Hadron production measurements from NA61 for LBL experiments

Alexander Korzenev, University of Geneva

on behalf of the NA61/SHINE collaboration

EPS-HEP 2015, Vienna, July 23

Outline
- Introduction
- Results on hadron cross sections
- The T2K replica target results
- Future program of NA61/SHINE
Motivation for an ancillary hadron production experiment

Uncertainty on the neutrino flux is a dominant contribution to systematics of measurements: 10 – 20 %

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Motivation for an ancilliary hadron production experiment

- Uncertainty on the neutrino flux is a dominant contribution to systematics of measurements: 10 – 20 %
- Uncertainty on hadronic interactions is dominant contribution to the flux uncertainty
Few examples

Hadron production experiments

- HARP, CERN-PS214
  1.5-15 GeV beam

- NA20 & SPY/NA56, SPS
  400-450 GeV beam

- NA49, CERN-SPS
  160 GeV beam

- MIPP, FNAL-E907
  120 GeV beam

- NA61/SHINE CERN-SPS
  13-400 GeV beam

Neutrino experiments

- (Mini-, Sci-, Micro-)BooNE at Fermilab
- K2K (KEK to Super-Kamiokande)

- WANF (NOMAD, CHORUS)
- CNGS (OPERA, ICARUS)

- NuMI beamline in Fermilab
  (MINOS, MINERvA, NOvA)

- T2K (JPARC to Super-Kamiokande)
  NuMI (MINOS+,MINERvA, NOvA)
  LBNE, LBNO, T2HK

Normally results of several hadron production experiments are used
NA61/SHINE has been approved in 2007
Successor of NA49, situated at H2 beamline of CERN SPS
Secondary beam particles produced from 400 GeV SPS's protons: momentum range 13-350 GeV/c
Particle identification by ToF and dE/dx in TPC
Two target configurations:
- Thin: for the cross section measurements
- T2K replica: model independent way for hadron multiplicities
**SPS Heavy Ion and Neutrino Experiment**

- **NA61/SHINE** has been approved in 2007
- Successor of NA49, situated at H2 beamline of CERN SPS
- Secondary beam particles produced from 400 GeV SPS's protons: momentum range 13-350 GeV/c
- Particle identification by ToF and dE/dx in TPC
- Two target configurations:
  - Thin: for the cross section measurements
  - T2K replica: model independent way for hadron multiplicities

**Thin target:** graphite, $0.04 \cdot \lambda_i$

**T2K replica target:** graphite, 90 cm, $1.9 \cdot \lambda_i$
Phase space of hadrons contributing to the predicted $\nu$ flux at SK (250 kA)

Summary of data collected by NA61 for T2K

<table>
<thead>
<tr>
<th>beam</th>
<th>target</th>
<th>year</th>
<th>stat. $\times 10^6$</th>
<th>Status of analysis</th>
<th>The T2K beam MC</th>
</tr>
</thead>
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<tr>
<td>protons at 31 GeV/c</td>
<td>thin target 2cm (0.04$\lambda_p$)</td>
<td>2007</td>
<td>0.7</td>
<td>published: $\pi^\pm$, $K^\pm$, $K_S^0$, $\Lambda$</td>
<td>is used</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2009</td>
<td>5.4</td>
<td>prelim: $\pi^\pm$, $K^\pm$, $p$, $K_S^0$, $\Lambda$</td>
<td>currently being used</td>
</tr>
<tr>
<td>the T2K replica target 90 cm (1.9$\lambda_p$)</td>
<td>2007</td>
<td>0.2</td>
<td>published: $\pi^\pm$</td>
<td>method developed</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2009</td>
<td>2.8</td>
<td>preliminary release of $\pi^\pm$</td>
<td>to be integrated</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2010</td>
<td>$\sim$10</td>
<td>analysis ongoing</td>
<td>-</td>
</tr>
</tbody>
</table>
\[ p + C \rightarrow \pi^+ + X \]

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

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

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

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

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

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

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

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

\[ p + C \rightarrow K^0_s + X \]

Input to the beam simulation of T2K
Interactions chain for hadrons is stored, to be weighted later with real measurements.

