Results and Status from HARP and MIPP

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Neutrino 08, May 25-31, Christchurch (New Zealand)

Outline

- The experiments
- The data
- Hadron production for neutrino physics:
  - *Results for conventional accelerator-based neutrino beams*
  - *Results for advanced neutrino sources*
  - *Results for atmospheric neutrinos*
- Future prospects

See also MIPP poster contribution by J. Paley

The Experiments

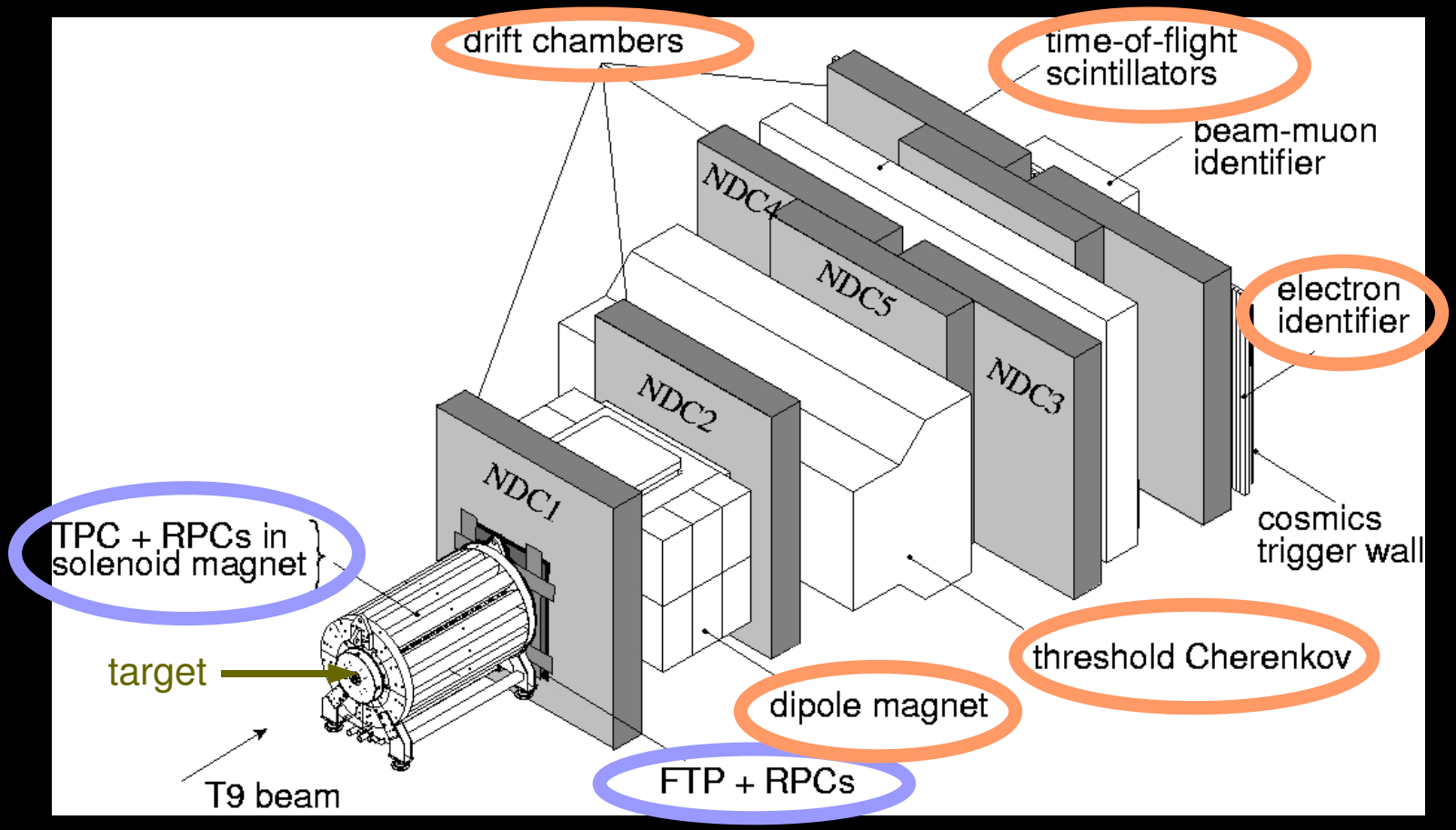
HARP (CERN, 2001-2002)

Forward Spectrometer:

- track reconstruction with drift chambers + dipole magnet
- PID with threshold Cherenkov + time-of-flight wall (+ electromagnetic calorimeter)

Large-Angle Spectrometer:

- track reconstruction and PID with solenoid magnet + TPC (+ RPCs)



MIPP (FNAL, 2004-2006)

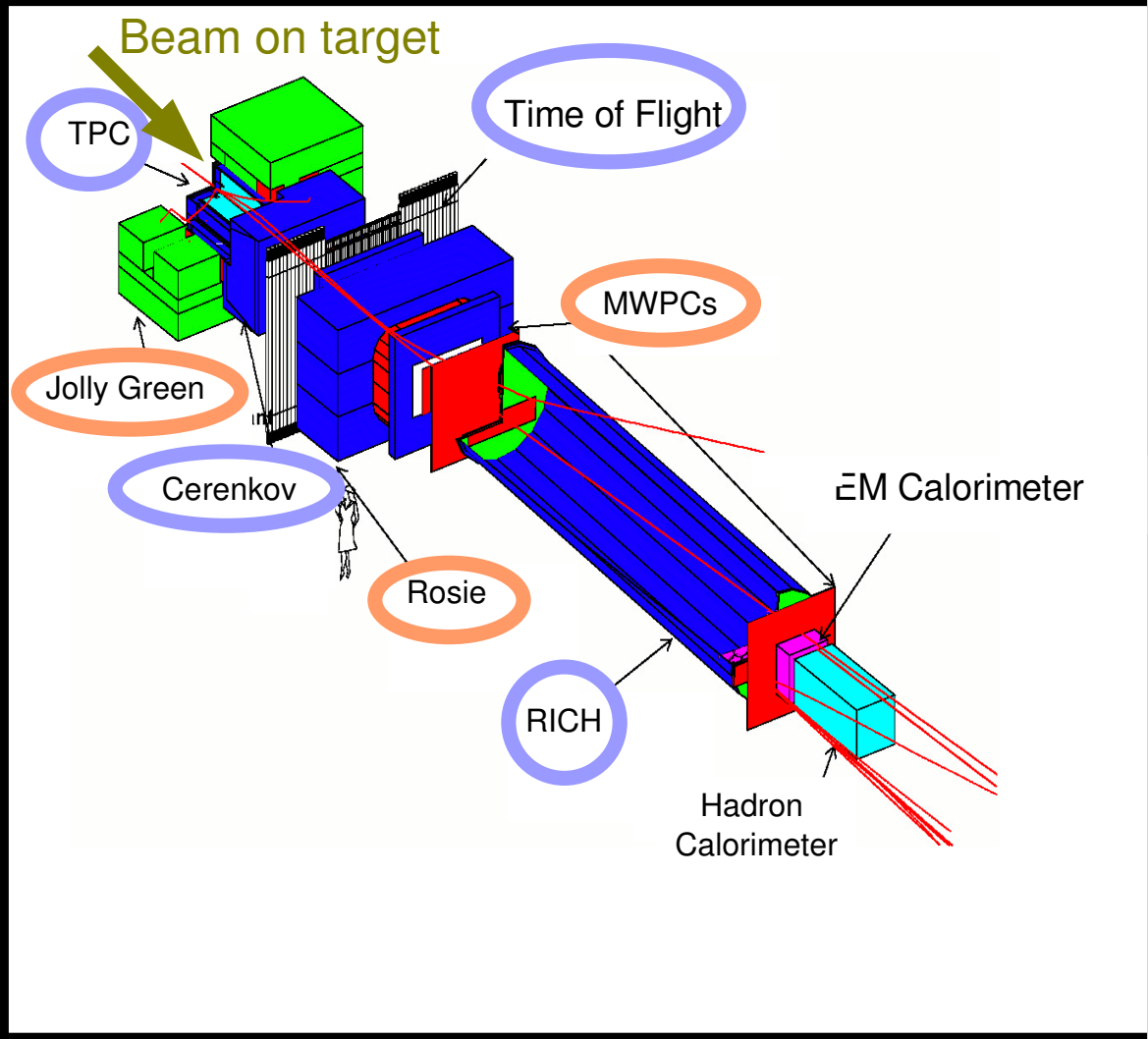
Track Reconstruction:

- two dipole magnets deflecting in opposite directions
- TPC + drift chambers + PWCs

Particle Identification:

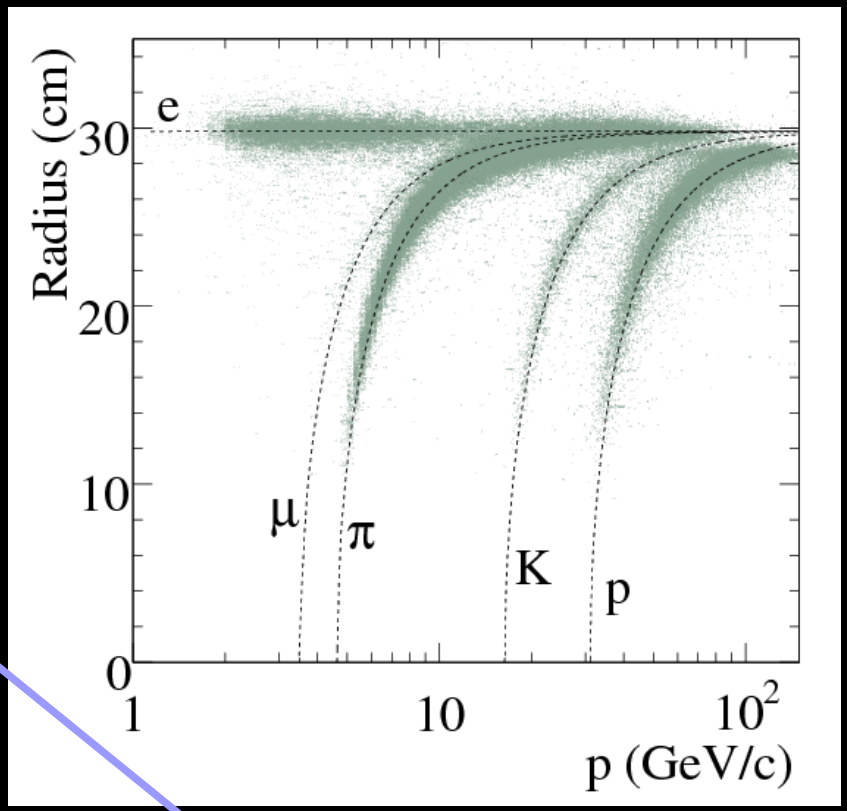
- Time Projection Chamber
- Time-of-Flight Wall
- Threshold Cherenkov Detector
- Ring Imaging Cherenkov Detector

•*Results presented here based on RICH-only PID*

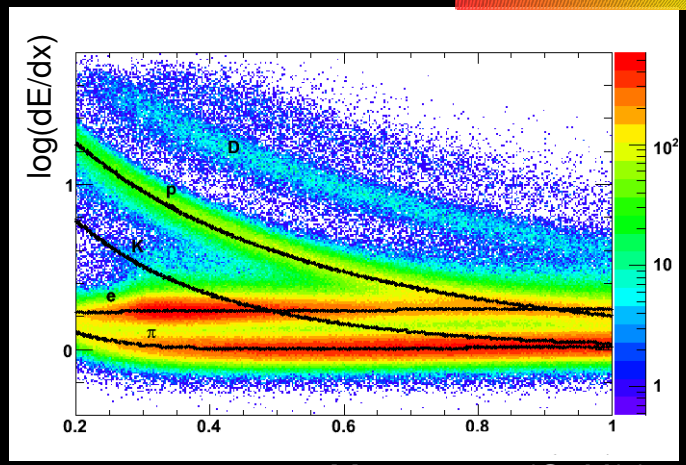


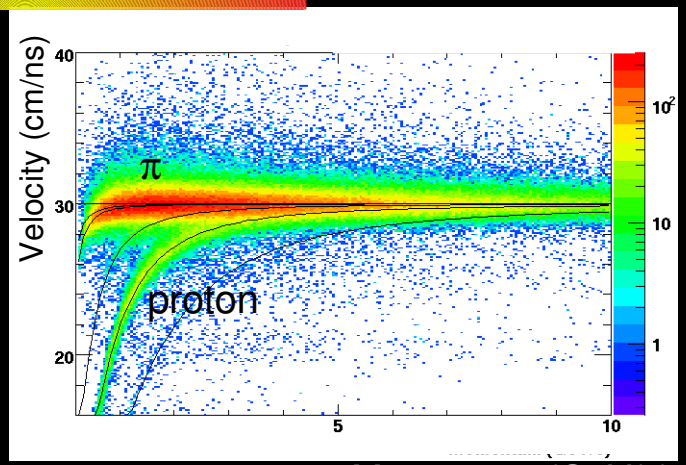
PID in MIPP

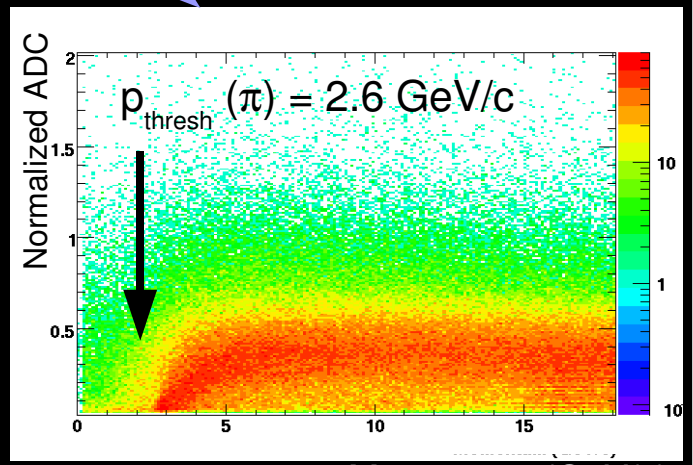
- PID from measurements of secondary momentum and:
  - RICH ring radius for p > 17 GeV/c
  - Cherenkov light yield for 2.5 < p (GeV/c) < 17
  - ToF Velocity for 0.5 < p (GeV/c) < 2
  - TPC dE/dx for 0.1 < p (GeV(c) < 1



J. Paley's MIPP Neutrino 08 poster







The Data

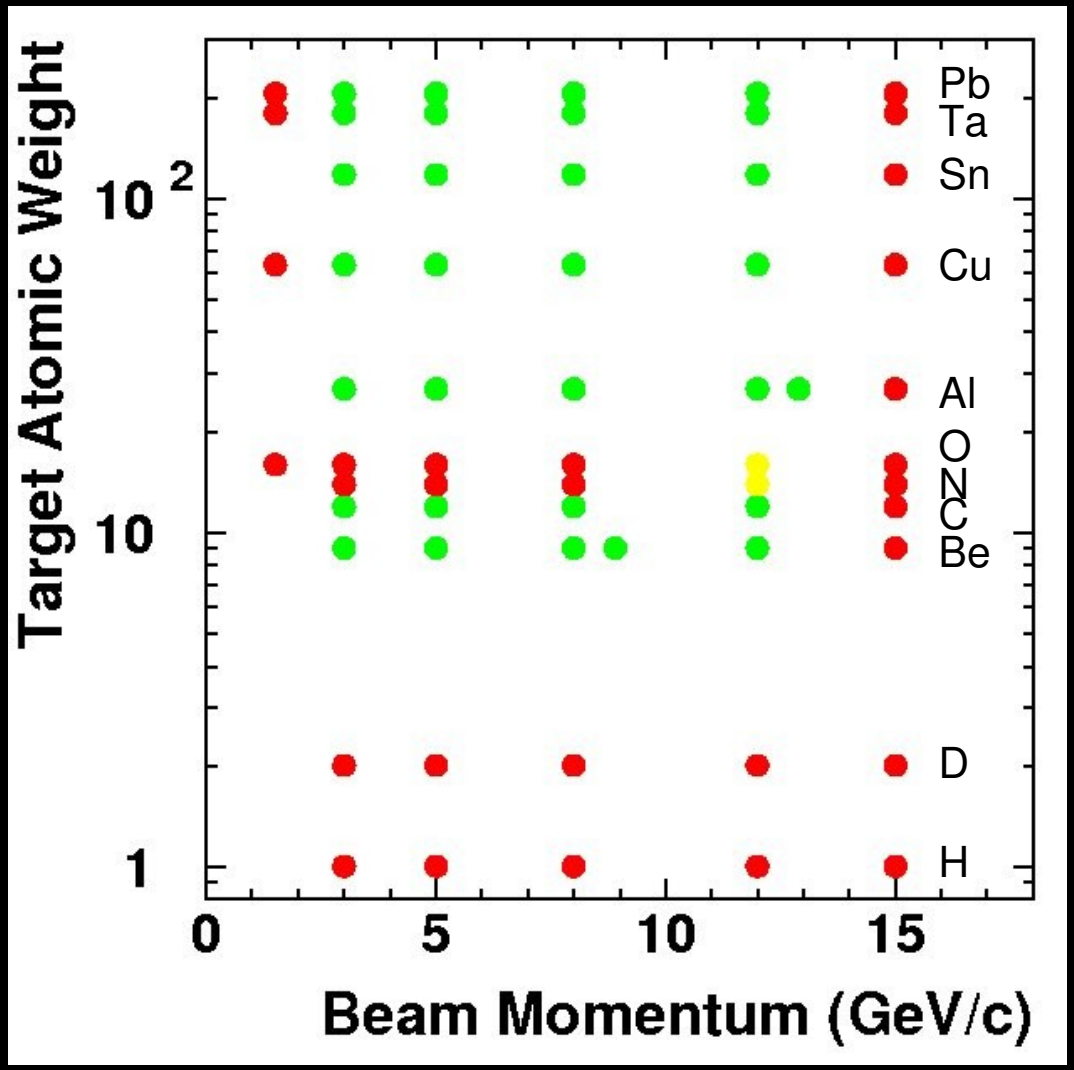
HARP (Beam, Target) Settings

Beam Settings:

- 2-15 GeV/c momenta
- Both postively and negatively-charged beams
- Pure p, π^+, π^- beams

Target Settings:

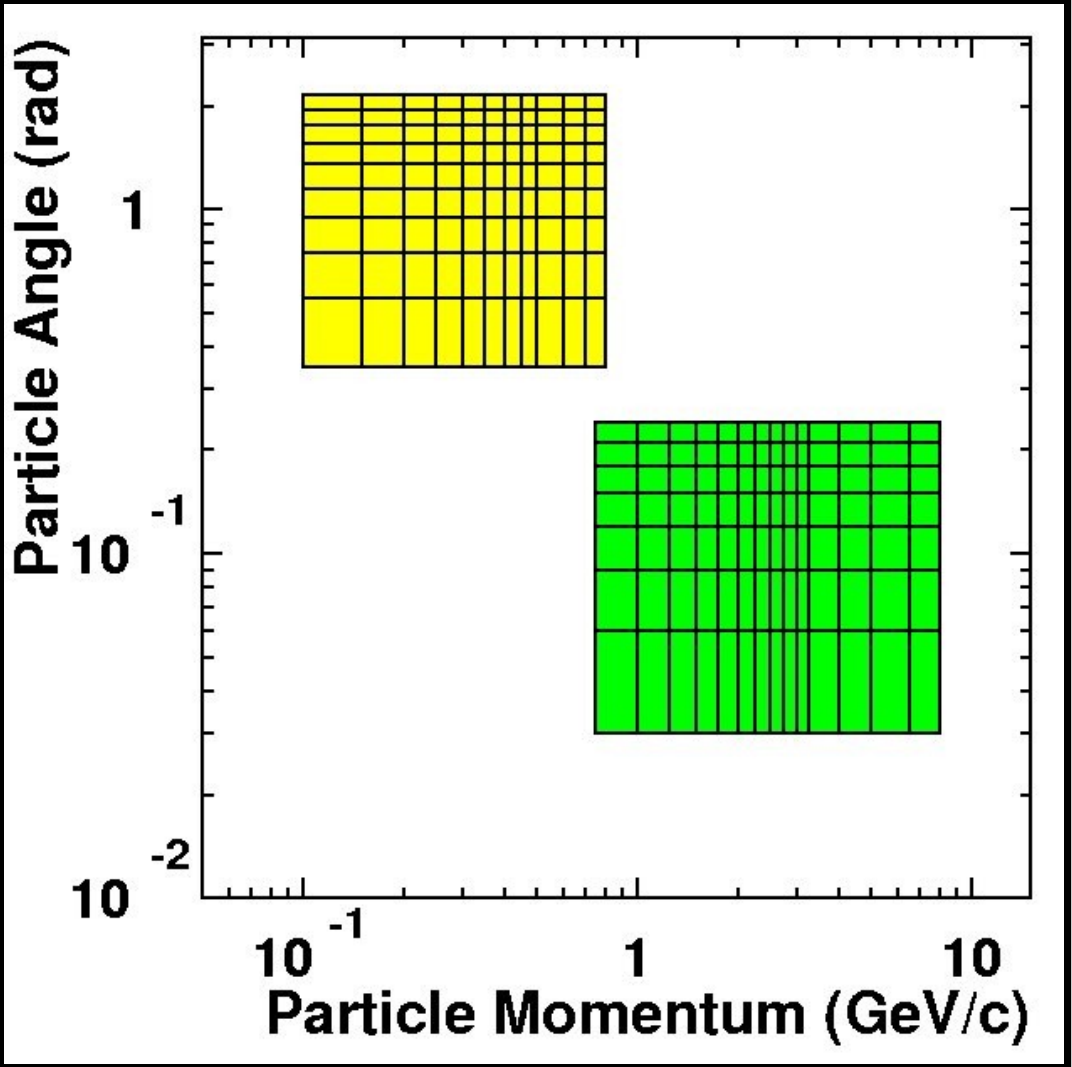
- From H to Pb (A = 1-207)
- 2%-200% λ_I thicknesses
- Only λ_I=5% discussed here



