Review of Hadron Production Experiments

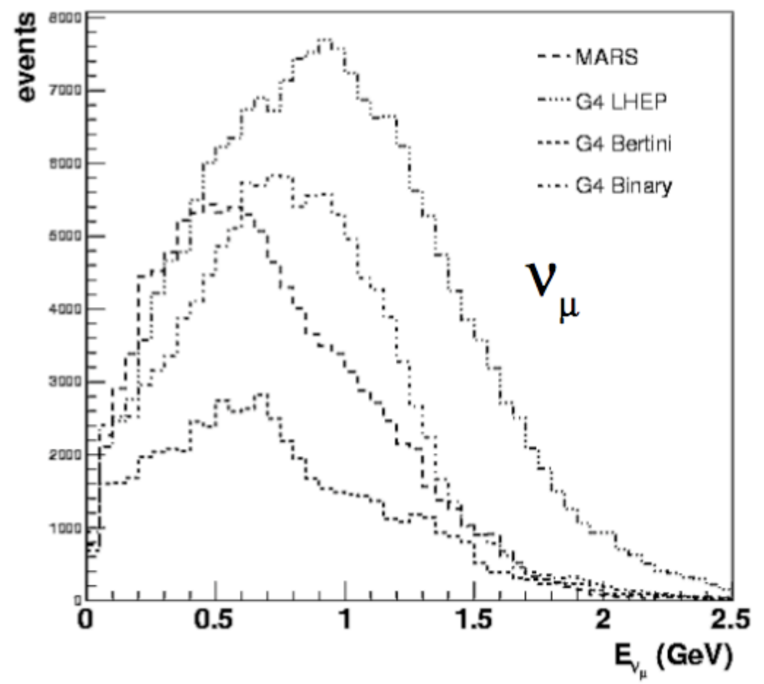
Raphaël Schroeter - Harvard University

- Motivations
- The Experiments
- HARP
- NA61/SHINE
- Future Prospects
- Summary

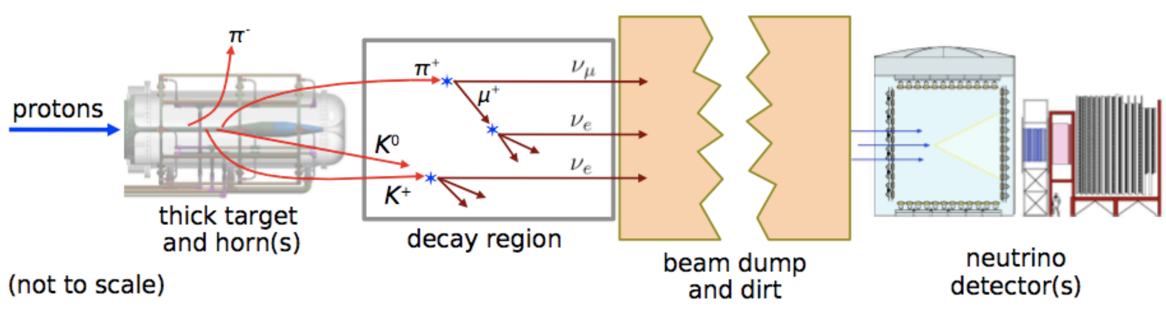
PITT PAC Workshop, Pittsburgh, December 6, 2012

Motivations

- Input for precise prediction of neutrino fluxes in modern accelerator neutrino experiments
- Hadron production uncertainties have big impact on the energy, composition, geometry of the neutrino beam
- Various models of Monte Carlo generators are used and show large differences in ν rate predictions, hadron production data can be used as input for validation/ tuning of Monte Carlo generators (GEANT4 and others)
- Pion/Kaon yield for the design of the proton driver and target system of Neutrino Factories and Super-Beams
- Dedicated experiments such as HARP, MIPP, NA61/ SHINE...



resulting ν_μ flux @ 550m detector from p(8 GeV/c)+(thick)Be hadron simulation by Dave Schmitz

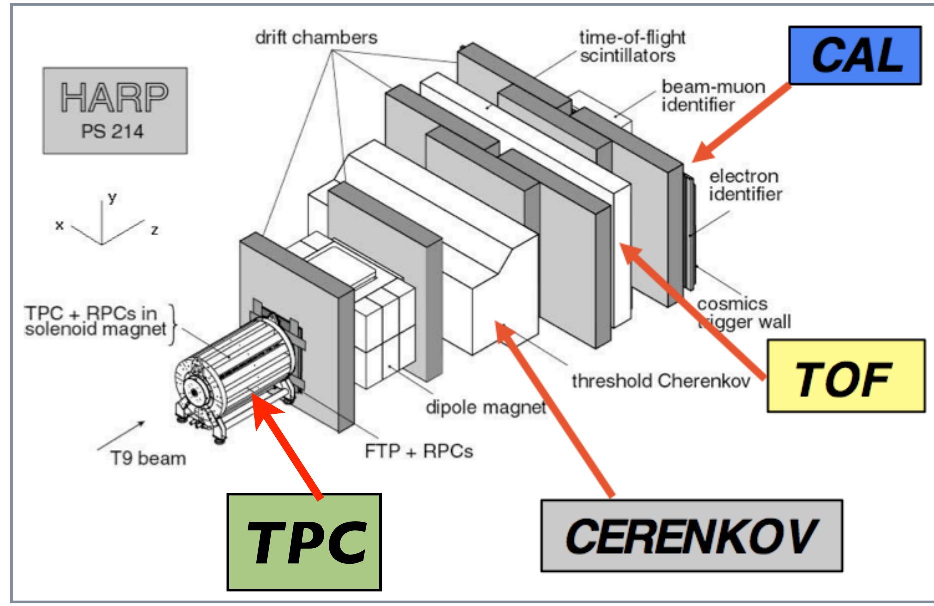


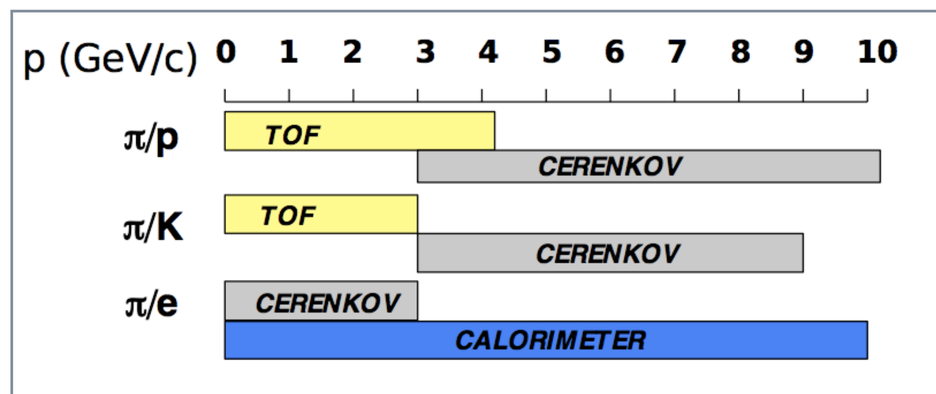
The Experiments

The HARP detector

- Forward Spectrometer
  $0.5 \leq p \leq 8.0$ GeV/c
  $25 \leq \theta \leq 250$ mrad
  - track reconstruction with drift chambers + dipole magnet
  - PID with threshold Cherenkov + time-of-flight wall + electromagnetic calorimeter

- Large-Angle Spectrometer
  $0.1 \leq p \leq 0.8$ GeV/c
  $350 \leq \theta \leq 2150$ mrad
  - track reconstruction & PID with solenoid magnet + TPC + RPCs

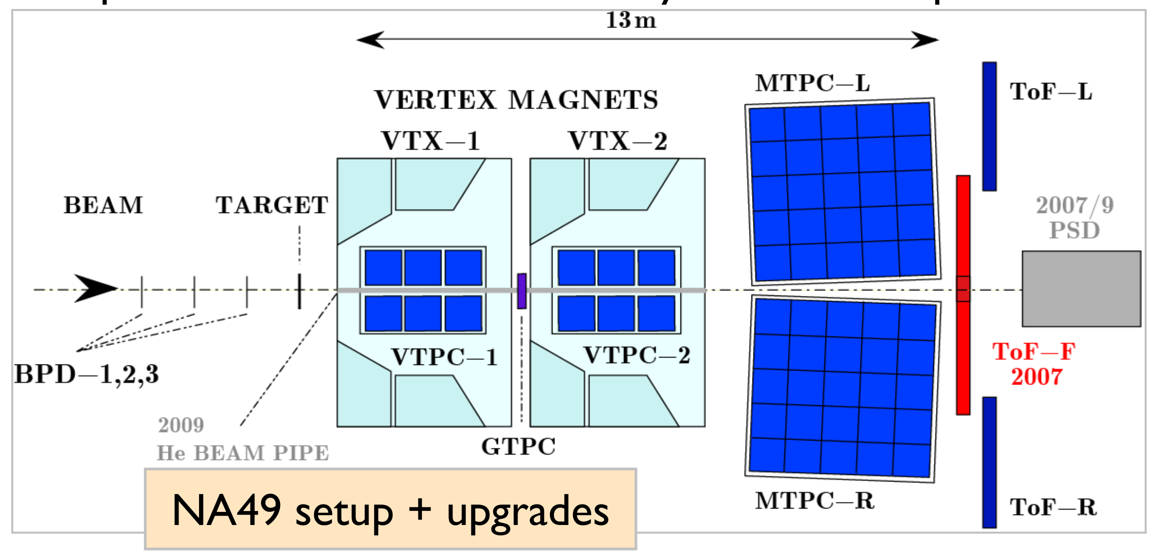


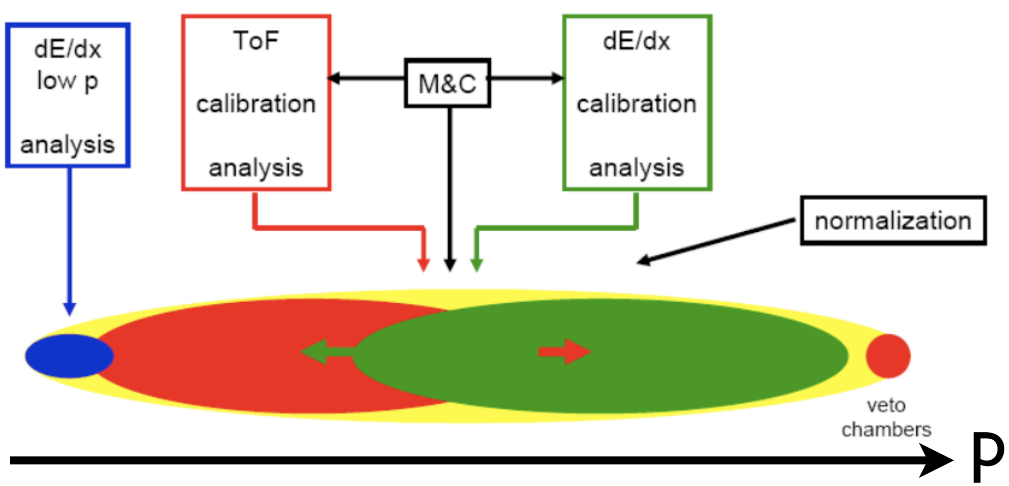


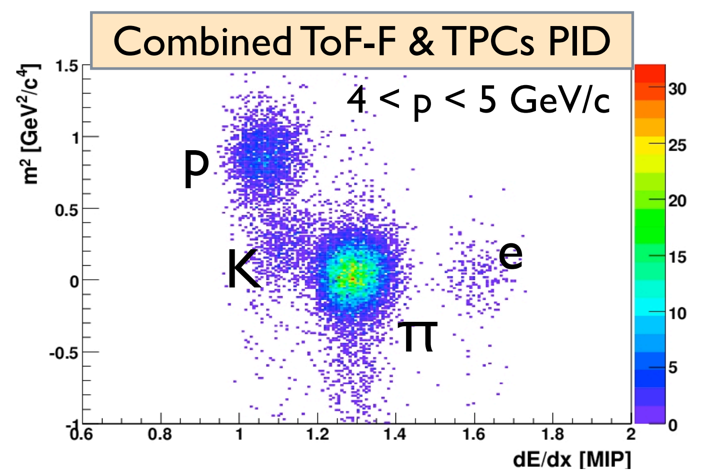
NA61 Detector

- Track reconstruction:
  - TPC as main tracking devices
  - 2 dipole magnets
- Particle Identification:
  - Time-of-flight wall L/R, speed for high momentum particles produced at small angle
  - New ToF-F, speed for low momentum particles produced at large angle
  - TPC, dE/dx

Updated detector covers entirely the T2K acceptance!

