

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

Hans Dembinski, TU Dortmund, Germany

ICRC, 15 July 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

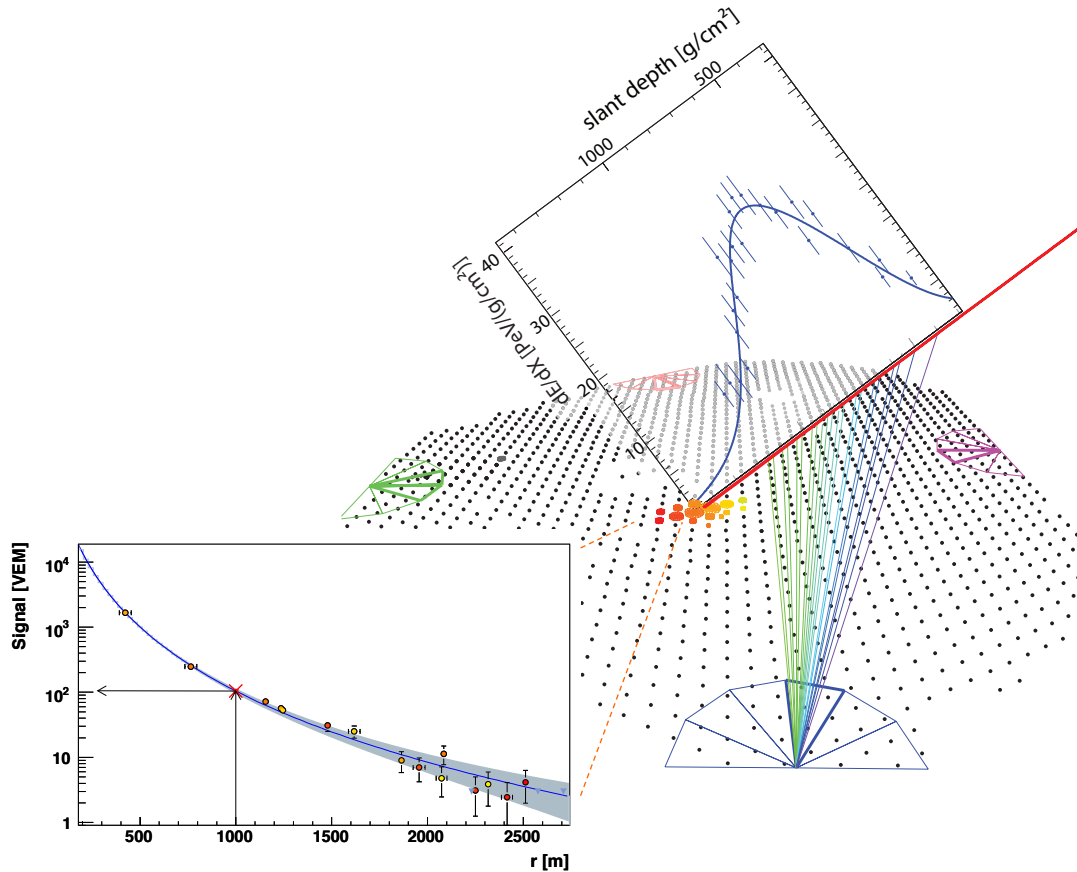
The Muon Puzzle in cosmic-ray induced air showers and its connection to the Large Hadron Collider
invited review submitted to *Astrophysics and Space Science* (2021) arXiv:2105.06148

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

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

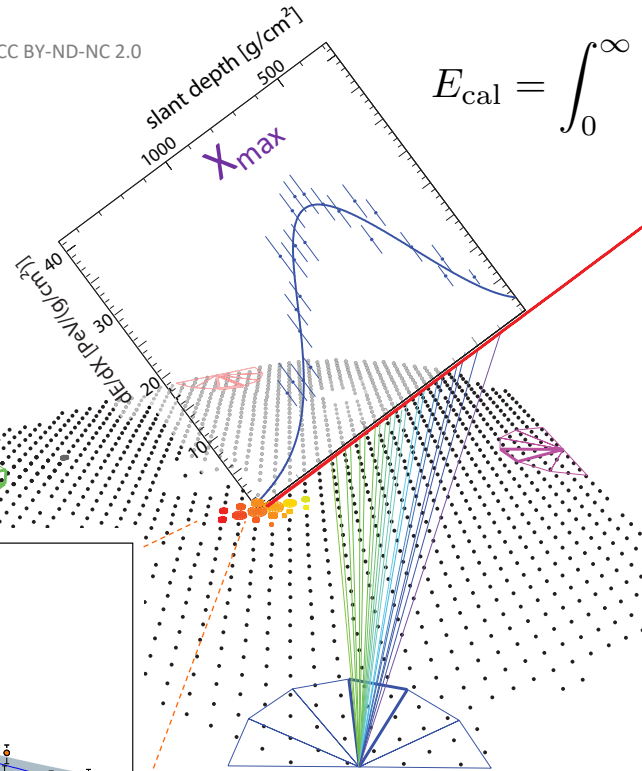


High-energy cosmic ray detection

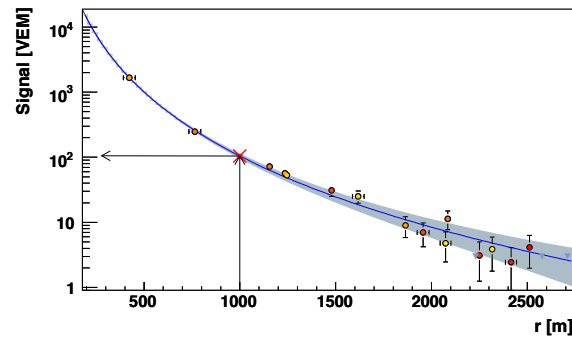
Example: event observed with Pierre Auger Observatory

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 **ey component**
- **Mass** from
 depth of shower maximum X_{max}
 size of muonic component N_{μ}

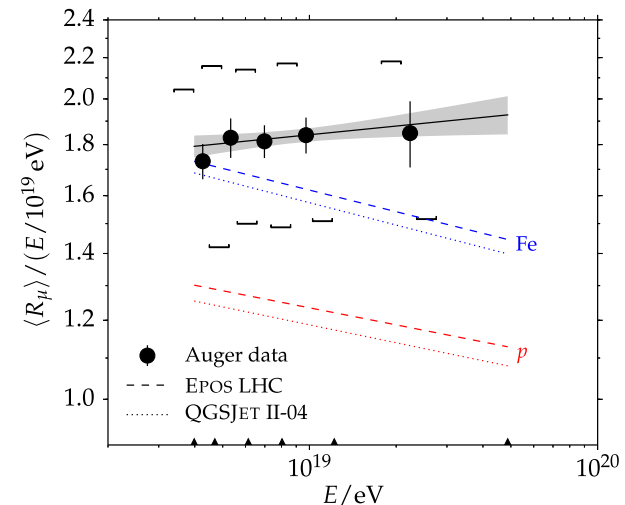
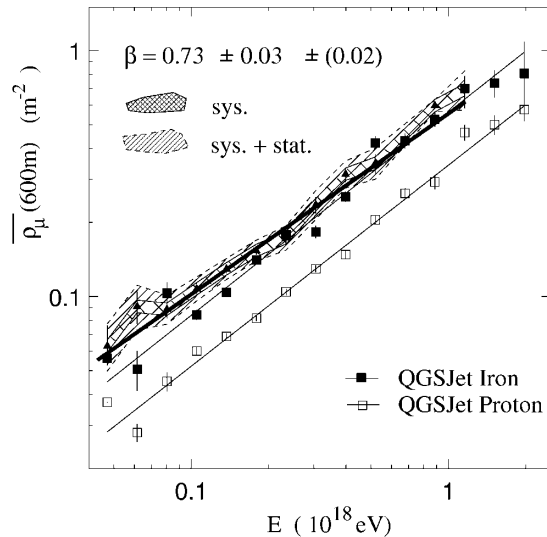
Ground signal = **electrons**, **photons**, **muons**

