Hadroproduction Experiments To Constrain Accelerator-Based Neutrino Fluxes

Laura Zambelli (LAPP - CNRS/IN2P3)

Phys. Rev. Lett. 30 335 (1973)

Outline:
- Need for hadroproduction experiments
- Several strategies for neutrino flux prediction
- Results!

Neutrino 2016 conference — July 6th 2016 — London
How to make a $\nu$ flux from accelerator

~ A general recipe ~

accelerator $\rightarrow$ Absorb everything apart neutrinos $\rightarrow$ detector(s)

<table>
<thead>
<tr>
<th>P</th>
<th>h$^+$</th>
<th>$\nu$</th>
<th>h$^-$</th>
<th>beam absorber</th>
</tr>
</thead>
<tbody>
<tr>
<td>target</td>
<td>focussing system</td>
<td>decay volume</td>
<td>Select and focus $\nu$ parents</td>
<td></td>
</tr>
<tr>
<td>Produce $\nu$ parents from p-N inelastic interactions</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

Precise flux predictions mandatory for cross section measurement and oscillation results!
Need for hadroproduction experiments

Ingredients needed to predict a $\nu$-flux:

- An accurate modeling of the secondary beamline
- Measure & reproduce the proton beam profile
- A knowledge of the hadrons produced and escaping the target

- External measurements needed to understand the yields of $\nu$-parents at the target level

hadronic interactions is the dominant contribution to the flux uncertainty
Need for hadroproduction experiments

Several dedicated hadroproduction measurement for neutrino experiments:

- HARP for K2K, {mini-, sci-, micro-}BooNE
- NA49, MIPP for NuMI {MINOS, MINERvA, NOvA}
- NA61/SHINE for T2K, NuMI {MINOS+, MINERvA, NOvA}, DUNE, HK

Results from single arm spectrometer experiment are also used

\[(p-\theta) \text{ or } (x_F-p_T)\] phase space of \(\pi^+\) producing a \(\nu_{\mu}\) compared to the hadroproduction experiment coverage:

- in T2K far detector
- in MINERvA
- in MiniBooNE

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**Figure:**

- HARP coverage
- NA49 coverage
- Focusing peak
- High energy tail

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**Equation:**

\[x_F = \frac{p^*_L}{p^*_L(\text{max})}\]
Two types of datasets: thin and thick targets

$\nu_\mu$ at T2K far detector (v-mode)

$\nu_e$ at T2K far detector (v-mode)

In T2K, at the peak energy:

60% of $\nu_\mu$ and $\nu_e$ originate from the decay of hadrons produced by the primary interaction

→ Thin target data to study the primary $p-N$ interaction and measure interaction cross section

90% of $\nu_\mu$ and $\nu_e$ originate from the decay of hadrons produced in the target

→ Thick target to measure hadrons escaping the target
Several $\nu$-tuning strategies

Using thin target datasets
Correct the multiplicity and interaction cross section for each inelastic interaction leading to the production of $\nu$ parent
→ Scalings needed to account for eventual lack of data (e.g. re-interactions in the target)
→ Can therefore use many datasets

Using thick target dataset
Correct the multiplicity of hadrons ($\pi^\pm$) at the surface of the target
→ Need a dedicated dataset with a replica of the $\nu$ beamline target

Using in-situ measurements
Low-$\nu$ technique
The differential $\nu$-CC interaction at low nucleon recoil energy ($\nu$) is almost constant; therefore its measurement approximates the flux shape.

$\nu$-e scattering constrain
$\nu e \rightarrow \nu e$ cross section is very well predicted by the standard model and can help to constrain the flux prediction

muon monitor, multi-beam fit, …
Several $\nu$-tuning strategies

**Using thin target datasets**
Correct the multiplicity and interaction cross section for each inelastic interaction leading to the production of $\nu$ parent

$\rightarrow$ Scalings needed to account for eventual lack of data (e.g. re-interactions in the target)

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**Using thick target dataset**
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**Using in-situ measurements**

**Low-$\nu$ technique**
The differential $\nu$-CC interaction at low nucleon recoil energy ($\nu$) is almost constant; therefore its measurement approximates the flux shape.

