NA61/SHINE

≈ 140 physicists from 14 countries and 28 institutions

**Strong interactions physics**

- search for the critical point of strongly interacting matter
- study of the properties of the onset of deconfinement
- heavy quarks: direct measurement of open charm at SPS energies

**Neutrino and cosmic ray physics**

- hadron measurements for the J-PARC neutrino program
- hadron measurements for the Fermilab neutrino program
- measurements for cosmic ray physics (Pierre-Auger and KASCADE experiments) for improving air shower simulations
- measurements of nuclear fragmentation cross sections of intermediate mass nuclei needed to understand the propagation of cosmic rays in our Galaxy

cosmic ray groups: KIT (Germany), Uni. Hawaii (USA), Uni. Silesia (Poland)
NA61/SHINE at the SPS H2 Beam Line
A precise (2% dp/p acceptance), robust, flexible **magnetic spectrometer**
NA61/SHINE Detector

- large acceptance $\approx 50\%$ at $p_T \leq 2.5$ GeV/c
- momentum resolution: $\sigma(p)/p^2 \approx 10^{-4}(\text{GeV/c})^{-1}$
- tracking efficiency: $> 95\%$, pid with dE/dx and ToF
Particle Production Measurement with NA61/SHINE

$\pi^- + C$ interaction at 158 GeV/c
Particle Production Measurement with NA61/SHINE

\[
p \times q
\]
The Cosmic-Ray Program of the NA61/SHINE Facility

- Particle Production in Air Showers
  - p+C Interactions
    - (31, 60, 90, 120 GeV/c)
  - π+C Interactions
    - (30, 60, 158, 350 GeV/c)

- Galactic Cosmic Rays
  - d, d̄ and p̄ Production
    - (p+p at 20, 31, 40, 80, 158, 400 GeV/c)
  - Nuclear Fragmentation
    - (C+C, C+CH₂ at 13.5 AGeV/c)

The Cosmic-Ray Program of the NA61/SHINE Facility

• Particle Production in Air Showers
  • p+C Interactions
    (31, 60, 90, 120 GeV/c)
  • π+C Interactions
    (30, 60, 158, 350 GeV/c)

• 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)

← this talk
The Cosmic-Ray Program of the NA61/SHINE Facility

- Particle Production in Air Showers
  - p+C Interactions
    (31, 60, 90, 120 GeV/c)
  - π+C Interactions
    (30, 60, 158, 350 GeV/c)

- 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)

\[\text{PRC 84} \ (2011) \ 034604, \ \text{PRC 85} \ (2012) \ 035210, \ \text{PRC 89} \ (2014) \ 025205, \ \text{EPJ C74} \ (2014) \ 2794, \ \text{EPJ C76} \ (2016) \ 84, \ \text{EPJ C76} \ (2016) \ 198, \ \text{EPJ C77} \ (2017) \ 671, \ \text{EPJ C77} \ (2017) \ 626, \ \text{PRD 98} \ (2018) \ 052001, \ \text{arXiv:2107.12275 (ICRC21)}, \ \text{PRD 107} \ (2023) \ 062004.\]
Energy Spectrum of Ultrahigh-Energy Cosmic Rays

\[ E^{-3.1} \]

\( \sqrt{s_{pp}} = 450 \text{ TeV} \)

\( E_{\text{beam}} = 7 \times 10^{12} \text{ eV} \)

Serena Williams' 2nd serve → ∼20 J!
using LHC magnets:
J. Cham & D. Whiteson "We have no idea", Penguin, 2018
Energy Spectrum of Ultrahigh-Energy Cosmic Rays

\[ E^{-3.1} \]

\[ \sqrt{s_{pp}} = 450 \text{ TeV} \]

\[ E_{\text{kin}} \sim 4 \text{ TeV} \]

\[ E_{\text{beam}}^{\text{LHC}} = 7 \times 10^{12} \text{ eV} \]

\[ \sim 20 \text{ J!} \]

Serena Williams’ 2nd serve

\[ \sqrt{s_{\text{pp}}} = 450 \text{ TeV} \]
### Energy Spectrum of Ultrahigh-Energy Cosmic Rays

