Recent results from LHC (and SPS) and their implication for cosmic ray physics

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Hadronic interaction models have large differences and uncertainties!

Hadronic interaction models are vital to interpret air shower data!
UHECR composition and interaction models

Combining muon data from 6 experiments:

\[ z = \frac{\ln N^{\text{det}}_\mu - \ln N^{\text{det}}_\mu}{\ln N^{\text{det}}_{\mu} - \ln N^{\text{det}}_p} \]

Relative to energy-dependent mass
→ increasing muon deficit (8\(\sigma\) significance)
Inconsistent interpretation of composition measurements!

Largely due to uncertainties in hadronic interaction models.

→ dedicated tests at accelerators needed

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

[H. Dembinski, ICRC 2019]
How to connect LHC and air showers

R. Ulrich et al. PRD 83 (2011) 054026:
Ad-hoc modify model features by energy-dependent factor
And propagate to full $10^{19.5}$ eV proton shower

Investigated features:
• inelastic cross section
• hadron multiplicity
• elasticity: $E_{\text{leading}} / E_{\text{total}}$
• charge ratio ($\pi^0$ fraction)
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$$R = \frac{E_{\pi^0}}{E_{\text{had}}}$$
What and where to measure

- Most particles are produced at central rapidity → focus for LHC experiments
- Most energy is carried by forward particles → most relevant for air showers
Experiments
(slightly biased personal selection)
CASTOR in CMS

- Tungsten-Quartz sampling calorimeter
- Coverage $-6.6 < \eta < -5.2$
- Segmentation in $\varphi$ and $z$
- Separated electromagnetic and hadronic sections with depth of $20 \, X_0 / 10 \, \lambda_{int}$
LHCf

~140 m from ATLAS interaction point
Coverage: $\eta > 8.4$

- Two towers per Arm
- Sampling and positioning calorimeters: Tungsten layers and plastic scintillators
  + 4 position sensitive layers
- Neutral particles only
Fixed target at CERN North Area: very versatile beam conditions
2 superconducting magnets and 4 time projection chambers
→ large acceptance, momentum resolution and tracking efficiency
→ PID and reconstruction with dE/dx and ToF
CMS: Forward energy spectra [JHEP 08 (2017) 046]

- Detailed energy distribution in CASTOR acceptance
- Differential cross-section as function of total energy
- Sensitive to the model elasticity
CMS: Forward energy spectra [JHEP 08 (2017) 046]

- Bulk of events at low energies: contribution from diffraction (1st bin)
- Sensitive to model elasticity
- Most models perform well
- Sibyll 2.3 overestimates this region → hint of too large elasticity
LHCf: Forward neutron spectra [JHEP 11 (2018) 073]

- Sensitive to elasticity
- Most models perform well
- QGSJet II-04 has too little forward neutrons
  → hint of too small elasticity
LHCf: Forward neutron spectra [JHEP 11 (2018) 073]

- Significant excess of high energy zero-degree neutrons
- Could be explained by diffractive single pion exchange
- Potential impact on air showers
  ($\pi$–nucleus interactions)
CMS: Forward-central correlation [arXiv:1908.01750]

- Correlate forward energy to central particle multiplicity

\[ \langle E_{\text{reco}} \rangle(N_{\text{tracks}}, |\eta|<2) \]
CMS: Forward-central correlation [arXiv:1908.01750]

Ratio of electromagnetic to hadronic energy → charge ratio R
CMS: Forward-central correlation [arXiv:1908.01750]

Ratio of electromagnetic to hadronic energy → charge ratio $R$

Models are at the lower bound:
→ no room for a significant reduction of $R$
→ little hope to solve the muon deficit by QCD tuning

Forward (high energy) $\pi^0$:  
- impact on early e.m. cascade  
- take energy away from muon production  
- No comparison to models yet

- Very important data, once fully analyzed and published
at LHC: first interaction(s)

Energy fraction for muon production scales with the generations:

\[ f = \left( \frac{2}{3} + \Delta \right)^n \]

\( \pi^\pm, K, \Lambda, p, n, \ldots \)

\( \pi \) – air interactions

[M. Unger, ICRC 2019]
NA61: Identified spectra in $\pi$-C (158 GeV/c)

\[ \rho^0 \text{ have a similar effect as } \pi^0 \rightarrow \gamma\gamma \rightarrow \text{feed the electromagnetic cascade} \]

\[ \bar{p} \text{ is proxy for baryon production } \rightarrow \text{feed the hadronic cascade} \]
Energy fraction carried by $\rho^0$ and $\bar{p}$ is poorly described.

Overproduction of $\bar{p}$ and underproduction of $\rho^0$ both lead to an increased muon number.
Summary

• Well founded interpretations of CR data require good hadronic interaction models
• Extensive and growing set of analyses
  → more complete and diverse picture of the forward particle production
• Benchmark tests for event generators:
  → model elasticity → constrains allowed shower maximum depth
  → fraction of hadronic energy → constrains allowed muon number
• A lot of work for model builders, no solution in sight yet
• Outlook: planned p-O collision for LHC Run3
  → better proxy for p-air
  → potential to measure π-O with LHCf+ATLAS
Backup
Big improvements after LHC Run 1

COSPA Brussels – S. Baur: LHC results and cosmic rays
Energy measurements with CASTOR

- Total energy: Sum all calorimeter towers above noise threshold
- Signal in the first two modules of CASTOR is sensitive to the electromagnetic component
- Back part measures the hadronic contribution

Corresponding particle level energies:
- Energy sum of
  - all stable particles except $\mu$, $\nu$
  - $e$, $\gamma$ (incl. $\pi^0$)
  - all stable particles except $\mu$, $\nu$, $e$, $\gamma$
LHCf: PID

Photons
- EM showers
- \(\Delta E/E < 5\%\)
- \(\Delta\text{pos} < 0.2\ \text{mm}\)

Neutrons
- Hadronic showers
- \(\Delta E/E \sim 40\%\)
- \(\Delta\text{pos} \sim 1.0\ \text{mm}\)
- deeper and longer than EM showers

\(\pi^0\)
- “Pairs” of EM showers
- \(\pi^0 \rightarrow 2\gamma\) (BR:98.8\%)
- \(E_{\pi}=E_{\gamma 1}+E_{\gamma 2}\)

[From Hiroaki Menjo, ICRC 2019]
Preliminary Result on Direct $^{10}$B + $^{11}$B Production

\[ \sigma(C+p \rightarrow B+X)/\text{mb} \]

- world $^{10}$B
- NA61 $^{10}$B + $^{11}$B preliminary
- world $^{11}$B
- world $^{10}$B + $^{11}$B

$\frac{p}{(\text{AGeV/c})}$
QGP and muon numbers

- QGP-like states enhance baryon production
- QGP-like effects are observed in p-p at the LHC
- Effects turn on earlier than predicted by EPOS-LHC
- Enhancement of the QGP phase space could lead to an increase of muon production