Some thoughts on neutrino beams for neutrino cross-section measurements.
Nuino Flux beam should be simple "!

The neutrino flux beam should be simple "!

The physics is complex...

Many channels have to be studied...
The region of interest is certainly between 100 MeV and 10 GeV.

Comparison of $E/E_\nu$ for QE and total processes between data and NUX.

Region of interest
Unfolding cross-sections

\[ \frac{\text{observed}}{\text{background}} \frac{N - 3}{N} = \mathcal{O} \]

Neutrino flux

Clean event

Reconstruction and classification

Detector systematics

Number of events
Goals

- Measure cross-section from kinematical threshold, through quasi-elastic dominated region, study single-pion production, study opening of multi-pions through quasi-elastic and meson decay kinematics less focalized at lower energy
- Sufficient flux also at the lowest energies (cross-section decreases and meson 
  - Systematics

Experimental aspects:
- Capability to measure exclusive final states (low density, high granularity)
- Capability to measure exclusive final states (high density, high granularity)
- Different types of target (nuclear effects)
  - Beam aspects

• Experimental aspects:
  - Study nuclear effects (i.e. compile various targets in same beam)
  - Measure both $v_e$ and $\bar{v}_e$
  - Study neutrino and antineutrino cross-sections
    - Final states $0.1 < E^\gamma < 3$ GeV

Statistics

- Different types of target (nuclear effects)
  - Capability to measure exclusive final states (low density, high granularity)

Beam aspects

- Different types of target (nuclear effects)
  - Capability to measure exclusive final states (low density, high granularity)

Statistics

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Statistics
Neutrino factories
- CERN AD
- FNAL Debuncher
- JHF
- NUMI-LE, ME, HE
- FNAL Booster
- K2K

Storage ring beams (e.g. antiproton accumulators)
- ...
<table>
<thead>
<tr>
<th>Flux uncertainty</th>
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<td>Numi HE</td>
<td>Numi ME</td>
<td>Numi LE</td>
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Traditional beams
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<th>Uncertainty Flux</th>
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<th>Anti-νe CC rate per ton/Year</th>
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<td>1000</td>
<td>νν CC Rate per ton/Year</td>
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<td>ν̄ν CC Rate per ton/Year</td>
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<td>1 GeV</td>
<td>Peak E^v</td>
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Running in 2002
Systematic error in the range 0.1 < E_n < 2 GeV?

Region of interest: 0.1 < E_n < 2 GeV

YEAR = 3 * 10^7 s * Live time (%)

RUN = 4 * 10^13 PoT/Spill - 1 Spill/Pulse - Pulse = 1.87 s

M.L. 120 GeV/c Proton

FNLAL (NUMI) beam characteristics (low energy configuration):
KEK beam characteristics:

- PS: 13 GeV/c Proton
- Ps: 13 GeV/c Proton
- 5.5 x 10^12 PoT/spill
- 1 spill (1.1 mm/s) / pulse = 2.2 s
- RUN time: 6 months/year = 1.5 x 10^7 s
- Systematics:
  - F. Cavanna
  - See talk of F. Cavanna

OFX-AXIS
A tough job!

Blue: tuning of yields to SPY data
Red: new transport + FLUKA standalone
Dashed: nubeam500 + FLUKA standalone
Black: nubeam500 + GEANT-FLUKA

νμ flux at NOMAD
Measure $\theta^n/E$ below $E_m \sim 2$ GeV

1. Use a muon beam:
   a. Low energy beam $E_m \sim 2$ GeV
   b. Low intensity beam
   c. Short baseline experiment $\sim 20$ meters
   d. Detector mass $\sim 100$ tons

2. Known flux and no contamination

3. Measurement of both $\nu$ and $\bar{\nu}$ cross sections (and both helicities !)

The assumptions...

Cross-sections at neutrino factories


Presented at NUFACT'01, Tsukuba
The machine could deliver very low intensities compared to neutrino factories (~ 5 orders of magnitude less).

