Recent results from NA61/SHINE

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NA61/SHINE – few facts

- Located at the CERN SPS
- Successor of NA49
- Large acceptance spectrometer for fixed target experiment on primary (ions) and secondary (ions, hadrons) beams
- Data taking since 2009
- NA61/SHINE is the second largest non-LHC experiment at CERN
Physics program

- **Strong interactions program**
  - search for the critical point of strongly interacting matter
  - study of the properties of the onset of deconfinement
  - study high $p_T$ particles production (energy dependence of nuclear modification factor)

- Hadron-production measurements for neutrino experiments
  - reference measurements of $p+C$ interactions for the T2K experiment for computing initial neutrino fluxes at J-PARC

- Hadron-production measurements for cosmic ray experiments
  - reference measurements of $p+C$, $p+p$, $\pi+C$, and $K+C$ interactions for cosmic-ray physics (Pierre-Auger and KASCADE experiments) for improving air shower simulations
NA61/SHINE 2D scan goals

Statistical Model of the Early Stage (SMES)

Facility
Available beams:

- Primary ions (13A - 158A GeV/c):
  - Argon
  - Xenon
  - Lead
- Secondary:
  - hadrons (p, π±, K±) 13 - 350 GeV/c
  - ions (Be, . . . ) 13A - 150A GeV/c

Secondary ion beam composition
(Pb fragmentation on Be target)
Experimental layout

Unique, multi-purpose facility to study hadron production in hadron-proton, hadron-nucleus and nucleus-nucleus collisions at the CERN SPS

Diagram showing the layout with various components labeled and connected by lines indicating their positions along the beam path.
Single particle spectra in p+p
Single particle spectra from p+p interactions
Rapid changes in \( p+p \) at SPS

\[ \frac{K^+}{\pi^+} \text{ ratio and inverse slop parameter of } m_T \text{ spectrum of } K^- \text{ exhibits rapid changes in the SPS energy range} \]
Rapid changes in $p+p$ at SPS – comparison with models

Monte-Carlo models provide poor description of data
NA61/SHINE results are consistent with world data

Other NA61/SHINE energies – work in progress
Single particle spectra in Be+Be
Centrality selection in ion collisions

- PSD (Projectile Spectator Detector) is located on the beam axis and measures the forward energy $E_F$ related to the non-interacting nucleons of the beam nucleus.
- Cuts on $E_F$ allows to select different centrality classes.
- Four event classes:
  - 0 - 5%
  - 5 - 10%
  - 10 - 15%
  - 15 - 25%
Inelastic $^7\text{Be}+^9\text{Be}$ cross section

- NA61 measurements together with 1A GeV/c Bevalac data established energy dependence of the inelastic cross section.
Rapidity distributions

![Graphs showing rapidity distributions for different energies and collision types.](image-url)
Asymmetry in $\pi^-$ distributions in $^7\text{Be}+^9\text{Be}$

- Fitted: double Gaussian function symmetrically displaced from mid-rapidity (both Gaussians have the same width, but they differ in amplitude)
- Asymmetry decreases from 0.86 (0-5%) to 0.97 (15-20%)
- Two opposite effects influence asymmetry of the spectra:
  - asymmetric system $^7\text{Be}$ projectile on $^9\text{Be}$ target (small effect),
  - centrality selection based on projectile spectators (large effect).
Mean multiplicities of $\pi^-$ in $^7$Be+$^9$Be

Transverse mass spectra of $\pi^-$

\[
\frac{d^2 n}{dydm_T} = A m_T \exp\left(\frac{-m_T}{T}\right)
\]

\[0.2 < m_T - m_\pi < 0.7 \text{ GeV/c}^2\]
Comparison of $\pi^-$ transverse mass spectra

- Ratio of normalized $m_T$ spectra at different energies allows to compare shape of the spectra

- From $m_T - m_{\pi^-} > 0.3$ GeV/c$^2$ the ratio increases with beam momentum
- Up to $m_T - m_{\pi^-} < 0.3$ GeV/c$^2$ the ratio decreases with beam momentum
- The beam momentum dependence of the ratio observed in $^{7}\text{Be} + ^{9}\text{Be}$ is not visible in Pb+Pb collisions
- The shape of the ratio indicates the presence of radial collective flow in $^{7}\text{Be} + ^{9}\text{Be}$
- The energy dependence of the ratio suggests that the radial flow increases with the collision energy
Collective effects

- Effect of radial flow for Pb+Pb at all energies
- Inverse slope parameter $T$ larger in $^7\text{Be} + ^9\text{Be}$ than in $p+p \rightarrow$ possible evidence of transverse collective flow in $^7\text{Be} + ^9\text{Be}$
Fluctuations and correlations
Theoretical fluctuations in presence of critical point

N-\(p_T\) fluctuations in p+p and centrality selected Be+Be

- No sign of any anomaly that can be attributed to the critical point (neither in p+p nor Be+Be)
Two-particle correlations in $\Delta \eta$, $\Delta \phi$ in p+p

- NA61/SHINE: maximum at $(\Delta \eta, \Delta \phi) = (0, \pi)$ probably due to resonance decays and momentum conservation
- NA61 results show stronger enhancement in $\Delta \phi \approx \pi$ and no “jet peak” at $\Delta \phi \approx 0$ (in comparison with ALICE)
Future of NA61/SHINE
Open charm measurements

D⁰ candidates selected by TPCs only

- Feasibility of the D⁰ meson measurements in two body decay channel: D⁰ \rightarrow K^+ + \pi^-, in central Pb+Pb collisions at the top SPS energy

