Need for proton-oxygen running at LHC for cosmic ray research

Meeting of LHC WG Forward Phys. and Diffraction, 17.12.2019

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Take-home message

- High-energy cosmic rays initiate air showers
  - Cosmic-ray mass composition can tell us about astrophysical sources
  - Requires accurate simulation of air showers (hadron cascades)
  - Background for IceCube and future neutrino observatories, and multi-messenger observations
  - Particle physics at $\sqrt{s} = 300$ TeV!

- Muon mystery
  - Data/MC mismatch in muon density in air showers, new particle/QCD physics?
  - Eight experiments combined muon density measurements from 0.5 PeV to 10 EeV and established mismatch at $8\sigma$

- Potential solution from the LHC
  - Smoking gun: Energy fraction carried by neutral pions too high?
  - proton-oxygen collisions to clarify nuclear effects, planned for 2023
  - Also needed: high precision forward measurements in pp and pPb
High-energy cosmic rays

Regime of air shower detection
Big ultra-high cosmic ray questions

- What are they?
- Where do they come from?
- How do they interact?
Air shower observables

Atmosphere as calorimeter

Telescopes measure dE/dX and timing

Surface detectors measure particle fluxes and timing

\[ X_{\text{max}} \propto \ln \left( \frac{E_0}{A} \right) \]
\[ E_0 = E_{\text{cal}} + E_{\text{invisible}} \]
\[ E_0 \propto S_{1000} \]
\[ N_\mu \propto S_\mu \propto \left( \frac{E_0}{A} \right)^\beta \] \((\beta \sim 0.9)\)
Based on Kampert & Unger, Astropart. Phys. 35 (2012) 660

Astrophysical models of cosmic rays?

- Mass composition (c.f. $\langle \ln A \rangle$) of cosmic rays carries imprint of sources and propagation
Cosmic ray mass composition

Astrophysical models of cosmic rays?

- Mass composition (c.f. $\langle \ln A \rangle$) of cosmic rays carries imprint of sources and propagation
- Accuracy of $\langle \ln A \rangle$ limited by uncertainty in description of hadronic interactions in air showers

Based on Kampert & Unger, Astropart. Phys. 35 (2012) 660
Astrophysical models of cosmic rays?

- Mass composition (c.f. $<\text{ln } A>$) of cosmic rays carries imprint of sources and propagation
- Accuracy of $<\text{ln } A>$ limited by uncertainty in description of hadronic interactions in air showers
- **Muon mystery (I):** Muon predictions in air showers are inconsistent with $X_{\text{max}}$

There is a general difficulty to predict muon production in air showers

Model dependence is large and not well understood

Based on Kampert & Unger, Astropart. Phys. 35 (2012) 660
Average longitudinal dE/dX profile

\[ f_{GH}(X) = (dE/dX)_{\text{max}} \left( \frac{X - X_0}{X_{\text{max}} - X_0} \right)^{\frac{X_{\text{max}} - X_0}{\lambda}} \exp \left( \frac{X_{\text{max}} - X}{\lambda} \right) \]

\[ 18 < \log(E/\text{eV}) < 18.2 \]
\[ \chi^2/\text{ndf} = 0.85 \]

\[ 18.8 < \log(E/\text{eV}) < 19.2 \]
\[ \chi^2/\text{ndf} = 0.47 \]

Gaisser-Hillas function

Transformation

\[ R = \sqrt{\frac{\lambda}{|X'_0|}} \]
\[ L = \sqrt{|X'_0|\lambda} \]
\[ X'_0 = X_0 - X_{\text{max}} \]
Longitudinal shower development

18 < lg(E/eV) < 18.2

Areas: all possible mass mixtures

Remarkable: shape of dE/dX profiles becomes sensitive to mass and models

18.8 < lg(E/eV) < 19.2
Signal deficiency at ground level

Attempt of consistent description of longitudinal and lateral shower data ... fails

Problems become worse at higher zenith angles
Hadron/Muon component in data is too large

- Scale E.M. and had. part of MC showers by $R_E$ and $R_{\text{had}}$ to fit data:

$$S_{\text{resc}}(R_E, R_{\text{had}}) = R_E S_{\text{EM}} + R_{\text{had}} R_E^{\alpha} S_{\text{had}}$$

- While $R_E = 1$ is possible and mostly consistent with data
- $R_{\text{had}}$ is significantly above 1
- None of the models/assumptions reproduces data

→ muon mystery (II)
Muon content at ground level

Inclined showers: 62 – 80 deg

→ electromagnetic component is ~absorbed

Phys. Rev. D 91 (2015) 032003
Muons mystery (III)

Muons number rises faster with energy than any model predicts. Non-zero positive slope at 8σ significance

What are we observing here?

