The Cosmic-Ray Program of the NA61/SHINE Facility

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NA35 3.2 TeV O+Pb interactions

ICRC 2019
The Super Proton Synchrotron (SPS) at CERN

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

H2 Beam Line: Primary Beam, fragments, $\pi^\pm$, $K^\pm$...
Beam Particle Id (Mass via Cherenkov Angle)

CEDAR (CErenkov Differential counters with Achromatic Ring Focus)

$\pi^-$

$K^-$

$p$

pressure [bar]

$10.2 \ 10.3 \ 10.4 \ 10.5 \ 10.6 \ 10.7 \ 10.8 \ 10.9 \ 11$

ratio

$\pi^-=9.4\times10^{-1}$

$K^-=4.4\times10^{-2}$

$r_0=4.0\times10^{-4}$

$\sigma=0.02$

$\Delta=0.07$

$\varepsilon=0.95$

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

installation of ToF cable along H2 beam line, Feb 2018

ToF and dE/dx, Fragmentation run Dec 2018
Interaction Target at NA61/SHINE (H₂, C, ...)
Particle Production Measurement at NA61/SHINE

- large acceptance $\approx 50\%$ at $p_T \leq 2.5$ GeV/c
- momentum resolution: $\sigma(p)/p^2 \approx 10^{-4}$ (GeV/c)$^{-1}$
- tracking efficiency: $>95\%$, pid with dE/dx and ToF
The Cosmic-Ray Program of the NA61/SHINE Facility

- Particle Production in Air Showers
  - \( p+C \) Interactions
    
    \[
    \begin{align*}
    \text{(31, 60, 90, 120 GeV/c)} \\
    \text{(30, 60, 158, 350 GeV/c)}
    \end{align*}
    \]
  - \( \pi+C \) Interactions

- Galactic Cosmic Rays
  - \( d, \bar{d} \) and \( \bar{p} \) Production
    
    \[
    \begin{align*}
    \text{(p+p at 20, 31, 40, 80, 158, 400 GeV/c)} \\
    \text{(C+C, C+CH}\_2\text{ at 13.5 AGeV/c)}
    \end{align*}
    \]
  - Nuclear Fragmentation
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• Particle Production in Air Showers
  • p+C Interactions
    (31, 60, 90 120 GeV/c)
  • π+C Interactions
    (30, 60, 158, 350 GeV/c)
  ← this talk

• Galactic Cosmic Rays
  • \(d, \bar{d}\) and \(\bar{p}\) Production
    (p+p at 20, 31, 40, 80, 158, 400 GeV/c)
  • Nuclear Fragmentation
    (C+C, C+CH\(_2\) at 13.5 AGeV/c)
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Muons in UHE Air Showers

- $2/3 E_0 \approx 0.67 E_0$
- $(2/3)^2 E_0 \approx 0.44 E_0$
- $(2/3)^3 E_0 \approx 0.30 E_0$
- $(2/3)^5 E_0 \approx 0.13 E_0$

energy fraction per interaction

- $f \sim (2/3 + \Delta)$ to $h^\pm$, baryons
- $(1 - f) \sim (1/3 - \Delta)$ to $\pi^0$
- after $n$ generations: $f = (2/3 + \Delta)^n \approx (2/3)^n (1 + 3/2 n \Delta)$

$\pi \rightarrow \mu^\pm + \nu$
Pion Production in $\pi^-$-C at 158 GeV/c ("the 2/3")

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

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

- $p_T$-integrated spectra
- area under curves: $\frac{1}{N_{\text{prod}}} \int p \frac{dn}{dp} dp = f_\pi \cdot p_{\text{beam}}$

\( \rho^0 \) and \( \bar{p} \) Production in \( \pi^- \)-C at 158 GeV/c ("the \( \Delta \")*

- Forward \( \rho^0 \) can replace \( \pi^0 \rightarrow \gamma \gamma \)
- \( \bar{p} \) is proxy for baryon production (p, \( \bar{p} \), n, \( \bar{n} \))

* and \( \Lambda, \bar{\Lambda}, K^\pm, K_S^0 \) ...
and $\bar{p}$ Production in $\pi^{-}$-C at 158 GeV/c ("the $\Delta$"*)

energy fraction of $\rho^0$ and $\bar{p}$:

$\rho^0$ energy fraction ($x_F > 0.15$)

