Hadron Production Experiments and Neutrino Beams
Why hadro-production measurements

Understand the neutrino source

solar neutrinos
  \( \nu \) flux predictions based on the solar model

reactor based neutrino sources
  \( \nu \) flux predictions based on fission models and reactor power

accelerator based neutrino sources
  \( \nu \) flux predictions based on \( \pi, K (\rightarrow \nu + X) \) hadro-production models
    (+ modeling of the focusing and decay channel)
  \( \nu \) flux at far detector predicted on the base of \( \nu \) flux measured
    in near detector

neutrino cross sections \( \circ \) absolute neutrino flux
  neutrino interaction physics

neutrino oscillations \( \circ \) compare measured neutrino spectrum “far” from the
  source with the predicted one (flux shape and Far / Near flux ratio)
deviations from expectations \( \Rightarrow \) evidence for neutrino oscillations
conventional accelerator based $\nu$ beam

atmospheric showers

$\nu_{\mu} \rightarrow ???$

Hadroproduction measurements

$p(\pi) + A \rightarrow h + X$

neutrino factory

MC generators
Single-Arm-Spectrometers

SHINE / NA61 CERN-SPS

MIPP/ FNAL-E907

HARP/ CERN-PS214

Hadroproduction measurements

\[ p(\pi) + A \rightarrow h + X \]
Conventional $\nu$ Accelerator Beams

high intensity proton beam from accelerator strike primary production target

protons produce pions and kaons + …

pions and kaons are focused with magnetic horns toward long decay region (by selecting the polarity of $B$ one selects positive or negative hadrons)

“shieldings” stops all particles but neutrinos

resulting beam composed mainly of $\nu_\mu$, with small $\nu_e$ ($\sim 1\%$) component

want to maximize $\pi, K \rightarrow \mu + \nu_\mu$ decays for highest $\nu_\mu$ fluxes
How To Make $\nu_\mu$ Beams

Proton Beam → Target → Focusing Devices → Decay Pipe → Beam Dump

Focusing device: Electromagnetic Horn

$p$ beam

Current

$\pi^+$

$\pi^+$

$\nu_\mu$ beam ($\geq 99\%$)

$\nu_e$ ($\leq 1\%$) from $\pi \rightarrow \mu \rightarrow e$ chain and K decays ($K_{e3}$)

$\nu_\mu / \bar{\nu}_\mu$ can be switched by flipping polarity of horns
on-axis beam:
ν detected in same direction as p beam

120 GeV protons (graphite target)

operating since 2005
1.5 x 10^{21} POT, beam power 300 kW

wide ν energy spectrum,
ν peak energies between 3.5 and 10 GeV
(target position w.r.t first horn)
T2K Off-Axis $\nu$ Beam

\[ \Delta m^2 = 3 \times 10^{-3} \text{eV}^2 \]

\[ E_{\nu}^{\text{max}} [\text{GeV}] \approx \frac{30}{\theta [\text{mrad}]} \]

\[ p_\pi (\text{GeV}/c) \]

Neutralino energy $E_\nu$ almost independent of parent pion energy

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

NOvA will also use an off-axis beam
Overview of T2K Beam

Decay volume

Muon monitor

Ingrid

Super-Kamiokande

Target and horn 1

0.75 MW

30 GeV
Which Hadron Cross-Sections Measurements

What is the composition of the $\nu_\mu$ and $\nu_e$ flux in terms of the hadrons exiting the target?

