Proton-oxygen collisions for cosmic ray research: an update

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CERN and cosmic rays

Cosmic rays = high-energy nuclei from space

\( \sqrt{s_{NN}/\text{GeV}} \)

HD et al., PoS(ICRC2017)533

SPS (NA61) and LHC cover three orders of magnitude in c.m.s. energy

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Where do cosmic rays come from?

No pointing (cosmic ray sky looks isotropic), but elemental composition is revealing

Elemental composition parametrized by $<\ln A> = \text{mean-logarithmic mass of cosmic rays as a function of cosmic ray energy (bands – empirical evidence, lines – astrophysical theories)}$


- $\ln A$ inferred from experimental data using simulated hadronic showers in air
- Experimental uncertainties: 10 % of proton-iron difference
- Theoretical uncertainties: Up to 100 % of proton-iron difference
- Muon puzzle: not enough muons produced in simulations by all models
- Only input from LHC can resolve this
- Need predictions to be better than 10 %
How to fix the issue?

- Hadronic interactions are complex
- No single “smoking gun”
- Need to accurately predict...
  - Pion spectra in forward rapidity
  - EM energy flow in forward rapidity
  - Inelastic cross-section
Nuclear effects poorly understood

Hadronic interaction models used in air shower simulation must predict \textbf{p-air (nitrogen & oxygen)}, but can only be tuned to \textbf{p-p} and \textbf{p-Pb} with current data

Non-trivial nuclear effects severely affect forward production of particles (most important in air showers, because dominant for energy transport)

Recent example: J/\Psi production measured by LHCb, Physics Letters B 774 (2017) 159-178

\begin{align*}
R_{pA} &= \frac{\text{cross-section for } pA}{A \times \text{cross-section for } pp} \\
\end{align*}

- Strong deviation from $R_{pA} = 1$ for forward production
- 50 \% uncertainty in PDF-based predictions
- Same effect expected in pion production

Cannot translate this from p-Pb to p-O
Interpolate pO from pp and pPb?

EPOS-LHC describes p-p, p-Pb, and Pb-Pb

...but underestimates central collisions in Xe-Xe

Need p-O
Light ions different from heavy irons (shape, core-corona, ...)

Explored nuclear systems at LHC

- **PbPb**
- **XeXe**
- **pPb**
- **pp**
- **pO**

**Graph:**
- A2 vs. A1
- Points: **pPb**, **PbPb**, **XeXe**, **pp**, **pO**

- **EPOS-LHC off**
- Although XeXe close to PbPb

No reason to trust prediction for **pO**
Impact of proton-oxygen collisions

- Simulations of hadron spectra with CRMC: [https://web.ikp.kit.edu/rulrich/crmc.html](https://web.ikp.kit.edu/rulrich/crmc.html)
- Bands indicate model spread from leading models: EPOS-LHC, QGSJet-II.04, SIBYLL-2.3

![Graphs showing hadron spectra with LHCb acceptance and forward production](image)

- Models tuned to proton-proton data at $|\eta| < 2$ so good agreement there, but 50% model spread in proton-oxygen
- Need to reduce to 10% spread in proton-oxygen
Summary

• Wanted: p-O collisions to accurately simulate hadronic showers in air
  o Current uncertainties 50 % in pion multiplicity, need better than 10 %
  o Needed by community of >900 scientists (Auger, TA, IceCube, ...)
    • Important topic at the big CR conferences ICRC and ISVHECRI
  o Moderate luminosity sufficient (100 M events)
  o Interest expressed by LHCf and members of LHCb, CMS, ATLAS

• Nuclear effects in proton-ion collisions poorly understood
  o Cannot simply interpolate p-O from p-p and p-Pb
  o Effects largest for forward production which dominates air showers

• Measurements in p-O
  o Inelastic cross-section
  o Spectra of light hadrons $\pi$, $K$, $p$
  o $\pi^0$, n with LHCf in very forward range
  o Identified energy flow, separated by hadrons and $e\gamma$
Backup
**em-hadron energy ratio**

- Hadronic energy “lost” to $\pi^0$s cannot produce muons in late shower
- “Energy loss” described by observable $E_{e\gamma}/E_{\text{hadrons}}$

- Model predictions differ by **13 %** and in **shape**: only EPOS has forward peaks
- Translates to **> 15 %** shift in $N_\mu$, best bet to solve muon puzzle
Air shower observables

Haungs et al., JoP Conf. Ser. 632 (2015) 012011

Direction from particle arrival times
Energy from size of $\gamma$ component
Mass from size of muonic component and depth of shower maximum
Limited by theoretical uncertainties

Number of muons and Mass
Iron = $1.4 \times$ proton yield at same CR energy

Shower depth and Mass
Iron = proton - $100 \text{ g cm}^{-2}$ at same CR energy
Phase space of air shower interactions as covered by various experiments (beam-beam collisions transformed to equivalent fixed-target system)

LHCb could significantly increases coverage
Sensibility depends on observable and parameter:

- effect of uncertainties at LHC on air shower observables

\[ f_{\text{LHC-pO}} = \text{modification factor@LHC} \]

- 20% difference in multiplicity is about

![Graphs showing relative N_{\mu}/N_{\mu\ell} vs. f_{\text{LHC-pO}} for Proton 10^{19} \text{ eV}]

- Plots with Sibyll model:
  - cross section
  - multiplicity
  - elasticity
  - \( \pi^0 \) fraction

\( \text{Mean } X_{\max} \text{ (g/cm}^2) \)

\( \text{RMS } X_{\max} \text{ (g/cm}^2) \)