Particle production vs energy

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Outline

• Targetry for Nufact
  - HARP
    • Large Angle Data analysis
    • Comparison with MC simulations
• Targetry for conventional neutrino beams
  - HARP for K2K, MINIBoone
  - NA56/SPY for WANF, CNGS, NuMI
• Targetry for EAS and atmospheric neutrino
• Future experiments
• Conclusions
Towards a Neutrino Factory: the challenges

- Target and collection (HARP/MERIT)
  - Maximize $\pi^+$ and $\pi^-$ production
  - Sustain high power (MW driver)
  - Optimize pion capture

  *INTENSE PROTON SOURCE (MW); GOOD COLLECTION SCHEME*

- Muon cooling (MICE)
  - Reduce $\mu^+/$$\mu^-$ phase space to capture as many muons as possible in an accelerator

- Muon acceleration
  - Has to be fast, because muons are short-lived!
Why dedicated Hadroproduction expts: conventional neutrino beams

Ingredients to compute a neutrino flux:
\( \pi \) (and k) production cross section (use same target and proton energy than proton driver of the experiment)

Reinteractions (take data with thin and thick target)

All the rest: Simulation of the neutrino line: An “easy” problem.
Simulation of neutrino beams

1. Primary target production
2. re-interactions in target
3. re-interactions in beamline

- Full Monte Carlo simulation (MARS, FLUKA, Geant 3 or 4)
  Good for study of systematics
- Fast simulation (parametrization of hadron production data, re-int models)
  Good for beamline optimization
Available data for simulations of $\nu$ beamlines

- Low energy beams (NuFact, K2K, MiniBOONE ...); mainly HARP
- High energy beams (WANF, CNGS, NuMI, ...): NA20, NA56/SPY and coming soon MIPP, NA61/SHINE
- In addition a lot of old not-dedicated hadron production experiments, mainly with big systematic errors and poor statistics

I will speak mainly of HARP (with a detour on NA56/SPY): see M.G. Catanesi’s talk for the others
Physics goals of HARP

2000 - 2001
Installation

2001 - 2002 Data taking

Systematic study of hadron production:
- Beam momentum: 3-15 GeV/c
- Target: from hydrogen to lead
- Acceptance over full solid angle
- Final state particle identification

- Input for prediction of neutrino fluxes for the MiniBooNE and K2K experiments
- Pion/ Kaon yield for the design of the proton driver of neutrino factories and SPL- based super-beams
- Input for precise calculation of the atmospheric neutrino flux and EAS
- Input for Monte Carlo generators (GEANT4, e.g. for LHC or space applications)
Harp detector layout and data taken.

Barrel spectrometer (TPC) + forward spectrometer (DCs) to cover the full solid angle, complemented by PID detectors.
• maximize $\pi^+(\pi^-)$ production yield as a function of:
  • proton energy
  • target material
  • geometry
  • collection efficiency ($p_L, p_T$)

• but different simulations show large discrepancies for $\pi$ production distributions, both in shape and normalization. Experimental knowledge is rather poor (large errors: poor acceptance, few materials studied)

⇒ **aim:** measure $p_T$ distribution with high precision for high Z targets
Beam momenta:  
3, 5, 8, 12 GeV/c  

Data:  
5% $\lambda_I$ targets Be, C, Al, Cu, Sn, Ta, Pb  

TPC tracks:  
>11 points and momentum measured and track originating in target  
PID selection  

 Corrections:  
Efficiency, absorption, PID, momentum and angle smearing by unfolding method  

Backgrounds:  
secondary interactions (simulated)  
low energy electrons and positrons (all from $\pi^0$)  
predicted from $\pi^+$ and $\pi^-$ spectra (iterative) and normalized to identified $e^+$-$e^-$.  

Full statistics analysed (“full spill data” with dynamic distortion corrections) although no significant difference is observed with the first analysis of the partial data (first 100-150 events in the spill).
The Target/TPC Region

- Target
- MWPCs
- TPC readout connectors
- Beam HALO veto
- RPC modules
Spectrometer performance

momentum resolution

Spectrometer performance

momentum calibration: cosmic rays elastic scattering

elastic scattering: absolute calibration of efficiency momentum angle (two spectrometers!)

