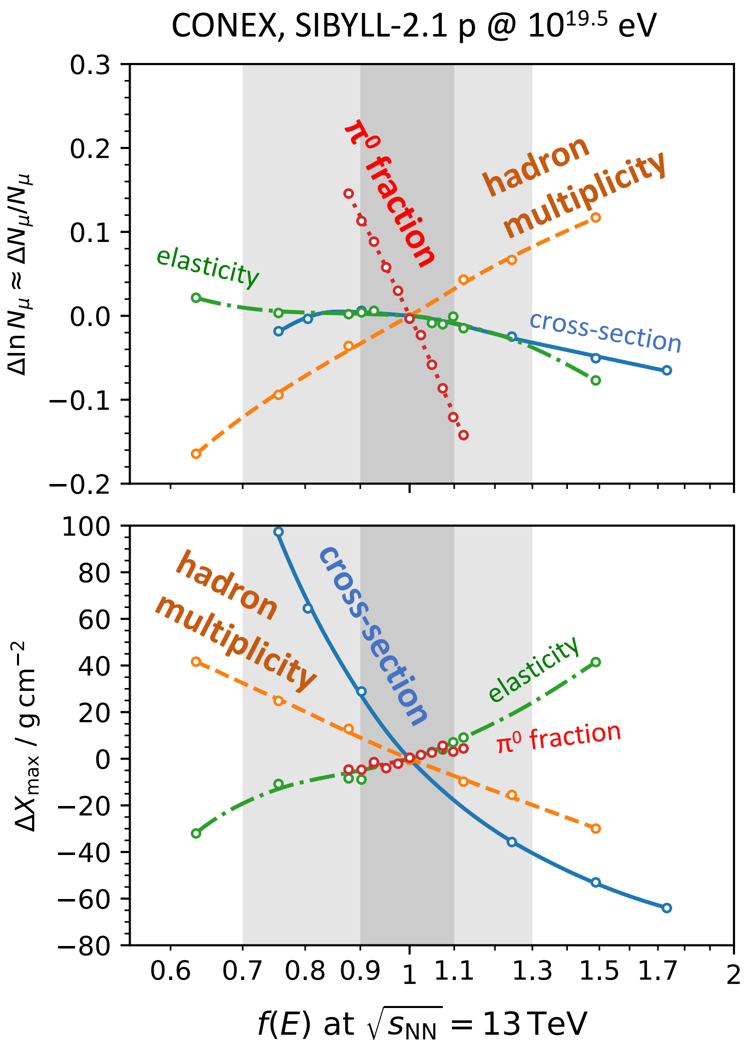
R. Ulrich, R. Engel, M. Unger, PRD 83 (2011) 054026

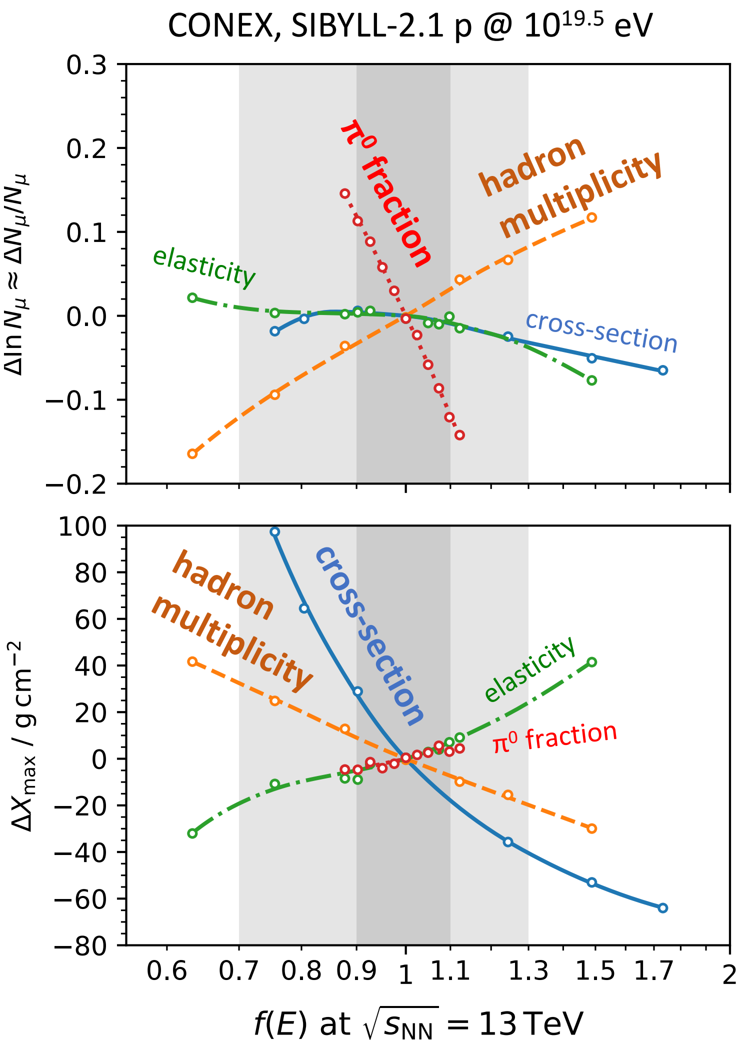


- Number of muons produced, N_μ
  - Very sensitive to π^0 fraction
  - Sensitive to hadron multiplicity
- Depth of shower maximum, X_{max}
  - Very sensitive to cross-section
  - Sensitive to hadron multiplicity
  - Insensitive to π^0 fraction

