Results from NA61/SHINE on Hadronic Interactions in Cosmic-Ray Air Showers

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NA35 3.2 TeV O+Pb Interactions

ISAPP School 2018
Air Shower Observables and Hadronic Interactions

- $X_{\text{max}}$ is dominated by first interaction
  → most relevant data from LHC

- muons from $\pi^\pm$ decay at late stage of cascade ($\lambda_{\text{dec}} \sim \lambda_{\text{int}}$)
  → all interaction energies relevant!
Muons in UHE Air Showers

energy of last interaction before decay to $\mu$

air shower $\rightarrow$ hadron + air $\rightarrow$ $\pi/K + X$

$\mu + \nu_\mu$

high-energy air shower

e.g. KASCADE:

$E_0 = 10^{15}$ eV

$r = 40-200$ m

$E_\mu \geq 250$ MeV

Muons in UHE Air Showers

energy of last interaction before decay to $\mu$
$\text{air shower} \rightarrow \text{hadron} + \text{air} \rightarrow \pi/K + X$

ultrahigh-energy air shower

e.g. Auger:

$E_0 = 10^{19}$ eV
$r = 1000$ m
$E_\mu \geq 150$ MeV

Muons in UHE Air Showers

- $2/3 \ E_0 \approx 0.67 \ E_0$

- simple model:
  - energy fraction $f \sim 2/3$ to $\pi^\pm$
  - energy fraction $(1 - f) \sim 1/3$ to $\pi^0$

→ fraction of initial energy in hadronic component after $n$ interactions: $f^n$

- $(2/3)^2 \ E_0 \approx 0.44 \ E_0$
- $(2/3)^3 \ E_0 \approx 0.30 \ E_0$
- $(2/3)^4 \ E_0 \approx 0.20 \ E_0$
- $(2/3)^5 \ E_0 \approx 0.13 \ E_0$

$\pi \to \mu^\pm + \nu$
Muons in UHE Air Showers

number of muons depends on energy fraction \( f \) of produced hadrons

\[
N_\mu \propto \Pi_{i=1}^{n_{\text{int}}} f_i
\]

- \( \pi^0 \rightarrow \) electromagnetic shower
- \( \pi^\pm \)
- \( \rho^0 \rightarrow \pi^+\pi^- \)
- (anti-) baryons

\[ \bar{\rho} \text{ energy fraction in } \pi^-\text{-C} \]

\[ \rho^0 \text{ energy fraction in } \pi^-\text{-C} \]

R.Prado ISVHECRI18, Pierog&Werner PRL17, Drescher PRD08
The Super Proton Synchrotron (SPS) at CERN

Maximum Beam Momentum: $Z \times 450 \text{ GeV/c}$, accelerates $p$, $\bar{p}$, $O$, $S$, $Ar$, $Pb...$
A precise (2% dp/p acceptance), robust, flexible magnetic spectrometer
Beam Particle Id (Mass via Cherenkov Angle)

CEDAR (CErenkov Differential counters with Achromatic Ring Focus)

H2

SPS

8 x PMT

Ring Image at Diaphragm

Corrector

Light path

Mirror

Beam

pressure [bar] 10.2 10.3 10.4 10.5 10.6 10.7 10.8 10.9 11

ratio

$\pi^-$

$K^-$

$\bar{p}$

$f(\pi^-) = 9.4 \times 10^{-1}$

$f(K^-) = 4.4 \times 10^{-2}$

$r_0 = 4.0 \times 10^{-4}$

$T = 296.7$ K

$\sigma = 0.02$

$\Delta = 0.07$

$\varepsilon = 0.95$

pressure scan
Beam Particle Id (A and Z with ToF, dE/dX, Č)

installation of ToF cable along H2 beam line, Feb 2018

$Z^2$ detector, Be run (Cherenkov in Quartz)
Interaction Target at NA61/SHINE (H$_2$, C, ...)
Particle Production Measurement at NA61/SHINE