$\bar{p}$ energy fraction

$*\text{ and } \Lambda, \bar{\Lambda}, K^{\pm}, K_S^0...$
The Cosmic-Ray Program of the NA61/SHINE Facility

- Particle Production in Air Showers
  - \( \text{p+C Interactions} \)
    - \( (31, 60, 90 \text{--} 120 \text{ GeV}/c) \)
  - \( \pi^+\text{C Interactions} \)
    - \( (30, 60, 158, 350 \text{ GeV}/c) \)

- Galactic Cosmic Rays
  - \( d, \bar{d} \) and \( \bar{p} \) Production
    - \( (\text{p+p at 20, 31, 40, 80, 158, 400 GeV}/c) \)
  - Nuclear Fragmentation
    - \( (\text{C+C, C+CH}_2 \text{ at 13.5 GeV}/c/\text{nucleon}) \)

Particle Production in the Galaxy

π^± → μ^± → e^±
Particle Production in the Galaxy

- CR-grammage $X$ ("target thickness") from secondary nuclei, e.g.

$$\frac{(B/C)}{\lambda_{\text{prod}}} \sim \frac{(1 - e^{-X/\lambda_{\text{prod}}})}{e^{-X/\lambda_{B}}} e^{-X/\lambda_{\text{prod}}}.$$ 

$$\lambda_{\text{prod}} = \frac{m_p}{\sigma_{\text{prod}}} = m_p \left( \frac{\sum \Psi_i \times \sigma(i + p \rightarrow B)}{\sum \Psi_i} \right)^{-1}, \quad i = \text{C, N, O, ...}$$

- $X \ll \lambda_{XB}$ and $X \ll \lambda_B$

$$X \sim (B/C) \frac{m_p}{\sigma_{\text{prod}}}$$

- prediction for e.g. anti-protons ($X \ll \lambda_{p\bar{p}}$):

$$(\bar{p}/p) \sim X/\lambda_{p\bar{p}} = (B/C) \frac{\sigma_{p\bar{p}}}{\sigma_{\text{prod}}}$$

- relative uncertainty $\delta_X = \delta(X)/X$

$$\delta_{\bar{p}/p}^2 \sim \delta_{(B/C)}^2 + \delta_{\sigma_{p\bar{p}}}^2 + \delta_{\sigma_{\text{prod}}}^2 \sim 0.03^2 + 0.2^2 + 0.2^2$$
Uncertainties of Fragmentation Cross Sections

Example: $^{12}\text{C} + \text{p} \rightarrow \text{B}$ (including $^{11}\text{C}$)

adapted from Reinert&Winkler, arXiv:1712.00002

asymptotic $^{12}\text{C} \rightarrow \text{B}$ cross section:

- 61.0 mb (WSKR03)
- (68.6 ± 2.6) mb (RW17a)
- (75.8 ± 4.2) mb (RW17b)
NA61/SHINE Pilot Run on Fragmentation, Dec 2018

SPS beam-fragment identification

reaction-fragment identification

- 2.5 days data taking at 13.5 AGeV/c
- events after upstream $^{12}$C selection:
  - $1.7 \times 10^5$ CH$_2$-target
  - $1.5 \times 10^5$ C-target
  - $0.4 \times 10^5$ empty-target
Preliminary Result on Direct $^{10}$B + $^{11}$B Production

$\sigma(C + p \rightarrow B) = 47.7 \pm 3.0 \text{ (stat.)} \pm 2.3 \text{ (syst.)} \text{ mb}$

*without “ghost nucleus” $^{11}$C

F. Sutter, Master Thesis KIT, Sept. 2019
Preliminary Result on Direct $^{10}\text{B} + ^{11}\text{B}$ Production

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

\[ p/(\text{AGeV/c}) \]

Fit: Evoli+19, Data: Korejwo+02, Korejwo+99, Webber+98, Webber90, Olson+83, Fontes+77
Summary and Outlook

- precise 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 for UHECR EAS
- first result from pilot run on nuclear fragmentation for GCR
- NA61/SHINE plans for $\geq 2021$:
  - TPC upgrade: increase readout rate from 80 Hz to 1000 Hz
  - high-statistics fragmentation data, all channels relevant for Li, Be, B, C, N GCRs

Impact of new measurements (from left to right) for Li

Error combination on $f_{abc}$
- Corr. (all)
- Uncorr. frag + corr. proj (all)
- Uncorr. (all)

Desired precision