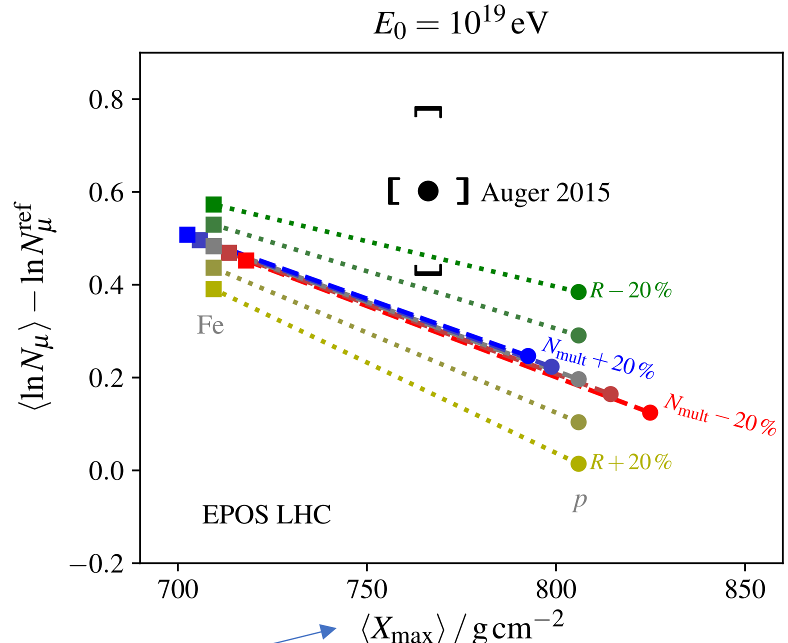
Changing π^0 fraction most promising

From shower muons to QCD

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



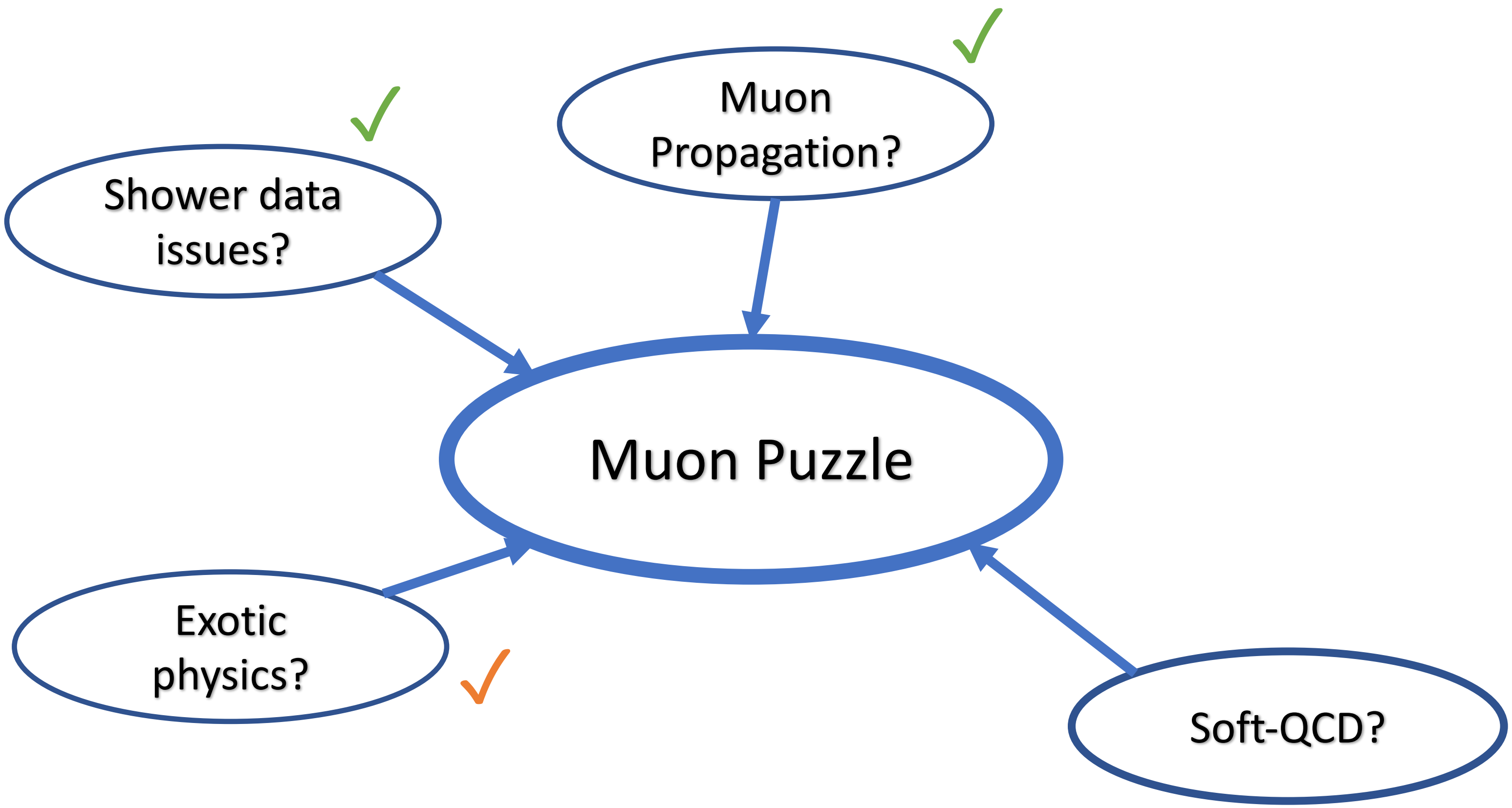
S. Baur, HD, M. Perlin, T. Pierog, R. Ulrich, K. Werner, arXiv:1902.09265



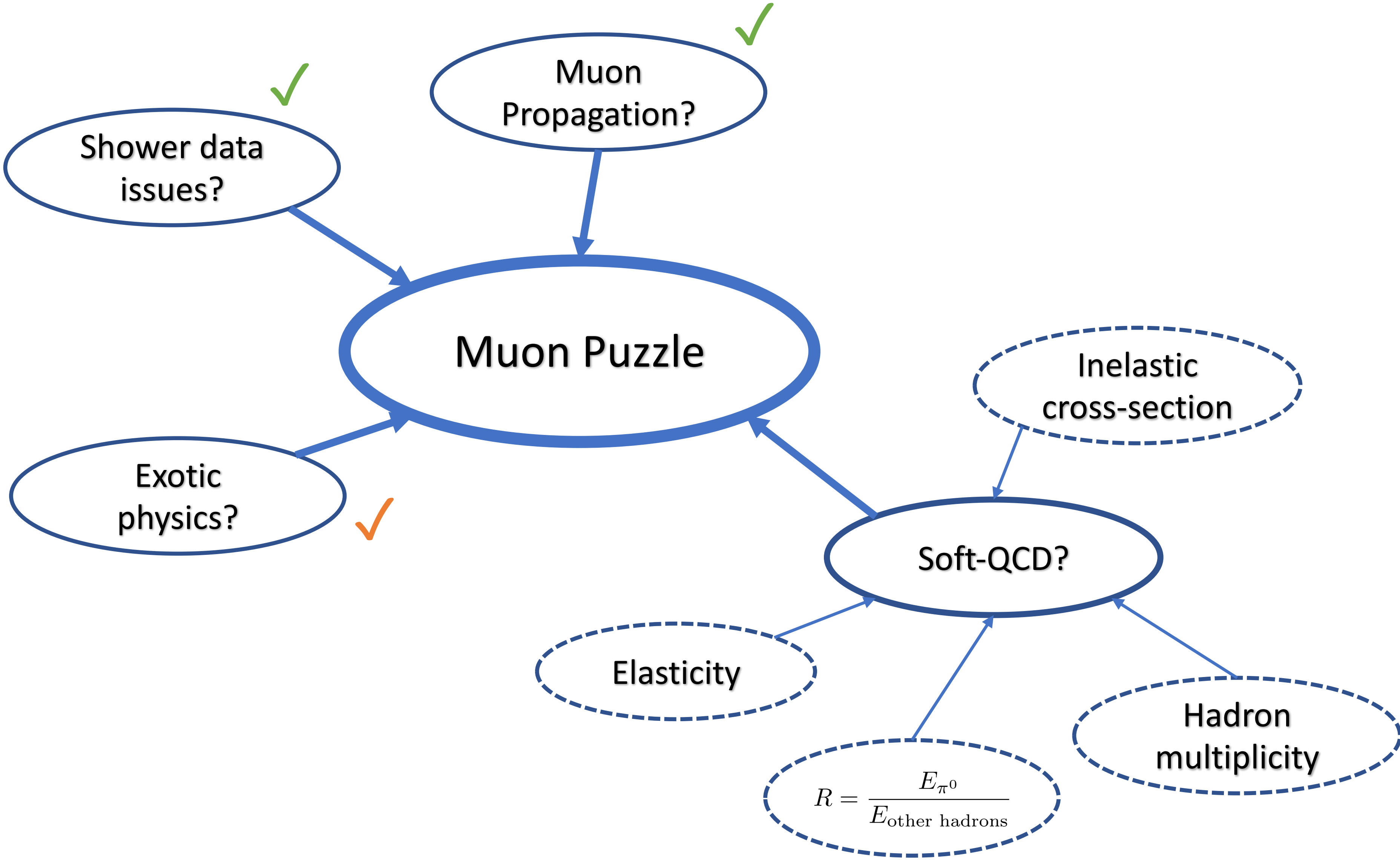
$$R = \frac{E_{\pi^0}}{E_{\text{other hadrons}}}$$