- Collective effects?  
- Strange fireball?  
  PRD 95 (2017) 063005
- Exotic physics?  
  arxiv:1307.2322 [astro-ph]
- ????  
  → unsolved !

- Converted very different muon measurements to universal z-scale
- Cross-calibrated energy scales of experiments by matching all-particle fluxes
Air shower cascades

10 GeV proton in cloud chamber with lead absorbers at 3027 m altitude

Heitler-Matthews model of air shower

Cascade stops after $O(10)$ steps (energy-dependent)
Pions/Kaons decay into GeV **muons** at the end of cascade
Air shower physics

Electromagnetic particles

- Electromagnetic shower features are very sensitive to high-energy interactions.
- Muon observables are a magnifying glass into small features of interactions over a wide energy range.

Consider 10 shower generation:  $\text{Total effect} \sim \text{effect}^{10}$

$\rightarrow$ 50% on muon number $\sim$ 4% per interaction
Modify hadronic interaction features

Ad-hoc modify features at LHC energy scale with factor $f_{\text{LHC-pO}}$ and extrapolate up to $10^{19}$ eV proton shower

(with $f_{\text{LHC-pO}}$: relative effect strength in LHC pO collisions at 9TeV)

Modified features

- **cross-section**: inelastic cross-section of all interactions
- **hadron multiplicity**: total number of secondary hadrons
- **elasticity**: $E_{\text{leading}}/E_{\text{total}}$ (lab frame)
- **$\pi^0$ fraction**: (no. of $\pi^0$) / (all pions)
Importance of interaction features

Large impact on muon number
• Neutral pion fraction
• Hadron multiplicity
Projected impact of changes

- Changing hadron multiplicity does not solve muon puzzle
- Need to change energy fraction $R$ of neutral pions

$$R = \frac{\sum E\pi^0}{\sum E_{\text{long-lived hadron}}}$$

Based on
Ulrich et al. PRD 83 (2011) 054026
Pierre Auger collab. PRD 91 (2015) 032003
Possibilities to reduce $R$

- Nuclear effects are very important for air shower phenomenology
- Are collective nuclear effects in $\pi N$ or $\pi O$ collisions reducing $R$?

Collective effects may reduce pion fraction, EPOS-LHC predicts drop in $R$ at $\eta = 0$

QGP in air showers could enhance strangeness production, reducing pion fraction

Enhancement of strangeness observed in central collisions in $pp$, $pPb$
...or is $R$ already too low?


- CMS measurements give higher $R$ than models for $5.2 < |\eta| < 6.6$
- Models should have higher $R$ and then would yield even fewer muons!
- But this is in $pp$, what about $pO$?
Nuclear effects in prompt $J/\Psi$ production

- Up to 50 % suppression in forward direction
- Especially strong where relevant for CR!
- But: how in pO collisions?
Nuclear effects in $\pi^0$ production

Very strong nuclear effects for $\pi^0$ production in far forward

But: How much in pO collisions?

Proton-oxygen collisions at the LHC

Collision systems at the LHC

Collision systems in air showers

- Only proton-oxygen collisions mimic interactions in air showers
- Need pp, pPb, and pO to understand nuclear effects

(p-N and p-O)

(n=1)

(π-N and π-O)

(n=2)

(π-N and π-O)

(n=3)

(and: N~O)
Nuclear “interpolation”

- Interpolation in A does not work well, system differences are too large
- $X_{\text{max}}$ sensitive to cross sections, hadron multiplicities
- Muons sensitive to multiplicity, e.m./had ratios, $\pi^0$ production
- Nuclear modifications in forward-direction expected and relevant
Tuning matters – and depends on data