$\frac{d\sigma}{d\nu} = A \left( 1 + \frac{B}{A \ E_\nu} - \frac{C}{A \ E_\nu^2} \right)$

$A, B, C$ : integral over structure functions

$\nu$ : recoil energy, $E_\nu$ neutrino energy

**$\nu$-e scattering constrain**
$\nu e \rightarrow \nu e$ cross section is very well predicted by the standard model and can help to constrain the flux prediction

muon monitor, multi-beam fit, …

*See Laura Field talk on MINERvA results [5/7/16]*
HARP and MIPP experiments

**HARP at CERN**

NIM A571 (2007) 524

300 settings for K2K and MiniBooNE

→ 17 published papers ([list](#))

**MIPP at FERMILAB**

p+NuMI target $[120 \text{ GeV}] \rightarrow \pi^\pm + X$

for NuMI experiments

$p$-Be $[8.89 \text{ GeV/c}] \rightarrow \pi^+ + X$

**π+ yields off NuMI target**


L. Zambelli - Neutrino 16 - Hadroproduction for $\nu$ flux
NA61/SHINE experiment

Large acceptance spectrometer at CERN SPS (successor of NA49)

JINST 9 P06005 (2014)

NA61/SHINE data taking for T2K:

<table>
<thead>
<tr>
<th>Target</th>
<th>Year</th>
<th>Stat ($\times 10^6$)</th>
<th>NA61/SHINE status</th>
<th>T2K status</th>
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</thead>
<tbody>
<tr>
<td>Thin [C, 4% $\lambda_f$]</td>
<td>2007</td>
<td>0.7</td>
<td>published: $\pi^\pm[1]$, $K^+$[2], $K_S^0$, $\Lambda[3]$</td>
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<td></td>
<td>2009</td>
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<td></td>
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<td>published: $\pi^\pm[5]$</td>
<td>method developed</td>
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<tr>
<td>Thick [T2K replica]</td>
<td>2009</td>
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<td>submitted: $\pi^\pm[6]$</td>
<td>analysis ongoing</td>
</tr>
<tr>
<td></td>
<td>2010</td>
<td>$\sim 10$</td>
<td>analysis ongoing</td>
<td>-</td>
</tr>
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</table>

NA61/SHINE particle identification

**Charged hadrons**

*ToF-dE/dx analysis*: Combines informations from time of flight \([m^2]\) and energy loss \([dE/dx]\) to identify \(\pi^\pm, K^\pm,\) proton for \(p > 1\) GeV/c.

\(dE/dx\) only is used for hadrons with \(p < 1\) GeV/c.

\(h^-\): consider all negative tracks as \(\pi^-

**Strange neutral hadrons ‘\(\nu^0\)’**

Invariant mass fit of 2 tracks of opposite charge having a vertex after the target
NA61/SHINE thin target

2009 dataset has been analyzed
→ Measurement of $\pi^\pm$, $K^\pm$, $p$, $K^0_s$ and $\Lambda$
→ Factor 2-3 improvement w.r.t. to 2007 results

→ Uncertainty in T2K relevant kinematics
  ‣ around 5% for $\pi^\pm$
  ‣ around 15% for $K^\pm$
  ‣ around 15% for $K^0_s$ and $\Lambda$

NA61/SHINE data compared to models.
FTF_BIC and QGSP_BERT are Geant4 physics lists

Generally, none of the models are able to fully reproduce the data.
NA61/SHINE thin target

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See Magda Posiadala-Zezula poster on NA61/SHINE thin target results [P1.038]

NA61/SHINE data compared to models.
FTF_BIC and QGSP_BERT are Geant4 physics lists

Generally, none of the models are able to fully reproduce the data.
NA61/SHINE thick target results

Use a T2K replica target [graphite, 90 cm long, 2.6 cm diameter]

Measurement of $\pi^\pm$ corrected yields at the surface of the target in bins of $(Z, p, \theta)$

→ ToF-dE/dx analysis used
→ Backward extrapolation to the target is the main source of uncertainty
→ Total error from 4 to 14%

π⁺ yield at the surface of the target, $\theta$: 0-100 mrad
NA61/SHINE thick target results

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→ Backward extrapolation to the target is the main source of uncertainty
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See Laura Zambelli et al poster on NA61/SHINE replica target results [P1.043]
**ν-tuning using thin target datasets**

For each neutrino produced in the simulation, look back at its history chain and correct the MC prediction to data.