- Tuning of tertiary pions requires extrapolation from NA61 data
- Extrapolation to different incident nucleon momenta is done assuming Feynman scaling ($x_F = p_L/p_{L_{max}}$)
- Extrapolation from carbon to aluminum using
- Precision of $\nu$ flux with the 2009 data of NA61 is improved by ~3%
The actual target measurements
Measurement of hadron yields at the target surface (no matter how they are produced)

Graphite rod 90 cm long and $\varnothing = 2.6$ cm. Replica target was delivered to CERN to be used in NA61.

Canister 90 cm long and $\varnothing = 3$ cm. 47 graphite segments soldered to water cooling line.

Ancillary experiment: NA61/SHINE in CERN

Ancillary experiment: MIPP in Fermilab

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The actual target measurements
Measurement of hadron yields at the target surface (no matter how they are produced)

About 40% of neutrinos are produced from hadrons which were created in secondary interactions.

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Canister 90 cm long and Ø = 3 cm. 47 graphite segments soldered to water cooling line.

Ancillary experiment: NA61/SHINE in CERN

Ancillary experiment: MIPP in Fermilab
NA61 data for the T2K simulation

- Hadron multiplicities are parametrized at the target surface (no interaction vertex reconstruction)
- Analysis in bins of \((p, \theta, z)\)
- Particle ID with ToF and dE/dx
- Method is published: *NIM A701(2013)99*
  - \(\pi^+\) analysis based on pilot data 2007

*Example of \(\pi^+\) multiplicities on the target surface, data 2009*
NA61 data for the T2K simulation

- Results of $\pi^\pm$ analysis is presently released
  - Data collected in 2009
- Estimation of the $\nu$ flux produced by $\pi^\pm$ assuming identical p beams in NA61 and T2K
  - Discrepancy is about 1 $\sigma$
- Integration of RT results in the T2K beam simulation program to be done
  - Beam profile is different in NA61 and T2K
  - Corrections as a function of time
- Analysis of the 2010 data is ongoing
Data of NA61 for Future LBL $\nu$ programme

- **Beam from J-PARC to Kamioka (295 km)**
  - $\nu$ of accelerator, atmospheric, astrophysics origin => CP violation, $\nu$ mixing parameters; proton decay

- **Beam from FNAL to S.Dakota (1300 km)**
  - $\nu$ of accelerator, atmospheric, astrophysics origin => CP violation, mass hierarchy, mixing parameters; proton decay
The goal is similar to the one for T2K: cross section + replica target

- 16 physicists from 6 US institutions joined NA61
- Data taking will start in October. 28 days allocated to the US-neutrino program
- Better ν flux for DUNE/LBNF, MINOS(+), NOvA, MINERvA
- Tension between NuMI’s MC and the full-target measurements by MIPP

### Plans for data taking

<table>
<thead>
<tr>
<th>Target</th>
<th>Incident proton/pion beam mom.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>120 GeV/c</td>
</tr>
<tr>
<td>NuMI spare targ.</td>
<td>future</td>
</tr>
<tr>
<td>LBNE replica</td>
<td>future</td>
</tr>
<tr>
<td>Thin graphite</td>
<td>3M</td>
</tr>
<tr>
<td>Thin Al</td>
<td>3M</td>
</tr>
<tr>
<td>Thin steel</td>
<td>future</td>
</tr>
<tr>
<td>Thin Be</td>
<td>3M</td>
</tr>
<tr>
<td>Thin concrete</td>
<td>future</td>
</tr>
</tbody>
</table>

future = 2016/7

- Upgrade of the spectrometer by the next summer
- Two new small-volume TPCs for the forward region
- Upgrade of electronics for ToF, PSD, BPD detectors (DRS4 digitizer)
- Target position closer to (or inside) the first TPC to improve the acceptance
Systematic uncertainties for Hyper-K

- Beam flux + near detector constraint
  - Conservatively assumed to be the same
- Cross section uncertainties not constrained by ND
  - Nuclear difference removed assuming water measurements
- Far detector
  - Reduced by increased statistics of atmospheric n control sample

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

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

(T2K 2014)