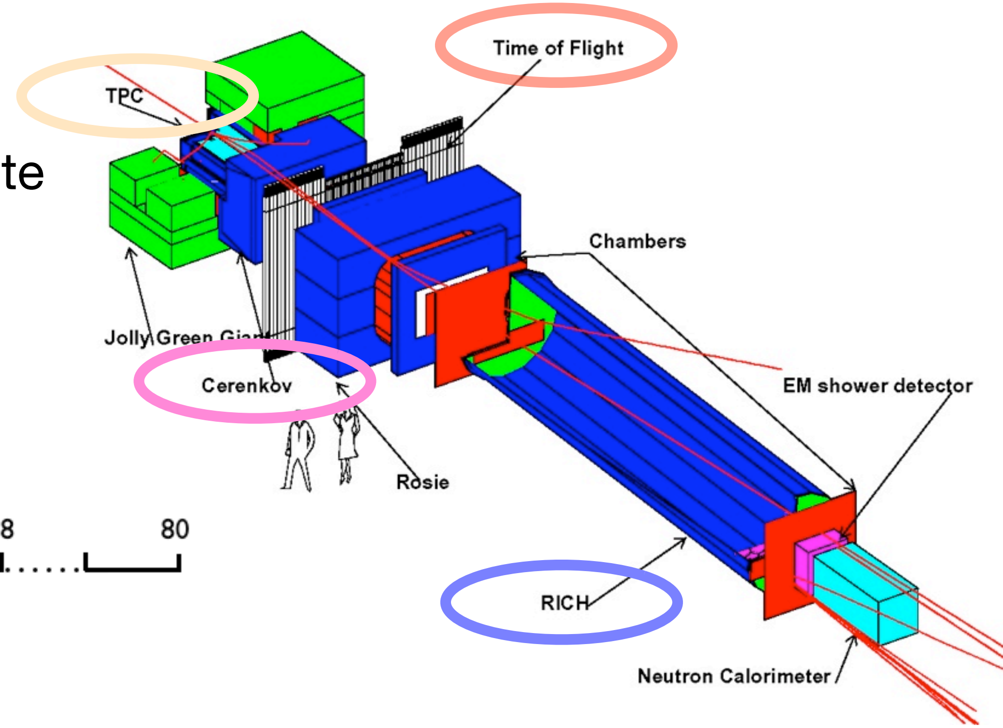


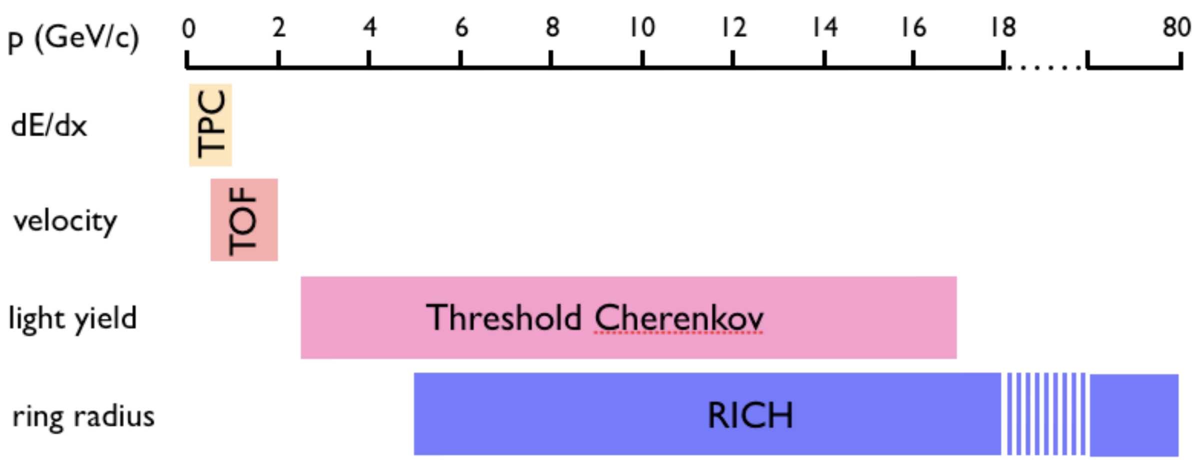


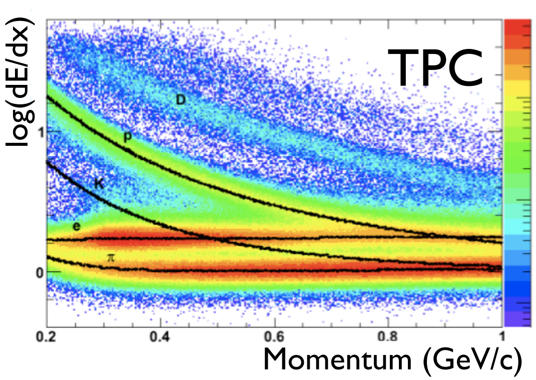


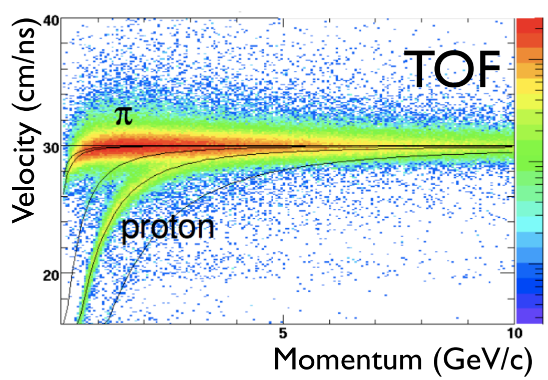
The MIPP detector

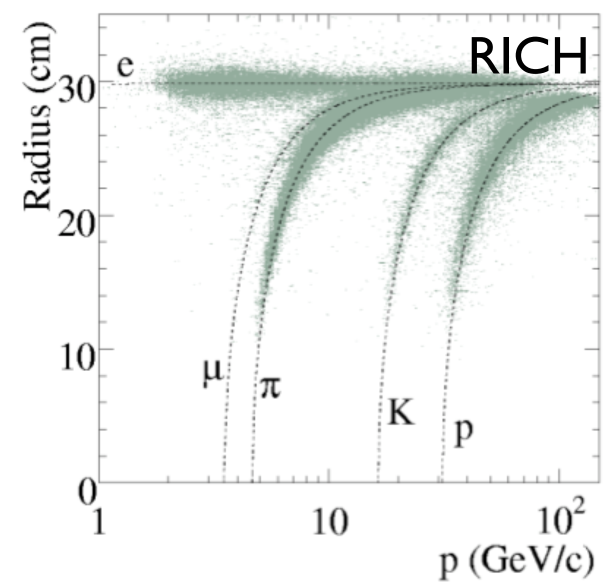
- Track Reconstruction:
    - Two dipole magnets deflecting in opposite direction
    - TPC + drift chambers + MWPCs
- Particle Identification











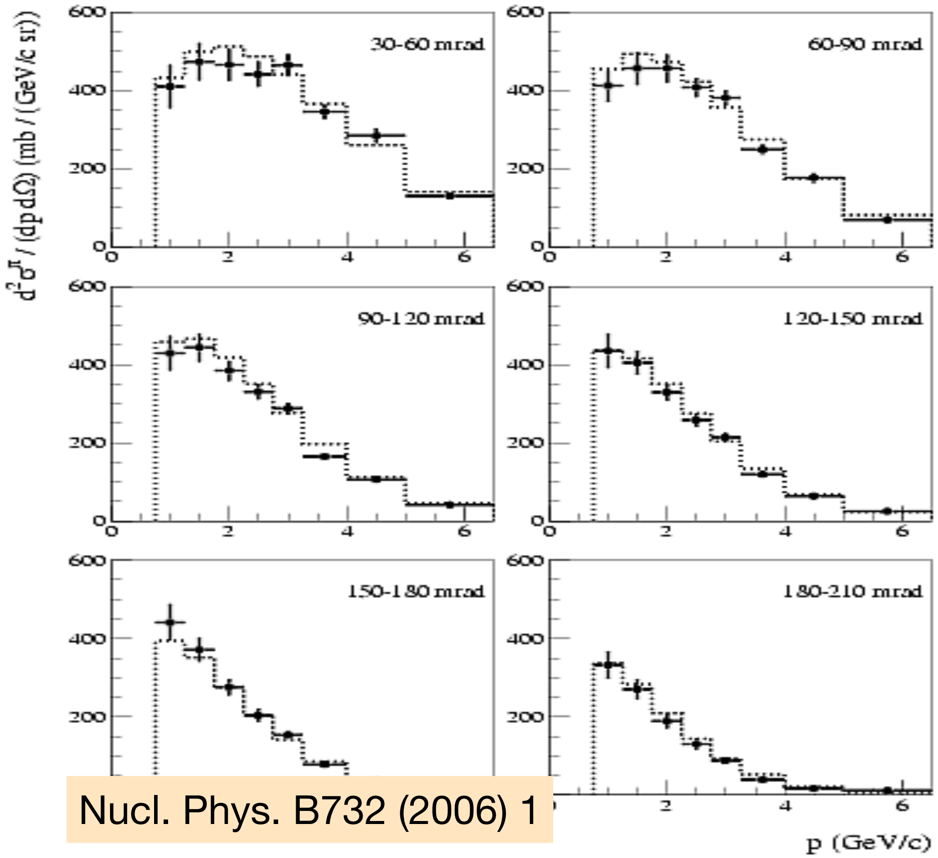
The Experiments

		HARP 2-15 GeV/c p, π^+, π^-	MIPP 5-120 GeV/c p, $\pi^\pm$, $K^\pm$	NA61 31 GeV/c p
Accelerator-based Neutrino Beams	K2K, MiniBooNE	X		
	MINOS		X	
	T2K off-axis			X
Neutrino Factory		X		
Atmospheric Neutrinos		X	X	X
Systematic Target Studies		H, D, Be, C, N, O, Al, Cu, Sn, Ta, Pb		
			H, Be, C, Bi, U	
				C

HARP
Studies for Accelerator-based Neutrino Beams

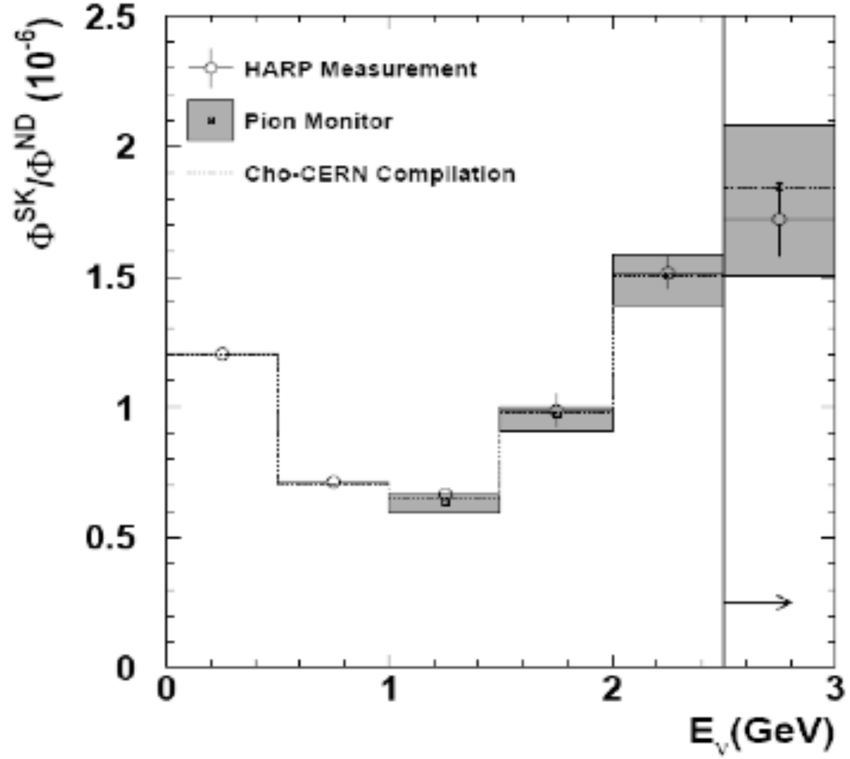
HARP/K2K

p(12.9 GeV/c) + Al → π^+ + X



Nucl. Phys. B732 (2006) 1

K2K Far-to-near flux ratio



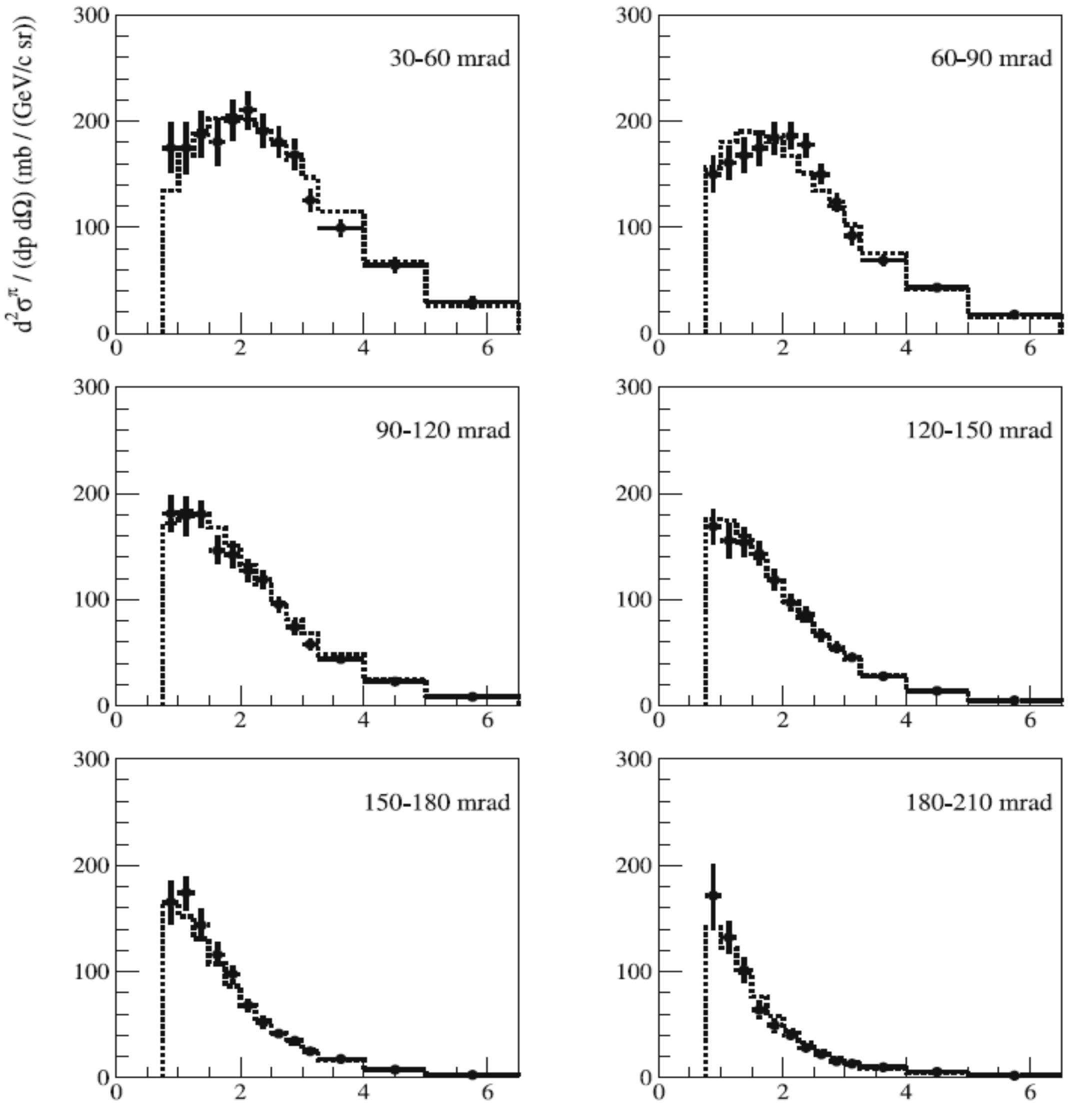
- F/N contribution to uncertainty in number of unoscillated muon neutrinos expected at Super-K reduced from 5.1% to 2.9% with HARP

Phys. Rev. D74 (2006) 072003

HARP/MiniBooNE

p(8.9 GeV/c) + Be → π^+ + X

- 5% λ, same (beam, target material) as FNAL Booster Neutrino Beam
- typical error on point = 9.8%
- error on integral = 4.9%
- analysis includes significant improvements relative to Al measurement in PID and momentum resolution description

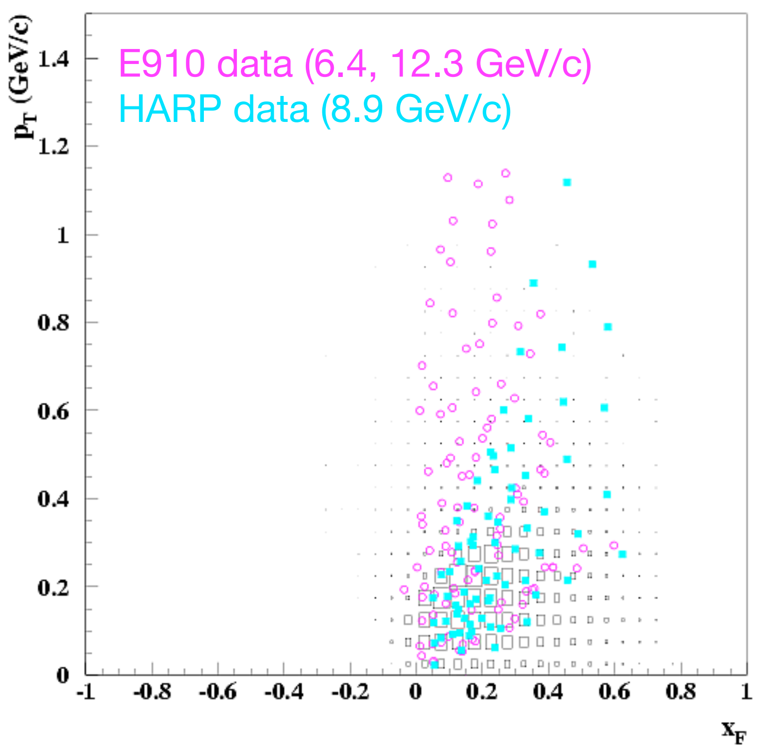


EPJ C 52 (2007) 29

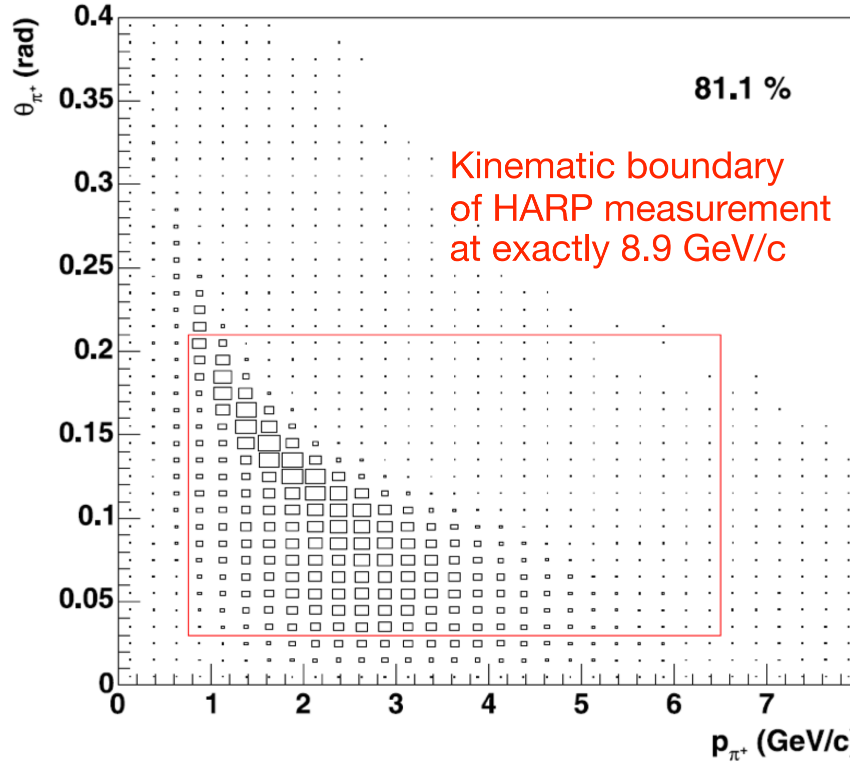
HARP/MiniBooNE

- Combining HARP and E910 data gives maximal coverage of the relevant pion phase space for MiniBooNE
- Use the parameterization of Sanford and Wang and fit to both data sets combined

p(8.9 GeV/c) + Be → π^+ + X



Black boxes are the distribution of π^+ which decay to a ν_μ that **passes through the MiniBooNE detector**

