pO runs at the LHC

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LHC Working Group on Forward Physics and Diffraction, 19 Dec 2018, CERN
Summary

• Recap
  – Cosmic ray mass composition is inferred from air shower measurements, carries important imprint of sources
  – Progress blocked by large uncertainties in hadronic interactions
  – **High accuracy (5%)** LHC measurements of pO expected to resolve this
  – Forward measurements very important: **energy flow**, separately for $\pi^0$ and hadrons $\pi$, K, p spectra

• News
  – **Muon puzzle** established at **8 sigma** (UHECR 2018)
  – p+O discussed in **HL-LHC yellow report**
  – Proposed run schedule: **2022** p-O at 9.9 TeV, Lint = 200 $\mu$b$^{-1}$ for experiments: ALICE, ATLAS, CMS, LHCb
UHE cosmic ray detection

*Artist impression of air shower*

Image credit: Rebecca Pitt, Discovering Particles, CC BY-ND-NC 2.0
UHE cosmic ray detection

Example: event observed with Pierre Auger Observatory
UHE cosmic ray detection

Example: event observed with Pierre Auger Observatory

Signal = electrons + photons + muons

\[ N_\mu \]
UHE cosmic ray detection

Example: event observed with Pierre Auger Observatory

Direction from particle arrival times ✔
Energy from size of $\gamma$ component ✔
Mass from depth of shower maximum and size of muonic component

Instrumental uncertainties (Auger)
Direction: negligible
Energy: 14 \%_{sys}
$X_{\max}$: 10 g cm$^{-2}_{sys}$ (Fe – p = 100 g cm$^{-2}$)
$N_{\mu}$: 11 \%_{sys} (Fe / p = 1.4)
Cosmic ray mass composition

- Mass composition ($<\ln A>$) carries imprint of cosmic-ray sources
- Uncertainties in hadronic interaction models dominate $<\ln A>$, not experimental uncertainties
- **Muon Puzzle**: Muon measurements have much larger spread and are not consistent with $X_{\text{max}}$

Indirect search for physics beyond the standard model at 100 TeV scale

Based on Kampert & Unger, Astropart. Phys. 35 (2012) 660
Model dependence of mass

Heitler-Matthews model (and simulations): \(<\ln A> = a + b \ X_{\text{max}} = c + d \ <\ln N_\mu>\)

\(a, b, c, d\) are model dependent

Using number of muons \(N_\mu\) and depth \(X_{\text{max}}\) of shower maximum produces conflicting results

\(A=220, \text{ radon?} \quad A=1\text{ to }4, \text{ } p\text{ to helium?}\)
Tests of EM component

- **Proton-air cross-section (next slide)**
- **Longitudinal shape**
  - F. Diogo (Auger), ICRC 2015 arXiv:1509.03732v1
    - Average profiles parameterized by width L and asymmetry R
    - Agreement for EPOS-LHC, QGSJet-II.04, some tension for SIBYLL-2.1
- **Moments of $X_{\text{max}}$ distribution**
    - First two moments of $X_{\text{max}}$ distribution converted to first two moments of lnA
    - EPOS-LHC, SIBYLL-2.3 ok; partially unphysical second moments for QGSJet-II.04
- **Lateral density profile**
  - S. de Ridder (IceCube) ICRC 2017 arXiv:1710.01194v1
    - $<\text{lnA}>$ computed from $<\beta>$ and in-ice energy loss (TeV muons)
    - Agreement for QGSJet-II.04, SIBYLL-2.3
    - Disagreement for SIBYLL-2.1, EPOS-LHC
- **Attenuation with zenith angle**
  - D. Ivanov (Telescope Array) TeVPA 2018
    - Agreement to 45 deg with QGSJet-II.03
Tests of Muon component

- **Lateral density (rest of talk)**
- **Production depth/height**
  - KASCADE-Grande: Astropart. Phys. 34 (2011) 476; disagreement with QGSJet-II.02
- **Attenuation with zenith angle**
  - KASCADE-Grande: Astropart. Phys. 95 (2017) 25; disagreement with all current models
- **High-energy muons: multiplicity**
  - ALICE: JCAP 1601 (2016) 032; consistent with QGSJet-II.04
- **TeV muons: flux**
  - IceCube: Astropart. Phys. 78 (2016) 1; disagreement for SIBYLL-2.1, potentially fixed by adding charm
  - T. Fuchs (IceCube), ECRS 2016, arXiv:1701.04067; agreement for SIBYLL-2.1
- **TeV muons: lateral-separation**
  - D. Soldin (IceCube), ISVHECRI 2018; partial agreement for SIBYLL-2.1/2.3, disagreement for EPOS-LHC, QGSJet-II.04
- **Rise-time**
  - Auger: PRD 96 (2017) 122003; disagreement for QGSJet-II.04 and EPOS-LHC
  - Auger: PRD 93 (2016) 072006; disagreement for EPOS-LHC (500-2000 m), QGSJet-II.04 (500-1000 m), agreement for QSGJet-II.04 (1000-2000 m)
Motivation summary

• Cosmic ray research would greatly benefit from precise knowledge of cosmic ray mass

• Air shower measurements are very accurate, accurate simulations of hadronic cascade missing

• Air shower measurements can narrow down where models fail, but only LHC measurements can pin-point and resolve it
News on Muon Puzzle