<table>
<thead>
<tr>
<th></th>
<th>v_e</th>
<th>v_µ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux &amp; ND</td>
<td>2.9</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td>4.7</td>
<td>4.9</td>
</tr>
<tr>
<td>Far Det. + FSI</td>
<td>3.5</td>
<td>5.6</td>
</tr>
<tr>
<td></td>
<td>6.8</td>
<td>8.1</td>
</tr>
</tbody>
</table>

M. Yokoyama, SWAPS2014
Y. Hayato, Neutrino2014
Systematic uncertainties for Hyper-K

- Beam flux + near detector constraint
  - Conservatively assumed to be the same
- Cross section uncertainties not constrained by ND
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- Far detector
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<th></th>
<th>$\nu$ mode</th>
<th>anti-$\nu$ mode</th>
<th>(T2K 2014)</th>
</tr>
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<tbody>
<tr>
<td>Flux &amp; ND</td>
<td>$\nu_e$ 3.0</td>
<td>$\nu_\mu$ 2.8</td>
<td>$\nu_e$ 2.9</td>
</tr>
<tr>
<td></td>
<td>$\nu_e$ 5.6</td>
<td>$\nu_\mu$ 4.2</td>
<td>$\nu_e$ 4.7</td>
</tr>
<tr>
<td>XSEC model</td>
<td>$\nu_e$ 1.2</td>
<td>$\nu_\mu$ 1.5</td>
<td>$\nu_e$ 3.5</td>
</tr>
<tr>
<td>Far Det. + FSI</td>
<td>$\nu_e$ 0.7</td>
<td>$\nu_\mu$ 1.0</td>
<td>$\nu_e$ 6.8</td>
</tr>
</tbody>
</table>

Homework for NA61/SHINE (replica target measurements)
Conclusion

- Precision hadron production data are required for the constraint of neutrino beams in LBL experiments
- NA61/SHINE data for T2K
  - Thin target data: measurement of cross section
    - Presently used by T2K in the \( \nu \) beam simulation
  - T2K replica target: multiplicities at the target surface
    - Pion multiplicities have been released (data 2009)
    - To be integrated to the T2K beam simulation
    - Large statistical sample (data 2010) to analyze
- Forthcoming run in October for the NuMI programme
  - Upgrade of the setup: new TPCs, electronics, target position
backup
Methods to constrain the $\nu$ spectrum vs energy

1) **Full chain simulation of the neutrino beamline**: includes the interaction of primary protons with the target, propagation of secondaries through the setup (accounting for the magnetic field and reinteractions) and finally production of $\nu$ in the decay
   a) Interaction chain of hadrons is stored to be reweighted later with real cross-sections which, in turn, obtained in ancillary experiment
   b) Constraining hadron multiplicities at the surface of a real (or replica) target

2) **Use of the muon monitor detector**: as in case of (1) the full chain simulation of the beamline is required. 'Weak' constrain since momentum of muons is not measured, only intensity and direction.

3) **Normalization to the previously well measured cross section or well known reaction** which can be measured at the same experiment (in situ techniques)
   a) Neutrino-electron scattering ($\nu_\mu e \rightarrow \nu_\mu e$): clear experimental signature: forward going electron. $Z$ exchange $\Rightarrow$ sum of neutrino and antineutrino fluxes is measured, flavor blind
   b) The “low-$\nu$” approach: determination of the relative neutrino flux as a function of $E_{\nu}$. Method based on a fact that the charged current differential cross section in the limit $\nu \rightarrow 0$ is independent of $E_{\nu}$
   c) Inverse muon decay ($\nu_\mu e \rightarrow \mu^- \nu_e$): only for neutrinos with energies above 11 GeV. The method was used in NOMAD
Pion multiplicity re-weighing has the largest effect at low energies, while the kaon multiplicity re-weighting is important at high energies.

Total flux uncertainty is dominated by the hadron interaction uncertainties.