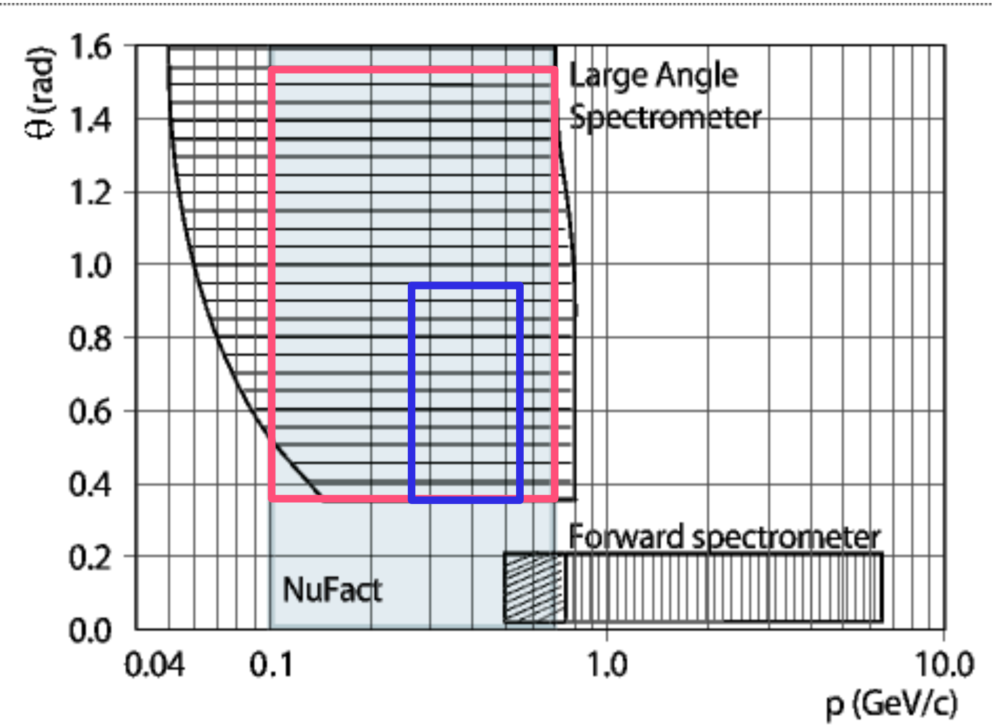


Phys. Rev. Lett. 98 (2007) 231801

Phys. Rev. D79 (2009) 072002

HARP/NuFact

$p + Pb \rightarrow \pi^{\pm} + X$



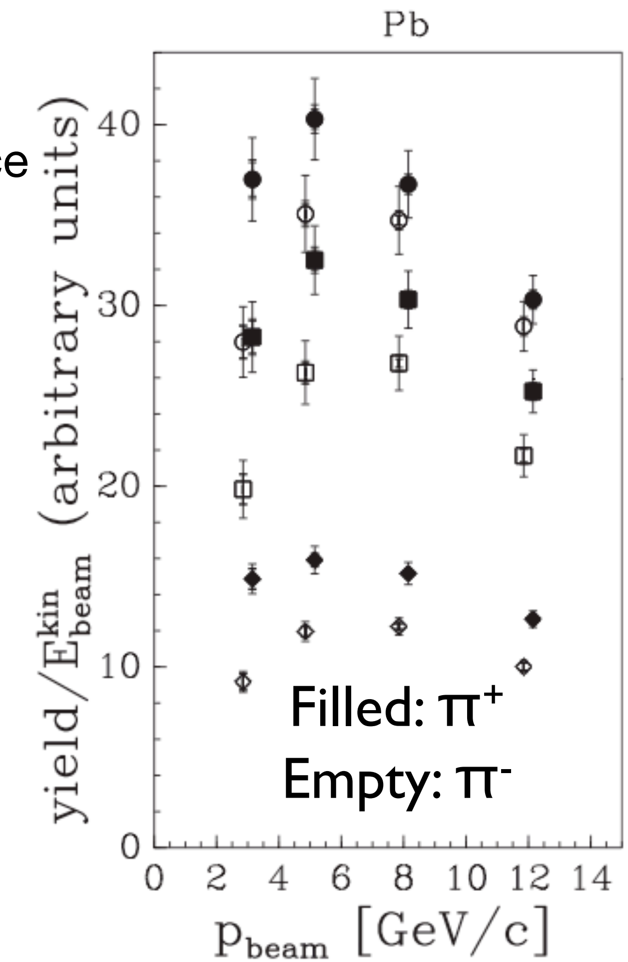
Full forward acceptance

↓

350 < θ < 950 mrad

↓

0.25 < p < 0.50 GeV/c



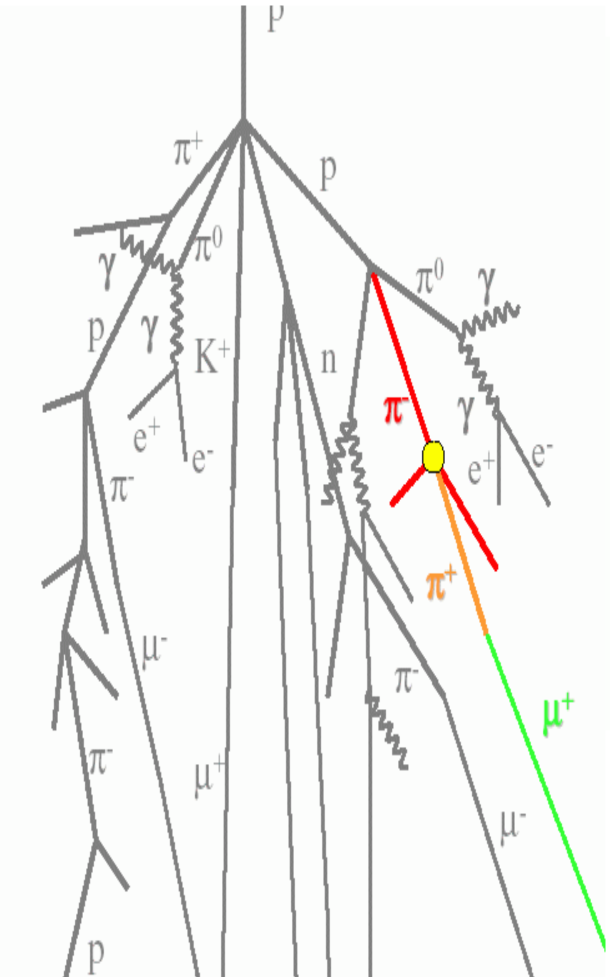
EPJC 54, 37 (2008)

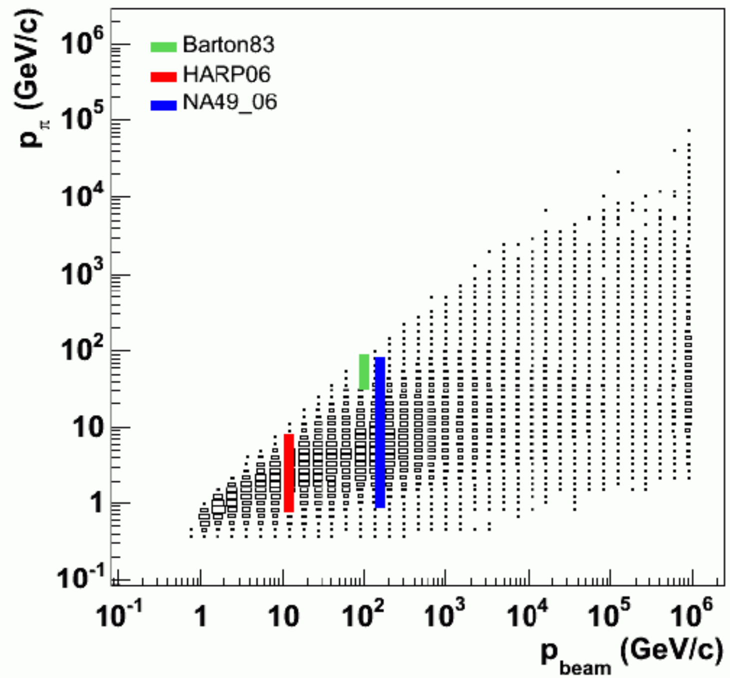
- Pion yield normalized to beam proton kinetic energy
- Restricted phase space most representative for NuFact design
- Optimum yield in HARP kinematic coverage for 5-8 GeV/c beam momenta
- Confirms Ta target results EPJC 51, 787 (2007)
- Quantitative optimization possible using full spectra range available for 4 beam momentum settings (3-12GeV/c)

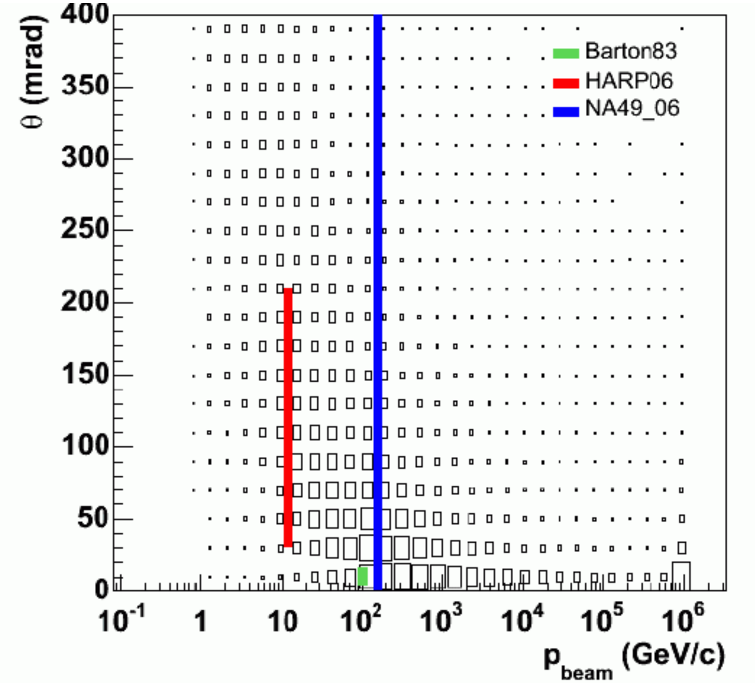
73	80	82
Ta	Hg	Pb

HARP
Atmospheric Neutrinos

Atmospheric Neutrinos







5 B	6 C	7 N	8 O	9 F

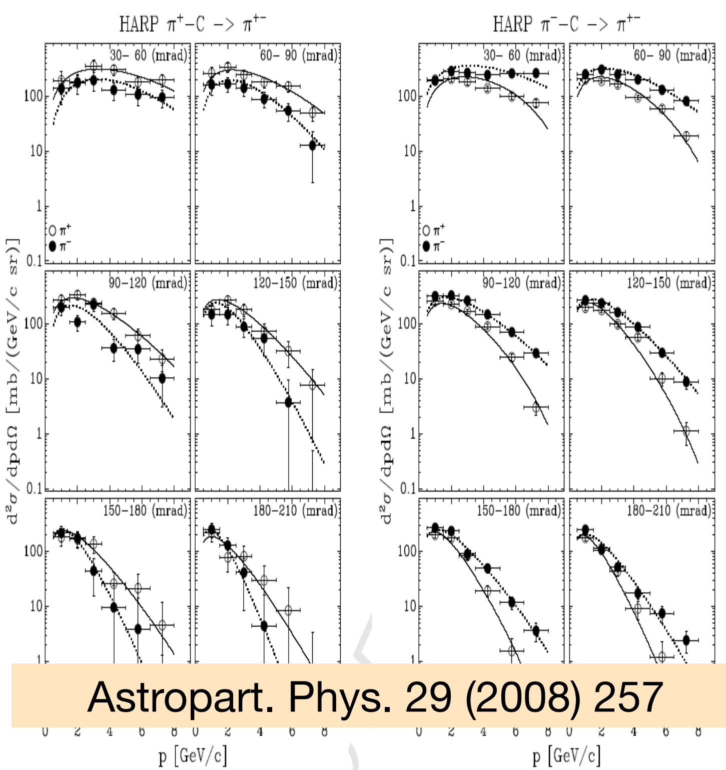
78% nitrogen
21% oxygen

- Challenge for accurate neutrino flux prediction: primary cosmic ray spectrum & hadronic interactions (primary with nuclei)
- Carbon is isoscalar as nitrogen and oxygen
- Simulations predict that collisions of protons with a carbon target are very similar to proton interactions with the air