1. The PS as a proton booster
2. The SPL tunnel to focus and accelerate p's
3. A 17 GeV storage ring (E_p ~ 2 GeV)

Example: CERN complex

This could fit into staging scenario of the neutrino factory (after discussions with H. Haseroth).

The « modest » machine...

The « modest » machine...
We assume, for definiteness, the following configuration:

- **Baseline**: \( \approx 10 \text{ m} \)
- **Radius**: \( \approx 1 \text{ m} \)
- **Accelerator straight section**: \( \approx 30 \text{ m} \)

**Total number of events**

<table>
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<tr>
<th>Event Type</th>
<th>Charge-Current (Total)</th>
<th>Quasi-elastic (QE)</th>
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<tr>
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<td>10^15/year</td>
<td>2 GeV</td>
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<td><strong>Neutrino</strong></td>
<td>100 ton detector</td>
<td>( \nu )</td>
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<tr>
<td><strong>Antineutrino</strong></td>
<td></td>
<td>( \bar{\nu} )</td>
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**Total number of events**

- **Neutrino**
- **Antineutrino**
100 MeV bins

Events / 0.1 GeV

Mean RMS

ν energy

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Relative Error (%)

10%

% 6%

Energy bins 100 MeV

1015 useful $\mu$ decays, $E = 2$ GeV, 100 Tons detector, 1 m radius, 10 m baseline, 30 m straight section
$E = 2 \text{ GeV}$, decays, $10^{-15}$ useful $\nu$. $100 \text{ Tons detector, 1 m radius, 10 m baseline, 30 m straight section}$
Antiprotons Accumulators

P-pbar physics is based on technique of beam cooling, which allows to accumulate pbar in sufficient number within a phase-space of an accelerator.

Design of pbar sources has led to extensive studies of production and capture of pbar in storage rings, in order to optimize the accumulation rate and capture of pbar in storage rings, in order to optimize the acceptance of an accelerator.

Two machines:

- CERN AC & AA, PS proton energy=26 GeV, p=3.57 GeV/c, admittance 200 m.m.mrad in both planes, δp/p=±3%, circumference = 182 m, four straight sections, longest account for 13% of total

- FNAL AD, p=8.9 GeV/c, admittance 25 m.m.mrad in both planes, δp/p=±2%, circumference = 200 m.m.mrad in both planes, δp/p=±3%, circumference = 182 m, four straight sections, longest account for 14% of total

Optimum choice of target, incident proton beam parameters, focusing optics to provide largest possible particle density inside transverse and longitudinal admittance of storage ring.
A parasitic run is fully justified!

- The ring to stay captured as well.
- The transverse emittance and a momentums within the required bite of
- Only a small fraction of the muons has a sufficiently small
- Storage ring, or within the storage ring itself.
- These decays can occur anywhere, that is, within the focusing
- The decays of the decays of \( \pi^- \) and \( K^- \)’s.
- The muons are produced in the decays of \( \pi^- \) and \( K^- \)’s.
- To a large extent, the optimization for the \( \pi^- \)’s is also an
- Particles, including \( \pi^- \), \( K^- \), \( \mu^- \), and \( e^- \)’s.
- During their normal operation, the ring accumulates negative

A parasitic run...
What do we expect?

- For simplicity we consider only particles stored into the ring.
- The lifetime of pions is such that they will decay within a few revolutions.
- The few captured muons that remain trapped into the ring will subsequently decay.
- This has been measured!

\[
\eta \to \varphi \pi^- \pi^+ \\
\eta \to K^- K^+ K^0_{s} K^0_{s}
\]
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<th>1.3 \times 10^{14}</th>
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<td>% 3.5 \text{GeV}/c \approx 3%</td>
<td>% 8.9 \text{GeV}/c \approx 2%</td>
<td>\text{Interaction acceptance}</td>
<td>\text{Circumference Empty}</td>
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<td>26 \text{GeV}</td>
<td>120 \text{GeV}</td>
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<td>\text{Proton beam energy}</td>
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10 m downstream of a CERN AD straight section

