NACI/SHINE: LATEST RESULTS AND PERSPECTIVES

- FACILITY
- NEUTRINOS
- STRONG INTERACTIONS
- COSMIC-RAYS - NEXT TIME

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FRANKFURT, KIELCE

CERN
NA61/SHINE - Unique Multipurpose Facility: Hadron Production in h+p, h+A, A+A at 13A - 150A (400) GeV/c

- Acceleration Chain
- H2 Beamline
- Detector
ACCELERATION CHAIN

Beams of protons and nuclei (Ar, Xe, Pb) at 13A - 150A (400) GeV/c

2015: Ar beam in SPS

8.5 sec
NAGI/SHINE DETECTOR: PERFORMANCE

\( \sigma_{(+\pi)} \approx 100 \text{ ps} \)

\( \sigma(dE/dx) \approx 4\% \)

\( \sigma(p)/p^2 \approx 10^{-9} (\text{GeV/c})^{-1} \)

(Full Field)
**NAG1/SHINE DETECTOR : FINAL PRODUCTS**

**SINGLE PARTICLE 2D SPECTRA OF IDENTIFIED HADRONS**

**MULTI-DIMENSIONAL DISTRIBUTIONS OF EVENT PROPERTIES**

**Typical Variables:**
- \( y - p_T (s1) \)
- \( p - Q (v) \)

**Ar+Sc 150A GeV/c**
**NEUTRINOS**

**WHAT HAPPENS WITH NEUTRINOS FLYING ACROSS JAPAN AND UNITED STATES?**

- Oscillations: rotation of states during propagation

\[
|\nu(x_0)\rangle = |\nu_e\rangle = c|\nu_1\rangle + s|\nu_2\rangle
\]

One given flavour produced by weak interaction

\[
|\nu(x)\rangle = c|\nu_1\rangle e^{i(Et-k_1 x)} + s|\nu_2\rangle e^{i(Et-k_2 x)}
\]

Mass eigenstates propagate at different velocities

\[
P(\nu \rightarrow \nu_\mu) = |\langle \nu_\mu | \nu(t) \rangle|^2
\]

Weak interaction selects component of one flavour

*After J. Panman*
JAPAN:
THE T2K LONG-BASELINE NEUTRINO OSCILLATION EXPERIMENT

T2K PILLARS:
- LARGE AND WELL UNDERSTOOD FAR DETECTOR
- WELL DESIGNED BEAM
- NEAR DETECTOR AND NAGI/SHINE

AFTER A. BLONDEL
T2K ACHIEVEMENTS AND NA61/SHINE

DISCOVERY OF $\nu_\mu \rightarrow \nu_e$ APPEARANCE

$\nu_\mu$ DISAPPEARANCE

$\nu_\mu$ CROSS-SECTION

INITIAL NEUTRINO FLUX DETERMINATION:

NEAR DETECTOR
NA61/SHINE

NEAR DETECTOR
NA61/SHINE

NA61/SHINE
Indication of Electron Neutrino Appearance from an Accelerator-Produced Off-Axis Muon Neutrino Beam


We compute the neutrino beam fluxes (Fig. 1) starting from models and tuning them to experimental data. Pion production in (p, θ) bins is based on the NA61 measurements [21], typically with 5%-10% uncertainties. Pions produced outside the experimentally measured phase

FIG. 1. Predicted neutrino fluxes at the far detector, in absence of oscillations. The shaded boxes indicate the total systematic uncertainties for each energy bin.
NAGI/SHINE DATA FOR $\nu$ FLUX DETERMINATION

\[ P \text{ AT 31 GeV/c} \]