---

**If the interaction is directly covered by hadroproduction data:**

→ Tune the MC multiplicity according to data:

\[ w_{\text{mult}}(p, \theta) = \frac{\left[ \frac{dN}{dp}(p, \theta) \right]_{\text{data}}}{\left[ \frac{dN}{dp}(p, \theta) \right]_{\text{MC}}} \]  

[Corrects the amount of hadrons produced]

→ Tune the MC interaction cross section:

\[ w_{\text{int.}} = \frac{\sigma_{\text{data}}}{\sigma_{\text{MC}}} \times \exp(-\rho d(\sigma_{\text{data}} - \sigma_{\text{MC}})) \]  

[Corrects the amount of interactions]
ν-tuning using thin target datasets

If there is no direct hadroproduction data:

→ Scale available data in momentum using Feynman-scaling hypothesis

When expressed in $x_F$-$p_T$ kinematics, differential hadroproduction cross section becomes invariant


→ Scale available data in target

Target dependency of differential hadroproduction cross section is parametrized by a function expressed in $x_F$-$p_T$


→ Make an educated guess

E.g. $K^0_L$ yield can be expressed as a mixture of $K^\pm$

→ Trust the MC prediction

For each neutrino produced in the simulation, look back at its history chain and correct the MC prediction to data
Tuned fluxes and their uncertainties [thin]

T2K

- interaction length is the bigger source of error
- 9% uncertainty at the peak energy

MINERvA

- nucleon-A interactions not covered directly by data
- 7% uncertainty at the peak energy due to hadroproduction

L. Aliaga W&C seminar, PhD FERMILAB-THESIS-2016-07
arXiv:1607.00704v1
**ν-tuning using thick target dataset**

The hadron is a pion produced in the target.

→ Tune the MC yield at the surface of the target according to data:

\[
w_{\text{mult}}(z, p, \theta) = \frac{[dN/dp](z, p, \theta)]_{\text{data}}}{[dN/dp](z, p, \theta)]_{\text{MC}}}
\]

[Corrects the amount of hadrons produced in the target; interaction tuning is no longer needed]

Any other case

→ Apply the thin target tuning method

[Thin and thick target data are important]

An other way to use the thick target data is to directly tune the hadron interaction model (multiplicities, cross sections) using all available data. Then use the tuned model to generate the flux.

→ Model-dependent but general approach (e.g. can handle a change in target design)

For each neutrino produced in the simulation, look back at its history chain and correct the MC prediction to data (when possible)
**Tuned fluxes and their uncertainties [thick]**

**T2K**
- Very preliminary!
- Generally thin tuning predicts higher flux in the peak region
- 4% uncertainty at the peak energy due to NA61/SHINE data

**MINERvA**
- Thin tuning also predicts higher flux
- Thin and thick tuning aren’t compatible
- 5% uncertainty at the peak energy
- Low-ν technique favors Gen2-thin
Tuned fluxes and their uncertainties [thick]

**T2K**
- Very preliminary!
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See Michael Kordosky poster on MINERvA flux [P3.092]
Other sources of flux uncertainties

MINERvA uncertainties other than hadroproduction

Accurate modeling of the beamline
→ E.g. of the effect of 1 mm cooling water layer around the horn inner conductor in NuMI flux predictions

Measure & reproduce the proton beam profile and direction
→ 2nd biggest source of error in T2K (off peak)

T2K total flux uncertainty $\nu_\mu$ at the far detector ($\nu$-mode)

T2K total flux uncertainty $\bar{\nu}_\mu$ at the far detector ($\bar{\nu}$-mode)

‘Previous Error’ is when NA61/SHINE 2007 thin target data was used
Future experiments requirements

DUNE goal is 2% uncertainty on $\nu_e$ signal normalization from uncertainties in the flux by using near detector constraints and new hadroproduction data by NA61/SHINE.