NA61 data for the T2K simulation

- Hadron multiplicities are parametrized at the target surface (no interaction vertex reconstruction)
- Model dependence of the $\nu$ flux prediction is reduced down to 10% as compared to 40% in the standard approach
- Analysis in bins of $(p, \theta, z)$
- Method is published: *NIM A701(2013)99*
- $\pi^{\pm}$ analysis based on pilot data 2007
- Ultimate precision will come with the analysis of data 2009 and 2010

(NA61) N.Abgrall et al., *NIM A701(2003)99*
T2K flux uncertainties

- propagate the uncertainties of T2K replica target measurements only to the fraction of the neutrino flux at SK that can be re-weighted
- very small contribution from statistical error of the T2K replica target measurements, they are considered as uncorrelated
- consistent comparison with the official T2K predictions using the thin target measurement is complex
- larger contribution comes from the interaction length; not present with the T2K replica target re-weighting

Thin target

T2K replica target

\[ \nu_\mu @ SK \]

\[ \pi \text{ contribution only} \]
Systematic Uncertainties

Six Components of systematic uncertainties:

- PID: 1 Gaussian versus 2 Gaussians to describe dE/dx
- Feed-down: 30% on model dependent corrections
- Reconstruction efficiency: evaluated to 2%
- FTOF efficiency: evaluated to 2%
- $\pi$ loss: effect on last point measured in TPCs
- Backward extrapolation: precision on reconstructed target position

Graph showing relative uncertainties with various contributions labeled as PID, Feed-down, rec. eff., tof. eff., $\pi$ loss, back extrap, and Total.
NA61 data in the T2K experiment

Interaction chain for hadrons is stored, to be weighted later with real measurements.

Tuning of tertiary pions requires extrapolation from NA61 data.

Extrapolation to different incident nucleon momenta is done assuming Feynman scaling ($x_F = p_L / p_L^{max}$).

Extrapolation from carbon to aluminum using

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

Red: parent produced in target
Blue: parent produced outside the target

Hadronic interaction in the target are modeled with FLUKA, outside the target with GEANT3 (GCALOR)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Beam p[GeV/c]</th>
<th>Target</th>
<th>Particle</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA61/SHINE</td>
<td>31</td>
<td>C</td>
<td>$\pi^\pm$, $K^\pm$, p</td>
</tr>
<tr>
<td>Eichten et al.</td>
<td>24</td>
<td>Be, Al,...</td>
<td>p, $\pi^\pm$, $K^+$</td>
</tr>
<tr>
<td>Allaby et al.</td>
<td>19.2</td>
<td>Be, Al,...</td>
<td>p, $\pi^\pm$, $K^+$</td>
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<tr>
<td>E910</td>
<td>6.4-17.5</td>
<td>Be</td>
<td>$\pi^+$</td>
</tr>
</tbody>
</table>

Major part of the T2K phase space

For forward kaons

For tertiary pions

Interaction chain for hadrons is stored, to be **weighted later with real measurements**

Tuning of tertiary pions requires extrapolation from NA61 data.

NA49 data for the NuMI simulation

$\pi^+$ which make a $\nu_\mu$ in MINERvA

$\pi^+$ leading to $\nu_\mu$ is tabulated at generation. Save kinematics & material.

In analysis, interactions reweighted as $\sigma$(data)/$\sigma$(MC).

- NA49 measurements at 158 GeV: $p+C \rightarrow (\pi^\pm, K^\pm, p)+X$
- MIPP measurements at 120 GeV: ratio of cross sections $K/\pi$

D.Harris, NuInt14, May 23, 2014
NA49 data for the NuMI simulation

- FLUKA is used to translate NA49 measurements to proton energies between 12 and 120 GeV
- Interactions not constrained by the NA49 data are predicted using FTFP
- Effect of corrections is < 5% at peak energy
- Flux uncertainty is a dominant contribution to the cross section systematics
- Hadron interactions dominates in the systematics of the flux

D.Harris, NuInt14, May 23, 2014
1.43x10^6 protons at 120 GeV on an actual NuMI target
Measurement of the $\pi^\pm$ yield in ~125 bins of $(p_z,p_T)$ across 2 orders of magnitude in momentum
There is no binning in $z$
For PID TPC ($dE/dx$) and RICH have been used
Combined statistical and systematic errors are <10% in nearly all bins

(MIPP collaboration) J.Paley et al., arXiv:1404.5882, Apr 2014
MIPP data for the NuMI simulation