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

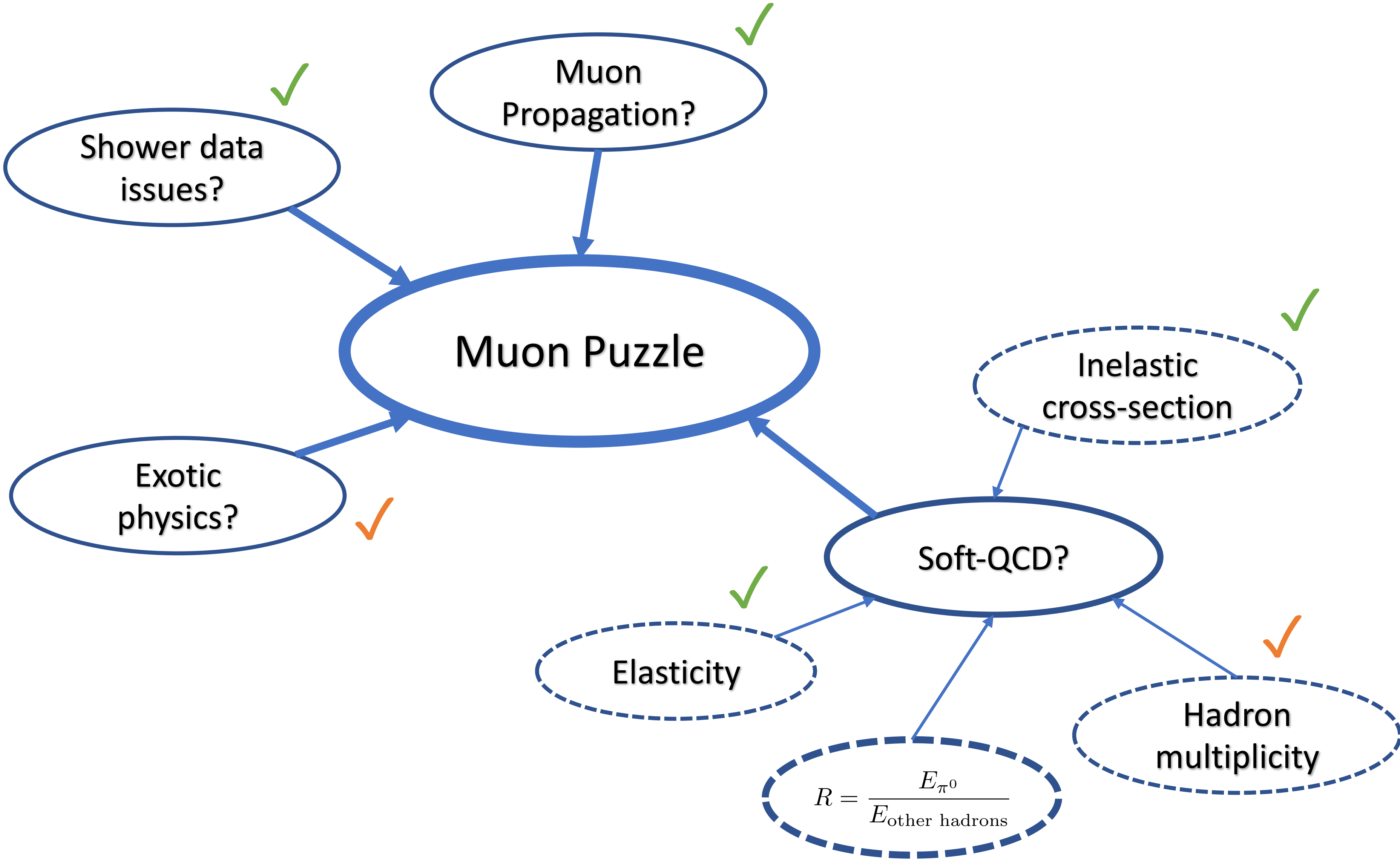
Attempts to explain muon puzzle



Attempts to explain muon puzzle

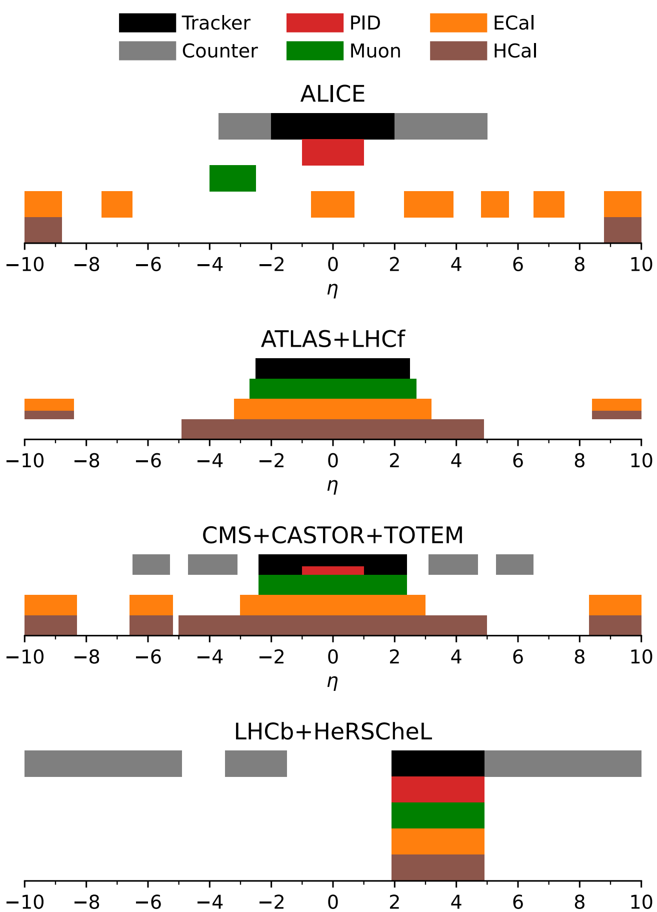


Attempts to explain muon puzzle

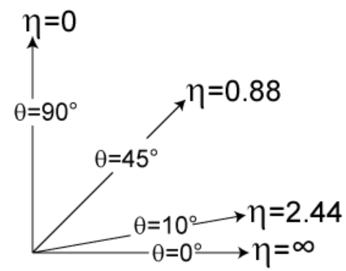


LHC experiments and Muon Puzzle

arXiv:2105.06148



pseudorapidity η



η related to emission angle

Image credit: JabberWok - Wikipedia CC BY-SA 3.0

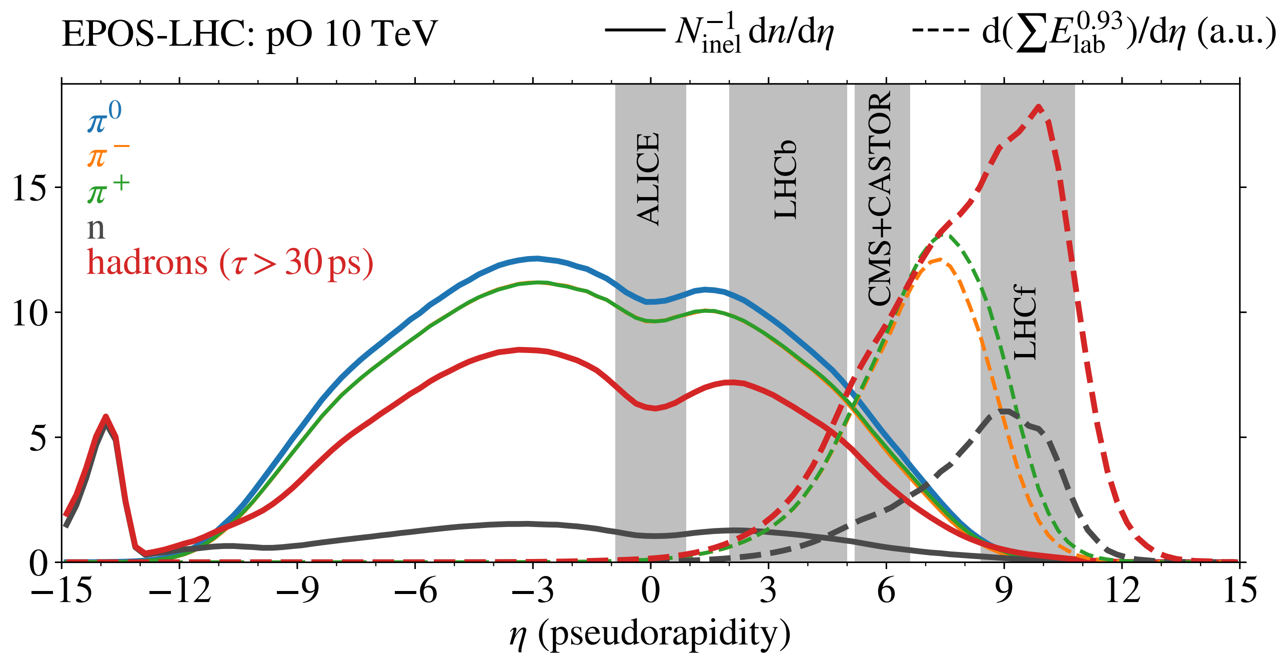
- Most LHC experiments focus on |η| < 2 region
  - Detectors well instrumented here