Hyper-Kamiokande goal is to a 5% uncertainty on the expected number of appearance events. This is based on the experience of T2K analysis and prospects (near detector constraints and flux prediction improvements).

NA61/SHINE has an agreement with NuMI experiments to measure the hadron production from the following configurations in the 2016~2018 period:

- $p/\pi^+$ from 30 to 120 GeV/c on various thin target (graphite, aluminum, beryllium, …) and thick targets (NuMI replica, DUNE replica)

NA61/SHINE SPSC-SR-171
Conclusions, Prospects

‣ It's a longstanding issue!
‣ Many collaborations between hadroproduction and neutrino experiments in past, present and future
‣ It's a fruitful collaboration:
  • \(~25\%) flux error with no hadroproduction constraints
  • \(~10\%) flux error with thin target constraints
  • \(~7\%) flux error with thick target constraints
  • Below 5\% in the future?
‣ Hadroproduction measurements provides important inputs to improve the hadronic models
  ➔ Not only relevant for neutrino physics
‣ Precise hadron production measurement is long, difficult but also interesting and very important for modern neutrino physics

arXiv: 1404.2026
Study of the Reaction $\nu p \rightarrow \mu^-\pi^+p^+$


Argonne National Laboratory, Argonne, Illinois 60439

(Received 9 October 1972)

We present an analysis of 153 events of the reaction $\nu p \rightarrow \mu^-\pi^+p$ at an average neutrino energy of 1 GeV. The results were obtained using the Argonne 12-ft hydrogen bubble chamber. The reaction is dominated by $\mu^-\Delta^+(1236)$ production for which the total cross section rises from threshold to a value of $(0.74 \pm 0.18) \times 10^{-38}$ cm$^2$ at $E_\nu \gtrsim 1.0$ GeV. The production and decay angular distributions of the $\Delta^+$ are given. There is no evidence for hadron-lepton mass enhancements.

FIG. 3. (a) Calculated $\nu$ and $\bar{\nu}$ flux incident on the bubble chamber. (b) Number of events found for different $E_\nu$ values. No significant narrow peaks are evident. The four overflow events have $2.5 < E_\nu < 6$ GeV. (c) Total cross section for the reaction $\nu p \rightarrow \mu^-\Delta^+$ as a function of $E_\nu$. The last point is averaged between $E_\nu = 5.5$ GeV and $E_\nu = 6$ GeV. The errors do not include the flux uncertainty as explained in the text. The theory curves are evaluated with $M_{\Delta} = 0.74$ and 0.94 GeV. (d) Four-momentum-transfer distribution $q^2$ between $\nu$ and $\mu^-$. 

"FIG.

L. ZAMBELLI - NEUTRINO 16 - HADRONS"
Extending thin target kinematical coverage

Data can be extrapolated to increase the kinematic coverage

**Using the BMPT parametrization**


\[
[E \times \frac{d^3\sigma}{dp^3}](x_R, p_T) = A(1 - x_R)^\alpha (1 + B x_R) x_R^{-\beta} \\
\times (1 + a'(x_R)p_T + b'(x_R)p_T^2) e^{-a'(x_R)p_T}
\]

\[
a'(x_R) = \frac{a}{x_R^\gamma} \\
b'(x_R) = \frac{a^2}{x_R^\delta} \\
x_R = E^*/E^*_{max}
\]

7 parameters

**S-W fits to HARP**

p-Be→π+X [8.89 GeV/c]

**Using the Sanford-Wang parametrization**

(BNL 11479 & BNL 11299 (unpublished))

\[
\frac{d^2N}{dpd\Omega}(p, \theta) = A p^B \left(1 - \frac{p}{p_{beam}}\right) \\
\times \exp\left(-\frac{C p^D}{p_{beam}^E} - F \theta(p - G p_{beam} \cos^H \theta)\right)
\]