M.Honda et al., Phys. Rev. D83 (2011) 123001

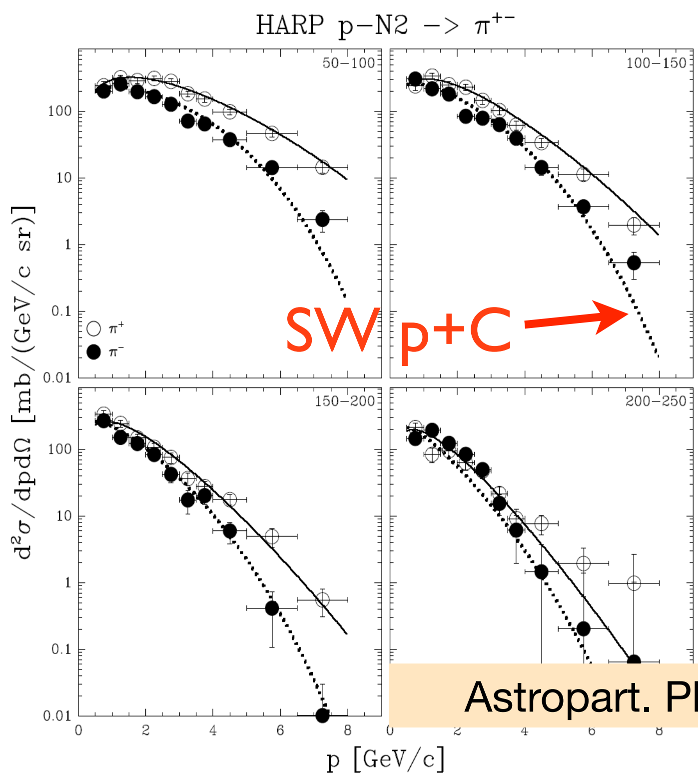
HARP/Atmospheric

$\pi^{\pm}$(12 GeV/c) + C → $\pi^{\pm}$ + X

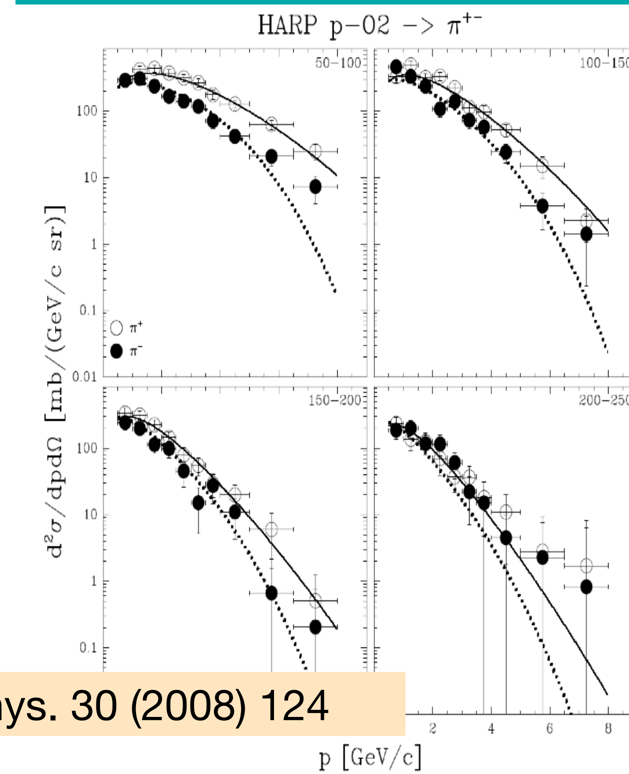


Astropart. Phys. 29 (2008) 257

p(12 GeV/c) + N → $\pi^{\pm}$ + X



p(12 GeV/c) + O → $\pi^{\pm}$ + X



Astropart. Phys. 30 (2008) 124

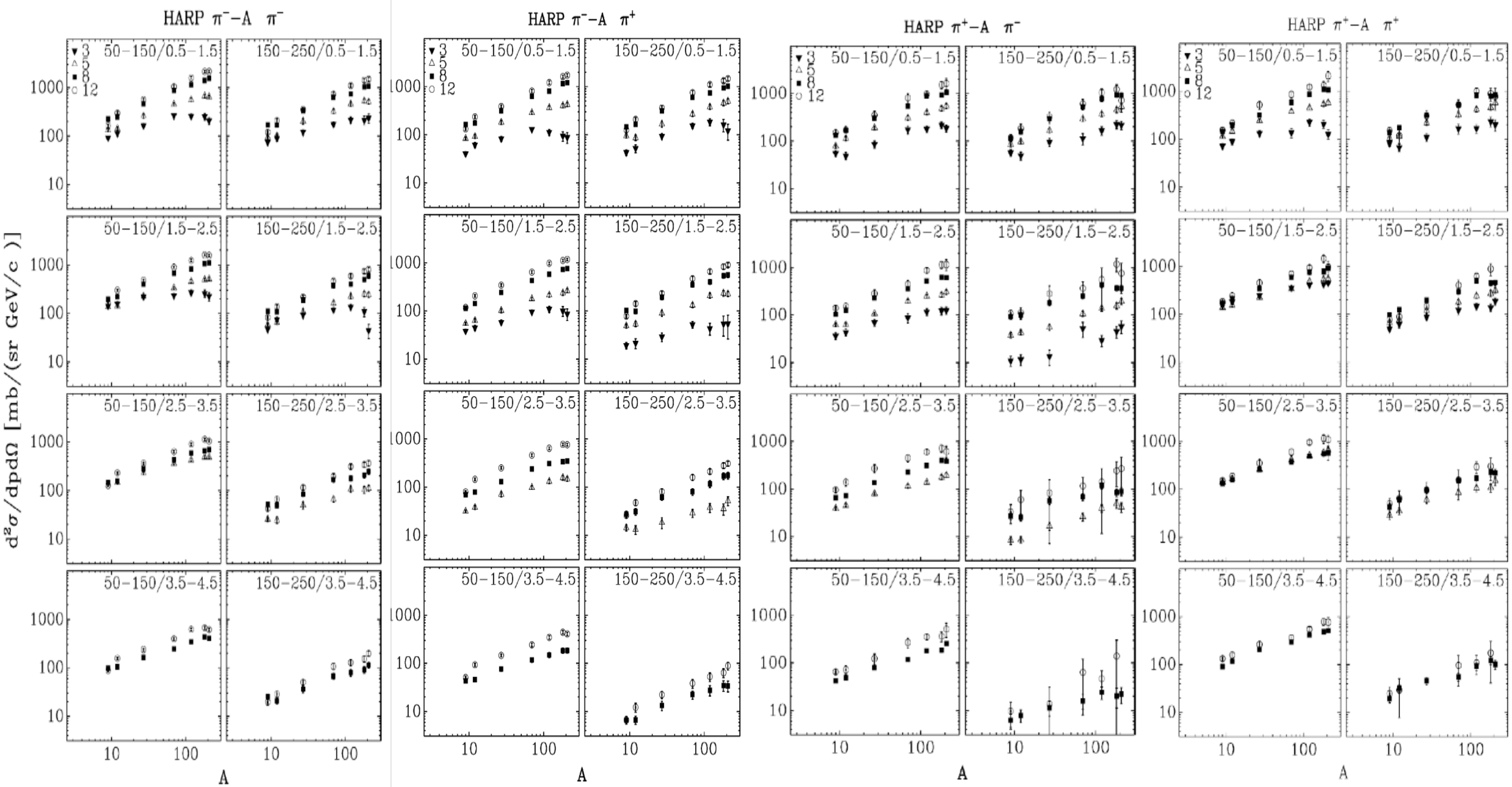
- Incoming charged pion HARP data were the first precision measurements in this kinematic region.
- Data relevant to the prediction of atmospheric neutrino fluxes and extensive air shower (EAS) simulations
- First precision measurement for N_2 and O_2 in this energy range
- HARP data confirmed that p+C data can be used to predict p+N_2 and p+O_2 pion production

HARP

Systematic Target Studies

HARP Forward π-A

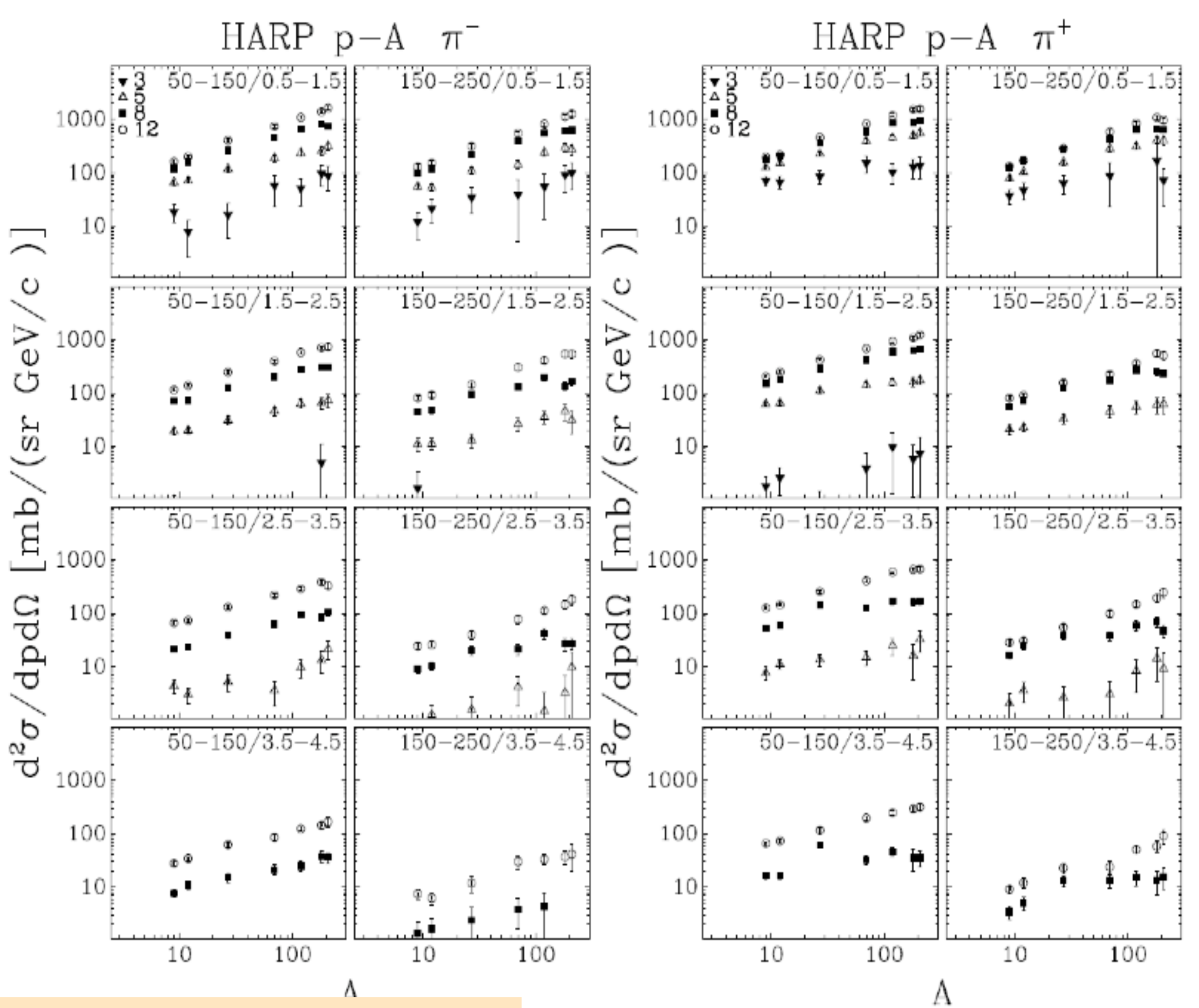
π⁻-A→π⁻ π⁻-A→π⁺ π⁺-A→π⁻ π⁺-A→π⁺



Nucl. Phys. A 821 (2009) 118

Dependence on the atomic number A of the pion yields in π-A interactions averaged over two FW angular regions ([50,150], [150,250] rad) and four momentum regions ([0.5-1.5], [1.5,2.5], [2.5,3.5], [3.5,4.5] GeV/c) for incoming beam momenta 3,5,8,12 GeV/c

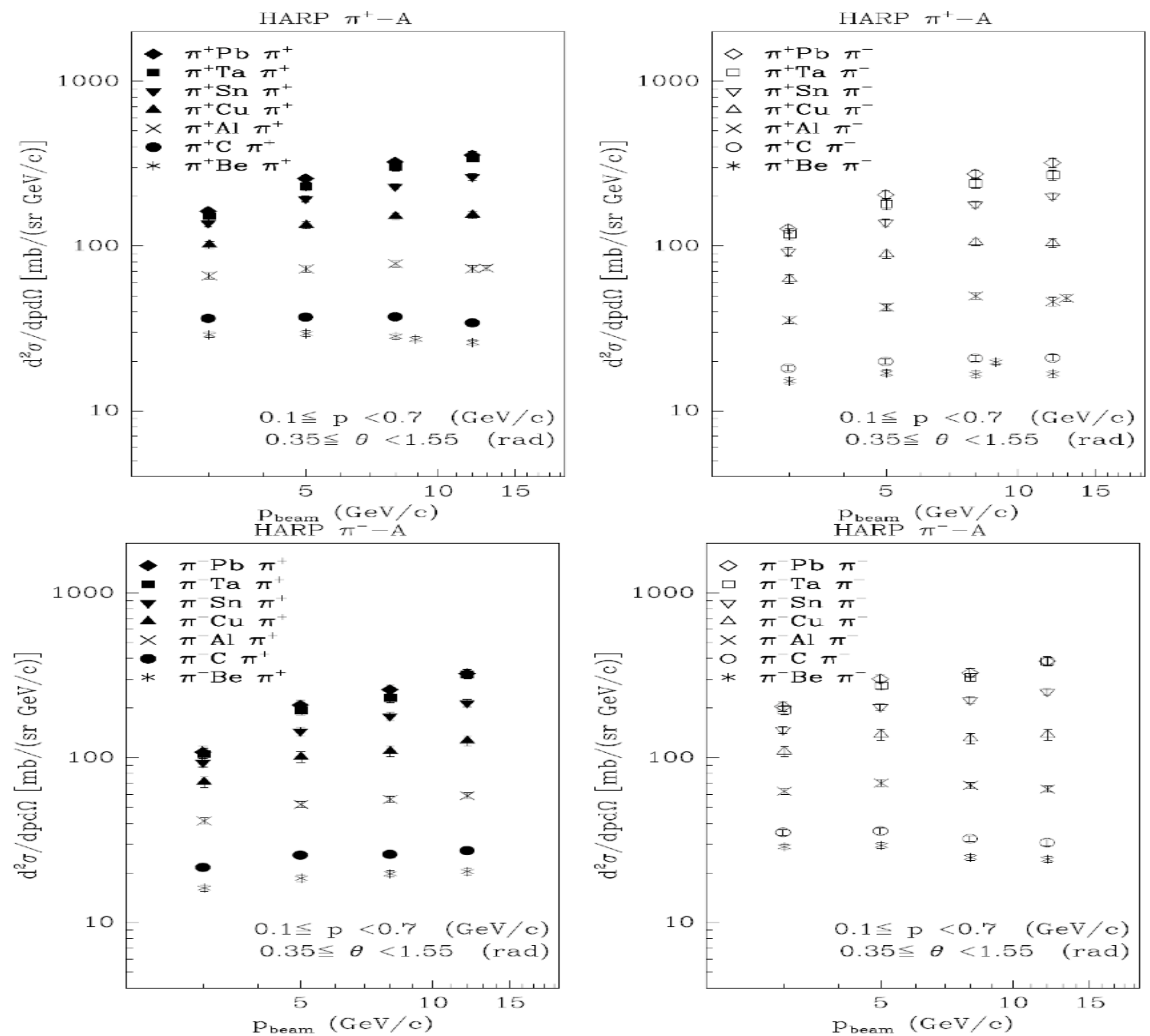
HARP Forward p-A



Phys. Rev. C80 (2009) 035208

Dependence on the atomic number A of the pion yields in p-A interactions averaged over two FW angular regions ([50,150], [150,250] rad) and four momentum regions ([0.5-1.5], [1.5,2.5], [2.5,3.5], [3.5,4.5] GeV/c) for incoming beam momenta 3,5,8,12 GeV/c

HARP LA π-A



0.1 < p < 0.7 (GeV/c)
0.35 < θ < 1.55 (rad)

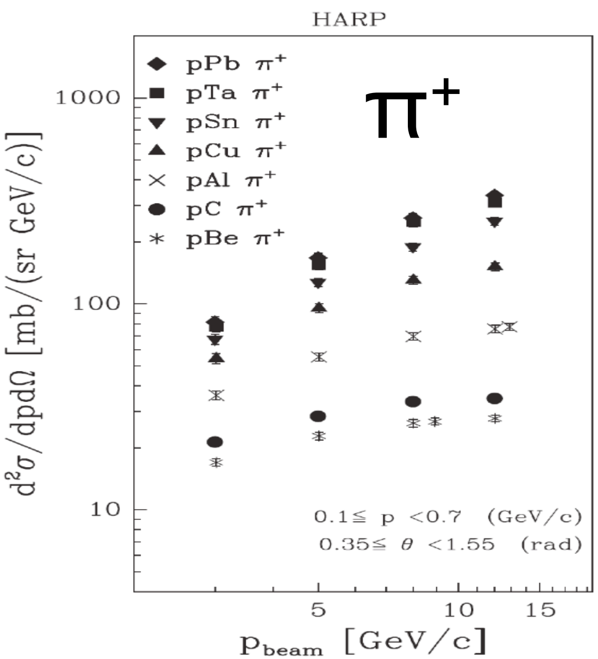
π^+

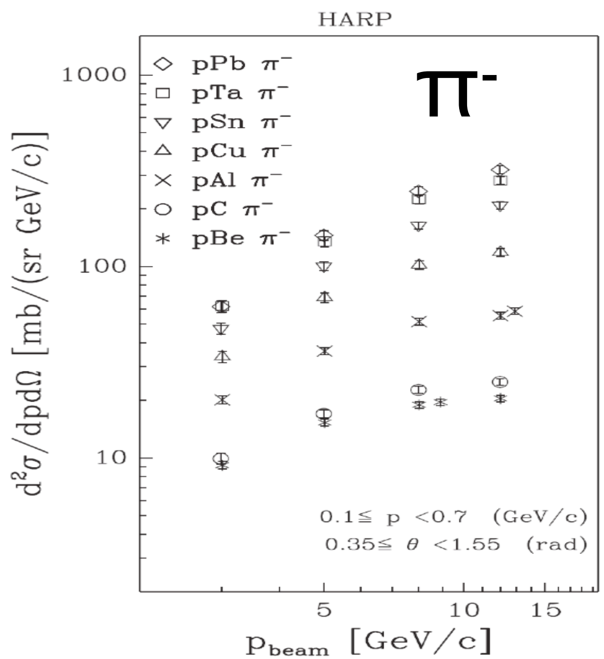
π^-

Phys. Rev. C80 (2009) 065207

A-dependence of the π+ and π- yields in π±-A interactions for Be, C, Al, Cu, Sn, Ta, Pb as a function of beam momentum (full spill data)