- Some results published (2006-2008), more to come
- Results to be published
- Data collected

HARP Particle Production Phase Space Measured

- π^+, π^-, proton production
- Regions indicate phase space covered:
  - Forward spectrometer:
    $0.75 < p$ (GeV/c) < 8
    $30 < \theta$ (mrad) < 240
  - Large-angle spectrometer:
    $0.1 < p$ (GeV/c) < 0.8
    $350 < \theta$ (mrad) < 2150
- Lines within regions indicate binning



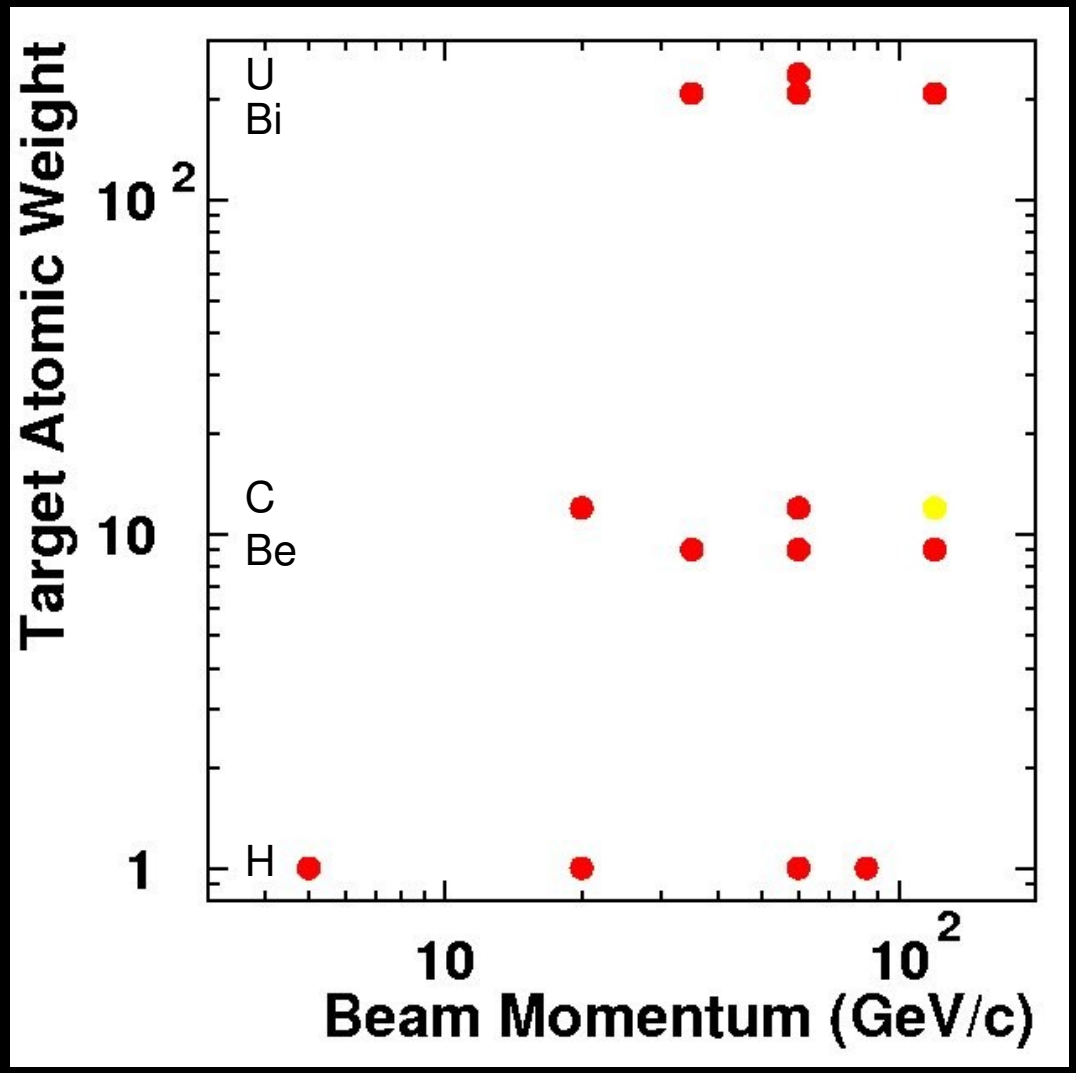
MIPP (Beam, Target) Settings

Beam Settings:

- 20-120 GeV/c momenta
- Both postively and negatively-charged beams
- Pure p, $\pi^{\pm}$, $K^{\pm}$ beams

Target Settings:

- From H to U (A = 1-238)
- 2%-165% λ_I thicknesses
- λ_I=2% and 165% (NuMI) discussed here



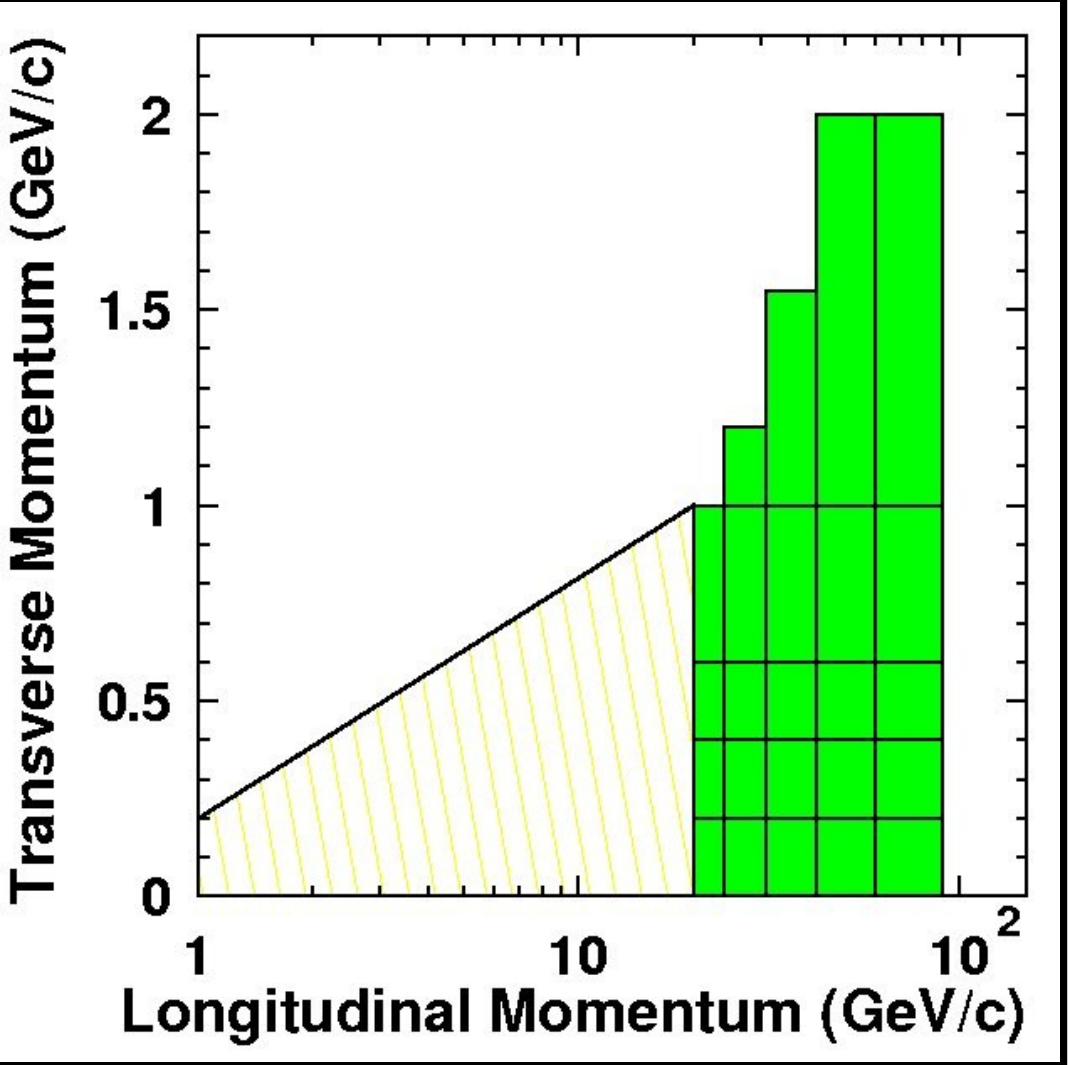
Preliminary Results

Collected

MIPP Particle Production Phase Space Measured

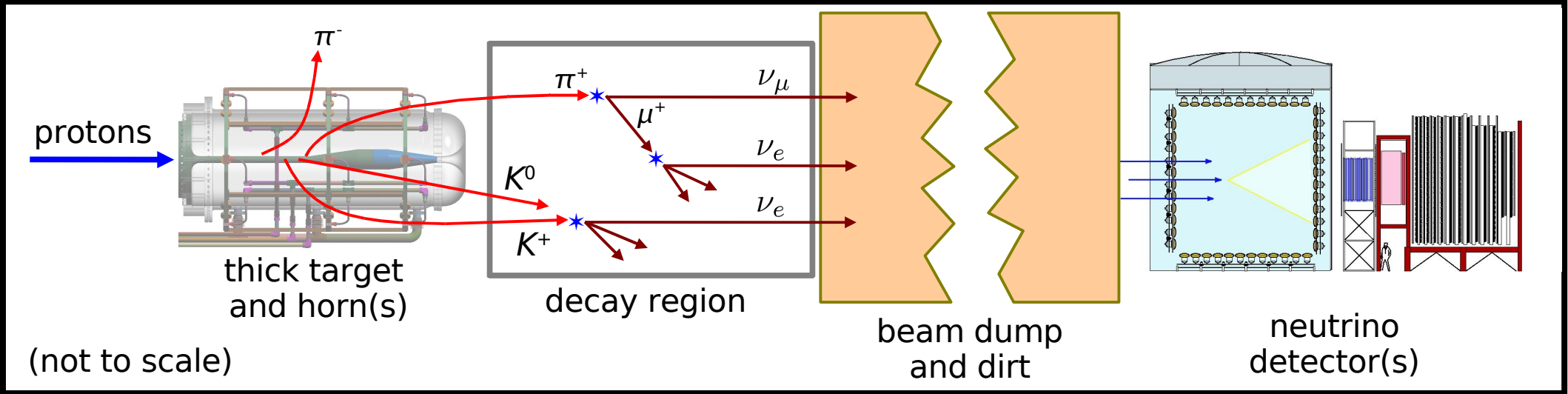
- π^+, π^-, K^+, K^- production
- Regions indicate phase space covered:
  - Results with RICH-only PID:

  $20 < p$ (GeV/c) < 90
  $0 < p_t$ (GeV/c) < 2
- Lines within regions indicate binning
- Use of Cherenkov, ToF, TPC will allow to extend PID to lower secondary particle momenta



Results For Conventional Accelerator-Based Neutrino Beams

Conventional Accelerator-Based Neutrino Beams

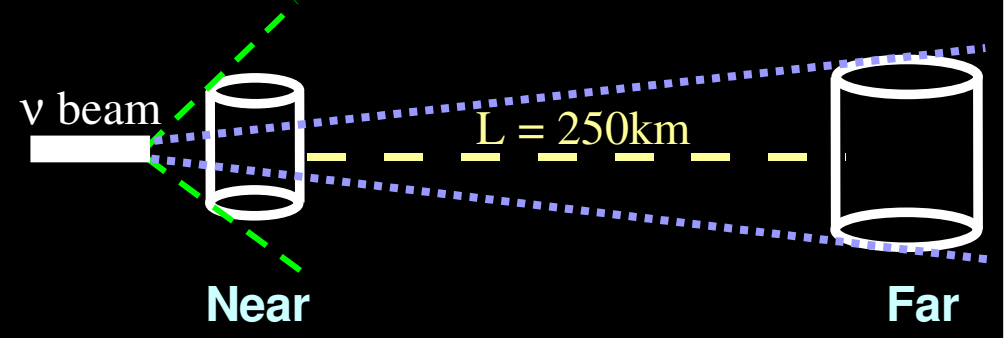


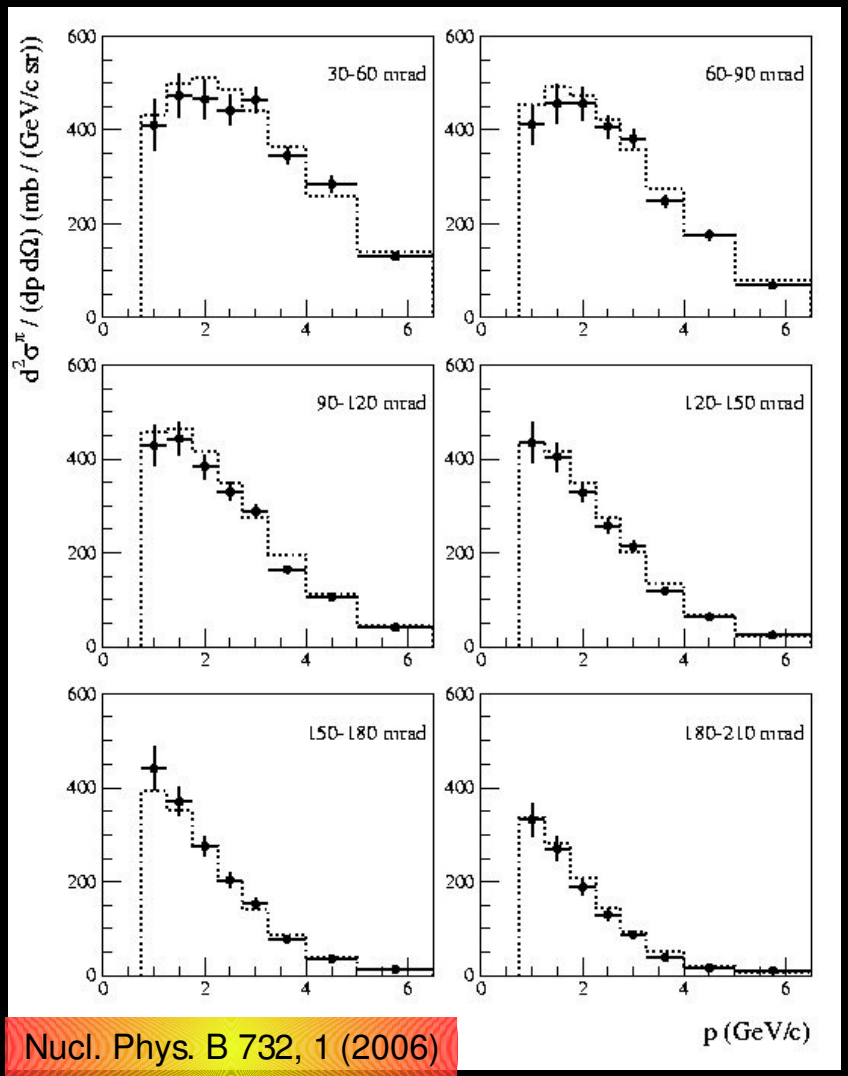
Challenges:

- Hadron production uncertainties have big impact on neutrino flux predictions: *overall flux, energy spectrum, flavor composition, etc.*
- Neutrino rate measurements: degeneracy between ν flux and ν cross-sections
- Oscillation experiments alleviate impact of flux uncertainties with two-detector setups and detectors tagging neutrino flavors
- Still, hadron production affects flux extrapolation between detector sites, and relation between, eg, muon and electron neutrino fluxes

Where we left off at Neutrino 06: HARP+K2K

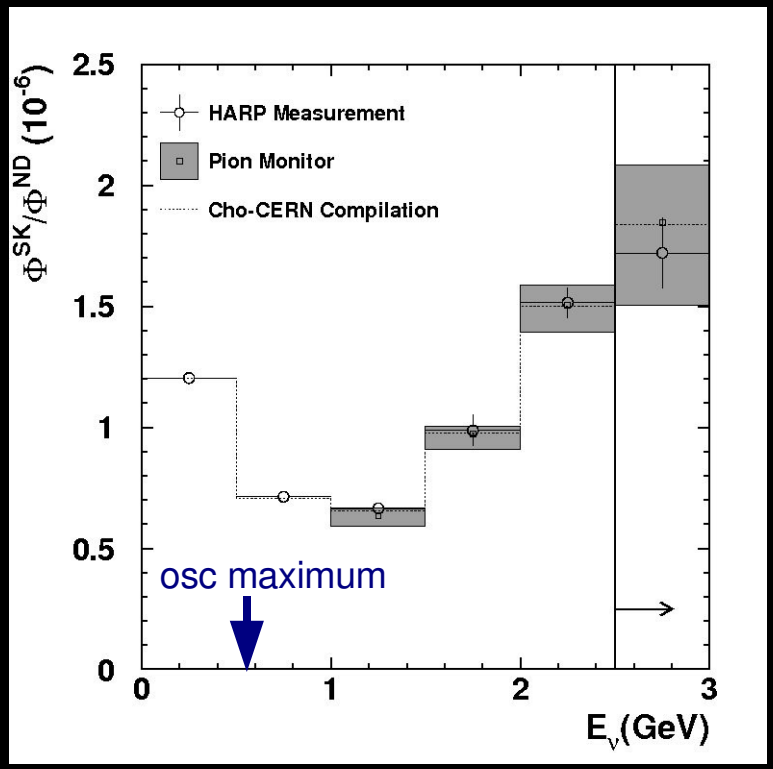
Experiment: HARP
Beam particle: proton
Beam momentum: 12.9 GeV/c
Target Material: Al
Target Thickness: 5% λ_I
Produced particle: π^+





Nucl. Phys. B 732, 1 (2006)

