Future proton-oxygen beam collisions at the LHC for air shower physics

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PoS(ICRC2019)235
Take-home message

- p-O and O-O collisions at LHC planned for 2023
  - 1 week of data taking to collect 2 nb$^{-1}$
  - Support from ATLAS, CMS, ALICE; strong support from LHCf and LHCb

- Primary motivation from understanding cosmic-ray induced air showers and solving *Muon Puzzle*
  - Solve Muon Puzzle by measuring **energy fraction** carried by $\pi^0$
  - Measure **nuclear effects** in light ion collisions
  - Measuring **rapidity spectra** and improve accuracy of depth of shower maximum predictions to better than 10 %
Motivation

Based on Kampert & Unger, Astropart. Phys. 35 (2012) 660

Astrophysical origins of cosmic rays?
- Mass composition \(<\ln A\>) carries imprint of sources & propagation, inferred from \(X_{\text{max}}\) & \(N_{\mu}\)
- Accuracy of \(<\ln A\>) limited by hadronic interaction generators used in air shower simulations (achievable is 10% of p-Fe distance)
- Muon Puzzle: 8σ discrepancy between air shower simulations and data from 8 experiments
- LHC can simulate first interaction of 50 PeV air shower with p-O collision at \(\sqrt{s} = 10\) TeV

\[X_{\text{max}}\] depth of shower maximum
\[N_{\mu}\] number of muons in shower

8σ Muon Puzzle, see L. Cazon et al. PoS(ICRC2019)214

Impact of hadronic interactions

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

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

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)
Impact of hadronic interactions

- $X_{\text{max}}$ sensitive to
  - inelastic cross-section (*very sensitive*)
    - High-precision measurements from LHC, see e.g. *LHCb collab. JHEP 1806 (2018) 100* and refs. therein
  - hadron multiplicity
- $N_\mu$ sensitive to
  - $\pi^0$ fraction (*very sensitive*)
  - hadron multiplicity
Impact of LHC measurements

- Need to reduce $\pi^0$ fraction to solve the Muon Puzzle or rather $R$
- Measure hadron multiplicity to improve $X_{\text{max}}$ and $N_\mu$ predictions
- Expected: nuclear modification of forward-produced hadrons

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

**Lines:** EPOS-LHC

- $E = 10^{19}$ eV
- $\langle \ln N_\mu \rangle - \ln N_\mu^{\text{Ref}}$

**Graphs:**
- Pseudorapidity $\eta$
- Hadron multiplicity $N_{\text{had}}$
- $X_{\text{max}}$ and $N_\mu$

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

**References:**
- ALICE Xe-Xe arXiv:1807.09061;
- ATLAS Pb-Pb arXiv:1504.04337;
- CMS p-Pb arXiv:1710.09355v2;
- CMS p-p arXiv:1507.05915v2;
- LHCb p-p arXiv:1402.4430
Possibilities to reduce $R$

\[ N_{\pi \text{-charged}} = 2N_{\pi \text{-neutral}} \text{ (isospin symmetry), but } \pi/\text{hadron ratio not fixed} \]

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

Also see T. Pierog et al. PoS(ICRC2019)387

Strangeness production in p-O underestimated?


Enhancement of strangeness production observed in central collisions in pp and p-Pb


$R$ in pp at \( 5.2 < |\eta| < 6.6 \) higher than in models

Also see S. Baur et al. PoS(ICRC2019)188
Nuclear modification uncertainties

- Simulation of pions, kaons, protons spectra with CRMC [https://web.ikp.kit.edu/rulrich/crmc.html]
- Model spread of EPOS-LHC, QGSJet-II.04, SIBYLL-2.3 for pions, kaons, protons

Models mostly tuned to pp data at $|\eta| < 2$, model spread pp 10%, p-O 50%
Proton-Oxygen at the LHC

Section 11.3 by HD, R. Ulrich, T. Pierog et al. with p-O science case
Proposed run schedule


