pO collisions for cosmic ray physics at the LHC

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In a Nutshell

• Why pO?
  – Cosmic rays interact with Earth’s atmosphere and produce air showers
  – Experiments need accurate simulation of air showers
  – pO collisions at LHC reproduce first interaction of cosmic ray with atmosphere

• What to measure?
  – $\pi$, K, p for cosmic ray experiments
    • Inclusive production, ($\eta$, pT) spectra
    • Multiplicity distributions
  – D mesons for IceCube
    • Inclusive production, ($\eta$, pT) spectra

• Required luminosity
  – $1\,\text{nb}^{-1}$ for $\pi$, K, p, D (500M events)

• Data of interest for several experiments
  – LHCb: full hadron PID for $2 < \eta < 5$
  – LHCf: gammas and neutrons at $\eta > 8.4$
  – ALICE, CMS, CASTOR, TOTEM ...
Air showers

Not this

This

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http://astro.uchicago.edu/cosmus/projects/aires/
Cosmic rays: naked high-energy nuclei from outer space

- Below $10^5$ GeV: elemental composition of cosmic rays well known
- Above $10^5$ GeV: elemental composition uncertain, inferred from observing air showers
Cosmic rays

HD et al., PoS(ICRC2017)533

\( \sqrt{s_{NN}}/\text{GeV} \) equivalent cms-energy of first CR interaction

- Air shower simulations needed to connect observables to cosmic ray properties
- Muons wrong in simulations, preventing better understanding: the **Muon Puzzle**
Air shower animation

hadrons muons electrons neutrino

https://web.ikp.kit.edu/corsika/movies/sincpr15xz03.gif

https://web.ikp.kit.edu/corsika/movies/Movies.htm
Air shower observables

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

**Direction** from particle arrival times  
**Energy** from size of $\gamma \gamma$ component  
**Mass** from size of muonic component

(muonic component energy proxy  
(nuclear fragments  
(nuclear interaction with air molecule  
(K, K$^0$  
($\pi^+$, $\pi^-$  
($\mu^+$, $\mu^-$  
($\gamma, \nu_\mu$  
(muonic component neutrinos  

hadronic component  

hadronic cascade

Energy proxy  

mass proxy  

(nuclear fragments  

hadronic interaction with air molecule

emission

hadronic component

electromagnetic component

energy proxy

Muons and Mass  
Iron-induced showers produce 40% more muons than proton-induced showers at the same energy
Bottleneck for a field: the mass

Test CR origin theories...

...with arrival directions
- Strongly discriminating, if point source
- Weakly discriminating, if anisotropy
- No point sources found

...with energy spectrum
- Weakly discriminating
- Small uncertainties

...with mass composition
- Strongly discriminating
- Large uncertainties (so far)

- Mass composition **differs a lot** in astrophysical theories about cosmic ray origin
- But: measurement accuracy poor, because of **uncertainties in air shower models**


SNR ... Super Nova Remnant
ankle ... Feature in cosmic-ray flux

AGN ... Active Galactic Nucleus
$E_{\text{max}}$ ... maximum energy of cosmic accelerators

Hans Dembinski | MPIK
Muon Puzzle

Muon number in simulated air showers inconsistent with air shower data

Muon number in data 20% higher than closest model (EPOS-LHC)
Air shower simulations

Ulrich et al., PRD 83 (2011) 054026

- MC study using modified hadronic interaction models
  - Hadron production properties adjusted with energy-dependent factor $f_{19}$
  - Muon number...
    - very sensitive to ratio of charged to neutral pions in forward direction
    - sensitive to particle multiplicity
  - Extreme changes required to increase muon number by observed 20%
LHC: Particles to investigate

Typical muons in air shower experiments

- Are of $10 - 100$ GeV energies, not collimated with the shower axis, produced late in shower
- Interesting parent/grandmother particles: **pions, kaons, protons**

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**Grandmother particles of observed muons**