- 1.43x10^6 protons at 120 GeV on an actual NuMI target
- Measurement of the $\pi^\pm$ yield in ~125 bins of $(p_z, p_T)$ across 2 orders of magnitude in momentum
- There is no binning in $z$
- For PID TPC ($dE/dx$) and RICH have been used
- Combined statistical and systematic errors are <10% in nearly all bins
- Data imply that MCs tend to over-estimate pion yields at higher $p$ and under-estimate at the focusing peak
- These data may be used to re-evaluate MC predictions of the NuMI flux and reduce the overall systematic uncertainty

J. Paley, Fermilab Wine & Cheese Seminar, Apr 8, 2014
Data for beamline of NA61/SHINE

- **NA61/SHINE** approved in 2007
- Successor of NA49, H2 beamline of CERN SPS
- Pilot run with pC data at 31 GeV in 2007. Main dataset in 2009 and 2010
- **New results** (run 2009) on $\pi^\pm$, $K^\pm$, p, $\Lambda$, $K^0_S$
- Thin and replica target measurements

Data for NuMI beamline in Fermilab

- NA49 data to constrain the $\nu$ flux
- **MIPP**: approved in 2001, datataking in 2005 and 2006
  - Ratio of hadron cross sections $\pi^-/\pi^+$, K$^-$/K$^+$, $\pi$/K released in 2007
  - **New results** on $\pi^\pm$ production yields off NuMI target: arXiv:1404.5882
- Extensive program is foreseen in NA61 (pilot data at 120 GeV in 2012)
Approaches for the $\nu$ flux constraint

1) Traditional: re-weighting at the interaction vertex
   - Model dependent: $x_F$ scaling assumed for extrapolation
   - Results of many hadron production experiments are used

3) The actual target measurements
   - Hadron yields on a surface of target
   - Never used so far
   - HARP, NA61, MIPP

5) Additional constraints come from
   - Muon monitor measurements
   - In situ techniques (direct measurement of the $\nu$ flux)
   - ...

One can feel safe if all methods give consistent results!
Low-$\nu$ technique for flux determination

- Differential CC neutrino DIS cross section as a function of energy transfer $\nu$
  \[
  \frac{d\sigma}{d\nu} = A \left( 1 + \frac{B}{A} \frac{\nu}{E} - \frac{C}{A} \frac{\nu^2}{2E^2} \right)
  \Rightarrow \quad \Phi(E) = \frac{1}{A} \cdot \left. \frac{dN}{d\nu} \right|_{\nu \to 0}
  \]

- $A$, $B$, $C$ depend on integrals over structure functions
  - Obtained from higher energy inclusive cross section
- Method developed by CCFR/NUTEV collaborations
- Neutrino energies should be relatively large

- Procedure was applied in MINOS for $E_\nu > 3.5$ GeV
- Going to be used in MINERvA
  - Advantage of totally active detector technology (low $\nu$ cut)
  - Can be applied to neutrino and antineutrino beams
  - Will be normalized to NOMAD carbon cross section 6-12 GeV
Direct measurement of $\nu$ flux with $\nu e \rightarrow \nu e$

- Well known reaction
  \[ \nu_\mu + e^- \rightarrow \nu_\mu + e^- \]
  \[ \bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^- \]
- Very small cross section (~1/2000 of $\nu$-nucleon scattering)
- Very forward electron final state
- Background reactions
  \[ \nu_e + n \rightarrow e^- + p \]
  \[ \nu_\mu A \rightarrow \nu_\mu A^{0} \]
  \[ \bar{\nu}_e + p \rightarrow e^+ + n \]
  \[ \nu_\mu N \rightarrow \nu_\mu N^{0} \]
- $\nu e$ events (LE) after all corrections:
  - 123.8±17.0(stat)±9.1(syst)
- Prediction from simulation:
  - 147.5±22.9(flux)
- In both cases precision is ~15%
- Similar signal/background rate for ME as for LE
  - Expected stat. error ~2%
  - Syst. error 7% → 5%
Ratios of charged hadrons from MIPP