**LONG (90cm) CARBON TARGET**

60% OF NEUTRINOS FROM DECAYS OF HADRONS PRODUCED IN PRIMARY INTERACTIONS

60% OF NEUTRINOS FROM DECAYS OF HADRONS EMITTED FROM THE TARGET SURFACE

NACI: $p + C$ AT 31 GeV/c

NACI: $p + LT$ AT 31 GeV/c
PRECISE DATA FOR T2K

\[ p+C \rightarrow \pi^+ + X \]
\[ p+C \rightarrow \pi^- + X \]

\[ \frac{d\sigma}{dp \, d\Omega} \text{[mb/(GeV/c sr)]} \]

comparison to FLUKA2008

\[ p \text{ [GeV/c]} \]

\[ p \text{ [GeV/c]} \]

comparison to Gheisha2002

(GEANT3 MODEL)

AT 31 GeV/c
**Precise Data for T2K**

$p + C$ at 31 GeV/c

**Na61:**
- Phys.Rev. C84 (2011) 034604
- Phys.Rev. C89 (2014) 2, 025205
- CERN-SPSC-2014-031 ; SPSC-SR-145
PRECISE DATA FOR T2K

\( p^+ (\text{LONG TARGET}) \) AT 31 GeV/c

\( p \) AT 31 GeV/c

CERN-SPSC-2014-031 ; SPSC-SR-145

PRELIMINARY
The next step: Measurements for Fermilab V beams

Fermilab Neutrino Program

- Booster Neutrino Beam (BNB)
  - 8 GeV Protons
  - Previously MiniBoone, SciBooNE
  - MicroBooNE
  - ICARUS in the future
- Neutrinos at the Main Injector (NuMI)
  - 120 GeV protons, currently ~500 kW
    - MINOS+
    - MINERvA
    - NOvA (off-axis)
- New High Intensity Beamline (proposed)

Input from NA61/SHINE expected

After A. Marino
The next step: Measurements for FERMILAB ν beams

Addendum to the T2K/Shine proposal October 2014 recommended by SPSC, approved by RB

Groups from US in T2K/Shine: Colorado, FERMILAB, Los Alamos, Pittsburgh

Ultimate goal: Dedicated measurements for

Experiment at the Long-Baseline Neutrino Facility

Sanford Lab
Lead, South Dakota

Fermilab
Batavia, Illinois

Sanford Lab
South Dakota (Proposed)

DUNE
POSSIBLE FUTURE: MEASUREMENTS FOR HYPER-K

Hyper-K Overview

- Total Volume: 0.99 Megaton
- Inner Volume: 0.74 Mton
- Fiducial Volume: 0.56 Mton (0.056 Mton x 10 compartments)
- Outer Volume: 0.2 Megaton
- Photo-sensors: 99,000 20° PMTs for Inner Det.
- Photo-coverage: (20%) and 25,000 8° PMTs for Outer Det.

Uncertainty on the expected number of events at Hyper-K (%):

<table>
<thead>
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<th></th>
<th>Ve</th>
<th>Vμ</th>
<th>anti-Ve</th>
<th>anti-Vμ</th>
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<tr>
<td>Flux&amp;ND</td>
<td>3.0</td>
<td>2.8</td>
<td>5.6</td>
<td>4.2</td>
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<tr>
<td>XSEC model</td>
<td>1.2</td>
<td>1.5</td>
<td>2.0</td>
<td>1.4</td>
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<tr>
<td>Far Det. +FSI</td>
<td>0.7</td>
<td>1.0</td>
<td>1.7</td>
<td>1.1</td>
</tr>
<tr>
<td>Total</td>
<td>3.3</td>
<td>3.3</td>
<td>6.2</td>
<td>4.5</td>
</tr>
</tbody>
</table>

(T2K 2014)

- Ve: 3.1, 2.7
- Vμ: 4.7, 5.0
- anti-Ve: 3.7, 5.0
- anti-Vμ: 6.8, 7.6

×25 of Super-K

This is why we are here!

CP-violation, mass hierarchy, proton decay, supernovae neutrinos; etc...
Top of the list in Japan science projects (with ILC)


Alain Blondel
CHIPP
2014Mar07
f) Rapid progress in neutrino oscillation physics, with significant European involvement, has established a strong scientific case for a long-baseline neutrino programme exploring CP violation and the mass hierarchy in the neutrino sector.

CERN should develop a neutrino programme to pave the way for a substantial European role in future long-baseline experiments.

Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan.

To succeed we need to proceed in steps

NACI/SHINE is the unique experiment for hadron production measurements for neutrino beams in Japan and US
**STRONG INTERACTIONS**

What happens when strongly interacting matter gets hotter/denser and its volume increases?

**Phase Diagram of Water**

**Heating Curve of Water**

- Heat used to vaporize water to water vapor
- Heating of water
- Heating of water vapor

[Diagram showing the phase transitions and heating curve of water]
ONSET OF DECONFINEMENT

THE NA49 OBSERVATION OF RAPID CHANGES IN COLLISION ENERGY DEPENDENCE OF HADRON PRODUCTION PROPERTIES

→ NA49/SHINE (COLLISION ENERGY) - (NUCLEAR MASS) SCAN

![Diagram showing the onset of deconfinement with NA49/SHINE data for different system sizes and beam momenta.](image-url)
ENERGY DEPENDENCE IN $p+p$

$p+p \rightarrow K^+ + X$
$0.0 < y < 0.2$

$$\frac{1}{p_T} \frac{dN}{dp_T} = \frac{1}{m_T} \frac{dN}{dm_T} \sim e^{-m_T/T}$$

($m_T = \sqrt{m_0^2 + p_T^2}$)

$T$ - INVERSE SLOPE OF $m_T$ SPECTRA
EVIDENCE FOR RAPID CHANGES IN \( p+p \) AT SPS

ONSET OF DECONFINEMENT IN Pb+Pb

ONSET OF DECONFINEMENT IN \( p+p \) ?

CERN-SPSC-2014-031; SPSC-SR-145
EVIDENCE FOR RAPID CHANGES IN $p+p$ AT SPS

COMPARISON WITH STRING-RESONANCE MODELS

In general poor fit of string-resonance models

arXiv:1502.07916
EVIDENCE FOR RAPID CHANGES IN $p+p$ AT SPS

EXPECTATIONS FOR THE ONSET OF DECONFINEMENT

$\frac{n_s}{s}$ vs $\sqrt{s_{NN}}$ (GeV)

$K^+/\pi^+$ at $y=0$

arXiv:1502.05650
SEARCH FOR THE CRITICAL POINT

Onset of Deconfinement:
early stage hits transition line

Critical Point:
freeze-out close to critical point
and system large enough
SEARCH FOR THE CRITICAL POINT

HILL OF FLUCTUATIONS

STATUS OF THE NA61/SHINE SEARCH

arXiv:1503.01619
SEARCH FOR THE CRITICAL POINT

CENTRALITY SELECTION OF A+A COLLISIONS

PSD CALORIMETER

\[ E_F \]

![Graphs showing centrality selection and energy distribution.](image-url)
SEARCH FOR THE CRITICAL POINT

STRONGLY INTENSIVE QUANTITIES

Σ AND Δ STRONGLY INTENSIVE QUANTITIES FOR FLUCTUATIONS

N - EVENT MULTIPLICITY

\( P_T = \Sigma |P_T^i| \) - EVENT TRANSVERSE MOMENTUM


arXiv:1503.01619
SEARCH FOR THE CRITICAL POINT

SOON RESULTS FROM Ar+Sc ENERGY SCAN COMPLETED IN FEBRUARY-APRIL 2015

NAGI/SHINE IS THE ONLY EXPERIMENT RUNNING 2D SCAN IN (COLLISION ENERGY)-(NUCLEAR MASS)
PLANS ON Pb+Pb ENERGY SCAN
WITH VERTEX DETECTOR FOR OPEN CHARM
SUMMARY

NA61/SHINE FACILITY:
UNIQUE MULTI-PURPOSE FACILITY FOR MEASUREMENTS
OF HADRON PRODUCTION IN h+p, h+A AND
A+A COLLISIONS AT 13A - 150A (350) GeV/c
**SUMMARY**

**Neutrinos:**
- Measurements for T2K are completed
- Measurements for Fermilab are starting
- Measurements for Hyper-K under discussion