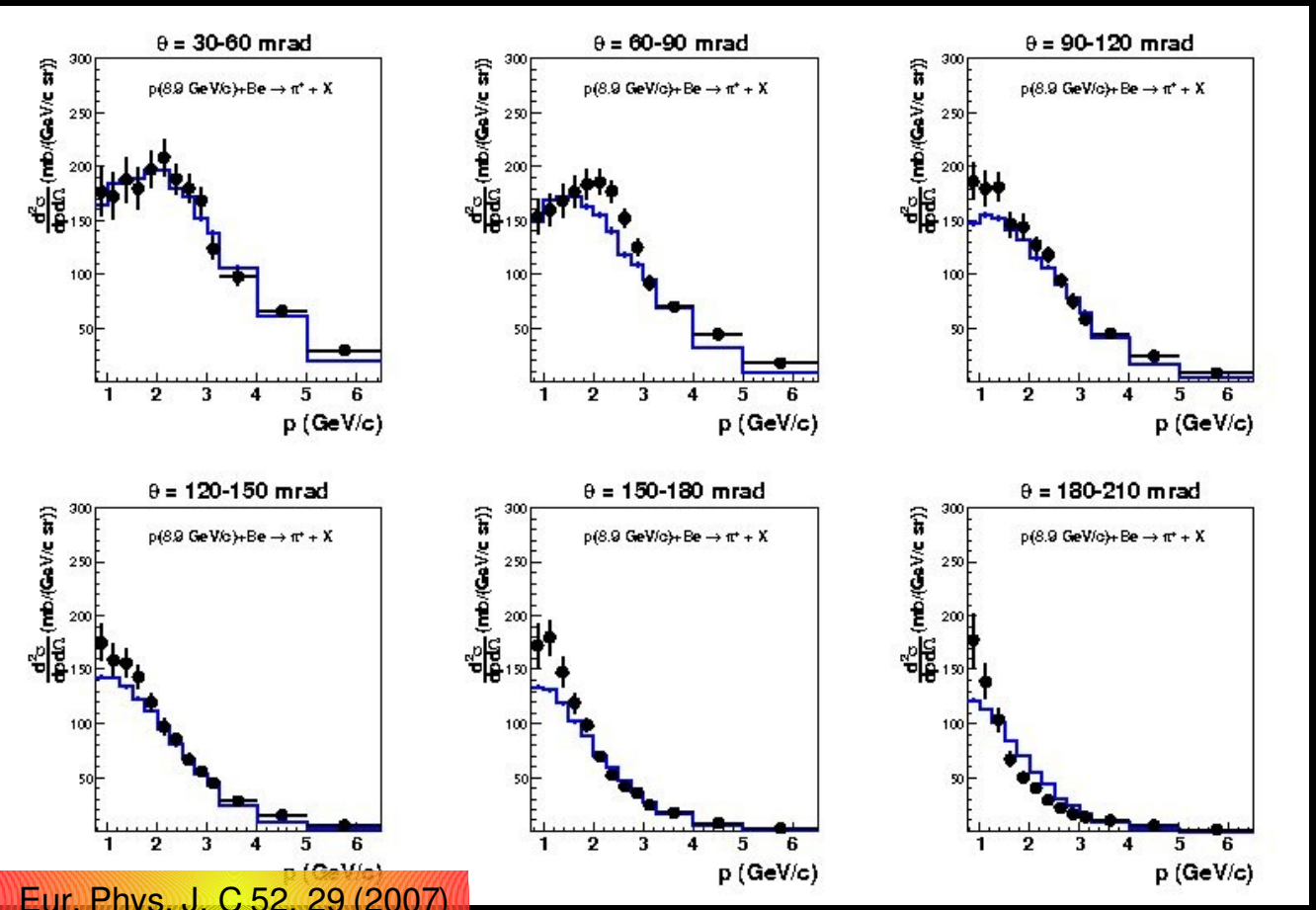
K2K Far-to-near flux ratio



- F/N contribution to uncertainty in number of unoscillated muon neutrinos expected at Super-K reduced from 5.1% to 2.9% with HARP

Experiment: HARP
Beam particle: proton
Beam momentum: 8.9 GeV/c
Target Material: Be
Target Thickness: 5% λ_I
Produced particle: π^+

Same (beam, target material) as FNAL Booster Neutrino Beam serving Mini/SciBooNE

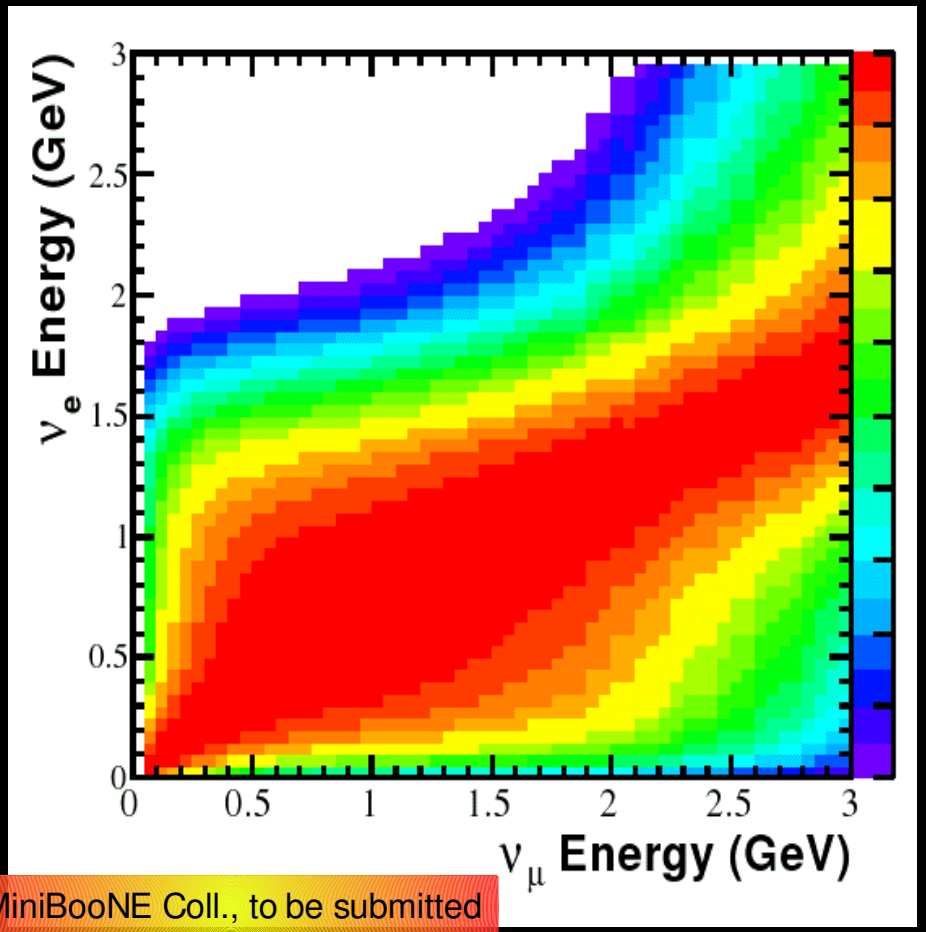


Eur. Phys. J. C 52, 29 (2007)

- 5% measurement over 0.75<p<6.5 GeV/c, 30<θ<210 mrad
- 10% bin-by-bin meas. (72 data points)
- Compares well with beam momentum-rescaled BNL E910 at 6, 12 GeV/c
- Blue histogram is beam MC prediction tuned with HARP+E910
- Preliminary proton, π^- production results also:
  - π^-: useful ongoing BNB antineutrino run
  - proton: reinteraction effects in BNB thick target

Implications for MiniBooNE, SciBooNE

- **MiniBooNE $\nu_\mu \to \nu_e$ oscillations:**
  HARP π^+ production + MB ν_μ interaction measurements put tight constraints on beam ν_e contamination from $\pi^+ \to \mu^+ \to \nu_e$, allowing not to spoil $\nu_\mu \to \nu_e$ sensitivity

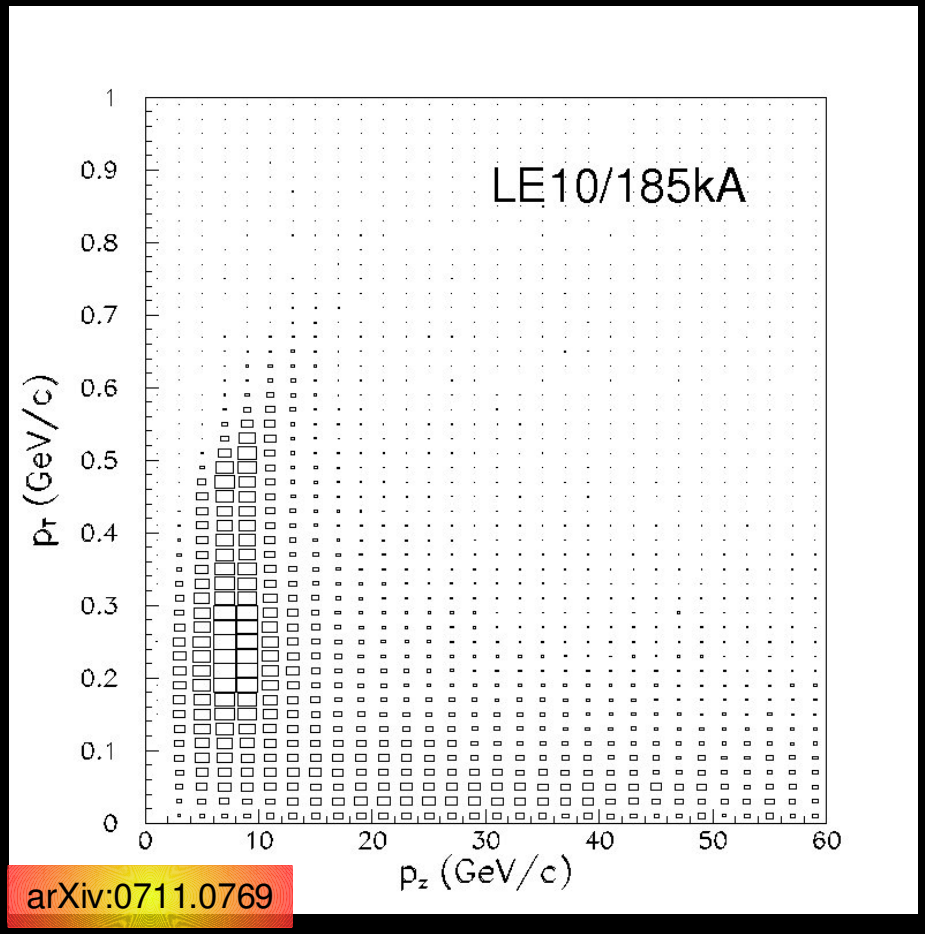


MiniBooNE Coll., to be submitted

- **SciBooNE/MiniBooNE neutrino cross section measurements:**
  Early estimates: 16% ν_μ flux normalization uncertainty from HARP π^+ production data.
  Ongoing work to reduce this by factor >2 via model-independent use of HARP data

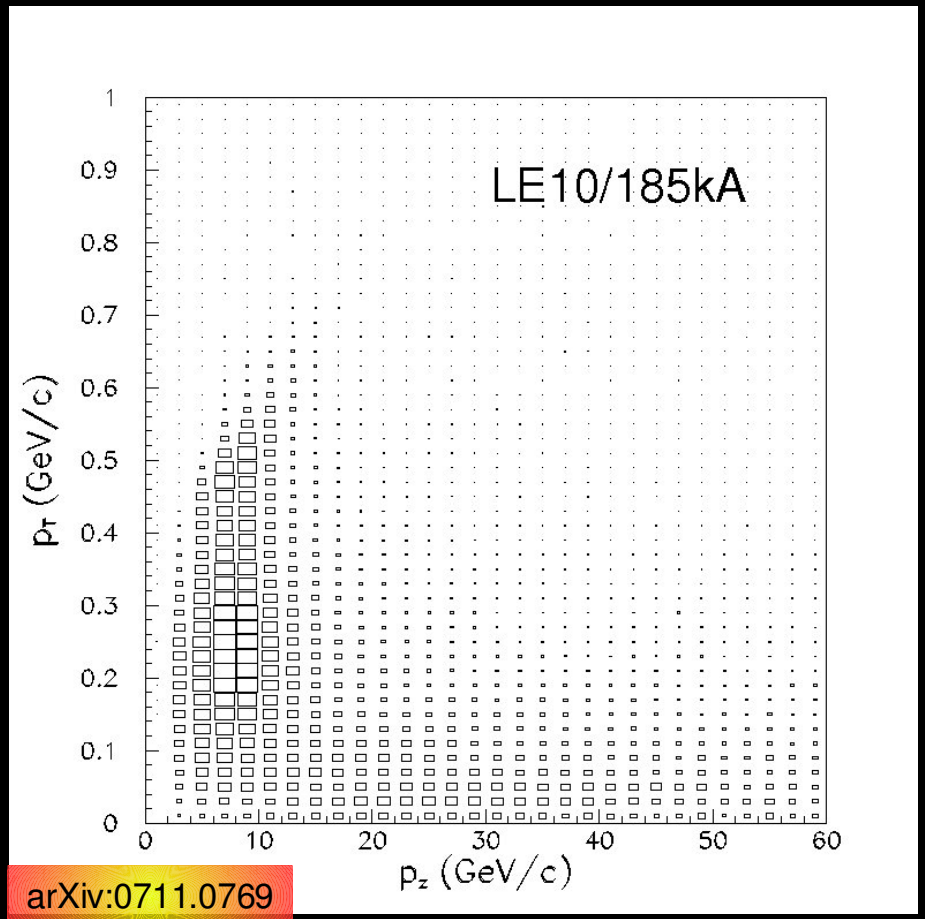
Hadron Production and MINOS

Phase space at production of π^+'s producing ν_μ CC interactions in MINOS far:



Hadron Production and MINOS

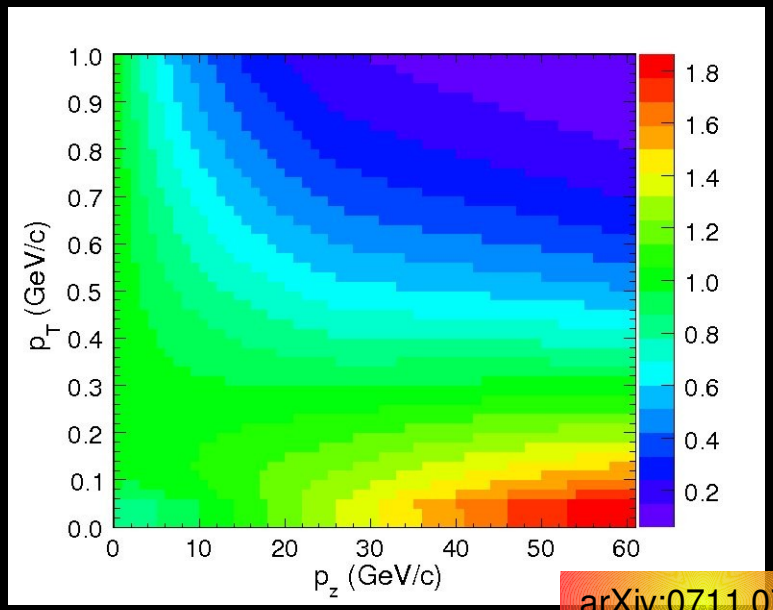
Phase space at production of π^+'s producing ν_μ CC interactions in MINOS far:



arXiv:0711.0769

- Hadron production constrained in two ways:
  - **1) MINOS near spectrum fit**
    Several beam configurations and fit parameters, including pion (p_z, p_t) yields and kaon yield normalization

π^+ weights wrt FLUKA MC from spectrum fit:



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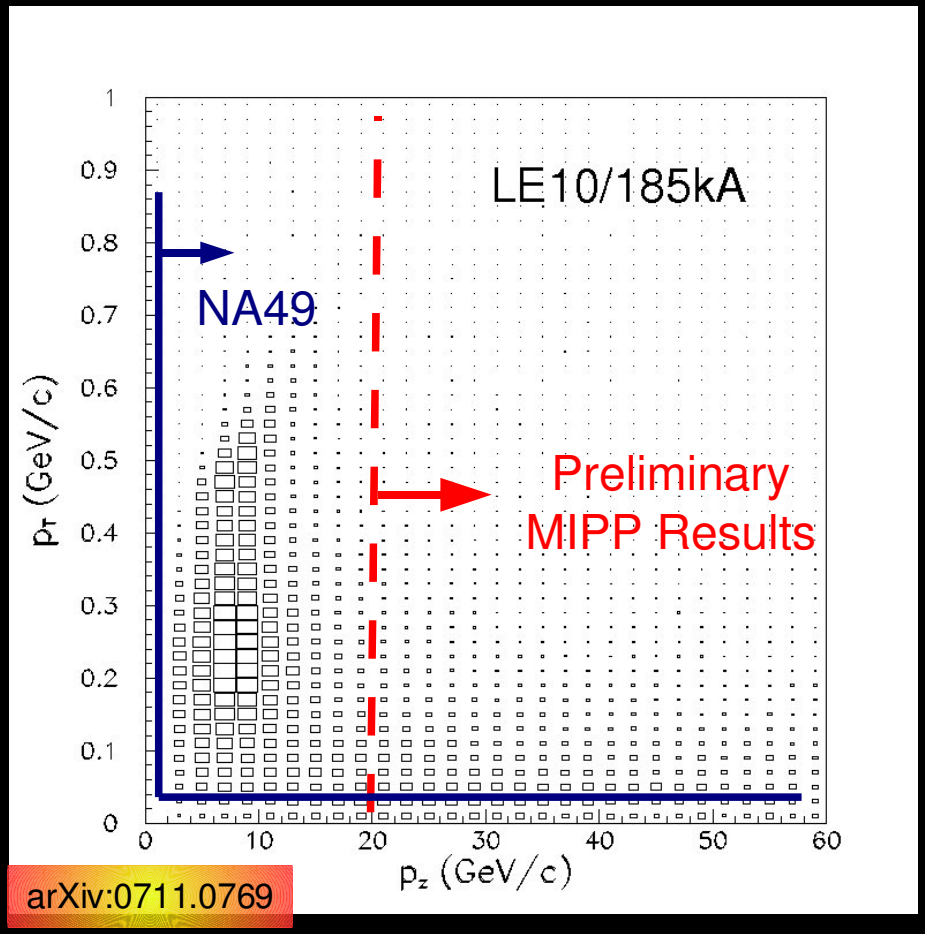
Hadron Production and MINOS

Phase space at production of π^+'s producing ν_μ CC interactions in MINOS far:



•Hadron production constrained in two ways:

2) Hadron production data

MIPP

- preliminary results only cover high E_ν
- NuMI beam momentum: 120 GeV/c
- both thin C and NuMI targets
- preliminary: fully corrected $\pi^\pm$, $K^\pm$ particle yield ratios only
- *$K^\pm$ important for MINOS ν_μ -> ν_e*

NA49

- excellent phase space coverage
- higher beam momentum: 158 GeV/c
- thin C target
- $\pi^\pm$ production cross sections

Experiment: MIPP
Beam particle: proton
Beam momentum: 120 GeV/c
Target Material: C
Target Thickness: 2% λ_I,NuMI
Produced particle: $\pi^{\pm}$, $K^{\pm}$

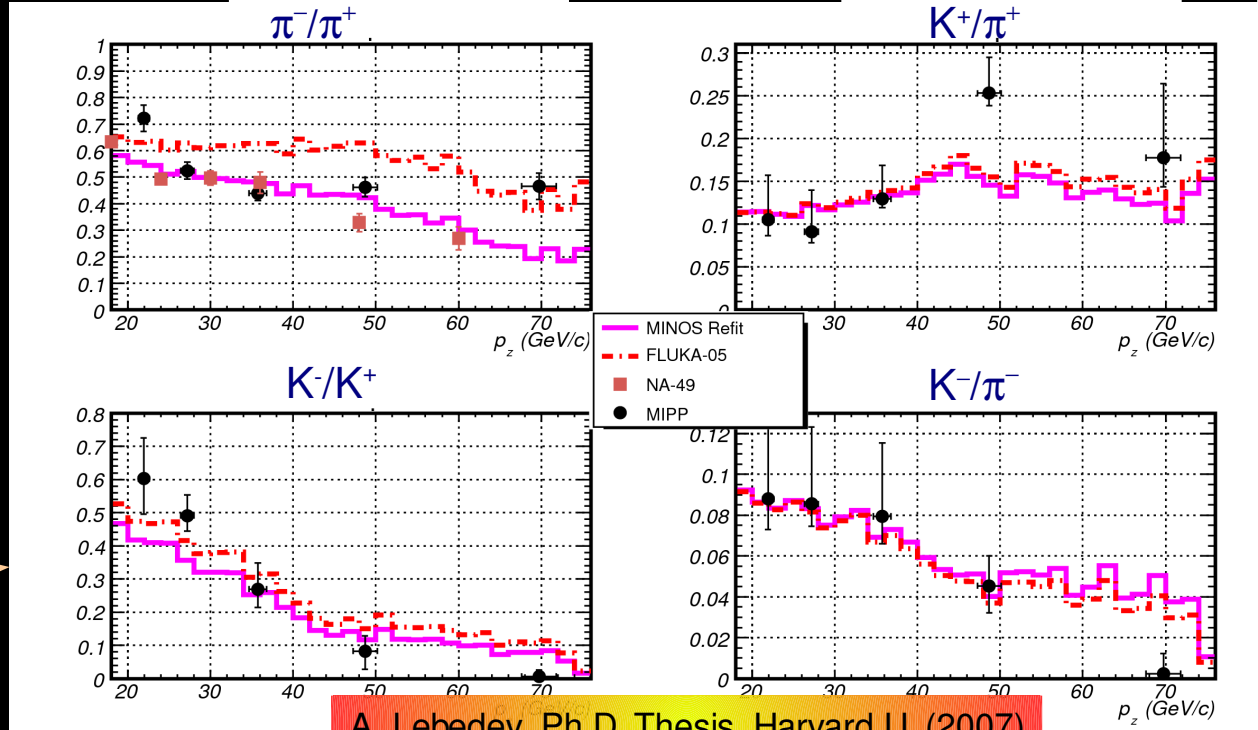
- p_t < 0.2 GeV/c particle ratios for:
  - thin C target
  - NuMI target