<table>
<thead>
<tr>
<th>Year</th>
<th>Systems, $\sqrt{s_{NN}}$</th>
<th>Time</th>
<th>$L_{\text{int}}$</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 nb$^{-1}$</td>
</tr>
<tr>
<td></td>
<td></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, O–O, p–O</td>
<td>5 weeks</td>
<td>3.9 nb$^{-1}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 week</td>
<td>500 µb$^{-1}$ and 200 µb$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>Pb–Pb 8.8 TeV, pp 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></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, pp 5.5 TeV</td>
<td>5 weeks</td>
<td>3.8 nb$^{-1}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 week</td>
<td>3 pb$^{-1}$ (ALICE), 300 pb$^{-1}$ (ATLAS, CMS), 25 pb$^{-1}$ (LHCb)</td>
</tr>
<tr>
<td>2028</td>
<td>Pb–Pb 8.8 TeV, pp 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></td>
<td>few days</td>
<td>1.5 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 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>

- Latest plans moved data taking to 2023
- 200 µb$^{-1}$ is enough statistics to push statistical error below 5 % in LHCb
- 2 nb$^{-1}$ (10 x minimum) will be requested, also allows to measure charm
Summary

• p-O and O-O collisions at LHC planned for 2023
  – 1 week of data taking to collect $2 \text{nb}^{-1}$
  – Support from ATLAS, CMS, ALICE; strong support from LHCf and LHCb

• Primary motivation from cosmic-ray induced air showers
  – Potentially solve Muon Puzzle by measuring $\pi^0$ energy fraction
  – Clarify size of nuclear effects in light ion collisions
  – Measure rapidity spectra to achieve $X_{\text{max}}$ accuracy better than 10 gcm$^{-2}$

• Proposed measurements at the LHC
  – ATLAS & CMS (no PID): measure separately energy flows in ECal, HCal
  – ALICE, LHCb (has PID): measure identified rapidity spectra of $\pi$, K, p
  – LHCf: measure $\pi^0$ and neutrons in very forward
Outlook

• $\pi$-O interactions with **forward neutron tagging**?
  – Need to tag "single diffractive" events with isolated neutron
  – Model-dependent pre-evolution (pomeron interactions of p-O)

• CORSIKA 8
  – Successor of CORSIKA 7 in modular C++
  – **Unified** tool to simulate air showers and LHC events
  – Allow for **ad hoc tuning** of generator output
  – See Posters 30-31 Jul, **Great Hall, 4th Floor**
    \[ D. Baack PS3-142, HD PS3-157, M. Reininghaus PS3-206 \]

• Bonus problem: simulations of **100 GeV air showers** very uncertain
  – Large discrepancies in muon & electron LDF found in 100 GeV showers
    \[ H. Schoorlemmer, A. Pastor, R.D. Parsons, PoS(ICRC2019)417; \]
    also see \[ arXiv:1904.0513 \] (accepted by PRD)
  – Potential to measure muon LDF of 100 GeV showers with CTA
    \[ A.M.W. Mitchell, HD, R.D. Parsons, PoS(ICRC2019)351; \]
    also see \[ Astropart. Phys. 111 (2019) 23 \]
Nuclear effects in prompt $J/\psi$ production

Up to 50% suppression in forward direction
Especially strong where relevant for CR!
Similar effects expected in pion production

- Model lines parallel, because of approx. superposition
- Model line offsets from nuclear effects (forward effects)

Only need to measure pO, not FeO!

LHCb collab.
LHC and data on pion production

- Most common interaction in air shower is $\pi$-N, use p-O as proxy
- Need more data on light hadron production in forward direction
- Do properties scale from pp to p-O to p-Pb or different regimes?
LDF spread


- CORSIKA simulations
  - 100 GeV to 100 TeV
  - UrQMD for E < 80 GeV
  - Varying high-energy model

- Huge discrepancies in $e\gamma$-LDF and $\mu$-LDF in 100 GeV showers

- Correlated effects in LDFs
  - QGSJet-II.04 high
  - UrQMD low