8 parameters
The off-axis trick

- Produces a narrow band neutrino beam at a given energy which maximize the $\nu_\mu \rightarrow \nu_e$ oscillation probability

- As compared to the on-axis flux, the intensity is higher at the peak

- Strongly suppress the high energy tail and favors neutrino interactions through the charged current quasi-elastic channel: $\nu_\mu + n \rightarrow p + \mu$

T2K far detector flux prediction at different off-axis angle

$\sin^2 2\theta_{23} = 1.0$
$\sin^2 2\theta_{13} = 0.1$
$\Delta m_{32}^2 = 2.4 \times 10^{-3} \text{ eV}^2$

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Thin tuning — Detailed

**Momentum scaling**

→ Rescale relevant data to the corresponding energy using the Feynman scaling hypothesis: Cross section becomes invariant when expressed in terms of $x_F \cdot p_T$

E.g: MINERνA uses NA49 $pC \rightarrow π^±X$ data at 158 GeV/c (scaled down to 120 GeV/c)

**Target scaling**

→ Rescale the relevant data in target

$$E \times \frac{d^3\sigma}{dp^3}(A_1) = \left[ \frac{A_1}{A_0} \right]^{\alpha(x_F, p_T)} E \times \frac{d^3\sigma}{dp^3}(A_0)$$

$$\alpha(x_F, p_T) = (a + bx_F + cx_F^2)(d + ep_T^2)$$

E.g: $\alpha$ function fits to Eichten $K^+$ data (from p-Be, p-Al interactions)

NA49 Data-MC comparison (Closed circles = statistical error < 2.5%, Open circles = statistical error 2.5-5.0%, Crosses > 5%)
Tuned fluxes with thin target datasets

**ν_µ at the far detector (ν-mode)**

- Total tuning
- Previous Tuning
- Pion tuning
- Kaon tuning
- $\nu_{\mu}$

**ν_µ at the far detector (ν-mode)**

- Total tuning
- Previous Tuning
- Pion tuning
- Kaon tuning
- 2ν nucleon tuning
- Int. Rate tuning

**ν_e at the far detector (ν-mode)**

- Total tuning
- Previous Tuning
- Pion tuning
- Kaon tuning
- 2ν nucleon tuning
- Int. Rate tuning

---

**Previous tuning using NA61 07 thin target data**

**MINERvA PRELIMINARY**

L. ZAMBELLI - NEUTRINO 16 - HADROPRODUCTION FOR $\nu$ FLUX
T2K multiplicity error (thin target tuning)

The graphs illustrate the fractional error in the energy scaling for different focusing modes and neutrino types, with comparisons made between the latest tuning using NA61 09 thin target data and the previous tuning using NA61 07 thin target data.

--- Latest tuning using NA61 09 thin target data
--- Previous tuning using NA61 07 thin target data
Thick tuning — Detailed

Format of thick target results can be:

- raw yields at the surface of the target (2007 NA61/SHINE replica target)
  → One has to smear the MC to compute the weights

- corrected yields at the surface of the target (2009 NA61/SHINE replica target, MIPP thick target). NA61/SHINE provides a binning along the target; MIPP released inclusive results.

MINERvA LE tuned Gen2 flux

T2K thin/replica tuning

\( \nu_{\mu} \) at the far detector

Results and Next Steps

Gen2-thin vs Gen2-thick

A comparison between these two predictions shows a significant disagreement.

To decide between two a priori predictions, we compare to an in-situ measurement: the "Low-nu" technique.

Leo Aliaga (College of William and Mary)

Fermilab Joint Experimental-Theoretical Seminar 49 / 67

T2K thin/replica tuning

\( \nu_{\mu} \) at the far detector
Interaction cross section - Definition

Inelastic cross section categorization

Production cross section: New mesons are created - used to normalize the NA61/SHINE spectra

\[
\frac{d^2n^\alpha}{dp d\theta} = \frac{1}{\sigma_{prod}} \frac{d^2\sigma^\alpha}{dp d\theta}
\]

\[
\sigma_{prod}(p - C, 31 \text{ GeV}) = 230.7 \pm 2.8(\text{stat.}) \pm 1.2(\text{det.})^{+6.3}_{-3.5}(\text{mod.}) \text{ mb}
\]

Quasi-elastic cross section: Incident particle kicks off one nucleon of the nucleus target
- Difficult to have an homogeneous definition among experiments and theoreticians
- Difficult to measure
- Difficult to parametrize

What sort of data is available?