- Errors include preliminary systematic uncertainty evaluation

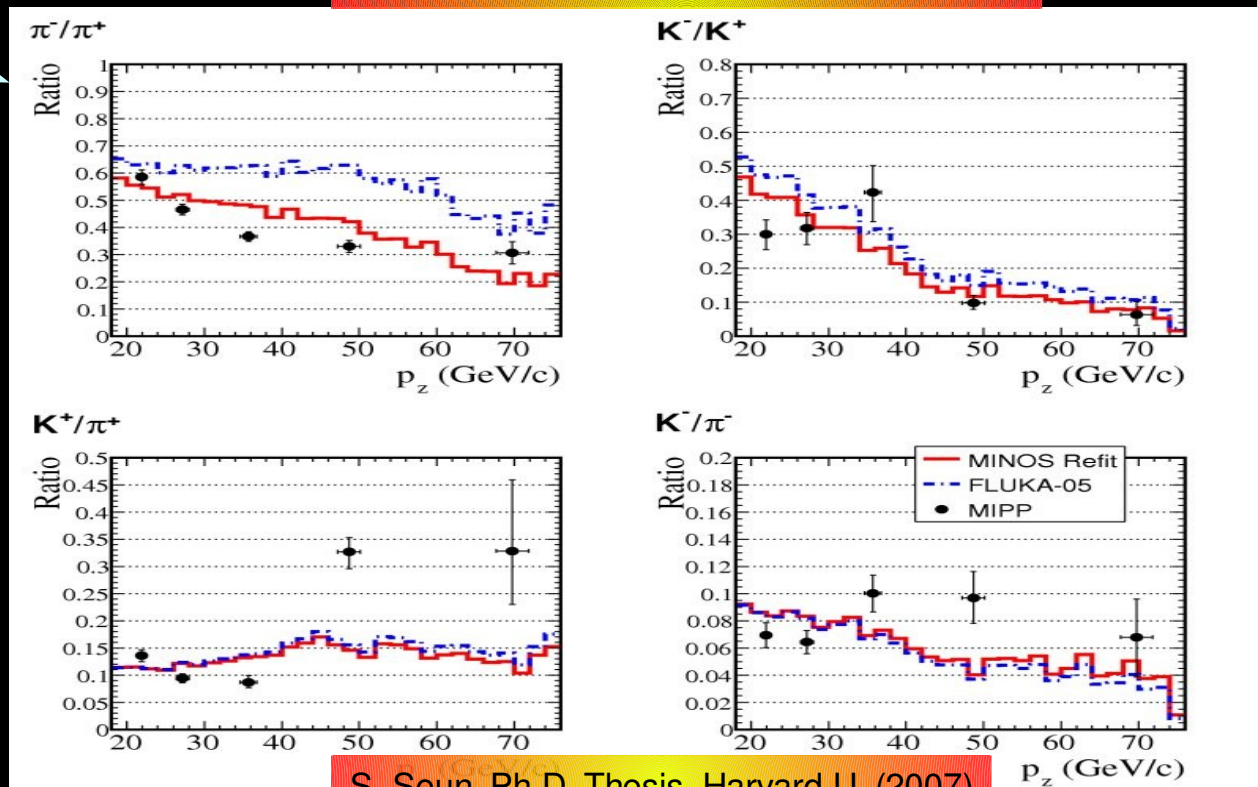
- Good agreement between thin and NuMI particle ratios

- Reasonable agreement of MIPP data with NA49 and MINOS spectrum fit results up to p ~ 40 GeV/c

- Discrepancies to investigate at high momenta



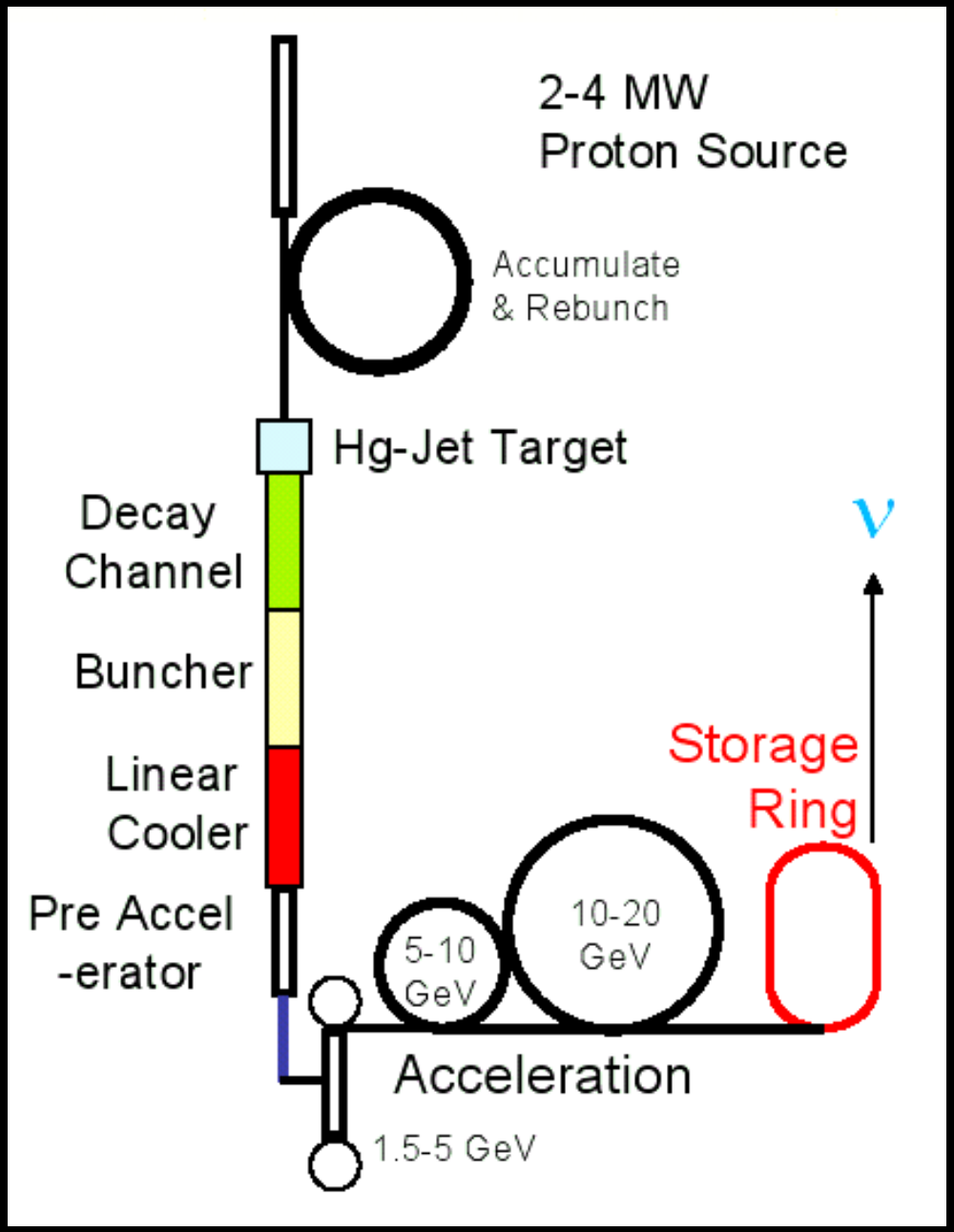
A. Lebedev, Ph.D. Thesis, Harvard U. (2007)



S. Seun, Ph.D. Thesis, Harvard U. (2007)

Results For Advanced Neutrino Sources

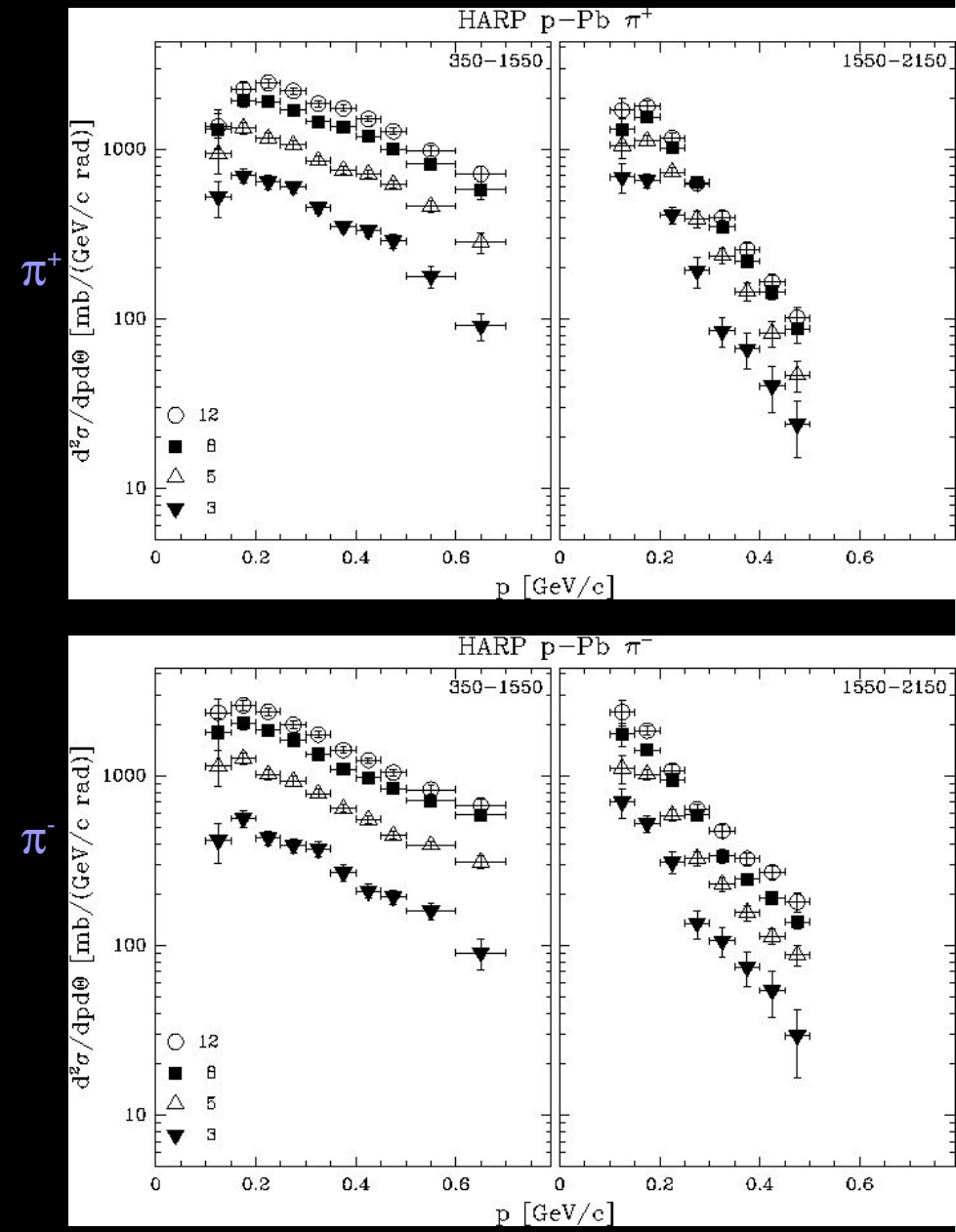
Neutrino Factory



- Proposed idea to store 4-50 GeV muons in a ring with long straight sections
- Stored beam properties and muon decay kinematics well known
  -> small neutrino flux uncertainties
- Challenge here is not flux uncertainty, but flux optimization:
  - need to optimize collection efficiency of π^+ and π^- produced in the collisions of protons with high-Z target (eg, Hg)
  - which proton beam momentum is best, which range acceptable?
  - accurate knowledge of produced pion kinematics needed for detailed design

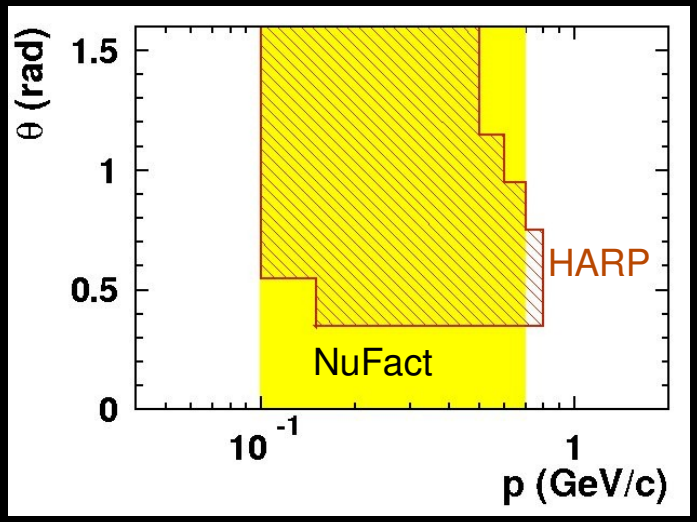
Experiment: HARP
Beam particle: proton
Beam momentum: 3-12 GeV/c
Target Material: Pb
Target Thickness: 5% λ_I
Produced particle: $\pi^{\pm}$

Forward production Backward production



Eur. Phys. J. C 54, 37 (2008)

- $\pi^{\pm}$ production measured over
  $0.1 < p$ (GeV/c) < 0.8, $350 < \theta$ (mrad) < 2150
- Good match with "typical" neutrino factory acceptance (~70%, design-dependent)

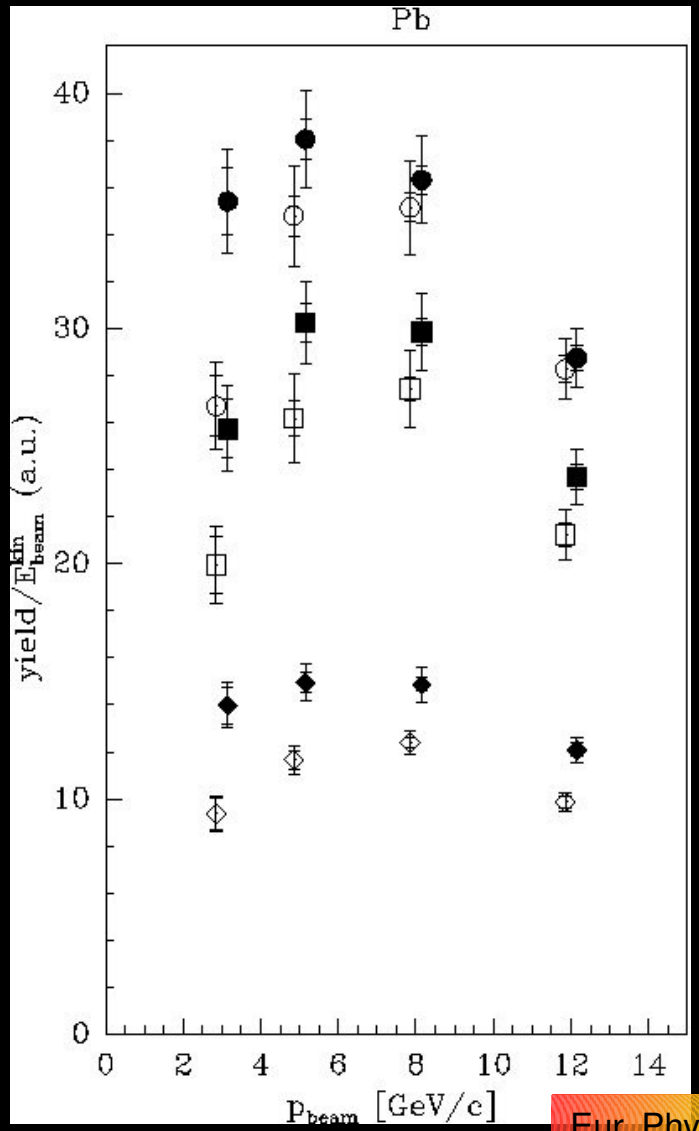


Implications for Neutrino Factory Designs

- Pion yield normalized to beam proton kinetic energy
- Restricted phase space shown most representative for NuFact designs
- Optimum yield in HARP kinematic coverage for 5-8 GeV/c beam momenta
- Same conclusions for Ta target results

Eur. Phys. J. C 51, 787 (2007)

- Quantitative optimization possible with detailed spectral information available: ~100 (p,θ) data points for 4 beam momentum settings (3-12 GeV/c) each



Full forward acceptance

↓

350 < θ (mrad) < 950

↓

0.25 < p (GeV/c) < 0.50

Filled: π^+
Empty: π^-

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Results For

Atmospheric Neutrinos

Atmospheric Neutrinos

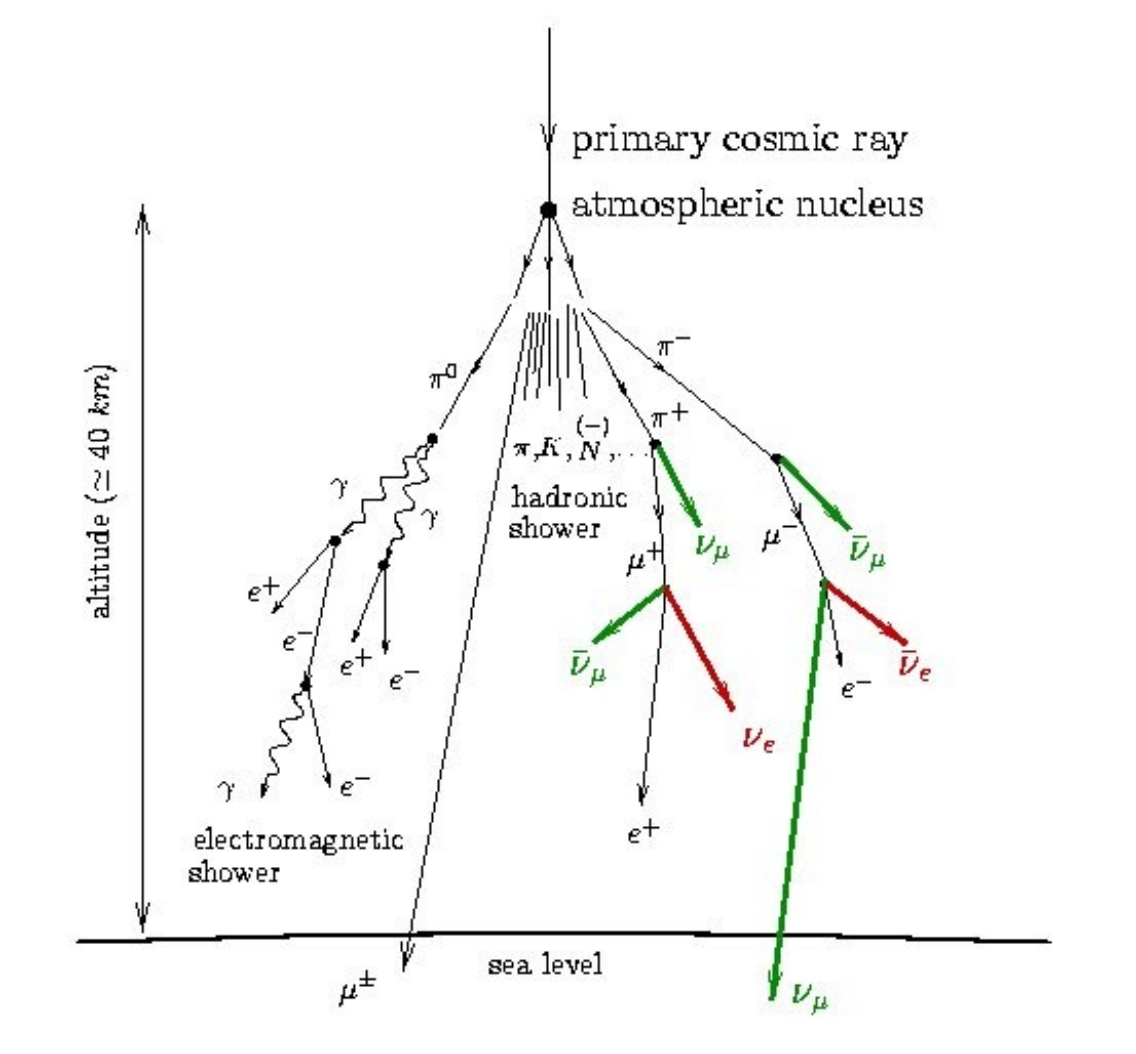
•Challenges for accurate atmospheric neutrino flux predictions:

- Primary cosmic ray spectrum
- Hadronic interactions determining shower development, particularly interaction of primary with nuclei

•As for accelerator-based beams, unoscillated flux ratios (flavor, direction) better known than absolute fluxes, but not error-free!