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



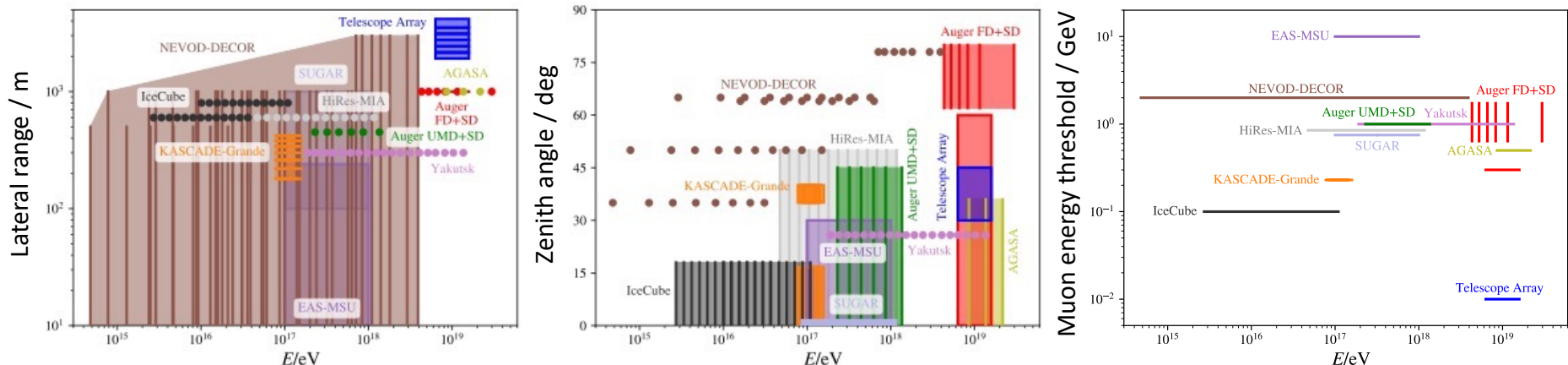
Muon measurements in air showers

- 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

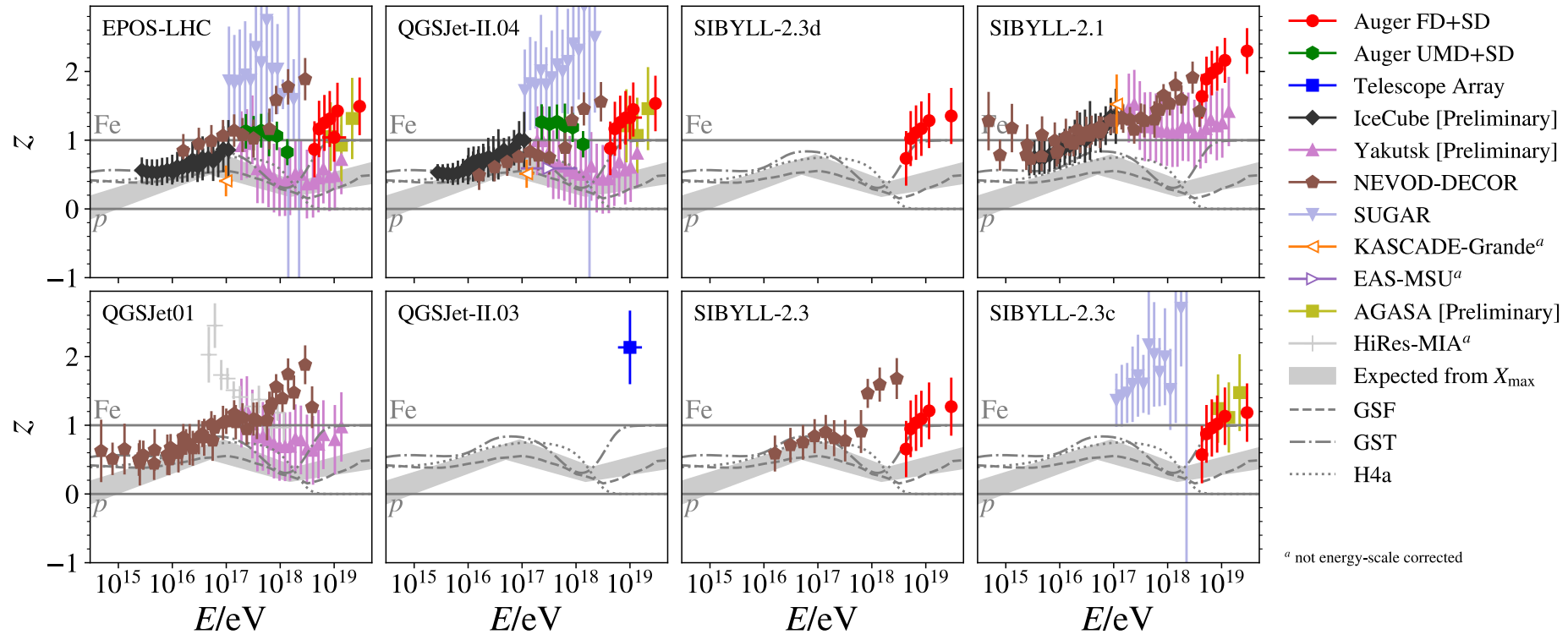


z-scale and energy-scale calibration

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

$$z = \frac{\ln(N_{\mu}^{\text{det}}) - \ln(N_{\mu p}^{\text{det}})}{\ln(N_{\mu}^{\text{sim}}) - \ln(N_{\mu p}^{\text{sim}})}$$

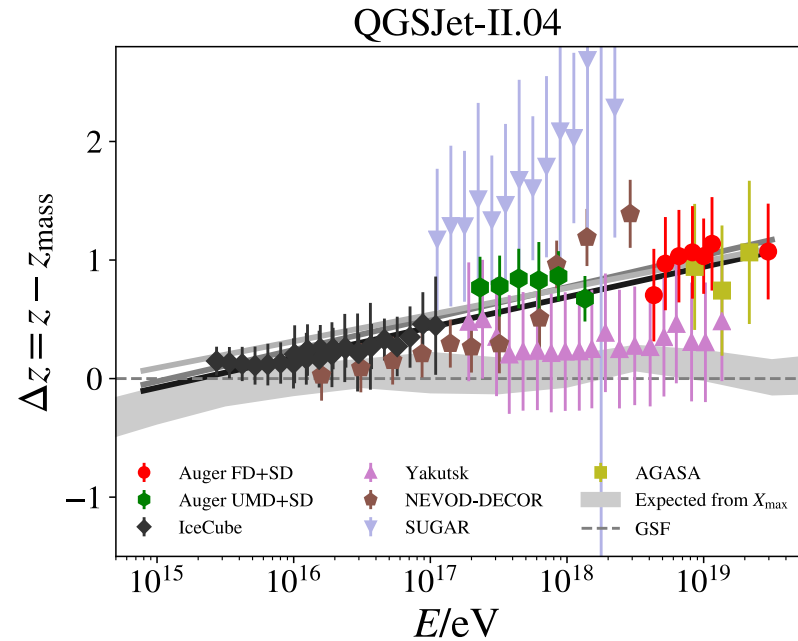
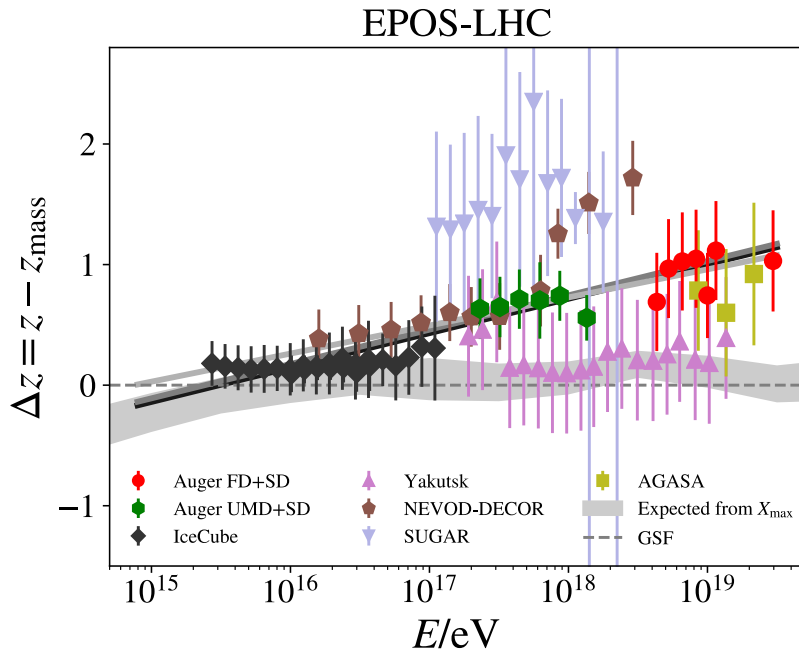
PoS(ICRC2021)349



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

Muon deficit in simulated showers

PoS(ICRC2021)349



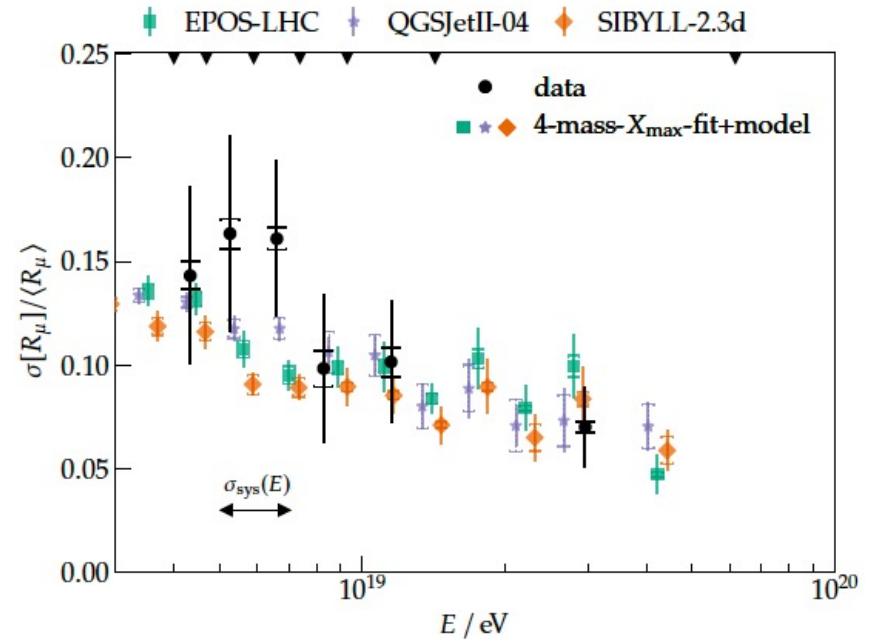
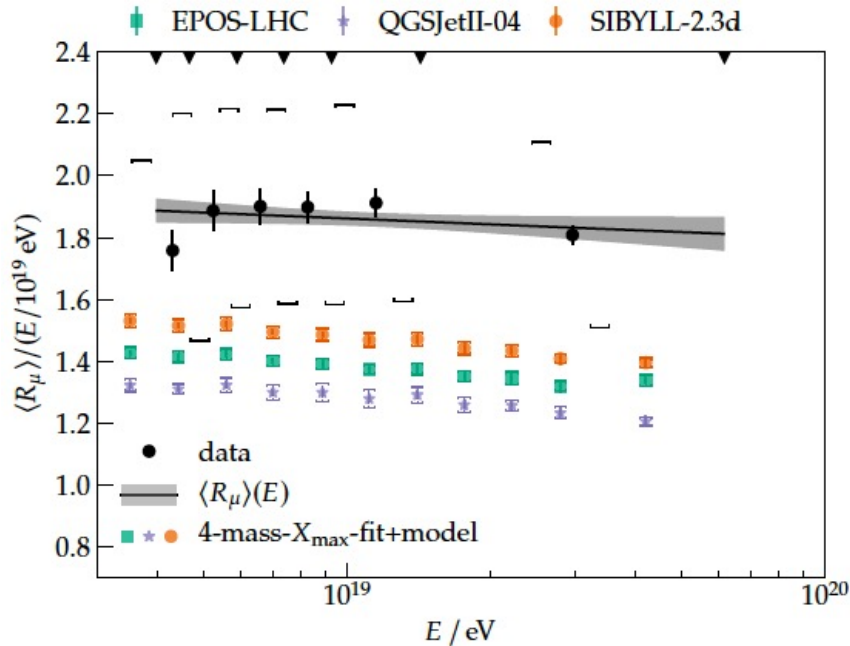
$$z = \frac{\ln(N_{\mu}^{\text{det}}) - \ln(N_{\mu_p}^{\text{det}})}{\ln(N_{\mu_{\text{Fe}}}^{\text{det}}) - \ln(N_{\mu_p}^{\text{det}})}$$

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

- Line model with slope fitted to $\Delta z = z - z_{\text{mass}}$
- Correction to $\chi^2/n_{\text{dof}} = 1$ 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