Data - MC Inelastic Cross Sections

The MC quasi-elastic component has been subtracted by looking at interactions where no new particles (p or K's) are created (geant4.2.p03 FTFP_BERT).

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→ QE subtracted
→ FTFP_BERT model
Gean4.2.p03

\[\begin{array}{|c|c|c|}
\hline
\text{Interaction} & \text{Inc. p} & \text{Inelastic x-sec (mb)} \\
\hline
\text{p+p Elastic} & 1 & 120 \\
\text{p+p Elastic fit} & 1 & 120 \\
\text{n+p Elastic} & 1 & 120 \\
\text{n+p Elastic fit} & 1 & 120 \\
\text{p+C Quasi-elastic} & 1 & 120 \\
\end{array}\]
Interaction cross section

p+C inelastic cross section [mb]

- NA61/SHINE 2009 data
- NA61/SHINE 2007 data
- Denisov et al.
- Denisov et al. (hodoscope)
- Bellettini et al.
- MIPP Collaboration

p+C production cross section [mb]

- NA61/SHINE 2009 data
- NA61/SHINE 2007 data
- Carroll et al.
(p-θ) production phase space of ν parents seen at T2K far detector [ν-mode]
NA61/SHINE thin target data for T2K


(p-θ) production phase space of ν parents seen at T2K far detector [ν-mode]
NA61/SHINE thin target results

\[ p+C \ [31 \text{ GeV}] \rightarrow \pi^{+}+X \]

\[ p+C \ [31 \text{ GeV}] \rightarrow \pi^{-}+X \]

\[ \frac{d^2\sigma}{dp\,d\Omega} \ [\text{rad GeV/c}^2] \]

\[ \theta \]

Data 2009

FTF_BIC - G496

QGSP_BERT - G410

**NA61/SHINE thin target results**

**p+C [31 GeV] → K^+ + X**

<table>
<thead>
<tr>
<th>Angle (mrad)</th>
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<td><img src="image2" alt="Graph" /></td>
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**p+C [31 GeV] → K^- + X**

<table>
<thead>
<tr>
<th>Angle (mrad)</th>
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<th>FTF_BIC - G410</th>
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<td>240 &lt; Θ &lt; 300</td>
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NA61/SHINE thin target results

**p+C [31 GeV]→p+X**

- 0 < θ < 10 mrad
- 10 < θ < 20 mrad
- 20 < θ < 40 mrad
- 40 < θ < 60 mrad
- 60 < θ < 100 mrad
- 100 < θ < 140 mrad
- 140 < θ < 180 mrad
- 180 < θ < 240 mrad
- 240 < θ < 300 mrad
- 300 < θ < 360 mrad

**p+C [31 GeV]→Λ+X**

- 0 < θ < 40 mrad
- 40 < θ < 60 mrad
- 60 < θ < 100 mrad
- 100 < θ < 140 mrad
- 140 < θ < 180 mrad
- 180 < θ < 240 mrad
- 240 < θ < 300 mrad
- 300 < θ < 420 mrad

Data 2009

GiBUU 1.6

Venus 4.12

p [GeV/c]
K0s yields from K± measurements using

- the isospin argument:
\[ N(K_S^0) = \frac{1}{2} (N(K^+) + N(K^-)) \]

- the quark-counting argument:
\[ N(K_S^0) = \frac{1}{8} (3N(K^+) + 5N(K^-)) \]
NA61/SHINE thin target results


**Figure 1:**

- **Top Graph:**
  - 20 < θ < 40 mrad
  - π⁺ - tof-dE/dx
  - Fractional error vs. p [GeV/c]
  - Contributions:
    - Total sys.
    - PID
    - Feed-down
    - Track cuts
    - Rec. algo
    - Rec. tof
    - K-Fixed
    - Fwd. Acc.