• Rule-of-thumb: E(primary) / E(ν) ~ 10

-> HARP data for sub-GeV neutrinos, MIPP data for multi-GeV neutrinos

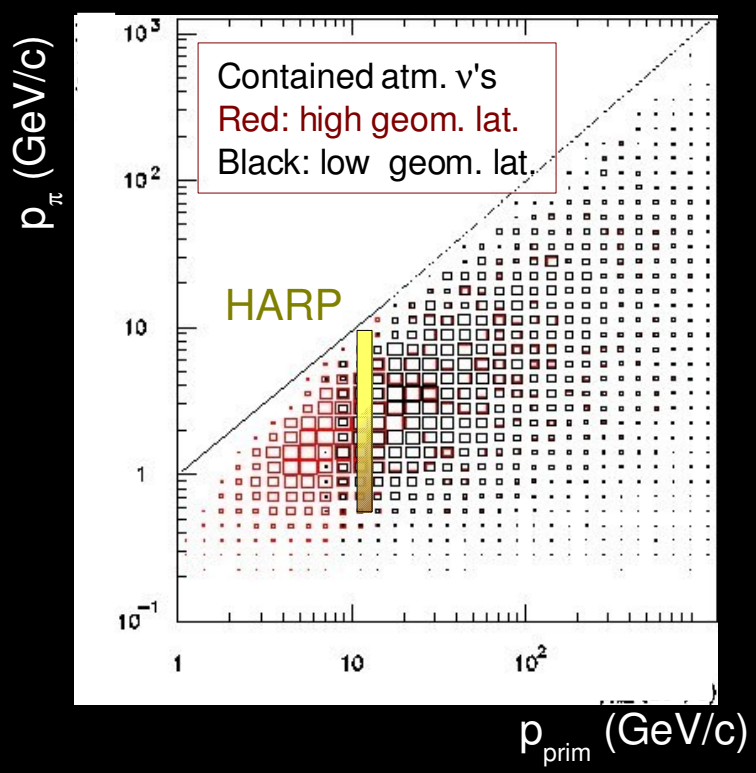


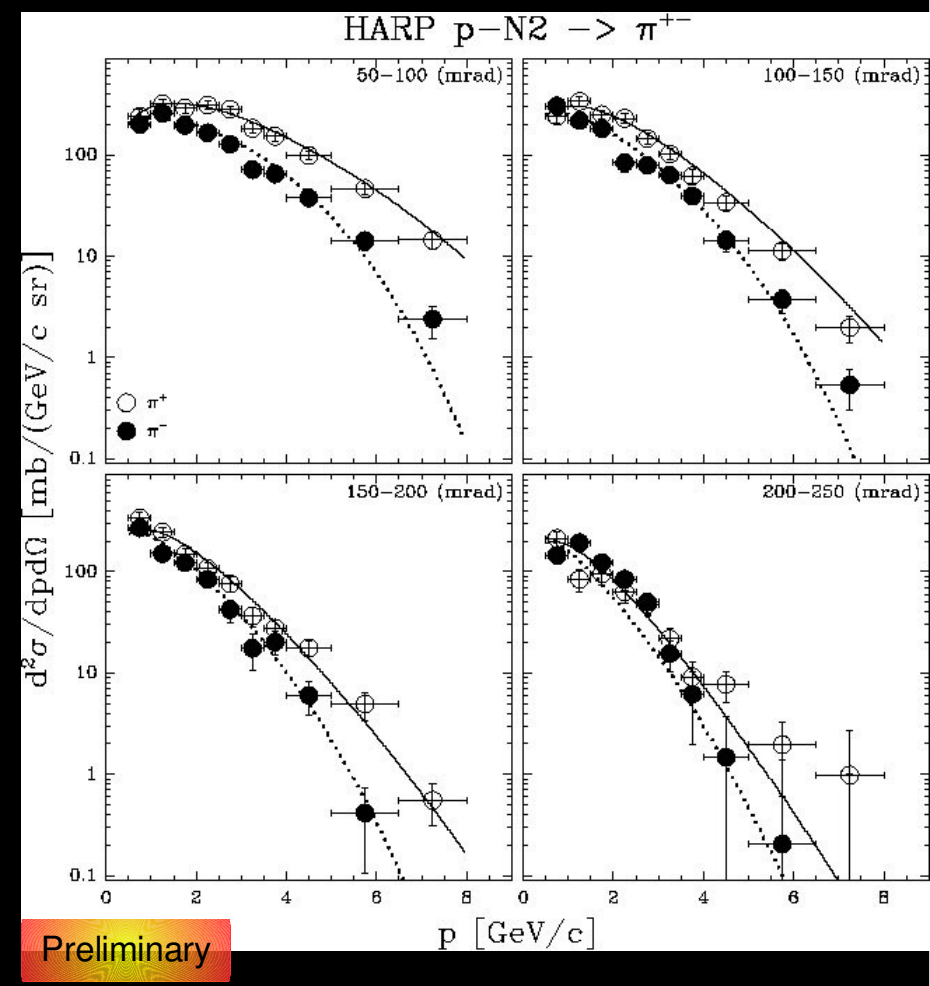
- Stat. + syst. uncertainties:
  - 6% measurement for $\pi^{\pm}$ over $0.5 < p\ (\mathrm{GeV/c}) < 8.0$, $50 < \theta\ (\mathrm{mrad}) < 250$
  - 15% bin-by-bin measurement (40 data points)
- Results also for oxygen, carbon targets, $\pi^{\pm}$ beams

Astropart. Phys. 29, 257 (2008)

- Useful resource to benchmark/tune hadronic interaction models used in air shower simulations

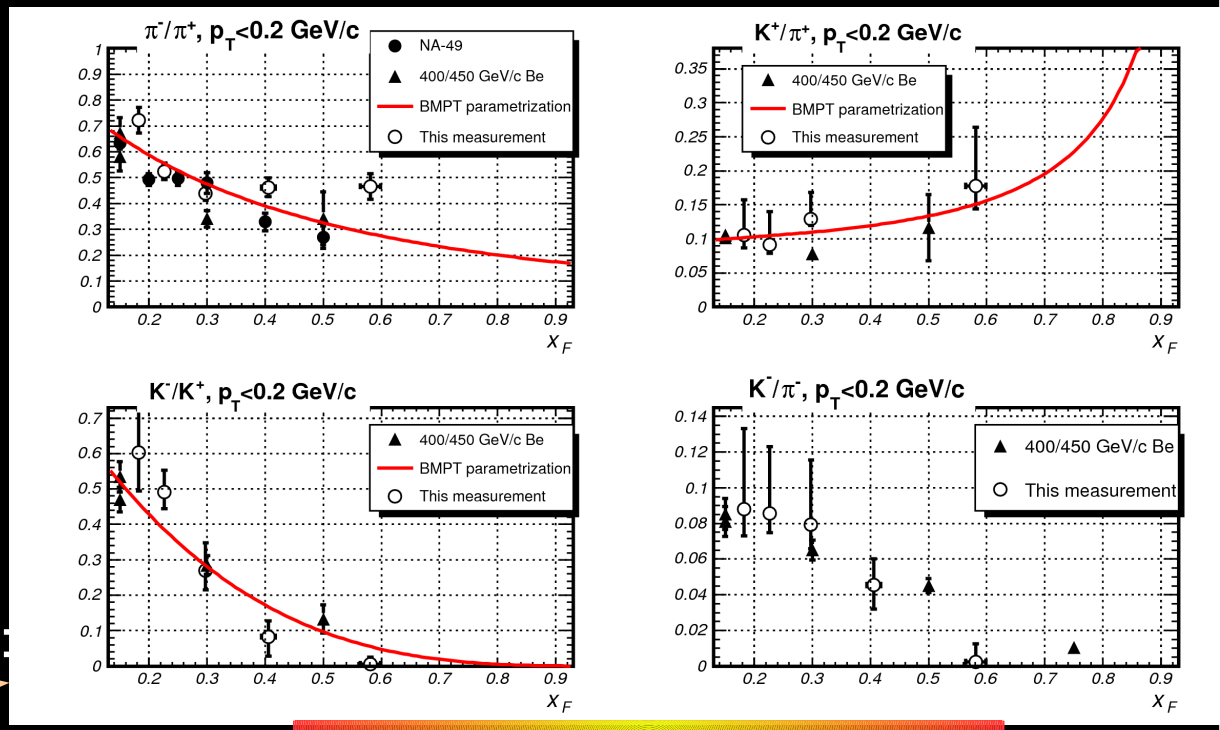
Experiment: HARP
Beam particle: proton
Beam momentum: 12 GeV/c
Target Material: N
Target Thickness: 5% λ_I
Produced particle: $\pi^{\pm}$





Experiment: MIPP
Beam particle: proton
Beam momentum: 120 GeV/c
Target Material: C
Target Thickness: 2% λ_I
Produced particle: $\pi^{\pm}$, $K^{\pm}$

- Important for multi-GeV contained, uncontained atmospheric neutrinos
- Particle ratios for two p_t slices shown:
  - $p_t < 0.2$ GeV/c
  - $0.2 < p_t < 0.4$ GeV/c
- Agreement with past C results and parametrization from Be data at ~30% level
- Opposite charge ratios important for atmospheric neutrino detectors with no final lepton charge ID



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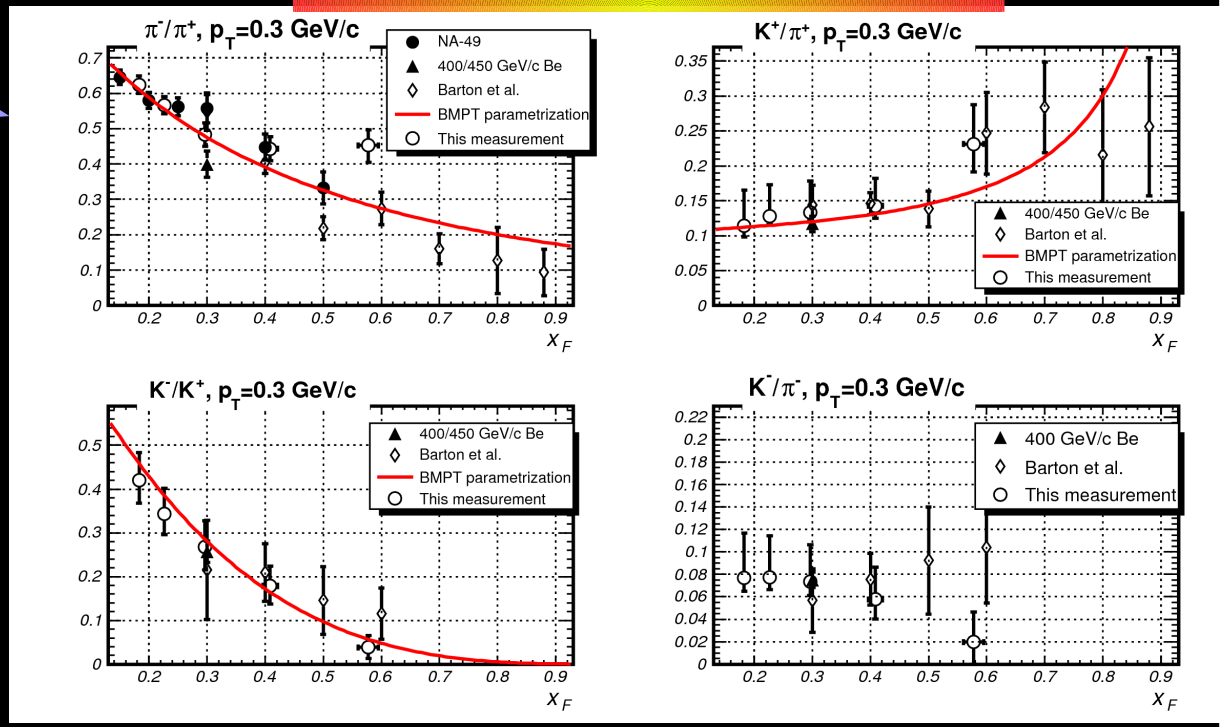


Future Prospects

MIPP

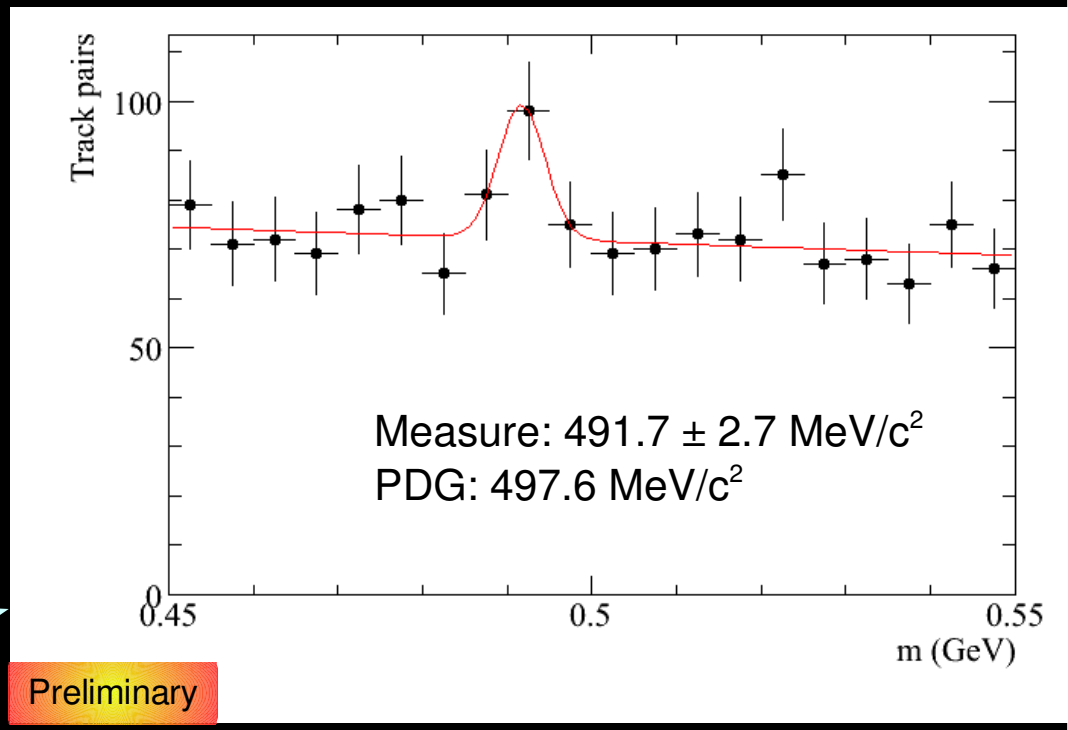
- First pion/kaon absolute differential cross-sections for 120 GeV/c protons:
  - NuMi target
  - C/Be/Bi thin targets

- Results will include $p < 20$ GeV/c secondary momenta as well

- n/p production ratio measurement for all beam momenta, all thin targets

- Pion/kaon production for 20, 60 GeV/c protons/pions/kaons on C thin target

- K0 production cross-sections



- First cross-sections expected later this year

MIPP Upgrade

•Proposal to upgrade the MIPP experiment under consideration

arXiv: hep-ex/0609057

•MIPP was limited by DAQ rate, dominated by the TPC readout time (~30 Hz)
-> ~1/5 of desired statistics for NuMI target run
In addition, the Jolly Green Giant magnet failed at end of run

•An upgrade of the TPC electronics can increase this readout speed by a factor of 100.
Other improvements would result in:

- more stable TCP performance
- greatly reduced ExB effects in the TPC
- an improved beamline for low (down to ~1 GeV/c) momentum running

•An upgraded MIPP would allow for the measurement of hadron production for any target in a matter of just a few days

•FNAL has purchased ALTRO chips for the TPC upgrade and repair of the JGG dipole magnet has begun

HARP

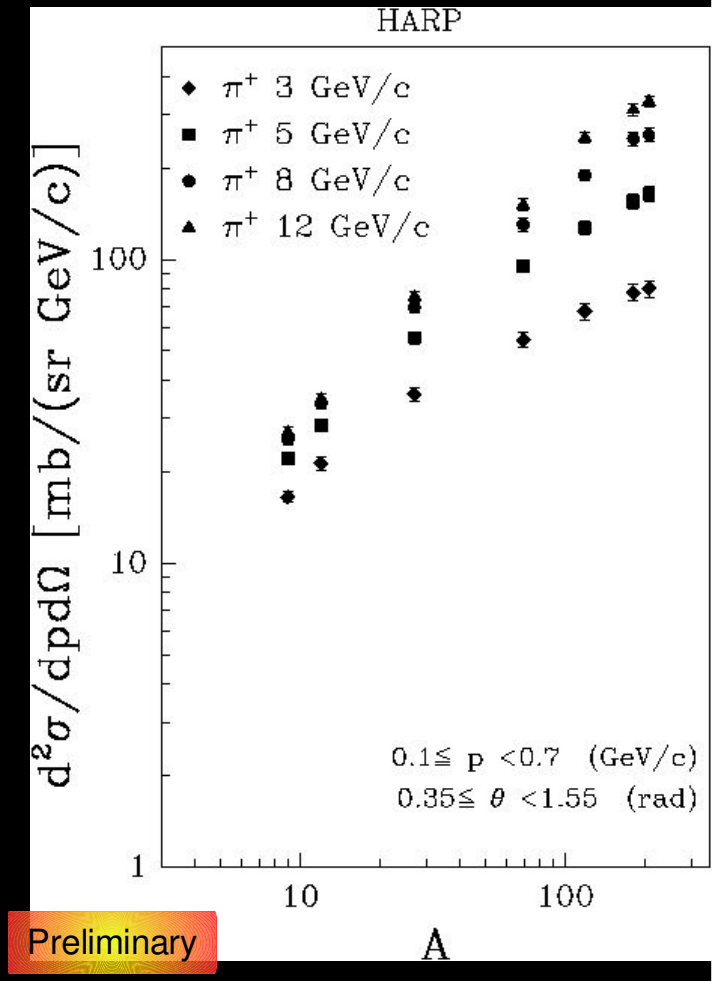
•Complete the analysis and publication of pion/proton production cross-sections in both forward direction and at large angles, for all (beam, thin target) settings

•Detailed study of particle production as a function of incoming particle momentum and target material. Unprecedented tuning and benchmarking tool for general-purpose hadronic interaction simulations