- Simulation for 200k events (0.5 day of data taking)

- Vertex detector:
  - four pixel detection stations
  - MIMOSA-26AHR sensor

\[ \text{Graph showing the distribution of } M_{K\pi} \text{ in } \text{GeV} \]
Extension of the data taking plan
Summary

- NA61/SHINE measures collisions of hadrons and ions for three physics programs: strong interactions, neutrinos and cosmic ray studies in SPS energy range.
- High precision double–differential pion spectra were measured in p+p and $^7\text{Be}+^9\text{Be}$ collisions at 5 different energies.
- Rapid changes in particle production observed in p+p interactions at mid-SPS energy.
- Collective effects are observed in $^7\text{Be}+^9\text{Be}$ reactions.
- No sign of any anomaly that can be attributed to critical point in p+p and $^7\text{Be}+^9\text{Be}$ interactions.
The Collaboration

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THANK YOU

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Secondary beryllium beam

- Fragmentation target length optimized to maximize the production of the desired fragment
- Double magnetic spectrometer separates fragments according to the selected magnetic rigidity
- Possible to use degrader, Cu plate where ions lose energy according to the charge
NA61/SHINE Detector

- Large acceptance: 50%
- High momentum resolution:
  - $\sigma(p)/p^2 \approx 10^{-4} \text{ (GeV/c)}^{-1}$ (at full $B=9 \text{T m}$)
- ToF walls resolution:
  - ToF-L/R: $\sigma(t) \approx 60\text{ps}$; ToF-F: $\sigma(t) \approx 120\text{ps}$
- Good particle identification:
  - $\sigma(dE/dx)/<dE/dx> \approx 0.04$; $\sigma(m_{\text{inv}}) \approx 5\text{MeV}$
- High detector efficiency: 95%
- Event recording rate: 70 events/sec

$^7\text{Be}+^9\text{Be}@158\text{A GeV/c}$
Energy loss ($dE/dx$) method

- In each $p$, $p_T$ bin sum of Gauss functions is fitted to the $dE/dx$ spectrum.
- For each track the probability for being a hadron of specific type is calculated based on the fitted $dE/dx$ distribution.
- Sum of these probabilities gives the mean multiplicity of the identified hadrons.
Energy loss (dE/dx) vs time of flight (tof) method

- Fit a two-dimensional weighted Gaussian function in the mass$^2$ vs dE/dx plane
V₀ – method

- Method example
  - Decay channel: \( \Lambda \rightarrow p + \pi^- \)
  - Invariant mass histograms in \( p_T \) and \( y \) bins
  - In each \( p, p_T \) bin sum of signal (i.e. Lorentzian) and background functions is fitted to the invariant mass spectrum

Lifetime is calculated based on the difference between position of the main and the decay vertex

\( \Lambda \) mass from PDG 1115.678\( \pm 0.006 \pm 0.006 \) GeV/c²

Results are consistent with PDG value (\( c\tau_\Lambda = 7.89 \) cm)
Majority (more than 90%) of negatively charged particles are $\pi^-$ mesons.

The small contribution of other particles ($K^-$, $\bar{p}$, and decays from $\Lambda$ and $K^0_S$) is subtracted based on data and model predictions.
Precise measurements ($\pi^-$ meson)

$p+p$ collisions

$^7\text{Be}+^9\text{Be}$ collisions
The T2K experiment published a measurement of $\theta_{13}$ angle in the neutrino mixing matrix (PRL 107, 041801 (2011))

Systematic error estimate was based on the NA61/SHINE results
Hadron-production measurements for neutrino experiments

High statistics 2009 p+C at 31GeV/c “thin-target” dataset

\[ s_{\text{inel}} = 261.3 \pm 2.8(\text{stat}) \pm 2.4(\text{det}) \pm 0.3(\text{mod}) \text{ mb} \]

\[ s_{\text{prod}} = 233.5 \pm 2.8(\text{stat}) \pm 2.4(\text{det}) \pm 3.6(\text{mod}) \text{ mb} \]
Extension of the neutrino program by measurements for FERMILAB experiments

- Six US-NA61
- Measurements with NuMi and LBNE replica target

<table>
<thead>
<tr>
<th>Target</th>
<th>Inc. proton/pion beam momentum</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>120 GeV/c</td>
</tr>
<tr>
<td>NuMI (spare) replica</td>
<td>(future)</td>
</tr>
<tr>
<td>LBNE replica</td>
<td>(future)</td>
</tr>
<tr>
<td>thin graphite (&lt; 0.05λ₁)</td>
<td>(future)</td>
</tr>
<tr>
<td>thin aluminum (&lt; 0.05λ₁)</td>
<td>3M</td>
</tr>
<tr>
<td>thin iron (&lt; 0.05λ₁)</td>
<td>(future)</td>
</tr>
<tr>
<td>thin beryllium (&lt; 0.05λ₁)</td>
<td>(future)</td>
</tr>
</tbody>
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Hadron-production measurements for cosmic ray experiments

Cosmic ray composition of central importance for understanding sources, kink, ankle...

Modern detector installations: high statistics/quality data

Indirect measurement (extensive air showers): simulations needed

Strong model dependence: due mainly to simulation of m production

m production related to hadronic interactions at fixed-target energies
Hadron-production measurements for cosmic ray experiments

Cross sections measurements

Input for validation/tuning of Monte Carlo generators