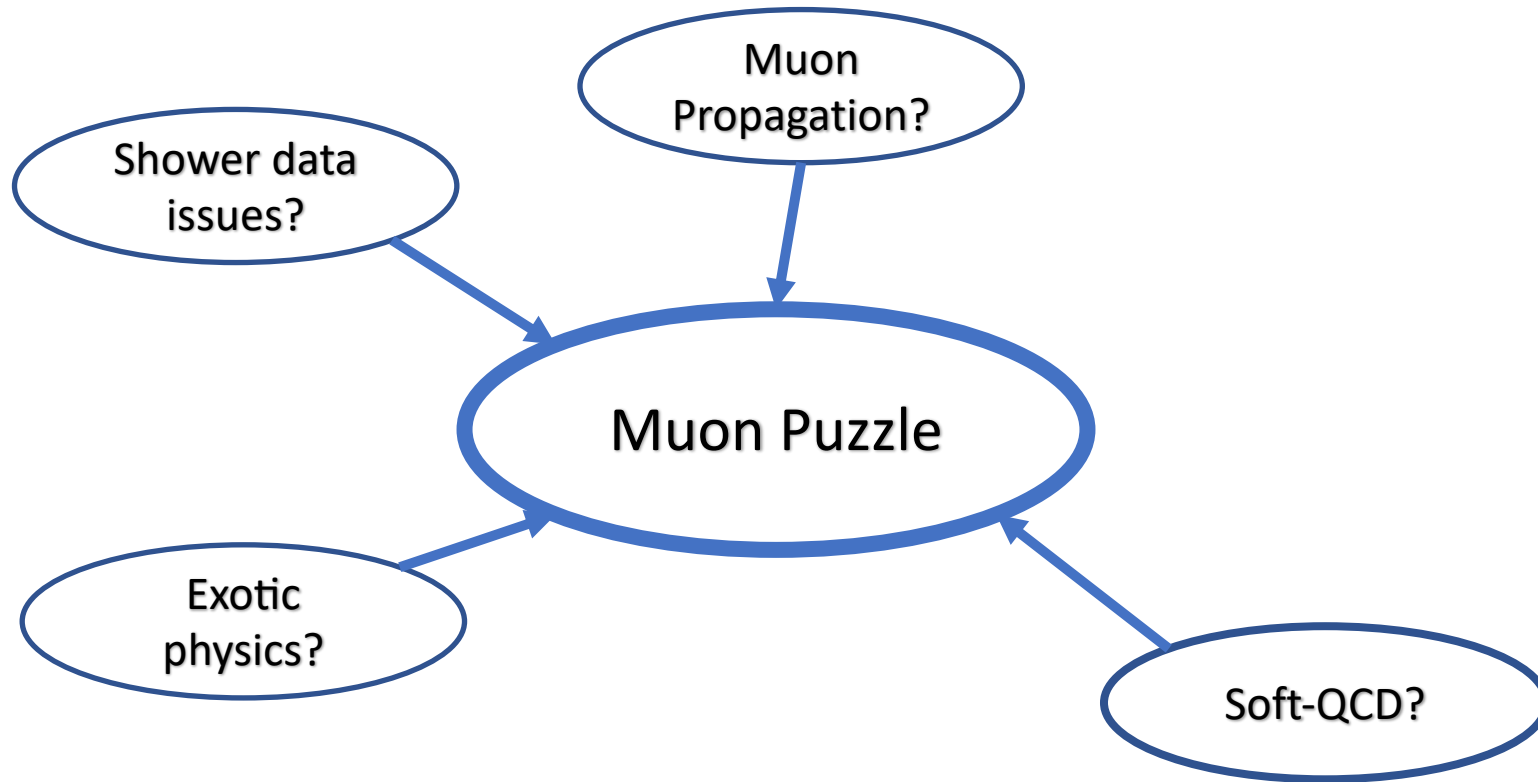
Muon number fluctuations

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

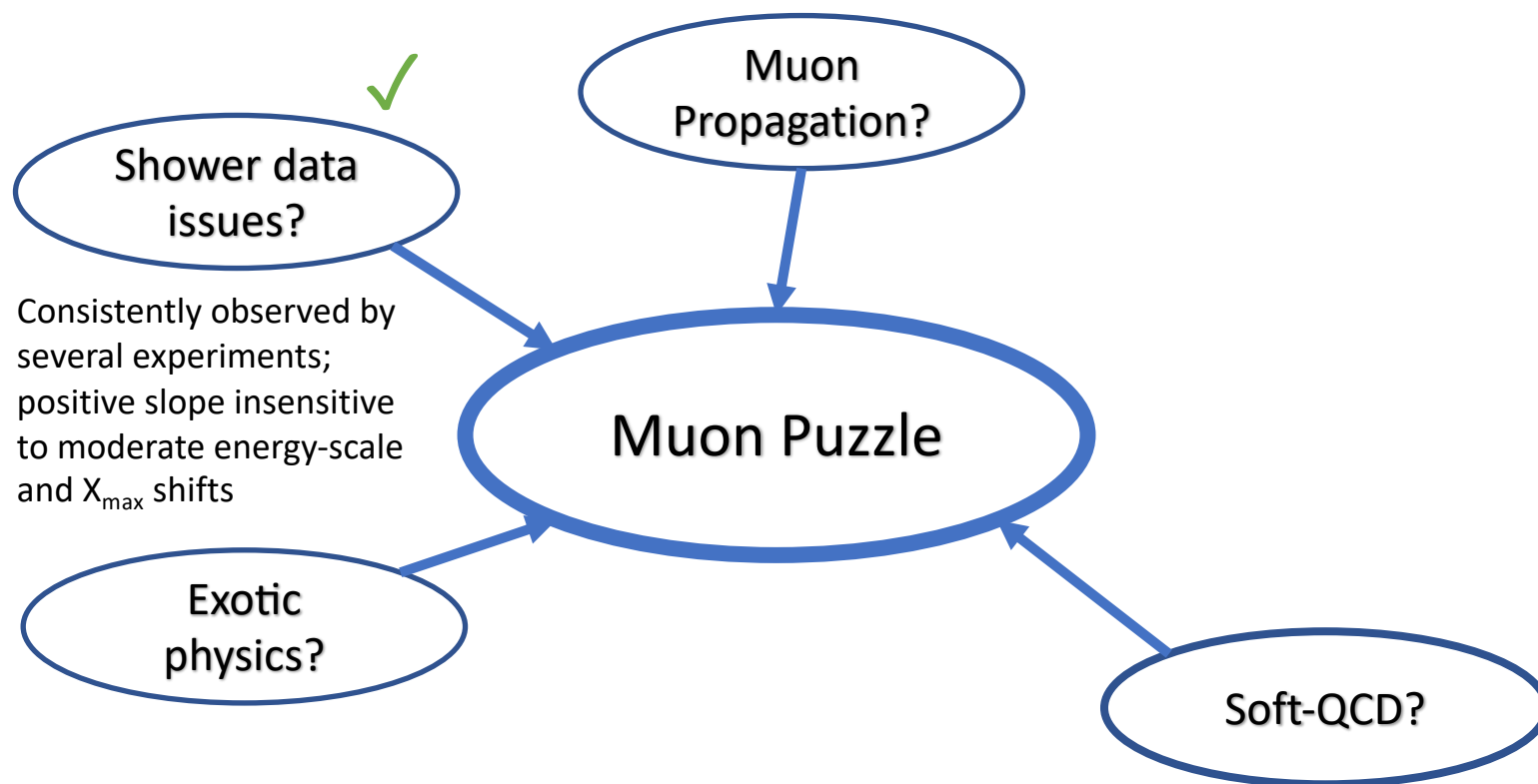


- First measurement of mean and **variance** of muon number distribution
- Variance of muon number consistent with current model predictions; mean deviates
- Constrains scenarios in which only first (or second) interaction is modified, e.g. in model with violation of Lorentz-invariance [PoS\(ICRC2021\)340](#)