- large acceptance $\approx 50\%$ at $p_T \leq 2.5 \text{ GeV/c}$
- momentum resolution: $\sigma(p)/p^2 \approx 10^{-4} \text{ (GeV/c)}^{-1}$
- tracking efficiency: $> 95\%$
$\pi^- + \text{C interaction at 158 GeV/c}$
Particle Production Measurement at NA61/SHINE

Particle identification via $dE/dx$ (and ToF)
**NA61 Data on Hadron+Carbon Interactions**

**T2K, MINERνA, MINOS, NOνA, DUνE**

<table>
<thead>
<tr>
<th>p</th>
<th>year</th>
<th>$N_{\text{trig}}/10^6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>p+C</td>
<td>31</td>
<td>2007/09</td>
</tr>
<tr>
<td>p+C</td>
<td>60</td>
<td>2016</td>
</tr>
<tr>
<td>p+C</td>
<td>90</td>
<td>2017</td>
</tr>
<tr>
<td>p+C</td>
<td>120</td>
<td>2012</td>
</tr>
<tr>
<td>p+C</td>
<td>120</td>
<td>2017</td>
</tr>
<tr>
<td>$\pi^+$ +C</td>
<td>30</td>
<td>2017</td>
</tr>
<tr>
<td>$\pi^-$ +C</td>
<td>60</td>
<td>2017</td>
</tr>
<tr>
<td>$\pi^-$ +C</td>
<td>158</td>
<td>2009</td>
</tr>
<tr>
<td>$\pi^-$ +C</td>
<td>350</td>
<td>2009</td>
</tr>
<tr>
<td>K$^+$ +C</td>
<td>60</td>
<td>2015</td>
</tr>
</tbody>
</table>

*without magnetic field,  $^\ast \sim 15 \times 10^6$ events in total
Cross Section Measurements with NA61

Schematic of Beam Line:

- Green: scintillator (coinc.)
- Red: scintillator (veto)
- Blue: MWPC
- Teal: TPC

Beam interaction

Pressure [bar]: $10.2, 10.3, 10.4, 10.5, 10.6, 10.7, 10.8, 10.9, 11$

Beam interaction ratio: $4 \times 10^{-1}, 4.4 \times 10^{-2}, 4 \times 10^{-3}, 4 \times 10^{-4}$

$\pi$: 9.4 \times 10^{-1}$

$\pi f$: 4.4 \times 10^{-2}$

$K$: 4 \times 10^{-4}$

$\sigma$: 0.02$

$\Delta$: 0.07$

$\epsilon$: 0.95$

Target: 3.7 m

CEDAR: 11.9 m

ADC

Entries 0 50 100 150 200 250

Entries 0 10000 20000 30000 40000 50000 60000 70000

beam

target

3.7 m

11.9 m
Cross Section Measurements with NA61

inelastic and production cross sections:

\[ \sigma_{\text{inel}} = \sigma_{\text{tot}} - \sigma_{\text{ela}} \]

\[ \sigma_{\text{prod}} = \sigma_{\text{tot}} - \sigma_{\text{qela}} - \sigma_{\text{ela}} \]

p+C at 31 GeV/c

\[ \pi^- + C \text{ at 158 and 350 GeV/c} \]


\( \pi^\pm \) and \( p \) multiplicities in \( p+C \) at 31 GeV/c

▶ also: \( K^\pm, K_S^0, \Lambda \)
Inclusive $\pi^\pm$ and $p$ spectra in $p+C$ at 31 GeV/c

colors: data/MC, dark-red = 0.5, green = 1, dark-blue = 2
\( \pi^\pm, K^\pm, p \) and \( \bar{p} \) spectra in \( \pi^- + C \) at 158 and 350 GeV/c

**Graphical Representation:**

- \( \pi^0 + C \rightarrow \pi^0 + X \) at 158 GeV/c
- \( \pi^0 + C \rightarrow \pi^0 + X \) at 350 GeV/c
- \( \pi^0 + C \rightarrow K^0 + X \) at 158 GeV/c
- \( \pi^0 + C \rightarrow K^0 + X \) at 350 GeV/c
- \( \pi^0 + C \rightarrow p^0 + X \) at 158 GeV/c
- \( \pi^0 + C \rightarrow p^0 + X \) at 350 GeV/c
$p_T$-integrated Spectra: $\pi^- + C \rightarrow \pi^\pm + X$