<table>
<thead>
<tr>
<th>$E / \text{eV}$</th>
<th>Flux / ($\text{km}^2 \text{ sr}^{-1} \text{ yr}^{-1} \text{ eV}^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{17}$</td>
<td>$10^{-12}$</td>
</tr>
<tr>
<td>$10^{18}$</td>
<td>$10^{-14}$</td>
</tr>
<tr>
<td>$10^{19}$</td>
<td>$10^{-16}$</td>
</tr>
<tr>
<td>$10^{20}$</td>
<td>$10^{-18}$</td>
</tr>
<tr>
<td>$10^{21}$</td>
<td>$10^{-20}$</td>
</tr>
<tr>
<td>$10^{22}$</td>
<td>$10^{-22}$</td>
</tr>
</tbody>
</table>

Auger 2019

- $E^{-3.1}$

Using LHC magnets:

- Serena Williams’ 2nd serve $\sim 20$ J!

- J. Cham & D. Whiteson “We have no idea”, Penguin, 2018

$E_{\text{LHC \ beam}} = 7 \times 10^{12}$ eV

$\sqrt{s}_{\text{pp}} = 450$ TeV
Energy Spectrum of Ultrahigh-Energy Cosmic Rays

10^{-3.1}

\begin{align*}
\text{Flux} & \left(\text{km}^2 \text{sr}^{-1} \text{yr}^{-1} \text{eV}^{-1}\right)
\end{align*}

\begin{align*}
E & = 7 \times 10^{12} \text{ eV}
\end{align*}

\begin{align*}
\sqrt{s_{pp}} & = 450 \text{ TeV}
\end{align*}

OK, NOW WAIT THERE FOR A THOUSAND YEARS.

J. Cham & D. Whiteson "We have no idea", Penguin, 2018
Detection of Ultrahigh-Energy Cosmic Rays

Detection of UHECRs: Air Showers

cosmic particle \rightarrow \text{fluorescence telescope \atop + particle detector = air shower}

fluorescence telescope

particle detector
Detection of Ultrahigh-Energy Cosmic Rays

Telescope Array

Pierre Auger Observatory
- 25 Gt air calorimeter
- readout:
  - 20 kt water-Cherenkov detector
  - 27 fluorescence telescopes
Muon Production in Air Showers

\[ R_\mu \sim N_\mu / (1.5 \times 10^7) \]
Muon Production in Air Showers

\[ R_\mu \sim \frac{N_\mu}{(1.5 \times 10^7)} \]
The UHE “Muon Puzzle”

![EPOS-LHC and QGSJet-II.04 plots showing Δz ≡ z − z_{mass} vs. E/eV for various experiments: Auger FD+SD, Auger UMD+SD, Yakutsk, NEVOD-DECOR, AGASA, expected from X_{max}, and GSF.](image-url)
Muons in UHE Air Showers

energy of last interaction before decay to $\mu$

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

→ $\mu + \nu_\mu$

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

simple model: $\pi^+, \pi^-, \pi^0$

- energy fraction $f \sim \frac{2}{3}$ to $\pi^\pm$
- energy fraction $(1 - f) \sim \frac{1}{3}$ to $\pi^0$

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

- $\frac{2}{3} E_0 \approx 0.67 E_0$
- $(\frac{2}{3})^2 E_0 \approx 0.44 E_0$
- $(\frac{2}{3})^3 E_0 \approx 0.30 E_0$
- $(\frac{2}{3})^4 E_0 \approx 0.13 E_0$

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

simple model: $\pi^+, \pi^-, \pi^0, ...$

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

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

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

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

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

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

\[ N_\mu \]

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

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

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

\[ \rho^0 \text{ energy fraction in } \pi^- - C \]
Particle Production Measurement with NA61/SHINE

$\pi^- + C$ interaction at 158 GeV/c
Particle Production Measurement with NA61/SHINE