- **Middle Graph:**
  - 20 < θ < 40 mrad
  - π⁺ - dE/dx
  - Fractional error vs. p [GeV/c]
  - Contributions:
    - Total sys.
    - PID
    - Feed-down
    - Track cuts
    - Rec. algo
    - Fwd. Acc.

- **Bottom Graph:**
  - 20 < θ < 40 mrad
  - π⁻ - h⁻
  - Fractional error vs. p [GeV/c]
  - Contributions:
    - Total sys.
    - Feed-down
    - Track cuts
    - Rec. algo
    - K⁻ and Π⁻
    - Λ weight
    - Fwd. Acc.
NA61/SHINE replica target results

\[ p+T2K \text{ replica } [31 \text{ GeV}] \rightarrow \pi^+ + X \text{ (0 to 140 mrad)} \]
NA61/SHINE replica target results

\[ p+T2K\ \text{replica} [31 \ \text{GeV}] \rightarrow \pi^+ + X \ (140 \ \text{to} \ 340 \ \text{mrad}) \]

\[ \frac{dN}{dp} \times \frac{1}{\text{p.o.t.}} \]

\( p \) [GeV/c] for different angular ranges:
- 140 to 180 mrad
- 180 to 220 mrad
- 220 to 260 mrad
- 260 to 300 mrad
- 300 to 340 mrad

NA61/SHINE: \( p+(T2K\ RT) @ 31 \ \text{GeV/c} \), data taken in 2009

NA61/SHINE replica target results

\[ p^+\text{T2K replica} \left[ 31 \text{ GeV} \right] \rightarrow \pi^- X \ (0 \text{ to } 140 \text{ mrad}) \]

NA61/SHINE replica target results

p+T2K replica [31 GeV]→π+X (140 to 340 mrad)

MIPP data with NuMI Target

- $1.43 \times 10^6$ protons at 120 GeV on an actual NuMI target
- $\pi^\pm$ yields in $(p_T,p_Z)$ bins
- No binning along the target
- Combined stat+syst uncertainty below 10% in most bins
- From a thin target of carbon dataset $\pi/\pi$, $K/\pi$ ratio also measured

MIPP results - $\pi^+$ yields of NuMI target

\[ p + \text{NuMI replica [120 GeV]} \rightarrow \pi^+ + X \]

\[ \frac{N(\pi^+)}{(\text{GeV/c})\text{POT}} \]

\[ p_z \text{ (GeV/c)} \]

\[ \pi^+ \text{ Combined Systematics} \]

\[ p_T \text{ (GeV/c)} \]

\[ \text{Uncertainty (\%)} \]

\[ 0.00 - 0.10 \text{ GeV/c} \]

\[ 0.10 - 0.20 \text{ GeV/c}, N \times 3.00 \]

\[ 0.20 - 0.30 \text{ GeV/c}, N \times 10.00 \]

\[ 0.30 - 0.40 \text{ GeV/c}, N \times 30.00 \]

\[ 0.40 - 0.50 \text{ GeV/c}, N \times 100.00 \]

\[ 0.50 - 2.00 \text{ GeV/c}, N \times 300.00 \]

MIPP results - $\pi^-$ yields of NuMI target

$p+$NuMI replica [120 GeV] → $\pi^+$X

- 0.00 - 0.10 GeV/c
- 0.10 - 0.20 GeV/c, N x 3.00
- 0.20 - 0.30 GeV/c, N x 10.00
- 0.30 - 0.40 GeV/c, N x 30.00
- 0.40 - 0.50 GeV/c, N x 100.00
- 0.50 - 2.00 GeV/c, N x 300.00


L. ZAMBELLI - NEUTRINO 16 - HADROPRODUCTION FOR $\nu$ FLUX
MIPP results - $\pi^-/\pi^+$, $K^-/K^+$, $K^+/\pi^+$ ratio

Figure 10.2: Comparison to existing measurements and parametrization of beryllium data.