PID: dE/dx used for analysis TOF used to determine efficiency

π-e PID with dE/dx

π-π PID with dE/dx

momentum calibration: cosmic rays elastic scattering
The two spectrometers match each other

HARP pBe 8.9 GeV/c

$0.5 \text{ GeV/c} \leq p < 0.75 \text{ GeV/c}$

$d^2\sigma/dp d\Omega$ [mb/(GeV/c sr)]

$\theta$ (rad)
9 angular bins: p-Ta $\pi^+$

Pion production yields

forward
$0.35 < \theta < 1.55$

backward
$1.55 < \theta < 2.15$
p-Ta $\pi^-$

HARP p-Ta $\pi^-$

Pion production yields

forward

$0.35 < \theta < 1.55$

backward

$1.55 < \theta < 2.15$
Neutrino factory study

Cross-sections to be fed into neutrino factory studies to find optimum design: Ta and Pb x-sections at large angle (see Eur. J. Phys C51 (2007) 787)
Comparisons with MC

Many comparisons with models from GEANT4 and MARS are being done, starting with C and Ta.

Some examples will be shown for C and Ta:
- Binary cascade
- Bertini cascade
- Quark-Gluon string models (QGSP)
- Frittiof (FTFP)
- LHEP
- MARS

Some models do a good job in some regions, but there is no model that describes all aspects of the data.
3 GeV/c p-Ta $\pi^{+/-}$
8 GeV/c $p$-Ta $\pi^{+/-}$ target

5% $\lambda$ target

MODELS
8 GeV/c p-C $\pi^{+/-}$

5% $\lambda$ target

MODELS
 Comparison with MC at Large Angle

1. Data available on many thin (5%) targets from light nuclei (Be) to heavy ones (Ta)
2. Comparisons with GEANT4 and MARS15 MonteCarlo show large discrepancies both in normalization and shape
   - Backward or central region production seems described better than more forward production
   - In general $\pi^+$ production is better described than $\pi^-$ production
   - At higher energies FTP models (from GEANT4) and MARS look better, at lower energies this is true for Bertini and binary cascade models (from GEANT4)
   - Parametrized models (such as LHEP) have big discrepancies

- CONCLUSIONS: MCs need tuning with HARP data for $p_{inc} < 15$ GeV/c
ν beams flux prediction

- **Energy, composition, geometry of a neutrino beam is determined by the development of the hadron interaction and cascade** ⇒ needs to know \( \pi \) spectra, \( K/\pi \) ratios
  - **K2K**: Al target, 12.9 GeV/c
    - Al targets 5%, 50%, 100% \( \lambda \) (all \( p_{\text{beam}} \)), K2K target replica (12.9 GeV/c)
    - special program with K2K replica target
  - **MiniBooNE**: Be target 8.9 GeV/c
    - Be targets: 5%, 50%, 100% \( \lambda \), MiniBoone target replica

Precise \( p_T \) and \( p_L \) spectra for extrapolation to far detectors and comparison between near and far detectors
HARP forward Particle identification

p (GeV/c) 0 1 2 3 4 5 6 7 8 9 10

\( \pi/p \) \hspace{1cm} TOF \hspace{1cm} CERENKOV
\( \pi/K \) \hspace{1cm} TOF \hspace{1cm} CERENKOV
\( \pi/e \) \hspace{1cm} CERENKOV \hspace{1cm} CALORIMETER

TOF for \( p = 2 \pm 0.25 \)  

Calorimeter  
E/p and E(1st layer)/E  
for p above pion threshold  

\( N_{\text{cherenkov}} \) for p below pion threshold
PID performance

\[ \beta = \frac{d}{tc} \]

- pions: 1-2%
- protons: 0.6 - 0.95

Cherenkov efficiency - pions

Cherenkov efficiency - protons

Data - solid points
Monte Carlo - dashed histogram
HARP Be 5% 8.9 GeV/c Results

HARP results (data points), Sanford-Wang parametrization of HARP results (histogram)

0.75<p<5 GeV/c
30<theta<210 mrad
relevance for MiniBooNE

Momentum and Angular distribution of pions decaying to a neutrino that passes through the MB detector.
HARP 12.9 GeV/c p+Al Results

HARP in black,
Sanford-Wang parametrization in red

Sanford-Wang parametrization

HARP data used to:
- in K2K and MiniBooNE beam MC
- Translate HARP pion production uncertainties into flux uncertainties
- Compare HARP results with previous results

HARP data on inclusive pion production fitted to Sanford-Wang parametrization:

\[
\frac{d^2\sigma(p+Al \to \pi^+ + X)}{dp d\Omega}(p, \theta) = c_1 p^2 (1 - \frac{p}{p_{beam}}) \exp[-c_3 \frac{p^4}{p_{beam}^4} - c_6 \theta (p - c_7 p_{beam} \cos^2 \theta)]
\]

where:
- \( X \): any other final state particle
- \( p_{beam} = 12.9 \): proton beam momentum (GeV/c)
- \( p, \theta \): \( \pi^+ \) momentum (GeV/c), angle (rad)
- \( d^2\sigma/(dp d\Omega) \) units: mb/(GeV/c sr), where \( d\Omega = 2\pi d(\cos \theta) \)
- \( c_1, ..., c_6 \): empirical fit parameters
p+Al versus GEANT4

