Pion Hadron Production in NA61

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NA61 Physics Program

Physics of strongly interacting matter in heavy ion collisions
Search of the QCD critical point (AA and pA collisions)

Hadron production measurements on the T2K target (p+C) to characterize the T2K neutrino beam soon also measurements for NuMI

Measurement of hadron production in p+C interactions needed for the description of cosmic-ray air showers (Pierre Auger Observatory and KASCADE experiments)
NA61/SHINE – unique multipurpose facility:

hadron production in $h + p$ (20 – 350 GeV/c), [$h = p, \pi^+, \pi^-$]
h + A (20 – 350 GeV/c), [$A = \text{Be}, \text{C}, \text{Al}, \text{Fe}, \text{Pb}, \ldots$]
A + A (13A - 150A GeV/c)
The NA61 Detector

large acceptance spectrometer for charged particles

4 large volume TPCs as main tracking devices

2 dipole magnets with bending power of max 9 Tm over 7 m length (T2K runs: \( \int Bdl \approx 1.14 \text{Tm} \))

high momentum resolution

good particle identification: \( \sigma(\text{ToF-L/R}) \approx 100 \text{ ps} \), \( \sigma(dE/dx)/<dE/dx> \approx 0.04 \), \( \sigma(m_{\text{inv}}) \approx 5 \text{ MeV} \)

new ToF-F to entirely cover T2K acceptance (\( \sigma(\text{ToF-F}) \approx 100 \text{ ps} \), \( 1 < p < 5 \text{ GeV/c} \), \( \theta < 250 \text{ mrad} \))

several additional upgrades are under way
Particle Identification in NA61

Energy loss in TPCs

Time of Flight measurements

Combined ToF + dE/dx

$dE/dx$

$m^2$

$2 < p \ [GeV/c] < 3$
The Off-Axis T2K $\nu$ Beam

2.5° off-axis neutrino beam

- Neutrino beam energy “tuned” to oscillation maximum
- Very narrow energy spectrum (narrow band)
- Neutrino beam energy almost independent of parent pion energy

Neutrino source created by interactions of 30 GeV protons on a 90 cm long graphite rod

Neutrino beam predictions rely on modeling the proton interactions and hadron production in the target

Horn focusing cancels partially the $p_T$ dependence of the parent pion

Precise hadron production measurements allow to reduce uncertainties on neutrino flux prediction
Required Acceptance for $\nu$ Flux Calculations

T2K $\nu$ parent hadron phase space
30 GeV proton beam on the 90 cm long T2K graphite target

$\pi^+$, $K^+$, and $p$ distributions shown

- Note: this is not a cross section
- It shows the distributions of $\pi$, $K$, and contributing to the $\nu$ flux at SK

Need to cover this kinematical region and identify the outgoing hadrons
- $K$ component important for $\nu_e$ appearance signal

Requires detector with large acceptance
- With excellent particle ID capabilities
- With high rate capabilities to accumulate sufficient statistics
The NA61 Targets

2 different graphite (carbon) targets

Thin Carbon Target
- length=2 cm, cross section 2.5 x 2.5 cm²
- $\rho = 1.84$ g/cm³
- $\sim 0.04 \lambda_{\text{int}}$

T2K Replica Target
- length = 90 cm, Ø=2.6 cm
- $\rho = 1.83$ g/cm³
- $\sim 1.9 \lambda_{\text{int}}$

2007 pilot run
Thin target: ~660k triggers
(⇒ 200 k $\pi^+$ tracks in T2K acc.)

2009 run
Replica target: ~230k triggers
~6 M triggers

2010 run
~2 M triggers
~10 M triggers
Analysis Methods

Different analysis procedures adopted depending on the kinematical region covered:

1) negative hadrons: at this beam energy (31 GeV/c) most (> 90%) negative hadrons are $\pi^-$ with small $K^-$ contamination (< 5%) pure tracking with no PID, large acceptance, global MC correction

2) $p < 1$ GeV/c PID based on $dE/dx$ only (below cross-over region in $dE/dx$)

3) $p > 0.8$ GeV/c PID combined ToF – $dE/dx$ analysis ($\pi / K / p$ separation) particles must reach the ToF, reduced acc.; factorize all corrections (i.e. acc., recon. eff., decays, etc.), some corrections estimated directly from data, rely less on MC

raw measured particle spectra corrected for:
  geometrical acceptance
  reconstruction efficiency
  non-pion contributions
  weak decays (feed-down)
  trigger bias
NA61 $p + C \rightarrow \pi^{+/−} + X @ 31 \text{ GeV/c}$

Relative uncertainty in the T2K region $\sim 4\%$
NA61 p + C → K^{+/-} + X @ 31 GeV/c

Relative uncertainty in the T2K region ~ 15%
NA61 p + C → p / Λ + X @ 31 GeV/c
NA61 $p + C \rightarrow \pi^+ + X$ Uncertainties (dN/dp)

Compared to 2007 data:
- statistical uncertainty improved by $\sim 3$
- systematical uncertainty reduced by $\sim 2$

NA61 preliminary
Already Published NA61 Data

Measurements of cross sections and charged pion spectra in proton-carbon interactions at 31 GeV/c

Measurement of production properties of positively charged kaons in proton-carbon interactions at 31 GeV/c