- Measurements for MINOS/ 120 GeV/c
  - Thin carbon target
  - NuMI replica target
- Preliminary results for ratios: $\pi^-/\pi^+$, $K^+/\pi^+$, $K^-/K^+$ and $K^-/\pi^-$
- The only experiment nearby in phase space is NA49 (thin target, 158 GeV/c beam)
- Reasonable agreement of MIPP with NA49 and the MINOS spectrum fit has been found for $p_{\text{sec}} < 40$ GeV/c
- BMPT parametrization (400 GeV/c protons on Be target) fits well the data


Update on physics lists

Composition of physics lists for proton interaction as a function of the energy

Now with **VMC 2.15 (Geant4.10)**

<table>
<thead>
<tr>
<th>List Type</th>
<th>Model 1</th>
<th>Model 2</th>
<th>Model 3</th>
<th>Model 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>QGSP_BERT</td>
<td>Bertini</td>
<td>FTFP</td>
<td>QGSP</td>
<td></td>
</tr>
<tr>
<td>QGSP_BIC</td>
<td>BIC</td>
<td>FTFP</td>
<td>QGSP</td>
<td></td>
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<td>QGS_BIC</td>
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<td>FTFB</td>
<td>QGSB</td>
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<td>QGSP</td>
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<tr>
<td>FTFP_BERT</td>
<td>Bertini</td>
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<tr>
<td>QBBC</td>
<td>BIC</td>
<td>Bertini</td>
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<tr>
<td>FTF_BIC</td>
<td>BIC</td>
<td>FTFB</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**BIC**: Binary Cascade Model  
**Bertini**: Bertini Model  
**FTF**: Fritiof Model  
**QGS**: Quark Gluon String  
**LHEP**: Low and High Energy Parametrized  
**-P**: Precoumpound  
**-B**: BIC

- 

GeV
**Table 4.5:** The dominant systematic uncertainties on the $\nu_e$ appearance signal prediction in MINOS and T2K and a projection of the expected uncertainties in LBNE. For the MINOS uncertainties *absolute* refers to the total uncertainty and $\nu_e$ is the effect on the $\nu_e$ appearance signal only. The LBNE uncertainties are the total *expected* uncertainties on the $\nu_e$ appearance signal which include both correlated and uncorrelated uncertainties in the three-flavor fit.

<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>MINOS Absolute/$\nu_e$</th>
<th>T2K $\nu_e$</th>
<th>LBNE $\nu_e$</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Beam Flux</strong> after N/F extrapolation</td>
<td>3%/0.3%</td>
<td>2.9%</td>
<td>2%</td>
<td>MINOS is normalization only. LBNE normalization and shape highly correlated between $\nu_\mu/\nu_e$.</td>
</tr>
<tr>
<td><strong>Detector effects</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy scale ($\nu_\mu$)</td>
<td>7%/3.5%</td>
<td>included above (2%)</td>
<td>Included in LBNE $\nu_\mu$ sample uncertainty only in three-flavor fit. MINOS dominated by hadronic scale.</td>
<td></td>
</tr>
<tr>
<td>Absolute energy scale ($\nu_e$)</td>
<td>5.7%/2.7%</td>
<td>3.4% includes all FD effects</td>
<td>2%</td>
<td>Totally active LArTPC with calibration and test beam data lowers uncertainty.</td>
</tr>
<tr>
<td>Fiducial volume</td>
<td>2.4%/2.4%</td>
<td>1%</td>
<td>1%</td>
<td>Larger detectors = smaller uncertainty.</td>
</tr>
<tr>
<td><strong>Neutrino interaction modeling</strong></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Simulation includes: hadronization cross sections nuclear models</td>
<td>2.7%/2.7%</td>
<td>7.5%</td>
<td>$\sim$ 2%</td>
<td>Hadronization models are better constrained in the LBNE LArTPC. N/F cancellation larger in MINOS/LBNE. X-section uncertainties larger at T2K energies. Spectral analysis in LBNE provides extra constraint.</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>5.7%</strong></td>
<td><strong>8.8%</strong></td>
<td><strong>3.6%</strong></td>
<td>Uncorrelated $\nu_e$ uncertainty in full LBNE three-flavor fit = 1.2%.</td>
</tr>
</tbody>
</table>