- Forward capabilities |η| > 2
  - ALICE, TOTEM: counters
  - CMS-CASTOR: Calorimeters for eγ and hadrons
  - LHCb: full tracking and PID at 2 < η < 5
  - LHCf: neutral particles η > 8

Importance of forward acceptance

„Muon production weight“

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

arXiv:2105.06148



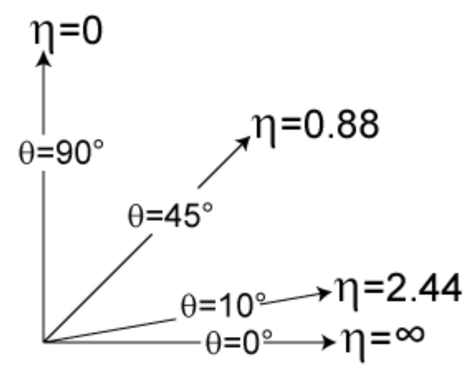
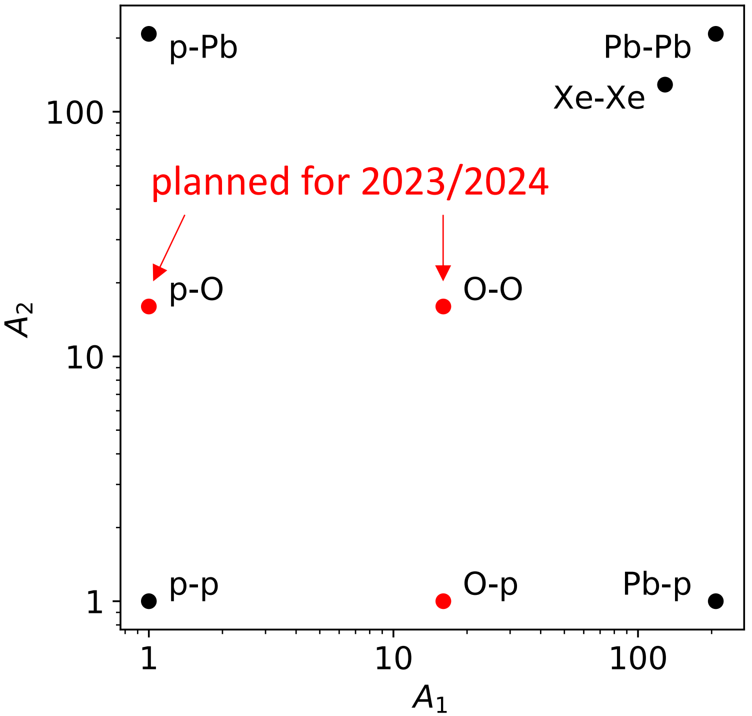


Image credit:
JabberWok - Wikipedia CC BY-SA 3.0

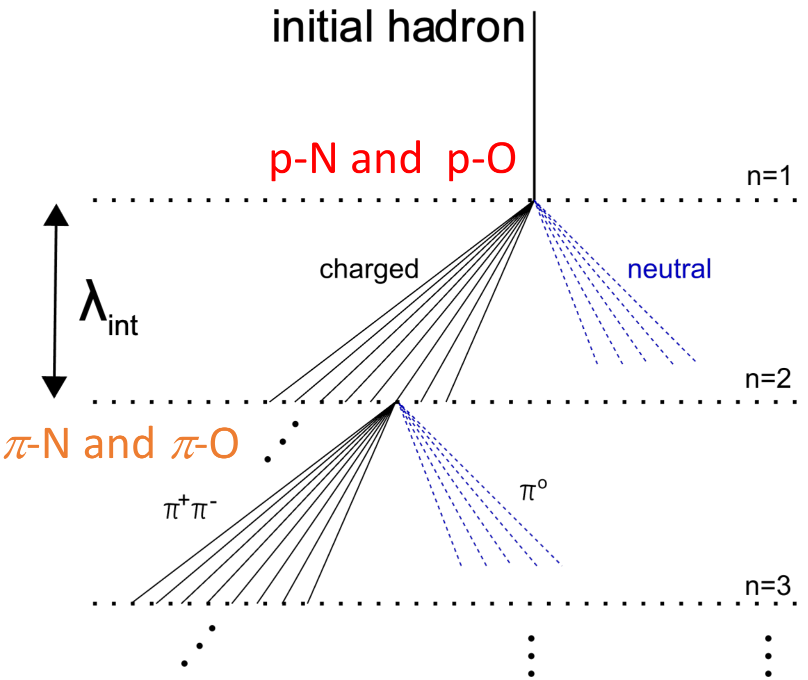
See PoS(ICRC2021)463 for full simulation of "muon production weight" with CORSIKA 8