Example: π^+ yield for $0.1 < p$ (GeV/c) < 0.7, $350 < \theta$ (mrad) < 1550

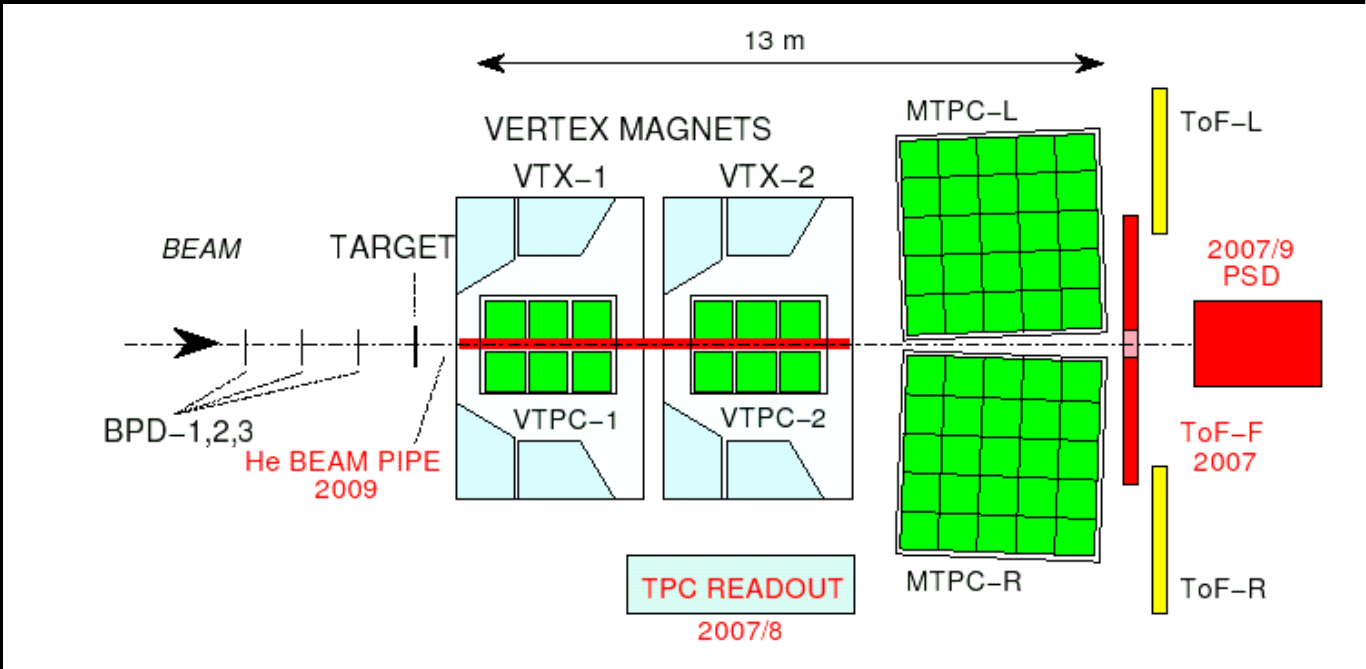
•*Kaon production in highest beam momentum* settings

•Particle yields from thick targets



NA61/SHINE

- New hadron production experiment at CERN
- Commissioning run in 2007, physics run late 2008
- Reuse NA49 detector, extended forward acceptance with new ToF wall



Neutrino physics in NA61 program:

- *Measurement of hadron production off the T2K target (p+C) needed to characterize the T2K neutrino beam*
- *Measurement of hadron production in p+C interactions needed for the description of cosmic-ray air showers (Pierre Auger Observatory and KASCADE experiments)*

Summary

Hadron production and neutrino physics:

- Precision ν oscillation and interaction measurements <-> precision ν production
- Hadron production knowledge is limiting factor in understanding and optimization of a variety of neutrino sources:

conventional & advanced accelerator-based neutrino beams, atmospheric neutrinos

HARP

- *NuFact and ~GeV neutrinos: K2K, MiniBooNE, SciBooNE, atmospheric neutrinos*
- *Lots of new results! Physics program completion well underway*

MIPP

- Multi-GeV neutrinos: *MINOS, atmospheric neutrinos , NuMI-future (MINERνA, NOνA)*
- Complete understanding of detector performance and physics analyses well underway. First MIPP hadron production cross sections later this year

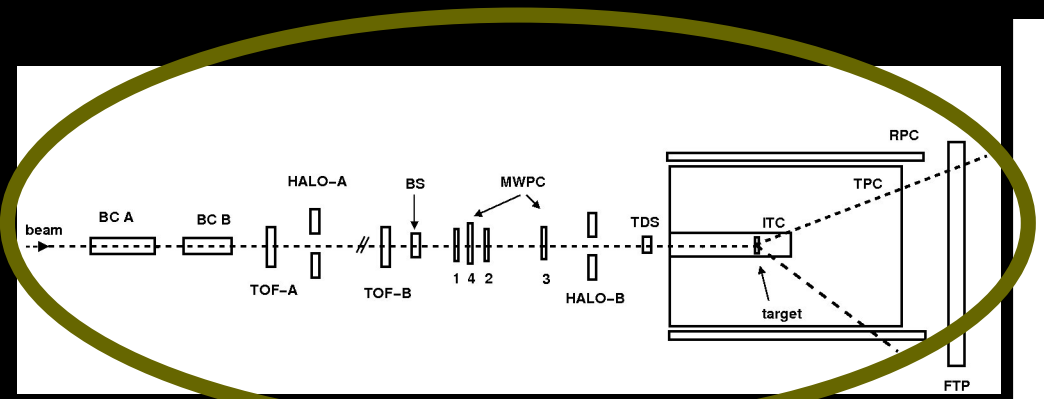
Backups

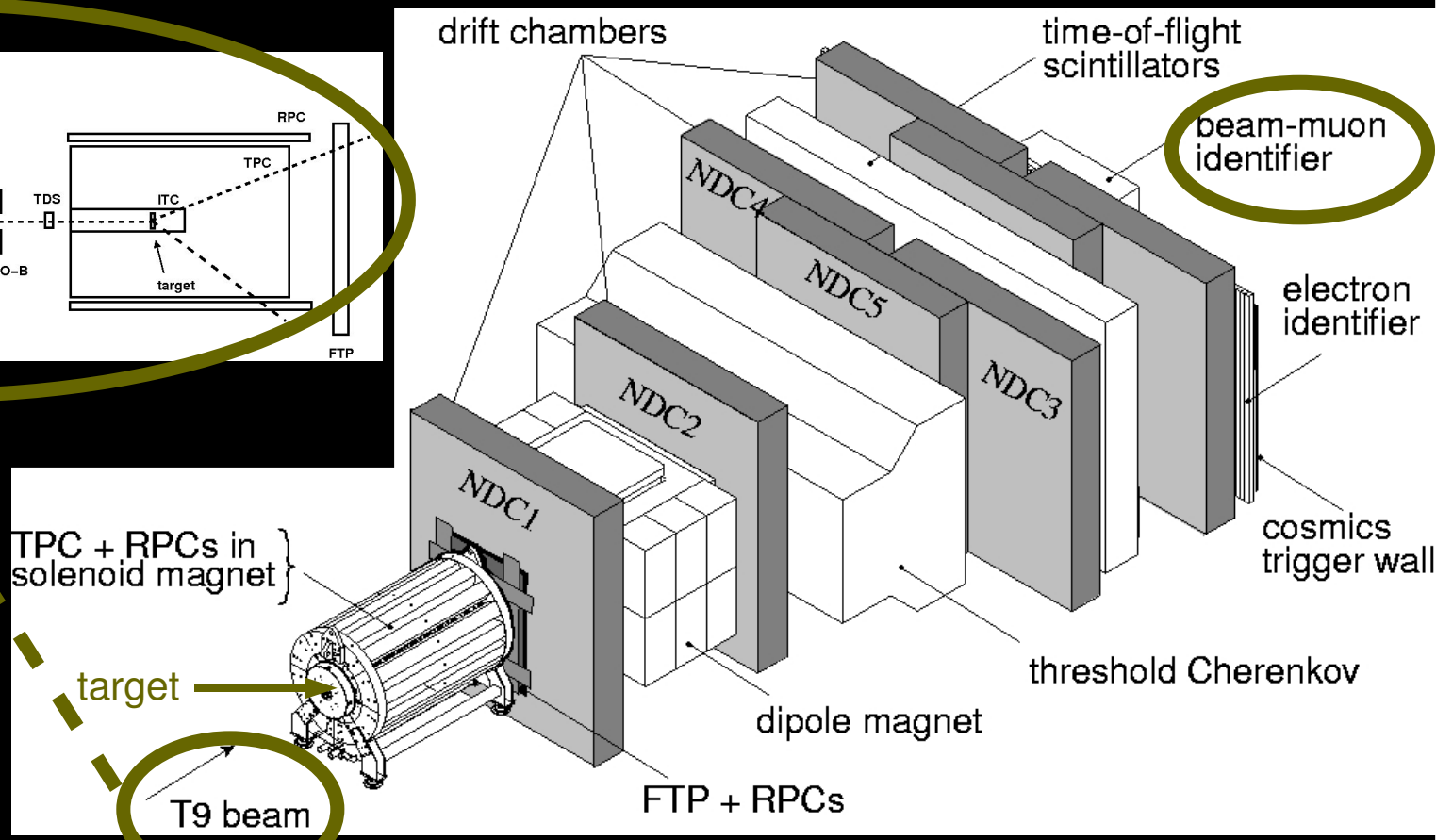
HARP Beam Instrumentation

Beam instrumentation:

- incoming particle impact point and direction with MWPC
- incoming particle ID with beam time-of-flight + theshold Cherenkov detectors

(+ beam muon-identifier)



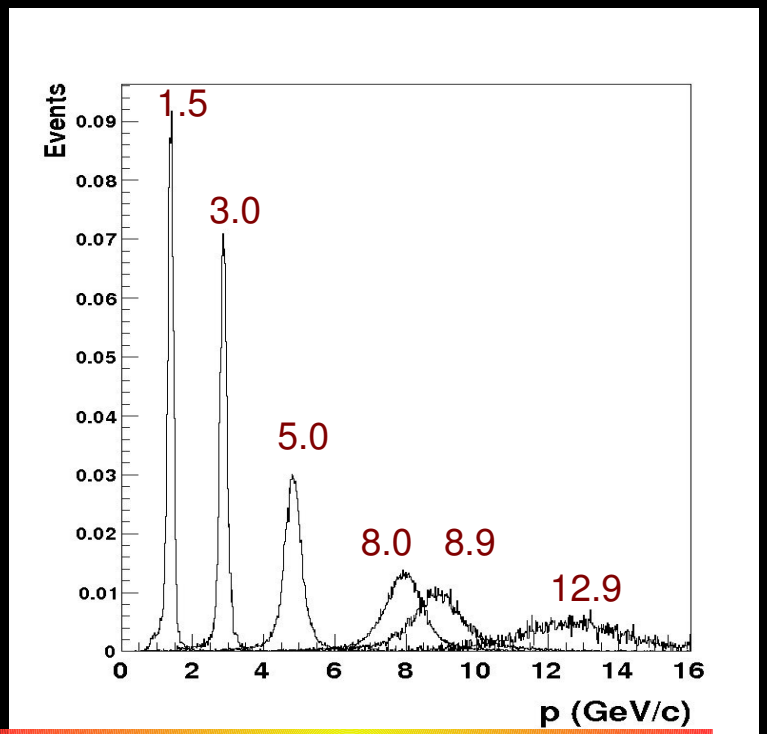


Track Reconstruction in HARP

Forward spectrometer

•Unit-area normalized momentum distributions of beam pions for different beam settings:

•*momentum scale understood to 2%*
•*4% momentum resolution at p=3 GeV/c*



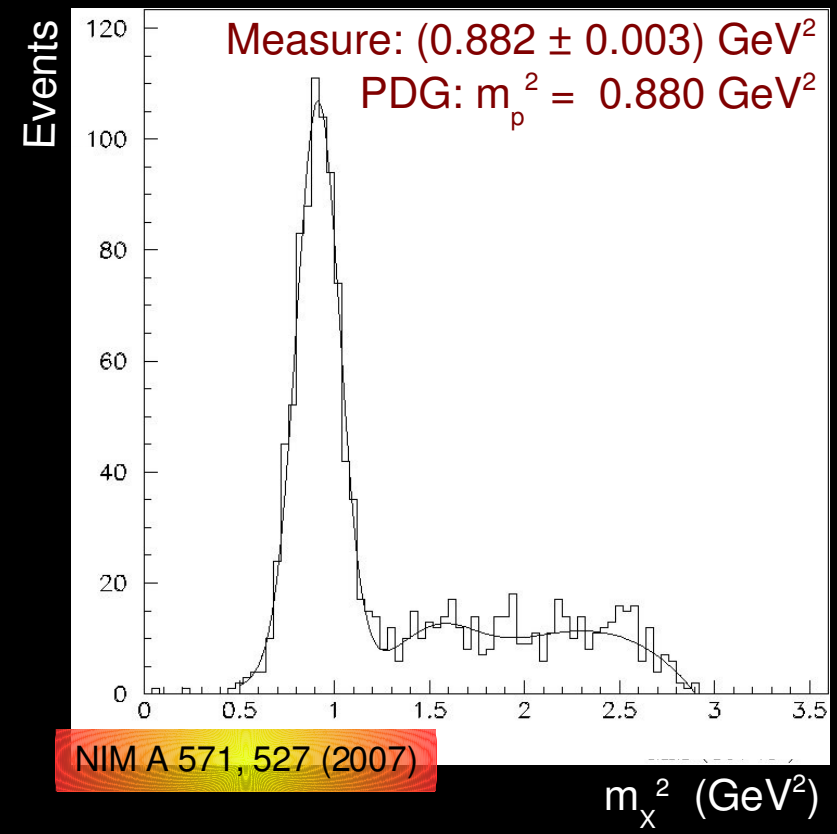
D. Schmitz, Ph.D. Thesis, Columbia U. (2008)

Large-angle spectrometer

•Missing mass squared in pp elastic data:

$$m_X^2 = (p_{beam}+p_{target}-p_{TPC})$$

•p_{beam}: incident protons from 3 GeV/c beam and beam instrumentation measurements
•p_{target}: target protons at rest in H target
•p_{TPC}: 4-momentum as measured by TPC

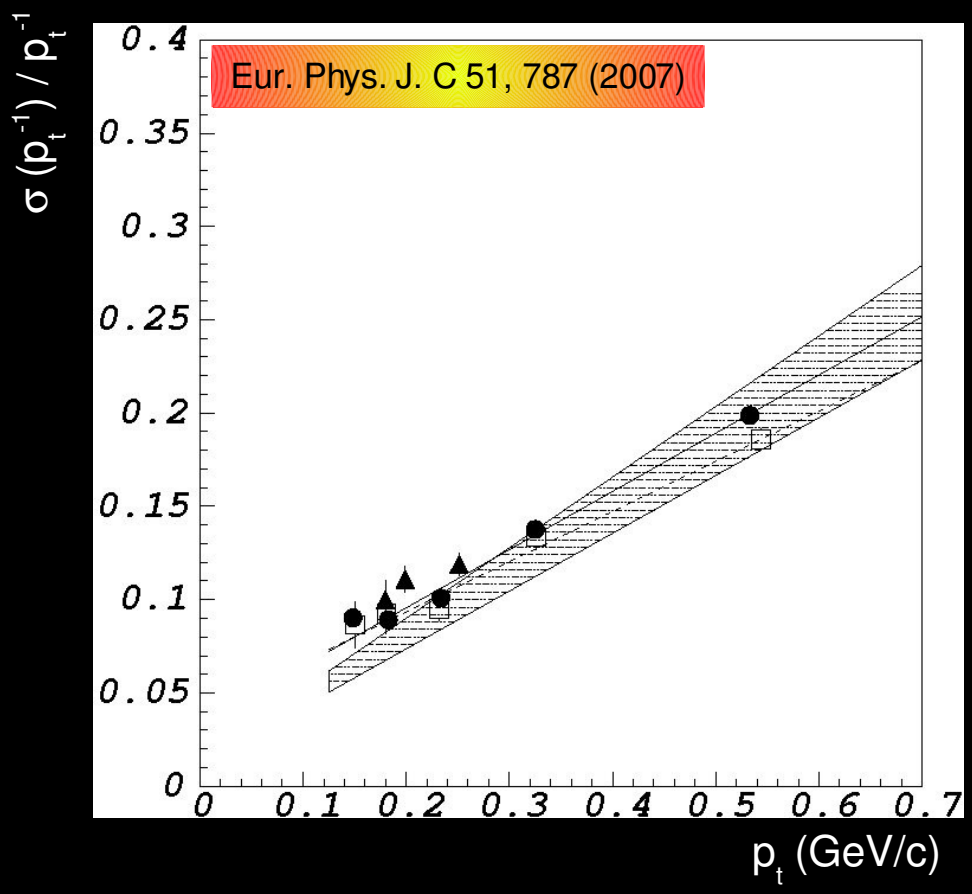


NIM A 571, 527 (2007)

More on HARP TPC Track Reconstruction

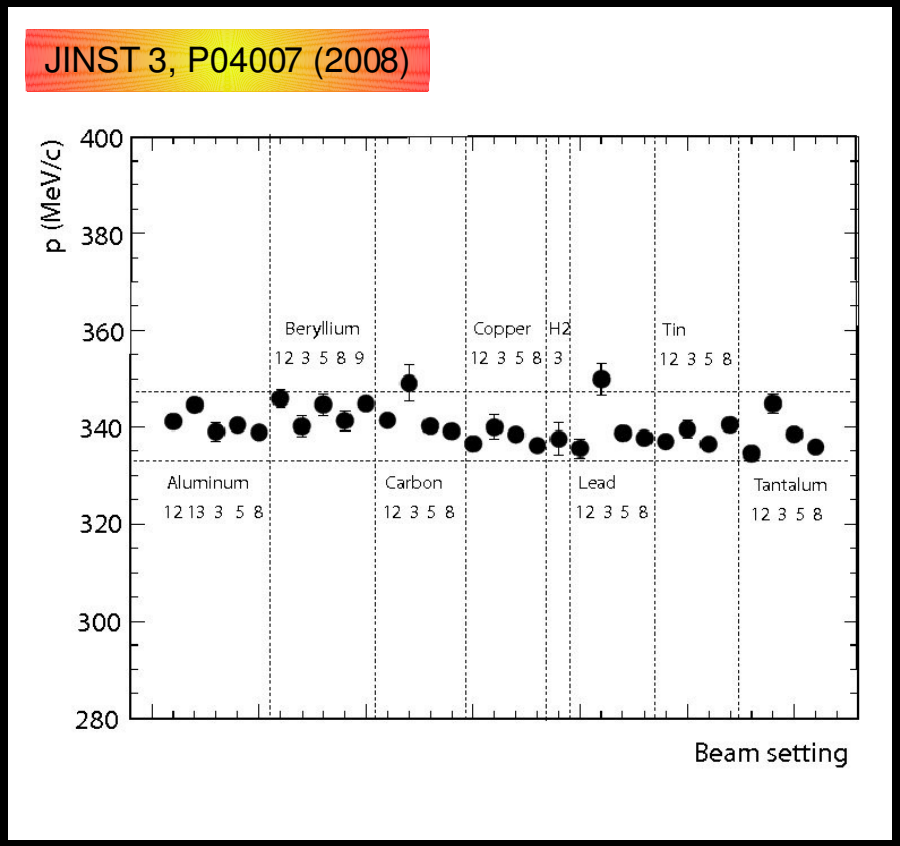
Momentum Resolution

- $1/p_t$ fractional resolution versus p_t from:
  - *separate fit of cosmic ray track halves*
  - *dE/dx in $1/\beta^2$ region (triangles)*
  - *MC simulation (shaded area)*



Momentum Scale

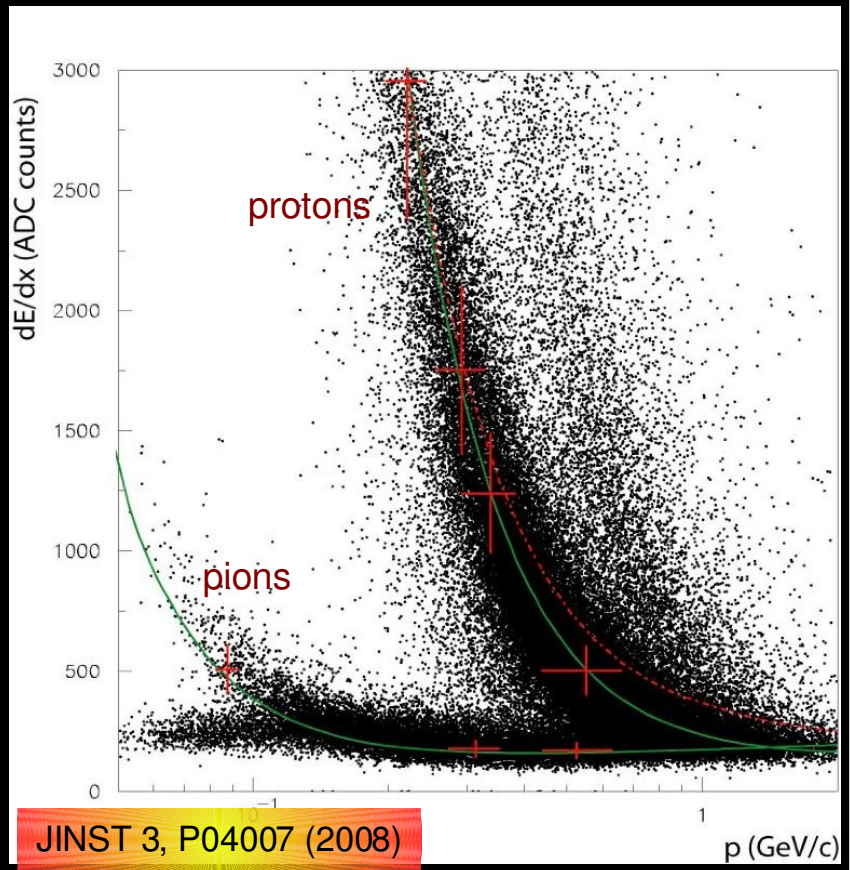
- Obtained from dE/dx slice in $1/\beta^2$ proton region
- Consistency within ±2% of all (beam, target) settings with one used in pp elastic analysis