<table>
<thead>
<tr>
<th>E [GeV]</th>
<th>dN/μ/d(ln E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^2$</td>
<td>250</td>
</tr>
<tr>
<td>$10^3$</td>
<td>200</td>
</tr>
<tr>
<td>$10^4$</td>
<td>150</td>
</tr>
<tr>
<td>$10^5$</td>
<td>100</td>
</tr>
<tr>
<td>$10^6$</td>
<td>50</td>
</tr>
</tbody>
</table>

- **Pions**: 5% spread
- **Nucleons**: 25% spread
- **Kaons**: 15% spread

**KASCADE**: $E_0 = 1$ PeV, $r = 20$-200 m

**Maris et al. (NA61 collab.) Proc. ICRC 2009, 1059**

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**Pierre Auger**: $E_0 = 10$ EeV, $r = 1000$ m
LHC: Particles to investigate

High-energy neutrinos from air showers main background for IceCube
- High-energy muon neutrino flux dominantly from D meson decays

Typical muon
10 – 100 GeV from decay of π, K

High-energy muon and neutrino
> 0.5 TeV from decay of D

Complementarity of LHC experiments

Exploit pO collisions with multiple experiments, maximize impact:

- Hadron PID up to mid rapidity
  - LHCb, ALICE

- Charged spectra up to mid rapidity
  - CMS+CASTOR

- Inelastic cross-section
  - TOTEM

- Energy flow in extreme forward
  - LHCf
**Forward spectrometer** fully instrumented in $2 < \eta < 5$

- Very good momentum and vertex resolution
  - $\delta p/p < 1\%$ for $2 < p < 200$ GeV/c, $\delta x \sim 20$ µm for high $p_T$ tracks
- **Good particle identification**
  - $K$: $\sim 90\%$ efficiency, mis-ID $< 5\%$
  - $\mu$: $\sim 97\%$ efficiency, mis-ID $\sim 1-3\%$

- **Optimal**: $\mu, p, K^+, \pi^+$ produced inside Vertex Locator
- **Ok**: $K^0_S, \Lambda^0, \gamma, e, \pi^0$
- **Challenging**: stable neutral hadrons

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**LHCb**

Only LHC detector with **hadron PID** in forward rapidity

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LHCb collab., JINST 3 (2008) S08005
LHCb collab., IJMP A 30 (2015) 1530022

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**Hadron PID (Kaon-Pion separation)**

- RICH: PID for $p > 10$ GeV/c
- TORCH: proposed to extend PID to $p < 10$ GeV/c
Data on pion spectra

Phase space of air shower interactions as covered by various experiments (beam-beam collisions transformed to equivalent fixed-target system)

LHCb significantly increases coverage
Why pO if we have pp?

Model spread: EPOS-LHC, QGSJet-II.04, SIBYLL-2.3


| Models mostly tuned to pp data at \(|\eta| < 1\) |
|---|
| • \(|\eta| < 1\): pp 10 % model spread, pO 50 % model spread |
| • \(\eta = 5\): pp and pO 50 % model spread |
Required luminosity (LHCb)

Mix of EPOS-LHC, QGSJet-II.04, SIBYLL-2.3

LHCb acceptance: $p > 10$ GeV/c, $2 < \eta < 5$


Raw $p_T$ spectra in eta bins

$\Delta \eta = 0.2$, $\Delta \log(p_T) = 0.2$

Projected stat. error for 500M events

$N_{ev} = 500$ M, $\Delta \eta = 0.2$, $\Delta \log(p_T) = 0.2$

500M events (1 nb$^{-1}$ for pO) sufficient even with fine binning in eta and $p_T$
pO and heavy-ion physics

EPOS-LHC model


- log(Multiplicity) scales with log(A) in pA: pO intermediate system between pp and pPb
- Investigate onset of collectivity and other phenomena observed in high multiplicity events
Feasibility of pO collisions at LHC

• Initial study by D. Mangluki in 2012
  – CERN can provide light nucleon beams
  – Collisions can be pA and AA

• ECR source can “deliver anything”, but takes time to commission the whole chain (LEIR/PS/SPS)
  – Oxygen already support gas for lead

• Required luminosity 1 nb⁻¹ can be acquired in a short time

• Strong support from cosmic ray community at this year’s Int. Cosmic Ray Conference
  Karl-Heinz Kampert, Tanguy Pierog, Ralph Engel, Anatoli Fedynitch...