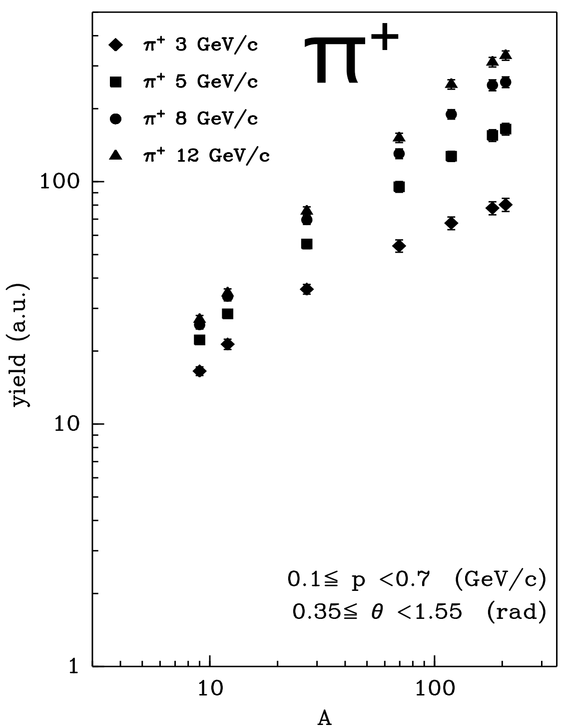
HARP LA p-A

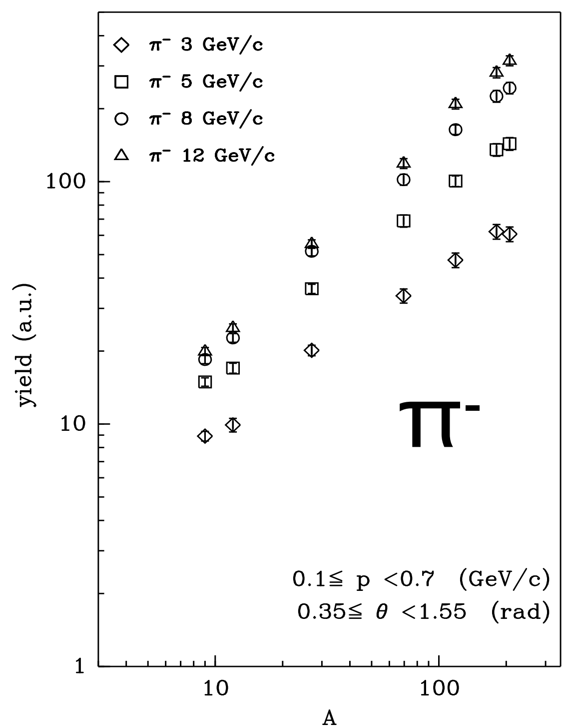




- Comparison of π+ and π- yields in p-A for Be, C, Al, Cu, Sn, Ta, Pb as a function of beam momentum (full spill data)

$0.1 < p < 0.7$ (GeV/c)
$0.35 < \theta < 1.55$ (rad)





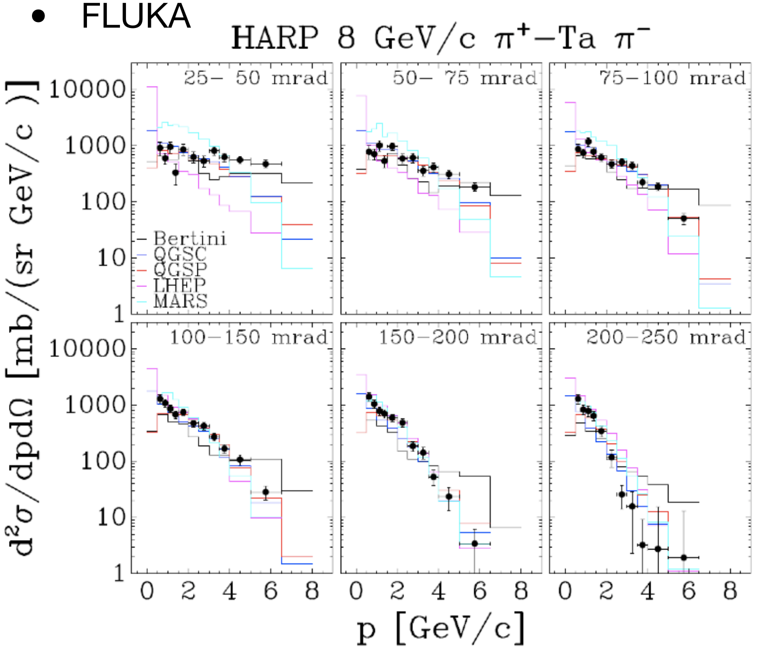
- A-dependence of the π+ and π- yields in p-A interactions for Be, C, Al, Cu, Sn, Ta and Pb (full spill data)

$0.35 < \theta < 1.55$ (rad)

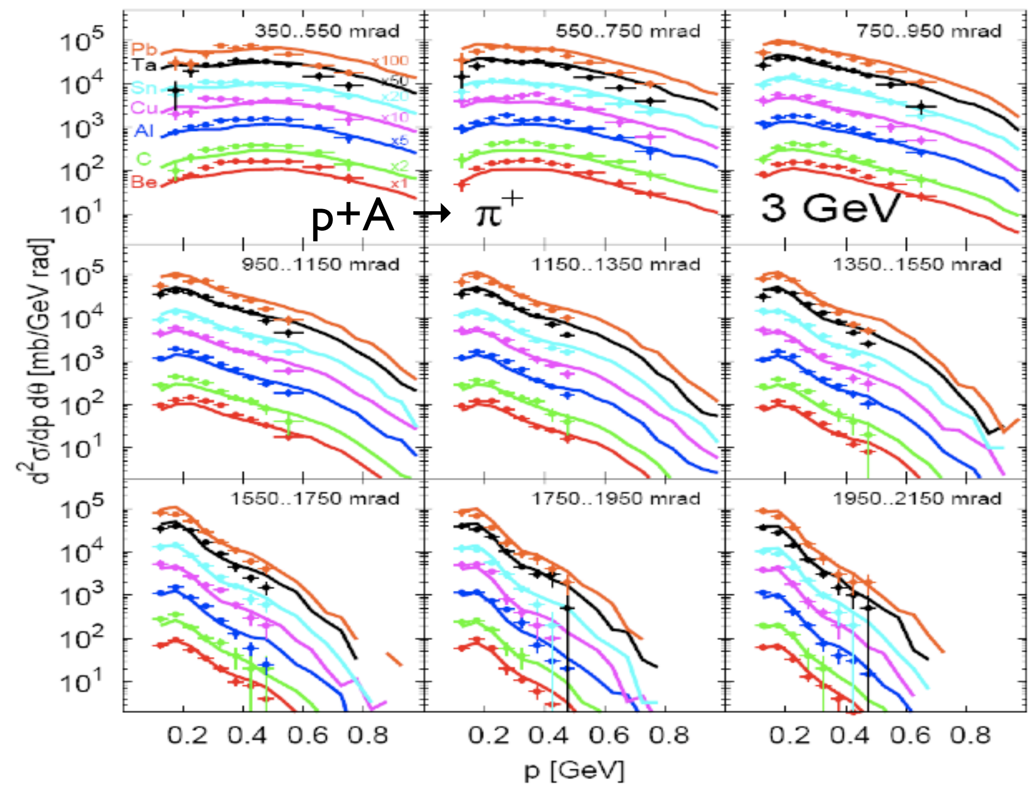
Phys. Rev. C 77 (2008) 055207

HARP Data-MC Comparison

- Many comparisons with models from GEANT4 and MARS
- Only some examples shown here
    - Binary Cascade
    - Bertini Cascade
    - Quark-Gluon string (QGS)
    - Fritiof (FTFP)
    - LHEP
    - MARS
    - GiBUU
    - FLUKA



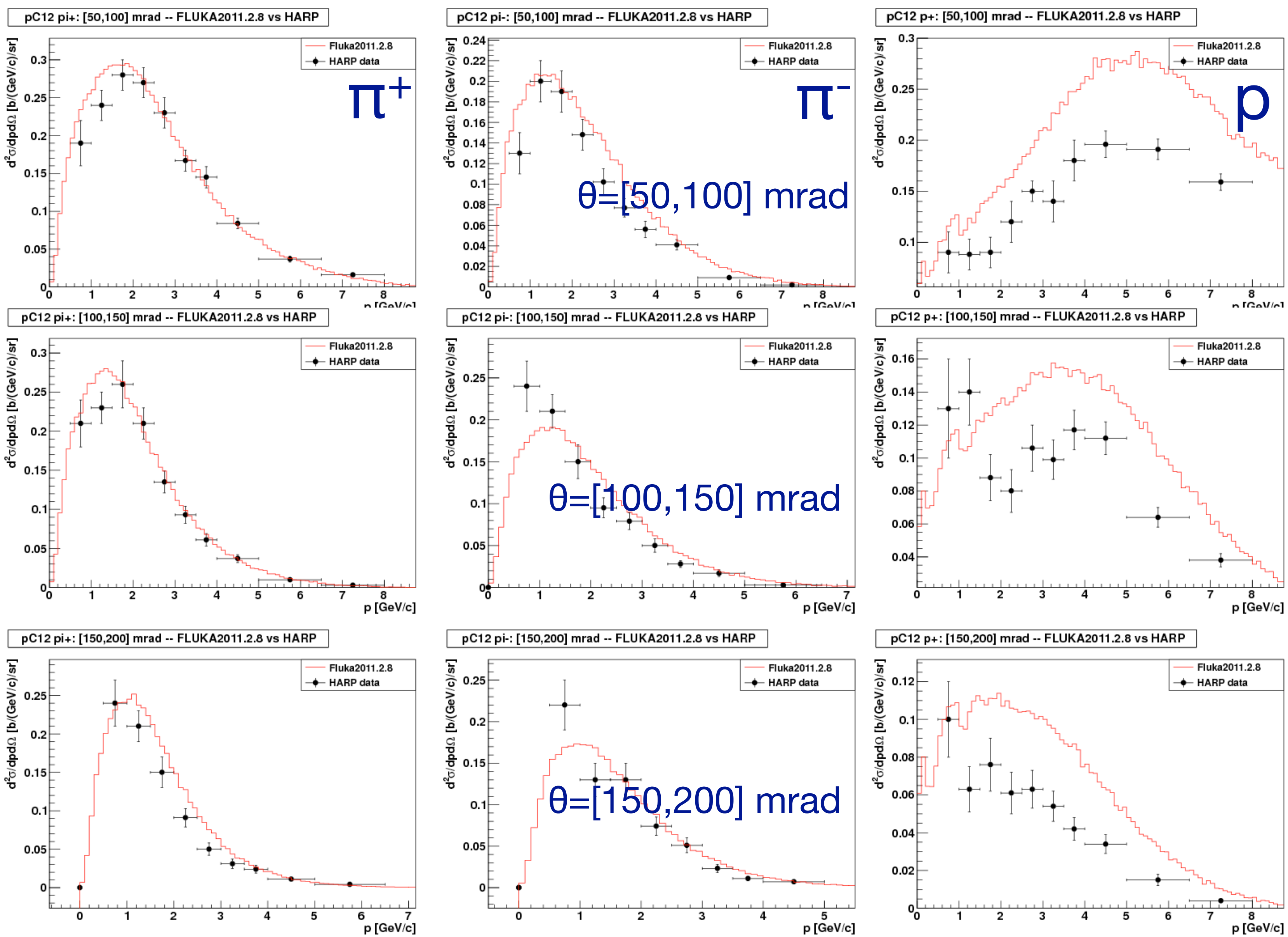
Nucl. Phys. A 821 (2009) 118
HARP collaboration



Nucl. Phys. A 826 (2009) 151
K. Gallmeister, U. Mosel

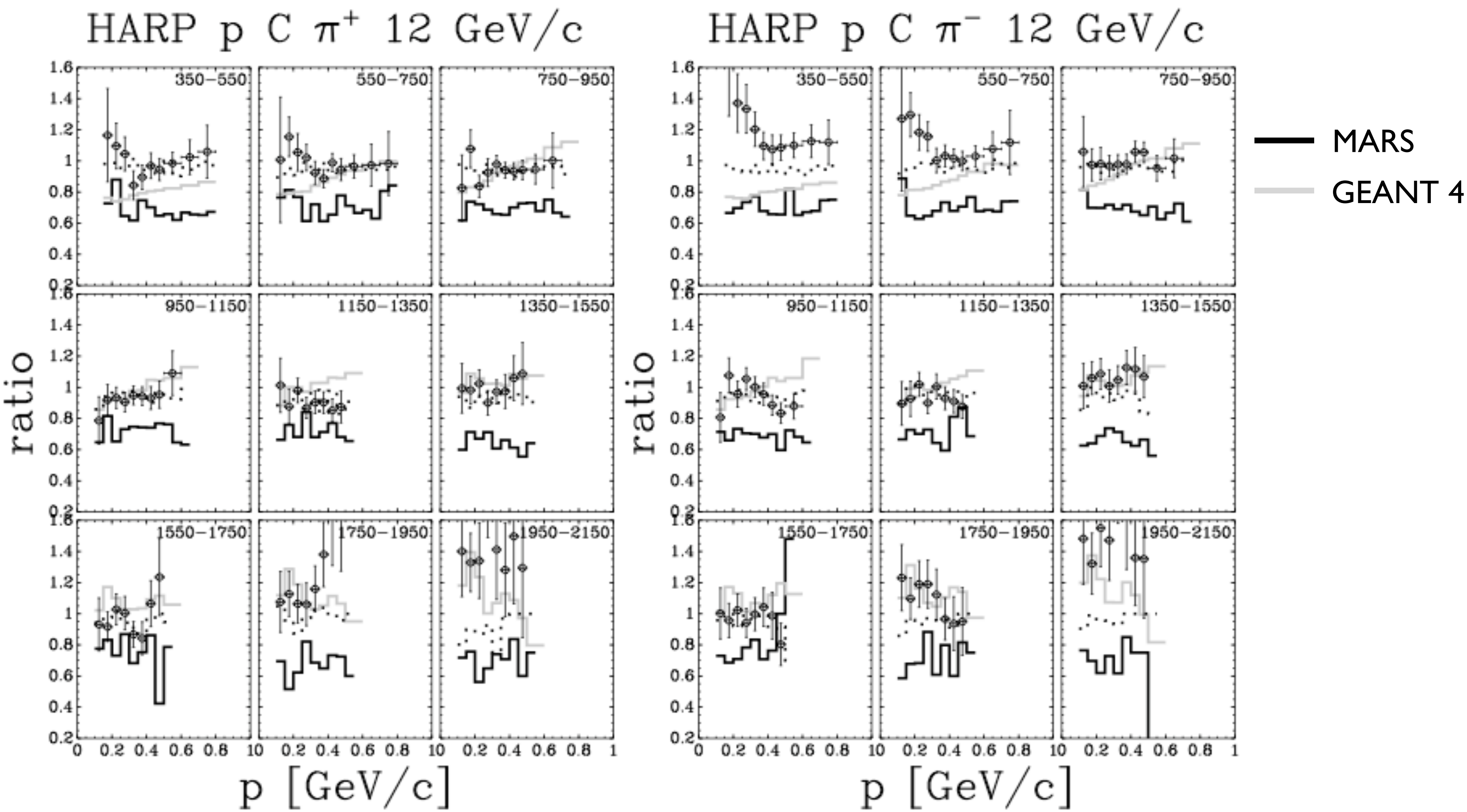
- GiBBU transport model covers the full energy range of HARP data
- Models do a good job in some regions, but no model that describes all aspects of the data

HARP Data-MC Comparison



A lot more comparison plots can be found in the technical notes https://edms.cern.ch/file/1184197/2/fluka2011_harp_updated.pdf https://edms.cern.ch/file/1218221/1/fluka2011_harp_ta.pdf for charged pion and proton production in proton- and charged pion- Interactions at 3, 5, 8 and 12 GeV/c on C, Al and Ta targets

HARP Long Target



Phys. Rev. C80 (2009) 065204

- Ratio of pion yields in 100% λ over 5% λ Carbon target
- Dotted line – ratio of pions produced by “first generation” beam proton to all pions produced by the beam in MARS