PID in HARP

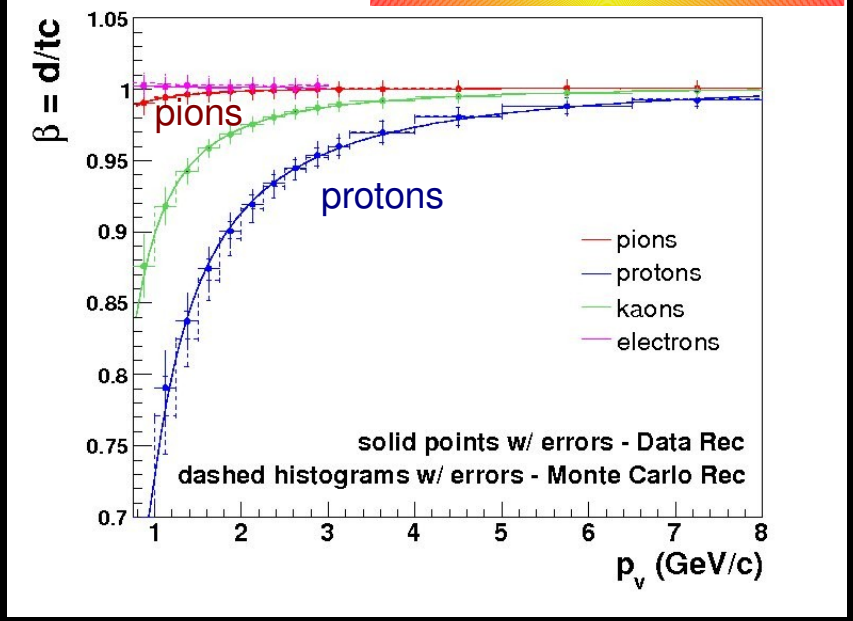
proton / pion separation:

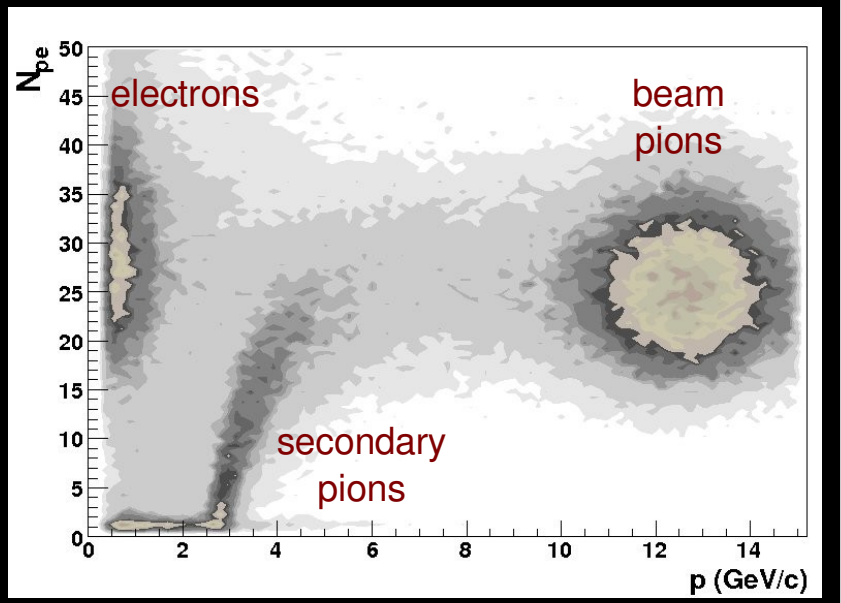
- with TPC for p < 0.8 GeV/c
  - with ToF for 0.5 < p (GeV/c) < 5
    - with Cherenkov for p > 2.6 GeV/c



JINST 3, P04007 (2008)

Eur. Phys. J. C 52, 29 (2007)





Particle Yield Corrections in HARP

Numbers for forward π^+ production from 8.9 GeV/c protons on Be as example:

- Track reconstruction efficiency: 3% up (data)
- Momentum scale, resolution, energy losses: affects shape (data/MC)
- Geometric acceptance: ~100-160% up (analytical)
- Pion ID efficiency: 2% up (data)
- Pion-to-proton migration: <1% down (data)
- Absorption/decay of secondaries: 20-30% up (MC)
- Tertiary production: 5% down (MC)
- Electron veto efficiency: 1% up (data)
- Kaon subtraction: 1-3% down (data/MC)
- Targeting efficiency: 1% up (data)
- Empty target subtraction: 20% down (data)
- π^0 subtraction (large-angle spectrometer analyses)

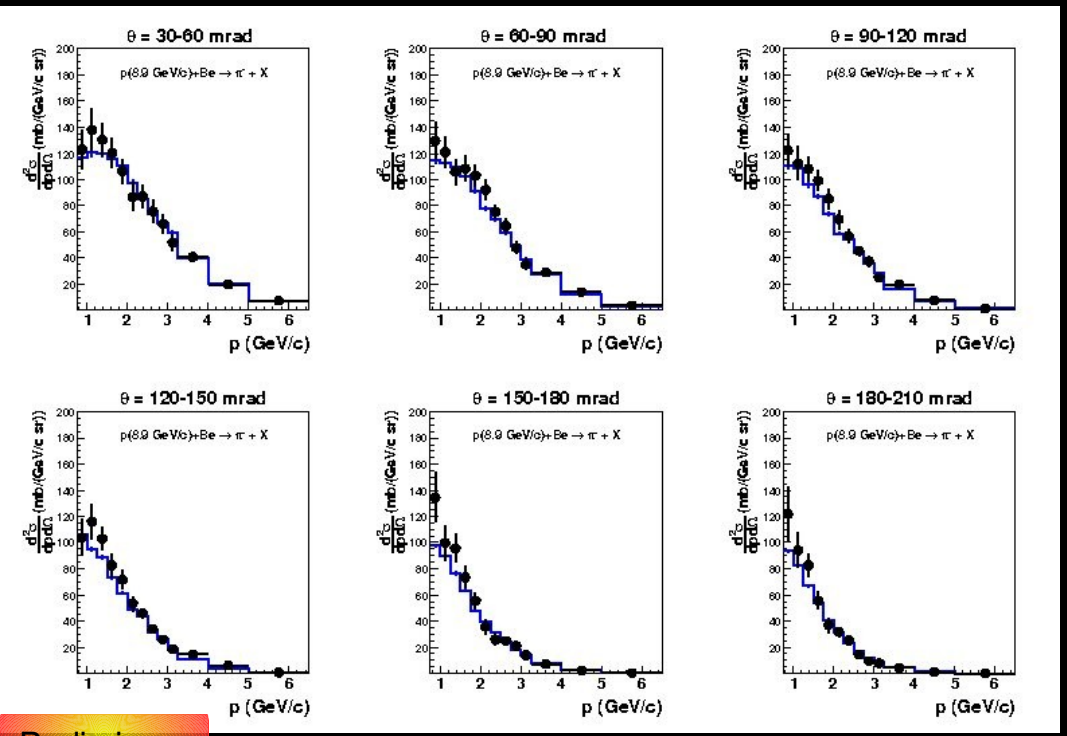
Typical dominant systematic uncertainties:

- pion absorption, momentum scale, momentum resolution unfolding (forward)
- momentum scale, π^0 subtraction, target region cut (large-angle)

Experiment: HARP
Beam particle: proton
Beam momentum: 8.9 GeV/c
Target Material: Be
Target Thickness: 5% λ_I
Produced particle: proton, π^-

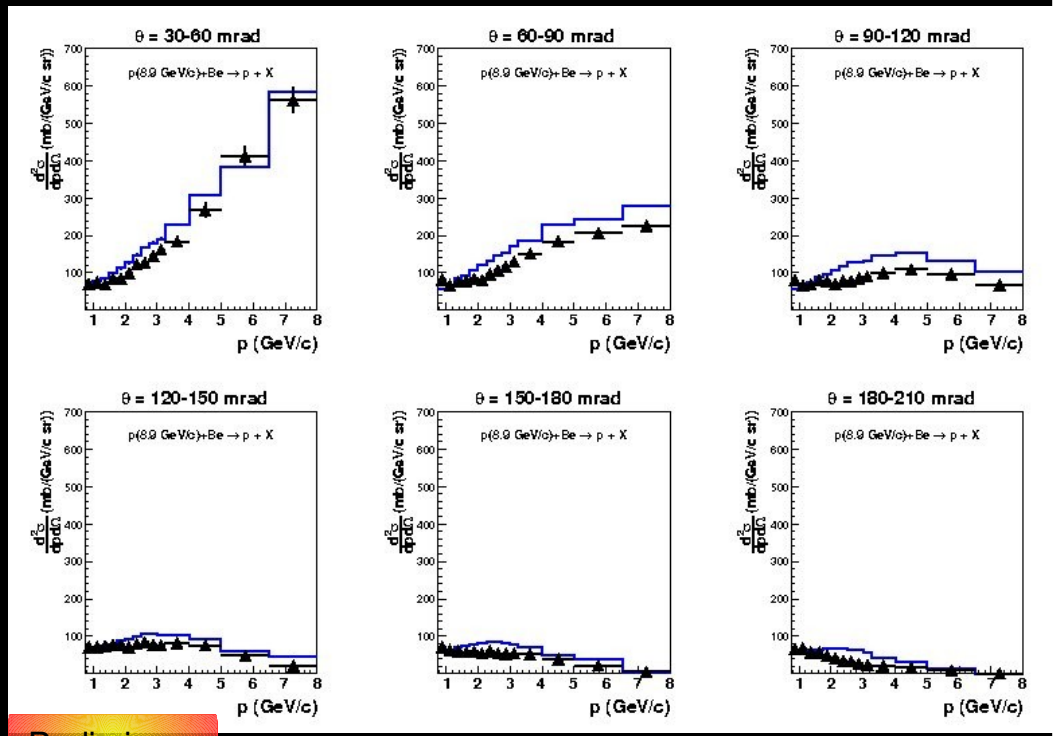
- Preliminary proton, π^- production results also available for same (beam, target) settings
  - π^-: useful for ongoing BNB antineutrino run
  - proton: useful for reinteraction effects in BNB thick target
- Blue beam MC histograms:
  - π^-: tuned with HARP+E910
  - proton: prediction independent from HARP

π^-



Preliminary

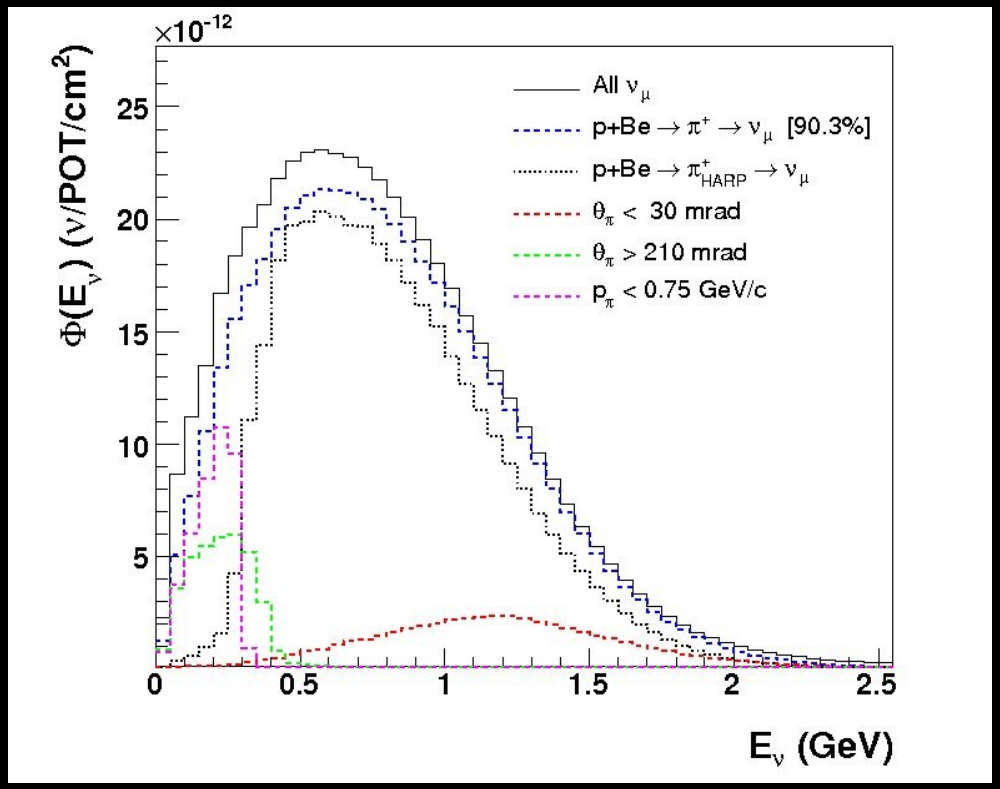
proton



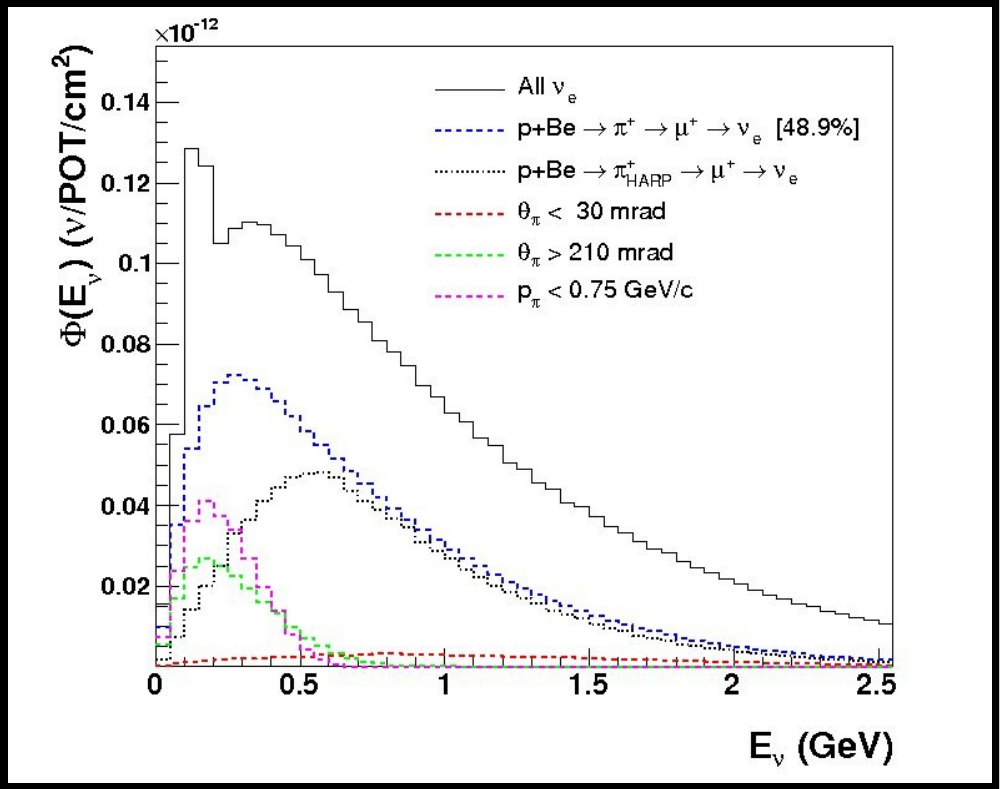
Preliminary

HARP & BNB

$\pi^+ \to \nu_\mu$



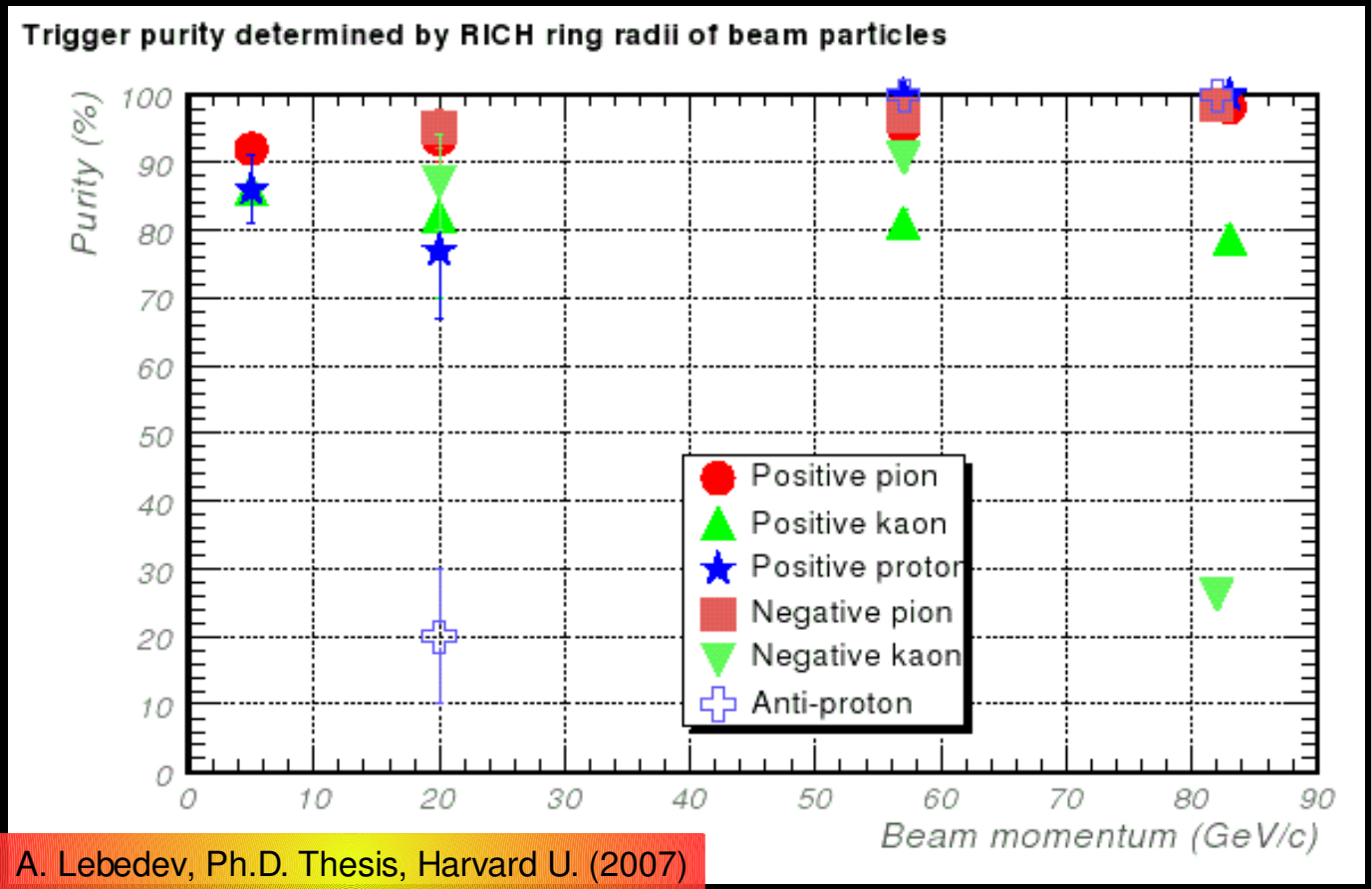
$\pi^+ \to \mu^+ \to \nu_e$



MIPP Beam Instrumentation

- Incoming particle impact point and direction with drift chambers
- Incoming particle ID with beam threshold Cherenkov detectors