**Strong Interactions:**
- Data taking for \( \sqrt{s} \) - a scan is well advanced
- Observation of rapid changes of hadron production properties in \( p+p \) at SPS
  (onset of deconfinement vs. resonance vs. string)
- No CP signal in \( p+p, B^0+\overline{B}^0 \); waiting for \( A^0+\overline{A}^0 \)
- Planned \( \sqrt{s} \) scan with \( Pb+Pb \) after construction of Vertex Detector

**Cosmic Rays:**
- Measurements for high- and ultra-high-energy cosmic rays: Pierre Auger Observatory, Telescope Array, KASCADE, ICETOP
MANY THANKS TO CERN FOR HOSTING AND SUPPORTING NA61/SHINE
Cosmic Rays

What is origin of very high energy cosmic rays?

Measuring cosmic-ray composition

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

Modern detector installations: high-statistics/quality data

Indirect measurement (extensive air showers): simulations needed

Strong model dependence: due mainly to simulation of muon production

Muon production related to hadronic interactions at fixed-target energies

Pierre Auger Observatory

The NAGI data are used to fit models relevant for simulations of extensive air showers
Production cross section for $\pi^- + C$ interactions

$\sigma_{\text{prod}}$ [mb]

- Red circles: NA61 preliminary
- Open circles: SELEX 2000
- Black dots: Schiz et al. 1980
- Dashed line: Glauber ($\lambda = 0.5$)
- Dotted line: Glauber ($\lambda = 0.6$)

NA61 significantly improves precision of the world data
CHARGED HADRON SPECTRA IN $\pi^- + C$ AT 350 GeV/c

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

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

$p = 0.6 \ldots 121$ GeV/c in steps of $\log p/(\text{GeV/c}) = 0.08$
CHARGED HADRONS IN $\pi^- + C$ AT 158 AND 350 GeV/c

(NA61 DATA)/EPQ5

NA61 DATA ARE USED FOR FITTING MODELS RELEVANT FOR SIMULATIONS OF EXTENSIVE AIR SHOWERS
Fitting Templates - Data

\[ p_{\text{beam}} = 158 \text{ GeV/c, } 0.5 < x_F < 0.6 \]

Production of leading \( \phi \) mesons is important for EAS simulations.

- EPOS templates
NAGI/SHINE DETECTOR: FINAL PRODUCTS

EFFICIENCY

RESOLUTION
ENERGY DEPENDENCE IN \( p+p \)
ENERGY DEPENDENCE IN p+p

Good agreement with NA49 at 158 GeV/c
ENERGY DEPENDENCE IN $p+p$

AGREEMENT BETWEEN NA61 RESULTS FROM DIFFERENT METHODS
Be+Be COLLISIONS

\[ \sigma_{\text{inel}} \] vs.\[ p [A \text{ GeV/c}] \]

- Be+Be, SPS (NA61/SHINE)
- Be+Be, BEVALAC
- \( g^{\text{tot}}(p+p) \times 10 \), PDG

NA61/SHINE preliminary
Be + Be COLLISIONS
SINGLE PARTICLE SPECTRA
ONSET OF DECONFINEMENT: "MAXIMUM" BARYON DENSITY

**Repulsive on**

\( R = 1 \text{ fm} \)

**PRC 88, 024902**

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**Repulsive off**

\( R = 0 \text{ fm} \)

POINT-LIKE HADRONS/NUCLEONS!

**PRC C74 047901**

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RESULTS DEPEND STRONGLY ON MODELLING OF REPULSIVE INTERACTIONS.

MAXIMUM OF \( 8 \) \text{ fm} \text{ at} 30A GeV FOR UNREALISTIC MODEL WITH NO REPULSIVE INTERACTIONS.
Onset of Deconfinement: Hadron Gas Model: Fit vs Explanation

Student correctly attributed collision energies to data points

Student incorrectly attributed collision energies to data points

In both cases hadron gas model equally well fits the data

⇒ Hadron gas model (approximately) fits measured energy dependence, it does not explain it.