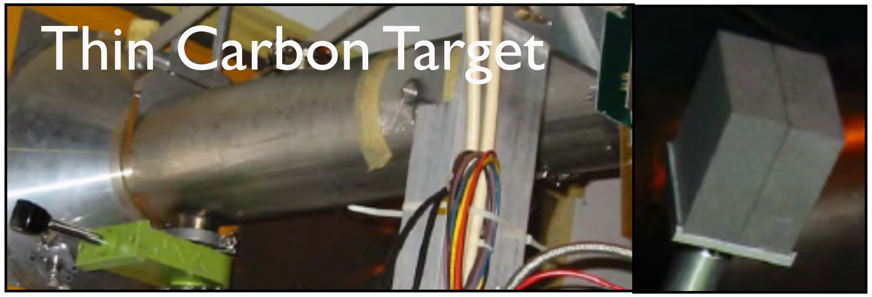
HARP Publications

- Measurement of the production cross-section of positive pions in p-Al collisions at 12.9 GeV/c, Nucl.Phys. B732(2006) 1
- Measurement of the Production of Charged Pions by Protons on a Tantalum Target, Eur. Phys. J. C51 (2007) 787, [arXiv:0706.1600]
- Measurement of the production cross-section of positive pions in the collision of 8.9GeV/c protons on beryllium, Eur. Phys. J. C52 (2007) 29, [hep-ex/0702024]
- Large-angle production of charged pions by 3 GeV/c-12 GeV/c protons on carbon, copper and tin targets, Eur. Phys. J. C53(2008) 177, [arXiv:0709.3464]
- Large-angle production of charged pions by 3 GeV/c-12.9 GeV/c protons on beryllium, aluminium and lead targets, EPJ C54(2008) 37, [arXiv: 0709.3458]
- Measurement of the production cross-sections of $\pi\pm$ in p-C and $\pi\pm$-C interactions at 12 GeV/c, Astr. Phys. 29 (2008) 257, [arXiv: 0802.0657]
- Forward $\pi\pm$ production in p-O2 and p –N2 interactions at 12 GeV/c, Astr. Phys. 30 (2008) 124, [arXiv: 0807.1025]
- Large-angle production of charged pions with incident protons on nuclear targets as measured in the Harp experiment, Phys. ReV.C77(2008)055207, [arXiv: 0805.2871]
- Forward production of charged pions with incident $\pi\pm$ on nuclear targets as measured at CERN PS, Nucl. Phys. A821(2009) 118 [arXiv: 0902.2105]
- Comparison of large-angle production of charged pions with incident protons on cylindrical long and short targets. Phys.Rev. C80 (2009) 065204 [arXiv:0909.0337]

Tables with HARP results are available e.g. from the DURHAM database

NA61/SHINE

NA61/SHINE

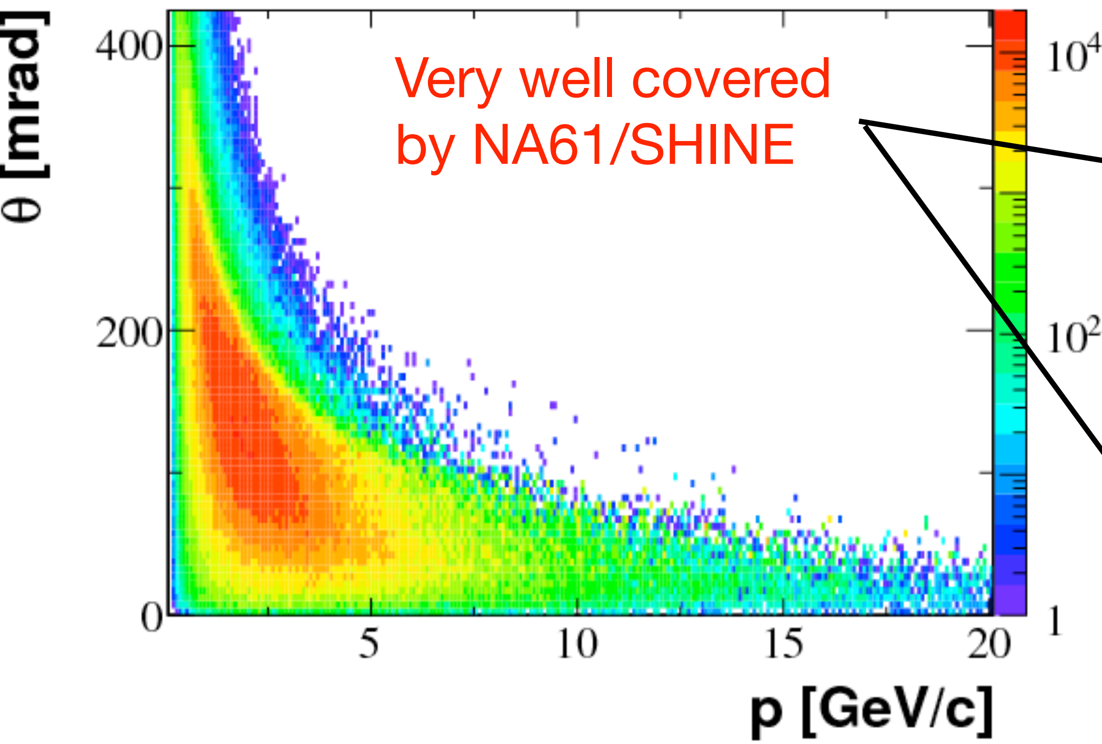


- Two different carbon (isotropic graphite) targets were used

Thin Carbon Target	T2K replica Target
- length=2 cm, cross section 2.5x 2.5 cm^2 - ρ = 1.84 g/cm^3 - ~0.04 λ_{int}	- length = 90 cm, Ø=2.6 cm - ρ = 1.83 g/cm^3 - ~1.9 λ_{int}

- Data for T2K with incoming 31 GeV/c protons collected:
  - 2007 run (~670k triggers on thin target and ~230k triggers on replica target). Analysis finalized and corresponding results published.
  - 2009 run (~6M triggers on thin target and ~2M triggers on replica target). These data are now fully calibrated and analysis is well advanced.
  - 2010 run (~10M triggers on replica target). Data being calibrated now. Ultimate data set for most precise neutrino flux predictions.
- Three complementary analysis techniques which differ by PID method

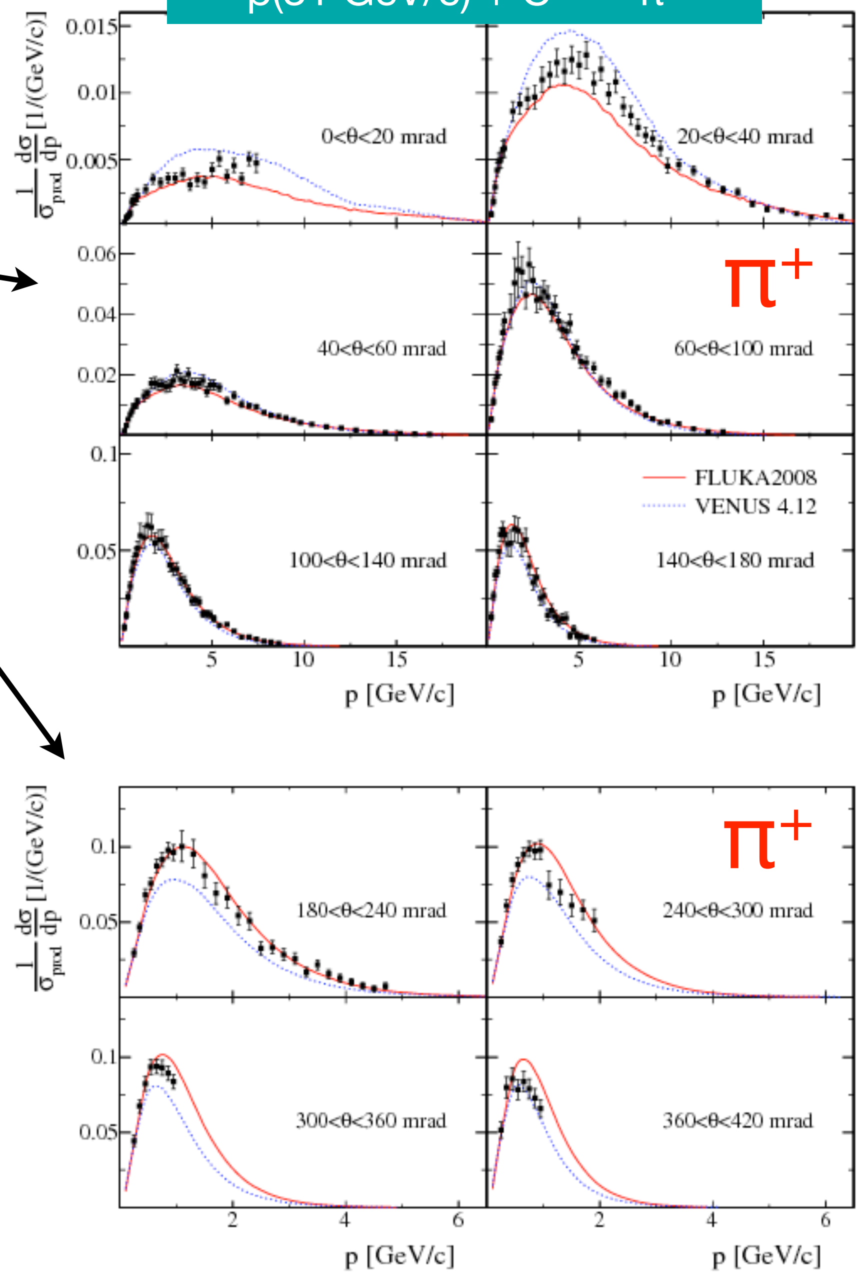
NA61/SHINE



Very well covered by NA61/SHINE

T2K beam simulation: the (p,θ) distribution for π^+ weighted by the probability that their decay produces a ν_μ passing through SK

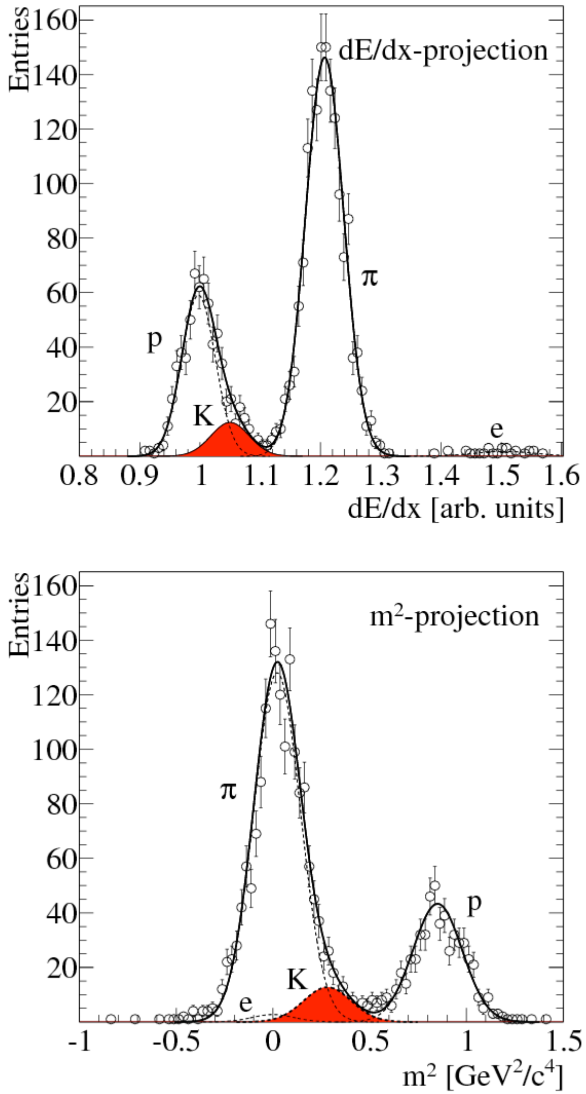
p(31 GeV/c) + C → $\pi^\pm$

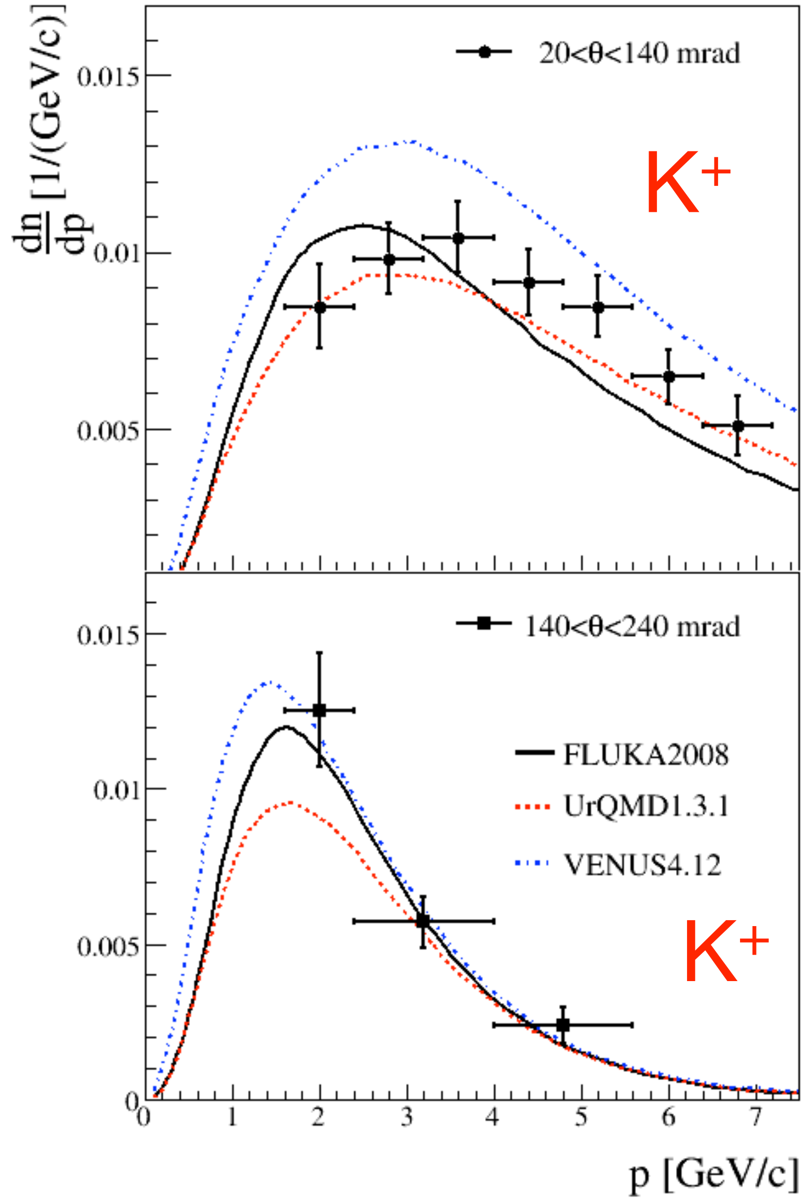


PRC 84 (2011) 034604

NA61/SHINE

p(31 GeV/c) + C → K^+





Relevant for high energy tail of ν_μ spectrum and intrinsic ν_e component in T2K

PRC 85 (2012) 035210

NA61/SHINE

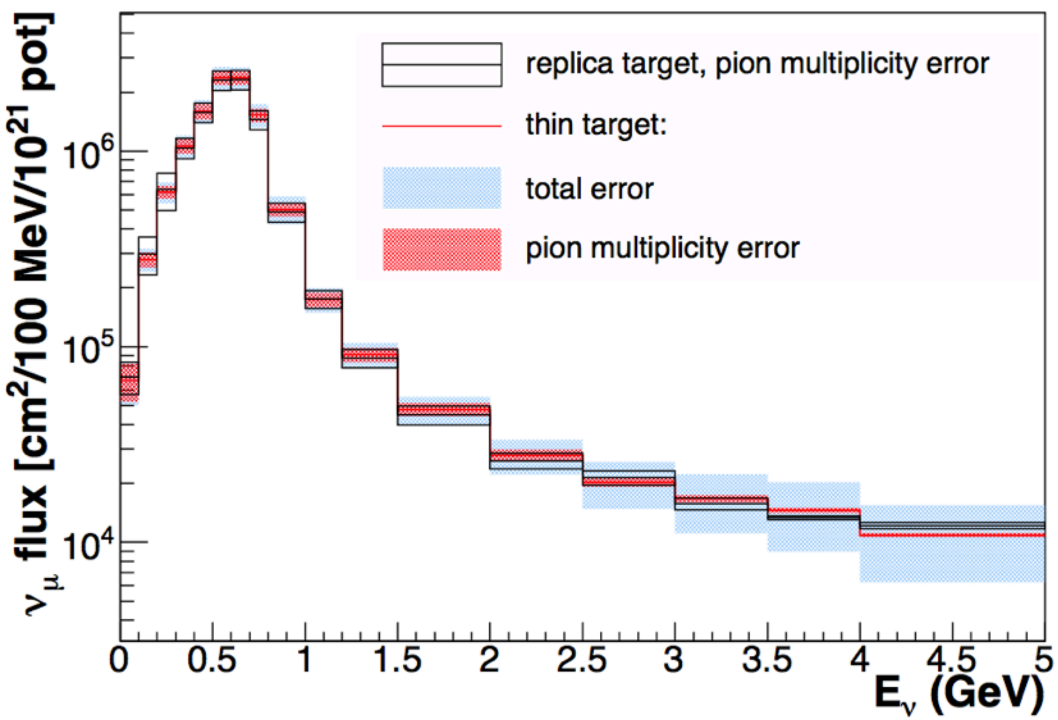
Replica Target Analysis

- Special reconstruction and analysis techniques developed for the replica target
- Pilot analysis on π+ emission from the replica target surface performed on 2007 data
- Replica target hadron production measurements allow to constrain up to 90% of neutrino flux in T2K
- Proof-of-principal neutrino flux re-weighting performed with NA61/SHINE replica target data
- Results consistent with the thin target tuning

NA61/SHINE

Replica Target Analysis

- Replica target data are used for the first time for neutrino flux predictions.
- Combination of thin and replica target measurements to better understand effects of re-interactions in the long target
- Ultimate precision on T2K neutrino flux will be achieved with replica target re-weighting, once 2010 NA61/SHINE data are analyzed.