- WHISP report at UHECR 2018 conference, Oct 8-12 2018
- Comprehensive compilation of muon measurements from 8 air shower experiments

All measurements converted to z-scale

\[ z = \frac{\ln N_{\mu}^{\text{det}} - \ln N_{\mu,p}^{\text{det}}}{\ln N_{\mu,\text{Fe}}^{\text{det}} - \ln N_{\mu,p}^{\text{det}}} \]

- Systematic discrepancies starting around $5 \times 10^{16}$ eV, equiv. to $\sqrt{s_{\text{nn}}} = 10$ TeV

Energy scales cross-calibrated (except KASCADE-Grande, EAS-MSU)
Muon Puzzle strongly confirmed

Fitted line to data \( \Delta z = a + b[\log_{10}(E/eV) - 16] \)

Fit corrected for over- and underestimation of uncertainties, assuming various levels of systematic correlation for points from the same experiment

Slope deviates from zero by 8 sigma
Main points

• Muon Puzzle is experimentally established
• Increasing deviation with shower energy, start in the reach of LHC
• Problem is likely not in the first interaction
  – muons are produced after about 6 hadronic interactions, Heitler-Matthews-model

\[
\frac{N_{\mu}}{N_{\mu,MC}} = \left( \frac{N_{\text{hadrons}}}{N_{\text{hadrons,MC}}} \right)^6 = ? \ (1.05)^6 \approx 1.34
\]

5 % measurements needed at the LHC to solve this
Modified hadronic interactions

Ad-hoc modify features at LHC energy scale with factor $f_{\text{LHC-po}}$
and extrapolate up to $10^{19}$ eV proton shower
R. Ulrich et al PRD 83 (2011) 054026

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 hadronic features

Modified features
- **cross-section**: inelastic cross-section of all interactions
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- **\( \pi^0 \) fraction**: (no. of \( \pi^0 \)) / (all pions)
Impact of LHC measurements

$E = 10^{19}$ eV

- $X_{\text{max}}$ sensitive to: inelastic cross-section, hadron multiplicity
- $N_{\mu}$ sensitive to: energy fraction lost to $\pi^0$, hadron multiplicity
- Nuclear modification in forward-produced hadrons expected and important

Based on Ulrich et al., PRD 83 (2011) 054026 and Auger: PRD 91 (2015) 032003

Section 2.5: technical feasibility of p-O run

Section 11: Opportunities of proton-ion collisions

Section 11.1: O+O, Ar+Ar, Kr+Kr

Section 11.3: p+O for cosmic ray research

Section 12: Luminosity requirements

<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</td>
<td>3 weeks</td>
<td>2.3 nb$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>pp 5.5 TeV</td>
<td>1 week</td>
<td>3 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 nb$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>O–O, p–O</td>
<td>1 week</td>
<td>500 µb$^{-1}$ and 200 µb$^{-1}$</td>
</tr>
<tr>
<td>2023</td>
<td>p–Pb 8.8 TeV</td>
<td>3 weeks</td>
<td>0.6 pb$^{-1}$ (ATLAS, CMS), 0.3 pb$^{-1}$ (ALICE, LHCb)</td>
</tr>
<tr>
<td></td>
<td>pp 8.8 TeV</td>
<td>few days</td>
<td>1.5 pb$^{-1}$ (ALICE), 100 pb$^{-1}$ (ATLAS, CMS, LHCb)</td>
</tr>
<tr>
<td>2027</td>
<td>Pb–Pb 5.5 TeV</td>
<td>5 weeks</td>
<td>3.8 nb$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>pp 5.5 TeV</td>
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<td>3 pb$^{-1}$ (ALICE), 300 pb$^{-1}$ (ATLAS, CMS), 25 pb$^{-1}$ (LHCb)</td>
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<td>2028</td>
<td>p–Pb 8.8 TeV</td>
<td>3 weeks</td>
<td>0.6 pb$^{-1}$ (ATLAS, CMS), 0.3 pb$^{-1}$ (ALICE, LHCb)</td>
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<tr>
<td>2029</td>
<td>Pb–Pb 5.5 TeV</td>
<td>4 weeks</td>
<td>3 nb$^{-1}$</td>
</tr>
<tr>
<td>Run-5</td>
<td>Intermediate AA</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>pp reference</td>
<td>1 week</td>
<td></td>
</tr>
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</table>
Measurements in p+O

- Differential cross-section for production of $\pi$, $K$, $p$
  - Needs hadron PID
  - ALICE: $|\eta| < 0.9$
  - LHCb: $2 < \eta < 5$

- Energy flow separated by hadrons and $e\gamma$
  - Needs good Ecal and Hcal
  - ATLAS, CMS & CASTOR up to $|\eta| = 6.6$

- LHCf: $\pi^0$, $n$ in very forward range for elasticity, $\eta > 8.4$
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Fitting data with correlated errors

10 points, two groups with systematic offset and correlated errors

Fit line $y = a + b \times$

Truth: $a = 1$, $b = 2$

Generalized least-squares, minimize

$$Q = (\vec{y} - \vec{y}_{\text{fit}})^T C^{-1} (\vec{y} - \vec{y}_{\text{fit}})$$

$C$ ... covariance matrix of data

$\chi^2 / \text{n.dof} = 9.70 / 8 = 1.21$

$C$ ... covariance matrix of data

$\chi^2 / \text{n.dof} = 8.14 / 8 = 1.02$

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