\( \pi^+ + C \) interaction at 158 GeV/c

\begin{align*}
\text{number of tracks} & = 10^3 \\
p [\text{GeV/c}] & = 0.6, 0.8, 1, 1.2, 1.4, 1.6, 1.8, 2, 2.2, 2.4, 2.6 \\
dE/dx [\text{mip}] & = 0.5, 0.6, 0.7, 0.8, 0.9, 1, 1.1, 1.2, 1.3
\end{align*}

\( q = +1 \)
Particle Production Measurement with NA61/SHINE

\[ \chi^2/\text{ndf} = 1.01 \]
Measurement of hadron production in \( \pi^-\)-C interactions at 158 and 350 GeV/c with NA61/SHINE at the CERN SPS

- **projectile**: \( \pi^- \) (charged pions are most numerous air-shower particles)
- **target**: C (very close to to air)
- **beam momenta**: 158 and 350 GeV/c
- **5 \times 10^6** minimum bias interactions at each energy
- **\( p-p_T \)** spectra of \( \pi^+, \pi^-, K^+, K^-, p, \bar{p}, \Lambda, \bar{\Lambda}, K_S^0 \)
- **\( x_F \)** spectra of \( \rho^0, \omega \) and \( K^{*0} \)

→ precision data for the tuning of air shower simulations
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

$$\frac{1}{N_{\text{prod}}} \int p \frac{dn}{dp} dp = \langle f_\pi \rangle \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 \( \Lambda, \bar{\Lambda}, K^{\pm}, K_S^0 \) ...
$\rho^0$ and $\bar{p}$ Production in $\pi^-\text{-C}$ at 158 GeV/$c$ ("the $\Delta^*$")

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

* and $\Lambda$, $\bar{\Lambda}$, $K^\pm$, $K^0_S$...
Solution to the "Muon Puzzle"?

\[ P_{\pi^0 \rightarrow \rho^0} = 0.6 \times (x_F)^{0.4} \]

\[ P_{\pi\pi \rightarrow p\bar{p}} = 0.5 \times (x_F)^{0.7} \]
\[ P_{\pi^0 \to \rho^0} = 0.6 \times (x_F)^{0.4} \]

\[ P_{\pi\pi \to p\bar{p}} = 0.5 \times (x_F)^{0.7} \]
Particle Production in Air Showers

- p+C Interactions
  (31, 60, 90, 120 GeV/c)

- π+C Interactions
  (30, 60, 158, 350 GeV/c)

Galactic Cosmic Rays

- d, d̅ and p̅ Production
  (p+p at 20, 31, 40, 80, 158, 400 GeV/c)

Nuclear Fragmentation

- (C+C, C+CH₂ at 13.5 AGeV/c)
“A Cosmic Ray Renaissance”  
P. Blasi, EuCAPT 2021

slides from S. Ting / AMS Collaboration, CERN Colloquium June 8 2023
Particle Production in the Galaxy

https://physics.aps.org/articles/v6/40
• CR-grammage $X$ ("target thickness") from secondary nuclei e.g. boron/carbon flux ratio (B/C)
• halo size ("target length") from unstable secondaries e.g. $^{10}\text{Be}/^{9}\text{Be}$ → need to know fragmentation cross sections!
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) $(68.6 \pm 2.6)$ mb (RW17a), $(75.8 \pm 4.2)$ mb (RW17b)
Secondary/Primary CRs: F Anomaly and Li Excess

S. Ting / AMS Collaboration, CERN Colloquium June 8 2023

primary source of Li? spatial dependent diffusion? fragmentation cross sections?

Size of the Galactic Halo ("target length")

→ large uncertainties due to cross-section uncertainties!

Weinrich+20, Evoli+20, Luque+21, Maurin+22
New Measurements of Nuclear Fragmentation Needed!

relevant reaction channels for Li, Be, B:

→ study production of light nuclei at SPS!