Figure 10.3: Comparison to existing measurements and parametrization of beryllium data.

A Lebedev FERMILAB-THESIS-2007-76
The HARP experiment

Common features of hadron production experiments:
- beam instrumentation (PID, impact position on target);
- target under study with an elaborate trigger system;
- magnetic spectrometer with PID capabilities;

Beam

Halo A

Halo B

Target

Large angle spectrometer

Forward spectrometer

0.025 < θ < 0.25 rad

L. Zambelli - Neutrino 16 - Hadroproduction for ν Flux
The HARP experiment

HARP: Data taking summary

HARP took data at the CERN PS T9 beamline in 2001-2002
Total: 420 M events, ~300 settings

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| MiniBooNE: Be |                   |                   |                   |                   |                   |                   |                   |
| 5%            |                   |                   |                   |                   |                   |                   |                   |                   |
| 50%           |                   |                   |                   |                   |                   |                   |                   |                   |
| 100%          |                   |                   |                   |                   |                   |                   |                   |                   |
| Replica       |                   |                   |                   |                   |                   |                   |                   |                   |
| +8.9 GeV/c    |                   |                   |                   |                   |                   |                   |                   |                   |

| LSND: H$_2$O |                   |                   |                   |                   |                   |                   |                   |                   |
| 10%          |                   |                   |                   |                   |                   |                   |                   |                   |
| 100%         |                   |                   |                   |                   |                   |                   |                   |                   |
| Replica      |                   |                   |                   |                   |                   |                   |                   |                   |
| +1.5 GeV/c   |                   |                   |                   |                   |                   |                   |                   |                   |

L. ZAMBELLI - Neutrino 16 - Hadroproduction for ν Flux
Single arm spectrometers

Figure 7: Layout of the Cho et al. [81] spectrometer measurement of particle production at ANL. The extracted proton beam is directed at a target, and secondaries are bent toward a Cherenkov detector by a set of dipoles. Quadrupoles keep the secondary beam focused, and slits or collimators aid in the secondary momentum definition.

MINERvA flux vs Low-ν measurement

![Graphs showing νμ flux in low energy beam](image)

- **NuMI Low Energy Beam**
- **Flux in [2,22] GeV**
- **MINERvA Preliminary**

**Results and Next Steps**

Generation-2 thin and Low-nu Comparison

Leo Aliaga (College of William and Mary)

Fermilab Joint Experimental-Theoretical Seminar 51 / 67

Generation-2 thick and Low-nu Comparison

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MINERvA flux vs Low-$\nu$ measurement

We see consistency along the whole neutrino energy range
(low-$\nu$ flux predicts the flux for >2 GeV)

![Graph 1](image1)

We see consistency in the peak but significant disagreement in the $[5, 15]$GeV regime.

![Graph 2](image2)
MINERvA flux generation comparisons

Backup Slides

Generation-2 thin vs Gen0 MINERvA

Backup Slides

Generation-2 thin vs Gen1+ MINERvA

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L. ZAMBELLI - NEUTRINO 16 - HADROPRODUCTION FOR $\nu$ FLUX
MINER\textit{v}A and NO\textit{v}A flux prediction

Just HP errors are shown

NuMI Medium Energy Beam

MINER\textit{v}A Preliminary

Generation2 thin

MINER\textit{v}A

NO\textit{v}A

$\nu_\mu$

$\nu_\mu$ / m$^2$ / 10$^6$ POT / GeV

$\nu$ energy (GeV)

0 2 4 6 8 10 12

L. ZAMBelli - Neutrino 16 - Hadroproduction for $\nu$ Flux
T2K flux prediction correlation matrix

T2K Flux Prediction Correlation Matrix

Flux Bin

Correlation

ν
ν̅-mode
νμνeνe

near
far detector

L. Zambelli - Neutrino 16 - Hadroproduction for ν Flux
MINERvA flux predictions correlation matrices

Gen2-thin, bin-bin correlations

Gen2-thick, bin-bin correlations

FIG. 5.16: Energy bin to bin flux correlation.