Re-weighted ν_μ flux at the far detector based on the NA61/SHINE thin target and replica target measurements.

NIM, A (2013) 99-114

NA61/SHINE

- Additional preliminary results using the 2007 data:
  - p(31 GeV/c) + C → p
  - p(31 GeV/c) + C → K0S
- In 2007 data analysis statistical errors dominate.
- Further analysis of data collected for T2K in 2009 and 2010 with both thin and replica targets as well as for Cosmic Ray experiments (π-C @158 and @350 GeV/c) is on-going
- With 2009 data, hope to reduce statistical errors by a factor of 3.
- Systematic errors will become more important
- NA61/SHINE 2009 & 2010 pC@31GeV/c and pRT@31GeV/c data provide even a better coverage of phase space of interest for T2K
- Will allow to reach T2K requirements on neutrino flux predictions: 5% error on absolute neutrino fluxes in the near and far detectors (as well as 3% error on the far-to-near ratio)
- Both thin target and replica target with improved statistics expected in early 2013
- US groups involved in Fermilab neutrino experiments plan to join NA61 in order to perform required hadron production measurements
- See Alexis Hasler's talk on Friday

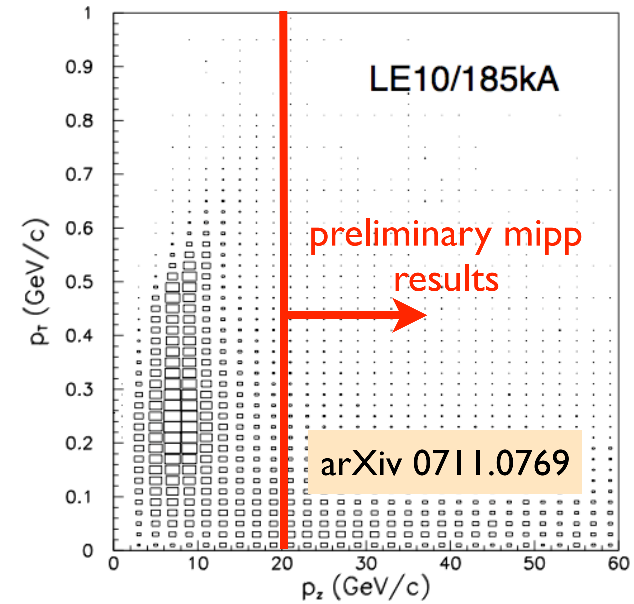
NA61/SHINE Publications

- Measurements of Cross Sections and Charged Pion Spectra in Proton-Carbon Interactions at 31 GeV/c, Phys.Rev. C84 (2011) 034604, arXiv:1102.0983
- Measurement of Production Properties of Positively Charged Kaons in Proton-Carbon Interactions at 31 GeV/c, Phys.Rev. C85 (2012) 035210, [arXiv:1112.0150]
- Pion emission from the T2K replica target: method, results and application, CERN-PH-EP-2012-188, [arXiv:1207.2114]

Future Prospects

MIPP

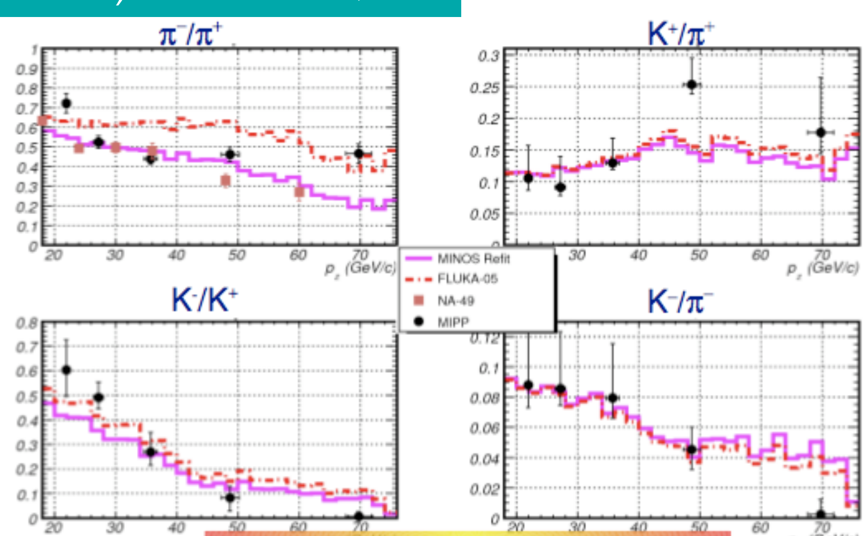
- Preliminary results cover high E_ν
- NuMI beam momentum: 120 GeV/c
- Both NuMI replica and thin C targets
- Preliminary: fully corrected $\pi^\pm$, $K^\pm$ particle yields ratios only ($p_t < 0.2$ GeV/c)



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

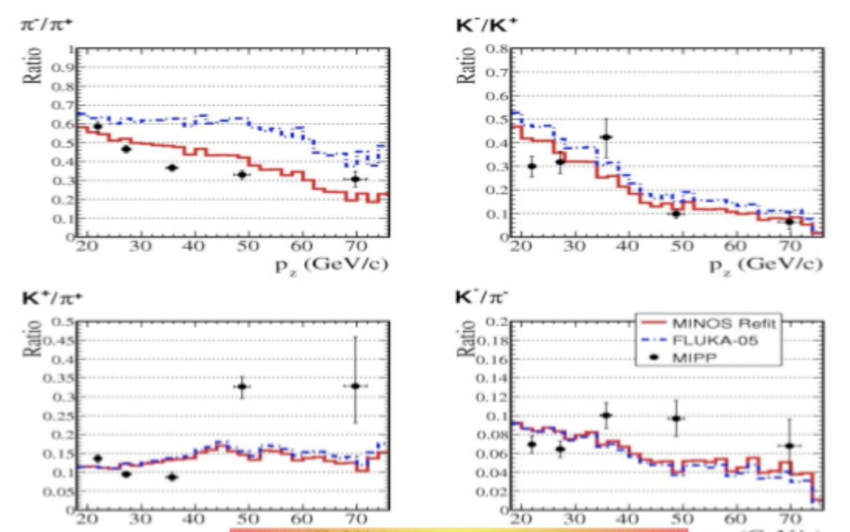
p(120 GeV/c) + C → $\pi^\pm$, $K^\pm$

Thin C target



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

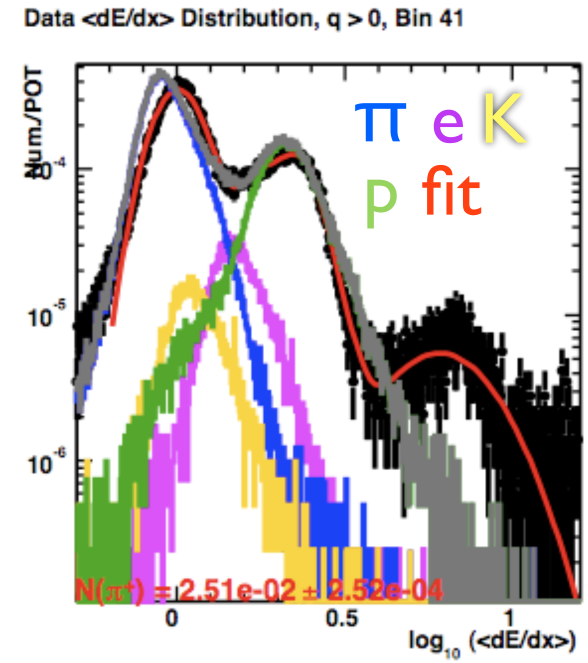
NuMI target



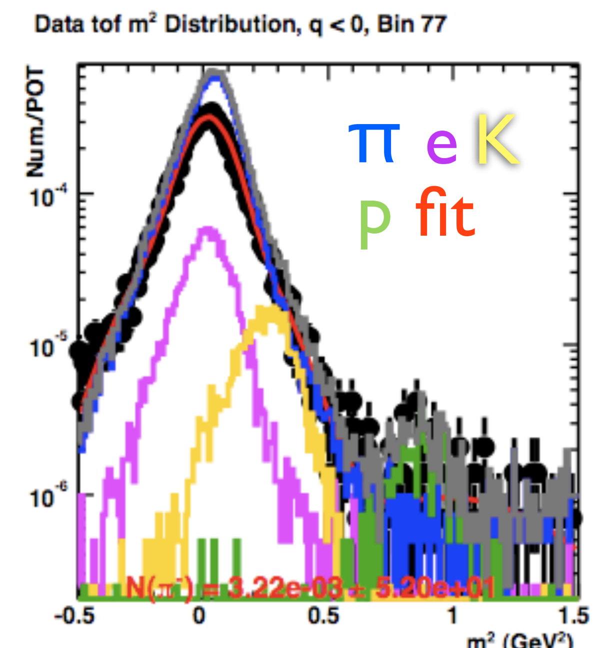
S. Seun, Ph.D. Thesis, Harvard U. (2007)

MIPP

- Current status:
  - Event selection has been finalized
  - MC has been mostly tuned (some further fine-tuning is required)
  - Acceptance corrections and efficiencies are understood
  - Reconstructed -> true unfolding and PID algorithm almost done
  - 4-6 months (full-time) to wrap current analysis
- Future plan:
  - Kaon production at low momenta relevant for the NOvA ND on surface prototype analysis
- See Jon Paley's talk on Friday



TPC dE/dx



TOF m^2

Interpolating Existing NA49/NA61Data

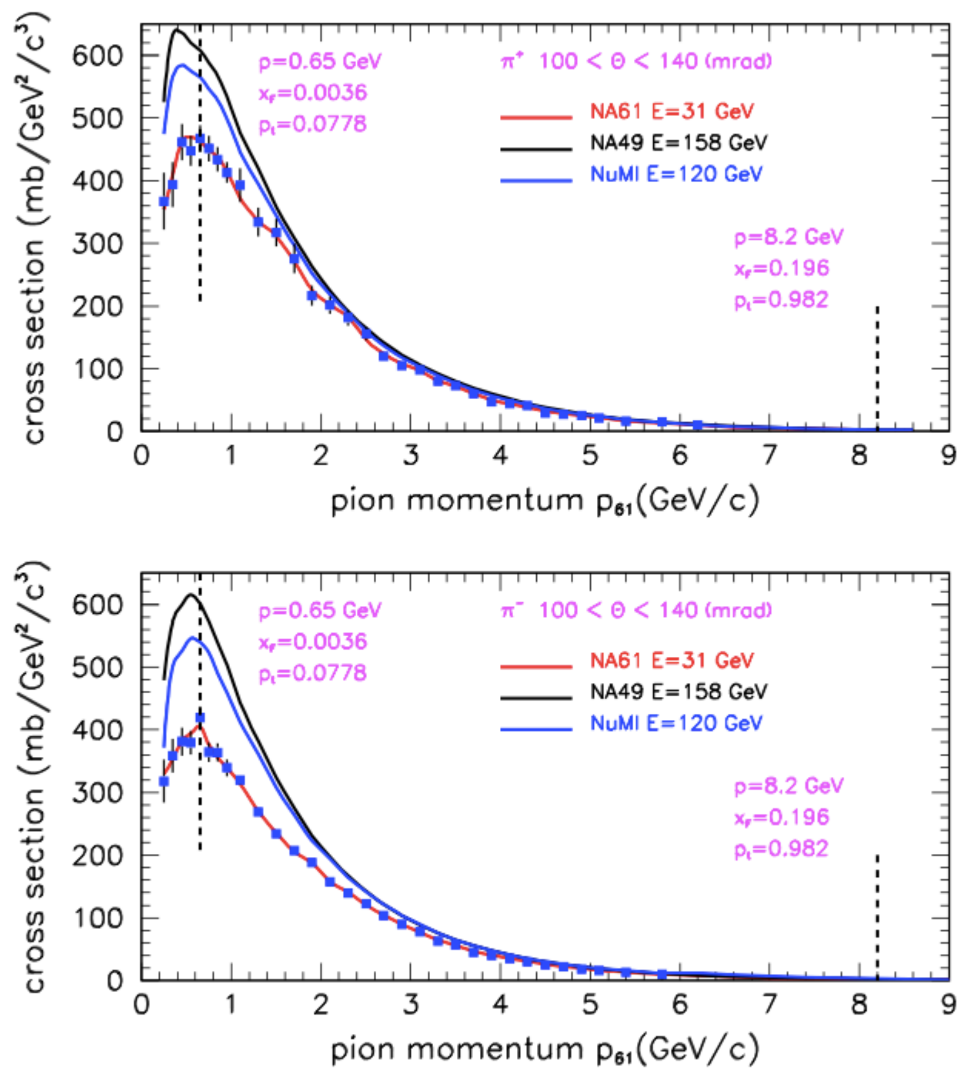
- Precise hadron production measurements in p + C collision at energy E=120 GeV are needed for improving calculation of the NuMI neutrino flux
- Charged pion spectra in p + C interactions were measured in NA61 and NA49 experiments at proton energies 31 and 158 GeV, respectively
- These data cover kinematic region of interest for charged pion $0.02 \leq x_F \leq 0.3$ and $0.1 \leq p_T \leq 0.5$(GeV/c) whose daughter muon neutrino gives the main contribution to NuMI neutrino flux
- Study energy dependence of the measured spectra to estimate the pion invariant cross section at proton energy 120 GeV
- Published NA49 and NA61(low statistic 2007 run) data used

MINERvA collaboration, FNAL

A. Butkevich, INR Moscow

Interpolating Existing NA49/NA61Data

- The measured NA61 differential cross section dσ/dp was transformed into invariant cross section $f(x_F, p_T)$.
- This cross section is interpolated using the effective variance recursive method and compared with interpolated NA49 data at the same values of $[x_F\ (p_{61}, \theta), p_T\ (p_{61}, \theta)]$.
- The invariant cross section at proton energy 120 GeV is evaluated and a "scaling violation" effect in the energy range E = 120 to 158 GeV is estimated.
- In the first calculation an effect of ≤ 10% is seen and depends on (x_F, p_T) and is of the same order as the statistical errors of the NA61 2007 data.



http://nova-docdb.fnal.gov:8080/cgi-bin/ShowDocument?docid=7674&version=1

US-NA61

- Measuring hadron production at the CERN NA61/SHINE experiment with 120GeV protons on NuMI replica target
- The data would be relevant for MINERvA, MINOS, MINOS+, NOvA and LBNE
- The program would take about four years to complete
- Pilot run in June 2012: primary goal to evaluate the capabilities of NA61/SHINE in a 120 GeV/c proton beam and the US-NA61 collaborators to get familiar with NA61/SHINE
- See Elena Guardincerri's talk later today