$\nu_\mu$ predominantly from $\pi^+$ decay at peak energy, higher energy tail from kaon decays

$\nu_e$ predominantly from $\mu^+$ and $K^+$ decay at peak energy, higher energy tail from kaon decays
Different Ways of Making $\nu$ Beams

**conventional $\nu$ beam**
- Protons $ightarrow$ $\pi,K$
- focus (maybe bend)
- $\pi,K,(\mu)$
- Let them decay
- $\nu_\mu$, $\nu_\mu^c$ or $\nu_e$
- Shielding

**beta beam**
- few % $p$
- $^6$He or $^{18}$Ne
- focus, accelerate
- $^6$He or $^{18}$Ne
- decay
- $\nu_e$ or $\nu_\mu$
- Shielding

**muon stored beam**
- Protons
- low energy $\pi$
- collect, focus, decay
- $\mu$
- cool, accelerate decay
- $\nu_\mu$, $\nu_e$ or $\nu_\mu^c$
- Shielding

For each of these beams, $\nu$ flux ($\Phi$) is related to boost of parent particles ($\gamma$)

$\Phi(\nu) \propto \gamma^2$

$\sigma \propto \gamma$
**ν-STORM**

- Short baseline oscillation physics
- \( ν \) cross sections
- \( ν \) fluxes and spectra
- Known with very high accuracy (\( μ \) current in ring)

Final state lepton charge identification tells you flavor of interacting neutrino

- 100 kW target station
- Horn collection after target
- Collection / transport channel with no muon cooling
- Decay ring
- Large aperture FODO
- 3.8 ± 10% momentum acceptance circumference ~ 350 m

Detectors similar to MINOS
- Magnetized iron + extruded scintillators with Si-PM readout
How Well Do We Know $\nu$ Fluxes Now

AGS $\nu$ experiment (~1960) knew its flux to 30%

Ingredients to flux prediction from upstream to downstream
- proton dynamics (protons on target, spot size, …)
- hadron production off target
  - (~60% from primary interactions, ~30% from reinteractions in target, ~10% from around target)
- need measurements on both thin and thick targets, same materials, same energies
- horn current $\rightarrow B$ (focusing), alignment, etc.

HADRON PRODUCTION most important of these ingredients
Need to do dedicated hadron production experiments

Two detector experiments (near and far), flux uncertainties partially cancel!

In situ measurements
- constraints from special in situ runs in modified beam optics
- constraints from muon monitor data with scans of horn current
- “low $\nu$” events to constrain flux from high energy measurements (A. Bodek et al.)

In 50 years we have gone from 30% uncertainties to 15% uncertainties while increasing proton fluxes on target by $\sim 10^3 - 10^4$. 
How Well Do We Know $\nu$ Fluxes Now (2)

MINER$\nu$A, D. Harris, NuFACT2012

the errors are of the order $\sim 15\%$ in the oscillation region (< 1 GeV)

uncertainty on secondary (tertiary) hadron production dominates
hadron production experiment

- NA20 & SPY/NA56
  400-450 GeV beam

- NA49 / CERN-SPS
  160 GeV beam

- HARP / CERN-PS214
  1.5-15 GeV beam

- SHINE / CERN-SPS-NA61
  30-160 GeV beam

neutrino experiment

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

- MINOS (Fermilab to Soudan)
  MINERvA

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

- T2K (JPARC to Super-Kamiokande)
  NuMI (MINERvA, NOvA)

+ many many other experiments that measured cross sections …
⇒ critical survey of all existing cross section measurements !,
HARP : Hardon Production Exp. at PS

- Measurement of secondary $\pi$, K, p production cross section for various nuclear targets with p / $\pi$ beams in 1.5-15 GeV/c momentum range

- Results of measurements have been used for $\nu$ flux prediction in
  - K2K: Al target, 12.9 GeV/c
  - Mini(Sci)BooNE: Be targ, 8.9 GeV/c

- Also to be used for the atmospheric $\nu$ flux calculations and for the high intensity $\mu$-stopped source

- Kinematic acceptance
  - Forward spectrometer
    - $0.5 < p < 8$ GeV/c, $0.025 < \theta < 0.25$ rad
  - Large angles (TPC + RPD)
    - $0.1 < p < 0.8$ GeV/c, $0.35 < \theta < 2.15$ rad

- Approved in 2000
- Data taking 2001-2002
- T9 beam line of CERN PS

M.G. Catanesi et al., NIM A571(2007)527
HARP Result (p-Al at 12.9 GeV)

HARP data points

HARP Sanford-Wang parametrization

results based on ~200 k reconstructed tracks

doubly differential cross-section comparison to previous data: large normalization uncertainty
K2K measured $\nu_\mu$ disappearance for $\theta_{23}$, $\Delta m_{23}^2$. 