Collisions at the LHC and air showers

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



Air shower collision systems



Fixed target data at sub-TeV (LHCb)

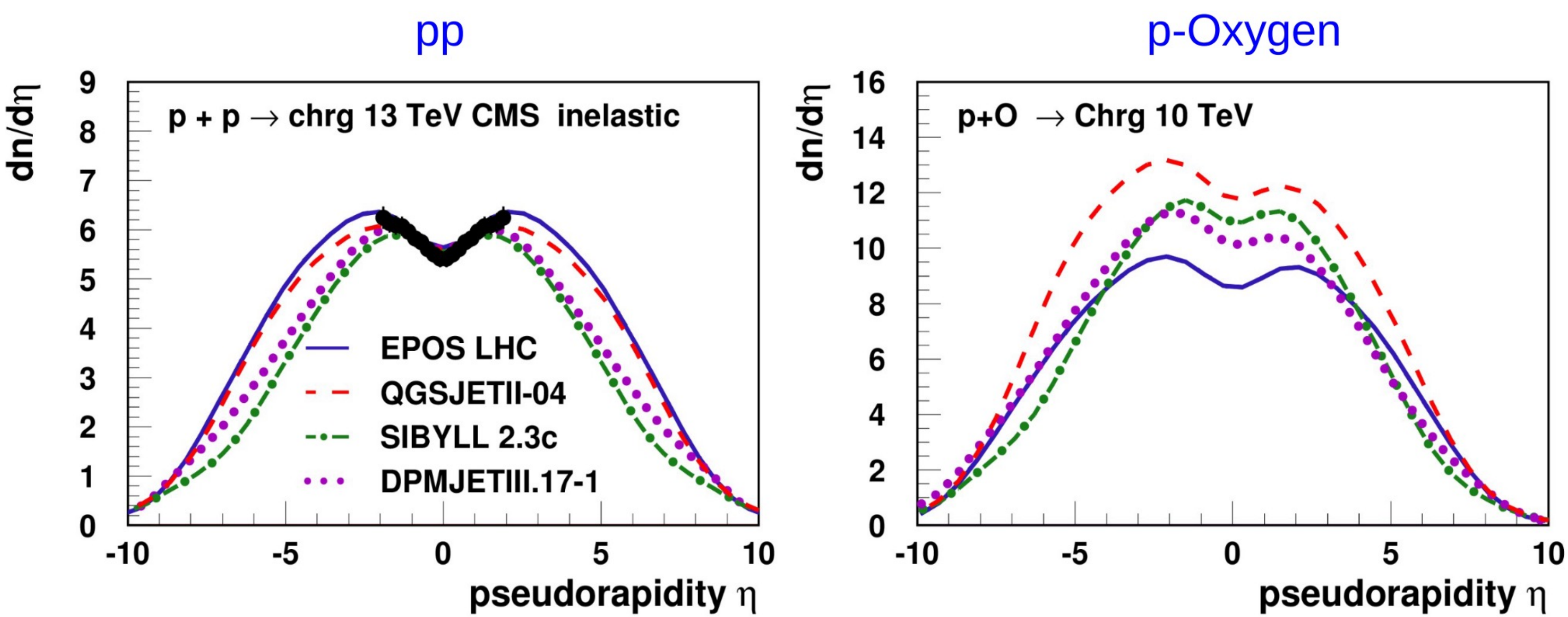
- p+(p,...,O,N,...) @ 110 GeV
- Pb+(p,...,O,N,...) @ 69 GeV
- O+O, O+p @ 81 GeV

(in Run 3)

p-O collisions mimic air shower interactions

Charged particle spectra

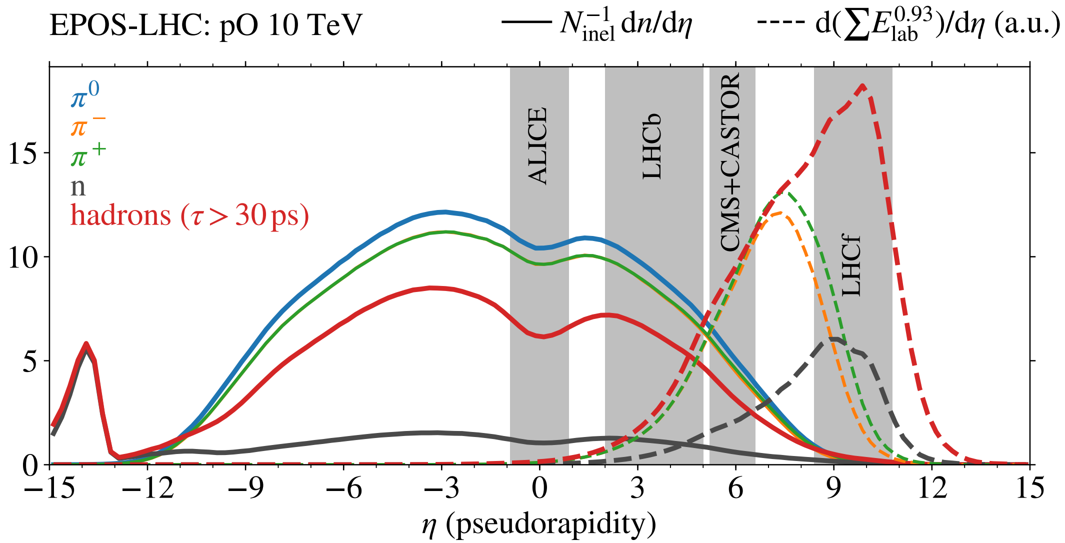
T. Pierog, ISVHECRI 2018



- Data available now up to |η| = 6.4 in p-p and partially in p-Pb
- Models agree at mid-rapidity in p-p due to tuning to LHC data
- Models do not agree on shape
- Models do not agree on extrapolation from p-p to p-O; new LHC data will fix this

Possibilities to reduce energy ratio *R*

- Difficult to change *R* within standard QCD
  - Fragmentation of strings and excited nuclear remnant believed to be universal
  - Iso-spin symmetry: $\pi^+ : \pi^- : \pi^0 \sim 1 : 1 : 1$