	Incident proton/pion beam momentum			
Target	120 GeV/c	90 GeV/c	60 GeV/c	8.9 GeV/c
NuMI (spare) replica	201X			
BNB replica				201X
LBNE replica	201X			
thin graphite ($< 0.05\lambda_I$)	**2012**	201X	201X	
thick graphite ($\sim 1\lambda_I$)	201X	201X	201X	

US-NA61 LOI

Summary

- Hadron production for neutrino experiments is a well established field
- Hadron production knowledge is limiting factor in understanding and optimization of a variety of neutrino sources (accelerator-based neutrino beams, atmospheric neutrinos)
- Search for smaller effects: characterization of actual neutrino beam targets to reduce MC extrapolation to the minimum
- Not mentioned in this talk but important:
  - Very precise NA49 measurements of π, K and p production in p-p (p-C) interactions at 158 GeV/c [Eur. Phys. J. C45 (2006) 343; Eur. Phys. J. C49 (2007) 897; Eur. Phys. J. C65 (2010) 9; Eur. Phys. J. C68 (2010) 1]
  - Reviews by M.Bonesini and A.Guglielmi, Phys. Rept. 433 (2006) 65 and by S.Kopp, Phys. Rept. 439 (2007) 101
- US-NA61 collaboration formed, pilot run in June 2012

Backup Slides

SW parameterization

$$\frac{d^2\sigma(\mathrm{p+A} \rightarrow \pi^+ + X)}{dpd\Omega}(p,\theta) = c_1 p^{c_2}(1 - \frac{p}{p_{\mathrm{beam}}}) \exp[-c_3 \frac{p^{c_4}}{p_{\mathrm{beam}}^{c_5}} - c_6\theta(p - c_7 p_{\mathrm{beam}} \cos^{c_8}\theta)]$$

- X : any other final state particle
- p_{beam} : proton beam momentum (GeV/c)
- p, θ : pion lab-frame momentum (GeV/c) and angle (rad)
- c_1,..., c_8 : empirical fit parameters

Parameter	Value
c_1	$(8.22 \pm 1.98) \cdot 10^1$
c_2	(6.47 ± 1.62)
c_3	$(9.06 \pm 2.03) \cdot 10^1$
$c_4 = c_5$	$(7.44 \pm 2.30) \cdot 10^{-2}$
c_6	(5.09 ± 0.49)
c_7	$(1.87 \pm 0.53) \cdot 10^{-1}$
c_8	$(4.28 \pm 1.36) \cdot 10^1$

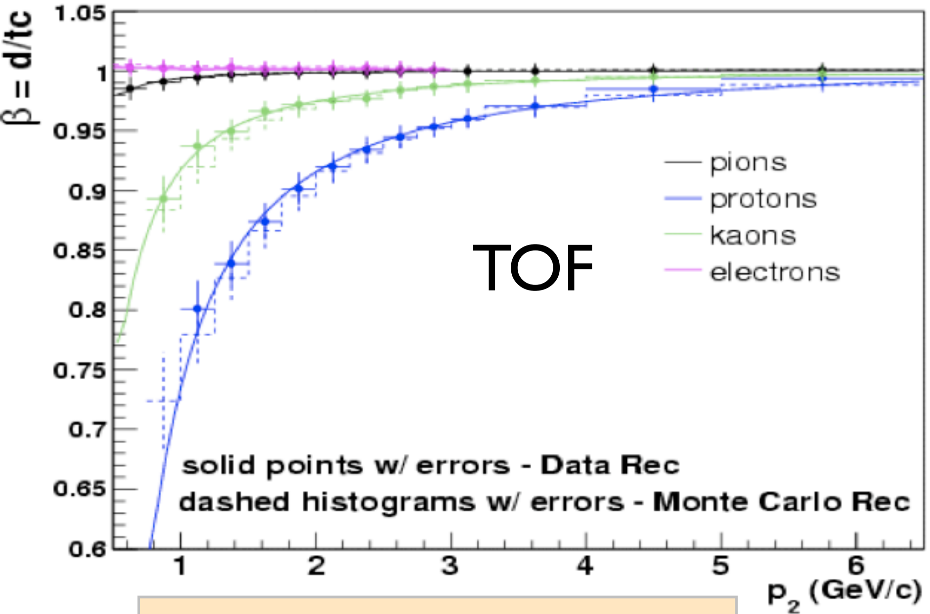
Parameter	c_1	c_2	c_3	$c_4 = c_5$	c_6	c_7	c_8
c_1	1.000						
c_2	0.327	1.000					
c_3	0.986	0.482	1.000				
$c_4 = c_5$	-0.559	0.596	-0.411	1.000			
c_6	0.091	-0.467	-0.006	-0.545	1.000		
c_7	0.011	-0.101	-0.004	-0.129	0.234	1.000	
c_8	-0.080	0.411	0.006	0.471	-0.776	0.215	1.000

HARP measurements for p+Be at 8.9 GeV/c

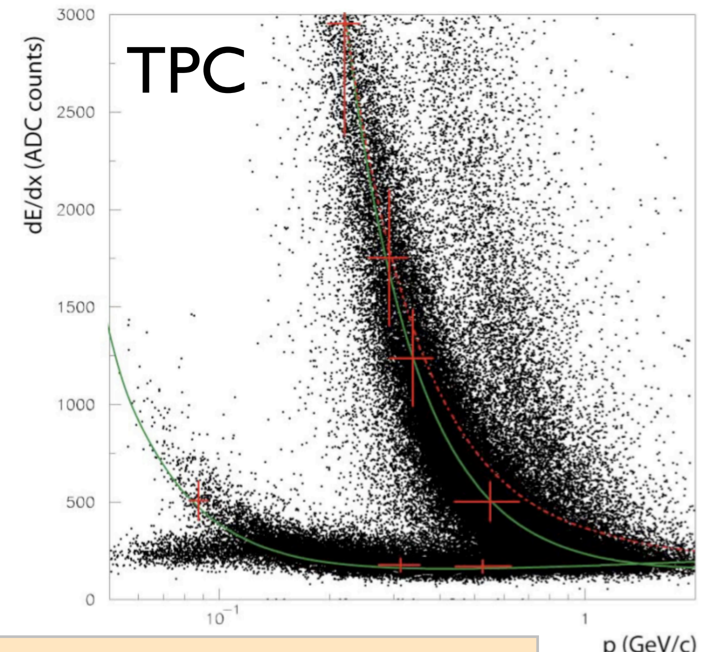
J. R. Sanford and C. L. Wang "Empirical formulas for particle production in p-Be collisions between 10 and 35 BeV/c", Brookhaven National Laboratory, AGS internal report, (1967) (unpublished)

EPJ C 52 (2007) 29

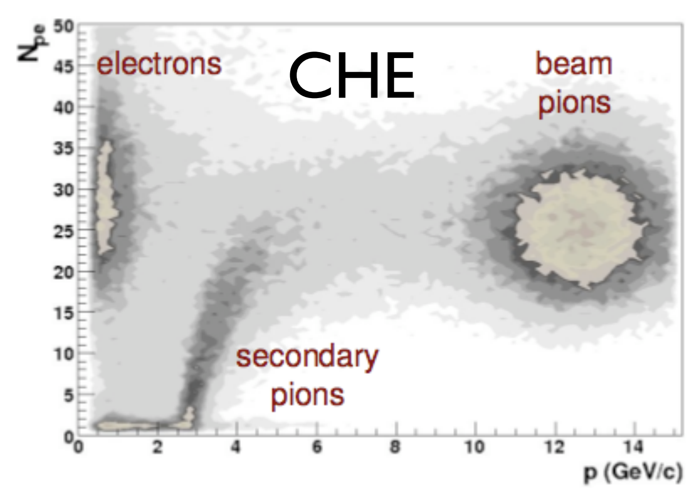
HARP PID



EPJC C 52, 29 (2007)



JINST 3, P04007 (2008)



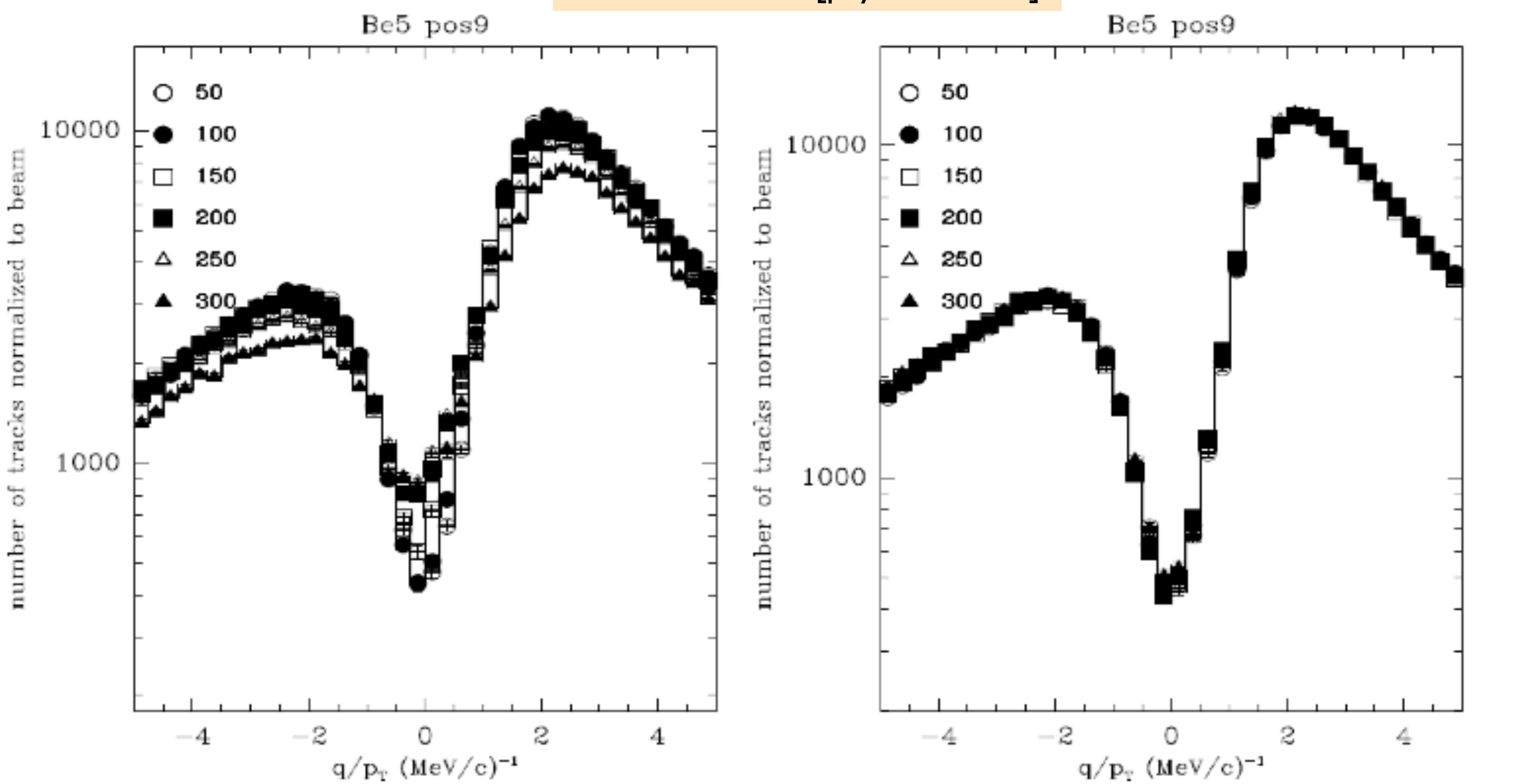
- TPC for p < 0.8 GeV/c
- TOF for 0.5 < p < 5 GeV/c (p/π)
- CHE for p > 2.6 GeV/c

HARP TPC dynamic distortion corrections

BEFORE

arXiv:0903.4762 [physics.ins-det]

AFTER



Full statistics now analysed ("full spill data" with dynamic distortion corrections). No significant difference is observed with respect to first analyses of the partial data (first 100-150 events in spill)

Phys. Rev. C 77 (2008) 055207

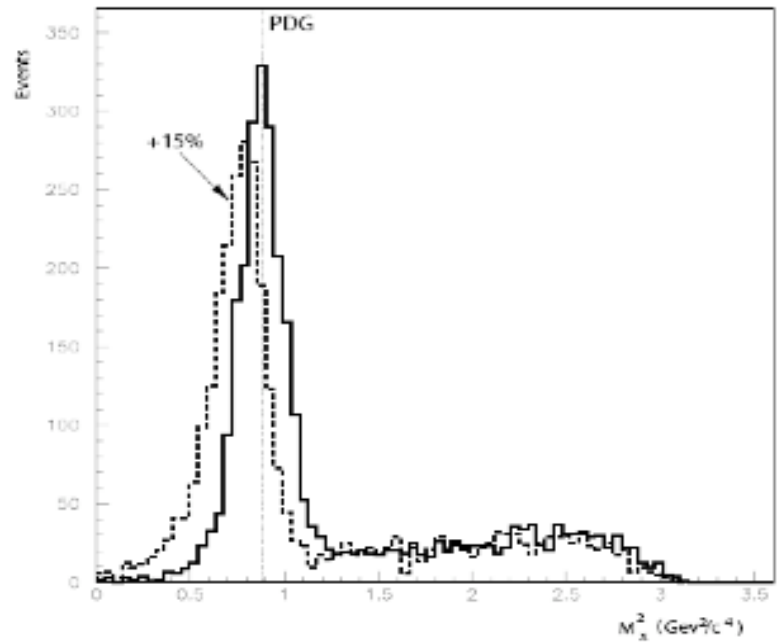
MIPP Upgrade

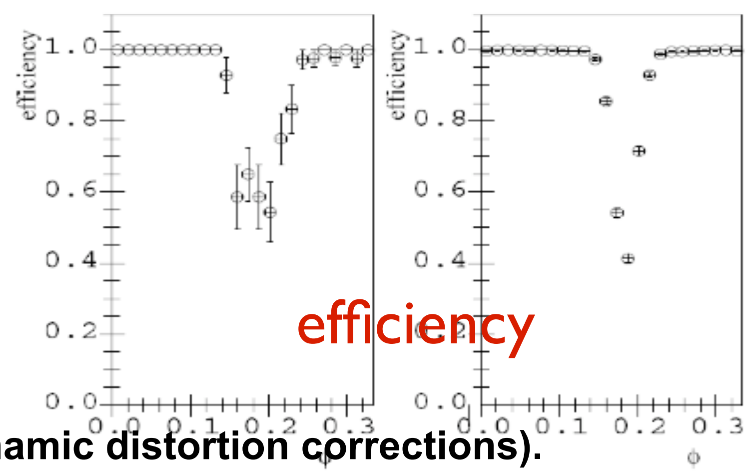
arXiv: hep-ex/0609057

- MIPP was limited by DAQ rate, dominated by the TPC readout time (~30 Hz). This is ~1/5 of desired statistics for NuMI target run.
- In addition, the Jolly Green Giant magnet failed at end of run (repair is now complete)
- Upgrade of the TPC electronics is expecting to increase the readout speed by a factor of 50
- Other improvements would result in:
  - more stable TPC 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 TPC calibration

- Elastic scattering benchmark
- Missing mass peak from large angle proton track (position of peak verifies momentum scale: +15% completely excluded)
- Comparison of predicted vs. measured tracks allows LA tracking benchmark





Full statistics now analysed ("full spill data" with dynamic distortion corrections). No significant difference is observed with respect to first analyses of the partial data (first 100-150 events in spill)

NA61 2008-9 upgrade

- New DAQ
  - 70Hz, but ToF not yet in DAQ stream
- new trigger logic (FPGA based) with trigger mixing
  - successfully tested during test run
  - adds multihit TDC to monitor pileup
- Increased ToF-F acceptance (p_{min} ~1 GeV/c-> 0.6 GeV/c) two new ToF modules under construction, hopefully on time
- New beam detectors (> acc. for wide beam)
  - tested during test run, some more work required
- 2 forward tracking chambers (bigger acc. at small θ), not tested during test run