Interesting facts about the ECR source: http://alicematters.web.cern.ch/?q=DetlefKuchler
Summary

• Why pO?
  – Cosmic rays (nuclei, proton to iron) interact with Earth’s atmosphere and produce air showers
  – pO collisions at LHC reproduce first interaction in 50 000 TeV cosmic ray
  – Experiments rely on accurate simulation of air showers; goal: 10 % model spread
  – Only data on pp at these energies, no data on pO; 50 % model spread
  – What about HeO ... FeO? HeO ... FeO predictions relative to pO seem ok, pO can fix all!

• What to measure?
  – \( \pi, K, p \) to solve Muon Puzzle
    • Inclusive production, (eta, pT) spectra
    • Multiplicity distributions
  – D mesons for IceCube
    • Inclusive production, (eta, pT) spectra

• Luminosity
  – 1 nb\(^{-1}\) for \( \pi, K, p, D \) (500M events)

• Exploit data with multiple experiments
  – LHCb: hadron PID for 2 < \(|\eta|\) < 5
  – ALICE: hadron PID for \(|\eta|\) < 1
  – LHCf: gammas and neutrons for \(|\eta|\) > 8.4
  – TOTEM: total inelastic cross-section
  – CMS+CASTOR: charged spectra \(|\eta|\) < 6.6
BACKUP
Air showers and arrays

Energy from size of \( \gamma \) component
Mass from size of muonic component
(other mass proxies also exist)
Mass uncertainty

- **Mass** inferred from number of muons
  - Relationship **muons <-> mass** taken from air shower simulations
  - Uncertainties of air shower simulations dominated by soft-QCD physics
  - Only phenomenological models (EPOS, ...), need **collider data** for tuning
  - Inferred cosmic-ray mass composition limited by **model accuracy**

- **pO runs**: lab measurement of first interaction in a **5x10^7 GeV air shower**
Matthews-Heitler model of air shower


- Only pions produced: $N_{ch} + N_0$
- Charged pions interact if $E_{\pi} > \xi_c^\pi$
  $\xi_c^\pi$ ... critical energy
- No. of muons = No. of charged pions at critical energy

$$E_{\pi} \overset{1}{=} \xi_c^\pi \rightarrow n_c = \frac{\ln[E_0/\xi_c^\pi]}{\ln[N_{ch} + N_0]}$$

$n_c$ ... cascade steps until decay to muons, typical 4 to 5

No. of muons very sensitive to “energy loss” from neutral pions

Muons and Mass

$N_\mu(E, A) = A N_\mu \left( \frac{E}{A}, 1 \right) = A^{1-\beta} N_\mu(E, 1) \rightarrow N_\mu(Fe) \approx 1.4 N_\mu(p)$

Whole shower development relevant for final muon number

Important properties of shower secondaries: multiplicities, IDs, energy distribution
Muon Puzzle

Muon number in simulated air showers inconsistent with data

HiRes-MIA collab. PRL 84, no. 19 (2000) 4276


- Muon Puzzle confirmed by several experiments at small and large zenith angles
- Discrepancies in old and latest models
Muon Puzzle

μ-LDF (Lateral Density Function) shape differs from simulations

Ateaga-Velazquez et al. (KASCADE-Grande collab.), PoS(ICRC2017)316

Discrepancy in μ-LDF larger at higher energies and near shower axis
Muon Puzzle: Particles to investigate

“Lateral” muons
- Air shower arrays only sensitive to lateral muons
- Muon Puzzle is about them

“Forward” muons
- Only IceCube is sensitive
- Forward muon neutrinos are important background to astrophysical neutrinos
- D mesons dominant

Fedynitch et al., PoS(ICRC2017)1019
LHC detectors

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Multiplicities of individual particles

pp@13TeV  pO@9.2TeV  pPb@8.2TeV

EPOS-LHC + LHCb acceptance

Hans Dembinski | MPIK
pHe(gas) @ 6.5 TeV
Model spread: EPOS-LHC, QGSJet-II.04, SIBYLL-2.3

\[ dN/d\eta \]

\[ dE/d\eta / \text{GeV} \]