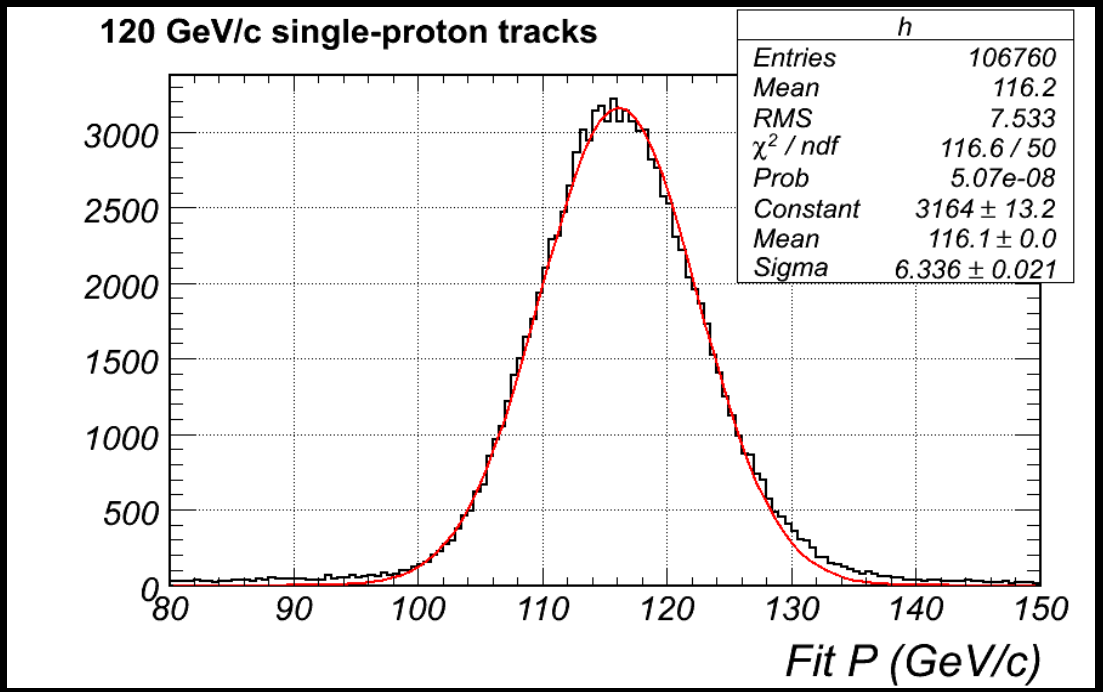
- *Beam Cherenkov detector performance as measured by RICH:*



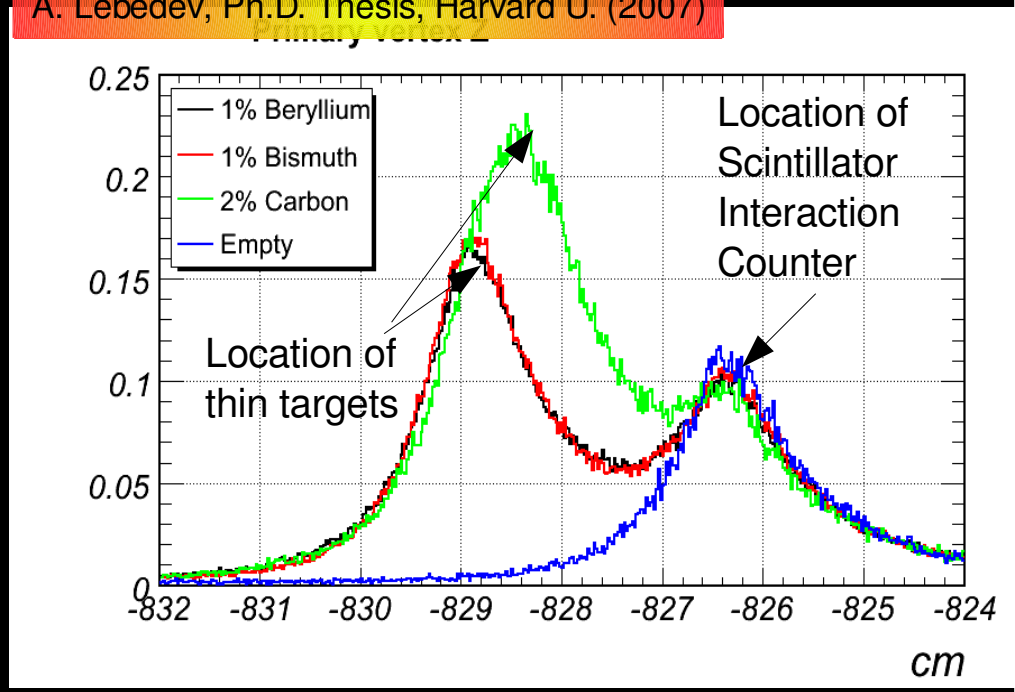
A. Lebedev, Ph.D. Thesis, Harvard U. (2007)

Track and Vertex Reconstruction in MIPP

- Primary vertex resolution is ~8 mm
- Momentum resolution is ~5% at 120 GeV/c, better at lower momenta
- Reconstructed track momenta systematically underestimated by 2-3%

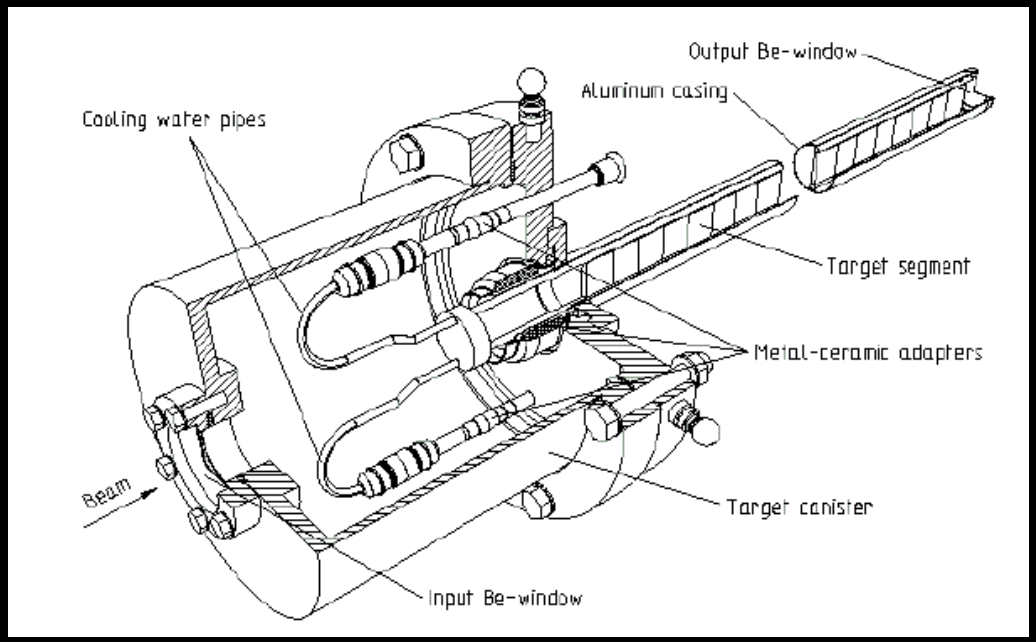


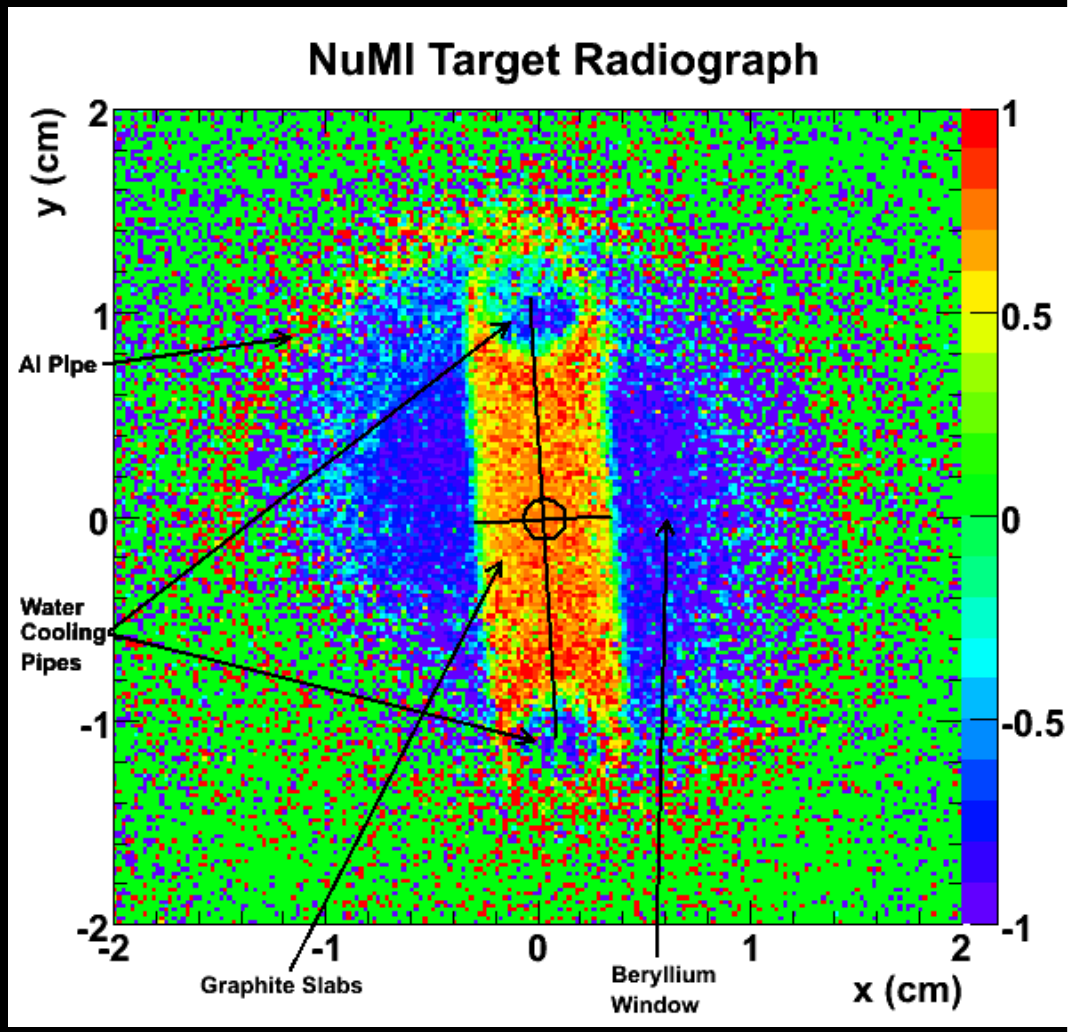
A. Lebedev, Ph.D. Thesis, Harvard U. (2007)



NuMI Target Radiograph with MIPP

- Color coding related to material density, using beam tuning data
- Sub-mm beam-target alignment:
  - Circle: beam centroid from trigger
  - Cross hairs: center of graphite slabs





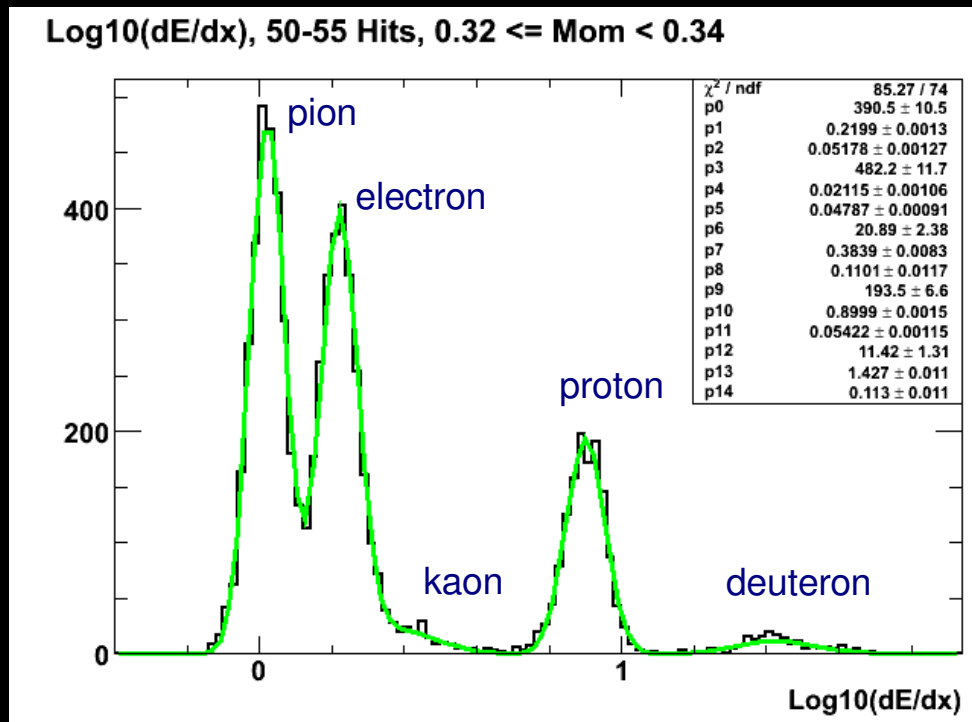
More on MIPP PID

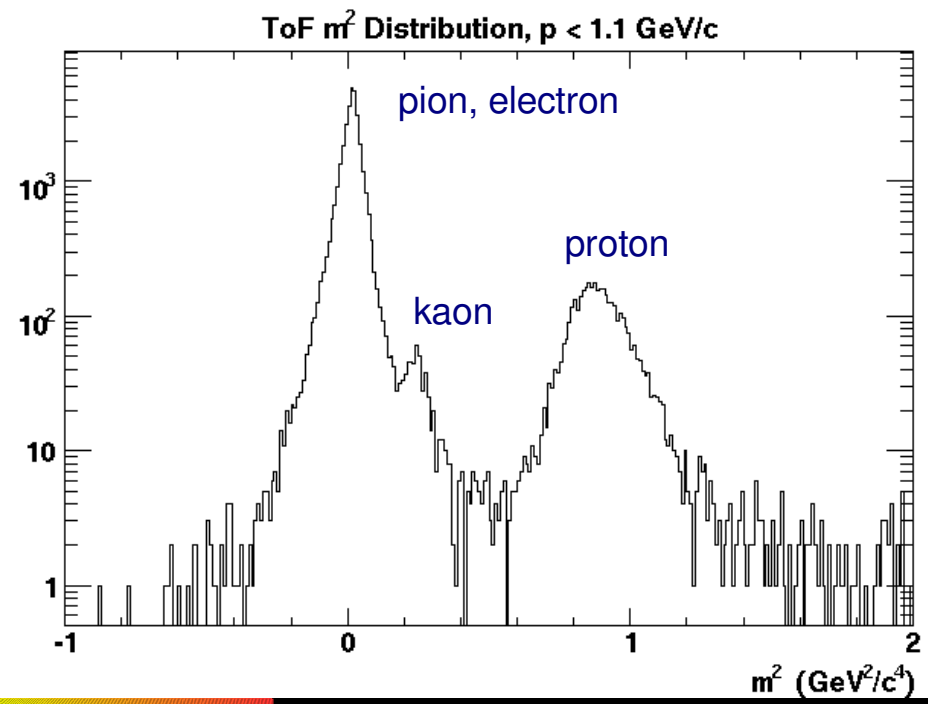
TPC

dE/dx for 0.32 < p (GeV/c) < 0.34 secondaries:

ToF

$m^2 = p^2 (1/\beta^2 - 1)$ for p < 1.1 GeV/c:





J. Paley's MIPP Neutrino 08 poster

Particle Yield Corrections in MIPP

Overall correction applied to extract particle yield ratios typically <10%. Those are:

- RICH geometric acceptance
- Pileup removal
- Target-out subtraction
- Interaction trigger efficiency
- Interactions/decays in detector
- Particle ID efficiency
- Misidentified particles subtraction
- Momentum reconstruction performance

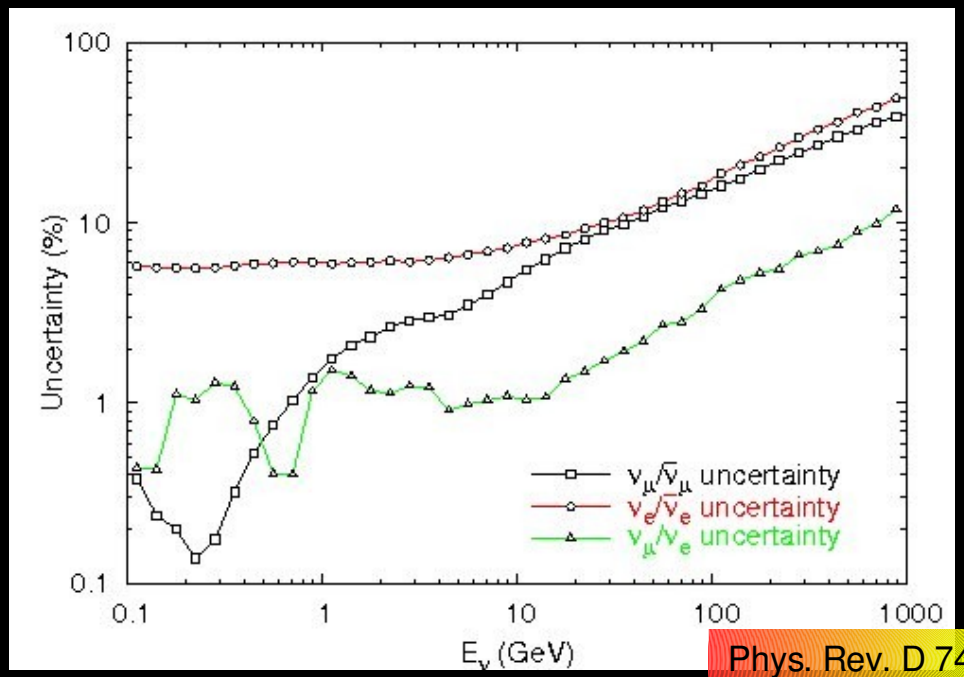
Dominant systematic uncertainties:

- detector modeling in MC simulation, misidentified particles modeling, momentum scale

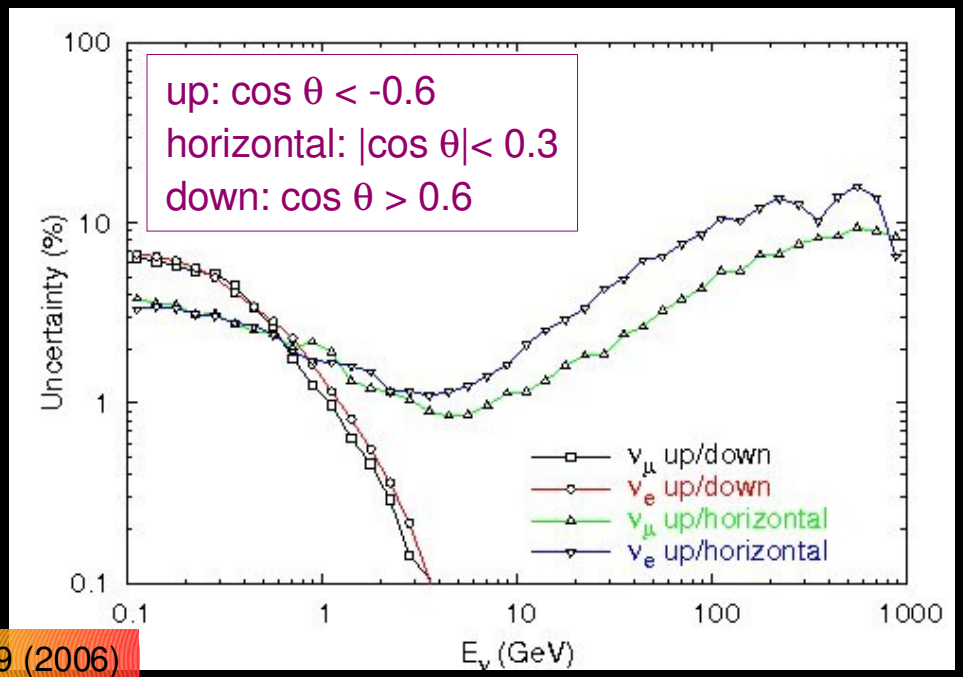
Atmospheric Neutrino Flux Predictions

- Rule-of-thumb: (primary cosmic ray energy) / (atmospheric ν energy) ~ 10-20
  -> HARP data for sub-GeV neutrinos, MIPP data for multi-GeV neutrinos
- The situation prior to HARP and MIPP:
  - *absolute flux uncertainties at 15-20% level*
  - *flux flavor ratio and flux directional ratio uncertainties at few % level*
- Energy-dependent and dominated by hadron production uncertainties

Flux flavor ratios



Flux directional ratios



Phys. Rev. D 74, 094009 (2006)