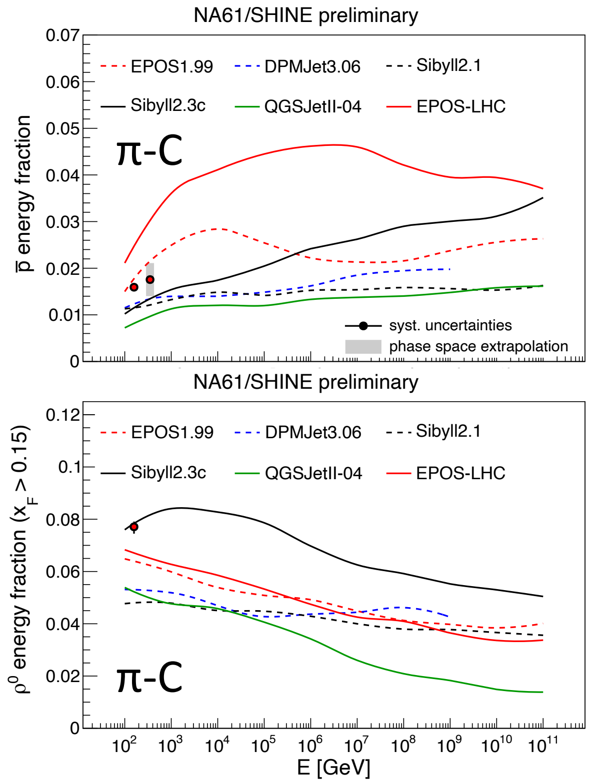
$$R = \frac{E_{\pi^0}}{E_{\text{other hadrons}}}$$

Possibilities to reduce energy ratio *R*

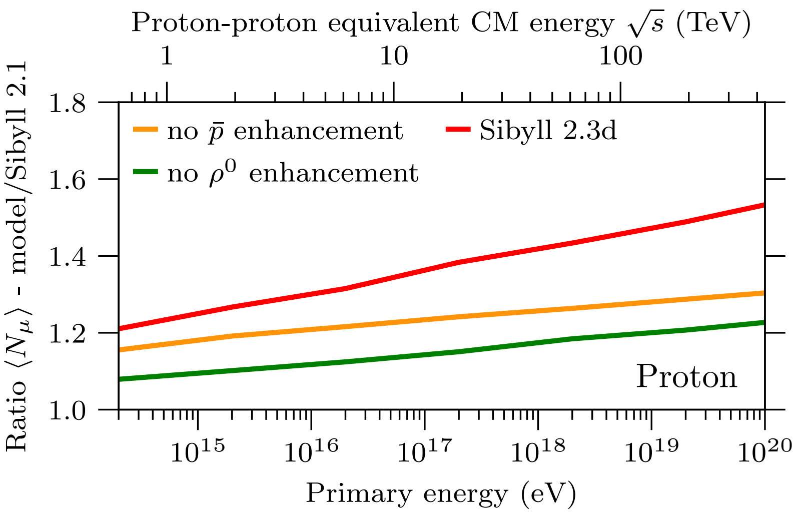
- Difficult to change *R* within standard QCD
  - Fragmentation of strings and excited nuclear remnant believed to be universal
  - Iso-spin symmetry: $\pi^+ : \pi^- : \pi^0 \sim 1:1:1$
- Changes to baryon production and ρ^0 production in π-air collisions

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



Lab energy (fixed-target)

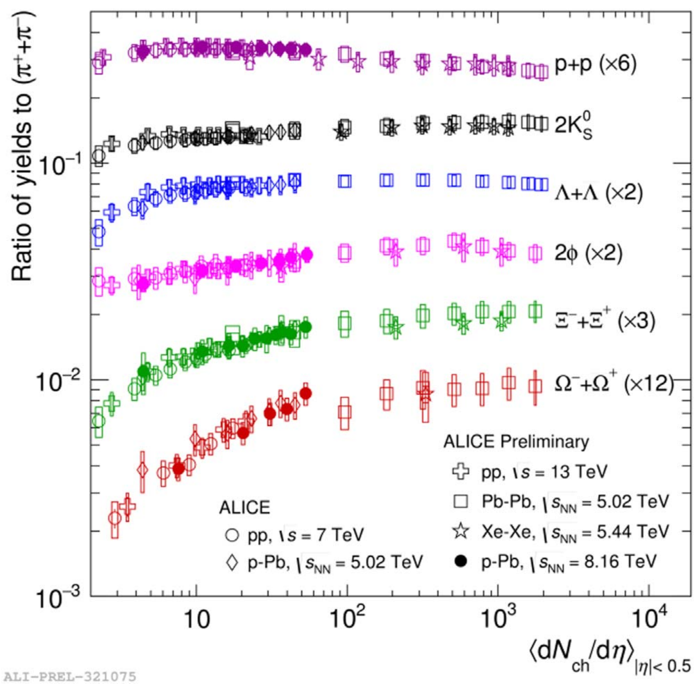


- Large increase of muon number compared to SIBYLL 2.1, but not enough to solve muon puzzle
- No data for pion interactions at $\sqrt{s}$ > 100 GeV

Possibilities to reduce energy ratio R

- Difficult to change R within standard QCD
  - Fragmentation of strings and excited nuclear remnant believed to be universal
  - Iso-spin symmetry: $\pi^+ : \pi^- : \pi^0 \sim 1:1:1$
- Changes to baryon production and ρ^0 production in π-air collisions
- Strangeness enhancement