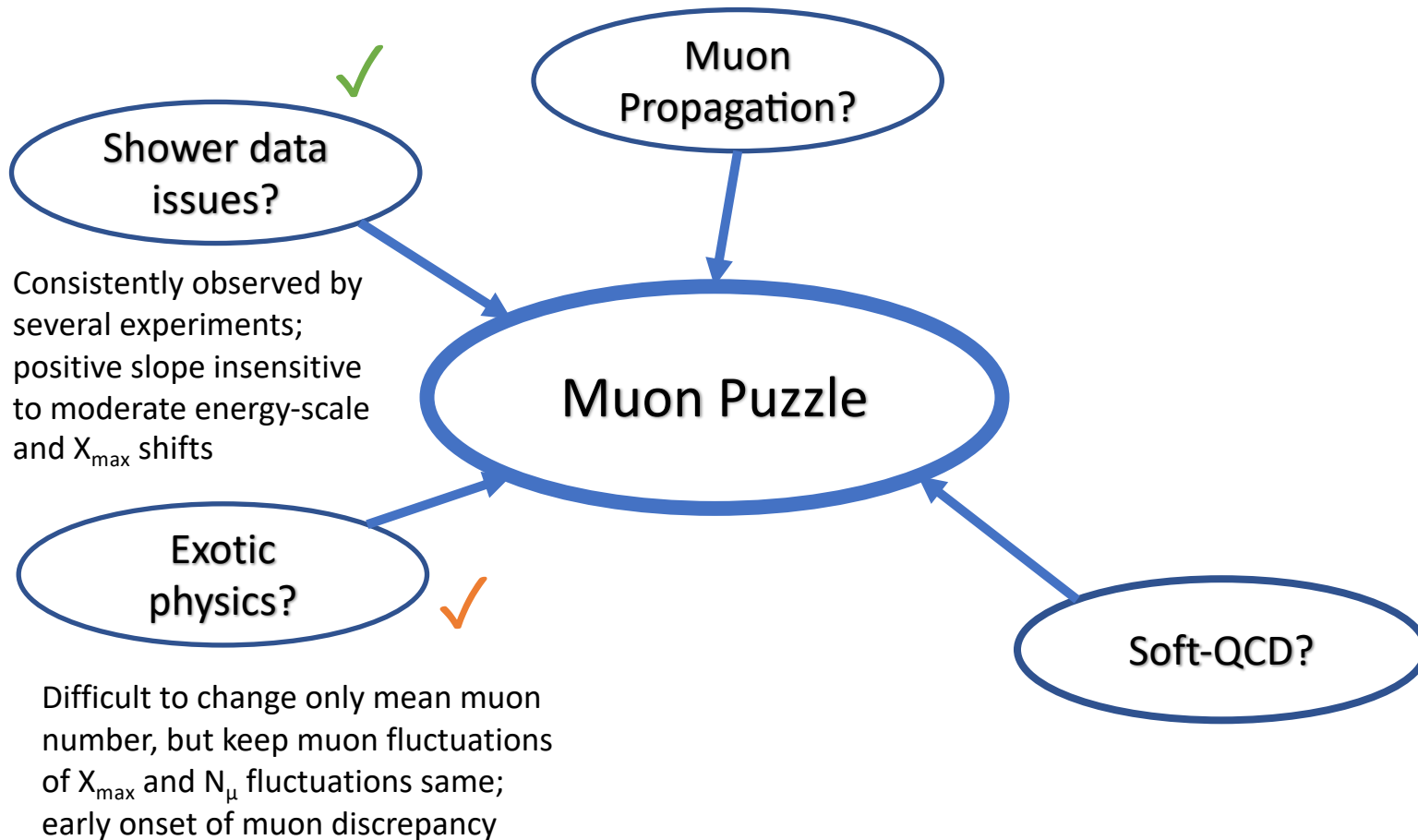
Attempts to explain muon puzzle



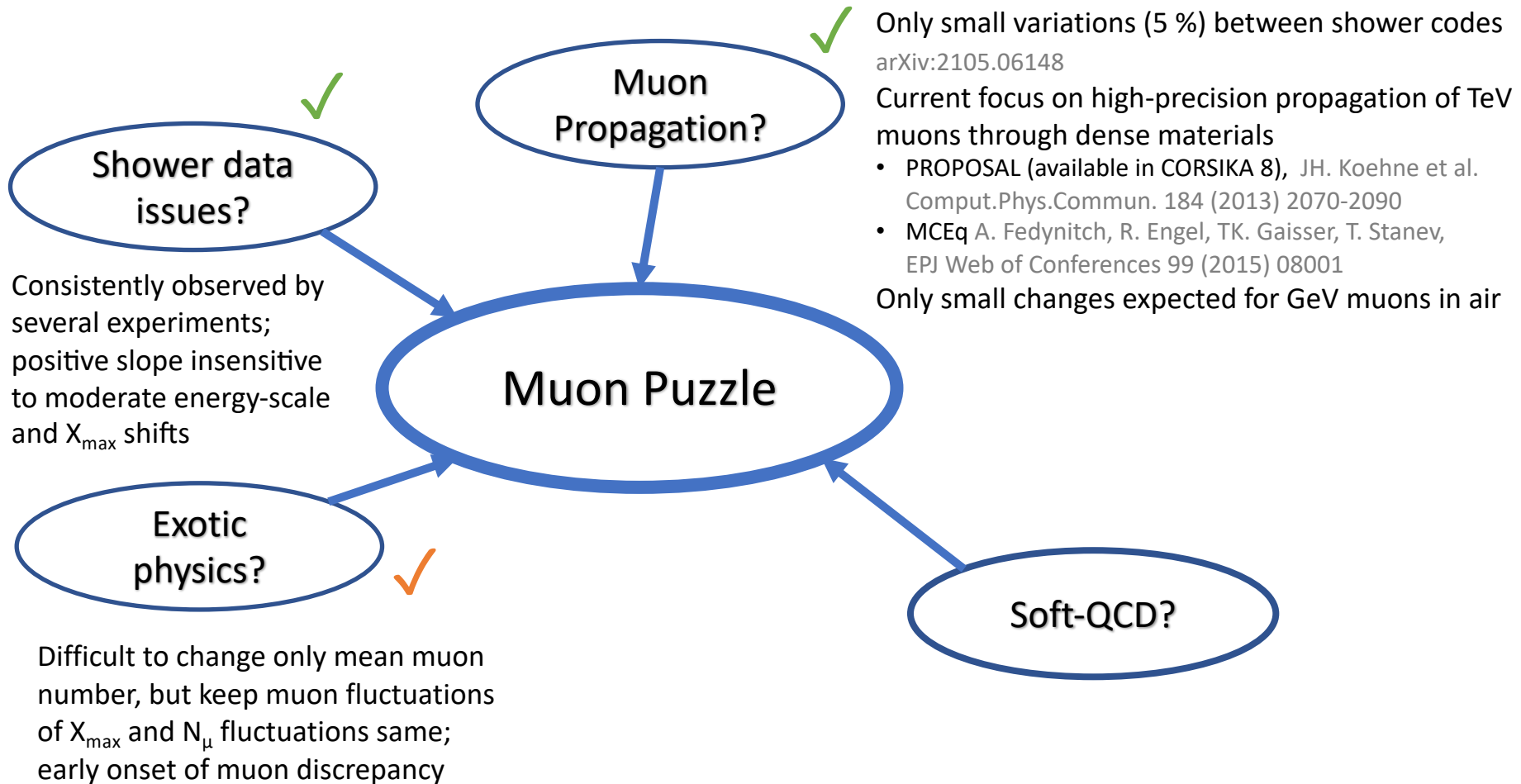
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Attempts to explain muon puzzle



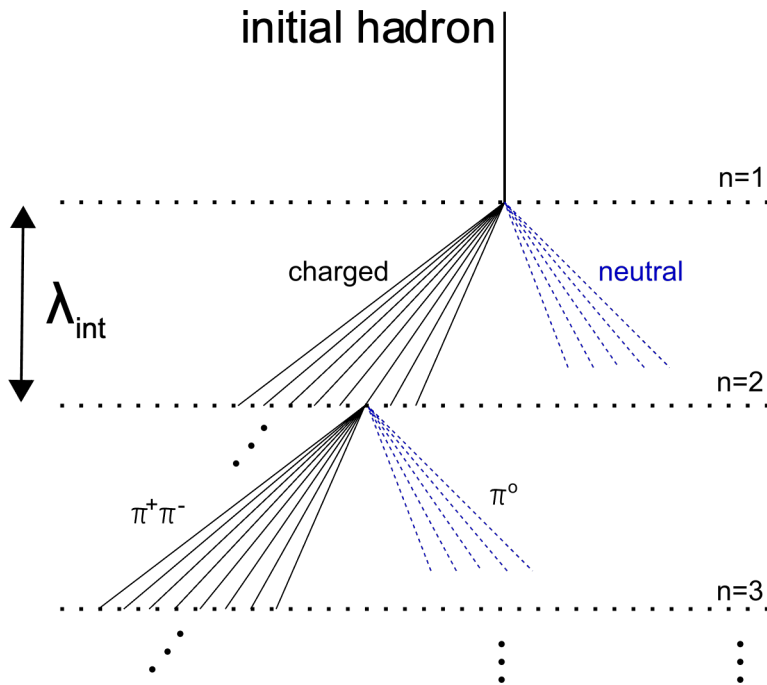
Attempts to explain muon puzzle



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

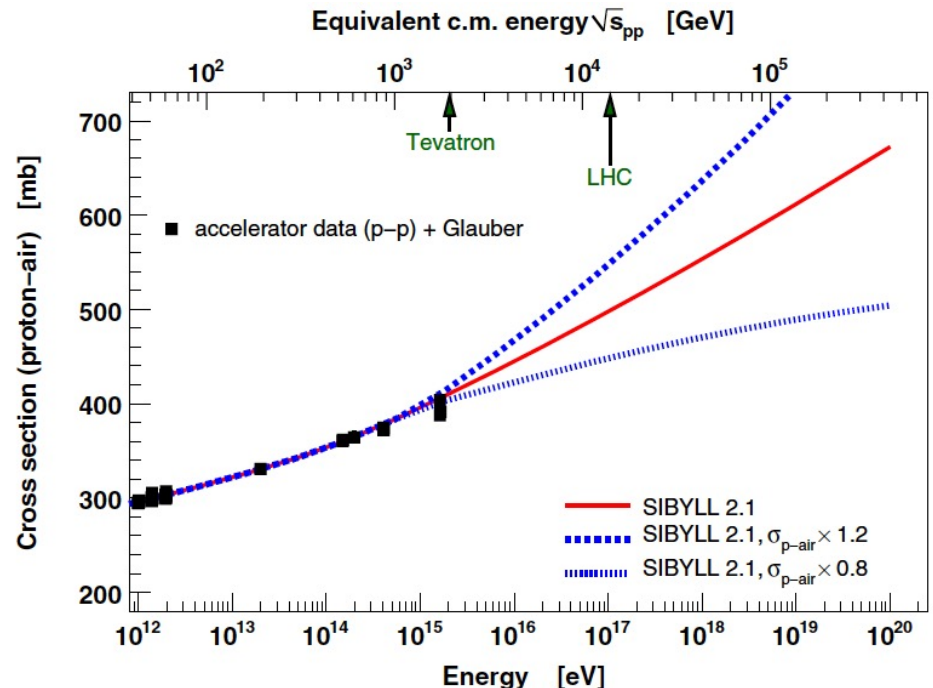
R. Ulrich, R. Engel, M. Unger, PRD 83 (2011) 054026

- 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

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

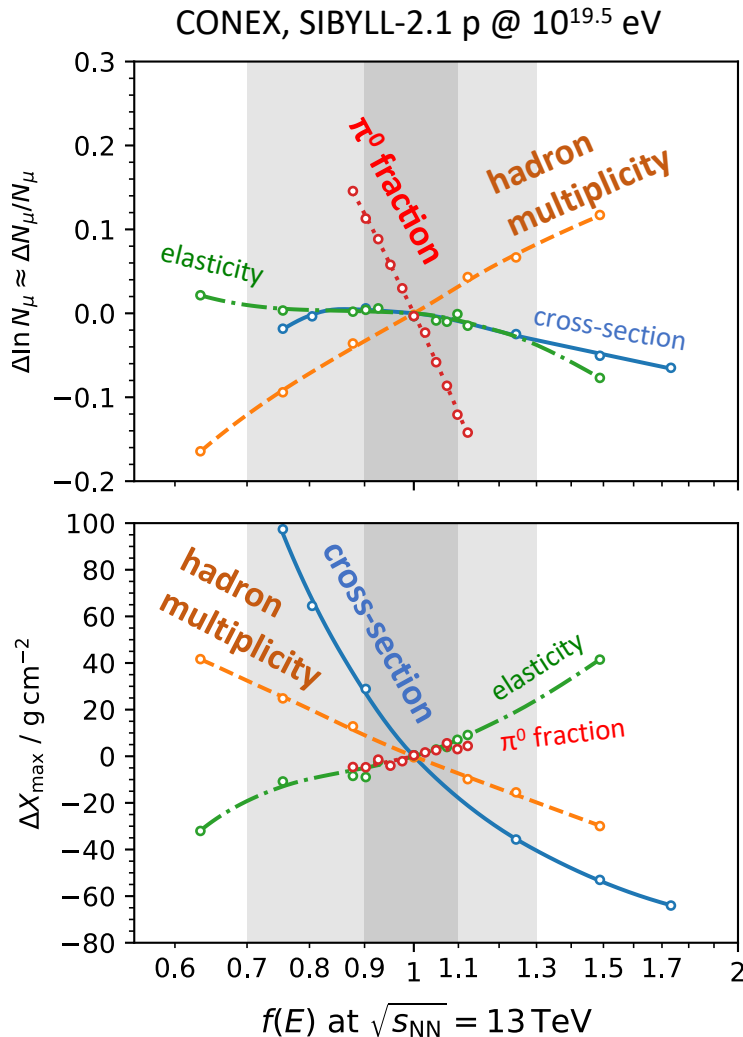
Modified features

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



From shower muons to QCD

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



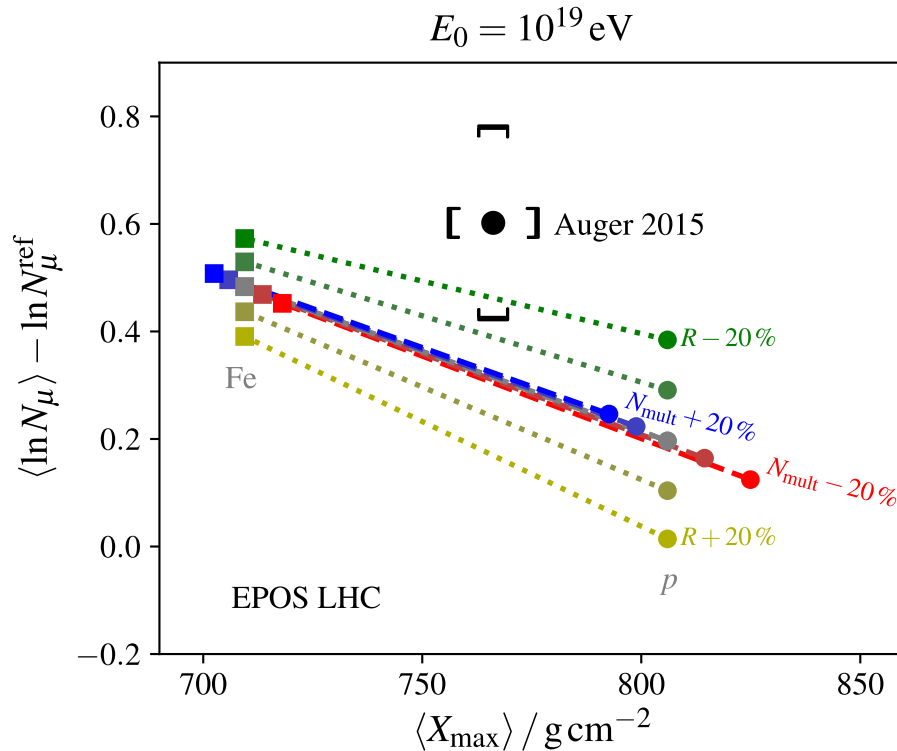
- Number of muons produced, N_μ
 - Very sensitive to π^0 fraction
 - Sensitive to hadron multiplicity