Tomassetti 2018
• 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
Particle Id in TPC: a) $Z^2$ via $dE/dx$
Particle Id in TPC: b) A/Z via in deflection in B-field carbon fragments:

Experimental parameters:
- Fermi Widths ($\sigma_F$ in cm):
  - $\sigma_F$(1C) = 1.15 ± 0.06
  - $\sigma_F$(10C) = 1.81 ± 0.27
  - $\sigma_F$(11C_reInt) = 0.73 ± 0.01
- Experimental parameter:
  - $\theta$ = 2.4 ± 0.08 TV cm
- $dE/dx$ = 151.50 ± 0.003 cm
- $\chi^2$/ndf = 37.53/43

<table>
<thead>
<tr>
<th>Key</th>
<th>No. of events (expected)</th>
<th>No. of events (observed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12C</td>
<td>127399.47 ± 233.96</td>
<td>121.51 ± 36.57</td>
</tr>
<tr>
<td>11C</td>
<td>664.29 ± 36.77</td>
<td>36.57 ± 36.57</td>
</tr>
<tr>
<td>10C</td>
<td>79.73 ± 3.47</td>
<td>3.47 ± 3.47</td>
</tr>
<tr>
<td>11C_reInt</td>
<td>121.51 ± 36.57</td>
<td>121.51 ± 36.57</td>
</tr>
</tbody>
</table>

PE

Experimental parameters:
- Fermi Widths ($\sigma_F$ in cm):
  - $\sigma_F$(11C) = 1.24 ± 0.08
  - $\sigma_F$(10C) = 1.60 ± 0.26
  - $\sigma_F$(11C_reInt) = 0.73 ± 0.01
- Experimental parameter:
  - $\theta$ = 1.22 ± 0.03 TV cm
- $dE/dx$ = 131.99 ± 0.004 cm
- $\chi^2$/ndf = 78.34/80

<table>
<thead>
<tr>
<th>Key</th>
<th>No. of events (expected)</th>
<th>No. of events (observed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12C</td>
<td>147239.36 ± 171.39</td>
<td>147239.36 ± 171.39</td>
</tr>
<tr>
<td>11C</td>
<td>1124.04 ± 118.63</td>
<td>1124.04 ± 118.63</td>
</tr>
<tr>
<td>10C</td>
<td>83.72 ± 71.34</td>
<td>83.72 ± 71.34</td>
</tr>
<tr>
<td>11C_reInt</td>
<td>118.63 ± 118.63</td>
<td>118.63 ± 118.63</td>
</tr>
</tbody>
</table>

NA61/SHINE@ICRC21, arXiv:2107.12275
Results from Pilot Run on Boron Production (preliminary)

\[ \sigma(C+p \rightarrow B)[mb] \]

- world $^{10}\text{B}$
- world $^{11}\text{B}$
- world $^{10}\text{B} + ^{11}\text{B}$

NA61/SHINE 2018 pilot run (preliminary)

- $^{10}\text{B} + ^{11}\text{B}$
- $^{11}\text{B}$
- $^{10}\text{B}$
- $^{11}\text{C}$
- total B production ($^{10}\text{B} + ^{11}\text{B} + ^{11}\text{C} \rightarrow ^{11}\text{B}$)

Timeline towards a Physics Run

2017
- first ideas at XSCRC at CERN
- Proposal of Test Run CERN-SPSC-2017-035

2018
- quantification of needed data Phys. Rev. C 98, 034611 (Editors’ Suggestion)
- Proposal of early post-LS2 Measurements CERN-SPSC-2018-008
- three days of pilot data taking in December 2018

2019
- preliminary release of $\sigma(^{12}\text{C} + \text{p} \rightarrow \text{B} + \text{X})$ at ICRC and at XSCRC at CERN
- NCN/DFG Beethoven grant for NA61 upgrade (cosmic rays)
- SPSC recommendation
  
  “The SPSC notes with satisfaction the promising results the pilot run with the fragmented ion setup to understand cosmic radiation, and is looking forward to further measurements and results with the setup.”