$\nu_\mu$ beam was produced by 12.9 GeV/c protons scattered off 5% Aluminum target.

almost factor of 2 error reduction


MIPP : Main Injector Particle Production Exp.

120 GeV proton beam from Main Injector on a variety of targets including NuMI replica target

“tomography” of NuMI target

Ratios of Charged Hadron Yields

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)

Forward neutron production in MIPP

Phys. Rev. D83 (2011) 012002
understanding and planning of ν oscillation experiments

450 GeV/c protons interact with Be target

production angle up to 30 mrad

yields of \( \pi^\pm, K^\pm, p \) and \( \bar{p} \) have been studied

secondary momentum range 7-135 GeV/c (0.02<\( x_F \)<0.3) and \( p_T<600 \) MeV/c

complementary to NA20 (Atherton et al.) measurements at 400 GeV/c and 0.15<\( x_F \)<0.75

G.Ambrosini et al., EPJ. C10 (1999) 605
SPY Data in NOMAD / WANF

450 GeV/c protons from SPS

Towards CHORUS & NOMAD

FLUKA 2000 used to calculate rates
rates modified to account for cross-sections measured by SPY and NA20
weight = data / FLUKA

NOMAD $\nu$ flux
$\rightarrow$ reweighting functions FLUKA / data
8% $\nu_\mu$ and $\nu_e$, 10% $\nu_\mu$ bar and 12% for $\nu_e$ bar

Reweighting functions

Histo is FLUKA, points from SPY & NA20

$\nu_{\text{sub}}$ graphs

$\pi^+$ graphs

$\pi^-$ graphs
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: ∫Bdl ~ 1.14 Tm)
- High momentum resolution
- Good particle identification: \( \sigma(\text{ToF-L/R}) \approx 100 \text{ ps} \), \( \sigma(\text{dE/dx}/\langle\text{dE/dx}\rangle) \approx 0.04 \), \( \sigma(\text{m}_{\text{inv}}) \approx 5 \text{ MeV} \)
- New ToF-F to entirely cover T2K acceptance (\( \sigma(\text{ToF-F}) \approx 120 \text{ ps} \), \( 1<p<4 \text{ GeV/c} \), \( \theta < 250 \text{ mrad} \))

NB Forward-ToF wall used to identify low mom. particles produced at large angles and bent back into the detector acceptance by the vertex magnets
NA61 Physics Program

Physics of strongly interacting matter in heavy ion collisions
Search of the QCD critical point

Super-Kamiokande

Measurement of hadron production off the T2K target (p+C) needed to characterize the T2K neutrino beam

Extensive air shower

Measurement of hadron production in p+C interactions needed for the description of cosmic-ray air showers (Pierre Auger Observatory and KASCADE experiments)
NA49 Charged Pion Spectra

charged pion spectra in pC interactions at 158 GeV/c measured by NA49 over broad kinematical range

NA49 with empirical fits to the data

systematic error

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<thead>
<tr>
<th>Source</th>
<th>Error</th>
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<tr>
<td>Normalisation</td>
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<td>Tracking efficiency</td>
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<td>Trigger bias</td>
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<td>Feed-down</td>
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<td>Detector absorption</td>
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<tr>
<td>Pion decay ( \pi \to \mu + \nu_\mu )</td>
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<tr>
<td>Re-interaction in the target</td>
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<tr>
<td>Binning</td>
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<td>Total (upper limit)</td>
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<tr>
<td>Total (quadratic sum)</td>
<td>3.8%</td>
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C. Alt et al., EPJ C49 (2007) 897
NA49 Charged Kaon Spectra

