The main part of this contribution is devoted to looking at the NA61/SHINE experiment through the prism of the needs of neutrino oscillation experiments. An overview is shown of the results on hadron production measurements from p+C interactions at 31 GeV/c registered during 2007. In addition, the new preliminary results from 2009 data are presented.
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Outline

• **Physics Program**
  ◦ Physics of strongly interacting matter
  ◦ Data for Neutrino and cosmic ray experiments

• **NA61/SHINE detector**

• **Particle Identification**

• **Selected results** from 2007 and 2009 runs

• **Status and plans**
Physics Program (I)

Search for the critical point of strongly interacting matter

Precision measurements:
Study properties of the onset of deconfinement

= $2 \cdot 10^6$ registered collisions
Physics Program (II)
Accelerator long baseline oscillation neutrino experiments

- Tokai to Kamioka

Main aims of T2K:
- Search for and measurement of the $\nu_\mu \rightarrow \nu_e$ appearance
  » improved sensitivity to the so far unknown mixing angle $\theta_{13}$
- Refinement of $\nu_\mu$ disappearance measurements
  » improved determination of $\theta_{23}$ and $\Delta m^2_{23}$

Both analysis rely on the $\nu$ spectra measured at SK and the predicted spectra at SK:

$$\Phi_{\nu}^{\text{ND}} \xrightarrow{\text{Extrapolation}} \Phi_{\nu}^{\text{SK(expected)}}$$

Comparison $\rightarrow$ $\nu$ oscillation parameters

$$\Phi_{\nu}^{\text{SK}}(E_\nu) = R_{\mu,e}(E_\nu) \times \Phi_{\mu,e}^{\text{ND}}(E_\nu)$$

Measured at ND

$$R_{F/N}(E_\nu) = \frac{\Phi_{\text{SK}}^{\text{exp}}(E_\nu)}{\Phi_{\text{ND}}^{\text{exp}}(E_\nu)} \quad \text{hadron production distributions}$$

v beam

295 km

Far-to-Near ratio

$\Phi^{\text{ND obs.}}(E_\nu) \times R_{F/N}(E_\nu) \rightarrow \Phi^{\text{SK exp.}}(E_\nu)$

$N_{\nu}^{\text{SK, exp.}}$
Physics Program (II)
Accelerator long baseline oscillation neutrino experiments

Uncertainty on the neutrino flux is a dominant contribution to systematic errors of $\nu$ oscillation parameters measurement: 10 – 20 %

Uncertainty on hadronic interactions is dominant contribution to the flux uncertainty
Physics Program (II)

Accelerator long baseline oscillation neutrino experiments

- It is of importance to measure charged pions and kaons, neutral kaons, and lambda hyperons because these particles contribute directly or via decays to the neutrino production.

\[ \nu_\mu \text{ (left) and } \nu_e \text{ (right) energy spectrum at T2K far detector. JNUBEAM simulations.} \]
Physics Program (III)
Other applications

- Cosmic ray physics
  - Transition between low- and high-energy models
  - Need phenomenological calibration

- Neutrino Factory

- MC Generators
Two types of measurements were done for T2K: 31GeV/c protons on Carbon:

1). Thin target (4% λint)- studies of primary interactions
2). Replica of the T2K target (1.9λint)- production of all hadrons along the target

<table>
<thead>
<tr>
<th>Year</th>
<th>Thin target</th>
<th>T2K Replica</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>6.3 * 10^5</td>
<td>2.3 * 10^5</td>
<td>Published</td>
</tr>
<tr>
<td>2009</td>
<td>4.4 * 10^6</td>
<td>2.4 * 10^6</td>
<td>Being analyzed</td>
</tr>
<tr>
<td>2010</td>
<td>10 * 10^6</td>
<td>10 * 10^6</td>
<td>Under Calibration</td>
</tr>
</tbody>
</table>
Particle Identification (I)

Analysis of negatively charged particles (h-analysis)

- Possible without PID because most of produced negatively charged particles at 30GeV proton carbon interactions are PI-
Particle Identification (II)
dE/dx at low momentum (below ~1GeV/c)

For region $p = [1, 4]$GeV/c Bethe Bloch curves crosses each other making particle separation not reliable $\rightarrow$ additional information from ToF
Particle Identification (III)

Combined energy loss and Time of Flight (ToF) measurements

\[ m^2 = p^2 \left[ \frac{c^2 t^2}{l^2} - 1 \right] \]

Particle momentum \( p \) and track length \( l \) are precisely measured in the TPCs. Tracks are then extrapolated to the ToF and associated to a scintillator which gives a value for \( t \).
Particle Identification (III)

$K_S^0$ and $\Lambda$ particle identification through the study of the invariant mass distributions

\[
K_S^0 \rightarrow \pi^+ + \pi^-, \quad \Lambda \rightarrow p + \pi^-
\]

• **Selected results**

• π⁺ multiplicities in p+C at 31 GeV/c from dE/dx +ToF analysis from 2009 data compared to 2007 results

• Total error plotted

• Improved statistical precision with 2009 data
Selected results
Selected results

K−

K+

Graphs showing distributions for different ranges of θ and p [GeV/c].
Selected results

\[ \Lambda \quad K^0_S \]
Selected results

proton
Impact of the NA61/SHINE

(Phys.Rev. D87, 012001, 2013)

Used $\pi^\pm$, $K^+$ measurements from 2007 run of NA61

peak at $E_\nu \sim 0.6$GeV
• **NA61/SHINE** is a large acceptance hadron spectrometer at the CERN SPS which precisely measures the particle production needed for T2K experiment and cosmic ray experiments
  - Thin target: for the determination of inclusive cross sections
  - T2K replica target: for the study of secondary interactions in the T2K target

New NA61 results based on data 2009. Precision improved by a factor 2-3 as compared to the pilot data 2007 (used so far by T2K)

**NA61 will study properties of the transition between hadron gas and quark-gluon plasma in order to establish fundamental features of strongly interacting matter**