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

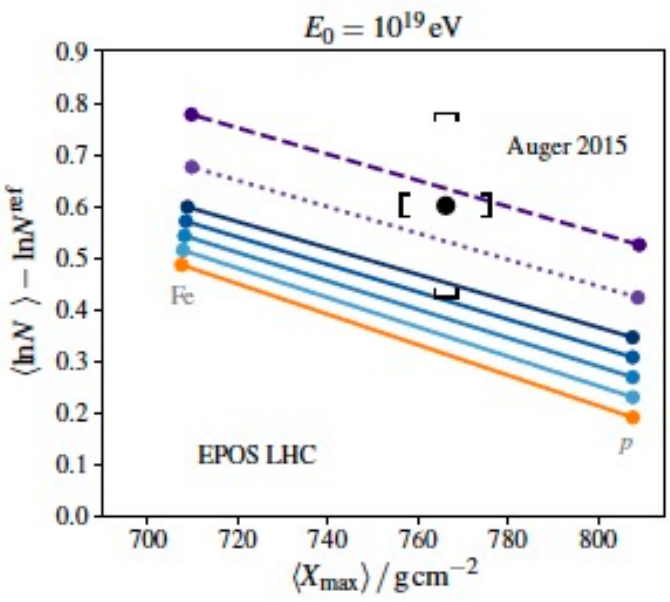


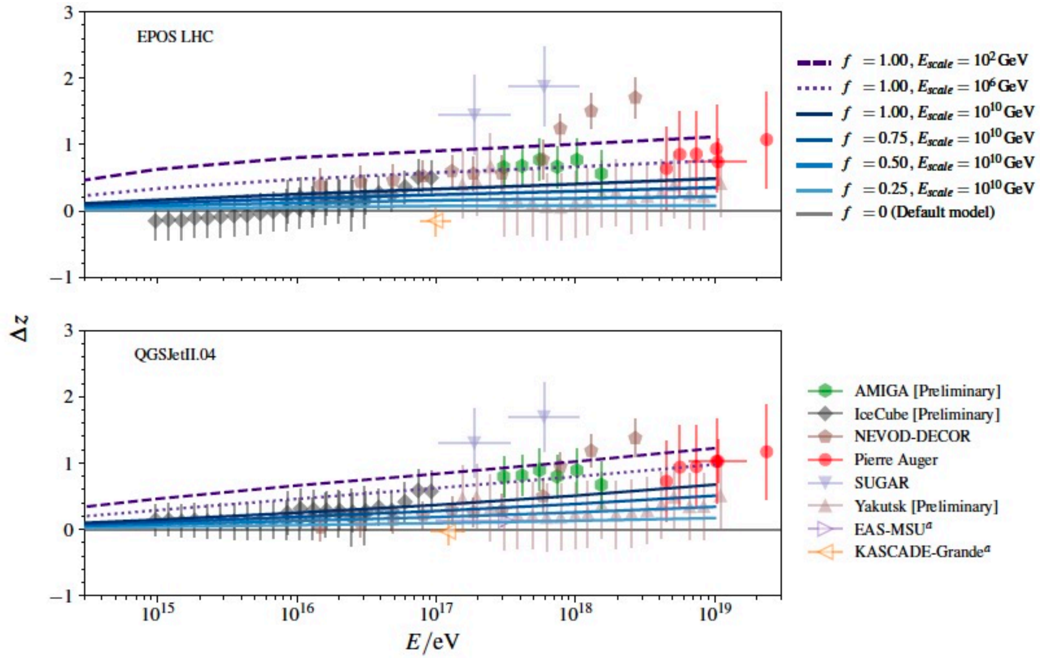
- ALICE discovered universal enhancement of strangeness production in *pp*, *p*Pb, PbPb
  ALICE, Nature Phys. 13 (2017) 535
- More strangeness → less π^0 → more muons in air showers
  $R \approx 0.41 - 0.45$ (low density) $R \approx 0.34$ (high density)
- Enhancement seems to depend **only** on density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

Statistical hadronization

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

PoS(ICRC2021)469



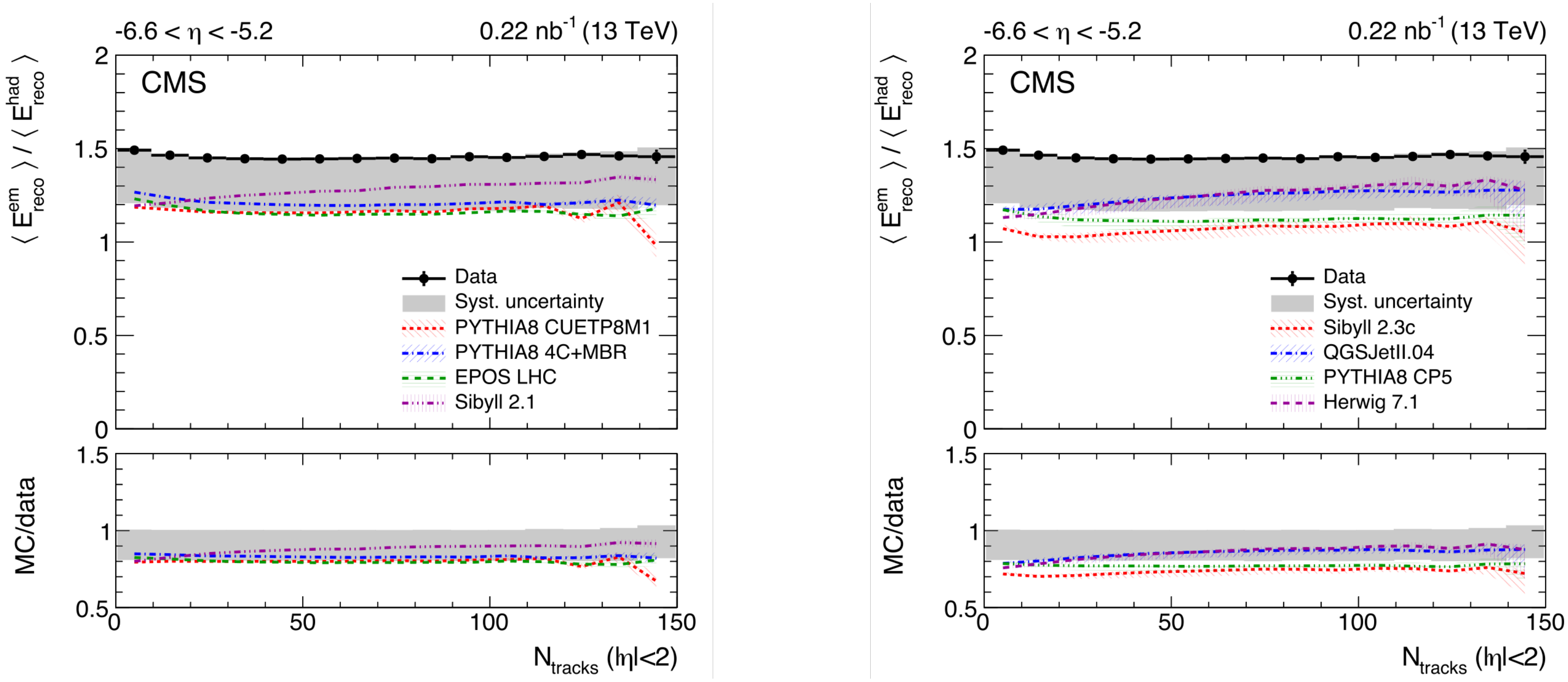


- Toy model with statistical hadronization (core) in addition to string/remnant fragmentation (corona)
  - Statistical hadronization needed to describe strangeness enhancement seen by ALICE
  - Can close muon number gap number in air showers and matches faster increase with energy
- Constrained by CMS-CASTOR measurements of *R*
- Can be tested further with data on forward strangeness production from LHCb and LHCf