$p + \text{Al} \rightarrow \pi^+ + \text{X}$ at 12.9 GeV/c

FTFP
QGSP
QGSC
Data
p+Be versus GEANT4

\[ \frac{d^2 \sigma}{dp d\Omega} \text{ (mb/GeV sr)} \]

\( p + \text{Be} \rightarrow \pi^+ + X \text{ at } 8.9 \text{ GeV/c} \)

- **30 - 60 mrad**
- **60 - 90 mrad**
- **90 - 120 mrad**
- **120 - 150 mrad**
- **150 - 180 mrad**
- **180 - 210 mrad**

FTFP
QGSP
QGSC
Data
A small detour: the NA56/SPY experiment at SPS

- Measure p, kaon fluxes by 450 GeV/c p on Be (5% precision) -> knowledge of neutrino spectra
- Measure k/p ratio (3% precision) -> knowledge $n_e/n_m$ ratio
- Equipped H6 beam from NA52 experiment in North Area
- Primary p flux measured by SEM
- Different Be targets (shapes, L)
- PID by TOF counters (low momenta) and Cerenkov (high momenta)

Available results were parametrized (BMPT parametrization) or used to tune available MC (such as Fluka). Used for the study of available high-energy neutrino beamlines: WANF at SPS, CNGS, NuMi
An application to NUMI (from M. Messier et al.)

- Comparison BMPT, Mars, GFLUKA in Minos near/far detector
Primary flux (70% p, 20% He, 10% heavier nuclei) is now considered to be known to better than 15% (AMS, Bess p spectra agree at 5% up to 100 GeV, worse for He).

Most of the uncertainty comes from the lack of data to construct and calibrate a reliable hadron interaction model.

Model-dependent extrapolations from the limited set of data leads to about 30% uncertainty in atmospheric fluxes.

→ cryogenic targets (or at least nearby C target data)
Extended Air Showers

Incoming protons and pions spectra: $\pi^+$ and $\pi^-$

- Several targets
- Forward direction
- Relevant energy range: 10-400 GeV
Hadron production experiments

Population of hadron-production phase-space for \( pA \rightarrow \pi X \) interactions.

\( \nu_\mu \) flux (represented by boxes) as a function of the parent and daughter energies.

Measurements.

- 1-2 \( p_T \) points
- 3-5 \( p_T \) points
- >5 \( p_T \) points

But with different targets (mainly Be)
Model comparison: HARP

\[ p + C \rightarrow \pi^+ + X \]
Model comparison: $p+C \rightarrow \pi^- + X$
\( \pi^+ + C \ @ 12 \text{ GeV/c} \) (lower statistics)

- stat error \( \sim 30-40\% \)
- syst error \( \sim 10\% \)
$\pi^- + \text{C } @ 12 \text{ GeV/c}$

(high statistics)

Stat error $\sim 10\%$

Syst error $\sim 10\%$
Measurements with N$_2$, O$_2$ cryogenic targets

HARP p–O$_2$ $\pi^-$

HARP p–O$_2$ $\pi^+$

Shape looks similar $\Rightarrow$ may use simpler C target data (solid, not cryogenic target)
Comparison with GEANT4
Covered phase space region

- New data sets
  \((p+C, \pi^+ + C \text{ and } \pi^- + C, pO_2, pN_2 \text{ at } 12 \text{ GeV/c})\)
- Important phase space region covered
- Data available for model tuning and simulations
- Results on N2 and O2 data are preliminary

HARP (PS)
Data with incident $\pi^+/\pi^-$

Just an example for FW production

HARP paper in preparation

- All thin target data taken in pion beams also available
- Interesting to tune models for re-interactions (and shower calculations in calorimeters etc.)
Next measurements/analyses

<table>
<thead>
<tr>
<th>Energy range and phase space of interest</th>
<th>0-300 mrad</th>
</tr>
</thead>
<tbody>
<tr>
<td>8-10000 GeV</td>
<td>p, 0.5-11.0 GeV/c, θ</td>
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p+C and π+C @ 30, 40, 50, 158GeV/c

p+C and π+C@3-15 GeV/c

N₂, O₂ targets with p+C and π+C at 20, 60, 120GeV/c
Summary

• HARP has provided results useful for conventional \( \nu \) beams study, \( \nu \) factory design, EAS, atmospheric \( \nu \) studies and in addition for general MC tuning (Geant4, FLUKA ...) with full solid angle coverage, good PID identification on targets from Be to Pb at low energies (< 15 GeV) with small total errors (syst+stat < 15 %). About 10 physics paper published or submitted

• More HARP results coming: forward production with incident pions, protons on Be to Ta targets; production with long targets, ...

• Comparison with available MC show some problems