Shown is spread between EPOS-LHC, QGSJetII.4 and SIBYLL 2.3

Models mostly tuned to p+p data at |η| < 2: p+p 10 % model spread, p+O 50 % model spread
## Proposed LHC schedule for Run 3

**Z. Citron et al., CERN-LPCC-2018-07**

<table>
<thead>
<tr>
<th>Year</th>
<th>Systems, $\sqrt{s_{NN}}$</th>
<th>Time</th>
<th>$L_{int}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2021</td>
<td>Pb–Pb 5.5 TeV, pp 5.5 TeV</td>
<td>3 weeks</td>
<td>$2.3 \text{ nb}^{-1}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 week</td>
<td>$3 \text{ pb}^{-1}$ (ALICE), 300 pb$^{-1}$ (ATLAS, CMS), 25 pb$^{-1}$ (LHCb)</td>
</tr>
<tr>
<td>2022</td>
<td>Pb–Pb 5.5 TeV</td>
<td>5 weeks</td>
<td>$3.9 \text{ nb}^{-1}$</td>
</tr>
<tr>
<td></td>
<td>O–O, p–O</td>
<td>1 week</td>
<td>$500 \text{ \mu}b^{-1}$ and 200 \mu b$^{-1}$</td>
</tr>
<tr>
<td>2023</td>
<td>p–Pb 8.8 TeV, pp 8.8 TeV</td>
<td>3 weeks</td>
<td>$0.6 \text{ pb}^{-1}$ (ATLAS, CMS), 0.3 pb$^{-1}$ (ALICE, LHCb)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>few days</td>
<td>$1.5 \text{ pb}^{-1}$ (ALICE), 100 pb$^{-1}$ (ATLAS, CMS, LHCb)</td>
</tr>
<tr>
<td>2027</td>
<td>Pb–Pb 5.5 TeV, pp 5.5 TeV</td>
<td>5 weeks</td>
<td>$3.8 \text{ nb}^{-1}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 week</td>
<td>$3 \text{ pb}^{-1}$ (ALICE), 300 pb$^{-1}$ (ATLAS, CMS), 25 pb$^{-1}$ (LHCb)</td>
</tr>
<tr>
<td>2028</td>
<td>p–Pb 8.8 TeV, pp 8.8 TeV</td>
<td>3 weeks</td>
<td>$0.6 \text{ pb}^{-1}$ (ATLAS, CMS), 0.3 pb$^{-1}$ (ALICE, LHCb)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>few days</td>
<td>$1.5 \text{ pb}^{-1}$ (ALICE), 100 pb$^{-1}$ (ATLAS, CMS, LHCb)</td>
</tr>
<tr>
<td>2029</td>
<td>Pb–Pb 5.5 TeV</td>
<td>4 weeks</td>
<td>$3 \text{ nb}^{-1}$</td>
</tr>
<tr>
<td>Run-5</td>
<td>Intermediate AA, pp reference</td>
<td>11 weeks</td>
<td>e.g. Ar–Ar 3–9 pb$^{-1}$ (optimal species to be defined)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 week</td>
<td></td>
</tr>
</tbody>
</table>

- one week can be enough to push uncertainties to $\sim 5\%$ (→ Auger)
- $2 \text{ nb}^{-1}$ (10 x minimum) will also allow to measure charm (→ IceCube)
- Latest planning moved oxygen-week to **2023**
Summary

- Muon Puzzle in air showers experimentally established
  - Statement by eight leading air shower experiments (8σ)

- Problem not in the data, theory has to change
  - None of the hadronic interaction models reproduces muon data (neither pre- nor post-LHC)
  - Suggests common missing QCD effect, perhaps QGP-related?

- pO and OO collisions planned for 2023
  - Probably 2 nb$^{-1}$ of pO
  - Data should be analyzed by ALICE, ATLAS, CMS, LHCb and LHCf

- Key forward measurements to be done at the LHC
  - In pp, pPb, and pO
    - Energy ratio $R$ of $\pi^0$ to long-lived hadrons at forward rapidity
    - Production cross-sections for $\pi^0$, $\pi^\pm$, K, p
    - Precise measurements needed to 5 % or better