Direct very forward measurement of R

CMS, Eur.Phys.J. C79 (2019) no.11, 893; S. Baur, HD, M. Perlin, T. Pierog, R. Ulrich, K. Werner, arXiv:1902.09265

p-p @ 13 TeV

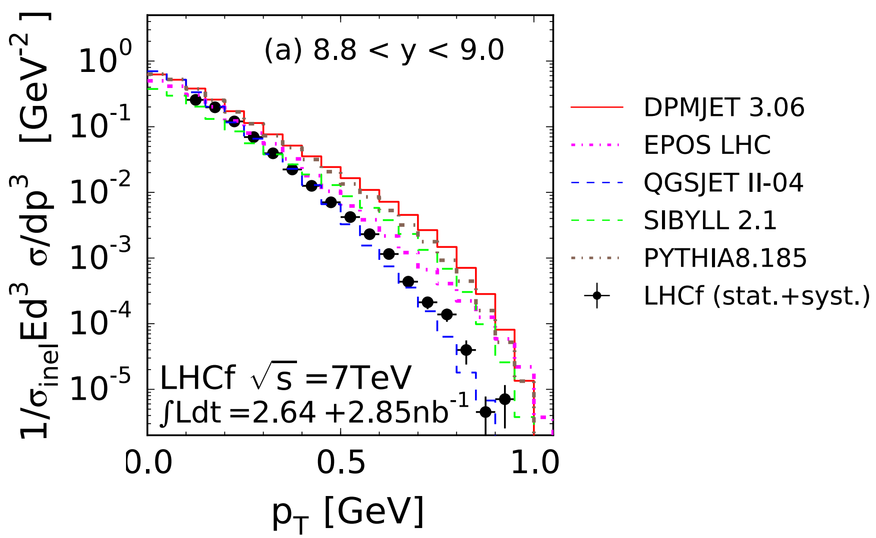


- Ideal measurement for muon puzzle in air showers, but precision important
- Measured R_{reco} value higher than predicted by models in p-p, but models mostly consistent
- $R_{reco} > R$ here, because of detector effects

Very forward neutral particles

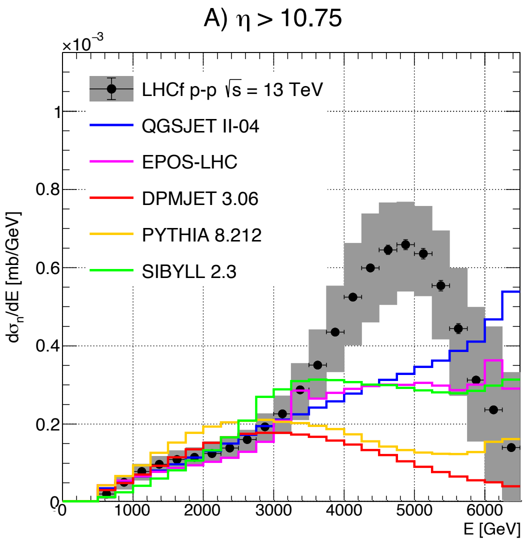
LHCf, Phys.Rev.D 94 (2016) 3, 032007

π^0 production in p-p @ 7 TeV



LHCf, JHEP 07 (2020) 016

neutron production in p-p @ 13 TeV



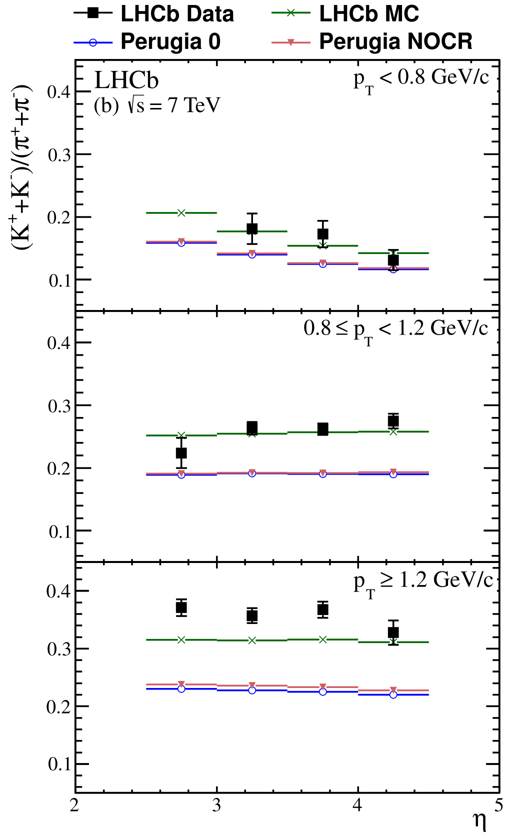
- LHCf: zero degree calorimeters ($\eta > 8$) around ATLAS to detect neutral particles
- *R* constrained by photon, π^0, neutron production cross-sections in p-p, p-Pb from 0.9 to 13 TeV
- Reasonable description of π^0 data, but peak in neutron energy spectrum absent in models

- RHICf: Further studies in p-p at 0.51 TeV PoS(ICRC2021)301
- Plans to study strangeness production via $K^0_S \longrightarrow 4\gamma$ (requires large samples) PoS(ICRC2021)301
- Well prepared for studies of p-O collisions PoS(ICRC2021)348

Forward spectra of identified hadrons

LHCb, EPJC (2012) 72:2168

p-p @ 7 TeV



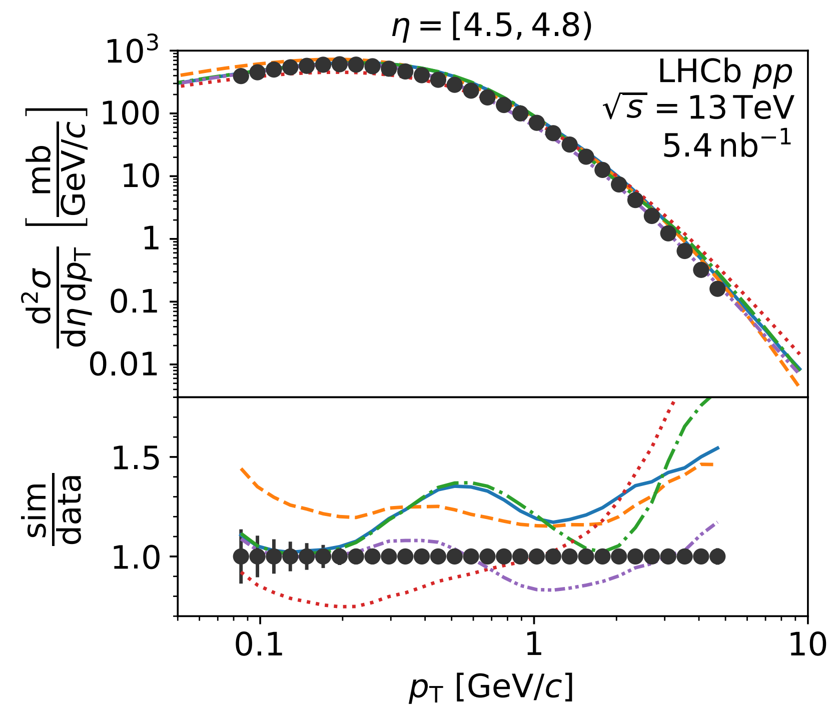
Prompt charged particles

LHCb-PAPER-2021-010, arXiv:2107.10090

p-p @ 13 TeV

LHCb-PAPER-2021-015, arXiv:2107.10090

p-p, p-Pb @ 5 TeV



- LHCb: forward spectrometer with particle identification $2 < \eta < 5$
- 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 about to be released
- Potential of fixed target studies: $\bar{p}$ production in p-He at 0.11 TeV LHCb, PRL 121 (2018) 22, 222001

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 2024/25
  - Will resolve large model spread in charged particle density
  - Need to study hadron composition & strangeness production over wide η range

- More precise muon data from enhanced and new 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

Muons and radio: great match

Muon energy spectrum: additional information