- 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

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

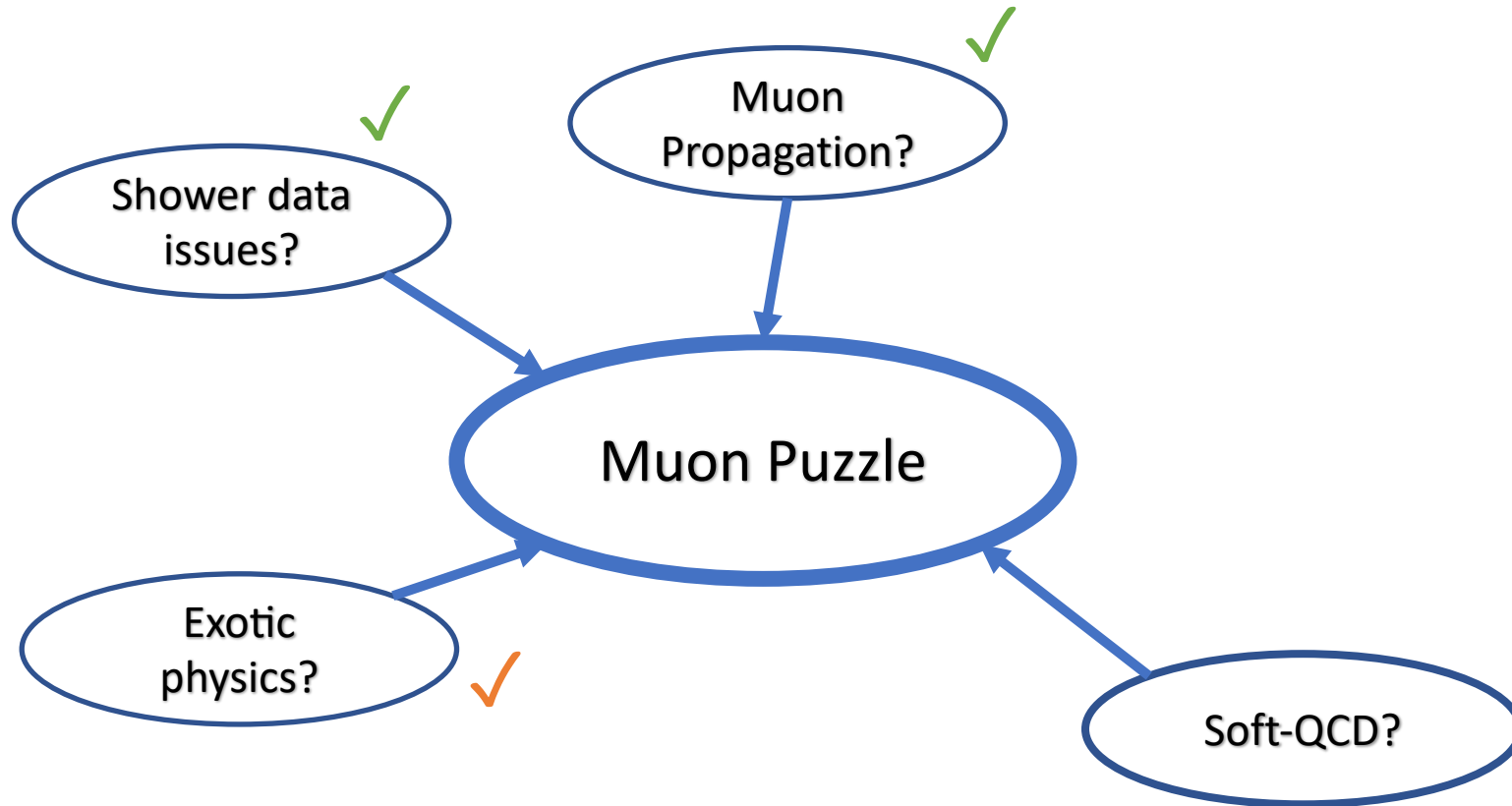


accessible experimental variable

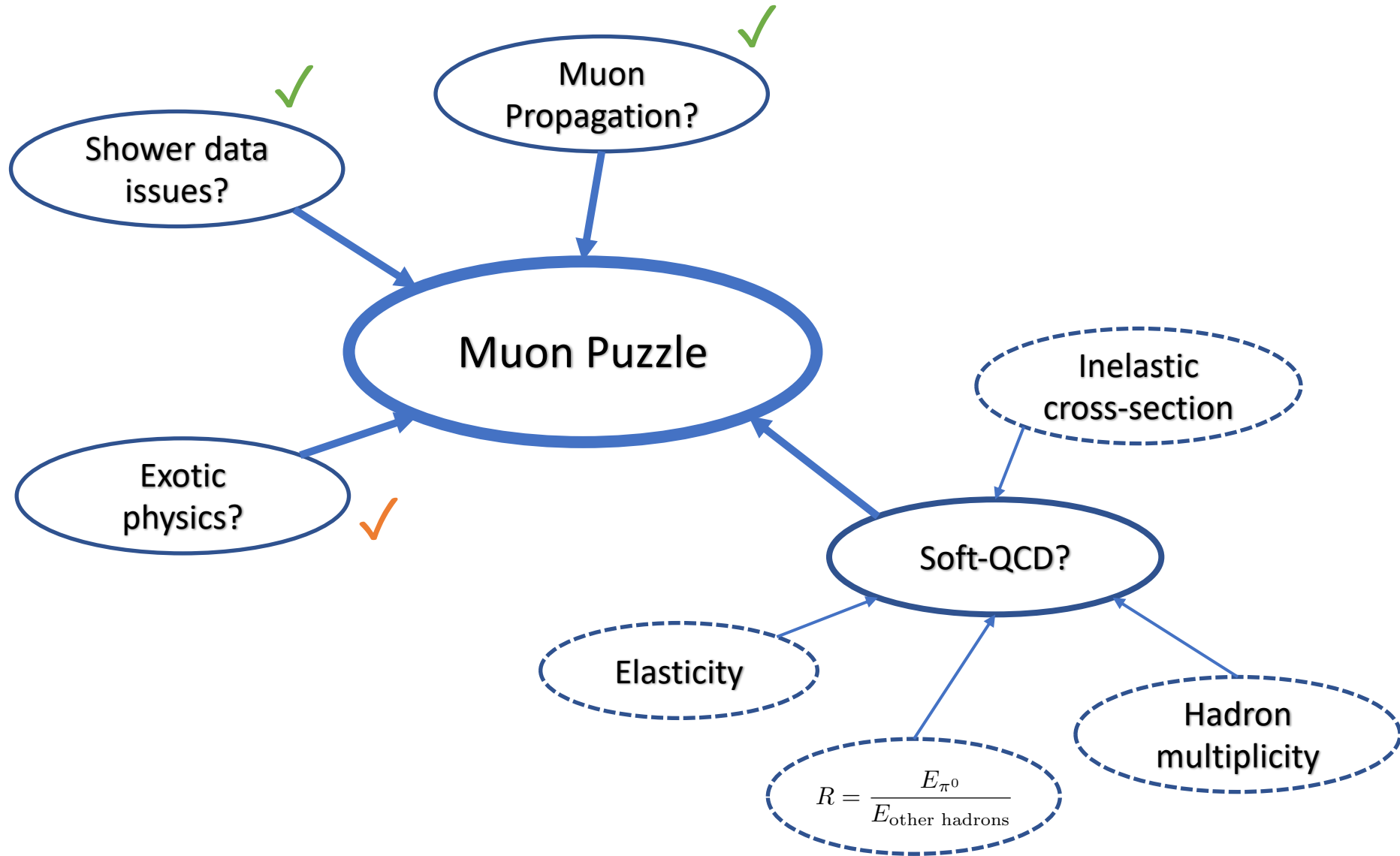
$$R = \frac{E_{\pi^0}}{E_{\text{other hadrons}}}$$

- Changes to hadron multiplicity cannot solve puzzle, if effect on X_{max} is considered
- Small changes to energy ratio R have large effect on muon number
 - R needs to be known to about 5 %