K identified using dE/dx in the TPCs

systematic error

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<th></th>
<th>$x_F \leq 0.2$</th>
<th>$x_F \geq 0.25$</th>
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<td>Particle identification</td>
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<td>Binning</td>
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<td>Total (upper limit)</td>
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<tr>
<td>Total (quadratic sum)</td>
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<td>4.6–12.2%</td>
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T. Anticic et al., arXiv:1004.1889
Particle Identification

Time of Flight measurements

ToF with dE/dx PID

Energy loss in TPCs

Bethe-Bloch curves (dE/dx) for different particles

5 $\sigma$ $\pi$/$K$ separation up to 4 GeV/c

$\sigma(dE/dx)/<dE/dx> < 5\%$
Particle Identification (2)

Combined ToF + dE/dx
(positively charged particles)
NA61 $p + C \rightarrow \pi^+ + X \ @ \ 30 \ GeV$

Very well covered by NA61/SHINE

T2K beam simulation: the $\{p, \theta\}$ distribution for $\pi^+$ weighted by the probability that their decay produces a $\nu_\mu$ passing through SK

NA61/SHINE measurements

$\sigma_{\text{prod}} (pC@31\text{GeV/c}) = 229.3 \pm 1.9 \pm 9.0 \text{ (mb)}$

Published in PRC 84 (2011) 034604
Systematical Errors

Systematical error due to uncertainty of the feeddown correction is larger for $\pi^-$ than for $\pi^+$ due to contribution from $\Lambda$ hyperon decays. NA61/SHINE measurements of neutral strange particle production will allow to reduce this systematic error.

Typical value 6%
Hope to reduce down to 3-4%
NA61 $p + C \rightarrow K^+ + X @ 30$ GeV

Published in PRC 85 (2012) 035210

Relevant for high energy tail of $\nu_\mu$ spectrum and intrinsic $\nu_\tau$ component in T2K
NA61 $p + C \rightarrow p + X @ 30$ GeV
The NA61 Targets

2 different graphite (carbon) targets

**Thin Carbon Target**
- length=2 cm, cross section 2.5x 2.5 cm$^2$
- $\rho = 1.84 \text{ g/cm}^3$
- $\sim 0.04 \, \lambda_{\text{int}}$

**T2K replica Target**
- length = 90 cm, Ø=2.6 cm
- $\rho = 1.83 \text{ g/cm}^3$
- $\sim 1.9 \, \lambda_{\text{int}}$

Important to study hadro-production with replica targets since $\sim 30\%$ of $\pi$, $K$ from secondary interactions, which in general are very difficult to model. Both targets required to model reliably the $\nu$ flux.

2007 pilot run
- Thin target: $\sim 660k$ triggers
- Replica target: $\sim 230k$ triggers

2009 run
- Thin target: $\sim 6 \text{ M triggers}$ $\Rightarrow 200 \text{ k } \pi^+$ tracks in T2K phase space
- Replica target: $\sim 2 \text{ M triggers}$

2010 run
- Replica target: $\sim 10 \text{ M triggers}$
we see only particles coming out of the target
we do not see what happens inside the target
hadron multiplicities are parametrized at the target surface
(no vertex reconstruction)
model dependence is reduced down to 10% as compared to 40%

comparison ν flux predictions
thin target vs. replica target
in very good agreement
just an accident or real?

N. Abgrall et al., arXiv:1207.2114 [hep-ex]
Conclusions

50 years of accelerator based neutrino beams have taught us a lot about particle physics in general and $\nu$ in particular

We have more to learn about understanding neutrino fluxes to get to precision cross section measurements and next steps in oscillation physics

Promising ideas for new beam techniques are developing

In 50 years we have gone from 30% uncertainties to 15% (10%) uncertainties, while increasing proton fluxes on target by $\sim 10^3 – 10^4$.

Hadro production measurements are essential to make further progress:
- flux prediction for conventional accelerator $\nu$ beams
- improved calculations for atmospheric $\nu$ flux
- MC generator tuning

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