Pion emission from the T2K replica target: Method, results and application
Nucl. Inst. and Meth. A 701 (2013) 99–114

Measurement of negatively charged pion spectra in inelastic p+p interactions at $p_{\text{lab}} = 20, 31, 40, 80$ and 158 GeV/c

Measurements of production properties of $K^0_S$ mesons and hyperons in proton-carbon interactions at 31 GeV/c
$\pi^-$ Spectra in $p + p \rightarrow \pi^- + X$ Energy Scan

$p_{\text{lab}} = 20, 30, 40, 80, 158 \text{ GeV}/c$

$p + p$ symmetric in rapidity (and $x_F$) negative $y$ ($x_F$) by reflection

$(y = 0 \rightarrow x_F = 0)$
Transverse Mass Spectra at Mid-Rapidity

\[ p + p \rightarrow h + X @ 158 \text{ GeV/c} \]

transverse mass: \[ m_T^2 = m_0^2 + p_T^2 \]

mid-rapidity: \[ y = 0 \ (x_F = 0) \]

Transverse mass spectra are approximately exponential in \( p + p \) interactions

NA61, EPJC 74 (2014) 2794
$p + p \rightarrow h + X : \text{dn/dy (Energy Scan)}$

NA61 preliminary
π Multiplicities and $K/\pi$ Ratios

Fermi energy

$$F \equiv \left[ \frac{(\sqrt{s_{NN}} - 2m_N)^3}{\sqrt{s_{NN}}} \right]^{1/4}$$

NA61, EPJC 74 (2014) 2794

NA61 preliminary
Charged $\pi$ spectra in $\pi^- + C$ Interactions

$\pi^- + C \rightarrow \pi^+ + X$ @ 350 GeV/c

$\pi^- + C \rightarrow \pi^- + X$ @ 350 GeV/c
Some Observations

p + p and p + C data is unexpectedly interesting

None of the hadroproduction models describes satisfactorily ensemble of the p + C → h + X hadroproduction data

Models do not describe well the NA61/SHINE data on p + p interactions

High precision NA61/SHINE data presents a challenge for models and allow for significant improvement of models

Even in p + p the energy dependence of the K⁺/π⁺ ratio exhibits rapid changes in the SPS energy range

Soon p + C data at different energies (60 GeV/c, 120 GeV/c)
Also Be, Al, Pb

Soon comparison of p + p and p + A hadroproduction data
→ A dependence
→ energy dependence

Input to hadroproduction models → improvements?
Neutrino Source Production

**direct contribution:**
secondary hadrons exit the target
and decay into $\nu$

**target contribution:**
secondary and tertiary hadrons exiting
the target and decaying into $\nu$

**non-target contribution:**
re-interaction in the target surrounding material

We see only particles coming out of the target.
We do not see what happens inside the target.

\[ \nu_\mu \text{ composition at SK} \]
- 90 %
- 60 %

\[ \nu_e \text{ composition at SK} \]
- 90 %
- 60 %
Hadron multiplicities are measured at the target surface in bins of \(\{p, \theta, z\}\).

Tracks are extrapolated backwards to the target surface (point of closest approach).

The target is sliced in 5 bins in \(z\) + downstream exit face.

No interaction vertex reconstruction can study also as a function of \(r\).

Statistical precision \(\sim 5\%\).

Systematic error \(\sim 5\%\).
$\pi^+$ Spectra on Target Surface

beam

$\times 10^{-3}$

$\times 10^{-3}$

$\times 10^{-3}$

NA61 preliminary
Perform hadron production measurements to characterize the NuMI ν beam using the NA61 detector at CERN mainly US groups.

Data taking to start this fall.

<table>
<thead>
<tr>
<th>proton+pion event totals</th>
<th>Incident proton/pion beam momentum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target</td>
<td>120 GeV/c 60 GeV/c 30 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>3M 3M (T2K data)</td>
</tr>
<tr>
<td>thin aluminum (&lt; 0.05λ₁)</td>
<td>3M (future)</td>
</tr>
<tr>
<td>thin steel (&lt; 0.05λ₁)</td>
<td>(future) (future)</td>
</tr>
<tr>
<td>thin beryllium (&lt; 0.05λ₁)</td>
<td>3M 3M (future)</td>
</tr>
</tbody>
</table>

Upgrades:
- add forward tracking
- forward calorimetry (neutrons)
- new DAQ based on the DRS
- better trigger

2 new Forward TPCs
Conclusions

NA61 is providing valuable data to constrain the T2K neutrino flux

**NA61 initial goals for T2K:**
- 5% error on absolute neutrino fluxes
- 3% error on the far-to-near ratio

**Hadroproduction measurements require**
- large acceptance detectors with PID over whole kinematical range
- large statistics
- different targets to study various particle production effects

**Hadroproduction** of $\pi^{+/-}$, $K^{+/-}$, $p$, $K^0_s$, $\Lambda$ in $p + p$ and $p + C$ interactions at different energies

Soon also on Be, Al, and Pb targets
- comparison of $p + p$ and $p + A$ data
- $A$ dependence

**Hadroproduction measurements also with** $\pi$ beams

High precision NA61/SHINE data presents a challenge for hadroproduction models

NA61 to continue with hadron production measurements for NuMI, starting this fall