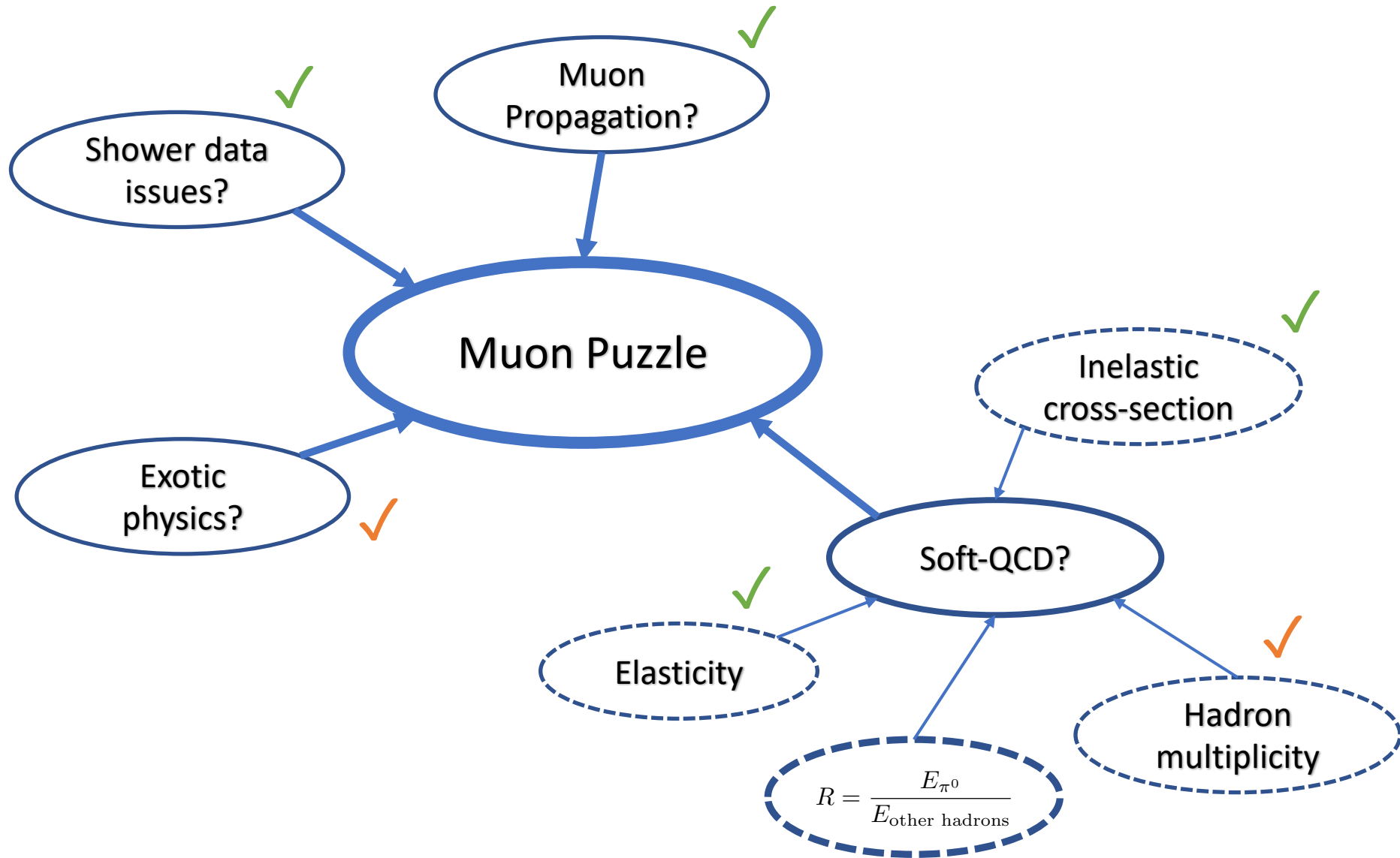
Attempts to explain muon puzzle



Attempts to explain muon puzzle

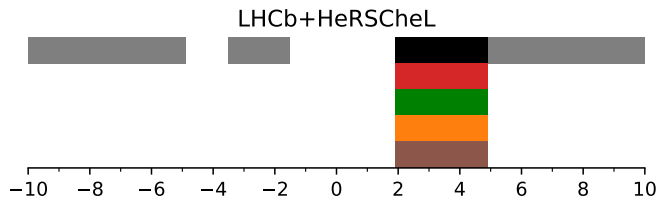
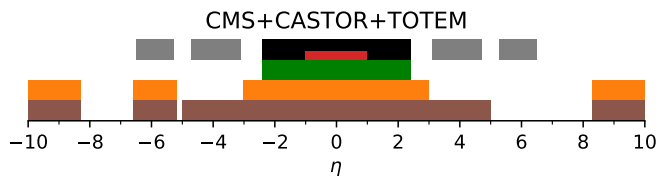
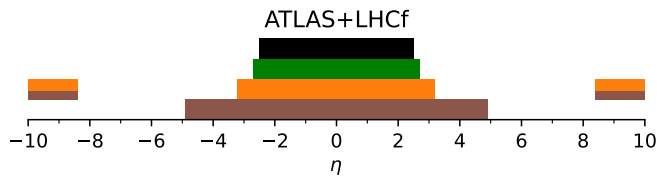
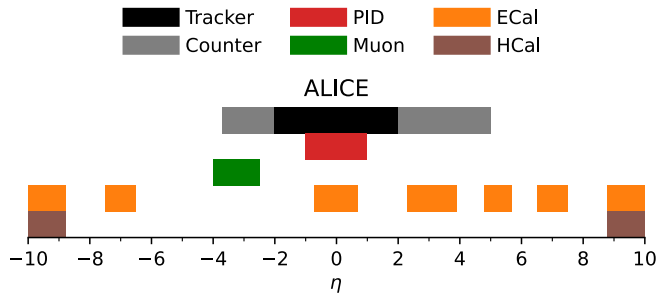


Attempts to explain muon puzzle

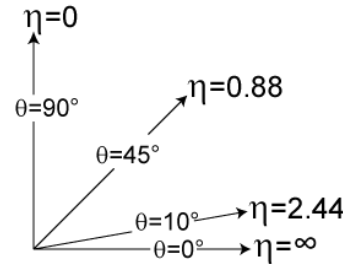


LHC experiments and Muon Puzzle

arXiv:2105.06148



pseudorapidity η



η related to emission angle

Image credit: JabberWok - Wikipedia CC BY-SA 3.0

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

Importance of forward acceptance

„Muon production weight“
 how many muon would be produced in shower
 by secondaries in this collision

arXiv:2105.06148

EPOS-LHC: pO 10 TeV

— $N_{\text{inel}}^{-1} dn/d\eta$ ---- $d(\sum E_{\text{lab}}^{0.93})/d\eta$ (a.u.)

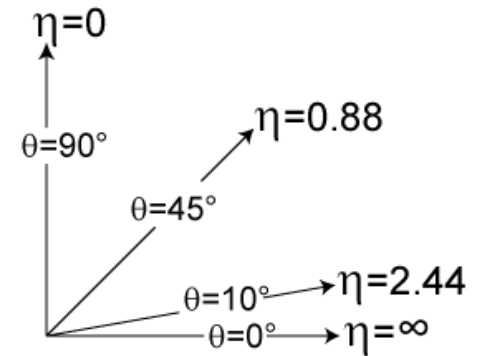
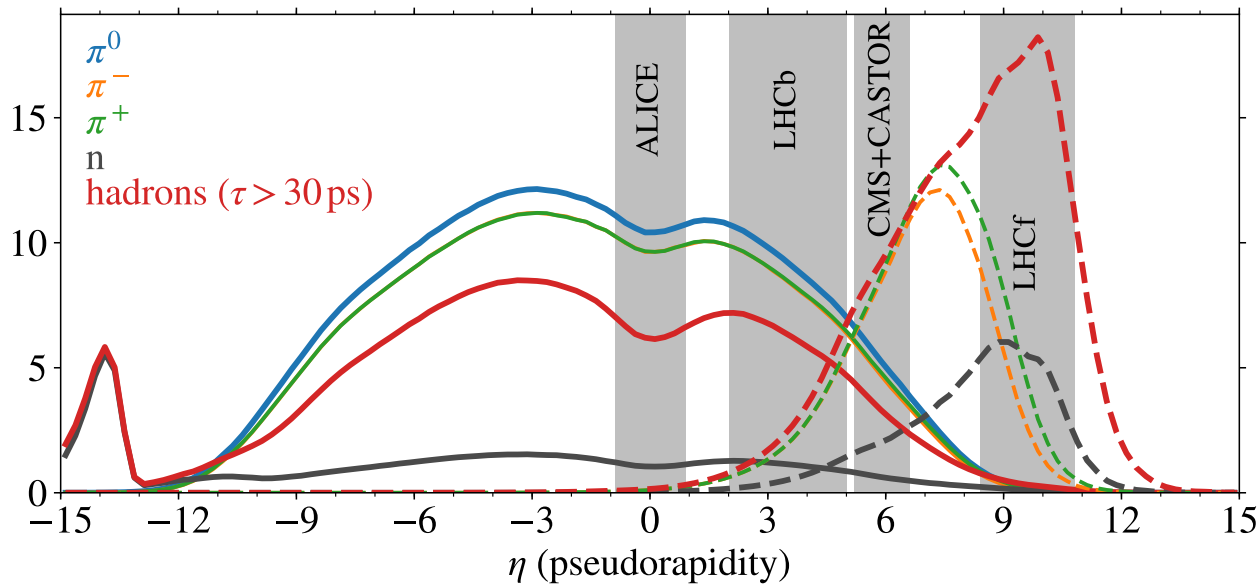


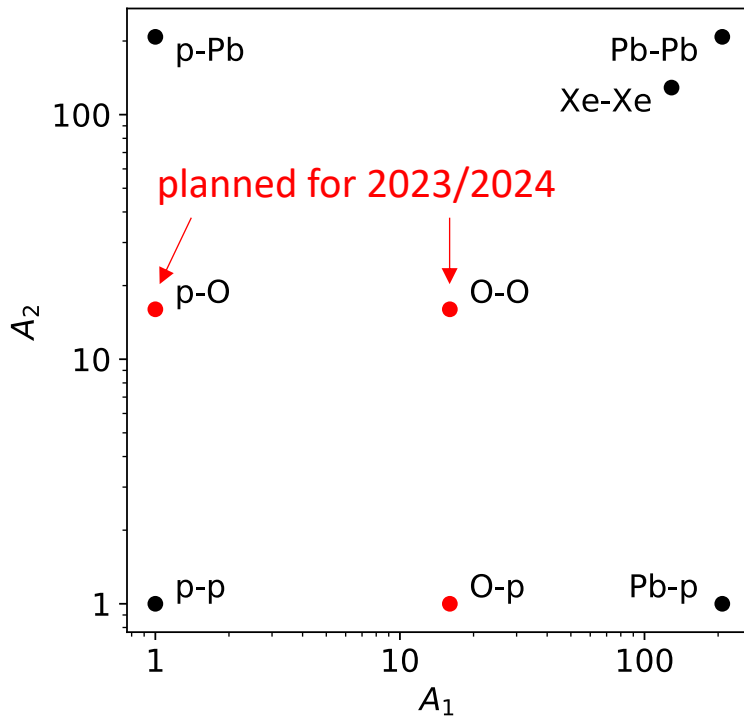
Image credit:
 JabberWok - Wikipedia CC BY-SA 3.0

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

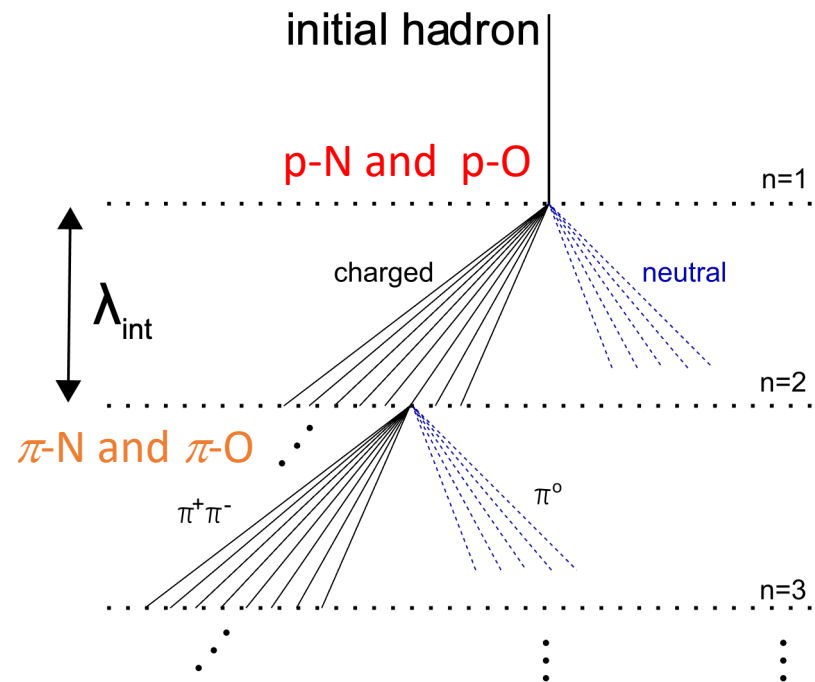
Run 3: p-p @ 14 TeV, p-O @ 10 TeV



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)