NA61/SHINE preliminary

$\pi^- + C \rightarrow \pi^+ + X$

at 158 GeV/c

$\pi^- + C \rightarrow \pi^- + X$

at 158 GeV/c

$\pi^- + C \rightarrow \pi^+ + X$

at 350 GeV/c

$\pi^- + C \rightarrow \pi^- + X$

at 350 GeV/c

R.Prado for NA61/SHINE, ICRC2017

- EPOS1.99
- Sibyll2.1
- Sibyll2.3c
- QGSJetII-04
- EPOS-LHC
$p_T$-integrated Spectra: $\pi^- + C \rightarrow K^\pm + X$

NA61/SHINE preliminary

$\pi^- + C \rightarrow K^+ + X$

at 158 GeV/c

$\pi^- + C \rightarrow K^- + X$

at 158 GeV/c

$\pi^- + C \rightarrow K^+ + X$

at 350 GeV/c

$\pi^- + C \rightarrow K^- + X$

at 350 GeV/c

R.Prado for NA61/SHINE, ICRC2017
$p_T$-integrated Spectra: $\pi^- + C \rightarrow p/\bar{p} + X$

NA61/SHINE preliminary

$\pi^- + C \rightarrow p^+ + X$

at 158 GeV/c

$\pi^- + C \rightarrow p^- + X$

at 158 GeV/c

$\pi^- + C \rightarrow p^+ + X$

at 350 GeV/c

$\pi^- + C \rightarrow p^- + X$

at 350 GeV/c

R.Prado for NA61/SHINE, ICRC2017

EPOS1.99, Sibyll2.1, Sibyll2.3c, QGSJetII-04, EPOS-LHC
Production in $\pi^- + C$ at 158 and 350 GeV/c

two-track invariant mass fit:

$(0.3 < x_F < 0.4)$ of the 158 GeV/c
**Measured Energy Fractions**

\[ \rho^0 \text{ energy fraction in } \pi^--C \]

**\( \rho^0 \)**

\[ \rho^0 \text{ energy fraction in } \pi^--C \]

\[ \bar{p} \text{ energy fraction in } \pi^--C \]

In a previous analysis [54], [70], the change of the parameters needed to describe the rapidity gap correctly (the diffractive cross-section and the diffractive mass distribution) affected both proton and pion interactions because the same parameters were used for both types of projectile. While the change of diffraction is incompatible with [54], [70], large rapidity gaps (high elasticity) predicts deep MPD as well (and probably incompatible with any current model). The one extracted from the data since very close to EPOS). One of the most sensitive measurements of how muons are produced in an air shower is the muon energy spectrum of the produced muons. This is an important factor for the attenuation length of the produced muons. For instance, using updated hadronic interaction models. In fact, in one particular case, the update of EPOS leads to the energy fraction that is not well reproduced by the current models.

**E [GeV]**

- 10^2
- 10^3
- 10^4
- 10^5
- 10^6
- 10^7
- 10^8
- 10^9
- 10^10
- 10^11

**Energy fraction**

- p
- \( \bar{p} \)

**Figure 8:**

Mean number of muons at the ground divided by the primary energy to the power 0.925 (left-hand side).

R. Prado for NA61/SHINE, ICRC2017
Summary and Outlook

- precise lab measurements of last stages of UHECR air shower development with NA61/SHINE
- spectra of $\pi^{\pm}$, $K^{\pm}$, $p$, $\bar{p}$, $\rho^{0}$, $\omega$, $K^{*0}$, $K_S^{0}$, $\Lambda$, $\bar{\Lambda}$ in $\pi^{-}$+C interactions at 158 and 350 GeV/c
- energy fractions of (anti-)baryon and $\rho^{0}$ production relate directly to muon production in air showers
- next up in CR-related program: measurement of nuclear fragmentation*

* mainly C+p for Galactic CRs, but C+C-fragmentation at $E = 180$ GeV could also be interesting for air shower fluctuations (see CERN-SPSC-2017-035)