2021
- preliminary release of $\sigma(^{12}\text{C} + \text{p} \rightarrow ^{11}\text{C} + \text{X})$ at ICRC

2022
- fragmented lead beam canceled due to early YETS

2023
- 1 week fragmented lead? (CERN-SPSC-2022-034)
Detector Upgrades for Run 3

- Construction of Vertex Detector (VD) for charm decay reconstruction
- New trigger and data acquisition system
- Upgrade of Projectile Spectator Detector (two detectors, new electronics)
- New Beam Position Detectors, based on single-sided silicon strip detectors
- Replacement of the TPC read-out electronics to increase data rate to 1 kHz
- New Time-of-Flight detectors (MRPC-based)
- New Geometry Reference Chamber (drift velocity meas.)
- New read-out system based on the DRS4 chip (full waveform is measured and stored)
Impact of One Week of Fragmented Pb at NA61/SHINE

Diffusion coefficient from CR secondaries, “Galactic target thickness”

\[ \Delta D_0 / D_0 \text{ [%]} \]

\[ \Delta \delta / \delta \text{ [%]} \]

**diffusion coefficient** \( D \propto D_0 (E/Z)^\delta \)

Sci.Bull. 67 (2022) 2162

Genolini, Maurin, Moskalenko, MU in preparation
Impact of One Week of Fragmented Pb at NA61/SHINE

anti-protons at Earth

\[ \Phi_{TOA} \bar{p} \left[ \text{GV}^{-1} \text{m}^{-2} \text{s}^{-1} \text{sr}^{-1} \right] \times R^3 \]

AMS-02 (\( \sigma_{\text{tot}} \))

Boudaud et al. (2020)

Residuals [%]

Current uncertainty

Updated XS (w/o He)

Residuals between AMS-02 and [Bo20] prediction

Genolini, Maurin, Moskalenko, MU in preparation
Impact of One Week of Fragmented Pb at NA61/SHINE

size of Galactic halo from “cosmic clock” $^{10}\text{Be}$

- AMS best fit 2023: $L = 3.6^{+0.5}_{-0.4} \text{ (stat.) kpc}$ soon to improve further (HELIX)
- but: current cross section uncertainty on derived $L \sim 30\%$

Genolini, Maurin, Moskalenko, MU in preparation
Summary

CR studies at SPS with NA61/SHINE:
- precise measurement of $\pi + C \rightarrow$ particle production in air showers
- nuclear fragmentation
  $\rightarrow$ particle production in Galaxy

Outlook

Upcoming Cosmic-Ray Possibilities:
- **2023** fragmented Pb beam? 
  production of GCR secondaries Li, Be, B
- **2024** primary/fragmented oxygen? 
  energy dependence, low-mass CR fragmentation
- **2025** high statistics p-p? 
  nucleon coalescence, anti-deuterons
- physics program after LS3 (> 2028)?
backup slides
Propagation of GCRs: High-Mass Nuclei

Particle Data Group 2022

High-Mass Nuclei: Experimental Challenges

fragmented Pb beam

upstream isotope identification (∼240 m ToF)

- pilot run at 14 AGeV/c: $\sigma$(ToF) ~ 30 ps
- $\Delta t$($^{12}$C − $^{13}$C) = 300 ps
- $\Delta t$($^{56}$Fe − $^{57}$Fe) = 75 ps

→ high-mass group can saturate DAQ

→ difficult, but feasible
Model Predictions: Heavy Nuclei

**Naive superposition:**
mean: \( \mu_X(A, E) = \mu_X(p, E/A) \)
fluctuations: \( \sigma_X(A) = \frac{1}{\sqrt{A}} \sigma_X(p) \)

**Nuclear cross sections and fragmentation:**
mean: \( \mu_X(A, E) \approx \mu_X(p, E/A) \) (!)
fluctuations: \( \sigma_X(A) \ll \frac{1}{\sqrt{A}} \sigma_X(p) \)

**Extreme cases:**
- spectator nucleons: \( s_X(A) \)
- single spectator nucleus: \( S_X(A) \)

![Diagram showing nuclear fragmentation in air showers](image)

**Image Caption:**
- RMS(\(X_{max}\)) = 29 g/cm\(^2\)
- 21 g/cm\(^2\)
- 16 g/cm\(^2\)

**Text:**
Nuclear fragmentation is important for quantitative predictions

*Engel&Pierog ISVHECRI 2010*