Estimated event rate for 5 x 10^{19} pots in a 0.1 kton detector

\begin{tabular}{|c|c|c|c|}
\hline
\text{Anti-\(\nu^e\)} & \text{Anti-\(\nu^\tau\)} & \text{\(\nu^\tau\)} & \text{\(\nu^e\)} \\
\hline
670 & 415 & 1080 & \\
2245 & 1165 & 3410 & \\
4290 & 4230 & 8525 & (total) \\
\hline
\text{DIS} & \text{\(p\bar{p} = 3.57\) GeV/c} & \text{\(-3\%\)} & \\
\text{GE} & \text{CC} & & \\
\hline
\end{tabular}

\(p\bar{p} = 3.57\) GeV/c(\(-3\%\)),
Consistent with measurement at FNAL

\[
N \times 2.5 \times 10^{-5} \approx (0.03) \times (0.02) \times (0.04) \times 3 \times \Lambda \times n \times N = n' N
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<td>3 × 10^17</td>
<td>4.7 × 10^12</td>
<td>6.7 × 10^17</td>
<td>7.3 × 10^7</td>
<td>1.2 × 10^13</td>
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</tr>
</tbody>
</table>
Expected number of neutrinos reaching the detector (5*10^19 protons)

Normalized to 5*10^19 protons on target

CERN AD:

Prompt

Delayed
Normalized to \(5 \times 10^{19}\) protons

Very strong energy-angle correlation

Lowest energies (unfortunately) are cut out

Energy bins 200 MeV

CERN AD:

\(\vec{E}\)
The prompt neutrinos are much more than the delayed ones, and all are much more than 20% statistics.

Energy bins:
- 200 MeV
- 500 MeV
- 1000 MeV

Energy bins:
- 200 MeV
- 500 MeV
- 1000 MeV

Statistics ≈ 3%
Estimated event rate for 4 years running in a 0.1 kton detector 15m downstream of a FNAL-Debuncher FNAL-Debuncher straight section.

<table>
<thead>
<tr>
<th>Events / 0.1 kt-years</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>54600</td>
<td>( \pi^+ )</td>
</tr>
<tr>
<td>181000</td>
<td>( \pi^- )</td>
</tr>
<tr>
<td>4370</td>
<td>( \eta )</td>
</tr>
<tr>
<td>14500</td>
<td>( \eta )</td>
</tr>
<tr>
<td>1440</td>
<td>( \varphi )</td>
</tr>
<tr>
<td>6330</td>
<td>( \varphi )</td>
</tr>
<tr>
<td></td>
<td>( \eta' )</td>
</tr>
</tbody>
</table>

FNAL PROPOSAL P-860, December 1992
4 years running in a 0.1 kton detector 15m downstream

200 MeV energy bins

20% 10%
Systematics ≈ 1% for ~10^15 muons

Statistics ≈ 5-10% for ~10^15 muons

Bending arcs of storage ring
- Not dominant
- Muon polarization

- Negligible

In particular, muons are the cleanest way to measure neutrino cross-sections

Storage ring of pions or muons provide the cleanest method to measure neutrino cross-sections

(Could aim at ~10^16 muons)
Effect of muon polarization

ΔR/R for P = 0.05

\[ +2\% \]

\[ -2\% \]

Not dominant
Conclusion

- Pion and muon decays offer interesting features
  - A parasitic run is possible
  - They already exist

Antiproton accumulators are certainly an interesting compromise.
  - But is it (financially) realistic?
  - Flux systematics small, certainly at the level of few %
  - Equal amount of neutrinos and antineutrinos

measure cross-sections

But antiproton factors will provide the "cleanest" environment to

- But systematics dominated
- Event rates are generally very high
- Already existing

neutrino cross-section measurements

Traditional "pion beams are the most realistic choice for performing