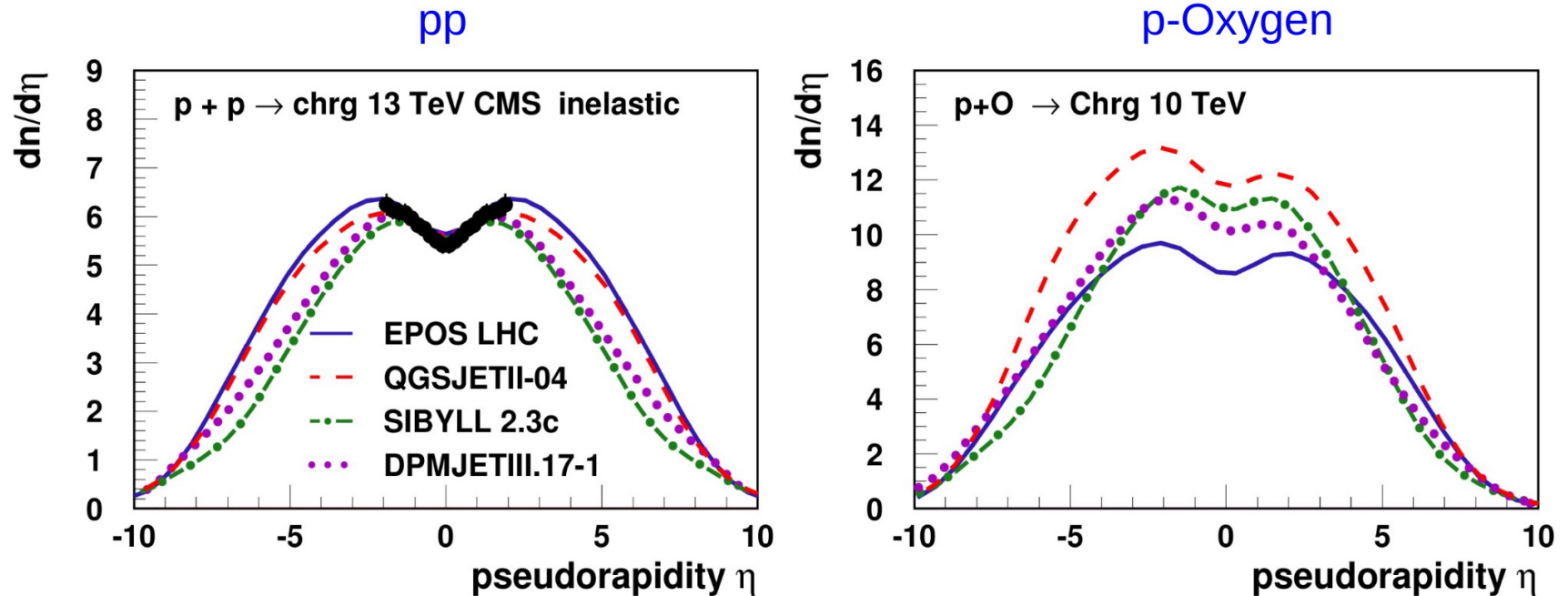
Air shower collision systems



p-O collisions mimic air shower interactions

Charged particle spectra

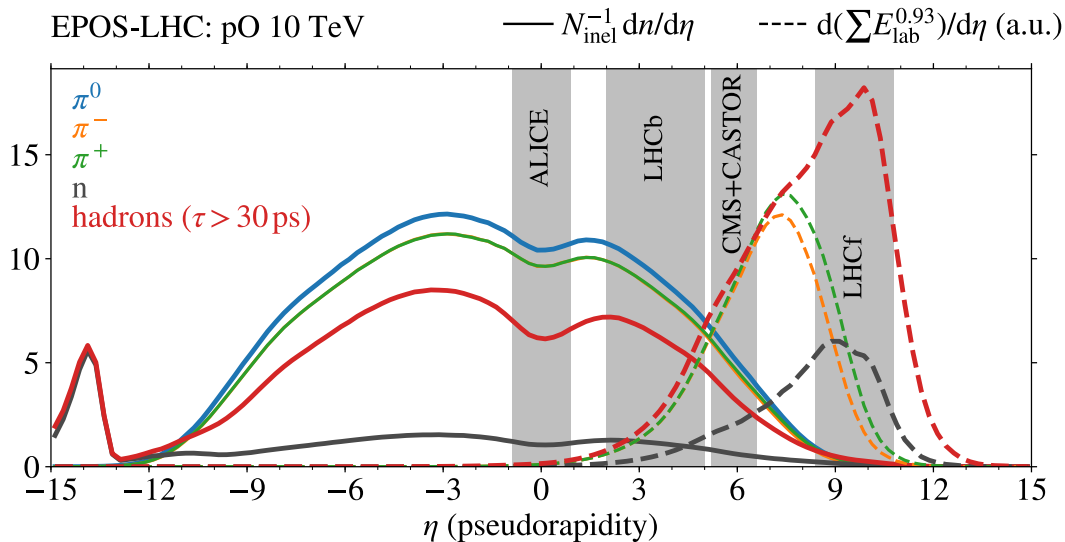
T. Pierog, ISVHECRI 2018



- Data available now up to $|\eta| = 6.4$ 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: $\pi^+ : \pi^- : \pi^0 \sim 1 : 1 : 1$



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

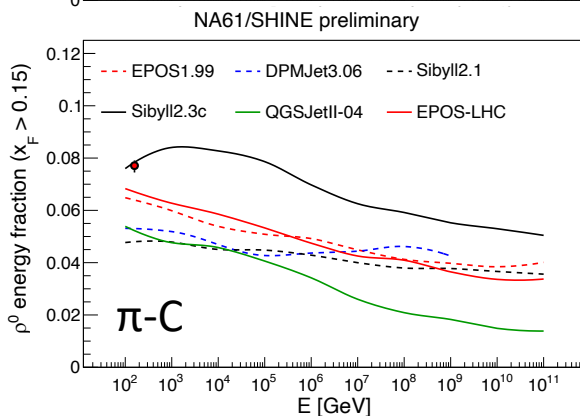
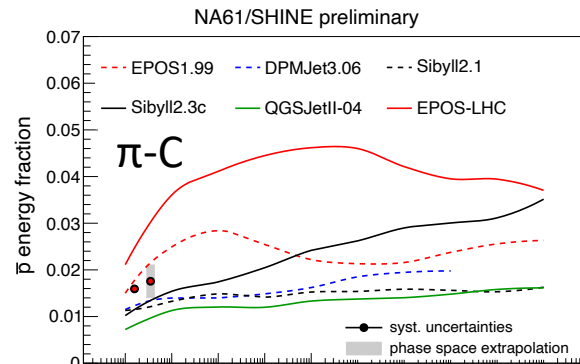
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- Changes to baryon production and ρ^0 production in π -air collisions

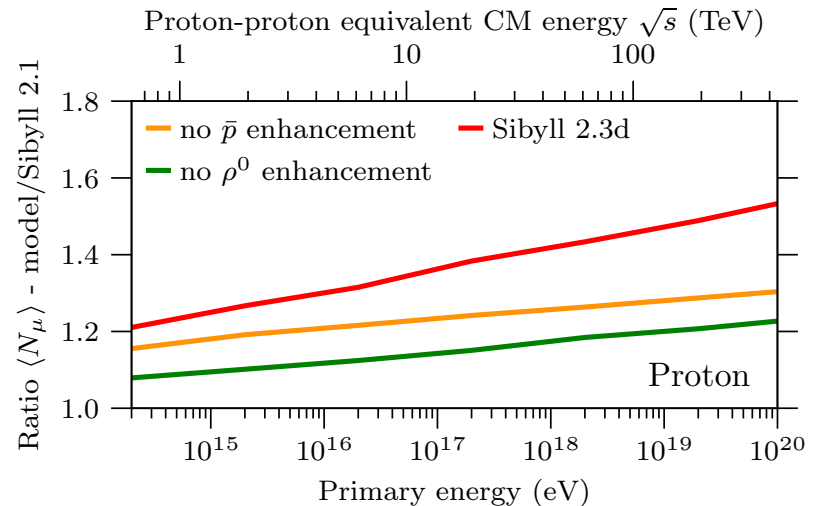
M. Unger for NA61/SHINE, PoS ICRC2019 (2020) 446

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)

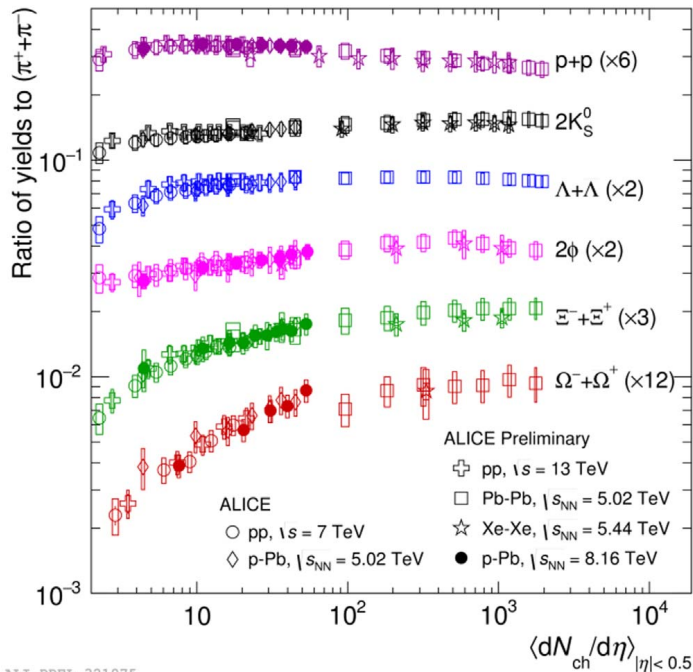


- Large increase of muon number compared to SIBYLL 2.1, but not enough to solve muon puzzle
- No data for pion interactions at $\sqrt{s} > 100$ GeV

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



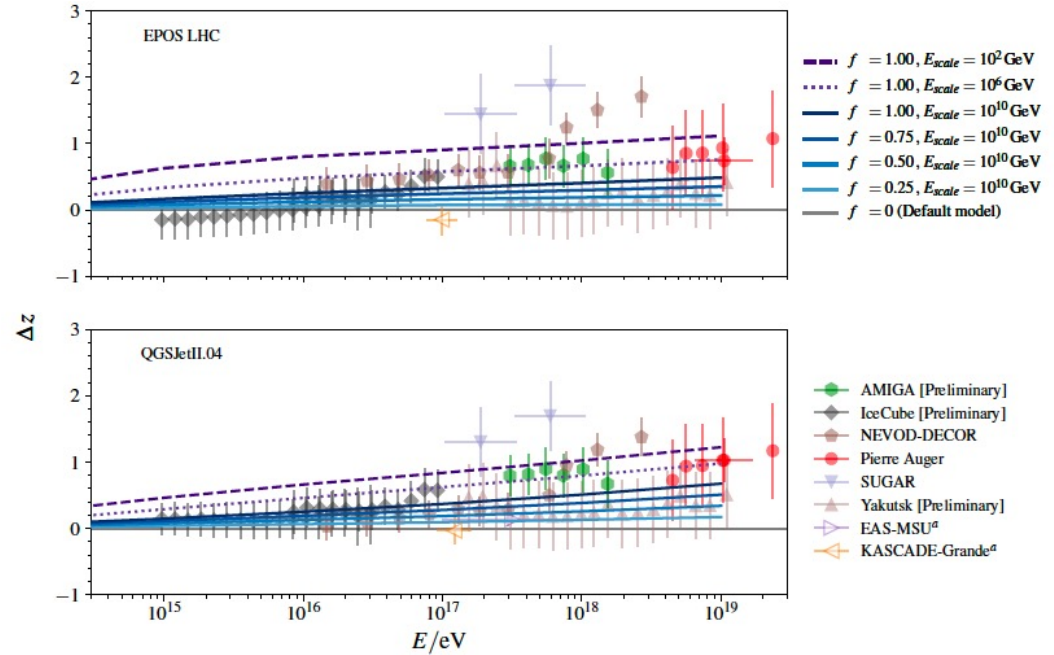
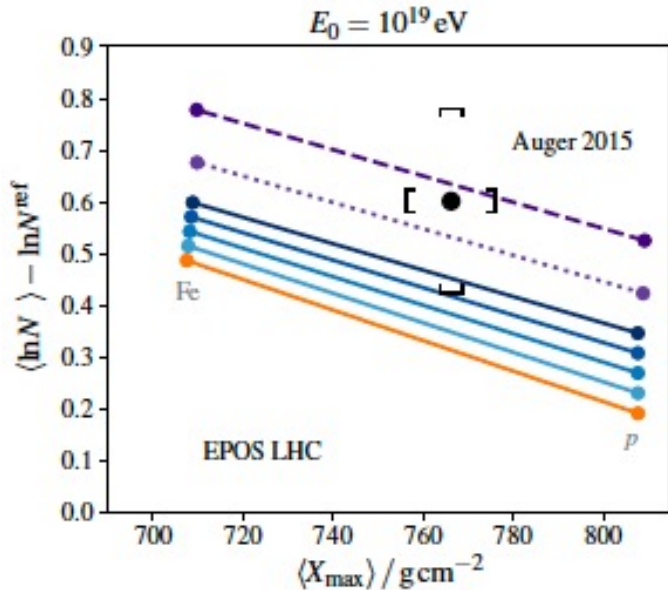
ALI-PREL-321075

- ALICE discovered universal enhancement of strangeness production in pp , pPb , $PbPb$
ALICE, Nature Phys. 13 (2017) 535
- More strangeness \rightarrow less $\pi^0 \rightarrow$ 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 \rightarrow 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

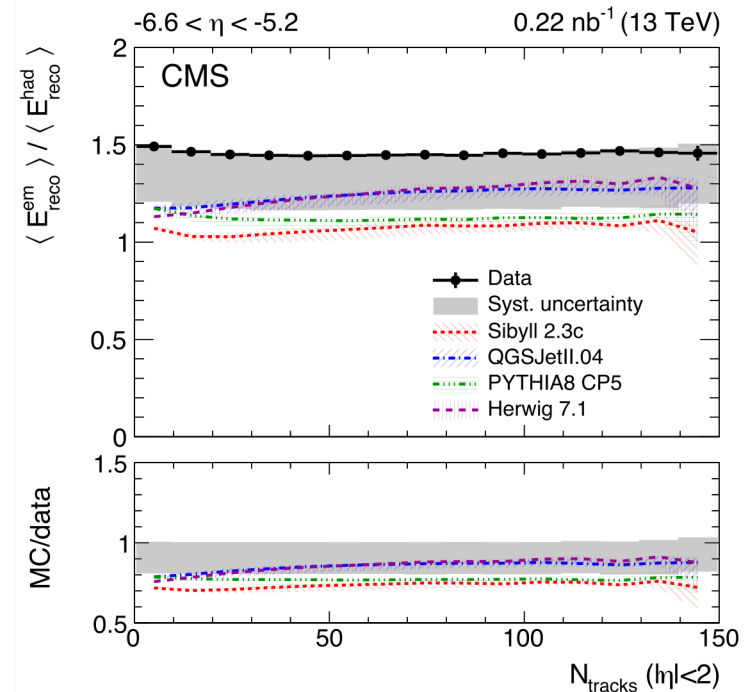
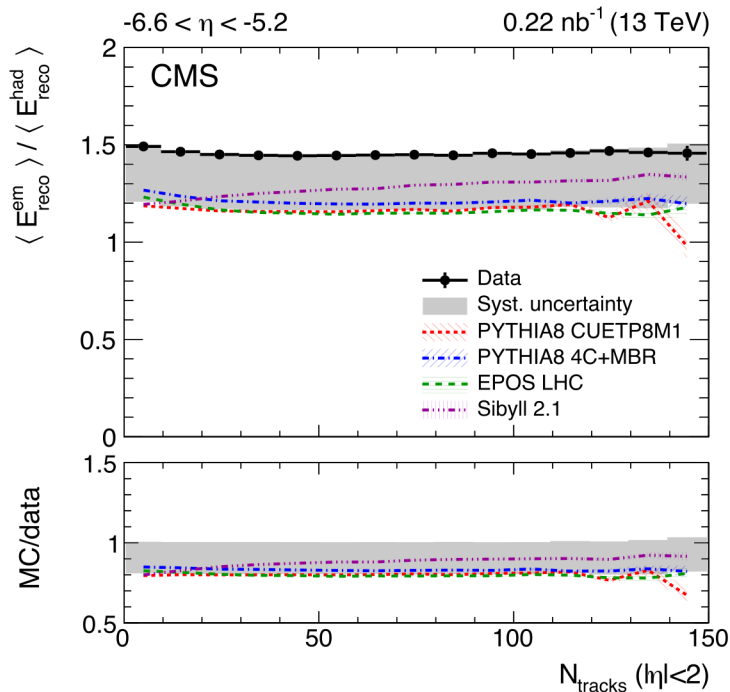


- Toy model with statistical hadronization (core) in addition to string/remnant fragmentation (corona)
 - Statistical hadronization needed to describe strangeness enhancement seen by ALICE
 - Can close muon number gap number in air showers and matches faster increase with energy
- Constrained by CMS-CASTOR 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

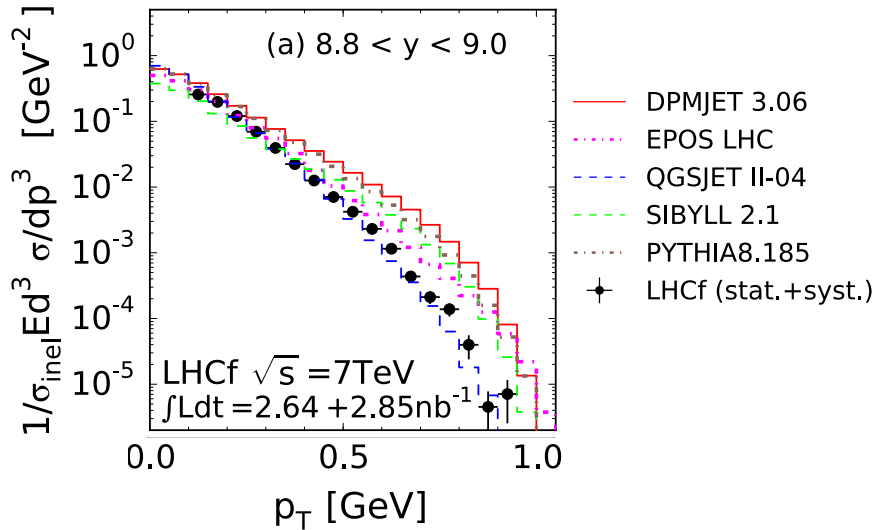
p-p @ 13 TeV



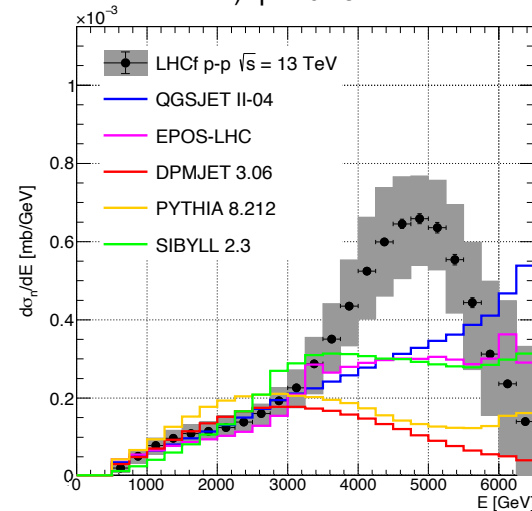
- Ideal measurement for muon puzzle in air showers, but precision important
- Measured R_{reco} value higher than predicted by models in p-p, but models mostly consistent
- $R_{\text{reco}} > R$ here, because of detector effects

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
 A) $\eta > 10.75$

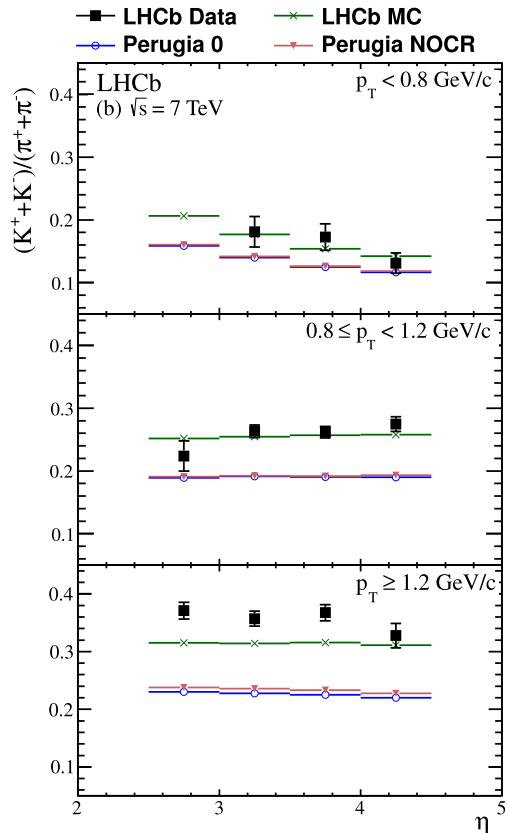


- LHCf: zero degree calorimeters ($\eta > 8$) around ATLAS to detect neutral particles
- R constrained by photon, π^0 , neutron production cross-sections in p-p, p-Pb from 0.9 to 13 TeV
- Reasonable description of π^0 data, but peak in neutron energy spectrum absent in models
- RHICf: Further studies in p-p at 0.51 TeV [PoS\(ICRC2021\)301](#)
- Plans to study strangeness production via $K^0_S \rightarrow 4\gamma$ (requires large samples) [PoS\(ICRC2021\)301](#)
- Well prepared for studies of p-O collisions [PoS\(ICRC2021\)348](#)

Forward spectra of identified hadrons

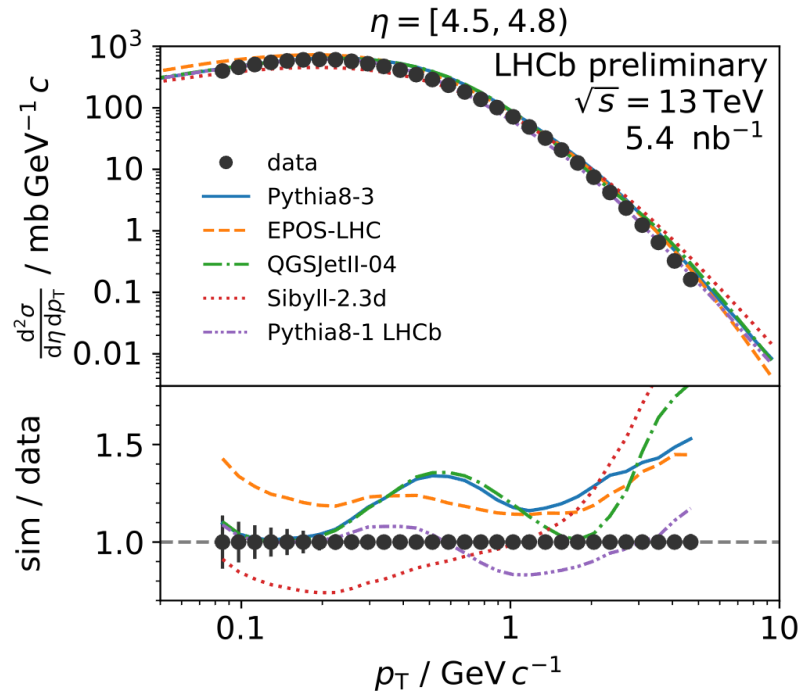
LHCb, EPJC (2012) 72:2168

p-p @ 7 TeV



LHCb-PROC-2021-009

p-p @ 13 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
- 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
- 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](#)

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

Muons and radio: great match

Muon energy spectrum: additional information